Constraining cosmological parameters with **BAO** and **RSD** from ***BOSS*** & ***eBOSS*** galaxy clustering datasets

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CosmoBack: From inhomogeneous gravity to cosmological back-reaction

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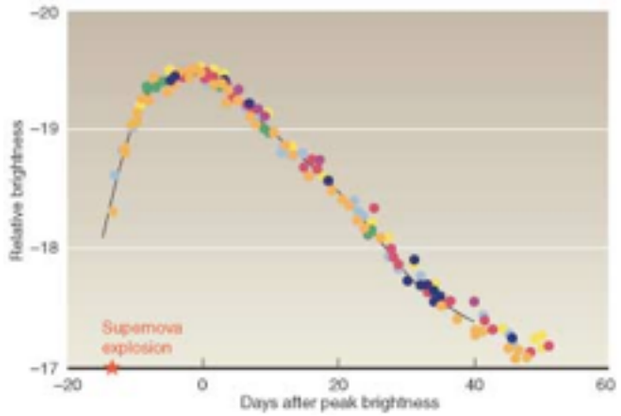
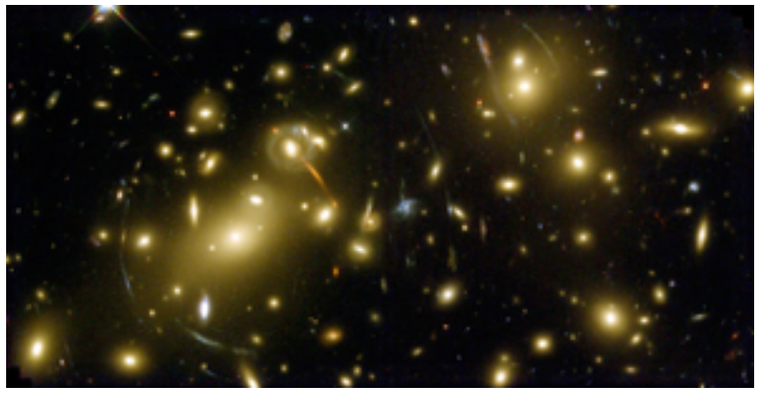
Cosmological Standard Model

Probes to test Dark Energy on late-time Universe

- Standard Candle Supernovae



- Weak lensing

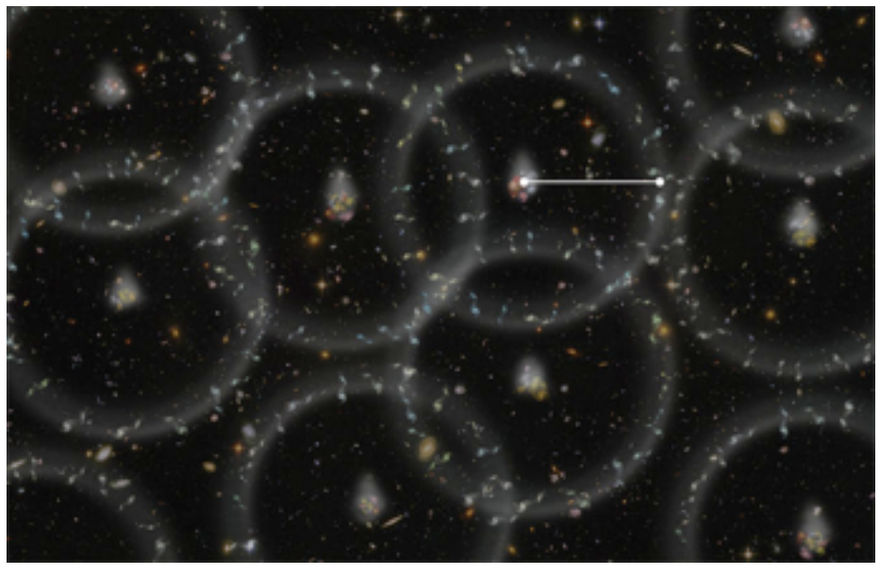


- Cluster counting

- **Standard Ruler BAO & RSD**

How?

Observe dark matter tracers with high precision redshift covering a large area/ volume of the sky



Main Goal of redshift surveys: BAO & RSD

- **Standard Ruler BAO & RSD**

Growth of structure: Ratio monopole to quadrupole ~ $f\sigma_8$

BAO peak position: in monopole ~ $(D_A^2/H)^{1/3} / r_s \longrightarrow D_V / r_s$

BAO relative peak position: monopole, 'quadrupole' ~ $D_A H$

Cosmological Parameters

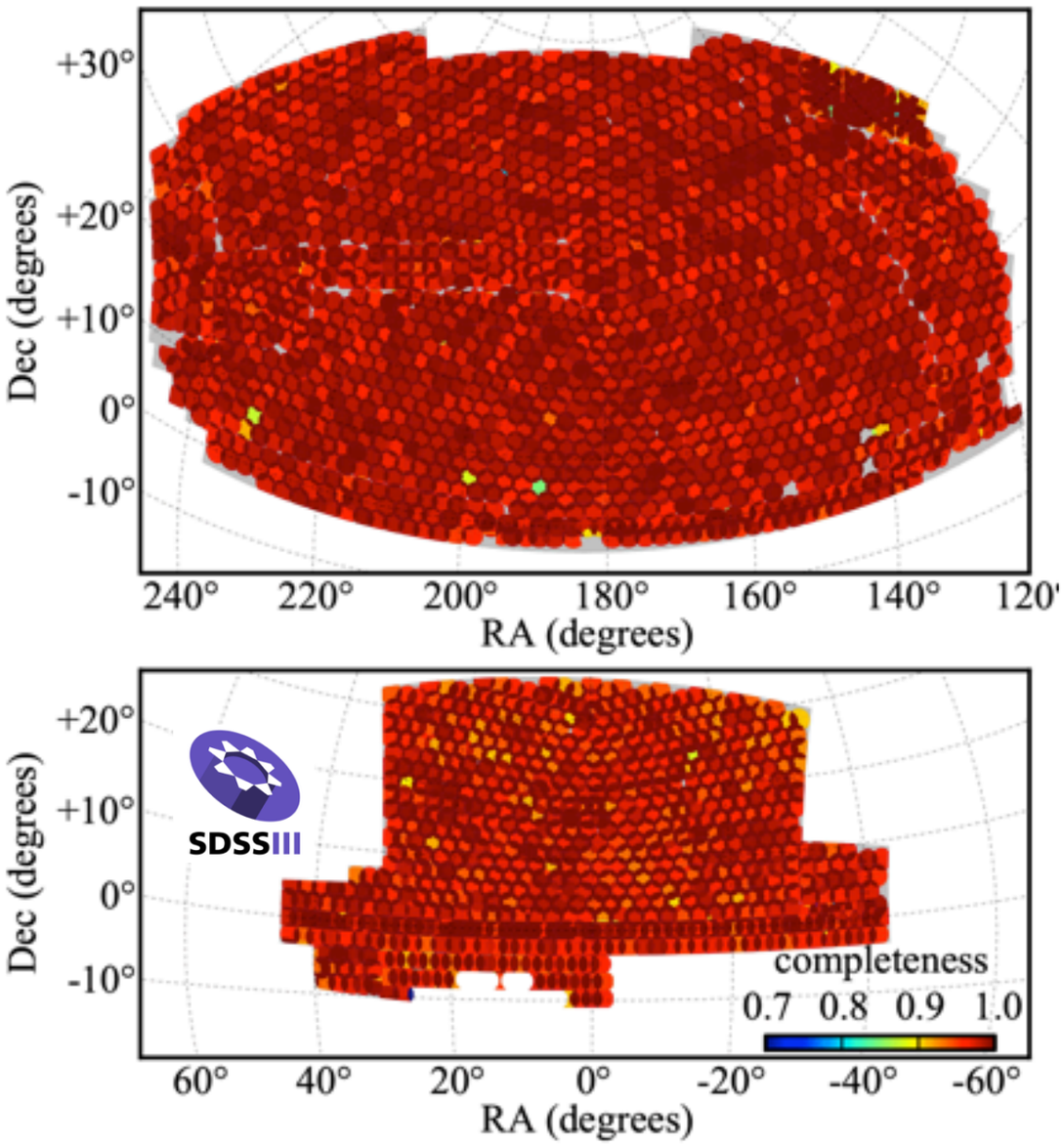
$f\sigma_8(z)$ $H(z)r_s$ $D_A(z)/r_s$ (D_V/r_s)

non-Cosmological Parameters

Galaxy bias physics: $b_1\sigma_8$ $b_2\sigma_8$ σ_{FoG} .....

