Robust and Precise Physical Measurements using Galaxy Surveys: Successes from BOSS and Lessons for the Future

THE OHIO STATE UNIVERSITY

CCAPP

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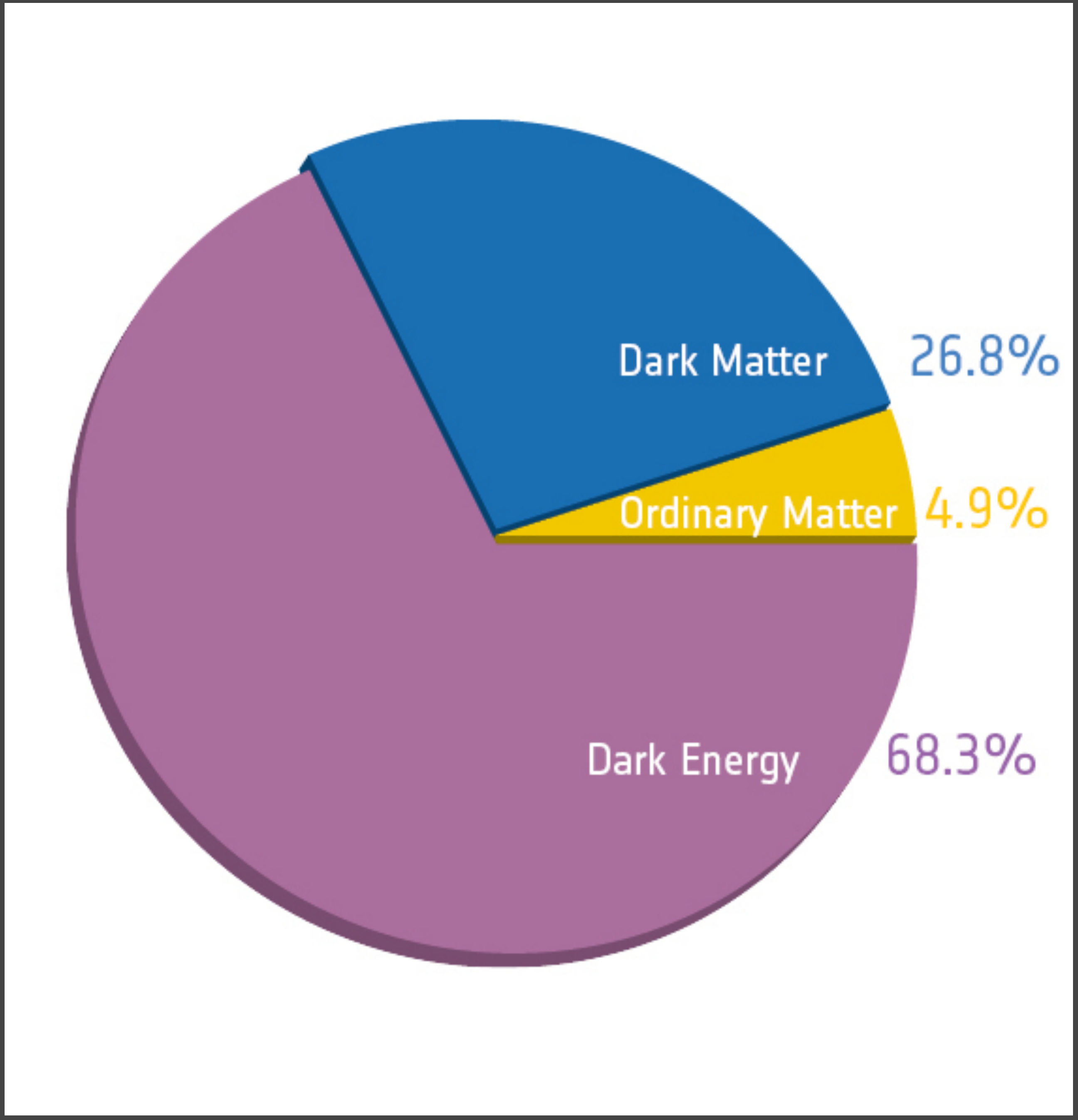
BOSS Galaxy Clustering working group, DES LSS working group, eBOSS Quasar and Galaxy Clustering working group

Outline

- Fundamental cosmological questions
- The Baryon Oscillation Spectroscopic Survey (BOSS): a galaxy redshift survey
  - Measuring galaxy clustering
  - Addressing fundamental questions with BOSS
- Details
  - Observational systematics
  - (Theoretical systematics)
- (very) Recent and Future results
  - BOSS DR12, eBOSS, DES, DESI

Current Cosmological Model

- Flat, 96% "dark"
- what is dark energy?
- modify GR?*
- why is there structure at all?*
- what is the mass of the neutrino?



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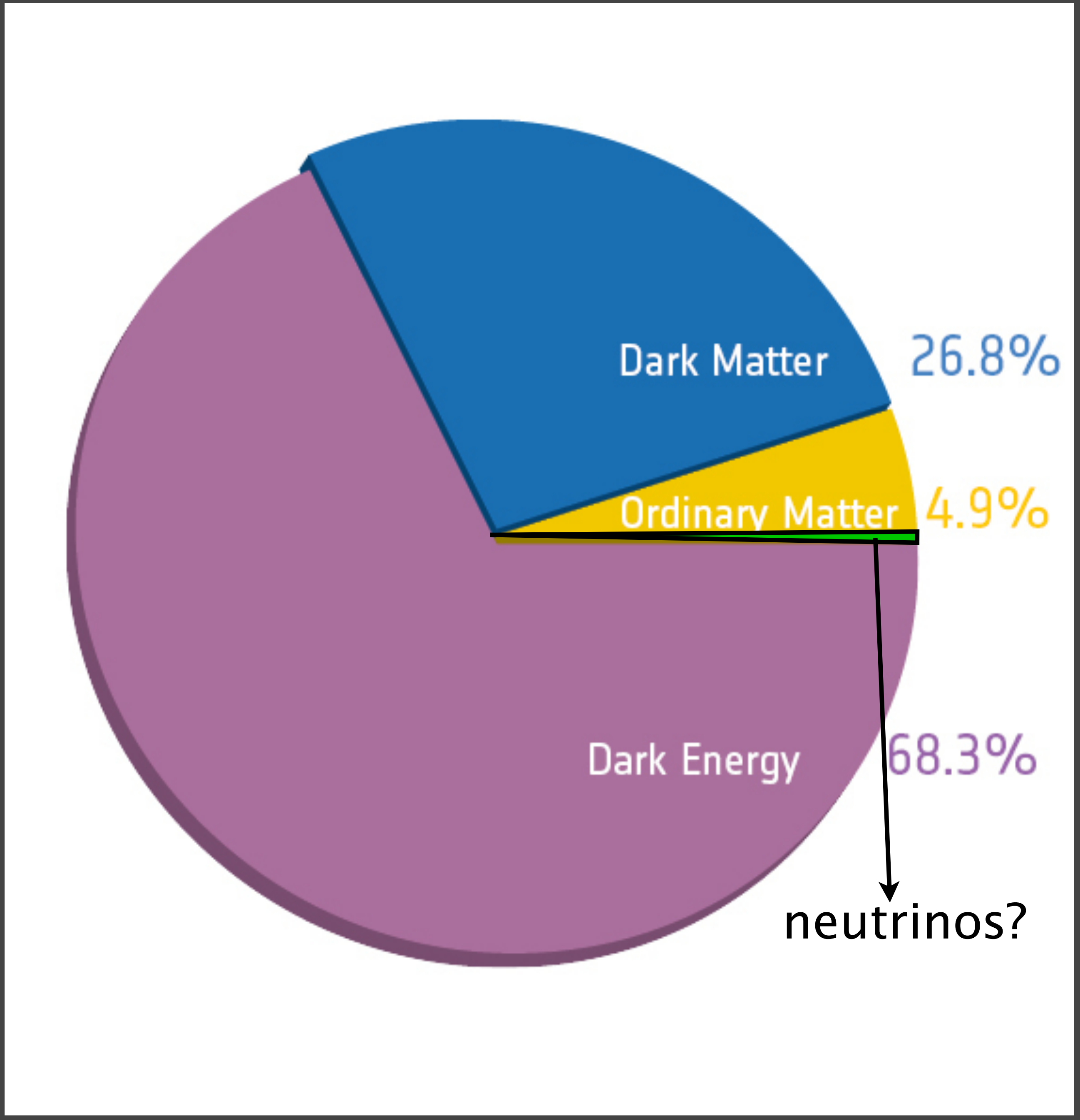
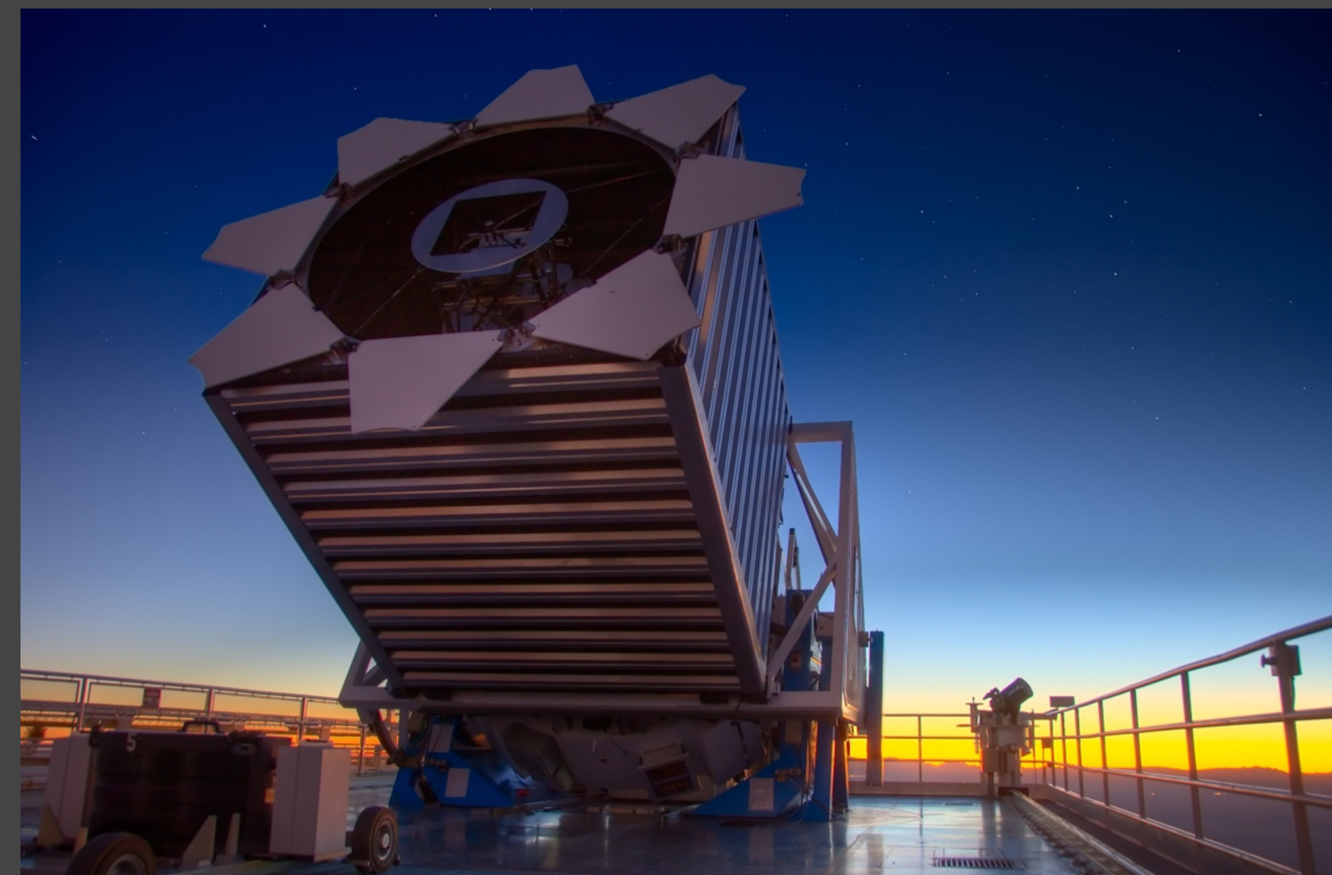


The SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS): Mapping the structure of the Universe

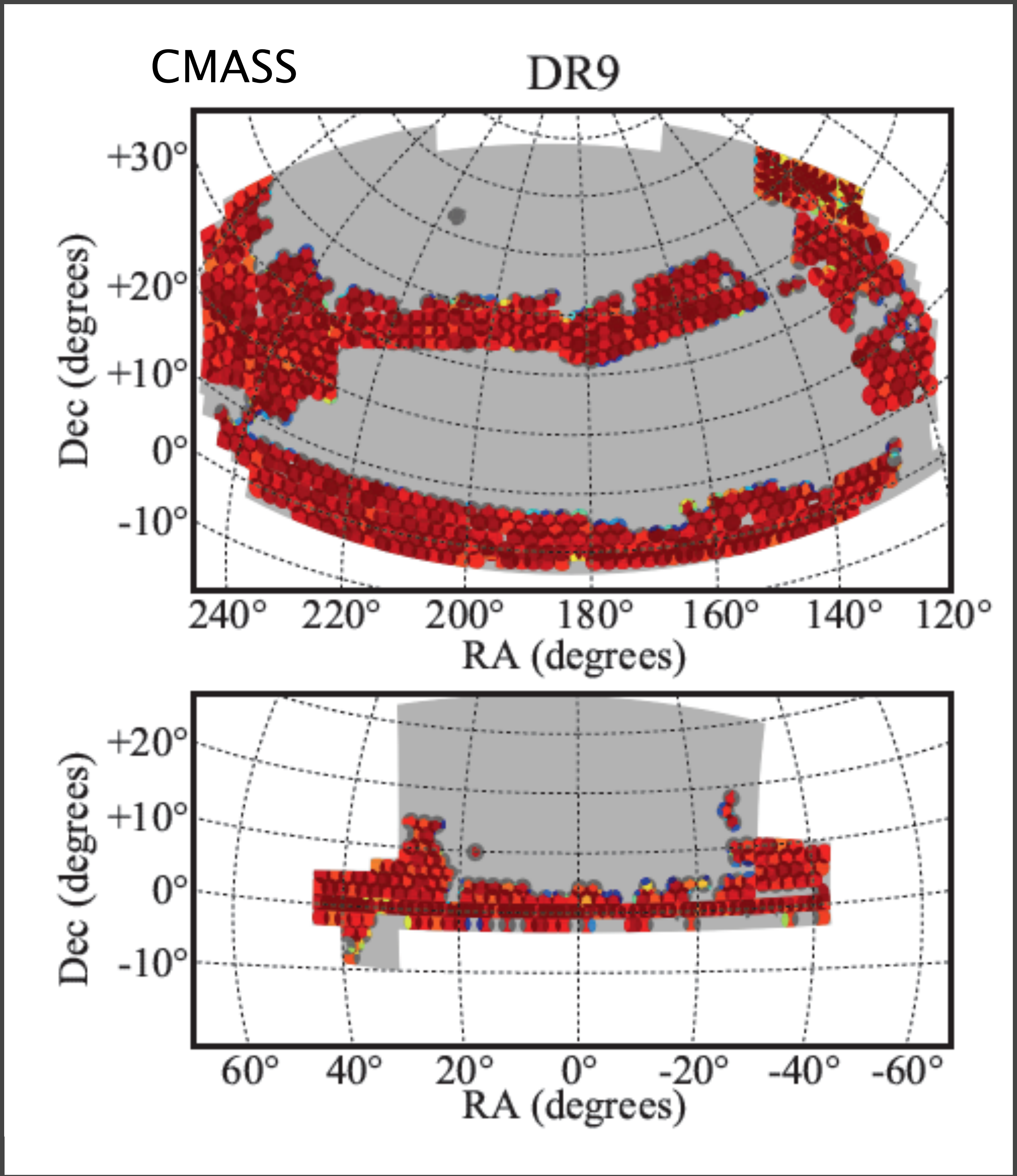
SDSS-III BOSS

- Sloan Digital Sky Survey
- Uses Sloan telescope at Apache Point NM
- BOSS uses:
- SDSS *ugriz* imaging to select:
  1.5 million galaxies
  1.5×10^5 quasars
  (out of 3.6×10^8 sources)
- BOSS spectrograph
  $3600Å < \lambda < 10{,}000Å$
  $R = \lambda/\Delta\lambda = 1300 - 3000$
  1000 spectra at a time



BOSS Galaxies

- DR8 imaging 14,555 deg^2
- 10,000 deg^2 good for BOSS
- DR9 footprint 3345 deg^2
- DR10 6300 deg^2
- DR11 8500 deg^2 (current published results)
- DR12 10,000 deg^2; raw data public, results imminent



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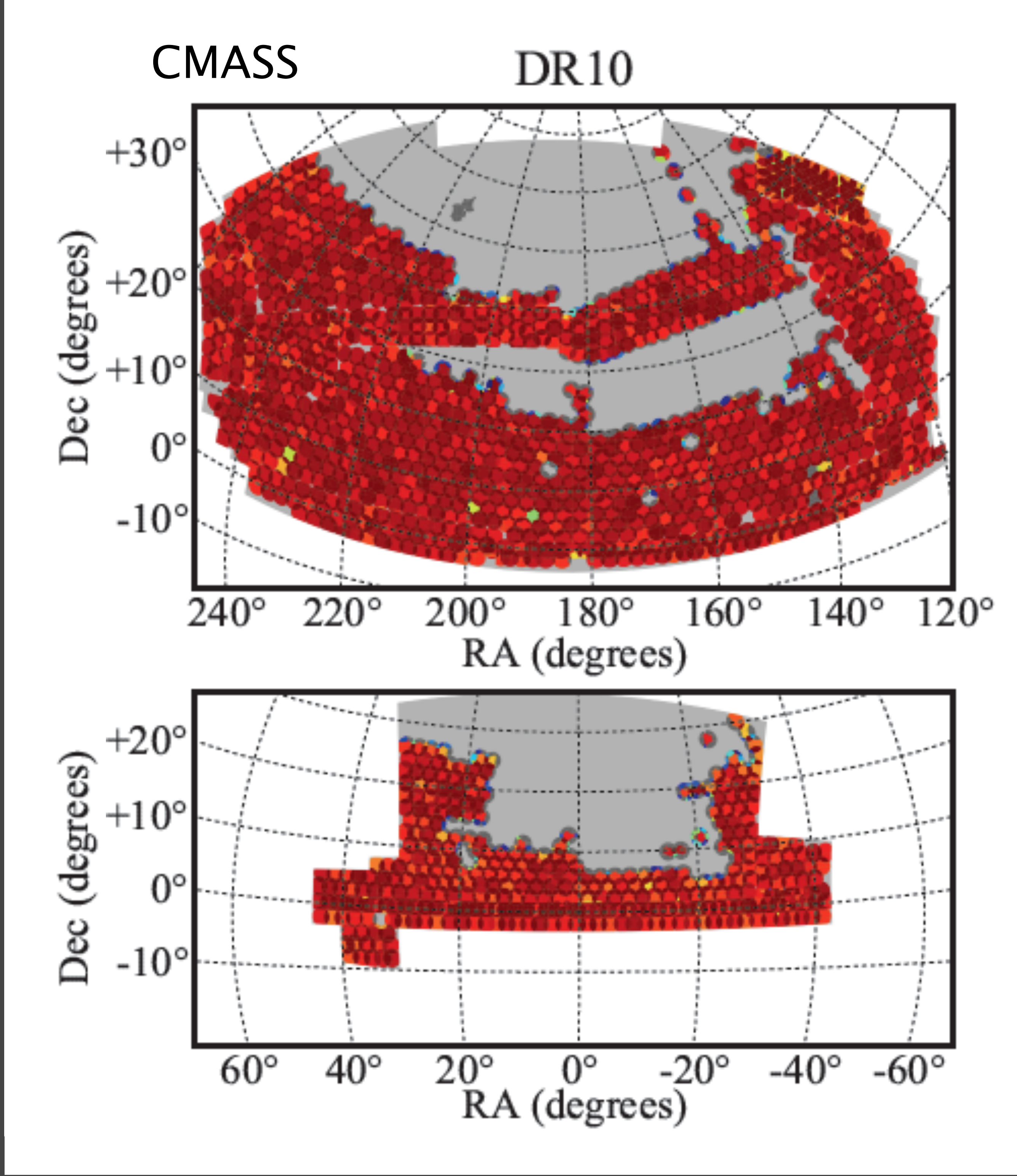

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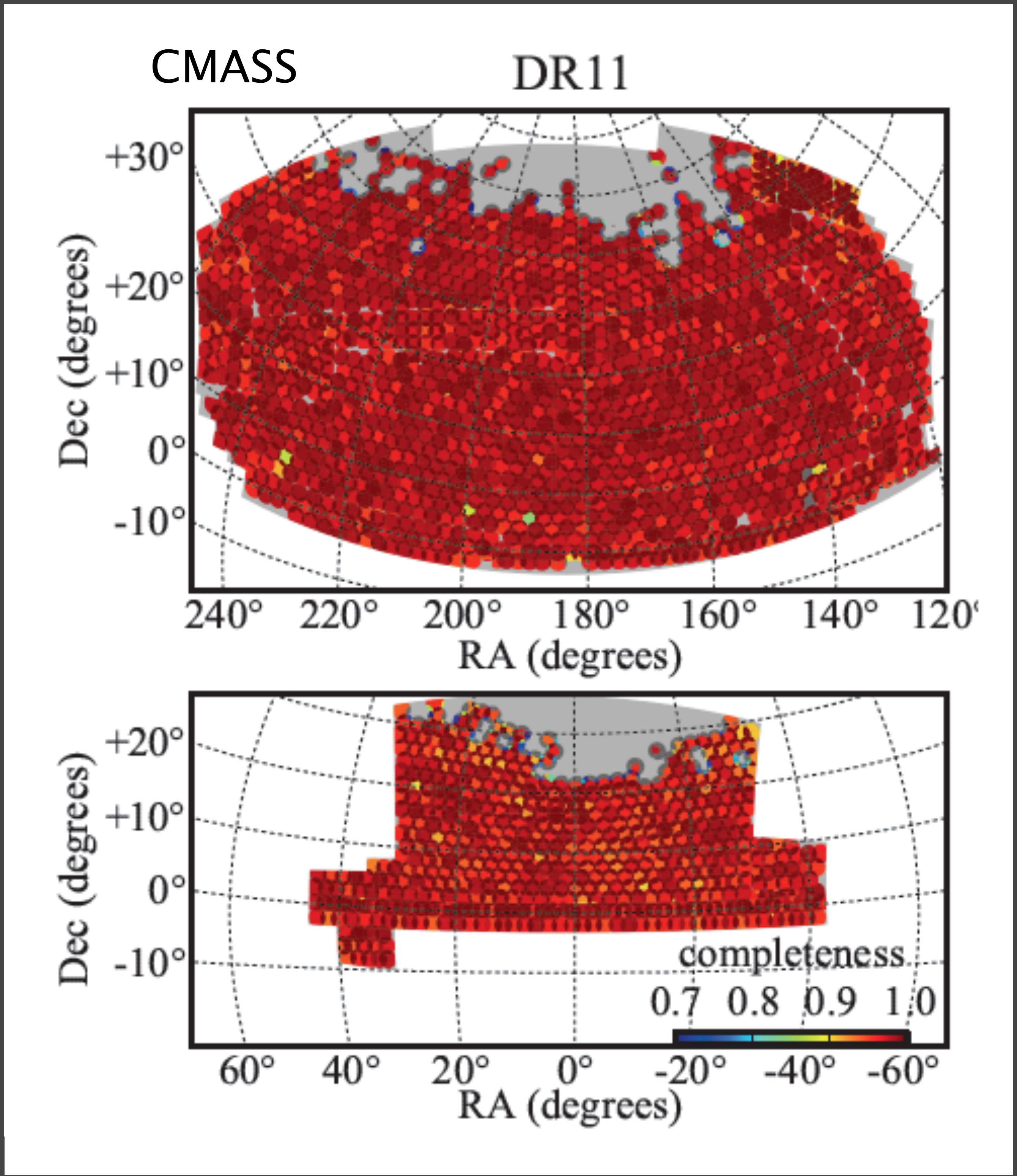

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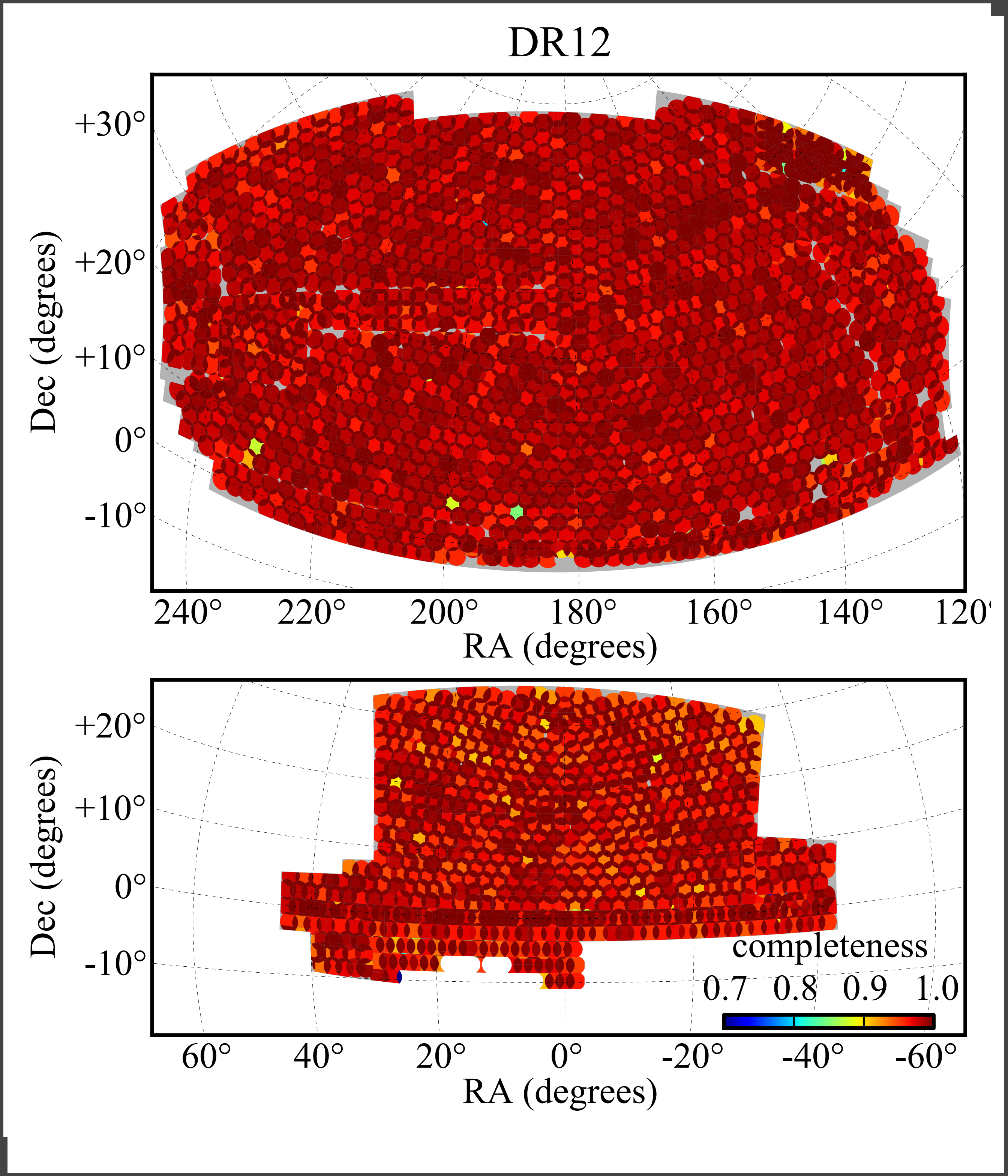
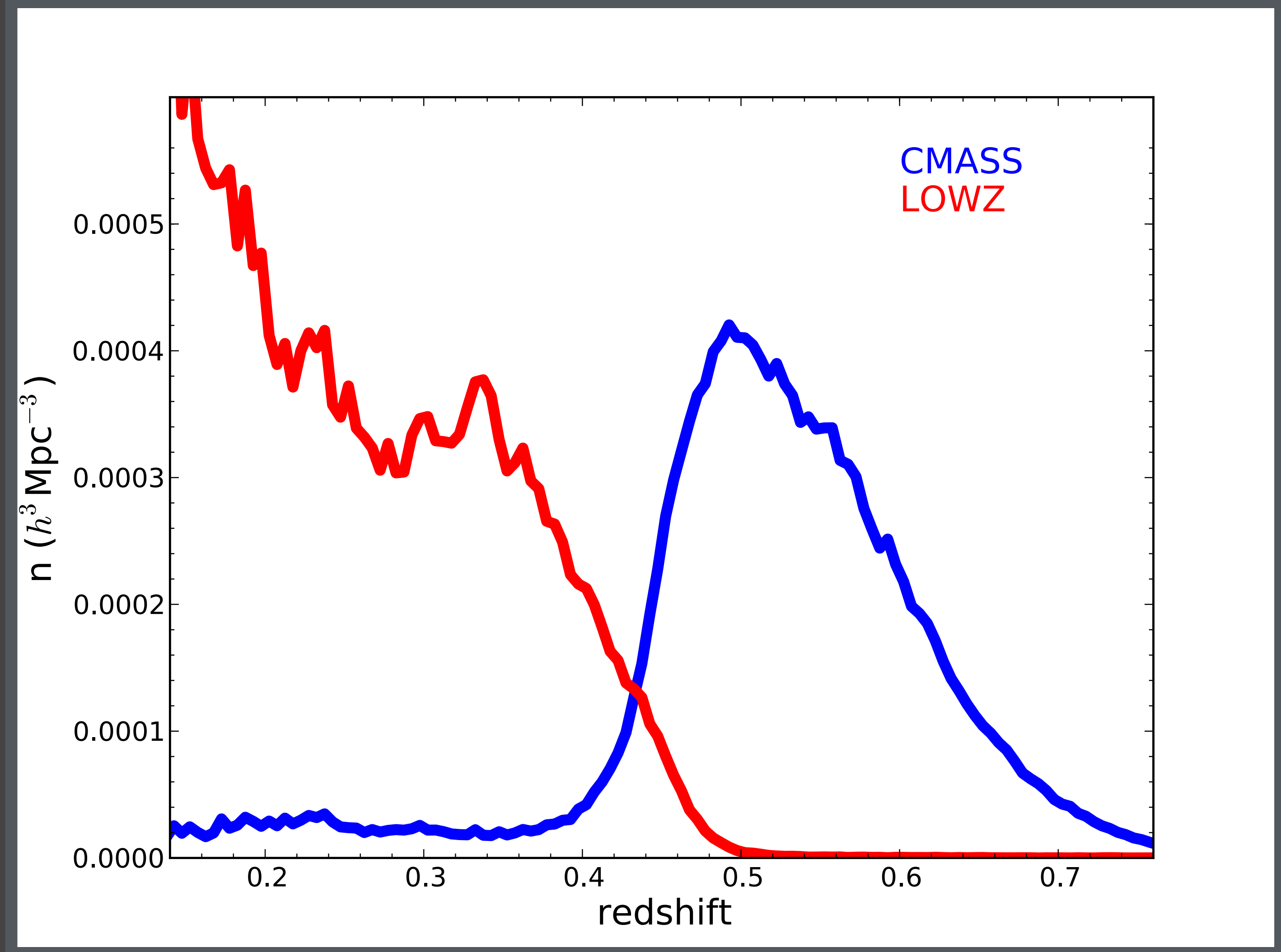


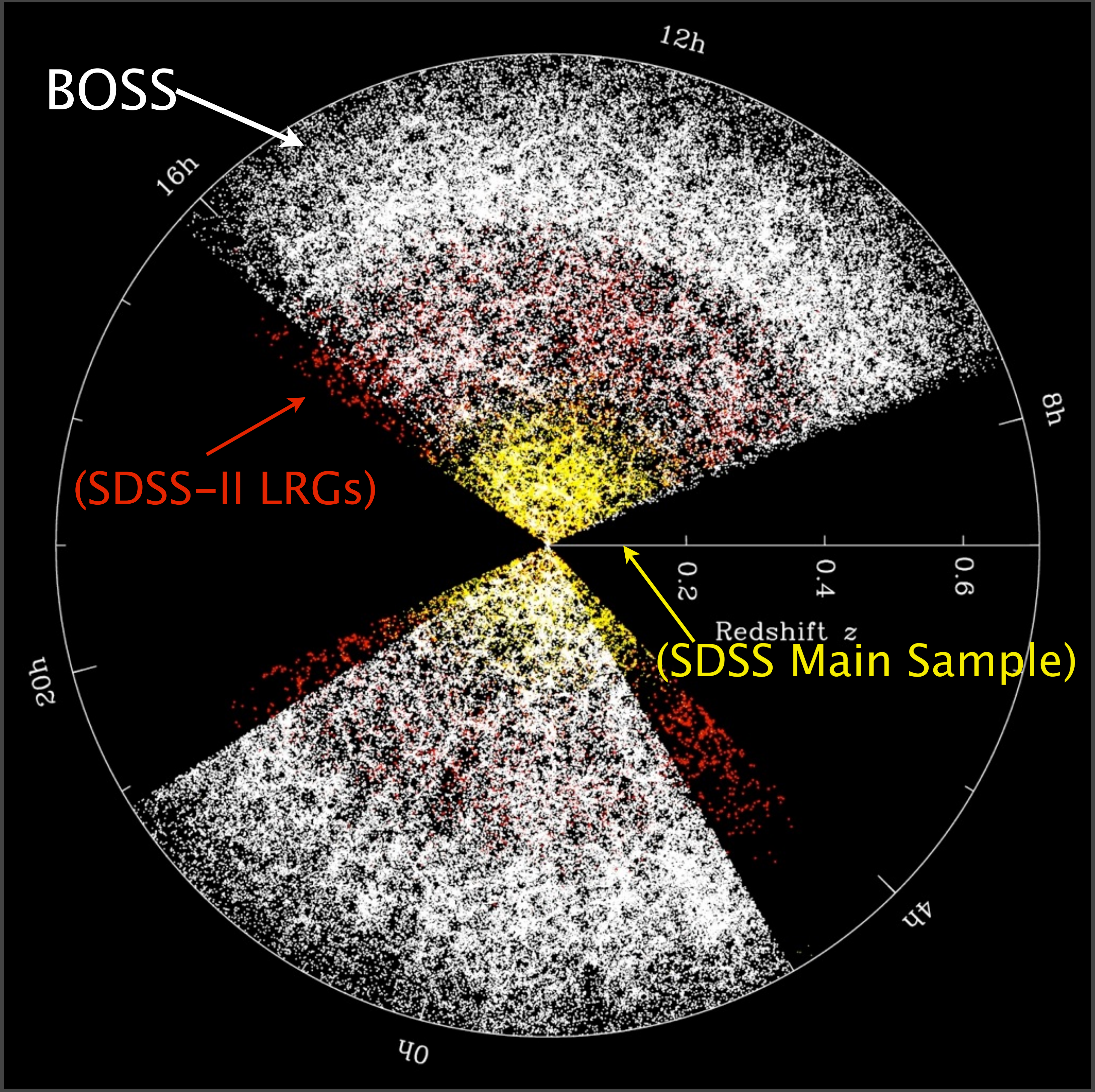
BOSS Galaxies

- Two samples:
- 'CMASS':
- i < 19.9 + color cuts
- redshifts 0.43<z<0.7
- 'LOWZ':
- r < 19.5 + color cuts
- 0.15<z<0.43

