Structure and Contents of Cosmic Voids

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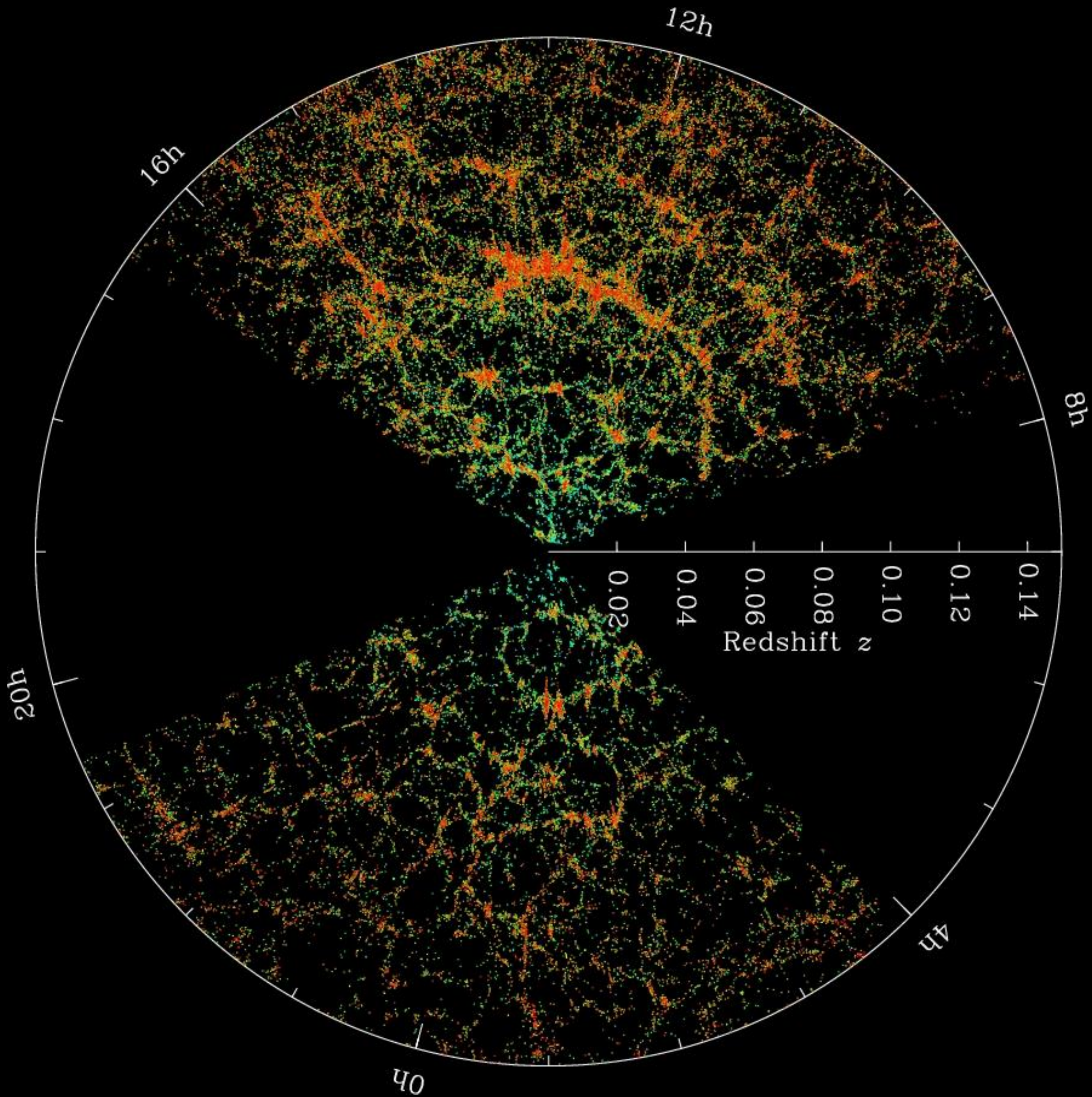
12h
16h
8h
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Redshift z

Building the Laboratory: Finding Voids in Galaxy Redshift Surveys

Hoyle & Vogeley 2002, ApJ 566, 641 (CfA, PSCz)

Hoyle & Vogeley 2004, ApJ 607, 751 (2dFGRS)

Pan, Vogeley, Hoyle, Choi, & Park 2010 (SDSS DR7)

The Void Finder Algorithm

Goal: identify large voids that are *dynamically distinct elements of large-scale structure* = “bucket-shaped” voids with flat density profiles and sharp edges, $\delta\rho/\rho<-0.8$

Procedure:

- Initial classification of galaxies as wall/void galaxies
- Detection of empty cells
- Growth of maximal spheres
- Unification of overlapping voids
- Calculation of void underdensity, profile

