Cosmological Constraints from the Redshift Dependence of the Alcock-Paczynski Effect

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WITH Changbom Park &

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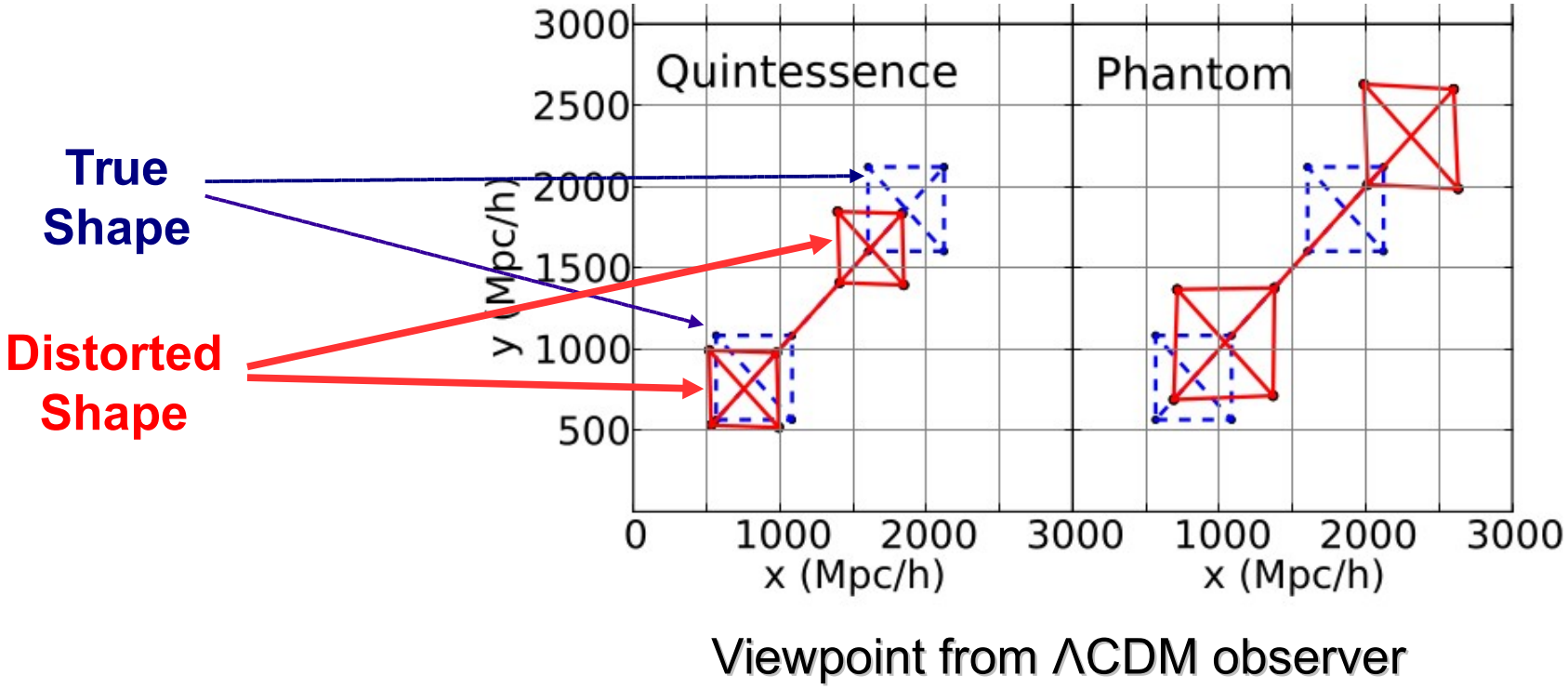
The Alcock-Paczynski Test



Viewpoint from ΛCDM observer

Incorrect cosmology → apparent distortion

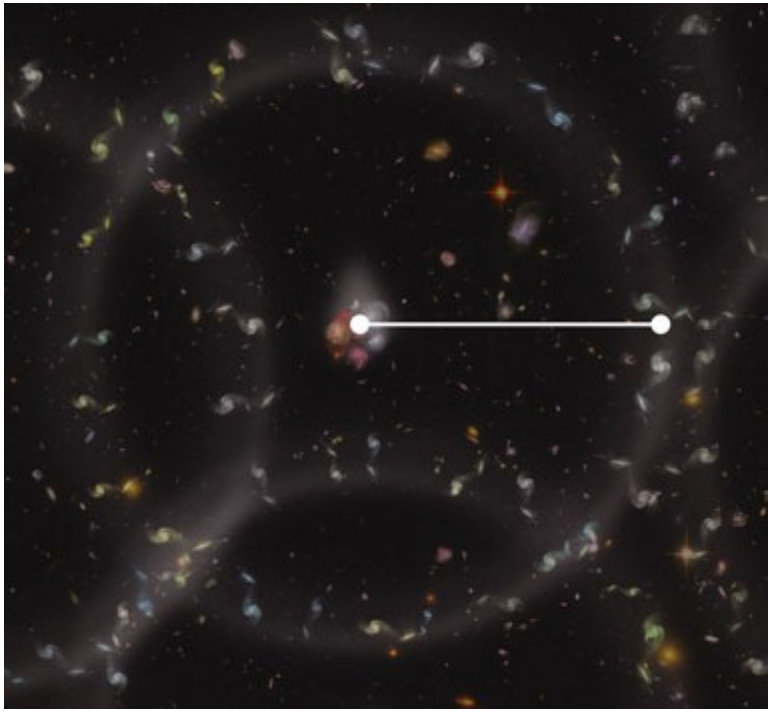
$$\Delta r_{\parallel} = \frac{c}{H}\Delta z, \quad \Delta r_{\perp} = (1+z)D_A(z)\Delta\theta$$

Attention: distortion evolves with redshift

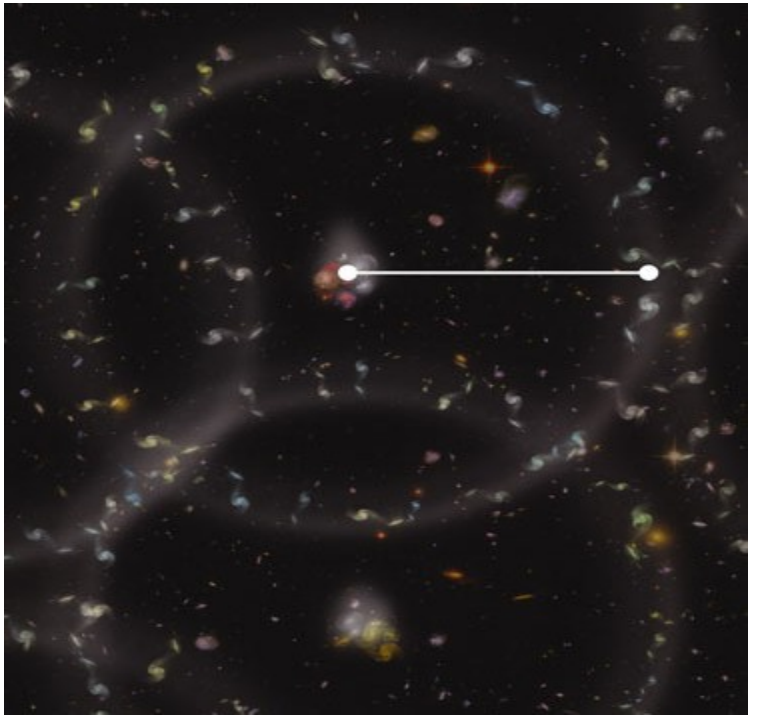
AP test from Clustering of Galaxies

Ballinger et al.1996; Matsubara & Suto 1996

Applications: 2dFGS; WiggleZ; SDSS-II; SDSS-III; ...



