Results from eBOSS
Late Session

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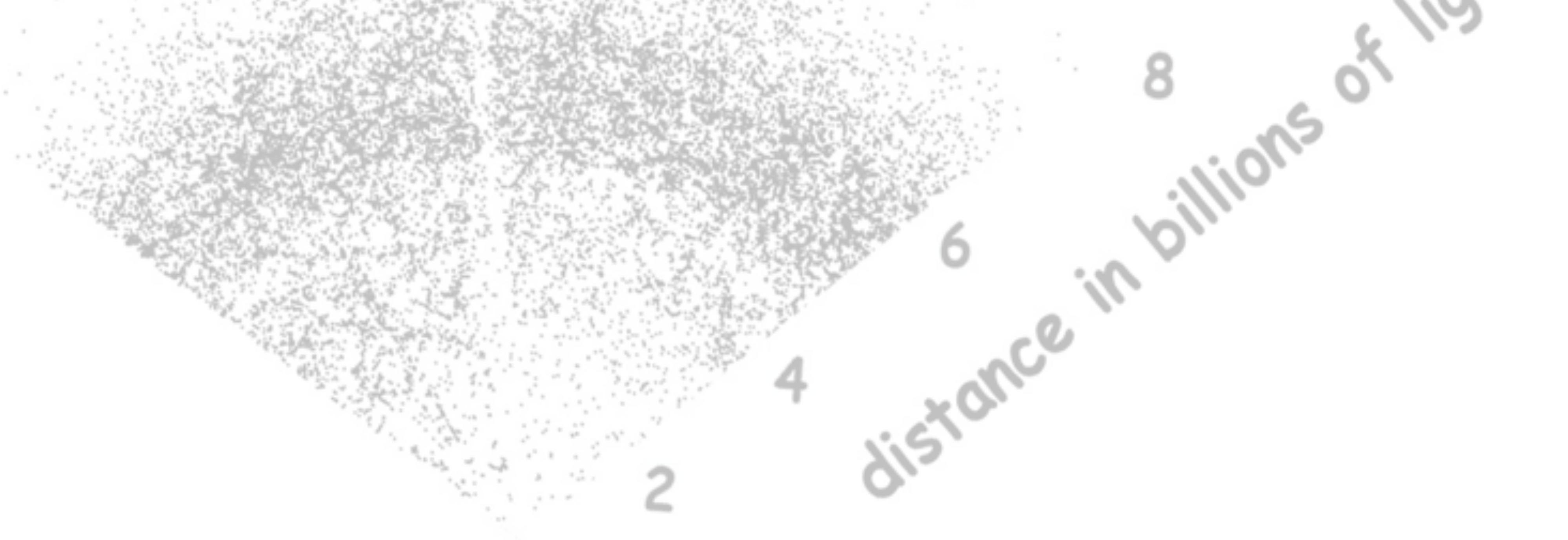

eBOSS Videos

- **Video I** : Introduction to eBOSS & Cosmology
  J. Bautista & E. Muller (20min).
- **Video Late Session**: BAO with eBOSS & Multitracer Analysis
  M. Vargas-Magaña & GongBo-Zhao(30min)
- **Video Early Session**: RSD with eBOSS & Voids Analysis
  H. Gil-Marin & S. Nadathur. (30min)

BAO from eBOSS

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extended Baryon Oscillations Spectroscopic Survey

2014-2019

Scientific Goal(s):

- Dark Energy

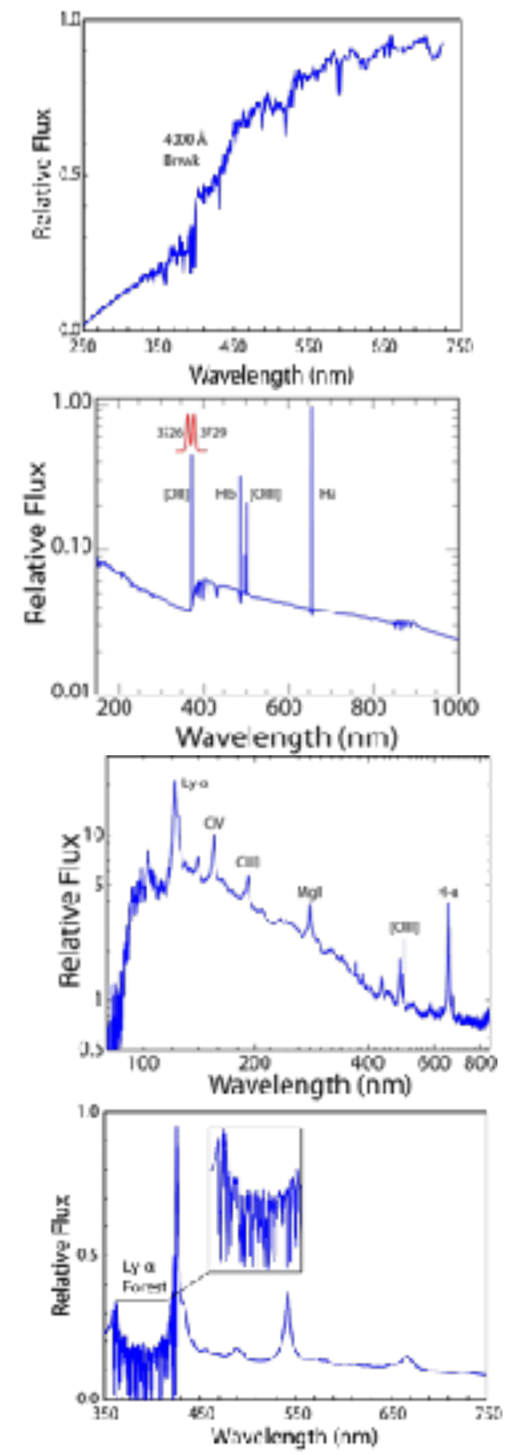
Key Observables:

- BAO , RSD

Precision:

- LRG's DA(z) 1.2% and H(z) to 2.1%
- ELG's DA(z) 3.1% and H(z) to 4.7%.
- QSO DA(z) 2.8% and H(z) to 4.2%.
- Lya forest DA(z) and H(z) at z > 2.1 by a factor of 1.44 relative to BOSS.

For a Intruduction to eBOSS Survey see "video eBOSS I" with J- Bautista & E. Muller



