# Non-fiducial cosmological test from geometrical and dynamical distortions around voids

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OAC Observatorio Astronómico de Córdoba

**Mock Córdoba – Galaxy formation for gravity and cosmology**
**April 2019 - Córdoba - Argentina**

# VOIDS AS COSMOLOGICAL LABS

- **AP tests: shape evolution** analysis. *(Ryden 1995; Lavaux & Wandelt 2012; Sutter et al. 2014; Mao et al. 2017)*. Expansion history and geometry of the Universe.
- **RSD studies:** take advantage of the fact that dynamics can be modelled with **linear theory**, since velocities are dominated by coherent flows. *(Paz et al. 2013; Cai et al. 2016; Achitouv 2017; Hawken et al. 2017; Nadathur et al. 2019a, 2019b)*. Growth rate of cosmic structures.
- **Modified Gravity theories:** predict deviations from GR to be most pronounced in **unscreened** low density **environments**. *(Cai et al. 2015; Barreira et al. 2015; Cautun et al. 2018; Paillas et al. 2019)*.
- **Abundance of voids: excursion set formalism + spherical expansion**. *(Sheth & van de Weygaert 2004; Furlanetto & Piran 2006; Jennings et al. 2013)*.
- **Others:** ISW, weak gravitational lensing, thermal Sunyaev-Zeldovich.
- **AP + RSD** with the **void-galaxy correlation** function. *(Hamaus et al. 2015, 2016; **Correa et al. 2019**)*.

# VOID-GALAXY CROSS CORRELATION

- **Statistical tool** and fundamental **observable** of the test.
- Describes the structure, **environment** and **dynamics** inside and around voids.
- **Non fiducial** : measured directly in terms of **angular distances** and **redshift differences** between void-galaxy pairs.
- SYSTEMATICS

PHYSICAL

- DYNAMICAL DISTORTIONS (RSD)
  Kaiser (1987)
- GEOMETRICAL DISTORTIONS (GD)
  Alcock & Paczyński (1979)

TECHNICAL

- BIN SIZE (PROJECTION)
- SHIFTING OF CENTRES

# NON FIDUCIAL CORRELATION

**Observables** $(\theta, z, z')$

$\theta$ **Angular distance** between the void centre - galaxy pair measured on the **plane of the sky** (POS)

$z$ **Redshift of the galaxy**

$z'$ **Redshift of the void-centre** (provided by the void finder)

**Observable space** $(\theta, \zeta)$

$\zeta = |z - z'|$ **Redshift difference** between the void centre - galaxy pair measured along the **line of sight** (LOS)

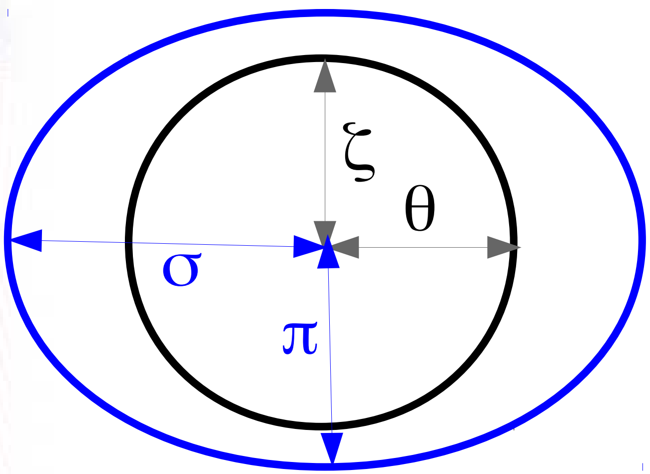
$$\boxed{\xi(\theta, \zeta)}$$

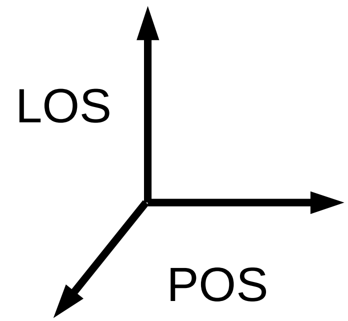
**Real space** $(r_\perp, r_\parallel)[h^{-1}\mathrm{Mpc}]$

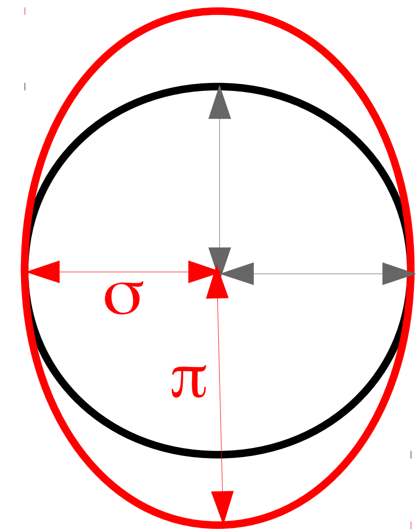
**Distorted space** $(\sigma, \pi)[h^{-1}\mathrm{Mpc}]$