BOSS & eBOSS spectroscopic surveys

DR12 footprint for the LRG sample



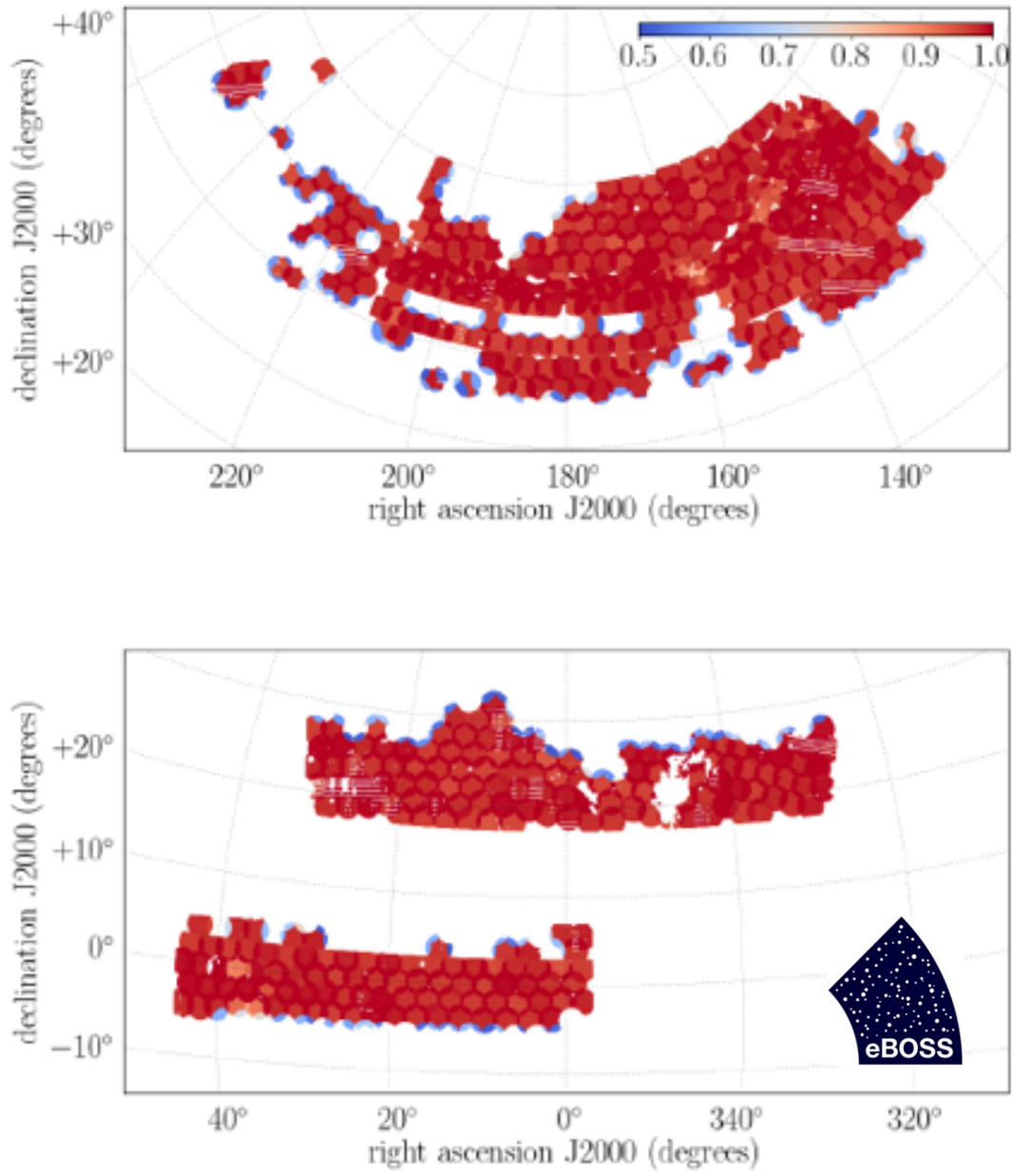
Area = 9376 deg²

~10⁶ LRG targets

3overlapping z-bins

0.2<z<0.5
0.4<z<0.6
0.5<z<0.75

DR14 footprint for the quasar sample



Area = 2112.9 deg²

~1.5·10⁵ quasar targets

0.8<z<2.2

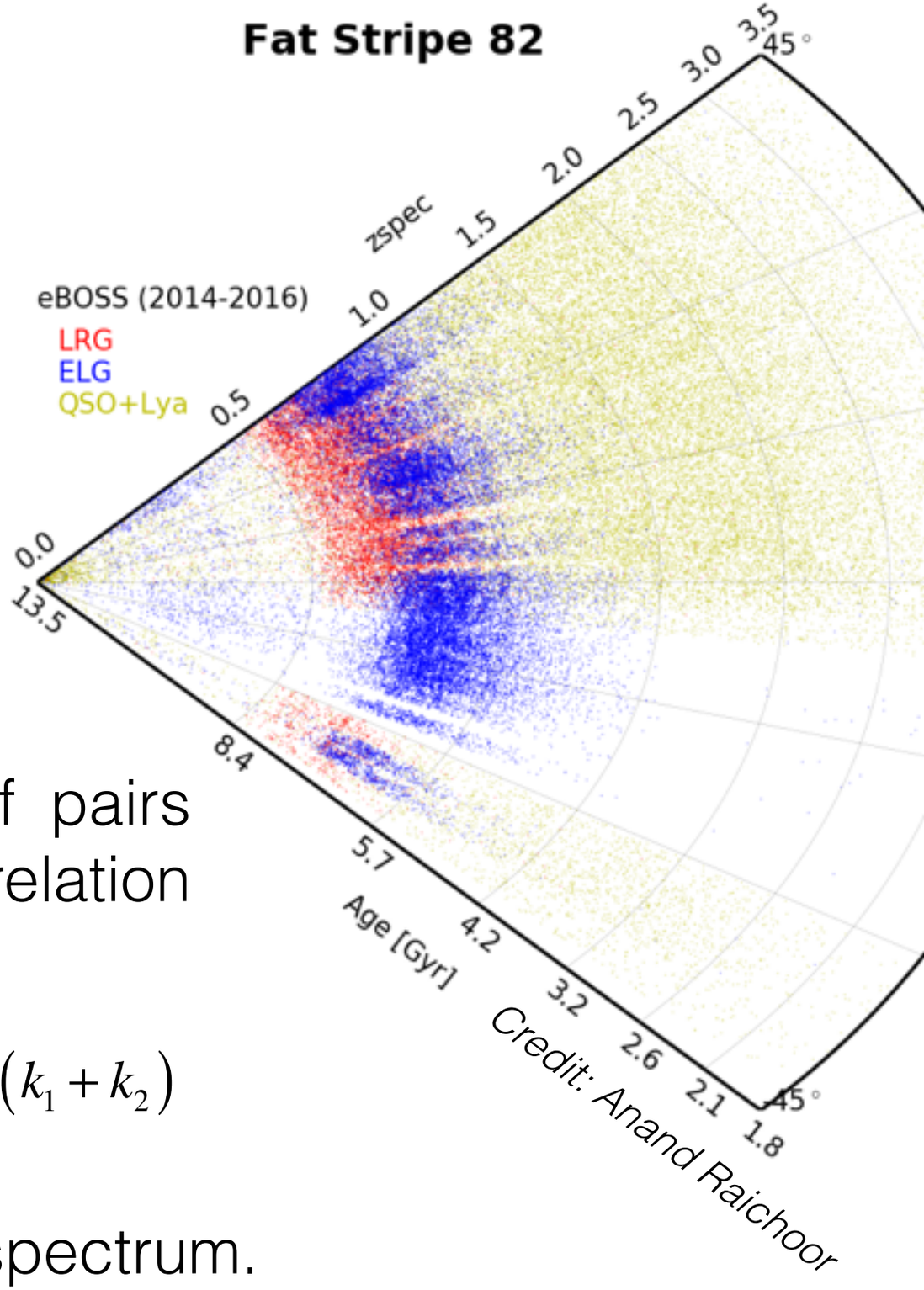
Clustering of Tracers: What do we measure?

The redshift survey catalogues deliver: **angles** and **redshifts** for each galaxy

$$r(z) = \int_0^z \frac{c dz'}{H(z', \Omega_m)}$$

FLRW Universe

$$H(z, \Omega_m) = H_0 \sqrt{\Omega_m (1+z)^3 + 1 - \Omega_m}$$



3D galaxy maps

Clustering strength: Quantify number of pairs over a uniform random distribution: correlation function, ξ(R), or Power Spectrum, P(k)

$$\langle \delta(r_1)\delta(r_2) \rangle = \xi(r_1 - r_2) \qquad \langle \delta(k_1)\delta(k_2) \rangle = P(k_1)\delta^D(k_1 + k_2)$$

… and higher order functions, such as bispectrum.

Baryonic Acoustic Oscillation peak

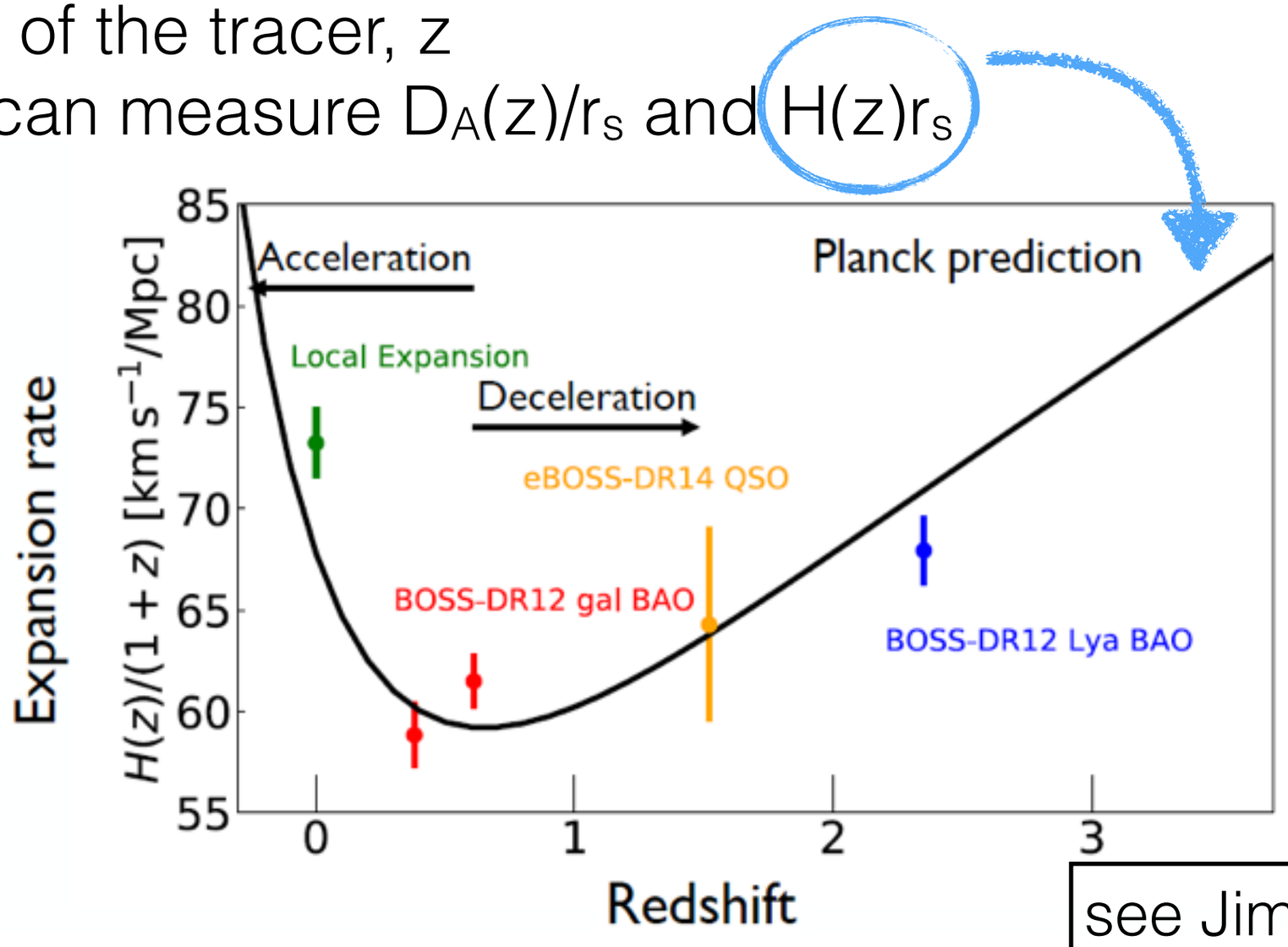
Using BAO/RSD as a standard ruler, galaxies, Lya, … measure,

