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

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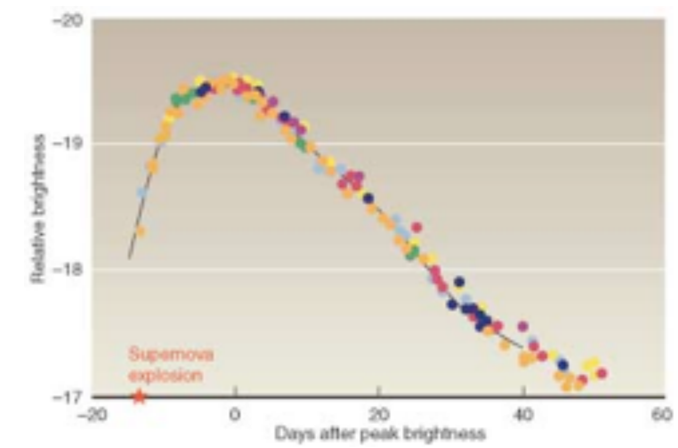
Tensions in the LCDM paradigm

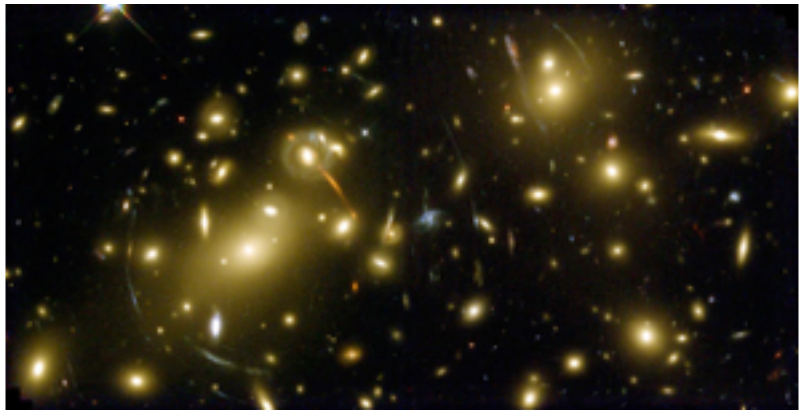
Mainz, 16th May 2018

Cosmological Standard Model

Probes to test Dark Energy on late-time Universe



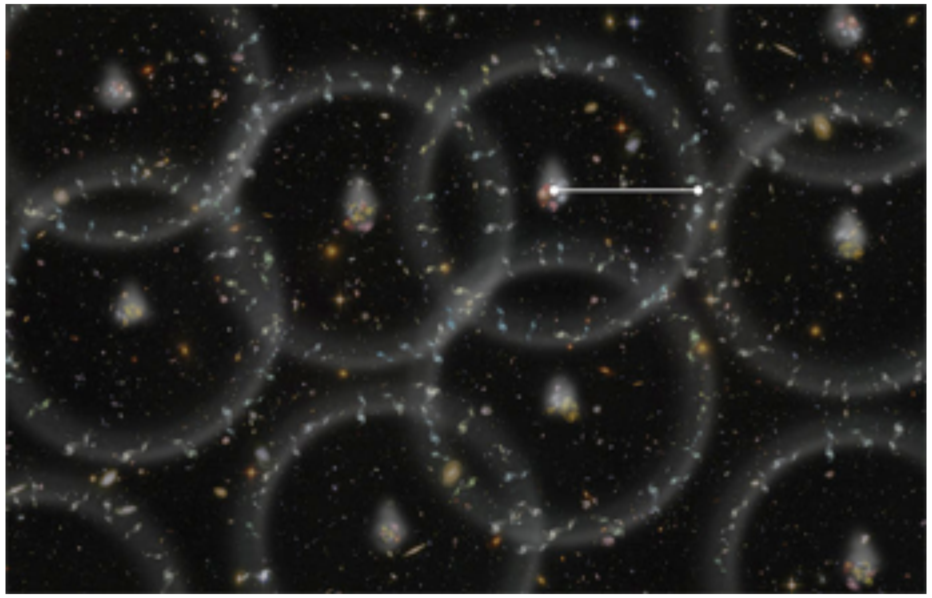
- Standard Candle Supernovae
- Weak lensing
- Cluster counting



- **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

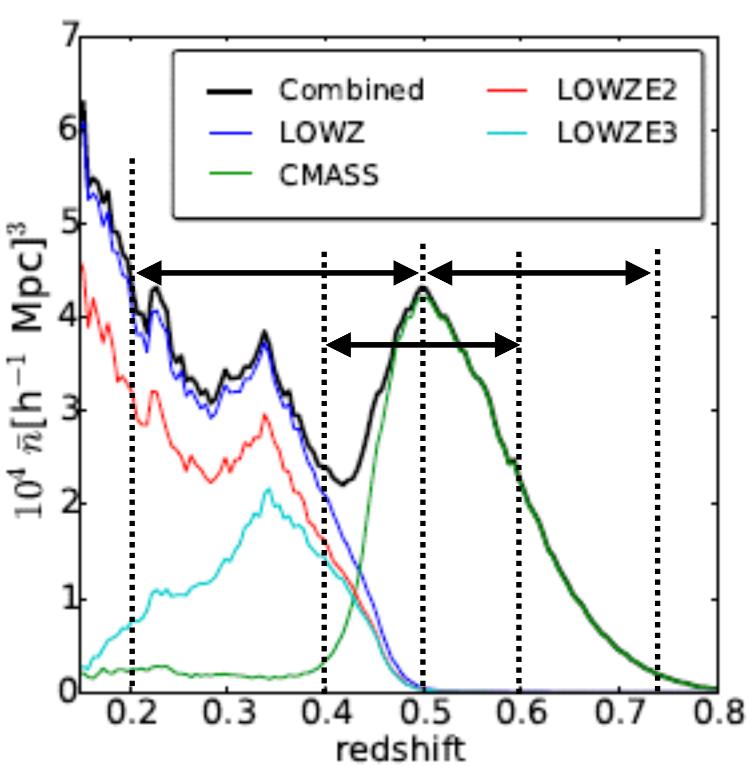
Galaxy bias physics: $b_1\sigma_8$ $b_2\sigma_8$ σ_{FoG} .....

BOSS in a nutshell

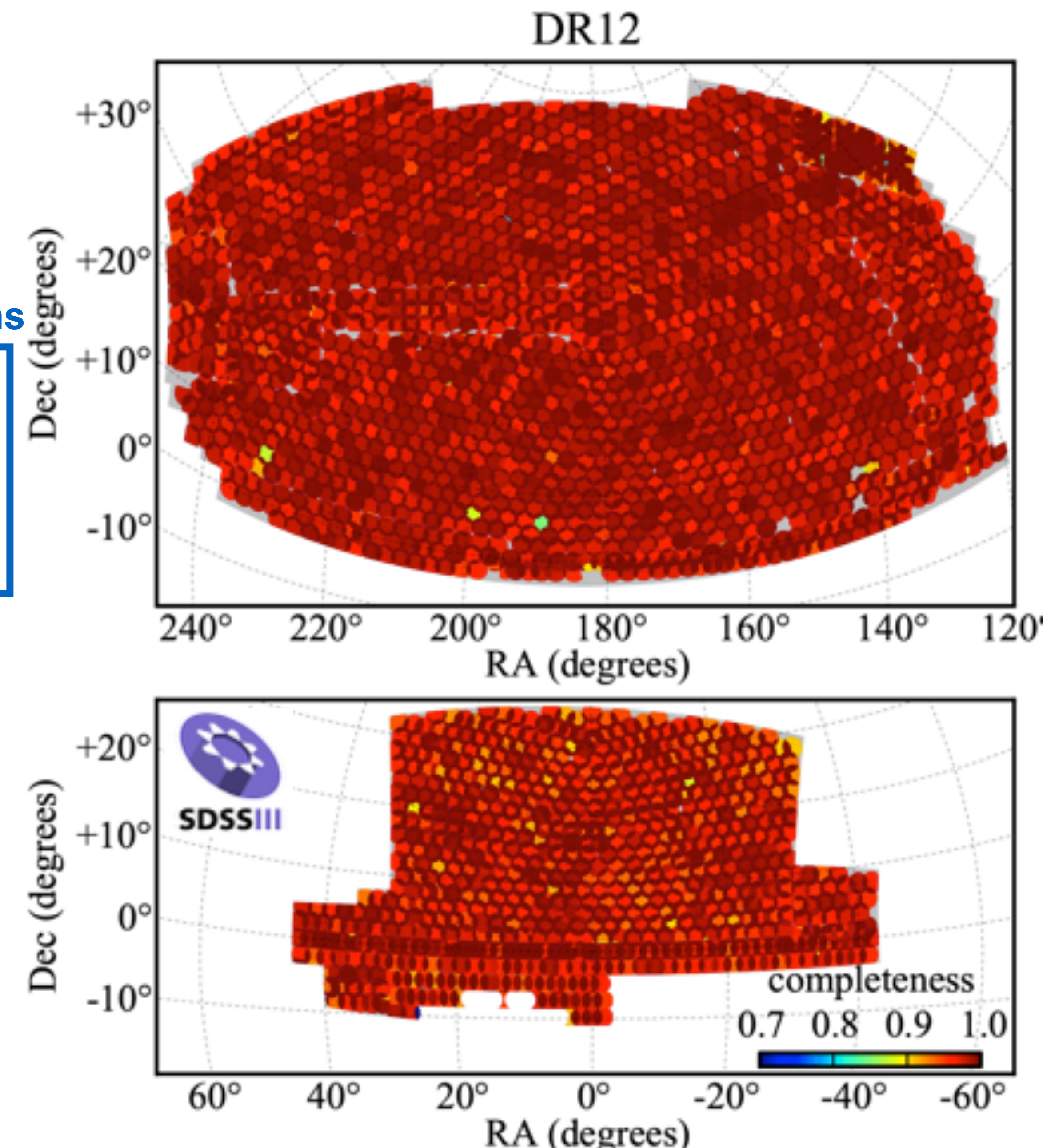
- Part of SDSS-III collaboration
- Apache Point Telescope 2.5m
- 2009 - 2014 observing period
- LOWZ-LRGs (0.15<z<0.43),
- CMASS-LRGs (0.43<z<0.70),
- Ly-α (z~2.5)

3overlapping z-bins

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



DR12 footprint for the LRG sample



Alam et al. 2016

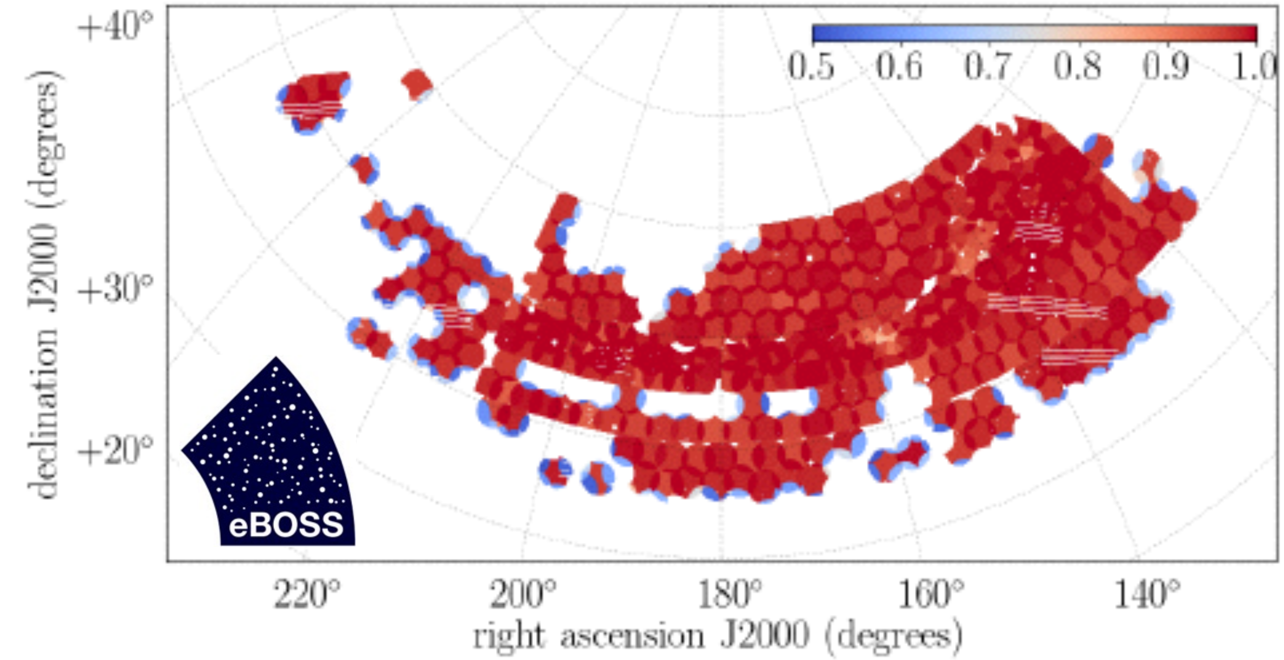
- 0.2 < z < 0.75
- ~10^6 LRG targets
- high density of tracers 4×10^{-4} h/Mpc
- High density variation

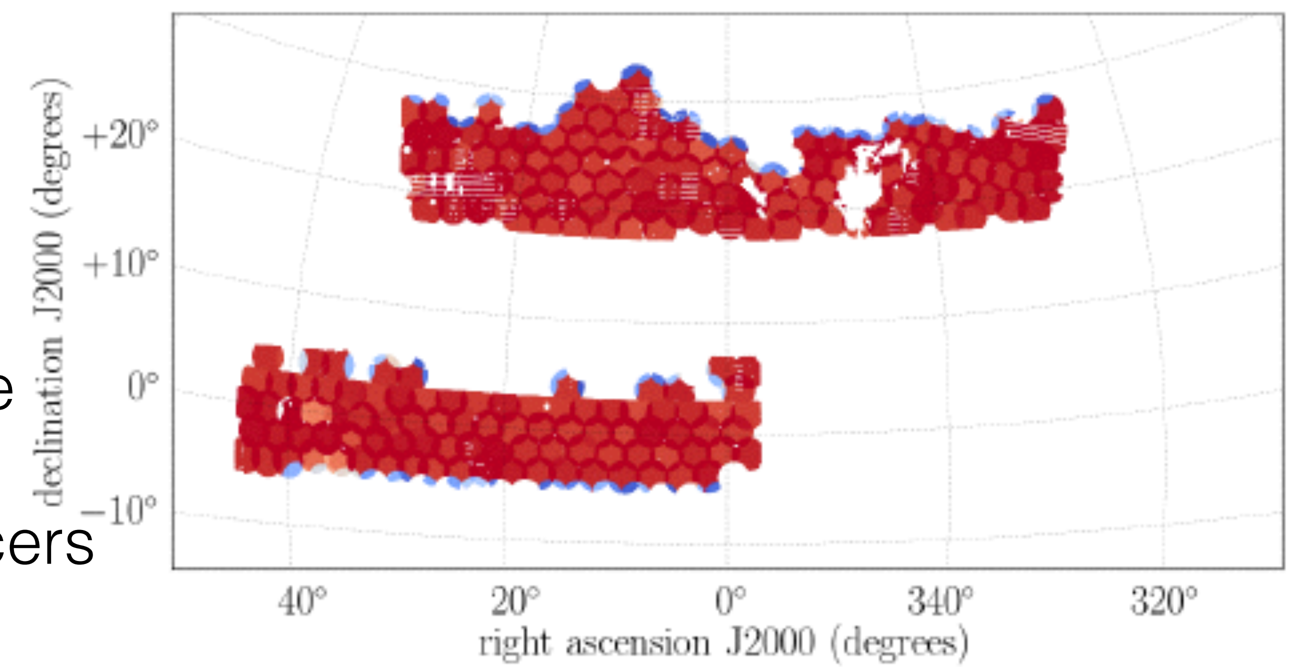
Area = 9376 deg^2

eBOSS in a nutshell

- Part of SDSS-IV collaboration
- Apache Point Telescope 2.5m
- 2014 - 2019 observing period
- LRGs & ELGs ($0.6 < z < 1.1$),
- Quasars ($0.8 < z < 2.2$)
- Ly-α (z~2.5)

DR14 footprint for the quasar sample

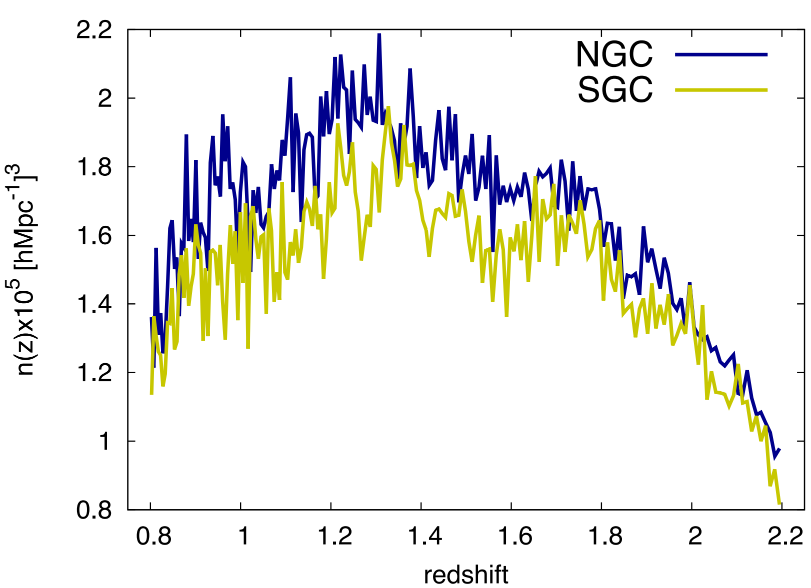




Ata et al. 2017

Area = 2112.9 deg^2

Quasar Sample (DR14)