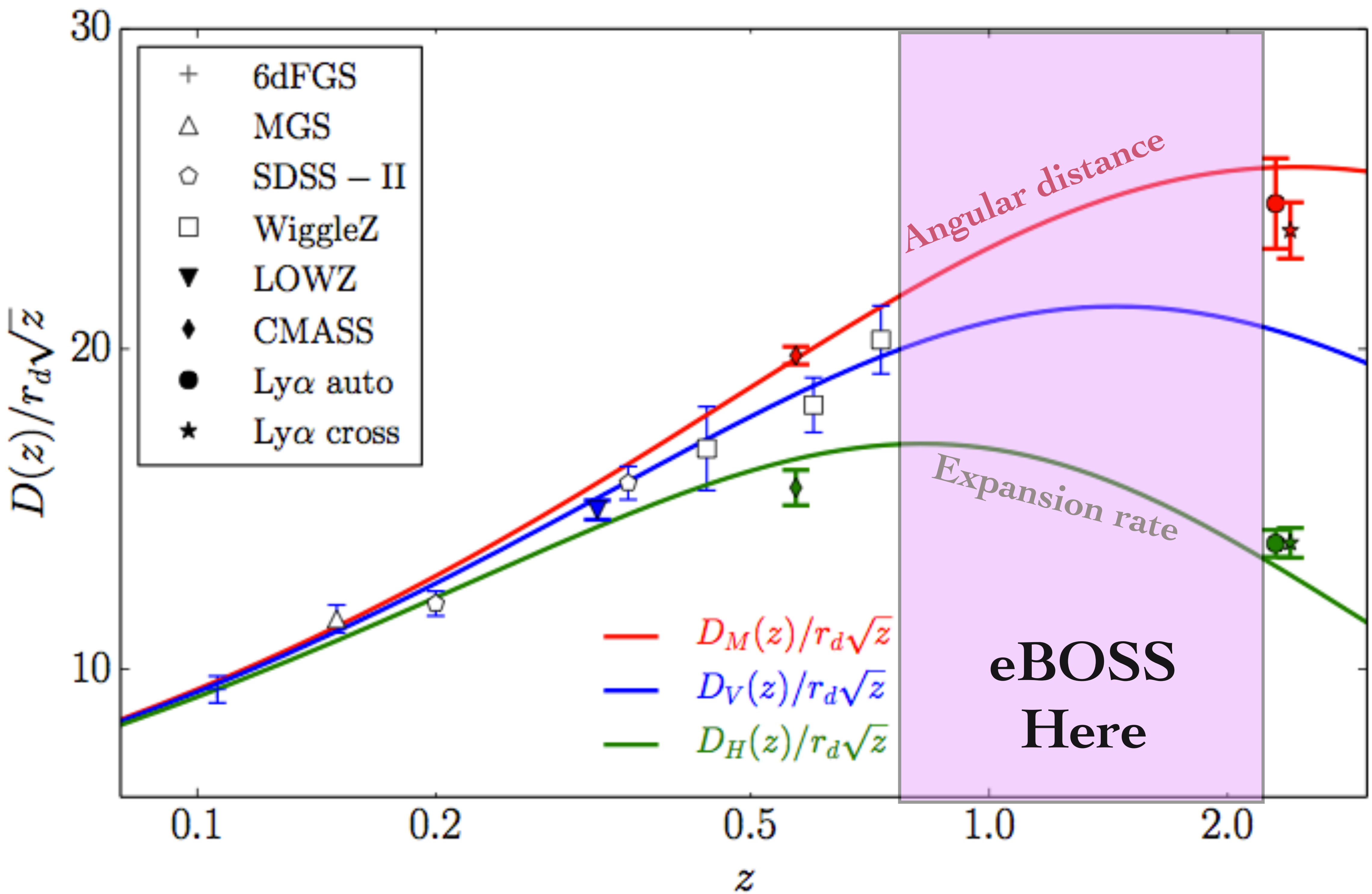
377,458
0.6 < z < 1.1

173,736
0.6 < z < 1.1

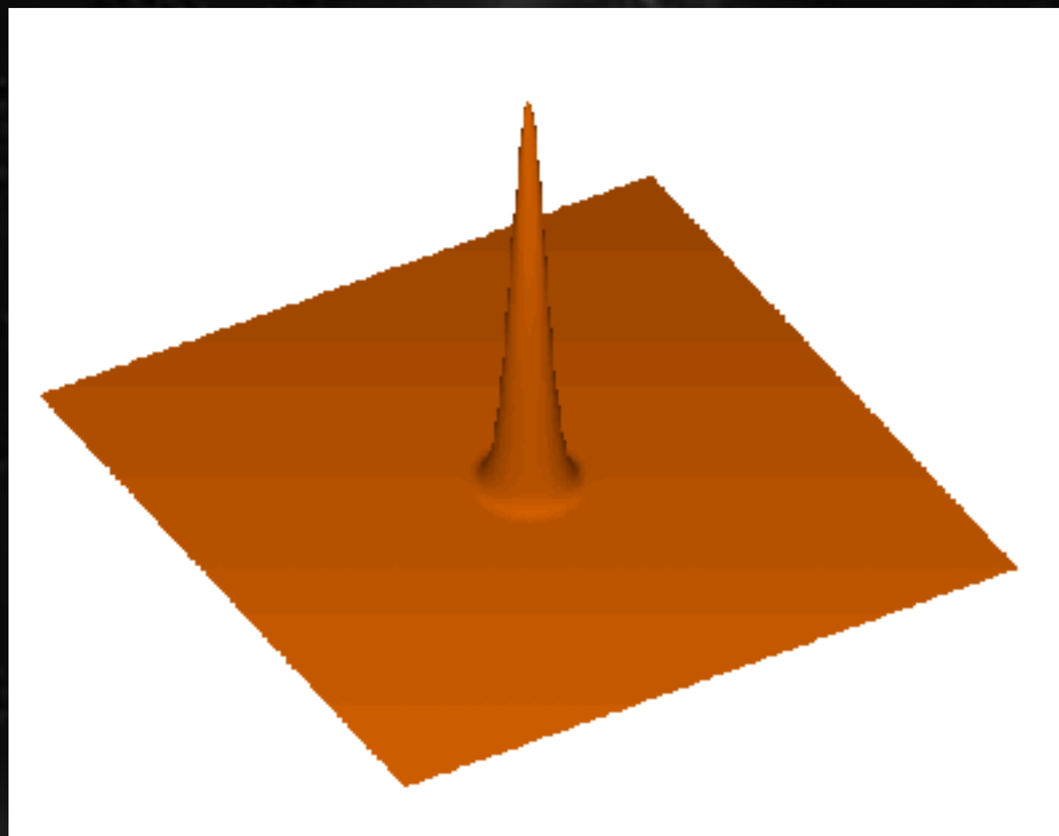
210,005
0.8 < z < 2.2

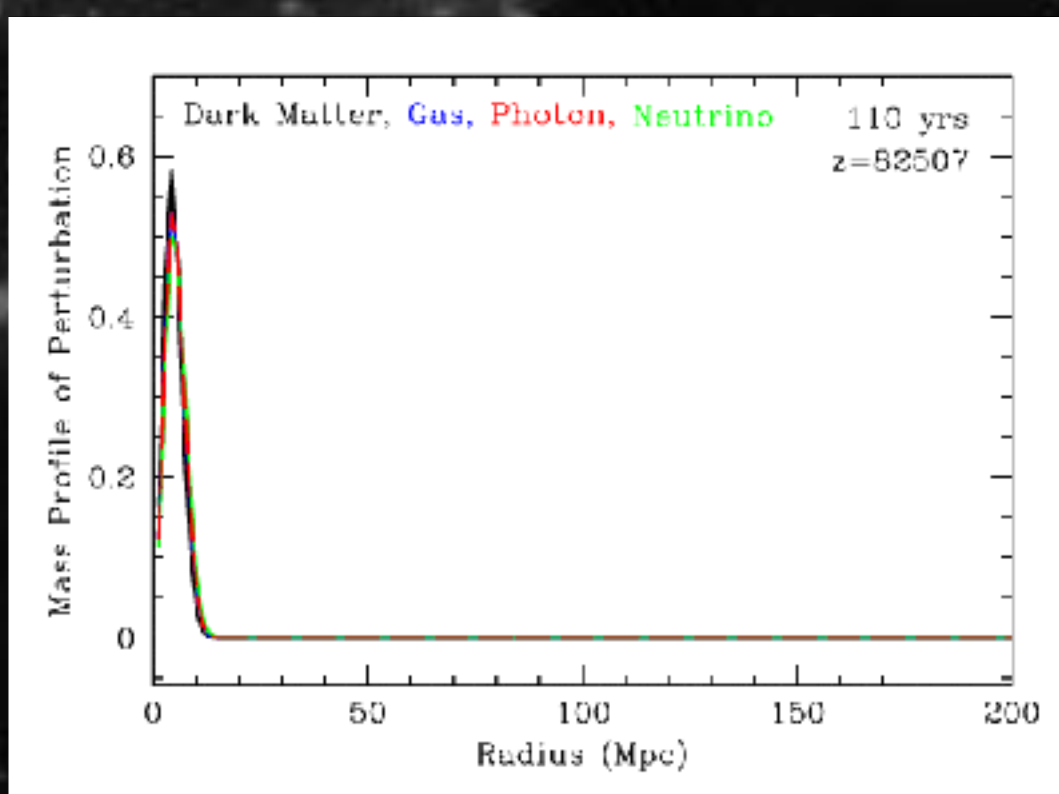
343,708
z >2.1

eBOSS filling the gap !



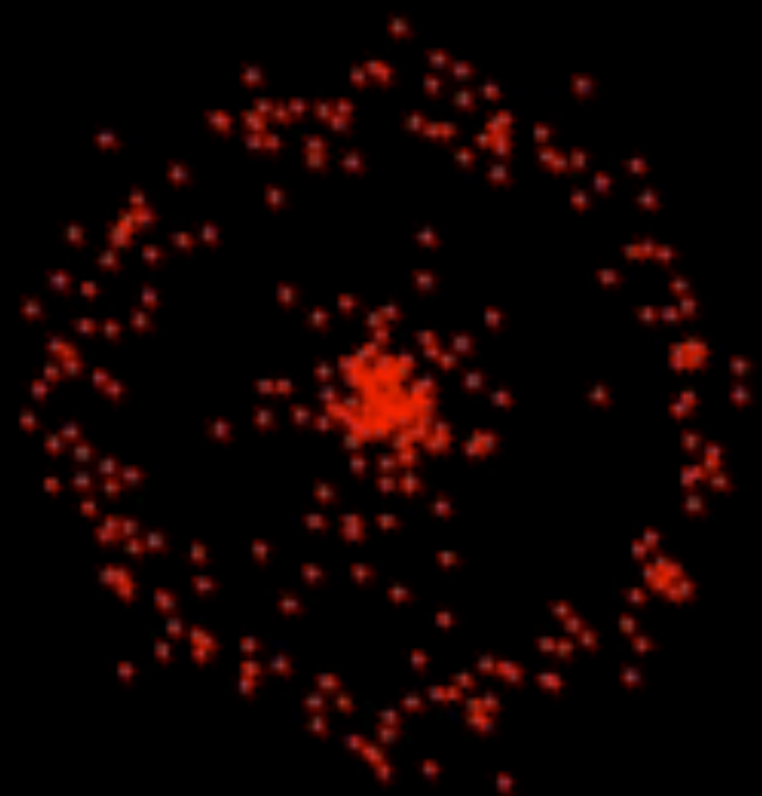
What are the BAO?



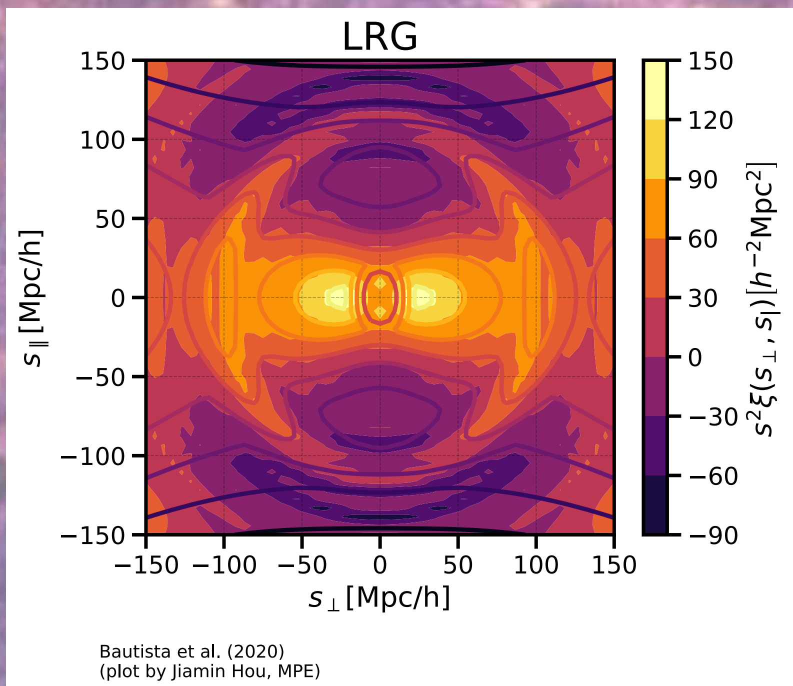


- Most robust probe for exploring expansion history Universe.
- Gravitational attraction of the overdense regions.
- pressure imbalance from the light opposes compression.
- density fluctuations oscillate like sound waves for all k modes, resulting in an expanding spherical sound wave.
- Sound wave expands until recombination, then photons decouple, and baryons remains frozen at the BAO escale

We observe an spherical shell surrounding every single over density….

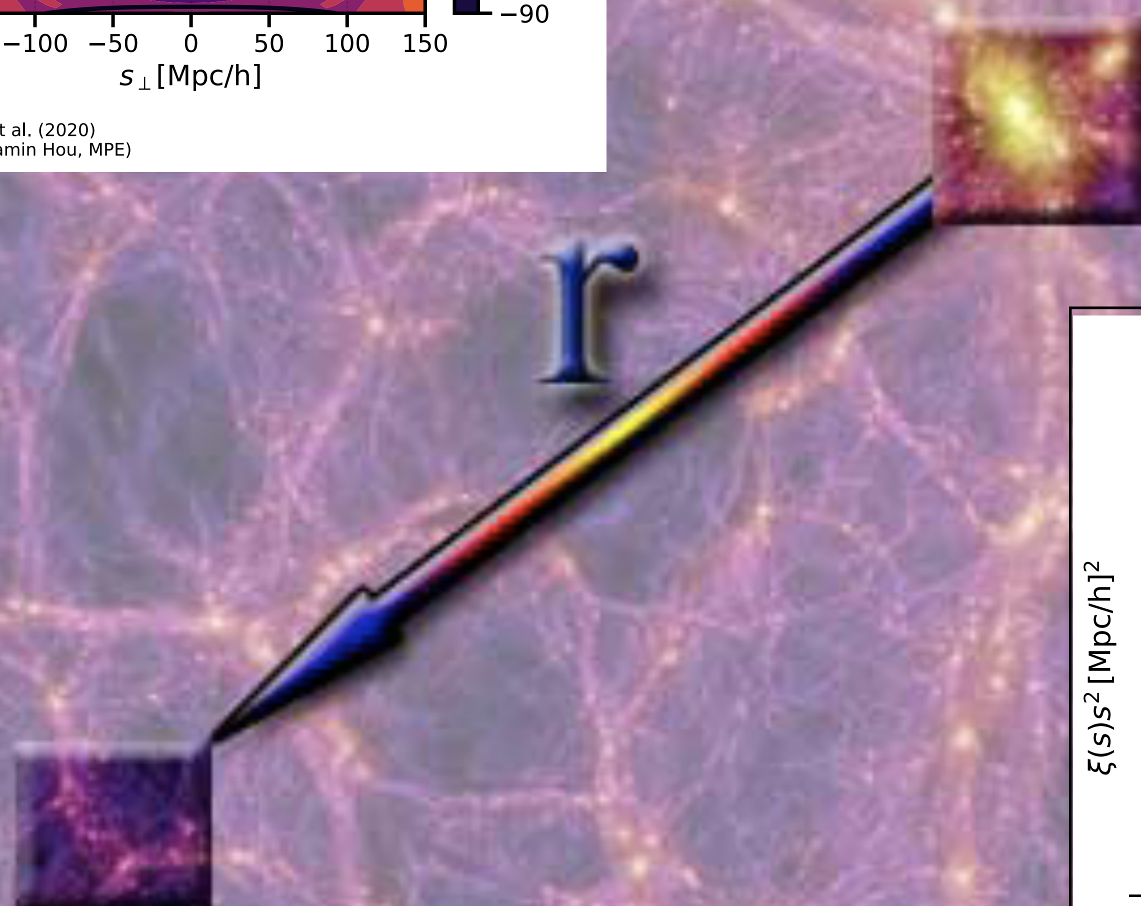


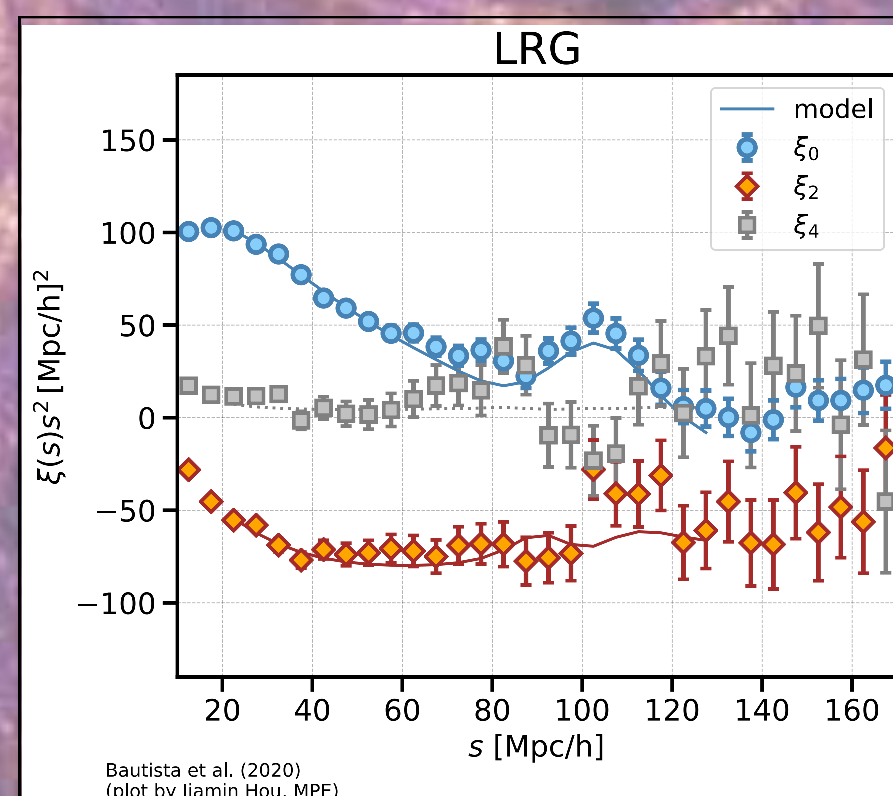
Measuring Clustering



$$\xi(r) = \langle \delta(x)\delta(x+r) \rangle$$

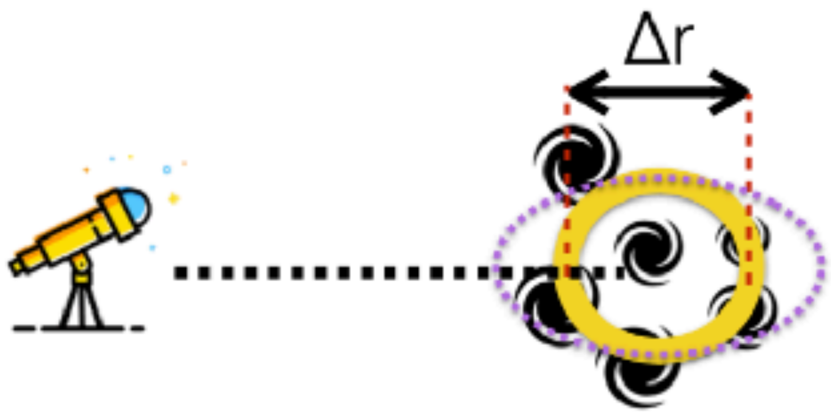
$$\xi(\mathbf{r}') = \sum_{\ell'=0}^{\infty} \xi_{\ell'}(\mathbf{r}')L_{\ell'}(\mu'),$$

