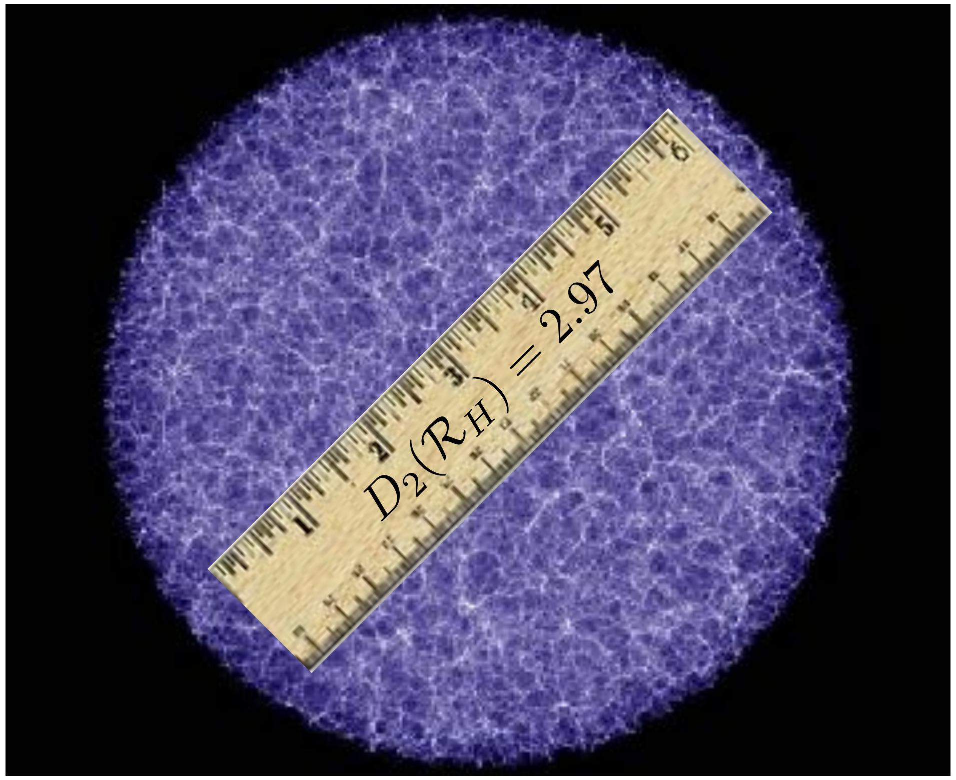
Cosmic Homogeneity as standard ruler

Pierros Ntelis

Collaborators:
J. Rich
J.C. Hamilton
J.M. Le Goff
A.Ealet
S. Escoffier
A.J. Hawken
A. Tilquin

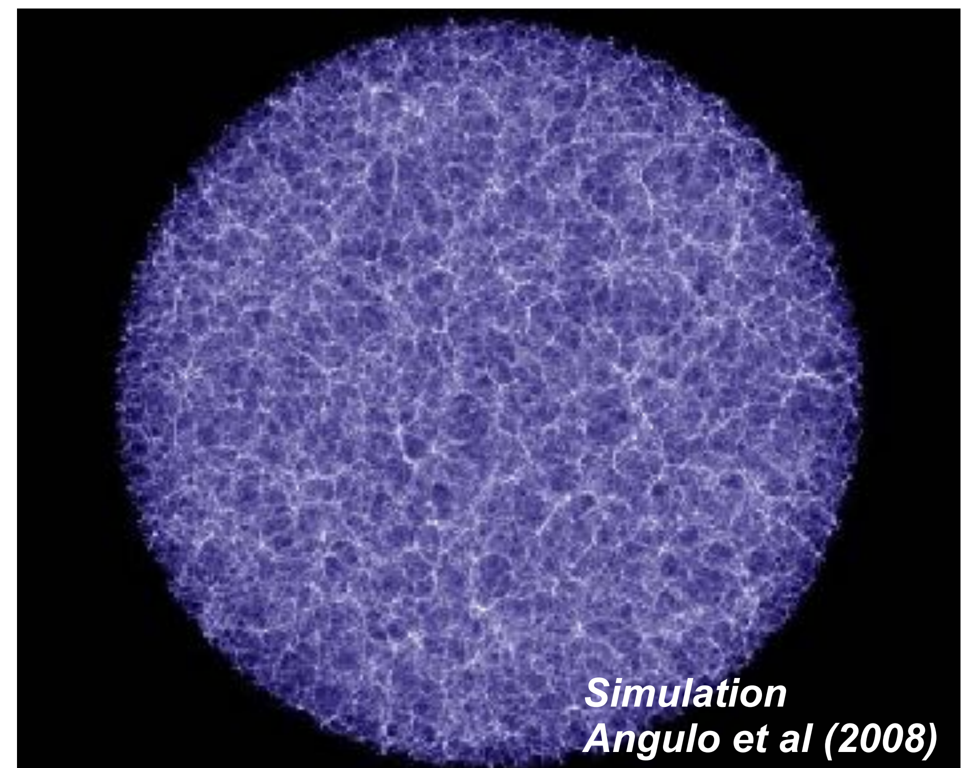


Post Doc
Aix-Marseille University, CPPM

What can fractality tell us about the universe?

Romansco Broccoli, Italy since 16th c.

$$D_2(r) = \frac{d \ln N(<r)}{d \ln r}$$



Outline

ΛCDM Phenomenology

Challenges of Cosmological Principle

Standard Rulers and Candles

Homogeneity scale as a standard Ruler

Conclusion and Outlook

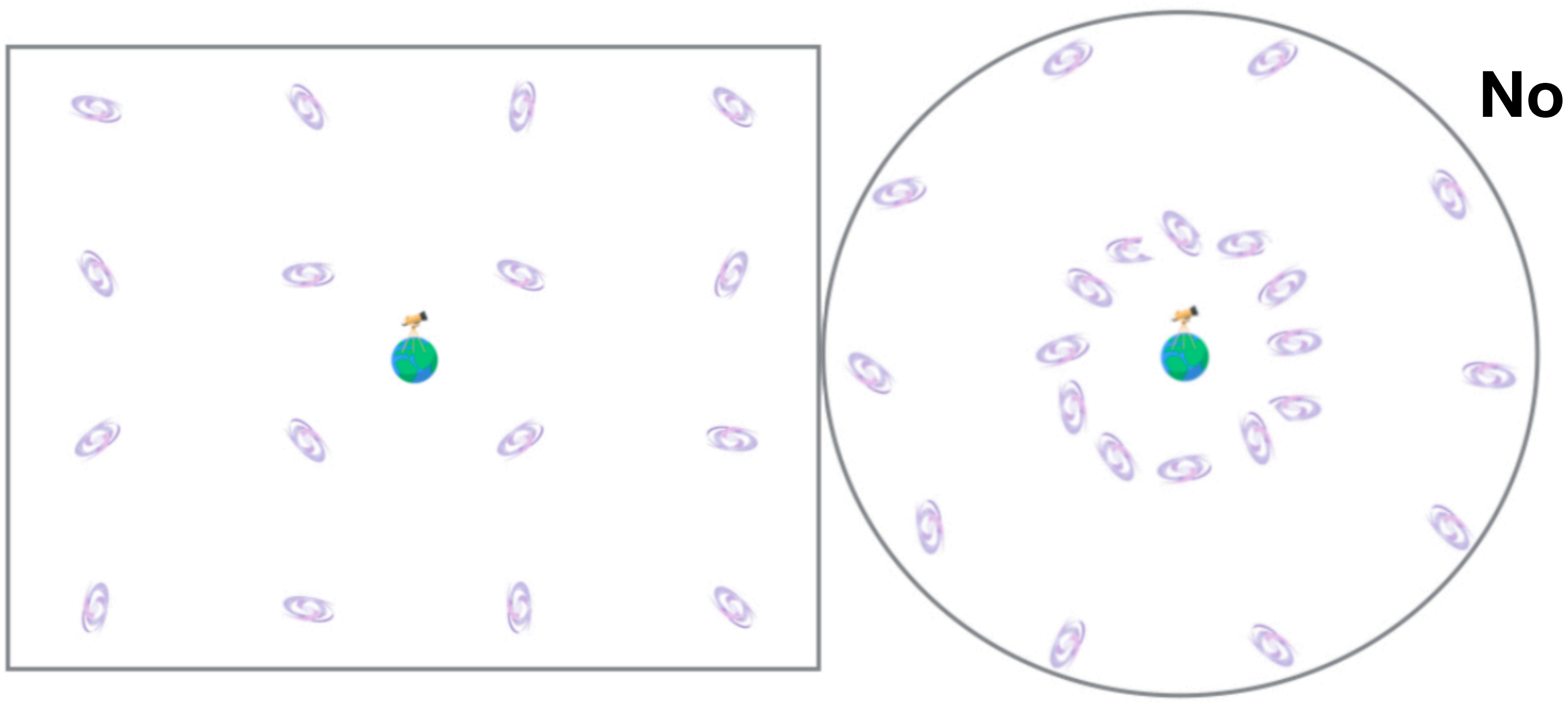
Cosmic Homogeneity as standard ruler

Standard Phenomenology ΛCDM

Cosmological Principle = Statistical Homogeneity + Isotropy

On enough large scales

Homogeneous + Isotropic



Non Homogeneous + Isotropic

FIGURE 2.2: *Left*: 2D representation of homogeneous (and isotropic) galaxy distribution *Right*: 2D representation of an isotropic (but not homogeneous) galaxy distribution [See text for explanation][Credit on [13]] **M.Stolpovskiy**

