Cosmological Constraints from Redshift Dependence of Galaxy Clustering Anisotropy

CosKASI 2017 April 18, 2017

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Park & Kim (2010); Li, Park, Forero-Romero, Kim (2014); Li, Park, Sabiu, Kim(2015); Li, Park et al. (2016)

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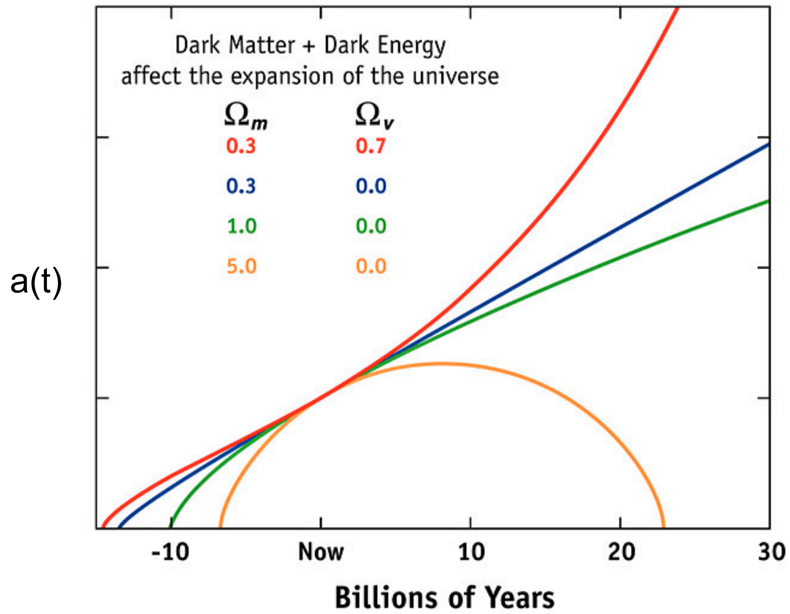
We develop a new method for measuring the cosmological parameters governing the expansion history of the universe. The method uses the Alcock-Paczynski (AP) test applied to the shape of the galaxy two-point correlation function along and across the line-of-sight. The redshift-space distortion (RSD) effects have been the major obstacle for the AP test. We find that the RSD effects on the correlation function are big at a given redshift but do not vary much as redshift increases, and that the shape of the correlation function is nearly conserved. If a wrong cosmology is adopted, the conversion from the observed galaxy redshift to comoving distance results in distortion of the shape of the correlation function that varies systematically in redshift. We applied to this method to simulated data and also to the recent SDSS DR12 galaxy survey data to obtain constraints on the dark energy equation of state w and matter density parameter Ω_m.

Expansion History vs Matter Contents of the Universe

Observation
The Universe is expanding (1929).
The expansion has been accelerating recently (1998).

General relativity
Properties of spacetime vs
Amount and type of the energy contents in the universe.



Expansion history a(t) vs the energy contents in FRW universe

$$\left(\frac{\dot{a}}{a}\right)^2 = H_0^2[\Omega_k a^{-2} + \Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_{DE}\ a^{-3(1+w)}]$$

Distance

$$r(z) = c\int \frac{dt}{a(t)} = c\int \frac{dz}{H(z)}$$

A Test for the Cosmic Expansion History based on Geometrical Shape of Cosmic Structures

An evolution free test for non-zero cosmological constant

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The cosmological constant has recently been questioned because of difficulties in fitting the standard $\Lambda = 0$ cosmological models to observational data[1,2]. We propose here a cosmological test that is a sensitive estimator of Λ. This test is unusual in that it involves no correction for evolutionary effects. We present here the idealised conception of the method, and hint at the statistical problem that its realisation entails.

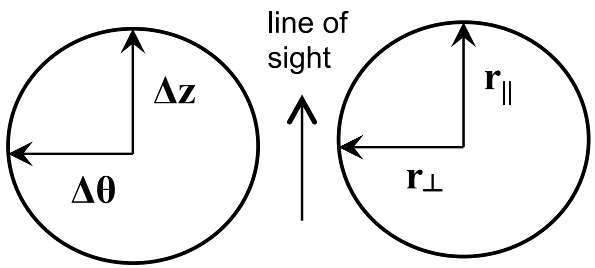
(Alcock & Paczynski, 1979, Nature, 281, 358)

Geometrical shape of cosmic structures in comoving space

- **Comoving sizes**

$$r_{\parallel} = \frac{c\Delta z}{H(z)}$$

$$r_{\perp} = (1+z) D_A(z) \Delta\theta$$



where

$$D_A(z) = \frac{c}{1+z}\int_0^z \frac{dz}{H(z)}$$

$$\mathrm{H(z)} = \sqrt{\frac{\Omega_m h^2}{1-\Omega_X}}\sqrt{\Omega_m(1+z)^3 + \Omega_X \exp\left[3\int_0^z \frac{1+w(z)}{1+z}dz\right]}$$

(flat universe)

- **Suppose, for some particular object, we know the ratio**

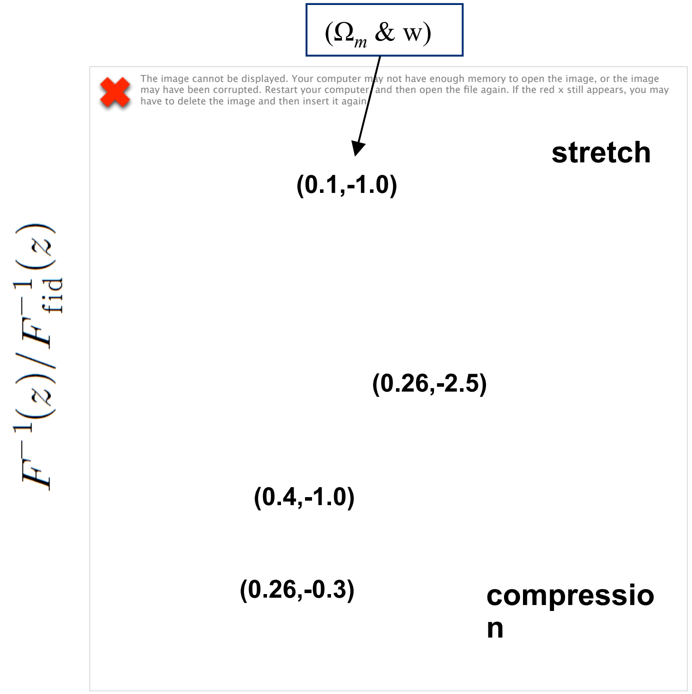
$$\frac{r_{\parallel}}{r_{\perp}} = \frac{c}{(1+z)D_A(z)H(z)} \cdot \frac{\Delta z}{\Delta\theta} = F(z)^{-1} \cdot \frac{\Delta z}{\Delta\theta}$$

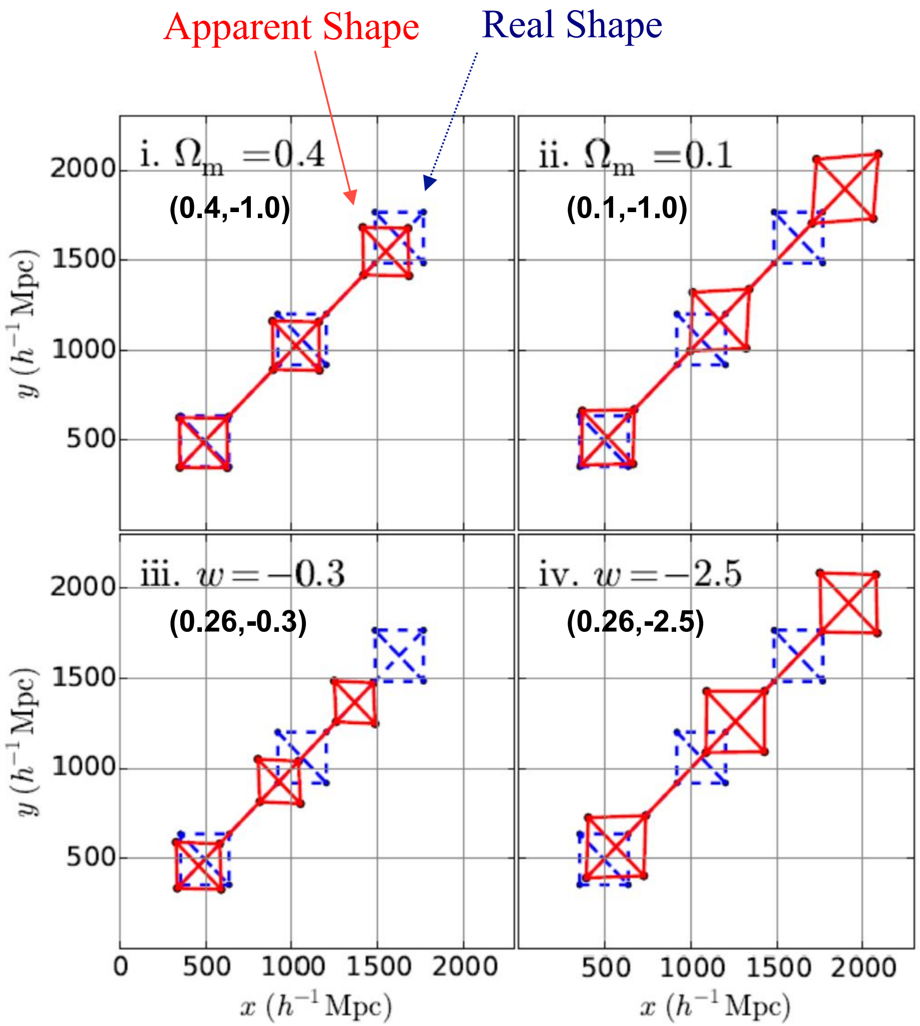
where $\boxed{F(z) \equiv \frac{(1+z)}{c} D_A(z) H(z)}$

If we adopt a wrong cosmology in the 'z→r' transformation, we see apparent shape distortion by a factor $F^{-1}(z)/F_{\mathrm{true}}^{-1}(z)$ **!**

Shape of structures in comoving spaces

in true (Ω_m=0.26 & w=-1) and wrong cosmologies





Objects with **known shape** $\mathbf{r_{||}/r_\perp}$ or **volume** $\mathbf{r_{||}r_\perp^2}$ can be standard rulers

(actual objects or features in clustering statistics)

