Measuring cosmological parameters in the large scale structure through redshift space distortions and Alcock-Paczynski effects

Héctor Gil-Marin
Institut de Ciències del Cosmos ICCUB (U. Barcelona)

Laboratório Interinstitucional de e-Astronomia
13th June 2019

ICCUB Institut de Ciències del Cosmos UNIVERSITAT DE BARCELONA

EXCELENCIA MARÍA DE MAEZTU

"la Caixa" Foundation

Outline

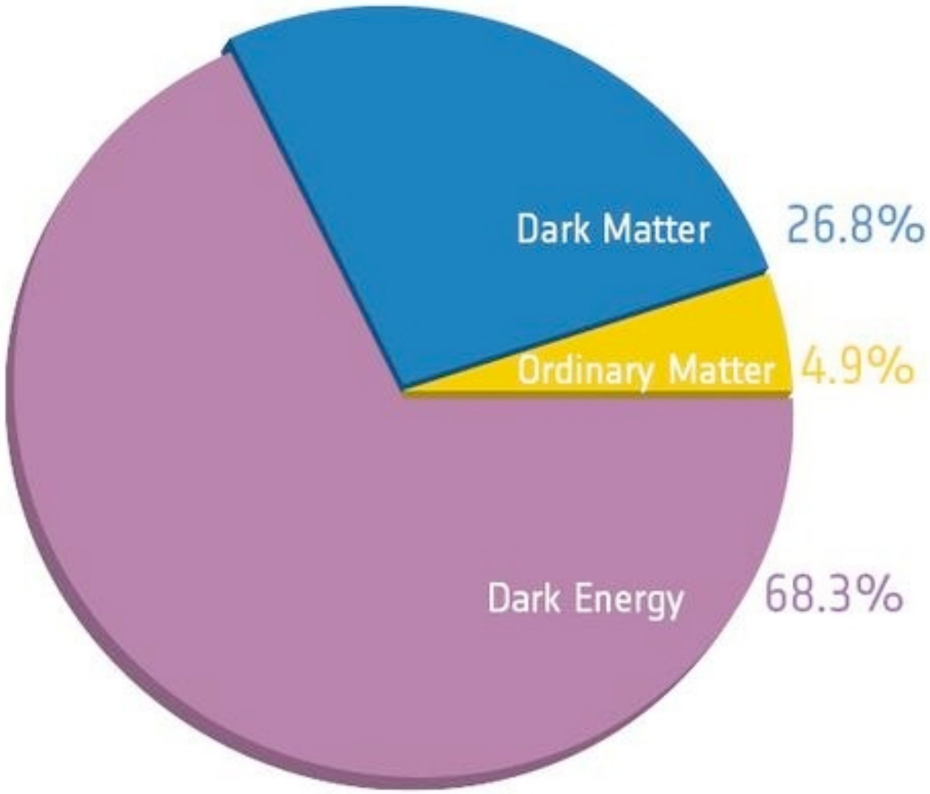
1. Introduction to cosmology with LSS: BAO and RSD

2. Cosmology with galaxy surveys: BOSS & eBOSS

3. Higher-order statistics: the bispectrum

4. Future analyses: DESI

Cosmological Standard Model



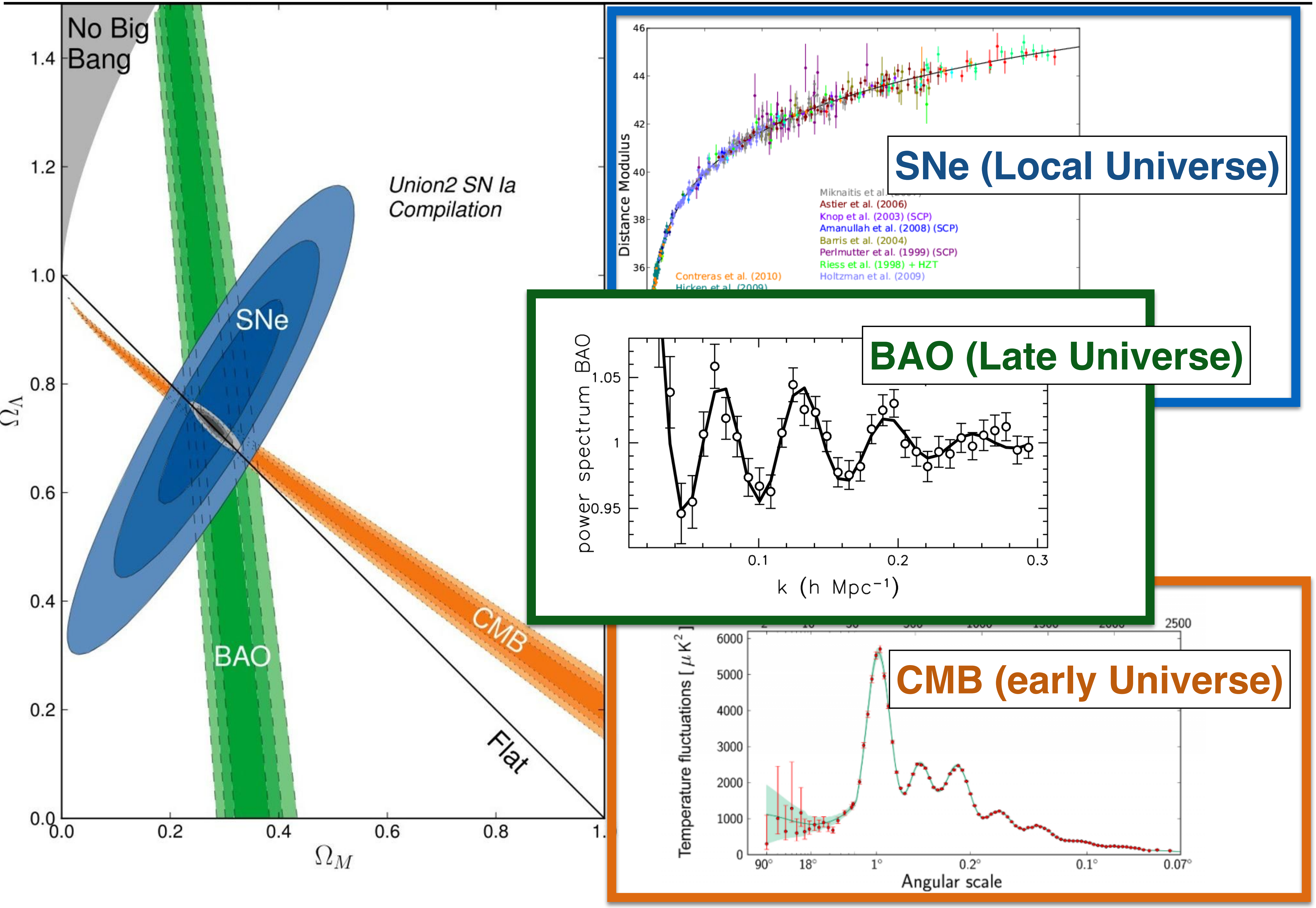
CMB observations (WMAP, Planck)

- Flat Universe
- Universe dominated by **dark** components

Within the context of GR **Dark Energy** is understood as a macroscopic manifestation of the quantum vacuum energy

Other possibilities: modify GR, scalar field, …

Different expansion rate through time and different logarithmic growth of structure factor.


No Big Bang
Union2 SN Ia Compilation
SNe
BAO
CMB
Flat
Ω_Λ
Ω_M
Distance Modulus
SNe (Local Universe)
Miknaitis et al
Astier et al. (2006)
Knop et al. (2003) (SCP)
Amanullah et al. (2008) (SCP)
Barris et al. (2004)
Perlmutter et al. (1999) (SCP)
Riess et al. (1998) + HZT
Holtzman et al. (2009)
Contreras et al. (2010)
BAO (Late Universe)
power spectrum BAO
k (h Mpc⁻¹)
CMB (early Universe)
Temperature fluctuations [μK²]
Angular scale

Baryon Acoustic Oscillations

Before recombination **After recombination**

at z~1100

$p^+ + e^- \longrightarrow H$

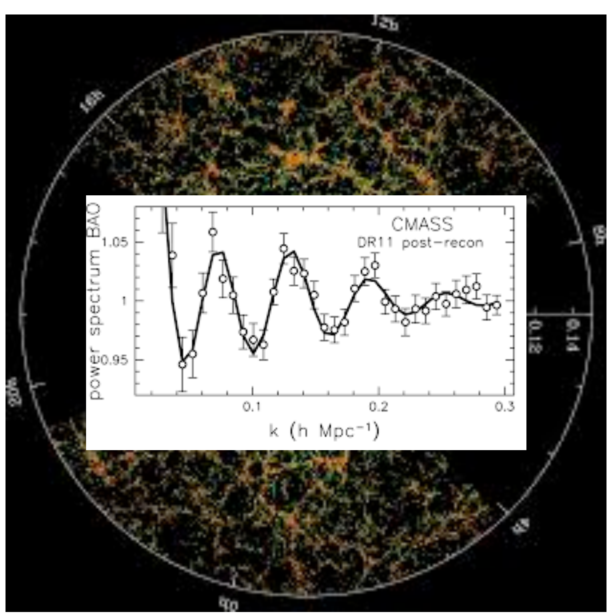
Baryons+DM

Wave propagation frozen

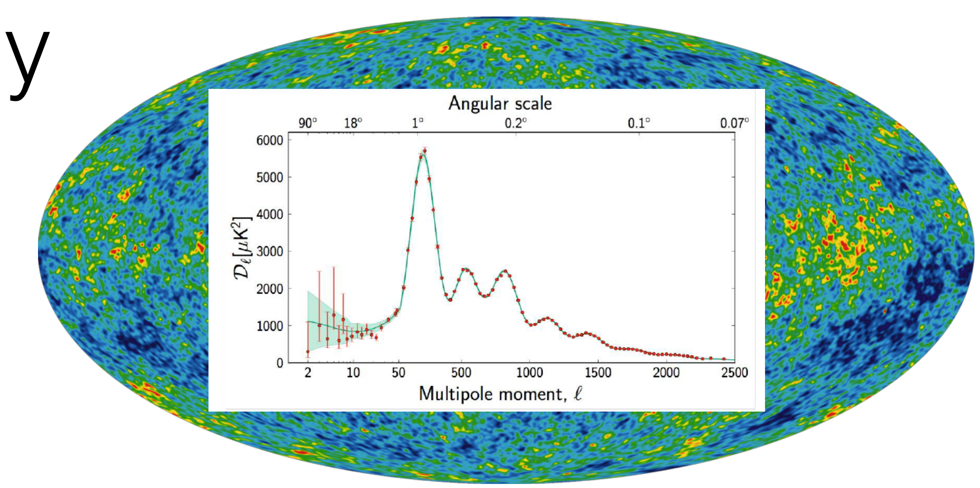
photons

Galaxies

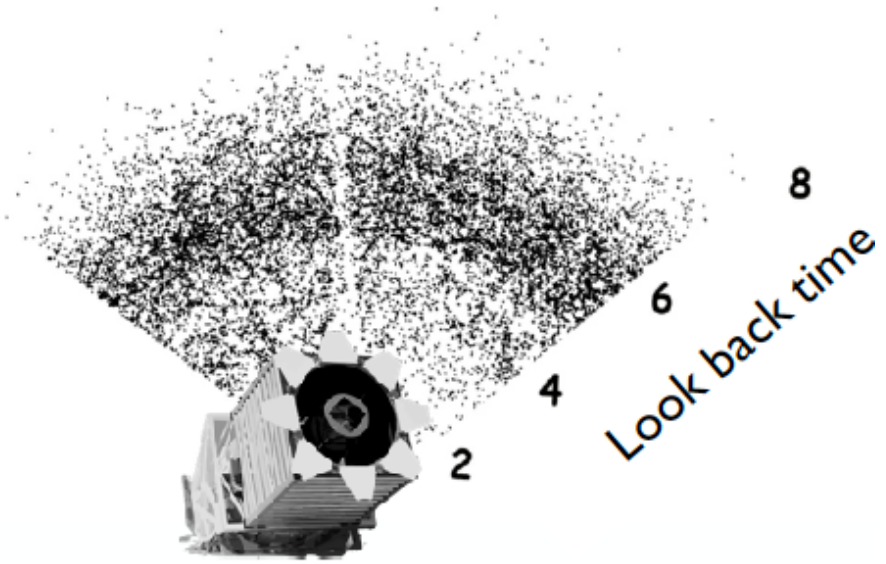
CMB

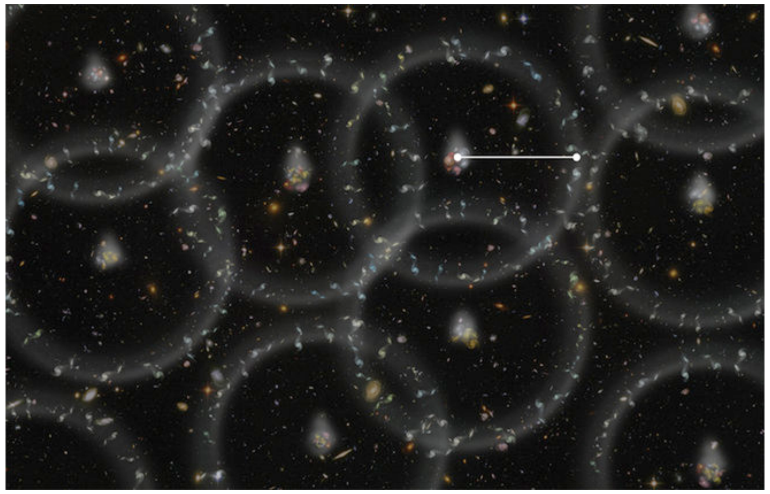


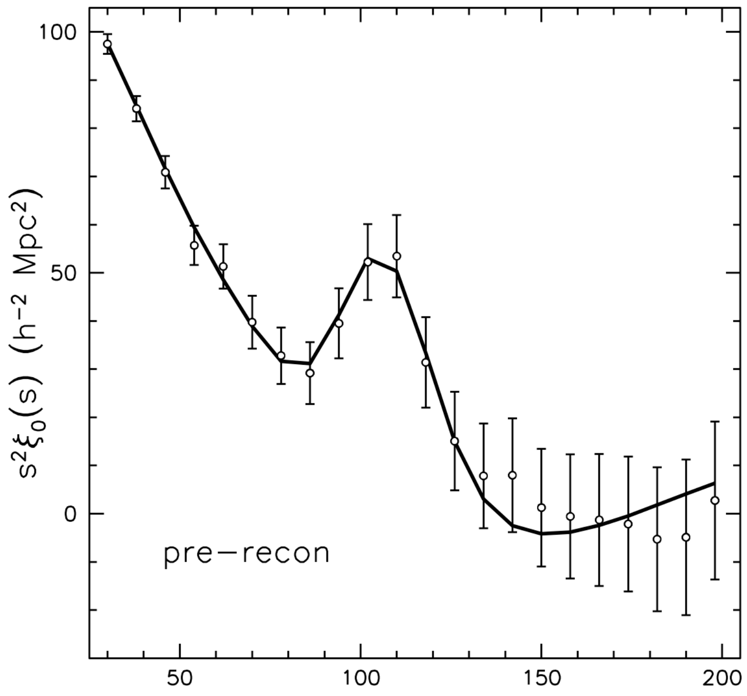
- Physics in early Universe
- Accelerated expansion at late times



Main Goal of redshift surveys: BAO & RSD







Main Goal of redshift surveys: BAO & RSD

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

BAO peak position: Isotropic signal ~ $(D_A{}^2/H)^{1/3} / r_s$

BAO relative peak position: isotropic vs. anisotropic ~ $D_A H$

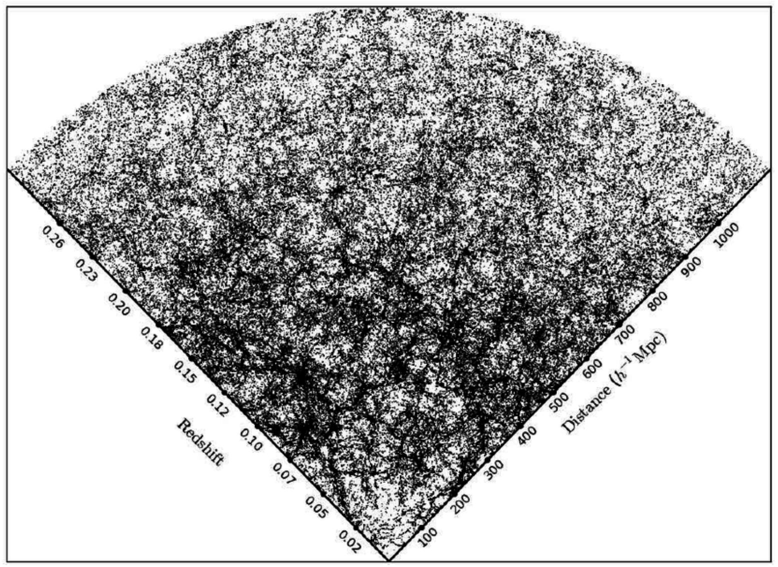
$$H(z, \boldsymbol{\Omega}) = H_0 \sqrt{\Omega_m^0 (1+z)^3 + \Omega_\Lambda}$$

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

$$f(z, \boldsymbol{\Omega}) = \frac{d \log D_{\rm lin}(z, \boldsymbol{\Omega})}{d \log a(z)} = \Omega_m(z, \boldsymbol{\Omega})^\gamma$$

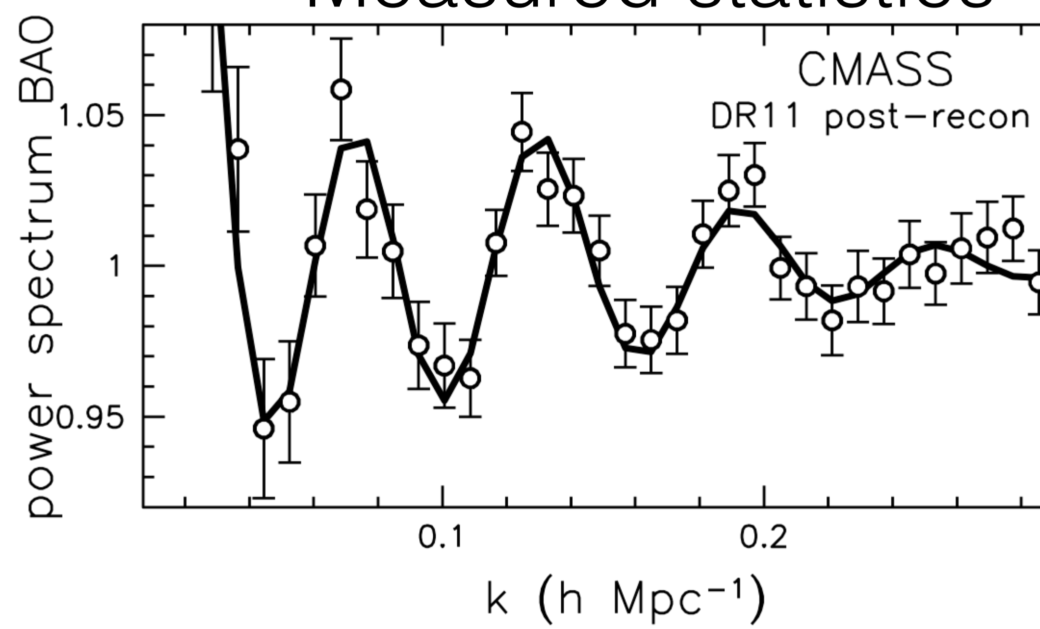
Clustering of Tracers: What do we measure?