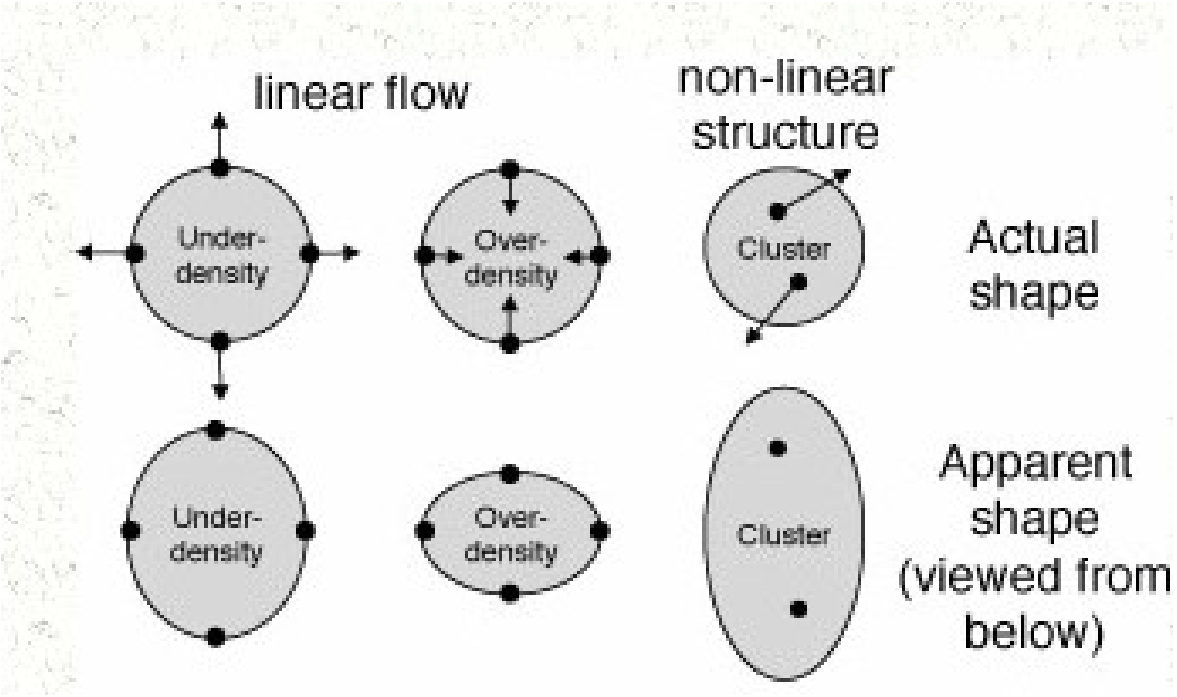
Isotropic clustering in true universe



Anisotropic clustering in incorrect cosmologies

Illustration Credit: Zosia Rostomian (LBNL), SDSS-III, BOSS

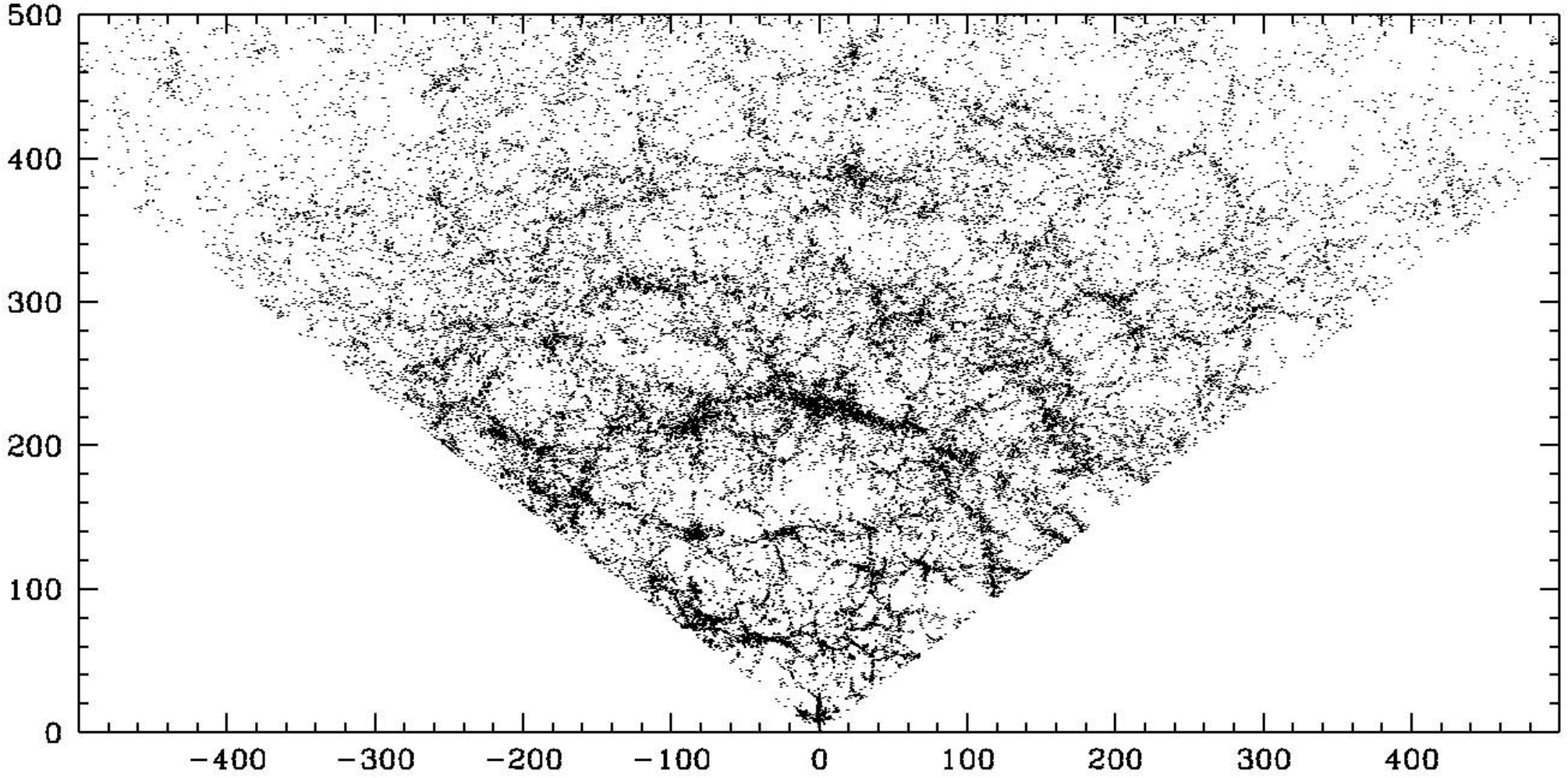
The great difficulty of RSD



– Redshift Space Distortion (RSD) produces distortions much more significant than AP

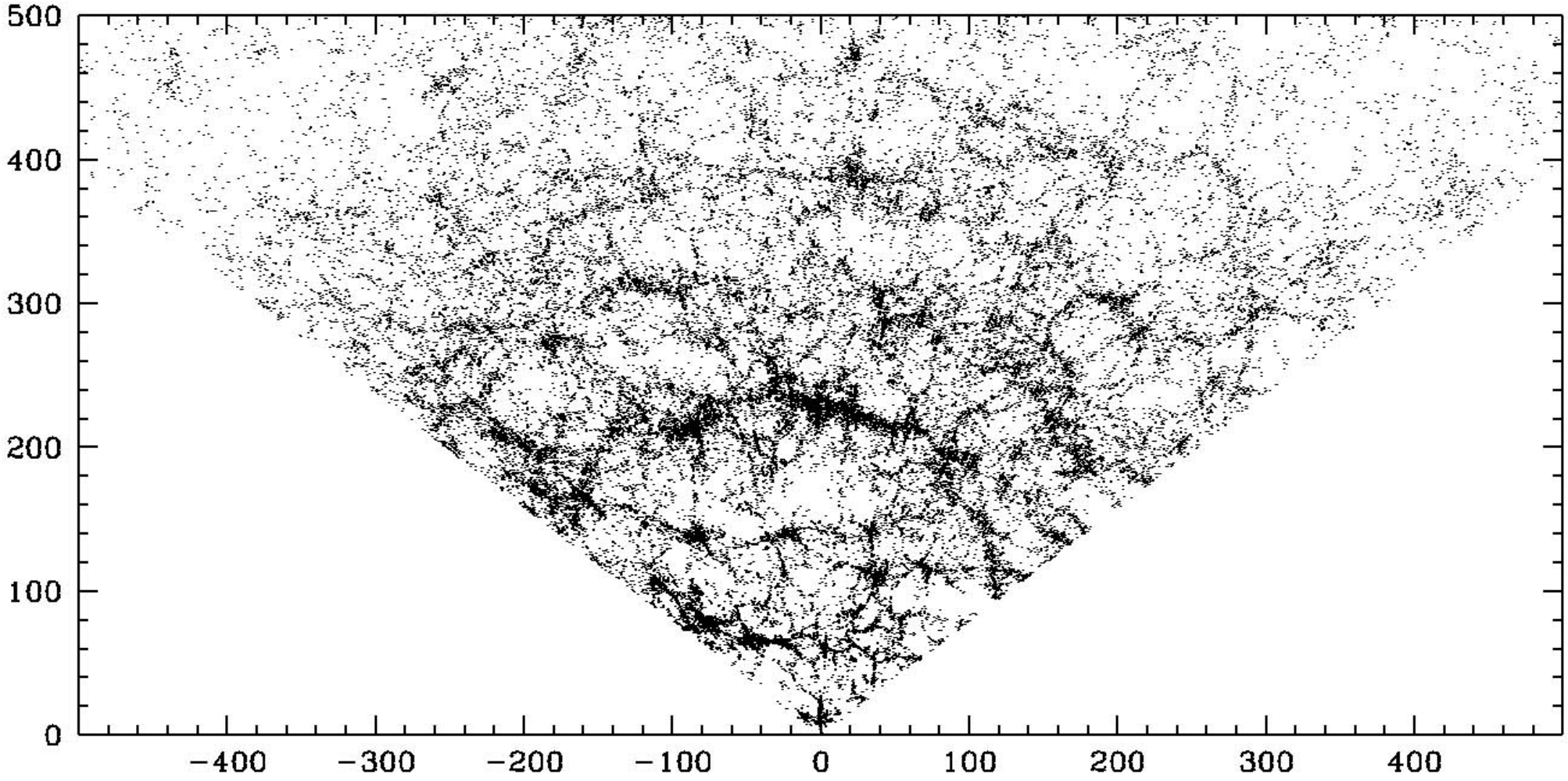
$$r = \int_0^{z_{\rm cosmo}+\Delta z} \frac{dz'}{H(z')}, \quad \Delta z = \frac{v_{\rm LOS}}{c}(1+z_{\rm cosmo})$$

– Difficult to overcome (clustering in NL;... headache)



