Testing Gravity using BOSS

Will Percival

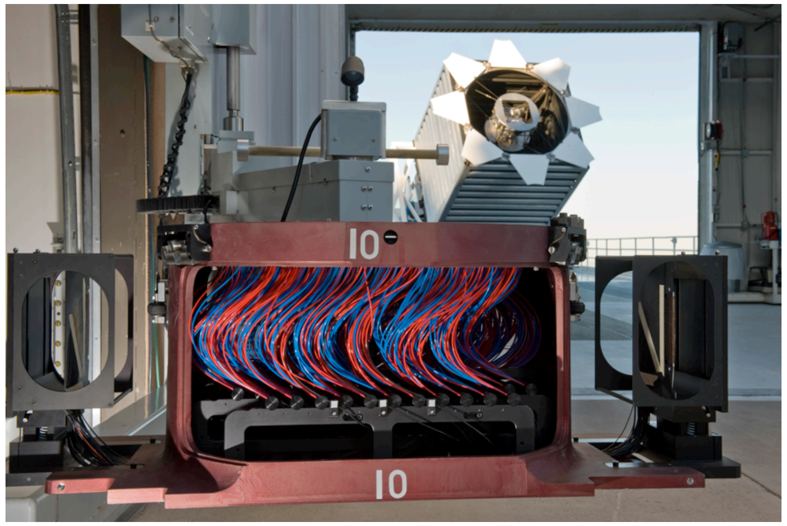
Eva-Maria Mueller

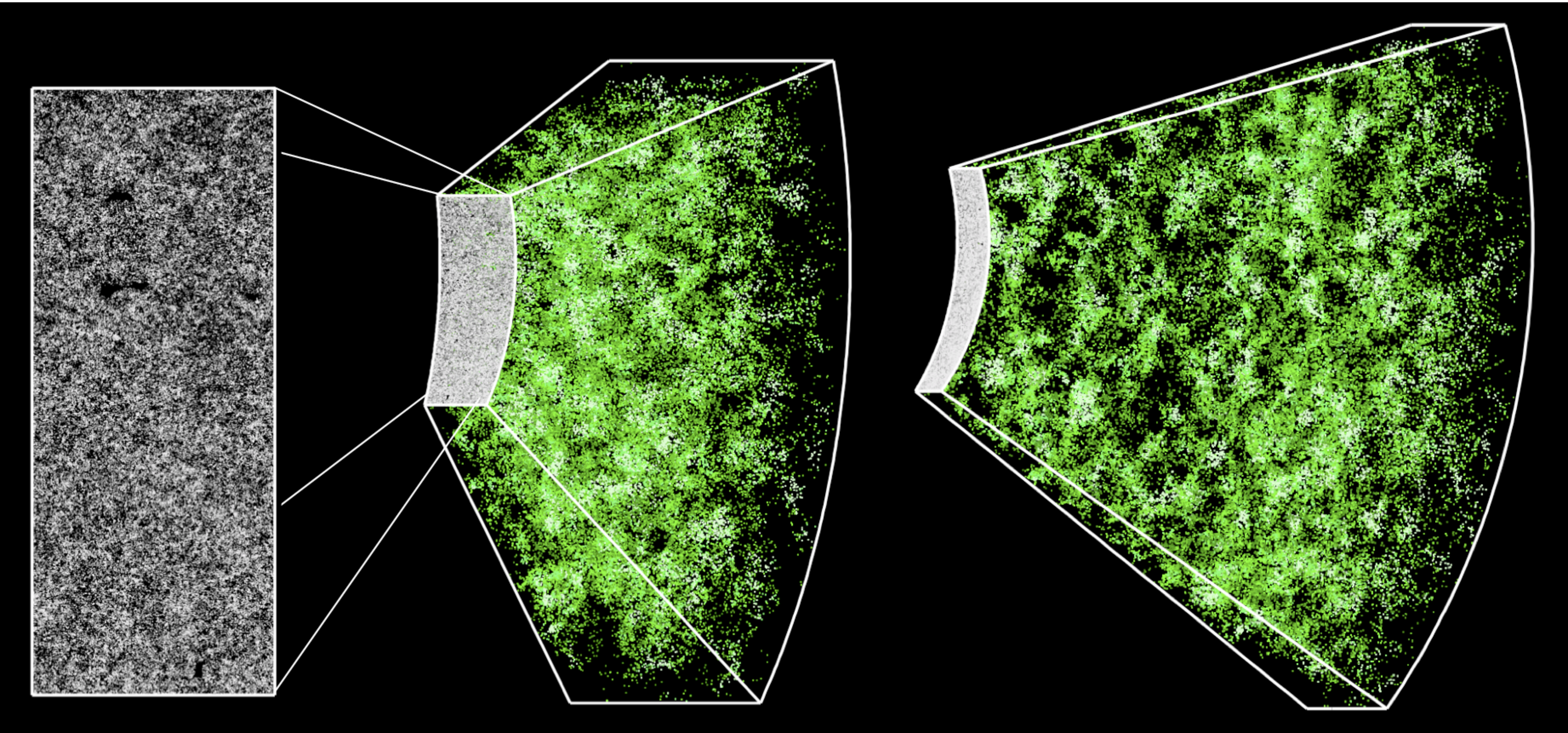
+ the BOSS team

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:

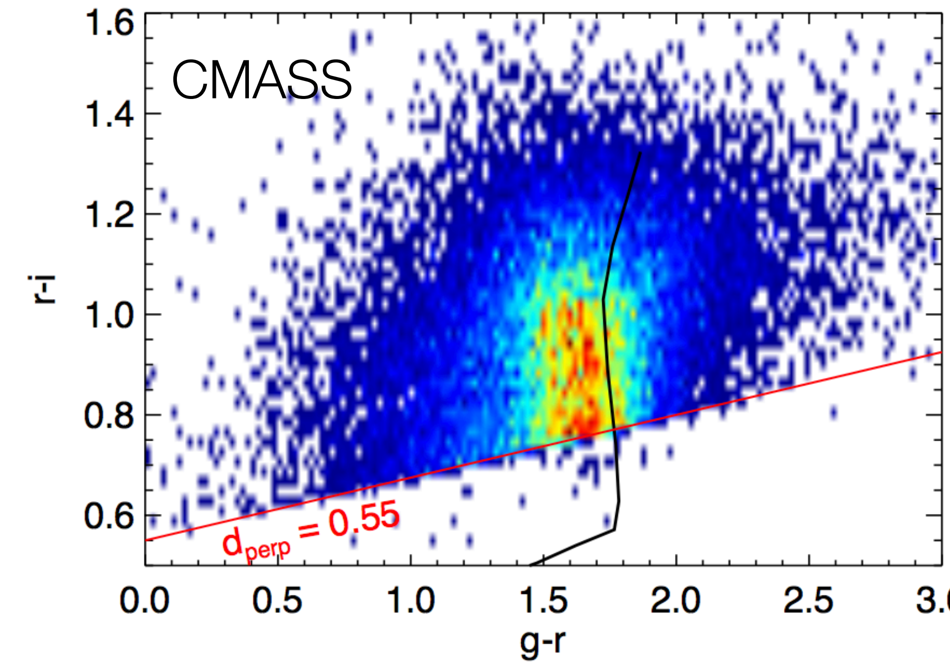
  http://data.sdss3.org/sas/dr12/boss/lss/

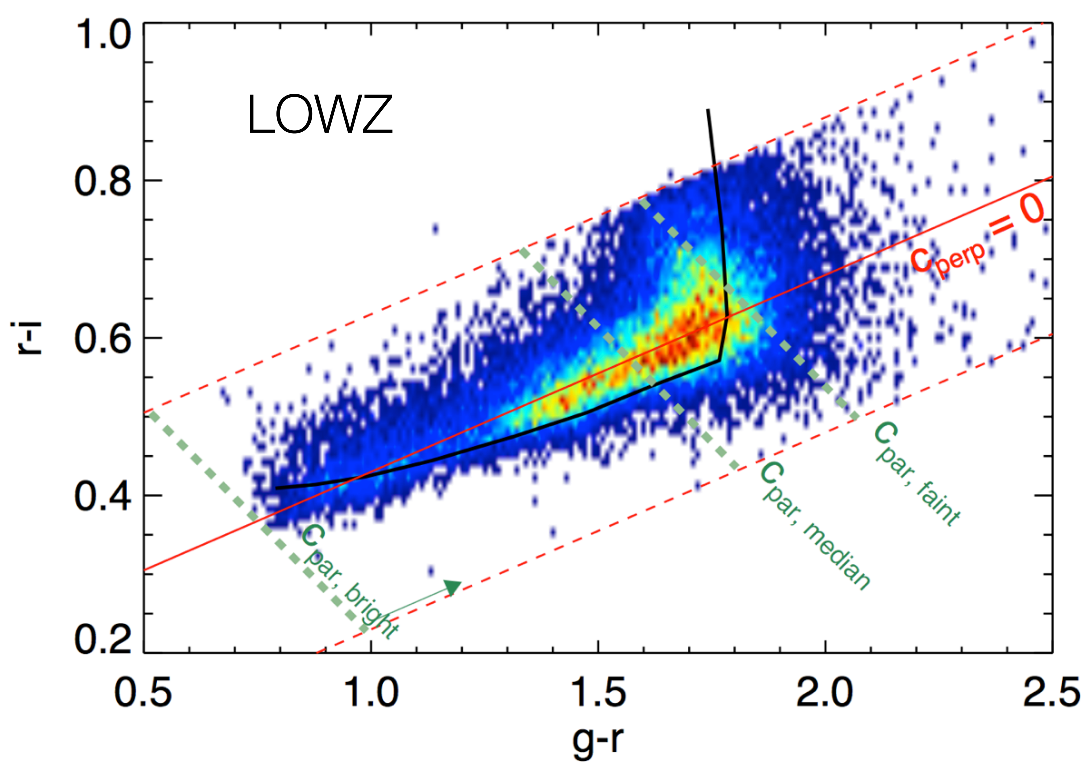


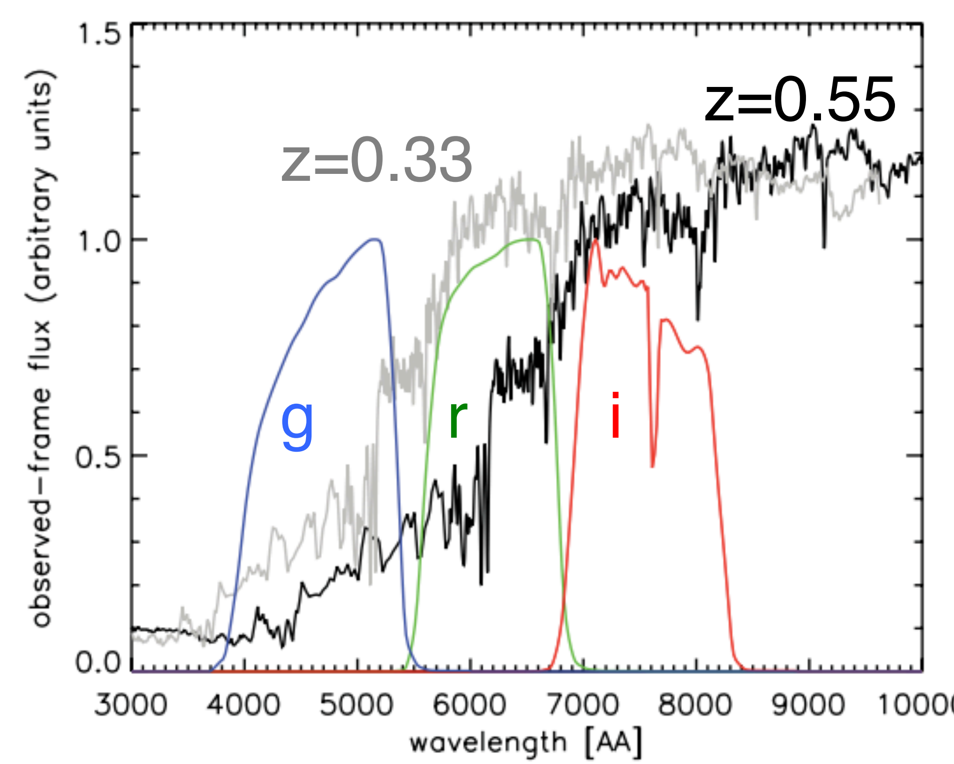


BOSS Data Release 12 galaxies

- Two galaxy samples targeted: LOWZ and CMASS
- Colour cuts to select old, massive galaxies for easy redshift measurement and high bias
- Based on locus of passive galaxies
- CMASS broader (in colour) than LOWZ with a cut $d_{\perp} = (r_{\mathbf{mod}} - i_{\mathbf{mod}}) - (g_{\mathbf{mod}} - r_{\mathbf{mod}})/8 > 0.55$ to select to an approximate stellar mass limit