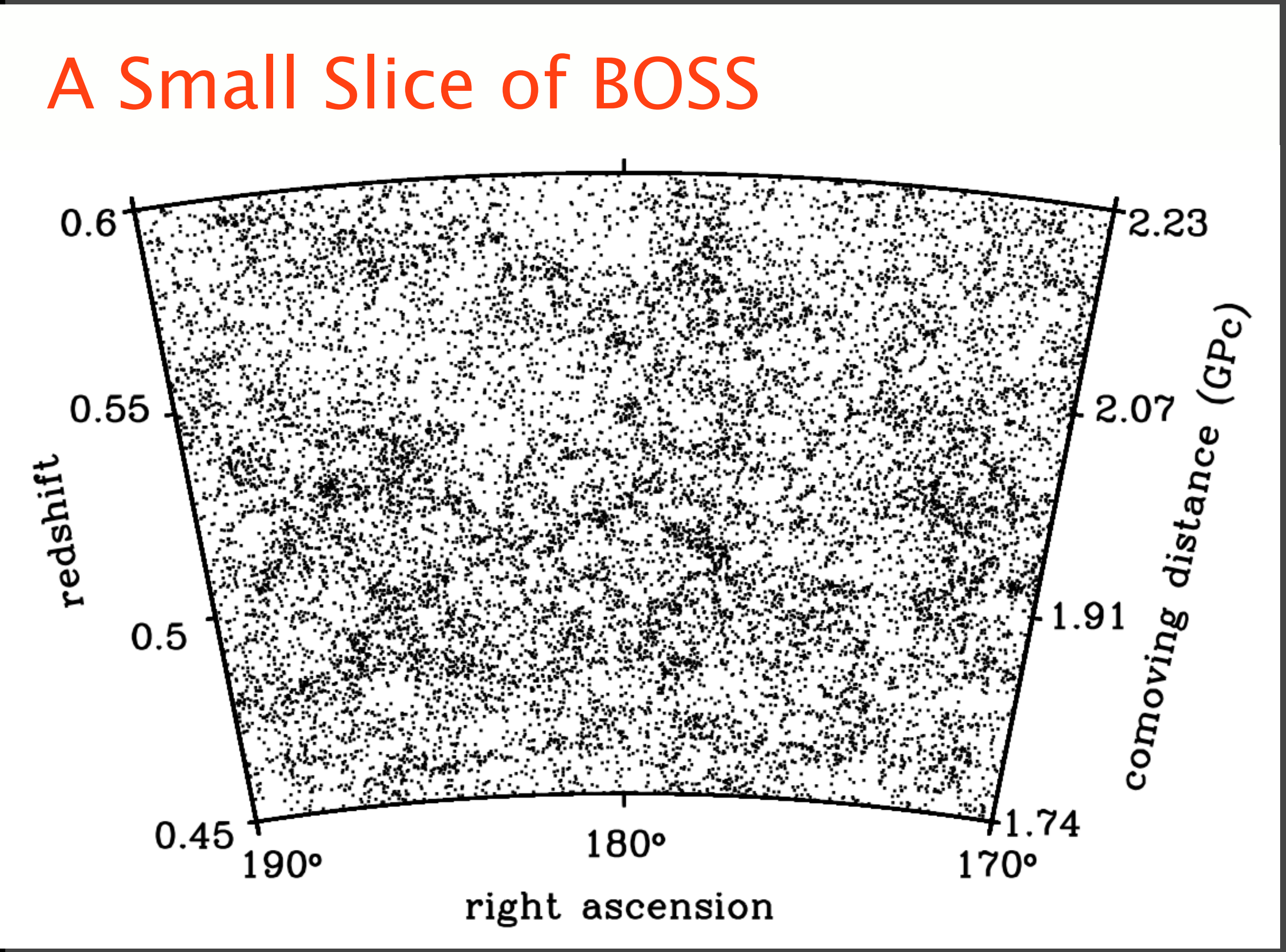


BOSS Galaxies

- Largest 3D map of galaxies



Observed Galaxies to 3D Map



- angles, redshifts → comoving distance

$$r = a r_{\text{physical}};\, a = \frac{1}{1+z}$$

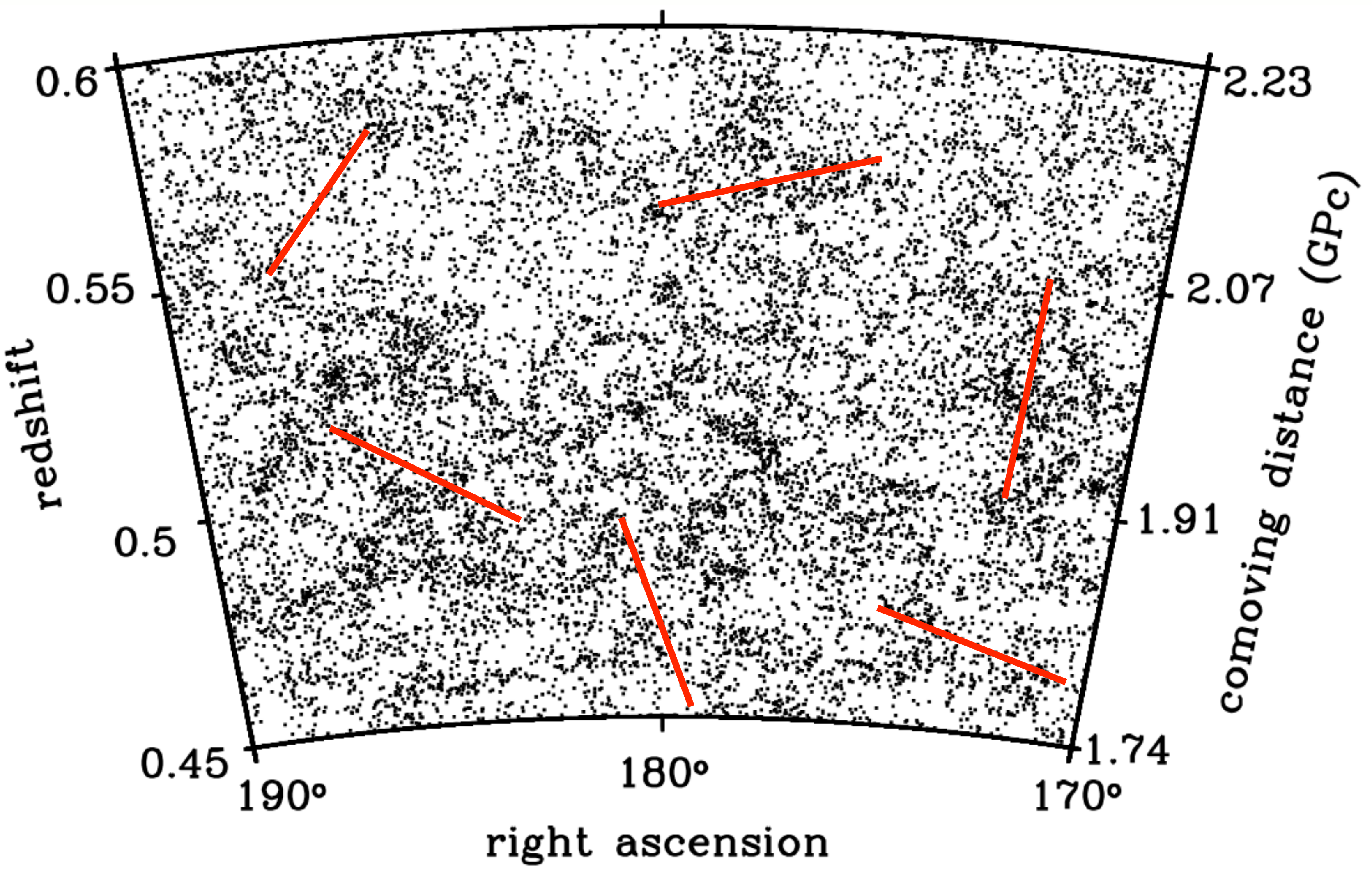
$$r(z_1, z_2) = c \int_{z_1}^{z_2} \frac{dz}{H(z)}$$

$$H(z) = \frac{\dot{a}}{a} = H_0 \left(\Omega_m (1+z)^3 + \Omega_\Lambda\right)^{\frac{1}{2}}$$

(flat ΛCDM)

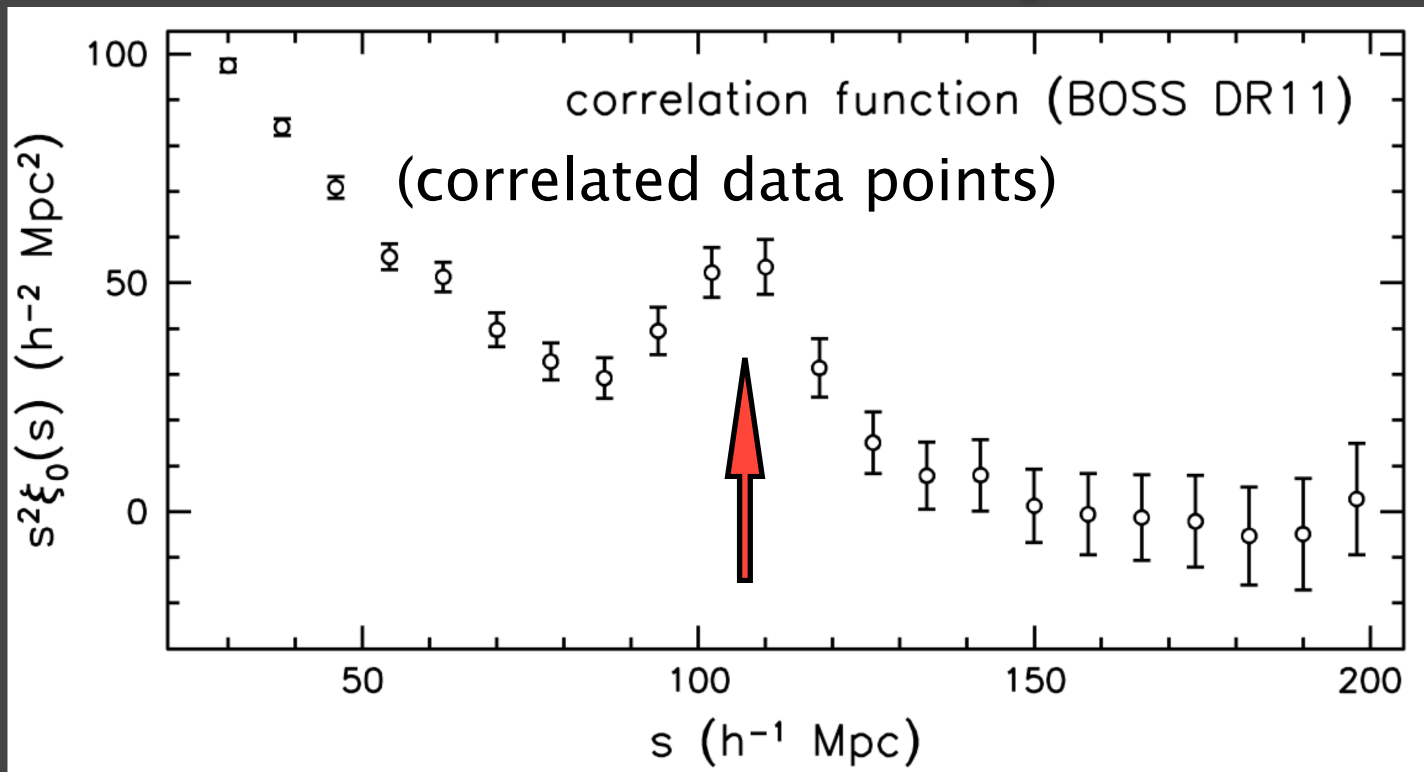
Galaxy Clustering

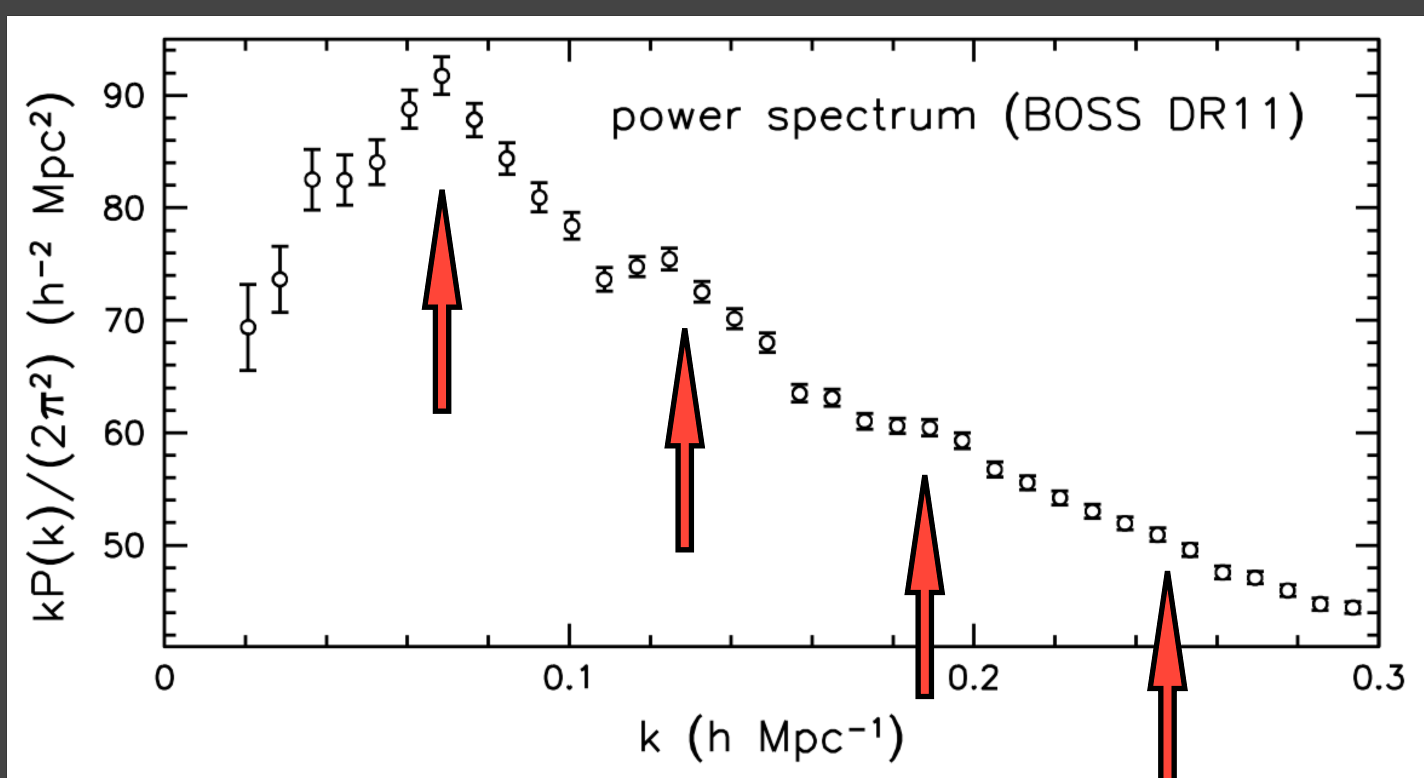
A Small Slice of BOSS



- Need to quantify structure we see
- Clustering strength = number of galaxy pairs beyond uniform random
- Power spectrum $P(k) = \langle \delta_k(k)^2 \rangle$
- Correlation function $\xi(r) = \langle \delta(x)\delta(x+r) \rangle$

Galaxy Clustering





- Power spectrum $P(k) = \langle \delta_k(k)^2 \rangle$
- Correlation function $\xi(r) = \langle \delta(x)\delta(x+r) \rangle$

- k~2π/r
- r and s interchangeable

Baryon Acoustic Oscillations (BAO)

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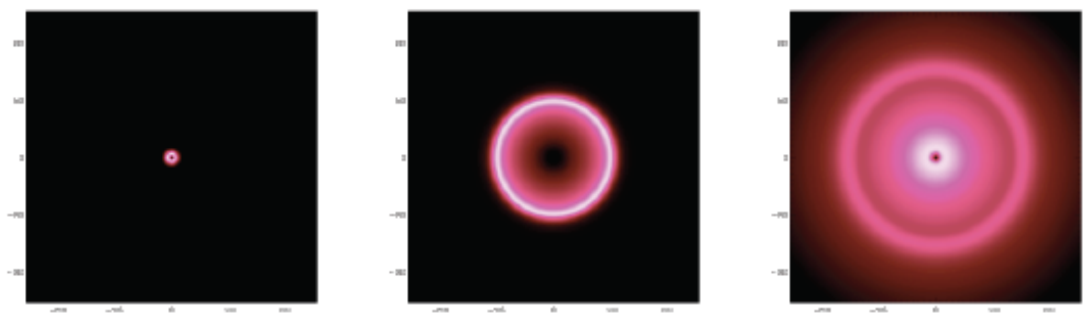
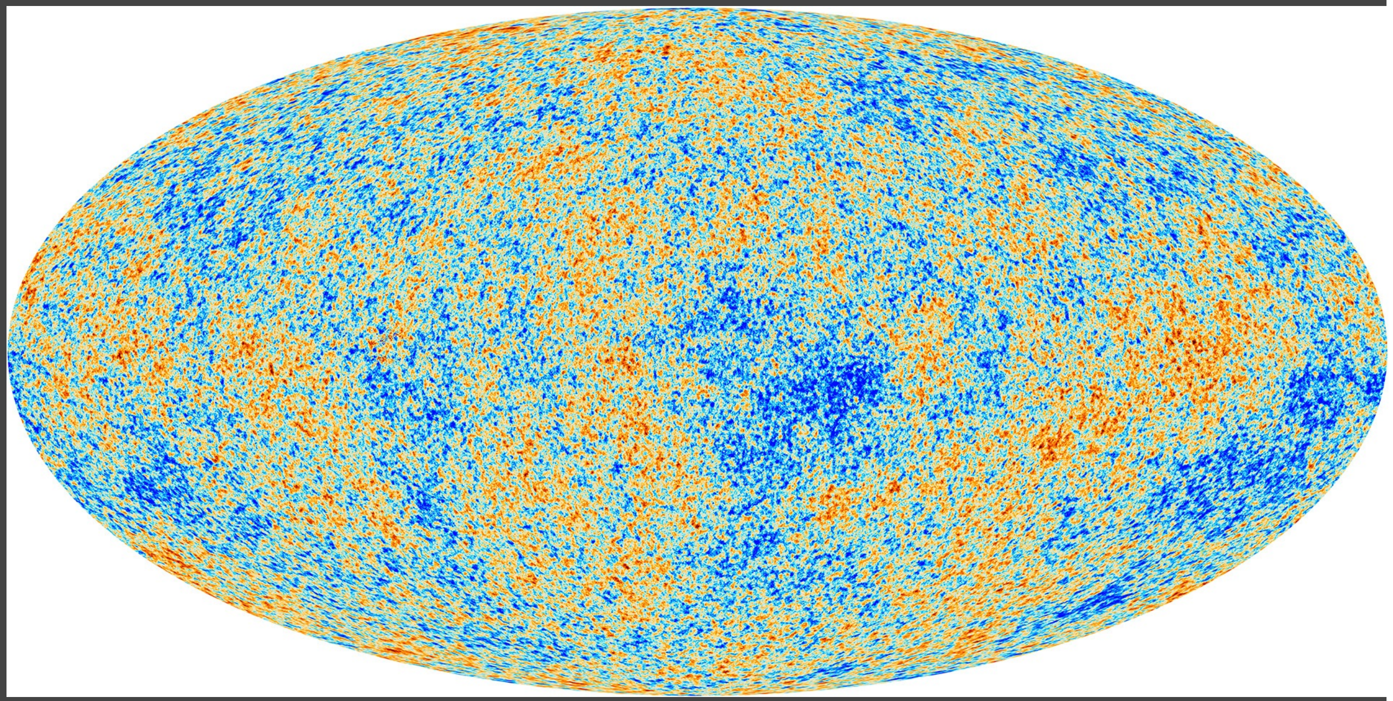
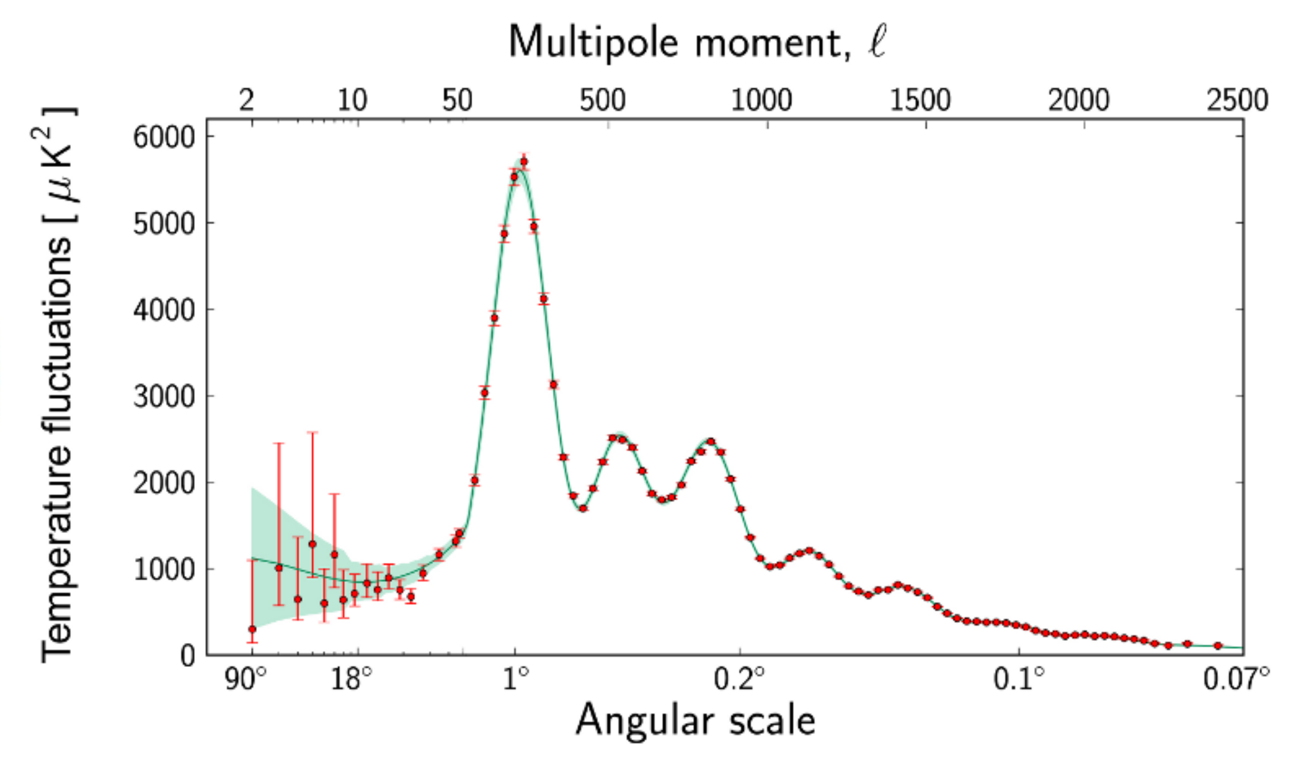
- early Universe radiation pressure/ matter density -> standing wave in baryon density



(images from Martin White)





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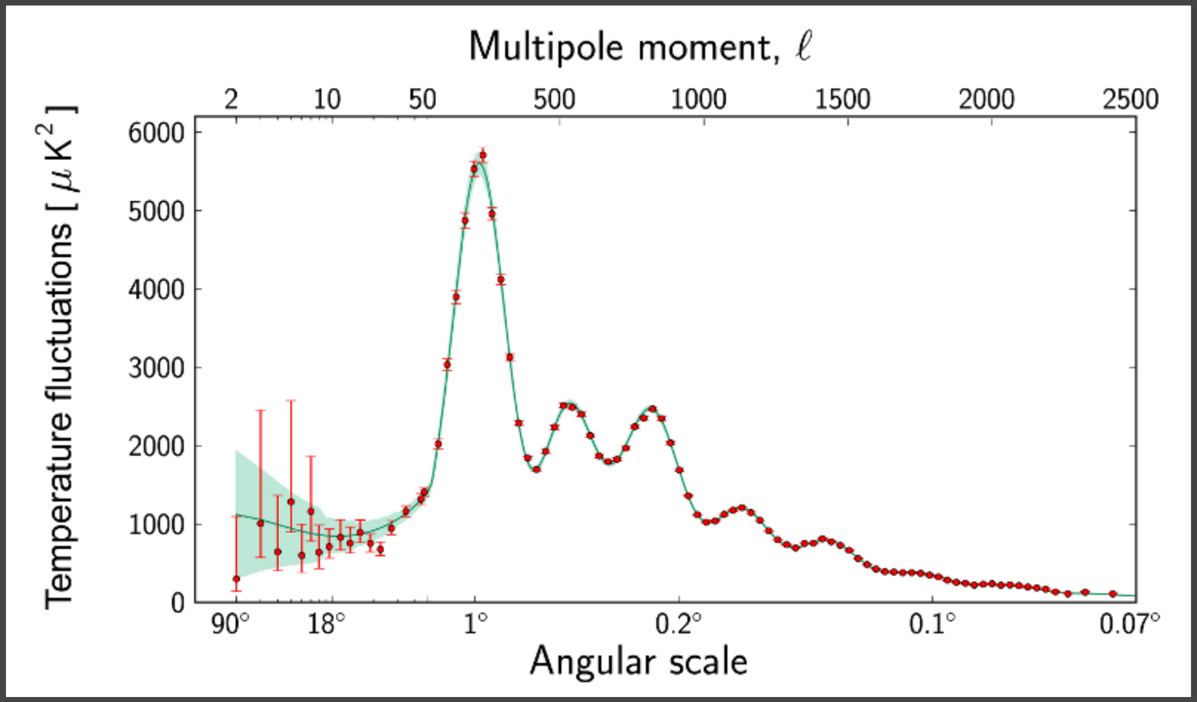
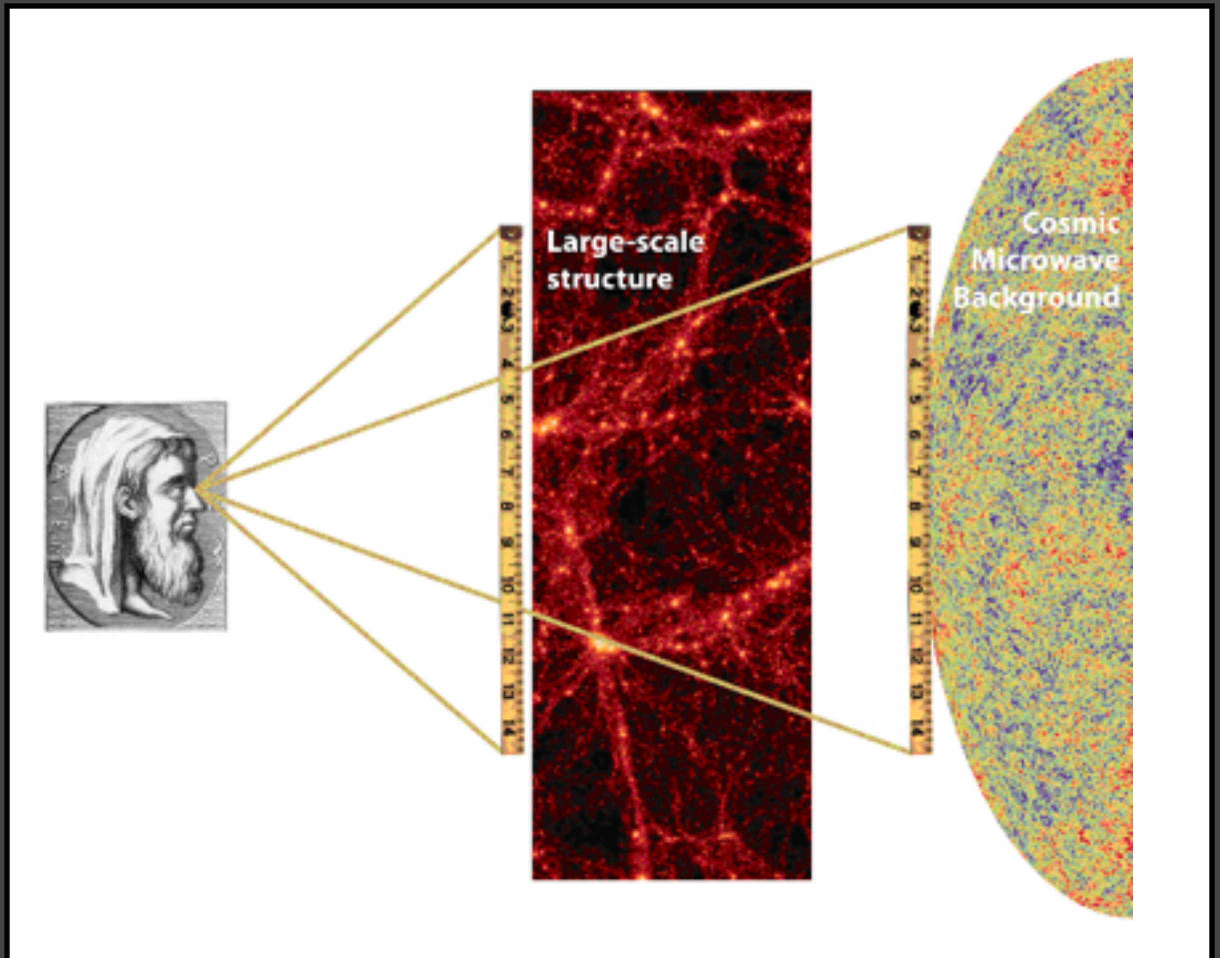
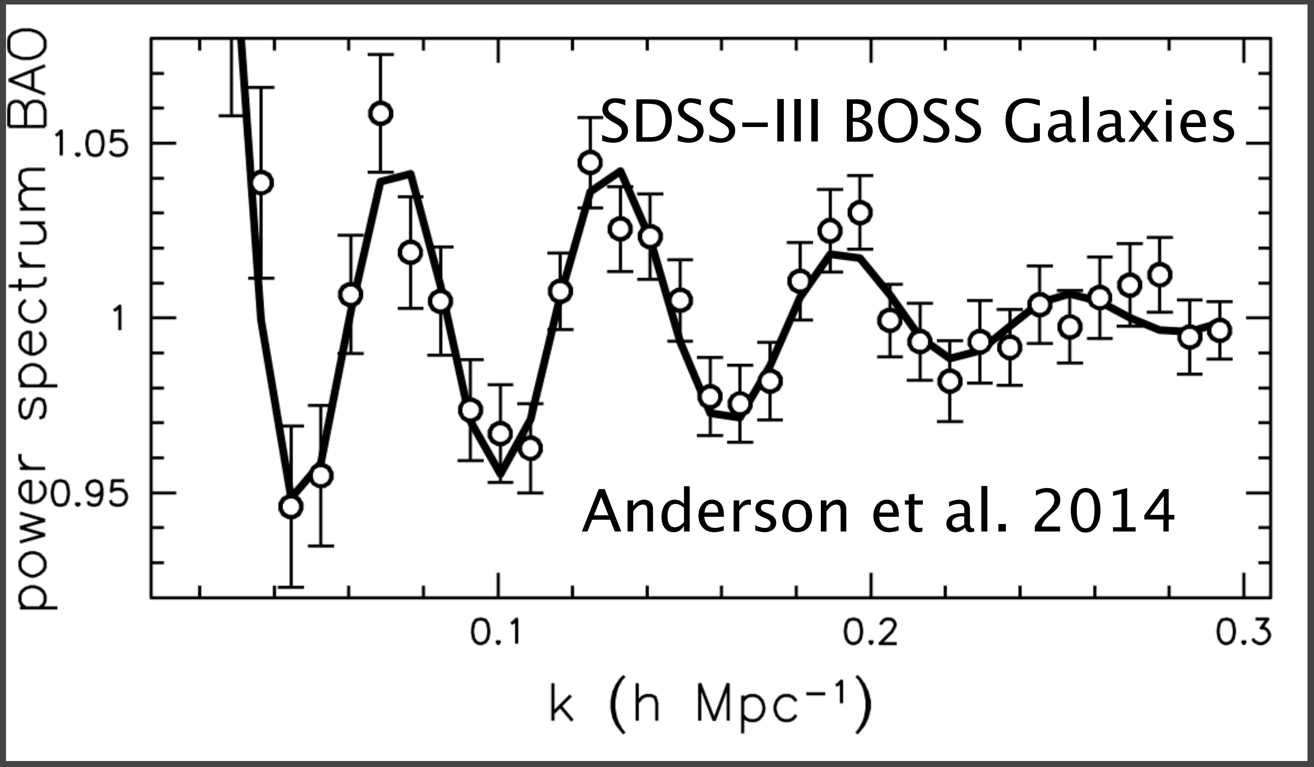