Galaxy distribution in real space

SDSS DR7 after FoF contraction. 8.8h<RA<15.7h, 0<DEC<6deg

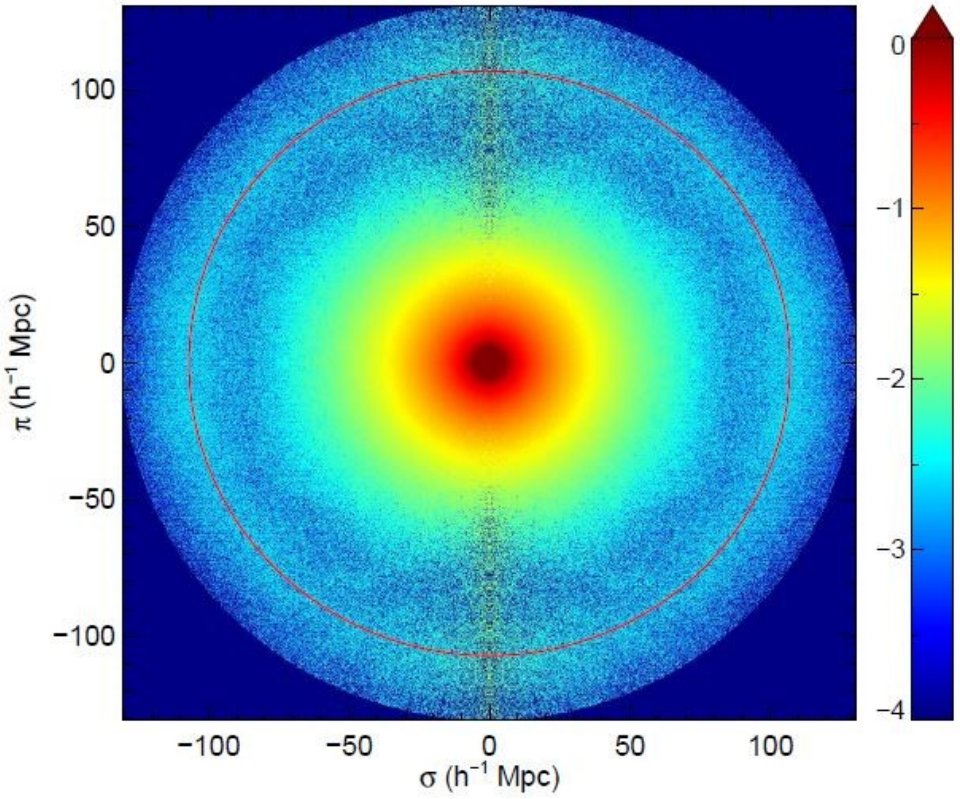


Galaxy distribution in redshift space

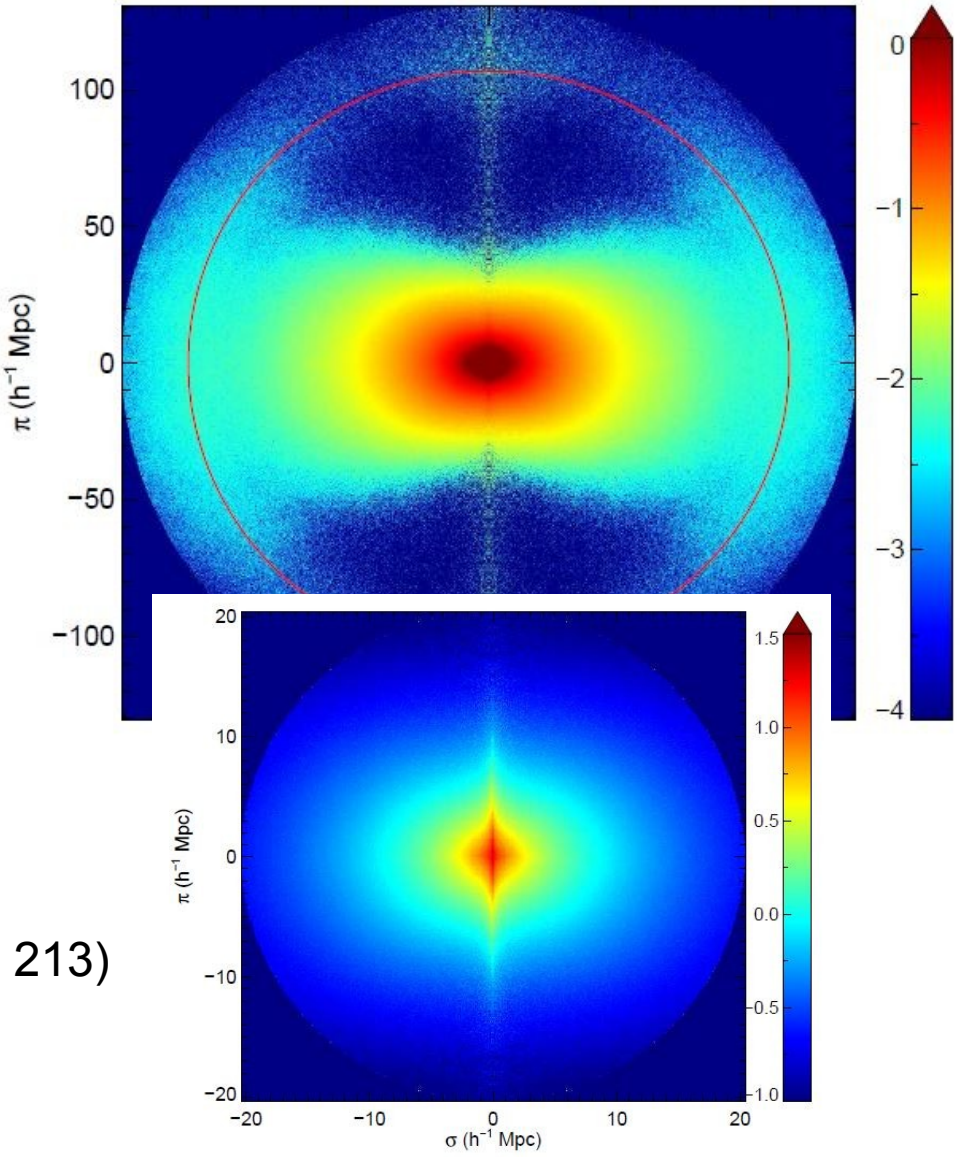
SDSS DR7 before FoF contraction. 8.8h<RA<15.7h, 0<DEC<6deg

Redshift-space distortion effects

on 2-point correlation function along (π) & across (σ) LOS

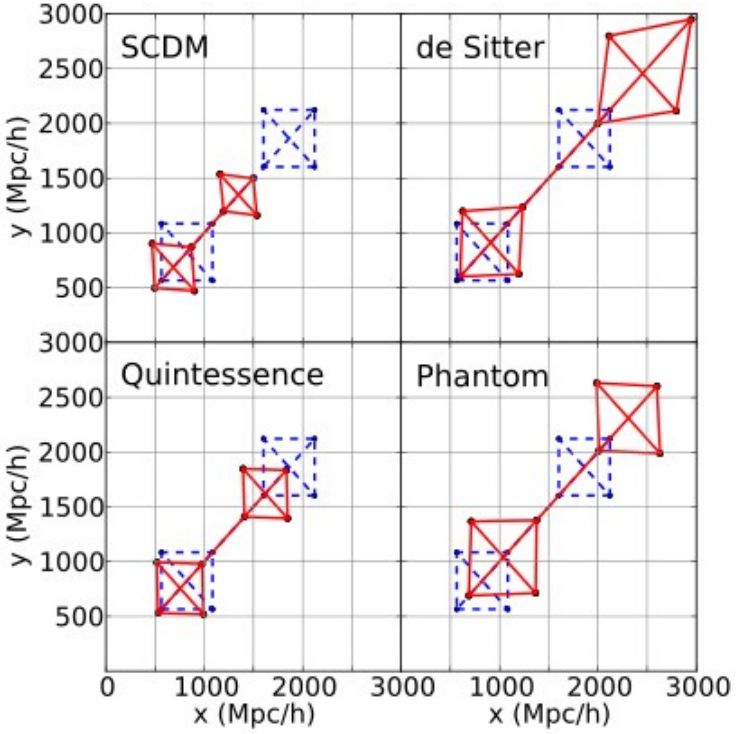


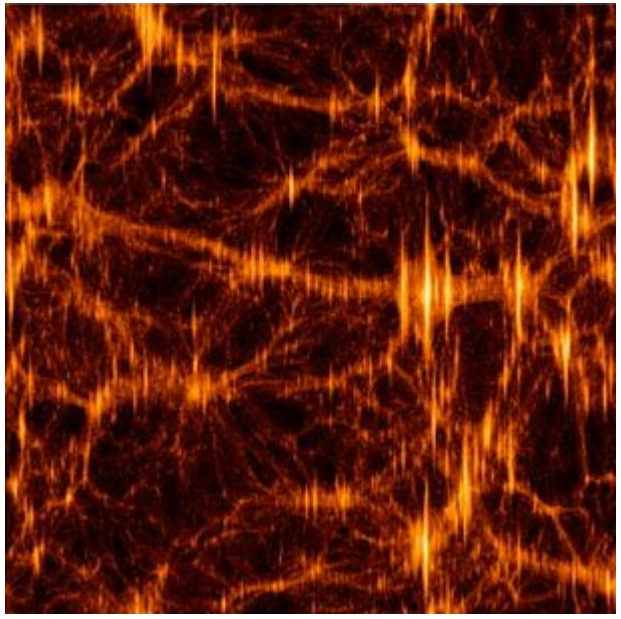
(a) real space



Horizon-Run 4 (Kim et al. 2015, JKAS, 48, 213)

