Cosmic Voids as cosmological laboratories

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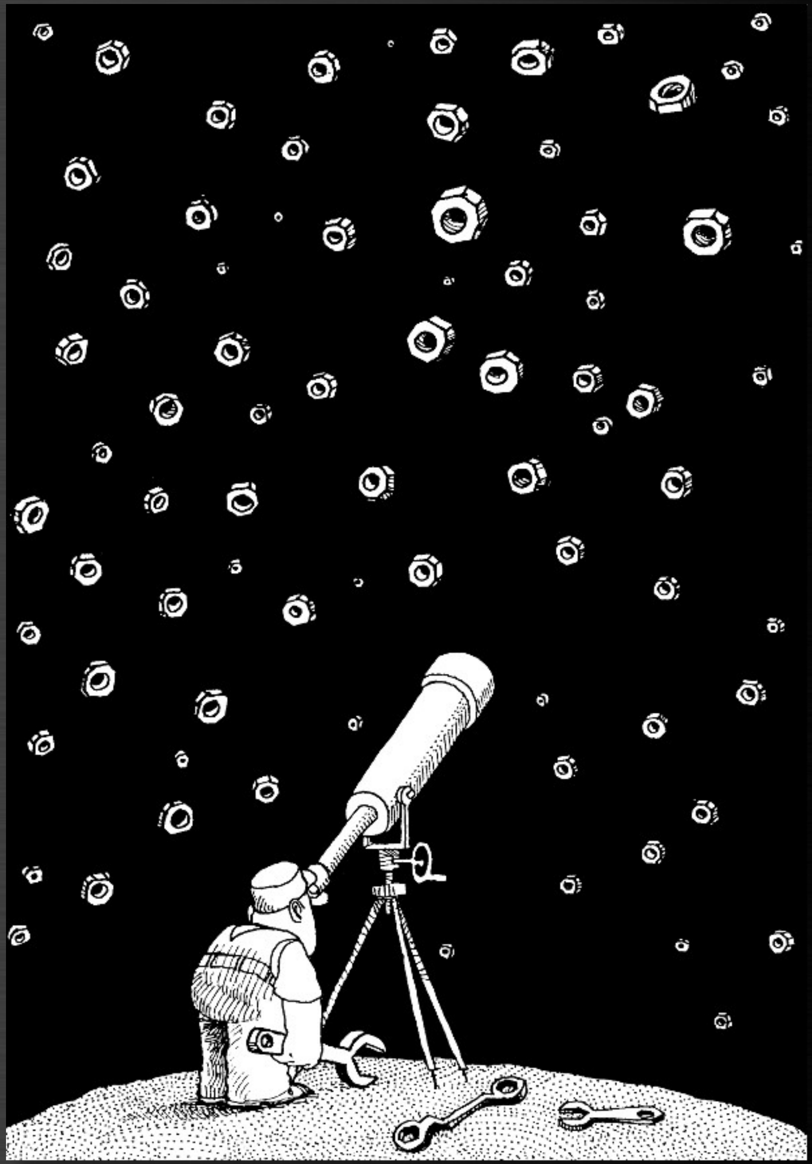

Quino (1987) – “Dejenme inventar”

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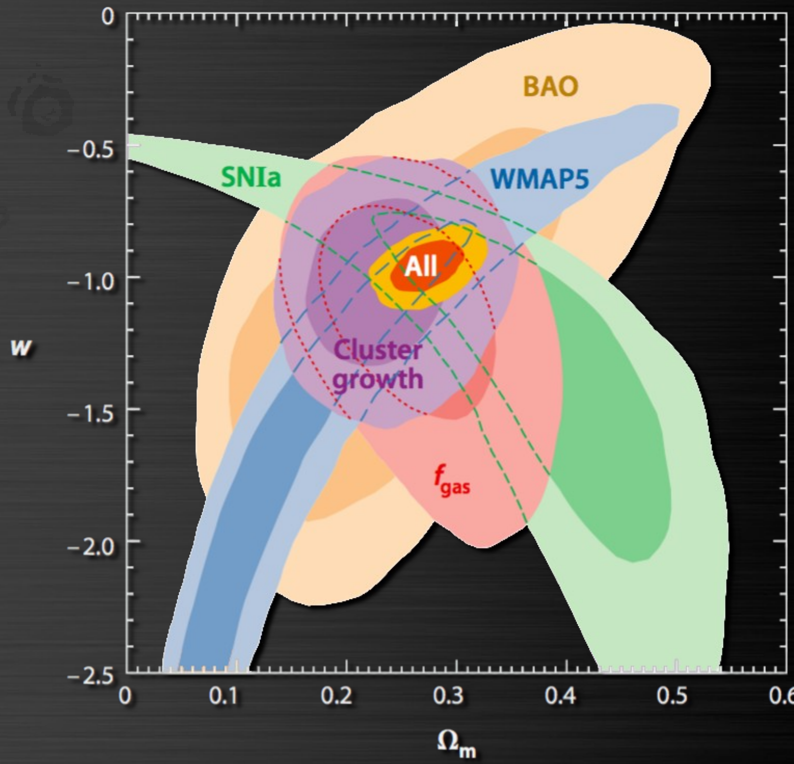
Probes for cosmological parameters

There are several methods:

- Hubble diagram
- Ia supernova
- Light elements abundance
- Cosmic shear (lensing)
- Lyman-α Forest
- Gunn-Peterson trough
- CMB Anisotropy
- Galaxy distribution (Large scale structure)
  - Baryon Acoustic Oscillation
  - Galaxy clusters (abundances and mass to light ratios)
  - Cosmic Voids (abundances and galaxy cross-correlations) new!

Allen et al. 2013



Voids as cosmo labs

There are 3 types of probes proposed in the cominuty:

- Statistics of its abundance, or void size function (VSF):
  - Excursion set theory can be used to fit VSF (Sheth & van de Weygaert 2004, Jennings et al. 2013)
- Cross-correlation with galaxy tracers (VGCF):
  - Linear theory + Gaussian streaming model fit well VGCF (Paz et al. 2013, Hamaus et al. 2015, Cai et al. 2016)
- Void intrinsic ellipticities (Park & Lee 2007)

The main problem: Systematic errors!

- Redshift space distortions
  - VGCF has to be applied only for voids identify in real space (via reconstruction technique, Nadathur et al. 2016, Correa et al. 2020)
- Void definition/identification (watershed, integrated density...)
- Galaxy bias
  - The VSF modeling has become challenging due to galaxy bias

Void definition

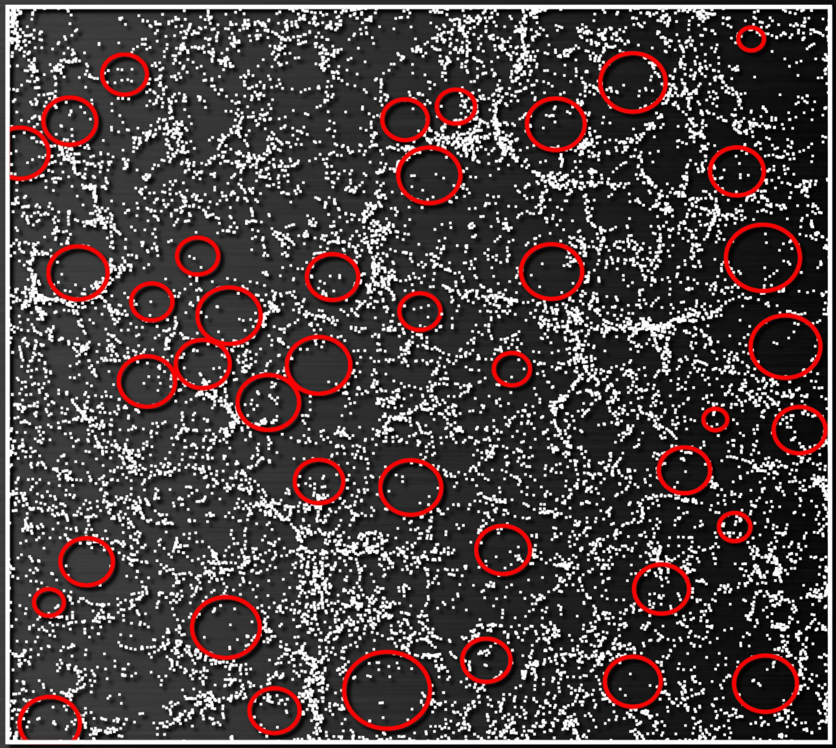
- We define voids as spherical underdense regions (SVF)

  (Padilla et al. 2005, Ruiz et al. 2015)

  – Picks centres in low density regions and grows spheres until the density crosses a barrier δ_v:

  $$\rho(S)/\bar{\rho} - 1 \leq \delta_v = -0.9$$

  After this the algorithm rejects from all overlapping spheres the smaller ones starting from the largest candidate.



