Cosmic Homogeneity with Euclid

Part I : Theory and Data

Part II : Check Homogeneity (2 different Methods)

Part III: Use Homogeneity —> Constrain Cosmology

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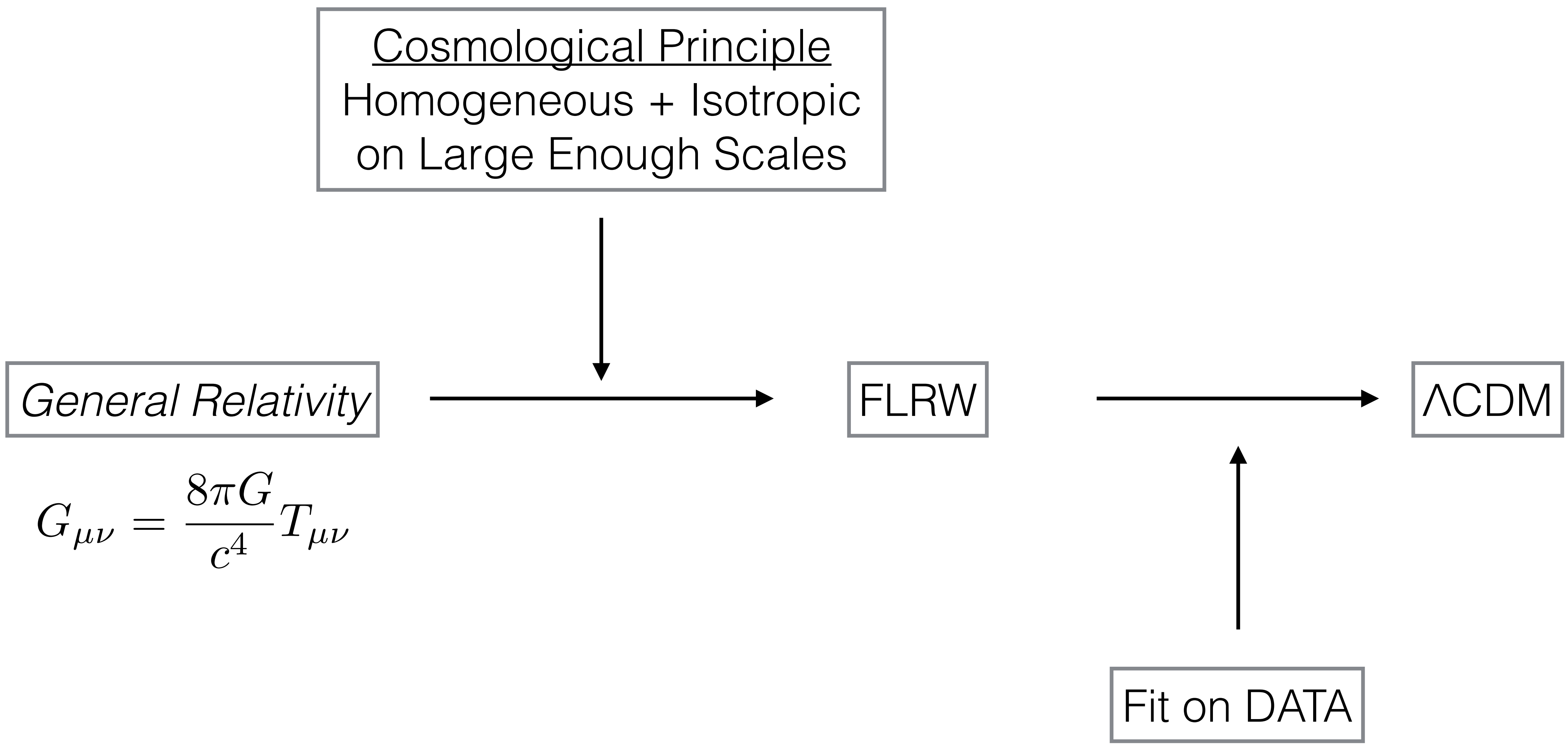
P Ntelis et al 2017
arXiv:1702.02159

Theoretical Framework



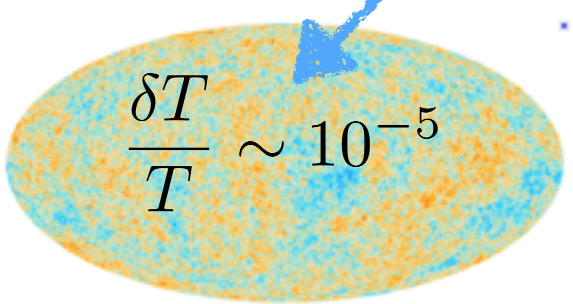
Theoretical Framework

Cosmological Principle
Homogeneous + **Isotropic**
on Large Enough Scales

General Relativity → FLRW → ΛCDM

Fit on DATA ↑

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



Theoretical Framework

Is this assumption data-motivated ?

Cosmological Principle
Homogeneous + Isotropic
on Large Enough Scales

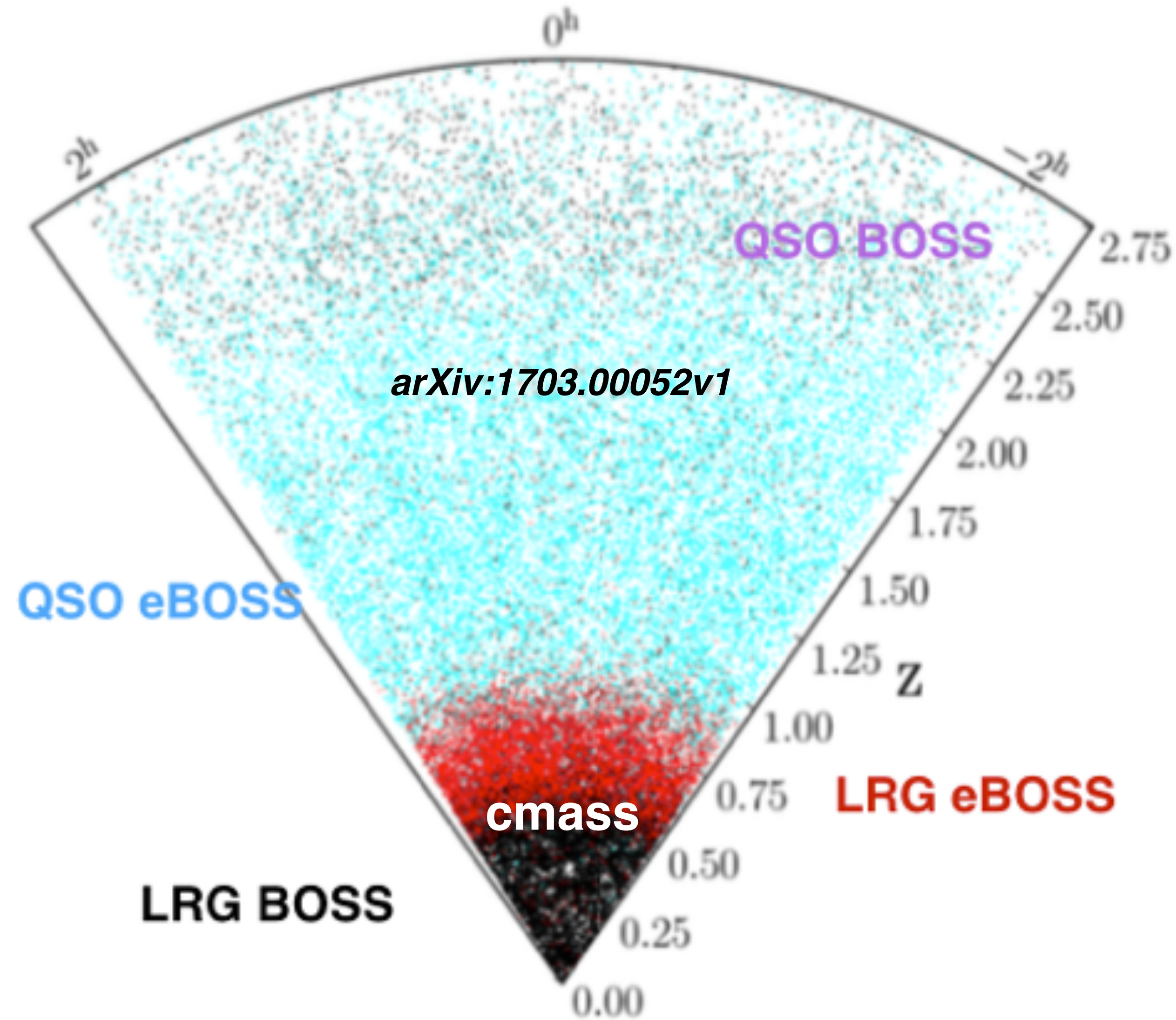
General Relativity → FLRW → ΛCDM

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Fit on DATA

Sloan Digital Sky Survey (SDSS)

- Main project:
  - Telescope (New Mexico, USA)
  - 2.5 m diameter
- Photometry (ugriz) (SDSS-II)
- Spectroscopic Survey:
  - 360 nm < λ < 1000 nm
  - A_{surv}: 10 400 deg^2:
  - 10^6 LUMINOUS RED GALAXIES @ z~0.5
  - 10^5 QUASARS, Lyman-α Forests @ z~2.2
- Objectives:
  - Large Scale Structure Science
  - Cosmological Parameters



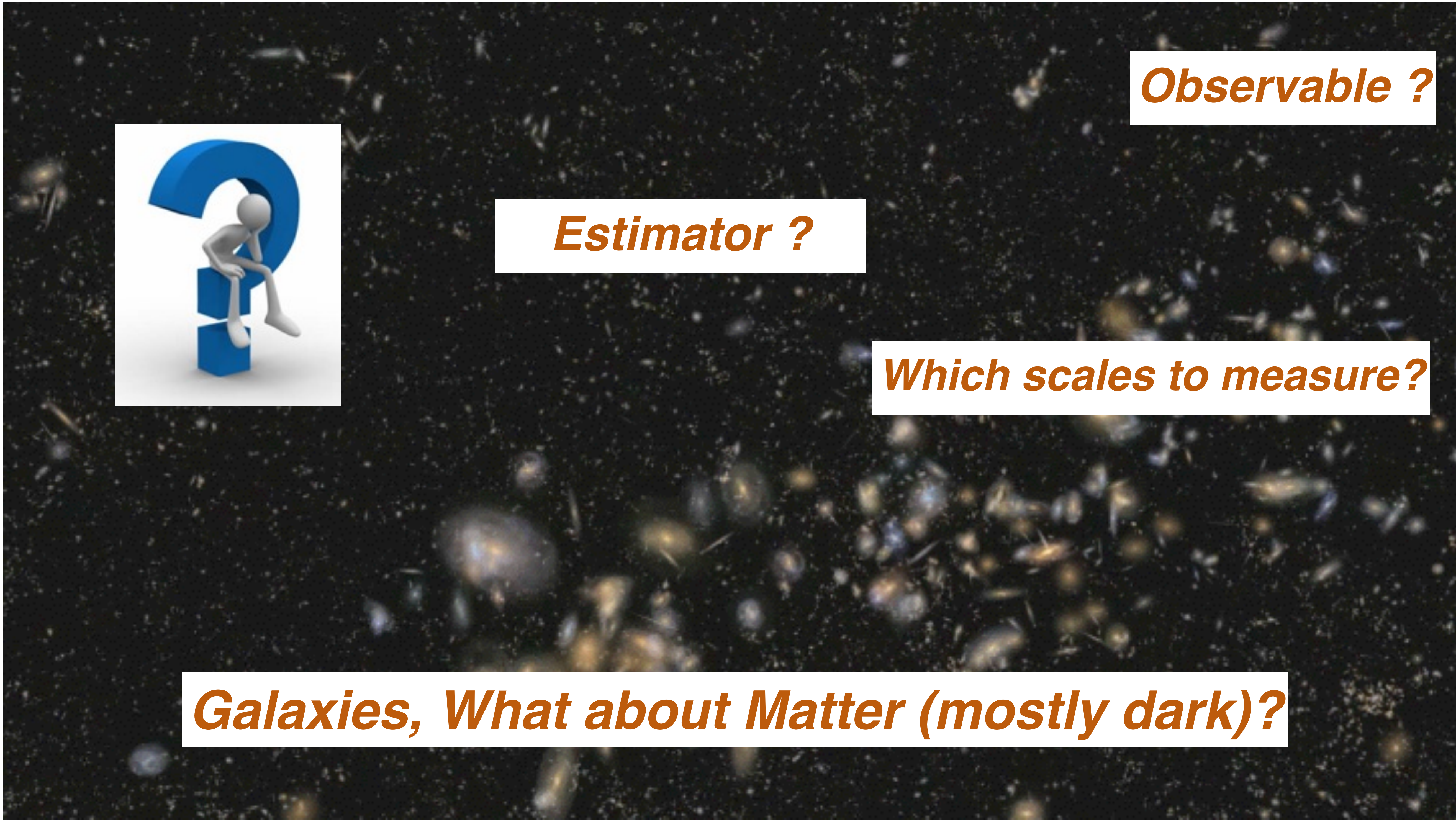
BAO detection

SDSS

2000 2005 2020

BOSS

How to check for Homogeneity?



Observable ?

Estimator ?

Which scales to measure?

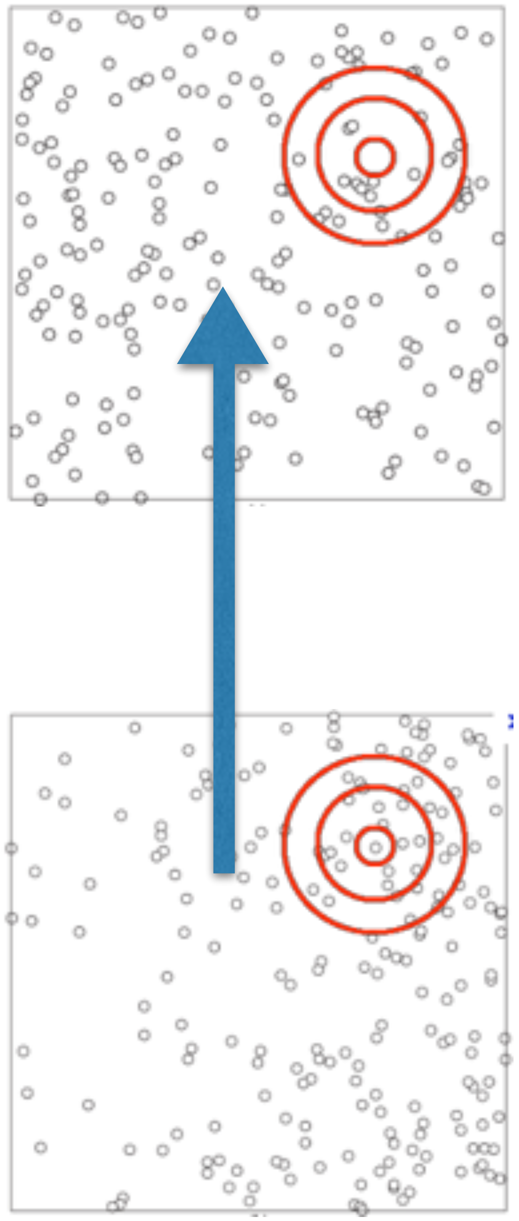
Galaxies, What about Matter (mostly dark)?

Homogeneity Scale Observable

- Counts-in-Spheres: $N(<r) \propto r^{D_2}$
- 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:

$$D_2(R_H) = 3 \text{ @ } 1\%$$

Arbitrary Choice



GALAXIES BIASED TRACERS

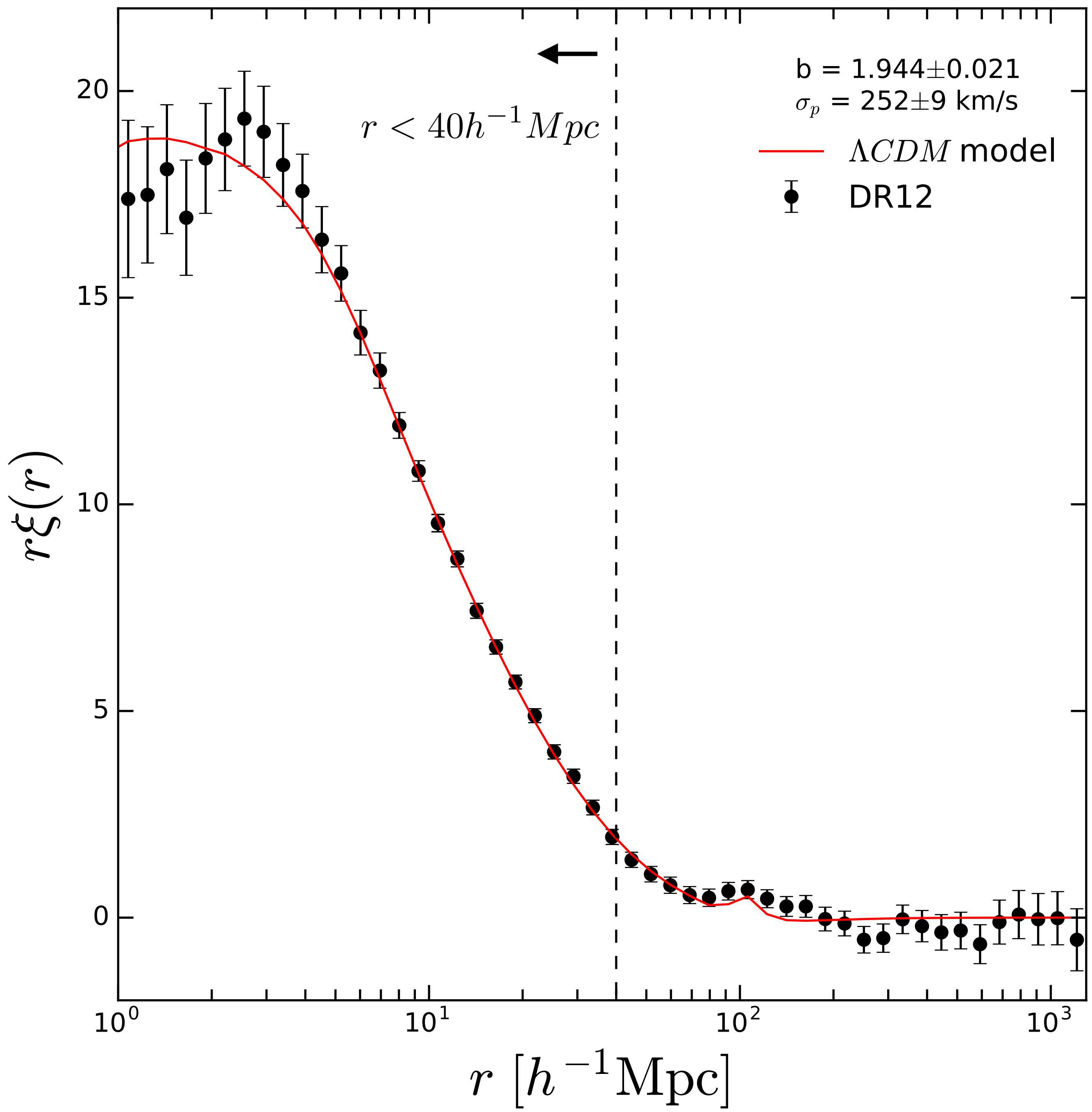
- Fitting Choices on Sims
- Lower Part (r < 40h[-1] Mpc)

Redshift Space Distortion:

- Kaiser b (N. Kaiser 1987)
- FoG σ_P (J.A.Peacock1 & S.J.Dodds 1994)

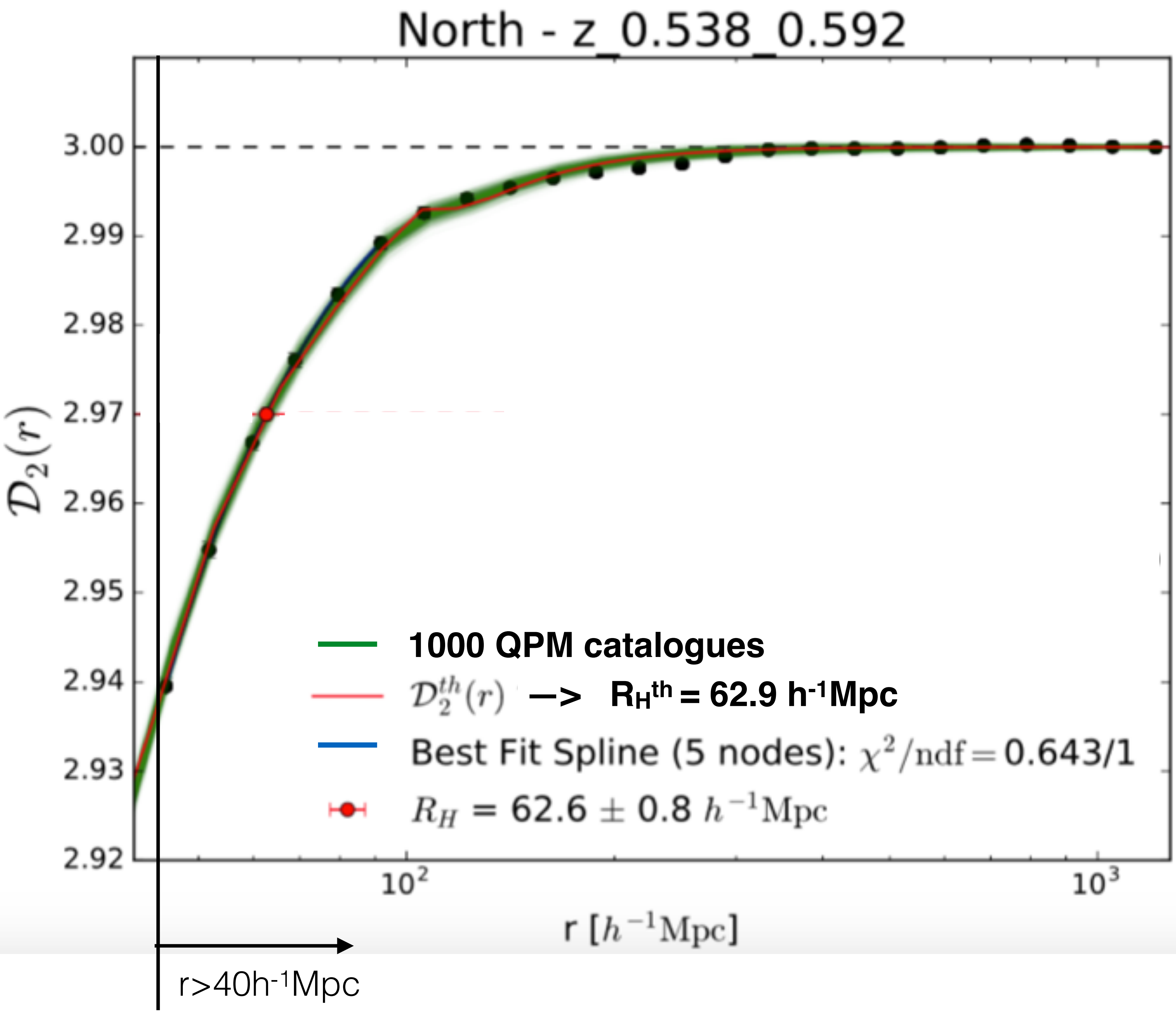
$$\xi(r; b, \sigma_p) = F_{RSD}(r; b, \sigma_p) \otimes \xi_M(r)$$

z = 0.538 - 0.592

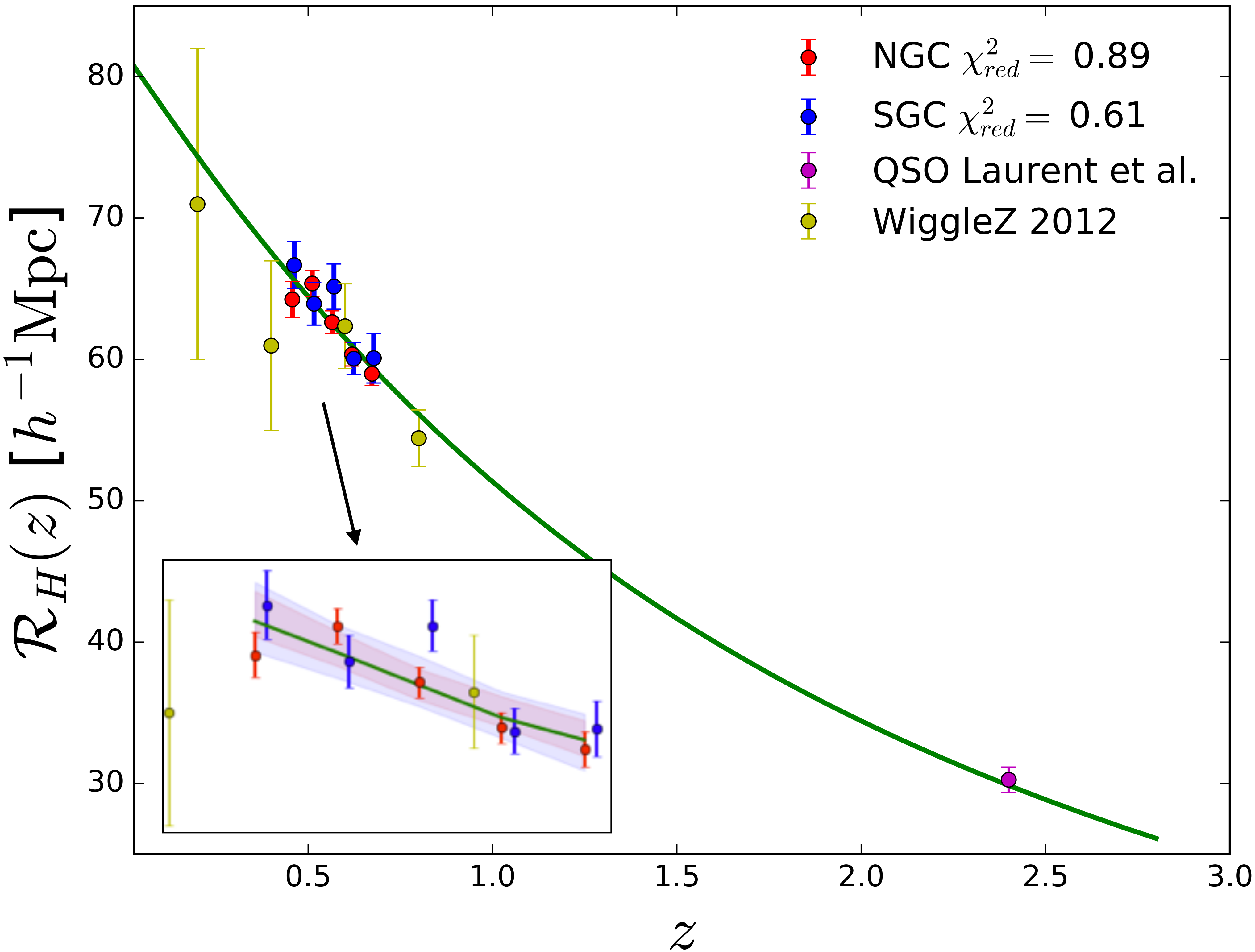


Results

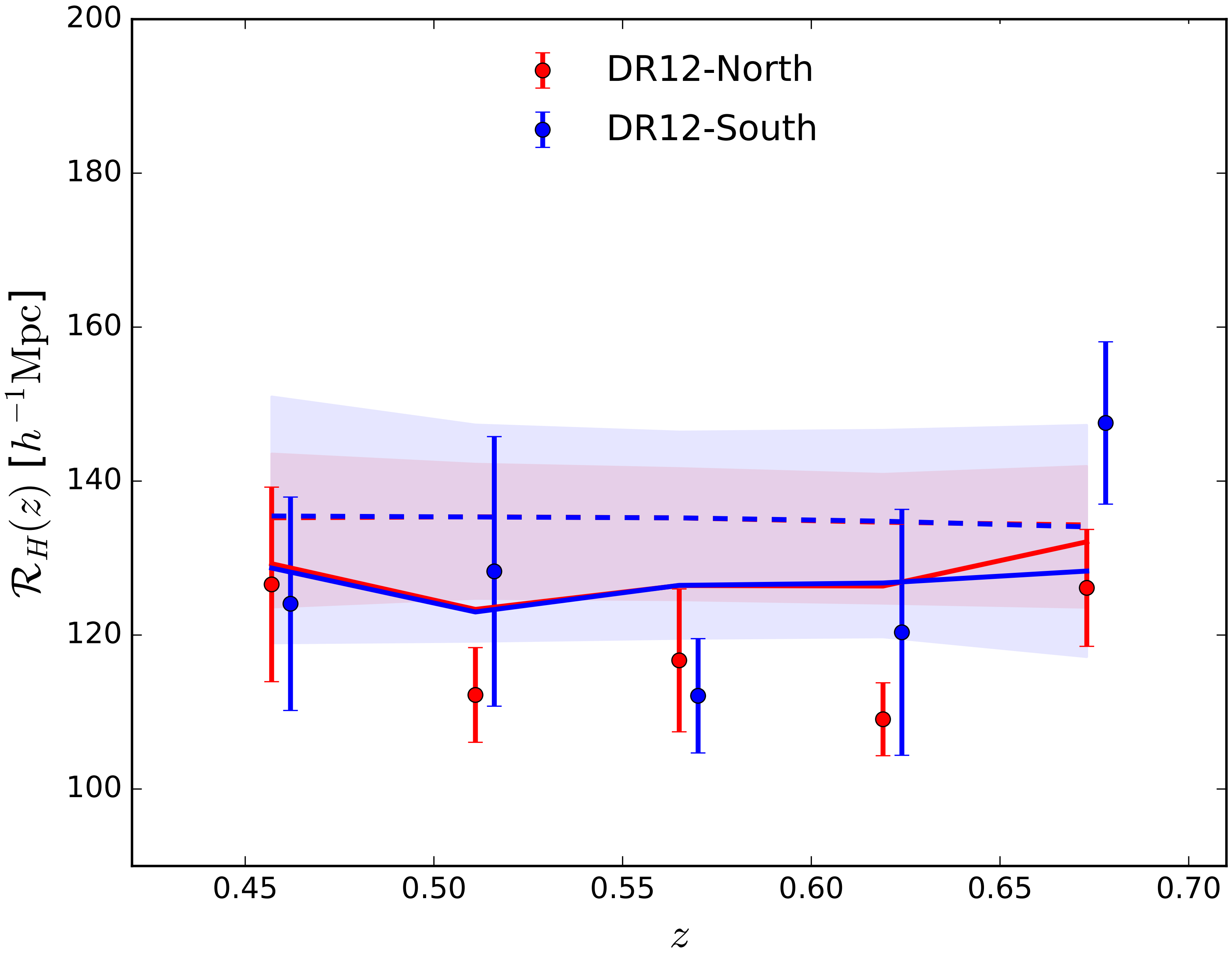
- r_{min}=40h^{-1}Mpc
- applied bias on N
- Compute D_2
- DR12 DATA
- 1000 QPM-ΛCDM
- ΛCDM PLANCK 2015



