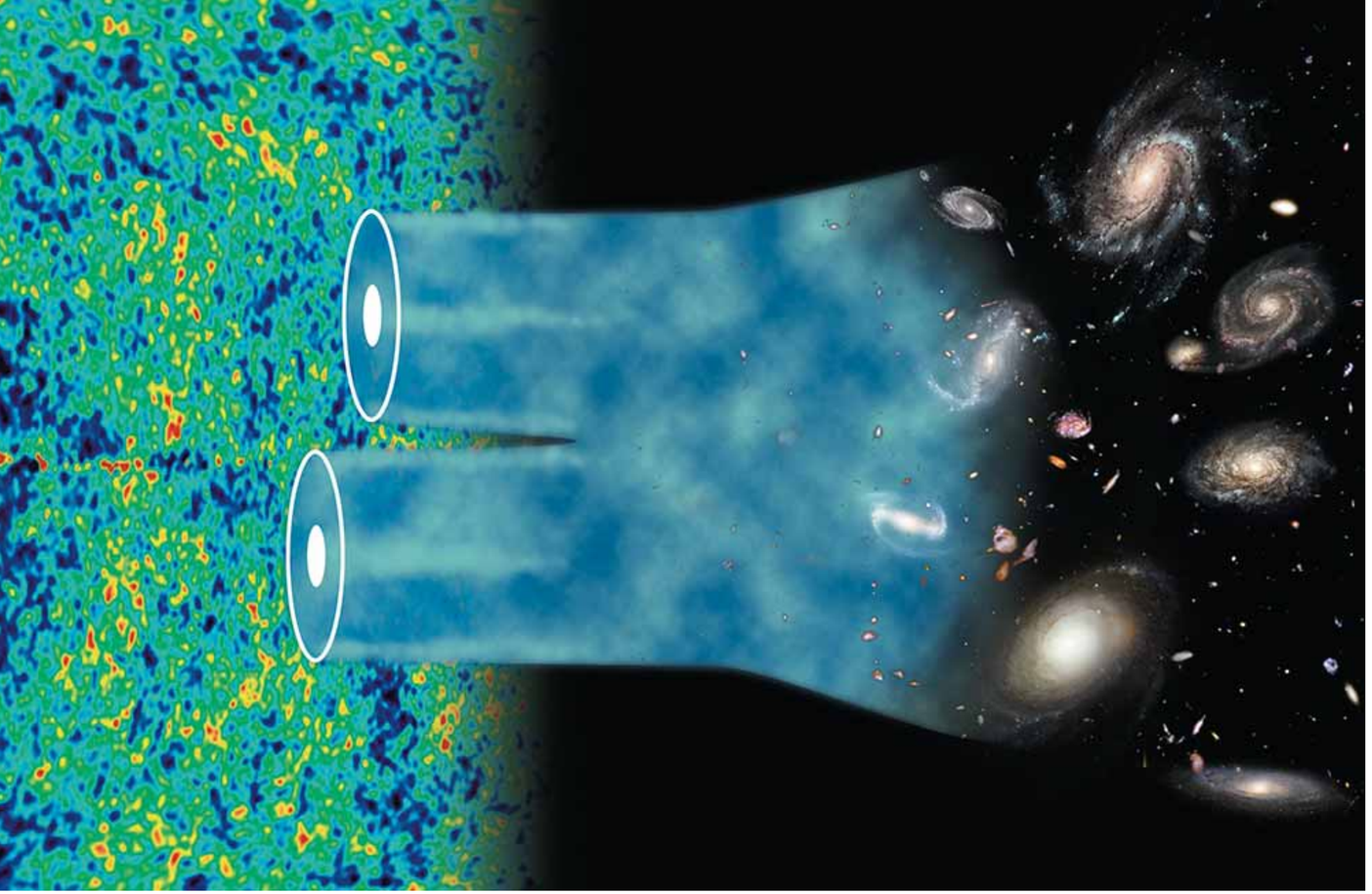

Redshift Space Distortions from the extended Baryon Oscillation Spectroscopic Survey

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eBOSS SDSS "la Caixa" Foundation ICCUB Institut de Ciències del Cosmos UNIVERSITAT DE BARCELONA

Galaxy Surveys 101

eBOSS contains 4 tracers

Catalogue	Range	Objects
LRG	0.6<z<1.0	250k
ELG	0.6<z<1.1	190k
Quasars	0.8<z<2.2	350k
Ly-α	0.9<z<3.5	350k

*see J. Bautista & E. Müller talk for more eBOSS tracers

$\delta(x)$ **stochastic field**

$$\delta(x) \equiv \frac{\rho(x)}{\bar{\rho}} - 1 \qquad \delta(k) = \int dx\, \delta(x) e^{-ikx}$$

Cosmology information
2-point function statistics

$$\langle \delta(x)\delta(x+R) \rangle = \xi(R) \qquad \textbf{Config. Space}$$

$$\langle \delta(k)\delta(k') \rangle = P(k)\delta^D(k+k') \qquad \textbf{Fourier Space}$$

Main Goal of redshift surveys: BAO & RSD

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

BAO peak position: Isotropic signal $\propto [D_M^2(z)/H(z)]^{1/3}/r_{\rm drag}$

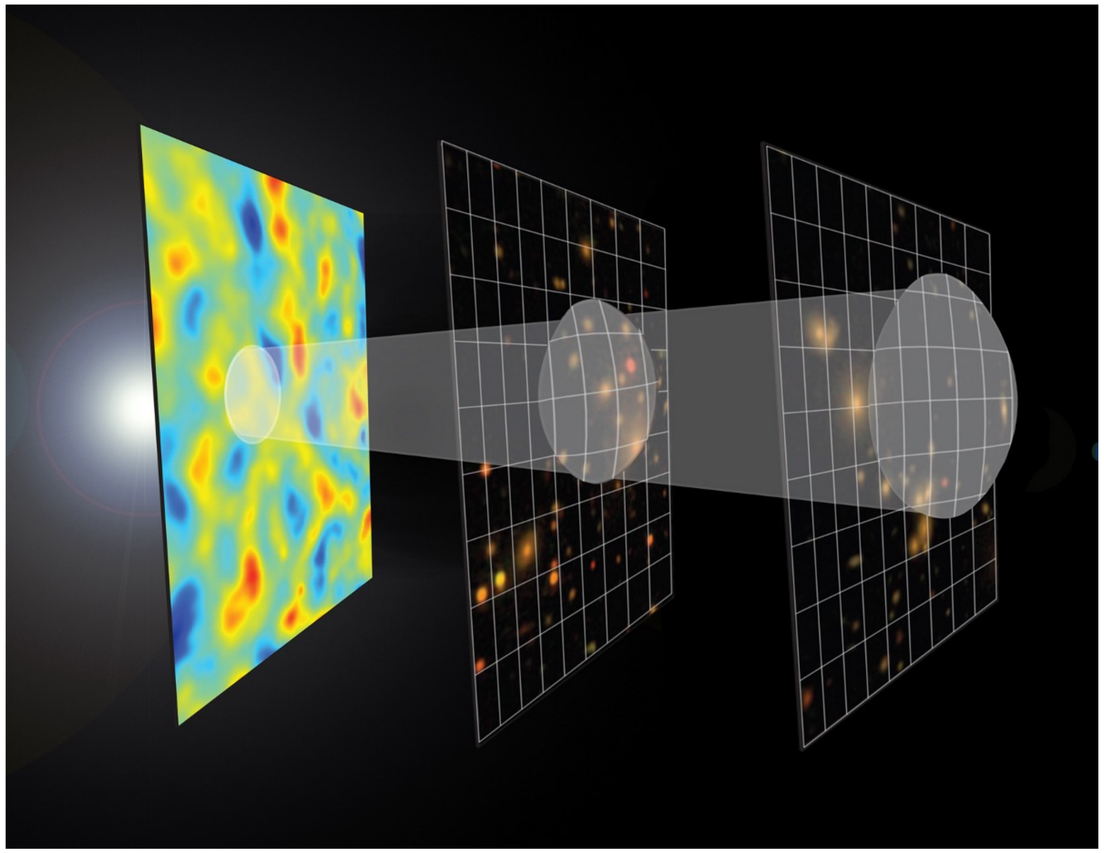
BAO relative peak position: isotropic vs. anisotropic $\propto D_M(z)H(z)$

