Constraints to wCDM model with the redshift dependence of the Alcock–Paczyński (AP) effect from galaxy clustering

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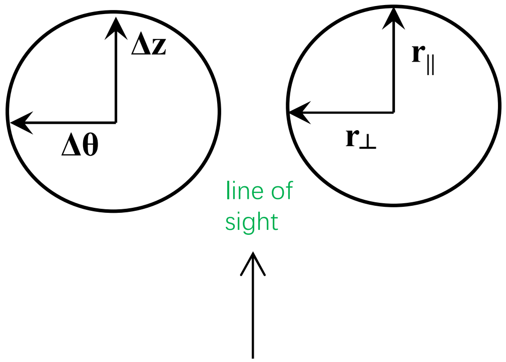
Geometrical shape of cosmic structures

Comoving sizes

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

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

Different dependence on cosmology



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

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

(flat universe)

Suppose, for some particular object, we know the ratio

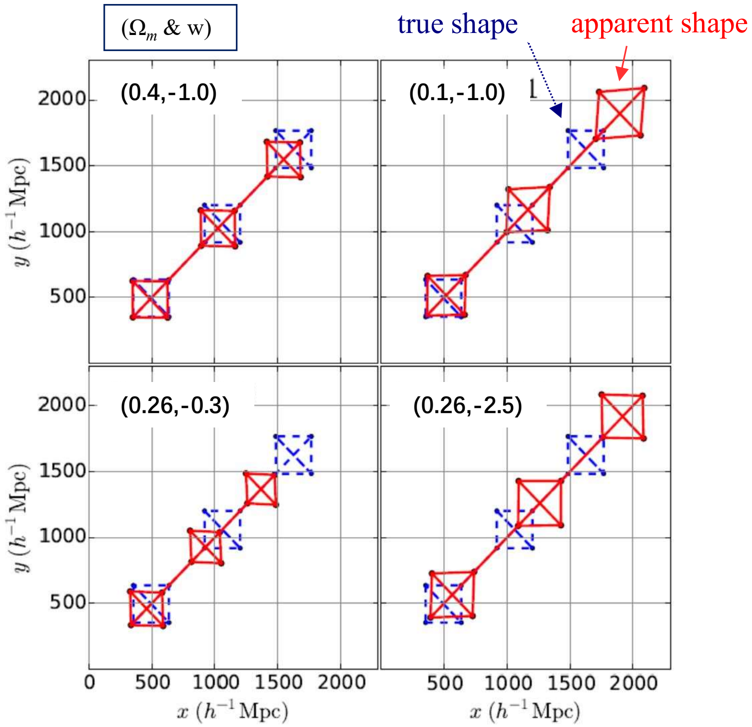
$$\frac{r_{\parallel}}{r_{\perp}} = \frac{c}{(1+z)D_A(z)H(z)} \cdot \frac{\Delta z}{\Delta\theta} = F(z)^{-1} \cdot \frac{\Delta z}{\Delta\theta}$$ **where** $$F(z) \equiv \frac{(1+z)}{c}D_A(z)H(z)$$

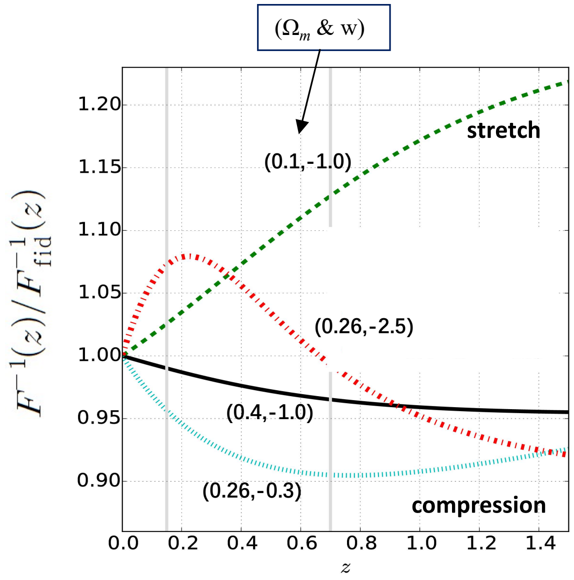
Choosing a wrong cosmology in r(z) transformation will distort the apparent shape by a factor $F^{-1}(z)/F^{-1}_{\text{true}}(z)$

Shape of structures

in a flat universe with Ω_Λ=0.74, Ω_m=0.26 & w=-1
: z of blue corners given

In real space, ideal case of r(z).