# GD

# RSD




$$\begin{cases} \sigma = d_{\mathrm{com}}(z')\ \theta \\ \pi = |d_{\mathrm{com}}(z) - d_{\mathrm{com}}(z')| \end{cases}$$

$$\begin{cases} \sigma = r_{\perp} \\ \pi = r_{\parallel} + \dfrac{v_{\parallel}}{H(z)}(1+z) \end{cases}$$

$$d_{\mathrm{com}}(z) = c \int_0^z \frac{\hat{z}}{H(\hat{z})}$$

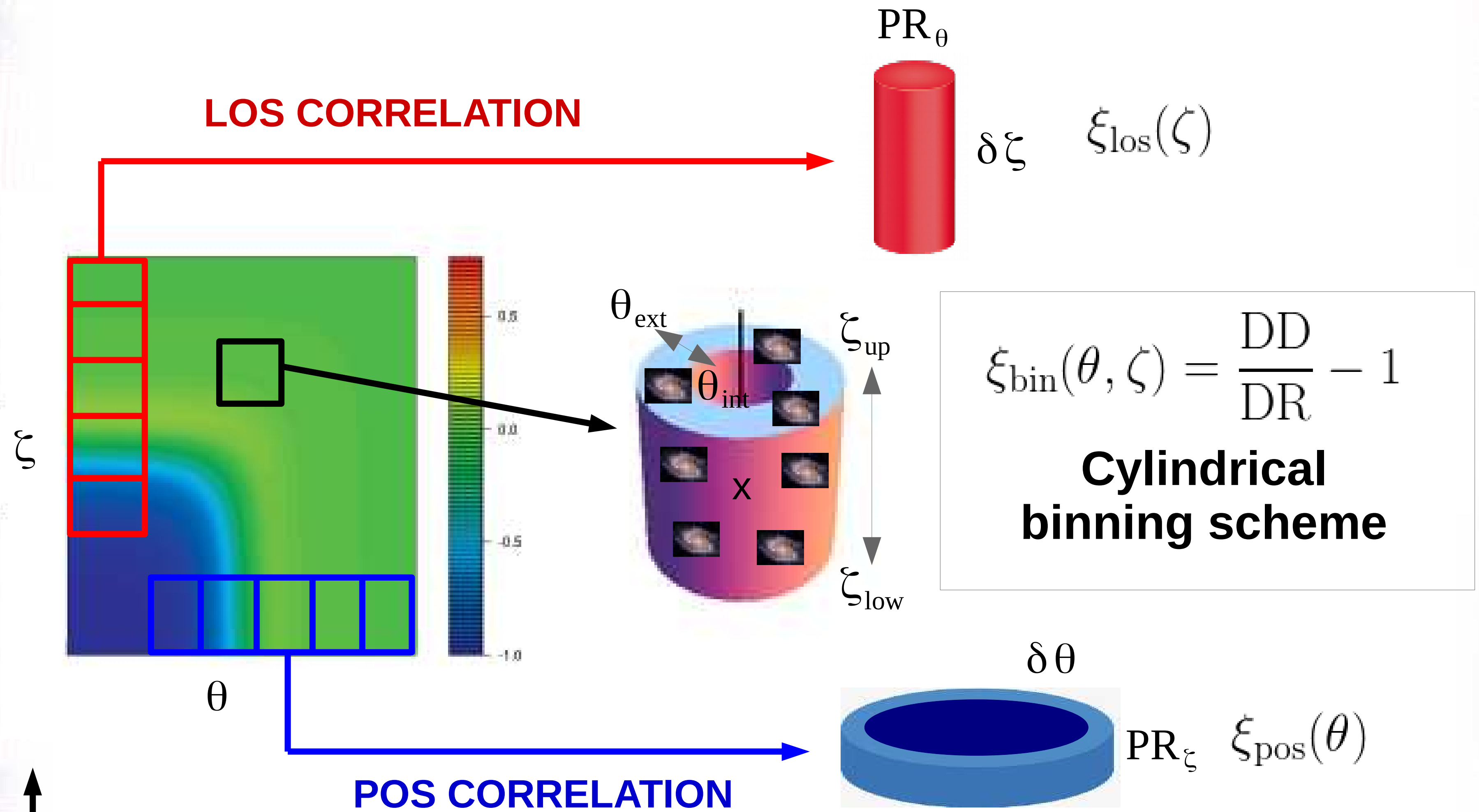
$$v(r) = -\frac{1}{3}\,\frac{H(z)}{(1+z)}\,\underbrace{\frac{f}{b}(z)}_{\beta(z)}\,r\ \Delta(r)$$

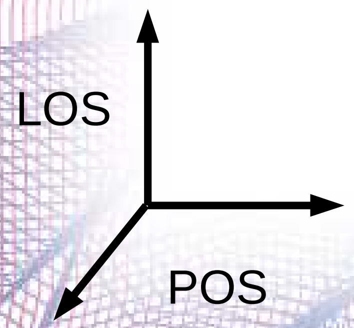
$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

