Boundary singularities of solutions of semilinear elliptic equations with critical Hardy potentials

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ABSTRACT

We study the boundary behavior of positive functions \(u\) satisfying (E)\(\quad -\Delta u - \frac{\kappa}{d^2(x)} u + g(u) = 0\) in a bounded domain \(\Omega\) of \(\mathbb{R}^N\), where \(0 < \kappa \leq \frac{1}{4}\). \(g\) is a continuous nondecreasing function and \(d(\cdot)\) is the distance function to \(\partial \Omega\). We first construct the Martin kernel associated to the linear operator \(L_\kappa = -\Delta - \frac{\kappa}{d^2(x)}\) and give a general condition for solving equation (E) with any Radon measure \(\mu\) for boundary data. When \(g(u) = |u|^{q-1}u\) we show the existence of a critical exponent \(q_c = q_c(N, \kappa) > 1\) with the following properties: when \(0 < q < q_c\) any measure is eligible for solving (E) with \(\mu\) for boundary data; if \(q \geq q_c\), a necessary and sufficient condition is expressed in terms of the absolute continuity of \(\mu\) with respect to some Besov capacity. The same capacity characterizes the removable compact boundary sets. At end any positive solution \((F)\)\(\quad -\Delta u - \frac{\kappa}{d^2(x)} u + |u|^{q-1}u = 0\) with \(q > 1\) admits a boundary trace which is a positive outer regular Borel measure. When \(1 < q < q_c\) we prove that to any positive outer regular Borel measure we can associate a positive solutions of \((F)\) with this boundary trace.

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1. Introduction

Let \(\Omega\) be a bounded smooth domain in \(\mathbb{R}^N\) and \(d(x) = \text{dist}(x, \Omega^c)\). In this article we study several aspects of the nonlinear boundary value associated to the equation

\[
-\Delta u - \frac{\kappa}{d^2(x)} u + |u|^{p-1}u = 0 \quad \text{in } \Omega,
\]

where \(p > 1\). The study of the boundary trace of solutions of (1.1) is a natural framework for a general study of several nonlinear problems where the nonlinearity, the geometric properties of the domain and the coefficient \(\kappa\) interact. On this point of view, the case \(\kappa = 0\) has been thoroughly treated by Marcus and Véron (e.g. [23,24,26,25]) and the synthesis presented in [31] and [27]). The associated linear Schrödinger operator

\[
u \mapsto L_\kappa u := -\Delta u - \frac{\kappa}{d^2(x)} u
\]

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There is a critical value \( \kappa \) that \( L \) we show that \( V \) associated to the linear equation which was obtained by Marcus [20]. In a more general setting, Véron and Yarur [32] constructed a capacity theory = \( \kappa \) \( K \) see [2, Remark p. 523]. Furthermore the kernel Green kernel is always assumed in the sequel representation under the form \( \mathcal{L}_\kappa u = 0 \) in \( \Omega \). (1.3)

When \( \kappa < \frac{1}{4} \), Ancona proved that \( \mathcal{L}_\kappa \) is weakly coercive in \( H^1_0(\Omega) \). Thus any positive solution \( u \) of (1.3) admits a representation under the form

\[
 u(x) = \int_{\partial \Omega} K_{\mathcal{L}_\kappa}(x, \xi) d\mu(\xi) \quad \text{in } \Omega,
\]

(1.4)

see [2, Remark p. 523]. Furthermore the kernel \( K_{\mathcal{L}_\kappa}(x, \xi) \) with pole at \( \xi \) is unique up to a multiplication [2, Th 3]. When \( \kappa = \frac{1}{4} \), then \( \mathcal{L}_\kappa \) is no longer weakly coercive in \( H^1_0(\Omega) \) and Ancona’s results cannot be applied. Ancona’s representation theorem turned out to be the key ingredient of the full classification of positive solutions of

\[
 -\Delta u + u^\alpha = 0 \quad \text{in } \Omega,
\]

(1.5)

which was obtained by Marcus [20]. In a more general setting, Véron and Yarur [32] constructed a capacity theory associated to the linear equation

\[
 \mathcal{L}_\kappa u := -\Delta u + V(x)u = 0 \quad \text{in } \Omega,
\]

(1.6)

where the potential \( V \) is nonnegative and singular near \( \partial \Omega \). When \( V(x) := -\frac{\kappa}{d(x)} \) with \( \kappa > 0 \), \( V \) is called a Hardy potential.

There is a critical value \( \kappa = \frac{1}{4} \). If \( \kappa > \frac{1}{4} \), no positive solution of (1.3) exists. When \( 0 < \kappa \leq \frac{1}{4} \), there exist positive solutions, and the geometry of the domain plays a fundamental role in the study of the miter linear equation (1.3). We define the constant \( c_\Omega \) by

\[
 c_\Omega = \inf_{v \in H^1_0(\Omega) \setminus \{0\}} \frac{\int_{\Omega} |\nabla v|^2 \, dx}{\int_{\Omega} \frac{\kappa}{d(x)} \, dx}.
\]

(1.7)

It is known that \( 0 < c_\Omega \leq \frac{1}{4} \), and if \( \Omega \) is convex then \( c_\Omega = \frac{1}{4} \) (see [21] and [6] for related results). When \( 0 < \kappa \leq \frac{1}{4} \), which is always assumed in the sequel and \( -\Delta d \geq 0 \) in the sense of distributions, it is possible to define the first eigenvalue \( \lambda_\kappa \) of the operator \( \mathcal{L}_\kappa \). If we define the two fundamental exponents \( \alpha_+ \) and \( \alpha_- \) by

\[
 \alpha_+ = 1 + \sqrt{1 - 4\kappa} \quad \text{and} \quad \alpha_- = 1 - \sqrt{1 - 4\kappa},
\]

(1.8)

then the first eigenvalue is achieved by an eigenfunction \( \phi_\kappa \) which satisfies \( \phi_\kappa(x) \approx d^{\frac{\alpha_-}{2}}(x) \) as \( d(x) \to 0 \). Similarly, the Green kernel \( G_{\mathcal{L}_\kappa} \) associated to \( \mathcal{L}_\kappa \) inherits this type of boundary behavior since there holds

\[
 \frac{1}{C_\kappa} \min \left\{ \frac{1}{|x-y|^{N-2}}, \frac{d^{\frac{\alpha_-}{2}}(x) d^{\frac{\alpha_-}{2}}(y)}{|x-y|^{N+\alpha_-}} \right\} \leq G_{\mathcal{L}_\kappa}(x, y) \leq C_\kappa \min \left\{ \frac{1}{|x-y|^{N-2}}, \frac{d^{\frac{\alpha_-}{2}}(x) d^{\frac{\alpha_-}{2}}(y)}{|x-y|^{N+\alpha_-}} \right\}.
\]

(1.9)

We show that \( \mathcal{L}_\kappa \) satisfies the maximum principle in the sense that if \( u \in H^1_{0c} \cap C(\Omega) \) is a subsolution, i.e. \( \mathcal{L}_\kappa u \leq 0 \), such that

\[
 \begin{align*}
 \text{(i)} \quad & \limsup_{x \to y} \frac{u(x)}{d(x)} \leq 0 \quad \text{if } 0 < \kappa < \frac{1}{4}, \\
 \text{(ii)} \quad & \limsup_{x \to y} \frac{u(x)}{\sqrt{d(x)} |\ln d(x)|} \leq 0 \quad \text{if } \kappa = \frac{1}{4},
\end{align*}
\]

(1.10)

for all \( y \in \partial \Omega \), then \( u \leq 0 \). This result has to be compared with the result on the existence of positive subharmonic functions in \( \Omega \) given in [3, Theorem 2.3] which is associated to the maximum principle in neighborhood of \( \partial \Omega \) stated in [3, Lemma 2.4].

If \( \xi \in \partial \Omega \) and \( r > 0 \), we set \( \Delta_r(\xi) = \partial \Omega \cap B_r(\xi) \). We prove that a positive solution of \( \mathcal{L}_\kappa u = 0 \) which vanishes on a part of the boundary in the sense that

\[
 \begin{align*}
 \text{(i)} \quad & \lim_{x \to y} \frac{u(x)}{d(x)} = 0 \quad \forall y \in \Delta_r(\xi) \text{ if } 0 < \kappa < \frac{1}{4}, \\
 \text{(ii)} \quad & \lim_{x \to y} \frac{u(x)}{\sqrt{d(x)} |\ln d(x)|} = 0 \quad \forall y \in \Delta_r(\xi) \text{ if } \kappa = \frac{1}{4},
\end{align*}
\]

(1.11)

satisfies

\[
 \frac{u(x)}{\phi_\kappa(x)} \leq C_1 \frac{u(y)}{\phi_\kappa(y)} \quad \forall x, y \in \Delta_2(\xi),
\]

(1.12)

for some \( C_1 = C_1(\kappa, \Omega) > 0 \).
For any $h \in C(\partial \Omega)$ we construct the unique solution $v := v_h$ of the Dirichlet problem

$$L_x v = 0 \quad \text{in } \Omega,$$
$$v = h \quad \text{on } \partial \Omega,$$

(1.13)

noting that the boundary data $h$ is achieved in the sense that

$$\lim_{x \to y} \frac{u(x)}{d^{kr}(x)} = h(y) \quad \text{if } 0 < \kappa < \frac{1}{4} \quad \text{and} \quad \lim_{x \to y} \frac{u(x)}{\sqrt{d(x)|\ln d(x)|}} = h(y) \quad \text{if } \kappa = \frac{1}{4}.$$

Using this construction and estimates (1.10) we show the existence of the $L_x$-measure, which is a bounded Borel measure $\omega^x$ with the property that for any $h \in C(\partial \Omega)$, the above function $v_h$ satisfies

$$v_h(x) = \int_{\partial \Omega} h(y) d\omega^x(y).$$

(1.14)

Because of Harnack inequality, the measures $\omega^x$ and $\omega^z$ are mutually absolutely continuous for $x, z \in \Omega$, and for any $x \in \Omega$ we can define the Radon–Nikodym derivative

$$K(x, y) := \frac{d\omega^x}{d\omega^y}(y) \quad \text{for } \omega^y\text{-almost } y \in \partial \Omega.$$

(1.15)

There exists $r_0 := r_0(\Omega)$ such that for any $x \in \Omega$ verifying $d(x) \leq r_0$, there exists a unique $\xi = \xi_x \in \partial \Omega$ with the property that $d(x) = |x - \xi_x|$. If we denote by $\Omega'_0$ the set of $x \in \Omega$ such that $0 < d(x) < r_0$, the mapping $\Pi$ from $\Omega'_0$ to $[0, r_0] \times \partial \Omega$ defined by $\Pi(x) = (d(x), \xi_x)$ is a $C^1$ diffeomorphism. If $\xi \in \partial \Omega$ and $0 \leq r \leq r_0$, we set $x_r(\xi) = \Pi^{-1}(r, \xi)$. Let $W$ be defined in $\Omega$ by

$$W(x) = \begin{cases} d^{kr}(x) & \text{if } \kappa < \frac{1}{4}, \\
\sqrt{d(x)|\ln d(x)|} & \text{if } \kappa = \frac{1}{4}. \end{cases}$$

(1.16)

We prove that the $L_x$-harmonic measure can be equivalently defined by

$$\omega^x(E) = \inf \left\{ \psi : \psi \in C_+(\Omega), \quad \text{a.s. } \omega^x\text{-}superharmonic \text{ in } \Omega \text{ and } \liminf_{x \to \xi} \frac{\psi(x)}{W(x)} \geq 1 \right\},$$

(1.17)

on compact sets $E \subset \partial \Omega$ and then extended by regularity to Borel subsets of $\partial \Omega$.

The $L_x$-harmonic measure is connected to the Green kernel of $L_x$ by the following estimates:

**Theorem A.** There exists $C_3 := C_3(\Omega) > 0$ such that for any $r \in (0, r_0)$ and $\xi \in \partial \Omega$, there holds

$$\frac{1}{C_3} r^{N + \frac{\alpha - 2}{2}} G_{L_{x_r}(\xi), x} \leq \omega^x(\Delta_r(\xi))$$

$$\leq C_3 r^{N + \frac{\alpha - 2}{2}} G_{L_{x_r}(\xi), x} \quad \forall x \in \Omega \setminus B_{4r(\xi)},$$

(1.18)

if $0 < \kappa < \frac{1}{4}$, and

$$\frac{1}{C_3} r^{N - 2 + \frac{\alpha}{2}} |\ln d(x)| G_{L_{x_r}(\xi), x} \leq \omega^x(\Delta_r(\xi))$$

$$\leq C_3 r^{N - 2 + \frac{\alpha}{2}} |\ln d(x)| G_{L_{x_r}(\xi), x} \quad \forall x \in \Omega \setminus B_{4r(\xi)},$$

(1.19)

when $\kappa = \frac{1}{4}$.

As a consequence $\omega^x$ has the doubling property. The previous estimates allow to construct a kernel function of $L_x$ in $\Omega$, prove its uniqueness up to an homothety. When normalized, the kernel function denoted by $K_{L_{x}}$ is the Martin kernel, defined by

$$K_{L_{x}}(x, \xi) = \lim_{x \to \xi} \frac{G_{L_{x}(x, y)}}{G_{L_{x}(x, x_0)}} \quad \forall \xi \in \partial \Omega,$$

(1.20)

for some $x_0 \in \Omega$. Thank to this kernel we can represent any positive $L_x$-harmonic function $u$ by mean of a Poisson type formula which endows the form

$$u(x) = \int_{\partial \Omega} K_{L_{x}}(x, \xi) d\mu(\xi)$$

(1.21)

for some unique positive Radon measure $\mu$ on $\partial \Omega$. The measure $\mu$ is called the boundary trace of $u$. Furthermore $K_{L_{x}}$ satisfies the following two-side estimates:
Theorem B. There exists $C_3 := C_3(\Omega, \kappa) > 0$ such that for any $(x, \xi) \in \Omega \times \partial \Omega$ there holds
\[
\frac{1}{C_3} \frac{d^{\frac{u}{\alpha}}}{|x - \xi|^{N+\alpha+2}} \leq K_{L_x}(x, \xi) \leq C_3 \frac{d^{\frac{u}{\alpha}}}{|x - \xi|^{N+\alpha+2}}. \tag{1.22}
\]

In Sections 3–5 and Appendix of this paper we develop the study of the semilinear equation (E) and emphasize the particular case of Eq. (1.1). With the help of the previous estimates we adapt the approach developed in [16] and generalized in [31] to prove the existence of weak solutions to the nonlinear boundary value problem
\[
-\Delta u - \frac{\kappa}{d^2(x)} u + g(u) = v \quad \text{in } \Omega
\]
\[
u = \mu \quad \text{in } \partial \Omega, \tag{1.23}
\]
where $g$ is a continuous nondecreasing function such that $g(0) \geq 0$ and $v$ and $\mu$ are Radon measures on $\Omega$ and $\partial \Omega$ respectively. We define the class $X_\epsilon(\Omega)$ of test functions by
\[
X_\epsilon(\Omega) = \left\{ \eta \in L^2(\Omega) \text{ s.t. } \nabla \left( d^{\frac{u}{\alpha}} \eta \right) \in L^2(\Omega) \text{ and } \phi_x^{-1}L_x \eta \in L^\infty(\Omega) \right\}, \tag{1.24}
\]
and we prove

Theorem C. Assume $g$ satisfies
\[
\int_1^\infty (g(s) + |g(-s)|) s^{-\frac{N-1}{N+\alpha+2}} ds < \infty. \tag{1.25}
\]
Then for any Radon measures $\nu$ on $\Omega$ and such that $\int_\Omega \phi_x d|\mu| < \infty$ and $\mu$ on $\partial \Omega$ there exists a unique $u \in L^1(\Omega)$ such that $g(u) \in L^1(\Omega)$ which satisfies
\[
\int_\Omega (uL_x \eta + g(u) \eta) \, dx = \int_\Omega (\eta \, dv + [K_{L_x} \mu] L_x \eta) \, dx \quad \forall \eta \in X(\Omega). \tag{1.26}
\]

When $g(r) = |r|^{q-1} r$ the critical value is $q_c = \frac{N+\alpha}{N+\frac{\alpha}{2}}$ and (1.25) is satisfied for $0 \leq q < q_c$ (the subcritical range). In this range of values of $q$, existence and uniqueness of a solution to
\[
-\Delta u - \frac{\kappa}{d^2(x)} u + |u|^{q-1} u = 0 \quad \text{in } \Omega
\]
\[
u = \mu \quad \text{in } \partial \Omega, \tag{1.27}
\]
has been recently obtained by Marcus and Nguyen [22]. However, when $q \geq q_c$ not all the Radon measures are eligible for solving problem (1.27).

We prove the following result in the statement of which $C^{\frac{r(N-1)}{2-2\mu\alpha}}(E)$ denotes the Besov capacity associated to the Besov space $B^{\frac{r(N-1)}{2-2\mu\alpha}}(\mathbb{R}^N)$.

Theorem D. Assume $q \geq q_c$ and $\mu$ is a positive Radon measure on $\partial \Omega$. Then problem (1.27) admits a weak solution if and only if $\mu$ vanishes on Borel sets $E \subset \partial \Omega$ such that $C^{\frac{r(N-1)}{2-2\mu\alpha}}(E) = 0$.

Note that a special case of this result is proved in [22] when $\mu = \delta_k$ for a boundary point and $q \geq q_c$. In that case $\delta_k$ does not vanish on $\{a\}$ although $C^{\frac{r(N-1)}{2-2\mu\alpha}}(\{a\}) = 0$.

This capacity plays a fundamental for characterizing the removable compact boundary sets which can only exist in the supercritical range $q \geq q_c$.

Theorem E. Assume $q \geq q_c$ and $K \subset \partial \Omega$ is compact. Then any function $u \in C(\Omega \setminus K)$ which satisfies
\[
-\Delta u - \frac{\kappa}{d^2(x)} u + |u|^{q-1} u = 0 \quad \text{in } \Omega
\]
\[
u = 0 \quad \text{in } \partial \Omega \setminus K, \tag{1.28}
\]
is identically zero if and only if $C^{\frac{r(N-1)}{2-2\mu\alpha}}(K) = 0$. 

Theorem H. Assume where
\( \partial q \) vanishes of \( \partial \). We prove that if \( q \) < \( q_1 \) or there exist \( \epsilon_0 > 0 \) and a positive Radon measure \( \lambda \) on \( \partial \Omega \cap B_{\epsilon_0}(a) \) such that for any \( Z \in C(\overline{\Omega}) \) with support in \( \Omega \cup (\partial \Omega \cap B_{\epsilon_0}(a)) \), there holds
\[
\lim_{\delta \to 0} \int_{\Sigma(\partial \Omega \cap B_{\epsilon_0}(a))} Zd\omega = \int_{\partial \Omega \cap B_{\epsilon_0}(a)} Zd\lambda.
\] (1.30)

The set of points \( a \in \partial \Omega \) such that (i) (resp. (ii)) holds is closed (resp. relatively open) and denoted by \( \delta_a \) (resp \( R_a \)).

Theorem G. Assume \( u \) is a positive solution of (1.1) such that \( u \geq u_{\infty,a} \).

In order to go further in the study of boundary singularities, we construct separable solutions of (1.1) in \( \Omega_{1-2} = \{ x = (x', x_N) : x_N > 0 \} = \{ x, \sigma \in \Omega_+ \times S_{N-1} \} \) which vanish on \( \partial \Omega_{-1} \setminus \{ 0 \} \) under the form \( u(r, \sigma) = r^{-\frac{2}{N-1}} + |\sigma|^{q-1} \). They are solutions of
\[
-\Delta_{S_{N-1}} \omega - \ell_{q,N} \omega - \frac{\kappa}{e_N \cdot \sigma} \omega + |\sigma|^{q-1} \omega = 0 \quad \text{in } S_{N-1} \setminus \{ 0 \},
\]
where \( \Delta_{S_{N-1}} \) is the Laplace–Beltrami operator, \( e_N \) the unit vector pointing toward the North pole and \( \ell_{q,N} \) a positive constant.

We prove that if \( q < q_c \), then problem (1.32) admits a unique positive solution \( \omega_k \) while no such solution exists if \( q \geq q_c \). To this phenomenon is associated a result of classification of the positive solutions of (1.1) in \( \Omega \) which vanishes of \( \partial \Omega \setminus \{ 0 \} \) (here we assume that \( 0 \in \partial \Omega \) and that the tangent hyperplane to \( \partial \Omega \) at \( 0 \) is \( \{ x : x \cdot e_N = 0 \} \), and that there exists \( r_0 > 0 \) such that \( B_{r_0}(r_0 e_N) \subset \Omega \) and \( \Omega \cap B_{r_0}(r_0 e_N) \subset \{ x : x \cdot e_N \geq 0 \} \) and \( d(r_0 e_N) = |r_0 e_N| = r_0 \).

Theorem F. Let \( u \) be a positive solution of (1.1) in \( \Omega \) and \( a \in \partial \Omega \). Then
(i) either \( u \geq u_{\infty,a} \) and
\[
\lim_{r \to 0} r^{\frac{2}{N-1}} u(r, a) = \omega_k
\] (1.33)
locally uniformly in \( S_{N-1} \),
(ii) or there exists \( k \geq 0 \) such that \( u = u_{b_k} \) and
\[
u(x) = kK_{b_k}(x, a)(1 + o(1)) \quad \text{as } x \to 0.
\] (1.34)

If \( q < q_c \), we prove that to any couple \((F, \mu)\) where \( F \) is a closed subset of \( \partial \Omega \) and \( \mu \) a positive Radon measure on \( \partial \), we can associate a positive solution \( u \) of (1.1) in \( \Omega \) with the property that \( Tr_{\partial \Omega}(u) = (F, \mu) \). The construction is based upon the existence of barrier functions which allow to prove local a priori estimates that is satisfied by any positive solution with boundary trace \((F, 0)\). The delicate proof of the existence of this barrier is presented in Appendix A.1. A priori estimates which follow from the barrier method are presented in Appendix A.2. In Appendix A.3 we develop some regularity results based upon Moser’s iterative scheme adapted to the framework of the Hardy operator.

The results presented here are announced in [15].
2. The linear operator $\mathcal{L}_\kappa = -\Delta - \frac{\kappa}{d^2(x)}$

Throughout this article, $c_j$ (j = 1, 2, . . .) denote positive constants the value of which may change from one occurrence to another. The notation $\kappa$ is reserved to the value of the coefficient of the Hardy potential.

2.1. Classical results on Hardy’s inequality and the operator $\mathcal{L}_\kappa$

We first recall some known results concerning Hardy’s inequalities and the associated eigenvalue problem (see [11,14]).

1—The constant $c_4$ defined in (1.7) has value in $(0, \frac{1}{4}]$. If $\Omega$ is convex or if the function $d$ is super-harmonic then $c_4 = \frac{1}{4}$.

Moreover this equality is verified if and only if there exists no minimizer to the problem (1.7) [21]. For any $\kappa \in (0, \frac{1}{4}]$ there exists

$$\inf \left\{ \int_\Omega \left( |\nabla u|^2 - \frac{\kappa}{d^2} u^2 \right) \, dx : \int_\Omega u^2 \, dx = 1 \right\} = \lambda_0 > -\infty. \quad (2.1)$$

Furthermore $\lambda_0 > 0$ if $\kappa < c_4$ or if $\kappa \leq \frac{1}{4}$ and $d$ is a superharmonic function in $\Omega$. (See [7].)

2—If $0 < \kappa < \frac{1}{4}$ the minimizer $\phi_0$ of (2.1) belongs to the space $H^1_0(\Omega)$ and it satisfies

$$\phi_0 \approx d^{-\frac{1}{2}}(x), \quad (2.2)$$

where $\alpha_+$ (as well as $\alpha_-$) are defined by (1.8).

3—If $\kappa = \frac{1}{4}$ there is no minimizer in $H^1_0(\Omega)$, but there exists a non-negative function $\phi_\kappa \in H^1_{loc}(\Omega)$ such that

$$\phi_\kappa \approx d^{\frac{1}{2}}(x), \quad (2.3)$$

and it solves

$$-\Delta u - \frac{1}{4d^2} u = \lambda_\kappa u \quad \text{in} \quad \Omega \ \text{in the sense of distributions.}$$

In addition, the function $\psi_\kappa = d^{-\frac{1}{2}}\phi_\kappa$ belongs to $H^1_0(\Omega; d(x)\,dx)$.

4—Let $H^1_0(\Omega, d^\alpha(x)\,dx)$ denote the closure of $C_0^\infty(\Omega)$ functions under the norm

$$\|u\|^2_{H^1_0(\Omega, d^\alpha(x)\,dx)} = \int_\Omega |\nabla u|^2 d^\alpha(x) \, dx + \int_\Omega |u|^2 d^\alpha(x) \, dx. \quad (2.4)$$

If $\alpha \geq 1$ there holds [14, Th. 2.11]

$$H^1_0(\Omega, d^\alpha(x)\,dx) = H^1(\Omega, d^\alpha(x)\,dx) \quad \forall \alpha \geq 1. \quad (2.5)$$

5—Let $0 < \kappa \leq c_4$. Let $H_\kappa(\Omega)$ be the subset of functions of $H^1_{loc}(\Omega)$ satisfying

$$\int_\Omega \left( |\nabla \phi|^2 - \frac{\kappa}{d^2} \phi^2 \right) \, dx < \infty. \quad (2.6)$$

Then the mapping

$$\phi \mapsto \left( \int_\Omega \left( |\nabla \phi|^2 - \frac{\kappa}{d^2} \phi^2 \right) \, dx \right)^{\frac{1}{2}} \quad (2.7)$$

is a norm on $H_\kappa(\Omega)$. The closure $W_\kappa(\Omega)$ of $C_0^\infty(\Omega)$ into $H_\kappa(\Omega)$ satisfies

$$W_\kappa(\Omega) = H^1_0(\Omega) \quad \forall \ 0 < \kappa < c_4 \quad \text{and} \quad W_\frac{1}{4}(\Omega) \subset W^{1,q}_0(\Omega) \quad \text{if} \quad \lambda_\frac{1}{4} > 0 \ \forall 1 \leq q < 2, \quad (2.8)$$

see [4, Th B]. As a consequence $W_\kappa(\Omega)$ is compactly embedded into $L^r(\Omega)$ for any $r \in [1, 2^*)$.

6—Let $\alpha > 0$ and $\Omega \subset \mathbb{R}^2$ be a bounded domain. There exists $c^* > 0$ depending on diam$(\Omega)$, $N$ and $\alpha$ such that for any $v \in C_0^\infty(\Omega)$

$$\left( \int_\Omega |v|^{2(N+\alpha)} d^\alpha \, dx \right)^{\frac{N+\alpha-2}{N+\alpha}} \leq c^* \int_\Omega |\nabla v|^2 d^\alpha \, dx. \quad (2.9)$$

For a proof see [14, Th. 2.9].

The boundary behavior of the first eigenfunction yields a two-side similar estimate of the Green kernel for Schrödinger operators with a general Hardy type potentials [14, Corollary 1.9].
Proposition 2.1. Consider the operator \( E := -\Delta - V \), in \( \Omega \) where \( V = V_1 + V_2 \), with
\[
|V_1| \leq \frac{1}{4d^2(x)} \quad \text{and} \quad V_2 \in L^p(\Omega), \quad p > \frac{N}{2}.
\]
We also assume that
\[
0 < \lambda_1 := \inf_{u \in H^1_0(\Omega)} \frac{\int_\Omega (|\nabla u|^2 - Vu^2) \, dx}{\int_\Omega u^2 \, dx},
\]
and that to \( \lambda_1 \) is associated a positive eigenfunction \( \phi_1 \). If, for some \( \alpha \geq 1 \) and \( C_1, C_2 > 0 \), there holds
\[
c_1 d^{\frac{\alpha}{2}}(x) \leq \phi_1(x) \leq c_2 d^{\frac{\alpha}{2}}(x) \quad \forall x \in \Omega,
\]
then the Green kernel \( G^\Omega_{e_2} \) associated to \( E \) in \( \Omega \) satisfies
\[
G^\Omega_{e_2}(x, y) \approx c_3 \min \left( \frac{1}{|x-y|^{N-2}}, \frac{d^{\frac{\alpha}{2}}(x)d^{\frac{\alpha}{2}}(y)}{|x-y|^{N+\alpha-2}} \right). \tag{2.10}
\]

Next we define the sets \( \Omega_\delta, \Omega'_\delta \) and \( \Sigma_\delta \) by
\[
\Omega_\delta = \{ x \in \Omega : d(x) < \delta \}, \quad \Omega'_\delta = \{ x \in \Omega : d(x) > \delta \} \quad \text{and} \quad \Sigma_\delta = \{ x \in \Omega : d(x) = \delta \}. \tag{2.11}
\]

Definition 2.2. Let \( G \subset \Omega \) be open and let \( H^1_0(G) \) denote the subspace of \( H^1(G) \) of functions with compact support in \( G \). A function \( h \in W^{1,1}_0(G) \) is \( \mathcal{L}_\kappa \)-harmonic in \( G \) if
\[
\int_G \nabla h \cdot \nabla \psi \, dx - \kappa \int_G \frac{1}{d^2(x)} \psi \, dx = 0 \quad \forall \psi \in H^1_0(G).
\]
A function \( h \in H^1_0(G) \cap C(G) \) is \( \mathcal{L}_\kappa \)-subharmonic in \( G \) if
\[
\int_G \nabla h \cdot \nabla \psi \, dx - \kappa \int_G \frac{1}{d^2(x)} \psi \, dx \leq 0 \quad \forall \psi \in H^1_0(G), \, \psi \geq 0.
\]
We say that \( h \) is a local \( \mathcal{L}_\kappa \)-subharmonic function if there exists \( \delta > 0 \) such that \( h \in H^1_0(\Omega_\delta) \cap C(\Omega_\delta) \) is \( \mathcal{L}_\kappa \)-subharmonic in \( \Omega_\delta \). Similarly, (local) \( \mathcal{L}_\kappa \)-superharmonics \( h \) are defined with "\( \geq \)" in the above inequality.

Note that \( \mathcal{L}_\kappa \)-harmonic functions are \( C^2 \) in \( G \) by standard elliptic equations regularity theory. The Phragmen–Lindelöf principle yields the following alternative [3, Theorem 2.6].

Proposition 2.3. Let \( \kappa \leq \frac{1}{4} \). If \( h \) is a local \( \mathcal{L}_\kappa \)-subharmonic function, then the following alternative holds:

(i) either for every local positive \( \mathcal{L}_\kappa \)-superharmonic function \( H \)
\[
\limsup_{d(x) \to 0} \frac{h(x)}{H(x)} > 0.
\] \( \tag{2.12} \)

(ii) or for every local positive \( \mathcal{L}_\kappa \)-superharmonic function \( H \)
\[
\limsup_{d(x) \to 0} \frac{h(x)}{H(x)} < \infty.
\] \( \tag{2.13} \)

Definition 2.4. If a local \( \mathcal{L}_\kappa \)-subharmonic function \( h \) satisfies (i) (resp. (ii)) it is called a large \( \mathcal{L}_\kappa \)-subharmonic (resp. a small \( \mathcal{L}_\kappa \)-subharmonic).

The next statement is [3, Theorem 2.9].

Proposition 2.5. Let \( h \) be a small local \( \mathcal{L}_\kappa \)-subharmonic of \( \mathcal{L}_\kappa \).

(i) If \( \kappa < \frac{1}{4} \), then the following alternative holds:
\[
\text{either } \limsup_{x \to \partial \Omega} \frac{h(x)}{(d(x))^\frac{\alpha}{2}} > 0 \quad \text{or} \quad \limsup_{x \to \partial \Omega} \frac{h(x)}{(d(x))^\frac{\alpha}{2}} < \infty.
\]
(ii) If \( \kappa = \frac{1}{4} \), then the following alternative holds:

\[
\limsup_{\kappa \to 0^+} \frac{h(x)}{(d(x))^{\frac{1}{2}} \log \left( \frac{1}{\kappa} \right)} > 0 \quad \text{or} \quad \limsup_{\kappa \to 0^+} \frac{h(x)}{(d(x))^{\frac{1}{2}}} < \infty.
\]

**Definition 2.6.** Let \( f_0 \in L^2_{\text{loc}}(\Omega) \). We say that a function \( u \in H^1_\text{loc}(\Omega) \) is a solution of

\[
\mathcal{L} u = f_0 \quad \text{in} \quad \Omega,
\]

if there holds

\[
\int_\Omega \nabla u \cdot \nabla \psi \, dx - \kappa \int_\Omega \frac{1}{d^2(x)} \, u \psi \, dx = \int_\Omega f_0 \psi \, dx \quad \forall \psi \in C_0^\infty(\Omega).
\] (2.14)

\[
\int_\Omega \nabla u \cdot \nabla \psi \, dx - \kappa \int_\Omega \frac{1}{d^2(x)} \, u \psi \, dx = \int_\Omega f_0 \psi \, dx \quad \forall \psi \in C_0^\infty(\Omega).
\] (2.15)

### 2.2. Preliminaries

In this part we study some regularity properties of solutions of linear equations involving \( \mathcal{L}_\kappa \).

**Lemma 2.7.** (i) If \( \alpha > 1 \) and \( d^{-\frac{\alpha}{2}} u \in H^1(\Omega, d^\alpha(x) \, dx) \), then \( u \in H^1_0(\Omega) \).

(ii) If \( \alpha = 1 \) and \( d^{-\frac{1}{2}} u \in H^1(\Omega, d(x) \, dx) \), then \( u \in W^{1,p}_0(\Omega) \), \( p < 2 \).

**Proof.** There exists \( \beta_0 > 0 \) such that \( d \in C^2(\overline{\Omega_{\beta_0}}) \) and set \( v = d^\frac{\alpha}{2} v \). In the two cases (i)–(ii), our assumptions imply

\[
u \in L^2(\Omega) \quad \text{and} \quad \nabla u - \frac{\alpha}{2} ud^{-1} \nabla d \in L^2(\Omega).
\] (2.16)

(i) Since \( v \in H^1(\Omega, d^\alpha(x) \, dx) \), by (2.5) there exists a sequence \( v_n \in C_0^\infty(\Omega) \) such that \( v_n \to v \) in \( H^1(\Omega, d^\alpha(x) \, dx) \).

Set \( u_n = d^\alpha v_n \). Let \( 0 < \beta \leq \frac{\beta_0}{2} \) and \( \psi_\beta \) be a cut of function such that \( \psi_\beta = 0 \) in \( \Omega_{\beta} \) and \( \psi_\beta = 1 \) in \( \Omega_{\frac{\beta_0}{2}} \). Then

\[
u_n = d^\frac{\alpha}{2} (\psi_\beta v_n + (1 - \psi_\beta) v_n).
\]

Thus it is enough to prove that \( \tilde{u}_n = d^\frac{\alpha}{2} \psi_\beta v_n \) remains bounded in \( H^1(\Omega) \) independently of \( n \).

Set \( \nu_n = \psi_\beta v_n \), then

\[
\int_\Omega |\nabla \tilde{u}_n|^2 \, dx = \int_\Omega |\nabla v_n|^2 \, dx \leq c_4 \left( \int_{\Omega_{\beta}} d^\alpha |\nabla v_n|^2 \, dx + \int_{\Omega_{\beta}} d^{\alpha - 2} w_n^2 \, dx \right).
\]

Note that \( \alpha - 2 > -1 \). Now

\[
\int_{\Omega_{\beta}} d^{\alpha - 2} w_n^2 \, dx = \frac{1}{\alpha - 1} \int_{\Omega_{\beta}} w_n^2 \, dx - \frac{1}{\alpha - 1} \int_{\Omega_{\beta}} d^{\alpha - 1} \Delta d \, w_n^2 \, dx.
\]

Now since \( |\Delta d(x)| < c_5 \), \( \forall x \in \Omega_{\beta_0} \), we have

\[
\left| \frac{1}{\alpha - 1} \int_{\Omega_{\beta}} d^{\alpha - 1} \Delta d \, w_n^2 \, dx \right| \leq \frac{c_5 \beta_0^2}{\alpha - 1} \int_{\Omega_{\beta}} w_n^2 \, dx.
\]

Also

\[
\int_{\Omega_{\beta}} w_n^2 \, dx \leq 2 \int_{\Omega_{\beta}} w_n d^\frac{\alpha}{2} d^\frac{\alpha}{2} \nabla d \cdot \nabla w_n \, dx \leq c_6 \int_{\Omega_{\beta}} d^\alpha |\nabla v_n|^2 \, dx + \delta \int_{\Omega_{\beta}} d^{\alpha - 2} w_n^2 \, dx,
\]

where \( c_6 = c_6(\delta) > 0 \). The result follows in this case, if we choose \( \delta \) small enough and then let \( n \to \infty \).

(ii) By the same calculations we have

\[
\int_\Omega d^{-\frac{\alpha}{2}} |w_n|^p \, dx \leq c_7 \int_{\Omega_{\beta}} d^\frac{\alpha}{2} |\nabla w_n|^p \, dx \leq c_7 \left( \int_\Omega d(x) \, dx \right)^\frac{\alpha}{2} \int_{\Omega_{\beta}} d|\nabla w_n|^2 \, dx.
\]

In the following statement we prove regularity up to the boundary for the function \( \frac{u}{d^\kappa} \).
Proposition 2.8. Let \( f_0 \in L^2(\Omega) \). Then there exists a unique \( u \in H^1_{\text{loc}}(\Omega) \) such that \( \phi_x^{-1} u \in H^1(\Omega, d^r(\phi_x^2)dx) \), satisfying (2.14). Furthermore, if \( f_1 := \frac{f_0}{\phi_x} \in L^q(\Omega, \phi_x^2 dx) \), \( q > \frac{N + \kappa}{2} \), then there exists \( 0 < \beta < 1 \) such that

\[
\sup_{x, y \in \Omega, x \neq y} |x - y|^{-\beta} \left| \frac{u(x)}{\phi_x(x)} - \frac{u(y)}{\phi_x(y)} \right| < c_8 \| f_1 \|_{L^q(\Omega, \phi_x^2 dx)}.
\] (2.17)

Proof. If there exists a solution \( u \), then \( \psi = \frac{u}{\phi_x} \) satisfies

\[
-\phi_x^{-2} \text{div}(\phi_x^2 \nabla \psi) + \lambda_x \psi = \phi_x^{-1} f_0,
\] (2.18)

and we recall that \( \phi_x(x) \approx d^r_+ (x) \). We endow the space \( H^1(\Omega, \phi_x^2 dx) \) with the inner product

\[
\langle a, b \rangle = \int_{\Omega} (\nabla a \cdot \nabla b + \lambda_x ab) \phi_x^2 dx.
\]

By a solution \( \psi \) of (2.18) we mean that \( \psi \in H^1_0(\Omega, \phi_x^2 dx) \) satisfies

\[
\langle \nabla \psi, \nabla \zeta \rangle = \int_{\Omega} \nabla \psi \cdot \nabla \zeta \phi_x^2 dx + \lambda_x \int_{\Omega} \psi \phi_x^2 dx = \int_{\Omega} f_0 \phi_x dx \quad \forall \zeta \in H^1_0(\Omega, \phi_x^2 dx).
\] (2.19)

By Riesz’s representation theorem we derive the existence and uniqueness of the solution in this space. Since \( H^1(\Omega, \phi_x^2 dx) = H^1_0(\Omega, \phi_x^2 dx) \) by [14, Th. 2.11], any weak solution \( u \) of (2.14) such that \( \phi_x^{-1} u \in H^1(\Omega, \phi_x^2 dx) \) is obtained by the above method.

Finally if \( f_0 \in L^q(\Omega, \phi_x^2 dx) \), where \( q > \frac{N + \kappa}{2} \), thanks to (2.9) we can prove the estimate

\[
\| \psi \|_{L^\infty(\Omega)} \leq c_8 \| f_0 \|_{L^q(\Omega, \phi_x^2 dx)},
\] (2.20)

where \( c_8 = c_8(\kappa, \kappa, \kappa, q) \). Then we can apply the Moser iteration (see Appendix A.3) to derive the Hölder regularity up to the boundary. \( \Box \)

In the next results we make more precise the rate of convergence of a solution of (2.14) to its boundary value.

Proposition 2.9. Assume \( \kappa < \frac{1}{4} \). If \( f_0 \in L^2(\Omega) \) and \( h \in H^1(\Omega) \) there exists a unique weak solution \( u \) of (2.14) belonging to \( H^1_{\text{loc}}(\Omega) \) and such that \( d^{a+} (u - d^r h) \in H^1(\Omega, d^{r+}(\phi_x^2)dx) \). Furthermore, if \( f_1 := \frac{f_0}{\phi_x} \in L^q(\Omega, \phi_x^2 dx) \), \( q > \frac{N + \kappa}{2} \), and \( h \in C^2(\Omega) \), then there exists \( 0 < \beta < 1 \) with the property that

\[
\lim_{x \to \alpha \gamma} u(x) = h(y) \quad \forall y \in \partial \Omega,
\]
uniformly with respect to \( y \),

\[
\left\| \frac{u}{d^r} \right\|_{L^\infty(\Omega)} \leq c_9 \left( \| h \|_{C^2(\gamma)} + \| f_1 \|_{L^q(\Omega, \phi_x^2 dx)} \right),
\]

and

\[
\sup_{x, y \in \Omega, x \neq y} |x - y|^{-\beta} \left| \frac{u(x)}{(d(x))^r} - \frac{u(y)}{(d(y))^r} \right| \leq c_{10} \left( \| h \|_{C^2(\gamma)} + \| f_1 \|_{L^q(\Omega, \phi_x^2 dx)} \right),
\] (2.21)

with \( c_9 \) and \( c_{10} \) depending on \( \Omega, N, q, \) and \( \kappa \).

Remark. By Lemma 2.7 we already know that \( u - d^r h \in H^1_0(\Omega) \).

Proof. Let \( \beta \leq \beta_0 \) and \( \eta \in C^2(\Omega) \) be a function such that \( \eta = d^r(\phi_x^2)(x) \) in \( \Omega_\beta \) and \( \eta(x) > c > 0 \), if \( x \in \Omega_\beta \). We set \( u = \phi_x v + \eta h \). Then \( \phi_x v \) is a weak solution of

\[
-\frac{\text{div}(\phi_x^2 \nabla u)}{\phi_x^2} + \lambda_x v = \frac{1}{\phi_x} \left( f_0 + \left( \Delta \eta + \kappa \frac{\eta}{d^2} \right) h + 2 \nabla \eta \cdot \nabla h + \eta \Delta h \right),
\] (2.22)

in the sense that

\[
\int_{\Omega} \nabla u \cdot \nabla \psi \phi_x^2 dx + \lambda_x \int_{\Omega} u \psi \phi_x^2 dx = \int_{\Omega} \left( f_0 + \left( \Delta \eta + \kappa \frac{\eta}{d^2} \right) h + 2 \nabla \eta \cdot \nabla h \right) \psi \phi_x dx
\]

\[
- \int_{\Omega} \nabla h \cdot \nabla (\eta \phi_x) dx \quad \forall \psi \in C_0^\infty(\Omega).
\] (2.23)
Let $\psi \in \mathcal{C}_0^\infty(\Omega_\rho)$. By an argument similar to the one in the proof of Lemma 2.7, we have
\[
\int_\Omega \psi^2 \, dx = \int_{\Omega_\rho} \psi^2 \, dx = \int_{\Omega_\rho} \text{div}(d\nabla d) \left| \psi \right|^2 \, dx - \int_{\Omega_\rho} d\Delta \left| \psi \right|^2 \, dx,
\]
which implies
\[
\int_{\Omega_\rho} \psi^2 \, dx \leq c_{10} \int_{\Omega_\rho} d^2 \left| \nabla \psi \right|^2 \, dx \leq c_{11} \int_{\Omega_\rho} d^{\alpha^+} \left| \nabla \psi \right|^2 \, dx.
\]
Now
\[
\left| \int_{\Omega_\rho} \left( (\Delta \eta + \kappa \frac{\eta}{d^2}) + 2 \nabla \eta \cdot (\nabla h) \right) \psi \phi_\xi \, dx \right| \leq c_{12} \int_{\Omega_\rho} \psi^2 \, dx,
\]
and
\[
\int_{\Omega_\rho} \left| \nabla \phi_\xi \right| \, dx \leq c_{13} \left( \int_{\Omega_\rho} \left| \nabla h \right|^2 \, dx + \int_{\Omega_\rho} d^{\alpha^+} \left| \nabla \psi \right|^2 \, dx + \int_{\Omega_\rho} \psi^2 \, dx \right).
\]
By (2.24) we can take $\psi \in H^1(\Omega, d^{\alpha^+}(x))$ for test function. Thus we derive that there exists a weak solution $v \in H^1(\Omega, d^{\alpha^+}(x))$ of (2.23).

