

Highlights of multi-wavelengths surveys in the Zone of Avoidance

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Abstract. Rather than giving a complete overview on extragalactic Zone of Avoidance (ZOA) research, this paper will highlight some interesting discoveries in the ZOA, such as new near-to far-infrared observations (IRSF, *Spitzer*) of the most massive disk galaxy found to-date (HI-ZOA 0836-43), and deep multi-wavelength observations of a spiral galaxy WKK 6167 undergoing transformation while infalling along the Great Attractor Wall into the Norma cluster – reminiscent of similar incidences observed in only two galaxies at higher redshifts ($z \sim 0.2$; Cortese et al. 2007). While the recent systematic multi-wavelengths approaches to uncover the large-scale structure of galaxies across the ZOA have proven quite successful, in particular in the Great Attractor region, they lack the required depth to answer open questions with regard to our understanding of the dynamics in the Local Universe. The actual mass distribution is poorly understood and does not satisfactorily explain the observed peculiar velocity fields and the CMB dipole. We will present future HI survey strategies to be pursued with the South African SKA Pathfinder MeerKAT in the ZOA, that can – amongst others – resolve the long-standing Great Attractor/Shapley controversy, and determine at which distance range the cumulative peculiar motion of the Local Group flattens off and the Universe becomes homogeneous.

Keywords. Zone of Avoidance, Great Attractor, HI-massive galaxies, galaxies in transformation, current and future HI-surveys,

The dust, stars and gas in the plane of the Milky Way result in a Zone of Avoidance (ZOA) in the extragalactic sky, the size and shape of which depends on the wavelength. An unbiased "whole-sky" map of galaxies is essential, however, for understanding the dynamics in our local Universe, i.e. the peculiar velocity of the Local Group (LG) with respect to the Cosmic Microwave Background (CMB) and velocity flow fields such as in the Great Attractor (GA) region.

Enormous progress has been achieved in the last 20 years in narrowing this ZOA through various systematic observational multi-wavelength surveys — and sometimes serendipitous discoveries. These efforts and subsequent results were reviewed in great detail in Kraan-Korteweg & Lahav (2000) with an update by Kraan-Korteweg in 2005, and will not be repeated. This paper will focus on some particularly interesting objects discovered behind the Milky Way next to future perspectives for ZOA research.

1. A supermassive HI galaxy

The galaxy HIZOA J0836-43 was first discovered in the deep Parkes (64m single dish telescope) MultiBeam (MB) systematic HI-survey of the southern Galactic Plane ($|b| \leq 5^\circ$ (see Kraan-Korteweg 2005, Kraan-Korteweg et al. 2005, for preliminary results). It was also identified in the more shallow HIPASS survey, the systematic all sky HI Parkes

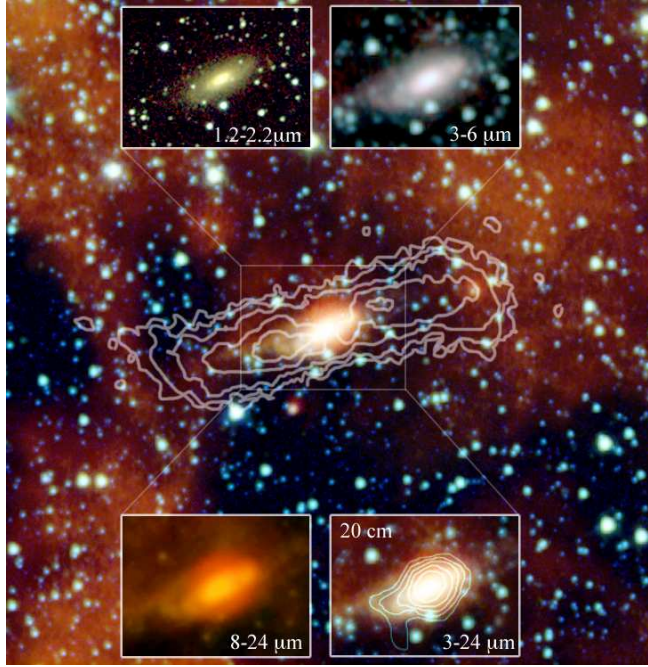


Figure 1. Infrared view of HIZOA J0836-43 through the Vela region of the Milky Way. The main image (FOV $\sim 4'$; ~ 170 kpc) is a composite of the NIR J, H, K , the Spitzer IRAC (3.6, 4.5, 5.8, $8.0 \mu\text{m}$) and MIPS ($24 \mu\text{m}$) bands. The contours reflect the extended HI distribution (levels 0.1, 0.2, 0.4, 0.8, 1.2, and $1.6 \text{ Jy beam}^{-1} \text{ km/s}$; Donley et al. 2006). The insets ($\sim 1'$) display various composite images; the bottom right 3 - $24 \mu\text{m}$ image, related to starformation, also shows the 20cm radio contours. Figure from Cluver et al. (2008).