→ measure $r_{||}/r_\perp$ or $r_{||}r_\perp^2$ → $D_A(z)$*$H(z)$ or $D_A(z)^2/H(z)$ → Ω_m, Ω_X, w

$$r_{||} = \frac{c\Delta z}{H(z)}$$

$$r_\perp = (1+z)D_A(z)\Delta\theta$$

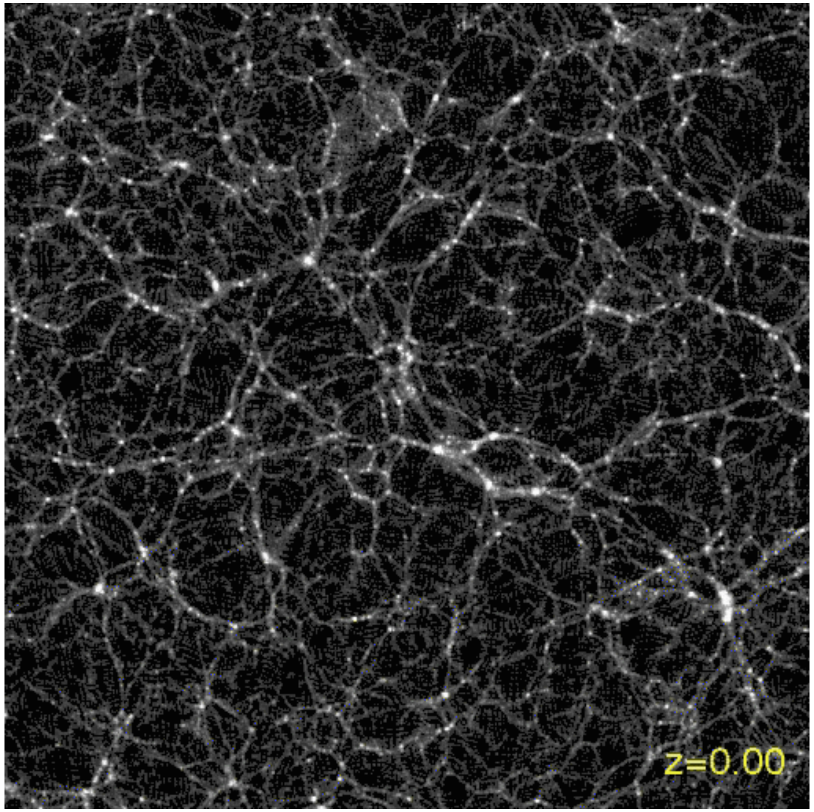
Li+ 2014
Li+ 2015
Li+ 2016

Park&Kim 2010
Blake+ 2013
Speare+2015

Galaxy clustering should be statistically isotropic on all scales
(Gravity does not depend on direction!)

→ Allows us to use the small-scale clustering

→ Achieve higher statistics



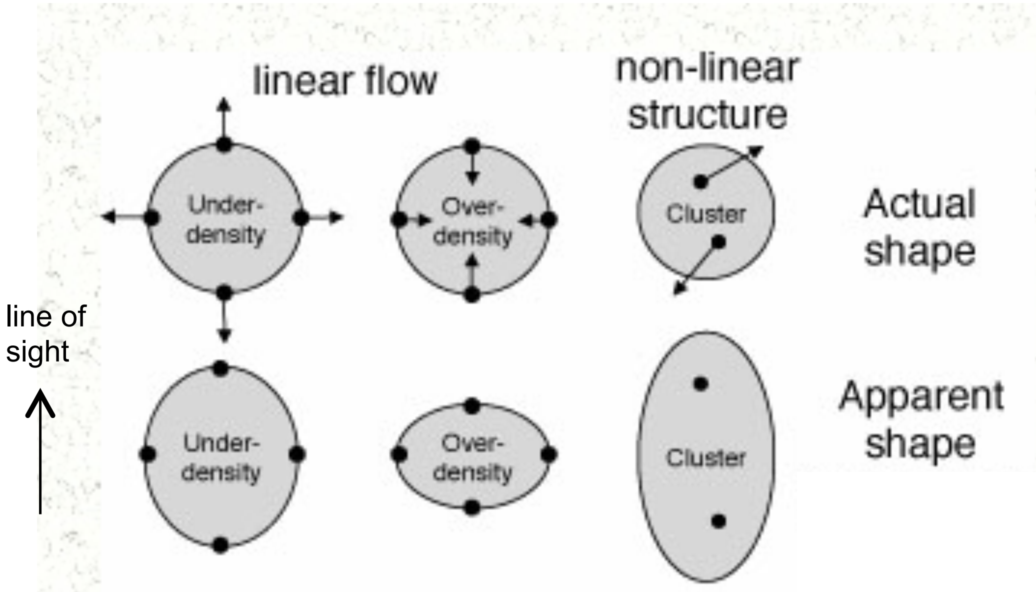
[Kim & Park 2005]

A biggest obstacle:

Redshift-space Distortion

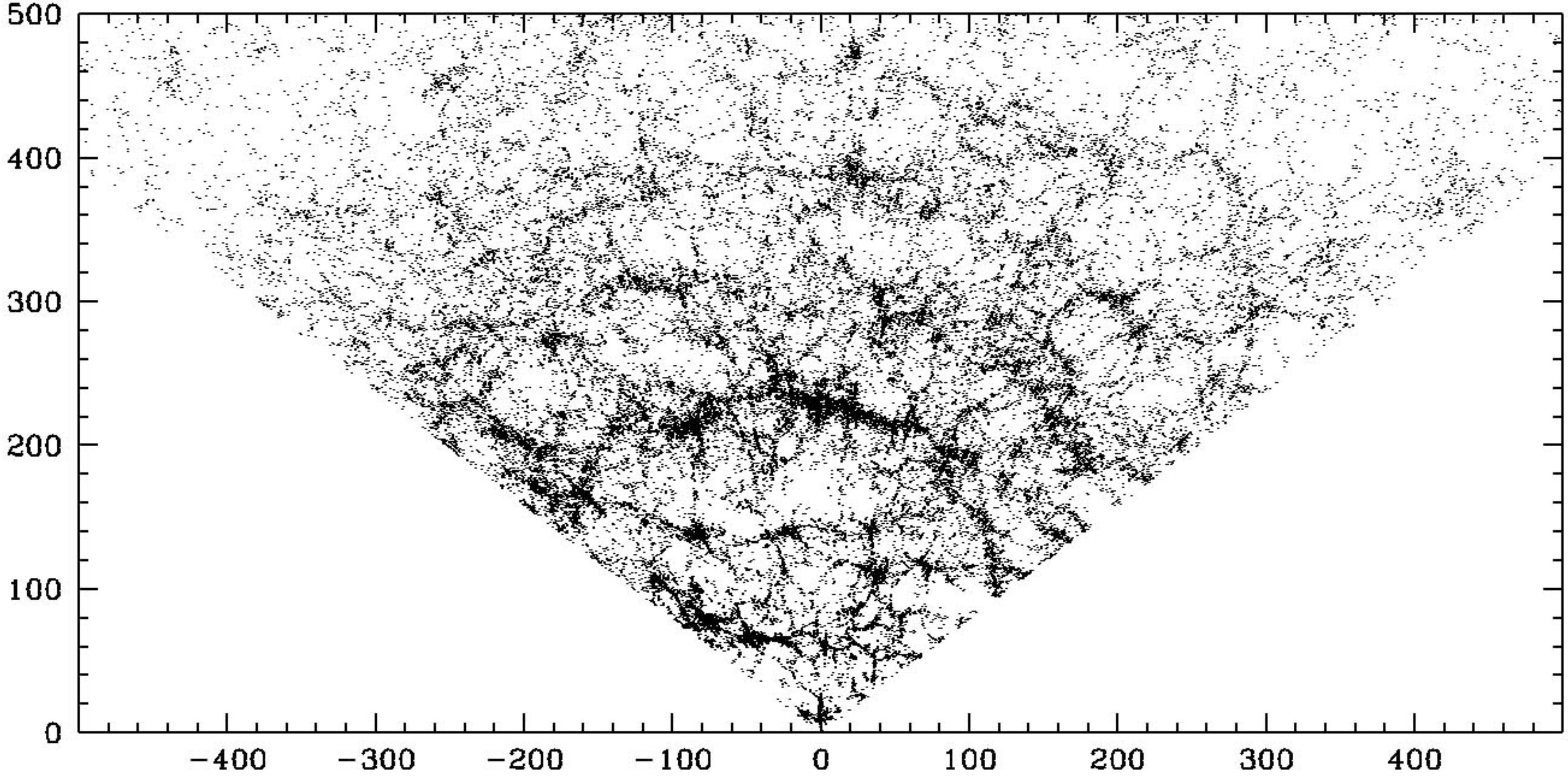
Galaxy redshifts are contaminated by peculiar velocities!

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



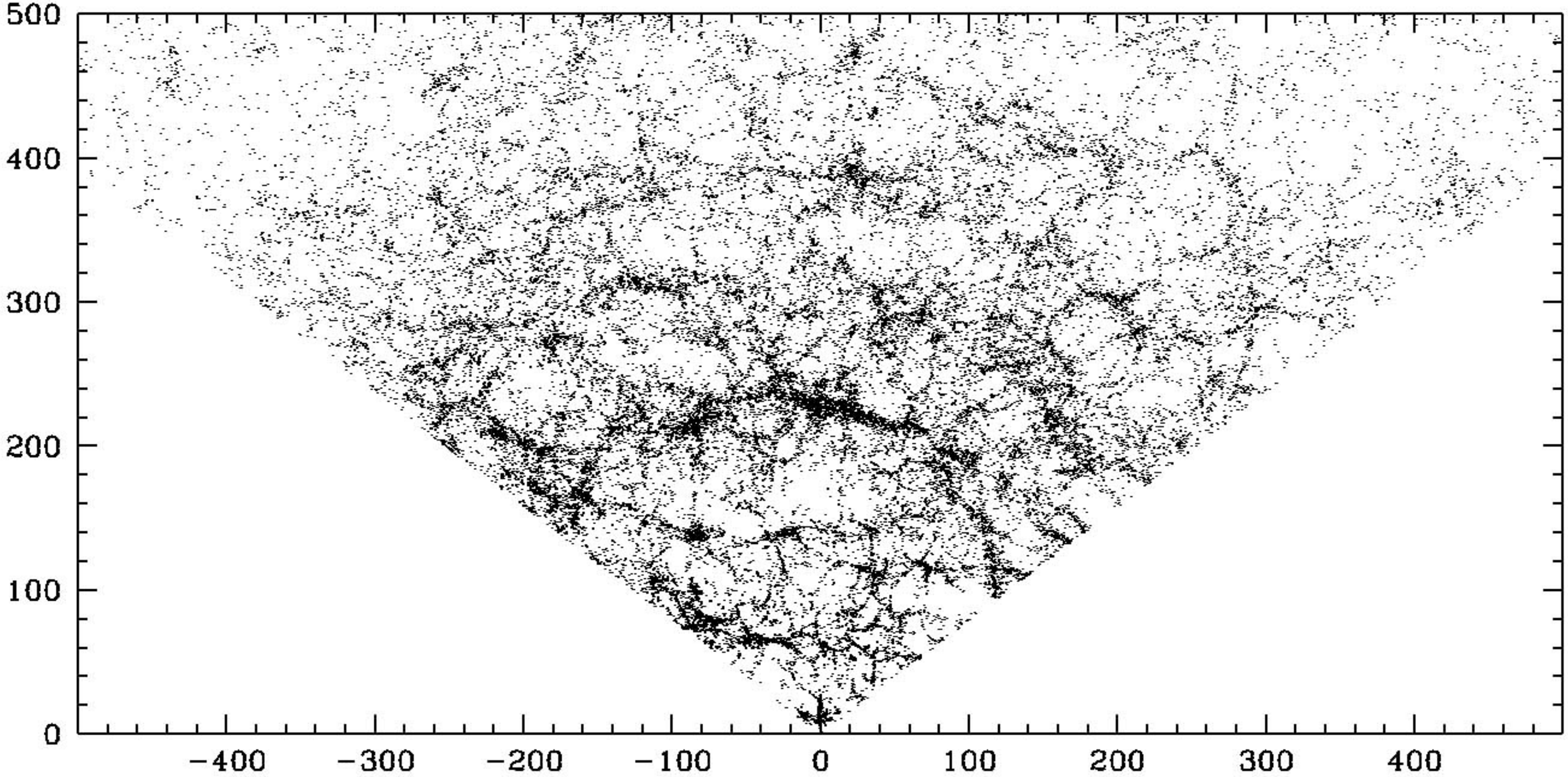
A. Small scale finger-of-god effect: LOS stretch, due to random motions of galaxies.

