Is the Universe Homogeneous?

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Adv: J.C. Hamilton

on behalf of eBOSS

arXiv:1702.02159

OUTLINE

- *Theoretical Framework*
- *BOSS Galaxy Survey*
- *Methodology*
- *Results with DR12*
- *Forecasts*
- *Conclusions*

Theoretical Framework

Cosmological Principle
Homogeneous + Isotropic
on Large Enough Scales

General Relativity → FLRW → ΛCDM

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

$$ds^2 = -c^2 dt^2 + a^2(t) d\vec{x}^2$$

Fit on DATA

Theoretical Framework

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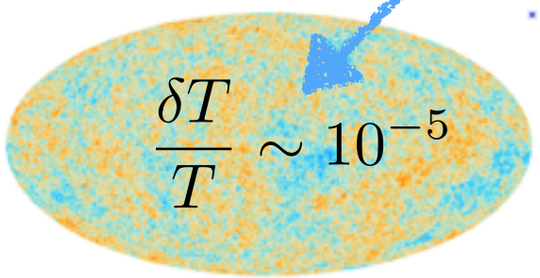


Fit on DATA

Theoretical Framework

Is this assumption data-motivated ?

Cosmological Principle
Homogeneous + Isotropic
on Large Enough Scales

General Relativity → FLRW → ΛCDM

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

$$ds^2 = -c^2 dt^2 + a^2(t) d\vec{x}^2$$

Fit on DATA

How to check for Homogeneity?

Where to look?

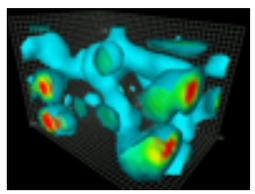
Observable ?

Which scales to measure?

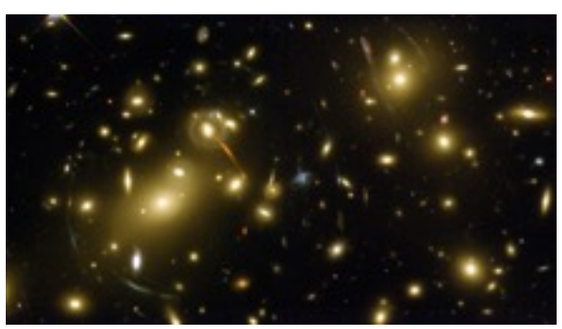
Theory?

- ***ΛCDM,***
- ***wCDM,***
- ***sCDM,***
- ***Modified Grav***
- ***Back-Reaction***

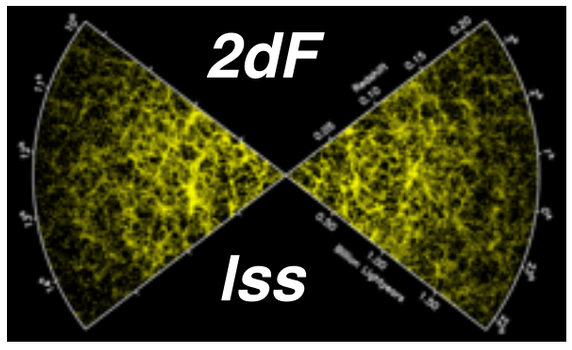
What is a structure??



$q^{\pm}, H^{0}, l^{\pm}, \gamma, W^{\pm}, g^{c}, GW?$



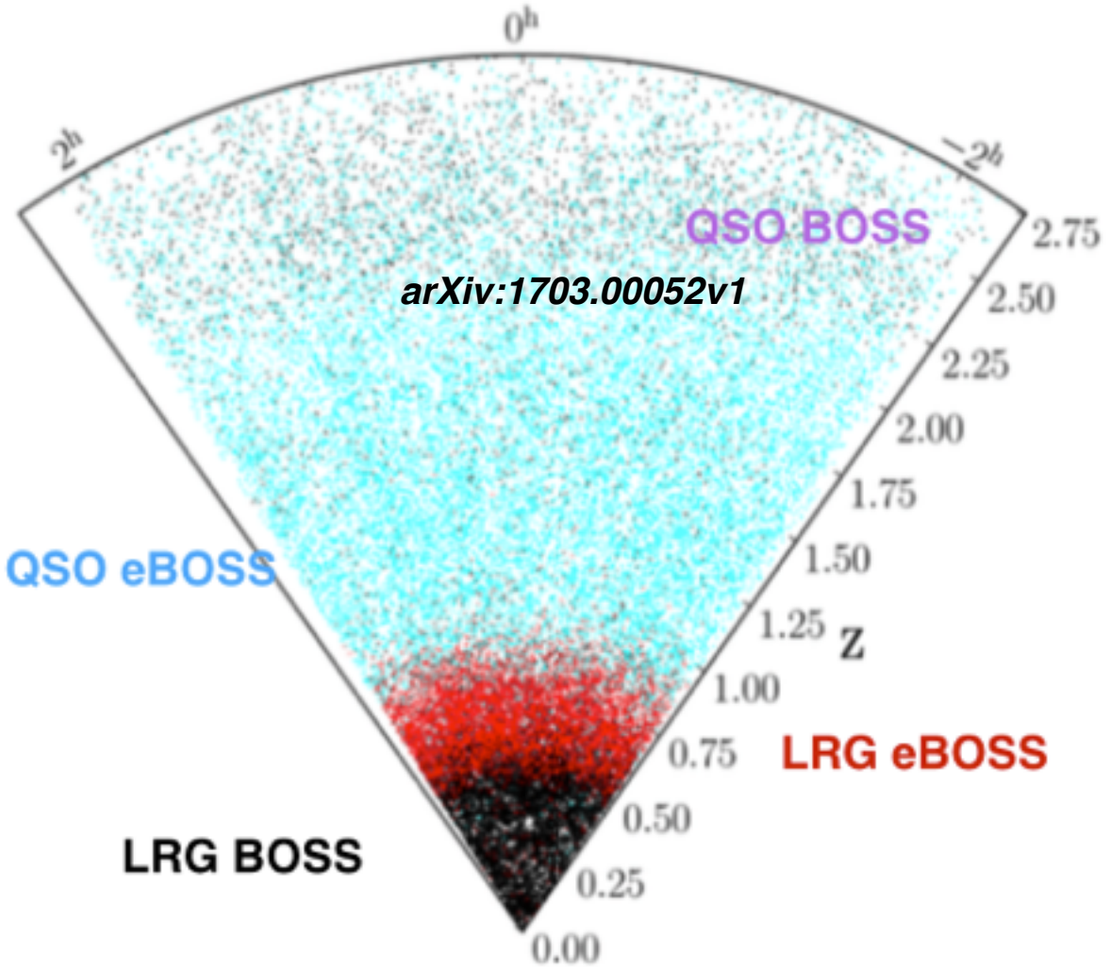
CW: Voids, Nodes, Filaments & Sheets

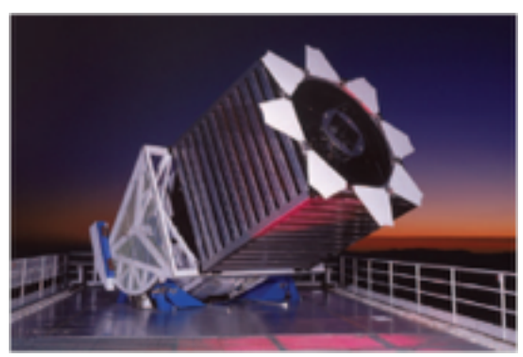


Different Observables: n, T.F. , SZ, FoF, …

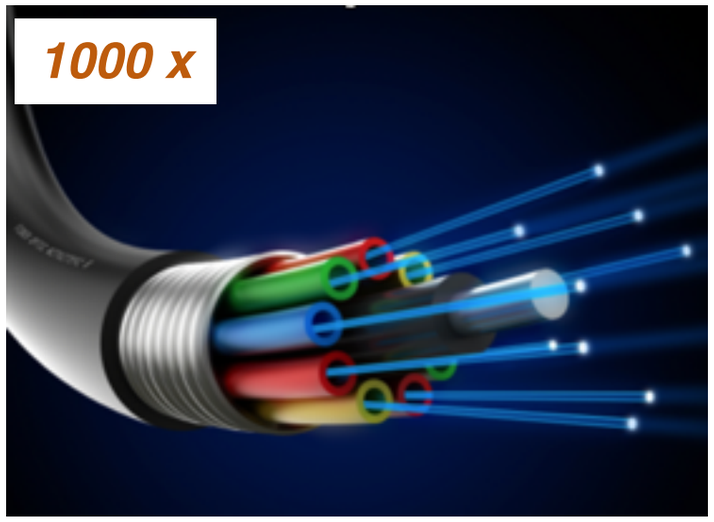
SDSS-III(IV) / (e)BOSS

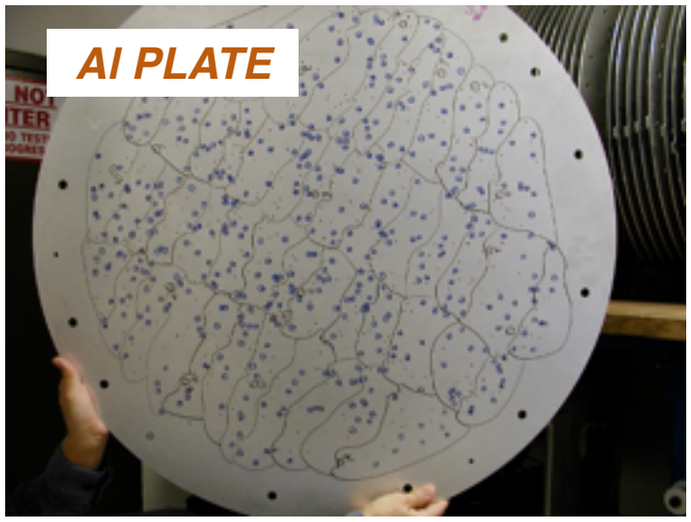
- Main project:
  - APO telescope (New Mexico, USA)
  - 2.5 m diameter
- Spectroscopic Survey:
  - 360 nm < λ < 1000 nm
  - FoV: 10 400 deg^2:
    - 10^6 Gal @ z ~ 0.6 (Gyr)
    - 10^5 QSO + Ly-α F @ z ~ 2.4 (Gyr)
- Objectives:
  - Galaxy Clustering Science
  - Cosmological Parameters

