Cosmology with cosmic homogeneity

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arXiv:1904.06135

Outline:

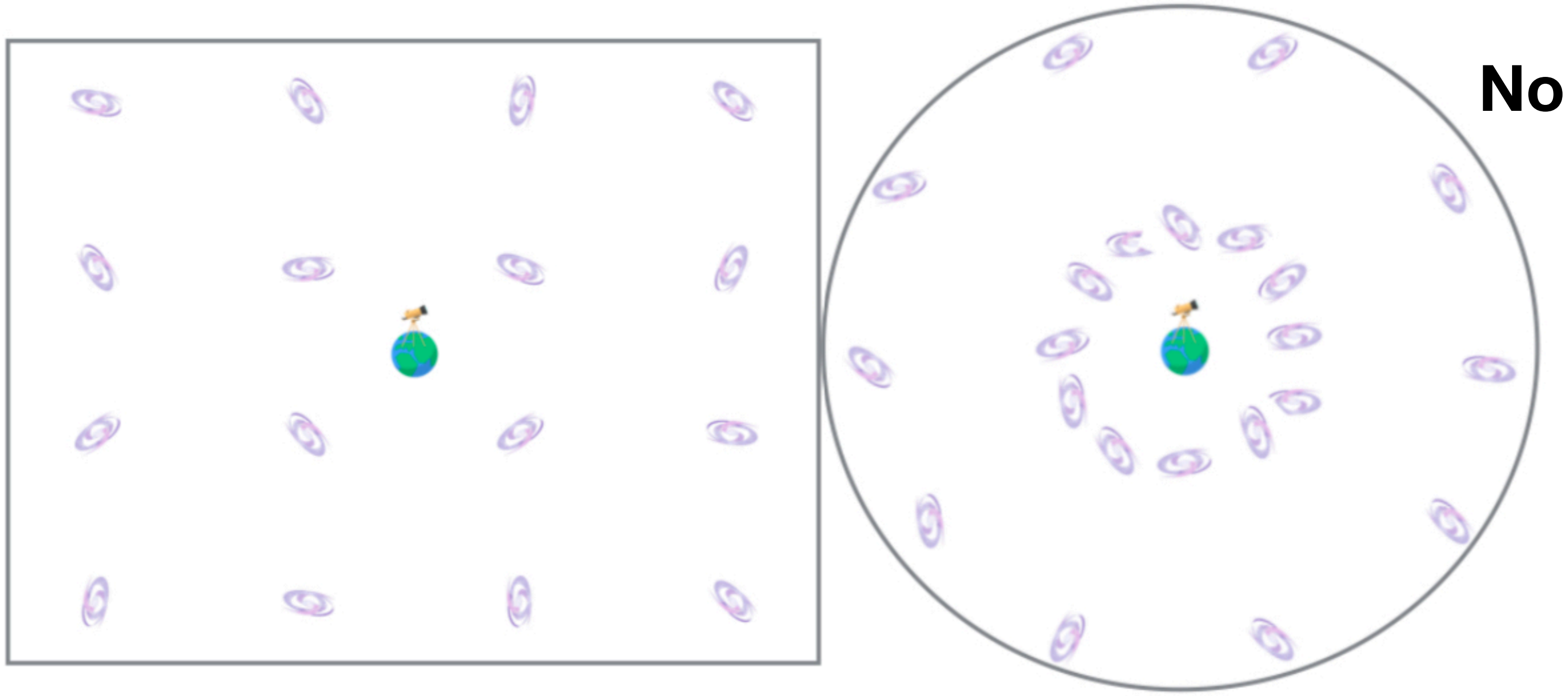
- **Motivation**
- **Method**
- **Results**
- **Alternative tests**
- **Conclusion/outlook**

Cosmology with cosmic homogeneity

Standard Phenomenology ΛCDM

Cosmological Principle = Statistical Homogeneity + Isotropy **On enough large scales**

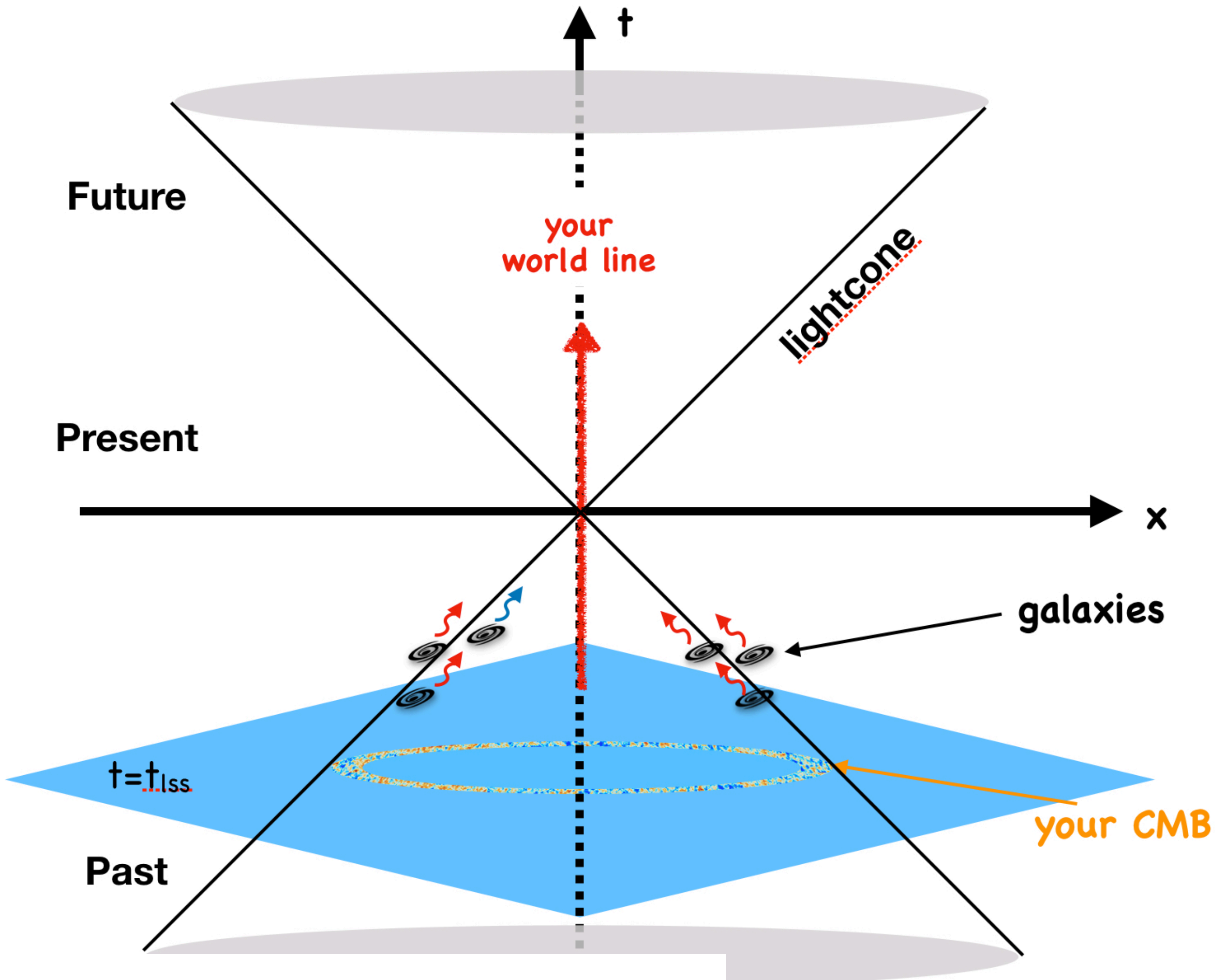
Homogeneous + Isotropic



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**

Main Challenges of Cosmologically Principled Universes:



c finite speed

Information only on the past lightcone
Cosmology dependence
(Redshift -> Distance)

$$d_C(z) = d_H \int_0^z \frac{dz'}{\sqrt{(\Omega_{\rm cdm} + \Omega_{\rm b})(1+z)^3 + \Omega_\Lambda}}$$

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How do you study Homogeneity?

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

Observation

Theory

Most Optimal Estimator

$$\xi(r) = \frac{dd(r) - 2dr(r) + rr(r)}{rr(r)}$$

Landy & Szalay 1993

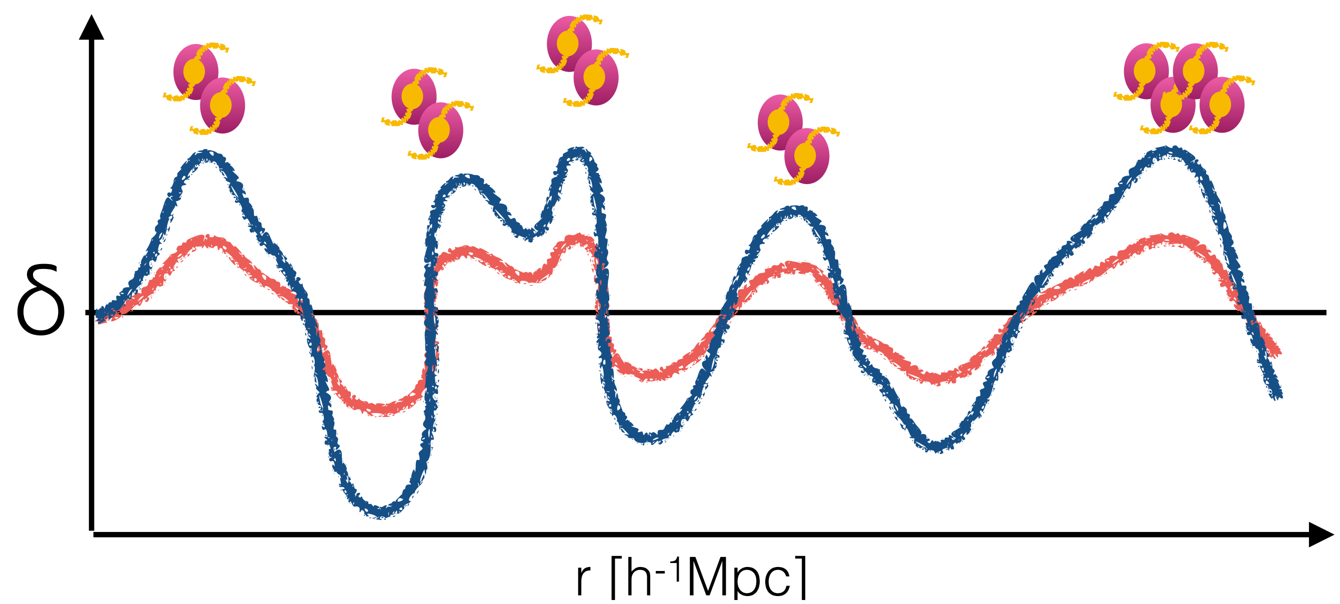
$$\xi(r) = \frac{1}{2\pi^2}\int dk k^2 \frac{\sin(kr)}{kr} P(k)$$

CLASS
Einstein-Boltzmann Solver

https://github.com/lontelis/cosmopit

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

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



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

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

$$R_H^{tracer} = b_{RH} R_H^{Matter}$$, **NEW!**

Extract Cosmology

$$\chi^2(b_0,\Omega|\Omega_F) = \sum_{z\in\Delta z}\left[\frac{O(z;\Omega_F) - M(z;b_0,\Omega|\Omega_F)}{\sigma_O(z)}\right]^2$$

$$O(z;\Omega_F) = \frac{\mathcal{R}_H^{Gal}(z;\Omega_F)}{d_V(z;\Omega_F)}$$ **Observable**

$$M(z;b_0,\Omega|\Omega_F) = \frac{b(z;b_0) * \mathcal{R}_H^{Mat,Th}(z;\Omega_F)}{d_V(z;\Omega)}$$ **Theoretical Model**

