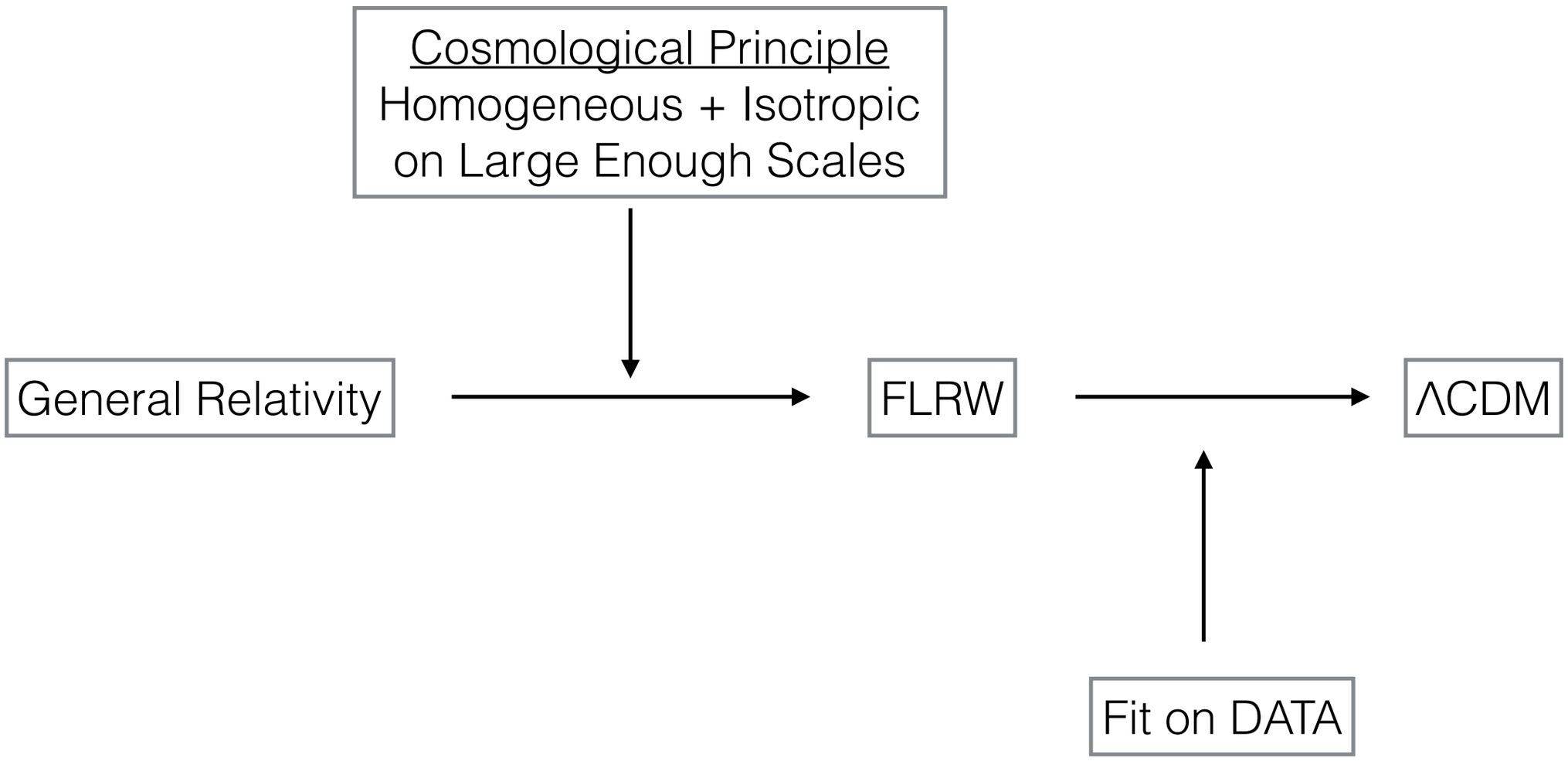
The Homogeneity Scale of the Universe with Large Scale Structure Surveys

PhD student: P. Ntelis

PhD advisor: J.C. Hamilton

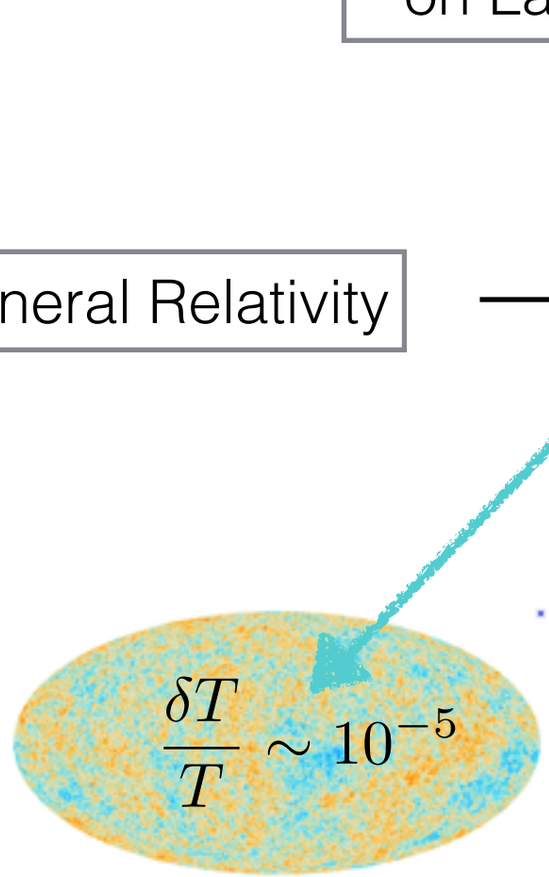
10 Nov 2016


Cosmological Principle
Homogeneous + Isotropic
on Large Enough Scales
General Relativity
FLRW
ΛCDM
Fit on DATA

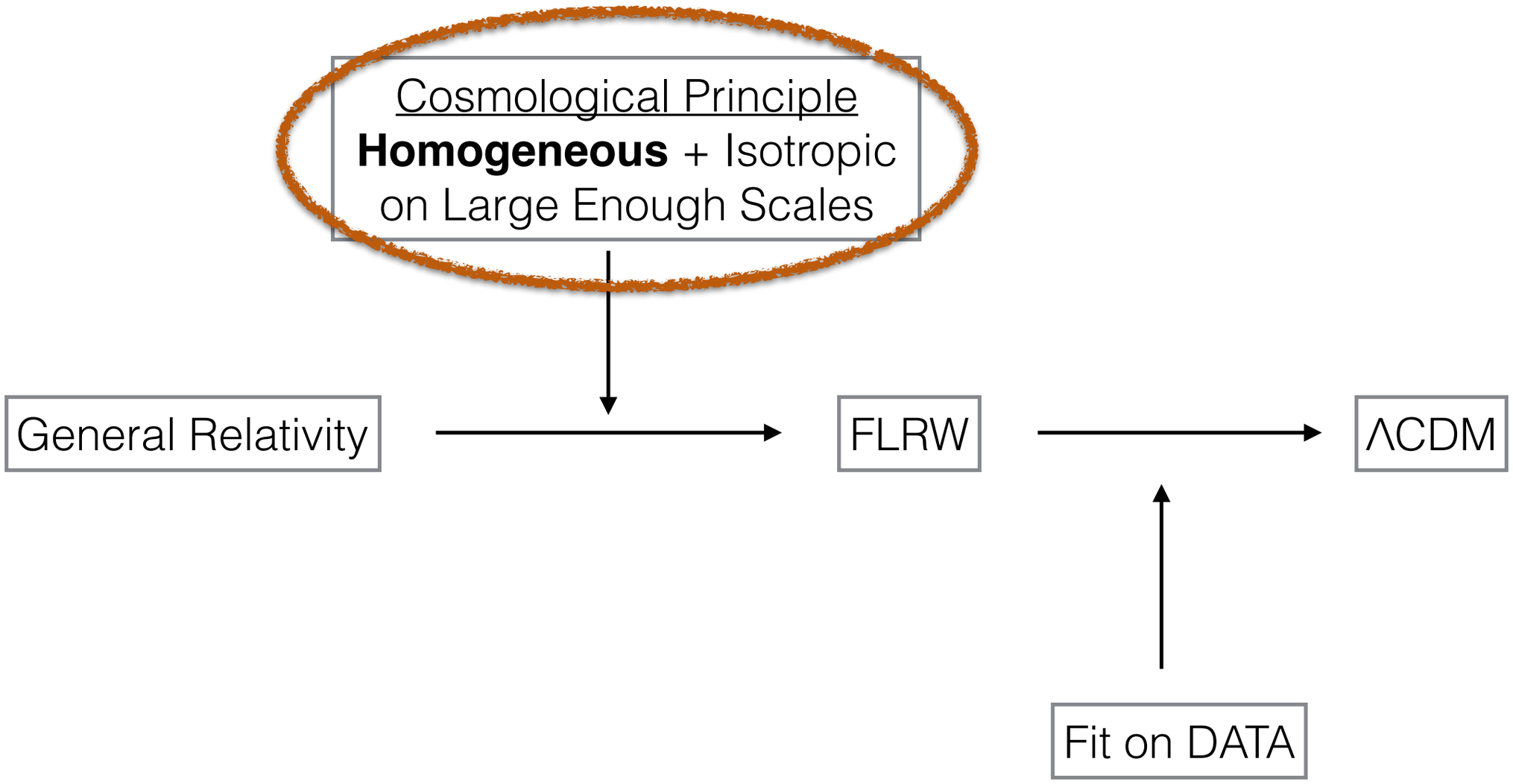
Cosmological Principle
Homogeneous + **Isotropic**
on Large Enough Scales

General Relativity → FLRW → ΛCDM

Fit on DATA



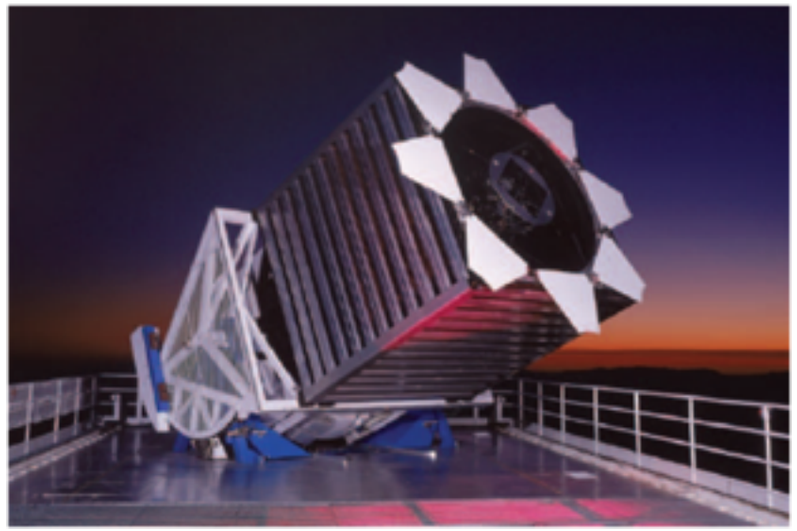
Is this assumption data-motivated ?

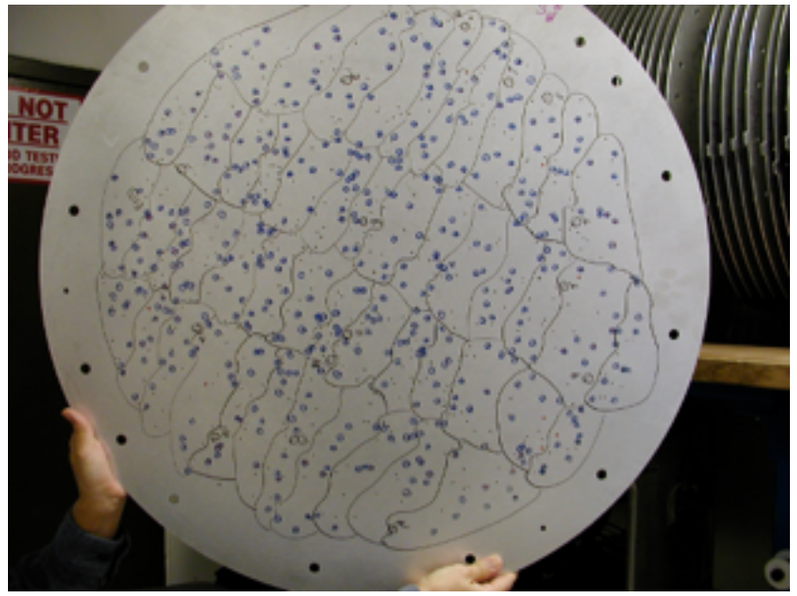


How to check for Homogeneity ?

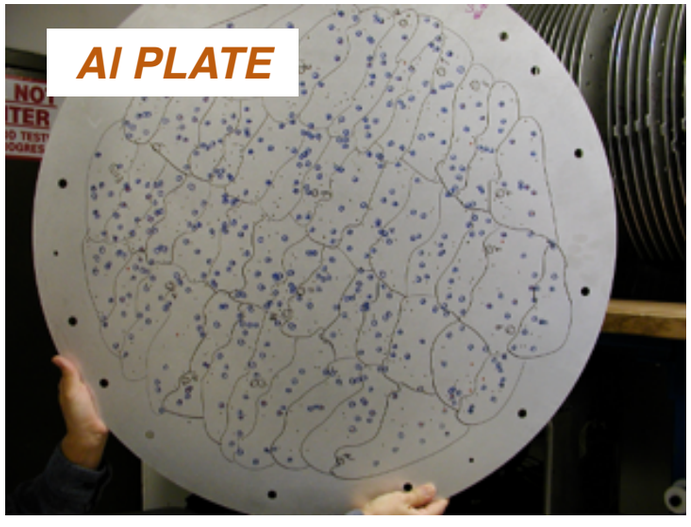
SDSS-III / BOSS

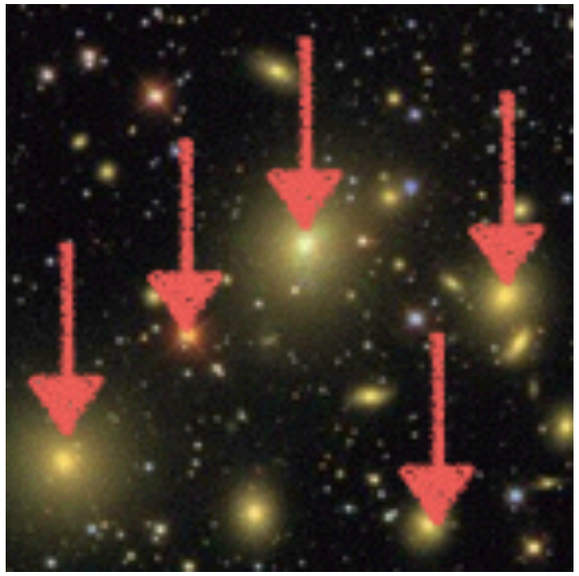
- Main project:
  - APO telescope (New Mexico, USA)
  - 2.5 m diameter
- Spectroscopic Survey:
  - 360 nm < λ < 1000 nm
  - FoV: 10 400 deg^2 :
    - 1.5×10^6 LRG $at \langle z \rangle \sim 0.6$
    - 150 000 QSO, $Ly\text{-}a\ Forests\ at \langle z \rangle \sim 2.5$
- Objectives:
  - Galaxy Clustering Science
  - Cosmological Parameters