Our solution: the redshift evolution





AP Distortion

Distortion of shape depends on z systematically

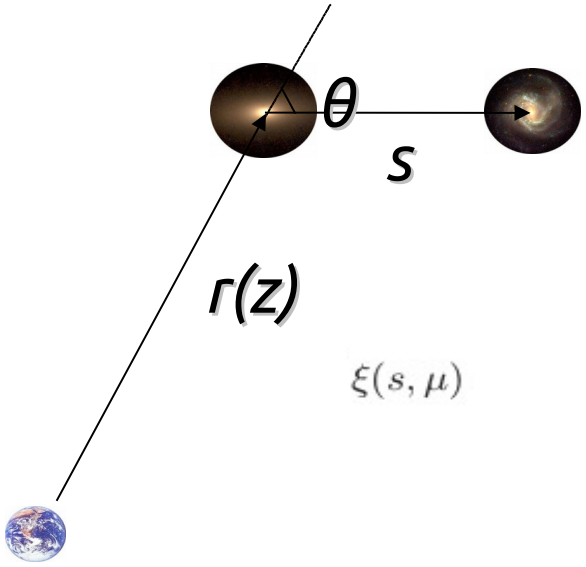
RSD Effect

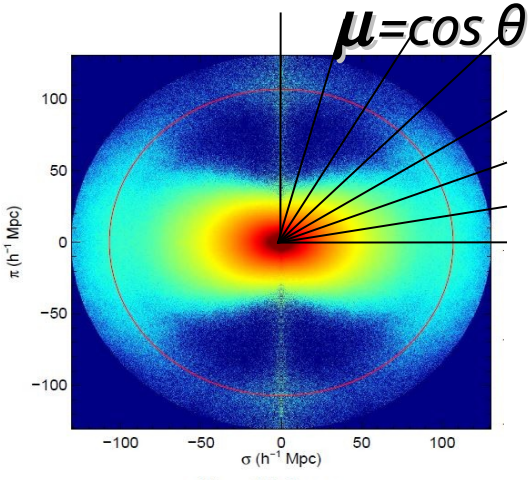
Kaiser effects on large scales and FoG effects on small scales

(~independent of redshift)

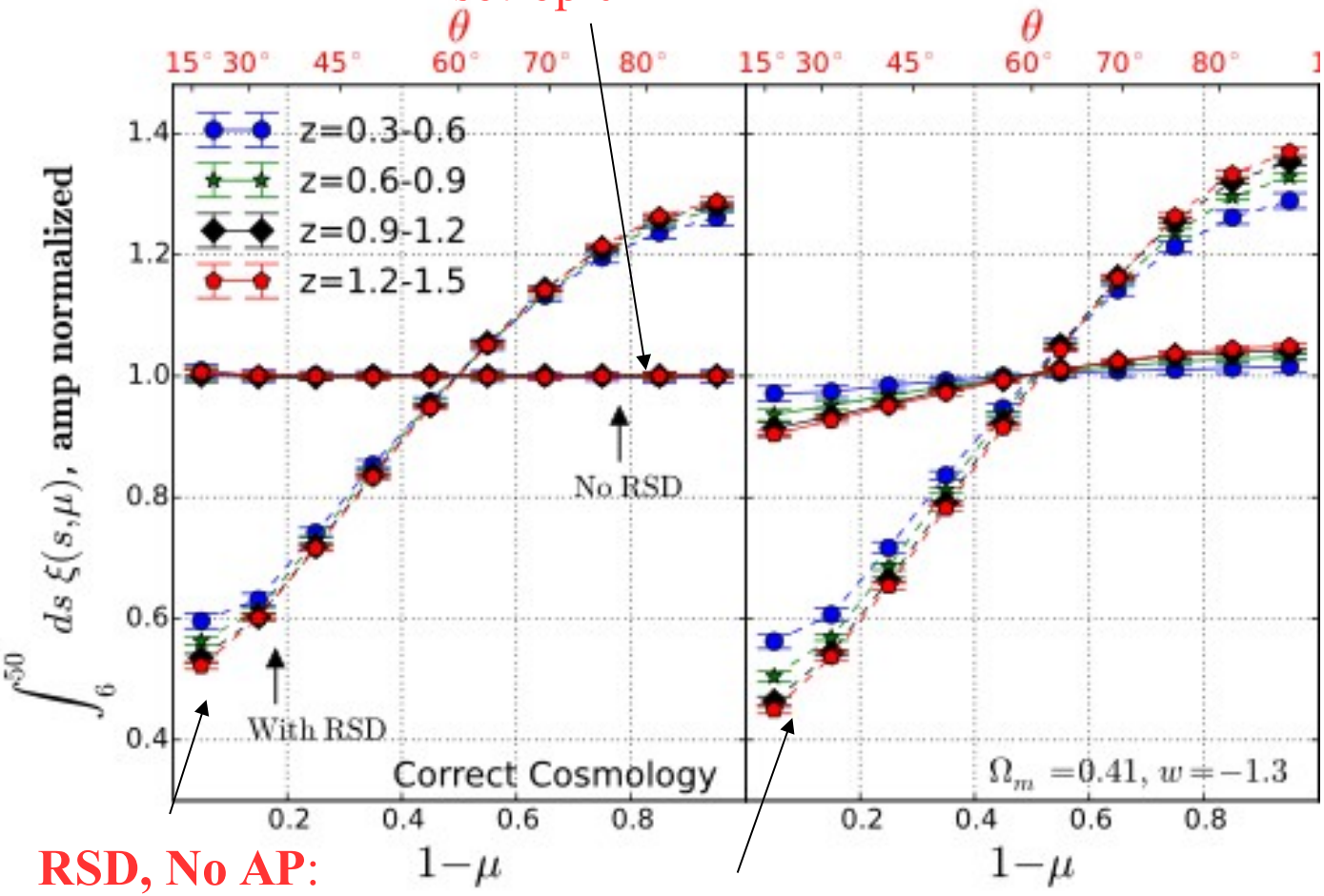
Proof-of-concept on simulations (anisotropic 2pCF)

X.-D. Li, Changbom Park, Cris G. Sabiu, Juhan Kim 2015 MNRAS





No RSD, No AP:
Isotropic

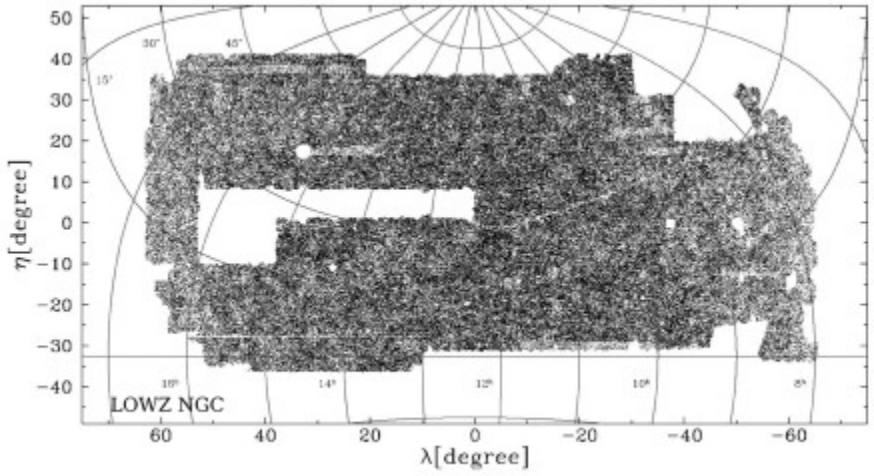


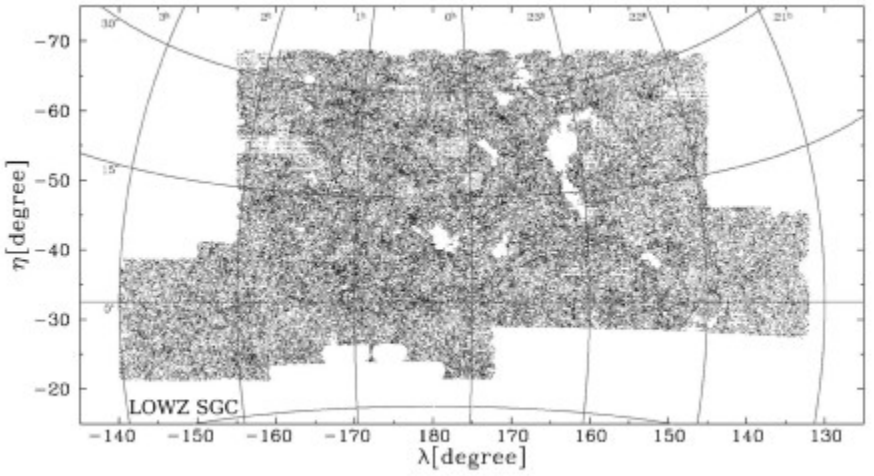
RSD, No AP:
anisotropic, but no significant redshift evolution