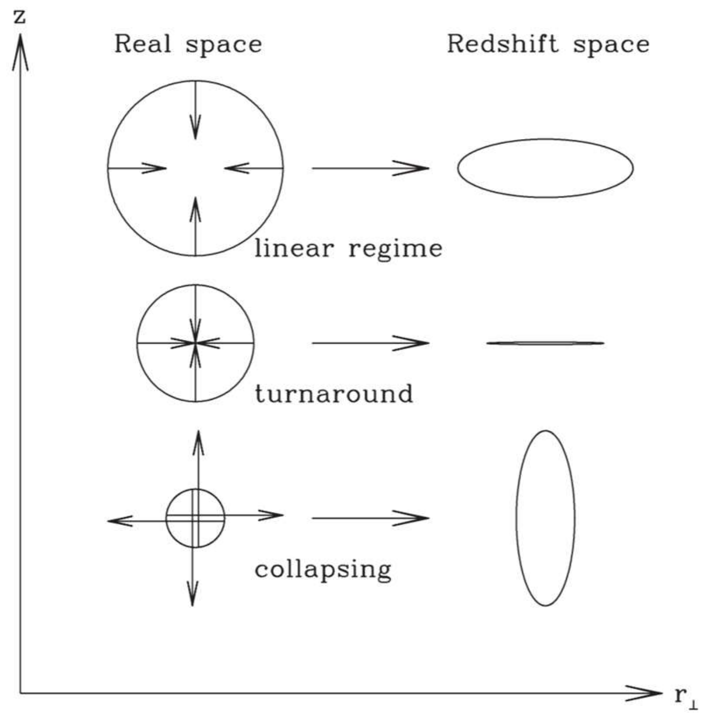


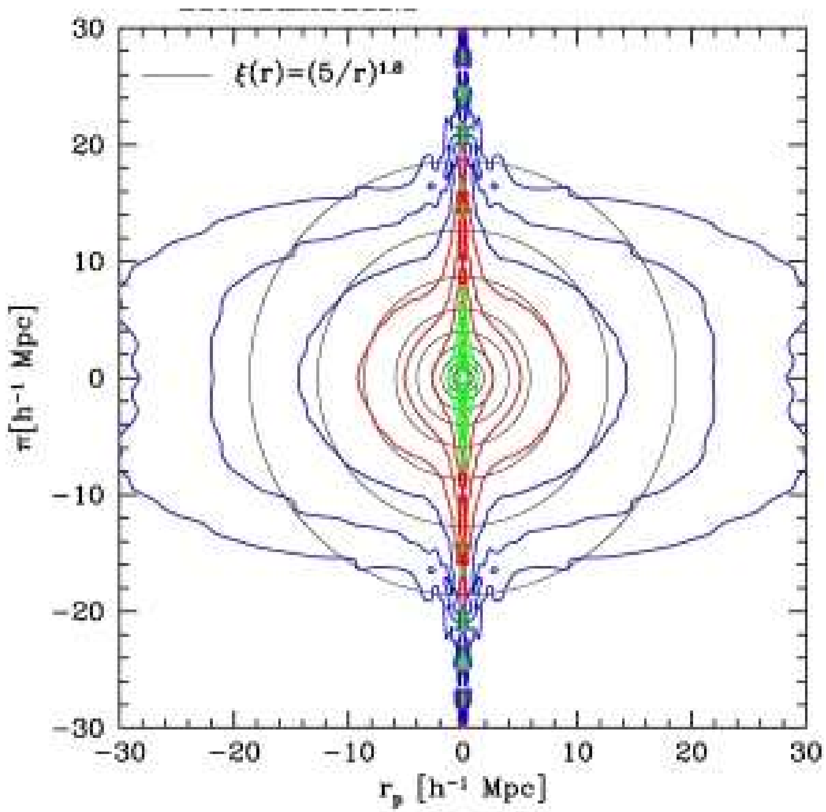


where $F(z) \equiv \frac{(1+z)}{c} D_A(z) H(z)$

Standard ruler, if we can find a shape quantity that does not evolve with redshift.

Redshift Distortion effect can also result in anisotropy

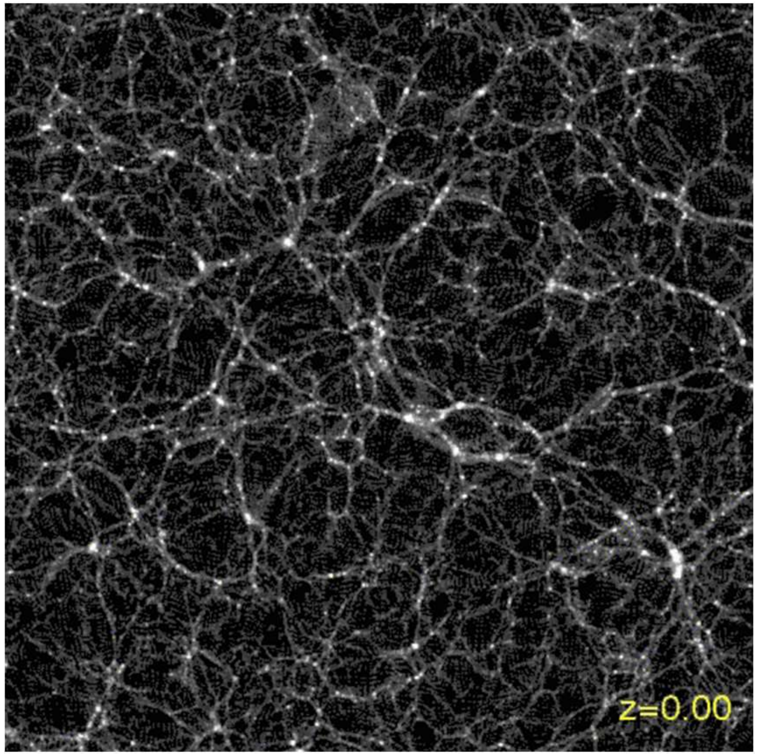




Any good standard shape in the existence of RSD?
Redshift-space distortion due to peculiar velocities!

The Extended AP Test

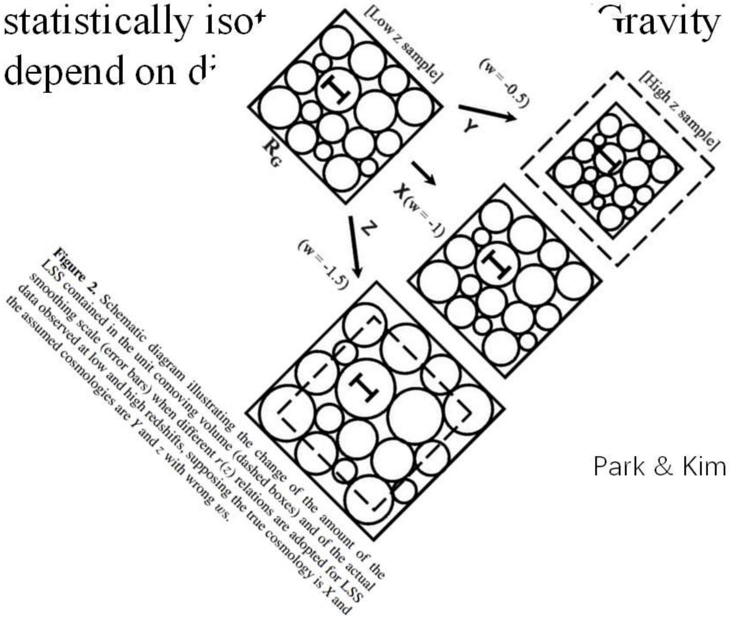
LSS as the standard ruler ?



Use 'shape difference' across redshift shells

- Choose objects/statistics whose shape do not evolve.
∴ Do not require the kn ledge on shape itself.

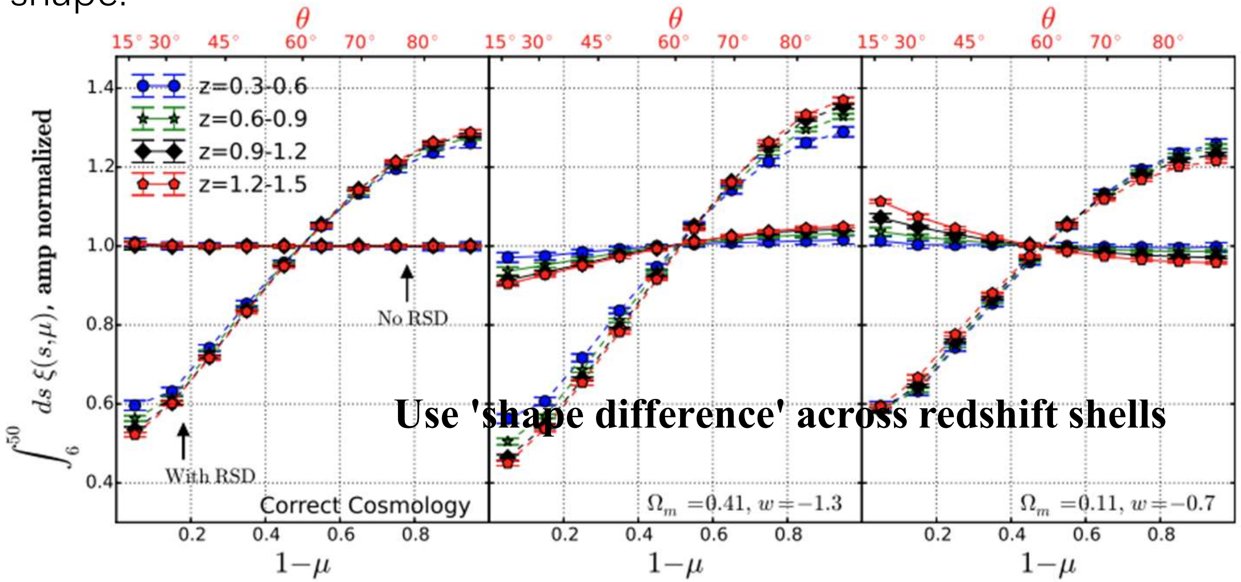
- Choose shape or Galaxy clustering is
statistically iso Gravity does not
depend on d