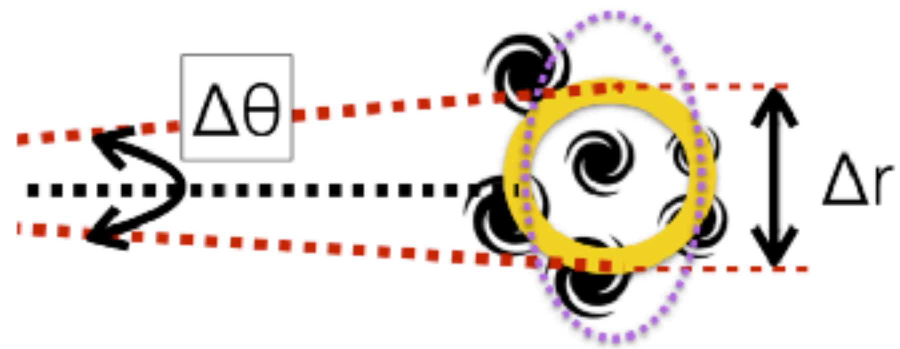




BAO as standar ruler

* aka reference cosmology



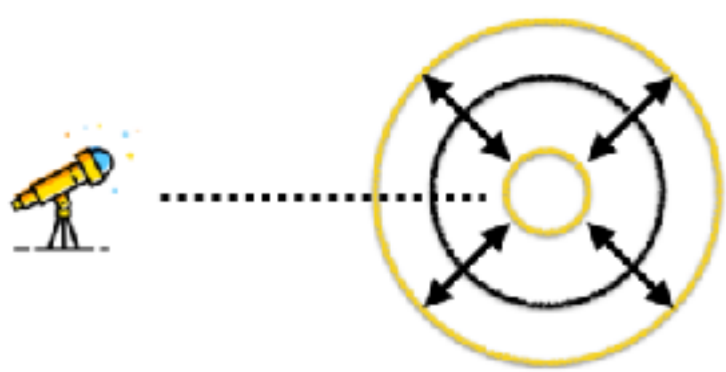


Radial distance

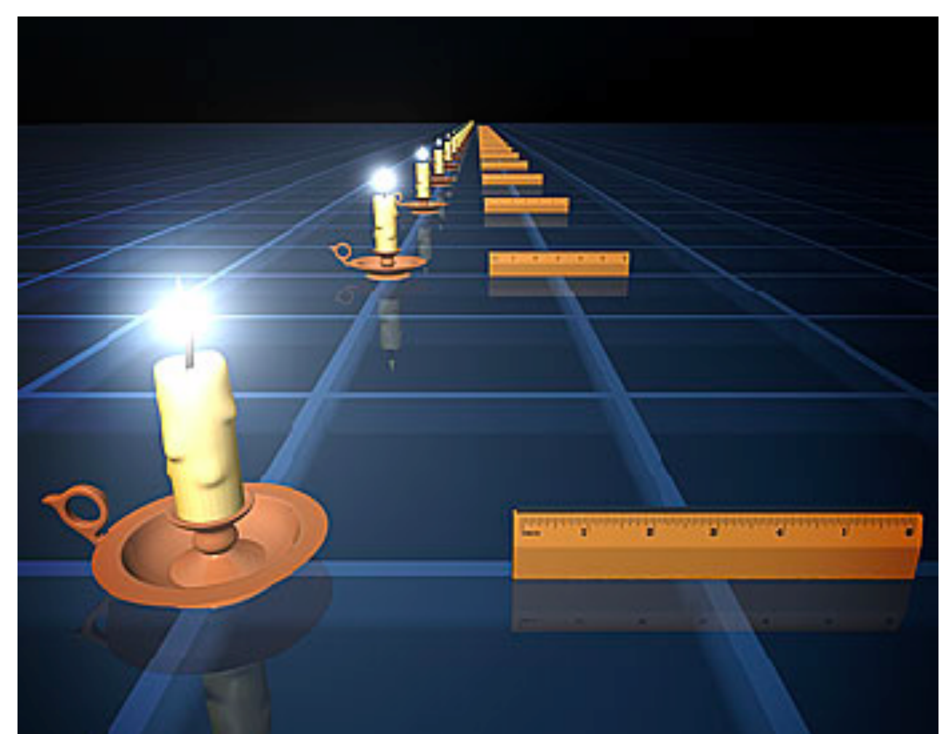
$$\Delta r_{\parallel}(z_1,z_2;\Omega_m)=\int_{z_1}^{z_2}\frac{c\,dz'}{H_0\sqrt{\Omega_m(1+z')^3+1-\Omega_m}}\approx\frac{c\Delta z}{H(\bar{z},\Omega_m)}\sim\frac{1}{H(z)}$$

Angular diameter distance

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

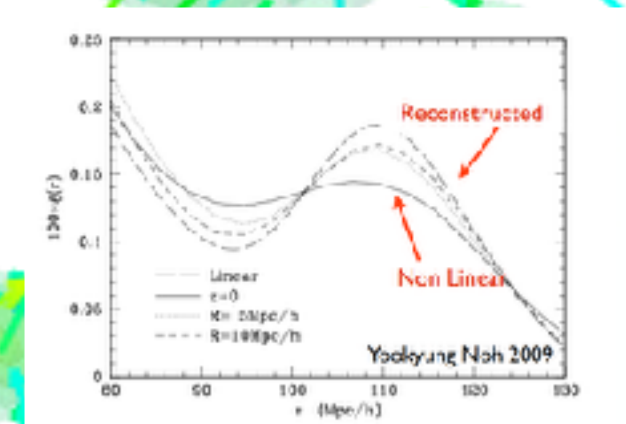


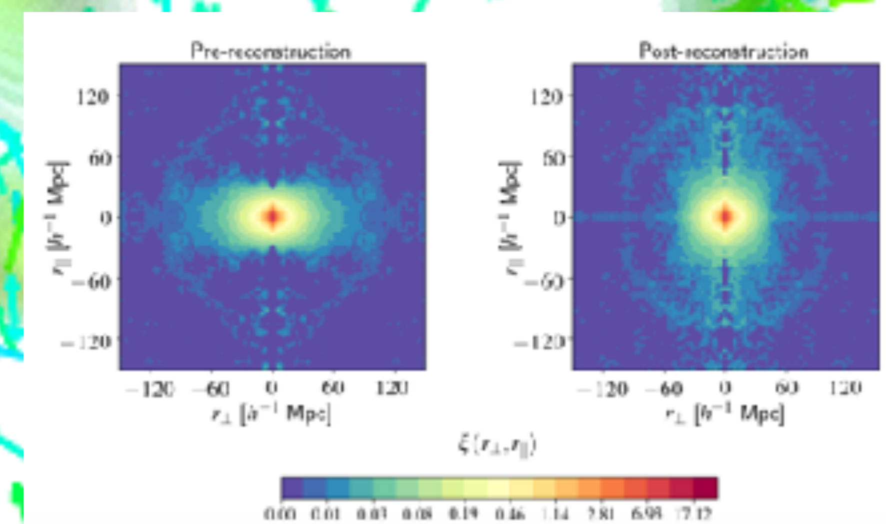
$\sim (D_M^2/H)^{1/3} = D_V$

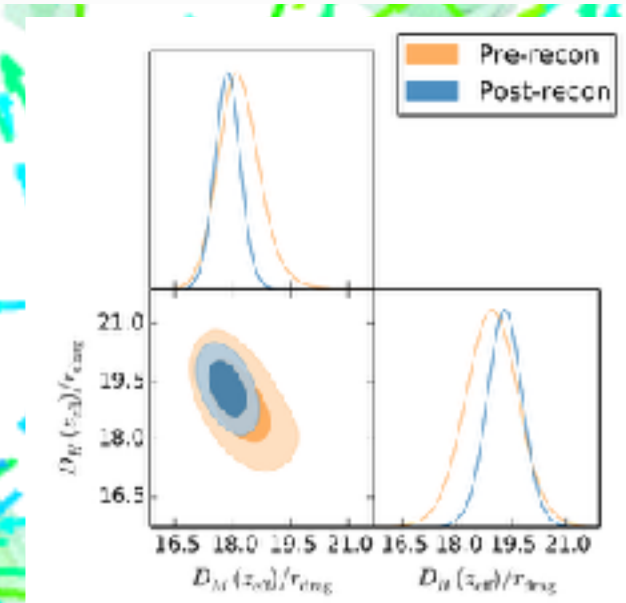


Reconstruction

- Reconstruction is part of standard BAO analysis.
- Enhance the BAO signal by un-doing the non-linear bulk flows
- Reduce the error in the BAO measurement (and NL BAO shift).
- Reconstruction applied in LRG & ELG analysis.
- QSO =>Given the low density reconstruction technique cannot be applied successfully.







BAO Modelling I: template

RSD Kayser

$$\Sigma_{NL}(\mu) = \Sigma_{\parallel}^2\mu^2 + \Sigma_{\perp}(1-\mu^2)$$

$$P(k, mu) = \frac{b^2[1+\beta(1-S(k))\mu^2]^2}{(1+k^2\mu^2\Sigma_s^2/2)} \times [P_{no-wiggle}(k) + (P_{lin}(k) - P_{no-wiggle}(k))e^{-k^2\Sigma_{NL}(\mu)/2}]$$

Fingers of God

Non Linear Broadening

arbitrary fiducial cosmology for P_{lin}

$$S(k) = e^{-2\Sigma_r/2}$$

Pre-reconstruction $\Sigma_r = 0$

Post-reconstruction $\Sigma_r = 15\mathrm{Mpc/h}$

Fourier Space

$$P_\ell(k) = \frac{2\ell+1}{2}\int_{-1}^{1} P(k,\mu)L_\ell(\mu)\mathrm{d}\mu$$

Configuration Space

$$\xi_\ell(r) = \frac{i^\ell}{2\pi^2}\int_0^\infty k^2 j_\ell(kr)P_\ell(k)\mathrm{dk}$$

BAO Modelling

$$\xi_\ell(r) = \xi(\alpha_\parallel, \alpha_\perp, r) + \sum_{i_{min}}^{i_{max}} a_{\ell,i} r^i$$

BAO template + Broadband polynomial fit

Anisotropic BAO

$$\alpha_\parallel = \frac{D_M(z_{eff})/r_d}{D_M^{fid}(z_{eff})/r_d^{fid}}$$

$$D_M = (1+z)D_A(z)$$

$$\alpha_\perp = \frac{D_H(z_{eff})/r_d}{D_H^{fid}(z_{eff})/r_d^{fid}}$$

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

Isotropic BAO

$$\alpha = \frac{D_V(z_{eff})/r_d^{fid}}{D_V^{fid}(z_{eff})/r_d}$$

$$D_V = [D_M^2(z) c z H(z)^{-1}]^{1/3}$$

Mocks & Systematics

EZ Mocks

OuteRim

NSERIES

Covariance mocks

Cheng et al (2020)