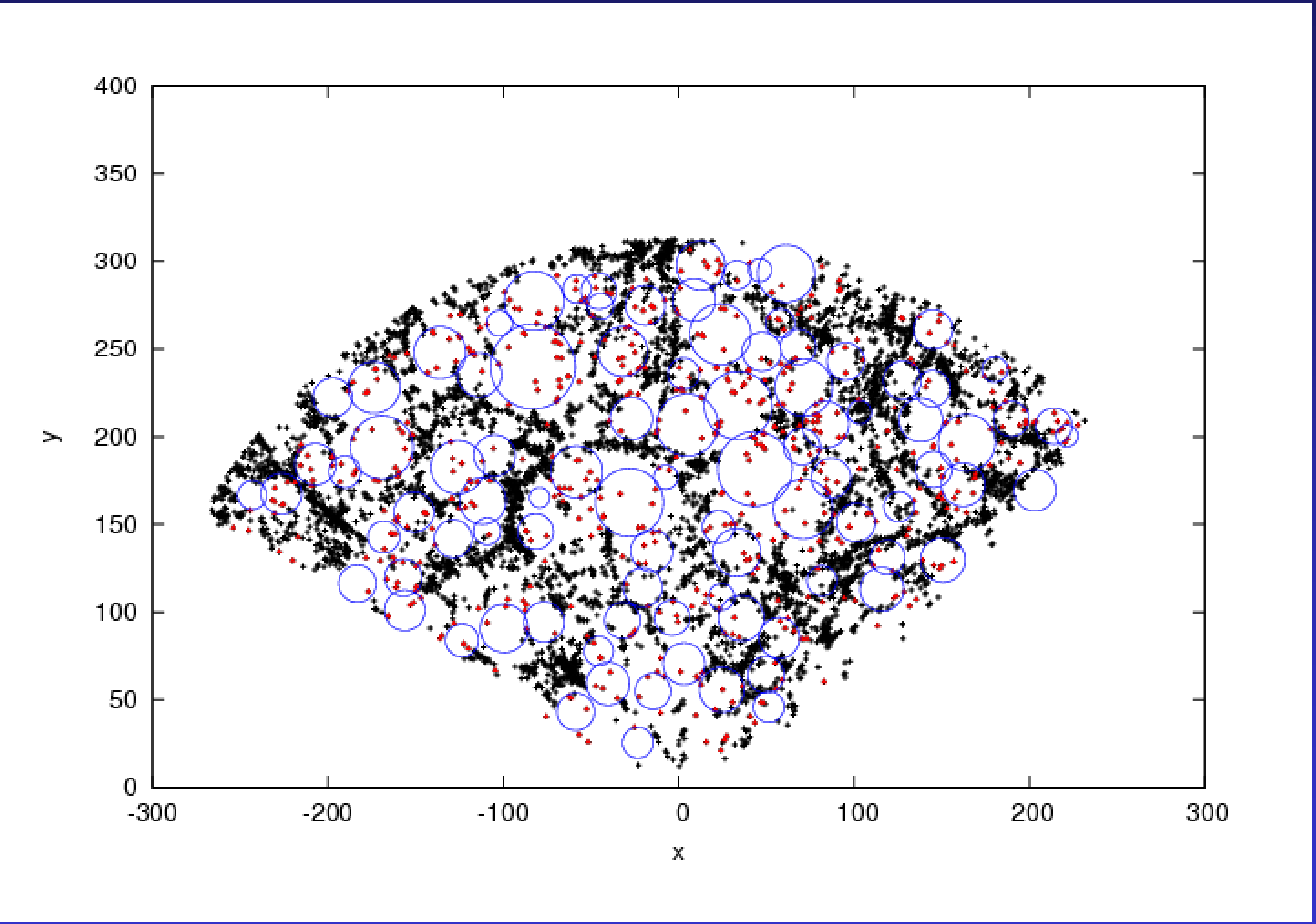
Hoyle & Vogeley 2002, ApJ, 566, 641

Initial Classification of Void vs. Wall Galaxies

If $d_3>7h^{-1}$ Mpc, then $\delta\rho/\rho<-0.6$

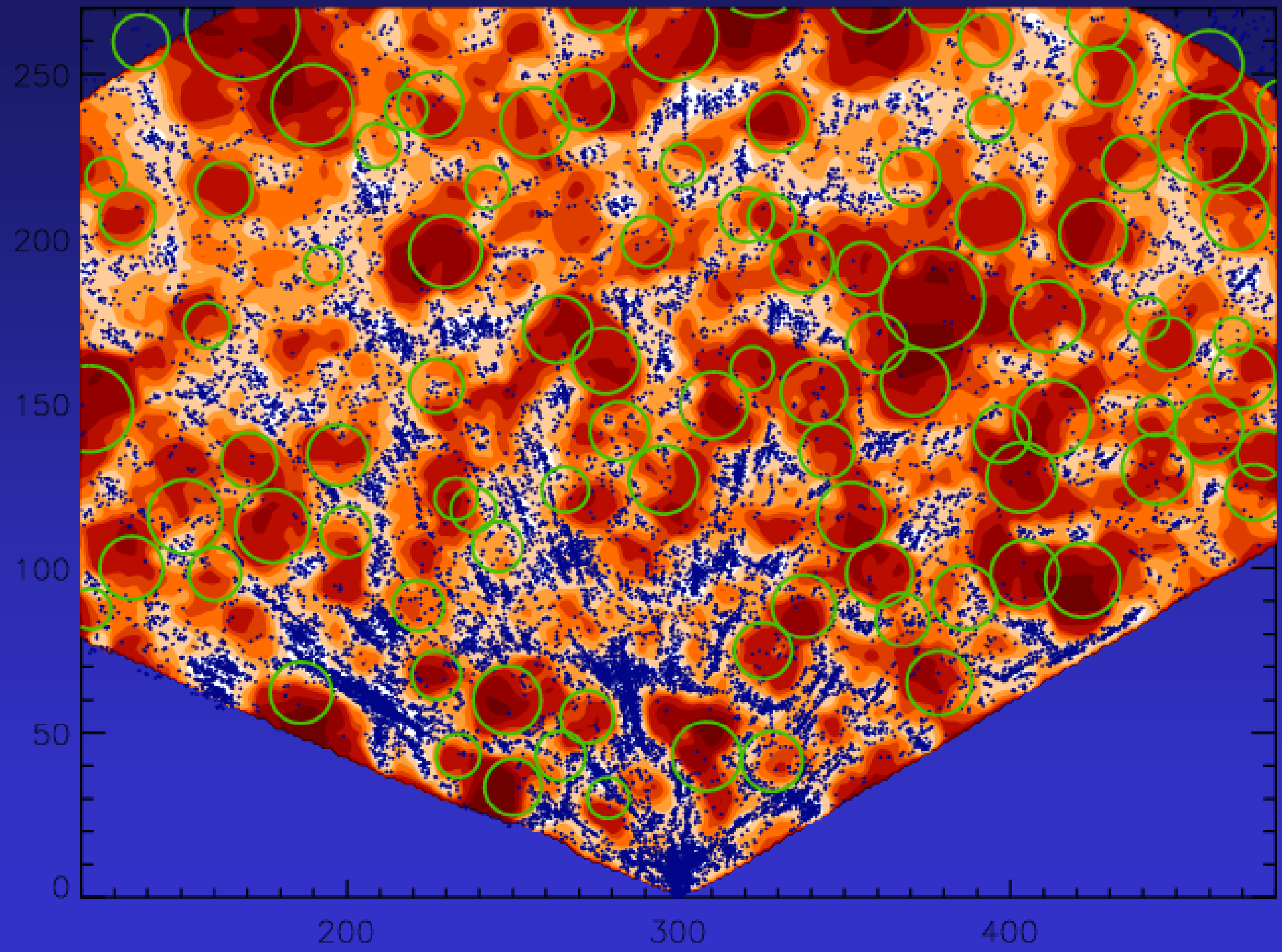
Then grow maximal spheres bounded by wall galaxies

Voids in DR7: intersection with 10 h^{-1} Mpc Slice



Pan, Vogeley, Hoyle, Choi, & Park 2010

Voids in DR7 and Smoothed Galaxy Density



Pan, Vogeley, Hoyle, Choi, & Park, & 2010

Voids in SDSS DR7

Parent galaxy sample:

r<17.77, z<0.107, area = 8000 sq deg, 708,788 galaxies (after boundary cuts)

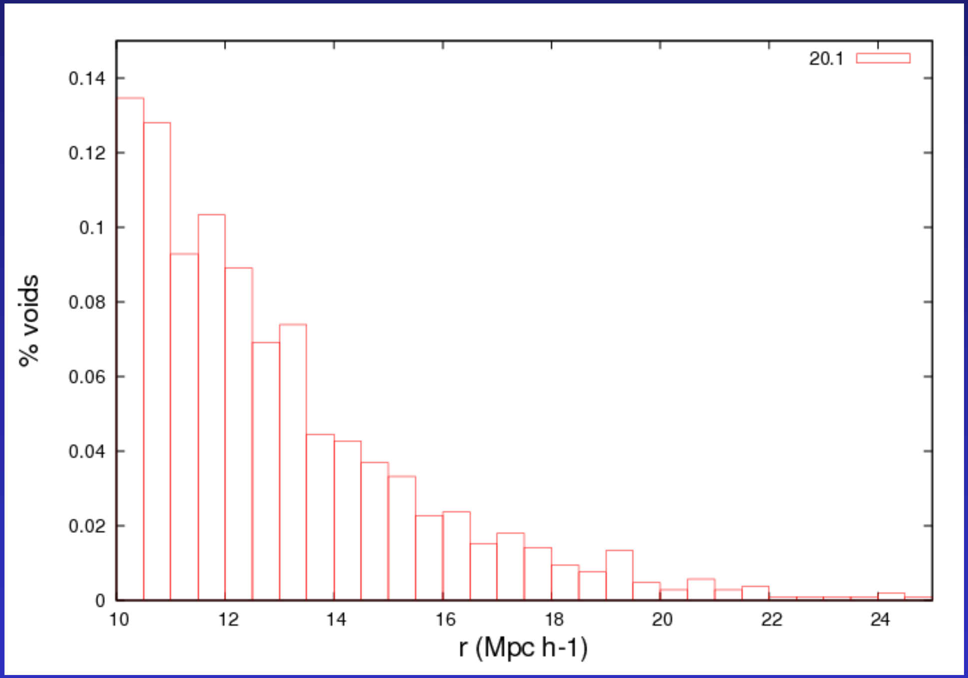
Volume-limited sample:

density field from 120,606 galaxies, M<-20.1

Results of voidfinder:

1054 voids R>10 Mpc/h

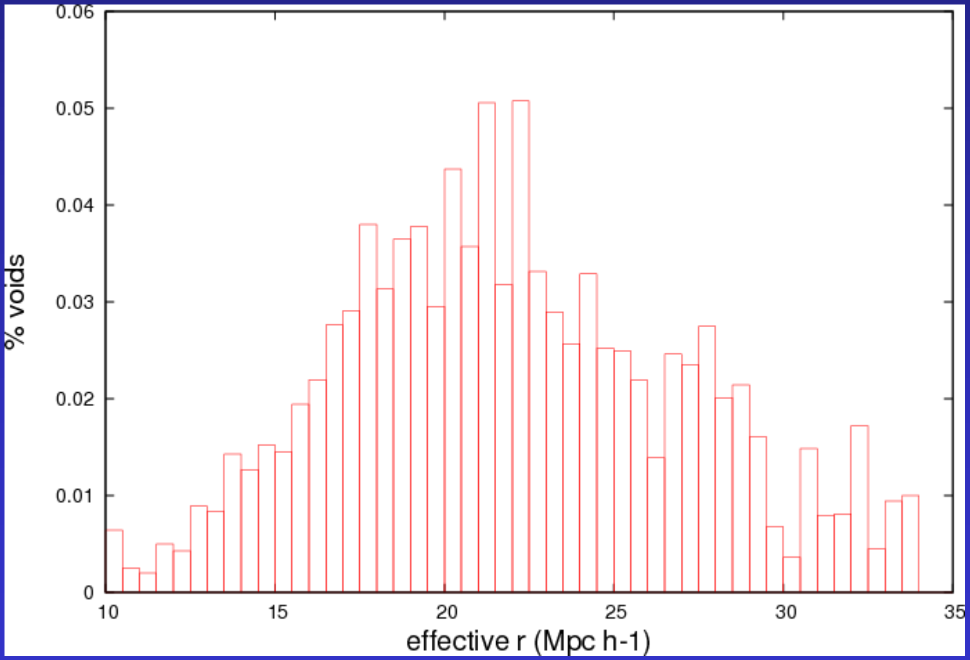
79,947 void galaxies r<17.77 (10% of galaxies are in voids)



