Lensing Measurements of SDSS Voids and Filaments

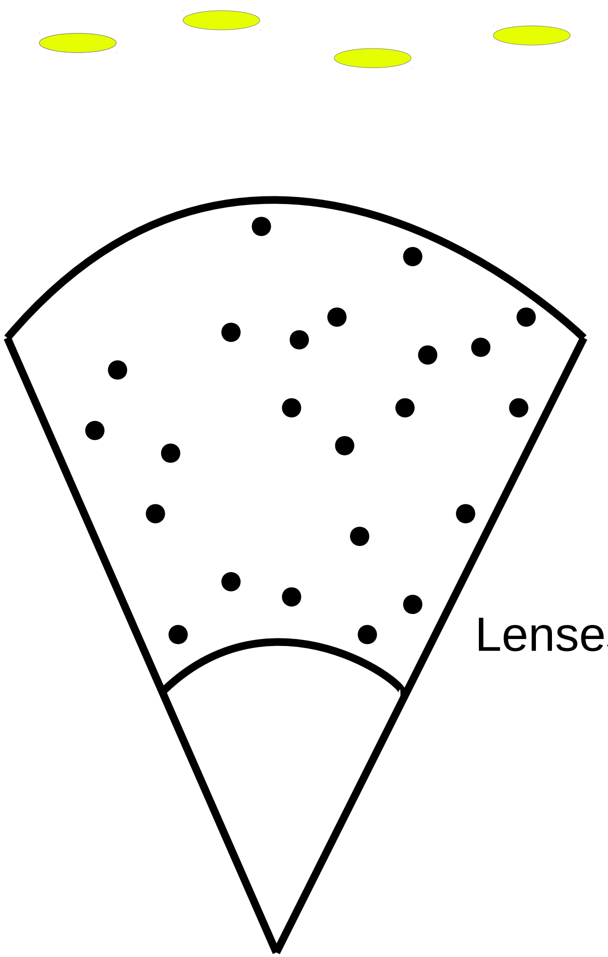
Joseph Clampitt

University of Pennsylvania

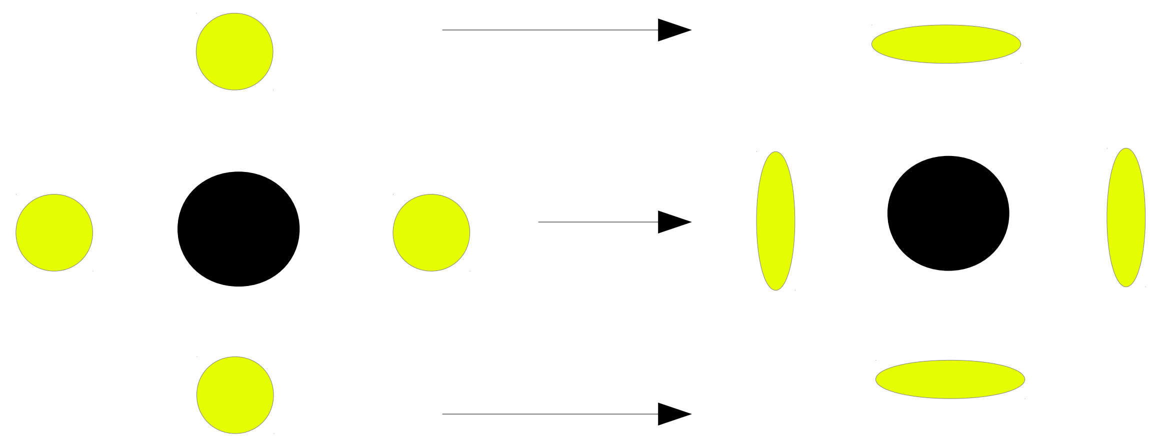
UC Berkeley Cosmology Seminar

October 28, 2014

Weak Gravitational Lensing



Photons from the sources are deflected by the lenses. The observer sees circles become ellipses:



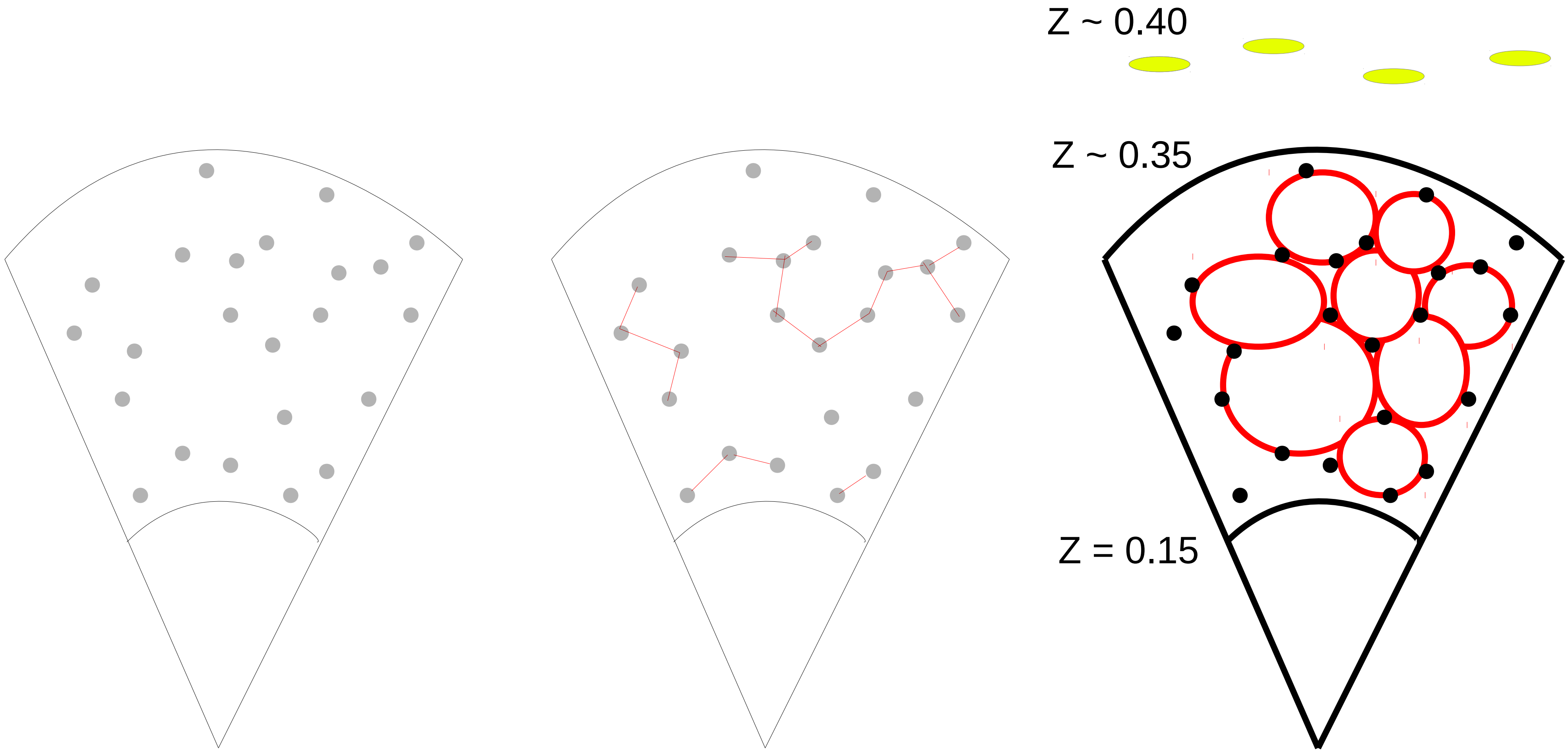
(This tangential, relative to lens, change in shape we call γ_t)

But galaxies are not circles, they are already elliptical. The **weak** lensing effect is only ~1% of the galaxy intrinsic ellipticity, and often even smaller than that. So we need:

1. Very accurate measurements of source galaxy ellipticity.

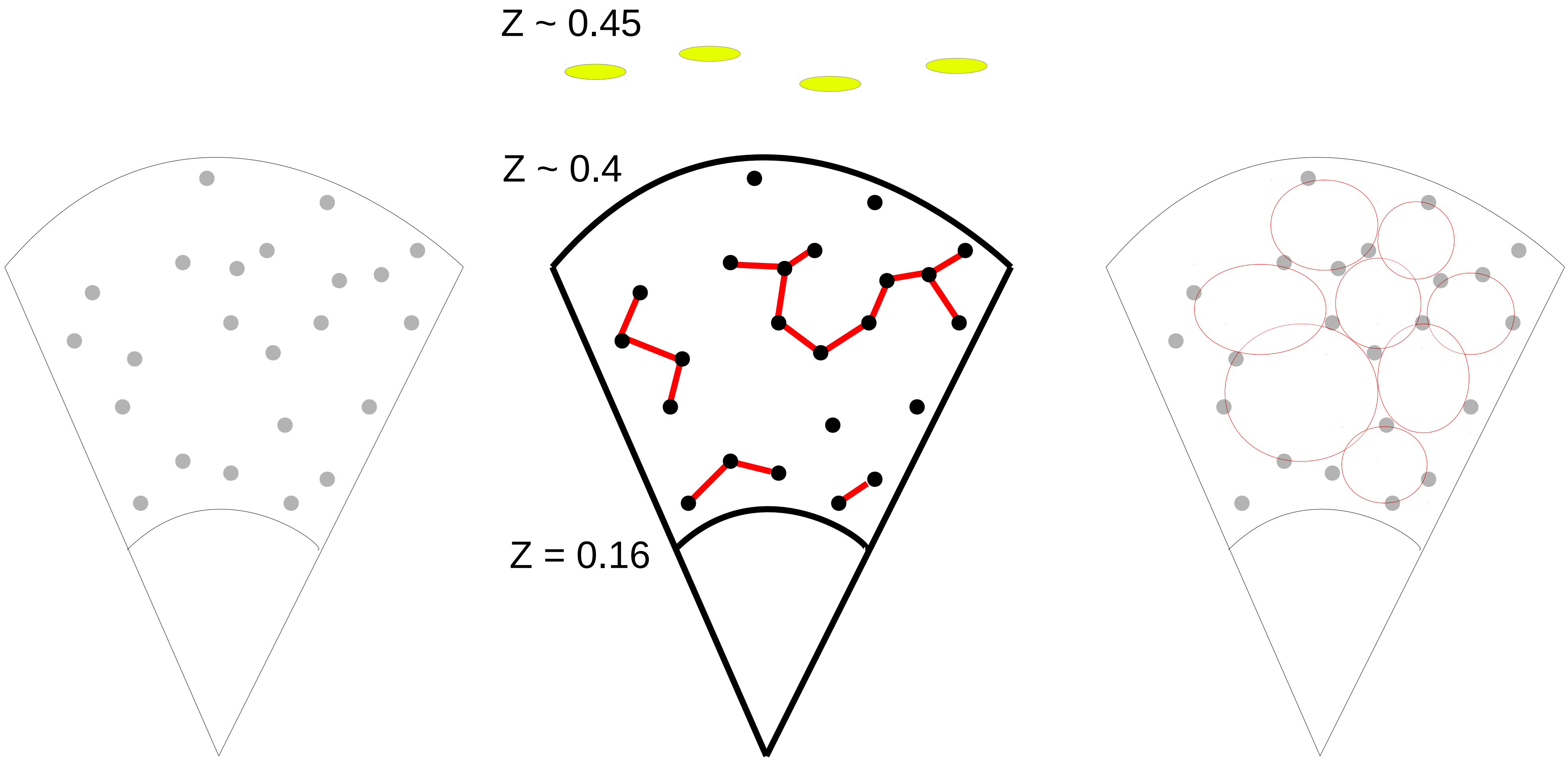
2. Many, many source galaxies.

