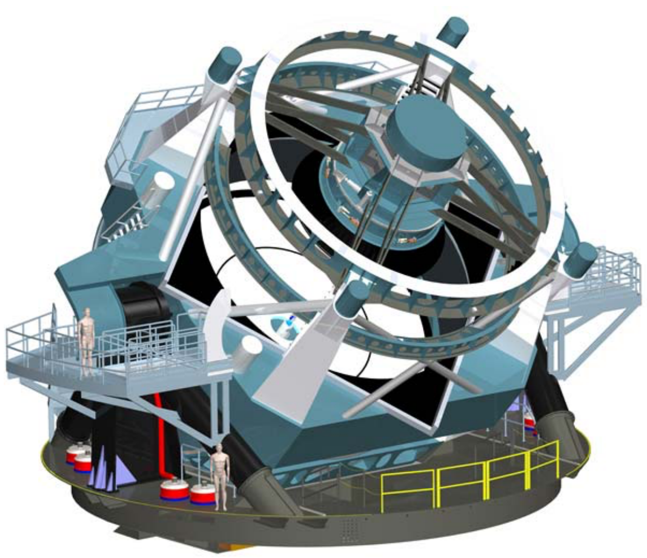
Cosmology in the next Decade

Fundamental Physics, Systematics and Synergies between cosmological probes



Sukhdeep Singh

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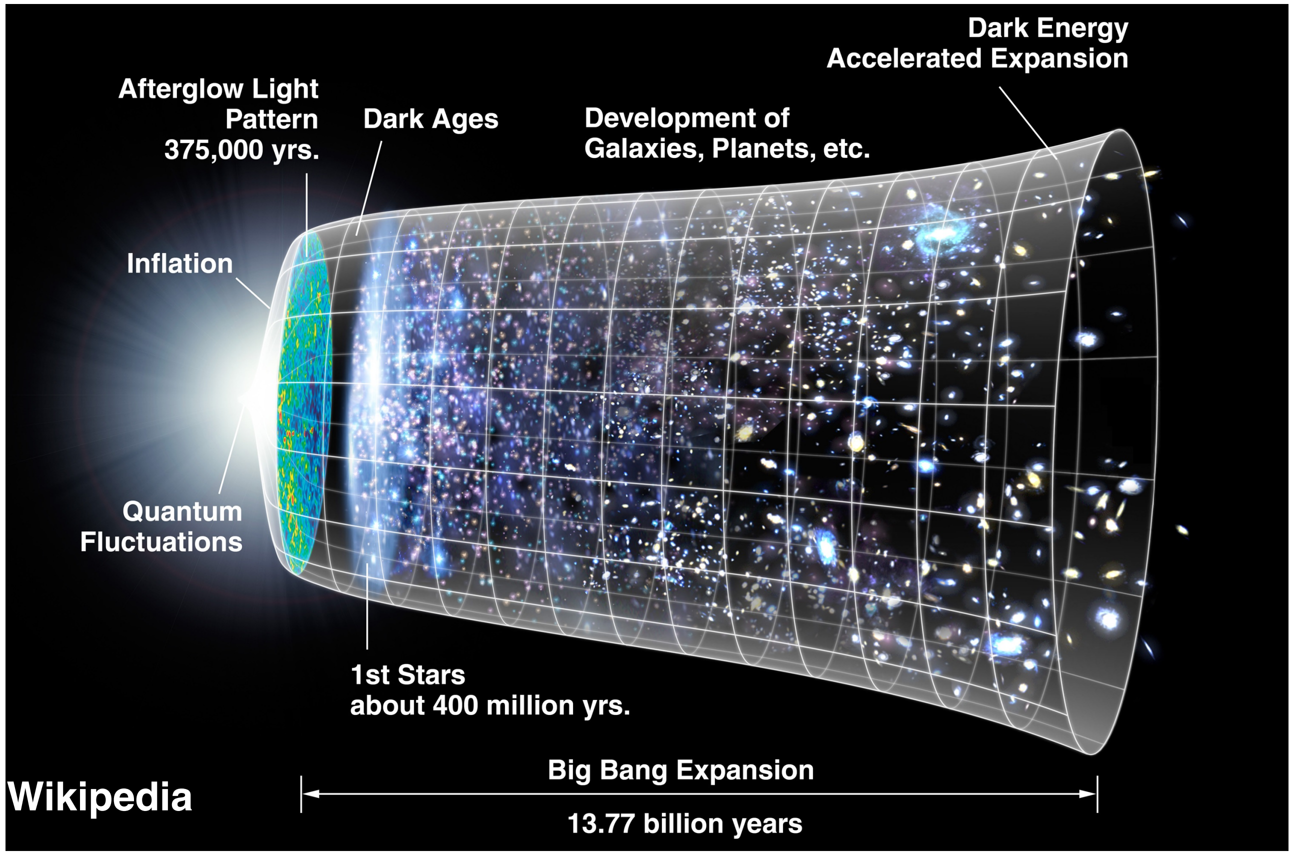
Physics Seminar
University of Wisconsin-Madison
February 2020

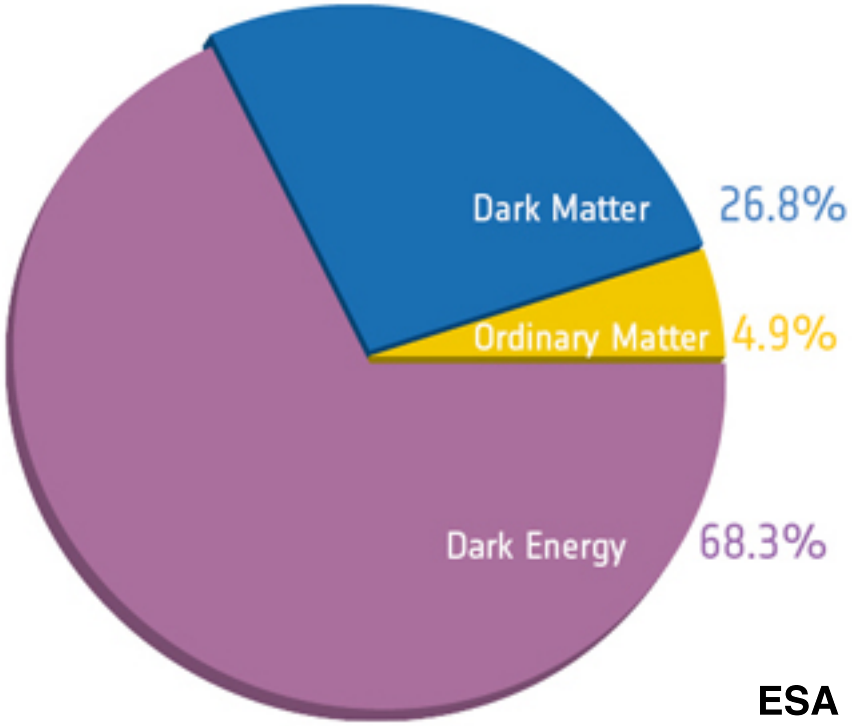
Outline

- **Overview**
  - The large scale structure and fundamental physics
- **Galaxy-Lensing cross correlations**
  - Cosmological constraints
- **The upcoming stage-IV surveys**
  - Synergies and Challenges
    - Covariance matrices
    - Photometric redshifts