- $[D_A(z)^2/H(z)]^{1/3}/r_s$ (isotropic)
- $D_A(z)H(z)$ (anisotropic)
- $f\sigma_8(z)$ (anisotropic)

at the redshift of the tracer, z

With this, we can measure $D_A(z)/r_s$ and $H(z)r_s$

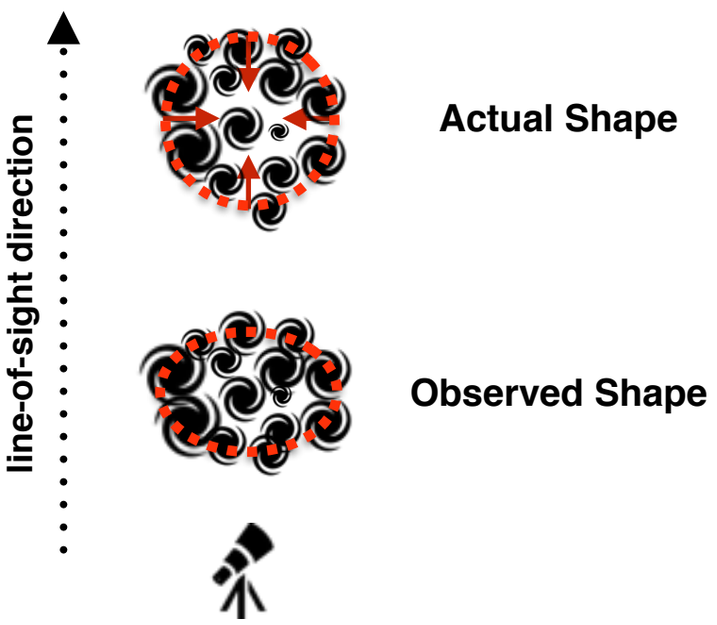
r_s given by CMB / BBN

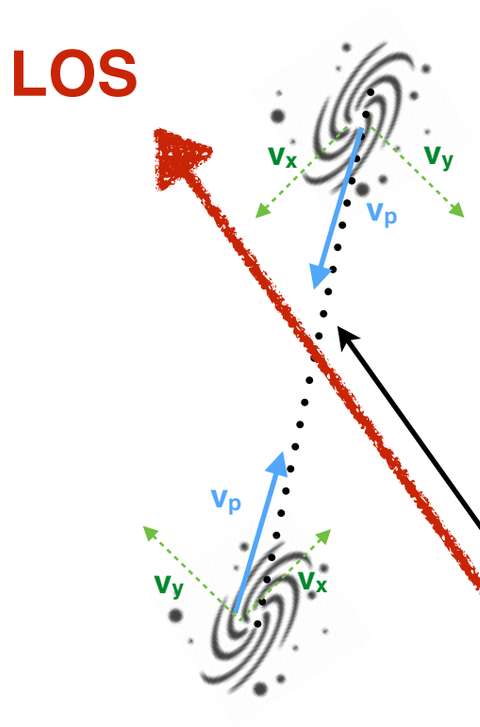


see Jim's Talk

Redshift Space Distortions

- Universe assumed **isotropic** and **homogeneous**
- **RSD**: Enhancement / reduction of the clustering along the line-of-sight (LOS) direction due to peculiar velocities (Kaiser 1987)





not detected

$$\overrightarrow{V_p} = \hat{x}_{\parallel} V_{\parallel} + \hat{x}_{\perp} V_{\perp}$$

$$f(z) = \Omega_m(z)^{\gamma}$$

logarithmic growth of structure

$$z_{obs} = z_{true} \oplus z_{pec} \equiv \left[(1 + z_{true}) \times (1 + z_{pec}) \right] - 1$$

1. Hubble flow

2. Coherent with growth of structure

Alcock-Paczynski effect

- Universe assumed **isotropic** and **homogeneous**
- **AP effect**: Anisotropy induced by transforming redshifts into coming distances assuming a *wrong cosmology*

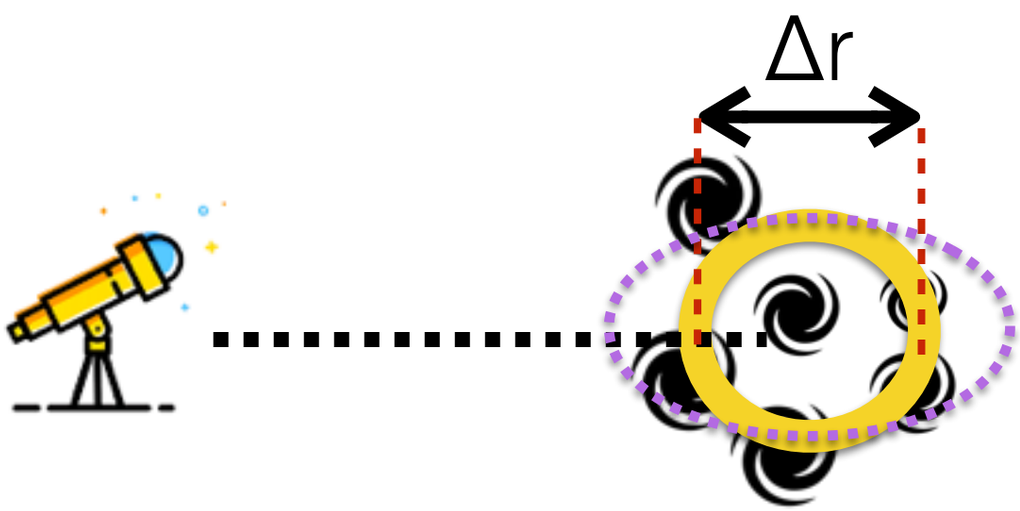
Both transverse and longitudinal modes are modified by Ω_m

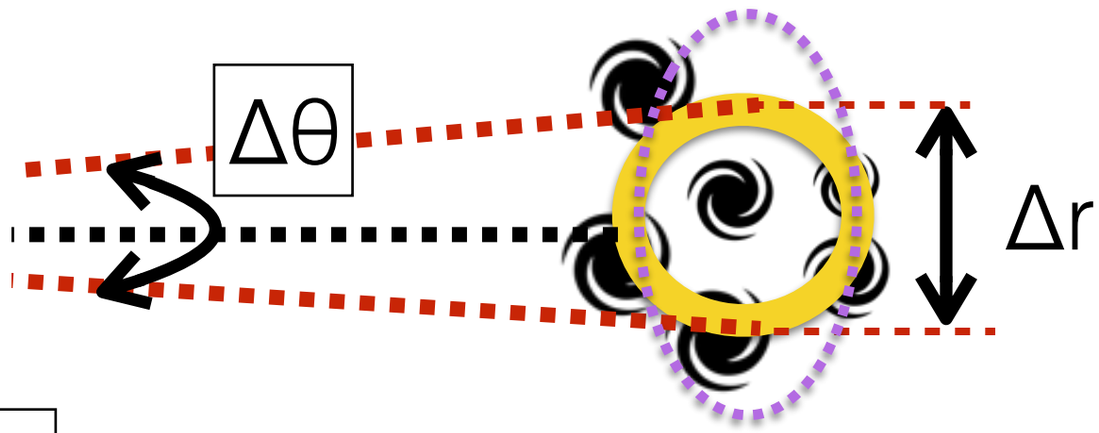
Radial distance

$$\Delta r_{\parallel}(z_1, z_2; \Omega_m) = \int_{z_1}^{z_2} \frac{c dz'}{H_0 \sqrt{\Omega_m (1+z')^3 + 1 - \Omega_m}} \approx \frac{c \Delta z}{H(\bar{z}, \Omega_m)}$$

Angular diameter distance

$$\Delta r_{\perp}(\theta_1, \theta_2; z, \Omega_m) = \Delta\theta \int_0^{z} \frac{c dz'}{H(z', \Omega_m)}$$