Galaxy Catalogue



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

Measured statistics



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} & $\Omega_{\mathrm{fiducial}}$

- Dark matter over-density, $\delta(r) \equiv \frac{\rho(r)}{\bar{\rho}} - 1 \quad \delta(k) = \int \delta(r) e^{ikr}\, dx$

- 2-point correlation function (2pCF), $\langle \delta(r)\delta(r+R) \rangle = \xi(R)$

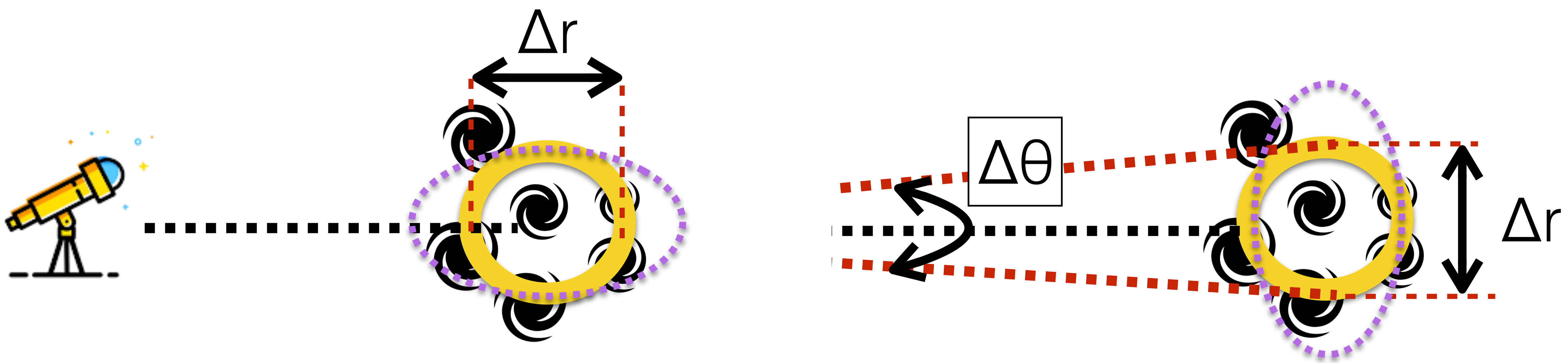
- Power Spectrum (PS) $\langle \delta(k)\delta^*(k') \rangle = (2\pi)^3 P(k) \delta^D(k+k')$

The PS and 2pCF are the *observables* for RSD and BSO

δ-field is fully characterised by PS/2pCF if δ is Gaussian

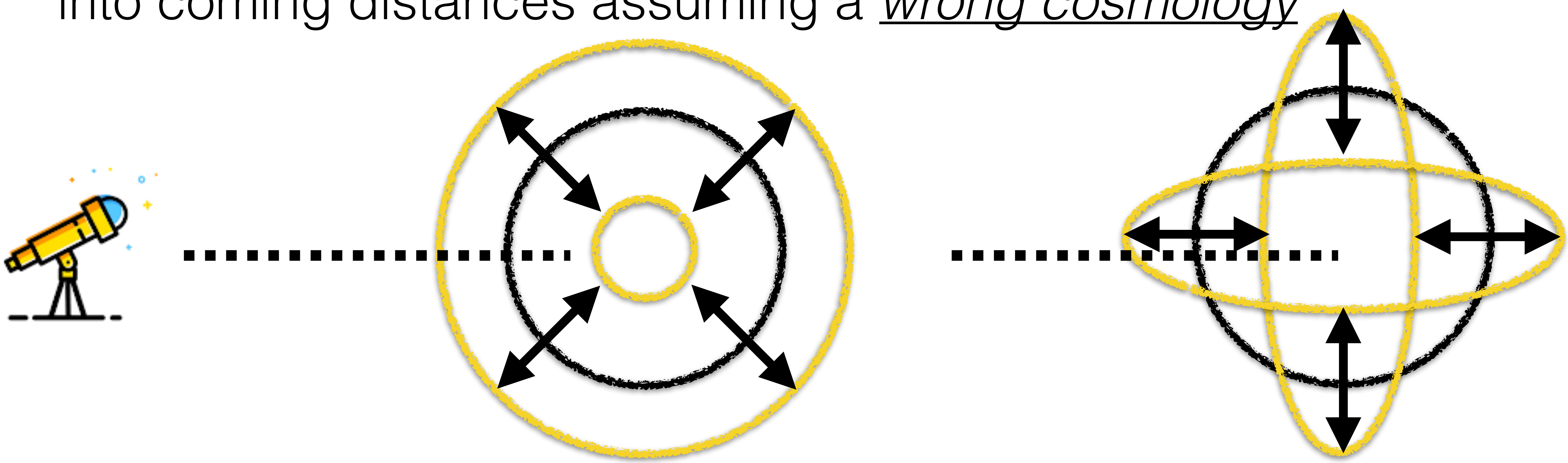
Alcock-Paczynski & Redshift Space Distortions

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



Alcock-Paczynski & Redshift Space Distortions

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



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

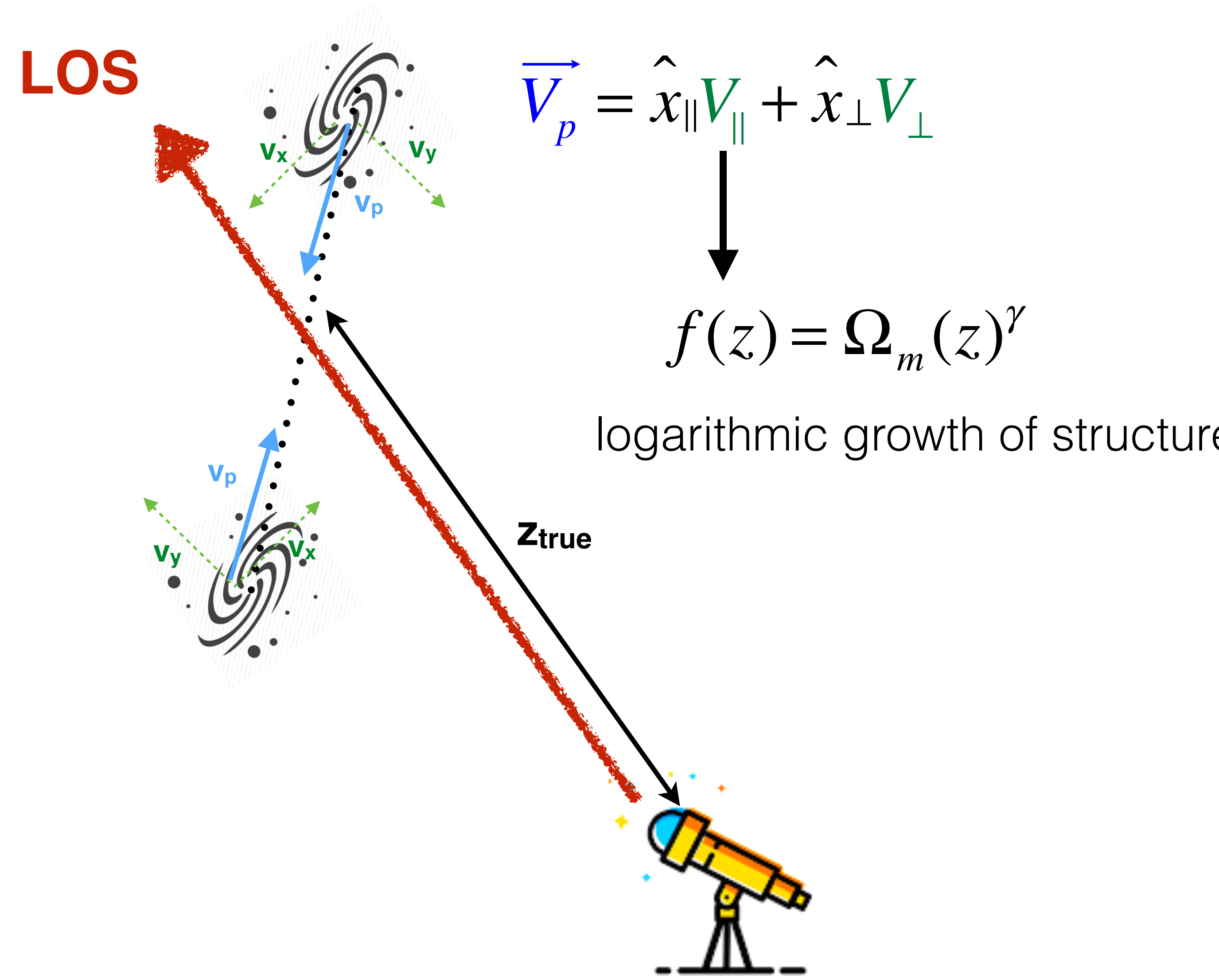
$\sim D_A H$

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

$\sim f\sigma_8$



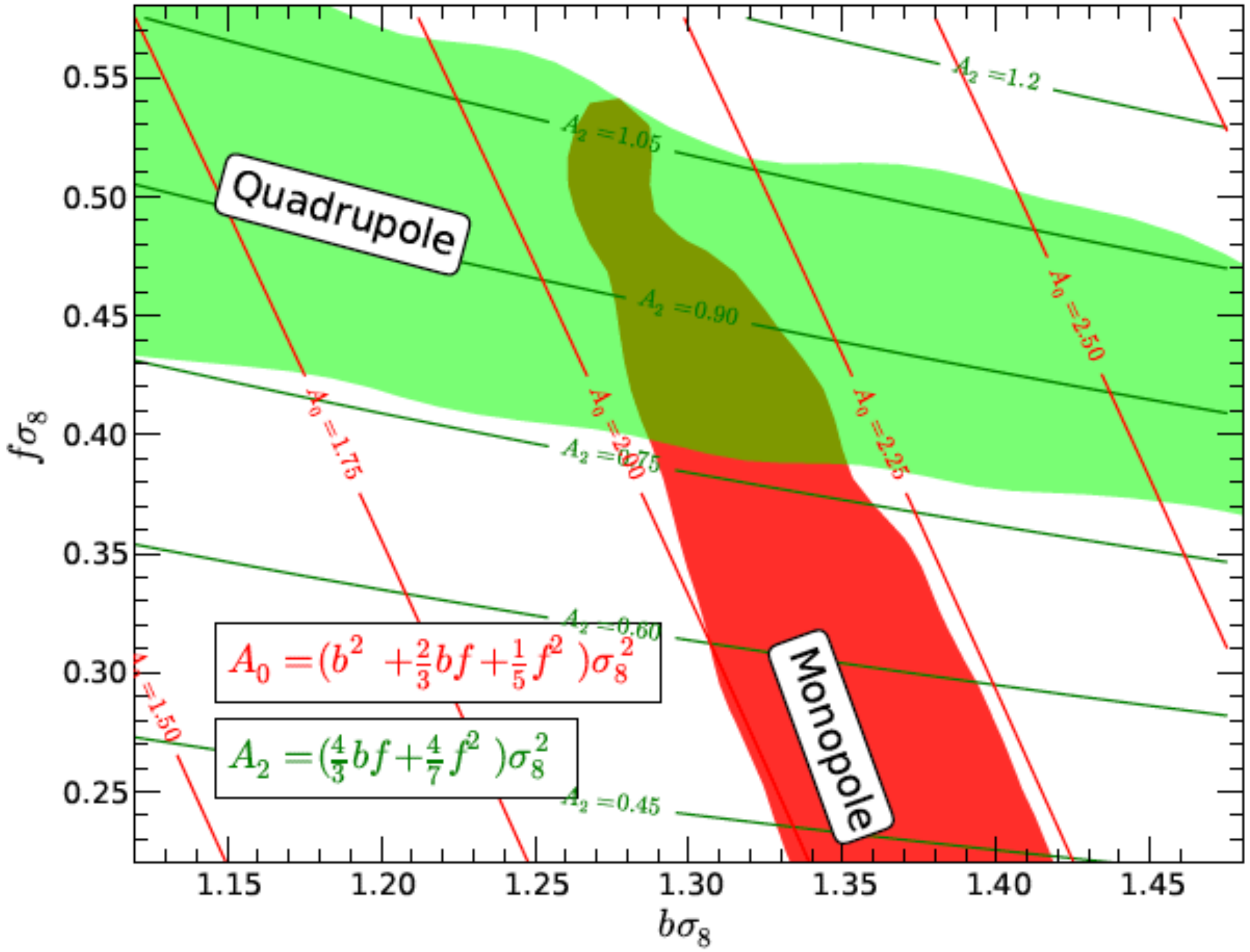
Redshift Space Distortions

$$P_g^{(s)}(k,\mu)=\left[b+f\mu^2\right]^2 P_m(k) \longrightarrow \text{Measure } \boldsymbol{f}$$

$$P^{(s)}(k,\mu)=P^{(0)}(k)L_0(\mu)+P^{(2)}(k)L_2(\mu)+P^{(4)}(k)L_4(\mu)$$

monopole quadrupole hexadecapole

(Samushia et al. 2013)



$$P^{(0)}(k)=(b^2+\frac{2}{3}bf+\frac{1}{5}f^2)P_m(k)$$

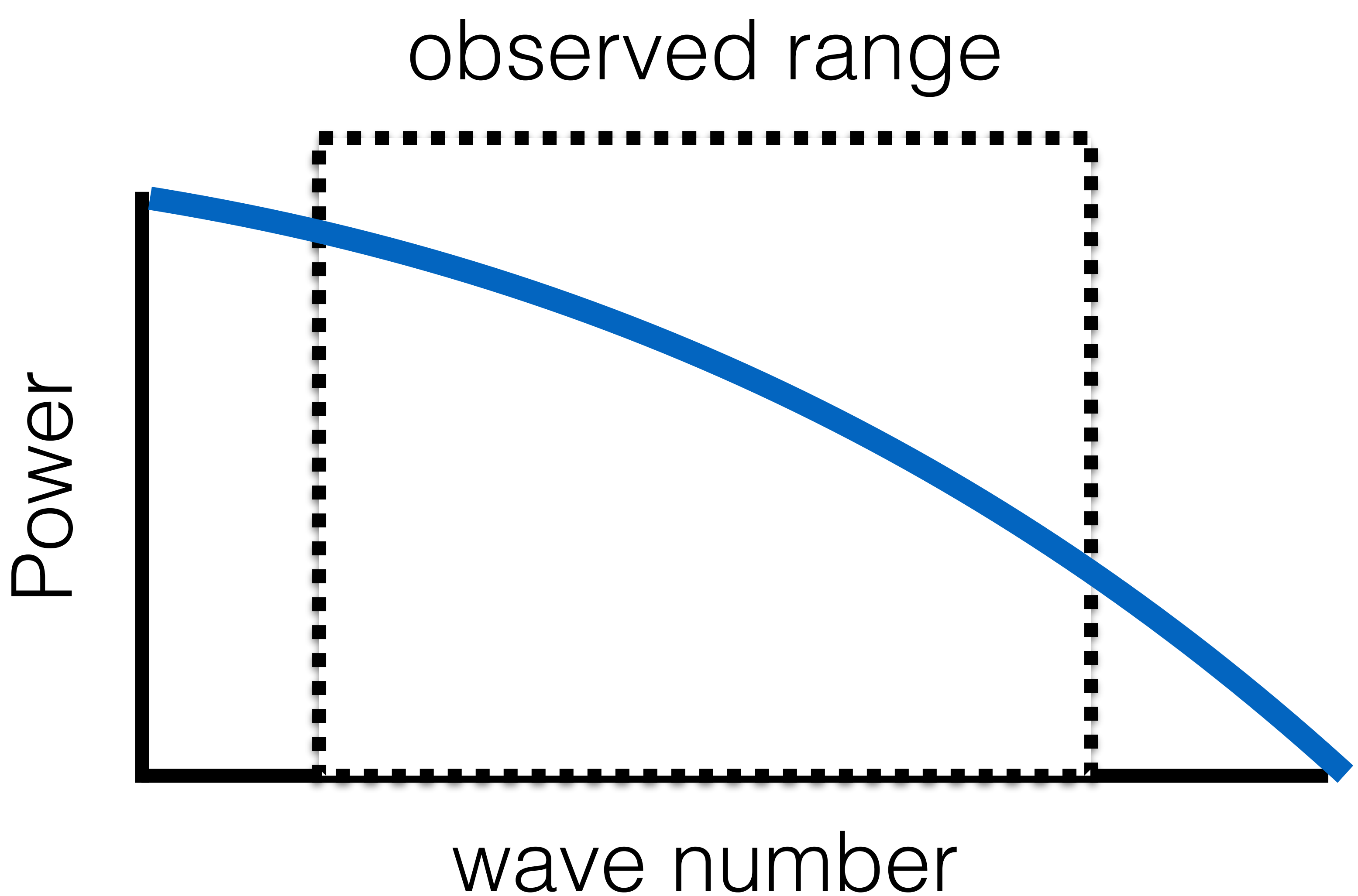
$$P^{(2)}(k)=(\frac{4}{3}bf+\frac{4}{7}f^2)P_m(k)$$

$$P^{(4)}(k)=(\frac{8}{35}f^2)P_m(k)$$

- Degeneration between f and b is broken when at least 2 multipoles are considered.
- In the limit f $\longrightarrow$ 0 we recover the expressions for no-RSD (isotropy)