Our Universe



Consistent with six parameter ΛCDM model

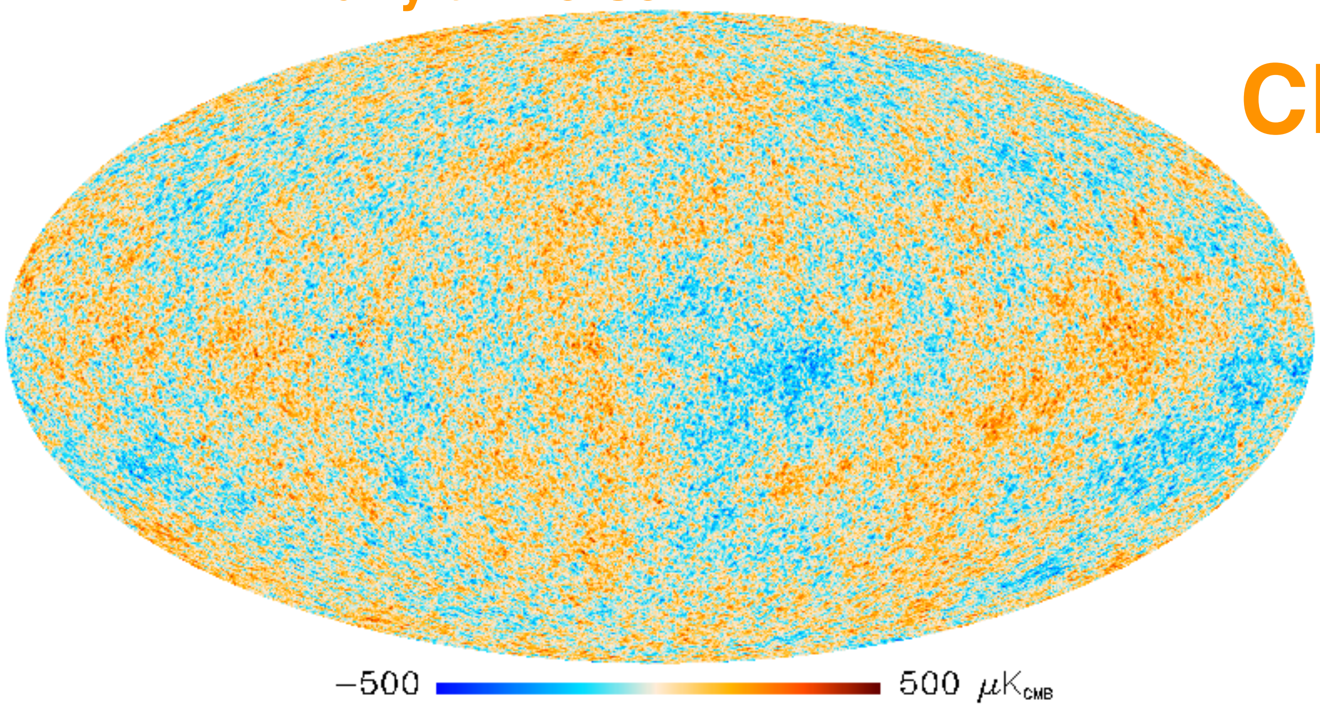


ESA

Simple yet mysterious

Cosmological Probes

Early universe



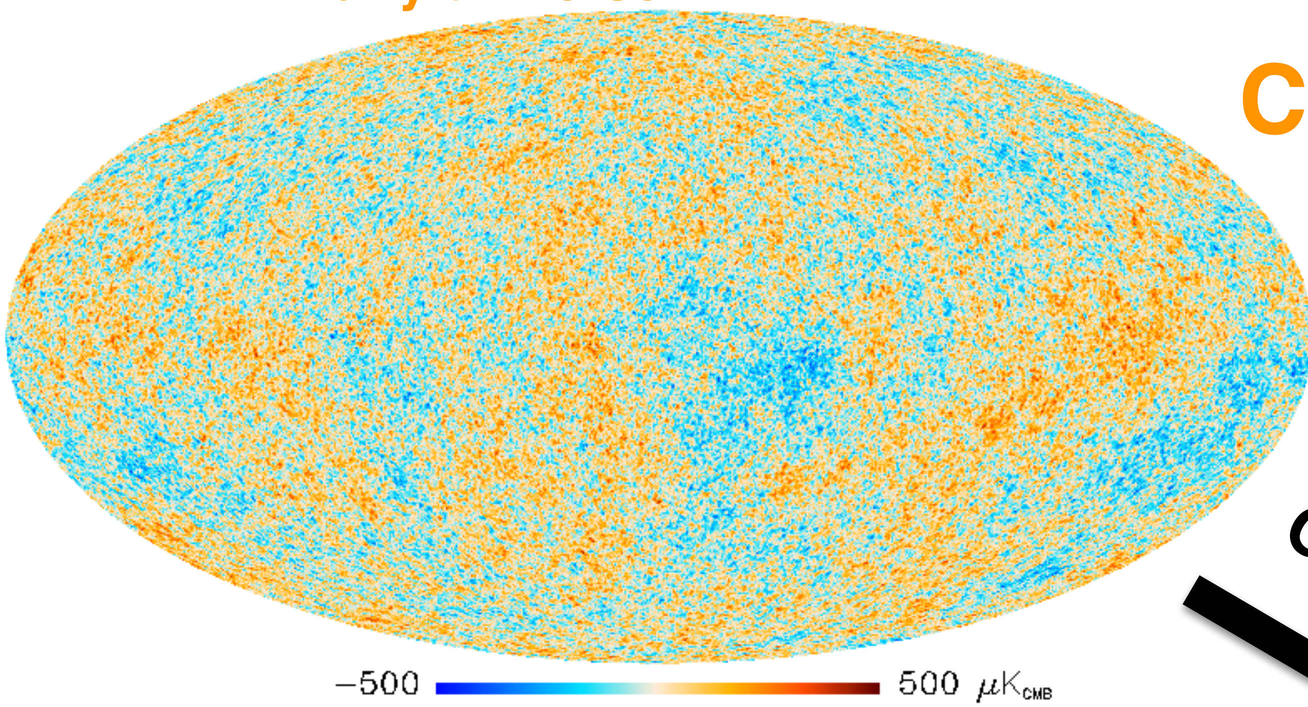
Planck Collaboration

CMB

- Initial conditions
- Expansion history of the universe

Cosmological Probes

Early universe



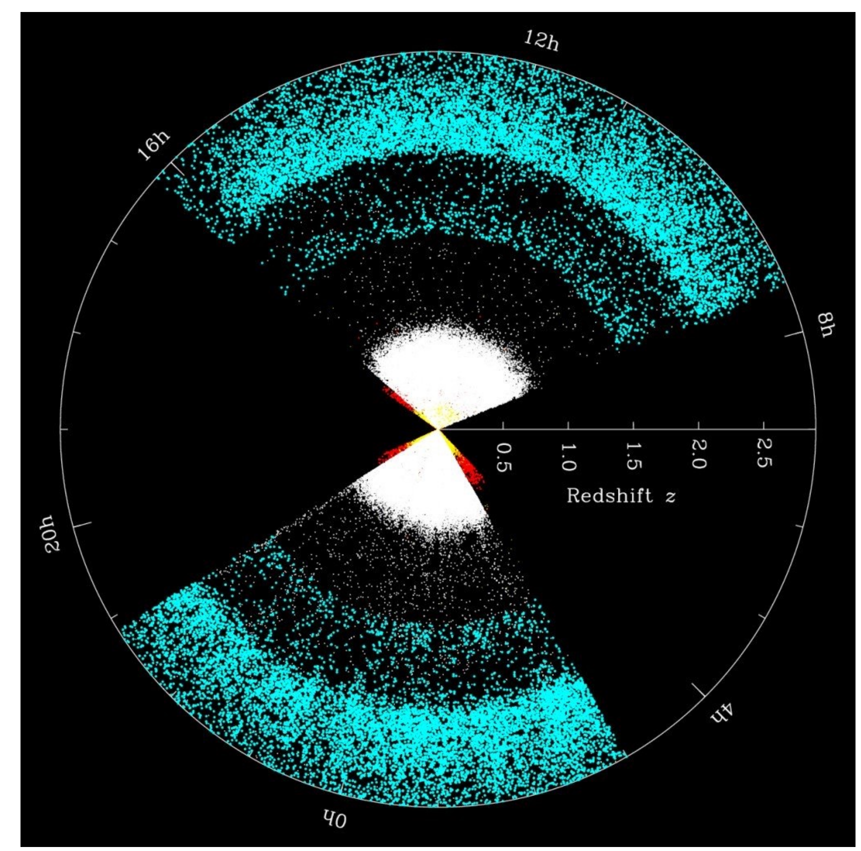
Planck Collaboration

CMB

- Initial conditions
- Expansion history of the universe

Gravity

Late time universe



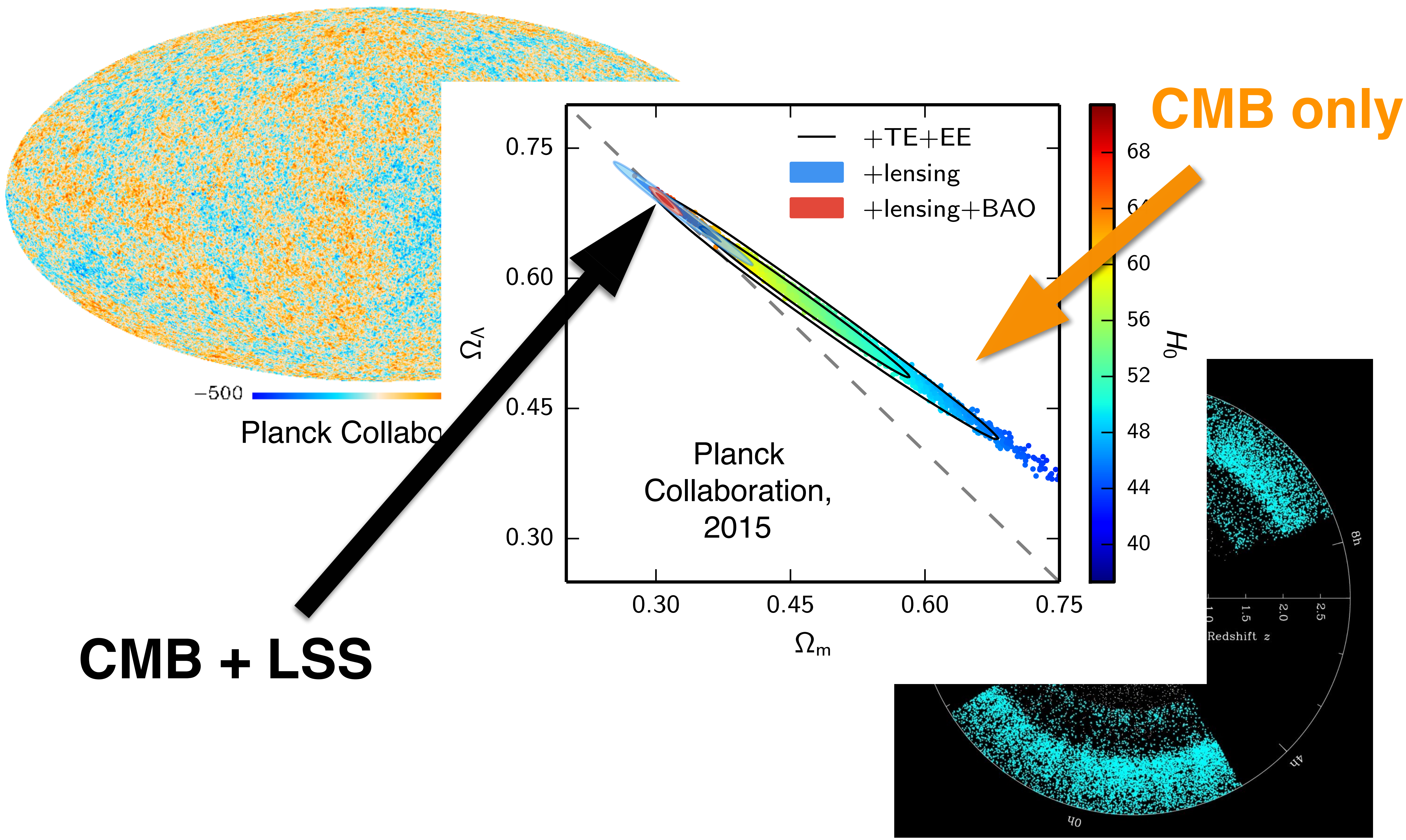
BOSS collaboration

Clustering of matter and galaxies

The Large Scale Structure

- Growth of the large scale structure
- Tests of gravity
- Expansion history of the universe
- Inflation

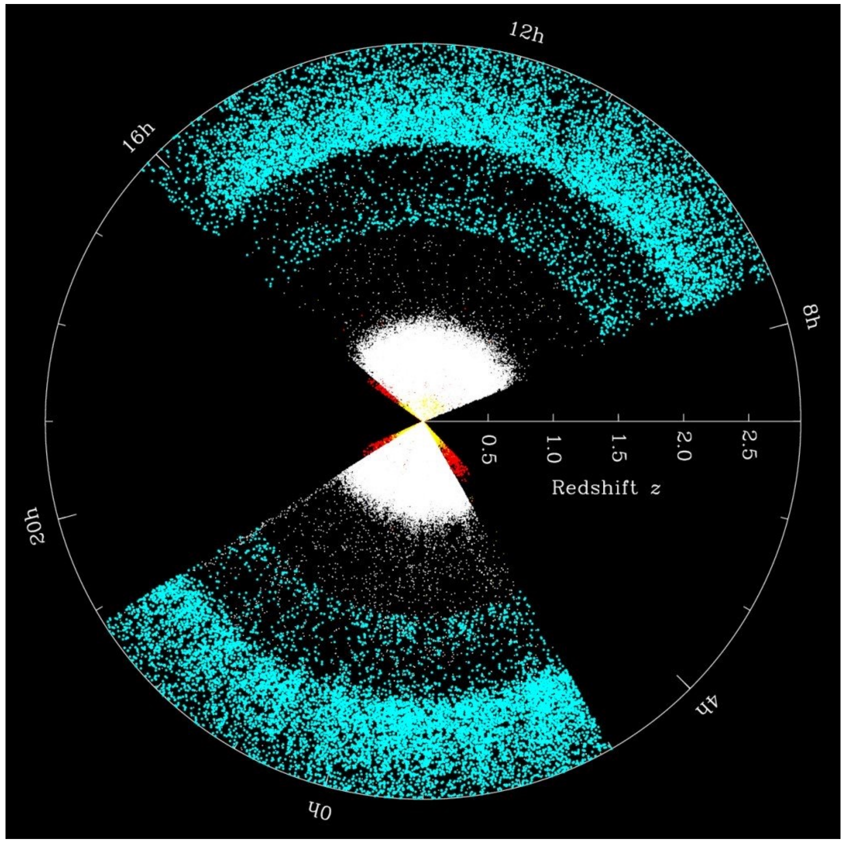
Cosmological Probes



BOSS collaboration

Cosmological Probes

Late time universe



BOSS collaboration

Focus of this Talk

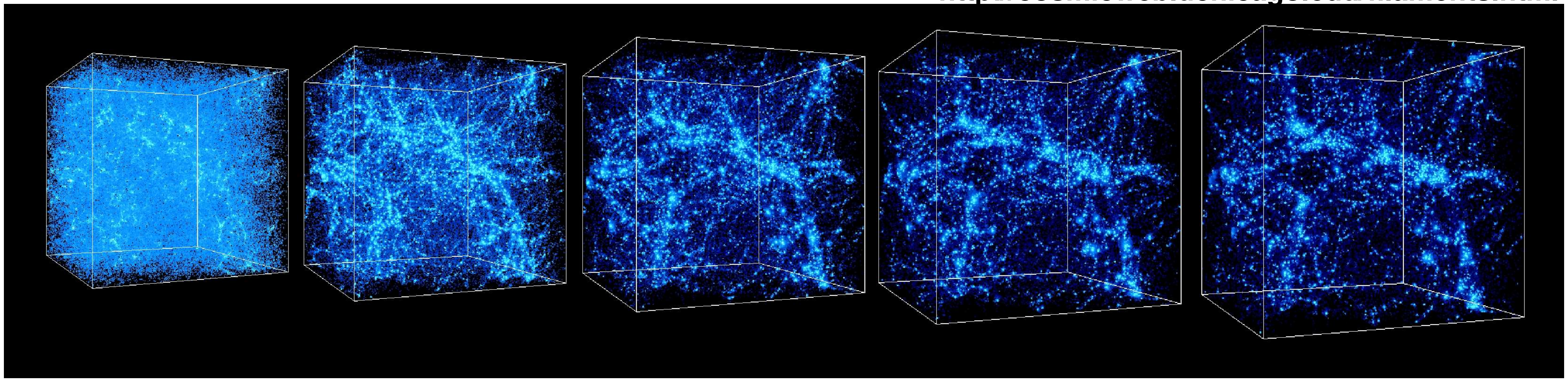
Clustering of matter and galaxies

The Large Scale Structure

- Growth of the large scale structure

The Large Scale structure

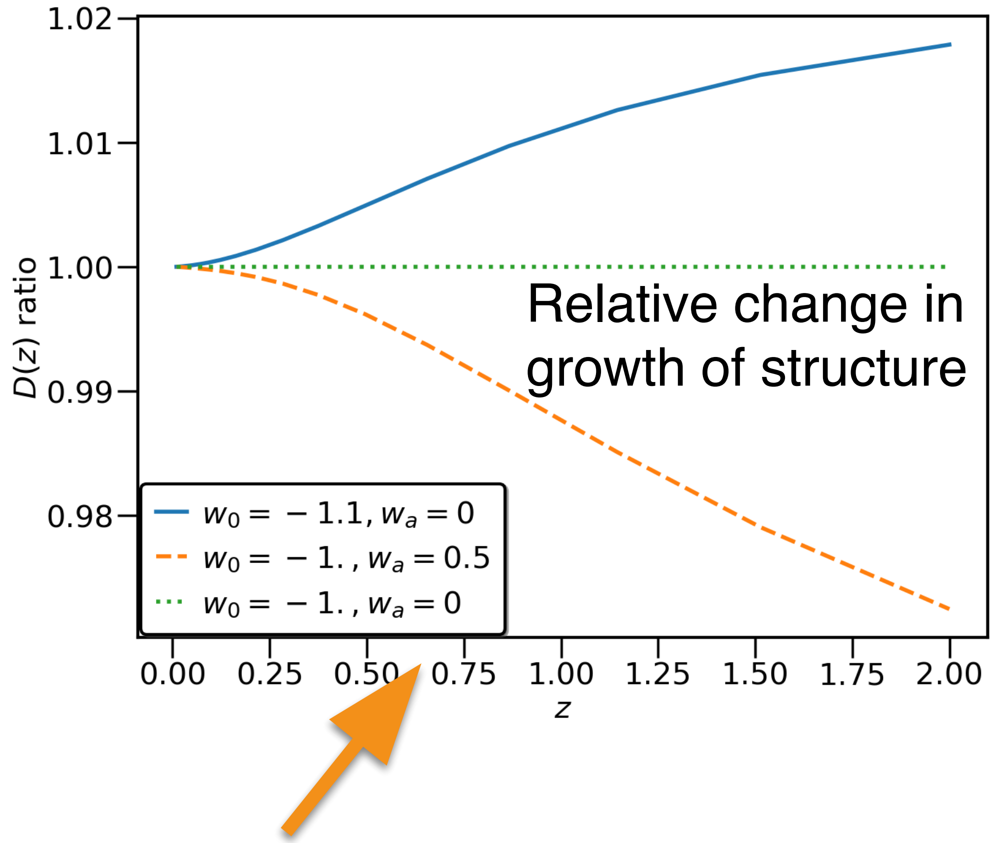
http://cosmicweb.uchicago.edu/filaments.html

