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# A structure in the early Universe at $z \sim 1.3$ that exceeds the homogeneity scale of the R-W concordance cosmology

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## ABSTRACT

A large quasar group (LQG) of particularly large size and high membership has been identified in the DR7QSO catalogue of the Sloan Digital Sky Survey. It has characteristic size (volume$^{1/3}$) ∼500 Mpc (proper size, present epoch), longest dimension ∼1240 Mpc, membership of 73 quasars and mean redshift $\bar{z} = 1.27$. In terms of both size and membership, it is the most extreme LQG found in the DR7QSO catalogue for the redshift range $1.0 \leq z \leq 1.8$ of our current investigation. Its location on the sky is ∼8.°8 north (∼615 Mpc projected) of the Clowes & Campusano LQG at the same redshift, $\bar{z} = 1.28$, which is itself one of the more extreme examples. Their boundaries approach to within ∼2° (∼140 Mpc projected). This new, Huge-LQG appears to be the largest structure currently known in the early Universe. Its size suggests incompatibility with the Yadav et al. scale of homogeneity for the concordance cosmology, and thus challenges the assumption of the cosmological principle.

**Key words:** galaxies: clusters: general – quasars: general – large-scale structure of Universe.



## 1 INTRODUCTION

Large quasar groups (LQGs) are the largest structures seen in the early Universe, of characteristic size ∼70–350 Mpc, with the highest values appearing to be only marginally compatible with the Yadav, Bagla & Khandai (2010) scale of homogeneity in the concordance cosmology. LQGs generally have ∼5–40 member quasars. The first three LQGs to be discovered were those of Webster (1982), Crampton, Cowley & Hartwick (1987, 1989) and Clowes & Campusano (1991). For more recent work see, for example, Brand et al. (2003) (radio galaxies), Miller et al. (2004), Pilipenko (2007), Rozgacheva et al. (2012) and Clowes et al. (2012). The association of quasars with superclusters in the relatively local Universe has been discussed by, for example Longo (1991), Söchting, Clowes & Campusano (2002), Söchting, Clowes & Campusano (2004) and Lietzen et al. (2009). The last three of these papers note the association of quasars with the peripheries of clusters or with filaments. At higher redshifts, Komberg, Kravtsov & Lukash (1996) and Pilipenko (2007) suggest that the LQGs are the precursors of the superclusters seen today. Given the large sizes of LQGs, perhaps they are instead the precursors of supercluster complexes such as the Sloan Great Wall (SGW; Gott et al. 2005).

In Clowes et al. (2012), we presented results for two LQGs as they appeared in the DR7 quasar catalogue ('DR7QSO'; Schneider et al. 2010) of the Sloan Digital Sky Survey (SDSS). One of these LQGs, designated U1.28 in that paper, was the previously known Clowes & Campusano (1991) LQG (CCLQG) and the other, designated U1.11, was a new discovery. (In these designations U1.28 and U1.11, the 'U' refers to a connected unit of quasars, and the number refers to the mean redshift.) U1.28 and U1.11 had memberships of 34 and 38 quasars, respectively, and characteristic sizes (volume$^{1/3}$) of ∼ 350, 380 Mpc. Yadav et al. (2010) give an idealized upper limit to the scale of homogeneity in the concordance cosmology as ∼370 Mpc. As discussed in Clowes et al. (2012), if the fractal calculations of Yadav et al. (2010) are adopted as reference then U1.28 and U1.11 are only marginally compatible with homogeneity.

In this paper, we present results for a new LQG, designated U1.27, again found in the DR7QSO catalogue, which is noteworthy for both its exceptionally large characteristic size, ∼500 Mpc, and its exceptionally high membership, 73 quasars. It provides further interest for discussions of homogeneity and the validity of the cosmological principle.

For simplicity we shall also refer to U1.27 as the Huge-LQG and U1.28 as the CCLQG.

The largest structure in the local Universe is the SGW at $z = 0.073$, as noted in particular by Gott et al. (2005). They give its length (proper size at the present epoch) as ∼450 Mpc, compared

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with ∼240 Mpc for the Geller & Huchra (1989) Great Wall ($z = 0.029$). Although Gott et al. (2005) do not discuss in detail the compatibility of the SGW with concordance cosmology and Gaussian initial conditions, from visual inspection of simulations they did not expect any incompatibility. Sheth & Diaferio (2011) have investigated this question of compatibility further and concluded that, given the assumptions of their analysis, there is a potential difficulty, which can, however, be avoided if the SGW, in our cosmological neighbourhood, happens to be the densest structure of its volume within the entire Hubble volume.