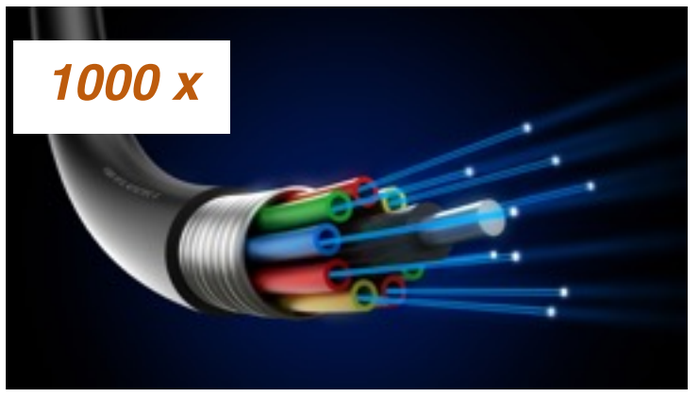




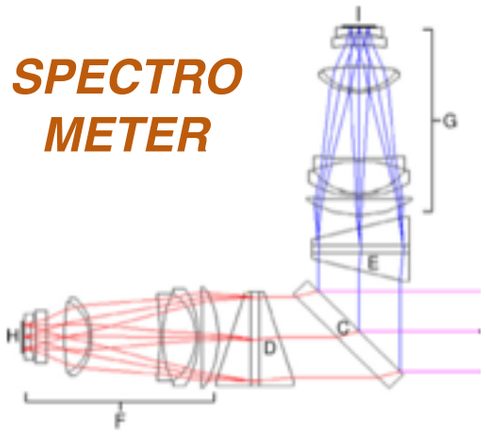
BOSS in a Nutshell



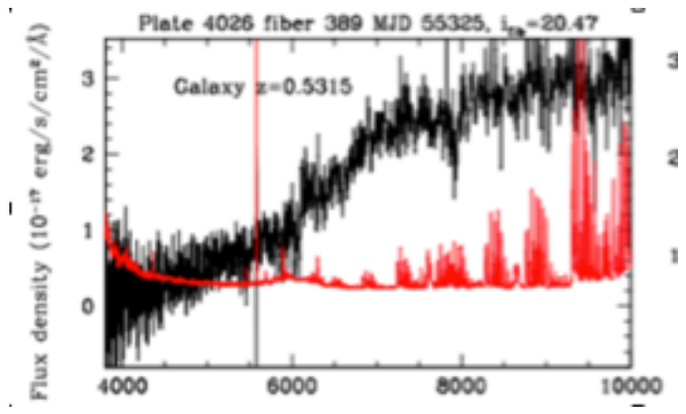




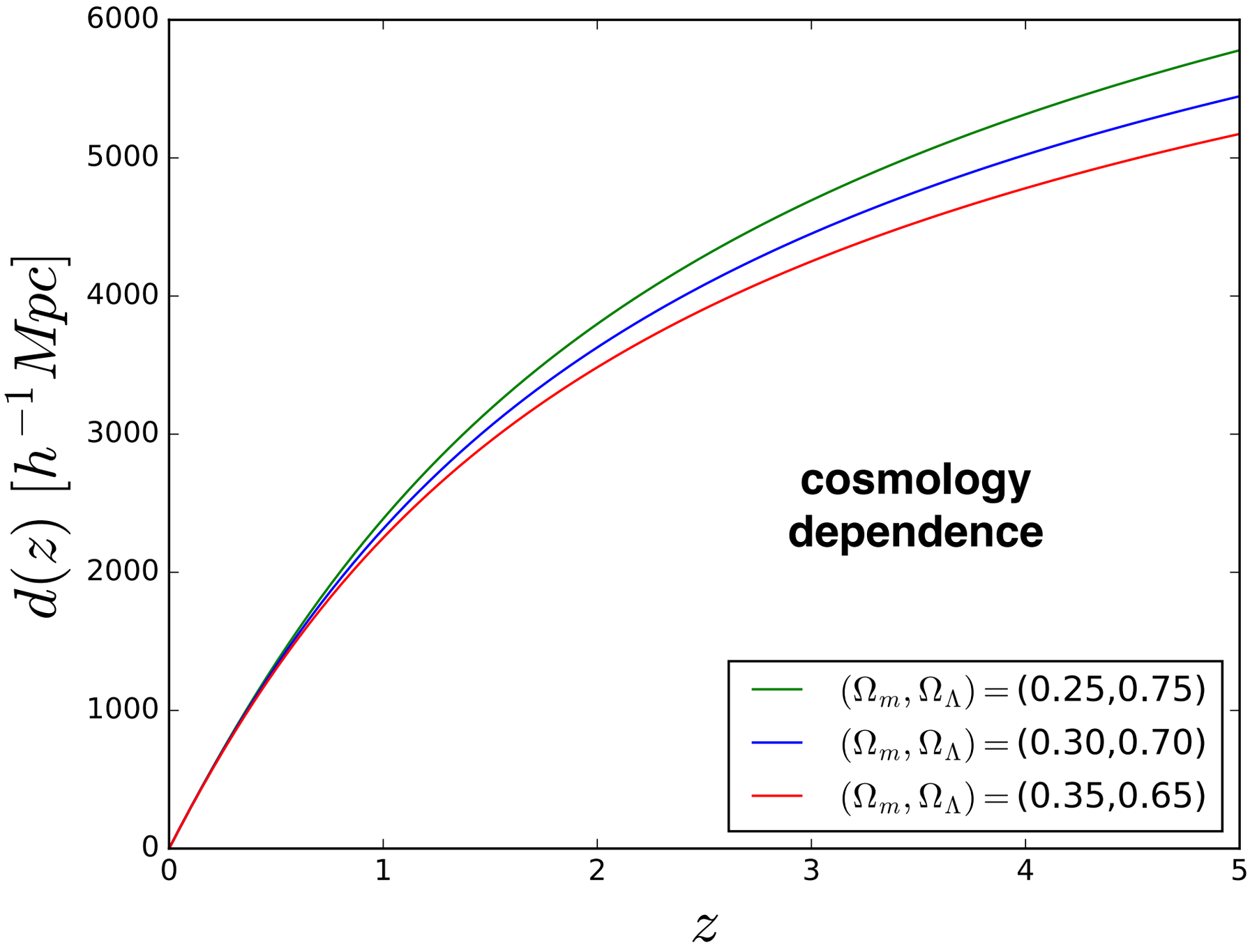
SPECTRO METER



SPECTROSCOPY



Measure distances in the Universe



Observable ?

Which range to measure?

Observable ?

Which range to measure?

Account for RSD ?

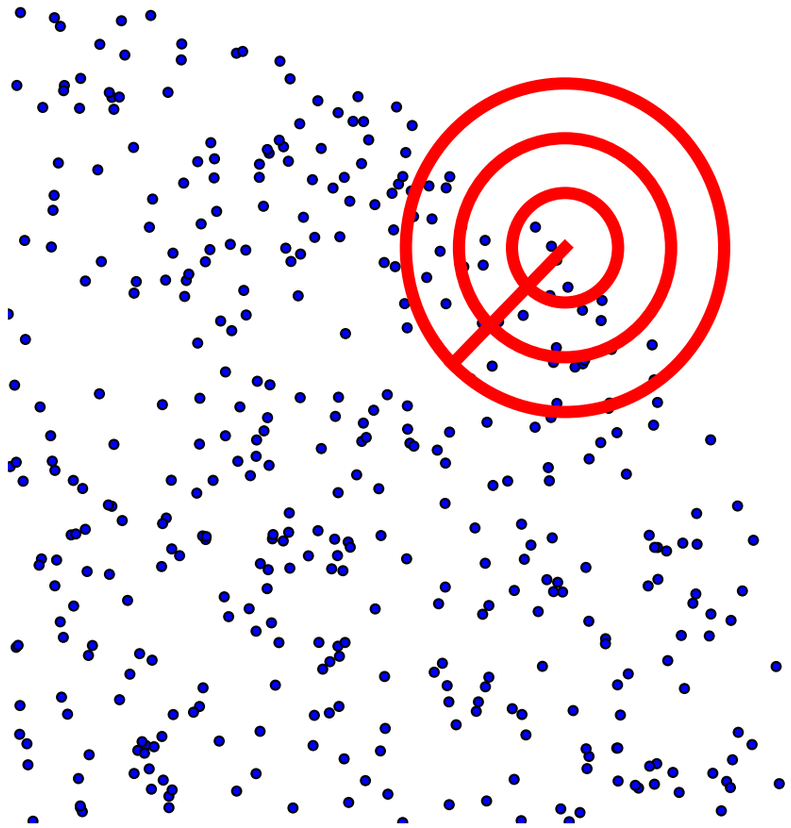
Theory?

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

How to measure density

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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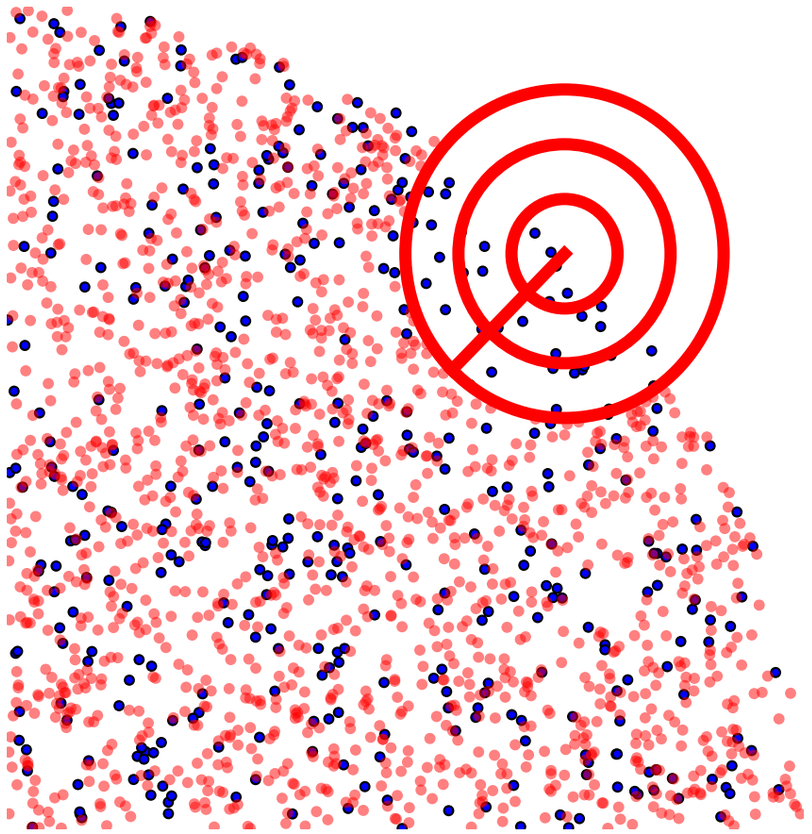

Homogeneity Scale Estimator

- 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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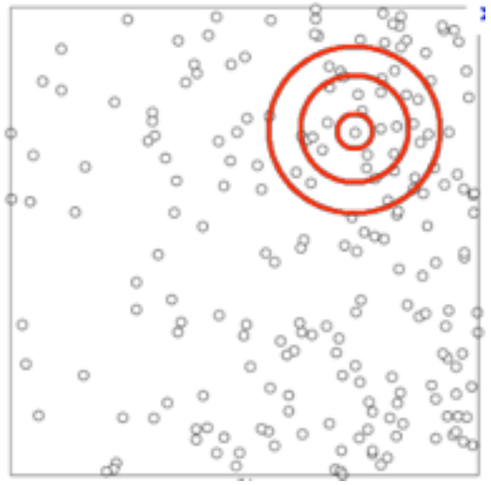

- Inhomogeneous :
  @ small scales (clustering) $D_2(r) < 3$

- Homogeneous
  @ large scales

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

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  @ large scales $D_2(r) = 3$

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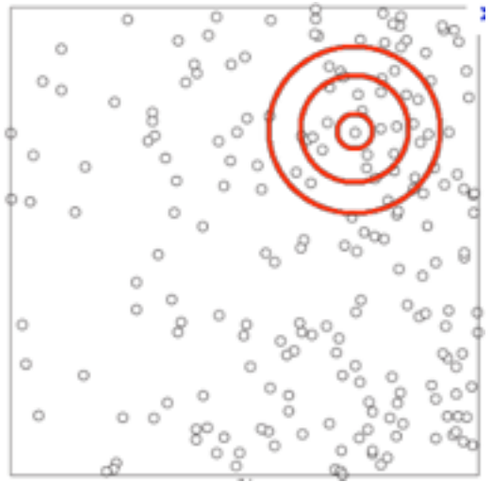
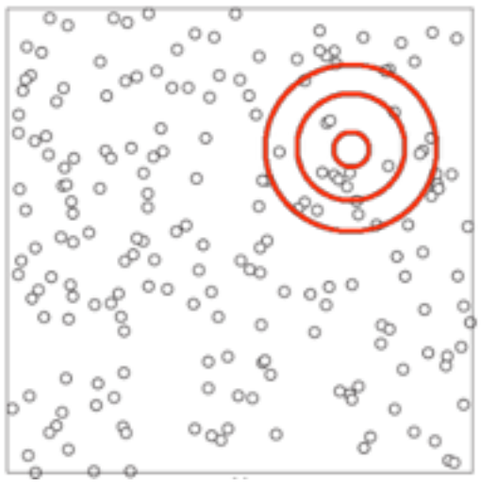




Homogeneity Scale Estimator

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

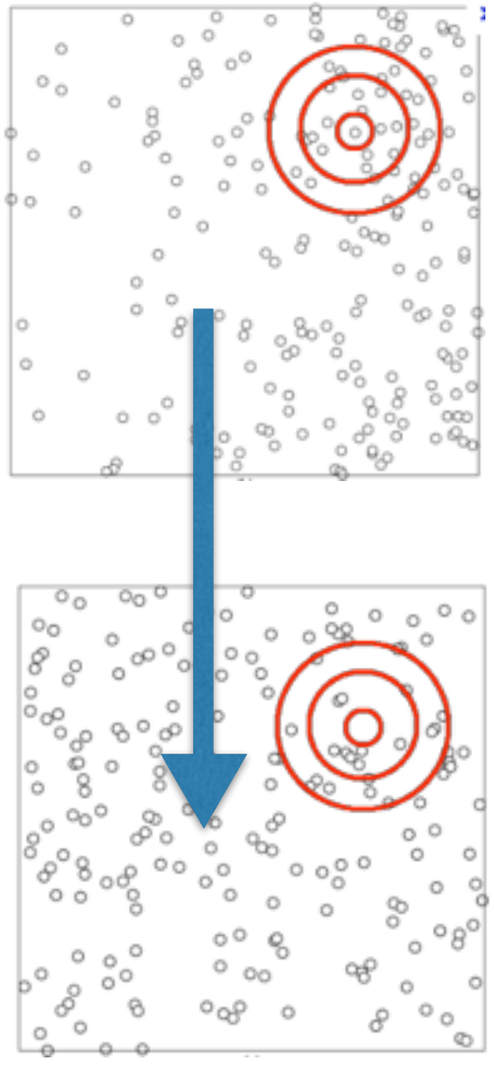
- Inhomogeneous :
  @ small scales (clustering) $D_2(r) < 3$

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

- Transition to Homogeneity at:

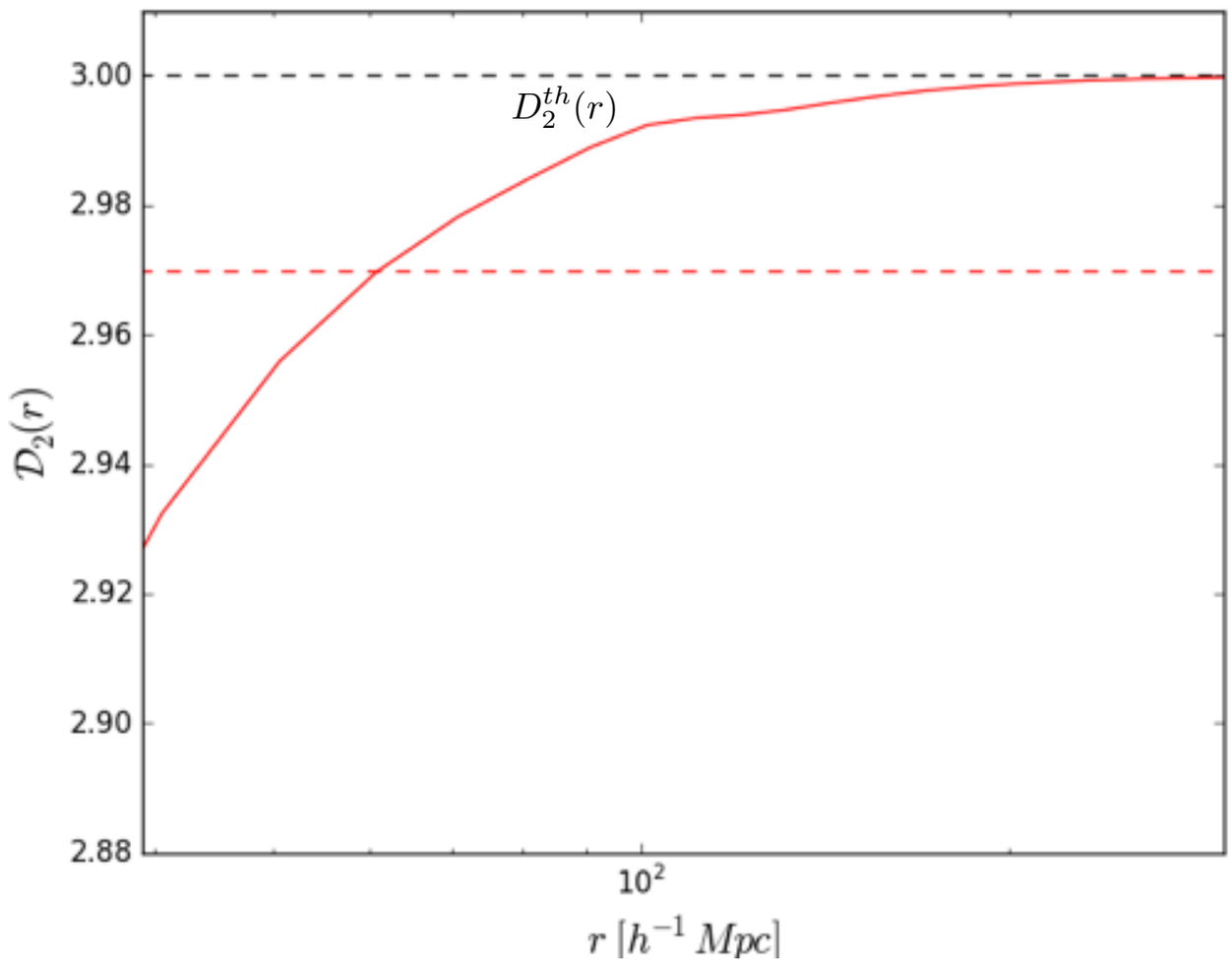
$$D_2(R_H) = 3 \ @ \ 1\%$$

Arbitrary Choice



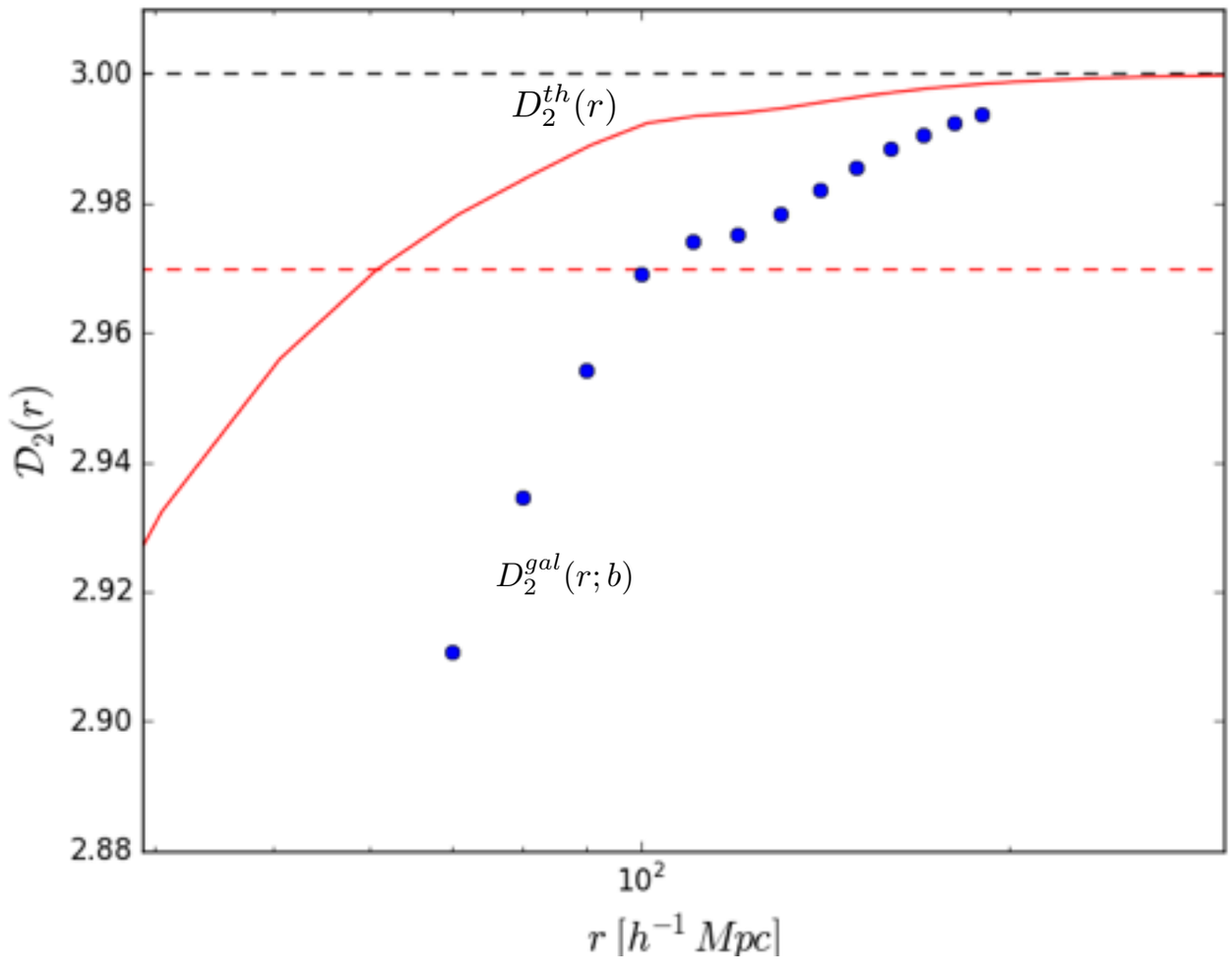
Matter-Observable Reconstruction

- Theory $D_2^{th}(r)$



Matter-Observable Reconstruction

- Theory $D_2^{th}(r)$
- Simulated galaxy distribution $D_2^{gal}(r;b)$



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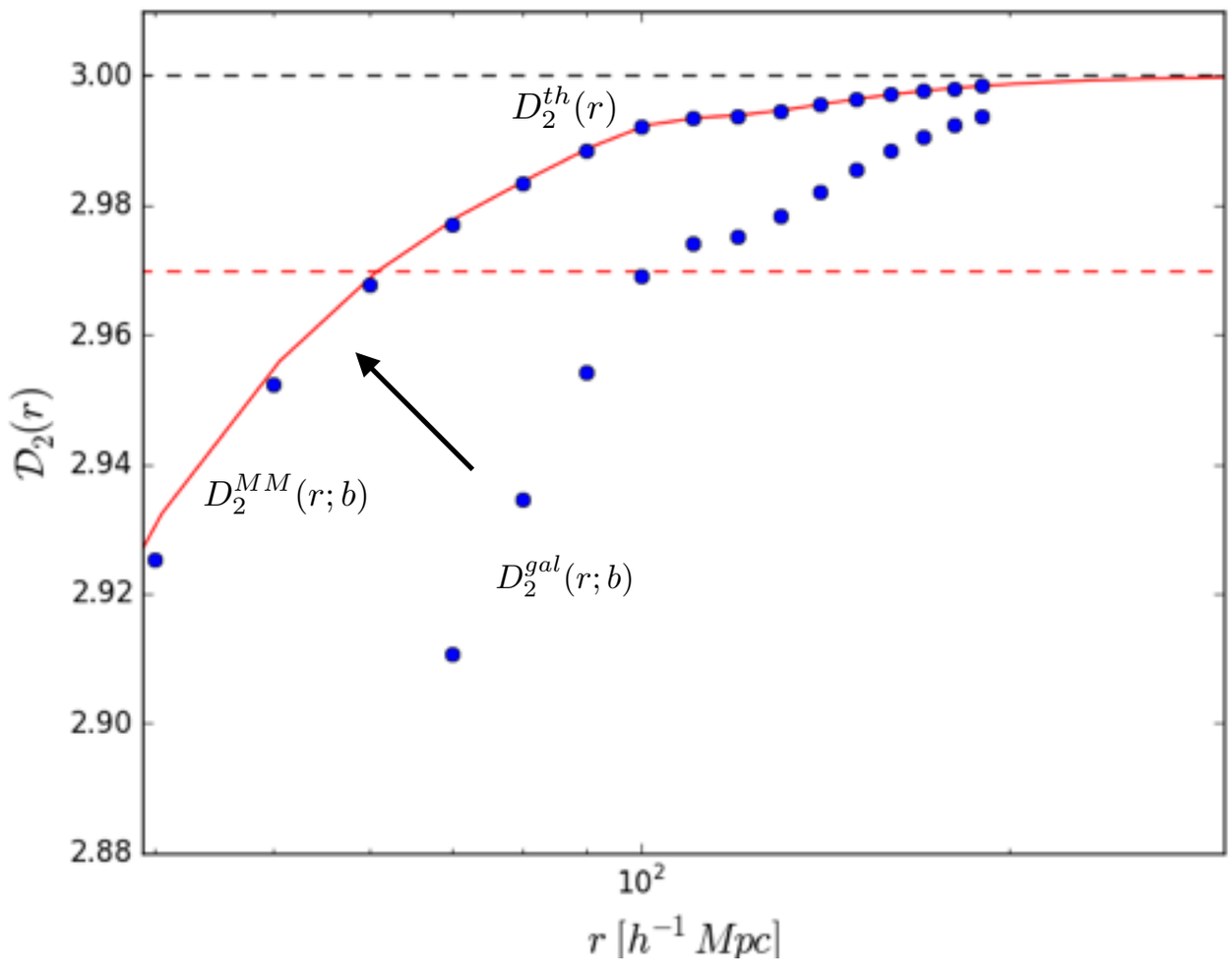
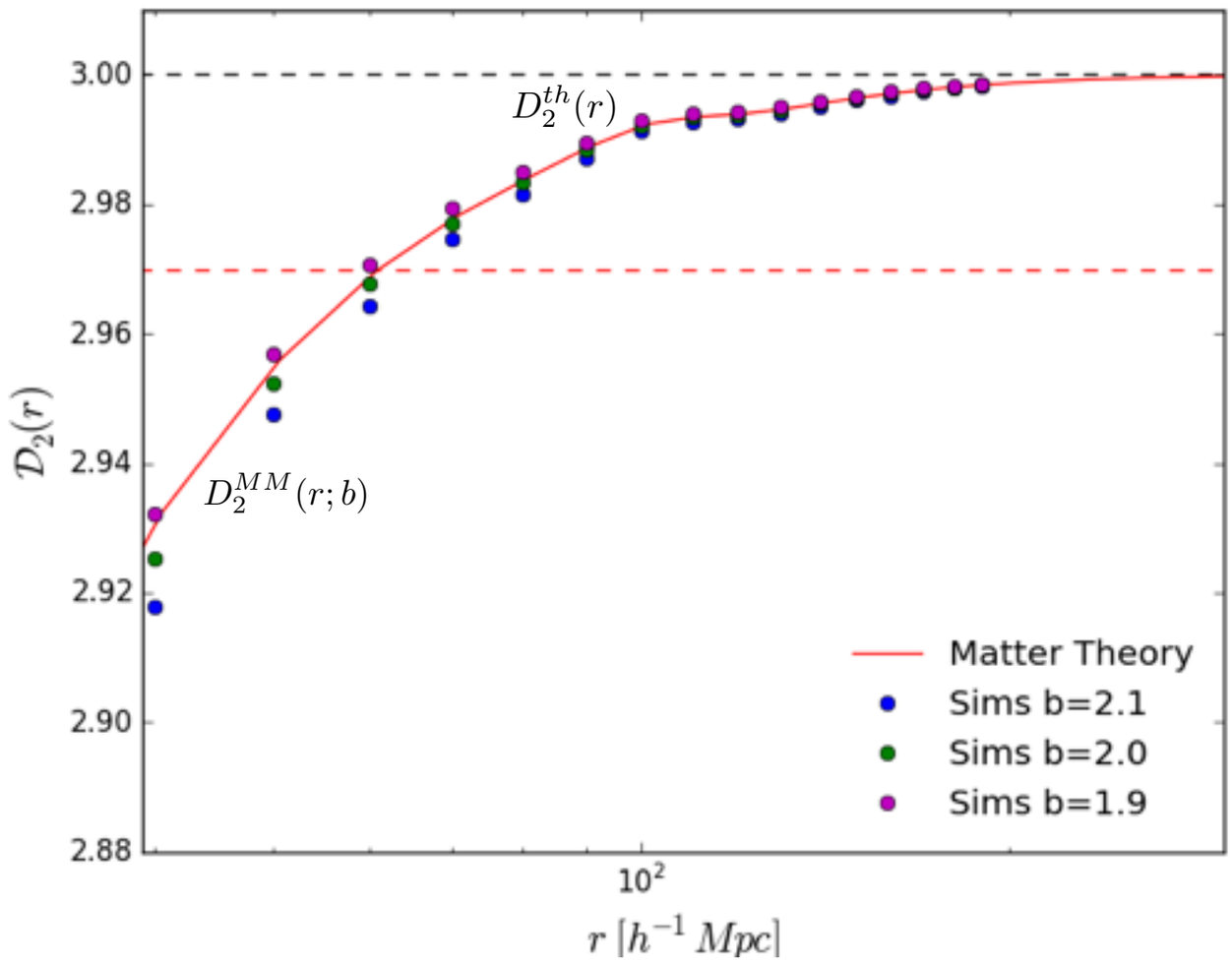
- Convert to $D_2^{MM}(r;b)$



Matter-Observable Conversion

- Theory $D_2^{th}(r)$
- Simulated galaxy distribution $D_2^{gal}(r;b)$
- Convert to $D_2^{MM}(r;b)$
- 3 diff Distributions

Need to account for bias

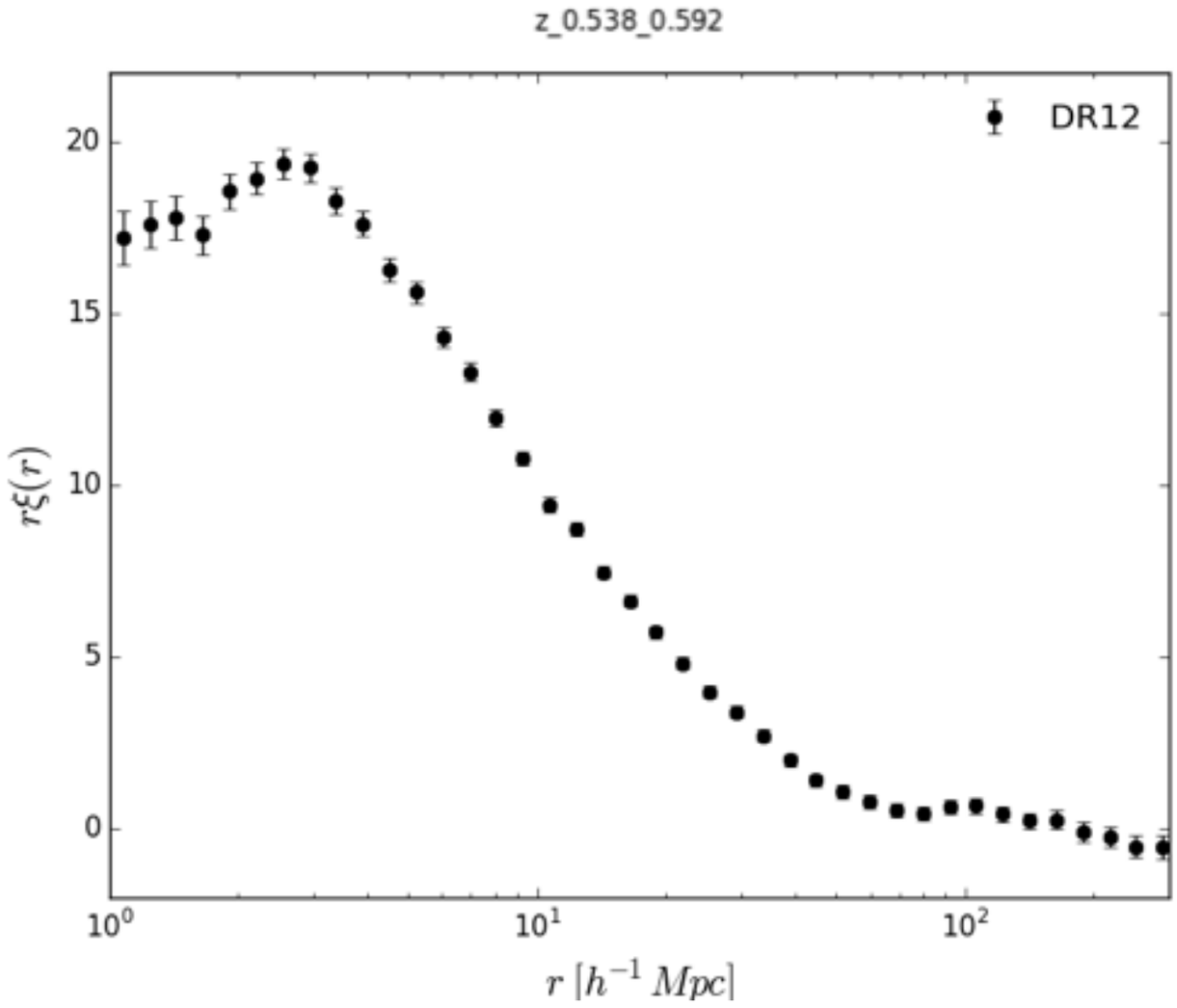


RSD Analysis

Determination:

bias, peculiar velocities

- Kaiser @ r>10Mpc/h
- FoG @ r<10Mpc/h



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- Kaiser @ r>10Mpc/h
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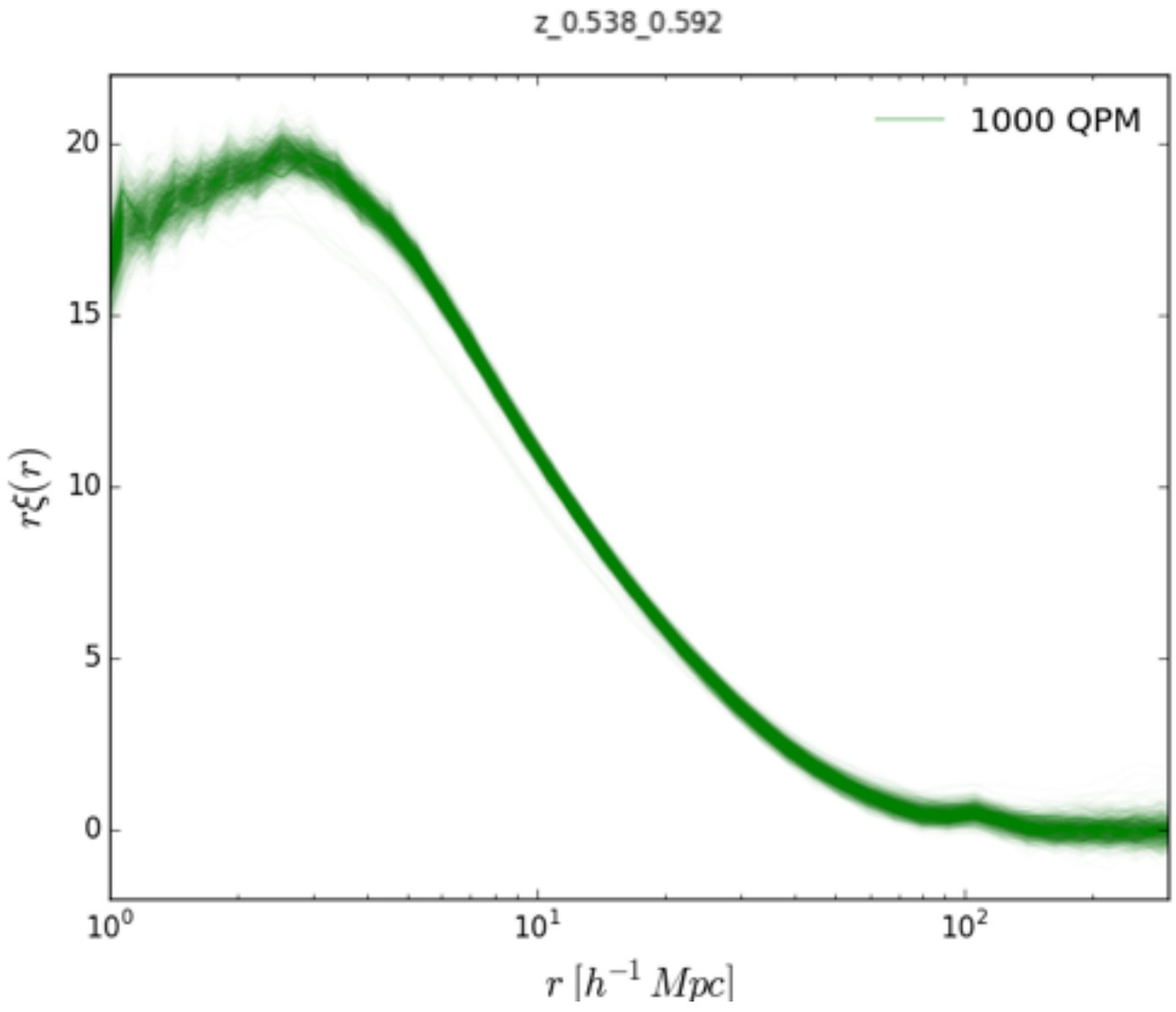