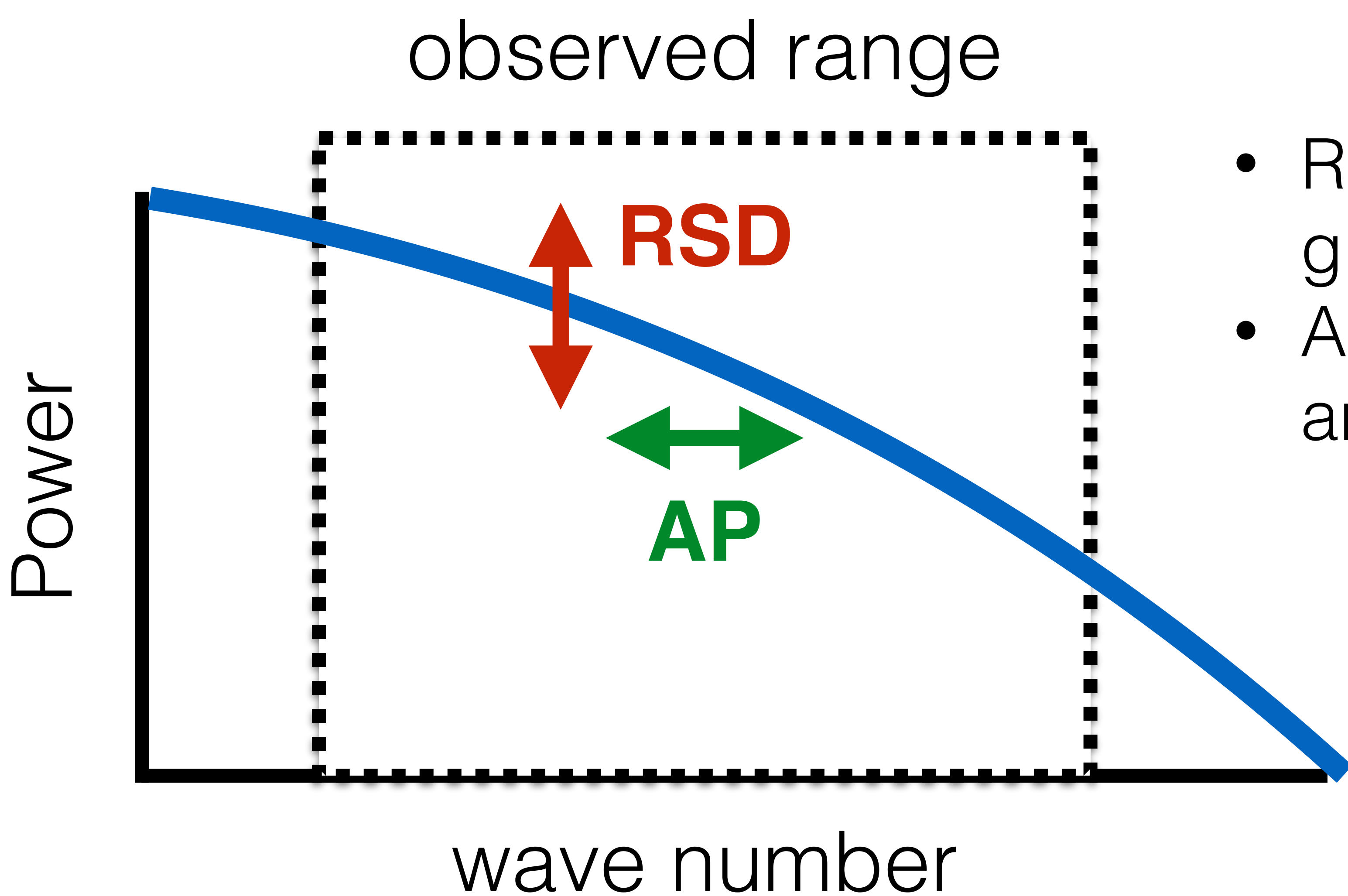
BAO as standard ruler

- 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



BAO as standard ruler

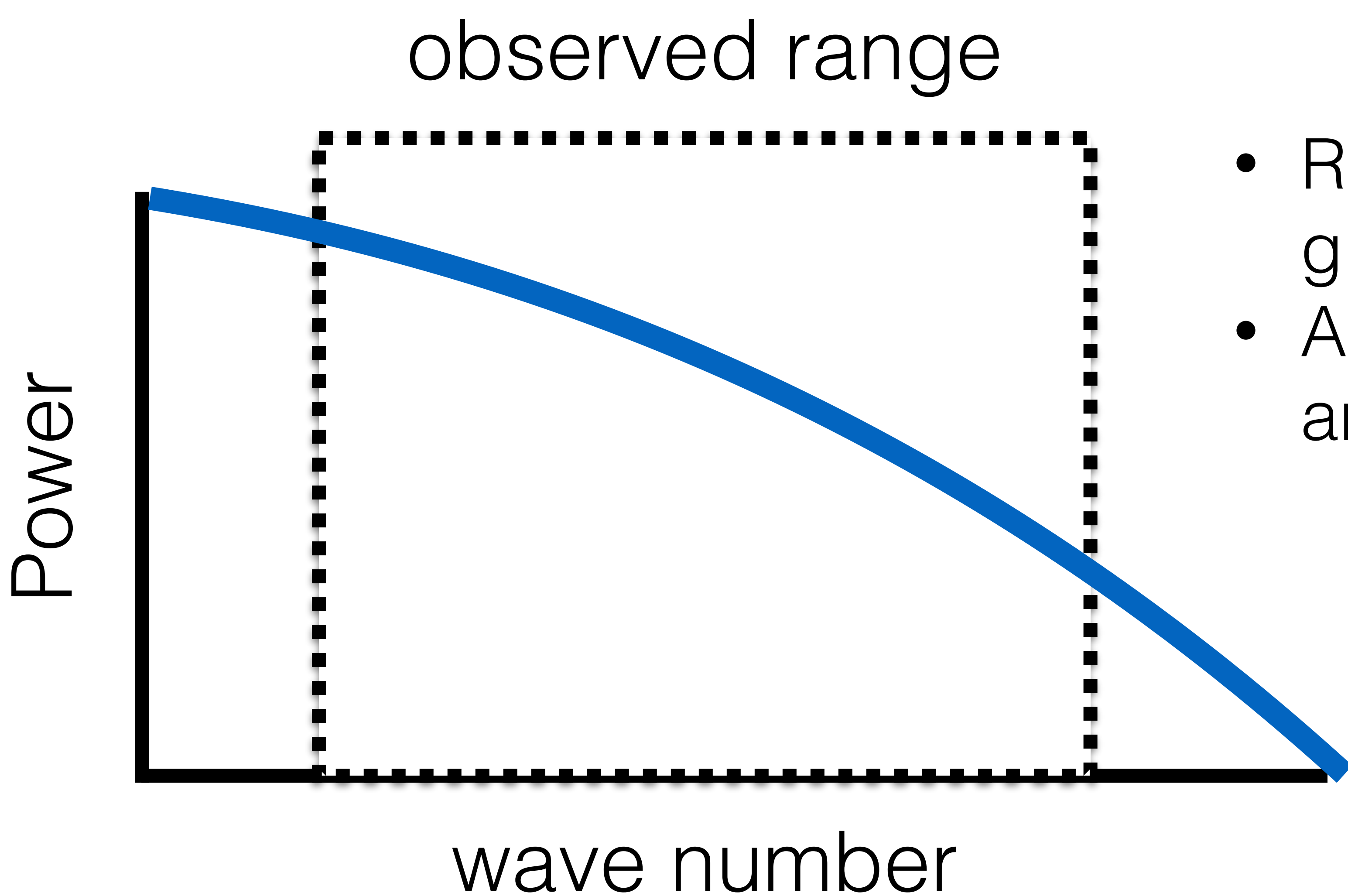
- The sound horizon scale is well determined by CMB measurements (helps to calibrate)
- We can separate the effect of cosmological distortions (AP) from other effects such as RSD



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

BAO as standard ruler

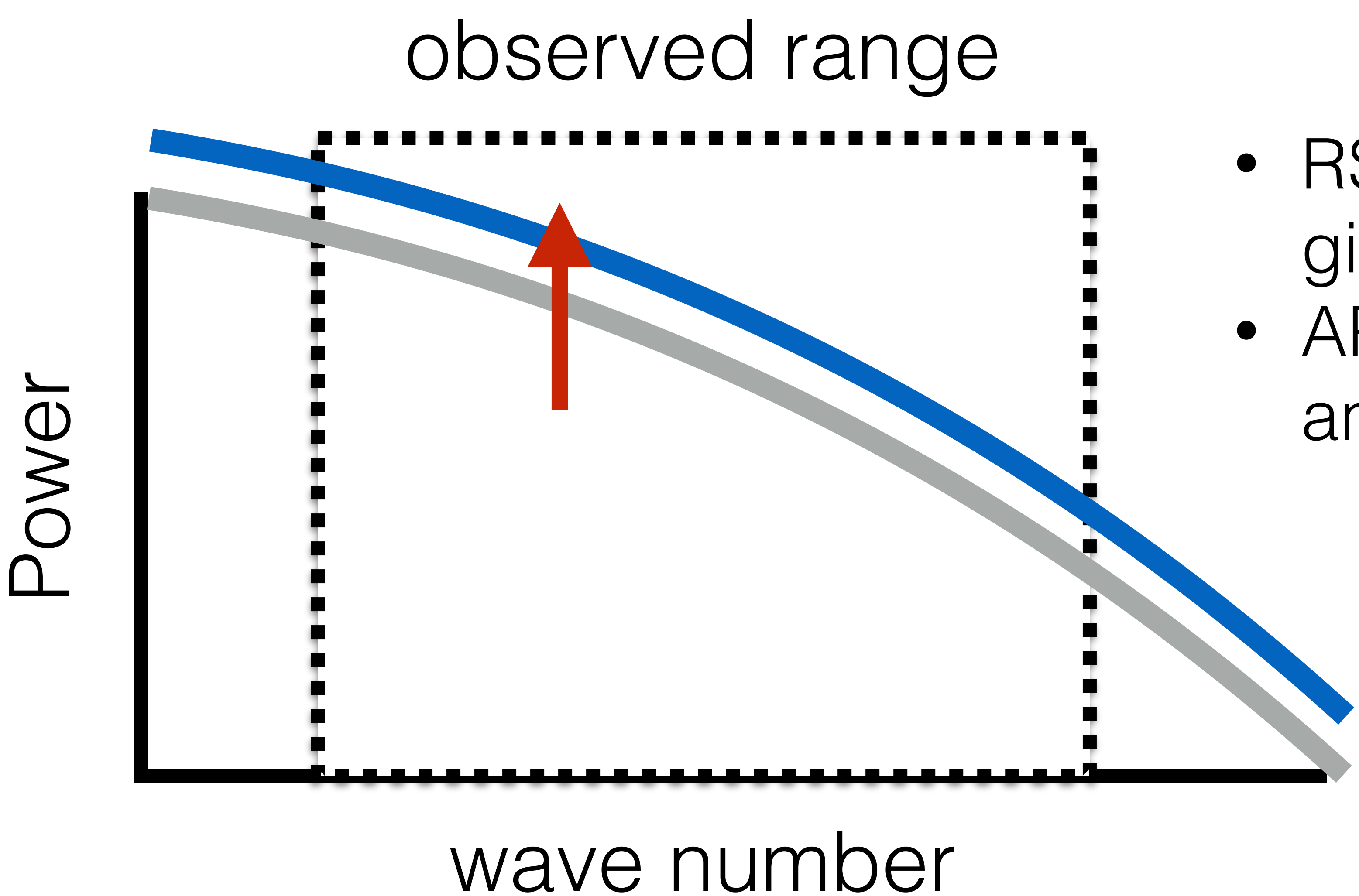
- The sound horizon scale is well determined by CMB measurements (helps to calibrate)
- We can separate the effect of cosmological distortions (AP) from other effects such as RSD



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

BAO as standard ruler

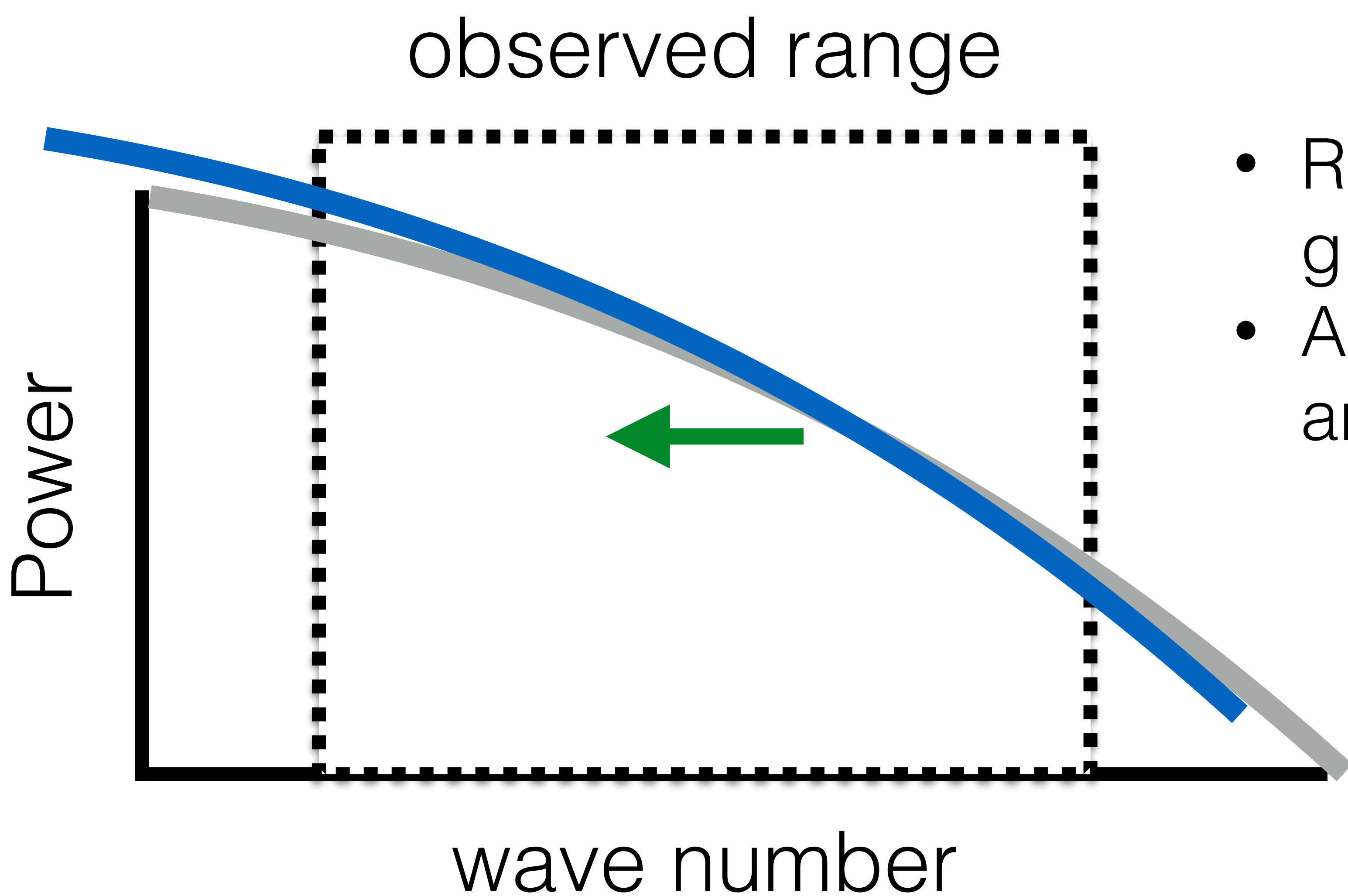
- The sound horizon scale is well determined by CMB measurements (helps to calibrate)
- We can separate the effect of cosmological distortions (AP) from other effects such as RSD



