# FEASIBILITY STUDY OF THE ALCOCK-PACZYŃSKI COSMOLOGICAL TEST USING COSMIC VOIDS

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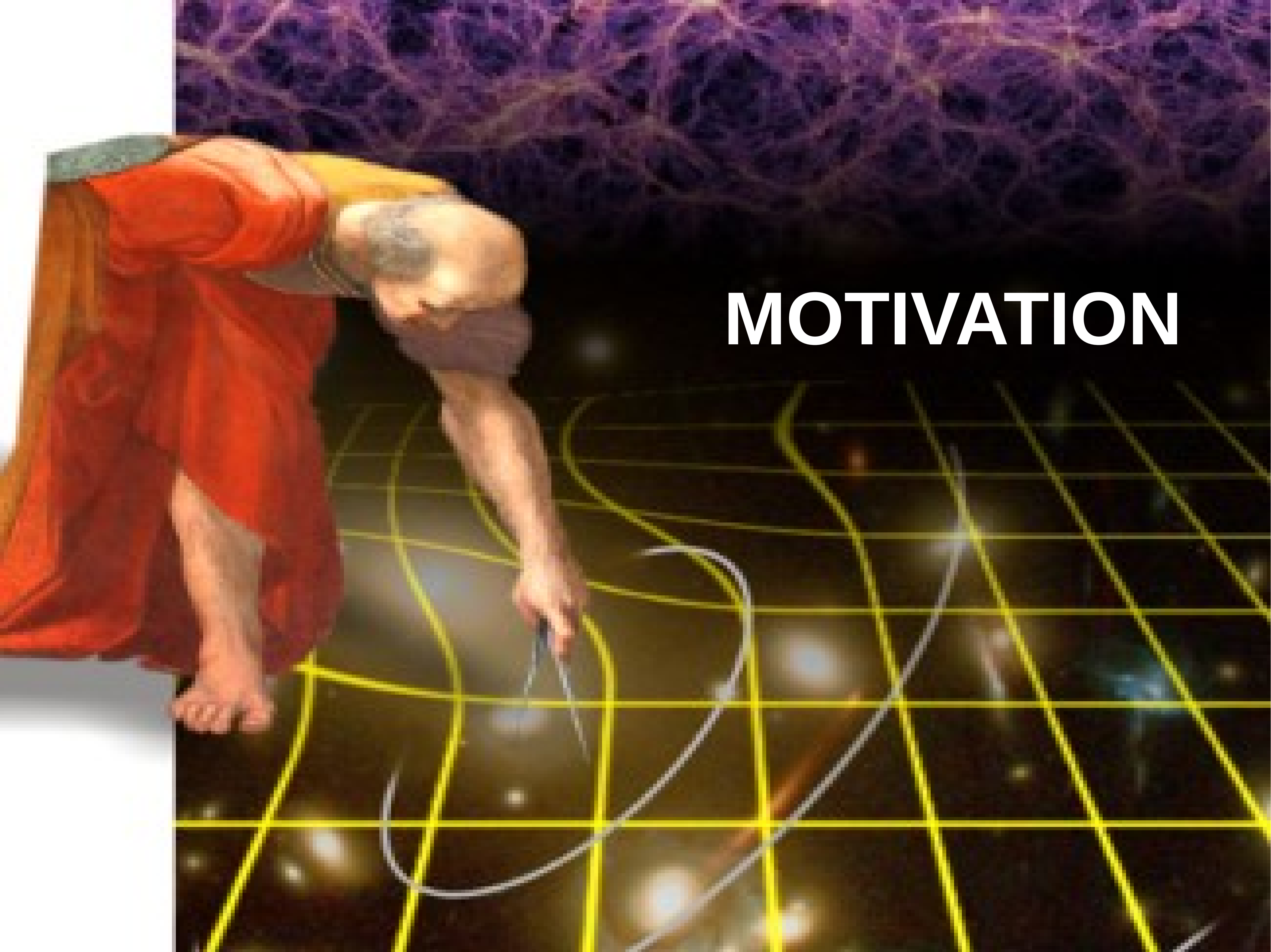
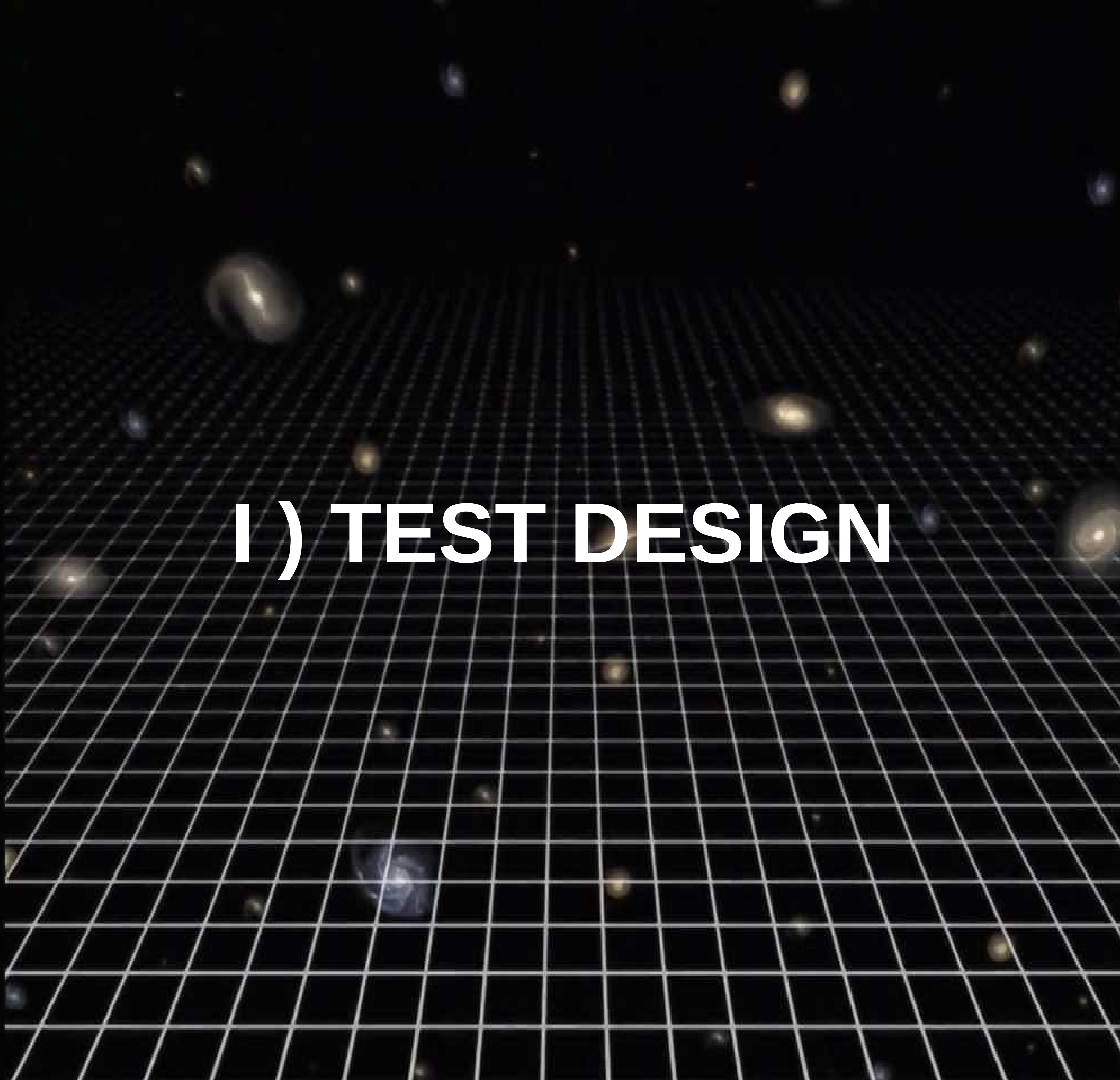


