A WISE Take on the Mid-IR Properties of Void and Wall Galaxies

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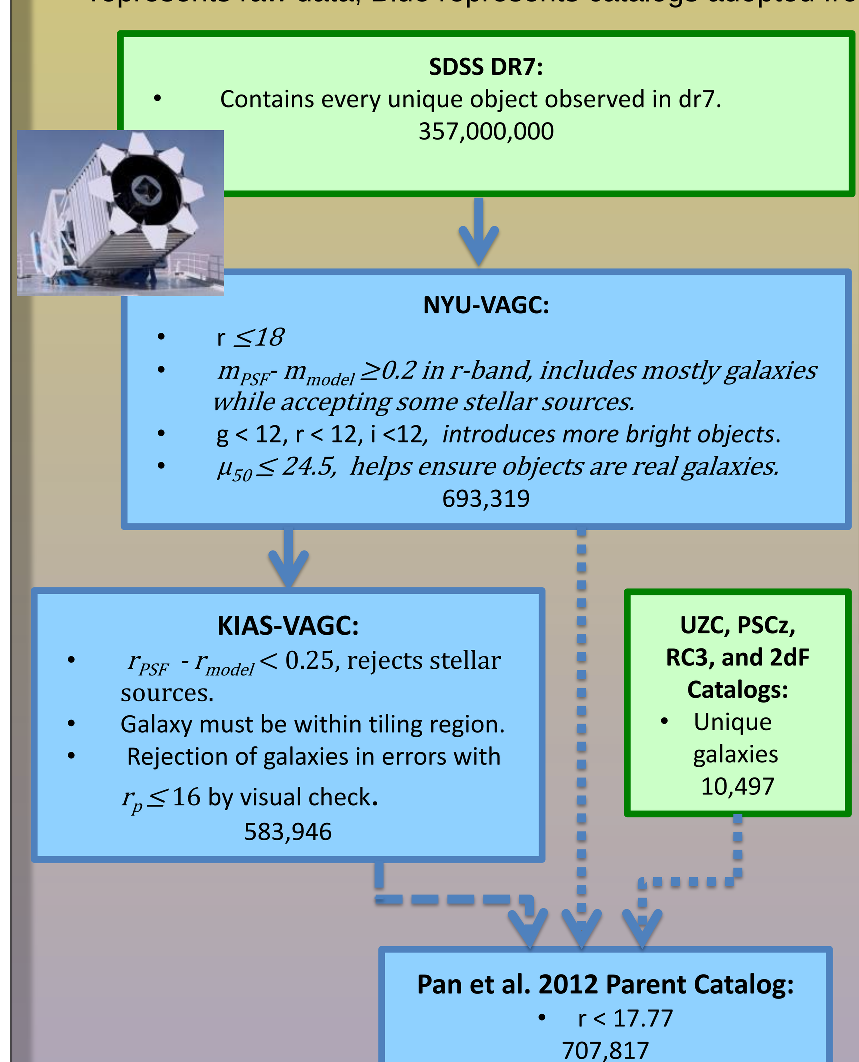
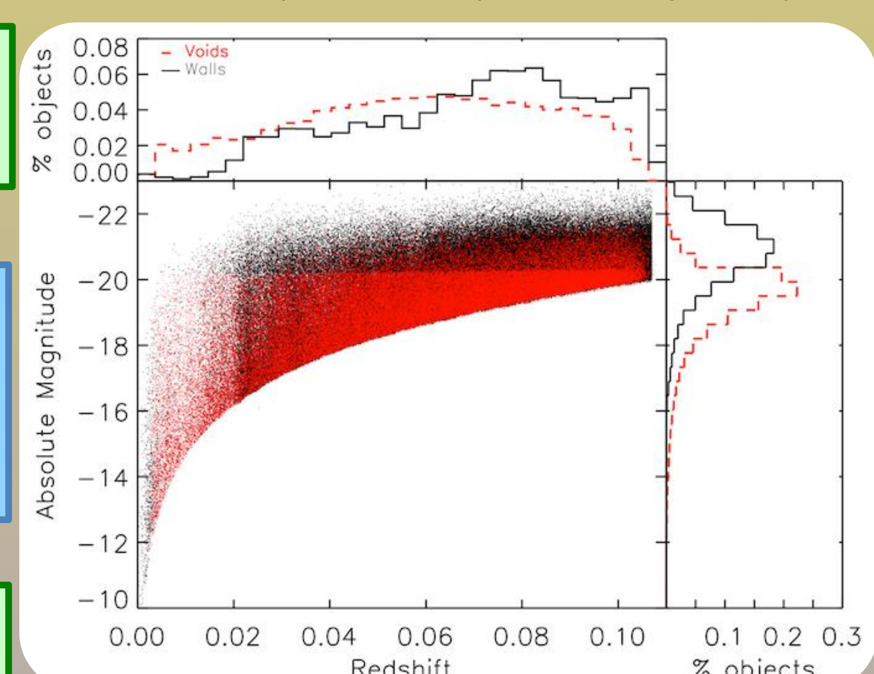
Abstract