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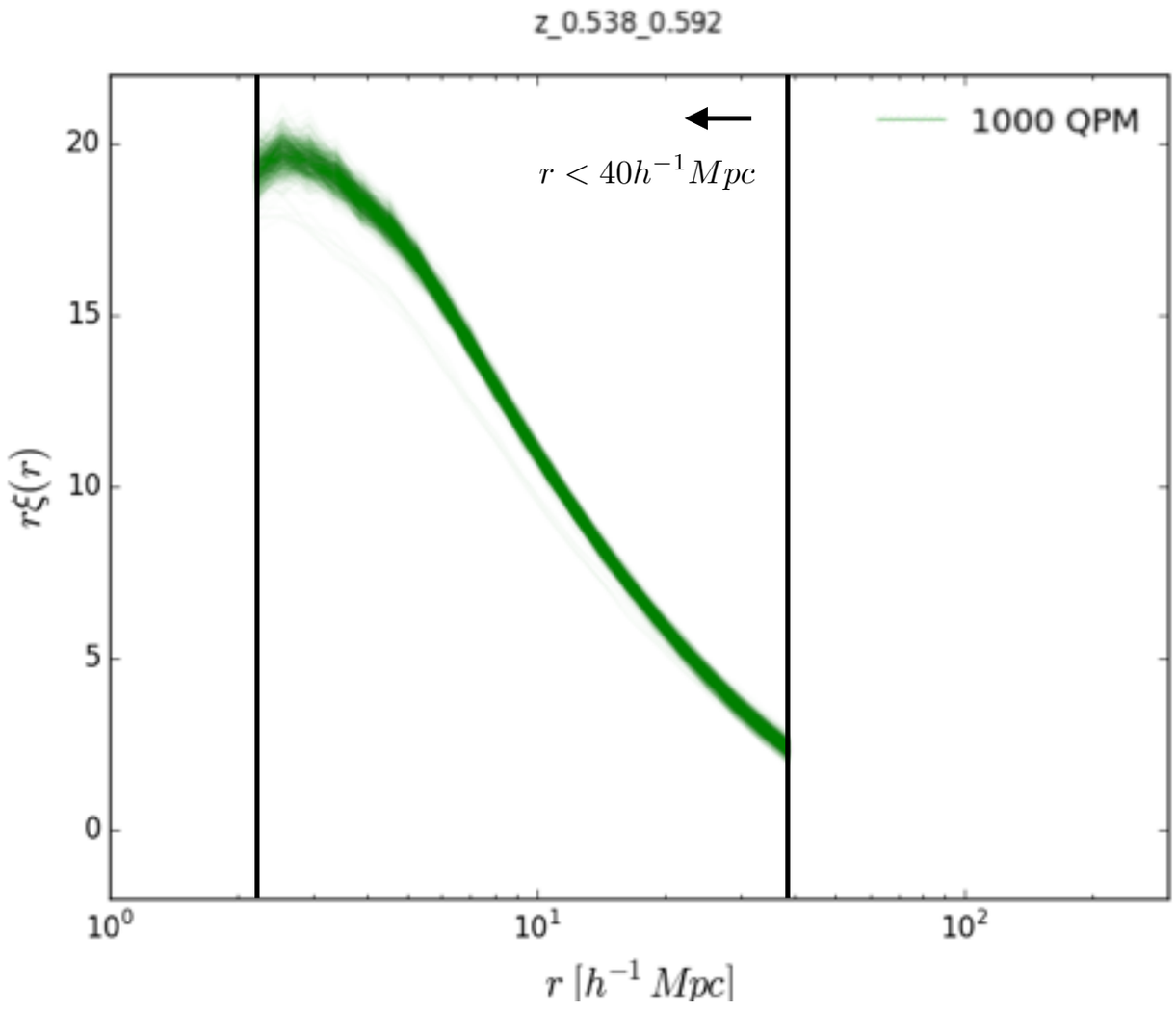
- Theoretical Model
- CLASS soft (+Halofit)

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



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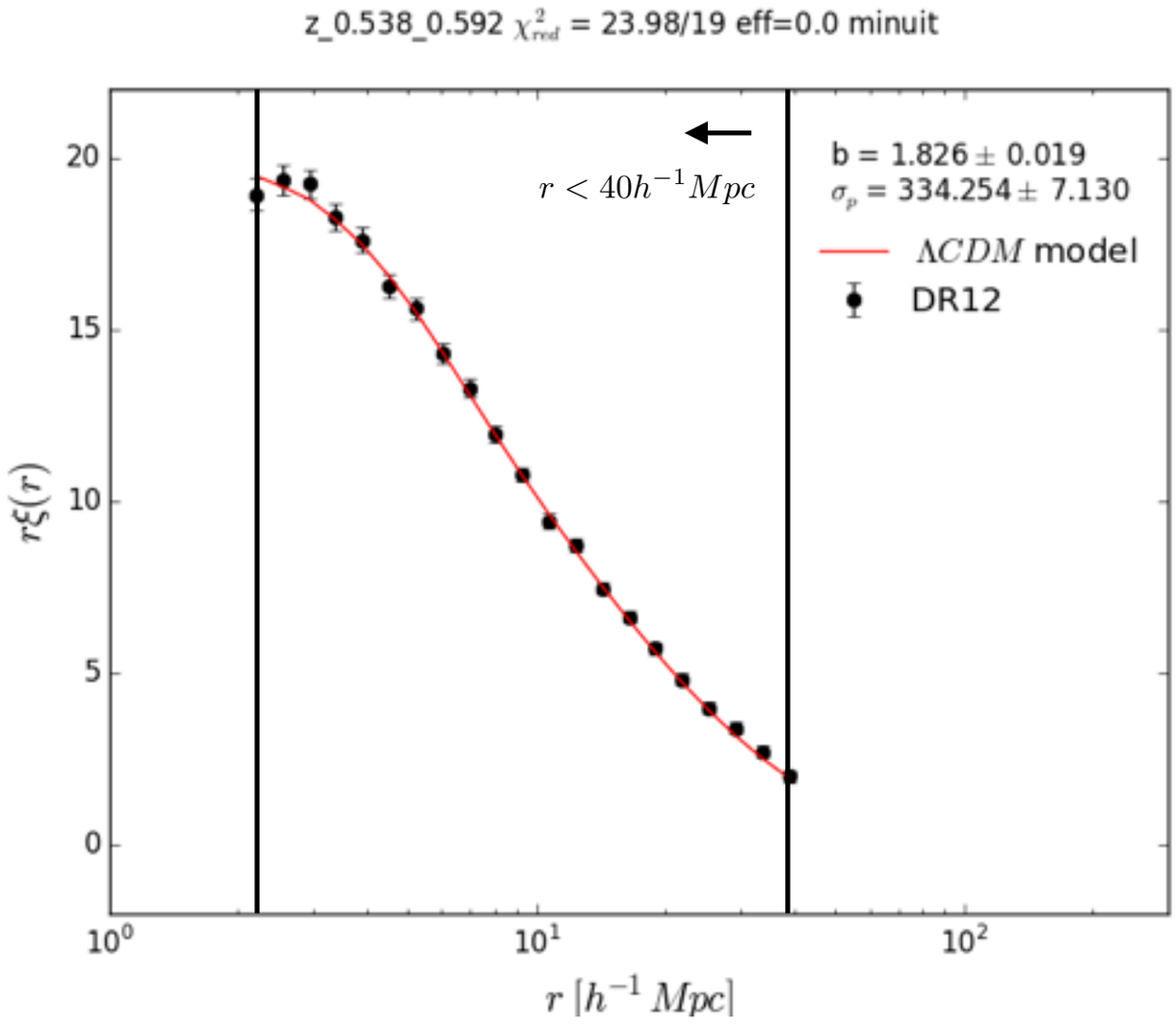

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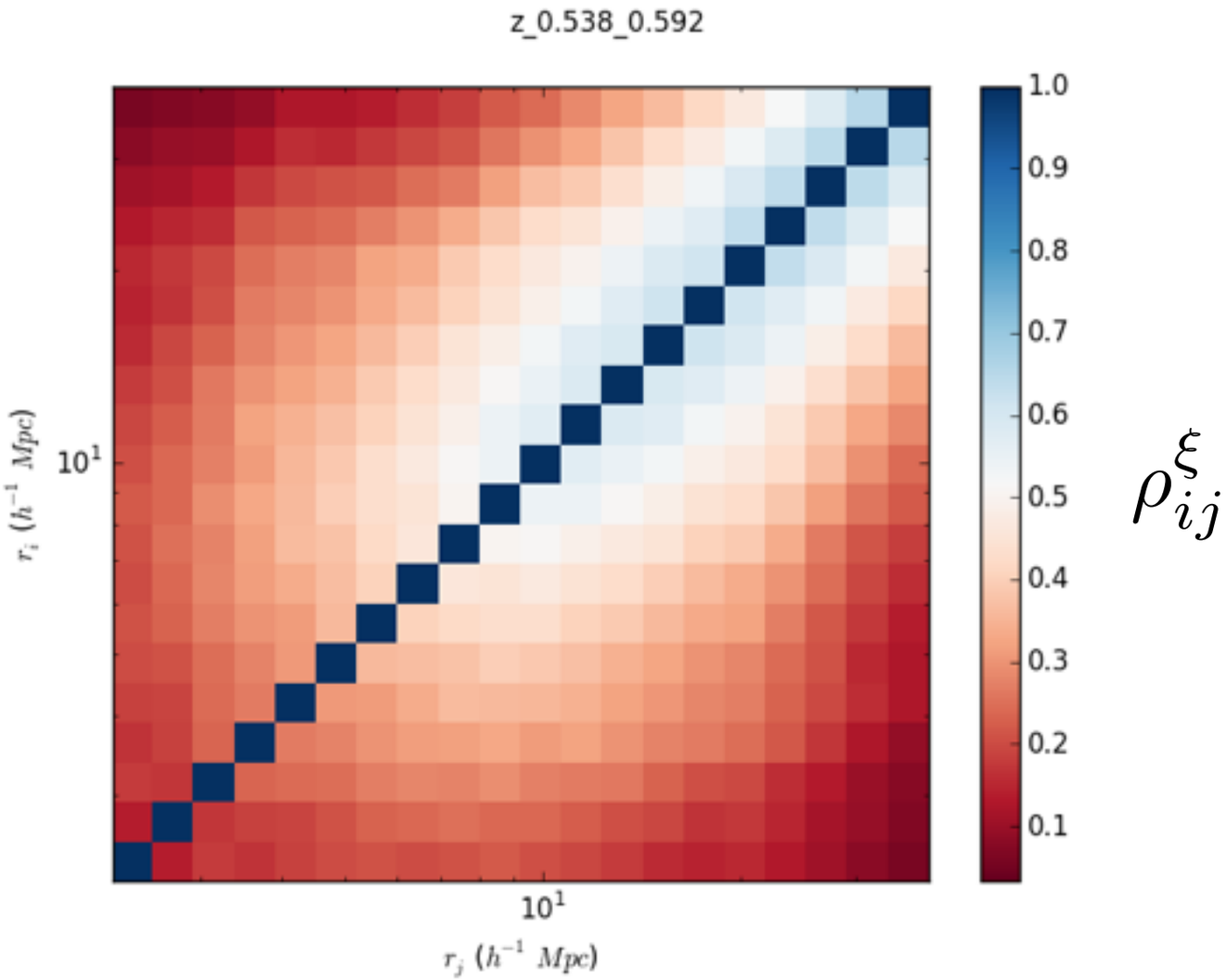
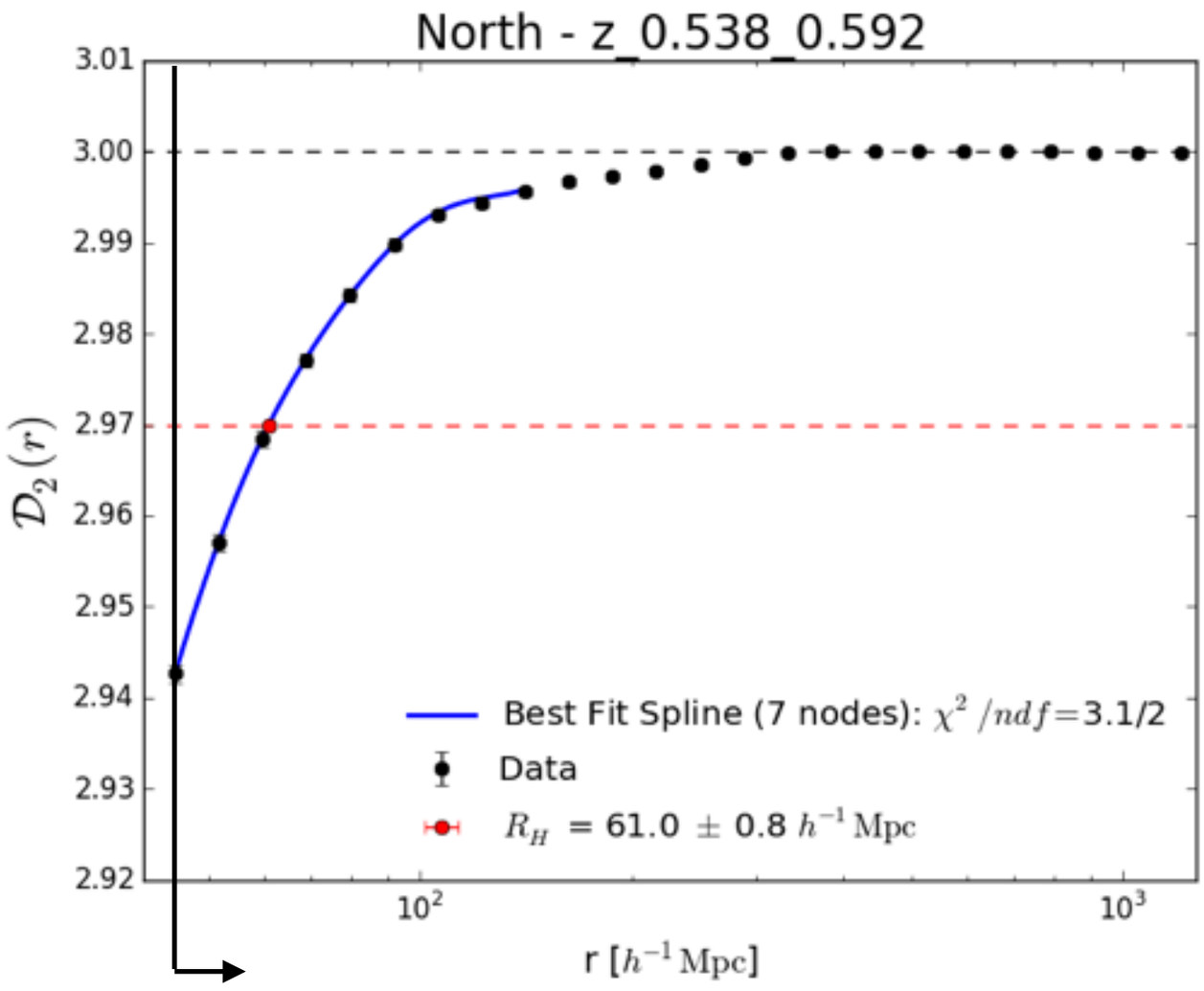


Results

- Well Distinct Fitting Space
- $\mathcal{D}_2$ increases with scale

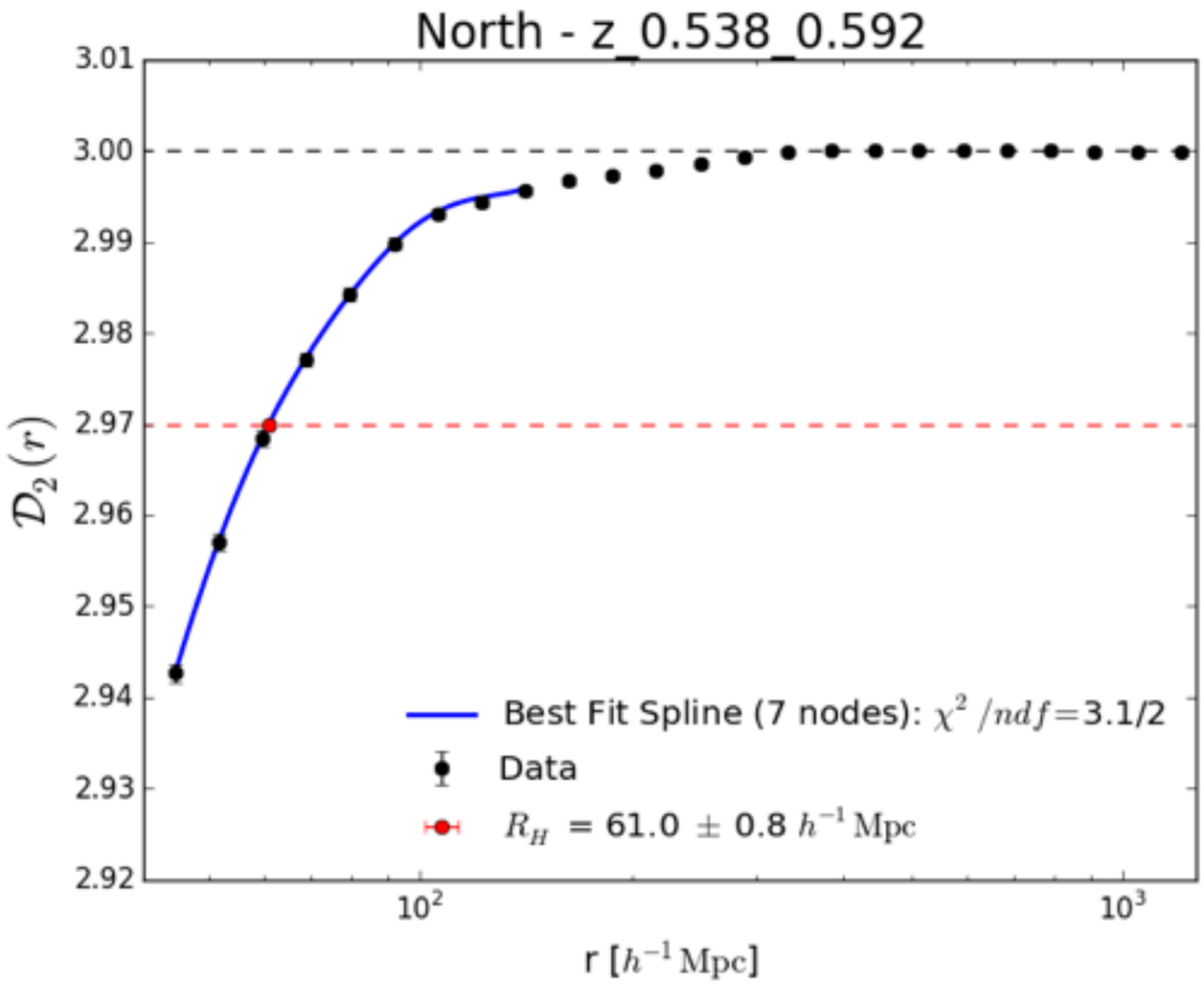


$r > 40h^{-1}Mpc$

$$\delta R_H = f\left(\delta a_i^{spl}; R_H\right)$$

Results

- Well Distinct Fitting Space
- increases with scale
- Cosmological Principle confirmed:
  - DR12 DATA