# MOTIVATION

Objective: test the geometry and expansion of the universe.

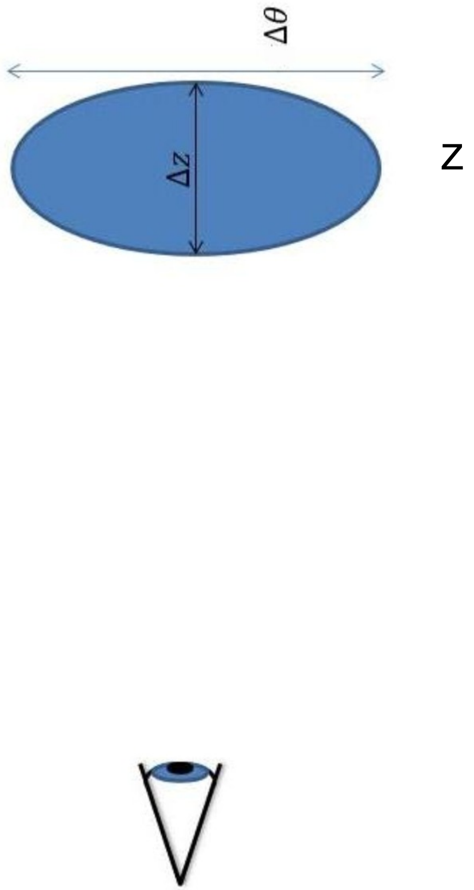
Method: design an own version of the **Alcock & Paczyński (1979) cosmological test** using the distribution of galaxies and cosmic voids in the large scale structure of the universe.

# I ) TEST DESIGN



# I.1) Alcock-Paczyński cosmological test

Alcock & Paczyński (1979) (**AP test**)




- Standard ruler at redshift z
- To determine its dimensions, we measure:
  - Δθ: **angular extension along the plane of the sky**;
  - Δz: **redshift extension along the line of sight**.

- To have physical dimensions [$h^{-1}$Mpc] we need to do the transformation

$$(\Delta\theta, \Delta z) \rightarrow (\sigma, \pi)$$

- σ: **physical extension along the plane of the sky**;
- π: **physical extension along the line of sight**.
- This cosmological transformation depends on the cosmological parameters and the redshift:

$$\sigma = D_A(\mathbf{z})\Delta\theta = \frac{c\,\Delta\theta}{\boldsymbol{H_0}(1+\mathbf{z})}\int_0^{\mathbf{z}} \frac{dz'}{\sqrt{\boldsymbol{\Omega_m}(1+z')^3+\boldsymbol{\Omega_\Lambda}}}$$

$$\pi = \frac{dd_{com}}{dz}(\mathbf{z})\,\Delta z = \frac{c\,\Delta z}{\boldsymbol{H_0}\sqrt{\boldsymbol{\Omega_m}(1+\mathbf{z})^3+\boldsymbol{\Omega_\Lambda}}}$$

- We need to assume values for the cosmological parameters (**fiducial cosmology**). Wrong values will produce distortions in the spacial distribution of the object.
- The ratio σ/π is known.