Void Lensing



JC and Jain, arxiv:1404.1834

Filament Lensing



JC, Jain, Takada, arxiv:1402.3302

State of the Field

Galaxy-galaxy Lensing:

First detection **20 years ago** by Brainerd et al. (1996).

Void Lensing:

Theoretical work by Krause et al. (2013) predicted that ambitious future surveys (in particular, Euclid, which will have data **10 years from now**) would be needed for measurements with signal-to-noise of ~ 15-20.

Melchior et al. (2013) carried out a lensing analysis of the Sutter et al. (2013) void catalog. Their marginal success may have been due to the small number of voids.

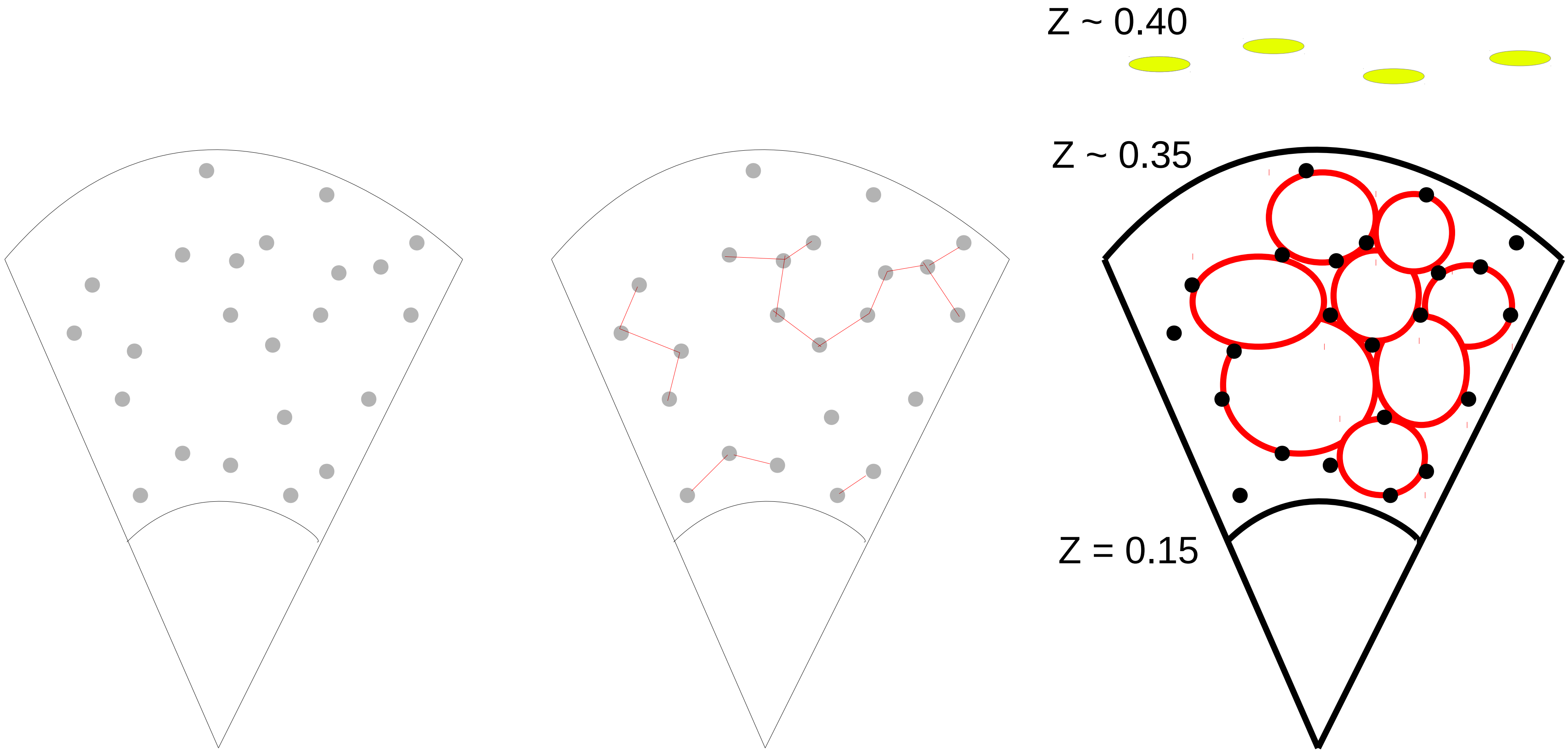
Filament Lensing:

Dietrich et al. (2012) and Jauzac et al. (2012) identify single filaments by carrying out a weak lensing analysis of single cluster pairs.

Predictions for stacked filament lensing by Mead et al. (2010) use lens and source redshifts that make their lensing strength a factor of 2 greater than ours, and a galaxy number density at least a factor of 30 higher. With a lower mass limit of M = 4e14 Msolar/h, they estimate that 20 cluster pairs are necessary to obtain a detection. DES will have a lesser source number density, but many more clusters. These numbers trade off in S/N, so we estimate **5 years from now** for a detection using the Mead et al. (2010) predictions.

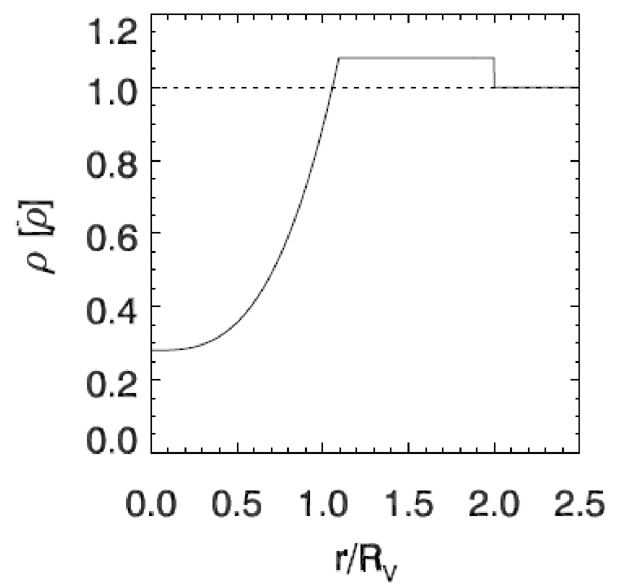
We have managed to make ~10-20 sigma detections of filament and void lensing **without new ground or space data.**

