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Cosmological observations

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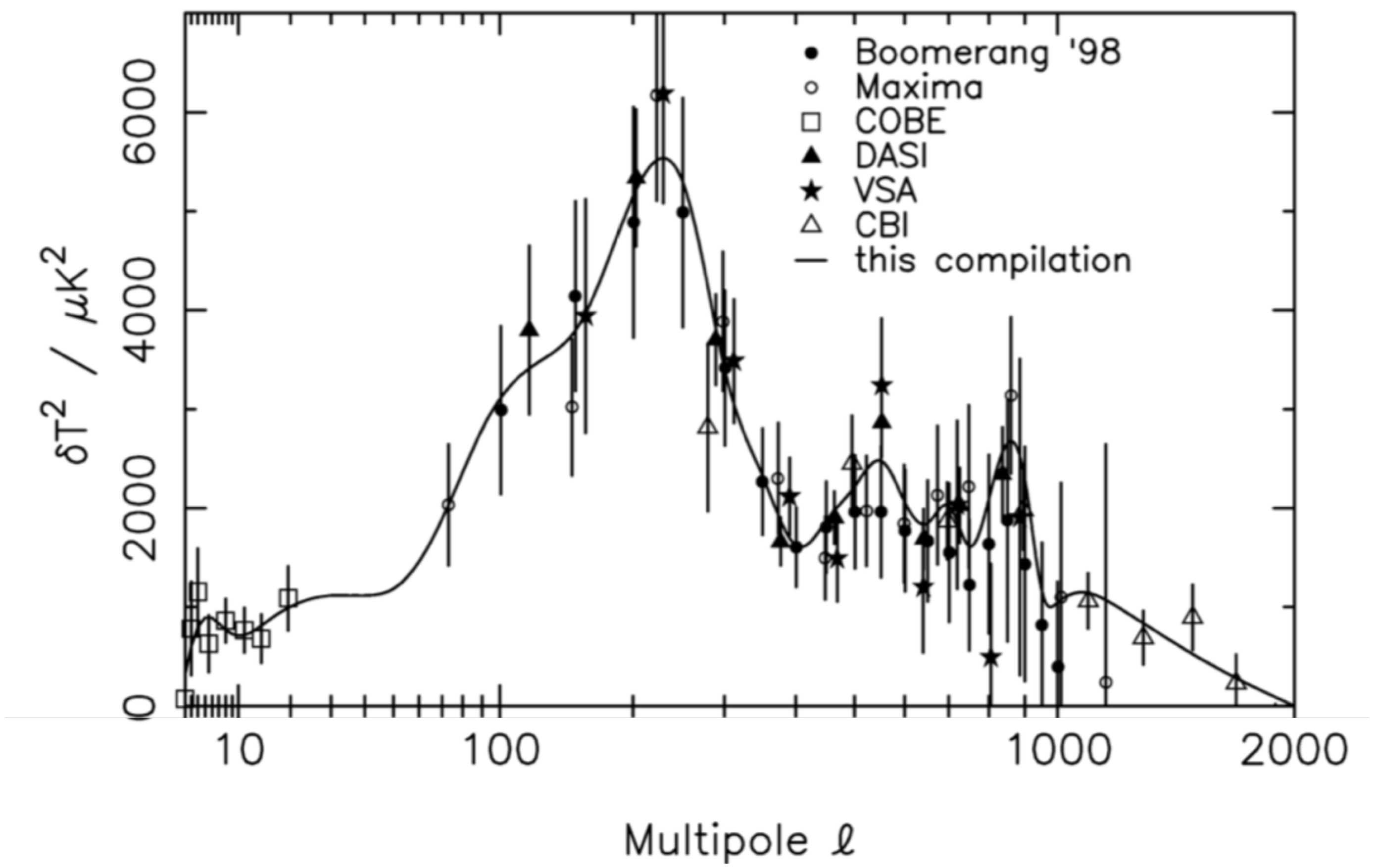
Current: CMB

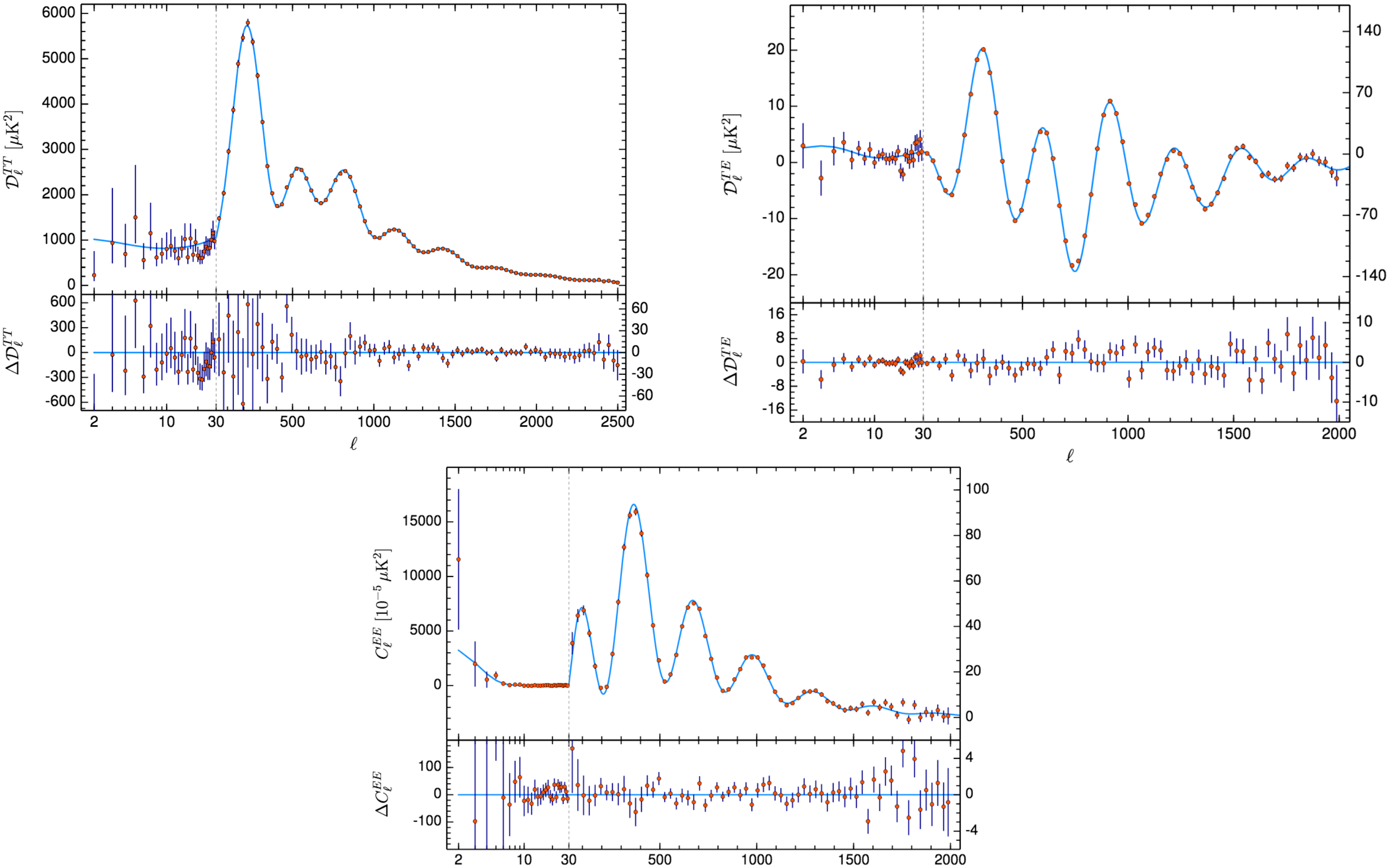
Pre-WMAP



	Parameter	Results: scalar only		Results: with tensor component	
		CMB	CMB + 2dFGRS	CMB	CMB + 2dFGRS
	$\Omega_b h^2$	0.0205 ± 0.0022	0.0210 ± 0.0021	0.0229 ± 0.0031	0.0226 ± 0.0025
	$\Omega_c h^2$	0.118 ± 0.022	0.1151 ± 0.0091	0.100 ± 0.023	0.1096 ± 0.0092
	h	0.64 ± 0.10	0.665 ± 0.047	0.75 ± 0.13	0.700 ± 0.053
Using the	n_s	0.950 ± 0.044	0.963 ± 0.042	1.040 ± 0.084	1.033 ± 0.066
CMB data	n_t	–	–	0.09 ± 0.16	0.09 ± 0.16
compilation	r	–	–	0.32 ± 0.23	0.32 ± 0.22
of Section 2	Ω_m	0.38 ± 0.18	0.313 ± 0.055	0.25 ± 0.15	0.275 ± 0.050
	$\Omega_m h$	0.226 ± 0.069	0.206 ± 0.023	0.174 ± 0.063	0.190 ± 0.022
	$\Omega_m h^2$	0.139 ± 0.022	0.1361 ± 0.0096	0.123 ± 0.022	0.1322 ± 0.0093
	Ω_b / Ω_m	0.152 ± 0.031	0.155 ± 0.016	0.193 ± 0.048	0.172 ± 0.021

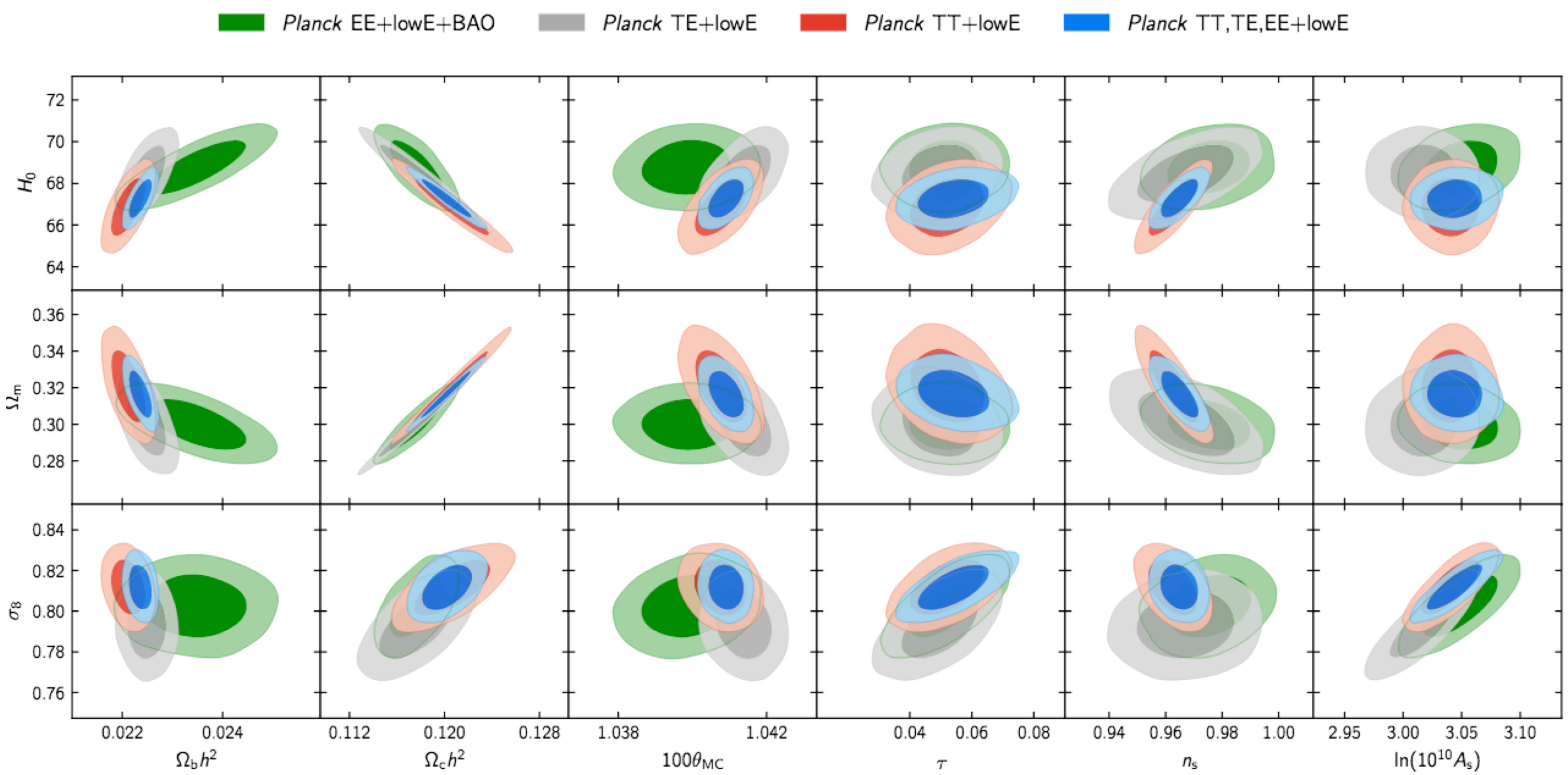
The CMB in 2002; astro-ph/0206256

CMB today: Planck



Planck et al. 2018; arXiv:1807.06209

Planck is awesome



Parameter	Plik best fit	Plik [1]	CamSpec [2]	$([2]-[1])/\sigma_1$	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	-0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	-0.3	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	-0.2	1.04089 ± 0.00031
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	-0.1	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	-0.3	3.043 ± 0.014
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	$+0.2$	0.9652 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011	-0.3	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}] . . .	67.32	67.36 ± 0.54	67.39 ± 0.54	$+0.1$	67.37 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074	-0.2	0.3147 ± 0.0074
Age [Gyr]	13.7971	13.797 ± 0.023	13.805 ± 0.023	$+0.4$	13.801 ± 0.024
σ_8	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060	-0.3	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ . .	0.8331	0.832 ± 0.013	0.828 ± 0.013	-0.3	0.830 ± 0.013
z_{re}	7.68	7.67 ± 0.73	7.61 ± 0.75	-0.1	7.64 ± 0.74
$100\theta_*$	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031	-0.1	1.04108 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26	147.26 ± 0.28	$+0.6$	147.18 ± 0.29

Planck et al. 2018; arXiv:1807.06209

Where next for cosmology?

- Inflation
  Tensors: CMB B-modes (Litebird, Simons, S-4)
  f_{nl}: low redshift surveys

- Dark Energy
  We cannot explain Λ with known physics
  why is Λ so small?

$$\rho_\Lambda|_{\rm obs} = \frac{\Lambda}{8\pi G} \sim (10^{-3}\,{\rm eV})^4$$

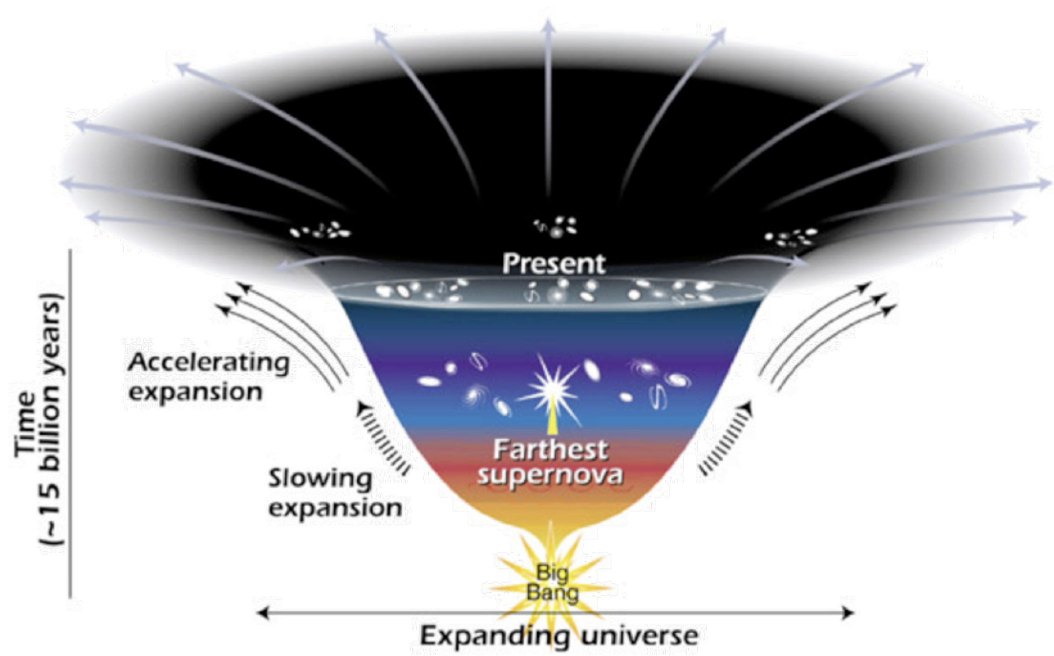
$$\rho_\Lambda|_{\rm theory} \sim (M_{\rm new\ physics})^4 \sim (1\,{\rm TeV})^4 >> \rho_\Lambda|_{\rm obs}$$

$$\rho_\Lambda \lesssim \rho_m \ \ : \ \text{crucial for structure formation}$$

$$\text{but } \rho_\Lambda \propto a^0 \text{ while } \rho_m \propto a^{-3}$$

- why so fine tuned?