**Expansion and geometry**

**Growth rate of structures**

# BIN SIZE AND PROJECTED CORRELATIONS




Plane parallel approximation

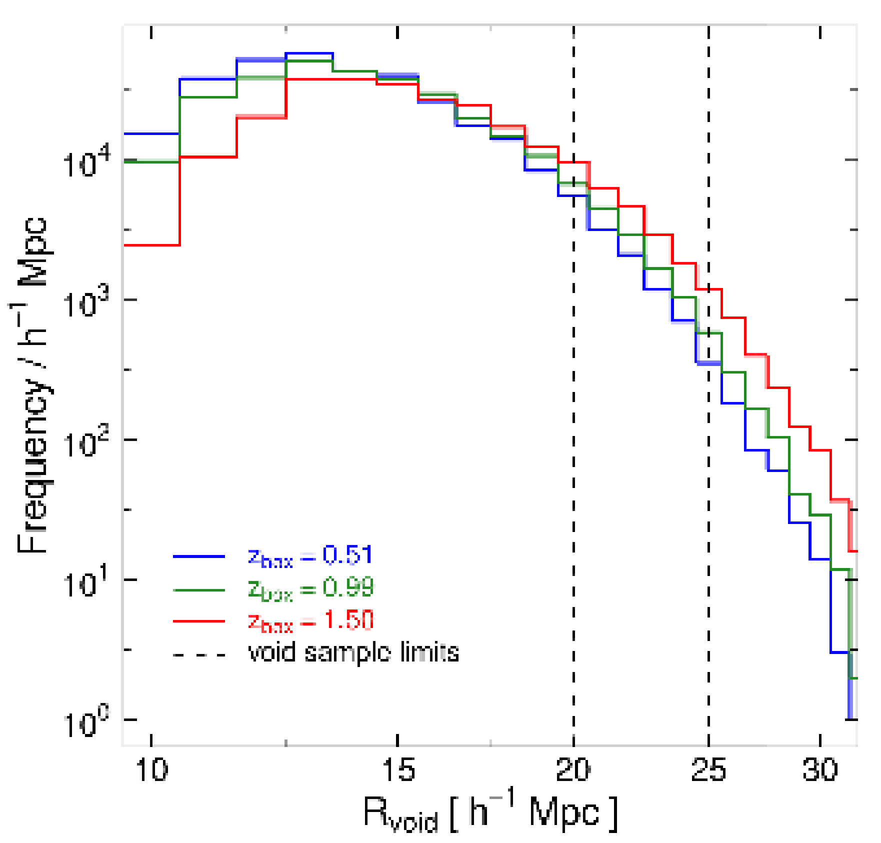
- **Mixing of scales** due to bin size.
- Models must take into account the volume and **geometry of bins**.
- **Projections** are special cases.

# DATA SET

| SIMULATION | |
|---|---|
| **Name** | **Millennium XXL**<br>Angulo et al. (2012) |
| **Cosmology** | • **$\Omega_m$ = 0.25**<br>• **$\Omega_\Lambda$ = 0.75**<br>• **$H_0$ = 73 km $s^{-1}$ $Mpc^{-1}$** |
| **Dimensions** | 3 $h^{-1}$ Gpc size |
| **Resolution** | $6720^3$ dm particles |
| **Matter tracers** | **Dark matter haloes** |
| **Snapshots** | **0.51; 0.99; 1.50** |
| **Impact** | Resolution and volume (future surveys) |

| VOIDS | |
|---|---|
| **Identificator** | Ruiz et al. (2015) |
| **Description** | **Spherical void finder** |
| **Radius criterion** | Redshift dependent<br>Spherical collapse model |