Park & Kim [2010]

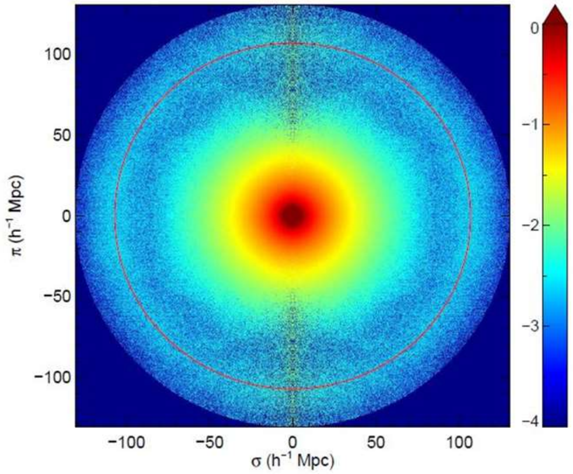
1D shape of 2pcf, Li(2015)

Angular shape:

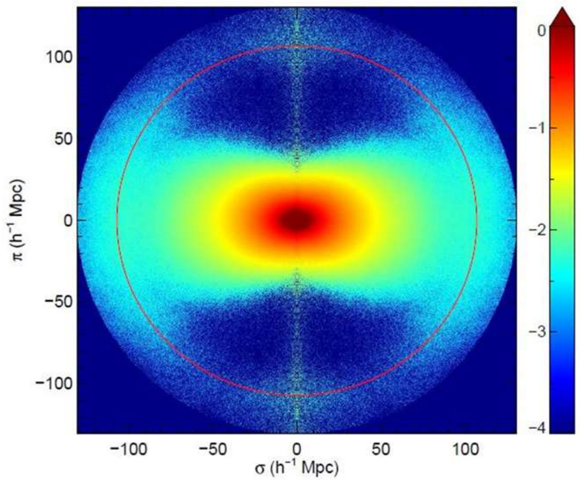


Use 'shape difference' across redshift shells

Figure 3. The 2pCF measured in four redshift bins, in the correct cosmology (left) and two wrongly assumed cosmologies (middle: $\Omega_m = 0.11$, $w = -0.7$; right: $\Omega_m = 0.41$, $w = -1.3$). The clustering signal is measured as a function of $1-\mu$, where $\mu = \cos(\theta)$ and θ is the angle between the LOS and the vector joining the pair of galaxies. Dashed and solid lines show the results with and without the RSD effect, respectively. *Upper panel*: In the wrongly assumed cosmologies, we observe a clear change in the amplitudes and shapes of ξ due to the volume and AP effect. Additionally, due to the redshift dependence of volume and AP effect, the amplitudes and shapes in the four redshift bins are different from each other. *Lower panel*: The same as the upper panel, except that the amplitudes of curves are normalized to 1.



(a) real space



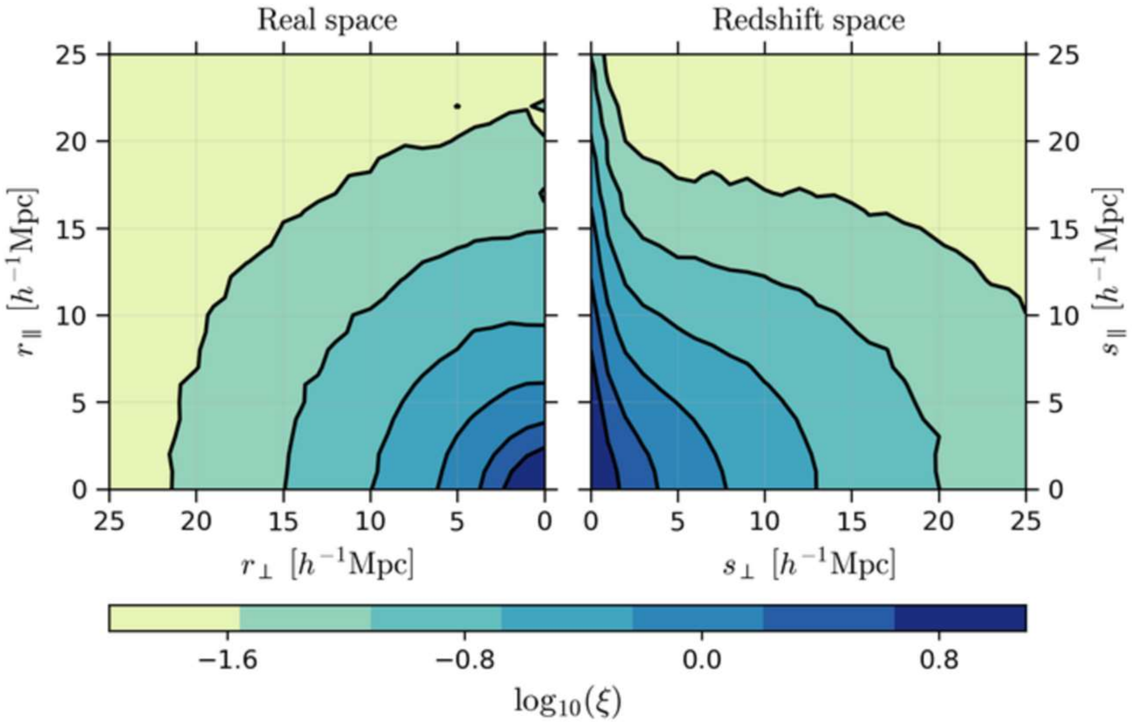
(b) redshift space

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

Note : 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, 2016).

