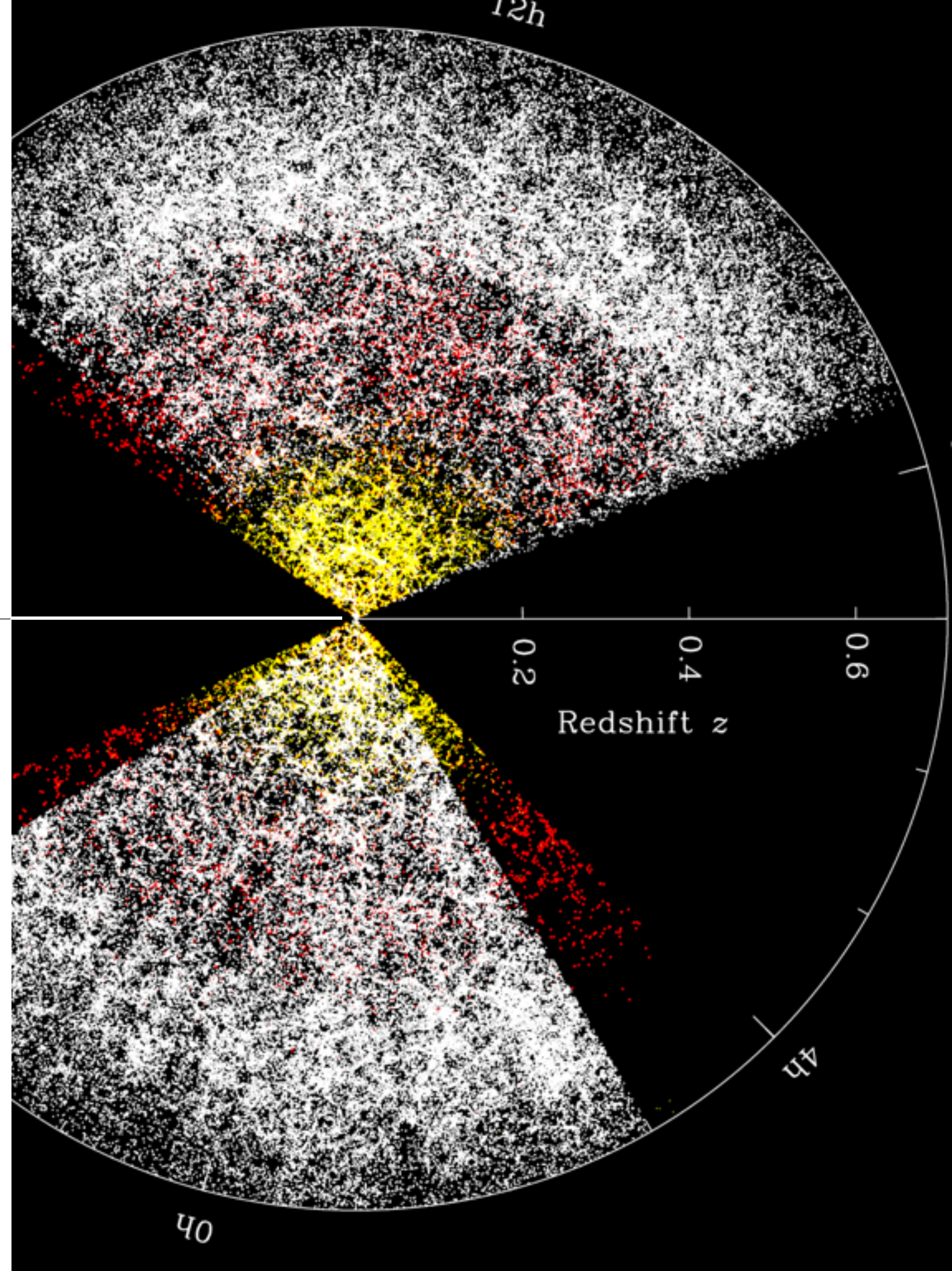
The final clustering results from BOSS

Rita Tojeiro
for the (e)BOSS collaboration
University of St. Andrews

MOS in the next decade
La Palma, 5 March 2015



The ~~final~~ latest clustering results from BOSS and some stuff about eBOSS

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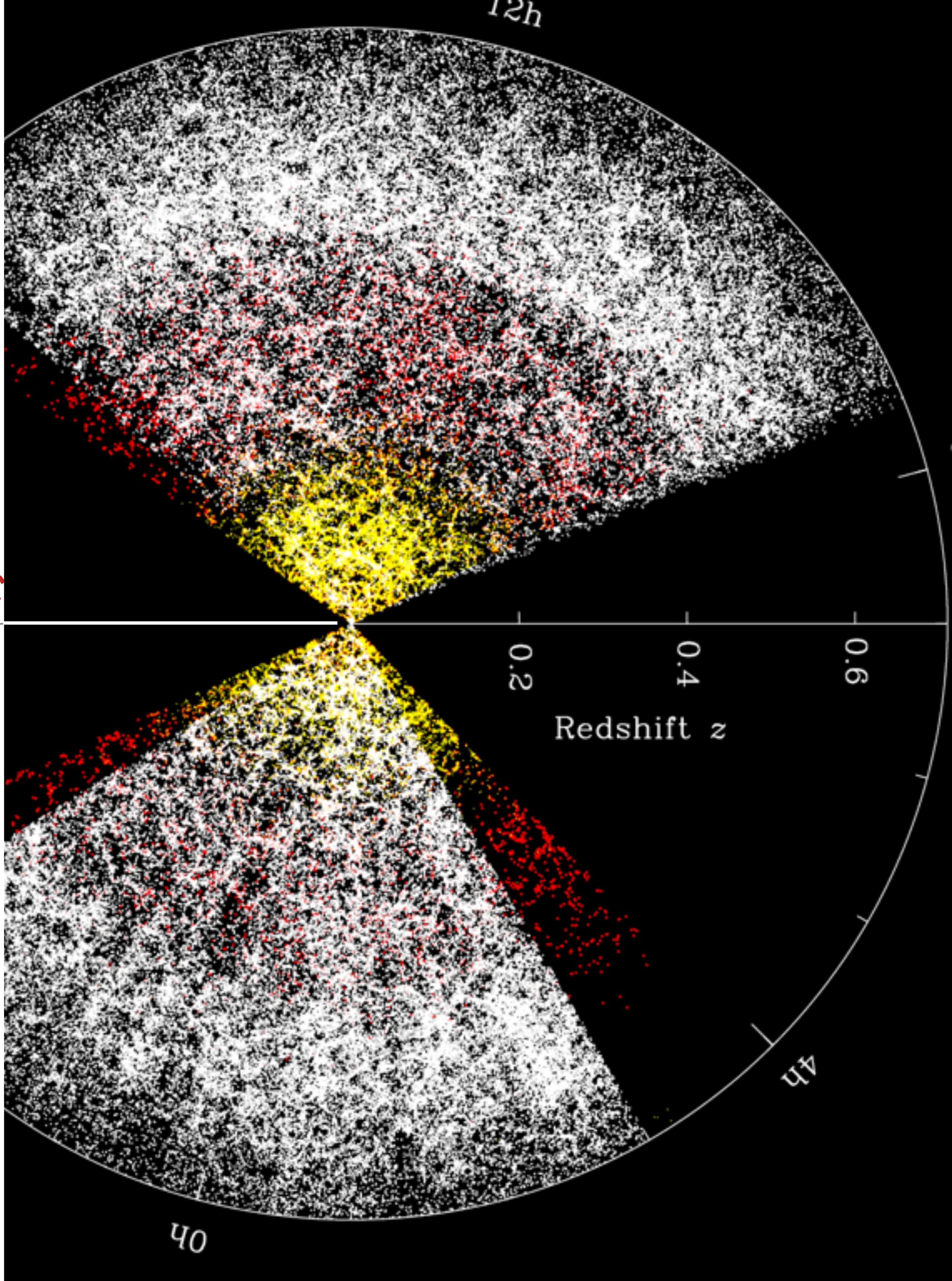
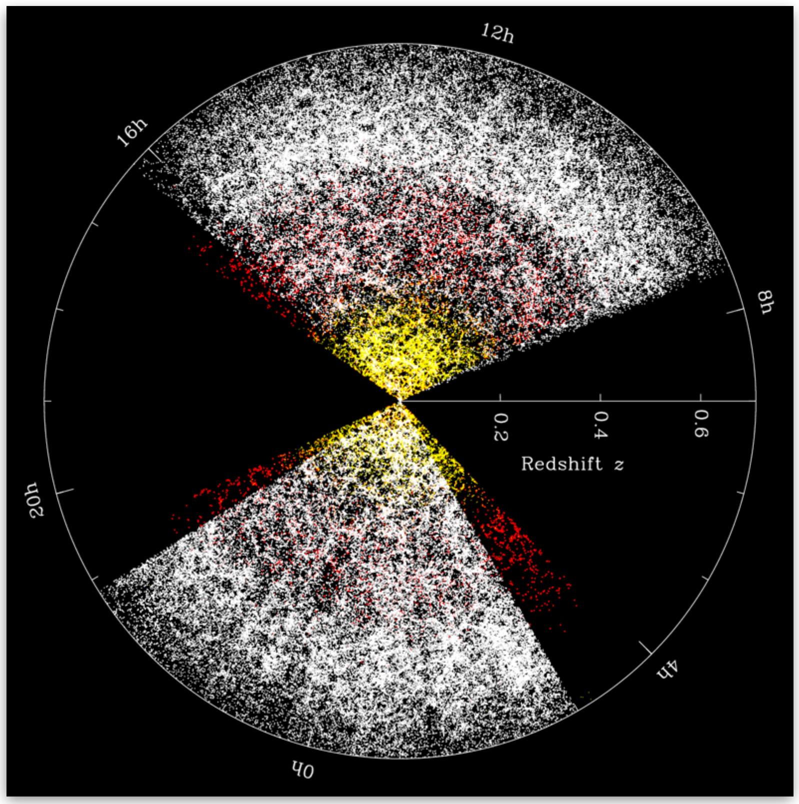
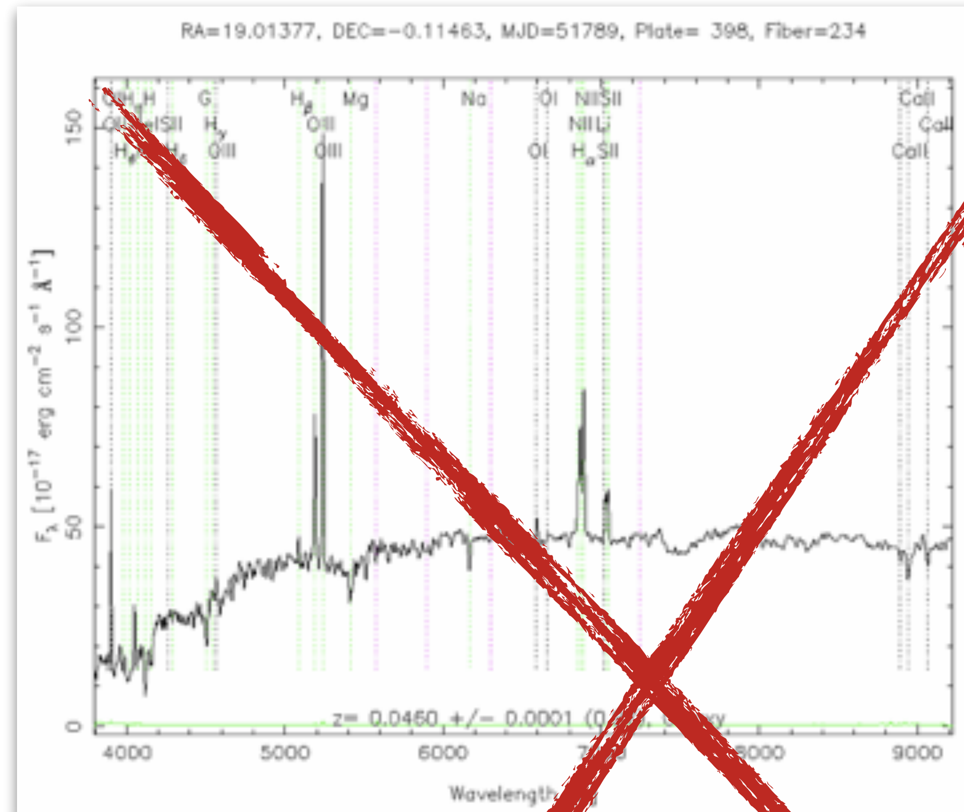
SDSS III



MOS = precise 3-dimensional positions + spectra





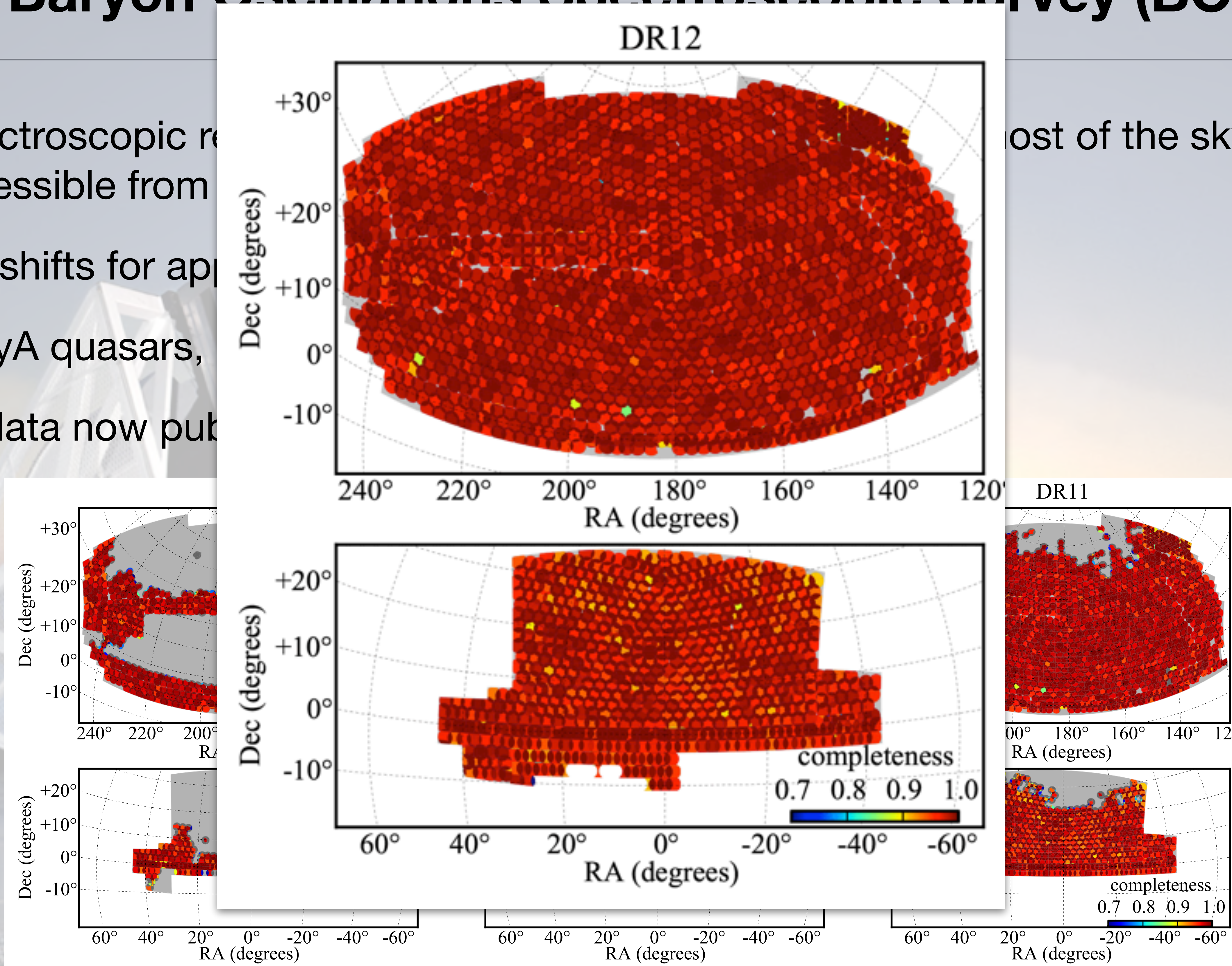
two-point statistics
higher-point statistics
small-scale clustering
topology / voids
cross-correlations with […]