Voids are the most underdense regions of the universe, and while they account for roughly half of the universe's volume, they contain only a tenth of all galaxies. In the standard cosmological paradigm, the void and their counterparts in regions of normal densities (a.k.a, walls, comprising wall galaxies) are expected to follow different evolutionary paths, as disturbing processes via galaxy interactions are expected to play a significantly lesser role within the voids. Most importantly, it is of interest to investigate the relationship between the general galaxy properties and those of the energetics of their centers, which, in the nearby universe proves difficult to disentangle between star-formation and active accretion of matter onto supermassive black hole (SMBHs; millions to billions more massive than the Sun) that is usually identified as active galactic nuclei (AGNs). Observations in visible wavelengths cannot provide a complete census of AGNs in galaxy samples due to obscuration of the central source or contamination of the observed emission by the host galaxy, however, infrared observations can uncover them because hot dust surrounding AGNs produces a strong mid infrared continuum and infrared spectral energy distribution that clearly distinguish these sources from star forming galaxies. By employing public data from the all-sky survey carried out by the Wide-field Infrared Survey Explorer (WISE), and the most extensive current catalogs of voids and void galaxies, we conduct an exhaustive comparative analysis of the void and wall systems in mid-infrared, with the goal of quantifying the fraction of AGN systems and their most extreme environmental dependence, in conjunction with the role of dust played in their mid-IR color distributions as well as their optical spectral properties derived based on high quality Sloan Digital Sky Survey (SDSS) data.