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

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

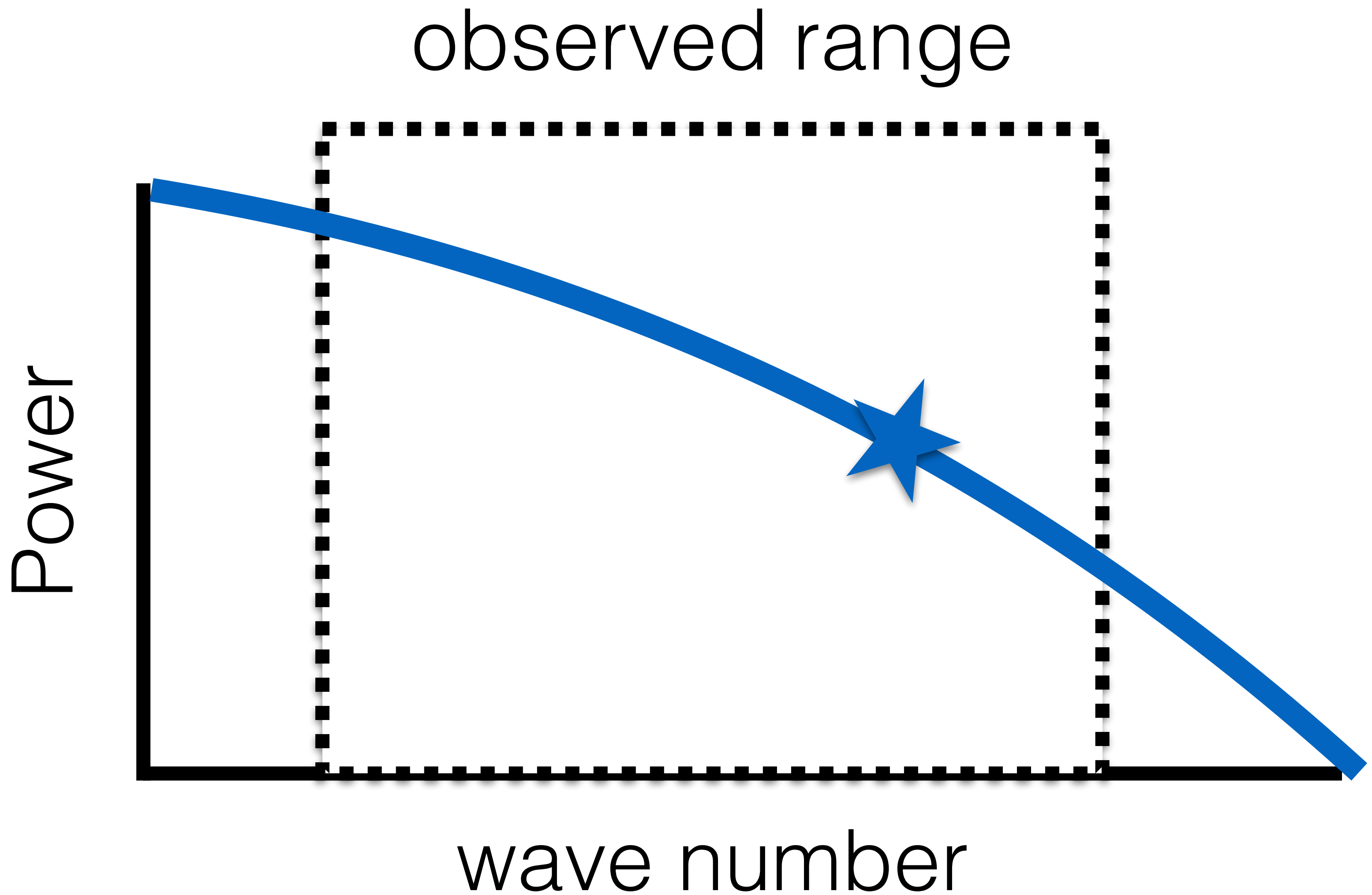


- RSD enhance the Power at a given scale
- AP shift the power of a scale to another scale

Difficult to disentangle: RSD & AP

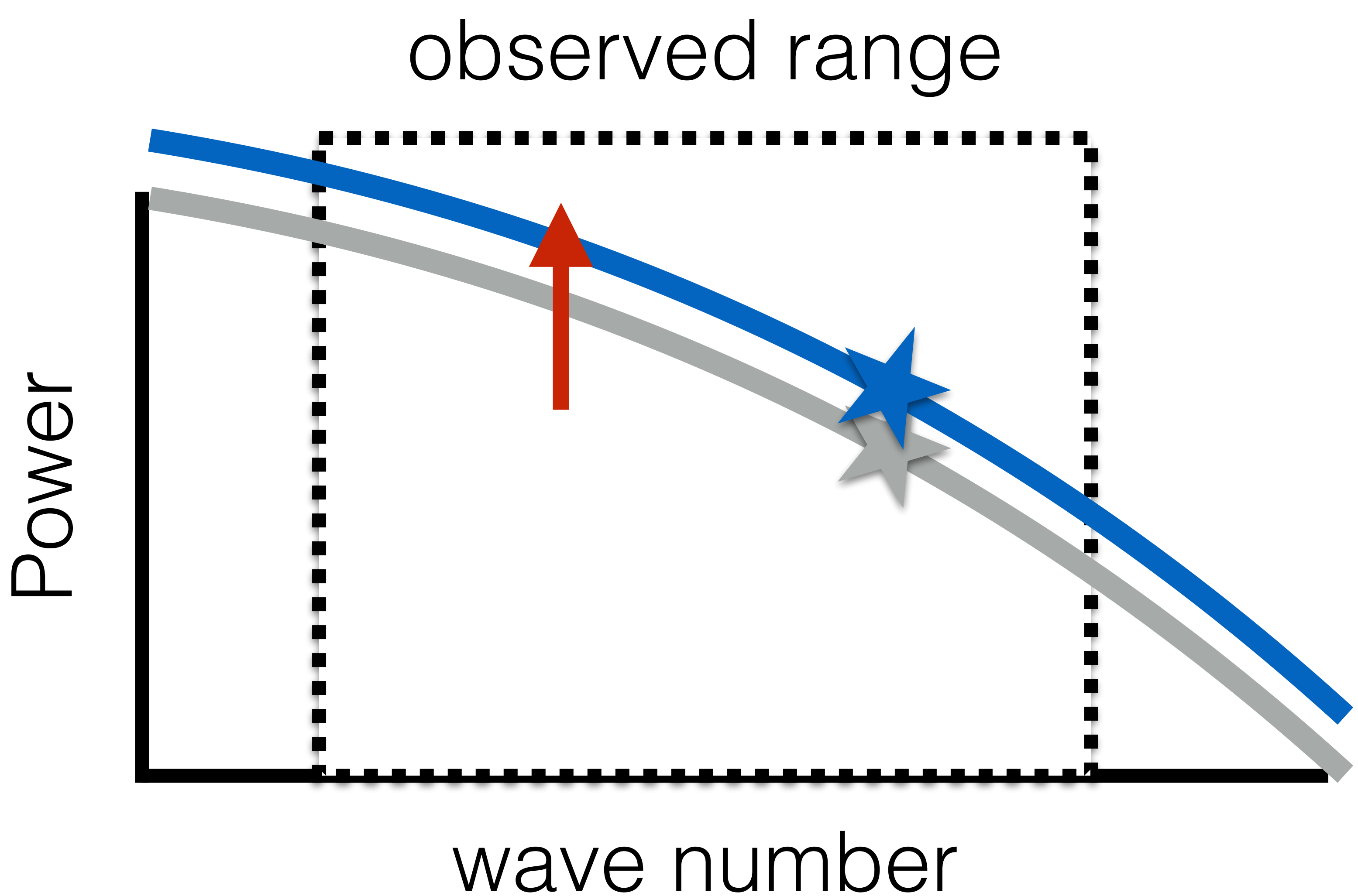
BAO as standard ruler

- 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



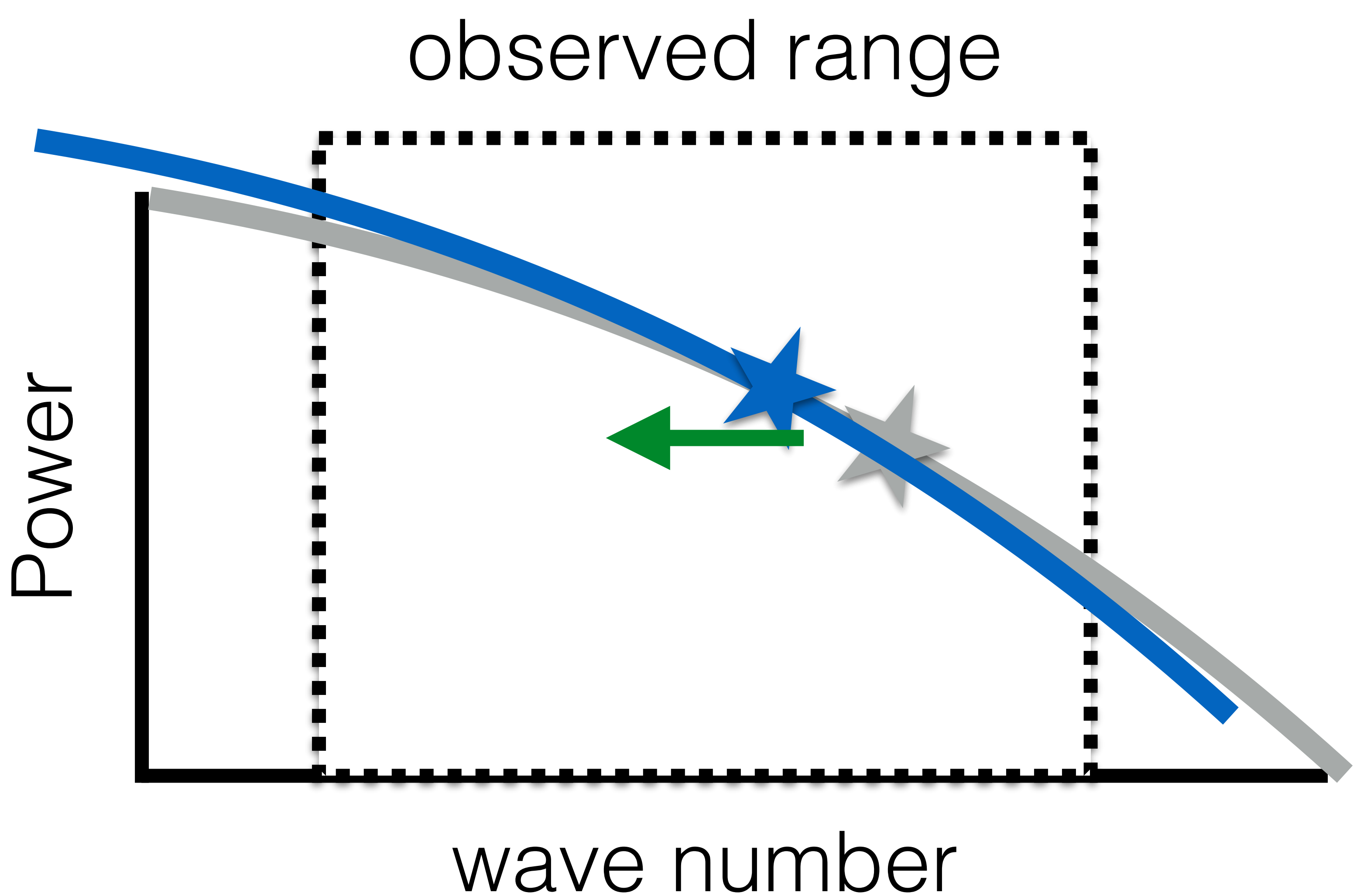
BAO as standard ruler

- 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



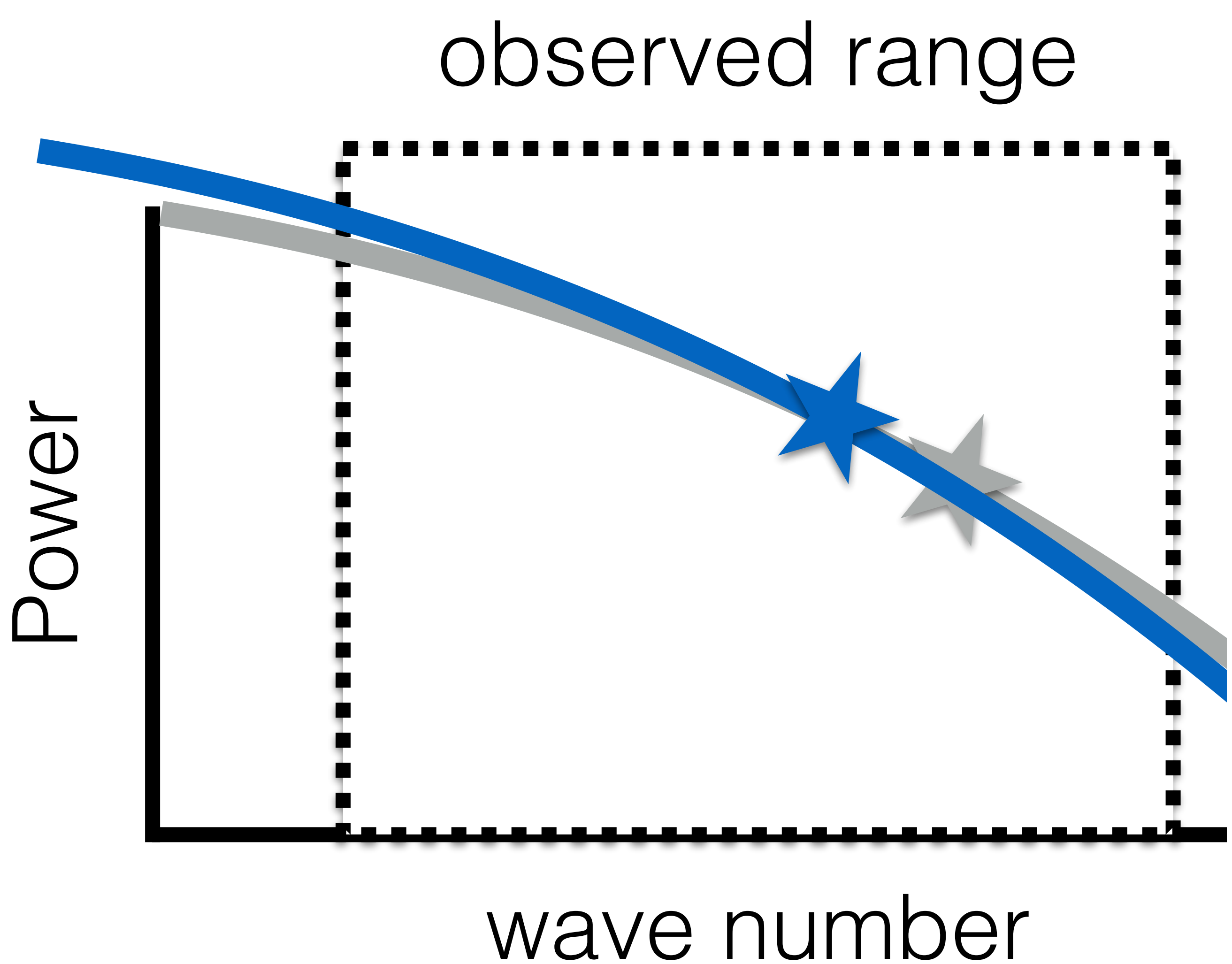
BAO as standard ruler

- 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



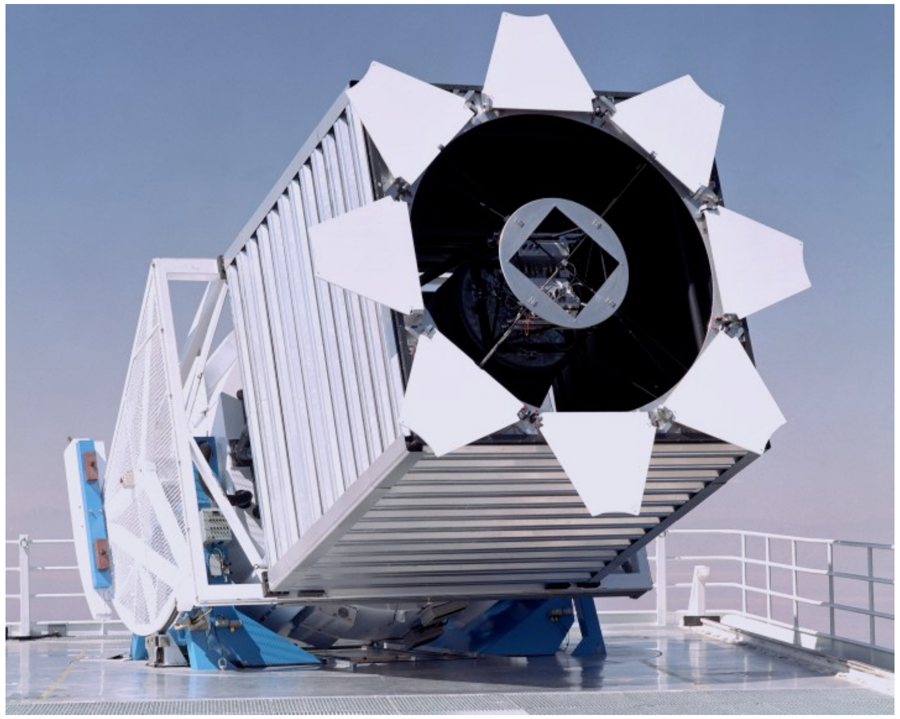
BAO as standard ruler

- 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



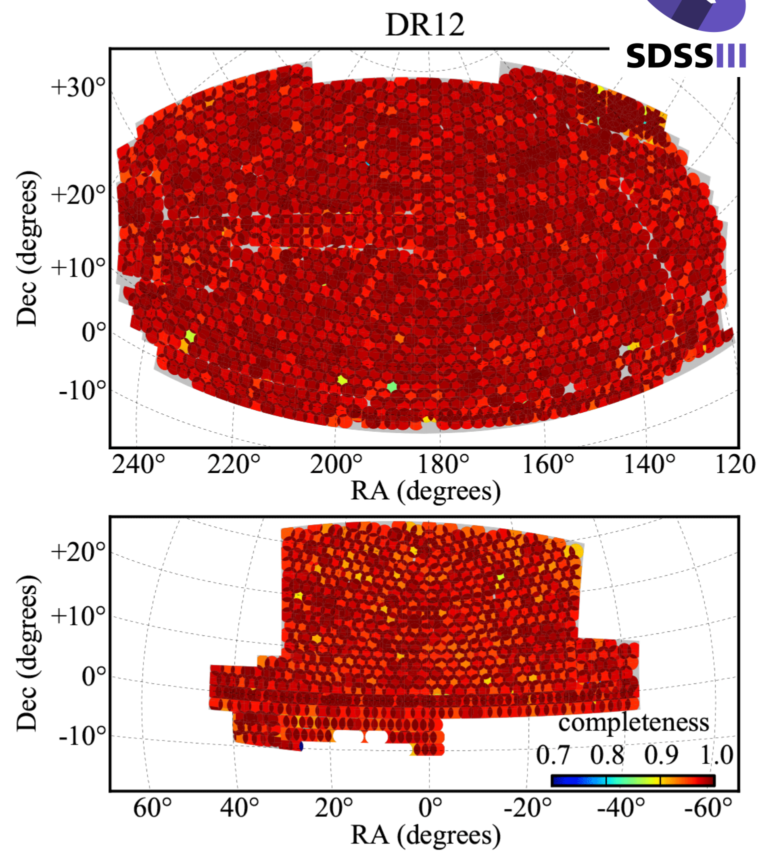
- BAO is the most distinct feature in ξ(s) and P(k) to look at.
- Position is robust under potential systematics:
- Non-linear effects are >1%
- BAO position not affected by bias or Kaiser boost
- However, the feature is damped by non-linear velocity bulks (can be solved using reconstruction)