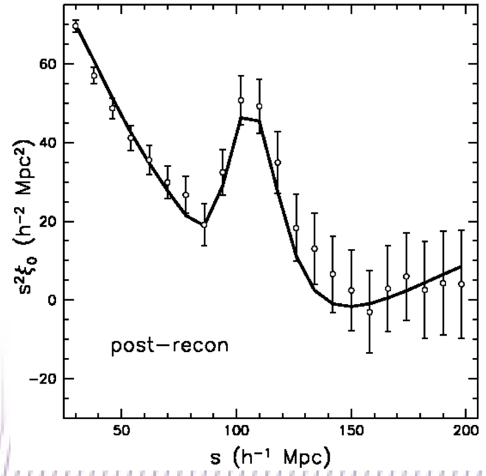
$$\frac{\sigma}{\pi} = \frac{\Delta\theta}{\Delta z(1+\mathbf{z})}\int_0^{\mathbf{z}} dz'\sqrt{\frac{\boldsymbol{\Omega_m}(1+\mathbf{z})^3+\boldsymbol{\Omega_\Lambda}}{\boldsymbol{\Omega_m}(1+z')^3+\boldsymbol{\Omega_\Lambda}}}$$

- We can adjust de right term varying the cosmological parameters until we get the desired value on the left. In this way, we can obtain the cosmological parameters.

# I.2) Complications

## 1) Absence of genuine standard rulers

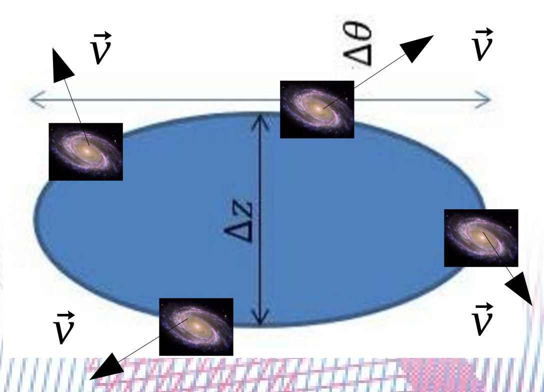
- Indirect standard ruler.
- Any distinctive feature in the correlation function $\xi(r)$ of an object distribution.
- Measure the distortions of this feature revealed as anisotropies in the isocontours of $\xi(\sigma,\pi)$, the correlation function projected on redshift space $(\sigma,\pi)$.
- **Void-galaxy cross correlation function $\xi_{vg}(\sigma,\pi)$.**




Anderson et al. (2013)

## 2) Contamination by dynamic distortions (redshift space distortions)

- The radial component of the peculiar velocities of the galaxies that surround the void pollute their redshifts and bias the estimation of $\pi$.
- Additional and spurious anisotropies in the isocontours of $\xi_{vg}(\sigma,\pi)$ ONLY along $\pi$.
- We need a model for $\xi_{vg}(\sigma,\pi)$ that takes into account the voids dynamics.



# I.3) Enviroment & dynamic

Sheth & van de Weygaert (2004)

ENVIROMENT determines the DYNAMIC

TWO TYPES OF VOIDS

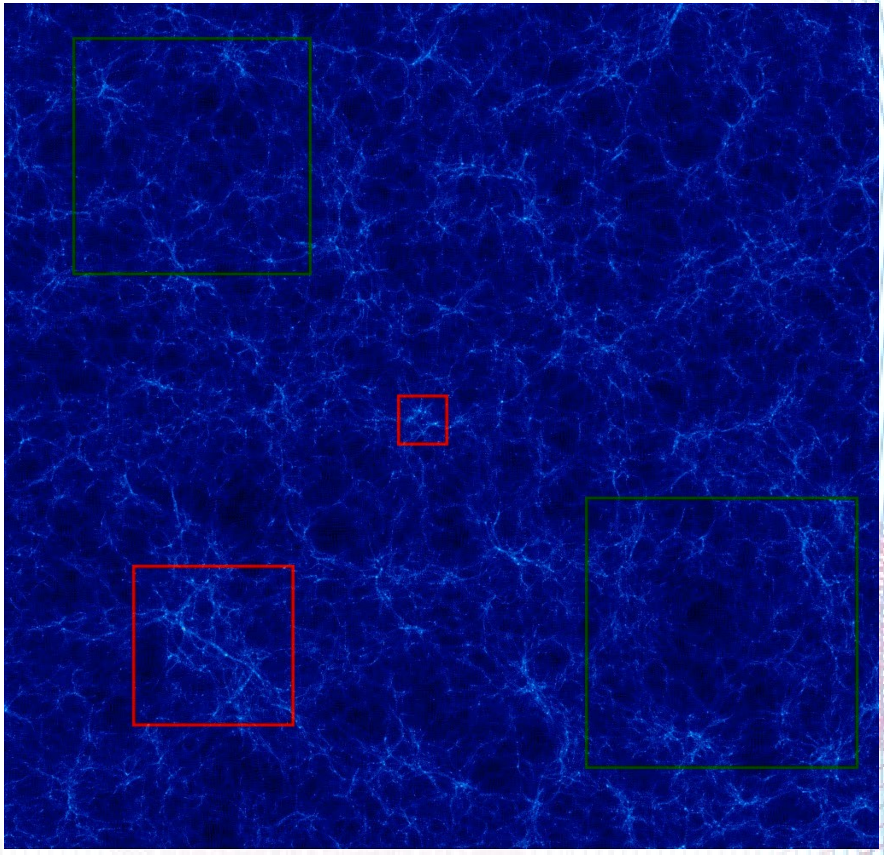
MEAN ENVIROMENT → EXPANSION

OVERDENSE ENVIROMENT → COLAPSE

**Density profiles**

$$\Delta(r) := \frac{1}{V_r}\int_{V_r} \delta(r)\, dV$$

Model for $\Delta(r)$ → Model for $\xi_{vg}(\sigma,\pi)$



Ceccarelli et al. (2013); Paz et al. (2013)