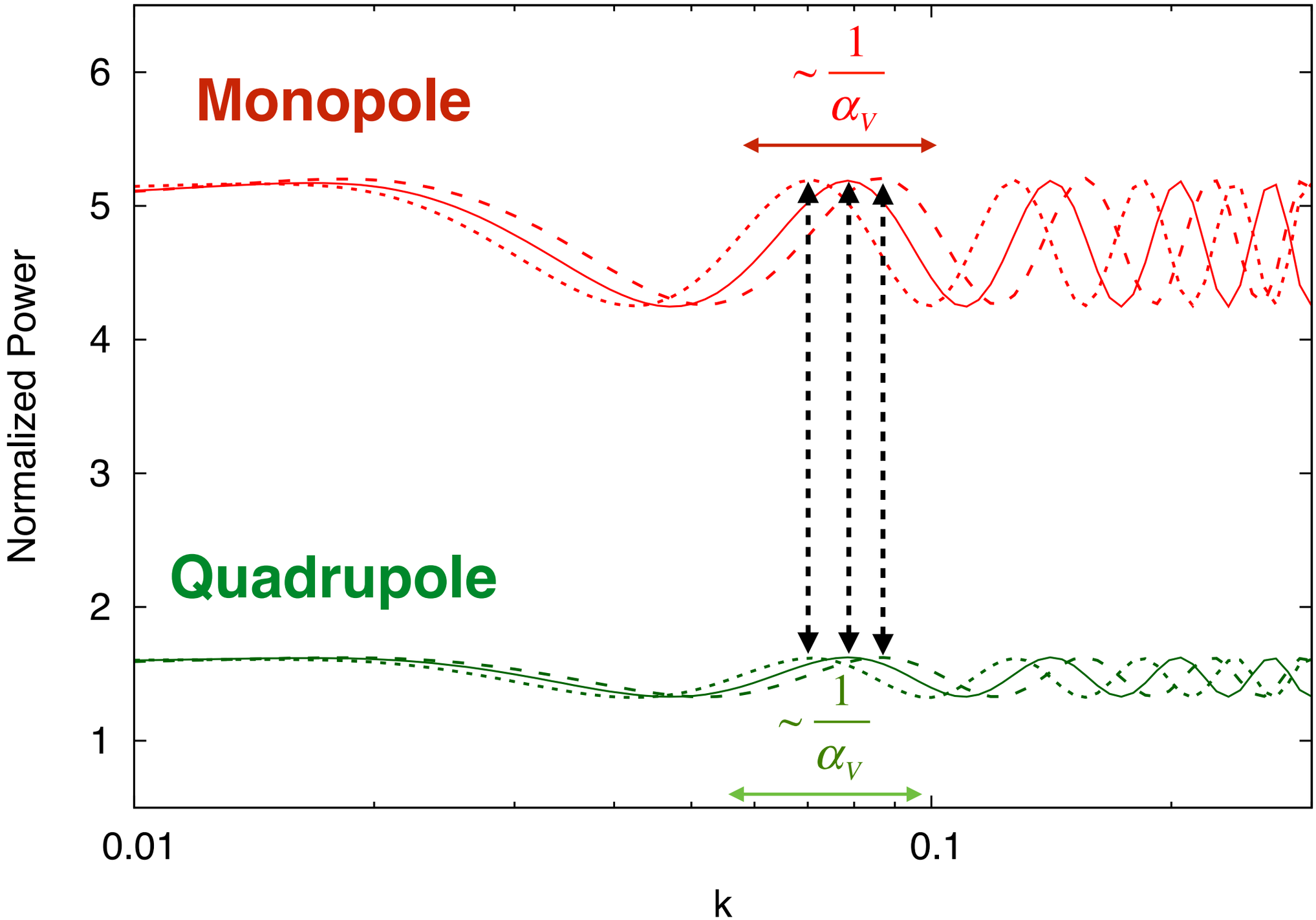




cluster is modified along both directions

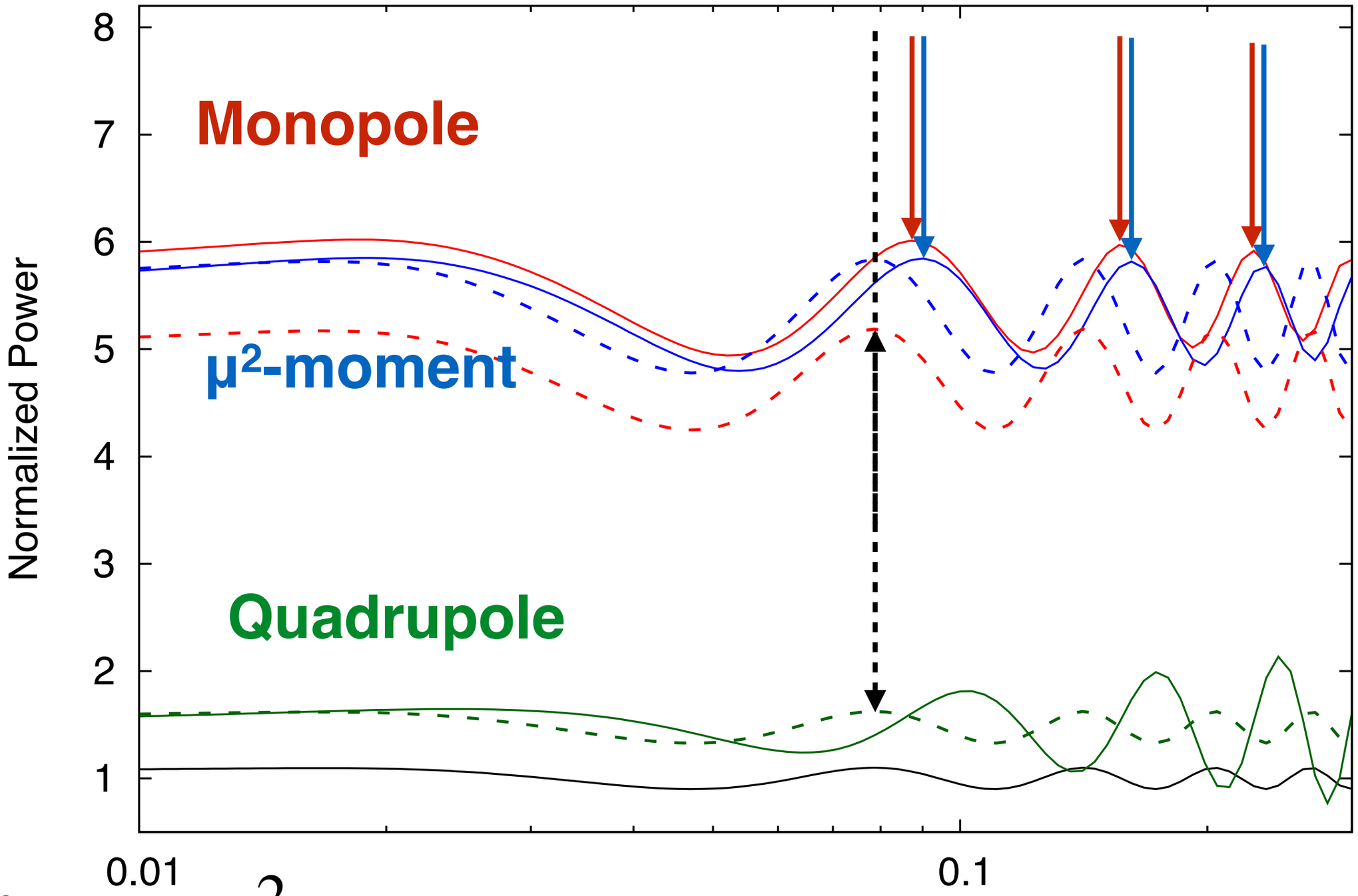
Physical Interpretation

$\alpha_V \sim (D_A^2/H)^{1/3} / r_s$



Physical Interpretation

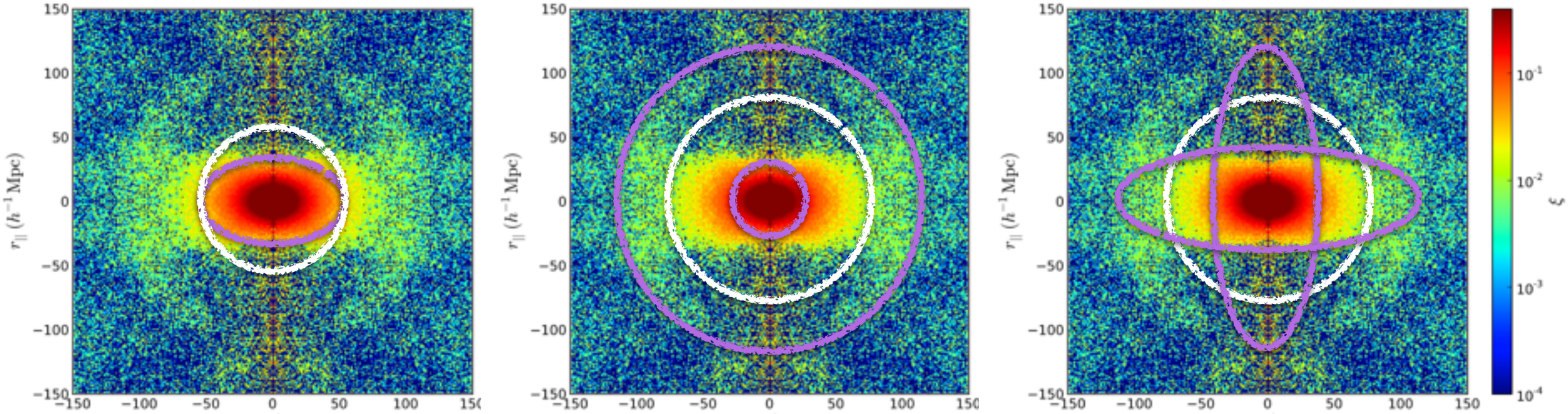
$\alpha_\varepsilon \sim D_A H$

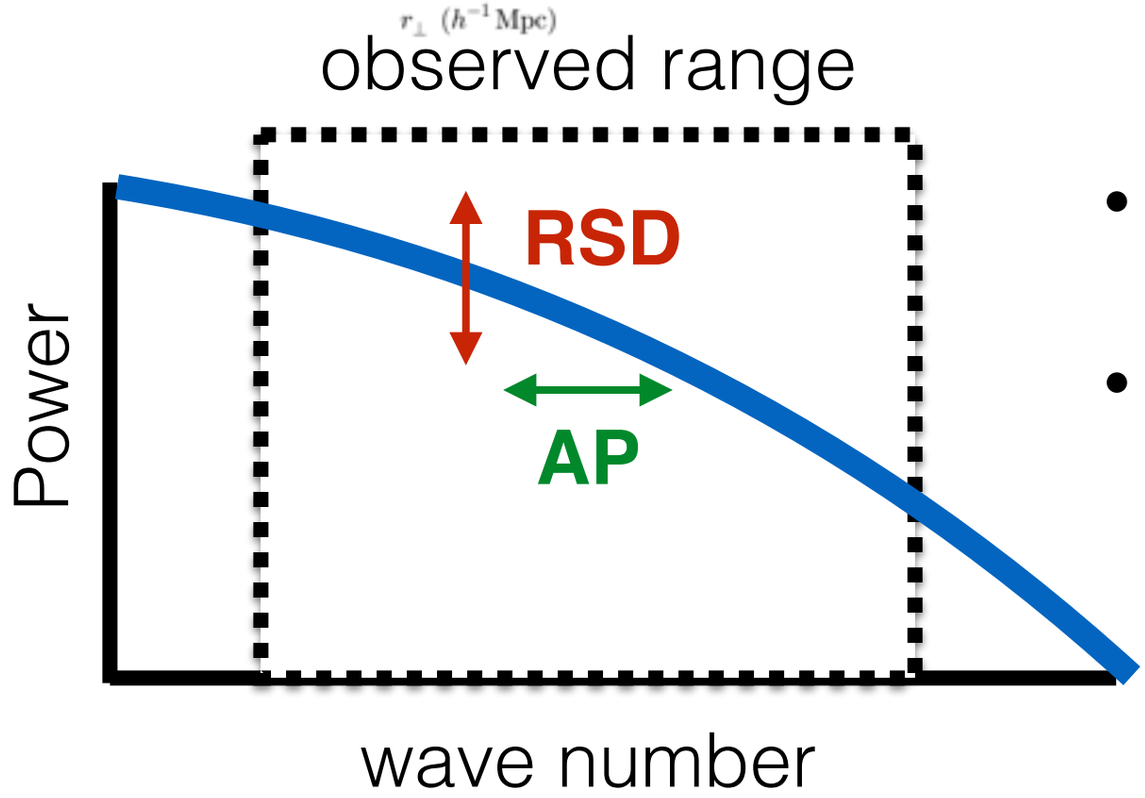