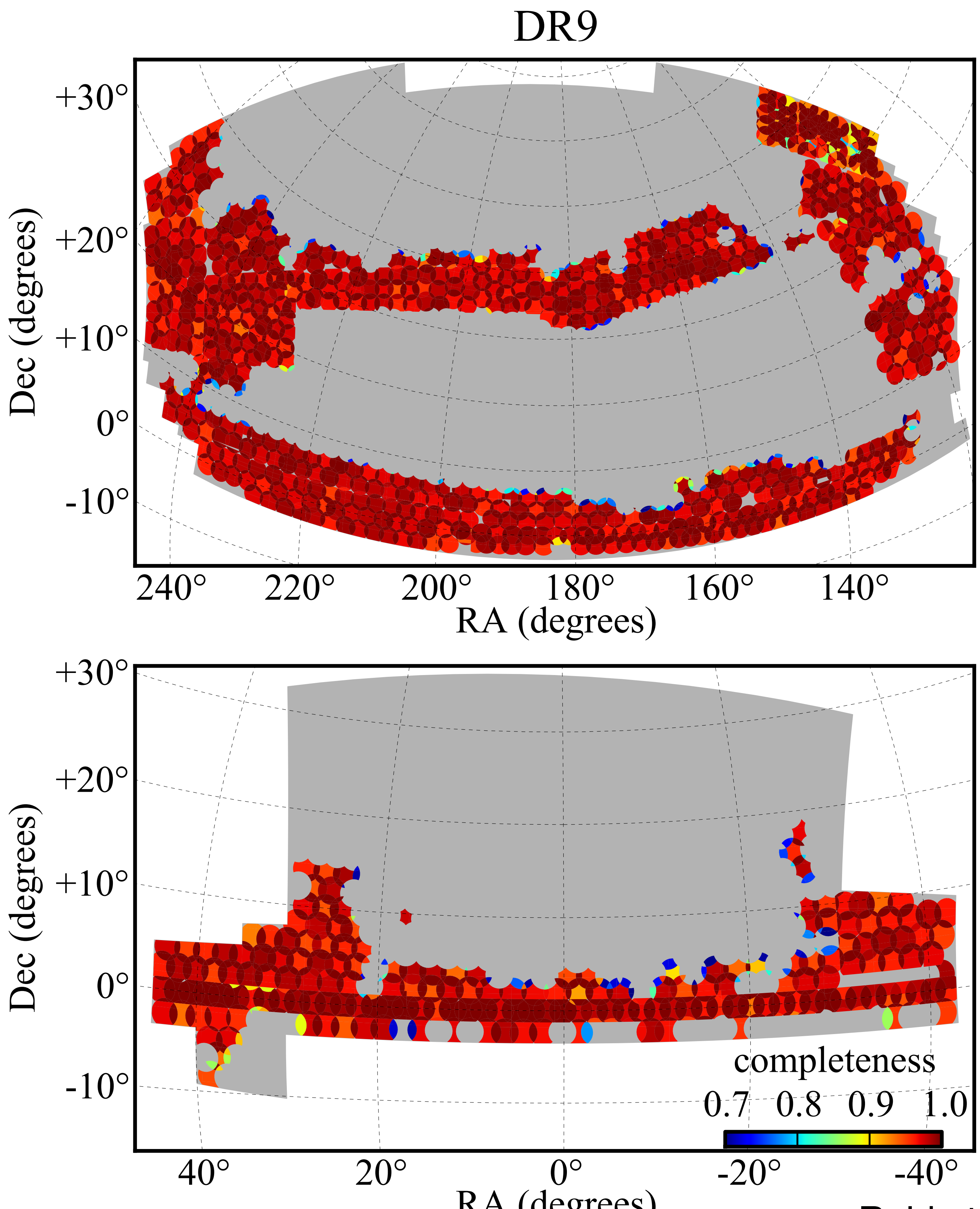






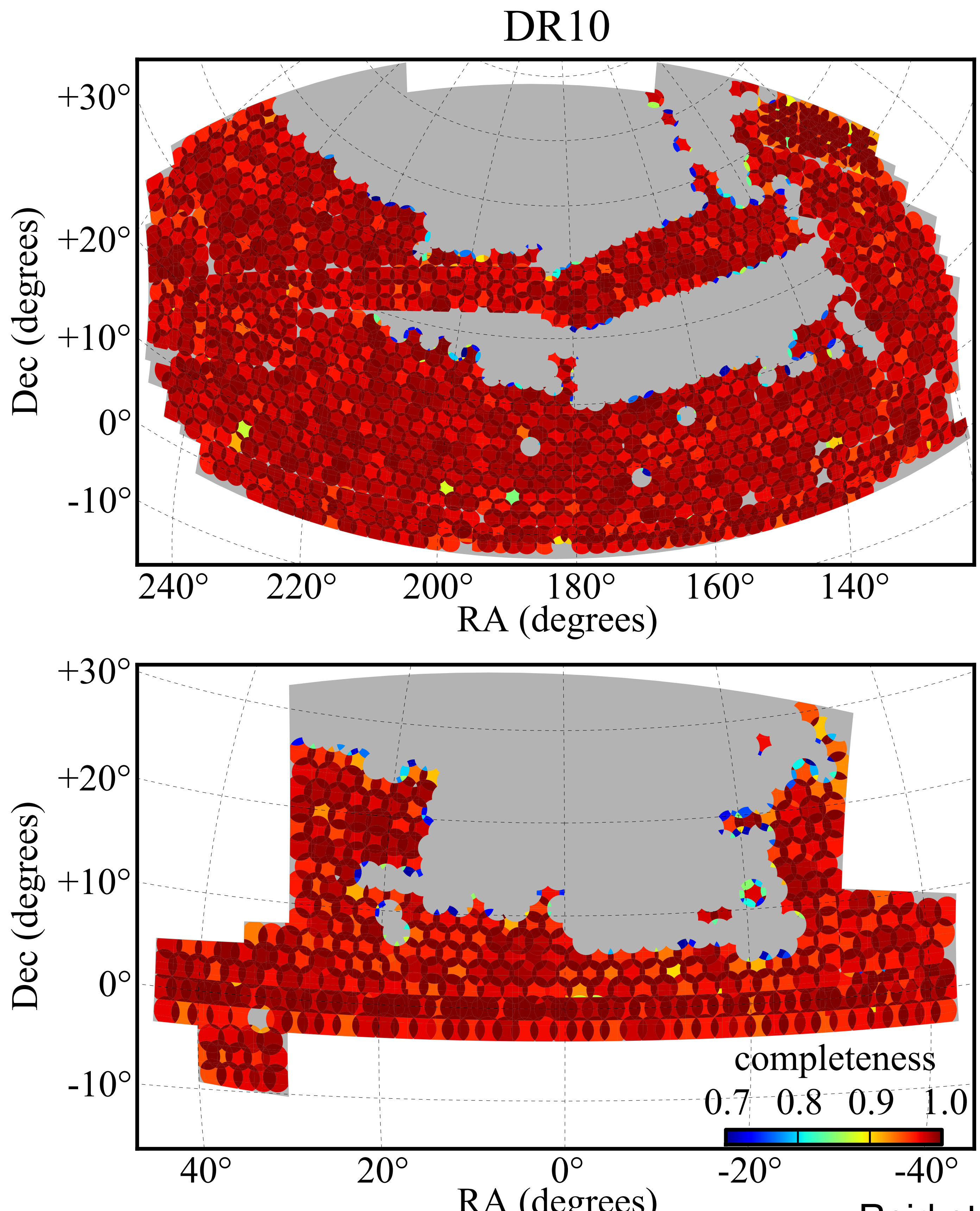
Reid et al. 2015, arXiv:1509.06529

BOSS Data Release 9 galaxies



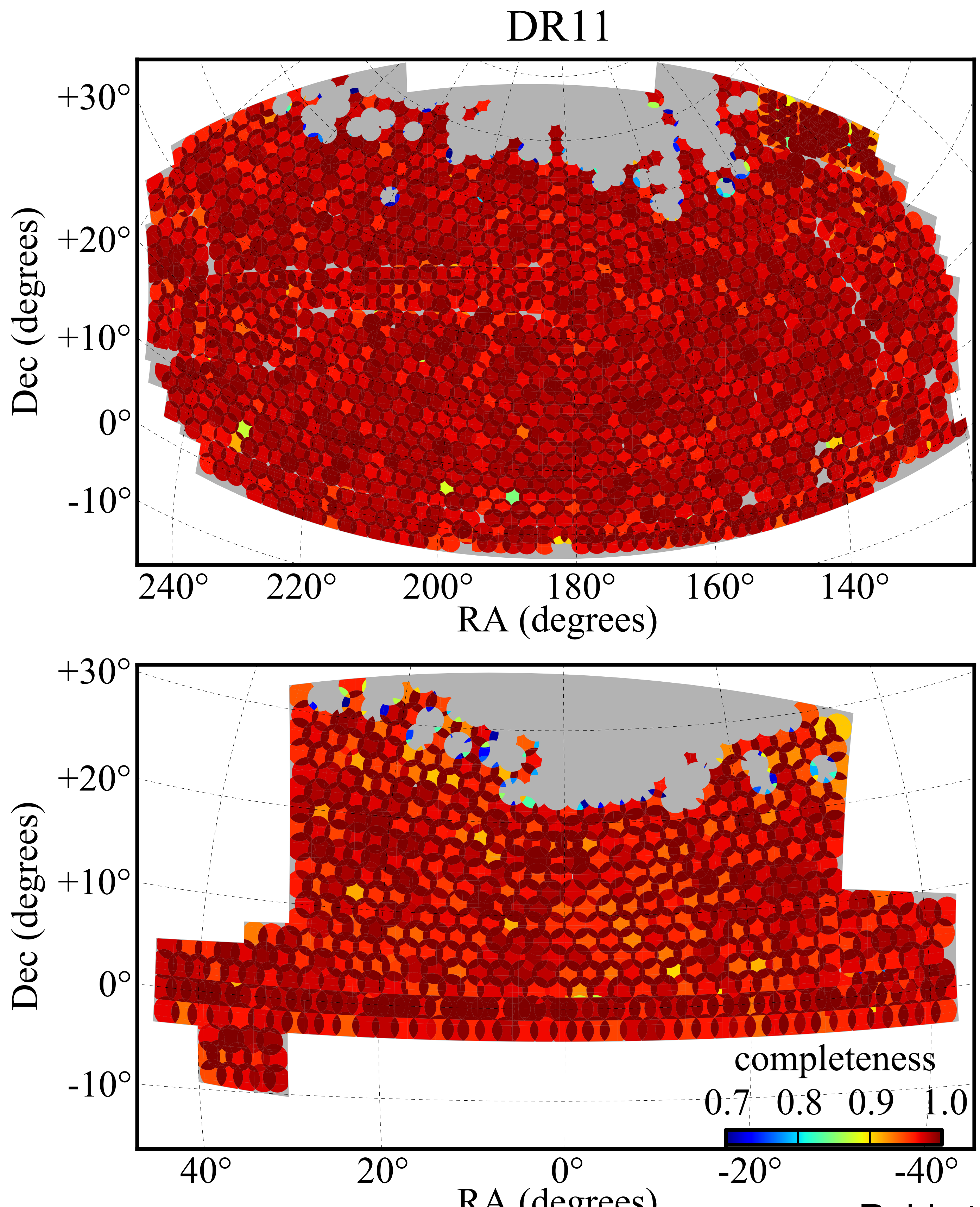
Reid et al. 2015, arXiv:1509.06529

BOSS Data Release 10 galaxies



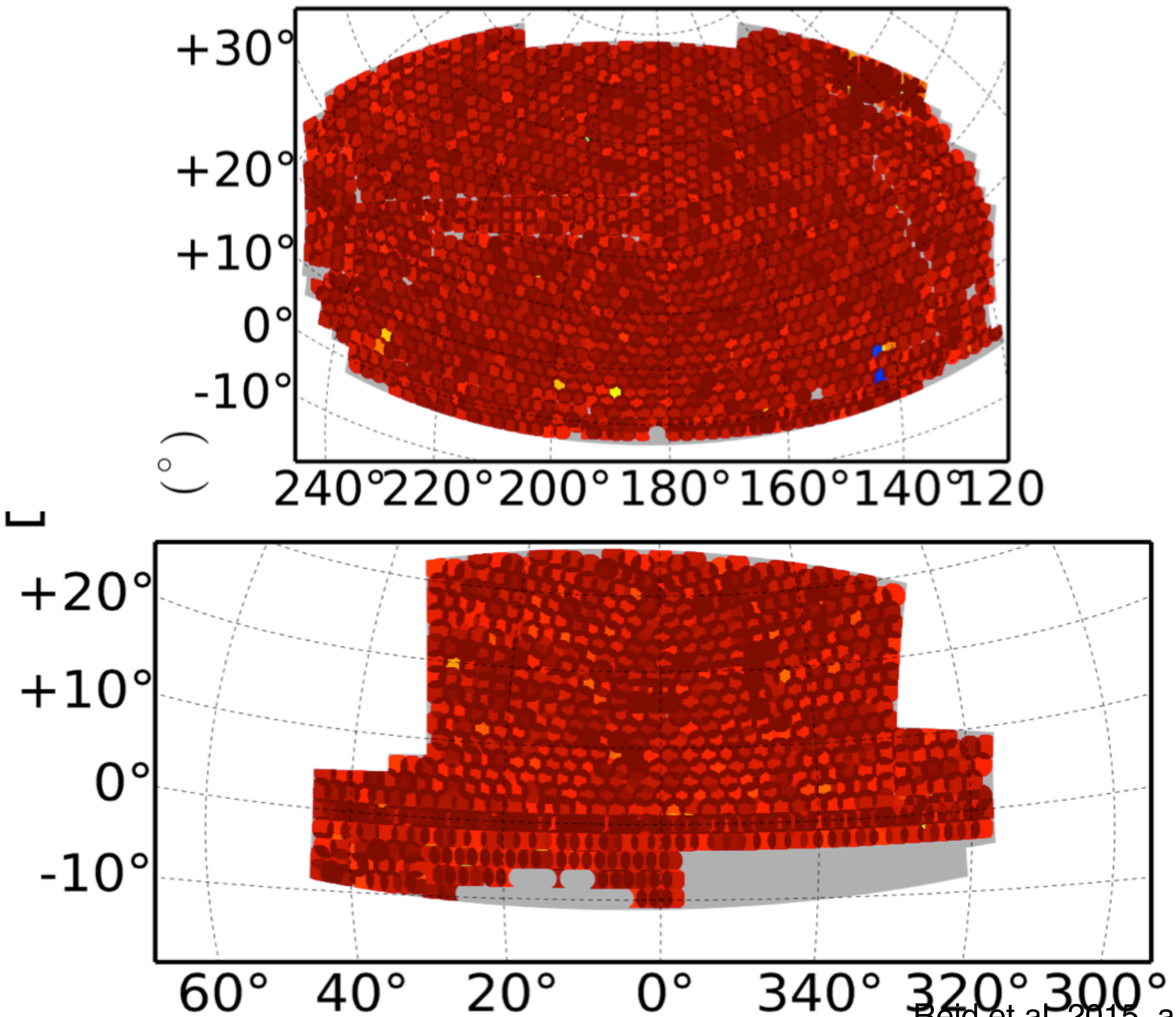
Reid et al. 2015, arXiv:1509.06529

BOSS Data Release 11 galaxies



Reid et al. 2015, arXiv:1509.06529

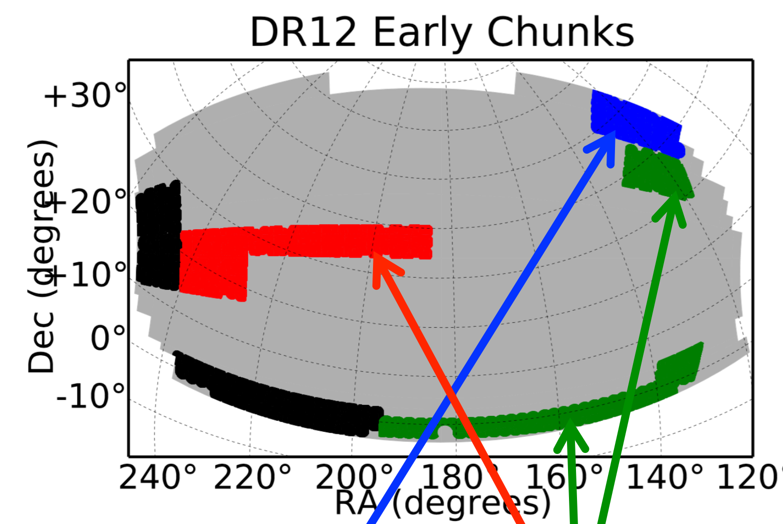
BOSS DR12 galaxies



Reid et al. 2015, arXiv:1509.06529

ICG Portsmouth

The galaxy sample

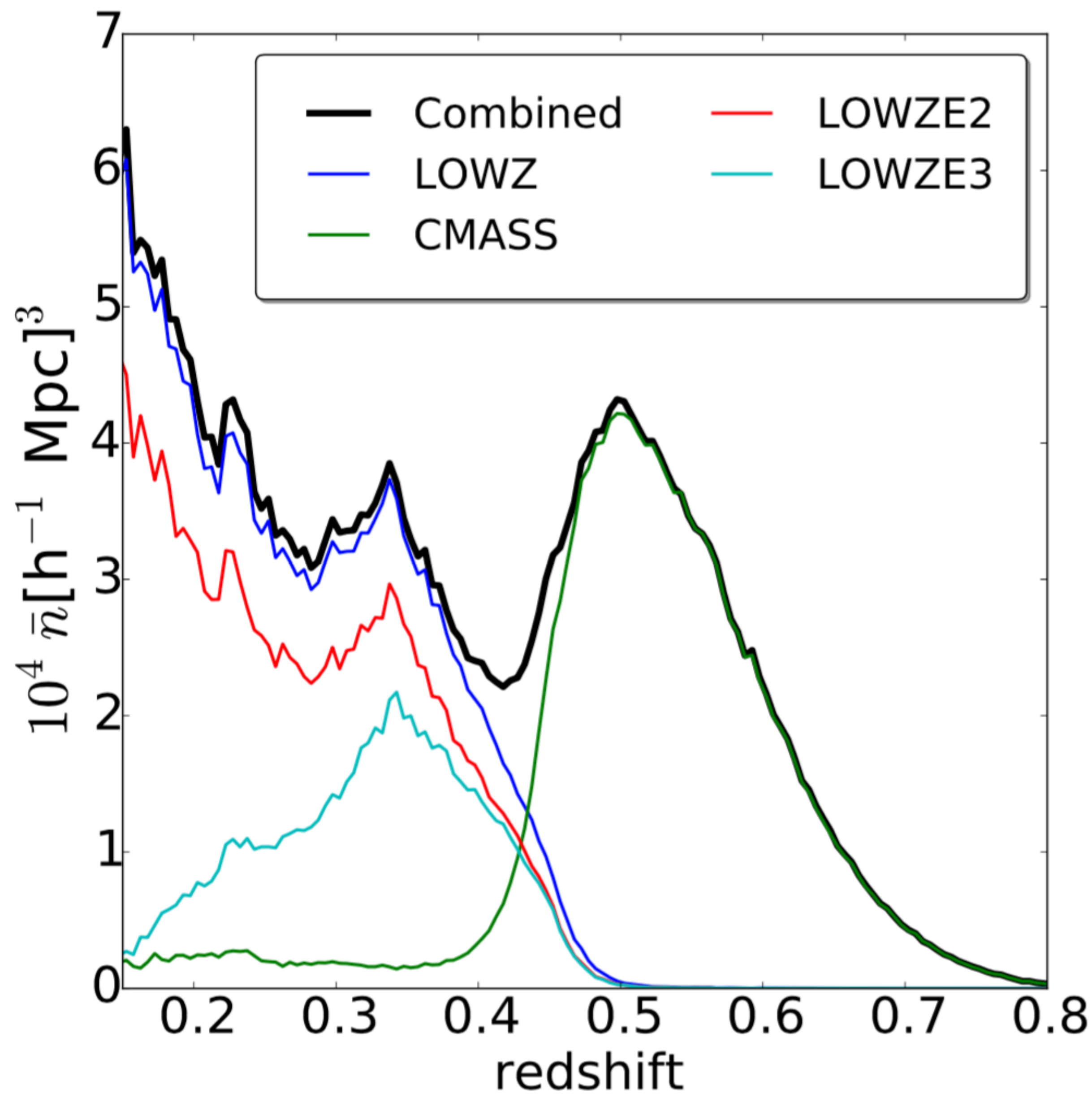


Property	NGC	SGC	total	NGC	SGC	total	NGC	NGC
Sample		CMASS			LOWZ		LOWZE2	LOWZE3
$\bar{N}_{\rm gal}$	607,357	228,990	836,347	177,336	132,191	309,527	2,985	11,195
$\bar{N}_{\rm known}$	11,449	1,841	13,290	140,444	13,073	153,517	2,730	6,371
$\bar{N}_{\rm star}$	14,556	8,262	22,818	1,043	976	2,019	24	61
$\bar{N}_{\rm fail}$	10,188	5,157	15,345	868	602	1,470	21	55
$\bar{N}_{\rm cp}$	34,151	11,163	45,314	4,459	4,422	8,881	16	167