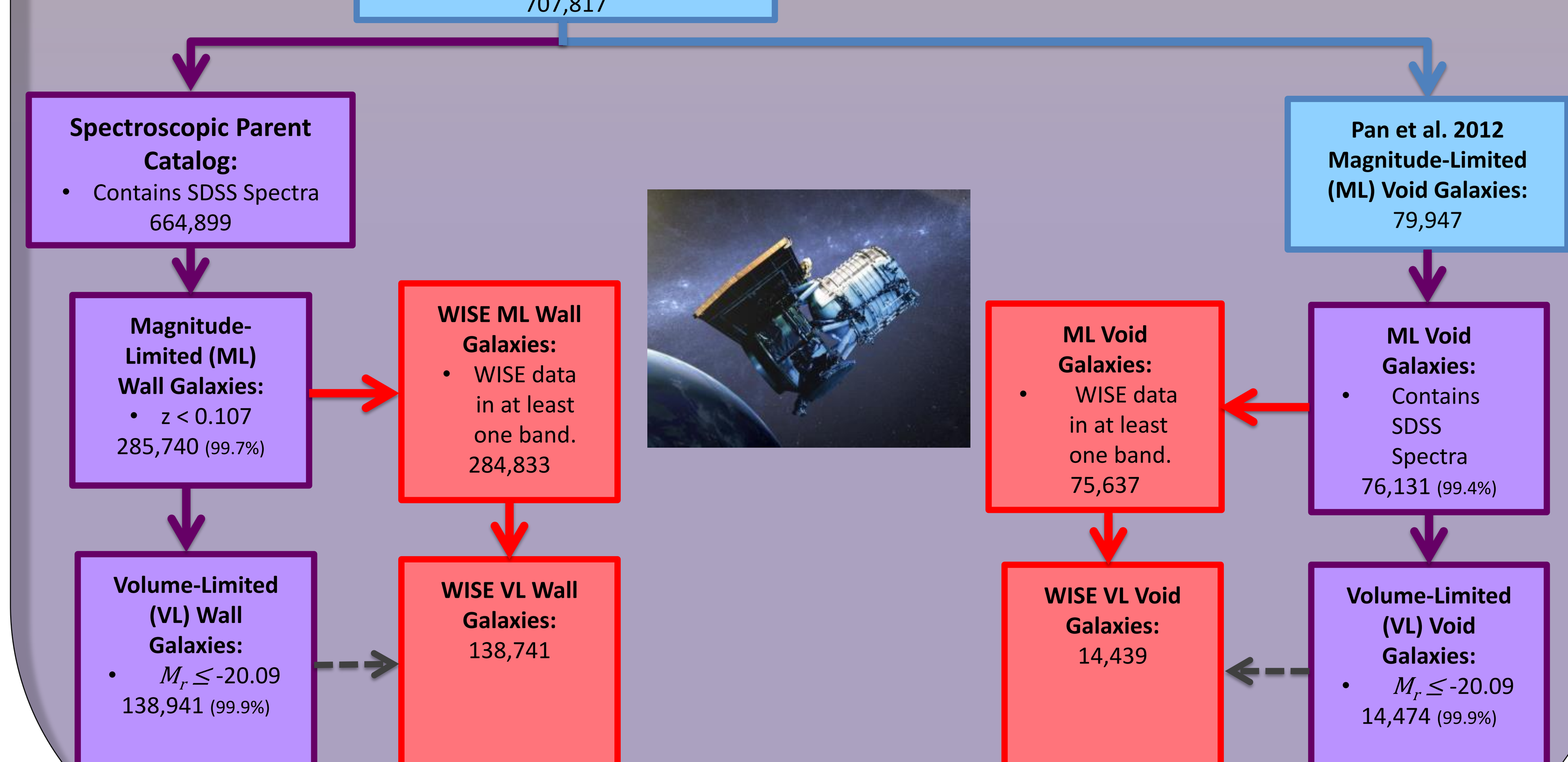
The Void and Wall Samples: Optical (SDSS) and Mid-IR (WISE) Data

Pan et al. 2012 is the largest public catalog of void galaxies to date. Using the VoidFinder algorithm created by El-Ad & Piran (1997) and first put into use by Hoyle & Vogeley (2002), Pan et al. find 1054 voids and nearly 80,000 void galaxies. These void galaxies are extracted from a complete and well studied sample of galaxies put together by the Korean Institute for Advanced Study (KIAS; **Choi** et al. 2010).
Wide-Field Infrared Survey Explorer (WISE) is a space-based telescope that surveyed the entire sky in 4 mid-IR wavebands. This survey aided in discovering optically hidden AGN by picking up the strong mid-IR continuum and mapping a spectral energy distribution that can be differentiated from star-forming and other non-active galaxies. The results of our cross-matching the Pan et al. void galaxy catalogs, as well as the complementary non-void (wall) systems with WISE/Infrared Processing and Analysis Center (IPAC) database, are illustrated in the flow chart below. The Green represents raw data, Blue represents catalogs adopted from the literature, Purple and Red represent catalogs built by us.

