

Galaxy-Lensing Cross Correlations

Measurements and Applications

Sukhdeep Singh

The McWilliams Center for Cosmology
Carnegie Mellon University

Berkeley Cosmology Seminar
December 2016

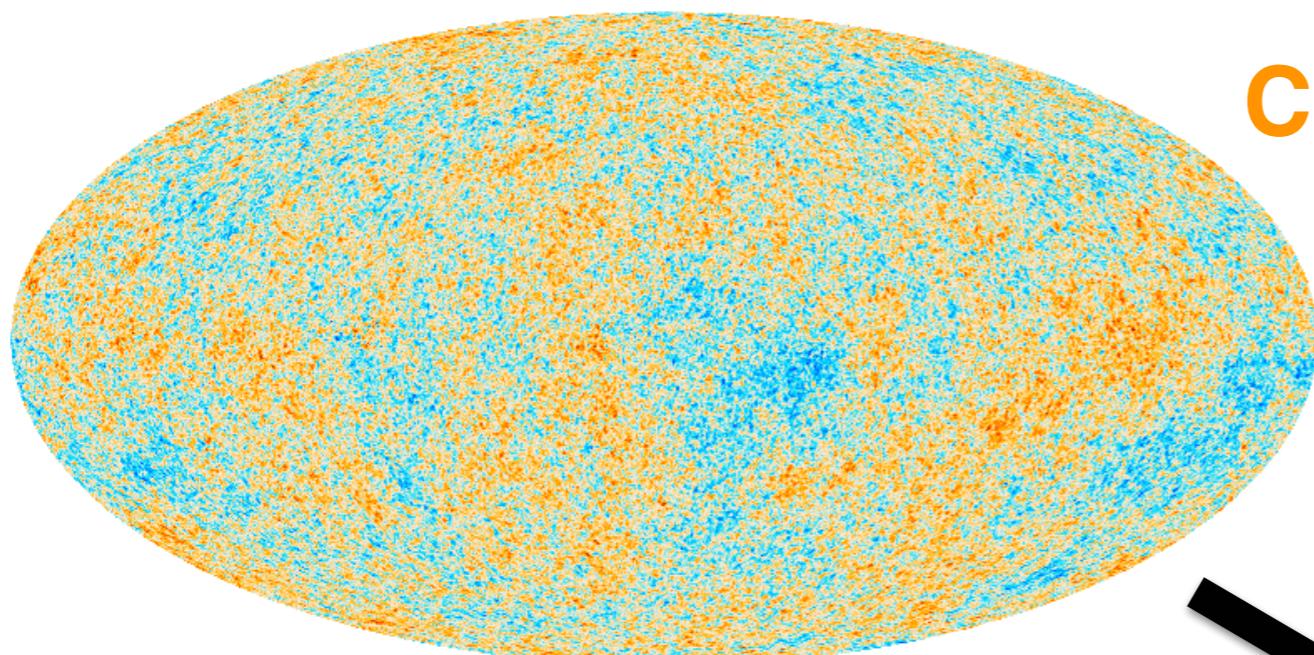
with

Rachel Mandelbaum, Shadab Alam, Shirley Ho
Uros Seljak, Anze Slosar, Jose Vazquez, Sergio Rodriguez

Outline

- **Introduction**
- **Measurements** SS+ 2016b, MNRAS, 1606.08841
 - Covariance estimations SS+ 2016c, 1611.00752
- **Applications**
 - Constraining lensing systematics SS+ 2016b, 1606.08841
 - E_G measurement SS+, in prep
 - Cosmological constraints SS, JV+, in prep

Overview

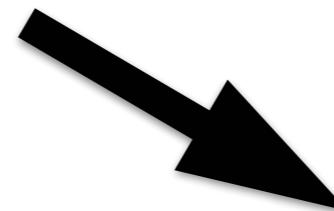


Planck Collaboration

CMB

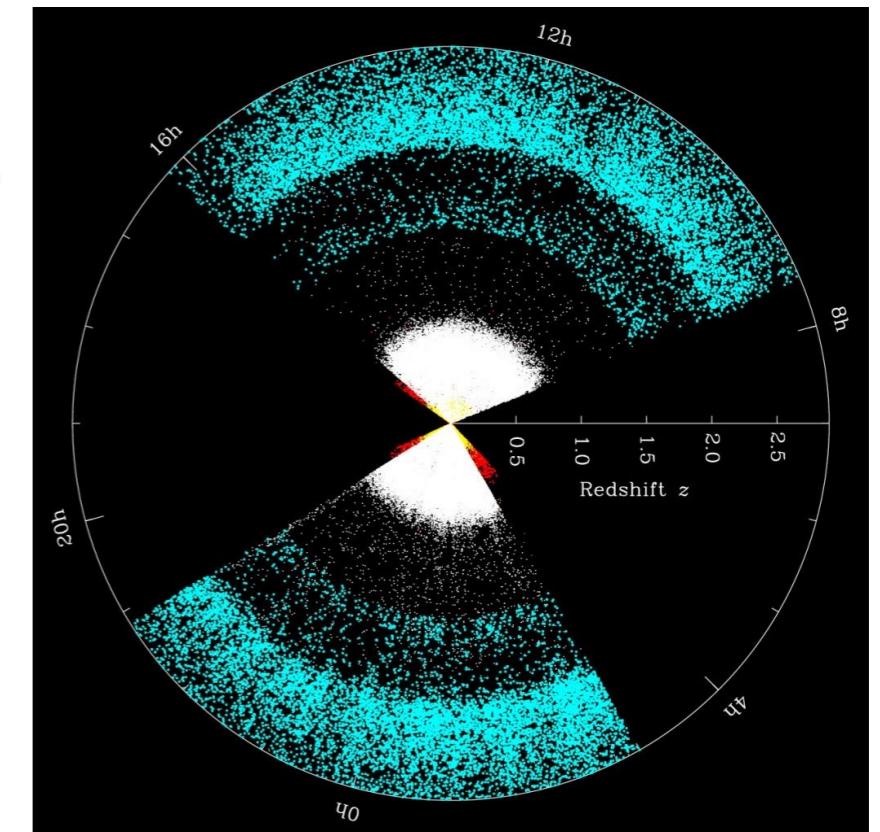
- Probes initial conditions
- Linear Physics
- Gaussian statistics

$\mathbf{GR + \Lambda CDM}$



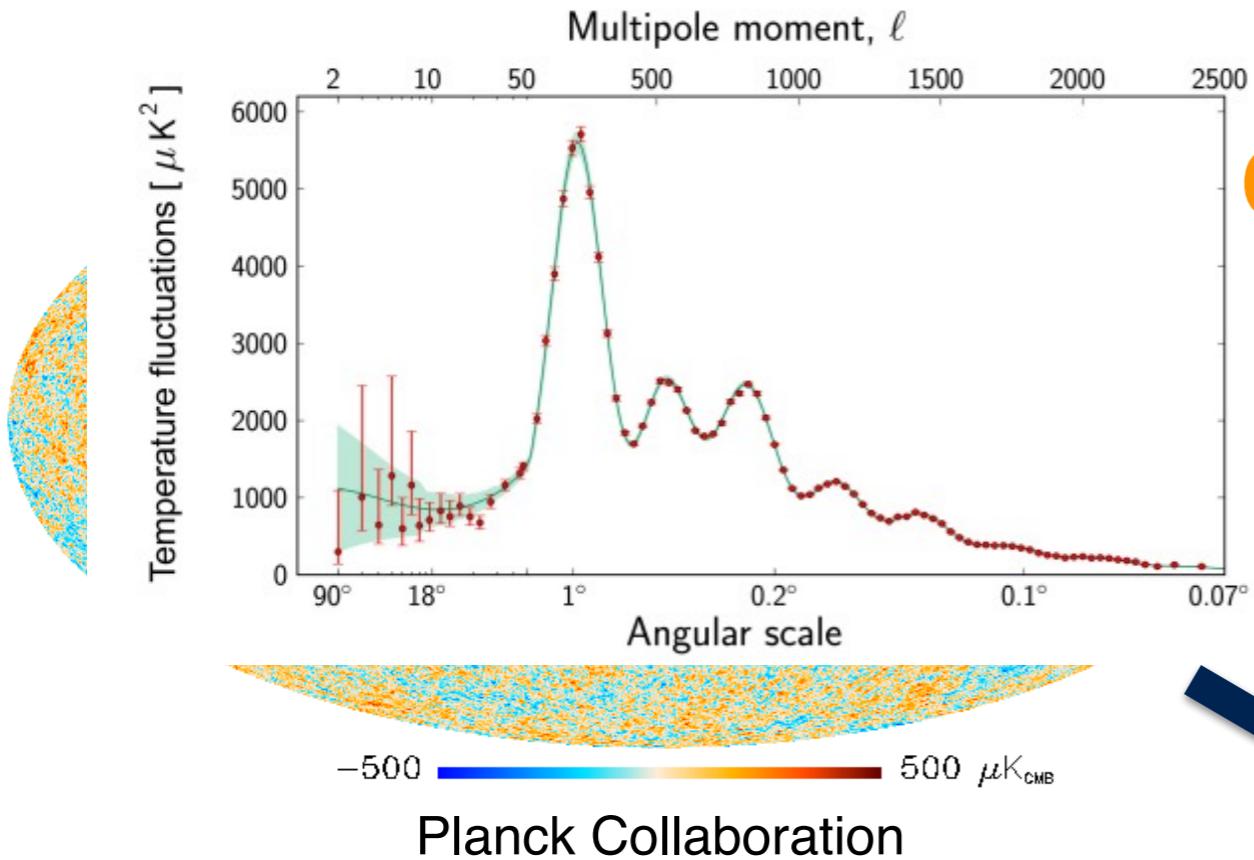
Large Scale Structure

- Growth of structure: **Clustering, RSD, Lensing**
- Geometric Probes: **BAO, SNe, Lensing**



BOSS collaboration

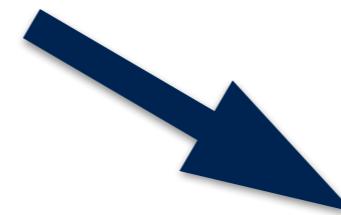
Overview



CMB

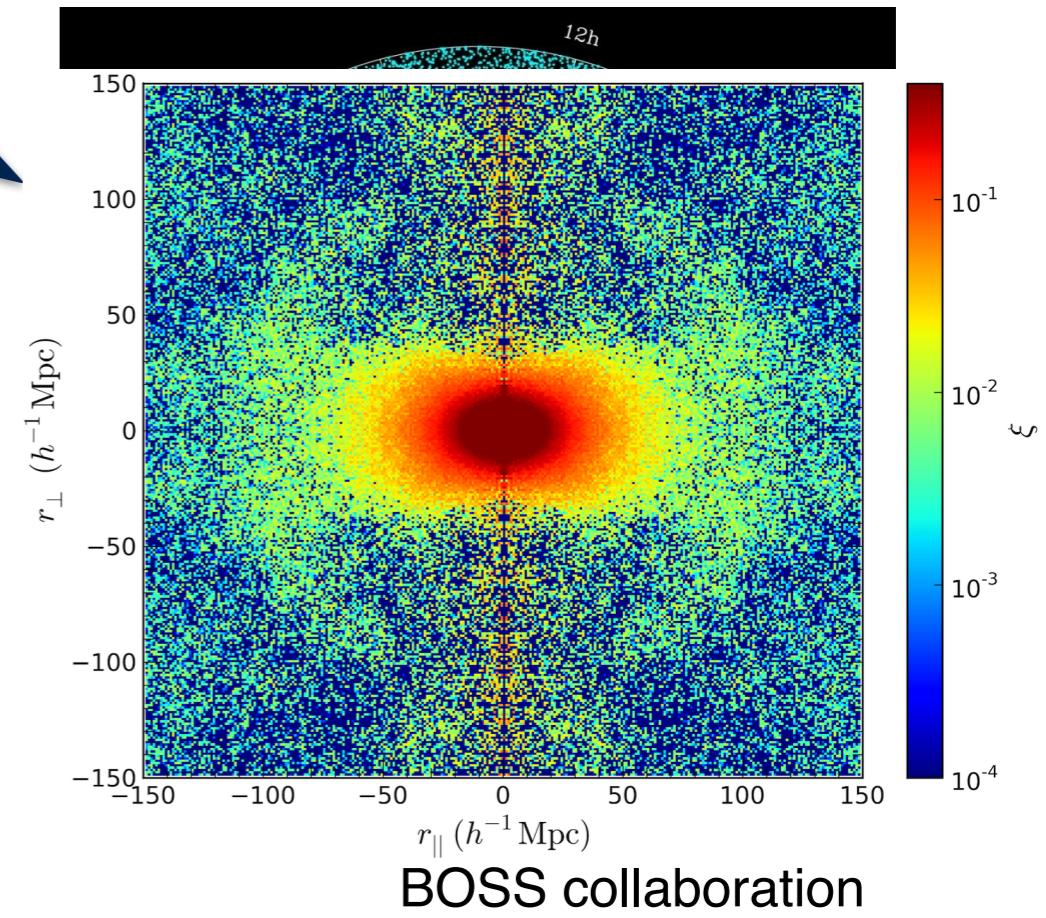
- Primordial fluctuations
- Linear Physics
- Gaussian statistics