Cosmic Homogeneity as standard ruler

Standard Phenomenology ΛCDM

Perturbed Einstein-Boltzmann Equations

Least Action Principle

$$\mathcal{S}_{EH} = c^4 \int d^4x \sqrt{-g} \frac{R}{16\pi G}$$

$$G_{\mu\nu} \propto T_{\mu\nu}$$

Metric Ansatz

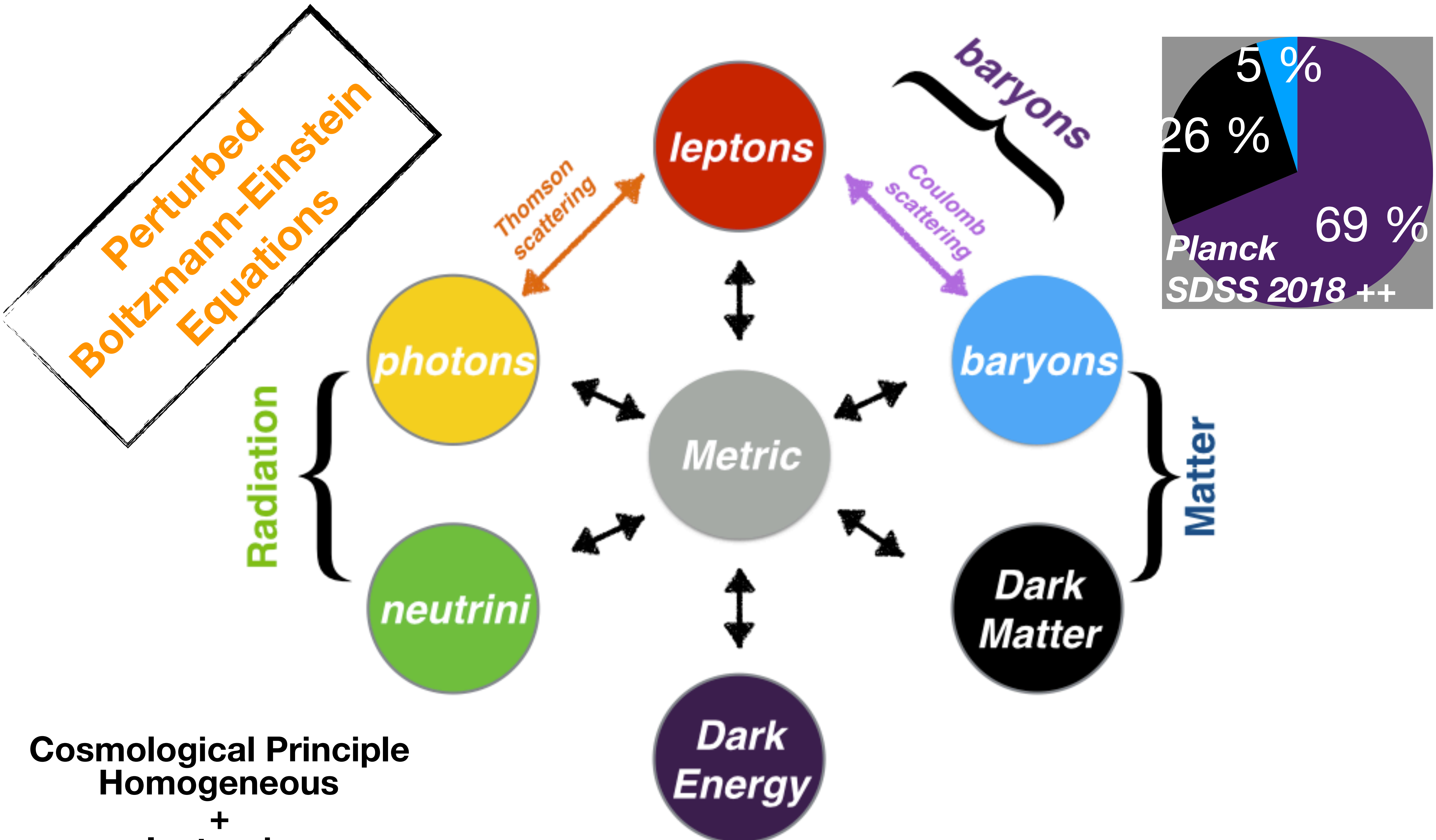
$$g_{\mu\nu} \simeq \bar{g}_{\mu\nu} + \delta g_{\mu\nu}$$

+ *X*, Cosmic Components, (b,CDM,DE,...)

$$\mathcal{D}_t \delta f_X(\vec{x}, \vec{p}, t) = \mathcal{C}[\delta f_X(\vec{x}, \vec{p}, t)]$$

8 coupled non linear differential

Cosmic Homogeneity as standard ruler



Cosmological Principle
Homogeneous
+
Isotropic

Cosmic Homogeneity as standard ruler

standard ΛCDM phenomenology

Basic aspects of this model:

- **Initial Conditions: Primordial fluctuations, Inflation?**
- **Expansion**
- **Acceleration**
- **Statistical homogeneity and isotropy on large scales**
- **Baryon Acoustic Oscillations (BAO)**

Cosmological Constant Problem
Can these phenomenological aspects, be described in a better way than standard GR, Λ?

Outline

- ΛCDM Phenomenology
- **Challenges of Cosmological Principle**
- Standard Rulers and Candles
- Homogeneity scale as a standard Ruler
- Conclusion and Outlook

Cosmic Homogeneity as standard ruler

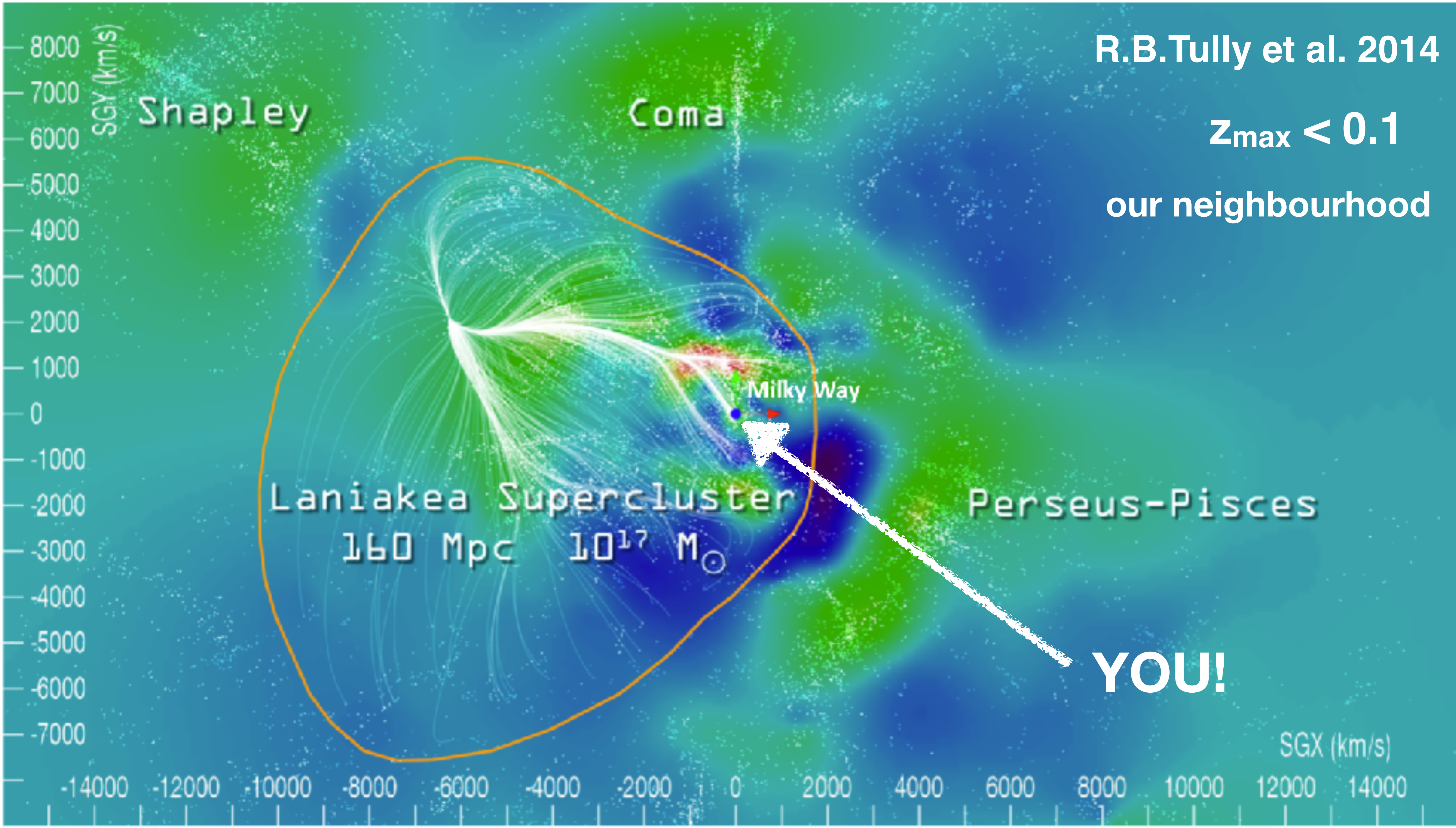
Challenges of Cosmologically Principled Universes:

A historical list of large scale structures(LSS):

Year	Name	Size (Mpc)	Detection Method	Notes	Dedication
1983	Webster (5)LQG	100	no-info	no-info	A.Webster
1987	Pisces-Cetus SuperCluster Complex	350	spectro-z, percolation analysis L_0=70 h^{-1} Mpc, 10 members, $L>L_0$ no significant	h=75	R.B.Tully
1987	Giand Void	350	L_0=200 h^{-1} Mpc, Spectro-z, FoF	Flat, $\Lambda=0$, H0=50km/s/Mpc,q_0=0.5	A.I.Kopylov et al.
1989	Great Wall	240	spectro-z	blocked by MW gal plain	Hunchra & Geller
2003	Sloan Great Wall	420	By comparison of Great Wall	Flat	J.R.Gott
2006	Newfound Blob	65	FOCAS,Subaru, Lya emitters	Flat,0.3,0.70,z~3.1	0510762v1
2007	Super Void	140	NVSS, Waveletes+ISW, Counts+Brighnes	Close to cmb cold Spot	Rudnick et al. 0704.0908v2
2012	Huge CC (73)LQG	500/1240	SDSS, FoF,L_0=100 h_{70}^{-1}Mpc	Flat,0.27,0.73,1.0<z<1.8	1211.6256v1
2013	**Hecules-CoronaBorelis**	**2.2Gpc**	SGRBM, γ-Ray Bursts, (θϕ)-KS test, z-independent	h=0.6780	1311.1104
2014	Lianakea	160h^{-1}	Velocities Wiener Filter	no-info	1409.0880v1
2016	BOSS Great Wall	271 h^{-1}	SDSS, 8h^{-1}Mpc smoothing , $L>5L_0$	Flat,0.27,0.73,z~0.47	1602.08498v1

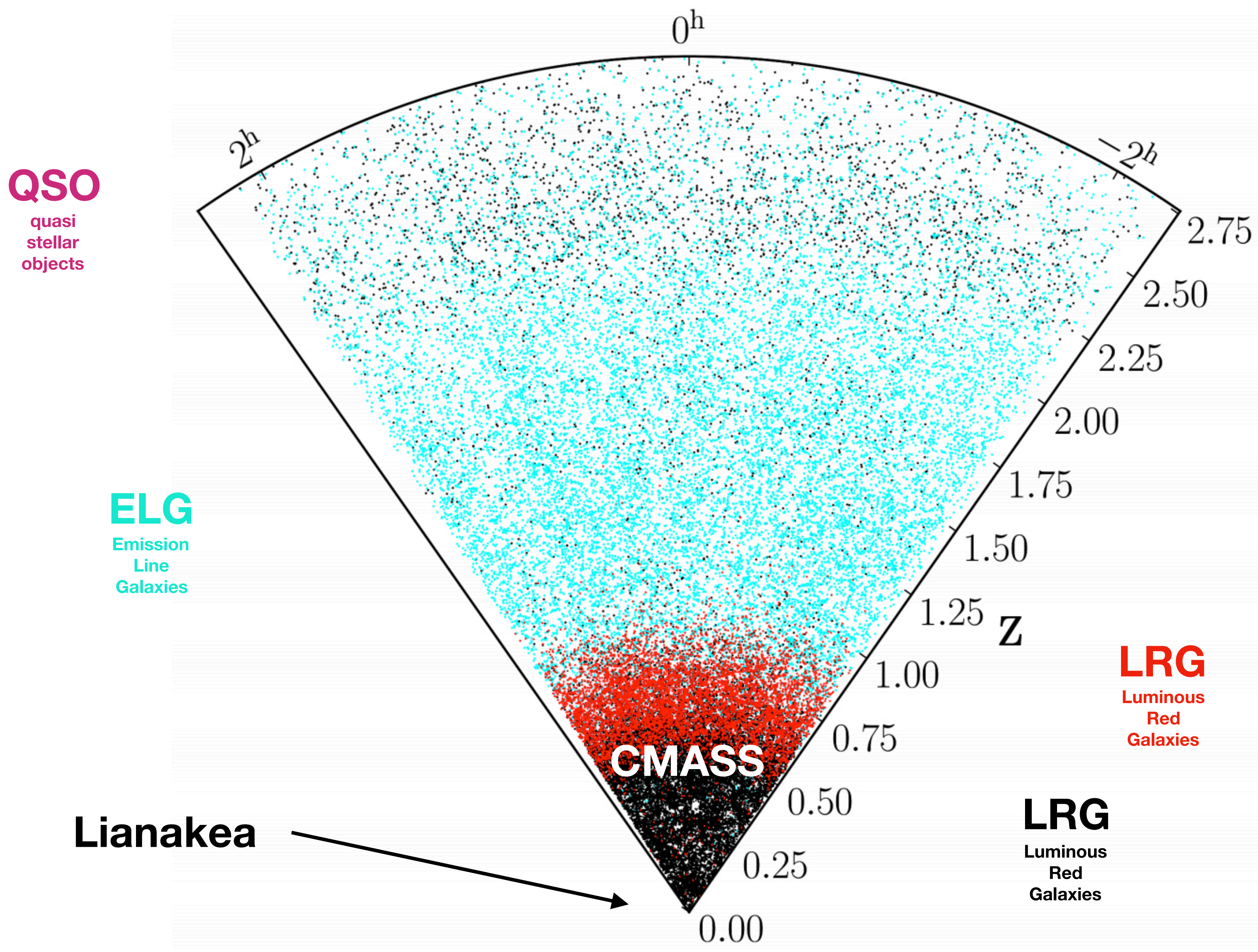
Cosmic Homogeneity as standard ruler

Challenges of Cosmologically Principled Universes:



Cosmic Homogeneity as standard ruler

Challenges of Cosmologically Principled Universes:



1703.00052
SDSS-IV

SDSS-IV telescope

Cosmic Homogeneity as standard ruler

Challenges of Cosmologically Principled Universes:

Fractal Universe and cosmic acceleration in a LTB scenario: **SN-Ia** — arXiv:1810.06318

no Λ, re-analyses UNION2

The projected mass distribution and the transition to homogeneity: **Gal-Clustering** — arXiv:1810.03539