$$D_H(z,\mathbf{\Omega}) = \frac{c}{H(z,\mathbf{\Omega})}$$

$$D_M(z,\mathbf{\Omega}) = \int_0^z \frac{c dz'}{H(z',\mathbf{\Omega})}$$

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

BAO as a standard ruler



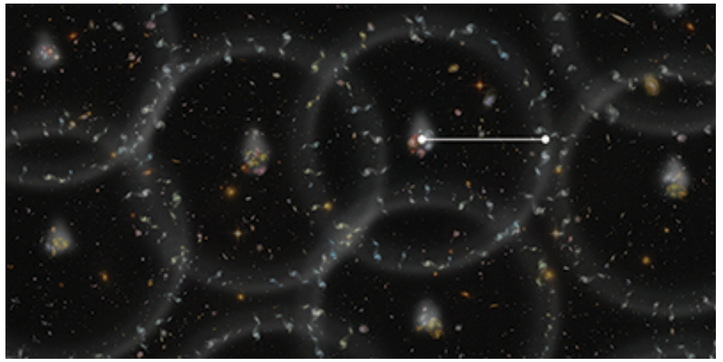
- Cleanest probe to measure expansion in the LSS
- Provide expansion along and across the line-of-sight
  - → requires knowledge of the horizon scale at recombination times: r_{drag}
- Systematic floor beyond BOSS/eBOSS statistical precision

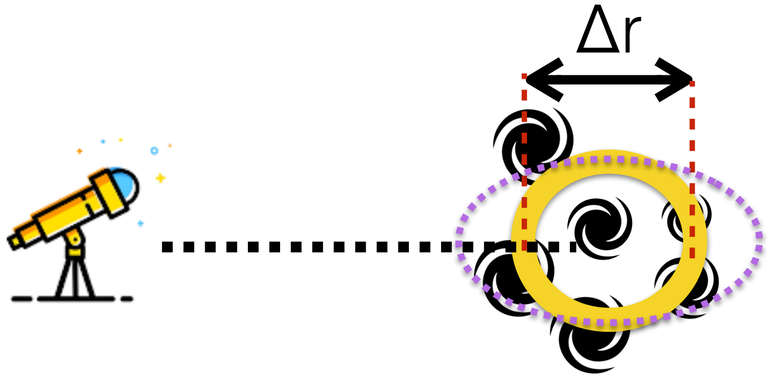
***see M. Vargas-Magaña talk for more BAO in eBOSS**

Alcock-Paczynski

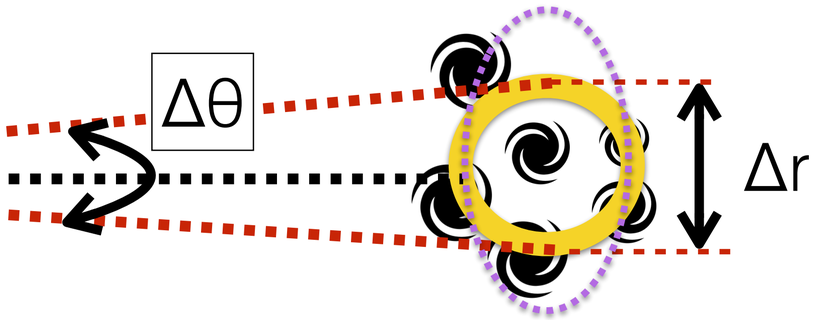
- Universe assumed **isotropic** and **homogeneous**
- **AP effect**: Anisotropy induced by transforming redshifts into coming distances assuming an *arbitrary cosmology*

*** aka reference cosmology**





Radial distance



Angular diameter distance

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

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

BAO provides a reference-structure for the AP effect

Alcock-Paczynski

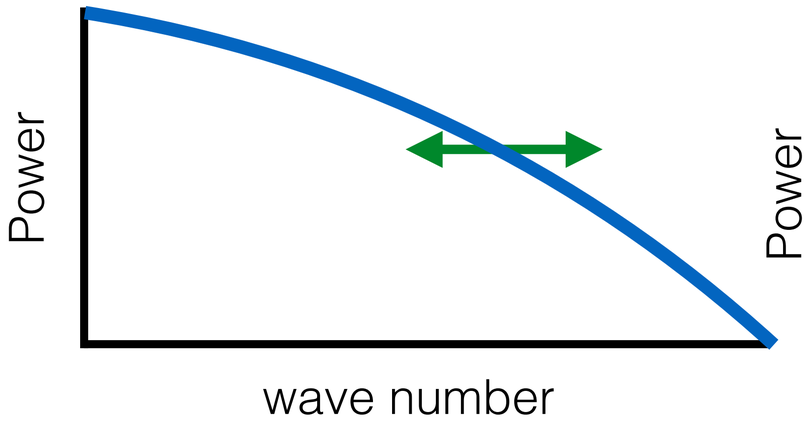
$$k_{\parallel} = q_{\parallel} k'_{\parallel} \longrightarrow q_{\parallel}(z) = \frac{D_H(z)}{D_H^{\rm fid}(z)}$$

$$k_{\perp} = q_{\perp} k'_{\perp} \longrightarrow q_{\perp}(z) = \frac{D_M(z)}{D_M^{\rm fid}(z)}$$

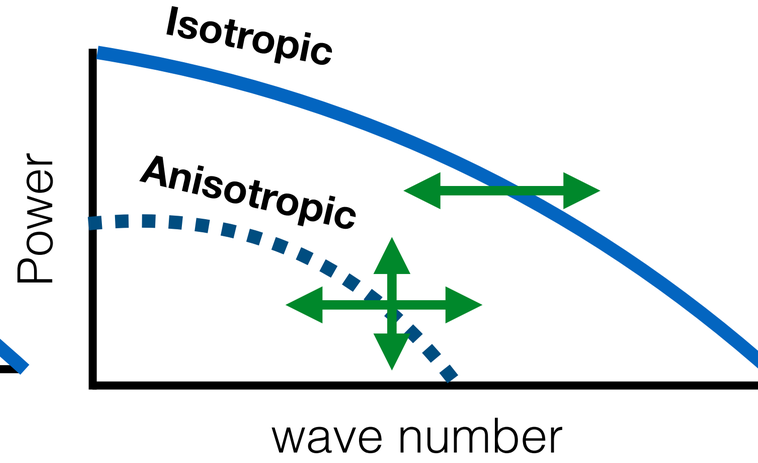
Observed wave-vector

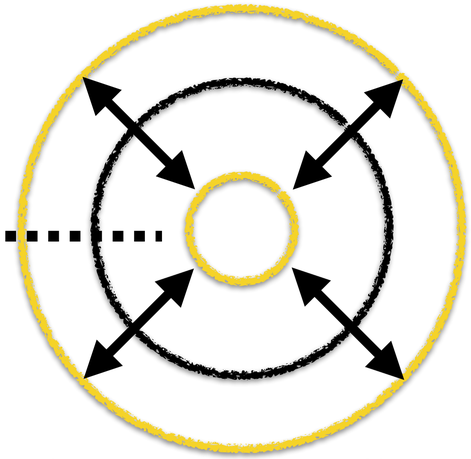
True wave-vector

BAO Isotropic shift

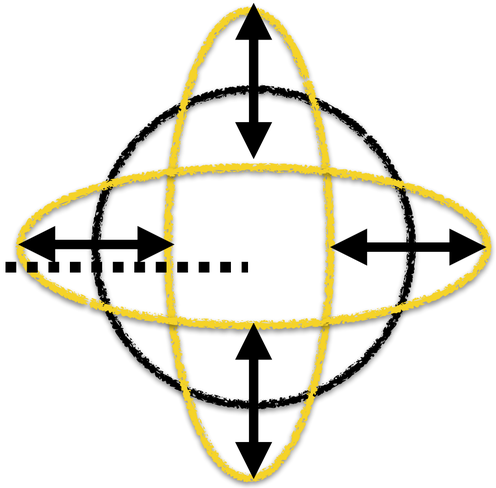


BAO Warping (AP-effect)





$$\propto [D_M^2(z) D_H(z)]^{1/3} \equiv D_V(z)$$



$$\propto D_M(z)/D_H(z)$$

Horizon Scale r_{drag}

LSS is not sensitive to the horizon scale at CMB times.
Need to assume one fixed template (or a functional form)

