Detecting cosmic voids via maps of geometric-optics parameters

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Cosmic Voids

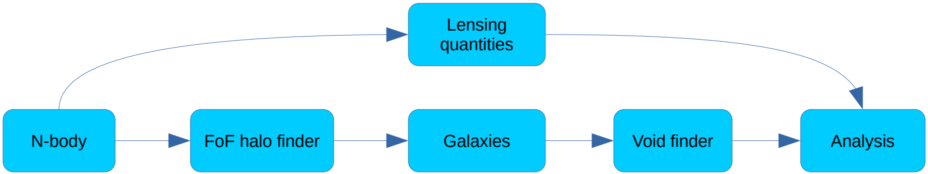
- There are several void finders, e.g. using the 3D density:
  - Spherical (Padilla et al. 2005)
  - Watershed (Platen et al. 2007)
- or using the weak lensing signal
  - Troughs (Gruen et al. 2016)
  - Tunnels (Davies et al. 2018)
- Voids are an excellent tool to probe cosmological models (e.g. Contarini et al. 2022)
- The definition of a void is crucial yet still ambiguous (Nadathur et al. 2015, Libeskind et al. 2018)

Can we trace voids based on other data, i.e. its gravitational lensing signal, and correlate these to the intrinsic (3D) voids?

Software pipeline

- We present a highly reproducible pipeline following the Maneage template (Akhlaghi et al. 2021)
- Please check out (Peper et. al. 2023): `https://codeberg.org/mpeper/lensing`
- The main steps are as follows:

$N_{\mathrm{DM}} = 256^3, L_{\mathrm{box}} = 120\mathrm{Mpc}/h, \Omega_M = 0.3, \Omega_\Lambda = 0.7, h = 0.7$



Lens Plane

Image Credit: Bartelmann, Schneider 2001, Physics Reports

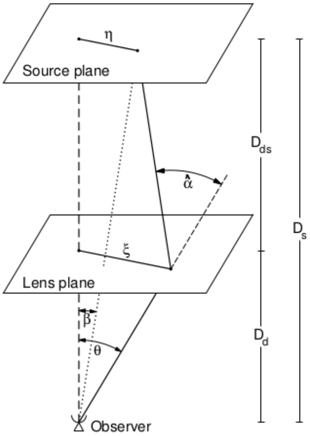
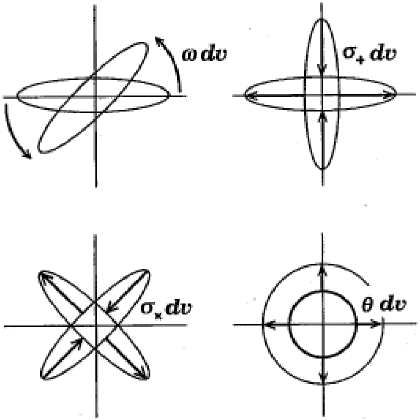


Image Credit: Sasaki 1993, Progress of Theoretical Physics



Method: Mathematical basis

Blue variables are taken from the N-body simulation; Red variables are used to detect voids

$$ds^2 = a^2 \left[-(1+2\Phi)\mathrm{d}\eta^2 + (1+2\Phi)\delta_{ij}\mathrm{d}x^i\mathrm{d}x^j \right] \tag{1}$$

Weak lensing approximation

$$\Sigma(\hat{n}) = \int_{\chi_{\min}}^{\chi_{\max}} (\rho(\hat{\chi},\Omega) - \bar{\rho})\mathrm{d}\chi \tag{2}$$

$$A = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2-\omega \\ -\gamma_2+\omega & 1-\kappa+\gamma_1 \end{pmatrix} \tag{3}$$