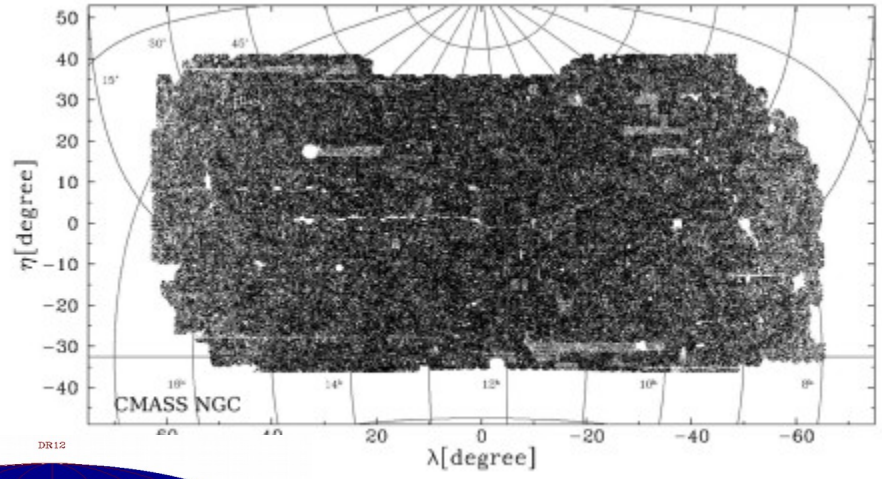
RSD & AP:
Redshift Evolution

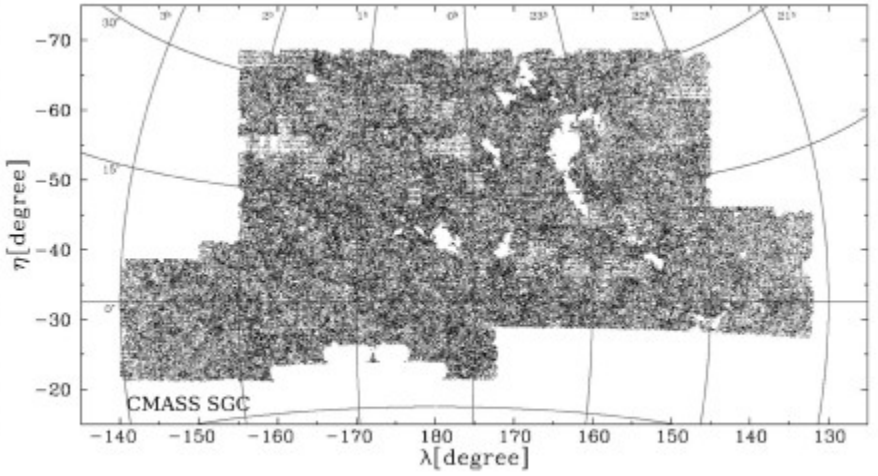
Application to BOSS DR12 galaxies

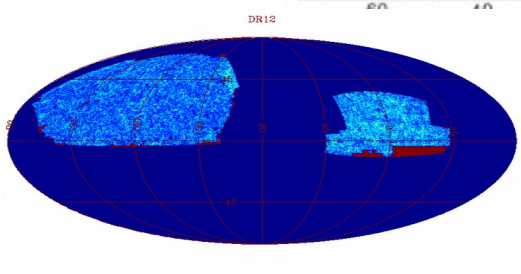
X.-D. Li, Changbom Park, C.G. Sabiu, et al., to appear









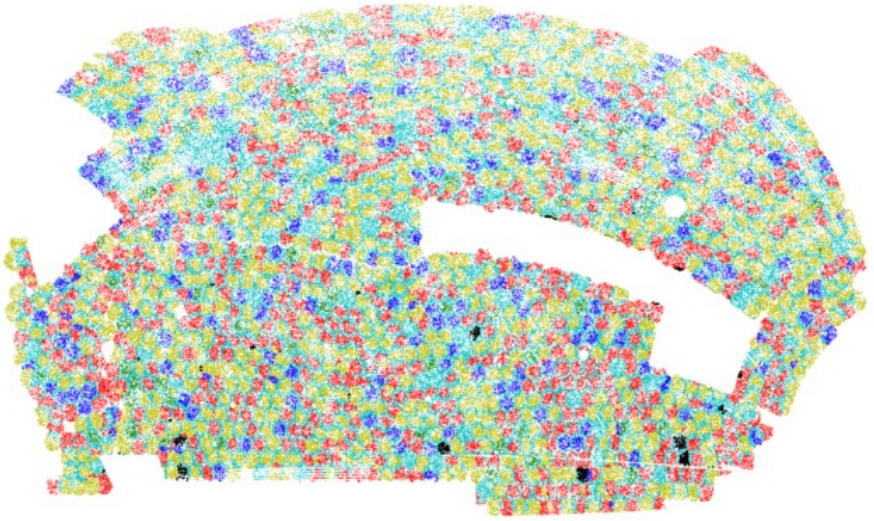


LOWZ 8,337 deg ^{2} . CMASS 9,376 deg ^{2} (~1/4 sky)

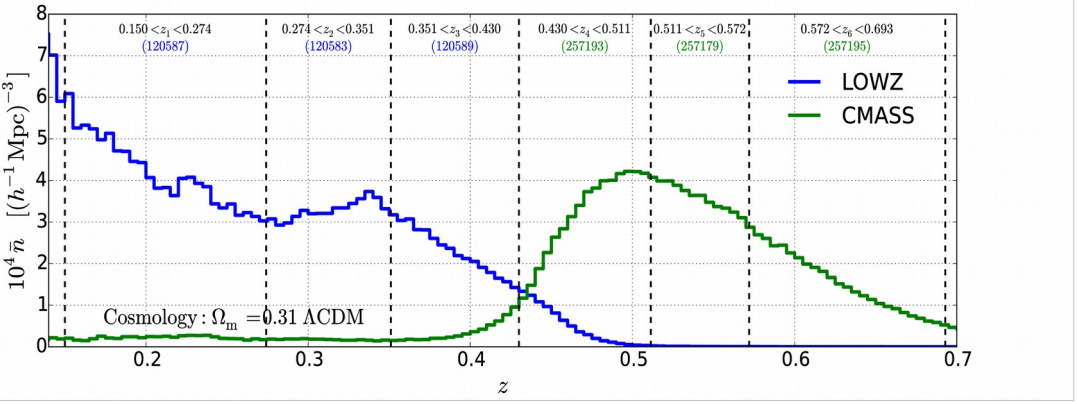
~1.13 M gals at $0.15 \le z \le 0.7$

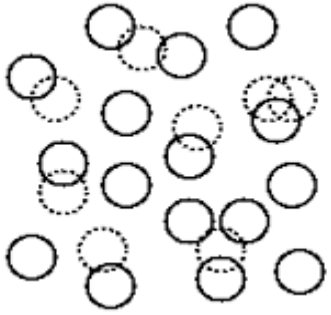
Systematics

1. Redshift evolution of RSD
(next order effect, but still not negligible)
2. Redshift evolution of gal bias
(related with RSD)



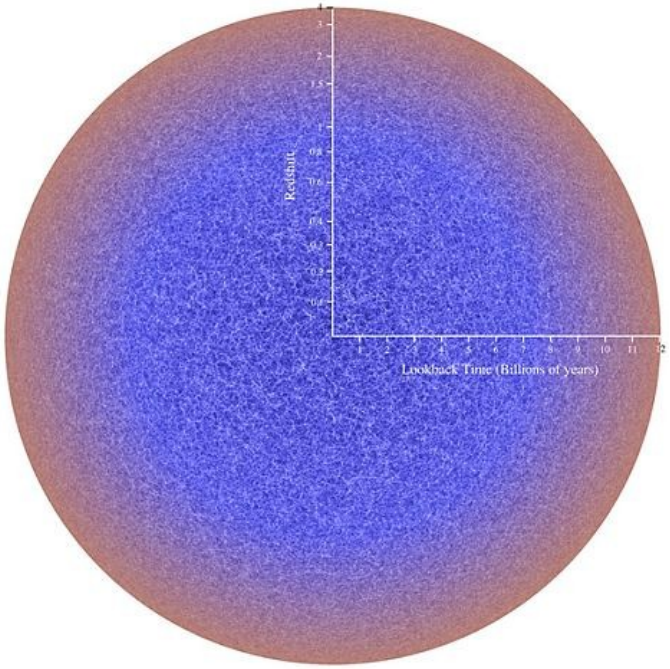
3. Angular selection function
4. Radial selection function
(incomplete LF coverage)
5. Fiber collision (high-density regions under-sampled)