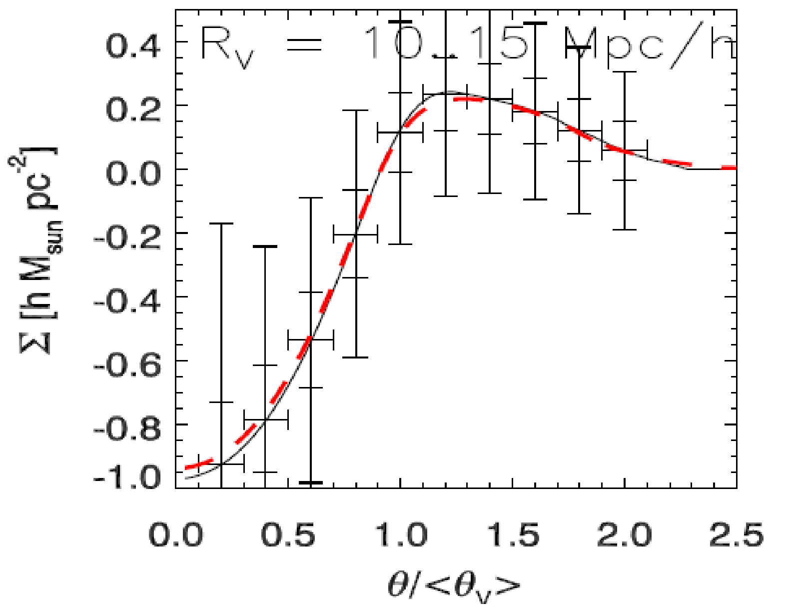
Void Lensing



JC and Jain, arxiv:1404.1834

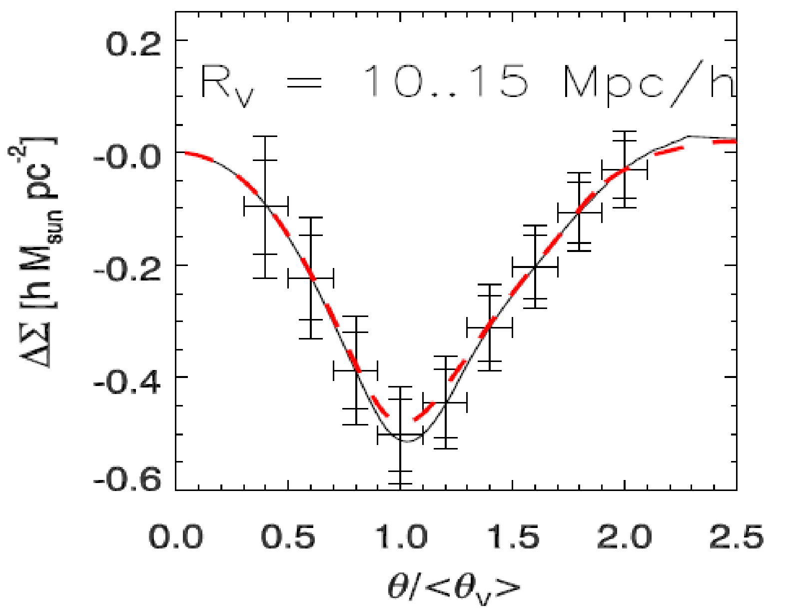
Voids in 3d, 2d and lensing





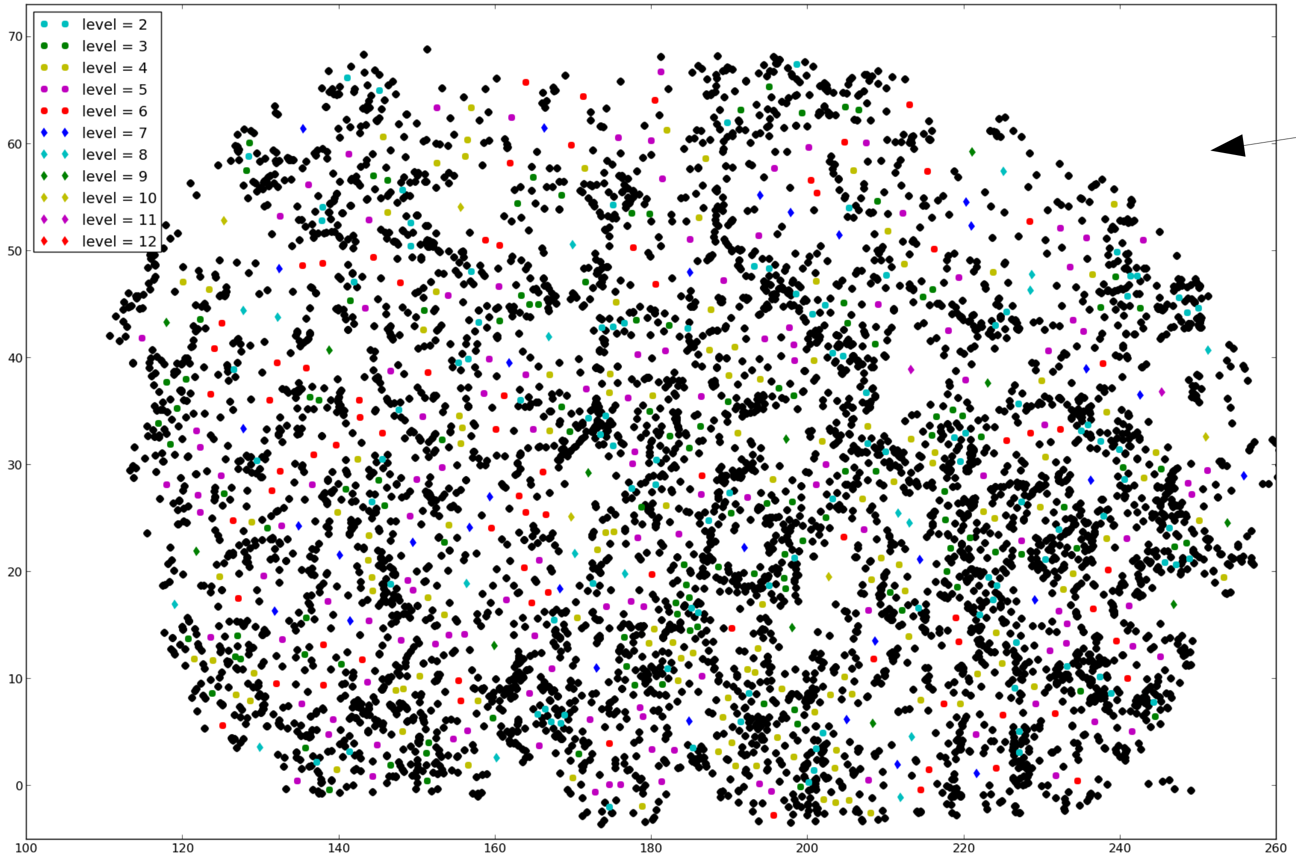
$$\langle \gamma_{\rm t} \rangle (\theta) = \frac{\Delta\Sigma(\theta)}{\Sigma_{\rm crit}},$$

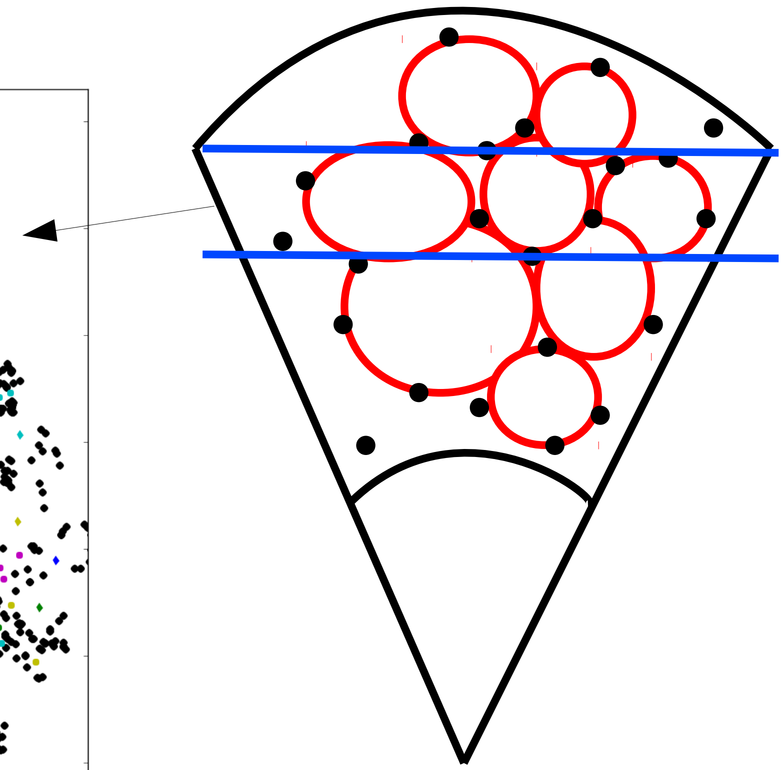
$$\Delta\Sigma(\theta) = \langle\Sigma(\theta)\rangle - \Sigma(\theta) = \Sigma_{\rm crit} \langle \gamma_{\rm t} \rangle (\theta) .$$



Krause et al. 2013

Void Finding Algorithm: 2 ½ D





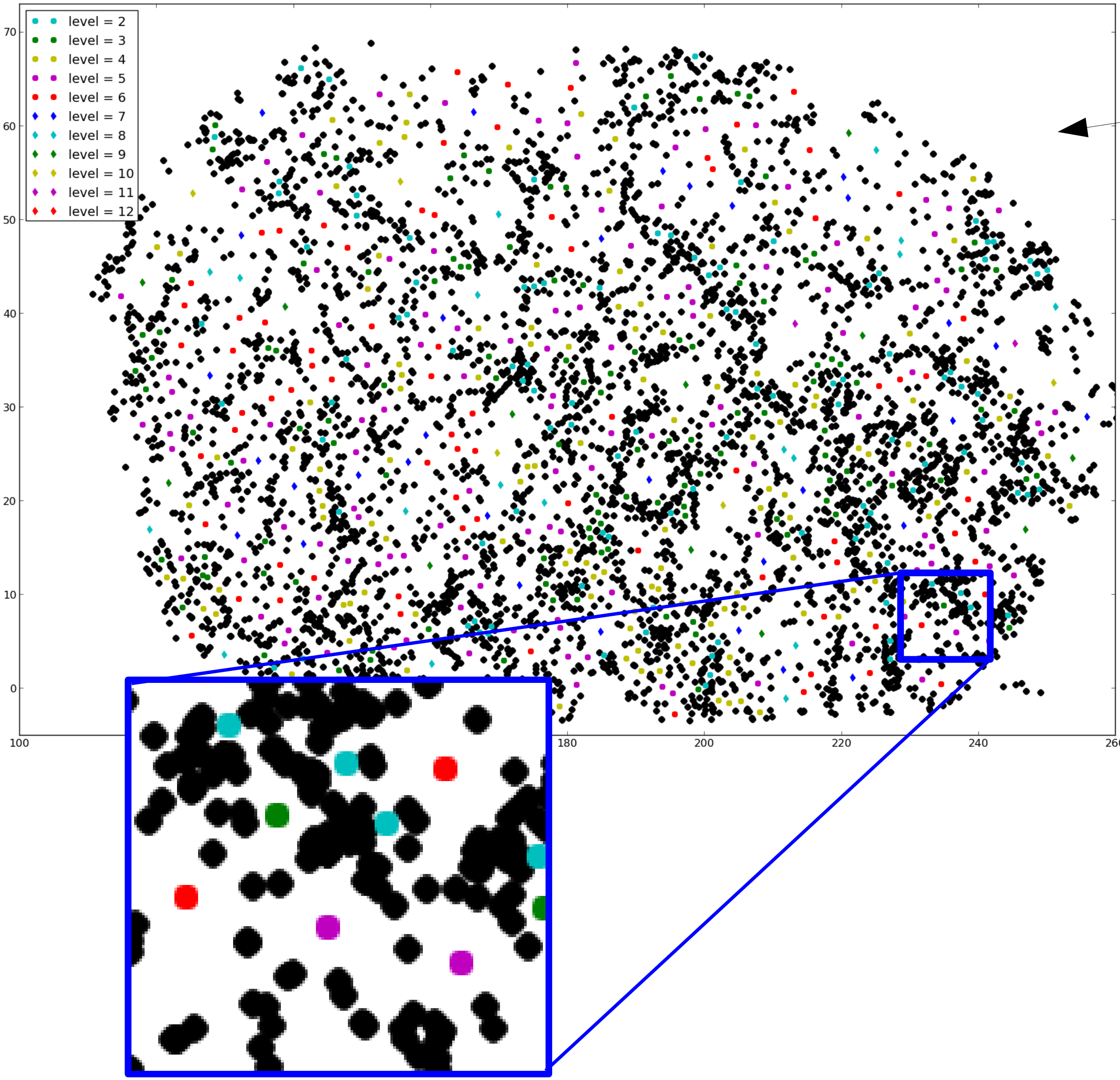
example 2D slice of width 50 Mpc/h through the 7,500 sq deg SDSS survey.

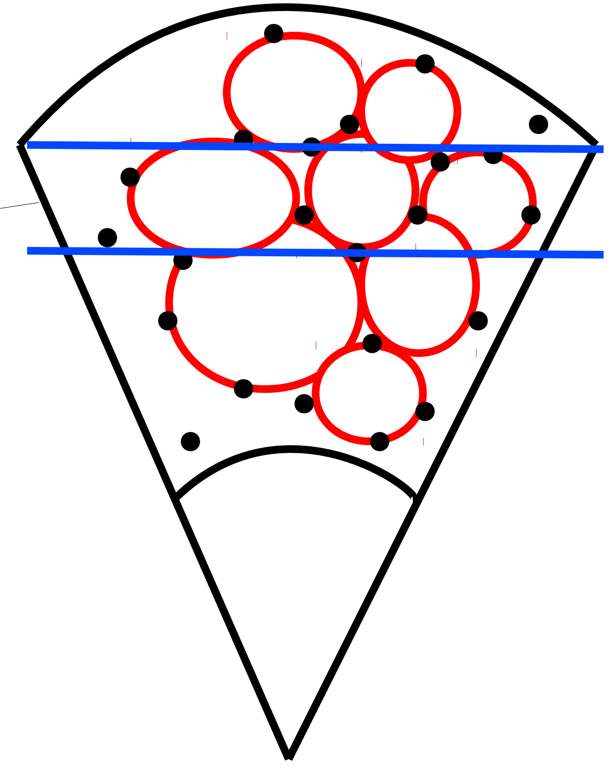
Black points – LRGs in the slice

Colored – Initial output of void-finding algorithm. Color and shape indicates angular size.

JC and Jain, arxiv:1404.1834

Void Finding Algorithm: 2 ½ D





example 2D slice of width 50 Mpc/h through the 7,500 sq deg SDSS survey.