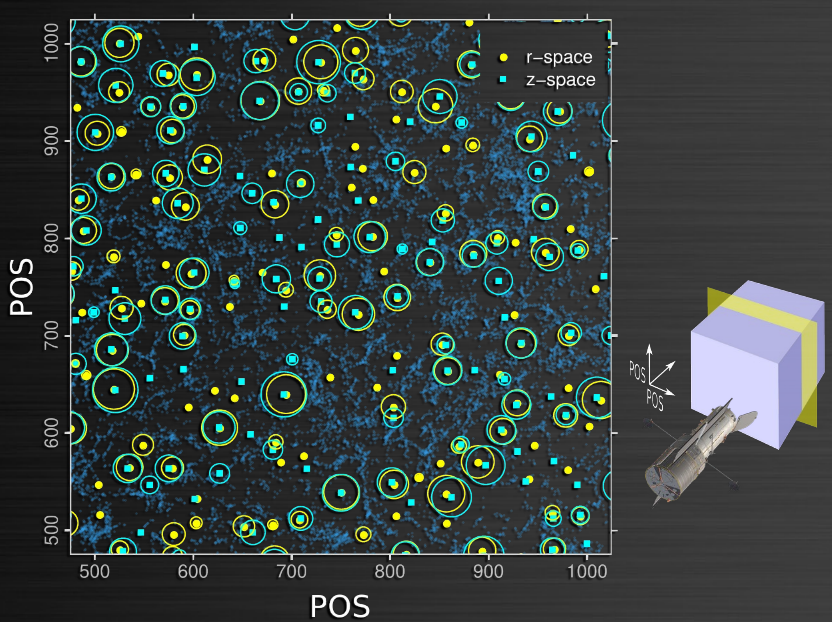
- SVF is simple and effective when is used on galaxy samples, and relates naturally with abundance predictions
- For clustering analysis it has a well defined center to compute correlation functions
- For this two reasons is our chosen void definition

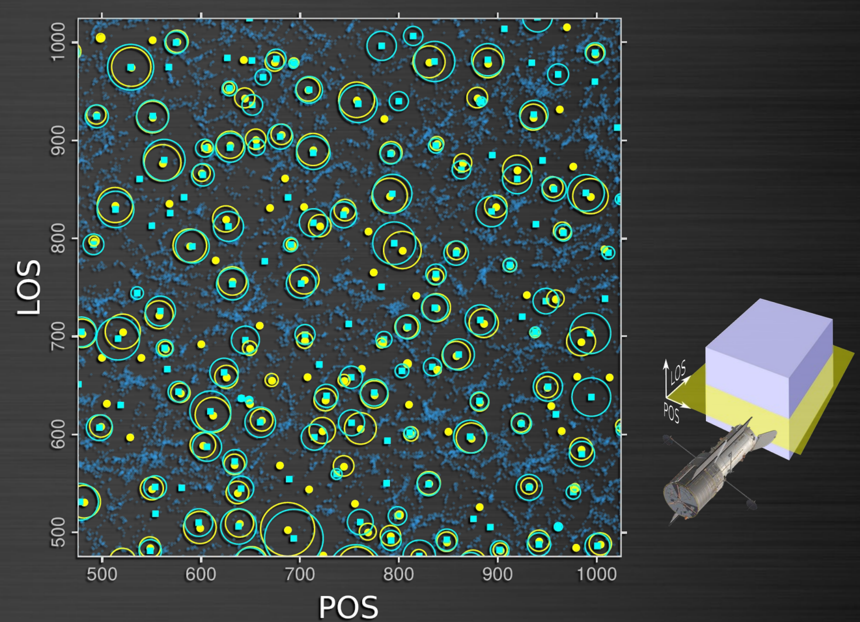
RSD in Voids

$$\tilde{r}_{\parallel} = r_{\parallel} + v_{\parallel}\frac{(1+z)}{H(z)}$$

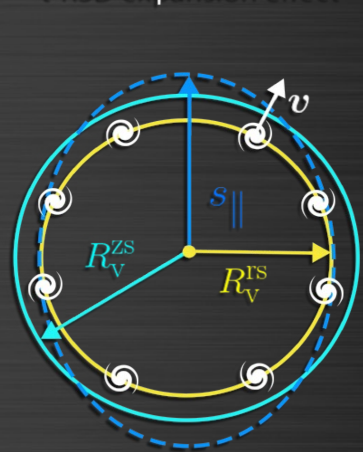
Correa et al. 2020

Millenium XXL simulation (Angulo et al. 2012)

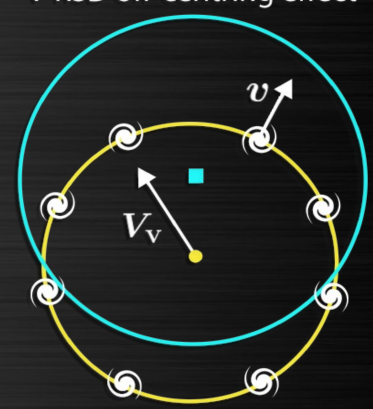




t-RSD expansion effect



v-RSD off-centring effect

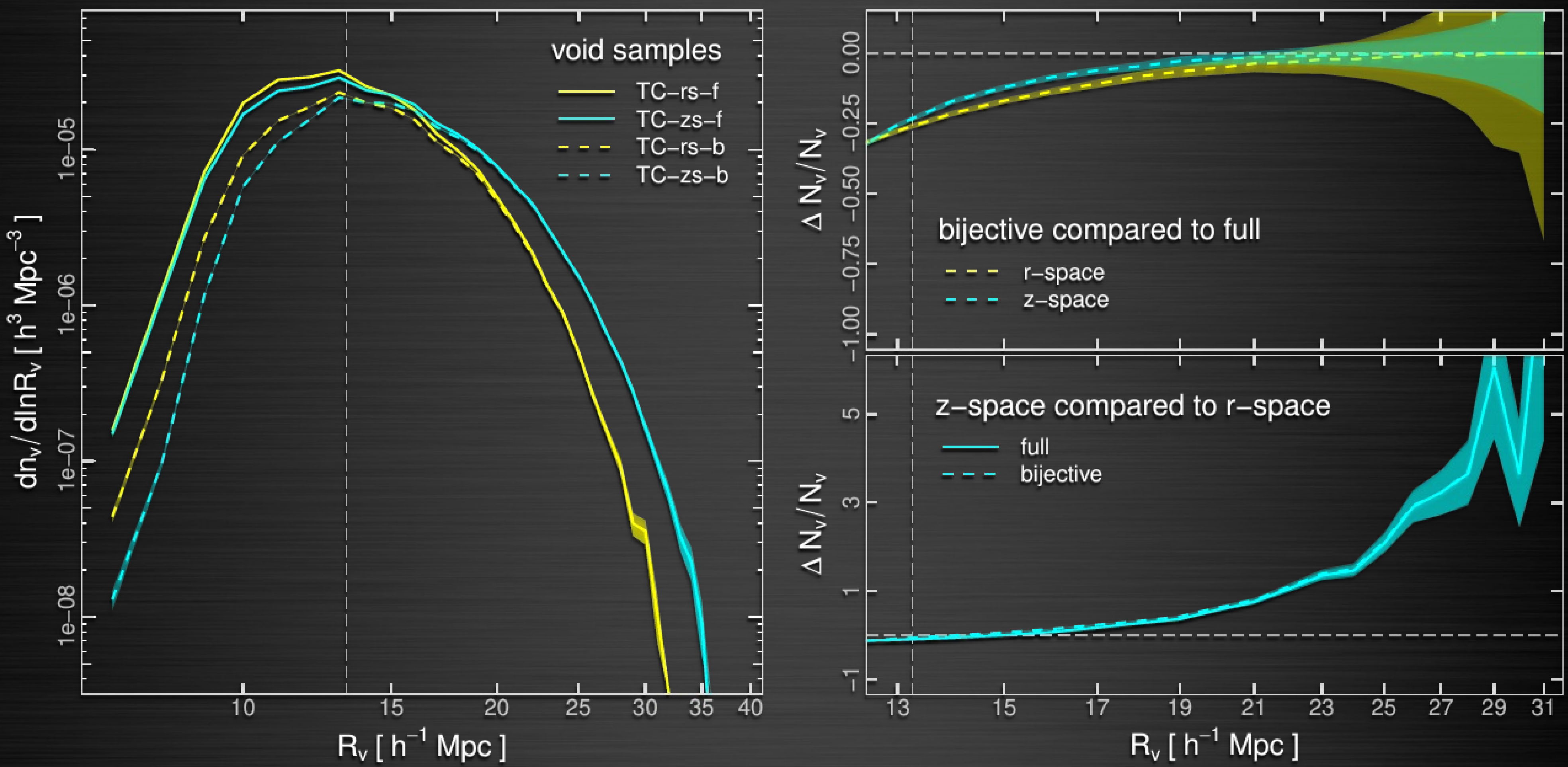


- Large voids are in a 1 to 1 map: real-space ↔ z-space
- Small voids (shot noise) may have no counterpart
- z-space voids are larger than real-space partners
- Off-centering in LOS is Gaussian distributed,
  in POS directions it is Lorentzian