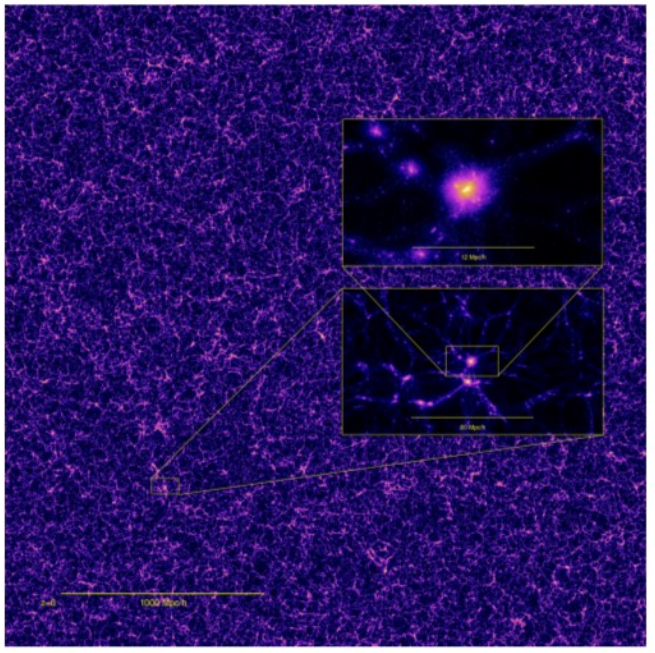




We create mock surveys to
model the sys and estimate the covariance

Horizon run *N*-body





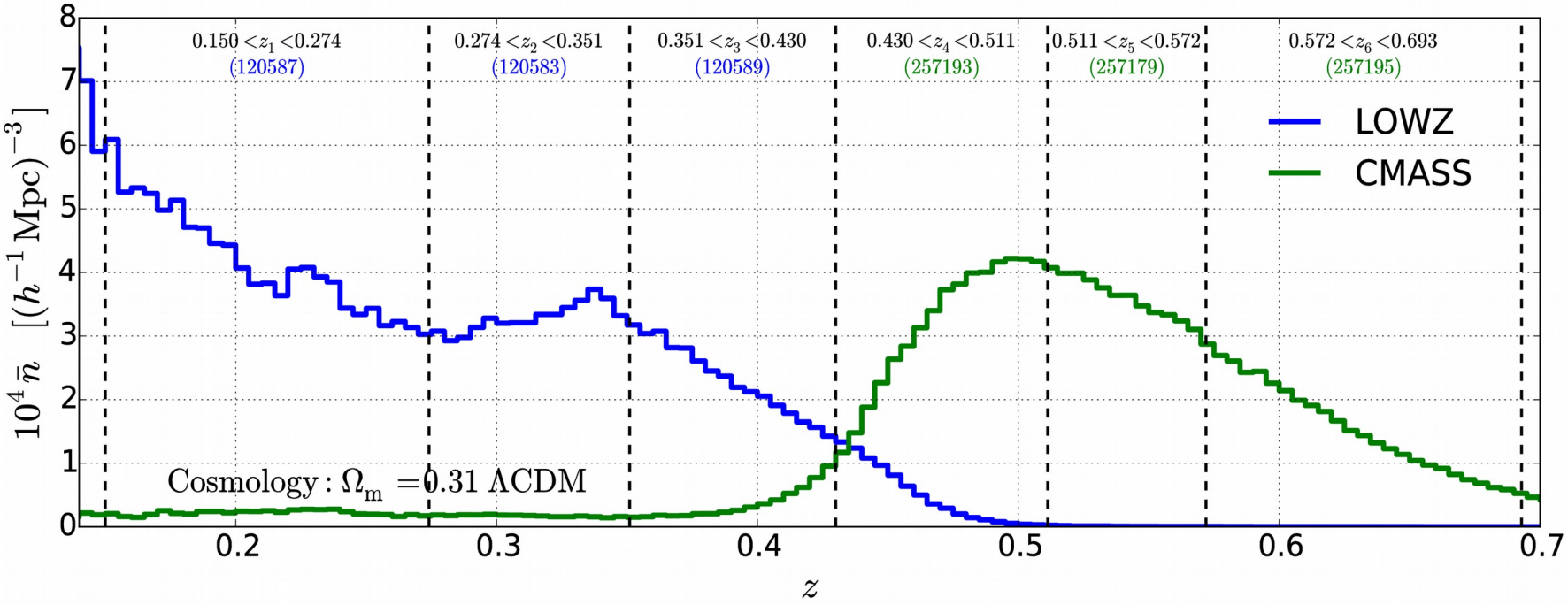
HR3 (Kim et al. 2012)
$(10.815\ h^{-1}\ \mathrm{Gpc})^3$
7120^3 particles
WMAP5 Cosmology

HR4 (Kim et al. 2015)
$(3.15 h^{-1}\ \mathrm{Gpc})^3$
6300^3 particles
WMAP5 Cosmology

27 all-sky mock surveys (for cov)

1 all-sky mock survey (for sys)

Methodology



Split CMASS & LOWZ into 3 redshift bins

1. Adopt a r(z) **[**in some cosmology**] and construct 3D position of galaxies**

2. Measure $\xi(s, \mu)$ **in each z-bin**

3. Quantify the evolution [ξ from 5 high-z bins compared to the lowest redshift**]**

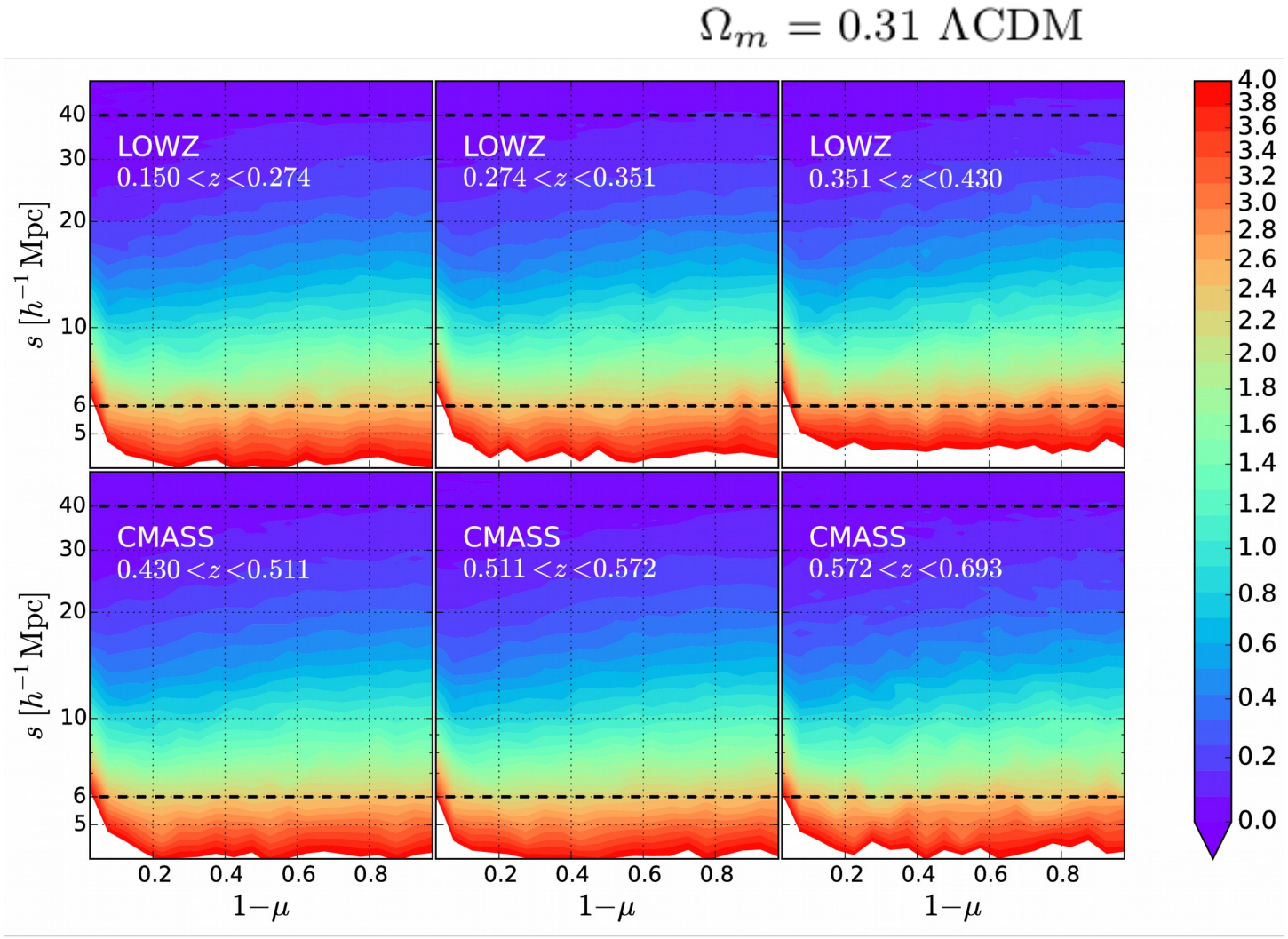
Wrong Cos. → Large redshift evolution → Disfavored

4. Try different cosmologies and repeat 1-3 → Cosmological Constraints

Sys Correction [redshift evolution coming from those other than AP]: HR4

Covariance Matrix: HR3

2-d 2pCF in six redshift bins



FOG at $1-\mu \to 0$ and Kaiser at $1-\mu > 0.1$

Similar to each other: Small redshift evolution of RSD

1-d 2pCF as a function of angle

We follow the procedure of Li et al. (2015) and integrate the ξ over the interval 6 Mpc/h < s < 40 Mpc/h. We evaluate