The extended AP test in this study, 2D shape of 2pcf

1. Shape of the two-point correlation function in redshift space. $\xi(s,\mu)$ normalized with $J_0=\int dr_{\parallel}\int dr_{\perp}|\xi(r_{\parallel},r_{\perp})|$

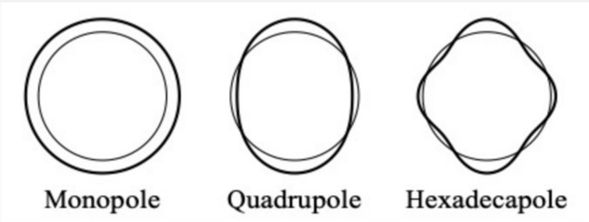


Park(2019)

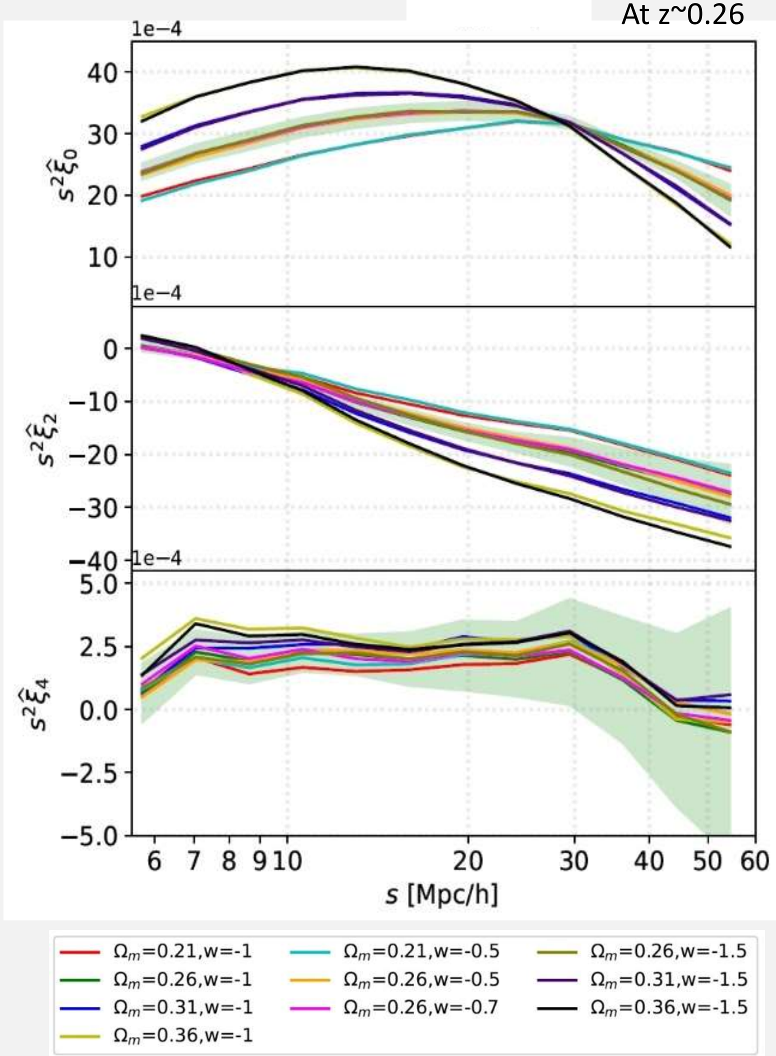
Angular shape & radial shape:

Cosmology-dependence of the shape of correlation function

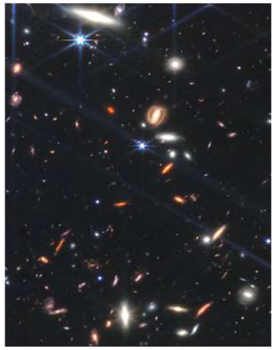
$$\widehat{\xi}(s,\mu,z) \approx \sum_{l=0,2,4} \widehat{\xi}_l(s,z) P_l(\mu)$$



At z~0.26



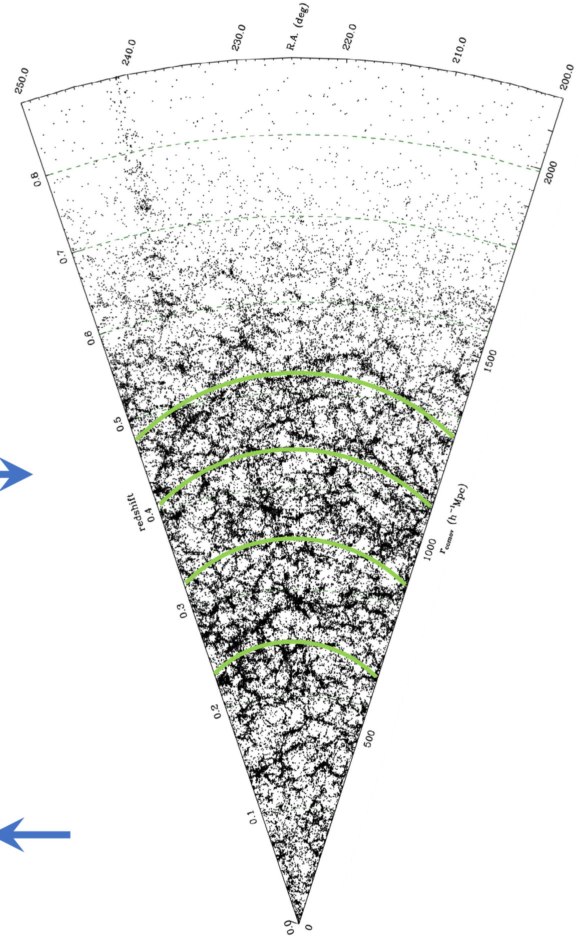
The Extended Alcock-Paczynski Test



Observed RA, DEC & redshifts of galaxies

Adopt a cosmology, i.e. r(z) relation

Calculated r, θ, ϕ of galaxies



Measure the two-point CF in a few redshift shells & normalize them

$$\widehat{\xi}(s, \mu, z)$$

Shape differences?