To prove (2.21) we first obtain that if $\psi \in \mathcal{C}_0^\infty(\Omega_\rho)$
\[
\int_\Omega \psi \, dx = -\int_{\Omega_\rho} \nabla d \cdot \nabla \psi \, dx - \int_{\Omega_\rho} \Delta d \psi \, dx.
\]
Since
\[
\left| \int_\Omega \left( \left( (\Delta \eta + \kappa \frac{\eta}{d^2}) + 2 \nabla \eta \cdot (\nabla h) \right) \psi \phi_\xi \right) \, dx \right| \leq c_{14} \left\| h \right\|_{L^2(\Omega)} \int_\Omega \left| \psi \right| \, dx \leq \frac{1}{2} \int_{\Omega_\rho} d^{\alpha^+} \left| \nabla \psi \right|^2 \, dx + c_{15}(\Omega, \kappa) \left\| h \right\|_{L^2(\Omega)}^2,
\]
we use again (2.9) and Moser’s iterative scheme as in Proposition 2.8, and we obtain
\[
\left\| v \right\|_{L^\infty(\Omega)} \leq c_9 \left( \left\| h \right\|_{L^2(\Omega)} + \left\| f_0 \right\|_{L^2(\Omega, \phi_\xi^2 \, dx)} \right),
\]
where $c_9 = c_9(\Omega, q, \kappa) > 0$. From inequality it follows that $v$ is Hölder continuous up to the boundary and the uniform convergence holds. \(\Box\)

**Proposition 2.10.** Assume $\kappa = \frac{1}{q}$. If $f_0 \in L^2(\Omega)$ and $h \in H^1(\Omega)$, there exists a unique function $u$ in $H^1_{\text{loc}}(\Omega)$ weak solution of
\[
\mathcal{L}_2 u = f_0
\]
verifying $d^{-\frac{1}{2}} (u - d^\frac{1}{2} \log d) \in H^1(\Omega, \phi_\xi \, dx)$. Furthermore, if $f_1 := \frac{f_0}{q} \in L^q(\Omega)$, $q > \frac{n+1}{2}$ and $h \in C^2(\overline{\Omega})$, then there exists $0 < \beta < 1$ such that
\[
\lim_{x \in \Omega, x \to y \in \partial \Omega} \frac{u}{d^\beta \left| \log d \right|} = h(y) \quad \forall y \in \partial \Omega,
\]
uniformly with respect to $y$,
\[
\left\| \frac{u}{\sqrt{d} \left| \log d \right|} \right\|_{L^\infty(\Omega)} \leq c_{16} \left( \left\| h \right\|_{C^2(\overline{\Omega})} + \left\| f_1 \right\|_{L^q(\Omega, \phi_\xi^2 \, dx)} \right),
\]
where $D_0 = 2 \sup_{x \in \Omega} d(x)$. Finally there holds
\[
\left| x - y \right|^{-\beta} \frac{u(x)}{\sqrt{d(x)} \left| \log \frac{d(x)}{D_0} \right|} - \frac{u(y)}{\sqrt{d(y)} \left| \log \frac{d(y)}{D_0} \right|} \leq c_{17} \left( \left\| h \right\|_{C^2(\overline{\Omega})} + \left\| f_1 \right\|_{L^q(\Omega, \phi_\xi^2 \, dx)} \right),
\]
(2.25)
Proposition 2.11. Let \( \delta > 0 \) be small enough, \( \xi \in \partial \Omega \) and \( u \in H^1_\text{loc}(B_\delta(\xi) \cap \Omega) \cap C(B_\delta(\xi) \cap \overline{\Omega}) \) be a positive \( L^2 \)-harmonic function in \( B_\delta(\xi) \cap \Omega \) vanishing on \( \partial \Omega \cap B_\delta(\xi) \) in the sense that
\[
\lim_{\text{dist}(x,K) \to 0} \frac{u(x)}{d^2(x)} = 0 \quad \forall K \subset \partial \Omega \cap B_\delta(\xi), \ K \text{ compact}.
\] (2.26)

Then there exists a constant \( c_{18} = c_{18}(N, \Omega, \kappa) > 0 \) such that
\[
\frac{u(x)}{\phi^2_\frac{1}{4}(x)} \leq c_{18} \frac{u(y)}{\phi^2_\frac{1}{4}(y)} \quad \forall x, y \in \Omega \cap B_\delta^\circ(\xi).
\]

Proof. We already know that \( u \in C^2(\Omega) \). Let \( \delta \leq \min(\beta_0, \frac{1}{2}) \) such that \( B_\delta(\xi) \cap \Omega \subset \Omega_\delta \subset \Omega_{\beta_0} \).

By [3, Lemma 2.8] there exists a positive supersolution \( \zeta \in C^2(\Omega_2) \) of (1.3) in \( \Omega_2 \) with the following behavior
\[
\zeta(x) \approx d^2(x) \log \frac{1}{d(x)} \left( 1 + c_{19} \left( \log \frac{1}{d(x)} \right)^{-\beta} \right),
\]
for some \( \beta \in (0, 1) \) and \( c_{19} = c_{19}(\Omega) > 0 \). Set \( v = \zeta^{-1} u \), then it satisfies
\[
-\zeta^{-2} \text{div}(\zeta^2 \nabla v) \leq 0 \quad \text{in } B_\delta(\xi) \cap \Omega.
\] (2.27)

Let \( \eta \in C_0^\infty(B_\delta(\xi)) \) such that \( 0 \leq \eta \leq 1 \) and \( \eta = 1 \) in \( B_\frac{\delta}{2}(\xi) \). We set \( v_s = \eta^2(v - s)_+ \). Since by assumption \( v_s \) has compact support in \( B_\delta(\xi) \cap \Omega \), we can use it as a test function in (2.27) and we get
\[
\int_{B_\delta(\xi) \cap \Omega} \zeta^2 \nabla v \cdot \nabla v_s dx = \int_{B_\delta(\xi) \cap \Omega} \zeta^2 \nabla (v - s)_+ \cdot \nabla v_s dx \leq 0,
\] (2.28)

which yields
\[
\int_{B_\delta(\xi) \cap \Omega} |(v - s)_+|^2 \zeta^2 \eta^2 dx \leq 4 \int_{B_\delta(\xi) \cap \Omega} |\nabla \eta|^2 (v - s)^2 \zeta^2 dx.
\]

Letting \( s \to 0 \) we derive
\[
\int_{B_\delta(\xi) \cap \Omega} |\nabla v|^2 \zeta^2 \eta^2 dx \leq 4 \int_{B_\delta(\xi) \cap \Omega} |\nabla \eta|^2 v^2 \zeta^2 dx.
\]

Since
\[
|\nabla (v - s)_+|^2 \zeta^2 \eta^2 \uparrow |\nabla v|^2 \zeta^2 \eta^2 \quad \text{as } s \to 0,
\]

and convergence of \( \nabla (v - s)_+ \) to \( \nabla v \) holds a.e. in \( \Omega \), it follows by the monotone convergence theorem
\[
\lim_{s \to 0} \int_{B_\delta(\xi) \cap \Omega} |\nabla (v - (v - s)_+)|^2 \zeta^2 \eta^2 dx = 0.
\] (2.29)

Finally \( \zeta v_s \to \eta^2 \zeta v \) in \( H^1(B_\delta(\xi) \cap \Omega) \), which yields in particular \( \eta^2 u = \eta^2 \zeta v \in H^1_0(B_\delta(\xi) \cap \Omega) \).

Step 2. By [3, Lemma 2.8] there exists a positive subsolution \( h \in C^2(\Omega_2) \) of (1.3) in \( \Omega_2 \) with the following behavior
\[
h(x) \approx d^2(x) \log \frac{1}{d(x)} \left( 1 - c_{20} \left( \log \frac{1}{d(x)} \right)^{-\beta} \right),
\]
where \( \beta \in (0, 1) \) and \( c_{20} = c_{20}(\Omega) > 0 \). Set \( w = h^{-1} u \) and \( w_s = \eta^2(w - s)_+ \). Then \( w_s \to \eta^2 w \) in \( H^1(B_\delta(\xi) \cap \Omega) \) by Step 1. Put \( u_s = hw_s \), thus, for \( 0 < s, s' \), we have
\[
\int_{B_\delta(\xi) \cap \Omega} |\nabla (u_s - u_{s'})|^2 dx - \frac{1}{4} \int_{B_\delta(\xi)} |u_s - u_{s'}|^2 d^2(x).
\]
\[
\begin{align*}
&= \int_{B_\delta(\xi) \cap \Omega} h^2 |\nabla (w_\xi - w_{\xi'})|^2 dx + \int_{B_\delta(\xi) \cap \Omega} |\nabla h|^2 |w_\xi - w_{\xi'}|^2 dx \\
&\quad + \int_{B_\delta(\xi) \cap \Omega} h \nabla h \cdot \nabla (u_\xi - u_{\xi'})^2 dx - \frac{1}{4} \int_{B_\delta(\xi) \cap \Omega} \frac{h^2 |w_\xi - w_{\xi'}|^2}{d^2(x)} dx \\
&\leq \int_{B_\delta(\xi) \cap \Omega} h^2 |\nabla (w_\xi - w_{\xi'})|^2 dx, 
\end{align*}
\]

(2.30)

where, in the last inequality, we have performed by parts integration and then used the fact that \( h \) is a subsolution. Thus we have by (2.29) that

\[
\lim_{s,s' \to 0} \int_{B(s)(\xi)} |\nabla (u_\xi - u_{s'})|^2 dx - \frac{1}{4} \int_{B(s)(\xi)} |u_\xi - u_{s'}|^2 dx = 0. 
\]

(2.31)

**Step 3.** Let \( \mathcal{W}(\Omega) \) denote the closure of \( C_0^\infty(\Omega) \) in the space of functions \( \phi \) satisfying

\[
\|\phi\|_H^2 := \int_{\Omega} |\nabla \phi|^2 dx - \frac{1}{4} \int_{\Omega} |\phi|^2 dx < \infty. 
\]

Thus \( \eta^2 u \in \mathcal{W}(\Omega) \), which implies

\[
\frac{\eta u}{\phi_{\frac{\alpha}{4}}} \in H^0(\Omega, d(x)dx).
\]

Next we set \( \tilde{v} = \phi_{\frac{1}{\alpha}}^{-1} u \); then \( \tilde{v} \in H^1(B_{\frac{\alpha}{4}}(\xi), d(x)dx) \) and it satisfies

\[
-\phi_{\frac{1}{\alpha}}^{-2} \text{div} \left( \phi_{\frac{1}{\alpha}}^2 \nabla \tilde{v} \right) + \lambda_{\frac{\alpha}{4}} \tilde{v} = 0.
\]

Put \( \tilde{v}^*(x, t) = e^{\lambda_{\frac{\alpha}{4}} t} \tilde{v} \), then \( \tilde{v}^* \) satisfies

\[
\tilde{v}^* - \phi_{\frac{1}{\alpha}}^{-2} \text{div} \left( \phi_{\frac{1}{\alpha}}^2 \nabla \tilde{v}^* \right) = 0
\]

(2.32)

in the weak sense of [14, Definition 2.9]. By [14, Theorem 1.5], \( \tilde{v}^* \) satisfies a Harnack inequality up to the boundary of \( \Omega \) in the sense that

\[
\text{ess sup} \left\{ \tilde{v}^*(y, t) : (y, t) \in \mathcal{B}_{\frac{3}{4}}(\xi) \times \left[ \frac{r^2}{4}, t^2 \right] \right\} \leq \text{ess inf} \left\{ \tilde{v}^*(y, t) : (y, t) \in \mathcal{B}_{\frac{3}{4}}(\xi) \times \left[ \frac{3r^2}{4}, t^2 \right] \right\}
\]

(2.33)

where \( \mathcal{B}_{\frac{3}{4}}(\xi) \) is a Lipschitz deformed Euclidean ball (see [14, p. 244] and Definition A.6). Since \( r \) is bounded and \( \tilde{v} \) satisfies the same estimate up to a constant depending on \( \Omega \) and finally there exists a constant \( c_{18} = c_{18}(\Omega) > 0 \) such that

\[
v(x) \leq c_{18} v(y) \quad \forall x, y \in B_{\frac{3}{4}}(\xi).
\]

The result follows. \( \square \)

In the case \( \kappa < \frac{1}{4} \), the result holds with minor modifications.

**Proposition 2.12.** Let \( \delta > 0 \) be small enough, \( \xi \in \Omega \), \( 0 < \kappa < \frac{1}{4} \) and \( u \in H^1_{\text{loc}}(B_\delta(\xi) \cap \Omega) \cap C(B_\delta(\xi) \cap \overline{\Omega}) \) be a nonnegative \( \mathcal{L}_\kappa \)-harmonic in \( B_\delta(\xi) \) vanishing on \( \partial \Omega \cap B_\delta(\xi) \) in the sense that

\[
\lim_{\text{dist}(x,K) \to 0} \frac{u(x)}{(d(x))^{-\kappa}} = 0 \quad \forall K \subset \partial \Omega \cap B_\delta(\xi), \ K \text{ compact}. 
\]

(2.34)

Then there exists \( c_{21} = c_{21}(\Omega, \kappa) > 0 \) such that

\[
\frac{u(x)}{\phi_{\kappa}(x)} \leq c_{21} \frac{u(y)}{\phi_{\kappa}(y)} \quad \forall x, y \in B_{\frac{3}{4}}(\xi) 
\]

**Proof.** As in the previous proof we apply [3, Lemma 2.8], we consider a super-solution \( \xi \approx d^{\beta^*}(1 + c_{19} d^{\beta}) \) and a sub-solution \( h \approx d^{\beta^*}(1 - c_{20} d^{\beta}) \) where \( \beta \in (0, \sqrt{1 - 4\kappa}) \). Thus

\[
\frac{\eta u}{\phi_{\kappa}} \in H^1(\Omega, d^{\beta^*}(x)dx),
\]
where \( \eta \) is a cut-off function adapted to \( B_r(\xi) \). The function \( \bar{v} = \phi_k^{-1}u \) satisfies
\[
-\phi_k^{-2}\text{div}(\phi_k^2 \nabla \bar{v}) + \lambda_\kappa \bar{v} = 0,
\]
and \( \bar{v} \in H^1_0(B_{\frac{r}{4}}(\xi), d^{\alpha+}(x)dx) \). Then the proof follows as in the previous proposition. \( \square \)

**Proposition 2.13.** Let \( u \in H^1_{loc}(\Omega) \cap C(\Omega) \) be a \( L_{\frac{1}{4}} \)-subharmonic function such that
\[
\limsup_{d(x) \to 0} \frac{u(x)}{d^\frac{1}{2}(x) \log d(x)} \leq 0.
\]
Then \( u \leq 0 \).

**Proof.** We set \( v = \max(u, 0) \) and we proceed as in the Step 1 of the proof of Proposition 2.11 with \( \eta = 1 \). The result follows by letting \( s \to 0 \). \( \square \)

Similarly we have

**Proposition 2.14.** Let \( u \in H^1_{loc}(\Omega) \cap C(\Omega) \) be a \( L_{\kappa} \)-subharmonic function such that
\[
\limsup_{d(x) \to 0} \frac{u(x)}{(d(x))^{\frac{\alpha}{\kappa}}} \leq 0.
\]
Then \( u \leq 0 \).

The two next statements shows that comparison holds provided comparable boundary data are achieved in way which takes into account the specific form of the \( L_{\kappa} \)-harmonic functions.

**Proposition 2.15.** Assume \( \kappa < \frac{1}{4} \) and \( h_i \in H^1(\Omega) \) (\( i = 1, 2 \)). Let \( u_i \in H^1_{loc}(\Omega) \) be two \( L_{\kappa} \)-harmonic functions such that
\[
\frac{d^{\frac{1}{2}}}{d^{\frac{1}{2}}} \left( u_i - d^{\frac{1}{2}} h_i \right) \in H^1(\Omega, d^{\alpha+}(x)dx).
\]
If \( h_1 \leq h_2 \) a.e. in \( \Omega \), there holds
\[
u_1(x) \leq u_2(x) \quad \forall x \in \Omega.
\]
If \( h_1 - h_2 \in H^1_0(\Omega) \), there holds
\[
u_1(x) = u_2(x) \quad \forall x \in \Omega.
\]

**Proof.** Set \( w = \phi_k^{-1}(u_1 - u_2) \), then \( w \in H^1(\Omega, \phi_k^2 dx) \) and
\[
-\text{div}(\phi_k^2 \nabla w) + \lambda_\kappa \phi_k^2 w = 0.
\]
Since \( H^1(\Omega, \phi_k^2 dx) = H^1_0(\Omega, \phi_k^2 dx) \) by (2.5) we derive that \( w \) and \( w_+ \) belong to \( H^1_0(\Omega, \phi_k^2 dx) \) and, integrating by part, we derive \( w_+ = 0 \). The proof of the second statement is similar. \( \square \)

In the same way we have in the case \( \kappa = \frac{1}{4} \).

**Proposition 2.16.** Assume \( \kappa = \frac{1}{4} \). Let \( h_i \in H^1(\Omega) \) (\( i = 1, 2 \)) and let \( u_i \in H^1_{loc}(\Omega) \) be two \( L_{\frac{1}{4}} \)-harmonic functions such that
\[
\frac{d^{\frac{1}{2}}}{d^{\frac{1}{2}}} (u_i - d^{\frac{1}{2}} |\log d| h_i) \in H^1(\Omega, d(x)dx).
\]
(i) If \( h_1 \leq h_2 \) a.e. in \( \Omega \), then
\[
u_1(x) \leq u_2(x) \quad \forall x \in \Omega.
\]
(ii) If \( h_1 - h_2 \in H^1_0(\Omega) \), then
\[
u_1(x) = u_2(x) \quad \forall x \in \Omega.
\]

We end with existence and uniqueness results for solving the Dirichlet problem associated to \( L_{\kappa} \).

**Proposition 2.17.** Assume \( \kappa = \frac{1}{4} \). For any \( h \in C(\partial \Omega) \) there exists a unique \( L_{\frac{1}{4}} \)-harmonic function \( u \) belonging to \( H^1_{loc}(\Omega) \) satisfying
\[
\lim_{x \to y, x, y \in \partial \Omega} \frac{u(x)}{d^\frac{1}{2}(x) |\log d(x)|} = h(y) \quad \text{uniformly for } y \in \partial \Omega.
\]
Furthermore there exists a constant \( c_{16} = c_{16}(\Omega) > 0 > 0 \)

\[
\left\| \frac{u}{d^\frac{\alpha}{2}} \log \frac{d}{D_0} \right\|_{L^\infty(\Omega)} \leq c_{24} \| h \|_{C(\partial \Omega)},
\]

where \( D_0 = 2 \sup_{x \in \Omega} d(x) \).

**Proof.** Uniqueness is a consequence of Proposition 2.13. For existence let \( m \in \mathbb{N} \) and \( h_m \) be smooth functions such that \( h_m \to h \in L^2(\partial \Omega) \). Then we can find a function \( H_m \in C^2(\overline{\Omega}) \) with value \( h_m \) on \( \partial \Omega \), and \( \| H_m \|_{L^\infty(\Omega)} \leq \| h_m \|_{L^\infty(\partial \Omega)} \). By Proposition 2.10 there exists a unique weak solution \( u_m \) of \( L_\frac{1}{2} u = 0 \) satisfying

\[
\lim_{x \to \Omega, x \to \partial \Omega} \frac{u_m}{d^\frac{\alpha}{2}} \log \frac{d}{D_0}(x) = h_m(y) \quad \text{uniformly for } y \in \partial \Omega.
\]

By Proposition 2.10 we have

\[
\left\| \frac{u_m - u}{d^\frac{\alpha}{2}} \log \frac{d}{D_0} \right\|_{L^\infty(\Omega)} \leq c_{16} \| h_m - h_n \|_{C(\partial \Omega)}.
\]

Thus there exists \( u \) such that

\[
\lim_{m \to \infty} \left\| \frac{u_m - u}{d^\frac{\alpha}{2}} \log \frac{d}{D_0} \right\|_{L^\infty(\Omega)} = 0
\]

and \( u \) is a solution of \( L_\frac{1}{2} u = 0 \).

Let \( x \in \Omega \), with \( d(x) < \frac{1}{\alpha} \) and \( y \in \partial \Omega \)

\[
\left| \frac{u}{d^\frac{\alpha}{2}} \log \frac{d}{D_0}(x) - h(y) \right| \leq \left| \frac{u}{d^\frac{\alpha}{2}} \log \frac{d}{D_0}(x) - \frac{u_m}{d^\frac{\alpha}{2}} \log \frac{d}{D_0}(x) \right| + \left| \frac{u_m}{d^\frac{\alpha}{2}} \log \frac{d}{D_0}(x) - h_m(y) \right| + |h(y) - h_m(y)|.
\]

The result follows by letting successively \( x \to y \) and \( m \to \infty \). \( \square \)

Similarly we have

**Proposition 2.18.** Assume \( \kappa < \frac{1}{\alpha} \). Then for any \( h \in C(\partial \Omega) \) there exists a unique \( L_\kappa \)-harmonic function \( u \in H^1_{\text{loc}}(\Omega) \) satisfying

\[
\lim_{x \to \Omega, x \to \partial \Omega} \frac{u}{d^\frac{\kappa}{2}}(x) = h(y) \quad \text{uniformly for } y \in \partial \Omega.
\]

Furthermore there exists a constant \( c_9 = c_9(\Omega, \kappa) > 0 \) such that

\[
\left\| \frac{u}{d^{\frac{\kappa}{2}}} \right\|_{L^\infty(\Omega)} \leq c_9 \| h \|_{C(\partial \Omega)}.
\]

A useful consequence of [3, Lemma 2.8] and Propositions 2.9 and 2.10 is the following local existence result.

**Proposition 2.19.** There exists a positive \( L_\kappa \)-harmonic function \( Z_\kappa \in C(\overline{\Omega}_{\beta_0}) \cap C^2(\Omega_{\beta_0}) \) satisfying

\[
\lim_{d(x) \to 0} \frac{Z_\frac{\kappa}{2}(x)}{\sqrt{d(x) \ln d(x)}} = 0
\]

if \( \kappa = \frac{1}{\alpha} \) and

\[
\lim_{d(x) \to 0} \frac{Z_{\kappa}(x)}{(d(x))^{\frac{\kappa}{2}}} = 0
\]

if \( 0 < \kappa < \frac{1}{\alpha} \).
2.3. $\mathcal{L}_\kappa$-harmonic measure

Let $x_0 \in \Omega$, $h \in C(\partial \Omega)$ and denote $L_{\kappa,h}(h) := v_h(x_0)$ where $v_h$ is the solution of the Dirichlet problem (see Propositions 2.17 and 2.18)

$$L_\kappa v = 0 \quad \text{in } \Omega$$
$$v = h \quad \text{in } \partial \Omega,$$

(2.37)

where $v$ takes the boundary data in the sense of Propositions 2.17 and 2.18. By Propositions 2.14 and 2.13, the mapping $h \mapsto L_{\kappa,h}(h)$ is a linear positive functional on $C(\partial \Omega)$. Thus there exists a unique Borel measure on $\partial \Omega$, called $\mathcal{L}_\kappa$-harmonic measure in $\Omega$, denoted by $\omega^{\kappa}_{0}$, such that

$$v_h(x_0) = \int_{\partial \Omega} h(y) d\omega_{0}^{\kappa}(y).$$

Thanks to Harnack inequality the measures $\omega^{\kappa}$ and $\omega^{\kappa}_{0}$, $x_0, x \in \Omega$ are mutually absolutely continuous. For every fixed $x$ we denote the Radon–Nikodym derivative by

$$K_{\mathcal{L}_\kappa}(x, y) := \frac{d\omega^{\kappa}_{x}}{d\omega_{0}^{\kappa}}(y) \quad \text{for } \omega^{\kappa}_{0}-\text{almost all } y \in \partial \Omega.$$

It is classical that the following formula is an equivalent definition of the $\mathcal{L}_\kappa$-harmonic measure: for any closed set $E \subset \partial \Omega$

$$\omega^{\kappa}_{0}(E) = \inf \left\{ \psi : \psi \in C_{c}(\Omega), \mathcal{L}_\kappa\text{-superharmonic in } \Omega \text{ s.t. } \liminf_{x \to \xi} \frac{\psi(x)}{W(x)} \geq 1 \right\},$$

where

$$W(x) = \begin{cases} d^{-\alpha} - (x) & \text{if } \kappa < \frac{1}{4}, \\
\frac{1}{2} \log d(x) & \text{if } \kappa = \frac{1}{4}. \end{cases}$$

The extension to open sets is standard. Let $\xi \in \partial \Omega$. We set $\Delta_r(\xi) = \partial \Omega \cap B_r(\xi)$ and $x_r = x_r(\xi) \in \Omega$, such that $d(x_r) = |x_r - \xi| = r$. Also $x_r(\xi) = \xi - r n_\xi$ where $n_\xi$ is the unit outward normal vector to $\partial \Omega$ at $\xi$. We recall that $\beta_0 = \beta_0(\Omega) > 0$ has been defined in Lemma 2.7.

**Lemma 2.20.** There exists a constant $c_{25} > 0$ which depends only on $\Omega$ and $\kappa$ such that if $0 < r \leq \beta_0$ and $\xi \in \partial \Omega$, there holds

\[
\frac{\omega^{\kappa}_{0}(\Delta_r(\xi))}{W(x)} \geq c_{25} \quad \forall \xi \in \Omega \cap B_{\frac{\beta_0}{4}}(\xi). \tag{2.38}
\]

**Proof.** Let $h \in C(\partial \Omega)$ be a function with compact support in $\Delta_r(\xi)$, $0 \leq h \leq 1$ and $h = 1$ on $\overline{B_{\frac{\beta_0}{4}}(\xi)}$. And let $v_h, v_1$ the corresponding $\mathcal{L}_\kappa$-harmonic functions with respective boundary data (in the sense of Propositions 2.17 and 2.18) $h$ and $1$. Then $v_1(x) \geq v_h(x) \geq 0$ and

$$\lim_{x \to \xi, x \neq x_0} \frac{v_1(x) - v_h(x)}{W(x)} = 0 \quad \forall x_0 \in \Omega \cap B_{\frac{\beta_0}{4}}(\xi).$$

By Propositions 2.12 and 2.11, and $\phi_\kappa \approx d^{-\alpha - \frac{1}{2}}$, there exists $c_{26} = c_{26}(\Omega, \kappa) > 0$ such that

$$\frac{v_1(x) - v_h(x)}{d^{\alpha}(x)} \leq c_{26} \frac{v_1(y) - v_h(y)}{d^{\alpha}(y)} \quad \forall x, y \in \Omega \cap B_{\frac{\beta_0}{4}}(\xi).$$

We consider first the case $\kappa = \frac{1}{4}$. By Proposition 2.10, we have

$$0 \leq \frac{v_1(y) - v_h(y)}{d^{\frac{1}{2}}(y)} \leq \frac{v_1(y)}{d^{\frac{1}{2}}(y)} \leq c_{24}|\log d(y)|.$$

Thus, combining all above we have that

$$\frac{v_1(x)}{d^{\frac{1}{2}}(x)|\log d(x)|} + c_{27} \frac{|\log d(y)|}{|\log d(x)|} \leq \frac{v_h(x)}{d^{\frac{1}{2}}(x)|\log d(x)|}.$$

Now by Proposition 2.10, there exists $\varepsilon_0 > 0$ such that

$$\frac{v_1(x)}{d^{\frac{1}{2}}(x)|\log d(x)|} > \frac{1}{2} \quad \forall x \in \Omega_{\varepsilon_0}.$$
Thus if we choose $y$ such that $d(y) = \frac{r}{4}$, there exists a constant $c_{27} = c_{27}(\Omega, \kappa) > 0$ such that
\[
\frac{c_{27}}{|\log d(y)|} = \frac{c_{27}}{|\log d(x)|} \leq \frac{c_{27}}{|\log \frac{r}{4}|} \leq \frac{1}{4} \quad \forall x \in \Omega, \\
\]
thus
\[
\frac{v_h(x)}{d^2(x)|\log d(x)|} \geq \frac{1}{4} \quad \forall x \in \overline{B_{\frac{r}{2}}(\xi)} \cap \Omega. \\
\]
(2.39)

In particular
\[
\frac{v_h(x_{a^r}(\xi))}{\sqrt{a^r} |\log(a^r)|} \geq \frac{1}{4}, \\
\]
(2.40)

where $a^* = (\max\{2, D_0\})^{-1}$. If $D_0 \leq 2$ we obtain the claim. If $D_0 > 2$, set $k^* = E[\frac{D_0}{2}] + 1$ (we recall that $E[x]$ denotes the largest integer less or equal to $x$). If $x \in \overline{B_{\frac{r}{2}}(\xi)} \cap \Omega'$, there exists a chain of at most $4k^*$ points $\{z_j\}^k_{j=0}$ such that $z_j \in \overline{B_{\frac{r}{2}}(\xi)} \cap \Omega$, $d(z_j) \geq a^*r$, $z_0 = x_{a^r}(\xi)$, $z_0 = x$ and $|z_j - z_{j+1}| \leq \frac{a^*r}{4}$. By Harnack inequality (applied $j_0$-times)
\[
v_h(x_{a^r}(\xi)) \leq c_{28}v_h(x). \\
\]
(2.41)

Since
\[
W(x_{a^r}(\xi)) \geq (a^*)^{\frac{1}{2}} W(x), \\
\]
we obtain finally
\[
\frac{1}{4} \leq \frac{\omega^k(\xi)}{\sqrt{a^r} |\log(a^r)|} \leq \frac{c_{28} \frac{1}{a^*} \omega^k(\xi) W(x)}{W(x)} \quad \forall x \in \Omega \cap B_{\frac{r}{2}}(\xi). \\
\]
(2.42)

In the case $\kappa < \frac{1}{4}$, the proof is simpler since no log term appears and we omit it. $\square$

The next result is a Carleson type estimate valid for positive $L_x$-harmonic functions.

**Lemma 2.21.** There exists a constant $c_{29}$ which depends on $\Omega$ and $\kappa$ such that for any $\xi \in \partial\Omega$ and $0 < r \leq s \leq \beta_0$,
\[
\frac{\omega^k(\xi)}{W(x)} \leq c_{29} \frac{\omega^k(\xi)}{W(x_{s}(\xi))} \quad \forall x \in \Omega \setminus B_{s}(\xi). \\
\]
(2.43)

**Proof.** Let $h \in C(\partial \Omega)$ with compact support in $\partial \Omega$ and $0 \leq h \leq 1$. We denote by $v_h$, $v_1$, the solutions of (2.37) with boundary data $h$ and 1 respectively. By **Propositions 2.17** and **2.18** there exists a constant $c_{30} > 0$ such that for $0 < r < \beta_0$,
\[
\frac{v_h}{W(x)} \leq \frac{\omega^k(\xi)}{W(x)} \leq \frac{\omega^k(\partial \Omega)}{W(x)} \leq c_{30} \quad \forall x \in \Omega. \\
\]
(2.44)

By **Propositions 2.17** and **2.18**, there holds
\[
\lim_{d(x) \to 0} \frac{v_1(x)}{W(x)} = 1, \\
\]
(2.45)

thus we can replace $W$ by $v_1$ in (2.43). Since $w_h = \frac{v_h(x)}{v_1(x)}$ is Hölder continuous in $\overline{\Omega}$ and satisfies
\[
-\text{div}(\nabla w_h) = 0 \quad \text{in } \Omega \setminus \overline{B_r(\xi)} \\
0 \leq w_h \leq 1 \quad \text{in } \Omega \setminus \overline{B_r(\xi)} \\
w_h = 0 \quad \text{in } \partial \Omega \setminus B_r(\xi), \\
\]
the maximum of $w_h$ is achieved on $\Omega \cap \partial B_r(\xi)$, therefore it is sufficient to prove the Carleson estimate
\[
w_h(x) \leq c_{29} w_h(x_{s}(\xi)) \quad \forall x \in \Omega \cap \partial B_r(\xi). \\
\]
(2.47)

If $x$ such that $|x - \xi| = s$ is "far" from $\partial \Omega$, $w_h(x)$ is "controlled" by $w_h(x_{s}(\xi))$ thanks to Harnack inequality, while if it is close to $\partial \Omega$, $w_h(x)$ is "controlled" by the fact that it vanishes on $\partial \Omega \cap \partial B_r(\xi)$.

We also note that (2.38) can be written under the form
\[
w_h(x) \geq c_{25} \quad \forall x \in \Omega \cap B_{\frac{r}{2}}(\xi). \\
\]
(2.48)
Step 1: \( r \leq s \leq 4r \). By Lemma 2.20, (2.44) and the above inequality we have that
\[
wh \left( x^r_2(\xi) \right) \geq \frac{c_{25}}{c_{30}} w_h(x) \quad \forall x \in \Omega.
\]
Applying Harnack inequality to \( w_h \) in the balls \( B_{\frac{34}{s}}(x^r_2(\xi)) \) for \( j = 0, \ldots, j_0 \leq 14 \), we obtain
\[
wh \left( x^r_{2j+1}(\xi) \right) \geq \frac{c_j}{c_{31}} w_h \left( x^r_2(\xi) \right) \quad \text{for } j = 1, \ldots, j_0.
\]
This implies
\[
wh(x_0(\xi)) \geq c_{32} w_h(x) \quad \forall x \in \Omega.
\] (2.49)
Step 2: \( \beta_0 \geq s > 4r \). We apply Propositions 2.11, 2.12 to \( w_h \) in \( B_{\frac{34}{s}}(\xi_1) \cap \Omega \) where \( \xi_1 \in \partial \Omega \) is such that \( |\xi - \xi_1| = s \) and we get
\[
w_h(x) \leq c_{18} w_h \left( x^r_2(\xi_1) \right) \quad \forall x \in B_{\frac{34}{s}}(\xi_1) \cap \Omega.
\] (2.50)
Then we apply six times Harnack inequality to \( w_h \) between \( x^r_2(\xi_1) \) and \( x_0(\xi) \) and obtain
\[
w_h \left( x^r_2(\xi_1) \right) \leq c_{33} w_h(x_0(\xi_1)).
\] (2.51)
Combining (2.50) and (2.51) we derive (2.47).
Step 3. For \( \epsilon > 0 \), set \( z_h = w_h - c_{33} w_h(x_0(\xi)) - \epsilon \). Then \( z_h^+ \) has compact support in \( \Omega \setminus B_{3}(\xi) \) and thus belongs to \( H^1_0(\Omega \setminus B_{3}(\xi)) \). Integration by parts in (2.46) leads to
\[
\int_{\Omega \setminus B_{3}(\xi)} v_0^2 |\nabla z_h^+|^2 dx = 0.
\] (2.52)
Then \( z_h^+ = 0 \) by letting \( \epsilon \to 0 \). Combining with (2.49) and \( h \uparrow x_0(\xi) \) implies (2.43). \( \square \)

**Theorem 2.22.** There exists a constant \( c_{34} \) which depends on \( \Omega \) and \( \kappa \) such that, for any \( 0 < r \leq \beta_0 \) and \( \xi \in \partial \Omega \), there holds
\[
\frac{1}{c_{34}} r^{N-\frac{1}{2}} |\log r| G_{\frac{1}{2}}(x_0(\xi), x) \leq \omega^{x}(\Delta_r(\xi)) \leq c_{34} r^{N-\frac{1}{2}} |\log r| G_{\frac{1}{2}}(x_0(\xi), x) \quad \forall x \in \Omega \setminus B_{4r}(\xi).
\] (2.53)

**Proof.** Let \( \eta \in C_0^\infty(B_{2r}(\xi)) \) such that \( 0 \leq \eta \leq 1 \) and \( \eta = 1 \) in \( B_{r}(\xi) \). We set
\[
u = \eta(-\ln d) \sqrt{d} := \eta \psi,
\]
(we assume that \( 4r < 1 \)), in order to have
\[
\lim_{k \to 0} \frac{u(x)}{\psi(x)} = \eta_{|_{\partial \Omega}}(x_0) = \xi(x_0) \quad \forall x_0 \in \partial \Omega,
\]
uniformly with respect to \( x_0 \). Since
\[
-\Delta \psi - \frac{1}{4} \psi \frac{\partial \psi}{\partial d} = \frac{2 + \ln d}{2\sqrt{d}} \Delta d = - \left( N - 1 \right) \frac{2 + \ln d}{2\sqrt{d}} K,
\]
where \( K \) is the mean curvature of \( \partial \Omega \). We have also
\[
|\nabla \eta| \leq c_0 \chi_{\Omega \cap B_{2r}(\xi)} \frac{1}{r} \quad \text{and} \quad |\Delta \eta(x)| \leq c_0 \chi_{\Omega \cap B_{2r}(\xi)} \frac{1}{r^2} \leq c_0 \chi_{\Omega \cap \Omega \cap B_{2r}(\xi)} \frac{1}{r} d^{-1}(x),
\]
thus \( u \) satisfies
\[
-\Delta u - \frac{1}{4} u \frac{\partial u}{\partial d} = - \psi \Delta \eta + \frac{2 + \ln d}{2\sqrt{d}} (2 \sqrt{d} \cdot \nabla \eta - \left( N - 1 \right) \eta) : f \quad \text{in} \quad \Omega
\]
\[
u = \xi \quad \text{on} \quad \partial \Omega.
\]
Furthermore \( |f| \leq \frac{c_0}{r} \left( - \frac{\ln d}{\sqrt{d}} \right) \chi_{\Omega \cap B_{2r}(\xi)} \) since \( \eta \) vanishes outside \( B_{2r}(\xi) \). We have by the representation formula [14]
\[
0 = u(x) = \int_{\Omega} G_{\frac{1}{2}}(x, y) f dy + \int_{\partial \Omega} h(y) d\omega^x(y) \quad \forall x \in \Omega \setminus B_{2r}(\xi).
\] (2.54)
By Proposition 2.1, we have that for any \( x \in \Omega \setminus B_{4r}(\xi) \) and \( y \in B_{2r}(\xi) \)
\[
G_{L_{x}}(x, y) \leq c_{36} G_{L_{x}}(x, x_{r}(\xi)),
\]
thus
\[
\omega^{\kappa}(\Delta_{r}(\xi)) \leq \frac{1}{r} \int_{\Gamma \cap B_{2r}(\xi)} G_{L_{x}}(x, y) |f(y)| dy \leq \frac{c_{37}}{r} G_{L_{x}}(x, x_{r}(\xi)) \int_{\Omega \cap B_{2r}(\xi)} \frac{|\ln d(y)|}{\sqrt{d(y)}} dy \leq c_{38} G_{L_{x}}(x, x_{r}(\xi)) r^{N-1-\frac{1}{2}} |\ln r|,
\]
(2.55)

since
\[
\int_{\Omega \cap B_{2r}(\xi)} \frac{|\ln d(y)|}{\sqrt{d(y)}} dy \leq c_{39} r^{N-1} \int_{0}^{2r} \frac{|\ln t| dt}{\sqrt{t}} \leq 2 c_{39} r^{N-\frac{1}{2}} |\ln r|.
\]

This implies the right-hand side part of (2.53). For the opposite inequality we observe that if \( x \in \partial B_{4r}(\xi) \cap \Omega \), there holds by (2.38)
\[
r^{N-1-\frac{1}{2}} |\ln r| G_{L_{x}}(x_{r}(\xi), x) \leq c_{40} r^{N-1-\frac{1}{2}} |\ln r| \min \left\{ \frac{1}{|x-x_{r}(\xi)|^{N-2}}, \frac{\sqrt{d(x)} \sqrt{d(x_{r}(\xi))}}{|x-x_{r}(\xi)|^{N-1}} \right\} \\
\leq c_{41} \sqrt{d(x)} |\ln r| \\
\leq c_{42} W(x) \\
\leq \frac{c_{42}}{c_{25}} \omega^{\kappa_{x}(\xi)}(\Delta_{r}(\xi)).
\]

We end the proof by Harnack inequality between \( \omega^{\kappa_{x}(\xi)}(\Delta_{r}(\xi)) \) and \( \omega^{\kappa_{x}(\xi)}(\Delta_{r}(\xi)) \) and by Harnack inequality between \( \omega^{\kappa}(\Delta_{r}(\xi)) \) and \( \omega^{\kappa_{x}(\xi)}(\Delta_{r}(\xi)) \) on \( \partial B_{4r}(\xi) \) and an argument like in the step 3 in Lemma 2.21. \( \square \)

Replacing, in the last proof, the function \( \psi = \sqrt{d}(-\ln d) \) by \( \tilde{\psi} = \frac{\sqrt{d}}{r^{\kappa_{x}(\xi)}} \), we obtain similarly the following two-side estimate.

**Theorem 2.23.** Assume \( \kappa < \frac{1}{4} \). There exists a constant \( c_{42} \) which depends only on \( \Omega \) and \( \kappa \) such that, for any \( 0 < r \leq \beta_{0} \) and \( \xi \in \partial \Omega \), there holds
\[
\frac{1}{c_{42}} \frac{r^{N-2}}{w^{\kappa}(\Delta_{r}(\xi))} G_{L_{x}}(x_{r}(\xi), x) \leq \omega^{\kappa}(\Delta_{r}(\xi)) \leq c_{42} \frac{r^{N-2}}{w^{\kappa}(\Delta_{r}(\xi))} G_{L_{x}}(x_{r}(\xi), x) \quad \forall x \in \Omega \setminus B_{4r}(\xi).
\]

As a consequence of Theorems 2.22 and 2.23 and the Harnack inequality, the harmonic measure for \( L_{x} \) possesses the doubling property.

**Theorem 2.24.** Let \( 0 < \kappa \leq \frac{1}{4} \). There exists a constant \( c_{42} \) which depends only on \( \Omega, \kappa \) such that for any \( 0 < r \leq \beta_{0} \), there holds
\[
\omega^{\kappa}(\Delta_{r}(\xi)) \leq c_{42} \omega^{\kappa}(\Delta_{r}(\xi)) \quad \forall x \in \Omega \setminus B_{4r}(\xi).
\]

The next result will be useful in the study of the Poisson kernel of \( L_{x} \).

**Lemma 2.25.** Let \( 0 < r \leq \beta_{0} \) and \( u \) be a positive \( L_{x} \)-harmonic function such that

(i) \( u \in C(\overline{\Omega \setminus B_{r}(\xi)}) \),

(ii) \( \lim_{x \to x_{0}} \frac{u(x)}{W(x)} = 0 \quad \forall x_{0} \in \Omega \setminus \overline{B_{r}(\xi)} \),

uniformly with respect to \( x_{0} \).

Then
\[
\frac{c_{42}}{w^{\kappa}(x_{r}(\xi))} u(x_{r}(\xi)) w^{\kappa}(\Delta_{r}(\xi)) \leq u(x) \leq \frac{c_{42}}{w^{\kappa}(x_{r}(\xi))} u(x_{r}(\xi)) w^{\kappa}(\Delta_{r}(\xi)) \quad \forall x \in \Omega \setminus \overline{B_{2r}(\xi)},
\]
with \( c_{42} \) depends only on \( \kappa \) and \( \Omega \).
Proof. It follows from Propositions 2.11 and 2.12 that there exists \( C > 0 \) such that
\[
\frac{1}{C} \frac{u(x)}{w^{2\alpha}(\Omega)} \leq \frac{u(x)}{w^{2\alpha}(\Omega)} \leq C \frac{u(x)}{w^{2\alpha}(\Omega)} \quad \forall x \in \Omega \cap \partial B_{2r}(\xi).
\]
Applying Harnack inequality between \( x_{2r}(\xi) \) and \( x_{r}(\xi) \) we obtain
\[
\frac{1}{C} \frac{u(x_{r}(\xi))}{w^{2\alpha}(\Omega)} \leq \frac{u(x)}{w^{2\alpha}(\Omega)} \leq C \frac{u(x_{r}(\xi))}{w^{2\alpha}(\Omega)} \quad \forall x \in \Omega \cap \partial B_{2r}(\xi).
\]
Also by Harnack inequality we have that
\[
w^{2\alpha}(\Delta_{r}(\xi)) \geq C w^{2\alpha}(\Delta_{r}(\xi)) > C_{r} W(x_{r}(\xi)),
\]
where in the last inequality above we have used Lemma 2.20.