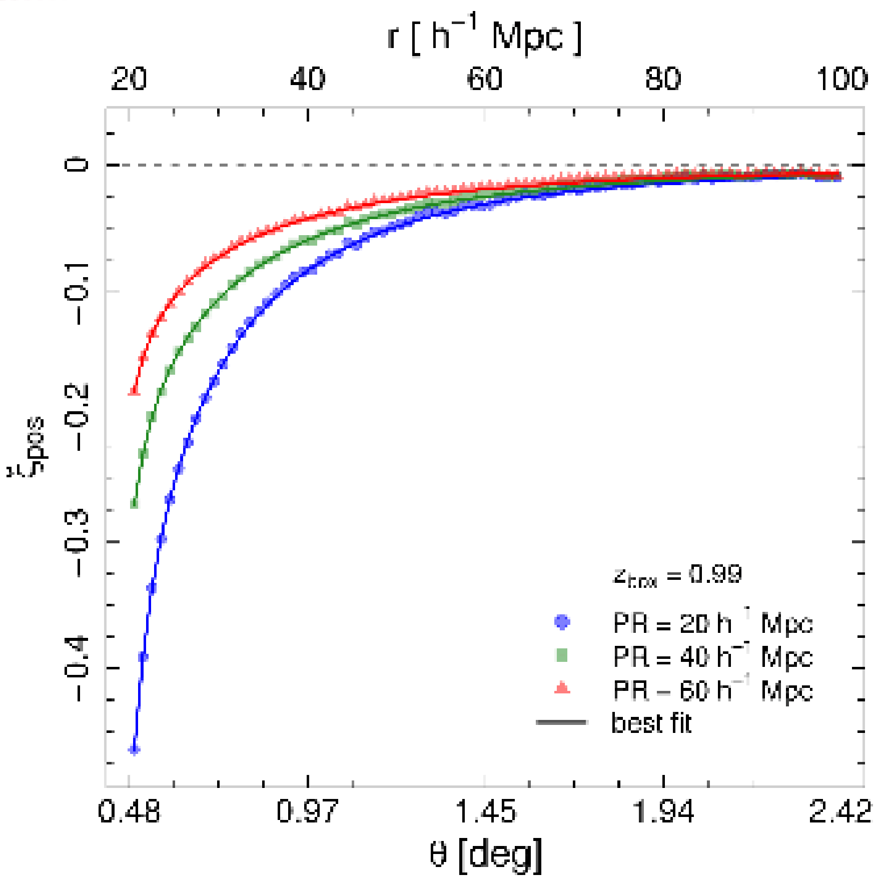
**VOID SAMPLES**

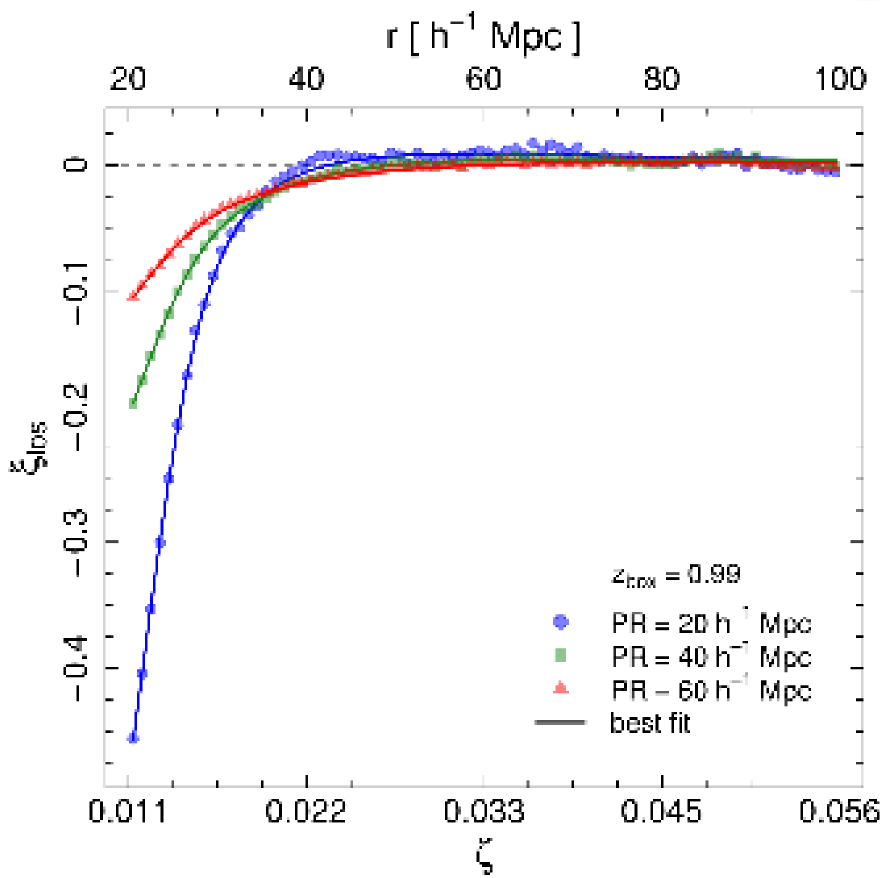



Correa et al. (2019)

# PROJECTED CORRELATIONS

Correa et al. (2019)




**Projection towards the POS in the redshift ranges given by PR**

**Projection towards the LOS in the angular ranges given by PR**

# MODEL

### 1) GD

$$\sigma = d_{\rm com}(z')\ \theta \qquad \pi = \left|d_{\rm com}(z) - d_{\rm com}(z')\right|$$

### 2) BIN SIZE

$$\mathrm{DD} = 2\,\hat{\pi} \int_{z'_{\rm min}}^{z'_{\rm max}} dz'\ d^2_{\rm com}(z')\ n_\nu(z')\ V_{\rm slice}$$
$$\left[\int_{z'+\zeta_{\rm low}}^{z'+\zeta_{\rm up}} dz\ \frac{dd_{\rm com}}{dz}(z)\ n_t(z) \int_{\theta_{\rm int}}^{\theta_{\rm ext}} d\theta\ \theta\ [1+\xi(\sigma,\pi)] + \int_{z'-\zeta_{\rm up}}^{z'-\zeta_{\rm low}} dz\ \frac{dd_{\rm com}}{dz}(z)\ n_t(z) \int_{\theta_{\rm int}}^{\theta_{\rm ext}} d\theta\ \theta\ [1+\xi(\sigma,\pi)]\right],$$

$$\mathrm{DR} = \hat{\pi}\left(\theta^2_{\rm ext} - \theta^2_{\rm int}\right) \int_{z'_{\rm min}}^{z'_{\rm max}} dz'\ d^2_{\rm com}(z')\ n_\nu(z')\ V_{\rm slice}$$
$$\left[\int_{z'+\zeta_{\rm low}}^{z'+\zeta_{\rm up}} dz\ \frac{dd_{\rm com}}{dz}(z)\ n_t(z) + \int_{z'-\zeta_{\rm up}}^{z'-\zeta_{\rm low}} dz\ \frac{dd_{\rm com}}{dz}(z)\ n_t(z)\right]$$

### 3) RSD

$$1+\xi(\sigma,\pi) = \int_{-\infty}^{\infty} [1+\xi(r)]\frac{1}{\sqrt{2\pi}\sigma_v}\exp\left[-\frac{(v_\parallel - v(r)\frac{r_\parallel}{r})^2}{2\sigma_v^2}\right] dv_\parallel$$

### 4) VELOCITY

$$v(r) = -\frac{1}{3}\frac{H(z)}{(1+z)}\beta(z) r \Delta(r),$$

### 5) REAL SPACE CORRELATION

$$\xi(r) = \begin{cases} Ar - 1 & \text{if } r < r_{\rm cut}, \\ -\xi_0\left[\left(\frac{r}{r_0}\right)^{-3} + \left(\frac{r}{r_0}\right)^{-\alpha}\right] & \text{if } r \geq r_{\rm cut}, \end{cases}$$