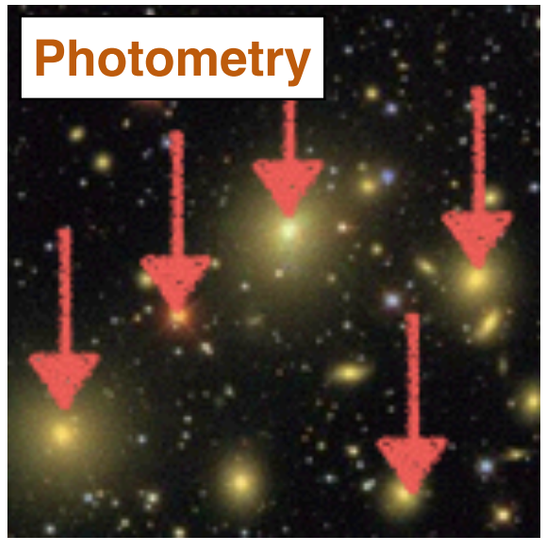


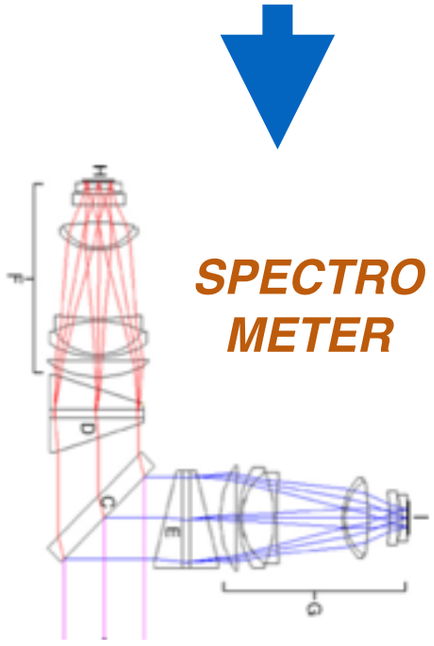


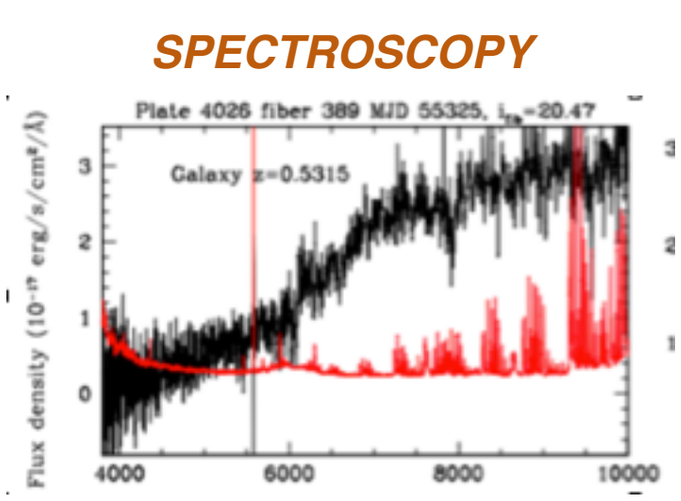
eBOSS in a Nutshell

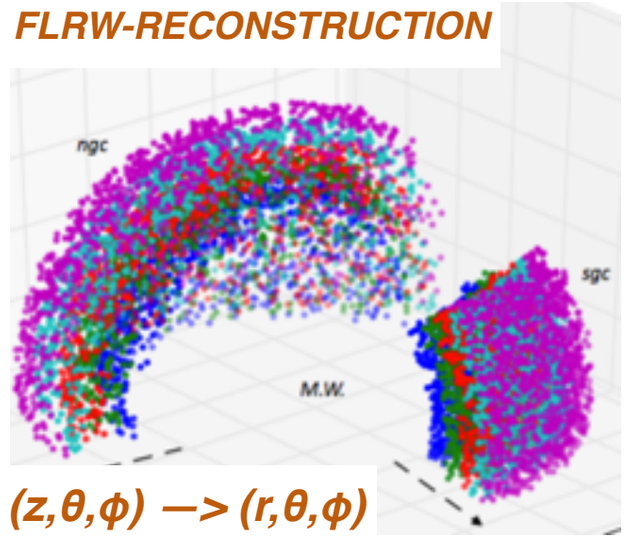








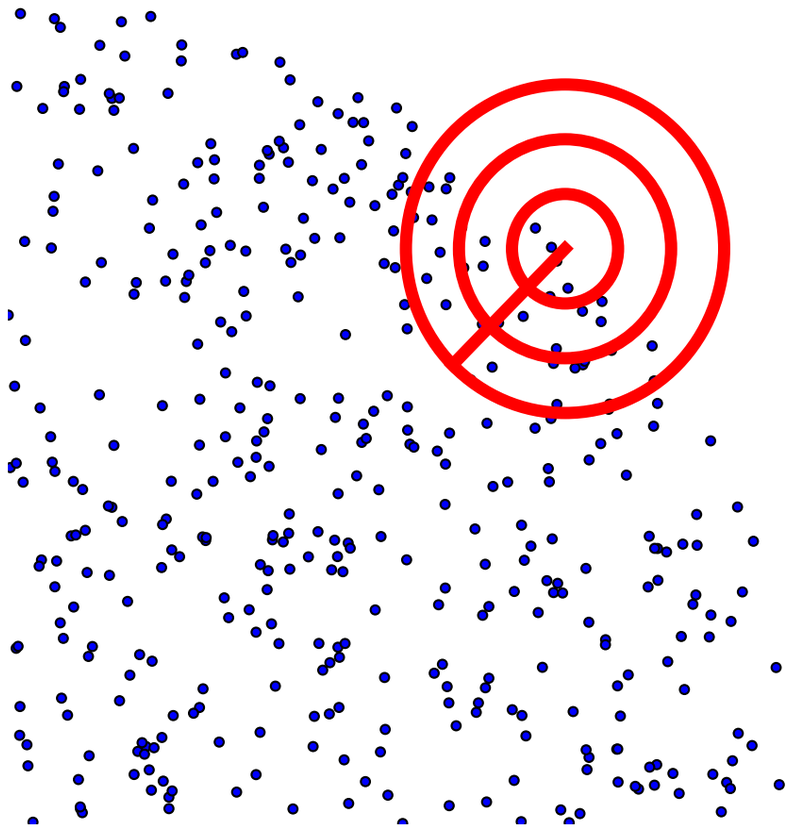




How to measure densities ?

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



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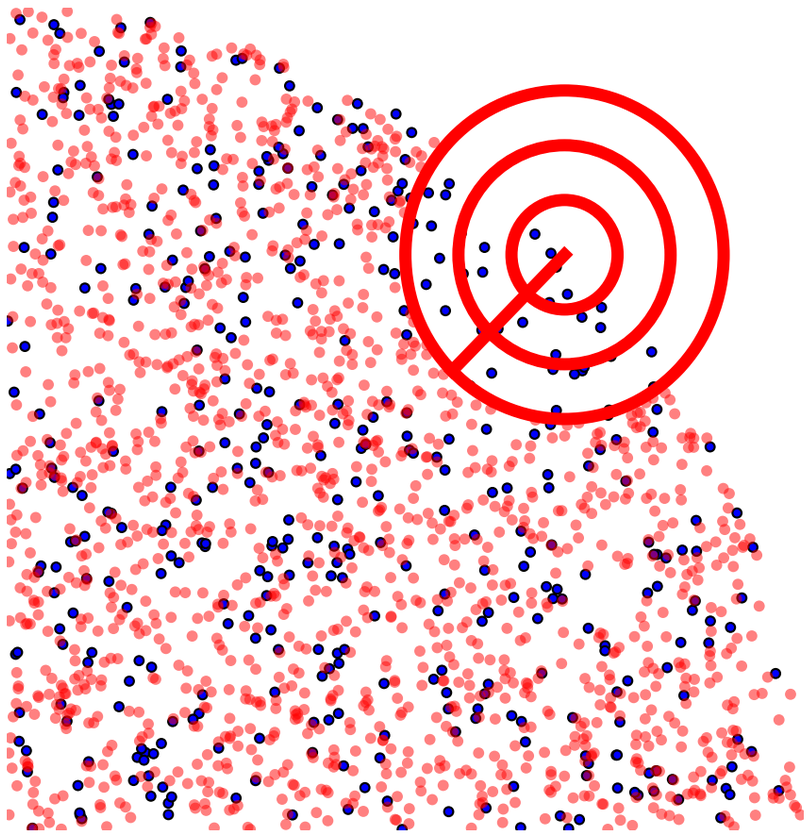

Random Pairs: Same Selection Function

Homogeneity Scale Estimator

- Fractal Dimension: $N(< r) \propto r^{D_2}$

- Inhomogeneous :
  @ small scales (clustering)

- Homogeneous
  @ large scales

- Transition to Homogeneity at:

  Arbitrary Choice

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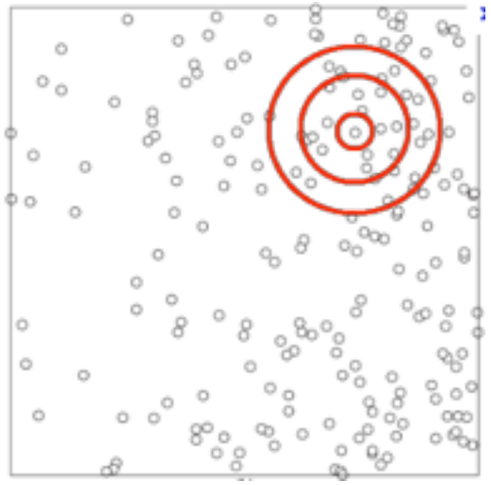

- Inhomogeneous :
  @ small scales (clustering) $D_2(r) < 3$

- Homogeneous
  @ large scales

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  @ large scales $D_2(r) = 3$

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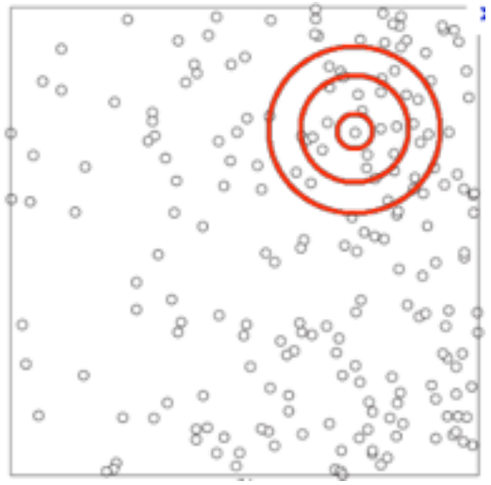
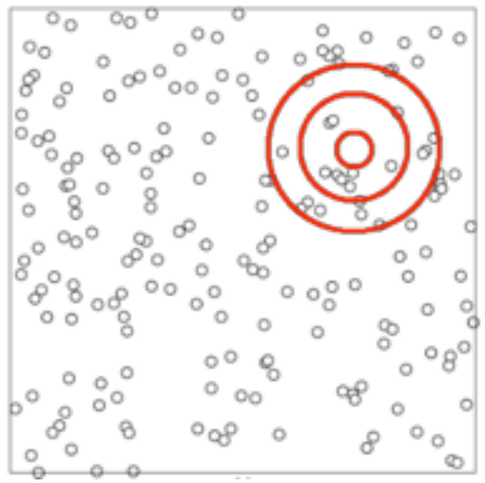




Homogeneity Scale Estimator

- Fractal Dimension: $N(< r) \propto r^{D_2}$

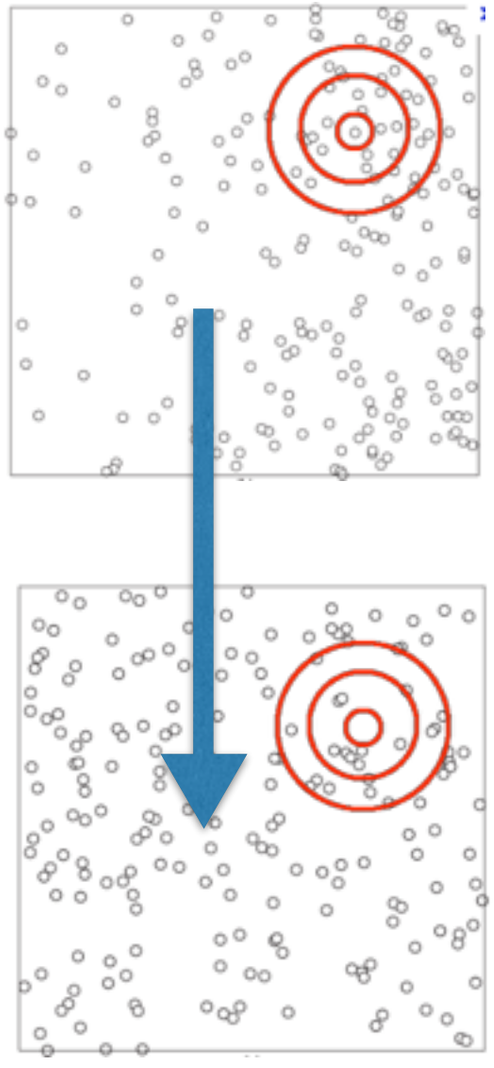
- Inhomogeneous :
  @ small scales (clustering) $D_2(r) < 3$

- Homogeneous
  @ large scales $D_2(r) = 3$

- Transition to Homogeneity at:

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

Arbitrary Choice

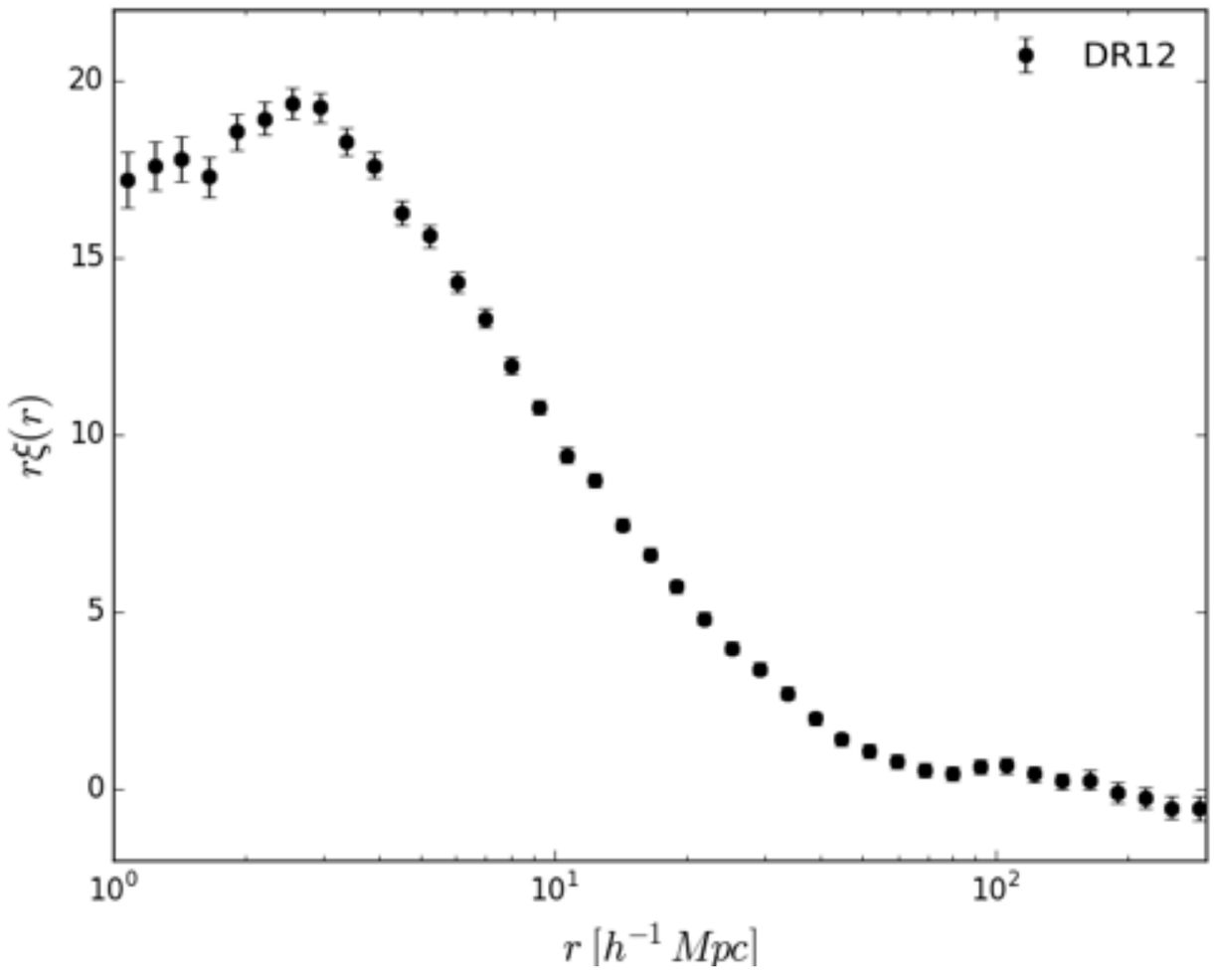


Galaxies: Biased Tracers

- RSD modelling
- bias + σ_P

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

z = 0.538 - 0.592



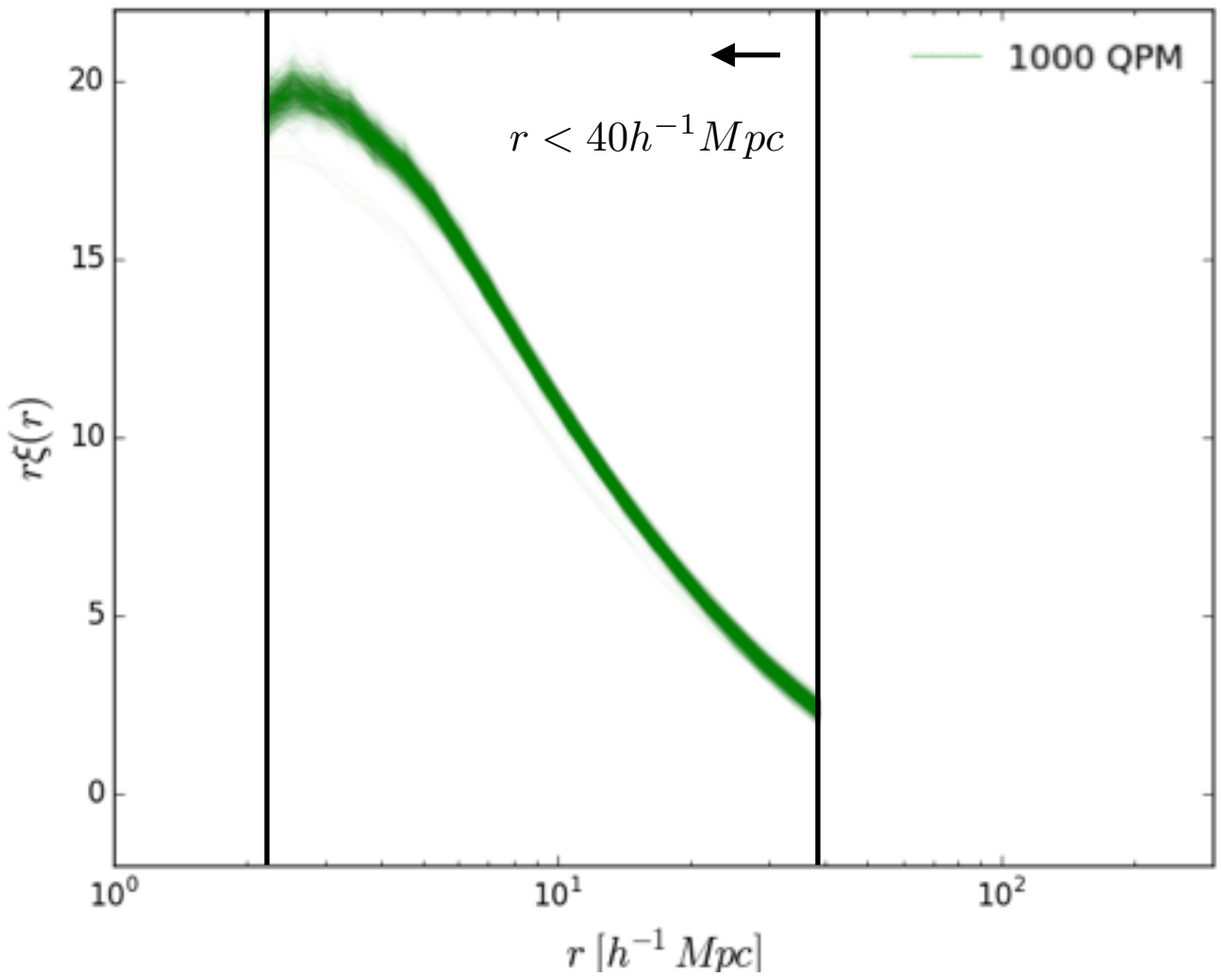
Galaxies: Biased Tracers

- RSD modelling
- bias + σ_P

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

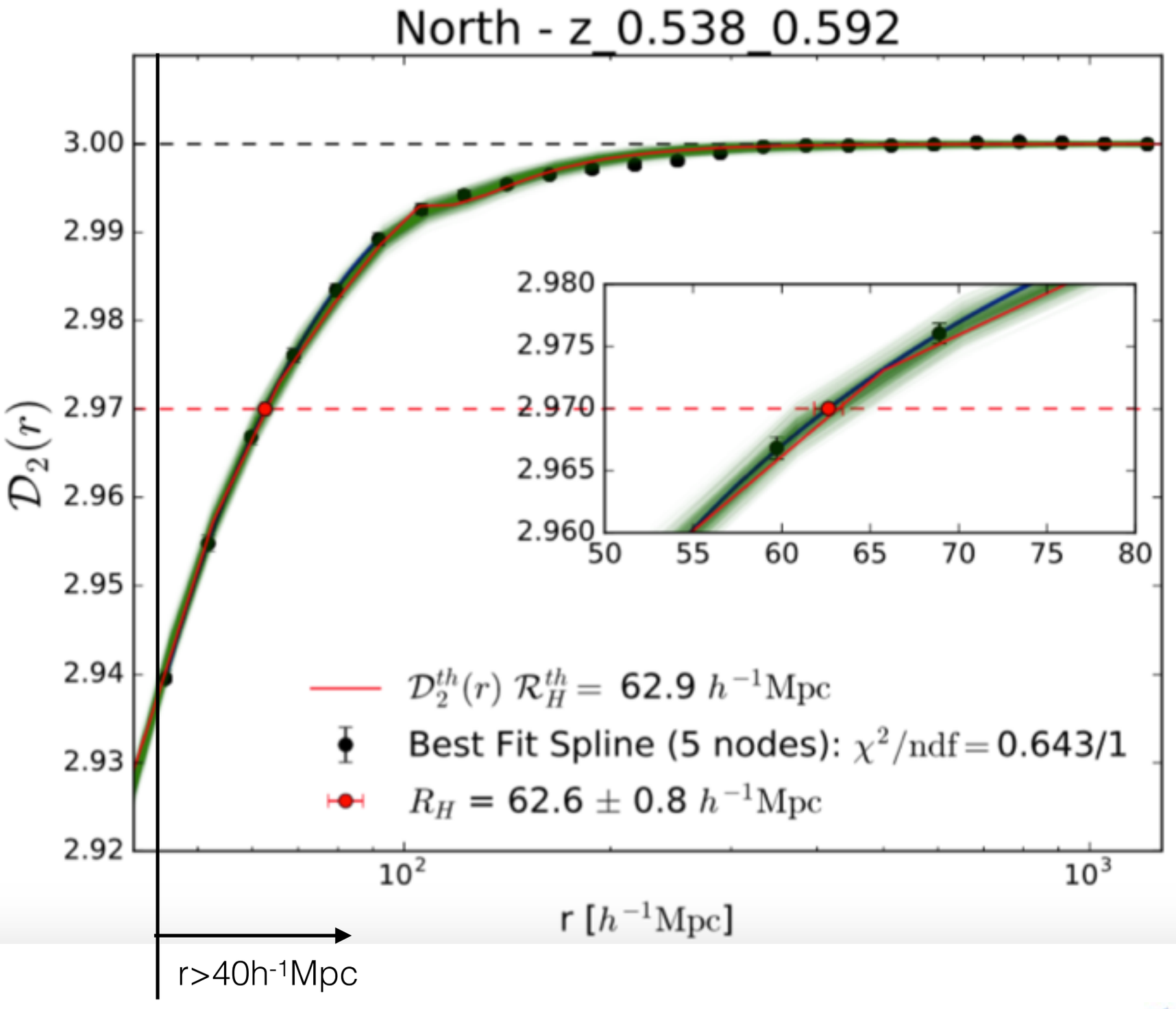
- Lower Part (r < 40h^{-1} Mpc)
- Fitting Choices on 1000 QPM

z = 0.538 - 0.592

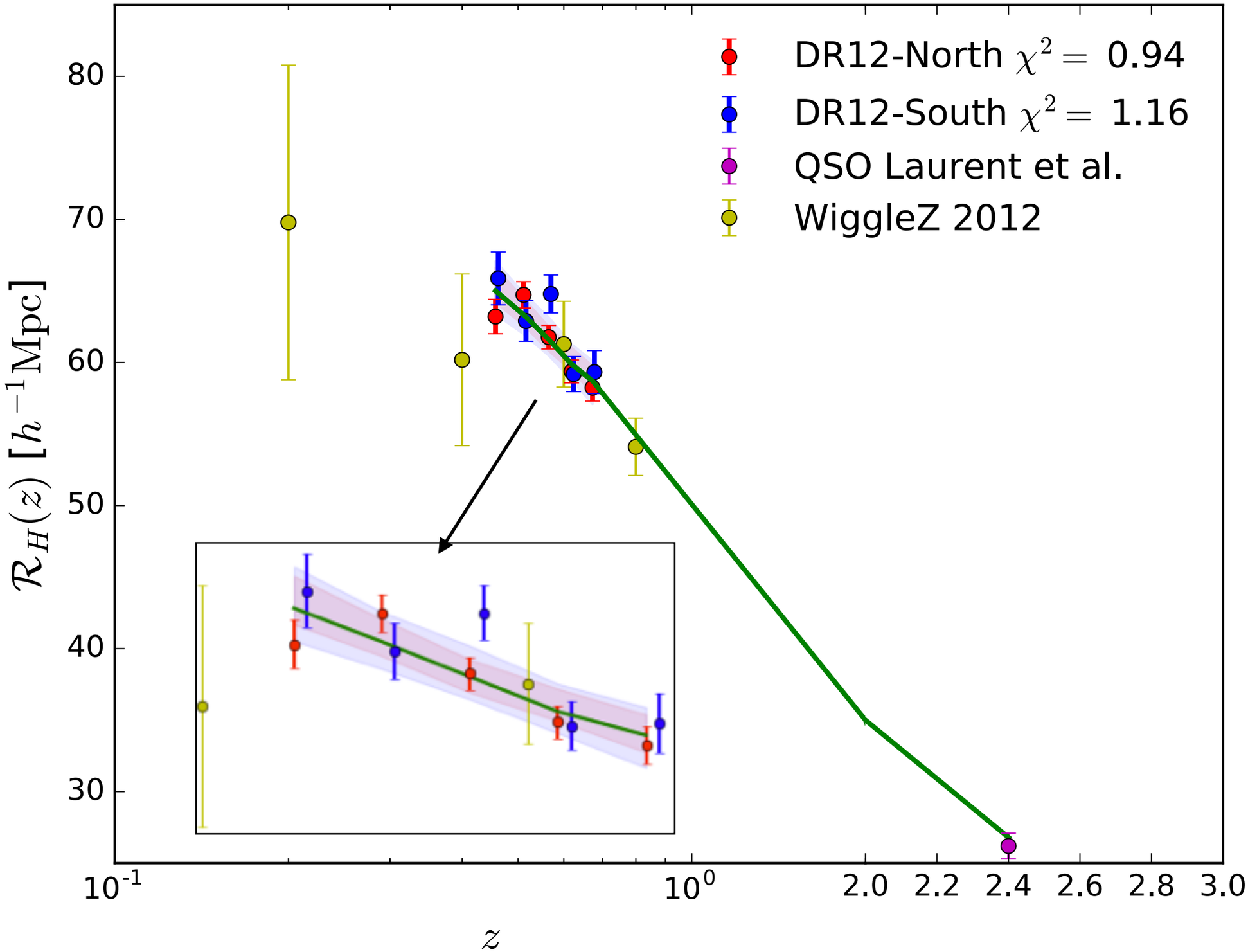


Cosmological Principle Confirmed!