N-body mocks

G.Ross et al, 2020

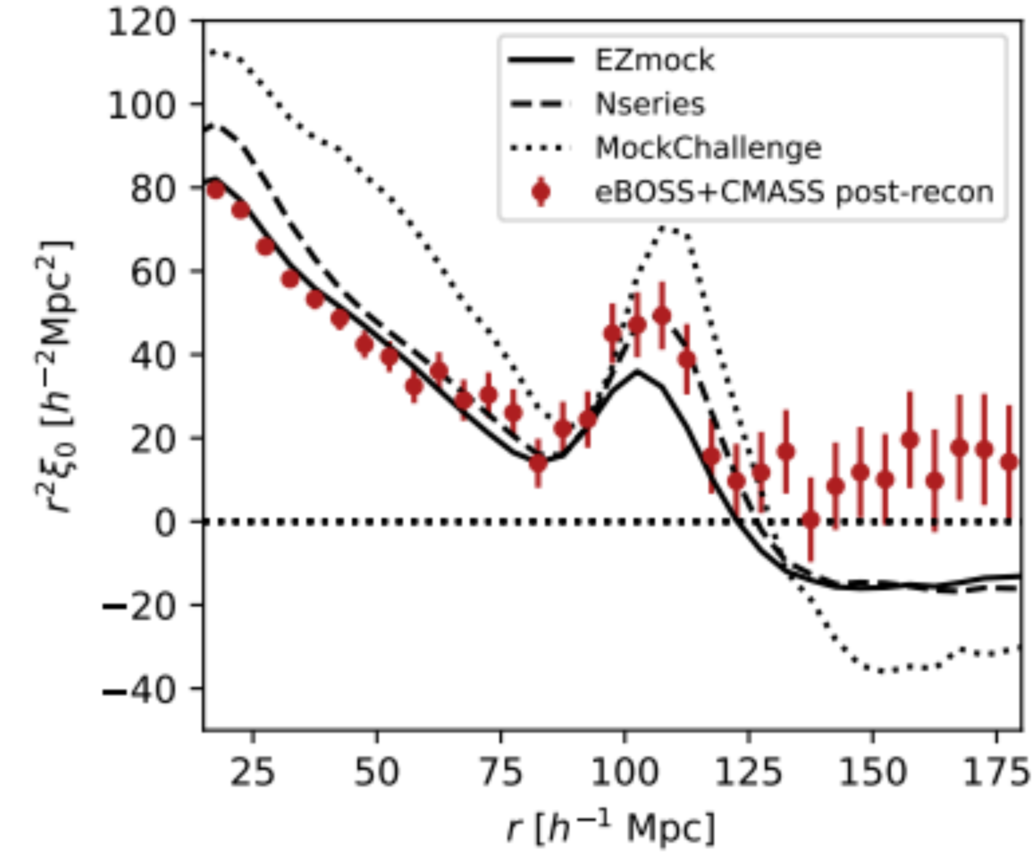
S.Alam et al,2020

S. Avila et al, 2020

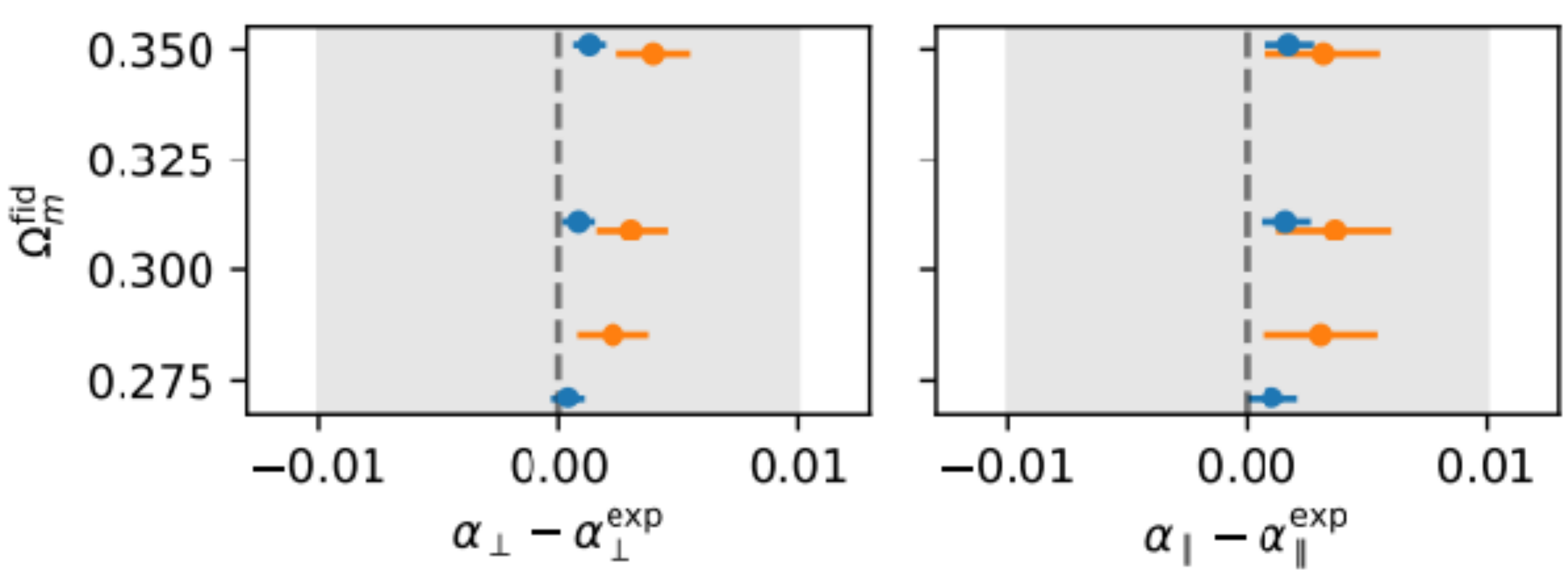
A. Smith et al 2020.

N-body mocks

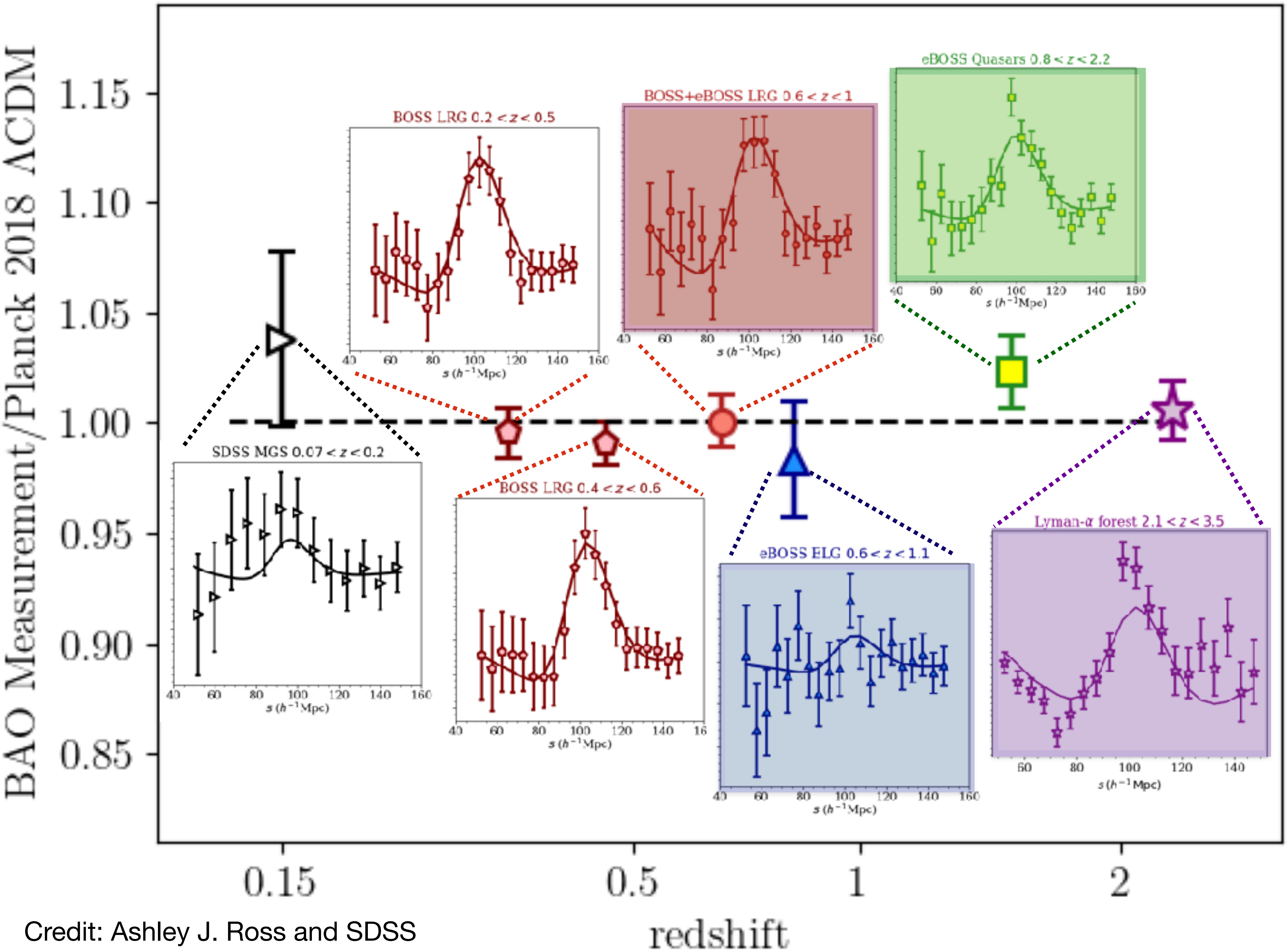
G. Alam et al (BOSS)



EZ Post-reconstruction **NSERIES**



SDSS BAO Distance Ladder



Credit: Ashley J. Ross and SDSS

Publications

Clustering Catalog Documentation	Ross et al. (2020)	Reid et al. (2016)	Reid et al. (2016)	Ross et al. (2020)	Raichoor et al. (2020)	Ross et al. (2020), Lyke et al. (2020)	du Mas des Bourboux et al. (2020), Lyke et al. (2020)	du Mas des Bourboux et al. (2020), Lyke et al. (2020)	
N-body and Mock Catalogs		Kitaura et al. (2016)	Kitaura et al. (2016)	Zhao et al. (2020), Rossi et al. (2020)	Zhao et al. (2020), Lin et al. (2020), Alam et al. (2020), Avila et al. (2020)	Zhao et al. (2020), Smith et al. (2020)	Farr et al. (2020)	Farr et al. (2020)	
Reference for final results	Ross et al. (2015)	BOSS Collaboration (2017)	BOSS Collaboration (2017)	Bautista et al. (2020), Gil-Marin et al. (2020)	Raichoor et al. (2020), de Mattia et al. (2020)	Hou et al. (2020), Neveux et al. (2020)	du Mas des Bourbuox et al. (2020)	du Mas des Bourbuox et al. (2020)	BAO
Reference for final results	Howlett et al. (2015)	BOSS Collaboration (2017)	BOSS Collaboration (2017)	Bautista et al. (2020), Gil-Marin et al. (2020)	Tamone et al. (2020), de Mattia et al. (2020)	Hou et al. (2020), Neveux et al. (2020)	du Mas des Bourbuox et al. (2020)	du Mas des Bourbuox et al. (2020)	