$\bar{N}_{\rm missed}$	7,997	3,488	11,485	10,295	3,499	13,794	114	609
$\bar{N}_{\rm used}$	568,776	208,426	777,202	248,237	113,525	361,762	4,336	15,380
$\bar{N}_{\rm obs}$	632,101	242,409	874,510	179,247	133,769	313,016	3,030	11,311
$\bar{N}_{\rm targ}$	685,698	258,901	944,599	334,445	154,763	489,208	5,890	18,458
Total area (deg^2)	7,429	2,823	10,252	6,451	2,823	9,274	144	834
Veto area (deg^2)	495	263	759	431	264	695	10	55
Used area (deg^2)	6,934	2,560	9,493	6,020	2,559	8,579	134	779
Effective area (deg^2)	6,851	2,525	9,376	5,836	2,501	8,337	131	755
Targets / deg^2	98.9	101.1	99.5	55.6	60.5	57.0	43.4	23.5

Reid et al. 2015, arXiv:1509.06529

The galaxy sample

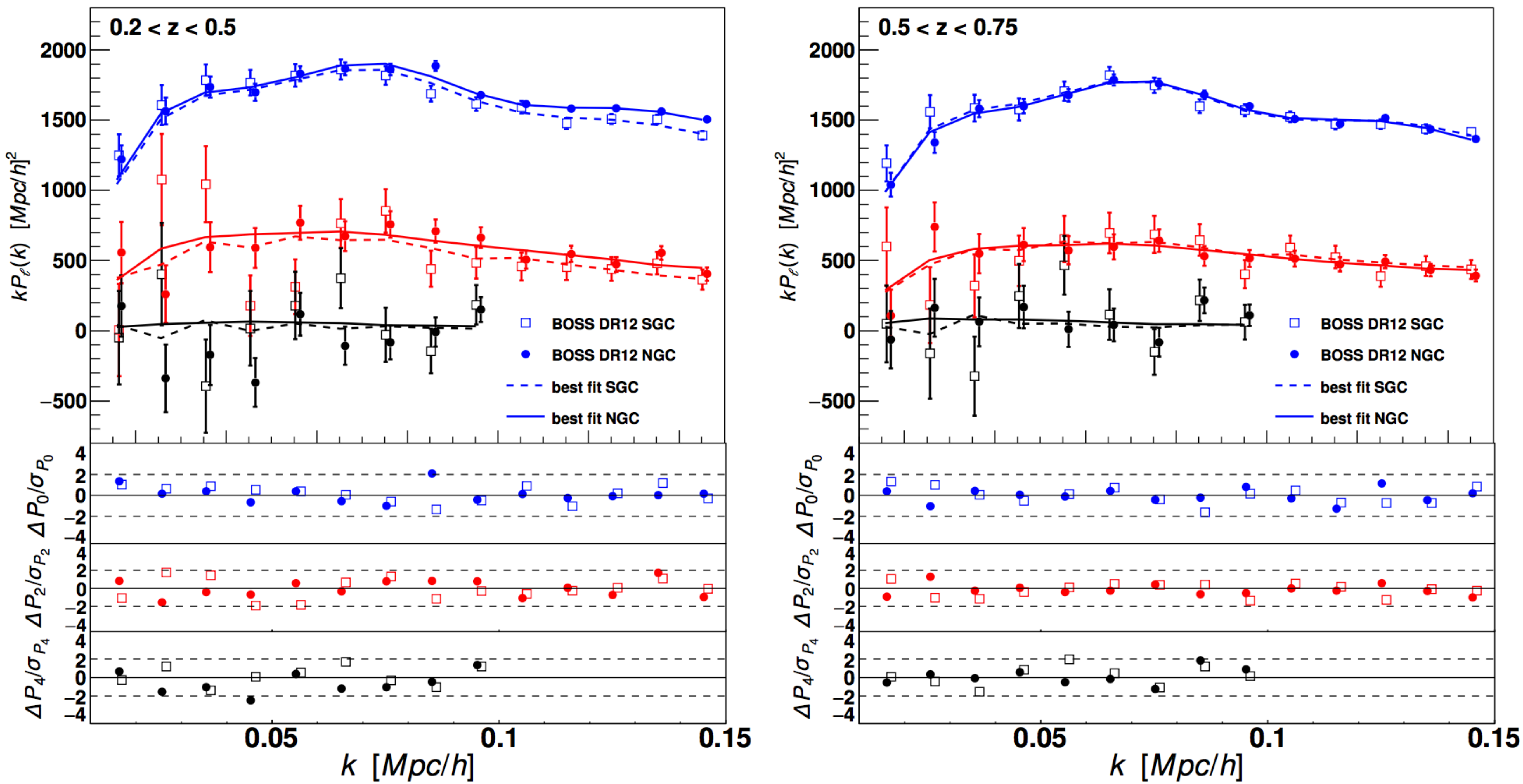
		N_{gals}	V_{eff} (Gpc^3)	V (Gpc^3)
$0.2 < z < 0.5$	NGC	429182	2.7	4.7
	SGC	174819	1.0	1.7
	Total	**604001**	**3.7**	**6.4**
$0.4 < z < 0.6$	NGC	500872	3.1	5.3
	SGC	185498	1.1	2.0
	Total	**686370**	**4.2**	**7.3**
$0.5 < z < 0.75$	NGC	435741	3.0	9.0
	SGC	158262	1.1	3.3
	Total	**594003**	**4.1**	**12.3**