- $0.8 < z < 2.2$
- Wide redshift range
- 148,659 quasars
- Low density of tracers 2×10^{-5} h/Mpc
- Low density variation

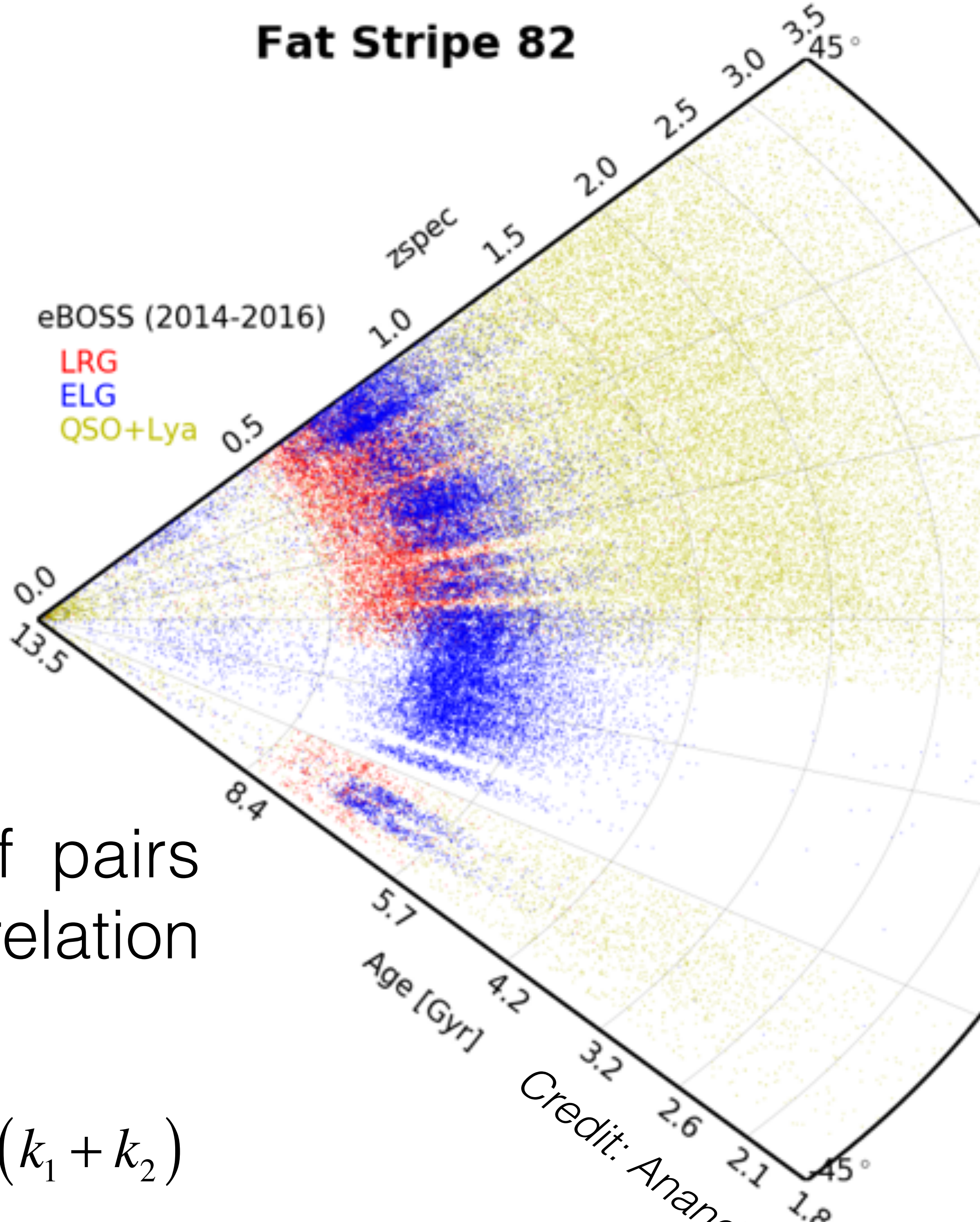
Clustering of Tracers: What do we measure?

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

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

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

3D galaxy maps



Credit: Anand Raichoor

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

Before recombination

- Photons and baryons are coupled
- Radiation pressure makes them oscillate
- Pressure waves within the fluid travelling at certain speed

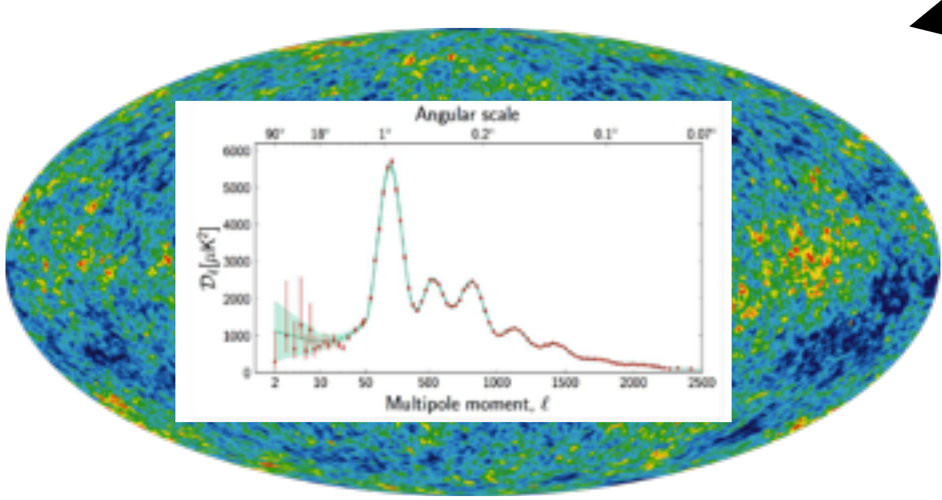
Decoupling at z~1000

- Universe become optically thin
- Decoupling between baryons and photons
- Sounds speed within the fluid decreases
- <u>Travelling wave freezes</u>

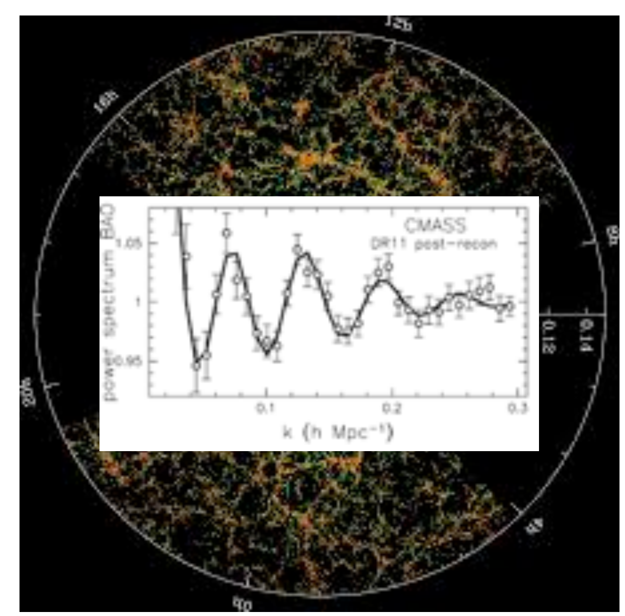
Baryons & photons are left a distinct imprint, a spherical peak, at a specific scale:
The sound horizon scale at recombination, ~150 Mpc.

photons ← → baryons+DM

CMB

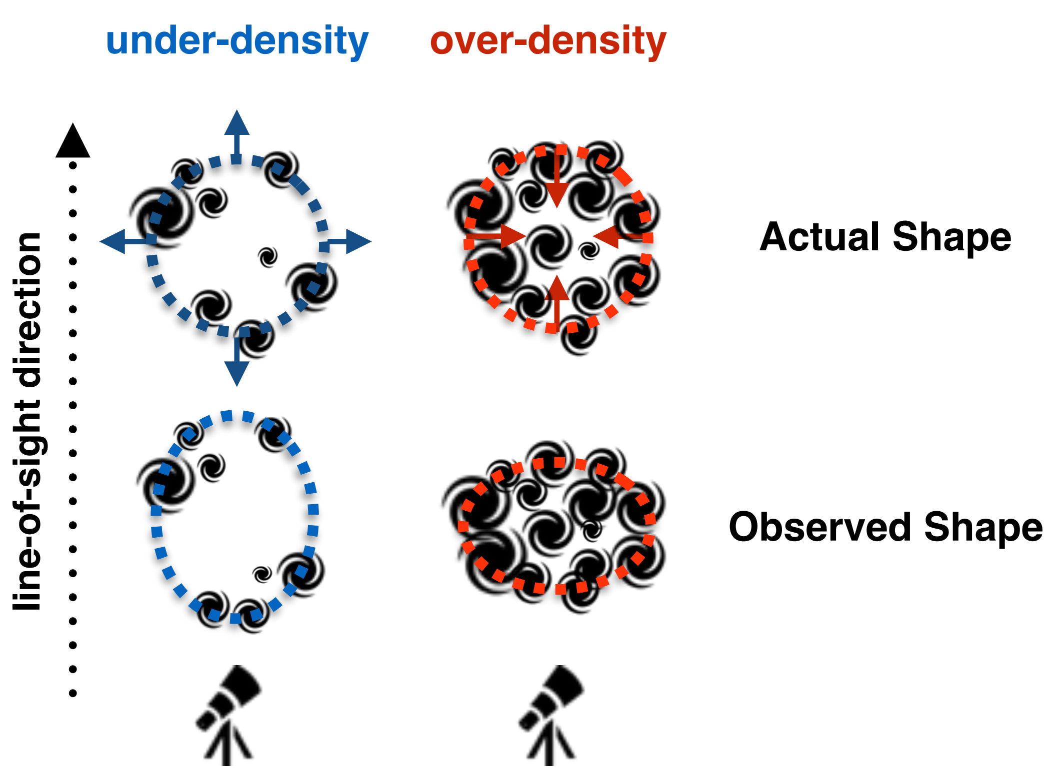


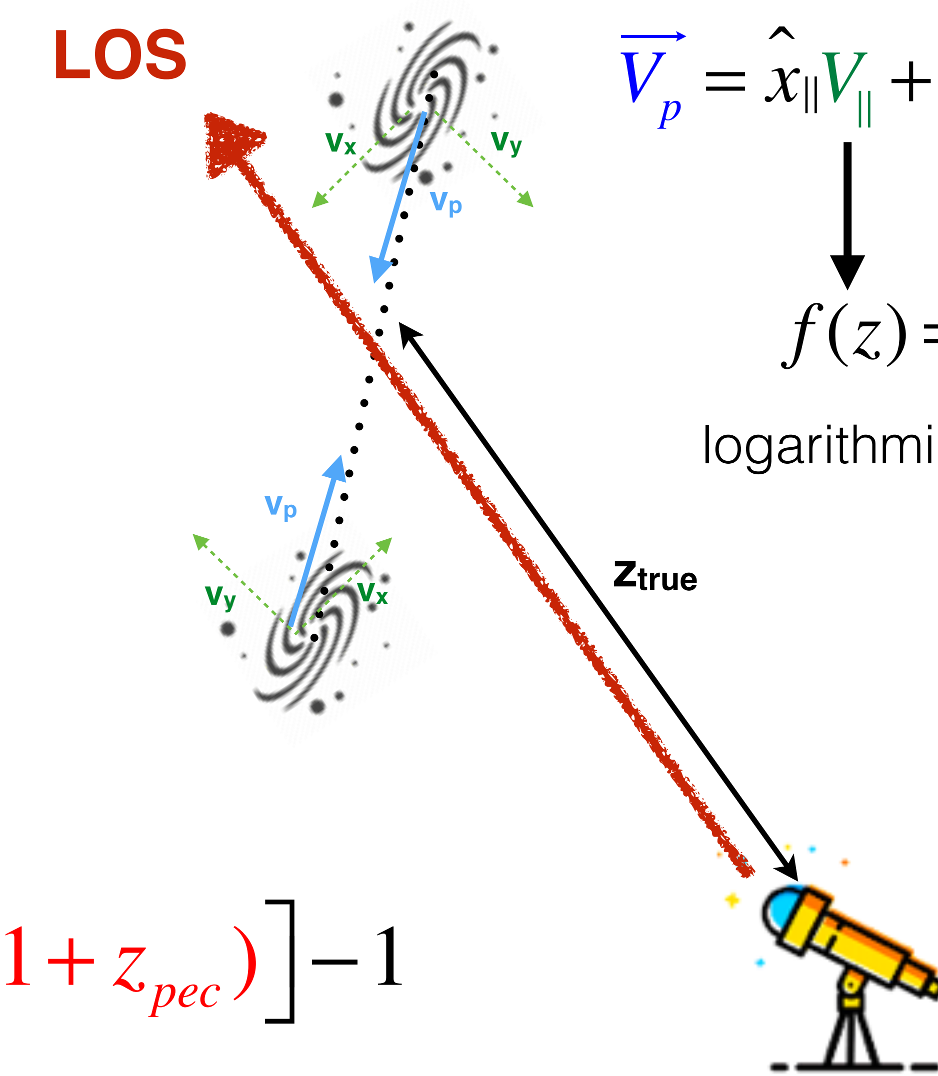
Galaxies



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

$$\vec{V}_p = \hat{x}_{\parallel} V_{\parallel} + \hat{x}_{\perp} V_{\perp}$$

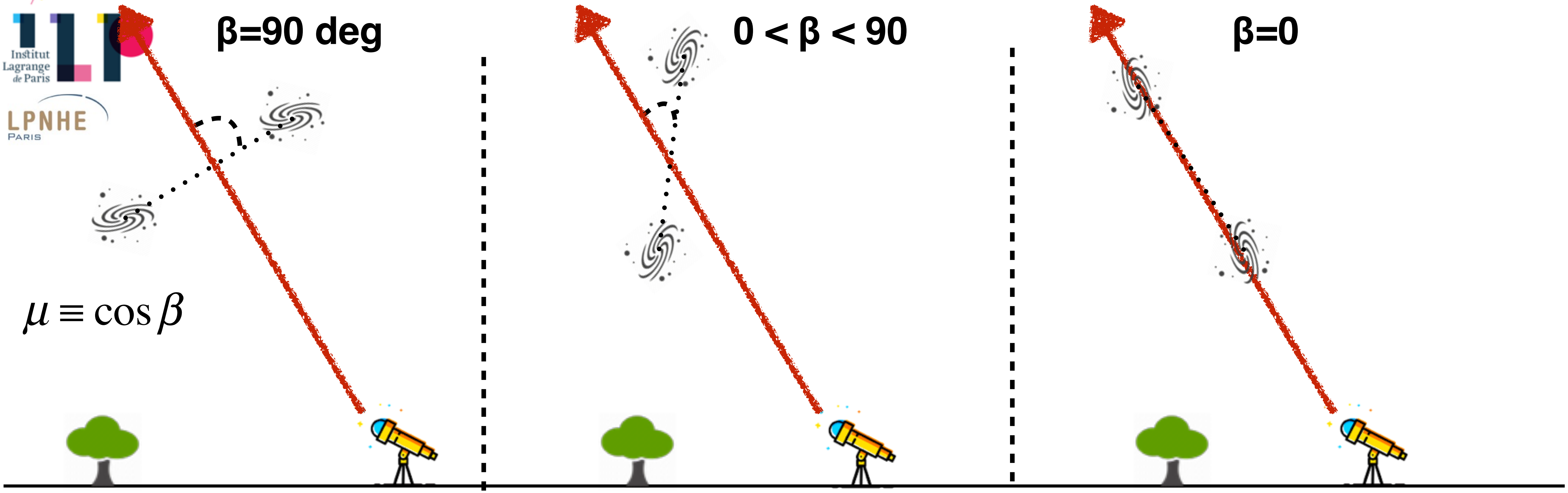
$$f(z) = \Omega_m(z)^{\gamma}$$

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



no-RSD	partial-RSD	maximum RSD
$\mu \equiv 0$	$0 < \mu < 1 \qquad -1 < \mu < 0$	$\mu \equiv \pm 1$

$$P_g^{(s)}(k,\mu;z) = \underbrace{[b(z) + f(z)\mu^2]^2}_{\textbf{boost}} P_m(k;z)$$

(Kaiser 87)

- Break isotropy: μ-dependence: monopole, quadrupole, hexadecapole
- Modify the clustering: boost depends on f(z)
- **Does not** change shape of $P_m(k)$