$\text{GR} + \Lambda\text{CDM}$

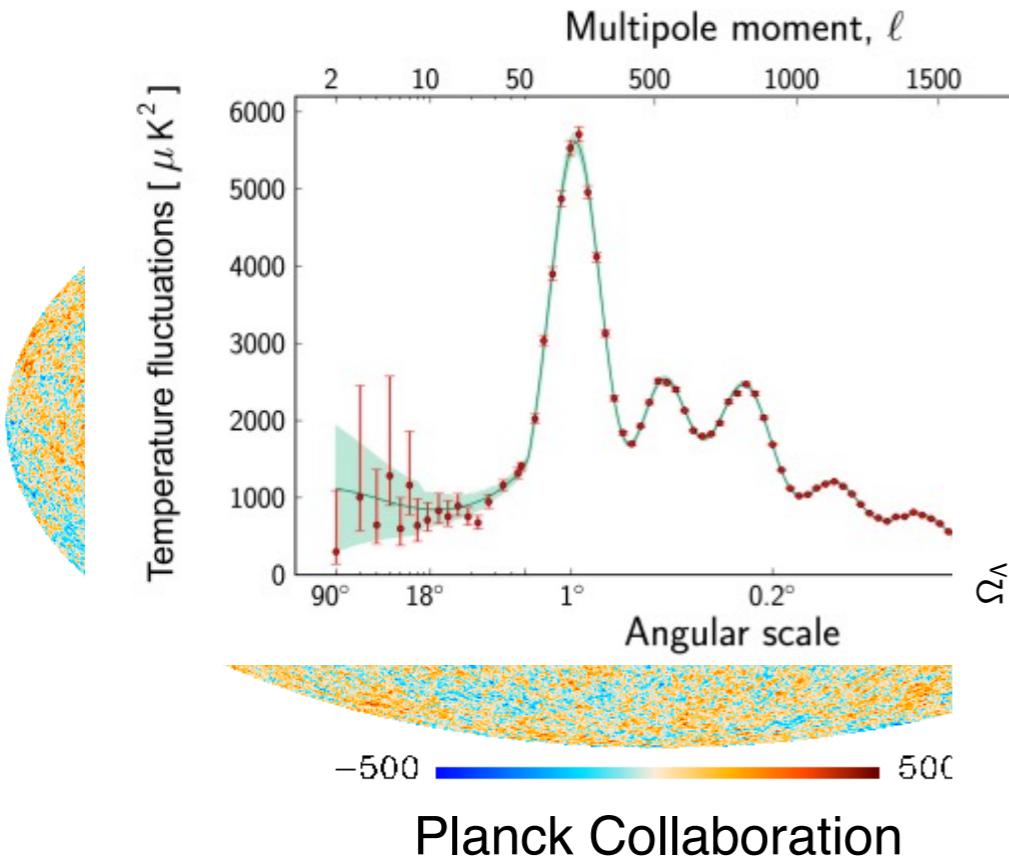


Large Scale Structure

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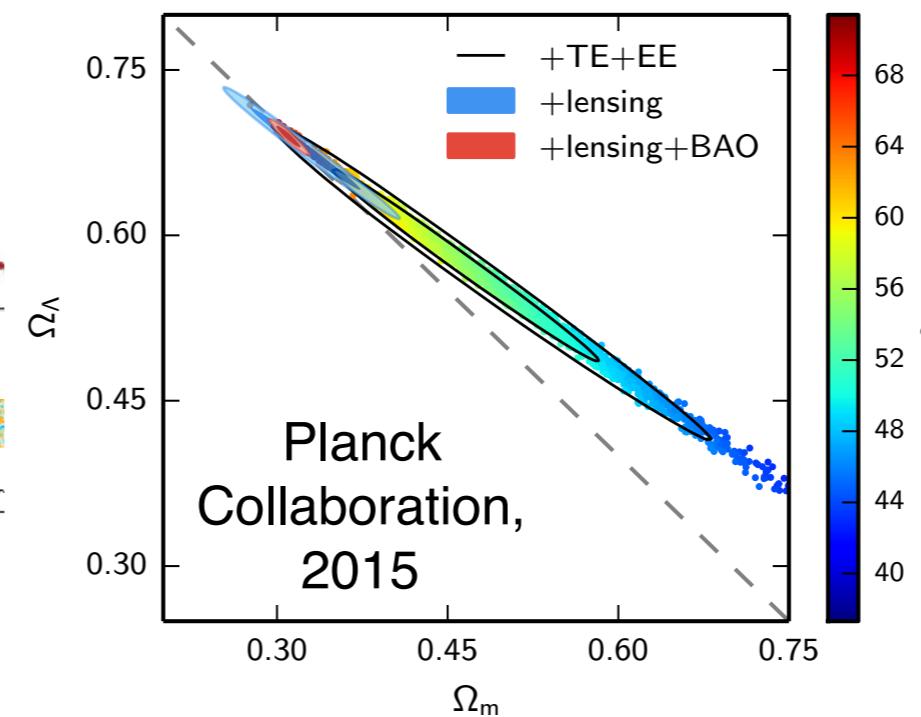


Overview

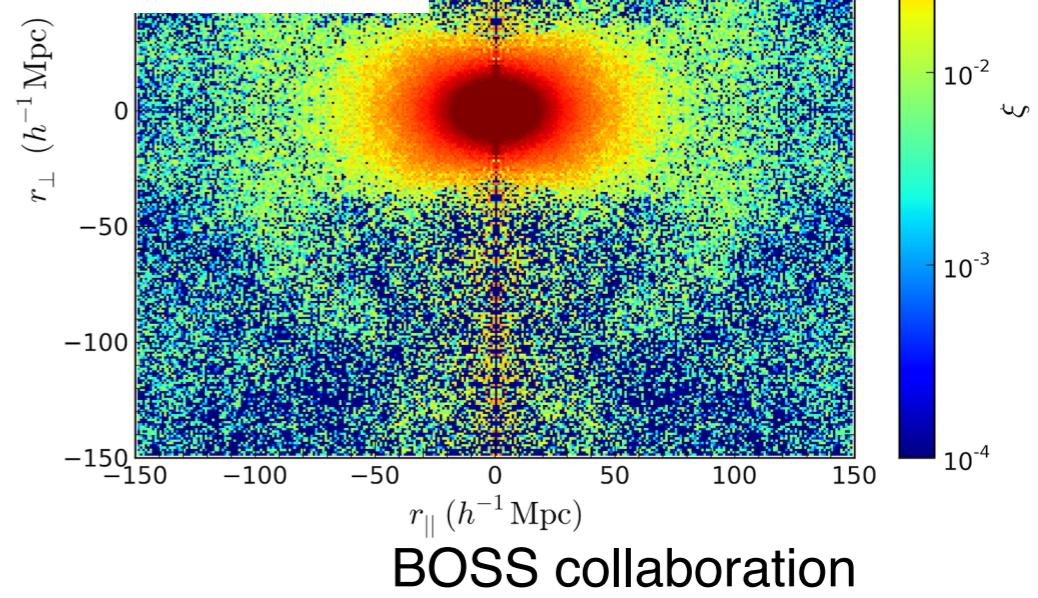


CMB

- Probes initial conditions
- Linear Physics



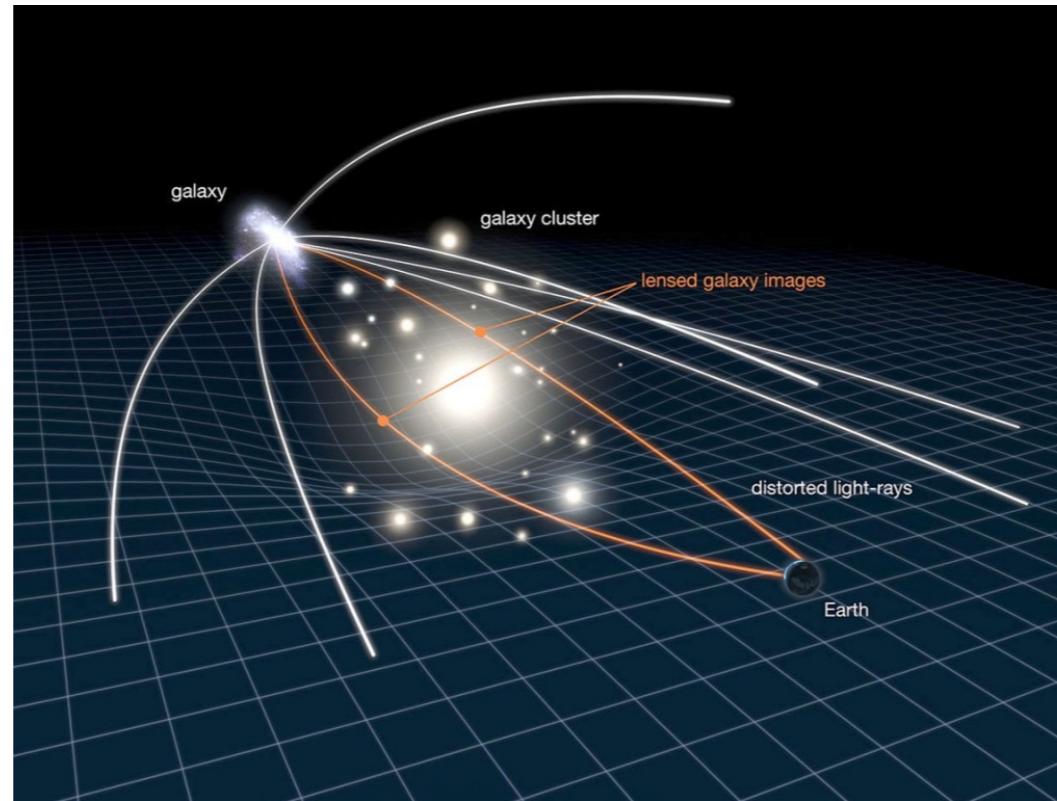
statistics



Large Scale Structure

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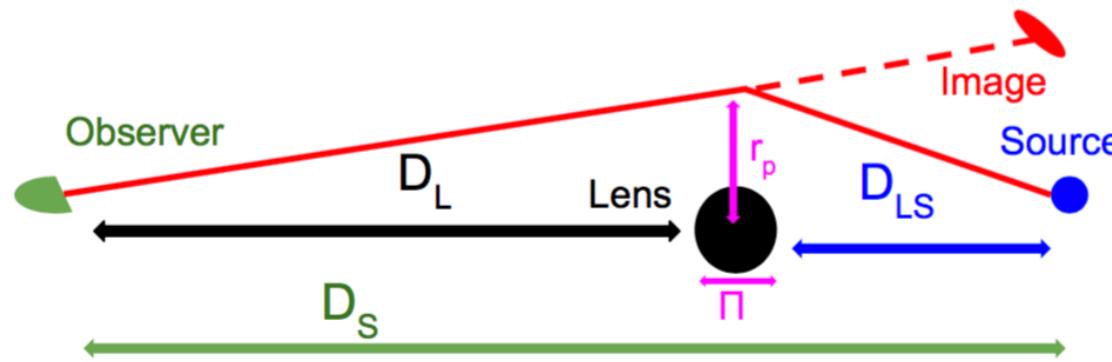
Lensing - Overview



NASA/ESA

- Light rays deflected by gravitational effects of large scale structure
- Distorts and magnifies background source.
- Sensitive to all structure between source and observer.
- **Probes growth of structure, geometry, gravity.**