State of the art of measurements: BOSS & eBOSS



- APO, 2.5-meter Telescope
- Spectroscopic Galaxy Survey
- 2009 - 2014 BOSS: LRG+Lya
- 2014-2019 eBOSS: ELG, LRG, QSO+Lya

DR12 LRG



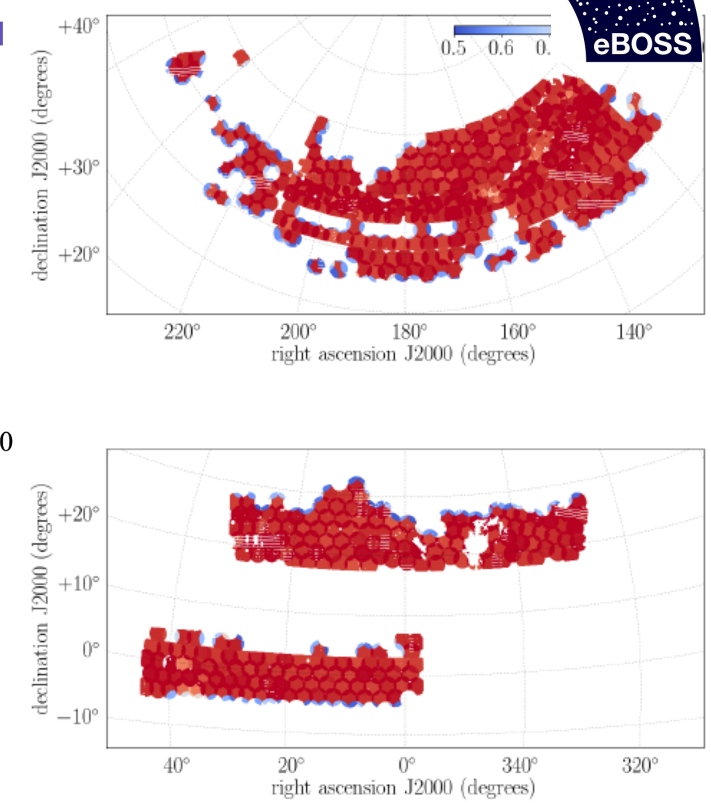
3overlapping z-bins

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

Area = 9376 deg^2

~10^6 LRG targets

DR14 Quasars



$0.8<z<2.2$

Area = 2112.9 deg^2
~$1.5\cdot10^5$ quasar targets

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
   - Constrain on $D_A(z)$ and $H(z)$ through the BAO-feature only
   - It only requires the modelling of the oscillation, not the shape/amplitude of the broadband signal
   - Usage of reconstruction algorithm to enhance the significance of the peak
2. **Full Shape analysis** (aka RSD): Based on the PS full shape and amplitude signal
   - Constrain the growth of structure, $f\sigma_8(z)$, $D_A(z)$ and $H(z)$ 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 (and bispectrum)

BAO Analysis

- Reconstruction suppresses RSD & non-linearities
- Quadrupole is close to be 0
- Work with monopole and μ²-moment

$$P^{(\mu^2)} \equiv {}^{2}\!/_{5} P^{(2)} + P^{(0)}$$

- BAO-peak position, α, is related to AP-dilation parameters,

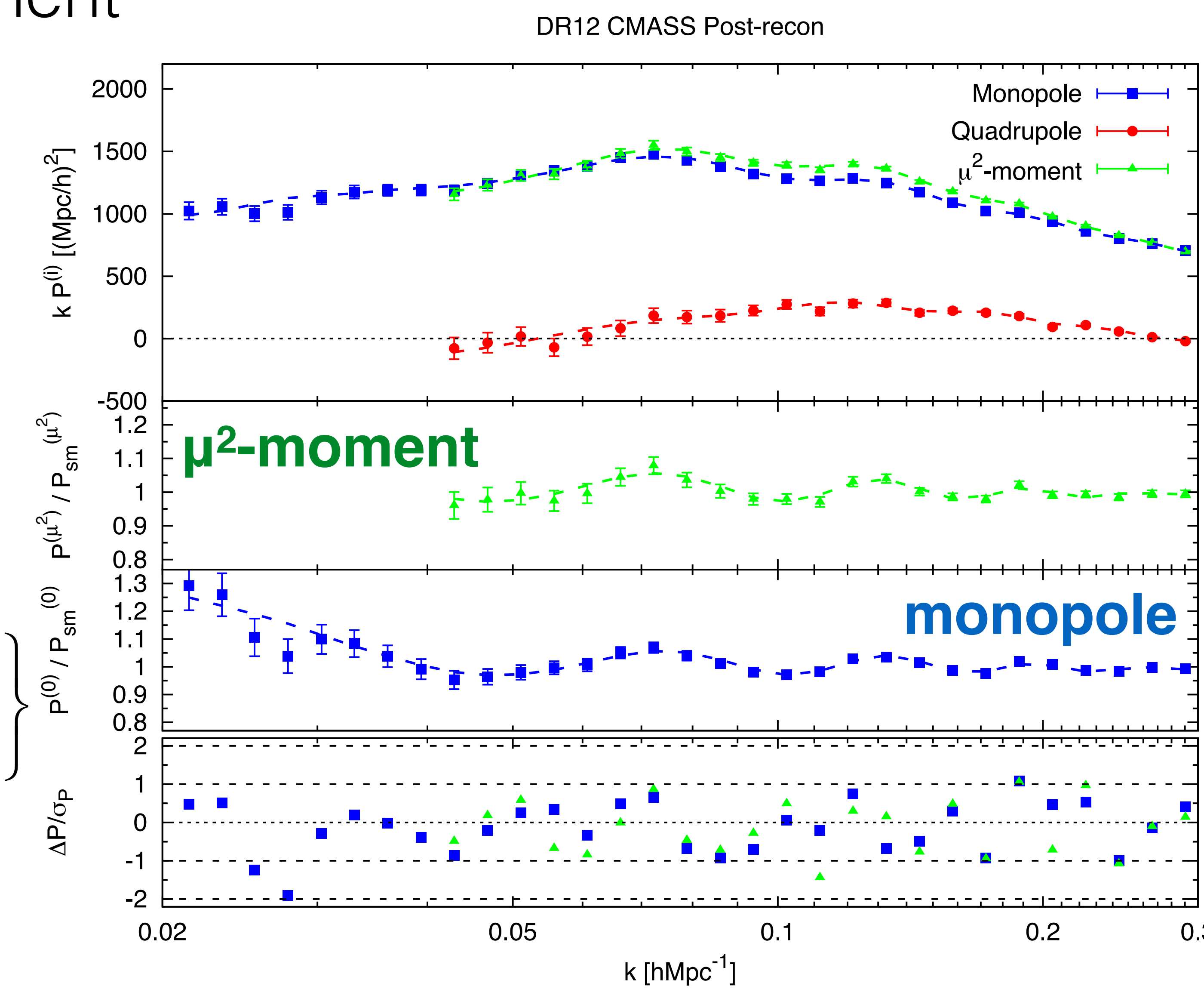
$$\alpha_{\parallel} = \alpha_0^{-3/2} \alpha_2^{5/2} \quad \alpha_{\perp} = \alpha_0^{9/4} \alpha_2^{-5/4}$$

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

where,

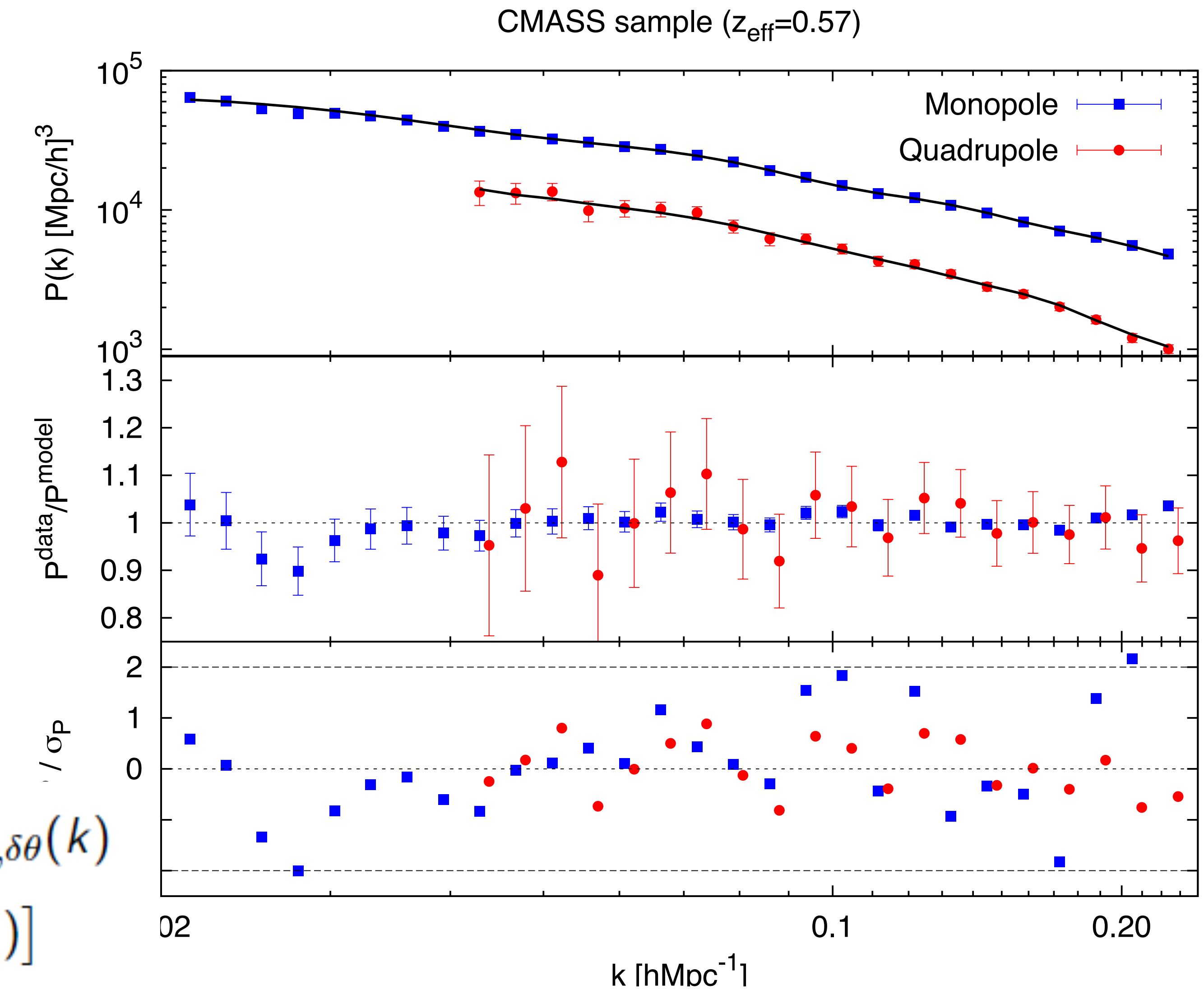
$$P_{sm}(k) = B^2 P_{lin,sm}(k) + A_1 k + A_2 + \frac{A_3}{k} + \ldots$$

models the broadband



Full Shape Analysis

- Non-linear dark matter PS shape
  Perturbation Theory 2-loop
- Galaxy bias,
  Non-linear & non-local
- Redshift Space distortions
  TNS-model



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

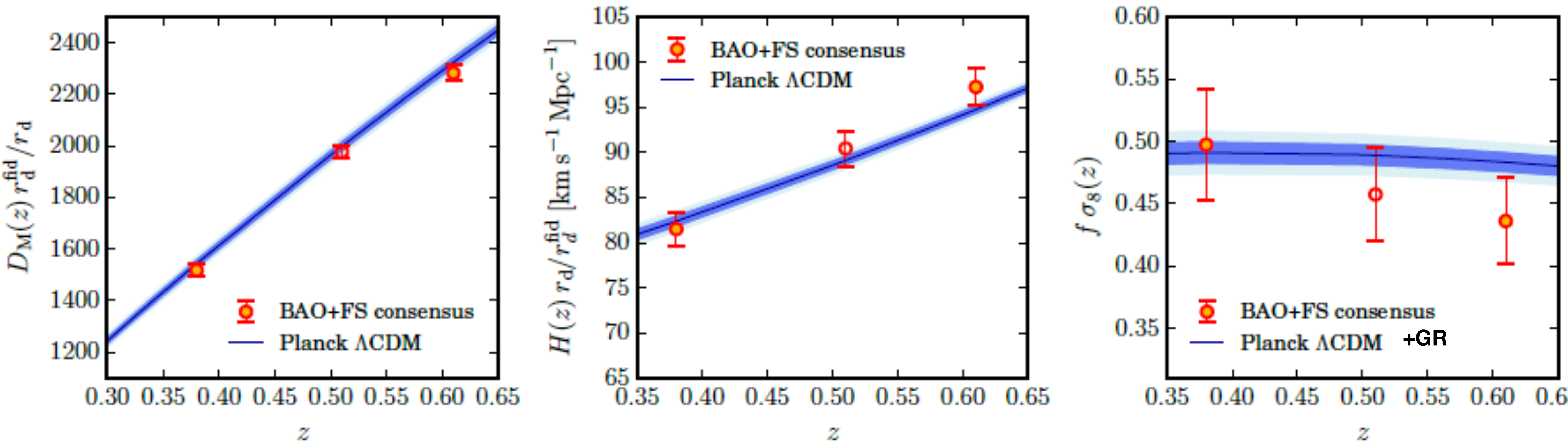
$P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ → Dark Matter non-linear models
$D^P_{\rm FoG}$ → 1-parameter Lorentzian damping term
A, B → TNS functions

The total number of free parameters of the model is,

- Bias Parameters: b_1, b_2
- **Cosmology Parameters:** f, σ_8
- **AP parameters:** $\alpha_\parallel$, $\alpha_\perp \rightarrow D_A/r_s(z_d)$ and $H(z)r_s(z_d)$
- Fingers-of-God: $\sigma_{\rm FoG}$
- Shot noise amplitude $A_{\rm Noise}$

8 free parameters → 4 cosmological, 4 “nuissance”