Combining all the above inequalities, we derive
\[
C^{-1} \frac{u(x_{r}(\xi))}{W(x_{r}(\xi))} w^{2\alpha}(\Delta_{r}(\xi)) \leq u(x) \leq C \frac{u(x_{r}(\xi))}{W(x_{r}(\xi))} w^{2\alpha}(\Delta_{r}(\xi)) \quad \forall x \in \Omega \cap \partial B_{2r}(\xi).
\]
The result follows by an argument similar to step 3 in Lemma 2.21. □

2.4. The Poisson kernel of \( \mathcal{L}_{\kappa} \)

In this section we establish some properties of the Poisson kernel associated to \( \mathcal{L}_{\kappa} \).

Definition 2.26. Fix \( \xi \in \partial \Omega \). A function \( K \) defined in \( \Omega \) is called a kernel function at \( \xi \) with pole at \( x_{0} \in \Omega \) if

(i) \( K(\cdot, \xi) \) is \( \mathcal{L}_{\kappa} \)-harmonic in \( \Omega \),
(ii) \( K(\cdot, \xi) \in C(\overline{\Omega} \setminus \{\xi\}) \) and for any \( \eta \in \partial \Omega \setminus \{\xi\} \)
\[
\lim_{x \to \eta} \frac{K(x, \xi)}{W(x)} = 0,
\]
(iii) \( K(x, \xi) > 0 \) for each \( x \in \Omega \) and \( K(x_{0}, \xi) = 1 \).

Proposition 2.27. There exists one and only one kernel function for \( \mathcal{L}_{\kappa} \) at \( \xi \) with pole at \( x_{0} \).

Proof. The proof is similar as the one of [8, Th. 3.1] and we indicate it for the sake of completeness. Set
\[
u_{n}(x) = \frac{w^{\alpha}(\Delta_{2^{-n}}(\xi))}{w^{\alpha}(\Delta_{2^{-n}}(\xi))}.
\]
Since
\[
u_{n} \geq 0,
\]
\( \mathcal{L}_{\kappa} \nu_{n} = 0 \) in \( \Omega \) and \( \nu_{n}(x_{0}) = 1 \) the sequence \( \{\nu_{n}\} \) is locally bounded in \( \Omega \) by Harnack inequality. Hence we can find a subsequence, again denoted by \( \{\nu_{n}\} \), which converges to a function \( \nu_{3} \), locally uniformly in \( \Omega \).

It is clear that \( \nu \geq 0 \) in \( \Omega \) and \( \mathcal{L}_{\kappa} \nu = 0 \) in \( \Omega \). Since \( \nu(x_{0}) = 1 \), \( \nu \) is strictly positive in \( \Omega \). Now fix \( P \in \partial \Omega \) and \( P \neq \xi \). Let \( n_{0} \in \mathbb{N} \) be such that \( P \in \Omega \setminus \overline{B}_{2^{-n_{0}+1}}(\xi) \). By Lemma 2.25 if we take \( n_{0} \) sufficiently large, we have
\[
u_{n}(x) \leq c_{42} \frac{u_{n}(x_{2^{-n_{0}}}(\xi))}{w^{\alpha}(\Delta_{2^{-n_{0}}}(\xi))} \quad \forall x \in \Omega \setminus \overline{B}_{2^{-n_{0}+1}}(\xi),
\]
which implies
\[
u(x) \leq c_{42} \frac{u(x_{2^{-n_{0}}}(\xi))}{w^{\alpha}(\Delta_{2^{-n_{0}}}(\xi))} \quad \forall x \in \Omega \setminus \overline{B}_{2^{-n_{0}+1}}(\xi),
\]
and thus
\[
\lim_{x \to P} \frac{\nu(x)}{W(x)} = 0.
\]

We now turn to the question of uniqueness of the kernel function. Let us consider two arbitrary kernel functions \( f \) and \( g \) for \( \mathcal{L}_{\kappa} \) in \( \Omega \) at \( \xi \). By Lemma 2.25 and the properties of \( f, g \) there holds
\[
\frac{1}{c_{42}} \frac{f(x_{r}(\xi))}{g(x_{r}(\xi))} \leq \frac{f(x)}{g(x)} \leq c_{42} \frac{f(x_{r}(\xi))}{g(x_{r}(\xi))} \quad \forall x \in \Omega \setminus \overline{B}_{2r}(\xi).
\]
In particular we can obtain if we take \( x = x_0 \)
\[
\frac{f(x_0(\xi))}{g(x_0(\xi))} \leq c^2_{42},
\]
and we obtain, using again Harnack,
\[
\frac{f(x)}{g(x)} \leq c^3_{42} = c \quad \forall x \in \Omega.
\]

We derive that for any two kernel functions \( f \) and \( g \) for \( \mathcal{L}_x \) at \( \xi \) there holds
\[
f(x) \leq cg(x) \leq c^2f(x) \quad \forall x \in \Omega. \tag{2.56}
\]

Obviously \( c \geq 1 \). If \( c = 1 \) the result is proved. If \( c > 1 \) then \( f + A(f - g) \) is also a Kernel function for \( \mathcal{L}_x \) at \( \xi \) with \( A = \frac{1}{c-1} \). Since (2.56) holds for any kernel functions,
\[
g \leq c(f + A(f - g)),
\]
and therefore
\[
f + A(f - g) + A(f + A(f - g)).
\]
is a kernel function at \( \xi \). Proceeding in the above manner and by induction we conclude that for each positive integer \( k \) there exists nonnegative numbers \( a_{1k}, \ldots, a_{kk} \) such that
\[
f + \left( kA + \sum_{i=1}^{k} a_{ik} \right) (f - g)
\]
is a kernel function at \( \xi \). Hence
\[
f + \left( kA + \sum_{i=1}^{k} a_{ik} \right) (f - g) \leq c^2f.
\]
This last inequality can hold for all \( k \) only if \( f \equiv g \). \( \Box \)

We recall here that we denote by
\[
K_{\mathcal{L}_x}(x, \xi) := \frac{du^x}{du^{x_0}}(\xi) \quad \text{for } \omega^x_0\text{-almost all } \xi \in \partial \Omega,
\]
the kernel function in \( \Omega \). Also in view of the proof of Proposition 2.27 and by uniqueness we can write
\[
K_{\mathcal{L}_x}(x, \xi) = \lim_{r \to 0} \frac{u^x(A_r(\xi))}{u^{x_0}(A_r(\xi))} \quad \text{for } \omega^x_0\text{-almost all } \xi \in \partial \Omega.
\]

**Proposition 2.28.** For any \( x \in \Omega \), the function \( \xi \mapsto K_{\mathcal{L}_x}(x, \xi) \) is continuous on \( \partial \Omega \).

**Proof.** The proof is an adaptation of the one of [8, Corollary 3.2]. Suppose that \( \xi_n \to \xi \) as \( n \to \infty \). Then the sequence, \( K(\cdot, \xi_n) \), of positive solutions of \( \mathcal{L}_x u = 0 \) has a subsequence which converges locally uniformly in \( \Omega \) to a function which must be a positive solution of \( \mathcal{L}_x u = 0 \) in \( \Omega \). Outside any fixed neighborhood, \( B \), of \( \xi \), \( K_{\mathcal{L}_x}(x, \xi_n) \) converges to zero uniformly in \( n \) as \( x \to P \in \partial \Omega \setminus B \). Hence the limit function of the subsequence is the kernel function for \( \mathcal{L}_x \) at \( \xi \). By uniqueness of the kernel function we conclude that the convergence
\[
K_{\mathcal{L}_x}(x, \xi_n) \to K_{\mathcal{L}_x}(x, \xi)
\]
holds for the entire sequence \( \{\xi_n\} \). \( \Box \)

We can now identify the Martin boundary and topology with their classical analogues. We begin by recalling the definitions of the Martin boundary and related concepts. For \( x, y \in \Omega \) we set
\[
\mathcal{K}_x(x, y) := \frac{G_{\mathcal{L}_x}(x, y)}{G_{\mathcal{L}_x}(x_0, y)}.
\]
Consider the family of sequences \( \{y_k\}_{k \geq 1} \) of points of \( \Omega \) without cluster points in \( \Omega \) for which \( \mathcal{K}_x(x, y_k) \) converges in \( \Omega \) to a harmonic function, denoted \( \mathcal{K}_x(x, \{y_k\}) \). Two such sequences \( y_k \) and \( y'_k \) are called equivalent if \( \mathcal{K}_x(x, \{y_k\}) = \mathcal{K}_x(x, \{y'_k\}) \) and each equivalence class is called an element of the Martin boundary \( \Gamma \). If \( Y \) is such an equivalence class (i.e., \( Y \in \Gamma \) then
$\mathcal{K}_x(x, Y)$ will denote the corresponding harmonic limit function. Thus each $Y \in \Omega \cup \Gamma'$ is associated with a unique function $\mathcal{K}_x(x, Y)$. The Martin topology on $\Omega \cup \Gamma'$ is given by the metric

$$
\rho(Y, Y') = \int A 1 + |\mathcal{K}_x(x, Y) - \mathcal{K}_x(x, Y')| \, dx \quad Y, Y' \in \Omega \cup \Gamma',
$$

where $A$ is a small enough neighborhood of $x_0$. $\mathcal{K}_x(x, Y)$ is a $\rho$-continuous function of $Y \in \Omega \cup \Gamma'$ for $\text{finx} \Omega$ fixed, $\Omega \cup \Gamma'$ is compact and complete with respect to $\rho$, $\Omega \cup \Gamma'$ is the $\rho$-closure of $\Omega$ and the $\rho$-topology is equivalent to the Euclidean topology in $\Omega$. We have the following results.

**Proposition 2.29.** There is a one-to-one correspondence between the Martin boundary of $\Omega$ and the Euclidean boundary $\partial \Omega$. If $Y \in \Gamma'$ corresponds to $\xi \in \partial \Omega$ then $\mathcal{K}_x(x, Y) = K_{\Omega}(x, \xi)$. The Martin topology on $\Omega \cup \Gamma'$ is equivalent to the Euclidean topology on $\Omega \cup \partial \Omega$.

**Proof.** The proof is similar as the one of Theorem 4.2 in [19] and we recall it for the sake of completeness. By uniqueness of the kernel function we have that

$$
\mathcal{K}_x(x, \{y_k\}) = K_{\Omega}(x, \xi),
$$

where $\{y_k\}$ is a sequence in $\Omega$ such that $y_k \to \xi \in \partial \Omega$. It follows that each point of $\Gamma'$ may be associated with a point of $\partial \Omega$. Lemma 2.25 clearly shows that $K_{\Omega}(\cdot, \xi) \neq K_{\Omega}(\cdot, \xi')$ if $\xi \neq \xi'$. Hence, the functions $\mathcal{K}_x(x, y_k)$ cannot converge if the sequence $y_k$ has more than one cluster point on $\partial \Omega$ and different points of $\partial \Omega$ must be associated with different points of $\Gamma'$. This gives a one-to-one correspondence between $\partial \Omega$ and $\Gamma'$ with $\mathcal{K}_x(x, Y) = K_{\Omega}(x, \xi)$ when $Y \in \Gamma'$ corresponds to $\xi \in \partial \Omega$. If $y_k \to \xi$ in the Euclidean topology then $\mathcal{K}_x(x, y_k) \to \mathcal{K}_x(x, Y)$ and, therefore, $Y_k \to Y$ in the $\rho$-topology by Lebesgue’s dominated convergence theorem. On the other hand suppose $Y_k \to Y$ in the $\rho$-topology. If $\xi_k$ does not converge to $\xi$ in the Euclidean topology there is a subsequence $\xi_{k_l}$ such that $\xi_{k_l} \to \xi' \neq \xi$ in the Euclidean topology. Then $Y_{k_l} \to Y'$ and $Y_0 \to Y$ in the $\rho$-topology with $Y \neq Y'$, which is impossible. Therefore, the Martin $\rho$-topology on $\Omega \cup \Gamma'$ is equivalent to the Euclidean topology on $\Omega \cup \partial \Omega$. \hfill $\Box$

By Propositions 2.29 and 2.1 we have the following result.

**Theorem 2.30.** Assume $0 < \kappa \leq \frac{1}{4}$. There exists a positive constant $c_{43}$ such that

$$
\frac{1}{c_{43}} \frac{d^+ \kappa}{|\xi - y|^{N+\alpha}+2} \leq K_{\Omega}(y, \xi) \leq c_{43} \frac{d^+ \kappa}{|\xi - y|^{N+\alpha}+2}. \tag{2.57}
$$

Let us give a lemma that we will use to prove the representation formula.

**Lemma 2.31.** Let $\xi \in \partial \Omega$, $r > 0$ be small enough and $u$ be a positive $\mathcal{L}_\alpha$-harmonic function in $\Omega$. There exists a super $\mathcal{L}_\alpha$-harmonic function $V$ such that

$$
V(x) = \begin{cases} 
 u(x) & \text{in } \Omega \setminus B_r(\xi) \\
 u(x) & \text{in } \Omega \cap B_r(\xi),
\end{cases}
$$

where $u$ satisfies

$$
\mathcal{L}_\alpha v = 0 \quad \text{in } \Omega \setminus B_r(\xi)
$$

$$
\lim_{x \to y} v(x) = u(y) \quad \forall y \in \partial B_r(\xi) \cap \Omega
$$

$$
\lim_{x \to y} W(x) = 0 \quad \forall y \in \partial \Omega \setminus \overline{B}_r(\xi). \tag{2.58}
$$

**Proof.** The function $u$ is $C^2$ in $\Omega$ since it is $\mathcal{L}_\alpha$-harmonic. Let $\xi_0 \in B_r(\xi) \cap \Omega$, and $r_0$ be such that $B_{r_0}(\xi_0) \subset \Omega$. We consider the problem

$$
\mathcal{L}_\alpha w = 0 \quad \text{in } \Omega \setminus \overline{B}_{r_0}(\xi)
$$

$$
\lim_{x \to y} w(x) = \eta(y)w(y) \quad \forall y \in \partial B_{r_0}(\xi) \cap \Omega
$$

$$
\lim_{x \to y} W(x) = 0 \quad \forall y \in \partial \Omega \setminus \overline{B}_{r_0}(\xi),
$$

where $\eta \in C^0(\overline{B}_{r_0}(\xi_0))$, $0 \leq \eta \leq 1$. In view of the proof of Propositions 2.9 and 2.10 we can find a positive solution of the above problem $w$. Also we note here that $w \leq u$, and by Harnack inequalities 2.11 and 2.12, we have that for any $\zeta \in \partial \Omega$

$$
\frac{w(x)}{\phi \kappa(x)} \leq C(\kappa, N, \Omega) \frac{w(y)}{\phi \kappa(y)} \quad \forall x, y \in B_{r_0}(\zeta),
$$
where \( \rho \leq \frac{1}{2} \text{dist}(\zeta, \partial B_r(\xi)) \). Thus we derive
\[
\frac{u(x)}{\phi_\kappa(x)} \leq C(\kappa, N, \Omega) \frac{u(y)}{\phi_\kappa(y)} \quad \forall x, y \in B_\rho(\zeta).
\]

The remaining of the proof is standard and we omit it. \( \square \)

We consider an increasing sequence of bounded smooth domains \( \{\Omega_n\} \) such that \( \overline{\Omega_n} \subset \Omega_{n+1}, \cup_n \Omega_n = \Omega \) and \( H^{N-1}(\Omega_n) \to H^{N-1}(\Omega) \). Such a sequence is a smooth exhaustion of \( \Omega \). For each \( n \), the operator \( L_{\kappa}^{\Omega_n} \) defined by
\[
L_{\kappa}^{\Omega_n}u = -\Delta u - \frac{\kappa}{d^2(x)} u
\]
(2.59)
is uniformly elliptic and coercive in \( H^1_0(\Omega_n) \) and its first eigenvalue \( \lambda_{\kappa}^{\Omega_n} \) is larger than \( \lambda_\kappa \). If \( h \in C(\partial \Omega_n) \) the following problem
\[
L_{\kappa}^{\Omega_n}v = 0 \quad \text{in} \ \Omega_n
\]
\[
v = h \quad \text{on} \ \partial \Omega_n.
\]
(2.60)
admits a unique solution which allows to define the \( L_{\kappa}^{\Omega_n} \)-harmonic measure on \( \partial \Omega_n \) by
\[
v(x_0) = \int_{\partial \Omega_n} h(y) d\omega^{\Omega_n}_{\kappa}(y).
\]
(2.61)

Thus the Poisson kernel of \( L_{\kappa}^{\Omega_n} \) is
\[
K_{\kappa}^{\Omega_n}(x, y) = \frac{d\omega^{\Omega_n}_{\kappa}(y)}{d\omega^{\Omega_n}_{\kappa}} \forall y \in \partial \Omega_n.
\]
(2.62)

**Proposition 2.32.** Assume \( 0 < \kappa \leq \frac{1}{4} \) and let \( x_0 \in \Omega \). Then for every \( Z \in C(\overline{\Omega}) \),
\[
\lim_{n \to \infty} \int_{\partial \Omega_n} Z(x) W(x) d\omega^{\Omega_n}_{\kappa}(x) = \int_{\partial \Omega} Z(x) d\omega^\kappa(x).
\]
(2.63)

**Proof.** We recall that \( d \in C^2(\overline{\Omega}_r) \) for any \( 0 < r \leq \beta_0 \) and let \( n_0 \in \mathbb{N} \) be such that
\[
\text{dist}(\partial \Omega_n, \partial \Omega) < \frac{\beta_0}{2} \quad \forall n \geq n_0.
\]
For \( n \geq n_0 \) let \( w_n \) be the solution of
\[
L_{\kappa}^{\Omega_n}w_n = 0 \quad \text{in} \ \Omega_n
\]
\[
w_n = W \quad \text{on} \ \partial \Omega_n.
\]
(2.64)
It is straightforward to see that the proof of **Propositions 2.17 and 2.18** it is inferred that there exists a positive constant \( c_{44} = c_{44}(\Omega, \kappa) \) such that
\[
\|w_n\|_{L^\infty(\Omega_n)} \leq c_{44} \quad \forall n \geq n_0.
\]
Furthermore
\[
w_n(x_0) = \int_{\partial \Omega_n} W(x) d\omega^{\Omega_n}_{\kappa}(x) < c_{45}.
\]
(2.65)

We extend \( \omega^{\Omega_n}_{\kappa} \) as a Borel measure on \( \overline{\Omega} \) by setting \( \omega^{\Omega_n}_{\kappa}(\overline{\Omega} \setminus \Omega_n) = 0 \), and keep the notation \( \omega^{\Omega_n}_{\kappa} \) for the extension. Because of (2.65) the sequence \( \{W \omega^{\Omega_n}_{\kappa}\} \) is bounded in the space \( \mathcal{M}_b(\overline{\Omega}) \) of bounded Borel measures in \( \overline{\Omega} \). Thus there exists a subsequence still denoted by \( \{W(x) \omega^{\Omega_n}_{\kappa}\} \) which converges narrowly to some positive measure, say \( \widetilde{\omega} \) which is clearly supported by \( \partial \Omega \) and satisfies \( \|\widetilde{\omega}\|_{\mathcal{M}_b} \leq c_{45} \) as in (2.65). For every \( Z \in C(\overline{\Omega}) \) there holds
\[
\lim_{n \to \infty} \int_{\partial \Omega_n} Z(x) W d\omega^{\Omega_n}_{\kappa} = \int_{\partial \Omega} Z \widetilde{d\omega}.
\]

Let \( \zeta := Z \mid_{\partial \Omega} \) and
\[
z(x) := \int_{\partial \Omega} K_{\kappa}(x, y) \zeta(y) d\omega^\kappa(y).
\]
Then
\[
\lim_{d(x) \to 0} \frac{z(x)}{W(x)} = \zeta \quad \text{and} \quad z(x_0) = \int_{\partial \Omega} \zeta \, d\mu^0.
\]

By Propositions 2.17 and 2.18, \(\frac{z}{W} \in C(\overline{\Omega})\). Since \(\frac{z}{W} \mid_{\partial \Omega_n}\) converges uniformly to \(\zeta\) as \(n \to \infty\), there holds
\[
z(x_0) = \sum_{n \geq 1} z \mid_{\partial \Omega_n} d\mu_0^\infty = \sum_{n \geq 1} W \frac{z \mid_{\partial \Omega_n} W}{W} d\mu_0^\infty \to \int_{\partial \Omega} \zeta \, d\tilde{\omega} \quad \text{as} \quad n \to \infty.
\]

It follows
\[
\begin{align*}
\int_{\partial \Omega} \zeta \, d\tilde{\omega} &= \int_{\partial \Omega} \zeta \, d\mu^0 \quad \forall \zeta \in C(\partial \Omega).
\end{align*}
\]

Consequently \(\tilde{\omega} = d\mu^0\). Because the limit does not depend on the subsequence it follows that the whole sequence \(W(x) d\mu_0^\infty\) converges weakly to \(w\). This implies (2.63). \(\square\)

**Theorem 2.33.** Let \(u\) be a positive \(\mathcal{L}_x\)-harmonic in the domain \(\Omega\). Then \(u \in L^1_{\mu_0}(\Omega)\) and there exists a unique Radon measure \(\mu\) on \(\partial \Omega\) such that
\[
u(x) = \int_{\partial \Omega} K_{\mathcal{L}_x}(x, \xi) d\mu(\xi).
\]

**Proof.** The proof which is presented below follows the ideas of the one of [19, Th 4.3]. Let \(B\) be a relatively closed subset of \(\Omega\). We define
\[
R_u^B(x) := \inf\{\psi(x) : \psi \text{ is nonnegative superharmonic in } \Omega \text{ with } \psi \geq u \text{ on } B\}.
\]

For a closed subset \(F\) of \(\partial \Omega\), we define
\[
\mu^x(F) := \inf\{R^{G^\infty}(x) : F \subset G, \ G \text{ open in } \mathbb{R}^N\}.
\]

The set function \(F \mapsto \mu^x(F)\) defines a regular Borel measure on \(\partial \Omega\) for each fixed \(x \in \Omega\). Since \(x \mapsto \mu^x(F)\) is a positive \(\mathcal{L}_x\)-harmonic function in \(\Omega\) the measures \(\mu^x\) are absolutely continuous with respect to \(\mu^0\) by Harnack’s inequality. Hence,
\[
\mu^x(F) = \int_F d\mu^x(F)(y) = \int_F \frac{d\mu^x(F)}{d\mu^0(F)} d\mu^0(F).
\]

We assert that \(\frac{d\mu^x(y)}{d\mu^0(y)} = K_{\mathcal{L}_x}(x, y)\) for \(\mu^0\) a.e. \(y \in \partial \Omega\). By Besicovitch’s theorem,
\[
\frac{d\mu^x(y)}{d\mu^0(y)} = \lim_{r \to 0} \frac{\mu^x(\Delta_r(y))}{\mu^0(\Delta_r(y))},
\]

for \(\mu^0\) a.e. \(y \in \partial \Omega\).

By Lemma 2.31 and in view of the proof of Proposition 2.27 we have that \(\frac{d\mu^x(F)}{d\mu^0(F)}\) is a kernel function, and by uniqueness of Kernel functions the proof of the assertion follows. Hence
\[
\mu^x(A) = \int_A K_{\mathcal{L}_x}(x, y) d\mu^0(y),
\]

for all Borel \(A \subset \partial \Omega\) and in particular
\[
u(x) = \mu^x(\partial \Omega) = \int_{\partial \Omega} K_{\mathcal{L}_x}(x, y) d\mu^0(y).
\]

Suppose now
\[
u(x) = \int_{\partial \Omega} K_{\mathcal{L}_x}(x, y) d\nu(y),
\]

for a Borel measure \(\nu\) on \(\partial \Omega\). For a closed set \(F \subset \partial \Omega\) we will show that \(\nu(F) = \mu^0(F)\).

Choose a sequence of open set \(\{G_k\}\) in \(\mathbb{R}^N\) such that \(\bigcap_{k=1}^\infty G_k = F\) and
\[
\mu^0(F) = \lim_{k \to \infty} R_u^{G_k}(x).
\]

Since
\[
R_u^B(x) \leq R_u^{G_k}(x) \quad \text{if} \quad B \subset A,
\]
we can choose $G_k$ such that $\overline{G}_{k+1} \subset G_k$, $\forall k \geq 1$ and $\Omega \setminus G_k$ to be a $C^2$ domain for all $k \geq 1$. We consider an increasing sequence of bounded smooth domains $\{\Omega_k\}$ such that $\overline{\Omega}_k \subset \Omega_{k+1}$, $\cup \Omega_k = \Omega$, $\Omega_k \cap G_k = \emptyset$, $\mathcal{H}^{N-1}(\Omega_k) \rightarrow \mathcal{H}^{N-1}(\Omega)$ and $\mathcal{H}^{N-1}(\overline{\Omega}_k \cap \overline{G}_k) \rightarrow \mathcal{H}^{N-1}(F)$.

Let $w^{\xi}_{\Omega_k}$ be the $L_\infty$-harmonic measure on $\partial \Omega_k$ (see (2.59)-(2.62)). Then

$$R^\alpha_u(x) = \int_{\partial \Omega_k} R^\alpha_u(y) d\omega^{\xi}_{\partial \Omega_k}(y) = \int_{\partial \Omega_k \cap \partial G_k} u(y) d\omega^{\xi}_{\partial \Omega_k}(y) = \int_{\partial \Omega_k \cap \partial G_k} K_\xi(y, \xi) d\nu(\xi) d\omega^{\xi}_{\partial \Omega_k}(y) = \int_{\partial \Omega_k \cap \partial G_k} K_\xi(y, \xi) d\omega^{\xi}_{\partial \Omega_k}(y) d\nu(\xi) \geq \int_{F_n} \int_{\partial \Omega_k \cap \partial G_k} K_\xi(y, \xi) d\omega^{\xi}_{\partial \Omega_k}(y) d\nu(\xi),$$

where $F_n \subset F$, $\cup F_n = F$ and dist$(F_n, \partial \Omega \setminus F) > \frac{1}{n}$. If $\xi \in F_n$ we have

$$K(x_0, \xi) = \int_{\partial \Omega_k \cap \partial G_k} K_\xi(y, \xi) d\omega^{\xi}_{\partial \Omega_k}(y) + \int_{\partial \Omega_k \setminus \partial G_k} K_\xi(y, \xi) d\omega^{\xi}_{\partial \Omega_k}(y).$$

But

$$K(y, \xi) \leq \frac{C}{n^{N+\omega_\xi-2}} d^{\frac{\omega_\xi}{\omega_\xi}}(y) \forall y \in \partial \Omega_k \setminus G_k,$$

thus by Proposition 2.32 we have that

$$\lim_{k \to \infty} \int_{\partial \Omega_k \setminus G_k} K_\xi(y, \xi) d\omega^{\xi}_{\partial \Omega_k}(y) = 0.$$

Combining all the above inequality and using Lebesgue's dominated convergence theorem we obtain

$$\mu^{\xi}(F) = \lim_{k \to \infty} R^\alpha_u(x) \geq \int_{F_n} \int_{\partial \Omega_k \cap \partial G_k} K_\xi(x_0, \xi) d\nu(\xi) = \nu(F_n),$$

which implies

$$\mu^{\xi}(F) \geq \nu(F).$$

For the opposite inequality, let $m \leq k - 1$, $k \geq 2$ then

$$R^\alpha_u(x) = \int_{\partial \Omega_k} R^\alpha_u(y) d\omega^{\xi}_{\partial \Omega_k}(y) = \int_{\partial \Omega_k \cap \partial G_m} R^\alpha_u(y) d\omega^{\xi}_{\partial \Omega_k}(y) + \int_{\partial \Omega_k \setminus \partial G_m} R^\alpha_u(y) d\omega^{\xi}_{\partial \Omega_k}(y).$$

In view of the proof of Lemma 2.31, we have that

$$R^\alpha_u(x) \leq Cd^{\frac{\omega_\xi}{\omega_\xi}}(x) \forall x \in \Omega \setminus G_m.$$

Thus by Proposition 2.32 we have

$$\lim_{k \to \infty} \int_{\partial \Omega_k \setminus \partial G_m} R^\alpha_u(y) d\omega^{\xi}_{\partial \Omega_k}(y) = 0.$$
and
\[
\int_{\partial \Omega_j \cap \partial \Omega_m} R_u^x(y) d\omega^x_{\Omega_j}(y) \leq \int_{\partial \Omega_j \cap \partial \Omega_m} u(y) d\omega^x_{\Omega_j}(y) = \int_{\partial \Omega_j \cap \partial \Omega_m} K_{\xi}(y, \xi) d\nu(\xi) d\omega^x_{\Omega_j}(y) = \int_{\partial \Omega_j} \int_{\partial \Omega_m} K_{\xi}(y, \xi) d\omega^x_{\Omega_j}(y) d\nu(\xi).
\]

If \( \xi \in \partial \Omega \setminus \overline{\Omega}_m \) we have again by Proposition 2.32 that
\[
\lim_{k \to \infty} \int_{\partial \Omega_j \cap \partial \Omega_m} K_{\xi}(y, \xi) d\omega^x_{\Omega_j}(y) = 0.
\]

If \( \xi \in \partial \Omega \cap \overline{\Omega}_m \), then
\[
\int_{\partial \Omega_j \cap \partial \Omega_m} K_{\xi}(y, \xi) d\omega^x_{\Omega_j}(y) \leq K_{\xi}(x_0, \xi).
\]

Combining all the above inequalities, we obtain
\[
\mu(\mathcal{F}) = \lim_{k \to \infty} R_u^x(x) \leq \int_{\partial \Omega \cap \overline{\Omega}_m} K_{\xi}(x_0, \xi) d\nu(\xi) = \nu(\partial \Omega \cap \overline{\Omega}_m),
\]

which implies
\[
\mu(\mathcal{F}) \leq \nu(\mathcal{F}),
\]

and the proof of Theorem follows. \(\square\)

Actually the measure \( \mu \) is the boundary trace of \( u \). This boundary trace can be achieved in a dynamic way as in [26, Section 2]. In the same way as the one they develop therein, we have

**Proposition 2.34.** Let \( x_0 \in \Omega_1 \) and \( \mu \in \mathcal{M}(\partial \Omega) \). Put
\[
v := \int_{\partial \Omega} K_{\xi}(x, y) d\mu(y),
\]
then for every \( Z \in C(\overline{\Omega}) \),
\[
\lim_{n \to \infty} \int_{\partial \Omega_n} Z(x) d\omega^x_{\Omega_n} = \int_{\partial \Omega} Z(x) d\mu.
\] (2.66)

**Proof.** The proof is same as the proof of Lemma 2.2 in [26] and we omit it. \(\square\)

The next result is an analogous of the Green formula for positive \( \mathcal{L}_x \)-harmonic functions.

**Proposition 2.35.** Let \( v \) be a positive \( \mathcal{L}_x \)-harmonic function in \( \Omega \) with boundary trace \( \mu \). Let \( Z \in C^2(\overline{\Omega}) \) and \( \tilde{G} \in C(\Omega) \) which coincides with \( G_{\mathcal{L}_x}(x_0, \cdot) \) in \( \Omega_\delta \) for some \( 0 < \delta < \beta_0 \) and some \( x_0 \notin \overline{\Omega}_\beta_0 \). Assume
\[
|\nabla \tilde{G} \cdot \nabla Z| \leq c_{\delta\mu} \phi_x.
\] (2.67)

Then, if we set \( \zeta = Z \tilde{G}, \) there holds
\[
\int_{\Omega} v \mathcal{L}_x \zeta dx = \int_{\partial \Omega} Z d\mu.
\] (2.68)

**Proof.** Let \( \{ \Omega_j \} \) be a smooth exhaustion of \( \Omega \) with Green kernel \( G_{\mathcal{L}_x}^{\Omega_j} \) and Poisson kernel \( \mathcal{P}_{\mathcal{L}_x}^{\Omega_j} = -\partial_n G_{\mathcal{L}_x}^{\Omega_j} \). We assume that \( j \geq j_0 \) where \( \overline{\Omega}_\delta \subset \Omega_j \). Set \( \xi_j = Z \tilde{G}, \) where the functions \( \tilde{G}_j \) are \( C^\infty \) in \( \Omega_j \), coincide with \( G_{\mathcal{L}_x}^{\Omega_j}(x_0, \cdot) \) in \( \Omega_j \cap \overline{\Omega}_\delta \) and satisfy \( \tilde{G}_j \to \tilde{G} \) in \( C^2(\Omega) \)-loc and such that \( |\nabla \tilde{G}_j \cdot \nabla Z| \leq c_{\delta\mu} \phi_x \).
\[
\int_{\Omega_j} v \mathcal{L}_x \zeta dx = \int_{\partial \Omega_j} v \frac{\partial \tilde{G}}{\partial n} dS = -\int_{\partial \Omega_j} v \frac{\partial \tilde{G}_j}{\partial n} dS = \int_{\partial \Omega_j} v \mathcal{P}_{\mathcal{L}_x}^{\Omega_j}(x_0, \cdot) dS = \int_{\partial \Omega_j} vZ \mathcal{P}_{\mathcal{L}_x}^{\Omega_j}(x_0, \cdot) dS.
\]
By (2.66)
\[ \int_{\partial \Omega} v Z d \omega^m_{\mu} \to \int_{\partial \Omega} Z(x) d \mu \quad \text{as } j \to \infty. \]

Next
\[ \mathcal{L}_\kappa \zeta = Z \mathcal{L}_\kappa \tilde{c}_j + \tilde{c}_j \Delta Z + 2 \nabla \tilde{c}_j \cdot \nabla Z. \]

Since \( v \in L^1_\psi (\Omega) \), the proof follows. \( \square \)

Similarly we can prove

**Proposition 2.36.** Let \( v \) be a positive \( \mathcal{L}_\kappa \)-harmonic function in \( \Omega \) with boundary trace \( \mu \). Let \( 0 \leq Z \in C^2(\overline{\Omega}) \) satisfy
\[ |\nabla \phi \cdot \nabla Z| \leq c_{45} \phi. \]

Then, if we set \( \xi = Z \phi \), there holds
\[ \int_{\Omega} v \mathcal{L}_\kappa \xi \, dx \geq c_0 \int_{\Omega} Z d \mu, \]
where the constant \( c_0 > 0 \) depends on \( \Omega \), \( N \) and \( \kappa \).

3. The nonlinear problem with measures data

3.1. The linear boundary value problem with \( L^1 \) data

In the sequel we denote by \( \omega = \omega^{\kappa_0} \) the \( \mathcal{L}_\kappa \)-harmonic measure in \( \Omega \), for some fixed \( x_0 \in \Omega \) and by \( \mathcal{M}_\psi (\Omega) \) be the space of Radon measures \( v \) in \( \Omega \) such that \( \phi \), \( d|v| \) is a bounded measure. We also denote by \( \mathcal{M}(\partial \Omega) \) the space of Radon measures on \( \partial \Omega \) with respective norms \( \|v\|_{\mathcal{M}_\psi (\Omega)} \) and \( \|\mu\|_{\mathcal{M}(\partial \Omega)} \). Their respective positive cones are denoted by \( \mathcal{M}_+ (\Omega) \) and \( \mathcal{M}^+ (\partial \Omega) \). By Fubini’s theorem and (2.10), for any \( v \in \mathcal{M}_\psi (\Omega) \) we can define
\[ G_{\mathcal{L}_\kappa} [v](x) = \int_{\Omega} G_{\mathcal{L}_\kappa} (x, y) d v(y), \]
and we have
\[ \|G_{\mathcal{L}_\kappa} [v]\|_{L^1_\psi (\Omega)} \leq c_{46} \|v\|_{\mathcal{M}_\psi (\Omega)}. \quad (3.1) \]

If \( \mu \in \mathcal{M}(\partial \Omega) \), we set
\[ K_{\mathcal{L}_\kappa} [\mu](x) = \int_{\partial \Omega} K_{\mathcal{L}_\kappa} (x, y) d \mu(y), \]
\[ \|K_{\mathcal{L}_\kappa} [\mu]\|_{L^1_\psi (\Omega)} \leq c_{47} \|\mu\|_{\mathcal{M}(\partial \Omega)}. \quad (3.2) \]

In the above inequalities \( c_{46} \) and \( c_{47} \) are positive constants depending on \( \Omega \) and \( \kappa \).

For \( 0 < \kappa \leq \frac{1}{4} \), we define the space of test functions \( X(\Omega) \) by
\[ X(\Omega) = \left\{ \eta \in H^1_{\text{loc}}(\Omega) : \frac{\eta}{d} \in H^1(\Omega, d^\kappa d x), \ (\phi \kappa)^{-1} \mathcal{L}_\kappa \eta \in L^\infty(\Omega) \right\}. \quad (3.3) \]

The next statement follows immediately from Propositions 2.9 and 2.10.

**Lemma 3.1.** Let \( 0 < \kappa \leq \frac{1}{4} \). Let \( m \in L^\infty(\Omega) \) and \( \eta_m \) be the solution of
\[ \mathcal{L}_\kappa \eta_m = m \phi \kappa \quad \text{in } \Omega, \]
\[ \eta_m = 0 \quad \text{on } \partial \Omega, \quad (3.4) \]
on obtained by Propositions 2.9 and 2.10 with \( f_0 = m \) and \( h = 0 \). Then \( \eta_m \) belongs to \( X(\Omega) \). Furthermore
\[ - \frac{\|m\|_{L^\infty(\Omega)}}{\lambda_{\kappa}} \phi \kappa \leq - \eta_m \leq \eta_m \leq \eta_m \leq \frac{\|m\|_{L^\infty(\Omega)}}{\lambda_{\kappa}} \phi \kappa. \quad (3.5) \]

In the next proposition we give some key estimates satisfied by weak solutions of
\[ \mathcal{L}_\kappa u = f \quad \text{in } \Omega, \]
\[ u = h \quad \text{on } \partial \Omega. \quad (3.6) \]
Proposition 3.2. For any \((f, h) \in L^1_{\phi_k}(\Omega) \times L^1(\partial \Omega, d\omega)\) there exists a unique \(u := u_{f,h} \in L^1_{\phi_k}(\Omega)\) such that

\[
\int_{\Omega} u_{f,h} \eta dx = \int_{\Omega} f \eta dx + \int_{\Omega} \mathcal{K}_{u_{f,h}} [h\omega] L_\xi \eta dx \quad \forall \eta \in X(\Omega).
\]  \hspace{1cm} (3.7)

There holds

\[
u = \mathcal{G}_{\xi_1}[f] + \mathcal{K}_{u_{f,h}} [h\omega],
\]  \hspace{1cm} (3.8)

and

\[
\|u\|_{L^1_{\phi_k}(\Omega)} \leq c_{46} \|f\|_{L^1_{\phi_k}(\Omega)} + c_{47} \|h\|_{L^1(\partial \Omega, d\omega)}.
\]  \hspace{1cm} (3.9)

Furthermore, for any \(\eta \in X(\Omega), \eta \geq 0\), we have

\[
\int_{\Omega} |u| L_\xi \eta dx \leq \int_{\Omega} f \eta sgn(u) dx + \int_{\Omega} \mathcal{K}_{u_{f,h}} [h\omega] L_\xi \eta dx,
\]  \hspace{1cm} (3.10)

and

\[
\int_{\Omega} u_+ L_\xi \eta dx \leq \int_{\Omega} f \eta sgn_+(u) dx + \int_{\Omega} \mathcal{K}_{u_{f,h}} [h_+\omega] L_\xi \eta dx.
\]  \hspace{1cm} (3.11)

Proof. Step 1: proof of estimate (3.9). Assume \(u\) satisfies (3.7). If \(\eta = \eta_{sgn(u)}\), we have

\[
\int_{\Omega} |u| \phi \eta dx = \int_{\Omega} u L_\xi \eta dx = \int_{\Omega} f \eta dx + \int_{\Omega} \mathcal{K}_{u_{f,h}} [h\omega] sgn(u) \phi \eta dx.
\]

By (3.1), (3.2)

\[
\int_{\Omega} f \eta dx \leq \frac{1}{\kappa_k} \int_{\Omega} |f| \phi \eta dx,
\]

\[
\int_{\Omega} \mathcal{K}_{u_{f,h}} [h\omega] sgn(u) \phi \eta dx \leq c_{47} \int_{\partial \Omega} |h| d\omega,
\]

which implies (3.9) and uniqueness.

Step 2: proof of existence. If \(f\) and \(h\) are bounded, existence follows from Propositions 2.9 and 2.10. In the general case let \(\{(f_n, h_n)\}\) be a sequence of bounded measurable functions in \(\Omega\) and \(\partial \Omega\) which converges to \((f, h)\) in \(L^1_{\phi_k}(\Omega) \times L^1(\partial \Omega, d\omega)\).

Let \(\{u_n\} = \{u_{f_n, h_n}\}\) be the sequence weak solutions of (3.6). By estimate (3.9) it is a Cauchy sequence in \(L^1_{\phi_k}(\Omega)\) which converges to \(u\). Letting \(n \to \infty\) in identity

\[
\int_{\Omega} u_n L_\xi \eta dx = \int_{\Omega} f_n \eta dx + \int_{\Omega} \mathcal{K}_{u_{f_n, h_n}} [h_n\omega] L_\xi \eta dx,
\]  \hspace{1cm} (3.12)

where \(\eta \in X(\Omega)\) implies that \(u = u_{f,h}\).

Step 3: proof of estimates (3.10), (3.11). We first assume that \(f\) is bounded and \(h\) is \(C^2(\overline{\Omega})\). Set \(\Omega_n = \Omega_{\frac{\kappa}{n}}\), let \(u_n\) be the unique solution of

\[
\begin{align*}
L_\xi u_n &= f & \text{in} & \Omega_n \\
u_n &= Wh & \text{on} & \partial \Omega_n.
\end{align*}
\]  \hspace{1cm} (3.13)

Then \(u_n\) can be written in the form

\[
u_n = \mathcal{G}^n_{\xi_1}[f](x) + w_n,
\]

where \(w_n\) satisfies

\[
\begin{align*}
L_\xi v &= 0 & \text{in} & \Omega_n \\
v &= Wh & \text{on} & \partial \Omega_n,
\end{align*}
\]  \hspace{1cm} (3.14)

and

\[
\mathcal{G}^n_{\xi_1}[f](x) = \int_{\Omega} G_{\xi_1}^n (x,y) f(y) dy.
\]

where \(G_{\xi_1}^n\) denotes the Green Kernel of \(L_\xi\) in \(\Omega_n\). Now note that \(G_{\xi_1}^n(x,y) \leq G_{\xi_1}^n(x,y) = G_{\xi_1}^n\), and for any \(x,y \in \Omega, x \neq y\)

\[
G_{\xi_1}^n(x,y) \uparrow G_{\xi_1}(x,y).
\]  \hspace{1cm} (3.15)
Also, in view of the proof of Proposition 2.32, there exists $c_0 > 0$ which depends on $\Omega, N, \kappa, \|h\|_{C^2(\overline{\Omega})}$ such that
\[
\sup_{x \in \Omega_n} |u_n| < c_0, \quad \forall n \in \mathbb{N},
\]
and $w_n \to \kappa_{L^\infty}[h\omega]$. Thus by the properties of Green kernel that we described above, there exists a constant $c_0 \Omega, N, \kappa, \|h\|_{C^2(\overline{\Omega})}, \|f\|_{L^\infty(\Omega)}$, such that
\[
\sup_{x \in \Omega_n} |u_n| < c_0, \quad \forall n \in \mathbb{N},
\]
and
\[
\lim_{n \to \infty} u_n = u = \kappa_{L^\infty}[f] + \kappa_{L^\infty}[h\omega].
\]

Let $\eta \in X(\Omega)$ be nonnegative function and let $\eta_n$ be the solution of the problem
\[
L_{\kappa} v = L_{\kappa}(\eta + \kappa_{L^\infty}[h\omega]) \quad \text{in } \Omega,
\]
\[
v = 0 \quad \text{on } \partial \Omega_n.
\]

Then there exists $c_0 = c_0(\|\Delta\eta\|_{L^\infty(\Omega)}, \kappa, N, \Omega)$ such that $|\eta_n| \leq c_0 \phi_{\kappa}$ and
\[
L_{\kappa} \eta_n \to L_{\kappa} \eta, \quad \eta_n \to \eta.
\]

Let $z_n$ be the solution of
\[
L_{\kappa} v = \text{sgn}(\eta_n) L_{\kappa} \eta \quad \text{on } \partial \Omega_n,
\]
\[
v = 0 \quad \text{on } \partial \Omega_n.
\]

Then $z_n \geq \max(\eta_n, 0)$ since
\[
L_{\kappa} |\eta_n| \leq \text{sgn}(\eta_n) L_{\kappa} \eta_n = \text{sgn}(\eta_n) L_{\kappa} \eta,
\]
and $|z_n| \leq c_0 \phi_{\kappa}$, $L_{\kappa} z_n \to L_{\kappa} \eta$, $z_n \to \eta$.