Galaxy Lensing



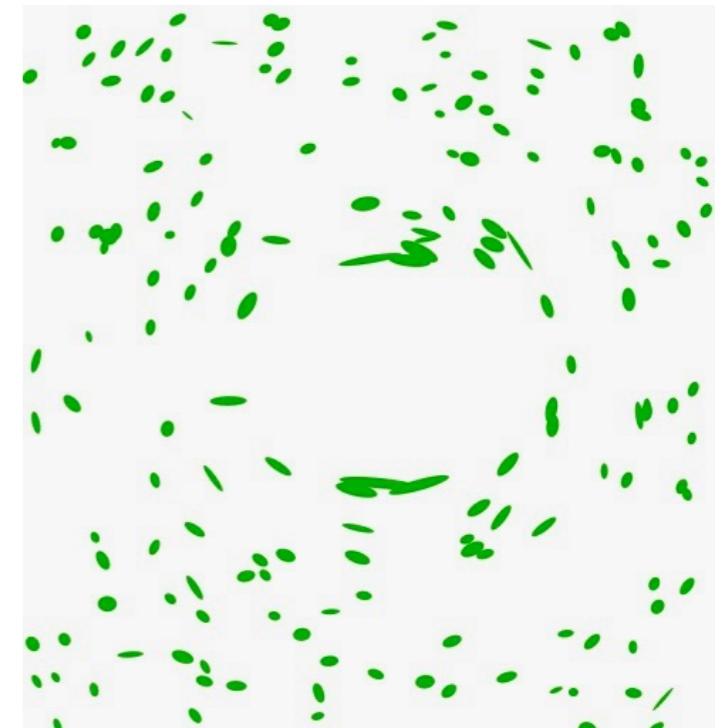
$$\Sigma_{\text{crit}} = \frac{c^2}{4\pi G} \frac{D_S}{(1 + z_l) D_L D_{LS}}$$

Galaxy Shear

$$\gamma_t = \frac{\Delta\Sigma(r_p)}{\Sigma_{\text{crit}}}$$

For Spherically symmetric lens $\Delta\Sigma(r_p) = \bar{\Sigma}(< r_p) - \Sigma(r_p)$

See Clampitt+ 2016; van Uitert+ 2016 for anisotropic lensing



Wikipedia

Galaxy-galaxy lensing estimator

$$\Delta\Sigma_{gR} = \Delta\Sigma_g - \Delta\Sigma_R$$

Galaxy-Shear
cross correlation

Randoms-Shear
cross correlation

$$\Delta\Sigma_g = \langle \Sigma_c \gamma_t \rangle$$

Randoms Subtraction

- Necessary for removing additive systematics
- Also improves covariance

Galaxy-galaxy lensing estimator

$$\Delta\Sigma(r_p) = \bar{\Sigma}(< r_p) - \Sigma(r_p)$$



Difficult to model

Contains information from small scales.

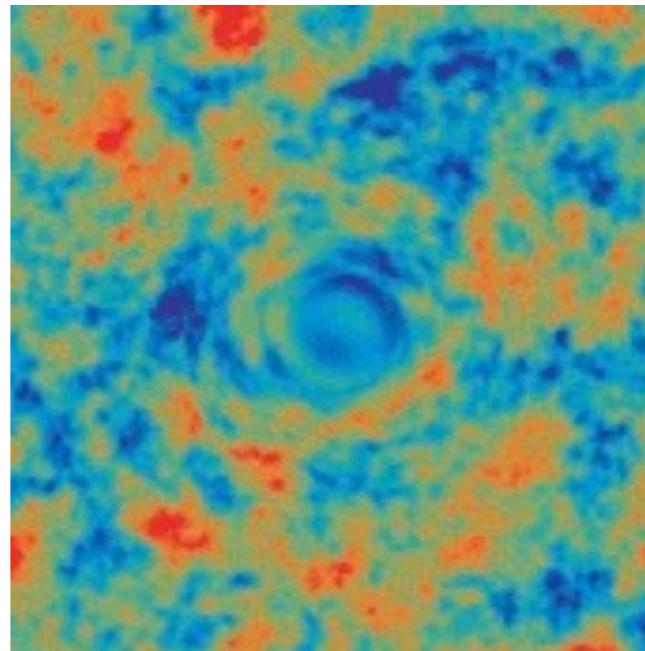
ADSD Estimator

Baldauf+ 2010

$$\Upsilon(r_p; r_0) = \Delta\Sigma(r_p) - \left(\frac{r_0}{r_p}\right)^2 \Delta\Sigma(r_0)$$

- Removes information from scales $< r_0$.
- Lowers impact of
 - non-linear bias and galaxy-matter correlation.
 - Baryon effects
 - RSD (projected clustering)
- **Cost:** Removing signal. Lowers S/N at small scales.

CMB lensing



Hu&Okamoto 2001

$$T(\hat{n}) \rightarrow T(\hat{n} + \alpha)$$

Convergence

$$\kappa(r_p) = \frac{\Sigma(r_p)}{\Sigma_{\text{crit}}} \qquad \Sigma_{\text{crit}} = \frac{c^2}{4\pi G} \frac{D_S}{(1+z_l)D_L D_{LS}}$$

Estimator $\Sigma_{gR} = \Sigma_g - \Sigma_R$

Galaxy-Lensing Cross correlations

- Robust to additive lensing systematics.
- Direct probe of galaxy-matter cross correlations
- Combined with clustering, provides matter-matter correlation function.

Baldauf et al. 2010, Mandelbaum et al. 2013, More et al. 2015, Kwan et al. 2016

Galaxy-Lensing Cross correlations

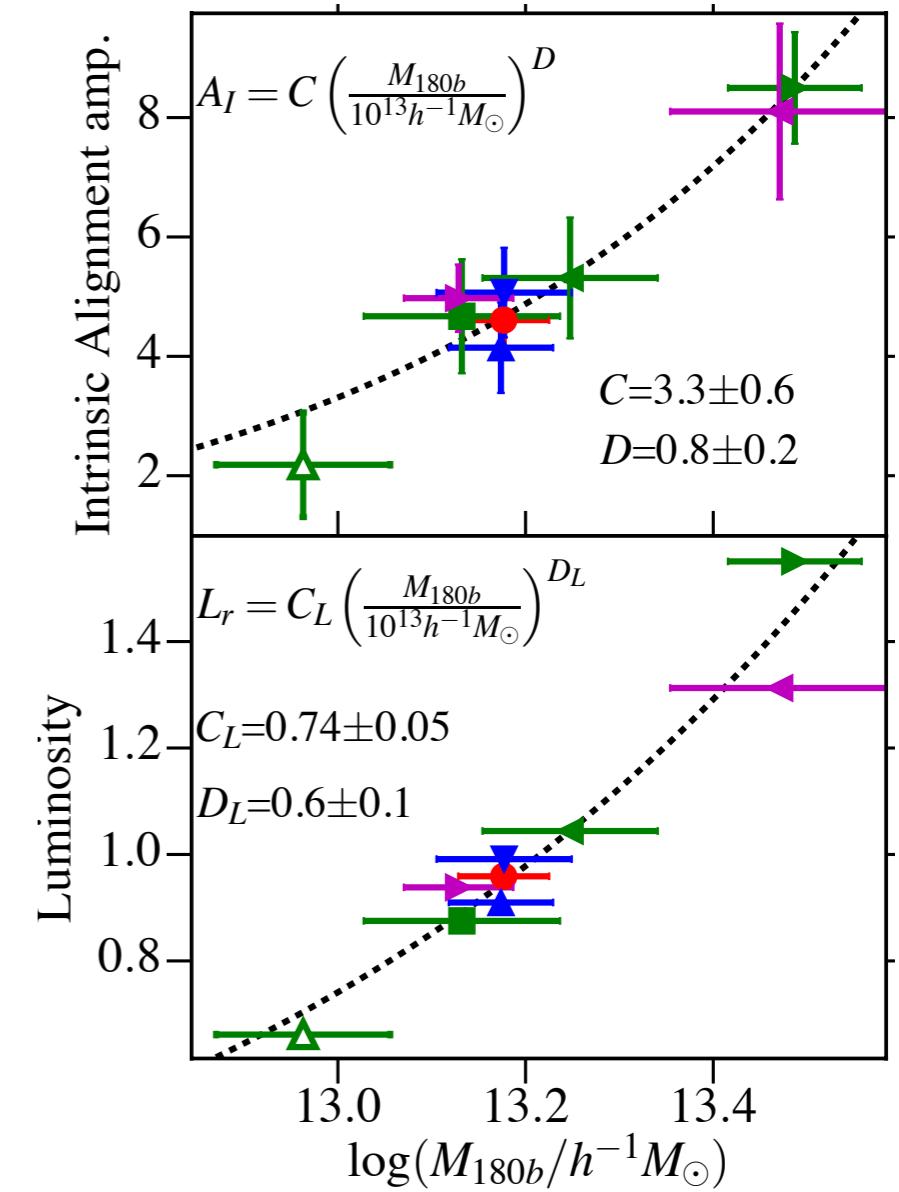
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Seljak et al. 2005, Baldauf et al. 2010, Mandelbaum et al. 2013, More et al. 2015, Kwan et al. 2016

Not In this Talk

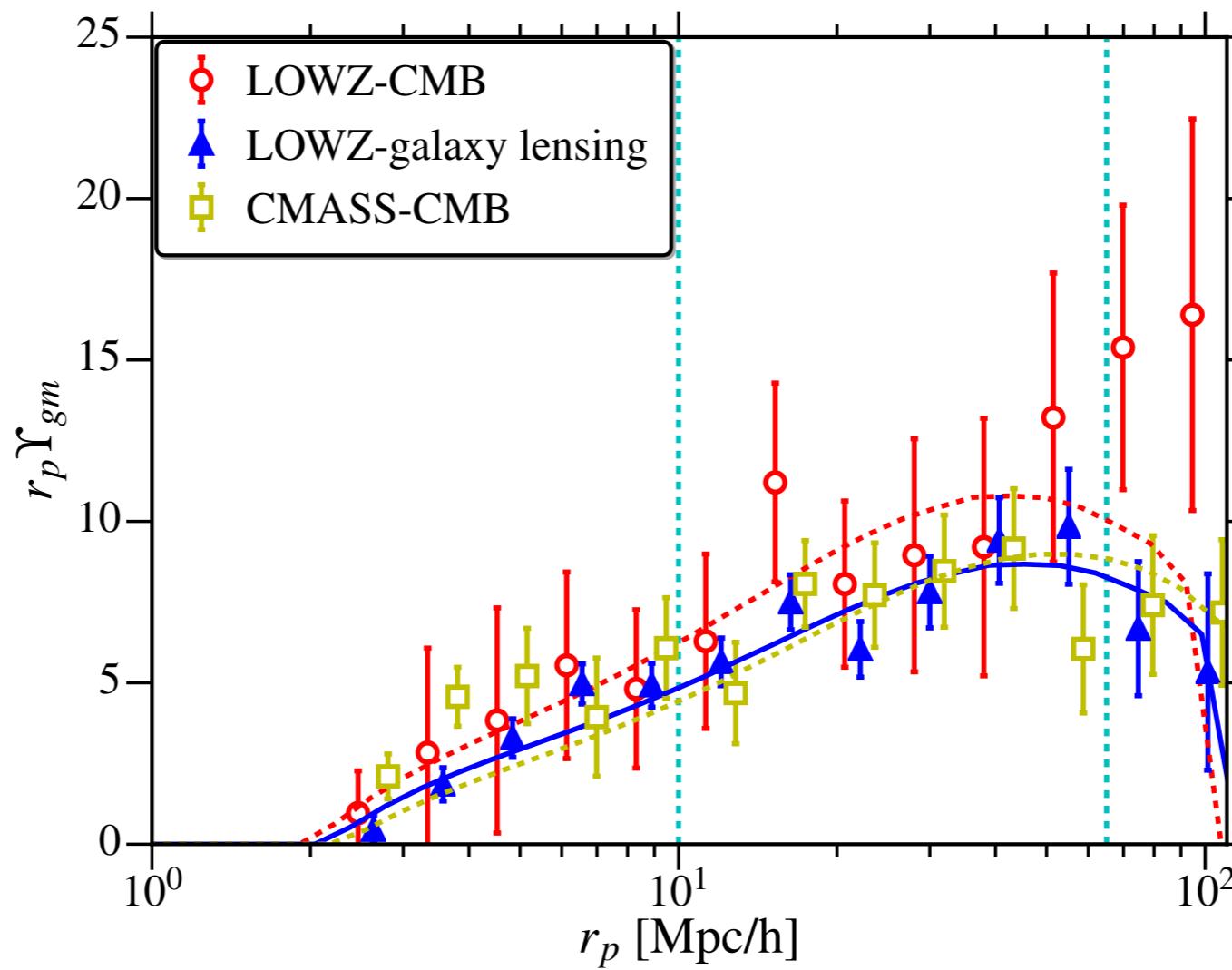
- A unique probe of galaxy-dark matter halo connection.