Main BOSS results from PS/CF FS+BAO



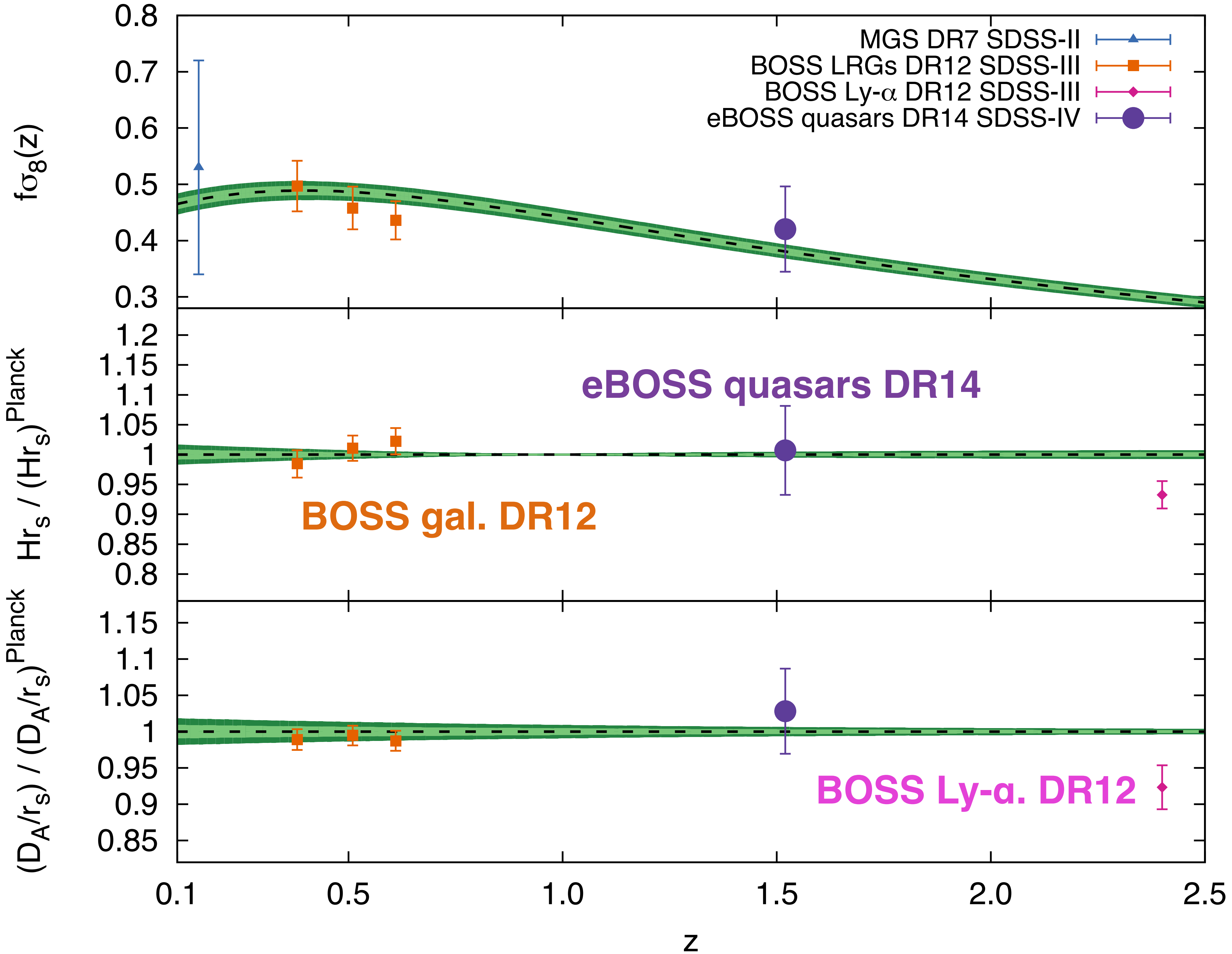
Alam et al. 2016

3overlapping z-bins

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

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

Main BOSS+eBOSS quasars

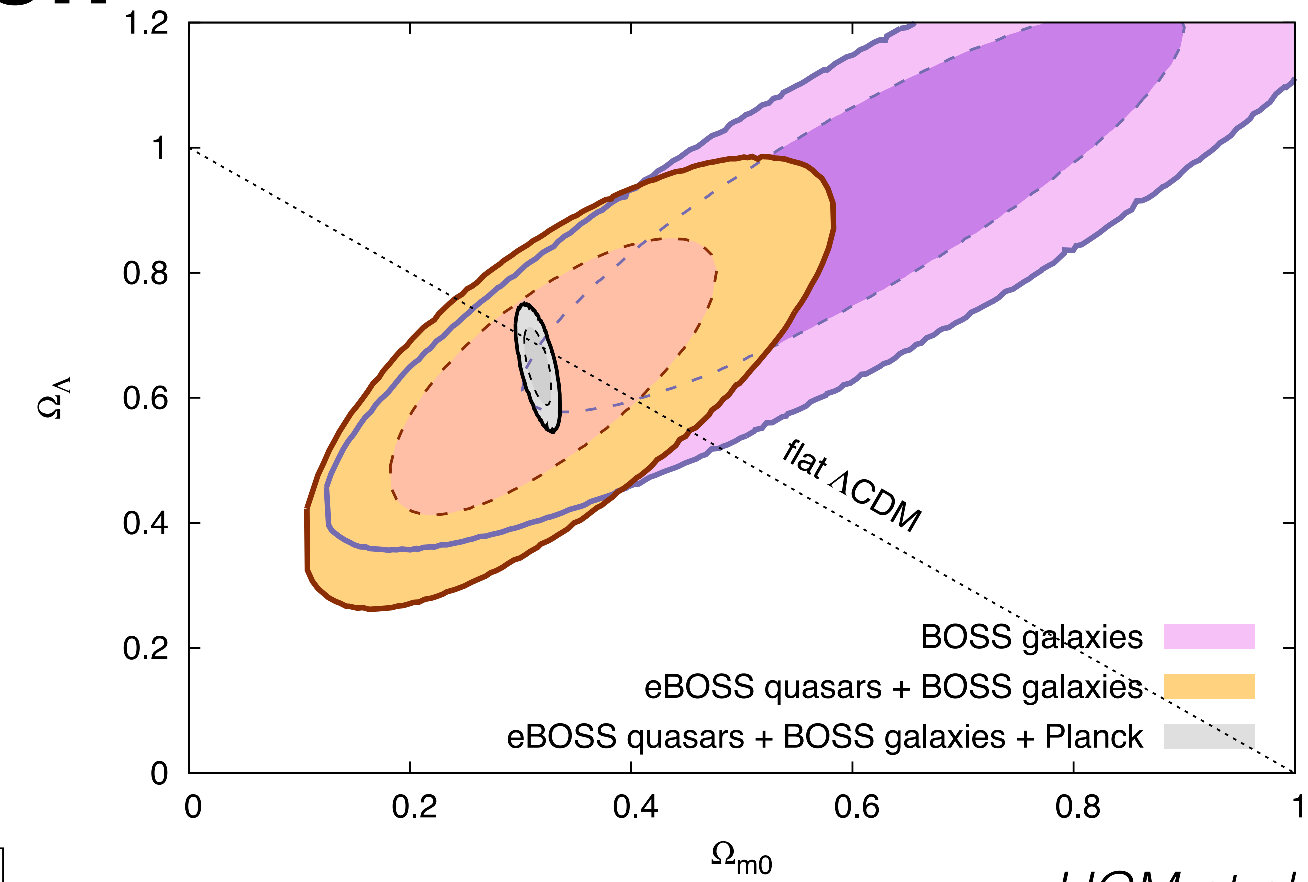


HGM et al. 2018

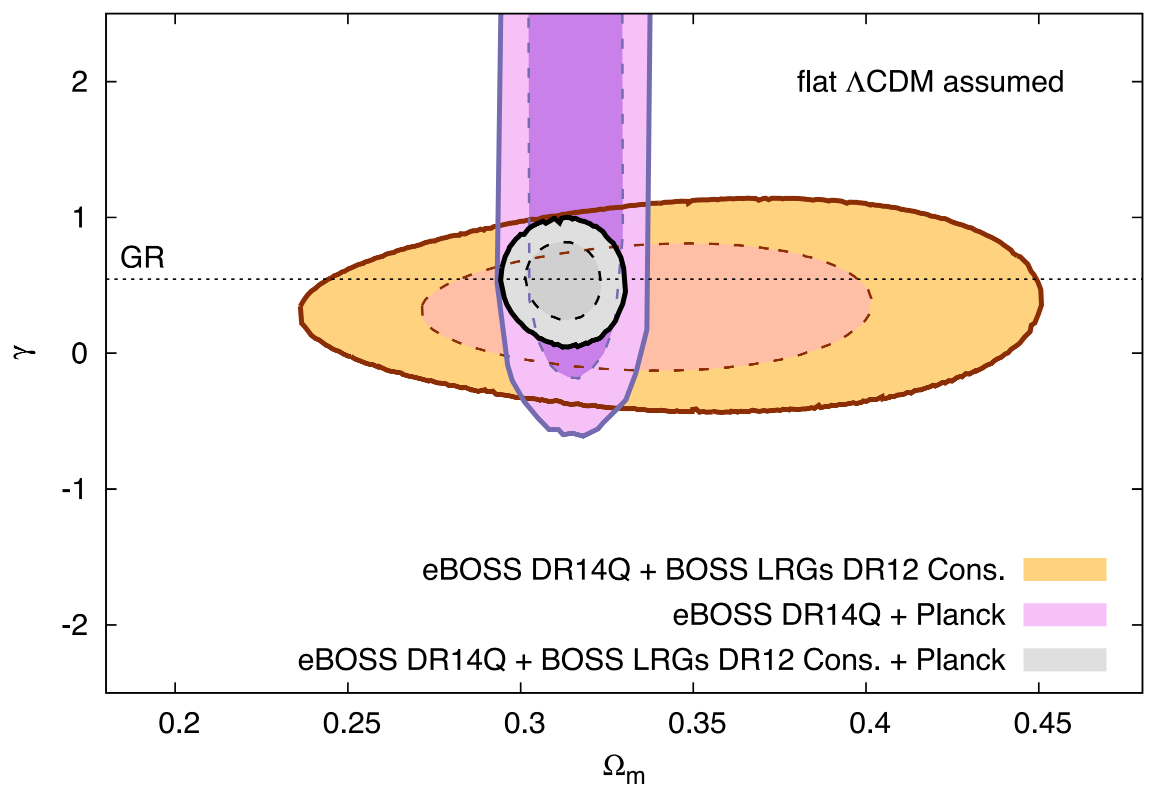
Cosmology Interpretation

GR & ΛCDM assumed

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



HGM et al. 2018



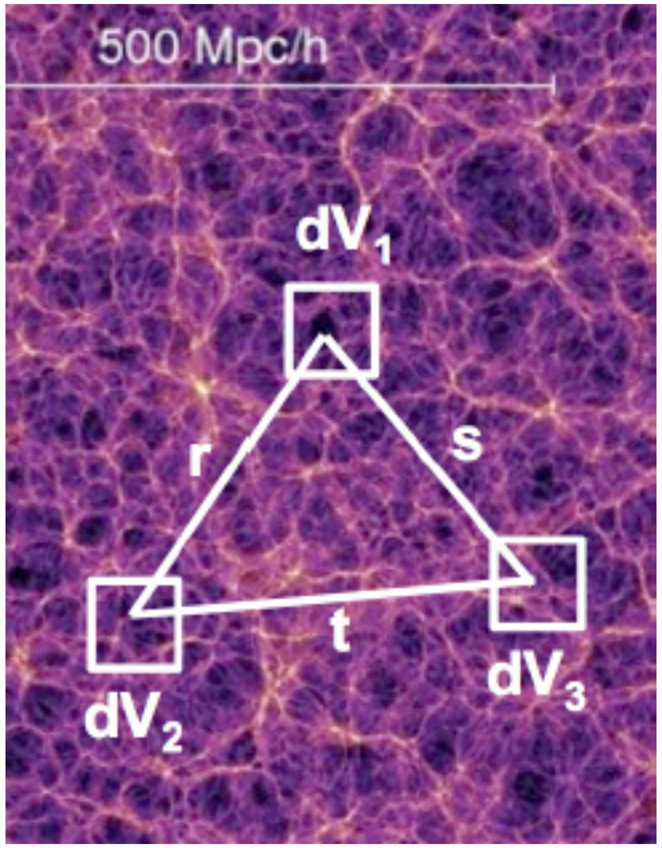
flat ΛCDM assumed

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

Beyond the 2-point statistics

- Quantity which is essentially non-linear

If all the $\boldsymbol{\delta}(\mathbf{k})$ modes evolve linearly (and the initial conditions are Gaussian) the bispectrum is 0 and all the information on the system of objects/galaxies is described by the power spectrum.



Probability of finding 3 galaxies separated by r, s and t: $P_3(r,s,t) = [1+\xi_2(r)+\xi_2(s)+\xi_2(t)+\zeta(r,s,t)]dV_1\,dV_2\,dV_3$

The bispectrum is defined as the FT of ζ,

$$B(\mathbf{k}_1,\mathbf{k}_2) \equiv \int d\mathbf{r}\,d\mathbf{s}\,\zeta(\mathbf{r},\mathbf{s})e^{-i\mathbf{r}\cdot\mathbf{k}_1}e^{-i\mathbf{s}\cdot\mathbf{k}_2}$$

Beyond the 2-point statistics

- Definition

$$\delta(x) \equiv \frac{\rho(x) - \bar{\rho}}{\bar{\rho}} \xrightarrow{FT} \delta_k$$

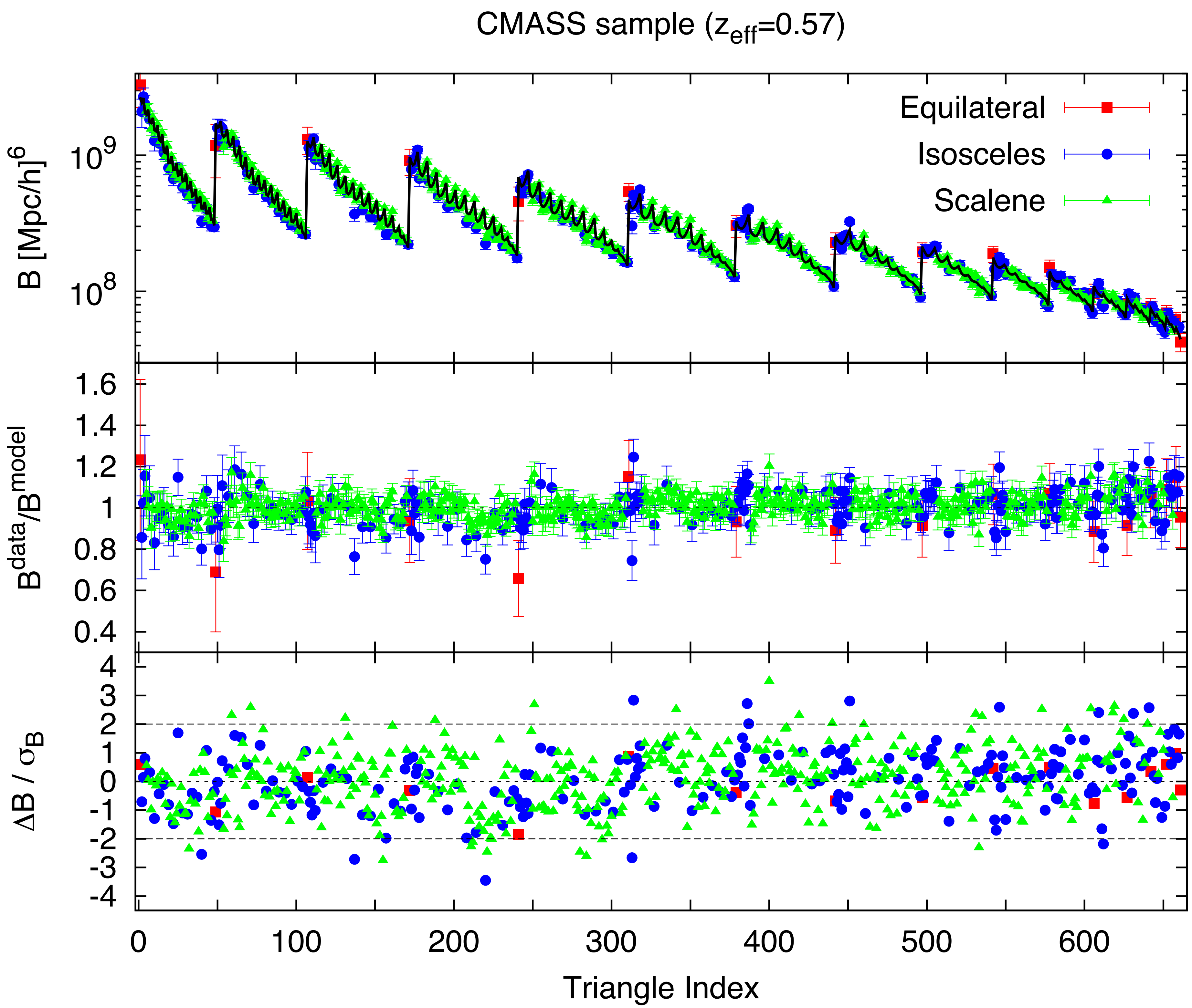
$$\langle \delta_{k1} \delta_{k2} \delta_{k3} \rangle = (2\pi)^3 B(k_1, k_2) \delta^D (k_1 + k_2 + k_3)$$

- Potential usage

Bispectrum is 0 when δ is a Gaussian field

- Mode-coupling leak BAO & RSD information from P into B, T, …
- Reconstruction 'Gaussianizes' **δ** and partially solve this issue (but assumes $\mathbf{\Omega_m}$ and need high density of tracers).
- B can break degeneracy between **f** and $\boldsymbol{\sigma_8}$ in RSD analyses when P(k) is used.
- Primordial non-Gaussian signal in P and B
- Modified-GR signal inside F-kernels (first order B)

Measurement BOSS LRGs 0.43 < z < 0.70



Modelling the Bispectrum (1st order)

- Real Space,

$$B_g(\vec{k}_1,\vec{k}_2)=b_1^{\,4}\sigma_8^{\,4}\left\{2P_{lin}(k_1)P_{lin}(k_2)\left[\frac{1}{b_1}F_2^{(s)}(\vec{k}_1,\vec{k}_2)+\frac{b_2}{2b_1^{\,2}}+\frac{2}{7b_1^{\,2}}(1-b_1)S_2(\vec{k}_1,\vec{k}_2)\right]+cyc.\right\}$$

$$F_2^{(s)}(\vec{k}_i,\vec{k}_j)=\frac{5}{7}+\frac{1}{2}\cos(\alpha_{ij})\left[\frac{k_i}{k_j}+\frac{k_j}{k_i}\right]+\frac{2}{7}\cos^2(\alpha_{ij})$$

- Redshift Space

$$B_g^{(s)}(\vec{k}_1,\vec{k}_2)=\sigma_8^{\,4}\left[2P_{lin}(k_1)P_{lin}(k_2)Z_1(\vec{k}_1)Z_1(\vec{k}_2)Z^{(s)}{}_2(\vec{k}_1,\vec{k}_2)+cyc.\right]$$

$$Z_1(\vec{k})=(b_1+f\mu^2)$$

$$Z_2(\vec{k}_i,\vec{k}_j)=b_1\left[F_2(\vec{k}_1,\vec{k}_2)+\frac{f\mu k}{2}\left(\frac{\mu_1}{k_1}+\frac{\mu_2}{k_2}\right)\right]+f\mu^2G_2(\vec{k}_1,\vec{k}_2)+\frac{f^3\mu k}{2}\mu_1\mu_2\left(\frac{\mu_2}{k_1}+\frac{\mu_1}{k_2}\right)+\frac{b_2}{2}+\frac{2}{7}(1-b_1)S_2(\vec{k}_1,\vec{k}_2)$$