The Sheth & Diaferio (2011) paper is, however, not an analysis of compatibility of the SGW with homogeneity. Homogeneity asserts that the mass–energy density (or, indeed, any global property) of sufficiently large volumes should be the same within the expected statistical variations. Sheth & Diaferio (2011) estimate the volume of the SGW as $\sim 2.1 \times 10^6$ Mpc$^3$, for the larger of two group-linkage estimates, which roughly reproduces the portrayal of the SGW by Gott et al. (2005). A characteristic size – (volume)$^{1/3}$ – is then ∼128 Mpc. The SGW is markedly elongated so this measure of characteristic size should not be compared with the overall length. The overdensity is given as $\delta_M \sim 1.2$ for mass and $\delta_n \sim 4$ for number of galaxies. Note that Einasto et al. (2011c) find that the SGW is not a single structure, but a set of superclusters with different evolutionary histories. For discussing potential conflicts of the SGW with homogeneity this result by Einasto et al. (2011c) means that the long dimension of ∼450 Mpc is misleading. The characteristic size of ∼128 Mpc is still relevant, but is much smaller than the upper limit of ∼370 Mpc for homogeneity (Yadav et al. 2010), and so it may be that the SGW does not present any particular problem. Indeed, Park et al. (2012) find from the 'Horizon Run 2' cosmological simulation that the SGW is consistent with concordance cosmology and with homogeneity. Park et al. (2012) also note that the properties of large-scale structures can be used as sensitive discriminants of cosmological models and models of galaxy formation.

The concordance model is adopted for cosmological calculations, with $\Omega_T = 1$, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$ and $H_0 = 70$ km s$^{-1}$Mpc$^{-1}$. All sizes given are proper sizes at the present epoch.

## 2 DETECTION OF THE HUGE-LQG (U1.27)

The new, Huge-LQG (U1.27) has been detected by the procedures described in Clowes et al. (2012). These procedures are briefly described here.

As mentioned above, the source of the quasar data is the SDSS DR7QSO catalogue (Schneider et al. 2010) of 105 783 quasars. The low-redshift, $z \lesssim 3$, strand of selection of the SDSS specifies $i \le 19.1$ (Vanden Berk et al. 2005; Richards et al. 2006). Restriction of the quasars to this limit allows satisfactory spatial uniformity of selection on the sky to be achieved, since they are then predominantly from this strand. Also, changes in the SDSS selection algorithms (Richards et al. 2002) should not then be important. The more general criteria for extraction of a statistical sample from the DR7QSO catalogue or its predecessors are discussed by Schneider et al. (2010), Richards et al. (2006) and Vanden Berk et al. (2005).

The DR7QSO catalogue covers ∼9380 deg$^2$ in total. There is a large contiguous area of ∼7600 deg$^2$ in the north galactic gap, which has some jagged boundaries. Within this contiguous area we define a control area, designated A3725, of ∼3725 deg$^2$ (actually 3724.5 deg$^2$) by RA: 123°.0 → 237°.0 and Dec.: 15°.0 → 56°.0.

We detect candidates for LQGs in the catalogue by three-dimensional single-linkage hierarchical clustering, which is equivalent to the three-dimensional minimal spanning tree (MST). Such algorithms have the advantage that they do not require assumptions about the morphology of the structure. As in Clowes et al. (2012), the linkage scale is set to 100 Mpc. The choice of scale is guided by the mean nearest-neighbour separation together with allowance for redshift errors and peculiar velocities; see that paper for full details. The particular algorithm we use for single-linkage hierarchical clustering is the *agnes* algorithm in the R package.[1] We are currently concentrating on detecting LQGs in the redshift interval $1.0 \le z \le 1.8$ and, of course, with the restriction $i \le 19.1$.

With this detection procedure the new Huge-LQG (U1.27) that is the subject of this paper is detected as a unit of 73 quasars, with mean redshift 1.27. It covers the redshift range 1.1742 → 1.3713. The 73 member quasars are listed in Table 1.

The Huge-LQG is ∼8°.8 north (∼615 Mpc projected) of the CCLQG at the same redshift. Their boundaries on the sky approach to within ∼2° (∼140 Mpc projected).

## 3 PROPERTIES OF THE HUGE-LQG

Groups found by the linkage of points require a procedure to assess their statistical significance and to estimate the overdensity. We use the CHMS method ('convex hull of member spheres'), which is described in detail by Clowes et al. (2012). The essential statistic is the volume of the candidate: a LQG must occupy a smaller volume than the expectation for the same number of random points.

In the CHMS method, the volume is constructed as follows. Each member point of a unit is expanded to a sphere, with radius set to be half of the mean linkage (MST edge length) of the unit. The CHMS volume is then taken to be the volume of the convex hull of these spheres. The significance of an LQG candidate of membership $N$ is found from the distribution of CHMS volumes resulting from 1000 sets of $N$ random points that have been distributed in a cube of volume such that the density in the cube corresponds to the density in a control area for the redshift limits of the candidate. The CHMS volumes for the random sets can also be used to estimate residual biases (see Clowes et al. 2012) and consequently make corrections to the properties of the LQGs.

In this way, with A3725 as the control area, we find that the departure from random expectations for the Huge-LQG is $3.81\sigma$. After correcting the CHMS volumes for residual bias the estimated overdensity of the Huge-LQG is $\delta_q = \delta\rho_q/\rho_q = 0.40$. (The volume correction is ∼2 per cent.) The overdensity is discussed further below, because of the cautious, conservative nature of the CHMS estimate, which, in this case, is possibly too cautious.

As discussed in Clowes et al. (2012), a simple measure of the characteristic size of an LQG, which takes no account of morphology, is the cube root of the corrected CHMS volume. For the Huge-LQG the volume is $\sim 1.21 \times 10^8$ Mpc$^3$, giving a characteristic size of ∼495 Mpc.