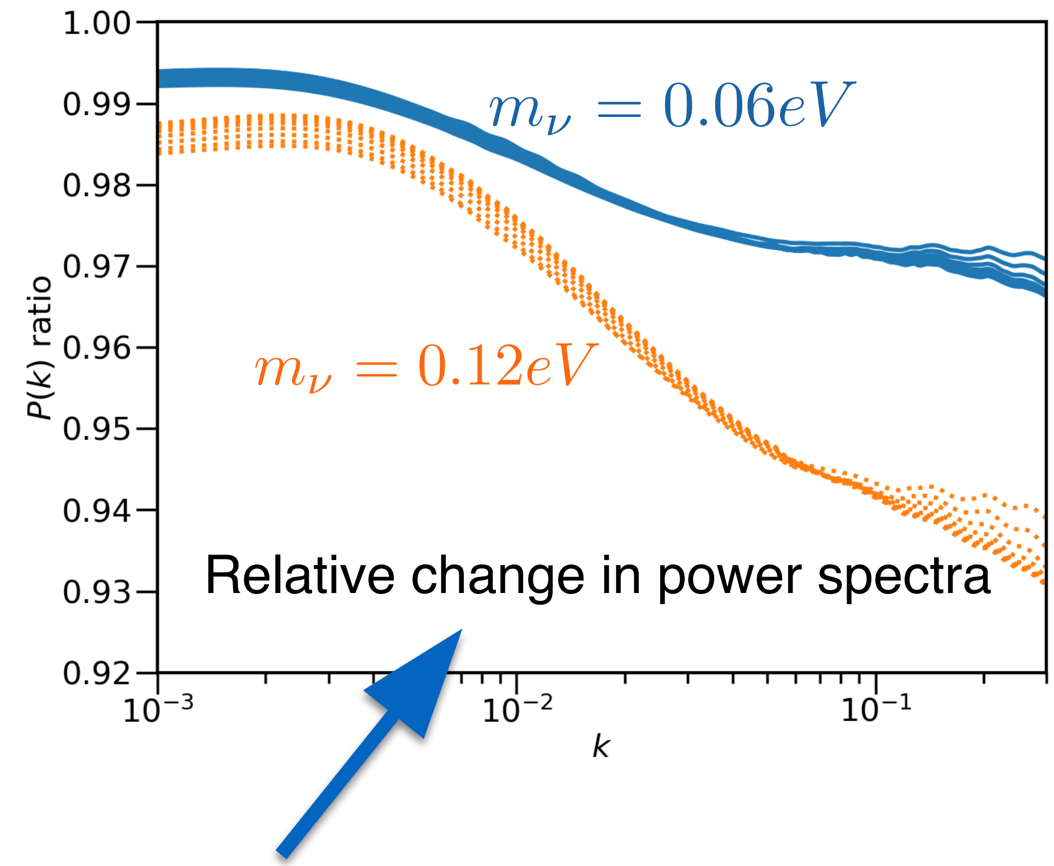


Structure grows over time →

- The initial perturbations grow under the influence of gravity.
- Growth of LSS over cosmological time scales is a sensitive probe of Dark energy, Gravity and neutrinos.

The Large Scale structure





Dark energy models change the growth of structure over time

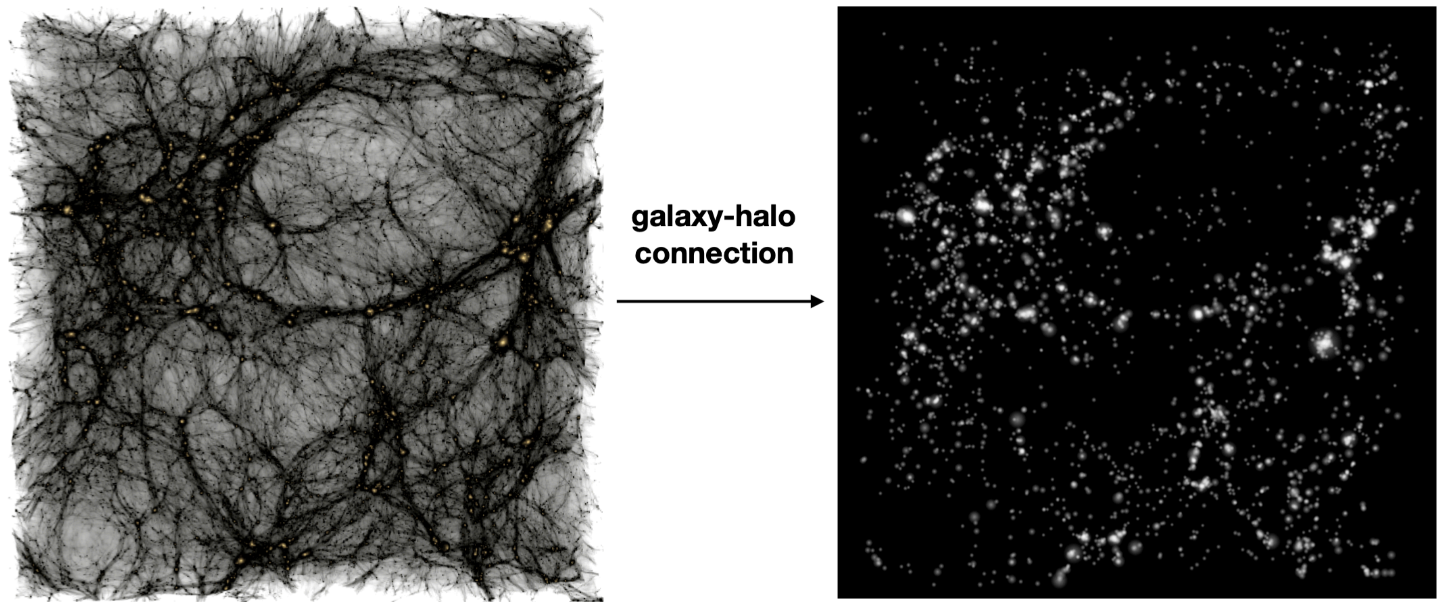
Massive neutrinos suppress the matter clustering

- **Clustering and Growth of LSS over cosmological time scales is a sensitive probe of Dark energy, Gravity and neutrinos.**

Probes of LSS

- **Galaxies**
  - Positions
  - Velocities
- **Weak gravitational lensing**
  - Traces matter
- **Gas** - Lyman alpha forest, HI, CIB, SZ, X-ray etc.

Galaxies - Overview

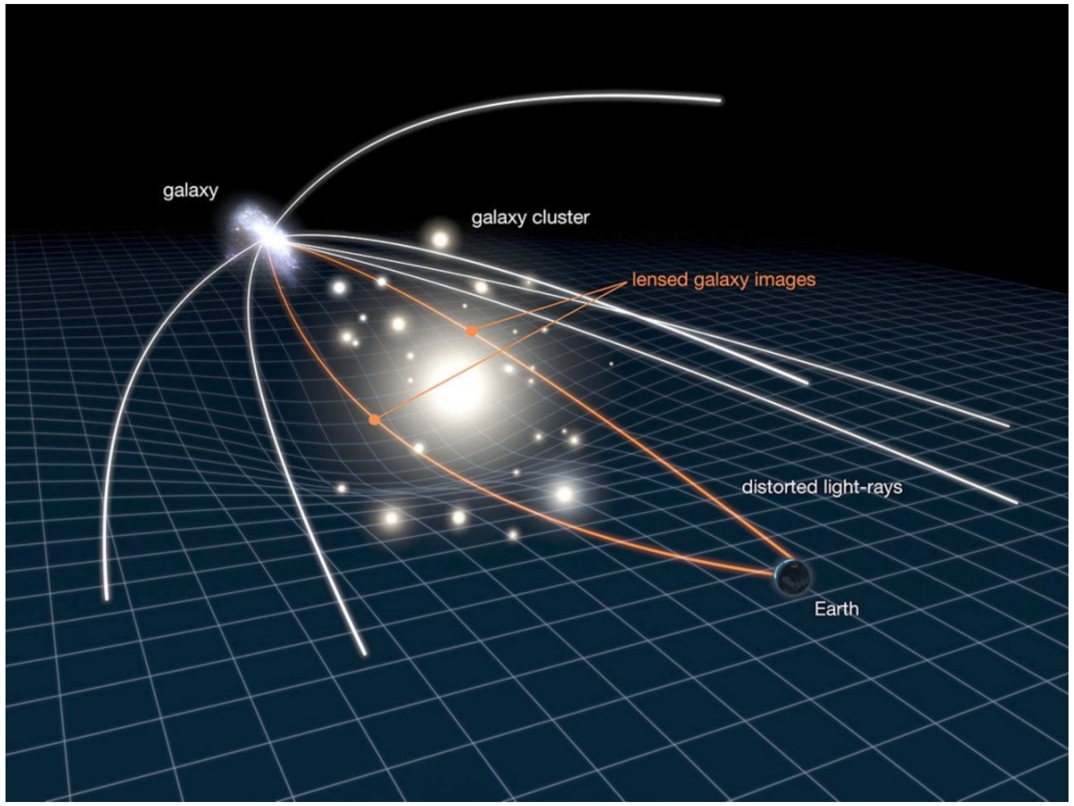


Wechsler & Tinker 2018

Dark matter Galaxies

- **Galaxies are biased tracers of matter.**
  - Galaxy bias is degenerate with growth parameter.
- **Galaxies live inside dark matter halos.**
  - Full model: Hydrodynamical simulations, expensive to run.
  - Complicated high dimensional empirical models for galaxy-halo connection.
  - Still not a fully solved problem.
- **Difficult to robustly extract cosmological information from galaxies alone.**

Weak gravitational Lensing - Overview



NASA/ESA

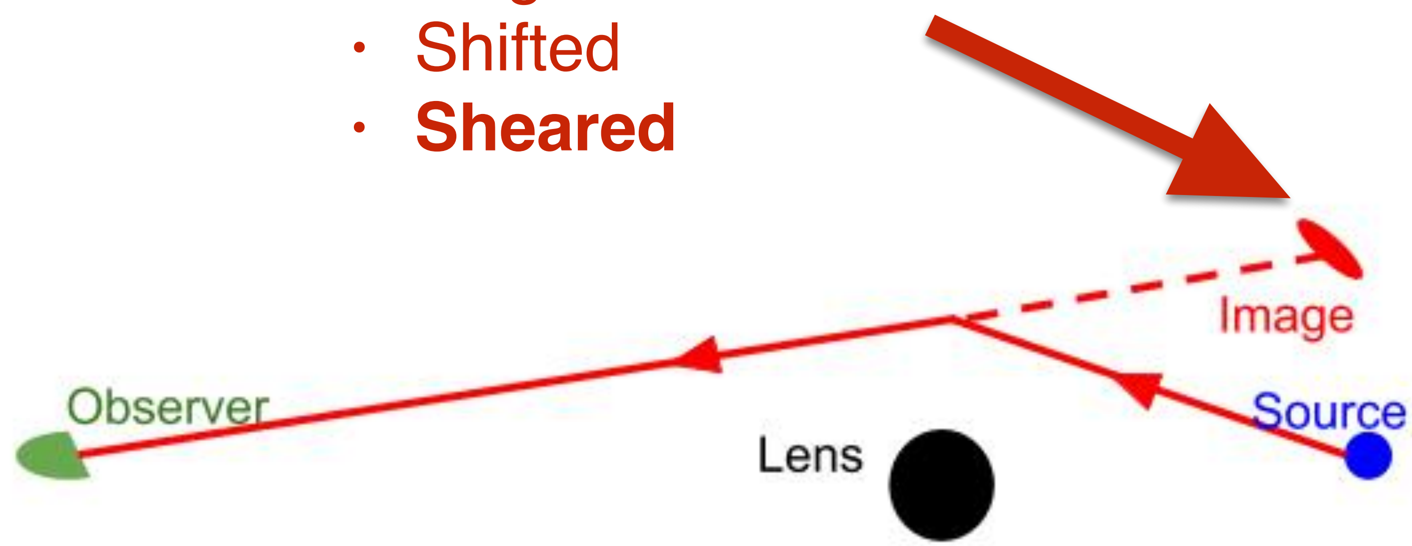
- Light rays deflected by gravitational effects of large scale structure
- Distorts and magnifies background source.
- Sensitive to all structure between source and observer.
- **Probes growth of structure, geometry, gravity.**

Weak gravitational Lensing - Overview

Galaxy Shear: Lensing Distorts the shape of the background source.

