Cosmology with Spectroscopic Surveys: Past, Present and Future

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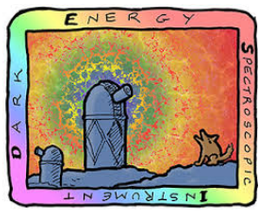
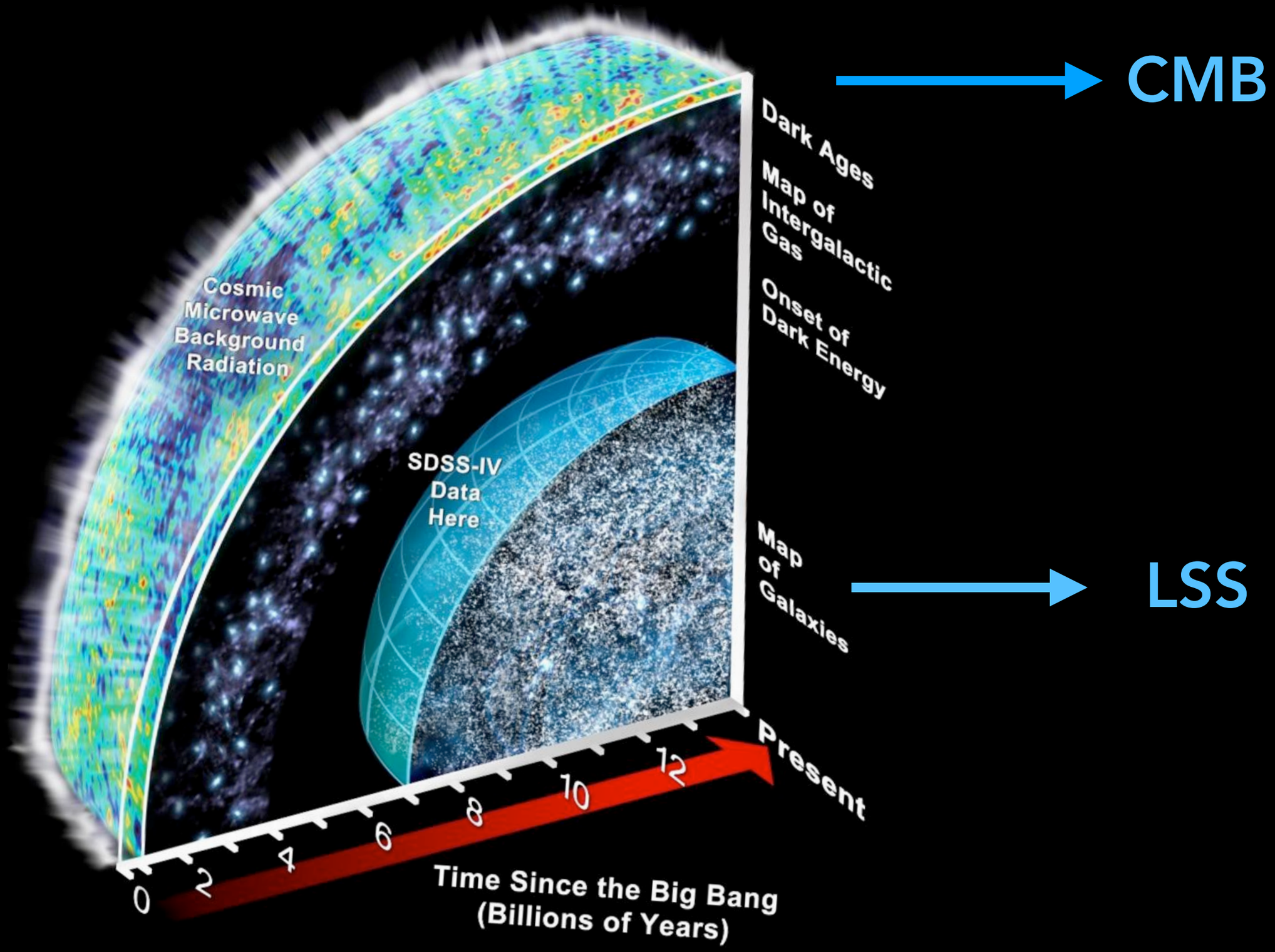


"la Caixa" Foundation


Cosmic Microwave Background Radiation
SDSS-IV Data Here
Dark Ages
Map of Intergalactic Gas
Onset of Dark Energy
Map of Galaxies
Present
0
2
4
6
8
10
12
Time Since the Big Bang (Billions of Years)
CMB
LSS

Baryon Acoustic Oscillations

Before recombination **After recombination**

at z~1100

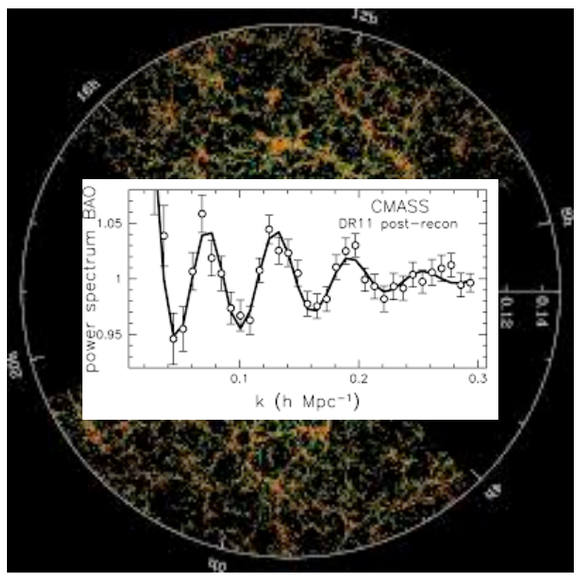
$p^+ + e^-$ H

Baryons+DM

Wave propagation frozen

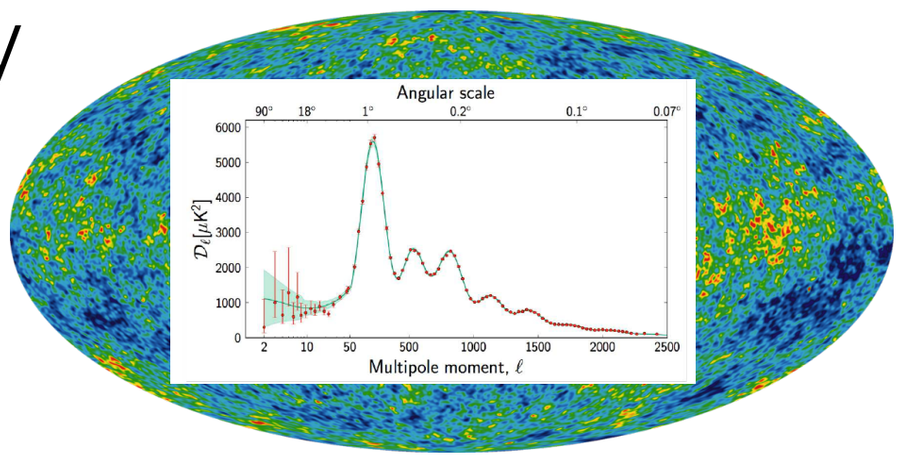
photons

Galaxies



CMB

- Physics in early Universe
- Accelerated expansion at late times

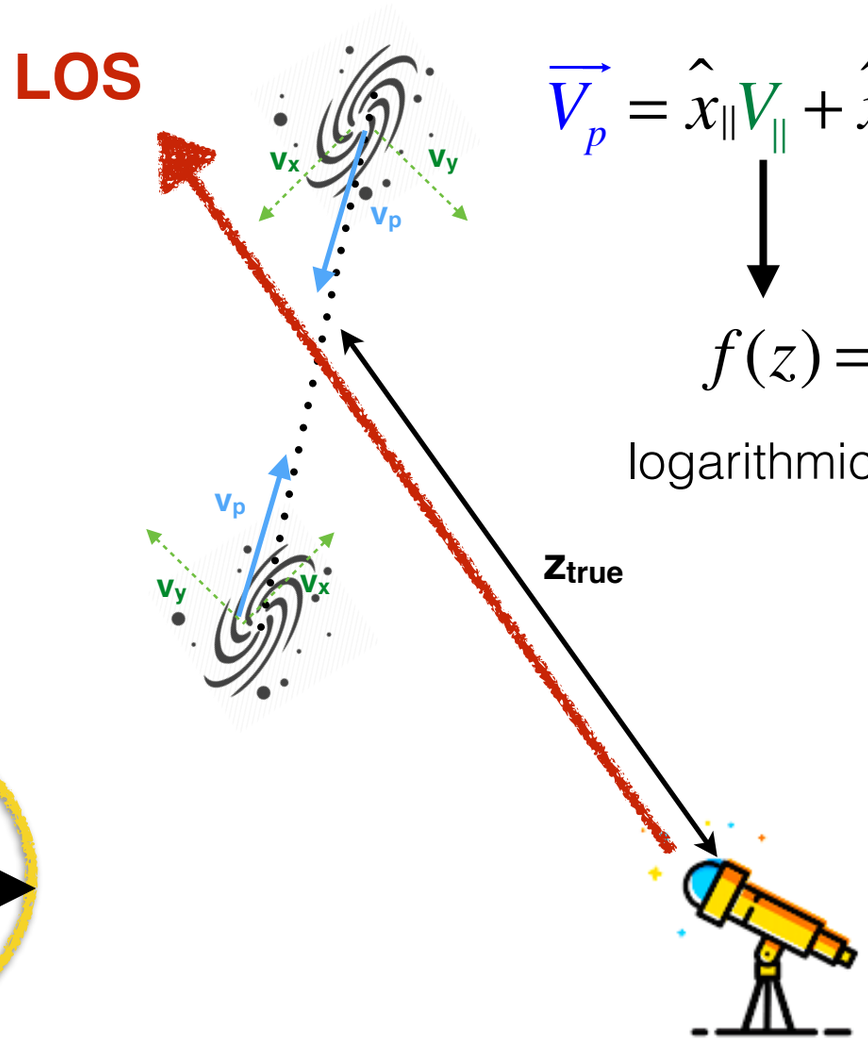


Redshift Space Distortions

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

Induces anisotropy but does not shift the BAO

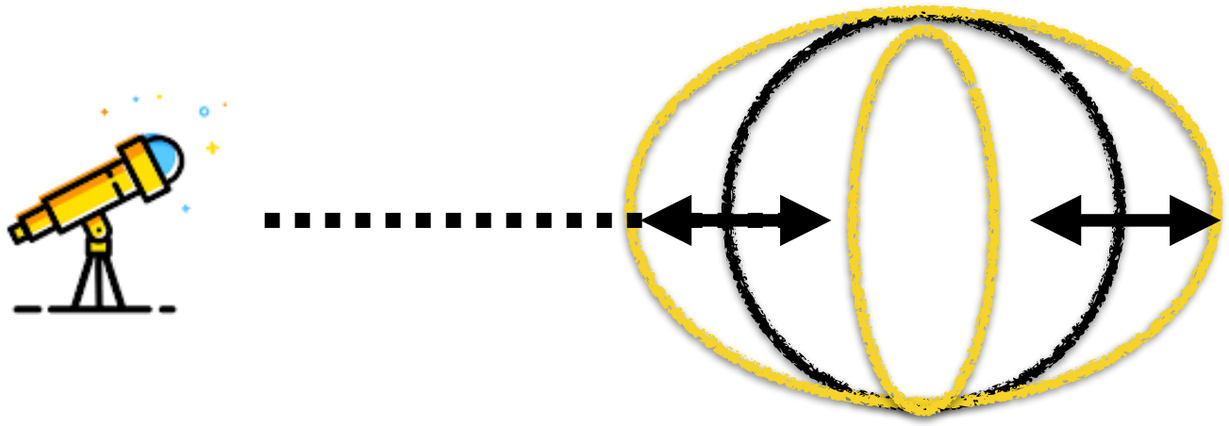
~ $f\sigma_8$



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

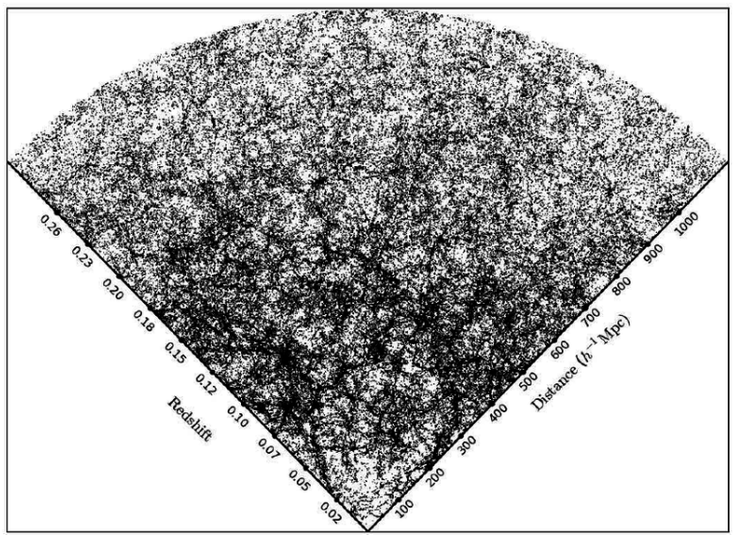
$$f(z) = \Omega_m(z)^{\gamma}$$

logarithmic growth of structure

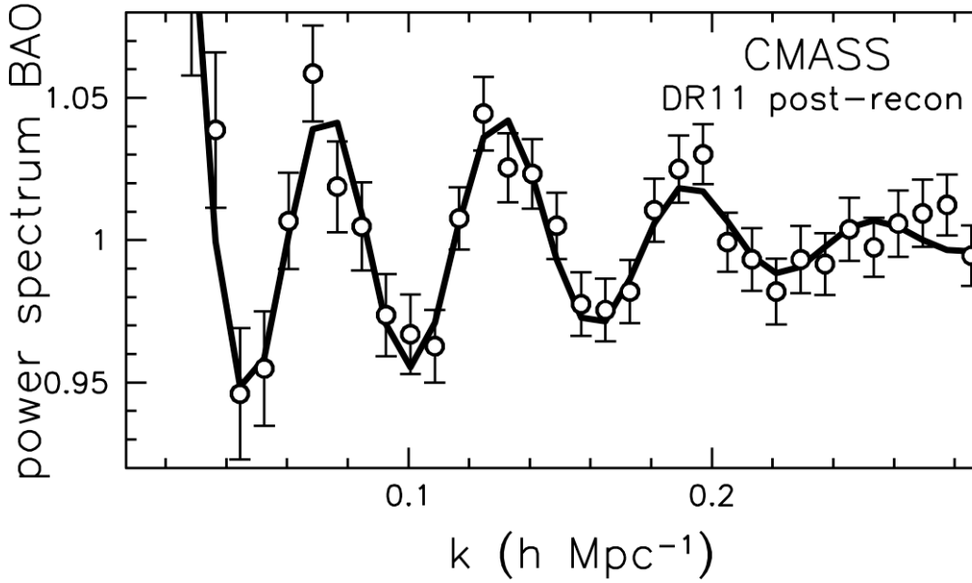


Clustering of Tracers: What do we measure?

Galaxy Catalogue



$$\Omega_{\text{fiducial}} \neq \Omega_{\text{true}}$$



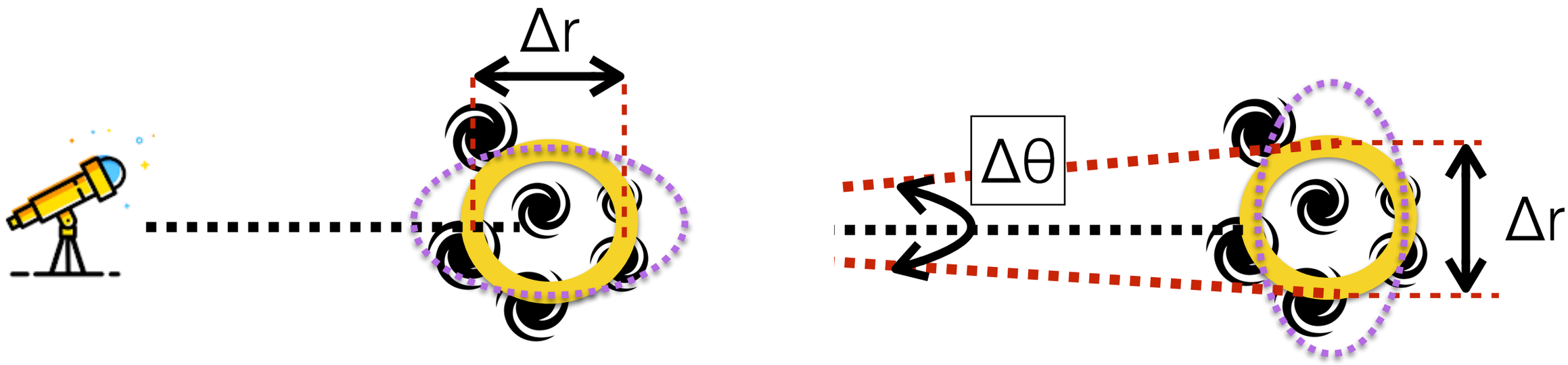
Distortions **along** and **across** the line of sight

Alcock-Paczynski effect

This effect distorts the homogeneity and isotropy of BAO as a function of Ω_{true} & Ω_{fiducial}

Alcock-Paczynski & Redshift Space Distortions

- **AP effect**: Anisotropy induced by transforming redshifts into coming distances assuming a *wrong cosmology*



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

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

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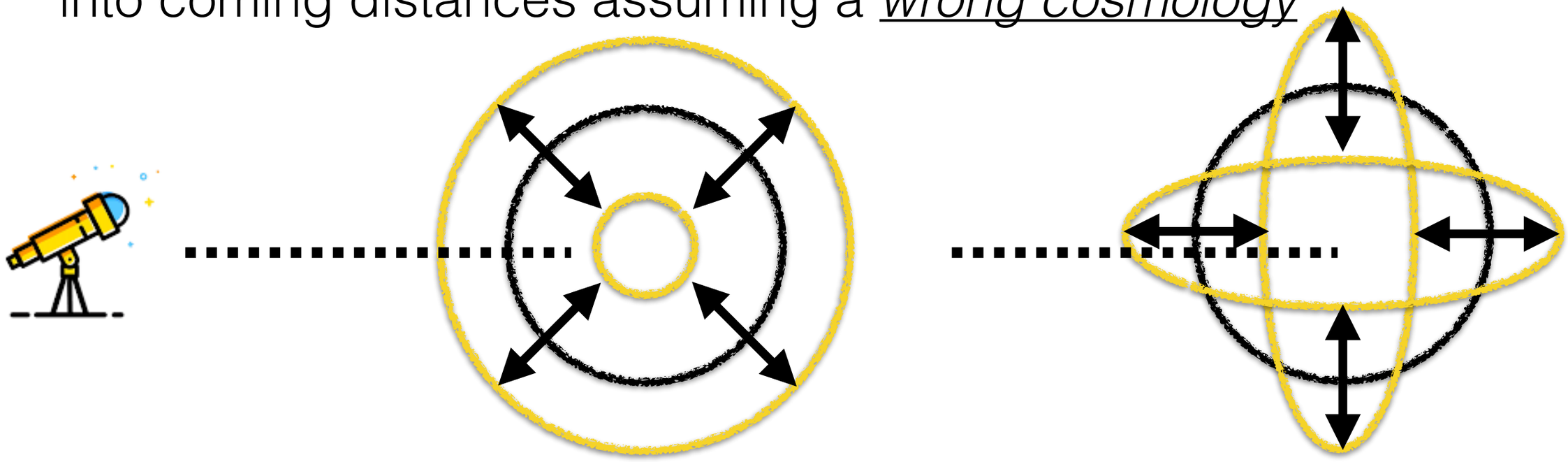