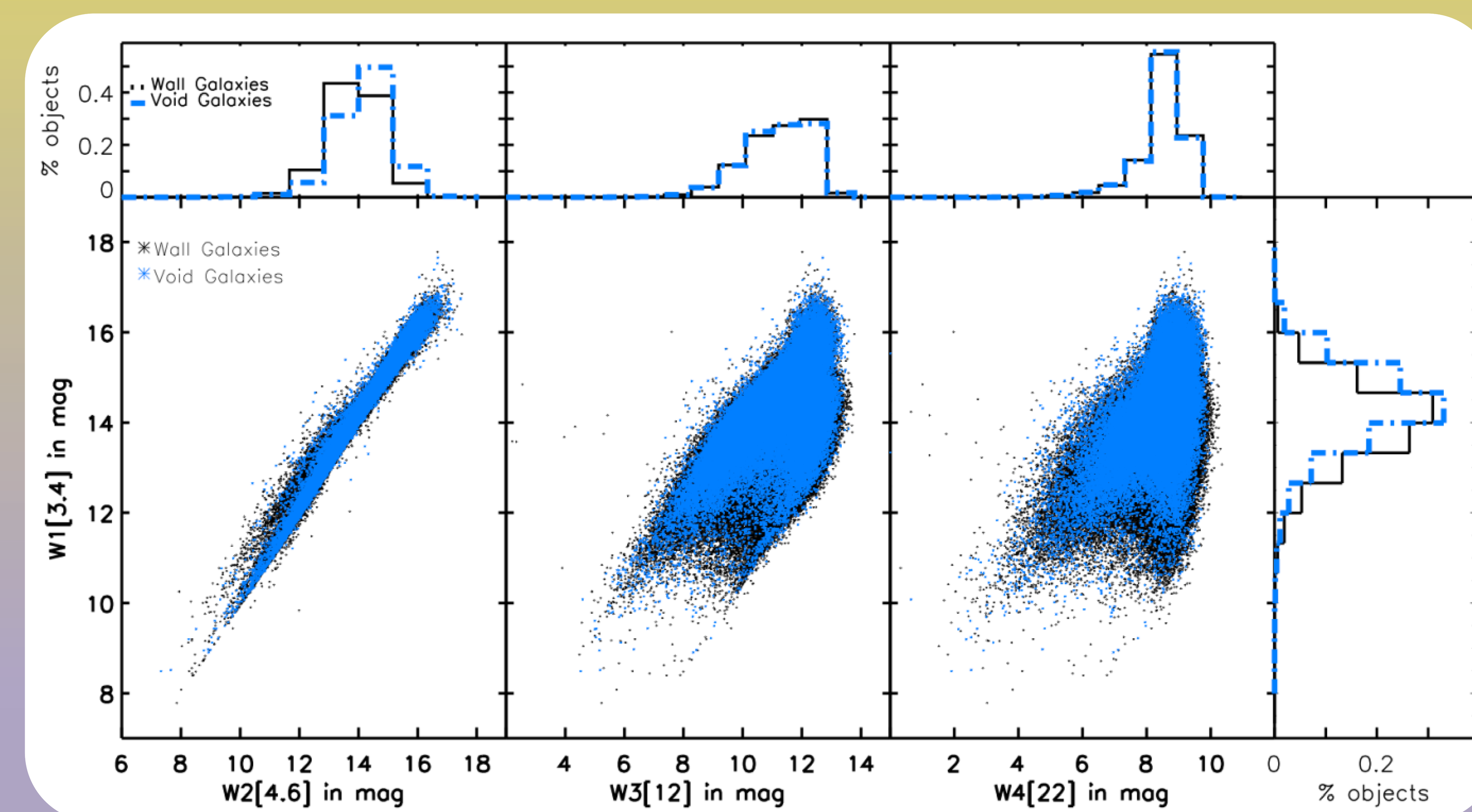




The above plot is graphing the absolute magnitude of void galaxies versus their redshift. The distinct curve is the result of the apparent magnitude of a galaxy following an inverse square law with respect to distance (redshift). The red is the volume-limited sample, which is a subset of the larger, but more biased, magnitude-limited sample in black. This bias skews the distribution to show a higher proportion of intrinsically bright objects as redshift increases.