Pan, Vogeley, Hoyle, Choi, & Park 2010

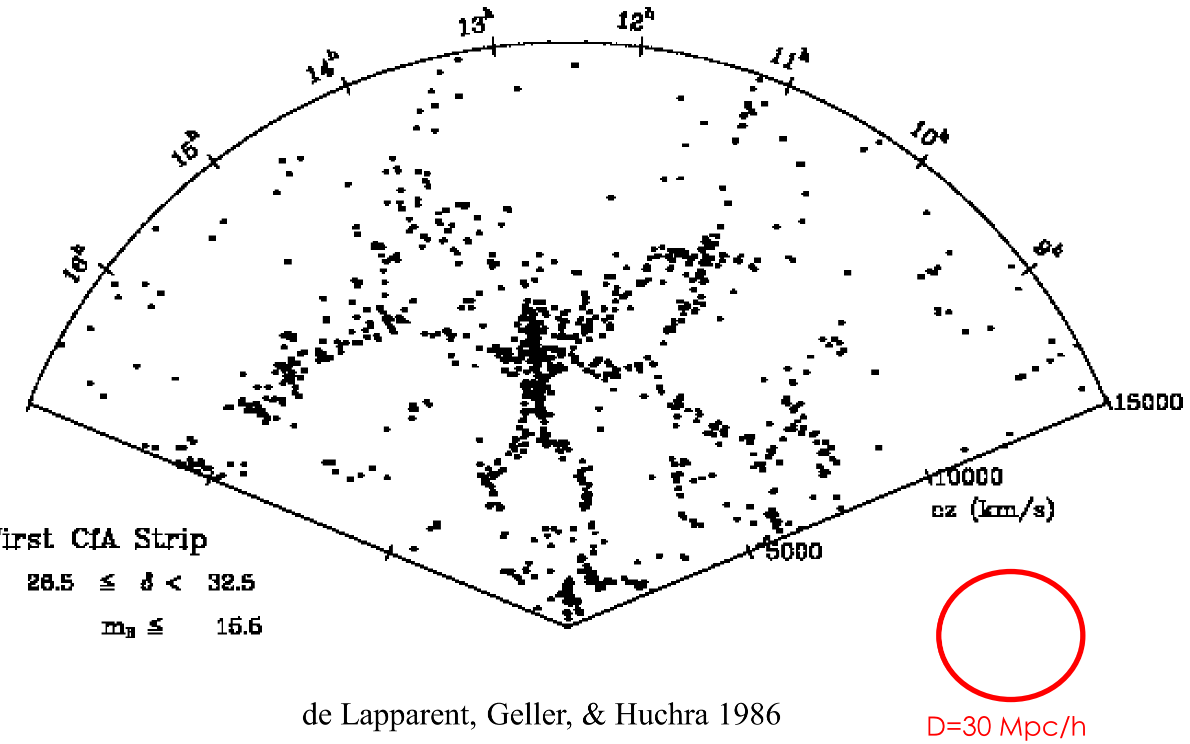
Filling Factor of Different Void Sizes

Voids with effective radii ~22 Mpc/h fill most of void volume. Total filling factor is 62% for voids. Average underdensity $\delta\rho/\rho$=-0.9 (10% of cosmic mean).



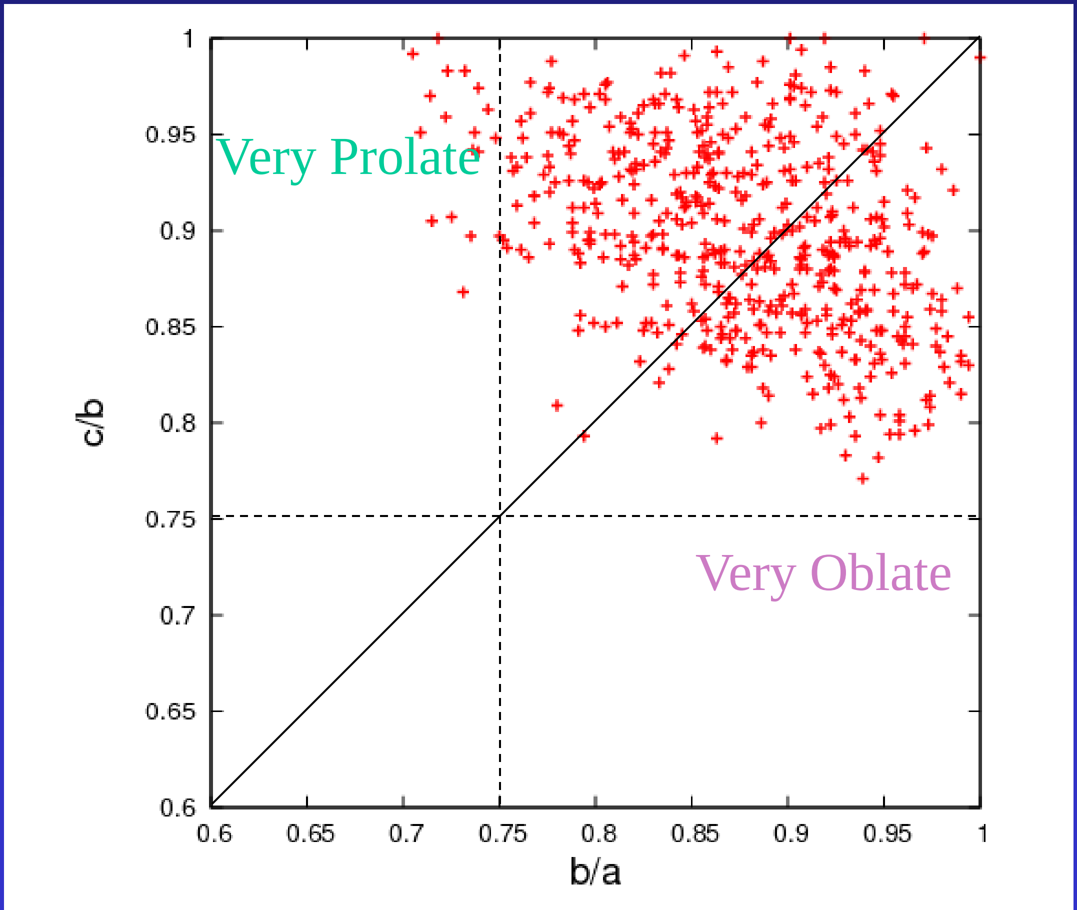
This explains why voids ~30-40 Mpc/h in diameter are dominant.

CfA Slice



de Lapparent, Geller, & Huchra 1986

Shapes of Voids: Oblate or Prolate?



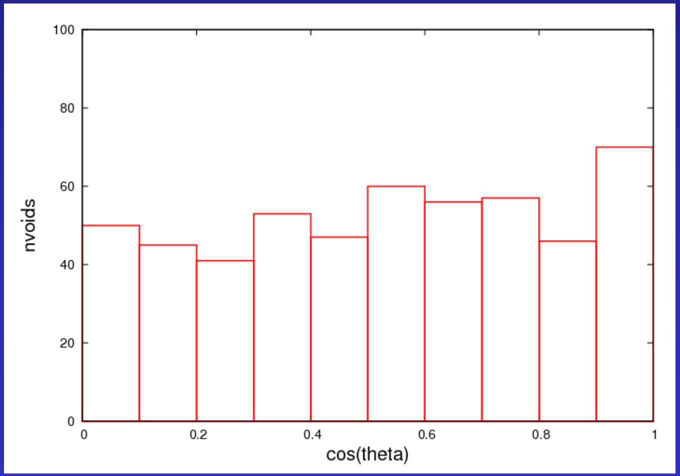
Fit triaxial ellipsoid to each void, with axes a, b, c (largest to smallest)

More very prolate voids (c/b>0.75) than very oblate. Very prolate voids are found to be caused by overlap of pairs of nearly spherical sub-voids.