Now note that $z_n \geq 0$ and $z_n \in C^1(\overline{\Omega})$. Also, the following inequality holds (see e.g. [30]),
\[
\int_{\Omega} |u_n| L_{\kappa} z_n dx \leq \int_{\Omega} f z_n \text{sgn}(u_n) dx - \int_{\partial \Omega} \frac{\partial z_n}{\partial v} |h| W dx
\]
\[
= \int_{\Omega} f z_n \text{sgn}(u_n) dx + \int_{\Omega} \tilde{\omega}_n L_{\kappa} z_n dx.
\]
\[
(3.16)
\]

where $\tilde{\omega}_n$ is the solution of
\[
L_{\kappa} v = 0 \quad \text{in } \Omega,
\]
\[
v = W |h| \quad \text{on } \partial \Omega_n.
\]
\[
(3.17)
\]

In view of the proof of Proposition 2.32 there exists $c_{02} > 0$ which depends on $\Omega, N, \kappa, \|h\|_{C^2(\overline{\Omega})}$ such that
\[
\sup_{x \in \Omega_n} |\tilde{\omega}_n| < c_{02}, \quad \forall n \in \mathbb{N},
\]
and $\tilde{\omega}_n \to \kappa_{L^\infty}[|h|\omega]$ as $n \to \infty$. Thus combining all above and taking the limit in (3.16) we have the proof of (3.10) in the case that $f$ is bounded and $h \in C^2(\overline{\Omega})$. We note here that for any $h \in C^2(\partial \Omega)$ there exists $H_m \in C^2(\overline{\Omega})$, such that $\|H_m\|_{C^2(\overline{\Omega})} \leq c_{03} \|h\|_{L^\infty(\partial \Omega)}$, for some constant $c_{03}$ which depends only on $\Omega$, and $H_m \to h$ in $L^\infty(\partial \Omega)$. Thus it is not hard to prove that (2.32) is valid if $f$ is bounded and $h \in C^2(\partial \Omega)$. In the general case we consider a sequence $(f_n, h_n) \subset L^\infty(\Omega) \times C^2(\partial \Omega)$ which converges to $(f, h)$ in $L^1(\Omega) \times L^1(\partial \Omega, d\omega)$. Since $u_{f_n, h_n}$ converges to $u_{f, h}$ in $L^1_{dx}(\Omega)$ we obtain (3.10) from the inequality verified by any $\eta \in X(\Omega)$
\[
\int_{\Omega} |u_{f_n, h_n}| L_{\kappa} \eta dx \leq \int_{\Omega} f_n \eta \text{sgn}(u) dx + \int_{\Omega} \kappa_{L^\infty}[|h_n|\omega] L_{\kappa} \eta dx.
\]
\[
\square
\]

The proof of (3.11) is follows by adding (3.7) and (3.10).
3.2. General nonlinearities

Throughout this section $\Omega$ is a smooth bounded domain and $\kappa$ a real number in the interval $(0, \frac{1}{2})$. Let $g : \mathbb{R} \mapsto \mathbb{R}$ be a nondecreasing continuous function, vanishing at 0 for simplicity. The problem under consideration is the following

$$-\Delta u - \frac{\kappa}{d^2} u + g(u) = v \quad \text{in } \Omega$$
$$u = \mu \quad \text{in } \partial \Omega,$$

where $v$ and $\mu$ are Radon measures respectively in $\Omega$ and $\partial \Omega$.

**Definition.** Let $u \in \mathcal{M}_g(\Omega)$ and $\mu \in \mathcal{M}(\partial \Omega)$. We say that $u$ is a solution of (3.18) if $u \in L^1(\Omega)$, $g(u) \in L^1(\Omega)$ and for any $\eta \in X(\Omega)$ there holds

$$\int_{\Omega} (u \mathcal{L}_e \eta + g(u) \eta) \, dx = \int_{\Omega} (\eta d\nu + \mathbb{K}_\mathcal{L}_e[\mu] \mathcal{L}_e \eta) \, dx. \tag{3.19}$$

Our main existence result for subcritical nonlinearities is the following.

**Theorem 3.3.** Assume $g$ satisfies

$$\int_1^{\infty} (g(s) - g(-s)) \, s^{-\frac{2-N+\frac{\alpha}{\mu}}{2}} \, ds < \infty. \tag{3.20}$$

Then for any $(v, \mu) \in \mathcal{M}_g(\Omega) \times \mathcal{M}(\partial \Omega)$ problem (3.18) admits a unique solution $u = u_{v,\mu}$. Furthermore the mapping $(v, \mu) \mapsto u_{v,\mu}$ is increasing and stable in the sense that if $\{(v_n, \mu_n)\}$ converge to $(v, \mu)$ in the weak sense of measures, $\{u_{v_n,\mu_n}\}$ converges to $u_{v,\mu}$ in $L^1_g(\Omega)$.

The proof is based upon estimates of $\mathcal{M}_\mathcal{L}_e$ and $\mathbb{K}_\mathcal{L}_e$ into Marcinkiewicz spaces.

**Lemma 3.4.** Let $v \in \mathcal{M}_g^+(\Omega)$, $\mu \in \mathcal{M}^+(\partial \Omega)$ and for $s > 0$, $E_s(v) = \{x \in \Omega : \mathcal{G}_{\mathcal{L}_e}[v](x) > s\}$ and $F_s(\mu) = \{x \in \Omega : \mathbb{K}_\mathcal{L}_e[\mu](x) > s\}$. If we denote

$$E_s(v) = \int_{E_s(v)} \phi_s \, dx \quad \text{and} \quad F_s(\mu) = \int_{F_s(\mu)} \phi_s \, dx,$$

there holds

$$E_s(v) + F_s(\mu) \leq c_{47} \left( \frac{\|v\|_{\mathcal{M}_g} + \|\mu\|_{\mathcal{M}(\partial \Omega)}}{s} \right)^{\frac{N+\frac{\alpha}{\mu}}{N-2+\frac{\alpha}{\mu}}}. \tag{3.21}$$

**Proof.** Step 1: estimate of $F_s(v)$. By estimate (2.57), for any $\xi \in \partial \Omega$,

$$F_s(\delta_\xi) \subset \tilde{F}_s(\delta_\xi) := \left\{ x \in \Omega : \frac{d^{\frac{\alpha}{\mu}}(x)}{|x - \xi|^{N+\frac{\alpha}{\mu}-2}} \geq \frac{s}{c_{48}} \right\} \subset B\left(\frac{\delta_\xi}{c_{48}}\right)^{\theta}(\xi),$$

with $\theta = \frac{1}{N-2+\frac{\alpha}{\mu}}$. From (2.2), (2.3)

$$F_s(\delta_\xi) \leq \int_{B\left(\frac{\delta_\xi}{c_{48}}\right)^{\theta}(\xi)} \phi_s \, dx \leq c_{49} \int_{B\left(\frac{\delta_\xi}{c_{48}}\right)^{\theta}(\xi)} |x - \xi|^{-\frac{\alpha}{\mu}} \, dx = c_{50}s^{-\frac{N+\frac{\alpha}{\mu}}{N-2+\frac{\alpha}{\mu}}}.$$

Therefore, for any $s_0 > 0$ and any Borel set $G \subset \Omega$

$$\int_G K_{\mathcal{L}_e}(x, \xi) \phi_s \, dx \leq s_0 \int_G \phi_s \, dx + \int_{F_{s_0}(\delta_\xi)} K_{\mathcal{L}_e}(x, \xi) \phi_s \, dx \leq s_0 \int_G \phi_s \, dx - \int_{s_0}^{\infty} s dF_s(\delta_\xi) \leq s_0 \int_G \phi_s \, dx + c_{50} \int_{s_0}^{\infty} s^{\frac{N+\frac{\alpha}{\mu}}{N-2+\frac{\alpha}{\mu}}} \, ds \leq s_0 \int_G \phi_s \, dx + c_{51}s_0^{-\frac{2}{N-2+\frac{\alpha}{\mu}}}.$$
Next we choose $s_0$ so that the two terms in the right part of the last inequality are equal and we get

$$\int_{G} K_{x_\xi}(x, \xi) \phi_x \, dx \leq c_{52} \left( \int_{G} \phi_x \, dx \right)^{\frac{2}{N+a-2}}.$$

(3.22)

Henceforth, for any $\mu \in \mathcal{M}(\partial \Omega)$, there holds by Fubini’s theorem,

$$\int_{G} \mathcal{K}_{x_\xi} [\mu \mu] \phi_x \, dx = \int_{G} \int_{\Omega} K_{x_\xi}(x, \xi) \phi_x(x) \mu(\xi) \mu(\xi) \, dx \leq c_{52} \|\mu\|_{\mathcal{M}(\partial \Omega)} \left( \int_{G} \phi_x \, dx \right)^{\frac{2}{N+a-2}}.$$  

(3.23)

If we take in particular $G = F_1(\{\mu\})$, we derive

$$sF_1(\{\mu\}) \leq c_{52} \|\mu\|_{\mathcal{M}(\partial \Omega)} (sF_1(\{\mu\}))^{\frac{2}{N+a-2}},$$

which yields to (3.21) with $v = 0$.

Step 2: estimate of $E_s(\nu)$. By estimate (2.10), for any $y \in \Omega$.

$$E_s(\delta_y) \subset \tilde{E}_s(\delta_y) := \left\{ x \in \Omega : \frac{d_{\mathcal{A}}^+ (y) d_{\mathcal{A}}^+ (x)}{|x-y|^{N+a-2}} \geq \frac{s}{c_s} \right\} \cap \left\{ x \in \Omega : \frac{1}{|x-y|^{N-2}} \geq \frac{s}{c_s} \right\}.$$

A simple geometric verification shows that there exists an open domain $\Theta \subset \tilde{\Theta} \subset \Omega$ such that $y \in \Theta$, $\text{dist}(y, \Theta^c) > \lambda_1 d(y)$, $\Theta \subset B_{\frac{\lambda_1}{2}d(y)}(y)$ for some $0 < \lambda_1 < \lambda_2 < 1$ independent of $y$ with the following properties

$$x \in \Theta \implies \frac{d_{\mathcal{A}}^+ (y) d_{\mathcal{A}}^+ (x)}{|x-y|^{N+a-2}} \leq \frac{1}{|x-y|^{N-2}}$$

and

$$x \in \Theta^c \implies \frac{d_{\mathcal{A}}^+ (y) d_{\mathcal{A}}^+ (x)}{|x-y|^{N+a-2}} \leq \frac{1}{|x-y|^{N-2}}.$$

Notice that if $\Omega = \mathbb{R}^N_+$ then $\Theta = B_{\frac{\lambda_1}{2}d(y)}$ where $d(y) = \frac{\lambda_1}{2}d(y)$. Set

$$\tilde{E}_s^1(\delta_y) = \left\{ x \in \Omega : \frac{1}{|x-y|^{N-2}} \geq \frac{s}{c_s} \right\} \cap \Theta,$$

and

$$\tilde{E}_s^2(\delta_y) = \left\{ x \in \Omega \setminus \Theta : \frac{d_{\mathcal{A}}^+ (y) d_{\mathcal{A}}^+ (x)}{|x-y|^{N+a-2}} \geq \frac{s}{c_s} \right\}.$$

We can easily prove

$$E_s(\delta_y) = \int_{E_s(\delta_y)} \phi_x \, dx \leq \int_{E_s(\delta_y)} \phi_x \, dx$$

$$\leq \int_{\tilde{E}_s^1(\delta_y)} \phi_x \, dx + \int_{\tilde{E}_s^2(\delta_y)} \phi_x \, dx \leq c_{53}s \left[ \frac{d_{N+a-2}^+}{d_{N+a-2}^+} (d(y)) \right] \frac{u_s(\frac{N+a-2}{N+a-2})}{s}.$$

As in step 1, for any Borel subset $\Theta \subset \Omega$, we write

$$\int_{\Theta} G_{x_\xi}(x, y) \phi_x \, dx \leq s_0 \int_{\Theta} \phi_x \, dx + \int_{E_s(\delta_y)} G_{x_\xi}(x, y) \phi_x \, dx$$

$$\leq s_0 \int_{\Theta} \phi_x \, dx - \int_{s_0}^{\infty} s dE_s(\delta_y)$$

$$\leq s_0 \int_{\Theta} \phi_x \, dx + c_{53} (d(y)) \left[ \frac{u_s(\frac{N+a-2}{N+a-2})}{s} \right] \frac{2}{s \left[ \frac{N+a-2}{N+a-2} \right]} ds$$

$$\leq s_0 \int_{\Theta} \phi_x \, dx + c_{54} (d(y)) \left[ \frac{u_s(\frac{N+a-2}{N+a-2})}{s} \right] \frac{2}{s \left[ \frac{N+a-2}{N+a-2} \right]}.$$
Then
\[
\int_{\Omega} G_{\mathcal{L}_x}(x, y) \phi_x \, dx \leq c_{S5}(d(y))^\frac{\alpha}{2} \left( \int_{\Omega} \phi_x \, dx \right)^{\frac{2}{N+\alpha}} \leq c_{S6} \phi_x(y) \left( \int_{\Omega} \phi_x \, dx \right)^{\frac{2}{N+\alpha}}. \tag{3.24}
\]
Thus, for any \( v \in \mathcal{M}_{\phi_x}(\Omega) \), we have
\[
\int_{\Omega} G_{\mathcal{L}_x}(x, y) \phi_x \, dx = \int_{\Omega} \int_{\Omega} G_{\mathcal{L}_x}(x, y) \phi_x(x) \, dx \, dy \leq c_{S5} \| v \|_{\mathcal{M}_{\phi_x}(\Omega)} \left( \int_{\Omega} \phi_x \, dx \right)^{\frac{2}{N+\alpha}}. \tag{3.25}
\]
Thus (3.21) holds. \( \square \)

**Proof of Theorem 3.3.** Step 1: existence and uniqueness. Let \( \{(v_n, \mu_n)\} \subset C^{1}(\Omega) \times C^1(\partial \Omega) \) which converges to \((v, \mu)\) in the weak sense of measures in \( \mathcal{M}_{\phi_x}(\Omega) \times \mathcal{M}(\partial \Omega) \). Set \( v_n = \mathbb{K}_{\mathcal{L}_x}[\mu_n \omega] \), then \( v_n \in L^\infty(\Omega) \) and it is \( \mathcal{L}_x \)-harmonic. Set \( \tilde{g}(t, x) = g(t + v_n(x)) - g(v_n(x)) \) and \( f(x) = v_n(x) - g(v_n(x)) \). Let \( J \) be the functional defined in \( L^2(\Omega) \) by the expression
\[
J(v) = \frac{1}{2} \int_{\Omega} |\nabla v|^2 - \frac{K}{d^2} w^2 + 2f(v) \, dx - \int_{\Omega} \tilde{g} \phi_x \, dx,
\]
where \( J(w) = \int_0^w \tilde{g}(t) \, dt \) with domain
\[
D(J) = \{ w \in H_1(\Omega) \cup J(w) \in L^1(\Omega) \}.
\]
(see definition in 2.1–5). By (2.8), \( J_x \) is a convex lower semicontinuous and coercive functional over \( L^2(\Omega) \). Let \( w_n = w_{\nu_n, \mu_n} \) be its minimum, then \( u_n = u_{\nu_n, \mu_n} = w_n + v_n \) is the solution of
\[
\mathcal{L}_x u_n + g(u_n) = v_n \quad \text{in} \quad \Omega,
\]
\[
u_n = \mu_n \quad \text{in} \quad \partial \Omega,
\]
and for any \( \eta \in X(\Omega) \), there holds
\[
\int_{\Omega} (u_n \mathcal{L}_x \eta + g(u_n) \eta) \, dx = \int_{\Omega} (v_n \eta + \mathbb{K}_{\mathcal{L}_x}[\mu_n \omega] \mathcal{L}_x \eta) \, dx. \tag{3.28}
\]
By Proposition 3.2 (3.10), there holds, with \( \eta = \phi_x \),
\[
\int_{\Omega} (\partial_x |u_n| + |g(u_n)|) \phi_x \, dx \leq \int_{\Omega} (|v_n| + \mathbb{K}_{\mathcal{L}_x}[|\mu_n| \omega]) \phi_x \, dx \leq c_{46} \| v_n \|_{\mathcal{M}_{\phi_x}(\Omega)} + c_{47} \| \mu_n \|_{\mathcal{M}_{\phi_x}(\Omega)} \tag{3.29}
\]
Moreover
\[
-\mathbb{G}_{\mathcal{L}_x}[v_n^+ - \mathbb{K}_{\mathcal{L}_x} \mu_n \omega] \leq u_n \leq \mathbb{G}_{\mathcal{L}_x}[v_n^+] + \mathbb{K}_{\mathcal{L}_x} \mu_n \omega]. \tag{3.30}
\]
By using the local \( L^1 \) regularity theory for elliptic equations we obtain that the sequence \( \{u_n\} \) is relatively compact in the \( L^1 \)-local topology in \( \Omega \) and that there exist a subsequence still denoted by \( \{u_n\} \) and a function \( u \in L^1_{\phi_x}(\Omega) \) such that \( u_n \to u \) a.e. in \( \Omega \). By (3.30)
\[
|g(u_n)| \leq g \left( \mathbb{G}_{\mathcal{L}_x}[v_n^+] + \mathbb{K}_{\mathcal{L}_x} \mu_n \omega \right) - g \left( -\mathbb{G}_{\mathcal{L}_x}[v_n^+] - \mathbb{K}_{\mathcal{L}_x} \mu_n \omega \right). \tag{3.31}
\]
We prove the convergence of \( |g(u_n)| \) to \( |g(u)| \) in \( L^1_{\phi_x}(\Omega) \) by the uniform integrability in the following way: let \( G \subset \Omega \) be a Borel subset. Then for any \( s_0 > 0 \)
\[
\int_G |g(u_n)| \phi_x \, dx \leq \int_G \left( g \left( \mathbb{G}_{\mathcal{L}_x}[v_n^+] \right) + g \left( \mathbb{K}_{\mathcal{L}_x} \mu_n \omega \right) - g \left( -\mathbb{G}_{\mathcal{L}_x}[v_n^+] \right) - g \left( -\mathbb{K}_{\mathcal{L}_x} \mu_n \omega \right) \right) \phi_x \, dx \leq s_0 \int \phi_x \, dx + \int_{E_{\phi_x}(v_n^+)} g \left( \mathbb{G}_{\mathcal{L}_x}[v_n^+] \right) \phi_x \, dx + \int_{E_{\phi_x}(\mu_n^+)} g \left( \mathbb{K}_{\mathcal{L}_x} \mu_n \omega \right) \phi_x \, dx \leq s_0 \int \phi_x \, dx - \int_{s_0}^{\infty} g(s) (dE_{\phi_x}(v_n^+)) + d\mathcal{F}_{\phi_x}(\mu_n^+) + \int_{s_0}^{\infty} g(-s) (dE_{\phi_x}(v_n^-)) + d\mathcal{F}_{\phi_x}(\mu_n^-)).
\]
But
\[- \int_0^\infty g(s)de_i(v_n^+) = g(s_0)e_i_0(v_n^+) + \int_0^\infty e_i(v_n^+)dg(s) \]
\[\leq g(s_0)e_i_0(v_n^+) + c_{47} \left( \|v_n^+\|_{\mathcal{M}_{\mathcal{B}}(\Omega)} \right)^{\frac{N+\frac{\alpha_+}{2}}{N-2+\frac{\alpha_+}{2}}} \int_0^\infty s^{-\frac{N+\frac{\alpha_+}{2}}{N-2+\frac{\alpha_+}{2}}}dg(s) \]
\[\leq \frac{2N+\alpha_+}{2N-4+\alpha_+}c_{47} \left( \|v_n^+\|_{\mathcal{M}_{\mathcal{B}}(\Omega)} \right)^{\frac{N+\frac{\alpha_+}{2}}{N-2+\frac{\alpha_+}{2}}} \int_0^\infty s^{-\frac{N+\frac{\alpha_+}{2}}{N-2+\frac{\alpha_+}{2}}}g(s)ds. \]

All the other terms yield similar estimates which finally yields to
\[\int_G |g(u_n)|\phi dx \leq s_0 \int_G \phi dx \]
\[+ c_{58} \left( \|v_n\|_{\mathcal{M}_{\mathcal{B}}(\Omega)} + \|\mu_n\|_{\mathcal{M}_{\mathcal{B}}(\Omega)} \right)^{\frac{N+\frac{\alpha_+}{2}}{N-2+\frac{\alpha_+}{2}}} \int_0^\infty s^{-\frac{N+\frac{\alpha_+}{2}}{N-2+\frac{\alpha_+}{2}}} (g(s) - g(-s))ds. \] \tag{3.32}

Since \(\|v_n\|_{\mathcal{M}_{\mathcal{B}}(\Omega)} + \|\mu_n\|_{\mathcal{M}_{\mathcal{B}}(\Omega)}\) is bounded independently of \(n\), we obtain easily, using (3.20) and fixing \(s_0\) first, that for any \(\epsilon > 0\), there exists \(\delta > 0\) such that
\[\int_G \phi dx \leq \delta \implies \int_G |g(u_n)|\phi dx \leq \epsilon. \] \tag{3.33}

Since
\[|u_n| \leq G_{L_\kappa}[|v_n|] + K_{L_\kappa}[|\mu_n|\omega], \]
we have by (3.23), (3.25)
\[\int_G |u_n|\phi dx \leq \left( c_{52}\|\mu_n\|_{\mathcal{M}_{\mathcal{B}}(\Omega)} + c_{55}\|v_n\|_{\mathcal{M}_{\mathcal{B}}(\Omega)} \right) \left( \int_G \phi dx \right)^{\frac{\frac{\alpha_+}{2}}{\frac{N+\frac{\alpha_+}{2}}{2}}} \tag{3.34} \]

This implies the uniform integrability of the sequence \(\{u_n\}\). Letting \(n \to \infty\) in identity (3.28), we conclude that (3.19) holds. Uniqueness, as well as the monotonicity of the mapping \((v, \mu) \mapsto u_{v,\mu}\), is an immediate consequence of (3.10), (3.11) and the monotonicity of \(g\).

**Step 2: stability.** The stability is a direct consequence of inequalities (3.32) and (3.34) which show the uniform integrability of the sequence \((u_n, g(u_n))\) in \(L^1_{\mathcal{B}}(\Omega) \times L^1_{\mathcal{B}}(\Omega)\). \(\square\)

Because of the uniqueness of the solution \(u_{v,\mu}\) of problem (3.18) and the fact that \(g(u_{\mu,v}) \in L^1_{\mathcal{B}}(\Omega)\) the following representation statement is valid, and its proof is obtained by approximation of the measures as is [28, Lemma 3.2, Definition 3.3].

**Proposition 3.5.** Let \((v, \mu) \in \mathcal{M}_{\mathcal{B}}(\Omega) \times \mathcal{M}(\partial \Omega)\) such that problem (3.18) admits a solution \(u_{v,\mu}\). Then
\[u_{\mu,v} = -G_{L_\kappa}[g(u_{\mu,v})] + K_{L_\kappa}[\mu]. \] \tag{3.35}

Conversely, if \(u \in L^1_{\mathcal{B}}(\Omega)\) such that \(g(u) \in L^1_{\mathcal{B}}(\Omega)\) satisfies (3.35), it coincides with the solution \(u_{v,\mu}\) of problem (3.18).

### 3.3. The power case

In this section we study in particular the following boundary value problem with \(\mu \in \mathcal{M}(\partial \Omega)\)
\[\mathcal{L}_\kappa u + |u|^{q-1}u = 0 \quad \text{in} \quad \Omega \]
\[u = \mu \quad \text{in} \quad \partial \Omega. \] \tag{3.36}

A Radon measure for which this problem has a solution (always unique) is called a *good measure*. The solution, whenever it exists, is unique and denoted by \(u_{\mu}\). For such a nonlinearity, the condition (3.20) is fulfilled if and only if
\[0 < q < q_c := \frac{N+\frac{\alpha_+}{2}}{N-2+\frac{\alpha_+}{2}}. \] \tag{3.37}

On the contrary, in the *supercritical case* i.e. if \(q \geq q_c\), a continuity condition with respect to some Besov capacity is needed in order a measure be good. We recall some notations concerning Besov space. For \(\sigma > 0, 1 \leq p < \infty\), we denote by \(W^{\sigma,p}(\mathbb{R}^d)\)
the Sobolev space over \( \mathbb{R}^d \). If \( \sigma \) is not an integer the Besov space \( B^{s,p}(\mathbb{R}^d) \) coincides with \( W^{s,p}(\mathbb{R}^d) \). When \( \sigma \) is an integer we denote \( \Delta_{x,y}f = f(x+y) + f(x-y) - 2f(x) \) and

\[
B^{1,p}(\mathbb{R}^d) = \left\{ f \in L^p(\mathbb{R}^d) : \frac{\Delta_{x,y}f}{|y|^{1+p}} \in L^p(\mathbb{R}^d \times \mathbb{R}^d) \right\},
\]

with norm

\[
\|f\|_{B^{1,p}} = \left( \|f\|_p^p + \int \int_{\mathbb{R}^d \times \mathbb{R}^d} \frac{|\Delta_{x,y}f|^p}{|y|^{p+1}} \, dx \, dy \right)^{\frac{1}{p}}.
\]

Then

\[
B^{m,p}(\mathbb{R}^d) = \left\{ f \in W^{m-1,p}(\mathbb{R}^d) : D_x^\alpha f \in B^{1,p}(\mathbb{R}^d) \ \forall \alpha \in \mathbb{N}^d |\alpha| = m - 1 \right\},
\]

with norm

\[
\|f\|_{B^{m,p}} = \left( \|f\|_{W^{m-1,p}}^p + \sum_{|\alpha|=m-1} \int \int_{\mathbb{R}^d \times \mathbb{R}^d} \frac{|D_x^\alpha f|^p}{|y|^{p+|\alpha|}} \, dx \, dy \right)^{\frac{1}{p}}.
\]

These spaces are fundamental because they are stable under the real interpolation method developed by Lions and Peetre. For \( \alpha \in \mathbb{R} \) we defined the Bessel kernel of order \( \alpha \) by \( G_\alpha(\xi) = \mathcal{F}^{-1}(1 + |.|^2)^{-\frac{\alpha}{2}} \mathcal{F}(\xi) \), where \( \mathcal{F} \) is the Fourier transform of moderate distributions in \( \mathbb{R}^d \). The Bessel space \( L_{1,p}(\mathbb{R}^d) \) is defined by

\[
L_{1,p}(\mathbb{R}^d) = \{ f = G_\alpha * g : g \in L^p(\mathbb{R}^d) \},
\]

with norm

\[
\|f\|_{L_{1,p}} = \|g\|_p = \|G_\alpha * f\|_p.
\]

It is known that if \( 1 < p < \infty \) and \( \alpha > 0 \), \( L_{1,p}(\mathbb{R}^d) = W^{\alpha,p}(\mathbb{R}^d) \) if \( \alpha \in \mathbb{N} \) and \( L_{1,p}(\mathbb{R}^d) = B^{\alpha,p}(\mathbb{R}^d) \) if \( \alpha \notin \mathbb{N} \), always with equivalent norms. The Bessel capacity is defined for compact subset \( K \subset \mathbb{R}^d \) by

\[
C_{\alpha,p}^{\mathbb{R}^d}(K) = \inf \{ \|f\|_{L_{1,p}}^p, f \in \mathcal{D}'(\mathbb{R}^d), f \geq \chi_K \}.
\]

It is extended to open set and then any set by the fact that it is an outer measure. Our main result is the following.

**Theorem 3.6.** Assume \( 0 < \kappa \leq \frac{1}{4} \). Then \( \mu \in \mathcal{M}^+ (\partial \Omega) \) is a good measure if and only if it is absolutely continuous with respect to the Bessel capacity \( C_{\alpha,p}^{\mathbb{R}^d-1} \) where \( q' = \frac{q}{q-\kappa} \), that is

\[
\forall E \subset \partial \Omega, \ E \ \text{Borel}, \ C_{\alpha,p}^{\mathbb{R}^d-1}(E) = 0 \implies \mu(E) = 0. \quad (3.38)
\]

The striking aspect of the proof is that it is based upon potential estimates which have been developed by Marcus and Véron in the study of the supercritical boundary trace problem in polyhedral domains [28]. Before proving this result we need a key potential estimate.

**Theorem 3.7.** Assume \( 0 < \kappa \leq \frac{1}{4} \) and \( q \geq q_c \). There exists a constant \( c_{59} > 1 \) depending on \( \Omega, q, \) and \( \kappa \) such that for any \( \mu \in \mathcal{M}^+ (\partial \Omega) \) there holds

\[
\frac{1}{c_{59}} \|\mu\|^q_{B^{\alpha,p}(\mathbb{R}^d)} \leq \int_{\mathbb{R}^d} \left( \mathbb{K}_{\mathcal{L}_{\alpha}}[\mu] \right)^q \phi_s \, dx \leq c_{59} \|\mu\|^q_{B^{\alpha,p}(\mathbb{R}^d)}. \quad (3.39)
\]

**Proof.** Step 1: local estimates. Denote by \( \xi = (\xi_1, \xi') \) the coordinates in \( \mathbb{R}_{+}^{N}, \xi_1 > 0, \xi' \in \mathbb{R}^{N-1} \) The ball of radius \( R > 0 \) and center \( a \) in \( \mathbb{R}^{N-1} \) is denoted by \( B_R(a) \) (by \( B_R \) if \( a = 0 \)). Let \( R > 0, v \in \mathcal{M}^+ (\mathbb{R}_{+}^{N-1}) \) with support in \( B_R \) and

\[
K[n](\xi) = \int_{B_R} \frac{dv(\xi')}{(\xi_1^2 + |\xi' - \xi|^2)^{N-2+u_+}}, \quad (3.40)
\]
Then, by [28, Th 3.1],

\[
\frac{1}{c_{60}} \|\mu\|^q \|_B^{-2+\frac{2+\alpha_k}{2q}} \leq \int_0^R \int_{B_R} \left( \int_{\xi_1^2}^{(q+1)\xi_1^2} \left( \int_{B_{\xi_1^2}}^\infty \frac{d\nu(\zeta')}{(\xi_1' + |\xi'|^2)^{N-2+\alpha_1}} \right)^q d\xi' \right) d\xi_1 d^q \xi' \leq c_{60} \left( 1 + R^{(q+1)\xi_1^2} \right) \|\mu\|^q \|_B^{-2+\frac{2+\alpha_k}{2q}}. \tag{3.41}
\]

There exists \( R > 0 \) such that for any \( y_0 \in \partial\Omega \), there exists a \( C^2 \) diffeomorphism \( \Theta := \Theta_{y_0} \) from \( B_R(y_0) \) into \( \mathbb{R}^N \) such that \( \Theta(y_0) = 0 \), \( \Theta_0(B_R(y_0)) = B_R \) and

\[
\Theta(\Omega \cap B_R(y_0)) = B_R^+ := B_R \cap \mathbb{R}^N_+, \quad \Theta(\partial \Omega \cap B_{\frac{R}{2}}(y_0)) = B_{\frac{R}{2}}', \quad \Theta(\partial \Omega \cap B_R(y_0)) = B_R'.
\]

Moreover, \( \Theta \) has bounded distortion, in the sense that since

\[
\phi_k(x) \int_{\partial \Omega \cap B_R(y_0)} \frac{d\mu(z)}{|x - z|^{N-2+\alpha_1}} = \phi_k \circ \Theta^{-1}(x) \int_{B_R'} \frac{d(\mu \circ \Theta^{-1})(\zeta)}{|(\Theta^{-1}(\xi) - \Theta^{-1}(\zeta))|^{N-2+\alpha_1}},
\]

there holds

\[
\frac{\xi_1^2}{c_{61}} \int_{B_{\frac{R}{2}}'} \frac{d(\mu \circ \Theta^{-1})(\zeta)}{(\xi_1^2 + |\xi'|^2)^{N-2+\alpha_1}} \leq \phi_k \circ \Theta^{-1}(x) \int_{B_R'} \frac{d(\mu \circ \Theta^{-1})(\zeta)}{|(\Theta^{-1}(\xi) - \Theta^{-1}(\zeta))|^{N-2+\alpha_1}} \leq c_{61} \frac{\xi_1^2}{\xi_1' + |\xi'|^2)^{N-2+\alpha_1}}.
\]

Since \( \mu \mapsto \mu \circ \Theta^{-1} \) is a \( C^2 \) diffeomorphism between \( \mathcal{M}(\partial \Omega \cap B_{\frac{R}{2}}(y_0)) \cap B^{-2+\frac{2+\alpha_k}{2q}} \) and \( \mathcal{M}(\partial \Omega \cap B_{\frac{R}{2}}(y_0)) \cap B^{-2+\frac{2+\alpha_k}{2q}} \), we derive, using (2.57) and (3.41),

\[
\frac{1}{c_{62}} \|\mu\|^q \|_B^{-2+\frac{2+\alpha_k}{2q}} \leq \int_{\Omega \cap B_{\frac{R}{2}}(y_0)} (\mathcal{K}_{\mathcal{L}_\alpha}[\mu])^q \phi_k dx \leq c_{62} \|\mu\|^q \|_B^{-2+\frac{2+\alpha_k}{2q}}. \tag{3.42}
\]

Clearly the left-hand side inequality (3.39) follows. Combining Harnack inequality and boundary Harnack inequality we obtain

\[
\int_\Omega (\mathcal{K}_{\mathcal{L}_\alpha}[\mu])^q \phi_k dx \leq c_{63} \int_{\Omega \cap B_{\frac{R}{2}}(y_0)} (\mathcal{K}_{\mathcal{L}_\alpha}[\mu])^q \phi_k dx, \tag{3.43}
\]

which implies the left-hand side inequality (3.39) when \( \mu \) has support in a ball \( B_{\frac{R}{2}}(y_0) \cap \partial \Omega \).

**Step 2: global estimates.** We write \( \mu = \sum_{j=1}^{l_0} \mu_j \) where the \( \mu_j \) are positive measures on \( \partial \Omega \) with support in some ball \( B_{\frac{R}{2}}(y_j) \) with \( y_j \in \partial \Omega \) and such that

\[
\frac{1}{c_{64}} \|\mu\|^q \|_B^{-2+\frac{2+\alpha_k}{2q}} \leq \|\mu_j\|^q \|_B^{-2+\frac{2+\alpha_k}{2q}} \leq c_{64} \|\mu\|^q \|_B^{-2+\frac{2+\alpha_k}{2q}}. \tag{3.44}
\]

Then

\[
\|\mathcal{K}_{\mathcal{L}_\alpha}[\mu]\|_{\Phi_k}^q \leq \sum_{j=1}^{l_0} \|\mathcal{K}_{\mathcal{L}_\alpha}[\mu_j]\|_{\Phi_k}^q \leq c_{59} \|\mu_j\|^q \|_B^{-2+\frac{2+\alpha_k}{2q}} \leq l_0 c_{64} c_{59} \|\mu\|^q \|_B^{-2+\frac{2+\alpha_k}{2q}}. \tag{3.45}
\]

On the opposite side

\[
\|\mathcal{K}_{\mathcal{L}_\alpha}[\mu]\|_{\Phi_k}^q \geq \max_{1 \leq j \leq l_0} \|\mathcal{K}_{\mathcal{L}_\alpha}[\mu_j]\|_{\Phi_k}^q \geq \frac{1}{c_{59}} \max_{1 \leq j \leq l_0} \|\mu_j\|^q \|_B^{-2+\frac{2+\alpha_k}{2q}} \tag{3.46}
\]
where it follows that 

\[ u \leq \frac{1}{c_{64}} \| \mu \| \| u \|_{\mathcal{B}^{-2+\frac{2q+1}{2q}q}}. \]

which ends the proof. □

**Proof of Theorem 3.6.** The condition is sufficient. Let \( \mu \) be a boundary measure such that \( |\mathcal{K}_{\mathcal{L}_k} \{ \mu \}|^q \in L^1_{\phi_k}(\Omega) \). For \( k > 0 \) set \( g_k(u) = \operatorname{sgn}(u) \min(|u|^q, k^q) \) and let \( u_k \) be the solution of

\[ \mathcal{L}_k u_k + g_k(u_k) = 0 \quad \text{in} \quad \Omega, \]
\[ u_k = \mu \quad \text{in} \quad \partial \Omega, \]

which exists a is unique by Theorem 3.3. Furthermore \( k \mapsto u_k \) is decreasing,

\[ 0 \leq u_k \leq \mathcal{K}_{\mathcal{L}_k} \{ \mu \}, \]

and

\[ 0 \leq g_k(u_k) \leq g_k(\mathcal{K}_{\mathcal{L}_k} \{ \mu \}) \leq (\mathcal{K}_{\mathcal{L}_k} \{ \mu \})^q. \]

and the first terms on the right of the two previous inequalities are integrable for the measure \( \phi_k \) by Theorem 3.7. Finally for any \( \eta \in \mathcal{X}_k(\Omega) \), there holds

\[ \int_{\Omega} (u_k \mathcal{L}_k \eta + g_k(u_k) \eta) \, dx = \int_{\Omega} \mathcal{K}_{\mathcal{L}_k} \{ \mu \} \mathcal{L}_k \eta \, dx. \]

Since \( u_k \) and \( g_k(u_k) \) converge respectively to \( u \) and \( g(u) \) a.e. and in \( L^1_{\phi_k}(\Omega) \); we conclude that

\[ \int_{\Omega} (u \mathcal{L}_k \eta + u^q \eta) \, dx = \int_{\Omega} \mathcal{K}_{\mathcal{L}_k} \{ \mu \} \mathcal{L}_k \eta \, dx. \]

If \( \mu \) is a positive measure which vanishes on Borel sets \( E \subset \partial \Omega \) with \( \mathcal{C}^{N-1}_{2-\frac{2q+1}{2q}q} \)-capacity zero, there exists an increasing sequence of positive measures in \( \mathcal{B}^{-2+\frac{2q+1}{2q}q} \{ \mu \} \) which converges to \( \mu \) (see [9, 13]). Let \( u_{\mu_k} \) be the solution of (3.36) with boundary data \( \mu_k \). The sequence \( \{u_{\mu_k}\} \) is increasing with limit \( u \). Since, by taking \( \phi_k \) as test function, we obtain

\[ \int_{\Omega} (\lambda_k u_{\mu_k} + g(u_{\mu_k})) \phi_k \, dx = \lambda_k \int_{\Omega} \mathcal{K}_{\mathcal{L}_k} \{ \mu_k \} \phi_k \, dx, \]

it follows that \( u, g(u) \in L^1_{\phi_k}(\Omega) \). Thus

\[ \int_{\Omega} (u \mathcal{L}_k \eta + g(u) \eta) \, dx = \int_{\Omega} \mathcal{K}_{\mathcal{L}_k} \{ \mu \} \mathcal{L}_k \eta \, dx \quad \forall \eta \in \mathcal{X}_k(\Omega), \]

and therefore \( u = u_\mu \).

**Definition.** A smooth lifting is a continuous linear operator \( R[\cdot] \) from \( C^0_0(\partial \Omega) \) to \( C^0_0(\overline{\Omega}) \) satisfying

(i) \( 0 \leq \eta \leq 1 \implies 0 \leq R[\eta] \leq 1, \quad R[\eta]|_{\partial \Omega} = \eta, \]
(ii) \( |\nabla \phi_k \cdot \nabla R[\eta]| \leq c_{65} \phi_k, \]

where \( c_{65} \) depends on the \( C^1 \)-norm of \( \eta \).

Our proof are based upon a modification of an argument developed by Marcus and Véron in [23].

**Lemma 3.8.** Assume there exists a solution \( u_\mu \) of (3.36) with \( \mu \geq 0 \). For \( \eta \in C^2(\Omega), 0 \leq \eta \leq 1 \leq 1 \) set \( \zeta = \phi_k(R[\eta])^q \) where \( R \) is a smooth lifting. Then

\[ \left( \int_{\partial \Omega} \eta d\mu \right)^q \leq c_{67} \int_{\Omega} u^q \zeta \, dx + c_{67} \left( \int_{\Omega} u^q \zeta \, dx \right)^{\frac{1}{q}} \left( \int_{\Omega} \phi_k \, dx \right)^{\frac{1}{q}} + q^{\frac{1}{q}} \left( \int_{\Omega} (L[\eta])^{q'} \, dx \right)^{\frac{1}{q'}}. \]

where

\[ L[\eta] = (R[\eta])^{q'-1} \left( 2\phi_k^{-\frac{1}{q}} |\nabla \phi_k \cdot \nabla R[\eta]| + \phi_k^{\frac{1}{q}} |\Delta R[\eta]| \right), \]

and \( c_{67} \) depends on \( \Omega, \lambda_k, q, \kappa, N \).
Lemma 3.9. There exist a smooth lifting $R$ such that $\eta \mapsto L[\eta]$ is continuous from $B^{2 - \frac{2 + \alpha}{\beta}}(\partial \Omega)$ into $L^{q'}(\Omega)$. Furthermore,

$$
\|L[\eta]\|_{L^{q'}(\Omega)} \leq c_{66}\|\eta\|_{L^{q'}(\partial \Omega)}^{q'-1} \|\eta\|_{B^{2 - \frac{2 + \alpha}{\beta}}(\partial \Omega)}.
$$

(3.48)

**Proof.** The construction of the lifting is originated into [26, Sec 1]. For $0 < \delta \leq \beta_0$, we set $\Sigma_\delta = \{x \in \Omega : d(x) = \delta\}$ and we identify $\partial \Omega$ with $\Sigma := \Sigma_0$. The set $\{\Sigma_{\delta}\}_{0 < \delta \leq \beta_0}$ is a smooth foliation of $\partial \Omega$. For each $\delta \in (0, \beta_0]$ there exists a unique $\sigma(x) \in \Sigma_{\delta}$ such that $d(x) = \delta$ and $|x - \sigma(x)| = \delta$. The set of couples $(\delta, \sigma)$ defines a system of coordinates in $\Omega_{\beta_0}$ called the flow coordinates. The Laplacian obtain the following expression in this system

$$
\Delta = \frac{\partial^2}{\partial \delta^2} + b_0 \frac{\partial}{\partial \delta} + \Lambda_{\Sigma},
$$

(3.49)

where $\Lambda_{\Sigma}$ is a linear second-order elliptic operator on $\Sigma$ with $C^1$ coefficients. Furthermore $b_0 \to K$ and $\Lambda_{\Sigma} \to \Delta_{\Sigma}$, where $K$ is the mean curvature of $\Sigma$ and $\Delta_{\Sigma}$ the Laplace–Beltrami operator on $\Sigma$. If $\eta \in B^{2 - \frac{2 + \alpha}{\beta}}(\partial \Omega)$, we denote by $H := H[\eta]$ the solution of

$$
\begin{align*}
\frac{\partial H}{\partial \delta} + \Lambda_{\Sigma} H &= 0 \quad \text{in } (0, \infty) \times \Sigma, \\
H(0, \cdot) &= \eta \quad \text{in } \Sigma.
\end{align*}
$$

(3.50)

Let $h \in C^\infty(\mathbb{R}_+)$ such that $0 \leq h \leq 1$, $h' \leq 0$, $h \equiv 1$ on $[0, \frac{\beta_0}{2}]$, $h \equiv 0$ on $[\beta_0, \infty]$. The lifting we consider is expressed by

$$
R[\eta](x) = \begin{cases} 
H[\eta](\delta^2, \sigma(x))h(\delta) & \text{if } x \in \Sigma_{\beta_0}^0, \\
0 & \text{if } x \in \Omega_{\beta_0}^0,
\end{cases}
$$

(3.51)

with $x \approx (\delta, \sigma) := (d(x), \sigma(x))$. Mutatis mutandis, we perform the same computation as the one in [23, Lemma 1.2], using local coordinates $\{\sigma_i\}$ on $\Sigma$ and obtain

$$
\nabla R[\eta] = 2\delta h(\delta) \frac{\partial H}{\partial \delta} (\delta^2, \sigma) \nabla \delta + \sum_{j=1}^{N-1} h(\delta) \frac{\partial H}{\partial \sigma_j} (\delta^2, \sigma) \nabla \sigma_j + h'(\delta) H(\delta^2, \sigma) \nabla \delta.
$$

Then there holds in $\Omega_{\beta_0}^0$

$$
\nabla R[\eta] \cdot \nabla \phi_k = 2\delta h(\delta) \frac{\partial H}{\partial \delta} (\delta^2, \sigma) \nabla \phi_k \cdot \nabla \delta + \sum_{j=1}^{N-1} h(\delta) \frac{\partial H}{\partial \sigma_j} (\delta^2, \sigma) \nabla \sigma_j \cdot \nabla \phi_k + h'(\delta) H(\delta^2, \sigma) \nabla \delta \cdot \nabla \phi_k.
$$

(3.52)

Moreover $\phi_k(x) \leq c_2(d(x))^{\frac{\alpha}{q} - 1} = c_2^\delta \delta^{\frac{\alpha}{q} - 1}$. Similarly as in [23, (1.13)]

$$
\nabla \phi_k = \frac{\partial \phi_k}{\partial \delta} \nabla d + \sum_{j=1}^{N-1} \frac{\partial \phi_k}{\partial \sigma_j} (\delta^2, \sigma) \nabla \sigma_j,
$$

(3.53)
Furthermore, the other term in the right-hand side of (3.56) yields to the same inequality as in (3.55).