$$\xi_{\Delta s}(\mu) \equiv \int_{s_{\rm min}}^{s_{\rm max}} \xi(s,\mu)\ ds.$$

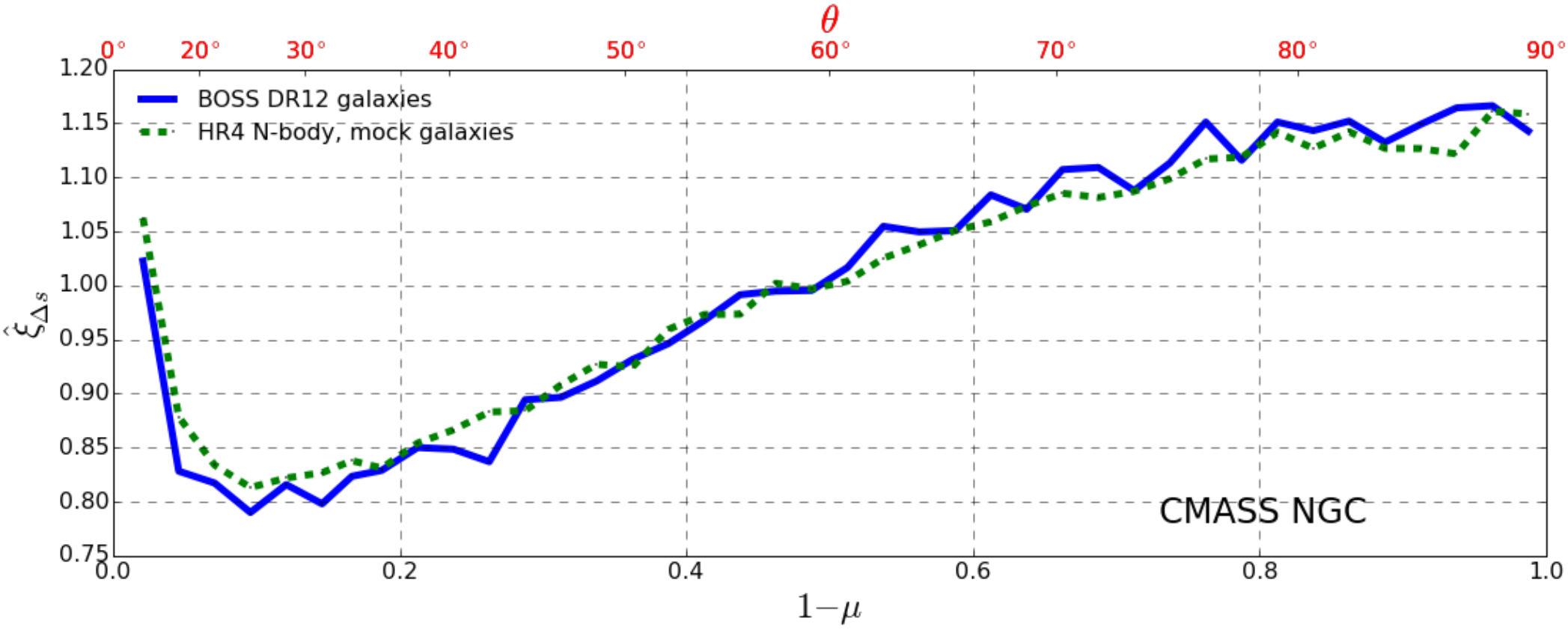
Focus on angular dependence

The redshift evolution of the bias of observed galaxies leads to redshift evolution of the strength of clustering, which is difficult to accurately model. To mitigate this systematic uncertainty we rely on the shape of $\xi_{\Delta s}(\mu)$, rather than its amplitude,

$$\hat{\xi}_{\Delta s}(\mu) \equiv \frac{\xi_{\Delta s}(\mu)}{\int_0^{\mu_{\rm max}} \xi_{\Delta s}(\mu)\ d\mu}.$$

Normalizing the amplitude; focus on shape of anisotropy [avoid sys from gal bias]

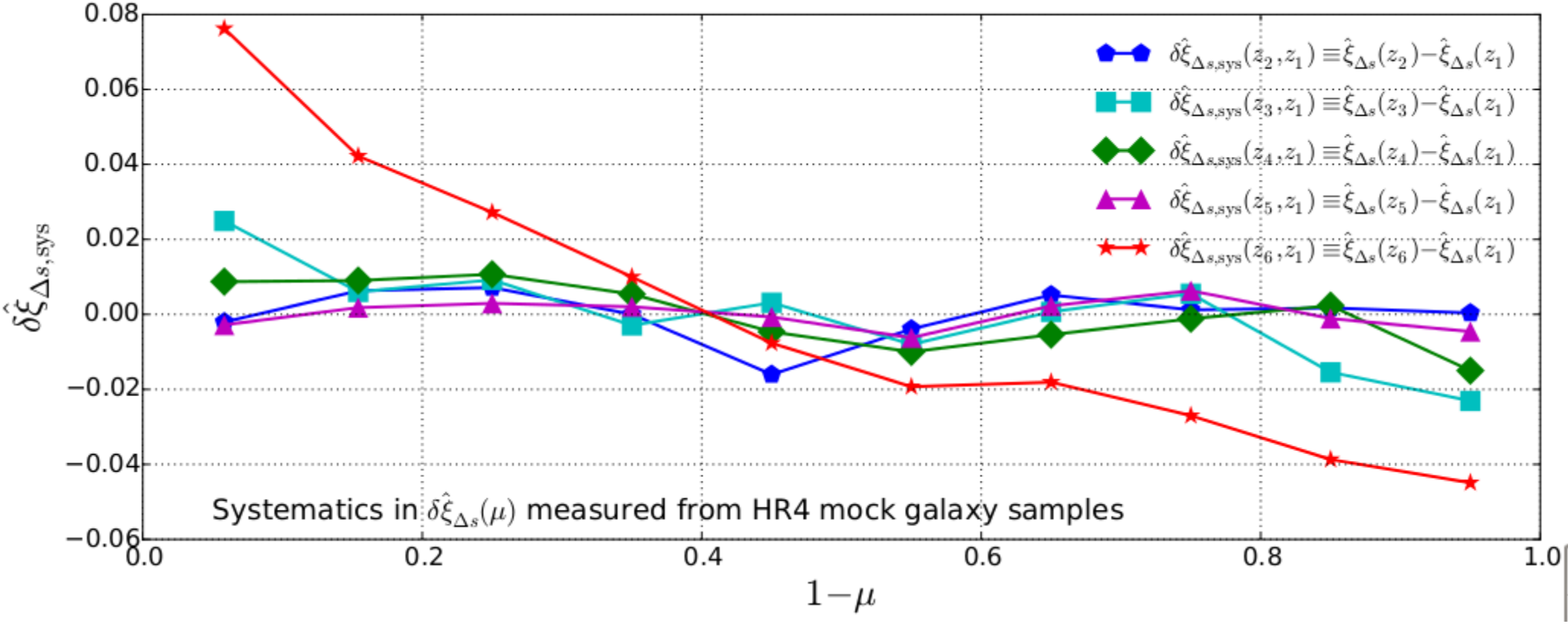
Observation VS Simulation



HR4 mock (green) reproduces observation (blue) very well

Estimating systematic

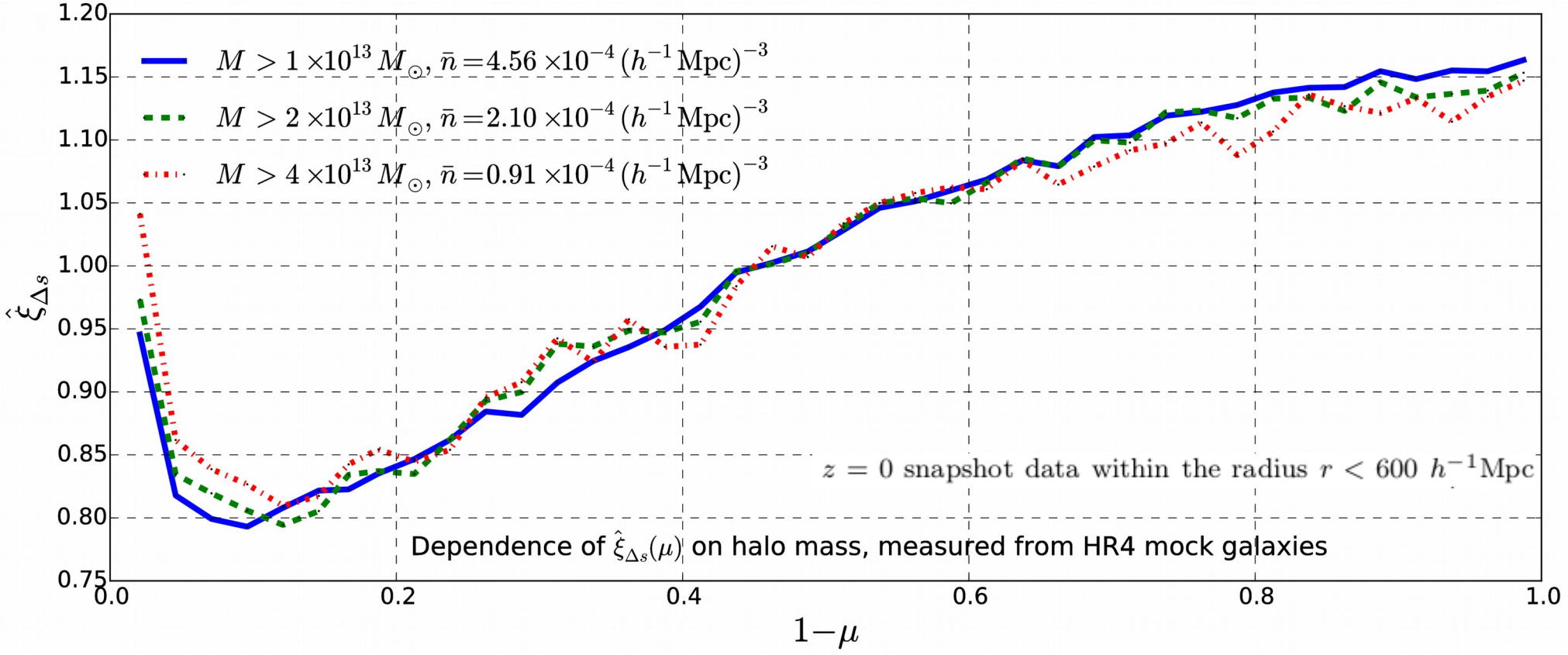
$$\delta\hat{\xi}_{\Delta s}(z_i, z_1, \mu_j) \equiv \hat{\xi}_{\Delta s}(z_i, \mu_j) - \hat{\xi}_{\Delta s}(z_1, \mu_j)$$



Redshift evolution from RSD, and so on

- Small in most redshift bins
- Relative large in the 6th bin but still correctable