TEST

$$b(z) = b_0\sqrt{1+z}$$ for all z

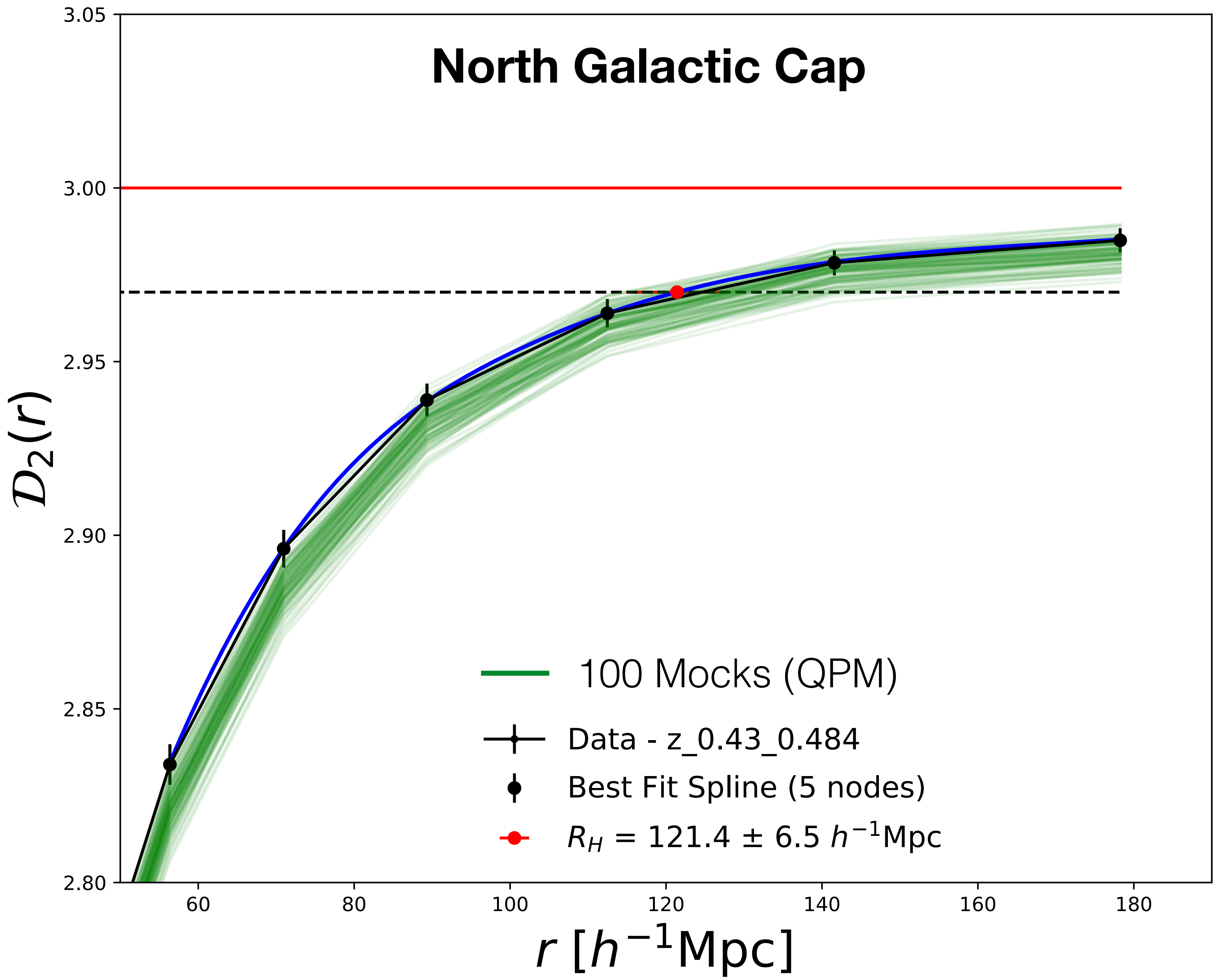
$$b_{2,\mathcal{R}_H}(z;b_0,z_\star) = b_0\begin{cases}\sqrt{1+z} & ,\ \text{for } z < z_\star \\ \left[\frac{1}{4}\frac{1}{(1+z_\star)^{3/2}}(1+z)^2 + \frac{3}{4}\sqrt{1+z_\star}\right] & ,\ \text{for } z > z_\star\end{cases}$$

Linear bias model

Outline:

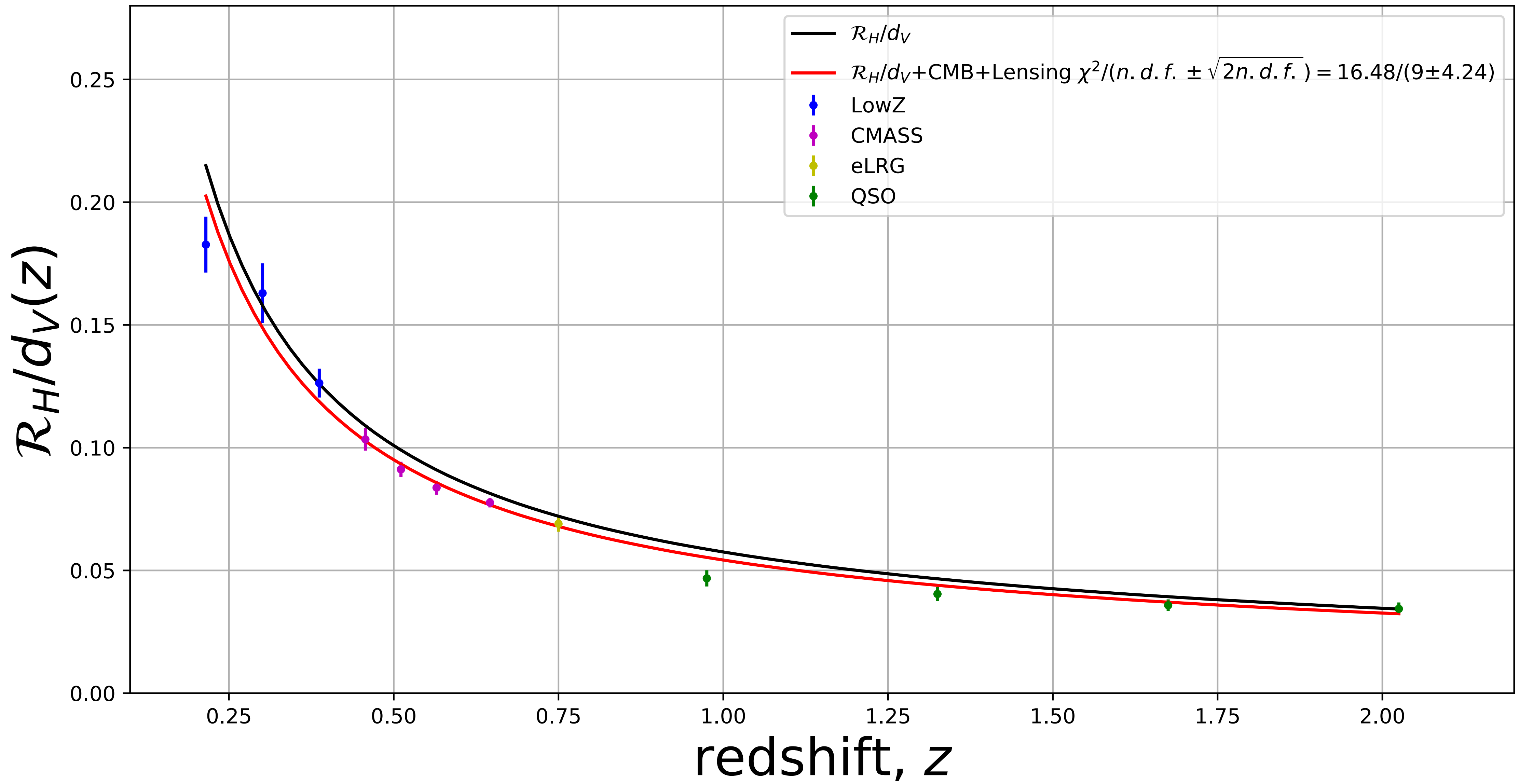
Cosmology with cosmic homogeneity

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

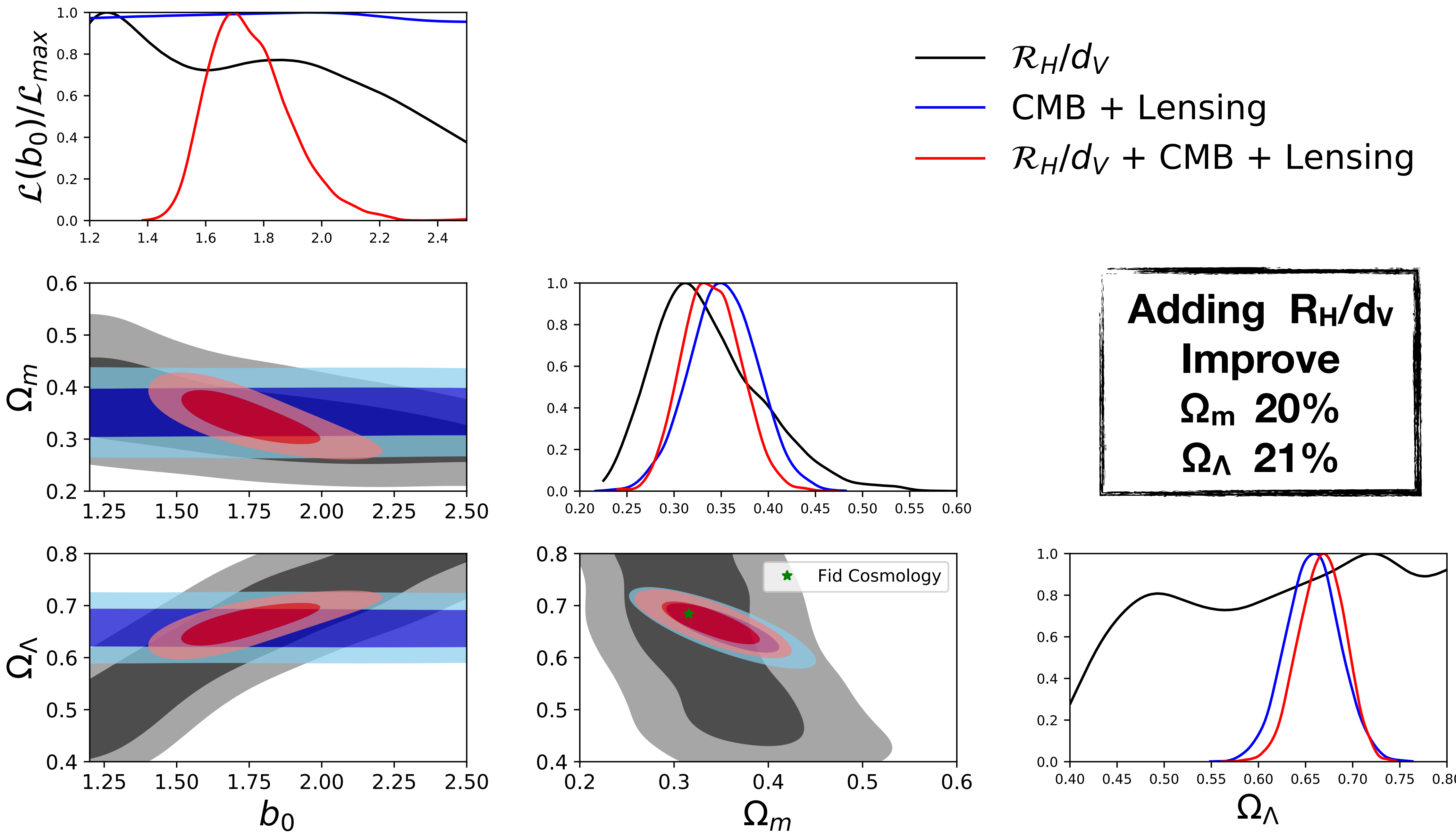


Cosmology with cosmic homogeneity

DR12-DR14



Cosmology with cosmic homogeneity



Adding R_H/d_V Improve
Ω_m 20%
Ω_Λ 21%

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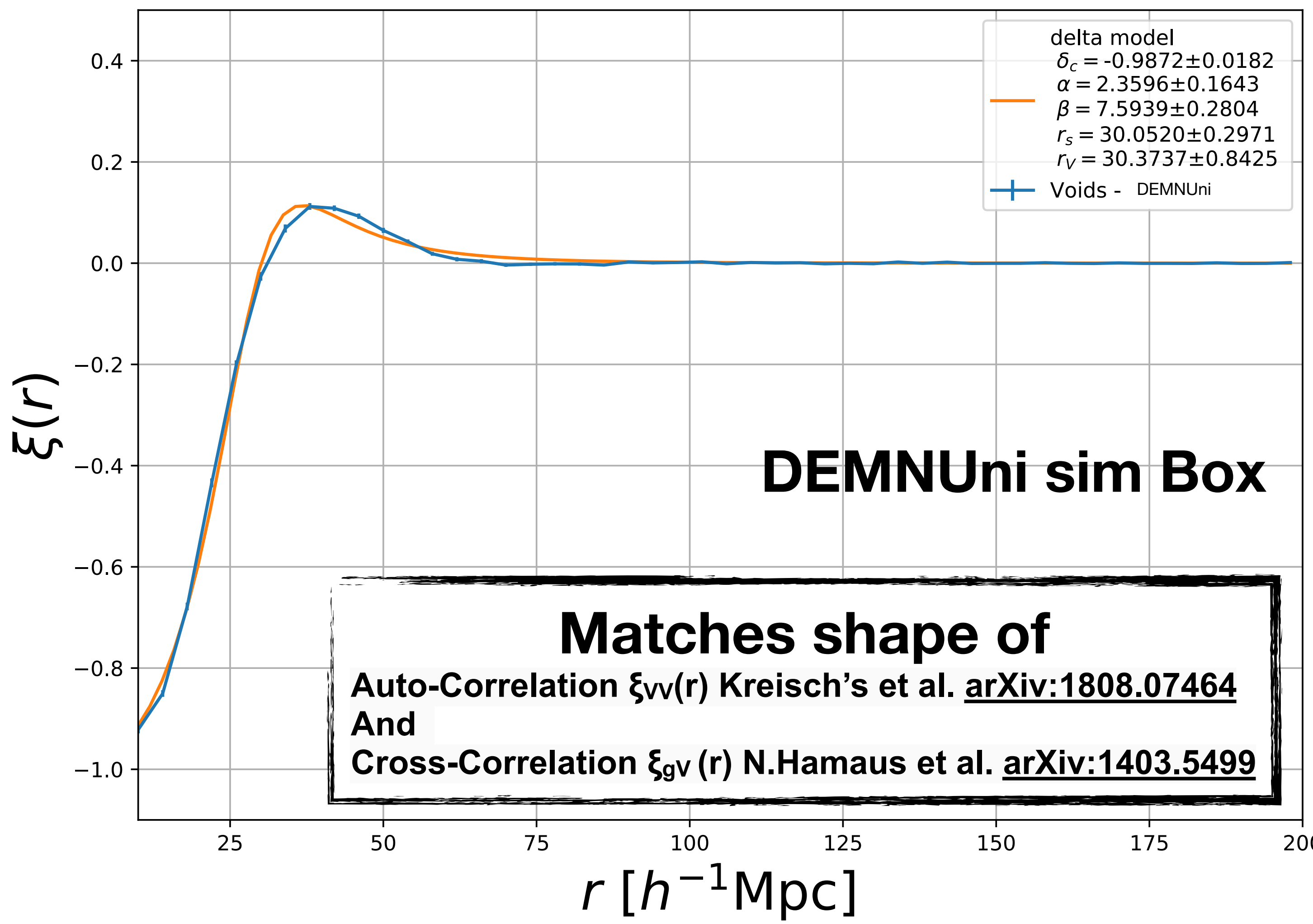
PN, AJHawken, A.Pisani, S.Escoffier et al in preparation

Empirical modelling of Void-Void 2PCF

$\xi_{Vg}(r) \sim \quad \xi_{VV}(r) \simeq \delta_g(r; \delta_c, r_s, r_V, \alpha, \beta) = \delta_c \frac{1-(r/r_s)^\alpha}{1+(r/r_V)^\beta}$

using
VIDE-voids
On DEMNUni
$[2Gpc/h]^3$
122,907 Voids
100 Bootstraps



Matches shape of
Auto-Correlation $\xi_{VV}(r)$ Kreisch's et al. arXiv:1808.07464
And
Cross-Correlation $\xi_{gV}(r)$ N.Hamaus et al. arXiv:1403.5499

In progress …

PN, AJHawken, A.Pisani, S.Escoffier et al in preparation

Empirical modelling of Void-Void 2PCF

$$\xi_{Vg}(r) \sim \quad \xi_{VV}(r) \simeq \delta_g(r; \delta_c, r_s, r_V, \alpha, \beta) = \delta_c \frac{1-(r/r_s)^\alpha}{1+(r/r_V)^\beta}$$

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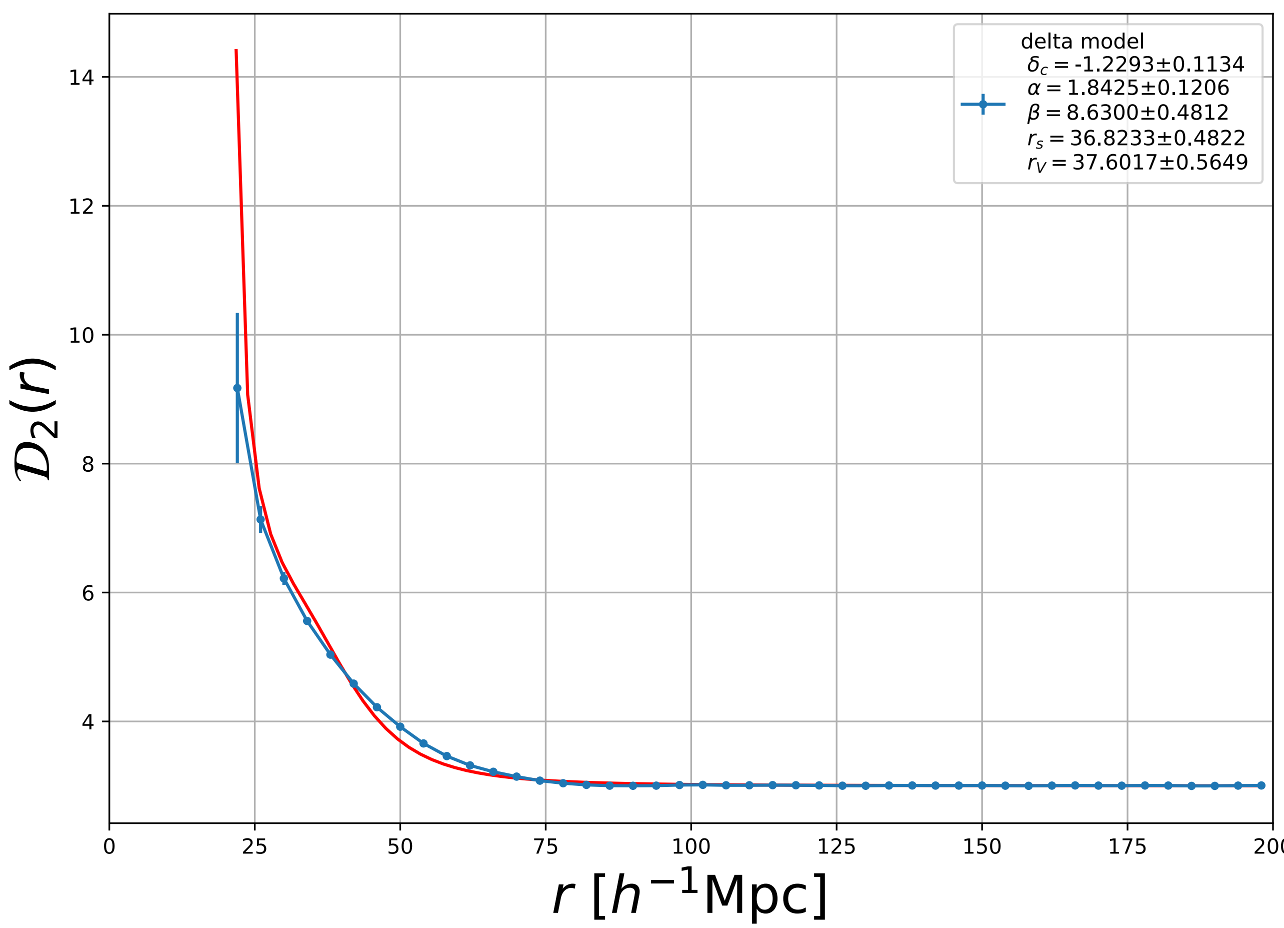


In progress …

Conclusions

- R_H/dV, new cosmological probe
- R_H/dV, improves the precision on $(\Omega_m,\Omega_\Lambda)$ 20%
- Fractality validates
  - ΛCDM phenomenology in ~% CL
  - Cosmological Principle
- Code publicly available

P.L et al. arXiv:1602.09010
P.N et al. arXiv:1702.02159
P.N et al. arXiv:1810.09362
P.N et al. arXiv:1904.06135

https://github.com/lontelis/cosmopit

Outlook

- Apply on DR16 data
  - Soon request for External Collaboration

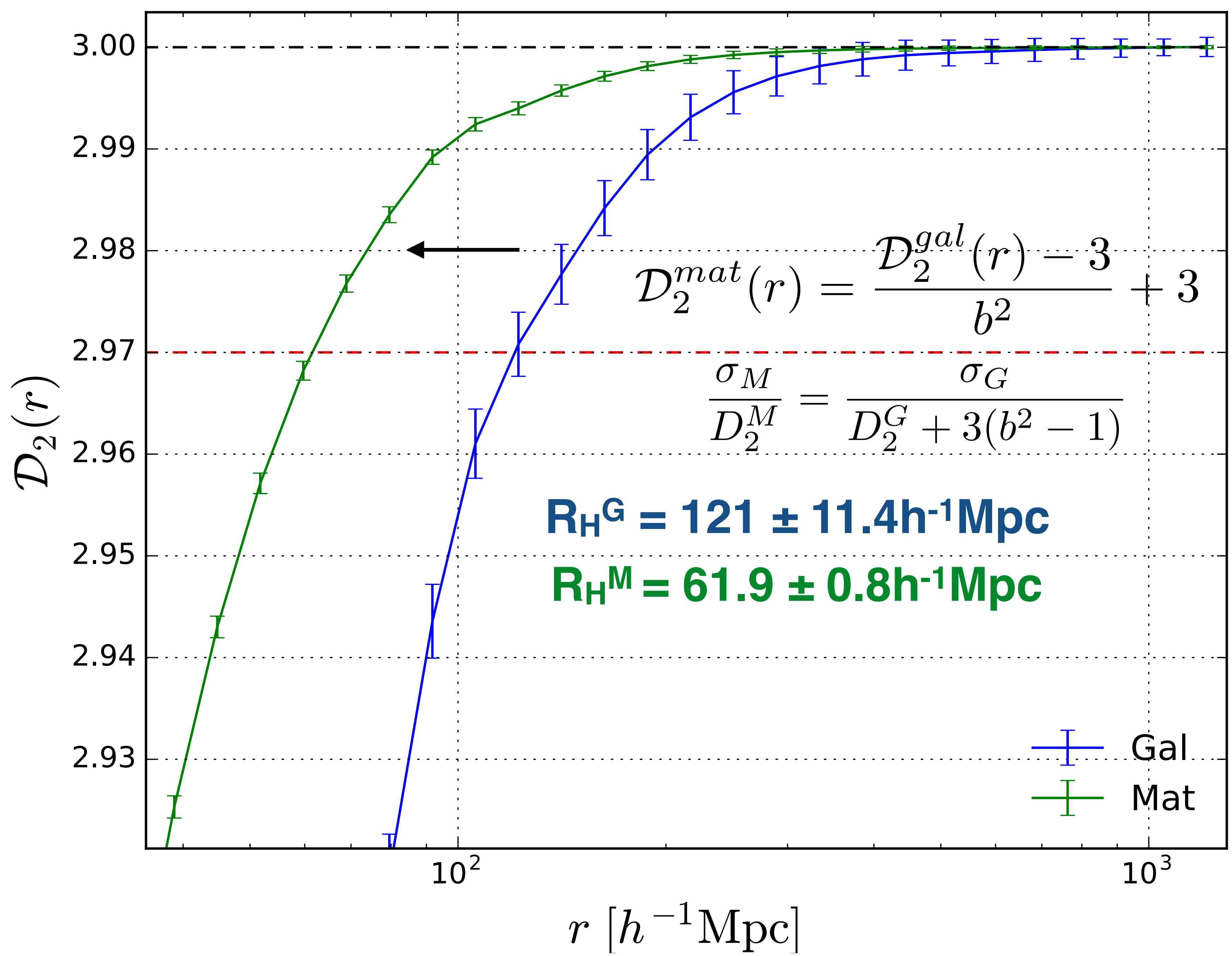
- Apply on DESI data
  - Request for Collaboration

- Additional tests of Homogeneity
- Additional tests with fractality ?
- R_H, D_2 on other Cosmic Structures ?