BAO shift, but no extra anisotropy

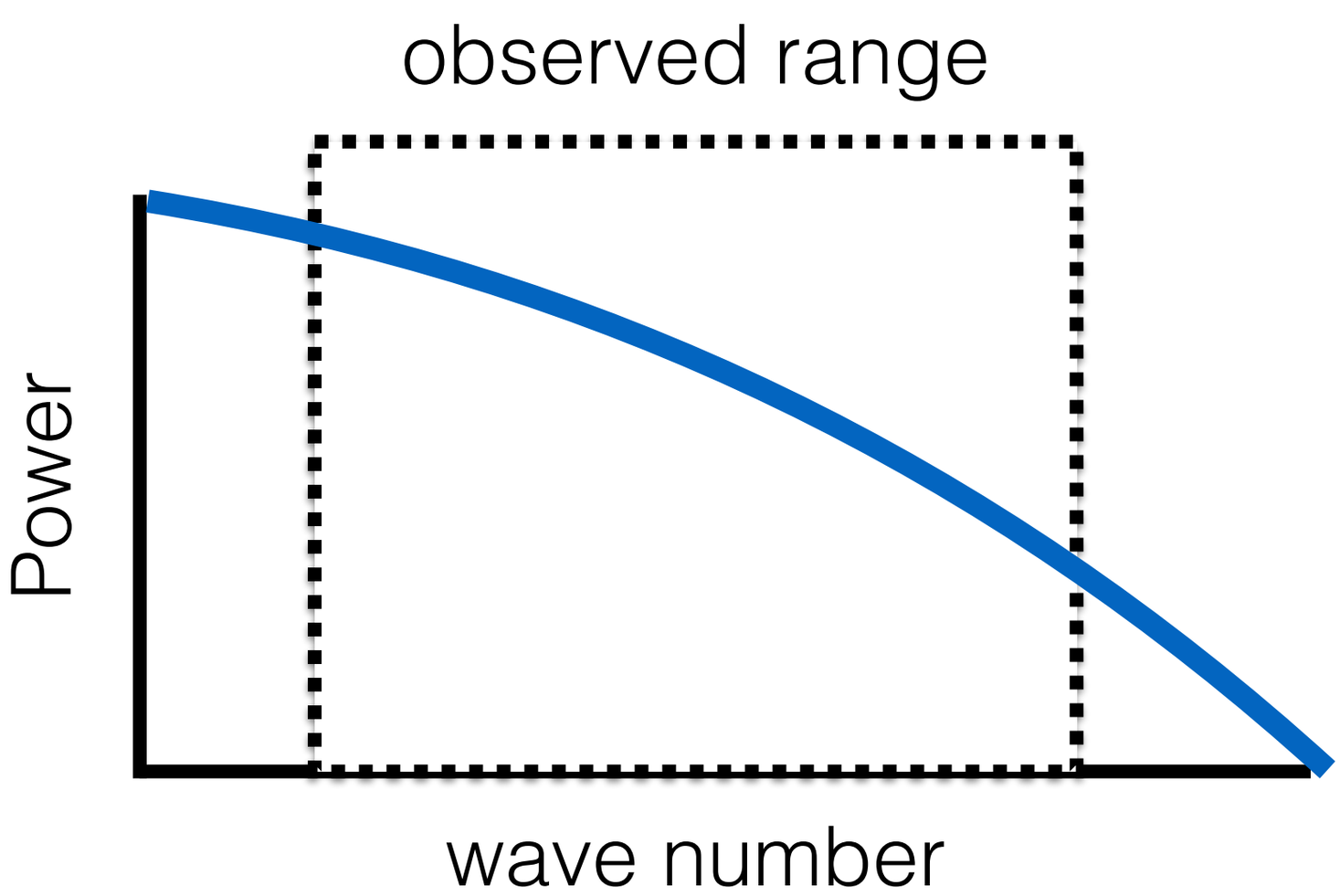
$\sim (D_A^2/H)^{1/3} / r_s$

Relative BAO shift along and across the line-of-sight + induced anisotropy

$\sim D_A H$

BAO as standard ruler

- The sound horizon scale is well determined by CMB measurements (helps to calibrate)
- We can separate the effect of cosmological distortions (AP) from other effects such as RSD



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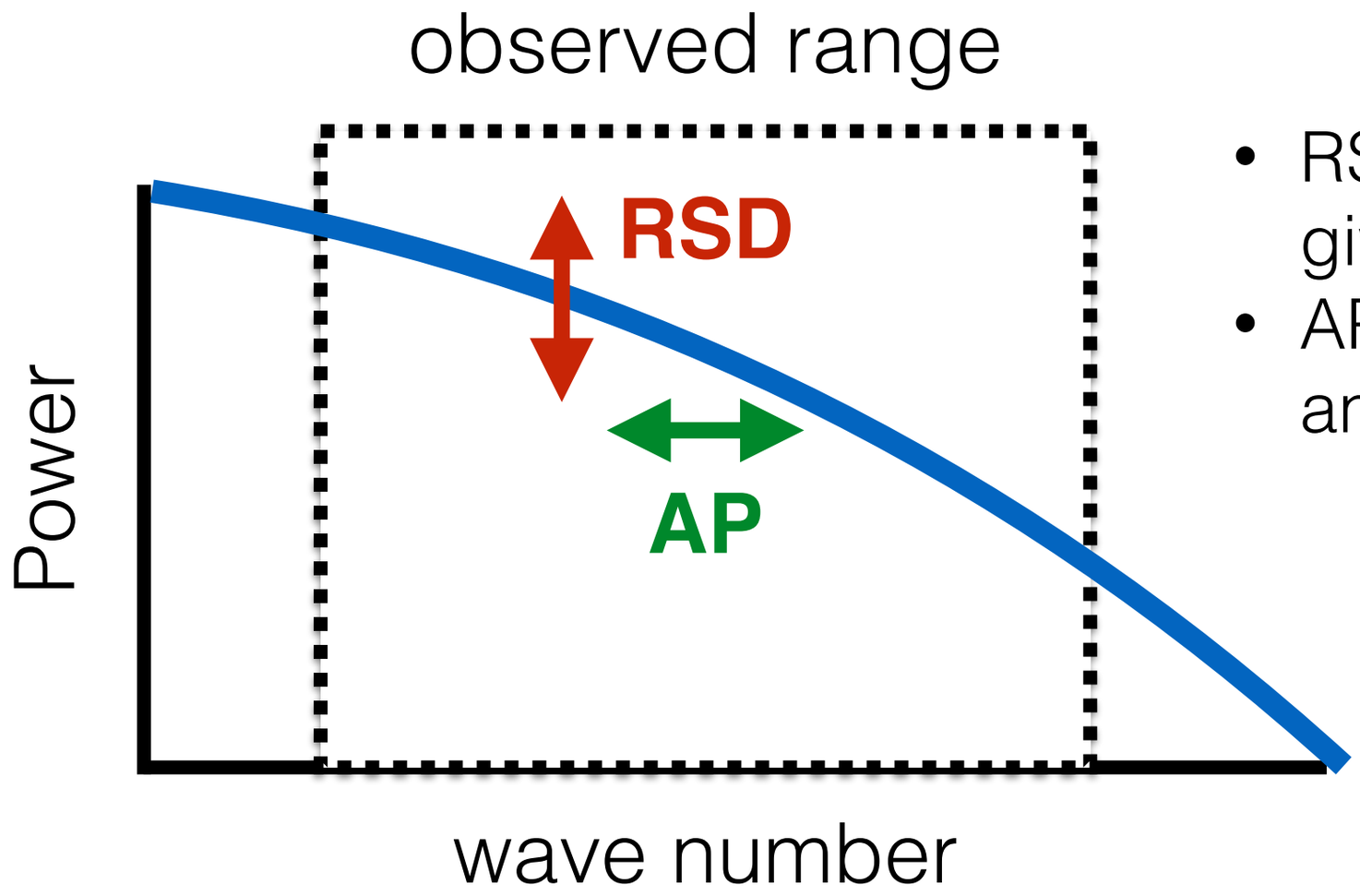

- RSD enhance the Power at a given scale
- AP shift the power of a scale to another scale

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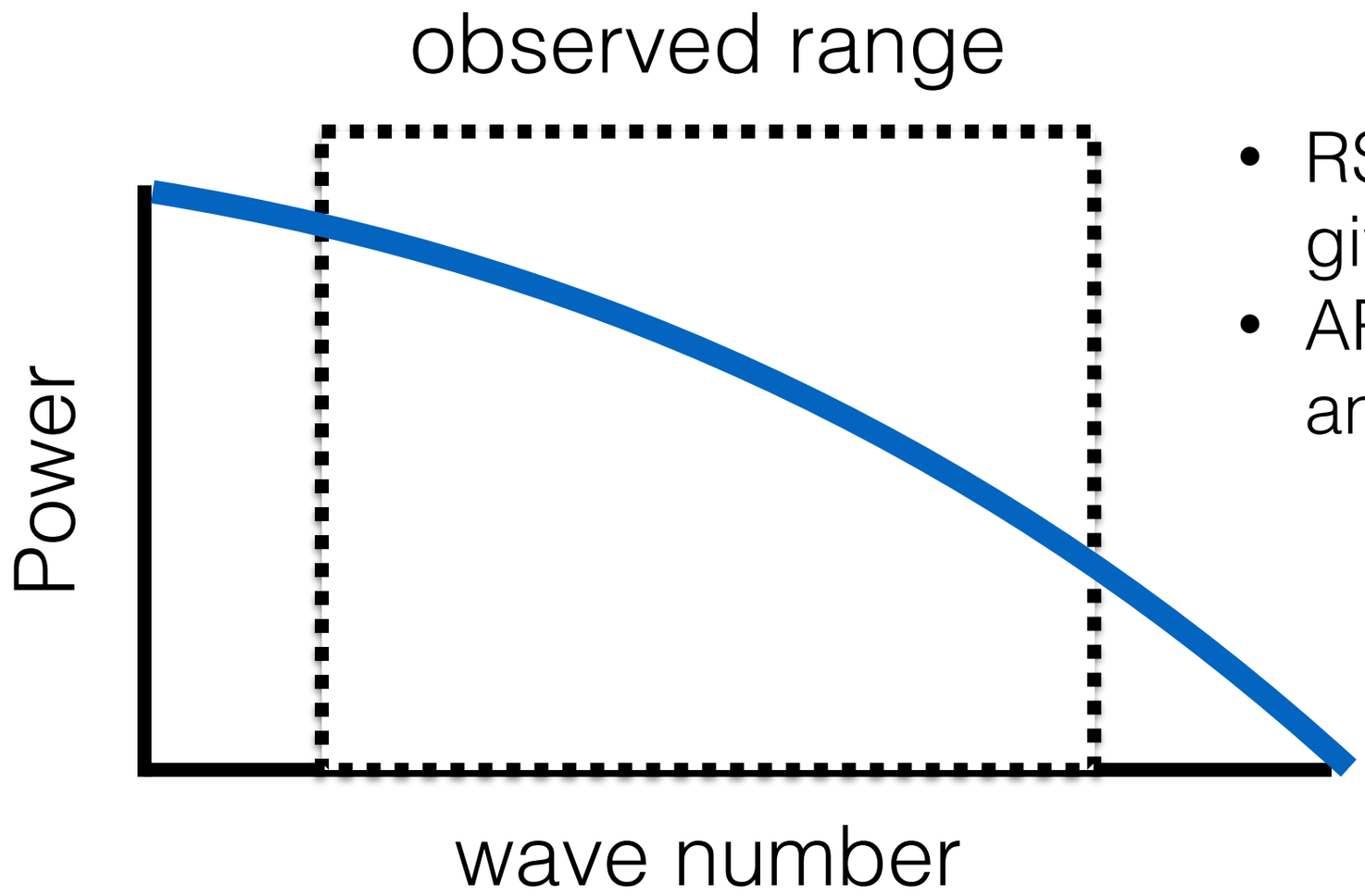

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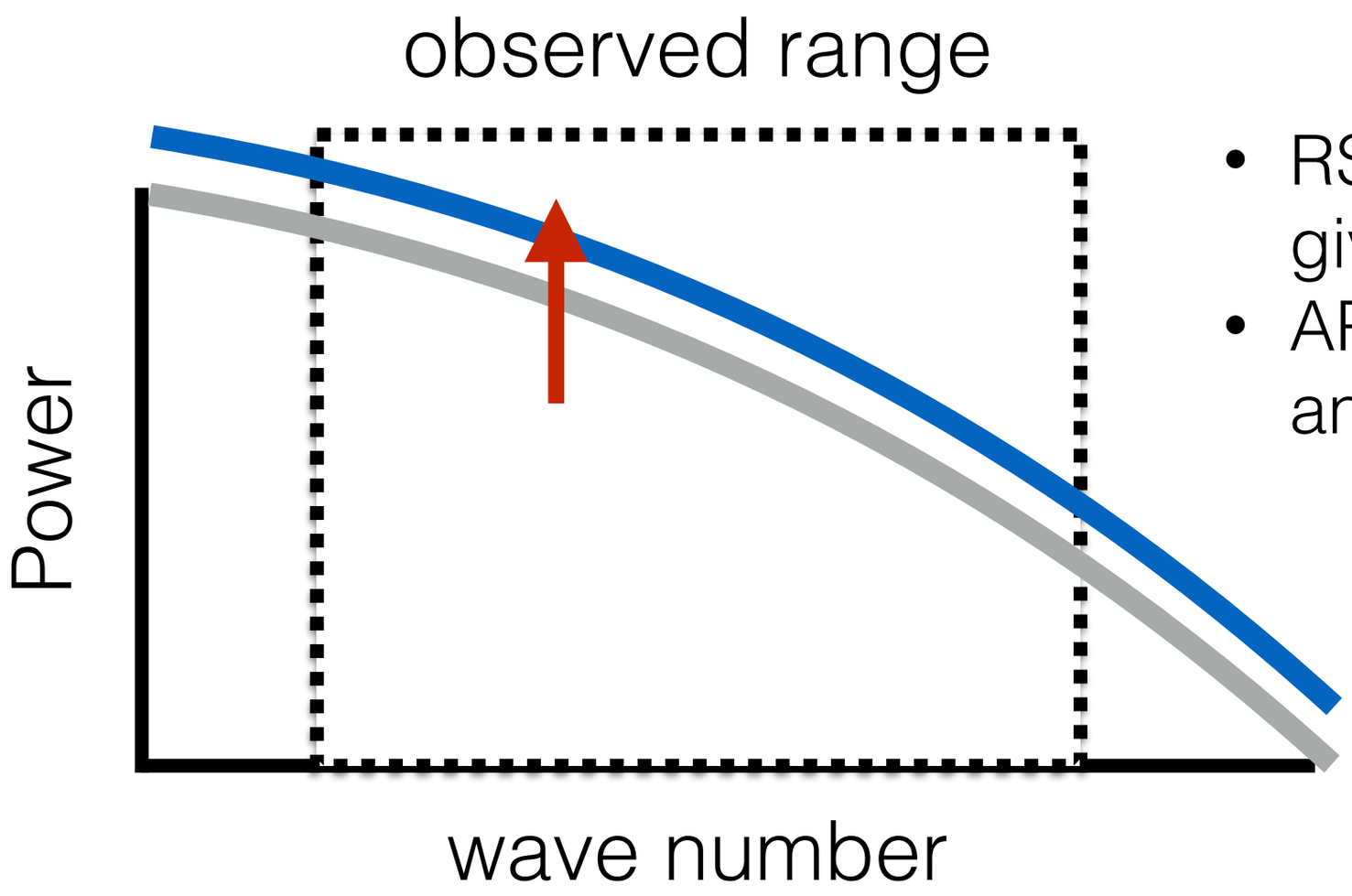

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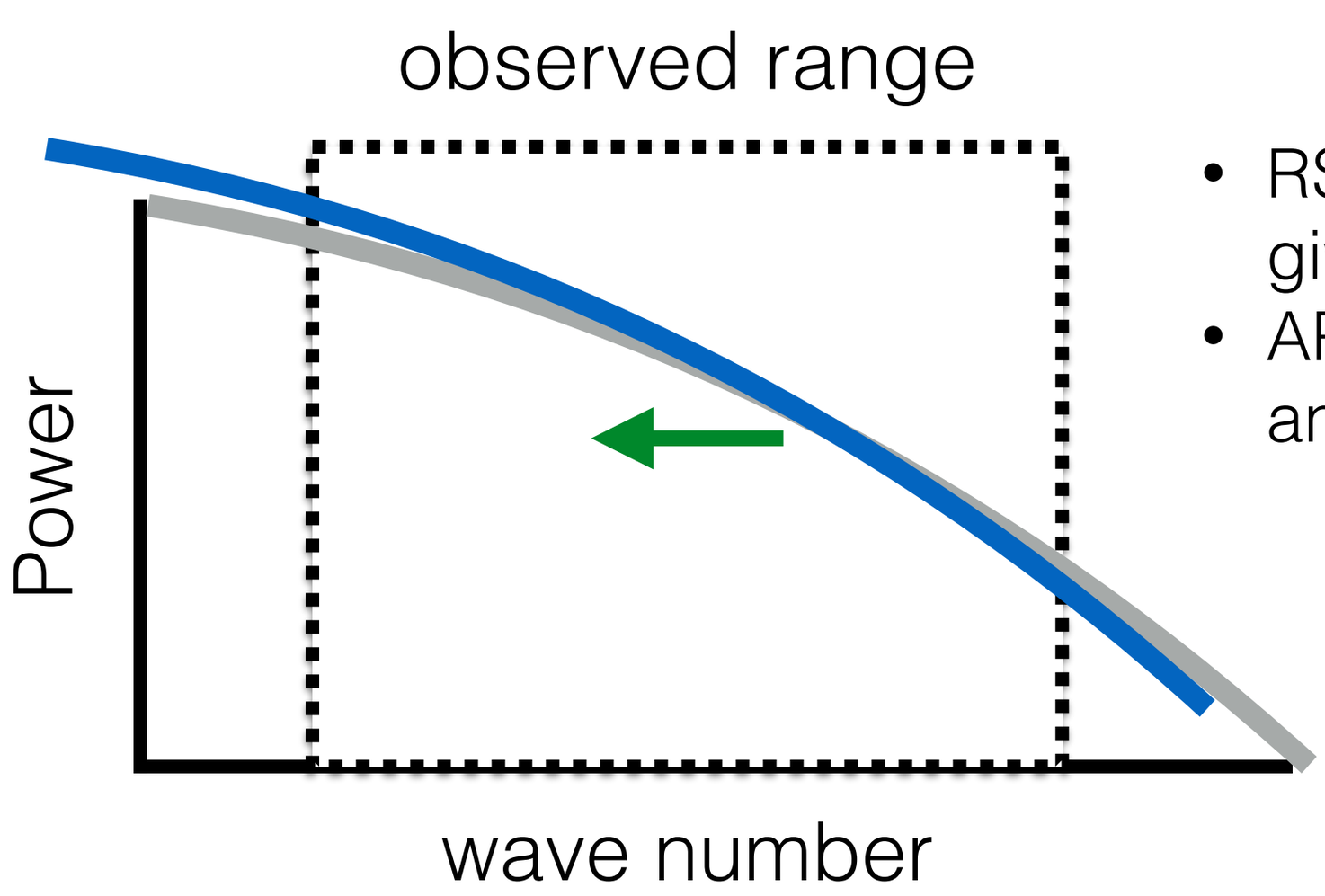