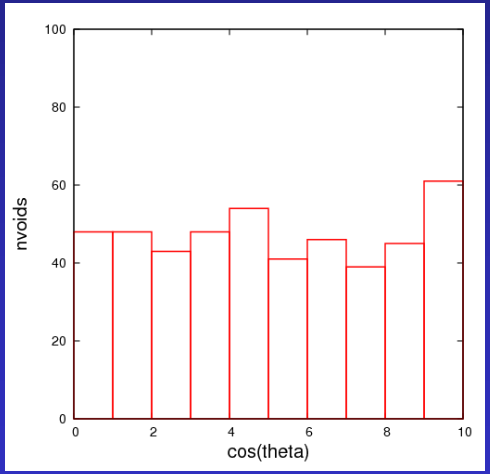
Same behavior in mock surveys from Park & Kim and no significant variation from real to redshift space.

Alignment of Voids

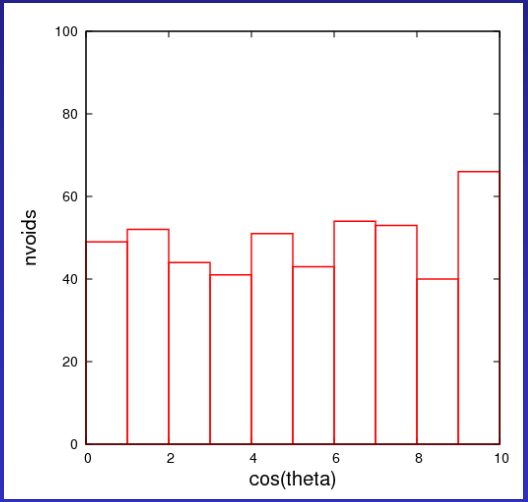
No statistically significant alignment of principal axis of voids with line of sight in observations or simulations (neither real or redshift space).



SDSS voids



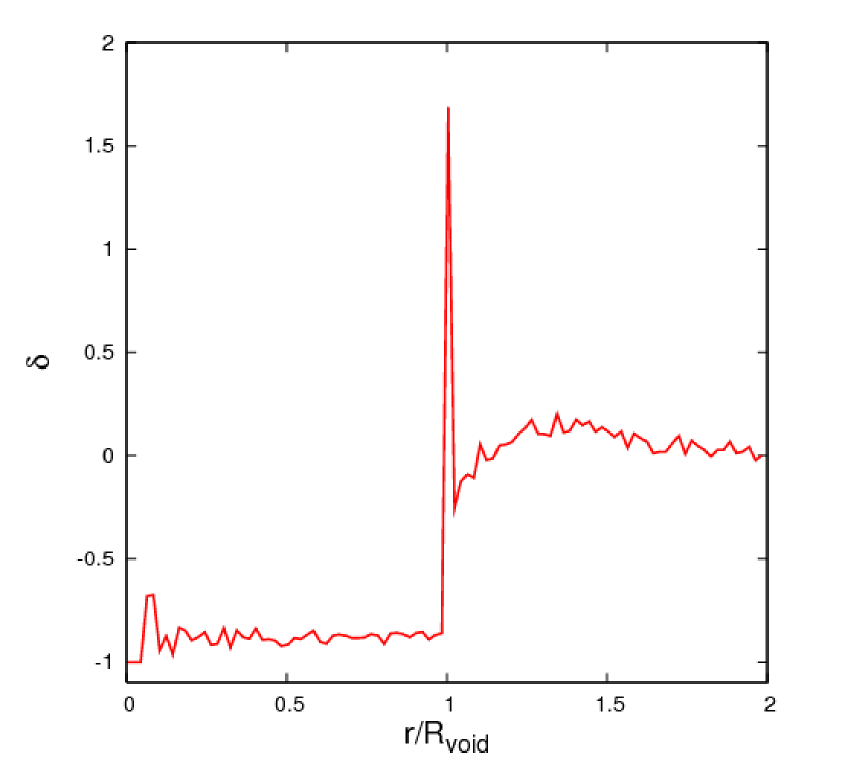
Simulations: Real Space



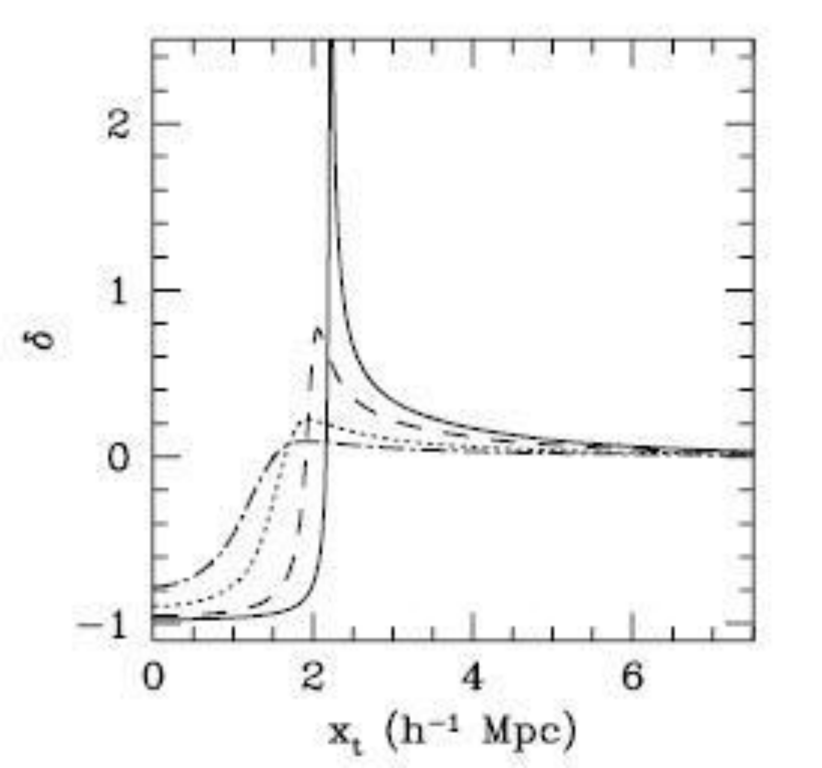
Redshift Space

Density Profiles

Observed voids show "bucket shape" profile with sharp edges, as predicted by linear gravitational theory.

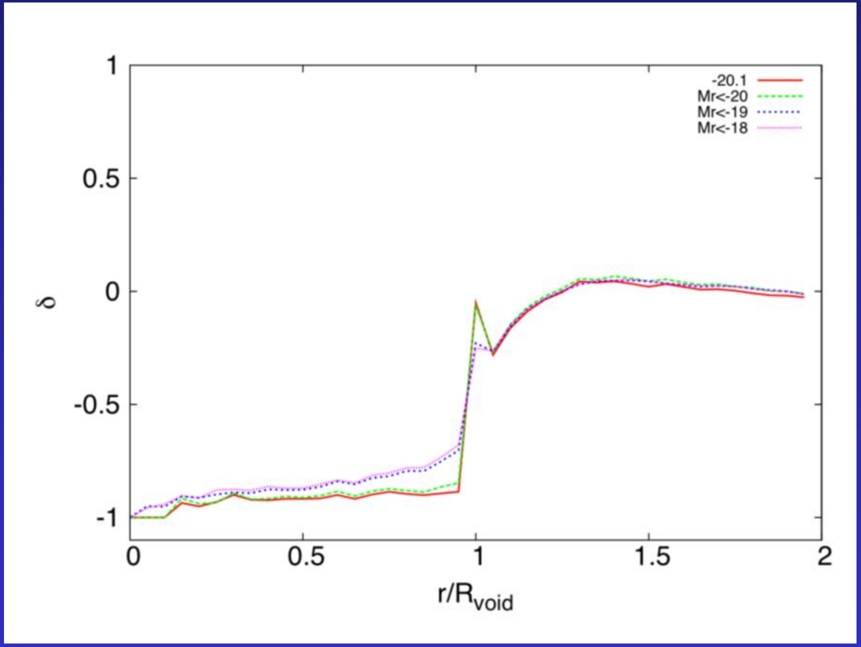


SDSS Voids



Linear Theory (Sheth & van de Weygaert)

Void Profiles for Fainter Galaxies



Radial profiles of voids change only slightly with galaxy luminosity.
Fainter galaxies do not fill in the voids.