Thus

\[
\phi_k^\ast \left| \nabla R[\eta] \cdot \nabla \phi_k \right| = \int_{\Omega} \frac{\partial H}{\partial \delta} (\delta^2, \sigma) \left( \frac{1}{\delta} \sum_{j=1}^{N-1} \frac{\partial H}{\partial \sigma_j} (\delta^2, \sigma) - \frac{h'(\delta)}{\delta} H(\delta^2, \sigma) \right) dx.
\]

Then

\[
\int_{\Omega} \phi_k^\ast \left| \nabla R[\eta] \cdot \nabla \phi_k \right|^q dx \leq c_{70} \int_{\Omega_{R_0}} \delta^{\frac{N+1}{q'}} \left| \frac{\partial H}{\partial \delta} (\delta^2, \sigma) \right|^q dx + c_{70} \left( \int_{\Omega_{R_0}} \delta^{\frac{N+1}{q'}} H^q (\delta^2, \sigma) dx \right) ^{\frac{1}{q'}}
\]

by using the classical real interpolation identity

\[
\left[ W^{2,q'} (\Sigma), L^q (\Sigma) \right] \leq B^\frac{-2+\alpha+\beta}{2q'} Q (\Sigma).
\]

Similarly (see [23, (1.17), (1.19)])

\[
\int_{\Omega} \phi_k |\Delta R[\eta]|^q dx \leq c_{72} \int_{\Omega_{R_0}} \delta^{\frac{N+1}{q'}} \left| \frac{\partial H}{\partial \sigma} (\delta^2, \sigma) \right|^q dx + c_{72} \int_{\Omega_{R_0}} \delta^{\frac{N+1}{q'}} H^q (\delta^2, \sigma) dx \leq c_{72} \left\| \eta \right\|^q_{W^{2+\alpha+\beta, 2q'} (\Sigma)}.
\]

Next we consider the second term. Adapting in a straightforward manner the computation in [23, p. 886–887] we obtain the following instead of [23, (1.21)]

\[
\int_{\Omega} \phi_k |\Delta R[\eta]|^q dx \leq c_{72} \int_{\Omega_{R_0}} \delta^{\frac{N+1}{q'}} \left| \frac{\partial^2 H[\eta]}{\partial \delta^2} \right|^q (\delta^2, \sigma) d\sigma d\delta
\]

Furthermore

\[
\int_{\Omega} \phi_k |\Delta R[\eta]|^q dx \leq c_{73} \left\| \eta \right\|^q_B B^\frac{-2+\alpha+\beta}{2q'} Q (\Sigma).
\]

The other term in the right-hand side of (3.56) yields to the same inequality as in (3.55).
Proof of Theorem 3.6. The condition is necessary. Let K ⊂ ∂Ω be a compact set and η ∈ C₀(∂Ω) such that 0 ≤ η ≤ 1 and η = 1 on K. Then, by (3.46)
\[
\begin{align*}
(\mu(K))^{q'} & \leq c_{67} \int_{\Omega} u^{q}(R[\eta])^{q'} \phi_{x} \, dx \\
& + c_{67} \left( \int_{\Omega} u^{q}(R[\eta])^{q'} \phi_{x} \, dx \right)^{\frac{1}{q'}} \left( \int_{\Omega} \phi_{x} \, dx \right)^{\frac{1}{q'}} + c'_{67} q' \| \eta \|_{B^{2-\frac{2+u_{+}}{2q'}}(\partial \Omega)}^{q'}.
\end{align*}
\]  
(3.59)

From this inequality, we obtain classically the result since if C^{\infty}_{0}(\Omega \setminus K) = 0 there exists a sequence \{\eta_{n}\} in C^{\infty}_{0}(\partial \Omega) with the following properties:
\[
0 \leq \eta_{n} \leq 1, \quad \eta_{n} = 1 \text{ in a neighborhood of } K \text{ and } \eta_{n} \to 0 \text{ in } B^{2-\frac{2+u_{+}}{2q'}}(\partial \Omega) \text{ as } n \to \infty.
\]  
(3.60)

This implies that u^{q}(R[\eta_{n}])^{q'} \to 0 in L^{1}_{\phi_{x}}(\Omega). Therefore the right-hand side of (3.59) tends to 0 if we substitute \eta_{n} to η and thus \mu(K) = 0 for any K compact with zero capacity and this relation holds for any Borel subset. □

Definition. We say that a compact set K ⊂ ∂Ω is removable if any positive solution u ∈ C(\overline{\Omega} \setminus K) of
\[
L_{u} u + |u|^{q-1} u = 0 \quad \text{in } \Omega,
\]  
(3.61)
such that
\[
\int_{\Omega} (u L_{u} \eta + |u|^{q-1} u \eta) \, dx = 0 \quad \forall \eta \in X^{K}_{x}(\Omega),
\]  
(3.62)
where X^{K}_{x}(\Omega) = { \eta \in X_{x}(\Omega) : s.t. \eta = 0 in a neighborhood of K}, is identically zero.

Theorem 3.10. Assume 0 < κ ≤ \frac{1}{4} and q ≥ 1. A compact set K ⊂ ∂Ω is removable if and only if\[
\begin{align*}
C^{\infty}_{0}(\Omega \setminus K) = 0.
\end{align*}
\]  

Proof. The condition is clearly necessary since, if a compact boundary set K has positive capacity, there exists a capacitary measure \mu_{K} ∈ M_{+}(\partial \Omega) ∩ B^{2-\frac{2+u_{+}}{2q'}}(\partial \Omega) with support in K (see e.g. [1]). For such a measure there exists a solution \mu_{K} of (3.36) with \mu = \mu_{K} by Theorem 3.6. Next we assume that C^{\infty}_{0}(\Omega \setminus K) = 0. Then there exists a sequence \{\eta_{n}\} in C^{\infty}_{0}(\partial \Omega) satisfying (3.60). In particular, there exists a decreasing sequence \{\eta_{n}\} of relatively open subsets of \partial \Omega, containing K such that \eta_{n} = 1 on \partial_{n} and thus \eta_{n} = 1 on K_{n} := \overline{\partial_{n}}. We set \tilde{\eta}_{n} = 1 - \eta_{n} and \tilde{\eta}_{n} = \phi_{K}(R[\tilde{\eta}_{n}]) of \tilde{\eta}_{n} where R is defined by (3.51). Then 0 ≤ \tilde{\eta}_{n} ≤ 1 and \tilde{\eta}_{n} = 0 on K_{n}. Therefore
\[
\tilde{\zeta}_{n}(x) \leq \phi_{x} \min \left\{ 1, c_{74}(d(x))^{1-N} e^{-4(d(x))^{-2}(\text{dist}(x,K_{n}))^{2}} \right\}.
\]  
(3.63)

Furthermore
\[
\begin{align*}
(i) \quad |\nabla R[\tilde{\eta}_{n}]| & \leq c_{75} \min \left\{ 1, (d(x))^{-2-N} e^{-4(d(x))^{-2}(\text{dist}(x,K_{n}))^{2}} \right\}, \\
(ii) \quad \Delta R[\tilde{\eta}_{n}] & \leq c_{75} \min \left\{ 1, (d(x))^{-4-N} e^{-4(d(x))^{-2}(\text{dist}(x,K_{n}))^{2}} \right\}.
\end{align*}
\]  
(3.64)

Step 1. We claim that
\[
\int_{\Omega} \left( u L_{u} \tilde{\zeta}_{n} + u^{q} \tilde{\zeta}_{n} \right) \, dx = 0.
\]  
(3.65)

By Proposition A.3 there exists \epsilon_{74} > 0 such that
\[
\begin{align*}
(i) \quad u(x) & \leq c_{76}(d(x))^{\frac{u_{+}}{2} - \epsilon_{74}^{-1} \text{dist}(x,K)} \leq \frac{u_{+}}{2} - \epsilon_{74}^{-1} \text{dist}(x,K), \\
(ii) \quad |\nabla u(x)| & \leq c_{76}(d(x))^{\frac{u_{+}}{2} - 1} \text{dist}(x,K) \leq \frac{u_{+}}{2} - 1 \text{dist}(x,K),
\end{align*}
\]  
(3.66)

for all x ∈ Ω. As in the proof of Lemma 3.8,
\[
|u L_{u} \tilde{\zeta}_{n}| \leq c_{77} (R[\tilde{\eta}_{n}])^{2q-2} u \left( \phi_{x} R^{2}[\tilde{\eta}_{n}] + R[\tilde{\eta}_{n}] \nabla \phi_{x} \cdot \nabla R[\tilde{\eta}_{n}] + \phi_{x}(R[\tilde{\eta}_{n}] \Delta R[\tilde{\eta}_{n}]) \right).
\]  
(3.67)
Let Θ be a relatively open neighborhood of K such that Θ ⊂ Θn. We set 

\[ G_{Θ, ρ_0} = \{ x \in Ω_{ρ_0} : σ(x) \in Θ \} \]

and 

\[ G_{Θ^c, ρ_0} = \{ x \in Ω_{ρ_0} \setminus G_Θ \} . \]

If \( x \in G_Θ \), dist(\( x, K_0 \)) ≥ \( τ > 0 \). Then, by (3.66)-(i) and (3.63), \( u^q ρ_{n, 0} \in L^q(Ω) \). Since \( u(\cdot) = o(W(\cdot)) \) in \( G_{Θ^c} \), it follows that \( u^q ρ_{n, 0} \in L^1(Ω_{ρ_0}) \) and thus \( u^q ρ_{n, 0} \) is integrable in \( Ω \). Similarly, using (N22)-(i) and (ii), \( uL_κ ρ_{n, 0} \in L^1(Ω) \). Since \( ρ_{n, 0} \) does not vanish in a neighborhood of \( K \), we introduce a cut-off function \( θ_ε \in C^2(Ω) \) for \( 0 < ε \leq \frac{ρ_{n, 0}}{2} \), with the following properties,

\[ 0 ≤ θ_ε ≤ 1, \quad θ_ε(x) = 0 \ \forall x \in G_{Θ^c, θ_ε}, \quad θ_ε(x) = 1 \ \forall x \in Ω \ \text{s.t. dist}(x, G_{Θ, ε}) ≥ ε \]

\[ |∇θ_ε| ≤ c_{79}ε^{-1}1_{G_{Θ^c, θ_ε}} \ \text{and} \ \ |D^2θ_ε| ≤ c_{78}ε^{-2}1_{G_{Θ^c, θ_ε}} \]

where we have taken ε small enough so that 

\[ G_{Θ^c, ε} := \{ x \in Ω : \text{dist}(x, G_{Θ, ε}) ≤ ε \} \subset G_{Θ^c, 2ε} = \{ x \in Ω_{2ε} : σ(x) \in K_0 \}. \]

Clearly \( θ_ε ρ_{n, 0} \in X^p(Ω) \), thus

\[ \int_Ω \left( uL_κ (θ_ε ρ_{n, 0}) + u^q θ_ε ρ_{n, 0} \right) dx = 0. \]

Next,

\[ \int_Ω \left( uL_κ (θ_ε ρ_{n, 0}) + u^q θ_ε ρ_{n, 0} \right) dx = \int_{G_{Θ^c, θ_ε}} \left( uL_κ (ρ_{n, 0}) + u^q ρ_{n, 0} \right) dx + \int_{G_{Θ^c, ε}} \left( uL_κ (θ_ε ρ_{n, 0}) + u^q θ_ε ρ_{n, 0} \right) dx \]

Clearly

\[ \lim_{ε → 0} I_ε = \int_Ω \left( uL_κ ρ_{n, 0} + u^q ρ_{n, 0} \right) dx, \]

and

\[ \lim_{ε → 0} \int_{G_{Θ^c, θ_ε}} u^q θ_ε ρ_{n, 0} dx = 0. \]

Finally, since \( L_κ (θ_ε ρ_{n, 0}) = θ_ε L_κ ρ_{n, 0} + ρ_{n, 0} ∆θ_ε + 2∇θ_ε • ∇ρ_{n, 0}, θ_ε \) is constant outside \( G_{Θ^c, θ_ε} \) and dist(\( G_{Θ^c, θ_ε} \) \( \setminus \) \( G_{Θ, ε} \)) \( ≥ τ > 0 \), independent of ε there holds, by (3.63)

\[ |L_κ (θ_ε ρ_{n, 0})| ≤ c_{79}ε^{-N+4}e^{-\frac{ε}{2τ}}. \]

Using (3.66)-(i) we derive

\[ \lim_{ε → 0} \int_{G_{Θ^c, θ_ε}} uL_κ (θ_ε ρ_{n, 0}) dx = 0, \]

which yields to (3.65).

Step 2. We claim that

\[ \int_Ω u^q φ_ε dx < \infty. \]  

(3.68)

Using the expression of \( L_κ ρ_{n, 0} \) in (3.65) where replace \( η_n \) by \( \bar{η}_n \), we derive

\[ \int_Ω u^q ρ_{n, 0} dx = \int_Ω \left( -λ_κ (R[\bar{η}_n])^{2q} φ_κ + 4q (R[\bar{η}_n])^{2q-1} νφ_κ • νR[\bar{η}_n] \right. \]

\[ \left. + 2q (R[\bar{η}_n])^{2q-2} φ_κ (R[\bar{η}_n] Δ R[\bar{η}_n] + (2q - 1) |ν R[\bar{η}_n]|^2) \right) dx \]

\[ ≤ c_{79} \left( \int_Ω u^q φ_κ dx \right)^\frac{1}{q} \left( \int_Ω (I[η_n])^{\frac{q}{q'}} dx \right)^\frac{1}{q}. \]  

(3.69)

where we have set

\[ I[η] = (φ_κ)^{-\frac{q'}{q'}} νφ_κ • νR[η] + (φ_κ)^{\frac{3}{q'}} |Δ R[η]| + (φ_κ)^{\frac{3}{q'}} |ν R[η]|^2. \]  

(3.70)

By Lemma 3.9 we know that

\[ \int_Ω (φ_κ)^{-\frac{q'}{q'}} |νφ_κ • νR[η]|^{\frac{q'}{q'}} + φ_κ |Δ R[η]|^{\frac{q'}{q'}} dx ≤ (c_{72} + c_{73}) \|η_n\|^{\frac{q'}{q'}} \frac{24π_n}{2q' - 2q} (Ω). \]  

(3.71)
The last term is estimated in the following way
\[
\int_\Omega \phi_n |\nabla R[\tilde{\eta}_n]|^{2q'} \, dx \leq c_{80} \int_0^R \int_{\Sigma} s^{q' + \frac{u_{q' + 2}}{s'}} \left| \frac{\partial H[\eta_n]}{\partial s} \right|^{2q'} \, ds \, ds \leq c_{80} \int_0^R \int_{\Sigma} s^{q' + \frac{u_{q' + 2}}{s'}} \left( |\nabla \Sigma H[\eta_n]|^{2q'} + (H[\eta_n])^{2q'} \right) \, ds \, ds,
\]
where \( \nabla \Sigma \) denotes the covariant gradient on \( \Sigma \). Since the following interpolation identity holds
\[
\left[ W^{2,2q'}(\Sigma), L^{2q'}(\Sigma) \right]_{1 - \frac{u_{q' + 2}}{2q'}} = B^{1 - \frac{u_{q' + 2}}{2q'}, 2q'},
\]
we obtain
\[
\int_0^R \int_{\Sigma} s^{q' + \frac{u_{q' + 2}}{s'}} \left| \frac{\partial H[\eta_n]}{\partial s} \right|^{2q'} \, ds \, ds \leq c_{81} ||\eta||^{2q'}_B \left( \frac{u_{q' + 2}}{2q'} \right)_{-1, \Sigma}.
\]
By the Gagliardo–Nirenberg inequality
\[
||\eta||^{2q'}_B \left( \frac{u_{q' + 2}}{2q'} \right)_{-1, \Sigma} \leq c_{82} ||\eta||^{q'}_B \left( \frac{u_{q' + 2}}{2q'} \right)_{-1, \Sigma} = c_{82} ||\eta||^{q'}_B \left( \frac{u_{q' + 2}}{2q'} \right)_{-1, \Sigma}.
\]
By the same inequality
\[
\int_{\Sigma} \left( |\nabla \Sigma H[\eta_n]|^{2q'} + (H[\eta_n])^{2q'} \right) \, ds \leq c_{82} ||H[\eta_n]|^{q'}_{L^{q'}(\Sigma)} \int_{\Sigma} \left( |\nabla \Sigma H[\eta_n]|^{q'} + (H[\eta_n])^{q'} \right) \, ds.
\]
Using the estimates on \( L[\eta] \) in Lemma 3.9 and the fact that \( 0 \leq H[\eta_n] \leq 1 \), we conclude that
\[
\int_0^R \int_{\Sigma} s^{q' + \frac{u_{q' + 2}}{s'}} \left( |\nabla \Sigma H[\eta_n]|^{2q'} + (H[\eta_n])^{2q'} \right) \, ds \, ds \leq c_{83} ||\eta||^{q'}_B \left( \frac{u_{q' + 2}}{2q'} \right)_{-1, \Sigma}.
\]
It follows from (3.69)
\[
\int_{\Omega_{2R}^0} u^q R[\tilde{\eta}_n] \, dx \leq c_{84} \int_{\Omega_{2R}^0} \tilde{\eta}_n \, dx \leq c_{85} ||\eta||^{q'}_B \left( \frac{u_{q' + 2}}{2q'} \right)_{-1, \Sigma}.
\]
Letting \( n \to \infty \) and using the fact that \( \eta_n \to 0 \), we obtain by Fatou’s lemma that
\[
\int_{\Omega_{2R}^0} u^q \phi_n \, dx = 0.
\]
Combining this with the fact that \( u \) is bounded in \( \Omega'_{2R} \), we obtain (3.68). Notice that \( ||u||^{q'}_{\phi_n}(\Omega) \) is bounded independently of \( u \).

Step 3. End of the proof. Since \( u^q \in L^1_{\phi_n}(\Omega) \), by Proposition 3.2 there exists a unique weak solution \( v \in L^1_{\phi_n}(\Omega) \) of
\[
\mathcal{L}_v u = u^q \quad in \Omega,
\]
\[
v = 0 \quad in \partial \Omega,
\]
and \( v \geq 0 \). Then \( w = u + v \) is \( \mathcal{L}_v \)-harmonic in \( \Omega \), and by Theorem 2.33 there exists a unique positive Radon measure \( \tau \) on \( \partial \Omega \) such that \( w = \mathbb{E}_{\mathcal{L}_v} \tau \). Since \( v \) and \( u \) vanish respectively on \( \partial \Omega \) and \( \partial \Omega \setminus K \), it follows from Propositions 2.34 and 2.35 that the support of \( \tau \) is included in \( K \). By Theorem 3.6, \( \tau \) vanishes on Borel subsets with zero \( C_{N-1}^{\frac{N-1}{2-2u_{q' + 2}}q'} \)-capacity. Since
\[
C_{N-1}^{\frac{N-1}{2-2u_{q' + 2}}q'}(K) = 0, \quad \tau = 0.
\]
This implies that \( u \) is a weak solution of
\[
\mathcal{L}_u u + u^q = 0 \quad in \Omega,
\]
\[
u = 0 \quad in \partial \Omega,
\]
and therefore \( u = 0 \). \( \square \)

Remark. Using the fact that \( u^+ \) and \( u^- \) are subsolutions of (3.61), it is easy to check that Theorem 3.10 remains valid for any signed solution of (3.61).
Remark. If $1 < q < q_c$ (see (3.37)) it follows from Sobolev embedding theorem that only the empty set has zero $C^0_{N-1} \cdot q^{-\frac{2}{2+\alpha_k}}$ capacity. As a consequence of the previous result, if $q \geq q_c$ any isolated boundary singularity of a solution of (3.61) is removable.

4. Isolated boundary singularities

We denote by $\{e_1, \ldots, e_N\}$ the canonical basis in $\mathbb{R}^N = \{x = (x', x_N) \in \mathbb{R}^{N-1} \times \mathbb{R}\}$ and by $(r, \sigma)$ the spherical coordinates therein. Then $\mathbb{R}^N_+ = \{= (x', x_N) : x' \in \mathbb{R}^{N-1}, x_N > 0\}$. We although denote by $S^{N-1}_-$ and $S^{N-1}_+$ the unit sphere and the upper hemisphere of $\mathbb{R}^N_+$, i.e. $S^{N-1} = \cap \mathbb{R}^N_+$. In this section we study the behavior near 0 of solutions of

$$-\Delta u - \frac{k}{d^2} u + |u|^{q-1} u = 0$$

(4.1)

in a bounded convex domain $\Omega$ of $\mathbb{R}^N$ with a smooth boundary containing 0 where $d$ is the distance function to the boundary, $\kappa$ a constant in $(0, \frac{1}{2}]$ and $q > 1$. Although it is not bounded, the model case is $\Omega = \mathbb{R}^N_+ = \{= (x', x_N) : x' \in \mathbb{R}^{N-1}, x_N > 0\}$ which is represented by $(r, \sigma), r > 0, \sigma \in S^{N-1}_+$ in spherical coordinates. Then

$$\mathcal{L}_x u = -u_{rr} - \frac{N-1}{r} u_r - \frac{\kappa}{r^2} \Delta_{S^{N-1}} u - \frac{\kappa}{r^2 (e_N \cdot \sigma)^2} u + |u|^{q-1} u.$$  

(4.2)

We also denote by $\nabla'$ the covariant gradient on $S^{N-1}$ in the metric of $S^{N-1}_+$ obtained by the embedding into $\mathbb{R}^N$.

4.1. The spherical $\mathcal{L}_x$-harmonic problem

It is straightforward to check that the Poisson kernel $K_{\mathcal{L}_x}$ of $\mathcal{L}_x$ in $\mathbb{R}^N_+$ has the following expression

$$K_{\mathcal{L}_x} (x, \xi) = c_{N, \kappa} \frac{x_N^\alpha}{|x - \xi|^{N+\alpha - 2}}.$$  

(4.3)

In spherical coordinates

$$K_{\mathcal{L}_x} (x, 0) = c_{N, \kappa} r^{2-N-\frac{\alpha}{2}} \psi (\sigma) \quad r > 0, \sigma \in S^{N-1}_+$$

where $\psi (\sigma) = \frac{\alpha}{|\sigma|} \frac{\alpha}{|S^{N-1}_+|} = (e_N \cdot \sigma)^\frac{\alpha}{2}$ solves

$$-\Delta_{S^{N-1}} \psi - \mu_x \psi - \frac{\kappa}{(e_N \cdot \sigma)^2} \psi = 0 \quad \text{in } S^{N-1}_+$$

$$\psi = 0 \quad \text{in } \partial S^{N-1}_+,$$

(4.4)

and

$$\mu_x = \frac{\alpha + 2}{2} \left( N + \frac{\alpha + 2}{2} - 2 \right).$$  

(4.5)

Notice that Eq. (4.4) admits a unique positive solution with supremum 1. We could have defined the first eigenvalue $\mu_x$ of the operator

$$\phi \mapsto \mathcal{L}_x^* w : = -\Delta_{S^{N-1}} w - \frac{\kappa}{(e_N \cdot \sigma)^2} w,$$

by

$$\mu_x = \inf \left\{ \int_{S^{N-1}_+} \left( |\nabla w|^2 - \kappa (e_N \cdot \sigma)^{-2} w^2 \right) dS : w \in H^1_0(S^{N-1}_+), w \neq 0 \right\}.$$  

(4.6)

By [10, Th. 6.1] the infimum exists since $\rho (\sigma) = x_N |S^{N-1}_+| e_N \cdot \sigma$ is the first eigenfunction of $-\Delta_{S^{N-1}}$ in $H^1_0(S^{N-1}_+)$. The minimizer $\psi_x$ belongs to $H^1_0(S^{N-1}_+)$ only if $1 < \kappa < \frac{1}{4}$. Furthermore

$$\psi_x \in Y(S^{N-1}_+) := \{\phi \in H^1_0(S^{N-1}_+) : \rho^\frac{\alpha}{2} \phi \in H^1(S^{N-1}_+, \rho^\alpha)\}. $$

(4.7)
We can also define $\mu_k$ by

$$
\mu_k = \inf \left\{ \int_{S_+^{N-1}} |\nabla'(\rho - \frac{a_k}{r} \omega)|^2 \rho^{\sigma+} dS : \omega \in Y(S_+^{N-1}), \int_{S_+^{N-1}} \omega^2 dS = 1 \right\}.
\tag{4.8}
$$

We can use the symmetry of the operator to obtain the second eigenvalue and eigenfunction of $L_k'$ on $S_+^{N-1}$. We first notice that for $j = 1, \ldots, N-1$, the function

$$
x \mapsto \frac{x_j}{x^N_N x_j} \tag{4.9}
$$

is $L_k'$-harmonic in $\mathbb{R}^{N-1}_+$, positive (resp. negative) on $\{x = (x_1, \ldots, x_N) : x_j > 0, x_N > 0\}$ (resp. $\{x = (x_1, \ldots, x_N) : x_j < 0, x_N > 0\}$) and vanishes on $\{x = (x_1, \ldots, x_N) : x_j = 0, x_N = 0\}$. We can then define $\psi_{k,j}$ by

$$
\sigma \mapsto \psi_{k,j}(\sigma) = \langle e_N \cdot \sigma, \frac{a_k}{r} e_j \cdot \sigma \rangle.
$$

satisfies

$$
L_k' \psi_{k,j} = (\mu_k + N - 1 + \alpha_+) \rho_{k,j} \tag{4.10}
$$
in $S_+^{N-1}$. It is positive (resp. negative) on $S_+^{N-1} \cap \{x = (x_1, \ldots, x_N) : x_j > 0\}$ (resp. $S_+^{N-1} \cap \{x = (x_1, \ldots, x_N) : x_j < 0\}$) and it vanishes on $\partial S_+^{N-1} \cap \{x = (x_1, \ldots, x_N) : x_j = 0\}$. The real number

$$
\mu_{k,2} = \mu_k + N - 1 + \alpha_+ \left( \frac{\alpha_+}{2} + 1 \right) \left( N + \frac{\alpha_+}{2} - 1 \right)
$$
is the second eigenvalue of $L_k'$ in $Y(S_+^{N-1})$.

**Proof.** There holds

$$
L_k' \psi_{k,j} = \rho_{k,j} \Delta_{S_+^{N-1}} e_j \cdot \sigma + 2 \nabla' \psi_{k,j} \cdot \nabla' e_j \cdot \sigma
$$

= $$(\mu_k + N - 1) \psi_{k,j} - \alpha_+ \langle e_N \cdot \sigma, \frac{a_k}{r^2} \nabla'(e_j \cdot \sigma) \rangle \cdot \nabla'(e_N \cdot \sigma).$$

Now

$$
\nabla' \left( \frac{x_j}{r} \right) = \left( \frac{x_j}{r} \right) - \frac{1}{r} \nabla' \left( \frac{x_j}{r} \right) = \frac{1}{r} \nabla' \left( \frac{x_j}{r} \right) - \frac{x_j}{r^2} \nabla'(e_j \cdot \sigma) \cdot \nabla'(e_N \cdot \sigma),
$$

thus

$$
\nabla' \left( \frac{x_j}{r} \right) \cdot \nabla' \left( \frac{x_N}{r} \right) = - \frac{x_j x_N}{r^4} \nabla'(e_j \cdot \sigma) \cdot \nabla'(e_N \cdot \sigma),
$$

which implies

$$
\nabla'(e_j \cdot \sigma) \cdot \nabla'(e_N \cdot \sigma) = - \frac{x_j x_N}{r^4} = - (e_j \cdot \sigma) (e_N \cdot \sigma),
$$

and finally

$$
L_k \psi_{k,j} = (\mu_k + N - 1 + \alpha_+) \psi_{k,j} \tag{4.11}
$$

Since $S_+^{N-1} = \{ (\sigma' \sin \theta, \cos \theta) : \sigma' \in S^{N-2}, \theta \in [0, \frac{\pi}{2}] \}$, $e_N \cdot \sigma = \cos \theta$, $e_j \cdot \sigma = e_j \cdot \sigma' \sin \theta$ and $dS = (\sin \theta)^{N-2} dS' d\theta$ where $dS$ and $dS'$ are the volume elements of $S^{N-1}$ and $S^{N-2}$ respectively, we derive from the fact that $\sigma' \mapsto e_j \cdot \sigma'$ is an odd function on $S^{N-2}$,

$$
\int_{S_+^{N-1}} \psi_{k,j} dS' = \int_{S_+^{N-2}} (e_N \cdot \sigma)^{\sigma+} e_j \cdot \sigma dS
$$

$$
= \int_{0}^{\frac{\pi}{2}} \left( \int_{S^{N-2}} e_j \cdot \sigma' dS' \right) (\cos \theta)^{\sigma+} (\sin \theta)^{N-1} d\theta
$$

$$
= 0.
$$
Hence $\psi_{k,j}$ is an eigenvalue of $L'_B$ in $Y(S^{N-1}_+)$ with two nodal domains and the space the $\psi_{k,j}$ span is $(N - 1)$-dimensional and any linear combination of the $\psi_{k,j}$ has exactly two nodal domains since

$$\sum_{j=1}^{N-1} a_j \psi_{k,j} = (e_n \cdot \sigma) \frac{\alpha_k}{2} \left( \sum_{j=1}^{N-1} a_j e_j \right) \cdot \sigma.$$  

This implies that $\mu_{k,2}$ is the second eigenvalue. □

4.2. The nonlinear eigenvalue problem

If we look for separable solutions under the form

$$u(x) = u(r, \sigma) = r^\alpha \omega(\sigma),$$

then necessarily $\alpha = -\frac{2}{q-1}$ and $\omega$ is a solution of

$$-\Delta_{S^{N-1}} \omega - \ell_{q,N} \omega - \frac{\kappa}{(e_n \cdot \sigma)^2} |\omega|^q \omega + |\omega|^{q-1} \omega = 0 \quad \text{in } S^N_+,$$

$$\omega = 0 \quad \text{in } \partial S^N_+.$$  

(4.12)

$$\ell_{q,N} = \frac{2}{q-1} \left( \frac{2}{q-1} + 2 - N \right),$$

(4.13)

and (4.6) is transformed accordingly. We denote by

$$\mathcal{E}_k = \{ \omega \in Y(S^N_+) \cap L^{q+1}(S^N_+) \text{ s.t. (4.12) holds} \}$$

(4.14)

and by $\mathcal{E}_k^+$ the set of the nonnegative ones. We also recall that $q_c := \frac{2 N + \omega_k}{2 N - 4 + \omega_k}$ and we define a second critical value $q_{\varepsilon} := \frac{2 N + 2 + \omega_k}{2 N - 2 + \omega_k}$.

The following result holds.

Theorem 4.2. Assume $0 < \kappa \leq \frac{1}{4}$ and $q > 1$, then

(i) If $q \geq q_c$, $\mathcal{E}_k = \{0\}$.

(ii) If $1 < q < q_c$, $\mathcal{E}_k^+$ is contains exactly two elements: $0$ and $\omega_k$. Furthermore $\omega_k$ depends only on the azimuthal angle $\theta$.

(iii) If $q_c < q < q_c$, $\mathcal{E}_k$ contains three elements: $0$, $\omega_k$, and $-\alpha_k$.

Proof. We recall that $q \geq q_c \iff \ell_{q,N} \leq \mu_k$. Then non-existence follows by multiplying by $\omega$ and integrating on $S^N_+$. For existence, we consider the functional

$$J_k(w) = \int_{S^N_+} \left( |\nabla'(w)|^2 + (\mu_k - \ell_{q,N}) w^2 + \frac{2}{q+1} \psi_k^{q-1} |w|^{q+1} \right) \psi_k^2 dS,$$

(4.15)

defined in $H^1(S^N_+, \psi_k^2 dS) \cap L^{q+1}(S^N_+, \psi_k^{q+1} dS)$. Since $\mu_k - \ell_{q,N} < 0$, there exists a nontrivial minimum $\omega_k > 0$, which satisfies

$$-\text{div}(\psi_k^2 \nabla' \omega_k) + (\mu_k - \ell_{q,N}) \psi_k^2 \omega_k + \psi_k^{q+1} \omega_k^q = 0.$$  

(4.16)

If we set $\omega_k = \psi_k \omega_k$, then $\omega_k$ satisfies

$$\mathcal{L}' \omega_k - \ell_{q,N} \omega_k + \omega_k^q = 0 \quad \text{in } S^N_+.$$  

(4.17)

By monotonicity we derive that $\omega_k \in L^p(S^N_+)$ for any $1 < p < \infty$ and finally, that $\omega_k$ satisfies the regularity estimates of Propositions 2.9 and 2.10. Moreover $\omega_k > 0$ by the maximum principle.

In the case $q \geq q_c$, or equivalently $\mu_k - \ell_{q,N} \geq 0$, the nonexistence of nontrivial solution is clear from (4.16).

Uniqueness. By Proposition 2.8 $\omega_k(\delta) \leq c_{\delta} \rho(\delta)^{\frac{q-1}{q-1}}$ and by standard scaling techniques $|\nabla \omega_k(x)| \leq c_{\delta} \rho(\delta)^{\frac{q-1}{q-1}}$. Assume now that two different positive solutions of (4.12) $\omega_k$ and $\omega_k'$ exist. Since $\max \{ \omega_k, \omega_k' \}$ and $\omega_k + \omega_k'$ are respectively a subsolution and a supersolution and they are ordered, we can assume that $\omega_k' < \omega_k < c \omega_k'$ for some $c > 1$. Let $\epsilon > 0$ and $\epsilon' = c^{-1} \epsilon$, then $c \omega_k' \geq \epsilon' \omega_k$. Set

$$\vartheta_{\epsilon} = \frac{(\omega_k' + \epsilon')^2 - (\omega_k + \epsilon)^2}{\omega_k + \epsilon}, \quad \vartheta'_{\epsilon} = \frac{(\omega_k' + \epsilon')^2 - (\omega_k + \epsilon)^2}{\omega_k' + \epsilon'},$$

(4.10)
and \(S_{\varepsilon+}=\{\sigma \in S_{+}^{N-1}: \omega_\varepsilon' + \varepsilon > \omega_\varepsilon + \varepsilon\}\). The assumption that \(S_{\varepsilon+} \neq \emptyset\) for any \(\varepsilon > 0\) then yields

\[
\int_{S_{\varepsilon+}} \left( \nabla \omega_\varepsilon' \cdot \nabla \theta_\varepsilon' - \nabla \omega_\varepsilon \cdot \nabla \theta_\varepsilon - \left( \ell_{q,N} + \frac{\kappa}{\rho^2} \right) \left( \omega_\varepsilon' \cdot \theta_\varepsilon' - \omega_\varepsilon \cdot \theta_\varepsilon \right) + \omega_\varepsilon^q \theta_\varepsilon' - \omega_\varepsilon^q \theta_\varepsilon \right) dS = 0.
\]

The first integrand on the l.h. side is equal to

\[
\int_{S_{\varepsilon+}} \left| \nabla \omega_\varepsilon' - \frac{\alpha_\varepsilon' + \varepsilon'}{\omega_\varepsilon} \nabla \omega_\varepsilon \right|^2 + \left| \nabla \omega_\varepsilon - \frac{\alpha_\varepsilon + \varepsilon}{\omega_\varepsilon} \nabla \omega_\varepsilon \right|^2 dS \geq 0.
\]

Since \(\varepsilon \omega_\varepsilon' < \epsilon' \omega_\varepsilon\) and \((\omega_\varepsilon' + \varepsilon')^2 > (\omega_\varepsilon + \varepsilon)^2\), the second integrand on the l.h. side is equal to

\[
- \int_{S_{\varepsilon+}} \left( \ell_{q,N} + \frac{\kappa}{\rho^2} \right) \left( \frac{\alpha_\varepsilon'}{\omega_\varepsilon} + \varepsilon' - \frac{\alpha_\varepsilon}{\omega_\varepsilon} + \varepsilon \right) \left( (\omega_\varepsilon' + \varepsilon')^2 - (\omega_\varepsilon + \varepsilon)^2 \right) dS \geq 0.
\]

At end, the last integrand is

\[
\int_{S_{\varepsilon+}} \left( \omega_\varepsilon'^q - \omega_\varepsilon^q \right) \left( (\omega_\varepsilon' + \varepsilon')^2 - (\omega_\varepsilon + \varepsilon)^2 \right) dS.
\]

If we let \(\varepsilon \to 0\), we derive

\[
\int_{S_{\varepsilon+}} \left( \omega_\varepsilon'^q - \omega_\varepsilon^q \right) \left( (\omega_\varepsilon' + \varepsilon')^2 - (\omega_\varepsilon + \varepsilon)^2 \right) dS \leq 0.
\]

This yields a contradiction. Therefore uniqueness holds.

Case \(q_\varepsilon \leq q < q_0\). Assume \(\omega_\varepsilon\) is a solution. Using the representation of \(S_{+}^{N-1}\) already introduced in the proof of Proposition 4.1, with \(\sigma = (\sigma', \theta)\) and

\[
\Delta_{S^{N-1}} \omega_\varepsilon = \frac{1}{(\sin \theta)^{N-2}} \frac{\partial}{\partial \theta} \left( (\sin \theta)^{N-2} \frac{\partial \omega_\varepsilon}{\partial \theta} \right) + \frac{1}{\sin \theta} \Delta_{S^{N-2}} \omega_\varepsilon,
\]

where \(\Delta_{S^{N-2}}\) is the Laplace–Beltrami operator on \(S^{N-2}\), we set

\[
\tilde{\omega}_\varepsilon(\theta) = \frac{1}{|S^{N-2}|} \int_{S^{N-2}} \omega_\varepsilon(\sigma', \theta) dS'(\sigma').
\]

Then \(\tilde{\omega}_\varepsilon\) is independent of \(\sigma' \in S^{N-2}\) and furthermore

\[
\int_{S_{\varepsilon+}} (\omega_\varepsilon - \tilde{\omega}_\varepsilon) \psi_\varepsilon dS = \int_0^{\frac{\pi}{2}} \left( \int_{S^{N-2}} (\omega_\varepsilon - \tilde{\omega}_\varepsilon) dS' \right) (\sin \theta)^{N-2} (\cos \theta)^{\frac{d+1}{2}} d\theta = 0,
\]

thus \(\tilde{\omega}_\varepsilon\) is the projection of \(\omega_\varepsilon\) onto the first eigenspace of \(L_\varepsilon\) and

\[
\int_{S_{\varepsilon+}} (\omega_\varepsilon - \tilde{\omega}_\varepsilon) \mathcal{L}_\varepsilon (\omega_\varepsilon - \tilde{\omega}_\varepsilon) dS \geq \mu_{k,2} \int_{S_{\varepsilon+}} (\omega_\varepsilon - \tilde{\omega}_\varepsilon)^2 dS.
\]

At end, noting that

\[
\int_{S_{\varepsilon+}} (g_\varepsilon \circ \omega_\varepsilon - g_\varepsilon \circ \tilde{\omega}_\varepsilon)(\omega_\varepsilon - \tilde{\omega}_\varepsilon) dS' = 0,
\]

where we have set \(g_\varepsilon \circ u = |u|^{q-1} u\) for brevity, and thus

\[
\int_{S_{\varepsilon+}} (g_\varepsilon \circ \omega_\varepsilon - g_\varepsilon \circ \tilde{\omega}_\varepsilon)(\omega_\varepsilon - \tilde{\omega}_\varepsilon) dS = \int_0^{\frac{\pi}{2}} \int_{S^{N-2}} (g_\varepsilon \circ \omega_\varepsilon - g_\varepsilon \circ \tilde{\omega}_\varepsilon)(\omega_\varepsilon - \tilde{\omega}_\varepsilon) dS'(\sin \theta)^{N-2} d\theta
\]

\[
= \int_0^{\frac{\pi}{2}} \int_{S^{N-2}} (g_\varepsilon \circ \omega_\varepsilon - (g_\varepsilon \circ \tilde{\omega}_\varepsilon)(\omega_\varepsilon - \tilde{\omega}_\varepsilon) dS'(\sin \theta)^{N-2} d\theta
\]

\[
\geq 2^{1-q} \int_{S_{\varepsilon+}} |\omega_\varepsilon - \tilde{\omega}_\varepsilon|^q dS,
\]

we derive that \(w = \omega_\varepsilon - \tilde{\omega}_\varepsilon\), satisfies

\[
\int_{S_{\varepsilon+}} \left( (\mu_{k,2} - \ell_{N,q})(\omega_\varepsilon - \tilde{\omega}_\varepsilon)^2 + 2^{1-q}|\omega_\varepsilon - \tilde{\omega}_\varepsilon|^q \right) dS \leq 0.
\]
which implies \( \omega_k = \tilde{\omega}_k \) and it satisfies
\[
\frac{1}{(\sin \theta)^{N-2}} \frac{d}{d\theta} \left( \frac{(\sin \theta)^{N-2} d\omega_k}{d\theta} \right) + \left( \ell_{q,N} + \frac{K}{\cos^2 \theta} \right) \omega_k - g_\theta \circ \omega_k = 0. \tag{4.18}
\]

Because \( \mu_{k,1} < \ell_{q,N} \leq \mu_{k,2} \), by [5, Th. 4, Corol. 1], this equation admits the three solutions, \( \omega_k, -\omega_k \) and 0. \( \square \)

**Remark.** For \( \epsilon > 0 \) small enough the function \( \epsilon \psi_\kappa \) is a subsolution for problem (4.12). This implies
\[
\omega_k(\sigma) \geq \epsilon \psi_\kappa(\sigma) \quad \forall \sigma \in S^{N-1}. \tag{4.19}
\]

### 4.3. Isolated boundary singularities

Throughout this section we assume that \( \Omega \subset \mathbb{R}^N, 0 \in \partial \Omega \) the tangent plane to \( \partial \Omega \) at 0 is \( \partial \mathbb{R}^N \) and that \( 1 < q < q_c \).