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Difficult to disentangle: RSD & AP

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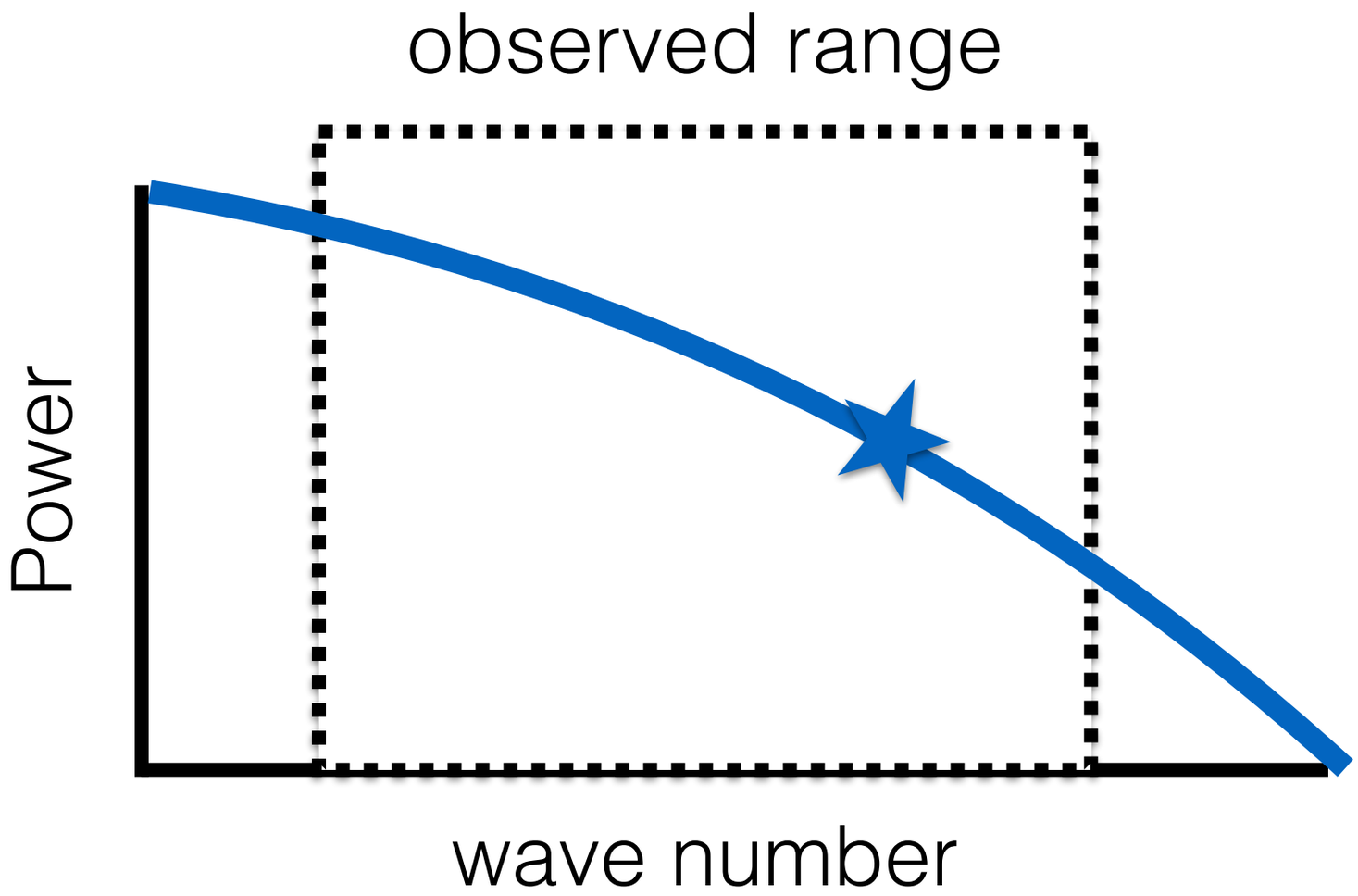

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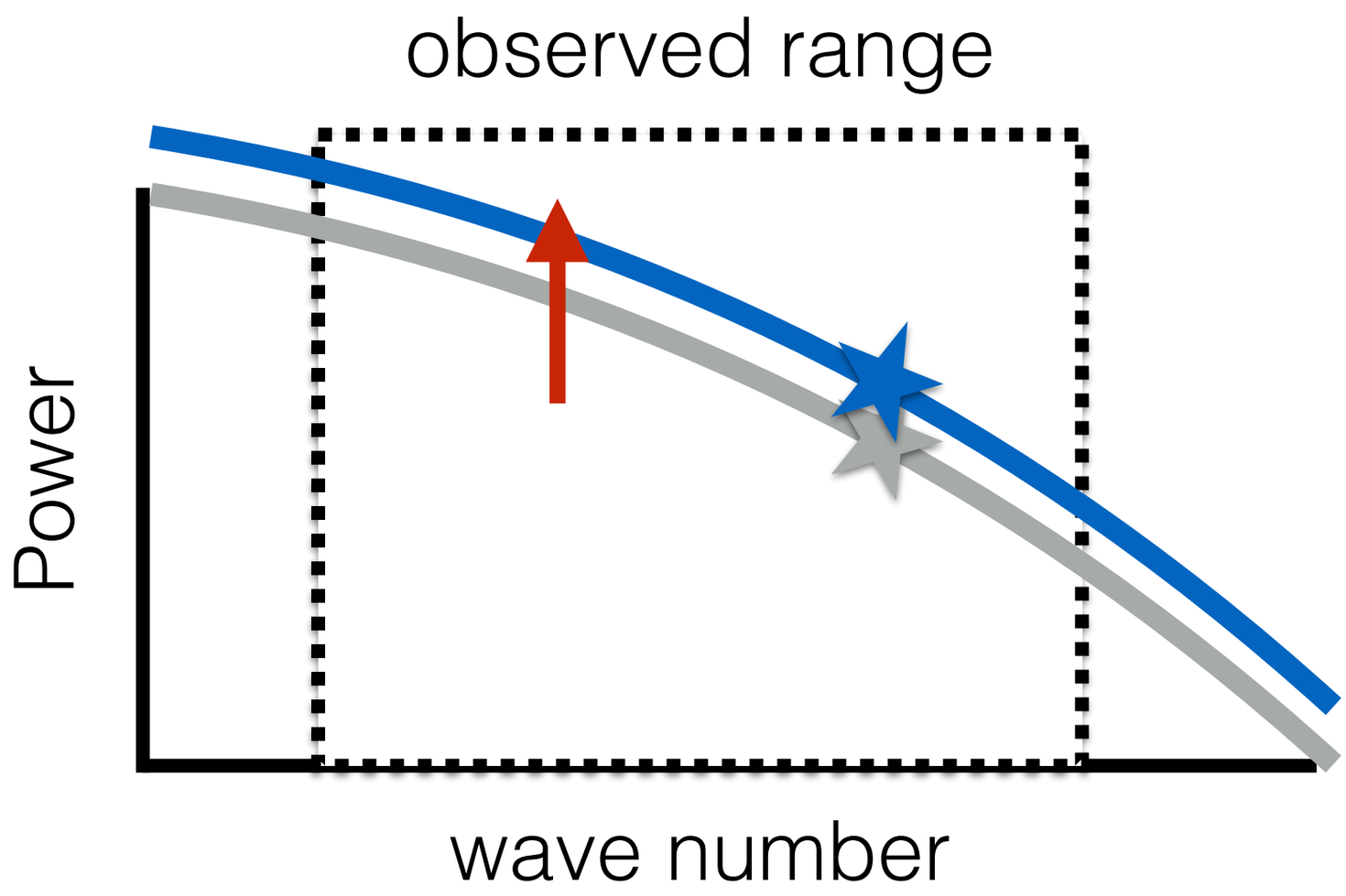

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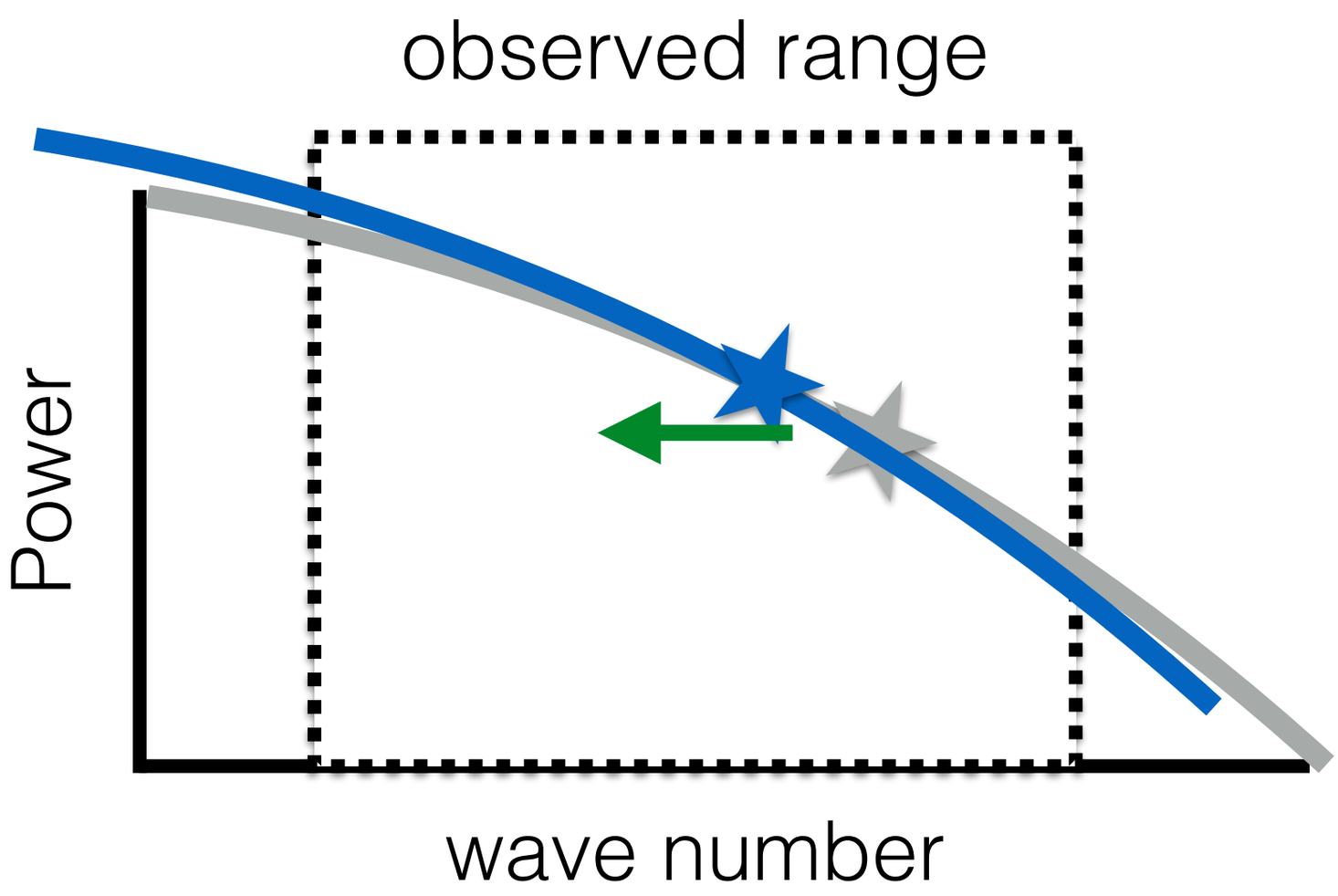

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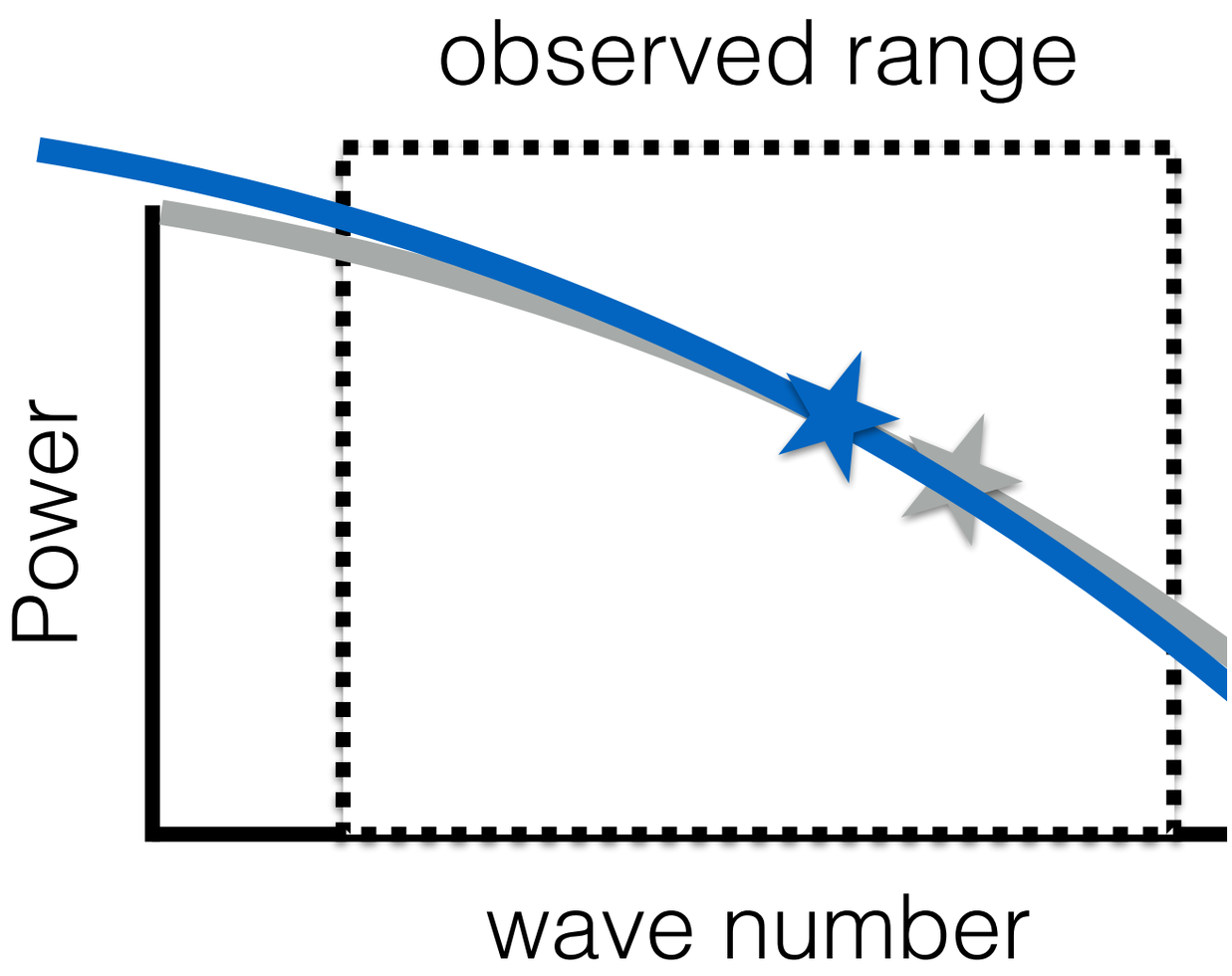
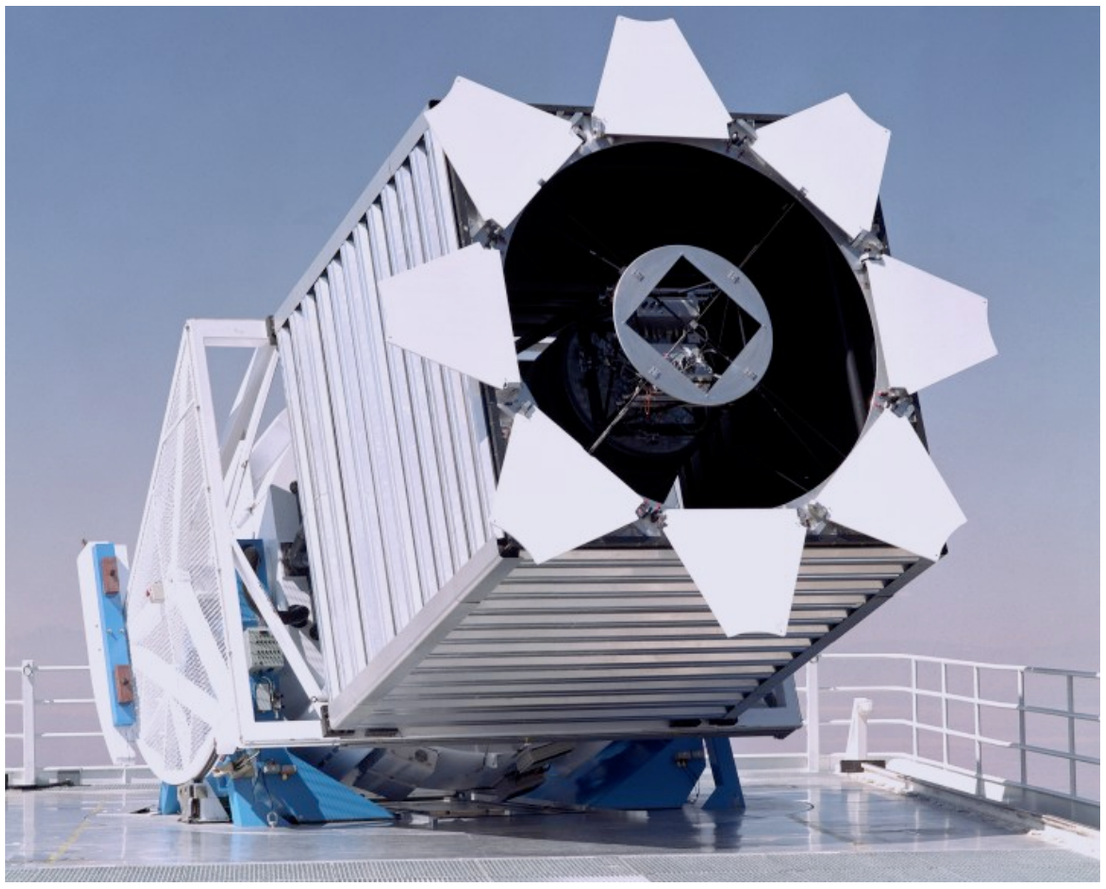


- BAO is the most distinct feature in ξ(s) and P(k) to look at.
- Position is robust under potential systematics:
- Non-linear effects are >1%
- BAO position not affected by bias or Kaiser boost
- However, the feature is damped by non-linear velocity bulks (can be solved using reconstruction)