- Fit on $r_{min}=40h^{-1}Mpc$
  - DR12 DATA
  - 1000 QPM-ΛCDM
  - ΛCDM PLANCK 2015

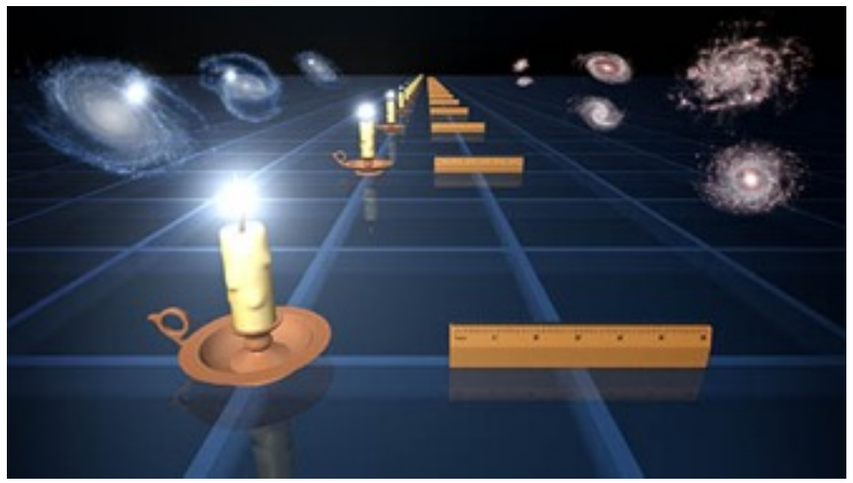


Homogeneity Scale ~ f_G



On Going Investigations

- Use R_H as Cosmo-Ruler:
  - Geometrical Properties
  - Acceleration of the Universe
  - Nature of Dark Energy



- Predictions for future projects:

CFIS
CANADA-FRANCE IMAGING SURVEY

DESI

EUCLID

LSST

WFIRST

DES

FISHEROLOGY

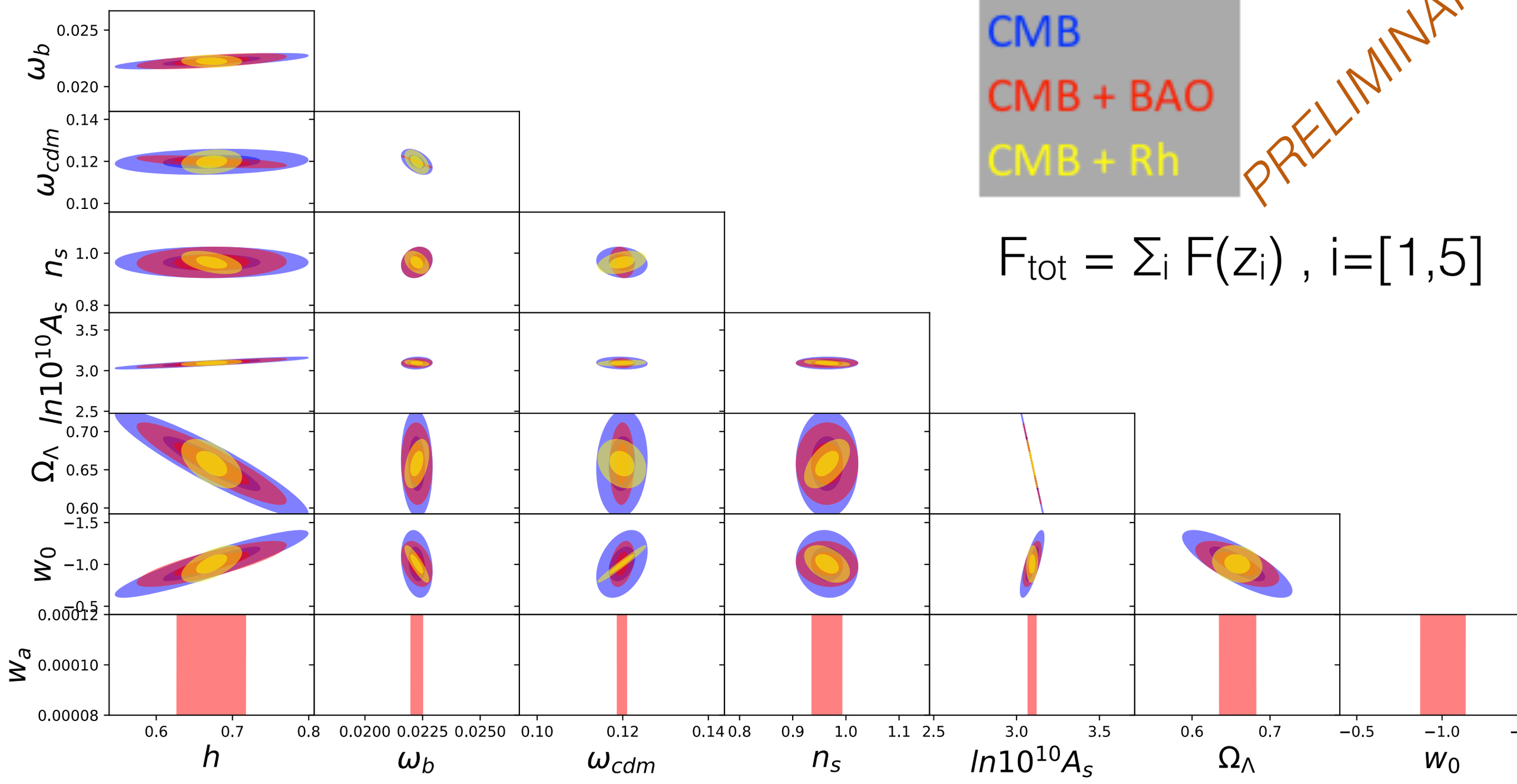
CMB

CMB + BAO

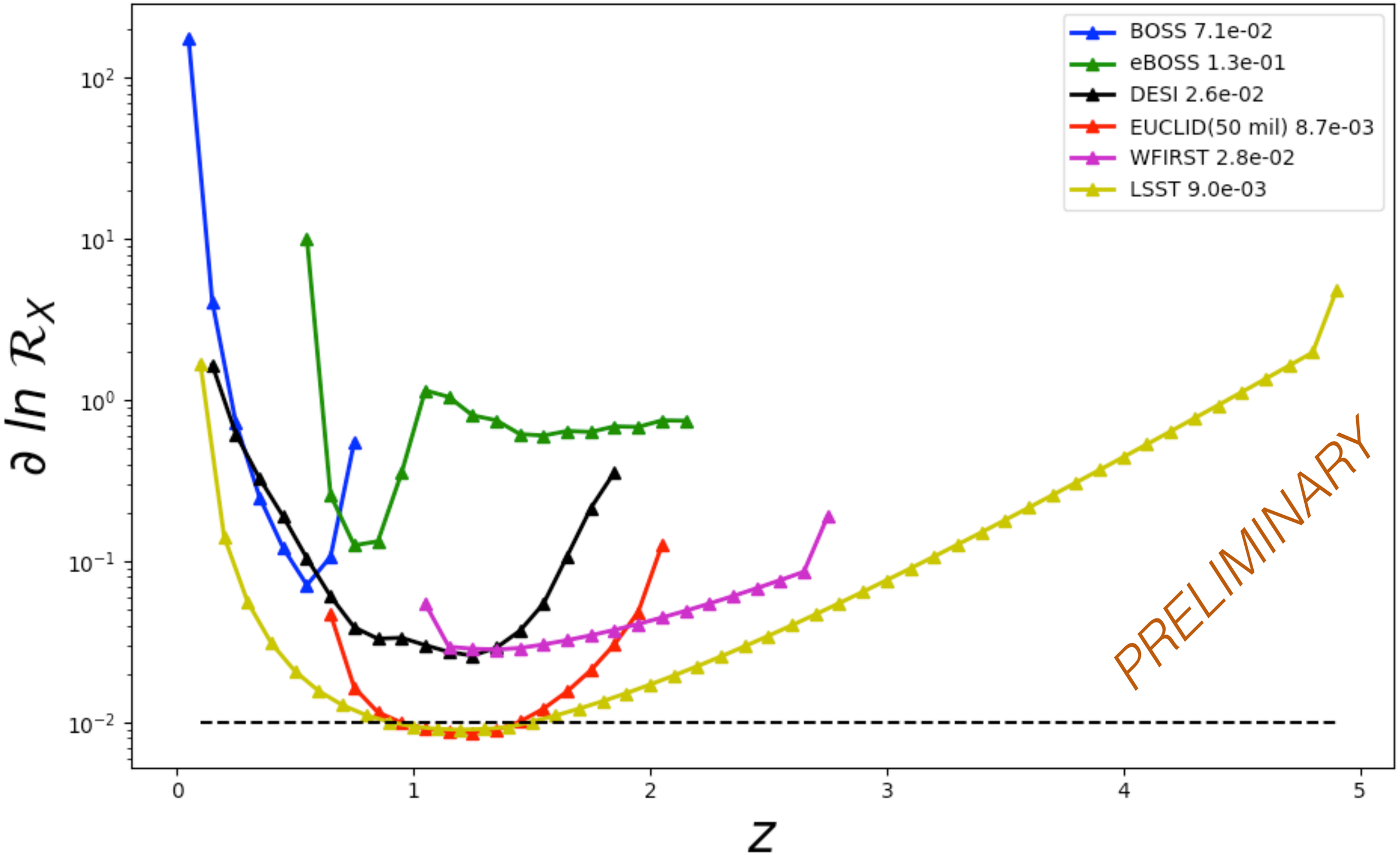
CMB + Rh

PRELIMINARY

$$F_{tot} = \Sigma_i F(z_i) \ , \ i=[1,5]$$



Sensitivity-Forecast



Take home message!

Main Features:

- Largest eff-Vol ever studied!
- Precision ~1% (Wz ~5%)
- Easy application on different surveys
- Complementary Cosmological Probe !!!
- Sensitivity on H_0 , Ω_Λ & w_0

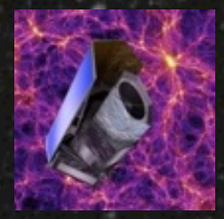
Main Limitations:

- Insensitive to ρ(z) dependence
- ΛCDM Assumption:
  - z —> $d_{comov}(z;\Omega)$
  - RSD Analysis

→

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

Thank you for your Attention !



The Universe on LSS & QMS seems blurry :)

Are we the center?