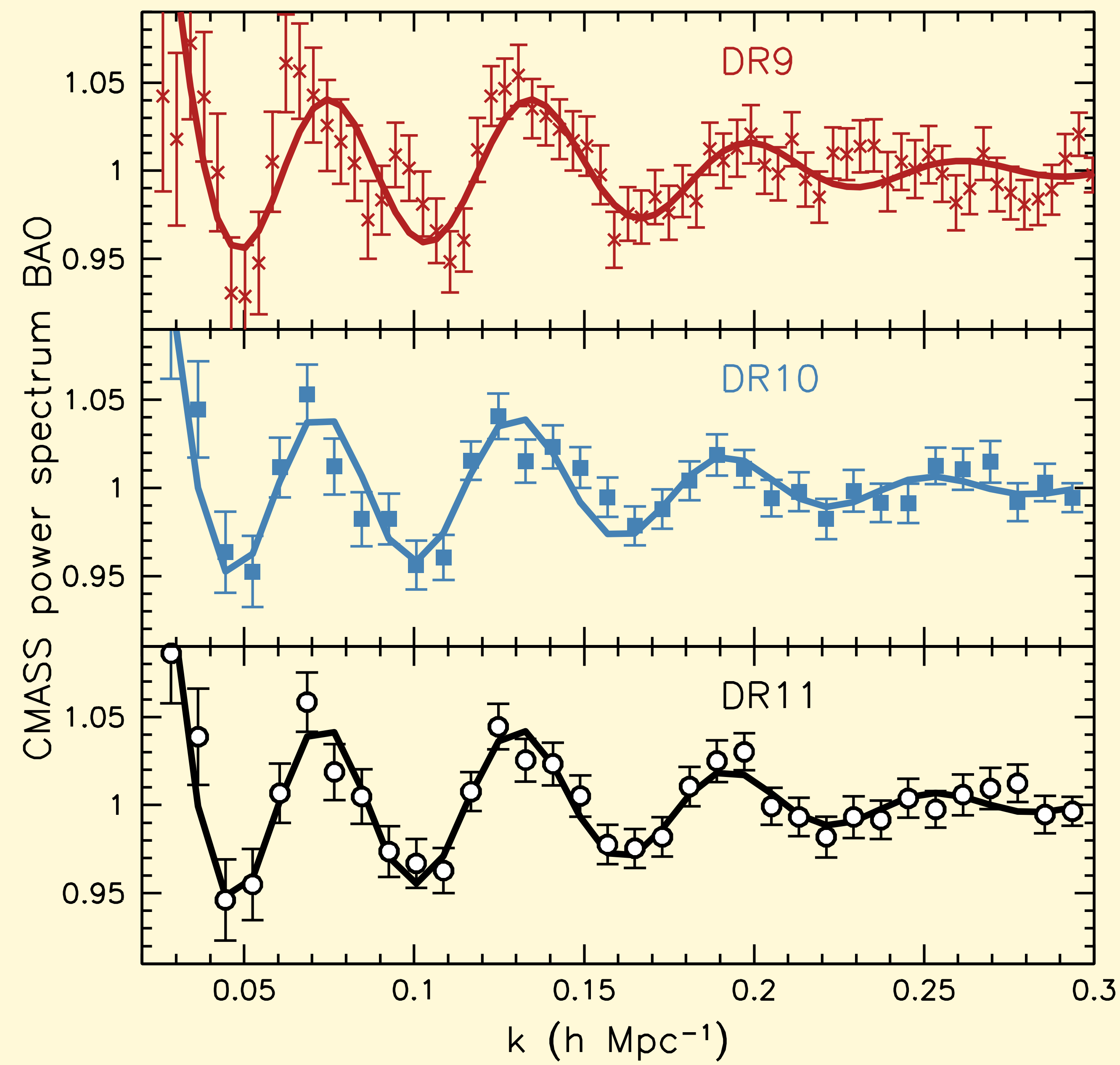
- CMB measurement gives calibrated "standard ruler" for feature found in galaxies





BOSS DR11 BAO

- 1% distance measurement to z = 0.57
- 2% distance measurement to z = 0.32
- distance is: $D_V(z) \equiv [czH^{-1}(z)D_A^2(z)(1+z)^2]^{1/3}$



Anderson et al. (2014)
Tojeiro et al. (2014)

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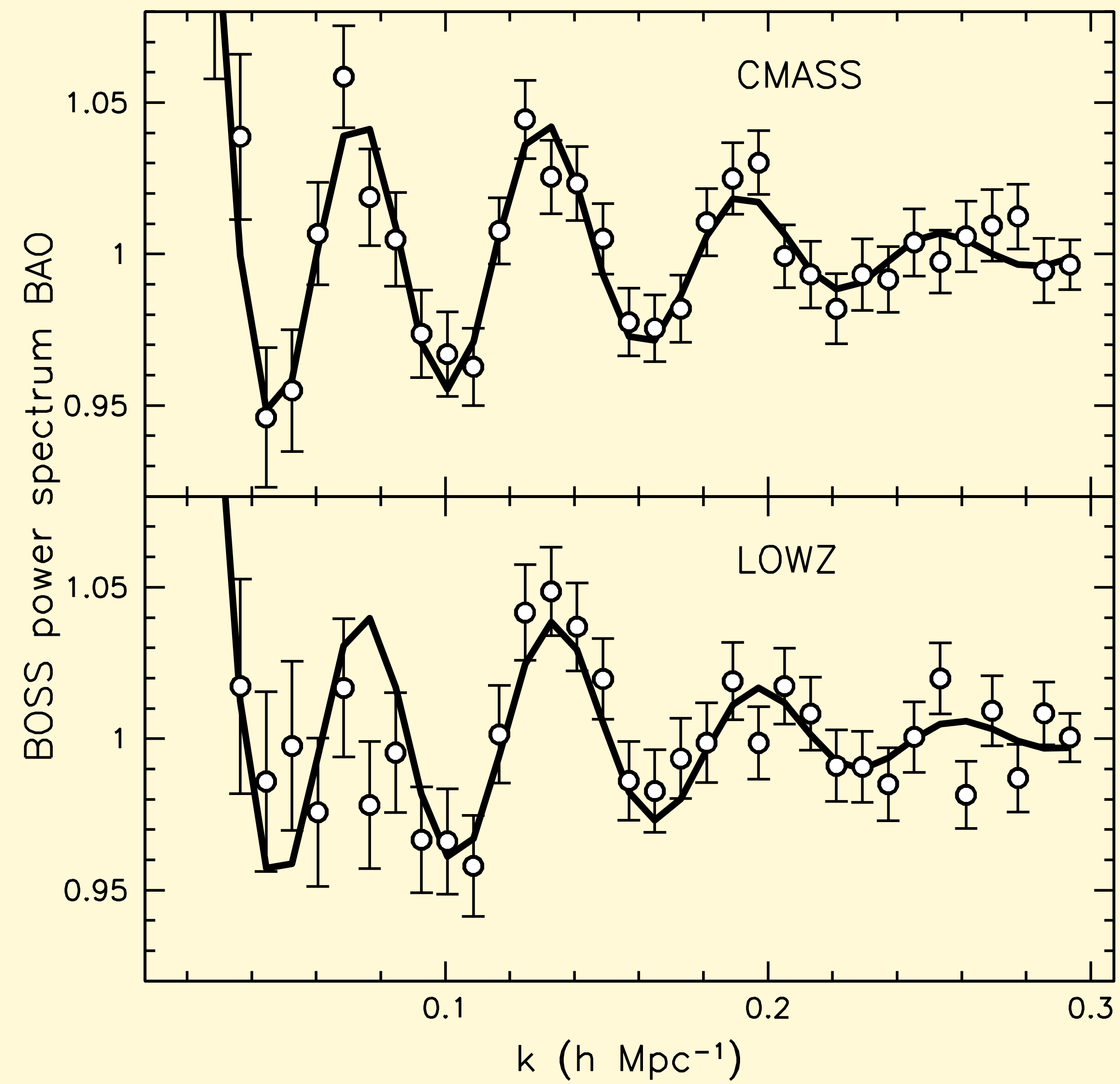

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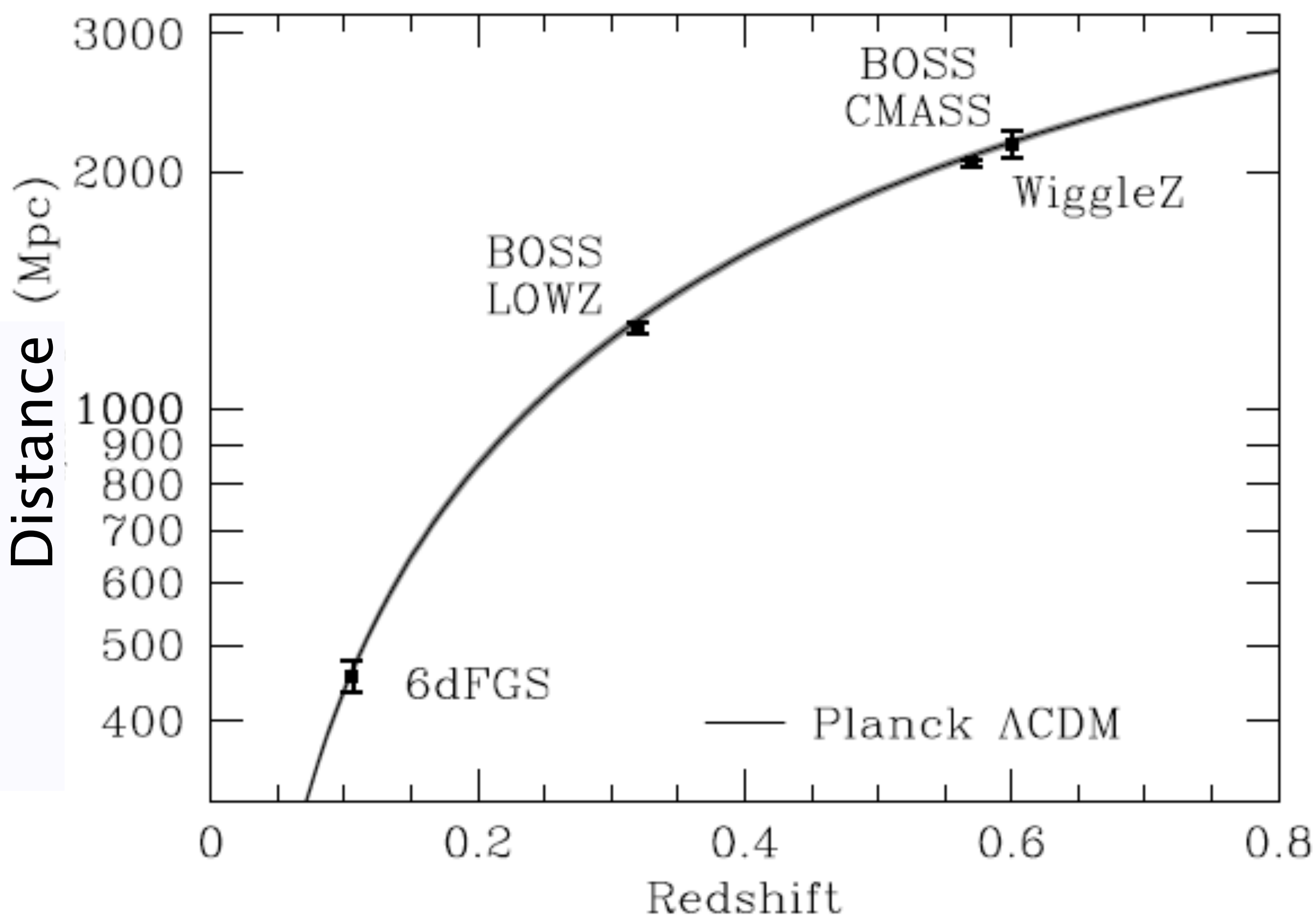
Expansion History with BAO



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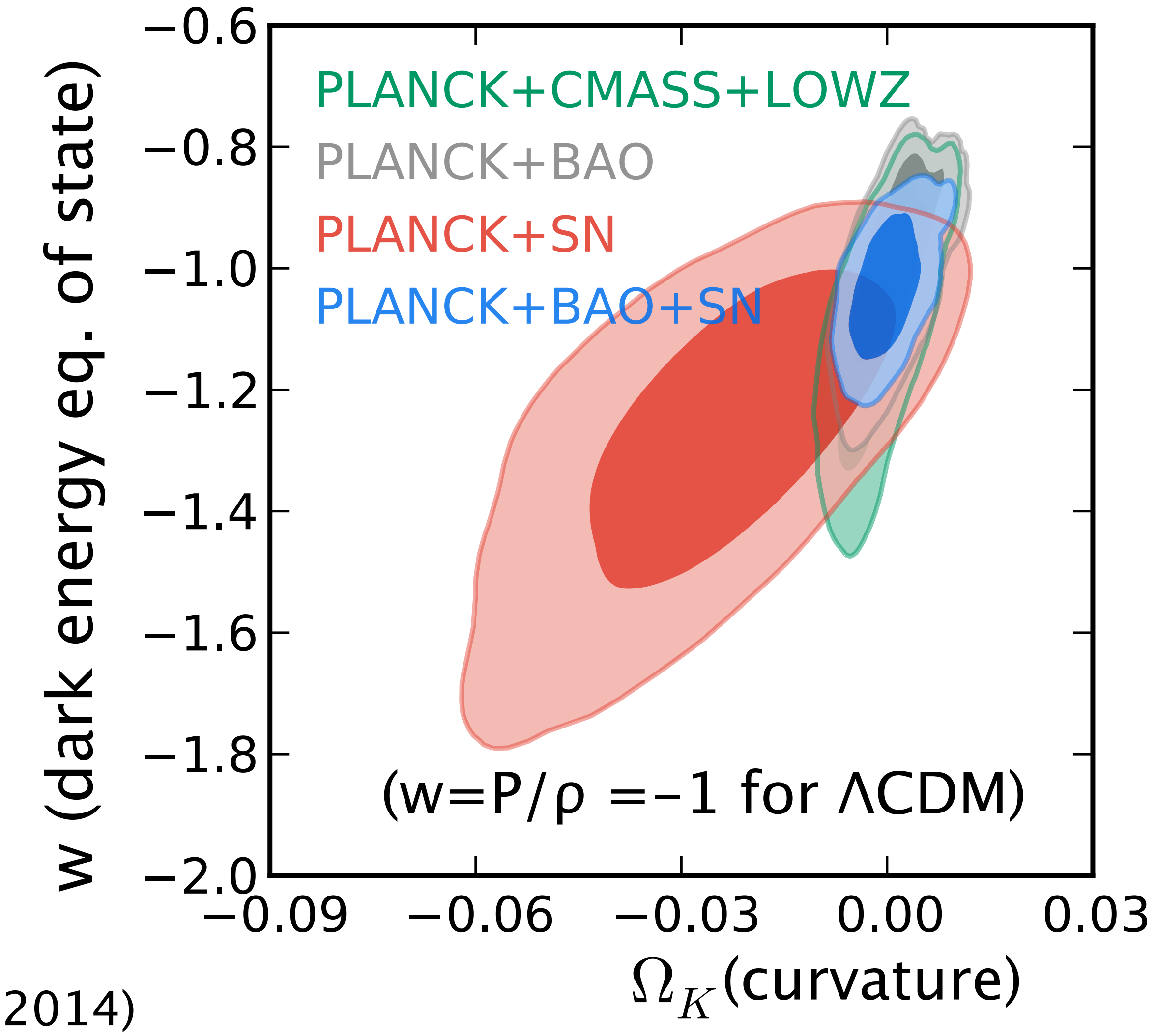
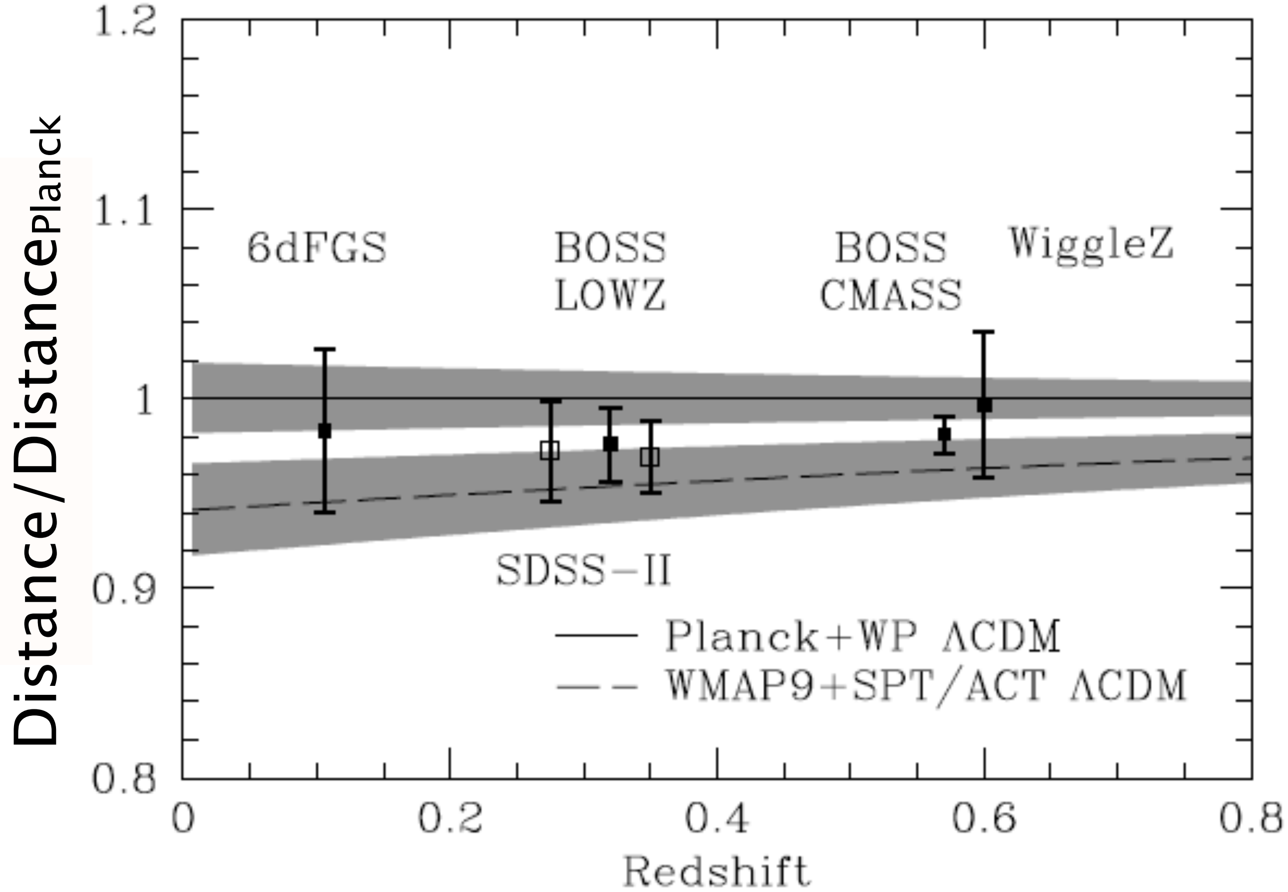


Expansion History with BAO compared to CMB



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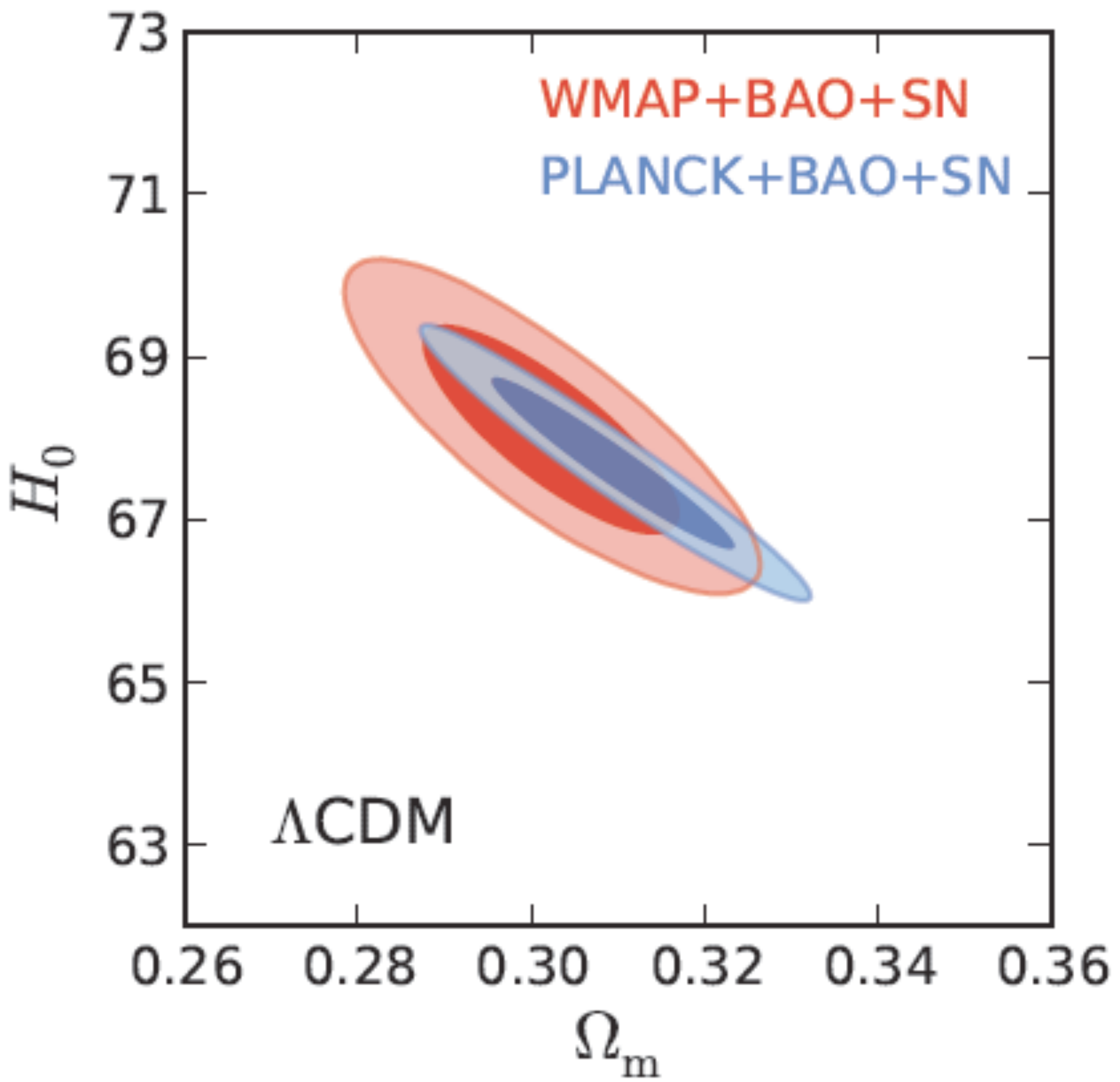

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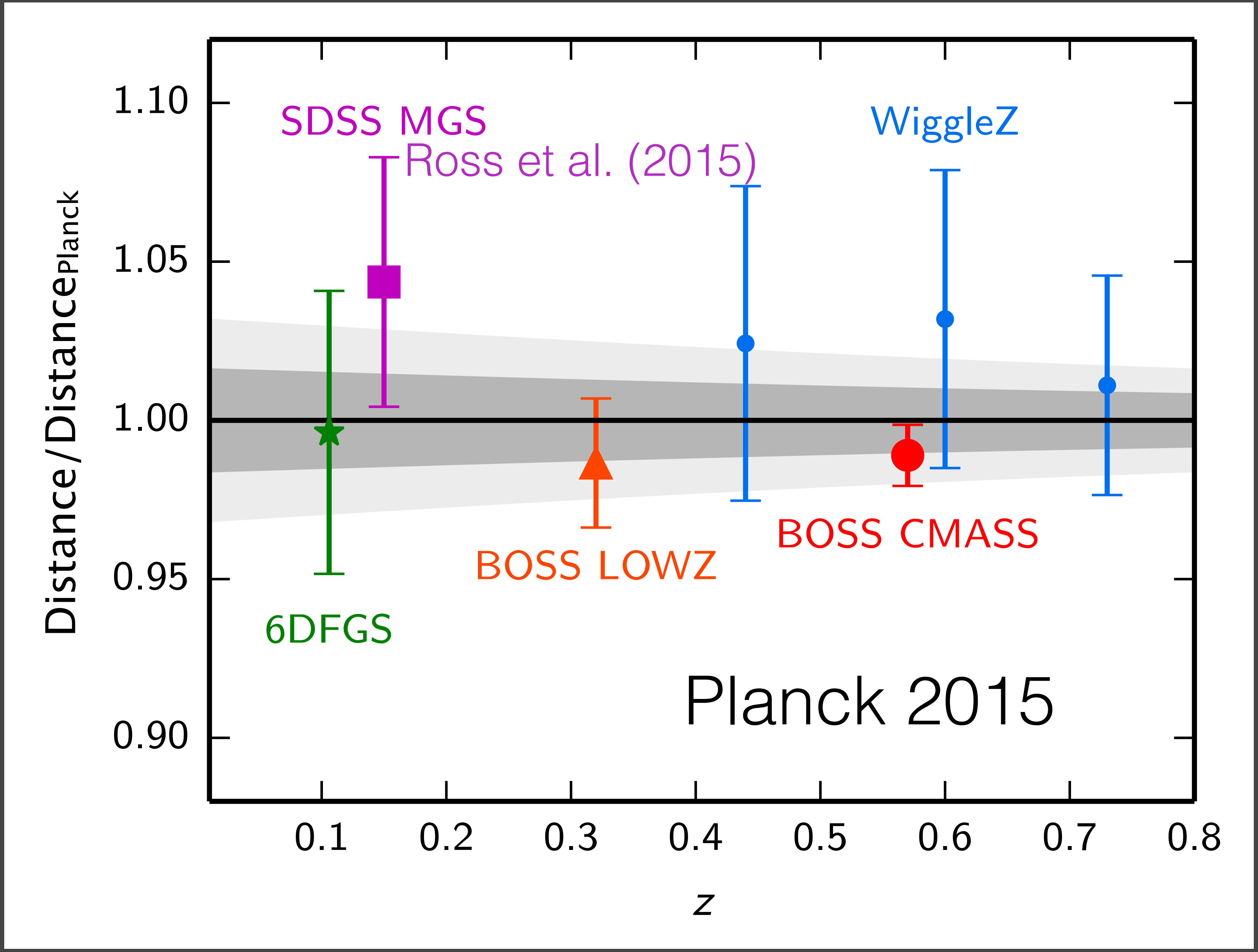
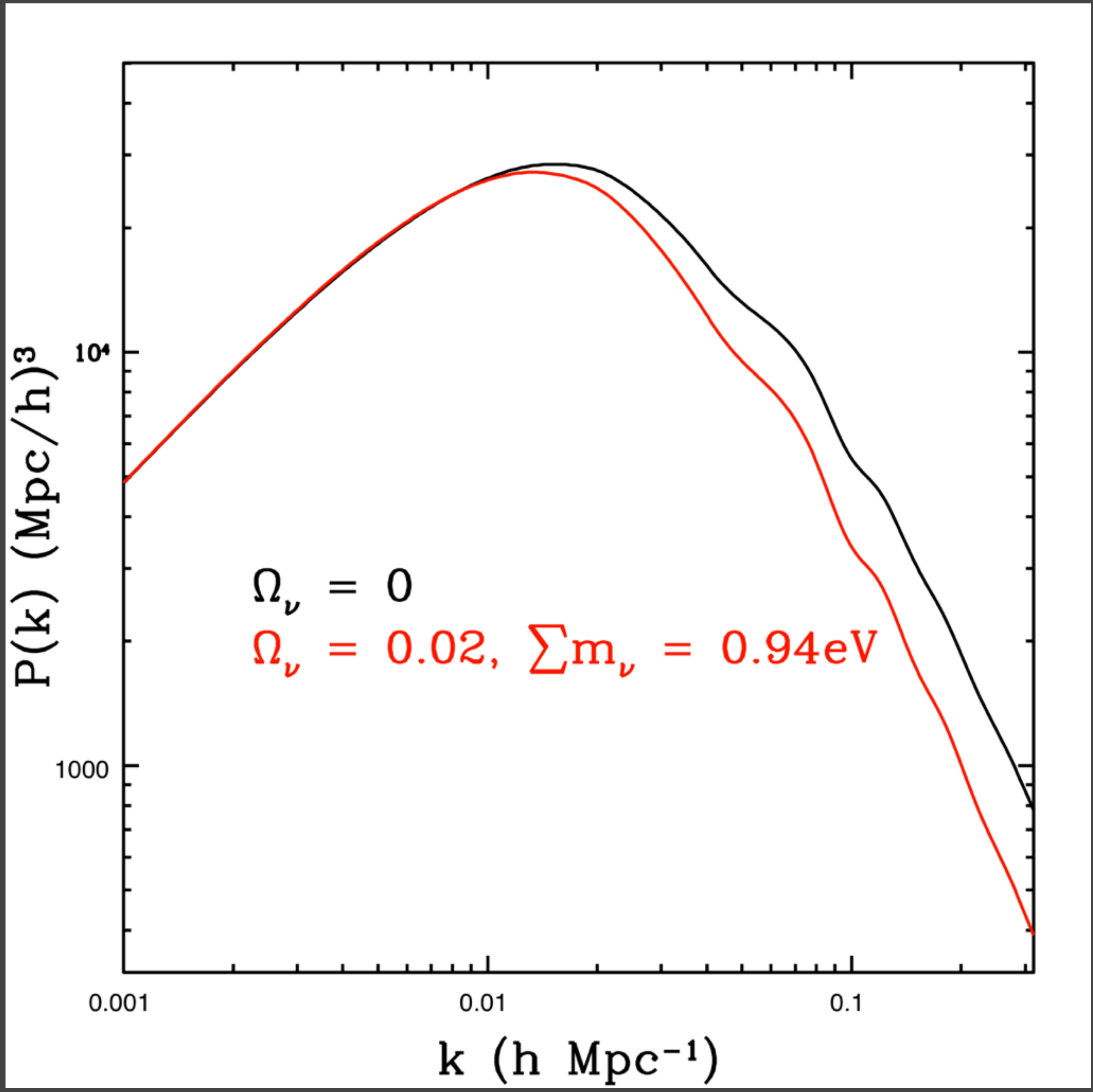