Back Up

Bias Dependence

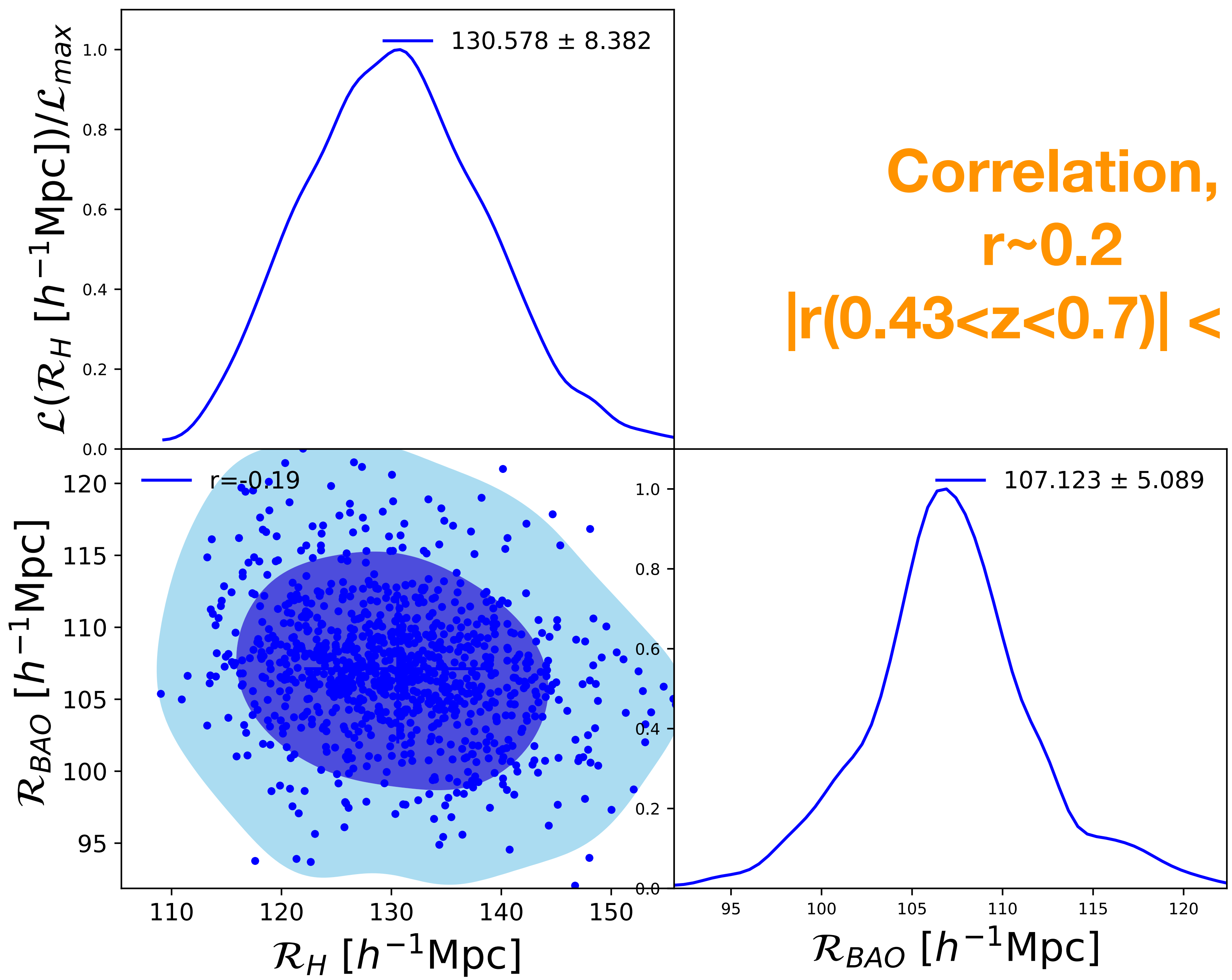
Matter <- - - - Galaxies



Precision increase:

- **Smaller Scales**
- **Bias Gain**

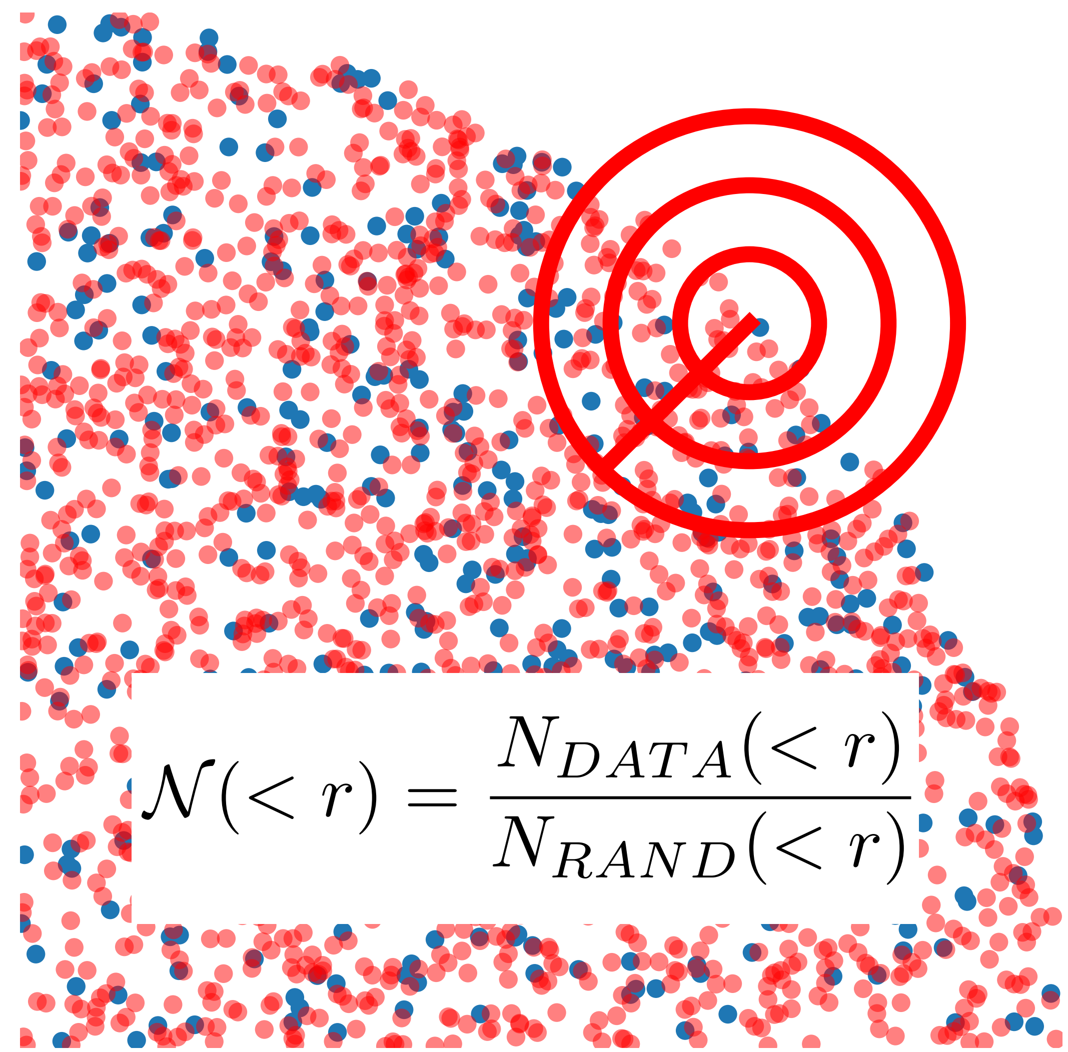
Cosmology with cosmic homogeneity



Correlation,
r~0.2
|r(0.43<z<0.7)| < 0.3

Observable: Count-in-spheres

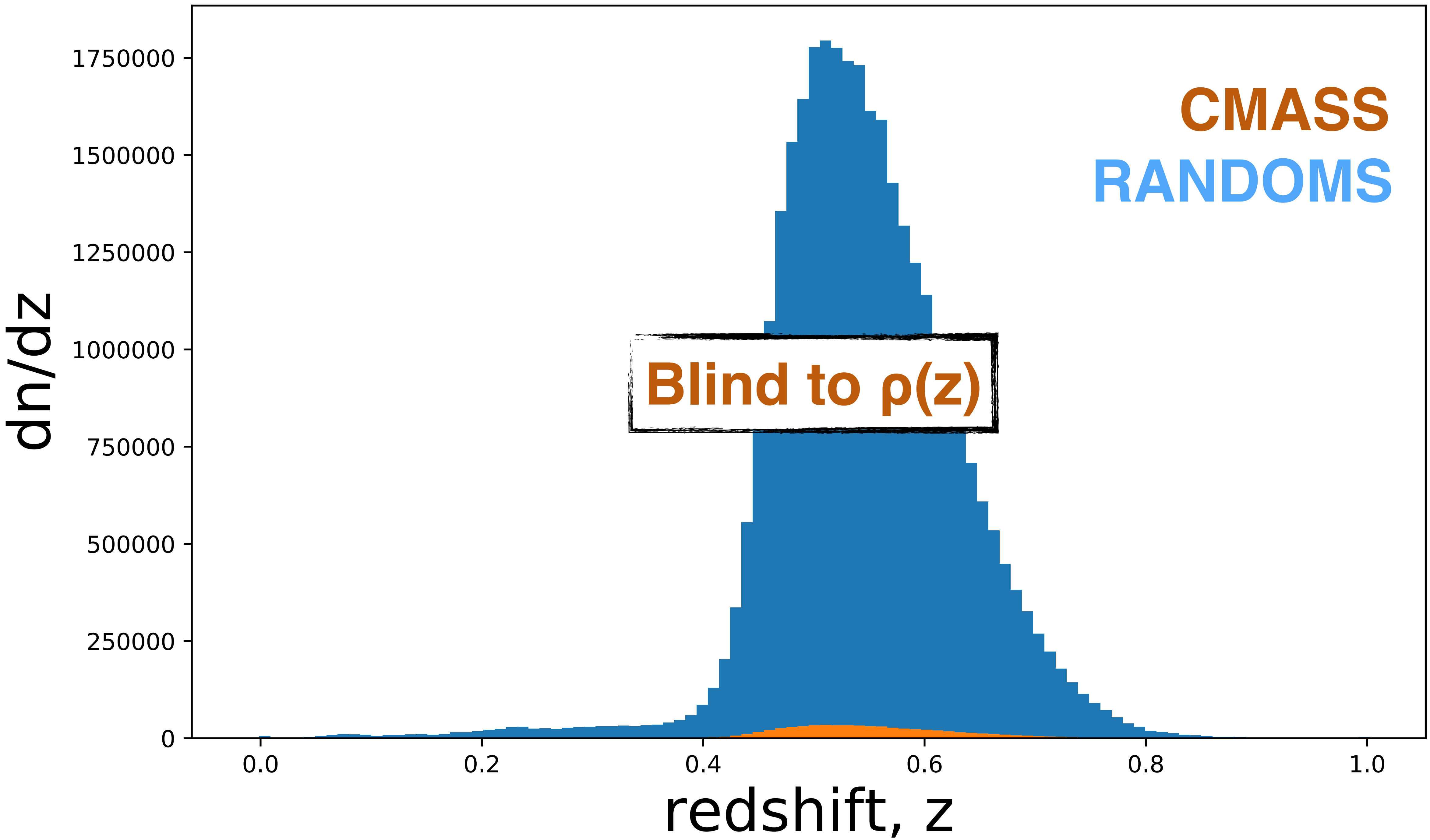
- Select a galaxy as a center
- Create a sphere of radius **r**
- Compute number of galaxies
- repeat for every galaxy
- compute the mean **N(<r)**
- repeat for different scales