Redshift Evolution of Homogeneity



Galaxy-$R_H(z)$=cnt

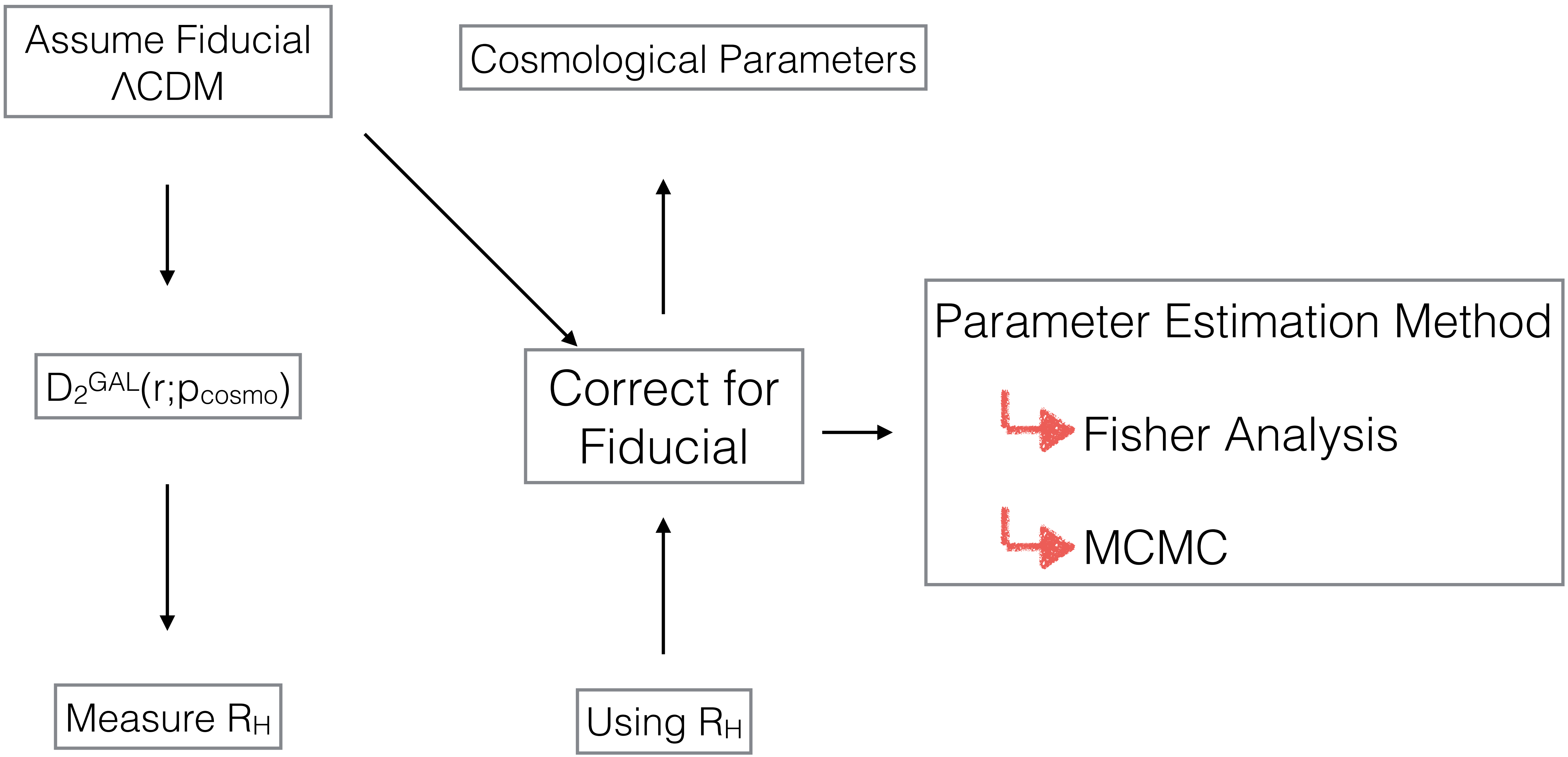


Systematic Tests

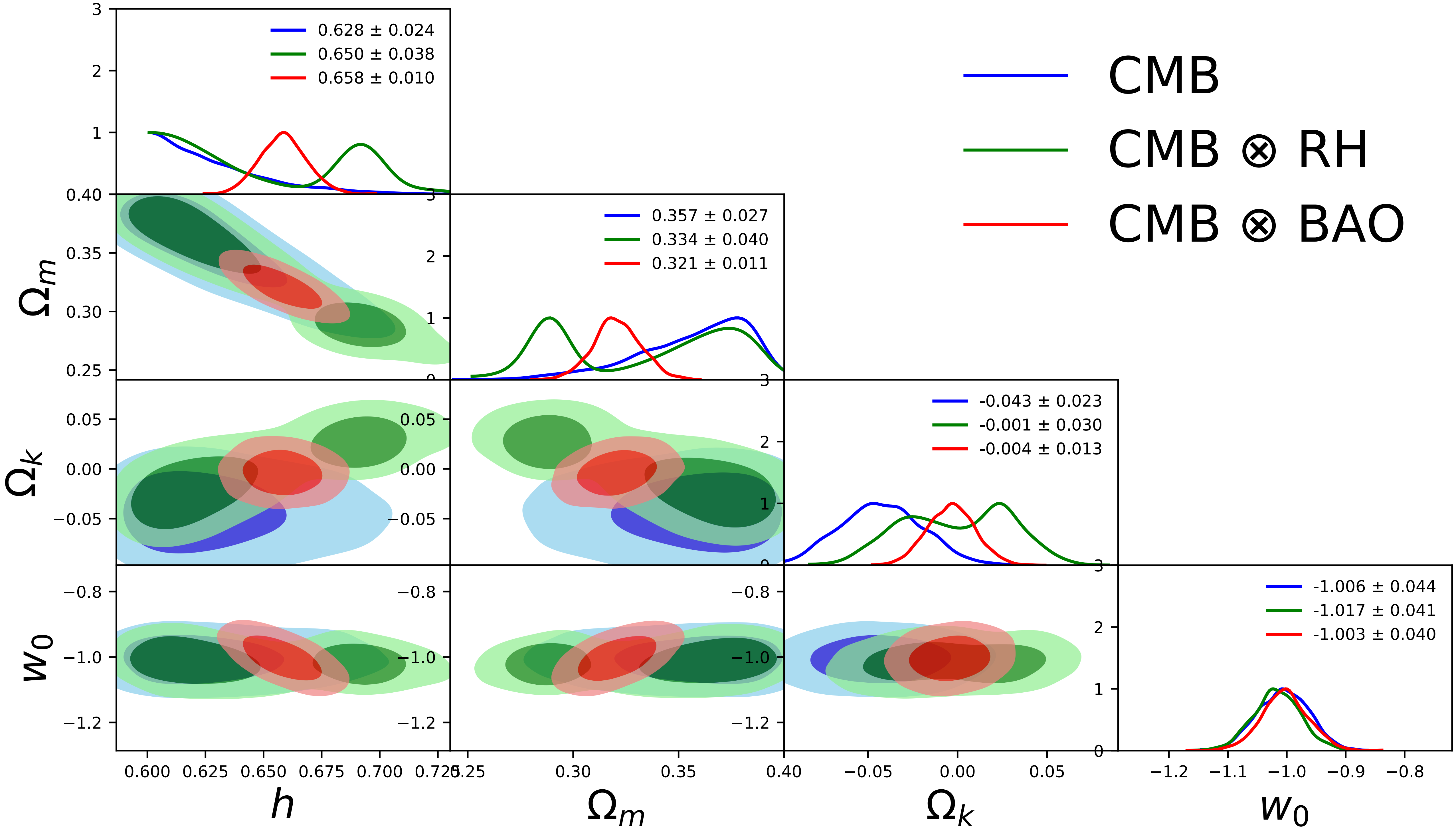
Investigation of:

- Redshift Space Distortion model choice
    - kaiser + FoG < 1% difference
- No Bias from choice of Fractal Analysis
    - <1% difference @ all z
- Spline error robustness
    - < 20% difference @ all z
- Small scales error systematic
    - < 0.2% difference @ all z
- Tests against choice of Weighing Scheme
    - <1% difference @ all z

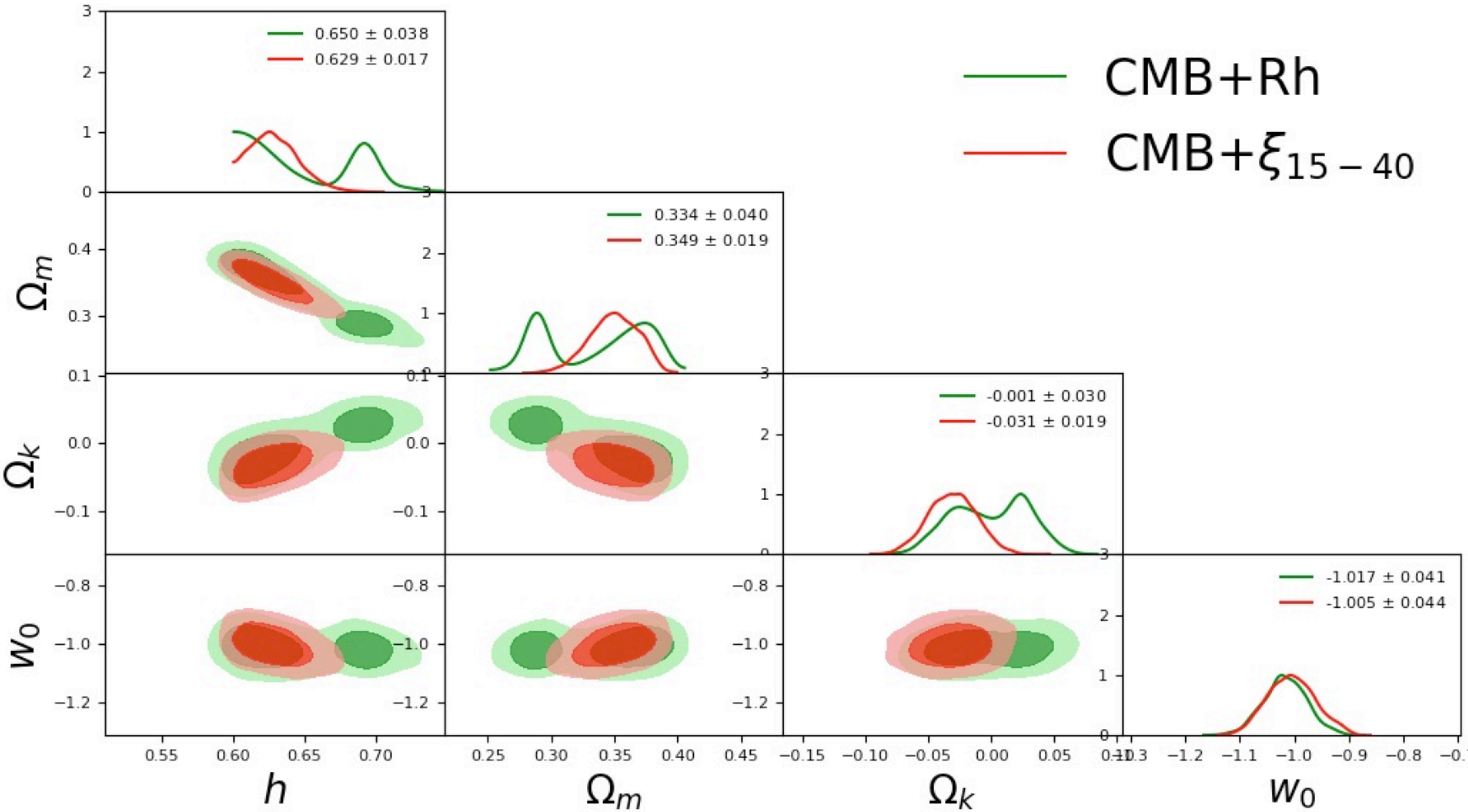
New Idea: R_H Standard Ruler!



R_H Standard Ruler - MCMC



R_H Standard Ruler - MCMC



Conclusions

Main Achievements:

- Largest eff-V ever studied! (~3 $h^{-3}Gpc^3$)
- Precision ~1% (Wz ~ 5%)
- Thorough investigation of Systematics
- Complementary Standard Ruler
- Model independent confirmation of Cosmological Principle (2nd method Not Explained)

Main Limitations:

- Blind to ρ(z):
  - Randoms for edge effects corrections

- Validation test of ΛCDM at %-level
- **Establishment of Cosmological Principle**

Future Prospects within EUCLID

Science goals:

- Establishing the Cosmological Principle and ΛCDM
- Combine probes (IST group)
    - Voids, Galaxies, CMB
    - BAO , RH
- Deep Learning Algorithms to extract most of Photo-Images

Requirements:

- Realistic Euclid Survey - simulations
- Mock catalogues generation (covariance)
- Different target selections (CMASS? LRG? ELG?)

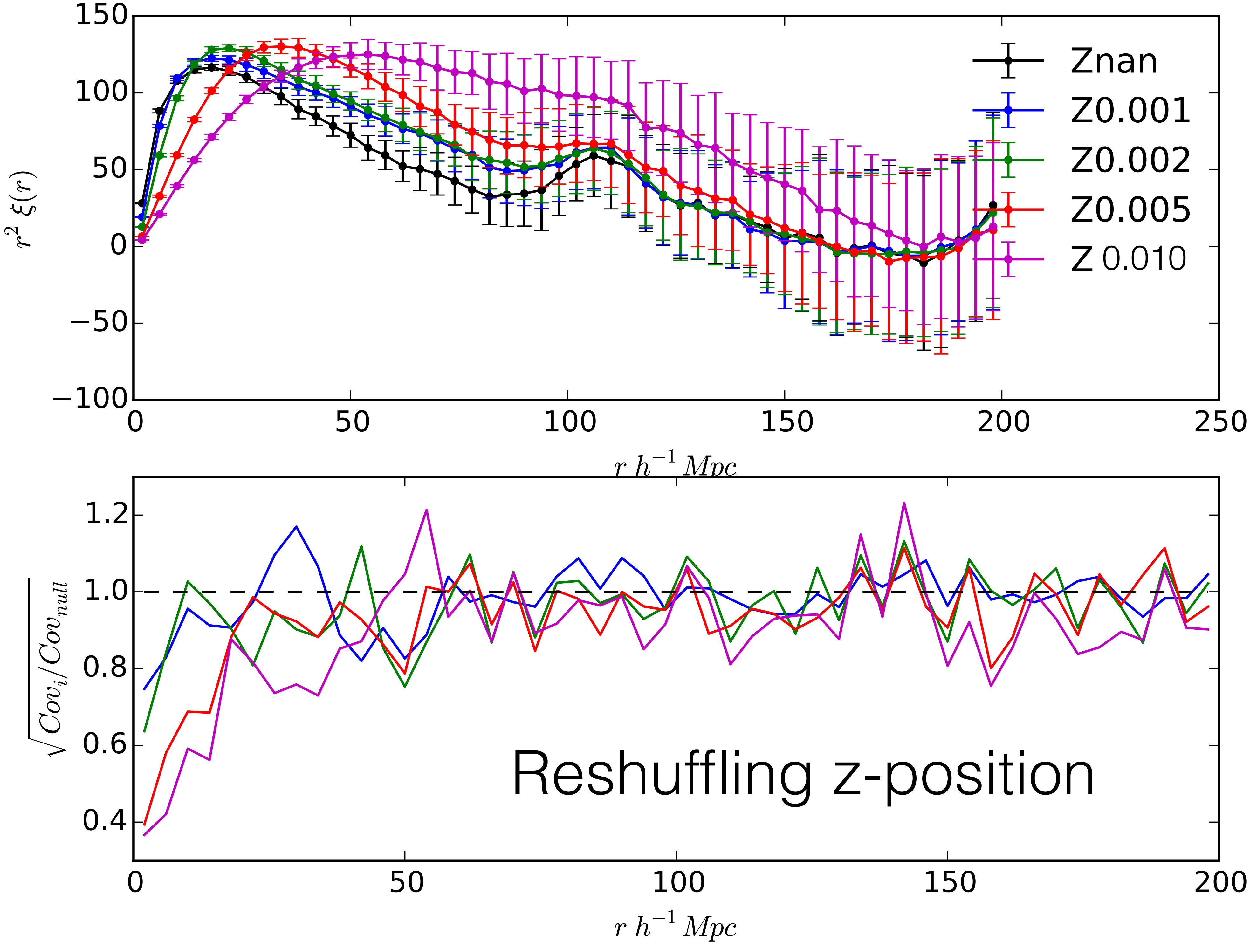
Thank you for your Attention !

Back -↑

Sensitivity of Future Surveys

How does it compare to BAO?

Phot vs Spect



Sensitivity of Future Surveys

Use: 100 QPM catalogues

Change:

- n: reducing density
- V: volume cuts
- σ_z: Adding z noise (Gaussian)

Investigate Scaling Laws:

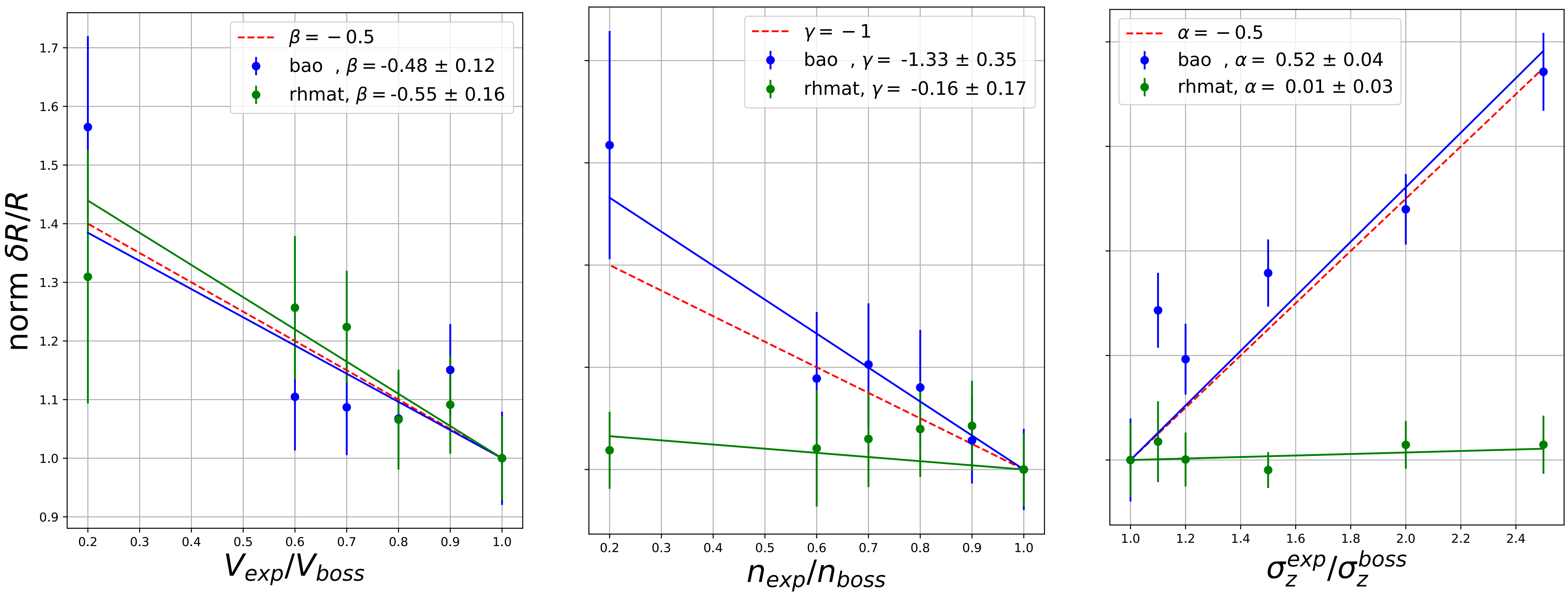
Fitting Formula - Blake et al. 2012

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

Expand to 1st order: $$\frac{\delta R}{R} = \frac{\delta R}{R}[\sigma_{z,0}, V_0, n_0] \left[1 + \alpha \epsilon_{\sigma_z} + \beta \epsilon_V + \gamma \frac{\epsilon_n}{nP}\right]$$

$$\alpha = 1/2 \qquad \beta = -1/2 \qquad \gamma = -1$$

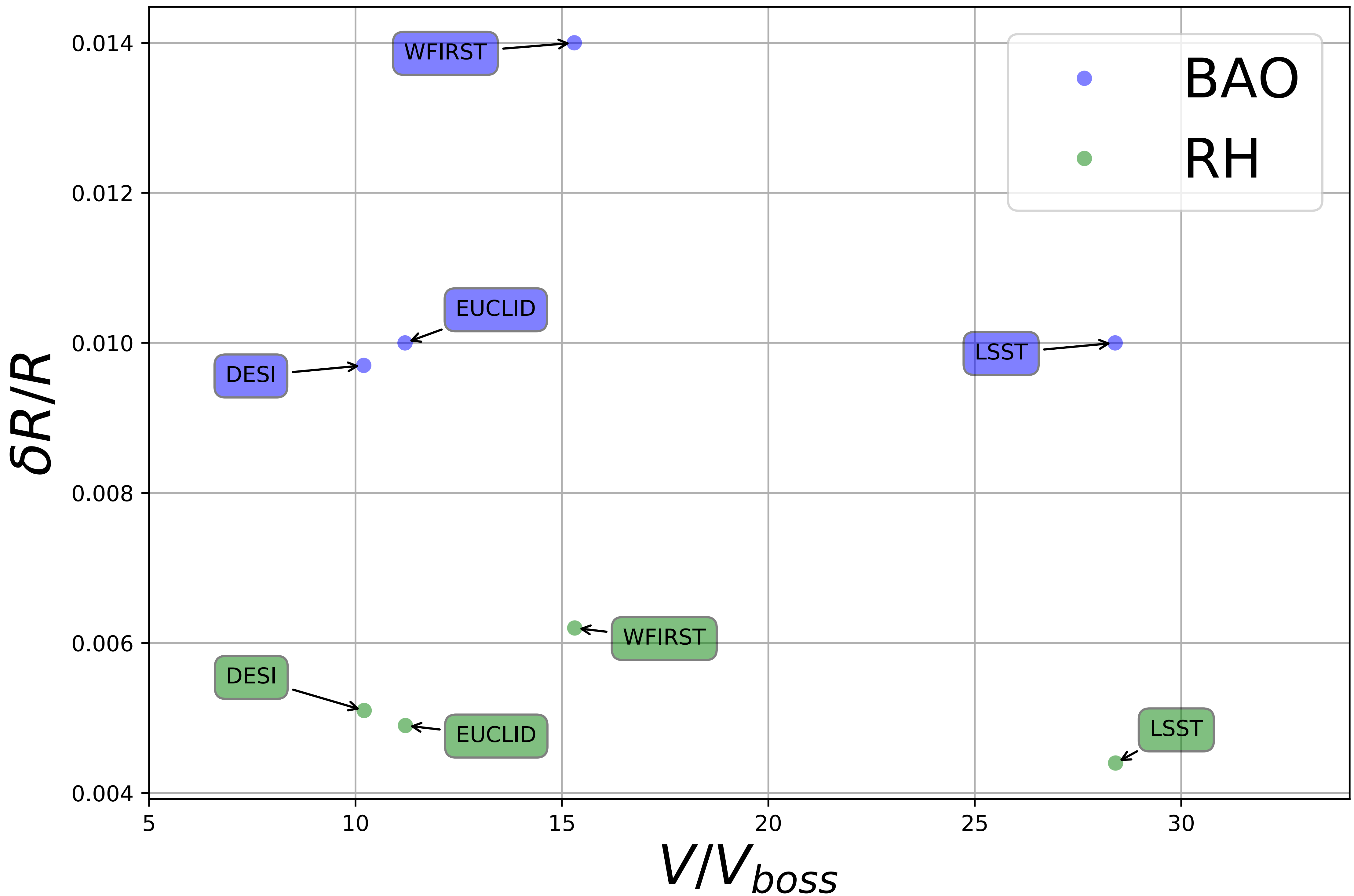
Fitting Formula 1st order



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

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

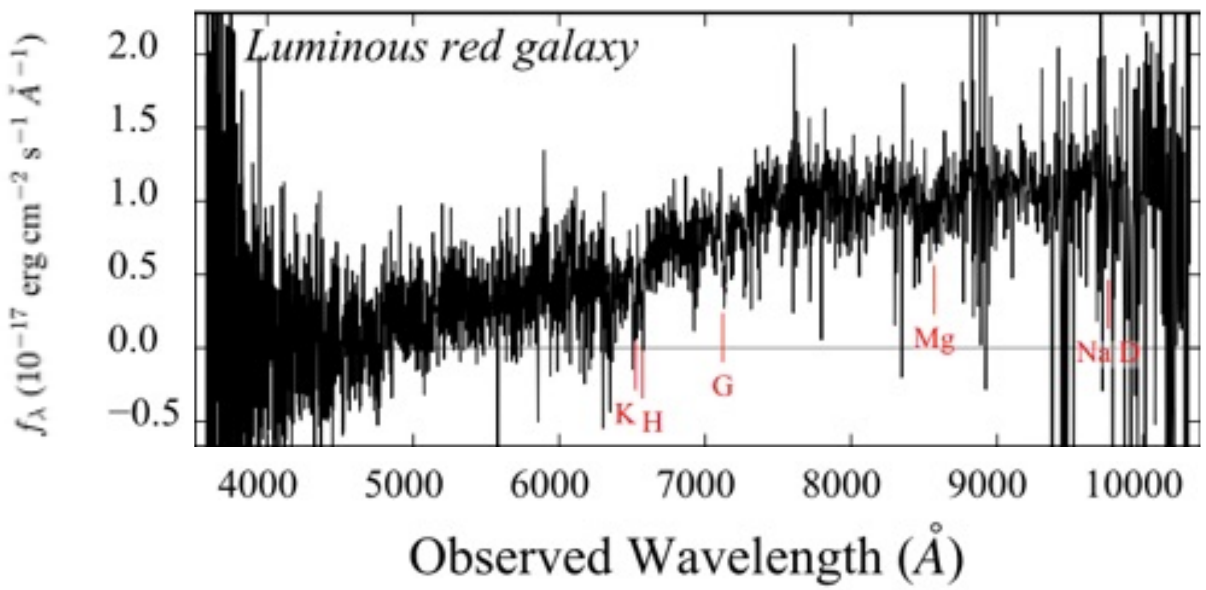
Sensitivity: Current and Future Surveys

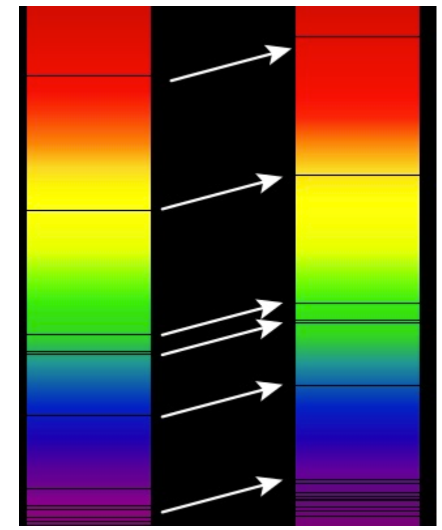


Conclusions IV

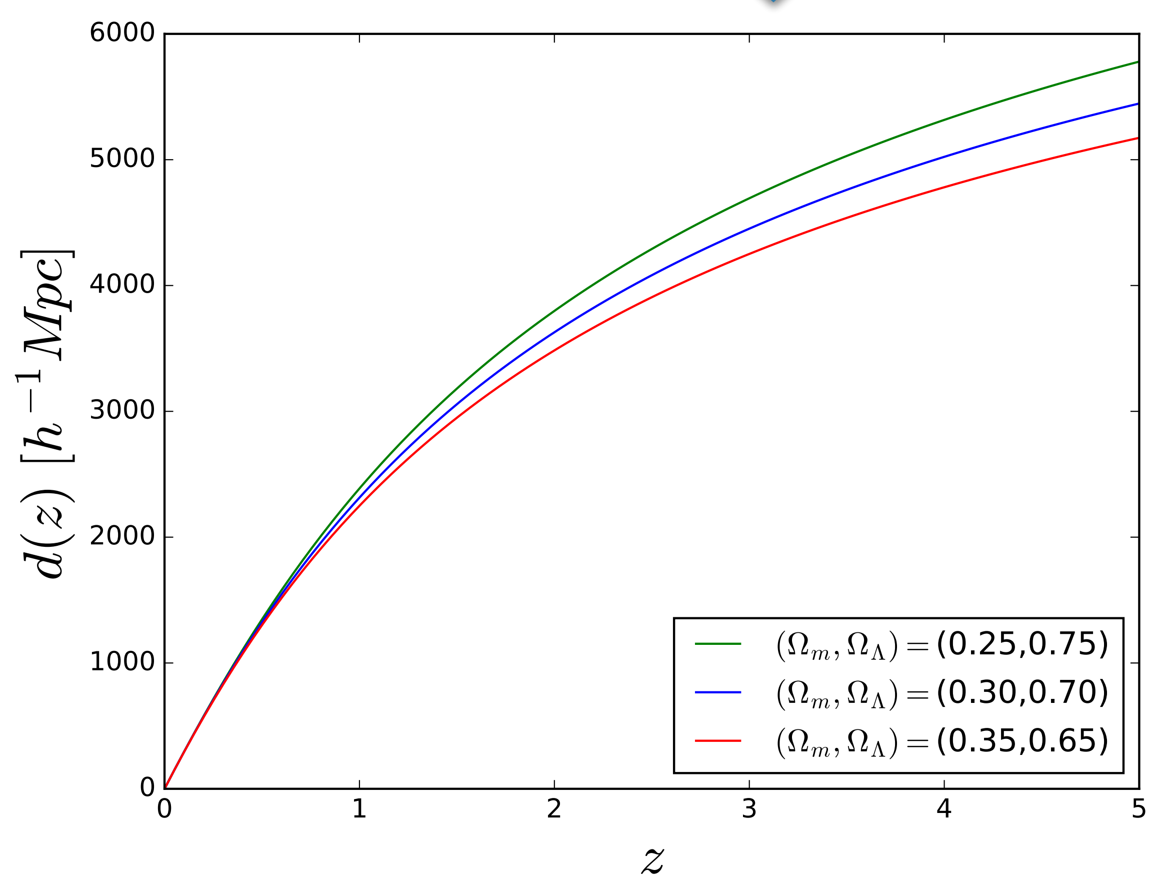
- Complementary Cosmological Probe
- Sensitive to h, Ω_m , Ω_Λ , w_0
- $$\frac{\delta R_H}{R_H} \propto \frac{1}{\sqrt{V}}$$
- Seems Better Probe for Photometric Surveys