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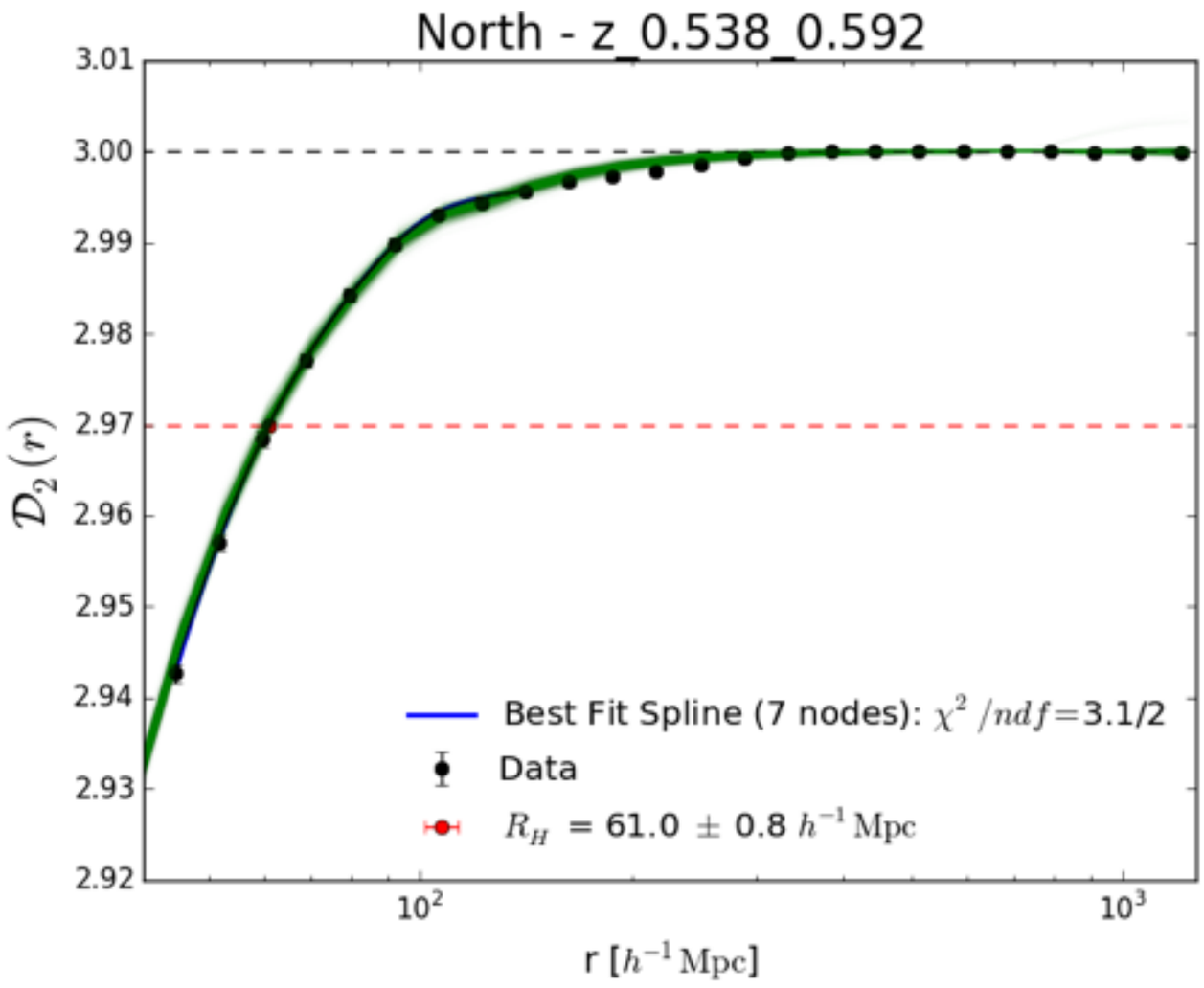
Results

- Well Distinct Fitting Space
- $\mathcal{D}_2$ increases with scale
- Cosmological Principle confirmed:
  - DR12 DATA
  - 1000 QPM-ΛCDM



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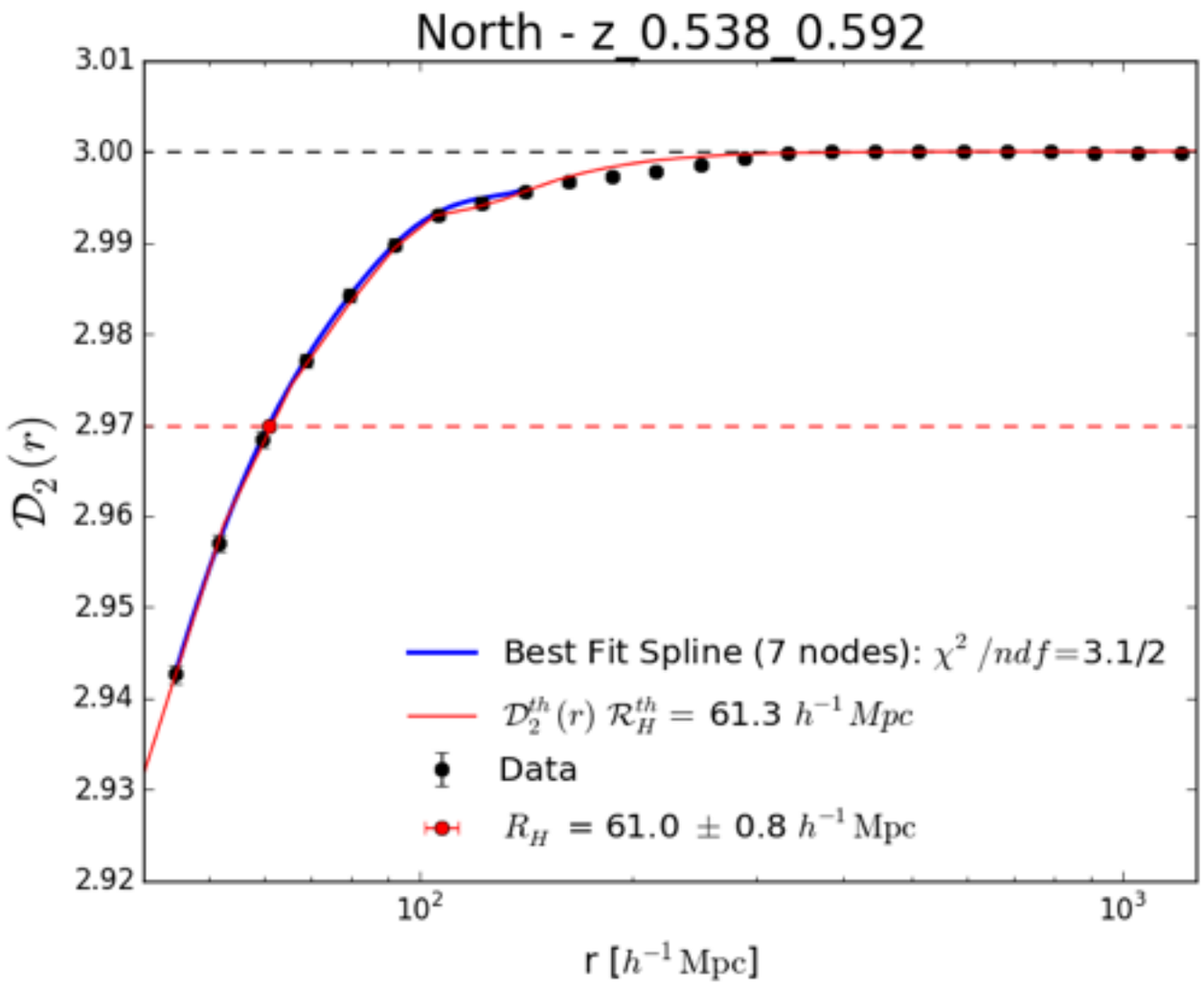
  - 1000 QPM-ΛCDM
  - ΛCDM PLANCK 2015



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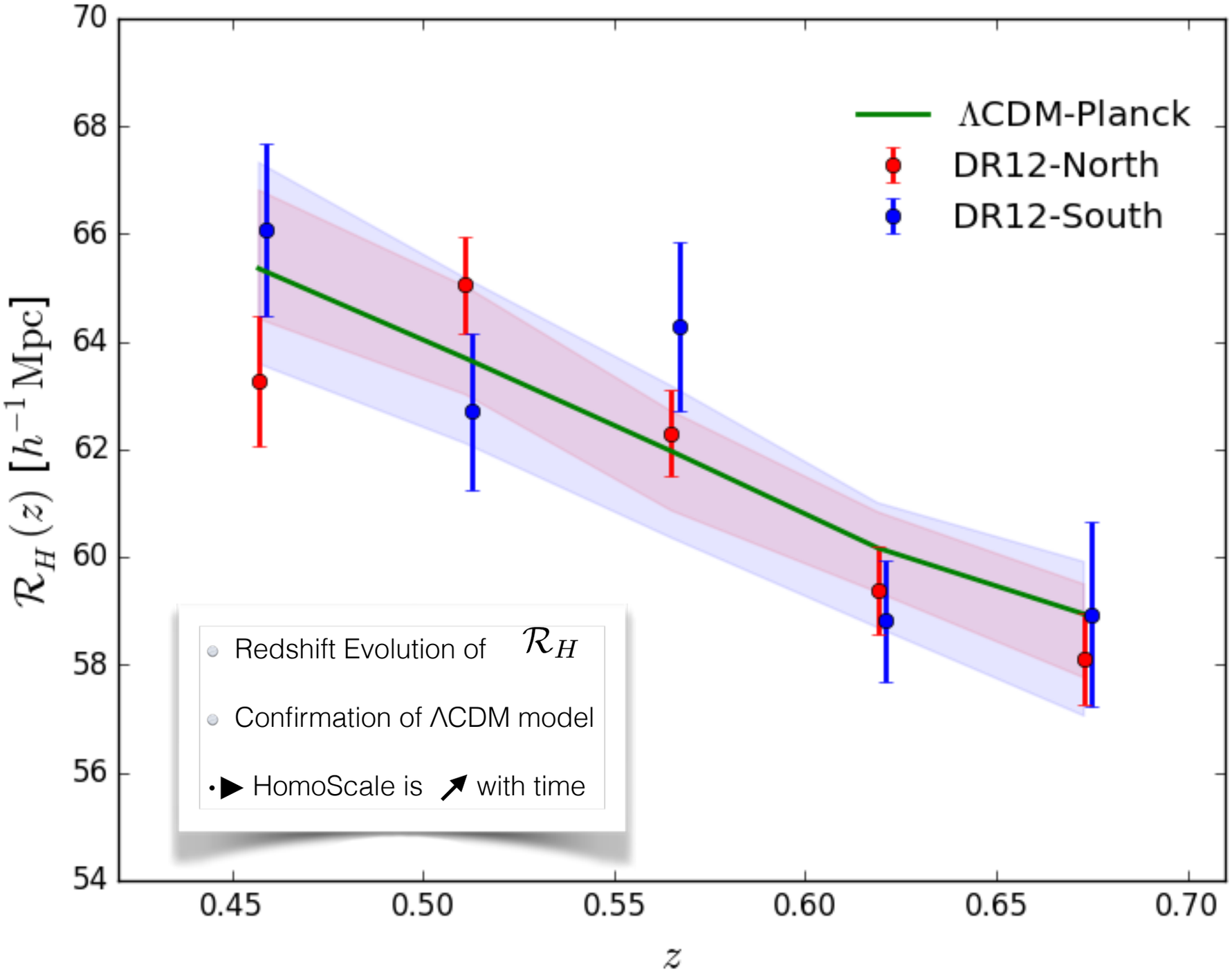
Results


ΛCDM-Planck
DR12-North
DR12-South
Redshift Evolution of $\mathcal{R}_H$
Confirmation of ΛCDM model
HomoScale is ↗ with time
$\mathcal{R}_H(z)$ $[h^{-1}\mathrm{Mpc}]$
z
70
68
66
64
62
60
58
56
54
0.45
0.50
0.55
0.60
0.65
0.70

Conclusion

Main Features:

- Largest Volume ever studied at z~0.5
- Precision of measurement ~1% (Wz ~5%)
- Easy application on different surveys
- High Robustness Through Mocks Tests

General limitations of these studies:

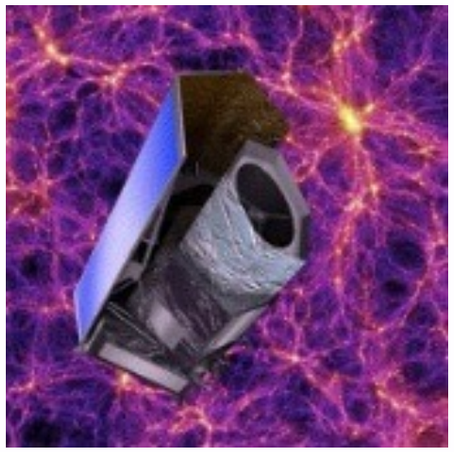
- Insensitive to radial density dependence
- Distance calculation assumes ΛCDM
- RSD Analysis assumes ΛCDM

→

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

Outlook

- Predictions for future projects (EUCLID, LSST)



- Use as Cosmological Standard Ruler
  - Cosmological Parameters
  - Nature of Dark Energy
  - Acceleration of the Universe

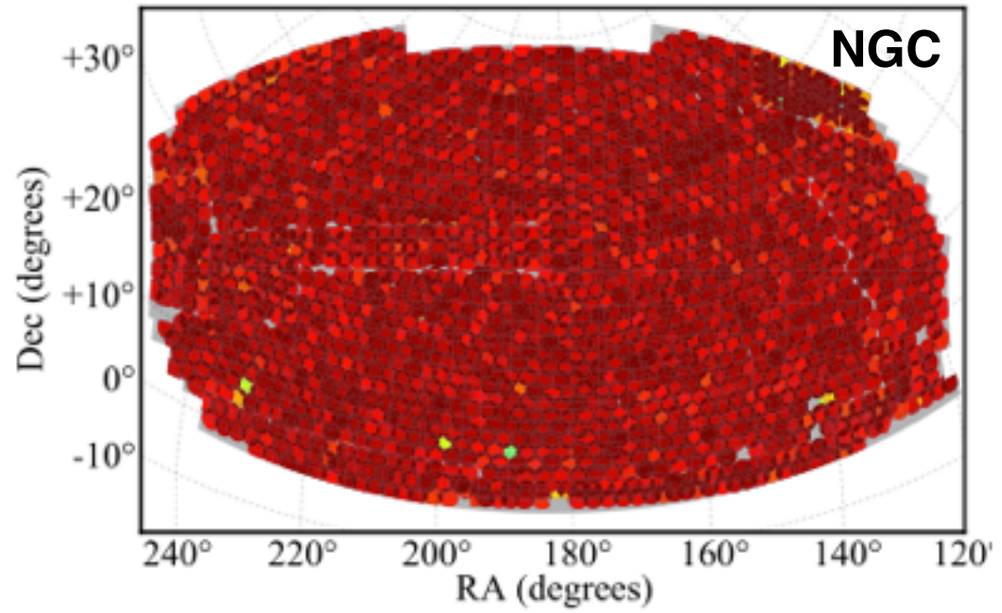
Thank you for your attention !