B. Large scale flow: LOS compression of filaments and walls and radial elongation of voids



Galaxy distribution in redshift space

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

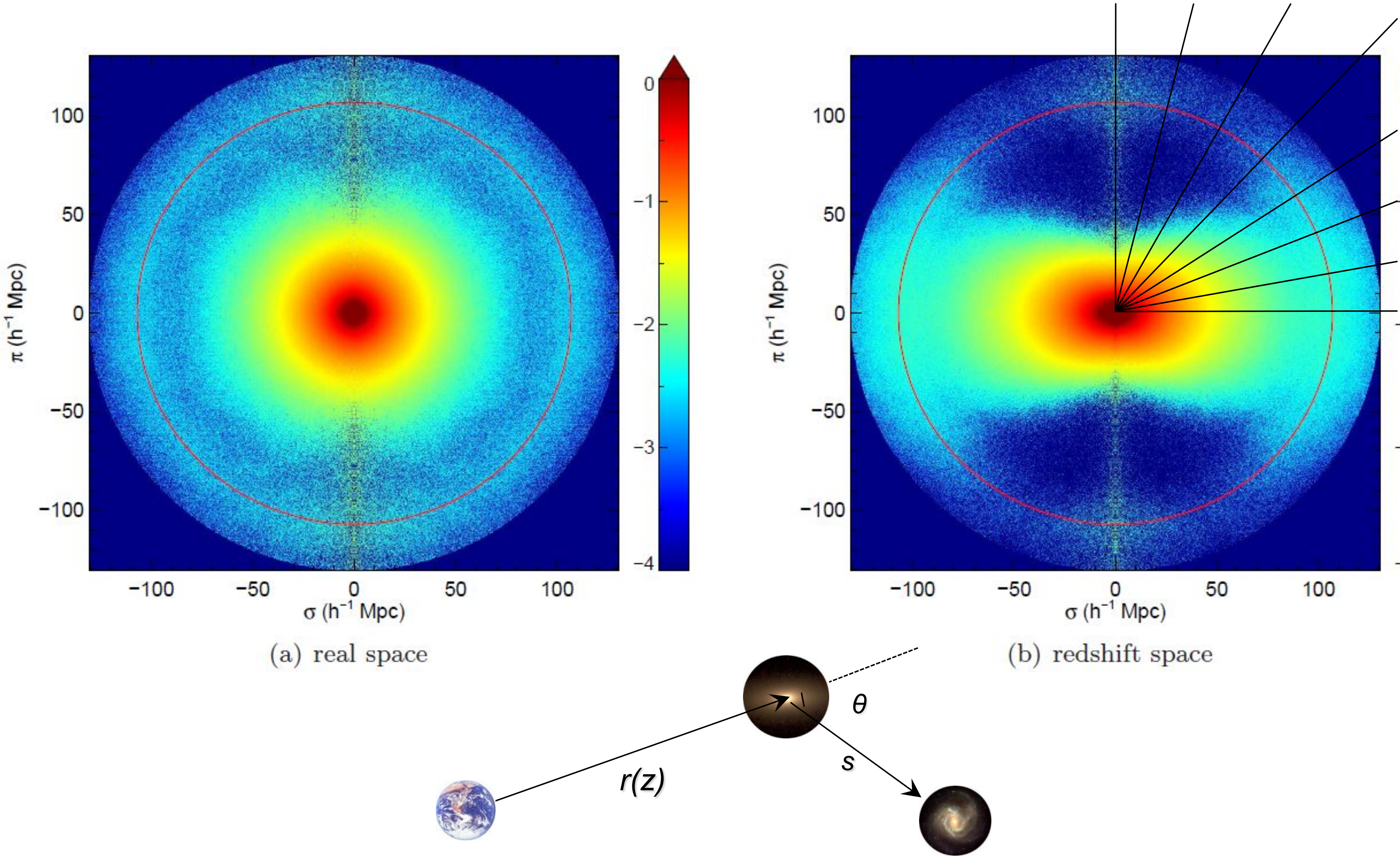


Galaxy distribution in real space

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

Redshift-space distortion effects **[Horizon-Run 4** : Kim et al. 2015, JKAS, 48, 213]

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



2-point CF in 6 redshift bins

(SDSS BOSS sample; FoG at $1-\mu \rightarrow 0$ and Kaiser effect at $1-\mu > 0.2$)

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θ = 0

θ = 90

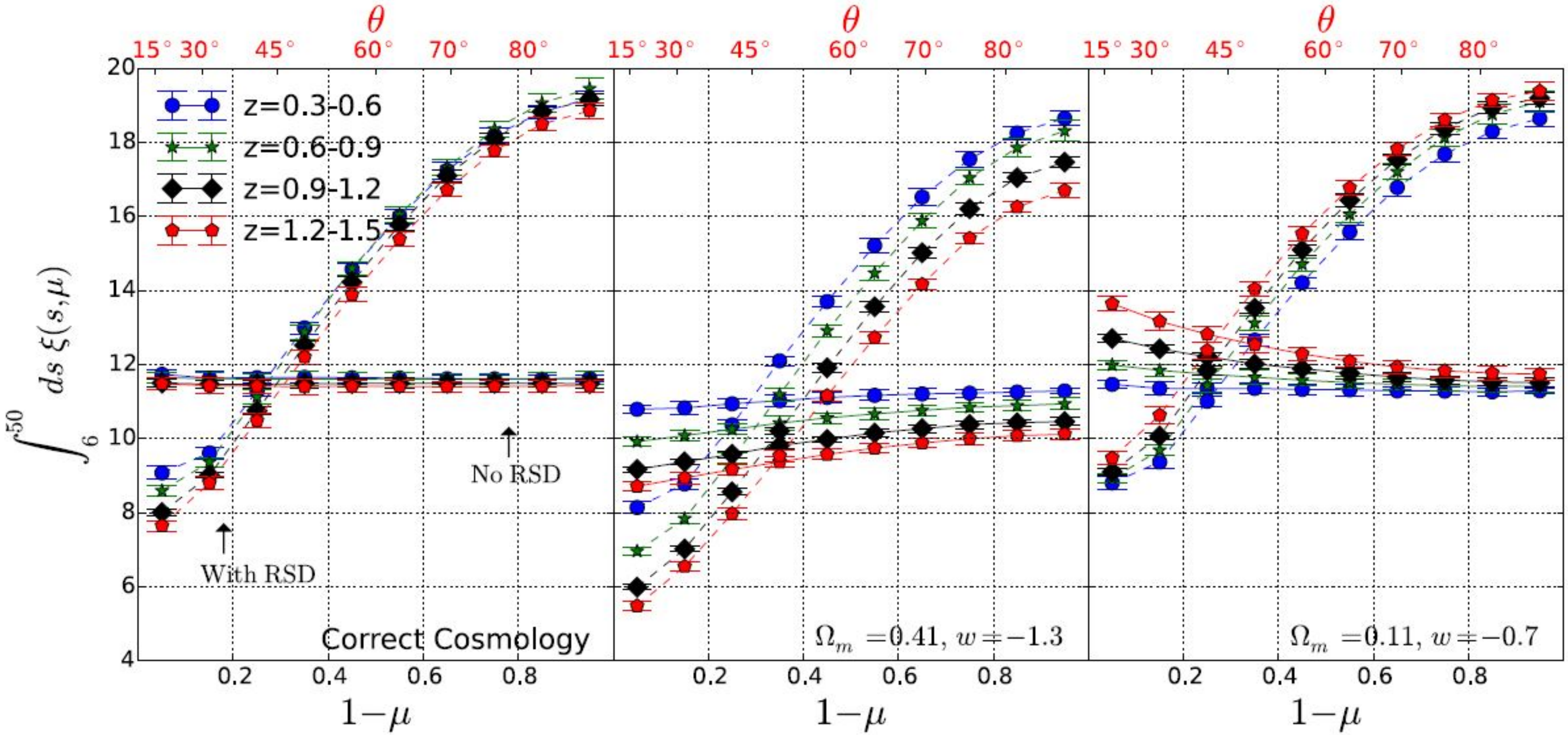
$\Omega_m = 0.31\ \Lambda\mathrm{CDM}$

adopted in these p
articular plots

: Even though RSD effects on CF is big, its redshift evolution is small!
Redshift evolution of CF is dominated by the cosmological effects (Li, Park+ 2015).