# I.4) Density profiles

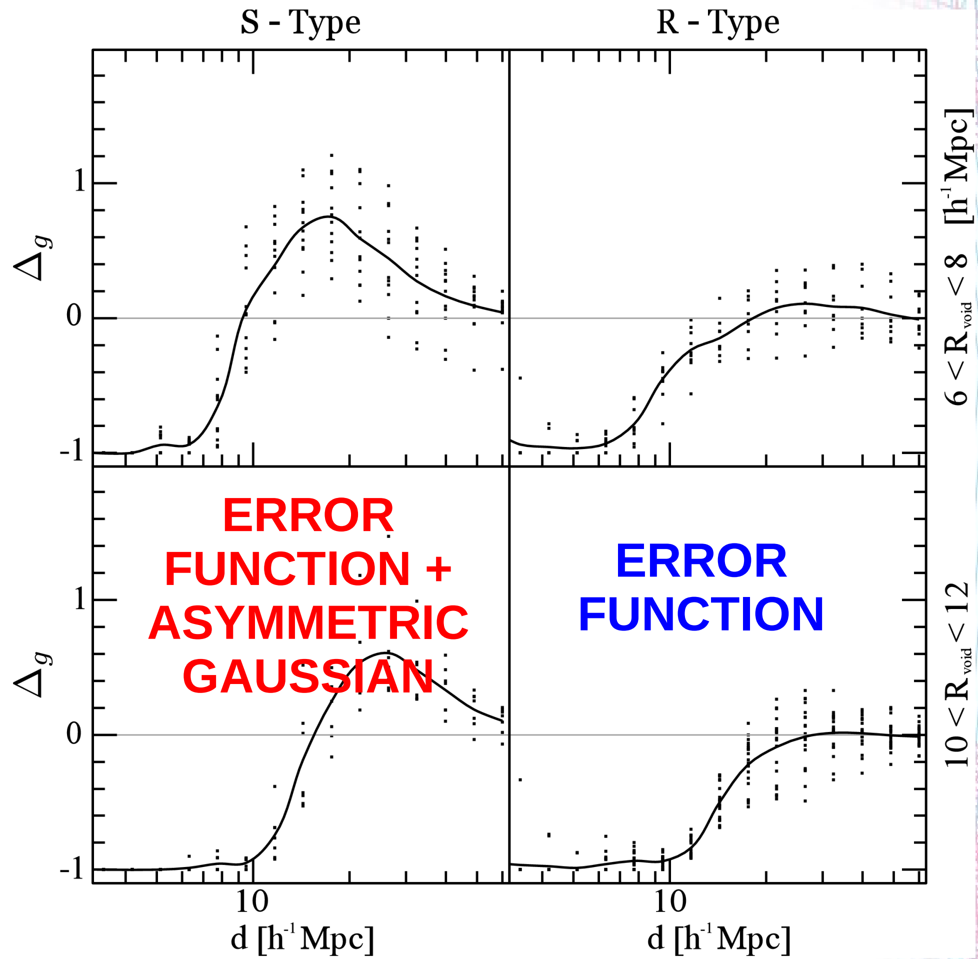
- It is convenient to build samples of voids according to:
  - same mean redshift;
  - similar sizes;
  - similar enviroments.
- A sample is completely characterized by its **mean density profile** $\bar{\Delta}(r)$

$$\bar{\Delta}_{OE}(r)=\frac{1}{2}\left[erf\left(\boldsymbol{S}\log_{10}\left(\frac{r}{\boldsymbol{R}}\right)\right)-1\right]+\boldsymbol{P}\exp\left[-\frac{\log_{10}^{2}\left(\frac{r}{\boldsymbol{R}}\right)}{2\Theta^{2}(r)}\right]$$

$$\Theta(r)=\begin{cases}\frac{1}{\sqrt{2}\boldsymbol{S}}, r<\boldsymbol{R}\\ \frac{1}{\sqrt{2}\boldsymbol{W}}, r>\boldsymbol{R}\end{cases}$$

OVERDENSE ENVIROMENT

MEAN ENVIROMENT




$$\bar{\Delta}_{ME}(r)=\frac{1}{2}\left[erf\left(\boldsymbol{S}\log_{10}\left(\frac{r}{\boldsymbol{R}}\right)\right)-1\right]$$

# I.5) Calculation of $\xi_{vg}(\sigma,\pi)$

Mean velocity profile

Peebles (1980)

$$1+\xi_{vg}(\sigma,\pi)=\int \frac{1}{\sqrt{2\pi}\sigma_v}\exp\left[-\frac{\left(v_{\parallel}-\bar{v}(r)\frac{r_{\parallel}}{r}\right)^2}{2\sigma_v}\right][1+\xi_{vg}(r)]d^3v$$

Peebles (1980) $\sigma_v \approx 400\, km/s$

Paz et al. (2013) $\xi_{vg}(r)=\frac{1}{3r^2}\frac{d}{dr}\left(r^3\bar{\Delta}(r)\right)$

Peebles (1976); Paz et al. (2013)
DYNAMIC LINEAR MODEL

$$\bar{v}(r)=\frac{-1}{3}H_0 r\bar{\Delta}(r)\Omega_m^{0.6}$$

$\bar{\Delta}_{ME}(r)$ $\bar{\Delta}_{OE}(r)$ $\{R,S,P,W\}$

sample of voids

# I.6) AP test design

<u>Assumptions</u>:

- **$H_0$** fixed
- Flat space: $\Omega_\Lambda = 1-\Omega_m$
- Sample of voids at **redshift z**

$$\{R, S, P, W, \Omega_m\}$$

1) COSMOLOGICAL TRANSFORMATION

$$\{(\Delta\theta, \Delta z) \rightarrow (\sigma, \pi)[h^{-1} Mpc]\}$$

$$\sigma = \frac{c\,\Delta\theta}{H_0(1+z)} \int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} \qquad \pi = \frac{c\,\Delta z}{H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}$$