The convergence κ and shear γ can be written down as

$$\kappa = \frac{\Sigma(\hat{n})}{\Sigma_{\mathrm{crit}}} \;, \quad \gamma = \frac{\Delta\Sigma}{\Sigma_{\mathrm{crit}}}, \tag{4}$$

$$\Sigma_{\mathrm{crit}} = \frac{c^2}{4\pi G}\frac{D_{\mathrm{OS}}}{D_{\mathrm{OL}}D_{\mathrm{LS}}} \text{ and } \Delta\Sigma = \tilde{\Sigma} - \Sigma(\hat{n}) \tag{5}$$

$$\tilde{\Sigma}(r) = \frac{\int_0^r \int_0^{2\pi} \Sigma(r',\varphi)\,\mathrm{d}\varphi\mathrm{d}r'}{\int_0^r \int_0^{2\pi} \mathrm{d}\varphi\,\mathrm{d}r'} \tag{6}$$

Sachs optical scalars

$$\frac{\mathrm{d}}{\mathrm{d}\nu}\theta = -R_{00} - 2|\sigma|^2 - \frac{1}{2}\theta^2 \tag{7}$$

$$\frac{\mathrm{d}}{\mathrm{d}\nu}\sigma = -(C_{1010} + iC_{1020}) - \sigma\theta. \tag{8}$$

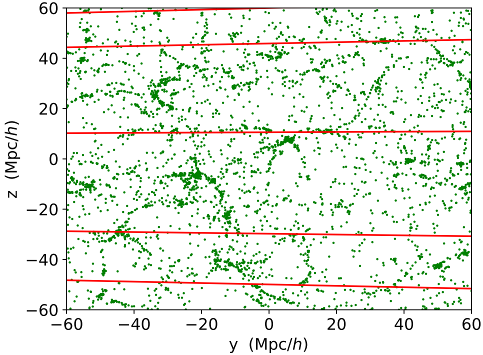
In the Newtonian approximation the Ricci and the Weyl tensor can be written as

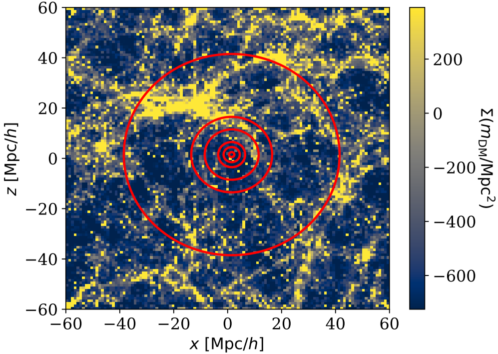
$$R_{00} = 8\pi G\rho(1+z)^2 \tag{9}$$

$$C_{A0B0} = (2\Phi_{;AB} - \delta_{AB}\Phi_{;C}^{;C})(1+z)^2 \tag{10}$$

$$= (2\Phi_{;\mu\nu}e_A^\mu e_B^\nu - \delta_{AB}\delta^{CD}\Phi_{;\mu\nu}e_C^\mu e_D^\nu)(1+z)^2 \tag{11}$$

Method: Void detection



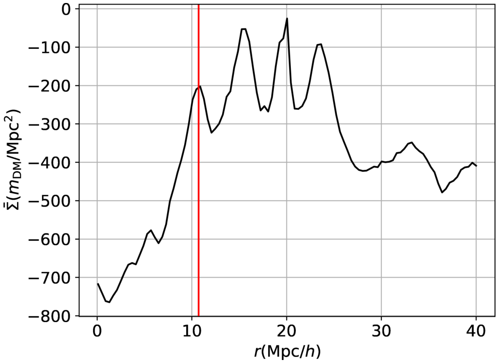


Send 120 $\times$ 120 light rays through the density distribution

Assume the void is at $z = 0.5$ and source galaxies are at twice the distance

$$\overline{\Sigma}_j(r) = \frac{\int_0^{2\pi} \Sigma(r, \varphi)\mathrm{d}\varphi}{\int_0^{2\pi} \mathrm{d}\varphi} \quad (12)$$