$$P^{(\mu^2)} \equiv P^{(0)} + \frac{2}{5} P^{(2)}$$

Physical Interpretation

RSD | **Isotropic dilation** | **Alcock-Paczynski**

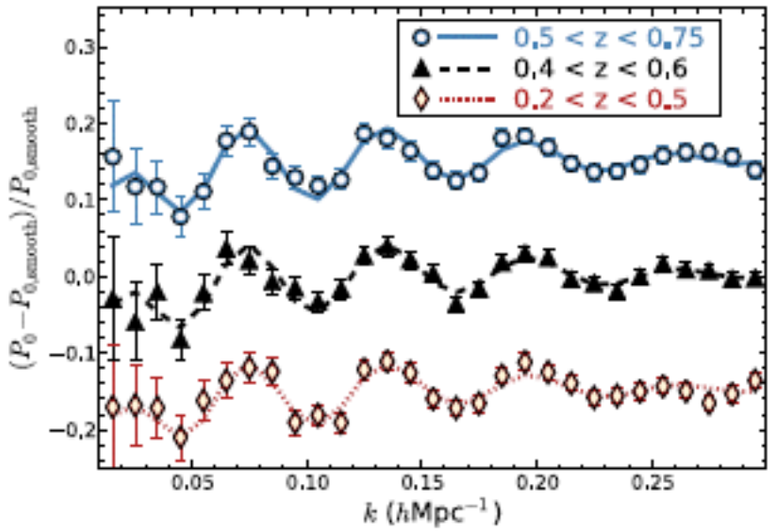


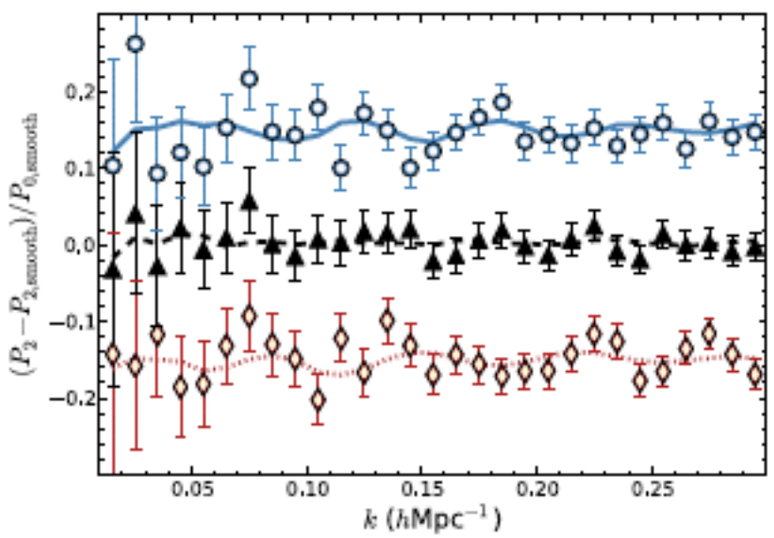


- These 3 effects are degenerated for a power law-like power spectrum
- Only when we have a scale of reference, we can constrain them independently