All Sky (southern) Survey performed with the same instrument (Meyer et al. 2004). It is one of the most HI-rich galaxies ($M_{\text{HI}} = 7.5 \cdot 10^{10} M_{\odot}$). Unlike other giant HI galaxies, (like e.g. Malin 1; Bothun et al. 1987; Pickering et al. 1997) this disk galaxy is not of low surface brightness. According to hierarchical structure formation they are only forming now ($z < 1$; Mo et al. 1998). Such massive spiral galaxies are extremely scarce ($1/3 \cdot 10^7 \text{ Mpc}^3$). At $v = 10700 \text{ km/s}$ ($D = 148 \text{ Mpc}$), HIZOA J0836-43 is the nearest of its kind. However, a detailed analysis is hampered by its location behind the Milky Way: we view it through 10mag of extinction (A_B) and only observations in the near-, mid- and far-infrared will prevail.

New results about this enigmatic galaxy were derived based on deep near infrared (JHK) images (IRSF, SAAO), mid- to far-infrared images and high resolution spectroscopy (IRAC, MIPS and IRS; *Spitzer* Space Telescope). A more detailed analysis of this galaxy based on this new data is given in Cluver et al. 2008. Further results will be detailed in forthcoming papers (Cluver et al. 2009, in prep., UCT PhD thesis, 2009).

Figure 1 presents an infrared view of HIZOA J0836-43. The HI contours (Donley et al. 2006) demonstrate the enormous size of the HI disk, while the galaxy's bolometric luminosity largely arises from infrared radiation, particularly at longer wavelengths. The $1 - 5 \mu\text{m}$ window traces the old stellar population (top panel, Fig. 1) and the galaxy appears as an inclined extended disk galaxy with a prominent bulge population. Its light distribution indicates an early Hubble Type of $\sim \text{S0/Sa}$. The MIR ($\lambda > 5 \mu\text{m}$) is sensitive to the interstellar medium, notably the warm dust continuum and emission from Polycyclic Aromatic Hydrocarbon (PAH) molecules. PAHs produce broad emission bands in the MIR linked to ongoing or recent star formation (Allamandola et al. 1985).

The $8 - 24 \mu\text{m}$ composite shows strong emission from PAH molecules and warm dust.

The 20 cm radio continuum is correlated with the $8 - 24\mu\text{m}$ emission, indicating a common star-formation origin. While the bulk of the infrared emission is concentrated in the central nuclear region, it is clearly extended and exhibits spiral-arm asymmetries.

In summary, the near-infrared properties of the galaxy appear typical for an S0 system, while radio observations suggest recent active star formation. The *Spitzer* observations find HIZOA J0836-43 to be a luminous infrared starburst galaxy with a star formation rate of $21\text{ M}_\odot/\text{yr}$, arising from exceptionally strong molecular PAH emission and far-infrared emission from cold dust. However, high-resolution spectroscopy of the galaxy reveals a weak mid-infrared continuum compared to other starforming galaxies and U/LIRGs.

An accompanying deep near-infrared survey (2.2°) finds this HI-rich galaxy to lie in a slightly enhanced density of fainter galaxies within a (newly identified) filamentary structure encircling a void (Cluver 2009). The conditions appear favourable for the galaxy to have grown this large HI disk, both through accretion of gas due to minor merging, as well as infall of gas along the filament. It also seems consistent with the observation that HI-massive galaxies are preferentially found in low density regions.