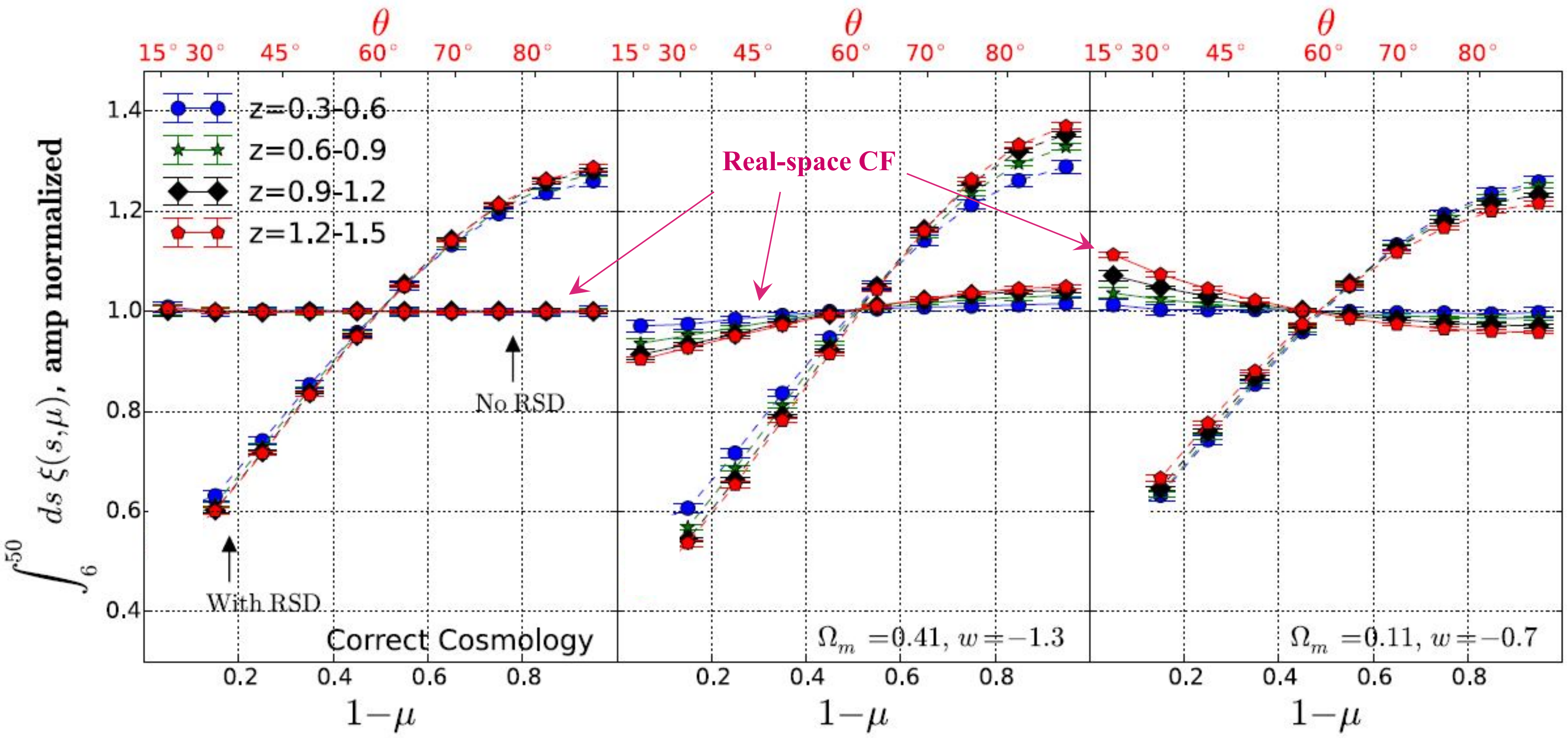
μ*- dependence of *CF

$$\xi_{\Delta s}(\mu) \equiv \int_{s_{\min}}^{s_{\max}} \xi(s,\mu)\ ds.$$ (s_{min}=6 & s_{max}=50 Mpc/h)



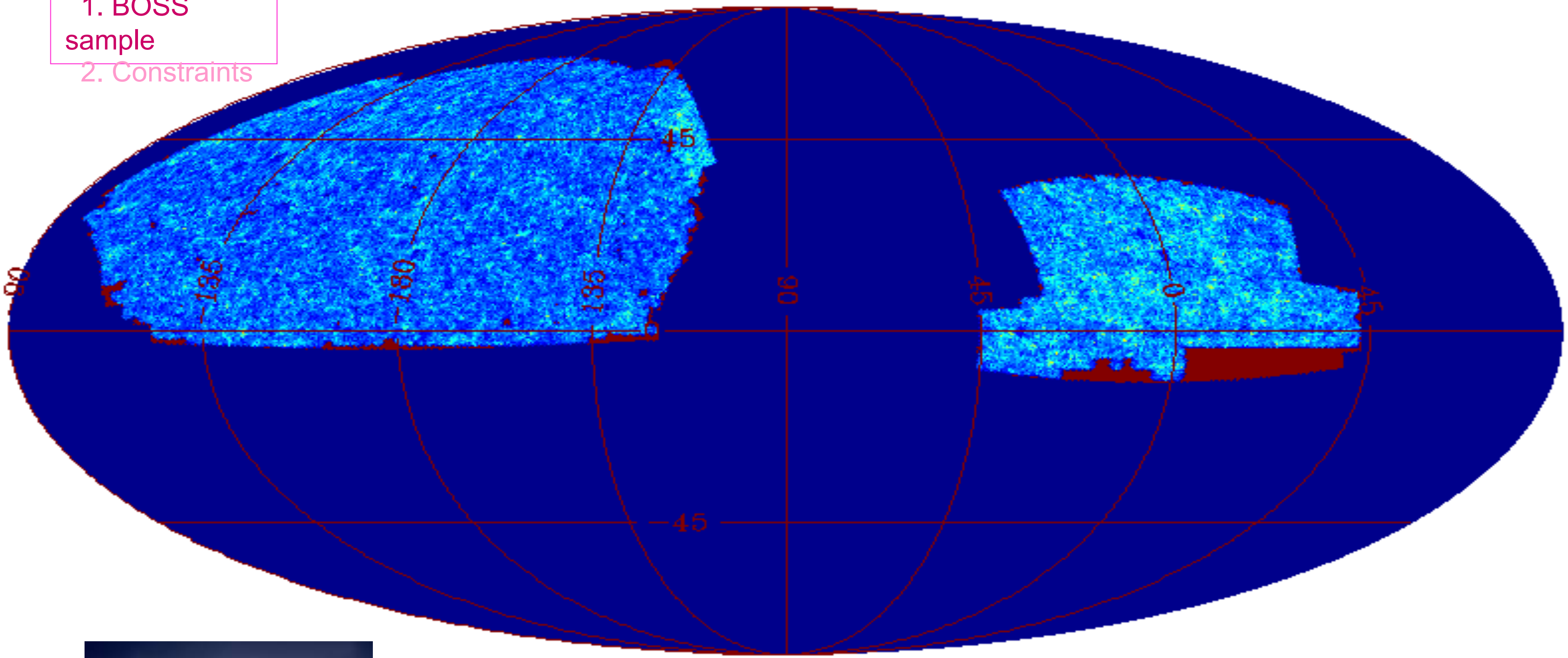
Normalized CF

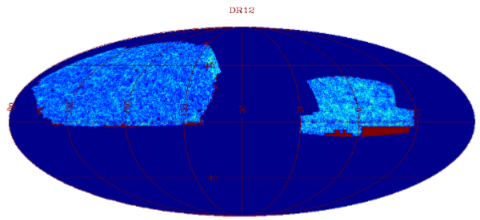
$$\hat{\xi}_{\Delta s}(\mu) \equiv \frac{\xi_{\Delta s}(\mu)}{\int_0^1 \xi_{\Delta s}(\mu)\, d\mu}.$$



Evolution of the RSD effects is very small and can be estimated.