From the inertia tensor of the member quasars of the Huge-LQG, the principal axes have lengths of ∼1240, 640 and 370 Mpc, and the inhomogeneity thus extends to the Gpc scale. The axis ratios are 3.32 : 1.71 : 1, so it is substantially elongated.

Fig. 1 shows the sky distributions of the members of both the new, Huge-LQG (U1.27), and the CCLQG. Much of the Huge-LQG is directly north of the CCLQG, but the southern part curves to the south-east and away from the CCLQG. The redshift intervals occupied by the two LQGs are similar (1.1742–1.3713 for the

[1] See http://www.r-project.org.

**Table 1.** Huge-LQG (U1.27): the set of 73 100 Mpc-linked quasars from the SDSS DR7QSO catalogue. The columns are: SDSS name; RA, Dec. (2000); redshift; *i* magnitude.

| SDSS name | RA, Dec (2000) | $z$ | $i$ |
|---|---|---|---|
| 104139.15+143530.2 | 10:41:39.15 +14:35:30.2 | 1.2164 | 18.657 |
| 104321.62+143600.2 | 10:43:21.62 +14:36:00.2 | 1.2660 | 19.080 |
| 104430.92+160245.0 | 10:44:30.92 +16:02:45.0 | 1.2294 | 17.754 |
| 104445.03+151901.6 | 10:44:45.03 +15:19:01.6 | 1.2336 | 18.678 |
| 104520.62+141724.2 | 10:45:20.62 +14:17:24.2 | 1.2650 | 18.271 |
| 104604.05+140241.2 | 10:46:04.05 +14:02:41.2 | 1.2884 | 18.553 |
| 104616.31+164512.6 | 10:46:16.31 +16:45:12.6 | 1.2815 | 18.732 |
| 104624.25+143009.1 | 10:46:24.25 +14:30:09.1 | 1.3620 | 18.989 |
| 104813.63+162849.1 | 10:48:13.63 +16:28:49.1 | 1.2905 | 18.593 |
| 104859.74+125322.3 | 10:48:59.74 +12:53:22.3 | 1.3597 | 18.938 |
| 104915.66+165217.4 | 10:49:15.66 +16:52:17.4 | 1.3459 | 18.281 |
| 104922.60+154336.1 | 10:49:22.60 +15:43:36.1 | 1.2590 | 18.395 |
| 104924.30+154156.0 | 10:49:24.30 +15:41:56.0 | 1.2965 | 18.537 |
| 104938.22+214829.3 | 10:49:38.22 +21:48:29.3 | 1.2352 | 18.805 |
| 104941.67+151824.6 | 10:49:41.67 +15:18:24.6 | 1.3390 | 18.792 |
| 104947.77+162216.6 | 10:49:47.77 +16:22:16.6 | 1.2966 | 18.568 |
| 104954.70+160042.3 | 10:49:54.70 +16:00:42.3 | 1.3373 | 18.748 |
| 105001.22+153354.0 | 10:50:01.22 +15:33:54.0 | 1.2500 | 18.740 |
| 105042.26+160056.0 | 10:50:42.26 +16:00:56.0 | 1.2591 | 18.036 |
| 105104.16+161900.9 | 10:51:04.16 +16:19:00.9 | 1.2502 | 18.187 |
| 105117.00+131136.0 | 10:51:17.00 +13:11:36.0 | 1.3346 | 19.027 |
| 105119.60+142611.4 | 10:51:19.60 +14:26:11.4 | 1.3093 | 19.002 |
| 105122.98+115852.3 | 10:51:22.98 +11:58:52.3 | 1.3085 | 18.127 |
| 105125.72+124746.3 | 10:51:25.72 +12:47:46.3 | 1.2810 | 17.519 |
| 105132.22+145615.1 | 10:51:32.22 +14:56:15.1 | 1.3607 | 18.239 |
| 105140.40+203921.1 | 10:51:40.40 +20:39:21.1 | 1.1742 | 17.568 |
| 105144.88+125828.9 | 10:51:44.88 +12:58:28.9 | 1.3153 | 19.021 |
| 105210.02+165543.7 | 10:52:10.02 +16:55:43.7 | 1.3369 | 16.430 |
| 105222.13+123054.1 | 10:52:22.13 +12:30:54.1 | 1.3162 | 18.894 |
| 105223.68+140525.6 | 10:52:23.68 +14:05:25.6 | 1.2483 | 18.640 |