BACKUP - SLIDES

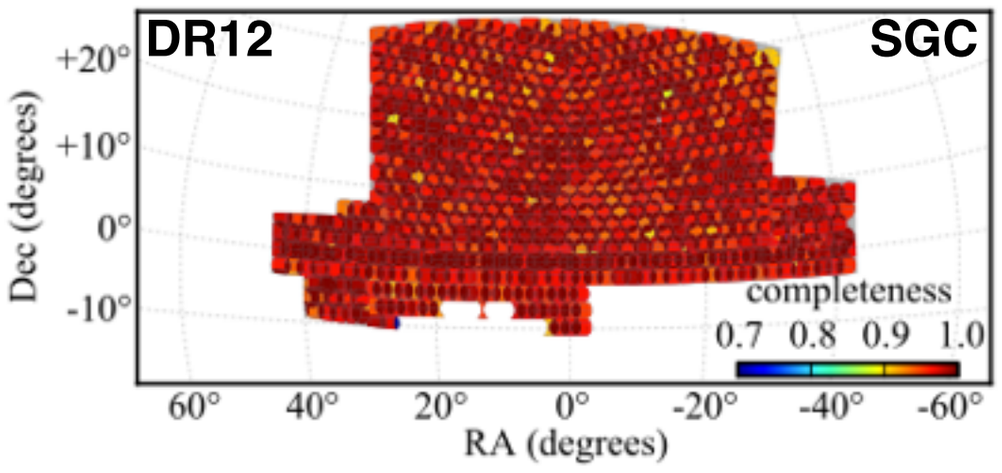
Uniform Galaxy Sample

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

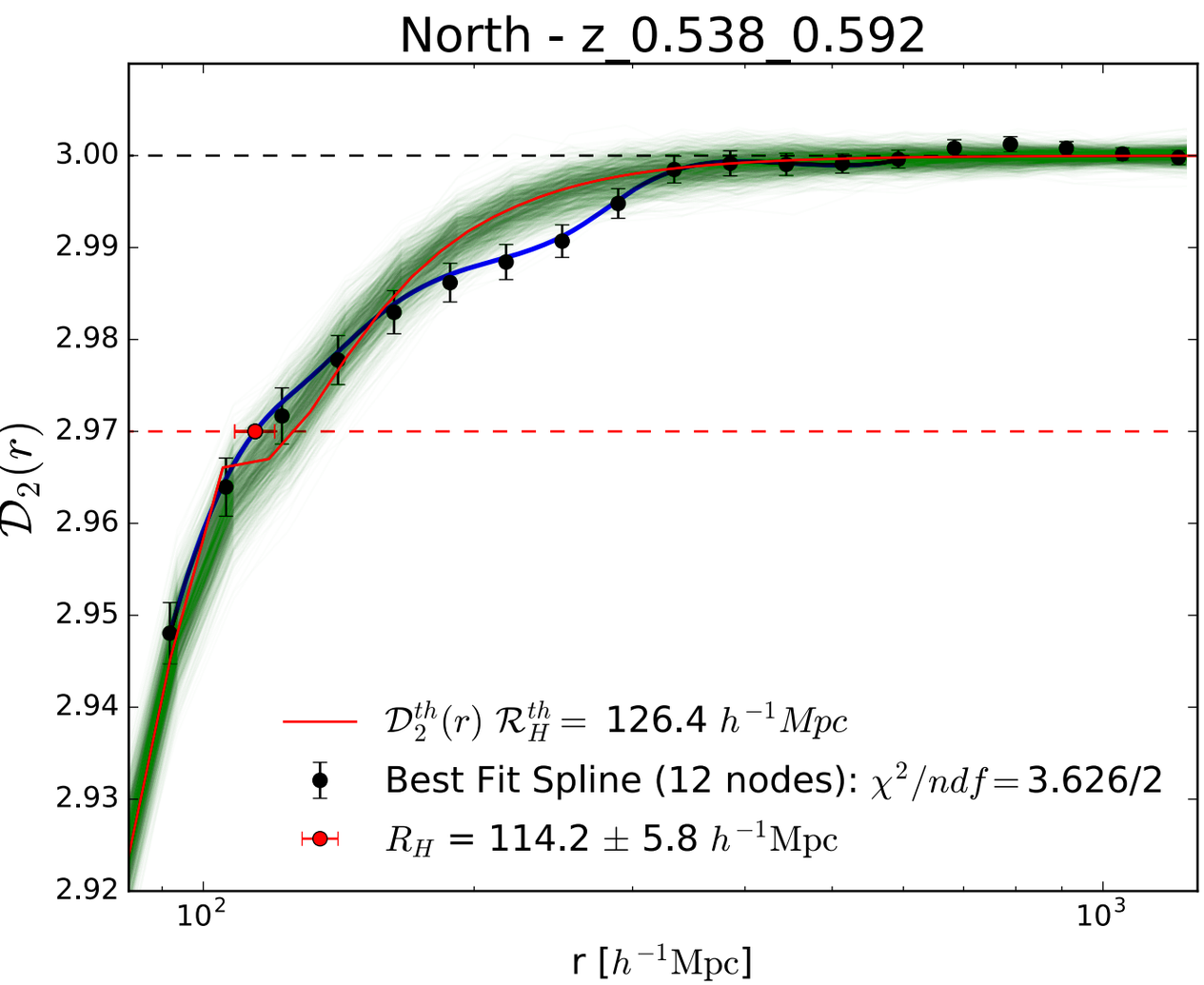
BOSS DR12 CMASS Sample

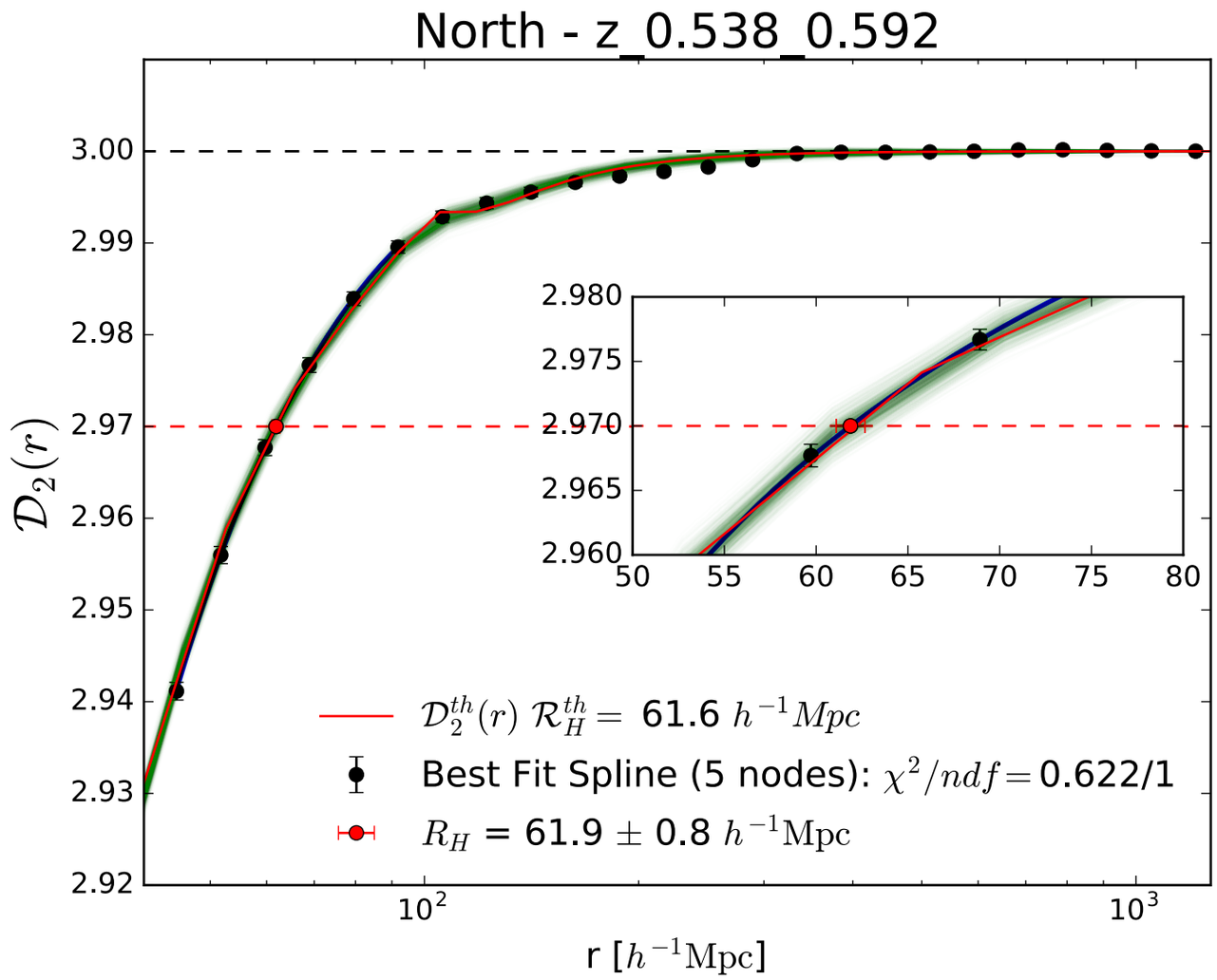


[S.Alam et al. 1501.00963]



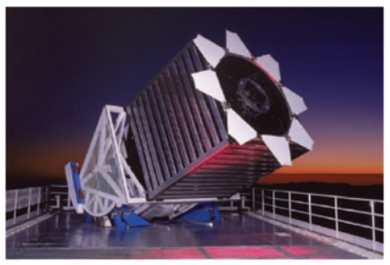
GALAXIES ---> MATTER





GALAXY SURVEYS

SDSS-IV 2016, 0.2<z<3.5

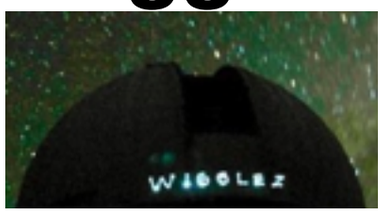


7500^o

1.5_x10^6 CMASS

7.5_x10^5 QSO

WiggleZ 2011, z<1



7500^o

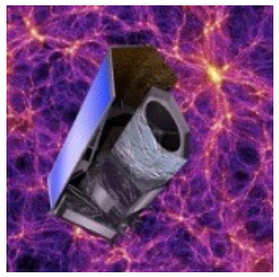
2.4_x10^5 ELG

2dF-GRS 2002, z<0.3

1500^o

3.3_x10^5 ELG

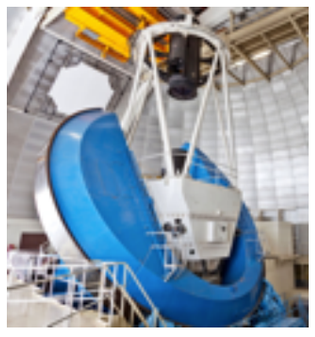
EUCLID 2022,



15000^o

10^9 Gal

DESI 2022,



14000^o

$30x10^6$ Gal z<2

Lya Forest z>2

LSST 2019,

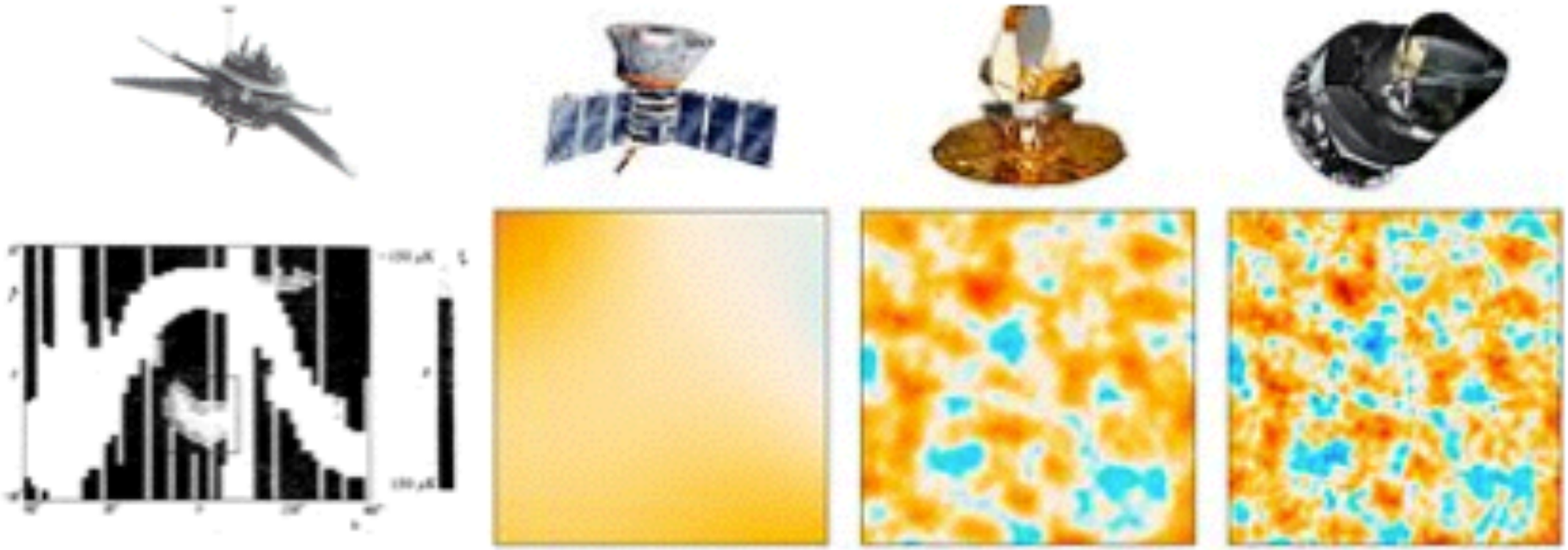
10000^o

10^9 Gal

CMB MAPS

Test of Isotropy

1992 **1993** **2011** **2013**



RELIKT1 COBE WMAP Planck

Optimal Homogeneity Estimators

- 2pt-Correlation function: Landy Szalay Estimator

$$\xi_{ls}(s) = \frac{DD(s) - 2 * DR(s) + RR(s)}{RR(s)}$$

- Average number galaxy density

$$\mathcal{N}(< r) = 1 + \frac{3}{r^3} \int_0^r \xi(s) s^2 ds$$

- Convert to Matter-distribution estimator

$$\mathcal{N}_M(< r) = \frac{\mathcal{N}_M^{th}(< r) - 1}{\mathcal{N}_{b,\sigma_p}^{th}(< r) - 1} [\mathcal{N}(< r) - 1] + 1$$