Mandelbaum et al. 2006, Tinker et al. 2012, Leauthaud et al. 2012, Sifon et al. 2015



Measurements

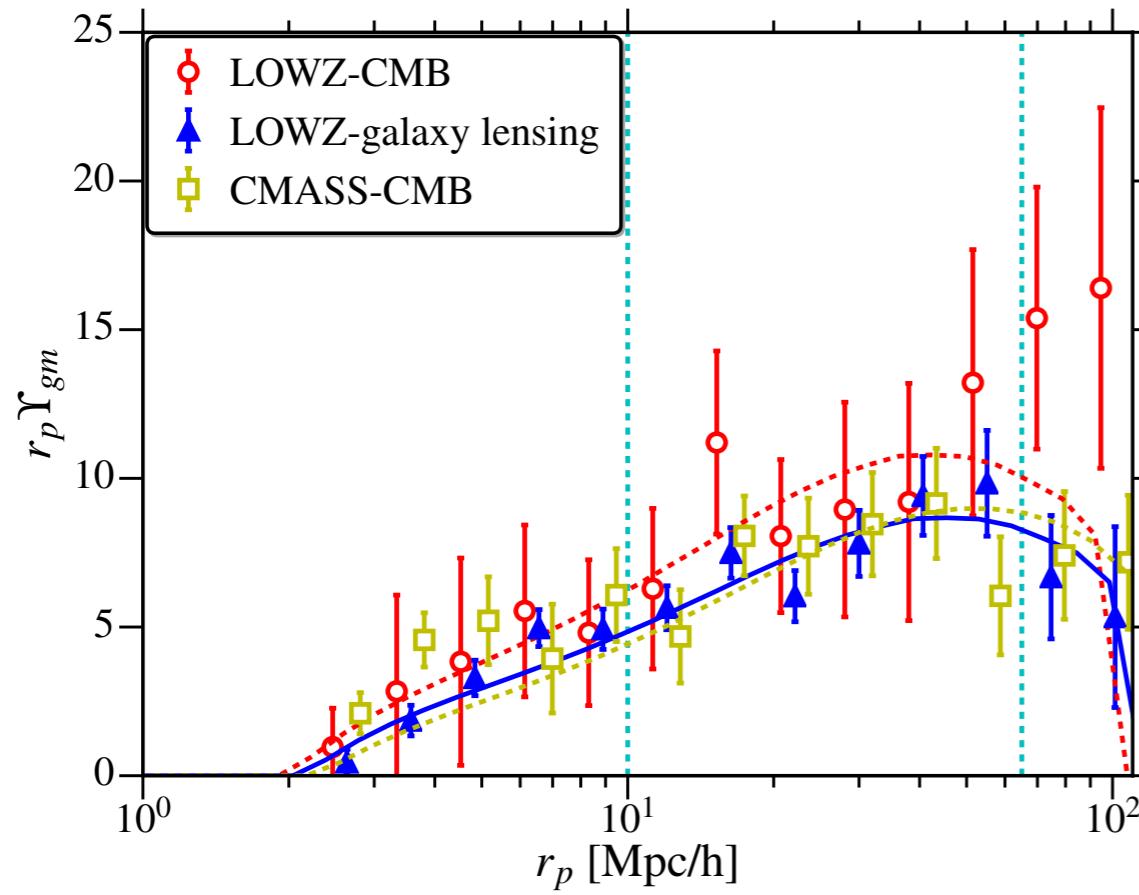
Galaxy-Lensing Cross correlations



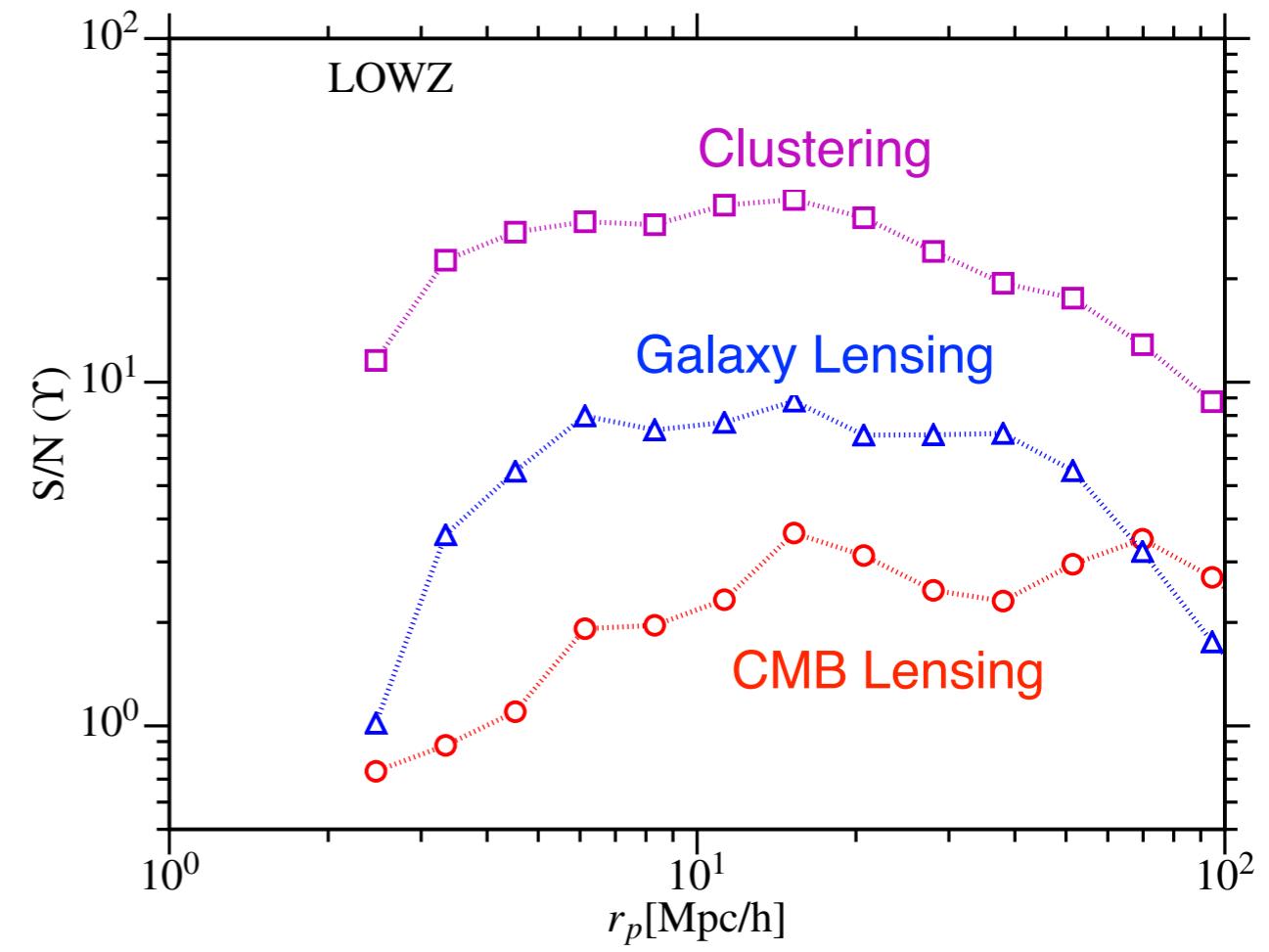
SS+ 2016b

Measurements

Galaxy-Lensing Cross correlations



SS+ 2016b



Covariance estimation

Methods

- Theoretical estimates
- Standard deviation across mock realizations (StD)
- Jackknife (J_k)
- Dividing data into subsamples

Covariance estimation

Estimator

$$\Delta\Sigma_{gR} = \Delta\Sigma_g - \Delta\Sigma_R$$

Gaussian

$$\text{Cov}(\Delta\Sigma_g)(|\vec{r}_{p,i}|, |\vec{r}_{p,j}|) = \frac{1}{\mathcal{N}} FT \left[(P_{gg}(k) + N_g) (P_{\gamma\gamma}(k) + N_\gamma) + P_{g\gamma}^2 \right]$$

$$+ \frac{1}{\mathcal{N}_2} FT \left\{ \tilde{W}(k)^2 (P_{\gamma\gamma}(k) + N_\gamma) \right\}$$

Additional term
if we do not subtract

$$\Delta\Sigma_R$$

Lens Clustering +
Shot noise

Shear correlations +
shape noise

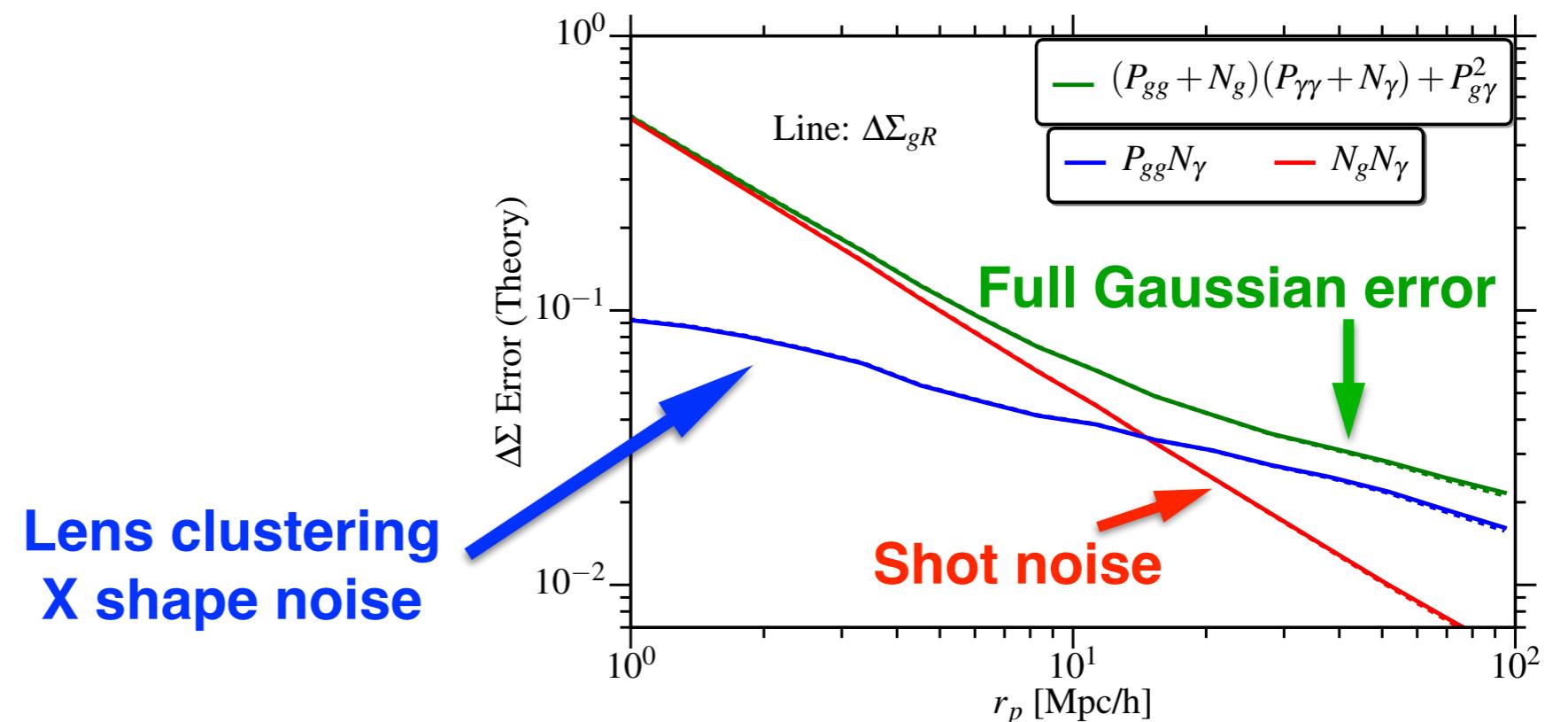
Lens-Shear
cross-correlation

Covariance estimation

Estimator

$$\Delta\Sigma_{gR} = \Delta\Sigma_g - \Delta\Sigma_R$$

$$\text{Cov}(\Delta\Sigma)(|\vec{r}_{p,i}|, |\vec{r}_{p,j}|) = \frac{1}{\mathcal{N}} FT \left[(P_{gg}(k) + N_g) (P_{\gamma\gamma}(k) + N_\gamma) + P_{g\gamma}^2 + T_{g\gamma g\gamma} \right]$$