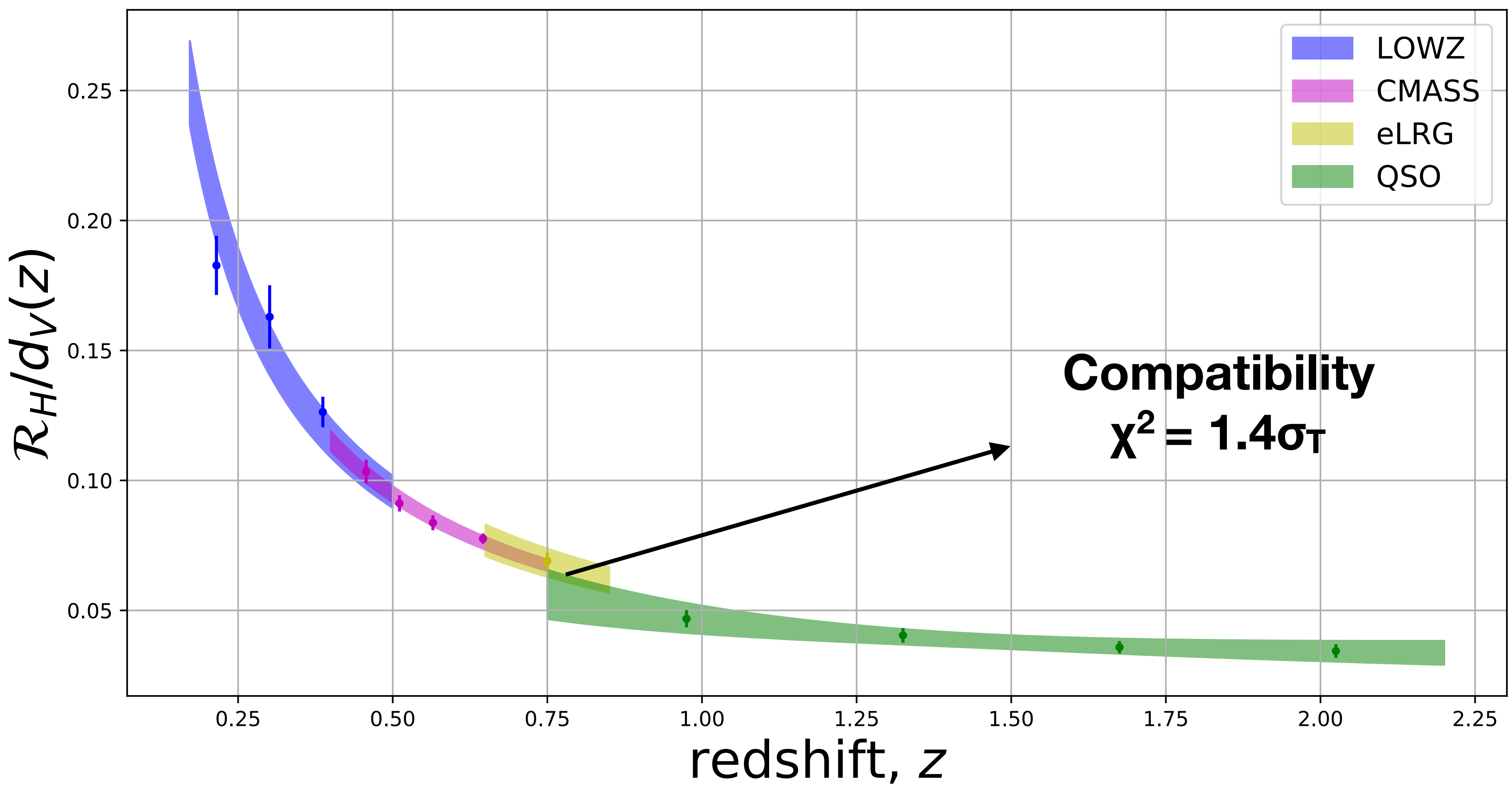
$$\mathcal{N}(<r) = \frac{N_{DATA}(<r)}{N_{RAND}(<r)}$$