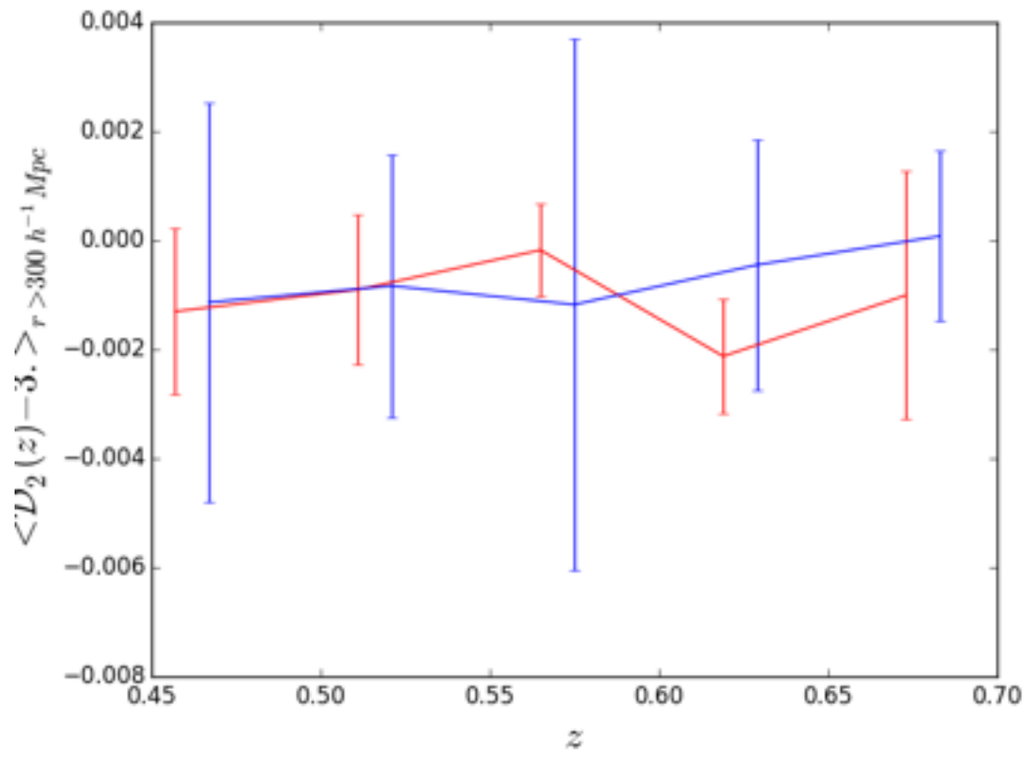
Back -

A dozen of Large Scale Structures

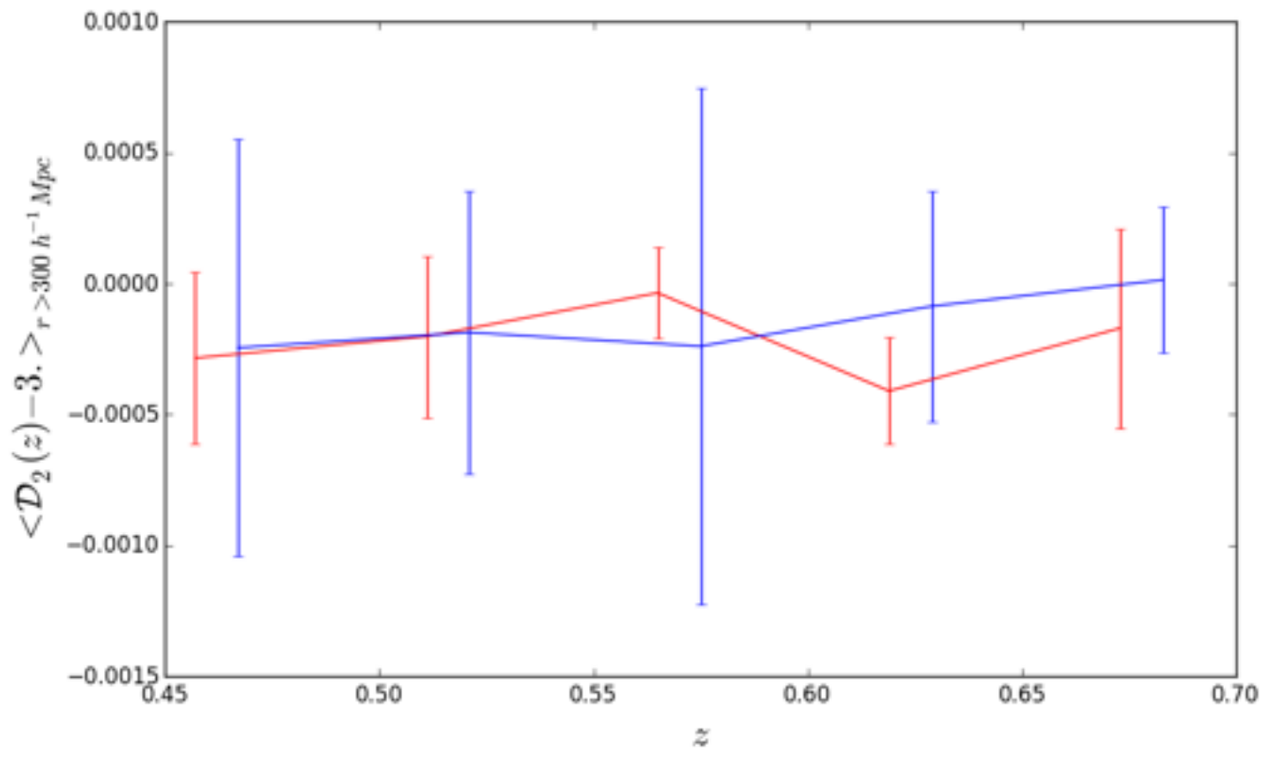
Year	Name	Size (Mpc)	Detection Method	Notes	Dedication
1983	Webster (5)LQG	100	no-info	no-info	A.Webster
1987	Pisces-Cetus SuperCluster Complex	350	spectro-z, percolation analysis L_0=70 h^{-1} Mpc, 10 members, $L>L_0$ no significant	h=75	R.B.Tully
1987	Giand Void	350	L_0=200 h^{-1} Mpc, Spectro-z, FoF	Flat, Λ=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-fid cosmo	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	Pure, identification?	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

Consistency with 3
$r>300h^{-1}Mpc$

Gal ~ 2%



Mat ~ 0.5%

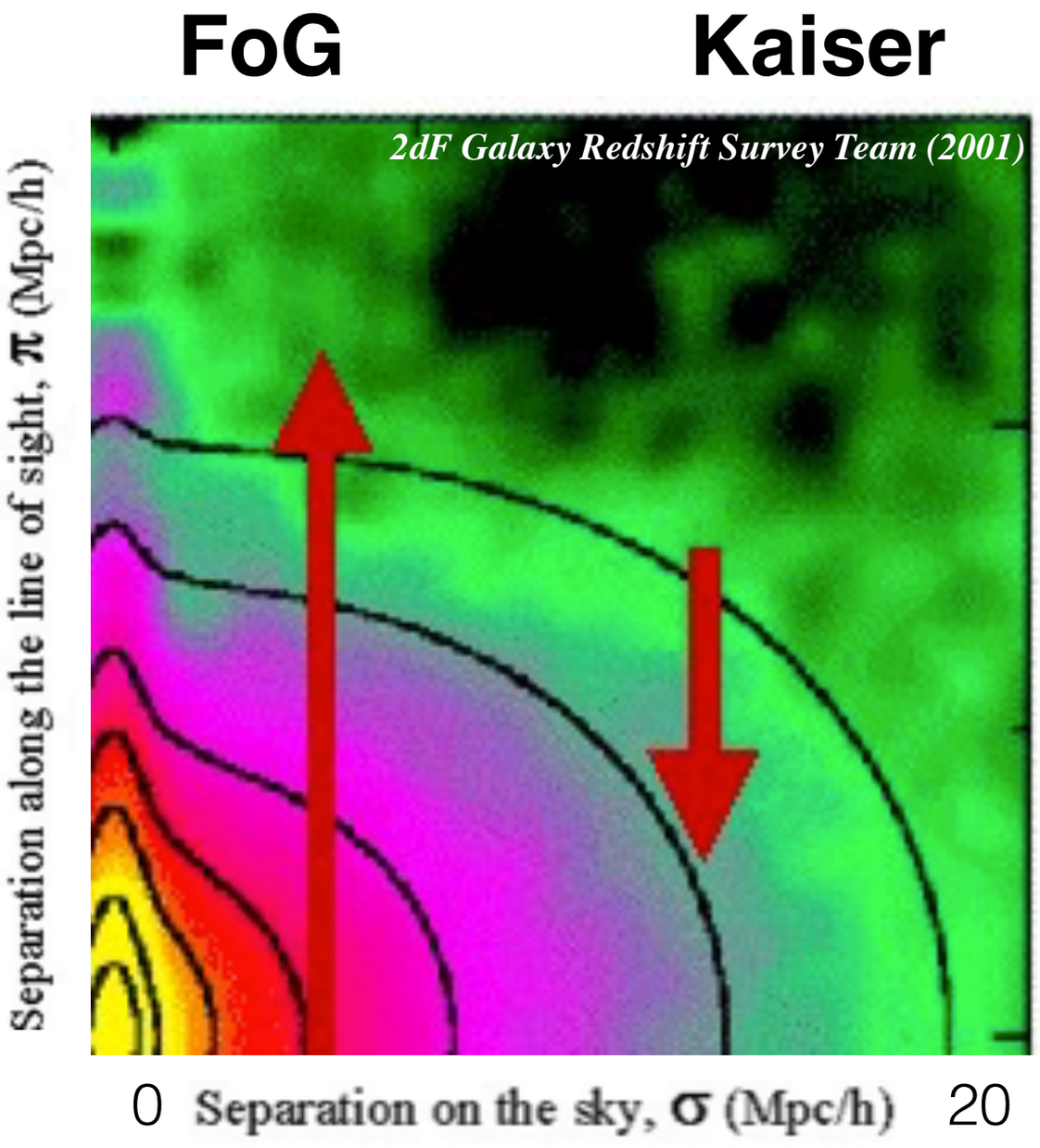


Galaxies: Biased Tracers

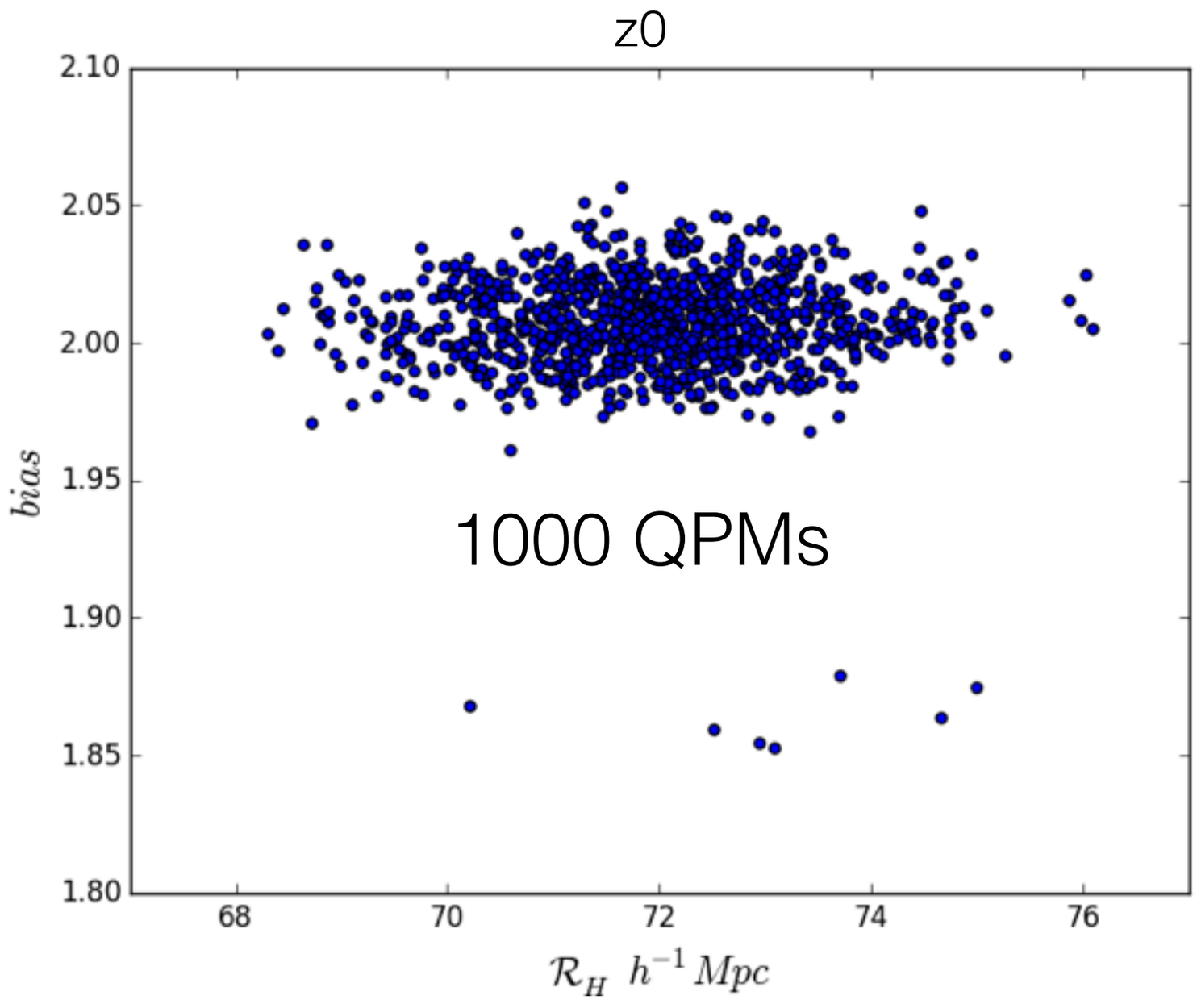
Redshift Space Distortions

- Kaiser: r > 20 h^{-1}Mpc
  GR infall V_{grav}
- FoG : r < 20 h^{-1}Mpc
  Peculiar Motions

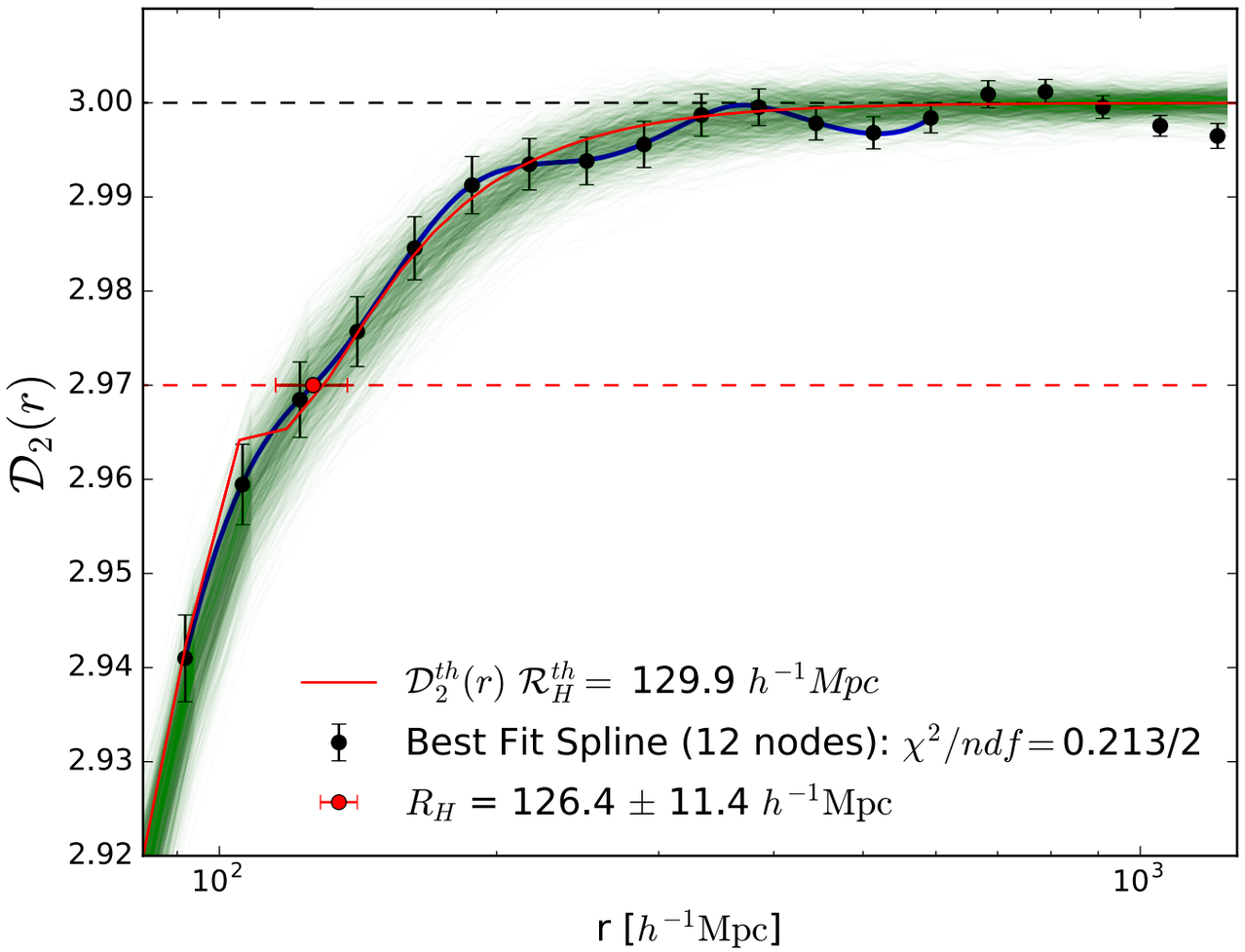
$$\mathcal{D}_2^{mat}(r) = \frac{\mathcal{D}_2^{gal}(r) - 3}{b^2} + 3$$