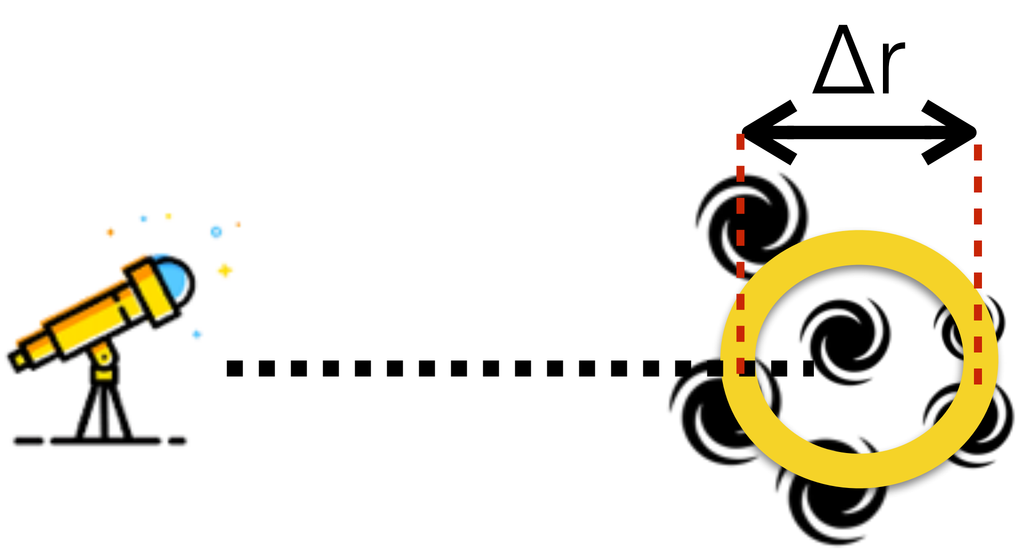
Alcock-Paczynski effect

- 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 $\mathbf{\Omega_m}$

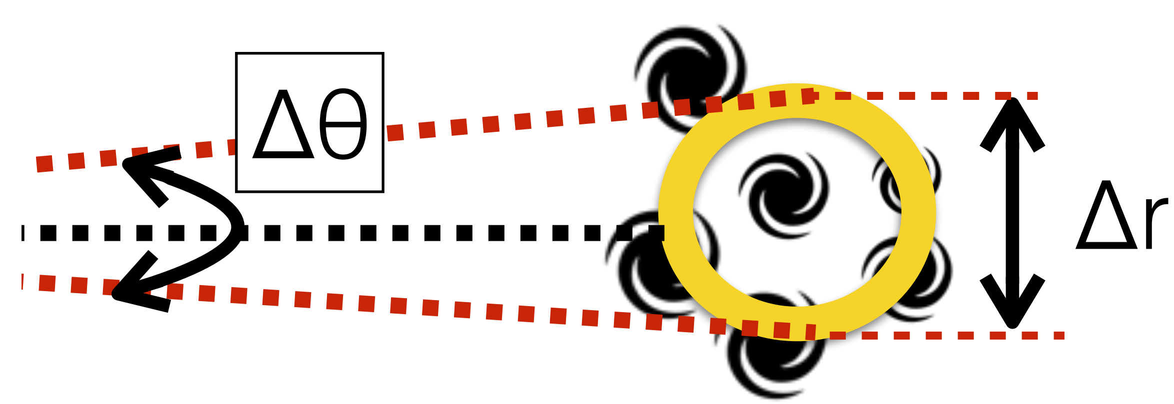
Radial distance

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



Angular diameter distance

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



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Radial distance

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

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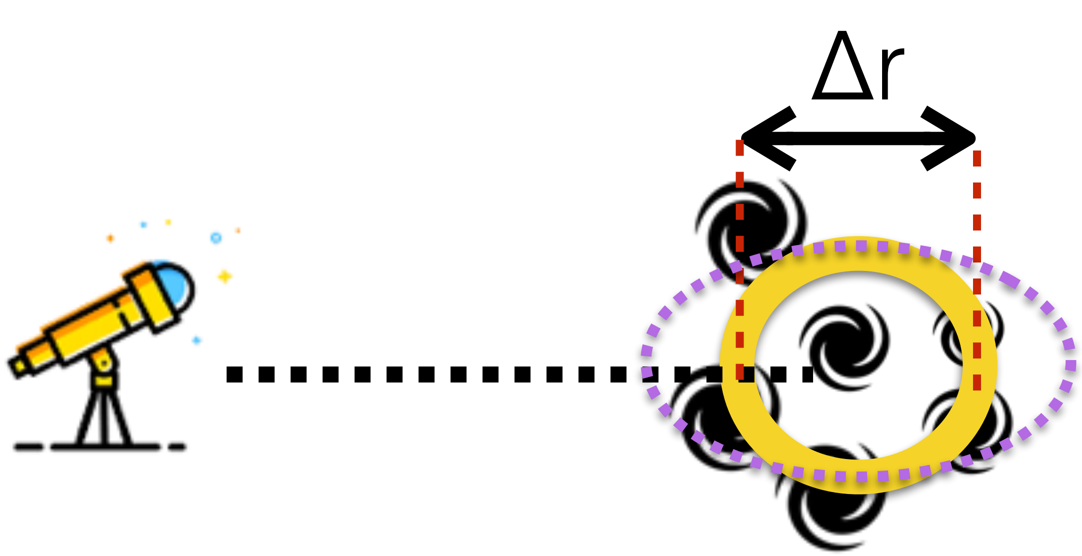
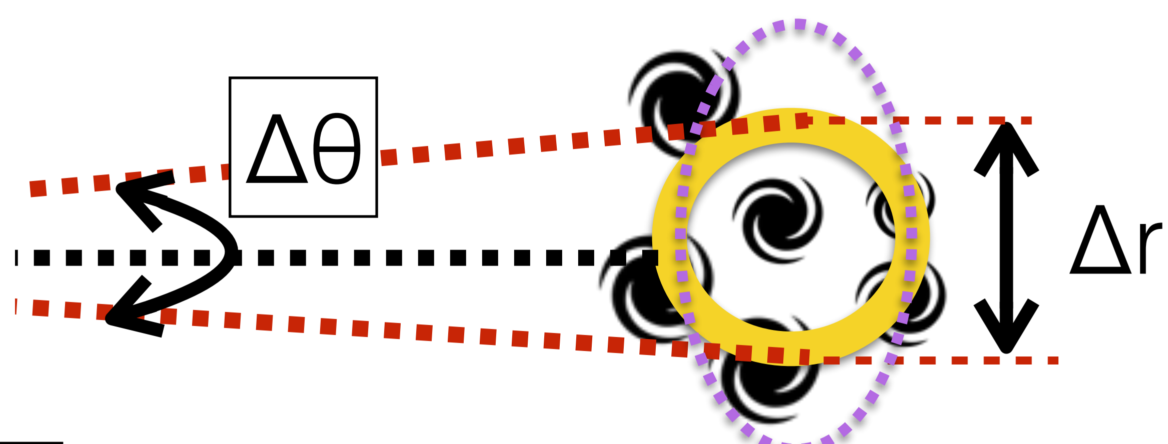
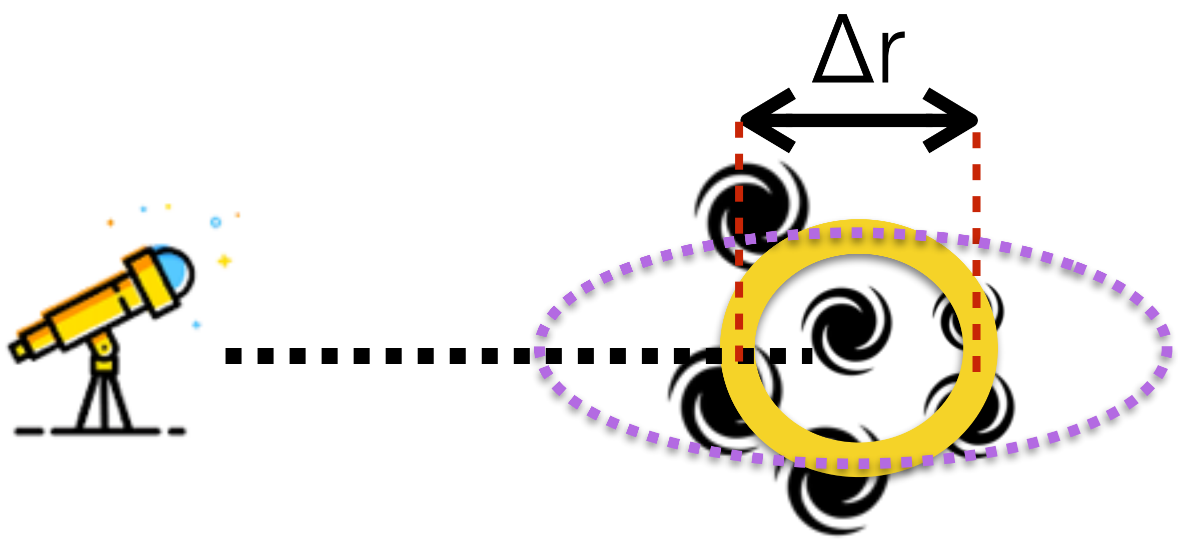




cluster is modified along both directions

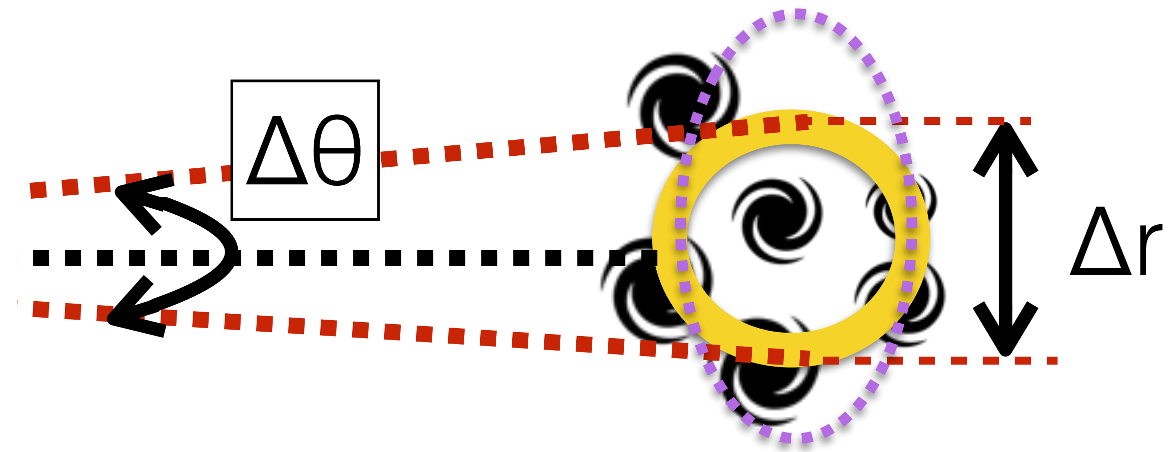
Radial distance

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



Angular diameter distance

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



$$k_{\parallel}=\alpha_{\parallel}k_{\parallel}' \rightarrow \alpha_{\parallel}=\frac{r_s^{fid}H^{fid}}{r_s H}$$

$$k_{\perp}=\alpha_{\perp}k_{\perp}' \rightarrow \alpha_{\perp}=\frac{D_A/r_s}{D_A^{fid}/r_s^{fid}}$$

new variables →

$$\alpha_V=\sqrt[3]{\alpha_{\perp}^2\alpha_{\parallel}}$$ Isotropic dilation

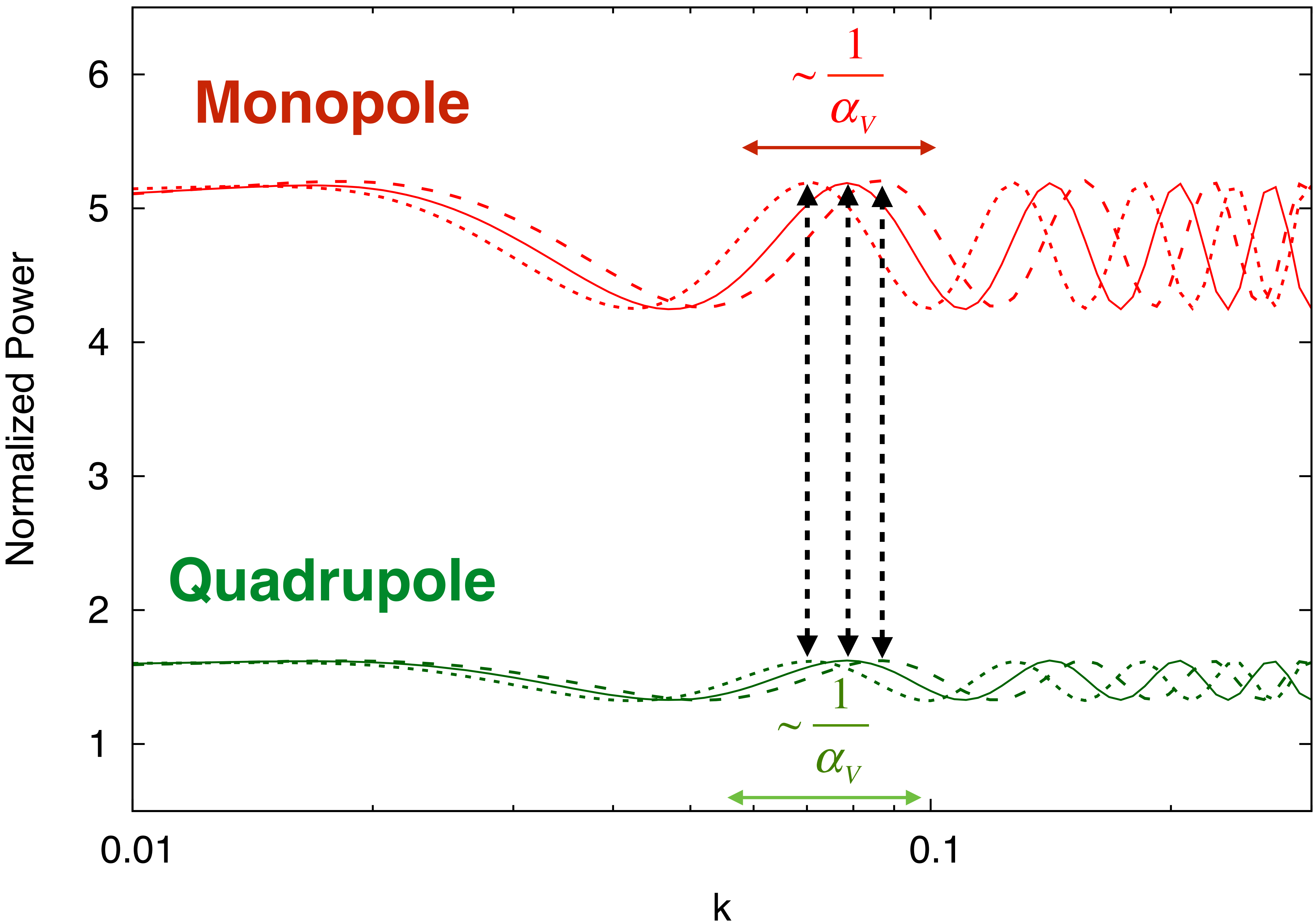
$$\alpha_{\varepsilon}=\alpha_{\perp}/\alpha_{\parallel}$$ AP-effect

α_V modify the k vector in the monopole

α_{ε} generates an anisotropy (distort symmetric 3D-features along and across the LOS)