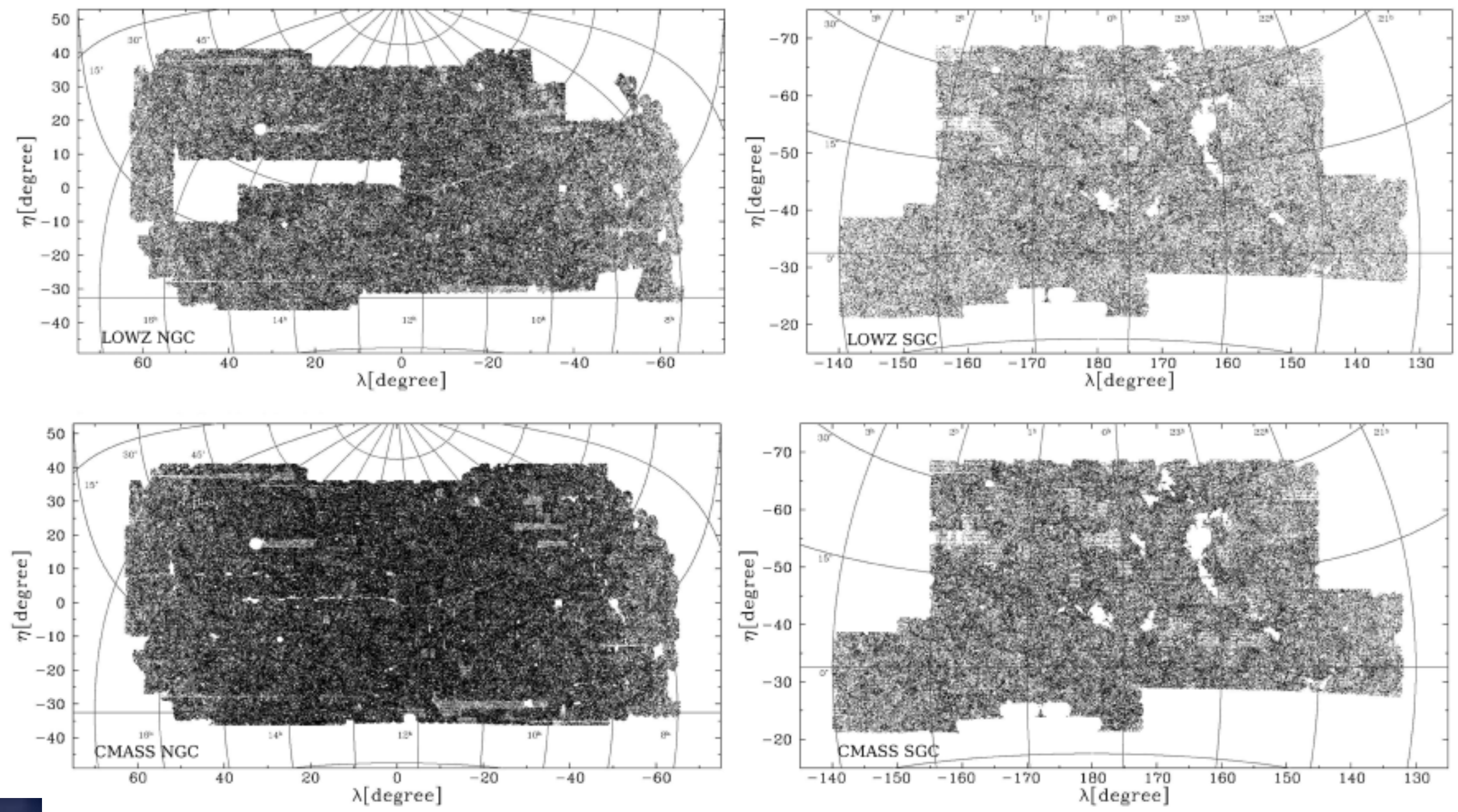
Application to BOSS DR12 Samples

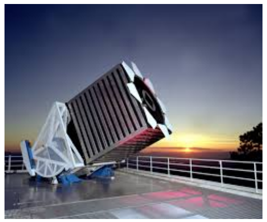




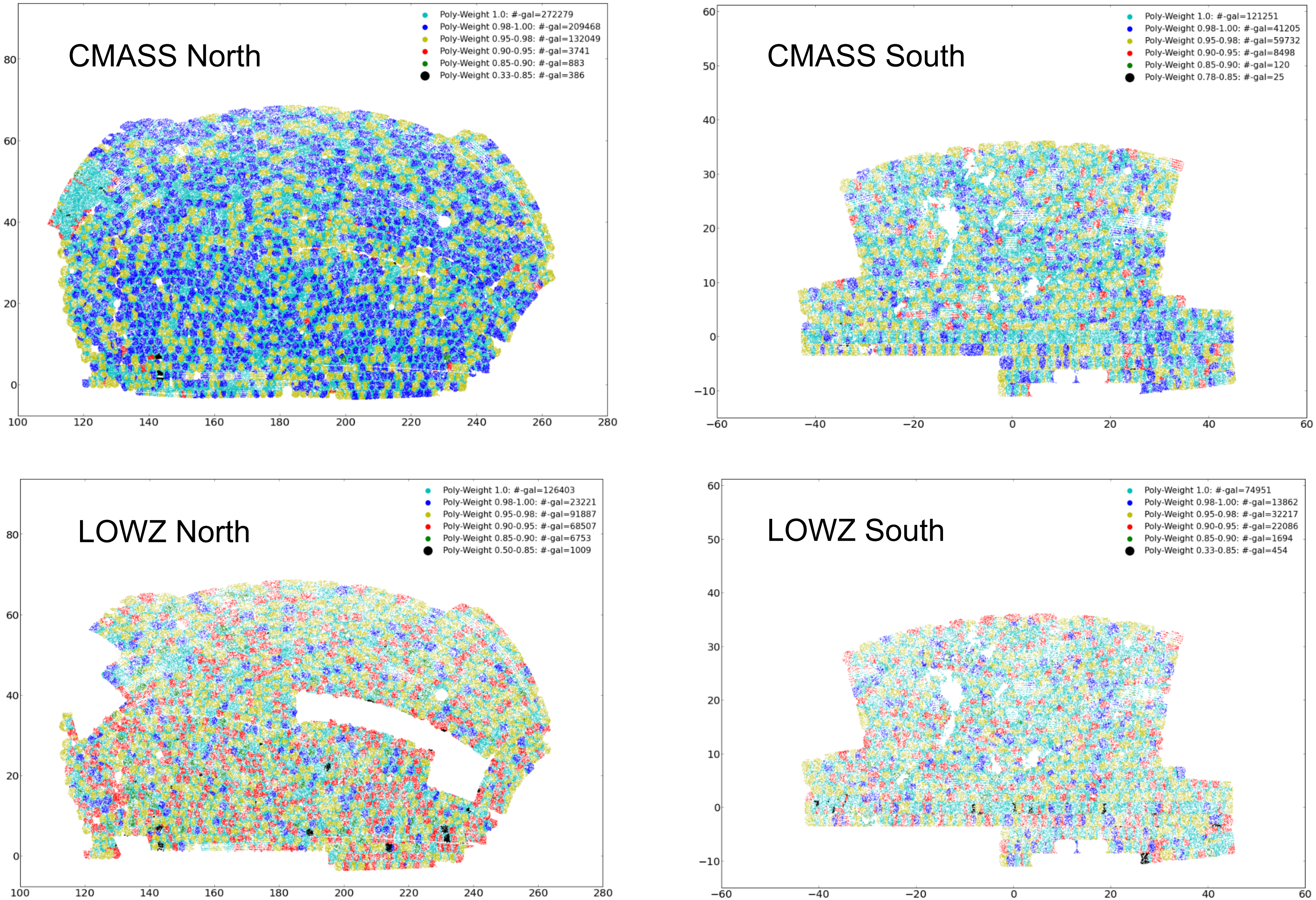
SDSS-III BOSS DR12 sample

LOWZ 8,337 deg ^{2} . CMASS 9,376 deg ^{2} (~1/4 sky). ~1.13 M gals at $0.15 \leq z \leq 0.7$





(Li, Park et al. 2016)


CMASS North
Poly-Weight 1.0: #-gal=272279
Poly-Weight 0.98-1.00: #-gal=209468
Poly-Weight 0.95-0.98: #-gal=132049
Poly-Weight 0.90-0.95: #-gal=3741
Poly-Weight 0.85-0.90: #-gal=883
Poly-Weight 0.33-0.85: #-gal=386
CMASS South
Poly-Weight 1.0: #-gal=121251
Poly-Weight 0.98-1.00: #-gal=41205
Poly-Weight 0.95-0.98: #-gal=59732
Poly-Weight 0.90-0.95: #-gal=8498
Poly-Weight 0.85-0.90: #-gal=120
Poly-Weight 0.78-0.85: #-gal=25
LOWZ North
Poly-Weight 1.0: #-gal=126403
Poly-Weight 0.98-1.00: #-gal=23221
Poly-Weight 0.95-0.98: #-gal=91887
Poly-Weight 0.90-0.95: #-gal=68507
Poly-Weight 0.85-0.90: #-gal=6753
Poly-Weight 0.50-0.85: #-gal=1009
LOWZ South
Poly-Weight 1.0: #-gal=74951
Poly-Weight 0.98-1.00: #-gal=13862
Poly-Weight 0.95-0.98: #-gal=32217
Poly-Weight 0.90-0.95: #-gal=22086
Poly-Weight 0.85-0.90: #-gal=1694
Poly-Weight 0.33-0.85: #-gal=454

Methodology

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0. 6 redshift bin samples from CMASS & LOWZ

1. Adopt a cosmology and r(z) relation

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

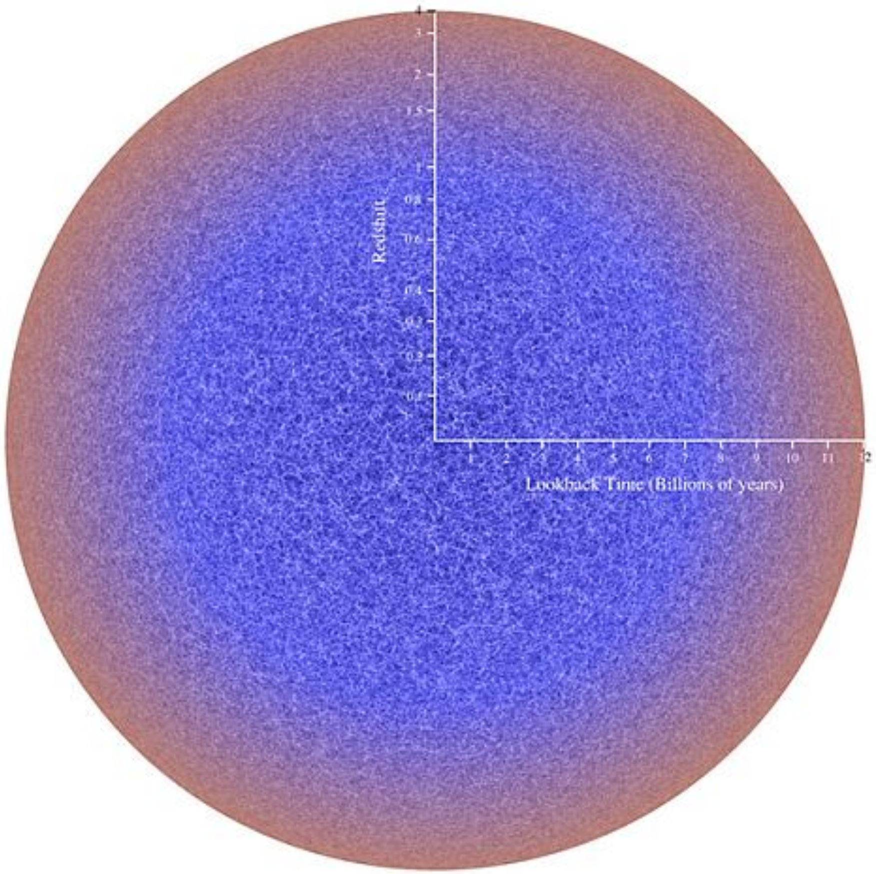
3. Quantify the redshift evolution of $\xi(s, \mu)$ by a chisq value

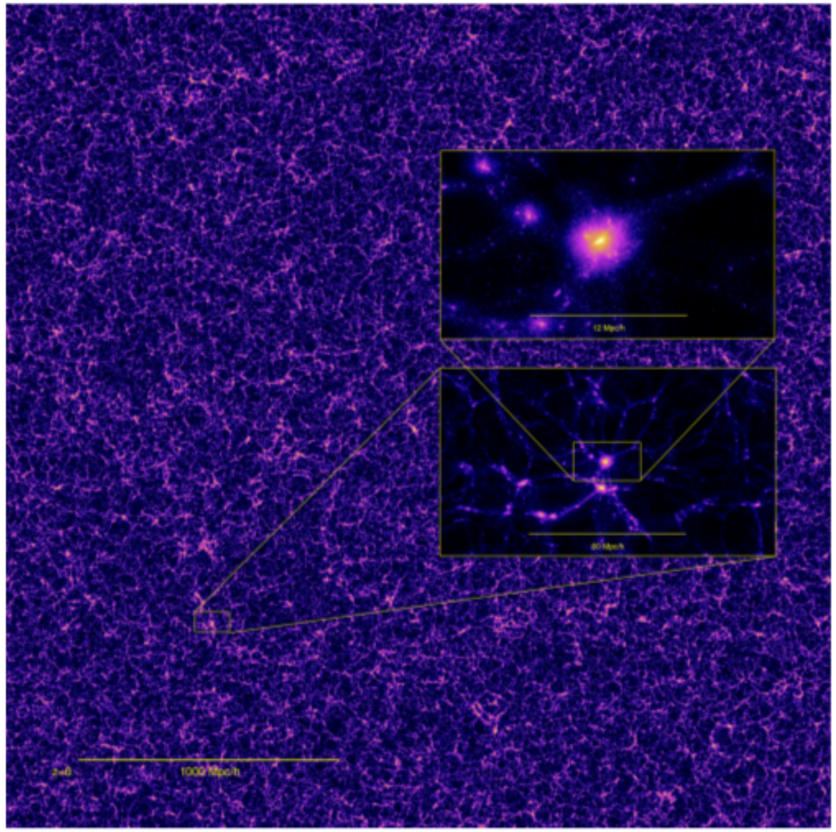
(Wrong Cos. → redshift evolution of ξ → chisq≠0 → Disfavored)

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

Systematics Correction (intrinsic redshift evolution): HR4 mock galaxy samples

Covariance Matrix: HR3 PSB subhalo samples





Horizon Run 3 (Kim et al. 2012)

V=(10.815 h^{-1} Gpc)^3 , 7120^3 particles

WMAP5 Cosmology

Dark matter halos in 27 whole-sky lightcones

→ Covariance Matrix

Horizon Run 4 (Kim et al. 2015)

V= (3.15h^{-1} Gpc)^3 , 6300^3 particles

WMAP5 Cosmology

Mock 'galaxies' in 1 whole-sky lightcone (Hong+ 2015)