*** aka template cosmology**

AP effect + r_{drag} unknown value

$$\alpha_{\parallel}(z) = q_{\parallel}(z)\frac{r_{\rm drag}^{\rm fid}}{r_{\rm drag}} = \frac{D_H(z)/r_{\rm drag}}{D_H^{\rm fid}(z)/r_{\rm drag}^{\rm fid}} \longrightarrow k_{\parallel} = \alpha_{\parallel}(z)k'_{\parallel}$$

$$\alpha_{\perp}(z) = q_{\perp}(z)\frac{r_{\rm drag}^{\rm fid}}{r_{\rm drag}} = \frac{D_M(z)/r_{\rm drag}}{D_M^{\rm fid}(z)/r_{\rm drag}^{\rm fid}} \longrightarrow k_{\perp} = \alpha_{\perp}(z)k'_{\perp}$$

This adds an extra factor to the isotropic BAO-shift, but not on the relative trans-to-long BAO

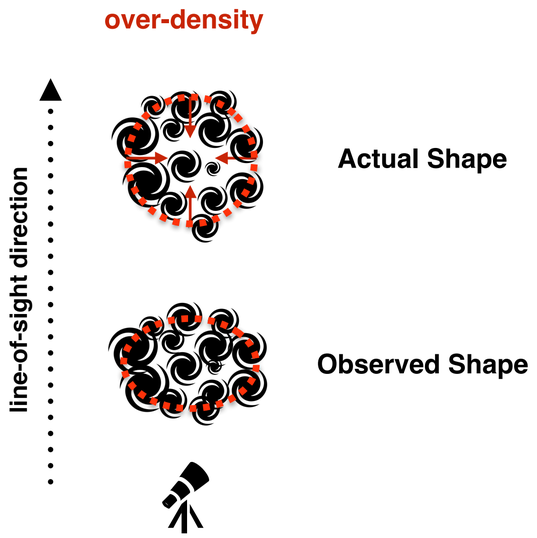
$$\propto [D_M^2(z)D_H(z)]^{1/3}/r_{\rm drag}$$

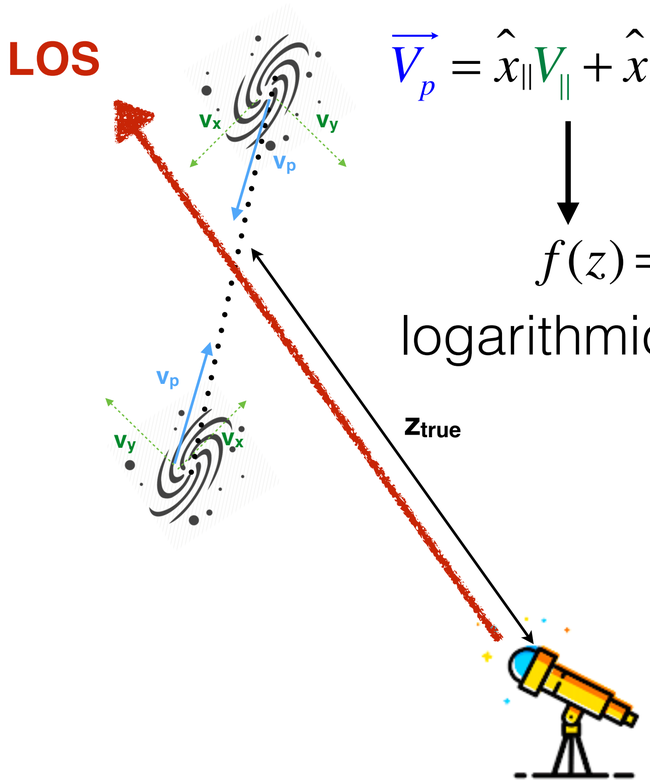
$$\propto D_M(z)/D_H(z)$$

For simplicity template & reference cosmology set to be the same (fid cosmology)

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)





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

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

logarithmic growth of structure

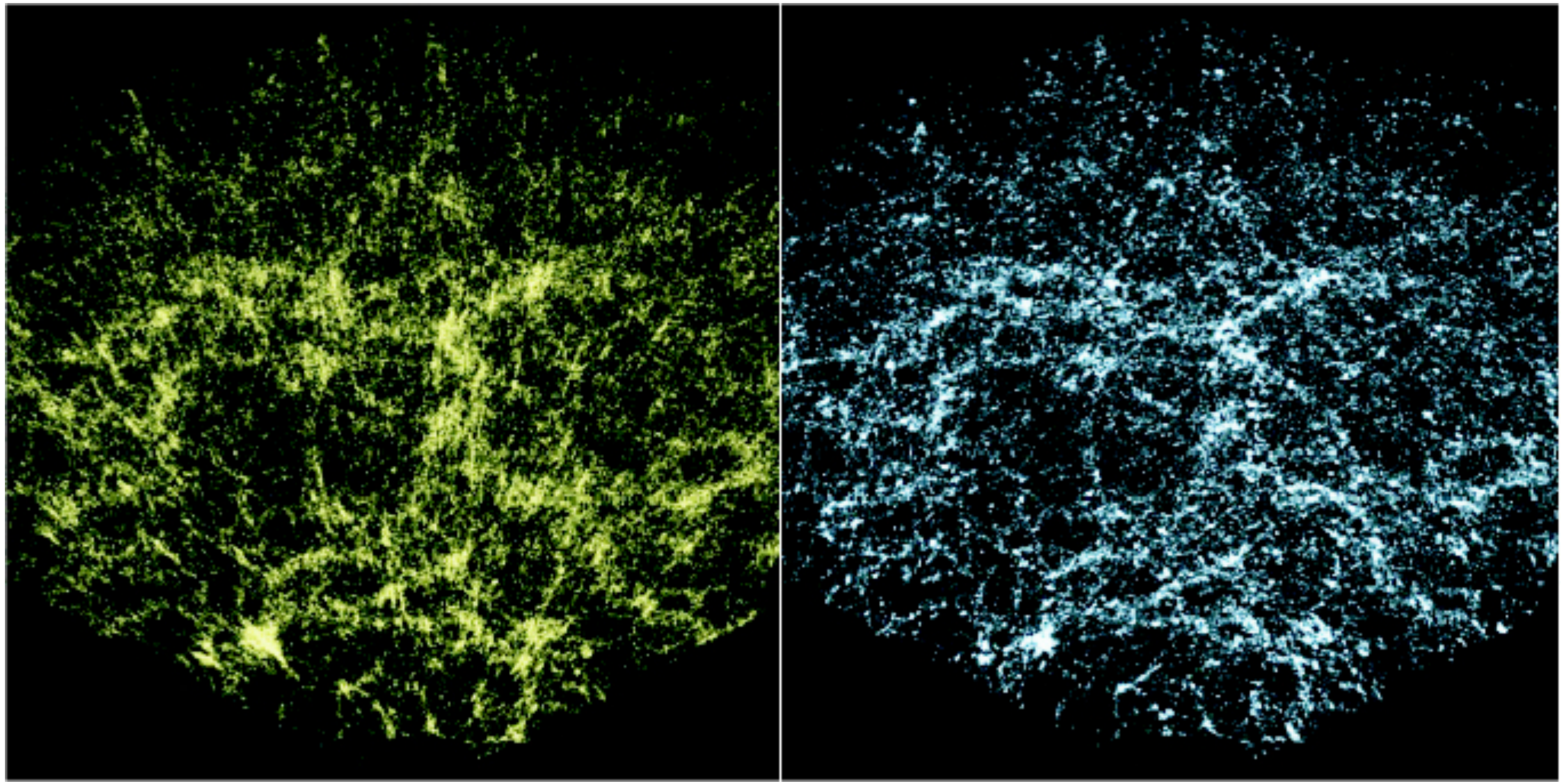
$$z_{obs} = z_{true} \oplus z_{pec} \equiv \left[(1 + z_{true}) \times (1 + z_{pec}) \right] - 1$$