Randoms: Same Selection function

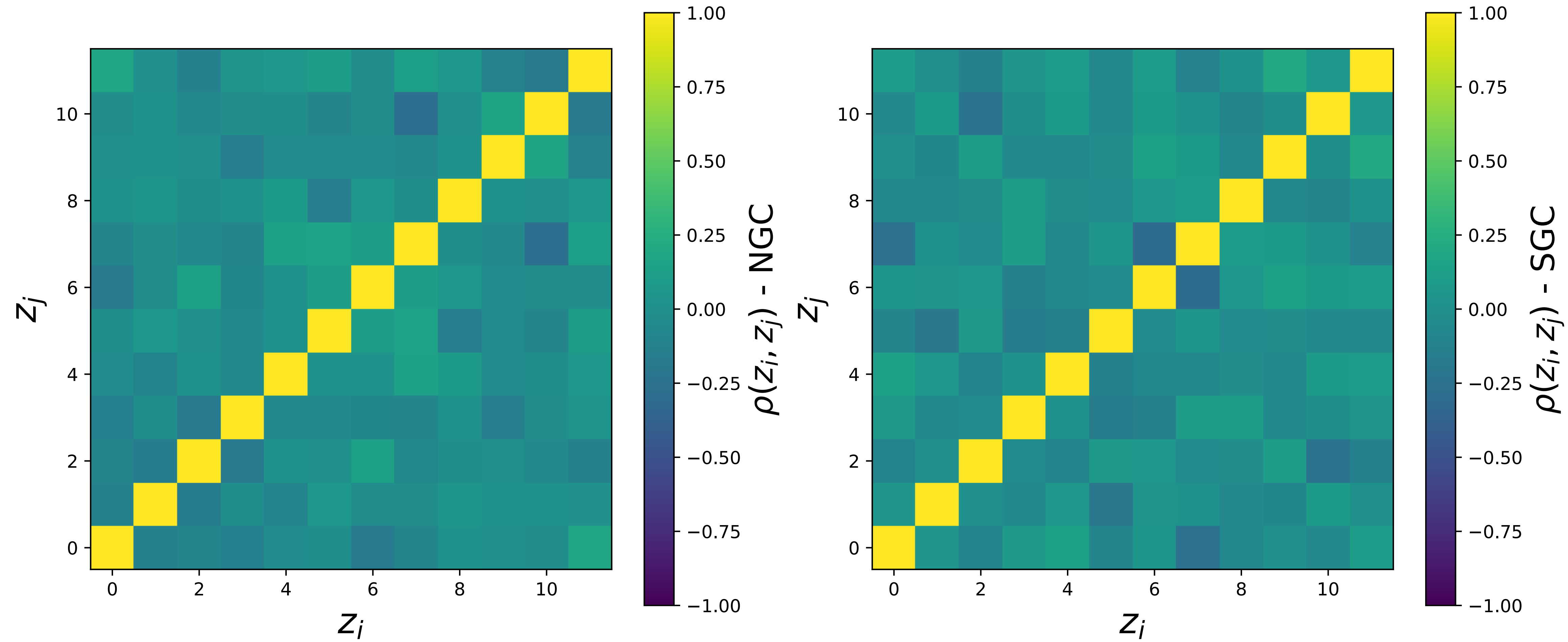
Redshift Profile of Galaxy Sample



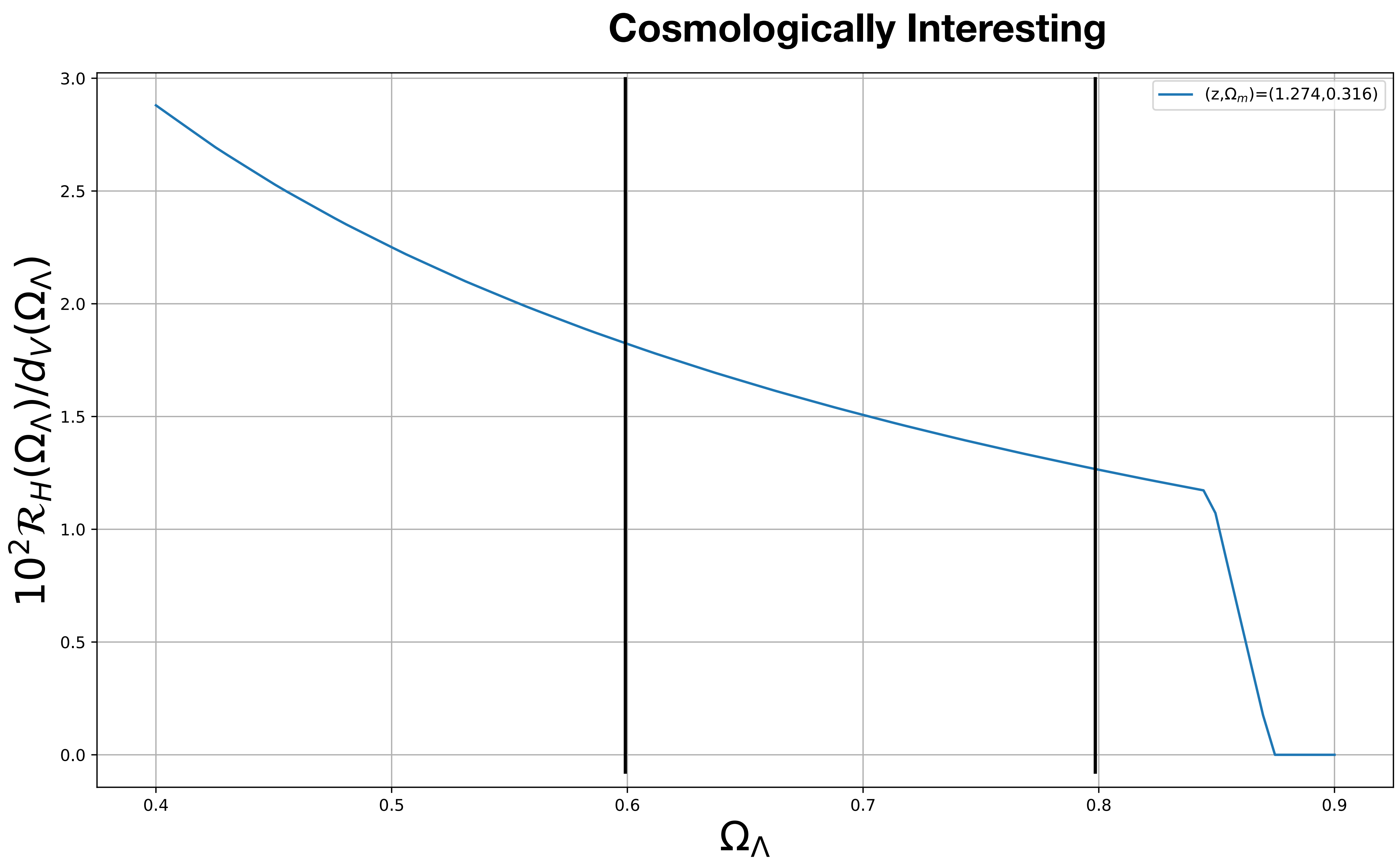
Empirical extraction of bias model



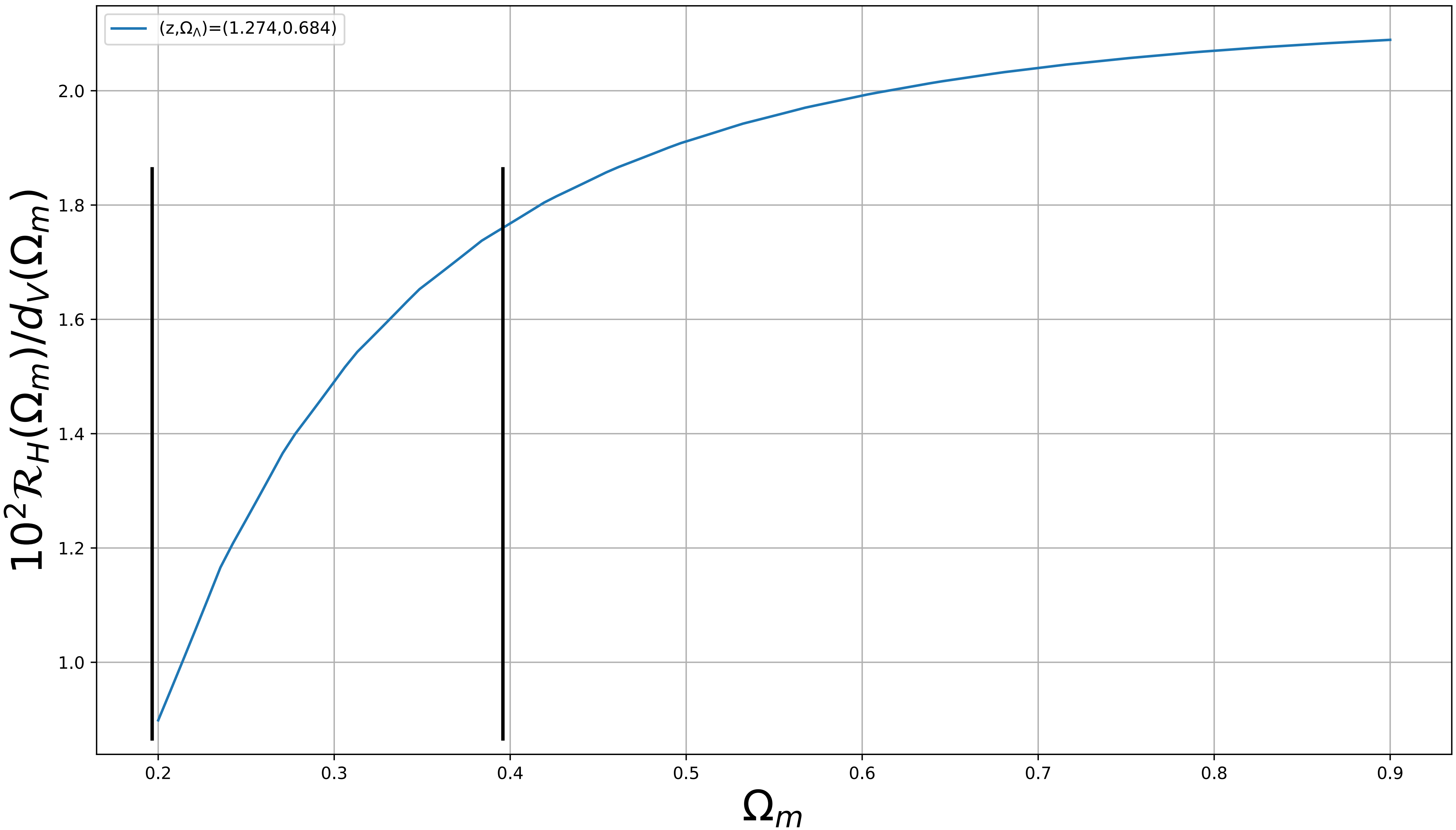
Correlation matrix for R_H/d_V



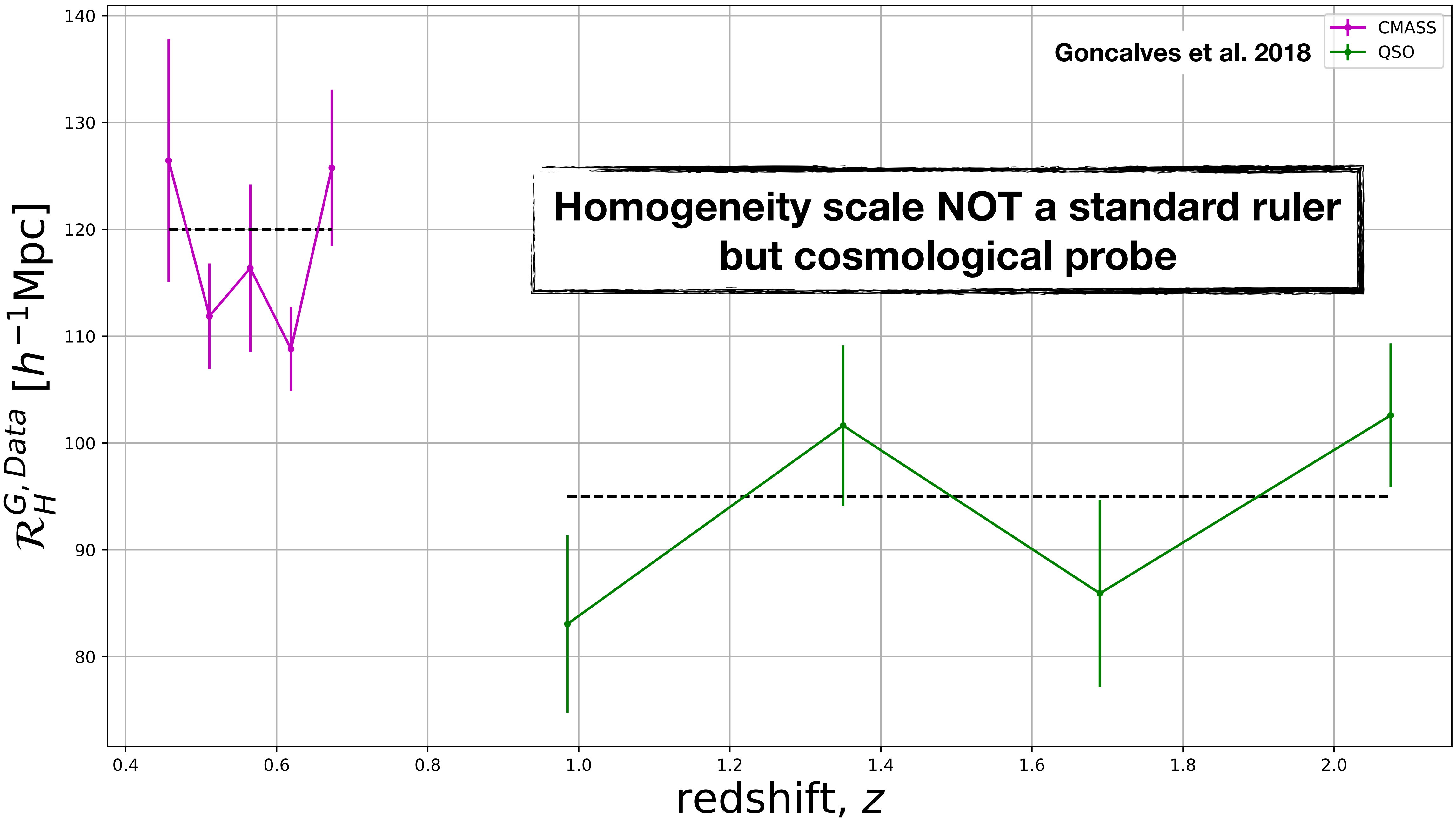
Cosmology with cosmic homogeneity



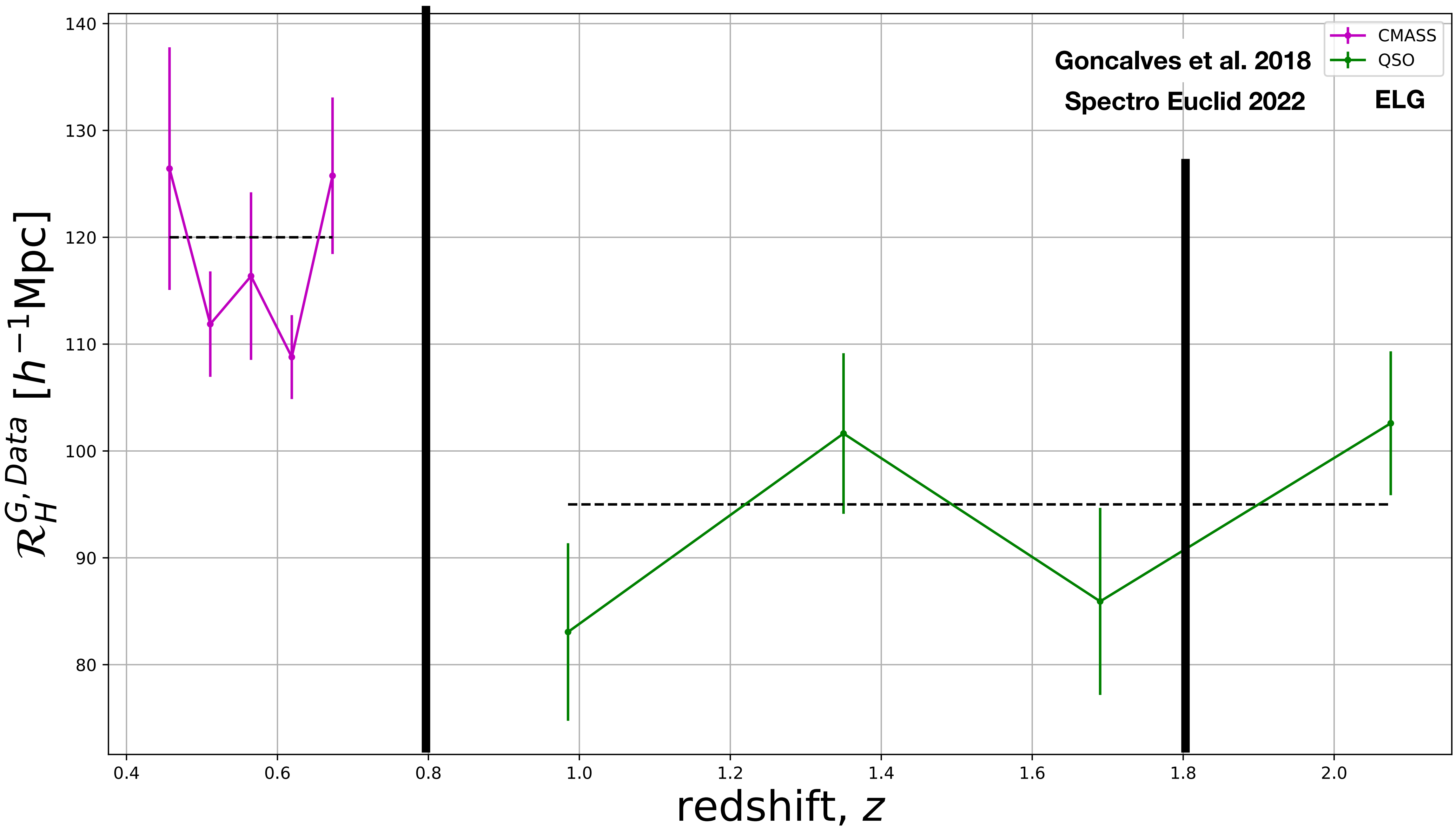
Cosmologically Interesting



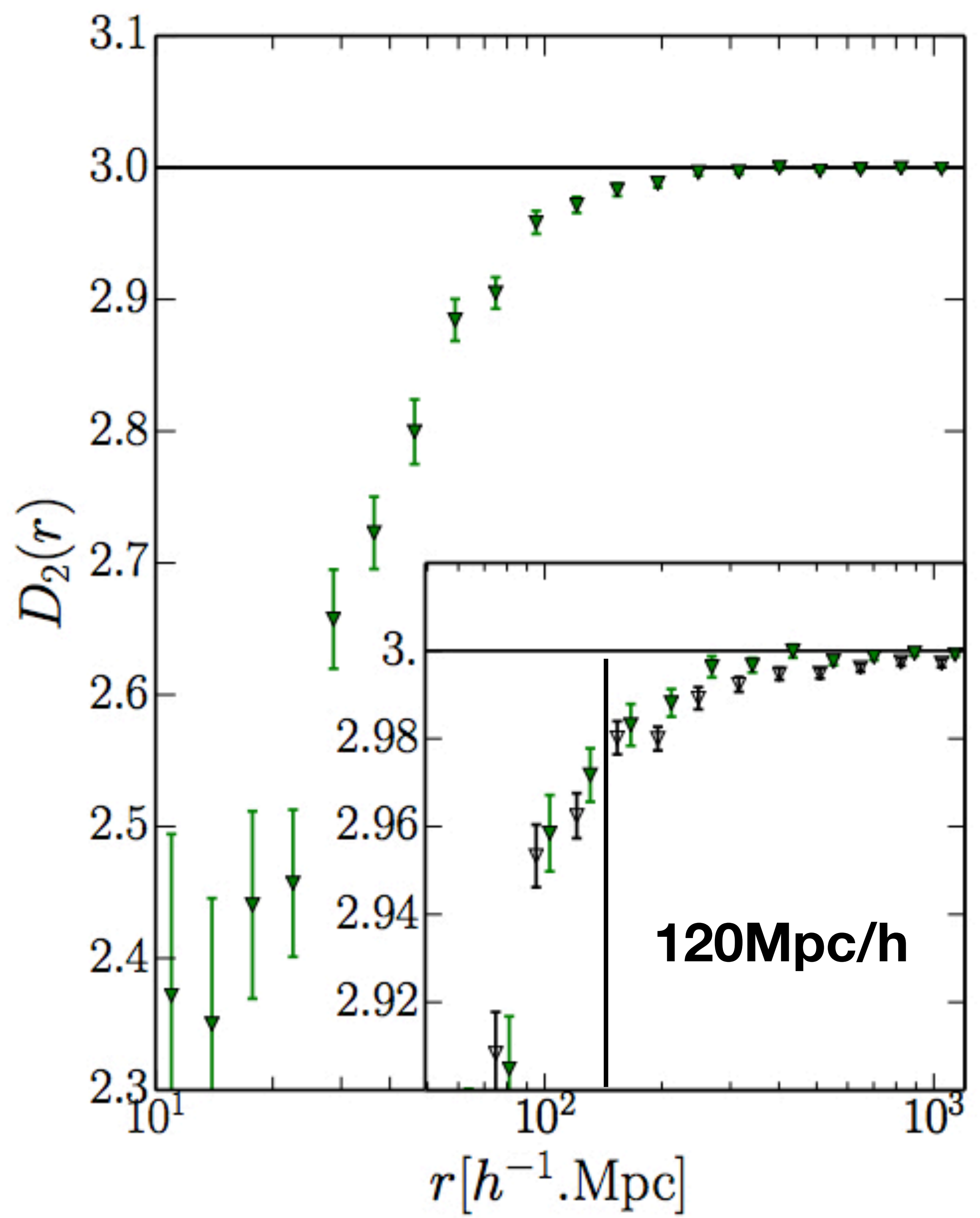
Cosmology with cosmic homogeneity



Cosmology with cosmic homogeneity



Laurent et al 2016



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

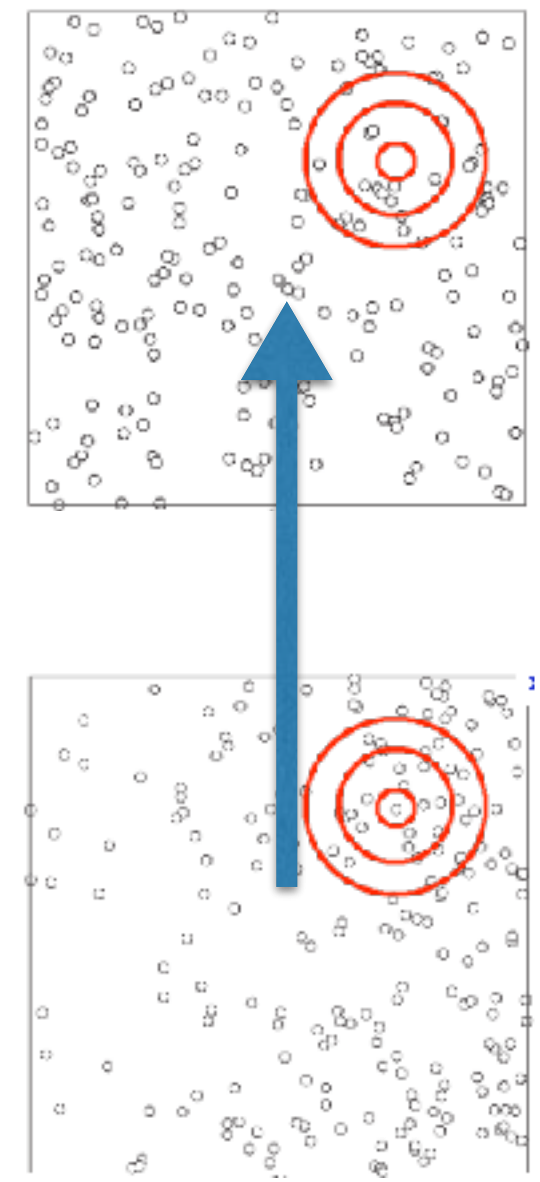