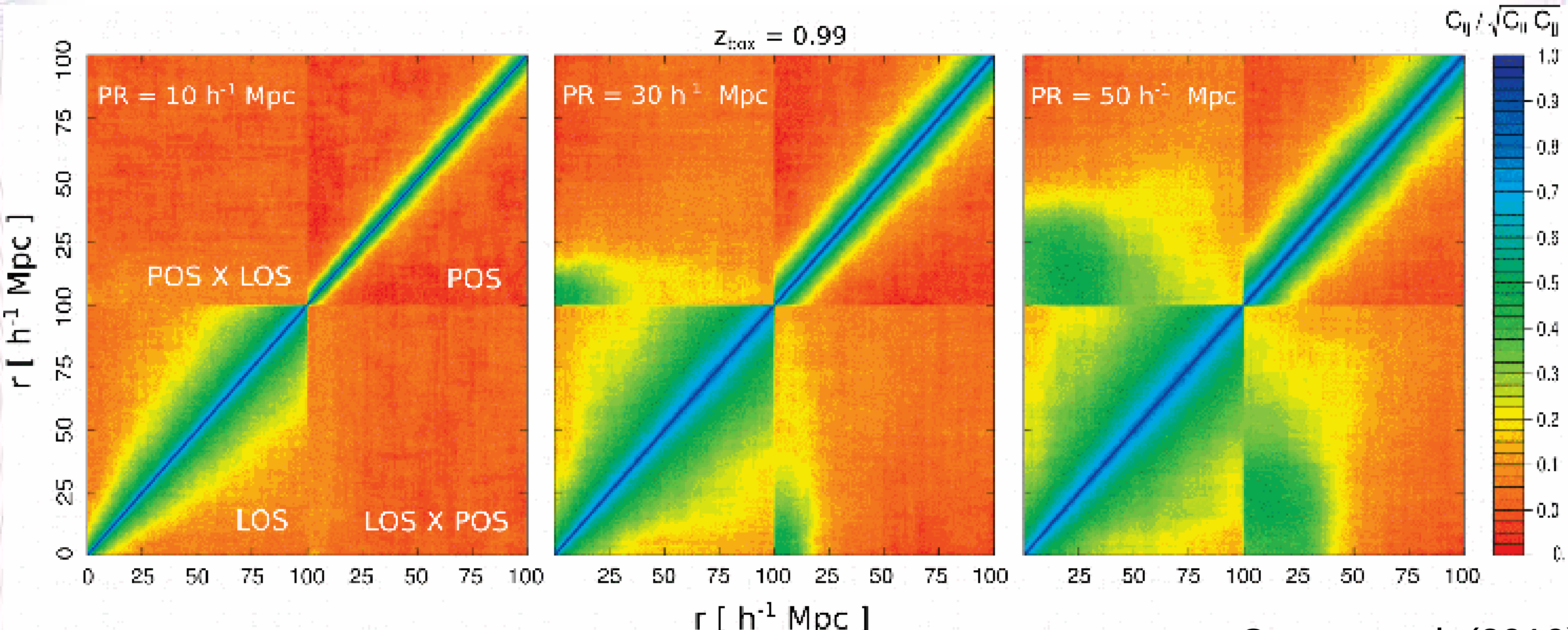
### 6) INTEGRATED DENSITY

$$\Delta(r) = \begin{cases} \frac{3}{4}Ar - 1 & \text{if } r < r_{\rm cut}, \\ \frac{3}{r^3}\left[\frac{ar^4}{4} - \frac{r_{\rm cut}}{3} + I(r) - I(r_{\rm cut})\right] & \text{if } r \geq r_{\rm cut}, \end{cases}$$