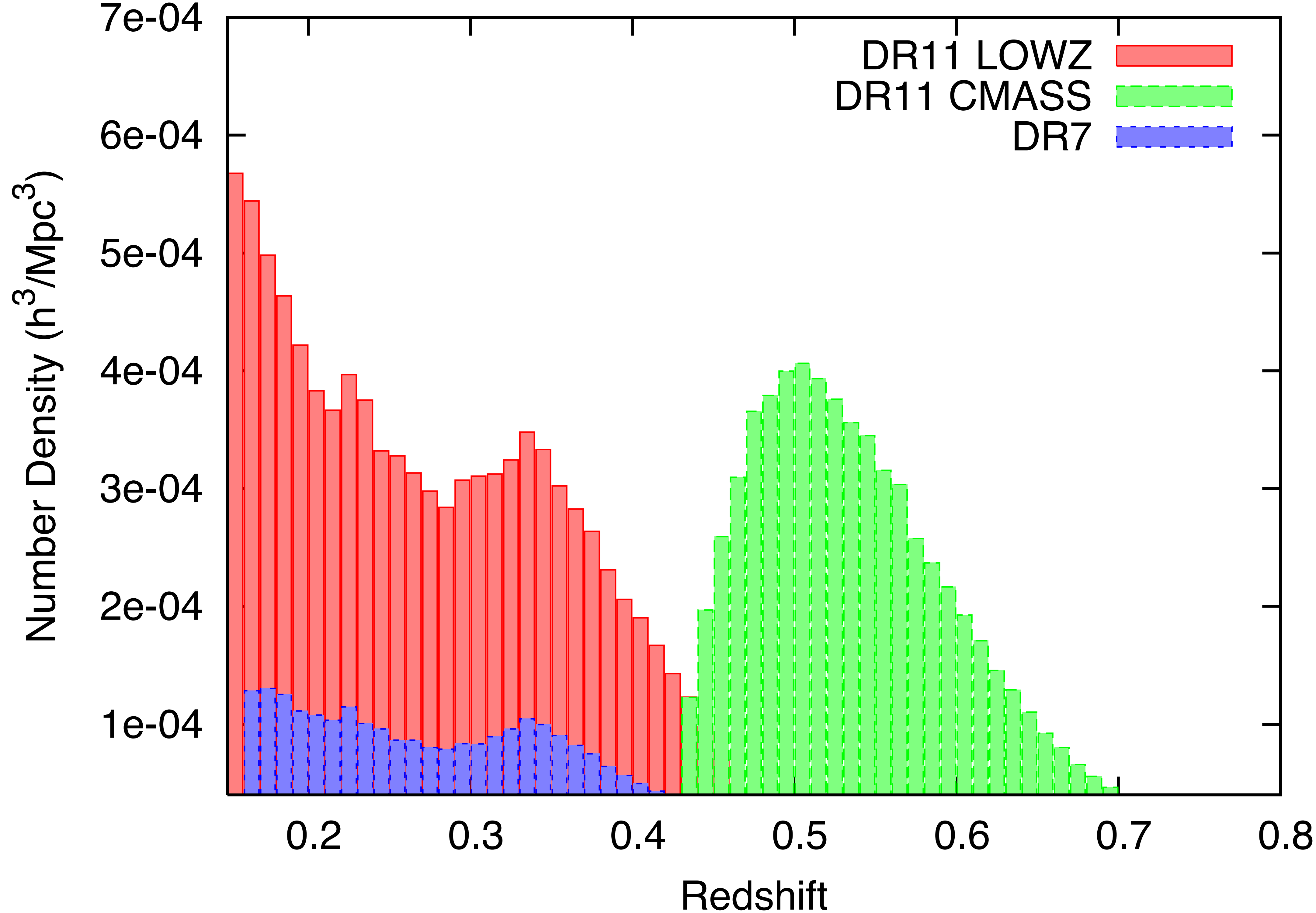
galaxy physics
quasar physics
LyA cosmology

-> expansion, neutrinos, inflation, gal evolution, gravity, composition, etc

The state of the art in LSS:
The Baryon Oscillations Spectroscopic Survey (BOSS)

- Spectroscopic r… …ost of the sky accessible from
- Redshifts for ap…
- [+ LyA quasars, …
- All data now pub…

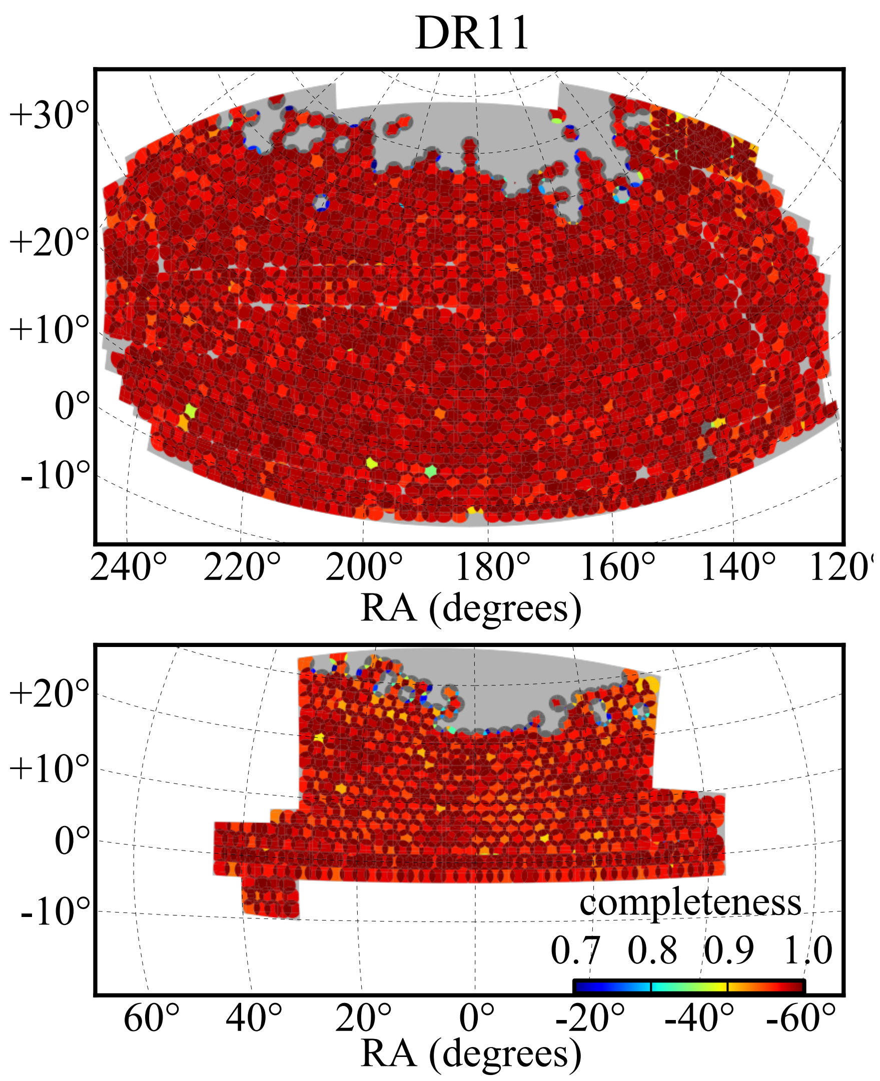




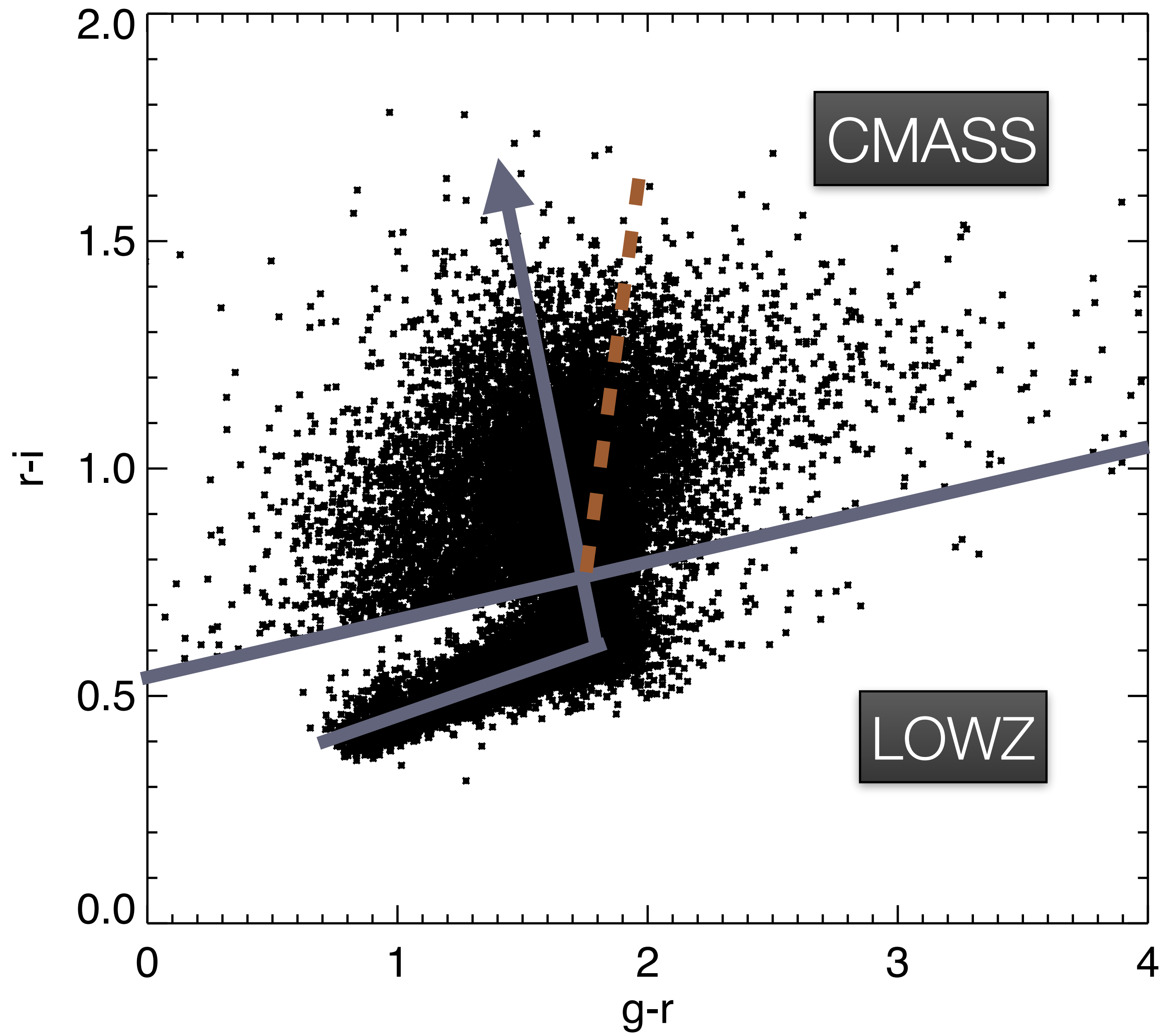
$$\sigma_P^2 \propto \frac{1}{V}\left(P + 1/\bar{n}\right)^2$$

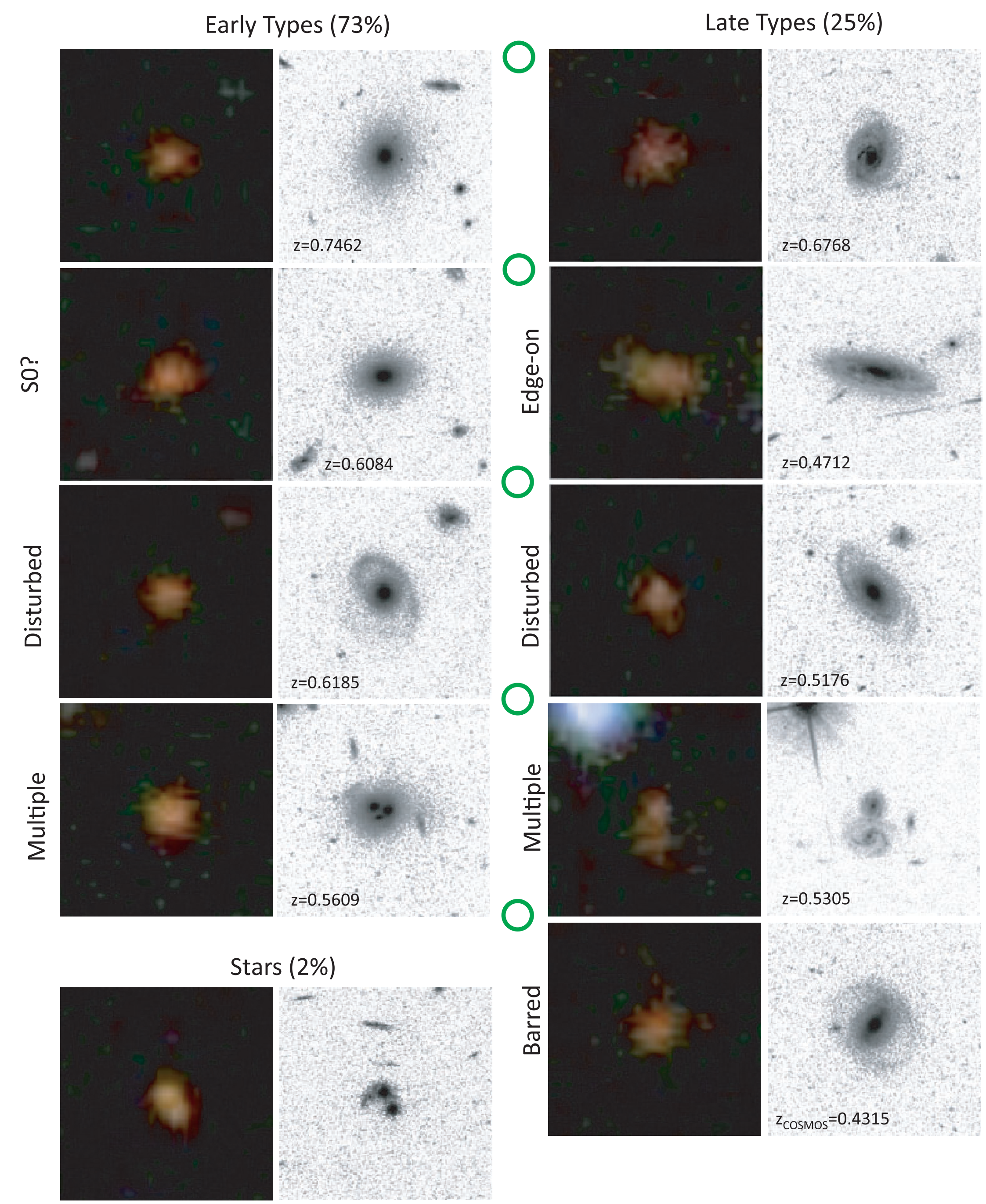
DR11 large-scale catalogues

	CMASS	LOWZ
Number objects used (LSS)	777,209	313,780
Total effective area (sq.deg)	8,377	7,341
Total volume (effective) (Gpc^3)	10.0 (6.0)	3.0 (2.4)