2. Mapping the Great Attractor

Following our deep optical galaxy search in the Great Attractor (GA) region, and the recently completed HIZOA 21-cm radio survey which encompassed the GA region, a clear outline was unveiled of a large-scale structure running nearly parallel to the Galactic plane at the distance of the GA. This large supercluster of galaxies, dubbed the Norma wall, has been the subject of a deep near-infrared follow up survey (44°) with the IRSF (JHK_s), in order to gauge its dynamical contribution to the overall galaxy flow in the GA region. At the core of the Norma wall, the rich and massive Norma cluster resides (Kraan-Korteweg et al. 1996, Woudt 1998). A dynamical analysis of this cluster has revealed various (infalling) subgroups (optical and X-ray) and a number of dynamically-peculiar galaxies in this clusters have been identified (Woudt et al. 2008). A particularly interesting one is discussed below.

2.1. A galaxy in transformation in the Norma cluster

Recently, the presence of a 70-kpc long X-ray tail and a 40-kpc $\text{H}\alpha$ tail, respectively, was reported by Sun et al. (2006), Sun et al. (2007), in WKK 6176, a spiral galaxy in the nearby ($cz = 4871 \pm 54\text{ km/s}$) and massive ($M_{R<2\text{ Mpc}} = 1 \times 10^{15}\text{ M}_\odot$) Norma cluster, Woudt et al. (2008). This galaxy is the low-redshift equivalent of the two recently detected spiral galaxies in massive rich clusters (Abell 2667 and Abell 1689) at $z \sim 0.2$ which show clear evidence for strong galaxy transformation, Cortese et al. (2007).

The X-ray tail of WKK 6176 is aligned with the major axis of the galaxy-density profile of the cluster which is indicated by the diagonal line in the right panel of Fig. 2, which itself is aligned with the main large-scale structure of the Norma Wall, Woudt et al. (2008). Fig. 2 shows our deep R_C image of WKK 6176 before and after star-subtraction; it demonstrates the effectiveness of the star-subtraction. Numerous low-luminosity filaments and bright knots (not foreground stars) stand out, giving the galaxy its ‘jelly-fish’ appearance.

Given the proximity of the Norma cluster, WKK 6176 provides an excellent opportunity to study the interaction of a galaxy with the intracluster medium (ICM) at high resolution and sensitivity. Deep BVR_CJHK_s photometry of WKK 6176 (already obtained) will be used to generate pixel-by-pixel colour-magnitude diagrams and colour-colour diagrams

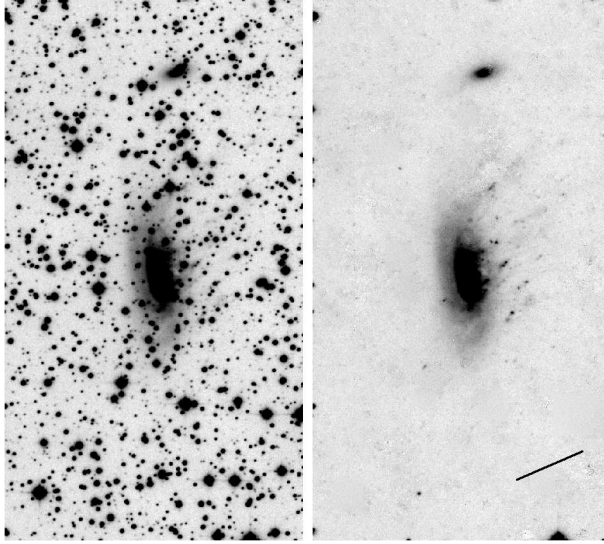


Figure 2. A deep R_C image of WKK 6176 ($2.2' \times 4.0' = 43 \times 77$ kpc). The left image shows the original data, the right image shows WKK 6176 after star subtraction using the KILLALL routine Buta & McCall (1999). Low surface brightness filaments and bright knots are clearly visible.

de Grijs et al. (2003) to study the star formation history of WKK 6176 in combination with GALEV, Bicker et al. (2004).

The GALEV models include an ever growing grid of refined models of undisturbed Sa, Sb, Sc and Sd galaxies falling into a cluster environment at a wide range of redshifts and experiencing various star formation scenarios (e.g., starbursts of varying strengths and time scales). For all those models, the evolution of the galaxies' spectra (ultraviolet, optical and near-infrared) and broad band spectral energy distribution is determined.

WKK 6176 is the nearest galaxy observed in a state of strong transformation through visible interactions with the ICM of a rich and massive cluster. Based on our multiwavelength observations and a comparison with galaxy evolution synthesis models, we aim to constrain the recent star formation history.