Method: Void detection in Σ, θ, σ



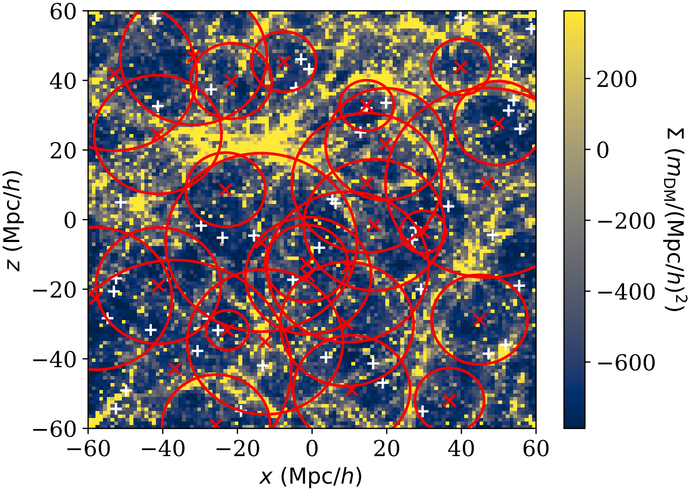
- 100 steps in r
- Find 4 successive steps with a slope larger than the mean slope, i.e.
  $\overline{\Sigma}' > \sum \frac{\overline{\Sigma}_i'}{N}$
- To avoid detecting noise also require:
  $\Delta\Sigma = \overline{\Sigma}_i - \overline{\Sigma}_{i-1} > f\,\mathrm{std}(\overline{\Sigma}(< r_i))$
  and
  $\overline{\Sigma}_i > g \sum \frac{\overline{\Sigma}(<r_i)}{N}$,
  where f and g are free parameter
- Return $1/r_{i_1}$ as **selection criterion**
- Identify local minima in the generated map

Results: Detected voids using the surface overdensity Σ

Compare voids in the projected plane (red crosses) with the intrinsic (3D) voids (white pluses)

$$\Sigma(\hat{n}) = \int_{\chi_{\min}}^{\chi_{\max}} (\rho(\hat{\chi}, \Omega) - \bar{\rho}) \mathrm{d}\chi$$

The surface overdensity Σ can be interpreted as a measure for how much matter is on the line of sight. It is the closest quantity we have compared to Gruen, Friedrich et. al. 2016.



Results: Radial profiles of detected voids using the surface overdensity Σ

Radial profiles of voids in the projected plane (red) and the intrinsic (3D) voids (blue)

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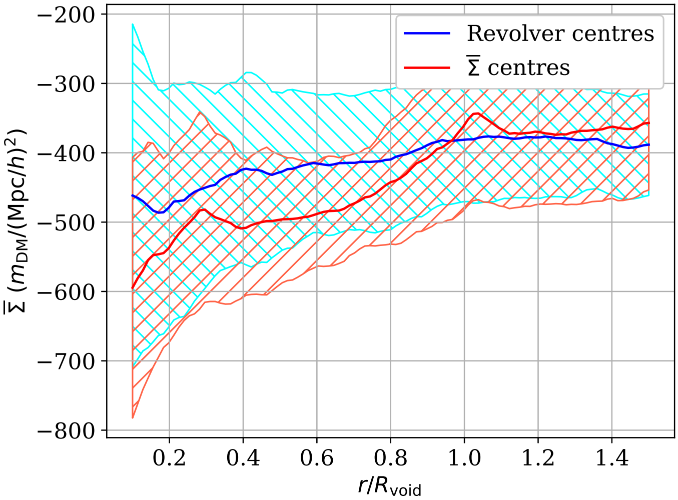