Investigating whole new phenomena

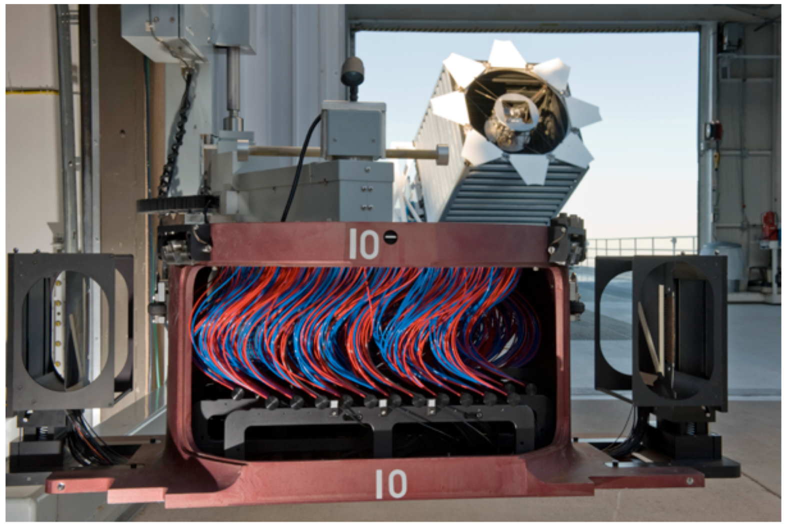


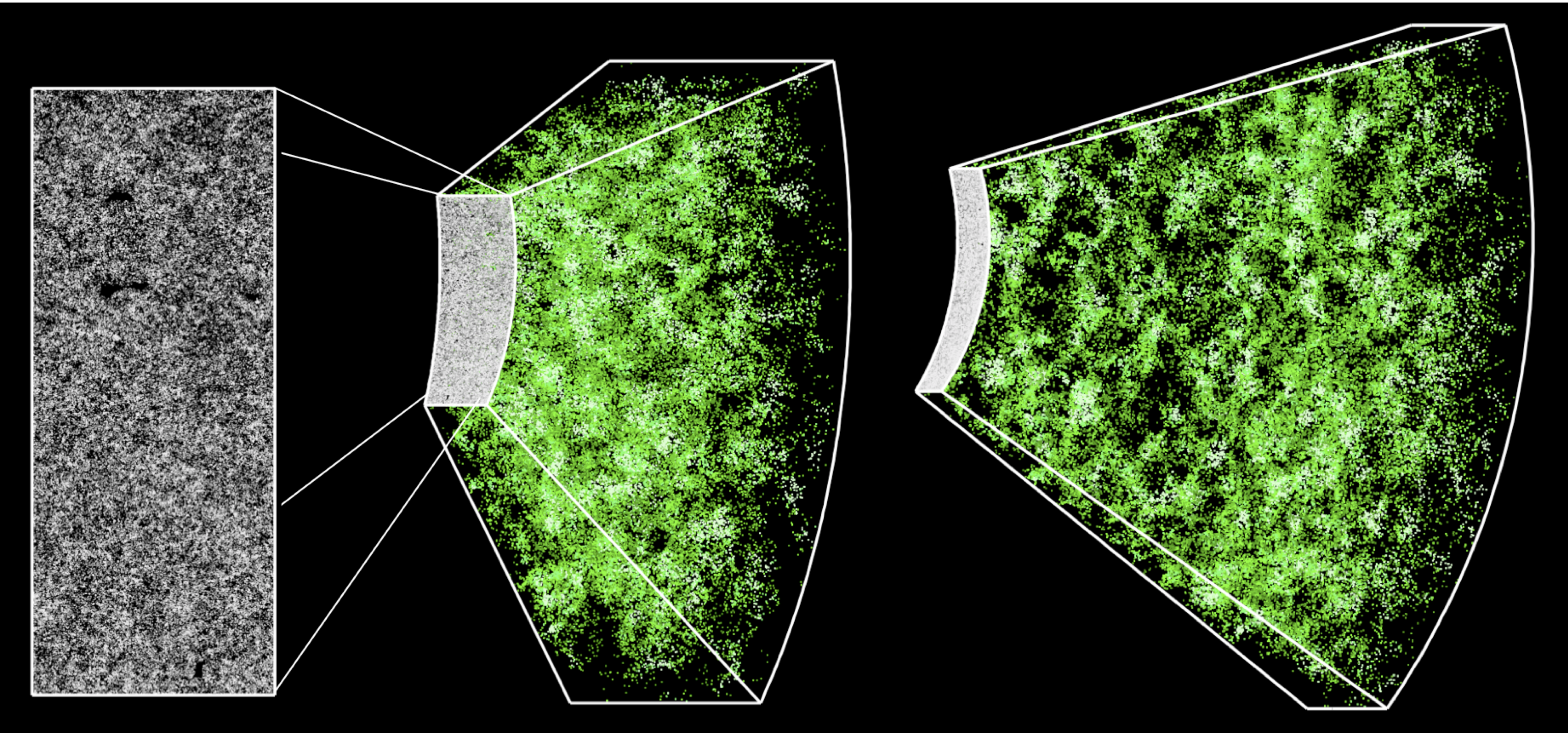
Current: galaxy clustering

The BOSS galaxy survey

- Survey now complete, with data taken over 5 years (2009-2014)
- Redshifts for 1,145,874 galaxies
- Two galaxy classes with different selections: LOWZ and CMASS
- Data Release 12 galaxy catalogues now available:

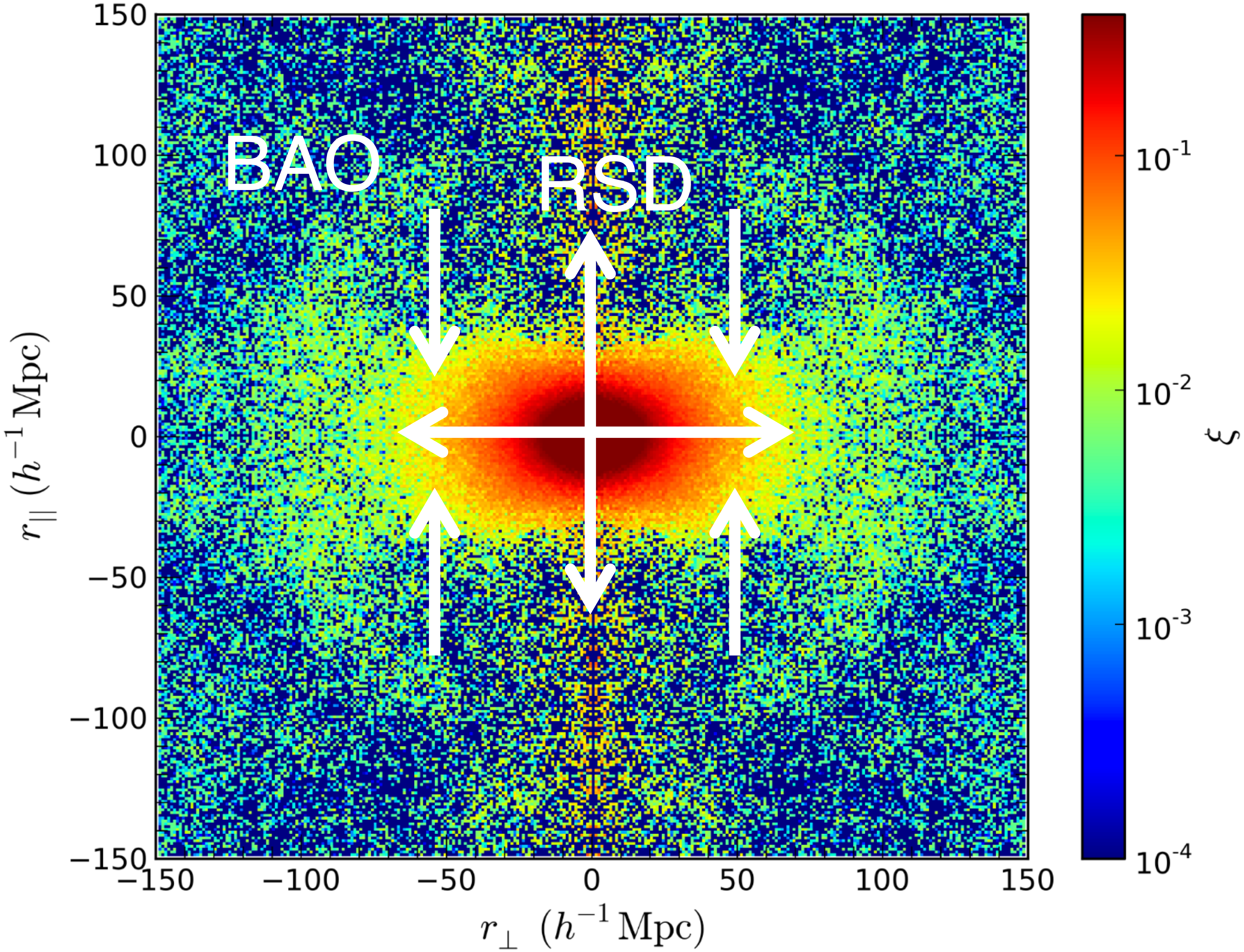
  http://data.sdss3.org/sas/dr12/boss/lss/

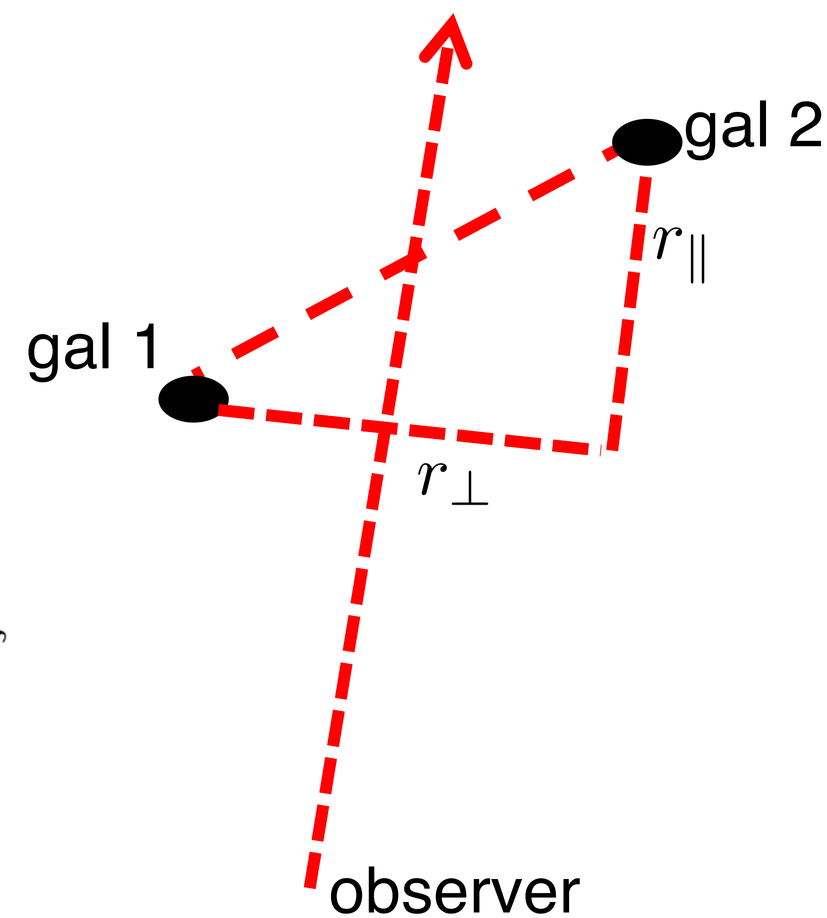




The galaxy clustering signal

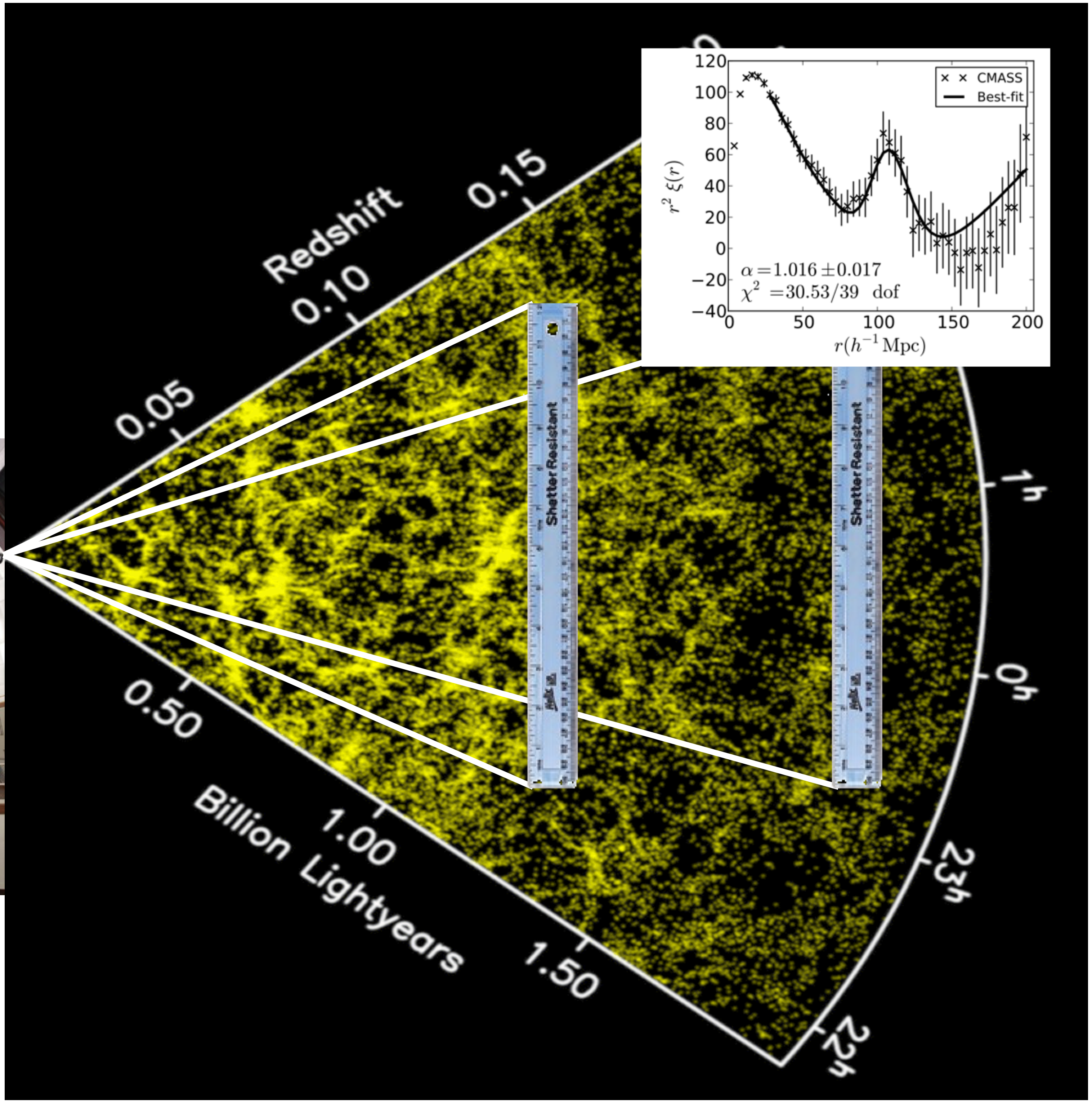
$$dP = \rho_0^2 \left[1 + \xi(r)\right] dV_1 dV_2$$