Fractal Dimension: $$D_2(r) = \frac{d\ \ln\ N(<r)}{d\ \ln\ r}$$

Homogeneous
@ large scales

$$D_2(r) = 3$$

Inhomogeneous
@ small scales (clustering)

$$D_2(r) < 3$$

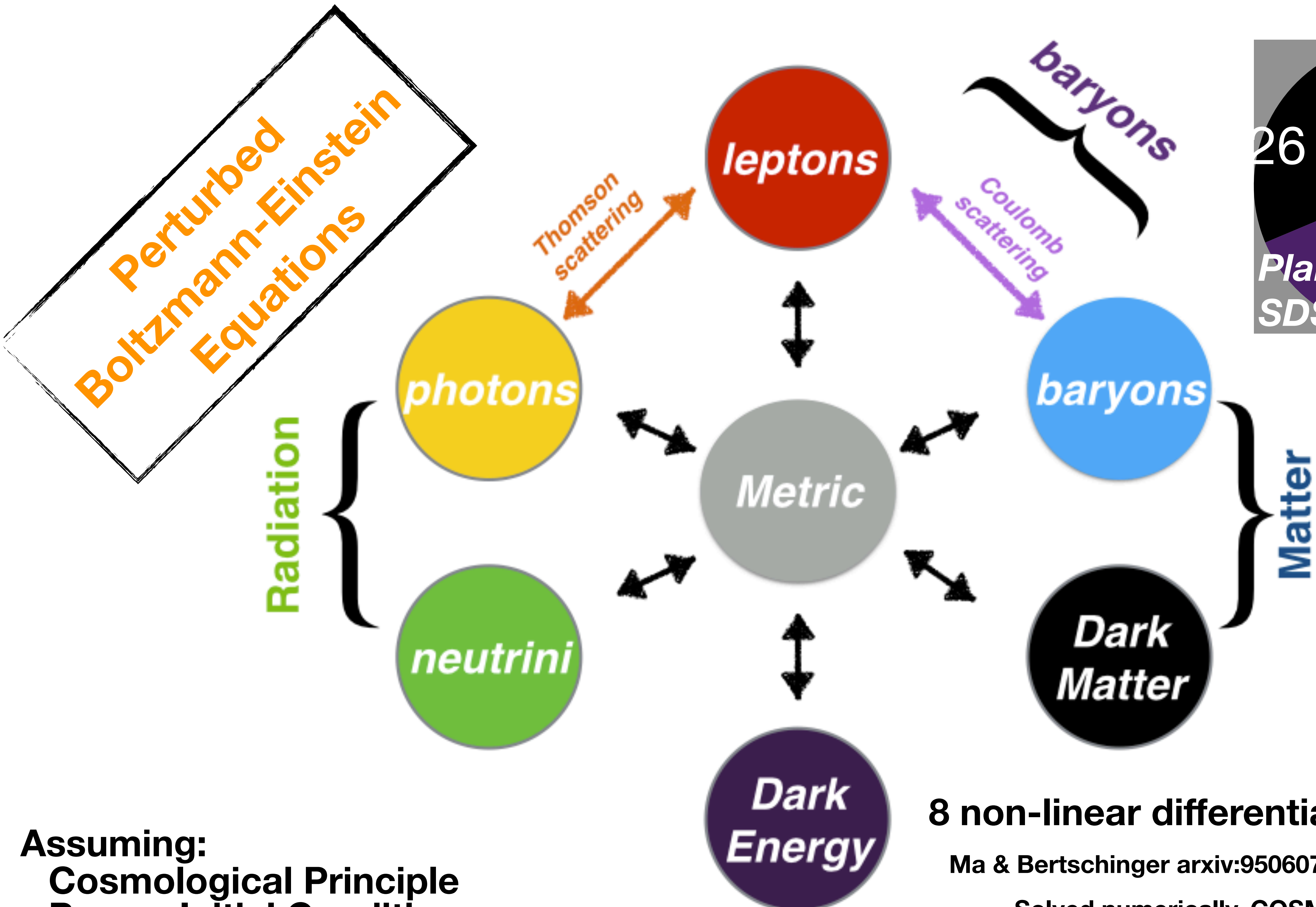


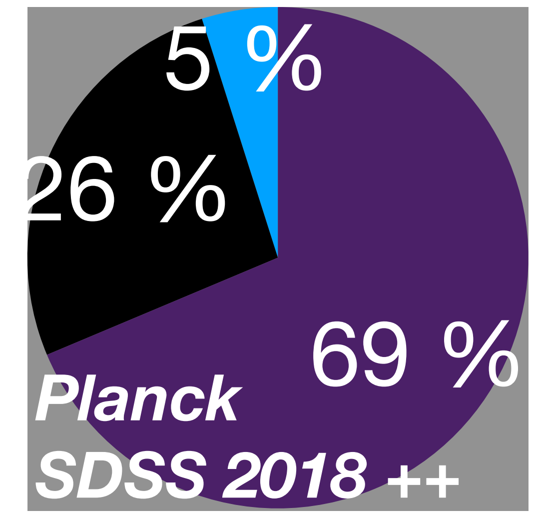
Transition to Homogeneity at:

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

- Arbitrary Choice
- Independent of survey
- Hidden cosmic info

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





8 non-linear differential equations,

Ma & Bertschinger arxiv:9506072 citations(1161)

Solved numerically, COSMOPIT code

that adapts CLASS

Assuming:

- Cosmological Principle
- Proper Initial Conditions

Cosmological Implications:

Fisher Analysis

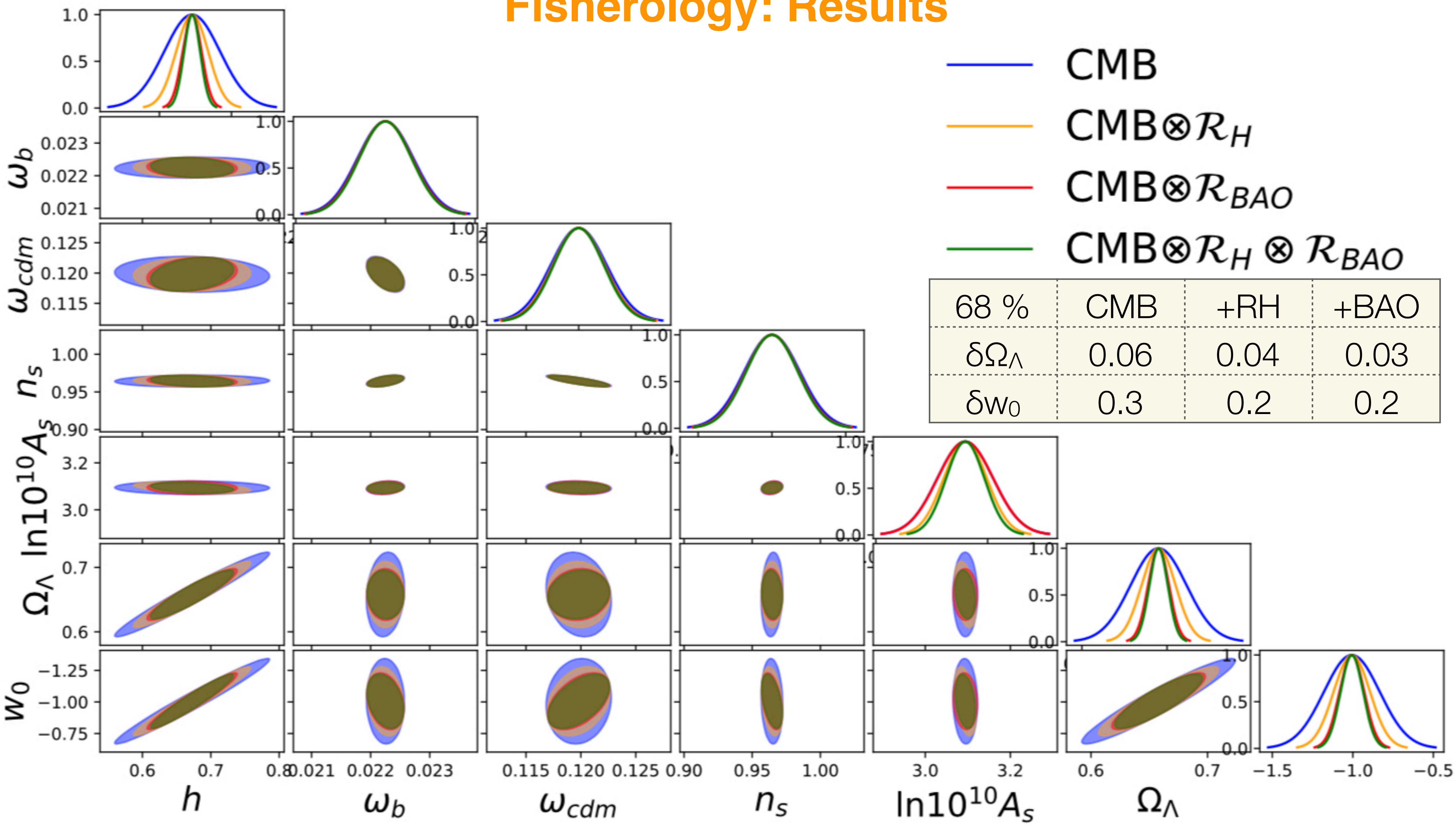
MCMC analysis

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

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

Error as estimated by CMASS analysis

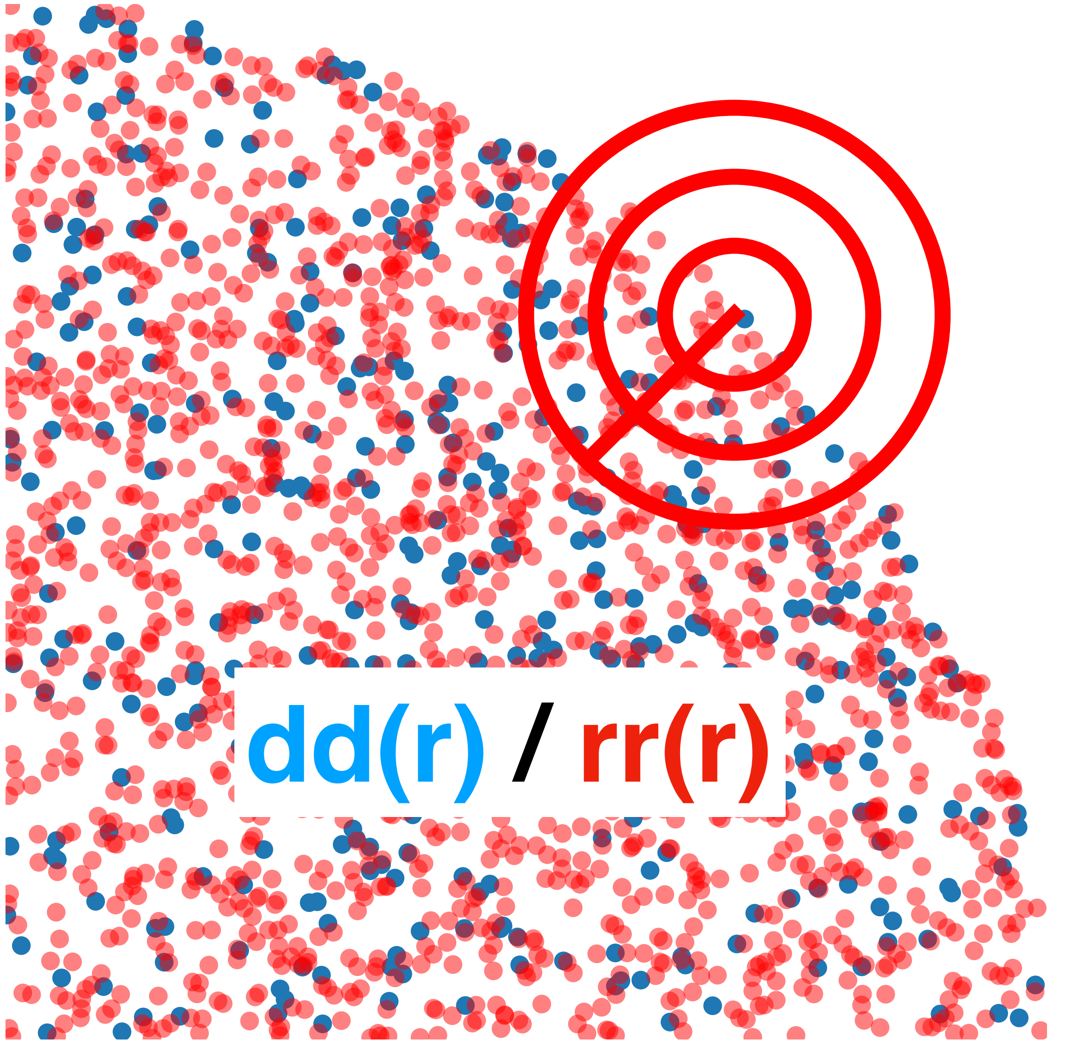
Fisherology: Results



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

Count-in-cells

- Select a galaxy as a center
- Create a cell at a radius **r**
- Compute number of galaxies
- repeat for every galaxy
- compute the mean **dd(r)**
- repeat for different scales



Randoms: Same Selection function

Cosmology with cosmic homogeneity

Table 2. Mean and standard deviation of the homogeneity scale, $\mathcal{R}_H$, as a function of redshift, z, for the different galaxy samples as explained in section 4.1. The second to last column is the expected homogeneity scale for the total matter of the universe, $\mathcal{R}_H^m$, while the last column is the fiducial volume distance, see d_V section 4.1.

	$\mathcal{R}_H^G$		$[h^{-1}\text{Mpc}]$		$\mathcal{R}_H^m[h^{-1}\text{Mpc}]$	$d_V[h^{-1}\text{Mpc}]$
	LowZ	CMASS	eLRG	QSO		
0.172 − 0.258	109.54 ± 6.81	-	-	-	73.87	600
0.258 − 0.344	132.51 ± 9.87	-	-	-	70.87	813
0.344 − 0.430	127.87 ± 5.95	-	-	-	68.0	1012
0.430 − 0.484	-	120.32 ± 5.33	-	-	65.80	1163
0.484 − 0.538	-	116.16 ± 3.98	-	-	64.16	1274
0.538 − 0.592	-	112.24 ± 3.97	-	-	62.55	1379
0.592 − 0.700	-	115.50 ± 3.00	-	-	60.25	1529
0.700 − 0.800	-	-	117.60 ± 5.50	-	57.45	1704
0.800 − 1.150	-	-	-	95.08 ± 6.72	51.96	2033
1.150 − 1.500	-	-	-	98.15 ± 6.87	44.78	2430
1.500 − 1.850	-	-	-	97.65 ± 6.50	38.96	2726
1.850 − 2.200	-	-	-	101.45 ± 7.67	34.17	2952

Table 3. Measurement of the cosmological parameters for the two different bias models, as described in section 4.2, considering the combination, $b_{i,\mathcal{R}_H}$-$\mathcal{R}_H/d_V$+CMB+Lensing.

Bias model	b_0	Ω_m	Ω_Λ	$\chi^2 \pm \sqrt{2.ndf}$, $ndf = 9$
$b_{1,\mathcal{R}_H}$	1.747 ± 0.136	0.340 ± 0.029	0.668 ± 0.023	16.476 ± 4.243
$b_{2,\mathcal{R}_H}$	1.886 ± 0.184	0.311 ± 0.030	0.690 ± 0.024	17.569 ± 4.243

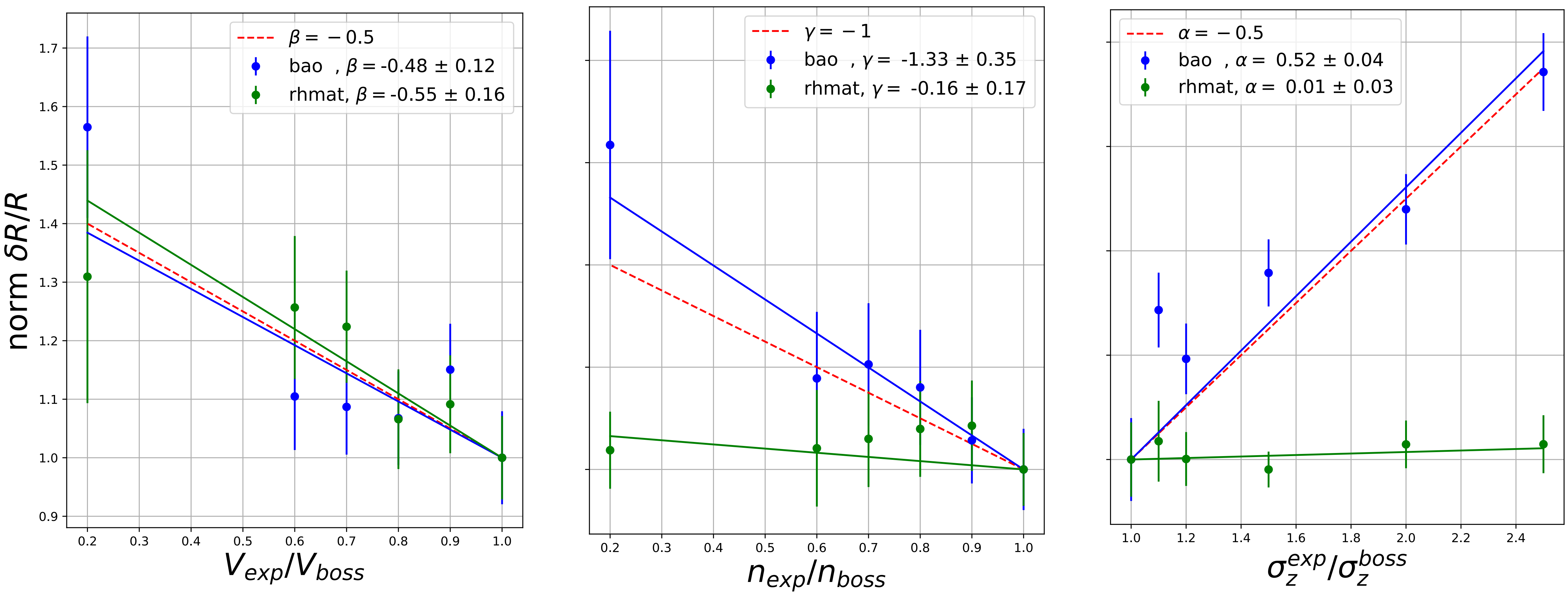
Table 4. Mean and standard deviation of the measured cosmological parameters $(\Omega_m, \Omega_\Lambda)$, using different combination of data. [See section 4.4]

Observable Combinations	Ω_m	Ω_Λ
CMB	0.473 ± 0.089	0.571 ± 0.070
CMB + Lensing	0.352 ± 0.036	0.658 ± 0.029
$\mathcal{R}_H/d_V$	0.338 ± 0.059	0.653 ± 0.133
$\mathcal{R}_H/d_V$ + CMB	0.369 ± 0.062	0.651 ± 0.073
$\mathcal{R}_H/d_V$ + CMB + Lensing	0.340 ± 0.029	0.668 ± 0.023

Table 5. Measurements of the model parameters using bias model 1, Eq. 3.16. [See section 4.5]

$b_{1,\mathcal{R}_H}(z)$	b_0	Ω_m	Ω_Λ	$\chi^2 \pm \sqrt{2.ndf}$, $ndf = 9$
p_F-$\mathcal{R}_H/d_V$+CMB	1.693 ± 0.218	0.369 ± 0.060	0.651 ± 0.052	23.708 ± 4.243
p_{qpm}-$\mathcal{R}_H/d_V$+CMB	1.690 ± 0.218	0.366 ± 0.059	0.653 ± 0.051	22.839 ± 4.243
p_F-$\mathcal{R}_H/d_V$+CMB+Lensing	1.747 ± 0.136	0.340 ± 0.029	0.668 ± 0.023	16.476 ± 4.243
p_{qpm}-$\mathcal{R}_H/d_V$+CMB+Lensing	1.740 ± 0.137	0.339 ± 0.030	0.668 ± 0.023	15.945 ± 4.243

Homogeneity Prediction for Future Surveys



(Simulations from CMASS)

BAO

$$\frac{\delta R}{R} = \sqrt{\frac{\sigma_z}{V}} \left(1 + \frac{1}{nP}\right)$$

HOMOGENEITY

$$\frac{\delta R_H}{R_H} \propto \frac{1}{\sqrt{V}}$$