Observed galaxy shape

- Magnified
- Shifted
- **Sheared**



Weak gravitational Lensing - Overview

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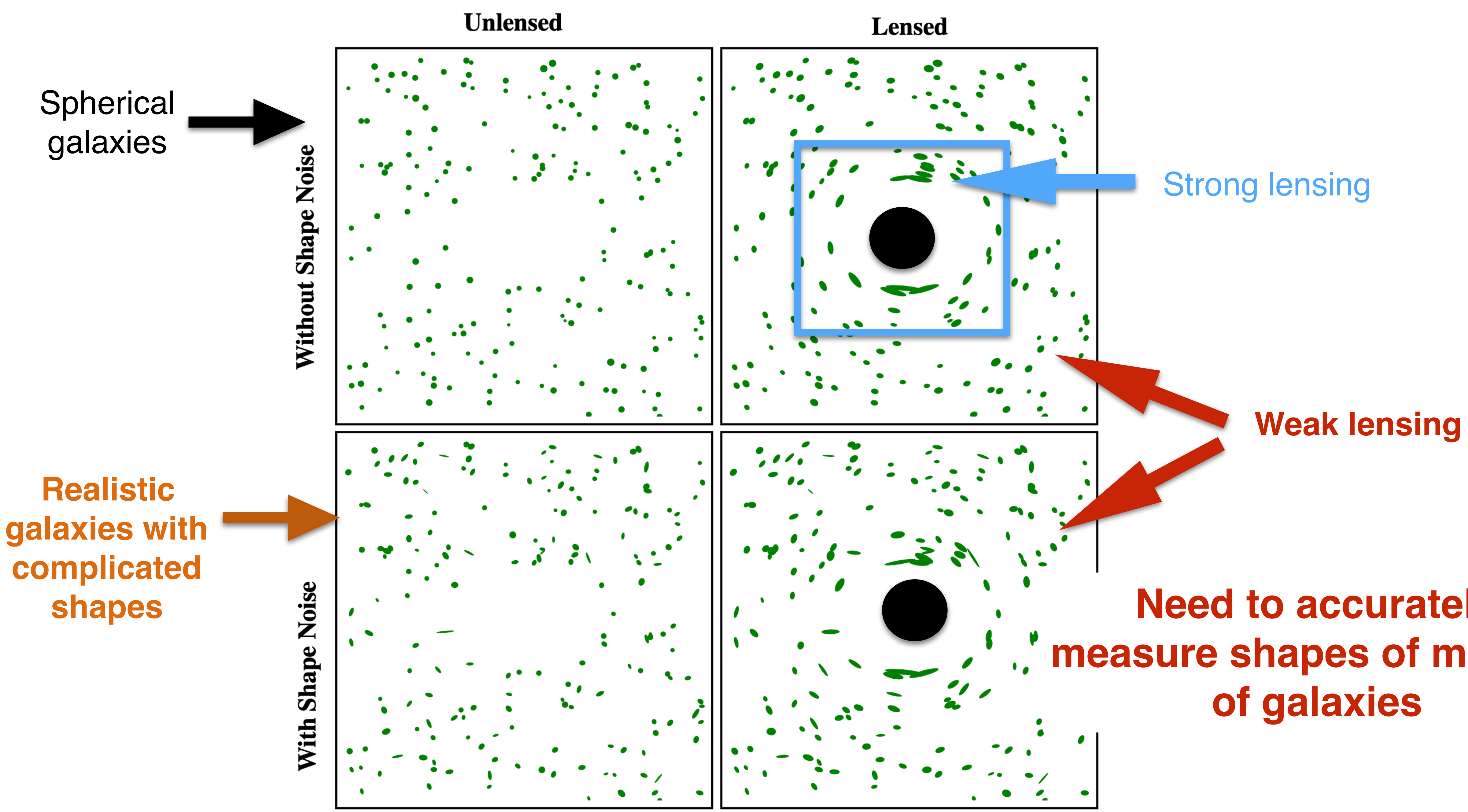
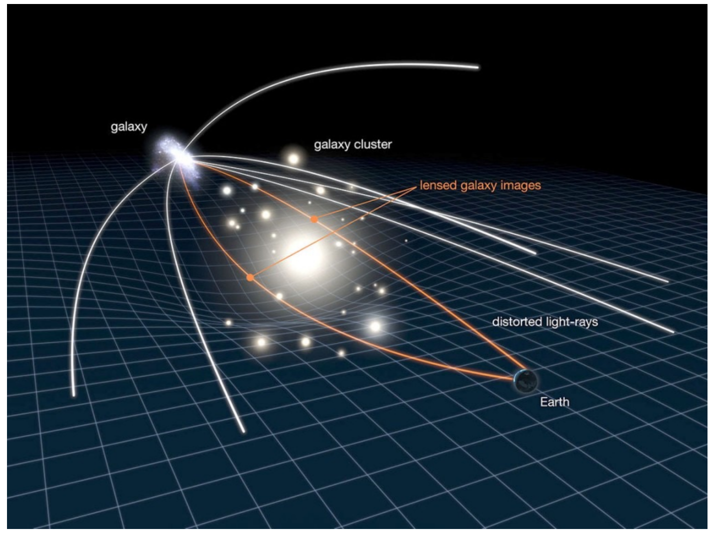
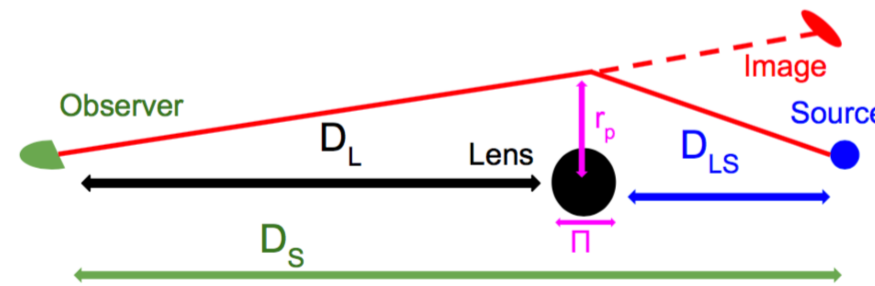


Need to accurately measure shapes of millions of galaxies

Wikipedia

Weak gravitational Lensing - Overview





Galaxy Shear

Integrated Lens Mass

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

Lensing efficiency

Sensitive only to the lens mass projected along the line of sight

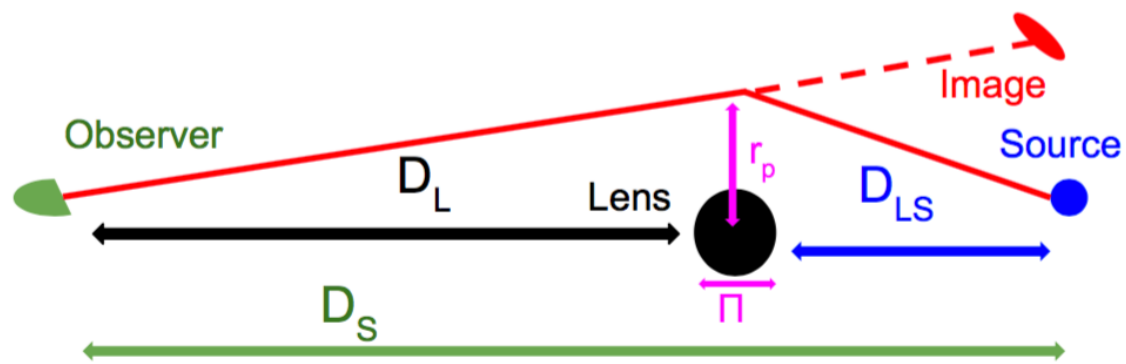
Need tomography

- Lensing efficiency depends on distances.
  - **Need good redshift estimates**

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

Galaxy-Lensing cross correlations

Measuring the lensing signal around galaxies



- Direct probe of galaxy-matter cross correlations.
    - **Combined with clustering, probes matter correlations.**
    - Sensitive to small scale galaxy physics
    - Sensitive to small scale dark matter physics

- Robust to some lensing and galaxy systematics.
- Provides tomography.

Galaxy-Lensing cross correlations

Data

- Galaxy survey covering ~20% of the sky.
- ~ 1 Million spectroscopic `lens' galaxies
- ~ 30 Million photometric `source galaxies'