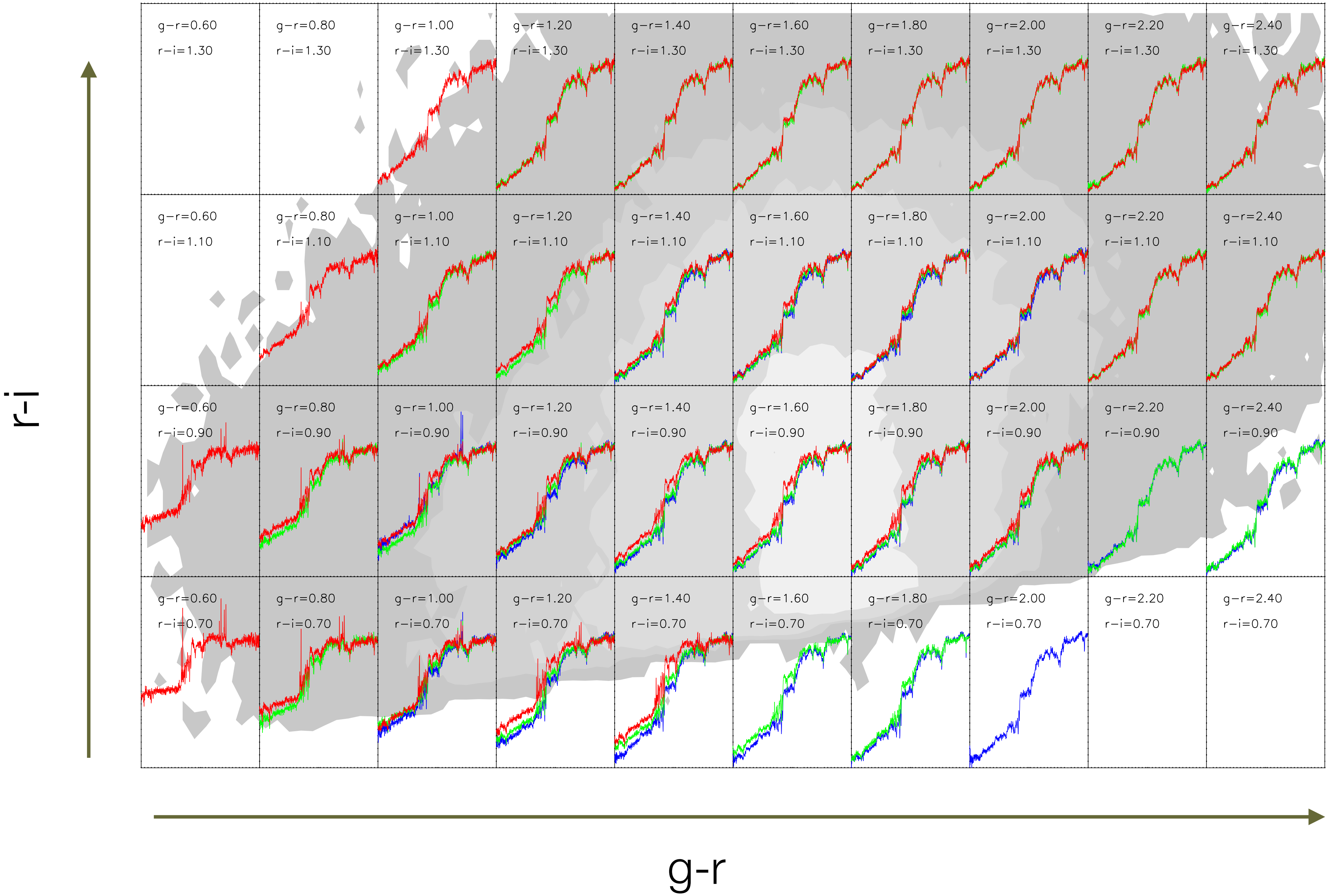


BOSS galaxies





[Masters et al. 2011]

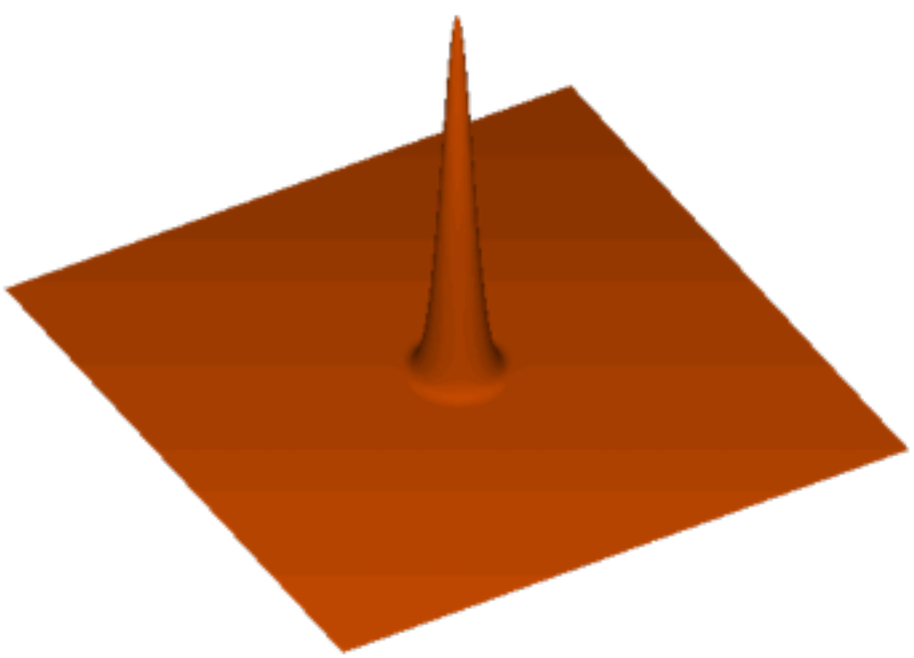


Most massive galaxies, large bias

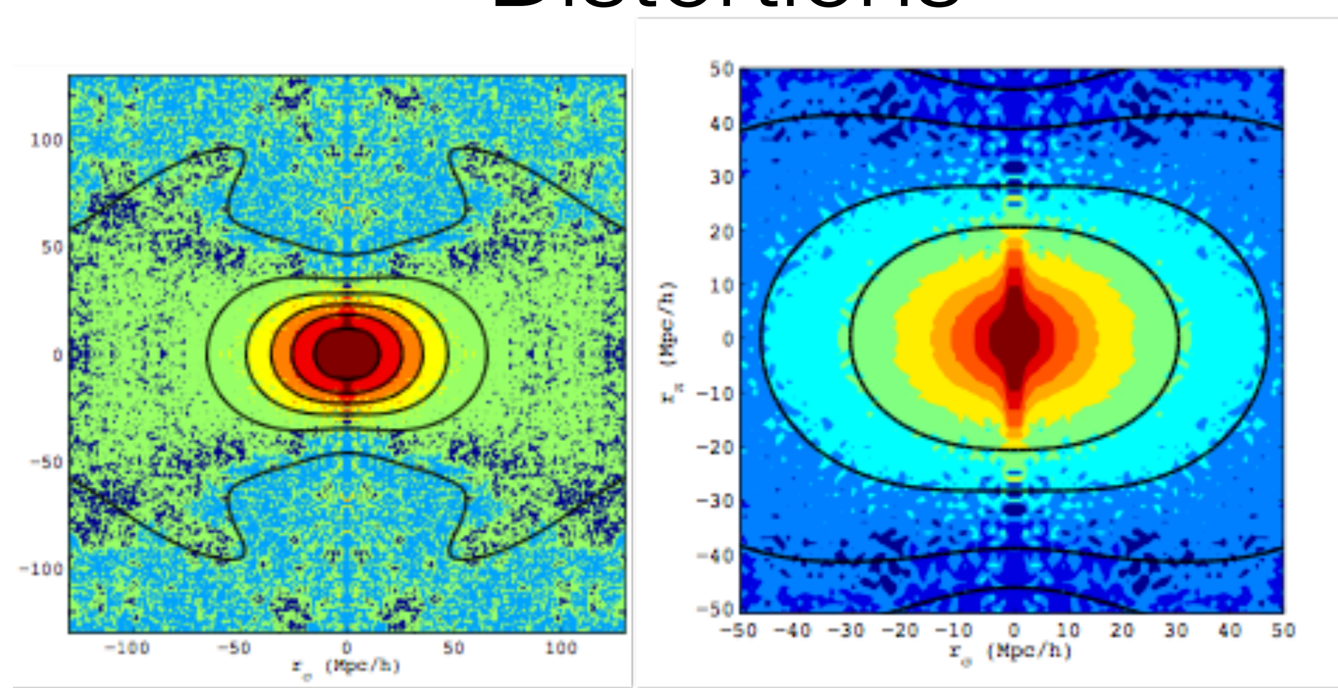
Good spread in colour and bias and galaxy type

Studying Dark Energy with BOSS galaxies

Baryon Acoustic Oscillations



Redshift-Space Distortions

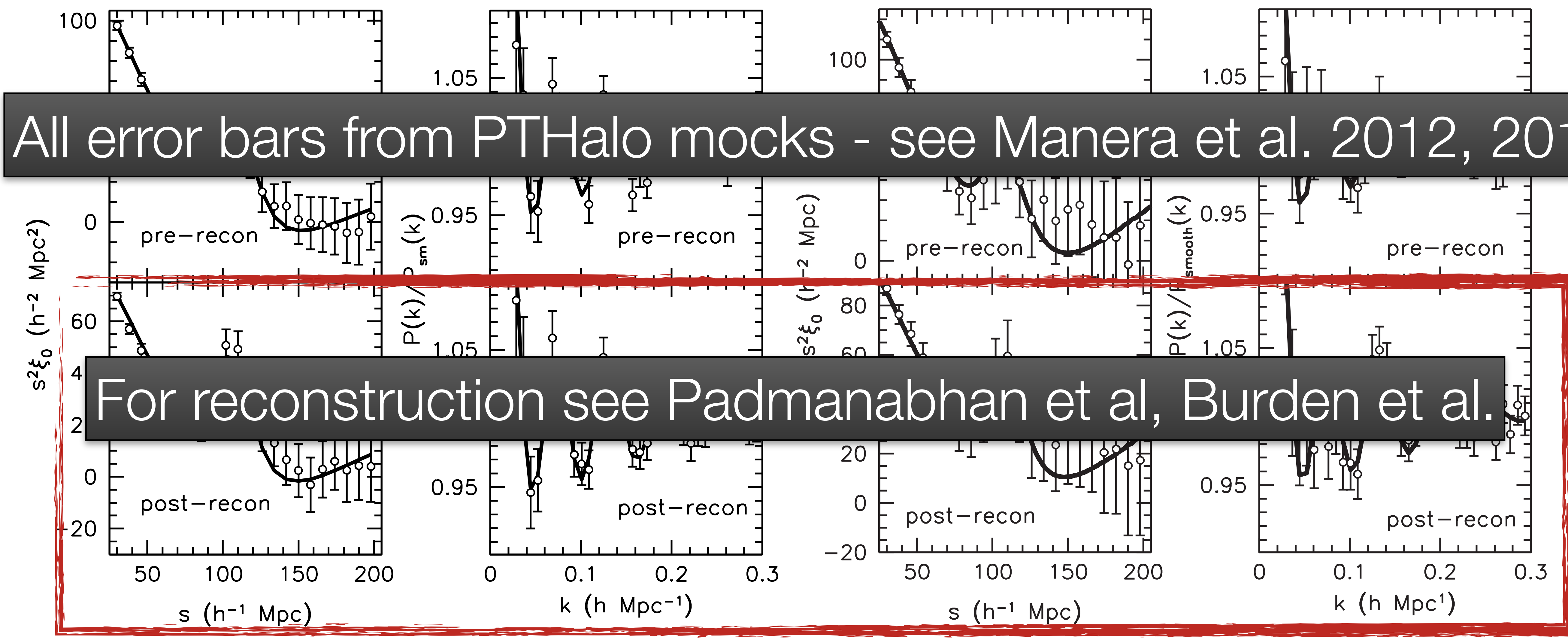


Mapping the expansion history of the Universe

$$D_V(z) \equiv \left[cz(1+z)^2 D_A(z)^2 H^{-1}(z)\right]^{1/3} \qquad \alpha \equiv \frac{D_V(z) r_{d,\mathrm{fid}}}{D_V^{\mathrm{fid}}(z) r_d}$$

CMASS (z=0.57)

LOWZ (z=0.32)