**COSMOLOGICAL SET** $\{\Omega_m, \beta\}$

**NUISANCE SET** $\{\sigma_v, \xi_0, r_0, \alpha\}$

# COVARIANCE MATRICES

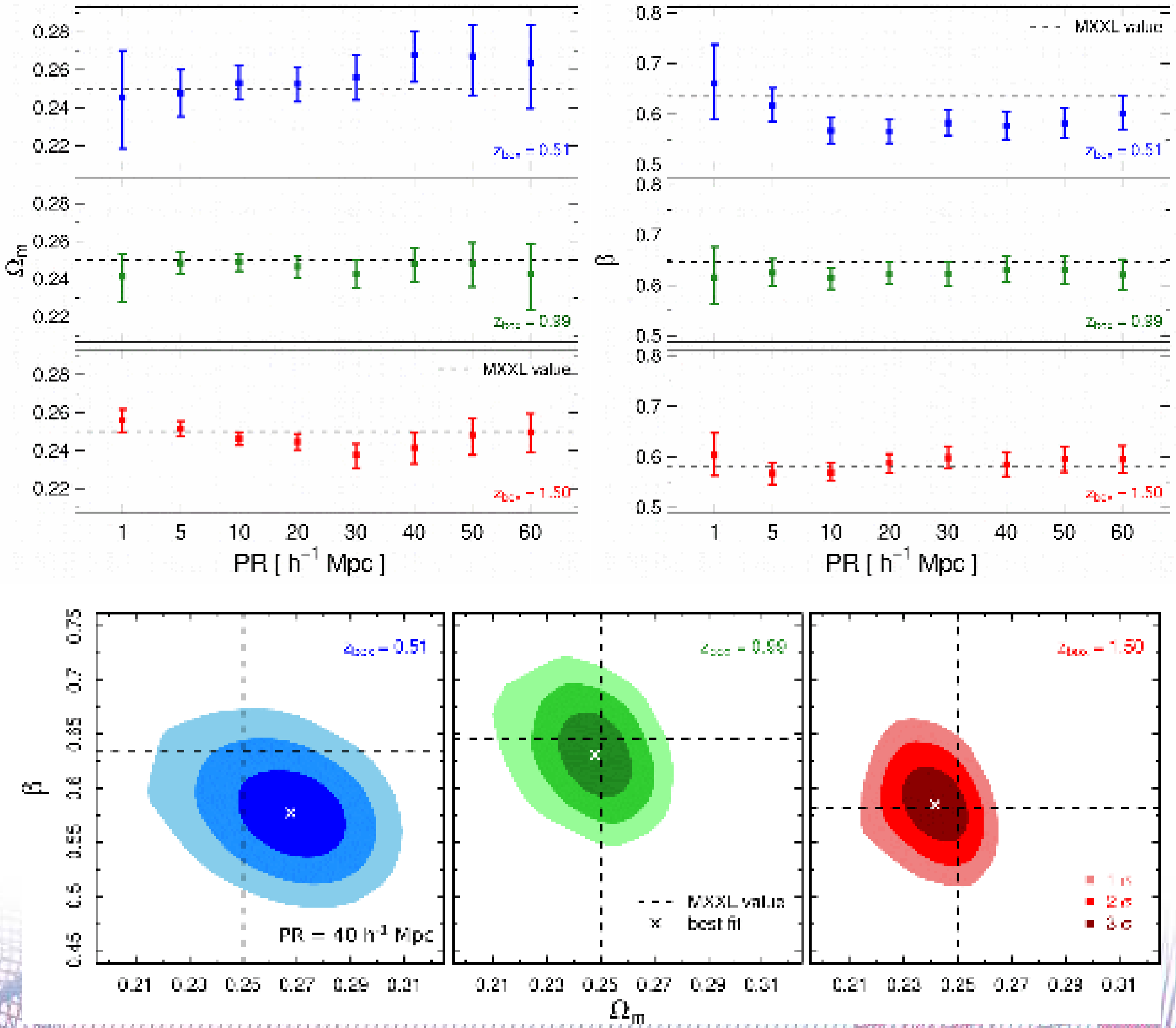



Correa et al. (2019)

- MCMC
- **Dimensionally** much **smaller** than the traditional case
- Inverse estimation is **numerically** more **stable**
- **Noise** in the likelihood analysis is **reduced**
- Allows to use a **smaller** number of **mock catalogues**

# COSMOLOGICAL CONSTRAINTS

Correa et al. (2019)



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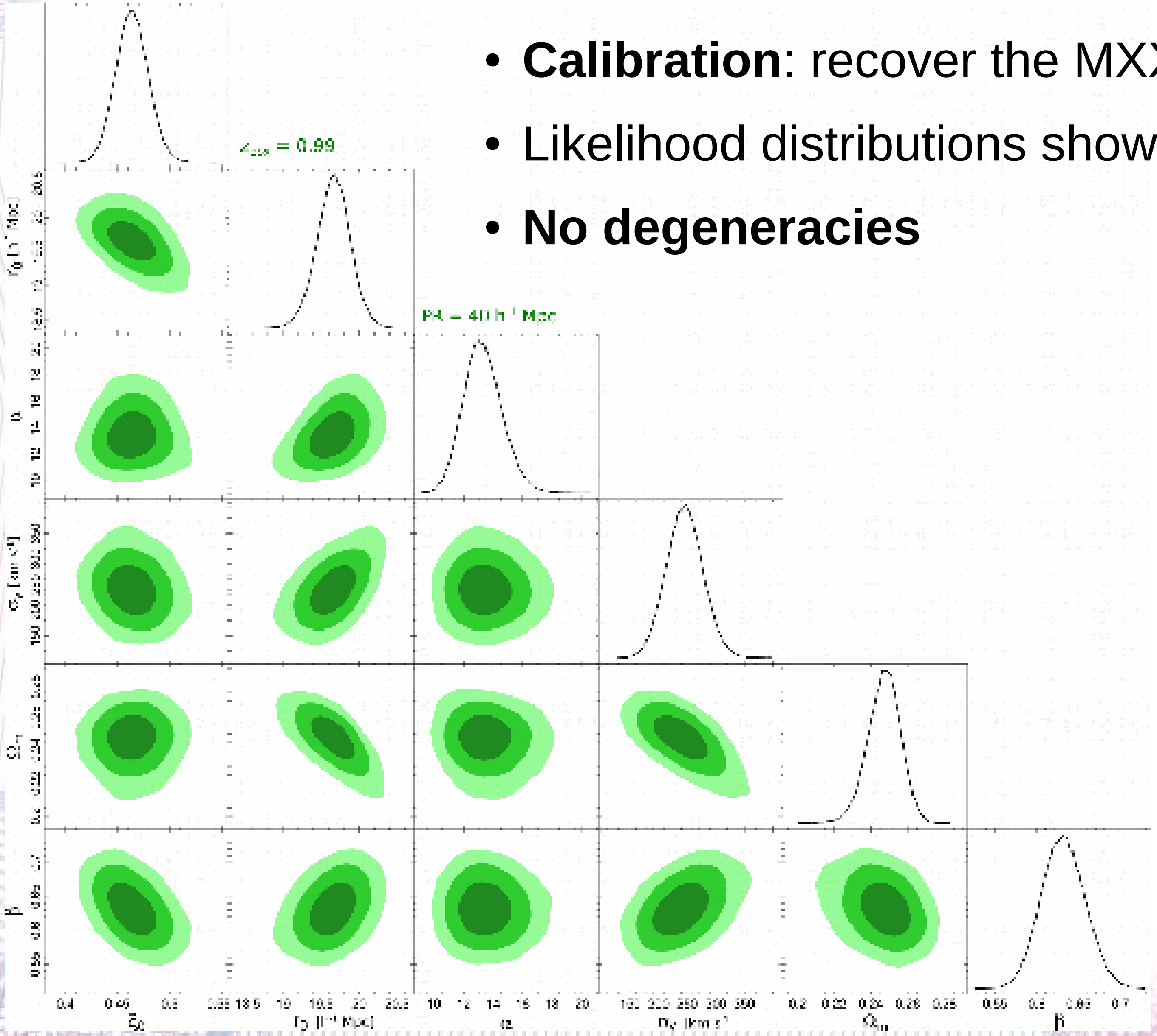