3. Future HI-surveys and the Great Attractor/Shapley Controversy

HI-surveys have proven the most effective in tracing (HI-rich) galaxies in areas of extreme star crowding and dust column density. They suffer no significant selection effects. However, even the deepest systematic HI ZOA surveys to date (Parkes MB; e.g. Kraan-Korteweg et al. 2005) remain very shallow, with e.g. a sky density of only less than 1 gal/ $^\circ$ in the GA overdensity. It does not probe deep into the GA Wall (mostly $\gtrsim M_{\text{HI}}^*$ galaxies). Deeper surveys would cause confusion problems due the limited spatial resolution of the Parkes MB ($4' \times 4' \times 26\text{km/s}$). The same holds for HIMF derivations. This low resolution does not permit a differentiation of low mass objects/satellites from neighbouring larger spirals, resulting in an underestimate of the number of low mass galaxies, while overestimating the mass of large galaxies. Covering a larger (or higher) redshift range would suffer such confusion problems even stronger. This is particular relevant in trying to solve the long-standing Great Attractor/Shapley controversy: who is the major attractor in the local Universe? Is the Shapley cluster concentration (SH) at 15000km/s the dominant contributor to the dipole motion of the LG (e.g. Saunders et al. 2000;

Basilakos & Plionis 2006; Kocevski et al. 2005), or does the cumulative velocity level off beyond $v \gtrsim 5000 \text{ km/s}$ (e.g. Erdogdu et al. 2006a,b).

Improved sensitivity is required (~ 2 orders of magnitude), better spatial resolution (at least $0.5 - 1'$), wider instantaneous bandwidth, increased number of channels, and a large FOV for survey speed. These ambitions will be achieved with the SKA Pathfinders. In the following, a survey strategy with MeerKAT, the South African Pathfinder (see <http://www.ska.ac.za>), will be presented to map the GA/Shapley overdensities.

3.1. MeerKAT, the South African SKA Pathfinder

MeerKAT will be constructed near Carnarvon in the Northern Cape (SA). A high speed data transfer network will link the telescope site in the Karoo to a remote operations facility. KAT-7, a 7-dish engineering testbed and science instrument will be commissioned towards the end of 2009. The full array of 80 or more dishes should be ready by 2012. It is anticipated that science projects will be performed at some intermediate stage to test and optimise the running of the telescope. Hence our simulations include calculations not only for a 7 and 80 dish array configuration, but also for 30.

At the time of the meeting (April 2008) the MeerKAT instrument specifications were 80 x 12m dishes, with cooled receivers (30K), single pixel feed, 2 polarisations, 1° beamsize, and a FOV of 0.8° . KAT-7 will have 256KHz instantaneous bandwidths, the full array 512MHz, possibly 1024 MHz. The frequency range will be 1.2-2.0 GHz for KAT-7 and 0.5 – 2.5GHz for MeerKAT (possibly 0.3 – 3GHz). The baseline for KAT-7 will be short (210m), but will extend to 10km for MeerKAT, with a dense core (70% within 700m). It will have 16k channels, allowing for excellent velocity and linewidth resolution.

3.2. Survey assumptions

The minimal survey region in the ZOA that will address both the mass and mass distribution in the GA Wall, as well as the suspected SH-extension across the ZOA — which at low Galactic latitude lies conveniently (or rather more like a conspiracy) exactly behind the GA-Wall — is of the order of 200° ($312^\circ \leq \ell \leq 332^\circ$; $|b| \leq 5^\circ$). This area overlaps with an ongoing deep near-infrared (JHK_s) survey using the IRSF, as well as a smaller areal survey with the *Spitzer* mid-infrared IRAC imager, an international collaboration including Riad (UCT), Jarrett (CalTech), Nagayama (Kyoto) and Wakamatsu (Gifu).