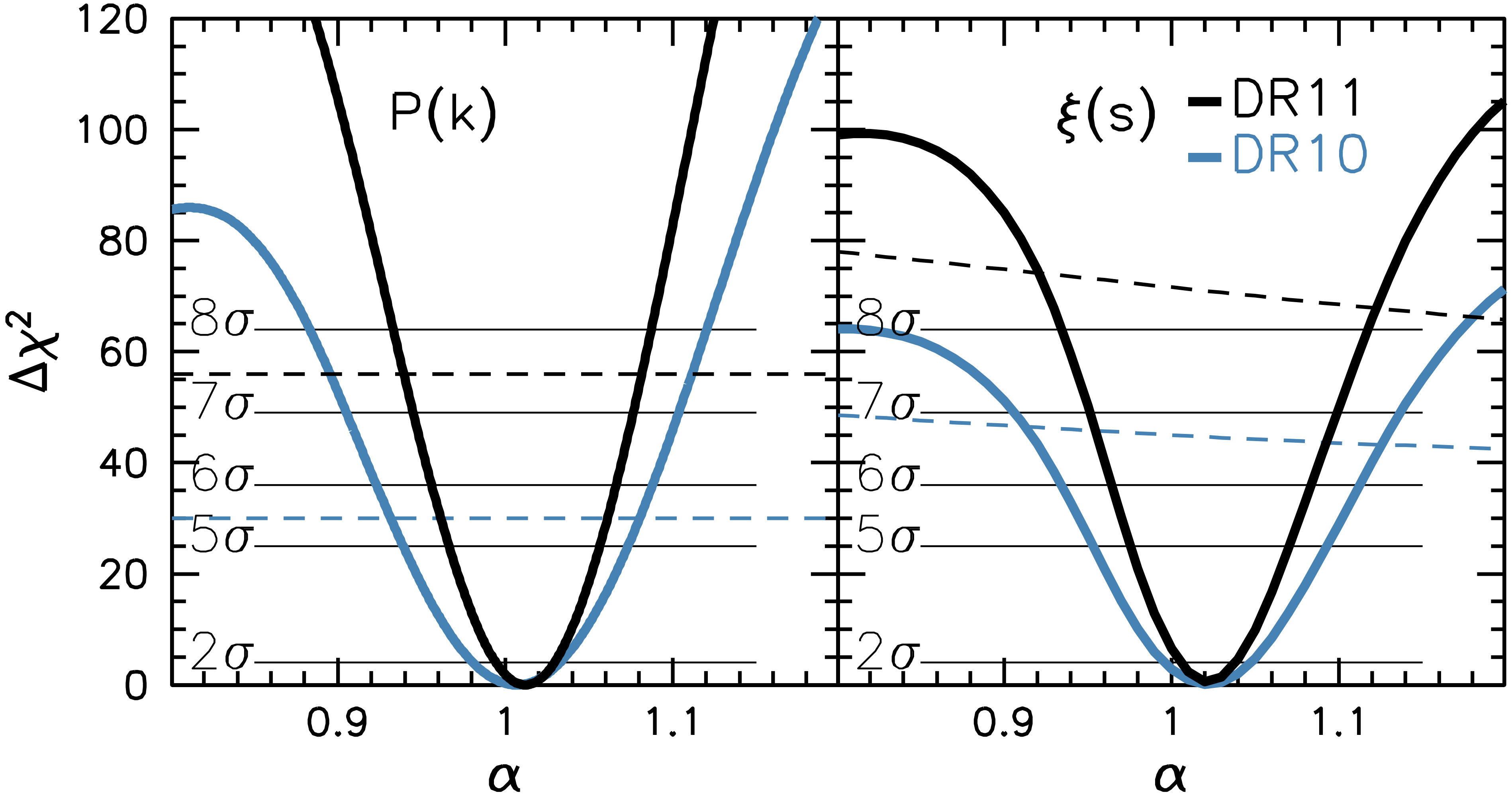
All error bars from PTHalo mocks - see Manera et al. 2012, 2014

For reconstruction see Padmanabhan et al, Burden et al.

[Anderson et al. 2014b]

[Tojeiro et al. 2014]

A 7 and 8 sigma detection



Combine power-spectrum and correlation function to give:

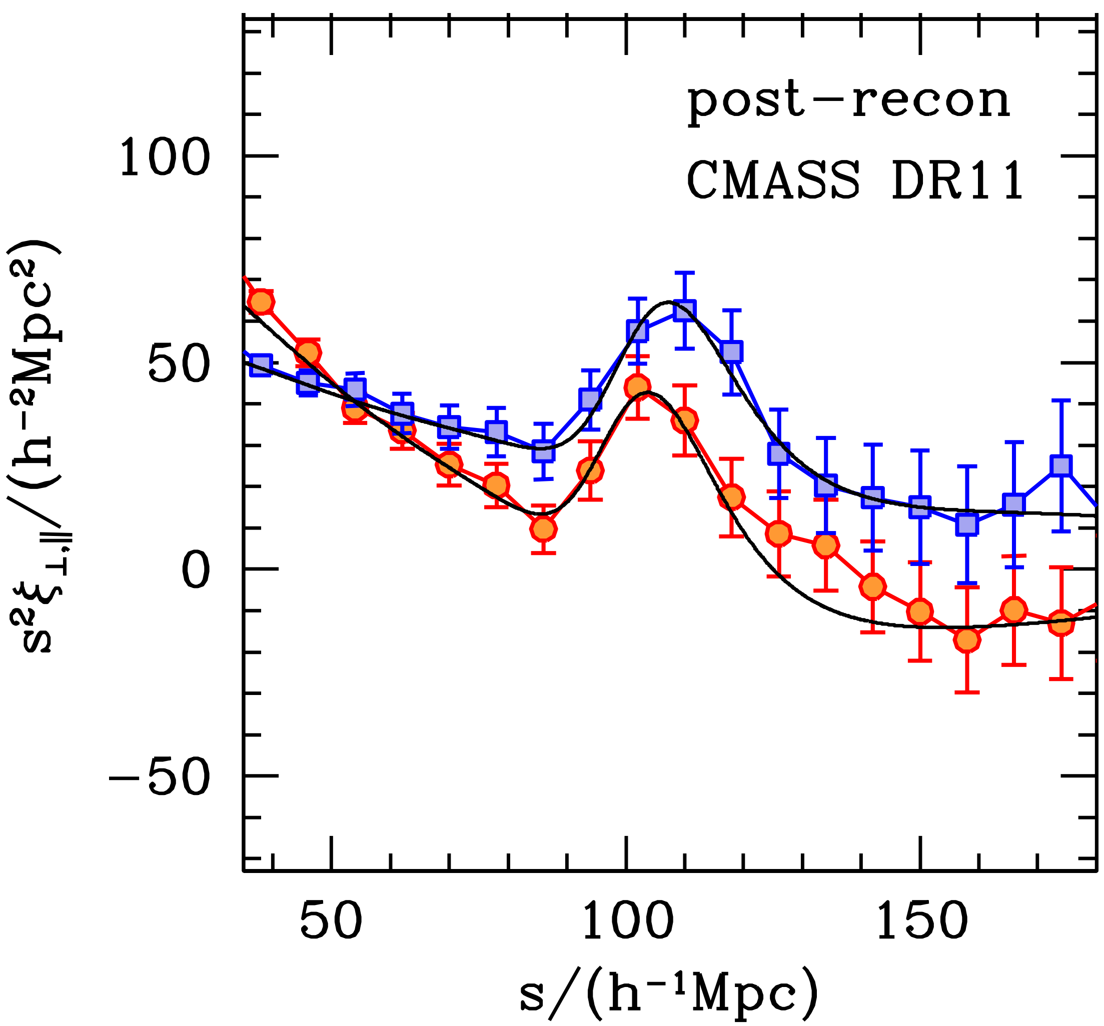
$$D_V(0.57) \quad = \quad (2056 \pm 20 \text{ Mpc}) \left(\frac{r_d}{r_{d,\text{fid}}} \right)$$ 0.9% (1.0% w/ sys)

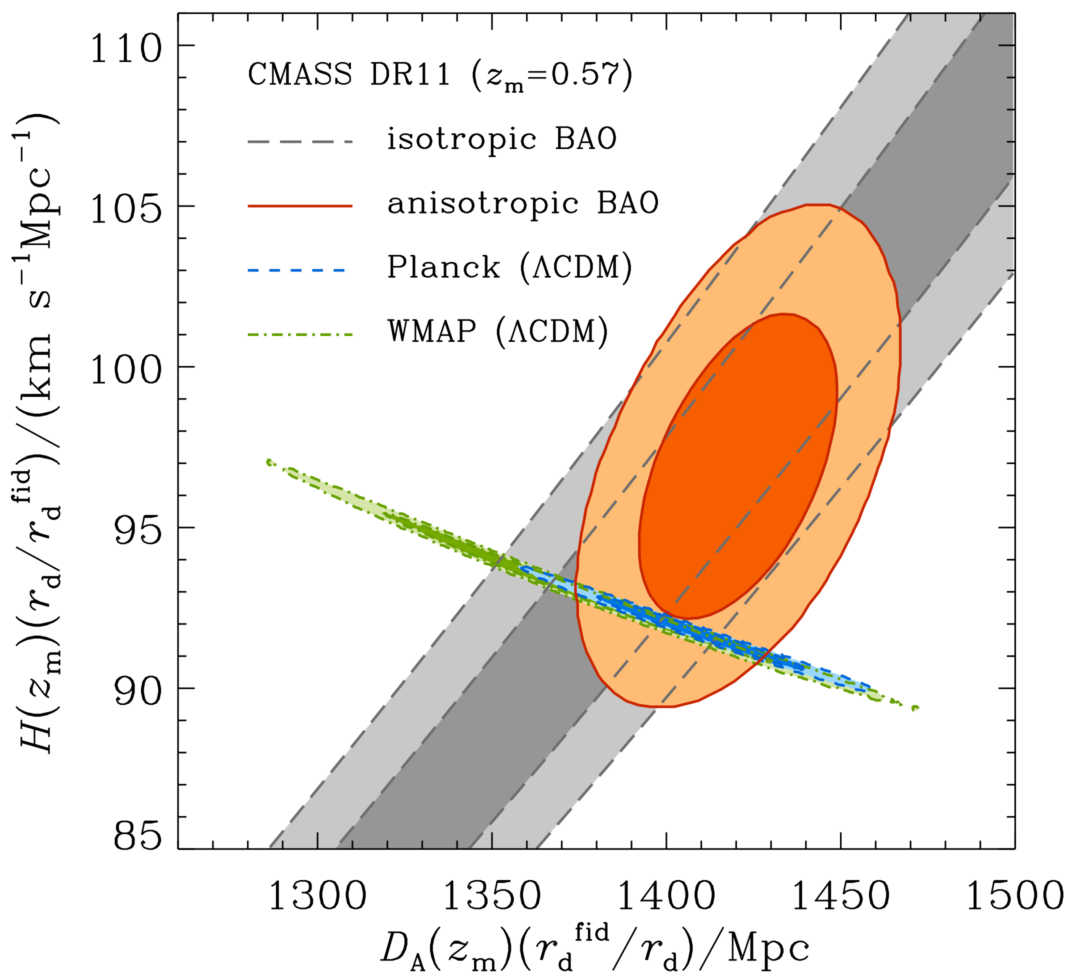
$$D_V(0.32) \quad = \quad (1264 \pm 25 \text{ Mpc}) \left(\frac{r_d}{r_{d,\text{fid}}} \right)$$ 1.9% (2.1% w/ sys)

Anisotropic fitting

$$\alpha_{||} = \frac{H^{\rm fid}(z) r_s^{\rm fid}}{H(z) r_s} \qquad \alpha_{\perp} = \frac{D_A(z) r_s^{\rm fid}}{D_A^{\rm fid} r_s}$$

[Anderson et al. 2014]