Reconstructed Sample



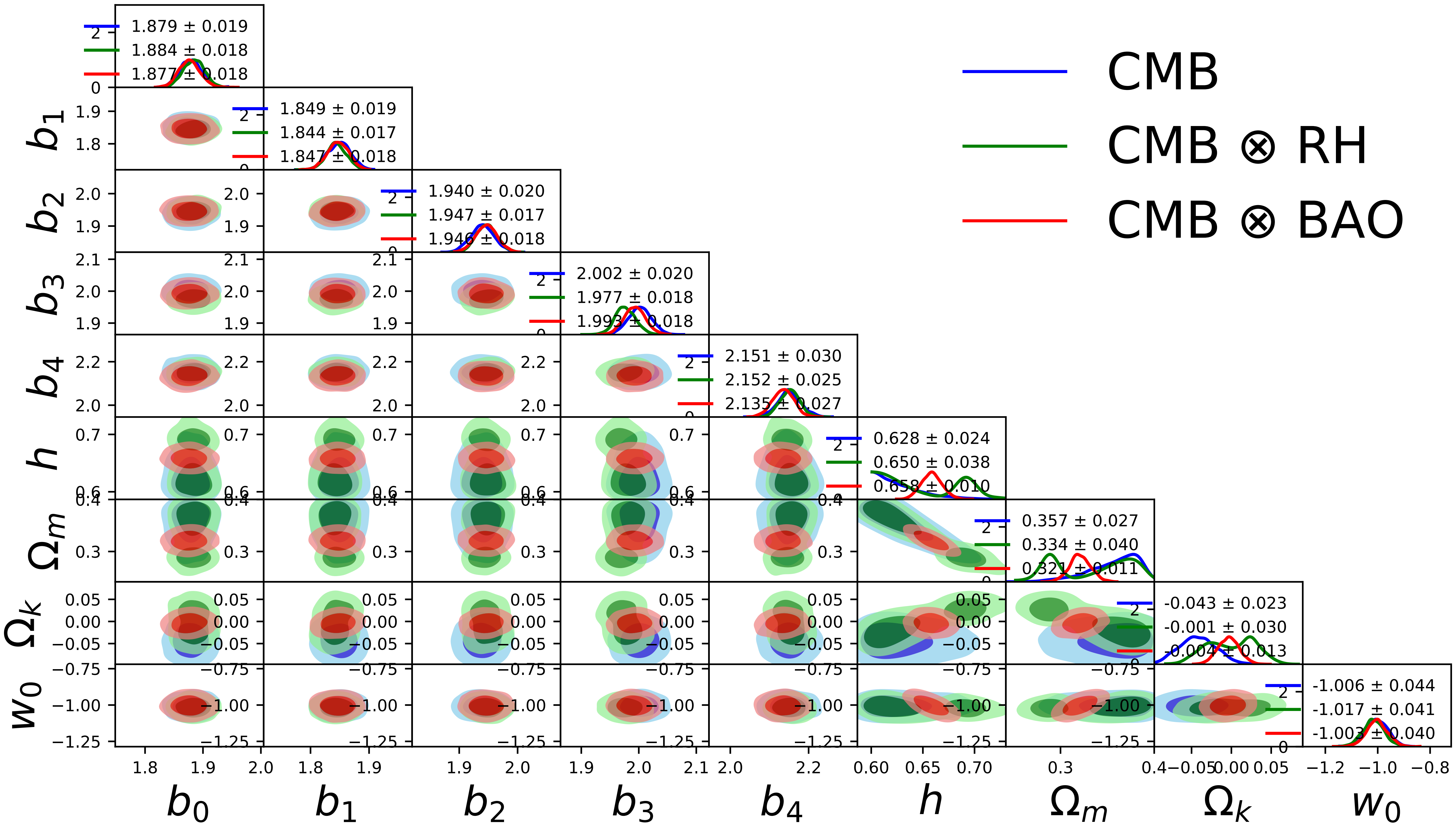


Redshift



cosmology dependent

R_H Standard Ruler - MCMC



Voids + RH -> Constrain Cosmology

Voids Galaxies

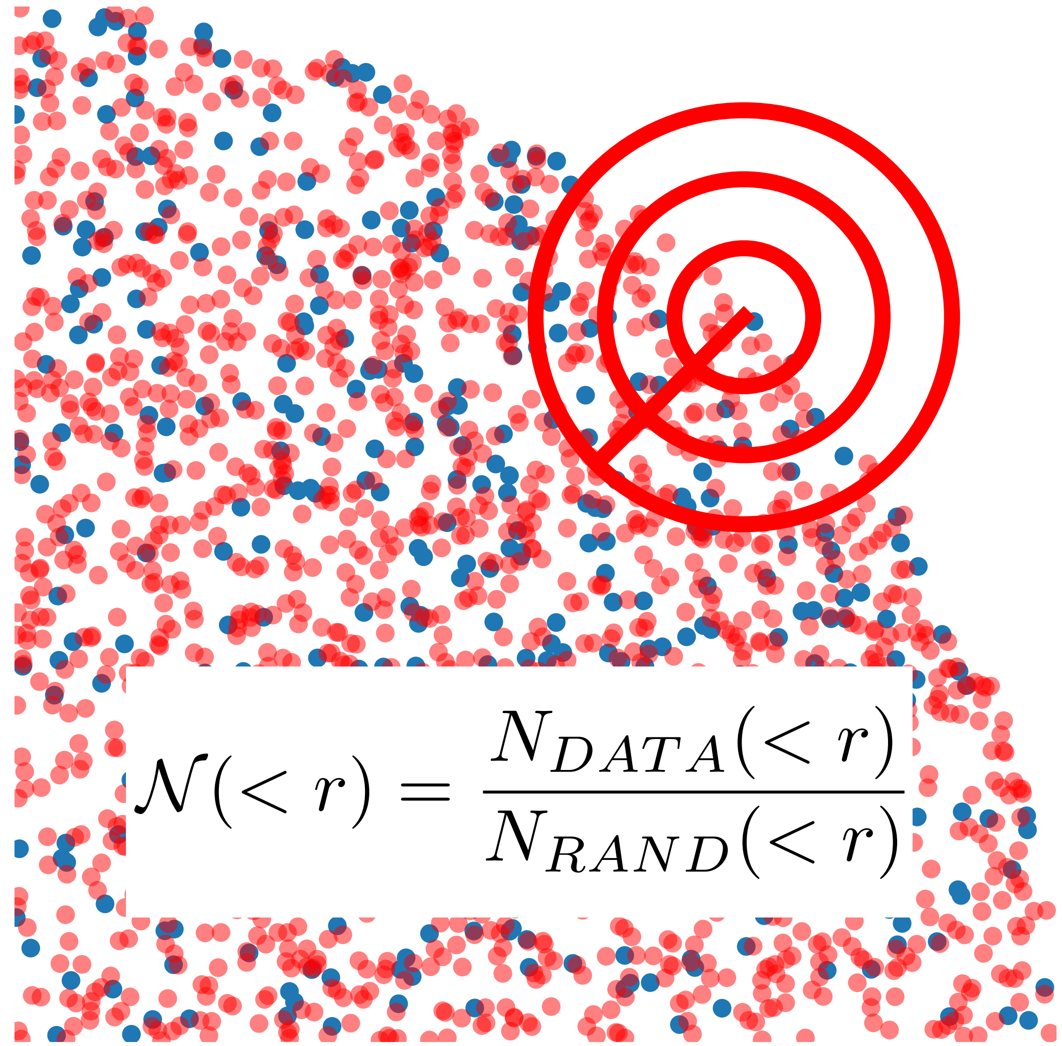
$$\mathcal{D}_2(r) = 3 + \frac{d\ln}{d\ln r}\left(1 + \frac{3}{r^3}\int_0^r s^2\xi(s)ds\right)$$

Voids + Galaxies

Adam J Hawken 2016
Alice Pisani et al 201?

Observable: Count-in-spheres

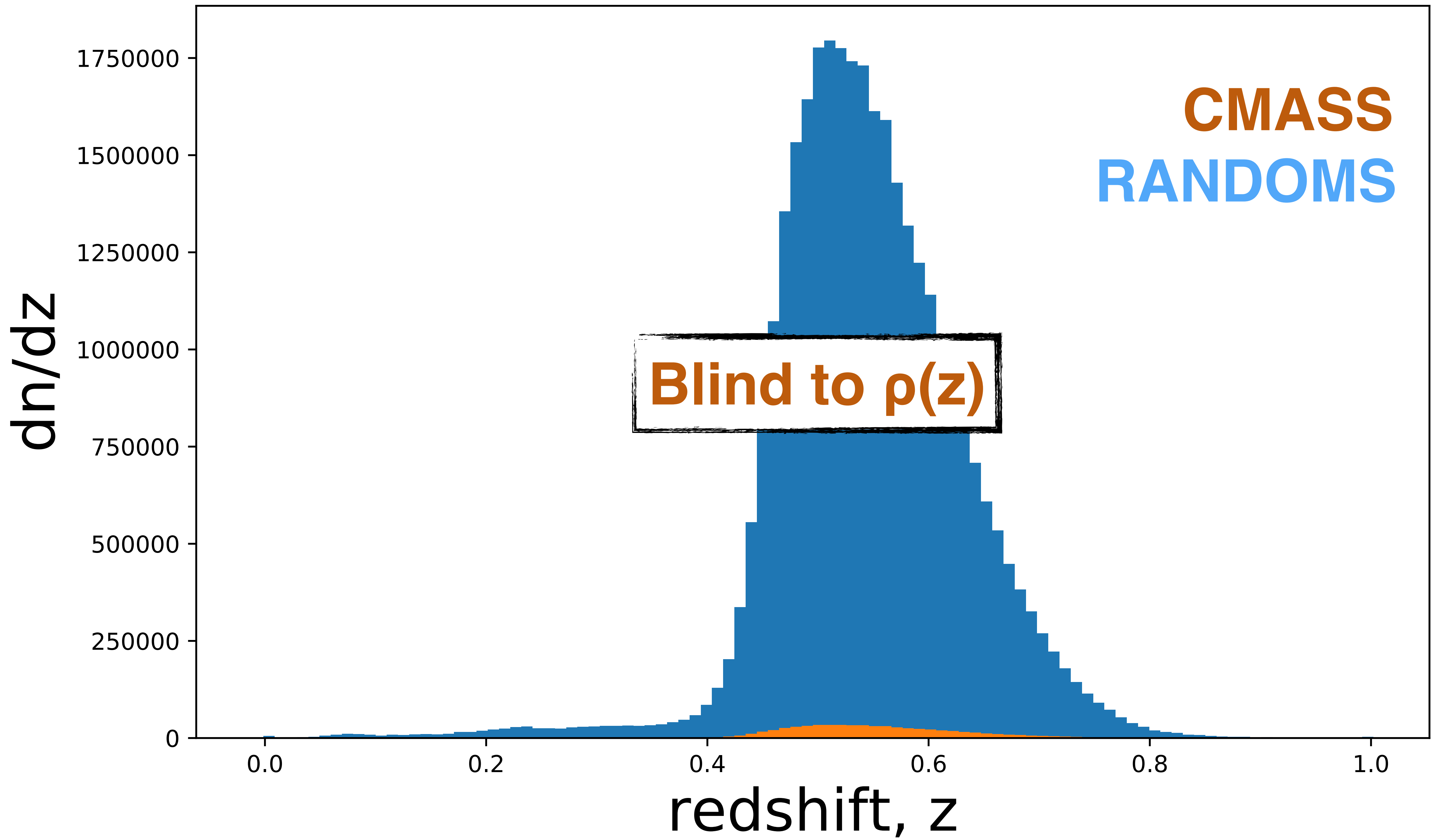
- Select a galaxy as a center
- Create a sphere of radius **r**
- Compute number of galaxies
- repeat for every galaxy
- compute the mean **N(<r)**
- repeat for different scales



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

Randoms: Same Selection function

Redshift Profile of Galaxy Sample



Check homogeneity so far

Assumptions:

- Metric Theory of Gravity
- Smooth expansion rate of the universe
- Cosmological Principle
- FLRW metric
- Flatness

$$(z, \theta, \phi) \xrightarrow{\text{FLRW metric}} (x, y, z)$$

Assumption of a Homogeneous Universe

Check homogeneity so far

Assumptions:

- Metric Theory of Gravity
- Smooth expansion rate of the universe
- Cosmological Principle
- FLRW metric
- Flatness

$$ds^2 = -c^2 dt^2 + \alpha^2(t)\left[dr_c^2 + S_k^2(r_c)d\Omega\right]$$

Radial: Cosmological Principle

Transverse: Curvature

$$S_k(d_c) = \begin{cases} \sqrt{k}^{-1}\sin\left(d_c\sqrt{k}\right) & , \ k > 0 \\ d_c & , \ k = 0 \\ \sqrt{|k|}^{-1}\sinh\left(d_c\sqrt{|k|}\right) & , \ k < 0 \end{cases}$$

Check homogeneity model independently

Alternative Assumptions:

- Metric Theory of Gravity
- Smooth expansion rate of the universe
- Stellar Population Synthesis model (Cosmic Clocks)
- Supernova Astrophysical Luminosity model (Type Ia SN)
- Any curvature

z		x
θ	Cosmic Clock -> H(z)	y
φ	Type Ia SN -> S_k	z

No Assumption of a Homogeneous Universe

Cosmic Clocks - Radial Distance

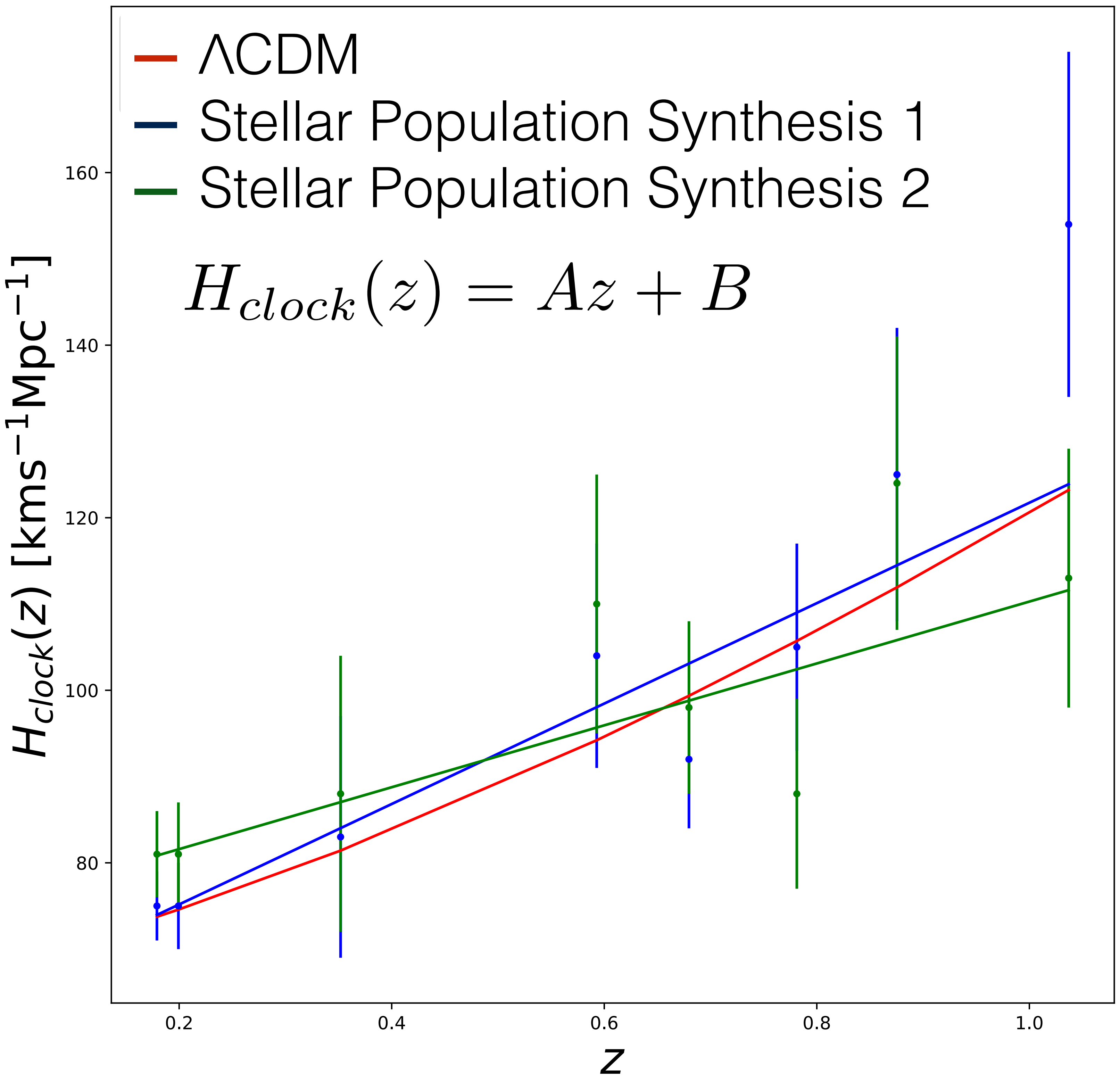
Stellar Population Synthesis Model:

- Galaxy Differential Age
- Differential redshift

$$H_{clock}(z) = -\frac{1}{1+z}\frac{dz}{dt}$$

M.Moresco et al. 2012

Radial Distance Calibration with Cosmic Clocks



Type Ia SN - Transverse Distance

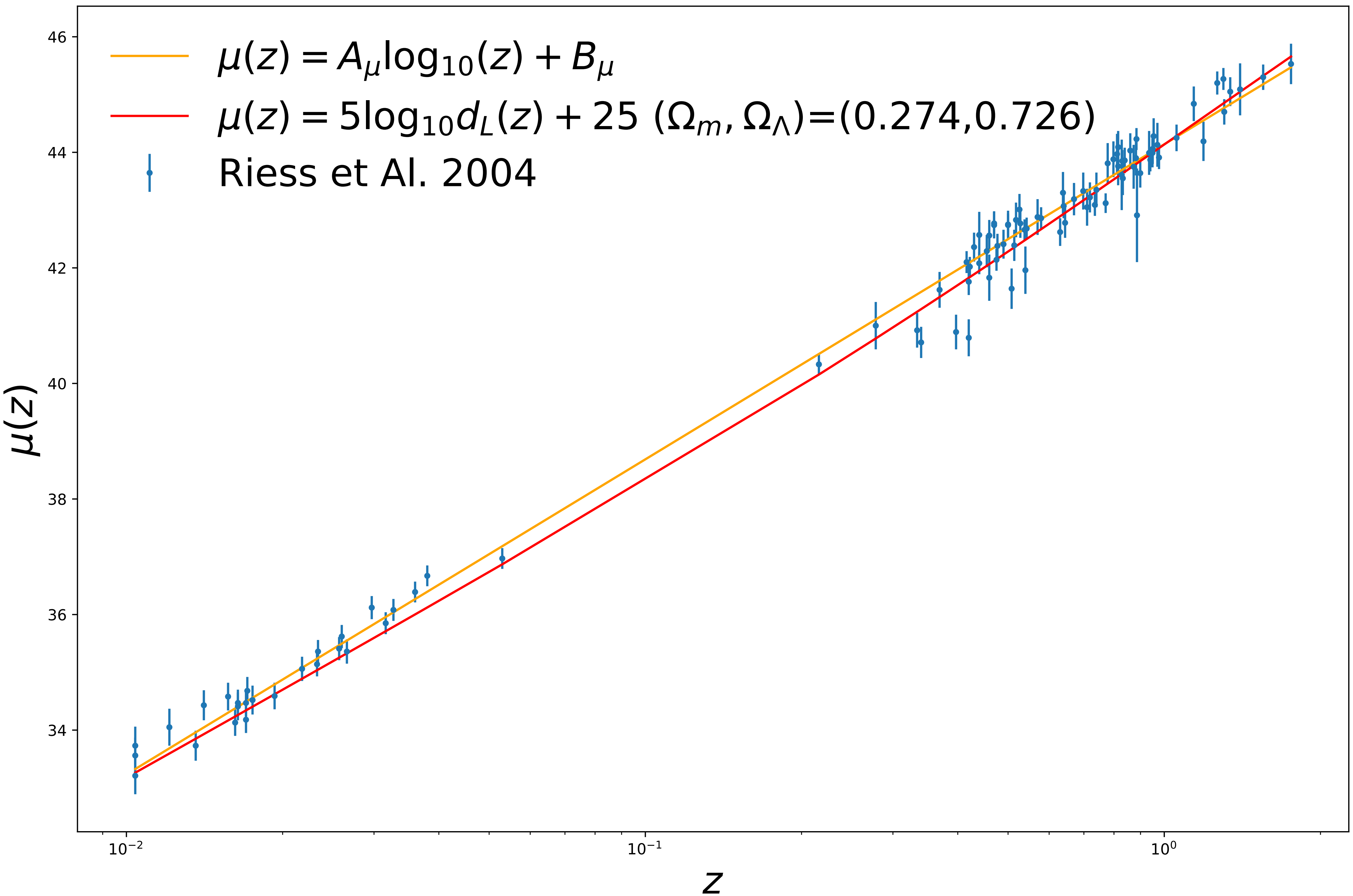
- *Supernova Astrophysical Luminosity model*

$$5\log_{10} d_L = \mu(z; p_{astro}) - 25$$

- Linear relation Transverse Distance & Luminosity Distance

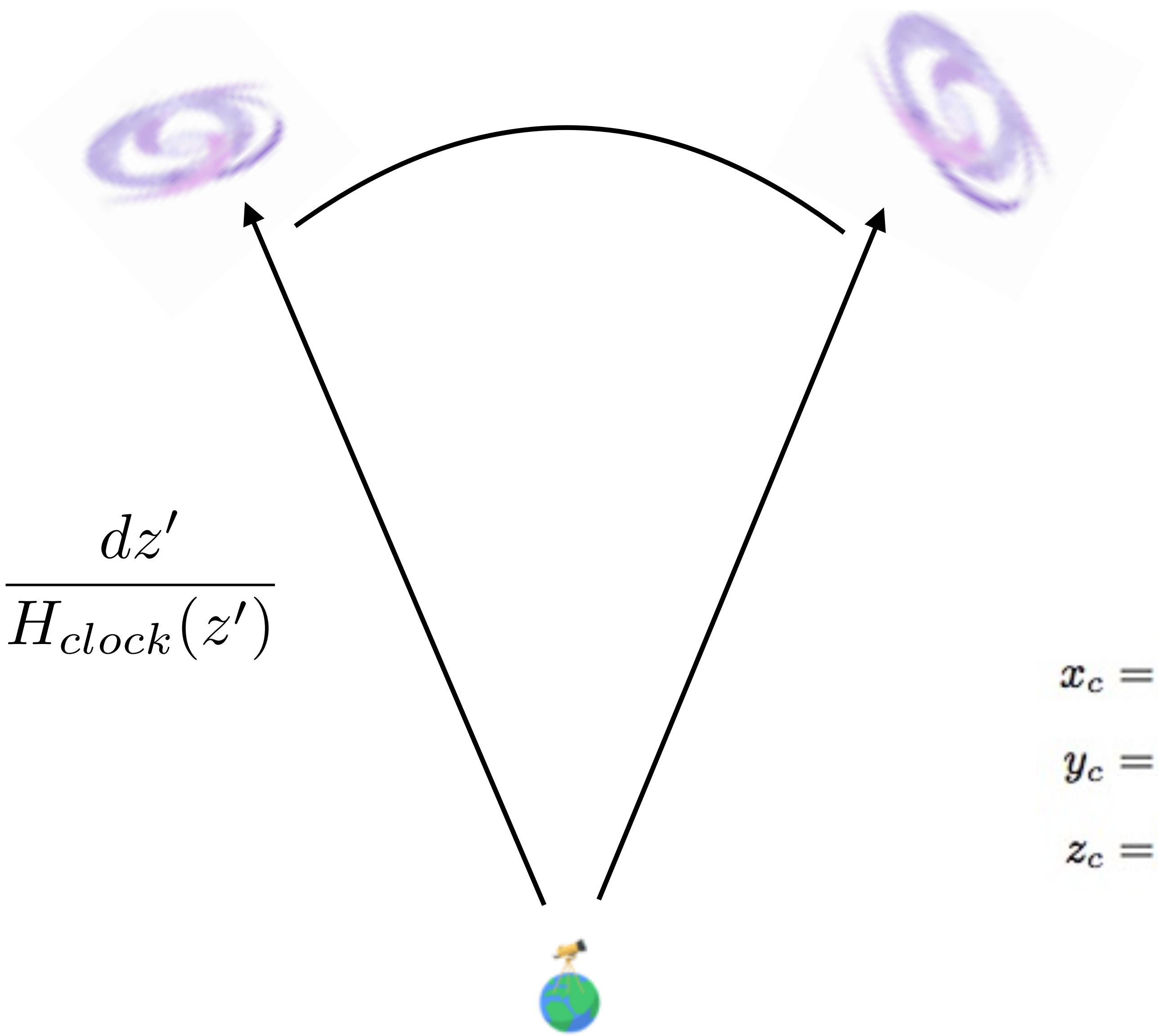
$$d_M(z) = a(z)d_L(z) = \frac{1}{1+z}d_L(z)$$

Module Distance Calibration with SN



Homogeneity Scale with Cosmic Clocks and type Ia SN!

$$d_M(z; A_\mu, B_\mu) = \frac{1}{1+z} 10^{[\mu(z;A_\mu,B_\nu)-25]/5}$$



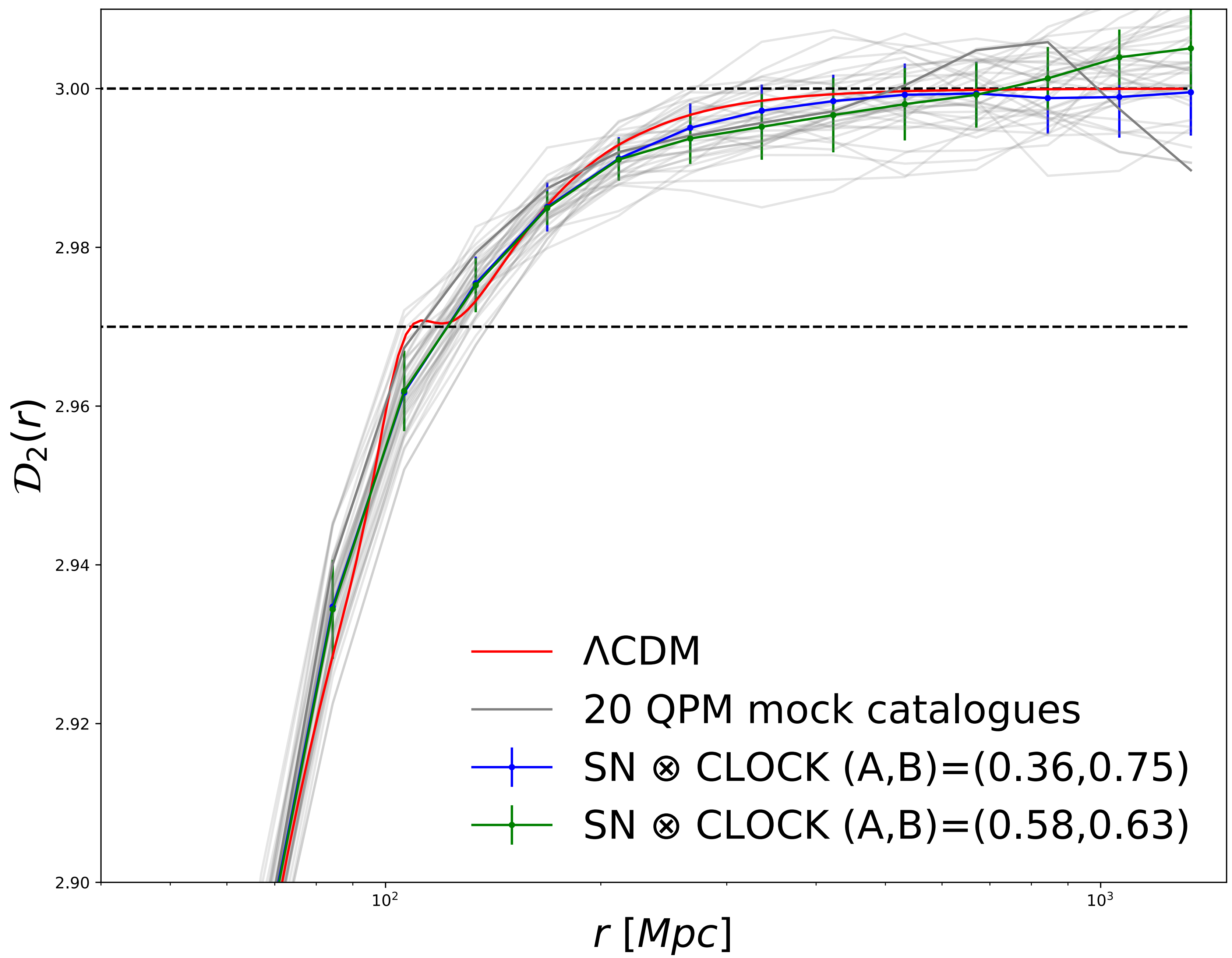
$$r_{clock}(z) = c\int_0^z \frac{dz'}{H_{clock}(z')}$$

$$x_c = d_M(z; A_\mu, B_\mu)\sin\theta\cos\phi$$

$$y_c = d_M(z; A_\mu, B_\mu)\sin\theta\sin\phi$$

$$z_c = d_{clock}(z; A, B)\cos\theta$$

Homogeneity Scale with Cosmic Clocks and type Ia SN!