Neutrino Mass

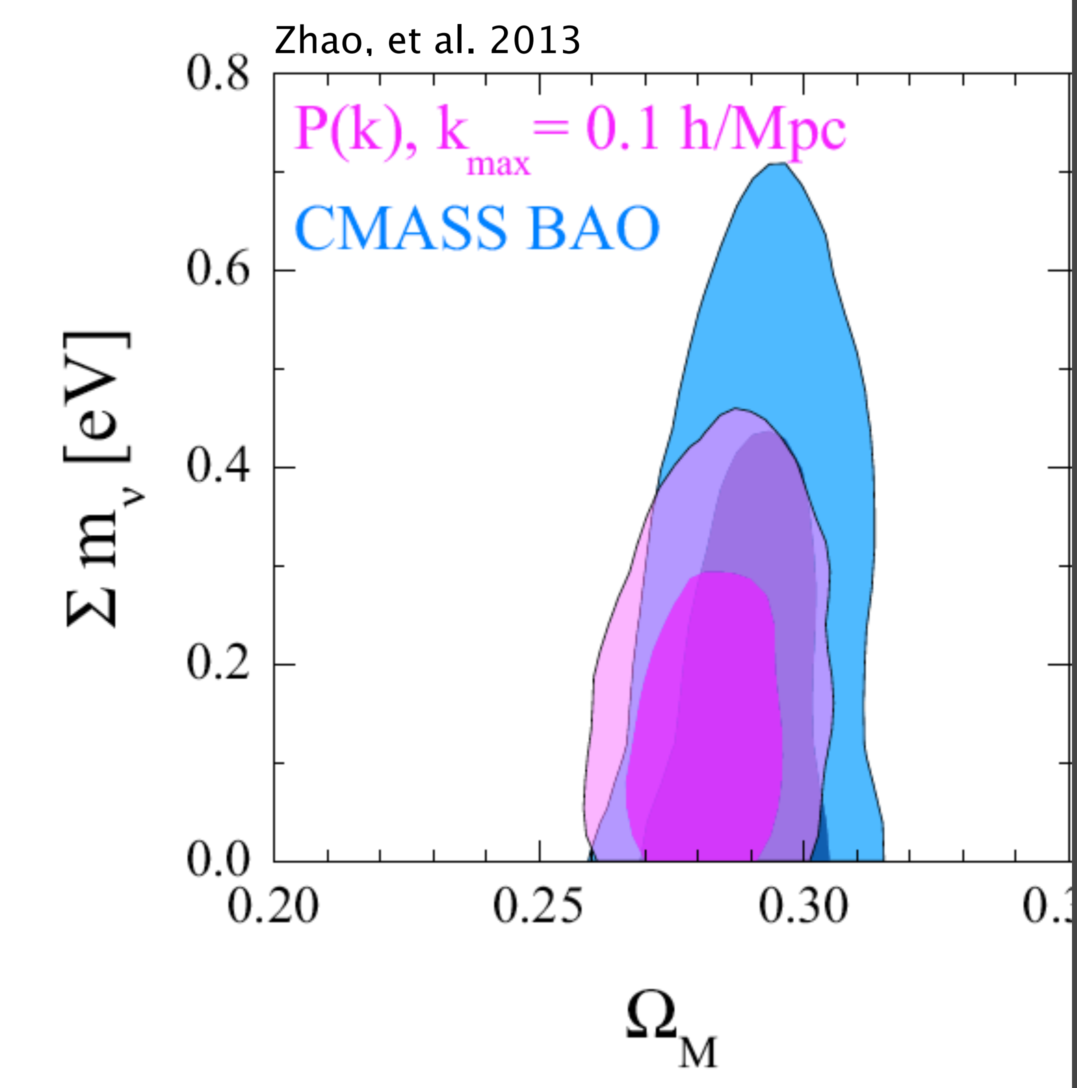
Neutrino Mass

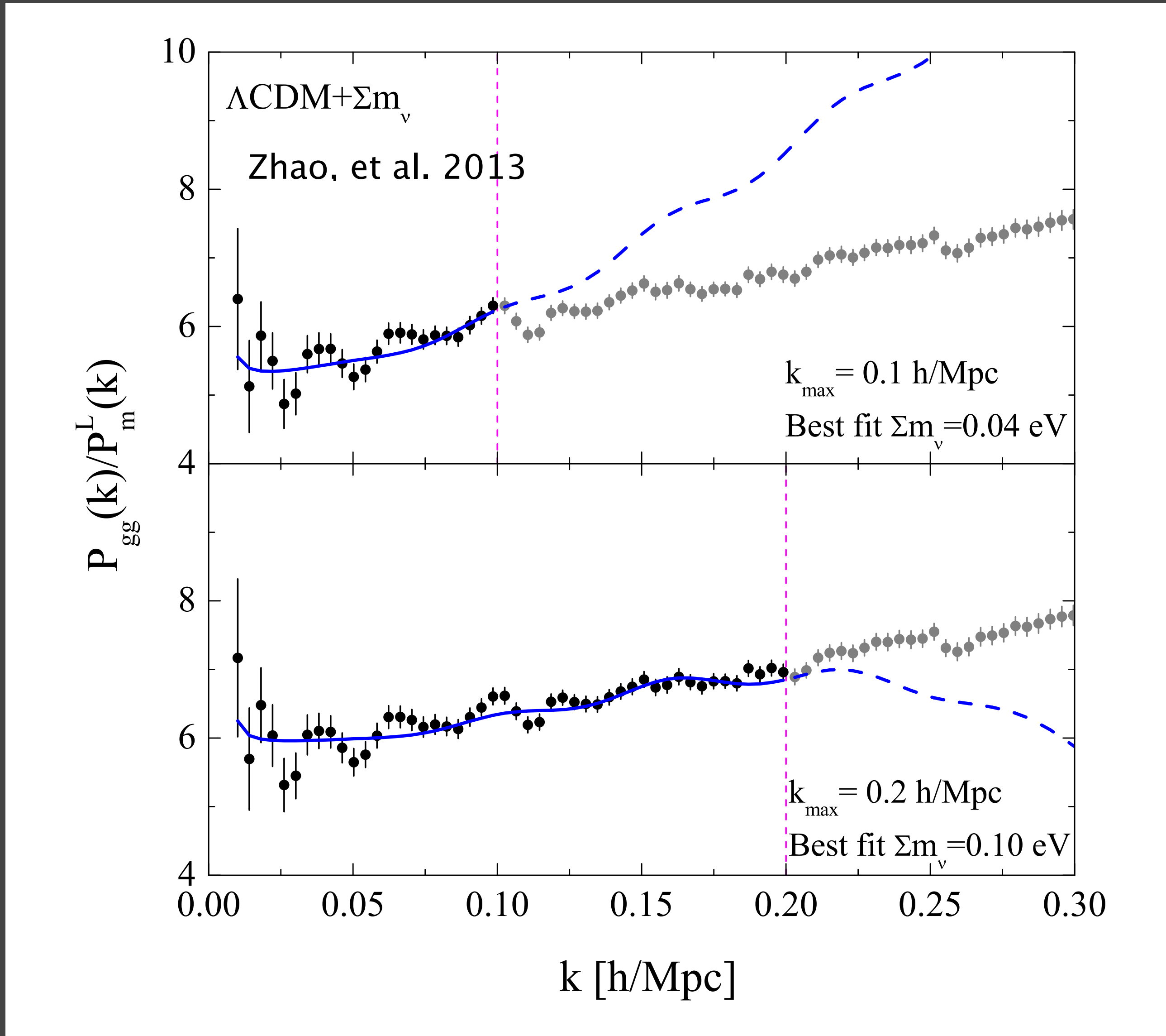
- Neutrinos remain relativistic at later times
- suppresses formation of smaller-scale structure
- (at least) 3 ways to measure with LSS:
  - –Direct effect on P(k)
  - –Effect on structure growth (e.g., Beutler et al. 2014)
  - –Use BAO measurements to break CMB degeneracies



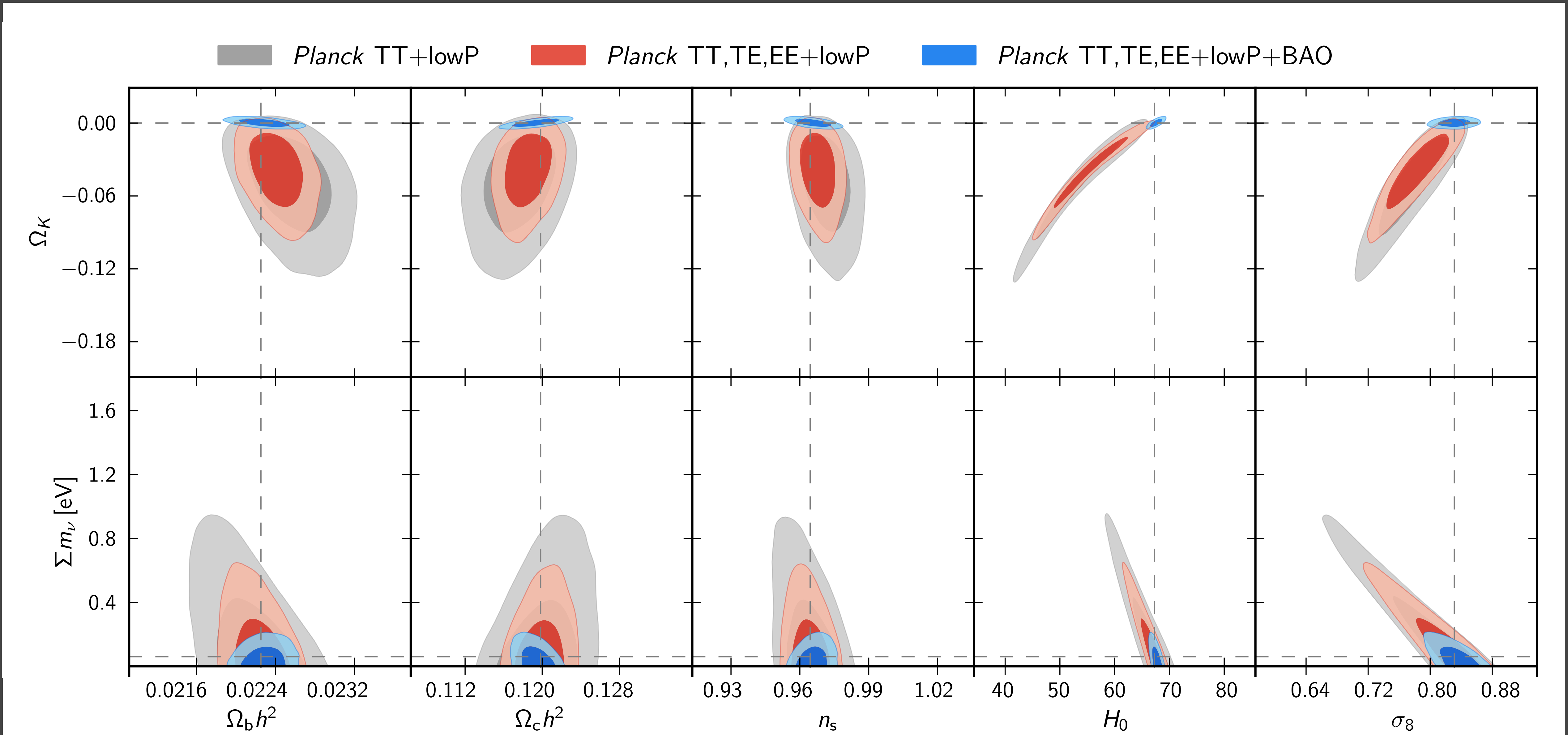
Neutrino mass constraints: P(k) shape

- DR9+WMAP (Zhao et al. 2013)
  - $\sum m_\nu < 0.34$ eV (95%; ΛCDM), < 0.58 eV (just BAO+CMB)





Neutrino mass constraints: CMB +BAO



Planck Collaboration 2015

Details

Details

theoretical clustering of matter

Theoretical systematics

clustering of galaxies

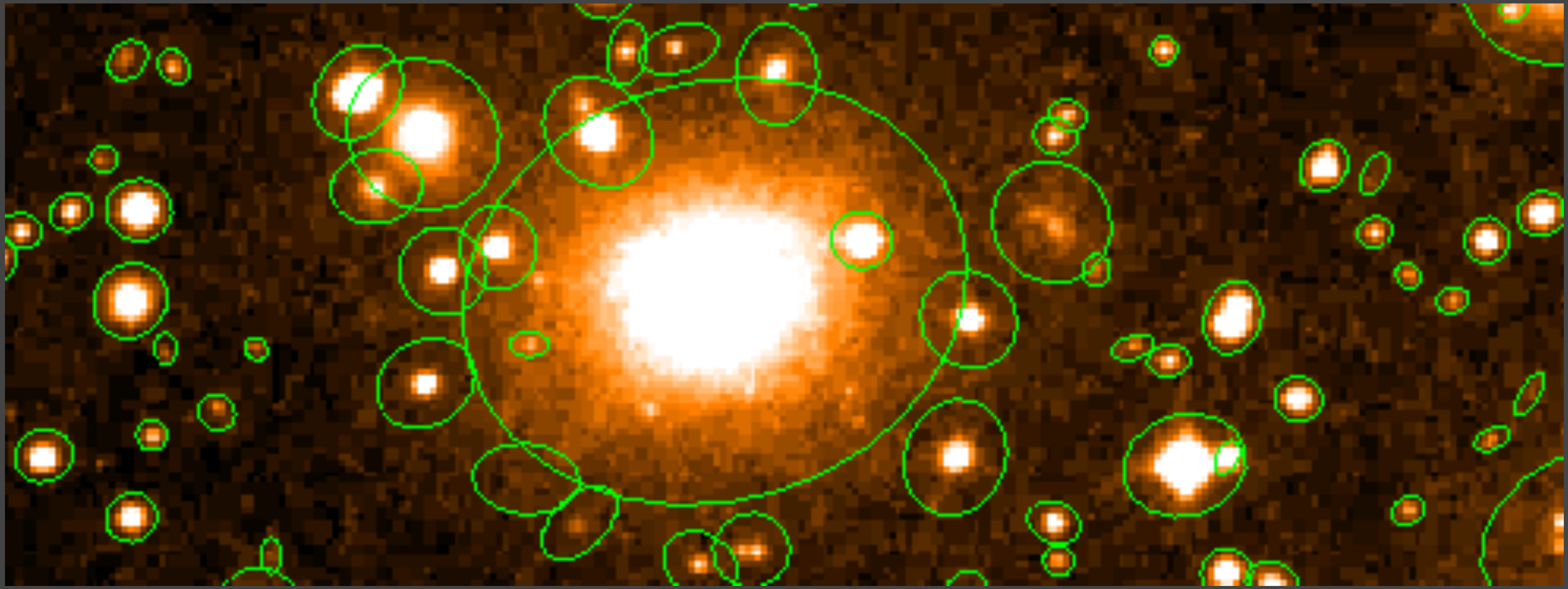
Observational systematics

Observed galaxies

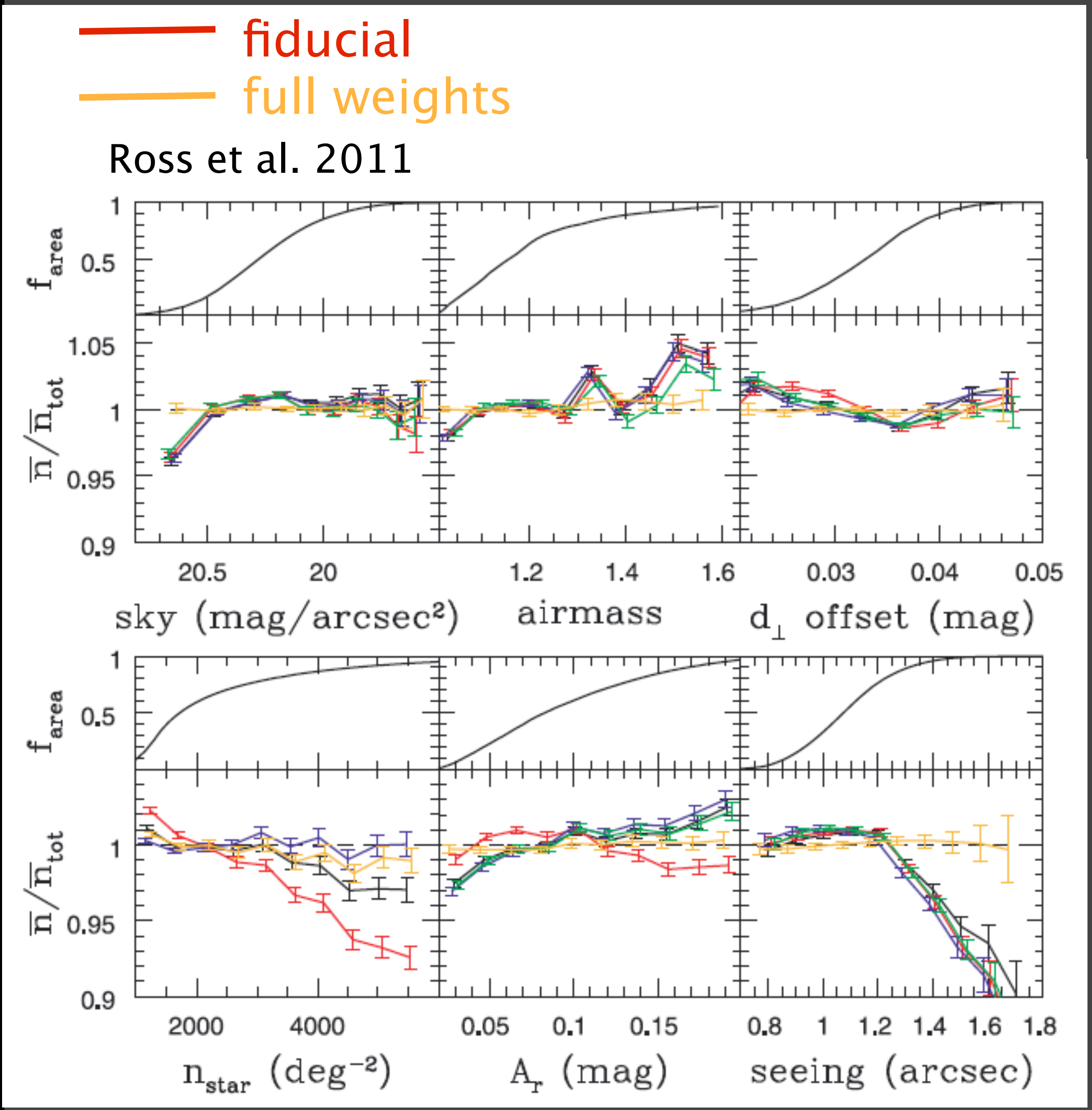
Observational Systematics

Potential Observational Systematics

- Atmospheric conditions (seeing, airmass)
- Background light (sky background)
- Foregrounds (stars, Galactic ‘dust’)
- Calibration uncertainties



BOSS imaging systematics



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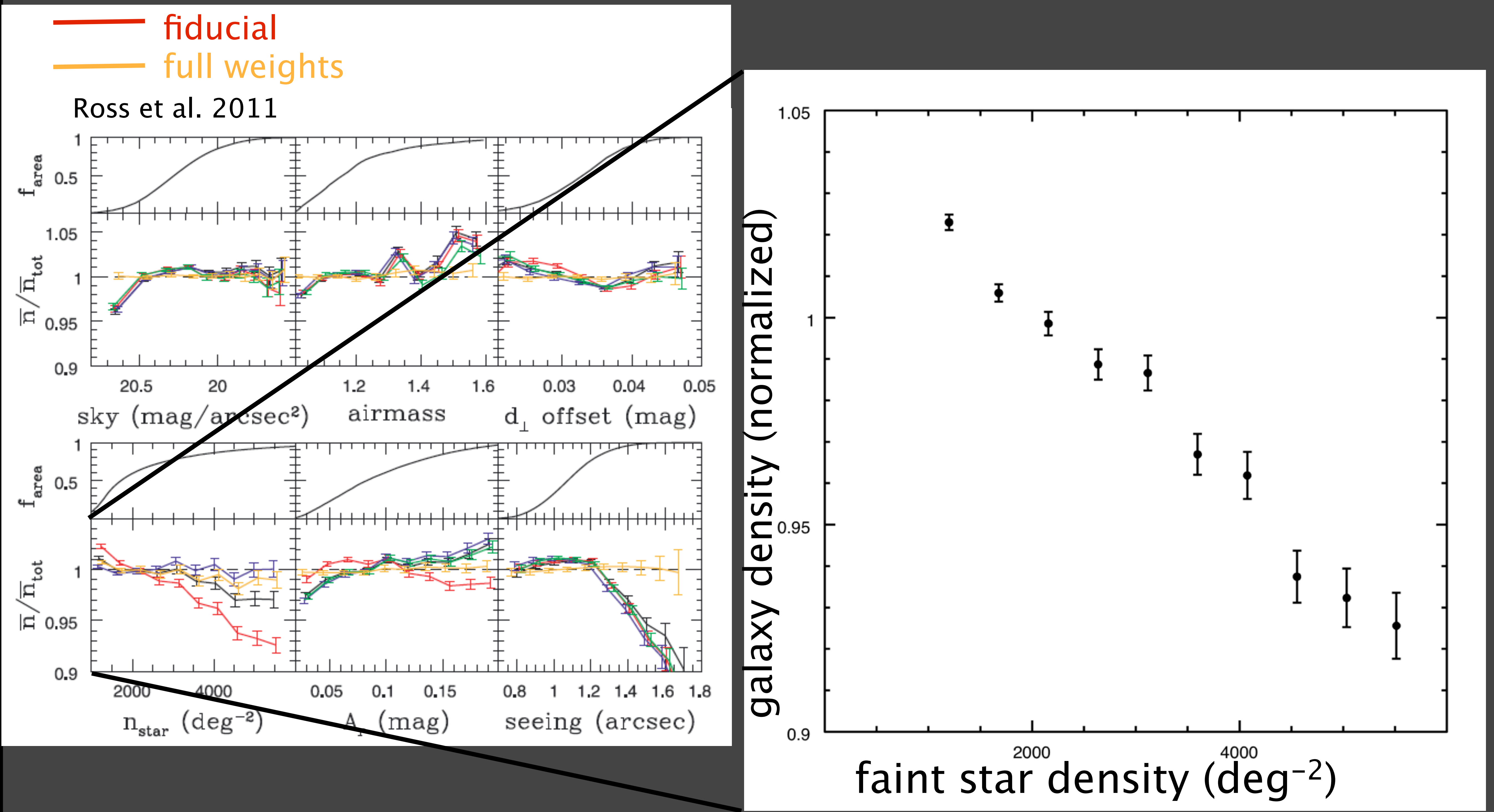
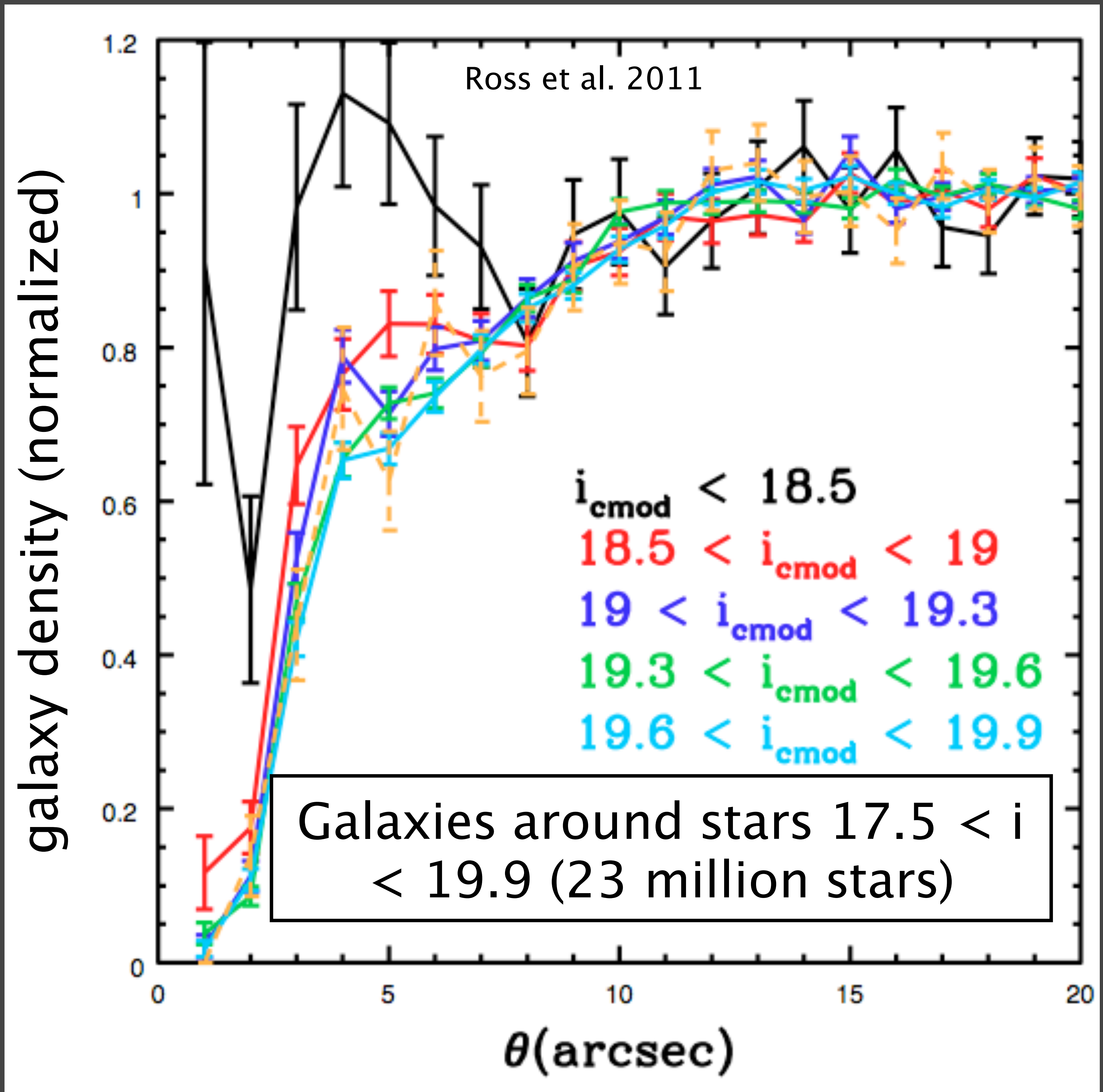
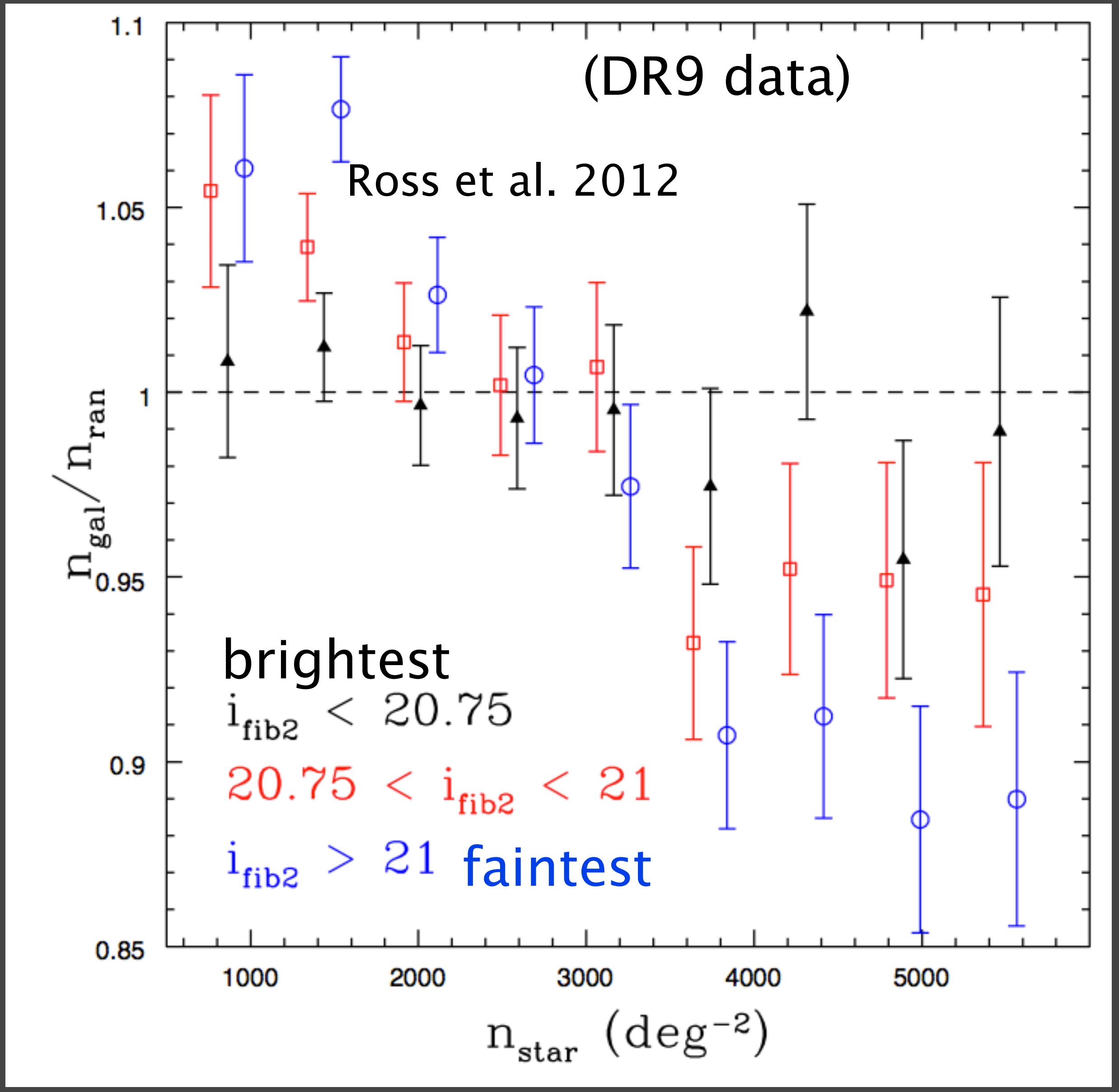


Stars Occult Area

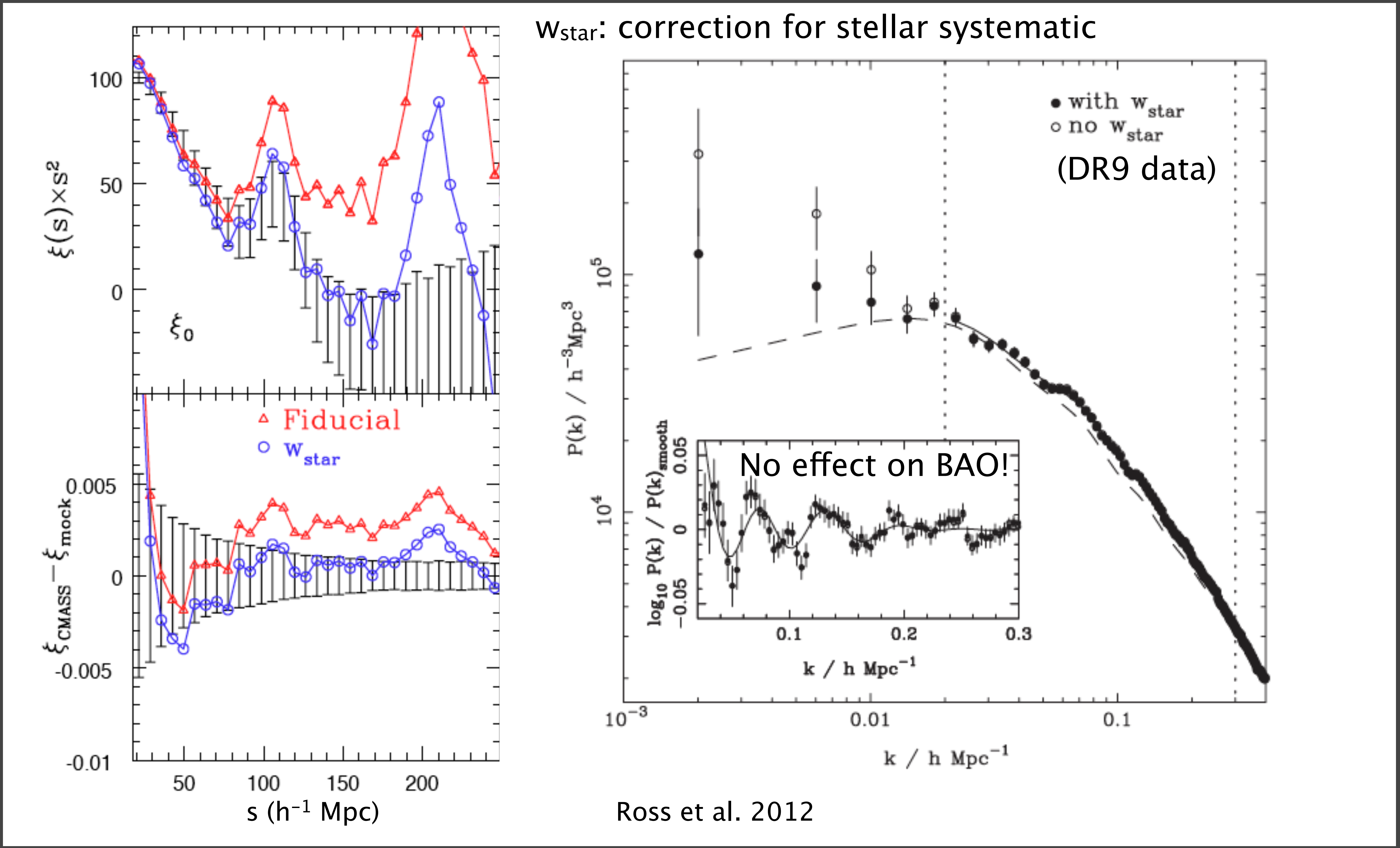


Stars and BOSS Surface Brightness

- Spectroscopic results confirm galaxy vs. stellar density relationship
- Depends on surface brightness
- Corrected with weights based on linear fits