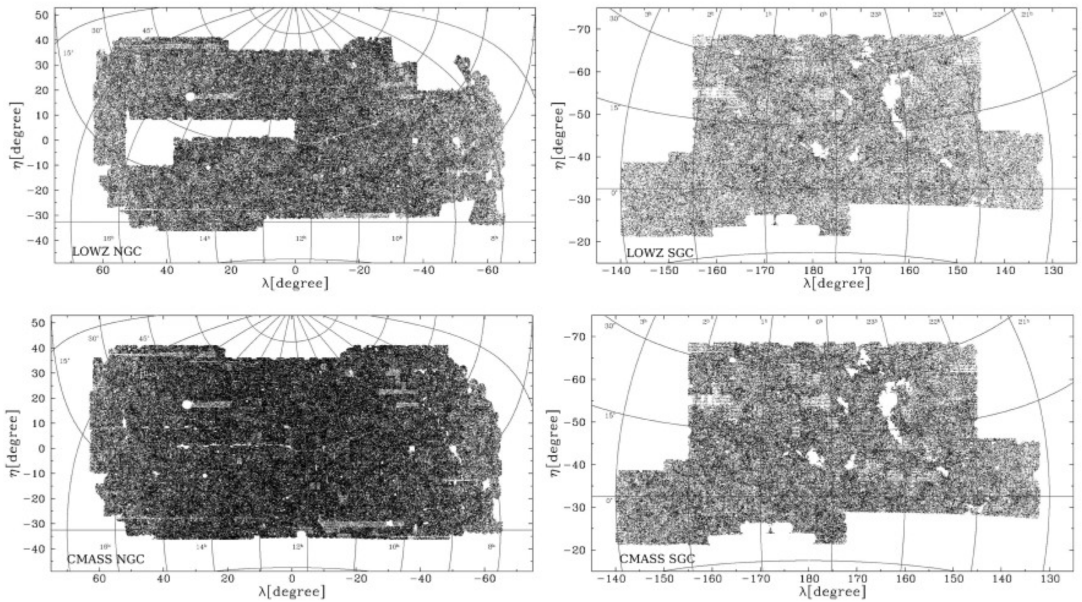
Observational Samples

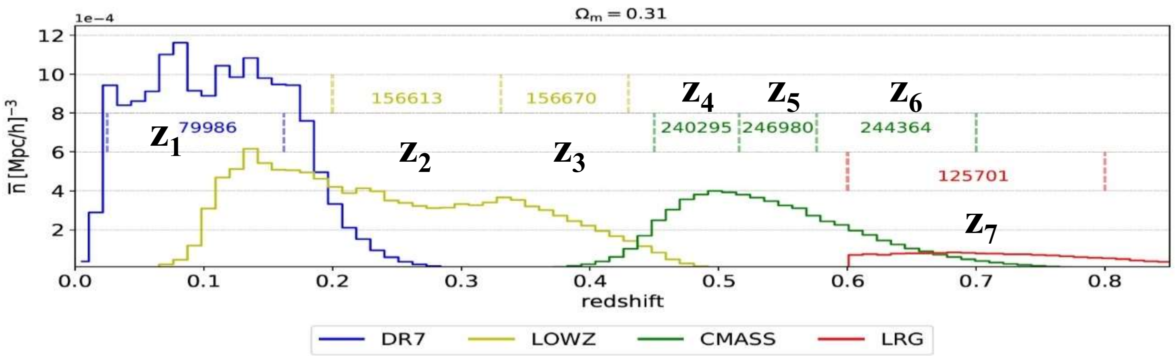
Sloan Digital Sky Survey

DR7: volume-limited (Mr<-21.07)
LOWZ: stellar mass $M^*>10^{11.1}M_\odot$
CMASS: stellar $M^*>10^{11}M_\odot$
eBOSS LRG: $M^*>10^{11}M_\odot$

LOWZ

CMASS

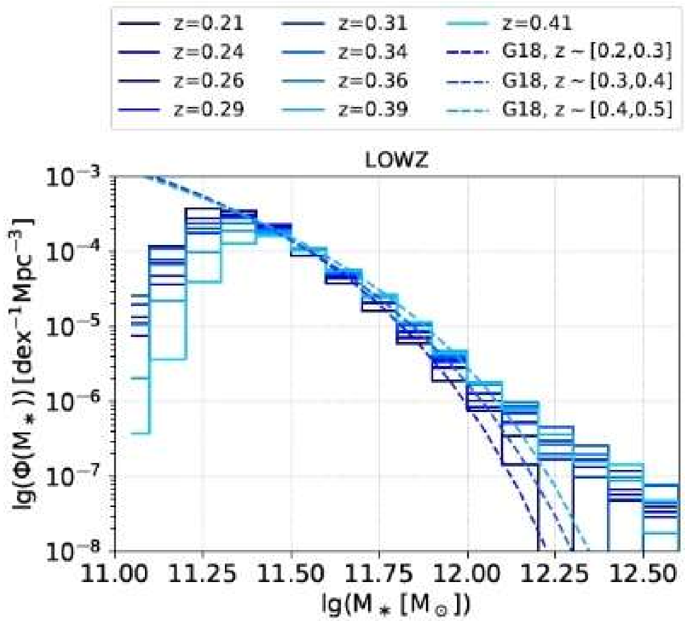




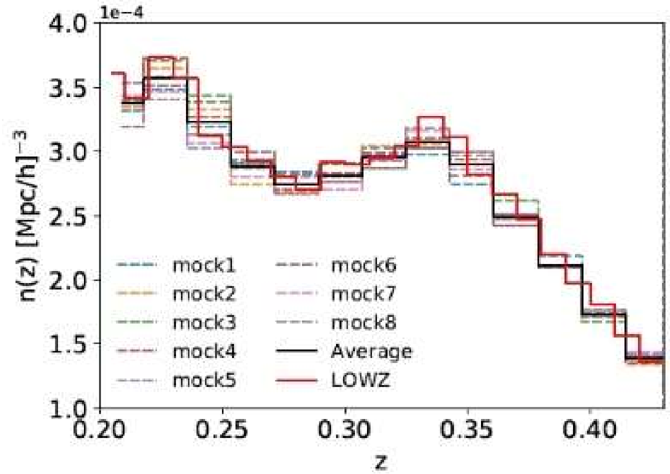
Observation samples

- complicated target selection

Complete M* function of the SDSS galaxies [Guo+2018]
==> M* selection function in each z-shell



==> Redshift distribution (radial selection function)
accurately recovered



Why simulation?

Tests with mock samples using

Horizon Run 4 simulation (6300^3 particles in $3150h^{-1}$Mpc box)

Multiverse simulations (Ten simulations of different cosmologies with 2048^3 particles in $1024h^{-1}$Mpc box)

==>

1. benefit of using cosmology-dependent correction for **systematic** shape evolution

2. results are insensitive to the choice of **zref**.