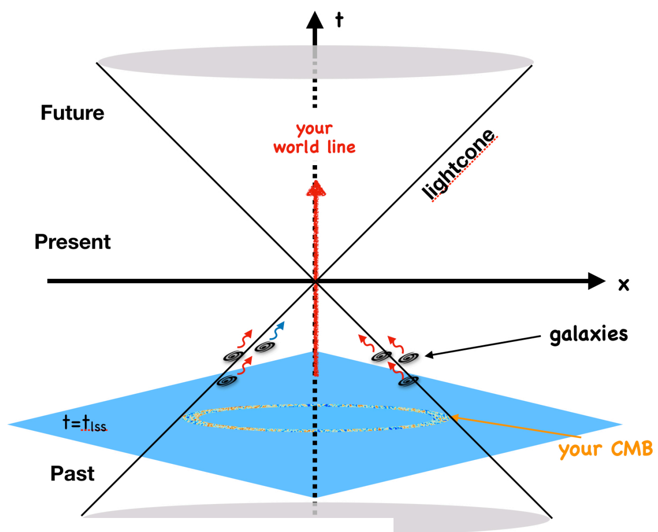
FLRW, re-analyses SDSS DR7

Cosmological Principle is not in the sky: **Gal-Clustering** — arXiv:1611.02139

FLRW, re-analyses SDSS DR7

Cosmic Homogeneity as standard ruler

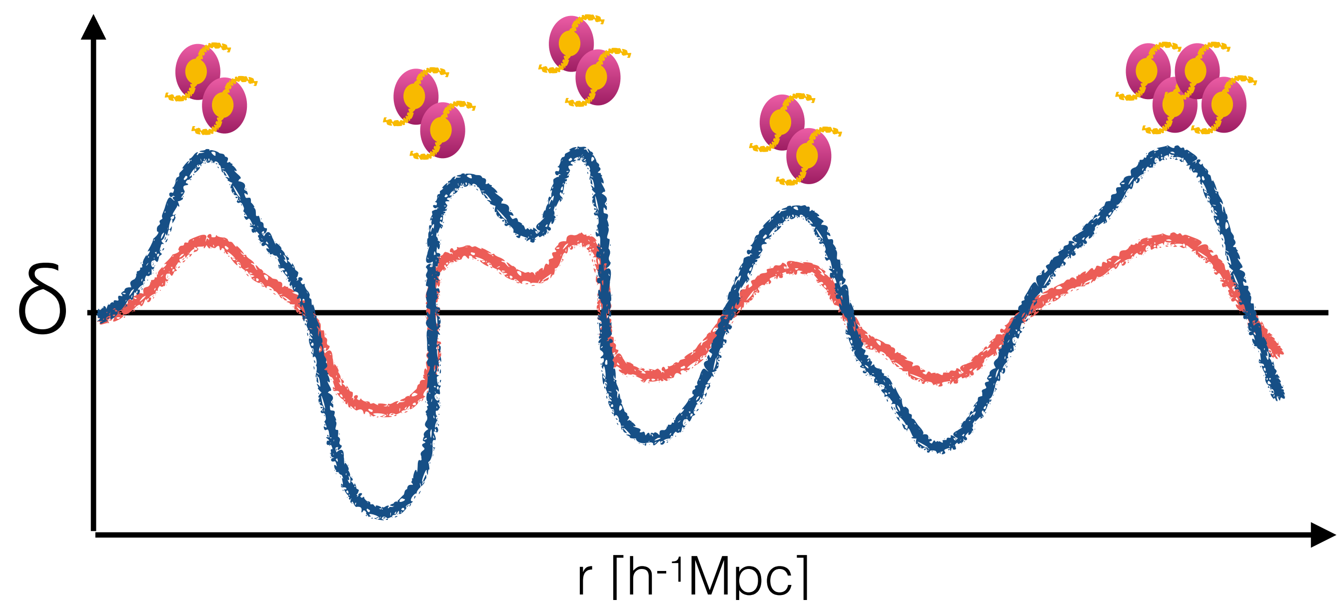
Challenges of Cosmologically Principled Universes:



Inspired by F.Leclercq et al. 2014

Information only on the past lightcone, c finite
Cosmology dependence (Redshift ->Distance)
Redshift Space Distortions (Gravity, Kaiser, FoG)

Galaxies are biased tracers of matter (Cosmic Bias quantifies the galaxy-type selection)



$$\delta_{tracer} = b \quad \delta_{matter}$$

$$\xi_{tracer} = b^2 \quad \xi_{matter}$$

By the way $R_H^{tracer} = b_{RH}\, R_H^{Matter}$, NEW!

Outline

ΛCDM Phenomenology

Challenges of Cosmological Principle

Standard Rulers and Candles

Homogeneity scale as a standard Ruler

Conclusion and Outlook

Cosmic Homogeneity as standard ruler

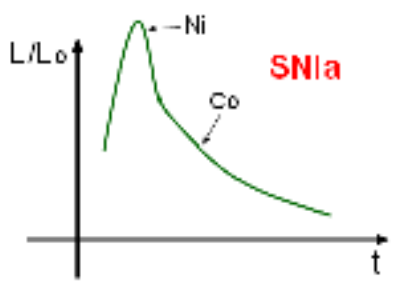
Standard Candles and Rulers

Standard Candles (1998)
Riess, Schmidt, Perlmutter
acceleration 2011

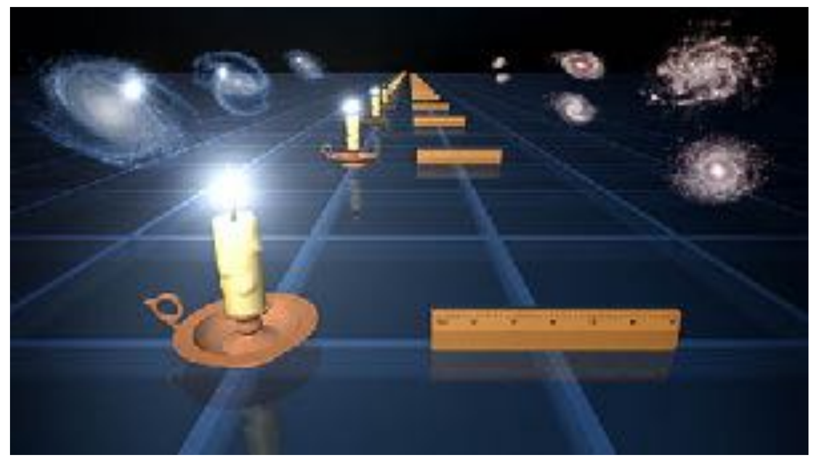
SN-Ia

Same L_{max}

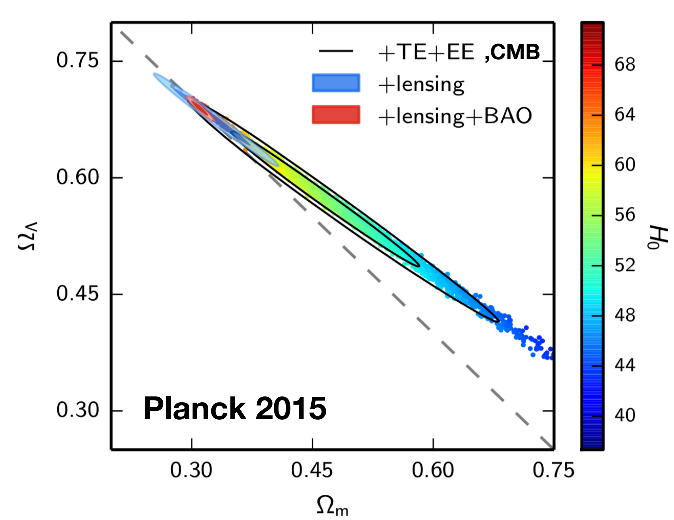
at explosion
at diff z,t



BAO peak
On $\Omega_k = 0$ @ % C.L.

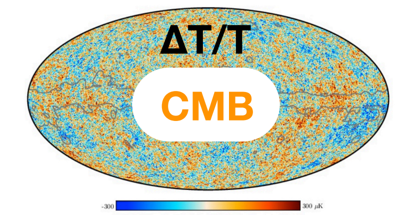


Improve Cosmology

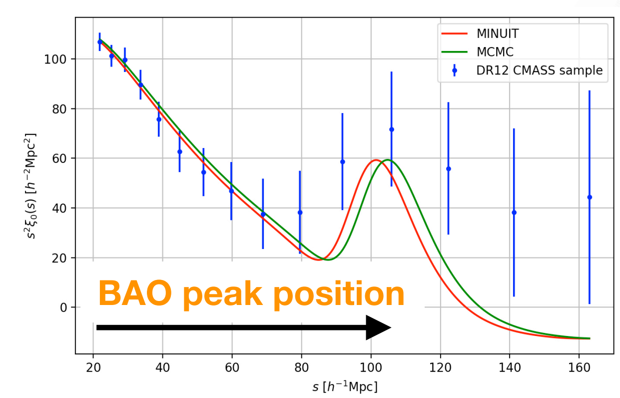


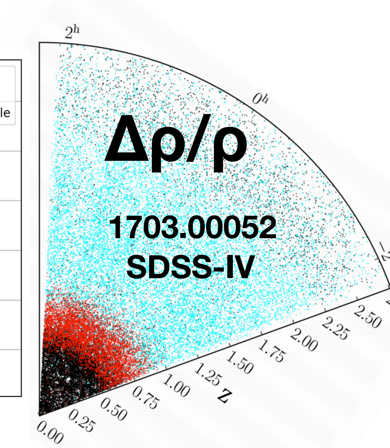
Standard Rulers (2005)
Eisenstein et al, ++

BAO peak position →



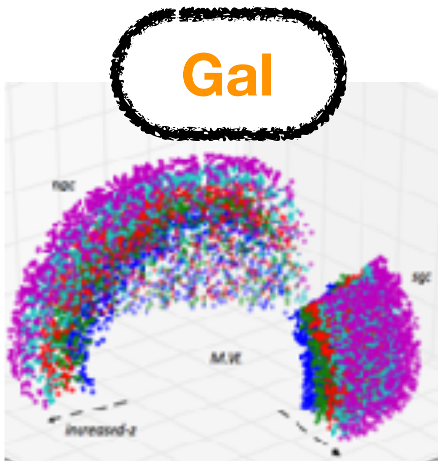
z,t

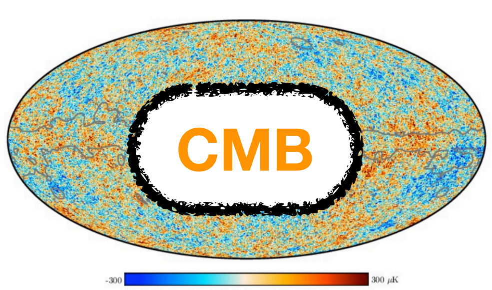




Outline

Cosmic Homogeneity as standard ruler





$$D_2(\mathcal{R}_H) = 2.97$$

$$+$$

P(Ω , δΩ)

Improved cosmological understanding

Improved cosmological Constraints

HOW?