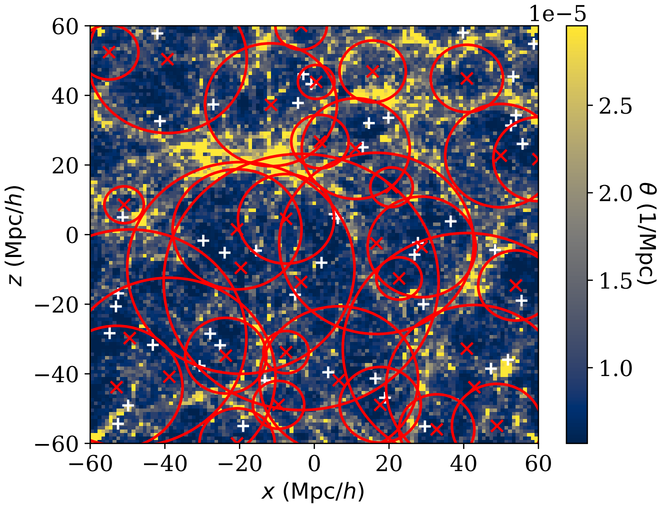
Results: Detected voids using the expansion θ

Compare voids in the projected plane (red crosses) with the intrinsic (3D) voids (white pluses)

$$\frac{\mathrm{d}}{\mathrm{d}\nu}\theta = -R_{00} - 2|\sigma|^2 - \frac{1}{2}\theta^2$$

$$\frac{\mathrm{d}}{\mathrm{d}\nu}\sigma = -(C_{1010} + iC_{1020}) - \sigma\theta.$$

The Sachs optical scalars measure the deformation of the observed image.



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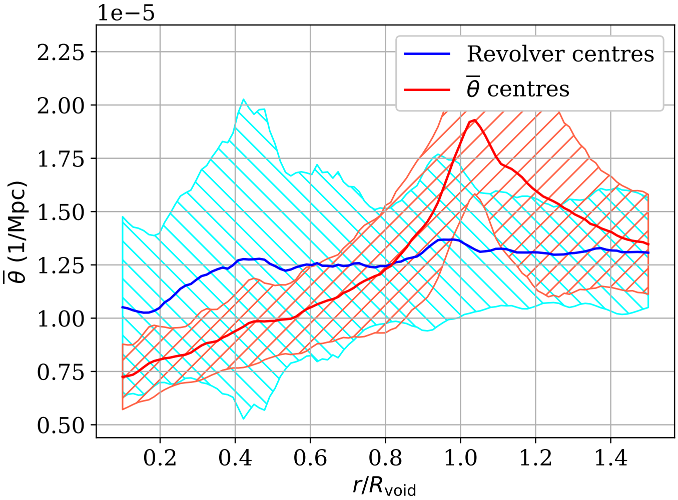

Results: Detected voids using the shear σ

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$$|\sigma| = \sqrt{\mathrm{Re}(\sigma)^2 + \mathrm{Im}(\sigma)^2}$$

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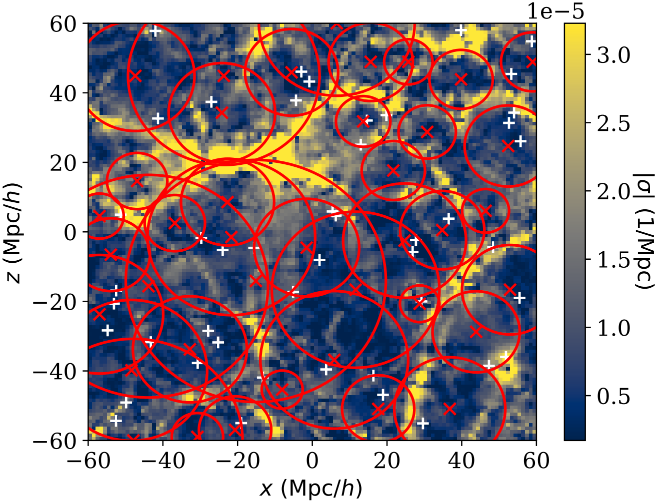