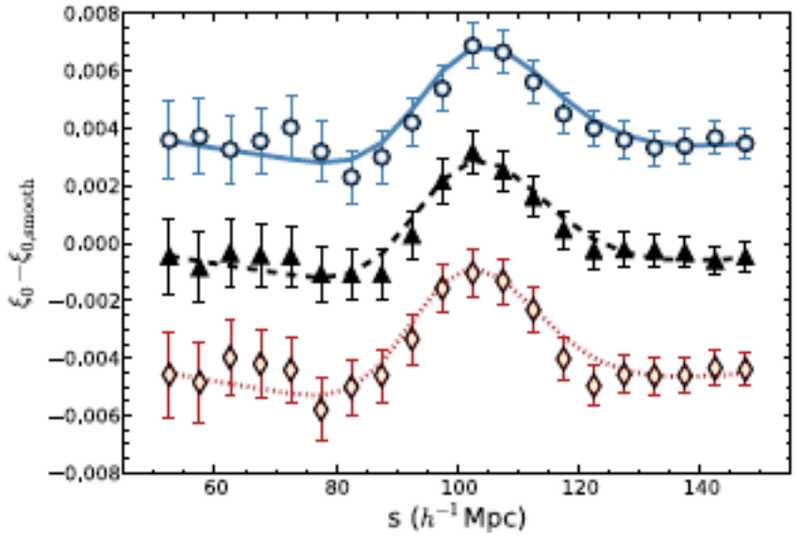
LRGs BAO/RSD from BOSS

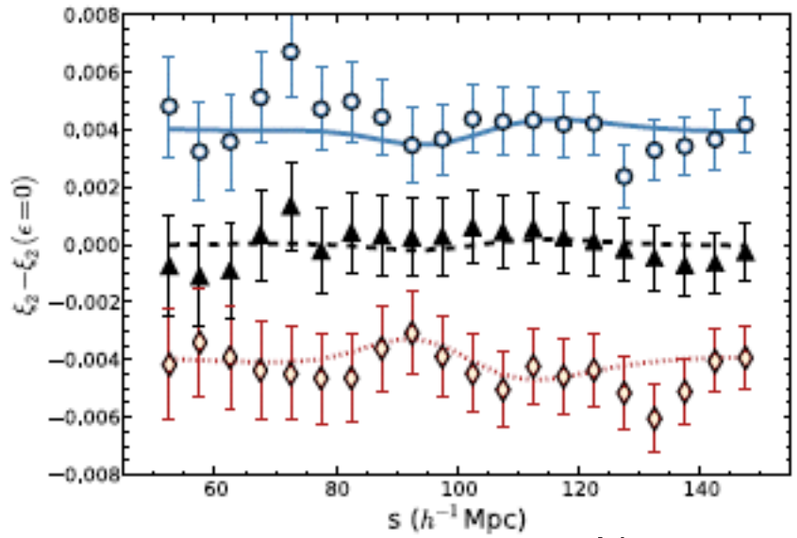
Power Spectrum





Correlation Function





3overlapping z-bins

0.2<z<0.5
0.4<z<0.6
0.5<z<0.75

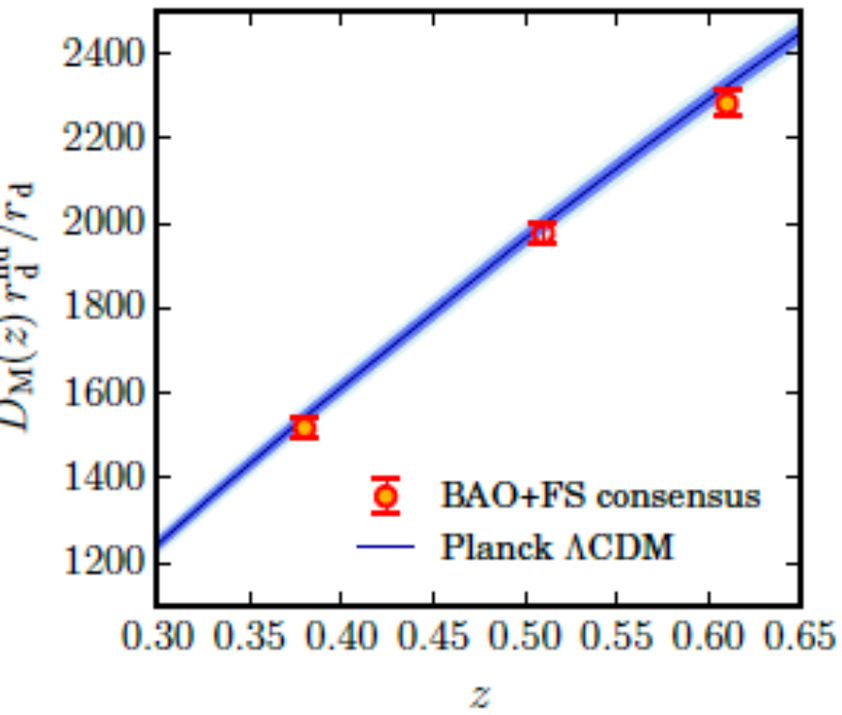
Alam et al. 2016

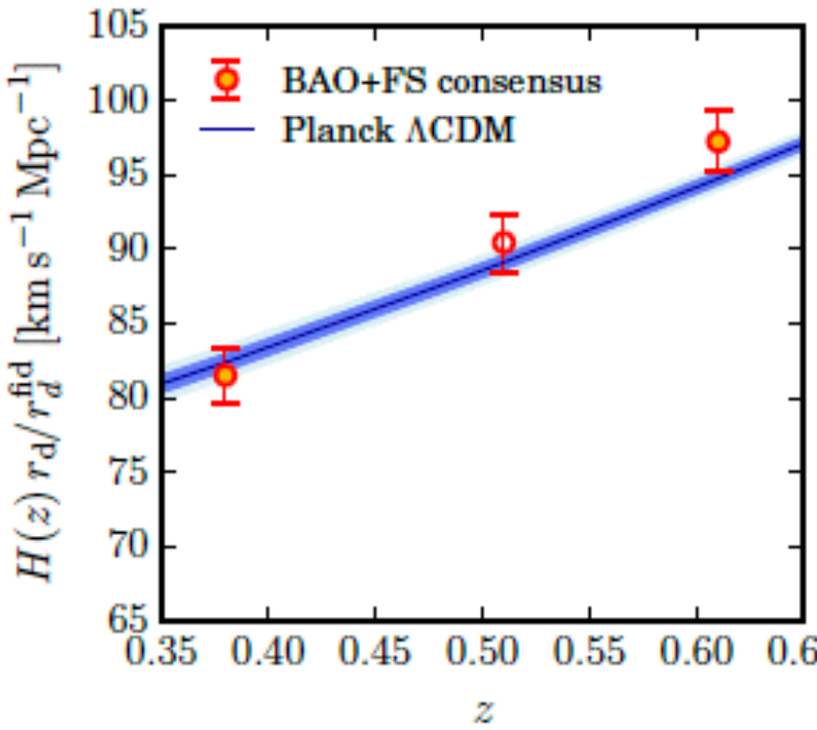
Type of analyses:

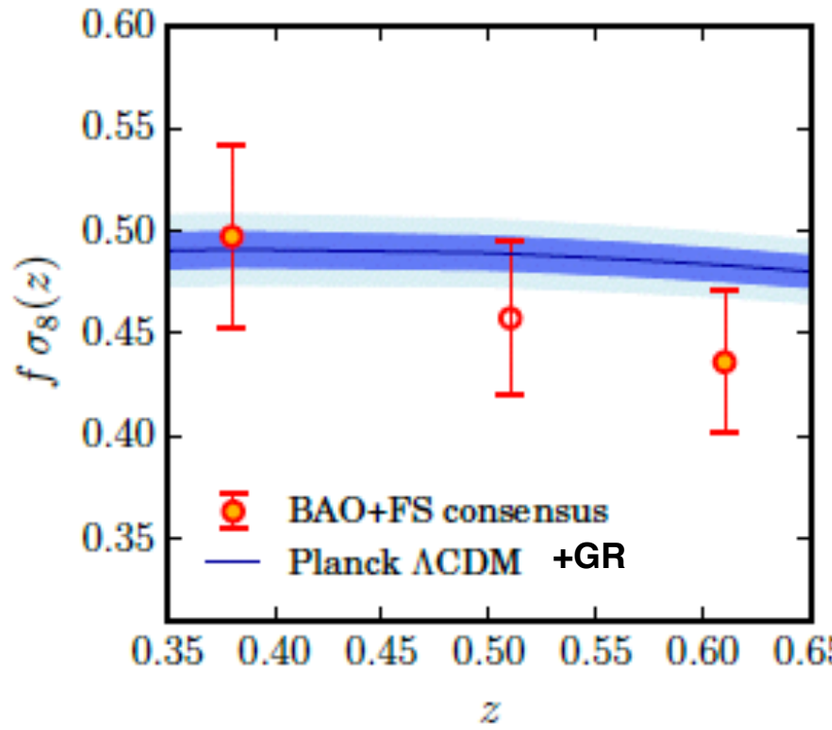
- RSD (full shape) vs. BAO,
- pre-recon vs. post-recon,
- configuration space vs. Fourier space

LRGs BAO/RSD from BOSS

Alam et al. 2016





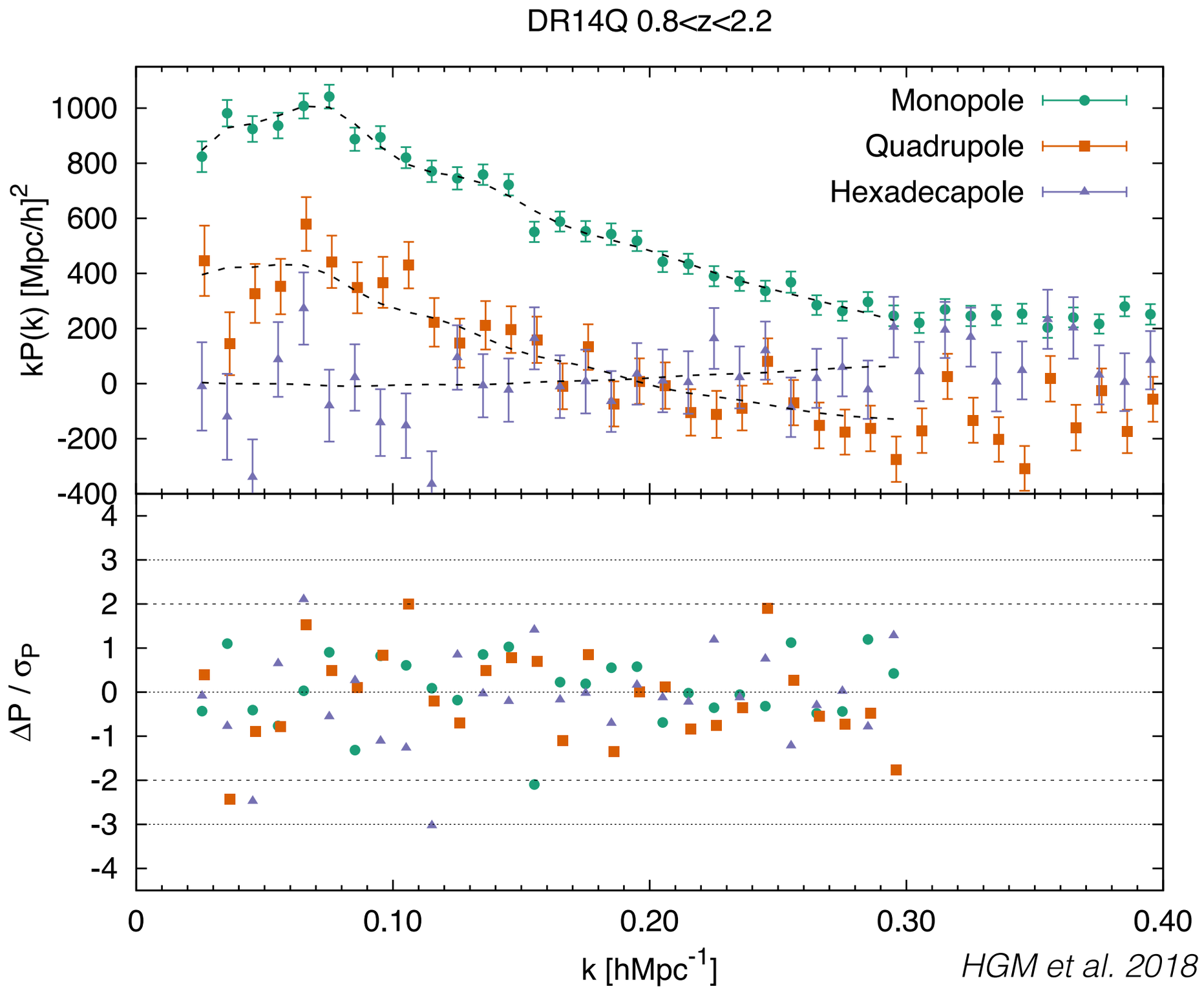


- Good Agreement with Planck+GR
- (!) Middle redshift bin point correlated
- First time 1% precision BAO measurement (reconstruction)