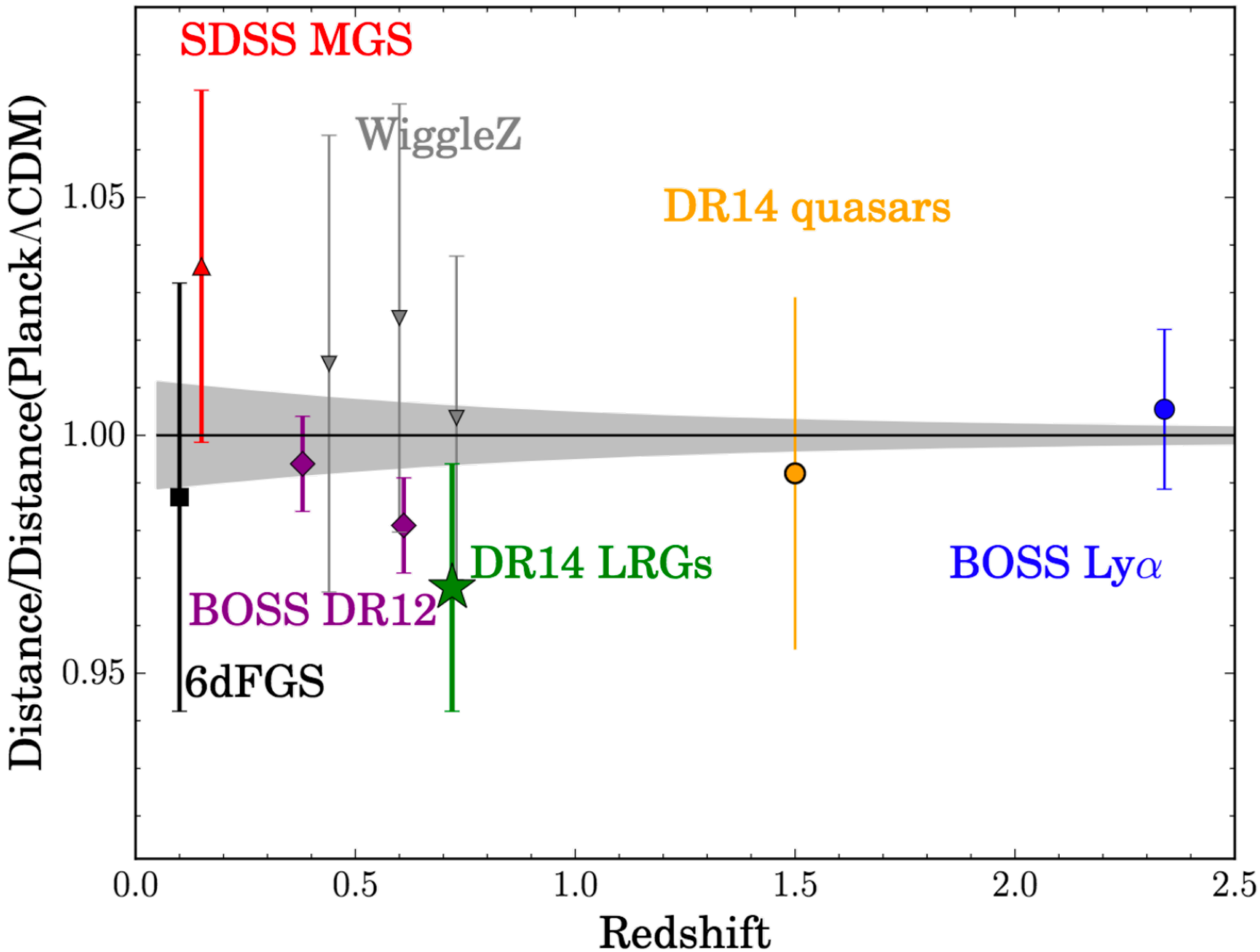


Samushia et al. 2013; MNRAS, 439, 3504

Clustering (BAO) as a standard ruler

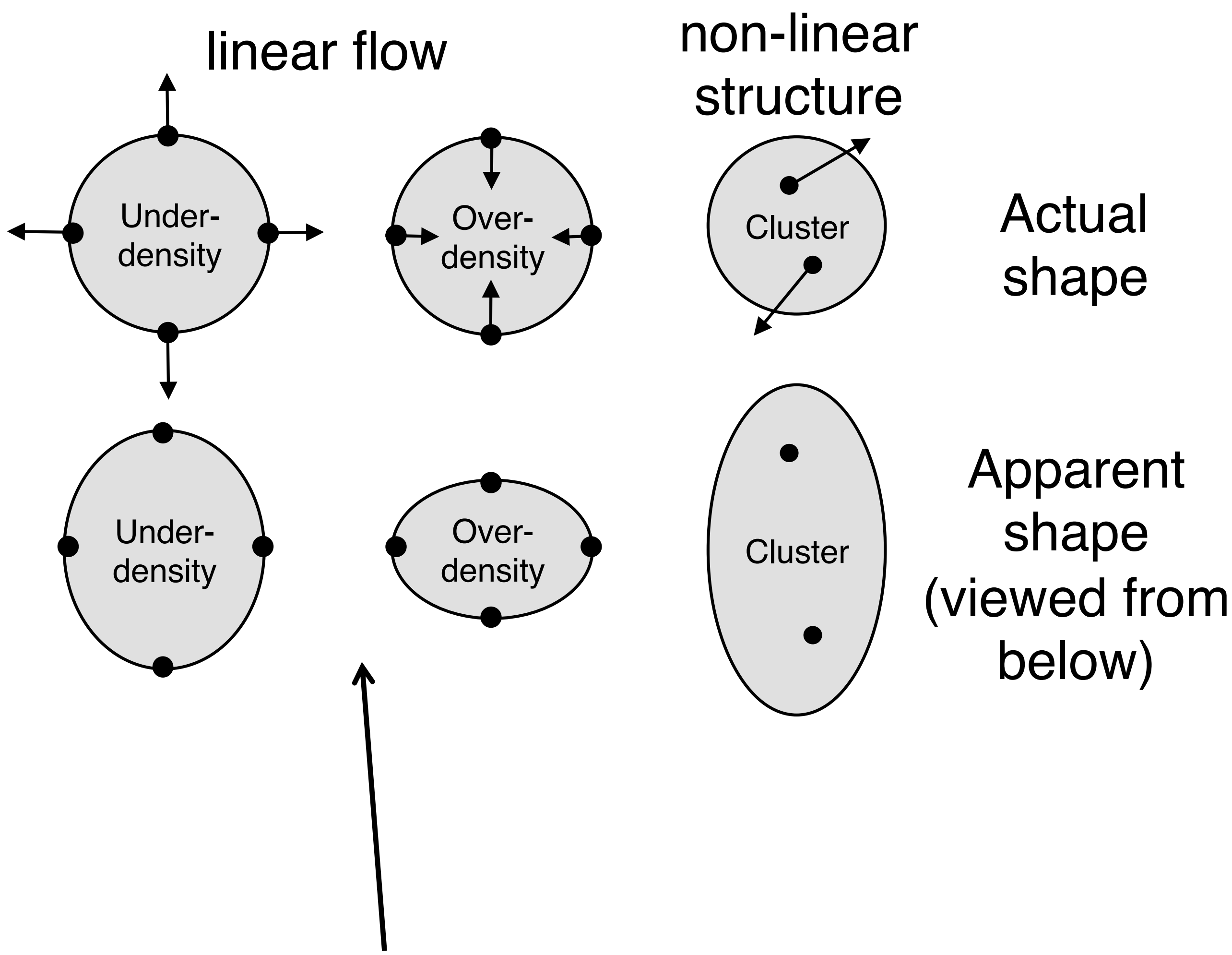


Current BAO measurements

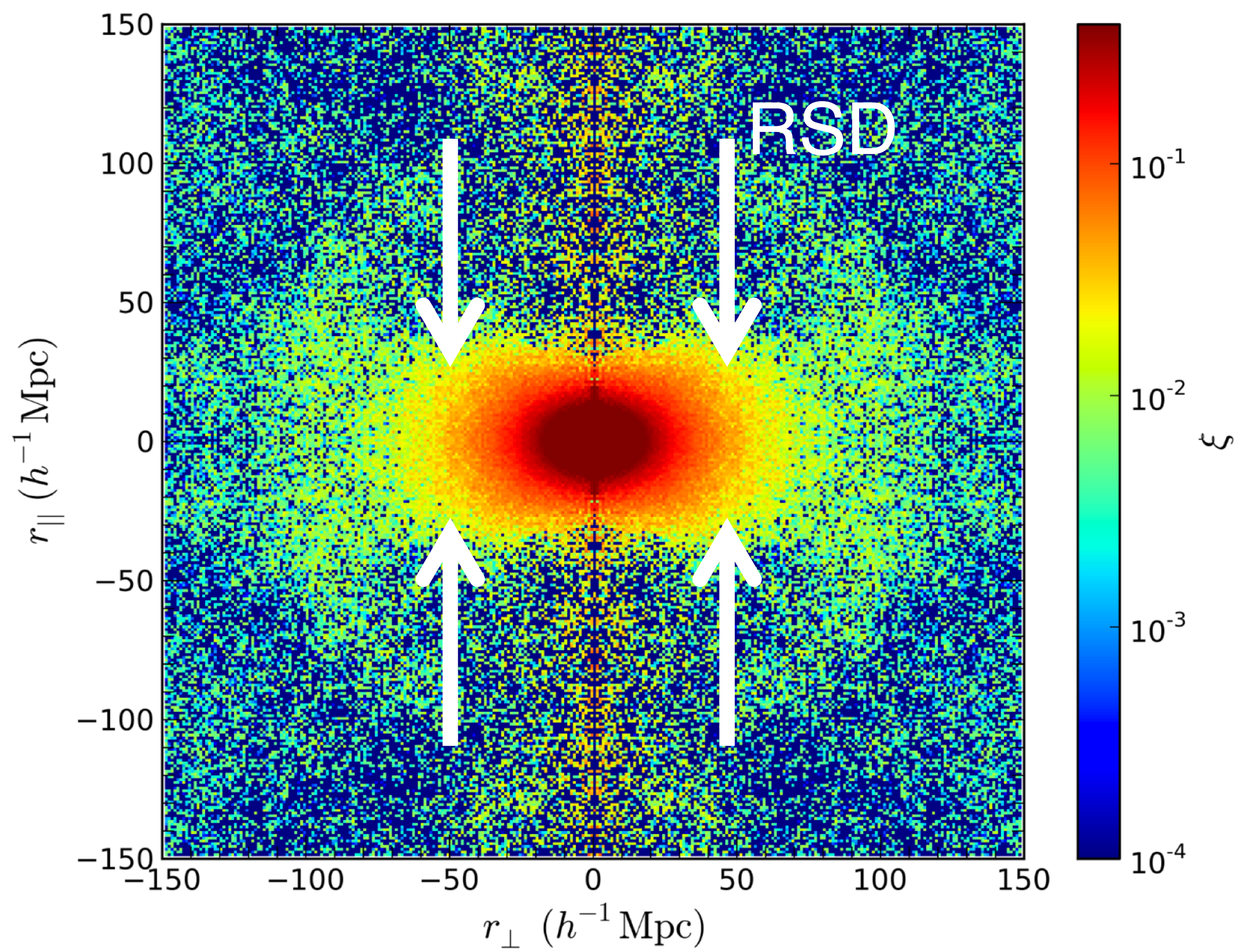


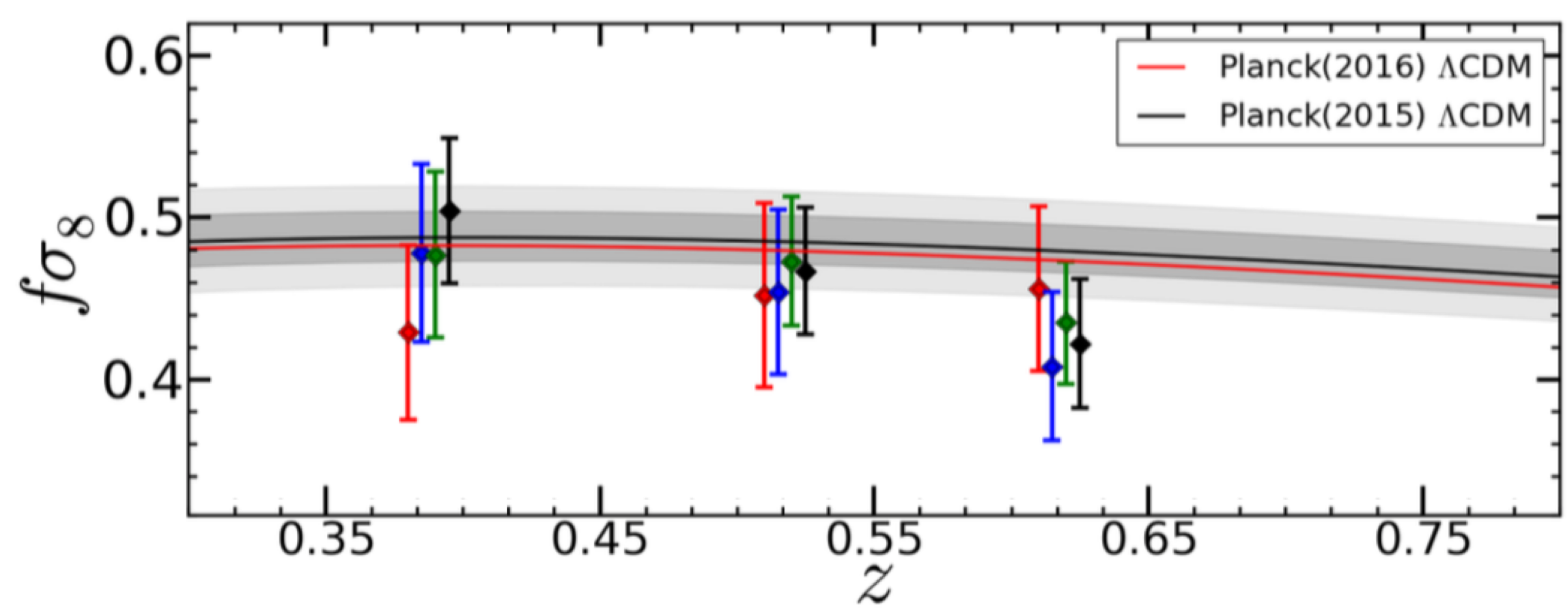
Plot from Bautista et al. 2017; arXiv:1712.08064

Redshift Space Distortions (RSD)