Model Independent Confirmation of Cosmological Principle!

Conclusions III

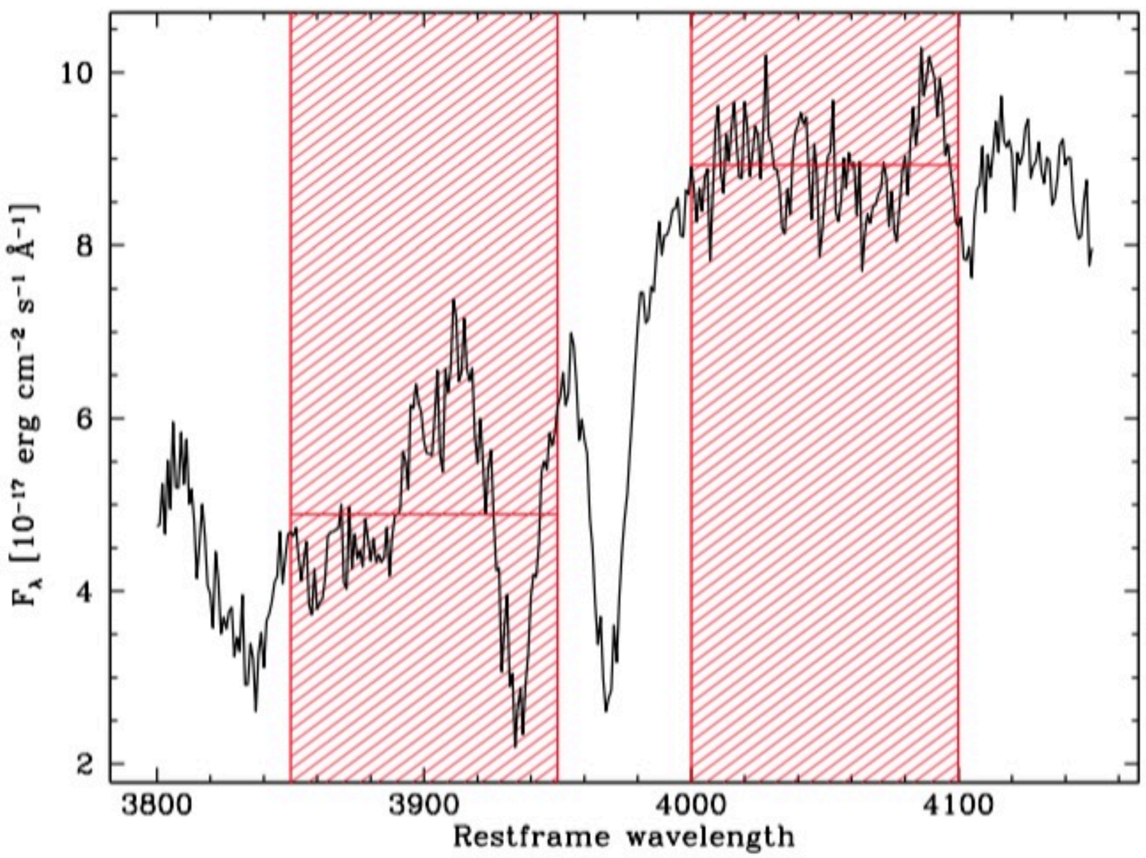
Main Achievements:

- Alternative way to exclude fractal universe
- Model Independent Confirmation of Cosmological Principle

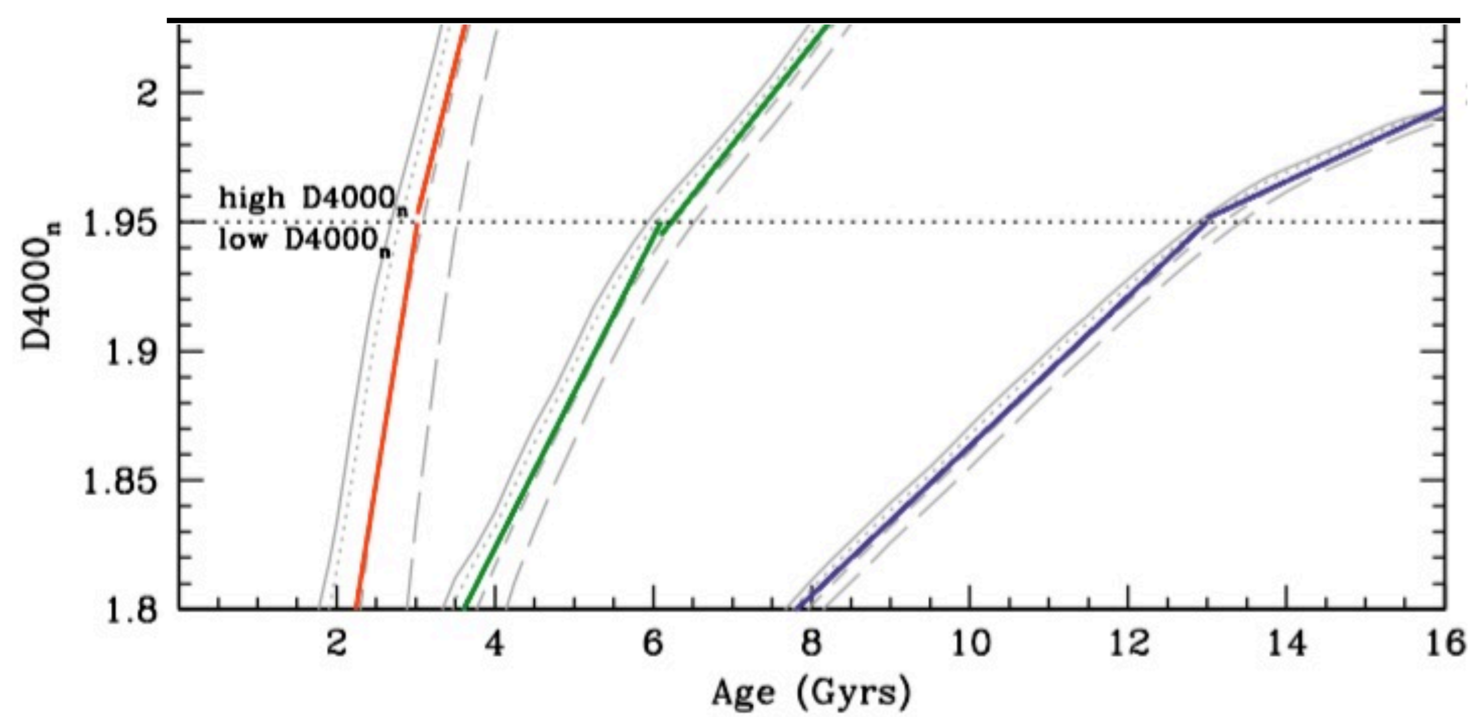
Main Limitations:

- Blind to $\rho(z)$:

Stellar Population Synthesis Model



······▸ dD4000/dz



taken from Moresco et al. 2011

Mock Galaxies Catalogues (QPM)

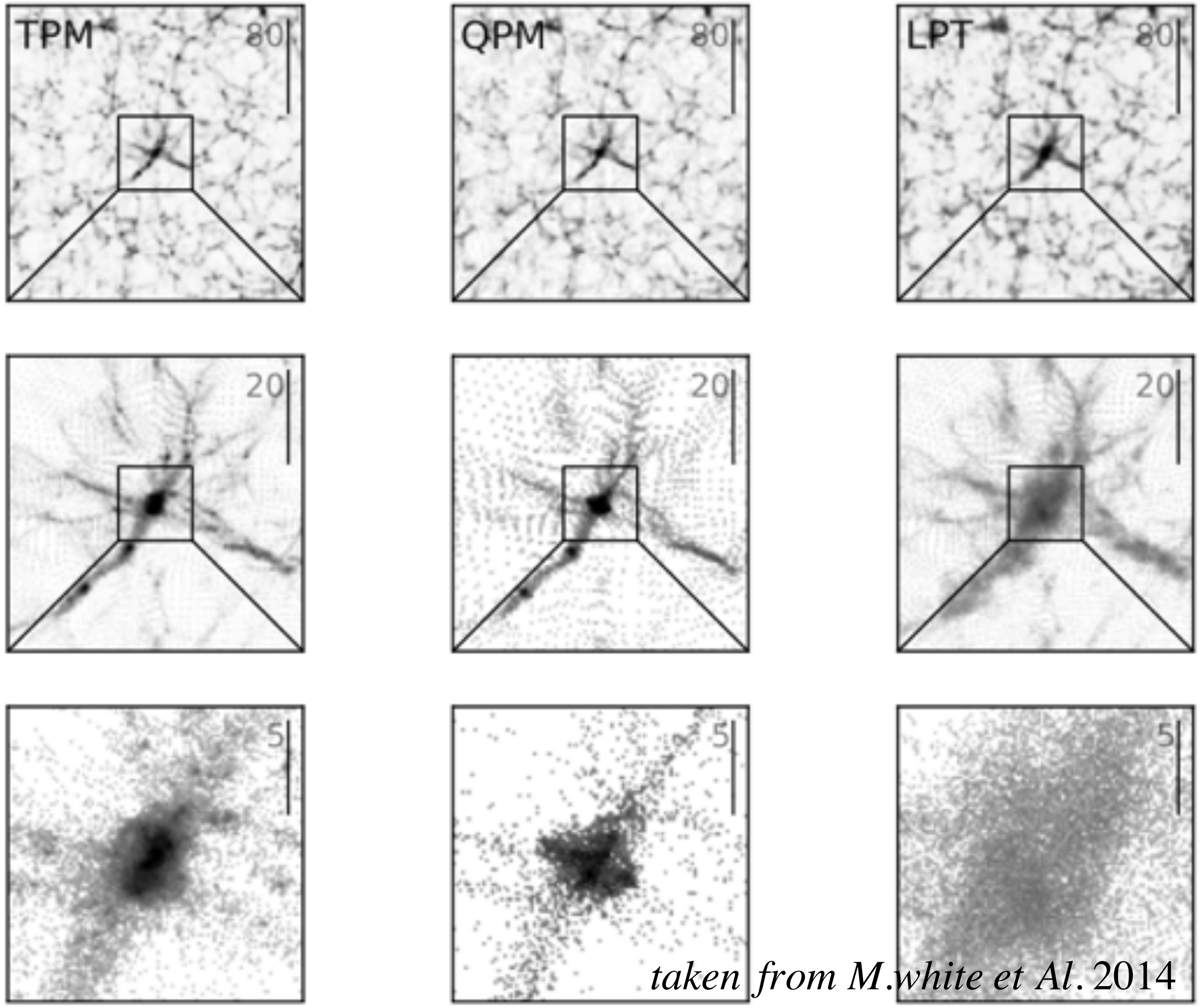
Basic Method

- Predict evolution of mass field
- Identify DM halos
- Populate Halos with Galaxies
- Apply survey characteristics

Analysis Usage

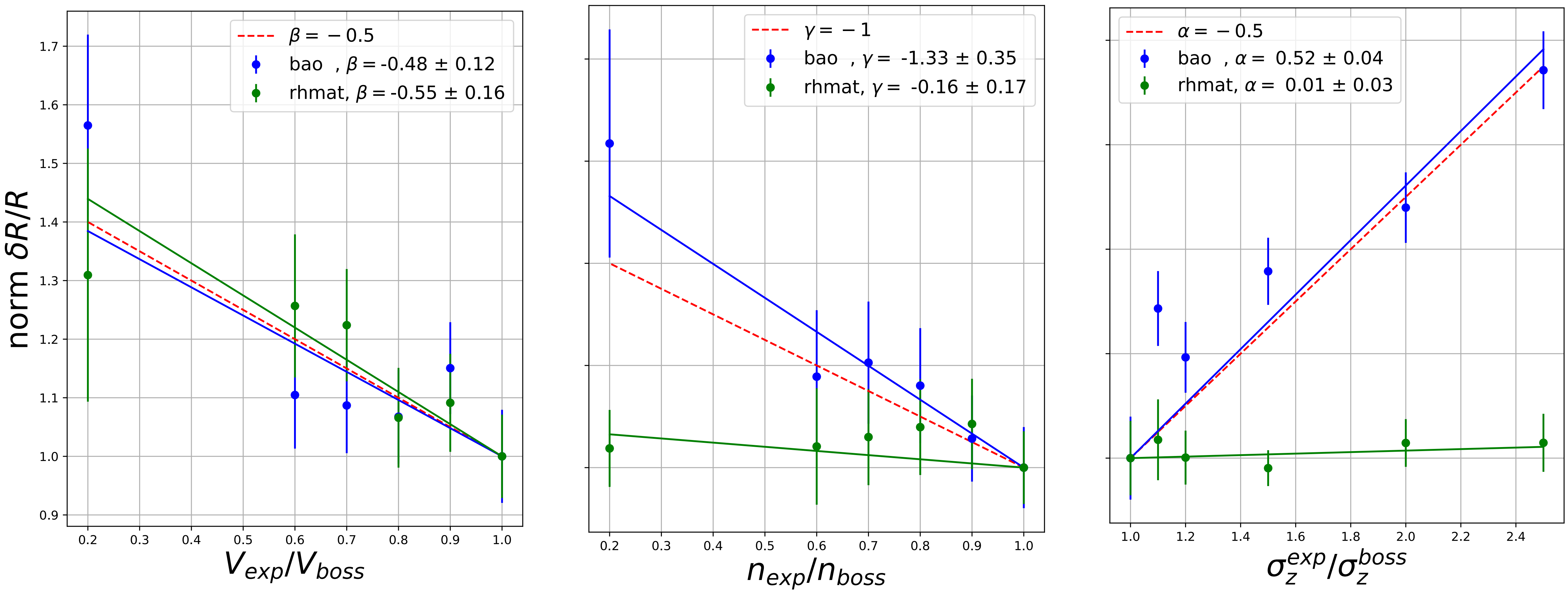
- Compute Covariance Matrices
- Use in Analysis Tests

ref: 1309.5532v2, 1203.6609v2



taken from M.white et Al. 2014

Prediction for Future Surveys: Simulations

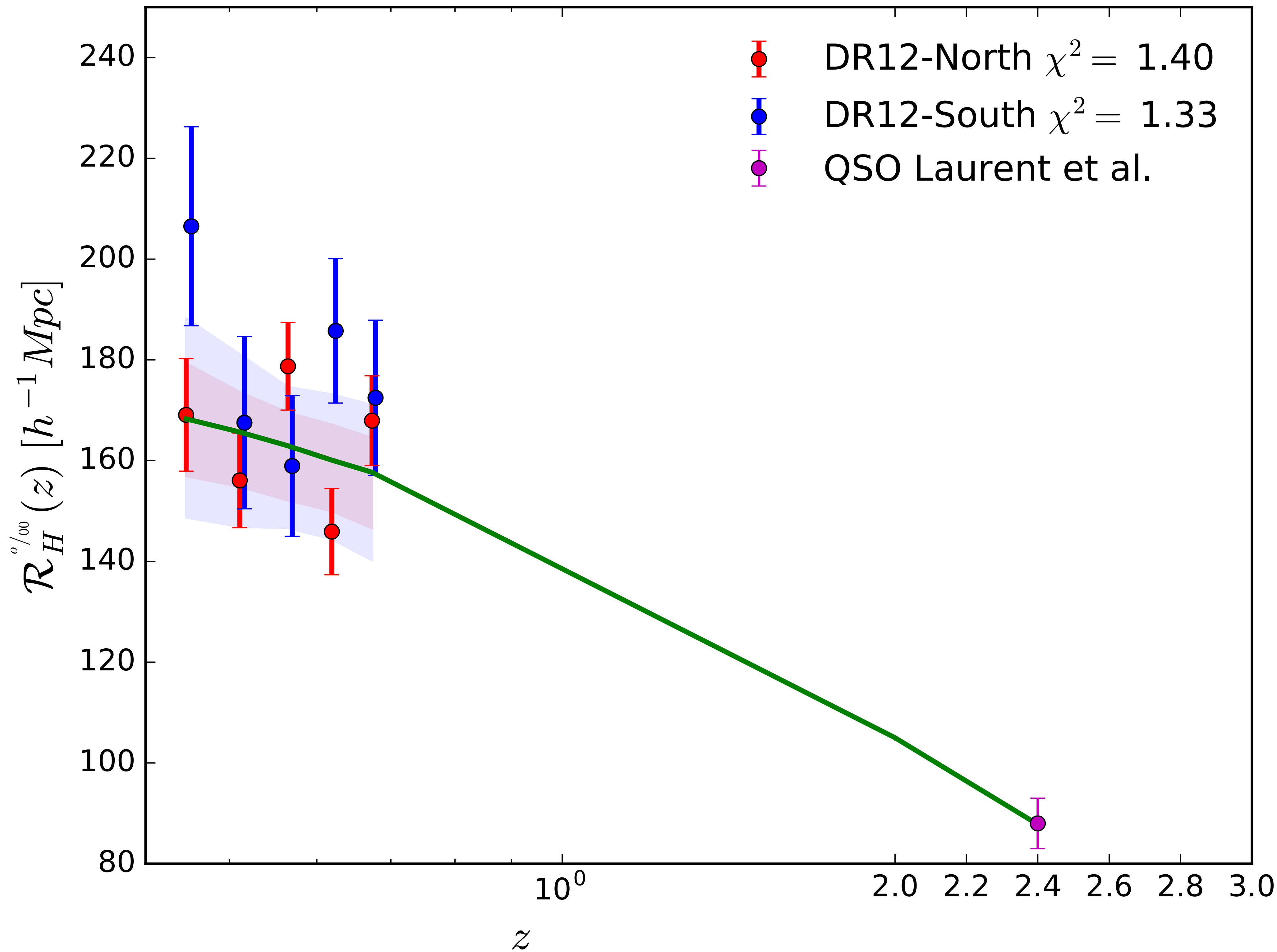


Blake et al. 2006 Fitting Formula expand in 1st order

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

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

Homogeneity Scale at 1‰



Clustering Estimators

2pt Correlation Function

$$dN(\vec{r}) = \bar{\rho}\,[1 + \xi(\vec{r})]\,d^3r$$

Optimal Estimator
(Landy & Szalay 1993)

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

Homogeneity Estimators

Scaled Counts-In-Spheres

$$\mathcal{N}(<r) = \frac{N_{DATA}(<r)}{N_{RAND}(<r)} = 1 + \frac{3}{r^3}\int_0^r \xi_{ls}(s)s^2 ds$$

Fractal Dimension

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

Optimal Homogeneity Scale Estimator

- Scaled Counts in Sphere

$$\mathcal{N}(<r) := \frac{N_g(<r)}{N_{rand}(<r)}$$

- Scaled Counts in Sphere and 2pt Correlation

$$\mathcal{N}_g(<r) = \frac{3}{4\pi r^3} \int_0^r \left[1 + b^2 \xi(s)\right] 4\pi s^2 ds$$

- Unbiased Scaled Count-in-Spheres

$$\mathcal{N}_m(<r) = \frac{\mathcal{N}_g(<r) - 1}{bias^2} + 1$$

- Fractal Correlation Dimension

$$D_2^m(r) = 3 + \frac{d\ \ln}{d\ \ln r} \mathcal{N}_m(<r)$$

- Homogeneity Scale

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

Homogeneity Scale Estimator

Theoretical Prediction:

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

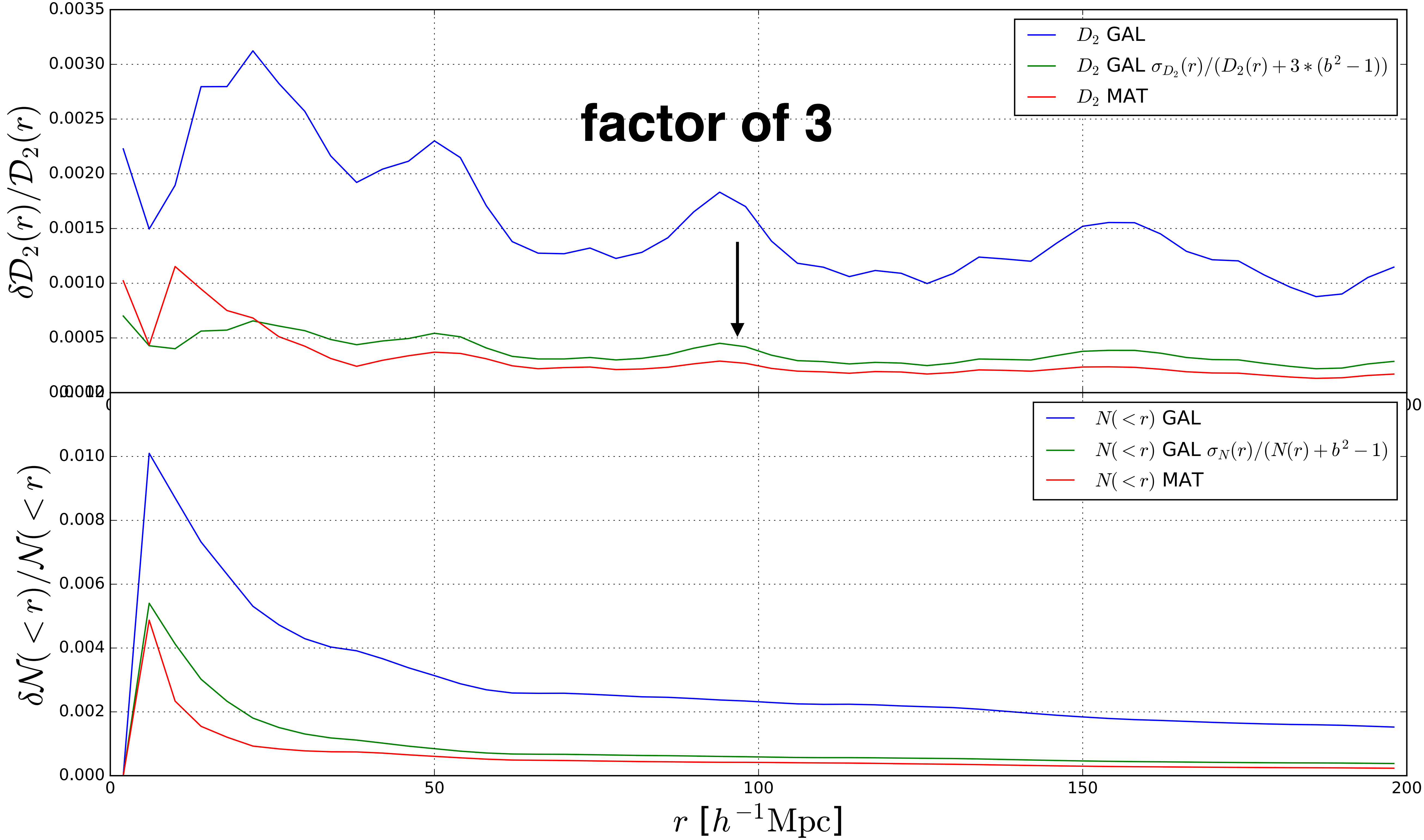
Optimal Estimator:

$$\mathcal{D}_2^{ls}(r) = f[\xi_{ls}](r)$$

Precision Estimator:

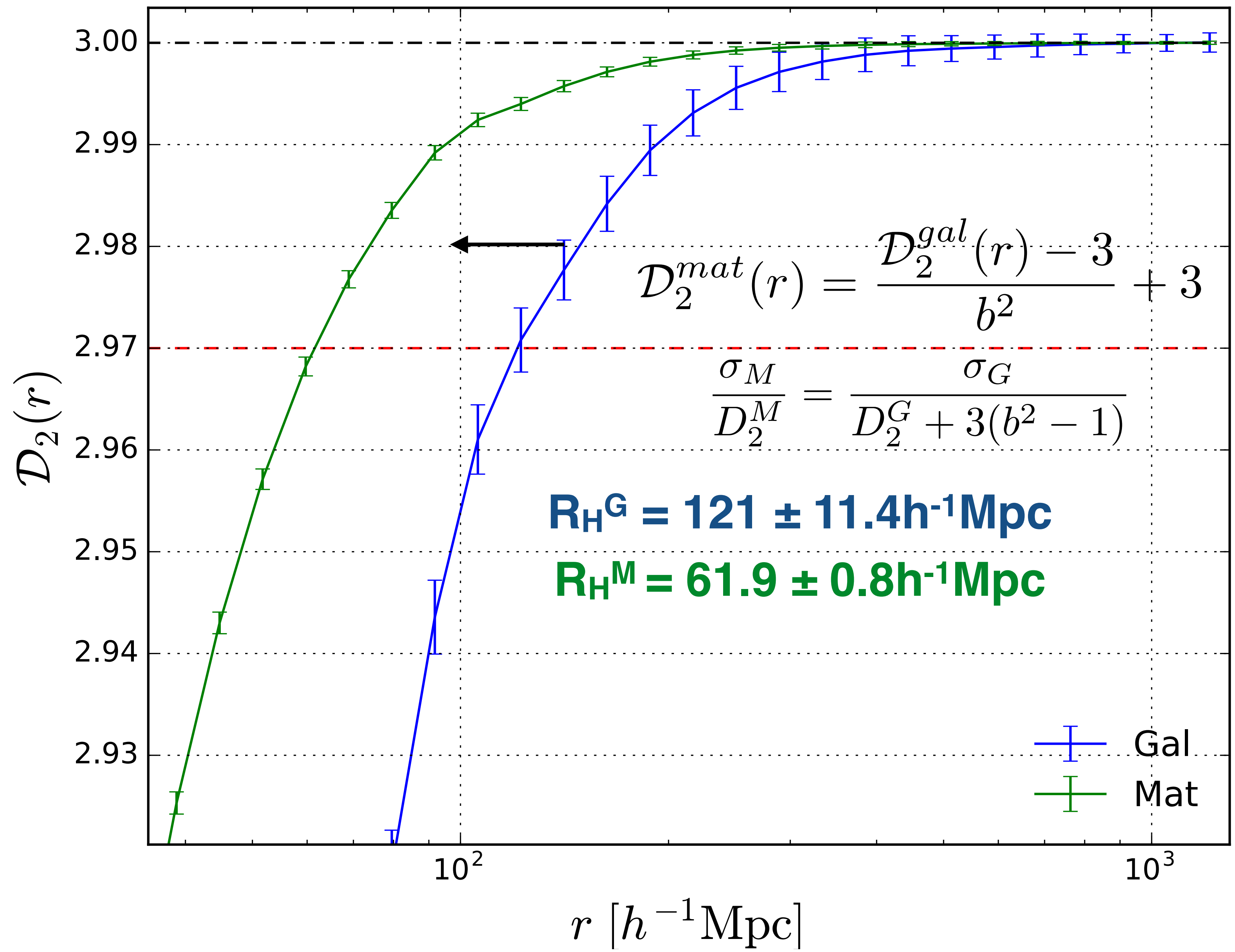
$$\frac{\sigma_M}{D_2^M} = \frac{\sigma_G}{D_2^G + 3(b^2 - 1)}$$