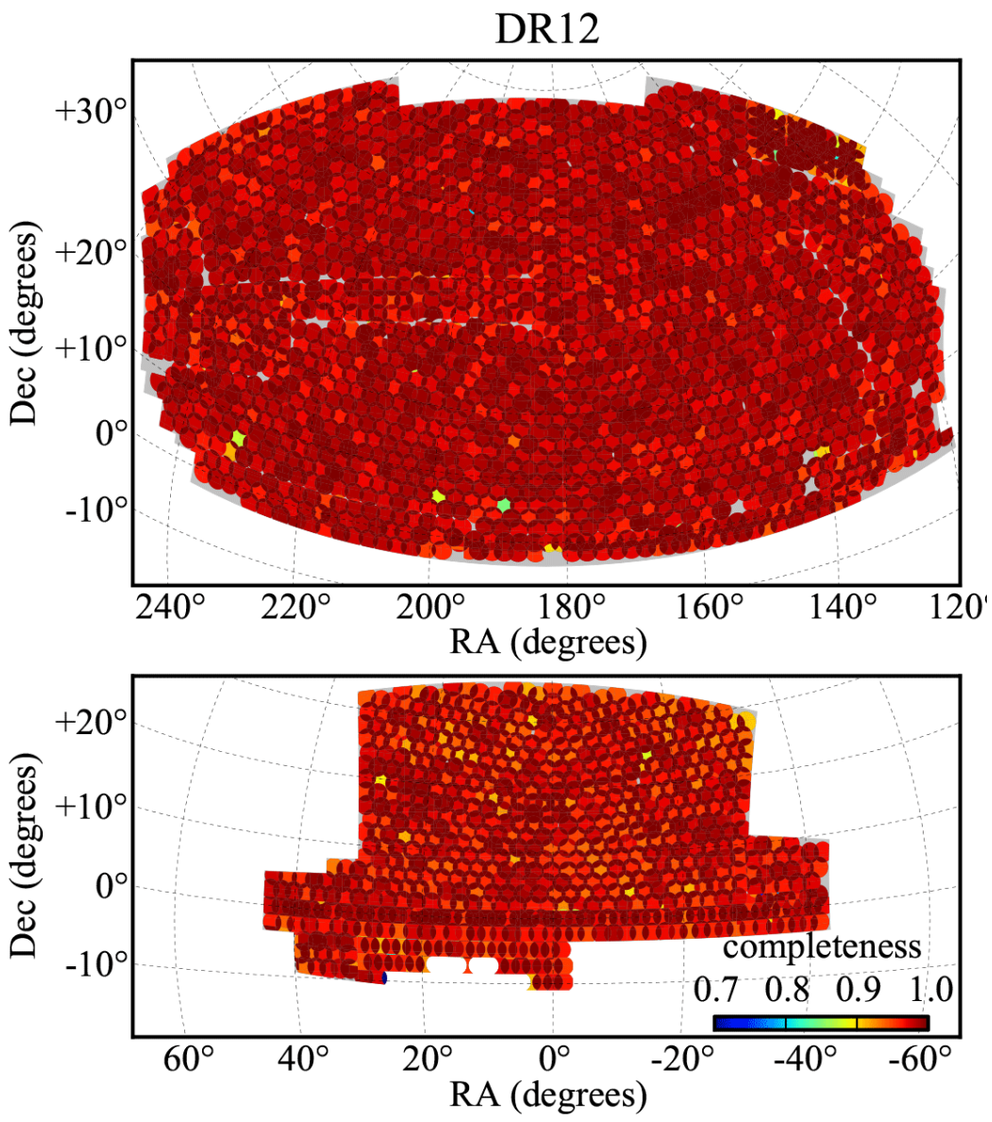
Cosmology with BOSS & eBOSS

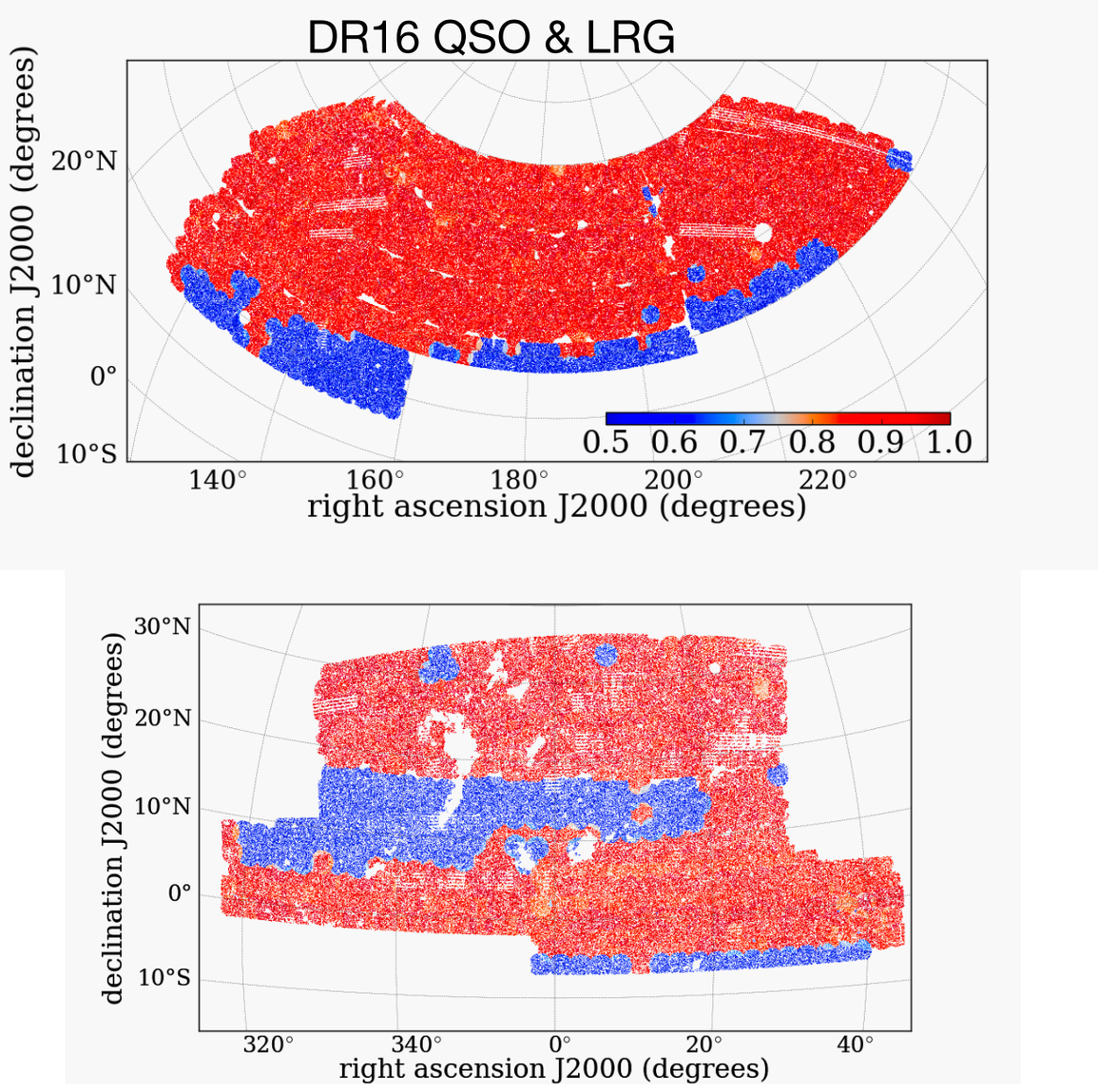


- Apache Point Observatory, 2.5-meter
- Spectroscopic Galaxy Survey
- 2009 - 2014 **BOSS**
- 2014-2019 **eBOSS**
- BOSS LRGs 0.15<z<0.75 (CMASS, LOWZ)
- eBOSS LRGs 0.6<z<1.1
- eBOSS ELGs 0.6<z<1.1
- eBOSS quasars 0.8<z<2.2
- + Ly-α spectra (Andreu's talk)

Main Goal: Measure BAO peak position with 1% accuracy
Other cosmology studies: growth of structure, mod-GR, neutrino mass, primordial non-Gaussianity, etc.

Cosmology with BOSS & eBOSS





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

Area = 9376 deg²

~10⁶ LRG targets

Area = ~4500 deg²

~3.3·10⁵ quasar targets
~2.2·10⁵ new LRG targets

0.6<z<1.0
0.8<z<2.2

Modelling the power spectrum: full shape vs. BAO

There are two main kind of complementary analyses:

1. **BAO analysis**: Based on the position of the BAO-peak

2. **Full Shape analysis** (aka RSD): Based on the PS full shape and amplitude signal

BAO analysis

- Fit broadband with polynomial fit & BAO template on oscillations

- Constrain on $D_A(z)/r_s$ and $H(z)r_s$ through the BAO-feature only

$$\alpha_{\parallel} = \alpha_0^{-3/2}\alpha_2^{5/2}$$
$$\alpha_{\perp} = \alpha_0^{9/4}\alpha_2^{-5/4}$$

- Damping terms for BAO due to bulk flows

BAO template

$$P_{bao}(k,\alpha_{0,2}) = P_{sm}(k)\left\{1+\left[O_{lin}(k/\alpha_{0,2})-1\right]e^{-\frac{1}{2}k^2\Sigma_{nl}{}^2}\right\}$$

Broadband

$$P_{sm}(k) = B^2 P_{lin,sm}(k) + A_1 k + A_2 + \frac{A_3}{k} + \ldots$$

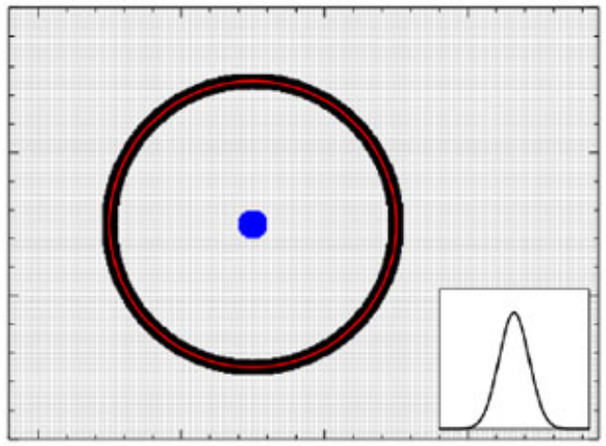
$$P^{(\mu^2)} \equiv P^{(0)} + \frac{2}{5}P^{(2)} \qquad P^{(0)},\quad P^{(2)} \rightarrow P^{(0)},\quad P^{(\mu^2)}$$

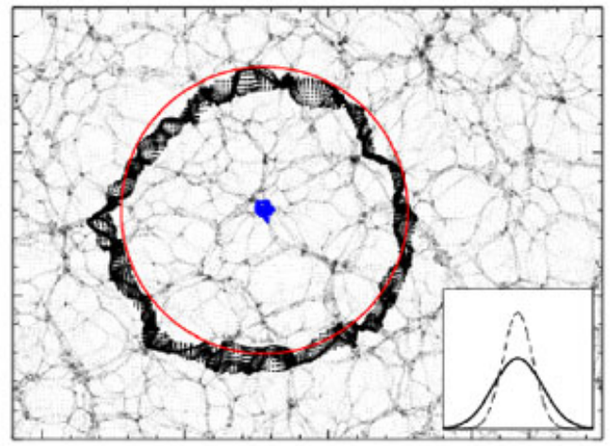
Reconstruction

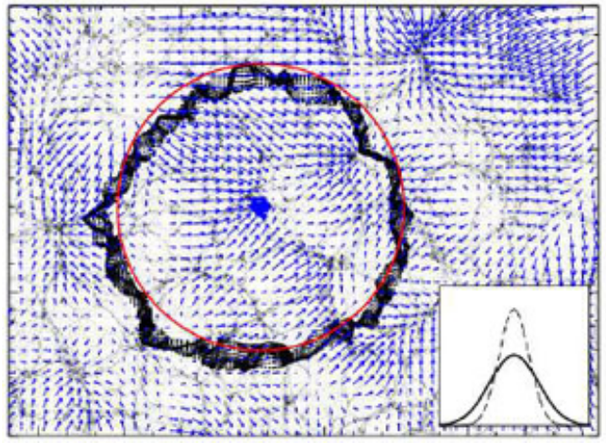
- Enhance BAO peak by un-doing the non-linear bulk flows

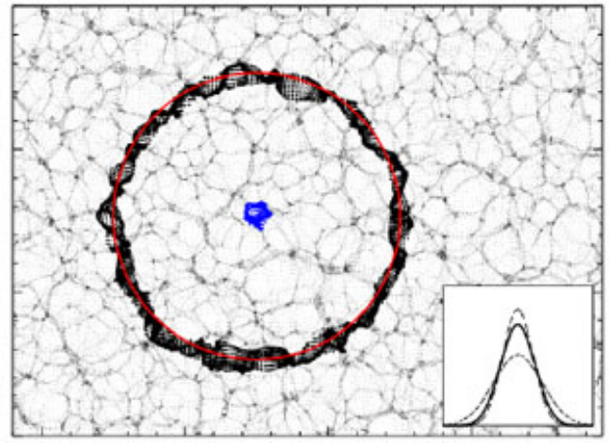
- Assumptions on gravity Ω_m and bias of tracer

- ‘Gaussianization’ of the galaxy field



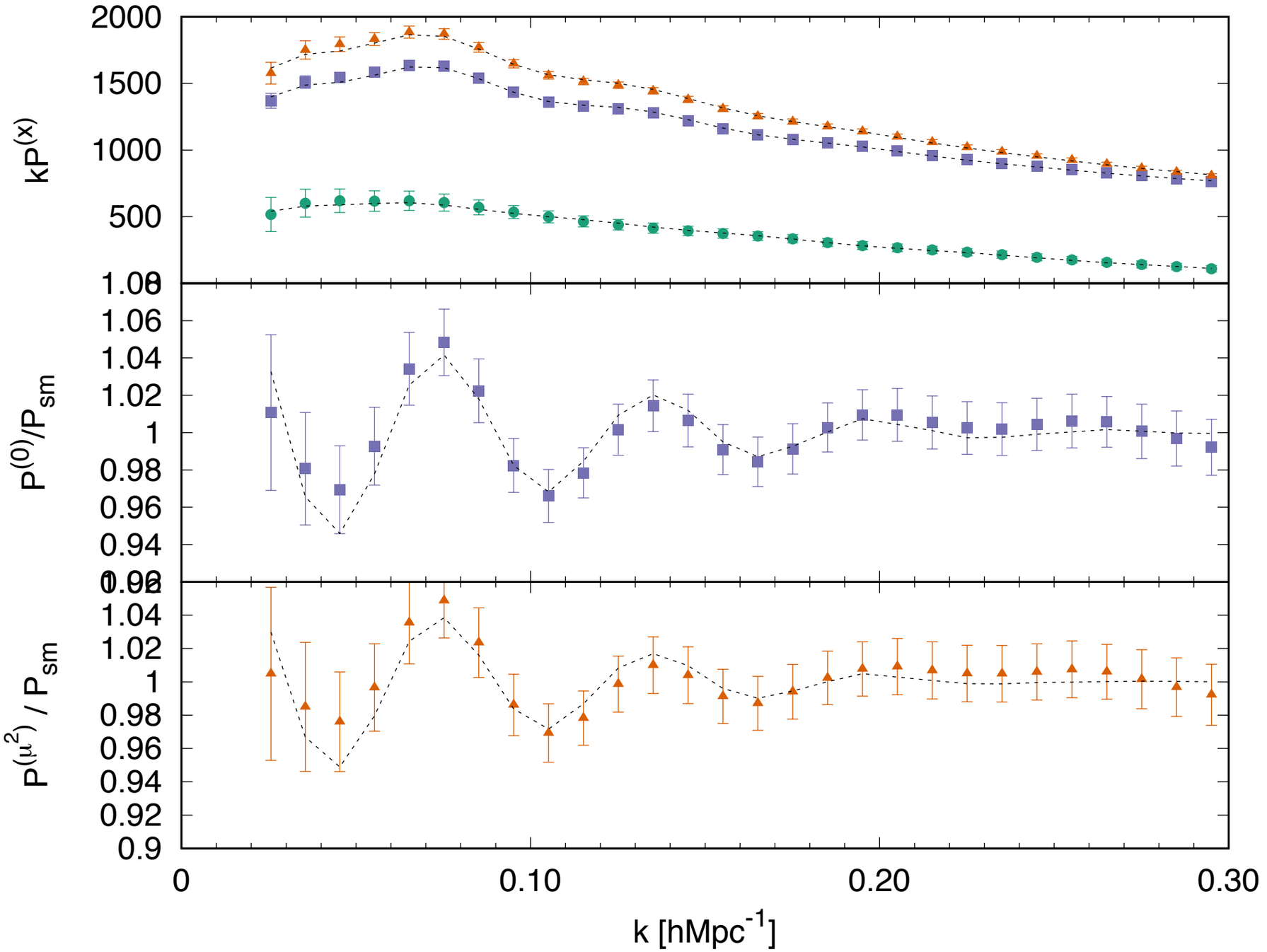




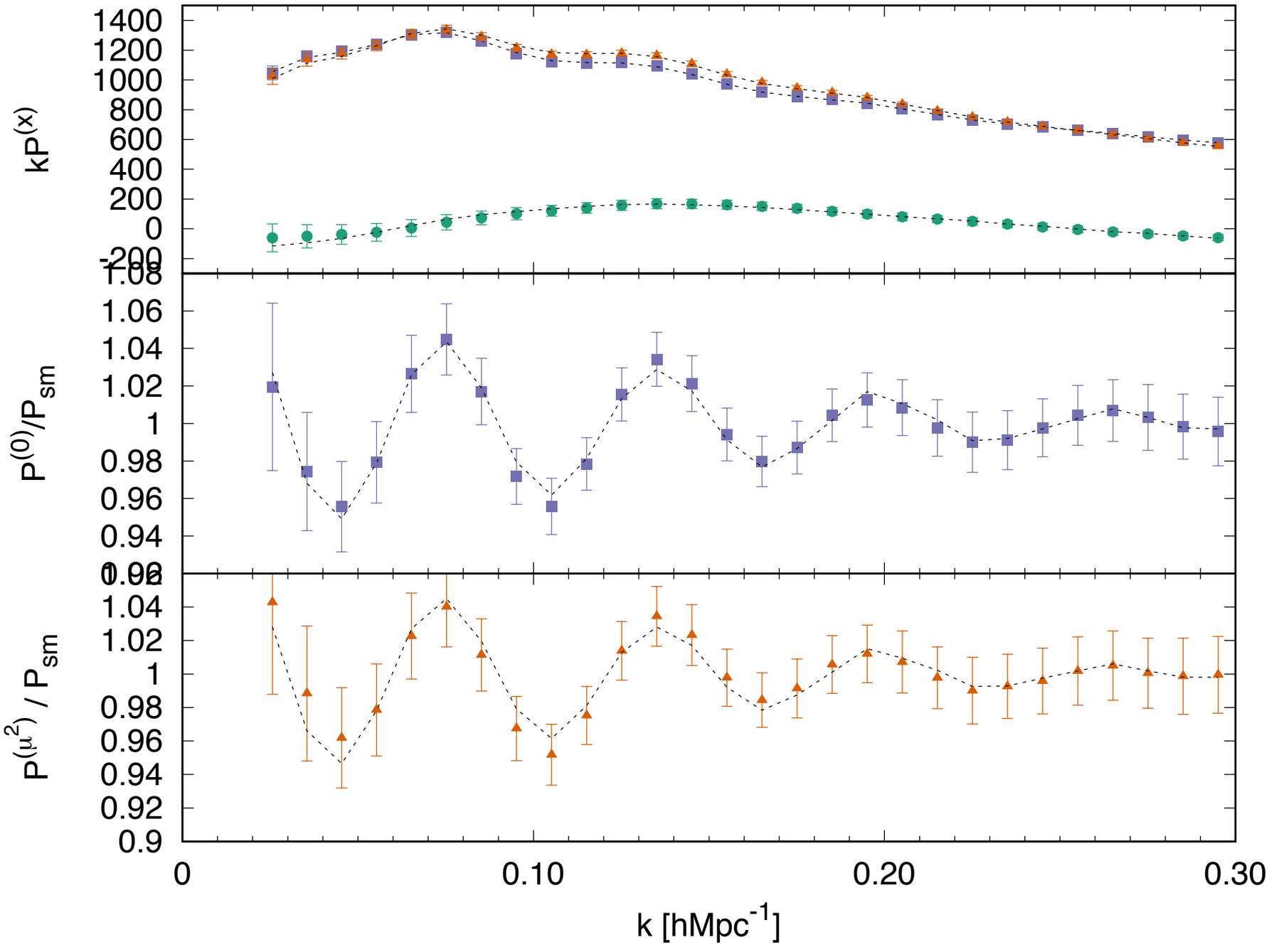


$$\nabla \cdot \mathbf{\Psi} + \frac{f}{b} \nabla \cdot (\mathbf{\Psi} \cdot \hat{\mathbf{r}}) \hat{\mathbf{r}} = -\frac{\delta_g}{b}$$