| 105224.08+204634.1 | 10:52:24.08 +20:46:34.1 | 1.2032 | 18.593 |
| 105245.80+134057.4 | 10:52:45.80 +13:40:57.4 | 1.3544 | 18.211 |
| 105257.17+105933.5 | 10:52:57.17 +10:59:33.5 | 1.2649 | 19.056 |
| 105258.16+201705.4 | 10:52:58.16 +20:17:05.4 | 1.2526 | 18.911 |
| 105412.67+145735.2 | 10:54:12.67 +14:57:35.2 | 1.2277 | 18.767 |
| 105421.90+212131.2 | 10:54:21.90 +21:21:31.2 | 1.2573 | 17.756 |
| 105435.64+101816.3 | 10:54:35.64 +10:18:16.3 | 1.2600 | 17.951 |
| 105442.71+104320.6 | 10:54:42.71 +10:43:20.6 | 1.3348 | 18.844 |
| 105446.73+195710.5 | 10:54:46.73 +19:57:10.5 | 1.2195 | 18.759 |
| 105523.03+130610.7 | 10:55:23.03 +13:06:10.7 | 1.3570 | 18.853 |
| 105525.18+191756.3 | 10:55:25.18 +19:17:56.3 | 1.2005 | 18.833 |
| 105525.68+113703.0 | 10:55:25.68 +11:37:03.0 | 1.2893 | 18.264 |
| 105541.83+111754.2 | 10:55:41.83 +11:17:54.2 | 1.3298 | 18.996 |
| 105556.22+184718.4 | 10:55:56.22 +18:47:18.4 | 1.2767 | 18.956 |
| 105611.27+170827.5 | 10:56:11.27 +17:08:27.5 | 1.3316 | 17.698 |
| 105621.90+143401.0 | 10:56:21.90 +14:34:01.0 | 1.2333 | 19.052 |
| 105637.49+150047.5 | 10:56:37.49 +15:00:47.5 | 1.3713 | 19.041 |
| 105637.98+100307.2 | 10:56:37.98 +10:03:07.2 | 1.2730 | 18.686 |
| 105655.36+144946.2 | 10:56:55.36 +14:49:46.2 | 1.2283 | 18.590 |
| 105714.02+184753.3 | 10:57:14.02 +18:47:53.3 | 1.2852 | 18.699 |
| 105805.09+200341.0 | 10:58:05.09 +20:03:41.0 | 1.2731 | 17.660 |
| 105832.01+170456.0 | 10:58:32.01 +17:04:56.0 | 1.2813 | 18.299 |
| 105840.49+175415.5 | 10:58:40.49 +17:54:15.5 | 1.2687 | 18.955 |
| 105855.33+081350.7 | 10:58:55.33 +08:13:50.7 | 1.2450 | 17.926 |
| 105928.57+164657.9 | 10:59:28.57 +16:46:57.9 | 1.2993 | 19.010 |
| 110006.02+092638.7 | 11:00:06.02 +09:26:38.7 | 1.2485 | 18.055 |
| 110016.88+193624.7 | 11:00:16.88 +19:36:24.7 | 1.2399 | 18.605 |
| 110039.99+165710.3 | 11:00:39.99 +16:57:10.3 | 1.2997 | 18.126 |
| 110148.66+082207.1 | 11:01:48.66 +08:22:07.1 | 1.1940 | 18.880 |
| 110217.19+083921.1 | 11:02:17.19 +08:39:21.1 | 1.2355 | 18.800 |
| 110504.46+084535.3 | 11:05:04.46 +08:45:35.3 | 1.2371 | 19.005 |
| 110621.40+084111.2 | 11:06:21.40 +08:41:11.2 | 1.2346 | 18.649 |
| 110736.60+090114.7 | 11:07:36.60 +09:01:14.7 | 1.2266 | 18.902 |
| 110744.61+095526.9 | 11:07:44.61 +09:55:26.9 | 1.2228 | 17.635 |
| 111007.89+104810.3 | 11:10:07.89 +10:48:10.3 | 1.2097 | 18.473 |
| 111009.58+075206.8 | 11:10:09.58 +07:52:06.8 | 1.2123 | 18.932 |
| 111416.17+102327.5 | 11:14:16.17 +10:23:27.5 | 1.2053 | 18.026 |
| 111545.30+081459.8 | 11:15:45.30 +08:14:59.8 | 1.1927 | 18.339 |
| 111802.11+103302.4 | 11:18:02.11 +10:33:02.4 | 1.2151 | 17.486 |
| 111823.21+090504.9 | 11:18:23.21 +09:05:04.9 | 1.1923 | 18.940 |
| 112019.62+085905.1 | 11:20:19.62 +08:59:05.1 | 1.2239 | 18.093 |
| 112059.27+101109.2 | 11:20:59.27 +10:11:09.2 | 1.2103 | 18.770 |
| 112109.76+075958.6 | 11:21:09.76 +07:59:58.6 | 1.2369 | 18.258 |