Cosmic Homogeneity as standard ruler

Counts-in-Spheres: $N(<r) = \int_0^r dd(s)ds \propto r^{D_2}$

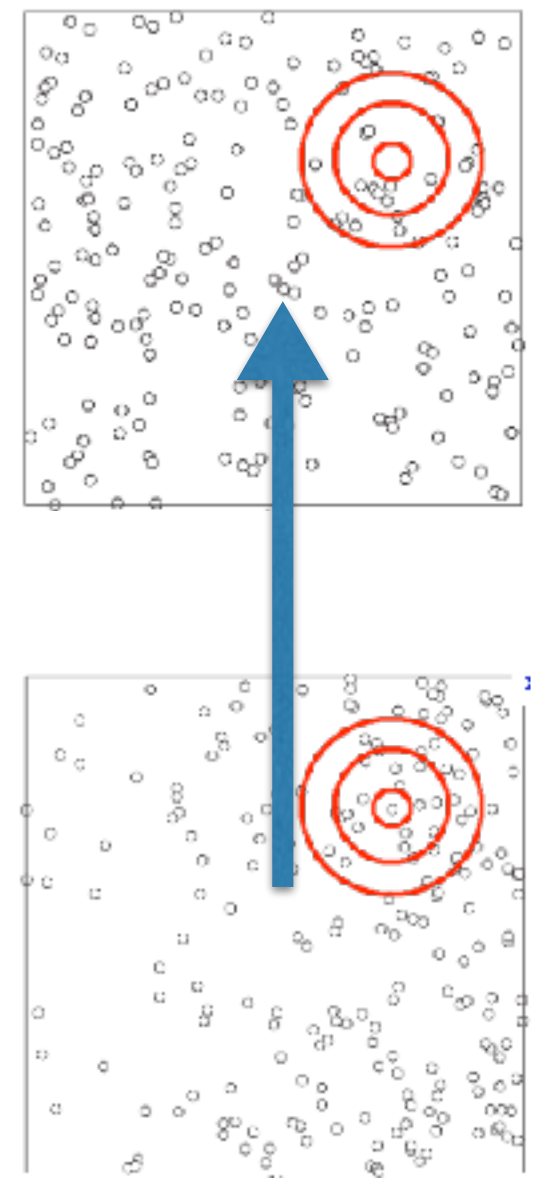
Fractal Dimension: $D_2(r) = \frac{d \ \ln \ N(<r)}{d \ \ln \ r}$

Homogeneous
@ large scales

$$D_2(r) = 3$$

Inhomogeneous
@ small scales (clustering)

$$D_2(r) < 3$$



Transition to Homogeneity at:

$$D_2(R_H) = 3 \ @ \ 1\%$$

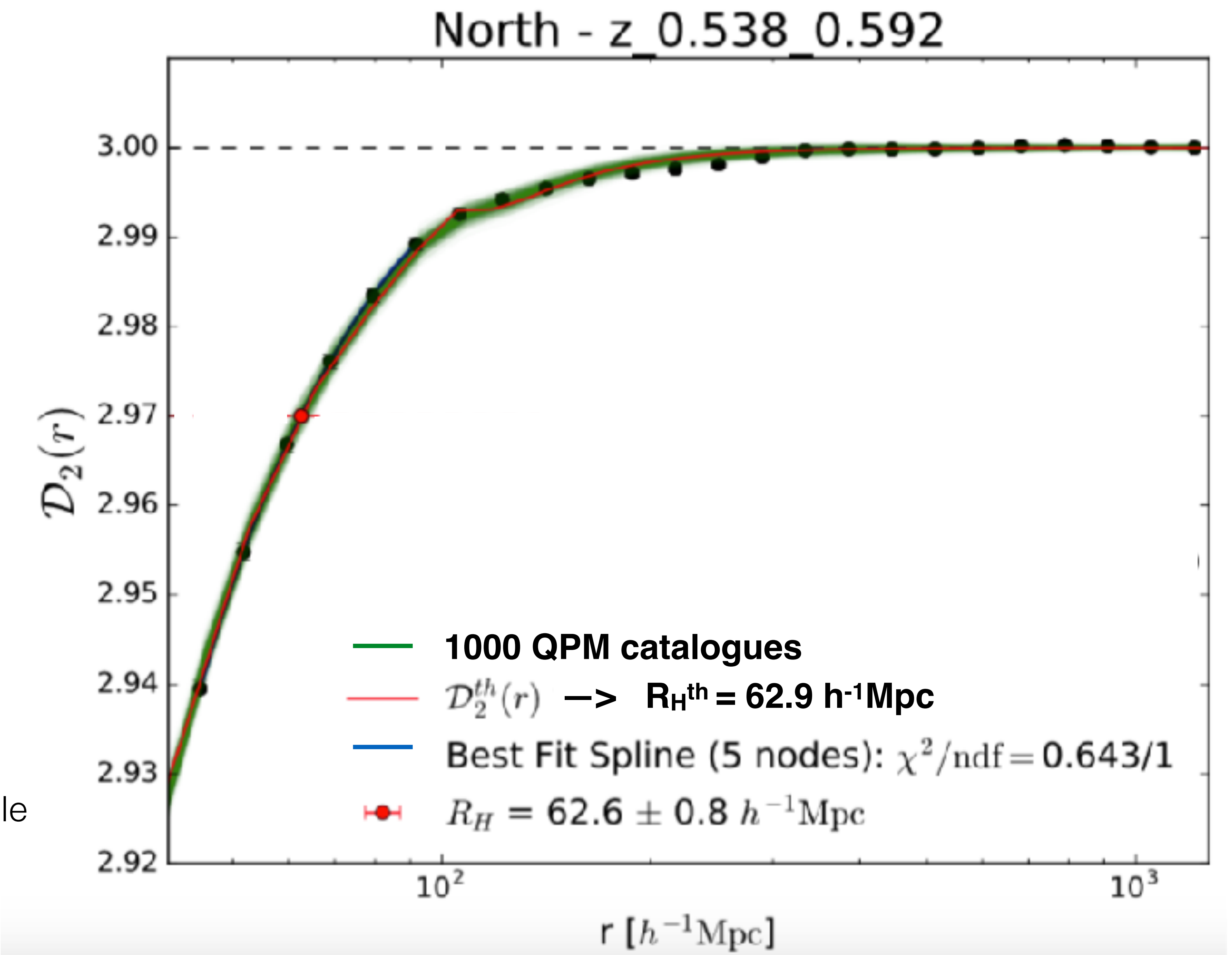
(Arbitrary Choice; Independent of survey)

$$\mathcal{D}_2(r) = 3 + \frac{d\ln}{d\ln r}\left[1 + \frac{3}{r^3}\int_0^r \xi(s)s^2 ds\right]$$

Cosmic Homogeneity as standard ruler

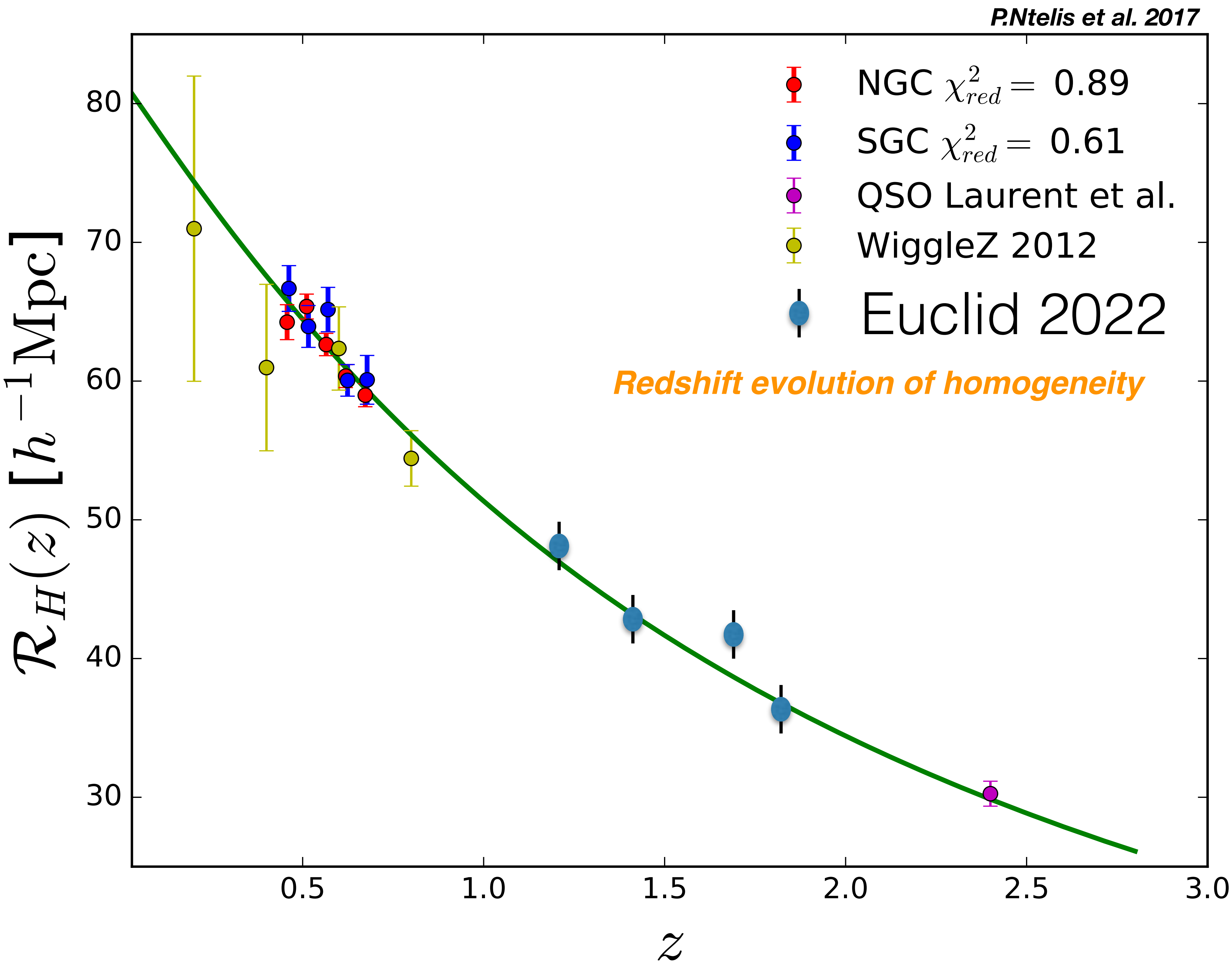
Measurement:

- Use of CMASS galaxy sample of SDSS/BOSS
- Small Scale:
  - clustering
  - fractality
- Large scales:
  - asymptotic smoothness
- Confirmation of
  - ΛCDM model
  - Cosmological Principle
  - Exclusion of fractal models @ LSS

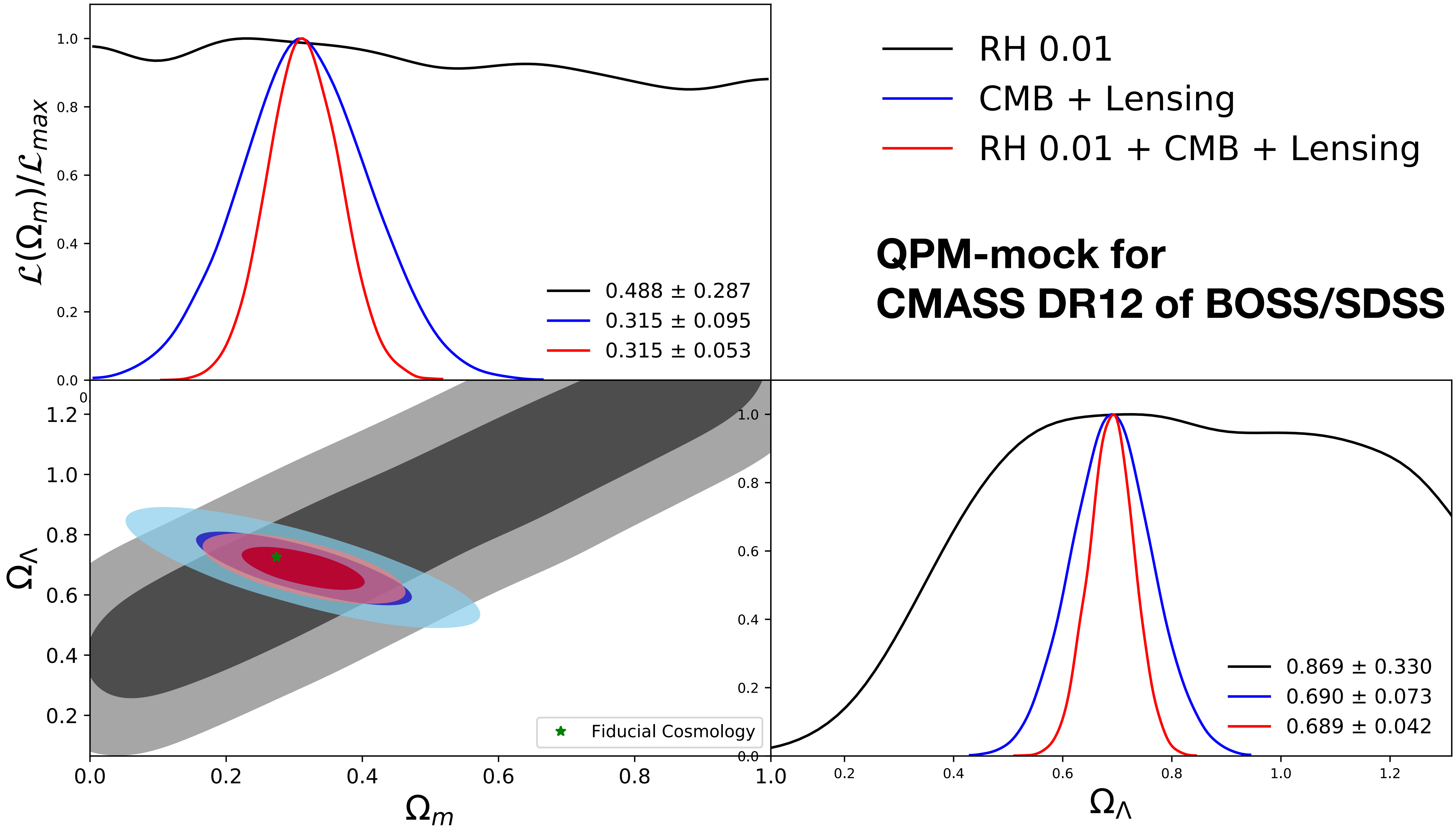


P.Ntelis et al. arXiv:1702.02159

Cosmic Homogeneity as standard ruler



Cosmic Homogeneity as standard ruler



QPM-mock for CMASS DR12 of BOSS/SDSS

Ameliorate Cosmology!

P.Ntelis et al. arXiv:1810.09362

Outline

ΛCDM Phenomenology

Challenges of Cosmological Principle

Standard Rulers and Candles

Homogeneity scale as a standard Ruler

Conclusion and Outlook

Thank you for your Attention!

Conclusions

- New complementary cosmological ruler, R_H!
- R_H Improves the precision on Ω_k , (Ω_m,Ω_Λ)
- D_2 Exclude fractal universes at large scales
- D_2 Exclude inhomogeneous universe at large scales
- D_2 Confirmation of ΛCDM phenomenology in ~% level
- D_2 Confirmation of Cosmological Principle