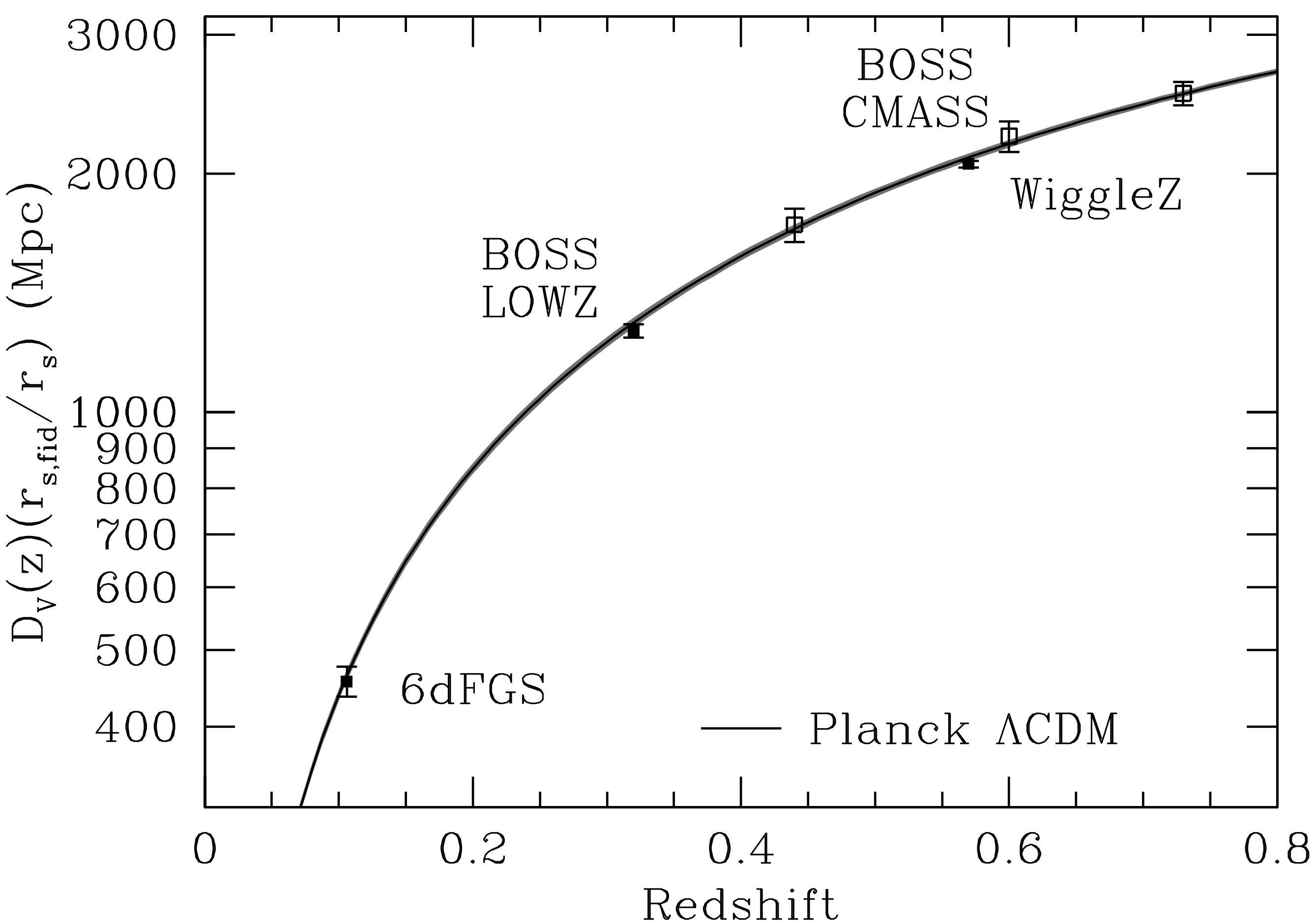




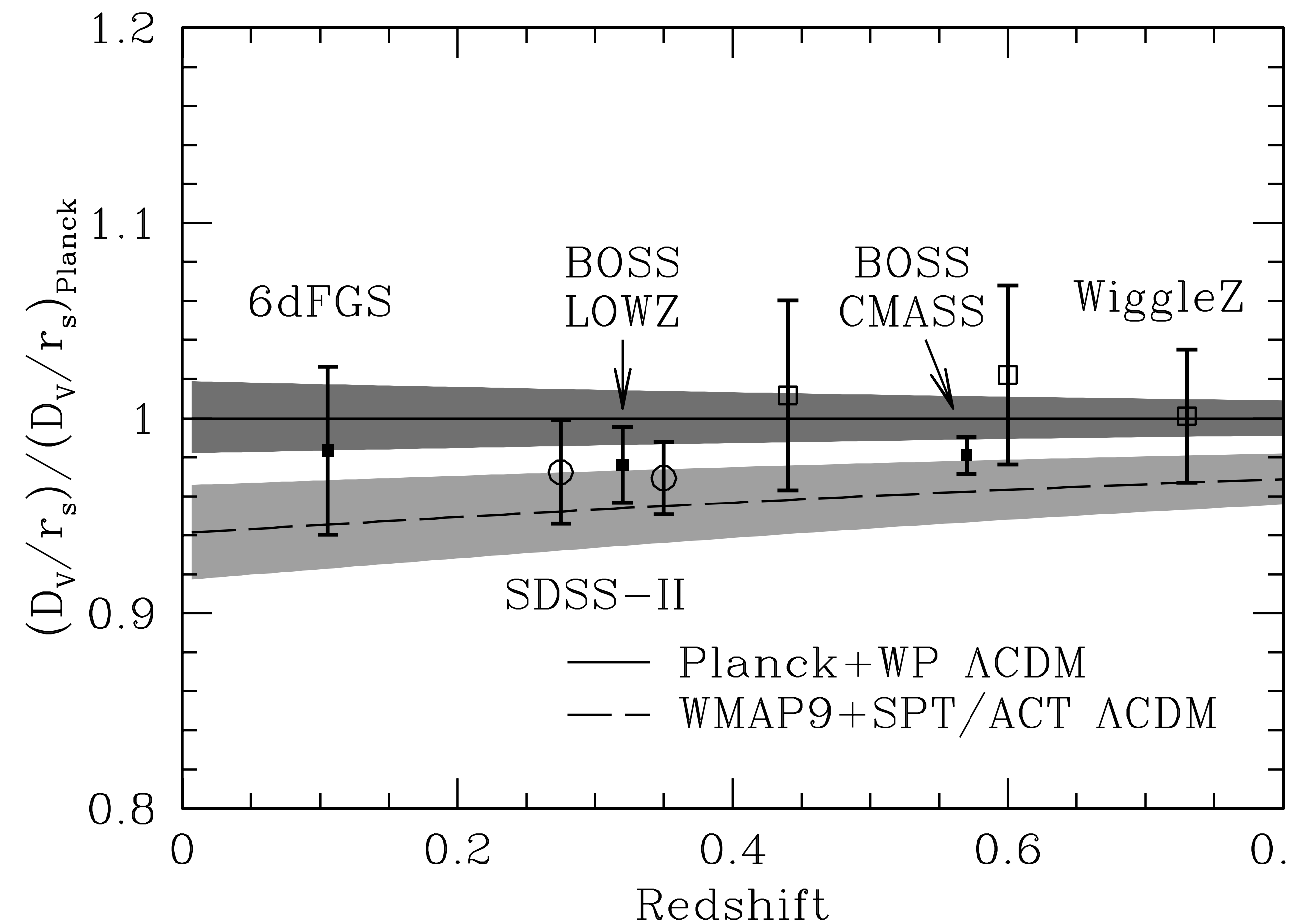
$$D_A(0.57) = (1421 \pm 20\,\mathrm{Mpc}) \left(\frac{r_d}{r_{d,\mathrm{fid}}}\right), \qquad 1.4\%$$

$$H(0.57) = (96.8 \pm 3.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}) \left(\frac{r_{d,\mathrm{fid}}}{r_d}\right) \qquad 3.5\%$$

Mapping the expansion history of the Universe



[Anderson et al. 2014]

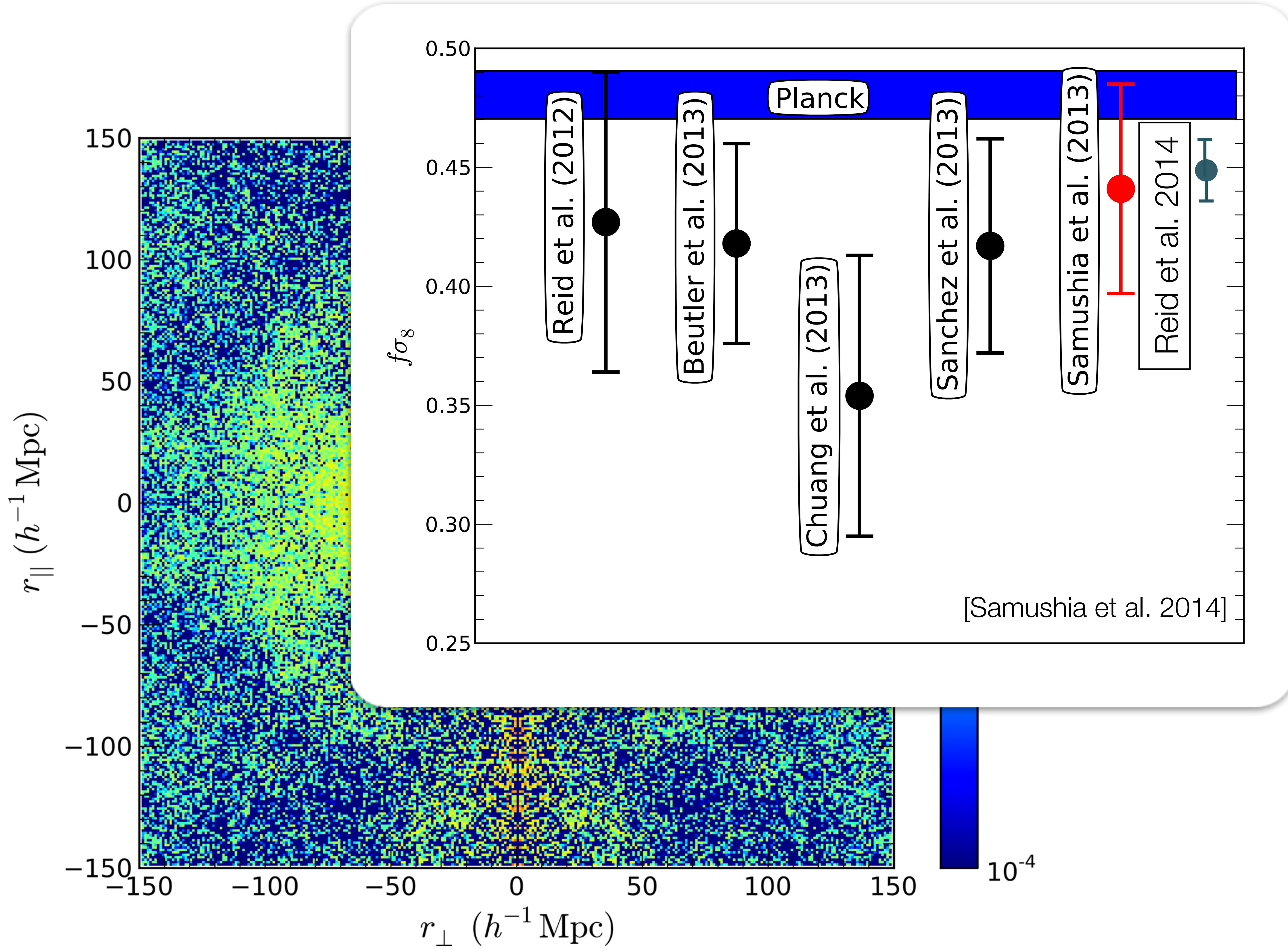


$$H^2(a) = H_0^2 \Big[\Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_{DE} \exp\left\{ 3 \int_a^1 \frac{da'}{a'} \left[1 + w(a')\right] \right\} \Big]$$

Cosmological Model	Data Sets	$\Omega_{\rm m} h^2$	$\Omega_{\rm m}$	H_0 km s^{-1} Mpc^{-1}	$\Omega_{\rm K}$	w_0	w_a
ΛCDM	Planck + CMASS-iso + LOWZ	0.1403 (14)	0.300 (8)	68.4 (6)	···	···	···
ΛCDM	Planck + CMASS + LOWZ	0.1416 (13)	0.309 (8)	67.7 (6)	···	···	···
ΛCDM	Planck + BAO	0.1418 (13)	0.310 (8)	67.6 (6)	···	···	···
ΛCDM	Planck + CMASS + LOWZ + SN	0.1415 (13)	0.308 (8)	67.8 (6)	···	···	···
ΛCDM	Planck + BAO + SN	0.1417 (13)	0.309 (8)	67.7 (6)	···	···	···
ΛCDM	WMAP + BAO + SN	0.1401 (22)	0.302 (8)	68.1 (7)	···	···	···
ΛCDM	*e*WMAP + BAO + SN	0.1414 (16)	0.302 (8)	68.4 (6)	···	···	···
oCDM	Planck + CMASS-iso + LOWZ	0.1419 (25)	0.301 (8)	68.7 (8)	+0.0021 (30)	···	···
oCDM	Planck + CMASS + LOWZ	0.1420 (25)	0.309 (8)	67.8 (7)	+0.0004 (30)	···	···
oCDM	Planck + BAO	0.1423 (25)	0.311 (8)	67.7 (7)	+0.0005 (29)	···	···
oCDM	Planck + CMASS + LOWZ + SN	0.1418 (25)	0.308 (8)	67.9 (7)	+0.0004 (30)	···	···
oCDM	Planck + BAO + SN	0.1421 (25)	0.310 (8)	67.8 (7)	+0.0005 (29)	···	···
oCDM	WMAP + BAO + SN	0.1385 (40)	0.301 (9)	67.9 (8)	-0.0020 (40)	···	···
oCDM	*e*WMAP + BAO + SN	0.1365 (34)	0.297 (9)	67.8 (7)	-0.0056 (35)	···	···
wCDM	Planck + CMASS-iso + LOWZ	0.1430 (22)	0.273 (21)	72.6 (32)	···	-1.18 (13)	···
wCDM	Planck + CMASS + LOWZ	0.1426 (22)	0.301 (16)	69.0 (22)	···	-1.06 (10)	···
wCDM	Planck + BAO	0.1419 (22)	0.310 (14)	67.7 (18)	···	-1.01 (8)	···
wCDM	Planck + CMASS + LOWZ + SN	0.1427 (19)	0.300 (12)	69.1 (16)	···	-1.06 (7)	···
wCDM	Planck + BAO + SN	0.1423 (19)	0.306 (12)	68.3 (14)	···	-1.03 (6)	···
wCDM	WMAP + BAO + SN	0.1383 (32)	0.308 (11)	67.1 (16)	···	-0.94 (8)	···
wCDM	*e*WMAP + BAO + SN	0.1382 (28)	0.313 (12)	66.5 (15)	···	-0.90 (7)	···
owCDM	Planck + CMASS-iso + LOWZ	0.1419 (25)	0.262 (31)	74.1 (46)	-0.0017 (39)	-1.26 (21)	···
owCDM	Planck + CMASS + LOWZ	0.1419 (25)	0.297 (24)	69.3 (28)	-0.0006 (49)	-1.08 (15)	···
owCDM	Planck + BAO	0.1421 (25)	0.314 (20)	67.3 (22)	+0.0017 (47)	-0.98 (11)	···
owCDM	Planck + CMASS + LOWZ + SN	0.1420 (25)	0.297 (14)	69.2 (16)	-0.0012 (34)	-1.08 (8)	···
owCDM	Planck + BAO + SN	0.1423 (26)	0.305 (13)	68.3 (14)	-0.0002 (33)	-1.04 (7)	···
owCDM	WMAP + BAO + SN	0.1372 (42)	0.306 (13)	67.0 (16)	-0.0013 (44)	-0.95 (8)	···
owCDM	*e*WMAP + BAO + SN	0.1356 (34)	0.305 (13)	66.7 (15)	-0.0041 (41)	-0.93 (8)	···
w_0w_aCDM	Planck + CMASS-iso + LOWZ	0.1434 (21)	0.305 (51)	69.4 (63)	···	-0.86 (50)	-0.90 (123)
w_0w_aCDM	Planck + CMASS + LOWZ	0.1433 (21)	0.350 (41)	64.4 (41)	···	-0.54 (39)	-1.40 (102)
w_0w_aCDM	Planck + BAO	0.1430 (21)	0.361 (31)	63.1 (29)	···	-0.44 (30)	-1.60 (85)
w_0w_aCDM	Planck + CMASS + LOWZ + SN	0.1434 (22)	0.304 (17)	68.7 (18)	···	-0.98 (18)	-0.33 (64)
w_0w_aCDM	Planck + BAO + SN	0.1431 (22)	0.311 (16)	67.9 (17)	···	-0.94 (17)	-0.37 (60)
w_0w_aCDM	WMAP + BAO + SN	0.1373 (43)	0.301 (16)	67.6 (17)	···	-1.02 (16)	0.21 (56)
w_0w_aCDM	*e*WMAP + BAO + SN	0.1367 (31)	0.300 (15)	67.6 (16)	···	-1.05 (14)	0.43 (40)
ow_0w_aCDM	Planck + CMASS-iso + LOWZ	0.1417 (25)	0.294 (48)	70.2 (60)	-0.0042 (41)	-0.84 (44)	-1.40 (115)
ow_0w_aCDM	Planck + CMASS + LOWZ	0.1416 (24)	0.343 (40)	64.6 (39)	-0.0043 (49)	-0.53 (35)	-1.71 (96)
ow_0w_aCDM	Planck + BAO	0.1420 (24)	0.359 (32)	63.0 (29)	-0.0021 (49)	-0.43 (29)	-1.72 (87)
ow_0w_aCDM	Planck + CMASS + LOWZ + SN	0.1418 (26)	0.306 (16)	68.2 (19)	-0.0046 (44)	-0.87 (20)	-0.99 (89)
ow_0w_aCDM	Planck + BAO + SN	0.1421 (25)	0.312 (16)	67.5 (17)	-0.0027 (42)	-0.87 (19)	-0.73 (80)
ow_0w_aCDM	WMAP + BAO + SN	0.1371 (43)	0.302 (16)	67.5 (18)	+0.0007 (59)	-1.01 (18)	0.21 (72)
ow_0w_aCDM	*e*WMAP + BAO + SN	0.1360 (36)	0.302 (15)	67.2 (17)	-0.0025 (54)	-0.99 (16)	0.17 (60)