Results: Radial profiles of detected voids using the shear σ

Radial profiles of voids in the projected plane (red) and the intrinsic (3D) voids (blue)

$$\frac{\mathrm{d}}{\mathrm{d}\nu}\theta = -R_{00} - 2|\sigma|^2 - \frac{1}{2}\theta^2$$

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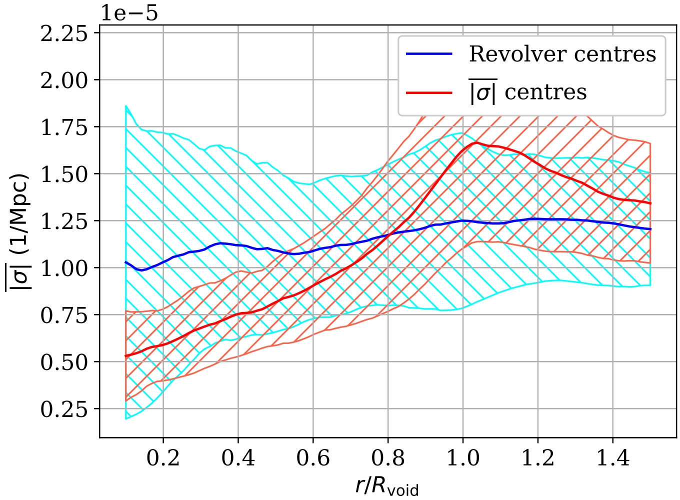
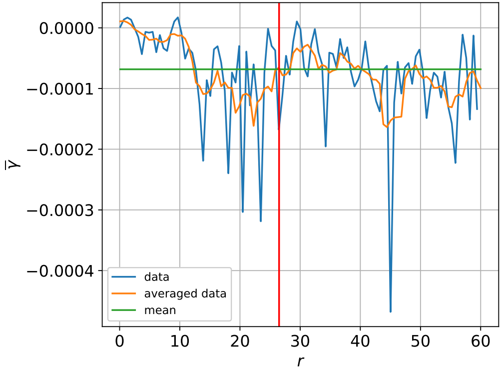


Method: Void detection in the weak lensing shear γ



$$\gamma = \frac{\tilde{\Sigma} - \Sigma(\hat{n})}{\Sigma_{\mathrm{crit}}}$$

$$\tilde{\Sigma}(r) = \frac{\int_0^r \int_0^{2\pi} \Sigma(r', \varphi)\, \mathrm{d}\varphi \mathrm{d}r'}{\int_0^r \int_0^{2\pi} \mathrm{d}\varphi\, \mathrm{d}r'}$$

- 100 steps in r
- To cope with the extreme noisy data (blue curve) we average by estimating $\overline{\gamma}(r_i) = \sum_{i-3}^{i+3} \gamma_i$
- **start of the drop**: Find location r_{i_1} where $\overline{\gamma}(r_i)$ (orange curve) drops below the mean of $\overline{\gamma}$ (green line)
- **edge of the void**: Find r_{i_2} where $\overline{\gamma}(r_i)$ raises over the mean again
- Return $1/r_{i_2}$ as **selection criterion**
- Identify local minima in the generated map

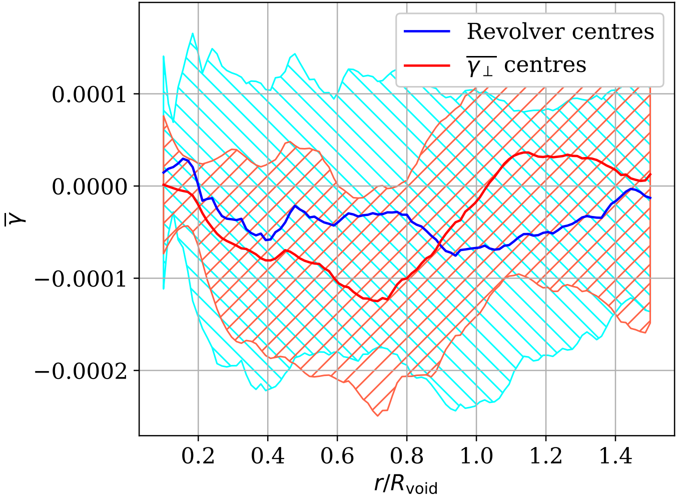
Results: Radial profiles of detected voids using the weak lensing shear γ