Estimator - Precision

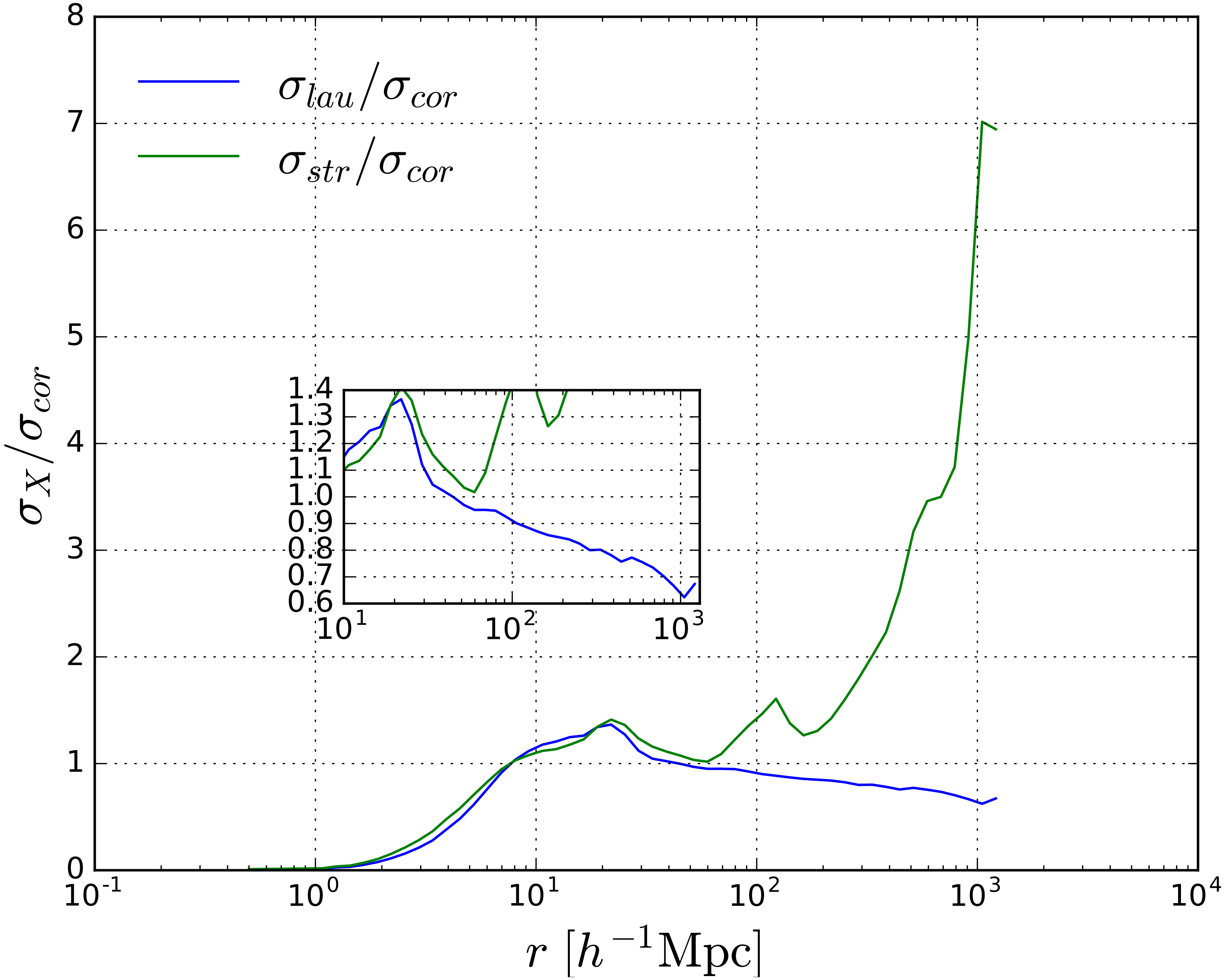


Increase of precision: Smaller Scales

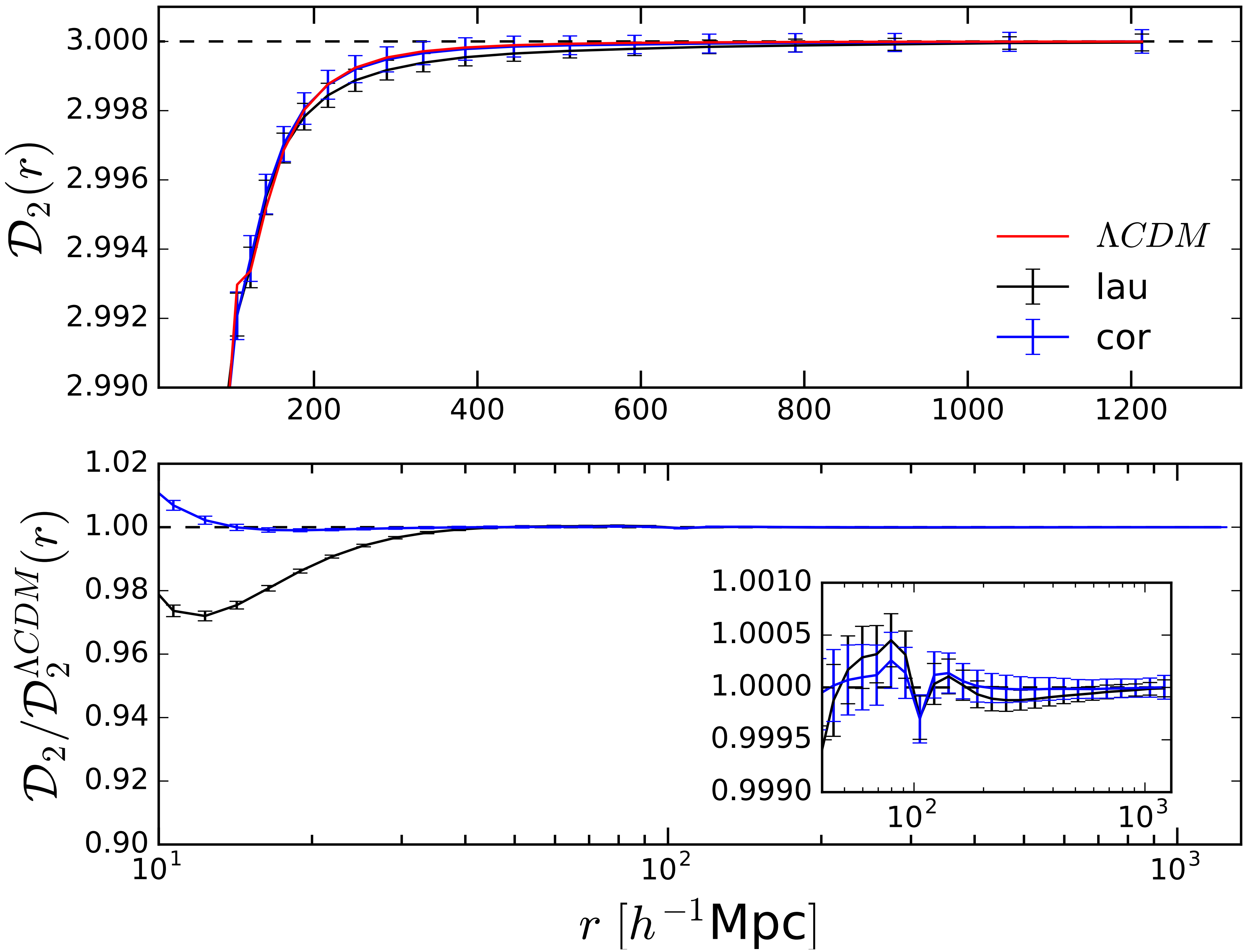
Matter **<- - -** **Galaxies**



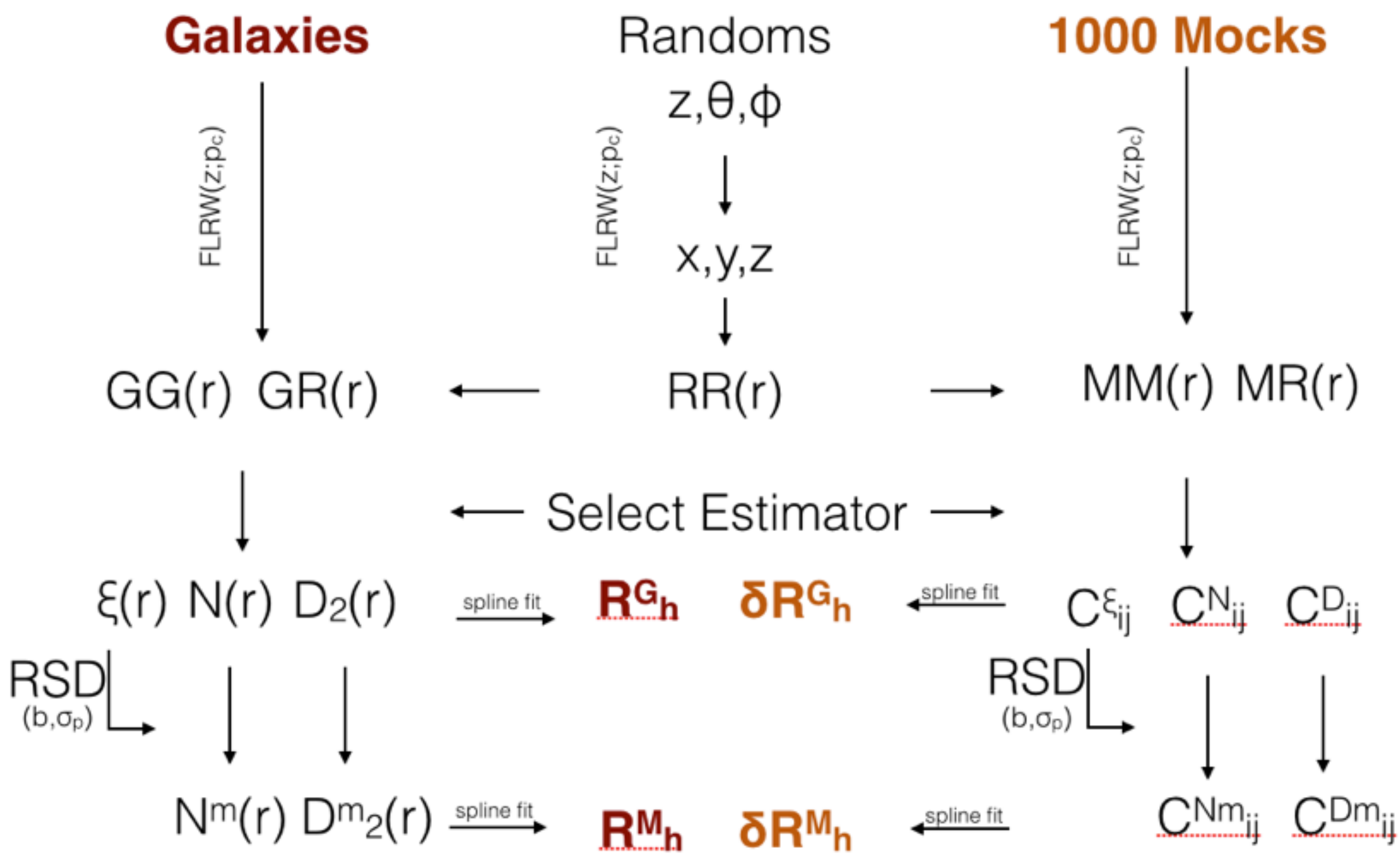
Estimator - selection



Estimator - selection

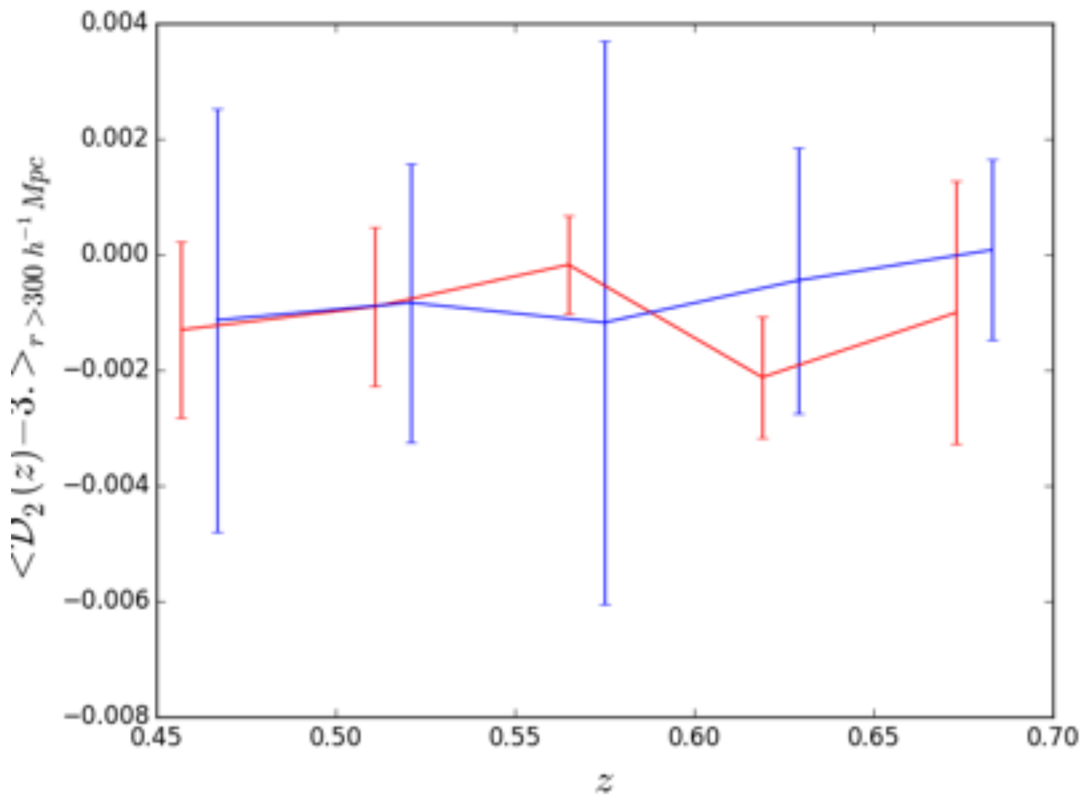


Algorithm Scheme

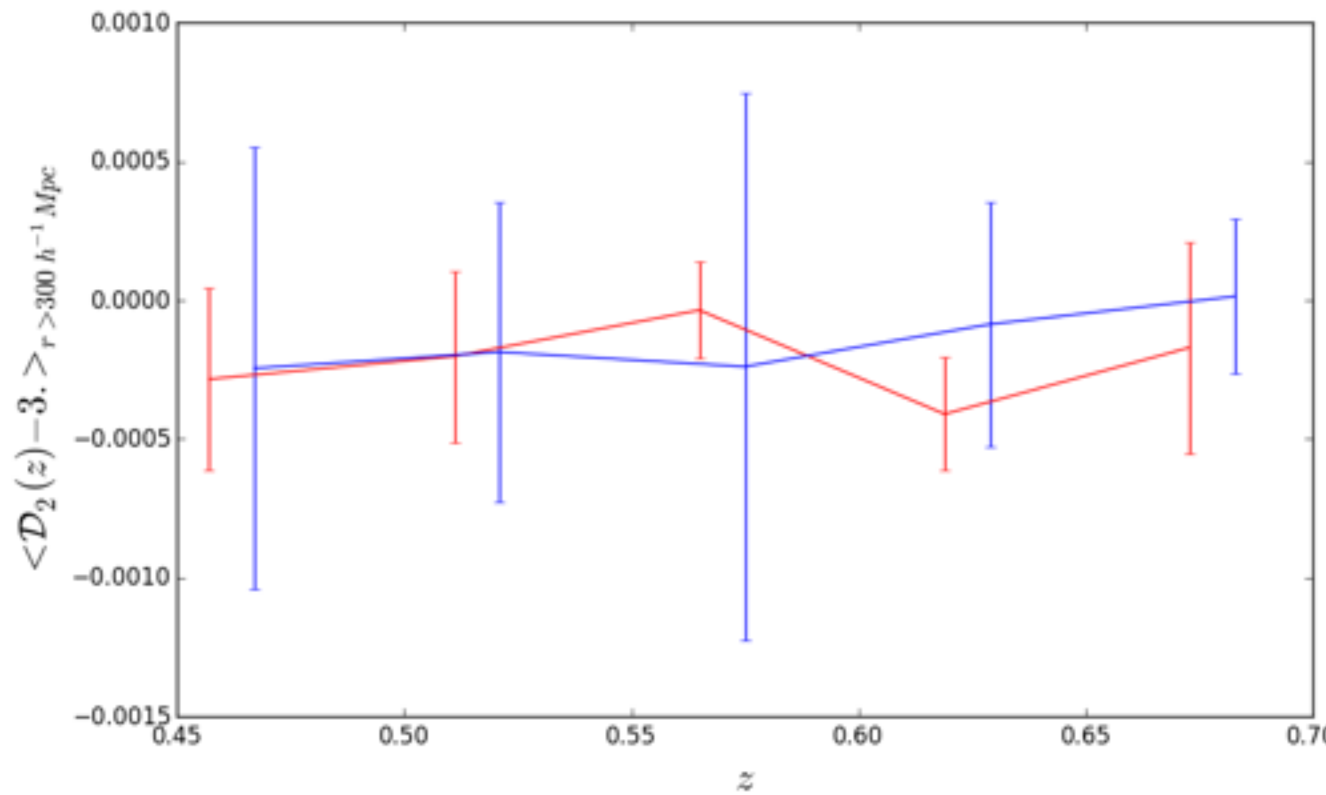


Consistency with 3
r>300h⁻¹Mpc

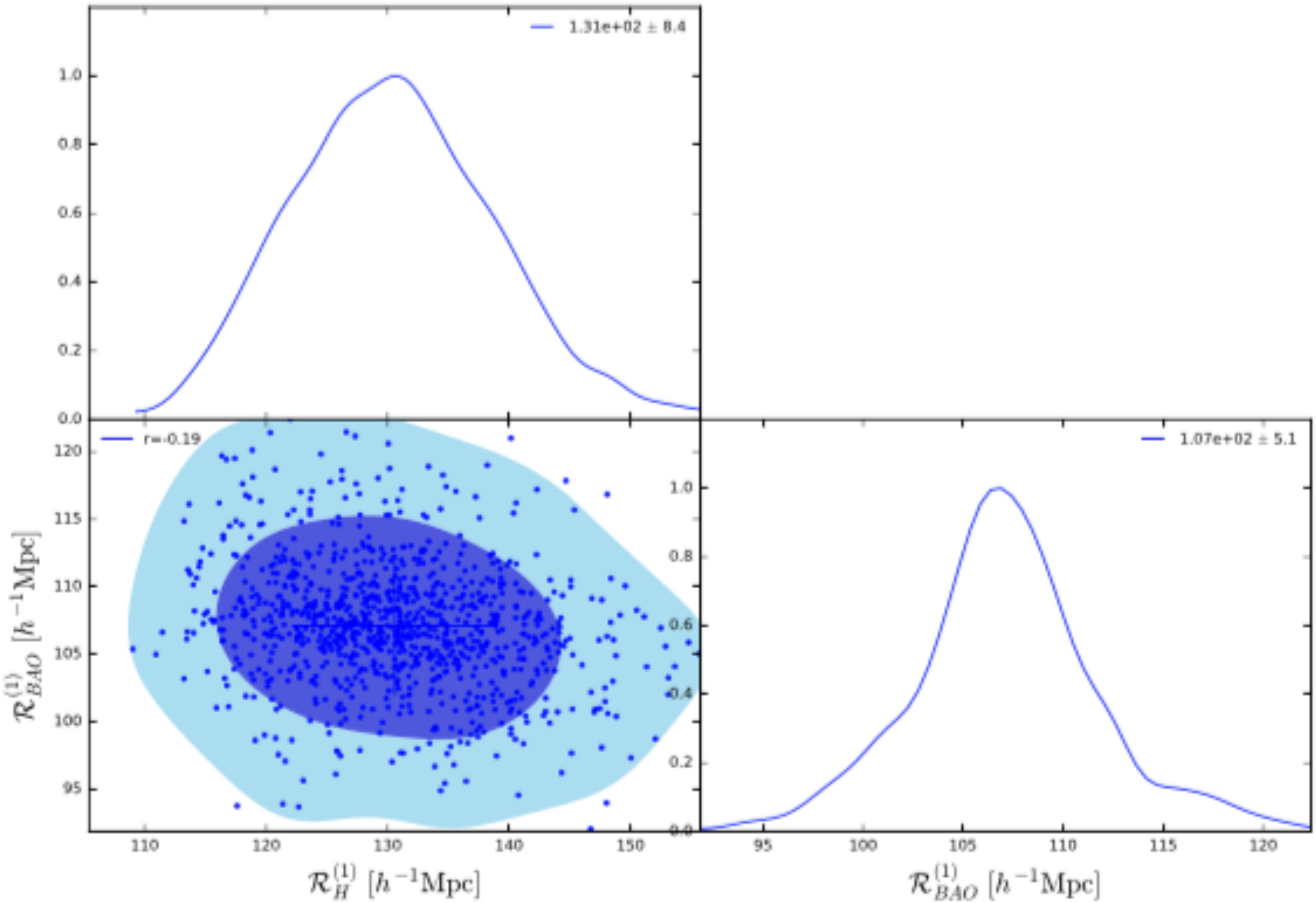
Gal ~ 2%



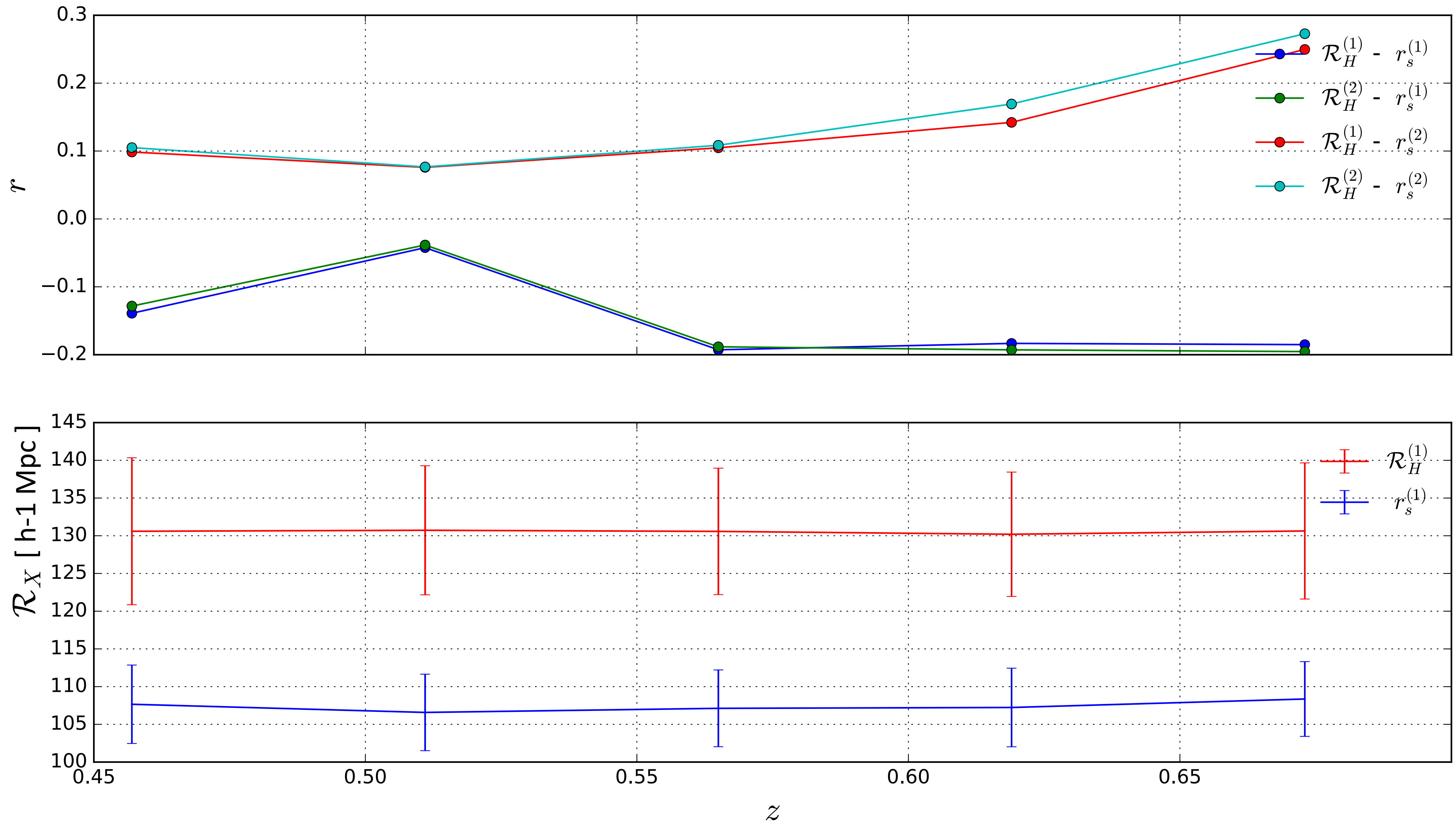
Mat ~ 0.5%



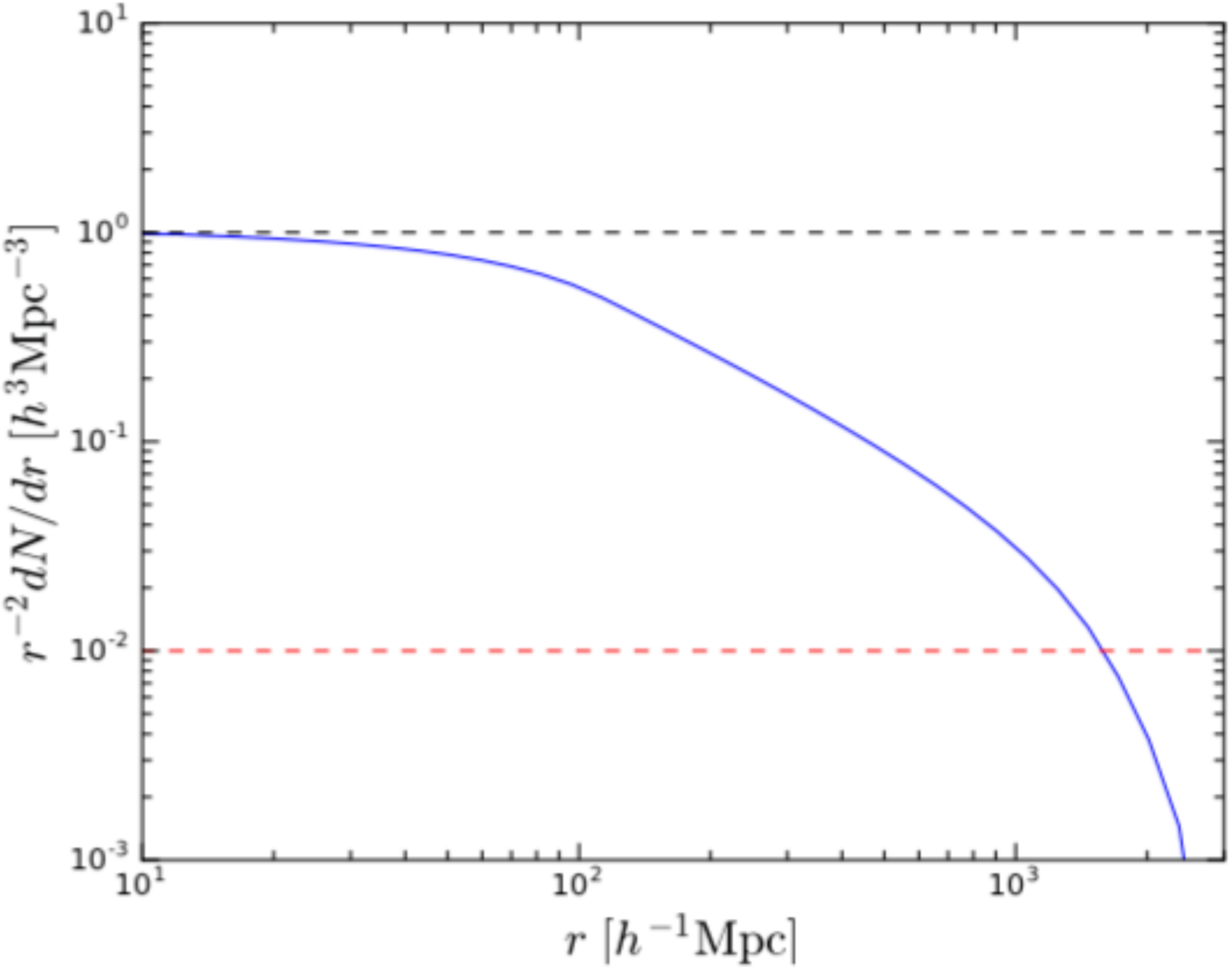
Correlation R_H - R_{BAO} ~ 20%



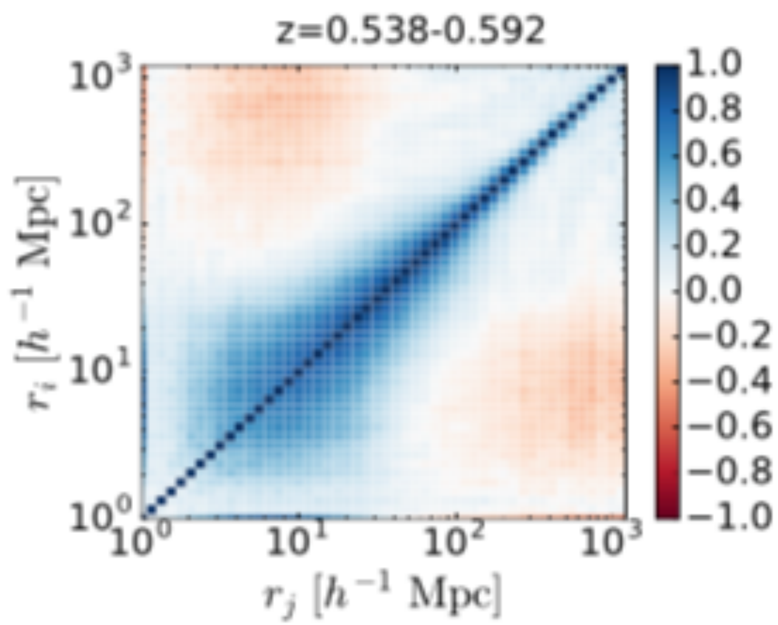
Correlation R_H - R_{BAO} ~20%



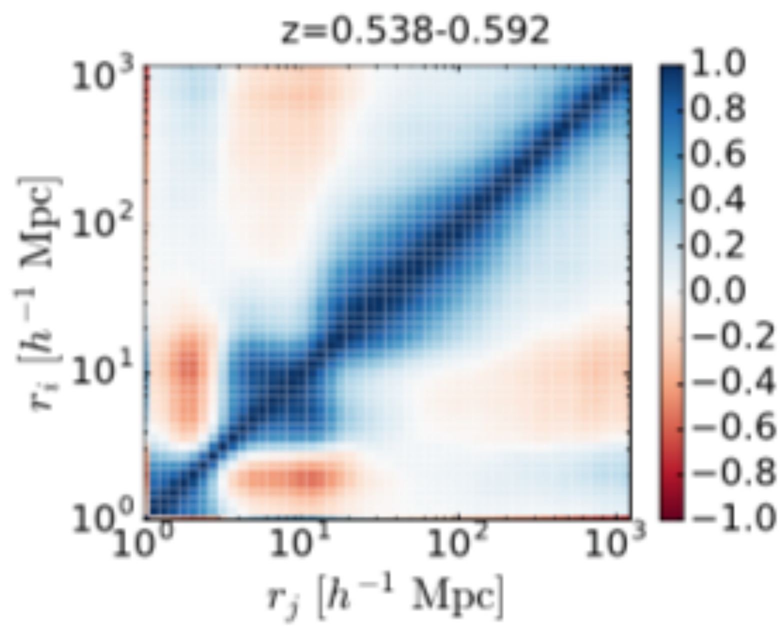
r-Range Selection (1% of total density)