1. Hubble flow

2. Coherent with growth of structure

Observed ‘redshift' space

True ‘real’ space

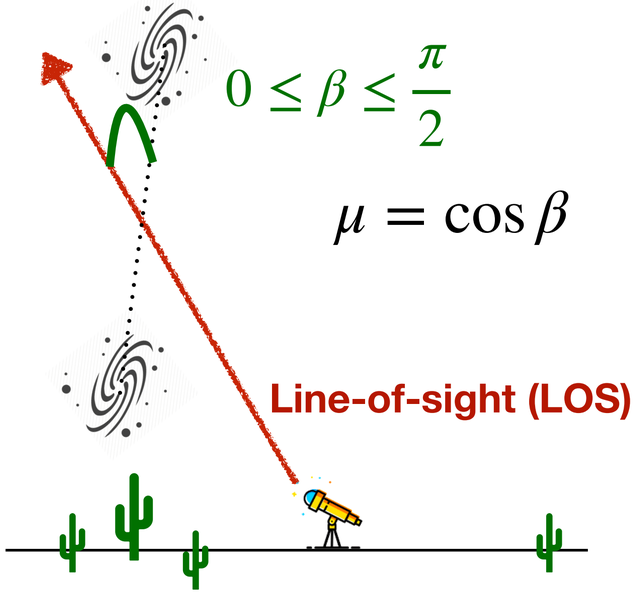


Redshift Space Distortions

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

$$P^{(s)}(k,\mu) = \underbrace{P^{(0)}(k)L_0(\mu)}_{\text{monopole}} + \underbrace{P^{(2)}(k)L_2(\mu) + P^{(4)}(k)L_4(\mu)}_{\text{quadrupole}\quad\text{hexadecapole}}$$

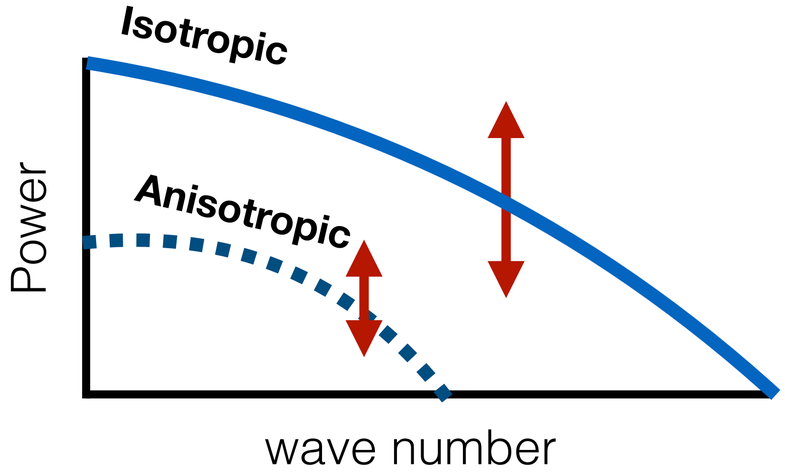
Isotropic signal — Anisotropic signal



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

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

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

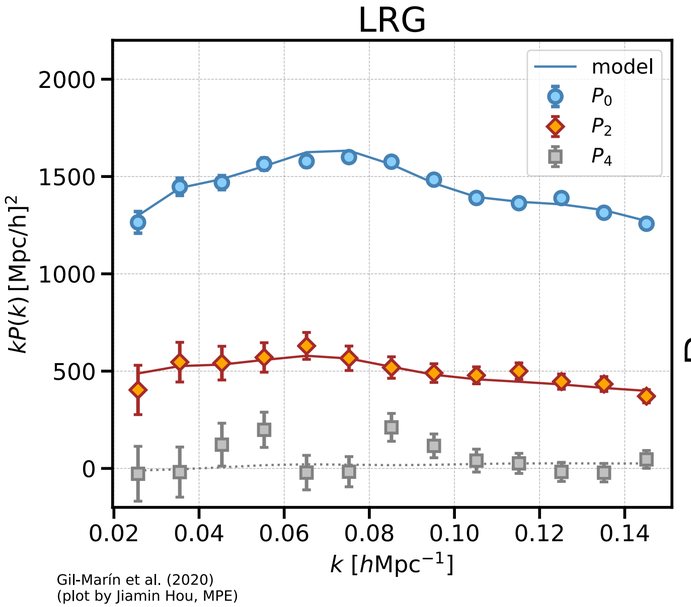


Full Shape analysis

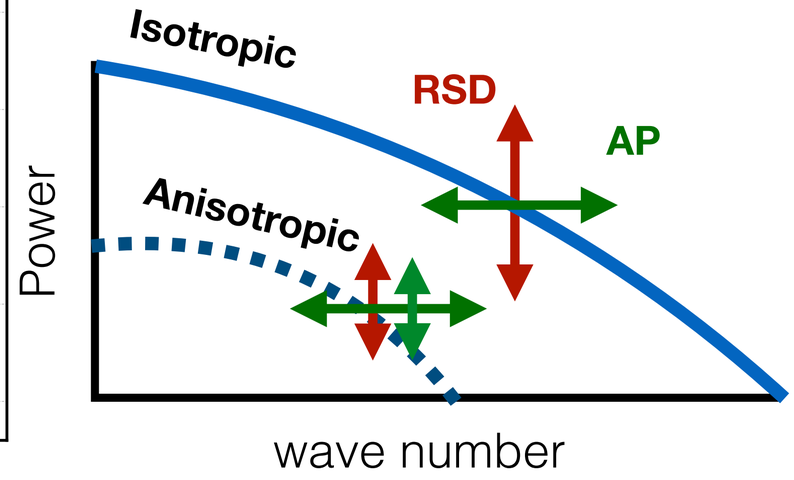
Simultaneous fit of,

$$f\sigma_8, \quad \alpha_{\parallel}\,(D_H/r_{\rm drag}), \quad \alpha_{\perp}\,(D_M/r_{\rm drag})$$

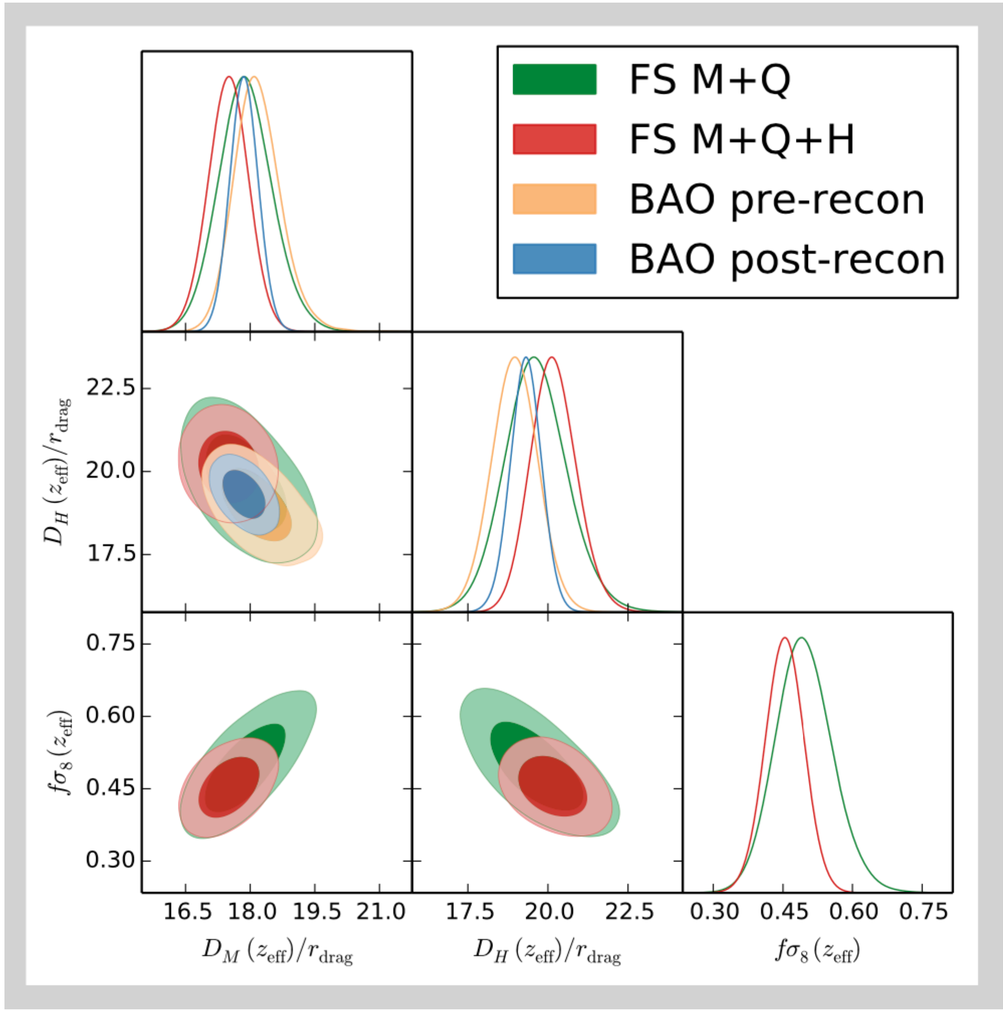
+ nuisance parameters (galaxy bias etc…)