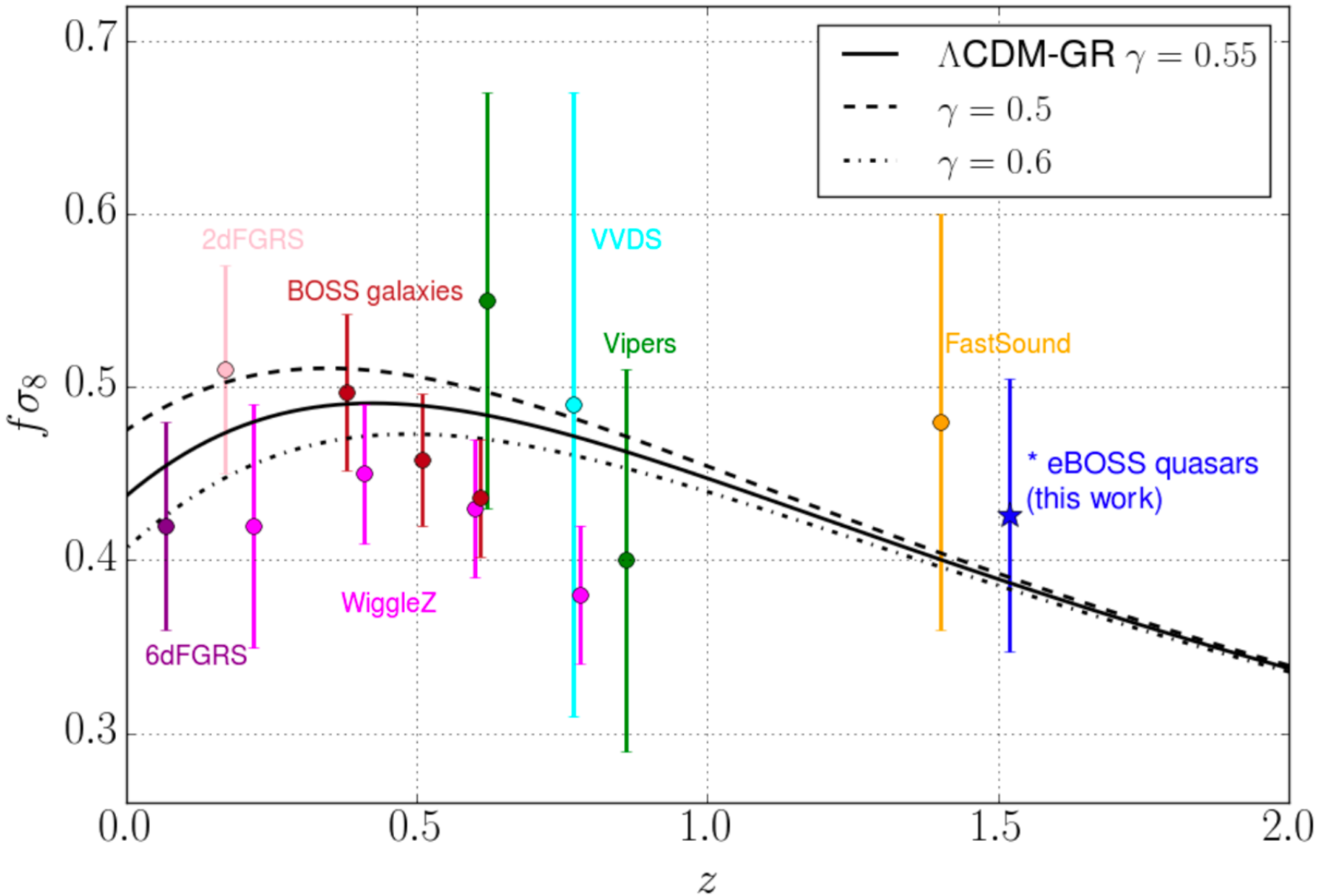
Boost to radial clustering depends on $f\sigma_8$





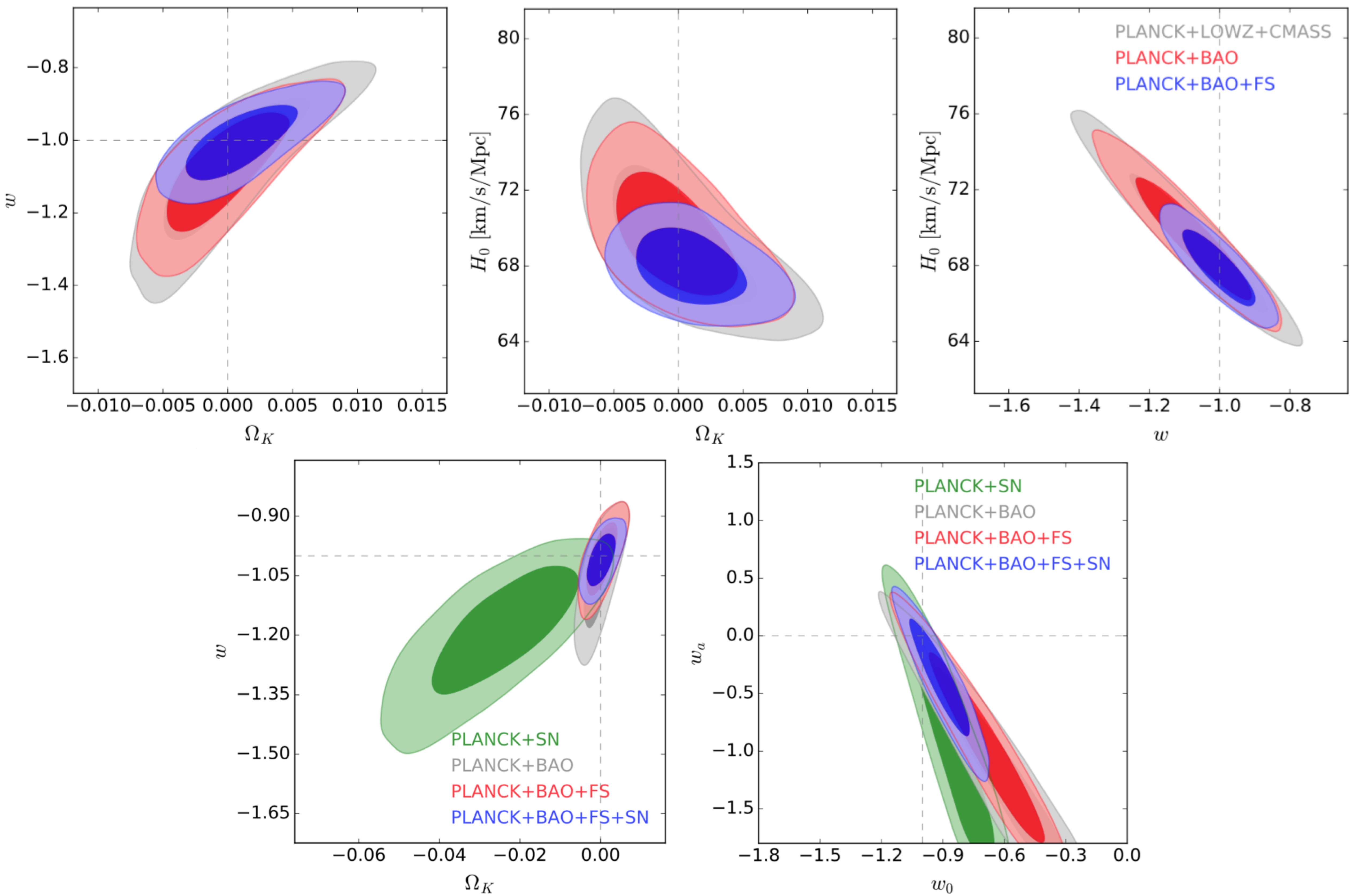
Samushia et al. 2013; MNRAS, 439, 3504; Alam et al. 2016, arXiv:1607.03155

Current RSD measurements



Zarrouk et al. 2018; arXiv:1801.03062

Combining with Planck data



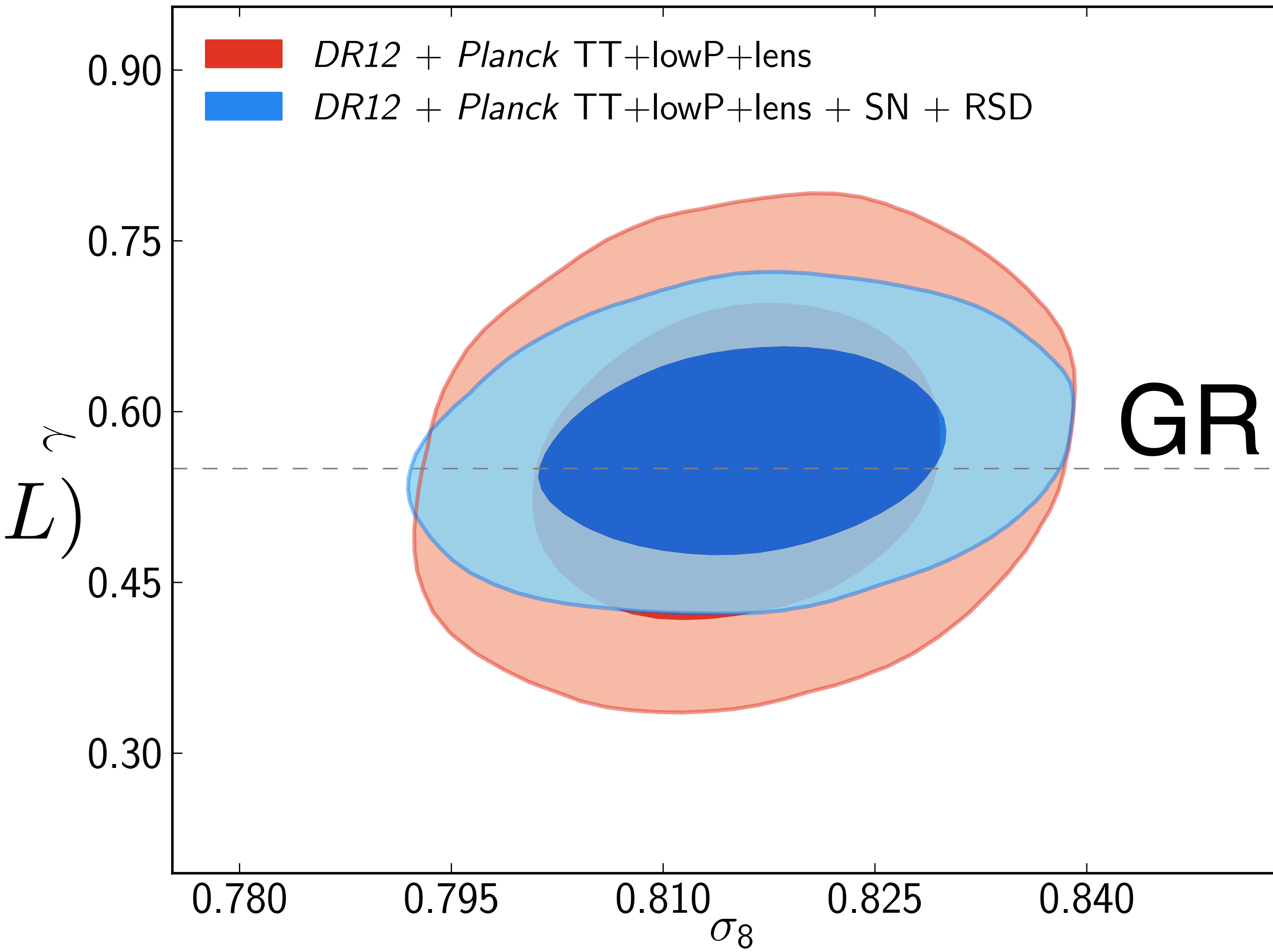
Alam et al. 2016, arXiv:1607.03155

Testing modified gravity: Growth Index

$$f(a) = \Omega_m(a)^\gamma$$

$$\gamma = 0.566 \pm 0.058 (68\% CL)$$

SN: JLA
RSD: 6dF, MGS, Vipers



Good agreement with GR

Mueller et al. 2016, arXiv:1612.00812

Testing modified Poisson equations

Newtonian potentials

$$ds^2 = a^2[-(1+2\psi)d\tau^2 + (1-2\phi)d\mathbf{x}^2] \qquad \gamma_{\rm slip} = \frac{\phi}{\psi}$$

Perturbation equations

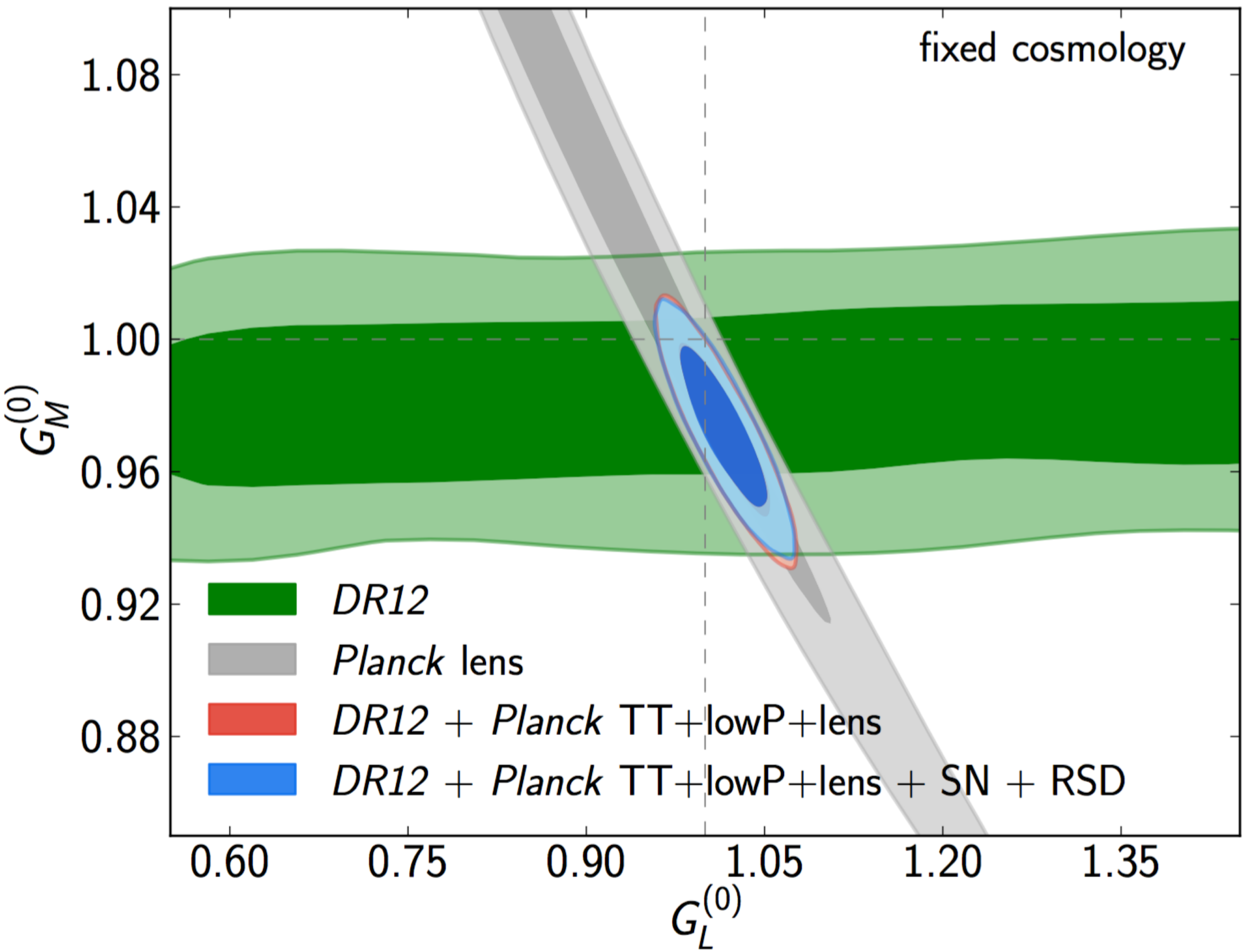
$$\nabla^2\psi = 4\pi G a^2 \rho\Delta \times G_{\rm M}$$ Growth of structure

$$\nabla^2(\psi+\phi) = 8\pi G a^2 \rho\Delta \times G_{\rm L}$$ Bending of light