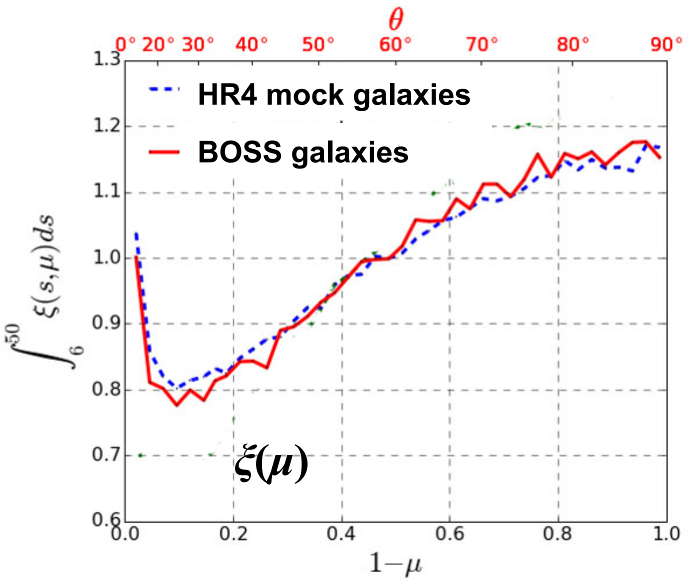
→ Systematics Correction

2-point CF from SDSS BOSS data and simulated mock samples

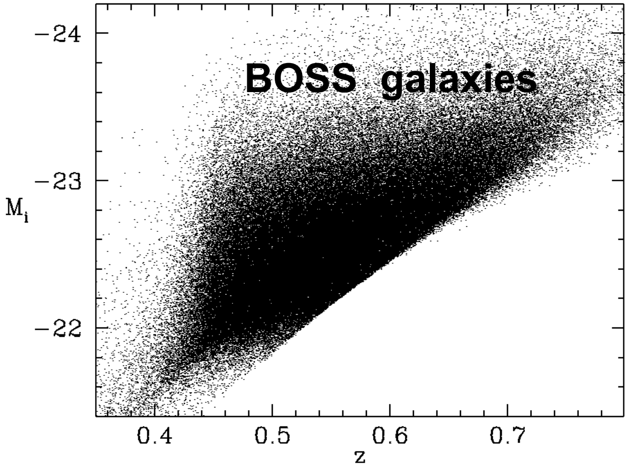
BOSS galaxies

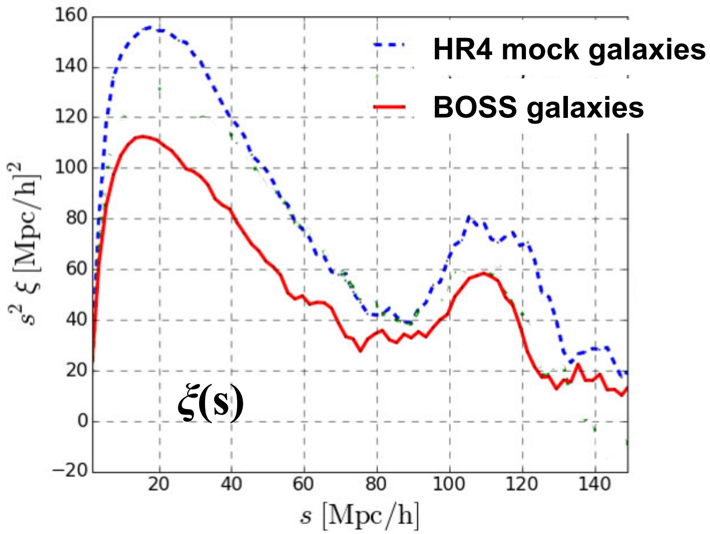
HR4 mock galaxies

redshift-dependent mock galaxy mass cut to match the radial # density distribution of BOSS galaxies



2-point CF from SDSS BOSS data and simulated mock samples





Constraints on cosmological parameters

$$\hat{\xi}_{\Delta s}(\mu) \equiv \frac{\xi_{\Delta s}(\mu)}{\int_0^1 \xi_{\Delta s}(\mu)\, d\mu}. \quad \text{where} \quad \xi_{\Delta s}(\mu) \equiv \int_{s_{\min}}^{s_{\max}} \xi(s,\mu)\, ds.$$

$\delta\xi = \xi$(other z-bin) – ξ(1st z-bin)

Systematics: $\delta\xi \rightarrow \delta\xi$ – (sys. est. from HR4)

$\chi^2 = \Sigma\, \delta\xi$ * Cov^{-1} * $\delta\xi$ (Covariance from 72 HR3 mock surveys)

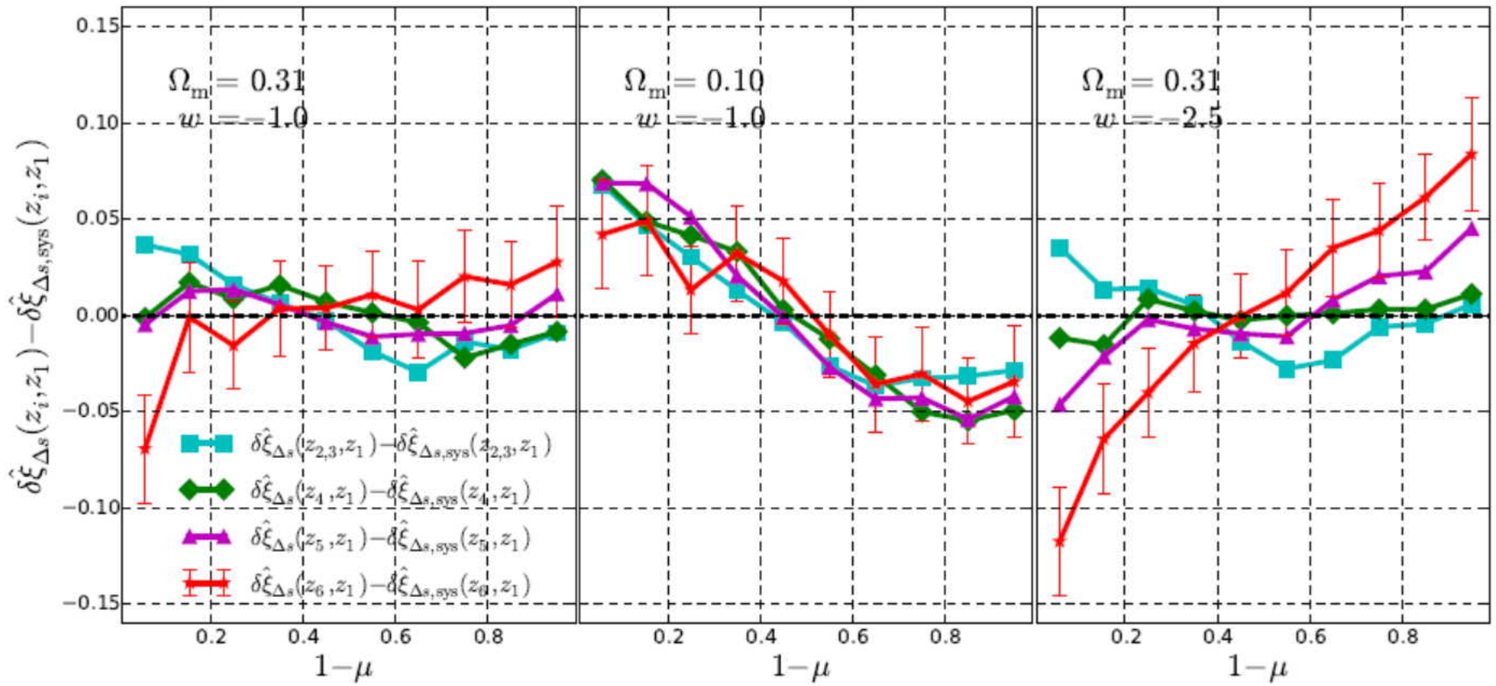
where the summation is over redshift bins and different μ bins.

The PDF of the cosmological parameters $\theta=(\Omega_m, w)$

$$P(\theta|\mathbf{D}) \propto \mathcal{L} \propto \exp\left[-\frac{\chi^2}{2}\right]$$

CF normalized & systematics corrected

$$\xi_{\Delta s}(\mu) \equiv \int_{s_{\min}}^{s_{\max}} \xi(s,\mu)\ ds. \rightarrow \hat{\xi}_{\Delta s}(\mu) \equiv \frac{\xi_{\Delta s}(\mu)}{\int_0^1 \xi_{\Delta s}(\mu)\ d\mu}. \rightarrow \delta\xi = \xi(\text{other z-bin}) - \xi(\text{1st z-bin})$$



The best model with the min. evolution (Ω_m=0.314, w= -1.09).

Constraints on cosmological parameters

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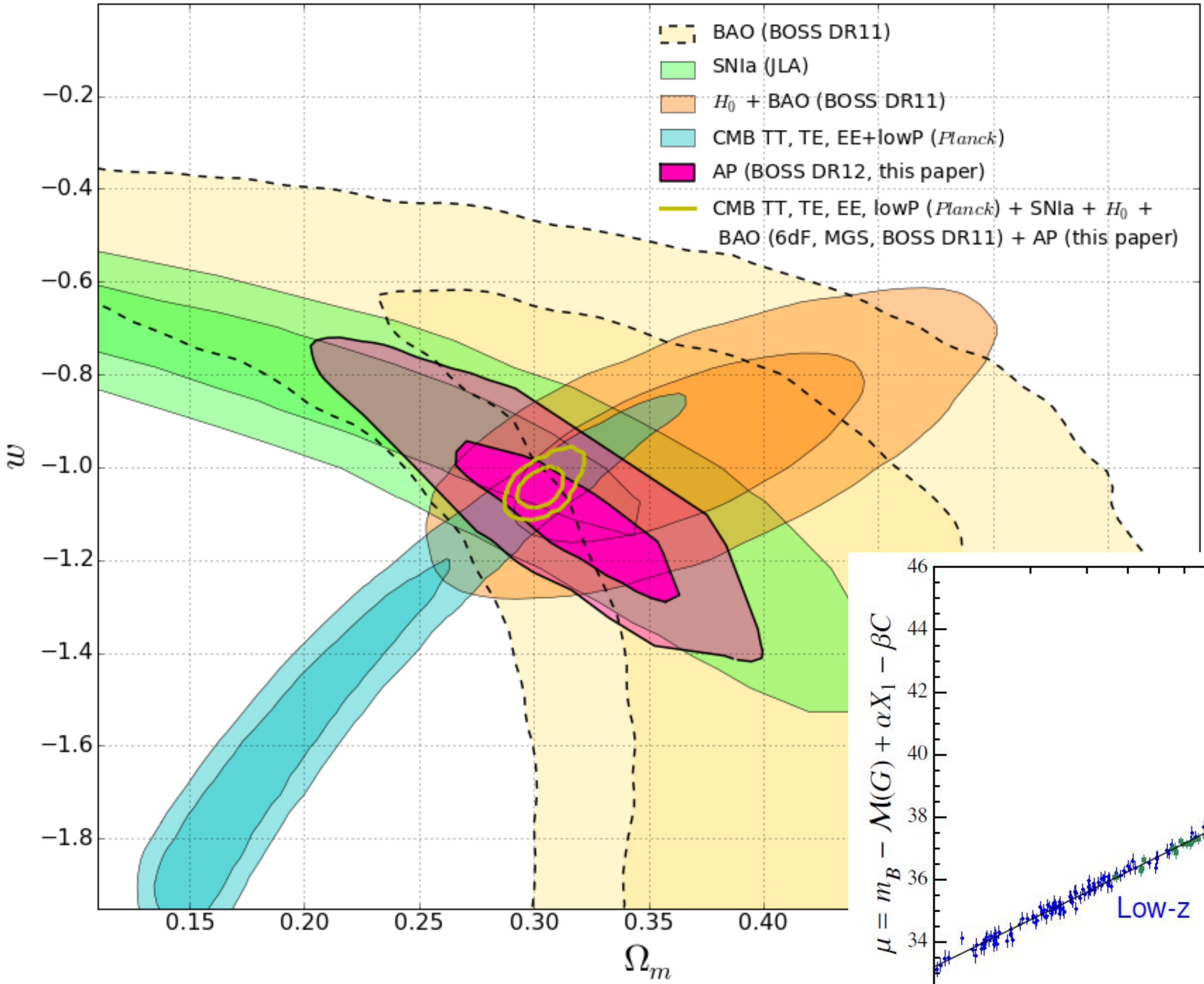
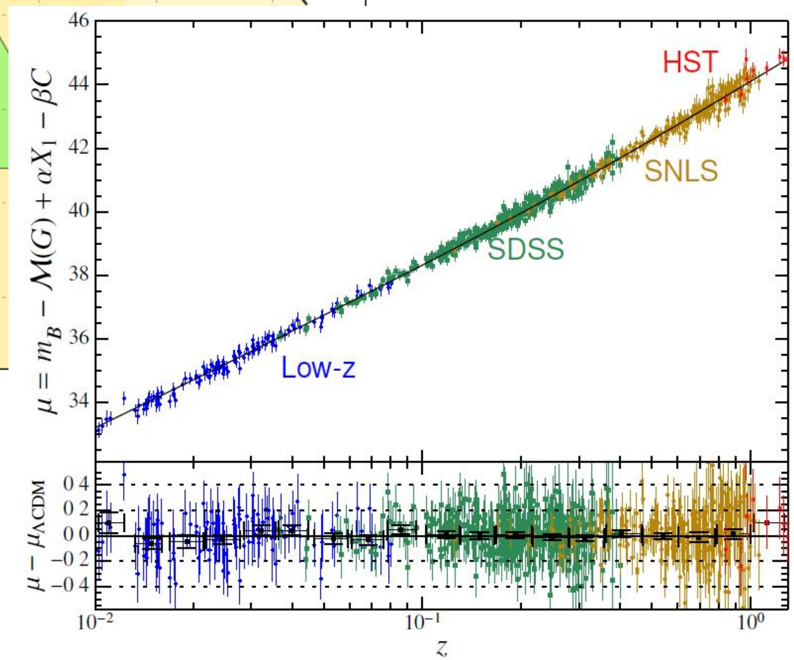
The PDF of the cosmological parameters θ=(Ω_m, w)