Radial profiles of voids in the projected plane (red) and the intrinsic (3D) voids (blue)

$\gamma = \frac{\tilde{\Sigma} - \Sigma(\hat{n})}{\Sigma_{\mathrm{crit}}}$ only holds true when Σ/κ is symmetric.

We could use $\gamma_1 = \Psi_{,11}$ and $\gamma_2 = \Psi_{,12}$ to access the full information.

In our approach we take an averaged version $\overline{\gamma_T}(r, \hat{n}) = \frac{\tilde{\Sigma} - \overline{\Sigma}(r, \hat{n})}{\Sigma_{\mathrm{crit}}}$



Part II - Void matching

Do we recover the intrinsic (3D) voids?

N_{3D}	N_{2D}^{Σ}	N_{2D}^{γ}	N_{2D}^{θ}	N_{2D}^{σ}
46	28	29	34	39

- We find fewer voids in the four detector variables
- We match the 2D and 3D voids based on proximity in the *xz*-distance and the size (effective radius).
  - Generate 100, 000 random sets for each quantity
  - Compare the median distance

$$P = \frac{N_{\mathrm{better-than-mock}}}{N_{\mathrm{total-mock}}}$$

The closer we are to zero the more significant is our result.

X	$P_{x,z}(3D\|2D)$	$P_{x,z}(2D\|3D)$
Σ	0.027	0.0038
$\overline{\gamma_\perp}$	0.01	3.0×10^{-5}
θ	0.0005	3.0×10^{-5}
$\|\sigma\|$	0.00014	1.0×10^{-5}

Summary

- We do not recover all voids
- We find a high significance between the positions of projected voids and the voids identified in the 3D density distribution
- With sufficient data it seems feasible to identify voids based on geometrical optics parameters, though the algorithm will need more work
- Pipeline available at: `https://codeberg.org/mpeper/lensing`

Future extensions:

- Use velocities and the Integrated-Sachs-Wolfe effect
- Add detector noise
- Give source galaxies a variety of redshifts
- Use full information of the shear
- Can we implement the routine for redshift bins similar to Sánchez et al. 2017

Weak lensing signal measurements

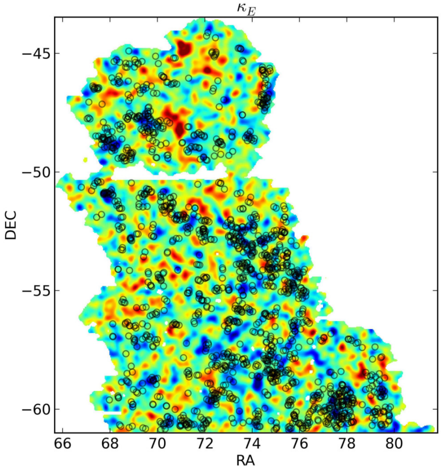
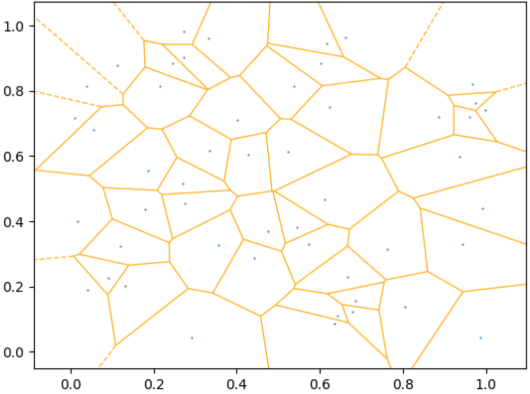