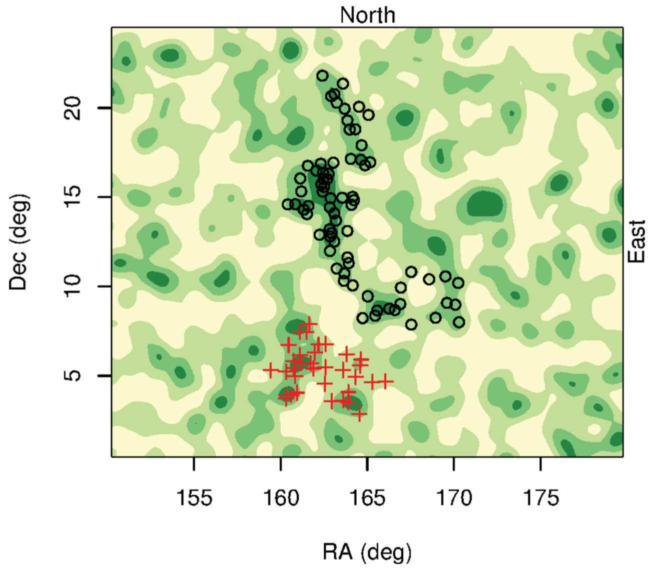


**Figure 1.** Sky distribution of the 73 quasars of the new, Huge-LQG (U1.27, $\bar{z} = 1.27$, circles), is shown, together with that of the 34 quasars of the CCLQG ($\bar{z} = 1.28$, crosses). The members of each LQG are connected at the linkage scale of 100 Mpc. The area shown is approximately 29°.5 × 24°.0. The DR7QSO quasars are limited to $i \le 19.1$. Superimposed on these distributions is a kernel-smoothed intensity map (isotropic Gaussian kernel, $\sigma = 0°.5$), plotted with four linear palette levels ($\le$0.8, 0.8–1.6, 1.6–2.4, $\ge$2.4 deg$^{-2}$), for all of the quasars in the joint redshift range of Huge-LQG and CCLQG ($z$: 1.1742 → 1.4232). No $\cos\delta$ correction has been applied to this intensity map.

Huge-LQG, 1.1865–1.4232 for the CCLQG), but on the sky Huge-LQG is clearly substantially larger.

Fig. 2 shows a snapshot from a visualization of the new, Huge-LQG, and CCLQG. The scales shown on the cuboid are proper sizes (Mpc) at the present epoch. The member points of both LQGs are shown expanded to spheres of radius 33.0 Mpc, which is half of the mean linkage (MST edge length) for the Huge-LQG (consistent with the CHMS method for this LQG). The morphology of the Huge-LQG is clearly strongly elongated, and curved. There is the appearance of a dense, clumpy part, followed by a change in orientation and a more filamentary part. Note that half of the mean linkage for the CCLQG is actually 38.8 Mpc, so, in this respect, the Huge-LQG is more tightly connected than the CCLQG. However, the CHMS density is lower for Huge-LQG than for CCLQG because of the effect of the change in orientation on the CHMS of Huge-LQG. That is, the Huge-LQG is more tightly connected than CCLQG (33.0 Mpc compared with 38.8 Mpc) but its curvature

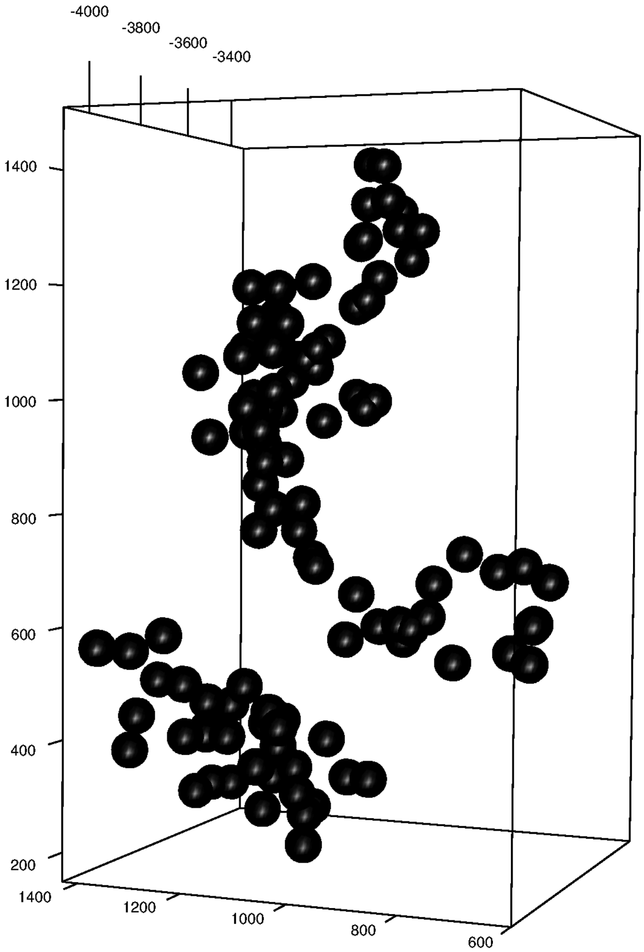


**Figure 2.** Snapshot from a visualization of both the new, Huge-LQG, and the CCLQG. The scales shown on the cuboid are proper sizes (Mpc) at the present epoch. The tick marks represent intervals of 200 Mpc. The Huge-LQG appears as the upper LQG. For comparison, the members of both are shown as spheres of radius 33.0 Mpc (half of the mean linkage for the Huge-LQG; the value for the CCLQG is 38.8 Mpc). For the Huge-LQG, note the dense, clumpy part followed by a change in orientation and a more filamentary part. The Huge-LQG and the CCLQG appear to be distinct entities.

causes its CHMS-volume to be disproportionately large (there is more 'dead space') and hence its density to be disproportionately low. Note that the Huge-LQG and the CCLQG appear to be distinct entities – their CHMS volumes do not intersect.