Reid et al. 2015, arXiv:1509.06529

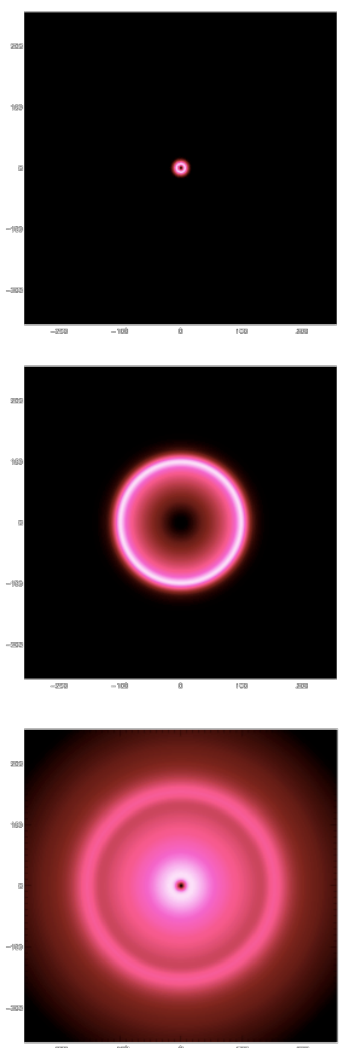
Clustering measurements

Measured power spectrum moments

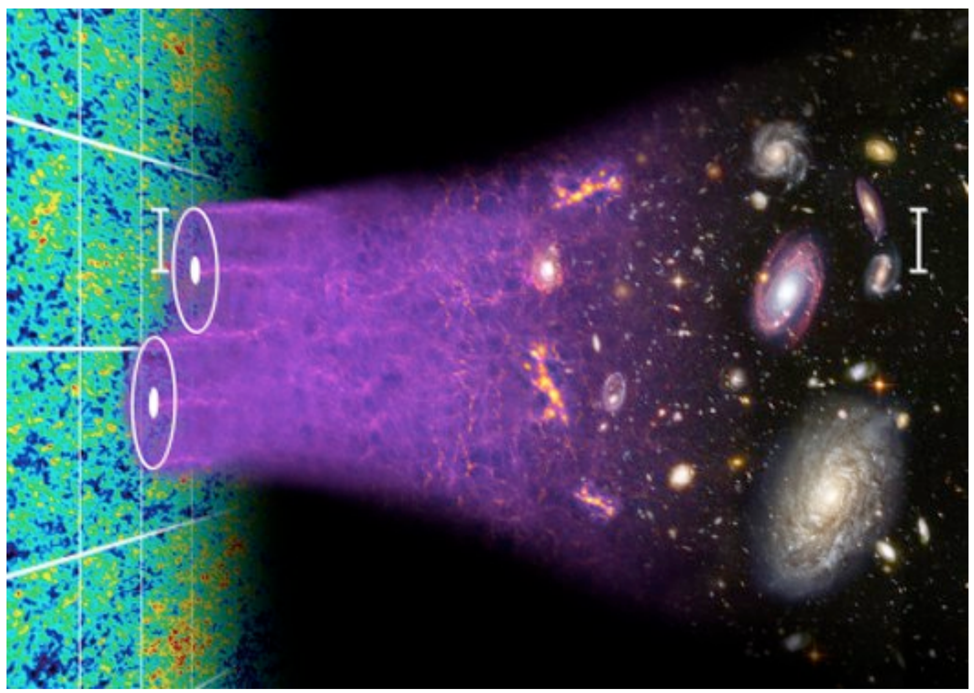


Beutler et al. 2016, arXiv:1607.03150

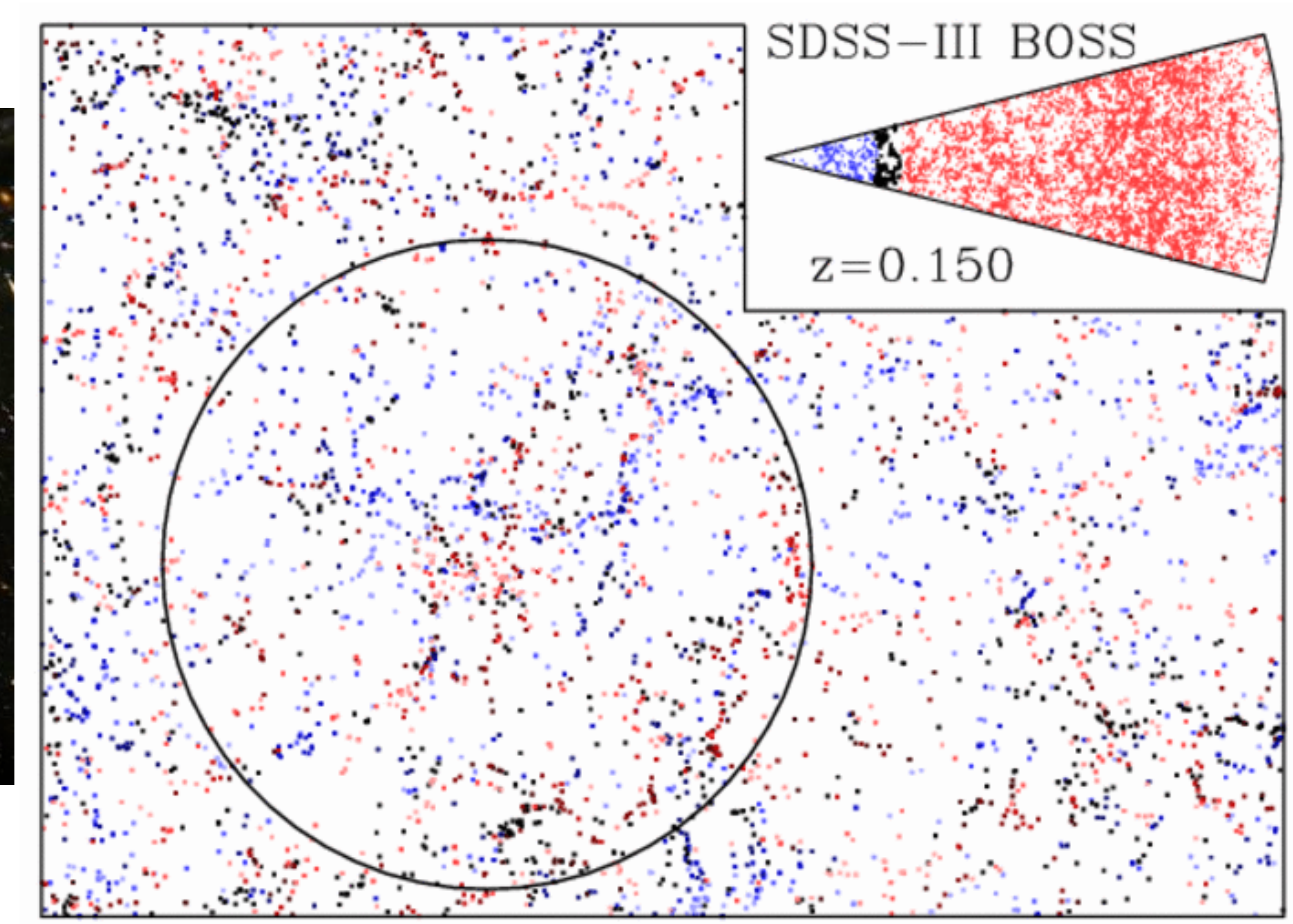
Baryon Acoustic Oscillations (BAO)



(images from Martin White)

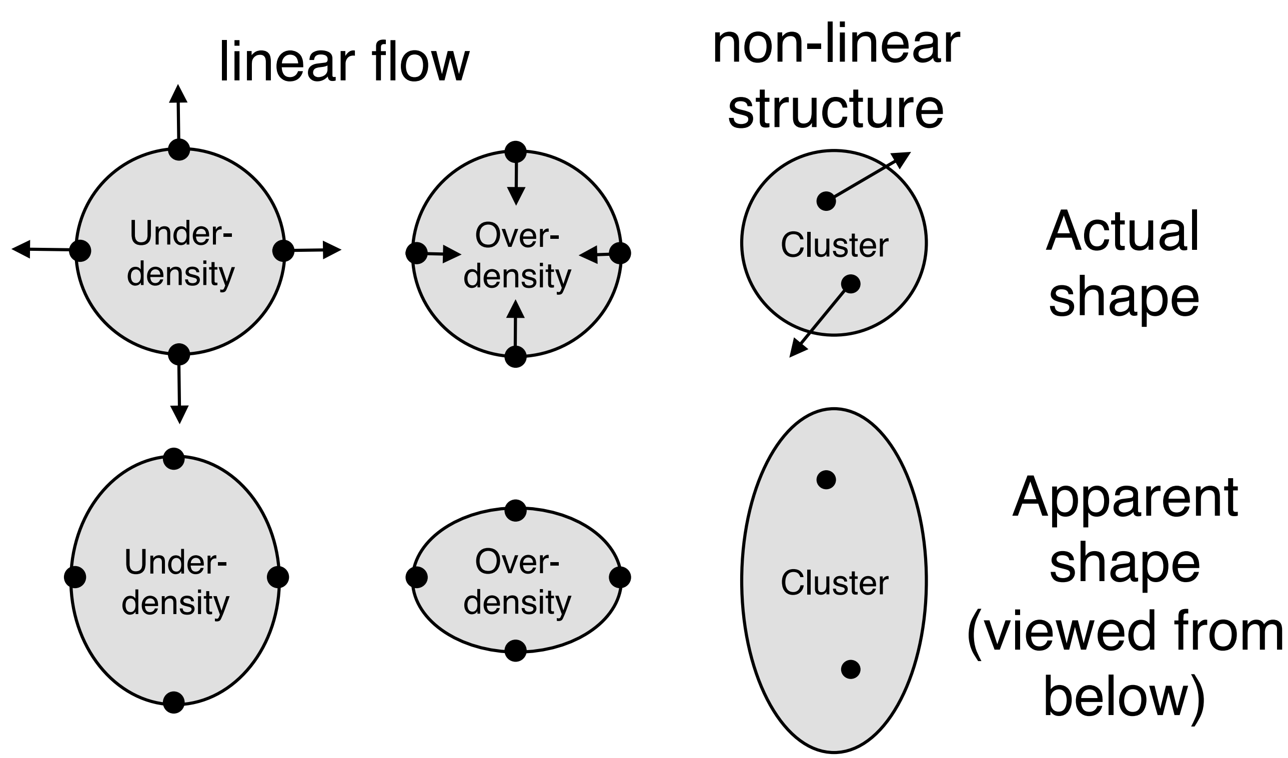


(image from Chris Blake and Sam Moorfield)



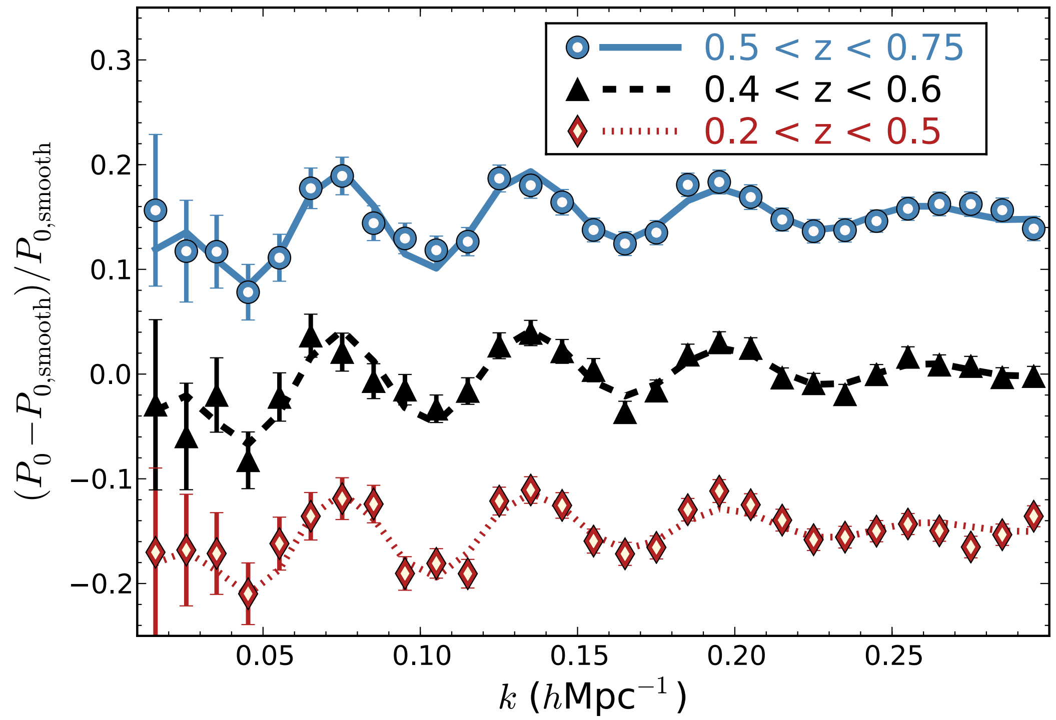
Observed position of BAO acts as standard ruler and constrains cosmological geometry through H(z) and $D_A(z)$