2) LINEAR DYNAMIC MODEL

$$\bar{v}(r) = \frac{-1}{3} H_0 r \bar{\Delta}(r) \Omega_m^{0.6}$$

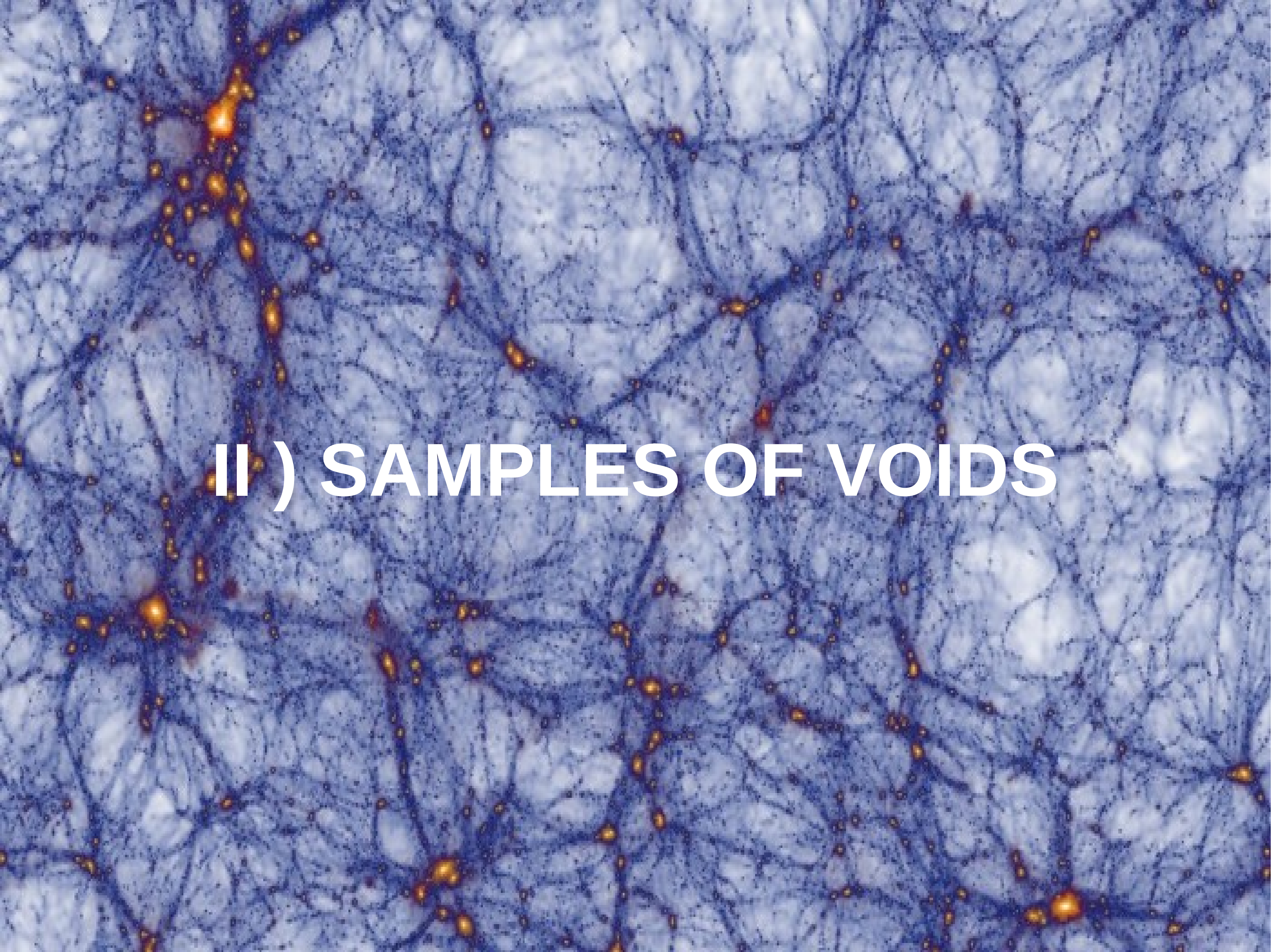
$$\xi_{vg}^{obs}(\Delta\theta, \Delta z) \qquad \{\xi_{vg}^{theo}(\sigma, \pi)\}$$