Conclusions

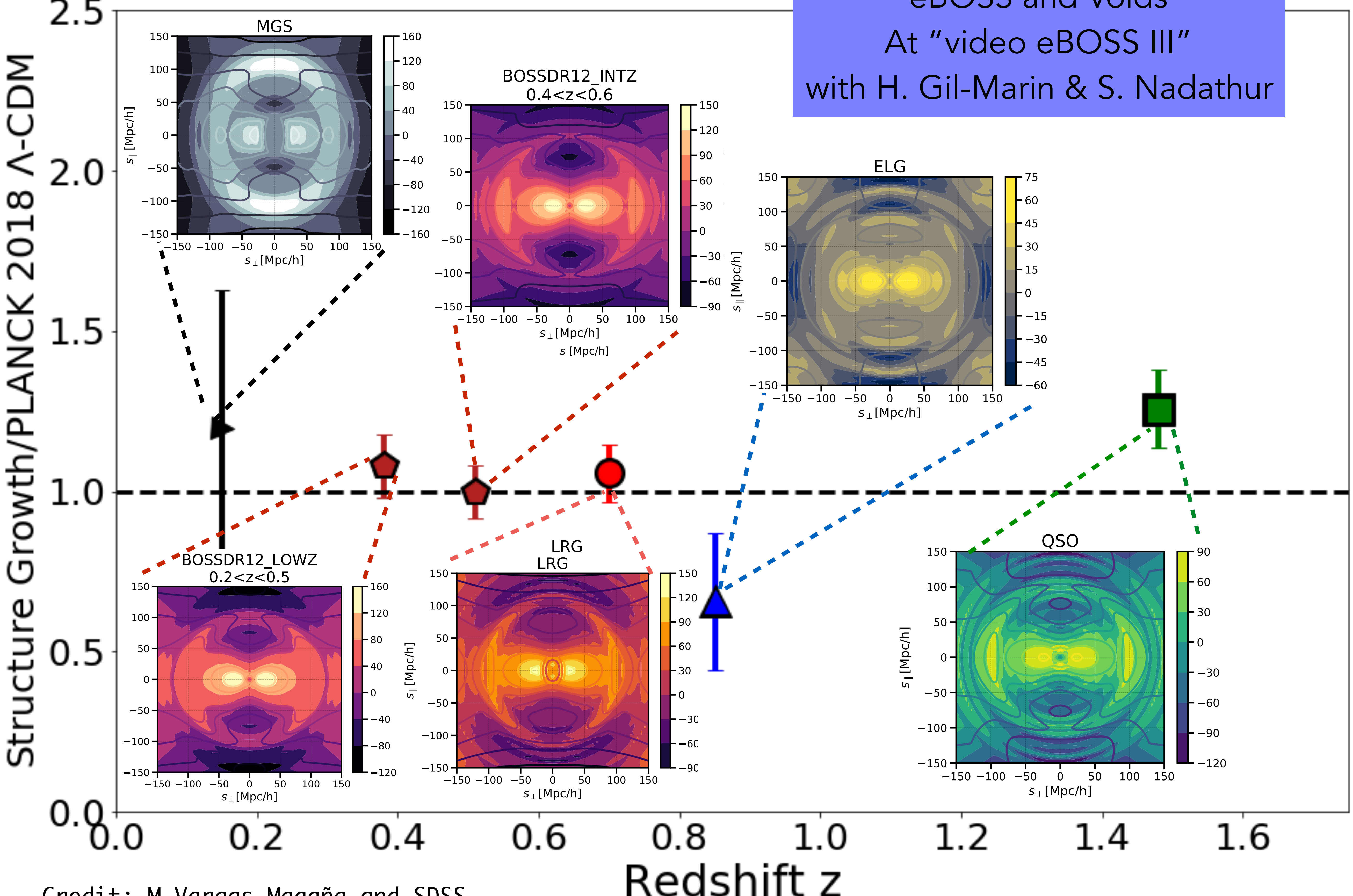
The state of the art in BAO measurements for stage III spectroscopic surveys:

- LRG's $D_M(z_{eff})$ 1.8% and $H(z_{eff})$ to 2.7%
- ELG's $D_V(z_{eff})$ 3.2%.
- QSO $D_M(z_{eff})$ 2.6% and $H(z_{eff})$ to 4.1%.
- Lyα forest $D_M(z_{eff})$ 2.8% and $H(z_{eff})$ to 2.1% .

All between 1.8-4.1 %

Quick Advertisement

A summary of RSD results from
eBOSS and Voids
At “video eBOSS III”
with H. Gil-Marin & S. Nadathur



Credit: M.Vargas-Magaña and SDSS.

eBOSS Multi-tracer Analysis

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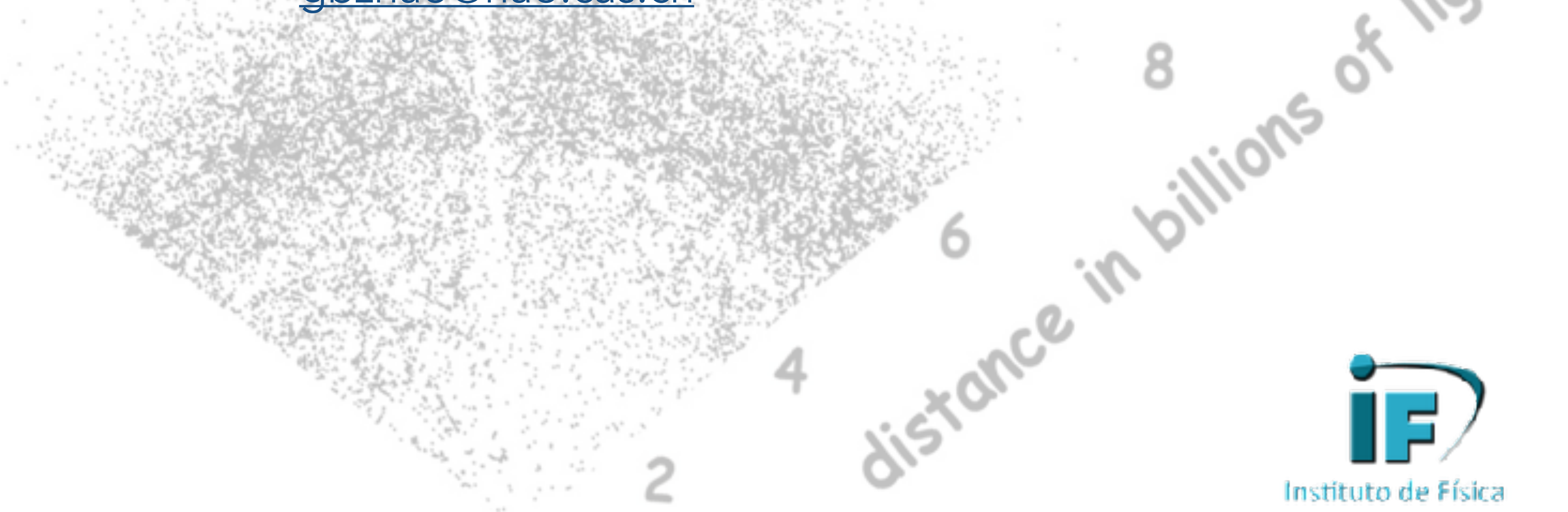
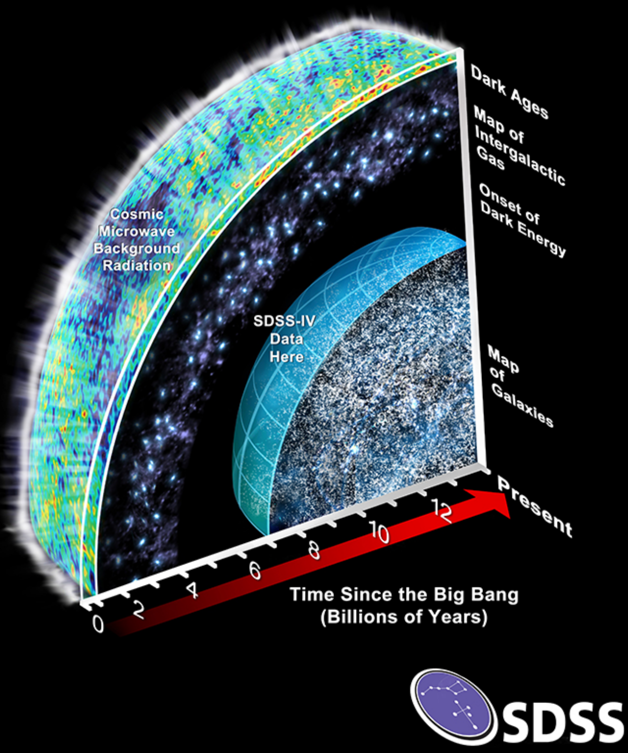
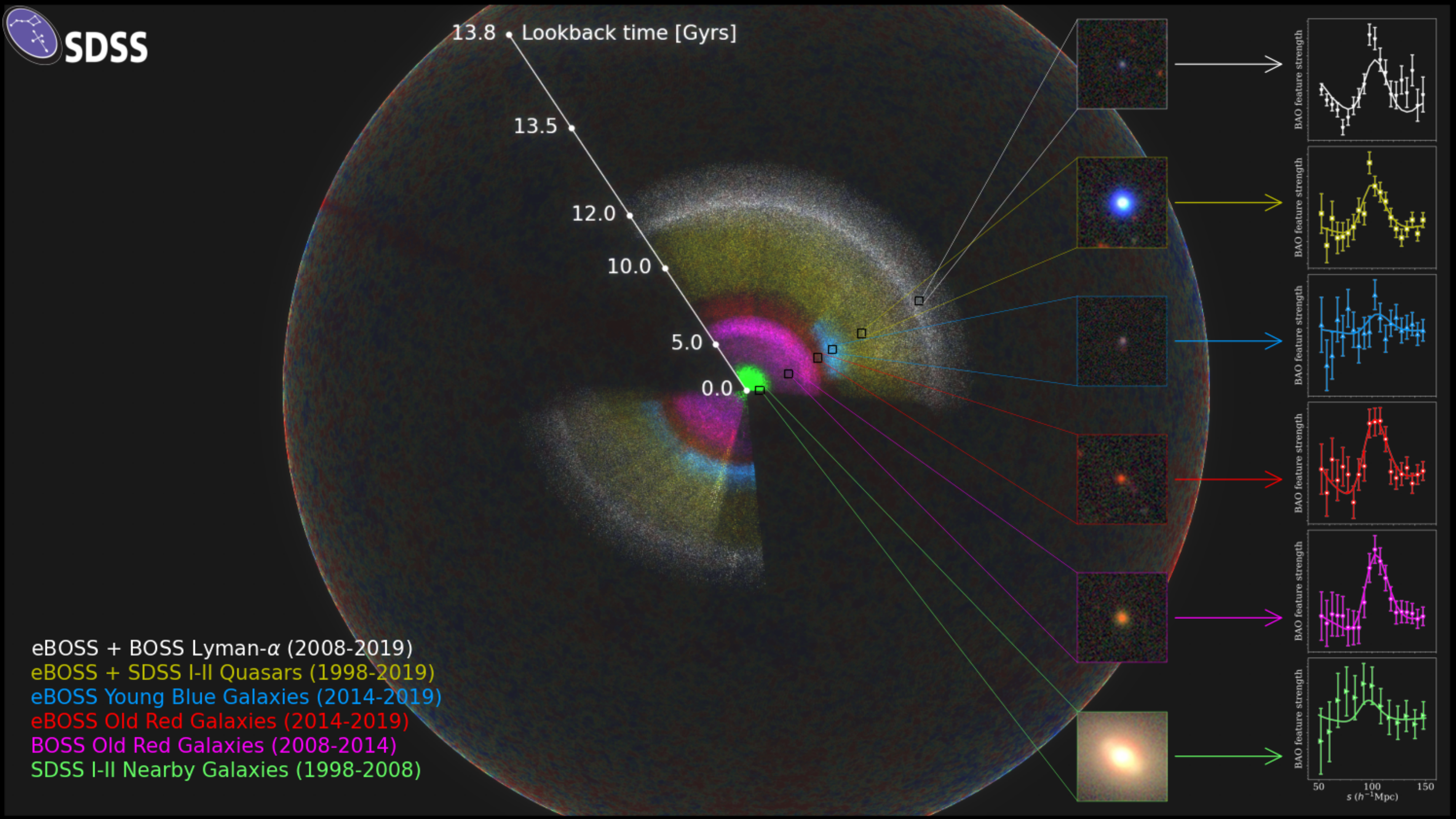
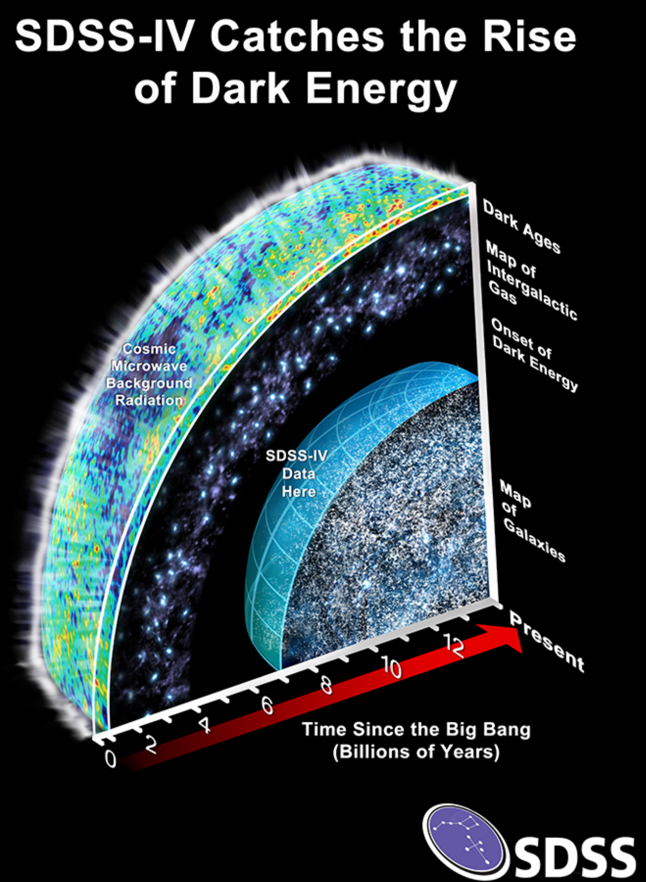
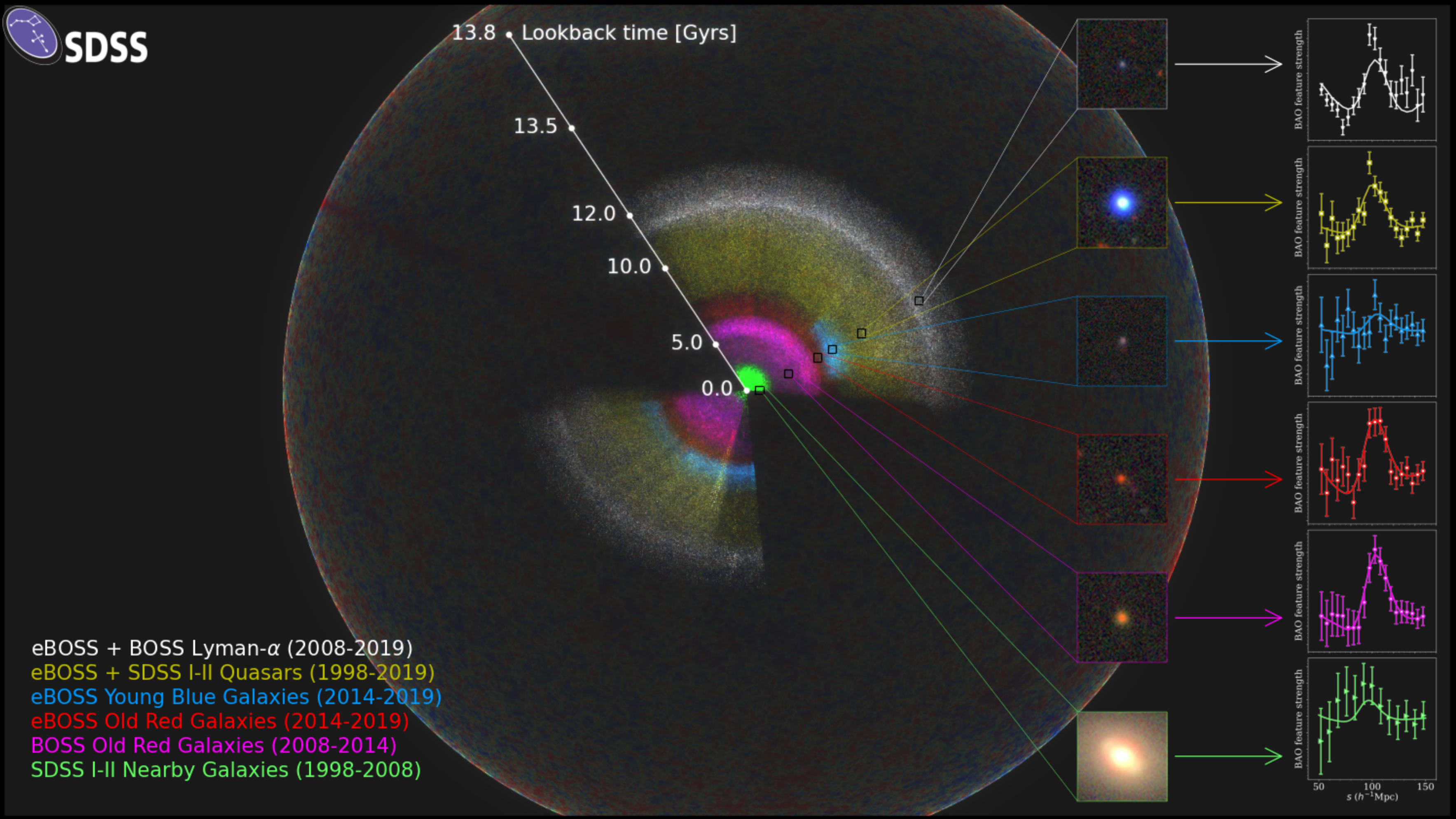