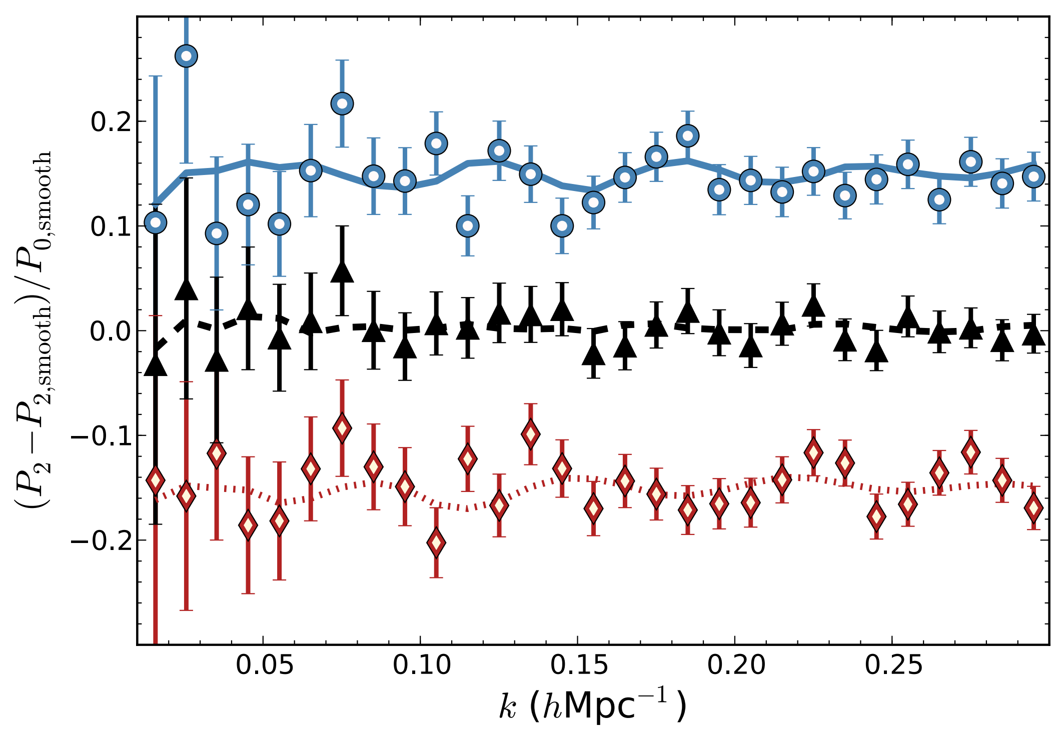
Redshift Space Distortions (RSD)

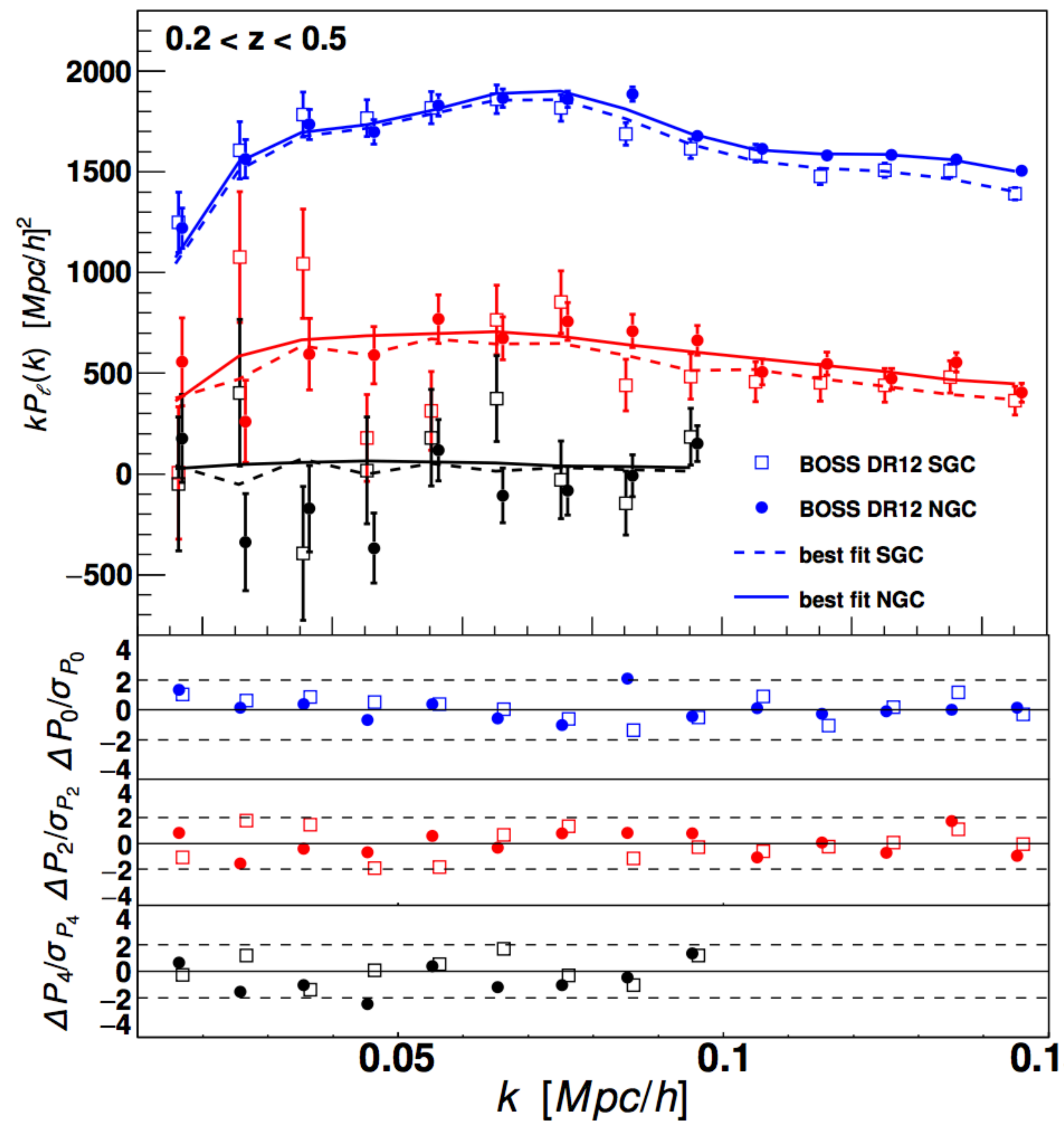


Strength of observed RSD (in the quadrupole clustering moment) constrains cosmological structure growth rate through $f\sigma_8$