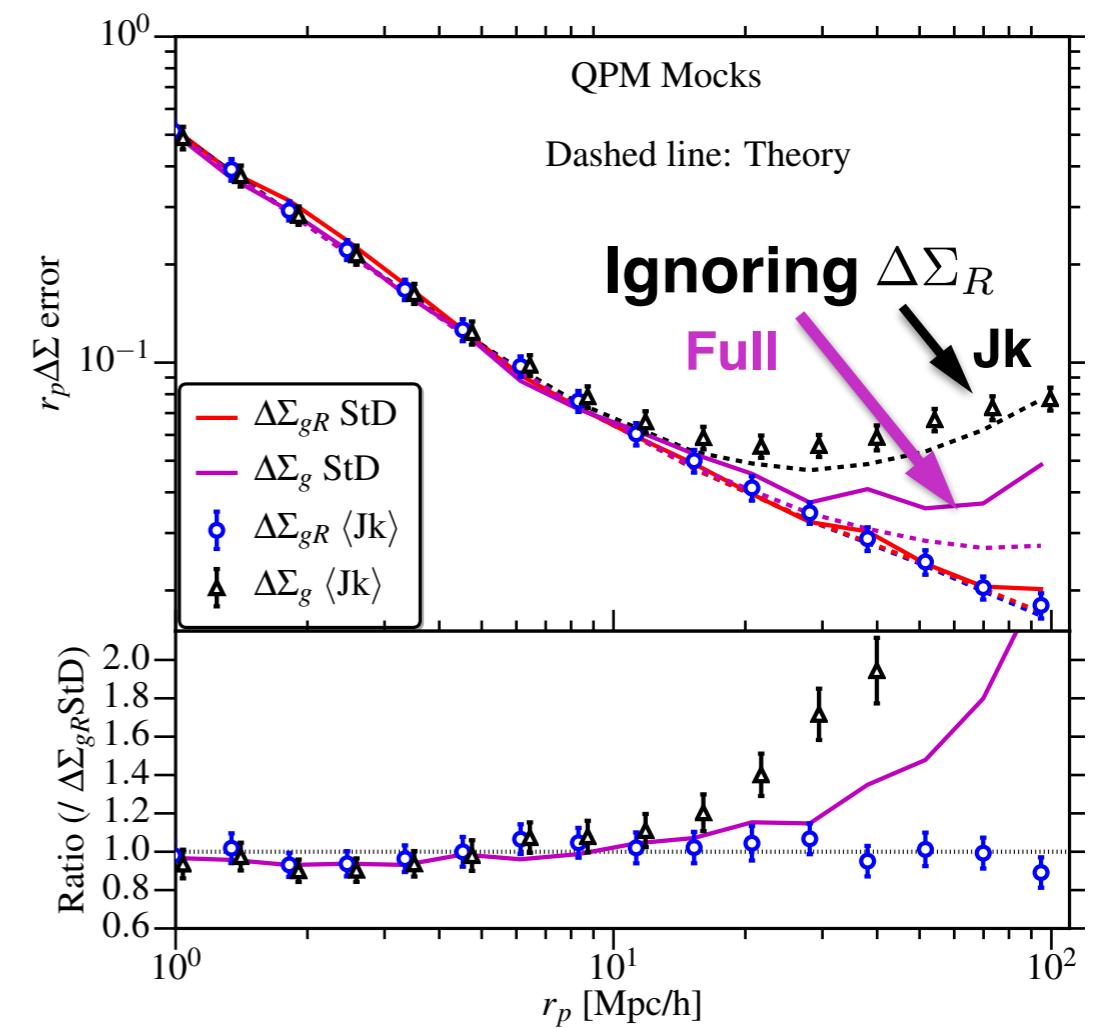
Covariance estimation

Estimator

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Covariance estimation

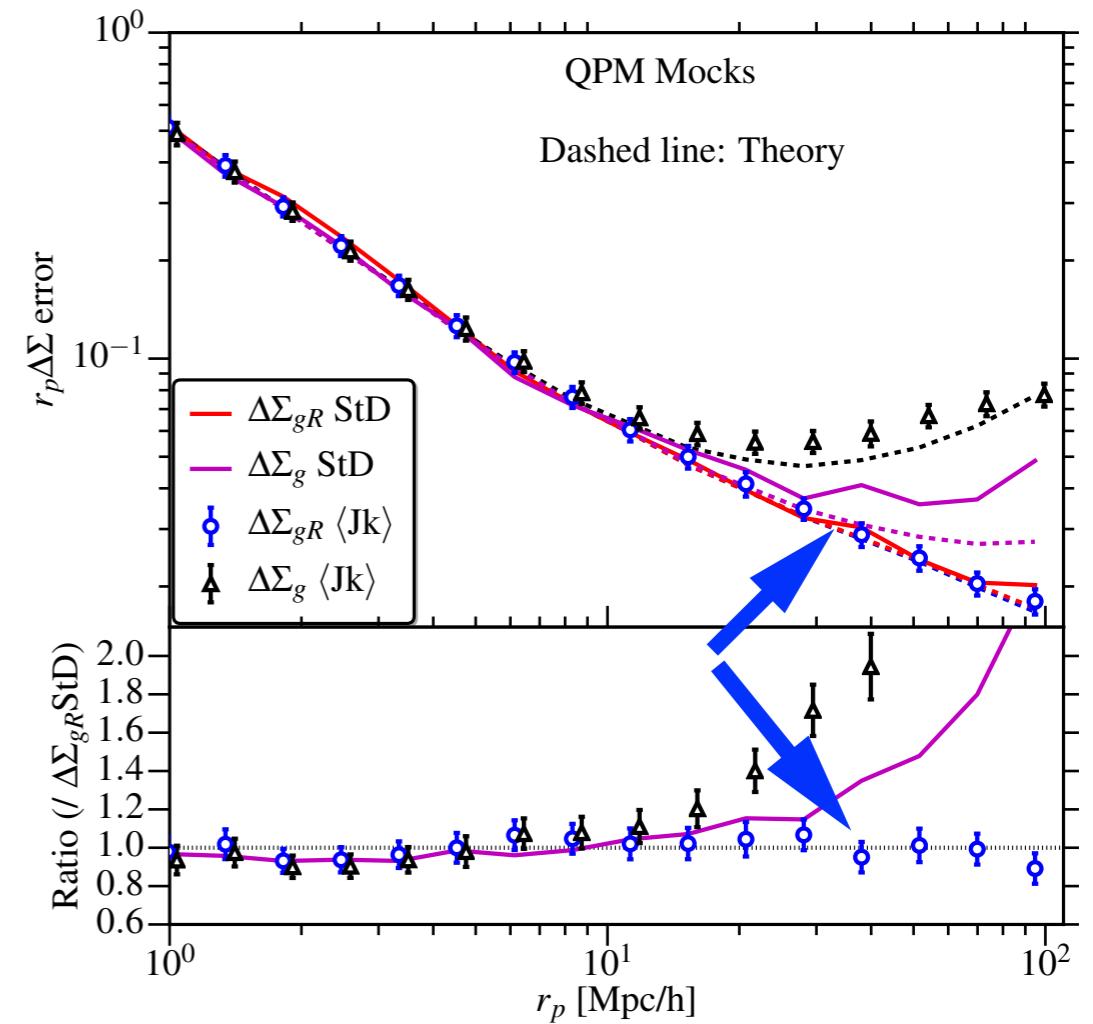
Estimator

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- Theoretical estimates
- Jackknife (J_k)
- Standard deviation across mock realizations (StD)

All methods agree for full estimator



Applications

Constraining lensing Systematics

The shape measurement Problem

$$\hat{e} = (1 + m) \langle e_i + \gamma_G + \gamma_{IA} \rangle + c$$

Multiplicative bias
Shape noise
Lensing Shear
Intrinsic Alignment
Additive Bias

Need image simulations to calibrate shape measurements.

See Great-3 challenge. Mandelbaum+ 2014, 2015.

- Multiplicative bias degenerate with linear power spectrum amplitude.
- IA, Photo-z bias can also show up as multiplicative bias.