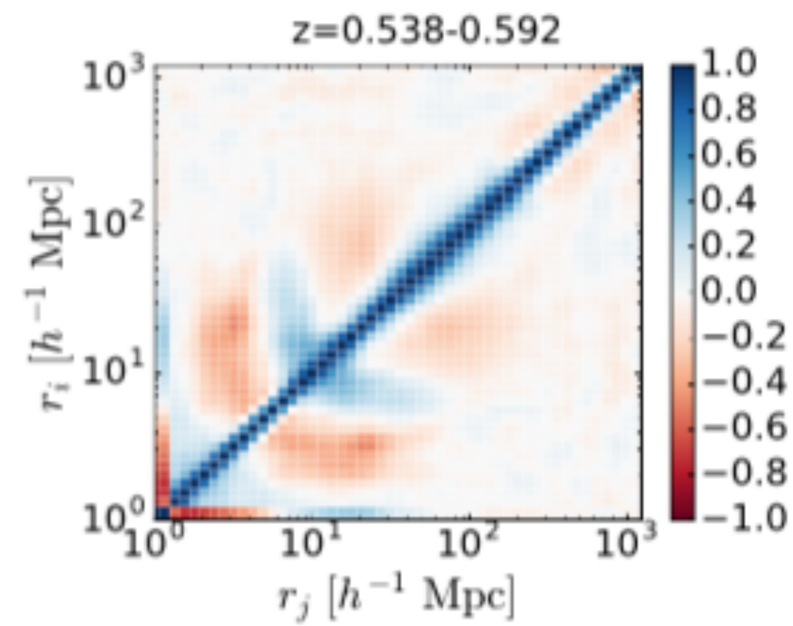
Correlation Matrices



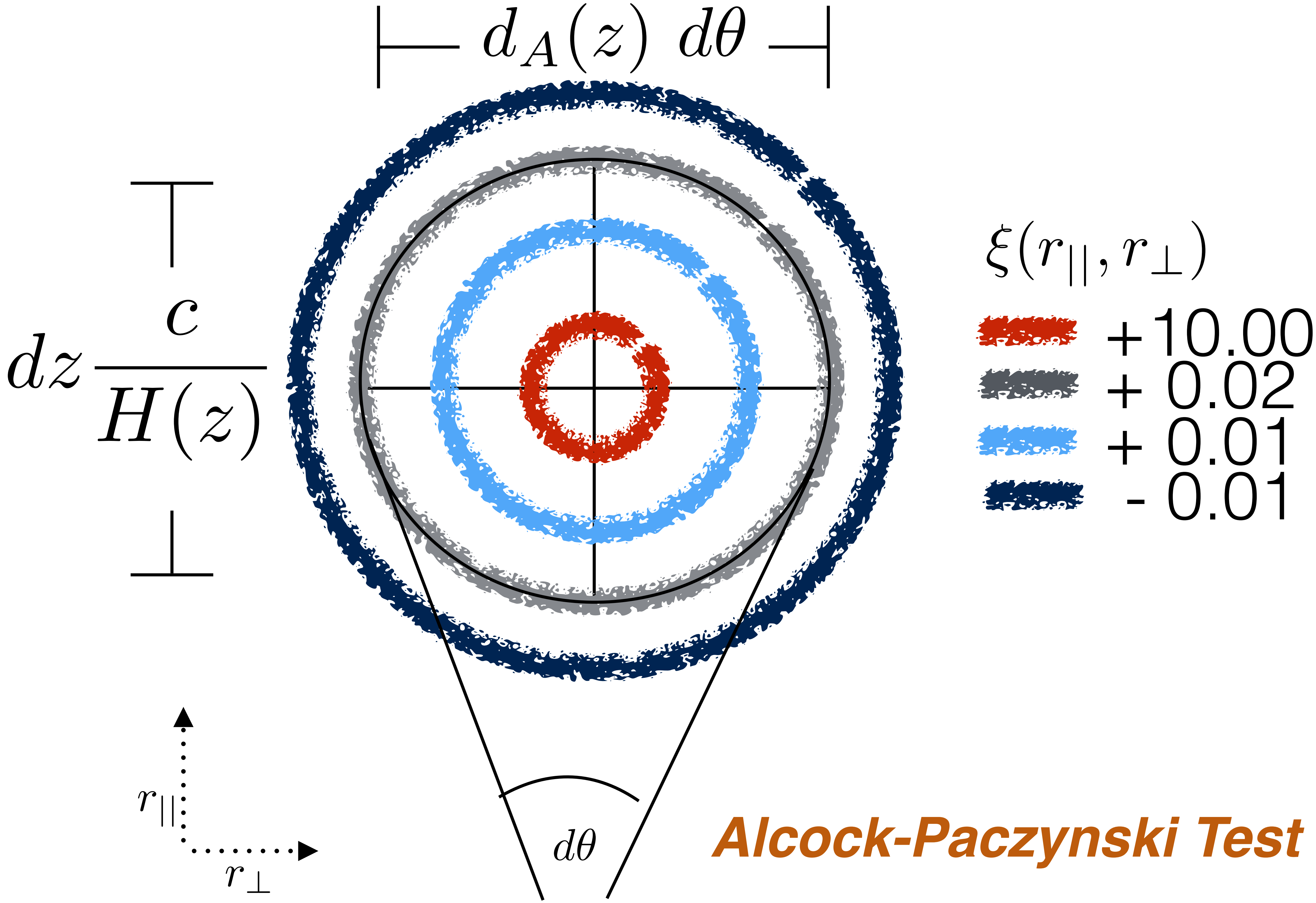
ξ(r)



N(<r)



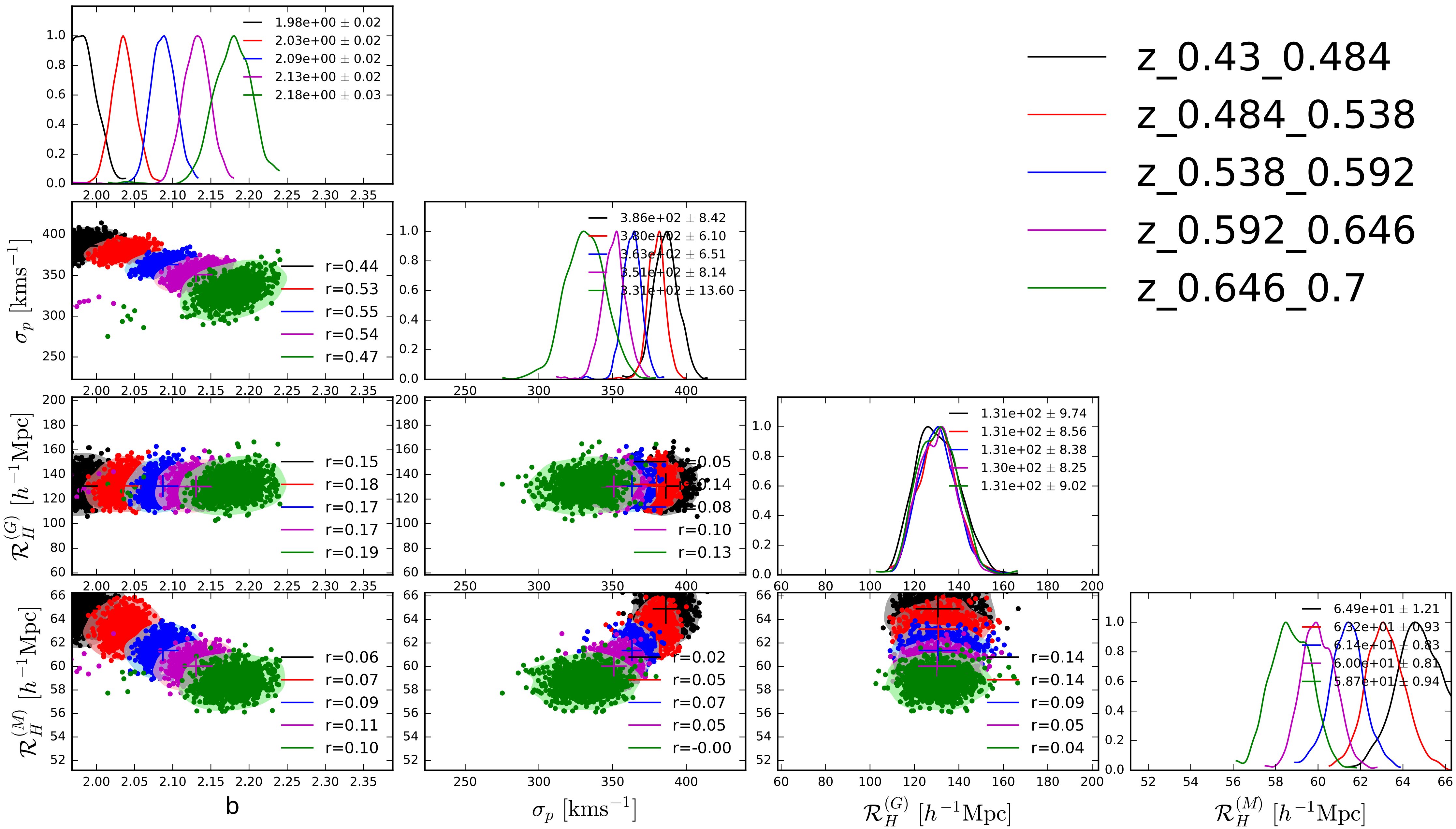
$D_2(r)$



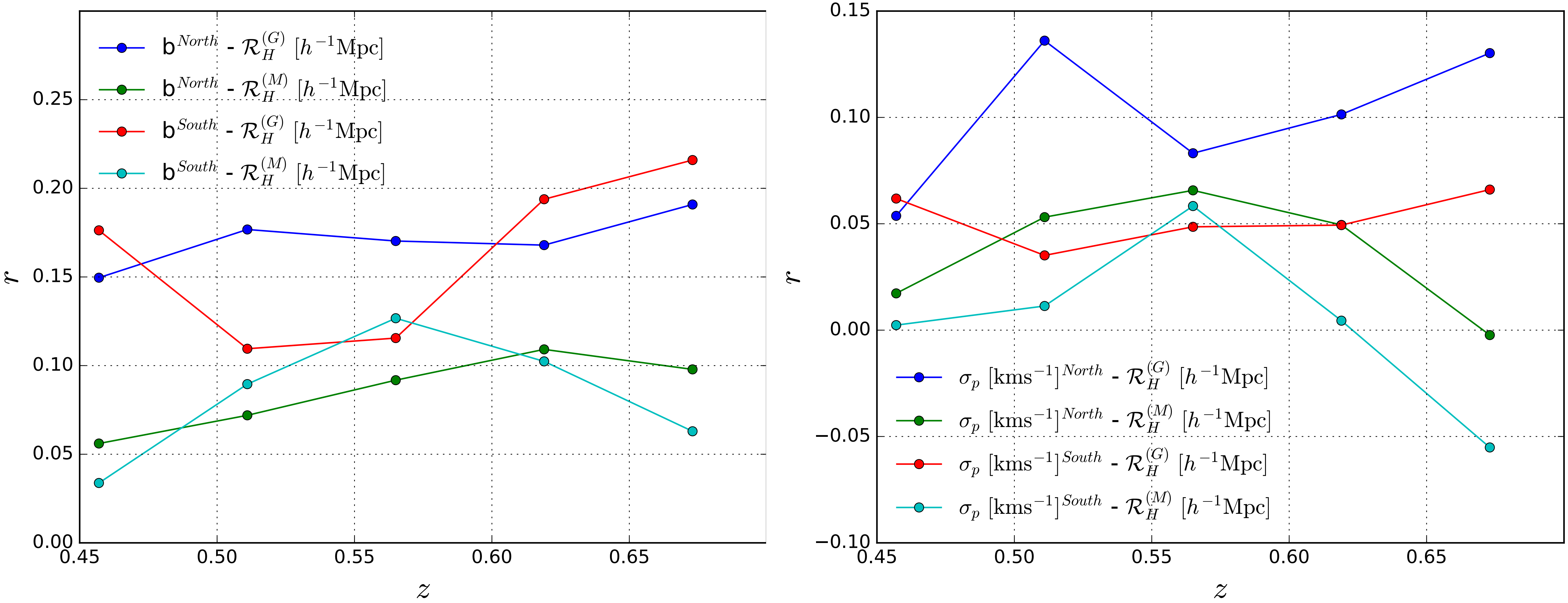
Alcock-Paczynski Test

bias - R_H relation

North



bias - R_H relation



Sensitivity RH

Power Spectrum

$$\delta P \propto \frac{\sqrt{\sigma_z}}{\sqrt{V}} \left(P + \frac{1}{n_{tot}} \right)$$

Fractal Dimension

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

Sensitivity Fractal Dimension

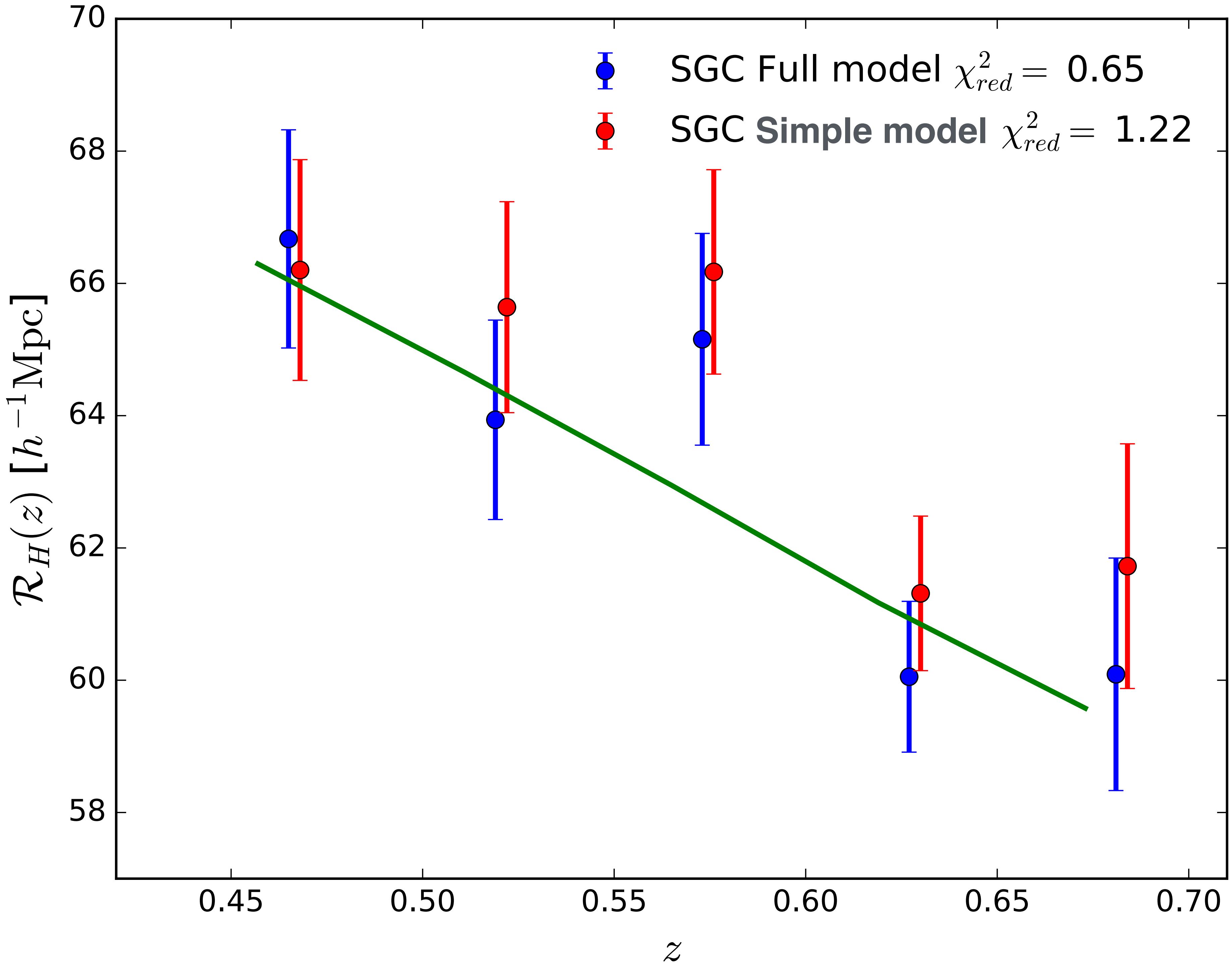
$$\delta \mathcal{D}_2(r) \propto \frac{\sqrt{\sigma_z}}{\sqrt{V}} \left[3 + \frac{d\ \ln}{d\ \ln\ r} \left(1 + \frac{1}{r^3} \int_0^r \int_{-\infty}^{+\infty} \left[P(k) + \frac{1}{n_{tot}} \right] e^{-iks} dk\ s^2 ds \right) \right]$$

$$\int_{-\infty}^{+\infty} dk e^{-iks} = 2\pi\delta(s) \qquad \int_{-\infty}^{+\infty} \delta(s) s^2 ds = 0$$

↓

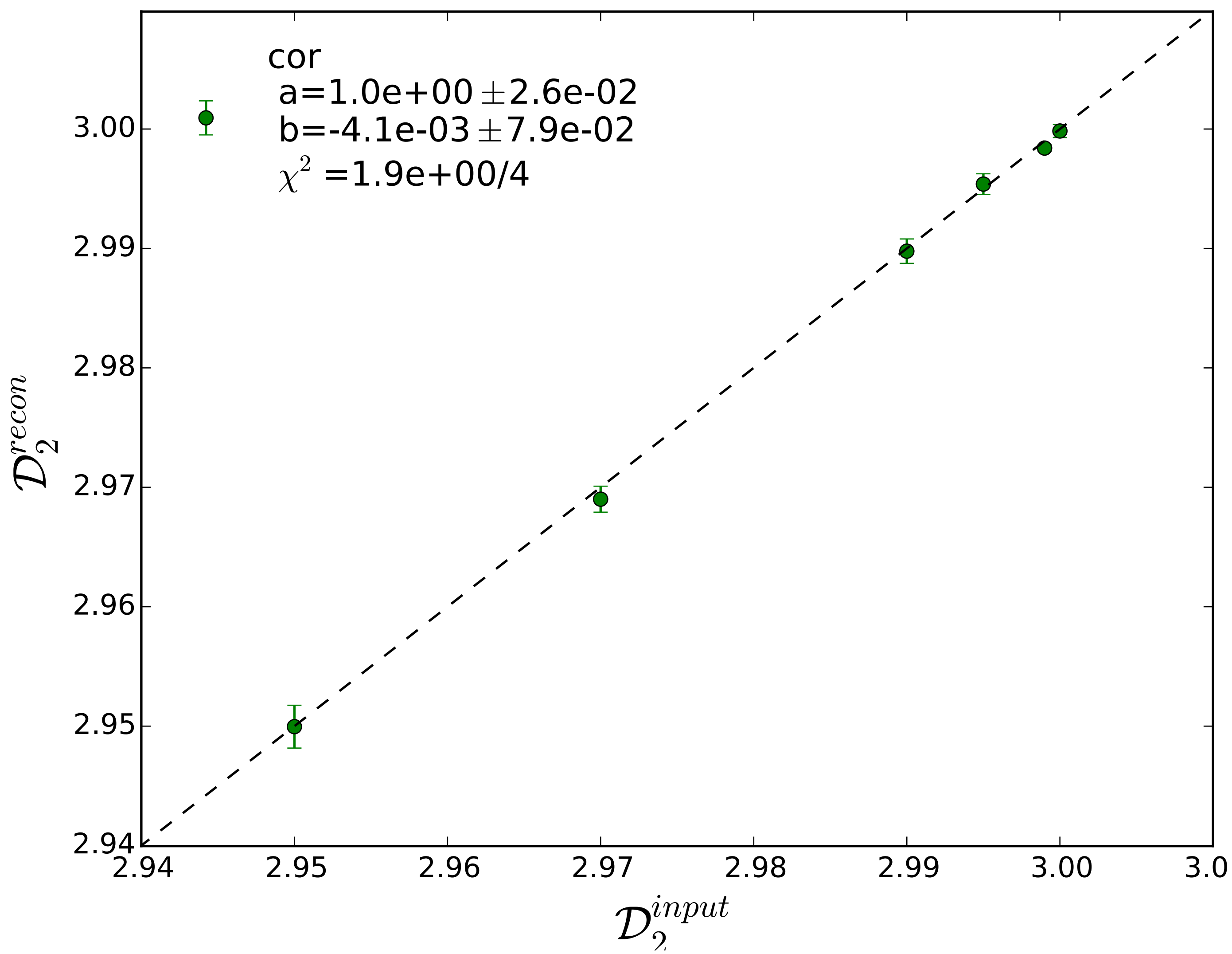
$$\delta \mathcal{D}_2(r) \propto \frac{\sqrt{\sigma_z}}{\sqrt{V}} \mathcal{D}_2(r)$$

Systematic1: <1% diff on choice of RSD



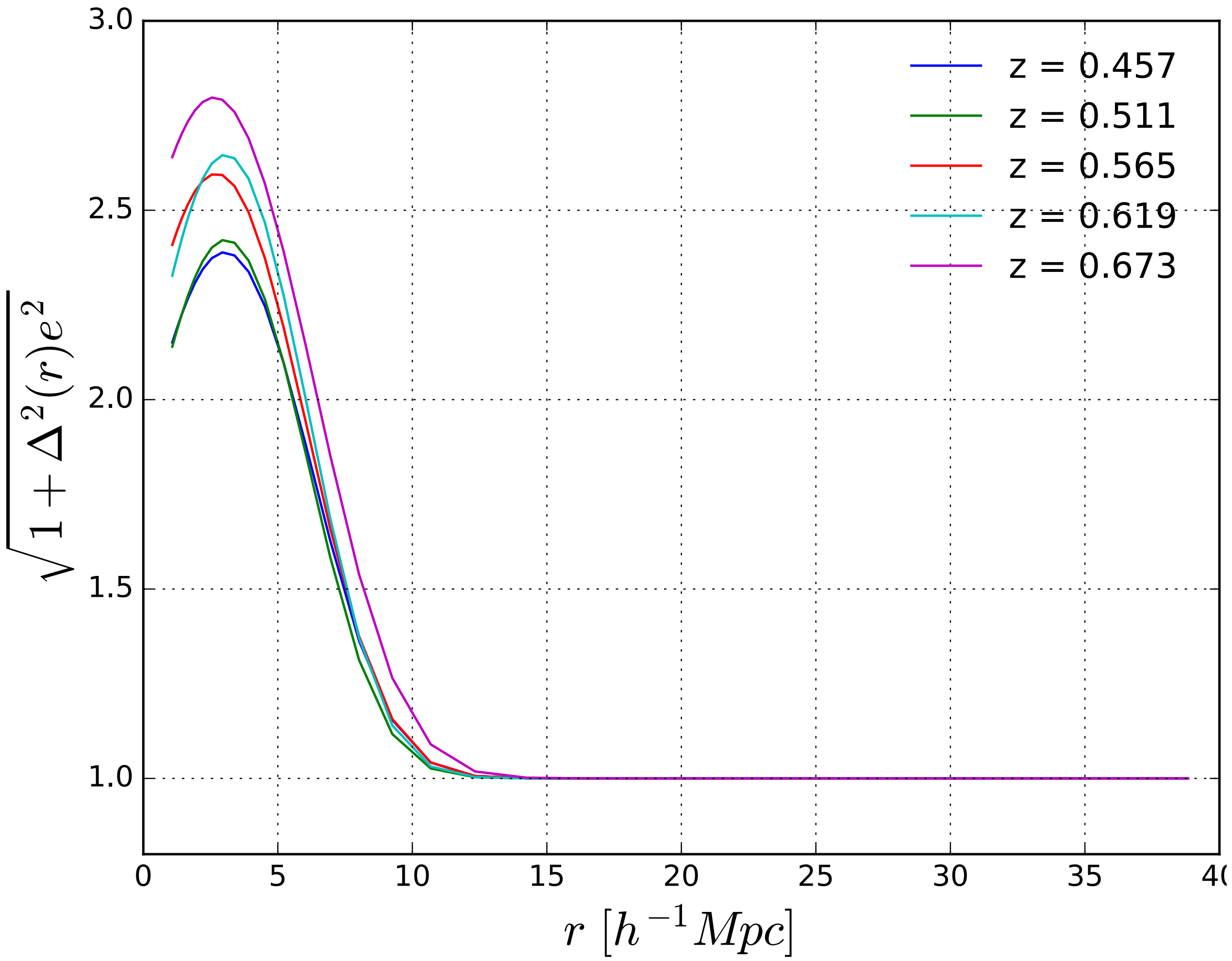
Systematic2: No bias from Analysis Pipeline

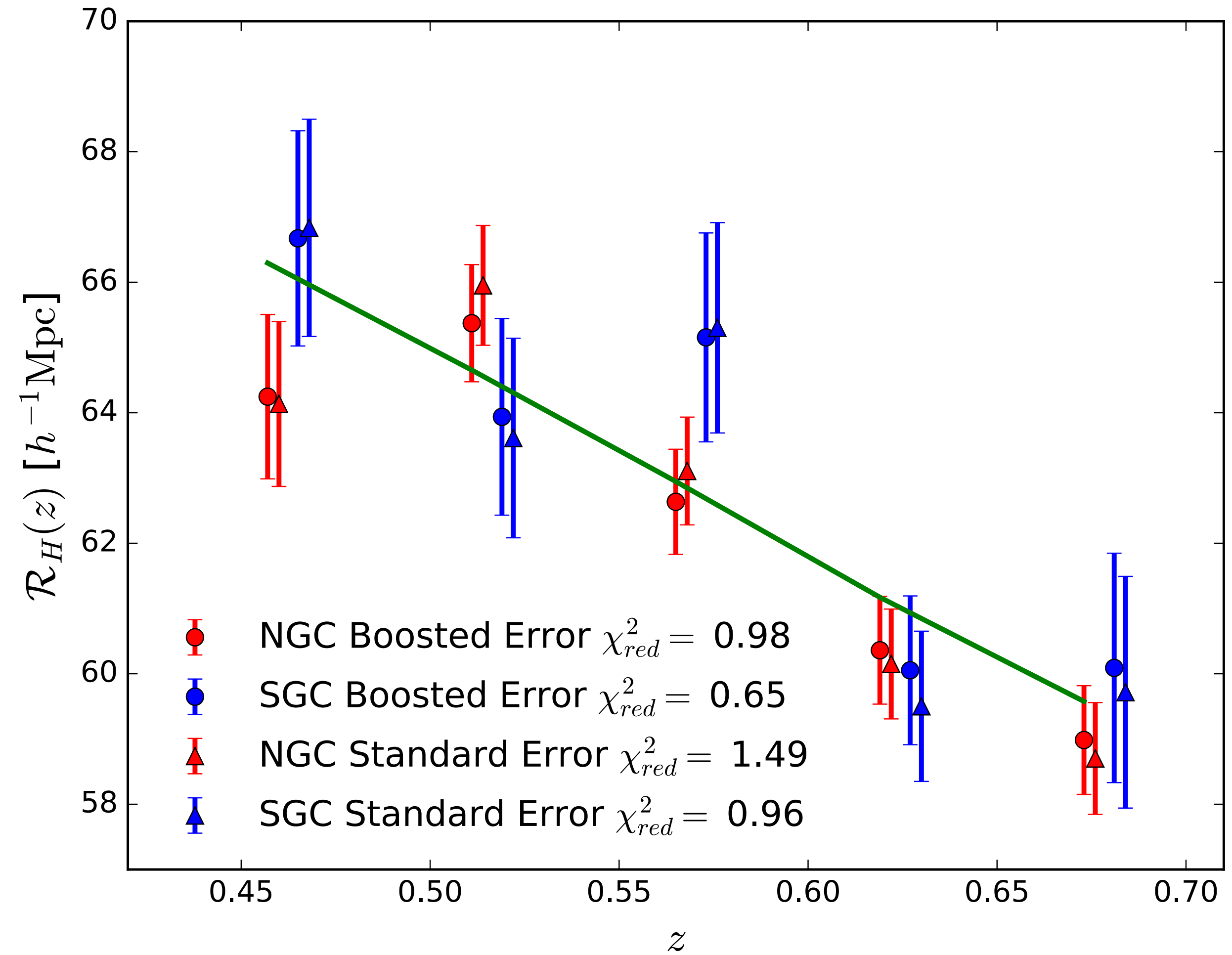
- Generate 500 Fractal Distr
  BOX: L ~ 4 Gpc
  9 iter { Divide in 8 sub boxes (L/2)
  Assign a surv.prob. ($p=2^{D2-3}$)
  Random Population (xyz)
- FLRW Reconstruction to (zθϕ)
- Redshift-RA-DEC cuts
- Reconstruct D_2^{recon} @ $r>15h^{-1}$Mpc