$$P(\theta|\mathbf{D}) \propto \mathcal{L} \propto \exp\left[-\frac{\chi^2}{2}\right]$$

➔ $\boxed{\Omega_m = 0.290 \pm 0.053, \quad w = -1.07 \pm 0.15}$ using our AP method alone.

Cosmological constraints (X. Li, C. Park et al. 2016)





Unlike BAO, dense sample can give much stronger constraints through the AP test, which uses only the isotropy of space and physics!

Planck temperature and polarization anisotropies: Ade et al. (2015)
JLA SNIa : Betoule et al. (2014)
BAO from BOSS DR11: Anderson et al. (2013)
BOSS DR11 BOSS combined with HST measurement (H0=70.6+-3.3)
: Riess et al. (2011), Efstathiou et al. (2014)

Combined constraints

If CMB, SN Ia, BAO, H_0, and our AP probes are statistically independent,

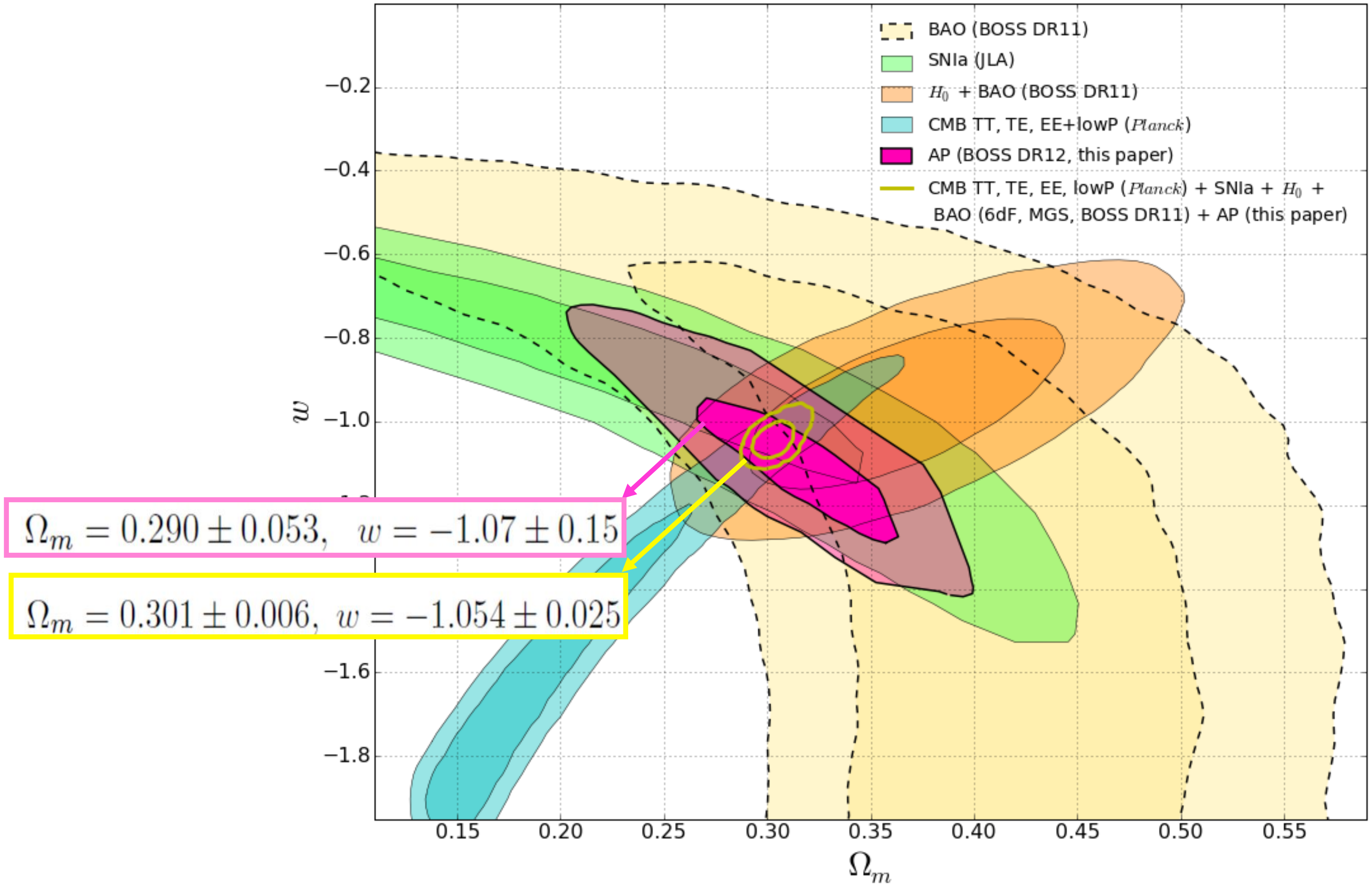
$$\mathcal{L}_{\rm total} = \mathcal{L}_{\rm CMB} \times \mathcal{L}_{\rm BAO} \times \mathcal{L}_{\rm SNIa} \times \mathcal{L}_{\rm H_0} \times \mathcal{L}_{\rm Our\ AP}$$

➔

$$\Omega_m = 0.301 \pm 0.006,\ \ w = -1.054 \pm 0.025$$

Combined constraints

If CMB, SN Ia, BAO, H_0, and our AP probes are statistically independent,



(X. Li, C. Park et al. 2016)