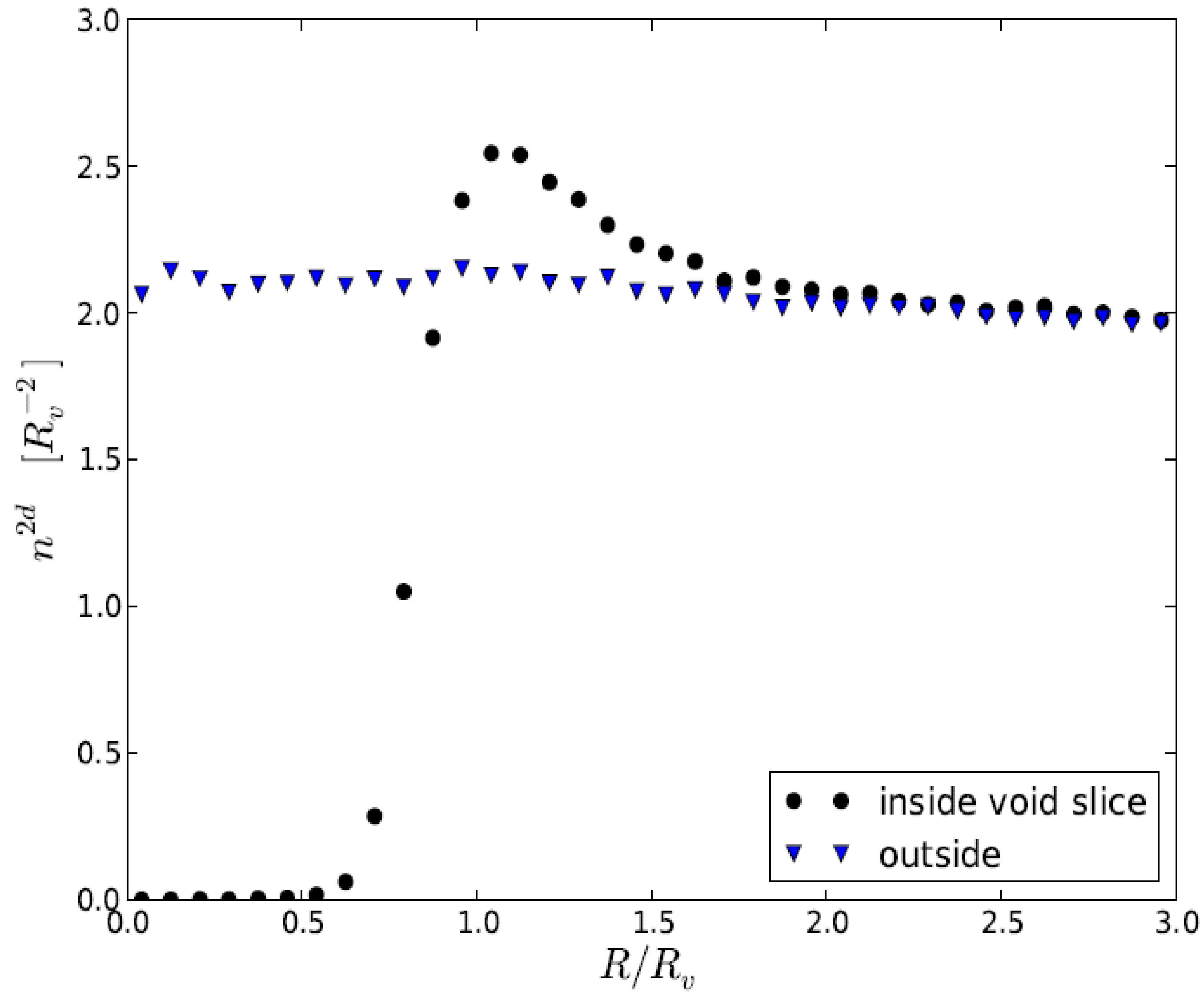
Black points – LRGs in the slice

Colored – Initial output of void-finding algorithm. Color and shape indicates angular size.

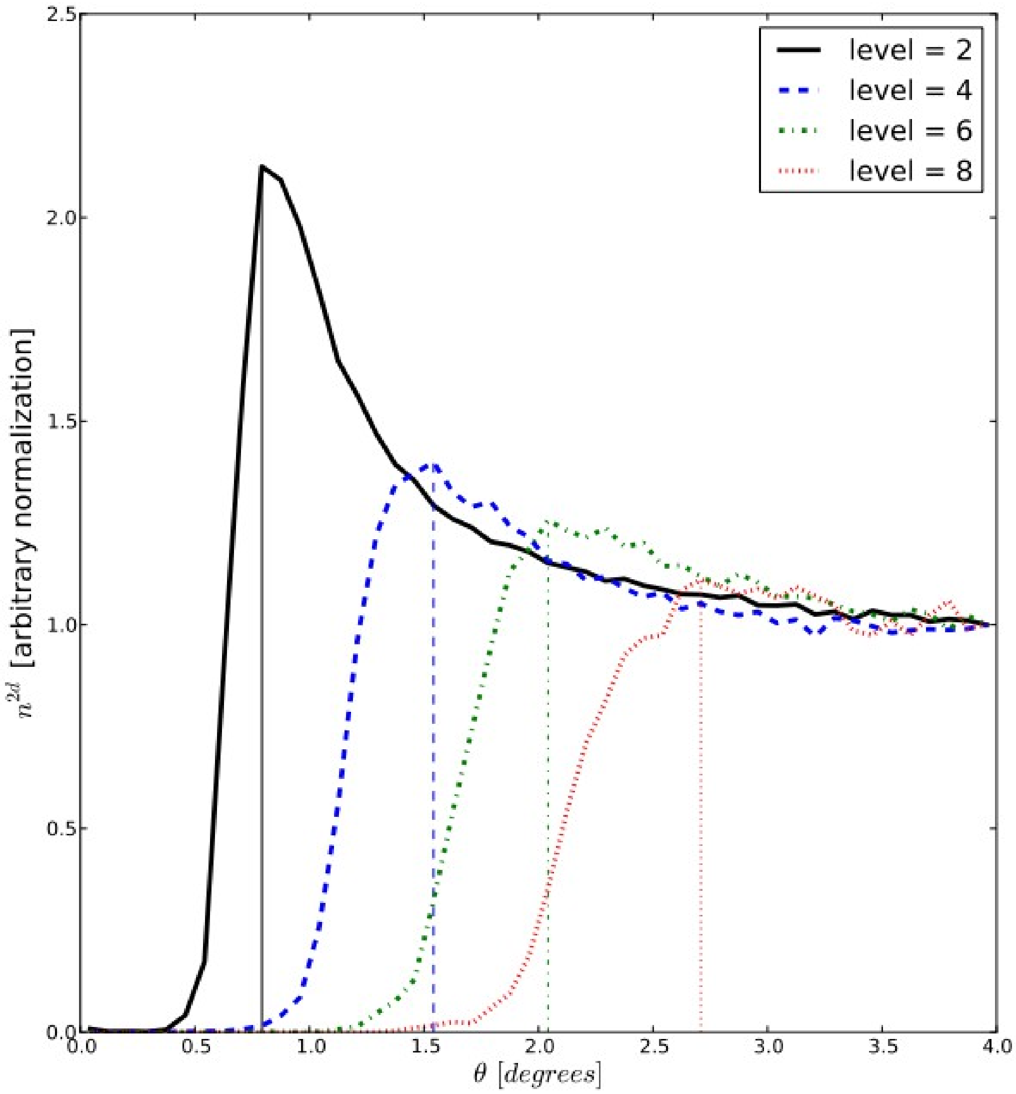
JC and Jain, arxiv:1404.1834

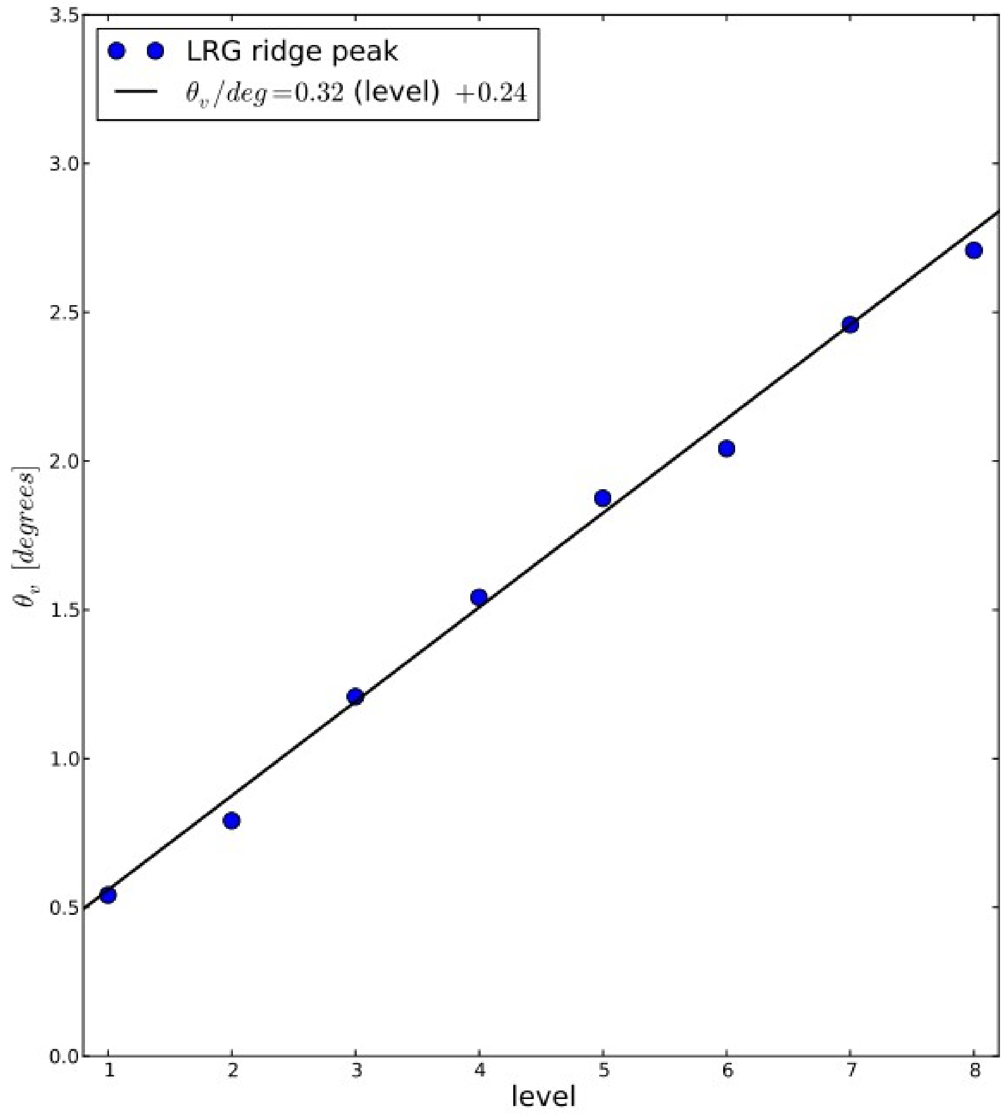
Galaxy Density: Inside and outside the slice

LRG density in annuli on the plane of the sky. The number inside the slice (black points) is zero near the void center, reaches its max at the void radius, and levels off to the mean. Just outside the slice (blue points) the LRG density is back at the mean value, indicating our 2D void finder accurately finds the voids' line-of-sight size.