Reconstruction



Reconstruction



Full Shape (RSD)

- Constrain the growth of structure, $f\sigma_8(z)$, $D_A(z)/r_s$ and $H(z)r_s$ through the shape and amplitude of a range of scales.
- It requires a full modelling of the amplitude and shape of the power spectrum multipoles
  - Non-linear dark matter PS shape

    Perturbation Theory 2-loop
  - Galaxy bias,

    Non-linear & non-local
  - RSD

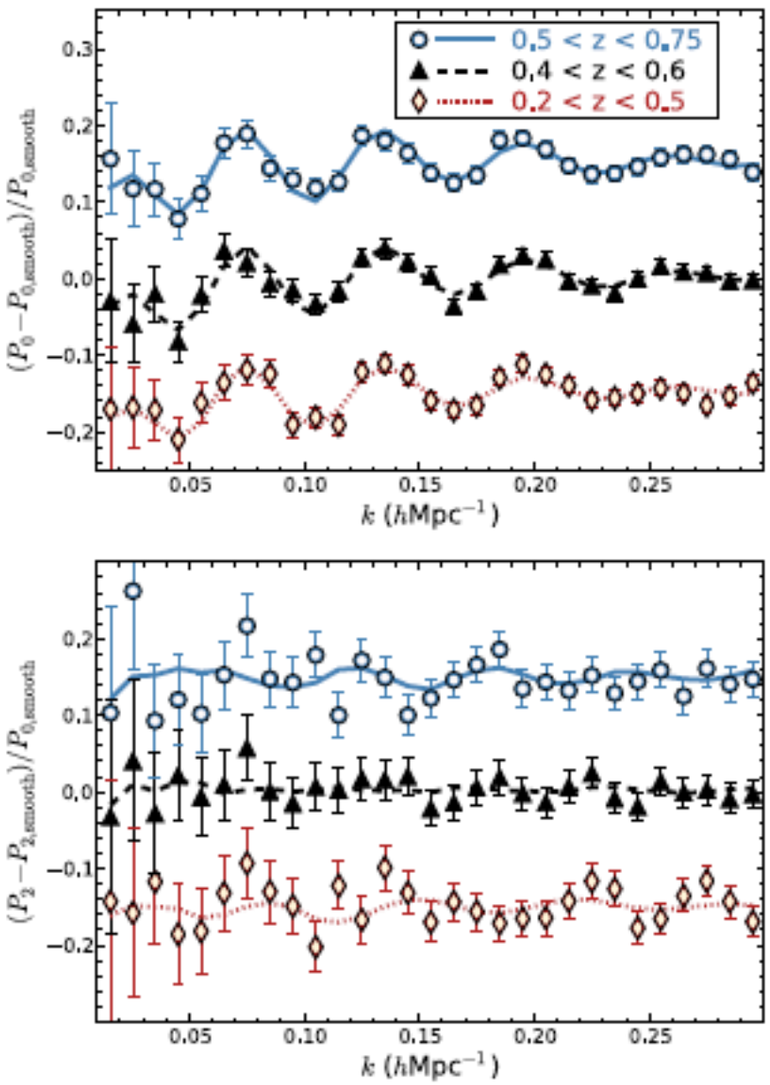
    TNS-model

$$P_g^{(s)}(k,\mu) = D^P_{\rm FoG}(k,\mu,\sigma^P_{\rm FoG}[z]) \left[P_{g,\delta\delta}(k) + 2f\mu^2 P_{g,\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k) + b_1^3 A(k,\mu,f/b_1) + b_1^4 B(k,\mu,f/b_1)\right]$$

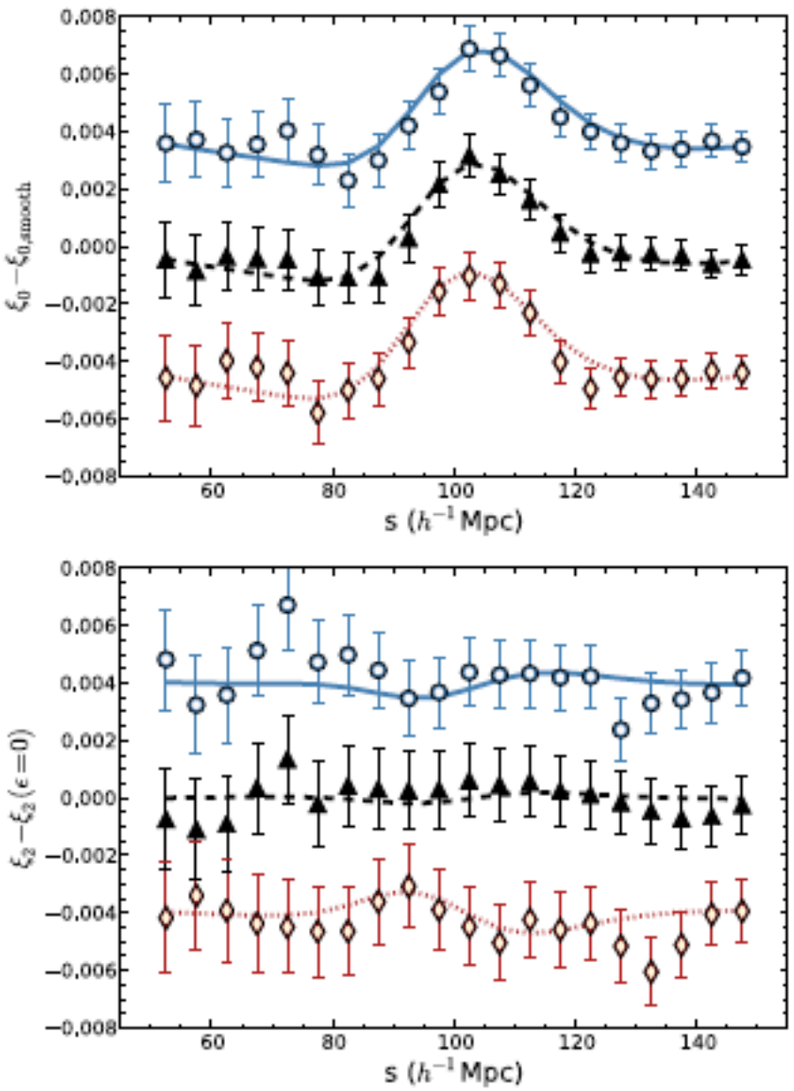
$P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ $\rightarrow$ Dark Matter non-linear models (2-loop RPT)
$D^P_{\rm FoG}$ $\rightarrow$ 1-parameter Lorentzian damping term
A, B $\rightarrow$ TNS functions

Main BOSS results

Power Spectrum



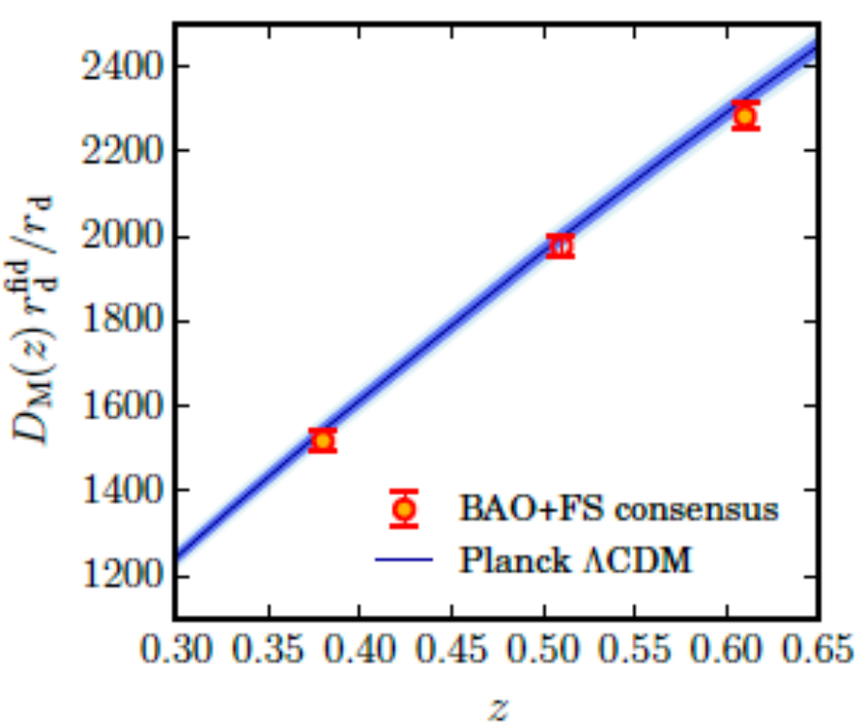
Correlation Function

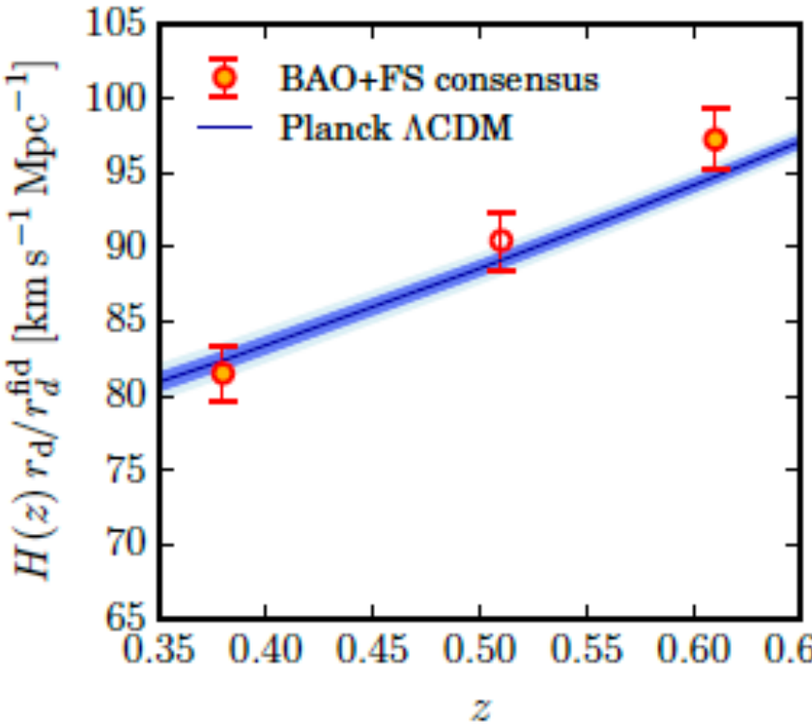


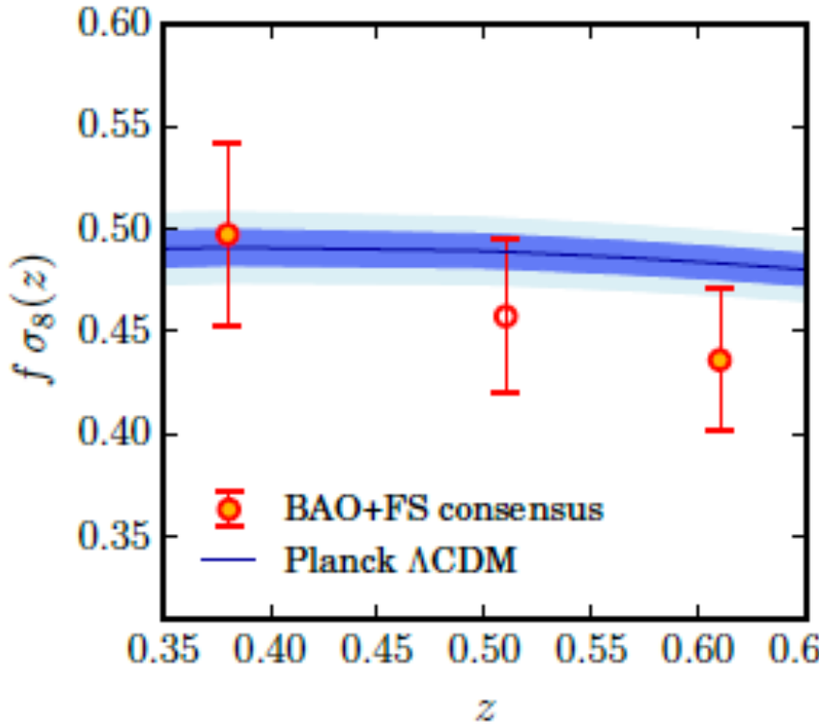
3overlapping z-bins

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

Main BOSS results







- Good Agreement with Planck+GR
- First time 1% precision BAO measurement

3overlapping z-bins

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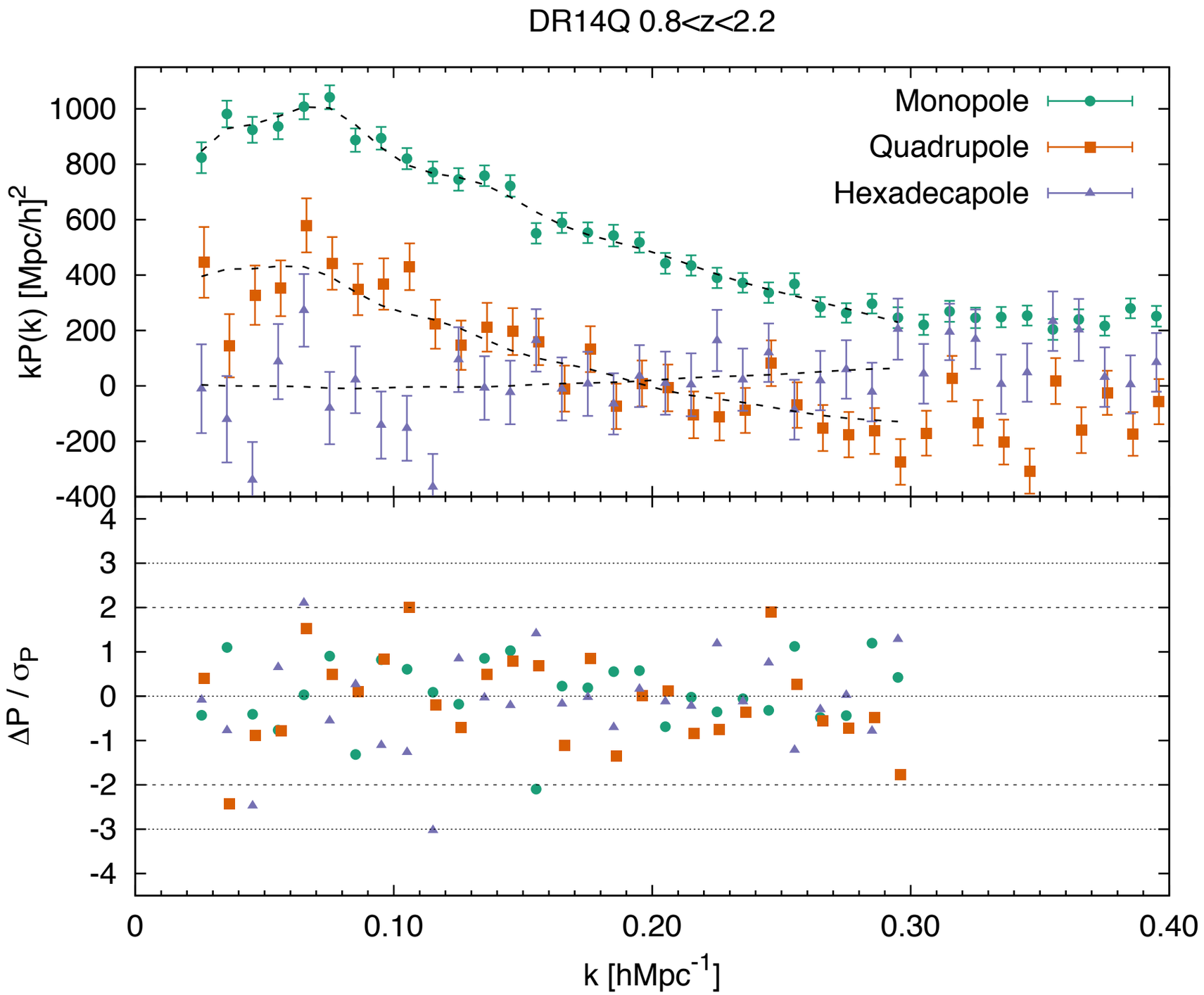
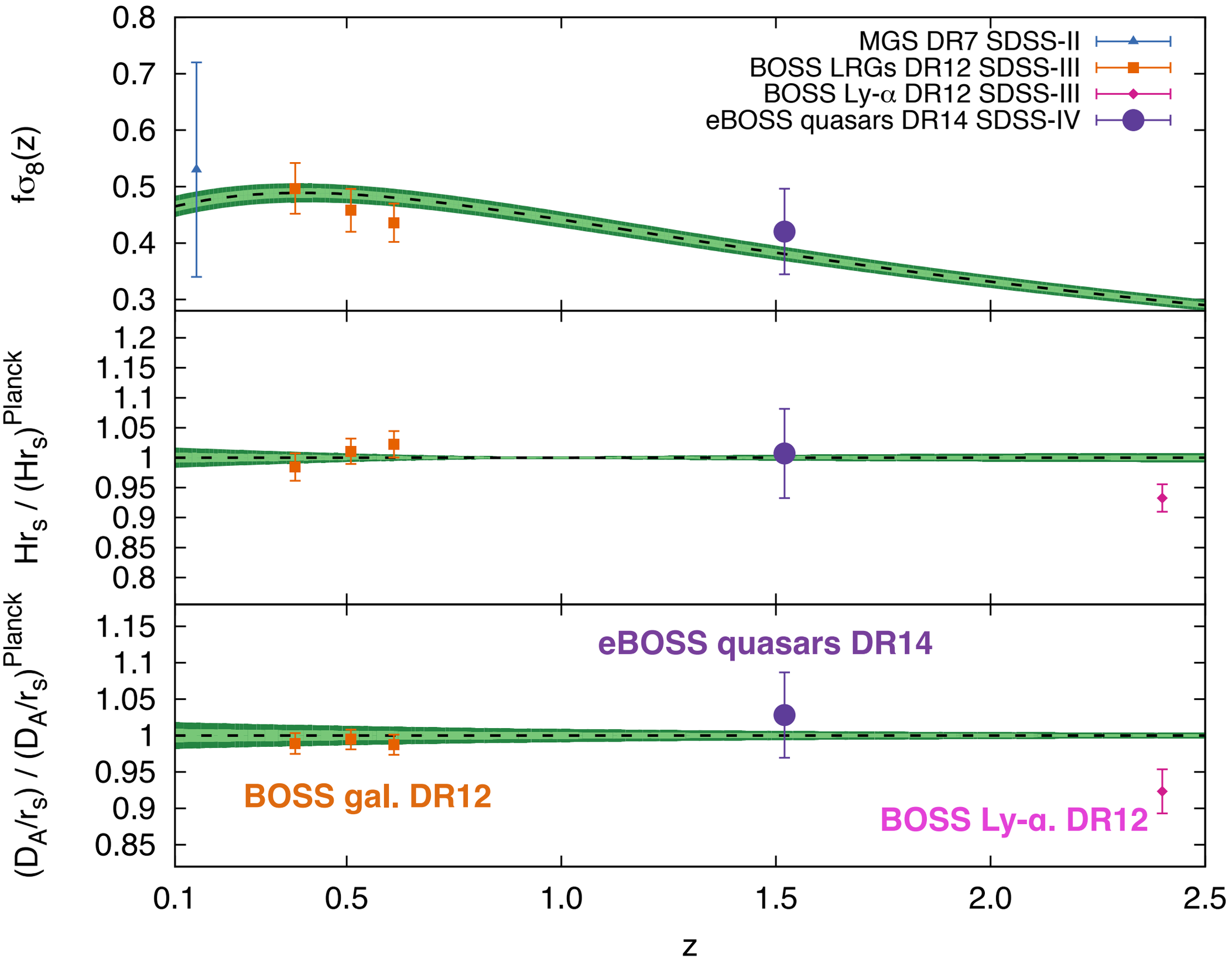
0.5<z<0.75