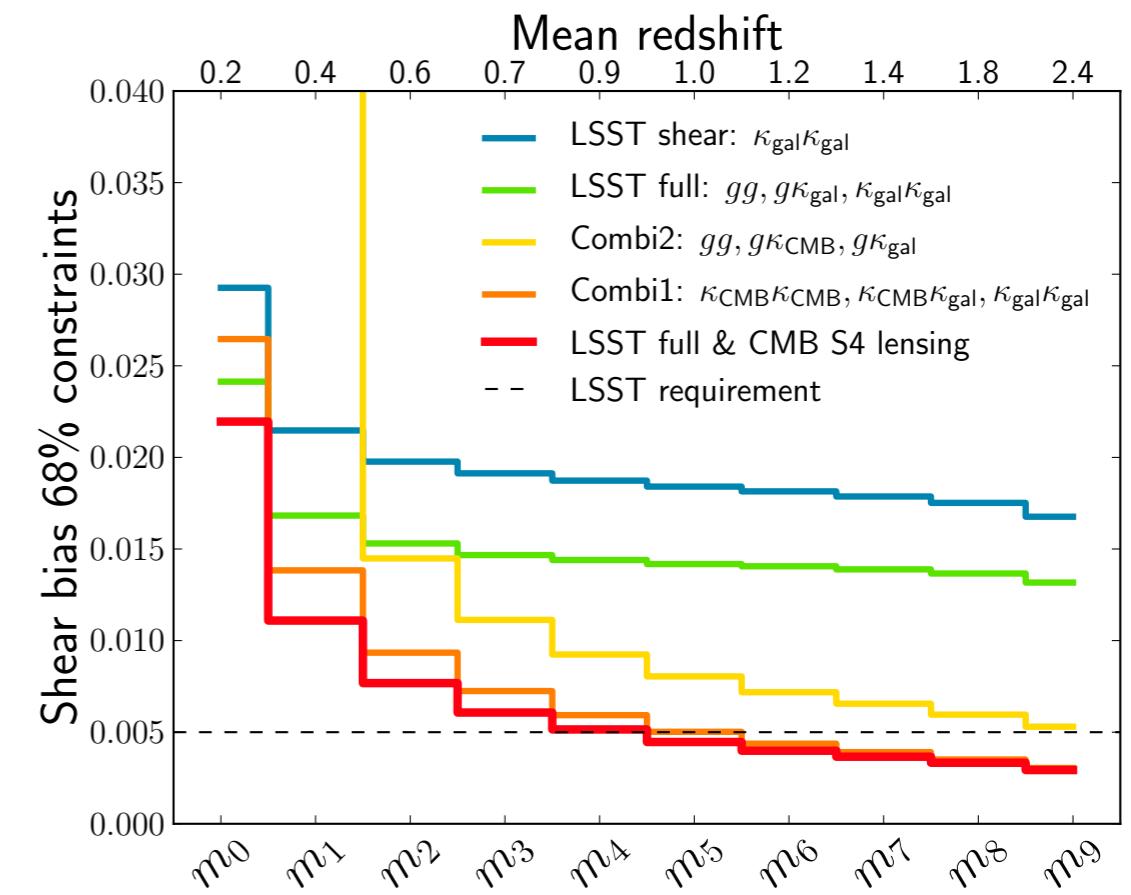
Constraining lensing Systematics

CMB and Galaxies lensing have

- Overlapping kernels: Lensing by same structure
- Very different systematics

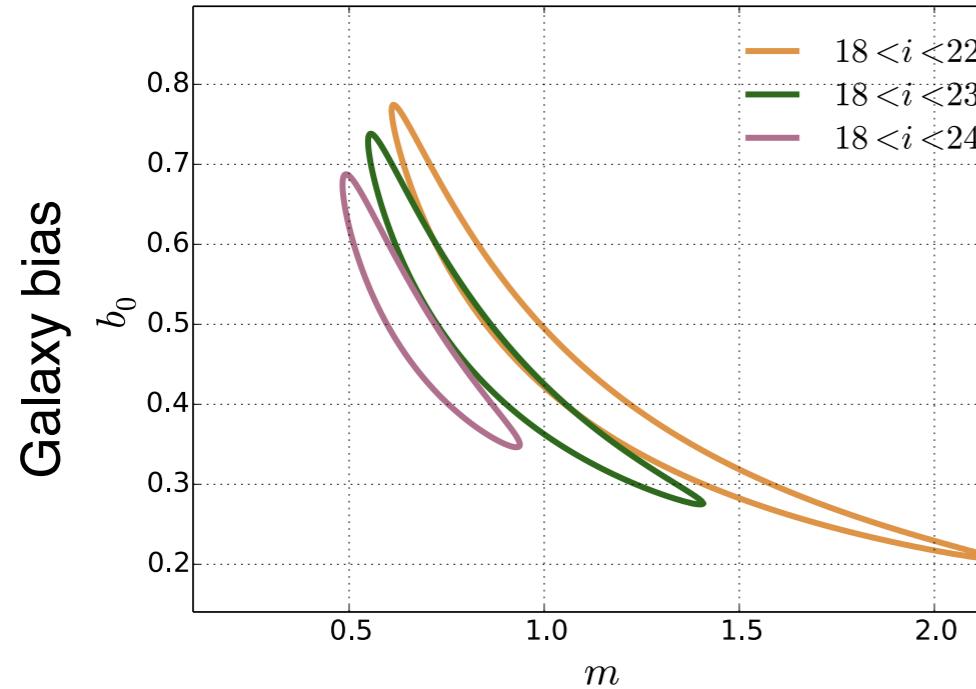
Cross-Correlations
Allow for self-calibration

Vallinotto 2012, Das+ 2013, Schaan+ 2016

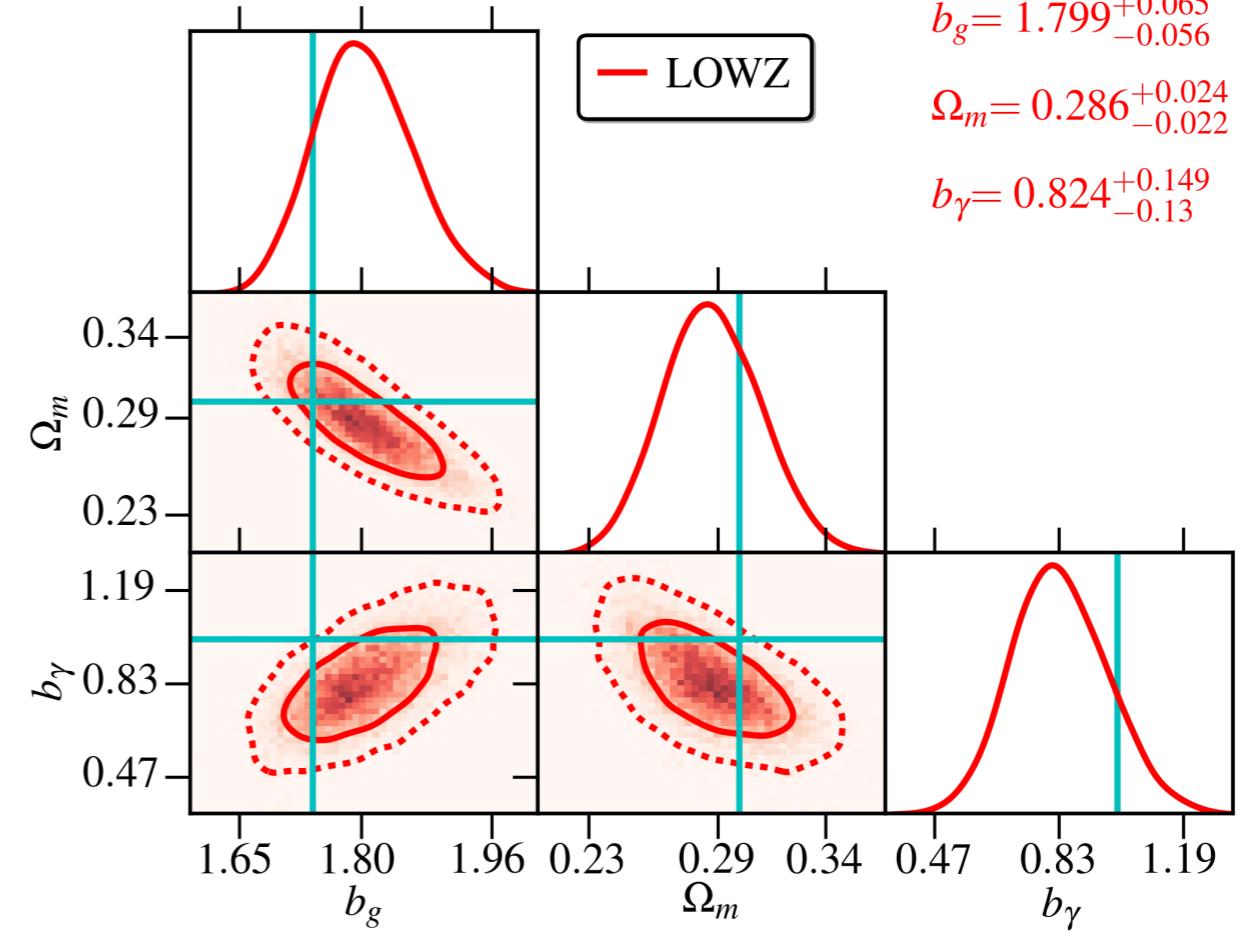


Schaan+ 2016

Constraining lensing Systematics



Liu+ 2016: CFHTLens+Planck



SS+ 2016b →

$$b_\gamma \equiv m$$

(assuming no systematics in CMB lensing)

See Van Engelen+ 2014 for discussion on systematics in CMB lensing

Cosmic Distance Ratio

$$\mathcal{R} = \frac{g\kappa_{CMB}}{g\kappa_{gal}} = \frac{\Sigma_c(z_l, z_s)}{\Sigma_c(z_l, z_*)} \frac{\Sigma(z_l)}{\Sigma(z_l)} \quad \text{Hu+ 2007b}$$

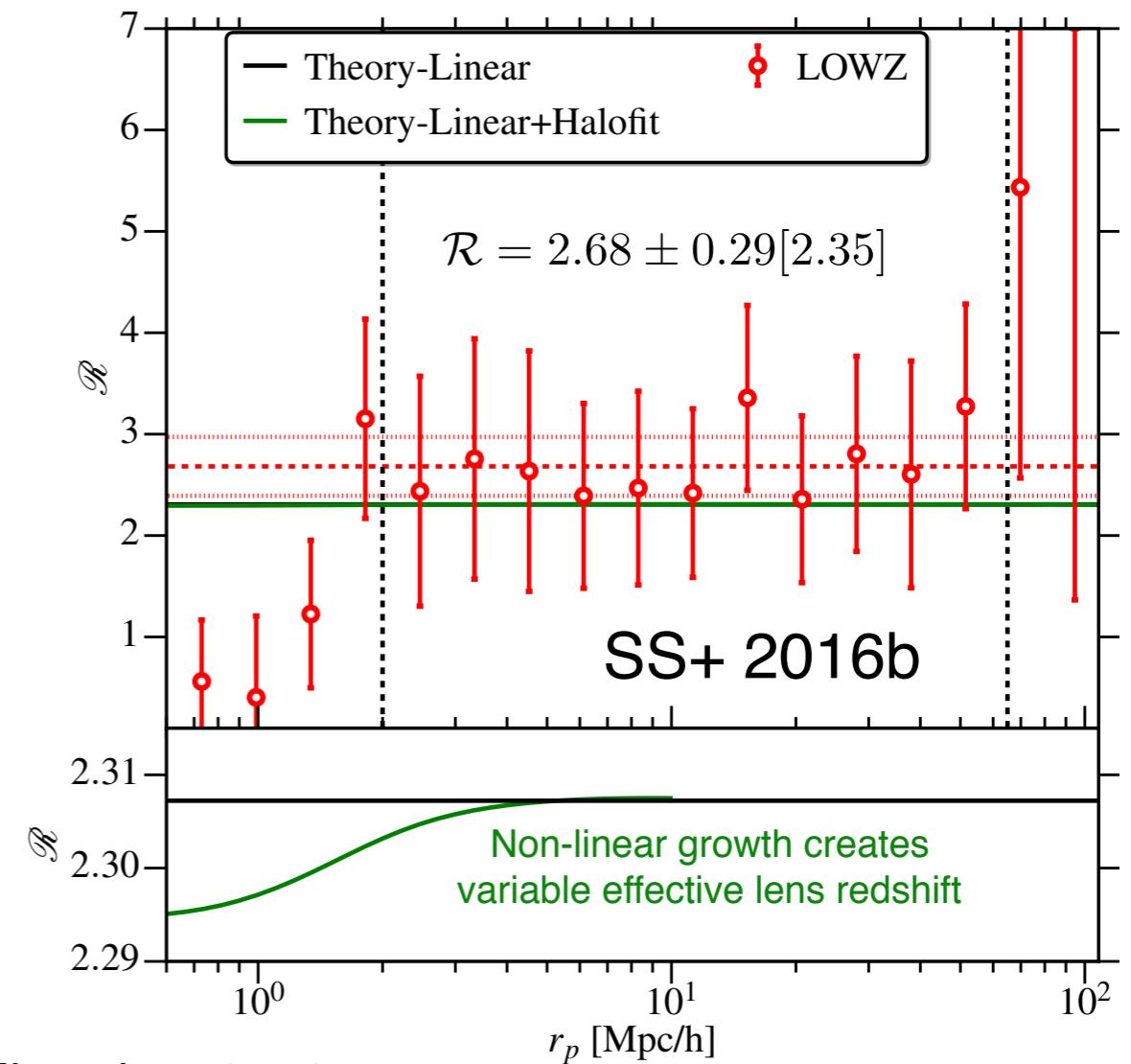
Geometric test, independent of power spectrum

Problems

- Not scale independent with non-linear growth.
(work with narrow lens redshift bins)
- Weak dependence on cosmology

A good test for lensing systematics

$$\frac{\mathcal{R}_{\Lambda CDM}}{\mathcal{R}_{\text{measured}}} \sim b_\gamma$$



See also Miyatake+ 2016

Testing ΛCDM

FRW Metric

$$ds^2 = a(\tau)^2 \{ -(1 + 2\psi)d\tau^2 + (1 - 2\phi)(dr^2 + r^2 d\Omega^2) \}$$

Newtonian Potential Curvature Potential

Within ΛCDM $\psi = \phi$ (in absence of anisotropic stress)

Constructing a null test,

$$\frac{\phi + \psi}{2\psi} \underset{\Lambda CDM}{=} 1$$

Lensing

Velocities (RSD)

E_G Parameter

$$E_G = \frac{1}{\beta} \frac{\rho_m}{\rho_{\text{crit}}} \frac{P_{gm}}{P_{gg}} = \frac{\Omega_m}{f(z)}$$

Zhang+ 2007

$$E_G = \frac{1}{\beta} \frac{\Upsilon_{gm}}{\Upsilon_{gg}}$$

Reyes+ 2010

See also, Pullen+ 2015, Leonard+ 2015

- Independent of linear galaxy bias and amplitude of matter fluctuations.
- Different theories of gravity predict different values of E_G.