$$L(R, S, P, W, \Omega_m)$$

*MCMC*

$$(R, S, P, W, \Omega_m)_{fit} + \mathit{CONFIDENCE\ REGION}$$

# II ) SAMPLES OF VOIDS

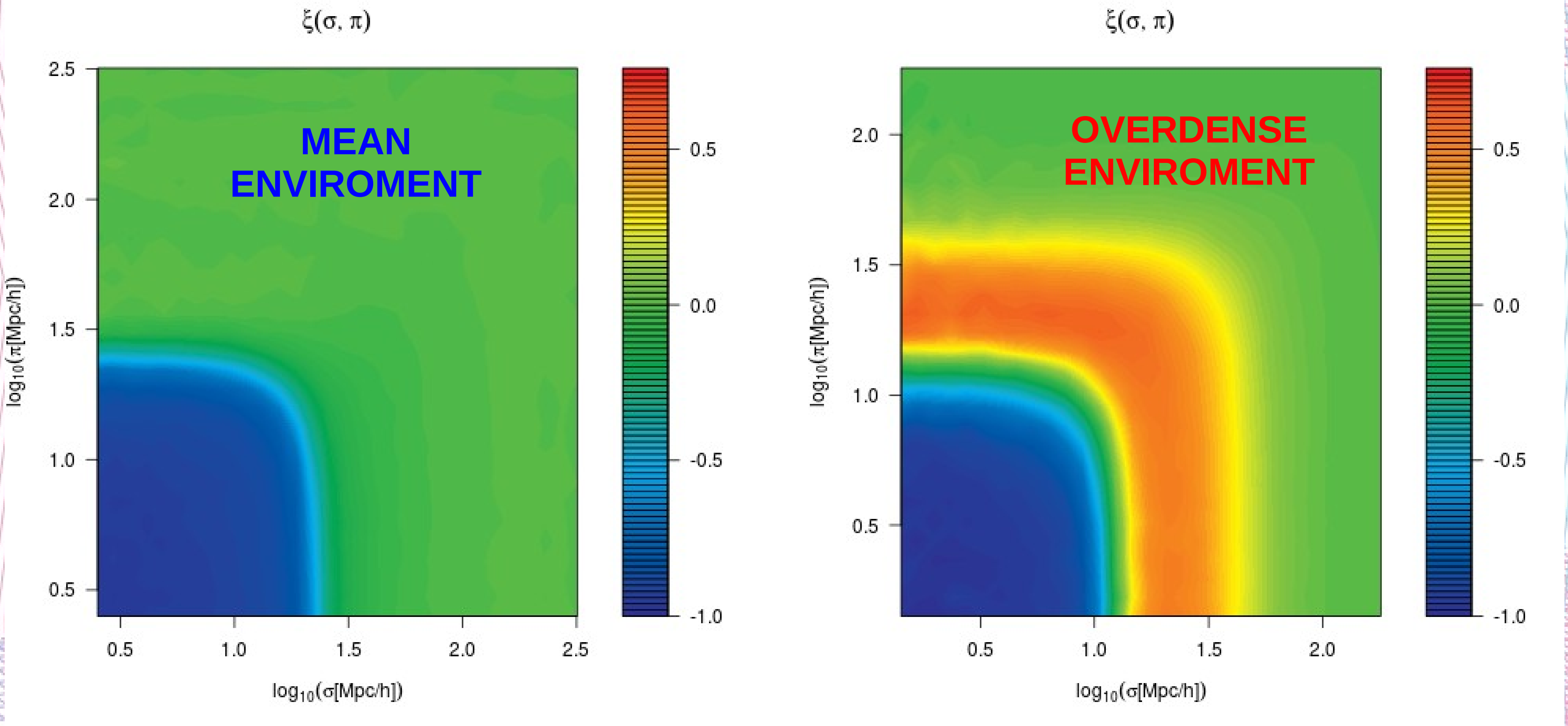


# II.1) Millennium XXL simulation

Angulo et al. (2012)

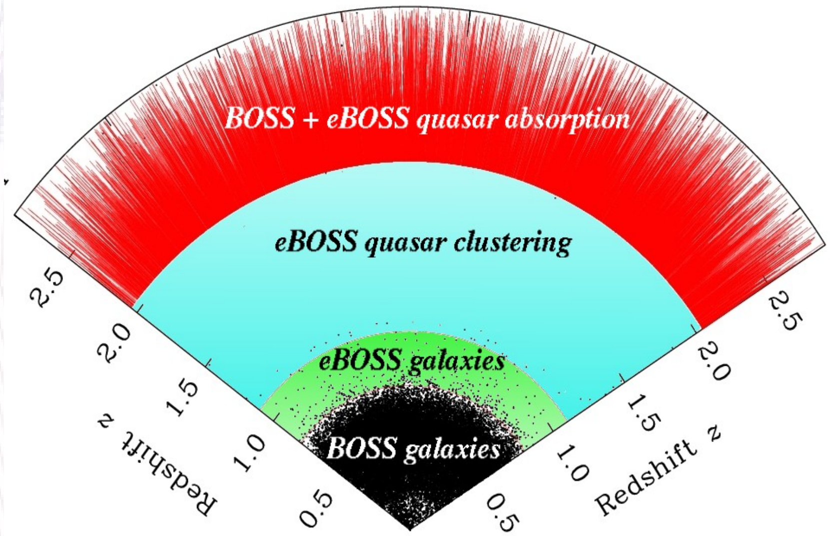
| | Characteristics |
| --- | --- |
| **Predecessor** | Millennium simulation (Springel et al. (2005) |
| **Code** | GADGET-3 |
| **Dimensions** | Periodic cubic region of **3 Gpc/h size** |
| **Particles** | • **Dark matter**<br>• # $6720^3 \sim 3 \times 10^{11}$ (**~ 300 billons**)<br>• $m_p = 8.456 \times 10^9\ M_O$ |
| **Cosmology** | • $\mathbf{\Omega_m = 0.25}$<br>• $\mathbf{\Omega_\Lambda = 0.75}$<br>• $\mathbf{H_0 = 73}$ **km/(s.Mpc)**<br>• $\sigma_8 = 0.9$ |
| **Impact** | Feasibility analysis and predictions for the next generation of galaxy surveys (**great resolution and volume**). |