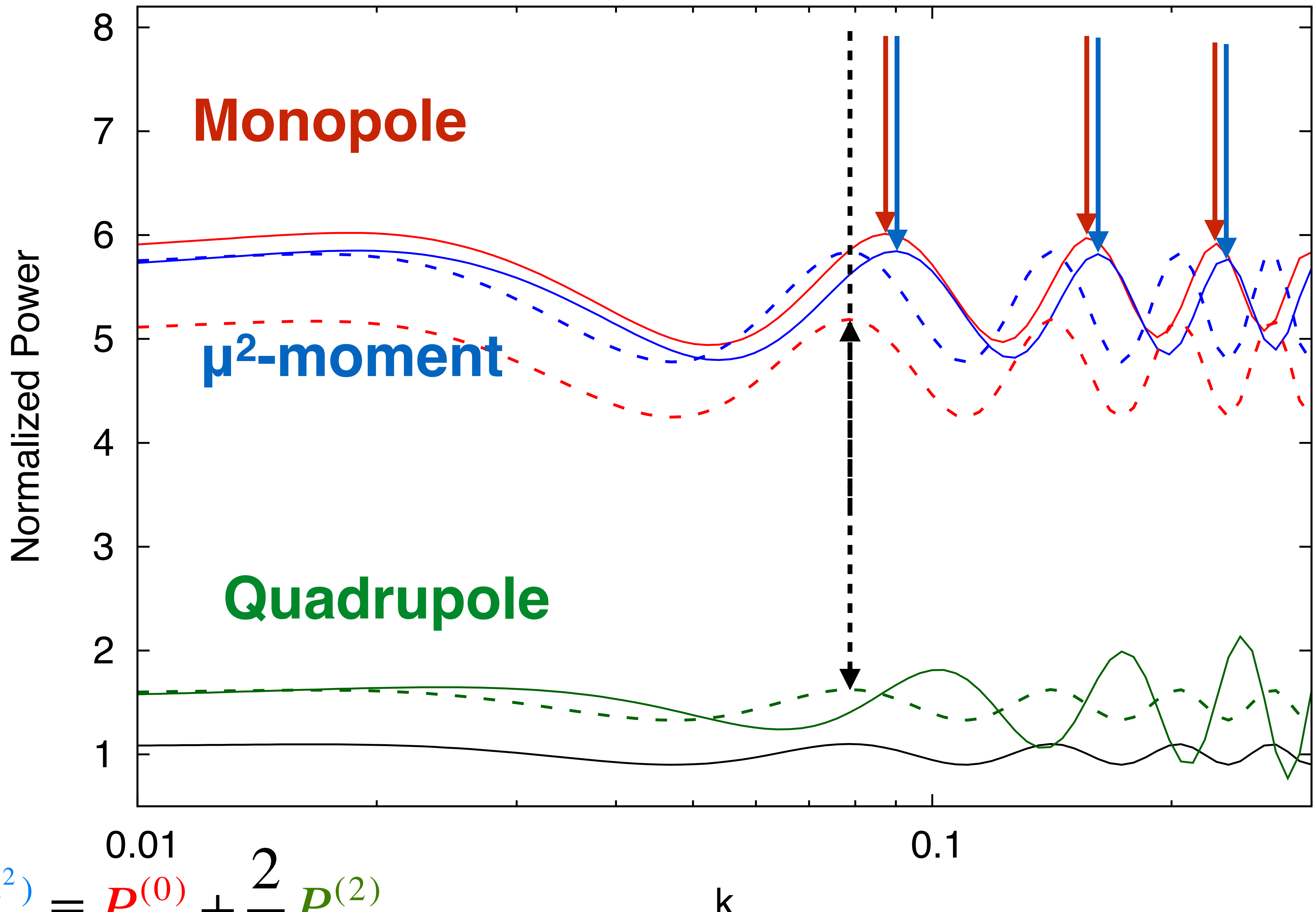
Physical Interpretation

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



Physical Interpretation

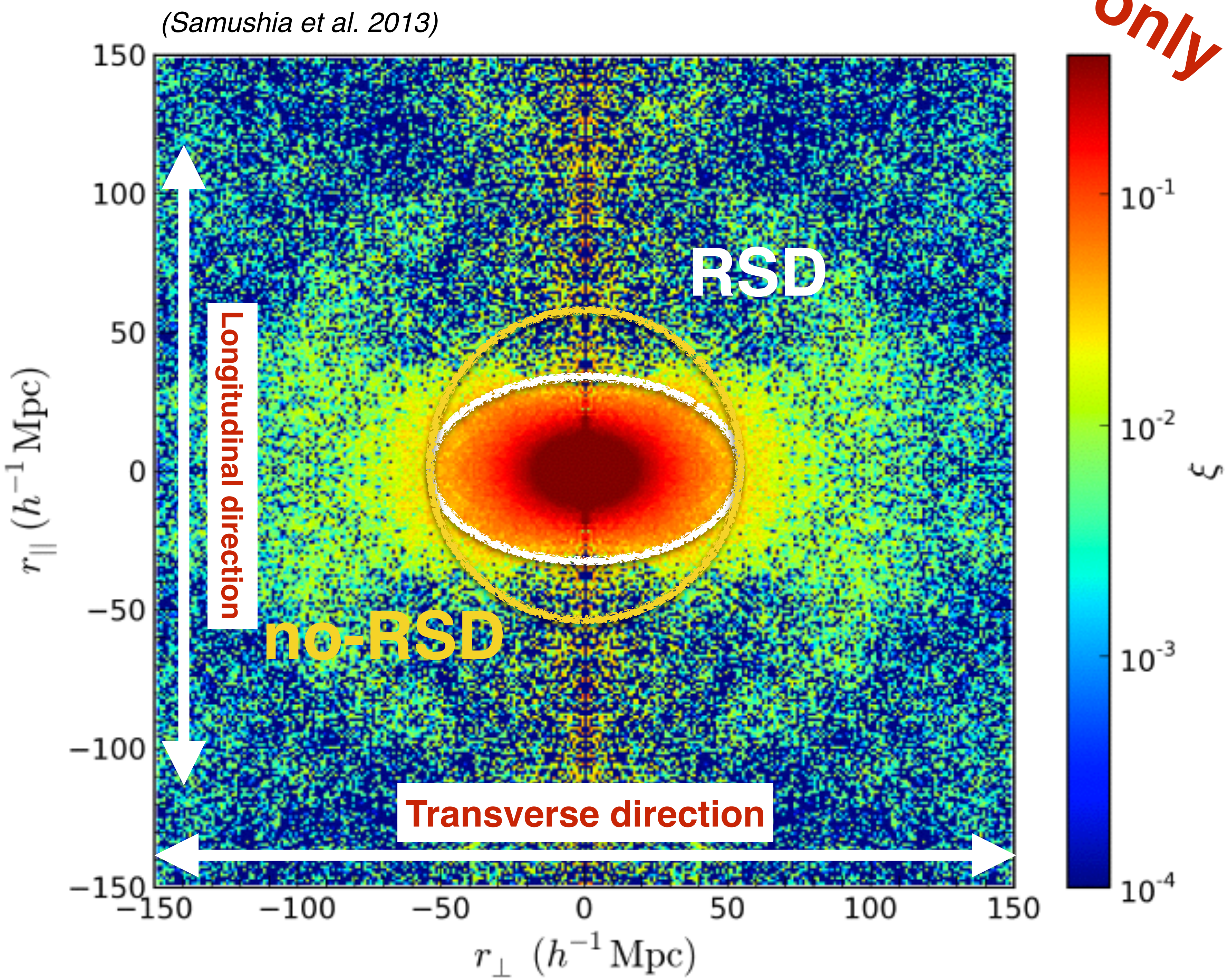
$\alpha_{\varepsilon} \sim D_A H$



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

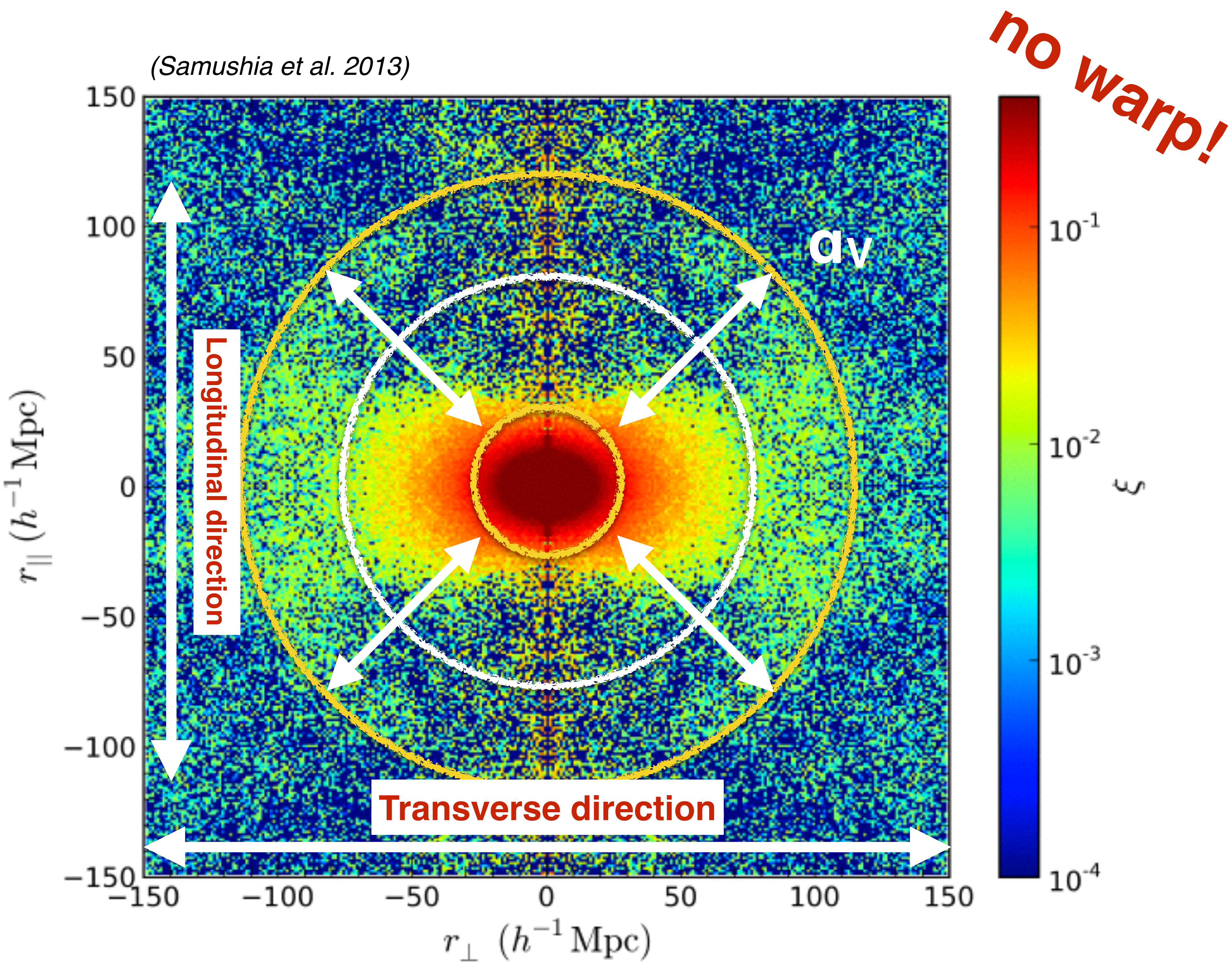
Physical Interpretation

LOS-only effect!

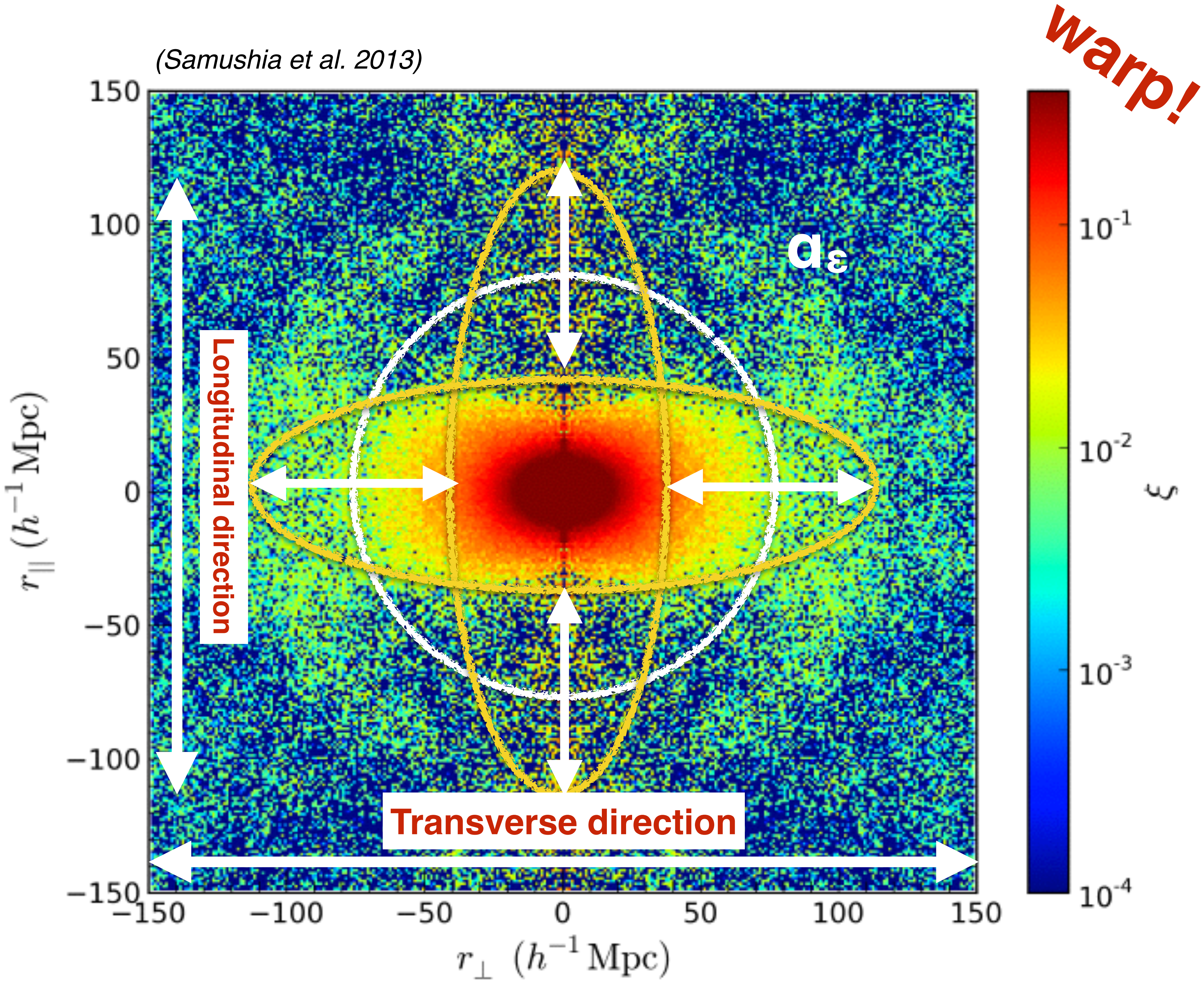


Physical Interpretation

(Samushia et al. 2013)



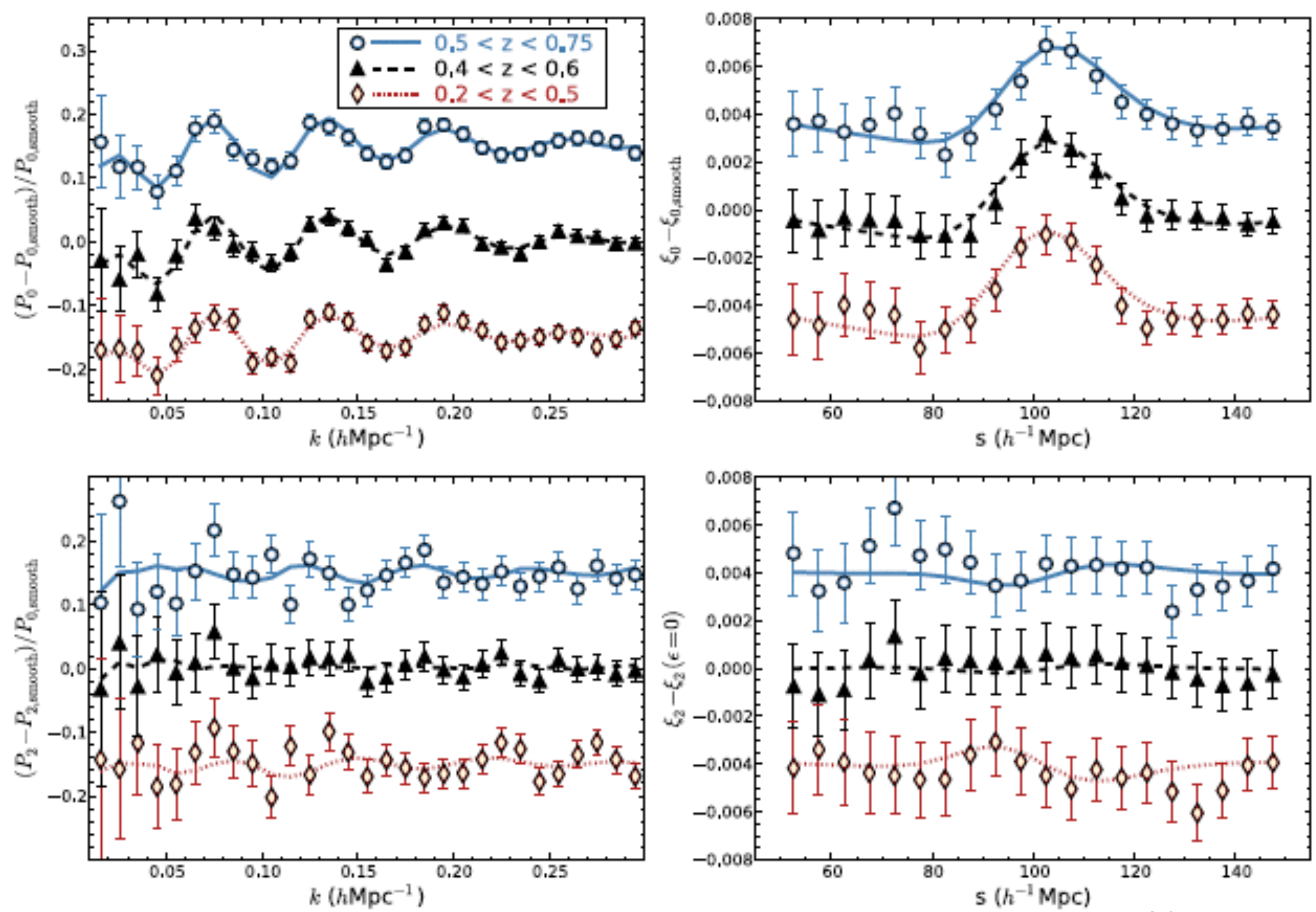
Physical Interpretation



RSD & AP are degenerated!