**Lemma 4.3.** There holds
\[
\lim_{|x| \to 0} \frac{G_{\mathcal{L}_x} \{ (K_{\mathcal{L}_x} (., 0))^{q} \}(x)}{K_{\mathcal{L}_x}(x, 0)} = 0. \tag{4.20}
\]

**Proof.** We recall the following estimates (1.9), (2.57)
\[
\begin{align*}
(i) \quad & G_{\mathcal{L}_x}(x, y) \leq c_3 \min \left\{ \frac{1}{|x - y|^{N-2}}, \frac{(d(x))^{\frac{q}{2}} (d(y))^{\frac{q}{2}}}{|x - y|^{N+\alpha - 2}} \right\}, \\
(ii) \quad & c_3^{-1} \frac{(d(x))^{\frac{q}{2}}}{|x|^{N+\alpha - 2}} \leq K_{\mathcal{L}_x}(x, 0) \leq c_3 \frac{(d(x))^{\frac{q}{2}}}{|x|^{N+\alpha - 2}}.
\end{align*}
\]

Then
\[
\frac{G_{\mathcal{L}_x} \{ K_{\mathcal{L}_x}^{q} (., 0) \}(x)}{K_{\mathcal{L}_x}(x, 0)} \leq c_3^{q+2} |x|^{N+\alpha - 2} \int_\Omega \frac{(d(y))^{(q+1)\omega_k}}{|x - y|^{N+\alpha - 2} |y|^{q(N+\alpha - 2)}} dy
\]
\[
\leq c_3^{q+2} |x|^{N+\alpha - 2 - q(N+\alpha - 2)} \int_{\mathbb{R}^N} \frac{dy}{|\xi - \eta|^{N+\alpha - 2} |\eta|^{q(N+\alpha - 2)}},
\]
where \( e_\kappa = |x|^{-1} x \). This last integral is finite and independent of \( x \). Since \( q < q_c \), (4.20) follows. \( \square \)

**Corollary 4.4.** Let \( u_{k\delta_0} \) be the unique solution of
\[
\mathcal{L}_x u + |u|^{q-1} u = 0 \quad \text{in} \ \Omega \quad u = k\delta_0 \quad \text{in} \ \partial \Omega. \tag{4.21}
\]

Then
\[
\lim_{x \to 0} \frac{u_{k\delta_0}}{K_{\mathcal{L}_x}(x)} = k. \tag{4.22}
\]

**Proof.** This is a consequence of (4.20) and the inequality
\[
k\tilde{G}_{\mathcal{L}_x} \left[ \delta_0 \right](x) - k^q \tilde{G}_{\mathcal{L}_x} \left[ (\tilde{G}_{\mathcal{L}_x} \left[ \delta_0 \right])^q \right] (x) \leq u_{k\delta_0}(x) \leq k\tilde{G}_{\mathcal{L}_x} \left[ \delta_0 \right](x). \tag{4.23}
\]

**Proposition 4.5.** There exists \( u_{\infty,0} = \lim_{k \to \infty} u_{k\delta_0} \) and there holds
\[
\lim_{\substack{x \to 0, x \in \Omega \\ x|x|^{-1} \to \sigma}} |x|^{\frac{2}{q-1}} u_{\infty,0}(x) = \omega_k(\sigma), \tag{4.24}
\]
uniformly on compact subsets of \( S^{N-1}_+ \).
Thus if we choose $K > 0$ and $\ell > 0$ small enough such that
\[
\ell > 0 \quad \text{is self-similar. Set } \ell = \frac{1}{M}, \quad \text{then there holds}
\]
\[
\ell \frac{2}{q-1} u_{\infty,0}(\ell e) \geq c_{01} k \ell \frac{2}{q-1} - c_{02} k \ell \frac{2}{q-1} \quad \forall k > 0.
\]

Now we set $k = \frac{1}{Mt}$, then there holds
\[
\ell \frac{2}{q-1} u_{\infty,0}(\ell e) \geq c_{01} - c_{02} \frac{1}{M^q},
\]
Thus if we choose $M$ big enough, we can easily show that there exists $c_{03} > 0$ which depends on $\kappa, \Omega, q, N$ such that
\[
\ell \frac{2}{q-1} u_{\infty,0}(\ell e) \geq c_{03} > 0 \quad \forall 0 < \ell < \ell_0.
\]
For $\ell > 0$, we put $T_\ell[v](x) = \ell \frac{2}{q-1} \nu(\ell, \Omega, \ell_1) = \ell^{-1} \Omega, d_\ell(y) = \text{dist}(y, \partial \Omega_\ell)$. If $v$ satisfies (4.1) in $\Omega$ and vanishes on $\partial \Omega_\ell \setminus \{0\}$, $T_\ell[v]$ vanishes on $\partial \Omega_\ell \setminus \{0\}$ and satisfies
\[
- \Delta T_\ell[v] - \frac{\kappa}{d_\ell^2} T_\ell[v] + |T_\ell[v]|^{q-1} T_\ell[v] = 0 \quad \text{in } \Omega_\ell.
\]
In order to avoid ambiguity, we set $u_{\infty,0} = u_{\infty,0}^\Omega, v_{\infty,0} = v_{\infty,0}^\Omega, u_{\infty,0} = u_{\infty,0}^\Omega$ and $v_{\infty,0} = v_{\infty,0}^\Omega$. Since inequalities (4.25) and (4.26) are invariant under the scaling transformation $T_\ell$, the standard elliptic equations regularity theory yields the following estimates
\[
u_{\infty,0}(y) \leq c_{02} (d_\ell(y))^{\frac{\alpha_+}{q-1}} |y|^{-\frac{\alpha_+}{q-1}} \quad \forall y \in \Omega_\ell,
\]
and
\[
|\nabla u_{\infty,0}(y)| \leq c_{02} (d_\ell(y))^{\frac{\alpha+}{q-1}} |y|^{-\frac{\alpha+}{q-1}} \quad \forall y \in \Omega_\ell,
\]
valid for any $0 < \ell \leq 1$. If we let $k \to \infty$, we obtain $T_\ell[u_{\infty,0}^\Omega] = u_{\infty,0}^\Omega$ and because of the group property of the transformations $T_\ell[u_{\infty,0}^\Omega]$, there holds $T_\ell[u_{\infty,0}^\Omega] = u_{\infty,0}^\Omega$ for any $\ell, \ell' > 0$. Estimates (4.29) and (4.30) imply that $u_{\infty,0}^\Omega$ is relatively compact for the topology of convergence on compact subsets of $\mathbb{R}^N_+$. Therefore there exist a sequence $\{\ell_n\}$ tending to 0 and a function $U$ such that $\{u_{\infty,0}^\Omega\}$ converges to $U$ uniformly on any compact subset of $\mathbb{R}^N_+$. By (4.27) this function is identically equal to zero. Therefore $U$ is a weak solution of
\[
- \Delta U - \frac{\kappa}{\beta_+} U + U^q = 0 \quad \text{in } \mathbb{R}^N_+.
\]
Furthermore
\[
u_{\infty,0}(y) \leq c_{02} \beta_+^q |y|^\frac{2}{\alpha_+} \quad \forall y \in \mathbb{R}^N_+.
\]
Since $T_\ell[u_{\infty,0}^\Omega] = u_{\infty,0}^\Omega$, we derive $T_\ell[U] = U$ for any $\ell > 0$, thus $U$ is self similar. Set $\omega(\frac{y}{|y|}) = U(\frac{y}{|y|})$. If we set $\sigma = \frac{y}{|y|}$, there holds
\[
\omega(\sigma) \leq c_{02} \psi_\kappa(\sigma) \quad \forall \sigma \in S^{N-1}_+.
\]
Therefore \( \omega \) satisfies (4.12) and it coincides with the unique positive element \( \omega_\kappa \) of \( \mathcal{E}_\kappa \), since by (4.27) \( U(\epsilon) \geq c_{03} > 0 \). Thus \( u_{\infty,0}^{O_1} \) converges to \( U \) on compact subsets of \( \mathbb{R}^N_+ \). In particular (4.24) holds on compact subsets of \( S^{N-1}_+ \). \( \square \)

5. The boundary trace of positive solutions

As before we assume that \( 0 < \kappa \leq \frac{1}{4}, q > 1 \) and \( \Omega \) is a bounded smooth domain, convex if \( \kappa = \frac{1}{4} \). Although the construction of the boundary trace can be made in a more general framework, we restrict ourselves to the class \( \mathcal{U}_+(\Omega) \) of positive smooth functions \( u \) satisfying

\[
\mathcal{L}_u u + |u|^{q-1} u = 0
\]

in \( \Omega \).

Lemma 5.1. Let \( f \in L^1_+(\Omega) \). If \( u \) is a nonnegative solution of

\[
\mathcal{L}_u u = f \quad \text{in } \Omega
\]

there exists \( \mu \in \mathcal{M}_+(\partial \Omega) \) such that \( u \) admits \( \mu \) for boundary trace and

\[
u = G_{\mathcal{L}_u}[f] + \mathcal{R}_{\mathcal{L}_u}[\mu].
\]

Proof. Let \( \nu = G_{\mathcal{L}_u}[f] \), then \( u - \nu \) is \( \mathcal{L}_u \)-harmonic and positive thus the result follows. \( \square \)

Definition. Let \( G \subset \Omega \) be a domain. A function \( u \in L^1_{\text{loc}}(G) \) is a supersolution (resp. subsolution) of (5.1) if

\[
\mathcal{L}_u u + |u|^{q-1} u \geq 0 \quad \text{(resp. } \mathcal{L}_u u + |u|^{q-1} u \leq 0)\]

in the sense of distributions in \( G \).

The following comparison principle holds [3, Lemma 3.2].

Proposition 5.2. Let \( G \subset \Omega \) be a smooth domain and \( \bar{u}, \underline{u} \) a pair of nonnegative supersolution and subsolution respectively in \( G \).

(i) If there holds

\[
\lim_{\text{dist}(x, \partial G) \to 0} (\bar{u}(x) - \underline{u}(x)) < 0,
\]

then \( \underline{u} < \bar{u} \) in \( G \).

(ii) Assume \( \bar{G} \subset \Omega \) and \( \underline{u}, \bar{u} \) belong to \( H^1(G) \cap C(\bar{G}) \). If \( \underline{u} \leq \bar{u} \) in \( \partial G \), then \( \underline{u} \leq \bar{u} \) in \( G \).

5.1. Construction of the boundary trace

We use the notations of [25].

Proposition 5.3. Let \( \nu \) be a non-negative function in \( C(\Omega) \).

(i) If \( \nu \) is a subsolution of (5.1), there exists a minimal solution \( u_\nu \) dominating \( \nu \), i.e. \( \nu \leq u_\nu \leq U \) for any solution \( U \geq \nu \).

(ii) If \( \nu \) is a supersolution of (5.1), there exists a maximal solution \( u^* \) dominated by \( \nu \), i.e. \( U \leq u^* \leq \nu \) for any solution \( U \leq \nu \).

Proof. (i) Let \( \{\Omega_n\} \) be a smooth exhaustion \( \Omega \) and for each \( n \in \mathbb{N}, u_n \) the positive solution of

\[
\mathcal{L}_u u + |u|^{q-1} u = 0 \quad \text{in } \Omega_n, \quad u = \nu \quad \text{in } \partial \Omega_n.
\]

By the comparison principle \( u_n \geq \nu \), which implies \( u_{n+1}(x) \geq u_n(x) \) \( \forall x \in \Omega_n \). Since \( \{u_n\} \) is uniformly bounded on compact subsets of \( \Omega \) and thus in \( C^2 \) by standard regularity arguments that \( u_n \uparrow u^* \), which is a positive solution of (5.1). Furthermore, if \( U \) is any solution of (5.1) dominating \( \nu \), it dominates \( u_n \) in \( \Omega_n \) and thus \( u_n \leq U \).

The proof of (ii) is similar: we construct a decreasing sequence \( \{u'_n\} \) of nonnegative solutions of (5.1) in \( \Omega_n \) coinciding with \( \nu \) on \( \partial \Omega_n \) and dominated by \( \nu \). It converges to some \( u^* \) which satisfies \( U \leq u^* \leq \nu \) for any solution \( U \) dominated by \( \nu \). \( \square \)

Proposition 5.4. Let \( 0 \leq u, \nu \in C(\Omega) \).

(i) If \( u \) and \( \nu \) are subsolutions (resp. supersolutions) then \( \max(u, \nu) \) is a subsolution (resp. \( \min(u, \nu) \) is a supersolution).

(ii) If \( u \) and \( \nu \) are supersolutions then \( u + \nu \) is a supersolution.

(iii) If \( u \) is a subsolution and \( \nu \) is a supersolution then \( (u - \nu)_+ \) is a subsolution.
**Proof**. The first two statements follow Kato’s inequality. The last statement is verified using that
\[-\Delta (u - v) \leq \text{sign}_+(u - v) (-\Delta (u - v)) \leq -\text{sign}_+(u - v) (u^q - v^q) + \kappa \frac{(u - v)_+}{d^2(x)} \leq -(u - v)_+^q + \kappa \frac{(u - v)_+}{d^2(x)}. \]

**Notation 5.5.** Let \( u, v \) be nonnegative continuous functions in \( \Omega \).

(a) If \( u \) is a subsolution, \([u]_\|\) denotes the smallest solution dominating \( u \).

(b) If \( u \) is a supersolution, \([u]_\|\) denotes the largest solution dominated by \( u \).

(c) If \( u, v \) are subsolutions then \( u \land v := [\max(u, v)]_\|\).

(d) If \( u, v \) are supersolutions then \( u \wedge v := [\min(u, v)]_\| \) and \( u \lor v = [u \lor v]_\| \).

(e) If \( u \) is a subsolution and \( v \) is a supersolution then \( u \oplus v := [(u - v)_+]_\| \).

The next result based upon local uniform estimates is due to Dynkin [12].

**Proposition 5.6.** (i) Let \( \{u_n\} \subset C(\Omega) \) be a sequence of positive subsolutions (resp. supersolutions) of (5.1). Then \( T := \sup u_k \) (resp. \( U := \inf u_k \)) is a subsolution (resp. supersolution).

(ii) Let \( T \subset C(\Omega) \) be a family of positive solutions of (5.1). Suppose that, for every pair \( u_1, u_2 \in T \) there exists \( v \in T \) such that
\[ \max(u_1, u_2) \leq v \quad \text{resp.} \quad \min(u_1, u_2) \geq v. \]

Then there exists a monotone sequence \( \{u_n\} \subset T \) such that
\[ u_n \uparrow \sup T \quad \text{resp.} \quad u_n \downarrow \inf T. \]

Furthermore \( \sup T \) (resp. \( \inf T \)) is a solution.

**Definition 5.7.** Let \( F \subset \partial \Omega \) be a closed set. We set
\[ U_F := \sup \left\{ u \in U_+(\Omega) : \lim_{x \to \xi} \frac{u(x)}{W(x)} = 0, \ \forall \xi \in \partial \Omega \setminus F \right\}, \] \[ (5.7) \]
and
\[ [u]_F = \sup \left\{ v \in U_+(\Omega) : v \leq u, \ \lim_{x \to \xi} \frac{v(x)}{W(x)} = 0, \ \forall \xi \in \partial \Omega \setminus F \right\}. \] \[ (5.8) \]

Notice that \( F \mapsto U_F \) and \( F \mapsto [u]_F \) are increasing with respect to the inclusion order relation in \( \partial \Omega \). As a consequence of Proposition A.3, \( U_F \) satisfies
\[ \lim_{x \to \xi} \frac{U_F(x)}{W(x)} = 0, \quad \forall \xi \in \partial \Omega \setminus K. \] \[ (5.9) \]

**Proposition 5.8.** Let \( E, F \subset \partial \Omega \) be closed sets. Then

(i) \( U_E \land U_F = U_{E\cap F} \).

(ii) If \( F_n \subset \partial \Omega \) is a decreasing sequence of closed sets there holds
\[ \lim_{n \to \infty} U_{F_n} = U_F \quad \text{where} \quad F = \cap F_n. \]

**Proof.** (i) \( U_E \land U_F \) is the largest solution dominated by \( \inf(U_E, U_F) \) and therefore, by definition, it is the largest solution which vanishes outside \( E \cap F \).

(ii) If \( V := \lim U_{F_n} \) then \( U_F \leq V \). But \( \text{supp} (V) \subset F_n \) for each \( n \in \mathbb{N} \) and consequently \( V \leq U_F \). \( \Box \)

For \( \beta > 0 \), we recall that \( \Omega_\beta, \Sigma_\beta \) and the mapping \( x \mapsto (d(x), \sigma(x)) \) have been defined in the proof of Lemma 3.9. We also set \( \Omega_\beta^\beta = \Omega \setminus \overline{\Omega_\beta} \) and, if \( Q \subset \partial \Omega, \Sigma_\beta(Q) = \{ x \in \Omega_\beta : \sigma(x) \in Q \} \).

**Proposition 5.9.** Let \( u \in U(\Omega) \).

(i) If \( A, B \subset \partial \Omega \) are closed sets. Then
\[ [u]_{A|B} = [u]_{A|B} = [u]_{A\setminus B}. \] \[ (5.10) \]
(ii) If \( \{F_n\} \) is a decreasing sequence of closed subsets of \( \partial \Omega \) and \( F = \cap F_n \), then
\[
[u]_{\partial \Omega} \downarrow [u]_F.
\]
(iii) If \( A, B \subset \partial \Omega \) are closed sets. Then
\[
[u]_\partial \leq |u|_{A \cap B} + |u|_{\overline{A \cap B}}.
\]

**Proof.** (i) It follows directly from definition that,
\[
[|u|_A]_B \leq \inf(u, U_A, U_B).
\]
The largest solution dominated by \( u \) and vanishing on \( A^C \cup \overline{B} \) is \( [u]_{A^C \cup B} \). Thus
\[
[|u|_A]_B \leq [u]_{A^C \cup B}.
\]
On the other hand
\[
[u]_{A^C \cup B} = [(|u|_A)]_B \leq [u]_A,
\]
which proves (5.10).
(ii) If \( F_n \downarrow F \), it follows by Proposition 5.8-(ii) that \( U_{F_n} \rightarrow U_F \), thus
\[
[u]_F \leq \lim_{n \to \infty} [u]_{F_n} = \lim_{n \to \infty} u \wedge U_{F_n} \leq \lim_{n \to \infty} \inf(u, U_{F_n}) \leq \inf(u, U_F).
\]
Since \( [u]_F \) is the largest solution dominated by \( \inf(u, U_F) \), \( [u]_{F_n} \) is the largest solution dominated by \( \inf(u, U_{F_n}) \) and \( U_{F_n} \downarrow U_F \).

(iii) Without loss of generality we assume that \( A \cap B \neq \emptyset \). Let \( O' \subset \partial \Omega \) be a relatively open set such that \( A \cap B \subset O \) and \( A \cap \overline{B'} \subset O' \).
Set \( v = [u]_A \) and let \( v^{i}_\beta \) be the solution of
\[
L_{\Sigma} w + |w|^{q-1} w = 0 \quad \text{in } \Omega^\beta
\]
\[
w = \chi_{\Sigma^{\beta \beta}} v \quad \text{on } \Sigma^\beta.
\]
Also we denote by \( v^2_\beta \) and \( v^3_\beta \) the solutions of the above problem with respective boundary data \( \chi_{\Sigma^\beta} v \) and \( \chi_{\Sigma(\partial \Omega \cap \Omega^\beta)} v \). Then
\[
v^i_\beta \leq v^i_{\partial \Omega} \leq v^2_\beta + v^3_\beta + v^3_i, \quad i = 1, 2, 3.
\]
Let now \( \{\beta_i\} \) be a decreasing sequence converging to 0 and such that
\[
v^i_{\beta_i} \to v^i \leq v^1 + v^2 + v^3, \quad i = 1, 2, 3 \text{ locally uniformly in } \Omega.
\]
By definition of \( v^i \) and Proposition A.1, we have that
\[
v^1 \leq [v]_\partial, \quad v^2 \leq [v]_{\partial \Omega} \quad \text{and} \quad v^3 \leq [v]_{\partial \Omega \cap \Omega^\beta}.
\]
But by (i) we have
\[
[v]_{\partial \Omega \cap \Omega^\beta} = [u]_{\partial \Omega \cap \Omega^\beta} = [u]_{A^C \cup \overline{B}} = 0.
\]
Thus
\[
v \leq [v]_\partial + [v]_{\partial \Omega}.
\]
We can consider decreasing sequences \( \{O_n\} \) and \( \{O'_n\} \) such that \( \cap O_n = A \cap B \) and \( \cap O'_n = A \cap \overline{B'} \).
By (ii) we obtain
\[
v \leq \inf(u, U_A, U_B) \leq [u]_{A^C \cup B} + [u]_{\overline{A \cap B}}.
\]
which is (iii). \( \square \)

**Remark.** Since any \( u \in \mathcal{U}_A(\Omega) \) is dominated by \( u_{A^C} \), it follows from (iii) that for any set \( A \subset \partial \Omega \), there holds
\[
u = [u]_{\partial \Omega} \leq [u]_A \leq [u]_{\partial \Omega} + [u]_{\overline{A \cap B}}.
\]

(5.12)

**Proposition 5.10.** Let \( u \) be a positive solution of (5.1). If \( u \in L^q_{\phi_k}(\Omega) \) it possesses a boundary trace \( \mu \in \mathcal{M}(\partial \Omega) \), i.e., \( u \) is the solution of the boundary value problem (3.36) with this measure \( \mu \).

**Proof.** If \( v := C_{\mathcal{L}_\lambda}(u^l) \) then \( v \in L^\infty_{\phi_k}(\Omega) \) and \( u + v \) is a positive \( L_{\mathcal{L}} \)-harmonic function. Hence \( u + v \in L^\infty_{\phi_k}(\Omega) \) and there exists a non-negative measure \( \mu \in \mathcal{M}(\partial \Omega) \) such that \( u + v = K_{\mathcal{L}} \mu \).

By Proposition 3.5 this implies the result. \( \square \)

**Proposition 5.11.** Let \( u \) be a positive solution of (5.1) and \( \mu \in \mathcal{M}(\partial \Omega) \). If for an exhaustion \( \{\Omega_n\} \) of \( \Omega \), we have
\[
\lim_{n \to \infty} \int_{\partial \Omega_n} Z(x)ud\omega_{\Omega_n}^{\lambda} = \int_{\partial \Omega} Z(x)d\mu \quad \forall Z \in C(\overline{\Omega}),
\]
where \( \omega_{\Omega_n}^{\lambda} \) is the \( L^- \)-harmonic measure of \( \Omega_n \) relative to a point \( x_0 \in \Omega_1 \), then \( u \) and \( |u|^p \) belong to \( L^1_{\phi_k}(\Omega) \). Furthermore \( u \) possesses the boundary trace \( \mu \in \mathcal{M}(\partial \Omega) \), i.e. \( u \) is the solution of the boundary value problem (3.36) with this measure \( \mu \).
Proof. Let $G^n_{\partial_\omega} \big|_{\partial_\omega}$ be the green function of $L_\omega$ in $\Omega_n$, then
$$G^n_{\partial_\omega}(x, y) \leq G^{n+1}_{\partial_\omega}(x, y) \quad \forall x, y \in \Omega_n$$
and
$$G^n_{\partial_\omega} \uparrow G_{\partial_\omega}.$$  
Since
$$\int_{\partial_\omega} u d\omega^x_{\partial_\omega} = u(x_0) + \int_{\Omega_n} G^n_{\partial_\omega}(x, x_0)|u(x)|^q dx,$$
we derive, as $n \to \infty$,
$$\mu(\partial_\Omega) = u(x_0) + \int_{\Omega_n} G^n_{\partial_\omega}(x, x_0)|u(x)|^q dx.$$
By Proposition 2.1 this implies $|u|^q \in L^1_{\partial_\omega}(\Omega)$, and the result follows by Proposition 5.10.

Proposition 5.12. If $F \subset \partial_\Omega$ is a closed set and $u$ a positive solution of (5.1) with boundary trace $\mu \in M(\partial_\Omega)$, then $[u]_F$ has boundary trace $\mu_F$.

Proof. The function $[u]_F$ belongs to $\mathcal{U}_+(\Omega)$ and is dominated by $u$ which satisfies (5.1), thus $[u]_F \in L^1_{\partial_\omega}(\Omega)$ and $[u]_F$ admits a boundary trace $\mu_F \leq \mu$ by Proposition 5.10. Let $\nu$ be the solution of (3.36) with boundary data $\mu_F$. Let $\Omega \subset \partial_\Omega$ relatively open such that $F \subset \Omega$. By (5.12) we have
$$\nu \leq [\nu]_\Sigma + [\nu]_{\partial_\Omega}.$$  
Let $A$ be an open set such that $F \subset A \subset \bar{A} \subset O$, and for exhaustion we take $\Omega_n = \Omega_n^A$ which is smooth for $n$ large enough, and $\partial \Omega_n = \Sigma_n$. Then
$$\int_{\partial \Omega_n} [\nu]_{\partial_\Omega} d\omega^x_{\partial_\Omega_n} = \int_{\Sigma_n} [\nu]_{\partial_\Omega} d\omega^x_{\partial_\Omega_n} = \int_{\partial \Omega_n \setminus \Sigma_n} [\nu]_{\partial_\Omega} d\omega^x_{\partial_\Omega_n} + \int_{\partial \Omega_n \setminus \Sigma_n} [\nu]_{\partial_\Omega} d\omega^x_{\partial_\Omega_n}.$$  
But
$$\int_{\Sigma_n} [\nu]_{\partial_\Omega} d\omega^x_{\partial_\Omega_n} \leq \int_{\Sigma_n} v d\omega^x_{\partial_\Omega_n} \to 0$$
and
$$\int_{\partial \Omega_n \setminus \Sigma_n} [\nu]_{\partial_\Omega} d\omega^x_{\partial_\Omega_n} \leq \int_{\partial \Omega_n \setminus \Sigma_n} U d\omega^x_{\partial_\Omega_n} \to 0,$$
as $n \to \infty$, thus $[\nu]_{\partial_\Omega} = 0$ by Proposition 5.11 and therefore $\nu \leq [\nu]_\Sigma \leq [u]_\Sigma$. Since $O$ be an arbitrary open set, take a sequence of open set $\{O_n\}$ such that $F \subset O_n \subset \bar{O}_n \subset O_{n-1}$ and $\cap O_n = F$. Using Proposition 5.9 we derive
$$\nu \leq [u]_F,$$
and thus $\mu_F \leq \mu$. Conversely, let $Z \in C(\bar{\Omega})$, $Z \geq 0$, 
$$\int_{\partial \Omega_n} Z[u]_F d\omega^x_{\partial_\Omega_n} = \int_{\partial \Omega_n \cap \Sigma_n} Z[u]_F d\omega^x_{\partial_\Omega_n} + \int_{\partial \Omega_n \setminus \Sigma_n} Z[u]_F d\omega^x_{\partial_\Omega_n} \leq nt_{\partial \Omega_n \cap \Sigma_n} Z u d\omega^x_{\partial_\Omega_n} + \int_{\partial \Omega_n \setminus \Sigma_n} Z U d\omega^x_{\partial_\Omega_n} \leq \sum_{n=1}^N L_n + L_n$$
Because of (5.9), $L_n \to 0$ as $n \to \infty$, thus
$$\int_{\partial \Omega} Z d\mu \leq \int_{\partial \Omega} Z \chi_F d\mu \implies \mu \leq \mu_F \chi_F,$$
and the result follow by regularity since $O$ is arbitrary.

The next result shows that the boundary trace has a local character.
Proposition 5.13. Let $u \in \mathcal{U}_+(\Omega)$ and $\xi \in \partial \Omega$. We assume that there exists $\rho > 0$ such that

$$
\int_{B_{\rho}(\xi) \cap \Omega} u^p(x) \phi_u(x) \, dx < \infty.
$$

(i) Then 

$$
[u]_{F}^p \in L^1_{\phi_u}(\Omega) \quad \forall F \subset \partial \Omega \cap B_{\rho}(\xi), \ F \ closed.
$$

Thus $[u]_F$ possesses a boundary trace $\mu_F \in \mathcal{M}(\partial \Omega)$, and $\text{supp}(\mu_F) \subset F$.

(ii) There exists a nonnegative Radon measure $\mu_\rho$ on $B_{\rho}(\xi)$ such that for any closed set $F \subset B_{\rho}(\xi) \cap \partial \Omega$

$$
\mu_F = \mu_\rho \chi_F,
$$

and for any exhaustion $\{\Omega_n\}$ of $\Omega$ and any $Z \in C(\overline{\Omega})$ such that $\text{supp}(Z) \cap \partial \Omega \subset \partial \Omega \cap B_{\rho}(\xi)$

$$
\lim_{n \to \infty} \int_{\partial \Omega_n} u(x)Z(x) \, d\omega_{\Omega_n}^q = \int_{\partial \Omega} u(x)Z(x) \, d\mu_\rho.
$$

Proof. (i) Let $F$ be a closed set and $0 < \rho' < \rho$ be such that

$$
F \subset \partial \Omega \cap B_{\rho'}(\xi).
$$

Since $[u]_F \leq \inf(u, U_F)$ and $U_F \in C(\overline{\Omega} \setminus F)$, we have

$$
\int_{\partial \Omega} [u]_{B_{\rho'}(\xi) \cap \partial \Omega}^p \phi_u(x) \, dx \leq \int_{B_{\rho}^p(\xi) \cap \partial \Omega} |u|^p \phi_u(x) \, dx + \int_{\partial \Omega \setminus B_{\rho}^p(\xi)} |U_F|^p \phi_u(x) \, dx < \infty.
$$

(ii) Let $0 < \rho_1 < \rho_2 < \rho$, then

$$
[u]_{\partial \Omega_2 \setminus \partial \Omega}^p \leq u \leq [u]_{\partial \Omega_1 \setminus \partial \Omega} + U_{\partial \Omega_2 \setminus \partial \Omega}^p(\xi).
$$

The function $[u]_{\partial \Omega_2 \setminus \partial \Omega}$ which belongs $L^1_{\phi_u}(\Omega)$ admits a boundary trace $\nu \in \mathcal{M}(\partial \Omega)$ and

$$
\lim_{n \to \infty} \int_{\partial \Omega_n} U_{\partial \Omega_2 \setminus \partial \Omega}^p Z(x) \, d\omega_{\Omega_n}^q = 0,
$$

for any $Z \in C(\overline{\Omega})$ such that $\text{supp}(Z) \cap \partial \Omega \subset \partial \Omega \cap B_{\rho_1}(\xi)$. Combined with Proposition 5.12 it follows identity (5.14) and finally statement (ii). \qed

Using a partition of unity it is easy to prove the following extension of the previous result.

Proposition 5.14. The set $\mathcal{R}_u$ of points $\xi$ such that there exists $r > 0$ such that (5.14) holds is relatively open. For any compact set $F \subset \mathcal{R}_u$ and any open set $G \subset \mathbb{R}^n$ such that $F \subset G \cap \partial \Omega \subset G \cap \partial \Omega \subset \mathcal{R}_u$, there holds

$$
\int_{\partial \Omega} u^q(x) \phi_u(x) \, dx < \infty.
$$

Then $[u]_F \in L^1_{\phi_u}(\Omega)$, $[u]_F$ possesses a boundary trace $\mu_F \in \mathcal{M}(\partial \Omega)$ with support in $F$. There exists a unique positive Radon measure $\mu_u$ on $\mathcal{R}_u$ such that

$$
\mu_F = \mu_u \chi_F,
$$

and for any $Z \in C(\overline{\Omega})$ such that $\text{supp}(Z) \cap \partial \Omega \subset \mathcal{R}_u$, there holds

$$
\lim_{n \to \infty} \int_{\partial \Omega_n} u(x)Z(x) \, d\omega_{\Omega_n}^q = \int_{\partial \Omega} u(x)Z(x) \, d\mu_u.
$$

Definition 5.15. The set $\delta_u := \partial \Omega \setminus \mathcal{R}_u$ is closed. The couple $(\delta_u, \mu_u)$ is the boundary trace of $u$, denoted by $\text{Tr}_{\delta \Omega}(u)$. The measure $\mu_u$ is the regular part of $\text{Tr}_{\delta \Omega}(u)$, the set $(\delta_u)$ is its singular part.

Proposition 5.16. Let $u$ be a positive solution in $\Omega$ and let $\{\Omega_n\}$ be an exhaustion of $\Omega$. If $y \in \delta_u$ then for every nonnegative $Z \in C(\overline{\Omega})$ such that $Z(y) > 0$ we have

$$
\lim_{n \to \infty} \int_{\partial \Omega_n} Z u \, d\omega_{\Omega_n}^q = \infty.
$$
Proof. Let $Z \in C^1(\overline{\Omega})$, $Z \geq 0$, such that $Z(y) \neq 0$ and
\[
\liminf_{n \to \infty} \int_{\partial \Omega_n} Z u \omega_\delta^{\alpha_0} < \infty.
\]
There exists a subsequence $\eta_j$ such that
\[
\lim_{j \to \infty} \int_{\partial \Omega_{\eta_j}} Z u \omega_\delta^{\alpha_0} = M < \infty.
\]
Let $r$ be such that $Z(x) > \frac{Z(y)}{2}$, $\forall x \in B_r(y) \cap \overline{\Omega}$, then for any $r' < r$ we have that
\[
\limsup_{j \to \infty} \int_{\partial \Omega_{\eta_j}} [u]_{B_{r'}(y) \cap \partial \Omega} \omega_\delta^{\alpha_0} < \infty.
\]
In view of the proposition of 5.11 the last fact implies that $[u]_{B_{r'}(y)} \in L^q(\Omega)$, which implies that $u \in L^q_{\phi_k}(B_{r'}(y))$ for all $r'' < r'$, which is clearly a contradiction, by Proposition 5.13. □

Proposition 5.17. Let $u$ be a positive solution of (5.1) in $\Omega$ with boundary trace $(\delta_u, \mu_u)$. If $F$ is a closed subset of $\mathcal{R}_u$, then
\[
\int_{\Omega} (u \mathcal{L}_u \xi + u^{\theta} \xi) \, dx = \int_{\Omega} \mathcal{K}_u \mathcal{L}_u \xi \, dx,
\]
for any $\xi \in \mathbf{X}(\Omega)$ such that $\text{supp}(\xi) \cap \partial \Omega \subset F$.

Proof. The proof is an adaptation to our situation of [26, Th 4.6]. Consider the function $\xi \in \mathbf{X}(\Omega)$ such that $\text{supp}(\xi) \cap \partial \Omega \subset F$. For $\varepsilon > 0$, set
\[
O_\varepsilon = \{ x \in \mathbb{R}^N : \text{dist}(x, F) < \varepsilon \},
\]
and let $\varepsilon_0 > 0$ be small enough such that
\[
\overline{O}_\varepsilon \cap \partial \Omega \subset \mathcal{R}_u, \quad \forall 0 < \varepsilon < \varepsilon_0.
\]
Let $\varepsilon < \frac{\varepsilon_0}{4}$ and $\eta$ be a cut off function such that $\eta \in C_0^\infty(O_\varepsilon)$, $0 \leq \eta \leq 1$ and $\eta \equiv 1$ on $\overline{O}_\varepsilon$. For $0 < \beta \leq \beta_0$, let $v_\beta$ be the solution of
\[
\mathcal{L}_u w + |w|^{q-1} w = 0 \quad \text{in } \Omega_\beta',
\]
\[
w = \eta u \quad \text{on } \Sigma_\beta.
\]
Since $v_\beta$ remains eventually locally uniformly bounded in $\Omega$, there exists a sequence $\{ \beta_j \}$ decreasing to 0 such that $v_{\beta_j} \to v$ locally uniformly, and
\[
v \leq [u]_{B_{\Omega} \cap \Sigma_\beta}.
\]
Thus $v$ has boundary trace $\mu_0$ such that
\[
\mu_0 \leq \mu_u \mathcal{X}_{\beta} \cap \Sigma_0.
\]
Let $v_\beta^1$ and $v_\beta^2$ be the solutions of
\[
\mathcal{L}_u w + |w|^{q-1} w = 0 \quad \text{in } \Omega_\beta',
\]
\[
w = \eta u \mathcal{X}_{\beta} \cap \Sigma_0 \quad \text{on } \Sigma_\beta
\]
and
\[
\mathcal{L}_u w + |w|^{q-1} w = 0 \quad \text{in } \Omega_\beta',
\]
\[
w = \eta u \mathcal{X}_{\beta} \cap \Sigma_0 \quad \text{on } \Sigma_\beta.
\]
respectively. Since $u \leq [u]_{B_{\Omega} \cap \Sigma_0} + U_{\beta_0 \cap \Sigma_0}$ we have that
\[
v_\beta \leq v_\beta^1 + v_\beta^2 \leq [u]_{B_{\Omega} \cap \Sigma_0} + v_\beta^2.
\]
Notice that $[u]_{B_{\Omega} \cap \Sigma_0} \in L^1_{\phi_k}(\Omega)$. From estimate (A.20) we derive
\[
\eta(x) U_{\beta \cap \sigma_0}(x) \leq c_9 d_{\beta}^{\frac{\sigma}{\gamma}}(x) \quad \forall x \in \Omega.
\]
where \(c_{90} > 0\) depends on \(N, q, \kappa\) and \(\text{dist}(\text{supp}(\eta), \partial \Omega \setminus \Omega_\kappa)\). Thus \(v^2_\beta(x) \leq c_{90}d^\omega(x)\) and

\[
v^\beta \leq [u]_{\partial \Omega \cap \Omega_\kappa} + c_{90}d^\omega(x), \quad \forall x \in \Omega_\beta'.
\]

(5.18)

Let \(w_\beta\) be the solution of

\[
\mathcal{L}_\kappa w + |w|^{q-1}w = 0 \quad \text{in } \Omega_\beta',
\]

\[
w = \chi_{\Sigma_\beta}(\frac{\partial \Omega \cap \Omega_\kappa}{2})[u]_F \quad \text{on } \Sigma_\beta.
\]

Then

\[
[u]_F \leq v^\beta + w_\beta \quad \text{in } \Omega_\beta'.
\]

We have that \(w_\beta \to 0\) locally uniformly in \(\Omega\), which implies that \(\lim_{\beta \to 0} [u]_F \leq v\).

Thus we have

\[
\mu_u \chi_F \leq \mu_0 \leq \mu_u \chi_{\partial \Omega' \cap \Sigma_\kappa}.
\]

(5.19)

Let \(\zeta_\beta\) be the solution of

\[
\mathcal{L}_\kappa w = \mathcal{L}_\kappa \zeta \quad \text{in } \Omega_\beta',
\]

\[
w = 0 \quad \text{on } \Sigma_\beta.
\]

Since \(\zeta \in X(\Omega)\), there exists a constant \(c_{91}\) such that \(\zeta_\beta \leq c_{91} \phi_\kappa\) in \(\Omega_\beta'\). Thus there exists a decreasing sequence \(\{\beta_j\}\) converging to 0 such that \(\zeta_{\beta_j} \to \zeta\) locally uniformly. For simplicity we will denote it by \(\{\beta\}\). Now,

\[
\int_{\Omega_\beta'} (u \mathcal{L}_\kappa \zeta_\beta + u^q \zeta_\beta)dx = -\int_{\partial \Omega_\beta'} \frac{\partial \zeta_\beta}{\partial \nu} u dS
\]

\[
= \int_{\Omega_\beta'} (v^\beta \mathcal{L}_\kappa \zeta_\beta + v^q \zeta_\beta)dx
\]

(5.20)

which yields, by the definition of \(\zeta_\beta\) and \(v_\beta\),

\[
\int_{\Omega_\beta'} (u \mathcal{L}_\kappa \zeta + u^q \zeta)dx = \int_{\Omega_\beta'} (v_\beta \mathcal{L}_\kappa \zeta + v^q \zeta)dx.
\]

(5.21)

Since \(\text{supp}(\zeta) \cap \partial \Omega \subset F\), then for \(\beta\) small enough \(u \in L^q_{\partial \Omega} (\Omega \cap \Omega_\kappa)\). Furthermore \(v^\beta \leq u|_{\partial \Omega_\beta'}\), therefore, it follows the following convergence relations by the dominated convergence theorem, (5.17) and (3.5):

\[
\lim_{\beta \to 0} \int_{\Omega_\beta'} u^q \zeta_\beta dx = \int_{\Omega} u^q \zeta dx \quad \text{and} \quad \lim_{\beta \to 0} \int_{\Omega_\beta'} v^q \zeta_\beta dx = \int_{\Omega} v^q \zeta dx,
\]

and

\[
\lim_{\beta \to 0} \int_{\Omega_\beta'} u \mathcal{L}_\kappa \zeta dx = \int_{\Omega} u \mathcal{L}_\kappa \zeta dx \quad \text{and} \quad \lim_{\beta \to 0} \int_{\Omega_\beta'} v_\beta \mathcal{L}_\kappa \zeta dx = \int_{\Omega_\beta'} v_\beta \mathcal{L}_\kappa \zeta dx.
\]

This implies

\[
\int_{\Omega} (u \mathcal{L}_\kappa \zeta + u^q \zeta)dx = \int_{\Omega} (v_\beta \mathcal{L}_\kappa \zeta + v^q \zeta)dx = \int_{\Omega} \mathcal{L}_\kappa [\mu_0] \mathcal{L}_\kappa \zeta dx
\]

by (3.19).

Letting \(\epsilon \to 0\) we have the desired result from (5.19). \(\Box\)

5.2. Subcritical case

We recall that

\[
q_c = \frac{N + \alpha_k}{N + \frac{\alpha_k}{2} - 2}
\]

is the critical exponent for the equation. If \(1 < q < q_c\), we have seen in Section 4 that for any \(a \in \partial \Omega\) and \(k \geq 0\) there exists \(u_{\kappa a}\) and \(\lim_{k \to \infty} u_{\kappa a} = u_{\infty, a}\). Furthermore, by Proposition 5.16, \(\text{Tr}_{\partial \Omega}(u_{\infty, a}) = ([a], 0)\).
Theorem 5.18. Assume $1 < q < q_c$ and $a \in \mathcal{A}_u$. Then
\[ u(x) \geq u_{x_0,a}(x) \quad \forall x \in \Omega. \tag{5.22} \]

For proof of the above inequality uses some ideas of the proof of Theorem 7.1 in [24] and needs several intermediate lemmas.