Gil-Marín et al. (2020)
(plot by Jiamin Hou, MPE)



For the LRG sample



Logarithmic growth factor interpretation

Interpretation of the best-fitting value

1. Find $f_{\text{best-fit}}$ for a given (arbitrary) template, $P_m(k)$
2. $f_{\text{best-fit}}$ signal degenerated with $P_m(k)$ amplitude of the template used, σ_8^{temp}: $$[f\sigma_8]^{\text{true}} = f_{\text{best-fit}}\sigma_8^{\text{temp}}$$

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3. σ_8 is the smoothed matter power spectrum in spheres of 8 Mpc/h. The size of these spheres is in [Mpc/h] units depends on the reference cosmology

Isotropic scale dilation $q_0 = q_{\parallel}^{1/3} q_{\perp}^{2/3}$

Affects the units of the smoothing spheres!

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Affects the units of the smoothing spheres!

4. Invariant σ_8 definition as a function of the best-fitting q_0

$$\sigma_{8\,\text{resc}}^2(q_0) = \frac{1}{q_0^3}\int_0^\infty dk k^2 P_{\text{lin}}(k/q_0) W_{\text{TH}}^2([8\text{Mpc}/h]k)$$

5. We need a prior on rs to infer q0 from a0: We approximate r_{drag} as $r_{\text{drag}}^{\text{temp}}$

$$\alpha_0 \simeq q_0$$

$$[f\sigma_8]^{\text{true}} = f_{\text{best-fit}}\sigma_{8\,\text{resc}}^{\text{temp}}(\alpha_0)$$

This correction only important for reference cosmology very different from true cosmo,

$$\alpha_0 \neq 1$$

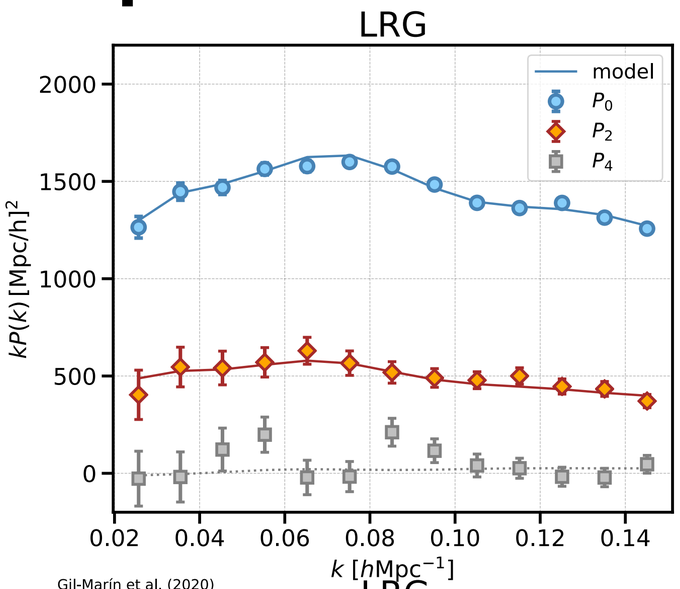
Redshift Space Distortions: beyond Kaiser

- **LRG**
  - **Fourier Space:** Resummed-PT + TNS
  - **Configuration Space:** RESPRESSO+TNS & CLPT-GS
- **ELG**
  - **Fourier Space** RegPT +TNS
  - **Configuration Space** CLPT-GS
- **QSO**
  - **Fourier Space** RegPT +TNS
  - **Configuration Space.** RESPRESSO+TNS

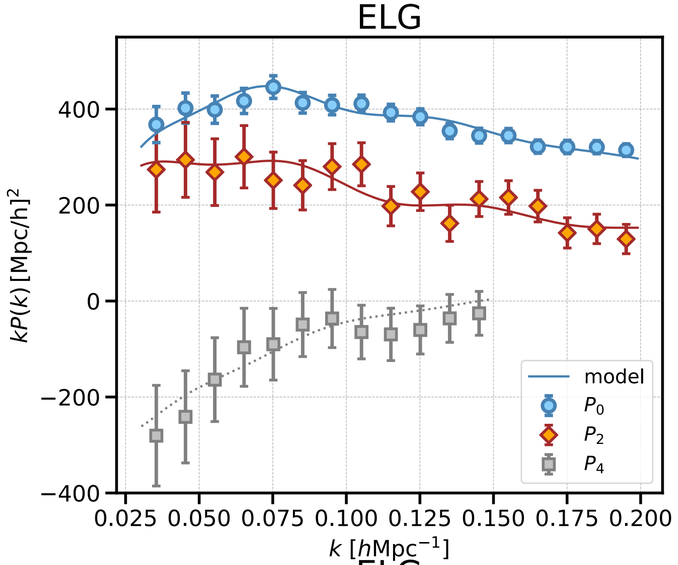
*see J. Bautista & E. Müller talk for more eBOSS tracers

eBOSS two-point statistics

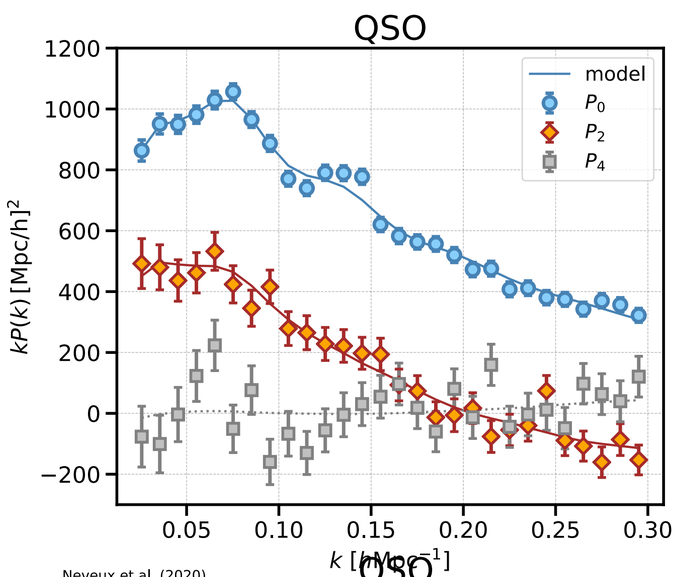
Fourier Space →



Gil-Marín et al. (2020)
(plot by Jiamin Hou, MPE)