The CHMS method is thus conservative in its estimation of volume and hence of significance and overdensity. Curvature of the structure can lead to the CHMS volume being substantially larger than if it was linear. If we divide the Huge-LQG into two sections at the point at which the direction appears to change then we have a 'main' set of 56 quasars and a 'branch' set of 17 quasars. If we calculate the CHMS volumes of the main set and the branch set, using the same sphere radius (33 Mpc) as for the full set of 73, and simply add them (neglecting any overlap), then we obtain $\delta_q = \delta\rho_q/\rho_q = 1.12$, using the same correction for residual bias (2 per cent) as for the full set. That is, we have calculated $\delta_q$ using the total membership (73) and the summed volume of the main set and the branch set, and the result is now $\delta_q \sim 1$, rather than $\delta_q = 0.40$, since much of the 'dead space' has been removed from the volume estimate.

We should consider the possibility that the change in direction is indicating that, physically if not algorithmically, we have two distinct structures at the same redshift. So, if we instead treat the main and branch sets as two independent LQG candidates and use their respective sphere radii for the calculation of CHMS volumes, including their respective corrections for residual bias, then we obtain the following parameters. Main set of 56: significance $5.86\sigma$; $\delta_q = 1.20$; characteristic size (CHMS volume$^{1/3}$) 390 Mpc; mean linkage 65.1 Mpc and principal axes of the inertia tensor ∼930, 410, 320 Mpc. Branch set of 17: significance $2.91\sigma$; $\delta_q = 1.54$; characteristic size (CHMS volume$^{1/3}$) 242 Mpc; mean linkage 67.7 Mpc and principal axes of the inertia tensor ∼570, 260, 150 Mpc. The similarity of the mean linkages suggests, after all, a single structure with curvature rather than two distinct structures. (Note for comparison that the CCLQG has mean linkage of 77.5 Mpc.) A two-sided Mann–Whitney test finds no significant differences of the linkages for the main and branch sets, which again suggests a single structure. Note also that the main set by itself exceeds the Yadav et al. (2010) scale of homogeneity.

We can estimate the masses of these main and branch sets from their CHMS volumes by assuming that $\delta_q \equiv \delta_M$, where $\delta_M$ refers to the mass in baryons and dark matter ($\Omega_M = 0.27$). We find that the mass contained within the main set is $\sim 4.8 \times 10^{18}\,M_\odot$ and within the branch set is $\sim 1.3 \times 10^{18}\,M_\odot$. Compared with the expectations for their volumes these values correspond to mass excesses of $\sim 2.6 \times 10^{18}$ and $\sim 0.8 \times 10^{18}\,M_\odot$, respectively. The total mass excess is then $\sim 3.4 \times 10^{18}\,M_\odot$, equivalent to ∼1300 Coma clusters (Kubo et al. 2007), ∼50 Shapley superclusters (Proust et al. 2006) or ∼20 SGW (Sheth & Diaferio 2011).

### 3.1 Corroboration of the Huge-LQG from Mg II absorbers

Some independent corroboration of this large structure is provided by Mg II absorbers. We have used the DR7QSO quasars in a survey for intervening Mg II $\lambda\lambda$2796, 2798 absorbers (Raghunathan et al., in preparation). Using this survey, Fig. 3 shows a kernel-smoothed intensity map (similar to Fig. 1) of the Mg II absorbers across the field of the Huge-LQG and the CCLQG, and for their joint redshift range ($z$: 1.1742 → 1.4232). For this map, only DR7QSO quasars with $z >$ 1.4232 have been used as probes of the Mg II – that is, only quasars beyond the LQGs, and none within them. However, background quasars that are known from the DR7QSO 'catalogue of properties' (Shen et al. 2011) to be broad-absorption line (BAL) quasars have been excluded because structure within the BAL troughs can lead to spurious detections of MgII doublets at similar apparent redshifts. The background quasars have been further restricted to $i \leq 19.1$ for uniformity of coverage. A similar kernel-smoothed intensity map (not shown here) verifies that the distribution of the used background quasars is indeed appropriately uniform across the area of the figure.

The Mg II systems used here have rest-frame equivalent widths for the $\lambda$2796 component of $0.5 \leq W_{r,\,2796} \leq 4.0$ Å. For the resolution and signal-to-noise ratios of the SDSS spectra, this lower limit of $W_{r,\,2796} = 0.5$ Å appears to give consistently reliable detections, although, being 'moderately strong', it is higher than the value of $W_{r,\,2796} = 0.3$ Å that would typically be used with spectra from larger telescopes. Note that apparent Mg II systems occurring shortwards of the Ly$\alpha$ emission in the background quasars are assumed to be spurious and have been excluded.

The RA–Dec. track of the Huge-LQG quasars, along the ∼12° where the surface density is highest, appears to be closely associated with the track of the Mg II absorbers. The association becomes a little weaker in the following ∼5°, following the change in direction