E_G Parameter

$$E_G = \frac{1}{\beta} \frac{\rho_m}{\rho_{\text{crit}}} \frac{P_{gm}}{P_{gg}} = \frac{\Omega_m}{f(z)}$$

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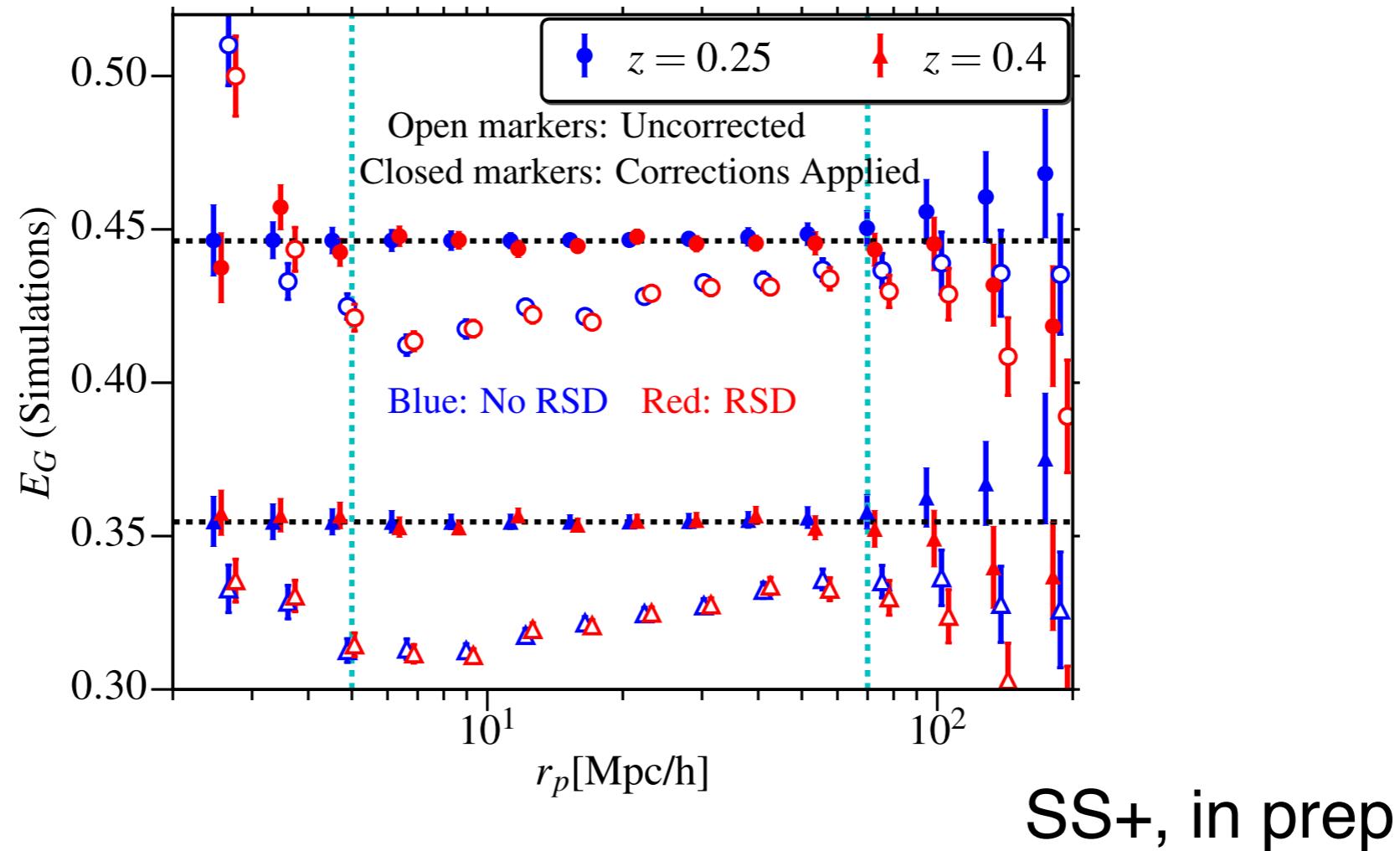
Problems

- Non-linear galaxy bias and galaxy-matter cross-correlation.
- Residual linear RSD in galaxy clustering

Baldauf+ 2010

Need to compute corrections from simulations and/or theory.

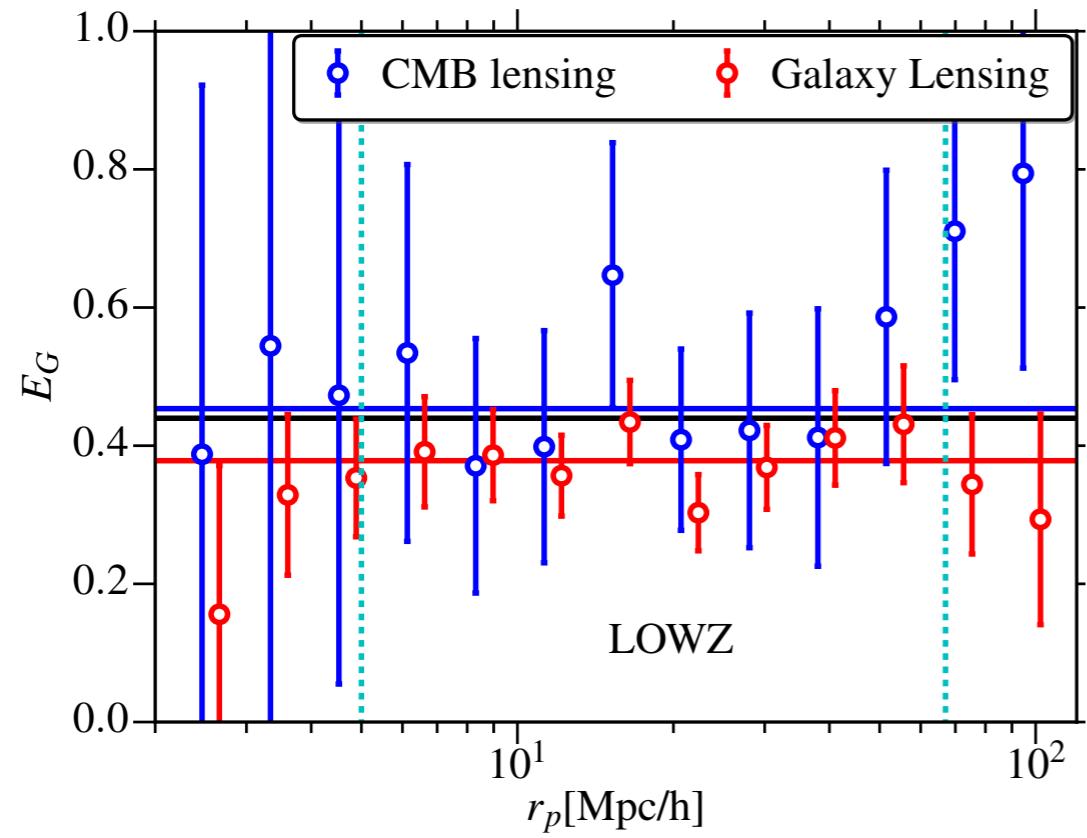
E_G in Simulations



Corrections applied:

- Non-linear galaxy bias and galaxy-matter cross correlations
- Linear RSD

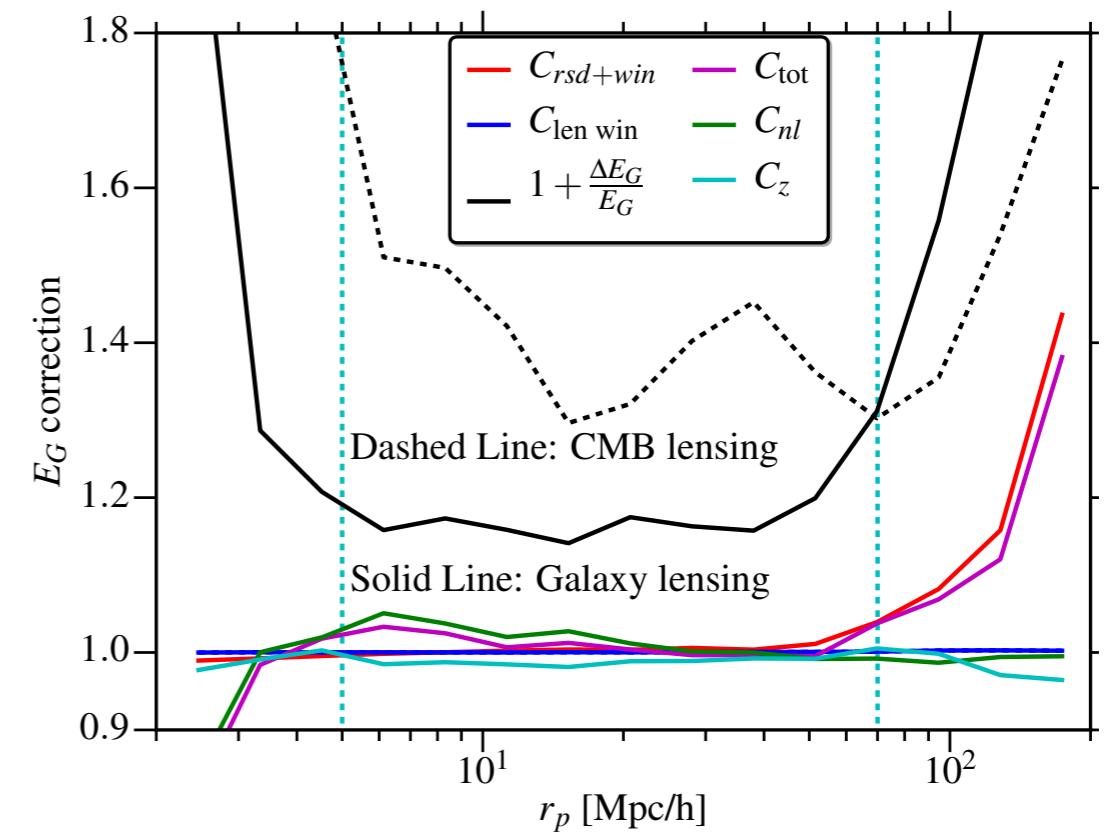
E_G Measurements



Corrections applied

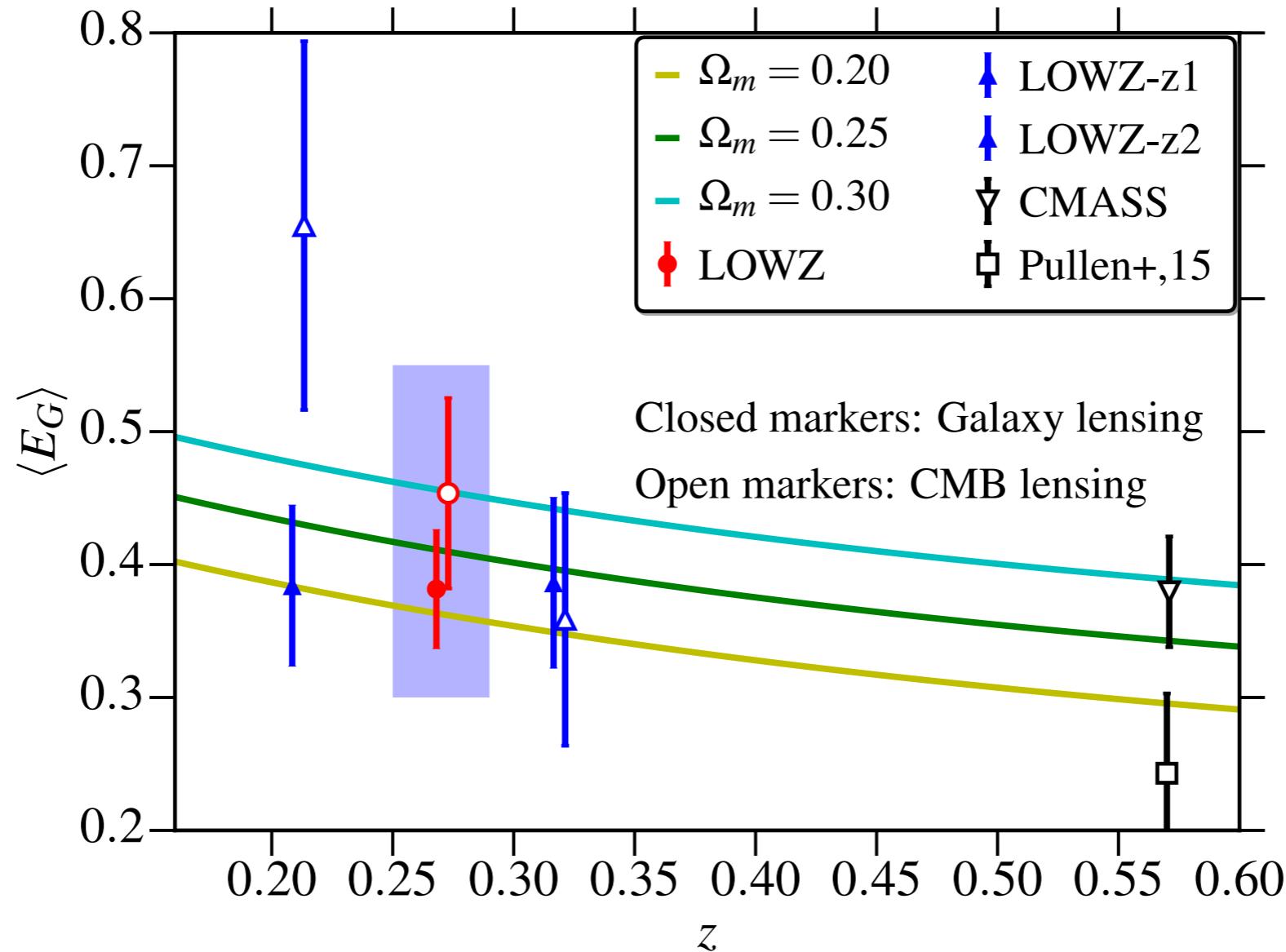


SS+, in prep



See also: Reyes et al. 2010, Blake et al. 2016, Pullen et al. 2016, Alam et al. 2016