# II.2) Void-halo correlation function $\xi_{vh}(\sigma,\pi)$

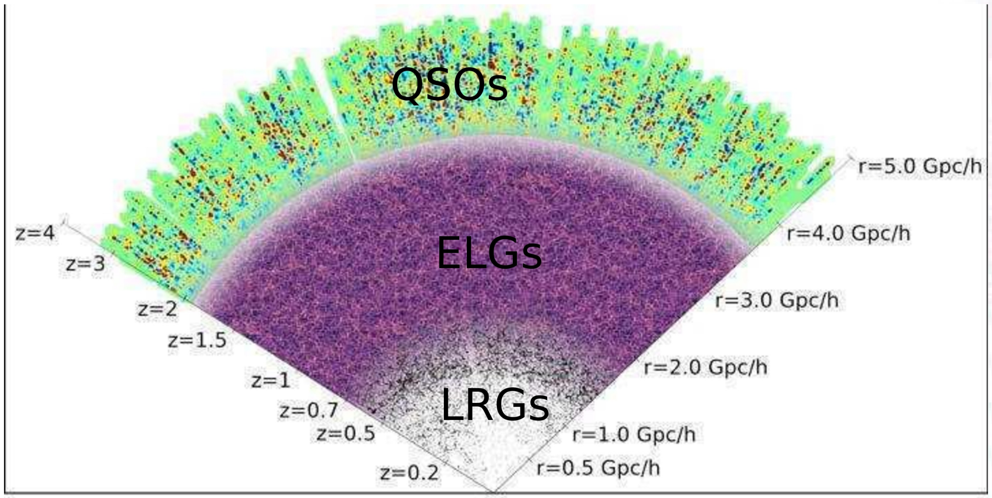


# III ) TEST APPLICATION

# III.1) Future surveys




BOSS




DESI

- The AP test is sensitive to the mean redshift for which the voids samples are built.
- The next generation of galaxy surveys will be very deep in redshift and will cover a great volume of universe (ideal to work with voids): BOSS (eBOSS); HETDEX; DESI; Euclid.
- $\bar{z}_{SDSS} = 0.1$ $\qquad \bar{z}_{NS} > 0.5$
- <u>Objective</u>: analyze the sensitivity of the AP test with mean redshift covering a wide range: $\mathbf{0.1 < \bar{z} < 2}$

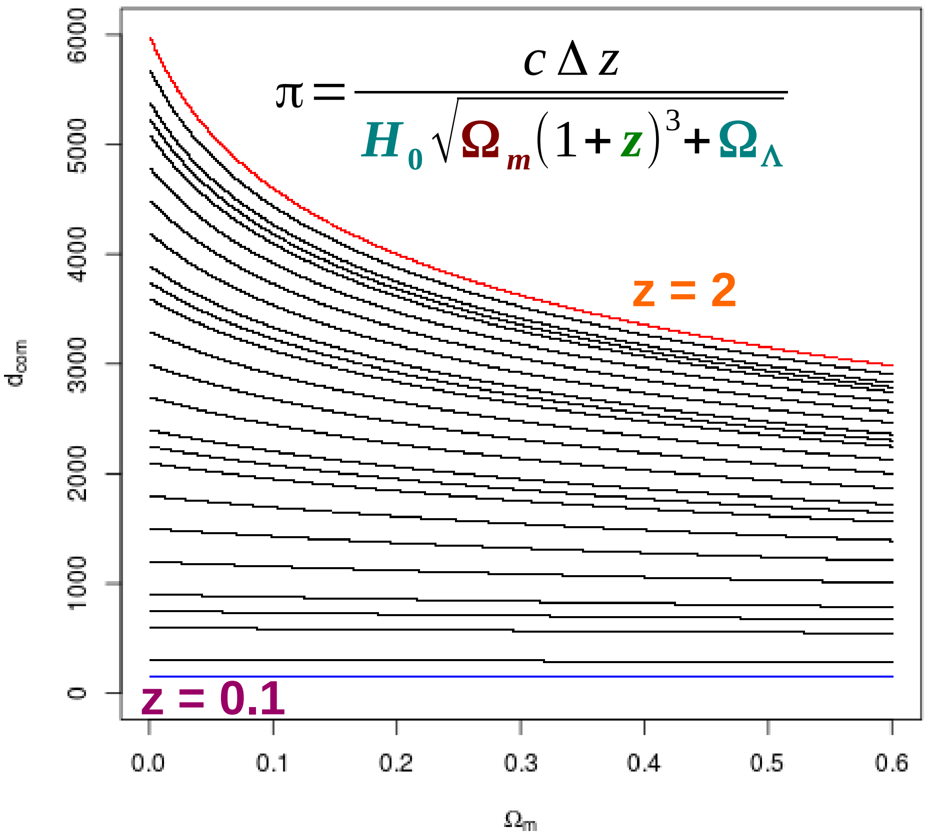
# III.2) Sensitivity of the AP test with mean redshift

1) COSMOLOGICAL TRANSFORMATION

$$\sigma=\frac{c\,\Delta\theta}{H_0(1+z)}\int_0^z\frac{dz'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}$$

$$\pi=\frac{c\,\Delta z}{H_0\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$

- If z is small, the cosmological transformation is insensitive to $\Omega_m$. In this regime, we expect that the <u>dynamic model</u> dominates the variation of $\Omega_m$ in the AP test.
- If z is large, the cosmological transformation is very sensitive to $\Omega_m$. In this regime, we expect that the <u>transformation</u> dominates the variation of $\Omega_m$ in the AP test.