Higher-order statistics: the bispectrum

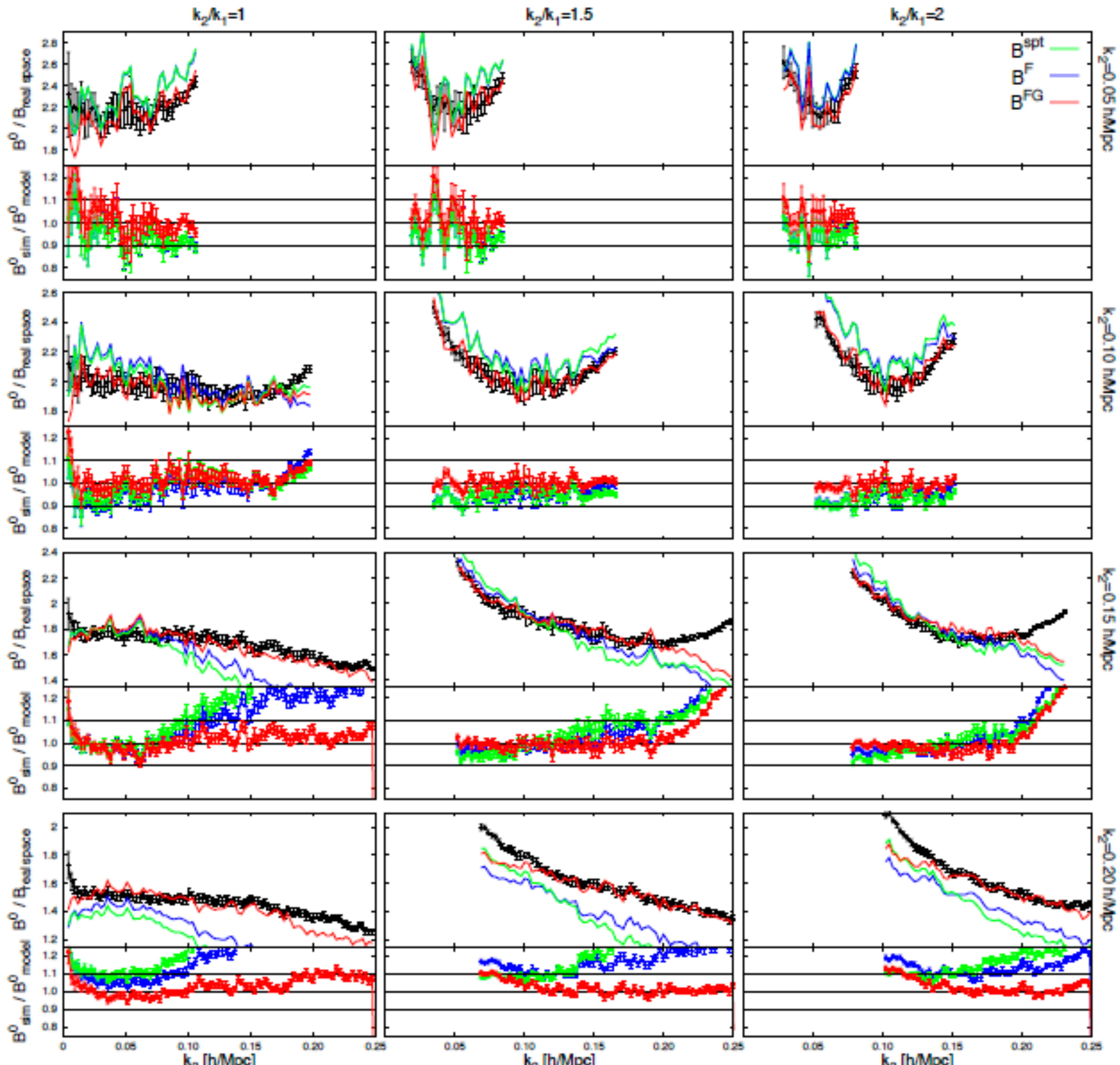
- Tree level only provides an accurate description at high redshift and large scales

- Empirical improvement of this formula though effective kernels method

$F_2 \rightarrow F_2^{eff}$ HGM et al 2012

$G_2 \rightarrow G_2^{eff}$ HGM et al. 2014

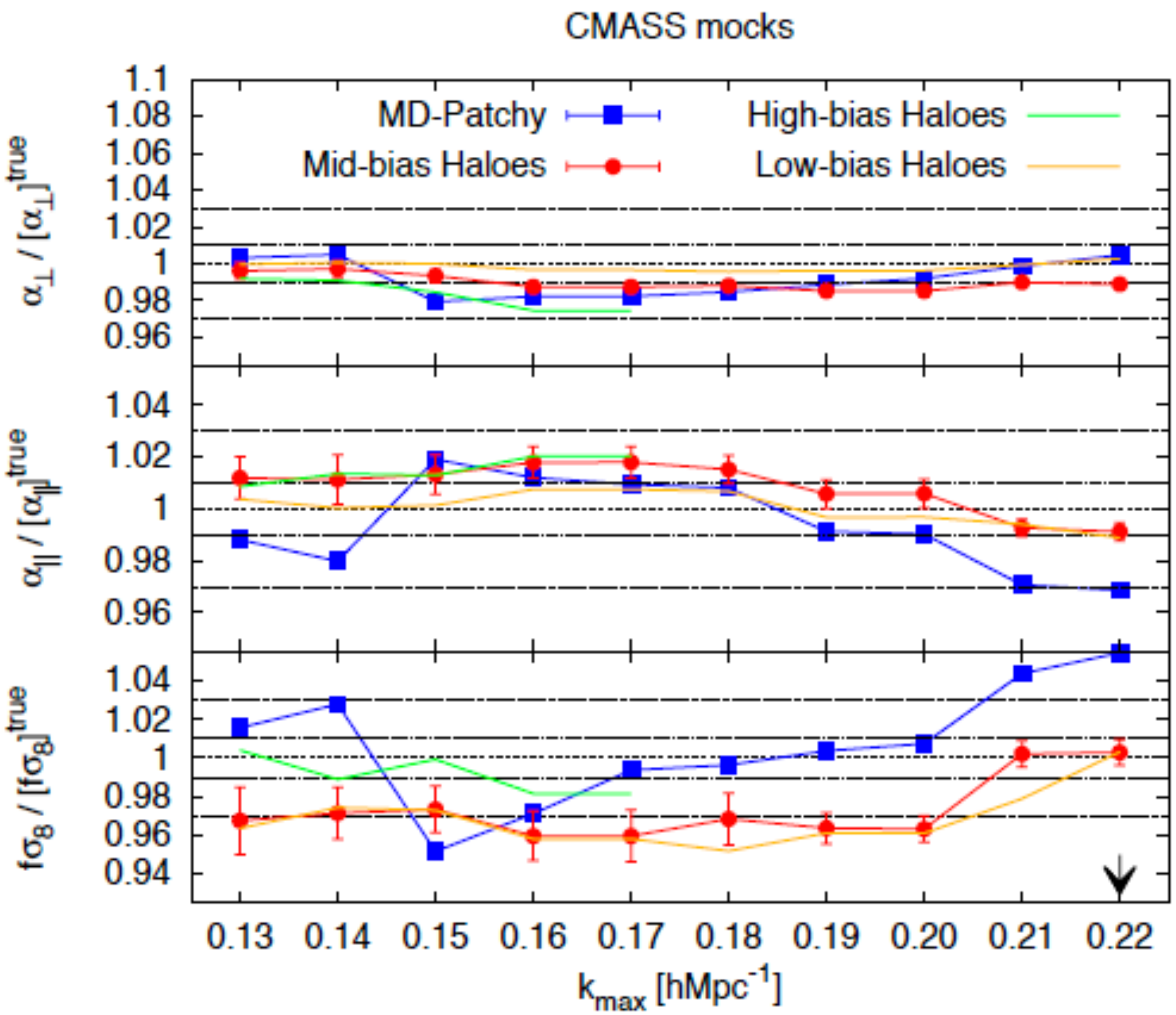
- 9 free parameters each kernel to be fitted from dark matter N-body simulations. Independent of scales/redshift



z=0.5

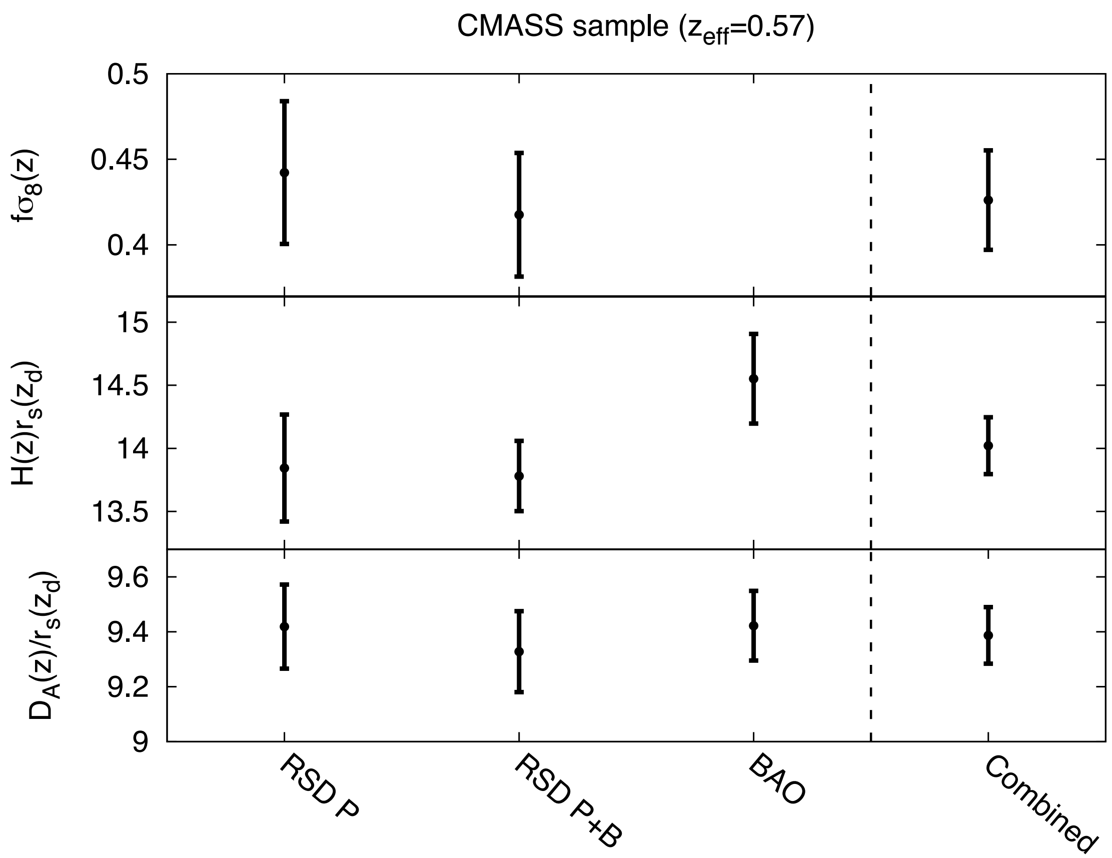
Testing for Systematics

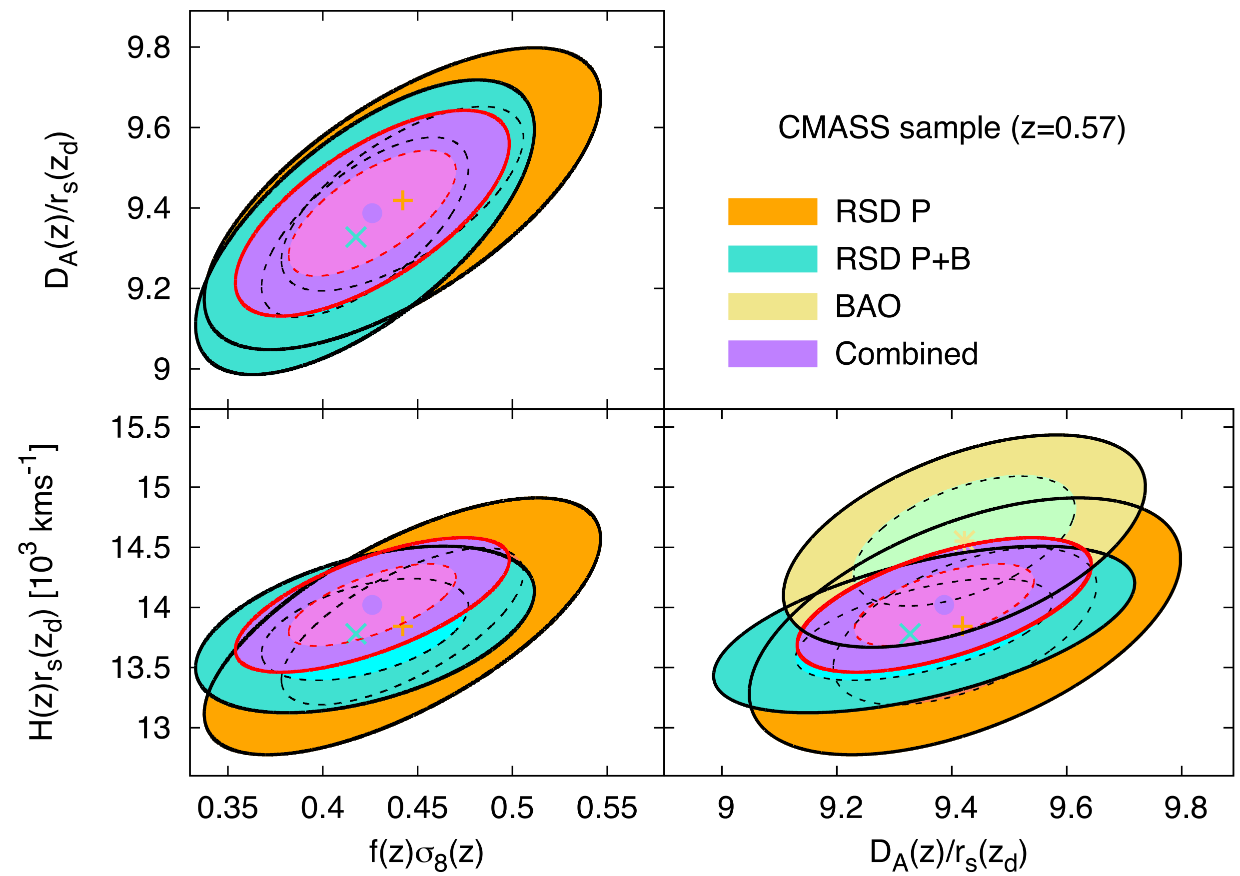
Name	$M^{\rm h}_{\rm min}$ (N_p)	b_1	b_2	$\bar{n} \times 10^4$
Low-bias N-body	3.80 (50)	1.75	-0.26	6.75
Mid-bias N-body	5.75 (75)	1.90	0.22	4.41
High-bias N-body	8.36 (110)	2.07	0.49	2.90
MD-Patchy (LOWZ)	-	2.08	0.43	4.0
MD-Patchy (CMASS)	-	1.97	0.29	4.5
Data (LOWZ)	-	2.08	0.92	4.0
Data (CMASS)	-	2.01	0.68	4.5



- We run our cosmology data 'pipeline' on mocks & full N-body sims
- Determine our systematic budget & k-range of validity

Results from BOSS





Sample	Analysis	$f\sigma_8(z_{\rm eff})$	$H(z_{\rm eff})r_s(z_d)$	$D_A(z_{\rm eff})/r_s(z_d)$
LOWZ	*RSD P*	0.394 ± 0.064	11.41 ± 0.56	6.35 ± 0.19
	BAO	–	11.60 ± 0.60	6.66 ± 0.16
	RSD P+B	0.460 ± 0.071	11.75 ± 0.55	6.74 ± 0.22
	Combined	0.427 ± 0.056	11.55 ± 0.38	6.60 ± 0.13
CMASS	*RSD P*	0.444 ± 0.042	13.92 ± 0.44	9.42 ± 0.15
	BAO	–	14.56 ± 0.37	9.42 ± 0.13
	RSD P+B	0.417 ± 0.036	13.78 ± 0.28	9.33 ± 0.15
	Combined	0.426 ± 0.029	14.02 ± 0.22	9.39 ± 0.10

Compression techniques for the Bispectrum

- Number of triangles (and information) grows as we reduce the binning.
- Bins highly correlated. How we deal with it? More mocks? Compression!
- For DESI / EUCLID information will need to be compressed in optimal way for maximising the outcome

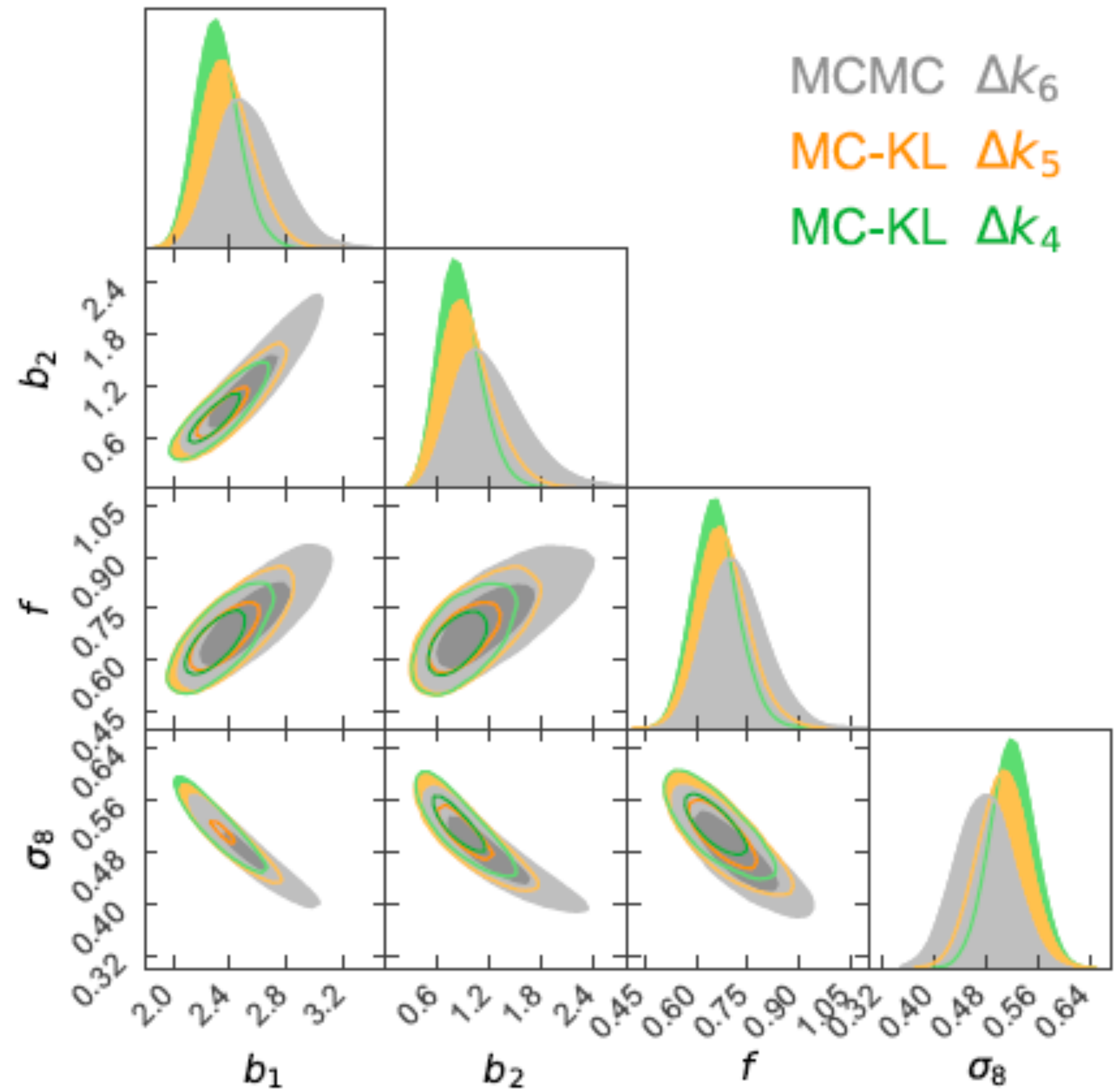
$$0.03 \leq k[h/Mpc] \leq 0.12$$

bin-size	**#triangles**
$\Delta k = 6k_f$	116
$\Delta k = 5k_f$	195
$\Delta k = 4k_f$	404
$\Delta k = 2k_f$	2734

Gualdi et al. 2018 for details

arxiv:1806.02853

Karhunen-Loeve algorithm+theoretical proposed cov.