We demand $S/N = 5$ for robust detection, and assume a channel width of 15 km/s . We apply optimal smoothing to the number counts, i.e. binning over the line width to optimise the signal-to-noise. The scientific assumptions are based on an HI mass function (HIMF) as determined in Zwaan et al. (2005) derived from the systematic HI survey HIPASS ($N = 4315$; Meyer et al. 2004). Their HIMF was fitted with a Schechter function. The resulting parameters are $\alpha = -1.37$ for the faint end slope, $\log(M_{\text{HI}}^*) = 9.80 M_\odot$ for the characteristic HI mass, and $\Omega^* = 6.0 \cdot 10^{-3} \text{ Mpc}^{-3} \text{ dex}^{-1}$ for the volume density. Their results are in good agreement with the HIPASS Bright Galaxy Catalogue, a complete but smaller, sub-sample of galaxies (Zwaan et al. 2003). We adopt the same cosmological parameters of $H_0 = 75 \text{ Mpc/km/s}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

Interestingly, they find tentative evidence for environmental effects: the HIMF becomes steeper towards higher density regions and lower in lowest density environments ($\alpha = -1.5, -1.2$ respectively). Considering that we are regarding high density areas, we adopt this steeper slope ($\alpha = -1.5$) for the redshift range of the GA and SH regions, i.e. $3500 < v < 6500 \text{ km/s}$ and $13500 < v < 18000 \text{ km/s}$. We furthermore adopt an overdensity of $\rho / < \rho > = 3$ and 9 for the GA and SH distance intervals. The first value is close to observational data for that area, while the latter is a minimal assumption, given that some papers (e.g. Kocevski et al. 2005) seem to indicate that the SH region, at 3 time

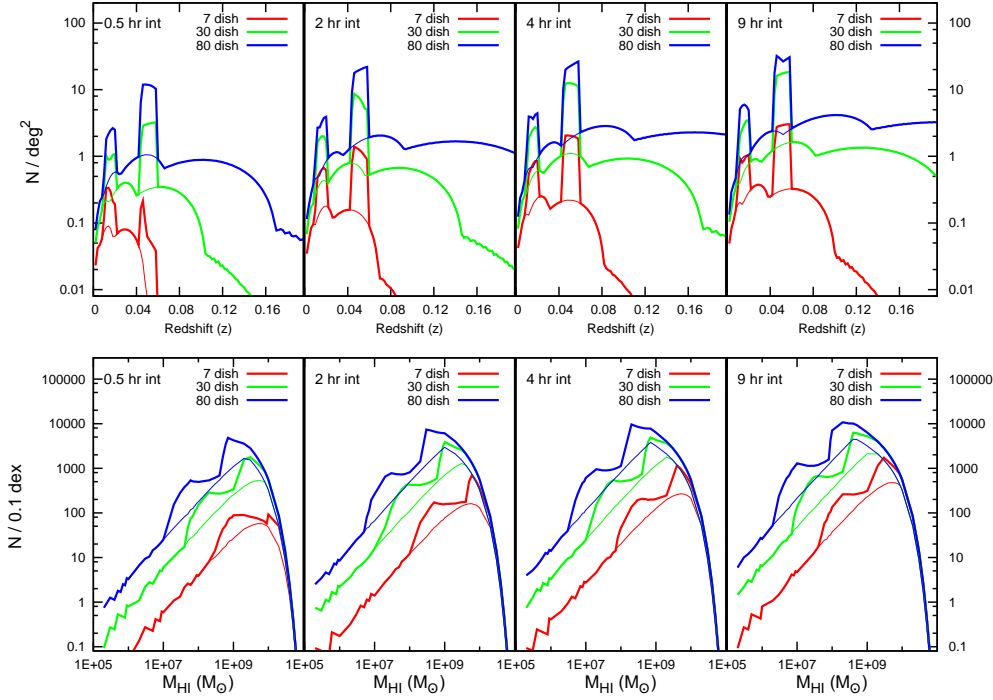


Figure 3. Various MeerKAT survey scenarios assuming overdensities of 3 and 9 in the GA and SH region respectively. The figure displays projected sky density versus redshift (top panel) and log HI-mass versus redshift (bottom panel) for integration times of 0.5, 2, 4, and 9hrs.

the distance of the GA, is exerting the same gravitational attraction on the LG as the GA overdensity.

3.3. The simulations

Results based on these simulations are illustrated through a variety of plots in Fig. 3 and some characteristic parameters in Table 1. The top panel of Fig. 3 displays detections as number N/\square° for increasing redshift z in intervals of $\Delta z = 0.002$ (corresponding to $\Delta v = 600 \text{ km/s}$) for integration times of 0.5, 2, 4, and 9 hours for the different KAT phases (7, 30 and 80 dishes). The bottom panel shows the HI mass distribution, where the numbers N are given in steps of $0.1 \text{ dex log}(M_{\text{HI}})$. The interpretation of these plots should be made in conjunction with Table 1, which lists the duration of the survey given the assumed integration times per pointing for the several KAT versions, resulting number density N/\square° as well as the HI-mass limit (in log) for the GA and SH overdensities.