LRGs BAO/RSD from BOSS

Power Spectrum   Correlation Function



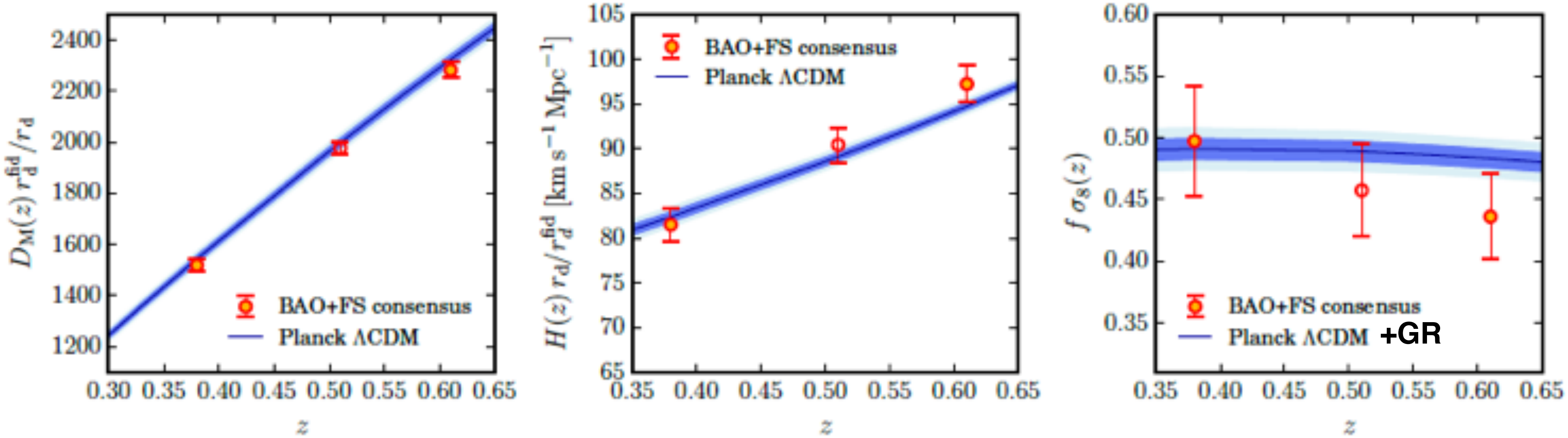
3overlapping z-bins

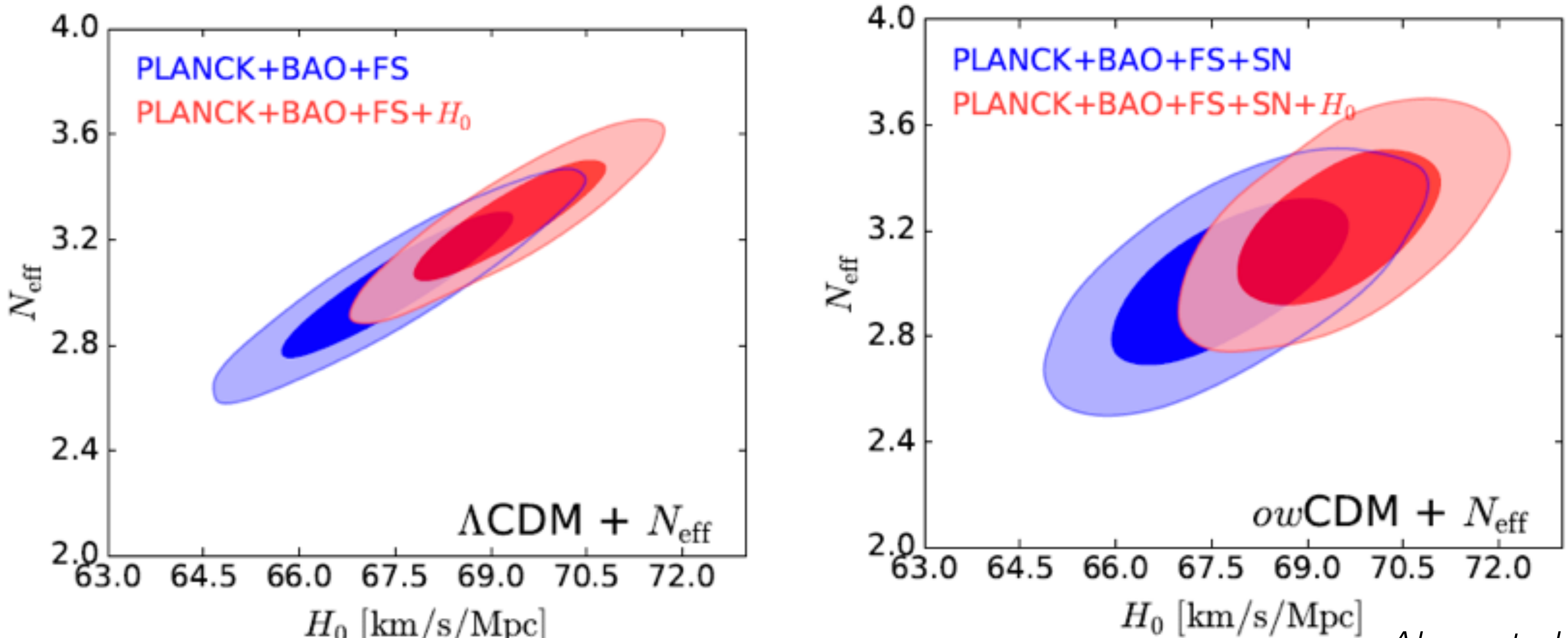
0.2<z<0.5
0.4<z<0.6
0.5<z<0.75

Alam et al. 2016

Type of analyses:

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

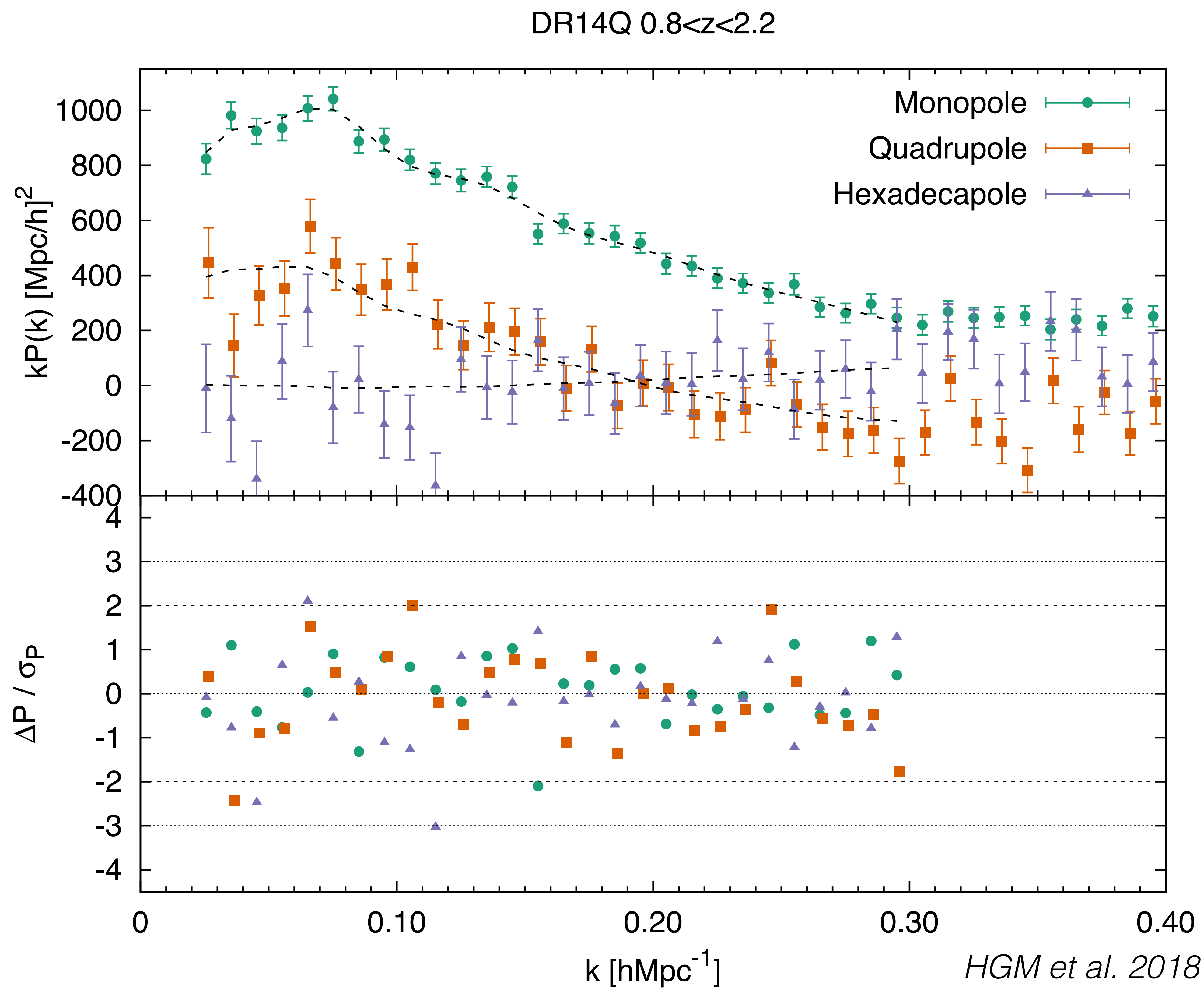




$H_0 = 73.0 \pm 1.8\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ measurement of Riess et al.