Summary of Void Properties

- Void distributions of 2dFGRS, PSCz, UZC, and SDSS agree; void properties are robust
- No detected evolution of void size with redshift in nearby universe
- Voids are on average ~12 h^{-1} Mpc in radius, but largest void larger in larger surveys?
- Density profiles plateau in center to $\delta\rho/\rho = -0.95$
- Density profiles reveal sharp void edges, as predicted from gravitational instability
- Filling factor 62% for average density contrast $\delta\rho/\rho = -0.9$
- Voids with effective radii ~20 h^{-1} Mpc occupy most of void volume
- Oblate or prolate: very slight tendency towards prolate
- Alignment: not statistically significant
- Evidence of redshift space effects? Not so far…
- *VoidFinder appears to detect dynamically distinct elements of large-scale structure (peaks in initial gravitational potential, outflows in velocity, sharp boundaries in density*)

What's in the Lab? Properties of Void Galaxies

Our work on photometric and spectroscopic properties of SDSS void galaxies found that void galaxies are *fainter, bluer, more disk-like*, and have *higher specific star formation rates*. See

Rojas, Vogeley, & Hoyle 2004, ApJ, 617, 50 (photometric properties)

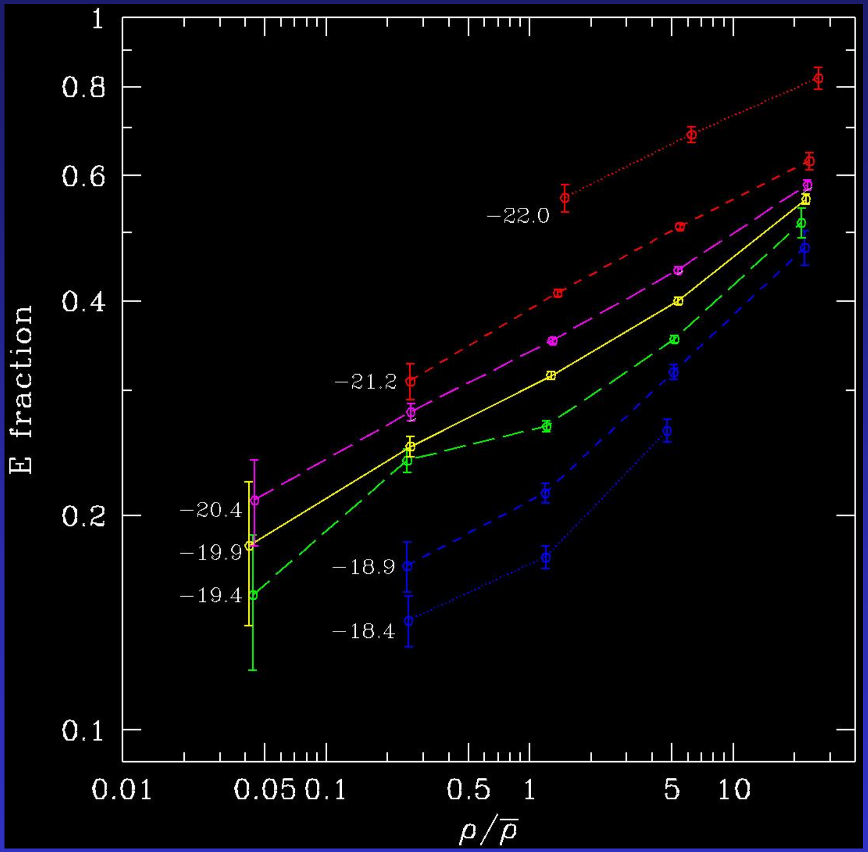
Rojas, Vogeley, & Hoyle 2005, ApJ, 624, 571 (spectroscopic properties)

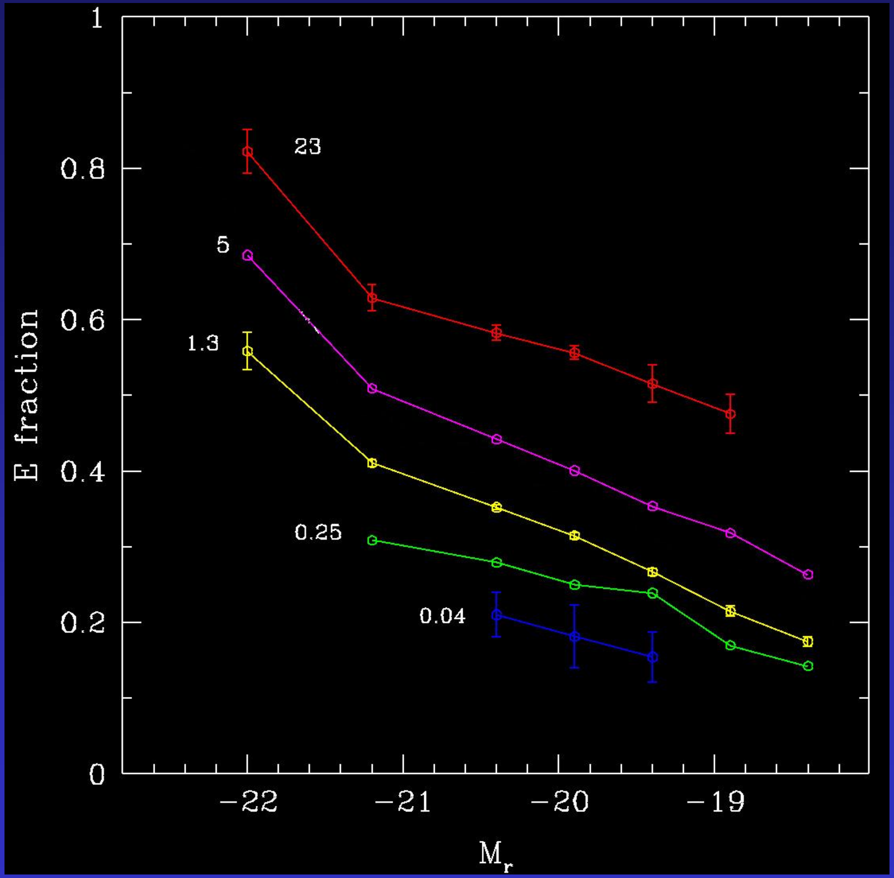
Hoyle, Rojas, & Vogeley 2005, ApJ, 620, 618 (luminosity function)

Newer evidence places these trends in context of a *Morphology-Luminosity-Local Density Relation* and reveals a few residual environmental effects peculiar to voids.