Galaxy-Lensing cross correlations

Model

$$\Upsilon_{gm} = r_{cc}^{\Upsilon} \sqrt{\Upsilon_{gg} \Upsilon_{mm}}$$

S. Singh+ 2020, 1811.06499

Galaxy-Lensing cross correlations

Model

Galaxy-lensing measurement

Bias model
Galaxy clustering measurement

$$\Upsilon_{gm} = r_{cc}^{\Upsilon}\sqrt{\Upsilon_{gg}\Upsilon_{mm}}$$

S. Singh+ 2020, 1811.06499

Galaxy-Lensing cross correlations

Model

Galaxy-lensing measurement

Bias model
Galaxy clustering measurement

$$\Upsilon_{gm} = r_{cc}^{\Upsilon}\sqrt{\Upsilon_{gg}\Upsilon_{mm}}$$

Galaxy physics
Learn from simulations

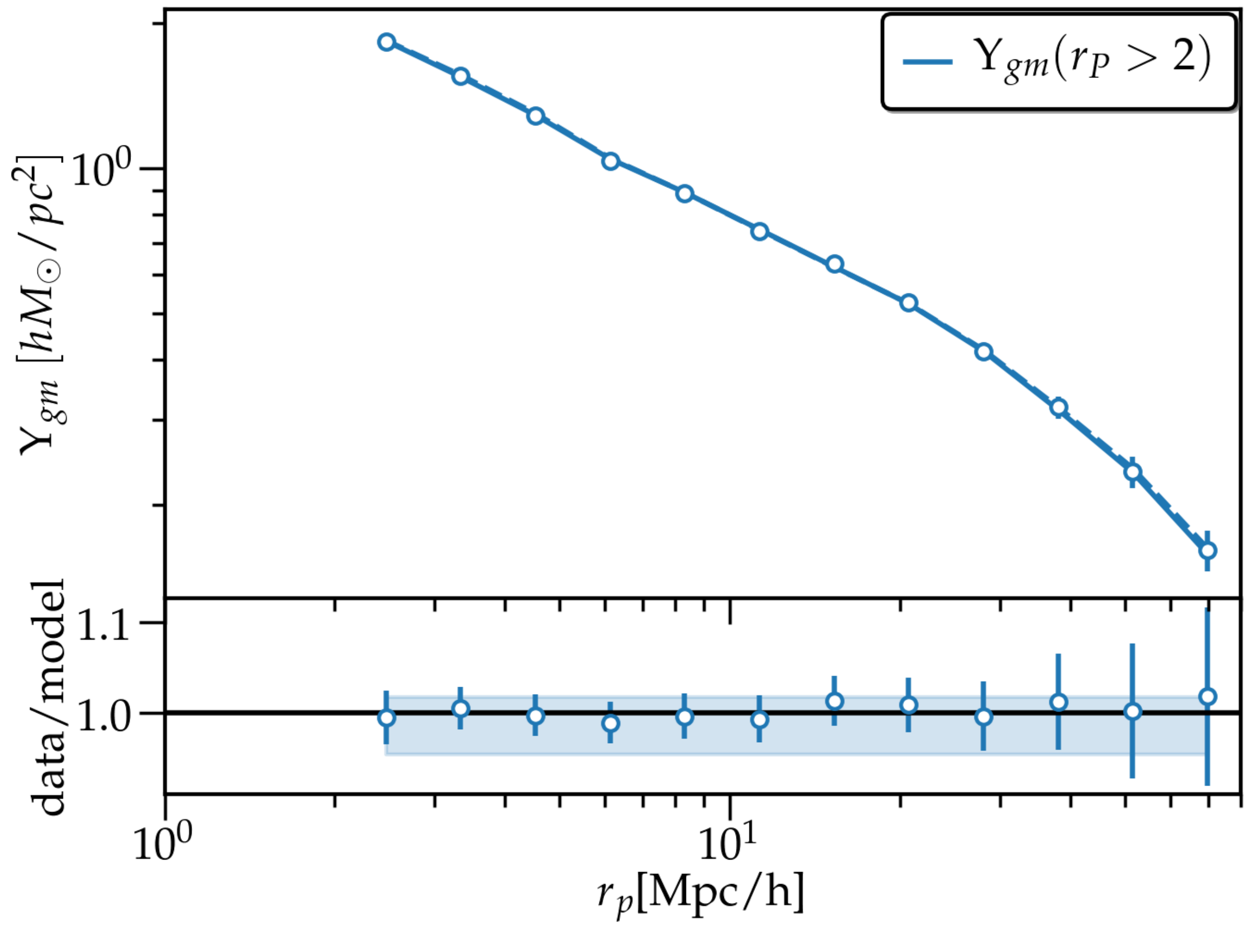
Cosmology
Matter clustering model

Clustering+Lensing breaks bias-growth degeneracy

S. Singh+ 2020, 1811.06499

Galaxy-Lensing cross correlations

Fit to Mock datasets

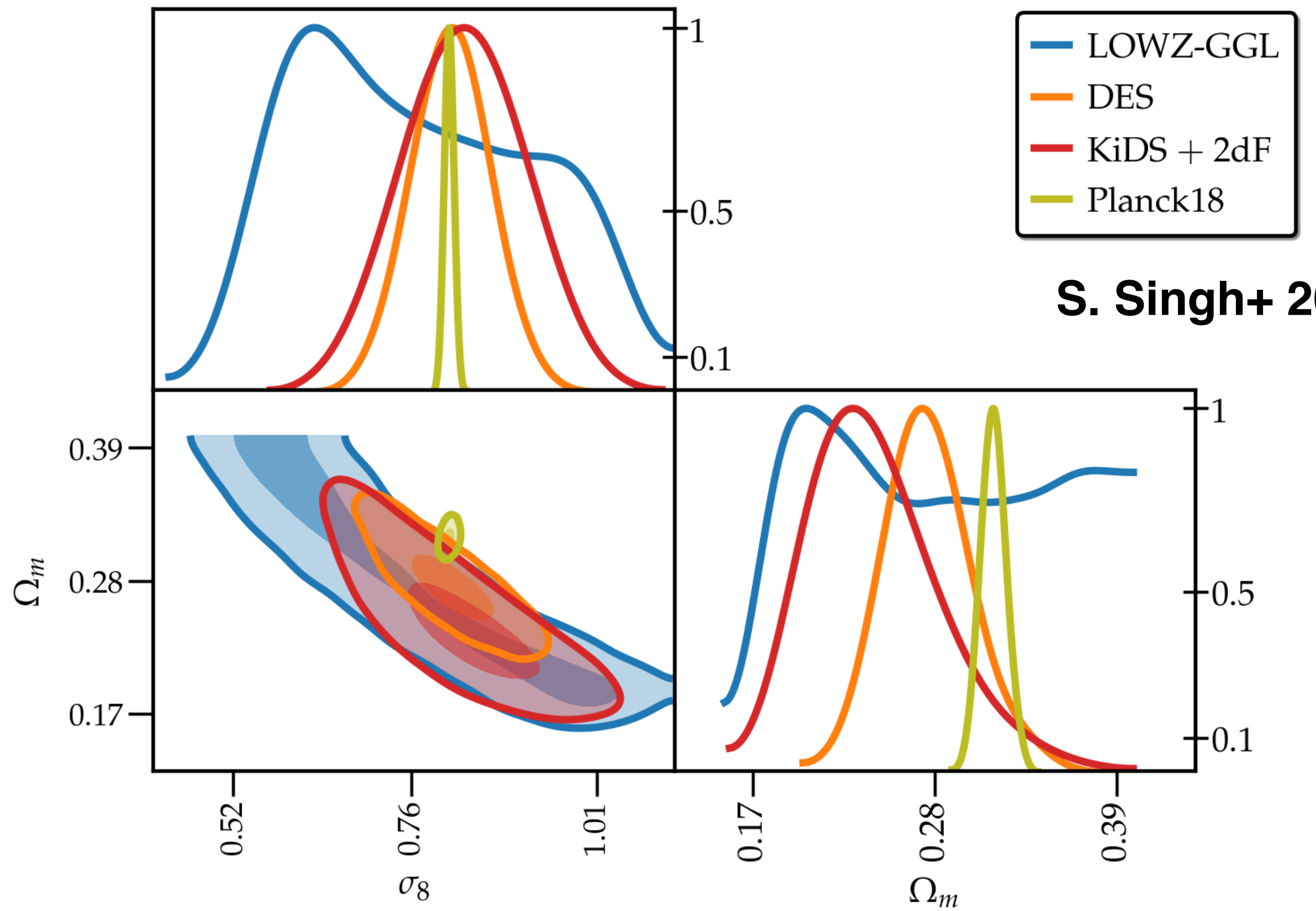


Accurate fit down to 1 Mpc/h
Recover correct cosmology with better than 2% accuracy.

S. Singh+ 2020, 1811.06499

Galaxy-Lensing cross correlations

Cosmological Parameter Estimation



S. Singh+ 2020, 1811.06499

$$S_8 = \left(\frac{\sigma_8}{0.8228}\right)^{0.8}\left(\frac{\Omega_m}{0.307}\right)^{0.6} = 0.85 \pm 0.05(stat) \pm 0.05(sys)$$

~ 6% measurement of lensing amplitude

Photometric redshifts dominate the systematics error budget

Summary - I

- **Large scale structure and its evolution provides sensitive probes of Fundamental physics.**

- **Joint analysis of probes help in breaking parameter degeneracies.**

- Current surveys are already providing interesting measurements
  - ~5% constraints on growth of LSS
  - ~10% constraints on gravity (S. Singh+ 2018, not shown)
  - Some tensions appearing with CMB measurements
  - **Rapidly approaching the systematics dominated regime.**

Cosmology
in the next decade

Upcoming cosmology surveys

DESI LSST WFIRST SPHEREx

Simons Observatory CMB S4

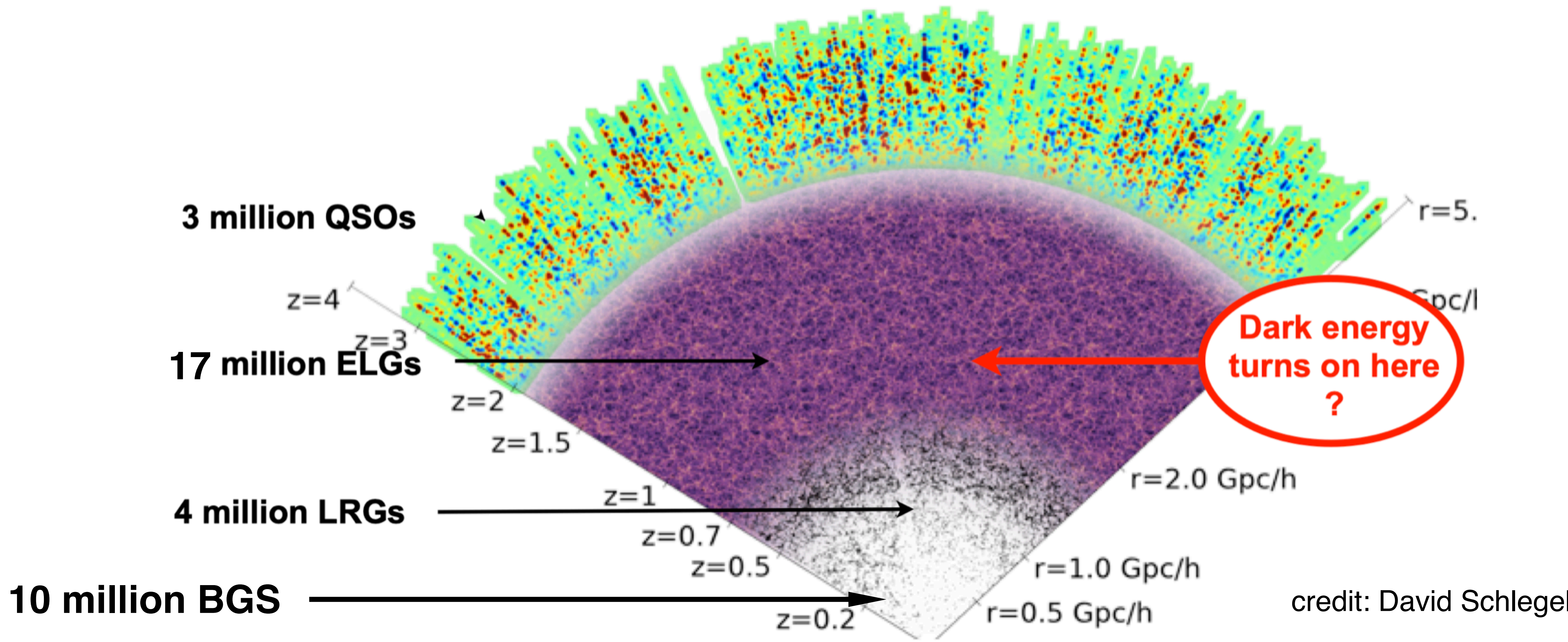
Map Matter and Galaxy distribution out to redshift 2 and beyond.

Fundamental Physics

- Dark energy and its evolution over time.
- Neutrino physics, Light relics.
- Inflation and primordial non-gaussianity, fNL
- Testing theories of gravity

DESI

Dark Energy spectroscopic survey

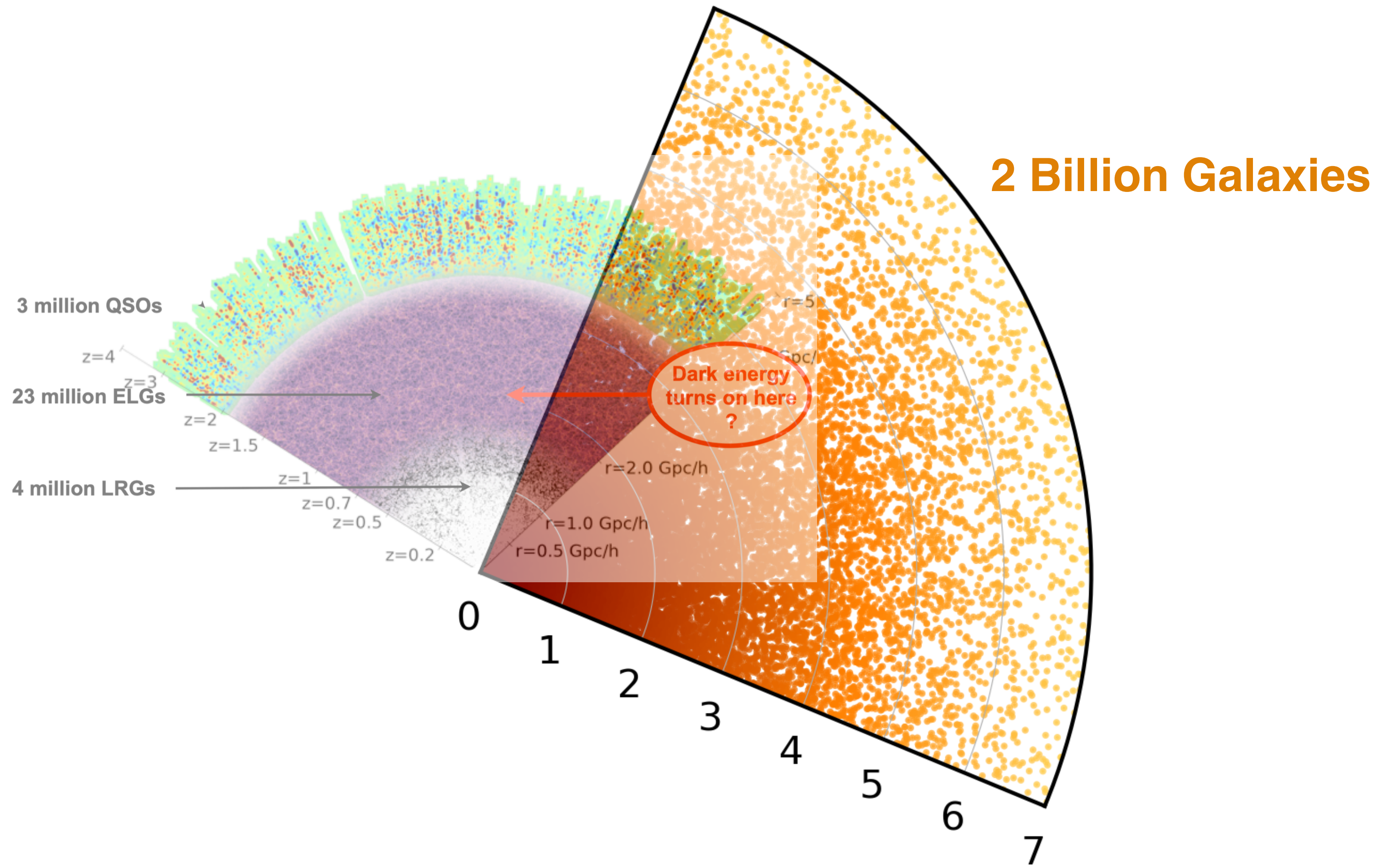


- Dark energy with BAO distance measurements; growth rate measurements
- ~10 X volume, ~20 X more galaxies than SDSS BOSS survey
- **Great for cross correlation science**
  - Dark energy   Tests of gravity   fNL   Galaxy and dark matter Physics
- Currently taking commissioning data

LSST

- Fast, Deep, Wide photometric survey
- 18,000 square degrees, observed once every few days
- Tens of billions of objects, each one observed ~900 times

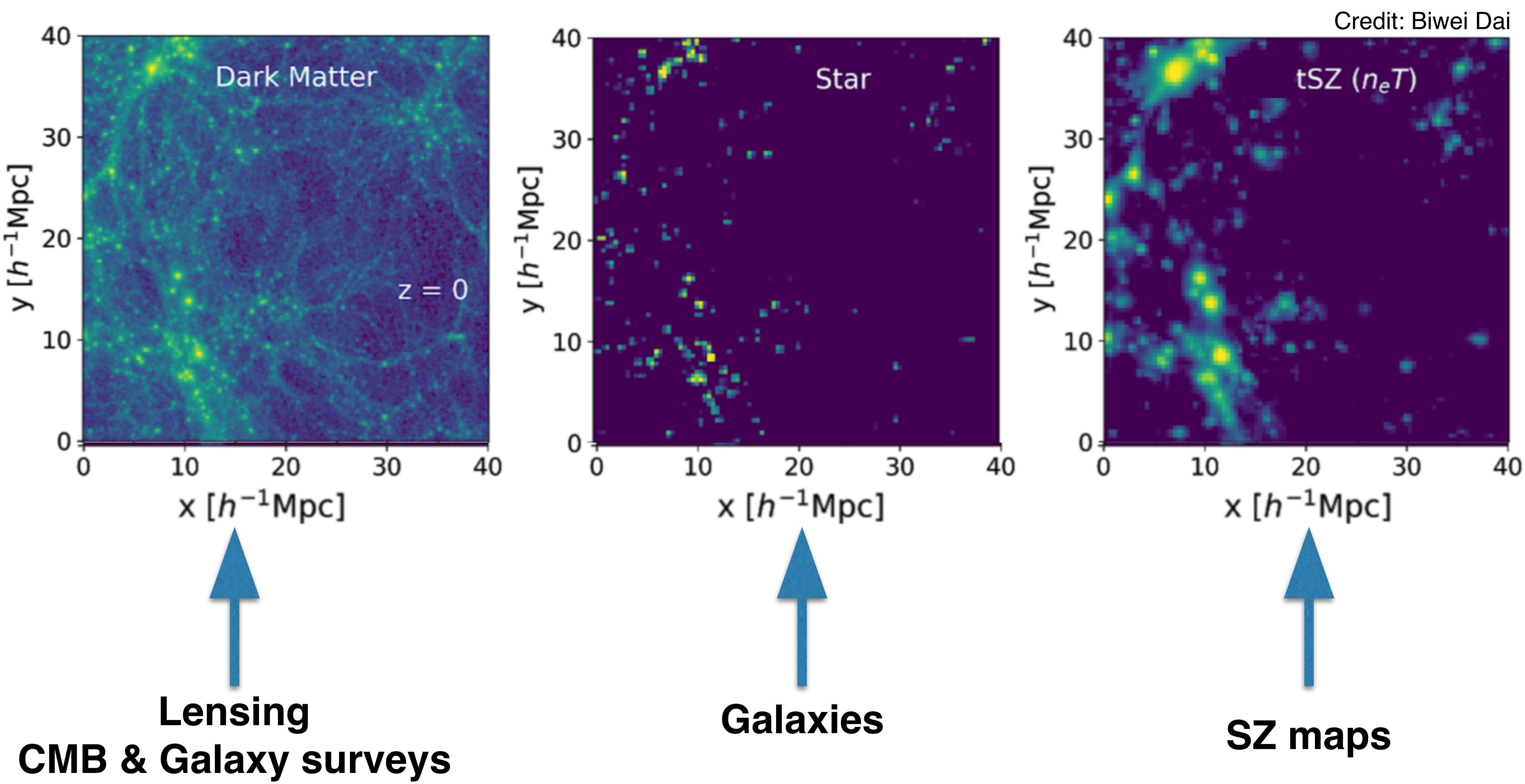
LSST



- Dark energy science
  - 2 Billion+ galaxies for cosmology
  - Supernova distance measurements
- **Cross correlations**
- **Will require excellent photometric redshift calibrations.**