- Nearly every large void are in both real and redshift space

Void abundances

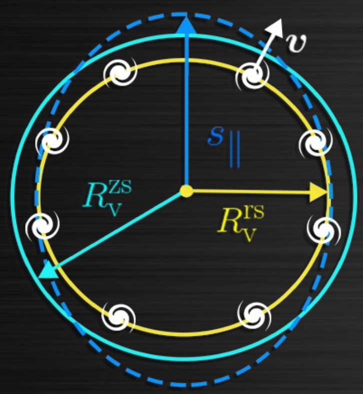
Void finders assume a fiducial cosmology (FC) to convert z to Mpc



- We define a bijective map: real-space ↔ z-space
- Just for small voids (shot-noise dominated) some voids can not be associated, for large sizes non bijective voids are despicable
- Then number is conserved for physically relevant voids and z-space voids are larger

Correa et al. 2020

Model of void expansion



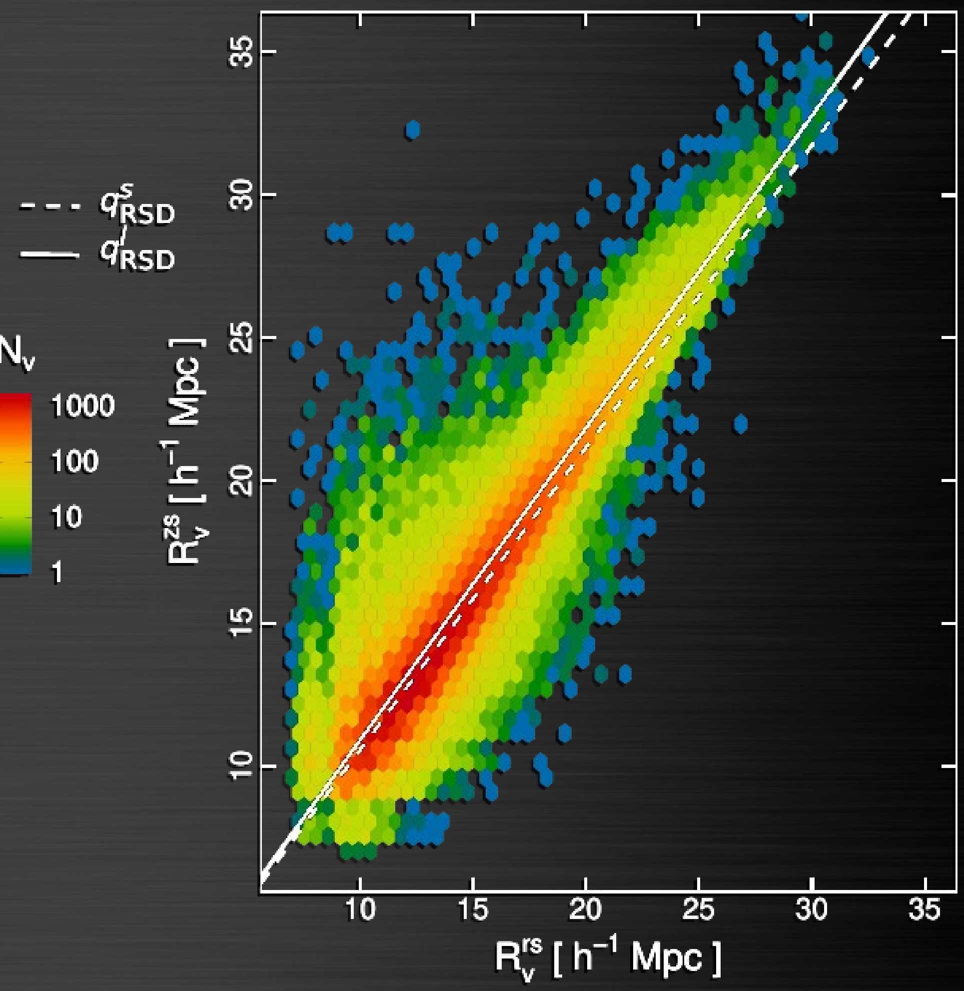
The elongation of a SV can be derived from GSM (Paz et al. 2013)

The first ansatz: z-space SV enclose an equivalent volume to the ellipsoidal RSD region:

$$R_V^{zs} = q^s_{RSD} R_V^{rs} \quad q^s_{RSD} = \sqrt[3]{1 - \frac{1}{3}\beta(z)\Delta_{id}}$$

More precisely SVF should identify a radius between the mayor axis of the ellipsoid and the first ansatz radius, taking half way:

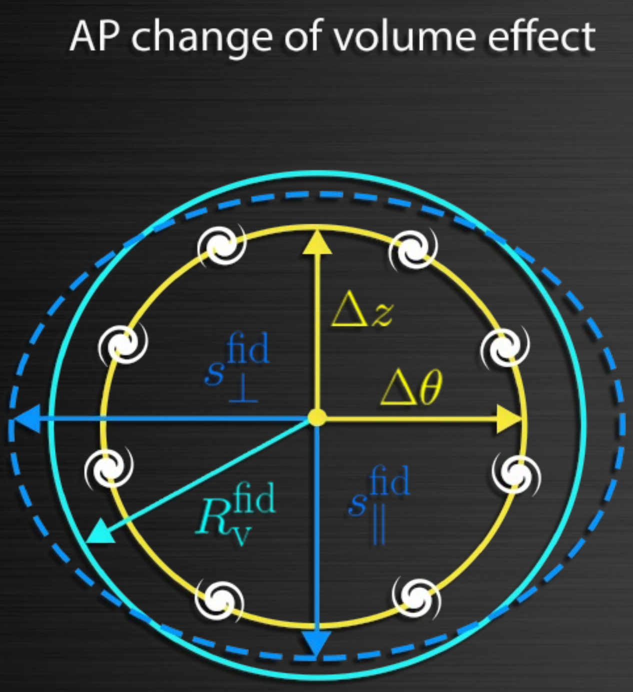
$$R_V^{zs} = q^l_{RSD} R_V^{rs} \quad q^l_{RSD} = 1 - \frac{1}{6}\beta(z)\Delta_{id}$$



- This correction depends on galaxy bias, b, times the coupling factor between density and velocity field: b*f(z)=β(z)
  (f is the growth rate of perturbation then depends on the gravity model)

Correa et al. 2020

Fiducial cosmology distortions



The spherical void in FC corresponds to an ellipsoid in TC:

$$s_\parallel^{\rm fid} = q_{\rm AP}^{\parallel} R_{{\rm v}\parallel}^{\rm true}$$

$$s_\perp^{\rm fid} = q_{\rm AP}^{\perp} R_{{\rm v}\perp}^{\rm true}$$

This change from true to fiducial cosmology is given by the comoving angular diameter distance and the Hubble parameter:

$$q_{\rm AP}^{\perp} = \frac{D_{\rm M}^{\rm fid}(z)}{D_{\rm M}^{\rm true}(z)} \qquad q_{\rm AP}^{\parallel} = \frac{H_{\rm true}(0)\,H_{\rm true}^{1/2}(z)}{H_{\rm fid}(0)\,H_{\rm fid}^{1/2}(z)}$$