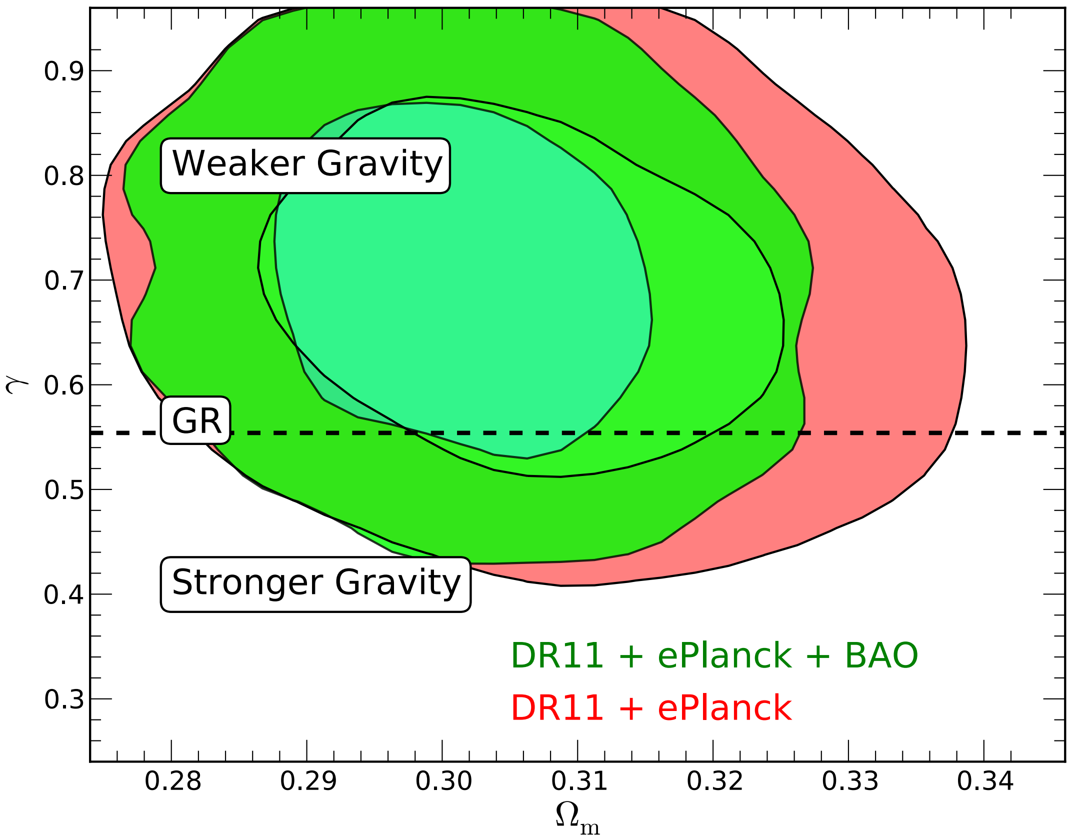
continued support for a flat LCDM cosmology

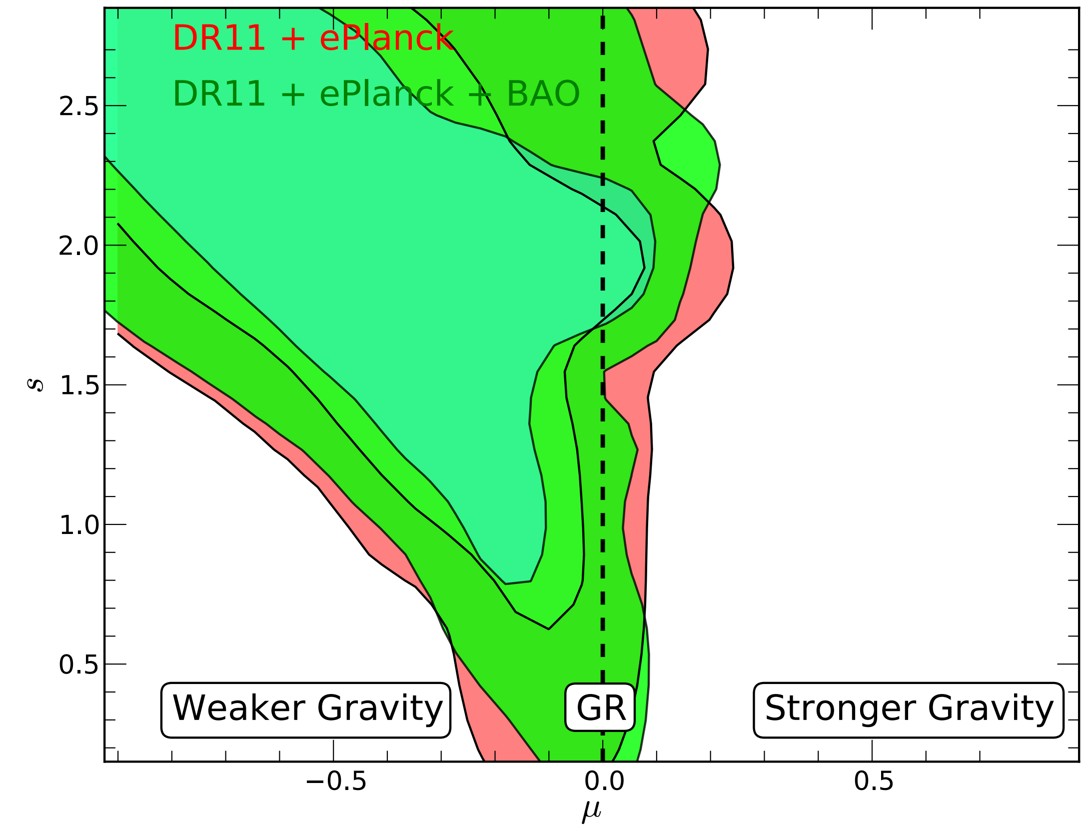
Probing gravity via the growth rate of structure



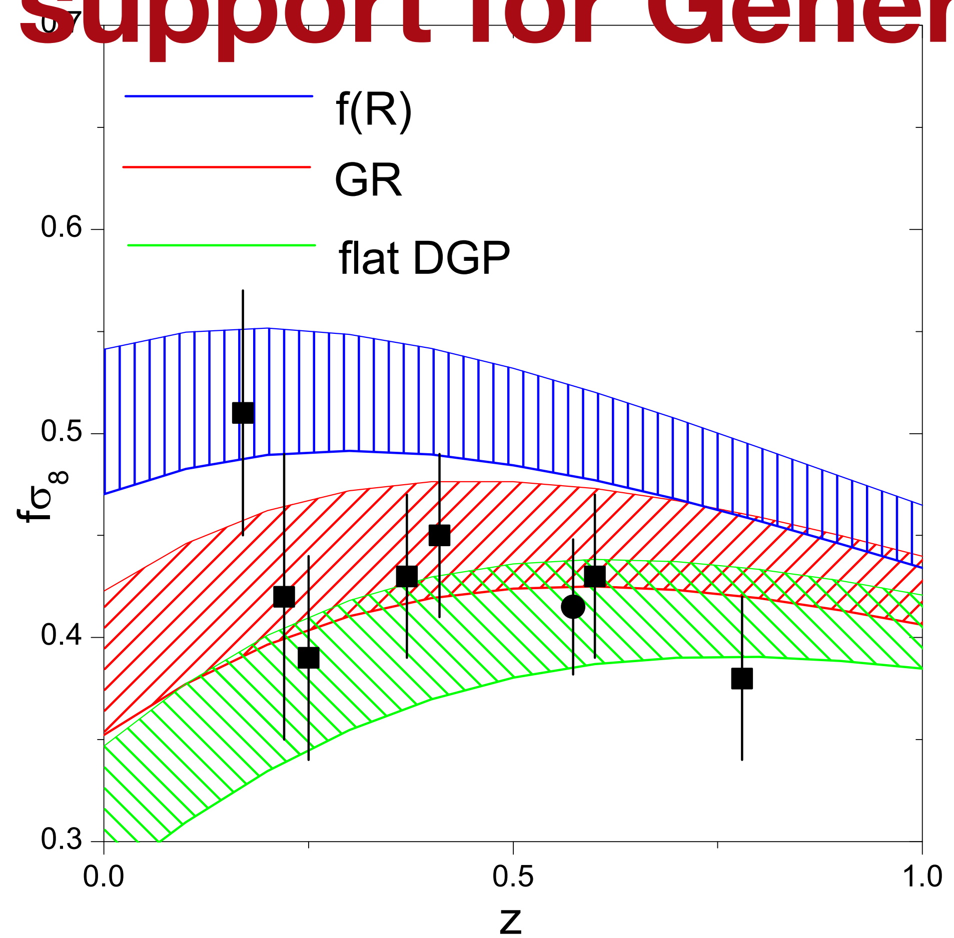
[Samushia et al. 2014]

[Samushia et al. 2014]



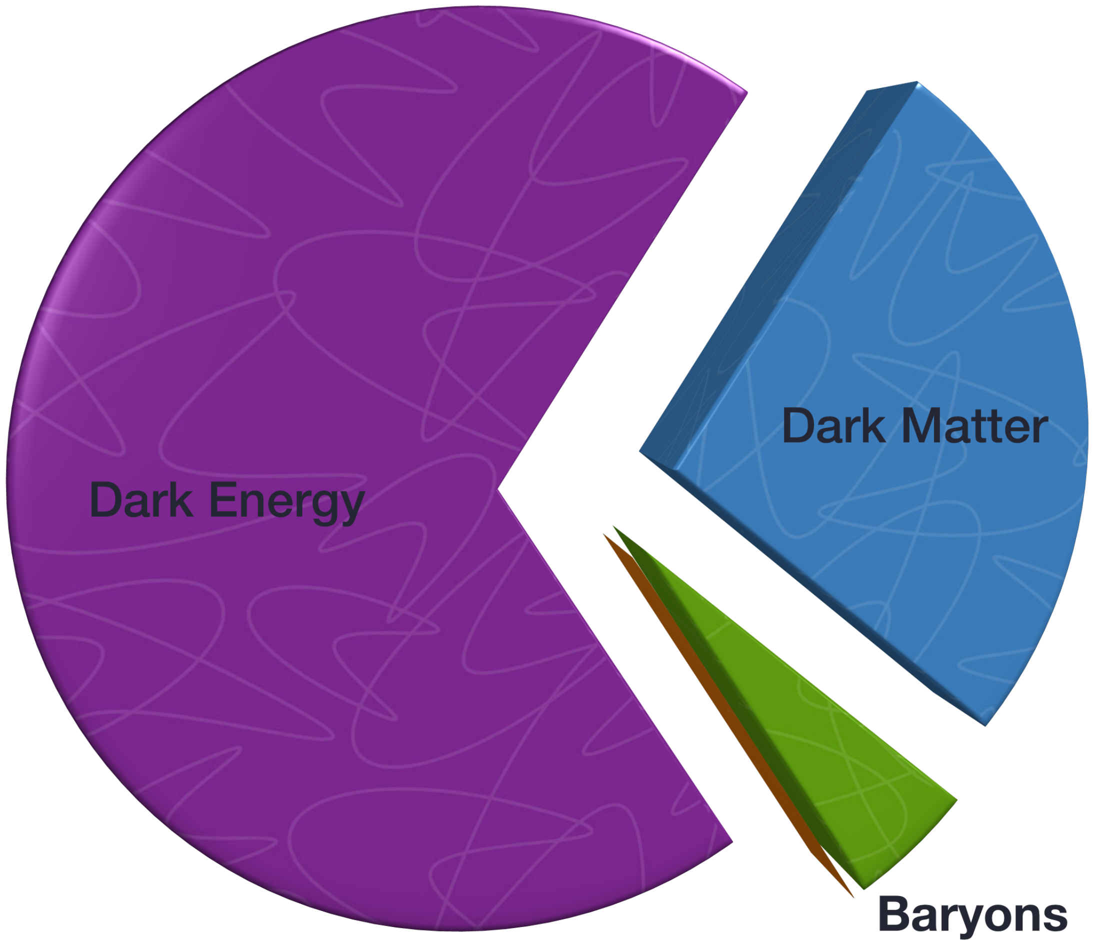


continued support for General Relativity



[Samushia et al. 2012]