Image Credit: Gruen et. al 2016, MNRAS

- Gruen, Friedrich et. al. 2016 investigate the lensing signal in the verification data of DES
- They define troughs as underdense cylinders using the projected galaxy positions
- The authors find a strong correlation between underdense troughs and a lensing signal around the centre of the trough

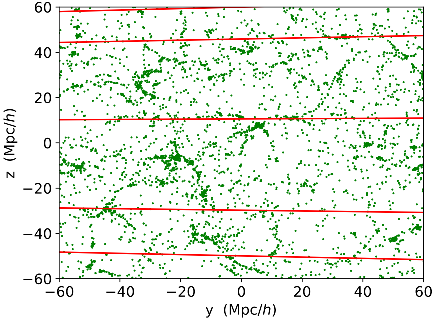
But can we correlate the signal to the 3D voids?

Voronoi tessellation



Method: Light tracing

- Trace the lensing signal on light rays in *N*-body simulations
- Assume the propagation of light rays is not affected by local inhomogeneities
- Send 120×120 light rays through the density distribution
- If a light ray leaves the box use the T^3 torus (periodic boundaries)



Light propagation

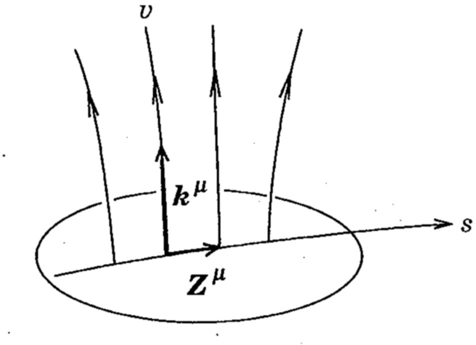


Image Credit: Sasaki 1993, Progress of Theoretical Physics

- The lensing effect will be studied by the effect on a bundle of geodesics (a light bundle)
- Assume an irrotational null geodesic
- The connection vector Z^μ related neighboring geodesics; the evolution of Z^μ contains all needed information

Matching

Do we recover the intrinsic (3D) voids?

N_{3D}	N_{2D}^{Σ}	N_{2D}^{γ}	N_{2D}^{θ}	N_{2D}^{σ}
46	28	29	34	39

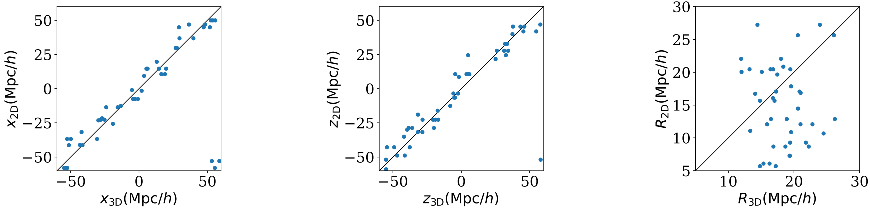
$$P^X_{(x,z)_{i,j}} = 1 - \mathrm{erf}\frac{d\left((x,z)^X_i,(x,z)^X_j\right)}{\sqrt{2}\sigma_{x,z}} \tag{13}$$

$$P^X_{R_{i,j}} = 1 - \mathrm{erf}\frac{\left|\log_{10}\left(R^X_i/R^X_j\right)\right|}{\sqrt{2}\sigma_{\log_{10} R}} \tag{14}$$

$$\sigma_{x,z} = 5\mathrm{Mpc}/h \ \text{ and } \ \sigma_{\log_{10} R} = 0.3 \tag{15}$$