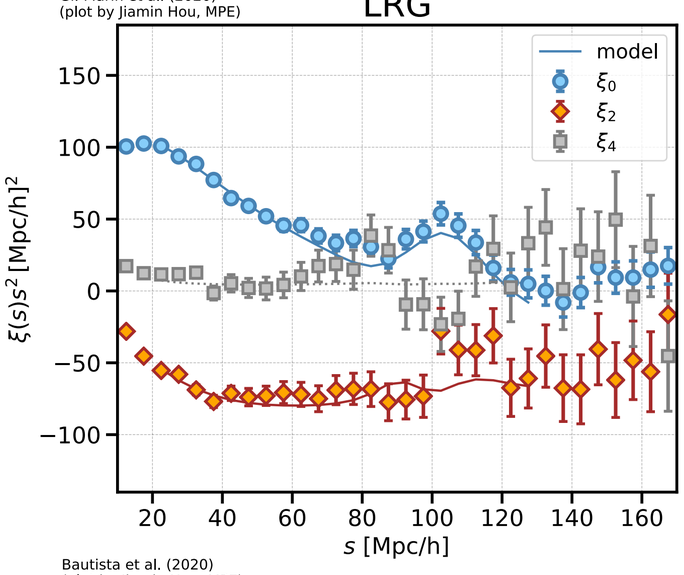


de Mattia et al. (2020)
(plot by Jiamin Hou, MPE)

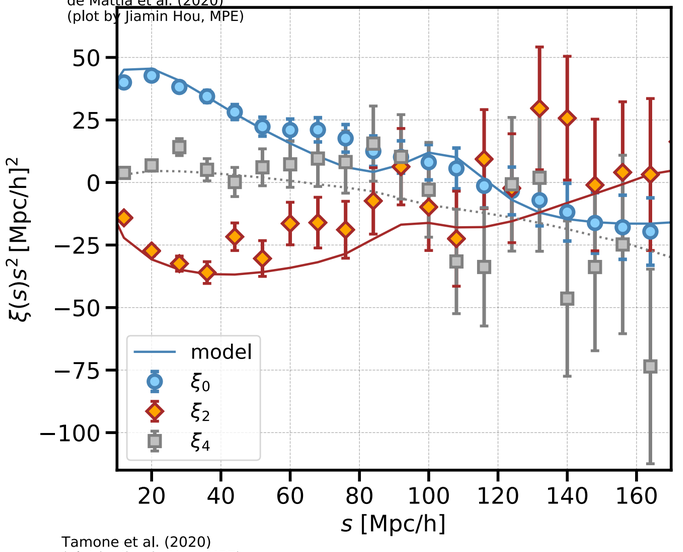


Neveux et al. (2020)
(plot by Jiamin Hou, MPE)

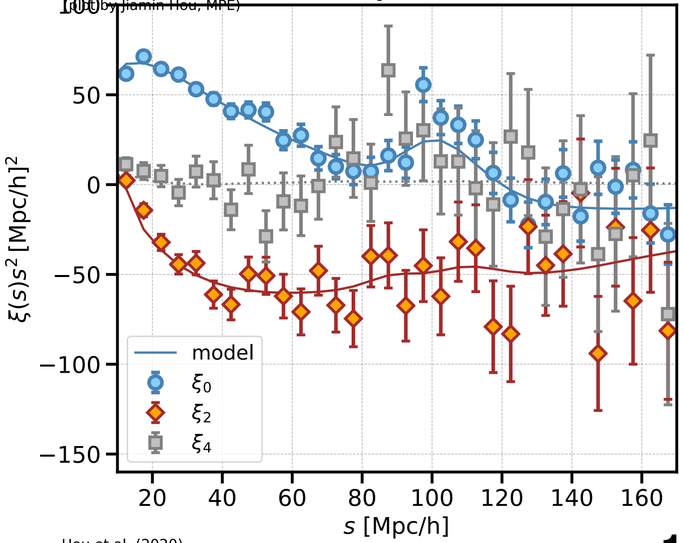
Config. Space →



Bautista et al. (2020)
(plot by Jiamin Hou, MPE)



Tamone et al. (2020)
(plot by Jiamin Hou, MPE)

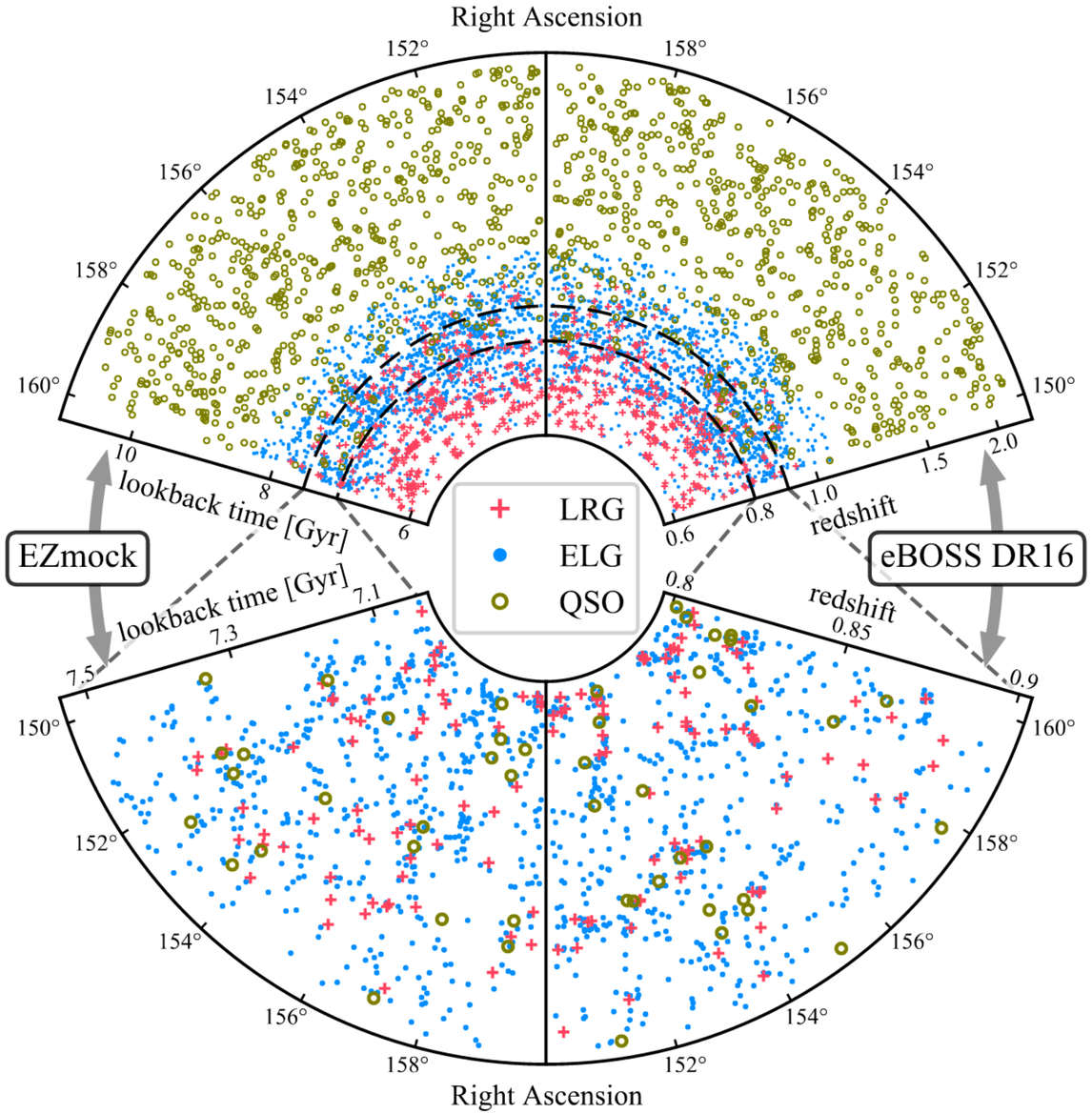


Hou et al. (2020)
(plot by Jiamin Hou, MPE)