Assigning Void Radii: Use the galaxy profile

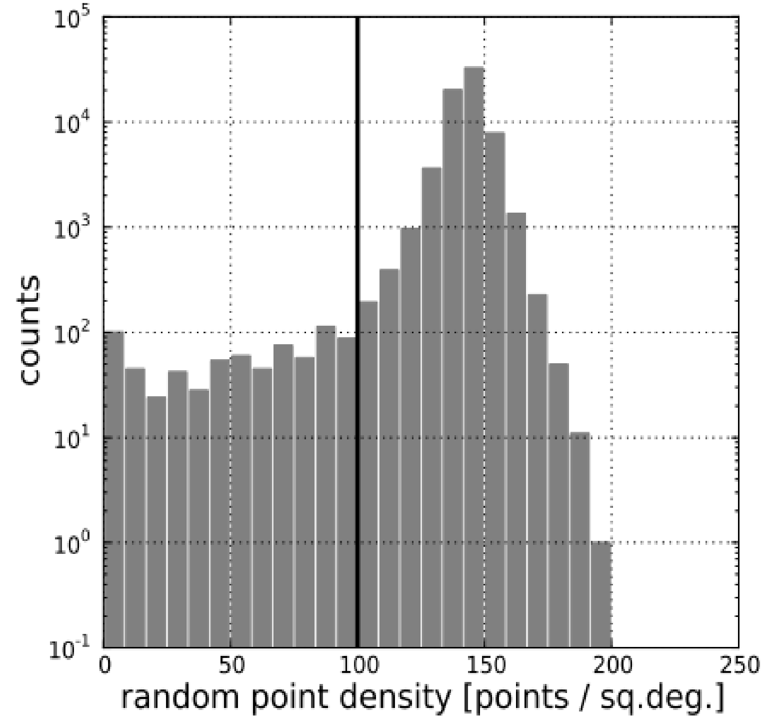




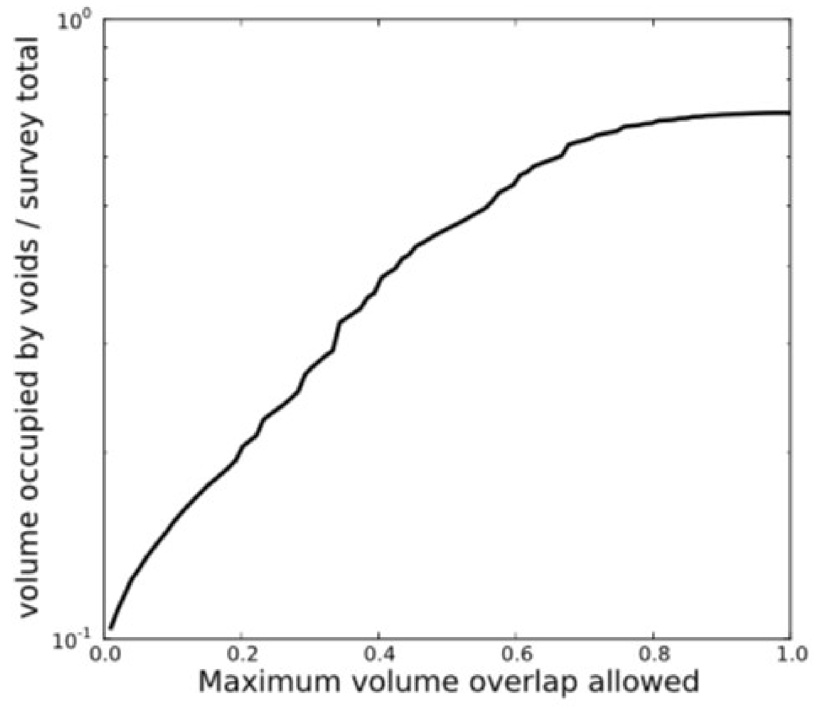
On the other hand, when using a more conventional void radius definition $R_{eff}=(3V/4\pi)^{(1/3)}$ the significance of the weak lensing detection drops by ~4-sigma.

Quality Cuts

SDSS Survey Mask
Remove voids at the edges and in heavily masked regions, where false detections are likely simply due to the lack of galaxies. Distribution of random points in voids is highly peaked, but with a long tail extending to low densities. Cut the tail.



Volume Overlap
The voidfinder is run independently in each slice, so it does not automatically return an entire void hierarchy for the entire survey volume, i.e., parent voids and nested subvoids. However, afterwards we can calculate the amount of volume unique to a given void, and make cuts on this quantity.



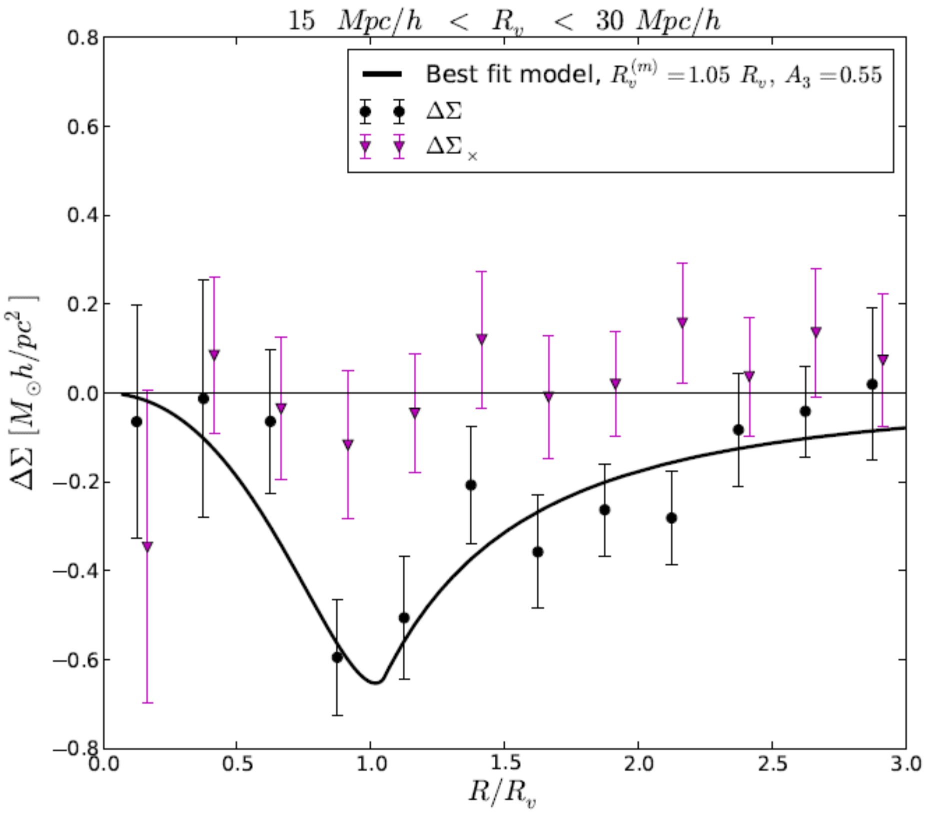
Void Lensing Measurement

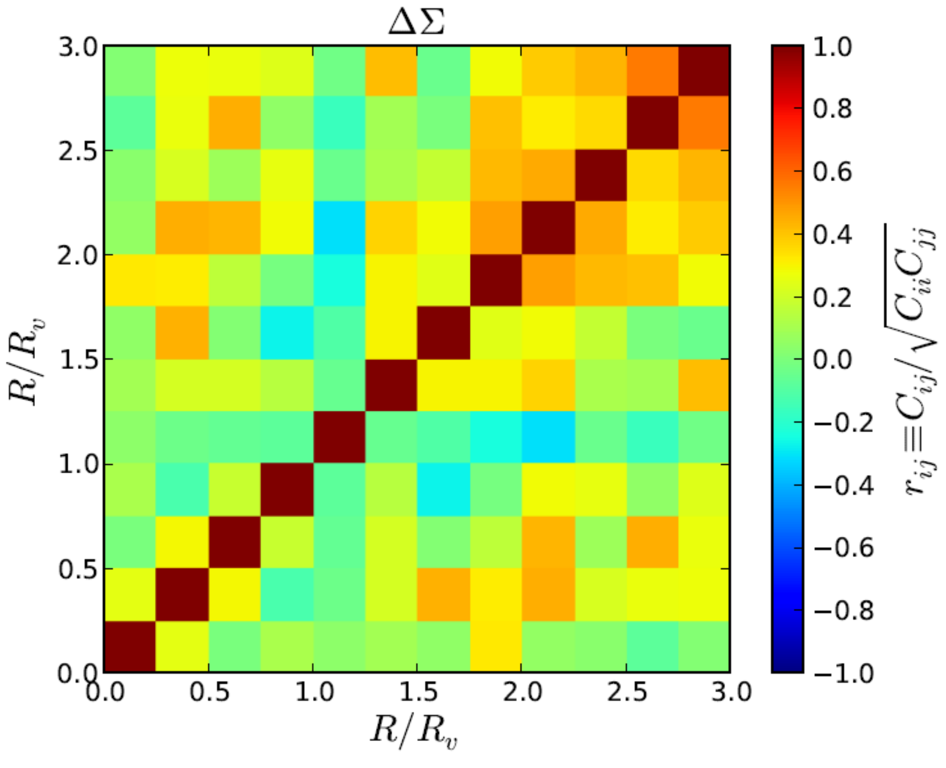
Null Tests, compare to null hypothesis: $\langle\chi^2\rangle = N - n \pm \sqrt{2N + 2n} = 12 \pm 4.9$