Phenomenological model

Mueller et al. 2016, arXiv:1612.00812

Testing modified Poisson equations

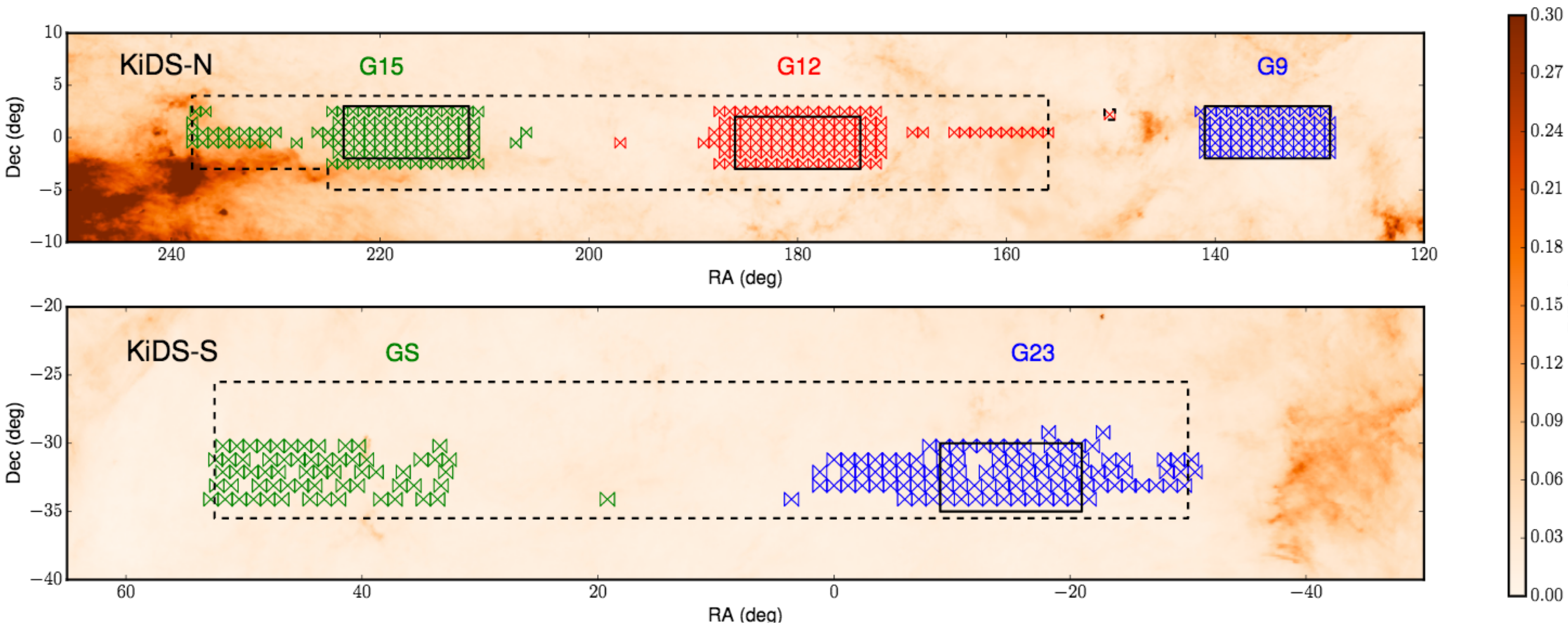


Good agreement with GR

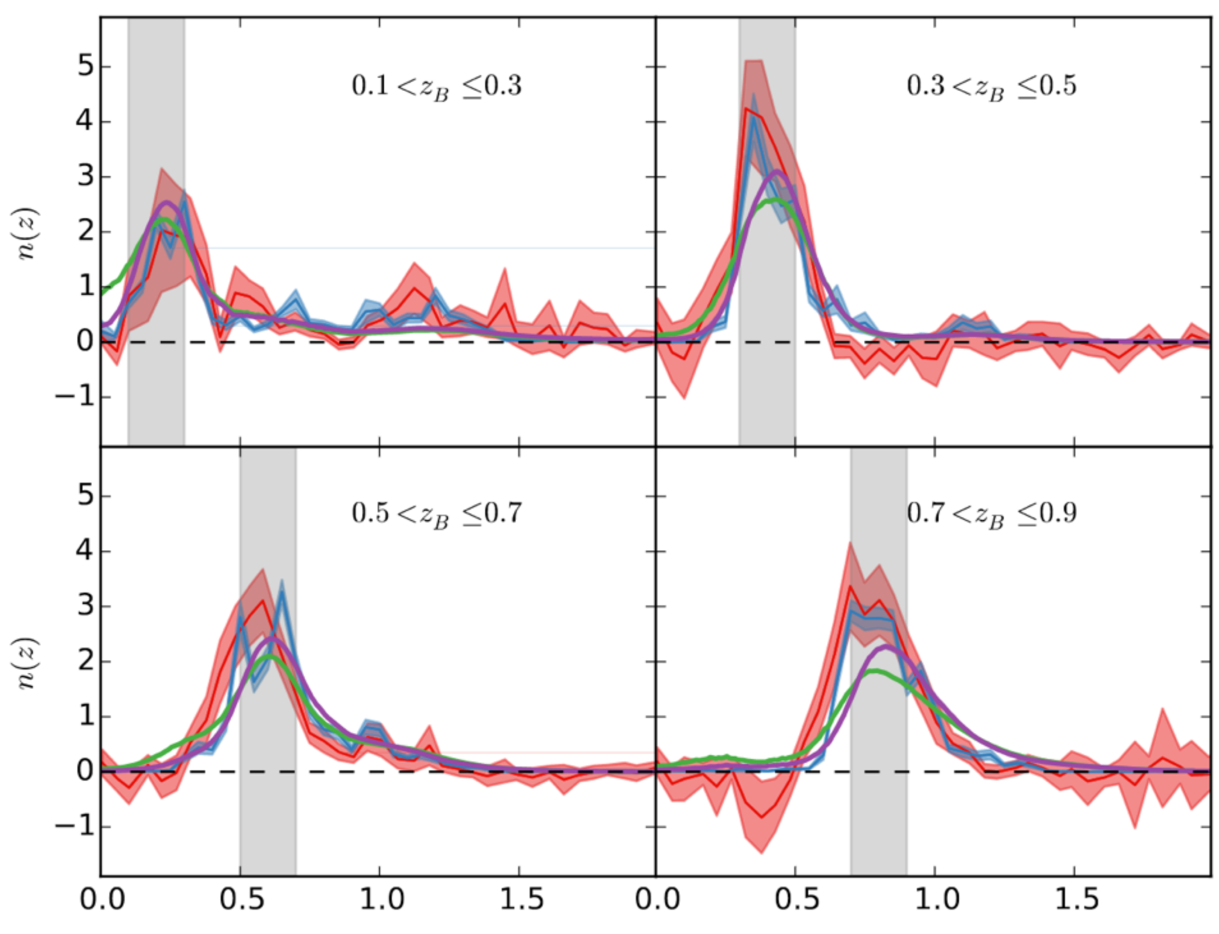
Mueller et al. 2016, arXiv:1612.00812

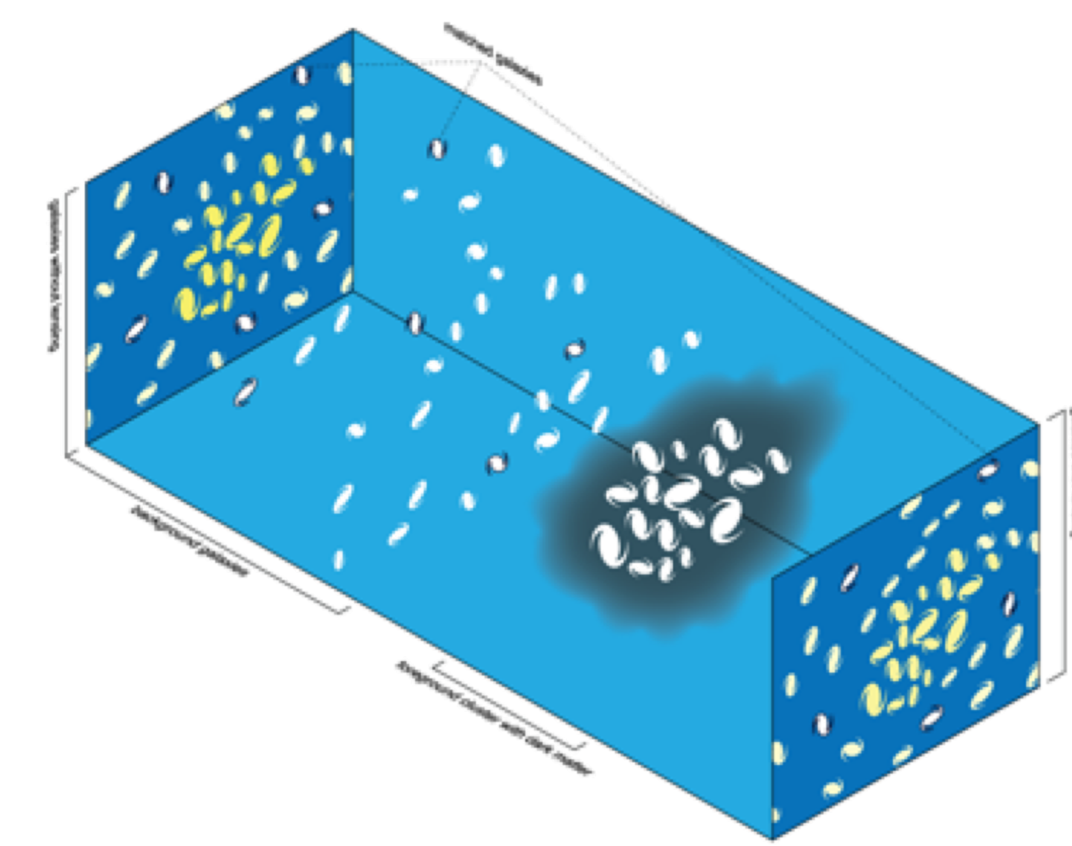
Current: weak lensing

KiDS-450 weak lensing data



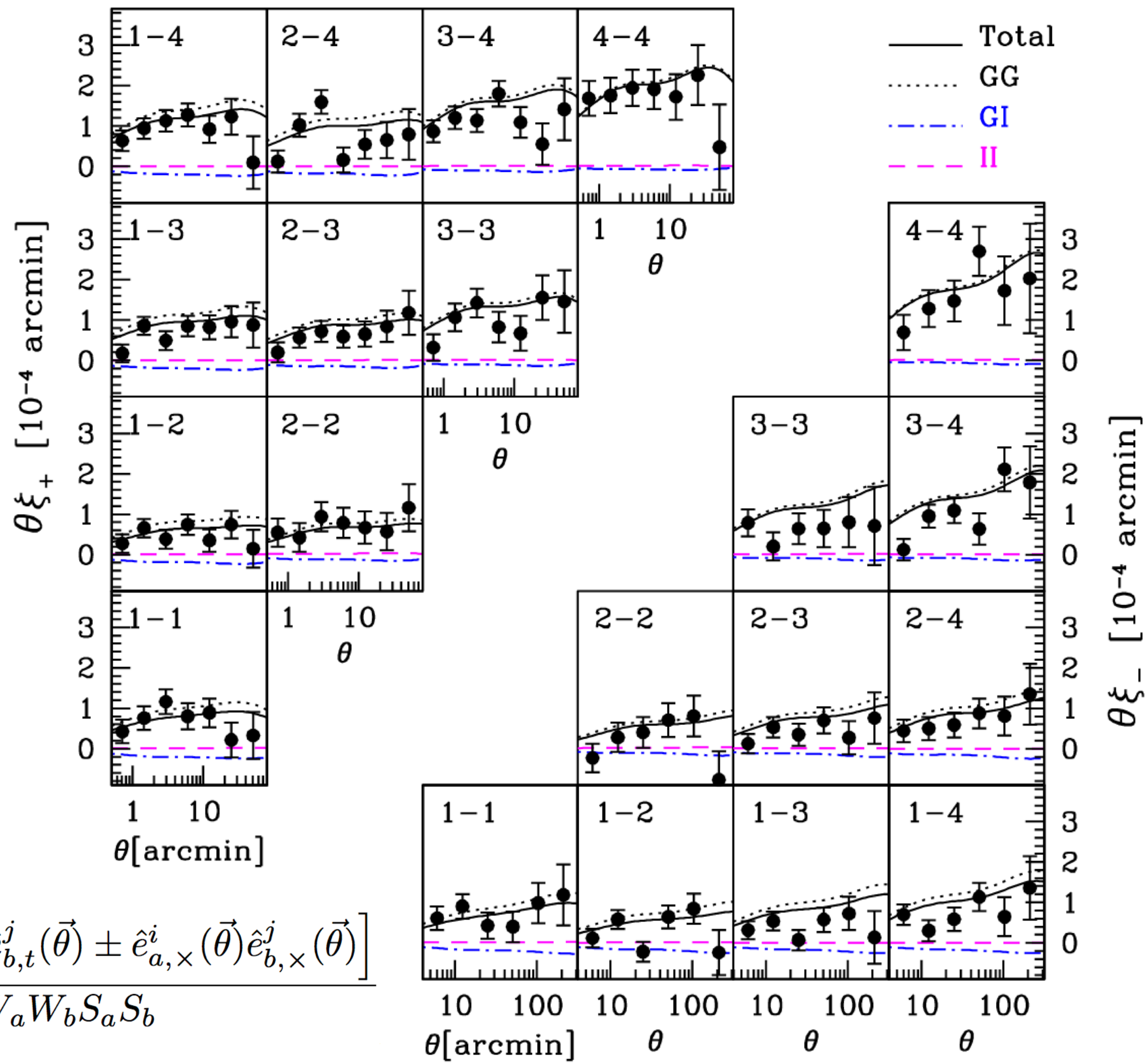
450 deg^2
15M gals
σ_e=0.29





Hildebrandt et al. (KiDS consortium) 2016, arXiv:1606.05338

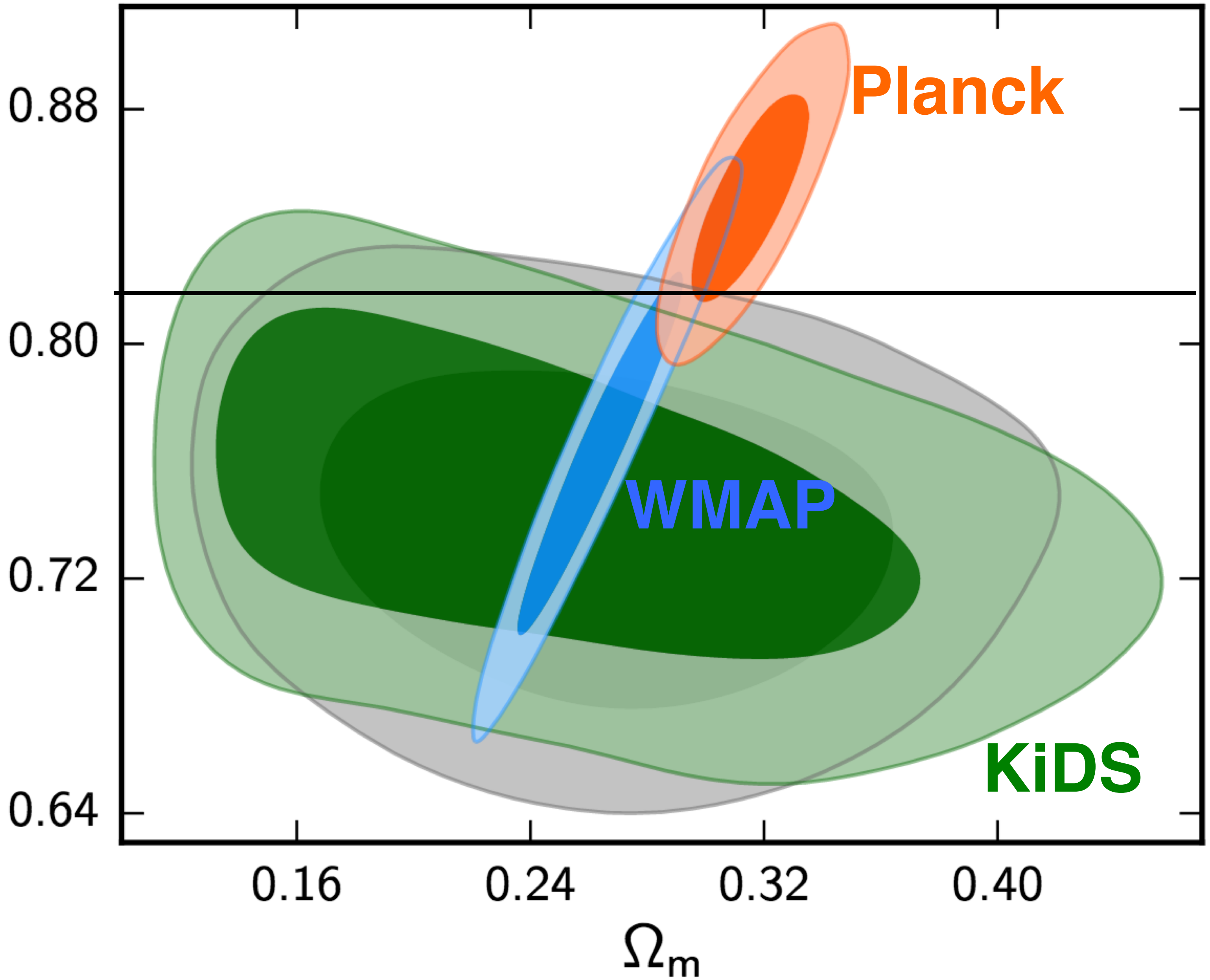
KiDS weak lensing data



$$\hat{\xi}^{ij}_{\pm}(\theta) = \frac{\sum_{ab} W_a W_b \left[\hat{e}^i_{a,t}(\vec{\theta})\hat{e}^j_{b,t}(\vec{\theta}) \pm \hat{e}^i_{a,\times}(\vec{\theta})\hat{e}^j_{b,\times}(\vec{\theta})\right]}{\sum_{ab} W_a W_b S_a S_b}$$