SDSS-IV Catches the Rise of Dark Energy









eBOSS makes it possible to probe the Universe using multiple kinds of tracers!

Why not cross-correlate them?

Why cross-correlation is cool?

- It can remove the cosmic variance, thus reduce the statistical uncertainty!

1-tracer: $\delta_{g1} = (b_1 + f\mu^2)\delta + \epsilon_1 = f\left(\beta^{-1} + \mu^2\right)\delta + \epsilon_1$

$$C = 2\langle\delta_{g1}^2\rangle \quad \frac{\sigma_\beta^2}{\beta^2} = \frac{(1+\beta)^2}{\beta^2}$$

2-tracers: $\delta_{g1} = f\left(\beta^{-1} + \mu^2\right)\delta + \epsilon_1 \;\; \delta_{g2} = f\left(\alpha\beta^{-1} + \mu^2\right)\delta + \epsilon_2$

$$C \equiv \begin{bmatrix} \langle\delta_{g1}^2\rangle & \langle\delta_{g1}\delta_{g2}\rangle \\ \langle\delta_{g2}\delta_{g1}\rangle & \langle\delta_{g2}^2\rangle \end{bmatrix} = \frac{P_{\theta\theta}}{2}\begin{bmatrix} \left(\beta^{-1}+\mu^2\right)^2 & \left(\beta^{-1}+\mu^2\right)\left(\alpha\beta^{-1}+\mu^2\right) \\ \left(\beta^{-1}+\mu^2\right)\left(\alpha\beta^{-1}+\mu^2\right) & \left(\alpha\beta^{-1}+\mu^2\right)^2 \end{bmatrix} + \frac{N}{2}$$

$$\frac{\delta_{g2}}{\delta_{g1}} = \frac{\alpha\beta^{-1} + \mu^2}{\beta^{-1} + \mu^2}.$$

McDonald & Seljak 2008; Seljak 2009

Why cross-correlation is cool?

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1-tracer: $\delta_{g1} = (b_1 + f\mu^2)\delta + \epsilon_1 = f\left(\beta^{-1} + \mu^2\right)\delta + \epsilon_1$

$$C = 2\langle\delta_{g1}^2\rangle \quad \frac{\sigma_\beta^2}{\beta^2} = \frac{(1+\beta)^2}{\beta^2}$$

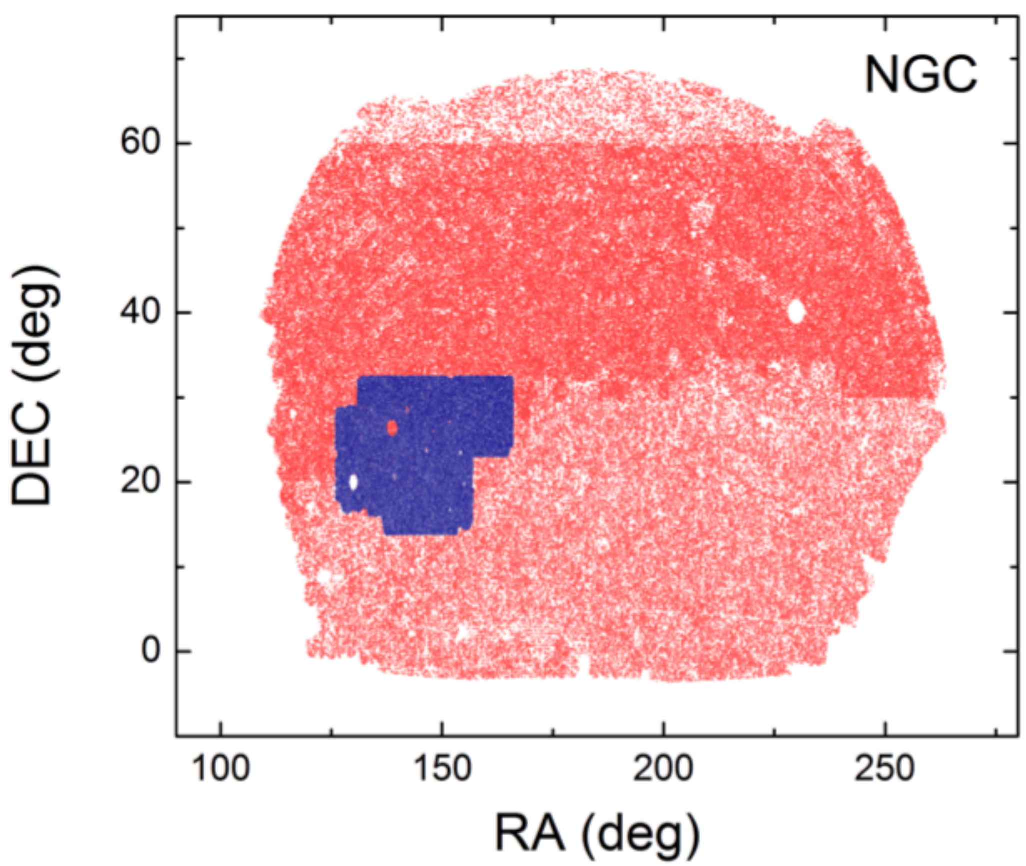
2-tracers: $\delta_{g1} = f\left(\beta^{-1} + \mu^2\right)\delta + \epsilon_1 \quad \delta_{g2} = f\left(\alpha\beta^{-1} + \mu^2\right)\delta + \epsilon_2$

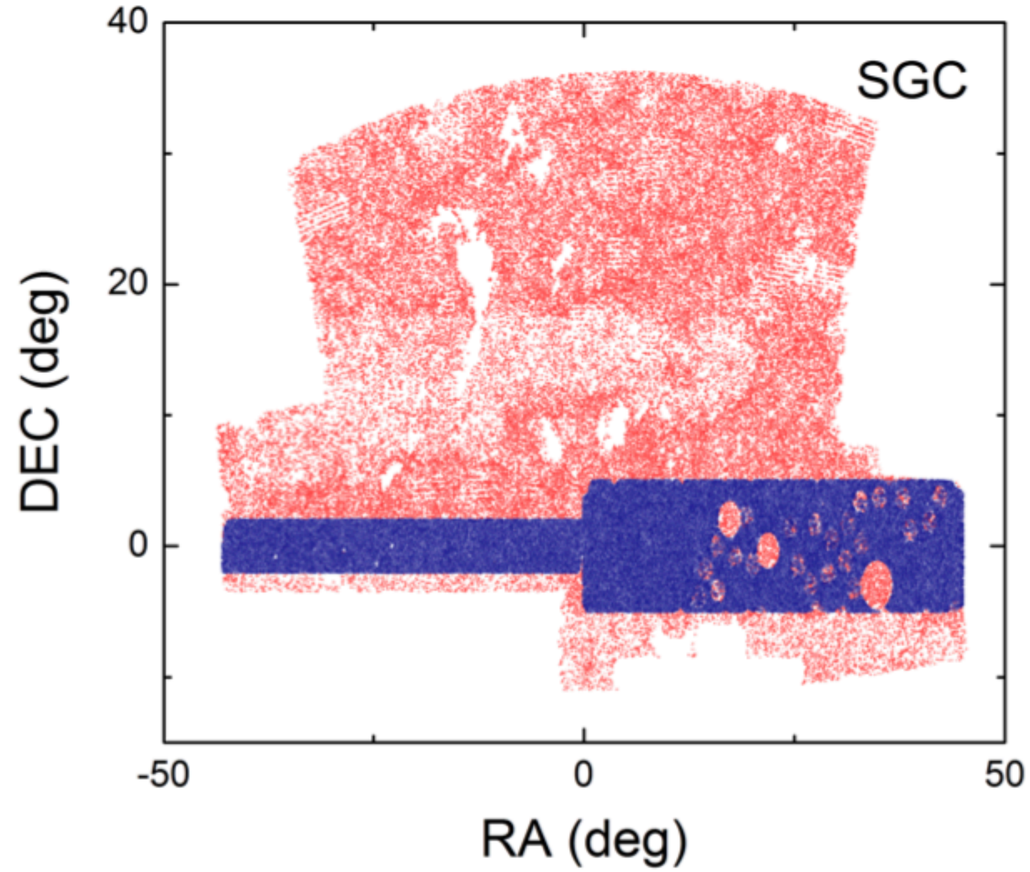
$$C \equiv \begin{bmatrix} \langle\delta_{g1}^2\rangle & \langle\delta_{g1}\delta_{g2}\rangle \\ \langle\delta_{g2}\delta_{g1}\rangle & \langle\delta_{g2}^2\rangle \end{bmatrix} = \frac{P_{\theta\theta}}{2}\begin{bmatrix} \left(\beta^{-1}+\mu^2\right)^2 & \left(\beta^{-1}+\mu^2\right)\left(\alpha\beta^{-1}+\mu^2\right) \\ \left(\beta^{-1}+\mu^2\right)\left(\alpha\beta^{-1}+\mu^2\right) & \left(\alpha\beta^{-1}+\mu^2\right)^2 \end{bmatrix} + \frac{N}{2}$$