P.Ntelis et al. '18 arXiv:1810.09362
P.Ntelis et al. '17 arXiv:1702.02159

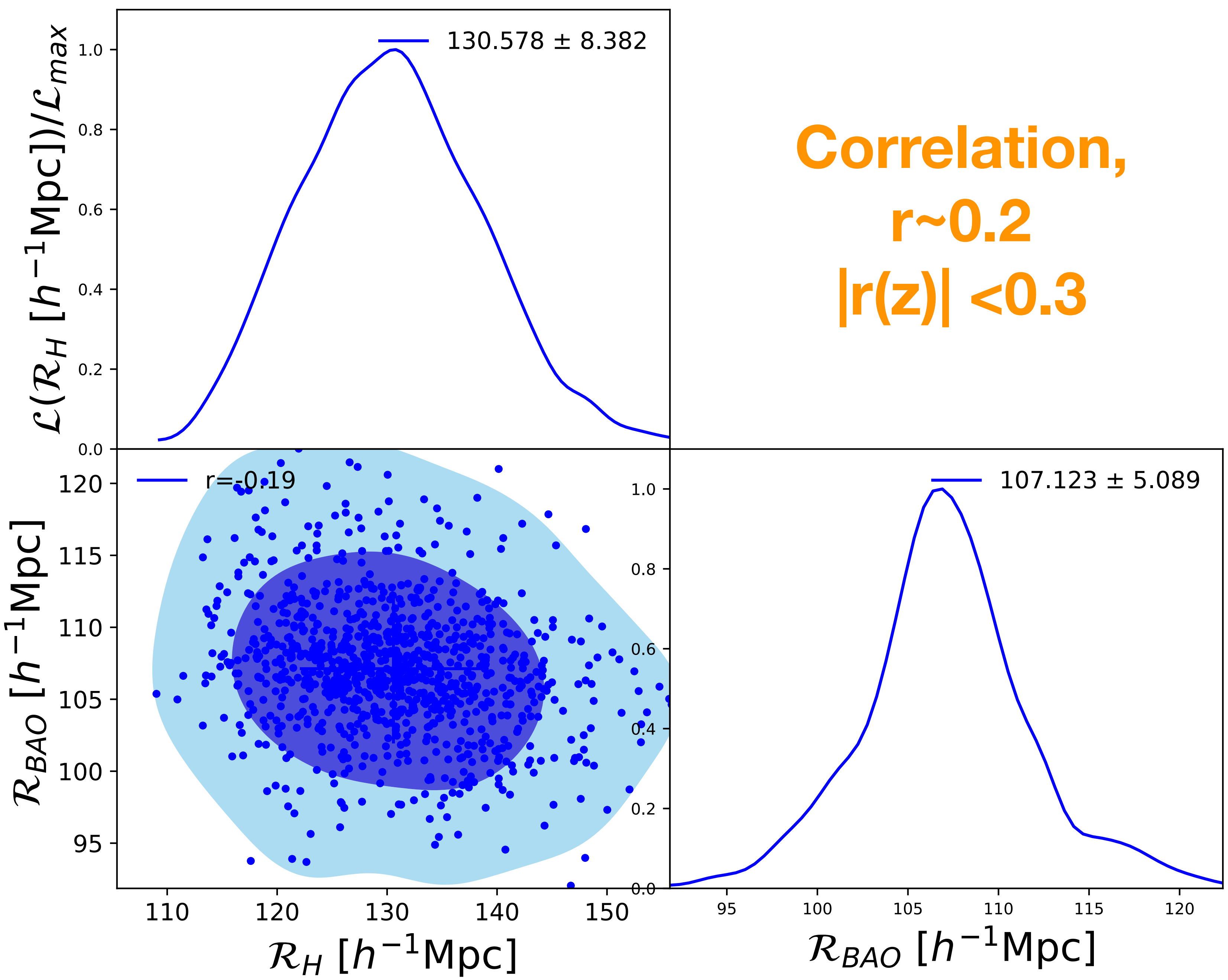
Outlook

RH cosmo-implications analysis is applicable on:

- QSO, ELG, (BBH …), …
- CMB TT map
- Cosmic Web (Nodes, Filaments, Sheets, Voids)
- SuperNovae Clustering?
- Modifications of Gravity Models, (w, γ, …)

Back Up

Cosmic Homogeneity as standard ruler



Correlation,
r~0.2
|r(z)| <0.3

Cosmic Homogeneity as standard ruler

Build the chi2 square MCMC method according to:

$\chi 2(A,B,p_T;p_F)$=

(Data) **(Theoretical model)**

$$\sum_{z=1}^{5}\left(\frac{\mathcal{R}_H^G(z;p_F)-\mathcal{R}_H^{M,th}(z;p_F)\times b(z;A,B)\times\alpha(z;p_F,p_T)}{\sigma_{\mathcal{R}_H^G}(z)}\right)^2$$

with

$$\alpha(z;p_F,p_T)=d_V(z;p_T)/d_V(z;p_F)$$

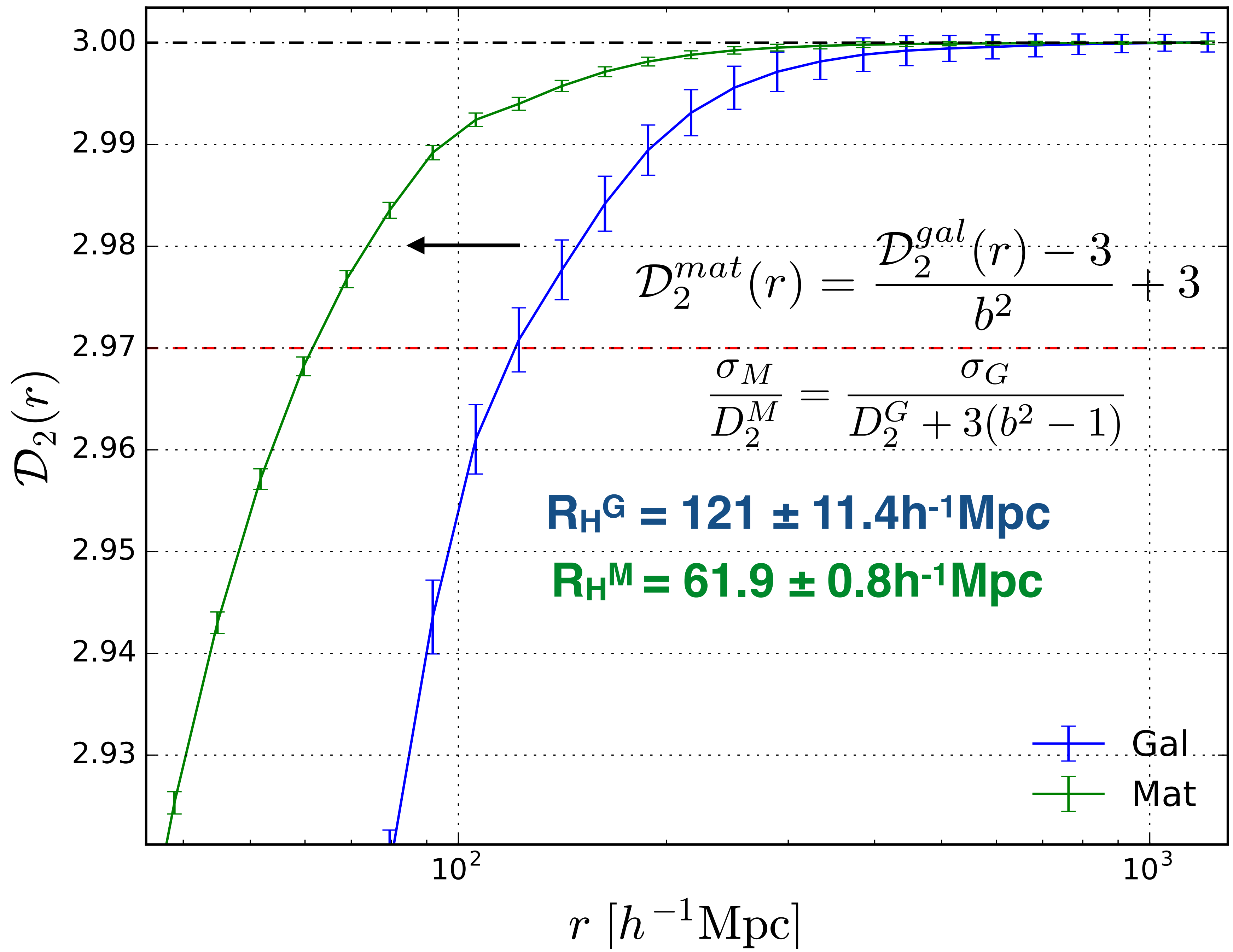
Where d_V is the volume distance, $p_T = (\Omega_m,\Omega_\Lambda)$
and F, stands for Fiducial (fixed parameters)
T, stands for the True (parameters we explore)

$$b(z,A,B)=A\left[\frac{1+z}{1+z_m}\right]^B$$

Bias Dependence

Matter <--- **Galaxies**

Precision increase:
- **Smaller Scales**
- **Bias Gain**



Cosmic Homogeneity as standard ruler

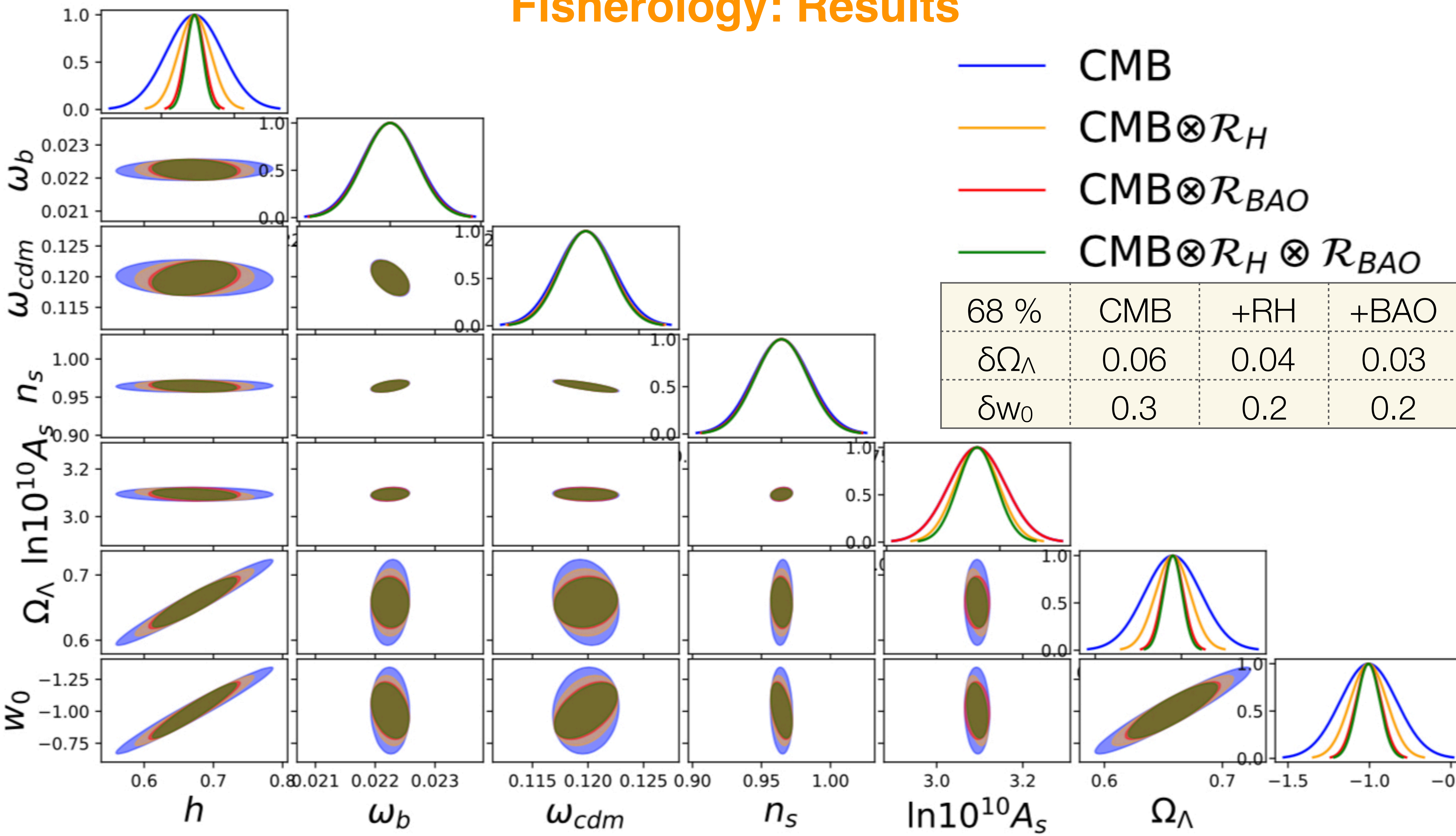
$$F_{ij}^{R_H} = \frac{1}{\sigma^2_{R_H - gal}} \sum_z \frac{\partial^2 R_H(z)}{\partial\theta_i \partial\theta_j}$$