Effect on BOSS clustering



Theoretical details

theoretical clustering of matter

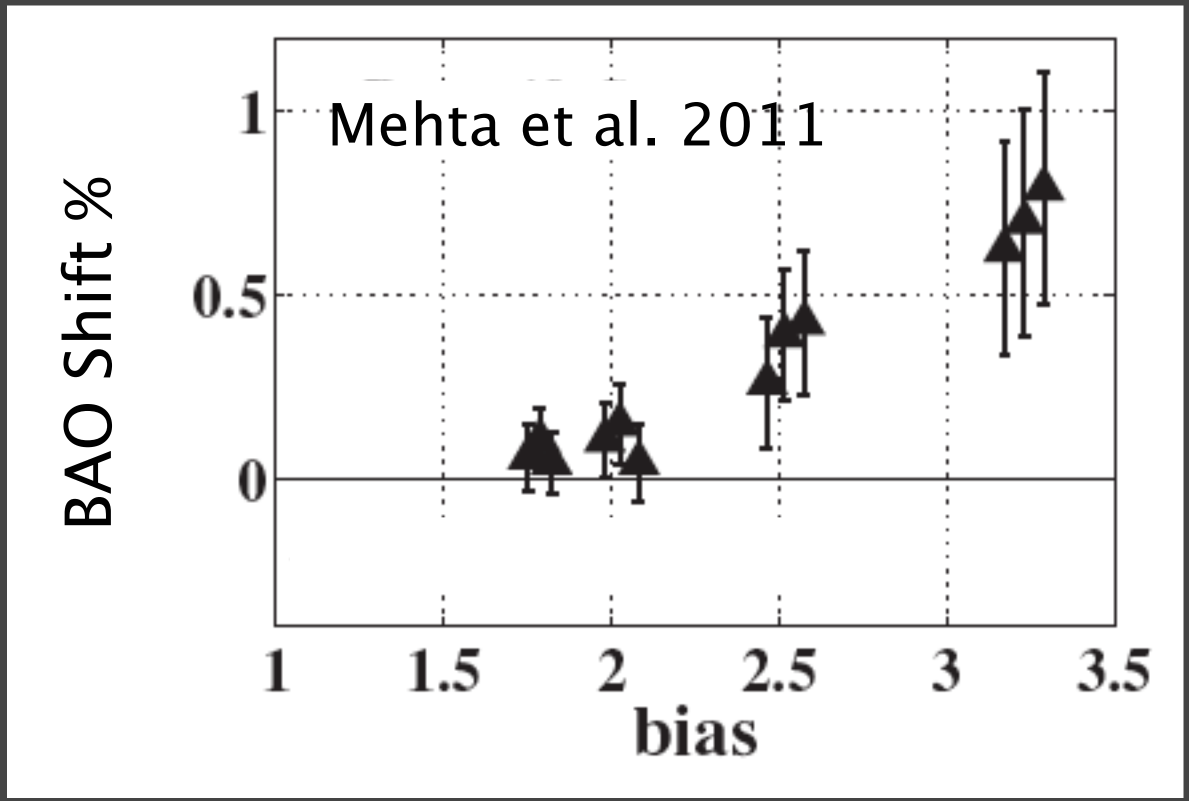
↔

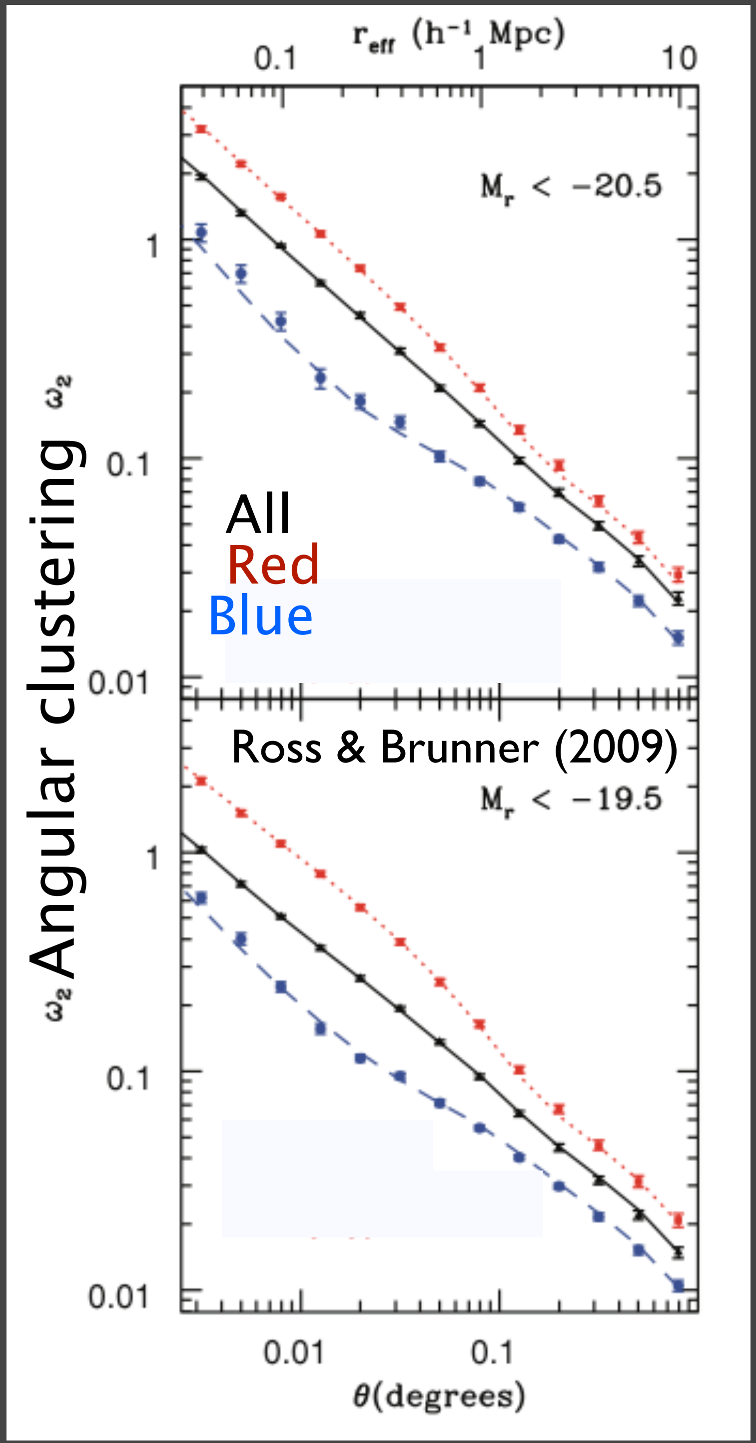
observed clustering of galaxies

Galaxy bias: light $\neq$ mass

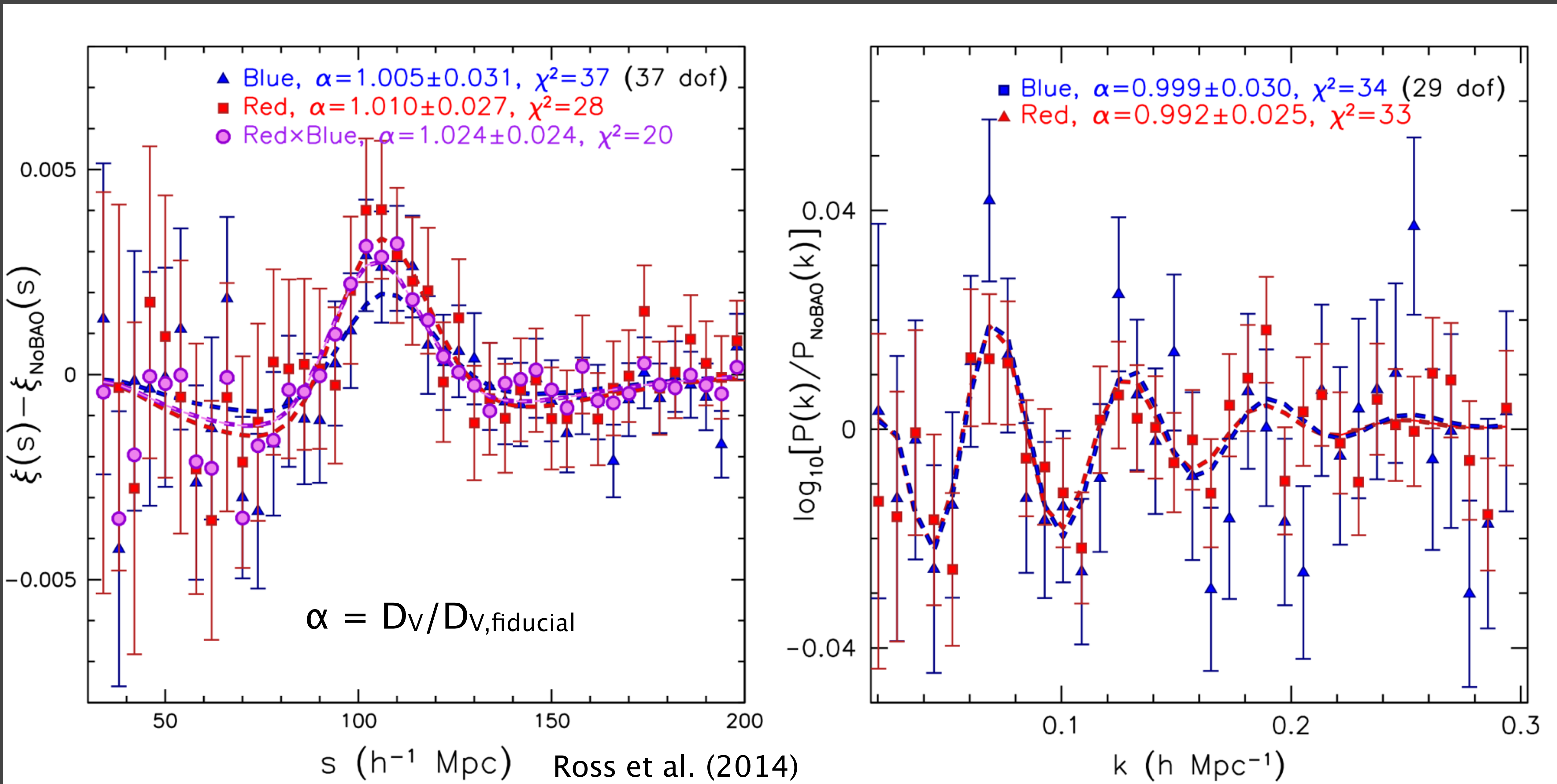
Red and Blue Galaxies

- Galaxy population bi-modal red/blue
- ideal for testing systematic effect from galaxy evolution



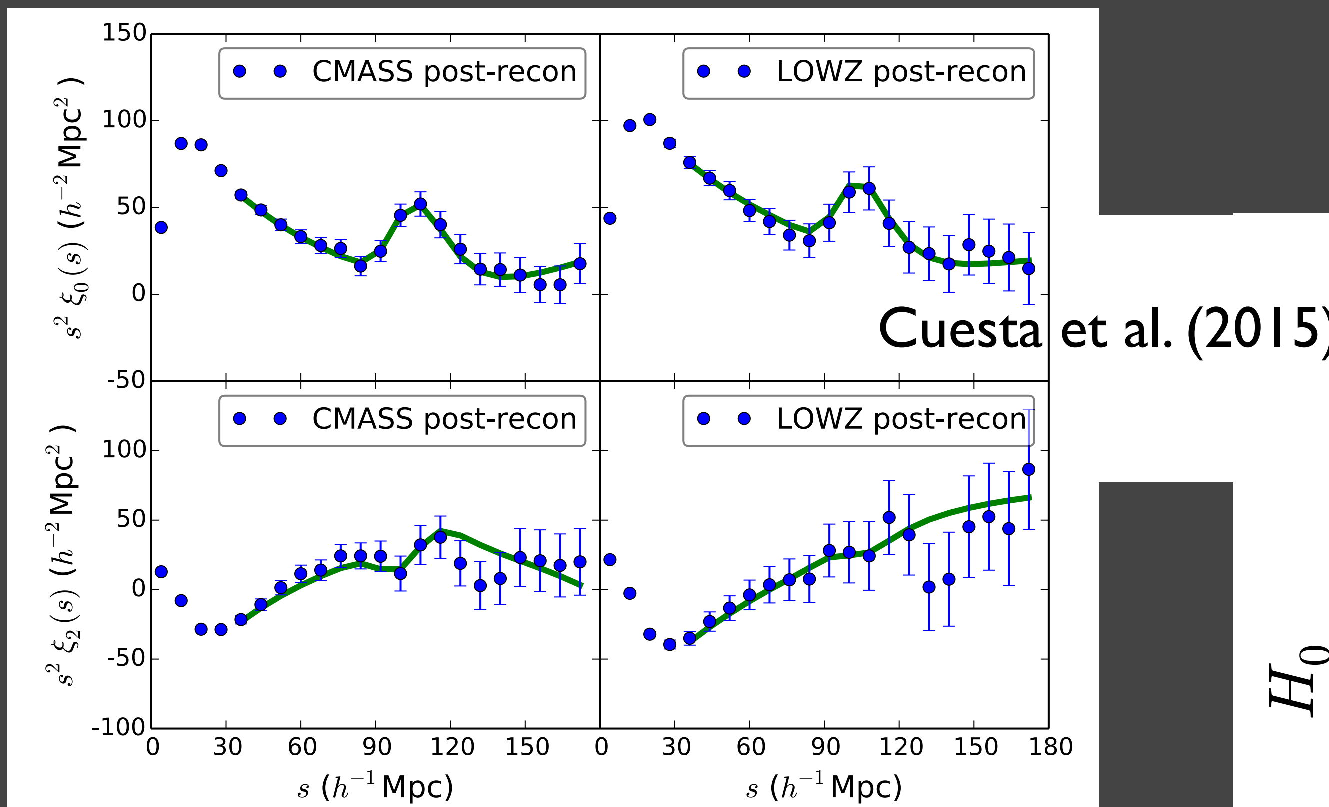


Red/Blue BOSS BAO



Ross et al. (2014)

BOSS DR12


CMASS post-recon
LOWZ post-recon
CMASS post-recon
LOWZ post-recon
Cuesta et al. (2015)
$s^2\,\xi_0(s)\ (h^{-2}\,\mathrm{Mpc}^2)$
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$s\ (h^{-1}\,\mathrm{Mpc})$
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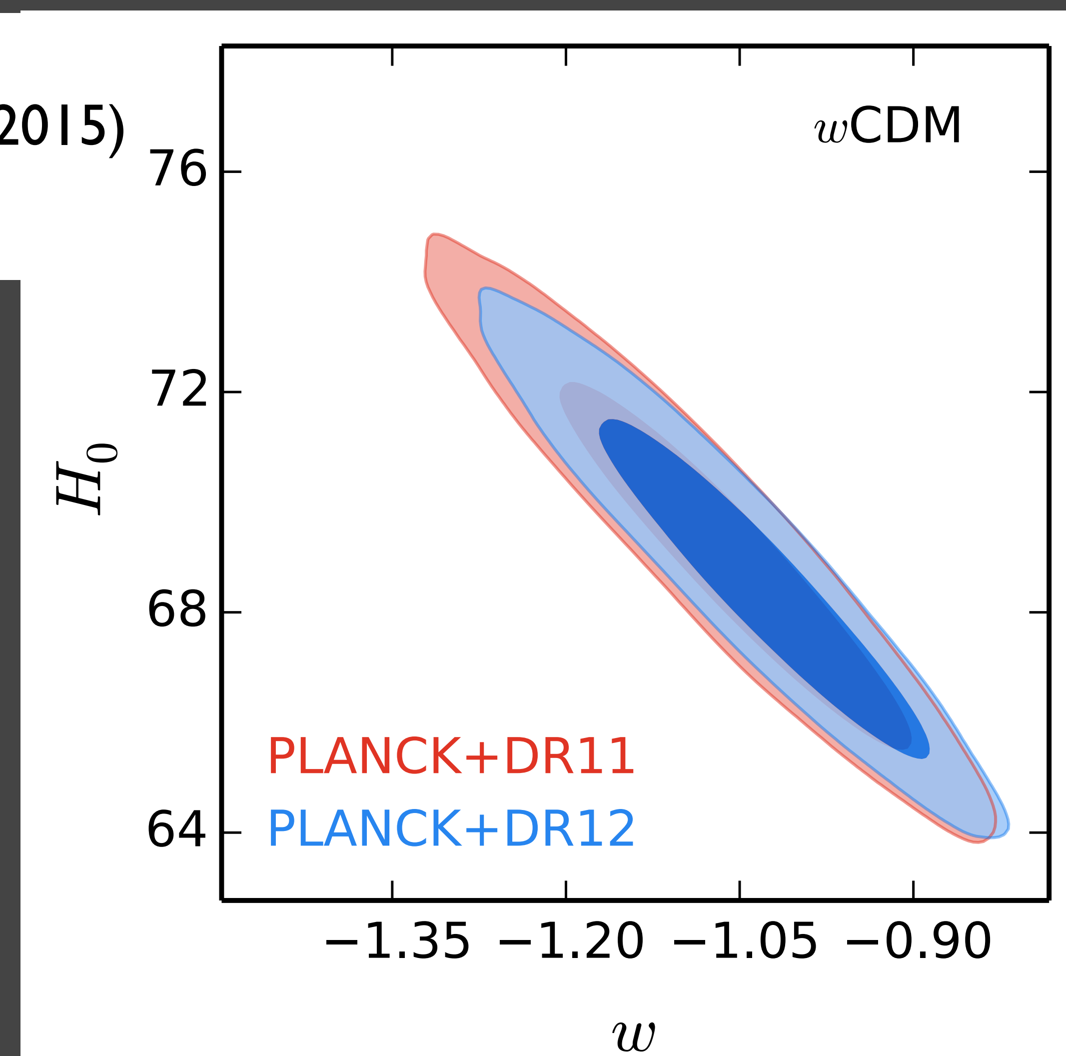
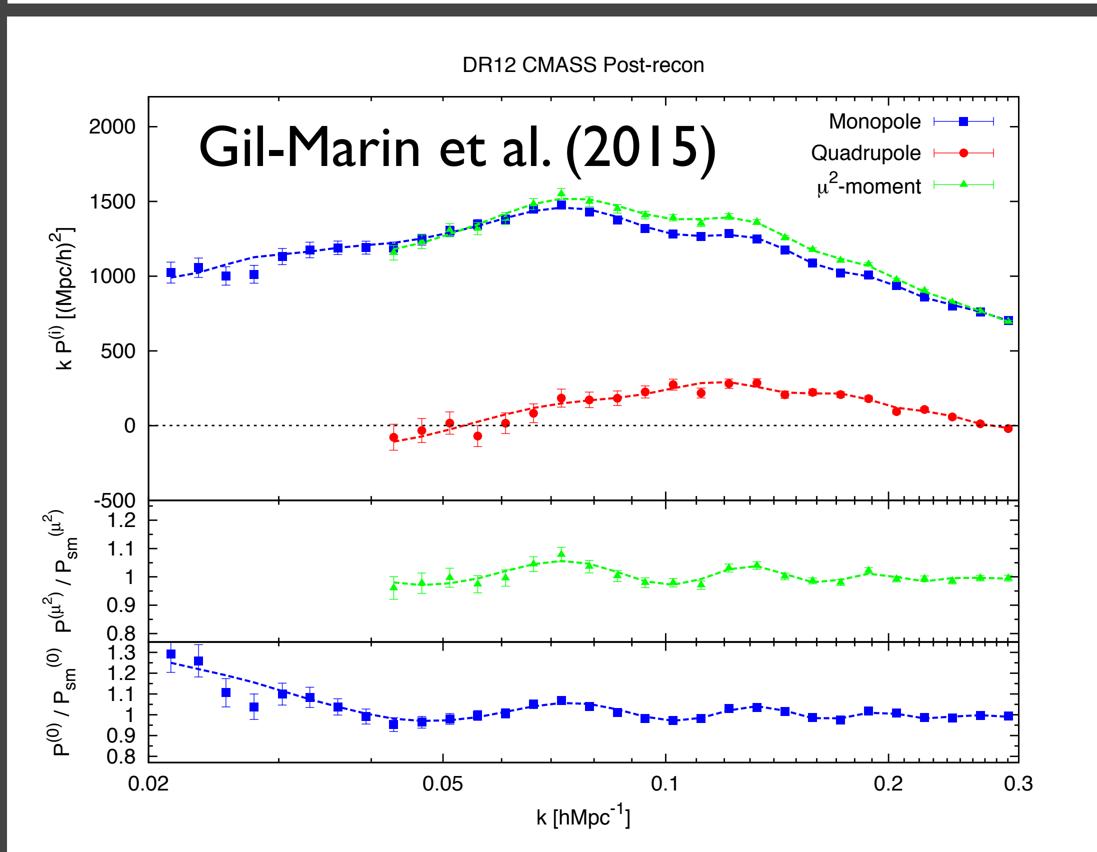
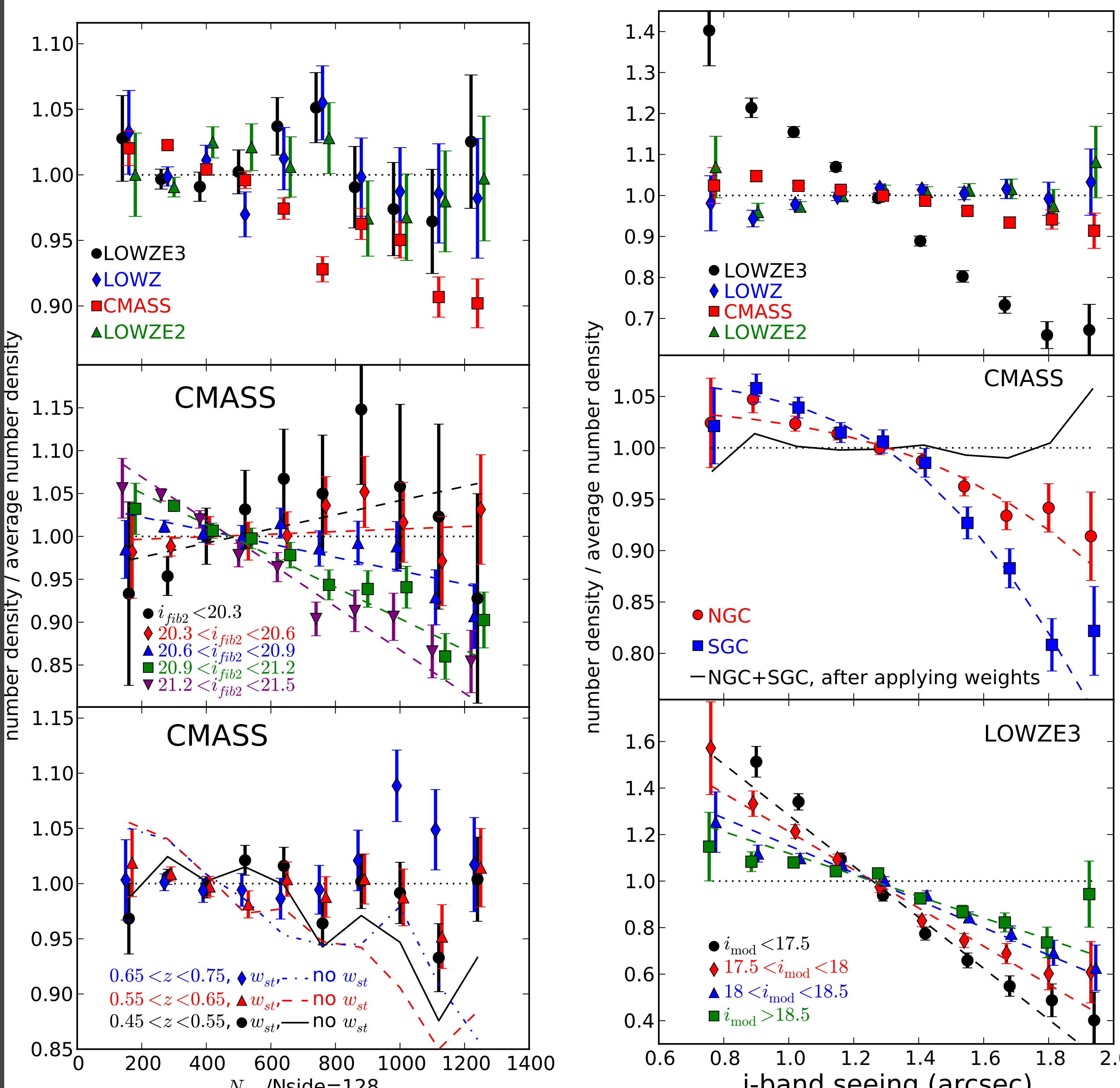
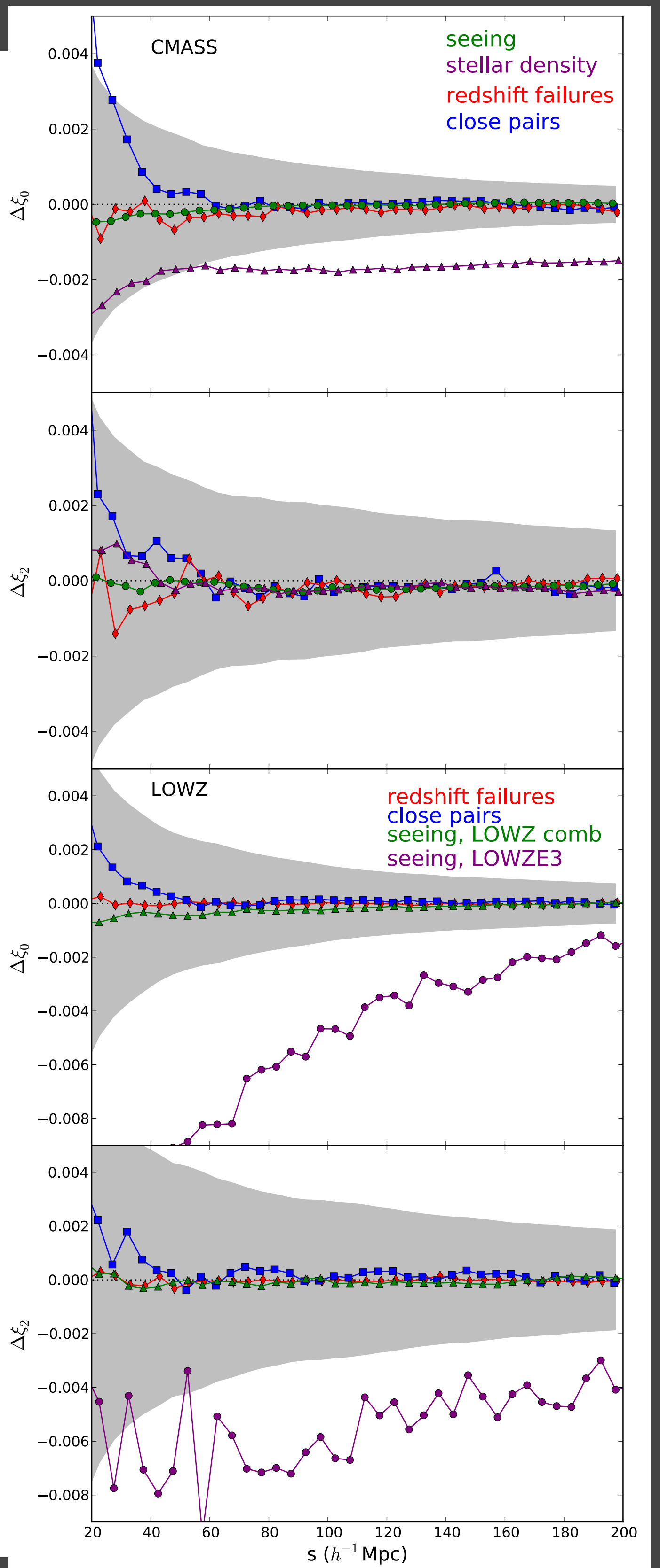

wCDM
PLANCK+DR11
PLANCK+DR12
H_0
w


DR12 CMASS Post-recon
Gil-Marin et al. (2015)
Monopole
Quadrupole
μ^2-moment
$k\,P^{(l)}$ [(Mpc/h)^2]
$P^{(\mu^2)} / P_{sm}^{(\mu^2)}$
$P^{(0)} / P_{sm}^{(0)}$
k [hMpc^{-1}]

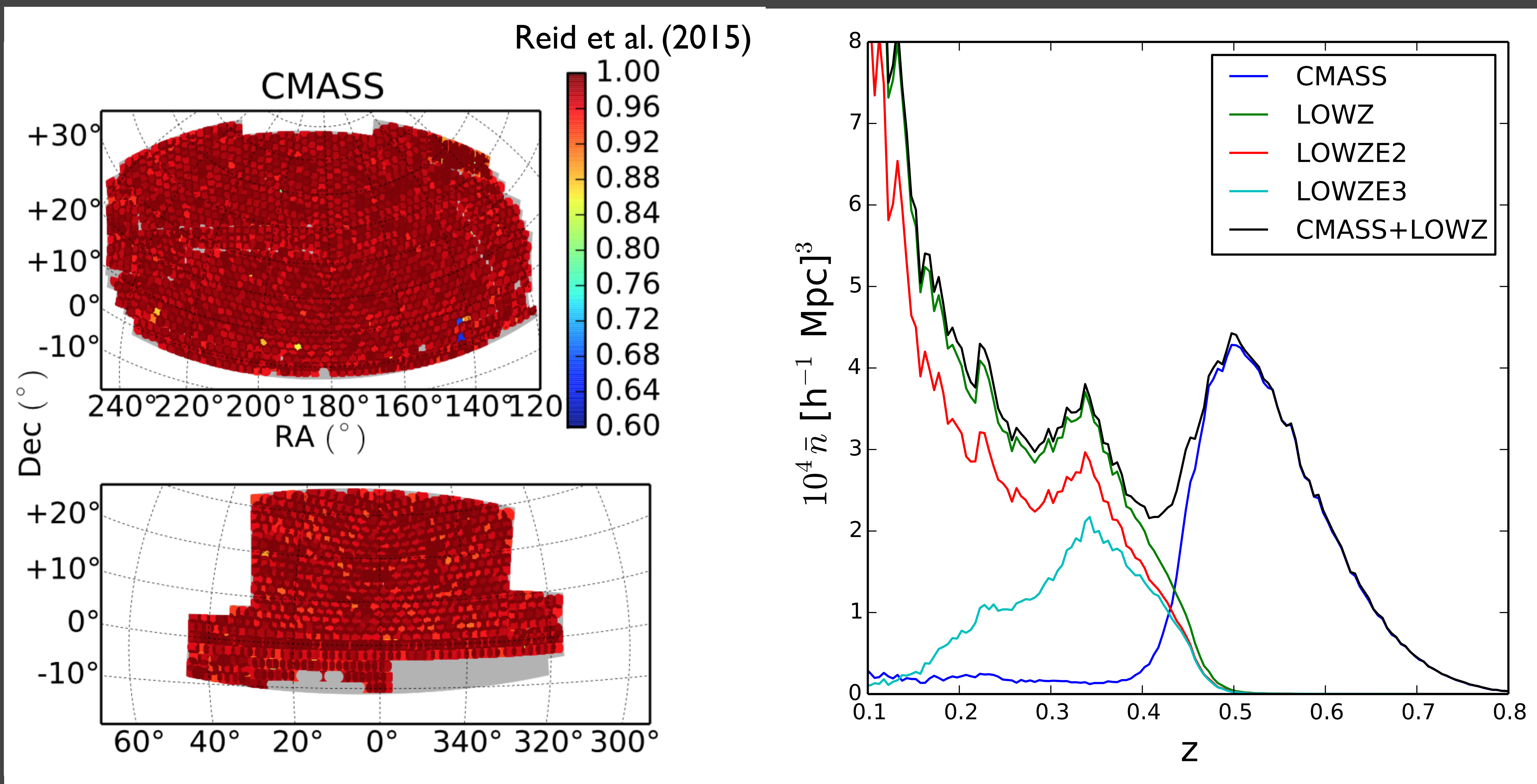
DR12: observational systematics



Ross et al. (in prep.)