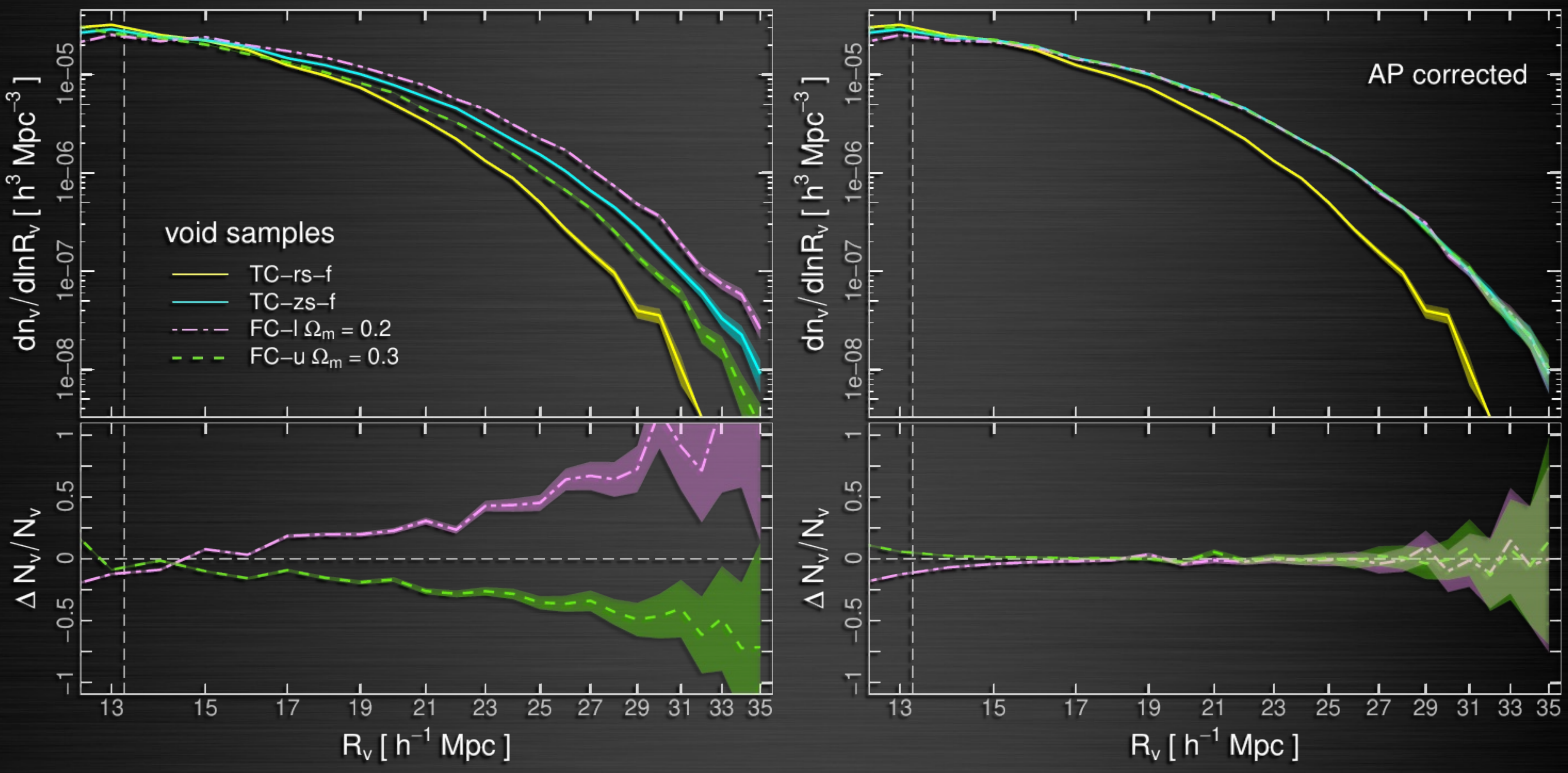
Equivalent volume radius are related by:

$$R_{\rm v}^{\rm fid} = q_{\rm AP} R_{\rm v}^{\rm rs} \qquad q_{\rm AP} = \sqrt[3]{(q_{\rm AP}^{\perp})^2 q_{\rm AP}^{\parallel}}$$

Correa et al. 2020

Geometrical and dynamical distortions of Void size function

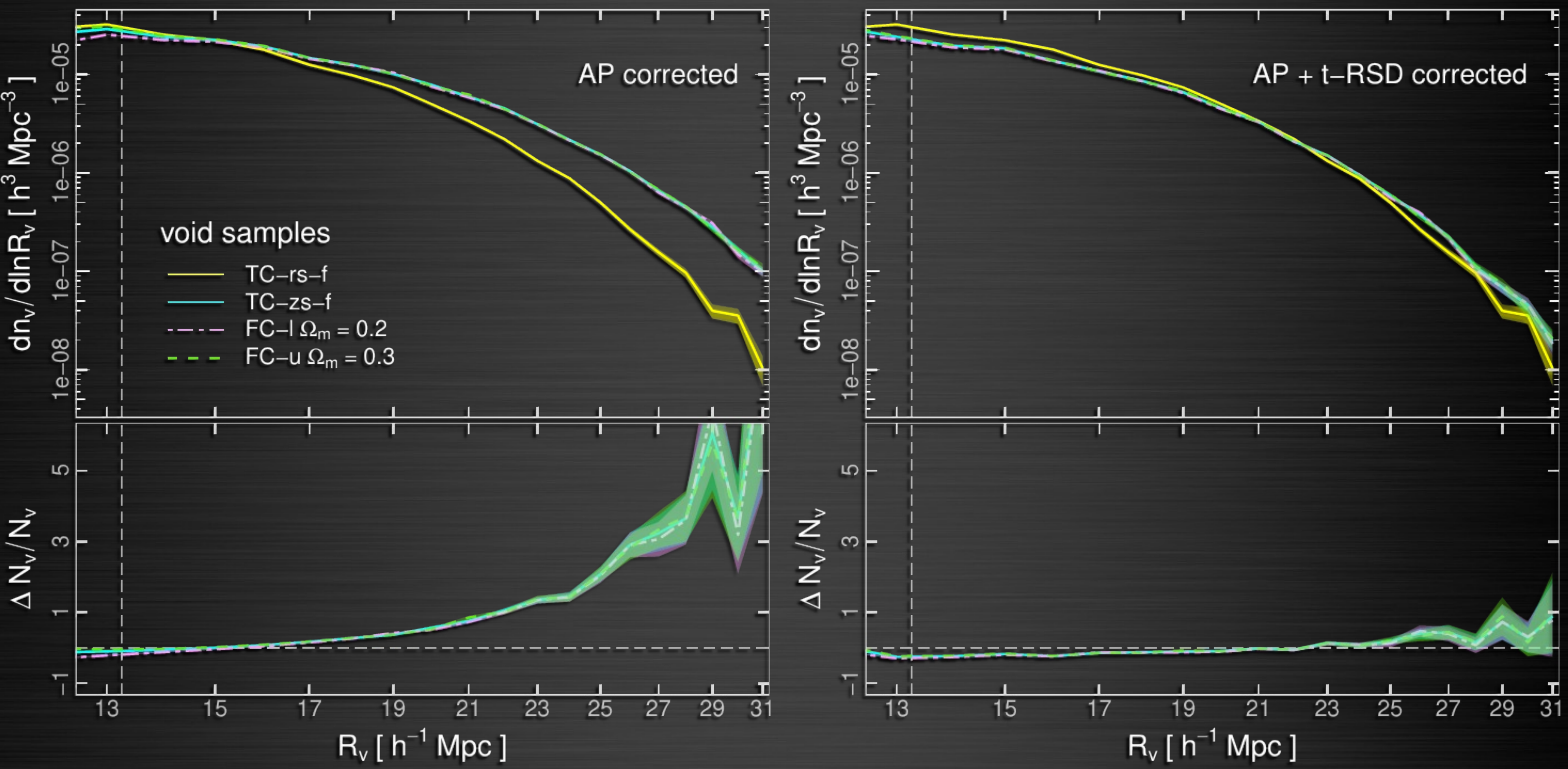
For different FC mocks we run SVF and measure VSF, then we apply the AP volume correction factors:



- There is no difference between different FC (the AP factors can be used to extract info)
- The difference between the true underlying abundance and the mock values are RSD

Correa et al. 2020

Geometrical and dynamical distortions of Void size function



Important:

Not only the Excursion set model of VSF encodes cosmological information:

The factors we derived are strongly cosmology dependent:

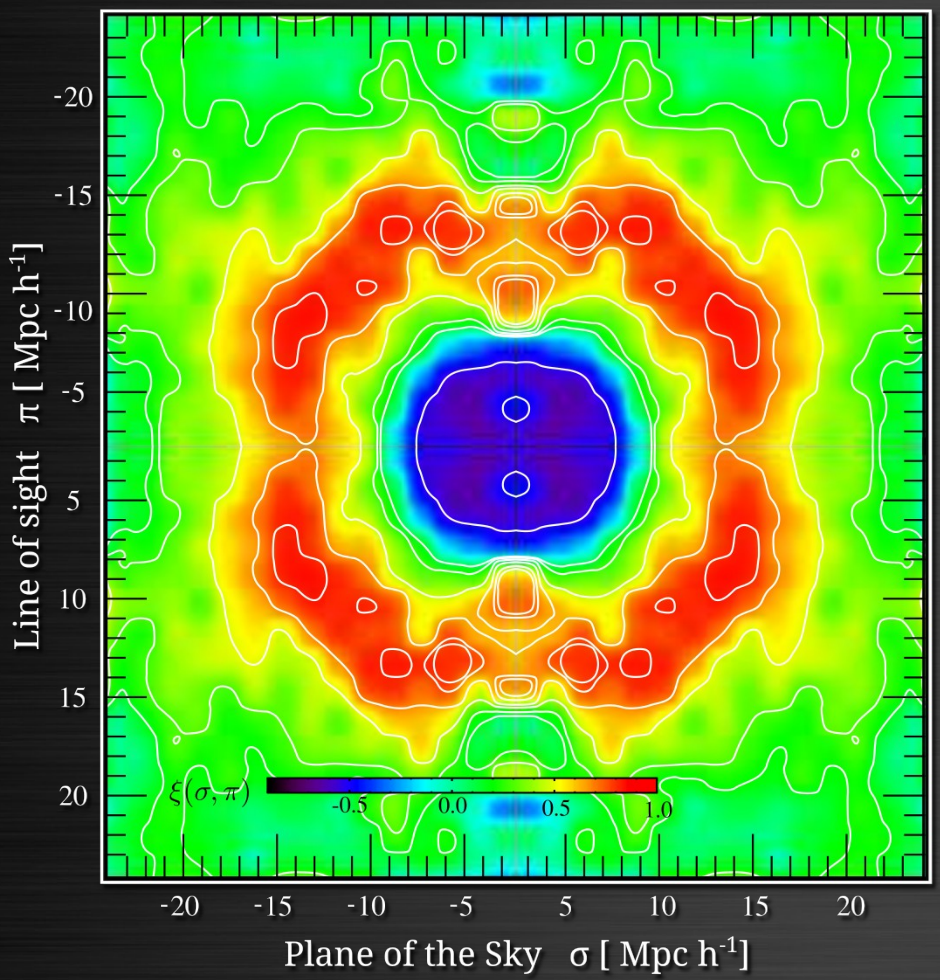
q_{AP} depends on expansion history and geometry of the Universe

q_{RSD} depends on the growth rate of cosmic structures.