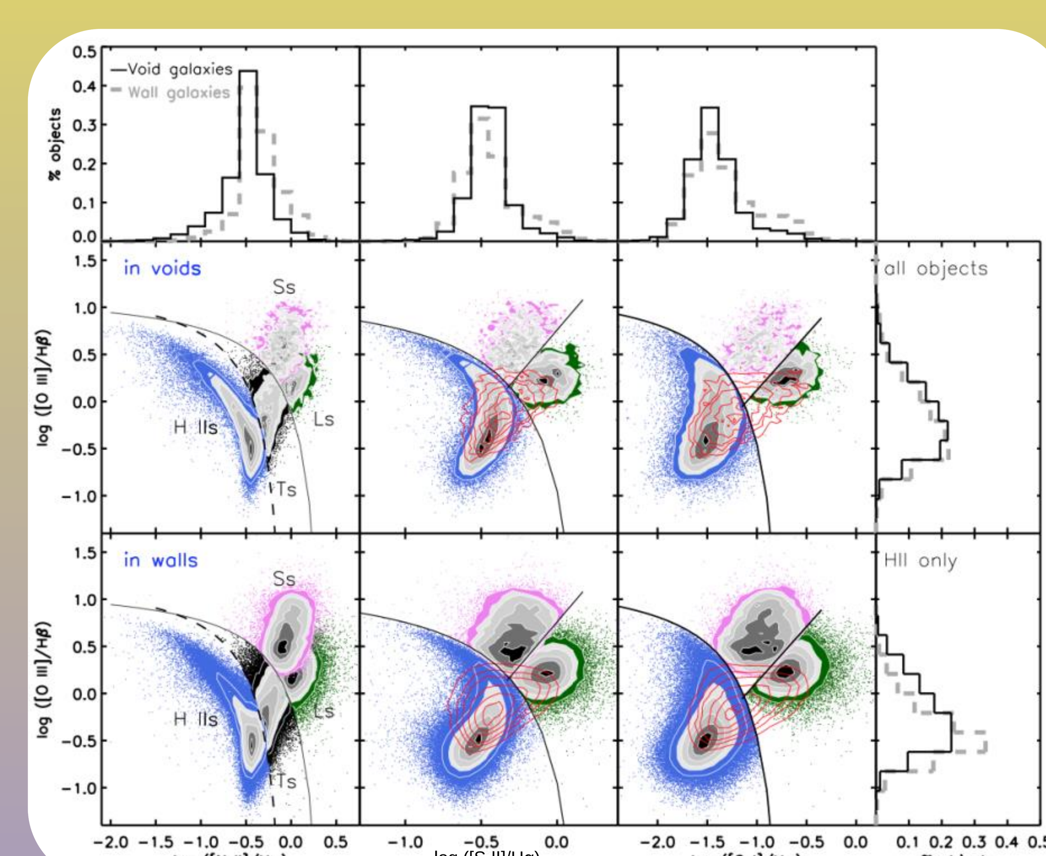


WISE Waveband Magnitude Comparison Between Magnitude-Limited Void and Wall



The comparison between WISE magnitudes allows us to determine some of the differences in properties between void and walls galaxies in the mid-IR. The plot shows that the void galaxies are fainter in both W1 (3.4μm) and W2 (4.6μm) emission, while there is no immediate difference that is apparent in the other two WISE bands.