- Fractal Correlation dimension

$$\mathcal{D}_2^M(r) = \frac{d\ ln\ \mathcal{N}_M(< r)}{d\ ln\ r} + 3$$

Mock Galaxies Catalogues

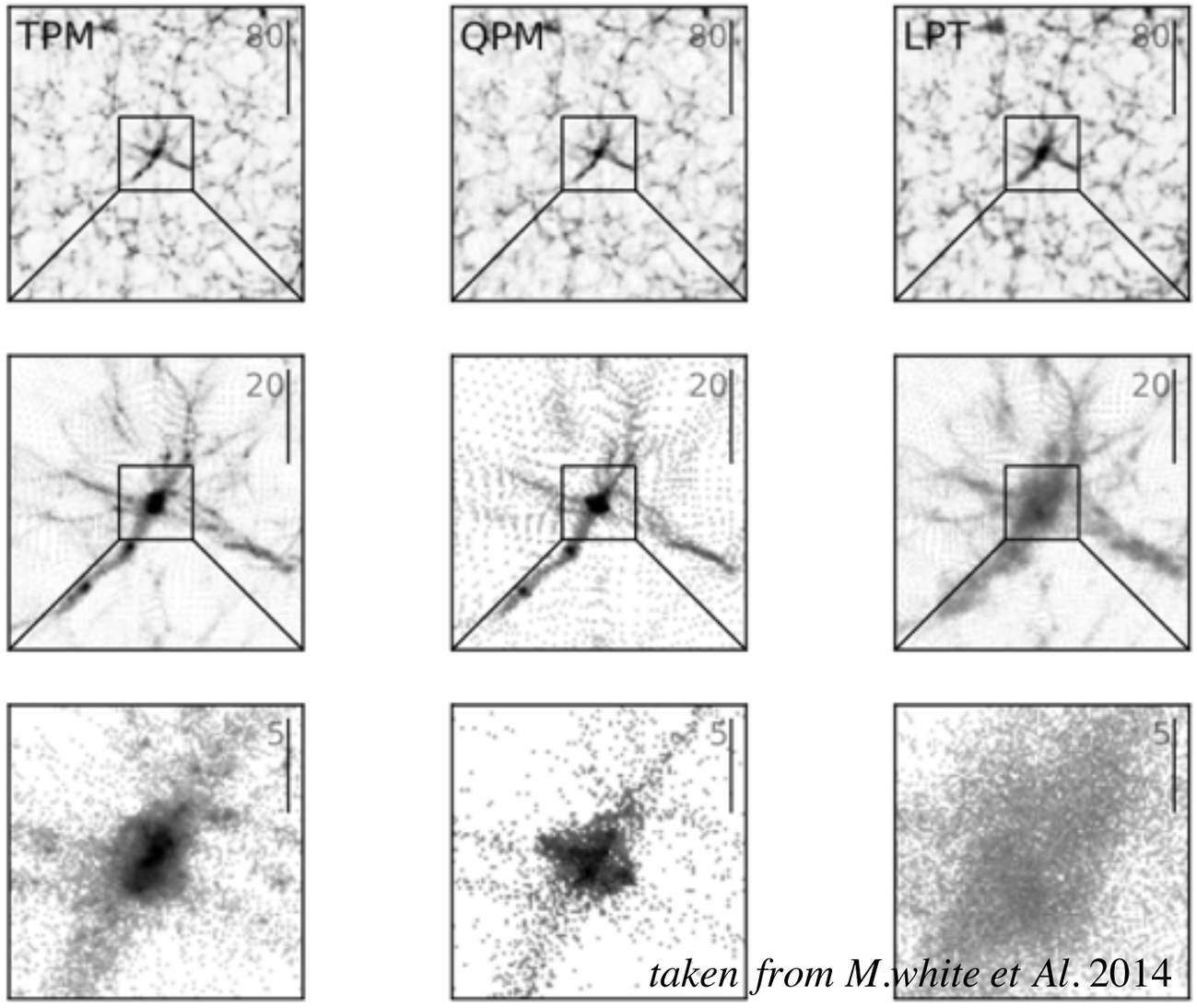
Basic Method

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

Analysis Usage

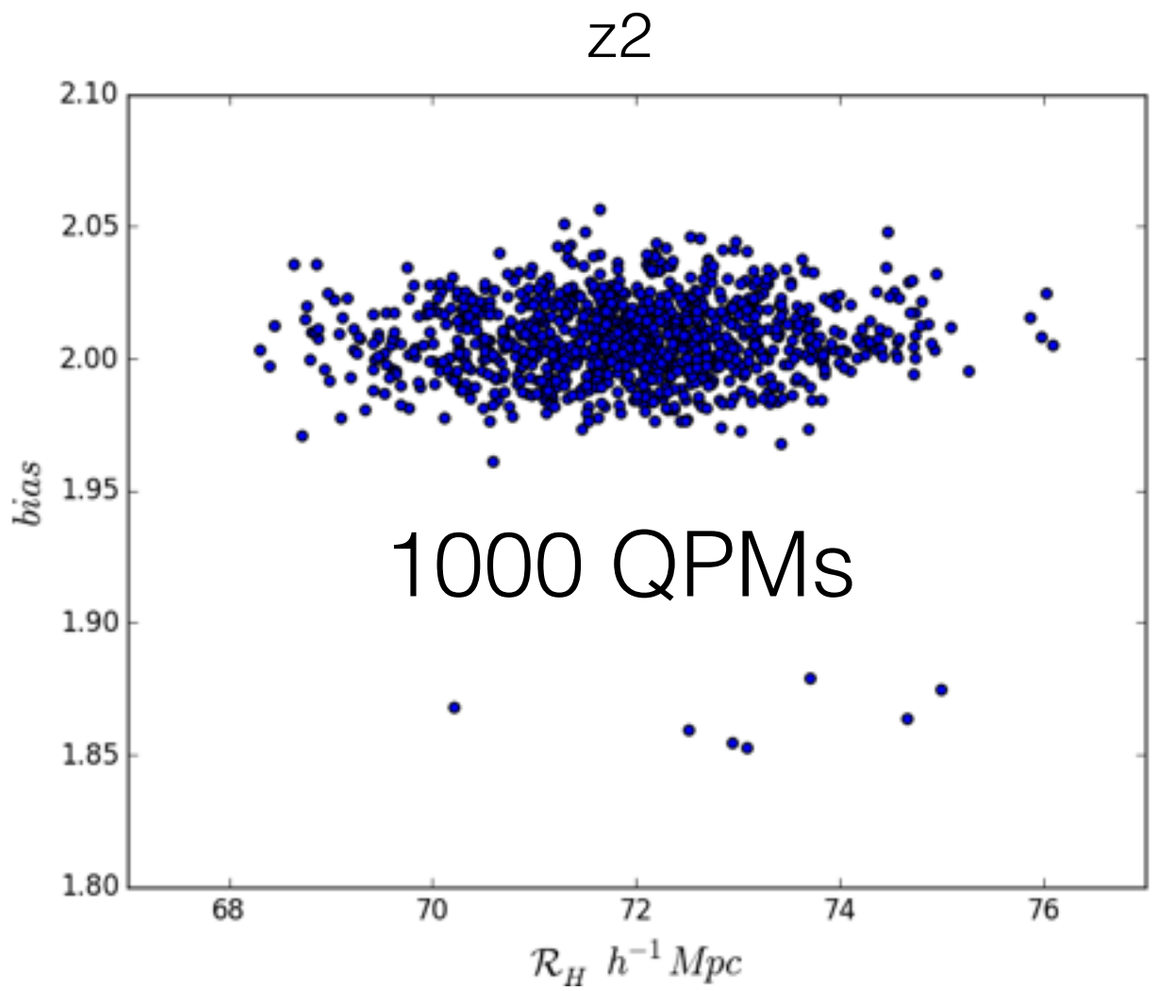
- Compute Covariance Matrices
- Use in Analysis Tests

ref: 1309.5532v2, 1203.6609v2



taken from M.white et Al. 2014

Un-Correlated



eff0.0 north 1000 qpm
factor: correcting for inv cov

Cosmology independence

$$\mathcal{D}_2(r) = \frac{d\ ln\ \mathcal{N}(< r)}{d\ ln\ r} \rightarrow \mathcal{D}_2(\alpha r) = \frac{d\ ln\ \mathcal{N}(< \alpha r)}{d\ ln\ r}$$