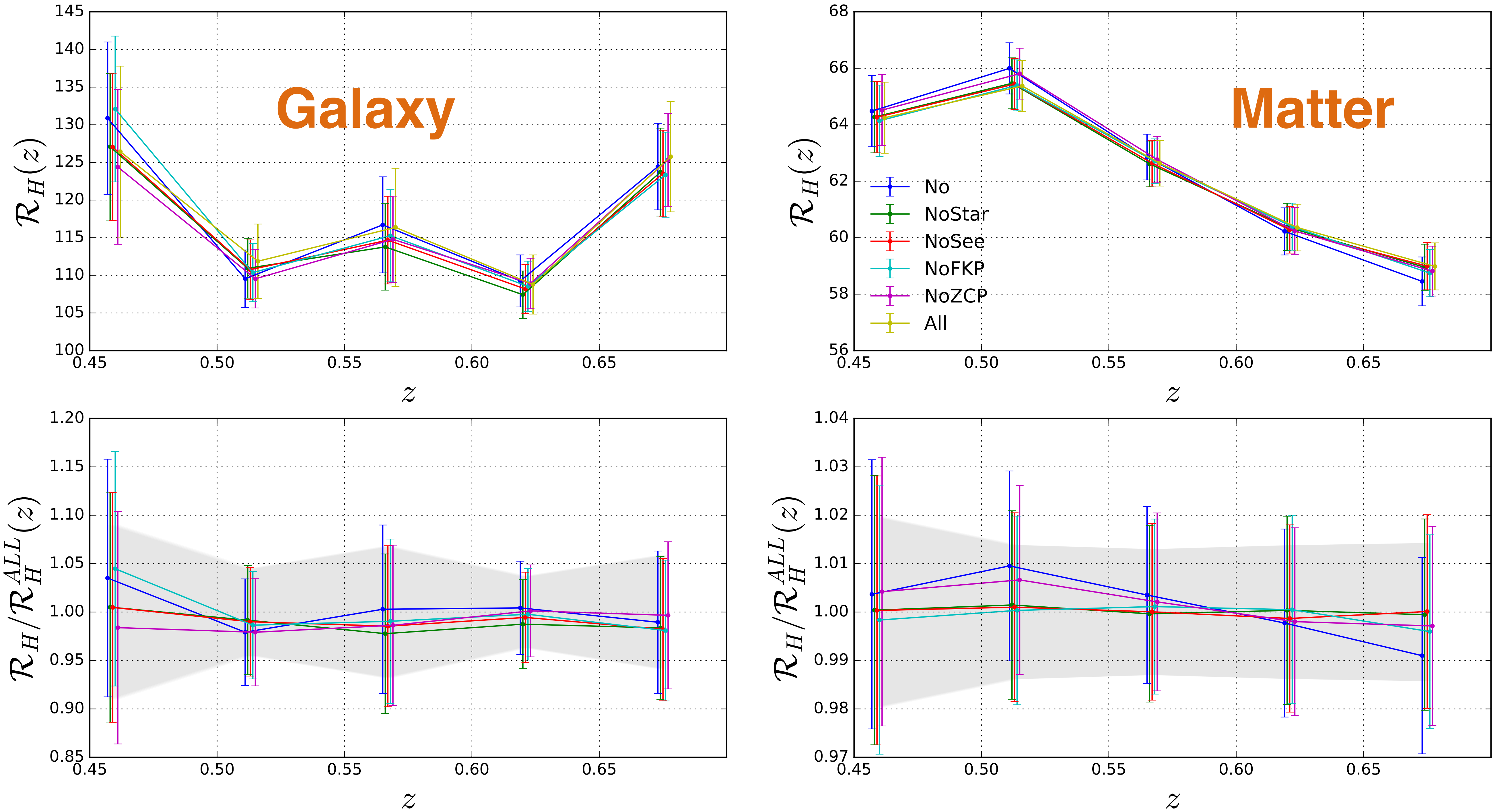
Help from P.Laurent

Systematic3: <1% diff on Boosting Error

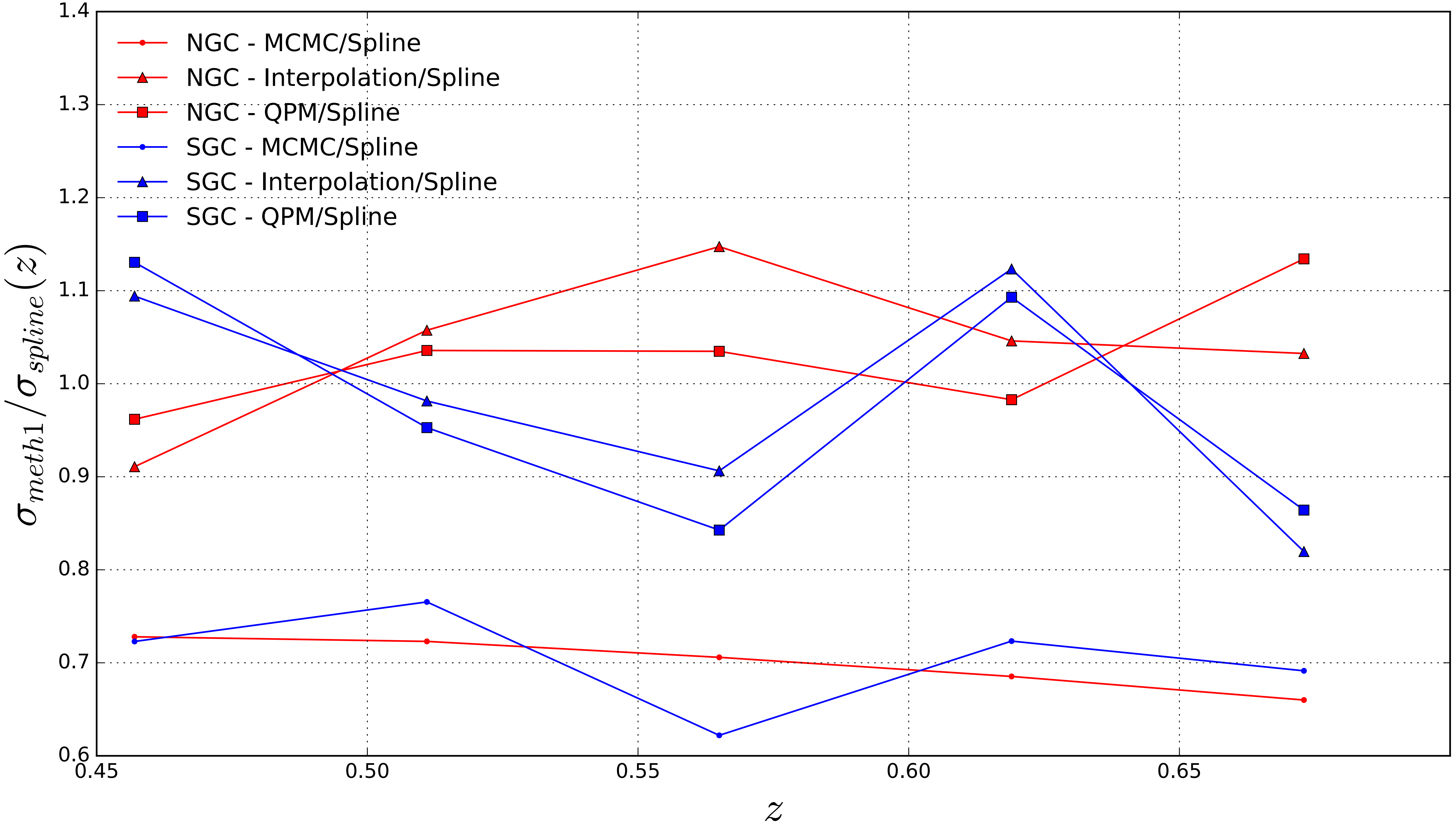




Systematic4: <1% diff from Weighing Scheme



Systematic5: Spline Error Robustness

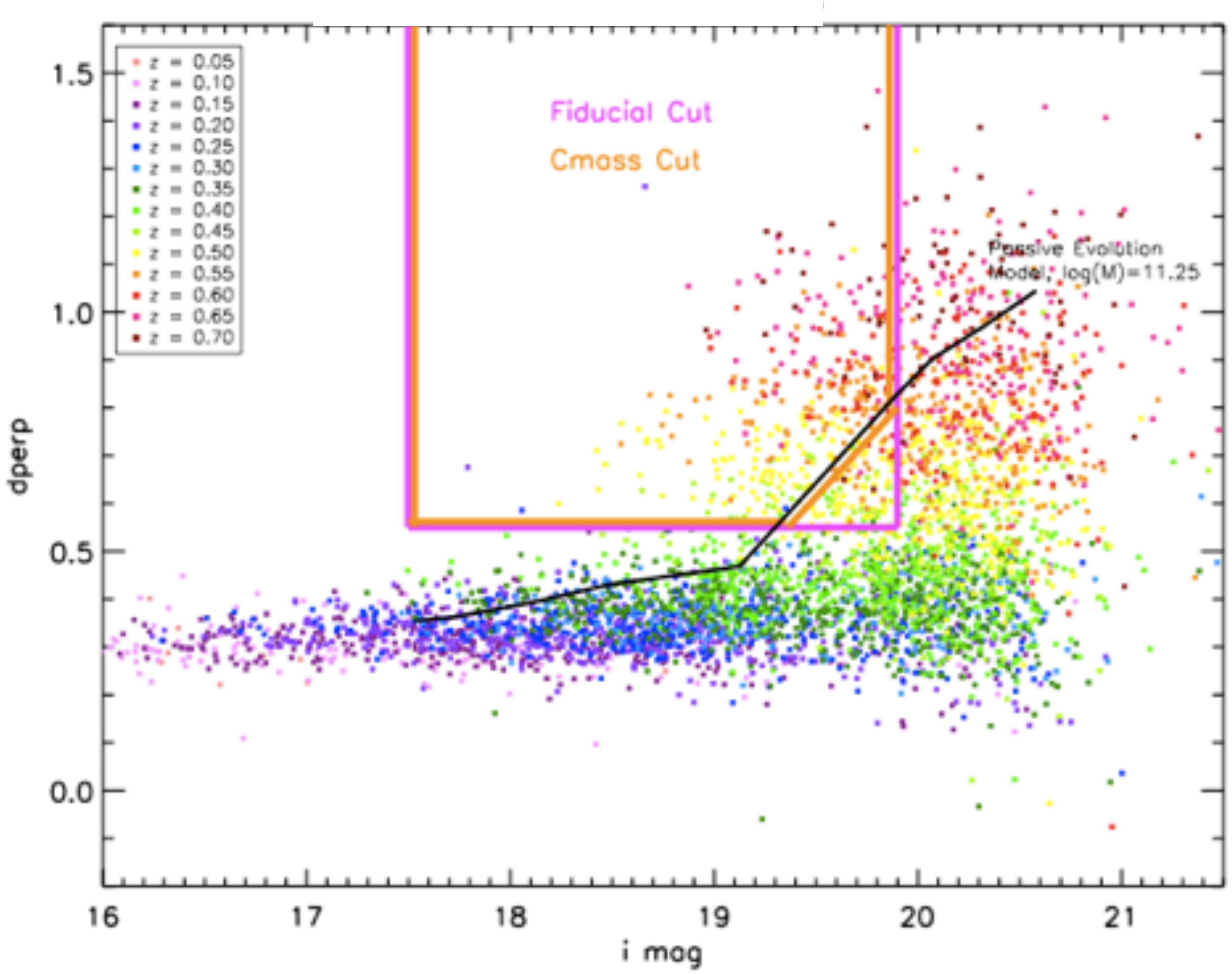


Why CMASS?

Sample Requirements:

- Uniform selection
- Time-invariant
- Mass-invariance

christy tremonti 2009

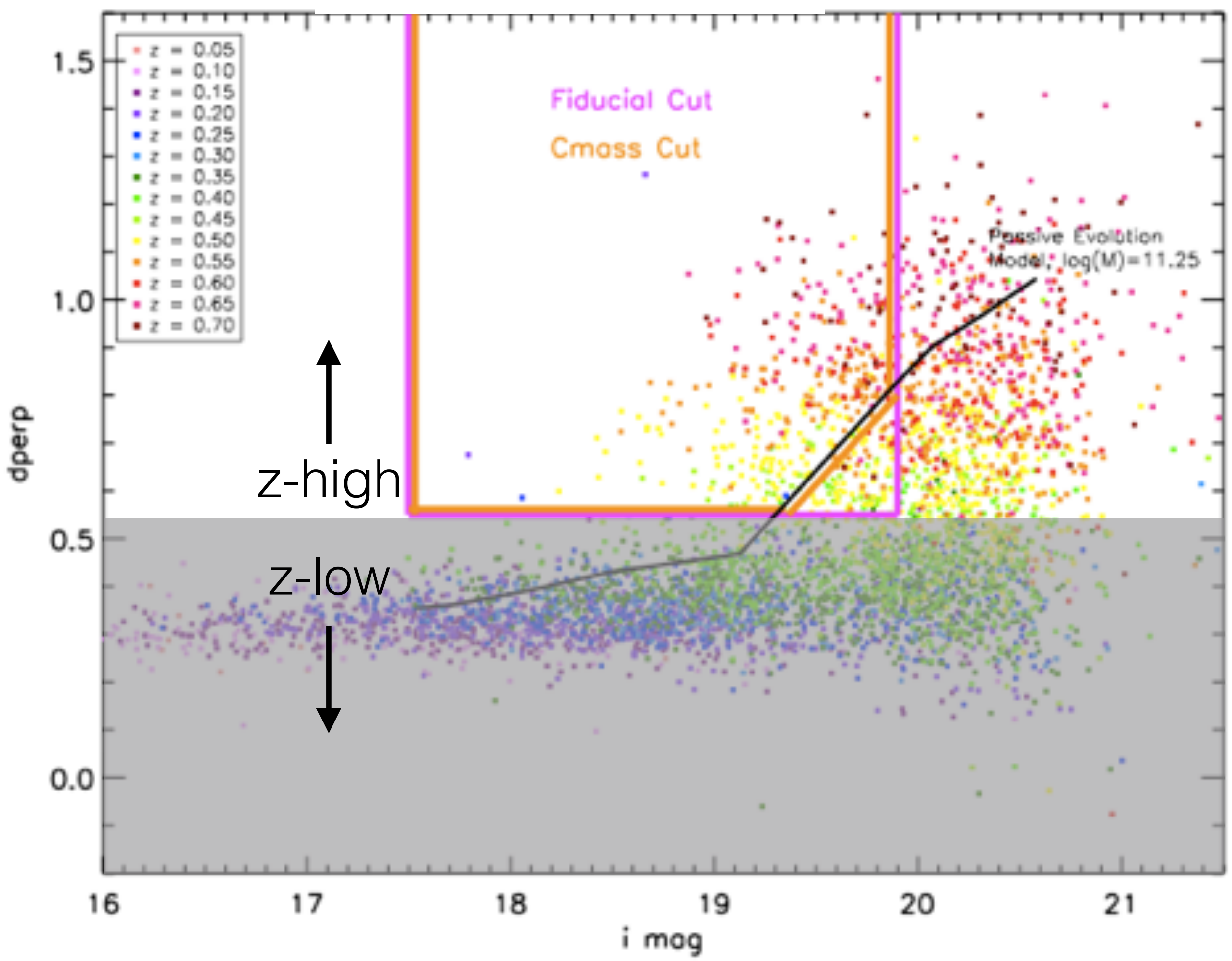


Why CMASS?

christy tremonti 2009

Sample Cuts:

- Redshift cut (0.43 < z <0.7)

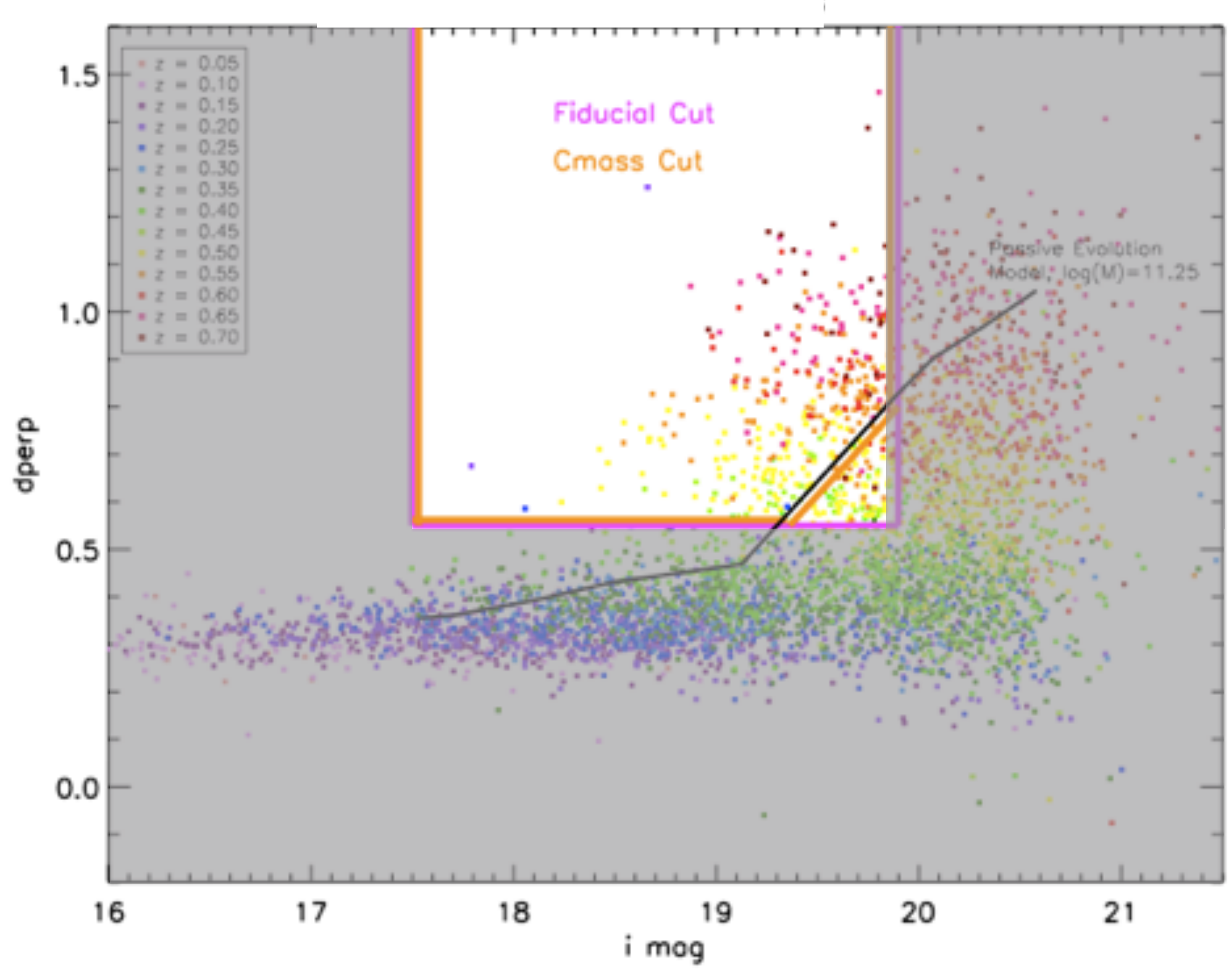


Why CMASS?

Sample Cuts:

- Redshift cut (0.43 < z <0.7)
- i magnitude cut
  Eliminate Faint-Bright

christy tremonti 2009

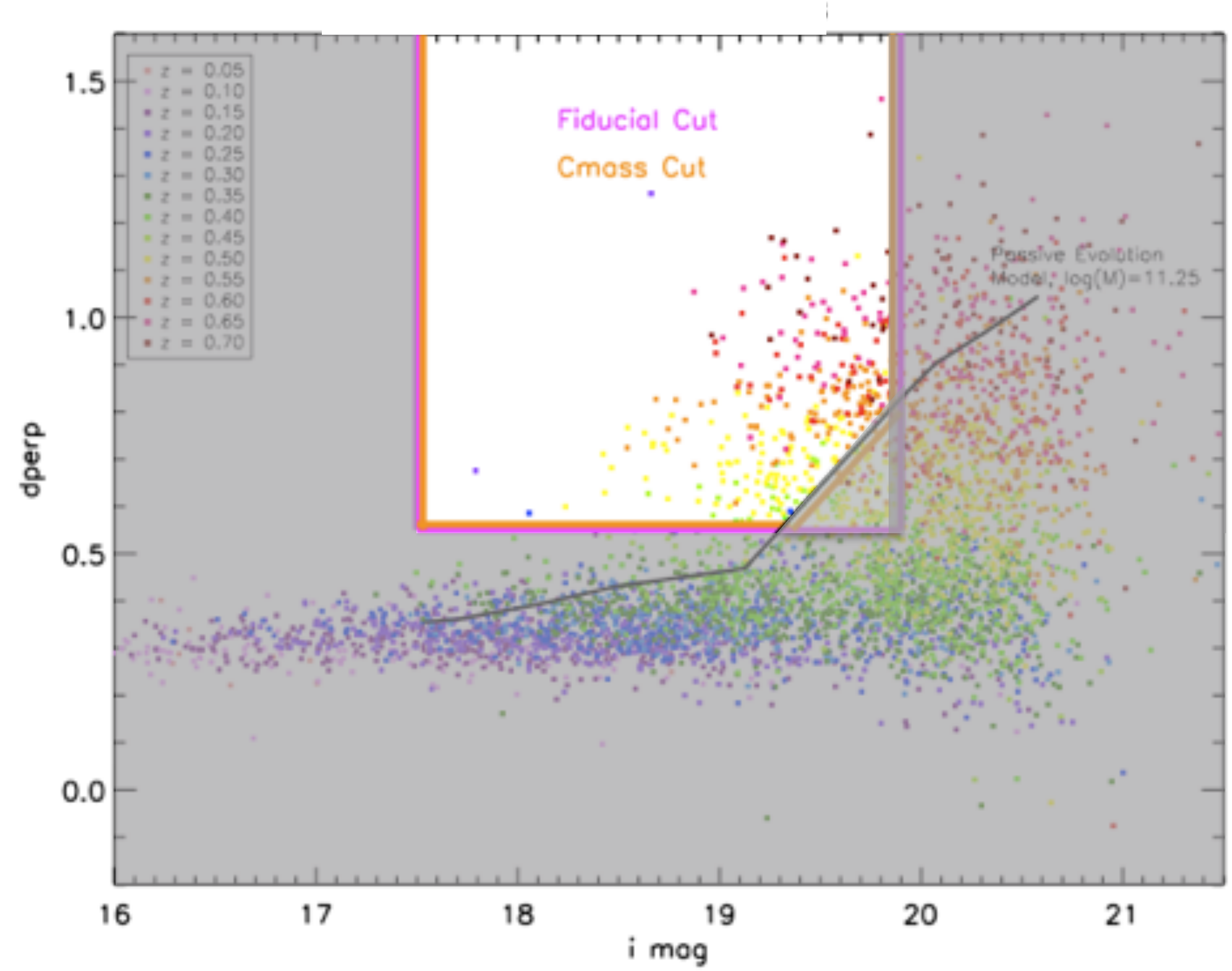


Why CMASS?

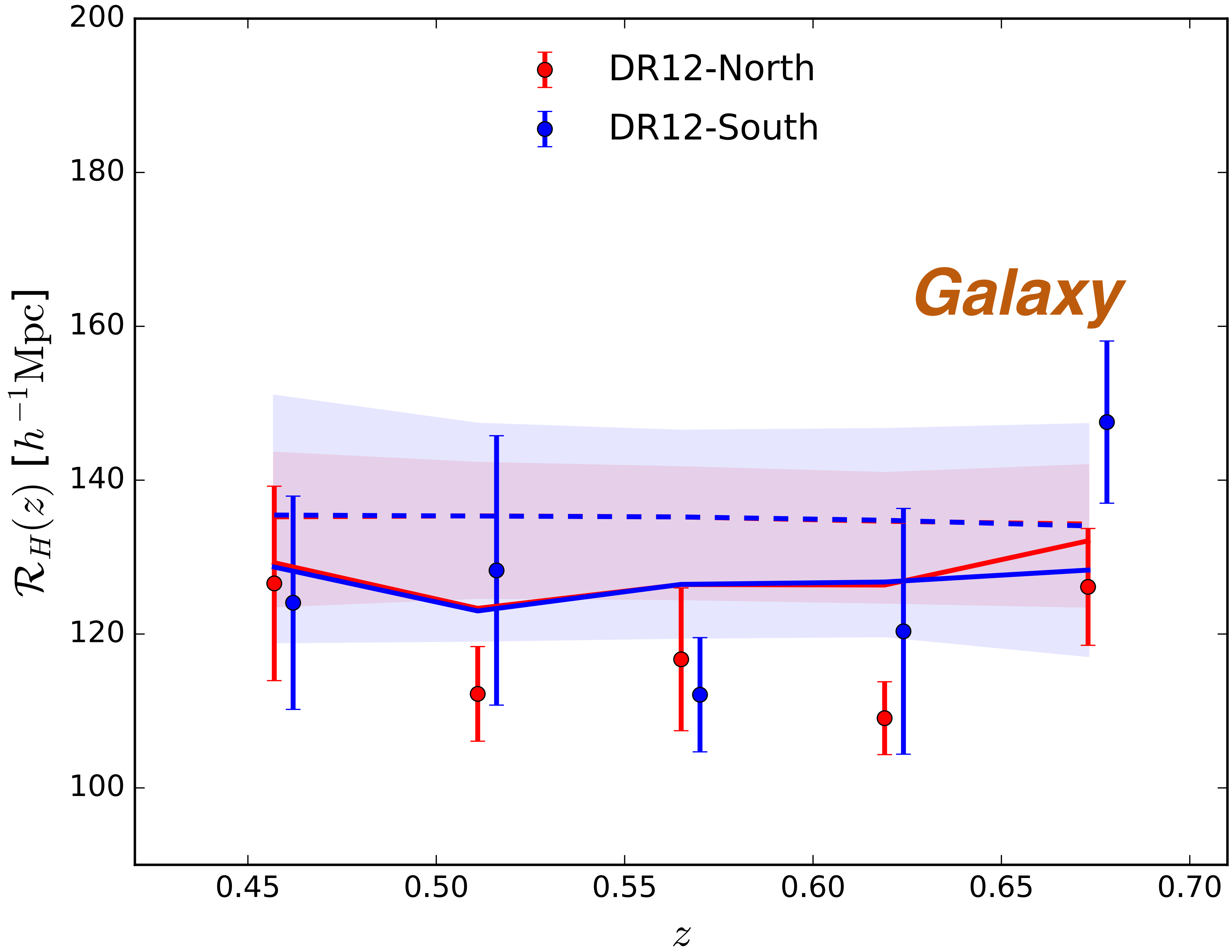
Sample Cuts:

- Redshift cut (0.43 < z <0.7)
- i magnitude cut
  Eliminate Faint-Bright
- constant-stellar-mass cut
  passively evolving galaxies

christy tremonti 2009



Homogeneity Scale



Galaxies: Biased Tracers

Redshift Space Distortions

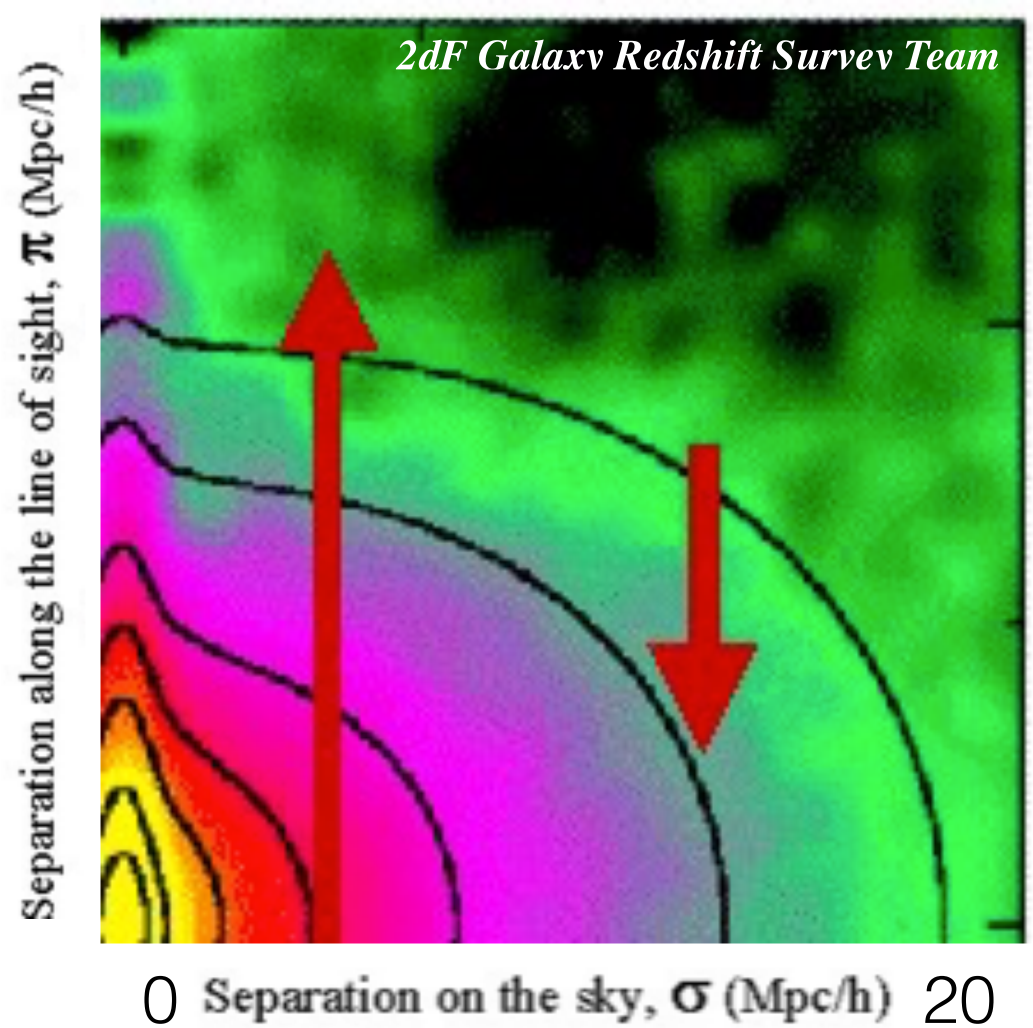
- Kaiser: r > 20 h^{-1}Mpc
  GR infall V_{grav} $K(\mu; f, b) = b^2(1 + \frac{f}{b}\mu^2)^2$