Check systematics from gal bias

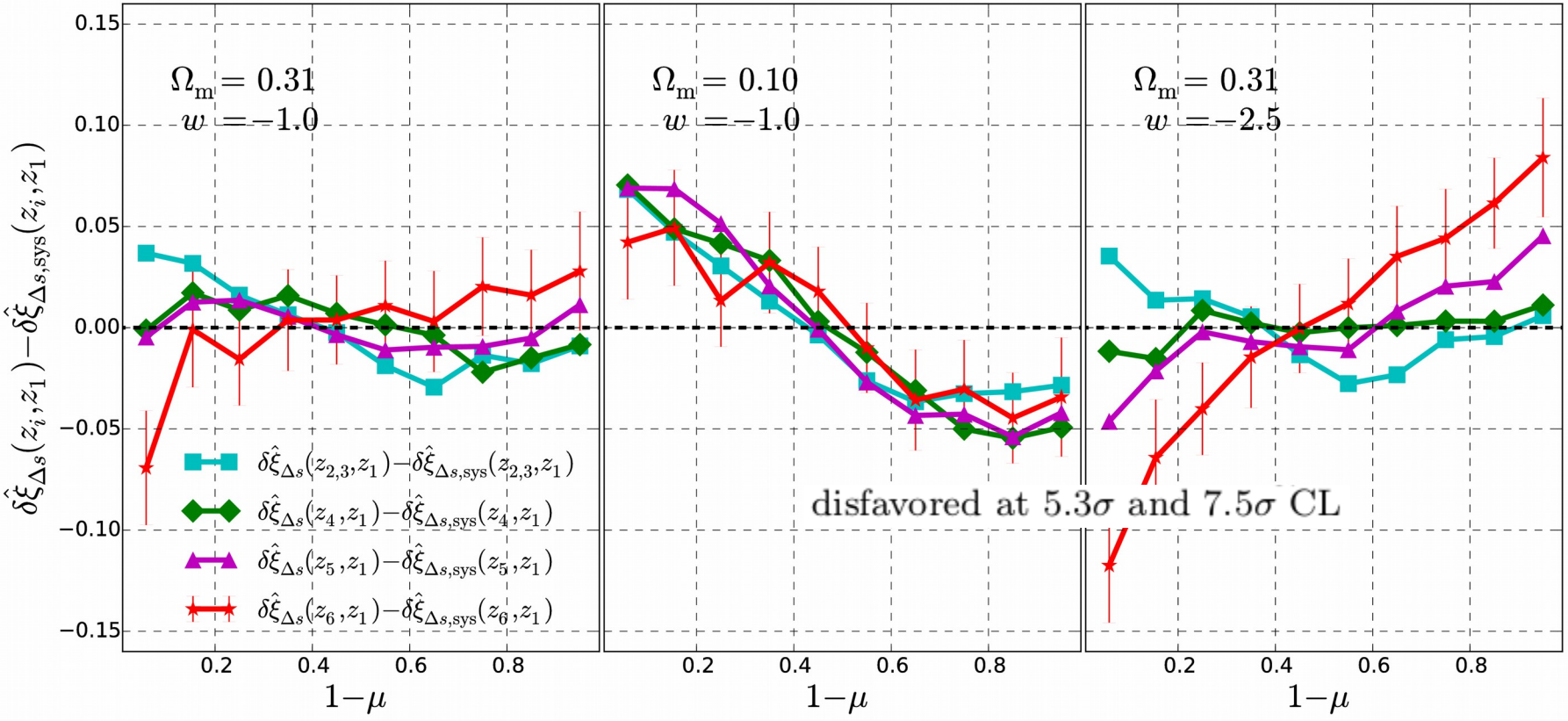


Considering the large variation of *M*, systematics not significant

Seeing AP

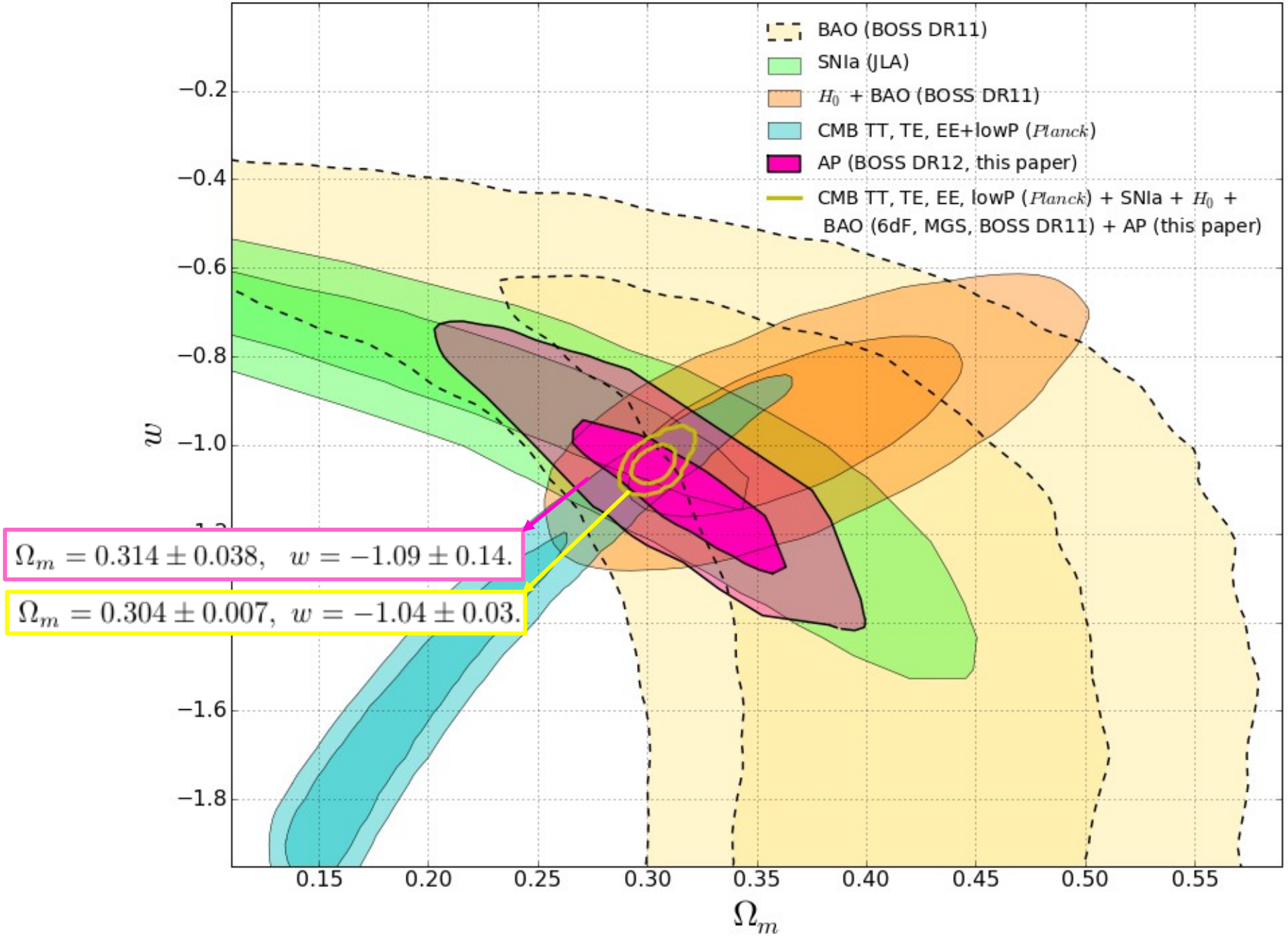
$$\delta\hat{\xi}_{\Delta s}(z_i, z_1, \mu_j) \equiv \hat{\xi}_{\Delta s}(z_i, \mu_j) - \hat{\xi}_{\Delta s}(z_1, \mu_j)$$

Evolution wrt lowest redshift; sys corrected

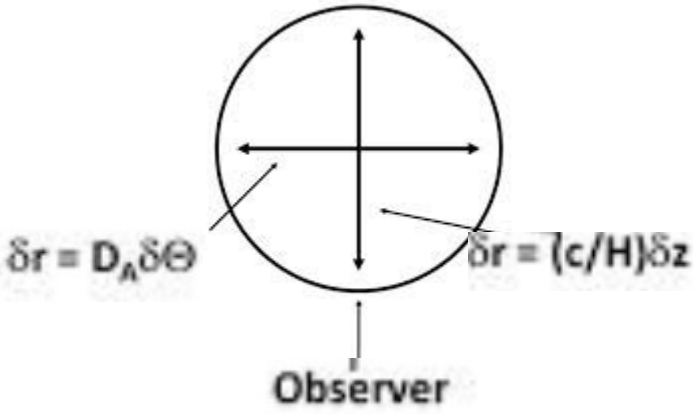


Redshift evolution from AP detected at high CL

Cosmological constraint: Looks Very Good!



Comparing the different probes of geometry



BAO: $D_A(z)/r_d$, $H(z)*r_d$

AP: $D_A*H(z)$

SNIa: $D_L(z)$

Our: $d\, D_A*H(z) / dz$

* Simple idea, successfully overcoming RSD

* Enter small scales (6 - 40 Mpc/*h*) difficult for most techniques

  – A lot of information encoded in small-scale clustering!

* Independent from others (combinable)

Concluding Remarks

Redshift dependence of AP from BOSS DR12

- Overcoming RSD through the redshift dependence
- Seems powerful: better than SNIa, BAO
- Complementary to BAO, RSD, WL, Clusters, Topology, …
  - Combining them to fully explore the physics in LSS
- Promising
  - Future surveys such as eBOSS, EUCLID, DESI have larger sample sizes and wider redshift coverage


The Truth of the Nature,
as perfect as a Circle,
is revealed in a path of Light.
The Enlightened Amitābha
What do we see?
Thank You!
The Reader of Nature