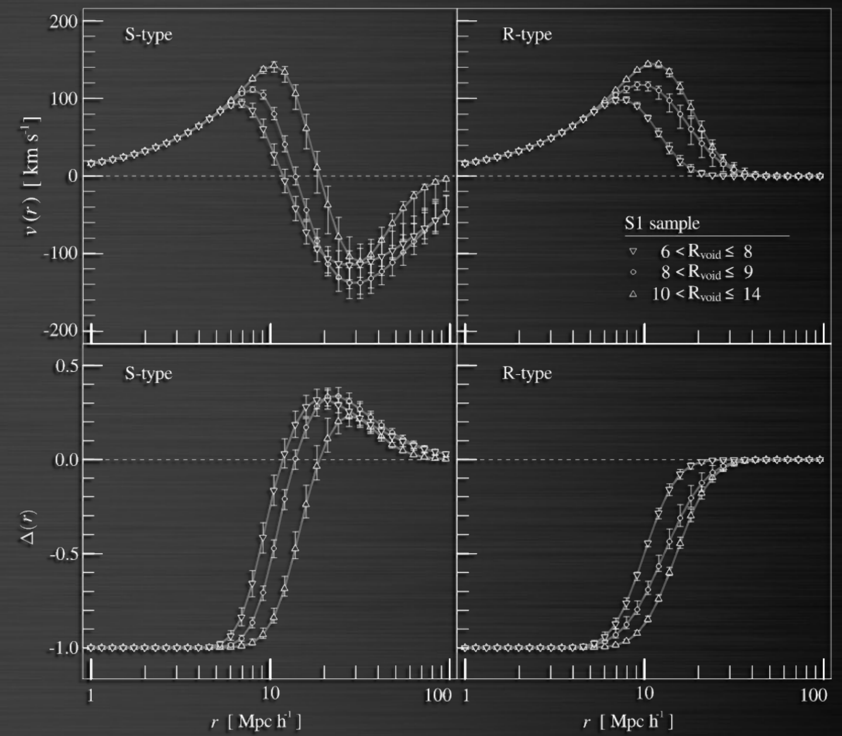
Correa et al. 2020

Void Galaxy cross correlation function

Redshift space distortions



SDSS SVF 6 < R_{void} < 8



- This cross correlation function is an estimate of the mean profile of galaxies around voids
- It shows asymmetries at all scales due to redshift space distortions induce by peculiar motions
- The v-in-v and v-in-c modes predicted by Sheth & van de Weygaert were confirm in observations

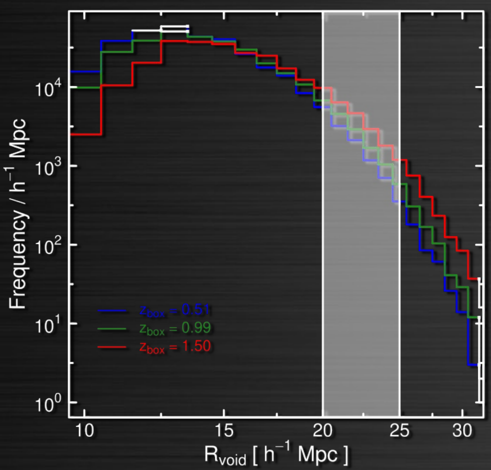
Paz et al. 2013

A non-fiducial cosmology test

Correa et al. 2019

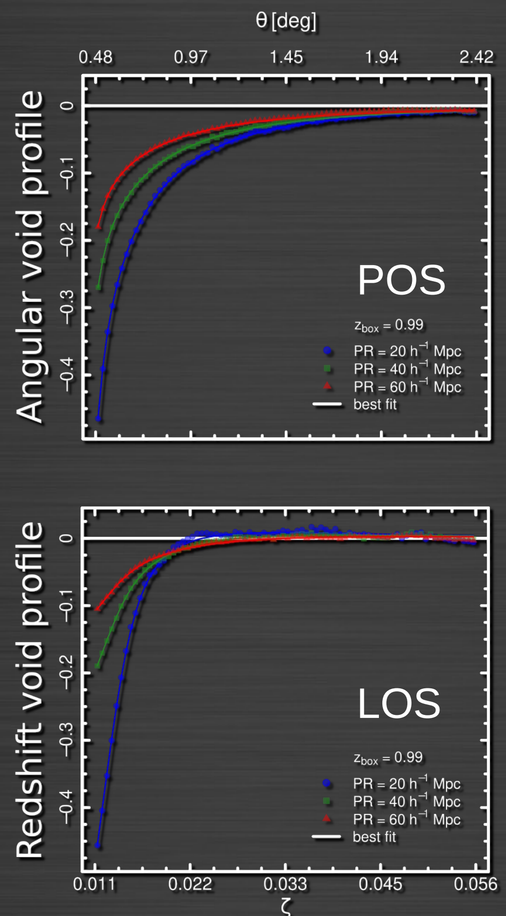
- Deep surveys allow to measure de evolution of the growth rate at different Z ranges (tomography)
- In a narrow Z range the correlation function can be measured directly using observables, without assuming a fiducial cosmology
- LOS correlation strongly depends on RSD, POS closely follows real space void profile.

Millenium XXL simulation



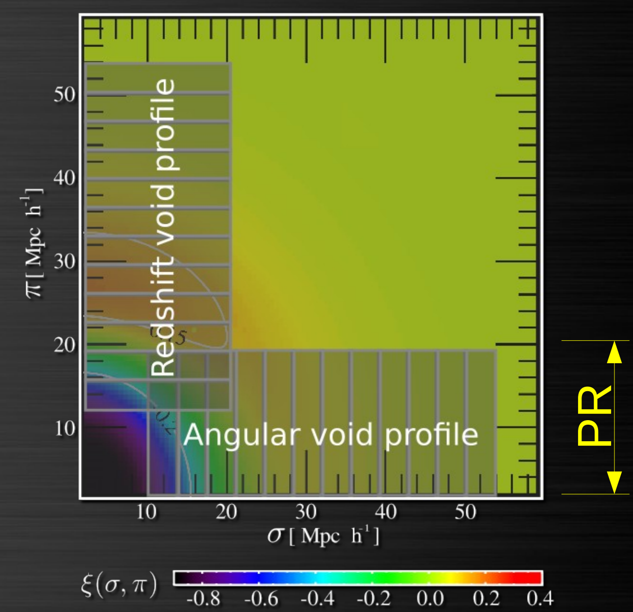
Biases arises if you use redshift space voids as centers.
To perform this test in redshift surveys, you may require a reconstruction technique

Mock measurement



Parameter exploration

Model



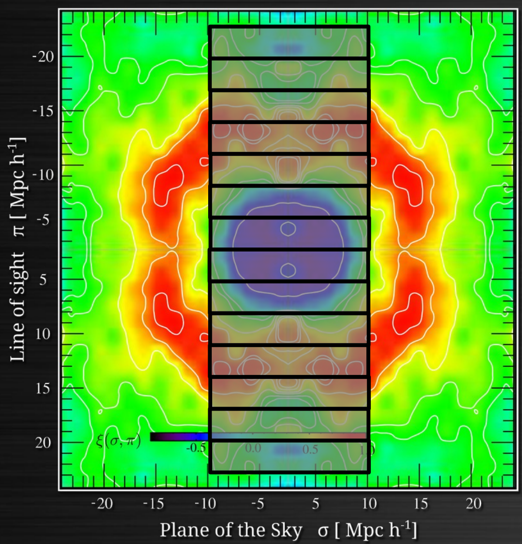
Larger projection range (PR) include more data, however this reduce the contrast