Synthetic Catalogues

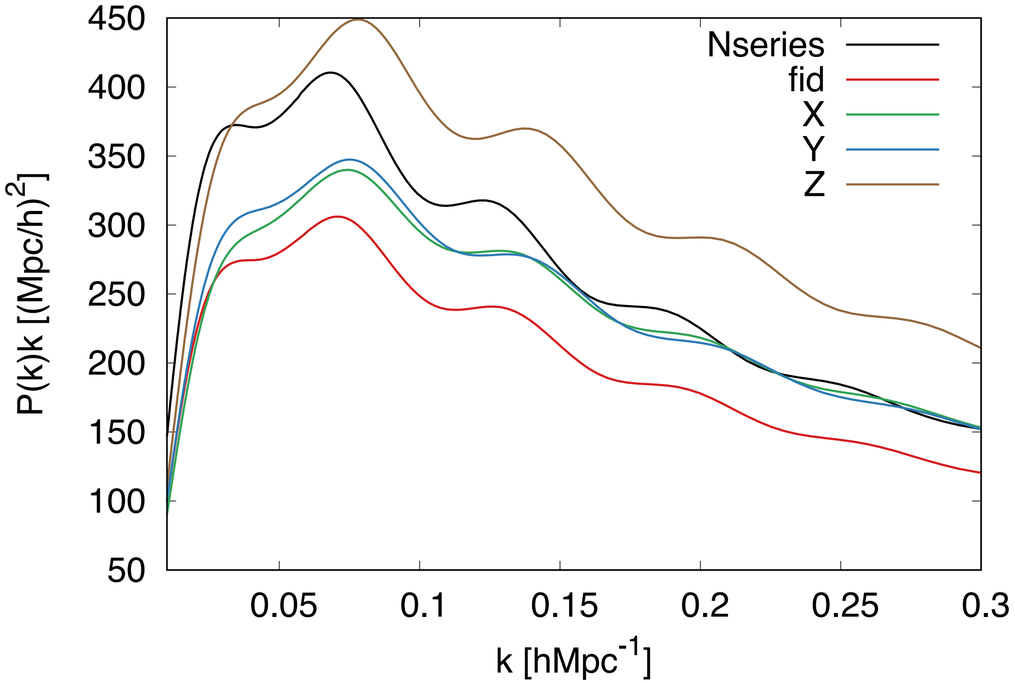
- Fast mocks: **Covariance**
  - **1000 realiz. EZmocks (ELG,LRG,QSO)**
  - **2000 realiz. GLAM-QPM (ELG)**

- N-body mocks: **Systematics**
  - **OuterRim + HOD mocks (QSO,LRG, ELG)**
  - **N-series mocks (LRG)**