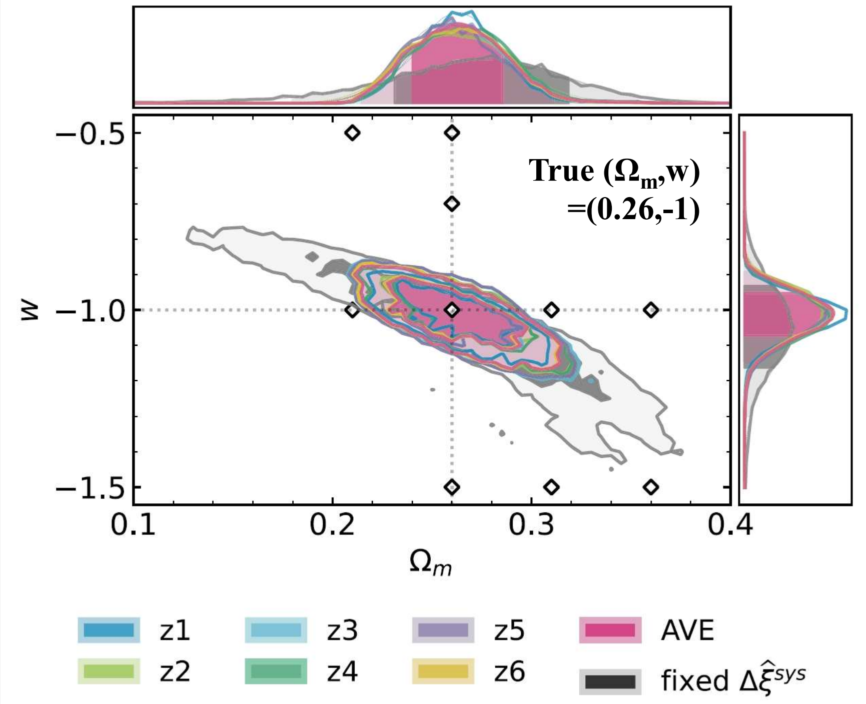
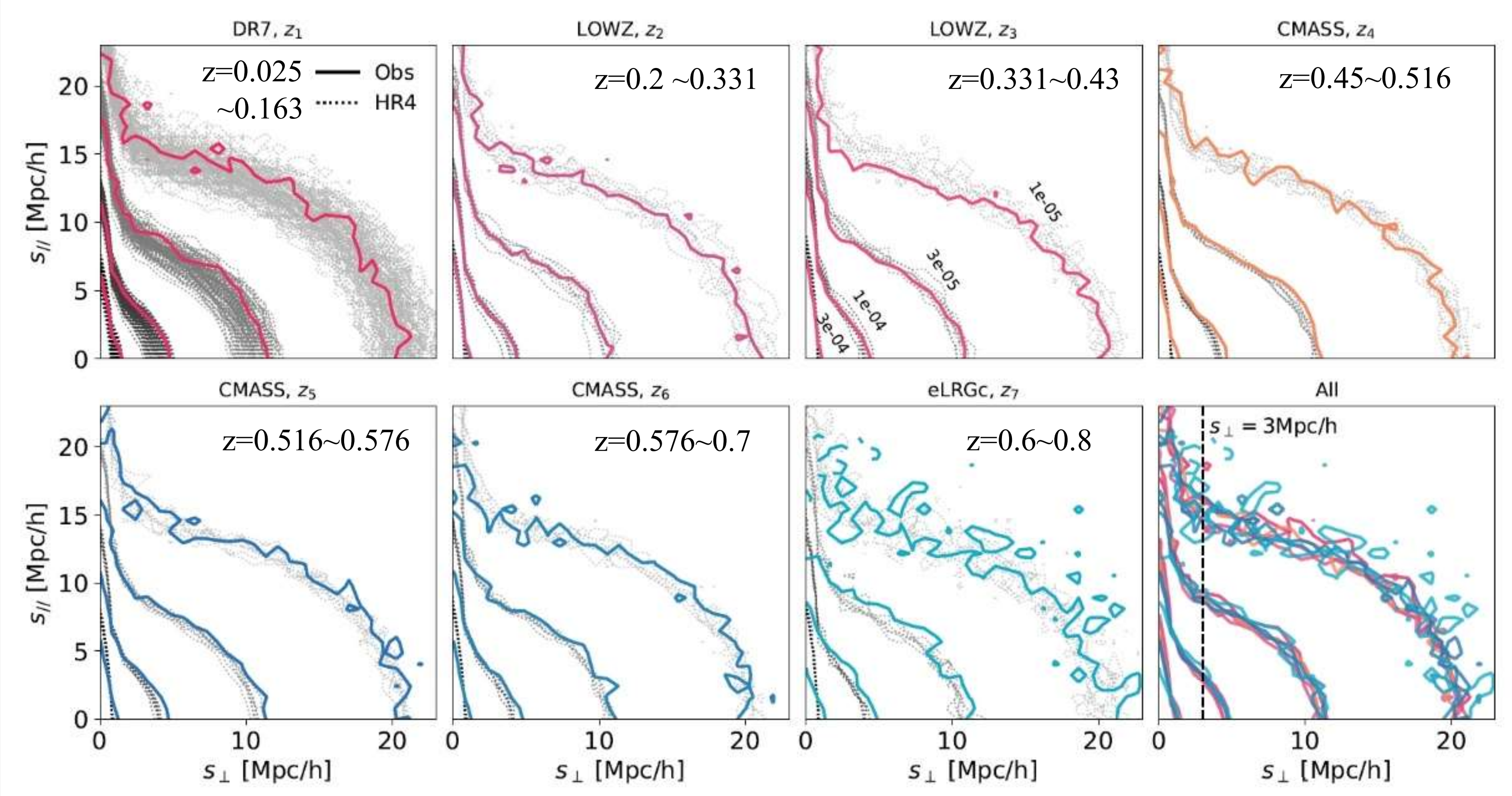


Figure 5. Likelihood function maps $\mathcal{L}(\Omega_m, w)$ from our extended AP test analysis using the baseline mock samples. The contours in different colors correspond to the cases where the slice at z_i is chosen as the reference for measuring the relative CF shape evolution across redshift slices. Cosmology-dependent systematic corrections to the shape evolution are made ($\Delta\hat{\xi}^{sys}(\Omega_m, w)$). We average over all choices of the reference slice for the final constraint (pink color). For comparison, the constraint assuming a

Normalized correlation function

$$\hat{\xi}(s,\mu) = \xi(s,\mu)/2\pi\int_0^1 d\mu\int_0^{s_{\max}} s^2 ds\ \xi(\mathrm{s},\mu)$$



Procedure under the flat wCDM paradigm to which the standard flat LCDM model belong.

Expansion history governed by Ω_m and w

0. Observational samples in many redshift bins

1. Adopt a cosmology (Ω_m, w) and r(z) relation

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

$$\hat{\xi}(s,\mu) = \xi(s,\mu)/2\pi \int_0^1 d\mu \int_0^{s_{\max}} s^2 ds \ \xi(s,\mu)$$

3. Quantify the radial & angular variations:

$$\hat{\xi}(s,\mu,z) \approx \sum_{l=0,2,4} \hat{\xi}_l(s,z) P_l(\mu)$$

4. Shape of $\hat{\xi}(s,\mu)$ changes across redshift bins?

$$\Delta\hat{\xi}(z_i,z_j) = \hat{\xi}(z_j) - \hat{\xi}(z_i) - \Delta\hat{\xi}^{sys}(z_i,z_j)$$

[Systematics correction (intrinsic shape evolution): HR4 mock galaxy samples & Multiverse simulations]

5. Try a different cosmology and repeat 1-4 to minimize evolution → Cosmological Constraints

6. Error analysis

Covariance matrices in $\chi^2 = \Sigma\ \delta\xi * \mathbf{Cov}^{-1} * \delta\xi$ from mock surveys in HR4(Kim+2015 for DR7), MultiDark PATCHY (Kitaura+2016 for BOSS, and EZmock (Zhao+2021 for eBOSS)