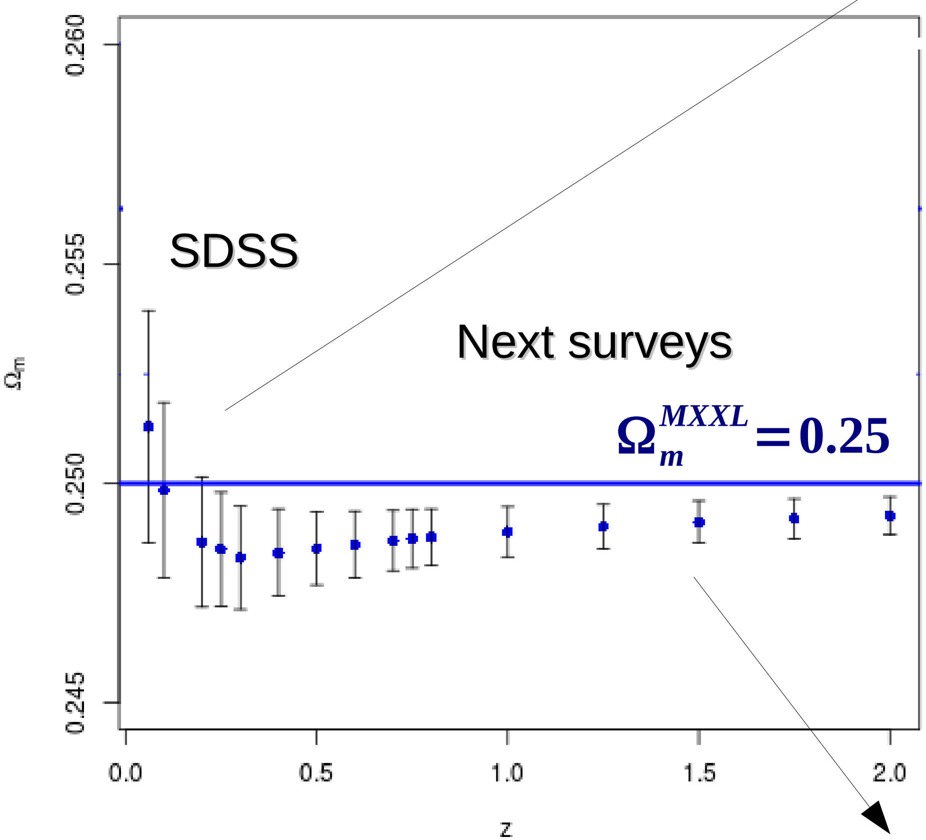



2) LINEAR DYNAMIC MODEL

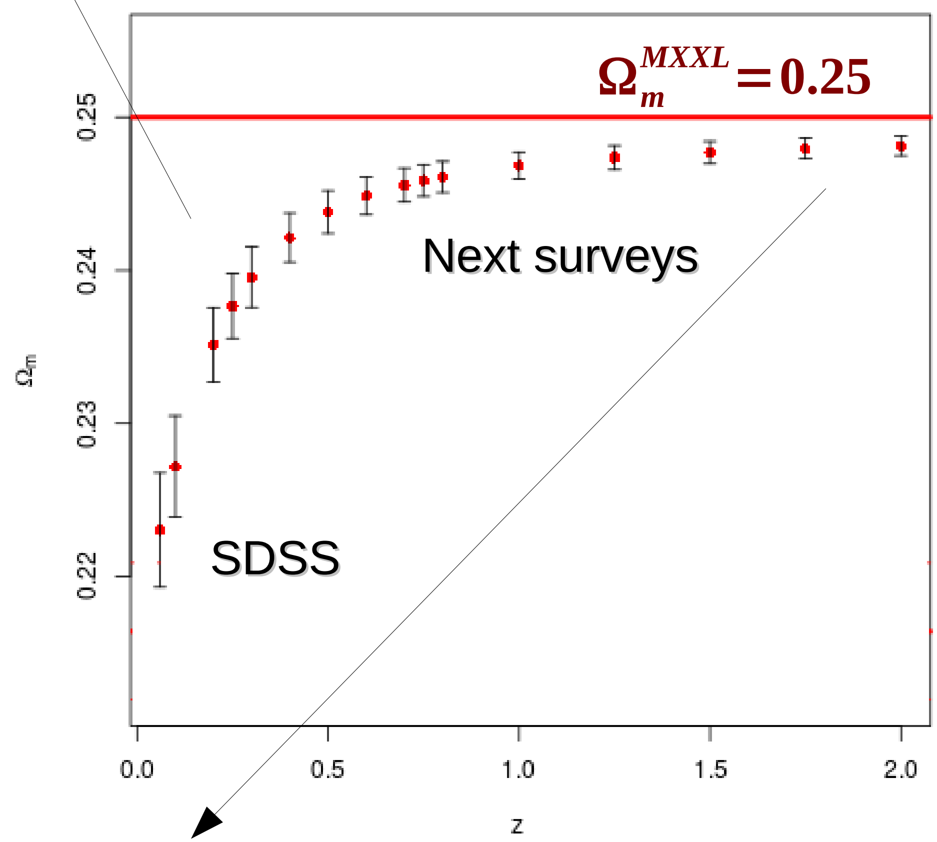
$$\bar{v}(r)=\frac{-1}{3}H_0\,r\,\bar{\Delta}(r)\,\Omega_m^{0.6}$$

**DYNAMIC DOMAIN:**
**bias due to a deficit in the model**

**MEAN ENVIROMENT**




**OVERDENSE ENVIROMENT**




**COSMOLOGICAL TRANSFORMATION DOMAIN:**
**the test improves with increasing redshift (fit values and confidence regions).**

# CONCLUSIONS

We proposed an own version of the Alcock & Paczyński (1979) cosmological test (AP test) using the distribution of galaxies and cosmic voids in the large scale structure of the universe, through the void-galaxy cross correlation function in redshift space $\xi_{vg}(\sigma,\pi)$.

Advantages:

- Simple test. It only depends on a geometrical effect.
- Clean test. It does not depend on galaxy evolution or other astrophysical processes.

Disadvantages:

- Absence of genuine standard rulers.
- Contaminación by dynamic distortions.

Treatment:

- Indirect standard ruler: any distinctive feature in the curve $\xi(r)$, due to spherical symmetry in real space.
- Linear model of the dycotomic dynamic of voids (mean and overdense enviroment) developed by Paz et al. (2013), based on the 4 parameters {R,S,P,W} from the mean density profile parametric model.

- The method consists in adding one more parameter: $\{R, S, P, W, \mathbf{\Omega}_m\}$
- In order to apply the designed test, we used data (dark matter halos and voids) from the Millennium XXL simulation. We built two representative samples of voids according to the two types of populitations.
- We evaluated the AP test sensitivity with mean redshift. At low redshifts, the dynamic model dominates. There are bias due to a deficit in the model. At large redshifts, the cosmological transformation dominates. The test improves (fit values and confidence regions), showing, in this way, the impact of the next generation of galaxy surveys.


THANK YOU FOR YOUR ATTENTION