BOSS combined sample



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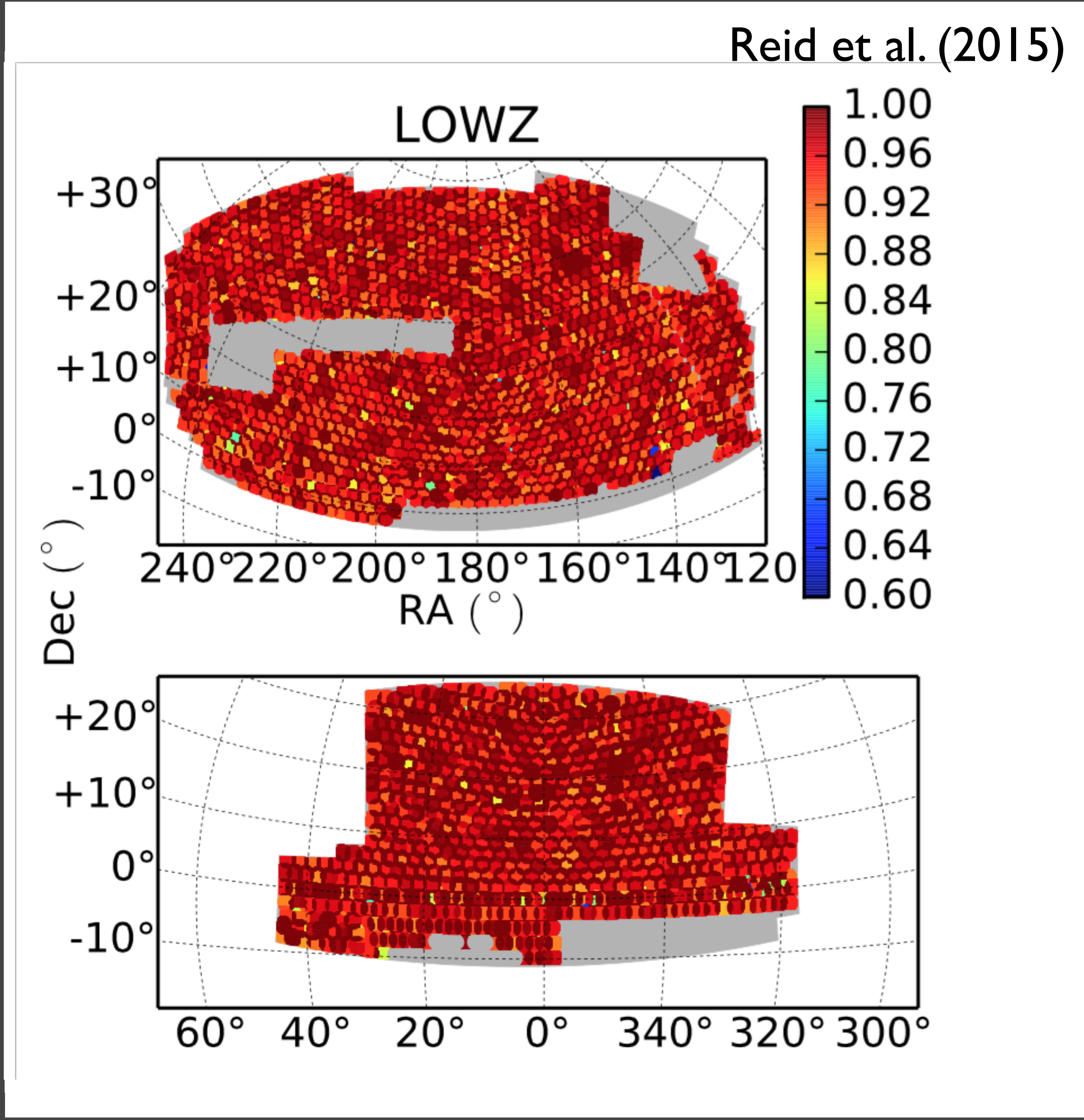
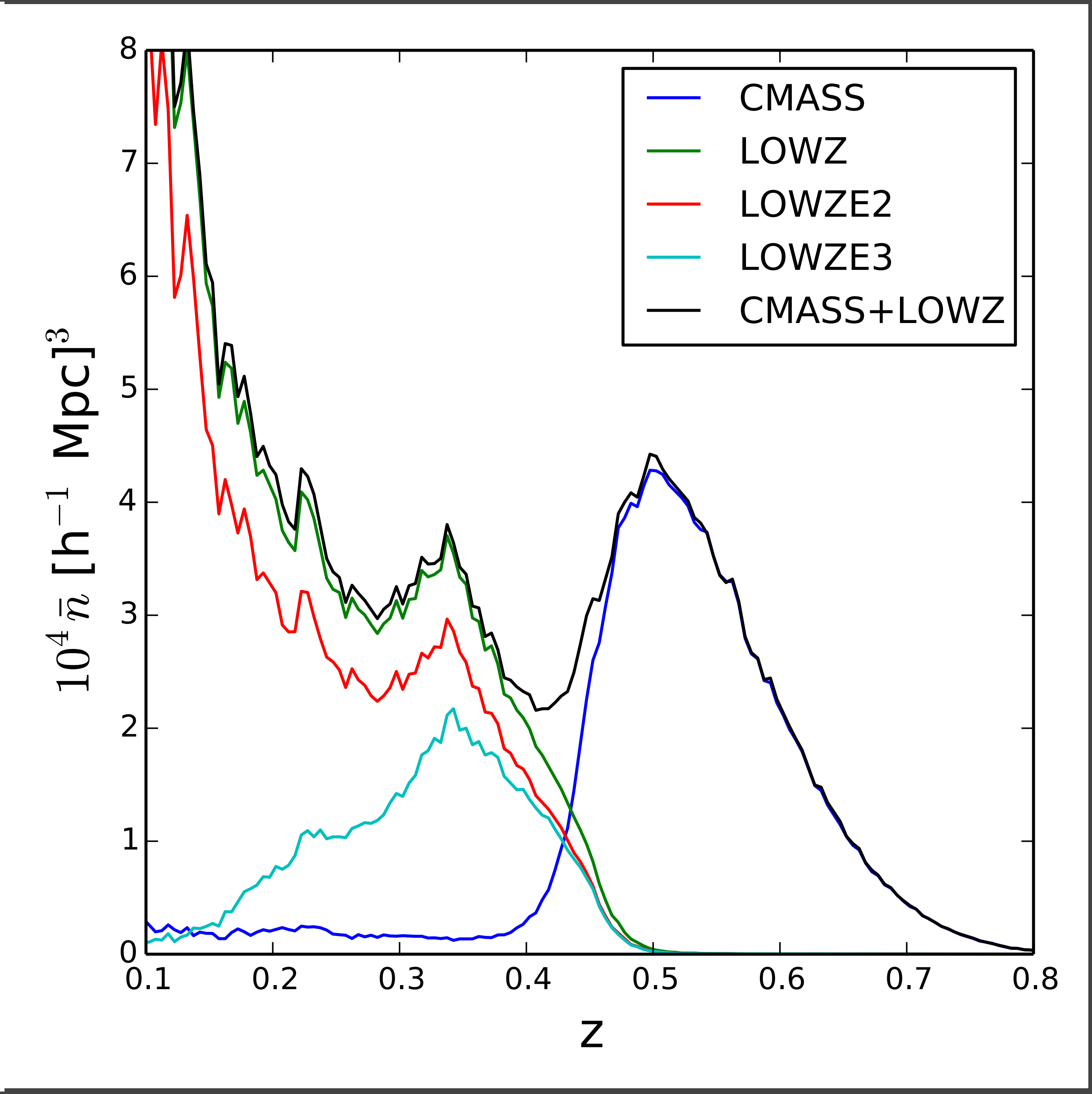
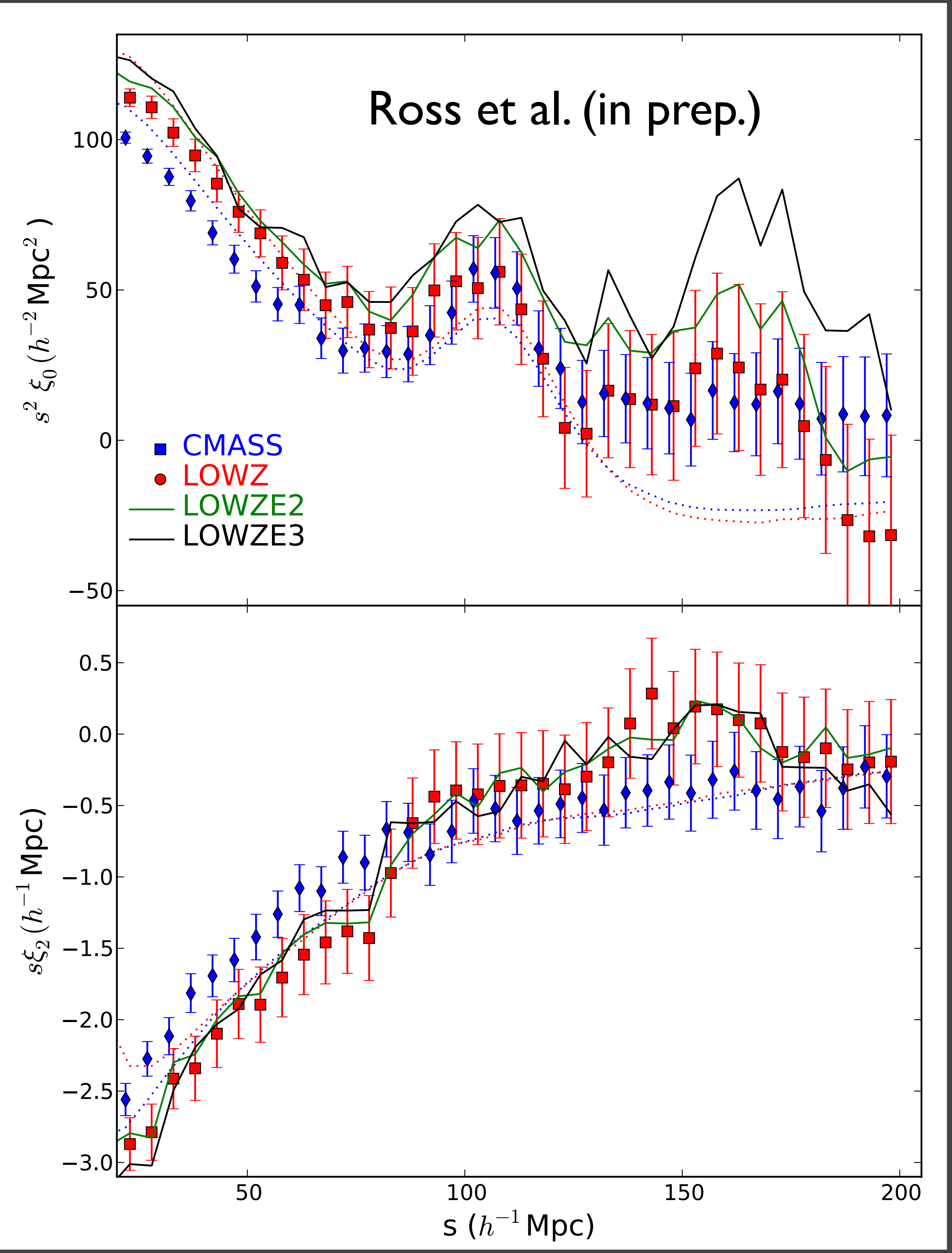
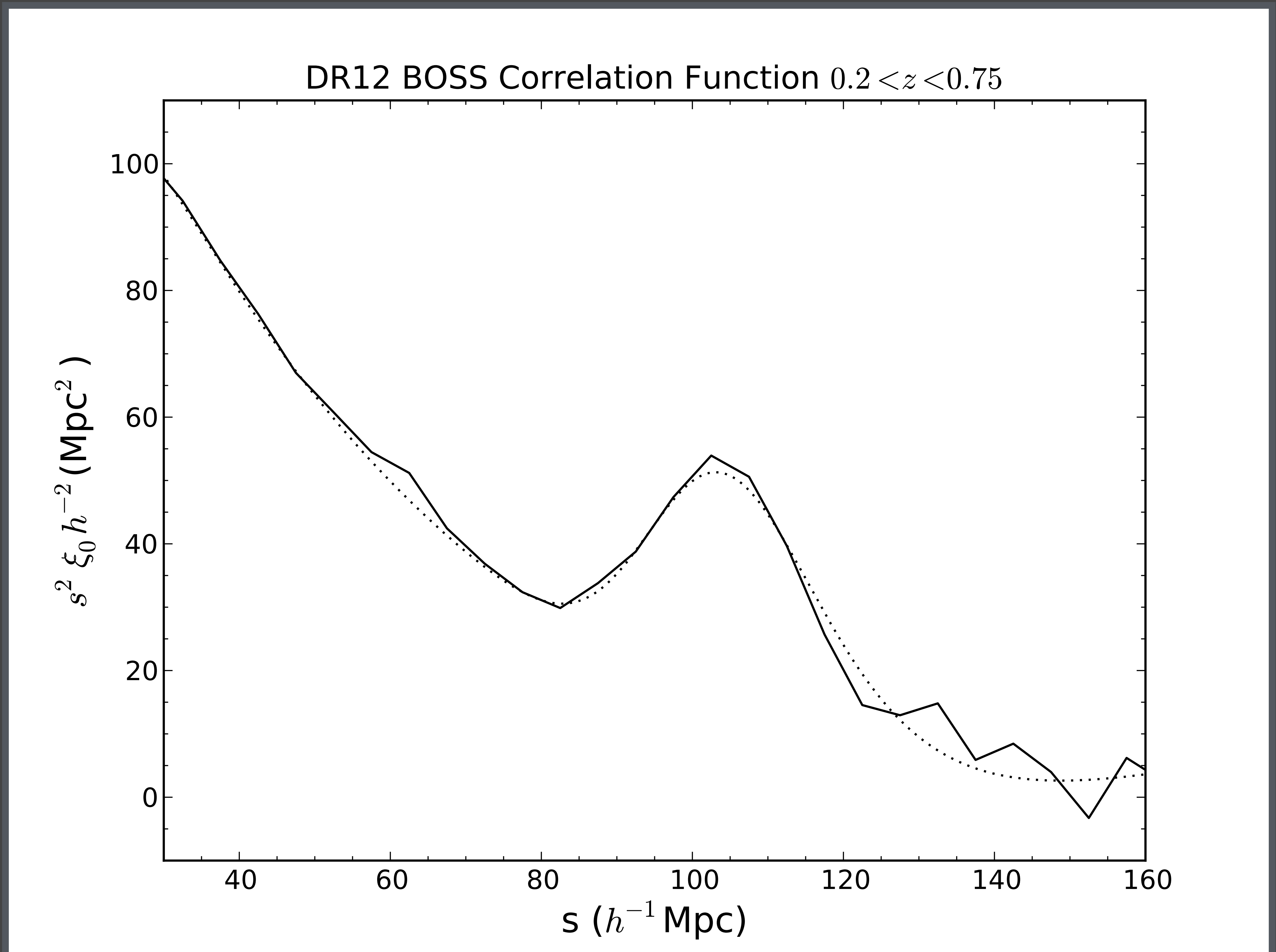




BOSS combined sample

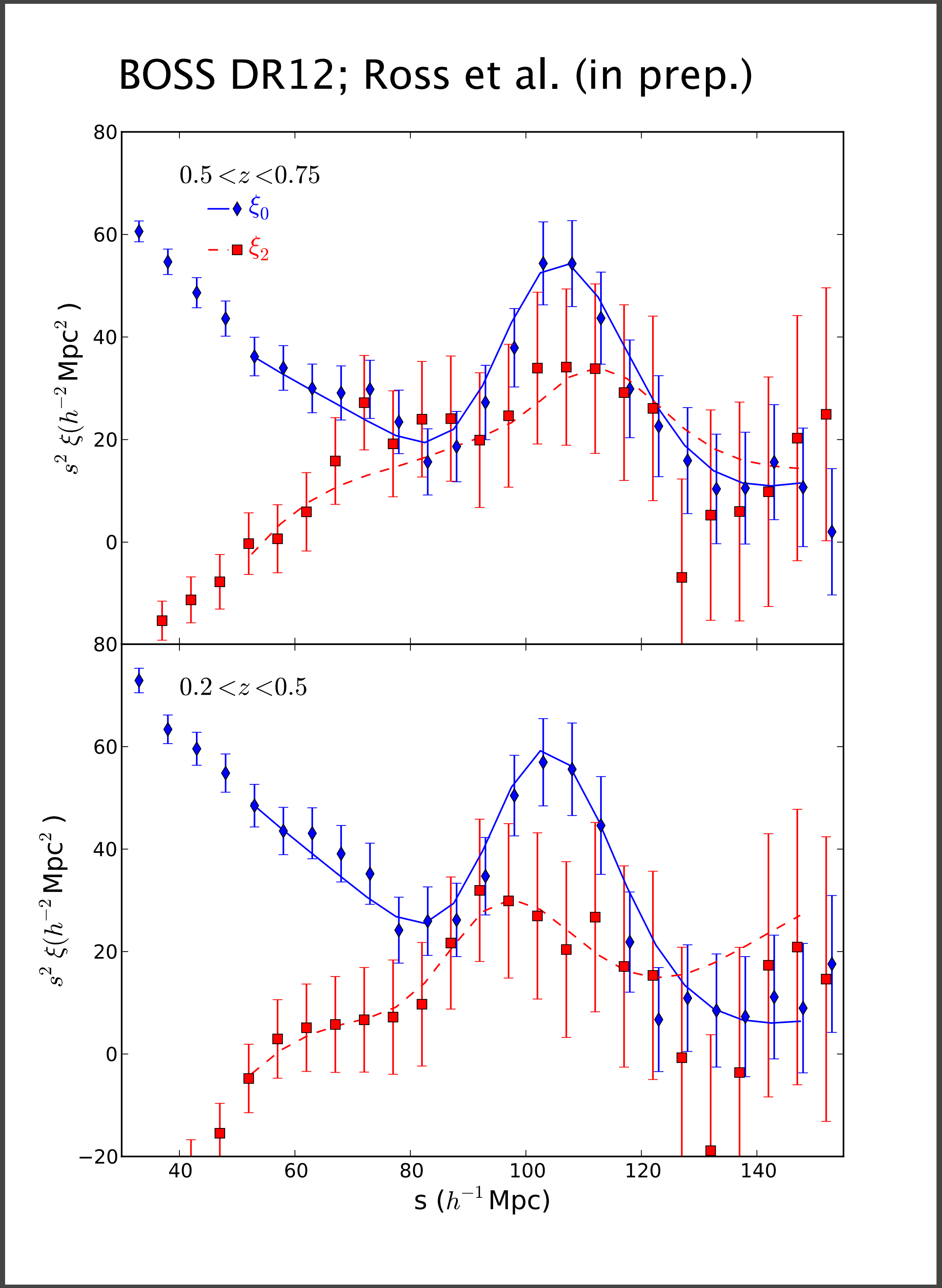


BOSS combined sample



BOSS DR12 (final) results

- CMASS/LOWZ results are out
- Combined sample results to follow
    - Final result will be one (set of) likelihood(s) that combines BAO/RSD results
    - Preliminary fits look good!

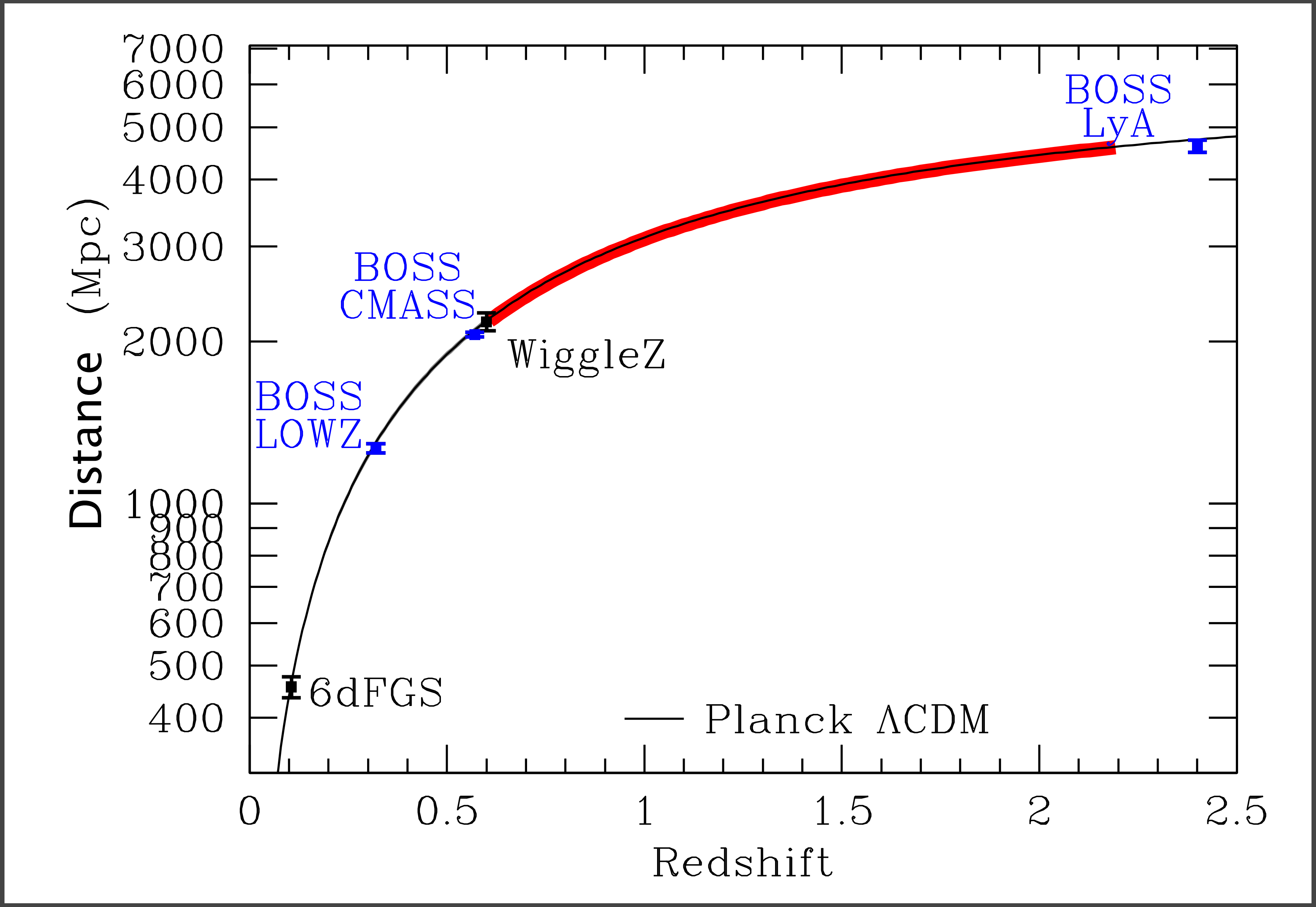


Future/Starting Surveys

Current/Future Surveys

- eBOSS
  - 1 year of observations
  - ~1 million more spectra, extending to higher redshift
- The Dark Energy Survey (DES)
  - 2 years of data taken
  - 300 million galaxies (photozs)
- Dark Energy Spectroscopic Instrument (DESI)
  - 20 million galaxy redshifts!

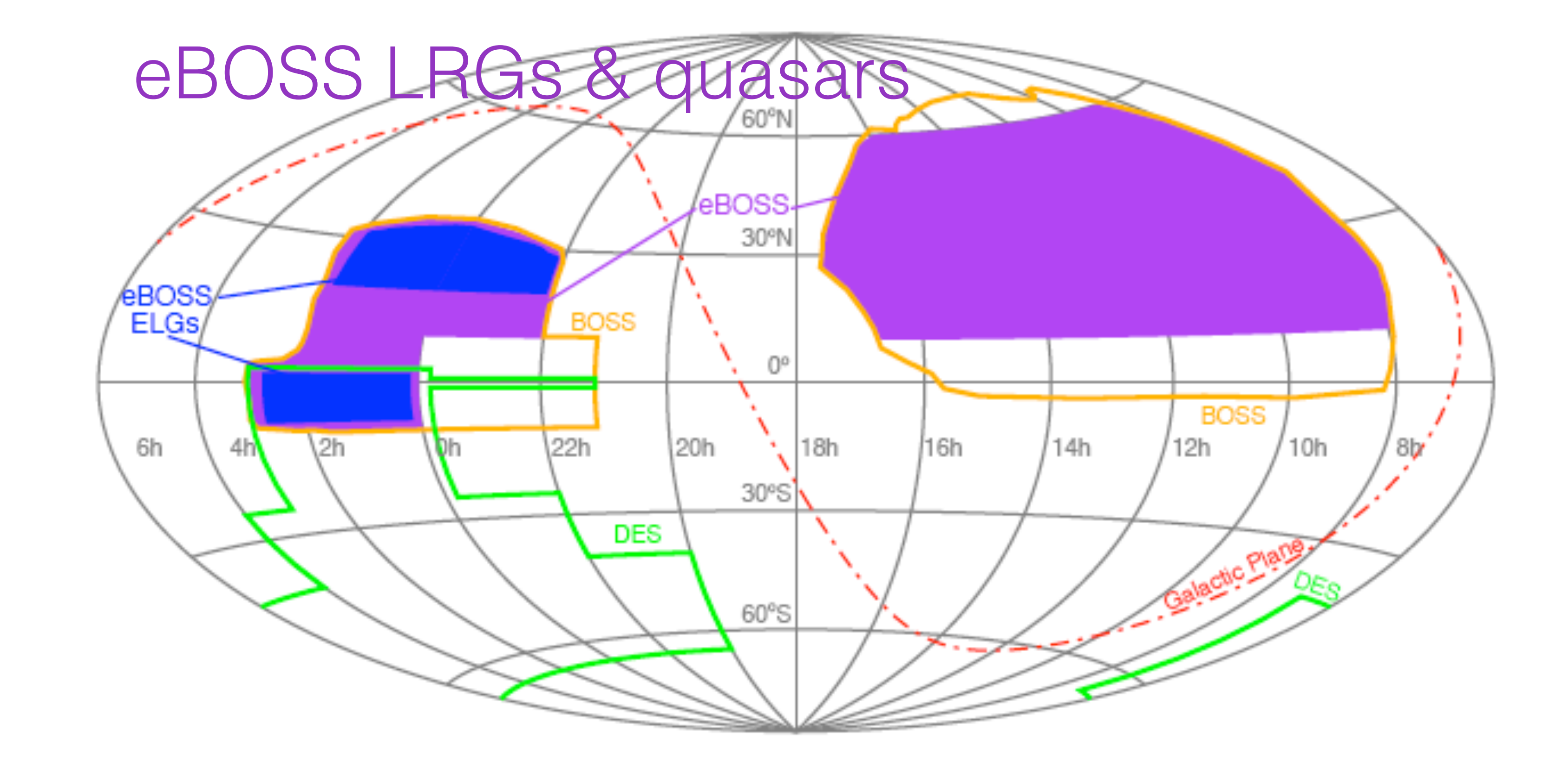
BAO Measurements



- Gap between $0.6 < z < 2.2$

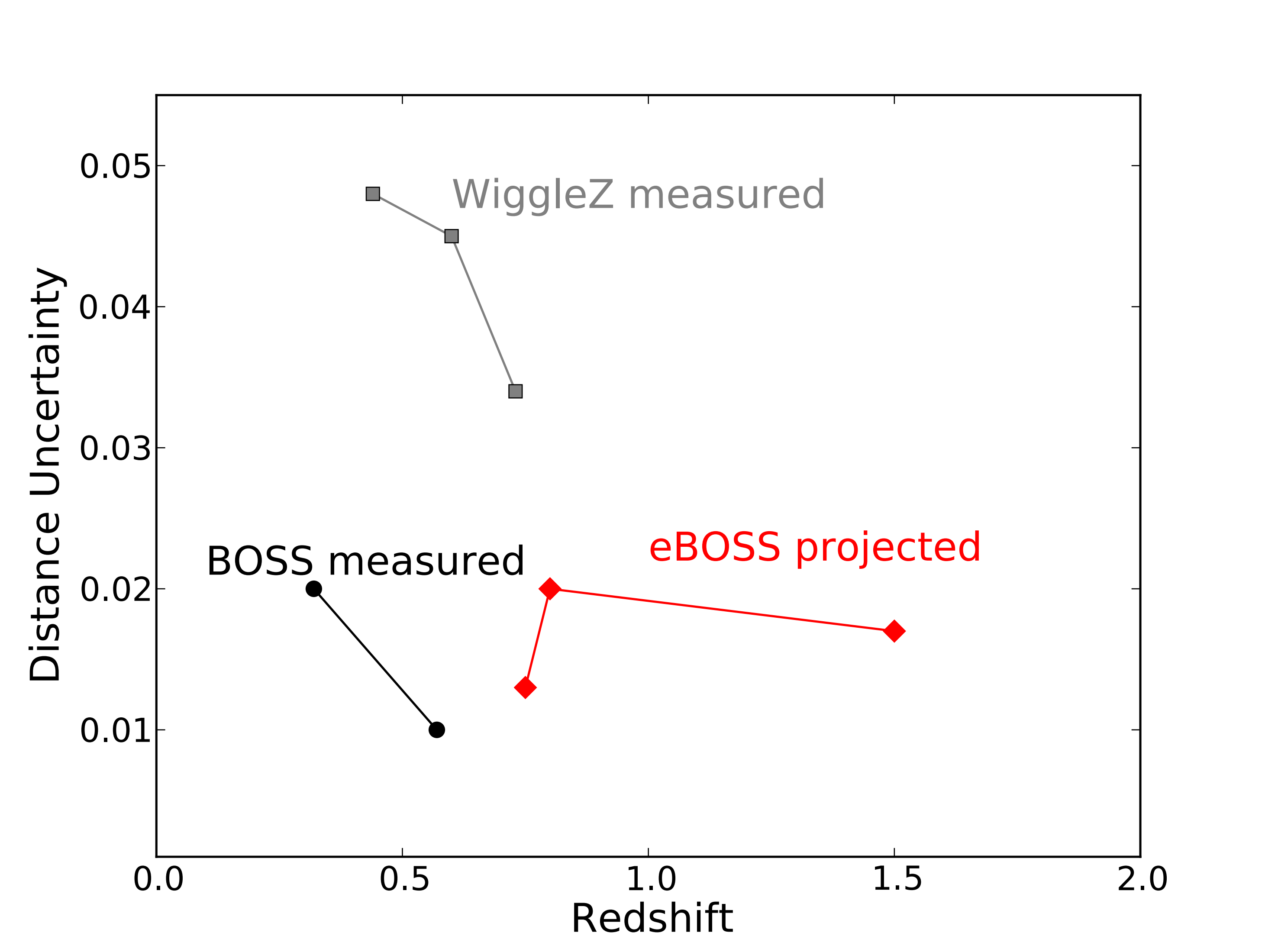
eBOSS

- Use SDSS telescope/spectrograph to extend BAO to > z
- 7500 deg² in SDSS imaging footprint
- Supplement SDSS with infrared data from WISE

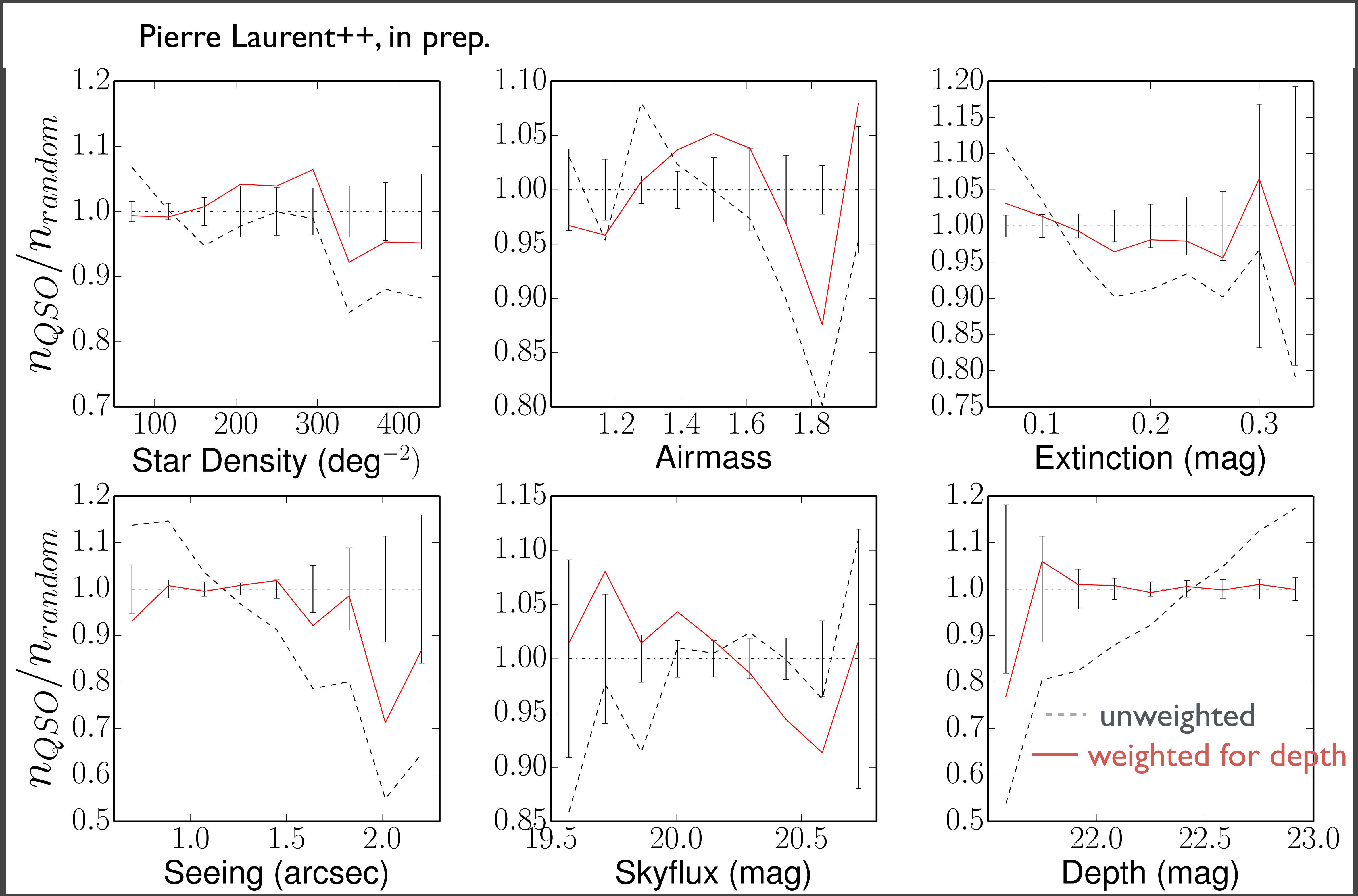


eBOSS projections

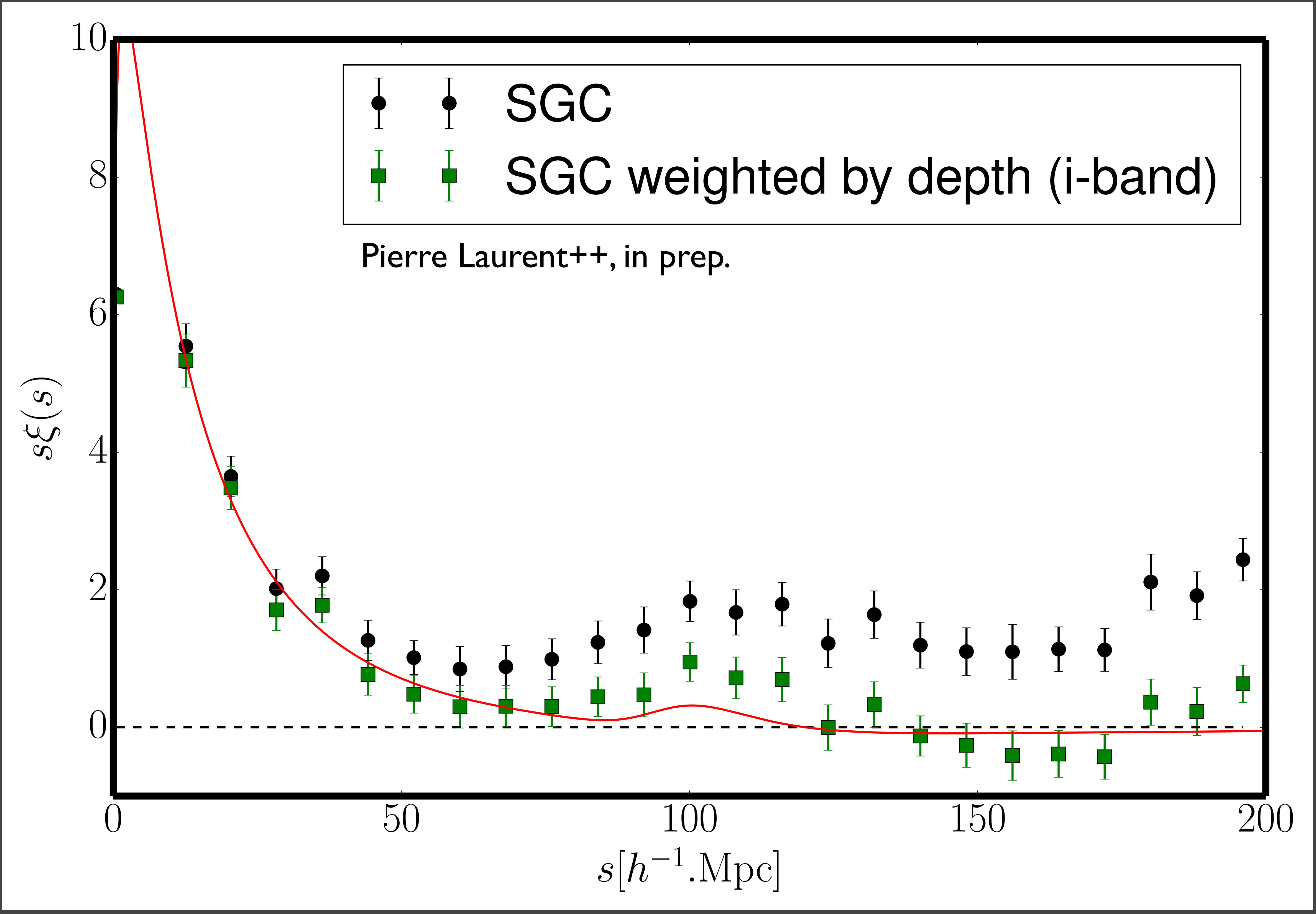
- $3x10^5$ LRGs $0.6 < z < 1.0$
- $2x10^5$ ELGs $0.7 < z < 1.1$
- $6x10^5$ quasars $0.9 < z < 2.2$
- x3 improvement in DE FoM
- Early clustering measurements consistent