Calculate $\chi^2 = \Sigma\ \delta\xi * \mathbf{Cov}^{-1} * \delta\xi$ (summation over z-bins, s-bins and Legendre polynomial expansion moments)

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

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

New constraints on the flat wCDM models

[Fuyu Dong et al. 2023]

$$w = -0.903^{+0.023}_{-0.023}$$

$$\Omega_m = 0.285^{+0.014}_{-0.009}$$

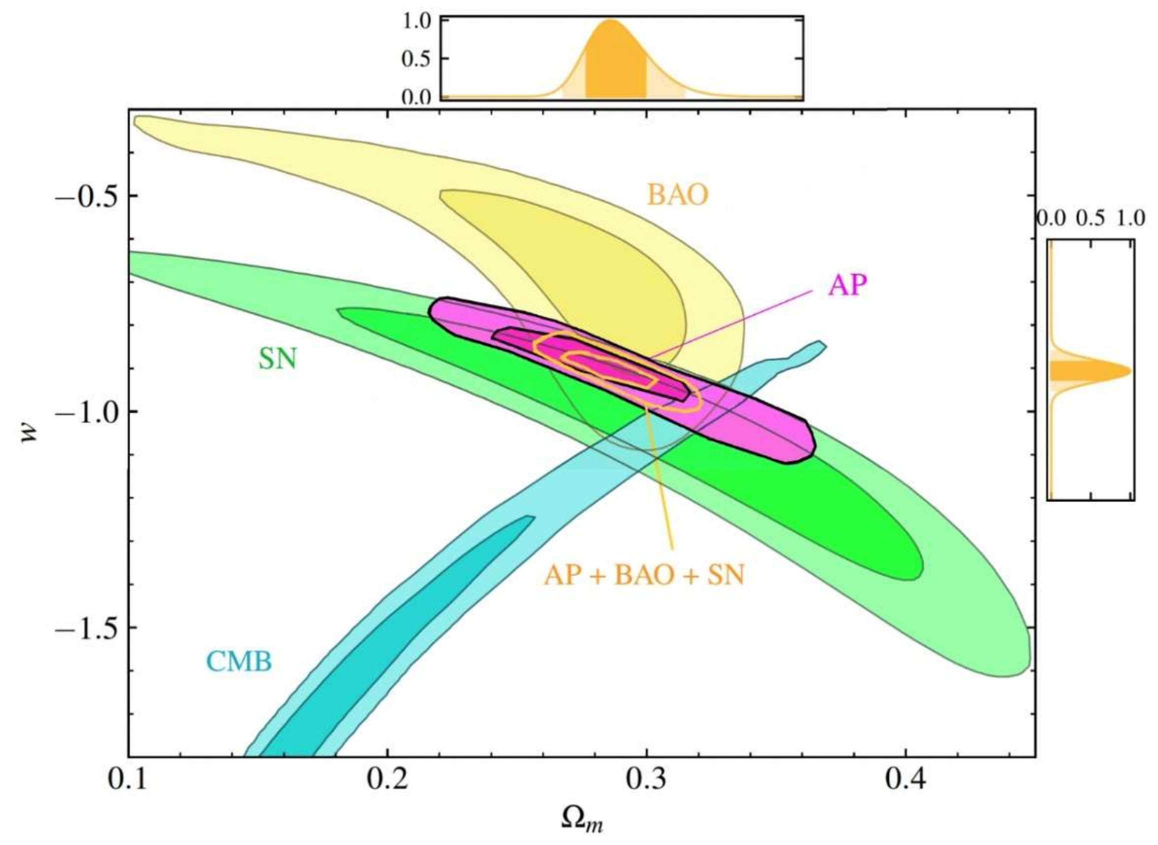
4.2σ away from w=-1!

from combining
AP + BAO + SN Ia

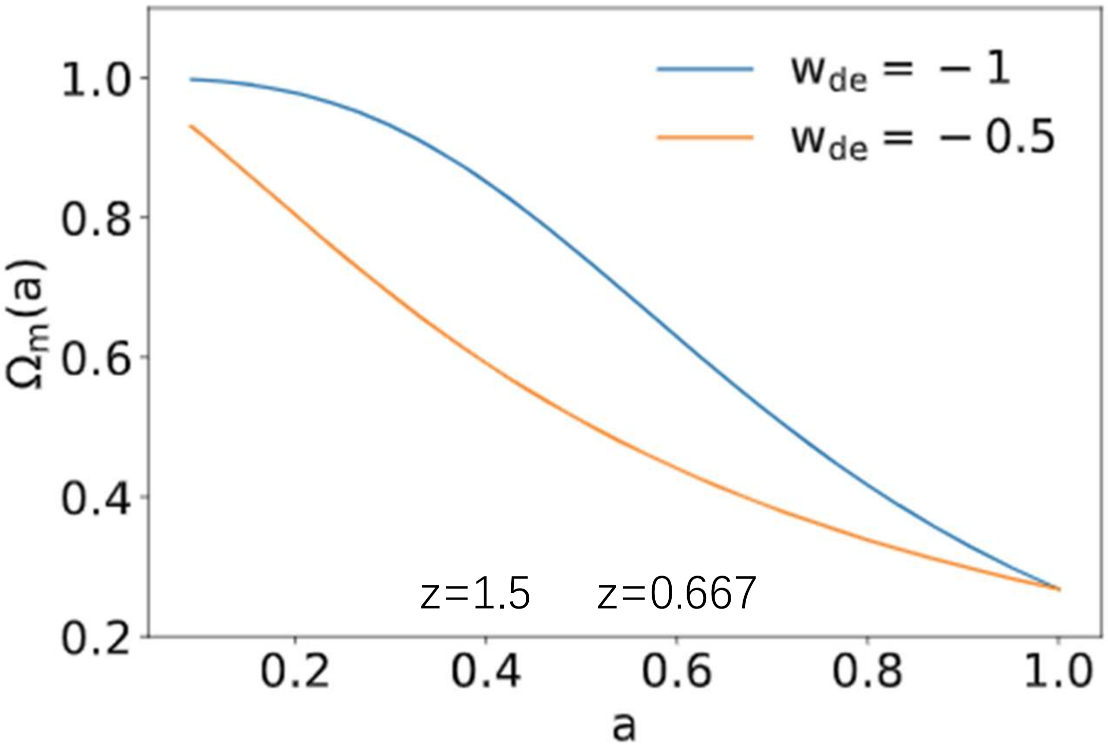
CMB not used.

In conflict with CMB!

AP: Dong+(2023) SDSS I/II + III
BAO: Howlett+(2015), Alam+(2017), de Mattia+(2021), Raichoor+(2021)
SN: Scolnic+ (2018)
CMB: Planck+(2020)



High redshift is important for distinguishing different DE model



Although the dark energy (DE) fraction is smaller at higher redshift, the difference between different DE model is more obvious.