$$\alpha = \frac{d_{model}(z_m)}{d_{fiducial}(z_m)}$$

$$d(z) = \left[D_A^2 \frac{cz}{H(z)} \right]^{1/3}$$

$$D_A(z) = \frac{c}{H_0 \sqrt{|\Omega_k|}} \int_0^z \frac{dz'}{H(z')}$$

Analysis Null tests

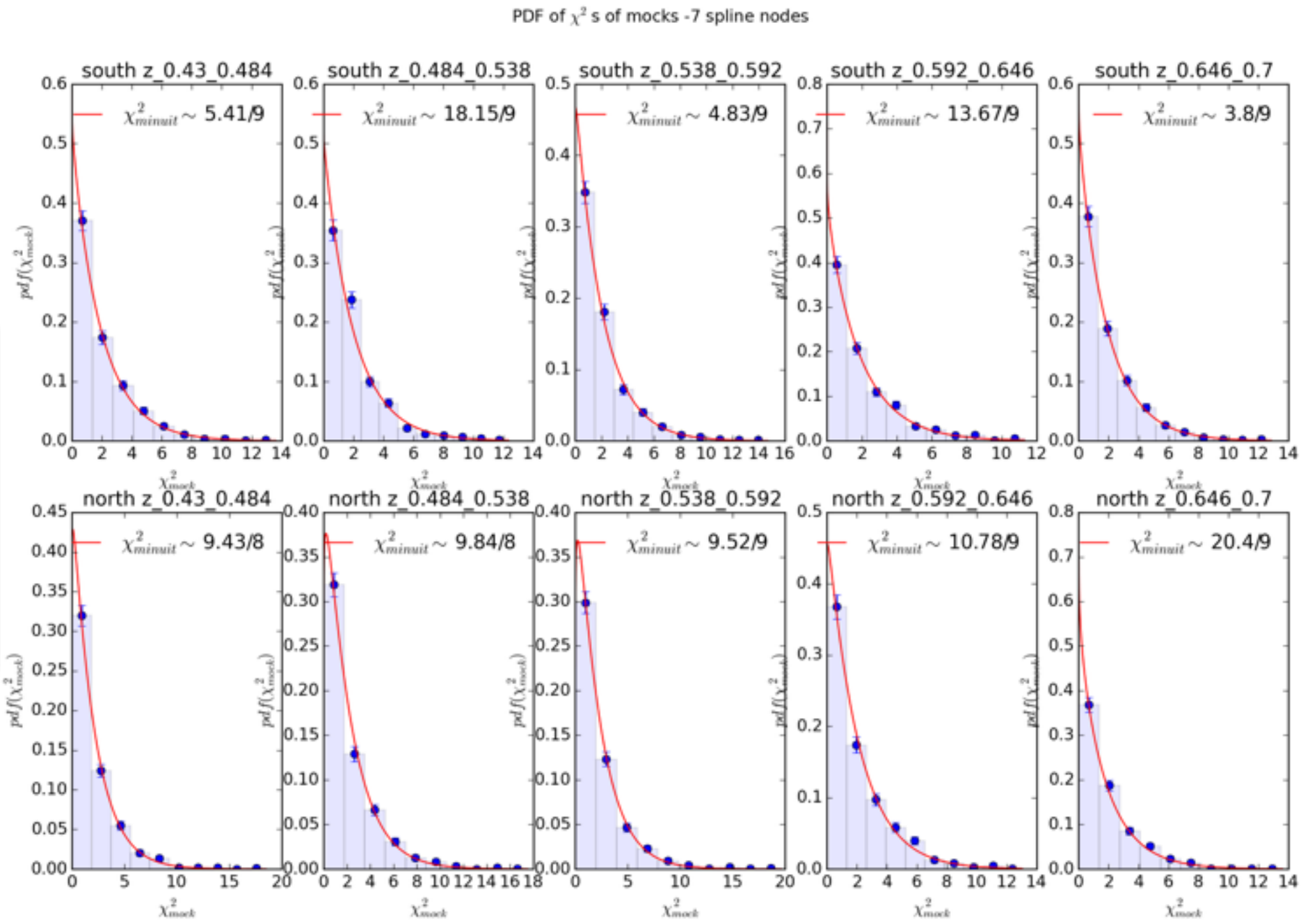
R_H measurement on mocks

↓

Spline fitting

↓

χ^2-*mock*



2 ndf

Analysis Null tests

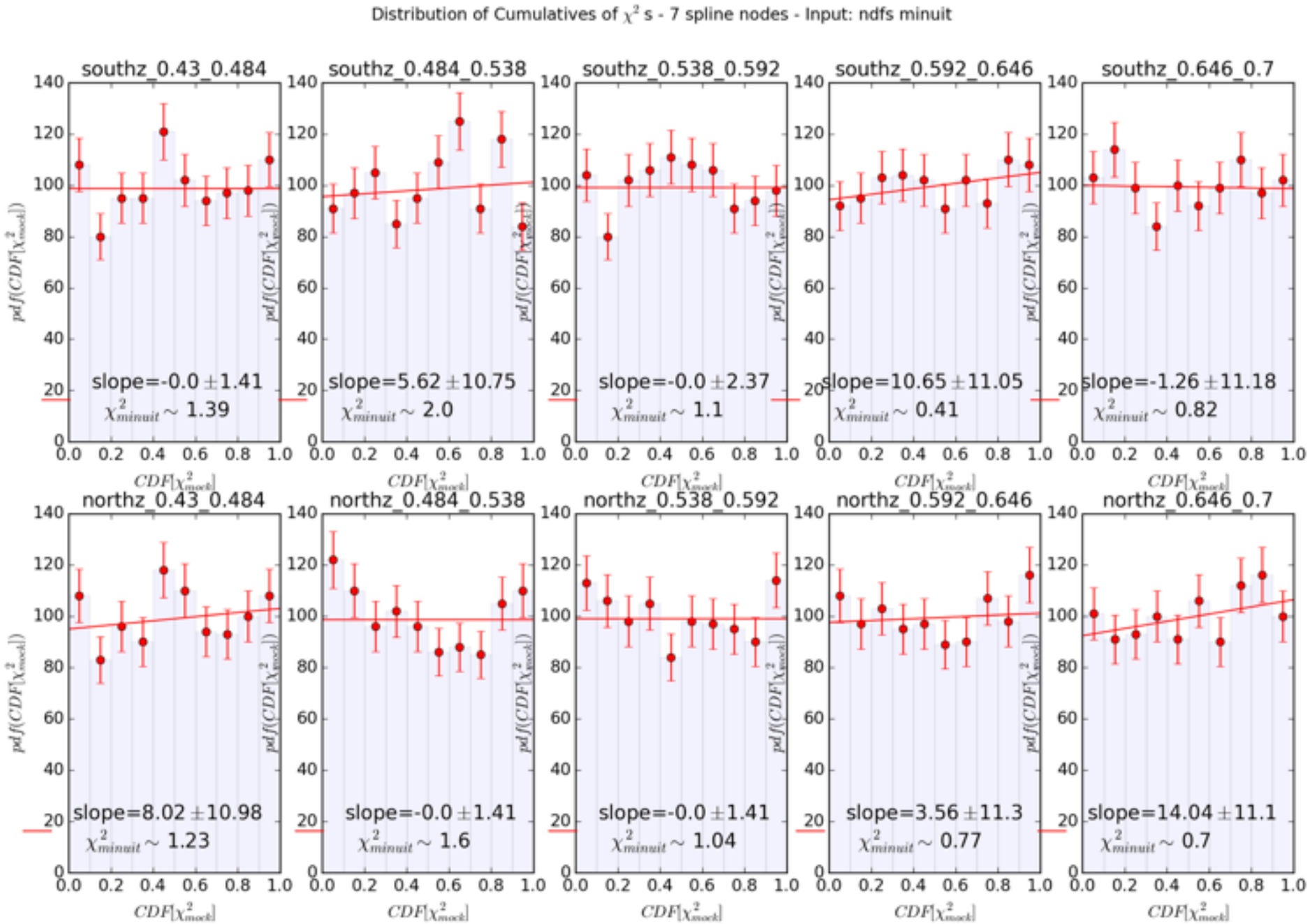
R_H measurement on mocks

↓

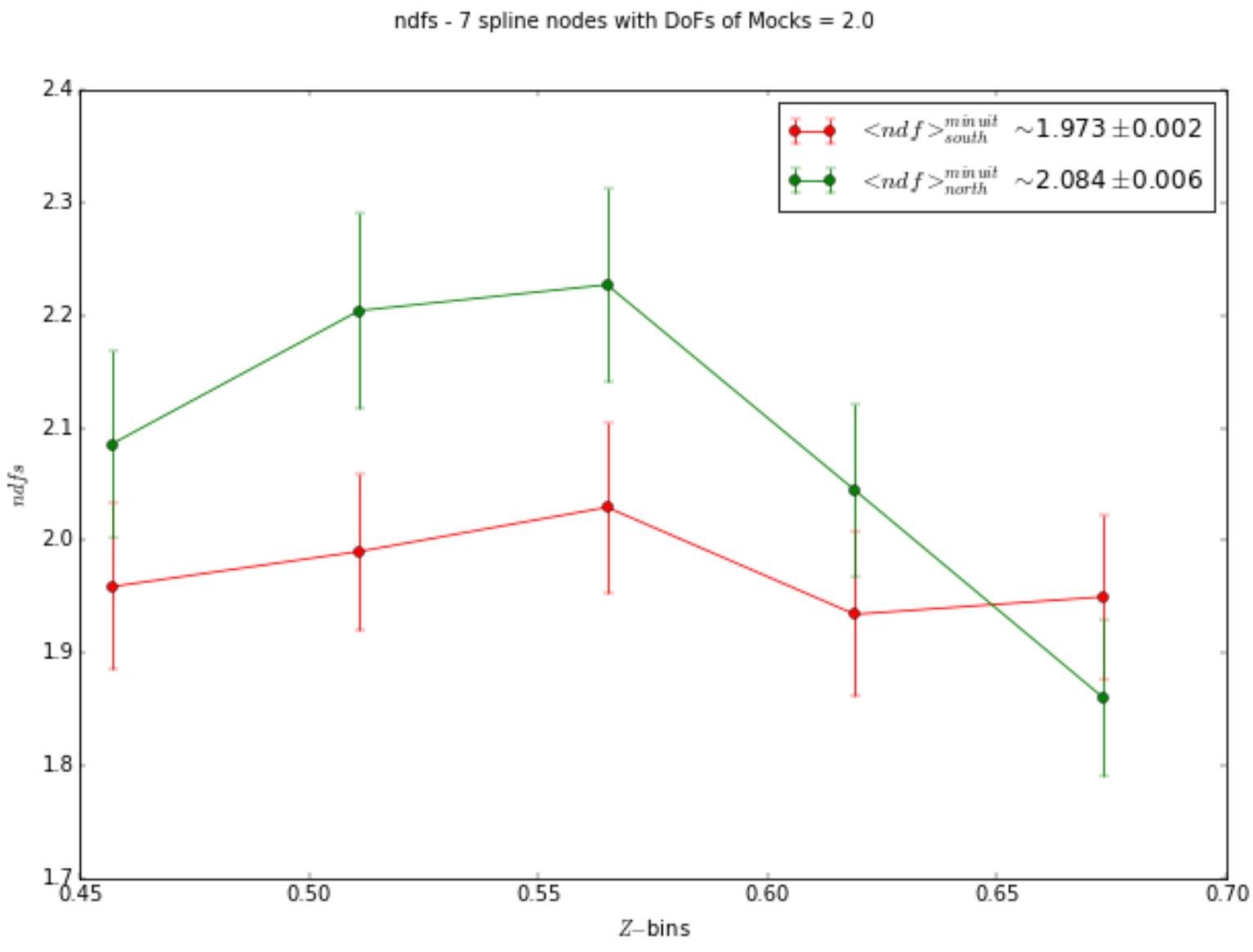
Spline fitting

↓

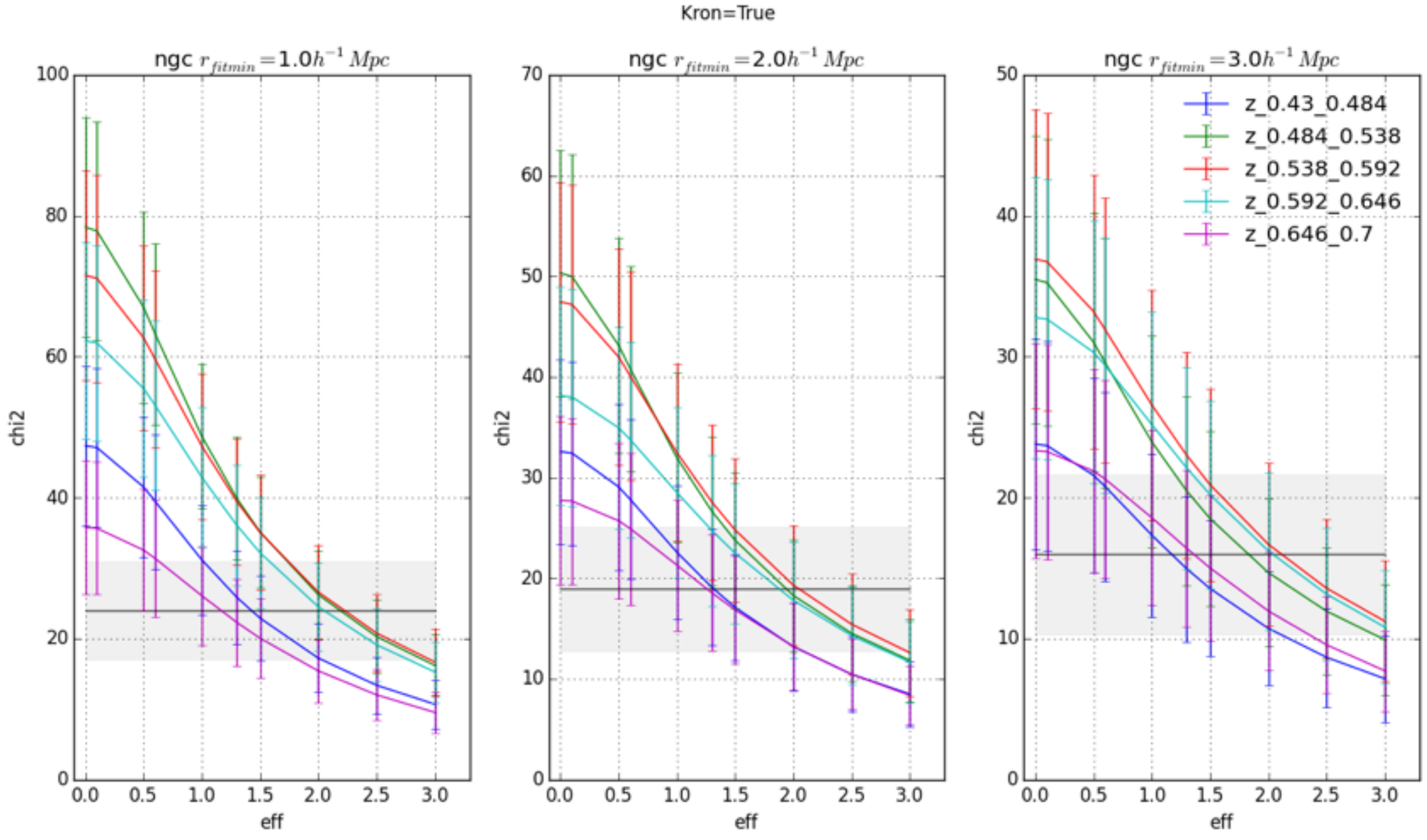
$CDF[\chi^2_{mock}]$



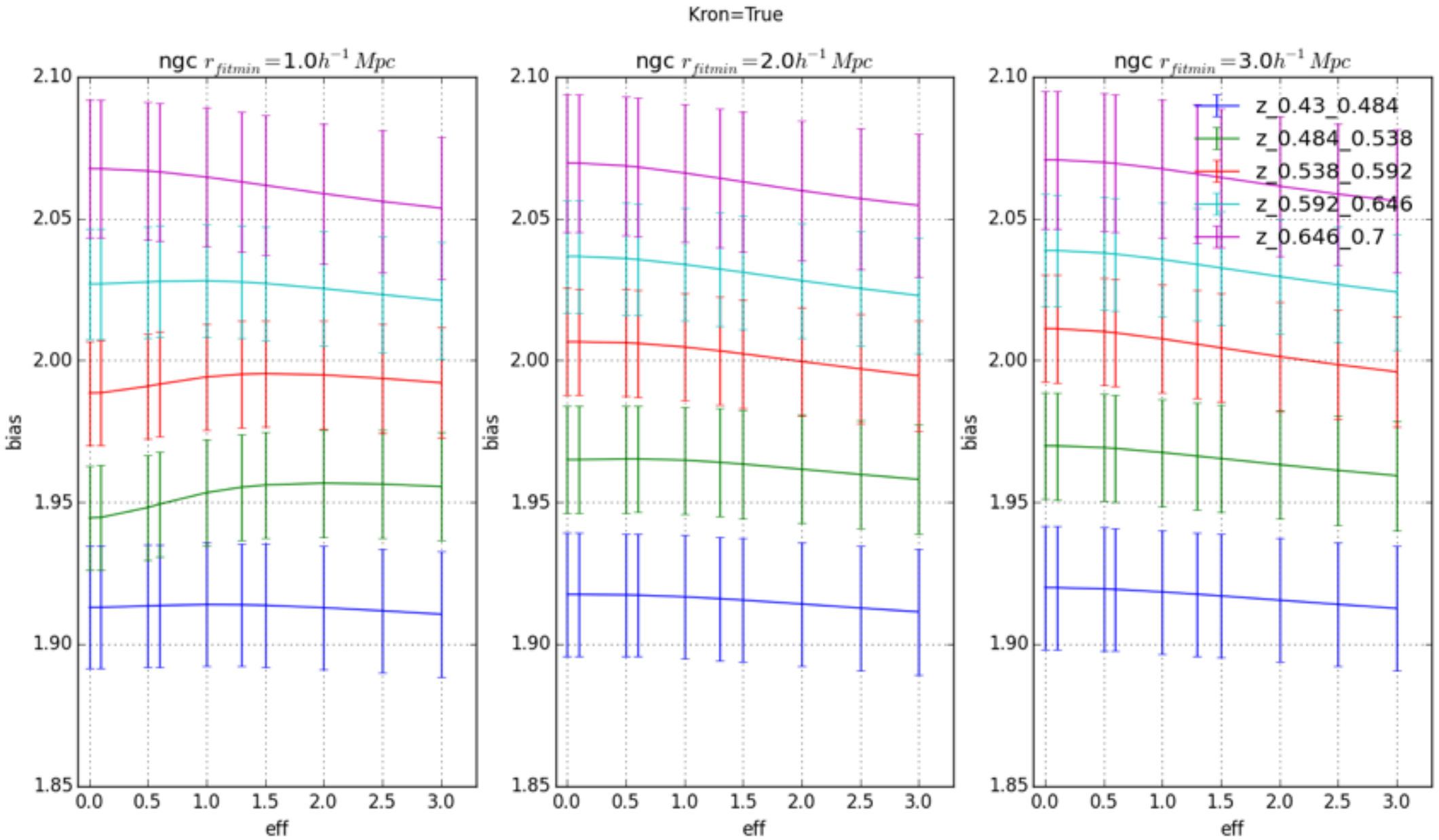
Analysis Null tests



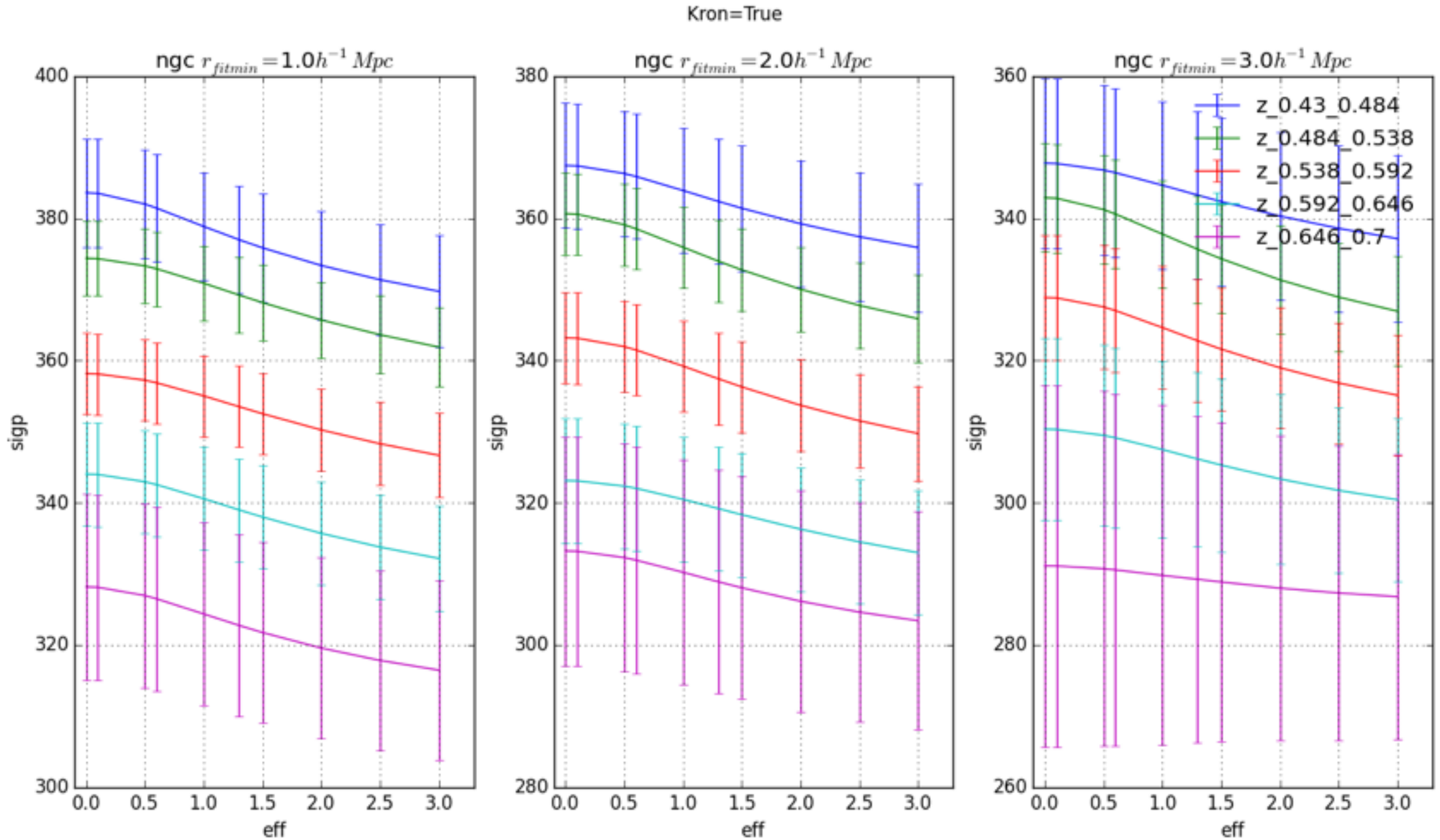
RSD-choices


Kron=True
ngc $r_{fitmin}=1.0h^{-1}\,Mpc$
ngc $r_{fitmin}=2.0h^{-1}\,Mpc$
ngc $r_{fitmin}=3.0h^{-1}\,Mpc$
z_0.43_0.484
z_0.484_0.538
z_0.538_0.592
z_0.592_0.646
z_0.646_0.7
chi2
eff

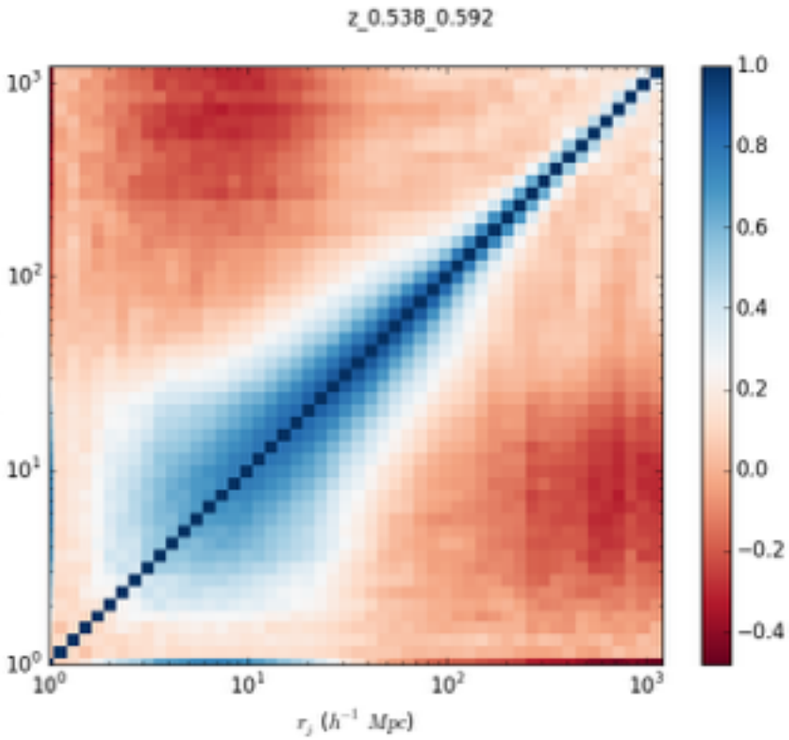
RSD-choices


Kron=True
ngc $r_{fitmin}=1.0h^{-1}\,Mpc$
ngc $r_{fitmin}=2.0h^{-1}\,Mpc$
ngc $r_{fitmin}=3.0h^{-1}\,Mpc$
z_0.43_0.484
z_0.484_0.538
z_0.538_0.592
z_0.592_0.646
z_0.646_0.7
bias
eff
2.10
2.05
2.00
1.95
1.90
1.85
0.0
0.5
1.0
1.5
2.0
2.5
3.0

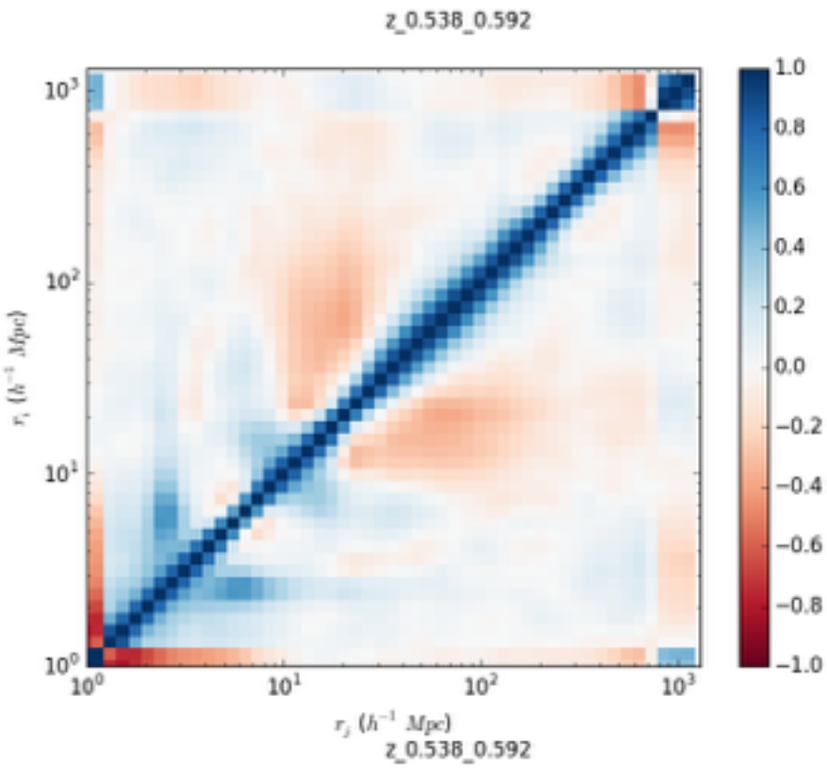
RSD-choices


Kron=True
ngc $r_{fitmin}=1.0h^{-1}\,Mpc$
ngc $r_{fitmin}=2.0h^{-1}\,Mpc$
ngc $r_{fitmin}=3.0h^{-1}\,Mpc$
z_0.43_0.484
z_0.484_0.538
z_0.538_0.592
z_0.592_0.646
z_0.646_0.7
sigp
eff

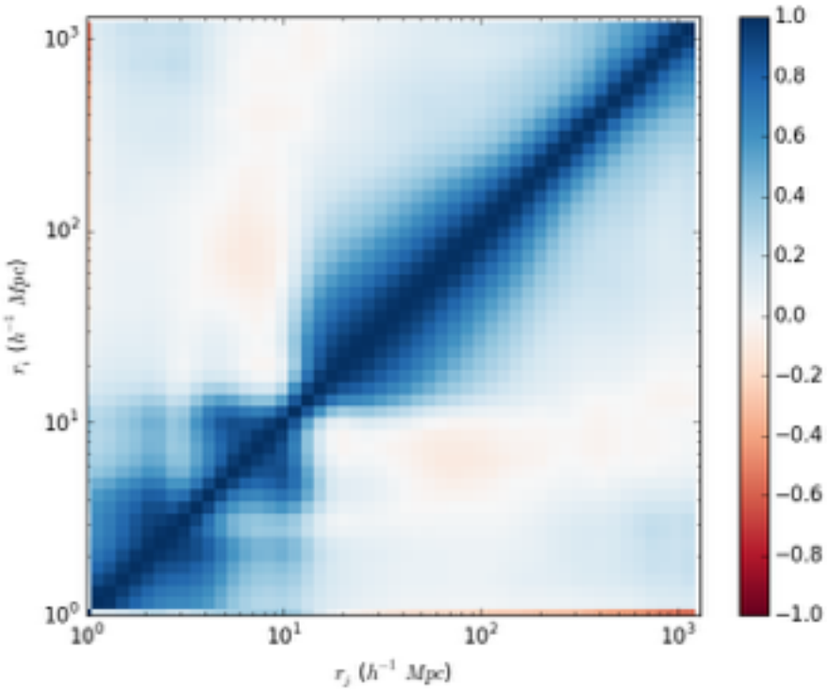
Correlation Matrices



ρ_{ij}^{ξ}



$\rho_{ij}^{\mathcal{D}_2}$



$\rho_{ij}^{\mathcal{N}}$

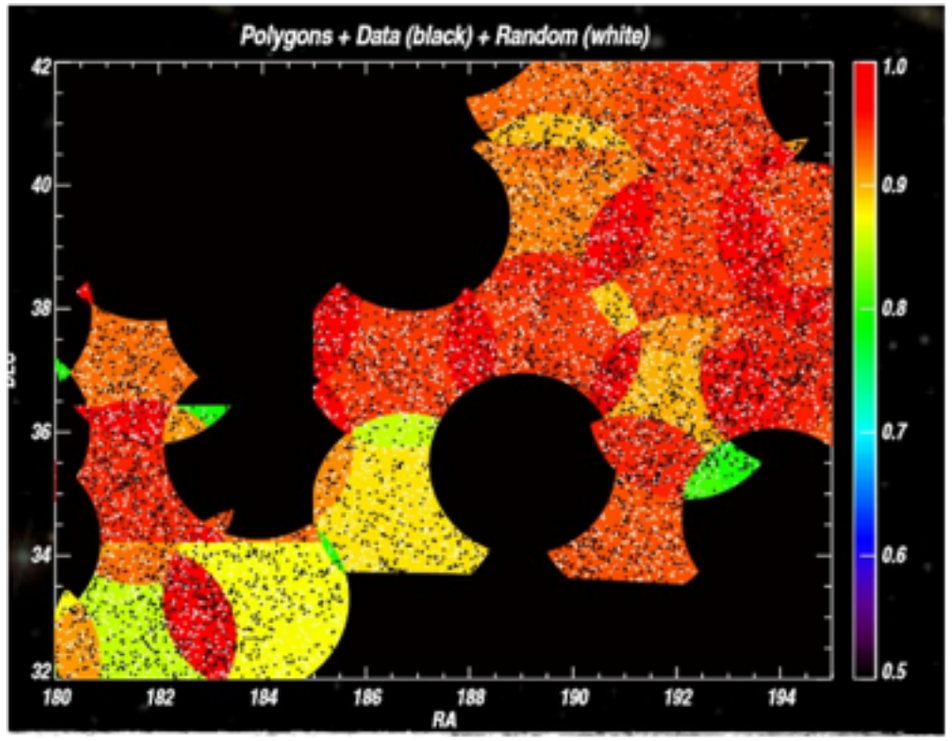
Systematic Effects

- 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]



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