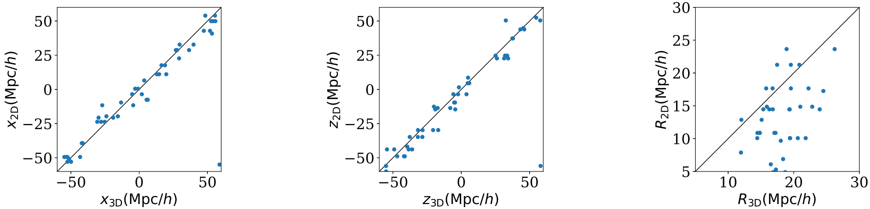
The best matched void is found via $P^X_{i,j} = P^X_{(x,z)_{i,j}} P^X_{R_{i,j}}$.

Matching Σ

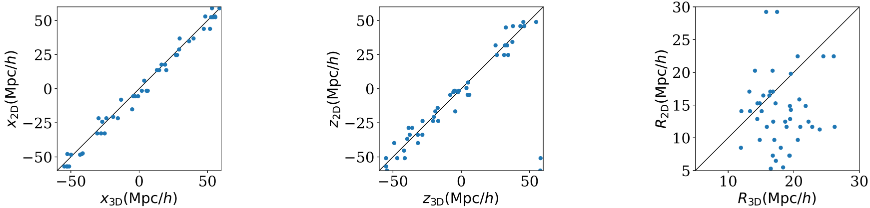


50
25
0
−25
−50
−50
0
50
x3D(Mpc/h)
x2D(Mpc/h)
z3D(Mpc/h)
z2D(Mpc/h)
30
25
20
15
10
5
10
20
30
R3D(Mpc/h)
R2D(Mpc/h)

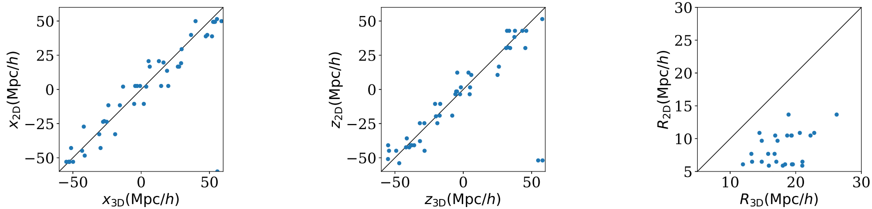
Matching θ



Matching σ



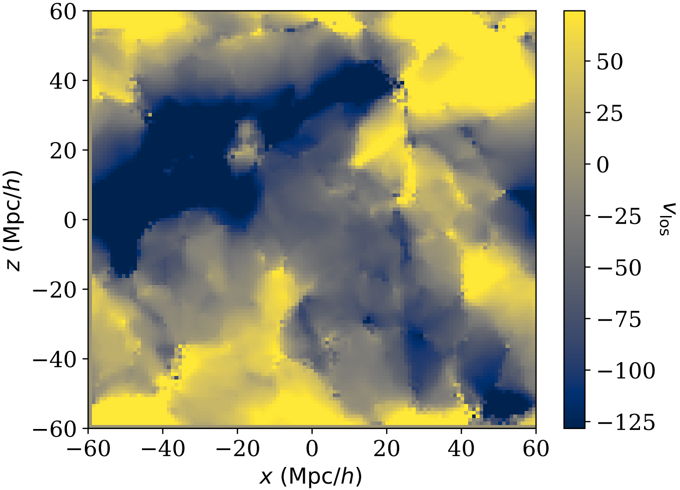
Matching γ



Future extensions - Line of sight velocity

$$v_{\rm los} = \vec{v} \cdot \hat{n}$$

Is it possible to extract information of the voids based on the line of sight velocity of galaxies?



Future extensions - Integrated Sachs Wolf Effect

$$\Delta T(\hat{n}) = \frac{2}{c^3}\bar{T}_0 \int_{\chi_{\min}}^{\chi_{\max}} \dot{\Phi} \mathrm{d}\chi$$

Can we extract cosmic voids from the ISW signal?