- Random points (not pictured): $\chi^2 = 16.7$ within 1σ

- Cross-component (magenta): $\chi^2 = 8.2$ within 1σ

Signal (black): $\chi^2 = 94.2$ 16.7σ



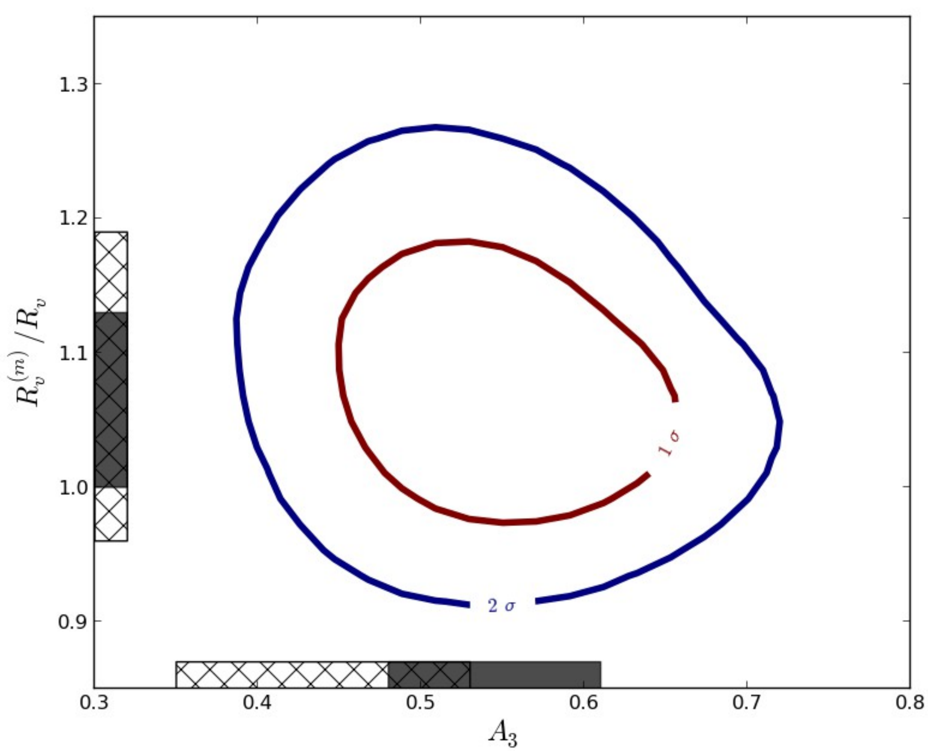


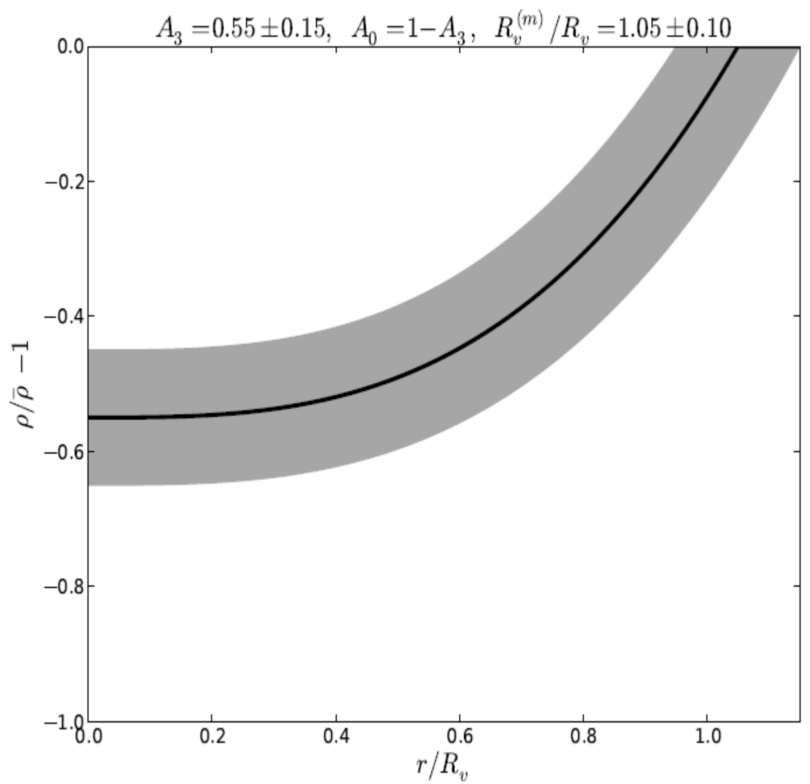
JC and Jain, arxiv:1404.1834

Density Profile Constraints

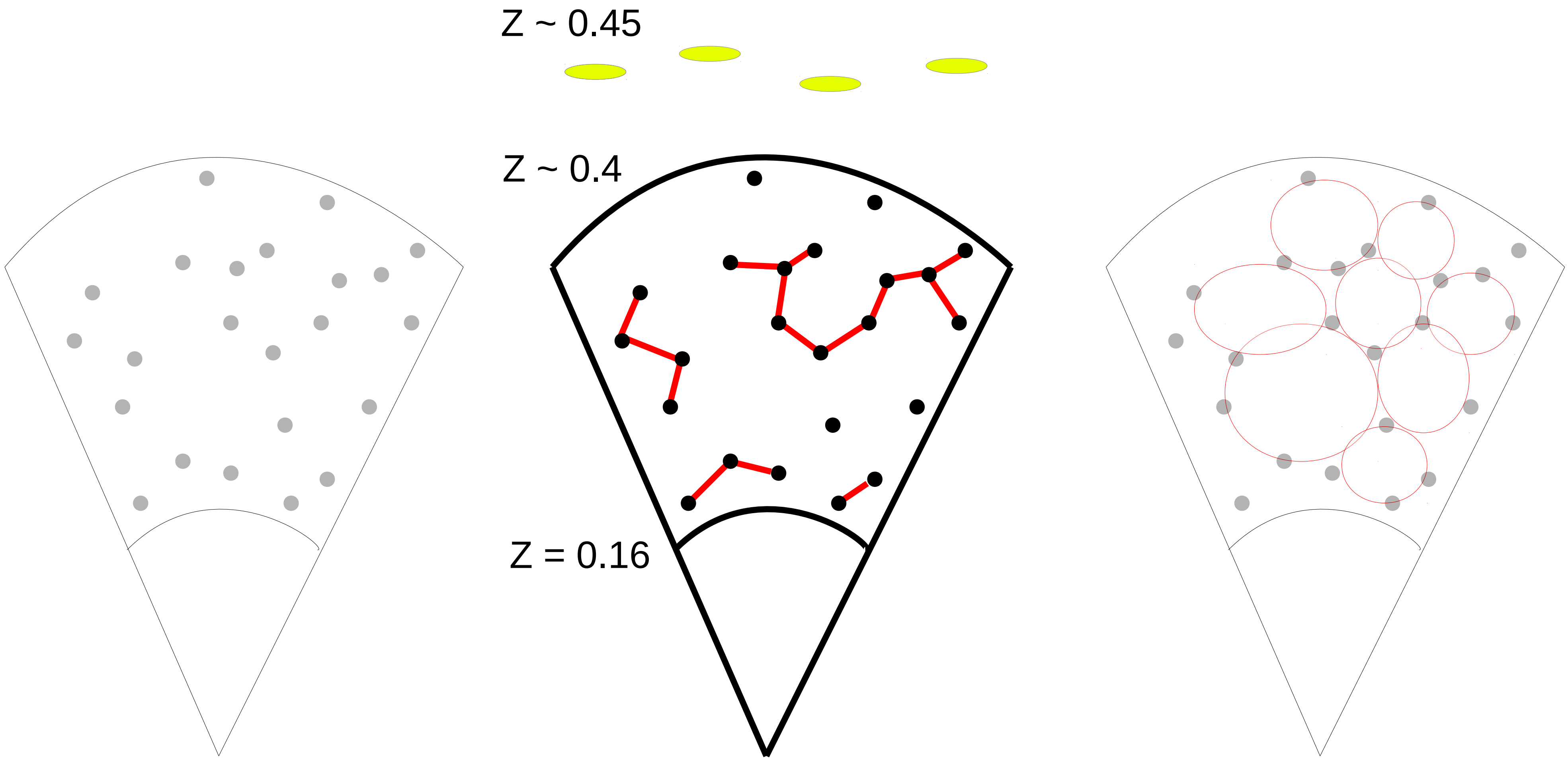
$$\rho(r, R_{\rm v}) = \begin{cases} \bar{\rho}[A_0 + A_3(r/R_{\rm v}^{(m)})^3] & \text{for } 0 < r < R_{\rm v}^{(m)} \\ \bar{\rho}[A_0 + A_3] & \text{for } R_{\rm v}^{(m)} < r \end{cases}$$

- Data consistent with sharply rising mass profile between $R_v/2$ and R_v
- Partially compensated mass distribution, approaching mean density at 2-3 R_v
- Underdensity inside void radius: -0.3 to -0.4
- Mass deficit: $10^{15\text{-}16}$ solar masses per void, as much mass as in the largest clusters