Next generation joint analysis

LSST+DESI+CMB experiments



Next generation joint analysis

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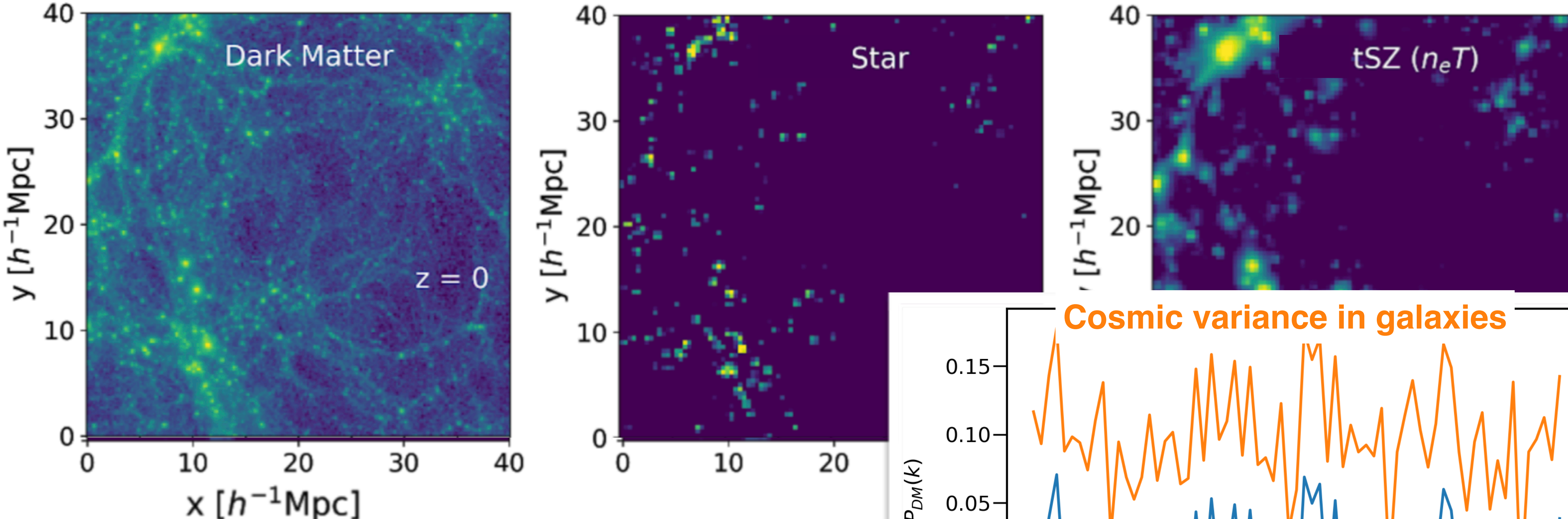

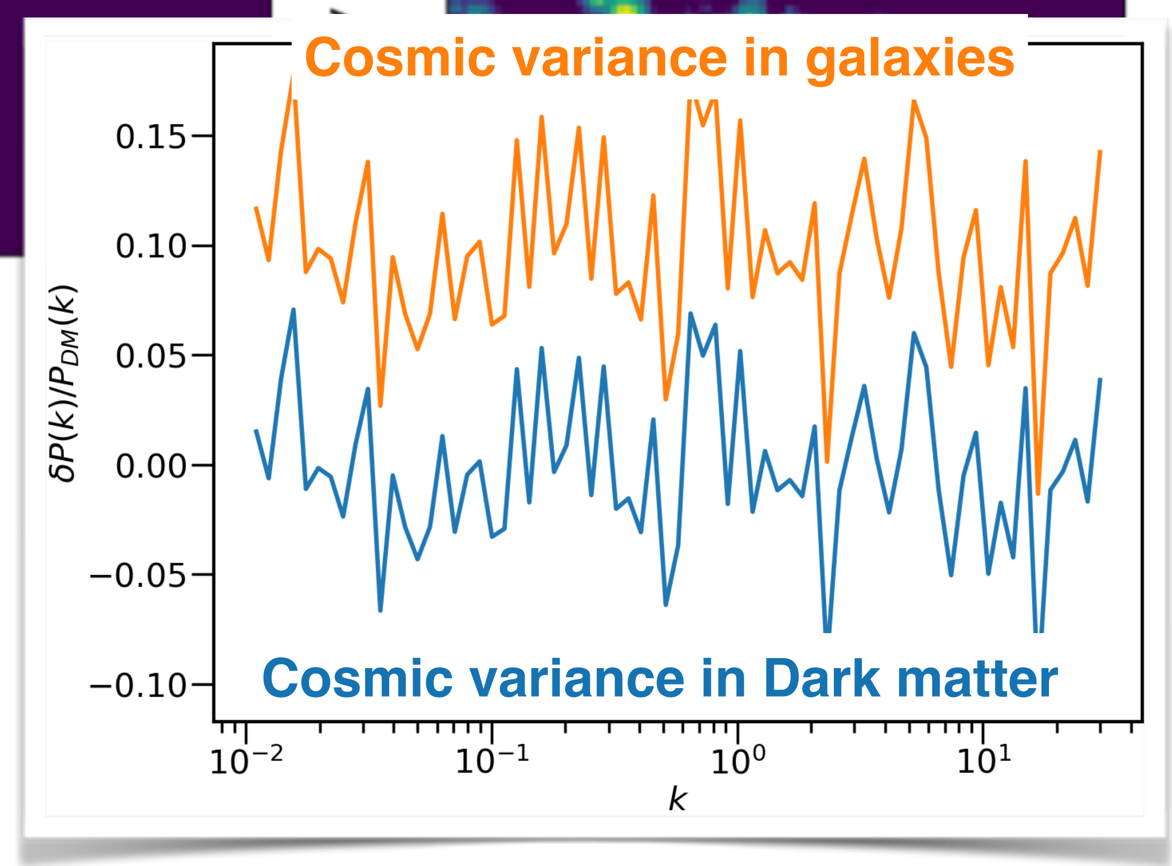

Overlapping measurements of the same LSS

- **Cancellation of cosmic variance.**
- Breaking parameter degeneracies
- Self calibration of systematics

Challenges

Systematics/ Nuisance parameters

- Astrophysical
  - Intrinsic alignments of galaxies
  - Galaxy physics, e.g. S. Singh+ 2020
- Observational systematics
  - Selection function of galaxies
  - Blending, fiber collisions
- Photometric redshift uncertainties

A biased and very incomplete list

Data

- Need to understand the estimators, selection effects.
- Covariance Matrices

S. Singh+ 2017; S. Singh+ in prep

Modeling

- Accurate predictions on non-linear scales. e.g. S. Singh+ 2020
- Accurate and high precision emulators.
- Modeling baryonic physics
- Speed

Challenges

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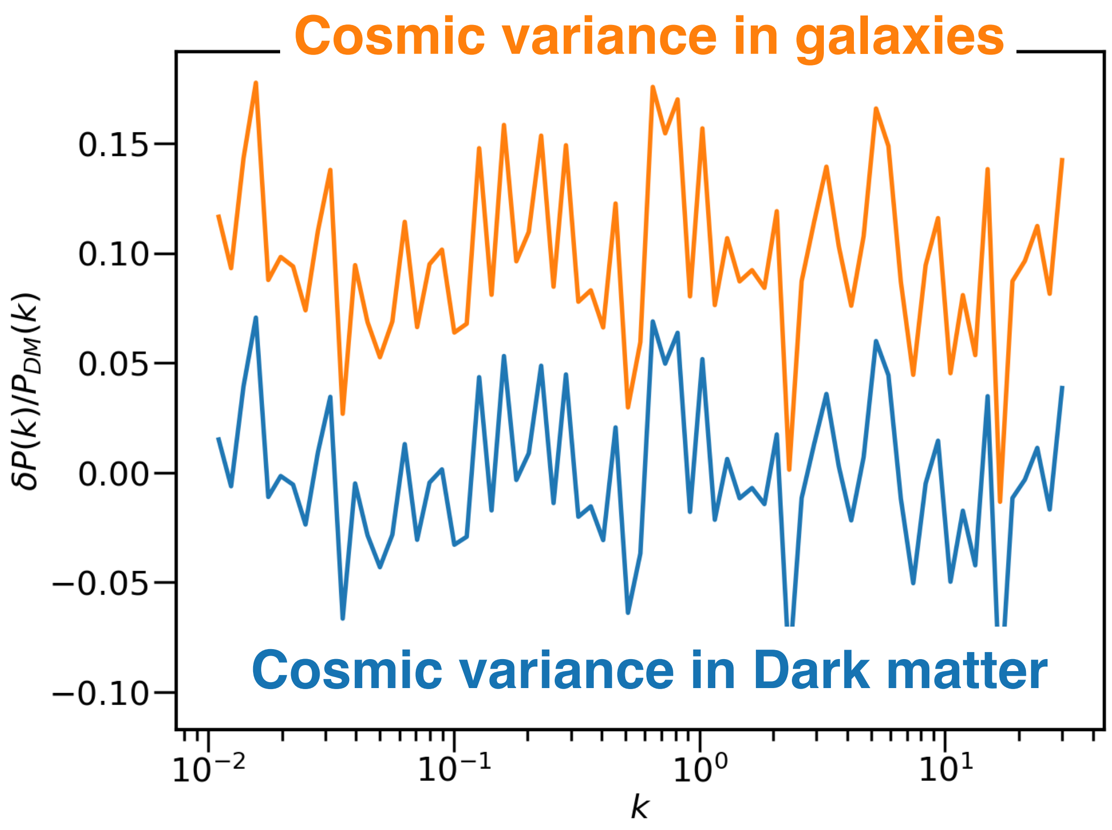
Covariance matrices

$$\chi^2 = (\text{data} - \text{Model})Cov^{-1}(\text{data} - \text{Model})$$

- **Important for optimal combinations of different datasets.**



Covariance matrices

$$\chi^2 = (\text{data} - \text{Model}) Cov^{-1} (\text{data} - \text{Model})$$

- Important for optimal combinations of different datasets.
- Scales as N^4_{probe}
  - DES: 5 Galaxy bins + 5 lensing bins ← **Current state of the art**
  - LSST: 10 Galaxy bins + 10 lensing bins
  - + DESI: 10+ Galaxy bins (2X multipoles each)
  - + CMB: CMB lensing, SZ, CIB, etc.

Covariance matrices

$$\chi^2 = (\mathrm{data} - \mathrm{Model}) Cov^{-1} (\mathrm{data} - \mathrm{Model})$$

- Important for optimal combinations of different datasets.
- Scales as N^4_{probe}
- **Common methods for computing covariances**
  - **Mock datasets**: Computationally expensive, noisy, wrong physics
  - **Analytical calculations**: Noiseless, wrong physics
  - **Data based**: Very noisy (e.g. Jackknife), limits the information we can use.