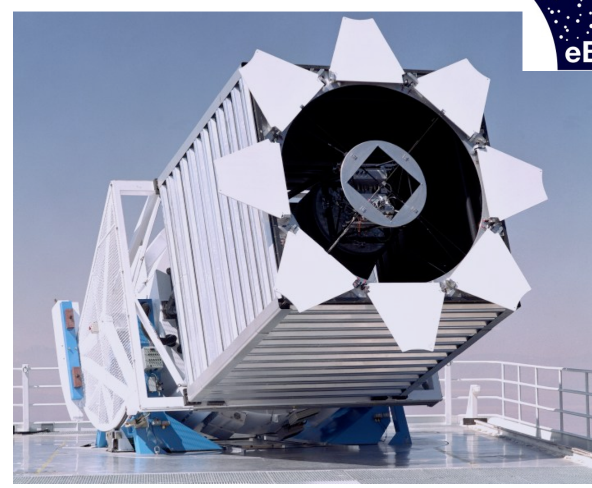


Cosmology with BOSS, eBOSS & DESI

BOSS

2009-2014

eBOSS



2014-2019

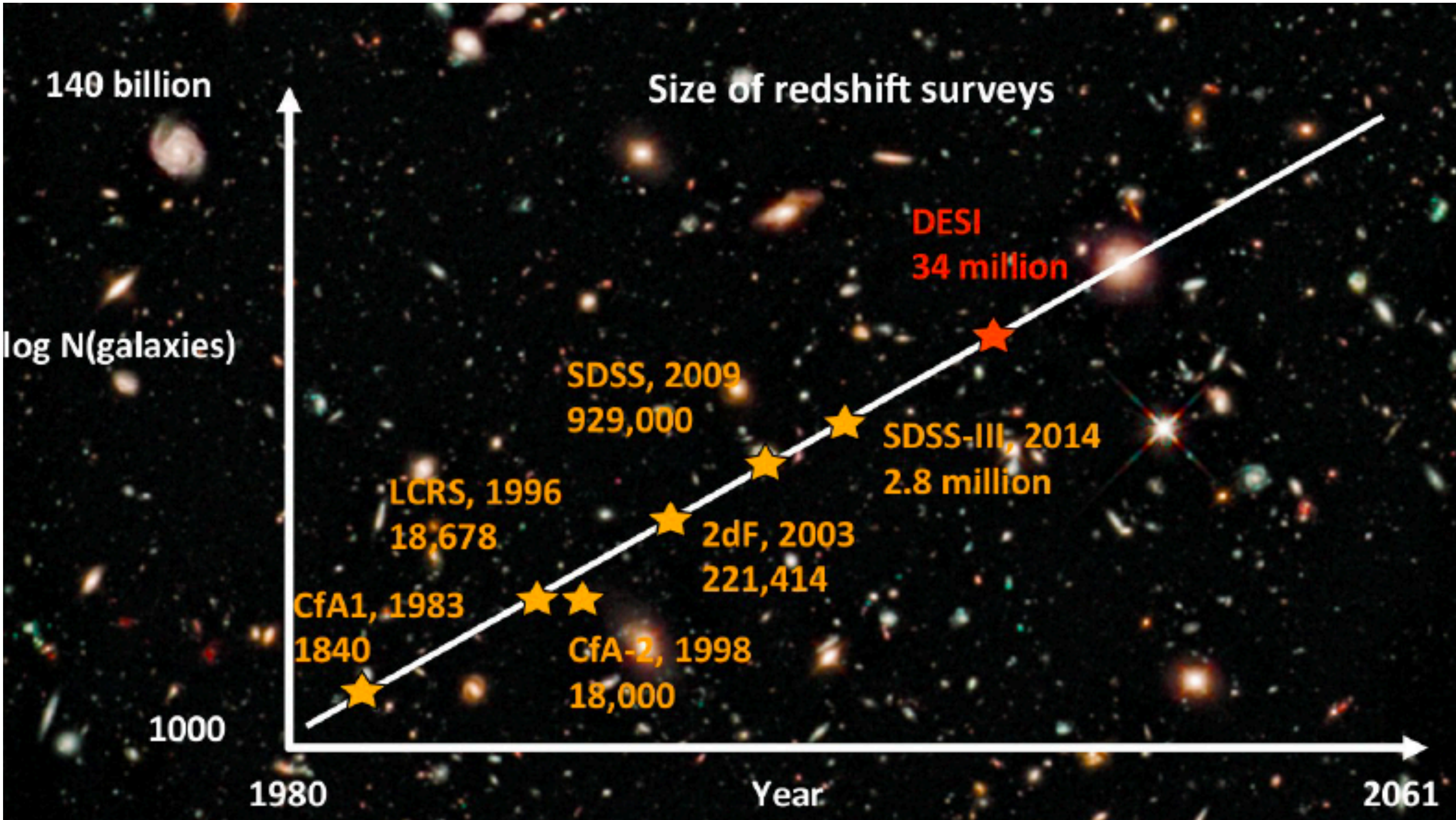
DESI

2020-2024

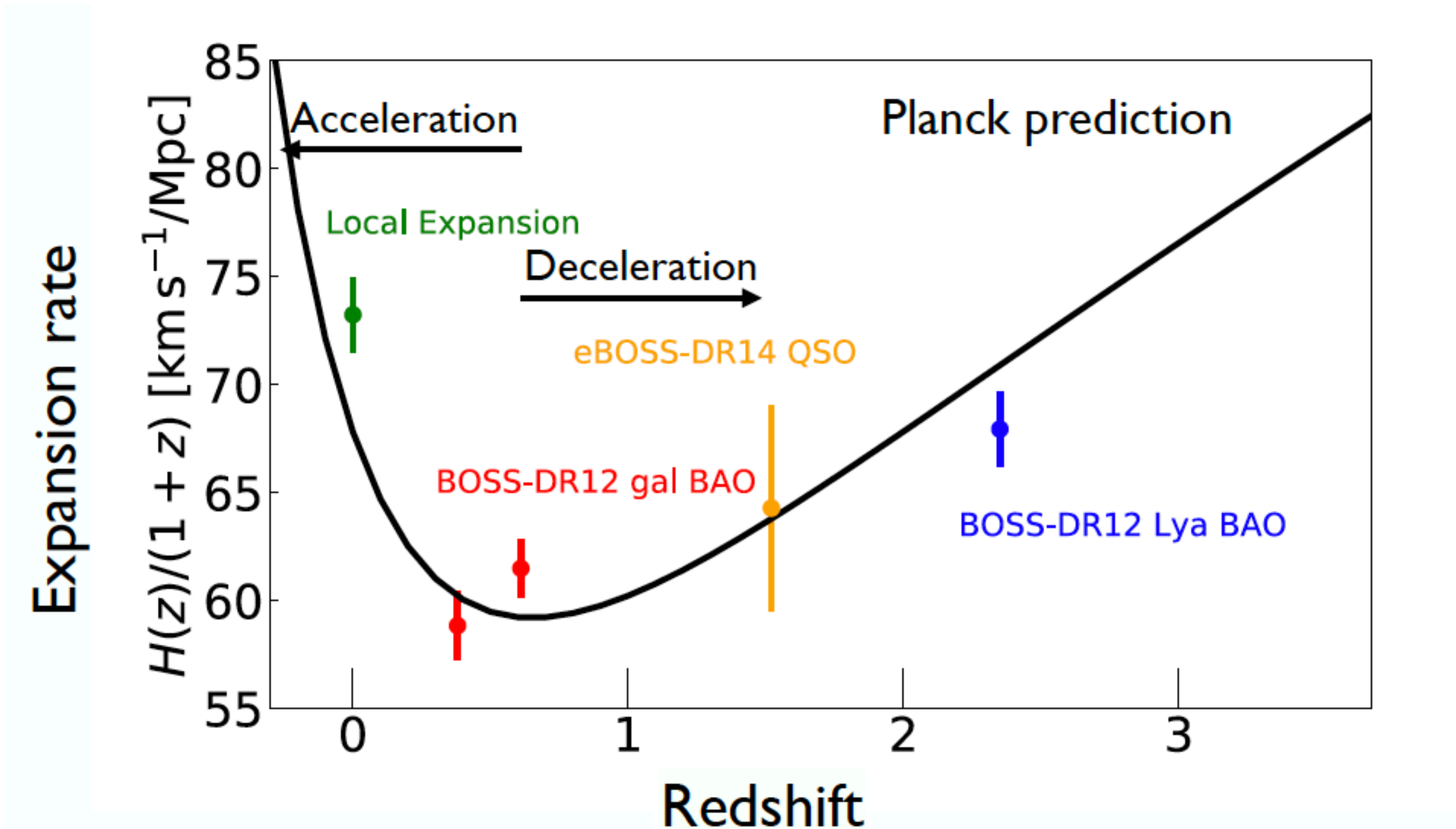
DESI in a nutshell

2.4M QSO 1<z<2	
17M ELG 1<z<2	14,000 deg2
4M LRG 0.2<z<1	50 [Gpc/h]3
10M BG z<0.2	

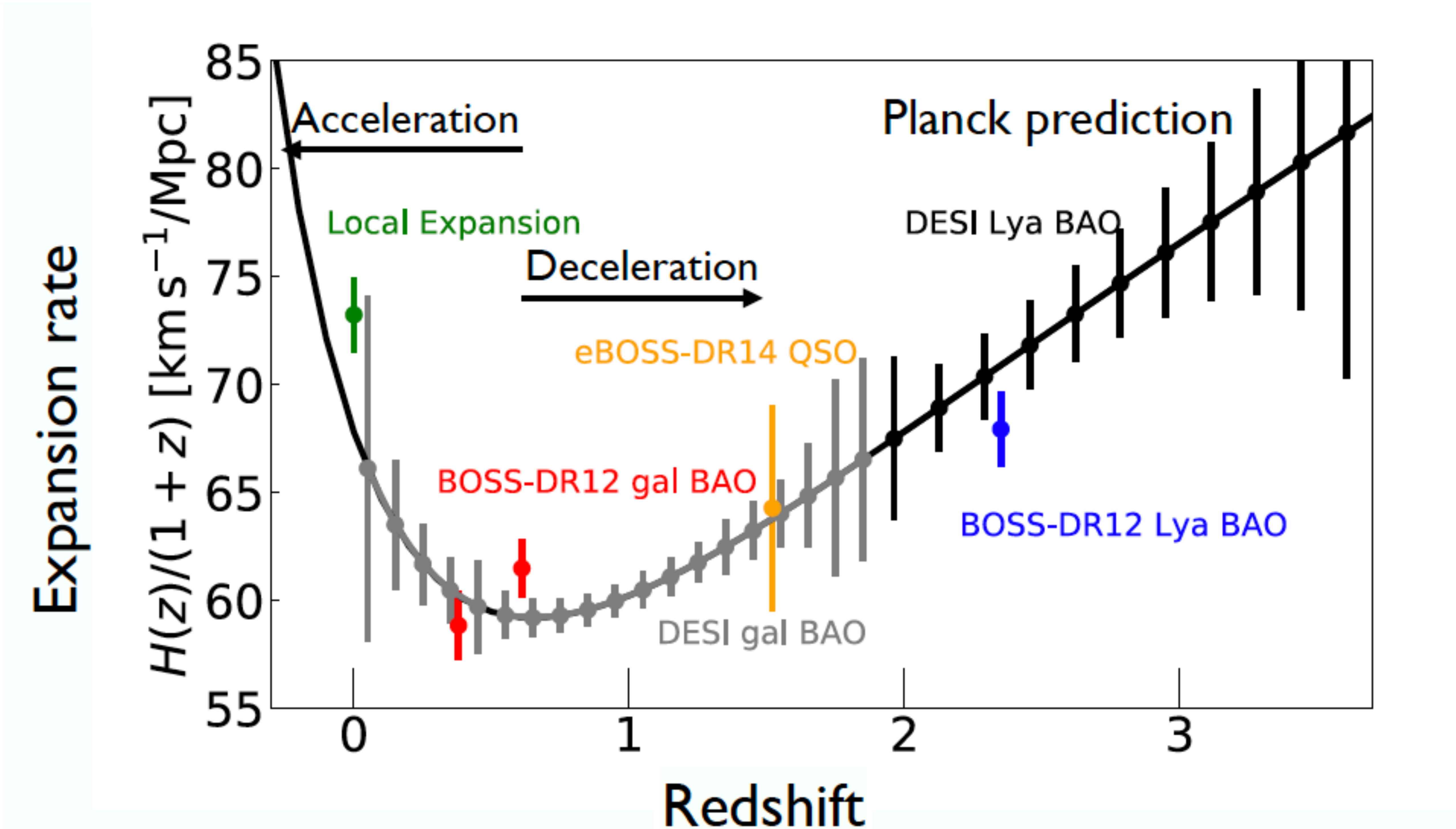
Numbers of Spectroscopic Galaxy Surveys



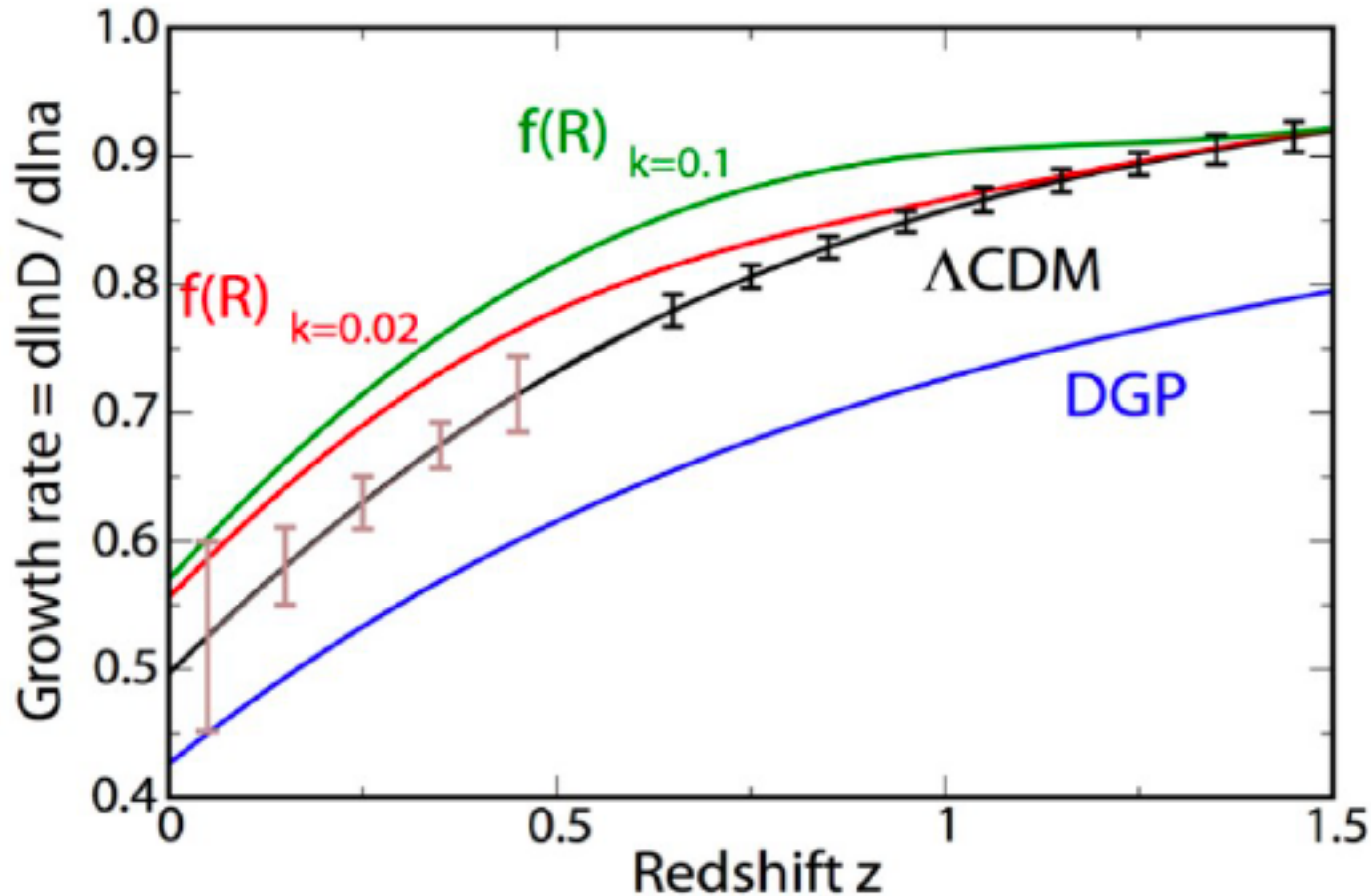
Current state of the art H(z) measurement



DESI H(z) forecast



DESI $f\sigma_8$ forecast



Conclusions

- Using RSD in combination with AP effect allow us to measure $H(z)$, $D_A(z)$ and $f\sigma_8(z)$ from 3D spectroscopic surveys
- BOSS and eBOSS have already demonstrated the power of BAO can be used to perform robust cosmological measurements
- Using 3PCF/Bispectrum allow us to shrink the statistical error-bars of cosmological parameters at a given volume (for free!)
- New approaches need to be developed to fully exploit the power of bispectrum on the next generation of spectroscopic surveys.