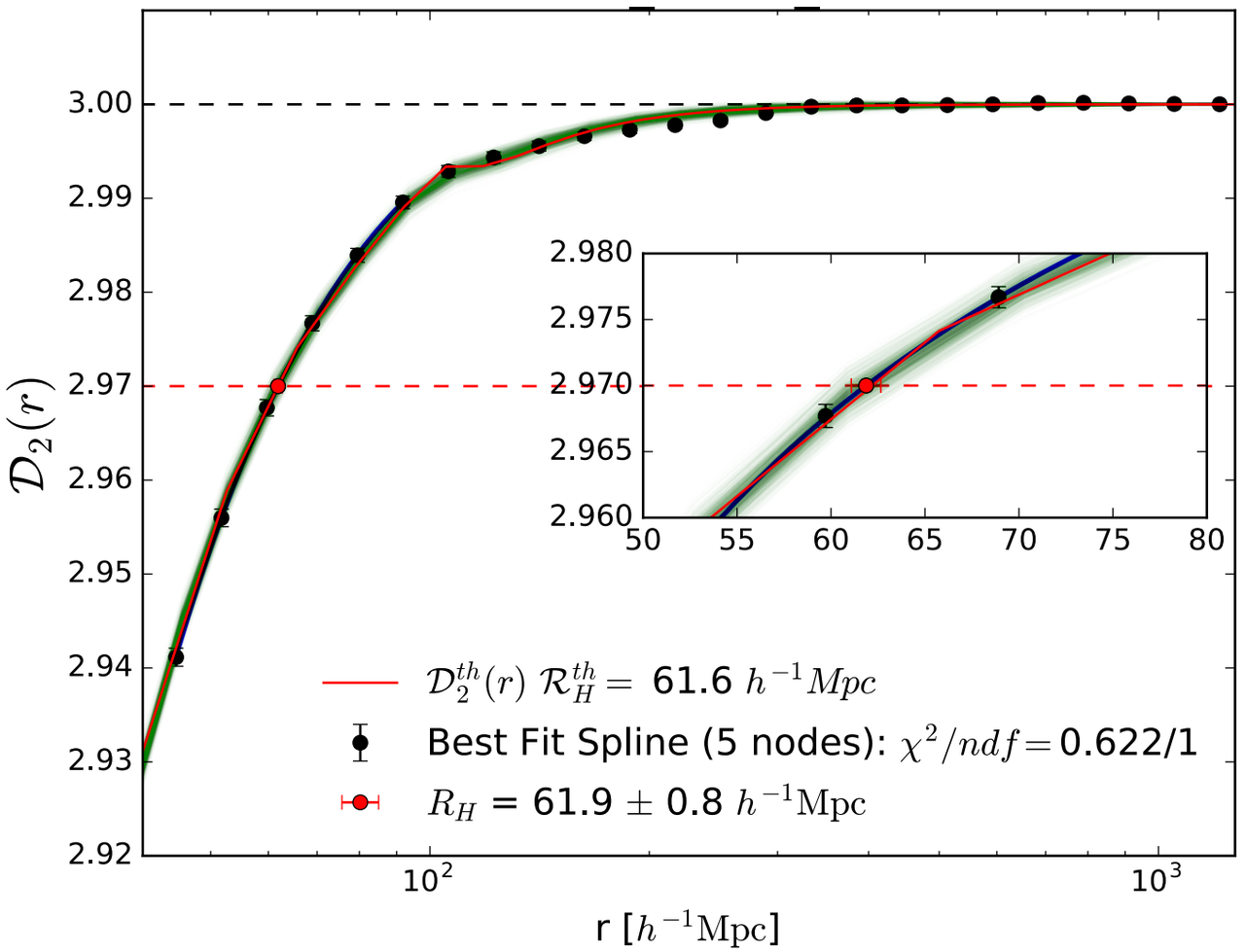


No-Correlation



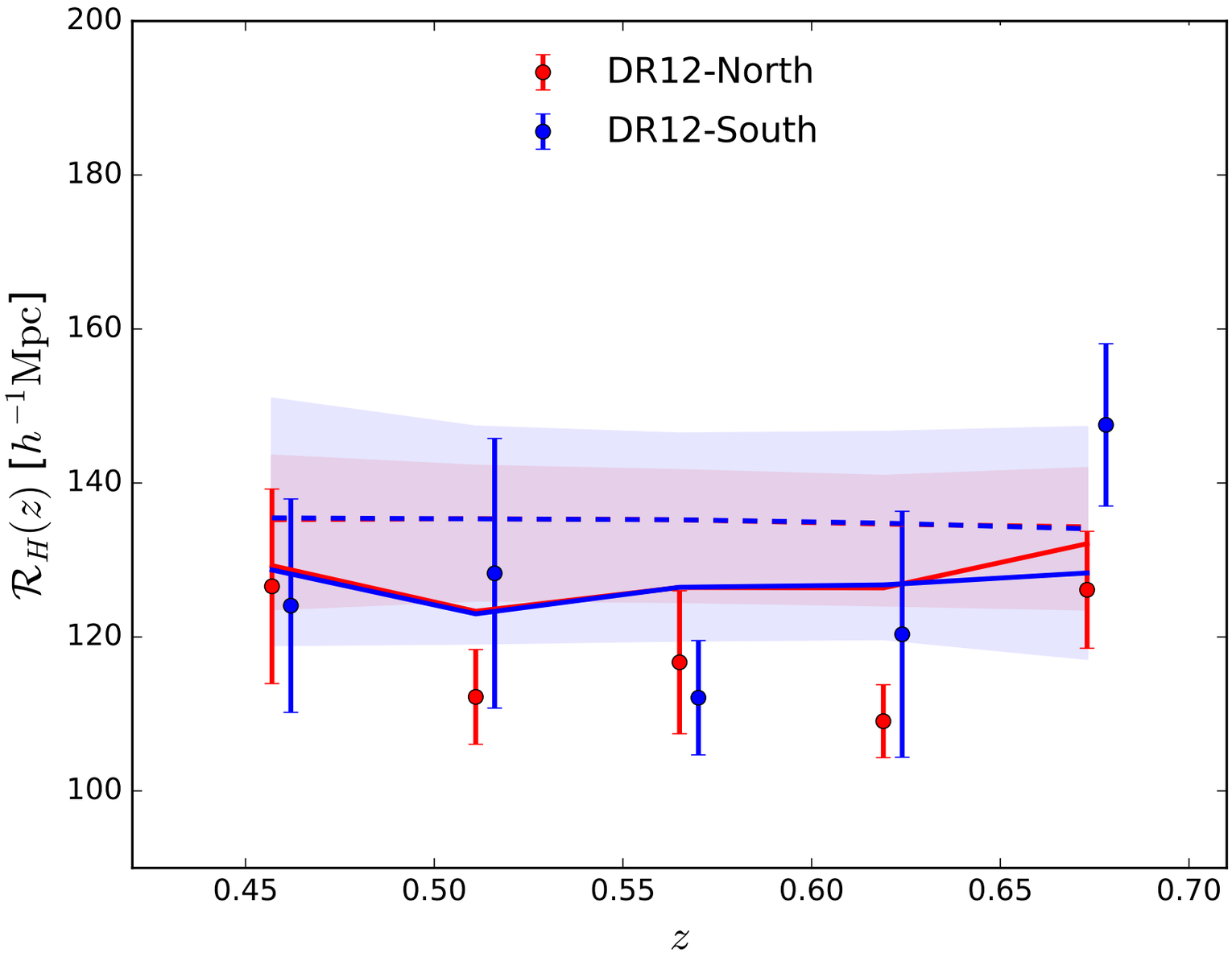
GALAXIES ---> MATTER





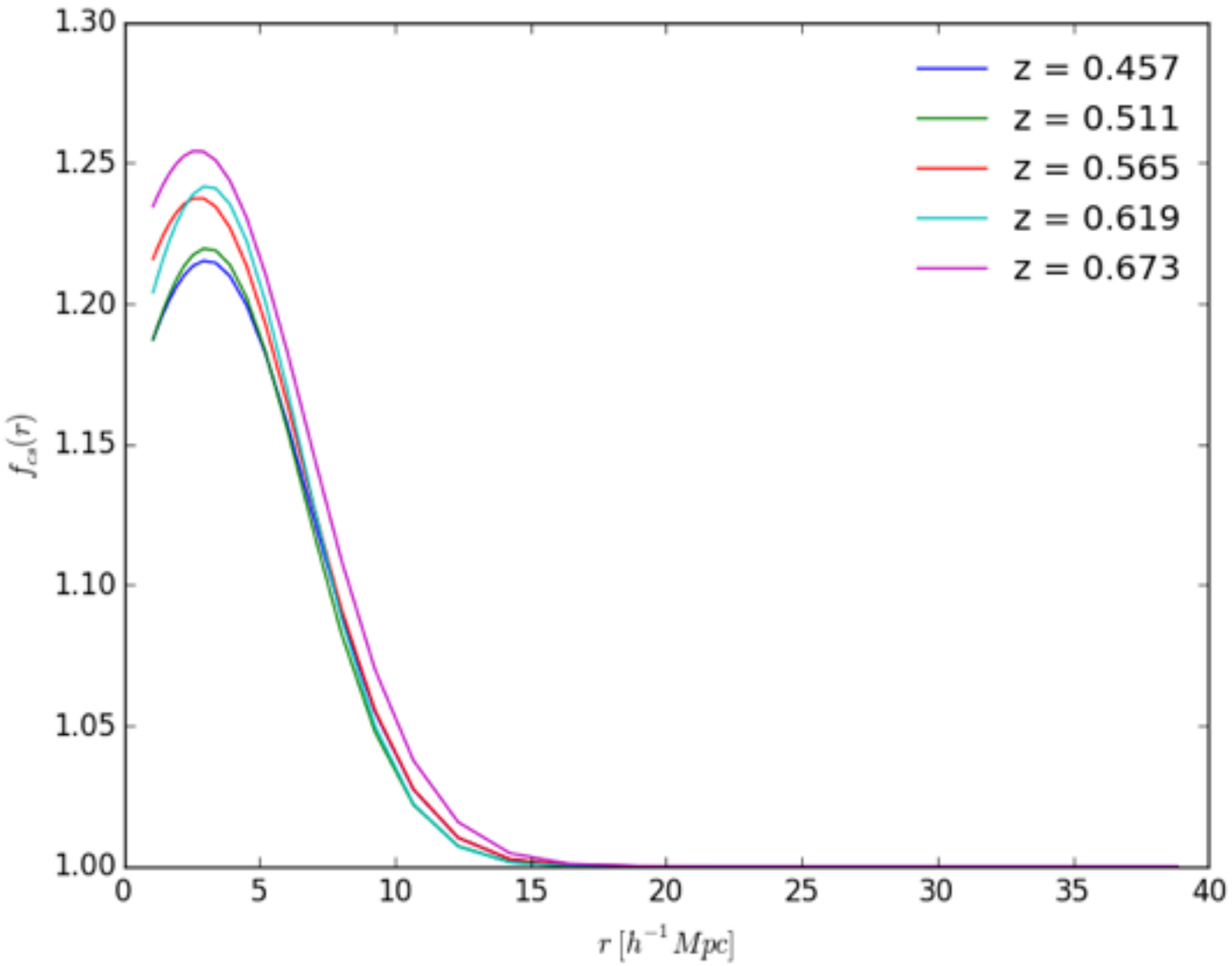
Increase of Precision (still under investigation)