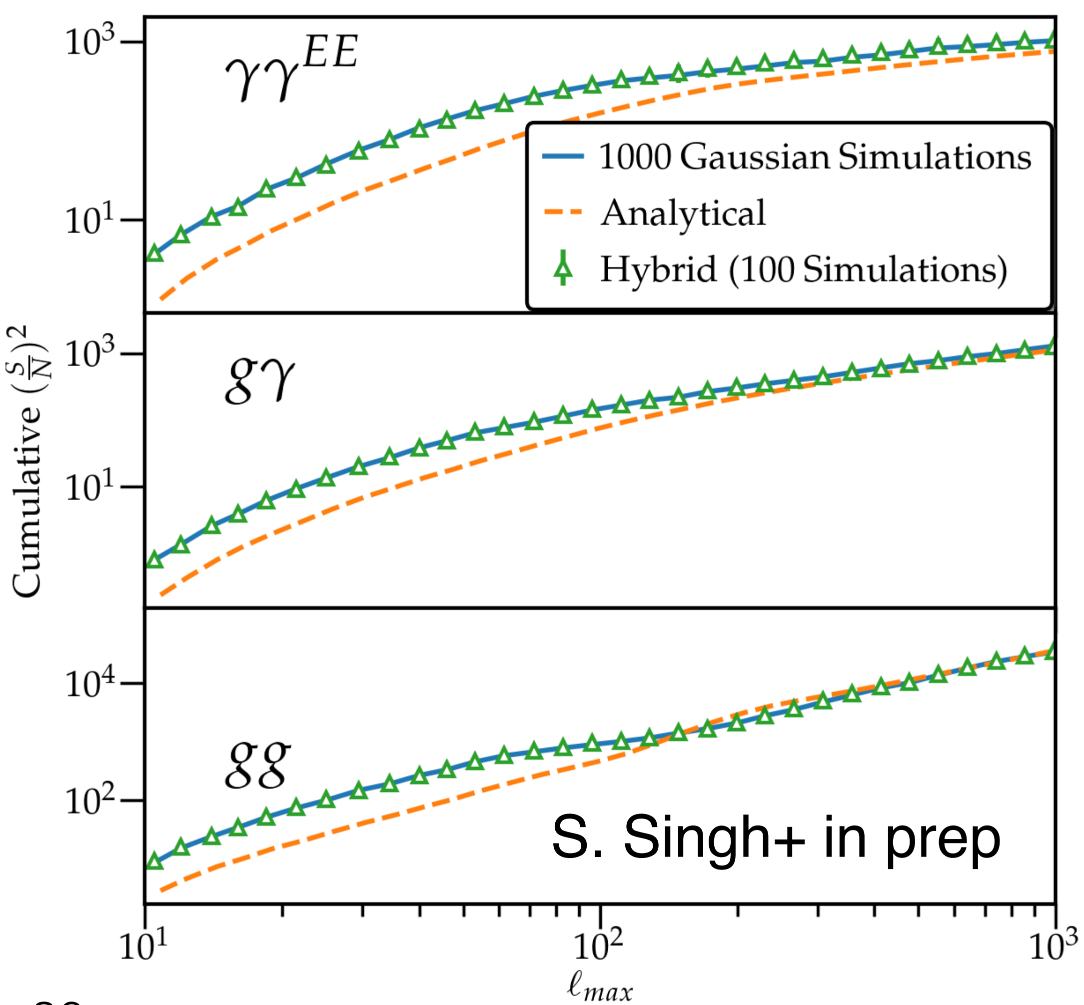
Covariance matrices

$$\chi^2 = (\text{data} - \text{Model})Cov^{-1}(\text{data} - \text{Model})$$

- **New approach: Hybrid covariances**
  - Analytical covariance with corrections from mocks or data based estimates.

Faster, accurate and very low noise covariance matrices

Li, S. Singh+ 2019; S. Singh+ in prep; Yu, S. Singh+ in prep



Challenges

Systematics/ Nuisance parameters

- Astrophysical
  - Intrinsic alignments of galaxies
  - Galaxy physics, e.g. S. Singh+ 2020
- Observational systematics
  - Selection function of galaxies
  - Blending, fiber collisions
- **Photometric redshift uncertainties**

A biased and very incomplete list

Data

- Need to understand estimators, selection effects. S. Singh+ 2017; S. Singh+ in prep
- Covariance Matrices

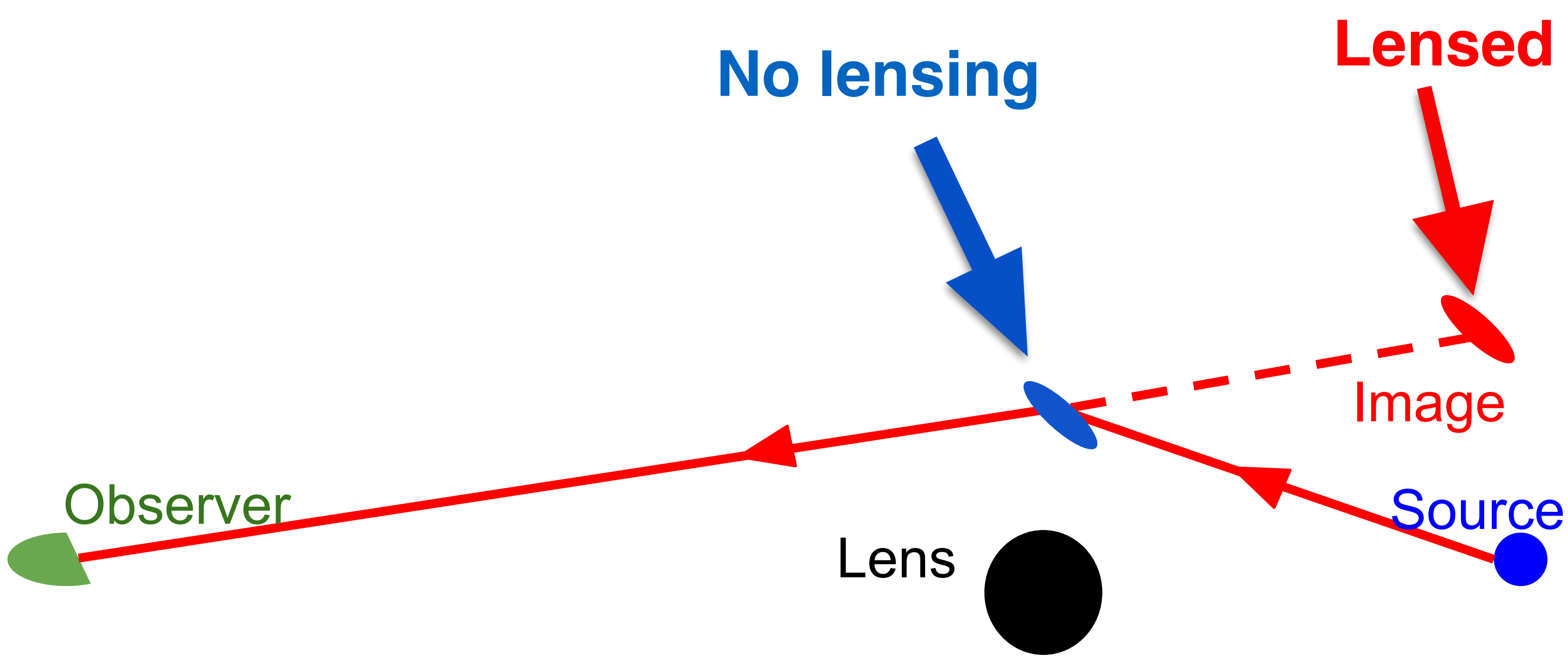
Modeling

- Accurate predictions on non-linear scales. e.g. S. Singh+ 2020
- Accurate and high precision emulators.
- Modeling baryonic physics
- Speed

Photometric Redshifts

The Problem

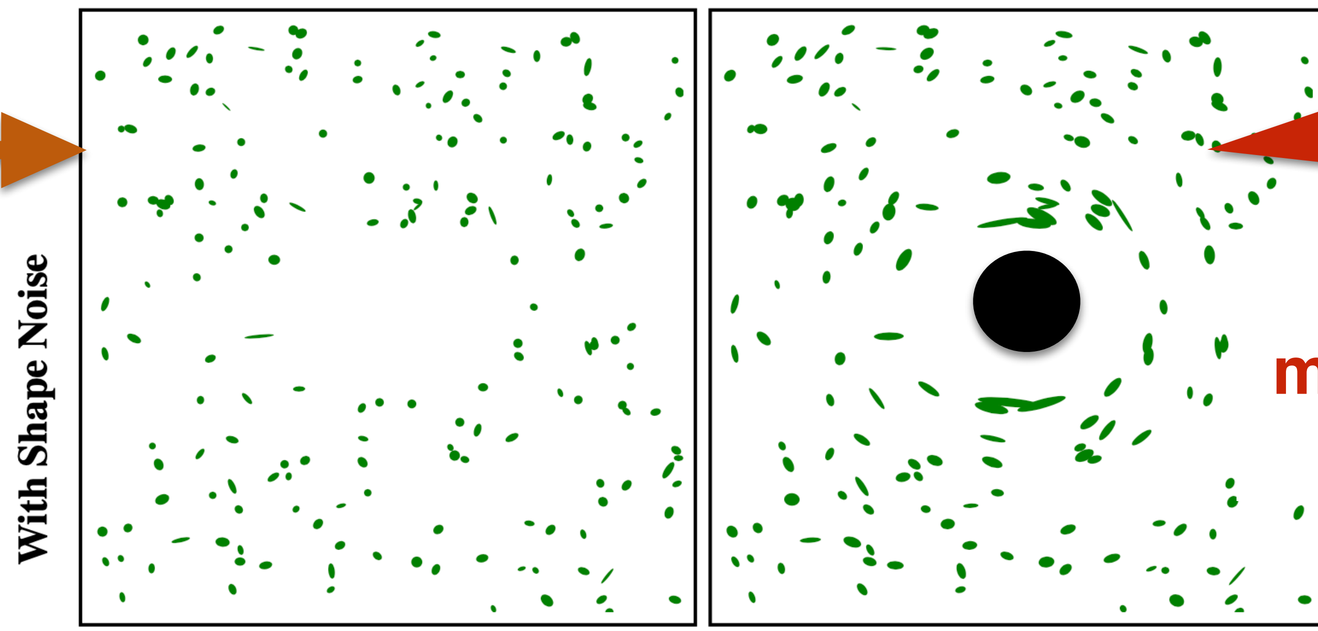
- Cosmological inferences depend on the distance estimates to galaxies.
  - **Need good redshift estimates**



Photometric Redshifts

The Problem

Realistic galaxies with complicated shapes



Weak lensing

Need to accurately measure shapes of Billion of galaxies

Wikipedia

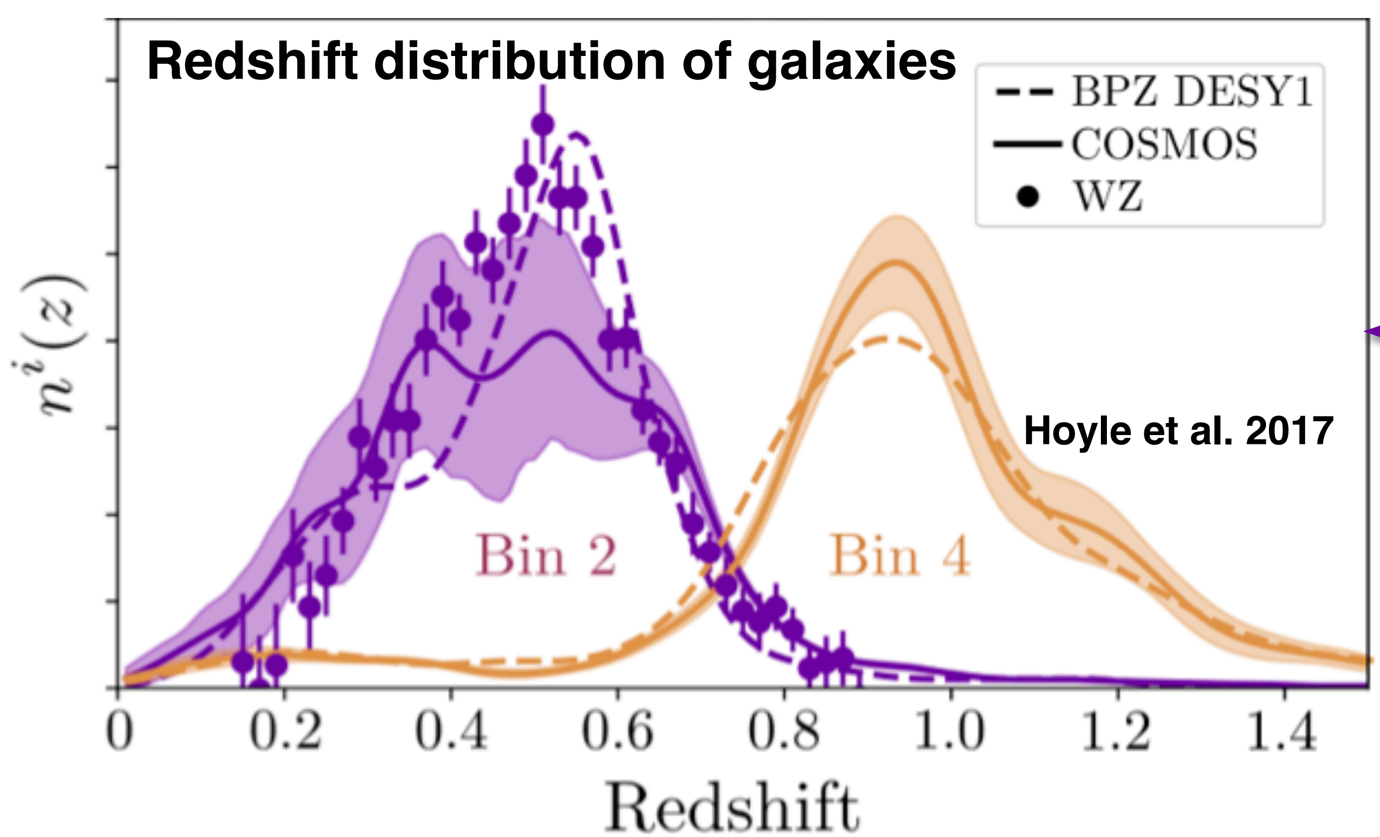
Need large number of galaxies for high precision measurements

Photometric surveys

Photometric Redshifts

The Problem

- Need large number of galaxies for high precision lensing measurements - Photometric surveys
- The lensing and galaxy clustering signals depend on the redshift distribution of galaxies - Need good redshift estimates