$$F_{ij}^{BAO} = \frac{1}{\sigma^2_{r_s - gal}} \sum_z \frac{\partial^2 r_s(z)}{\partial\theta_i \partial\theta_j}$$

Error as estimated by CMASS analysis

Cosmic Homogeneity as standard ruler

Fisherology: Results

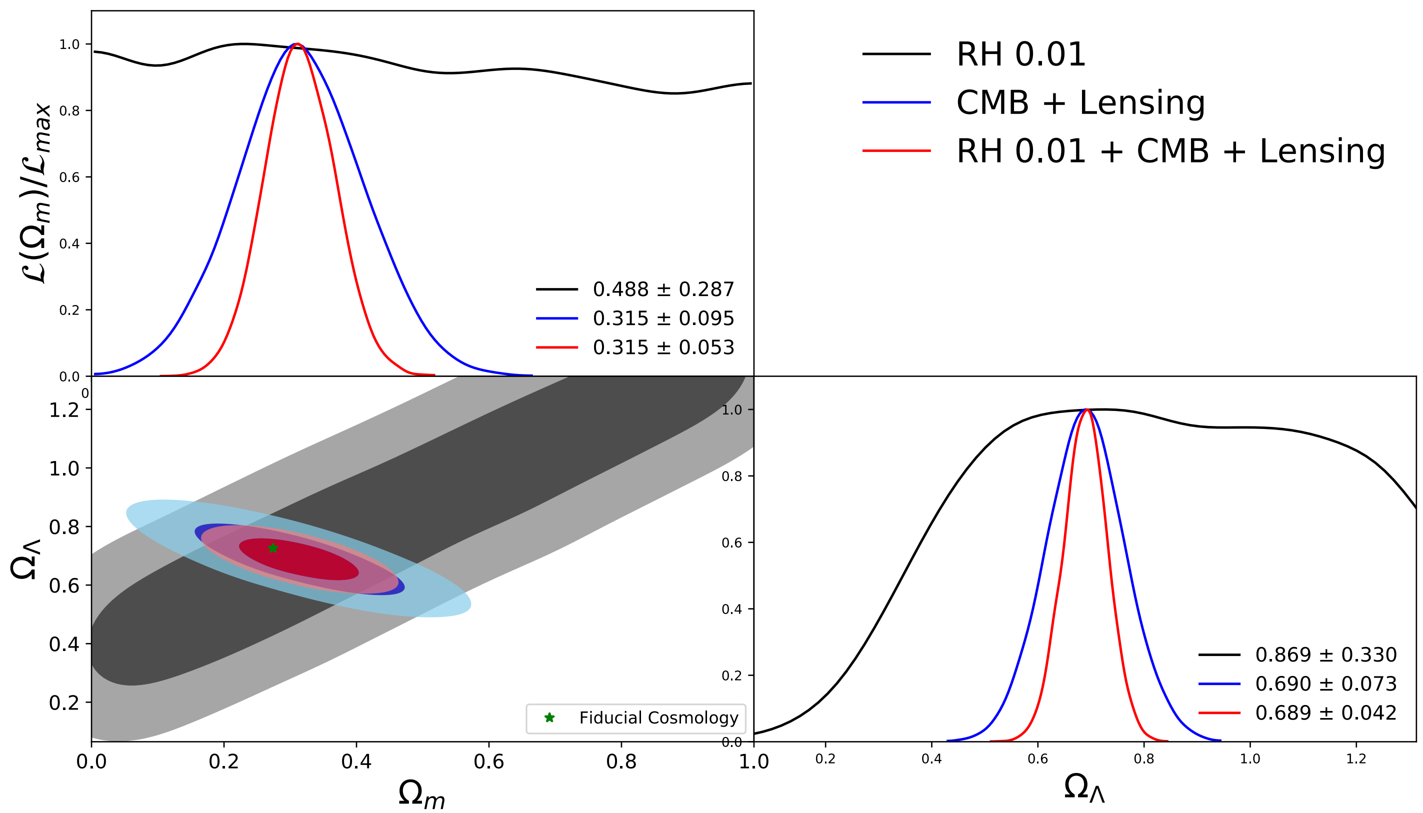


68 %	CMB	+RH	+BAO
$\delta\Omega_\Lambda$	0.06	0.04	0.03
δw_0	0.3	0.2	0.2

Cosmic Homogeneity as standard ruler

Qualitative comparison

Black ⟷ **Blue**



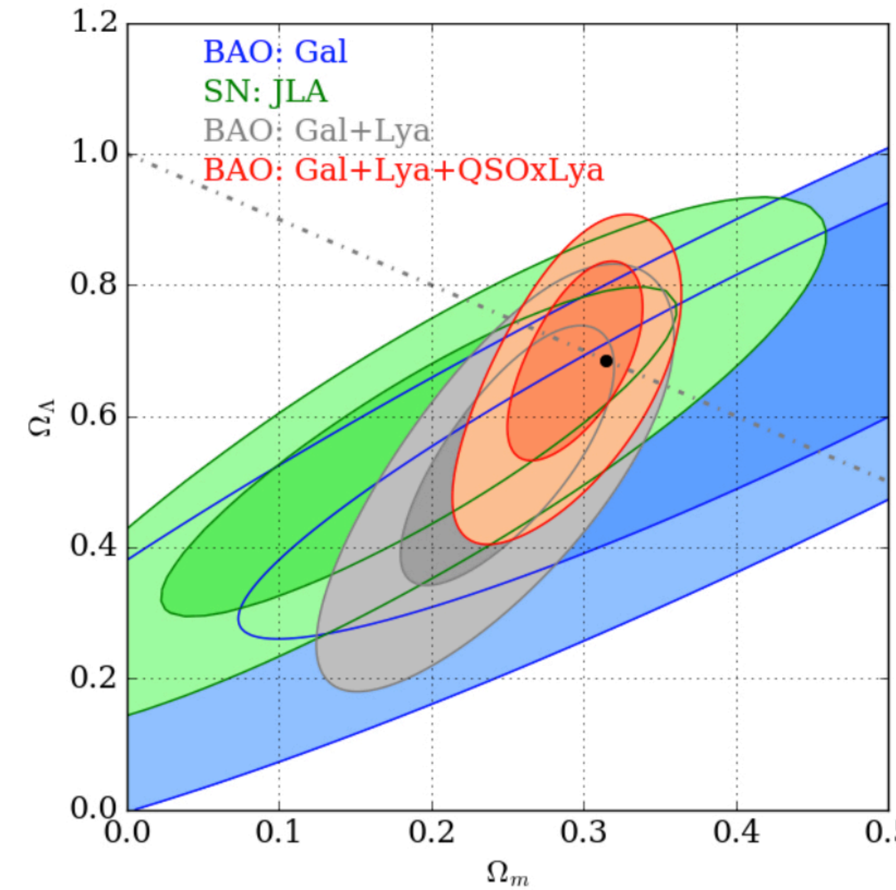


Fig. 18. One- and two-standard deviation constraints on the

P.Ntelis et al. arXiv:1810.09362

J.Bautista et al., arXiv:1702.00176

Cosmic Homogeneity as standard ruler

Weak challenging signal of gal-clustering in the back ground of gravitational waves

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.86.083512

Why not clustering from BBH?

Back Up