Clustering measurements



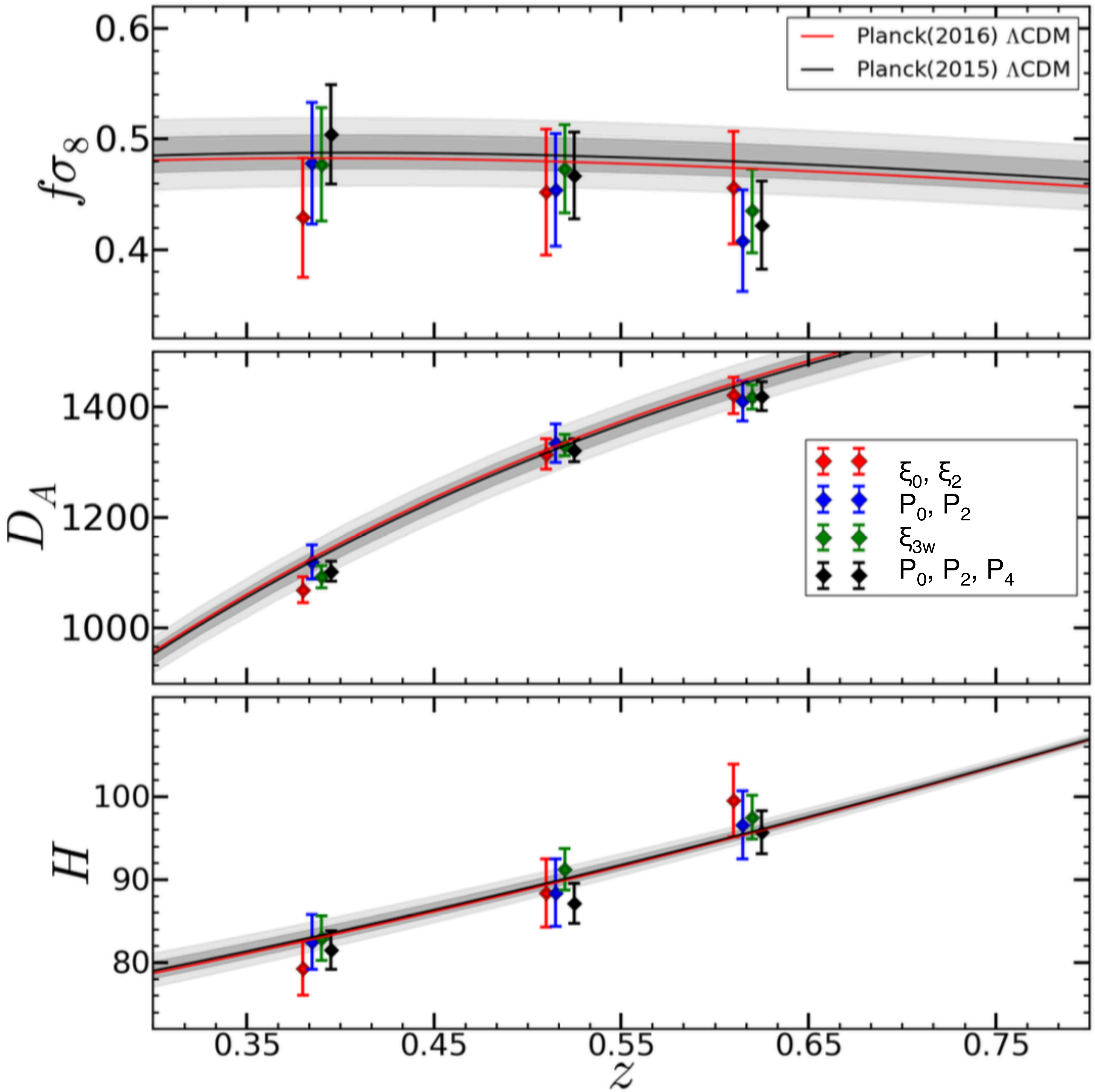




Insufficient signal for scale-dependent measurements: use effective k

Alam et al. 2016, arXiv:1607.03155, Beutler et al. 2016, arXiv:1607.03150

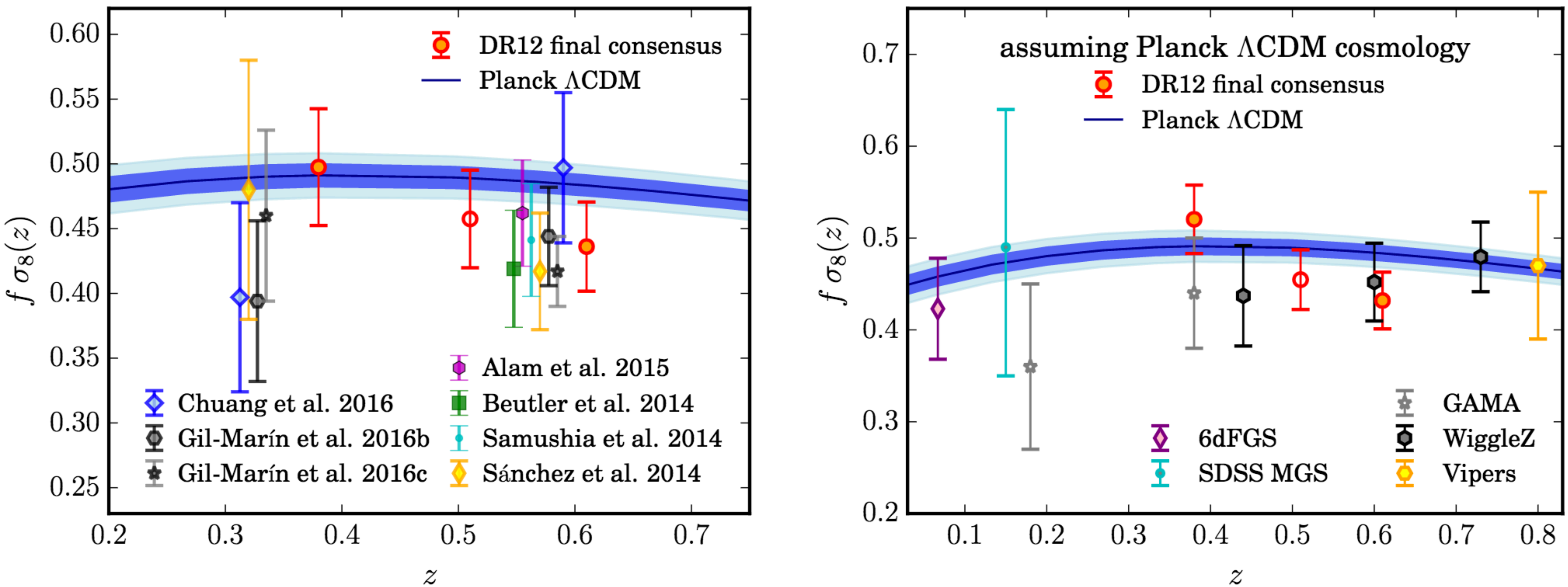
BAO + RSD joint measurements



BAO + RSD joint constraints are very powerful for testing modifications to GR

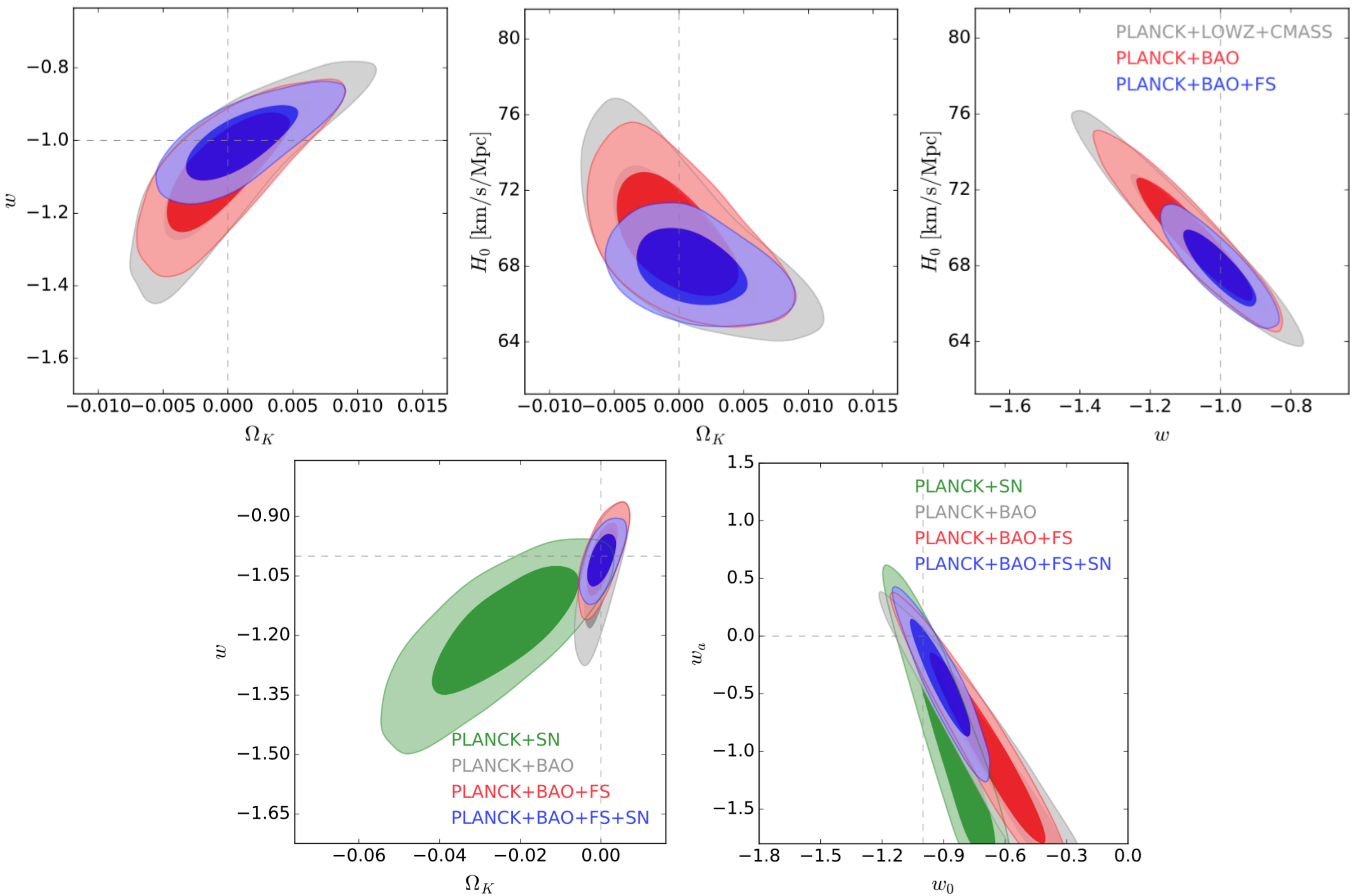
Alam et al. 2016, arXiv:1607.03155, and refs therein

Final BOSS $f\sigma_8$ measurements



Alam et al. 2016, arXiv:1607.03155

Combining with CMB: Dark Energy



Alam et al. 2016, arXiv:1607.03155

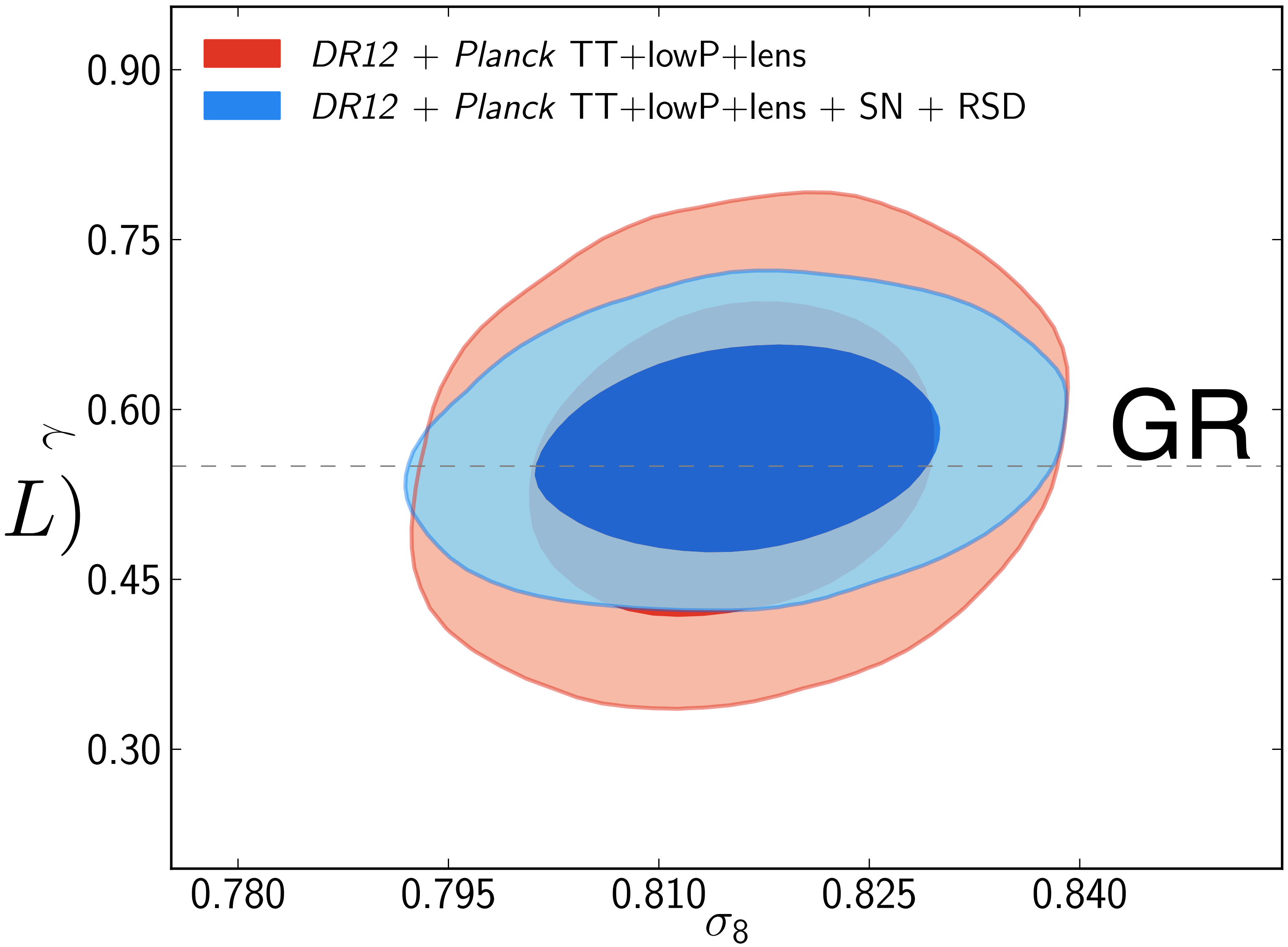
Testing gravity

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

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

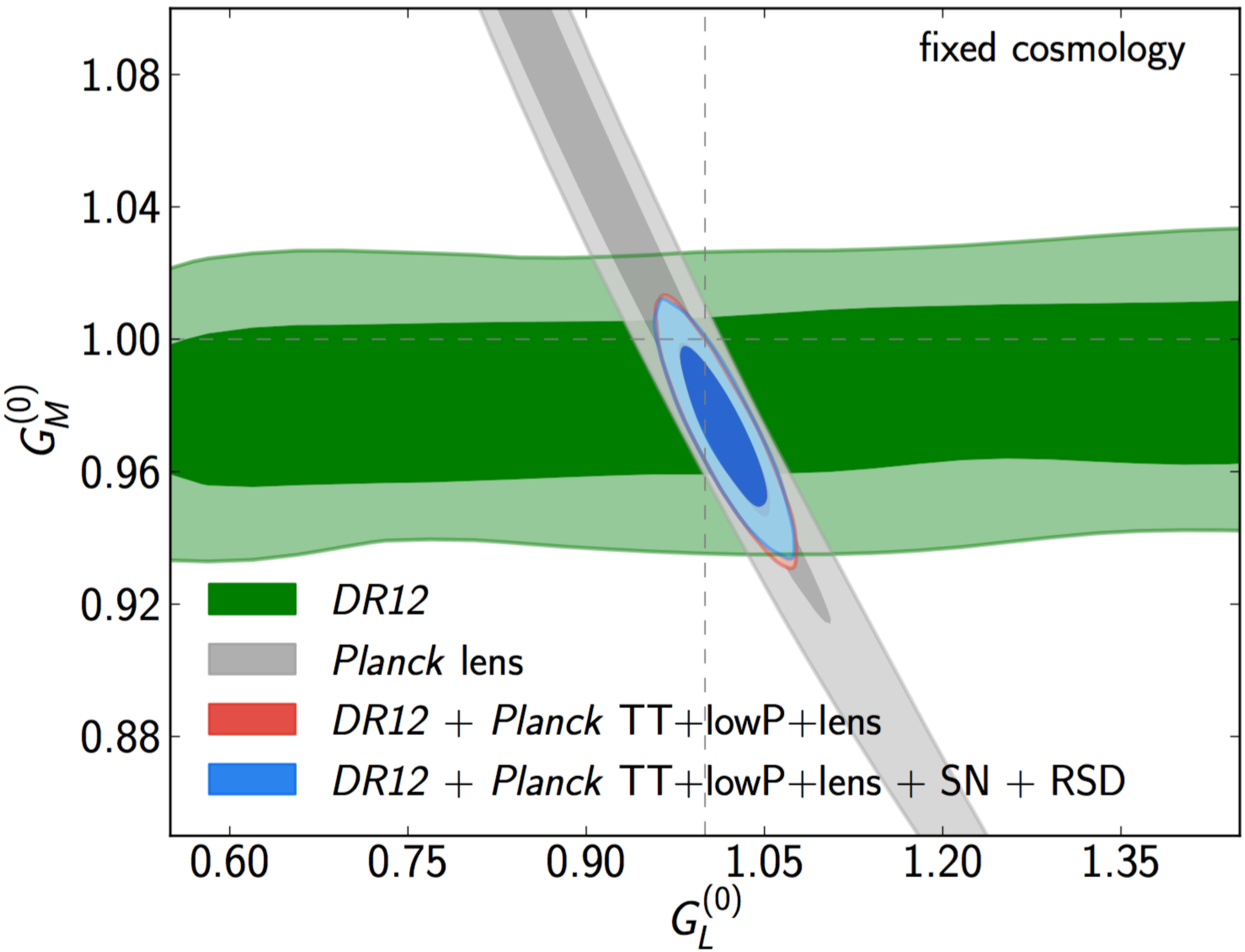
$$\nabla^2\psi = 4\pi G a^2 \rho\Delta \times G_{\rm M}$$ Growth of structure