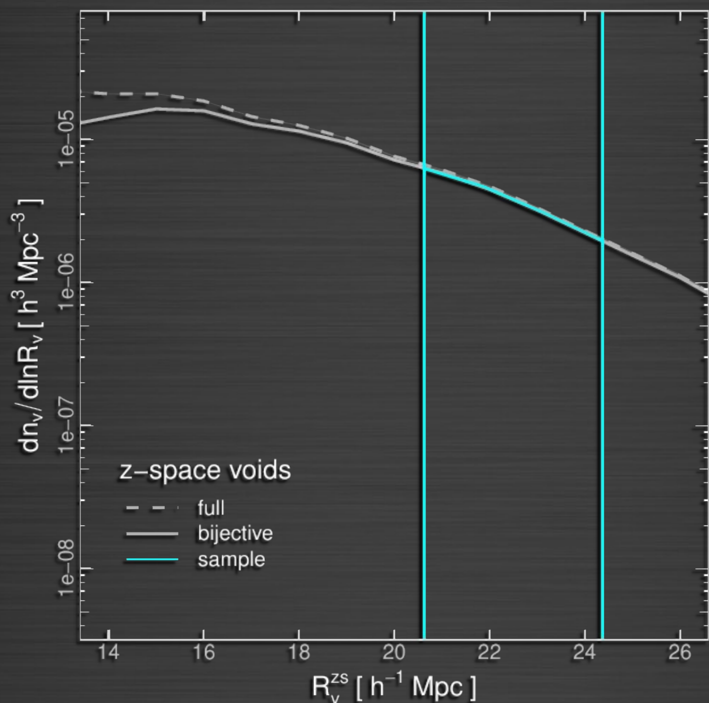
Correa et al. 2019, Nadathur & Percival 2019

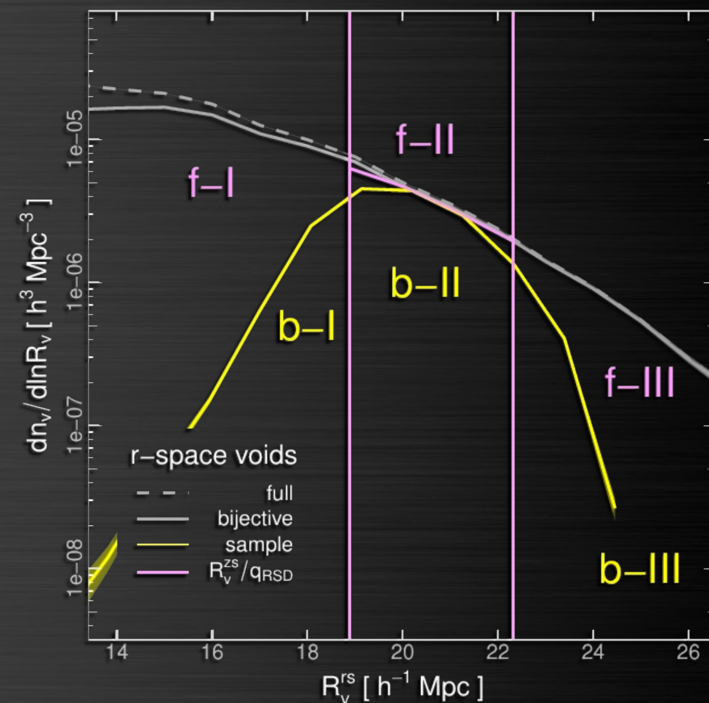
Void Galaxy cross correlation function

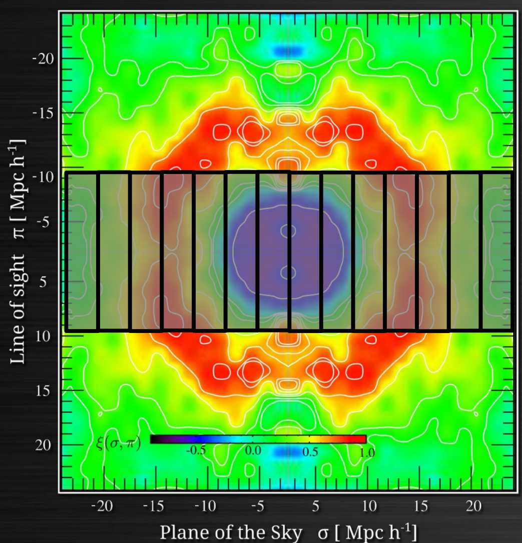
Why do we fail to use voids in z space?

ξ_{los}









ξ_{pos}

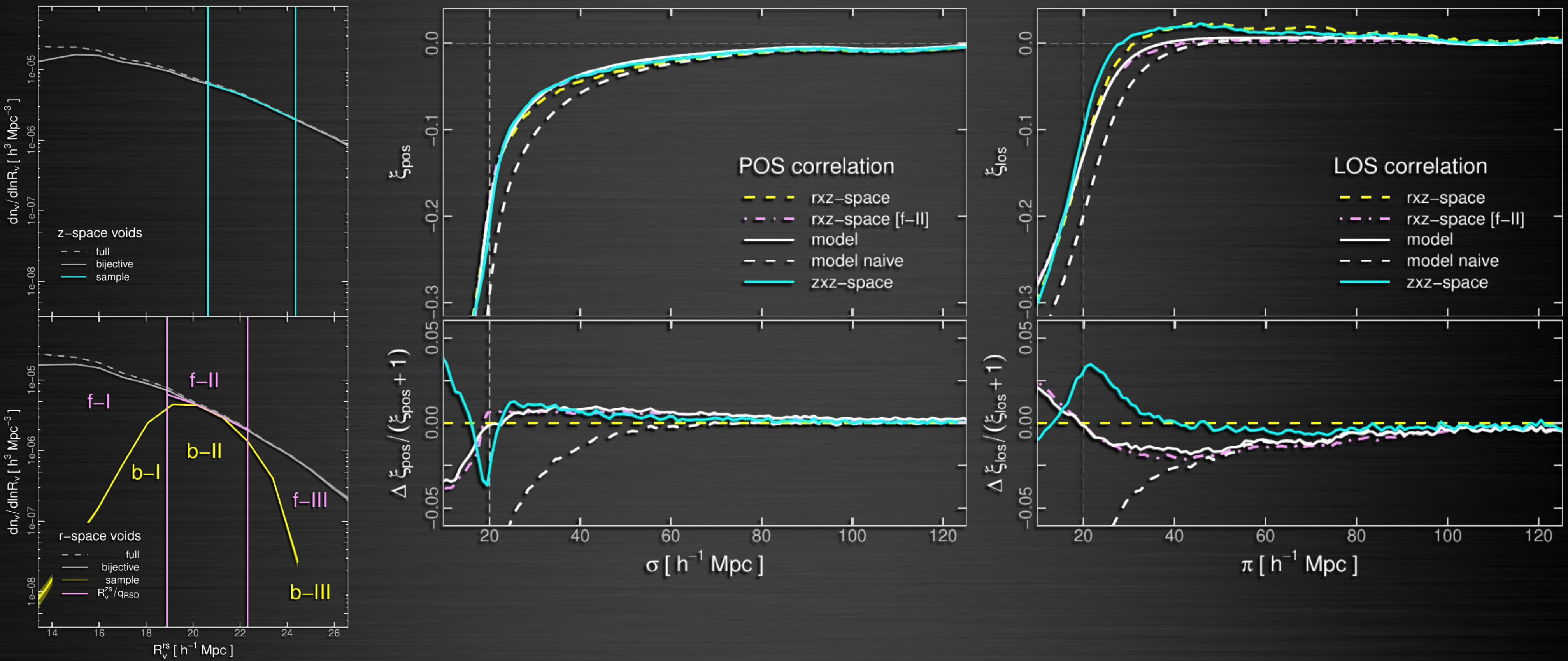
- The vertical cyan lines indicate the interval of centers in z-space
- The vertical pink lines are the equivalent r-space (times q_{RSD}^{-1})
- The sample cut in z-space radius spills in r-space sizes.

Correa et al. 2021, to be submitted
to arXiv and MNRAS soon

Void Galaxy cross correlation function

Why do we fail to use voids in z space?