Galaxy-$R_H(z)$=cnt



due to CMASS sample

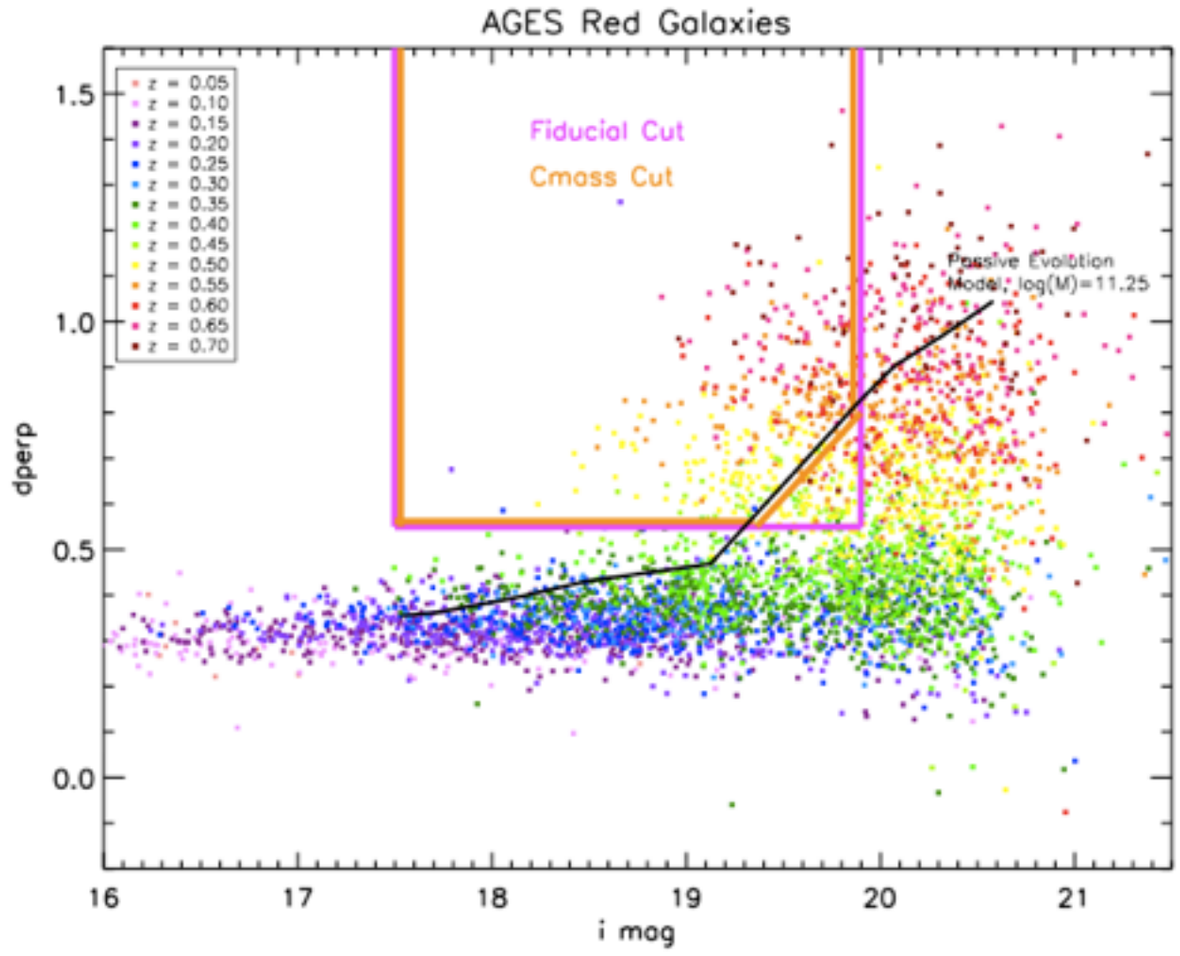
$$C_{ij}' = C_{ij}\,(\,1 + \delta_{ij}\,(f_i - 1)(f_j - 1)e^2\,)$$



$$f_i = RSD(QPM)/Linear(QPM)$$

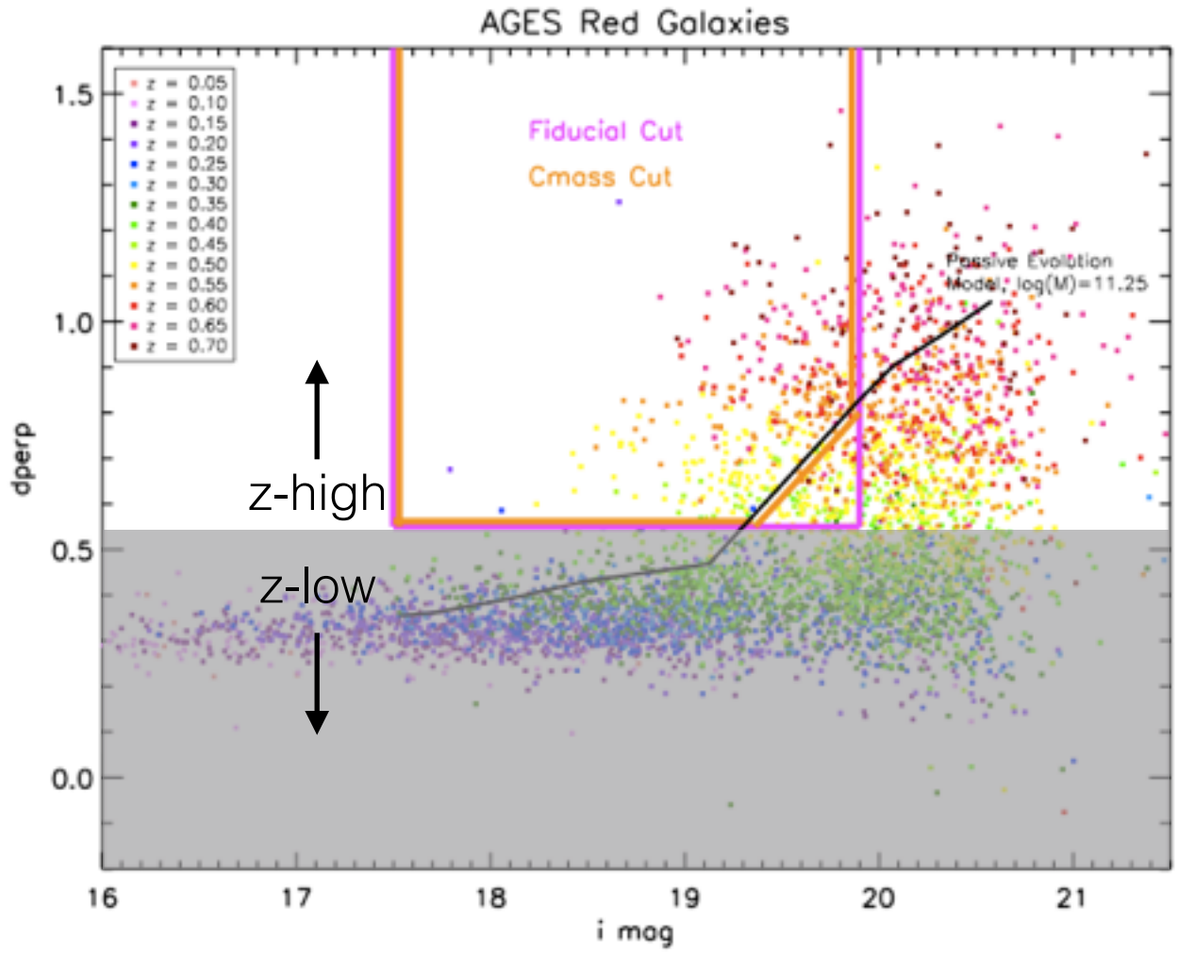
Uniform Galaxy Data Sample

- Uniform Sample in Redshift



Uniform Galaxy Data Sample

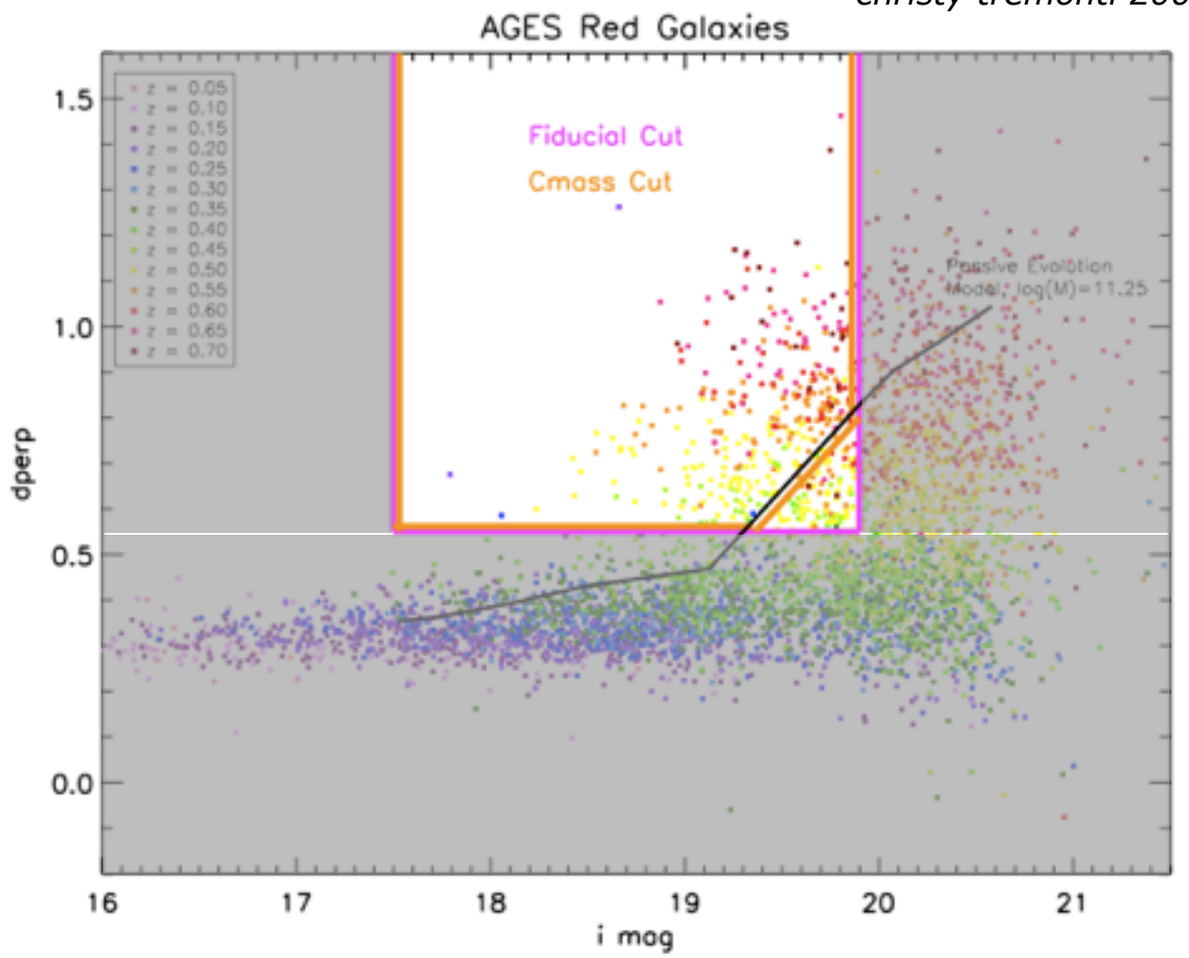
- Uniform Sample in Redshift
  - z-Cut ~ dperp-cut
    0.43 < z <0.7



Uniform Galaxy Data Sample

- Uniform Sample in Redshift
  - z-Cut ~ dperp-cut
    0.43 < z <0.7
  - i mag-Cut
    faint-bright limits