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

Phenomenological model

Mueller et al. 2016, arXiv:1612.00812

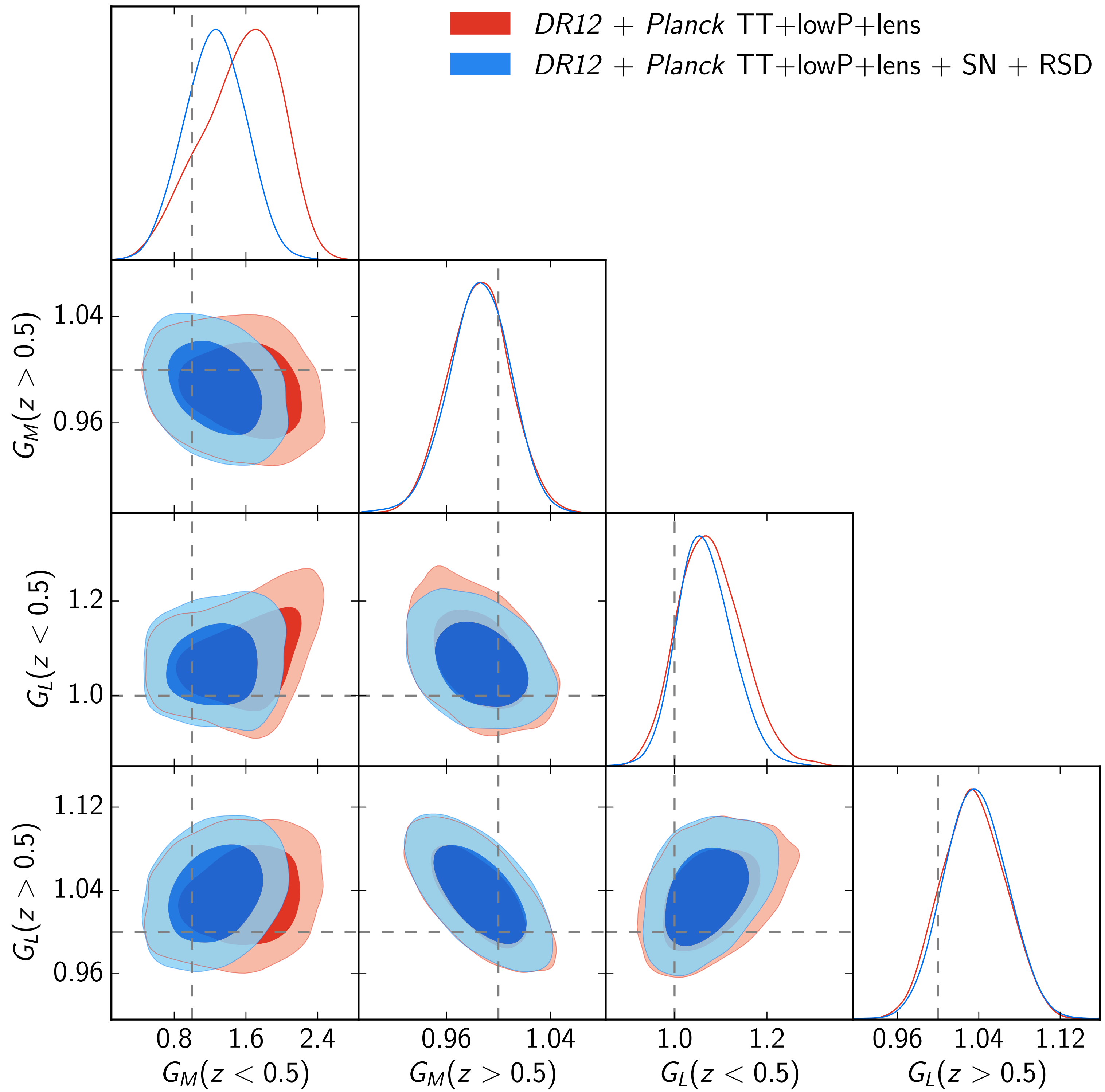
Modified Poisson Equations



Good agreement with GR

Mueller et al. 2016, arXiv:1612.00812

(1) variations with redshift



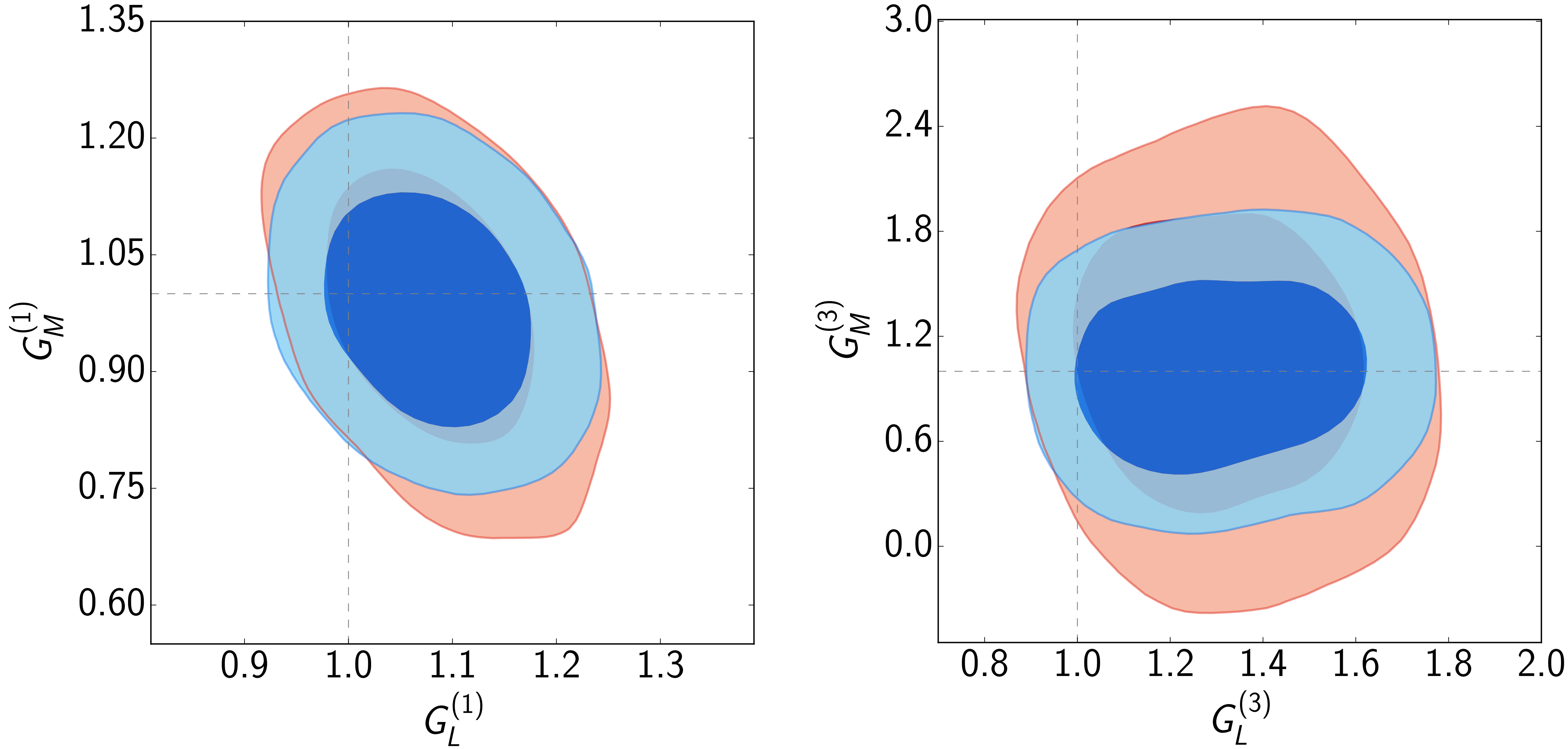
$$G_M(z < 0.5) = 1.26 \pm 0.32$$
$$G_M(z > 0.5) = 0.986 \pm 0.022$$
$$G_L(z < 0.5) = 1.067^{+0.050}_{-0.064}$$
$$G_L(z > 0.5) = 1.037 \pm 0.029$$

Good agreement with GR

Mueller et al. 2016, arXiv:1612.00812

(2) higher order deviations

$$G_X = 1 + (G_X^{(s)} - 1)a^s$$



s=1, linear

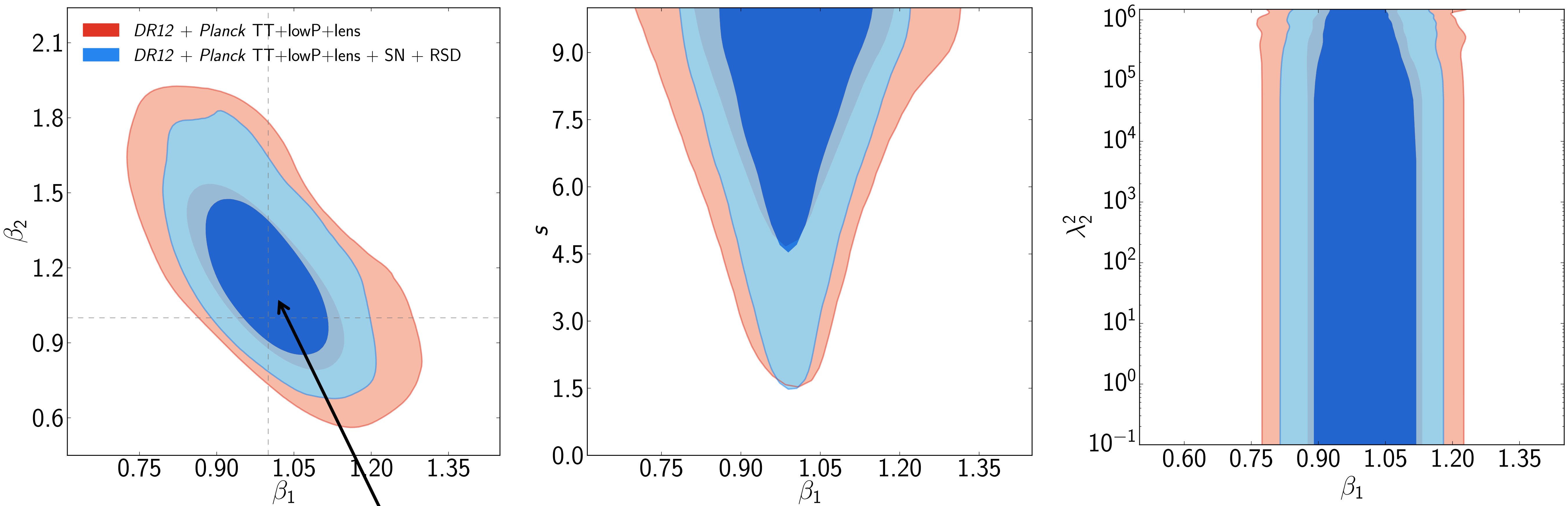
s=3, cubic

Good agreement with GR

Mueller et al. 2016, arXiv:1612.00812

(3) BZ parametrisation

$$G_M = \frac{1+\beta_1\lambda_1^2k^2a^s}{1+\lambda_1^2k^2a^s} \quad \gamma_{\rm slip} = \frac{1+\beta_2\lambda_2^2k^2a^s}{1+\lambda_2^2k^2a^s}$$



These are not constraints! (really need f(k,a))

Good agreement with GR

Bertschinger E., Zukin P., 2008, Phys. Rev., D78, 024015, Mueller et al. 2016, arXiv:1612.00812

Growth Index: a subtlety

- when including effects of CMB lensing, weak lensing or the ISW effect.

- approximate the Newtonian potential ψ in terms of γ and evolve the modified perturbation equation fixing
  - the ratio of the two potentials to unity, $\gamma_{\mathbf{slip}} = 1$ (as in MGCAMB),
  - fixing $G_L = 1$;
- denote the former as the {γ I slip} and the latter {γ I G_L}

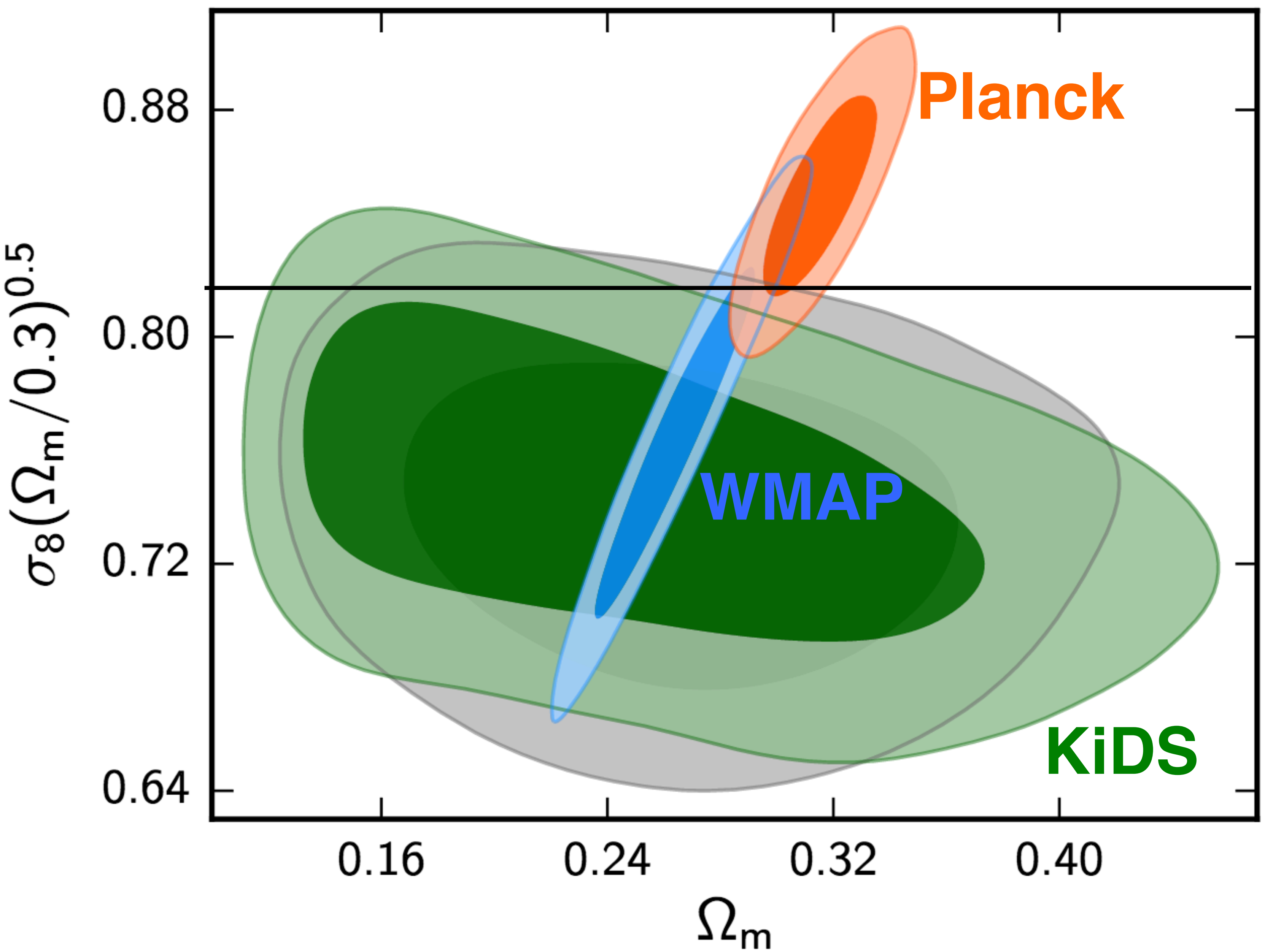
- We measure
  - $\gamma = 0.513 \pm 0.027$ at 68 % CL {γ I slip}
  - $\gamma = 0.529 \pm 0.067$ at 68 % CL {γ I G_L}

  including effects of CMB lensing and the ISW effect.