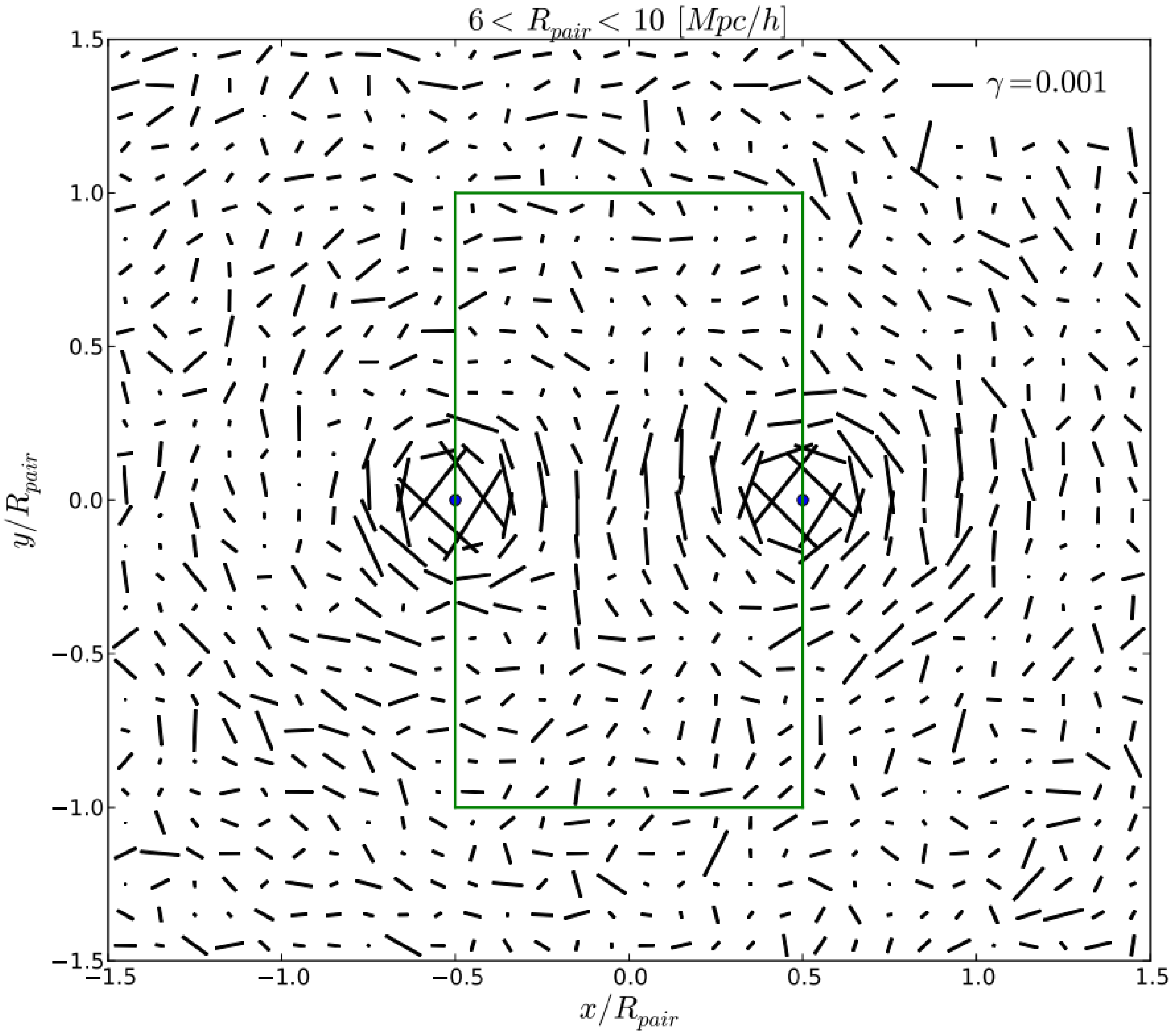


Filament Lensing



JC, Jain, Takada, arxiv:1402.3302

Selecting Halo Pairs



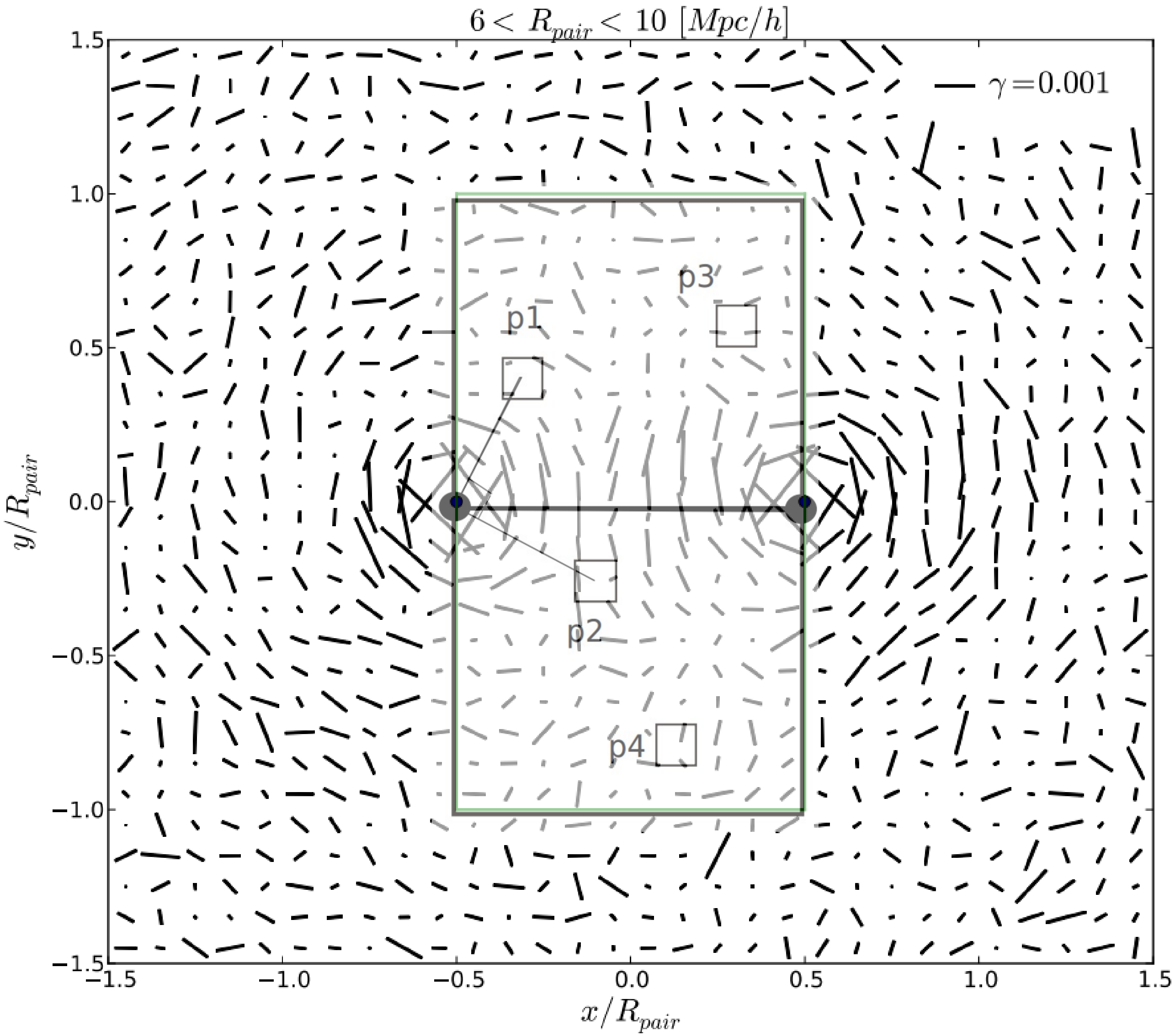
- Filaments are expected between close pairs of dark matter halos (Colberg et al. 2005).

- We use the Kazin et al. (2010) LRG catalog to find 200,000 pairs with separation
6 Mpc/h < Rpair < 18 Mpc/h
and 0.16 < z < 0.47.

- Also 34.5 million background sources from Sheldon et al. (2009).

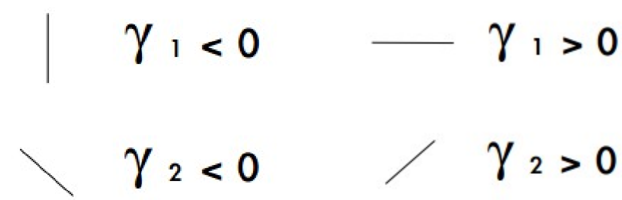
- However, the tangential shear pattern from these halos has a similar shape to that from filaments, and is much larger in amplitude.

Nulling Spherical Shear

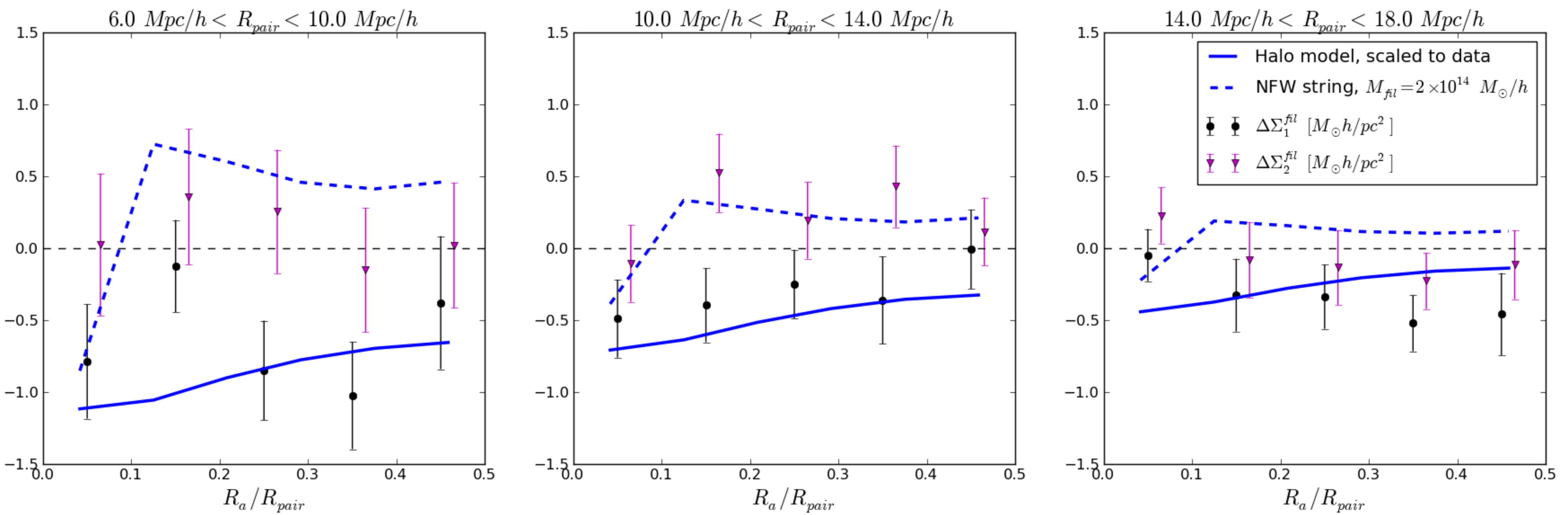


- We use an estimator that removes the shear signal from both halos.

- This requires binning the shear in quads of points, in a Cartesian coordinate system:



- The average of both shear components in p1 and p2 is zero w.r.t. the left halo.

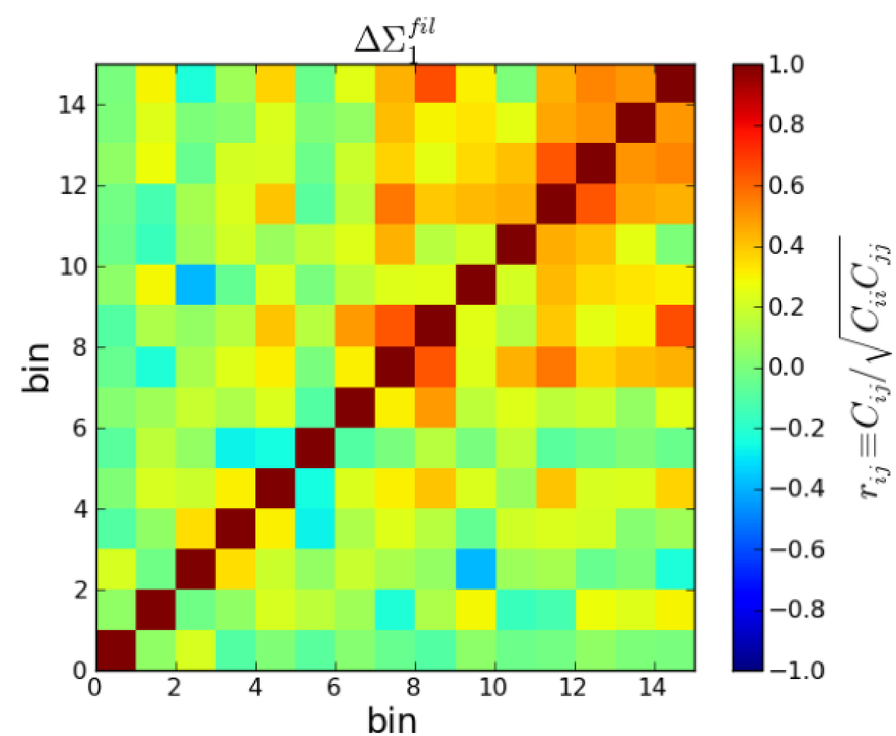


Thin filament: String of NFW Halos (dashed line)

- Wrong shape. Only gets the first data point right, then sign-flips to positive gamma_1.

Thick filament: Halo model theory (solid)

- Correct shape.
- Amplitude dependent on redshift space distortions, theory approximations, dilution from stacking LRG pairs without filaments.



JC, Jain, Takada, arxiv:1402.3302

Conclusions

We have made high signal-to-noise measurements of lensing by voids and filaments. While the light distribution of these cosmic structures was known, now we can study the mass distribution as well.

Voids act like objects with an effectively negative mass, bending light rays away from them. We have measured the resulting radial distortions of background galaxy images.