3overlapping z-bins

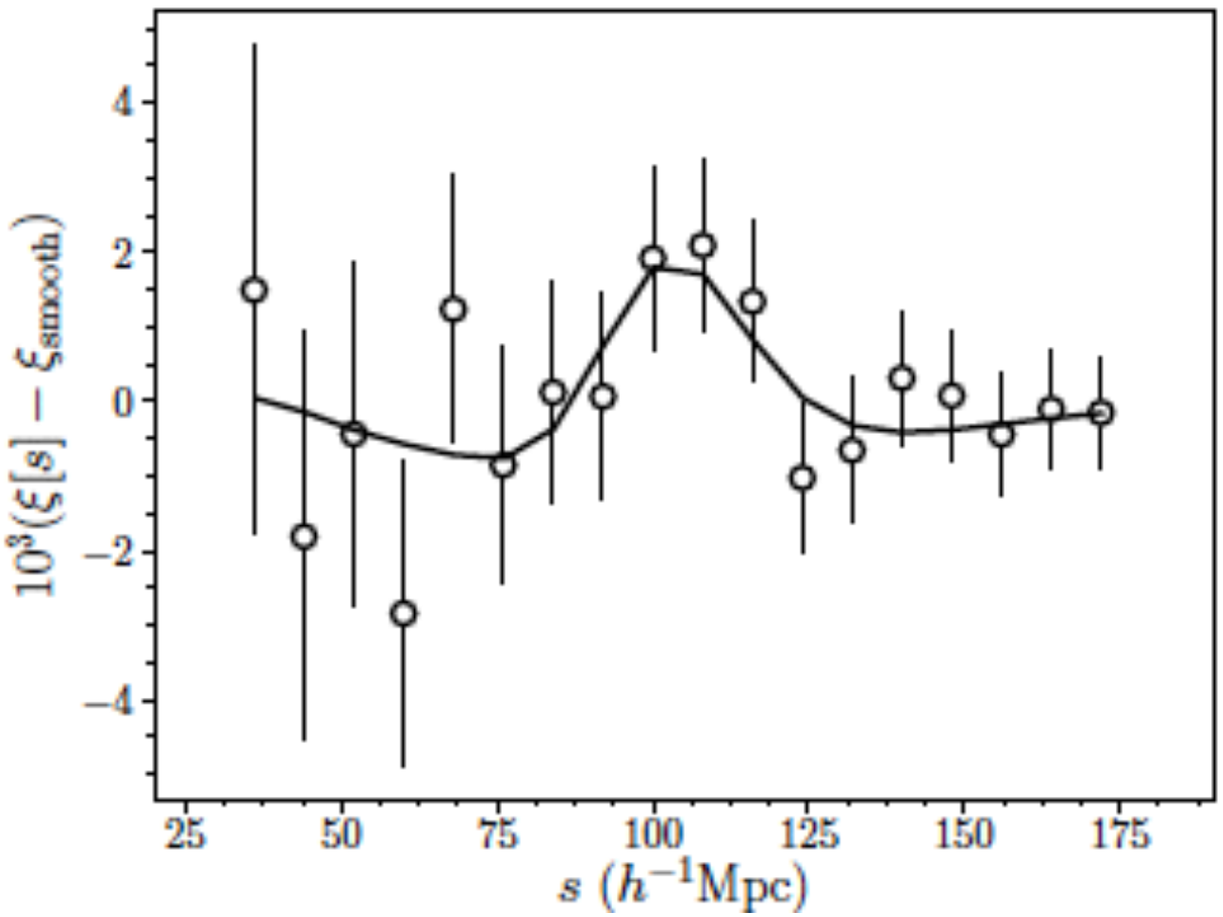
0.2<z<0.5
0.4<z<0.6
0.5<z<0.75

quasar BAO/RSD from eBOSS

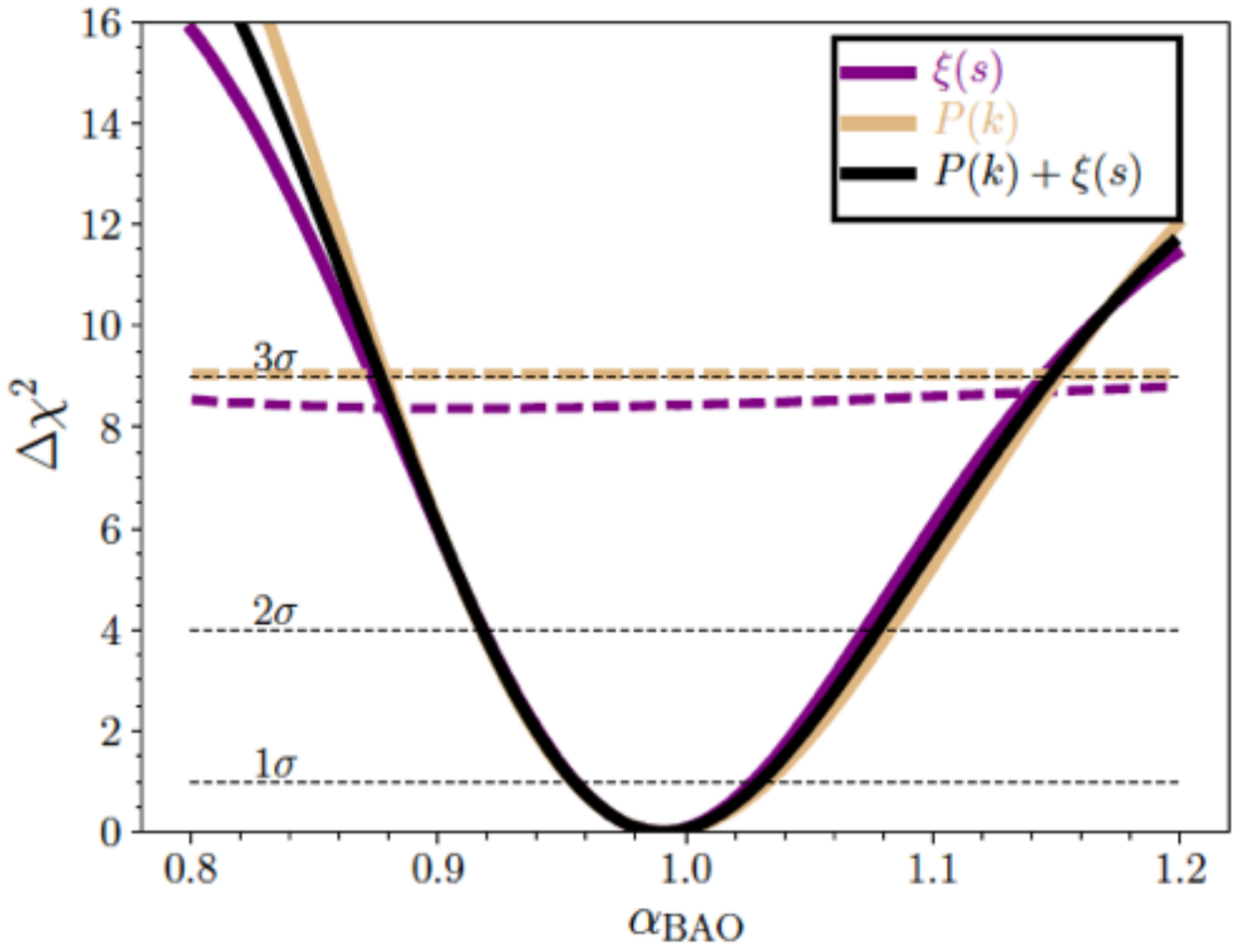


quasar BAO/RSD from eBOSS

Correlation Function



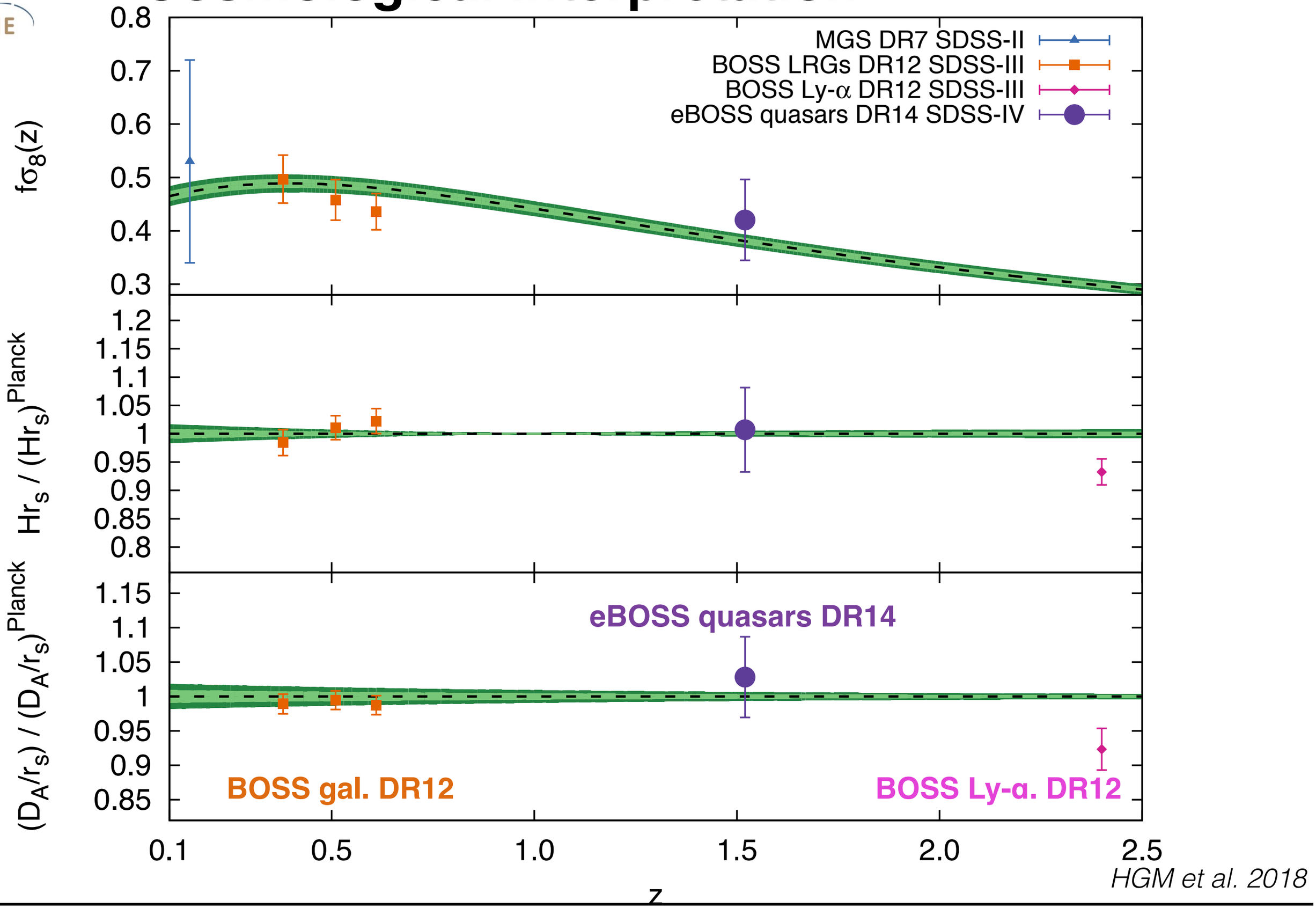
Significance of BAO peak



Ata et al. 2017

- 3σ detection
- In good agreement with Planck+GR
- $D_V(z=1.52)=3843 \pm 147$ Mpc (3.8%)