Mueller et al. 2016, arXiv:1612.00812

Discrepancies

Discrepancy (1): weak-lensing S_8

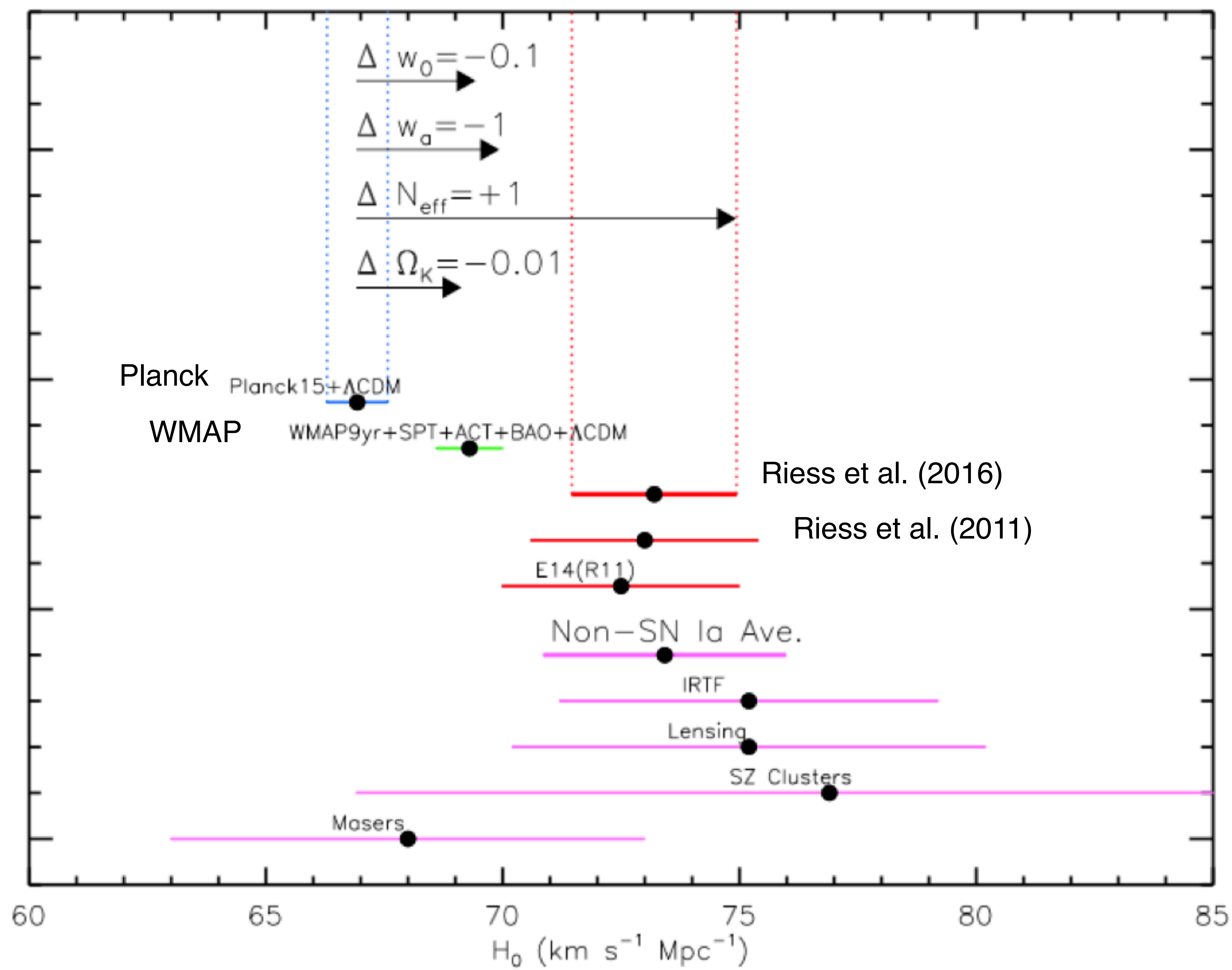


$S_8 = 0.82 \pm 0.05$ (DR12)

BOSS data: right in between

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

Discrepancy (2): H_0 tension



Riess et al. 2016, arXiv:1607.05617

Relativistic energy density?

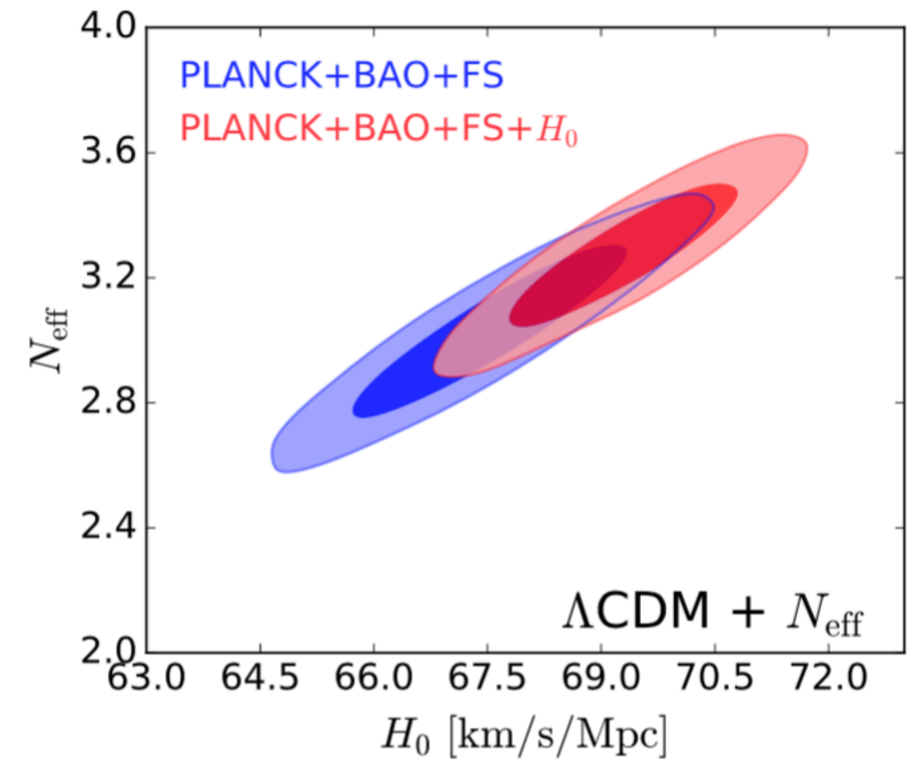
Parameterize by N_{eff}, N_{eff}=3.046 expected from standard neutrino decoupling

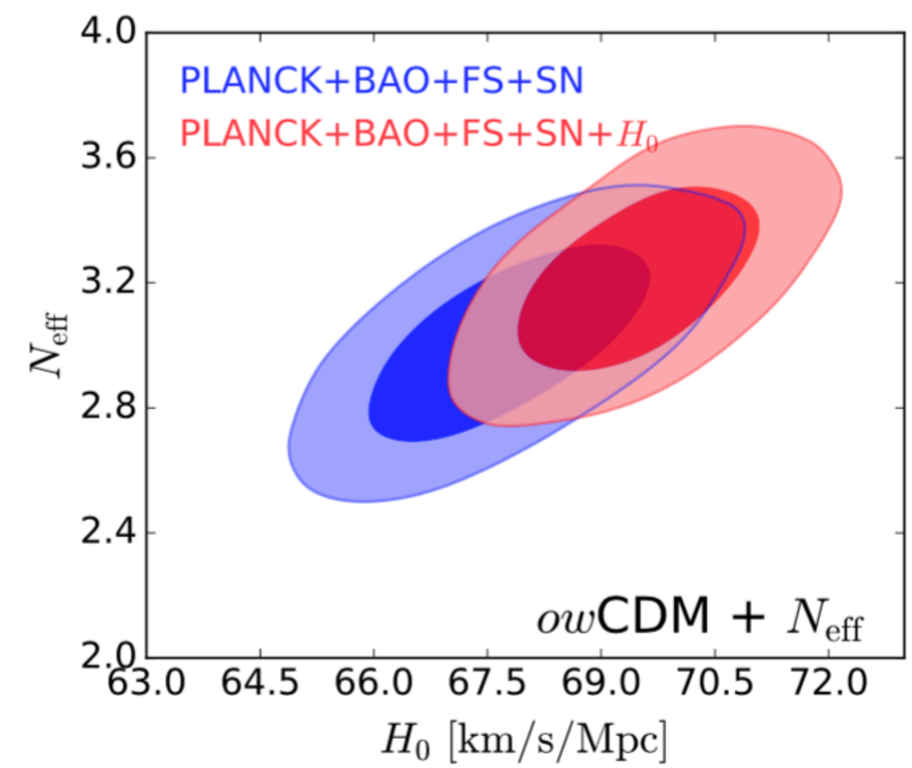
Large N_{eff} ➔ extra density in early Universe
➔ earlier recombination, lower r_d
➔ Higher low-redshift H_0 from BAO

Can we move along this degeneracy to reconcile Planck + low-z H_0 measurements?

No: Planck itself constrains the recombination H with Silk damping (and therefore N_{eff})

So low redshift BAO (+SN) data still inconsistent with low redshift H_0 data

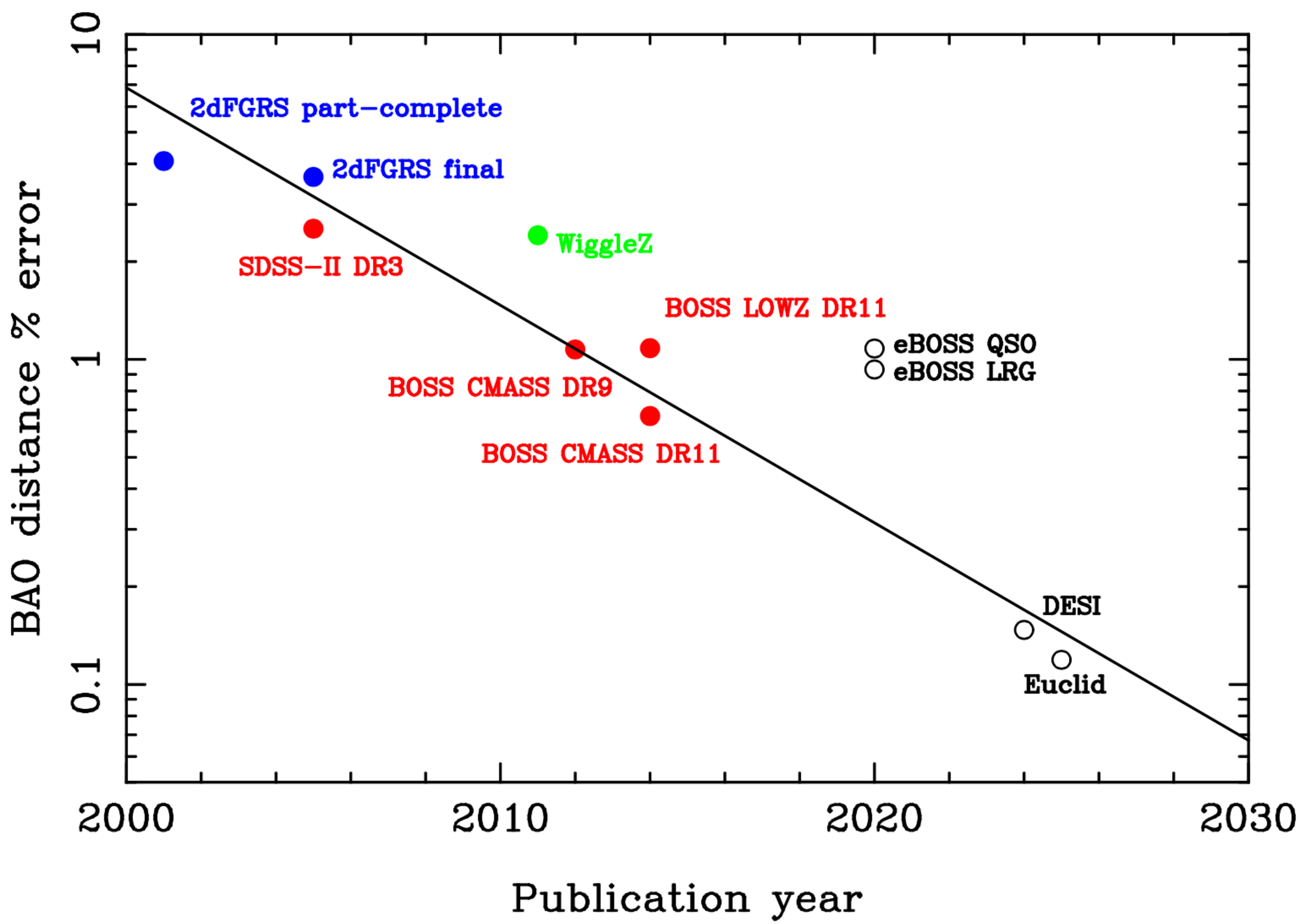




Alam et al. 2016, arXiv:1607.03155

Conclusions

- BOSS DR12 (final) data is consistent with GR on cosmological scales for all tests presented!



Reid et al. 2015, arXiv:1509.06529