Hildebrandt et al. (KiDS consortium) 2016, arXiv:1606.05338

KiDS weak lensing S_8

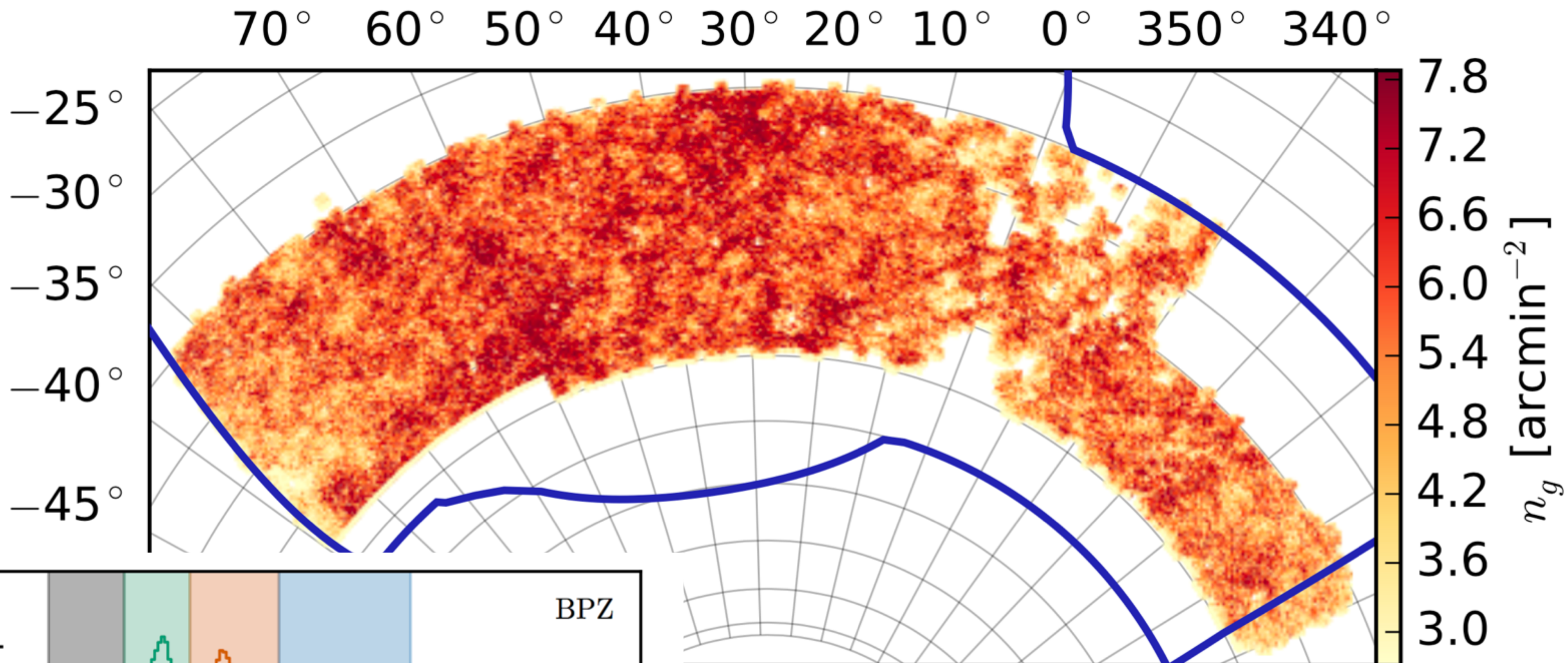


$$S_8 = 0.82 \pm 0.05 \ (\mathrm{DR12})$$

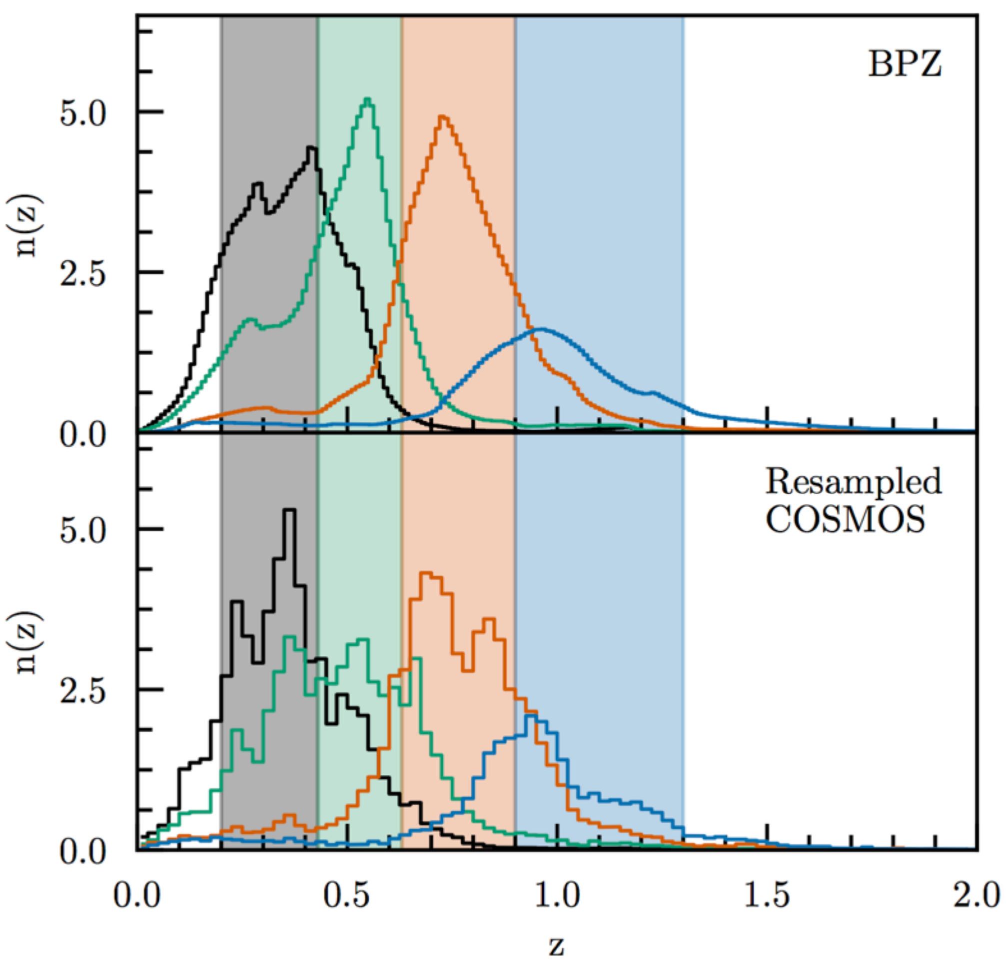
BOSS data: right in between

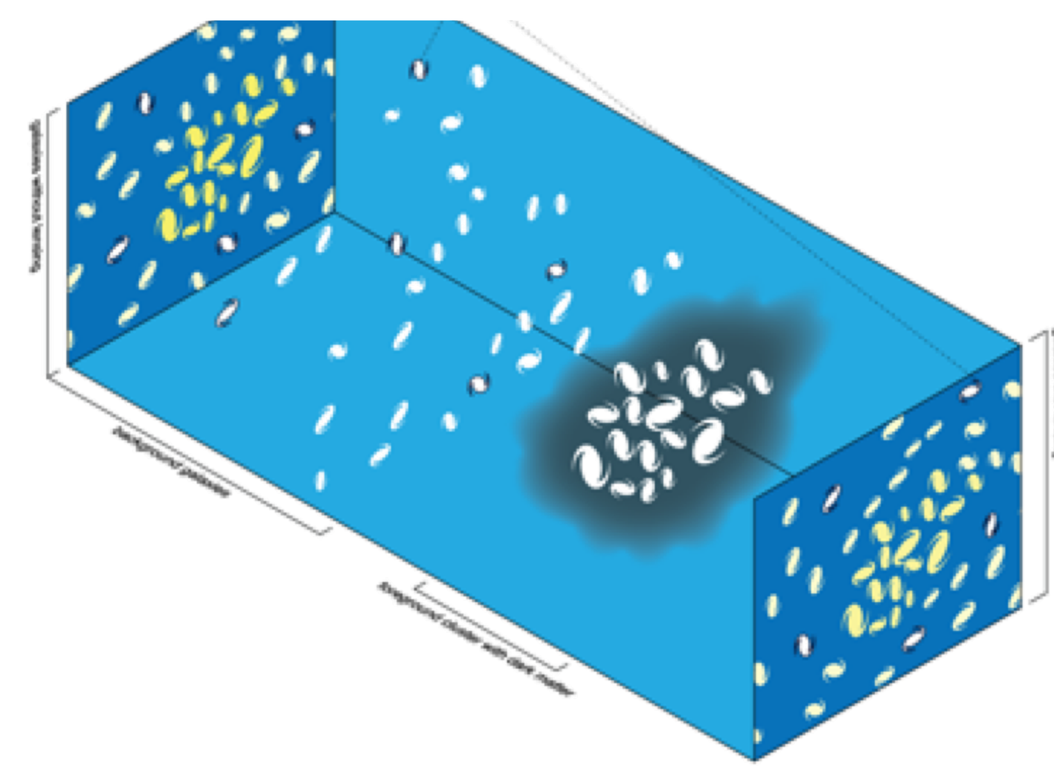
Hildebrandt et al. (KiDS consortium) 2016, arXiv:1606.05338

DES weak lensing data



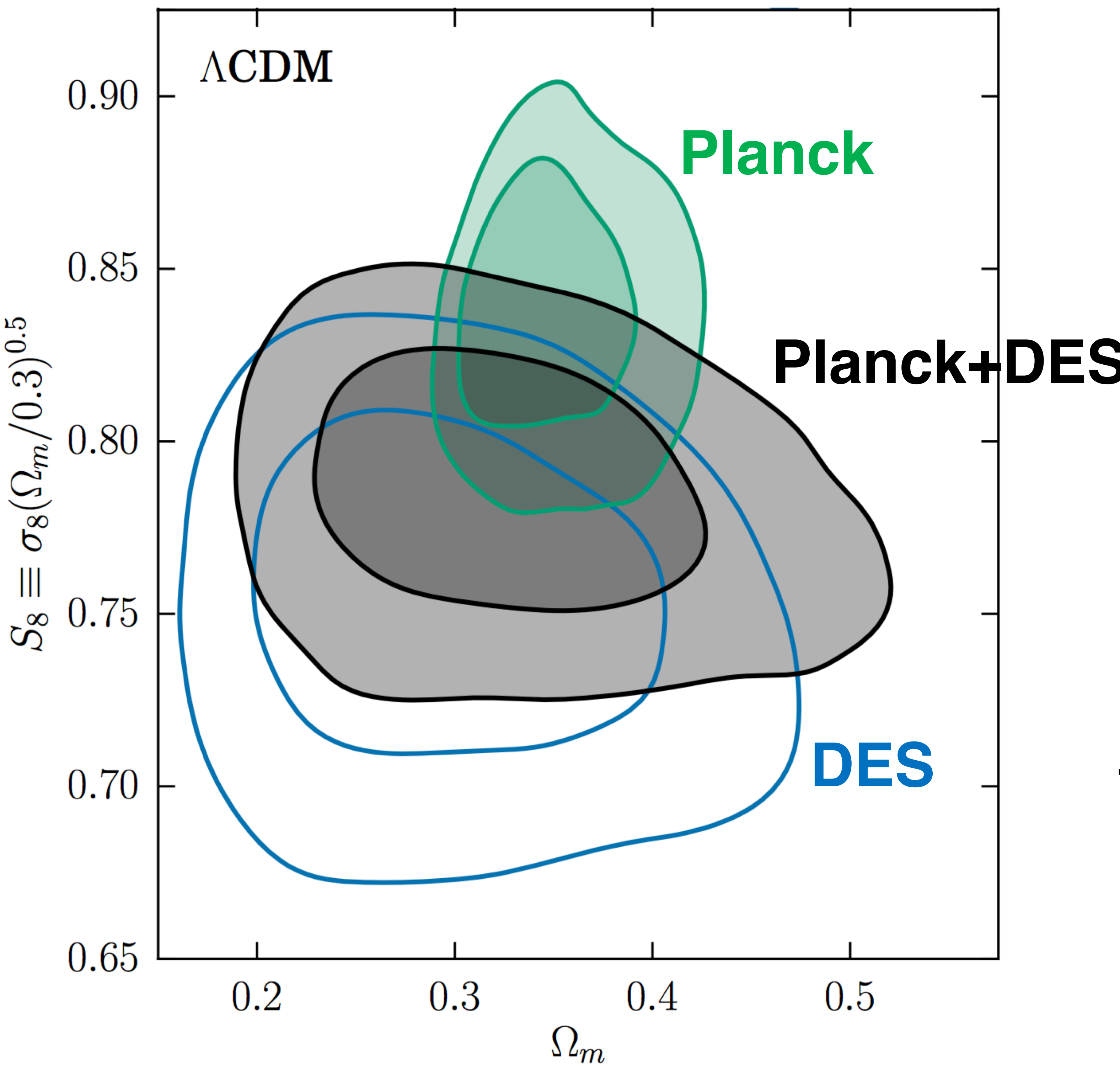
1321 deg^2
18M gals
σ_e=0.28





Troxel et al. (DES consortium) 2017, arXiv:1708.01538

DES weak lensing S_8



DES: difference from Planck in similar direction to KiDS, but of lower significance