Optical Spectral Signature for Nuclear Activity in Void and Wall Galaxies:



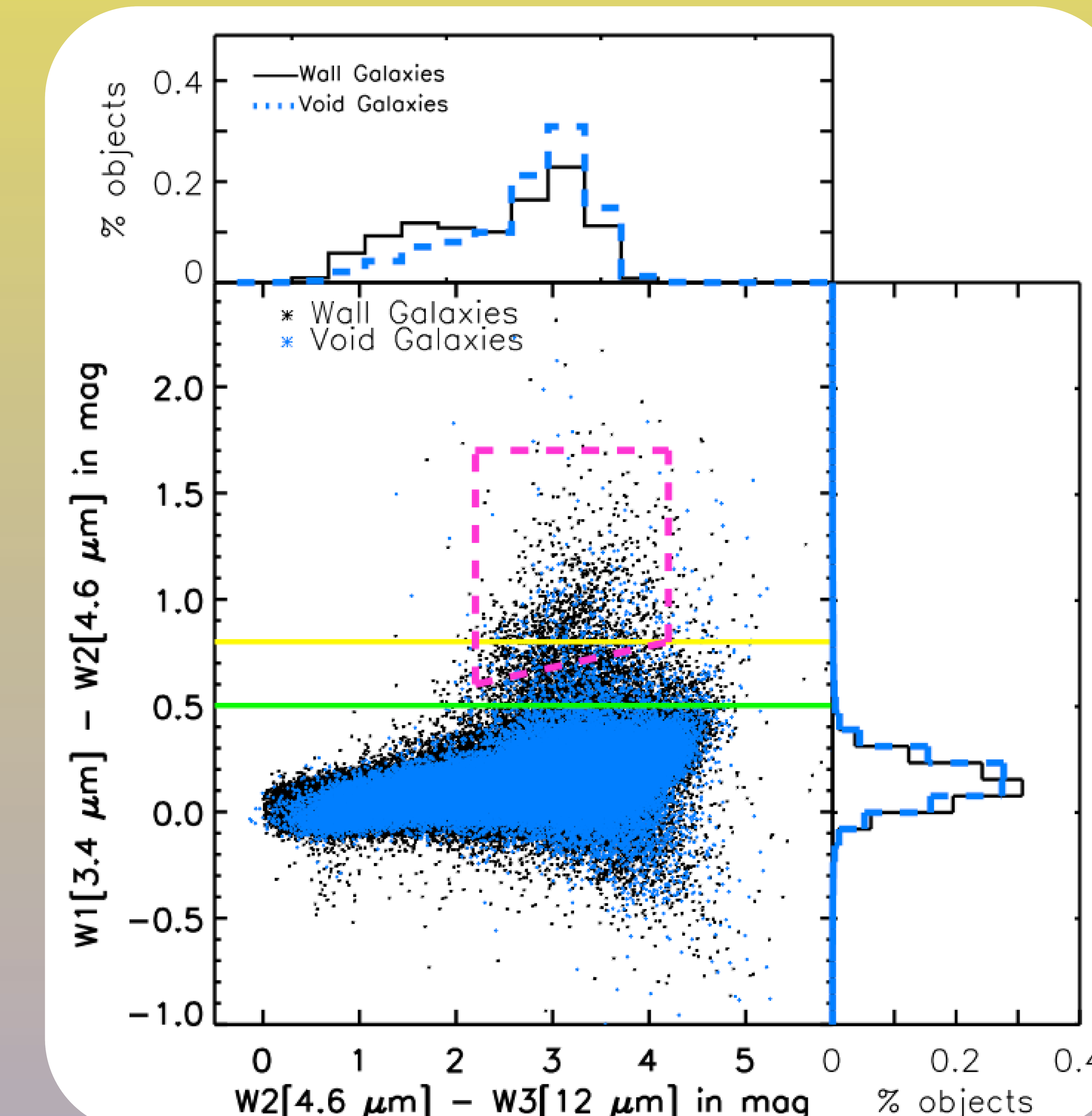
The optical line emission diagrams (shown here separately for all void and wall galaxies with line fluxes measured with a least 2-sigma confidence) offer the possibility to identify and separate among various ionization and excitation mechanisms in galaxy centers: Seyferts and Low Ionization Nuclear Emission Regions (LINERs) occupy the right branch, as they exhibit relatively strong forbidden features, while the Star-forming Galaxies (with most of the Hydrogen ionized, i.e., also called H II galaxies) show relatively weak emission in both high and low ionization lines, occupying the locus under the curves. The distinction between Seyferts and LINERs is usually given by their ionization level, which is easily gauged by the [O III]/Halpha ratio, with Seyferts showing larger values. The Transition systems straddle the borders between the Seyferts and LINERs and that of the H IIs.