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➔

$$\Omega_m = 0.301 \pm 0.006,\ \ w = -1.054 \pm 0.025$$

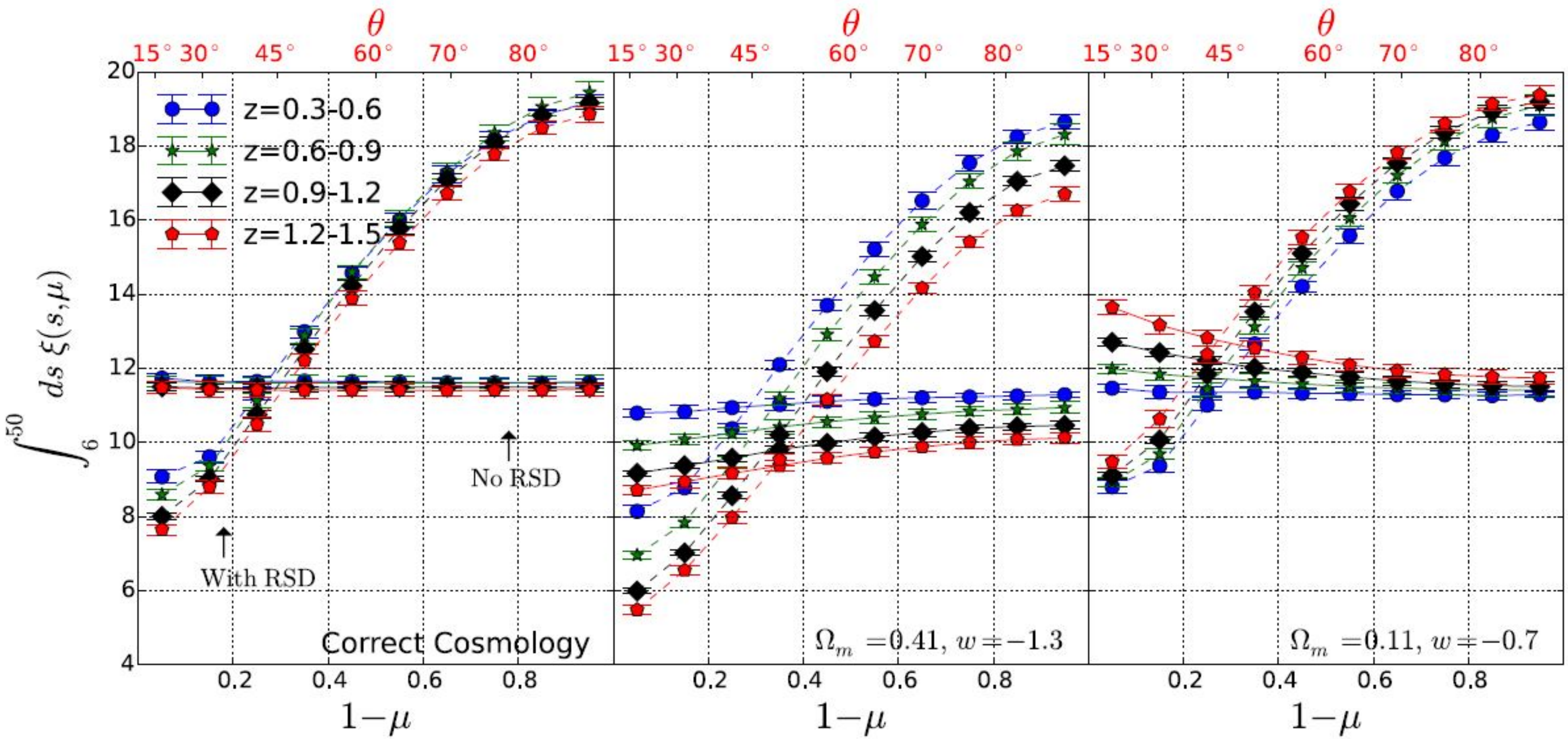
If only CMB and BAO are combined,

$\Omega_m = 0.306 \pm 0.013$, $w = -1.03 \pm 0.06$

If CMB, SN Ia, BAO and H_0 are combined,

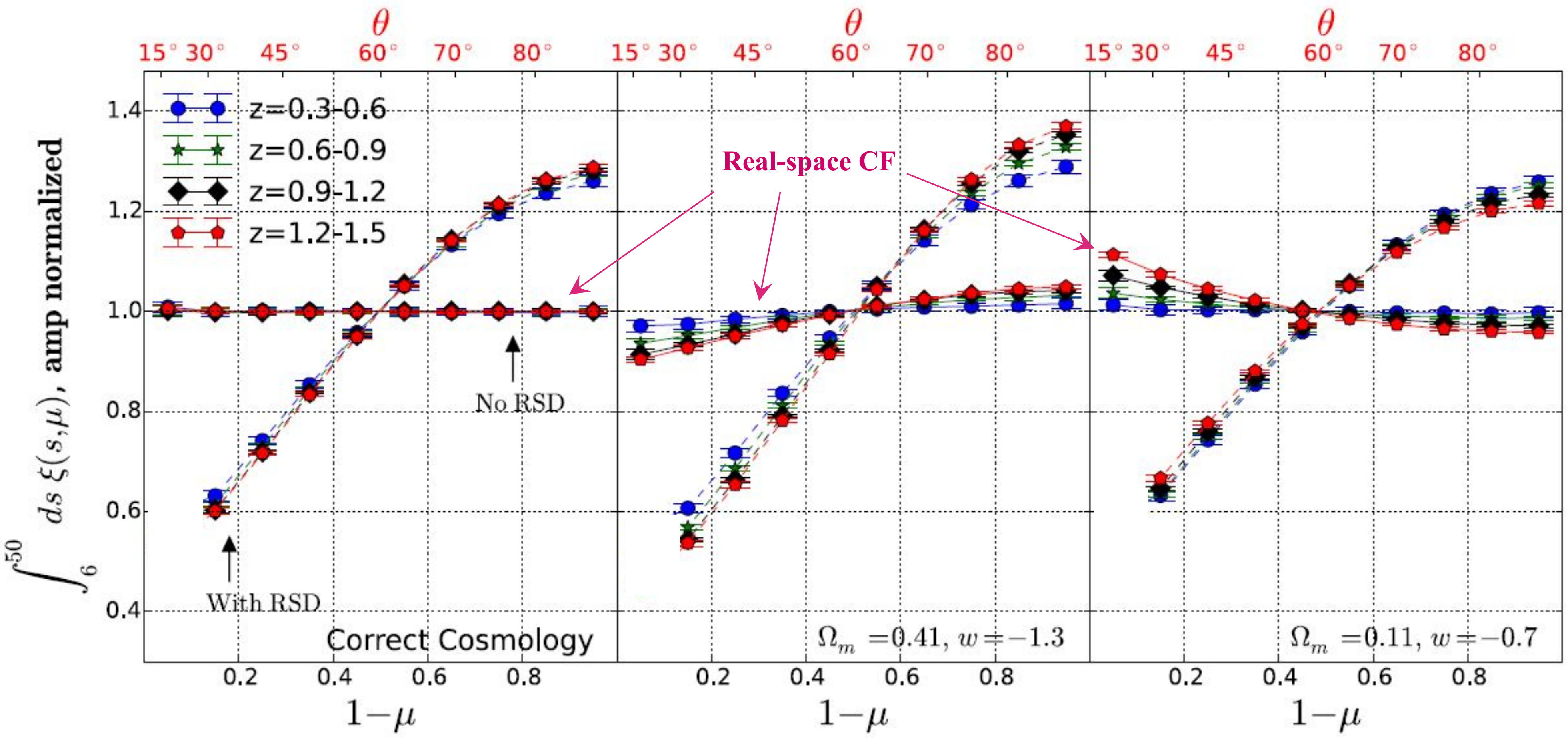
$\Omega_m = 0.306 \pm 0.009$, $w = -1.03 \pm 0.04$

μ- dependence of *CF* $\xi_{\Delta s}(\mu) \equiv \int_{s_{\min}}^{s_{\max}} \xi(s,\mu)\ ds.$ (s_{min}=6 & s_{max}=50 Mpc/h)

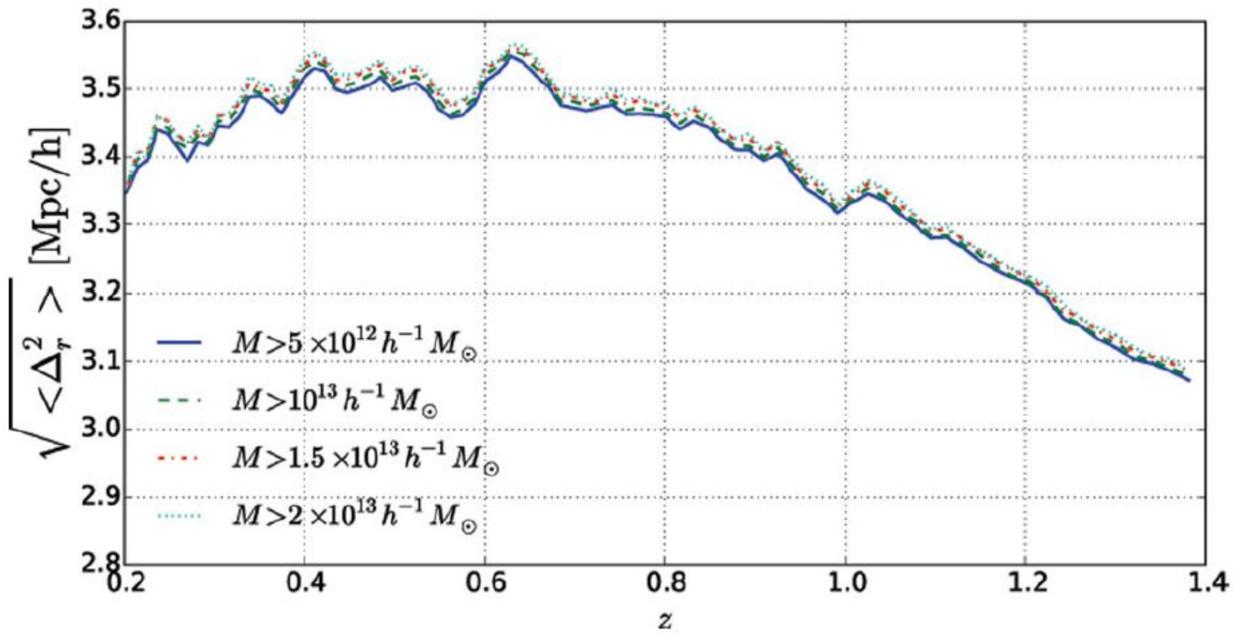


Normalized CF

$$\hat{\xi}_{\Delta s}(\mu) \equiv \frac{\xi_{\Delta s}(\mu)}{\int_0^1 \xi_{\Delta s}(\mu)\, d\mu}.$$



The redshift-space distortion effects very small.
In wrong cosmologies, the shape of 2-point CF evolves with redshift.



RMS displacement of galaxy positions in redshift space due to the peculiar velocities.

Summary

We propose to use the conservation of galaxy clustering isotropy to constrain a(t), which constrains $D_A * H(z)$ (or Ω_m and dark energy eq. of state w).

The method requires very small correctic $\Omega_m = 0.301 \pm 0.006,\ w = -1.054 \pm 0.025$
RSD effects, and yields impressive constraints of
in combination with other probes.

Stronger constraints on Ω_m-w than most other methods & complementary!
<u>Use of 'small-scale' clustering giving higher statistical constraining power!</u>
(AP → $D_A * H(z)$; Volume → $D_A^2/H(z)$; SN Ia → $D_L(z)$; BAO → $D_A(z)/r_S$ & $H(z)/r_S$)

The method applies not just to 2pCF, but can be used in combination with any clustering statistics (ex. genus - Park & Kim 2010; density gradient vector – Li+ 2014).

Mon. Not. R. Astron. Soc. **319**, 573–582 (2000)

Cosmic momentum field and mass fluctuation power spectrum

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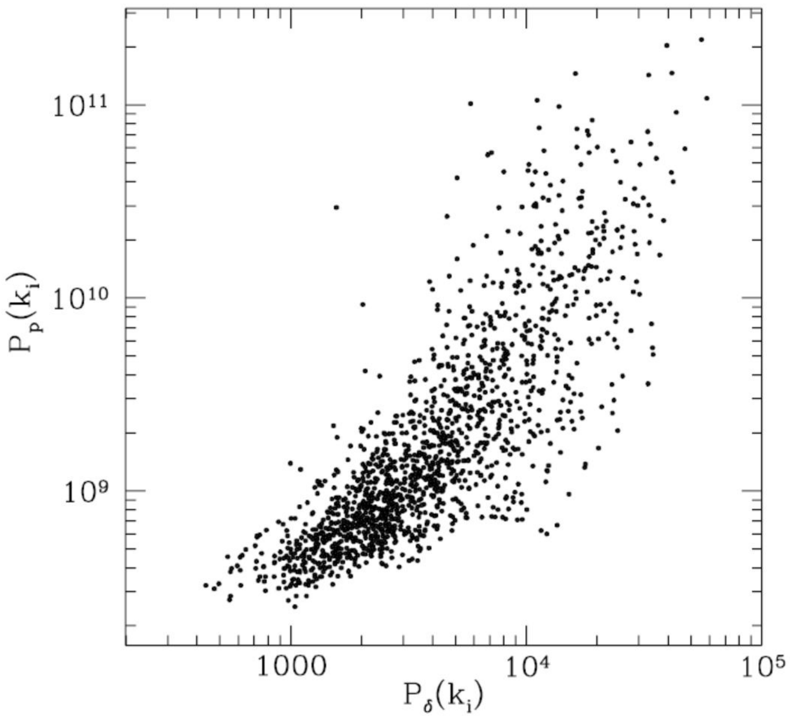

Figure 5. Correlation of the momentum power spectrum with the density power spectrum at each wavenumber. A pair of power spectra P_δ and P_p are calculated from each of the 100 mock MAT surveys in the OCDM20a model.

$$\bar{\beta} = (k/\bar{D}H)(P_p/P_{\delta_g})^{1/2}$$

= 0.51 (+0.13-0.08)

: multi-tracer /
multi-statistics method
(Park 2000)