Lemma 5.19. Assume $1 < q < q_c$. Let $\{\xi^n\}$ be a sequence of points in $\Omega$ converging to $a \in \partial \Omega$ and let $l \in (0, 1)$. We define the sets
\[ \Omega_n := \Omega_{d(\xi^n)} = \{x \in \Omega : d(x) > d(\xi^n)\} \quad \text{and} \quad \Sigma_n := \partial \Omega_n. \tag{5.23} \]
Let $x_0 \in \Omega_n'$ and denote by $\omega_n := \omega_{\ell \Omega_n}$ the $L_\infty$-harmonic measure in $\Omega_n$ relative to $x_0$. Put
\[ V_n = B_n(\xi^n) \cap \partial \Omega_n \quad \text{with} \quad r_n = d(\xi^n). \]
Let $h_n \in L^\infty(\Sigma_n)$ and denote by $\phi(\cdot, a)$ be a sequence of points in $\Omega$ converging to $a \in \partial \Omega$ and let $l \in (0, 1)$. We define the sets
\[ \Omega_n := \Omega_{d(\xi^n)} = \{x \in \Omega : d(x) > d(\xi^n)\} \quad \text{and} \quad \Sigma_n := \partial \Omega_n. \tag{5.23} \]
Let $x_0 \in \Omega_n'$ and denote by $\omega_n := \omega_{\ell \Omega_n}$ the $L_\infty$-harmonic measure in $\Omega_n$ relative to $x_0$. Put
\[ V_n = B_n(\xi^n) \cap \partial \Omega_n \quad \text{with} \quad r_n = d(\xi^n). \]
Let $h_n \in L^\infty(\Sigma_n)$, $n = 1, 2, \ldots$, and suppose that there exist numbers $c$ and $k$ such that
\[ \supp(h_n) \subset V_n \quad \text{and} \quad 0 \leq h_n \leq c r_n^{-N-\frac{q}{2}+2}, \tag{5.24} \]
and
\[ \lim_{n \to \infty} \int_{\Sigma_n} h_n \phi d\omega_{\ell \Omega_n} = k \phi(a) \quad \forall \phi \in C(\overline{\Omega}). \]

Let $w_n$ be the solution of the problem
\[ \mathcal{L}_\kappa w_n + |w_n|^{q-1} w_n = 0 \quad \text{in} \quad \Omega_n, \]
\[ w_n = h_n \quad \text{on} \quad \partial \Sigma_n. \]

Then
\[ w_n \to u_{k,a} \quad \text{locally uniformly in} \quad \Omega. \]

Proof. Let $\eta^n \in \partial \Omega$ be such that $d(\xi^n) = |\xi^n - \eta^n|$. By Theorem 2.30 we have
\[ \mathcal{K}_{\mathcal{L}_\kappa}(x, \eta^n) \geq \frac{1}{c_{43}} r_n^{-N-\frac{q}{2}+2} \geq \frac{1}{c_{43}} h_n(x), \quad \forall x \in \Sigma_n, \tag{5.25} \]
by the maximum principle,
\[ \mathcal{K}_{\mathcal{L}_\kappa}(x, \eta^n) \geq \frac{1}{c_{43}} w_n(x) \quad \forall x \in \Omega_n. \tag{5.26} \]
Moreover
\[ \int_{\Omega} \mathcal{K}_{\mathcal{L}_\kappa}(x, y) d\xi_n(x) dx \leq c(q, \Omega) \quad \forall 1 < q < q_c, \]
where $c(q, \Omega)$ is a constant independent of $y$. Since $q$ is subcritical, it follows that the sequences $\{\mathcal{K}_{\mathcal{L}_\kappa}(\cdot, \eta^n)\}$ and $\{\mathcal{K}_{\mathcal{L}_\kappa}(\cdot, \eta^n)\}$ are uniformly integrable in $L^1_\kappa(\Omega)$. Let $\overline{w}_n$ denotes the extension of $w_n$ to $\Omega$ defined by $\overline{w}_n = 0$ in $\Omega \setminus \Omega_n$. In view of (5.25) we conclude that the sequences $\{\overline{w}_n\}$ and $\{\overline{\eta}_n\}$ are uniformly integrable in $L^1_\kappa(\Omega)$ and locally uniformly bounded in $\Omega$. By regularity results for elliptic equations there exists a subsequence of $\{\overline{w}_n\}$, say again $\{\overline{w}_n\}$ that converges locally uniformly in $\Omega$ to a solution $w$ of (5.1). This fact and the uniform integrability mentioned above imply that
\[ w_n \to w \quad \text{in} \quad L^1_\kappa(\Omega) \cap L^1_\kappa(\Omega). \]
Since $w \in L^1_\kappa(\Omega)$ by Proposition 5.10 there exists $\mu \in \mathcal{M}(\Omega)$ such that
\[ \int_{\Omega} w \mathcal{L}_\kappa \eta dx + \int_{\Omega} |w|^{q-1} w \eta dx = \int_{\Omega} \mathcal{K}_{\mathcal{L}_\kappa}[\mu] \mathcal{L}_\kappa \eta dx \quad \forall \eta \in \mathcal{X}(\Omega). \]
Furthermore, using (5.25) we prove below that measure $\mu$ is concentrated at $a$. Let $\phi_{x_0,n}$ be the first eigenfunction of $\mathcal{L}_\kappa$ in $\Omega_n$ normalized by $\phi_{x_0,n}(x_0) = 1$ for some $x_0 \in \Omega_1$. Let $\eta \in \mathcal{X}(\Omega)$ be nonnegative function and let $\eta_n$ be the solution of the problem
\[ \mathcal{L}_\kappa \eta_n = \frac{\phi_{x_0,n}}{\phi_n} \mathcal{L}_\kappa \eta \quad \text{in} \quad \Omega_n, \]
\[ \eta_n = 0 \quad \text{in} \quad \partial \Omega_n. \]
Then $\eta_n \in C^2(\overline{\Omega})$ and since $\phi_{x,n} \rightarrow \phi_x$,

$$L_x \eta_n \rightarrow L_x \eta \quad \text{and} \quad \eta_n \rightarrow \eta \quad \text{as} \quad n \rightarrow \infty.$$ 

Then we have

$$\int_\Omega w_n L_x \eta_n dx + \int_\Omega |w_n|^{q-1} w \eta dx = \int_\Omega v_n L_x \eta_n dx,$$

where $v_n$ solves

$$L_x v_n = 0 \quad \text{in} \quad \Omega_n$$

$$v_n = h_n \quad \text{on} \quad \partial \Sigma_n.$$ 

By the same arguments as above there exists a subsequence of $\{v_n \chi_{\Omega_n}\}$, that we still denote by $\{v_n \chi_{\Omega_n}\}$, converging to a nonnegative $L_x$-harmonic function $v$ in $L^1_{\text{loc}}(\Omega)$. By (5.25) we have

$$\lim_{n \rightarrow \infty} L_x v_n = 0 \quad \text{in} \quad \Omega, \quad v = v_n \quad \text{on} \quad \partial \Omega.$$ 

But

$$k = \lim_{n \rightarrow \infty} \int_{\Sigma_n} h_n d\omega_{\Omega_n} = \lim_{n \rightarrow \infty} v_n(x_0) = v(x_0) = \int_{\partial \Omega} dv,$$

the results follows if we let $n$ tend to $\infty$ in (5.27). \hfill \square

**Lemma 5.20.** For every $l \in (0, 1)$ there exists a constant $c_1 = c(N, \kappa, q, l)$ such that, for every positive solution $u$ of (5.1) in $\Omega$ and every $x_0 \in \Omega$,

$$u(x) \leq c_1 u(y) \quad \forall x, y \in B_{r_0}(x_0) r_0 = d(x_0).$$

**Proof.** Put $r_1 = \frac{1+l}{2} r_0$. Then $u$ satisfies

$$L_x u + u^q = 0 \quad \text{in} \quad B_{r_1}(x_0).$$

Denote by $\Omega_{r_0}$ the domain

$$\Omega_{r_0} = \{y \in \mathbb{R}^n : r_0 y \in \Omega\}.$$

Set $v(y) = u(r_0 y)$, and $y_0 = \frac{x_0}{r}$, then $v(y)$ satisfies

$$-\Delta v - \frac{v}{\text{dist}^2(y, \partial \Omega_{y_0})} + r_0^2 |v|^{q-1} v = 0 \quad \text{in} \quad B_{\frac{1+l}{2}}(y_0).$$

Now note that

$$\frac{1}{\text{dist}^2(y, \partial \Omega_{y_0})} \leq \frac{4}{(1-l)^2} \quad \forall y \in B_{\frac{1+l}{2}}(y_0),$$

and by Keller–Osserman condition

$$r_0^2 |v(y)|^{q-1} = r_0^2 |u(r_0 y)|^{q-1} \leq C(\Omega, \kappa, N) r_0^2 \frac{1}{d^2(r_0 y)} \leq C(\Omega, \kappa, N) B_{\frac{1+l}{2}}(y_0).$$

Thus, by Harnack inequality, there exists a constant $c_1 > 0$ such that

$$v(z) \leq c_1 v(y) \quad \forall z, y \in B_{r_0}(y_0),$$

and the results follows. \hfill \square

For the proof of the next lemma we need some notations. Let $\beta > 0$ and $\xi \in \Sigma_{\beta} := \partial \Omega_{\beta}^\prime$. We set $\Delta_{\beta}^\prime(\xi) = \Sigma_{\beta} \cap B_r(\xi)$ and, for $0 < r < \beta < 2r$, $x_{\beta} = x_{\beta}^\prime(\xi) \in \overline{\Omega}_{\beta}$, such that $d(x_{\beta}) = |x_{\beta} - \xi| = r$. Also we denote by $\omega_{\Omega_{\beta}}^\prime$ the $L_x$-harmonic measure in $\Omega_{\beta}^\prime := \Omega \setminus \overline{\Omega}_\beta$ relative to $x$. 
Lemma 5.21. Let $r_0 = r_0(\Omega) > 0$ be small enough and $0 < r \leq \frac{r_0}{4}$. Then there exists a constant $c_{95}$ which depends only on $\Omega$, $N$ such that
\[
\omega^{r_0}_{1/4}(\Delta r(\xi)) > c_{95} \quad \forall x \in \Omega \cap B_{r/2}^{1}(\xi).
\] (5.30)

Proof. Since $x \mapsto \omega^{r_0}_{1/4}$ is positive and $L_\infty$-harmonic in $\Omega_{1/4}$, it is a positive superharmonic function (relative to the Laplacian) in $\Omega_{1/4}$. Thus
\[
\omega^{r_0}_{1/4} \geq \nu^{r_0}_{1/4} \quad \forall x \in \Omega_{1/4}.
\]
The result follows by [8, Lemma 2.1]. □

Lemma 5.22. Let $\kappa = \frac{1}{2}$, $\varepsilon \in (0, 1)$ and $x_0 \in \Omega_1$. Let $\{\xi^n\}$ be a sequence of points in $\Omega$ converging to $a \in \partial \Omega$. Then there exist $n_0 = n_0(\varepsilon, \Omega) \in \mathbb{N}$ and $c_{96}(\Omega, N, \varepsilon)$ such that
\[
\omega^{\log_{101}}_{\Omega_n}(B_{\delta}(\xi^n) \cap \partial \Omega_n) \geq c_{96}(\delta(\xi^n))N+\frac{1}{2}-2(-\log \delta(\xi^n))^{1-\varepsilon} \quad \forall n \geq n_0.
\] (5.31)

Proof. We recall that for any $n \in \mathbb{N}$ $\Omega_n$ is defined by (5.23), $\Omega_n^{G_{\frac{1}{4}}} \leq G_{\frac{1}{4}} := G_{\frac{1}{4}}$, and for a fixed point $y_0 \in \Omega_1$
\[
G_{\frac{1}{4}}^{\frac{1}{4}}(x, y) \uparrow G_{\frac{1}{4}}(x, y_0) \quad \text{locally uniformly in } \Omega \setminus y_0.
\] (5.32)

Set $x(\xi^n) = x^{2\varepsilon}_{1/2}(\xi^n)$, with $r_n = \frac{d(\xi^n)}{2}$. By (2.10) we have
\[
r_n^{N-2}G_{\frac{1}{4}}^{\frac{1}{4}}(x, x(\xi^n)) < c_{97} \quad \forall x \in \Omega_n \cap \partial B_n(\xi^n),
\]
and by Lemma 5.21 there exists $r_0 = r_0(\Omega) > 0$ such that for any $r_n \leq \frac{r_0}{4}$
\[
r_n^{N-2}G_{\frac{1}{4}}^{\frac{1}{4}}(x, x(\xi^n)) \leq c_{98}(\delta(\xi^n))N \cap \partial B_n(\xi^n) \quad \forall x \in \Omega_n \cap \partial B_n(\xi^n).
\]
Since $|x - y| > \varepsilon > 0$ there holds
\[
G_{\frac{1}{4}}^{\frac{1}{4}}(x, y) \approx c_{99}(\varepsilon, \Omega_1) \text{dist}(x, \partial \Omega_n) \text{dist}(y, \partial \Omega_n),
\]
thus we have by the maximum principle and properties of the Green function
\[
r_n^{N-2}G_{\frac{1}{4}}^{\frac{1}{4}}(x, x(\xi^n)) \leq c_{100}(\delta(\xi^n))N \cap \partial B_n(\xi^n) \quad \forall x \in \Omega_n \setminus \partial B_n(\xi^n).
\] (5.33)

By [3, Lemma 2.8] there exists $\beta_0 = \beta_0(\Omega, \varepsilon) > 0$ such that the function
\[
h_1(x) = d_1^2(x)(-\log d(x))(1 + (-\log d(x))^{-\varepsilon}),
\]
is a supersolution in $\Omega_{\beta_0}$ and the function
\[
h_2(x) = d_1^2(x)(-\log d(x))(1 - (-\log d(x))^{-\varepsilon}),
\]
is a subsolution in $\Omega_{\beta_0}$. Set
\[
c_{101} = \frac{1 - (-\log d(\xi^n))^{-\varepsilon}}{1 + (-\log d(\xi^n))^{-\varepsilon}}
\]
and
\[
H(x) = h_2(x) - c_{101}h_1(x).
\]
Let $n_0 \in \mathbb{N}$ such that $r_n \leq \frac{\beta_0}{4}, \quad \forall n \geq n_0$. Then the function $H(x)$ is a nonnegative subsolution in $\Omega_n \setminus \Omega_{\beta_0}$, and $H(x) = 0$, $\forall x \in \partial \Omega_n$. By (5.32) we can choose $n_1 \in \mathbb{N}$ such that
\[
G_{\frac{1}{4}}^{\frac{1}{4}}(x_0, x) \geq c(\Omega, N, \kappa)\beta_0^\frac{1}{2} \quad \forall x \in \partial \Omega_{\beta_0}.
\]
Thus we can find a constant $c_{102} = c_{102}(\beta_0) > 0$ such that
\[
c_{102}(x) \leq G_{\frac{1}{4}}^{\frac{1}{4}}(x_0, x) \quad \forall x \in \partial \Omega_{\beta_0}.
\]
Since $H$ vanishes on $\partial \Omega_n$ it follows by the maximum principle that
\[
c_{102} H(x) \leq G_{\frac{1}{4}}(x_0, x) \quad \forall x \in \overline{\Omega}_n \setminus \Omega_{r_0}.
\] (5.34)

But
\[
H(x(\xi^n)) \geq c_{103}(\beta_0) \geq c_{104}(\Omega, N) r_0\frac{1}{4} (- \log r_0)^{1-\varepsilon},
\]

thus the result follows by the above inequality combined with inequalities (5.34) and (5.33). \qed

**Lemma 5.23.** Let $\kappa < \frac{1}{4}$, $\varepsilon \in (0, \sqrt{1 - 4\kappa})$ and $x_0 \in \Omega_1$. Let $\{\xi^n\}$ be a sequence of points in $\Omega$ converging to $a \in \partial \Omega$. Then there exists $n_0 = n_0(\varepsilon, \kappa) \in \mathbb{N}$ such that
\[
\omega_{2\kappa}(B_{d_{\xi^n}}(\xi^n) \cap \partial \Omega_n) \geq c_{105}(\Omega, N, \kappa, \varepsilon) d(\xi^n)^{N + \frac{\alpha}{2} + \varepsilon - 2} \quad \forall n \geq n_0,
\]

where $\Omega_n$ is defined by (5.23).

**Proof.** The proof is similar as the one of Lemma 5.22. The only difference is that we use $d^{\varepsilon}(1 - d^{\varepsilon})$ and the supersolution $d^{\varepsilon}(1 - d^{\varepsilon})$ as a subsolution. \qed

**Proof of Theorem 1.8.** Step 1: if
\[
\limsup_{x \in \Omega, x \to a} (d(x))^{N + \frac{\alpha}{2} - 2} u(x) < \infty,
\]
then $a \in \mathcal{R}_u$. Thus we have to prove that there exists $r_0 > 0$ such that $u \in L^q_{\chi_0} (\Omega \cap B_{r_0}(a))$. By (5.35) there exists $r_1 > 0$ such that
\[
\sup_{x \in \Omega \cap B_{r_1}(a)} (d(x))^{N + \frac{\alpha}{2} - 2} u(x) = M < \infty.
\]

Let $U$ be a smooth open domain such that
\[
\Omega \cap B_{\frac{1}{2}}(a) \subset U \subset \Omega \cap B_{r_1}(a),
\]
and
\[
\overline{U} \cap \partial \Omega \subset \partial \Omega \cap B_{r_1}(a).
\]

For $\beta > 0$, set
\[
d_{U}(x) = \text{dist}(x, \partial U) \quad \forall x \in U, \quad U_\beta = \{x \in U : d_U(x) > \beta\}, \quad V_\beta = U \setminus U_\beta.
\]

Let $\beta_0 > 0$ be small enough such that $d_U \in C^2(\overline{U})$. Let $0 < \beta < \beta_0$ and $\zeta(x) = d_U(x) - \beta$. Then $u$ satisfies
\[
\int_{\partial V_\beta} u \sigma dS = \int_{V_\beta \setminus V_{\beta_0}} (u \Delta \xi + u^\alpha \xi) dx - \int_{\partial V_{\beta_0}} \frac{\partial u}{\partial n} \xi dS.
\]

Now
\[
\left| \int_{\partial V_{\beta_0}} \frac{\partial u}{\partial n} \xi dS \right| \leq c_{106}(\beta_0 - \beta),
\]

where $c_{106}$ depends on $q, \kappa, \Omega, \beta_0,
\[
\int_{V_\beta \setminus V_{\beta_0}} u \Delta \xi dx \leq \int_{V_\beta \setminus V_{\beta_0}} u \xi dx \leq c_{107} \int_{V_\beta \setminus V_{\beta_0}} u dx,
\]

and by (5.35)
\[
u^{q-1}(x) \leq c_{108}(d_U(x))^{-(q-1)(N + \frac{\alpha}{2} - 2)} \leq c_{108}(d_U(x))^{-(q-1)(N + \frac{\alpha}{2} - 2)} \quad \forall x \in U.
\]

Combining the above inequalities, we derive
\[
\int_{\partial V_\beta} u \sigma dS \leq c_{109} \left( \int_{\beta}^{\beta_0} \left( \sigma^{1-(q-1)(N + \frac{\alpha}{2} - 2)} + 1 \right) \int_{\partial V_0} u(x) \sigma dS + 1 \right).
\]
Multiplying the above inequality by $\beta^{\frac{q}{p} - \frac{2}{s}}$ we get
\[
\int_{\partial V^e} \frac{a_u}{d}_u \, dS \leq c_{109} \left( \int_{\beta}^{\beta_0} \left( \sigma^{1-(q-1)\left(N+\frac{\alpha}{p} - 2\right)} + 1 \right) U_{dS} \right) + 1 \, .
\]

Set
\[
U(\sigma) = \int_{\partial V^e} \frac{a_u}{d}_u (x) u(x) \, dS,
\]

then we have
\[
U(\beta) \leq c_{110} \left( \int_{\beta}^{\beta_0} \left( \sigma^{1-(q-1)\left(N+\frac{\alpha}{p} - 2\right)} + 1 \right) U_{d\sigma} \right) + 1 \, .
\] (5.36)

Set
\[
W(\beta) = \int_{\beta}^{\beta_0} \left( \sigma^{1-(q-1)\left(N+\frac{\alpha}{p} - 2\right)} + 1 \right) U_{d\sigma} + 1,
\]

then
\[
W'(\beta) = -\left( \beta^{1-(p-1)\left(N+\frac{\alpha}{p} - 2\right)} + 1 \right) U(\beta) = -h(\beta)U(\beta).
\]

Thus inequality (5.36) becomes
\[
-W'(\beta) \leq c_{110} h(\beta) W(\beta) \iff (H(\beta) W(\beta))' \geq 0,
\]

where
\[
H(\beta) = e^{-c_{110} \int_{\beta}^{\beta_0} h(\sigma) d\sigma}.
\]

Thus we have
\[
W(\beta) \leq \frac{1}{H(\beta)} W(\beta_0) \quad \forall 0 < \beta < \beta_0.
\]

But
\[
\frac{1}{H(\beta)} = e^{c_{110} \int_{\beta}^{\beta_0} h(\sigma) d\sigma} = e^{c_{110} \int_{\beta}^{\beta_0} \sigma^{1-(q-1)\left(N+\frac{\alpha}{p} - 2\right)} + 1 d\sigma} \leq \infty
\]

if and only if
\[
2 - (q - 1) \left(N + \frac{\alpha}{2} - 2\right) > 0 \iff q < q_c.
\]

Thus we have proved that
\[
\int_{\partial \Omega} u^q(\partial u(\partial u(\partial u(\partial u(\partial u^q dx < \infty,
\]

which implies the existence of a $r_2 > 0$ such that
\[
\int_{\Omega \cap B_2(a)} u^\alpha(\partial u(\partial u(\partial u(\partial u(\partial u dx < \infty,
\]

i.e. $a \in \mathcal{R}_u$, which is the claim.

Step 2. Since $a \in \delta_u$ the previous statement implies that there exists a sequence $\{\xi^n\} \subset \Omega$ such that
\[
\xi^n \rightarrow a \quad \text{ and } \quad \limsup_{n \to \infty} (d(\xi^n))^{N+\frac{\alpha}{\alpha} - 2} u(\xi^n) = \infty.
\] (5.37)

By Lemma 5.20, there exists a constant $c_l$ such that
\[
u(x) \leq c_l u(y) \quad \forall x, y \in B_{r_2}(\xi^n), \quad r_n = d(\xi^n).
\] (5.38)

Put $V_n := B_{r_2}(\xi^n) \cap \partial \Omega', \text{ and for } k > 0, h_n := \frac{k}{b_n} u \chi_{V_n}$. 

Case 1: $\kappa = \frac{1}{4}$. By (5.38) and Lemma 5.22 there exists a constant $c_{111} > 0$ such that

$$b_n := \int_{V_n} u dS \geq c_{111} A_n r_n^{N + \frac{1}{2} - 2} (-\log r_n)^{1 - \epsilon}, \quad A_n := \sup_{x \in B_{r_n}(0)} u(x).$$

Then

$$\int_{\partial^* \Omega'_n} h_{n,k} dS = k, \quad h_{n,k} \leq \frac{k}{c_2} r_n^{2 - \frac{n-2}{2} - k} \chi_{V_n} \forall n \geq n_0. \tag{5.39}$$

By (5.37),

$$b_n \to \infty, \quad r_n \to 0. \tag{5.40}$$

Hence, for every $k > 0$ there exists $n_k$ such that

$$u \geq h_{n,k} \quad \text{on $\partial \Omega'_n \forall n \geq n_k$.} \tag{5.41}$$

Let $w_{n,k}$ be defined as in Lemma 5.19 with $h_n$ replaced by $h_{n,k}$. By (5.39) and (5.40), the sequence $\{h_{n,k}\}_{n=1}^\infty$ satisfies (5.24) for every fixed $k > 0$. Therefore by Lemma 5.19

$$\lim_{n \to \infty} w_{n,k} = u_{k\delta_0} \quad \text{locally uniformly in $\Omega$.}$$

By (5.41), $u \geq w_{n,k}$ in $x \in \Omega : d(x) > r_n$. Hence $u \geq u_{k\delta_0}$ for every $k > 0$. The proof in the case $0 < \kappa < \frac{1}{4}$ is similar. \qed

As a consequence we provide a full classification of positive solution of (4.1) with a boundary isolated singularity.

**Theorem 5.24.** Assume $1 < q < q_c$ and $u \in C(\overline{\Omega} \setminus \{0\})$ is a positive solution of (4.1) which satisfies

$$\lim_{x \in \partial \Omega, \ x \to \xi} \frac{u(x)}{W(x)} = 0 \quad \forall \xi \in \partial \Omega \setminus \{0\}.$$

Then the following alternative holds:

(i) either there exists $k \geq 0$ such that

$$\lim_{x \to \infty, \ x \in \Omega} |x|^{\frac{N+2}{2} - 2} u(x) = k \psi_1(\sigma) \tag{5.42}$$

and $u$ solves

$$-\Delta u - \frac{\kappa}{d^2} u + u^q = 0 \quad \text{in $\Omega$}$$

$$u = k\delta_0 \quad \text{in $\partial \Omega$,} \tag{5.43}$$

(ii) or

$$\lim_{x \to 0, \ x \in \partial \Omega} |x|^{\frac{2}{N-2}} u(x) = \omega_k(\sigma) \tag{5.44}$$

locally uniformly on $S_+^{N-1}$.

The result is a consequence of the following result.

**Lemma 5.25.** Assume $1 < q < q_c$, $a \in \partial \Omega$ and $F_\epsilon(a) \cap \partial \Omega \cap \overline{B_\epsilon(a)}$. Then

$$\lim_{\epsilon \to 0} U_{F_\epsilon(a)}(0) = u_{\infty, a}. \tag{5.45}$$

**Proof.** Without loss of generality, we can assume $a = 0$. Clearly, $U_{\{0\}} := \lim_{\epsilon \to 0} U_{F_\epsilon(0)}$ is a solution of (5.1) which satisfies

$$\lim_{x \to \xi} \frac{U_{\{0\}}(x)}{W(x)} = 0 \quad \forall \xi \in \partial \Omega \setminus \{0\}$$

locally uniformly on $\partial \Omega \setminus \{0\}$. By (A.20) it verifies

$$U_{\{0\}}(x) \leq c |x|^{-\frac{2}{N-2}} \left( \frac{d(x)}{|x|} \right)^{\frac{N}{2}}. \tag{5.46}$$
By Proposition 4.5 and (A.24), we can follow the same argument like in the proof of Theorem 3.4.6-(ii) in [27] to prove that: there exists $c_0 = c_{122}(N, \kappa, q) > 1$ such that

$$
\frac{1}{c_0} |x|^{-\frac{N+1}{2}} \left( \frac{d(x)}{|x|} \right)^{\frac{\alpha}{4}} \leq u_{\infty,0}(x) \leq U_{0}(x) \leq c_0|x|^{-\frac{N+1}{2}} \left( \frac{d(x)}{|x|} \right)^{\frac{\alpha}{4}}
$$

which implies

$$U_{0}(x) \leq cu_{\infty,0}(x) \quad \forall x \in \Omega, \tag{5.47}$$

where $c = c_{122}(N, \kappa, q) > 1$.

Assume $U_{0}(x) \neq u_{\infty,0}$, thus $U_{0}(x) > u_{\infty,0}(x)$ for all $x \in \Omega$ and put $\tilde{u} = u_{\infty,0} - \frac{1}{2c}(U_{0}(x) - u_{\infty,0})$. By convexity $\tilde{u}$ is a supersolution of (5.1) which is smaller than $u_{\infty,0}$. Now $\frac{c+1}{2c}u_{\infty,0}$ is a subsolution, thus there exists a solution $u$ of (5.1) in $\Omega$ which satisfies

$$\frac{c+1}{2c}u_{\infty,0}(x) \leq u(x) \leq \tilde{u}(x) < u_{\infty,0}(x) \quad \forall x \in \Omega. \tag{5.48}$$

This implies that $\text{Tr}_{\alpha} u = (\{0\}, 0)$, and by Theorem 5.18, $u \geq u_{\infty,0}$, which is a contradiction.

**Proof of Theorem 5.24.** Assume $\alpha = 0$ without loss of generality. If $\alpha \in S_{u}$, then for any $\epsilon > 0$, $u \leq U_{\rho,0}(x)$ which is a maximal solution which vanishes on $\partial \Omega \setminus F_{\epsilon}(x)$. Thus, using (5.45)

$$u \leq \lim_{\epsilon \to 0} U_{\rho,0}(x) = U_{0}(x) = u_{\infty,0}.$$

If $0 \in S_{u}$, this implies that $\text{Tr}_{\alpha} u = (\{0\}, k\delta_{0})$ for some $k > 0$ and we conclude with Corollary 4.4. \( ^{\Box} \)

The next result can be proven by using the same approximation methods as in [24, Th 9.6].

**Theorem 5.26.** Assume $\delta \subset \partial \Omega$ is closed and $\nu$ is a positive Radon measure on $\mathcal{R} = \partial \Omega \setminus \delta$. Then there exists a positive solution of (4.1) in $\Omega$ with boundary trace $(\delta, \mu)$.

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**Appendix. Barriers and a priori estimates**

**A.1. Barriers**

Following a localization principle introduced in [24] we follow the same statement is at the core of the a priori estimates construction

**Proposition A.1.** Let $\Omega \subset \mathbb{R}^{N}$ be a $C^{2}$ domain $0 < \kappa \leq \frac{1}{4}$ and $p > 1$. Then there exists $R_{0} > 0$ such that for any $z \in \partial \Omega$ and $0 < R \leq R_{0}$, there exists a super solution $f := f_{\kappa,R}$ of (4.1) in $\Omega \cap B_{R}(z)$ such that $f \in C(\overline{\Omega} \cap B_{R}(z))$, $f(x) \to \infty$ when $d(x, K) \to 0$, for any compact subset $K \subset \Omega \cap \partial B_{R}(z)$ and which vanishes on $\partial \Omega \cap B_{R}(z)$, and more precisely

$$f(x) = \begin{cases} 
\frac{c_{\beta,q}}{8} |R^{2} - |x-z|^{2}|^{-\beta} \left( \frac{d(x)}{d} \right)^{\frac{\alpha}{4}} & \text{if } 0 < \kappa < \frac{1}{4} \\
\frac{c_{\beta,q}}{8} |R^{2} - |x-z|^{2}|^{-\beta} \sqrt{\left( \frac{d(x)}{d} \right)} \ln \left( \frac{\text{diam}(\Omega)}{|d(x)|} \right) & \text{if } \kappa = \frac{1}{4} 
\end{cases} \tag{A.1}
$$

for $\nu \geq \max\left\{ \frac{2}{q-1} + \gamma, \frac{N-2}{2}, 1 \right\}$.

**Proof.** We assume $z = 0$

Step 1: $\kappa < \frac{1}{4}$. Set $f(x) = \Lambda(R^{2} - |x|^{2})^{-\beta} d(x) \gamma$ where $\beta, \gamma > 0$ to be chosen later on. Then, with $r = |x|$

$$\Lambda^{-1} \mathcal{L} f = -\left( R^{2} - r^{2} \right)^{-\beta} \left( \Delta d^{\gamma} + \kappa d^{\gamma-2} \right) - d^{\gamma} \Delta \left( R^{2} - r^{2} \right)^{-\beta} - 2 \nabla \left( R^{2} - r^{2} \right)^{-\beta} \cdot \nabla d^{\gamma}. $$
Since $\Delta d(x) = (N-1)H_d$ where $H_d$ is the mean curvature of the foliated set $\Sigma_d := \{ x \in \Omega : d(x) = d \}$ and $|\nabla d|^2 = 1$.

\[
\Delta d' = (N-1)\gamma H_d d'' + \gamma (\gamma - 1)d' - 2
\]

\[
\Delta d' + \kappa d'' = (N-1)\gamma H_d d'' + (\gamma (\gamma - 1) + \kappa) d' - 2
\]

\[
\nabla d' = \gamma d'' \nabla d,
\]

\[
\nabla (R^2 - r^2)^{-\beta} = 2\beta (R^2 - r^2)^{-\beta-1}x,
\]

thus

\[
\nabla (R^2 - r^2)^{-\beta} \cdot \nabla d' = 2\beta \gamma d'' (R^2 - r^2)^{-\beta-1}x\nabla d
\]

\[
\Delta (R^2 - r^2)^{-\beta} = 2N\beta(R^2 - r^2)^{-\beta-1} + 4\beta(\beta + 1)(R^2 - r^2)^{-\beta-2}r^2
\]

\[
= 2\beta (R^2 - r^2)^{-\beta-2} (NR^2 + (2\beta + 2 - N)r^2)
\]

Then

\[
\Lambda^{-1} L_{\mathcal{A}} f = -(R^2 - r^2)^{\beta-2}d'' - (N-1)\gamma H_d d + \gamma (\gamma - 1) + \kappa + 2\beta d^2 (NR^2 + (2\beta + 2 - N)r^2) + 4\beta \gamma d(R^2 - r^2) x \cdot \nabla d
\]

Therefore

\[
L_{\mathcal{A}} f + f^\beta = \Lambda (R^2 - r^2)^{\beta-2}d'' - (R^2 - r^2)^{\beta-2} ((N-1)\gamma H_d d + \gamma (\gamma - 1) + \kappa)
\]

\[
- 2\beta d^2 (NR^2 + (2\beta + 2 - N)r^2) + 4\beta \gamma d(R^2 - r^2) x \cdot \nabla d
\]

(A.2)

If we fix $\beta \geq \max\left(\frac{2}{1-\gamma}, \frac{N-2}{2}\right)$, then holds

\[
2\beta d^2 (NR^2 + (2\beta + 2 - N)r^2) + 4\beta \gamma d(R^2 - r^2) x \cdot \nabla d \leq 4d^2 \beta (\beta + 1)NR^2 + 4\beta \gamma dR(R^2 - r^2).
\]

We choose $\frac{\alpha_0}{2} < \gamma < \frac{\alpha_0}{2}$ so that $\gamma (\gamma - 1) + \kappa < 0$. There exist $\delta_0, \epsilon_0 > 0$ such that

\[
(N-1)\gamma H_d d + \gamma (\gamma - 1) + \kappa < -\epsilon_0 < -1
\]

provided $d(x) \leq \delta_0$. We set

\[
A = \left\{ x \in \Omega \cap B_R : d(x) \leq \frac{\epsilon_0 (R^2 - r^2)}{16\beta R} \right\}
\]

and $B := A \cap \{ x \in \Omega \cap B_R : d(x) \leq \delta_0 \}$.

Then, if $x \in B$, there holds

\[
-(R^2 - r^2)^2 ((N-1)\gamma H_d d + \gamma (\gamma - 1) + \kappa) - 2\beta d^2 (NR^2 + (2\beta + 2 - N)r^2)
\]

\[
+ 4\beta \gamma d(R^2 - r^2) x \cdot \nabla d \geq \frac{(R^2 - r^2)^2 \epsilon_0}{2}.
\]

Finally, assume $x \in A^C \cap \{ x \in \Omega \cap B_R : d(x) \leq \delta_0 \}$ and thus

\[
d \geq c_1 \frac{R^2 - r^2}{R}.
\]

In order to have

\[
(i) \quad \Lambda^{q - 1} (R^2 - r^2)^{2 - (q-1)\beta} d^{(q-1)\gamma + 2} \geq d^2 R^2
\]

\[
(ii) \quad \Lambda^{q - 1} (R^2 - r^2)^{2 - (q-1)\beta} d^{(q-1)\gamma + 2} \geq dR(R^2 - r^2)
\]

or equivalently

\[
(i) \quad \iff \quad \Lambda^{\frac{q-1}{2}} d \geq (R^2 - r^2)^{\frac{\beta}{2}}
\]

\[
(ii) \quad \iff \quad \Lambda^{\frac{1}{q-1+1/2}} d \geq R^{\frac{1}{q-1+1/2}} (R^2 - r^2)^{\frac{1}{q-1+1/2}}
\]

(A.4)

it is sufficient to have, for (i)

\[
c_1 \frac{R^2 - r^2}{R} \geq (R^2 - r^2)^{\frac{\beta}{2}} \quad \forall r \in (0, R) \iff \Lambda \geq c_2 R^{2\beta - \gamma}
\]

(A.5)
and for (ii)
\[ c_1 \Lambda^{\frac{q-1}{q-1}+\gamma} \frac{R^2 - r^2}{R} \geq R^{\frac{q-1}{q-1}+\gamma} (R^2 - r^2)^{\frac{q-1}{q-1}+\gamma} \quad \forall r \in (0, R) \]  
\[ \iff \Lambda \geq c_2 R^{2\beta - \gamma} - \frac{\frac{1}{q-1}}{r^2} \]  
where \( c_2 = c_2(N, \gamma, \beta) > 0 \) since \( \beta > \gamma + \frac{2}{q-1} \).

At end, in the set \( C := \{ x \in \Omega : d(x) \geq \delta_0 \} \), it suffices that
\[ \Lambda \geq c_3 \max \left\{ R^{2\beta}, R^{8\beta - \frac{1}{q-1}} \right\} \]  
for some \( c_3 = c_3(N, \gamma, \beta, \max |H_d|, \delta_0) > 0 \) in order to insure

(i) \( A^{q-1}(R^2 - r^2)^{-\gamma} d^{q-1} \geq (R^2 - r^2)^{\gamma} |H_d| d \)
(ii) \( A^{q-1}(R^2 - r^2)^{-\gamma} d^{q-1} \geq 4d^2 \beta (\beta + 1) N R^2 \)
(iii) \( A^{q-1}(R^2 - r^2)^{-\gamma} d^{q-1} \geq 4 \beta d R (R^2 - r^2) \).

Noticing that \( 2\beta > 2\beta - \frac{1}{q-1}, 2\beta - \gamma > 2\beta - \gamma - \frac{1}{q-1} \), we conclude that there exists a constant \( c_4 = c_4(N, \gamma, \beta, \max |H_d|, \delta_0) > 0 \) such that if
\[ \Lambda \geq c_4 \max \left\{ R^{2\beta}, R^{8\beta - \frac{1}{q-1}} \right\} \]  
there holds
\[ \mathcal{L}_\kappa(f) + f^q \geq 0 \quad \text{in} \ \Omega. \]  

Step 2: \( \kappa = \frac{1}{2} \). Set \( f(x) = \Lambda (R^2 - r^2)^{-\beta} \sqrt{d} \ln \left( \frac{eR}{d} \right)^{\frac{1}{2}} \) for some \( \Lambda, \beta \) to be fixed. Then
\[ \Delta \sqrt{d} \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} = \frac{1}{\sqrt{d}} \left( \frac{1}{2} \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} - \frac{1}{2} \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} \right) H_d \]
\[ \Delta \sqrt{d} \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} = \frac{1}{\sqrt{d}} \left( \frac{1}{2} \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} - \frac{1}{2} \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} \right) H_d \]

Thus
\[ \Delta \sqrt{d} \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} + \kappa \sqrt{d} \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} = \frac{N - 1}{\sqrt{d}} \left( \frac{1}{2} \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} - \frac{1}{2} \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} \right) H_d \]
\[ \Delta \sqrt{d} \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} + \kappa \sqrt{d} \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} = \frac{1}{d^2} \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} \left[ \left( \frac{N - 1}{d} + 1 \right) \ln \left( \frac{eR}{d} \right)^{\frac{1}{2}} - \frac{1}{4} \right]. \]

Further
\[ \nabla (R^2 - r^2)^{-\beta} \nabla \sqrt{d} \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} = \frac{\beta (R^2 - r^2)^{-\beta - 1} (\ln \frac{eR}{d})^{\frac{1}{2}}}{\sqrt{d}} \left( \ln \left( \frac{eR}{d} \right) - 1 \right) \leq \nabla d. \]

Therefore
\[ \Lambda^{-1} \mathcal{L}_\kappa f = -(R^2 - r^2)^{-\beta - \frac{1}{2}} \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} \left[ (R^2 - r^2)^{\frac{1}{2}} \left( \frac{(N - 1) d H_d}{2} \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} - 1 \right) \leq \left( \ln \left( \frac{eR}{d} \right) \right) \leq \frac{1}{4} \right] \]
\[ + 2\beta (R^2 - r^2) d \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} + 2\beta d^2 \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} \left( N R^2 + (2\beta + 2 - N) r^2 \right) \]

Finally
\[ \mathcal{L}_\kappa f + f^q = \Lambda (R^2 - r^2)^{-\beta - \frac{1}{2}} \left( \ln \frac{eR}{d} \right)^{\frac{1}{2}} \left[ \Lambda^{q-1} (R^2 - r^2)^{(1-q)\beta + 2} d^{\frac{q-1}{q-1} + 2} \left( \ln \frac{eR}{d} \right)^{(q-1) + 2} \right] \]
\[ - (R^2 - r^2)^2 \left[ (N - 1) dH_d \left( \frac{1}{2} \left( \ln \frac{eR}{d} \right)^2 - \frac{1}{2} \left( \ln \frac{eR}{d} \right) \right) - \frac{1}{4} \right] \]

\[ - 2\beta (R^2 - r^2) d \left[ \left( \ln \frac{eR}{d} \right)^2 - \left( \ln \frac{eR}{d} \right) \right] x \cdot \nabla d - 2\beta d^2 \left( \ln \frac{eR}{d} \right)^2 \left[ NR^2 + (2\beta + 2 - N)r^2 \right] \right]. \]

(A.11)

Notice that \( \frac{eR}{d} \geq e \) thus \(-\frac{1}{2} \leq (\ln \frac{eR}{d})^2 - (\ln \frac{eR}{d}) \leq (\ln \frac{eR}{d})^2 \) If \( \beta \) is large enough, as in Step 1, there holds

\[ 2\beta (R^2 - r^2) d \left[ \left( \ln \frac{eR}{d} \right)^2 - \left( \ln \frac{eR}{d} \right) \right] x \cdot \nabla d - 2\beta d^2 \left( \ln \frac{eR}{d} \right)^2 \left[ NR^2 + (2\beta + 2 - N)r^2 \right] \right] \leq 4N\beta(\beta + 1) \left( \ln \frac{R}{d} \right)^2 ((R^2 - r^2)dR + d^2R^2). \]

There exists \( \delta_0 > 0 \) such that

\[ (N - 1) dH_d \left( \frac{1}{2} \left( \ln \frac{eR}{d} \right)^2 - \frac{1}{2} \left( \ln \frac{eR}{d} \right) \right) - \frac{1}{4} \leq -\frac{1}{8} < -1 \]

if \( d(x) \leq \delta_0 \). If we define \( A, B \) by

\[ A = \{ x \in \Omega \cap B_R : d(x) \leq \frac{e_0(R^2 - r^2)}{16\beta R (\ln \frac{eR}{d})^2} \} \]

and \( B := A \cap \{ x \in \Omega \cap B_R : d(x) \leq \delta_0 \} \),

there holds if \( x \in B \)

\[ -2\beta (R^2 - r^2) d \left[ \left( \ln \frac{eR}{d} \right)^2 - \left( \ln \frac{eR}{d} \right) \right] x \cdot \nabla d - 2\beta d^2 \left( \ln \frac{eR}{d} \right)^2 \left[ NR^2 + (2\beta + 2 - N)r^2 \right] \right] \geq \frac{(R^2 - r^2)^2}{16}. \]

If \( x \in A^c \cap \{ x \in \Omega \cap \Omega_R : d(x) \leq \delta_0 \} \), then

\[ d(x) \geq c_1 \frac{R}{R (\ln \frac{eR}{d})^2}. \]

(A.12)

In order to have

\[ (i) \ A^q - 1(R^2 - r^2)^{(1-q)\beta + 2} d^{\frac{2+\beta}{2}} \left( \ln \frac{eR}{d} \right)^{\frac{q+1}{q+1}} \geq \left( \ln \frac{eR}{d} \right)^2 (R^2 - r^2)dR \]

\[ (ii) \ A^q - 1(R^2 - r^2)^{(1-q)\beta + 2} d^{\frac{2+\beta}{2}} \left( \ln \frac{eR}{d} \right)^{\frac{q+1}{q+1}} \geq \left( \ln \frac{eR}{d} \right)^2 d^2R^2 \]

or equivalently

\[ (i) \ A^{\frac{2q-2}{q+1}} d \left( \ln \frac{eR}{d} \right)^{\frac{q-1}{q+1}} \geq (R^2 - r^2)^{\frac{2q-1}{q+1}} \frac{R}{R^2 - r^2} \]

\[ (ii) \ A^2d \ln \frac{eR}{d} \geq R^{\frac{4}{q+1}} (R^2 - r^2)^{2\beta - \frac{4}{q+1}}. \]

Up to taking \( c_1 \) small enough, (A.12) is fulfilled if

\[ \frac{eR}{d} \leq \frac{R^2}{R^2 - r^2} \left( \ln \left( \frac{R^2}{R^2 - r^2} \right) \right)^2 \iff d \geq \frac{e(R^2 - r^2)}{R} \left( \ln \left( \frac{R^2}{R^2 - r^2} \right) \right)^{-2}. \]

(A.15)

Inequality (A.13) (i) will be insured if

\[ A^{\frac{2q-2}{q+1}} \geq \frac{1}{e} (R^2 - r^2)^{\frac{(q-1)\beta - 1}{q+1}} \frac{R}{R^2 - r^2} \left( \ln \left( \frac{R^2}{R^2 - r^2} \right) \right)^{\frac{2}{q+1}}. \]
which holds if, for any \( \epsilon > 0 \), we have for any \( r \in (0, R) \)
\[
A_{\frac{4q-2}{q+1}} \geq C_r (R^2 - r^2)^2 \left( \frac{4q-11}{4q+1} \right) - 1 \left( \frac{R^2}{R^2 - r^2} \right)^{\epsilon}.
\]
A sufficient condition for such a task is, with the help of (A.15),
\[
A \geq c_3 R^{3\beta - \frac{2}{q-1}}.
\] (A.16)

As for (A.13) (ii), it will be insured if
\[
A \geq c_4 R^{2\beta - \frac{2}{q+1} - \frac{1}{2}}.
\] (A.17)

Thus, if
\[
A \geq c_5 \max \{ R^{2\beta - \frac{2}{q+1} - \frac{1}{2}}, R^{3\beta - \frac{2}{q+1}} \}
\] (A.18)

for some \( c_5 > 0 = c_5(N, \gamma, \beta, \delta_0, |H_d|) \), the function \( f \) satisfies (A.10). \( \square \)

**A.2. A priori estimates**

By the Keller–Osserman estimate, it is clear that any solution \( u \) of (4.1) in \( \Omega \) satisfies
\[
u(x) \leq C(q, \Omega, N)d^{-\frac{2}{q-1}}(x) \quad \forall x \in \Omega.
\] (A.19)

This estimate is also a consequence of the following result [3, Prop 3.4].