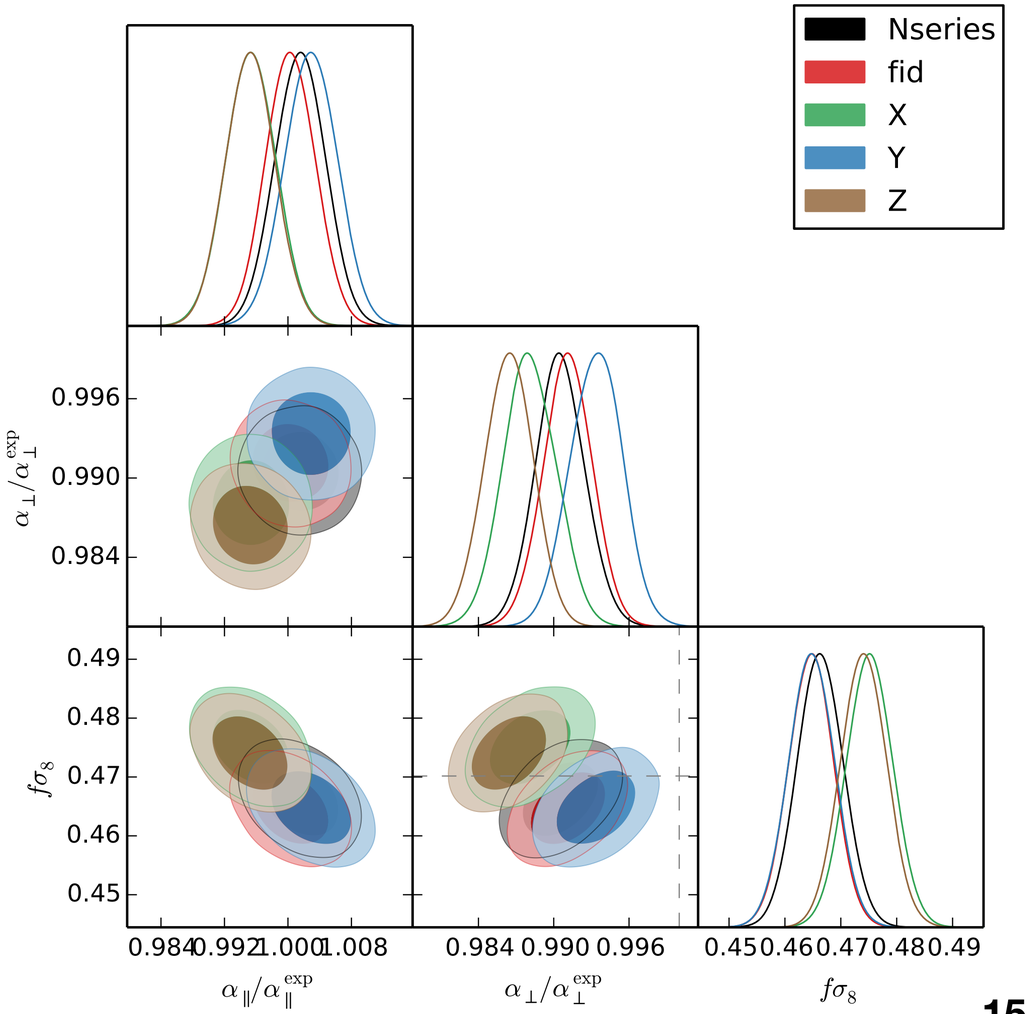
Systematic checks: template-dependence

Template shapes tested

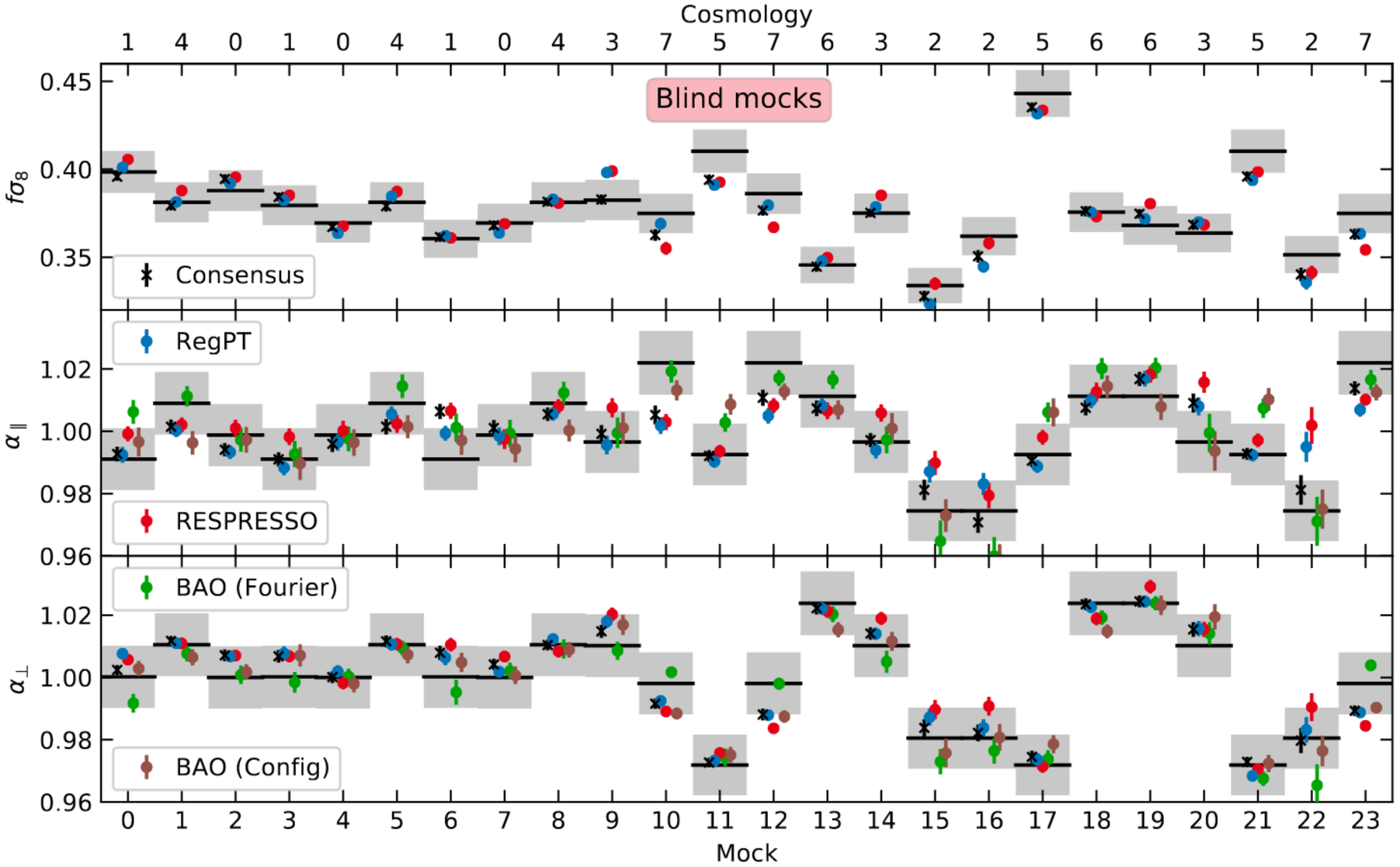


Model	Ω_m	$\Omega_m h^2$	Ω_b	$\Omega_b h^2$	$10^3 \times \Omega_\nu$	h	n_s	$A_s \times 10^9$	σ_8^0	$r_{\rm drag}$ [Mpc]	$N_{\rm eff}$
$\Theta_{\rm fid}$	0.310	0.1417	0.0481	0.0220	1.400	0.676	0.97	2.040	0.8	147.78	3.046
$\Theta_{\rm Nseries}$	0.286	0.1401	0.0470	0.0230	0	0.700	0.96	2.146	0.82	147.15	3.046
$\Theta_{\rm X}$	0.350	0.1599	0.0481	0.0220	1.313	0.676	0.97	1.767	0.814	143.17	3.046
$\Theta_{\rm Y}$	0.350	0.1599	0.0481	0.0220	1.313	0.676	0.97	2.040	0.814	138.77	4.046
$\Theta_{\rm Z}$	0.365	0.2053	0.0658	0.0370	0	0.750	0.96	2.146	0.9484	123.97	3.046

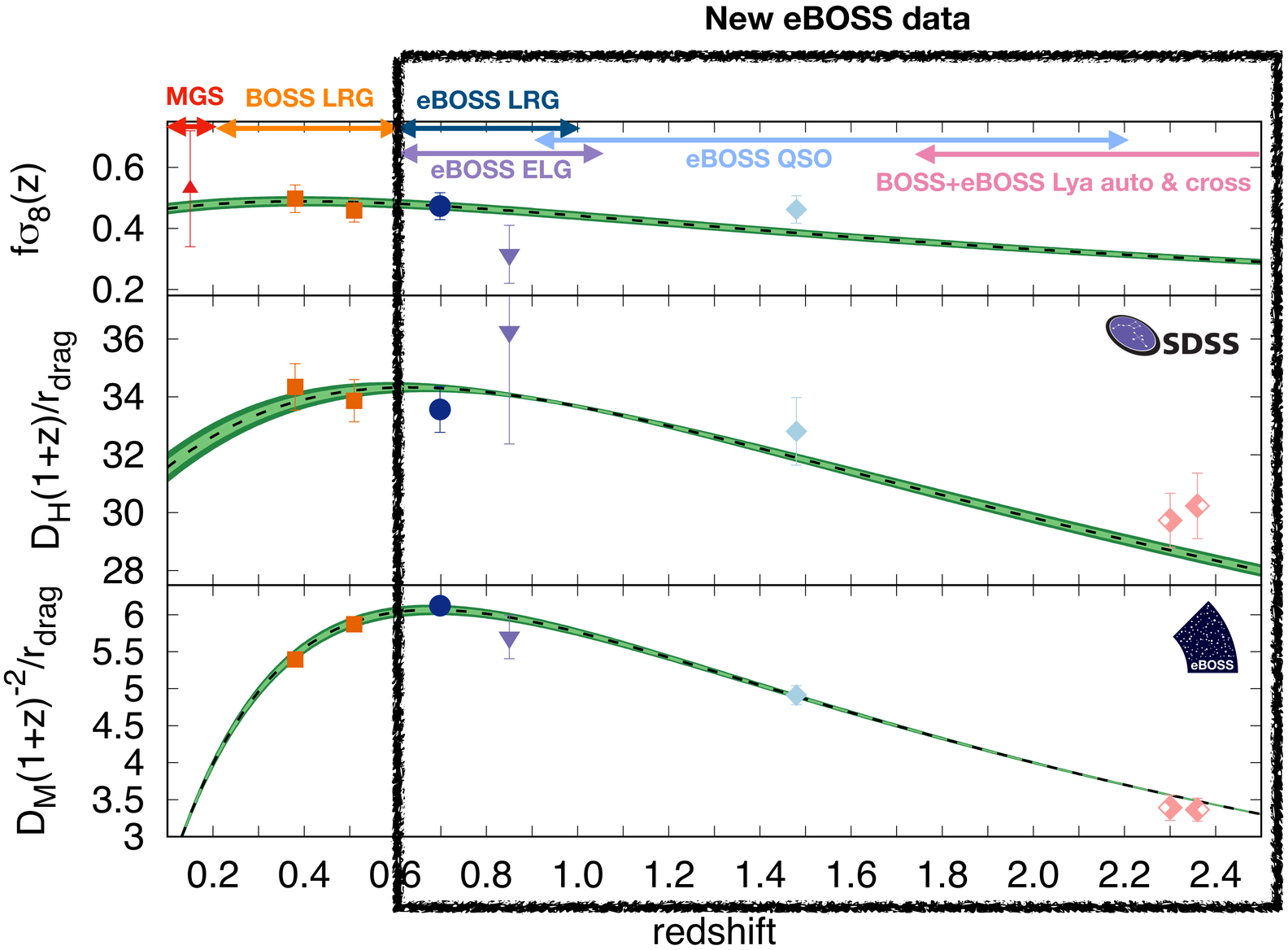
Performance on Nseries mocks



Systematic checks: cosmology-dependence



Conclusions



- SDSS-II, BOSS and eBOSS have provided direct measurements of D_M/r_{drag}, D_H/r_{drag} and $f\sigma_8$ in the redshift range from 0 up to 3 (up to 2 for $f\sigma_8$)

- So far, the largest spectroscopic galaxy survey: state-of-the-art measurements.

$f\sigma_8$ precision

• MGS SDSS-II	35%
• LRG BOSS (low-z)	9.0%
• LRG BOSS (mid-z)	8.2%
• LRG BOSS+eBOSS	9.4%
• ELG eBOSS	30%
• QSO eBOSS	9.7%

References

- Cosmology interpretation: eBOSS collaboration et al.
- Catalogues: Ross et al. (LRG & QSO), Raichoor et al. (ELG)
- LRG BAO & RSD: Bautista et al. (Config.), Gil-Marín et al. (Fourier)
- ELG BAO & RSD: Tamone et al. (Config.), de Mattia et al. (Fourier)
- QSO BAO & RSD: Hou et al. (Config.), Neveux et al. (Fourier)
- Ly-α BAO: du Mas des Bourboux et al. (Config.)
- Fast-mocks: Zhao et al. (EZmocks), Sicheng et al. (GLAM-QPM)
- Mock challenges: Rossi et al. (LRG), Smith et al. (QSO), Alam et al. (ELG), Ávila et al. (ELG)
- Other: Zhao et al. (Multi-tracer), Aubert et al. (Voids), Nadathur et al. (Voids), Mohammad et al. (PIP weights)