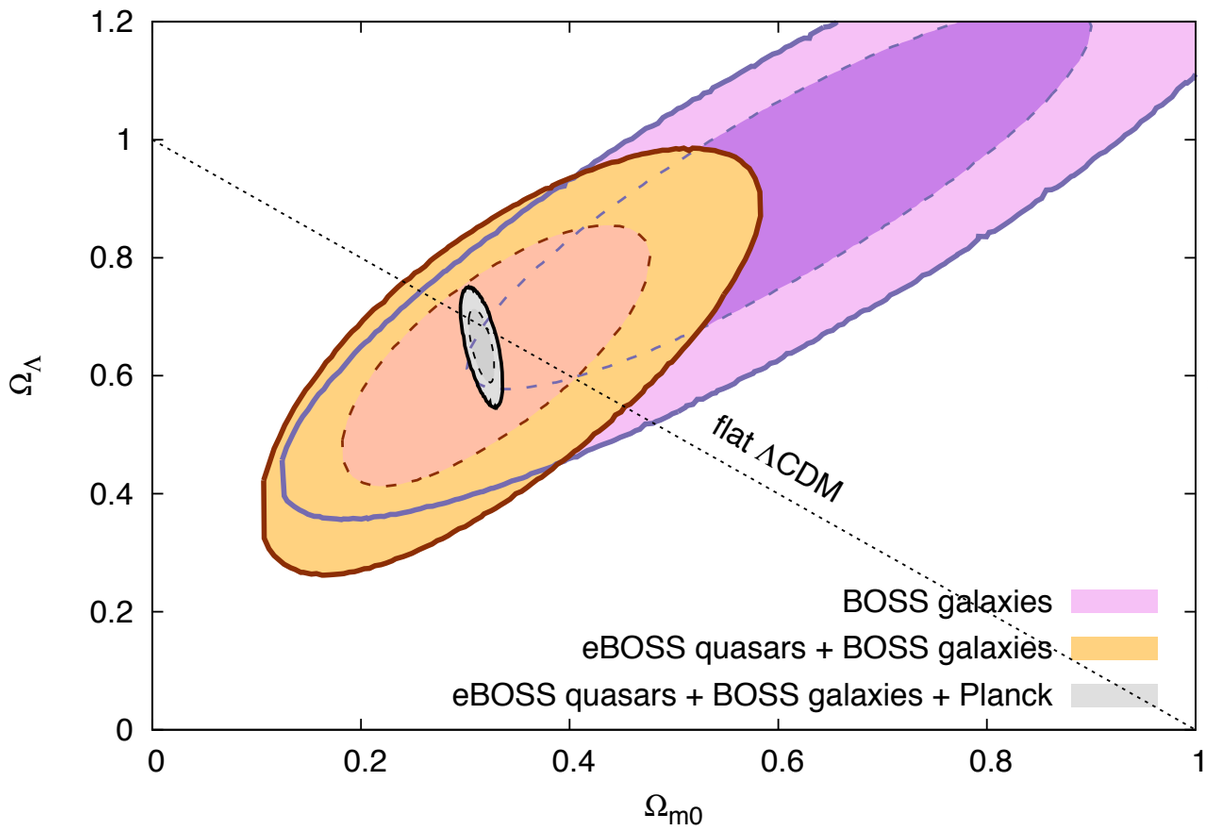
Main eBOSS results



HGM et al. 2018


MGS DR7 SDSS-II
BOSS LRGs DR12 SDSS-III
BOSS Ly-α DR12 SDSS-III
eBOSS quasars DR14 SDSS-IV
fσ8(z)
(DA/rs) / (DA/rs)Planck
Hrs / (Hrs)Planck
eBOSS quasars DR14
BOSS gal. DR12
BOSS Ly-α. DR12
z

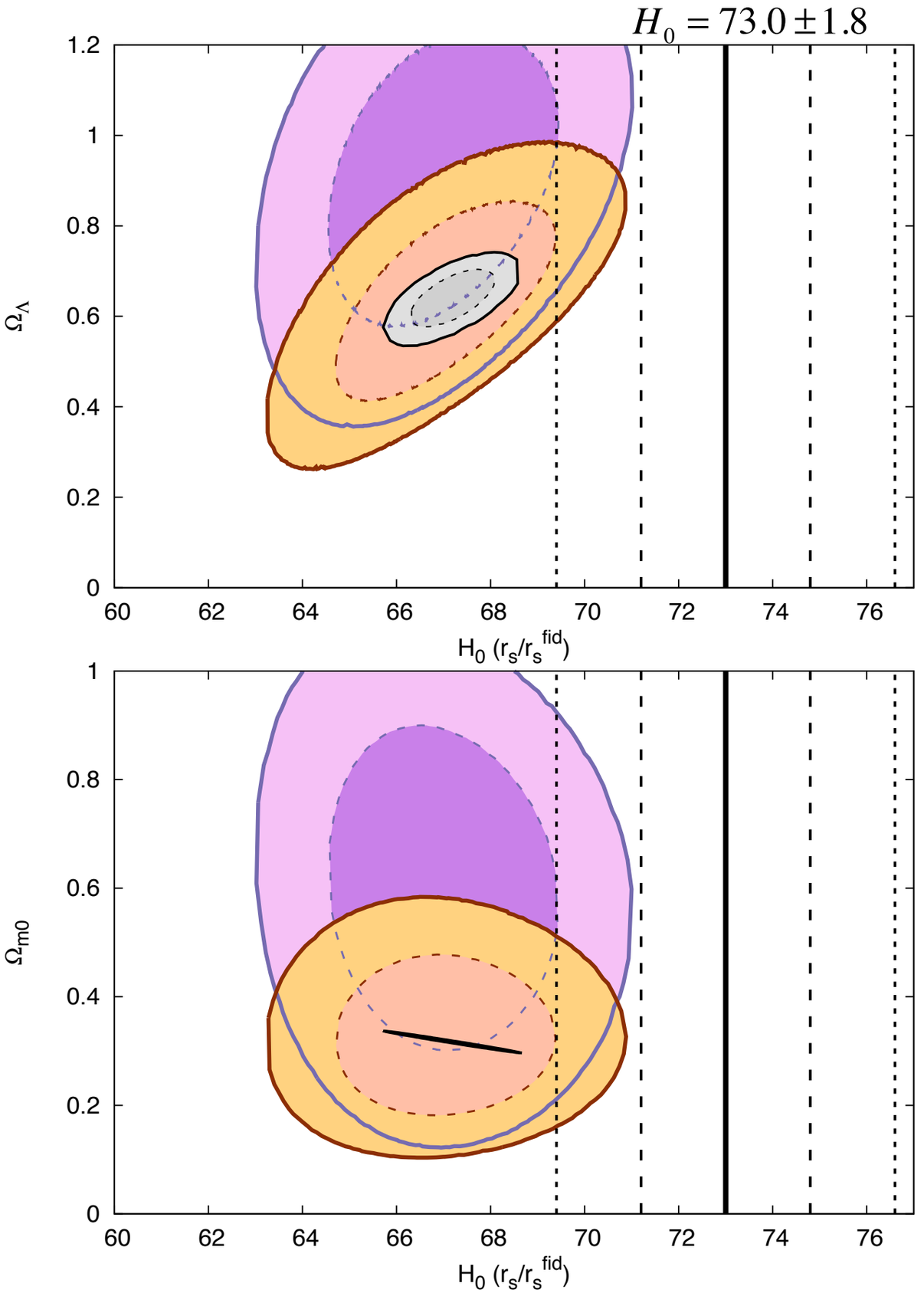
Cosmology with BOSS and eBOSS



GR & ΛCDM assumed

relax flatness

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



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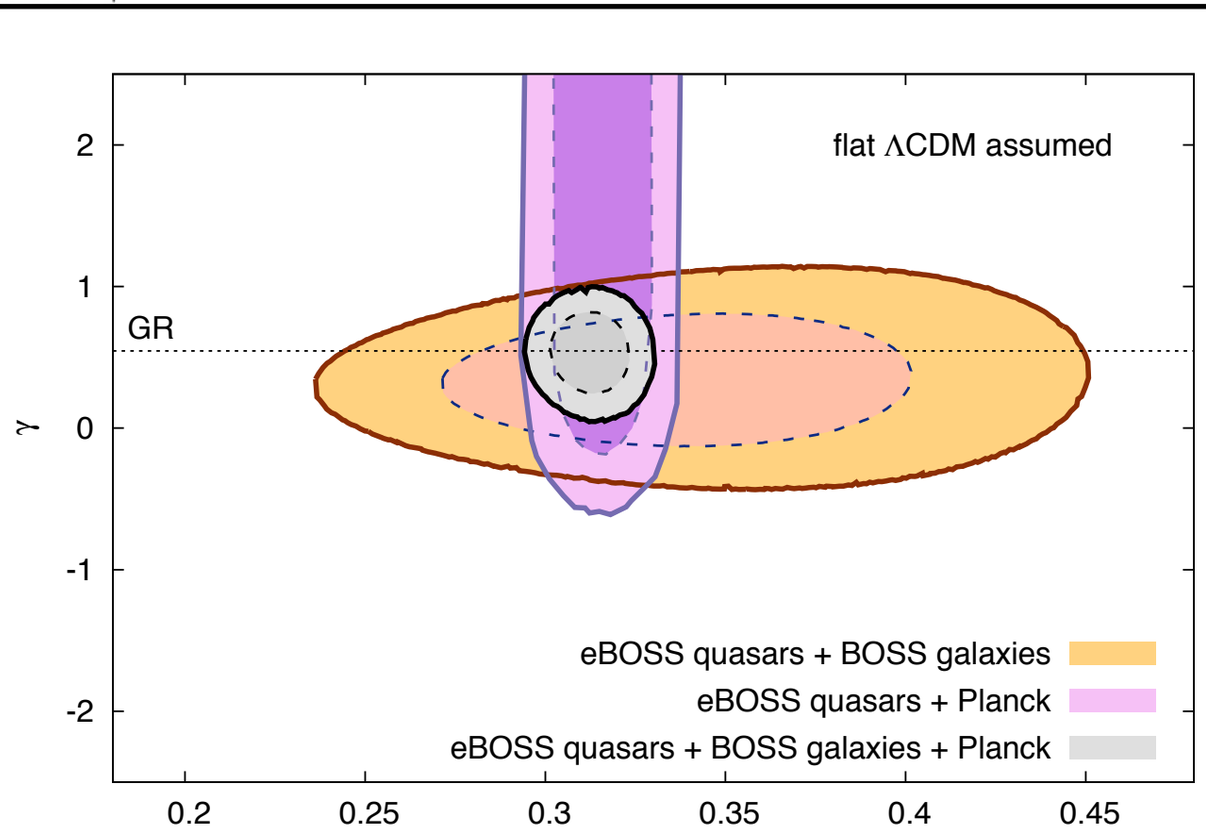

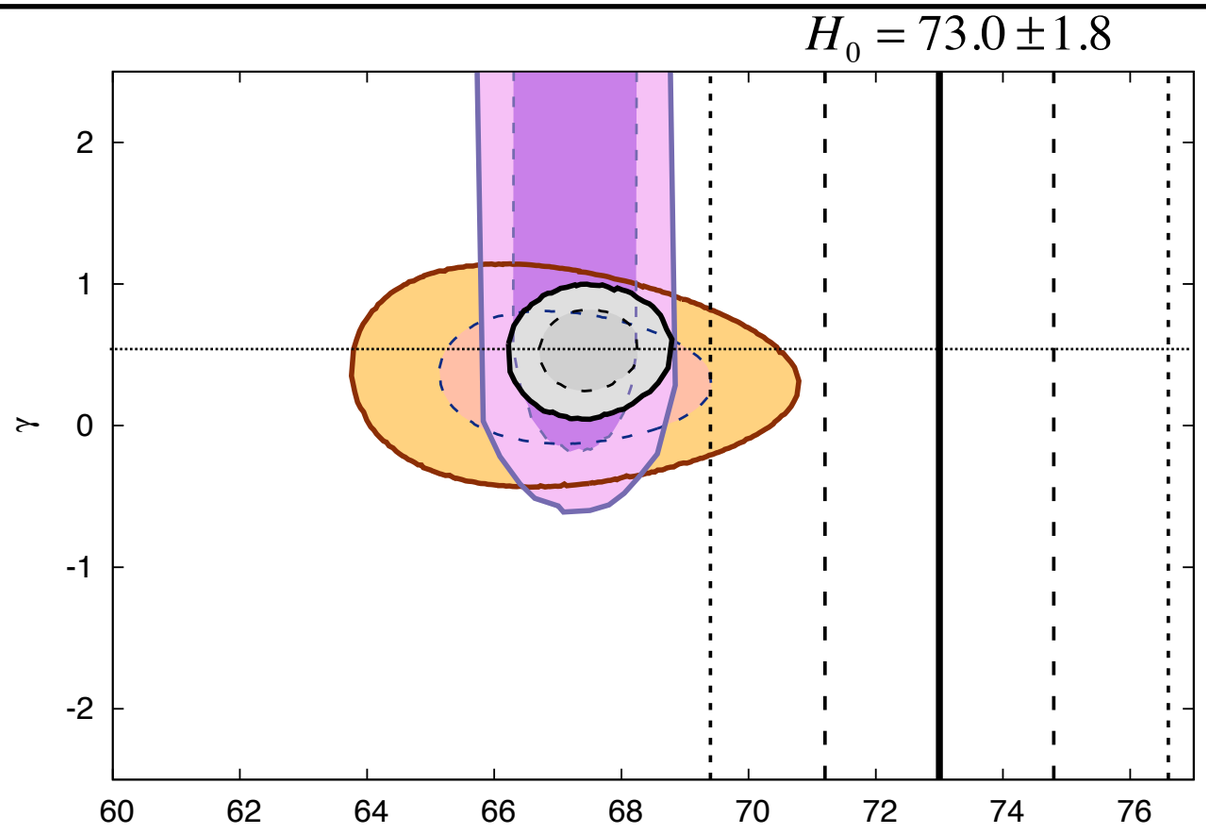

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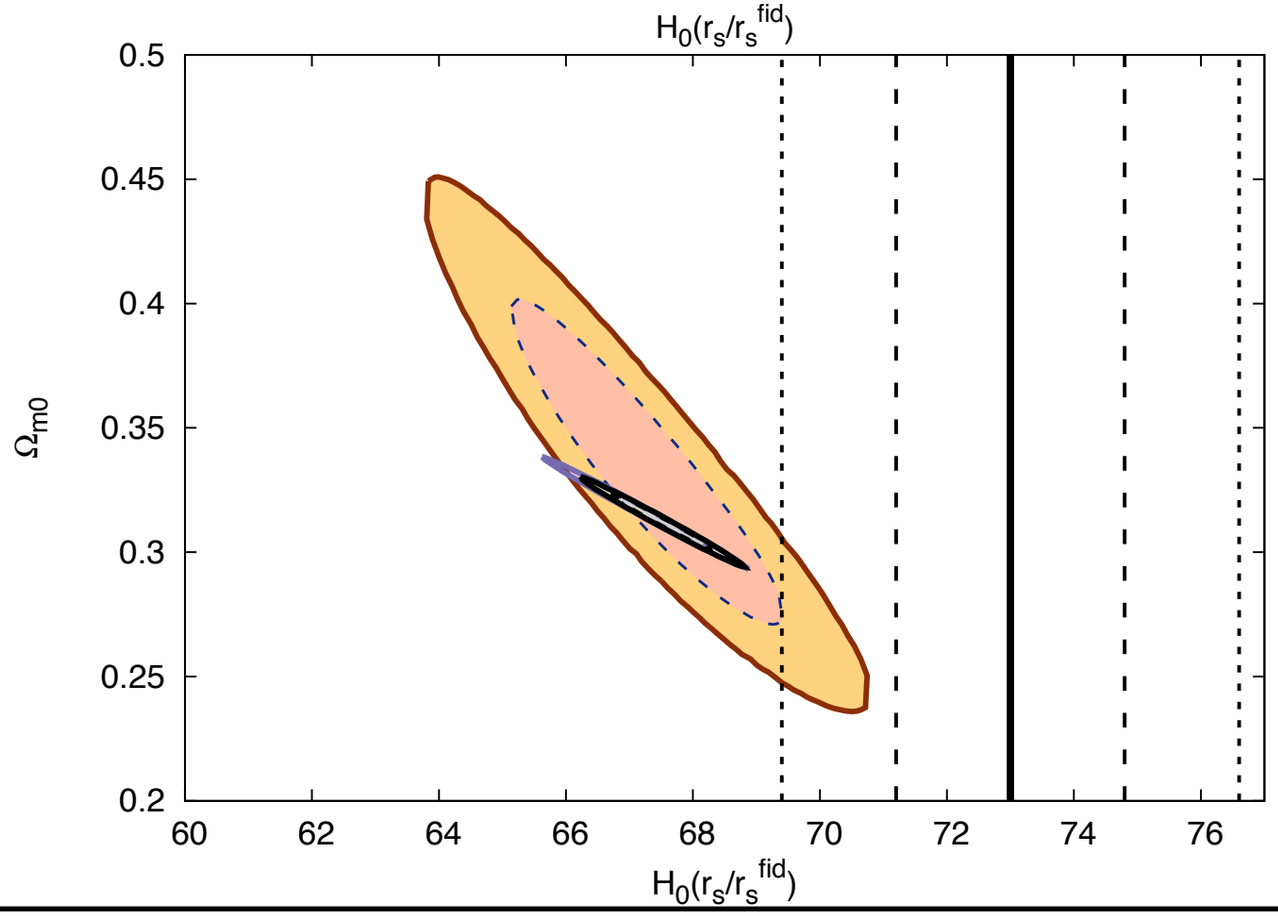