- **Calibration**: recover the MXXL values
- Likelihood distributions show a **Gaussian shape**
- **No degeneracies**

Correa et al. (2019)

# SHIFTING OF VOID CENTRES

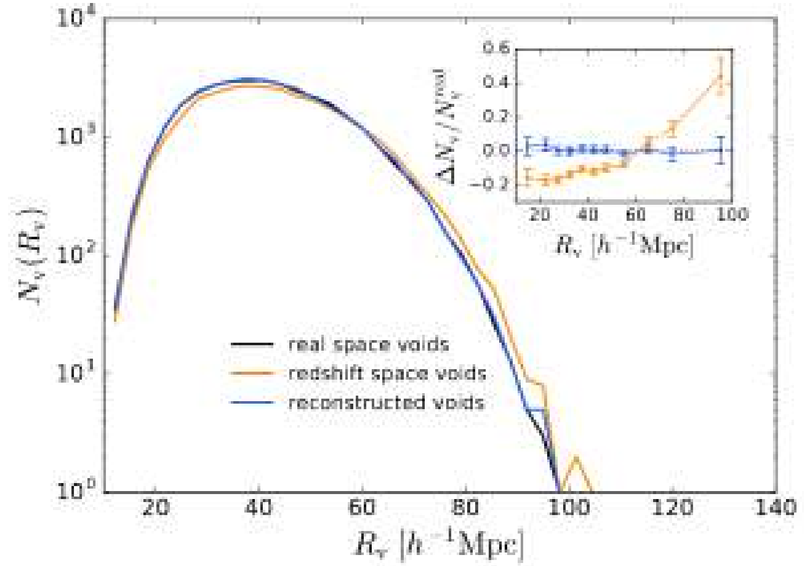
Nadathur et al. (2019)

(i) The number of voids is *conserved* under the redshift space mapping (Eq. 7)

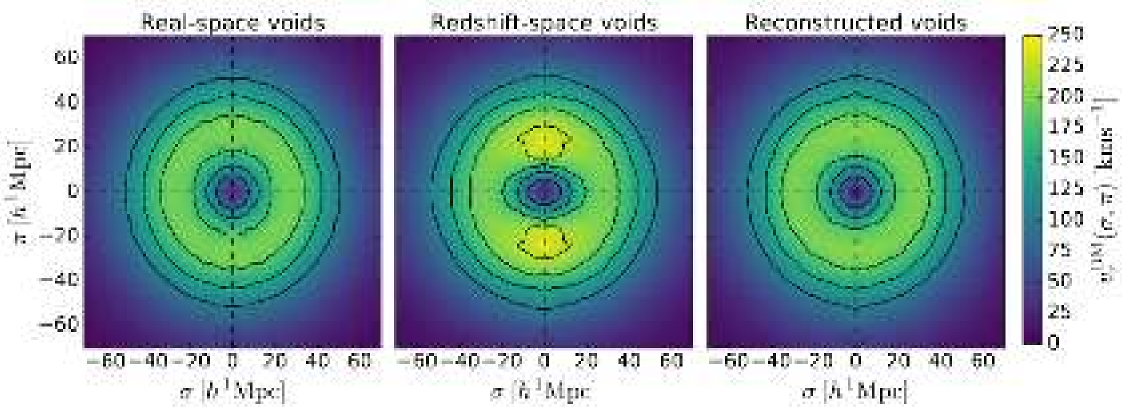
(ii) Void positions are *invariant* under the redshift space mapping, so that the transformation $\mathbf{r} \rightarrow \mathbf{s}$ depends on galaxy velocities only (Eq. 8)

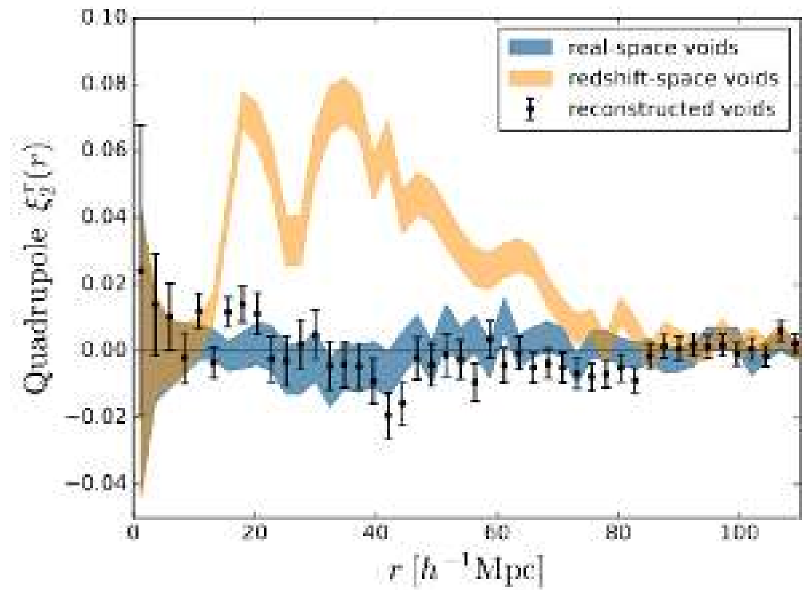
(iii) The average radial outflow velocity around voids is *isotropic* (Eq. 9)

(iv) The real space correlation is *isotropic*, $\xi^r(\mathbf{r}) = \xi^r(r)$




**Reconstruction**: density field reconstruction method based on the Zeldovich approximation to recover the real-space void positions from redshift space.