**Proposition A.2.** Let \( \phi_+ \) be the first positive eigenfunction of \( -\Delta \) in \( H_0^1(\Omega) \). For \( q > 1 \), there exists \( \gamma > 0 \) and \( \epsilon_0 > 0 \) such that
for any \( 0 \leq \epsilon \leq \epsilon_0 \) the function \( h_+ \epsilon = \gamma (\phi_+ - \epsilon)^{-\frac{2}{q-1}} \) is a supersolution of (4.1) in \( \Omega_{\epsilon, \phi_+} := \{ x \in \Omega : \phi_+(x) > \epsilon \} \).

We recall here that
\[
W(x) = \begin{cases} 
d_x^{-\alpha}(x) & \text{if } \kappa < \frac{1}{4} \\

\frac{1}{4} d_x^2(x) | \log d(x) | & \text{if } \kappa = \frac{1}{4},
\end{cases}
\]

**Proposition A.3.** Let \( \Omega \) be a bounded open domain uniformly of class \( C^2 \) and let \( F \) be a compact subset of the boundary. Let \( u \)
be a nonnegative solution of (5.1) in \( \Omega \) such that
\[
\lim_{x \in \Omega, x \to \xi} \frac{u(x)}{W(x)} = 0 \quad \forall \xi \in \partial \Omega \setminus F,
\]
locally uniformly in \( \partial \Omega \setminus F \). Then there exists a constant \( C \) depending only on \( q, \kappa \) and \( \Omega \) such that,
\[
|u(x)| \leq Cd_x^{-\frac{4}{q-1}}(x) (\text{dist}(x, F))^2 \quad \forall x \in \Omega,
\] (A.20)
\[
\left| \frac{u(x)}{d_x^{-\frac{4}{q-1}}(x)} - \frac{u(y)}{d_x^{-\frac{4}{q-1}}(y)} \right| \leq C |x - y|^\beta (\text{dist}(x, F))^2 \quad \forall (x, y) \in \Omega \times \Omega
\] (A.21)
such that \( \text{dist}(x, F) \leq \text{dist}(y, F) \)
\[
|\nabla u(x)| \leq Cd_x^{-\frac{4}{q-1}}(x) (\text{dist}(x, F))^2 \quad \forall x \in \Omega.
\] (A.22)

**Proof.** The proof is based on the proof of Proposition 3.4.3 in [27]. Let \( \xi \in \partial \Omega \setminus F \) and put \( d_\xi(\xi) = \frac{1}{2} \text{dist}(\xi, F) \). Denote by \( \Omega_{d_\xi} \) the domain
\[
\Omega_{d_\xi} = \{ y \in \mathbb{R}^n : d_\xi(\xi) y \in \Omega \}.
\]

If \( u \) is a positive solution of (5.1) in \( \Omega \), denote by \( u_{d_\xi} \) the function
\[
u_{d_\xi}(y) = |d_\xi(\xi)|^{-\frac{4}{q-1}} u(d_\xi(\xi)y) \quad \forall y \in \Omega_{d_\xi}.
\]
Then,
\[ -\Delta u^\xi - \kappa \frac{u}{\text{dist}(y, \partial \Omega^\xi)^2} + |u^\xi|^q = 0 \quad \text{in } \Omega^\xi. \]

Let \( R_0 \) be the constant in Proposition A.1. First, we assume that
\[ \text{dist}(\xi, F) \leq \frac{1}{1 + R_0}. \]

Set \( r_0 = \frac{3R_0}{4} \), then the solution \( W_{r_0, \xi} \) mentioned in Proposition A.1 satisfies
\[ u^\xi(y) \leq W_{r_0, \xi}(y) \quad \forall y \in B_{\frac{3R_0}{4}}(\xi) \cap \Omega^\xi. \]

Thus \( u^\xi \) is bounded in \( B_{\frac{3R_0}{4}}(\xi) \cap \Omega^\xi \) by a constant \( C > 0 \) depending only on \( n, q, \kappa \) and the \( C^2 \) characteristic of \( \Omega^\xi \). As \( d_F(\xi) \leq 1 \) a \( C^2 \) characteristic of \( \Omega \) is also a \( C^2 \) characteristic of \( \Omega^\xi \) therefore the constant \( C \) can be taken to be independent of \( \xi \). We note here that the constant \( 0 < R_0 < 1 \) depends on \( C^2 \) characteristic of \( \Omega \).

Now we note that
\[ \lim_{y \in \Omega^\xi, \; y \to P} \frac{u^\xi(y)}{W(x)} = 0 \quad \forall P \in \partial \Omega^\xi \cap B_{\frac{3R_0}{4}}(\xi). \]

Thus in view of the proof of Propositions 2.11 and 2.12, by the above inequality and in view of the proof of Theorem 2.12 in [14], we have that there exists \( C > 0 \) depending only on \( n, p, \kappa \) such that
\[ u^\xi(y) \leq \left| \text{dist}(y, \partial \Omega^\xi) \right|^{\frac{\alpha_+}{2}} \quad \forall y \in B_{\frac{3R_0}{4}}(\xi) \cap \Omega^\xi. \]

Thus in view of the proof of Propositions 2.11 and 2.12, by the above inequality and in view of the proof of Theorem 2.12 in [14], we have that there exists \( C > 0 \) depending only on \( n, p, \kappa \) such that
\[ u^\xi(y) \leq \left| \text{dist}(y, \partial \Omega^\xi) \right|^{\frac{\alpha_+}{2}} \quad \forall y \in B_{\frac{3R_0}{4}}(\xi) \cap \Omega^\xi. \]

Hence
\[ u^\xi(x) \leq d_F(\xi)^{-\frac{\alpha_+}{2}} \quad \forall x \in B_{\frac{3R_0}{4}}(\xi) \cap \Omega. \]

Let \( x \in \Omega_{\frac{3R_0}{4}} \) and assume that
\[ d(x) \leq \frac{R_0}{2} d_F(x). \]

Let \( \xi \) be the unique point in \( \partial \Omega \setminus F \) such that \( |x - \xi| = d(x) \). Then we have
\[ d_F(\xi) \leq d(x) + d_F(x) \leq (1 + R_0)d_F(x) < 1 \]

and
\[ |u(x)| \leq Cd_F^{-\frac{\alpha_+}{2}} ((1 + R_0)\text{dist}(x, F))^{-\frac{2}{\gamma_1} - \frac{\alpha_+}{2}}. \]

If \( d(x) > \frac{R_0}{4} d_F(x) \), then by (A.19) we have that
\[ |u(x)| \leq Cd_F^{-\frac{2}{\gamma_1}} \leq Cd_F^{-\frac{\alpha_+}{2}} \left( \frac{R_0}{2} \text{dist}(x, F) \right)^{-\frac{2}{\gamma_1} - \frac{\alpha_+}{2}}. \]

Thus (A.20) holds for every \( x \in \Omega_{\frac{3R_0}{4}} \) such that \( \text{dist}(x, F) < \frac{1}{1 + R_0} \).

Now we assume that \( x \in \Omega_{\frac{3R_0}{4}} \) and
\[ \text{dist}(x, F) \geq \frac{1}{1 + R_0}. \]

Let \( \xi \) be the unique point in \( \partial \Omega \setminus F \) such that \( |x - \xi| = d(x) \). Similarly with the proof of (A.23) we can prove that
\[ u(x) \leq Cd_F^{-\frac{\alpha_+}{2}} \left( (1 + R_0)\text{dist}(x, F) \right)^{-\frac{2}{\gamma_1} - \frac{\alpha_+}{2}} \quad \forall x \in B_{\frac{3R_0}{4}}(\xi) \cap \Omega. \]
Now if $x \in \Omega \setminus \Omega_{R_0}$, the proof of (A.20) follows by (A.19).

(ii) Let $x_0 \in \Omega$. Set

$$\Omega^{x_0} = \{y \in \mathbb{R}^n : d(x_0)y \in \Omega\},$$

and $d_{x_0}(y) = \text{dist}(y, \partial \Omega^{x_0})$. If $x \in B_{d_{x_0}(x_0)}(x_0)$ then $y = \frac{x}{d_{x_0}(y)}$ belongs to $B_{\frac{1}{2}}(y_0)$, where $y_0 = \frac{x}{d_{x_0}(y)}$. Also we have that $\frac{1}{2} \leq d_{x_0}(y) \leq \frac{3}{2}$ for each $y \in B_{\frac{1}{2}}(y_0)$. Set now $v(y) = u(d(x_0)y)$, $\forall y \in B_{\frac{1}{2}}(y_0)$. Then $v$ satisfies

$$-\Delta v - \kappa \left(\frac{u}{|d_{x_0}(y)|^2} + d^2(x_0) |v|^q\right) = 0 \text{ in } B_{\frac{1}{2}}(y_0).$$

By standard elliptic estimate we have

$$\sup_{y \in B_{\frac{1}{2}}(y_0)} |\nabla v| \leq C \left(\sup_{y \in B_{\frac{1}{2}}(y_0)} |v| + \sup_{y \in B_{\frac{1}{2}}(y_0)} d^2(x_0) |v|^q\right).$$

Now since $\nabla v(y) = d(x_0) \nabla u(d(x_0)y)$, by above inequality and (A.20) we have that

$$|\nabla u(x_0)| \leq C \left(\frac{d_{x_0}^{-\frac{1}{q}}(x_0) (\text{dist}(x_0, F) - \frac{1}{\sqrt{1-q}}) + d_{x_0}^{\frac{q}{q-1}+1}(x_0) (\text{dist}(x_0, F))^{-\frac{q}{2(1-q)}}}{d_{x_0}^{-\frac{1}{q}}(x_0)}\right).$$

Using $\frac{2q}{q-1} = \frac{2}{q} + 2$ and the fact that $x_0$ is arbitrary the result follows.  

\[\square\]

**Proposition A.4.** Let $O \subset \partial \Omega$ be a relatively open subset and $F = \overline{O}$. Let $U_F$ be defined by (5.7) be the maximal solution of (5.1) which vanishes on $\partial \Omega \setminus F$. Then for any compact set $K \subset O$, there holds

$$\lim_{\xi \to x} (d(\xi))^{\frac{2}{q-1}} U_F(x) = \xi_c = \left(\frac{q + 1}{q - 1}\right)^{\frac{1}{q-1}} \text{ uniformly with respect to } x \in K. \quad (A.25)$$

**Proof.** Step 1. We claim that for any $\epsilon > 0$ there exists $C_\epsilon$, $\tau_\epsilon > 0$ such that for any $z \in O$ such that $\overline{B}_{2\tau_\epsilon}(z) \subset O$, there holds

$$u(x) \leq (\epsilon + 1)^{\frac{q-1}{2}} \tau^{-\frac{2}{q-1}} + C_\epsilon \quad \forall \tau \in (0, \tau_\epsilon], \forall x \in \Sigma_r(\overline{B}_{\tau}(z)). \quad (A.26)$$

We recall that $\Sigma_r(\overline{B}_{\tau}(z)) = \{x \in O : x \approx (d(x), \sigma(x)), d(x) = \tau, \sigma(x) \in \overline{B}_{\tau}(z)\}$. Set $g(x) = \ell d^{-\frac{2}{q-1}}(x)$, then

$$\mathcal{L}_\epsilon g + g^q = \frac{2}{q - 1} H_d d^{-\frac{q}{q - 1} + 1} + \left(\ell^{q-1} - \ell^{q-1}\right) d^{-\frac{2q}{q-1}}, \quad (A.27)$$

where $H_d$ is the mean curvature of $\Sigma_d$. If $\Omega$ is convex we take $\ell = \ell_c$ and $g$ is a supersolution for $d(x) \leq R_0$ for some $R_0$. In the general case, we take $\ell = \ell_c = (\epsilon + 1)^{\frac{q-1}{2}} \tau^{-\frac{2}{q-1}}$, and $g = g_c = \ell d^{-\frac{2}{q-1}}$ is a supersolution in the set $\Omega_{R_0}$ where

$$\tau_c = \max \left\{\tau : 0 < \tau \leq \frac{R_0}{2} \left(\frac{2(N - 1)}{q - 1} \|H_d\|_{L^\infty(\Sigma_{R_0})} + \epsilon > 0\right)\right\}. \quad \text{Then } f_{2\tau_c,x} + g_c \text{ is a supersolution of (5.1) in } B_{2\tau_c}(z) \cap \Omega \text{ which tends to infinity on } \partial(B_{2\tau_c}(z) \cap \Omega) = \partial \Omega \cap B_{2\tau_c}(z) \cup \partial \Omega \cap \partial B_{2\tau_c}(z). \text{ Since we can replace } g_c(x) \text{ by } g_{c,\tau}, \text{ then } f_{2\tau_c,x} + g_{c,\tau} \text{ is a supersolution of (5.1) in } \Omega \text{ bounded from above by } f_{2\tau_c,x} + g_{c,\tau}, \text{ and therefore by } f_{2\tau_c,x} + g_c. \text{ This implies (A.26) with } C_\epsilon = \max(f_{2\tau_c,x}(y) : |y - z| \leq \tau_c), \text{ and it can be made explicit thanks to (A.1).}$$

Step 2. With the same constants as in step 1, we claim that

$$U_F(x) \geq (\ell^{q-1} - \epsilon)^{\frac{1}{q-1}} \tau^{-\frac{2}{q-1} - 1} + C_\epsilon \quad \forall \tau \in (0, \tau_\epsilon], \forall x \in \Sigma_r(\overline{B}_{\tau}(z)). \quad (A.28)$$

If in the definition of the function $g$, we take $\ell = \ell_c = (\epsilon + 1)^{\frac{q-1}{2}} \tau^{-\frac{2}{q-1}}$, then $g$ is a subsolution in the same set $\Omega_{\tau_c}$. Since $U_F + f_{2\tau_c,x}$ is a supersolution of (5.1) in $B_{2\tau_c}(z) \cap \Omega$ which tends to infinity on the boundary, it dominates the subsolution

$$g_{c,\tau} = \ell d(x) + \tau^{-\frac{2}{q-1}} \quad \text{for } \tau \in (0, \rho_c), \text{ and thus, as } \tau \to 0, g_{c,\tau} \leq U_F(x) + f_{2\tau_c,x}(x). \text{ This implies (A.28) with the same constant } C_\epsilon. \quad \text{Step 3. End of the proof. Since } K \subset O \text{ is precompact, for any } \epsilon > 0, \text{ there exists a finite number of points } z_j, j = 1, \ldots, k \text{ such that } K \subset \bigcup_{j=1}^k B_{\tau_c}(z_j) \subset \overline{B}_{2\tau_c}(z_j) \subset O. \text{ Therefore}

$$((\ell^{q-1} - \epsilon)^{\frac{1}{q-1}} \tau^{-\frac{2}{q-1}} - C_\epsilon) \leq U_F(x) \leq (\epsilon + 1)^{\frac{q-1}{2}} \tau^{-\frac{2}{q-1}} + C_\epsilon \quad \forall \tau \in (0, \tau_c], \forall x \in \Sigma_r(K). \quad (A.29)$$
Since $\epsilon$ is arbitrary, it yields to
\[
\lim_{\tau \to 0} \| \tau \frac{2}{\pi} U_{\tau} - \ell_{\kappa} \|_{L^\infty(B_{\tau}(x))} = 0
\] (A.30)
which is (A.25). ∎

**Corollary A.5.** Let $U_{\partial \Omega}$ be the maximal solution of (5.1) in $\Omega$, then
\[
\lim_{d(x) \to 0} (d(x)) \frac{2}{\pi} U_{\partial \Omega}(x) = \ell_{\kappa}.
\] (A.31)

### A.3. Moser iteration

In this subsection we always assume that $\Omega$ is a bounded smooth convex domain, $D = 2 \sup_{x,y \in \Omega} |x - y|$ and $f_0 \in L^q(\Omega)$, $q > \frac{n + \alpha}{2}$. The main goal of this subsection is to prove Boundary Harnack inequality for positive solutions of the problem
\[
-L_{\phi_k} v := -\frac{\text{div}(\phi_k^2 \nabla v)}{\phi_k^2} = f \quad \text{in} \; \Omega,
\] (A.32)
where
\[
|f(x)| \leq c_f \left| \frac{\log d(x)}{\phi_k} \right| + f_0(x) \phi_k \quad \forall x \in \Omega,
\] (A.33)
for some positive constant $c_f > 0$.

In the sequel we will use the following local representation of the boundary of $\Omega$. There exists a finite number $m$ of coordinate systems $(y_i', y_n)$ in $\partial \Omega$, $y_i' = (y_{m+1}, \ldots, y_{m+n-1})$ and the same number $m$ of functions $a_i(y_i')$ defined on the closure cubes, $\Lambda_i := \{x \in \mathbb{R}^n : |y_i - x_i| \leq b\}$. For $j = 1, \ldots, n$, and $i \in \{1, \ldots, m\}$ such that for each point $x \in \partial \Omega$ there is at least $i$ such that $x = (x_i', a_i(x_i'))$. The function $a_i$ satisfies the Lipschitz condition on $\Lambda_i$ with constant $A > 0$, that is
\[
|a_i(y_i') - a_i(z_i')| \leq A|y_i' - z_i'|.
\]
for $y_i', z_i' \in \Lambda_i$. Moreover there exists a positive constant $b < 1$ such that the set $B_i$ is defined for any $i \in \{1, \ldots, m\}$ by the relation $B_i = \{(y_i', y_m) : y_i' \in \Lambda_i, a_i(y_i') \leq y_m \leq a_i(y_i') + b\}$ and $\gamma_i = B_i \cap \partial \Omega = \{(y_i', y_m) : y_i' \in \Lambda_i, y_m = a_i(y_i')\}$. Furthermore, let us observe for any $y \in B_i$ where someone can make the following inequality on the distance function
\[
(1 + A)^{-1}(y_m - a_i(y_i')) \leq d(y) \leq y_m - a_i(y_i').
\]
Finally let $x \in \partial B$, and $v \in C^1(\Omega)$. Set $x_i = y_i$ for $i = 1, \ldots, n - 1$ and $x_n = y_n + a_i(y_i')$ then $\nabla y' v = \nabla x' v + v_{\partial \Omega} \nabla a_i(x')$ and $v_{\partial \Omega} = v_{\partial \Omega}$, thus
\[
C(\Lambda)|\nabla x v| \leq |\nabla y' v| \leq c(\Lambda)|\nabla x v|.
\] (A.34)

Let us now define the “balls” which we will use to prove some Poincaré, weighted Poincaré and Moser inequalities. More precisely we have the following definition.

**Definition A.6.** Let $\gamma \in (1, 2)$. For any $x \in \Omega$ and for any $0 < r < \frac{\min\{C, b\}}{2^\gamma}$, we define the ball centered at $x$ and having radius $r$ as follows.

(i) If $d(x) \leq \gamma r$ then
\[
\mathcal{B}(x, r) = \{(y_i', y_m) : |y_i' - x_i'| \leq r, d(x) - r \leq y_m - a_i(y_i') \leq r + d(x)\},
\]
where $i \in \{1, \ldots, m\}$ is uniquely defined by the point $x \in \partial \Omega$ such that $|x - x_i'| = d(x)$, that is by the projection of the center $x$ onto $\partial \Omega$.

(ii) If $d(x) \geq \gamma r$ then $\mathcal{B}(x, r) = B(x, r)$ the Euclidean ball centered at $x$.

We also define by
\[
V(x, r) = \int_{\mathcal{B}(x, r) \cap \Omega} \phi_k^2(y) dy,
\]
the volume of the “ball” centered at $x$ and having radius $r$.

We first recall some known results the proofs of which are in [14]. The first one [14, Lemma 2.2] is a two-sided estimates of $V(x, r)$. 

**Proposition A.7.** There exist positive constants $d_1$ and $d_2$ such that for any $x \in \Omega$ and $0 < r < \frac{\min\{C_d, b\}}{2^r}$, we have

$$d_1 \max\{d^a(x), r^a\} r^N \leq V(x, r) \leq d_2 \max\{d^a(x), r^a\} r^N. \quad (A.35)$$

From the previous lemma it follows the doubling property satisfied by $V(x, \cdot)$.

**Corollary A.8.** Let $N \geq 2$, $\alpha > 0$ and $\Omega$ be a smooth bounded domain. Then there exist positive constants $C(N, \gamma, \Omega, \alpha)$ and $\beta(\Omega, \gamma)$ such that for any $x \in \Omega$ and $0 < r < \beta$ we have

$$V(x, 2r) \leq CV(x, r).$$

The Local Poincaré inequality is proved in [14, Theorem 2.5].

**Proposition A.9.** There exist positive constants $C(N, \gamma, \Omega, \alpha_+)$ and $\beta(\Omega, \gamma)$ such that for any $x_0 \in \Omega$ and $r < \beta$ we have

$$\inf_{\xi \in \mathbb{R}} \int_{B(x_0, r) \cap \Omega} \left| \int_{B(x_0, r) \cap \Omega} |\nabla f(y)|^2 \phi^2(y) dy \right|^{1+\frac{2}{N}} \int_{B(x_0, r) \cap \Omega} |\nabla^2 f(y)|^2 \phi^2(y) dy \leq C m^r V(x, r)^{\frac{1}{2}} \left( \int_{B(x_0, r) \cap \Omega} |f(y)|^2 \phi^2(y) dy \right)^{\frac{1}{2}}.$$

As a consequence there holds a local weighted Moser inequality which is proved in [14, Th 2.6].

**Proposition A.10.** There exist positive constants $C_M(N, \Omega, \alpha_+)$ and $\beta(\Omega, \gamma)$ such that for any $v \geq N + \alpha$, $x_0 \in \Omega$, $r < \beta$ and $f \in C_0^\infty(\mathcal{B}(x_0, r) \cap \Omega)$ we have

$$\int_{\mathcal{B}(x_0, r) \cap \Omega} |\nabla f(y)|^2 \phi^2(y) dy \leq C_M r^2 V(x, r)^{-\frac{1}{2}} \left( \int_{\mathcal{B}(x_0, r) \cap \Omega} |f(y)|^2 \phi^2(y) dy \right)^{\frac{1}{2}} \left( \int_{\mathcal{B}(x_0, r) \cap \Omega} |\nabla^2 f(y)|^2 \phi^2(y) dy \right)^{\frac{1}{2}}.$$

Let us now make precise the notion of a weak solution.

**Definition A.11.** We will say that $v \in H^1_\phi(\mathcal{B}(x, r) \cap \Omega)$ is a weak solution of $L_\phi v = f$ in $\mathcal{B}(x, r) \cap \Omega$, if for each $\Phi \in C_0^\infty(\mathcal{B}(x, r) \cap \Omega)$, we have

$$\int_{\mathcal{B}(x, r) \cap \Omega} \nabla v \cdot \nabla \Phi dm = \int_{\mathcal{B}(x, r) \cap \Omega} f \Phi dm,$$

where $dm = \phi^2 dx$ and $\sigma > 0$.

We denote here by $H^1_\phi(\mathcal{B}(x, r) \cap \Omega)$ the space of all functions $u \in L^2_\phi(\mathcal{B}(x, r) \cap \Omega)$ such that $\nabla u \in L^2_\phi(\mathcal{B}(x, r) \cap \Omega)$, endowed with the norm

$$\|u\|_{H^1_\phi(\mathcal{B}(x, r) \cap \Omega)} = \left( \int_{\mathcal{B}(x, r) \cap \Omega} |\nabla u|^2 \phi^2 dx + \int_{\mathcal{B}(x, r) \cap \Omega} u^2 \phi^2 dx \right)^{\frac{1}{2}}.$$

Then we have the following Harnack inequality up to the boundary.

**Theorem A.12.** Let $v$ be a non-negative solution of $L_\phi v = f$ in $\Omega$ where $f$ satisfies (A.33). Then there exists a constant $A > 0$ such that the following estimate holds,

$$v(y) \leq Av(x) \quad \forall x, y \in \Omega.$$

In order to prove Theorem A.12 we use the Moser iteration technique as it is adapted to degenerate elliptic operators in [17,18,29]. In this approach one inserts in the weak form of the equation $L_\phi v = f$ suitable test functions $\Phi$. One of the key ideas is to use test functions $\Phi$ of the form $\eta^2 v^q$, where $v$ is the weak solution of the equation, $\eta$ is a cut off function and $q \in \mathbb{R}$. To this end one has to check that $\eta^2 v^q$ is in the right space of test function. In this direction the following density theorem is crucial, the proof of which is [14, Th 2.11].

**Theorem A.13.** Let $N \geq 2$, $\alpha \geq 1$ and $U \subset \mathbb{R}^n$ be a smooth bounded domain. Then we have

$$H^1_\phi(U, d^a(y)dy) = H^1(U, d^a(y)dy)$$

where we have set

$$H^1_\phi(U, d^a(y)dy) = \left\{ v = v(y) : \|v\|^2_{H^1} = \int_U d^a(|\nabla v|^2 + v^2)dy < \infty \right\}.$$
We note here the above theorem allows us to take the cut of function \( \eta \in C^\infty_c(\mathcal{M}(x, y)) \) instead of it as a usual taking in \( \eta \in C^\infty_0(\mathcal{M}(x, y) \cap \Omega) \). Clearly the two function spaces differ only if the “ball” intersects the boundary of \( \Omega \).

To explain what are the appropriate modifications of the standard iteration argument by Moser, we now present in detail the first step, which is the \( L^p \); \( p \geq 2 \) mean value inequality for any positive local subsolution of \( L_{\phi_k} v \leq f \). Similarly with Definition A.11, we call a function \( v \in H^1_{\phi_k}(\mathcal{M}(x, y) \cap \Omega) \) subsolution of \( L_{\phi_k} v \leq f \) in \( \mathcal{M}(x, y) \cap \Omega \), if for each \( 0 \leq \Phi \in C^\infty_0(\mathcal{M}(x, y) \cap \Omega) \) we have

\[
\int_{\mathcal{M}(x, y) \cap \Omega} \nabla v \cdot \nabla \Phi \phi_k^2 \, dx \leq \int_{\mathcal{M}(x, y) \cap \Omega} f \phi_k^2 \, dx. \tag{A.36}
\]

**Theorem A.14.** Let \( \gamma \in (1, 2) \) and \( p \geq 2 \). Then there exist positive constants \( c_0(\Omega) \) and \( C(\Omega, \gamma, \kappa, c_0) \) such that for any \( x \in \Omega \), \( R < c_0 \) and for any positive subsolution of \( L_{\phi_k} v \leq f \) in \( \mathcal{M}(x, y) \cap \Omega \), we have the estimate

\[
\sup_{\mathcal{M}(x, y) \cap \Omega} |v|^\gamma \leq \frac{C}{(1 - \sigma)^\gamma} \int_{\mathcal{M}(x, y) \cap \Omega} |v|^\gamma \phi_k^2 \, dx
\]

\[
+ C \left( R^{2-\alpha_{\gamma}} (\log R) c_\gamma + R^{2-\max\{\gamma, \frac{N+\alpha_{\gamma}}{4}\}} \int_{\mathcal{M}(x, y) \cap \Omega} |f|^\gamma \phi_k^2 \, dx \right)^\frac{1}{\gamma}
\]

for each \( 0 < \sigma < 1 \).

**Proof.** Let \( \gamma \in (1, 2) \) and \( x_0 \in \Omega \). First we assume that \( d(x_0) < \gamma R \), in other case the proof is standard and we omit it. Let \( R < \min(c_0, 1) \) we denote by \( \Omega^R \) the domain

\[ \Omega^R = \{ \xi \in \mathbb{R}^n : R \xi \in \Omega \}. \]

Set \( x_0 = R y_0 \), \( \tilde{\phi}_k(y) = \phi_k(Ry) \)

\[ \tilde{V}(y, r) = \int_{\mathcal{M}(y, r) \cap \Omega^R} \tilde{\phi}_k^2(\xi) \, dx, \]

\[ \tilde{d}(y) = \text{dist}(y, \Omega^R) = \frac{d(Ry)}{R}. \]

As \( R \leq 1 \) a \( C^2 \) characteristic of \( \Omega \) is also a \( C^2 \) characteristic of \( \Omega^R \) therefore the constant \( C \) can be taken to be independent of \( y \). We note here that the constant \( 0 < c_0 \leq 1 \) depends on \( C^2 \) characteristic of \( \Omega \).

Set \( \tilde{v}(y) = v(Ry) \), \( \tilde{c}_\gamma = 2R^{2-\alpha_{\gamma}} (\log R) c_\gamma \), \( \tilde{f}(y) = R^{2-\alpha_{\gamma}}(Ry) \), \( \tilde{f}_0(y) = R^{2-\alpha_{\gamma}}(Ry) u = \tilde{v} + k \), where \( k = \tilde{c}_\gamma + \|\tilde{f}_0\|_{L^1(\Omega^R, \phi_k^2 \, dx)} \).

Then \( u \) is bounded away from zero. Thus by (A.36) we have for any \( \Phi \in C^\infty_0(\mathcal{M}(y, 1) \cap \Omega^R) \)

\[
\int_{\mathcal{M}(y, 1) \cap \Omega^R} \nabla u \cdot \nabla \Phi \phi_k^2 \, dx \leq \int_{\mathcal{M}(y, 1) \cap \Omega^R} \Phi \tilde{f}_0 \tilde{\phi}_k^2 \, dx + \tilde{c}_\gamma \int_{\mathcal{M}(y, 1) \cap \Omega^R} \left| \log \frac{\tilde{d}(x)}{D} \right| \Phi \, dx.
\]

Let \( \beta > 0 \), we set

\[
u_m = \begin{cases} u & u \leq k + m \\ k + m & u > k + m \end{cases}
\]

and \( \Phi = \psi^2 \nu_m^\beta u \). Due to Theorem A.13 there exists a sequence of functions \( \Phi_k \in C^\infty(\mathcal{M}(y, 1) \cap \Omega^R) \) having compact support in \( \Omega \) such that \( \Phi_k \to \Phi \) in \( H^1(\mathcal{M}(y, 1) \cap \Omega^R, d^2 \mu) \). Since \( \psi \sim \bar{d}^{\alpha_{\gamma}^{\prime}} \), we have that \( \Phi_k \to \Phi \) in \( H^1_{\phi_k}(\mathcal{M}(y, 1) \cap \Omega^R) \).

Hence for any \( \psi \in C^\infty_0(\mathcal{M}(y, 1)) \) and \( m \geq 1 \) the function \( \Phi = \psi^2 \nu_m^\beta u \) is an admissible test function, that is, the following holds true:

\[
\int_{\mathcal{M}(y, 1) \cap \Omega^R} \nabla u \cdot \nabla (\psi^2 \nu_m^\beta u) \tilde{\phi}_k^2 \, dx \leq \int_{\mathcal{M}(y, 1) \cap \Omega^R} \psi^2 \nu_m^\beta u \tilde{f}_0 \tilde{\phi}_k^2 \, dx + c_0 \int_{\mathcal{M}(y, 1) \cap \Omega^R} \left| \log \frac{d(x)}{D} \right| \psi^2 \nu_m^\beta u \, dx
\]

\[
\leq \frac{1}{k} \int_{\mathcal{M}(y, 1) \cap \Omega^R} \psi^2 \nu_m^\beta u \tilde{f}_0 \tilde{\phi}_k^2 \, dx + \frac{\tilde{c}_\gamma}{k} \int_{\mathcal{M}(y, 1) \cap \Omega^R} \left| \log \frac{d(x)}{D} \right| \psi^2 \nu_m^\beta u \, dx.
\]

Thus by straightforward calculations and Hölder inequality we have

\[
\frac{1}{2} \int_{\mathcal{M}(y, 1) \cap \Omega^R} |\nabla u|^2 \nu_m^\beta u \psi^2 \tilde{\phi}_k^2 \, dx + \beta \int_{\mathcal{M}(y, 1) \cap \Omega^R} |\nabla \nu_m|^2 u \psi^2 \tilde{\phi}_k^2 \, dx
\]

\[
\leq c \int_{\mathcal{M}(y, 1) \cap \Omega^R} |\nabla \psi|^2 u \nu_m^\beta \tilde{\phi}_k^2 \, dx + \frac{1}{k} \int_{\mathcal{M}(y, 1) \cap \Omega^R} \psi^2 \nu_m^\beta u \tilde{f}_0 \tilde{\phi}_k^2 \, dx + \frac{\tilde{c}_\gamma}{k} \int_{\mathcal{M}(y, 1) \cap \Omega^R} \left| \log \frac{d(x)}{D} \right| \psi^2 \nu_m^\beta u \, dx.
\]
Now we have by Hölder inequality
\[
\frac{k}{\beta} \int_{\mathbb{B}(y_0,1) \cap \Omega^R} u^2 \phi^2 \partial^2 \phi \, dx \leq \frac{k}{\beta} \left( \int_{\mathbb{B}(y_0,1) \cap \Omega^R} |\partial^2 \phi|^2 \, dx \right)^{\frac{1}{2}} \left( \int_{\mathbb{B}(y_0,1) \cap \Omega^R} |u^2 \phi^2|^2 \, dx \right)^{\frac{1}{2}}.
\]
Since \( \frac{2(N+\alpha_\pm)}{N+\alpha_\pm-2} > \frac{2q}{q-1} > 2 \) if \( q > \frac{N+\alpha_\pm}{2} \), we have by interpolation inequality and (2.9)
\[
\left( \int_{\mathbb{B}(y_0,1) \cap \Omega^R} |u^2 \phi^2|^2 \, dx \right)^{\frac{q-1}{q}} \leq \varepsilon \left( \int_{\mathbb{B}(y_0,1) \cap \Omega^R} |u^2 \phi^2|^\frac{N+\alpha_\pm}{N+\alpha_\pm-2} \, dx \right)^{\frac{N+\alpha_\pm-2}{2(N+\alpha_\pm-2)}} \left( \int_{\mathbb{B}(y_0,1) \cap \Omega^R} u^2 \phi^2 \, dx \right)^{\frac{N+\alpha_\pm}{2(N+\alpha_\pm-2)}}.
\]
Also
\[
\int_{\mathbb{B}(y_0,1) \cap \Omega^R} \log \frac{\tilde{d}(x)}{D} \psi^2 u^2 \, dx = -\int_{\mathbb{B}(y_0,1) \cap \Omega^R} \log \frac{\tilde{d}(x)}{D} \psi^2 u^2 \, dx + \int_{\mathbb{B}(y_0,1) \cap \Omega^R} \log \frac{\tilde{d}(x)}{D} \Delta \tilde{u} \psi \tilde{u} \psi \, dx + \int_{\mathbb{B}(y_0,1) \cap \Omega^R} \psi^2 u^2 \, dx.
\]
Let \( 0 < \sigma < \sigma' < 1 \), we choose a function \( \psi = \xi(|y_n - x'|) \xi((|x_n - a(x') - \tilde{d}(y_0)|), where \( \xi \in C^\infty(\mathbb{R}) \) and satisfies \( 0 \leq \xi \leq 1 \), \( \xi(s) = 1 \) if \( s \leq \sigma' \) and \( \xi(s) = 0 \) if \( s > \sigma' \). Then clearly we have \( |\nabla \psi| \leq \frac{C}{\sigma - \sigma'} \).
\[
\int_{\mathbb{B}(y_0,1) \cap \Omega^R} \log \frac{\tilde{d}(x)}{D} \psi^2 u^2 \, dx \leq \frac{C}{\sigma - \sigma'} \int_{\mathbb{B}(y_0,1) \cap \Omega^R} \log \frac{\tilde{d}(x)}{D} \psi^2 u^2 \, dx + \frac{C}{\sigma - \sigma'} \int_{\mathbb{B}(y_0,1) \cap \Omega^R} \log \frac{\tilde{d}(x)}{D} \psi^2 u^2 \, dx.
\]
Working as the last two inequalities and using the fact that \( \phi \sim \tilde{d}^{\frac{\sigma}{\sigma'}} \), we can prove that there exists \( \varepsilon \in (0, 2 - \alpha_\pm) \), such that
\[
\int_{\mathbb{B}(y_0,1) \cap \Omega^R} \psi^2 u^2 \, dx \leq \frac{C}{\sigma - \sigma'} \left( \int_{\mathbb{B}(y_0,1) \cap \Omega^R} \psi^2 u^2 \, dx \right) + \frac{C}{\sigma - \sigma'} \left( \int_{\mathbb{B}(y_0,1) \cap \Omega^R} \psi^2 u^2 \, dx \right).
\]
Let \( \beta \geq 2 \), combining all above there exist \( \delta = \delta(N, \alpha_\pm, q) > 0 \) and \( C = C(N, \alpha_\pm, q) > 0 \) such that
\[
\int_{\mathbb{B}(y_0,1) \cap \Omega^R} |\nabla u|^2 u^2 \phi^2 \, dx + \int_{\mathbb{B}(y_0,1) \cap \Omega^R} |\nabla u|^2 u^2 \phi^2 \, dx \leq \frac{C\beta^2}{(R - r)^2} \int_{\mathbb{B}(y_0,1 \cap \Omega^R} u^2 \phi^2 \, dx.
\]
Thus by the same argument as before we have
\[ \int_{B(y_0, 1) \cap \Omega^c} |\nabla (\psi w)|^2 \, dx \leq C(\beta + 1) \left( \int_{B(y_0, 1) \cap \Omega^c} |\nabla u|^2 u_m^p \psi^2 \widetilde{\phi}_x^2 \, dx + \int_{B(y_0, 1) \cap \Omega^c} |\nabla u_m|^2 u_m^p \psi^2 \widetilde{\phi}_x^2 \, dx \right). \]

Thus we get
\[ \int_{B(y_0, 1) \cap \Omega^c} |\nabla (\psi w)|^2 \, dx \leq C \frac{\beta^{p+1}}{(R - r)^2} \int_{B(y_0, 1) \cap \Omega^c} w^2 \widetilde{\phi}_x^2 \, dx. \]

Using the above inequality Proposition A.10 we obtain
\[ \int_{B(y_0, \sigma) \cap \Omega^c} |w|^{2 + \frac{2}{\sigma}} \widetilde{\phi}_x^2 \, dx \leq \int_{B(y_0, 1) \cap \Omega^c} |\psi w|^{2 + \frac{2}{\sigma}} \widetilde{\phi}_x^2 \, dx \leq \frac{E}{\int_{B(y_0, 1) \cap \Omega^c} |\psi w|^{2 + \frac{2}{\sigma}} \widetilde{\phi}_x^2 \, dx} \left( \int_{B(y_0, \sigma) \cap \Omega^c} |w|^2 \widetilde{\phi}_x^2 \, dx \right)^{\frac{2}{\sigma}} \]
\[ \leq EC \beta^{p+1} \left( \frac{1}{(\sigma' - \sigma)^2} \int_{B(x, \sigma') \cap \Omega} |\nabla \psi|^2 \, dx \right)^{\frac{2}{\sigma}} \]
where \( E = C_M \widetilde{V}^{-\frac{2}{\sigma'}}(y_0, 1) \) is the constant in Proposition A.10.

Set \( \beta = p \) and let \( m \to \infty \), then we have by (A.38) and the definition of \( w \),
\[ \int_{B(y_0, \sigma') \cap \Omega} |u|^p (1 + \frac{2}{\sigma'}) \widetilde{\phi}_x^2 \, dx \leq A \left( \frac{\beta^{p+1}}{(\sigma' - \sigma)^2} \int_{B(x, \sigma') \cap \Omega} |\nabla u|^p \widetilde{\phi}_x^2 \, dx \right)^{\frac{1}{1 + \frac{2}{\sigma'}}}, \]
where \( A = EC \) the constant in (A.38).

We note that by iteration with \( p_0 = p, \ p_1 = p(1 + \frac{1}{\sigma}), \ldots, p_i = p \left( 1 + \frac{1}{\sigma'} \right)^i \),
\[ \int_{B(y_0, \sigma') \cap \Omega} u_i^p \widetilde{\phi}_x^2 \, dx \leq \int_{B(y_0, \sigma') \cap \Omega} u_1^p \widetilde{\phi}_x^2 \, dx < \infty \quad \forall \ i \geq 0 \text{ and } \sigma'' < r' \]
Thus by the same argument as before we have
\[ \int_{B(x, \sigma') \cap \Omega} u_i^p \widetilde{\phi}_x^2 \, dx \leq A \left( \frac{\beta^{p+1}}{(\sigma' - \sigma)^2} \int_{B(x, \sigma') \cap \Omega} u^p \widetilde{\phi}_x^2 \, dx \right)^{\frac{1}{1 + \frac{2}{\sigma'}}}, \]
where \( \Theta = 1 + \frac{2}{\sigma'} \). Observe now that \( r_i \to \delta \) as \( i \to \infty \), all sum above are finite and \( \sum_{j=0}^{\infty} \Theta^{-j} = \frac{v}{2} + 1 \).

Hence we have,
\[ \sup_{B(y_0, \sigma') \cap \Omega} |u|^p \leq A \frac{\beta^{p+1}}{(\sigma' - \sigma)^2} \int_{B(y_0, \sigma') \cap \Omega} u^p \widetilde{\phi}_x^2 \, dx \quad \forall \ p \geq 2 \]
where \( A = C_M \widetilde{V}^{-\frac{2}{\sigma'}}(x, 1) \).
Thus we have

\[ \sup_{y \in \mathcal{B}(y_0, \frac{R}{2}) \cap \mathbb{R}^n} |\overline{v}|^p \leq A^\frac{p}{2} 2^p \left( \int_{\mathcal{B}(y_0, 1) \cap \mathbb{R}^n} |\overline{v}|^p \phi_x^2 \, dx + k \right) \quad \forall \ p \geq 2, \]

which implies

\[ \sup_{y \in \mathcal{B}(y_0, \frac{R}{2}) \cap \mathbb{R}^n} |v|^p \leq \frac{1}{V(x, R)} \left( \int_{\mathcal{B}(y_0, 1) \cap \Omega} |v|^p \phi_x^2 \, dx + k \right) \quad \forall \ p \geq 2. \]

The estimate in \( \mathcal{B}(y_0, \sigma R) \cap \Omega \) can be obtained by applying the above result to \( \mathcal{B}(y_0, (1 - \sigma)R) \cap \Omega \) for any \( y \in \mathcal{B}(y, \sigma R) \cap \Omega \).

Using Moser’s iterative scheme we are now in a situation to prove.

**Proposition A.15.** Let \( u \) be a weak solution of \( (A.32) \). Then there exist two constants \( C > 0 \) and \( \alpha \in (0, 1] \), depending on \( \Omega, N \) and \( \kappa \) such that

\[ \sup_{x,y \in \Omega, x \neq y} \frac{|u(x) - u(y)|}{|x - y|^\alpha} \leq C \left( c_1 + \left( \int_{\mathcal{B}(x, R) \cap \Omega} |f_0|^q \phi_x^2 \, dx \right)^{\frac{1}{q}} \right). \]

**References**