Conclusions

- LSS as a complementary source of information to CMB
- BOSS & eBOSS have demonstrated over the last 8yr that BAO and RSD are robust techniques for estimating cosmological parameters from LSS
- Final DR16 eBOSS results December 2019
- So far no tension with ΛCDM+Planck
- LSS + CMB/BBN favours a low H_0 value

$$k_{\parallel} = \alpha_{\parallel} k_{\parallel}' \longrightarrow \qquad k_{\perp} = \alpha_{\perp} k_{\perp}' \longrightarrow$$

$$\alpha_{\parallel} = \frac{r_s^{fid} H^{fid}}{r_s H} \qquad \alpha_{\perp} = \frac{D_A / r_s}{D_A^{fid} / r_s^{fid}}$$

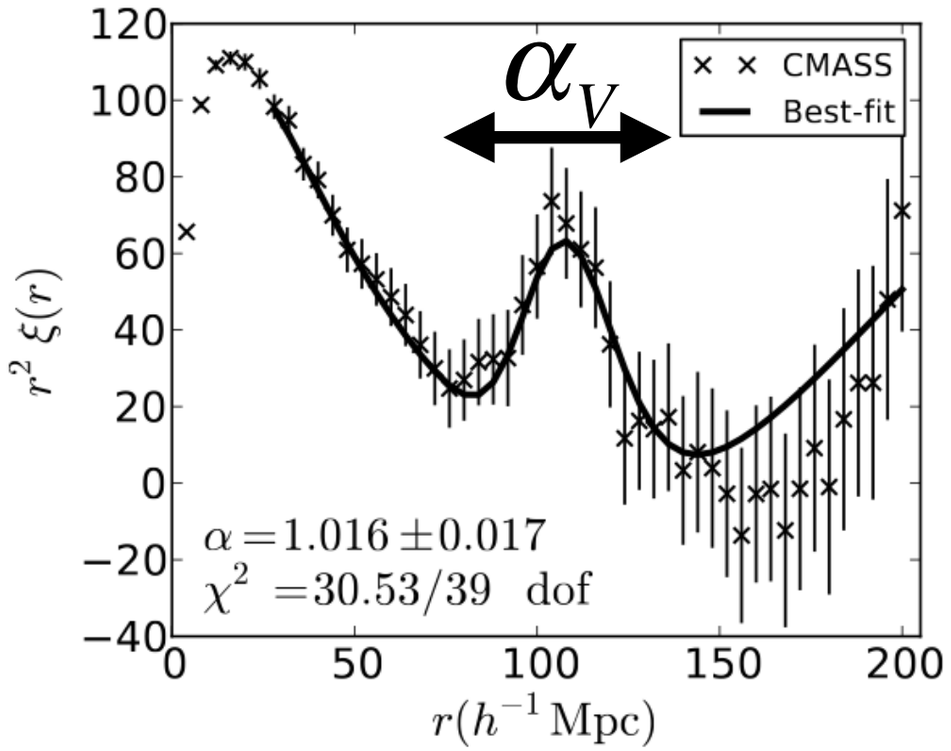
new variables →

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

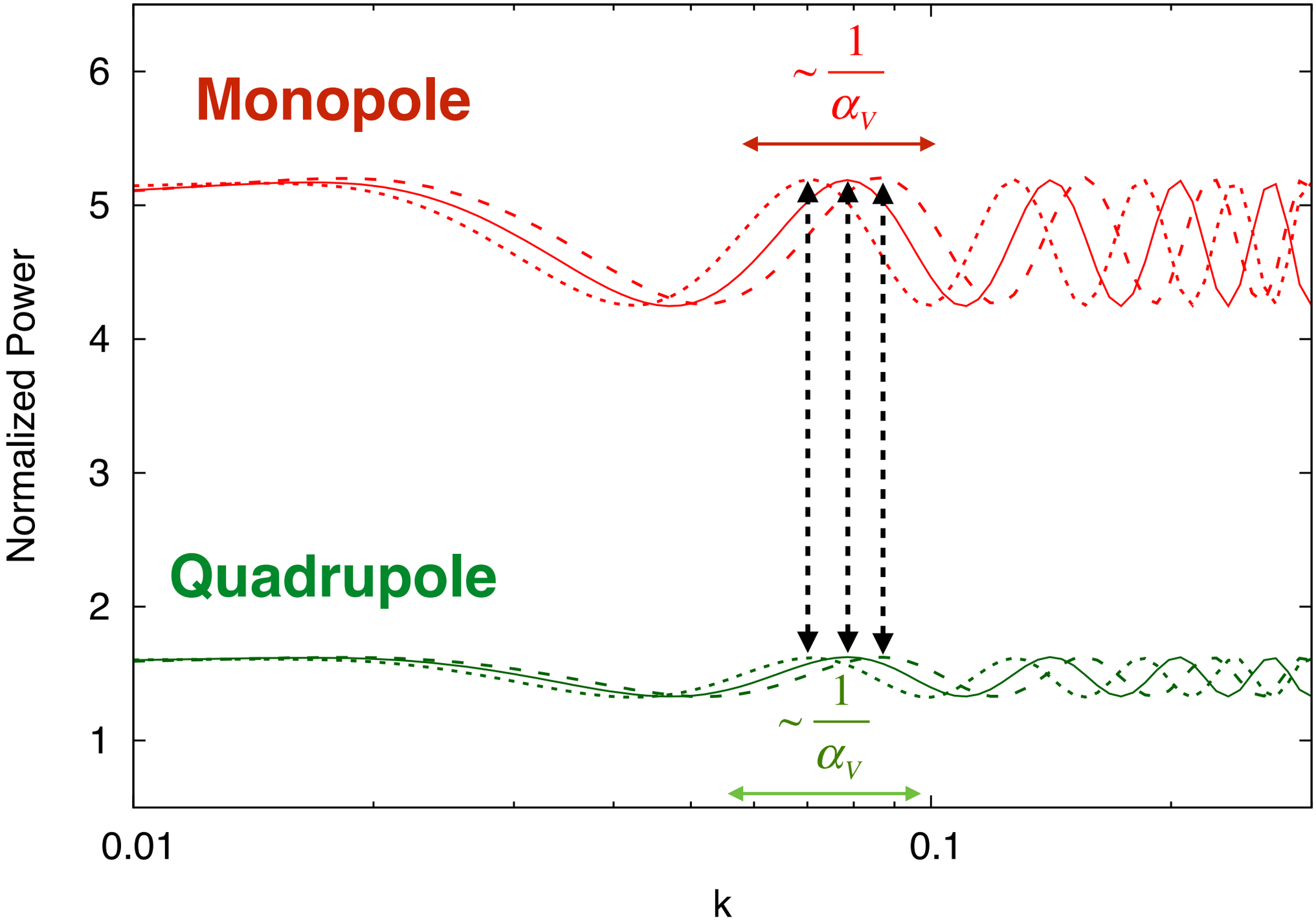


$$\alpha_V(z) = D_V(z) \Big/ D_V(z)^{fid} \times r_s^{fid} / r_s$$

$$D_V(z) = \left[(1+z)^2 D_A{}^2(z) \frac{cz}{H(z)} \right]^{1/3}$$

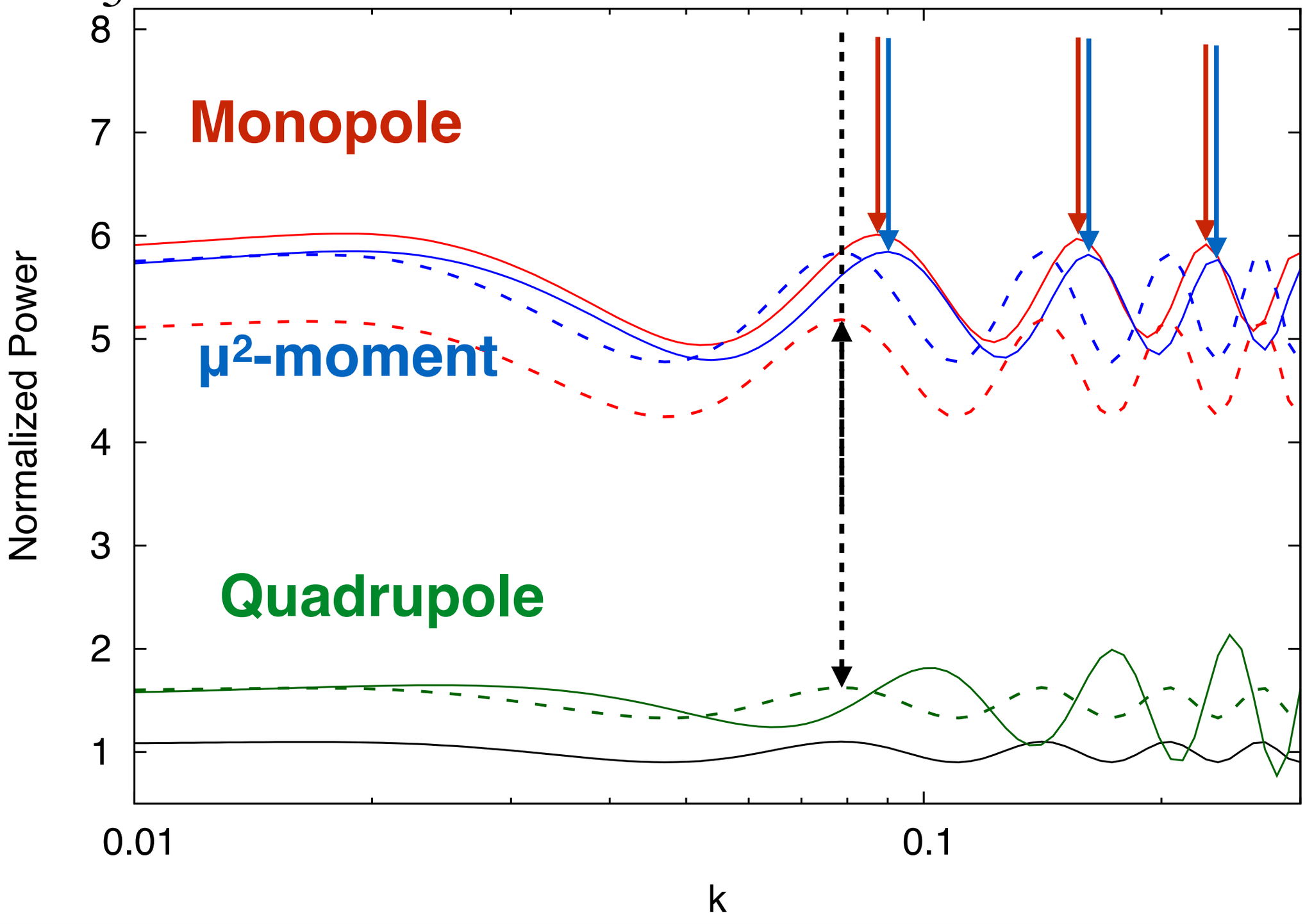
$$\alpha_{\varepsilon}(z) = \frac{D_A(z) H(z)}{[D_A(z) H(z)]^{fid}}$$

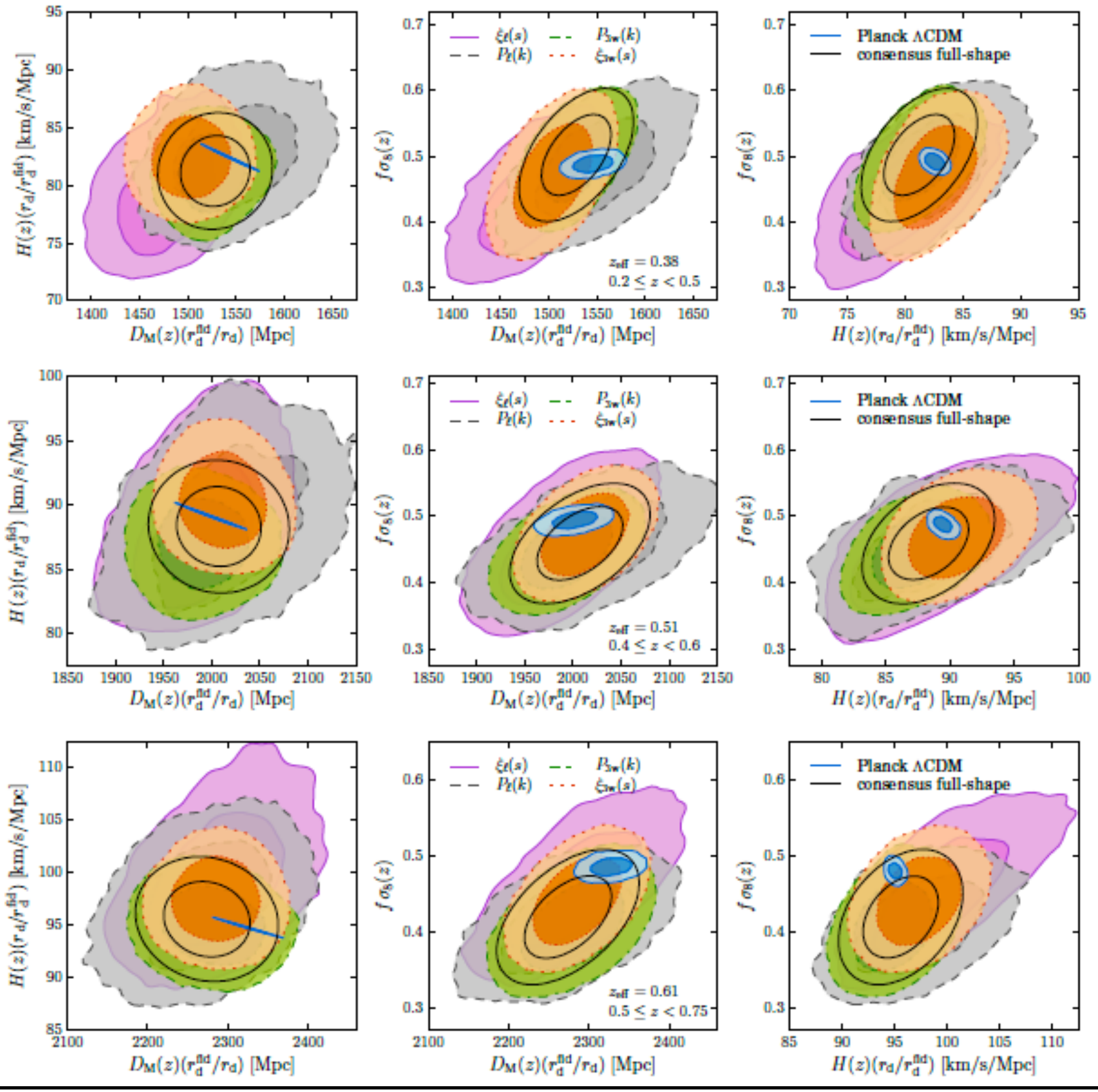
$\alpha_V \sim (D_A^2/H)^{1/3} / r_s$



$\alpha_\varepsilon \sim D_A H$

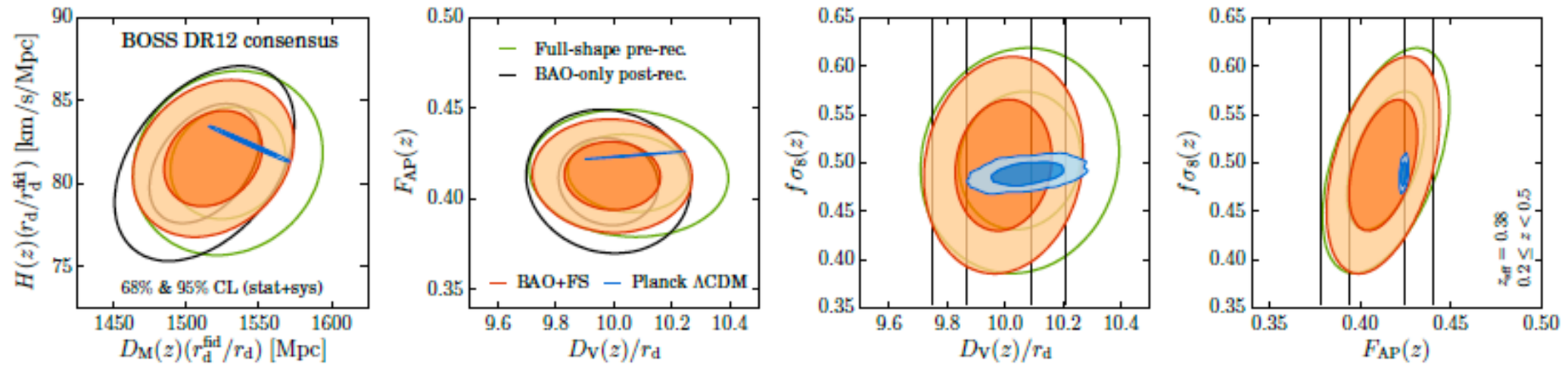
$$P^{(\mu^2)} \equiv P^{(0)} + \frac{2}{5} P^{(2)}$$