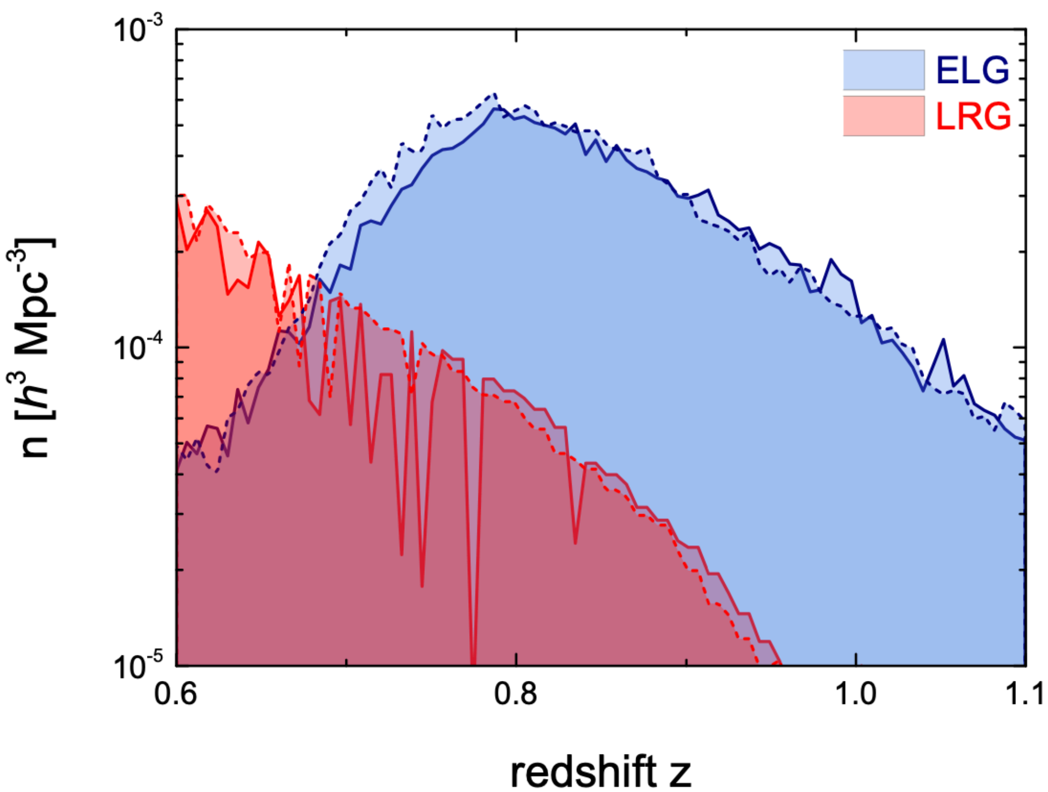
$$\frac{\delta_{g2}}{\delta_{g1}} = \frac{\alpha\beta^{-1} + \mu^2}{\beta^{-1} + \mu^2}.$$

McDonald & Seljak 2008; Seljak 2009

- It can reduce the systematics, as the photometry used for observing different tracers are usually uncorrelated!

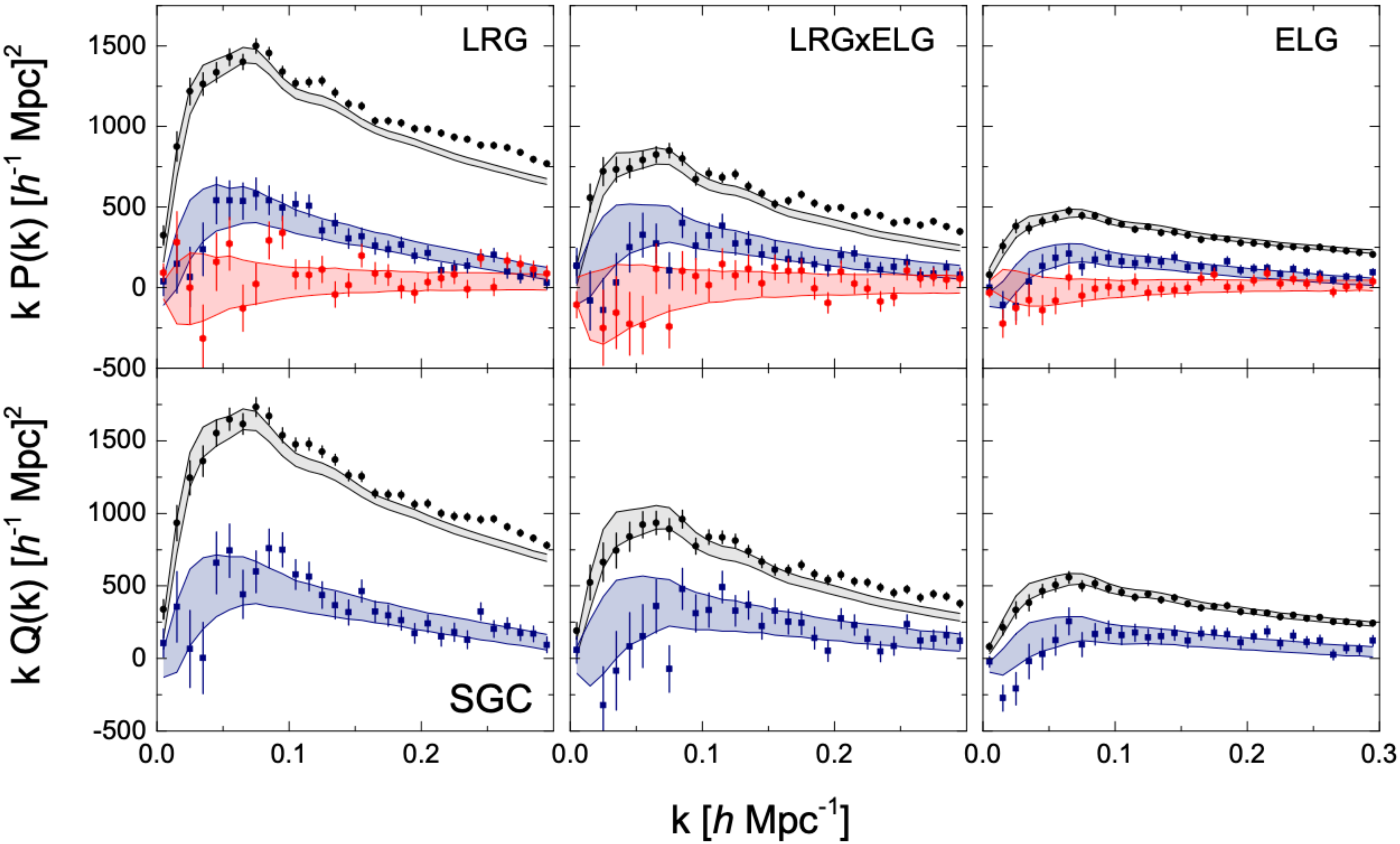




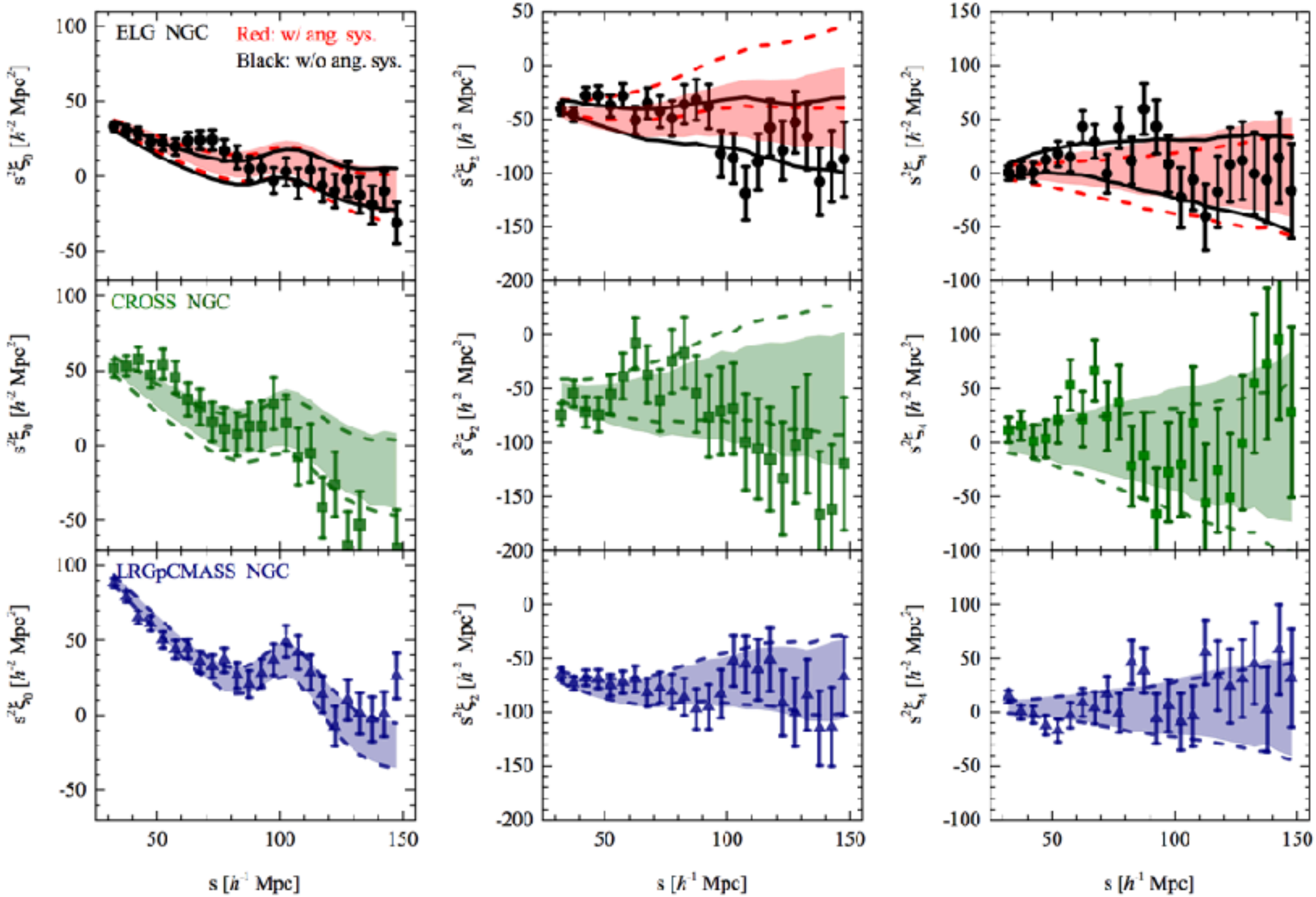


Decent overlap between eBOSS DR16 LRGs and ELGs in AREA ~ 800 deg^2 and in REDSHIFT [0.6,1.0]

Zhao, Wang et al, (eBOSS), 2007.09011 (k-space)
Wang, **Zhao** et al, (eBOSS), 2007.09010 (s-space)