DESI has advantage for AP test

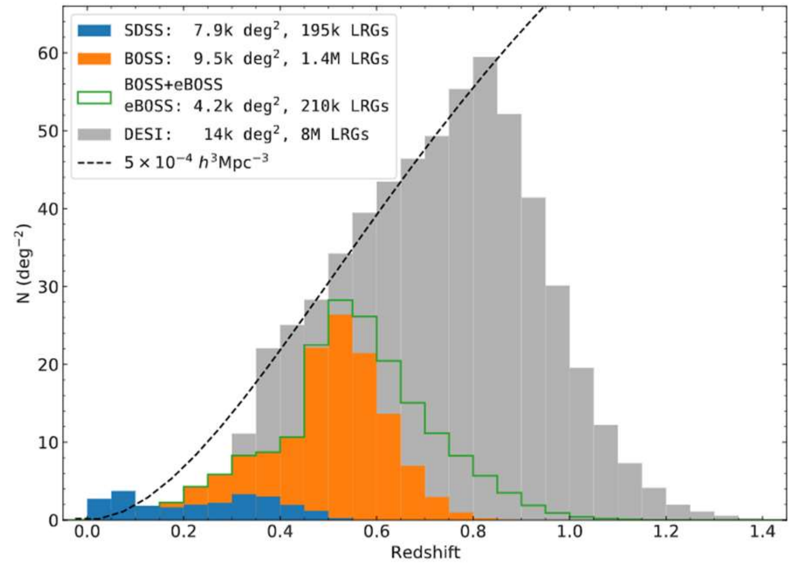
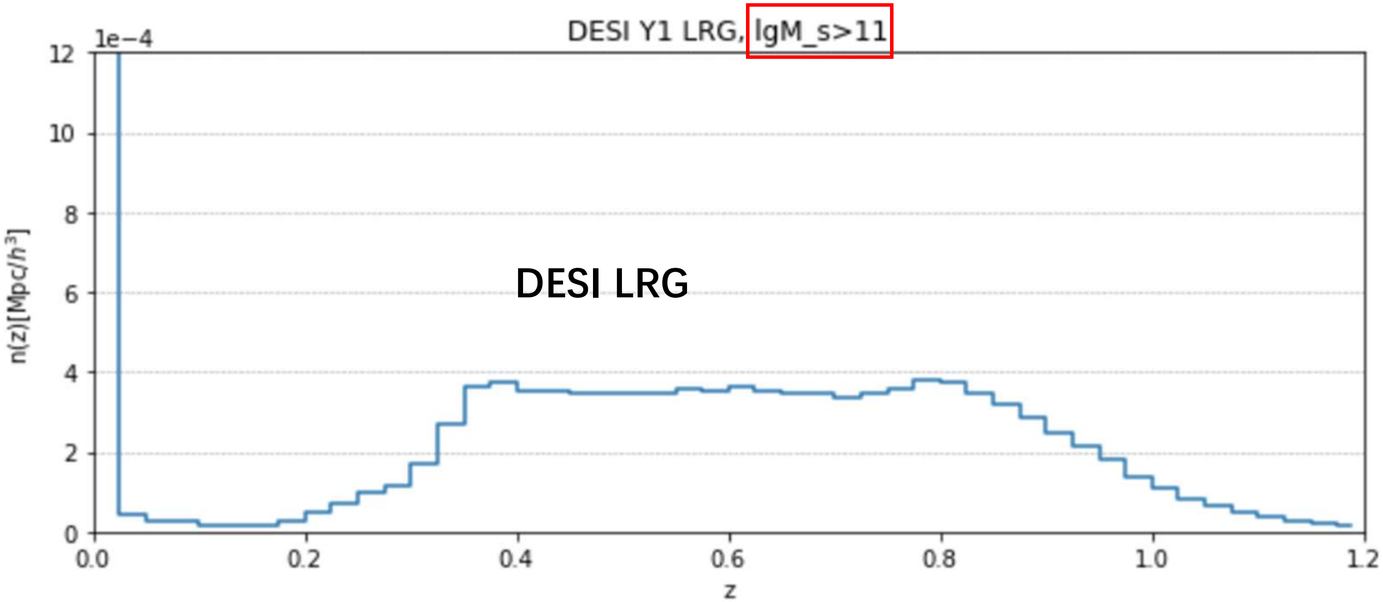


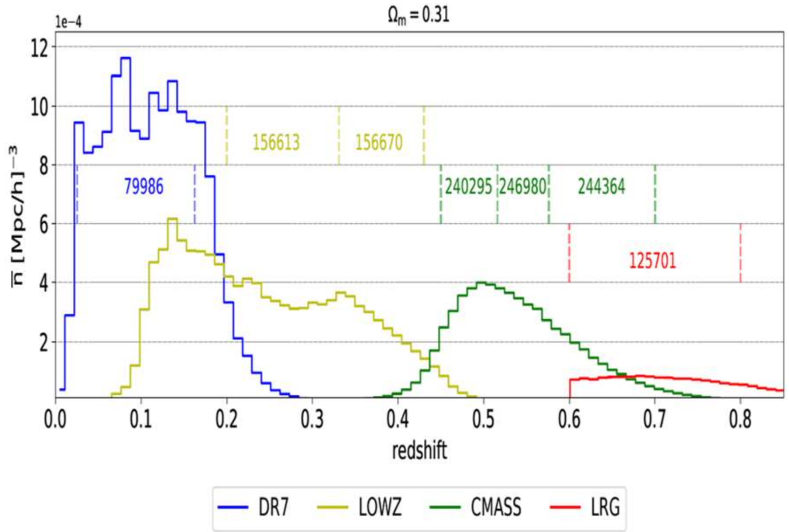
Figure 1. The redshift distribution of the DESI LRG sample and comparing it with LRG samples from earlier surveys. The y-axis is the number of objects in each redshift bin (of width $\Delta z = 0.05$) per deg^2. The survey area and the total number of LRGs that have or will be observed in each survey are listed in the legend. The dashed curve corresponds to the redshift distribution of a hypothetical sample with constant comoving density of $5 \times 10^{-4}\ h^3\mathrm{Mpc}^{-3}$, which is the approximate DESI LRG density in the redshift range of $0.4 < z < 0.8$; the area under the curve is proportional to the enclosed comoving volume.

arXiv:2208.08515v1, Rongpu Zhou

DESI LRG sample from Survey Validation (SV) and the first 2 months of the Main Survey.
deeper, wider, and denser than SDSS

Num_lrg from Y1 data is more than twice of our SDSS sample being used.





SDSS

The eBOSS LRG does not help to the constraint, too low number density.

conclusion

- **The extended AP test is promising in constraining the expansion history of universe;**
- **Our measurement $w^{eff} > -1$ implies the DE is not Λ (i.e. ΛCDM not correct ?);**
- **Higher redshift and larger sample will help to verify this conclusion.**

Thank you!