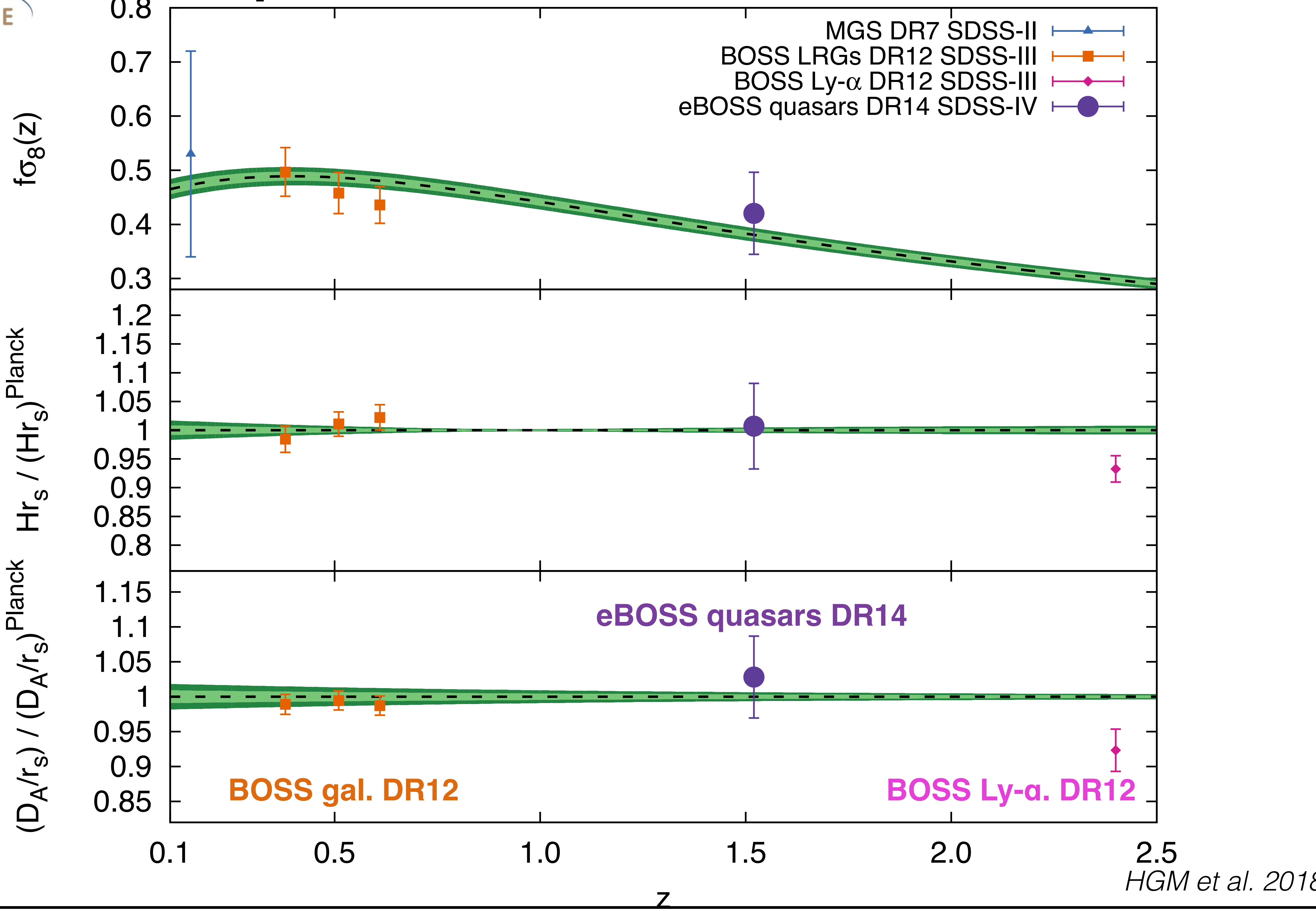
Alam et al. 2016

quasar BAO/RSD from eBOSS

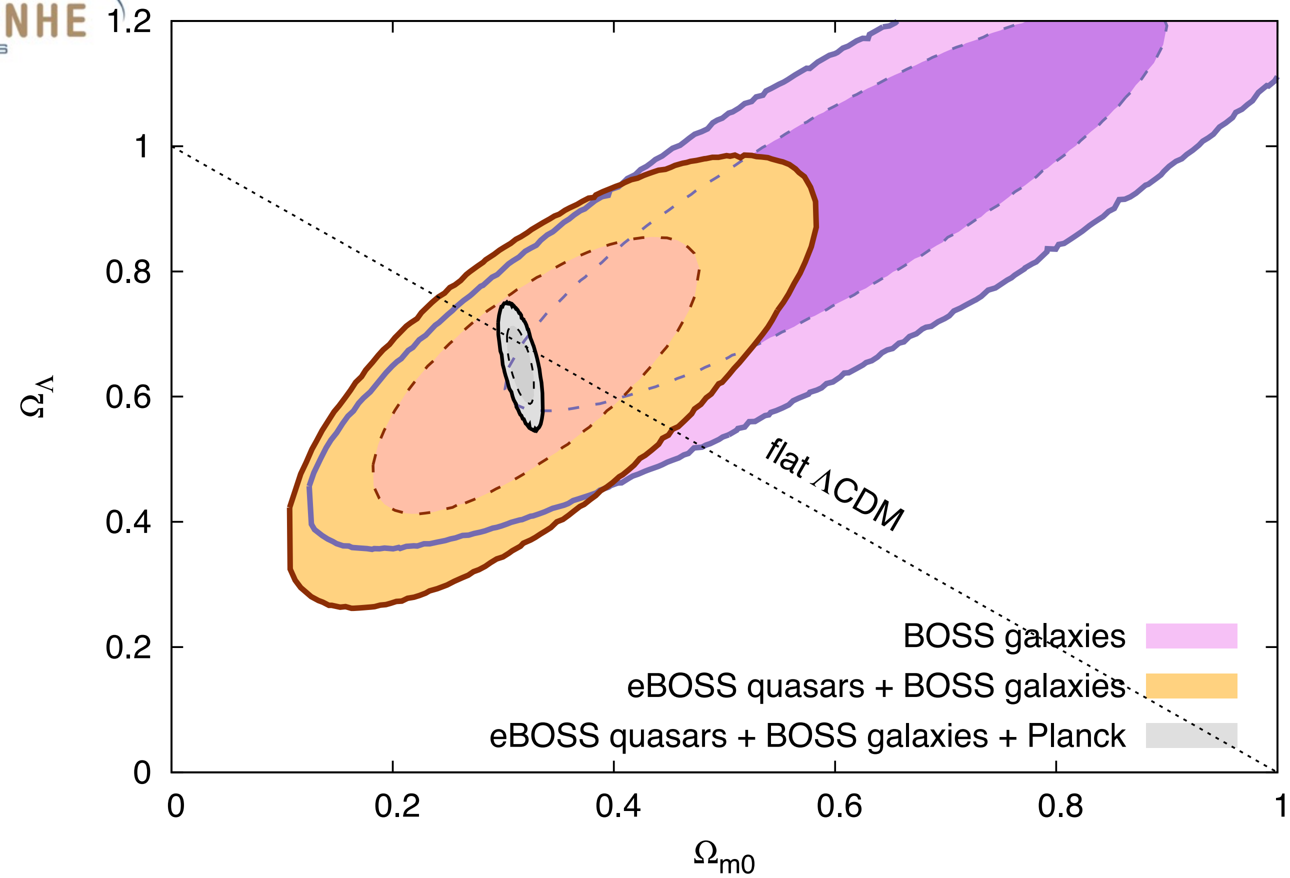


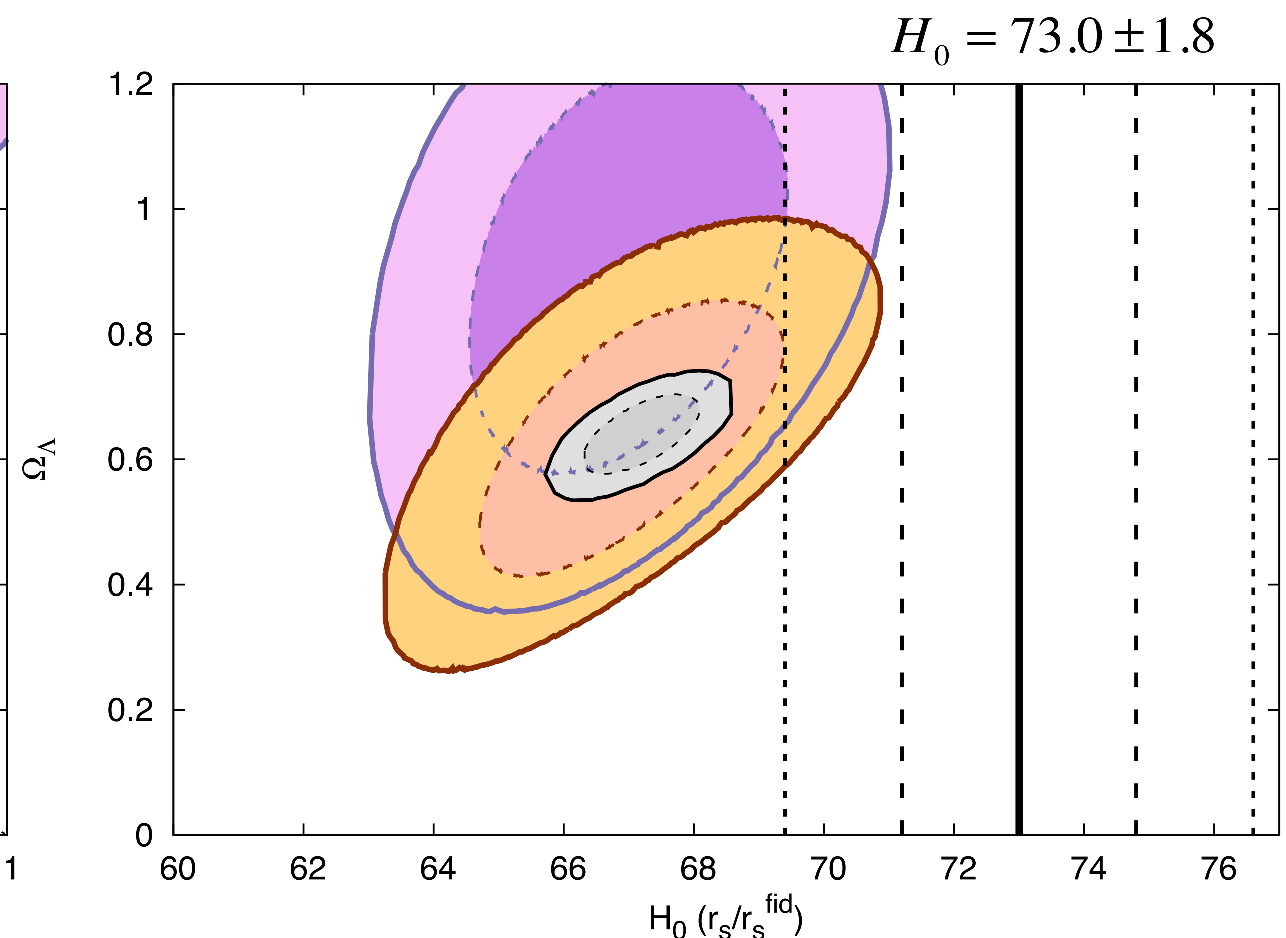
HGM et al. 2018

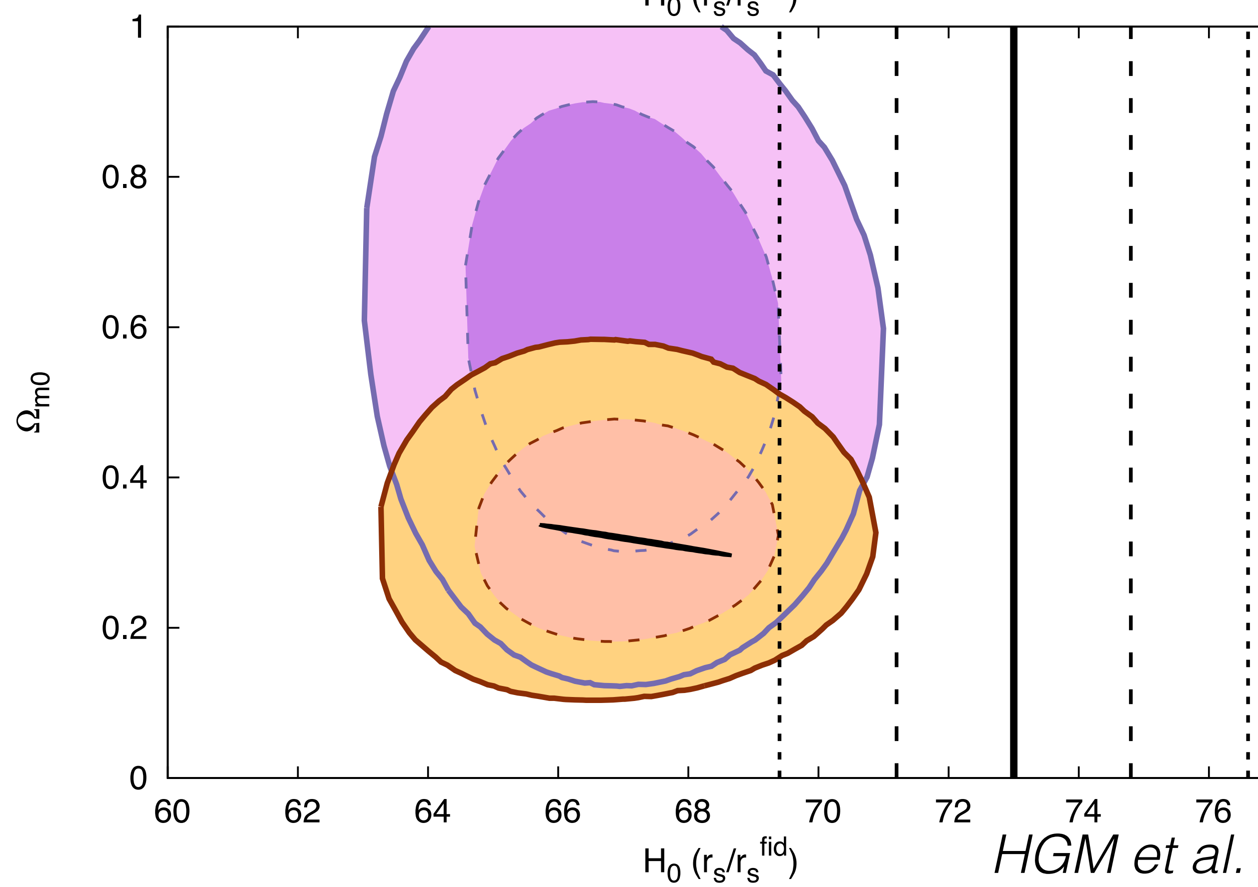
quasar BAO/RSD from eBOSS



Tensions with H_0







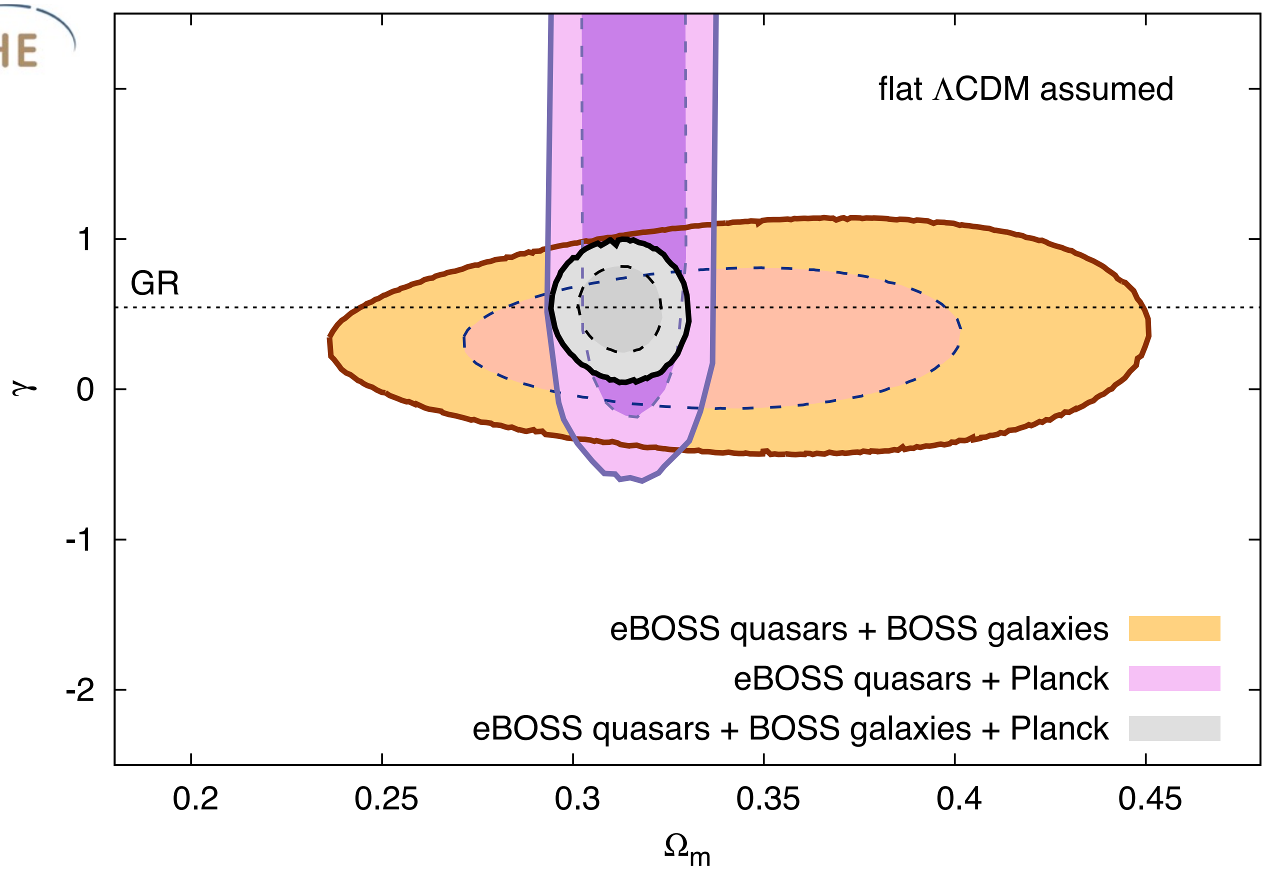
HGM et al. 2018

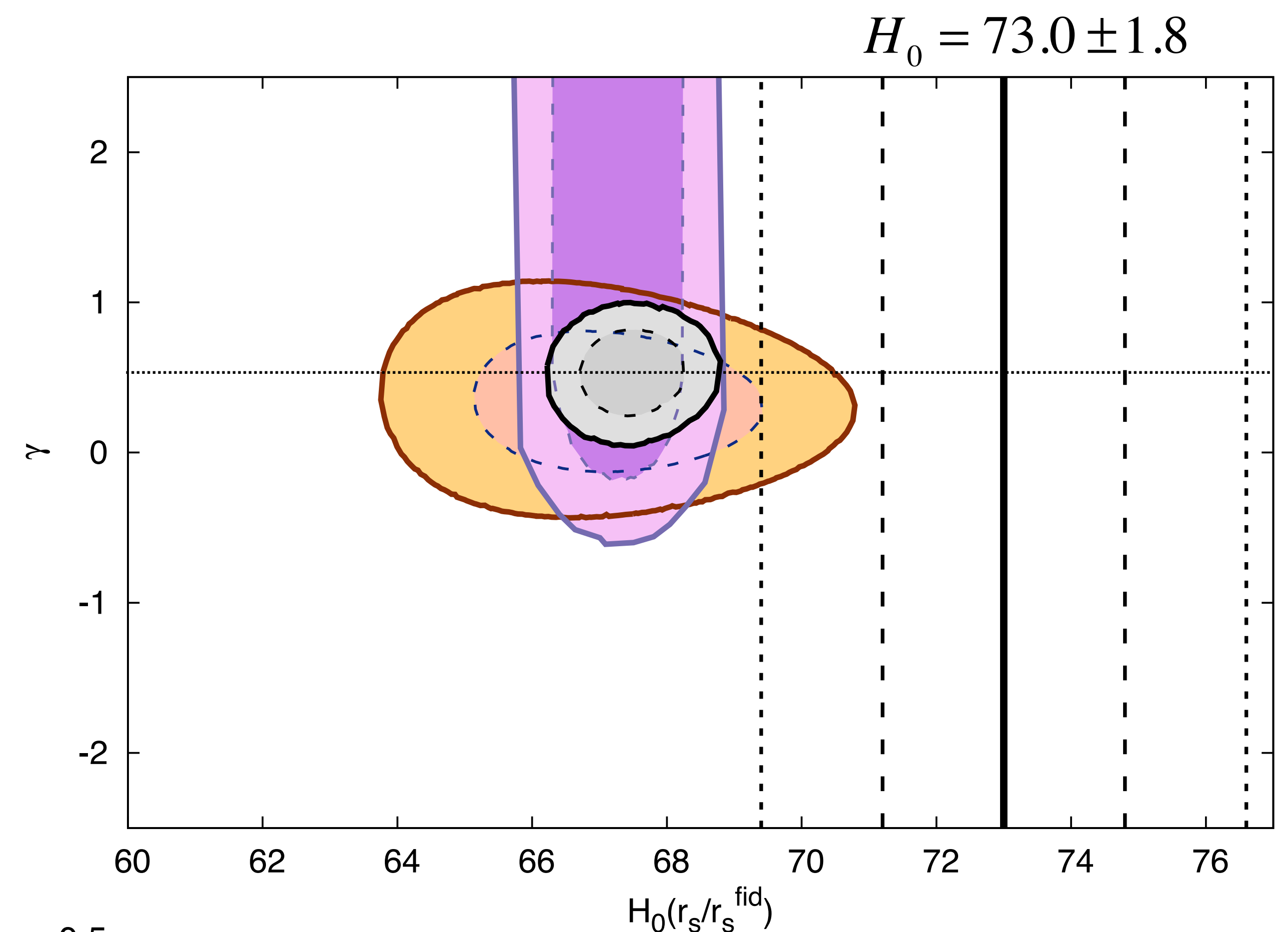
GR & ΛCDM assumed

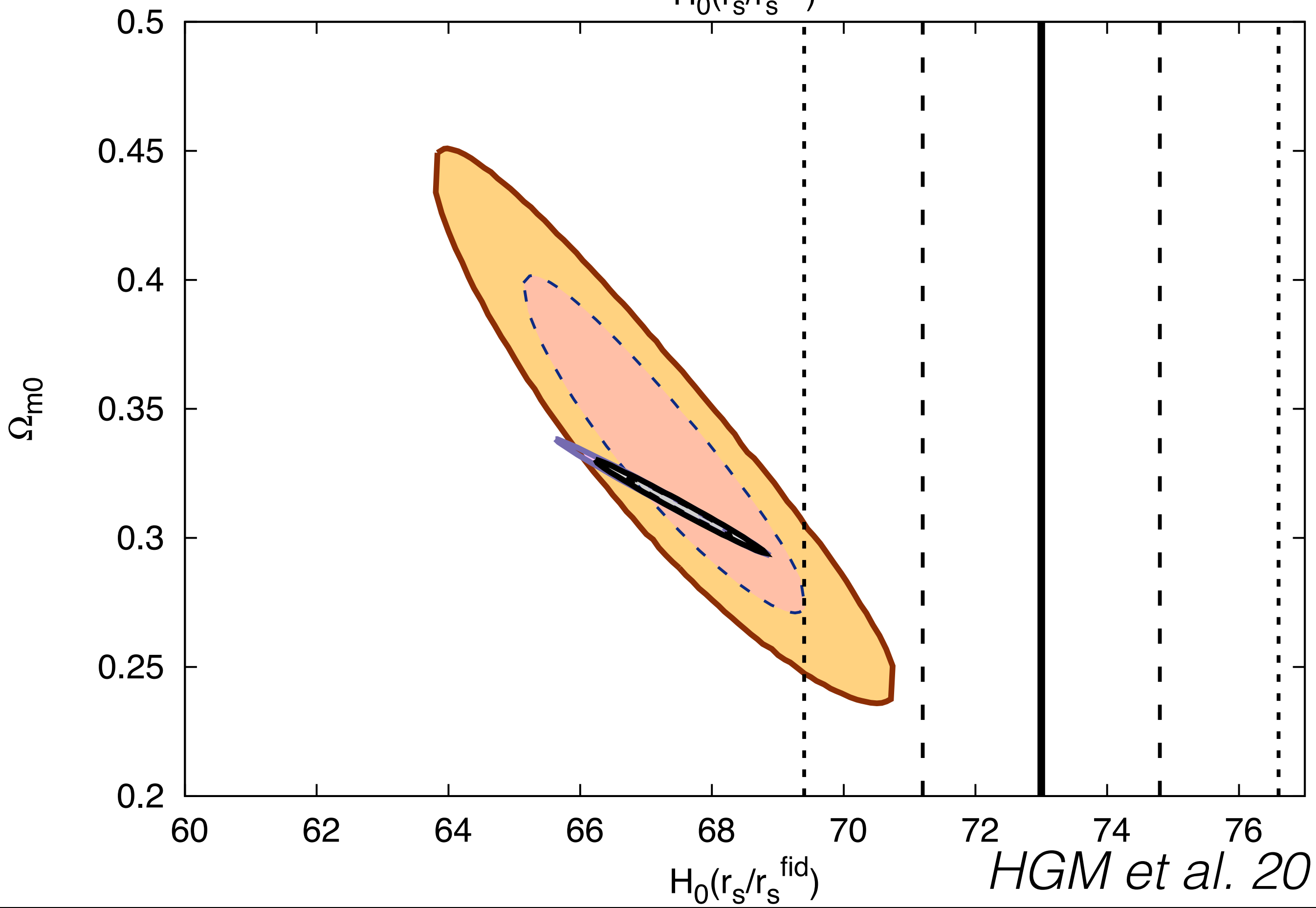
relax flatness

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

Tensions with H_0







HGM et al. 2018

flatness & ΛCDM assumed

relax GR

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

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 $0.8<z<2.2$

- If r_s taken from Planck or BBN, $H(z)r_s$ from eBOSS+BOSS galaxies in agreement with Planck+LCDM ('tension' with cosmic ladder at $\sim 3\sigma$)

- This disagreement doesn't reduce when flatness, GR, $N_{eff}=3$ conditions are relaxed

- 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

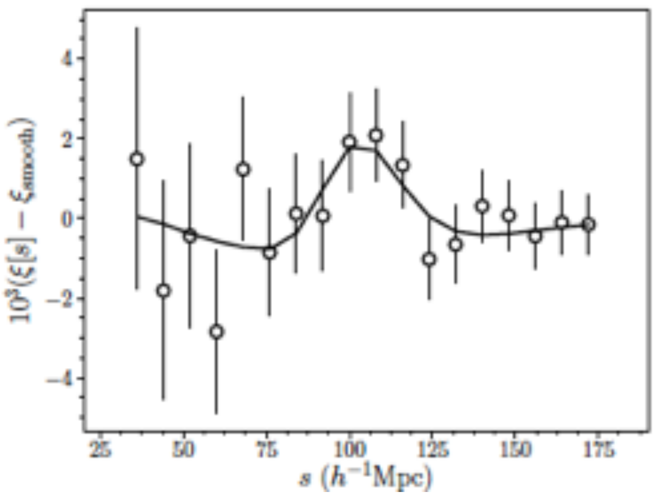
- Ly-α BAO at z=2.4 at 2.3σ from Planck (see next talk by Andreu)

- DESI will deliver more precise results within 5yr from now.