Correa et al. 2021, tbs

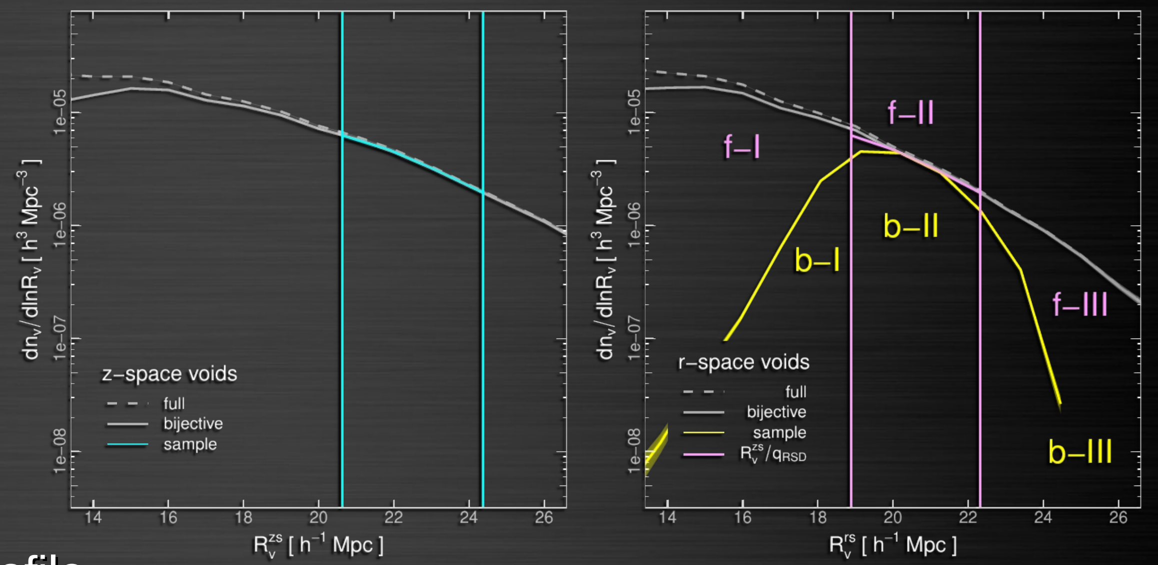


- Correlation function as in observations (cyan-solid, zxz-space) for voids between 20 – 25 Mpc
- GSM as in Paz et al. 2013 for voids between 20 – 25 Mpc (naive model, white-dashed)
- GSM but correcting sizes by q_{RSD} is the white solid line (white-solid).
- Voids center in r-space cross galaxies in z-pace are in yellow.
- Voids center in r-space but removing the wings of b-I and b-III (perfect agreement with model)

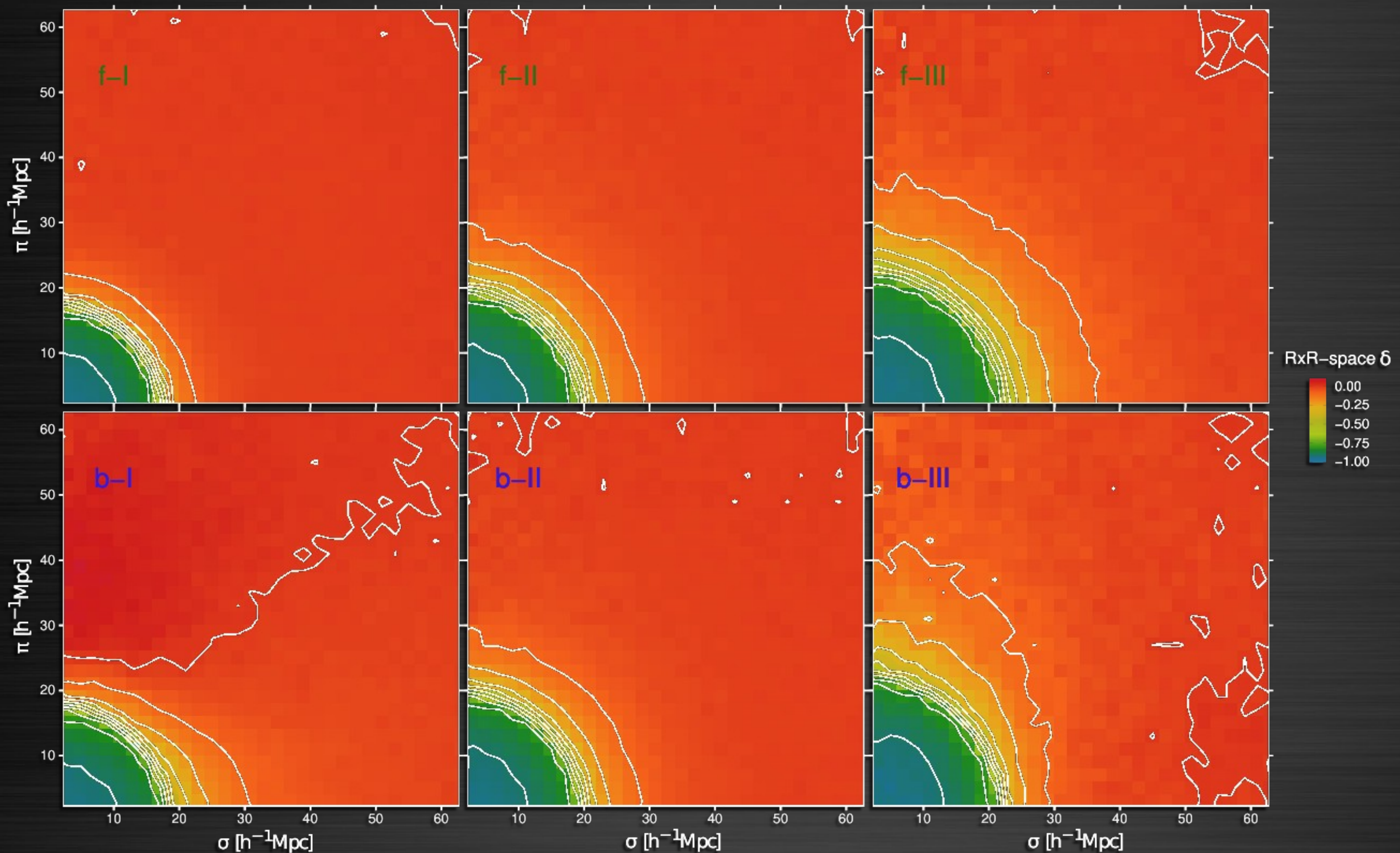
Super/Sub-expanding voids are the source of deviations?

Void sizes spreading by RSD

What physical mechanism is responsible for this?



2D (LOSxPOS) Real space density profile



Void sizes spreading by RSD

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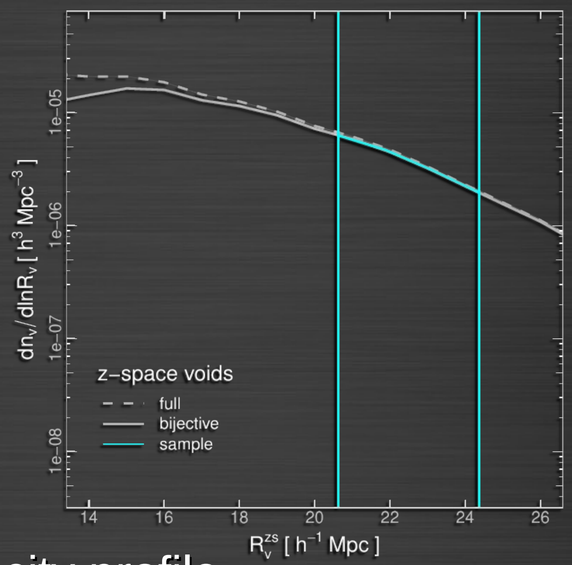
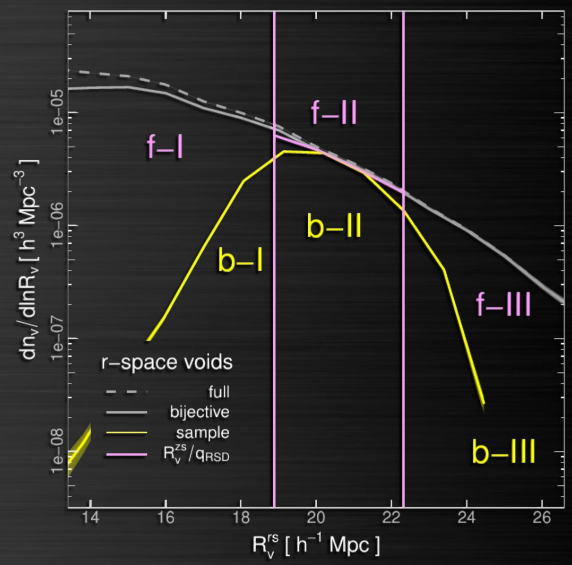
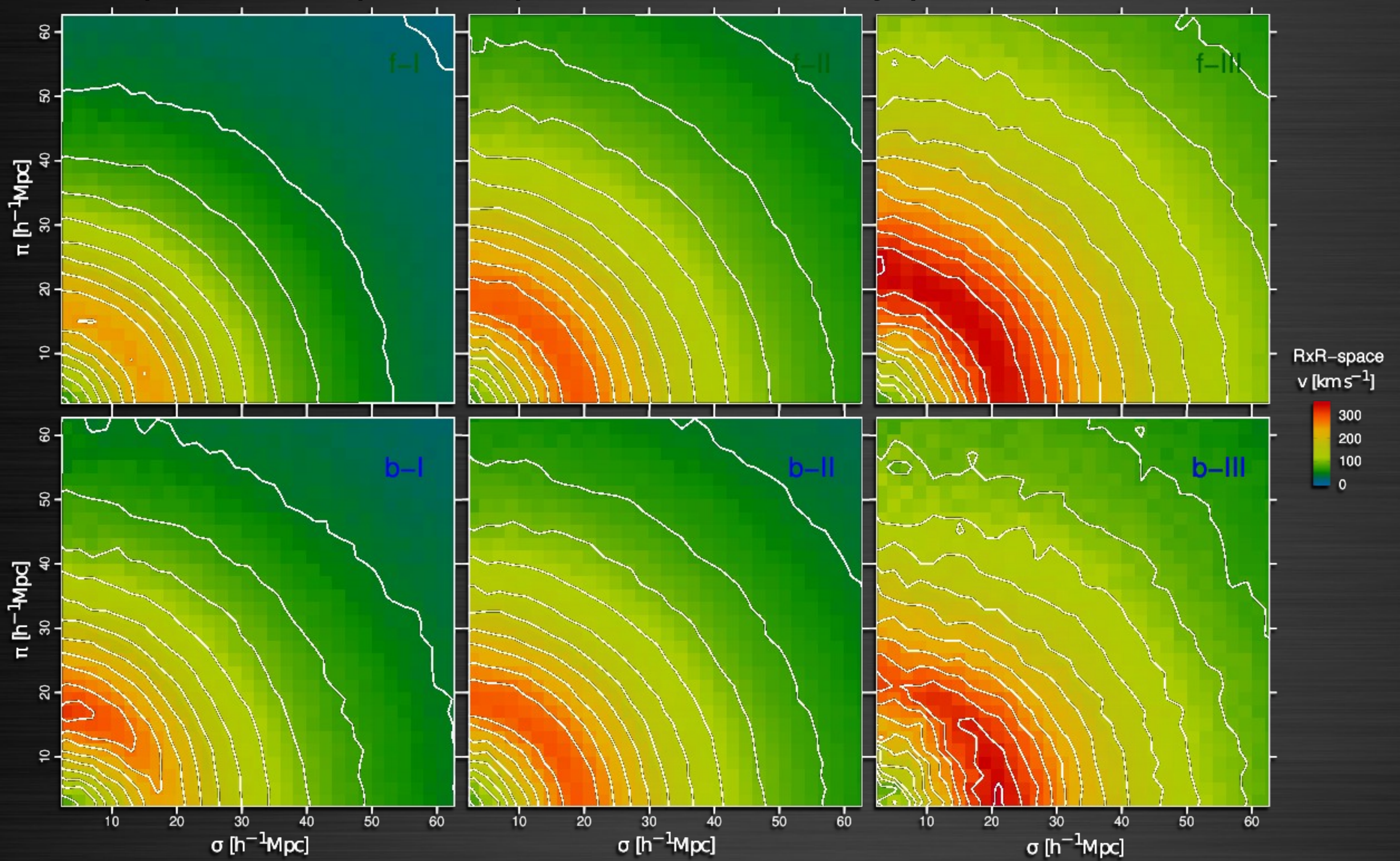