Park, Choi, Vogeley, Gott, & Blanton 2007, ApJ, 658, 898

Morphology-Luminosity-Local Density Relation



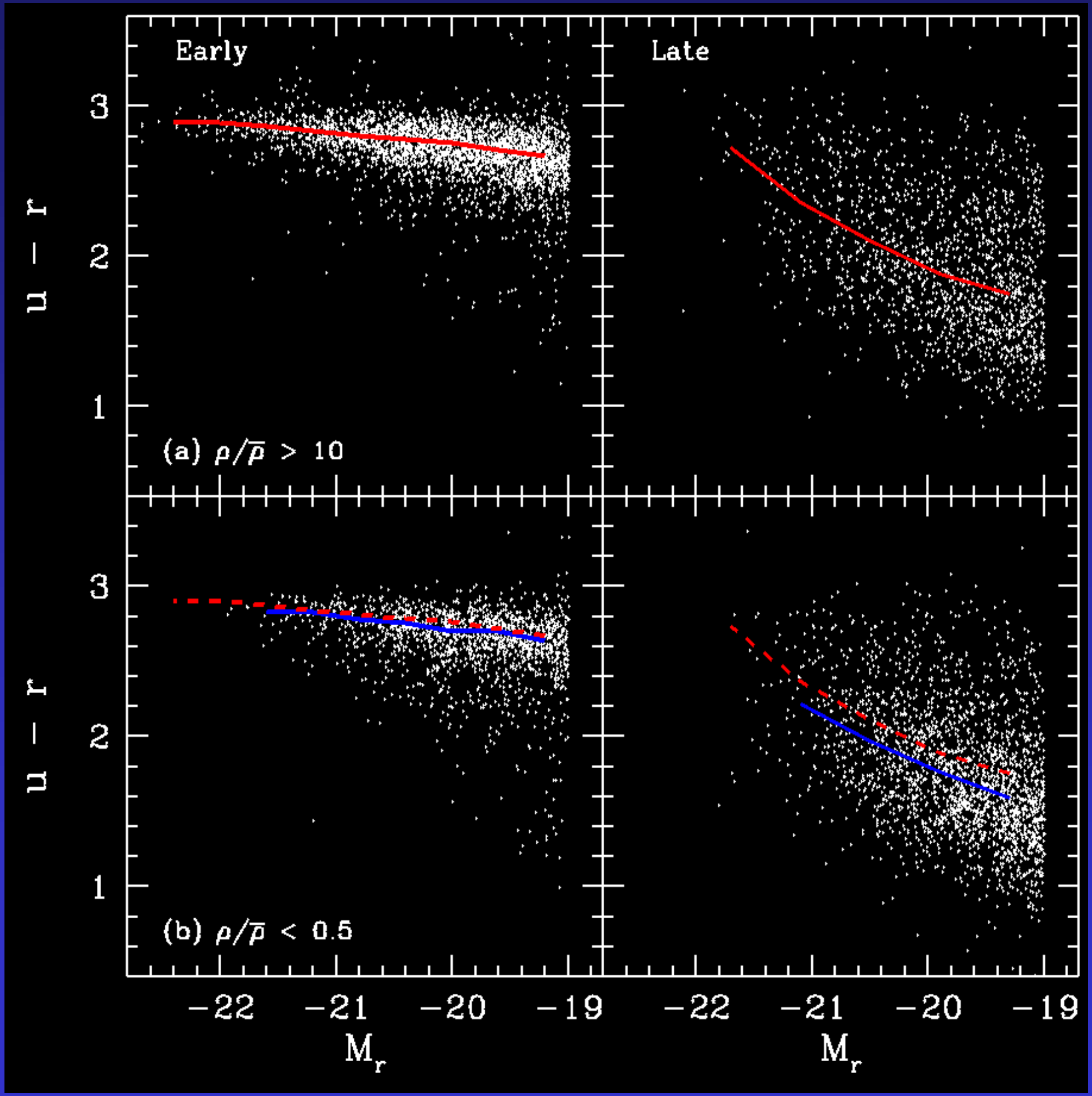


At fixed L, morphology is a strong function of density

At fixed density, morphology is a strong function of L

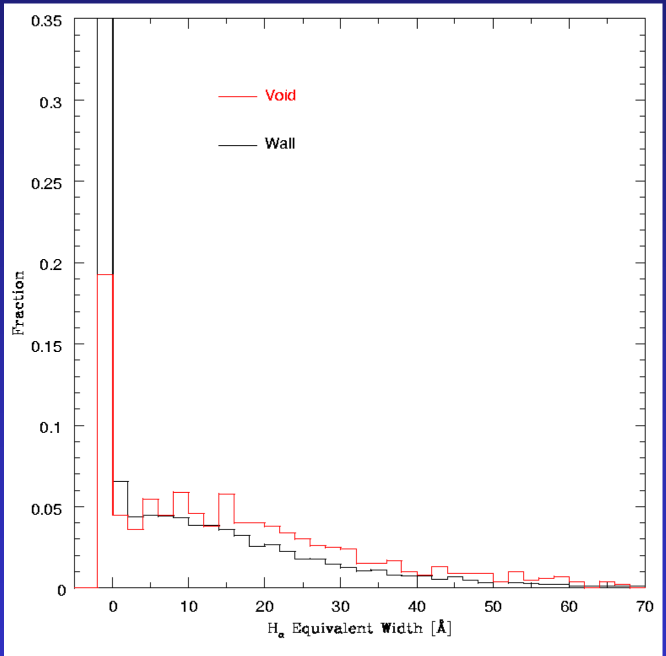
Color-magnitude relations

- Early type "red sequence" shifts blueward by 0.025 mag from high to low density
- Late type "blue sequence" shifts blueward by 0.14 mag at low density

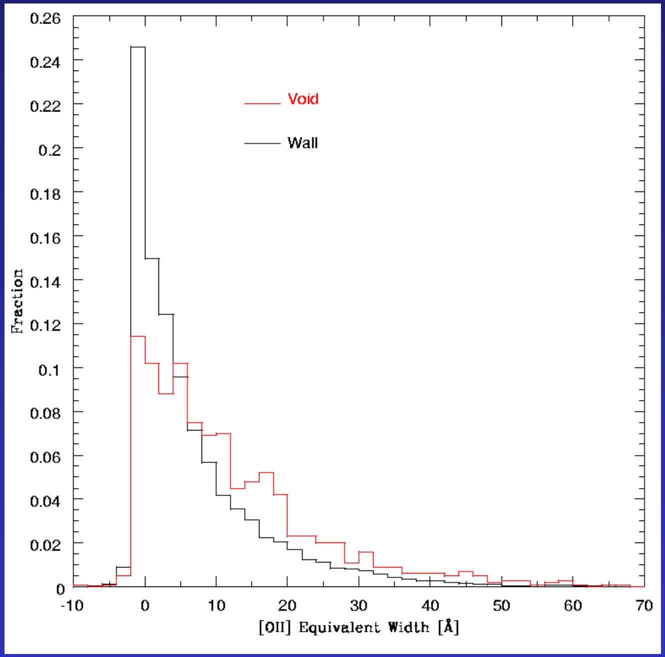


Void Galaxies Have Higher Star Formation Rates

Hα emission



[OII] emission



Void galaxies (red lines) have **stronger emission of Hα and [OII]**, implying higher specific SFR

Results on Environmental Dependence

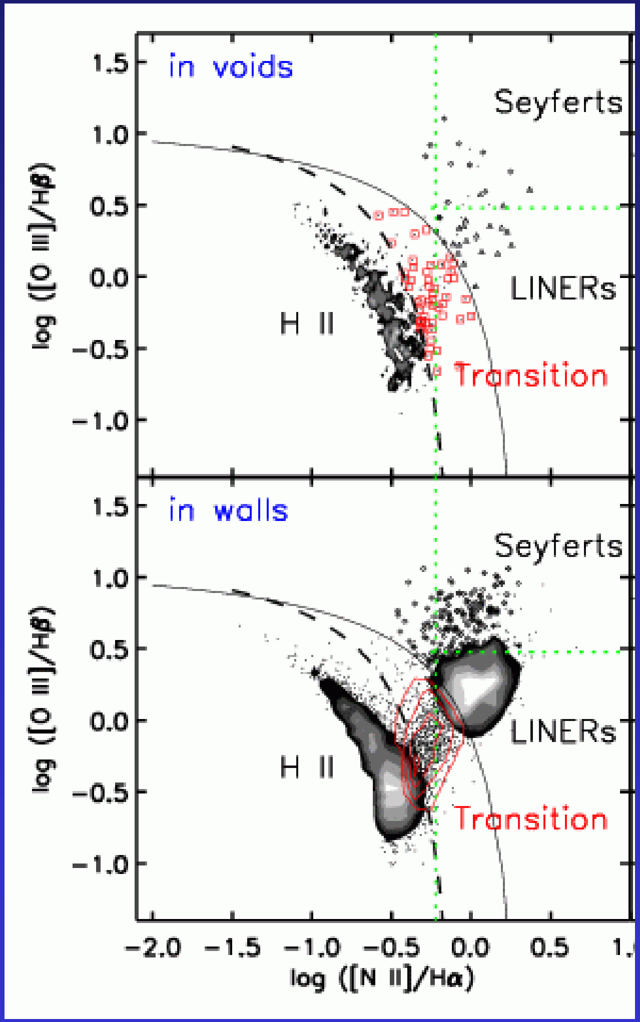
- Strong local density-morphology-luminosity relation. Environment matters down to very low density.
- At fixed luminosity and morphology, other galaxy properties show only weak dependence on density
- Residual effects at low density
  - Color-magnitude shifts blueward, particularly for late types
  - Sizes of galaxies are smaller
  - Star formation in late types is higher
- Higher star formation per stellar mass indicated by emission lines

Yes, there are Active Galactic Nuclei in voids!