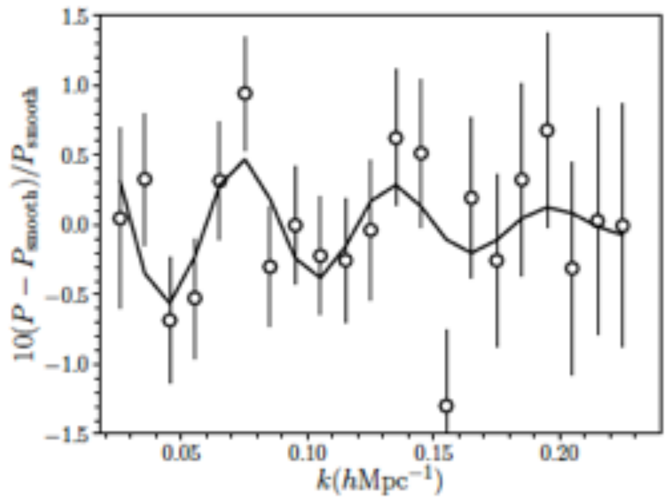
Back up slides

DR14Q BAO results

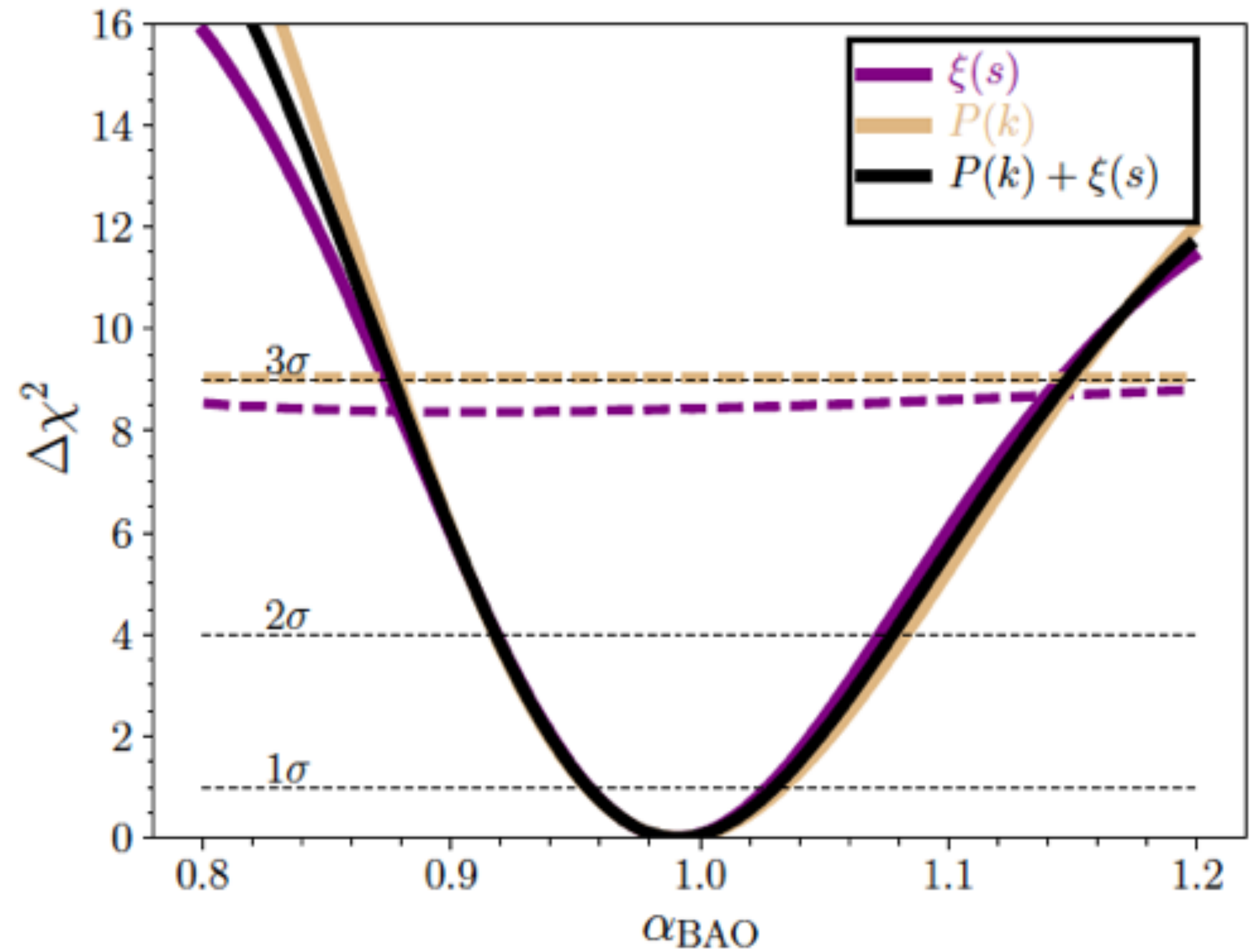
Correlation Function

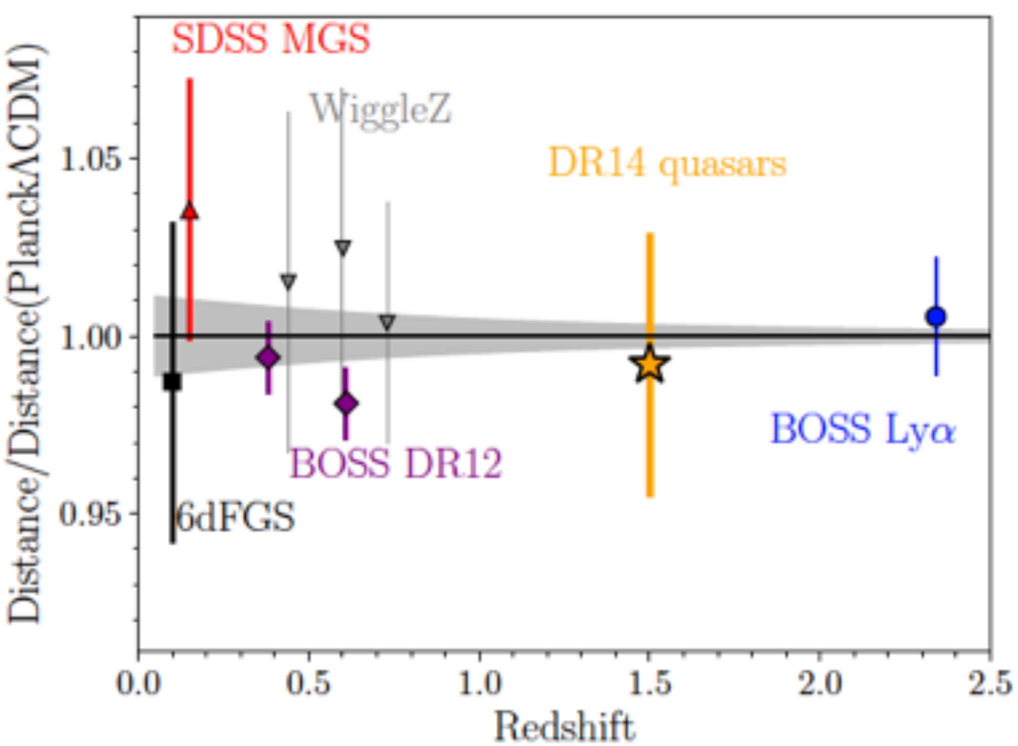


Power Spectrum



Significance of BAO peak





- Correlation factor ρ=0.97
- 3σ detection
- In good agreement with Planck+GR
- $D_V(z=1.52)=3843 \pm 147$ Mpc (3.8%)
- $\chi^2=6.2/13$ for ξ(R) and 27.7/33 for P(k)

Ata et al. 2017

Impact of potential systematics

BAO Systematics

- Very robust
- ~0.1% non-linear shift at z=1.5
- relative velocity between DM & bar (?)
- Reconstruction assumptions (bias and f)

RSD systematics

- model dependent
- Intrinsic alignments
- failures & collisions

Impact of systematics

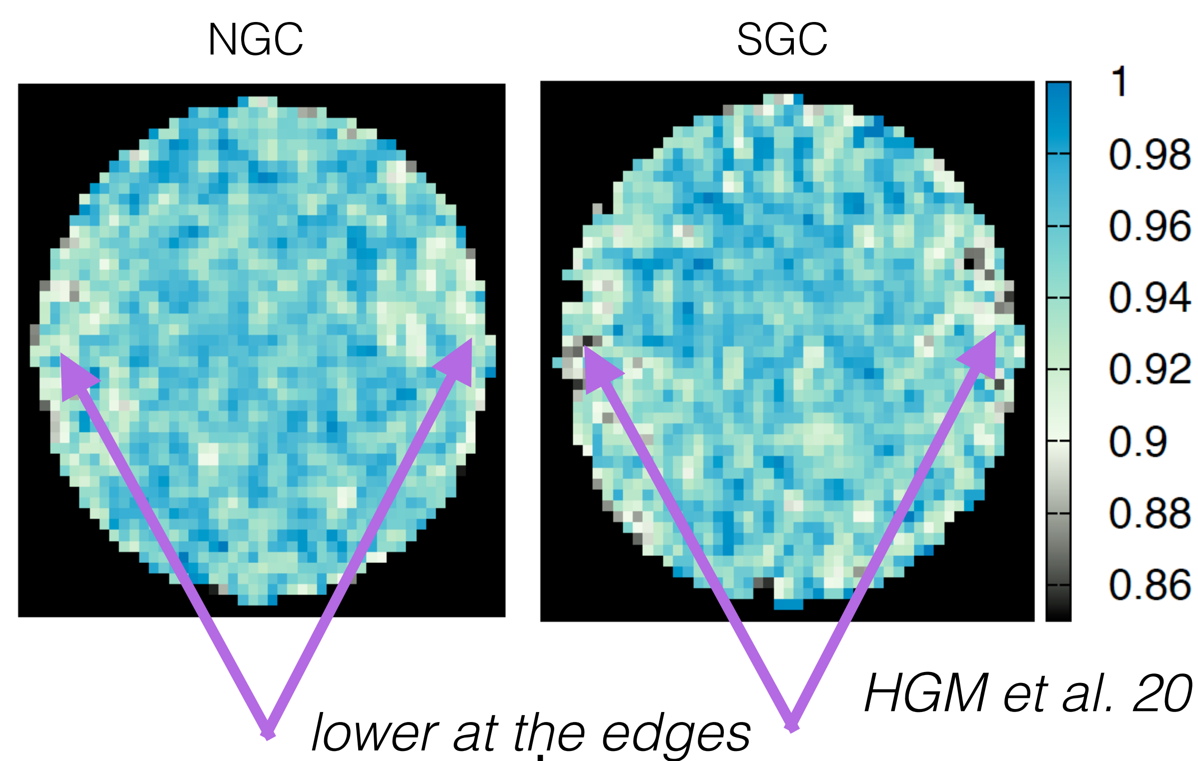
- **Redshift Failures:** *i)* Weight the nearest neighbour (NN), use in BOSS analysis. *ii)* Weight all observed galaxies by their position in the plate,

$$w_{spec}(x_{foc}, y_{foc}) \sim \frac{1}{P_{sucess}(x_{foc}, y_{foc})}$$

- **Collision Pairs:** Traditional nearest neighbour weighting (NN)

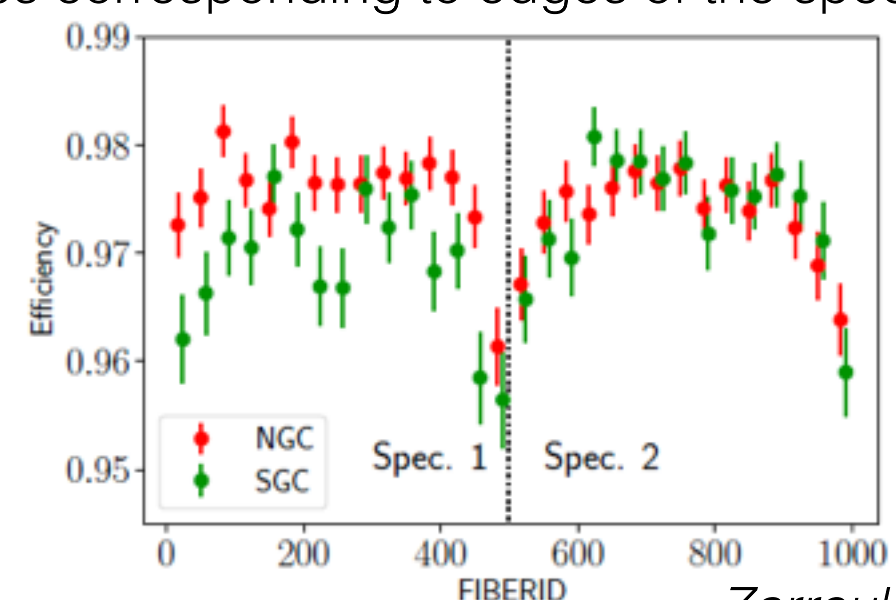
Imprint such effects on the mocks and check how these correction schemes perform