E_G Measurements



SS+, in prep

See also: Reyes et al. 2010, Blake et al. 2016, Pullen et al. 2016, Alam et al. 2016

Cosmological Parameter Estimation

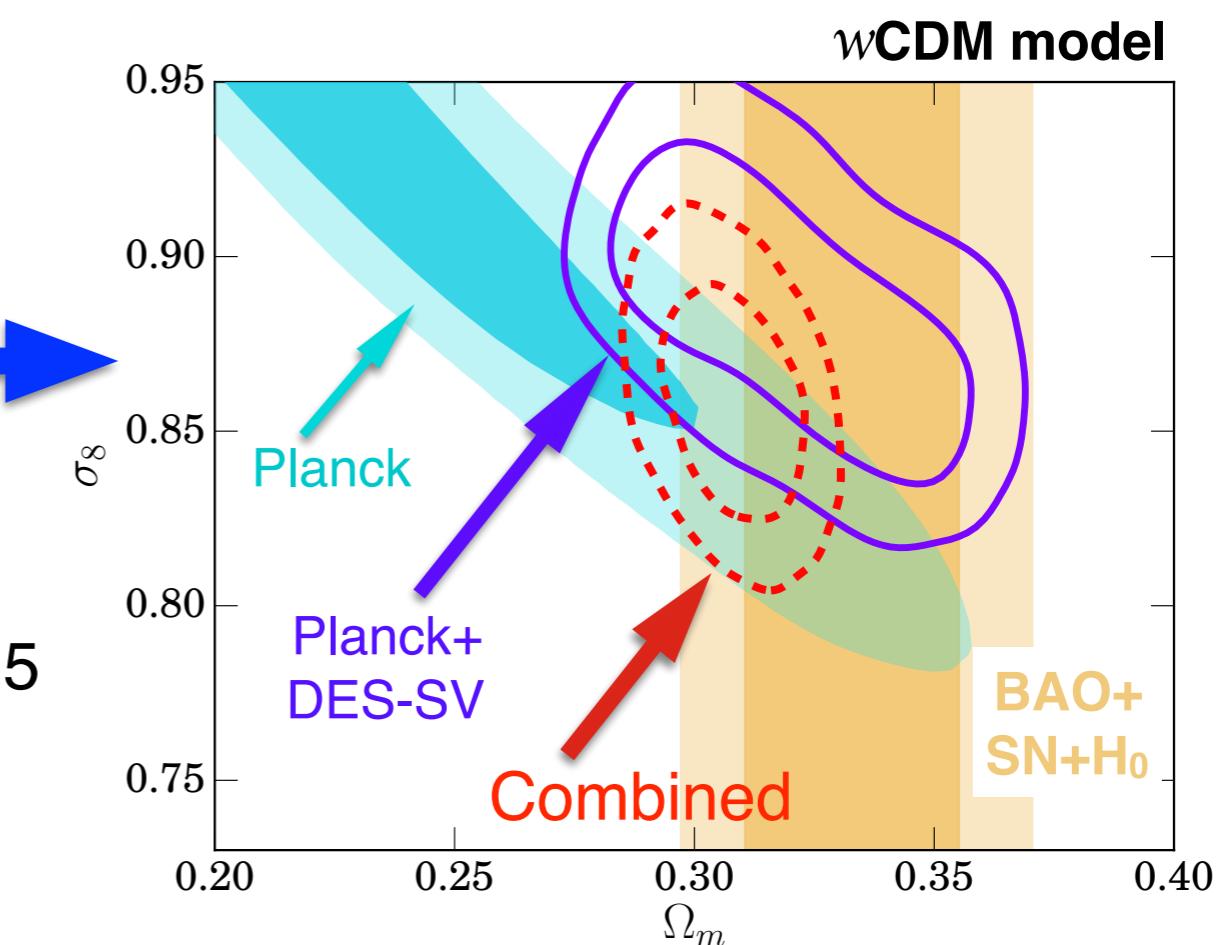
Clustering+Lensing breaks bias- σ_8 degeneracy

$$\frac{\Upsilon_{gm}^2}{\Upsilon_{gg}} = \bar{\rho}^2 r_{cc}^2 \Upsilon_{mm}$$

DES-SV results, Kwan et al. 2016



Baldauf et al. 2010,
Mandelbaum et al. 2013, More et al. 2015



Cosmological Parameter Estimation

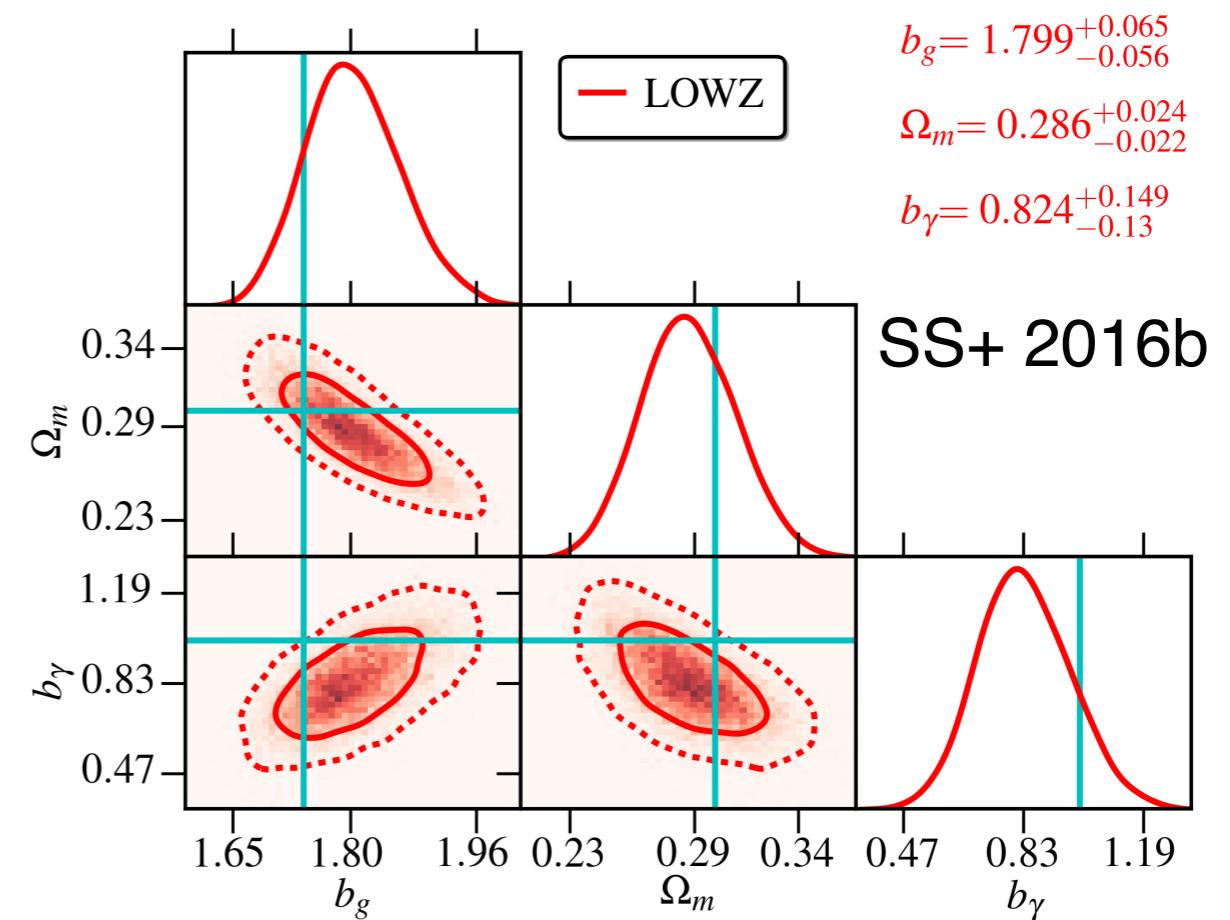
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LOWZ+SDSS+Planck

Conservative: Using large scales

Coming soon!
Results with better small scale
modeling
SS, JV+, in prep



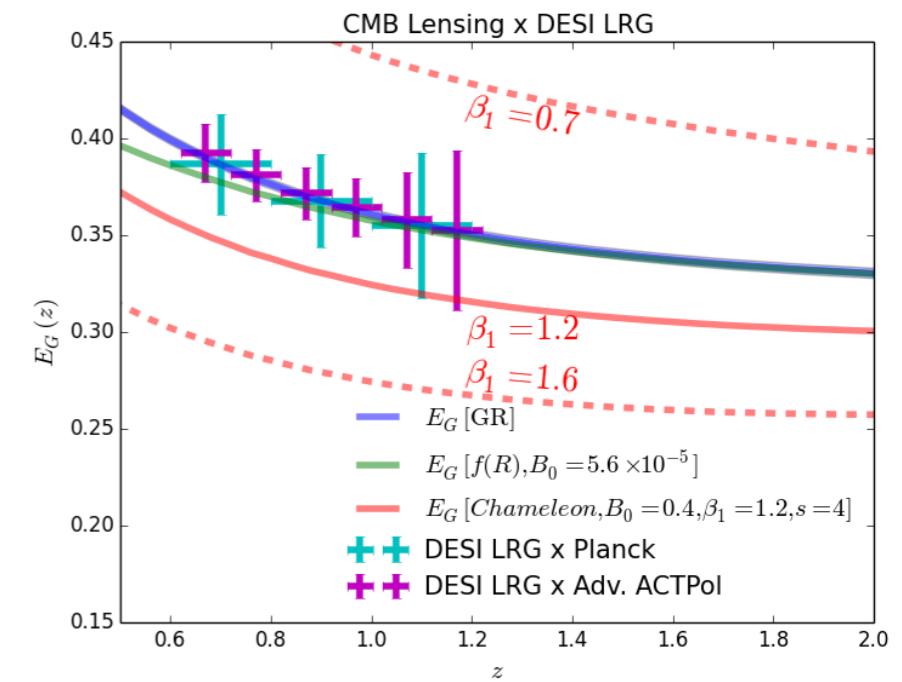
Summary

sukhdeep@cmu.edu

- Galaxy-Lensing cross correlations
 - Directly probe galaxy-matter correlations
 - Combined with clustering, breaks bias- σ_8 degeneracy
 - Combined with RSD, tests $\Lambda CDM + \text{GR}$
- Including CMB lensing constrains relative lensing calibration.

Outlook

- eBOSS+Planck/ACT+HSC/DES will probe higher redshifts
- DESI+LSST+CMB-stage IV – sub-percent level measurements + systematics control
- WFIRST+CMB-stage IV – High-z measurements



Pullen+ 2015

Summary

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- Galaxy-Lensing cross correlations
 - Directly probe galaxy-matter correlations
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- Including CMB lensing constrains shear multiplicative bias

Not covered in this talk

- **Intrinsic Alignments of galaxies**
SS+ 2015, 1411.1755; SS+ 2016a, 1510.06752
Tenneti, SS+ 2015, 1409.7297; Chen+ in prep.
- **Fundamental Plane of Galaxies and Intrinsic size correlations**
Joachimi, SS+ 2015, 1504.02662; SS+ in prep

Please come talk to me