Constantin & Vogeley 2006, ApJ 650, 727

Constantin, Hoyle, & Vogeley 2008, ApJ 673, 715

AGN of all types in voids and walls



Constantin, Hoyle, & Vogeley 2008 “AGN in Void Regions”

AGN in Voids: Populations

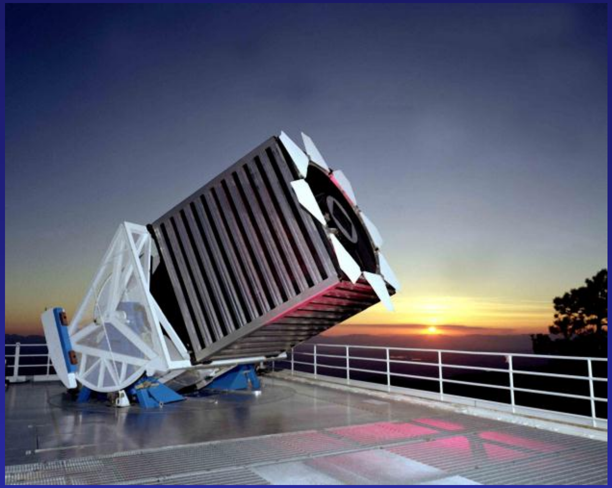
Constantin, Hoyle, & Vogeley (2008)

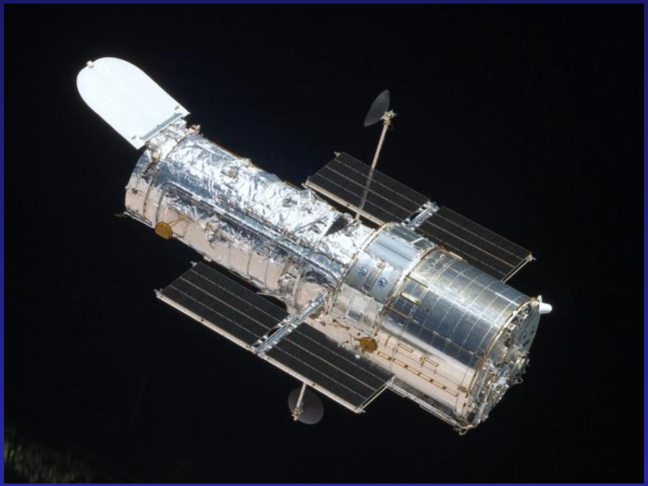
AGN of all types exist in voids:

	Fraction in voids	Fraction in walls
Seyferts	1.5%	1.5%
LINERs	2.0%	4.1%
Transition Objects	5.3%	6.4%
H IIs	32.8%	20.8%

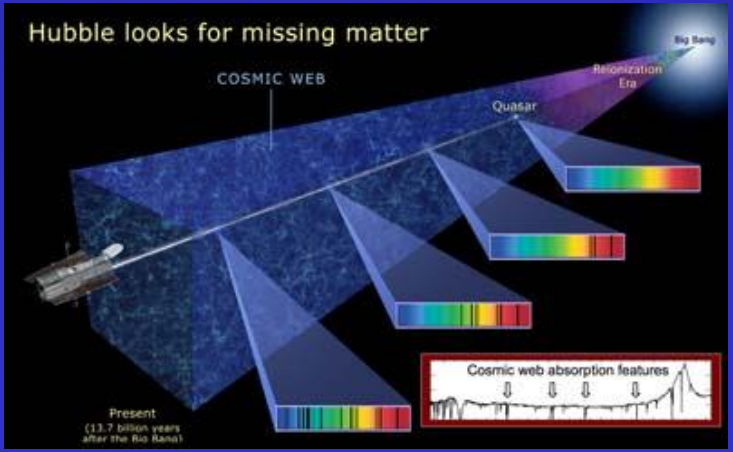
- No AGN in bright (L>>L*) void galaxies
- Seyferts more frequent among $M_r \sim -20$ mag void galaxies
- Otherwise very similar AGN occurrence rate for S's, L's, and T's (but not HII's!)

Mapping Gas in Voids with SDSS + HST/STIS

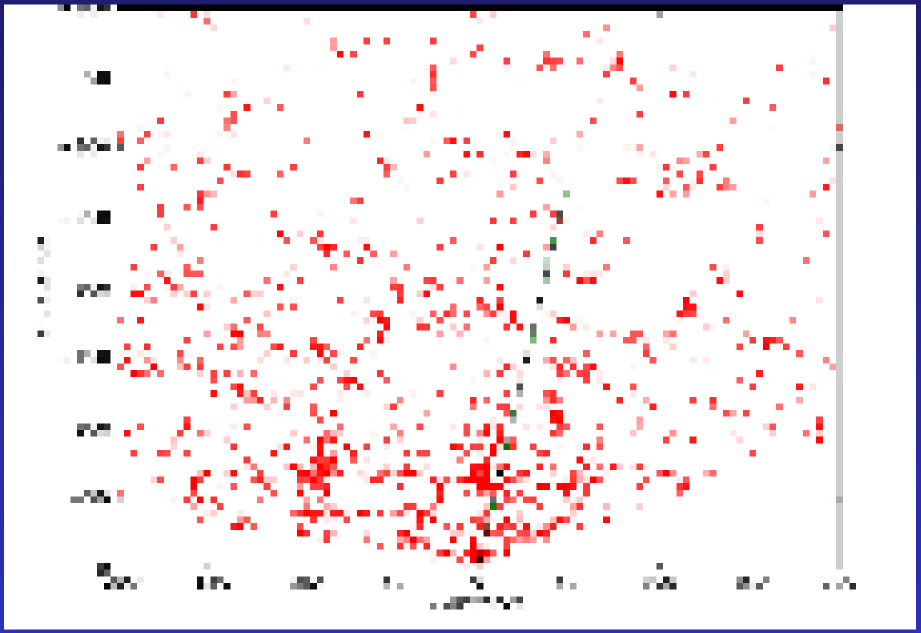




Observations using HST/STIS:157 Ly-α absorbers identified along 15 lines of sight toward quasars (Danforth & Shull 2008).



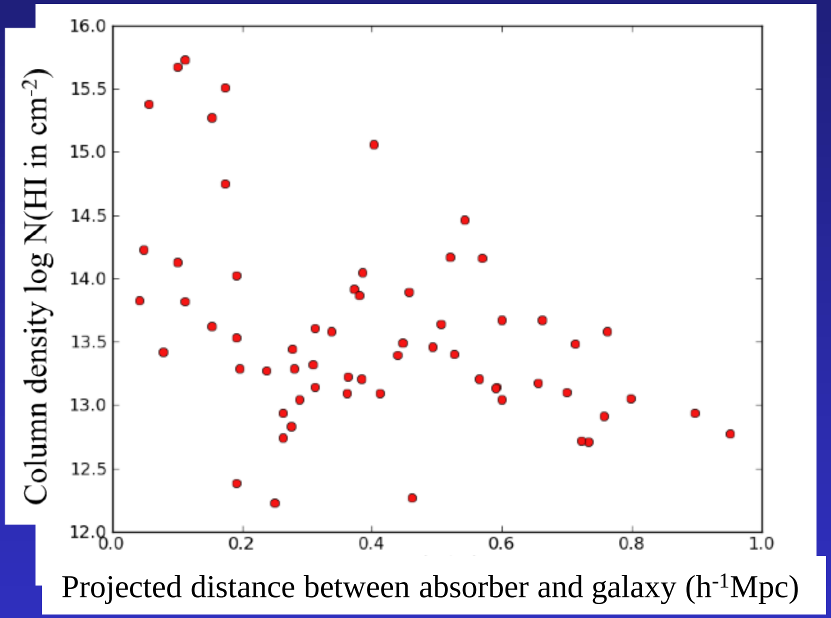
Where do Lyman-α absorbers live?