eBOSS quasars

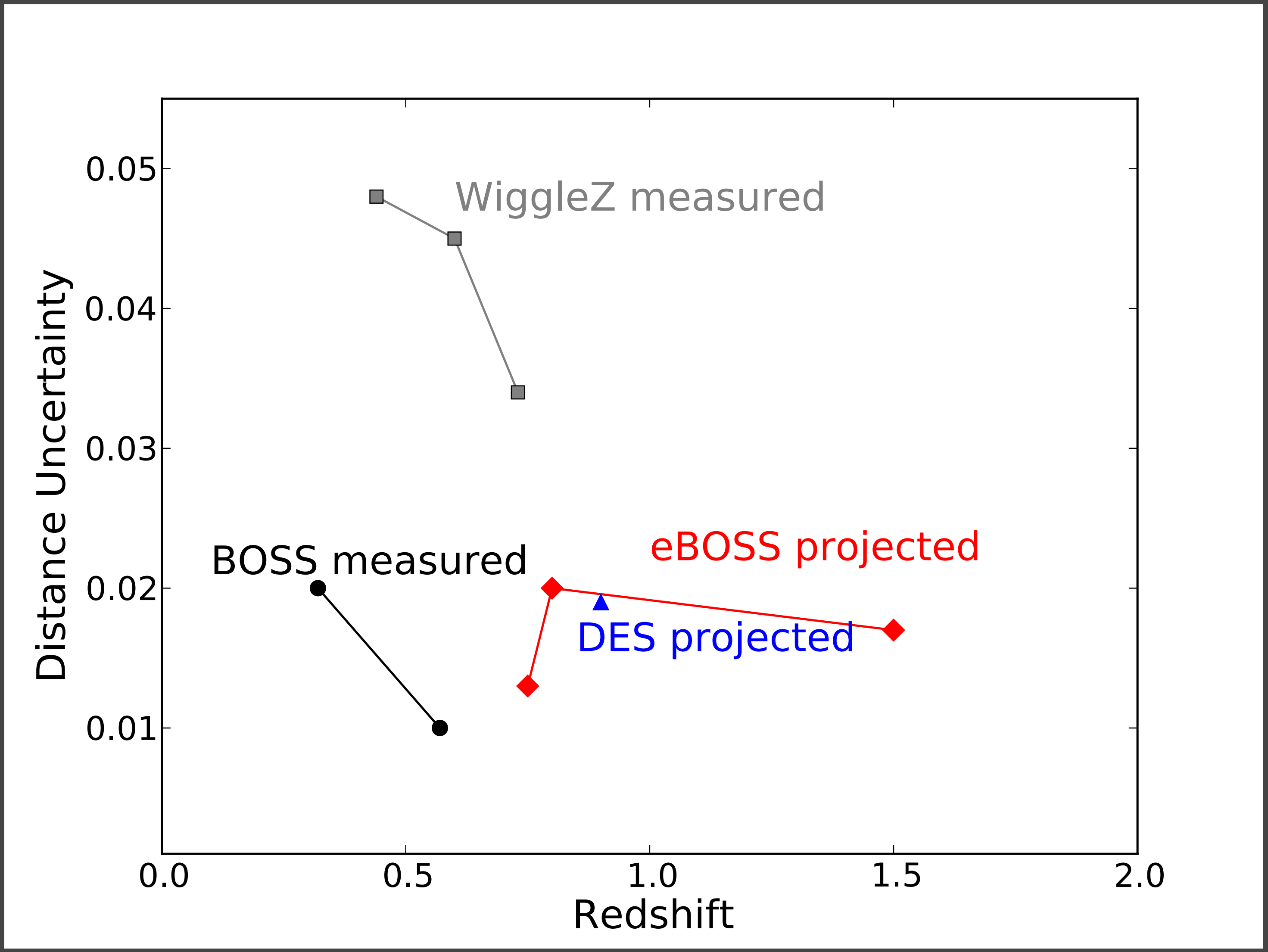


eBOSS quasars

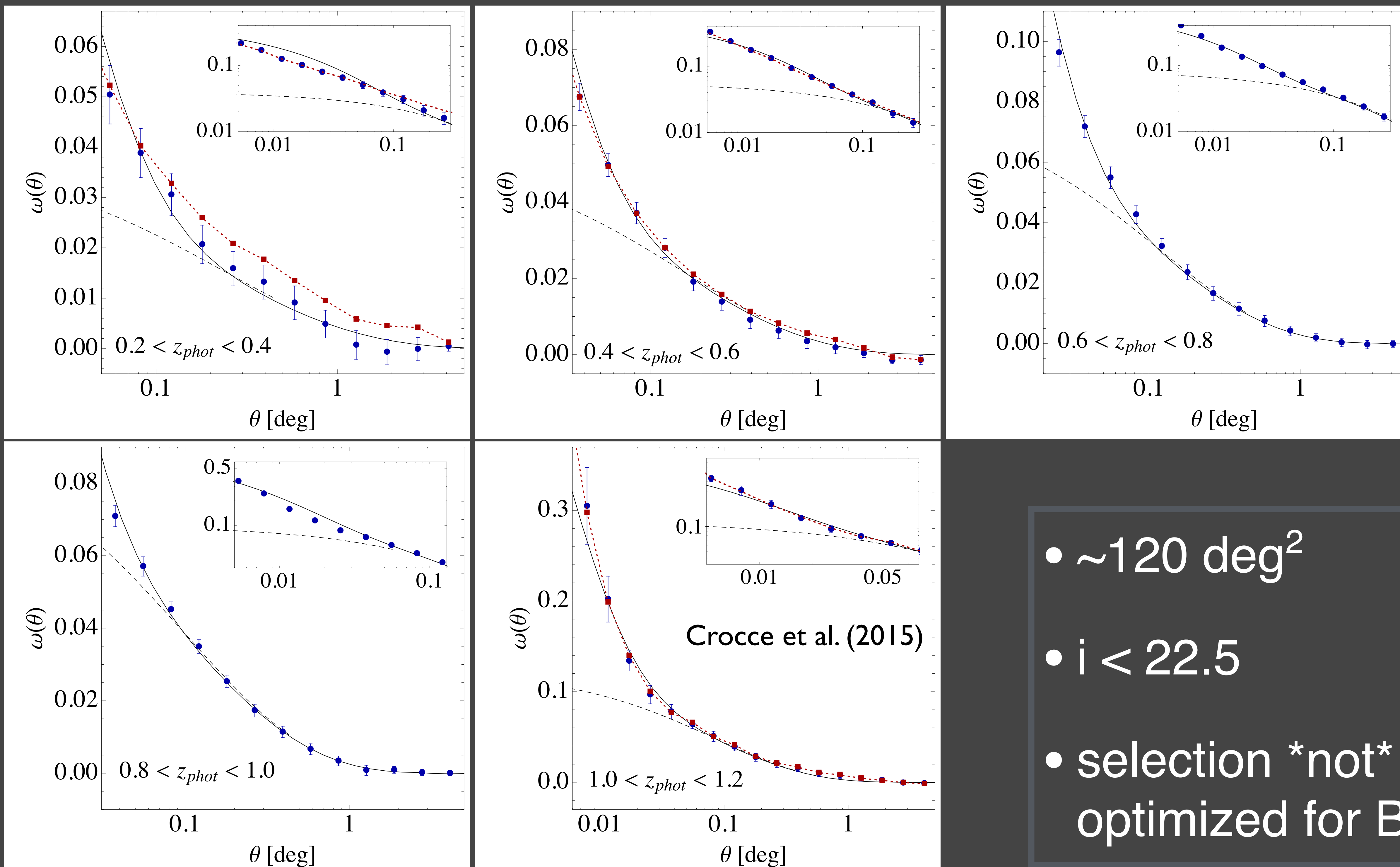


DES projections

- Extrapolating from science verification (SV) data:
- $>10^8$ photometric redshifts over 5000 deg^2 of SGC
- High number density will allow precise z~1 BAO measurement



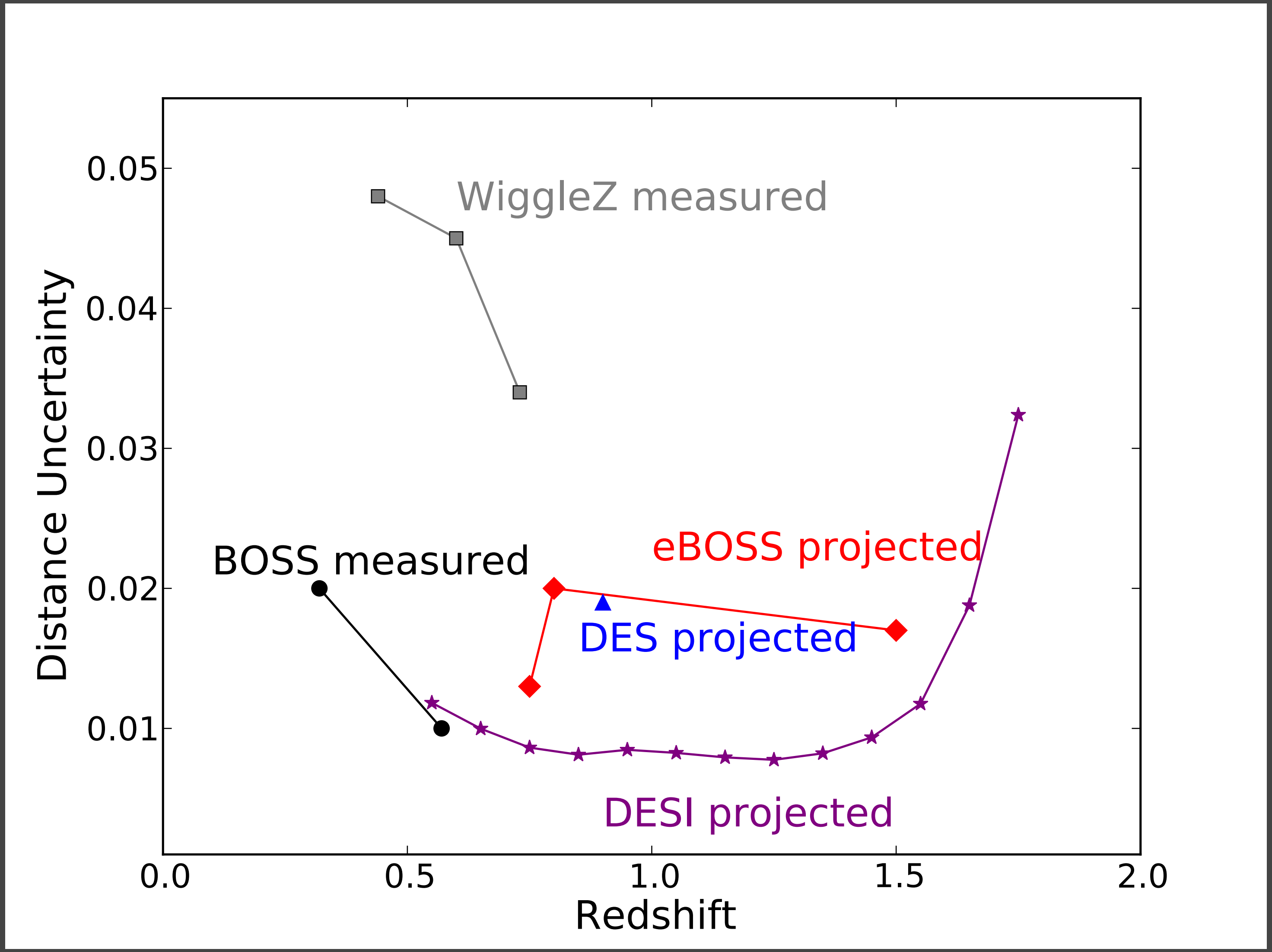
DES SV clustering



- ~120 deg^2
- i < 22.5
- selection *not* optimized for BAO

DESI

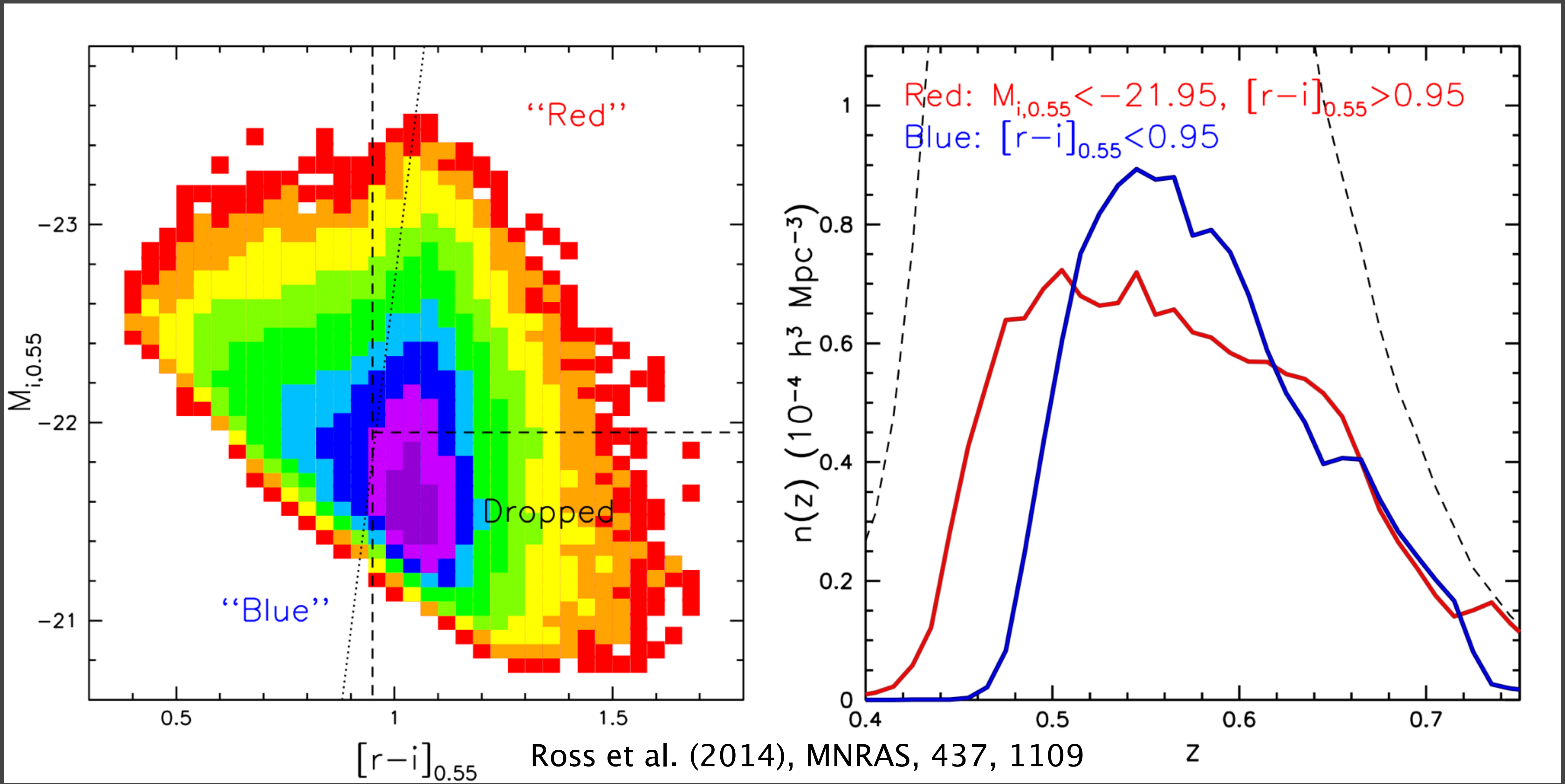
- New spectrograph on 4-meter Mayal telescope
- 20 million spectroscopic redshifts over 14,000 deg^2
- Starts 2018



Conclusions

- Galaxy surveys probe fundamental physics
  - Dark energy
  - Neutrino mass
  - Origin of structure
  - Test General Relativity
- BAO measurements are especially powerful and robust probe
  - Robust against systematics
  - 1% distance measurement for DR11, DR12 coming soon!
  - Future looks great: eBOSS, DES, DESI, (LSST, Euclid)!

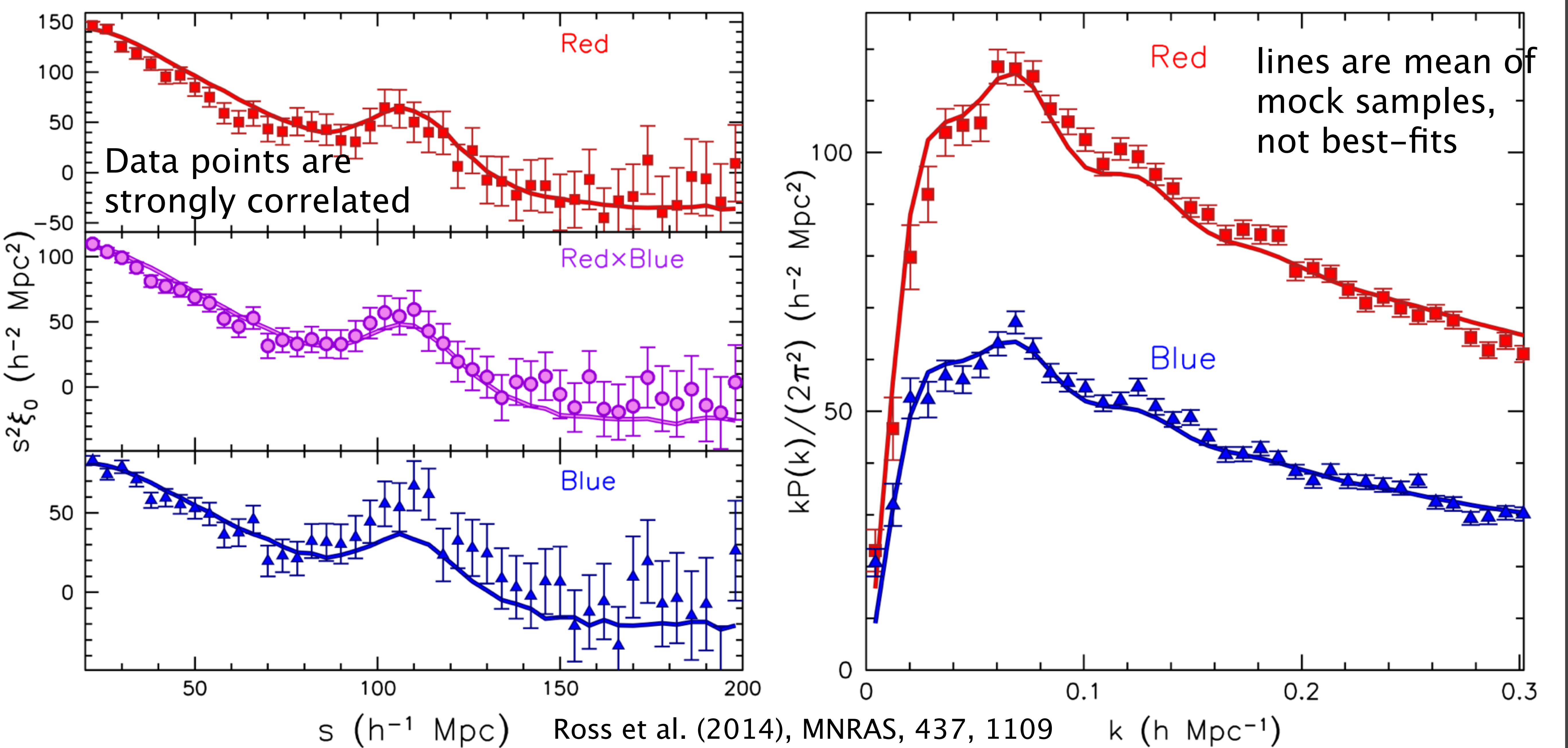
Splitting BOSS by color



Ross et al. (2014), MNRAS, 437, 1109

BOSS Red/Blue Clustering

$$\xi_{Red} \sim 2\xi_{Blue}$$



Ross et al. (2014), MNRAS, 437, 1109

BAO results

Measure shift, α, relative to model

Mocks:

$\langle \alpha \rangle_{\rm Red}$=1.005, $\langle \alpha \rangle_{\rm Blue}$=1.002; $\langle \sigma \rangle_{\rm Red}$=0.027, $\langle \sigma \rangle_{\rm Blue}$=0.038

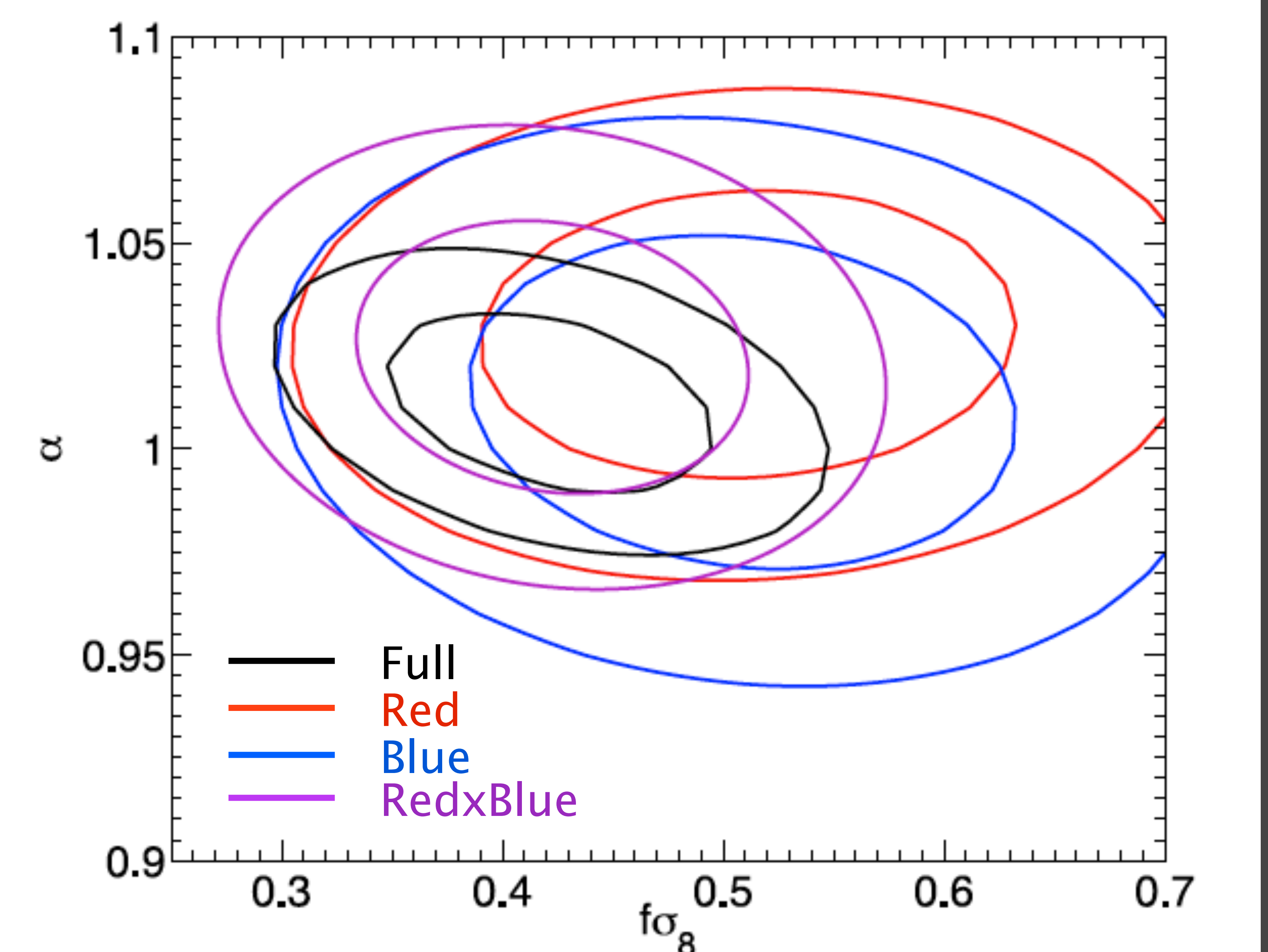
Applying reconstruction:

$\langle \alpha \rangle_{\rm Red}$=0.9994, $\langle \alpha \rangle_{\rm Blue}$=0.9993; $\langle \sigma \rangle_{\rm Red}$=0.020, $\langle \sigma \rangle_{\rm Blue}$=0.030

- Difference should not be measurable
- Finding a difference would mean
  - intra-halo processes indicate important differences in inter-halo clustering
  - halo-mass dependent tests of methodology not sufficient

Red/Blue RSD Results

- Consistent results
- Optimal combination gives 8% improvement in measurement of f



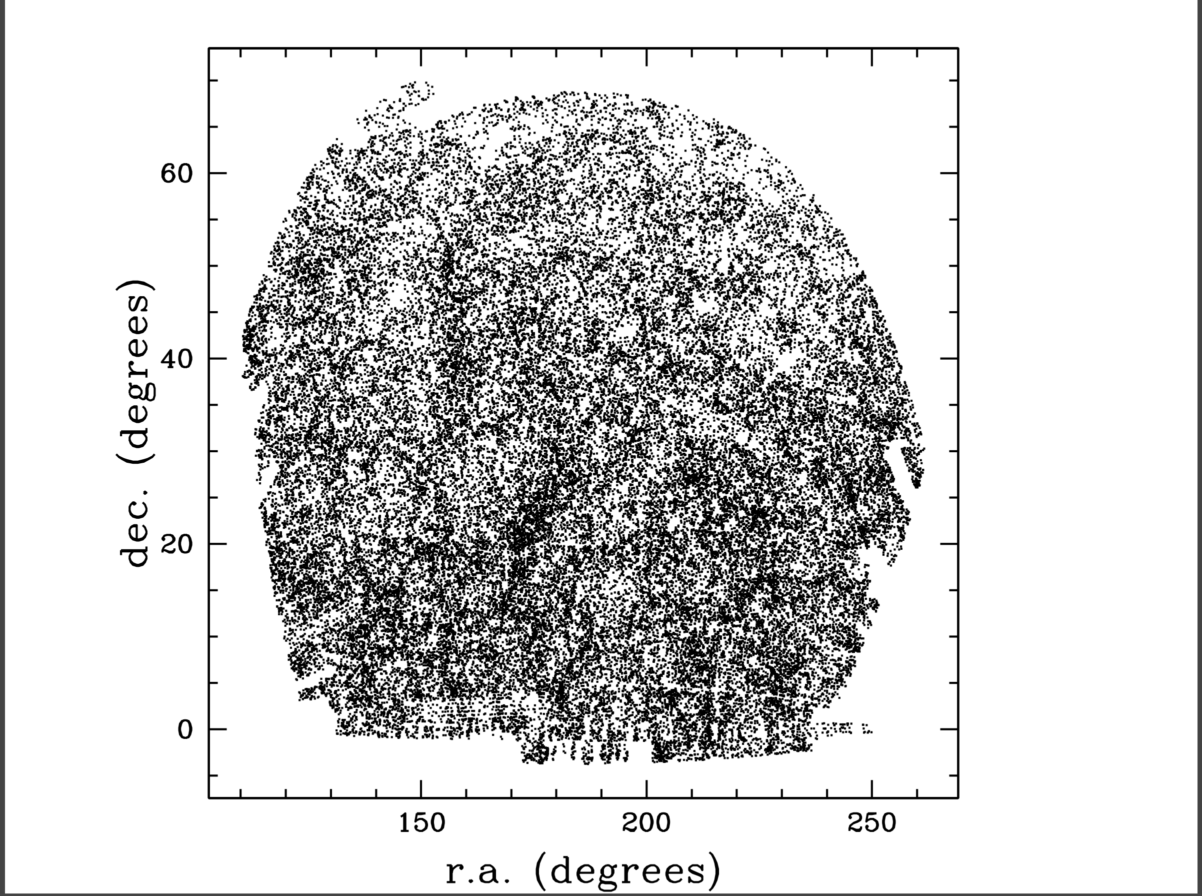
Ross et al. (2014), MNRAS, 437, 1109

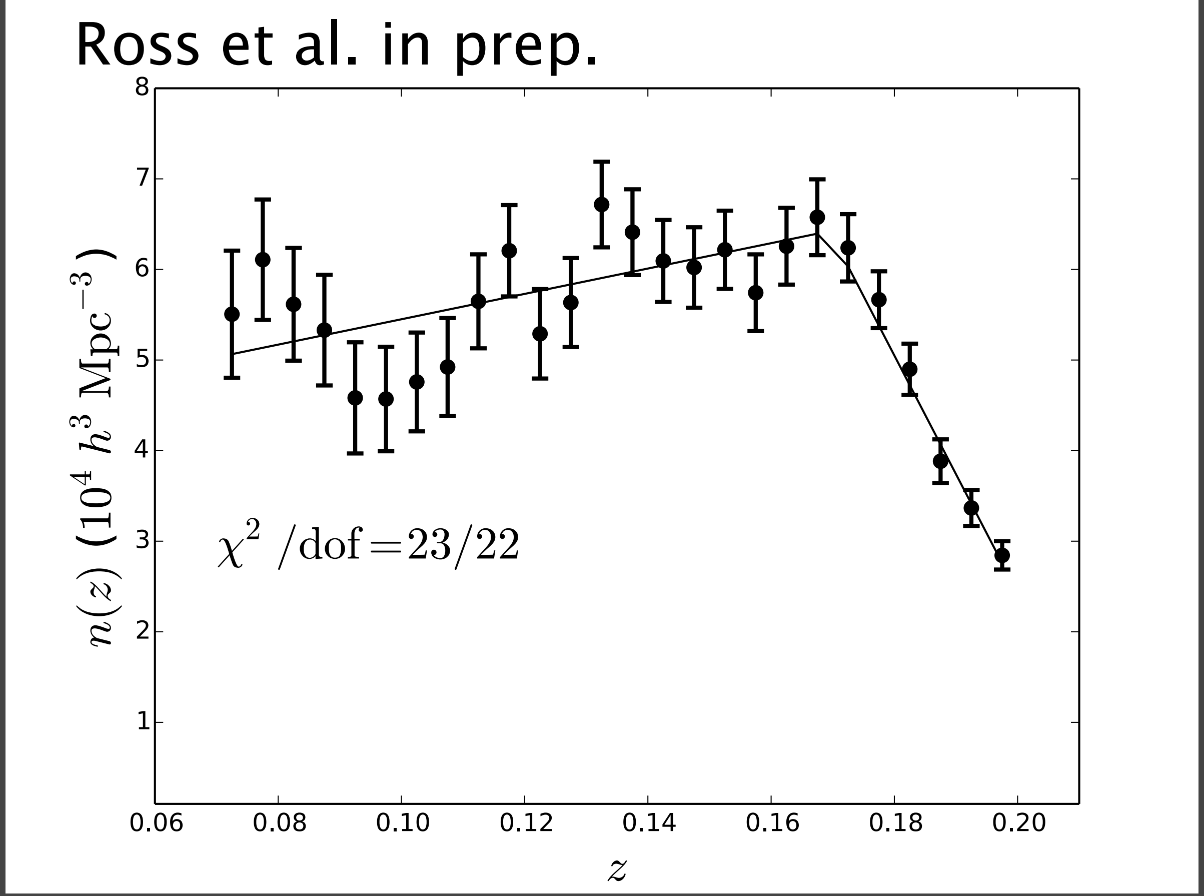
Theoretical Details

- Red and Blue samples yield consistent results
  - encouraging!
  - optimal results to be obtained by weighting samples
- Ongoing studies
  - Robustness of reconstruction methods
  - Combining RSD and BAO
  - Optimal redshift binning?
  - Optimal 2D BAO fitting?