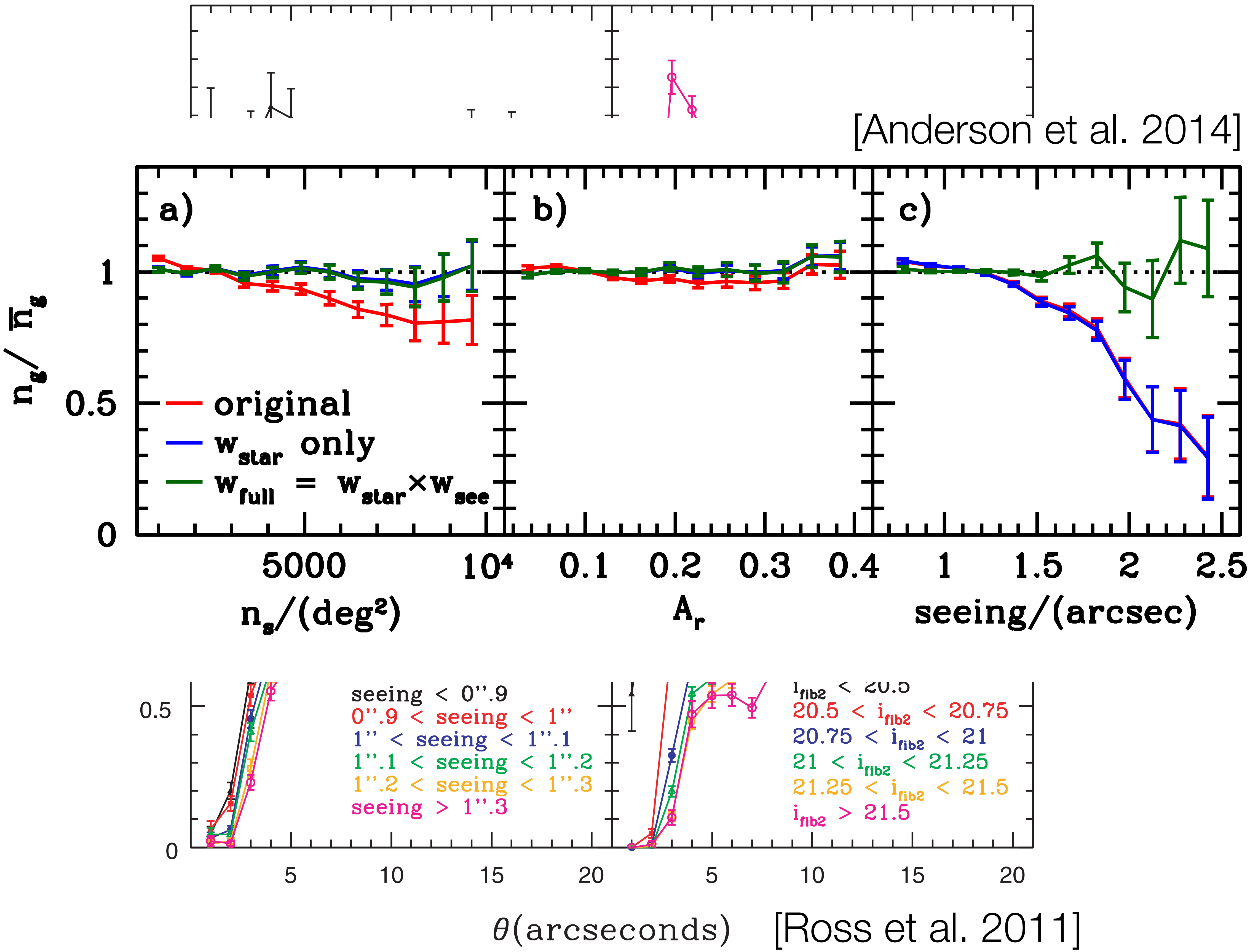
Lessons and challenges



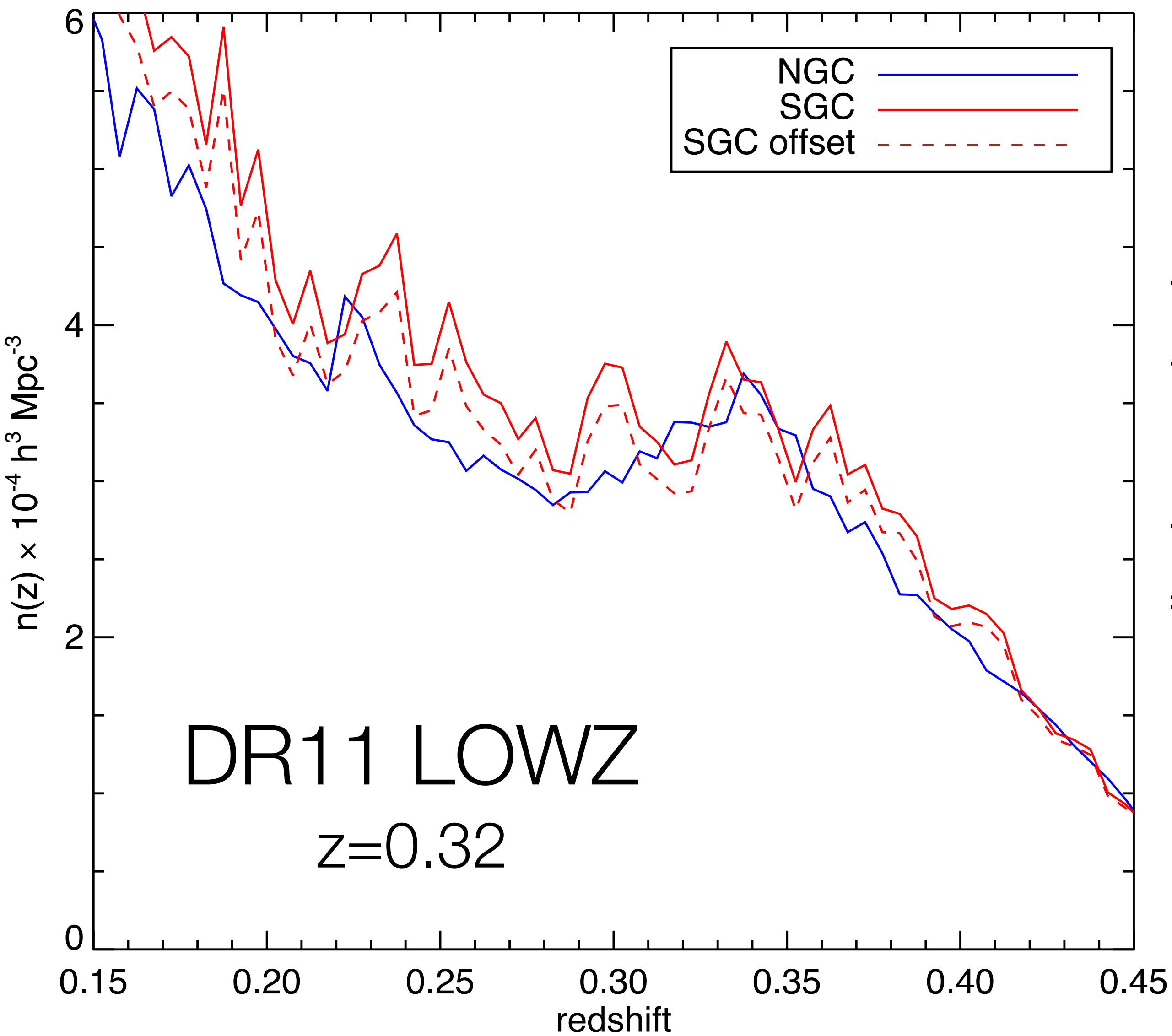
+ General Relativity
and
Homogeneity

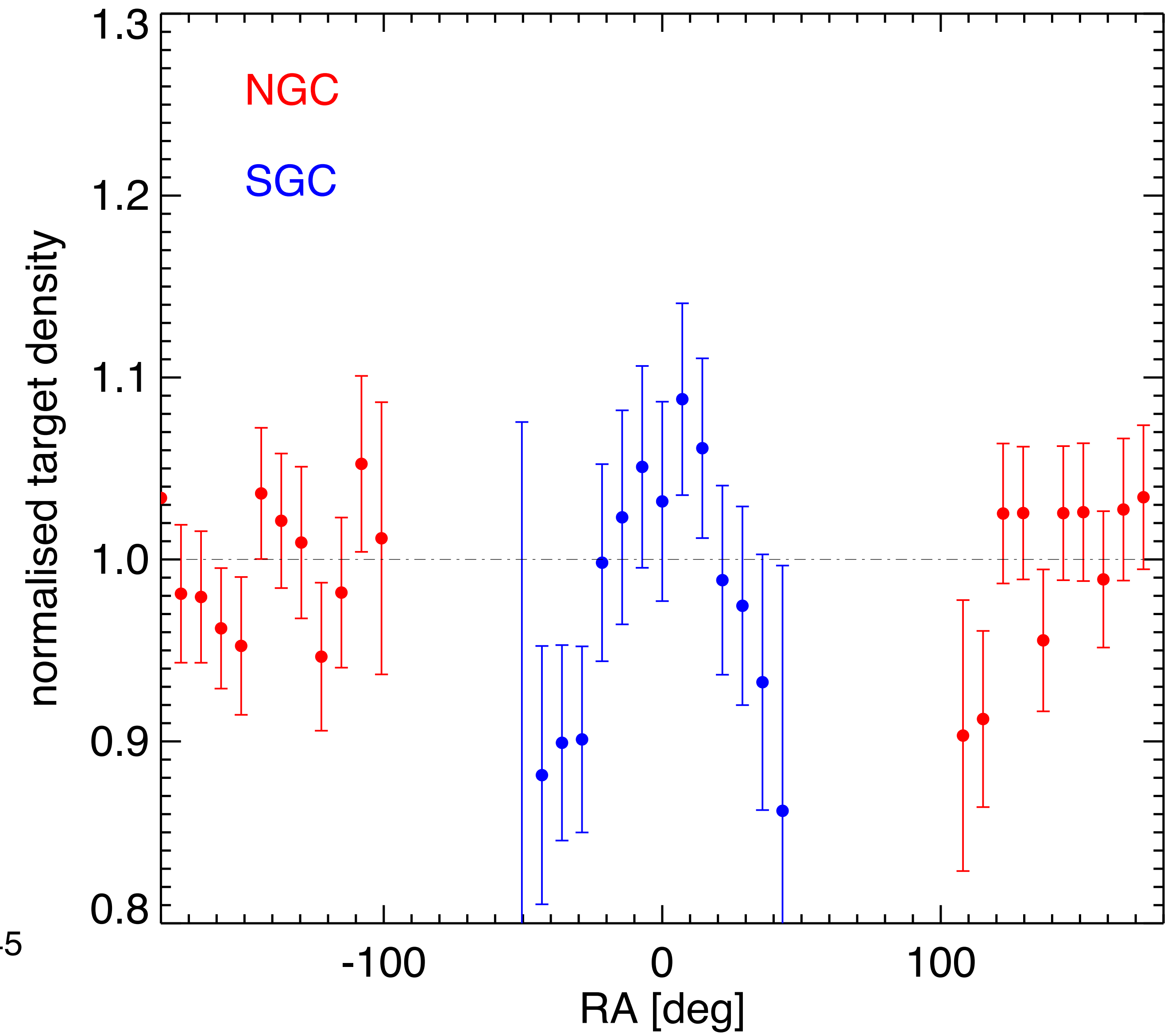
Way forward lies in improvements on the **modelling,** a better understanding of the **galaxy** population and a robust **analysis** of the data and **systematics**.

Stars matter, seeing matters.



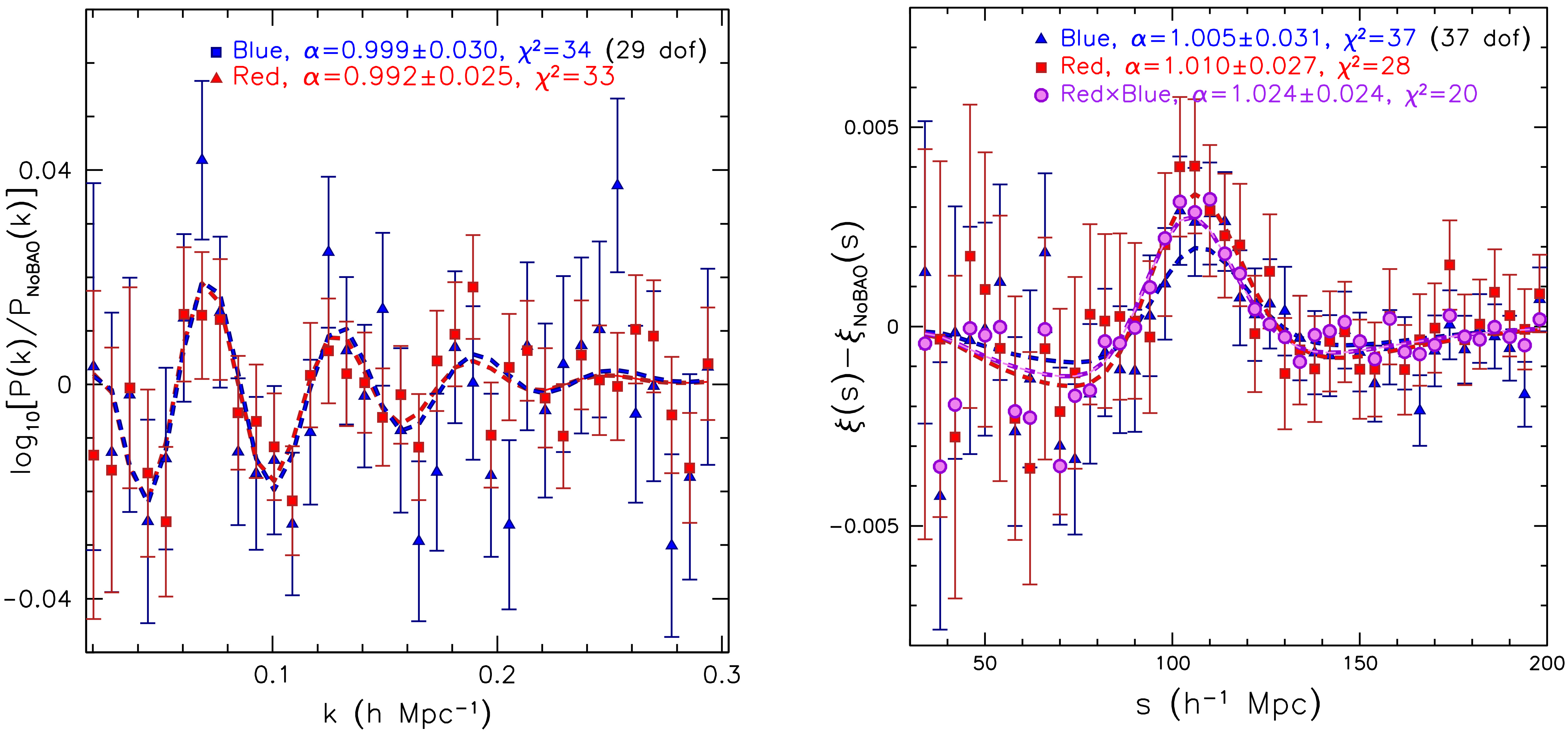
Accurate photometric calibrations matter





[Tojeiro et al. 2014]

Colour doesn't matter - for now.



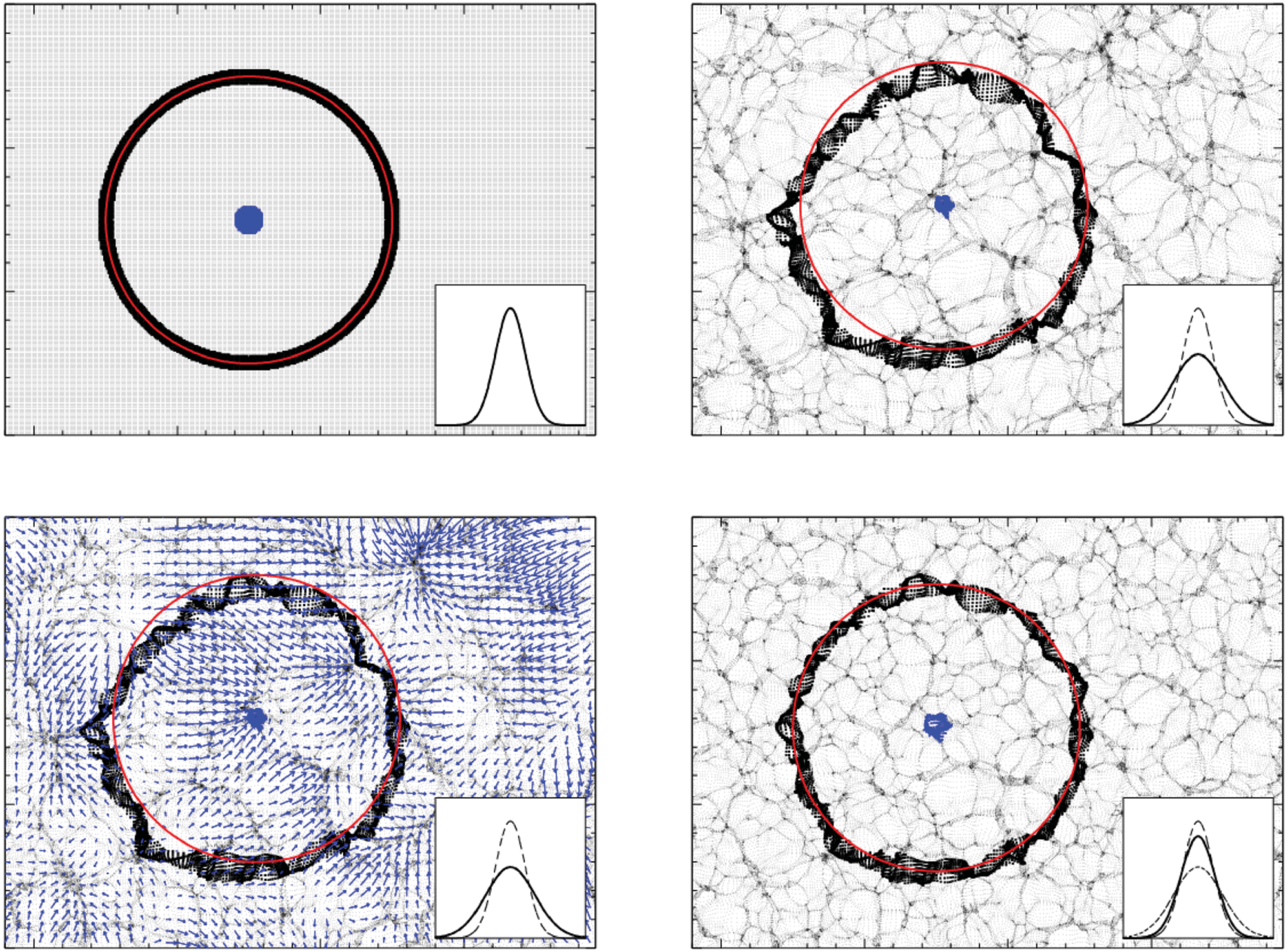
[Ross et al. 2013]

…almost everything matters (a little bit).