Troxel et al. (DES consortium) 2017, arXiv:1708.01538

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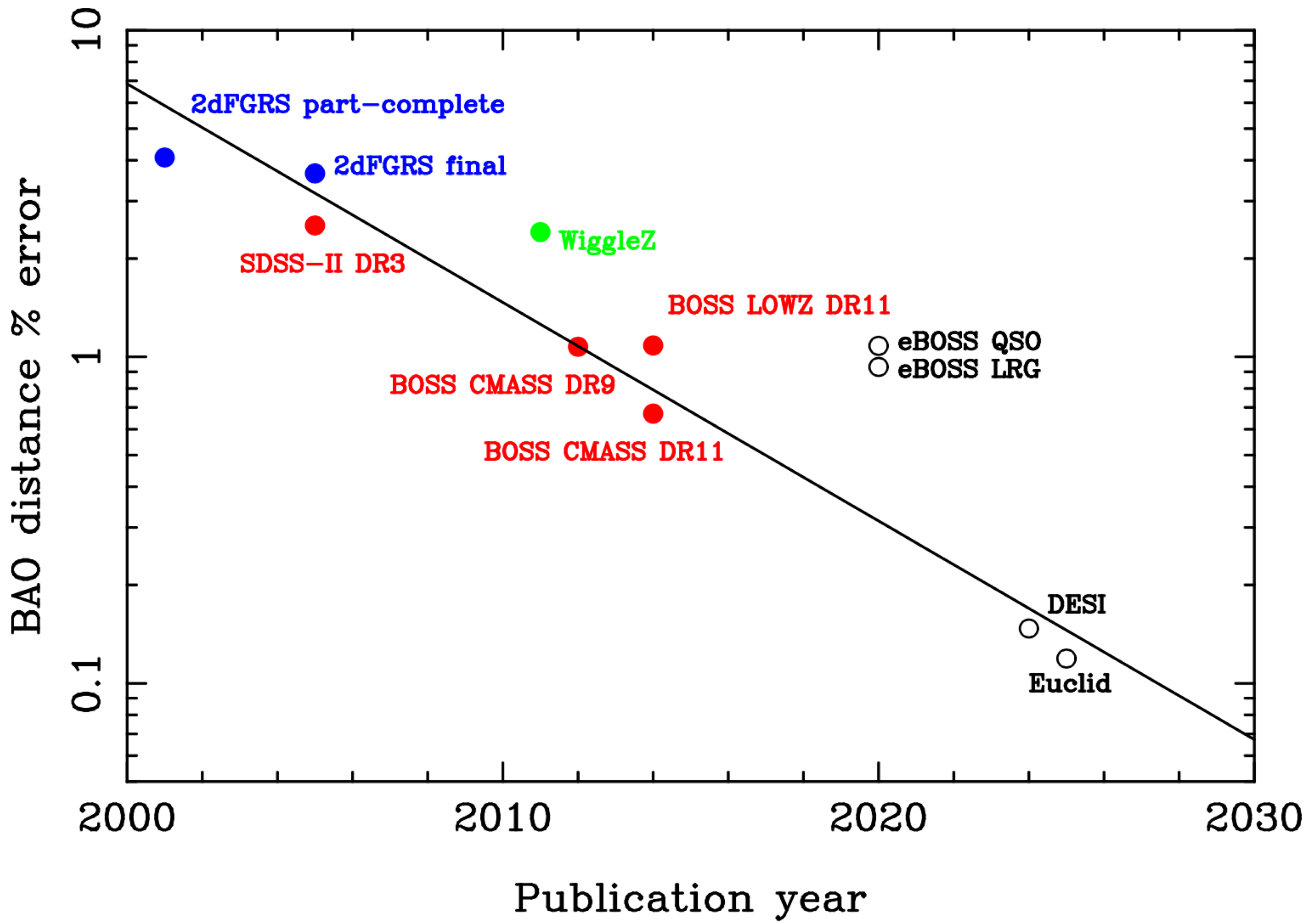
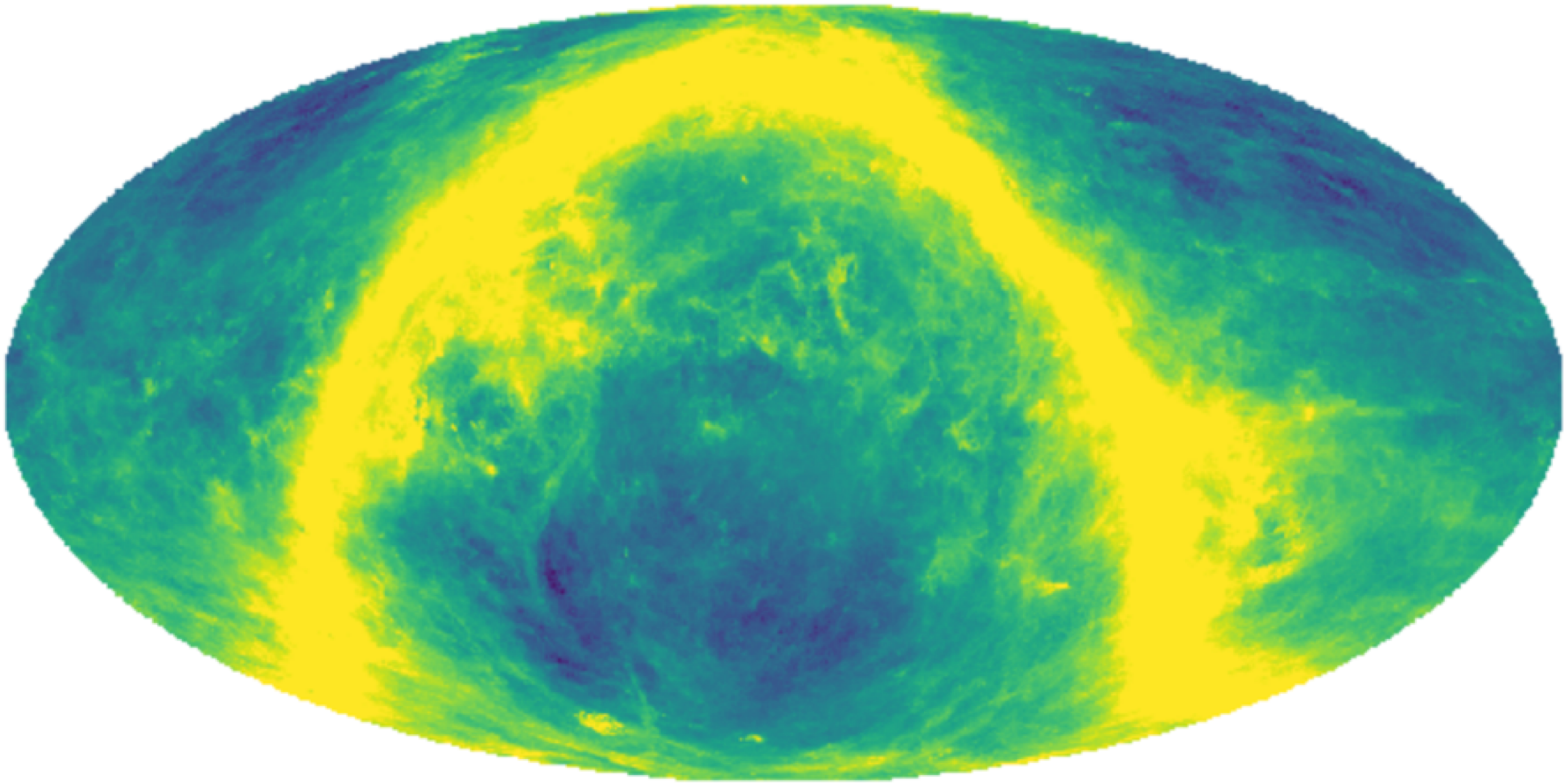
Concluding remarks … looking forwards