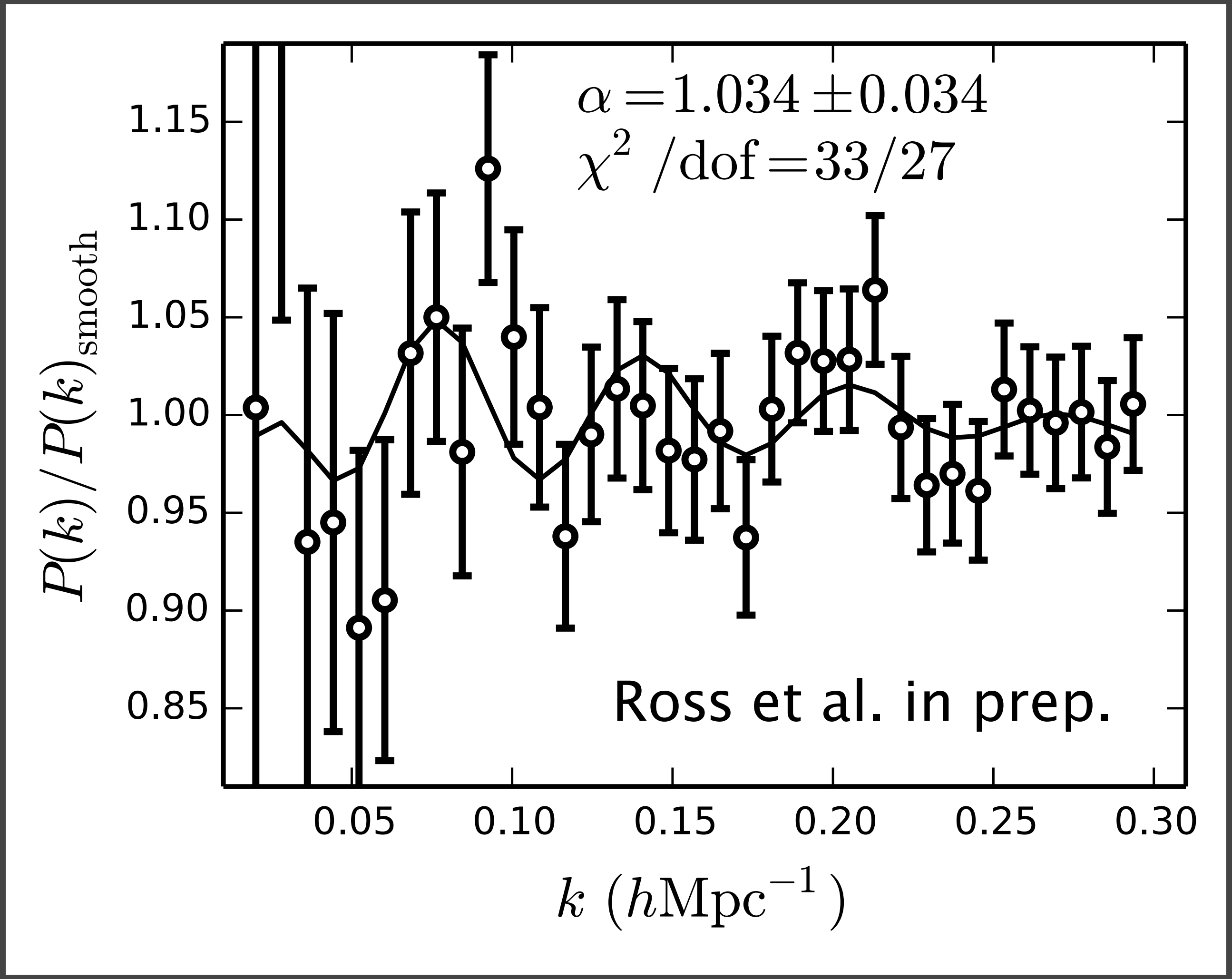
SDSS DR7 z < 0.2

- SDSS main galaxy sample (MGS):
  - 0.07 < z < 0.2; g-r > 0.8; M_r < -21.2
  - Cosmic variance limited
  - Able to create 1000 mock samples (Howlett et al in prep.)
  - Apply reconstruction to get BAO measurements

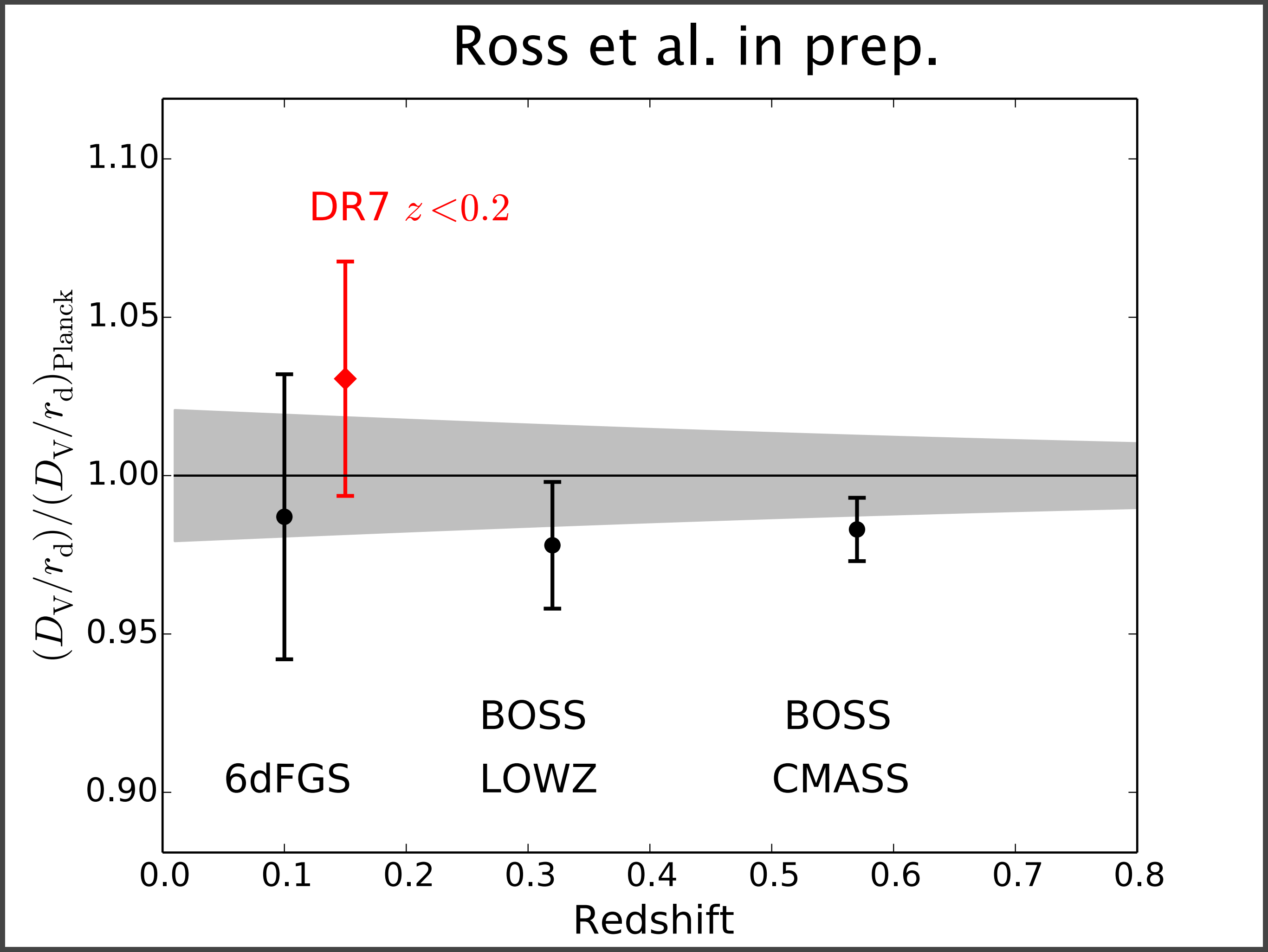




z < 0.2 BAO

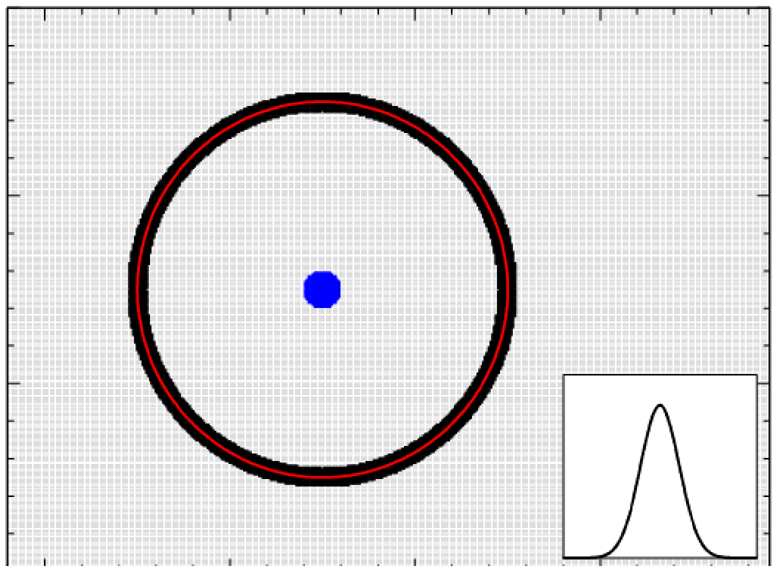


$\alpha = 1.034 \pm 0.034$
χ^2 /dof = 33/27
Ross et al. in prep.
$P(k)/P(k)_{\rm smooth}$
k (hMpc^{-1})
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.05
0.10
0.15
0.20
0.25
0.30



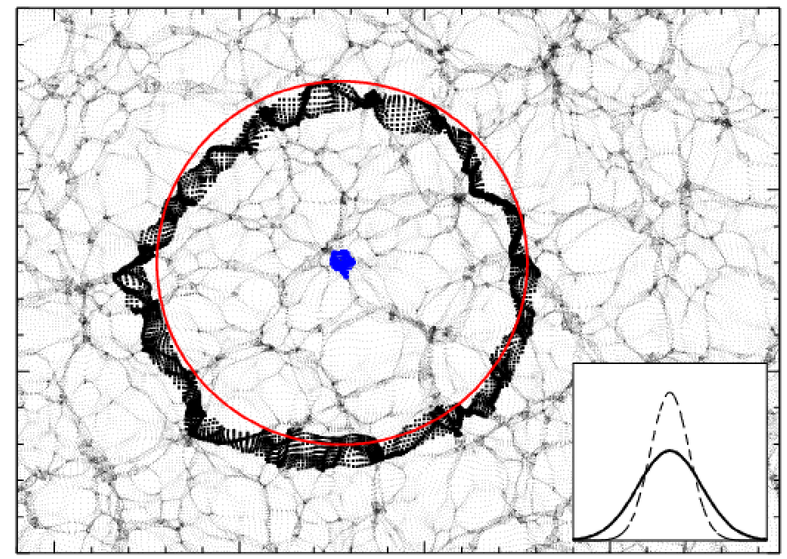
Ross et al. in prep.
DR7 $z<0.2$
6dFGS
BOSS
LOWZ
BOSS
CMASS
$(D_{\rm V}/r_{\rm d})/(D_{\rm V}/r_{\rm d})_{\rm Planck}$
Redshift
1.10
1.05
1.00
0.95
0.90
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

Reconstruction



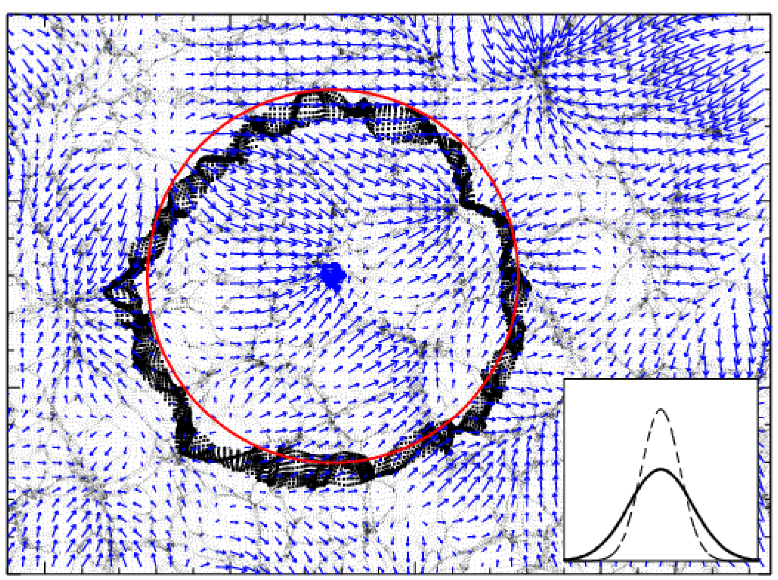
1.

- High z
- Uniform
- Sharp Gaussian



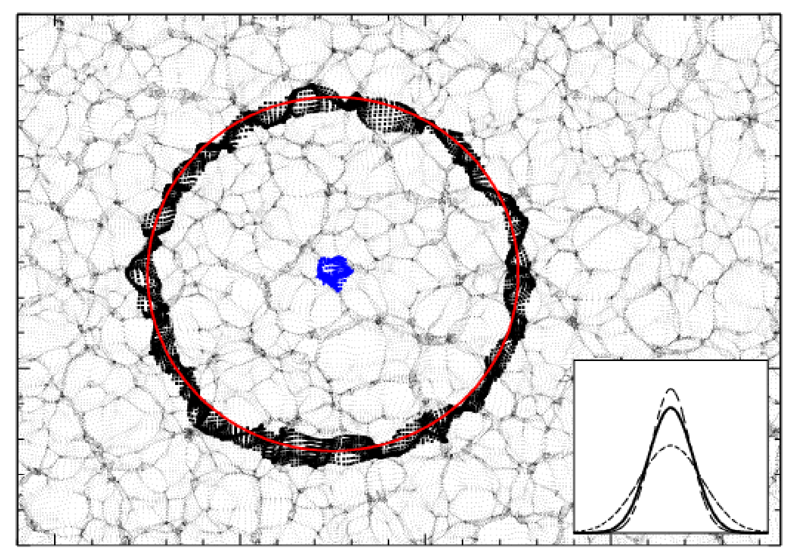
2.

- Evolved to z=0
- Ring distorted
- Gaussian wider



3.

- Lagrangian displacements



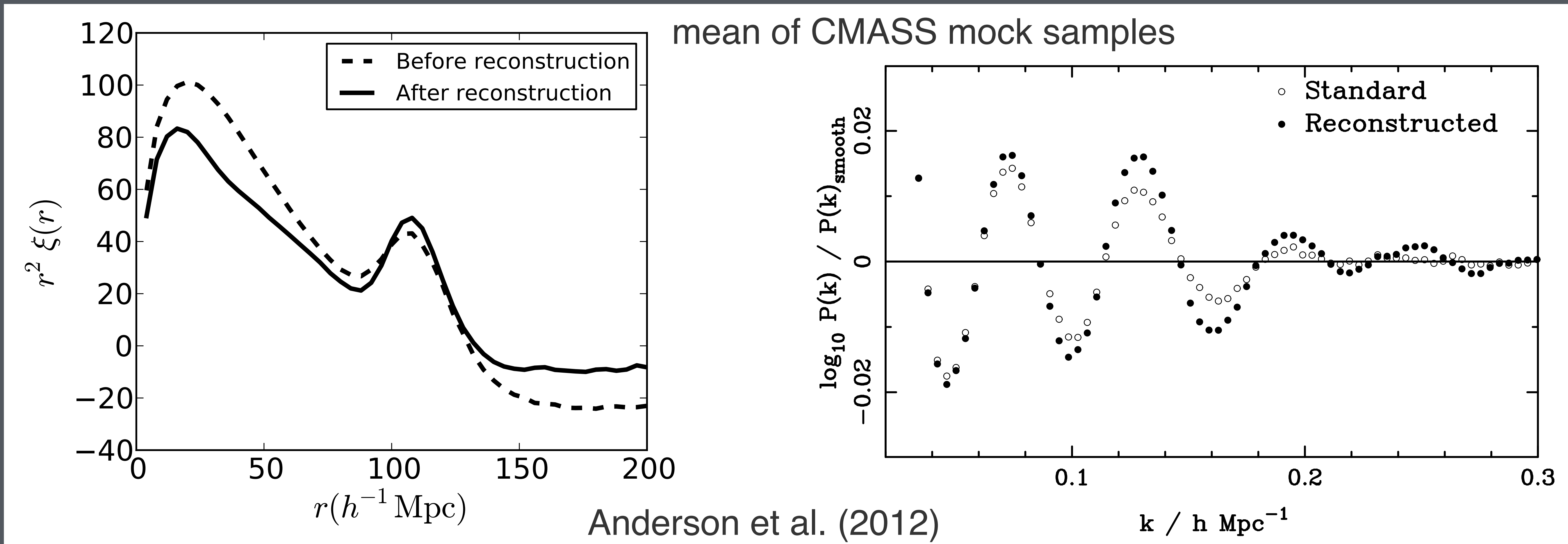
4.

- Particles moved back.
- Gaussian peak sharper

Figures from Padmanabhan et al. 2012

Reconstruction

- Sharpens BAO feature



Anderson et al. (2012)

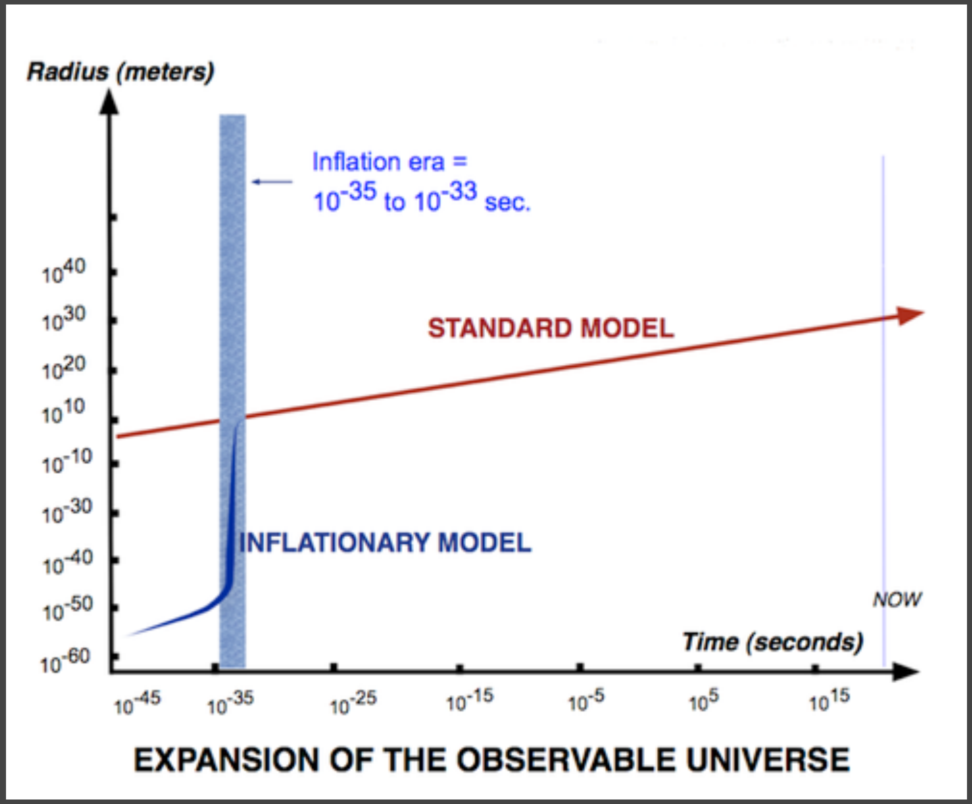
Primordial non-Gaussianity: Constraining models of the origin of structure

Inflation

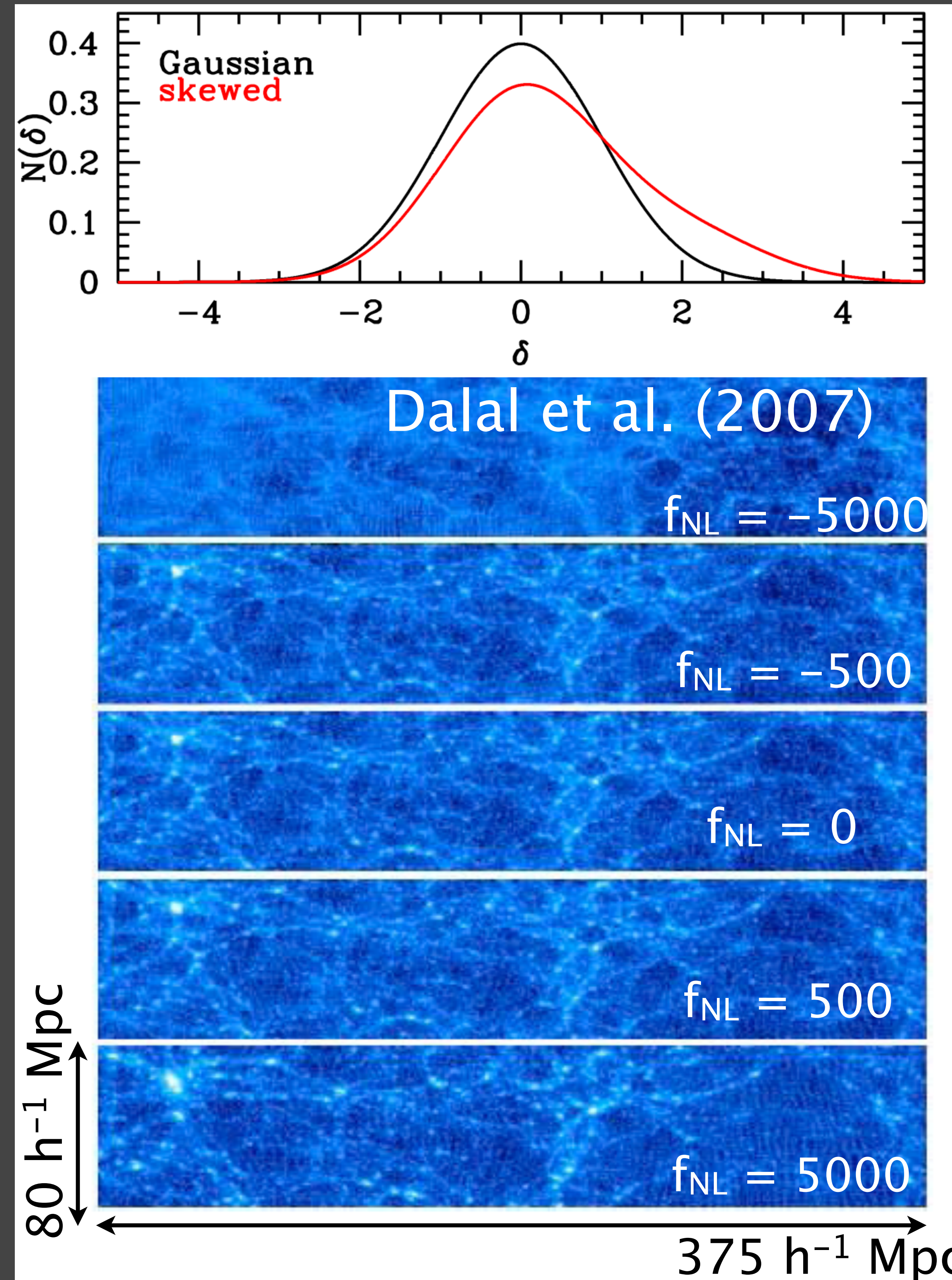
- explains origin of structure
- f_{NL} : ~normalized skewness of produced fluctuations

$$\phi = \phi_g + f_{NL}(\phi_g^2 - \langle \phi_g^2 \rangle)$$

- f_{NL} should be vanishingly small for "slow roll" inflation



Probing Inflation with Galaxies



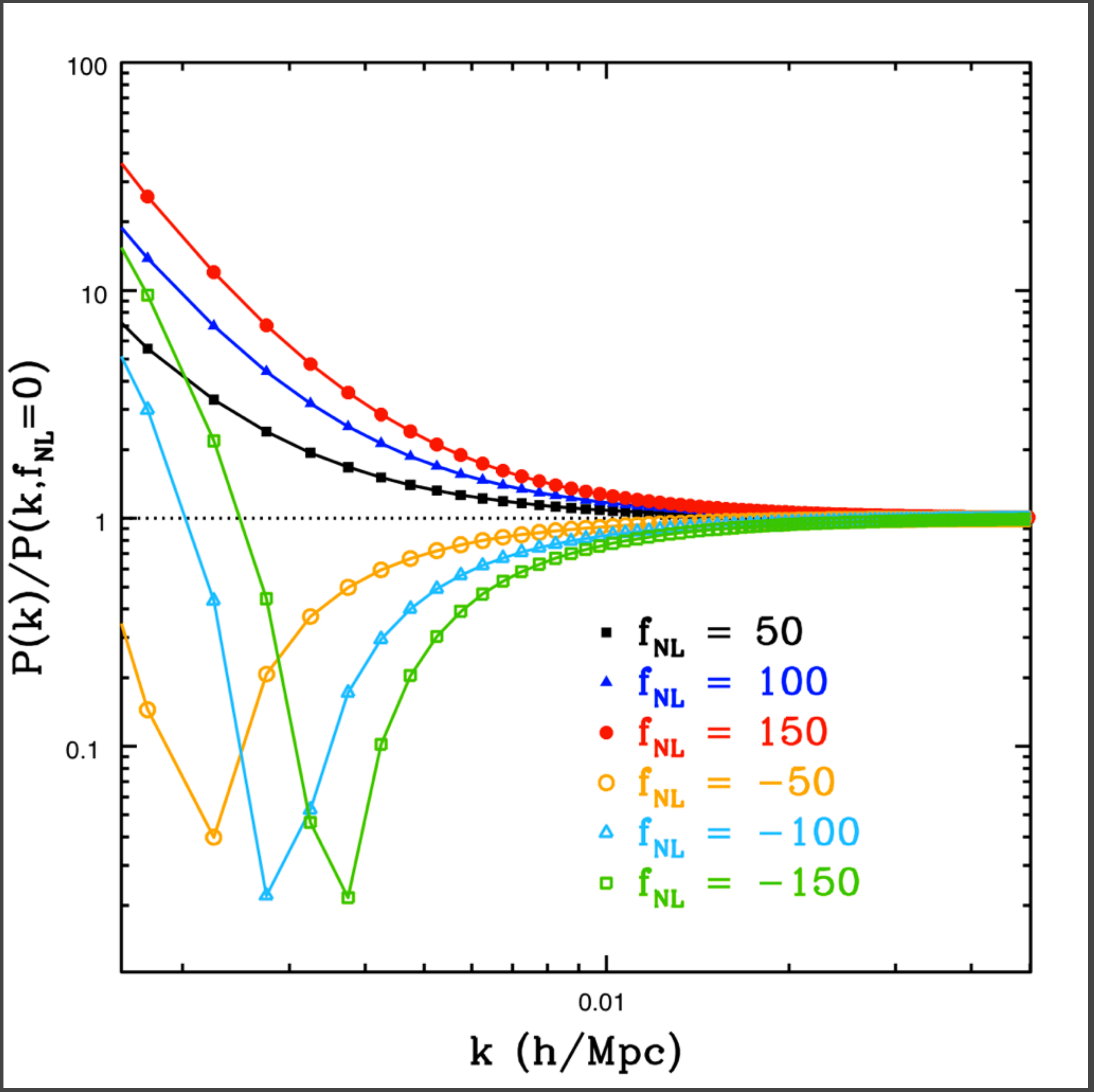
- f_{NL} : ~normalized skewness of primordial fluctuations

  $$\phi = \phi_g + f_{NL}(\phi_g^2 - \langle\phi_g^2\rangle)$$

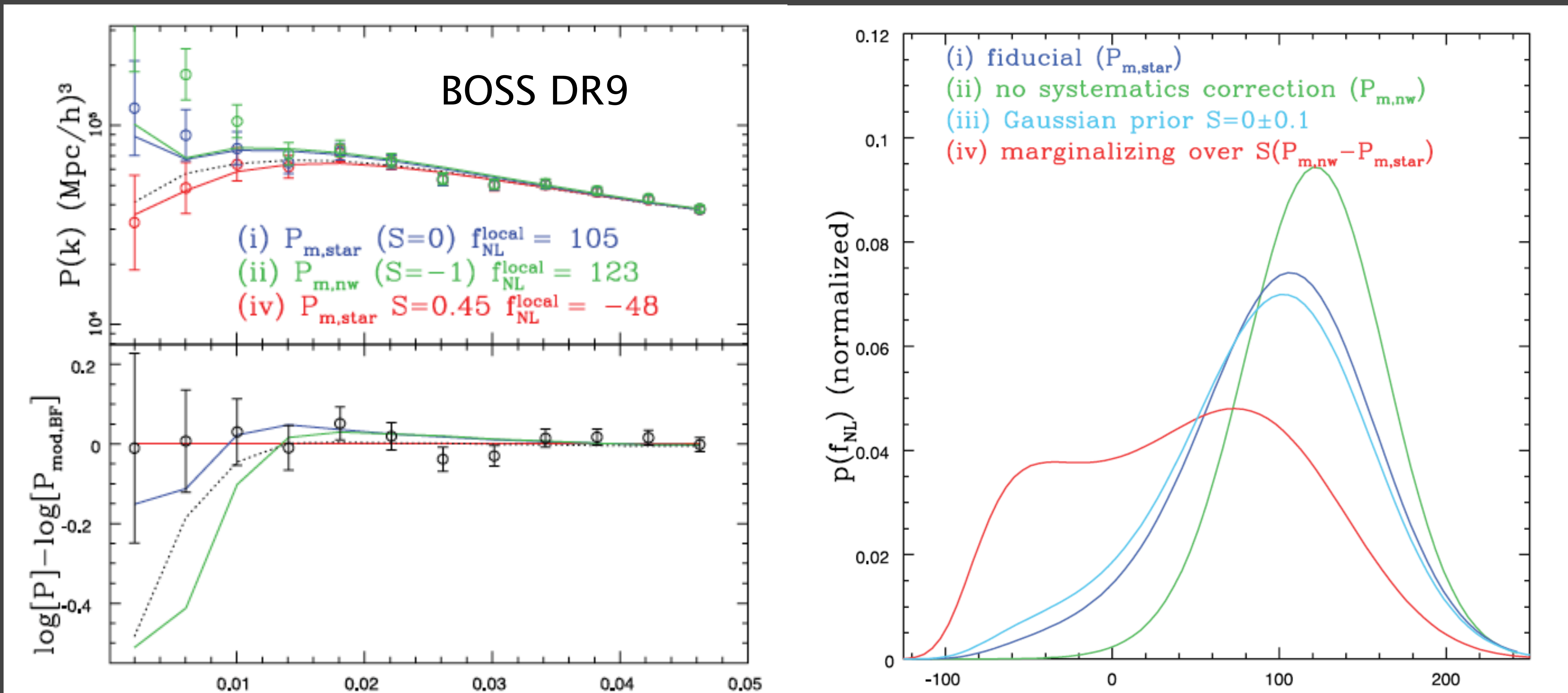
- should be vanishingly small for slow roll inflation

primordial non-Gaussianity (f_{NL})

- f_{NL} induces k^{-2} dependence in P(k)



Measuring f_{NL} with BOSS

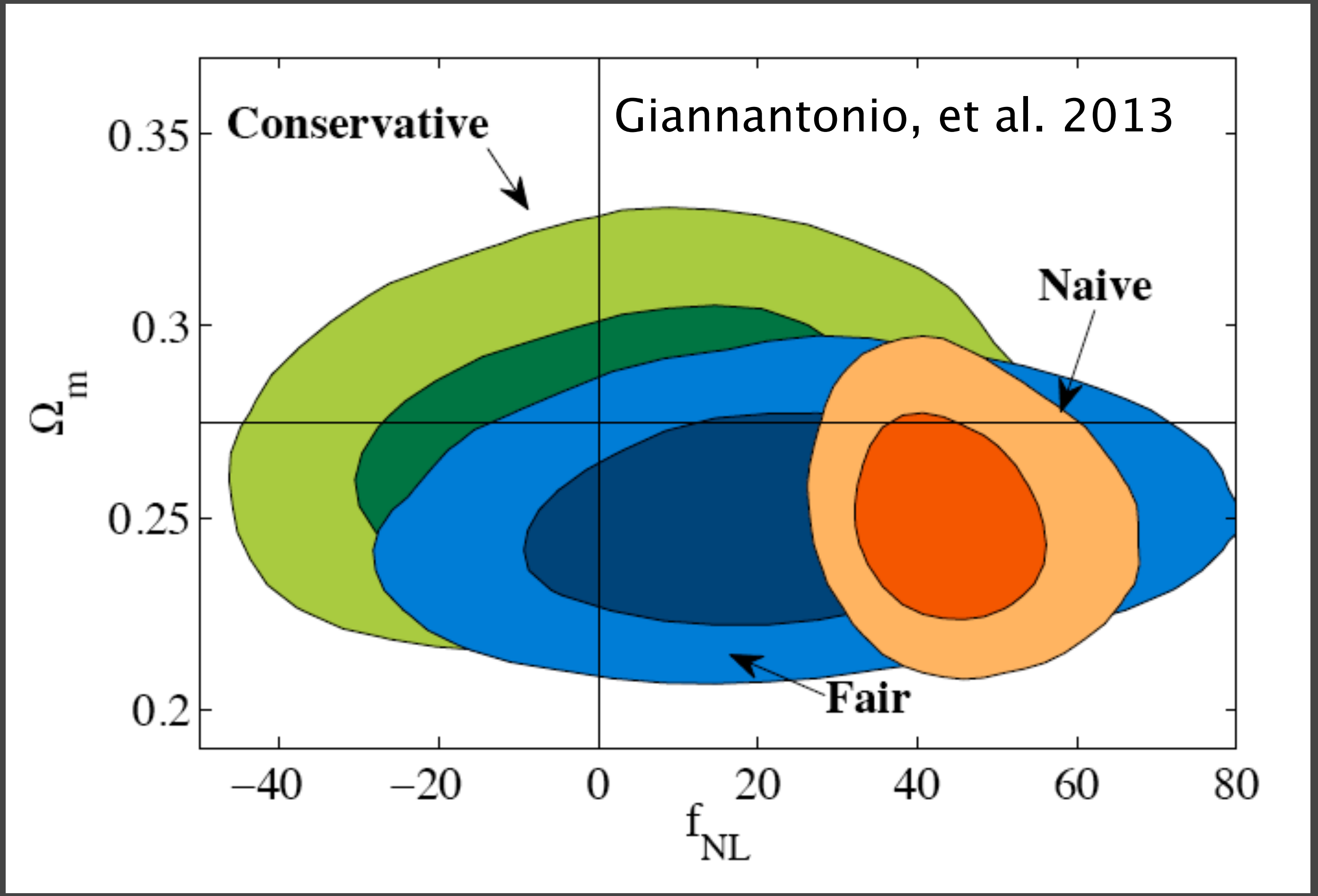


Ross et al. (2013), MNRAS, 428, 1116

- Sensitive to treatment of systematics; more on this later

BOSS photoz papers: non-Gaussianity

- BOSS photozs+SDSS quasars+NVSS radio galaxies+CMB+others
- "conservative": $f_{NL} = 5 \pm 21$
- "Naive": $f_{NL} = 48 \pm 8$
- WMAP9 CMB bispectrum: $-3 < f_{NL} < 77$ (95% CL; Hinshaw et al., 2013)



- Planck CMB bispectrum: 2.7±5.8 (Ade et al. 2013)