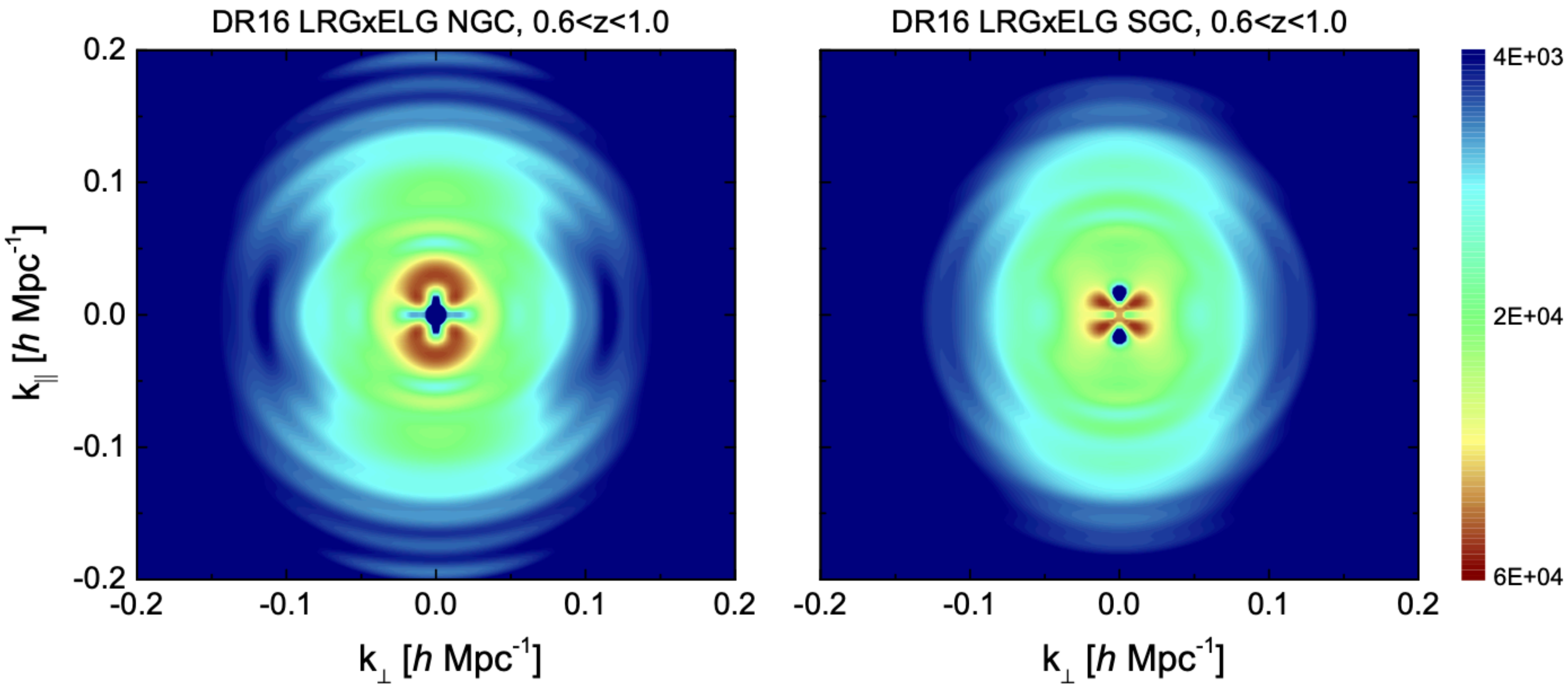


Zhao, Wang et al, (eBOSS), 2007.09011

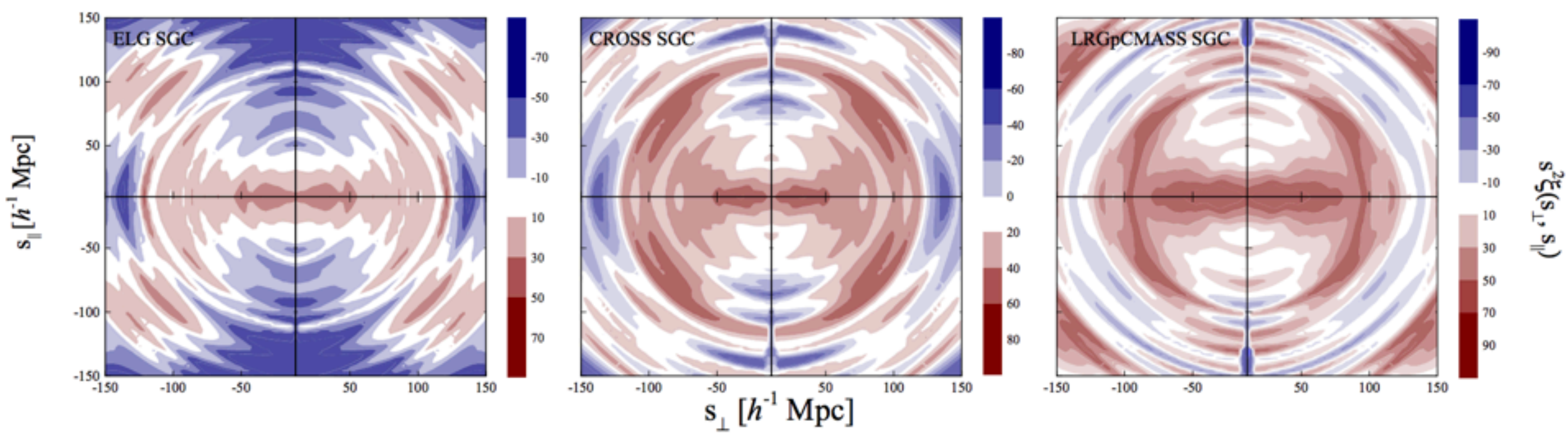


Wang, **Zhao** et al, (eBOSS), 2007.09010

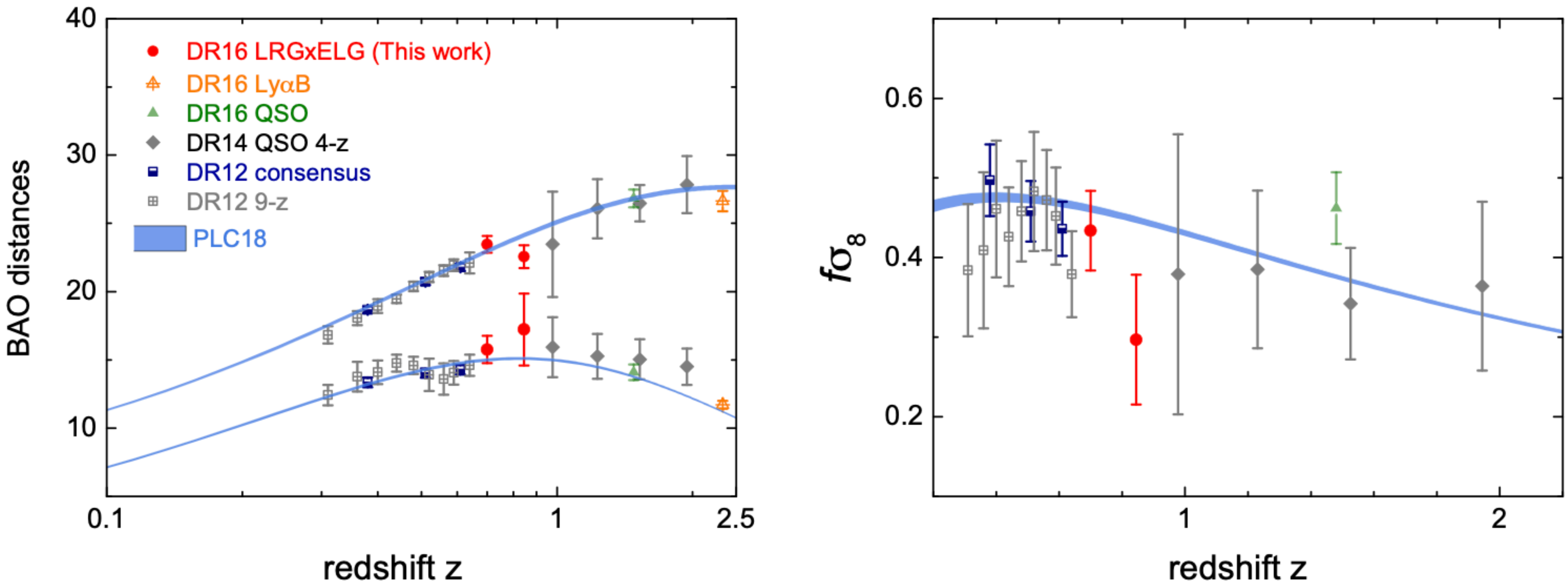
A 4σ detection of RSD from cross – power!



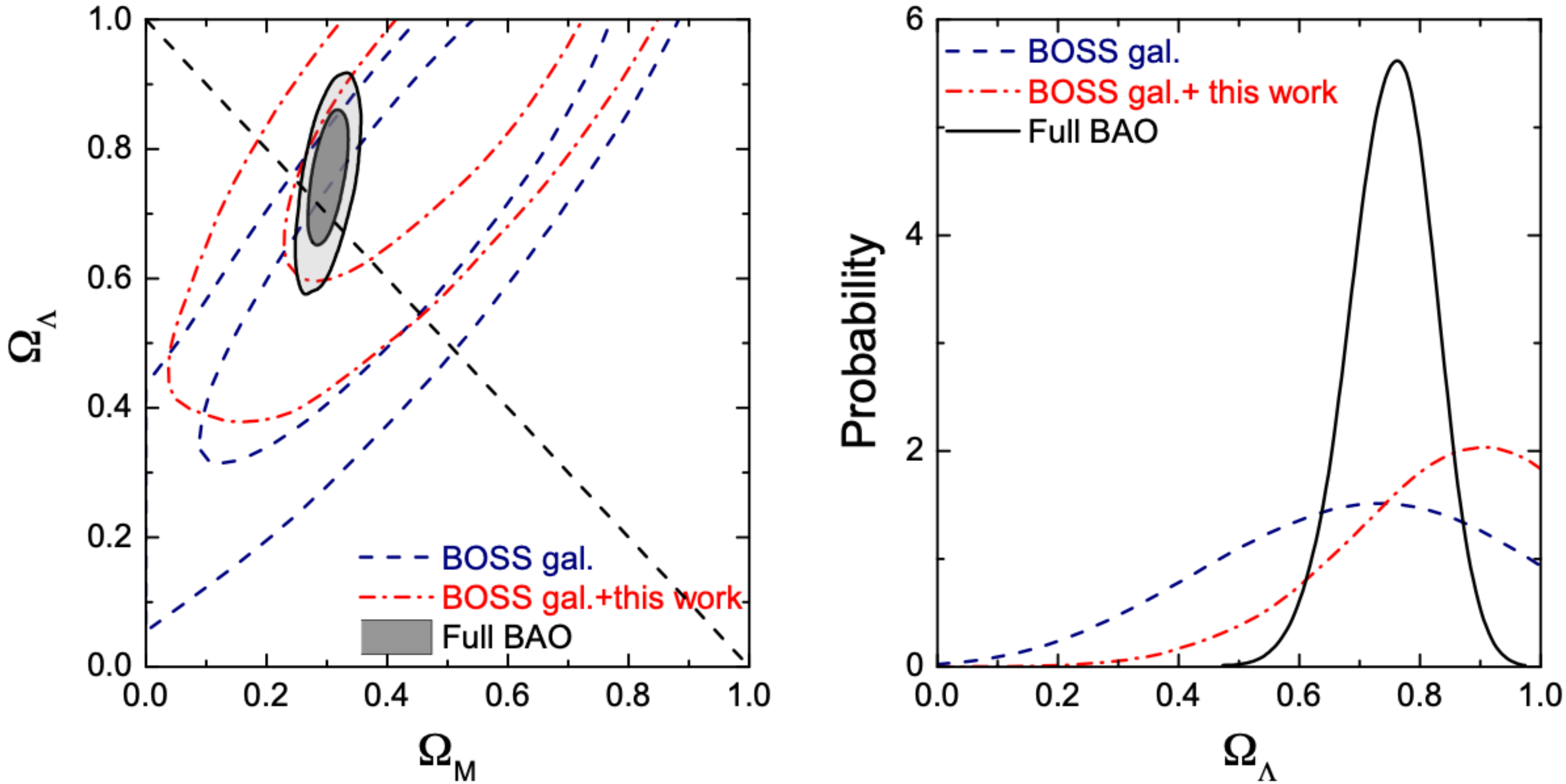
Zhao, Wang et al, (eBOSS), 2007.09011 (k-space)



Wang, **Zhao** et al, (eBOSS), 2007.09010 (s-space)



Zhao, Wang et al, (eBOSS), 2007.09011



A 11σ detection of $\Omega_\Lambda > 0$

Zhao, Wang et al, (eBOSS), 2007.09011

Summary

- The eBOSS final analysis is the most comprehensive analysis of the largest three-dimensional map of the Universe ever created, filling in the most significant gaps in our possible exploration of its history;
- eBOSS (with SDSS) provided the state of the art in BAO measurements for stage III spectroscopic surveys.

- We successfully performed a multi-tracer analysis on eBOSS DR16 tracers, and detected the RSD signal from the cross-correlation;
- We gain a 20% improvement on the RSD measurement;
- A Universe without dark energy is ruled out by BAO alone at 11 sigma level.