It is reassuring to note that the prediction based on the simulation for the GA region of the 30-dish configuration with a 0.5hr integration is in close agreement with observational results from the Parkes ZOA HI survey of that same area, namely $0.8/\square^\circ$ for the 25 min integrations of HIZOA, and a system temperature ($\sim 30 \text{ K}$) and aperture that closely correspond to the KAT-30 instrument specifications.

3.4. Conclusions

It is notable that all simulations predict a signal of these overdensities to be quite prominent in the distribution. Despite these clear peaks in the distributions, it is evident that KAT-7 is not a suitable option to take this project a step further. The resulting detec-

# Dishes	Int / pointing	Duration (for 200 deg ²)	GA	GA Mass Limit	SH	SH Mass limit
	(hrs)	(Days)	(#/deg ²)	Log(M _{sun})	(#/deg ²)	Log(M _{sun})
7	9	188	5.0	8.2	14.9	9.4
7	8	166	4.6	8.2	14.2	9.4
7	7	145	4.4	8.3	13.4	9.5
7	6	125	4.2	8.3	12.4	9.5
30	9	188	15.4	7.5	89.4	8.6
30	4	83	12.6	7.7	60.0	8.8
30	2	42	9.5	7.8	31.1	9.0
30	1	21	6.9	8.0	19.7	9.2
80	4	83	21.2	7.1	121.8	8.3
80	2	42	17.3	7.3	104.0	8.5
80	1	21	14.7	7.5	82.3	8.7
80	0.5	10	12.2	7.7	56.3	8.8

Table 1. Integration times per pointing for various KAT operation phases for various observing periods (in days) to attain reasonable number density and HI mass limits for both the GA and Shapley distance range.

tion rate will remain quite low even for the longest regarded integration time of 9 hrs (requiring half a year of observing time): only a few dozen high-mass galaxies in the SH region - although their detection would immediately indicate an overdensity (compare thick to thin line in Fig. 3), and at most a few more low mass galaxies in the GA region.

However, the 30-dish configuration will allow already quite significant results with, e.g., the 2hr integration time (requiring a total survey period of 42 days). Such a survey will trace galaxies into the dwarf regime ($7.8 \log M_{\odot}$) in the GA region with a good number density (though not too dense to run into confusion problems), and will satisfactorily trace galaxies in the SH region close to one order of magnitude below the characteristic HI-mass of $9.8 \log M_{\odot}$. The number densities are $\sim 31/\square^{\circ}$ - “if” the SH overdensity extends across the Galactic Plane and connects to the massive X-ray clusters Triangulum Australis cluster and CIZA J1652 at $b \sim -10^{\circ}$. These clusters, together with CIZA J1514 and CIZA J1518 above the plane ($b \sim +10^{\circ}$), give rise to a large fraction of the steep dipole increase at around the SH cluster concentration distance located at slightly higher latitudes (see Kocevski et al. 2005; Fig. 3). The full MeerKAT operations allow such a survey in only 10 days of half hour integration.

We can maintain that KAT-30 would be the ideal interim phase to conclusively resolve the GA/SH controversy for the first time while the full MeerKAT configuration the ideal survey instrument to extend this pilot GA/SH survey to the whole southern ZOA. The latter would require 90 days. An extension to higher latitudes around the Galactic Bulge would also be recommended, as mapping of extragalactic large-scale structures is limited there, even at medium extinction levels (Kraan-Korteweg et al. 2008).

Apart from being an ideal probe to track the large-scale structures of the mass distribution in the GA and SH regions, the proposed 2hr integration, 30-dish MeerKAT survey would provide a deeper insight into the HIMF, particularly with regard to the low mass end, which is still ill-constrained. Moreover, it will allow further insight into environmental effects, as we will probing high density areas that form part of the both GA/SH

overdensity, wall-like features that seem to connect these mass densities across the ZOA, as well as the substantially underdense spaces (voids) inbetween the GA overdensity and the suspected Shapley Wall (see e.g. Woudt et al. 2008).

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