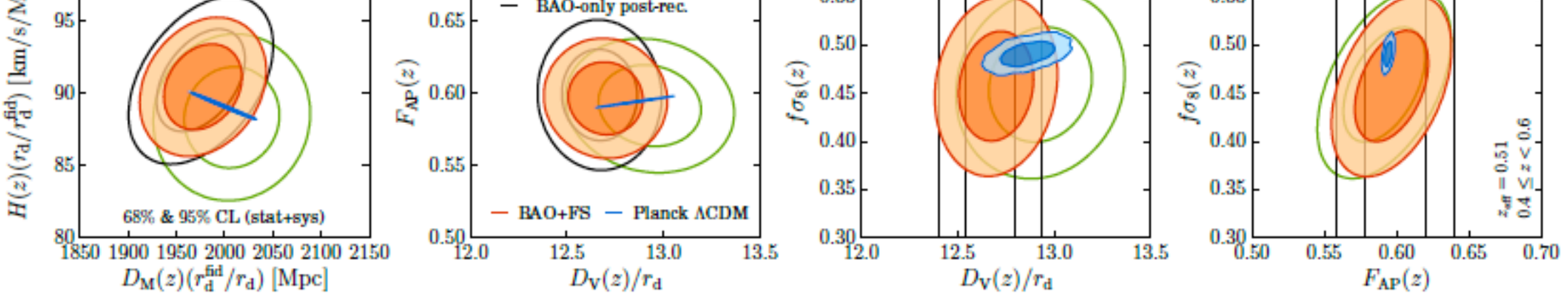


Alam et al. 2016

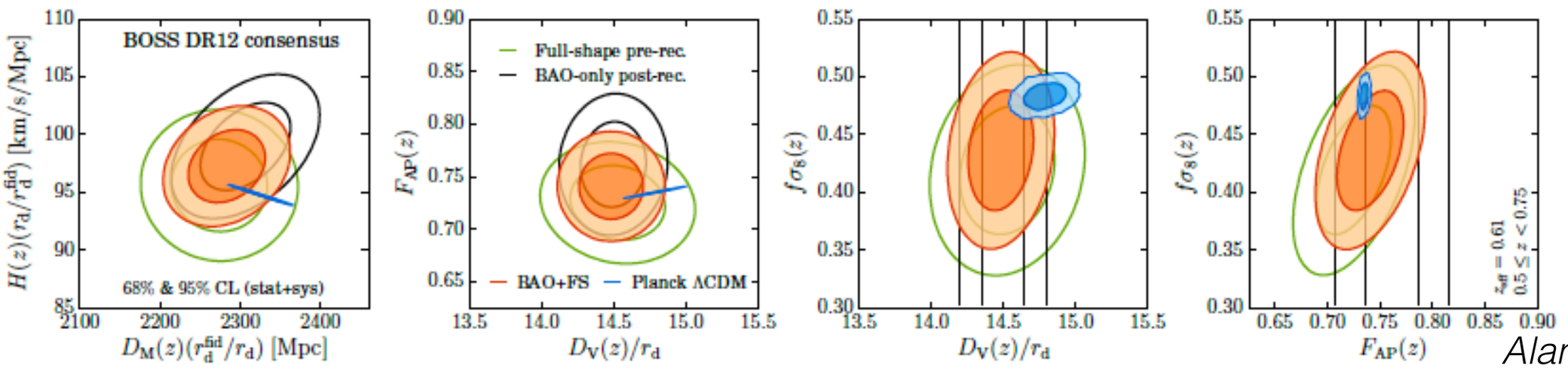
BAO post-recon **RSD Full Shape pre-recon** **Consensus** **Planck**



0.2<z<0.5

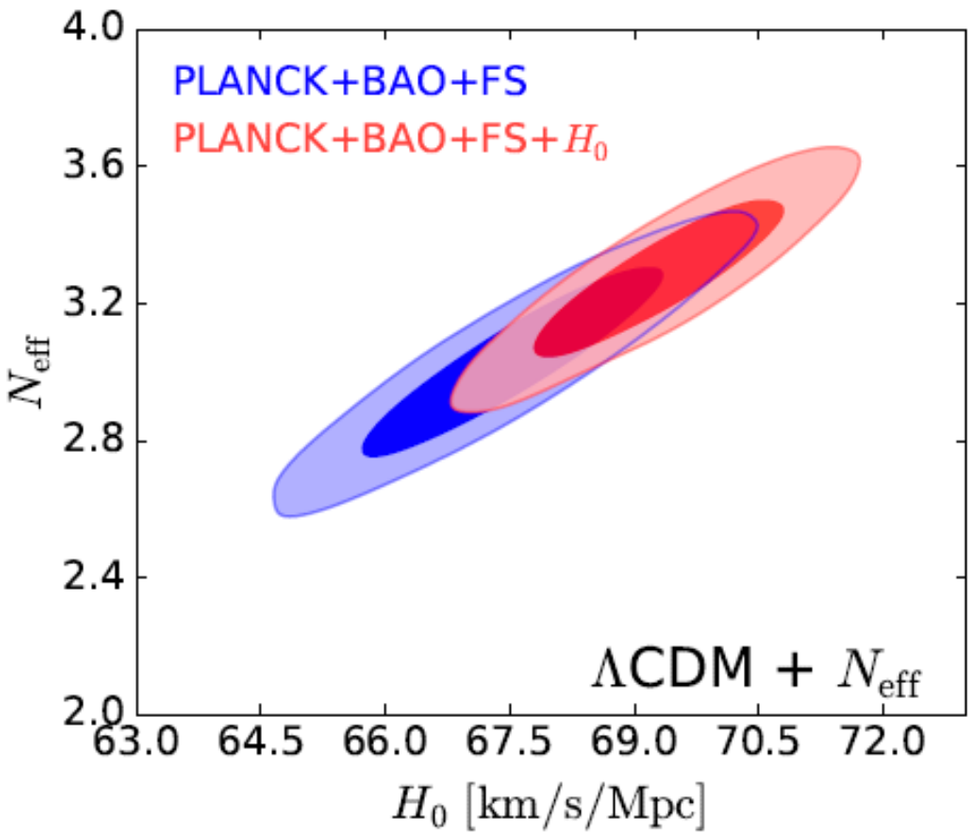


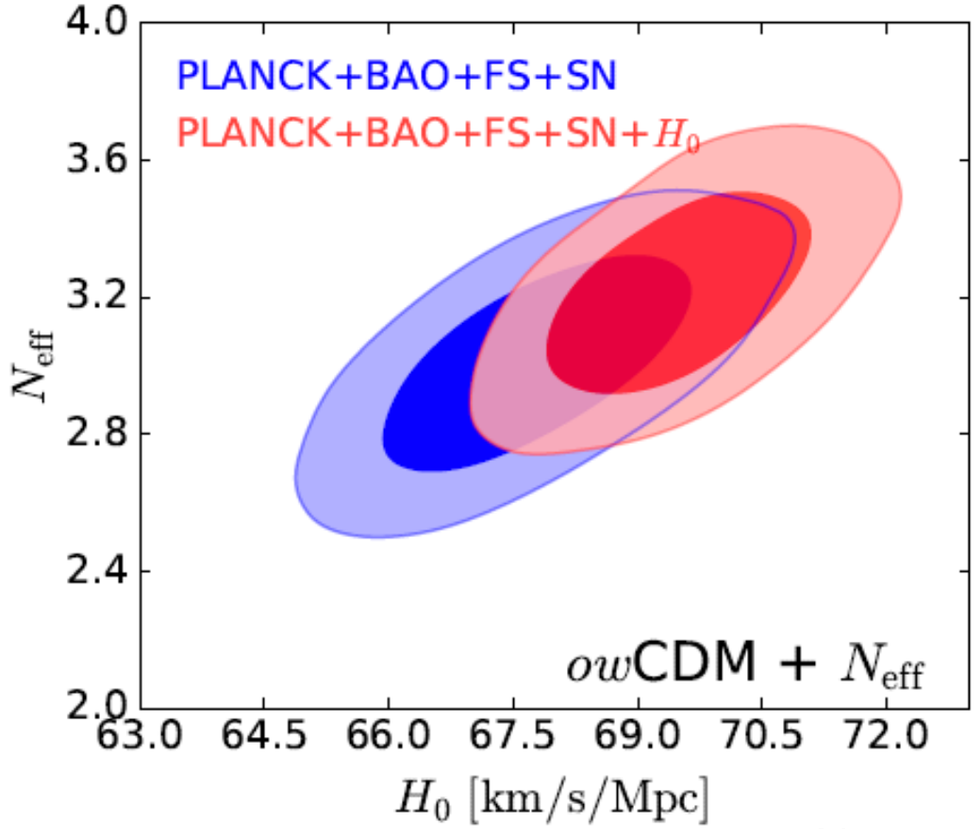
0.4<z<0.6



0.5<z<0.75

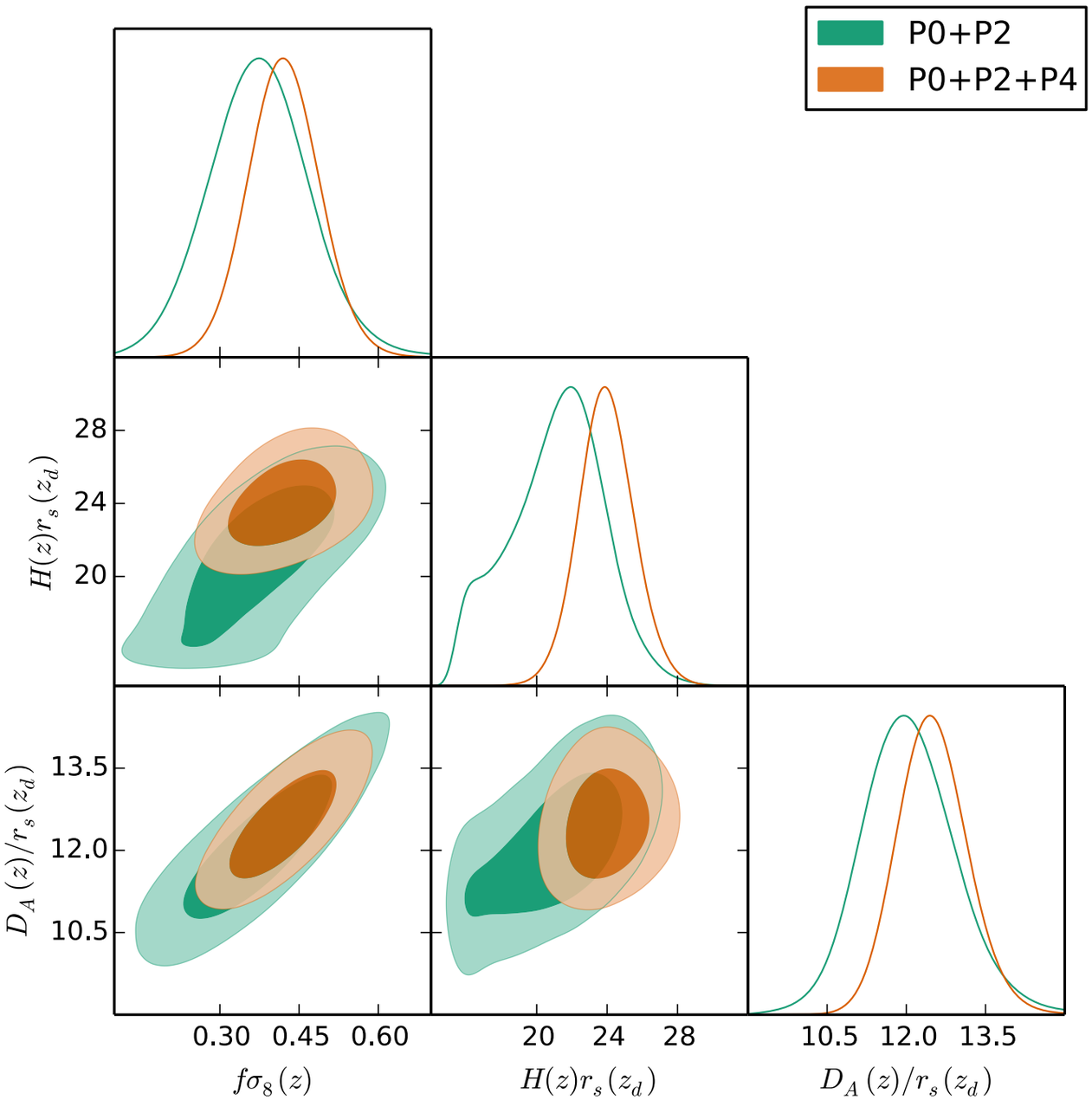
Alam et al. 2016

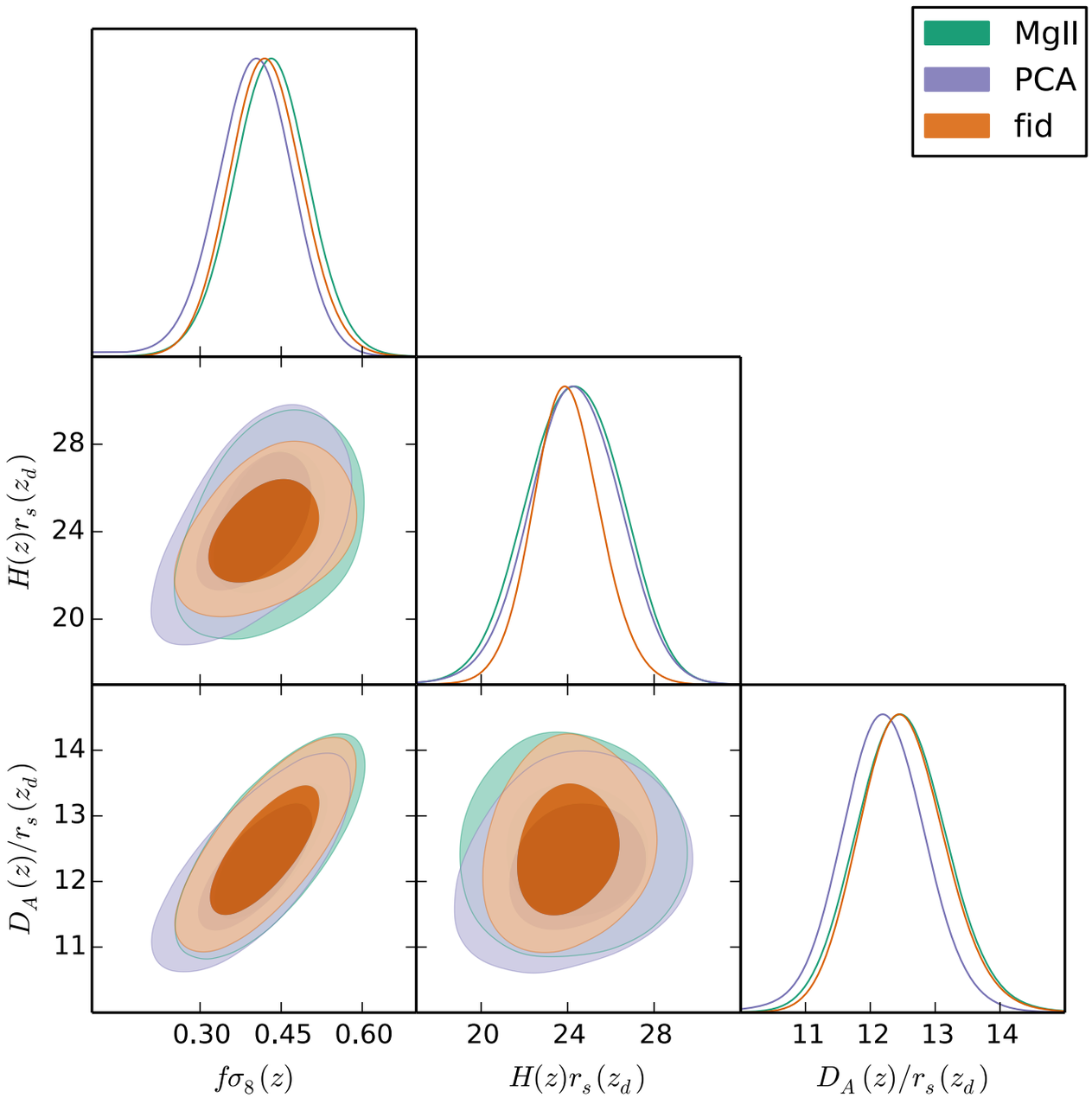




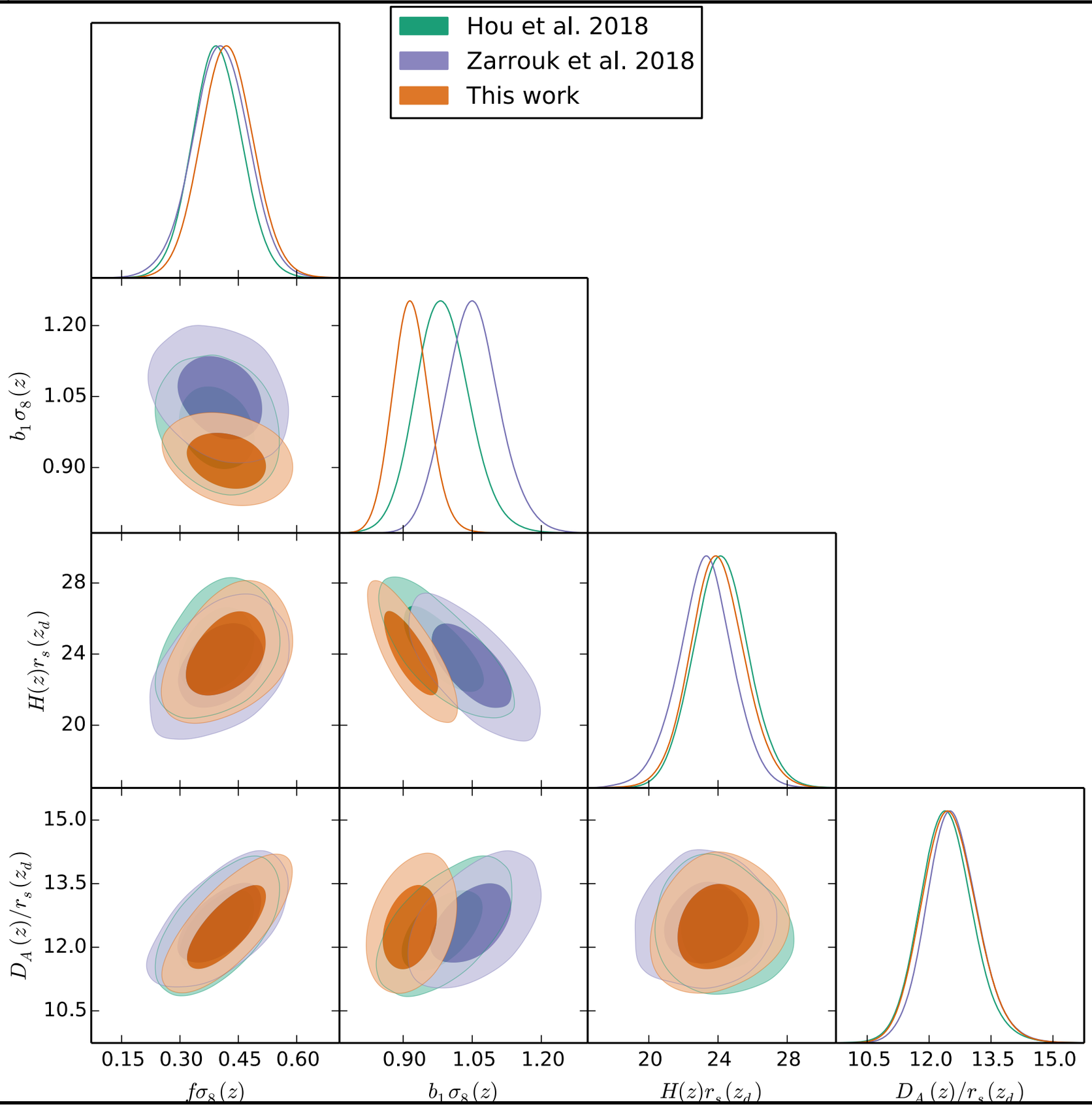
Alam et al. 2016

Tension with local H_0 measurement reduces with Neff>3





HGM et al. 2018



HGM et al. 2018