Estimator	Change	α	χ^2/dof
$P(k)$	fiducial	1.0114 ± 0.0093	18/27
	NGC only	1.0007 ± 0.0113	16/27
	SGC only	1.0367 ± 0.0167	15/27
	$0.02 < k < 0.25\,h\,\mathrm{Mpc}^{-1}$	1.0082 ± 0.0094	14/21
	$0.02 < k < 0.2\,h\,\mathrm{Mpc}^{-1}$	1.0121 ± 0.0113	11/15
	$0.05 < k < 0.3\,h\,\mathrm{Mpc}^{-1}$	1.0120 ± 0.0091	15/23
	$\Sigma_{nl} = 3.6 \pm 0.0 h^{-1}$Mpc	1.0111 ± 0.0085	19/28
	$\Sigma_{nl} = 4.6 \pm 0.0 h^{-1}$Mpc	1.0119 ± 0.0089	19/28
	$\Sigma_{nl} = 5.6 \pm 0.0 h^{-1}$Mpc	1.0116 ± 0.0097	18/28
	$A_1, A_2 = 0$	1.0136 ± 0.0095	40/29
	Spline fit	1.0109 ± 0.0094	17/24
	$\Delta k = 0.0032\,h\,\mathrm{Mpc}^{-1}$	1.0122 ± 0.0097	71/79
	$\Delta k = 0.004\,h\,\mathrm{Mpc}^{-1}$	1.0082 ± 0.0094	55/62
	$\Delta k = 0.006\,h\,\mathrm{Mpc}^{-1}$	1.0091 ± 0.0096	33/39
	$\Delta k = 0.01\,h\,\mathrm{Mpc}^{-1}$	1.0120 ± 0.0097	16/20
	$\Delta k = 0.012\,h\,\mathrm{Mpc}^{-1}$	1.0133 ± 0.0091	9/15
	$\Delta k = 0.016\,h\,\mathrm{Mpc}^{-1}$	1.0100 ± 0.0099	5/9
	$\Delta k = 0.02\,h\,\mathrm{Mpc}^{-1}$	1.0186 ± 0.0105	5/6

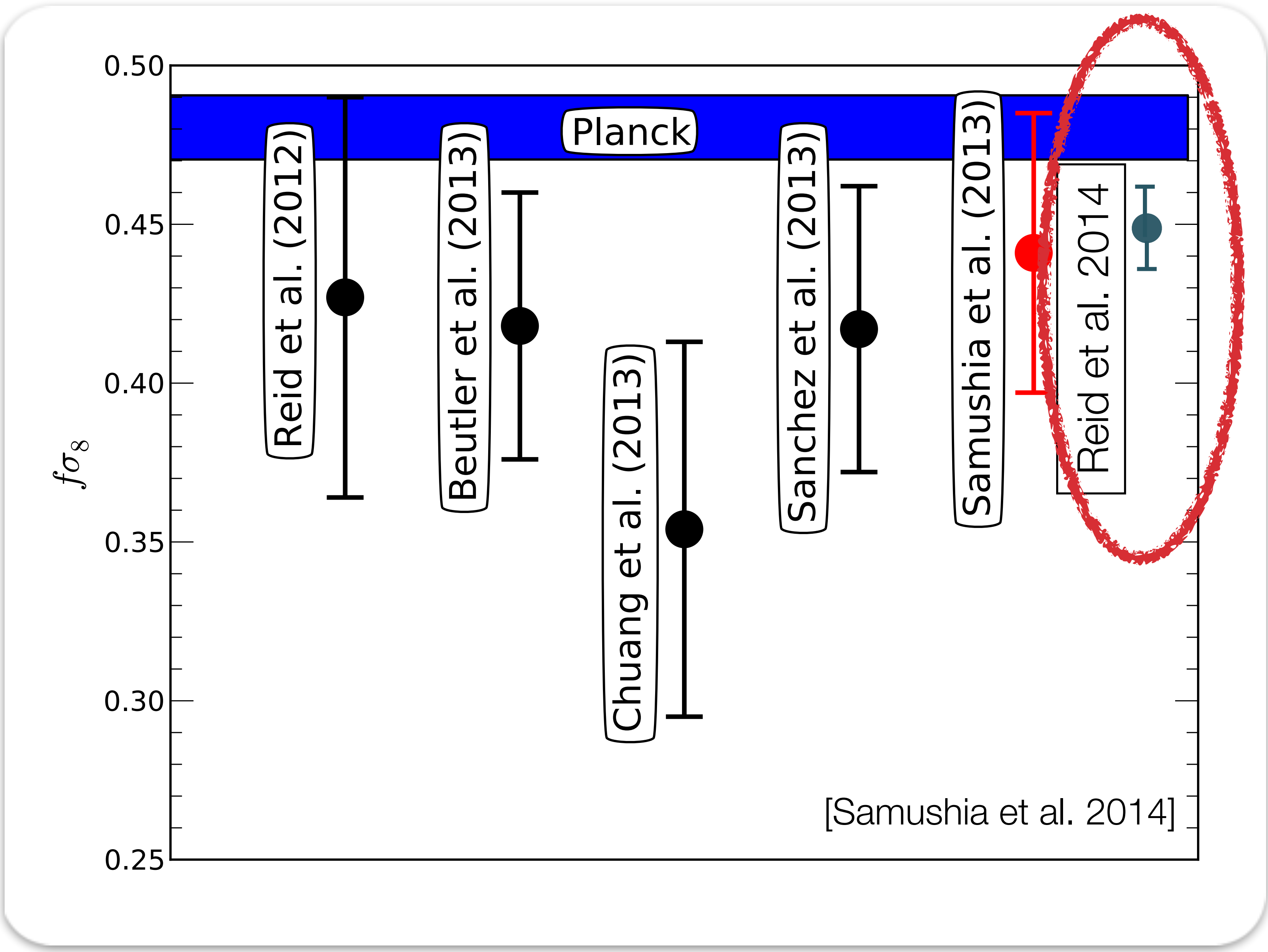
Mocks vital to validate methodologies and quantify **statistical *and* systematic** errors.

Reconstruction works

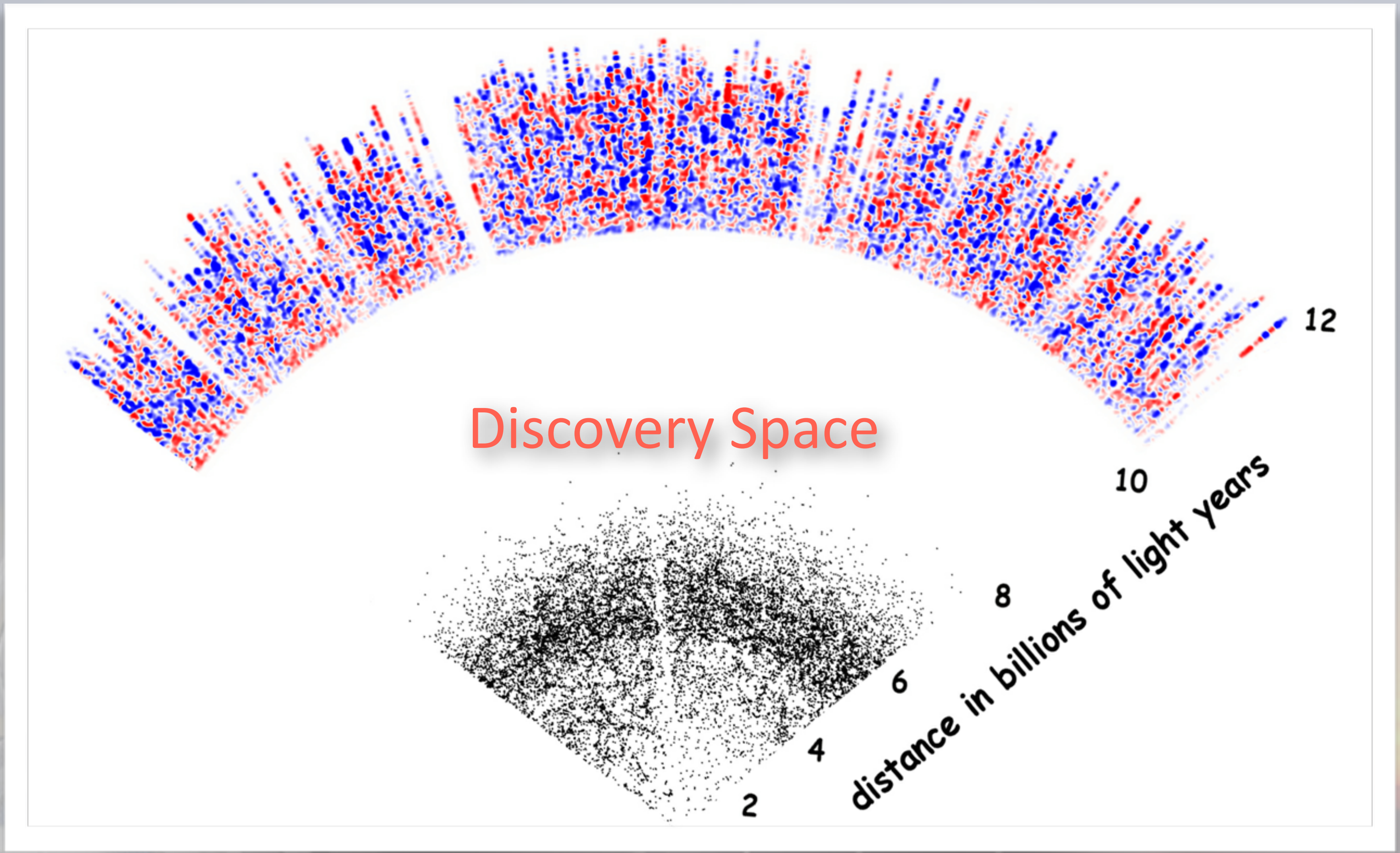


[Padmanabhan et al. 2012, Burden et al. 2014]

RSD in BOSS limited by modelling, not data



If you wanted to start a BAO survey today…



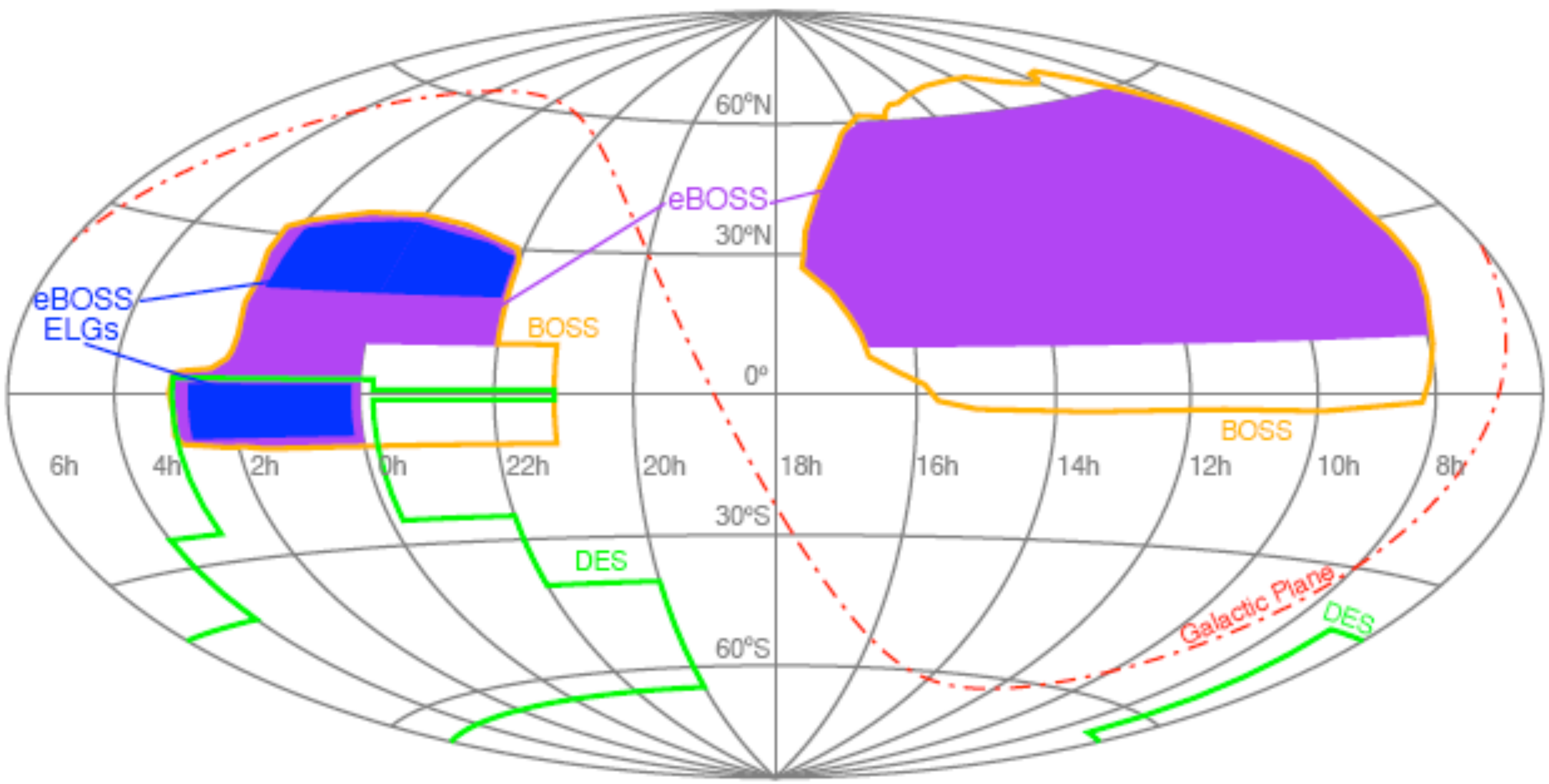
Use the SDSS telescope
Galaxies in $0.5 < z < 1$.
Quasars $z < 2$.

→ eBOSS

eBOSS samples

- Luminous red galaxies (LRGs)
  - 350,000 at $z > 0.6$ over 7500 deg^2
- Emission line galaxies (ELGs)
  - 190,000 at $0.6 < z < 1.0$ over 1500 deg^2
- Low-Redshift Quasars (QSOs)
  - 470,000 at $0.9 < z < 2.2$ over 7500 deg^2
- Lyman-α forest (Lyα)
  - 50,000 new, re-ob 70,000 with SNR < 3

eBOSS samples



eBOSS

- eBOSS will provide first precise BAO and RSD measurements for $0.7 < z < 2.2$, improve Lyα at z~2.5
  - Use multiple tracers (LRGs, ELGs, QSOs)
- Wealth of spectra for galaxy and quasar science
- projected factor of 3 DE FoM improvement

Thanks!

Rita Tojeiro
for the (e)BOSS collaboration
University of St. Andrews

MOS in the next decade
La Palma, 5 March 2015