christy tremonti 2009

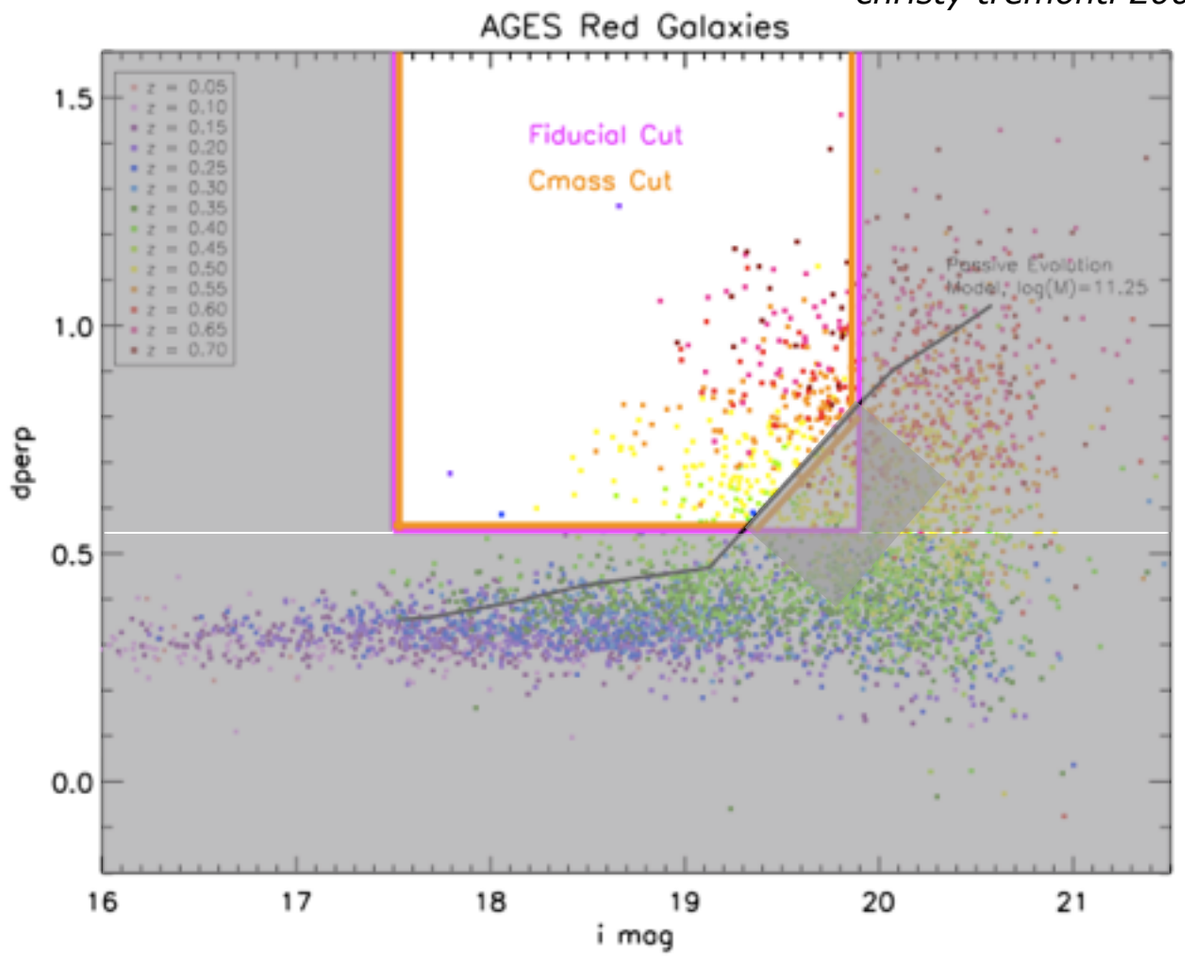


Uniform Galaxy Data Sample

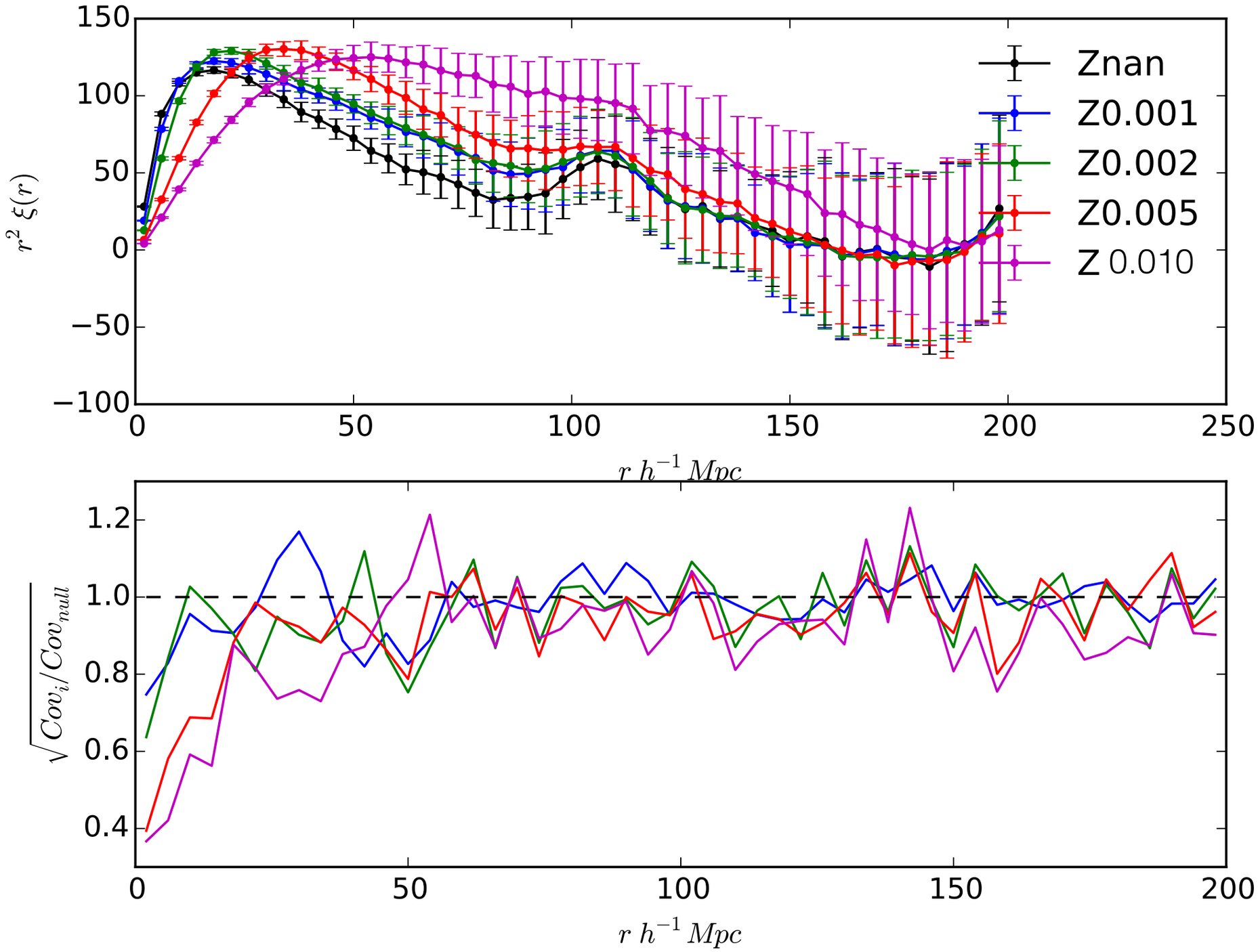
- Uniform Sample in Redshift
  - z-Cut ~ dperp-cut
    0.43 < z <0.7
  - i mag-Cut
    faint-bright limits
  - passively evolving gals
    constant-stellar mass

Best BOSS CMASS Sample

christy tremonti 2009



Phot vs Spect



Mock Galaxies Catalogues (QPM)

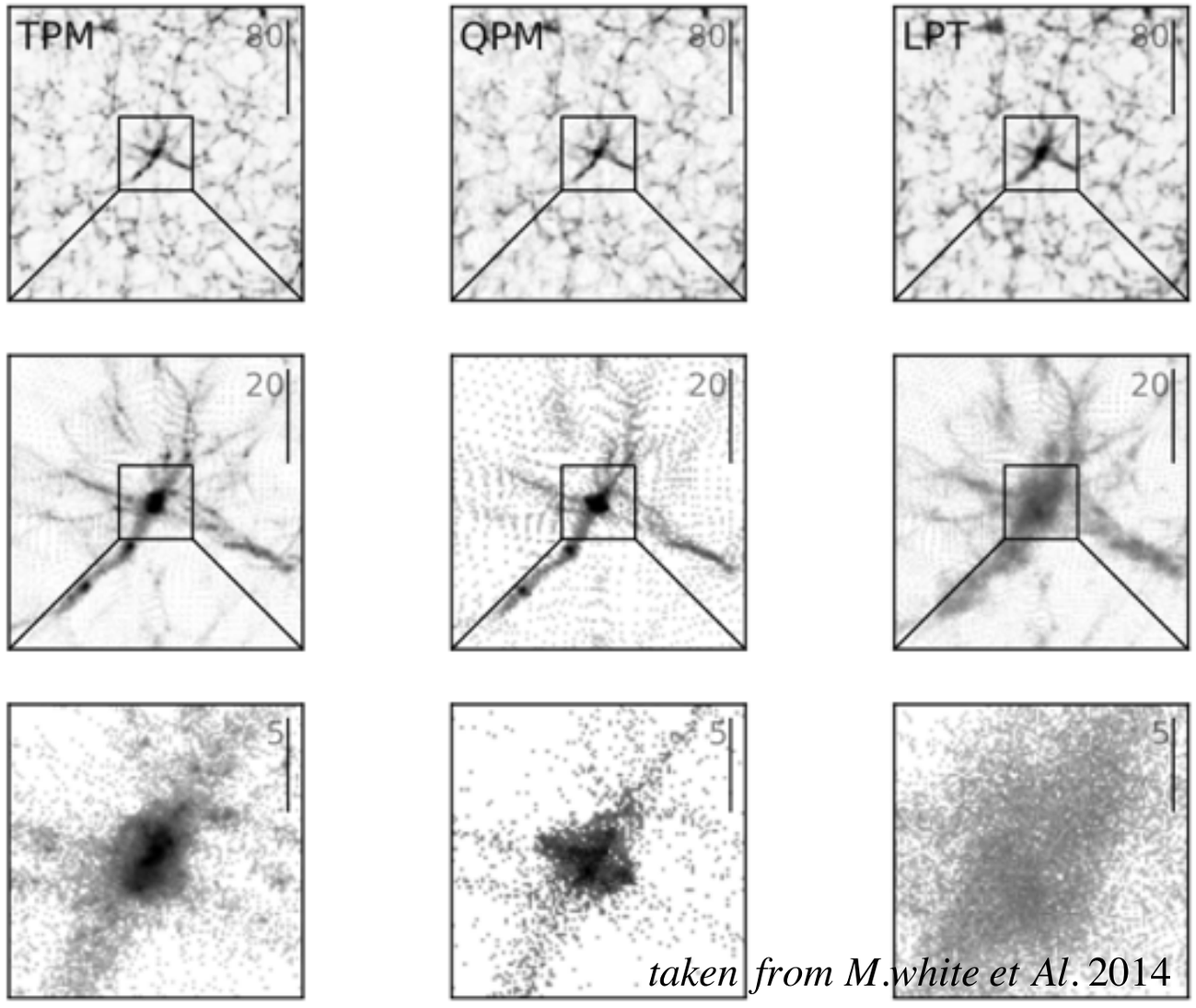
Basic Method

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

Analysis Usage

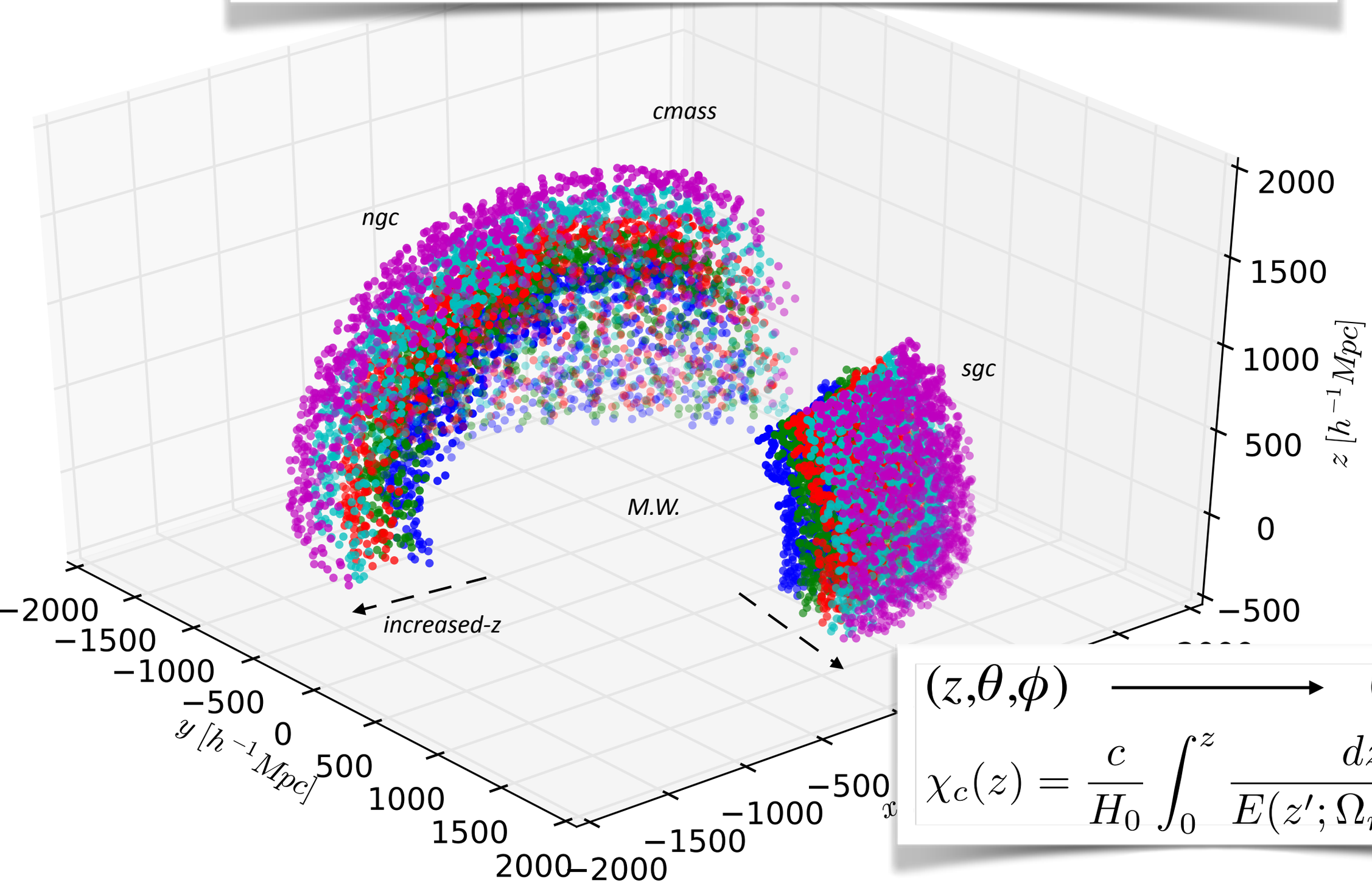
- Compute Covariance Matrices
- Use in Analysis Tests

ref: 1309.5532v2, 1203.6609v2



taken from M.white et Al. 2014

Distance Reconstruction



$$(z,\theta,\phi) \longrightarrow (r,\theta,\phi)$$

$$\chi_c(z) = \frac{c}{H_0}\int_0^z \frac{dz'}{E(z';\Omega_{m0},\Omega_\Lambda)}$$