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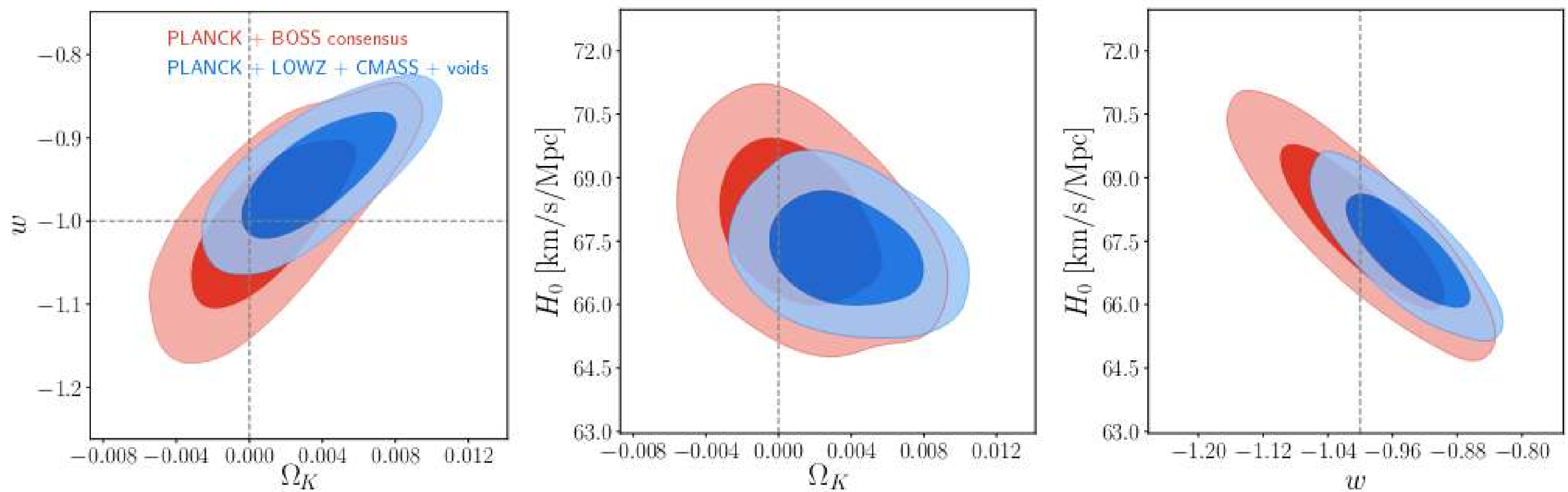
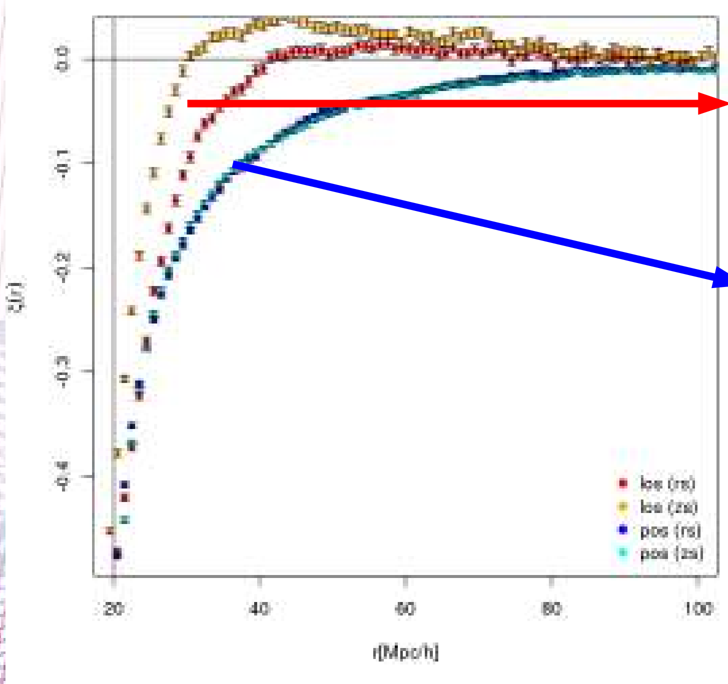



RECONSTRUCTION
+
RSD-GD MODELS




Additional RSD due to void centres shifting affects the LOS correlation

POS correlation unaffected

MODEL THE VOID FINDER ACTION

Correa et al.

# CONCLUSIONS

- **Voids** are powerful **cosmological labs**: AP tests, RSD studies, modified gravity, void abundance.
- **Non-fiducial** cosmological test using the **void-galaxy cross correlation function** (measured directly in terms of angles and redshifts).
- Model of **systematics**:
  - ✔ **Geometrical distortions (GD)** $\Omega_m$
  - ✔ **Dynamical distortions (RSD)** $\beta = f/b$
  - ✔ **Bin size (mixing of scales and projection)**
  - ⚙ **Void centres shifting**
- **Calibration** of the method using the **MXXL** simulation.
- Smaller and **dociler covariance** matrices.

**THANK YOU FOR YOUR ATTENTION**

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