Redshift efficiency pattern en eBOSS DR14Q



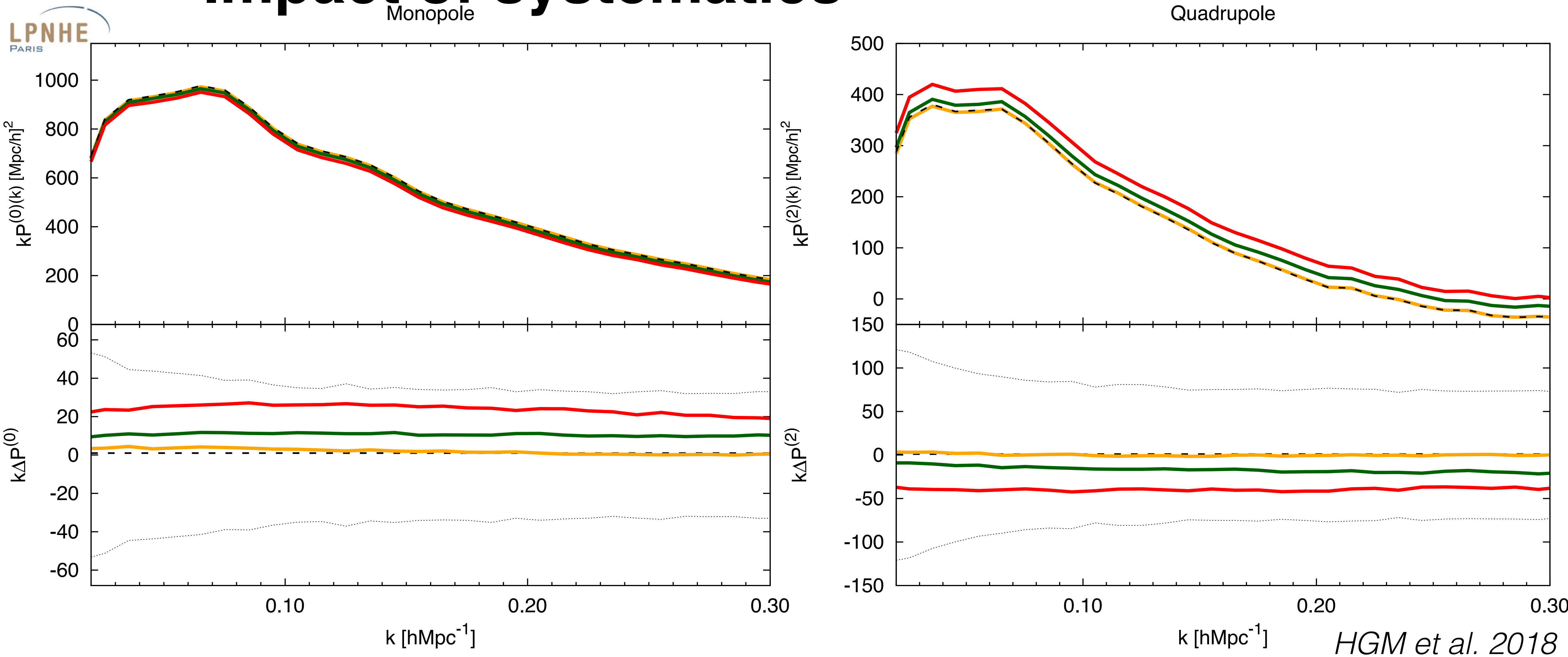
HGM et al. 2018

Fibres corresponding to edges of the spectrograph



Zarrouk et al. 2018

Impact of systematics



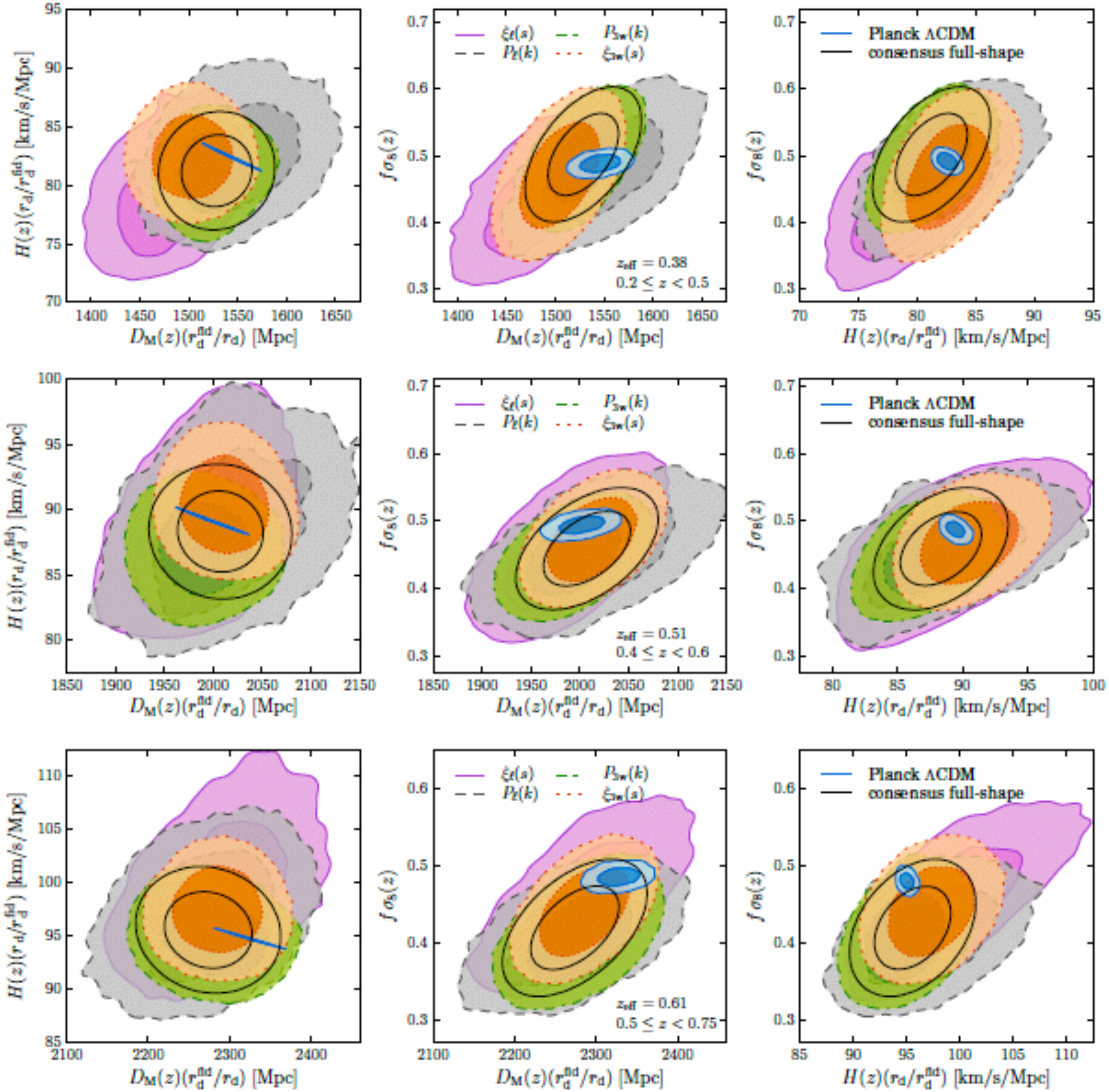
HGM et al. 2018

- - - - True signal (systematic effect not applied)

Corrected: redshift failures (focal weight) + close pairs (NN)

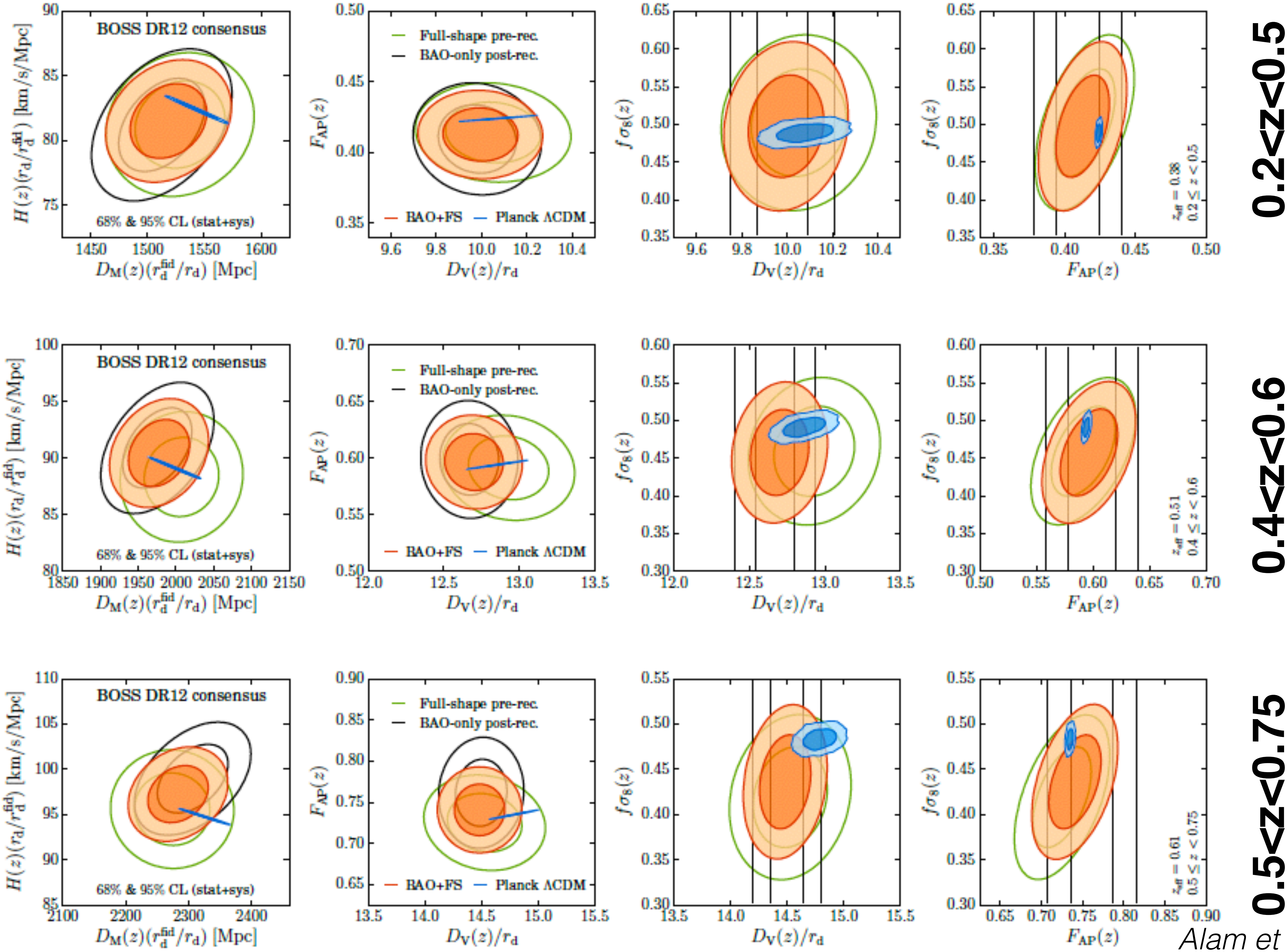
Corrected: redshift failures (NN) + close pairs (NN)

Corrected: redshift failures (focal weight) [close pairs not applied]

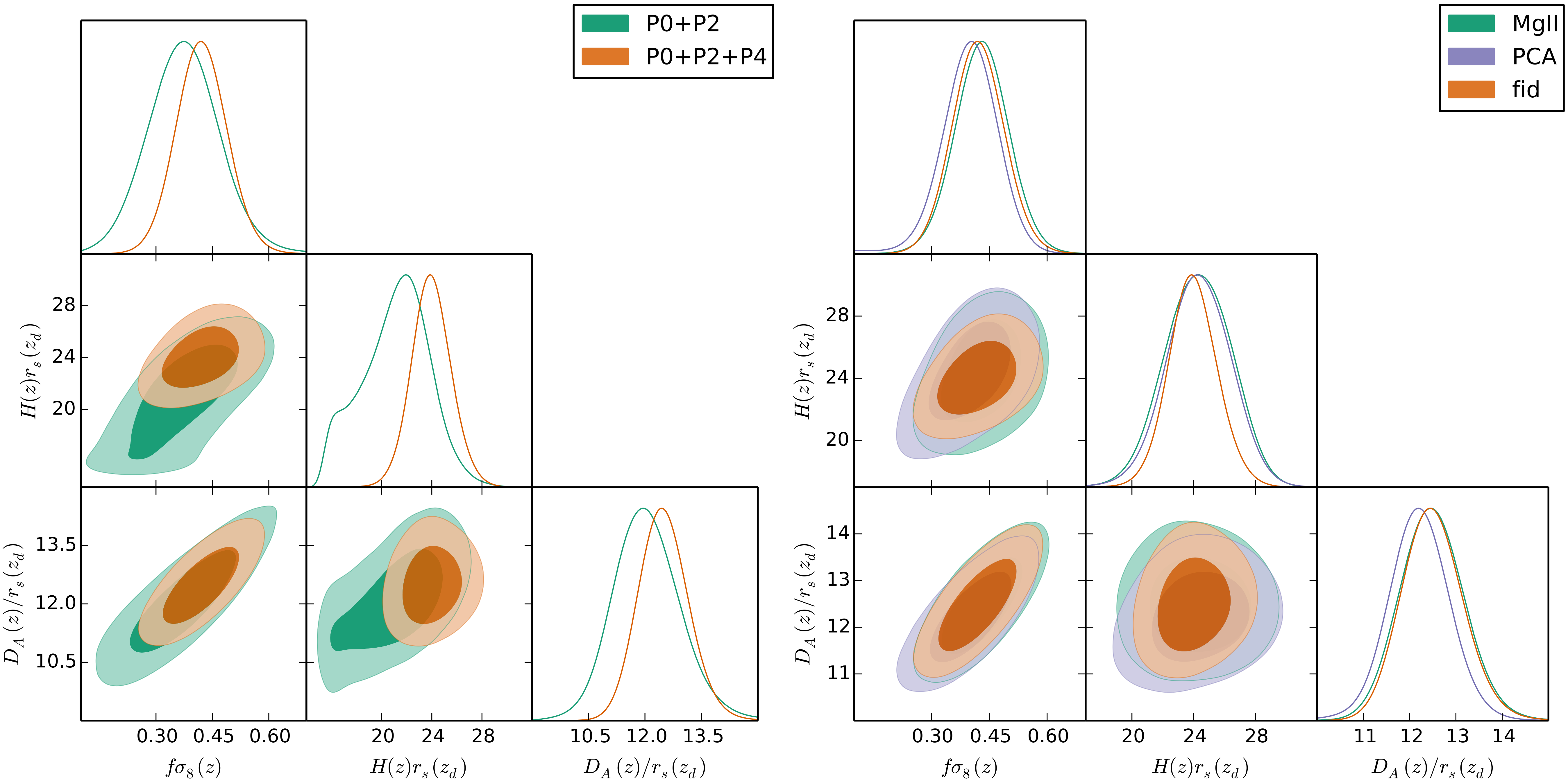


Alam et al. 2016

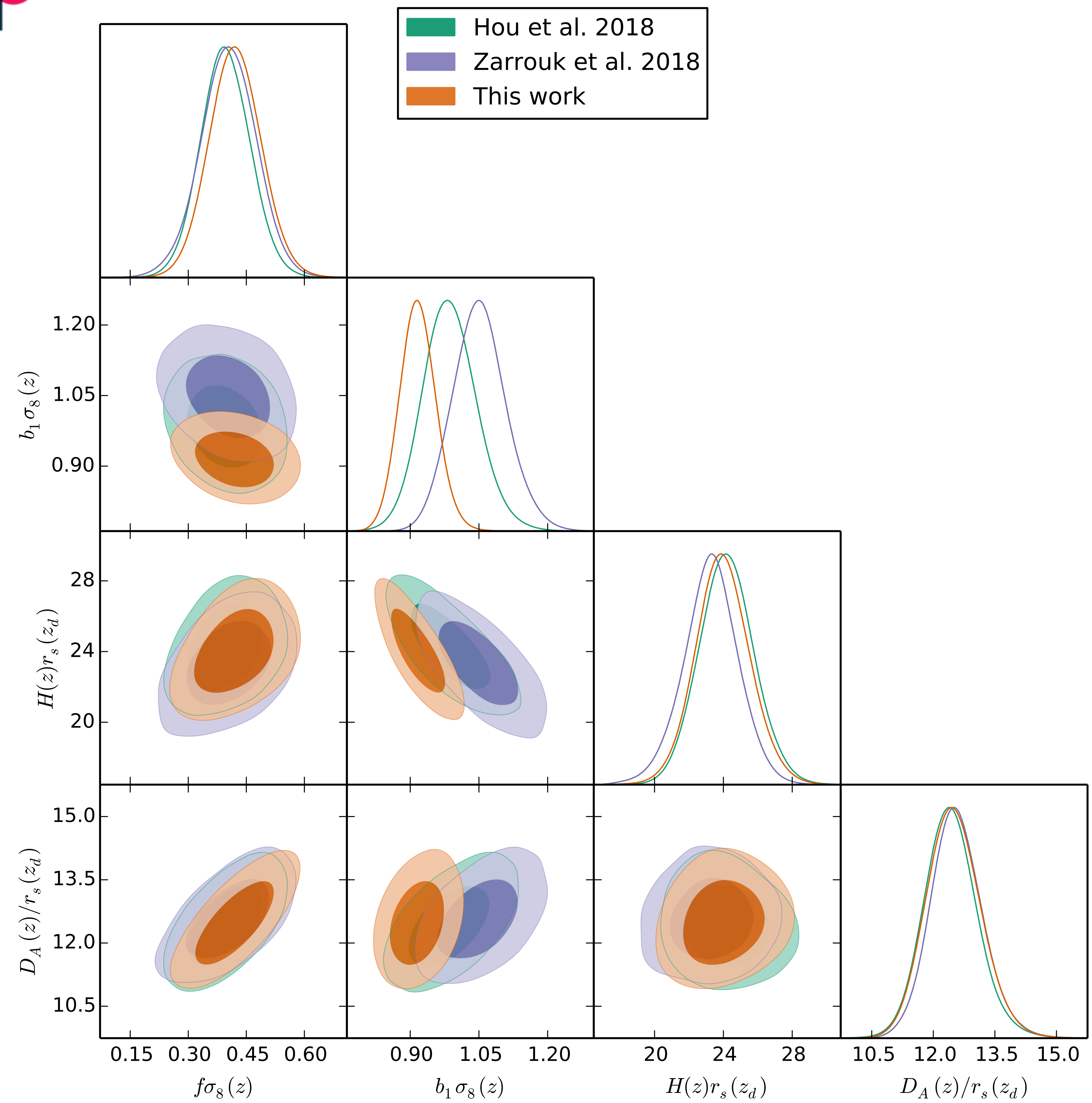
BAO post-recon RSD Full Shape pre-recon Consensus Planck



Alam et al. 2016



HGM et al. 2018



HGM et al. 2018