We have employed spectral measurements for the SDSS DR7 Main Galaxy Sample made publicly available at http://www.mpa-garching.mpg.de/SDSS/ (Brinchmann et al. 2004).

All object types are shown in density contours corresponding to factors of n of the total number of objects in each class, where n = 0.1, 0.2, 0.3, 0.5, 0.7, and 0.9 starting from the outermost contour. However if object density <0.1, the individual points are plotted. The solid and dashed black curves illustrate the Kewley et al. (2001) and Kauffmann et al. (2003c) separation lines and the blue diagonal lines illustrate the separation between Seyferts and LINERs by Kewley et al. (2006).

While the void and wall galaxies don't necessarily differ in their distributions of the line ratios, the overall incidence of each type varies significantly between void and wall regions: strong line-emission activity is clearly more common in voids than in walls, and the difference seems to be accounted for by the difference in the rate of occurrence of H II type emission.

WISE COLOR-COLOR Diagram with Three Previously Proposed AGN Selection Criteria



The WISE w1-w2 vs. w2-w3 color for the void and wall galaxies reveals that the void galaxies are bluer than their wall counterparts.
Nevertheless, a comparison of the WISE-based AGN fraction reveals very similar percentages in the AGN activity, regardless of the how stringent or lenient are the (three previously) proposed color cuts for mid-IR AGN selection (w1-w2 > 0.8, Jarett et al. 2010, yellow line; Jarett et al. 2011, magenta line; w1-w2 > 0.5, blue line)

Type of Sample	Type of Galaxy	W1-W2 > 0.5	Jarrett et al. 2011	W1-W2 > 0.8	Total Galaxies in Sample
Volume-Limited	Wall Galaxies	2,033 (1.47%)	875 (0.63%)	564 (0.41%)	138,741
	Void Galaxies	255 (1.77%)	93 (0.64%)	74 (0.51%)	14,439
Magnitude-Limited	Wall Galaxies	3,162 (1.11%)	1,276 (0.45%)	900 (0.32%)	284,833
	Void Galaxies	812 (1.07%)	255 (0.34%)	224 (0.30%)	75,637

Path from Here

1. compare the WISE and Optical AGN selection as a function of a variety of host galaxy properties, and in particular as a function of stellar mass and absolute (r-band) brightness, to test at the most extreme environments previously found trends for increasing WISE AGN at lower stellar masses (Satyapal et al. 2014), in striking contrast with findings of optical studies (e.g., Kauffman et al. 2004)
2. compare the mean oxygen abundances of the WISE AGN candidates in void and wall galaxies suing the various color cuts employed in this work, as a function of host galaxy mass and absolute brightness, in order to assess or dismiss the possibility that the red colors might originate from hard radiation fields produced by extreme star formation in low-metallicity environments (e.g., Campbell et al. 1986).
3. gather public multi-wavelength data (i.e., radio and X-ray) for void and wall counterparts, in an attempt to build high resolution spectral energy densities that should shed unprecedented light onto the possibly diverging nature of nuclear energetics in the extremely underdense regions of the universe.

References: **Blanton** et al. 2005; **Campbell**, A., Terlevich, R., & Melnick, J. 1986, MNRAS, 223, 811; **Choi** et al. 2010; **Jarrett** et al. 2011; **Kauffmann**, G., Heckman, T. M., Tremonti, C., et al. 2003, MNRAS, 346, 1055; **Pan** et al. 2012; **Satyapal** et al. 2014; **Satyapal**, S., Secrest, N. J., McAlpine, W., Ellison, S. L., Fischer, J., & Rosenberg, J. L., 2014, ApJ, 784, 113. **Wright** et al. 2010.

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