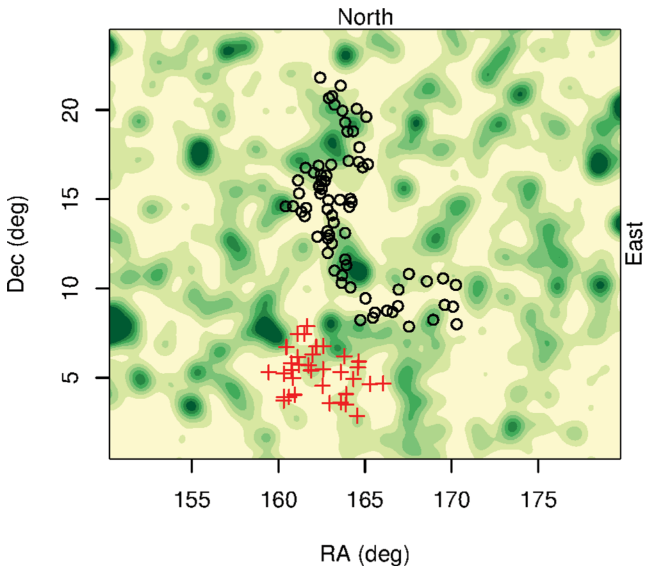


**Figure 3.** Sky distribution of the 73 quasars of the new, Huge-LQG ($\bar{z} = 1.27$, circles). is shown, together with that of the 34 quasars of the CCLQG ($\bar{z} = 1.28$, crosses). The members of each LQG are connected at the linkage scale of 100 Mpc. The area shown is approximately $29\overset{\circ}{.}5 \times 24\overset{\circ}{.}0$. The DR7QSO quasars are limited to $i \leq 19.1$ for the LQG members. Superimposed on these distributions is a kernel-smoothed intensity map (isotropic Gaussian kernel, $\sigma = 0\overset{\circ}{.}5$), plotted with seven linear palette levels ($\leq$0.62, 0.62–1.24, 1.24–1.86, 1.86–2.48, 2.48–3.10, 3.10–3.72, $\geq$3.72 deg$^{-2}$), for all of the Mg II $\lambda\lambda$2796, 2798 absorbers in the joint redshift range of the Huge-LQG and the CCLQG ($z$: 1.1742 $\rightarrow$ 1.4232) that have been found in the DR7QSO background quasars ($z > 1.4232$, non-BAL, and restricted to $i \leq 19.1$) using the Mg II absorber catalogue of Raghunathan (in preparation). The Mg II systems used here have rest-frame equivalent widths for the $\lambda$2796 component of $0.5 \leq W_{r,\,2796} \leq 4.0$ Å. Apparent Mg II systems occurring shortwards of the Ly$\alpha$ emission in the background quasars are assumed to be spurious and have been excluded. No $\cos\delta$ correction has been applied to this intensity map.

from the main set to the branch set, where the surface density of the quasars becomes lower. Note that the quasars tend to follow the periphery of the structure in the Mg II absorbers, which is reminiscent of the finding by Söchting et al. (2002, 2004) that quasars tend to lie on the peripheries of galaxy clusters.

Note that the CCLQG is less clearly detected in Mg II here, although it was detected by Williger et al. (2002). Williger et al. (2002) were able to achieve a lower equivalent-width limit $W_{r,\,2796} = 0.3$ Å with their observations on a 4 m telescope. Furthermore, Fig. 3 shows that the surface density of the Huge-LQG quasars is clearly higher than for the CCLQG quasars, which is presumably a factor in the successful detection of corresponding Mg II absorption. The high surface density of the members of the Huge-LQG seems likely to correspond to a higher probability of lines of sight to the background quasars intersecting the haloes of galaxies at small impact parameters.

## 4 DISCUSSION OF HOMOGENEITY, AND CONCLUSIONS

In Clowes et al. (2012), we presented results for the CCLQG, as it appeared in the SDSS DR7QSO catalogue, and also for U1.11, a newly discovered LQG in the same cosmological neighbourhood. We noticed that their characteristic sizes, defined as (CHMS volume)$^{1/3}$, of ∼350 and 380 Mpc, respectively, were only marginally compatible with the Yadav et al. (2010) 370 Mpc upper limit to the scale of homogeneity for the concordance cosmology. Their long dimensions from the inertia tensor of ∼630 and 780 Mpc are clearly much larger.

In this paper, we have presented results for the Huge-LQG, another newly discovered LQG from the DR7QSO catalogue, that is at essentially the same redshift as the CCLQG, and only a few degrees to the north of it. It has 73 member quasars, compared with 34 and 38 for the CCLQG and U1.11. Mg II absorbers in background quasars provide independent corroboration of this extraordinary LQG. The characteristic size of (CHMS volume)$^{1/3}$ ∼495 Mpc is well in excess of the Yadav et al. (2010) homogeneity scale, and the long dimension from the inertia tensor of ∼1240 Mpc is spectacularly so. It appears to be the largest feature so far seen in the early Universe. Even the 'main' set alone, before the change of direction leading to the 'branch' set, exceeds the homogeneity scale. This Huge-LQG thus challenges the assumption of the cosmological principle. Its excess mass, compared with expectations for its (main + branch) volume, is $\sim 3.4 \times 10^{18}$ M$_{\odot}$, equivalent to ∼1300 Coma clusters, ∼50 Shapley superclusters or ∼20 SGW.

The usual models of the Universe in cosmology, varying only according to the parameter settings, are built on the assumption of the cosmological principle – that is, on the assumption of homogeneity after imagined smoothing on some suitably large scale. In particular, the models depend on the Robertson–Walker metric, which assumes the homogeneity of the mass–energy density. Given the further, sensible assumption that any property of the Universe ultimately depends on the mass–energy content then homogeneity naturally asserts that any global property of sufficiently large volumes should be the same within the expected statistical variations. A recent review of *inhomogeneous* models is given by Buchert (2011).