SDSS galaxies vs. Ly-α absorbers

157 Ly-α absorbers identified along 15 lines of sight within SDSS volume r<300 h^{-1}Mpc.

Ly-α absorbers are associated with galaxies

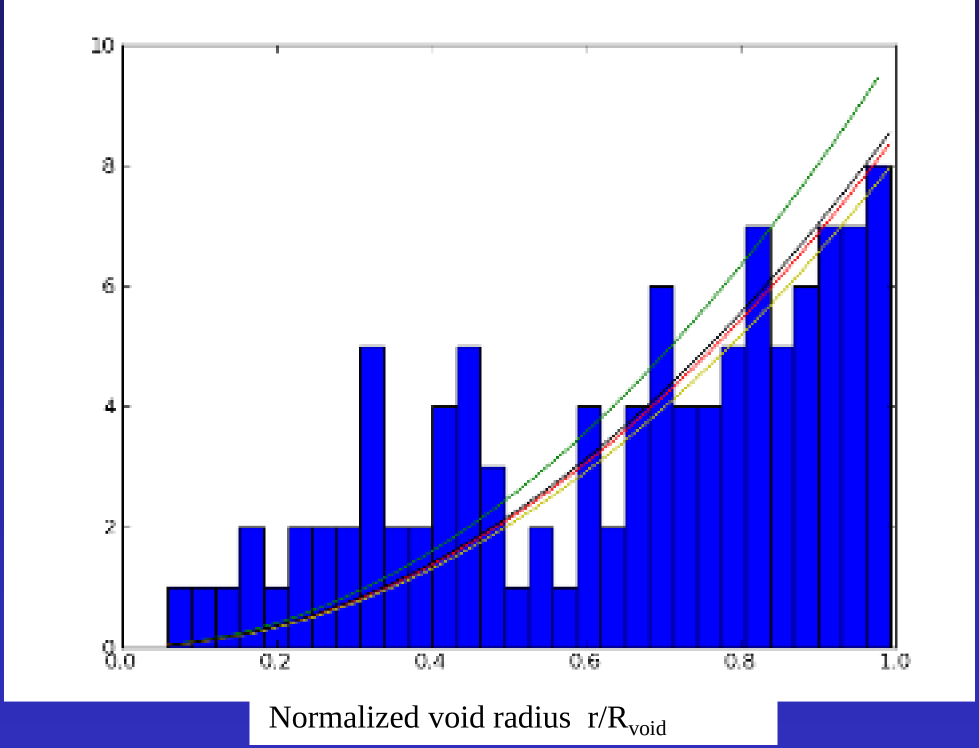


Match each absorber to nearest SDSS galaxy.

Most Ly-α absorbers have a SDSS galaxy within 1 h^{-1}Mpc.

Trend of higher N(HI) for closer matches.

Ly-α absorbers *prefer* the voids



- 67% of Ly-α absorbers (and 62% of the closest SDSS galaxies) live in voids (which fill 62% of volume), vs. only 10% of galaxies.
- No trend with column density N(HI) of the absorber void fraction.
- Ly-α absorbers are not clumped near edges of voids, but prefer the centers of voids.

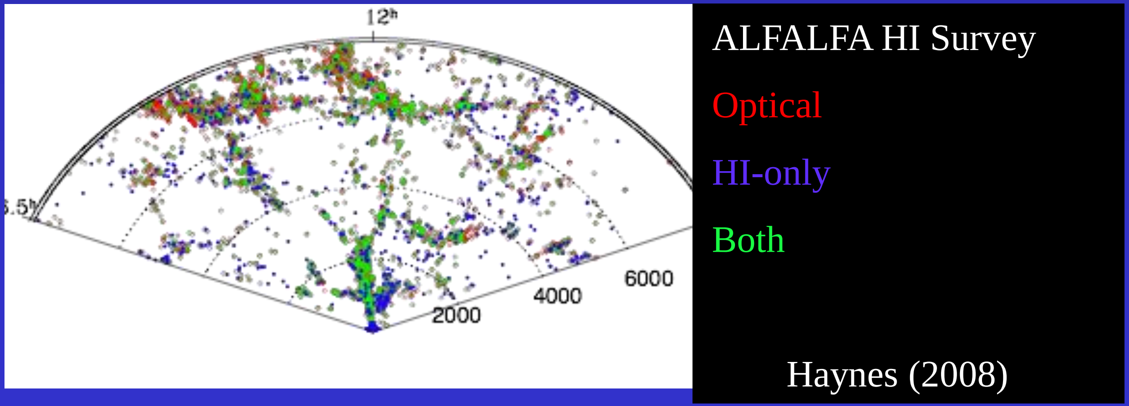
Ly-α absorbers do not cluster like galaxies

- 67% of Ly-α absorbers (and 62% of the closest SDSS galaxies) live in voids (which fill 62% of volume), vs. only 10% of galaxies.
- No trend with column density N(HI) of the absorber void fraction.
- Ly-α absorbers are not clumped near edges of voids, but prefer the centers of voids.
- For the first time, a population of objects that does not obey the voids.

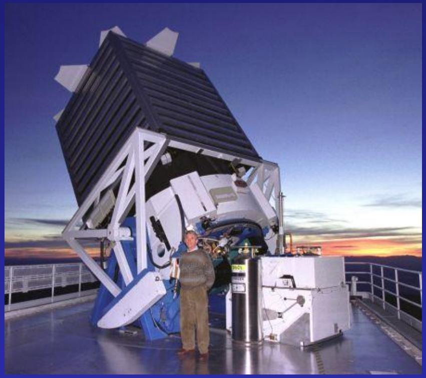
Pan, Vogeley, Jewell, Danforth, & Shull 2010, in preparation

Does the Void Phenomenon indicate an intrinsic failing of the ΛCDM model?

- Puzzle: Suppression of star formation in voids is required to match CDM theory to observation, but void galaxies actually have higher star formation rates than elsewhere.
- Neutral hydrogen found in Ly-α clouds that prefer the voids.
- Hypothesis: Higher star formation rate in void galaxies occurs because void galaxies retain a reservoir of baryons that continues to feed star formation long after it shuts down in denser regions.
- No evidence for “failed” galaxies in voids. Extensive searches for HI emission find gas-rich optically-detected void galaxies but no evidence for dark objects at the masses predicted by ΛCDM.



Research Program: Dwarf Galaxies in Voids



3000 dwarf galaxies in voids with optical SDSS images (u, g, r, i, z) and spectroscopy (3900-9000 Å).

NUV (2316 Å) and FUV (1539 Å) images from GALEX.

HI observations (21 cm) from ALFALFA (Arecibo).

Goals: measure faint end of the optical luminosity function, star formation rates on time scales 10 My to >2Gy, metallicities, gas masses (and HI mass function), star formation efficiencies, galaxy interactions, clustering

Publications about nothing

Methods for void finding

- VoidFinder (Hoyle & Vogeley 2002, 2004)
- Comparison of void finders (Colberg et al. 2008)

Statistics and Properties of Voids

- Void Probability Function (Hoyle & Vogeley 2004)
- Voids in SDSS DR7 (Pan*, Vogeley, Hoyle, Choi, Park, 2010)
- Void shapes and alignments (Pan*, Vogeley, Hoyle et al, in prep)

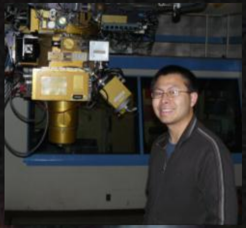
Properties of observed void galaxies

- Photometry (Rojas, Vogeley, Hoyle 2004)
- Spectroscopy (Rojas, Vogeley, Hoyle 2005)
- Luminosity Function (Hoyle, Rojas, Vogeley 2005)
- Mass function (Goldberg et al. 2005)
- AGN in voids (Constantin, Hoyle, & Vogeley 2008)
- Environmental dependence (Park, Choi, Vogeley, Gott, & Blanton 2007)
- Mergers in voids (Parejko,White, Pan*, & Vogeley, in prep)

Lyman-α clouds in voids (Pan*, Vogeley, Jewell, Danforth, Shull, in prep)

Simulations of void galaxies

- N-body + Semi-Analytic Models (Benson et al. 2003)
- Specialized void simulations (Goldberg & Vogeley 2004)



*Danny Pan, Ph.D. 2011