Survey improvement

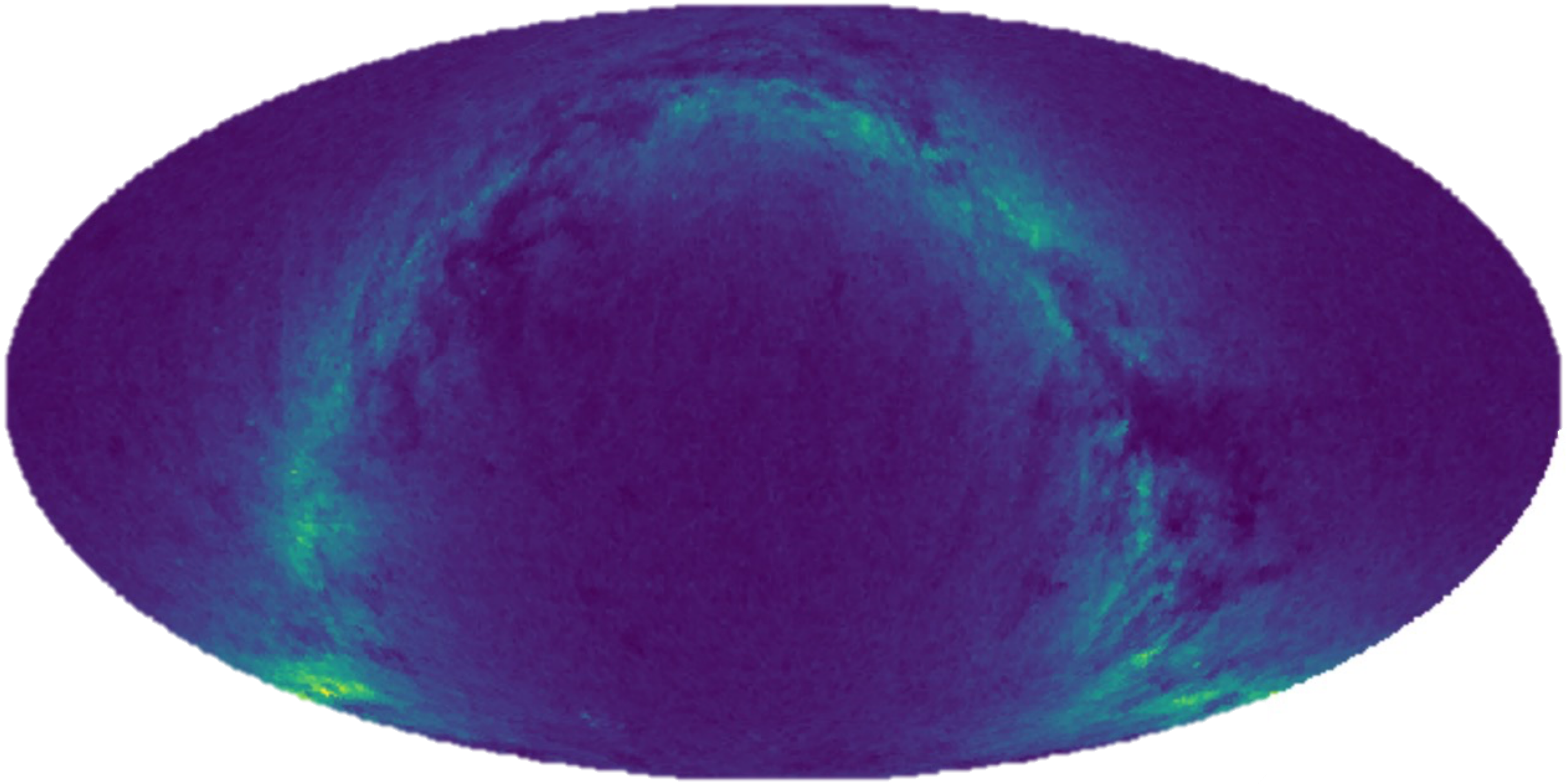


Reid et al. 2015, arXiv:1509.06529

Observational systematics

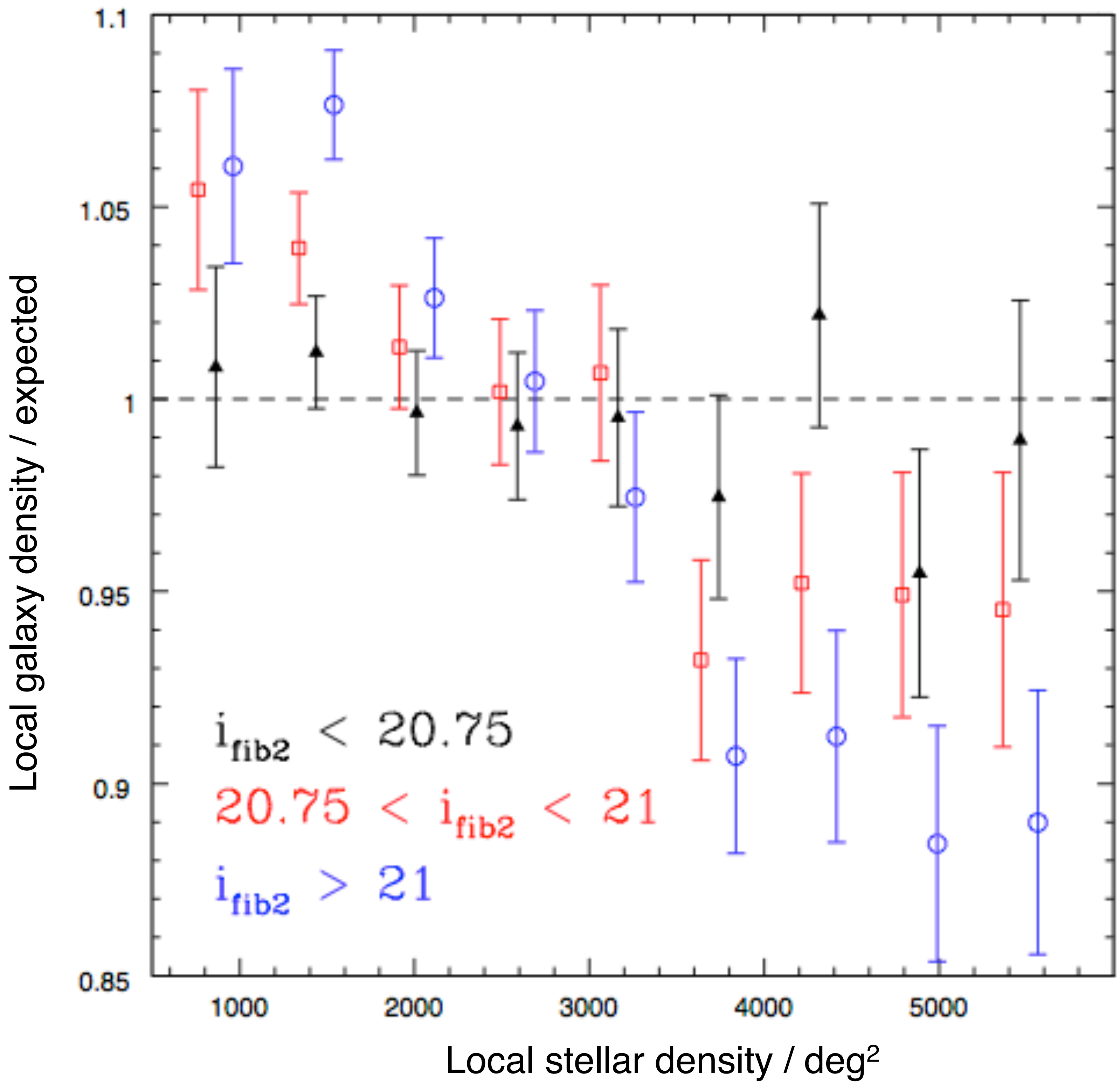


Extinction



Stellar density

Trend with stellar density



Ross et al. 2012; arXiv:1203.6499

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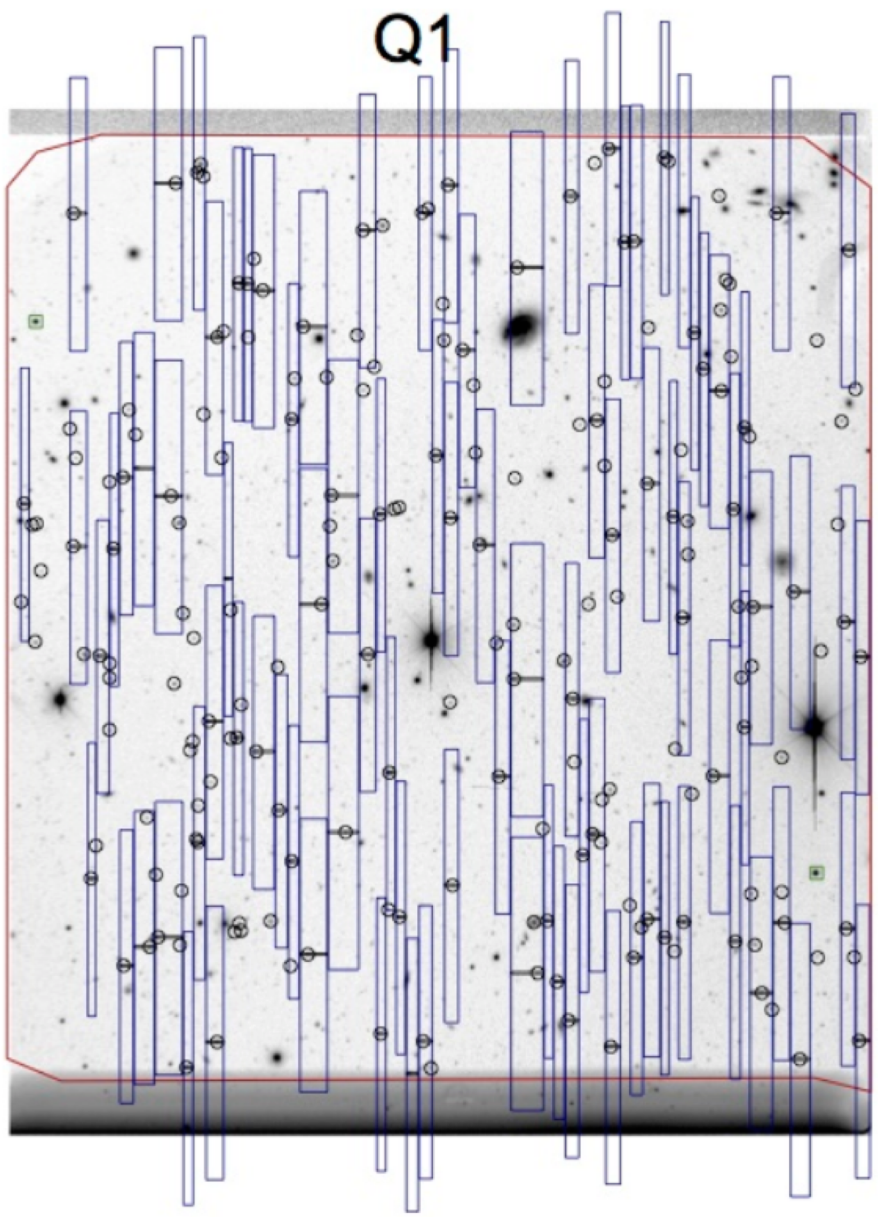
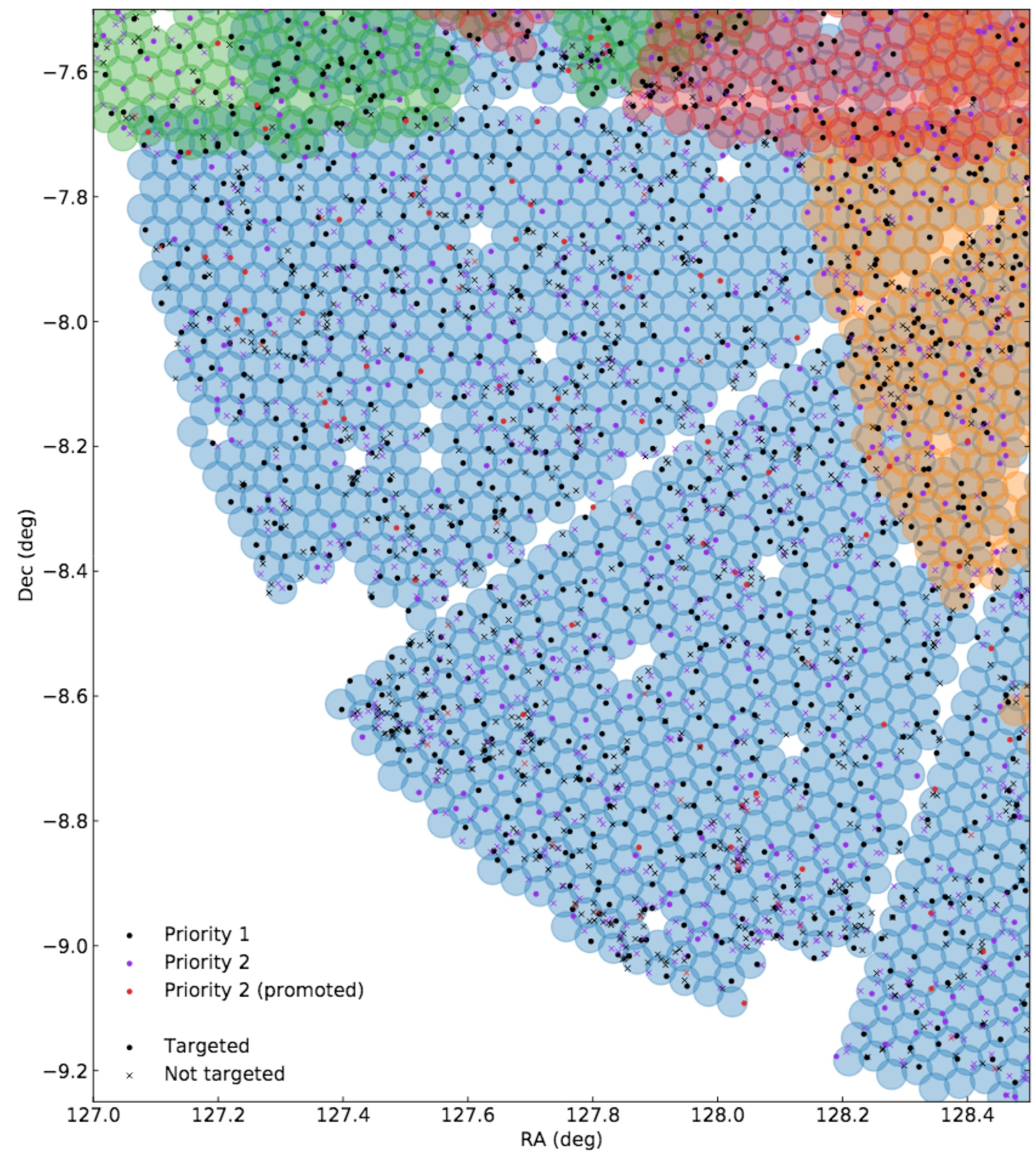
Comment on unknown unknowns

- We can correct for known unknowns
- We cannot correct for unknown unknowns
- We want to turn unknown unknowns into known unknowns by knowing as much as we can about the survey
- Survey must be designed with systematics as much as statistics in mind

Hardware imprint on sky



Close up of VIPERS observations
Mohammad et al. 2018; arXiv:1807.05999



Close up of expected DESI observations
Smith et al. 2018; arXiv:1809.07355

A practical algorithm

Link between observed and non-observed pairs based on selection probability:

- different random choices for observations
- different spatial positions of observations

To find the selection probabilities, need to rerun simulation of observing strategy ~1000 times

Potentially computationally challenging (storing probabilities), but introduce a new Monte-Carlo scheme based on bitwise weights stored per galaxy, so that pairwise weights can be determined “on the fly”

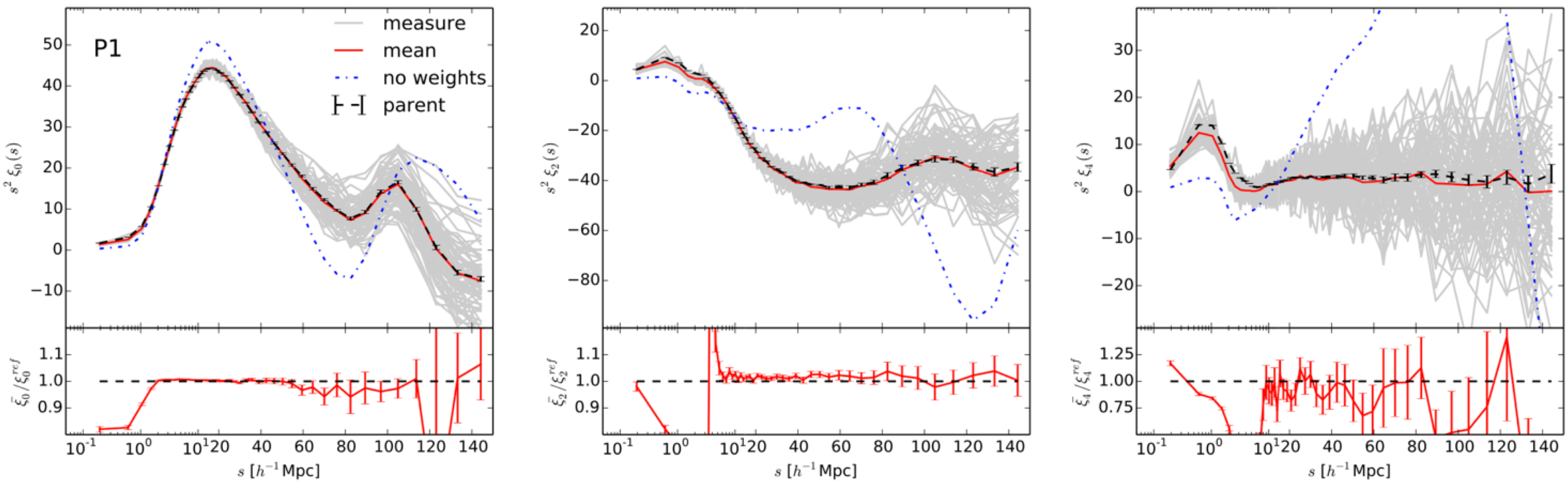
Runs of target algorithm
1 = observed
0 = not observed

Gal i	**Gal j**
1	1
0	0
1	0
1	1
0	0
1	1
1	0
1	0

Probability of observing pair *ij* is 3/8, so weight is 8/3

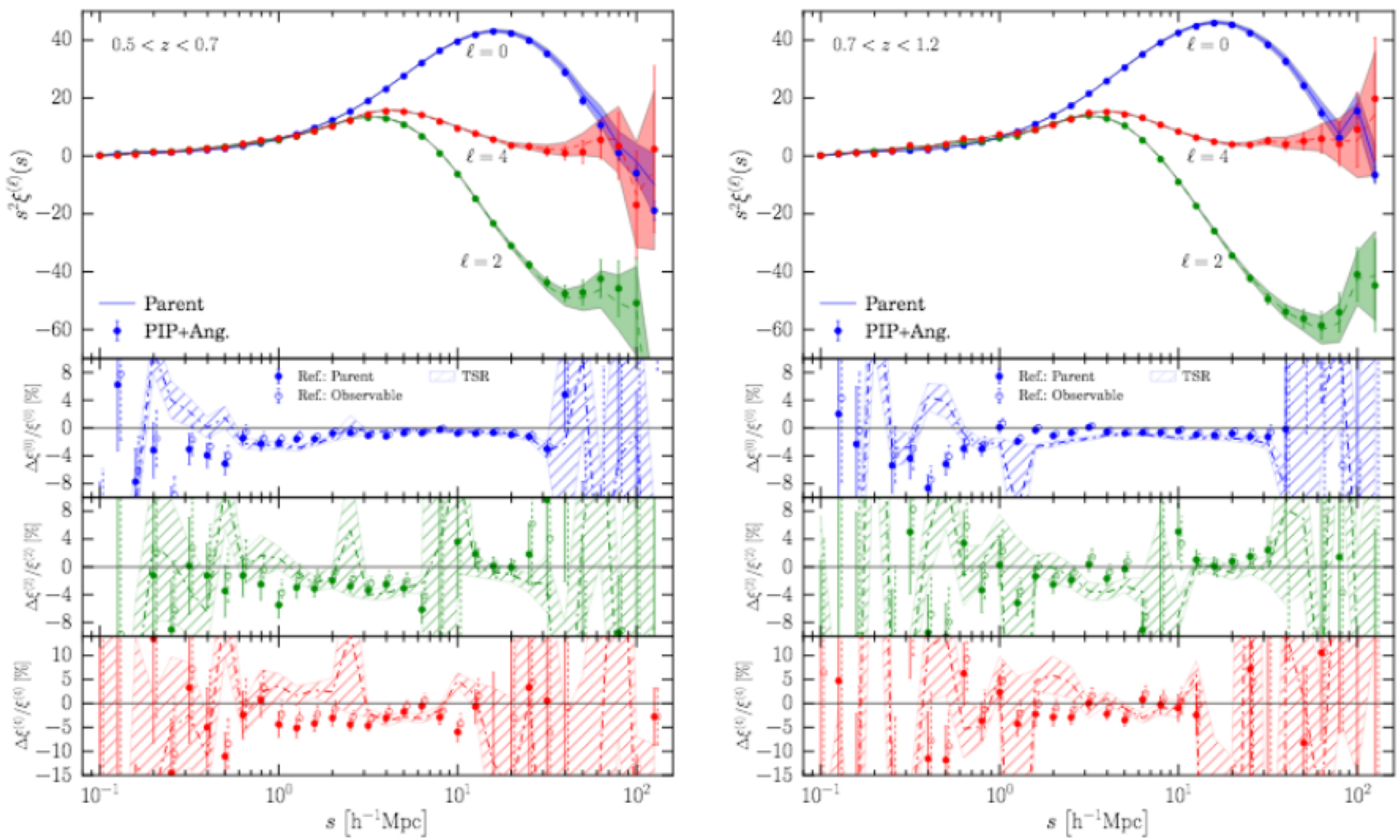
Bianchi & Percival 2017; arXiv:1703.02070

DESI: Fiber assignment



Bianchi & Percival 2017; arXiv:1703.02070

VIPERS: slit assignment



Mohammad et al. 2018; arXiv:1807.05999

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Summary

- Current large-scale structure observations agree with LCDM

- Huge progress in cosmology over the last 20 years
    - Post inflation, pre-recombination universe now very well understood
    - Huge questions remain: Inflation, Dark Energy, Dark Matter

- Current surveys have already shown the importance of systematics and this will become increasingly important for the next generation
    - better calibration, removal of contaminants
    - Faster, better calculations (computational data challenge)
    - including more information: weights, including Bispectrum
    - Better models (perturbation theory, EFT, baryons …)