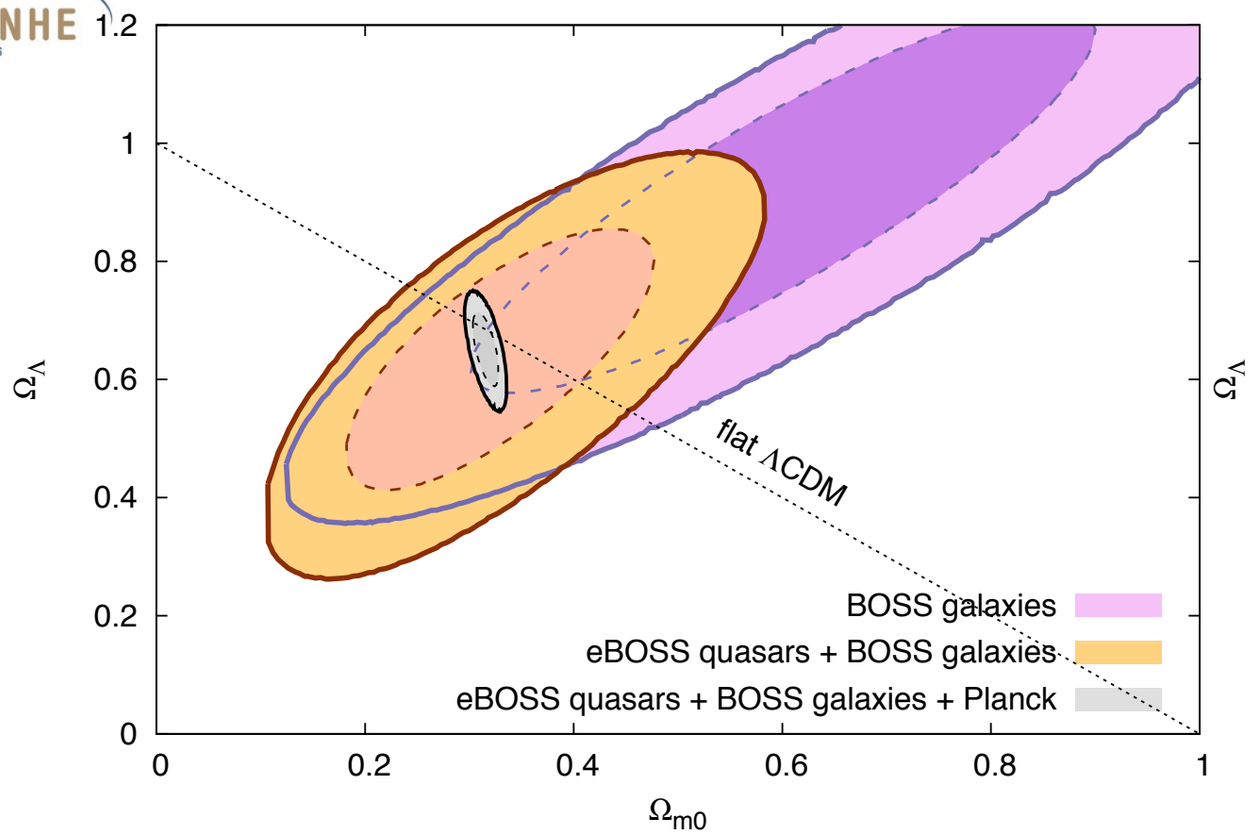
Cosmological Interpretation

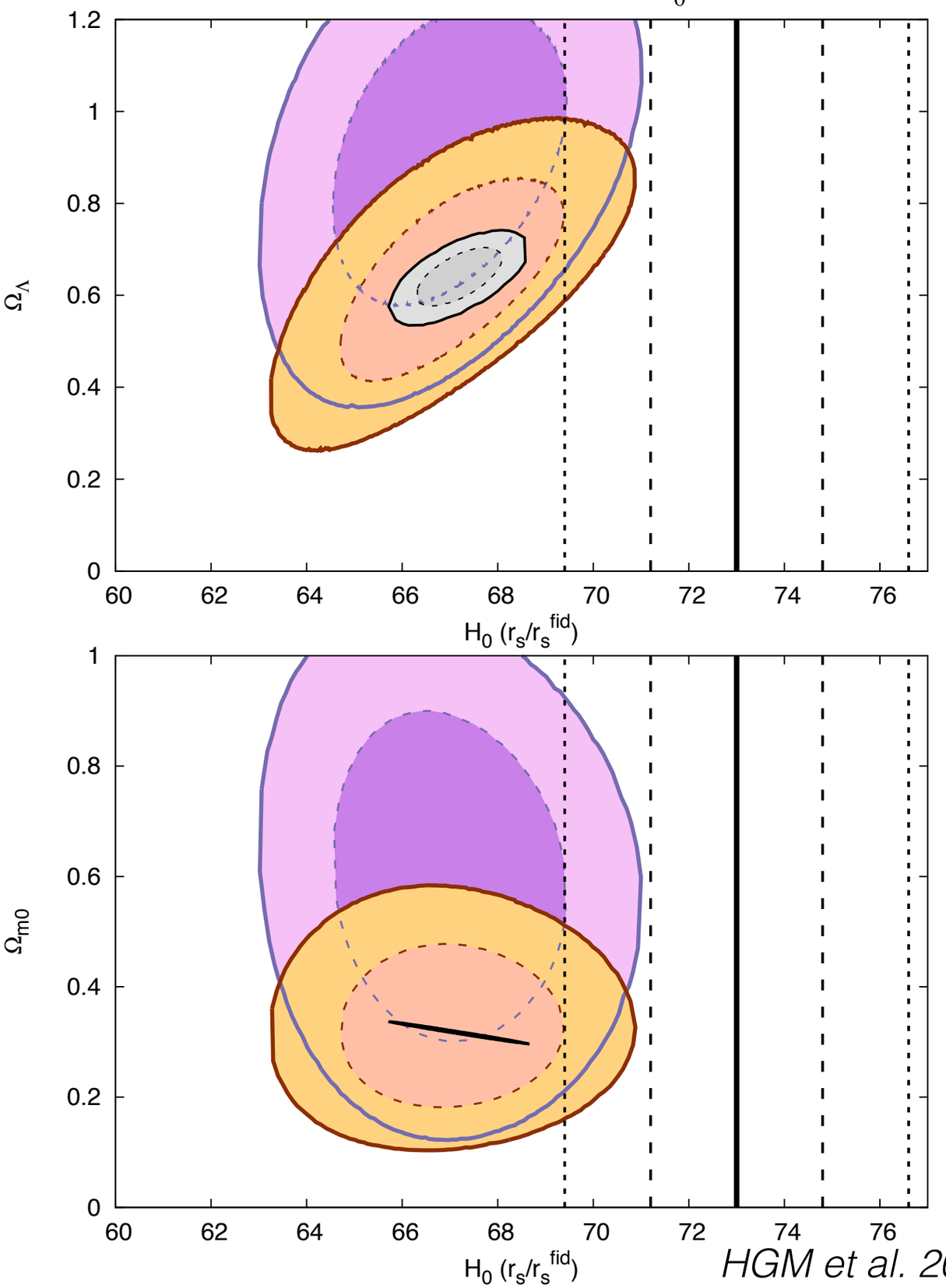


HGM et al. 2018

Cosmological Interpretation

$H_0 = 73.0 \pm 1.8$





GR & ΛCDM assumed

$D_A(z)$, $H(z)$, $f\sigma_8(z)$ from BOSS galaxies / eBOSS quasars

HGM et al. 2018

Impact of potential systematics

BAO Systematics

- Very robust!
  - (barely not affected by b_g, non-linearities, obs. systematics)
- ~0.1% non-linear shift at z=1.5 (Blas et al. 2016)
- Relative velocity between DM & gal. (Slepian et al. 2016, bv<0.01)
- Reconstruction assumptions (bias and f)
  - 2pcf, 3pcf, …, BAO should contain the same BAO information than post-recon without f or bias assumptions

RSD systematics

- Model dependent (PT, shell crossing)
  A. Galaxy bias model
  B. DM modelling
  C. RSD modelling
- Tidal alignments (Hirata 2009; Martens et al. 2018)
  - Observational selction of galaxies depending on their environment
- failures & collisions (camera sys.), but corrected by weighting schemes

Summary

- BOSS measured $H(z)r_s$ in the range $0.2<z<0.75$ using LRGs (high density)
- **First results from eBOSS** quasars measuring $H(z)r_s$ in the range $0.8<z<2.2$
- More eBOSS data coming in the next 1.5yr (ELG, LRG, quasars + Lyα): errors of quasars to ~1/2, measurements at z~0.75 from LRGs + ELGs
- Results strongly support LCDM+Planck (Tension with local H0 measurement with SN+Cosmic Ladder)
- (known) Uncorrected systematics not important for current statistical precision, but some of them need to be better controlled for future surveys.
- DESI will deliver more precise results within 5yr from now.