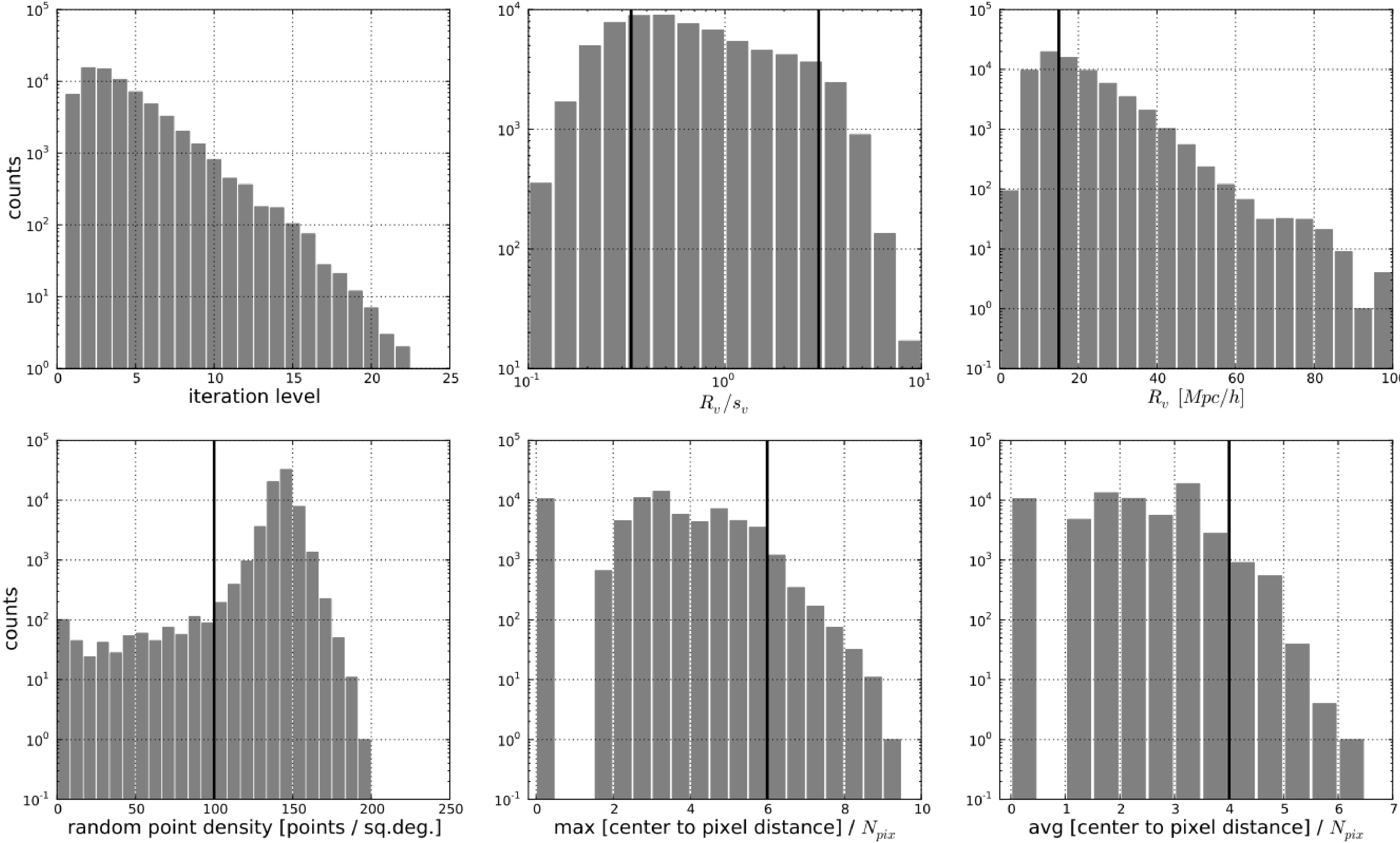
Voids are not as empty as they appear: dark matter permeates all the way to the center of the voids. The density at the center of a typical void is about half the mean density in the universe. That still leaves the voids with an enormous effective negative mass, as much as that bound up in the largest galaxy clusters.

Ongoing study of these 2D selected voids includes their clustering properties, both void-galaxy and void-void correlations.

The tangential shear signal of close halo pairs makes filament detection difficult, but it is possible with this technique for nulling spherical shear signals.

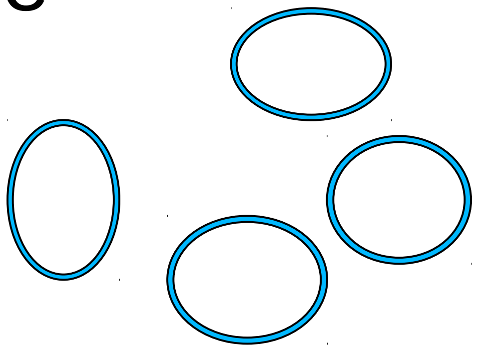
Stacked filaments are thick, extending beyond the virial radii of the halos on the filament endpoints.

Extra Slides



counts
iteration level
R_v/s_v
$R_v\ [Mpc/h]$
counts
random point density [points / sq.deg.]
max [center to pixel distance] / N_{pix}
avg [center to pixel distance] / N_{pix}

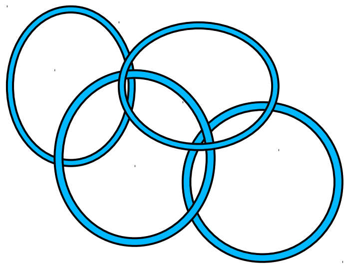
Lensing by voids: signal to noise



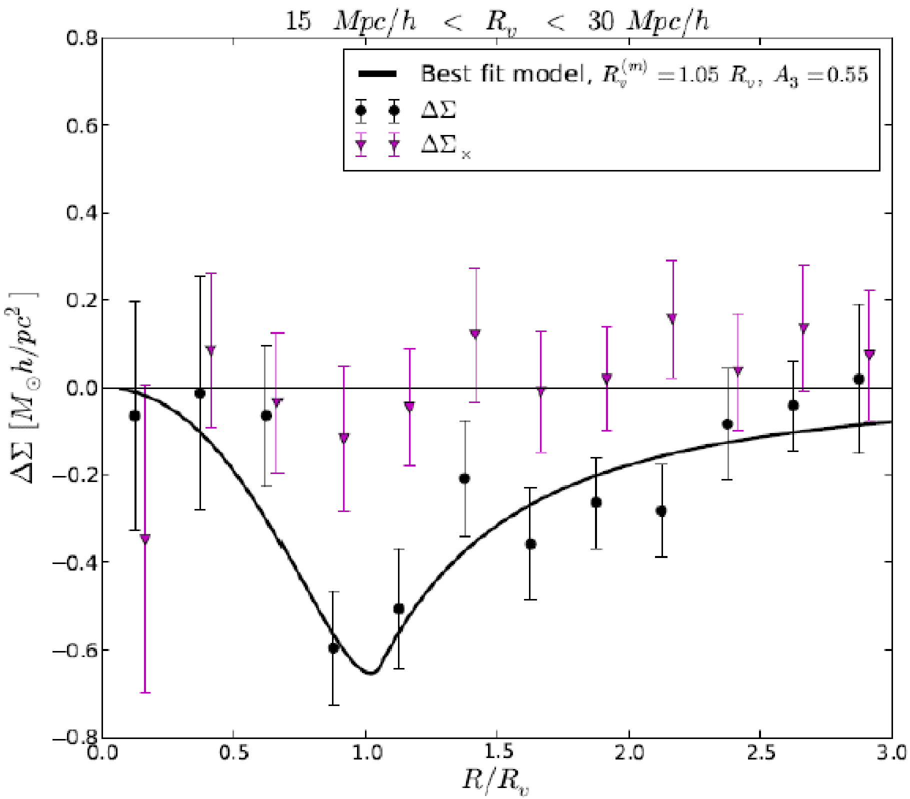
Theory: Signal-to-noise O(1) from current data if stack all “reliably empty” voids
Signal-to-noise (S/N) from Euclid survey ~15 *(Krause et al 2013)*

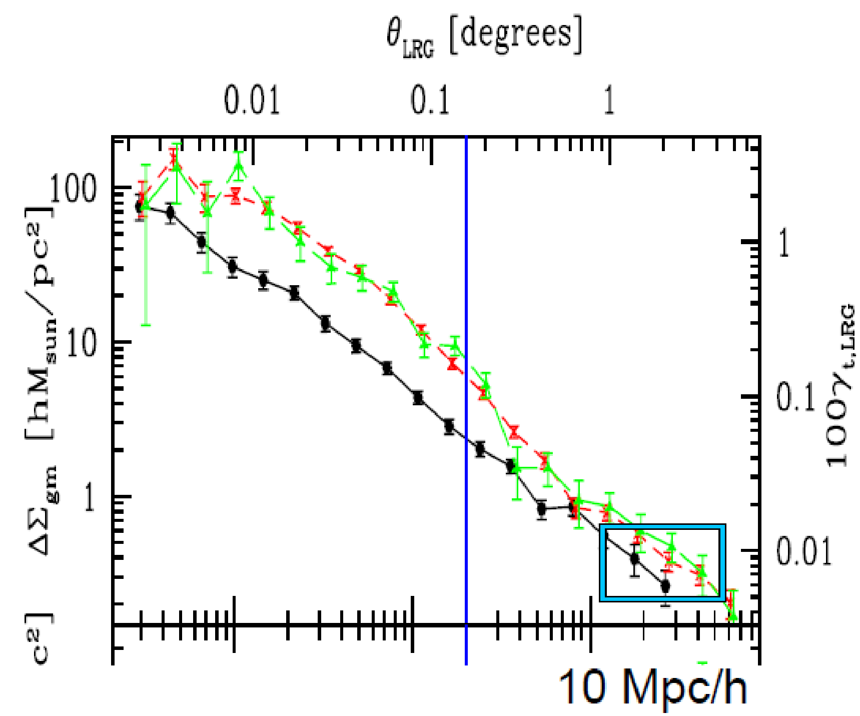
Our SDSS strategy:

- find voids in 2D
- stack ~20,000 overlapping voids, scaled by void radius
- project typical source galaxy ~30 times towards different void centers
- Result: S/N > 15



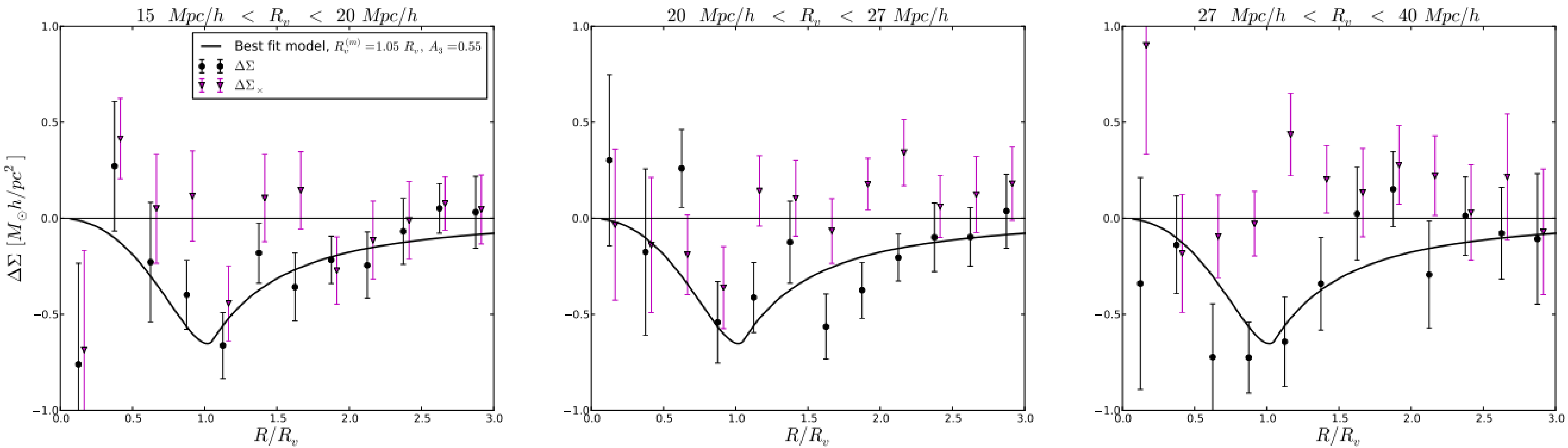
Void-galaxy vs. Galaxy-galaxy lensing





Mandelbaum et al.

Above 10 Mpc galaxy-galaxy lensing has similar amplitude and S/N to void-galaxy lensing!



$15\ \ Mpc/h\ \ <\ \ R_v\ \ <\ \ 20\ Mpc/h$
$20\ \ Mpc/h\ \ <\ \ R_v\ \ <\ \ 27\ Mpc/h$
$27\ \ Mpc/h\ \ <\ \ R_v\ \ <\ \ 40\ Mpc/h$
Best fit model, $R_v^{(m)} = 1.05\ R_v,\ A_3 = 0.55$
$\Delta\Sigma$
$\Delta\Sigma_\times$
$\Delta\Sigma\ [M_\odot h/pc^2]$
R/R_v