We adopt the Yadav et al. (2010) fractal calculations as our reference for the upper limit to the scale of homogeneity in the concordance model of cosmology: inhomogeneities should not be detectable above this limit of ∼370 Mpc. The Yadav et al. (2010) calculations have the appealing features that the scale of homogeneity is essentially independent of both the epoch and the tracer used. Note that the scale of ∼370 Mpc is much larger than the scales of ∼100–115 Mpc for homogeneity deduced by Scrimgeour et al. (2012), and, for our purposes, it is therefore appropriately cautious.

The cosmic microwave background (CMB) is usually considered to provide the best evidence for isotropy, and hence of homogeneity too, given the assumption of isotropy about all points. Nevertheless, there do appear to be large-scale features in the CMB that may challenge the reality of homogeneity and isotropy – see Copi et al. (2010) for a recent review. More recently still than this review, Rossmanith et al. (2012) find further indications of a violation of statistical isotropy in the CMB. Furthermore, Yershov, Orlov & Raikov (2012) find that the supernovae in the redshift range 0.5–1.0 are associated with systematic CMB temperature fluctuations, possibly arising from large-scale inhomogeneities. Observationally, for SDSS DR7 galaxies with $0.22 < z < 0.50$, Marinoni, Bel & Buzzi (2012) find that isotropy about all points does indeed apply on scales larger than ∼210 Mpc.

While Scrimgeour et al. (2012) find a transition to homogeneity on scales ∼100–115 Mpc, using WiggleZ data, Sylos Labini (2011) does not, on scales up to ∼200 Mpc, using SDSS galaxies. Large inhomogeneities in the distribution of superclusters (supercluster complexes) such as the SGW and in the voids have also been found on scales ∼200–300 Mpc by Einasto et al. (2011b), Liivamägi, Tempel & Saar (2012), Luparello et al. (2011) and earlier references given within these papers. Evidence for Gpc-scale correlations of galaxies has been presented by, for example, Nabokov & Baryshev (2008), Padmanabhan et al. (2007) and Thomas, Abdalla & Lahav (2011). The occurrence of structure on Gpc-scales from the Huge-LQG and from galaxies implies that the Universe is not homogeneous on these scales. Furthermore, if we accept that homogeneity refers to any property of the Universe then an intriguing result is that of Hutsemékers et al. (2005), who found that the polarization vectors of quasars are correlated on Gpc scales. Similarly, the existence of cosmic flows on approximately Gpc scales (e.g. Kashlinsky et al. 2010), regardless of their cause, is itself implying that the Universe is not homogeneous.

Of course, history and, most recently, the work of Park et al. (2012) indicate that one should certainly be cautious on the question of homogeneity and the cosmological principle. The SGW (Gott et al. 2005) – and before it, the Great Wall (Geller & Huchra 1989) – was seen as a challenge to the standard cosmology and yet Park et al. (2012) show that, in the 'Horizon Run 2' concordance simulation of box-side 10 Gpc, comparable and even larger features can arise, although they are of course rare. Nevertheless, the Huge-LQG presented here is much larger, and it is adjacent to the CCLQG, which is itself very large, so the challenges still persist.

Park et al. (2012) find that void complexes on scales up to $\sim$450 Mpc are also compatible with the concordance cosmology, according to their simulations, although the scales here are greater than the Yadav et al. (2010) scale of homogeneity and much greater than the Scrimgeour et al. (2012) scale. Also, Frith et al. (2003) find evidence for a local void on scales $\sim$430 Mpc. The question of what exactly is a 'void complex' might need further attention. It seems likely to correspond to the 'supervoid' of Einasto et al. (2011a) and earlier references given there.

Hoyle et al. (2012) have investigated homogeneity within the past light-cone, rather than on it, using the fossil record of star formation and find no marked variation on a scale of $\sim$340 Mpc for $0.025 < z < 0.55$

Jackson (2012) finds, from ultracompact radio sources limited to $z > 0.5$, that the Universe is not homogeneous on the largest scales: there is more dark matter in some directions than in others.

The Huge-LQG and the CCLQG separately and together would also indicate that there is more dark matter in some directions than in others. Such mass concentrations could conceivably be associated with the cosmic (dark) flows on the scales of $\sim$100–1000 Mpc as reported by, for example, Kashlinsky et al. (2008), Watkins, Feldman & Hudson (2009), Feldman, Watkins & Hudson (2010) and Kashlinsky et al. (2010). Of particular interest is the possibility raised by Tsagas (2012) that those living within a large-scale cosmic flow could see local acceleration of the expansion within a Universe that is decelerating overall. Tsagas notes that the proximity of the supernova dipole to the CMB dipole could support such an origin for the apparent acceleration that we see. With quasars mostly extinguished by the present epoch, we would probably have some difficulty in recognizing the counterparts today of such LQGs then that might cause such cosmic flows. Very massive structures in the relatively local Universe could conceivably be present, but unrecognized.

In summary, the Huge-LQG presents an interesting potential challenge to the assumption of homogeneity in the cosmological principle. Its proximity to the CCLQG at the same redshift adds to that challenge. Switching attention from galaxies in the relatively local Universe to LQGs at redshifts $z \sim 1$ may well have advantages for such testing since the broad features of the structures can be seen with some clarity, although, of course, the fine details cannot.

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