2D (LOSxPOS) Real space radial velocity profile



Void sizes spreading by RSD

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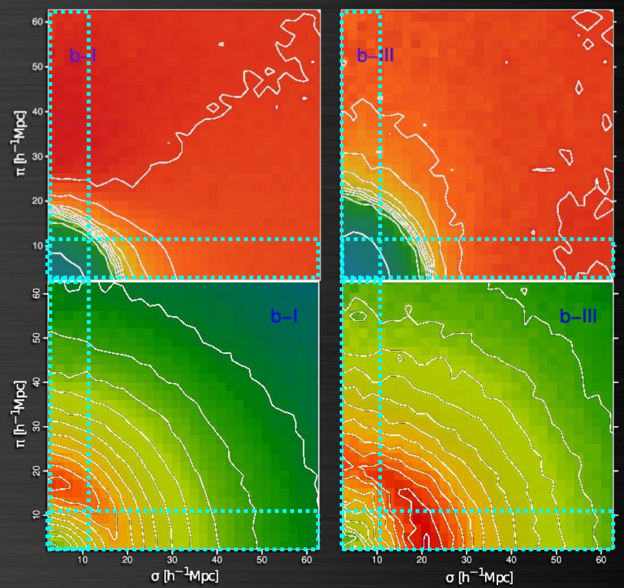
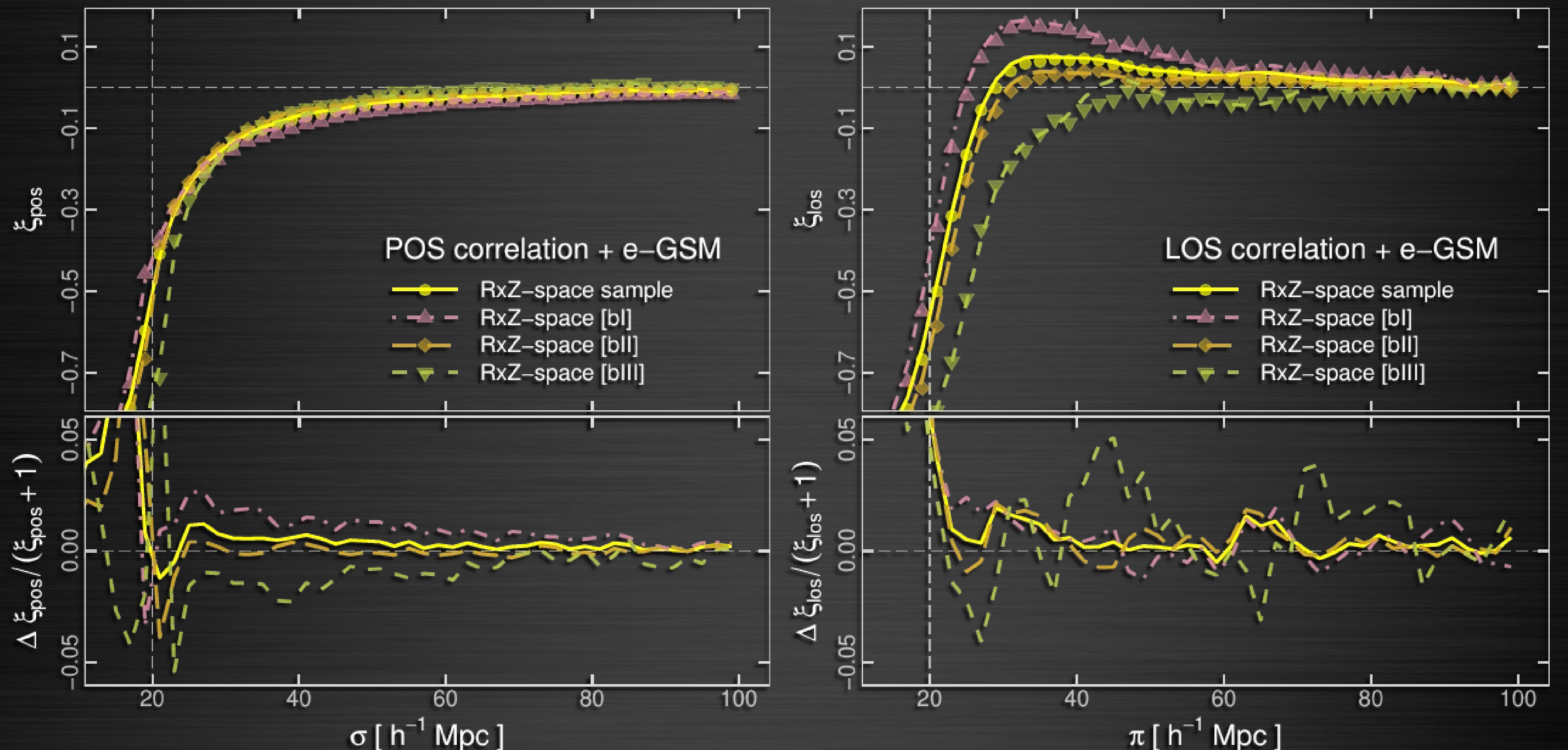


An elliptical gaussian streaming (e-GSM) model works:



Conclusions

- We have derived a formalism to correct the abundances of voids by RSD
- We have implemented the Alcock Paczynski test by exploiting the abundances of voids.
- This formalism provides additional cosmological information to that provided by the abundance models.
- q_{AP} depends on the expansion history and geometry of the universe, while q_{RSD} depends on the growth rate of structures.
- The expansion effect is the main RSD for the cross-correlation functions (model deviates around 2%), while correcting for off-centering gives smaller biases.
- To obtain better adjustments, it is required to use an ellipsoidal Gaussian model.
- By treating the systematics on void data we can obtain more physical information about the voids and new sources of cosmological information: For instance by deriving ellipticities with the e-GSM.

Work in progress:

- Joint test for abundances and correlations with BOSS data with a GSM with correct sizes.
- Take into account the bulk-flow motion of the underdense regions
- Complete our e-GSM to obtain better parameter constraints in BOSS data.