- FoG : r < 20 h^{-1}Mpc
  Peculiar Motions $S(k; \mu, \sigma_p) = exp(-\frac{1}{2}k^2\mu^2\sigma_p^2)$

$$P_g(k) = P_m(k)\int_0^1 d\mu K(\mu; f, b) S(k, \mu; \sigma_p)$$

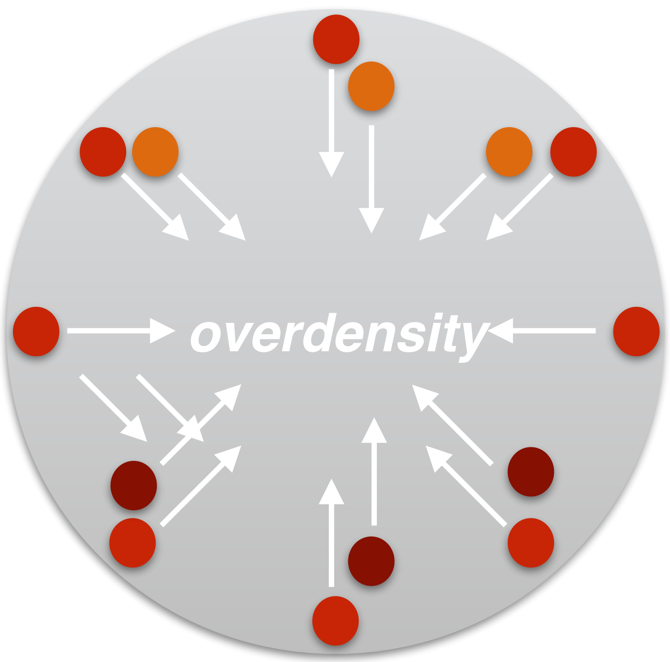
$$\mathcal{D}_2^{mat}(r) = \frac{\mathcal{D}_2^{gal}(r) - 3}{b^2} + 3$$

FoG **Kaiser**



Redshift Space Distortions 1

Kaiser effect (Large Scale 10 Mpc/h)

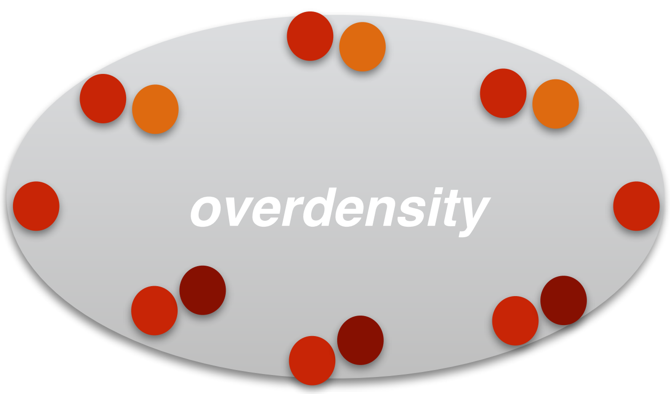


Real Configuration

$$z_{obs} = \frac{v_p}{c} + z_{cosmo}$$

Redshift Space Distortions 1

Kaiser effect (Large Scale 10 Mpc/h)



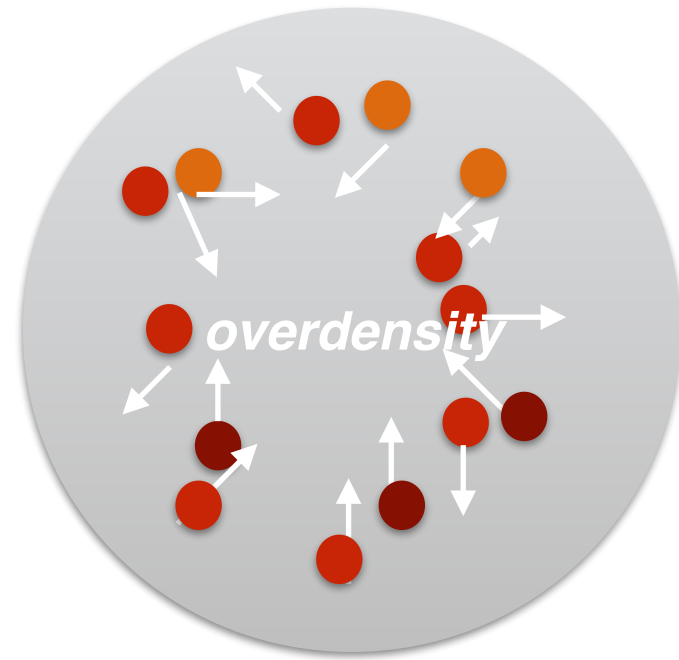
Apparent Configuration

Observer

$$z_{obs} = \frac{v_p}{c} + z_{cosmo}$$

Redshift Space Distortions 2

Finger of God
(Small Scales 1 Mpc/h)



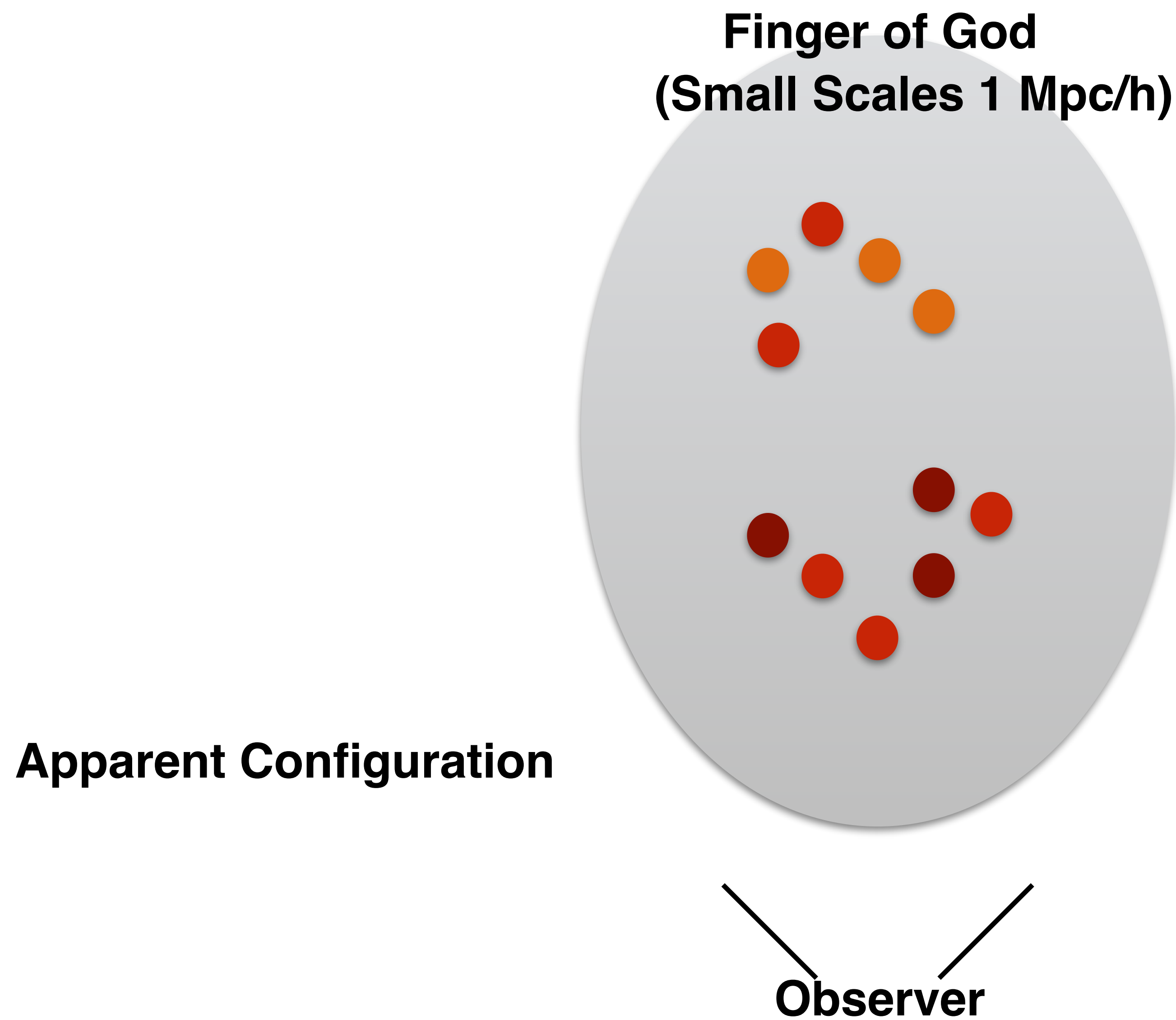
Real Configuration

Observer

$$z_{obs} = \frac{v_p}{c} + z_{cosmo}$$

SDSS

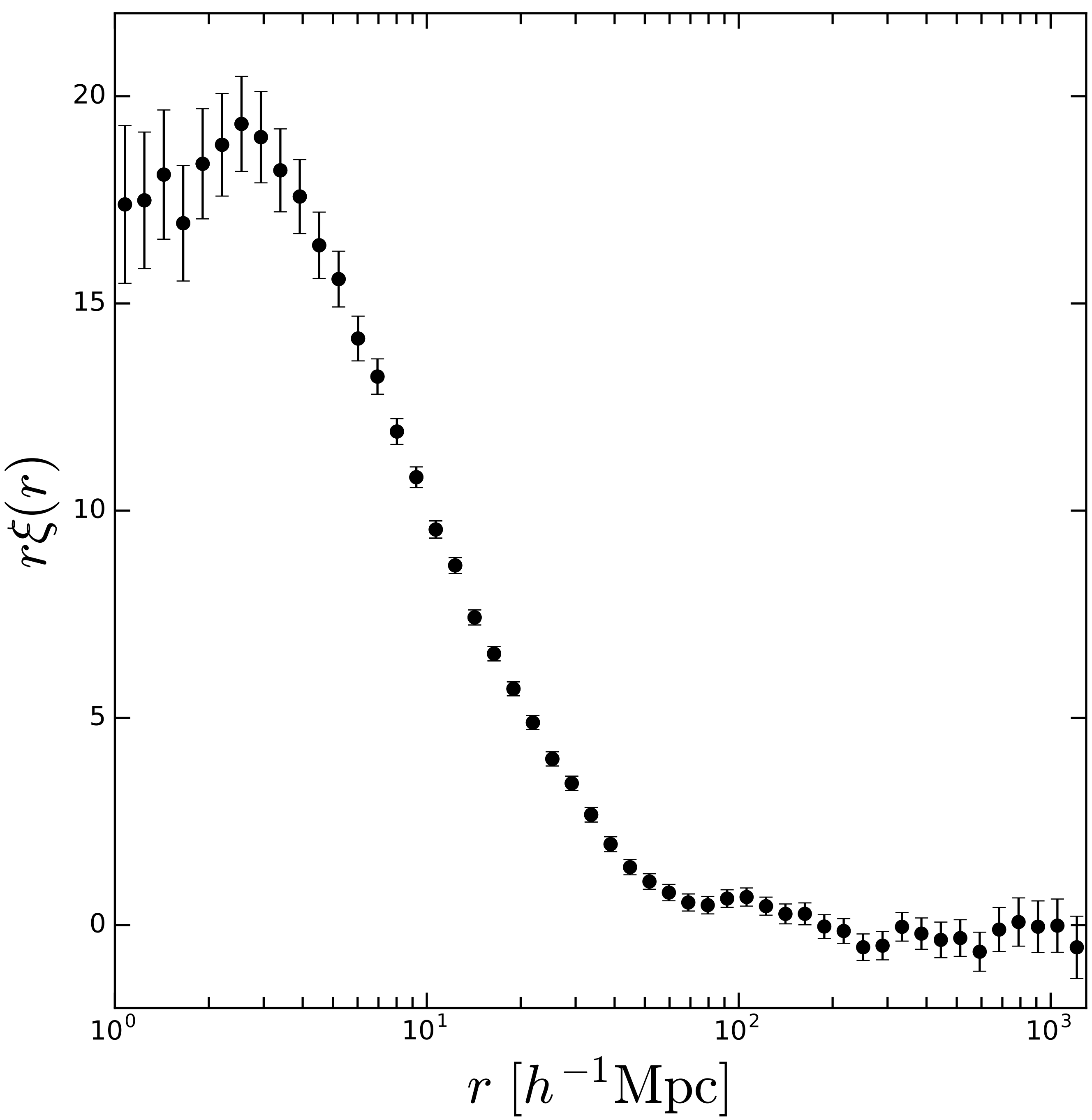
Redshift Space Distortions 2



$$z_{obs} = \frac{v_p}{c} + z_{cosmo}$$

GALAXIES BIASED TRACERS

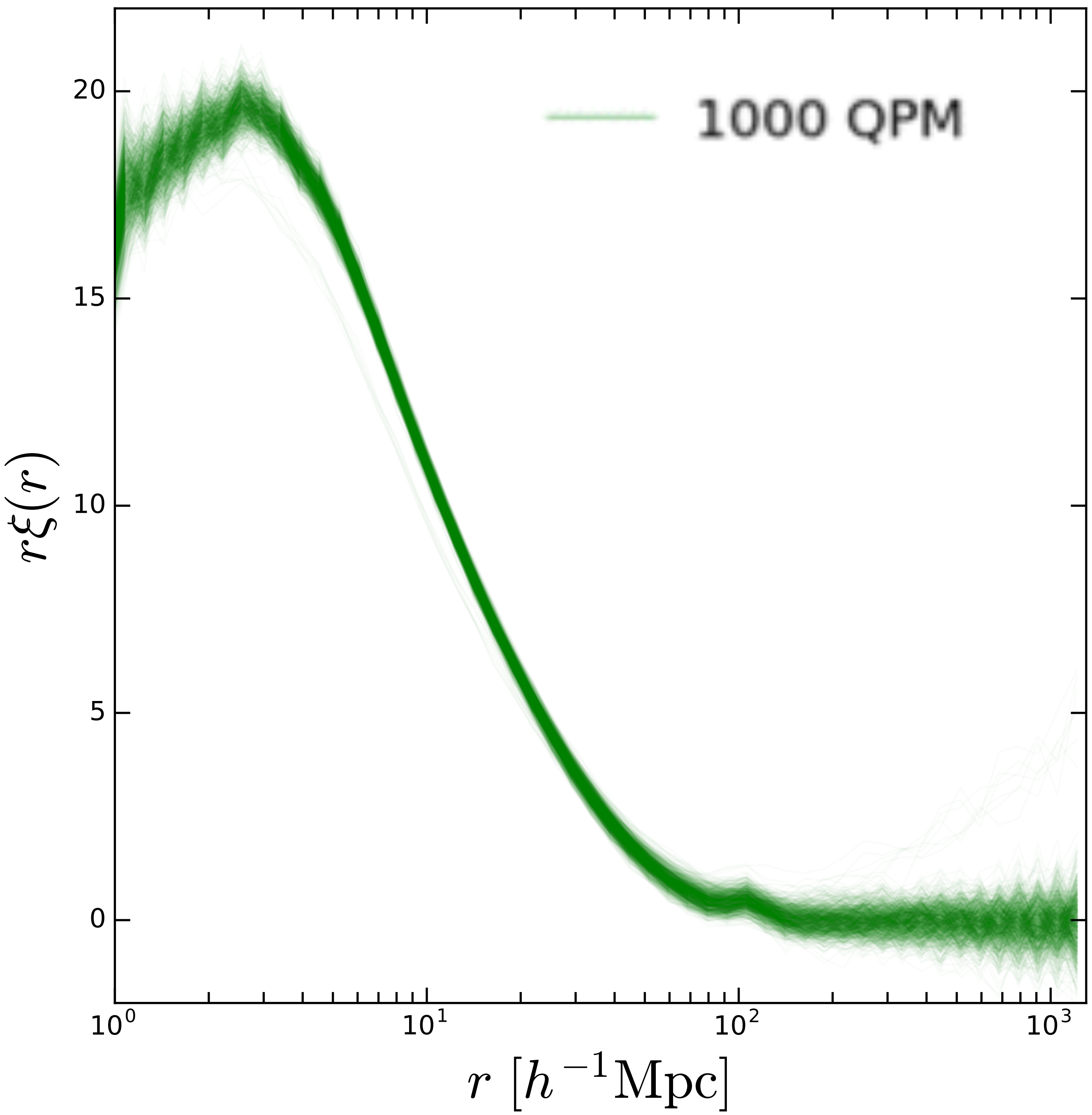
z = 0.538 - 0.592



GALAXIES BIASED TRACERS

- Fitting Choices on Sims

z = 0.538 - 0.592



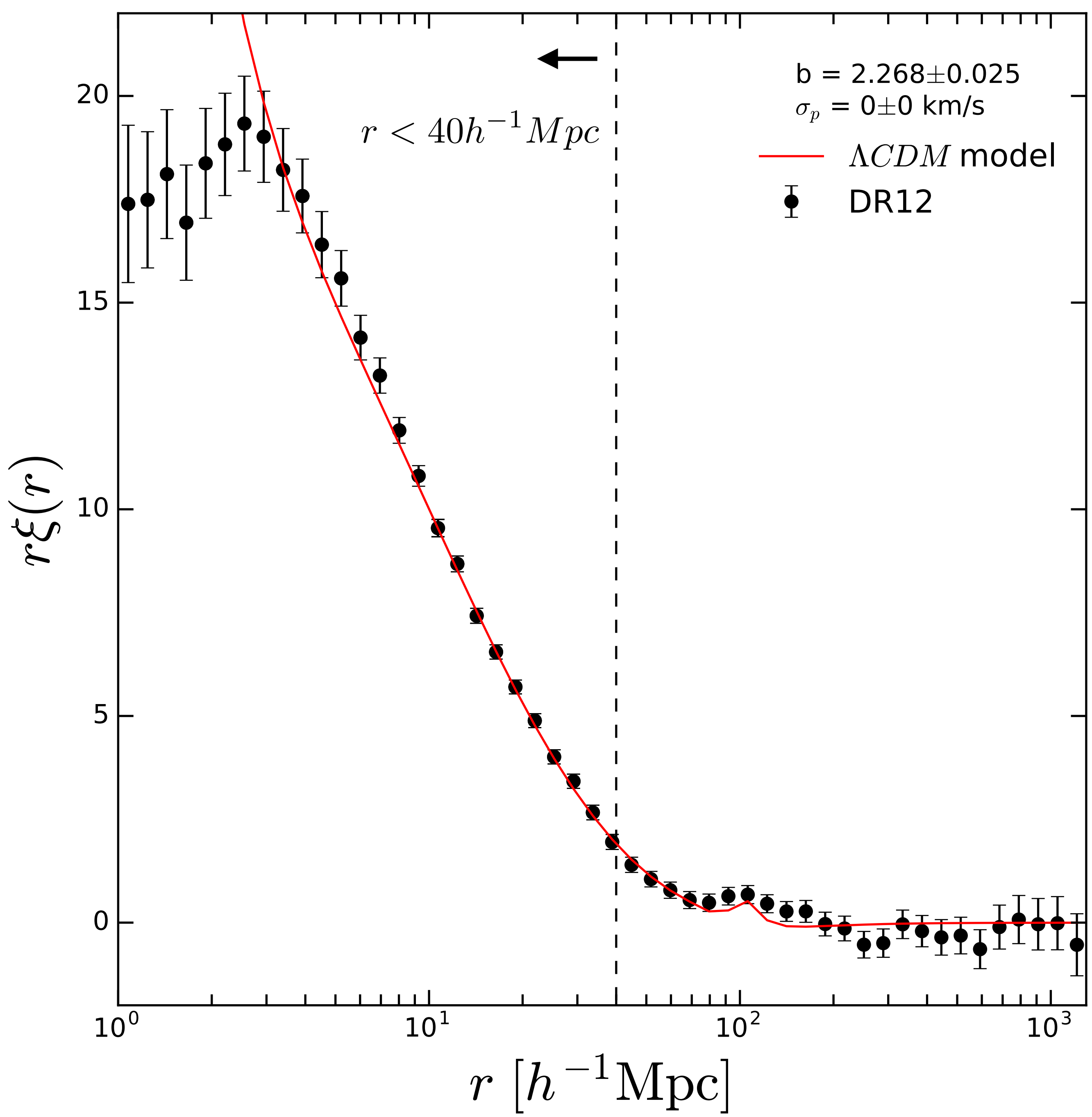
GALAXIES BIASED TRACERS

- Fitting Choices on Sims
- Lower Part (r < 40h^{-1} Mpc)

Fit only the Bias:

$$\xi_{galaxy}(r) = b^2 \xi_{matter}(r)$$

z = 0.538 - 0.592



R_H as Standard Ruler: MCMC

Large Scale Small Scale

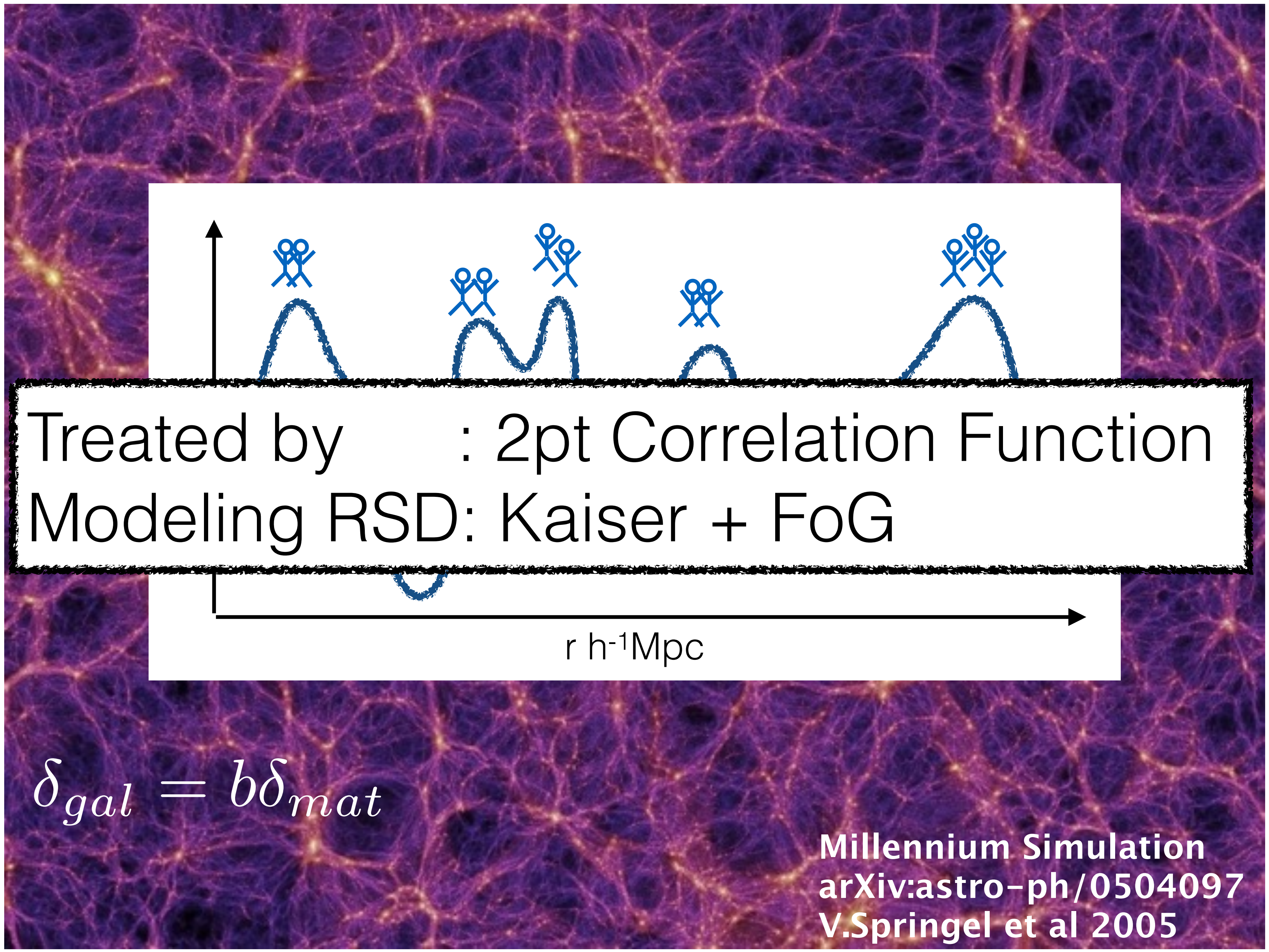
$$\chi^2(z;b,p_T) = \chi^2_{\mathcal{R}_H}(z;b,p_T) + \chi^2_\xi(z;b,p_T)$$

$$\left(\frac{\mathcal{R}_H^G(z;p_F) - \mathcal{R}_H^{G,th}(z;b,p_T) \times \alpha(z;p_F,p_T)}{\sigma_{\mathcal{R}_H^G}(z)}\right)^2$$

$$\chi^2_\xi(z;b,p_T) = \left[\xi^G(r_i;p_F) - \xi^G_{th}(\alpha^{-1}\cdot r_i;b,p_T)\right] C^{-1}_{r_i\,r_j} \left[\xi^G(r_i;p_F) - \xi^G_{th}(\alpha^{-1}\cdot r_i;b,p_T)\right]^T$$

$$\alpha(z;p_F,p_T) = \frac{d_V(z;p_F)}{d_V(z;p_T)}$$

GALAXIES BIASED TRACERS



Treated by : 2pt Correlation Function
Modeling RSD: Kaiser + FoG

$$\delta_{gal} = b\delta_{mat}$$

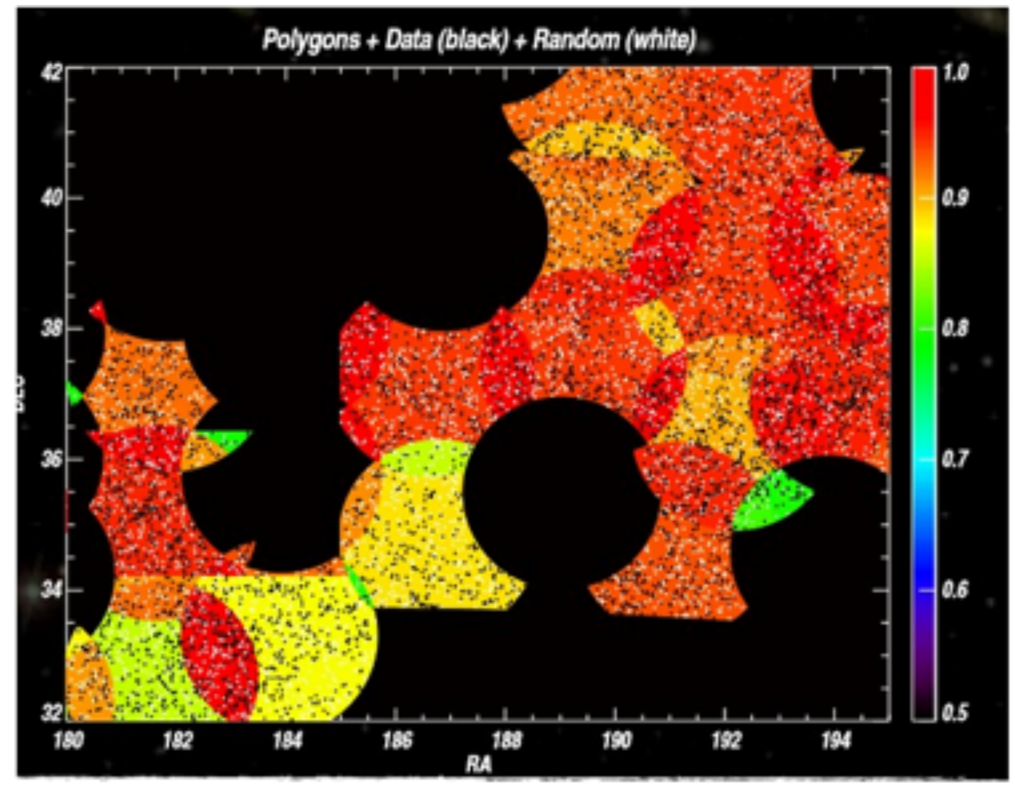
Systematic Effects

- Rarely 100%:
  - Survey in progress
  - Non-uniform success rate

- Definition:

$$Completeness = \frac{SPECTRA}{TARGETS}$$

- Importants Weights for:
  - Closed Pairs
  - z-failure
  - Contamination from Stars
  - Shot-noise, Cosmic Variance
    - [Feldman, Kaiser, Peacock,1993]



$$w_{tot} = (w_{cp} + w_{zf} - 1) w_{sys} w_{fkp}$$

Scientific Contribution

- Exploring cosmic homogeneity with the BOSS DR12 galaxy sample
  P. Ntelis et al. 2017

  arXiv:1702.02159

- A 14 $h^{-3}Gpc^3$ study of cosmic homogeneity using BOSS DR12 quasar sample
  P. Laurent et al. 2016

  arXiv:1602.09010

- Cosmological constrains using cosmic homogeneity
  In preparation

- Cosmic homogeneity with cosmic clocks and type Ia SN
  In preparation