DES estimates

Photometric Redshifts

The Problem

- Need large number of galaxies for high precision lensing measurements - Photometric surveys
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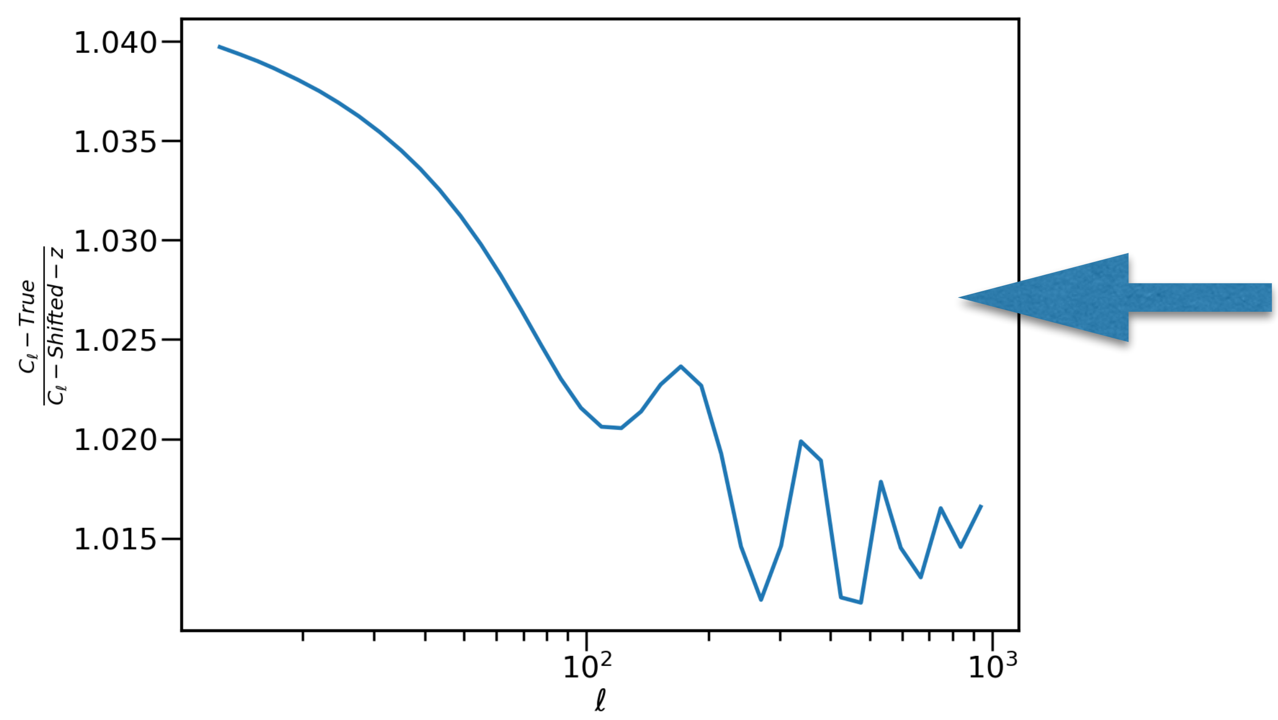
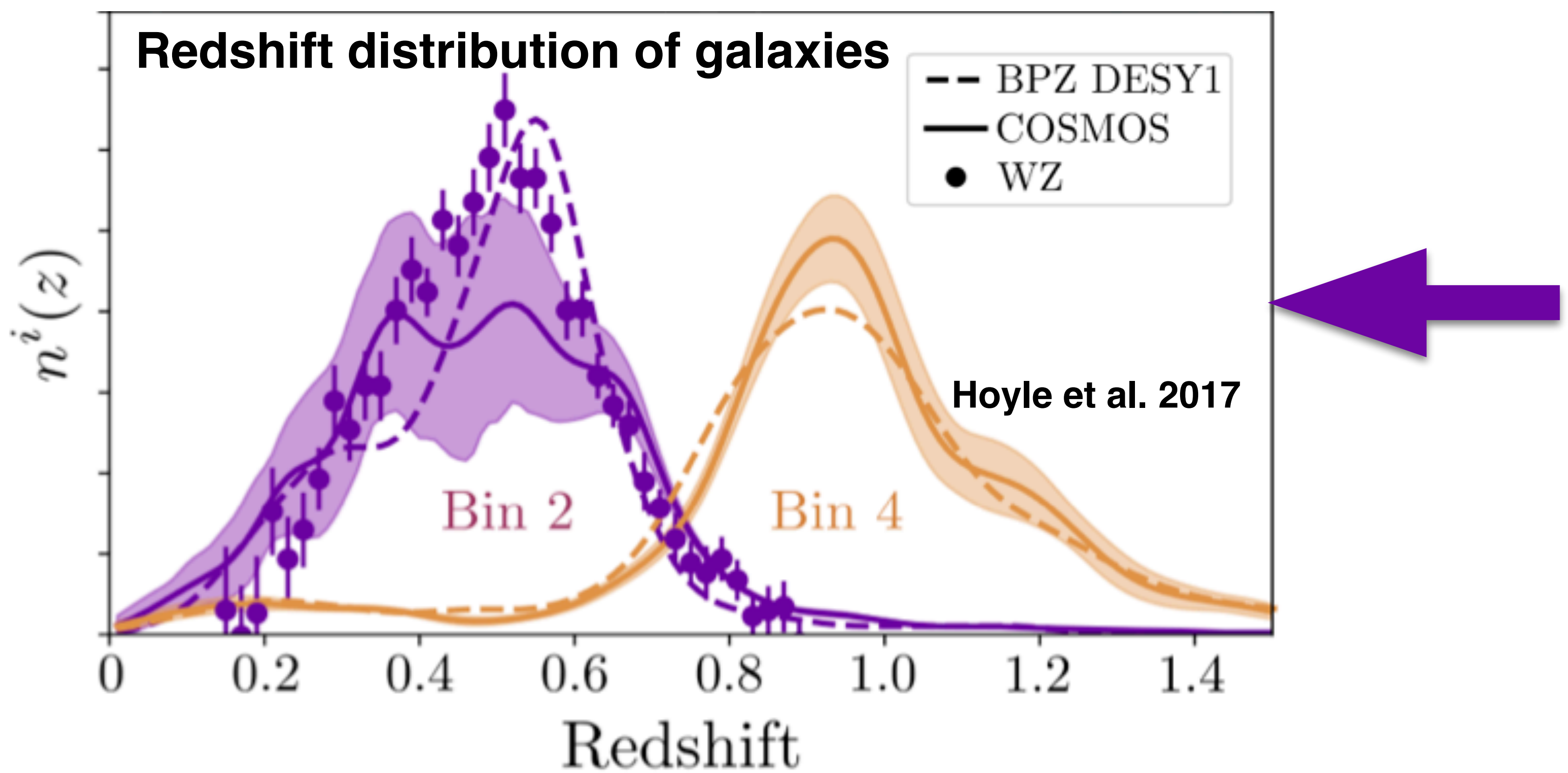


Change in lensing power spectrum, with shift in mean redshift ~ 0.01

Photometric Redshifts

What we need

- Understand the uncertainties in the obtained redshift distribution.



DES estimates

Photometric Redshifts

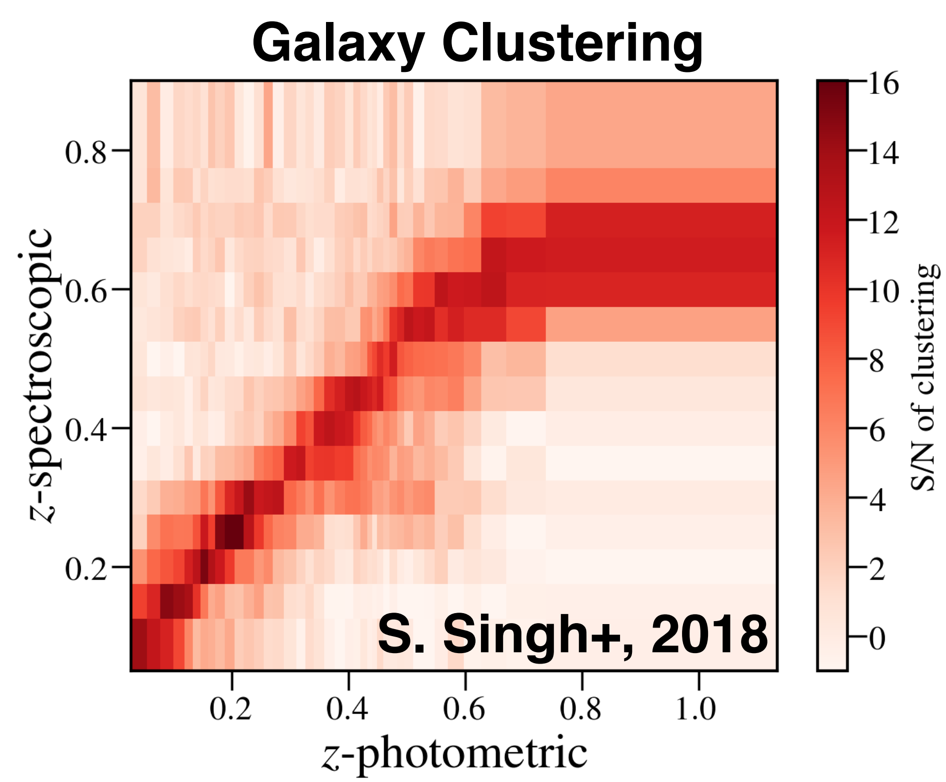
What we need

- Understand the uncertainties in the obtained redshift distribution.

- Cross correlations with the spectroscopic galaxy samples.
  - Degenerate with systematics, especially galaxy bias. (e.g. S. Singh+, 2018)

Need to develop strategies to properly marginalize over uncertainties.

Cross correlation between photometric and spectroscopic galaxy samples



Photometric Redshifts

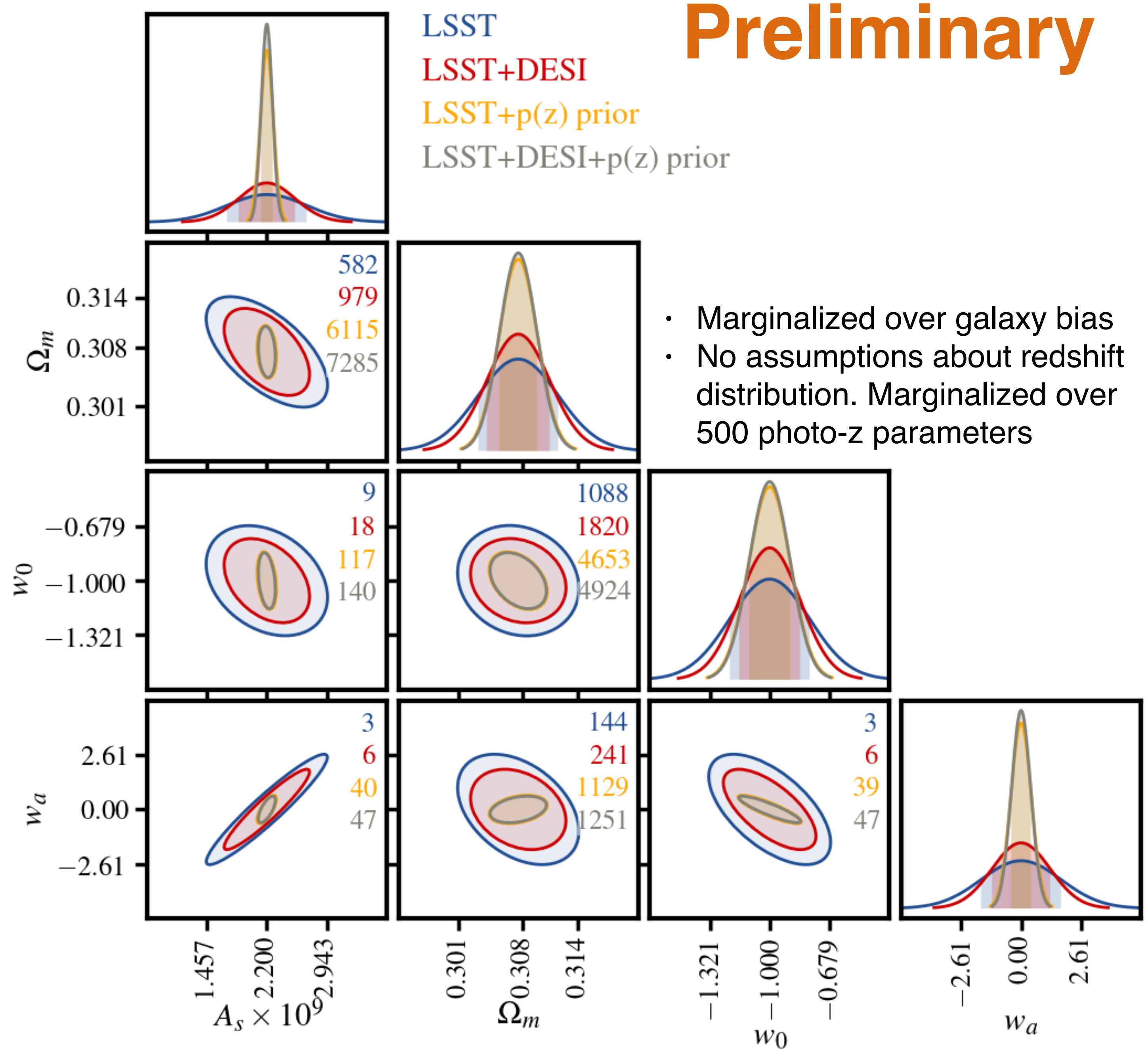
Next Decade

- Cross correlations with the spectroscopic galaxy samples.

DESI can improve the LSST constraining power

- Understand the uncertainties in the obtained redshift distribution.
    - **Sets the prior used**

Preliminary



- Marginalized over galaxy bias
- No assumptions about redshift distribution. Marginalized over 500 photo-z parameters

S. Singh+, in prep

Fundamental Plane of galaxies

A New Probe

Fundamental Plane of galaxies
A New Probe

Fundamental plane is an empirical relation between galaxy properties that can be used to predict galaxy sizes

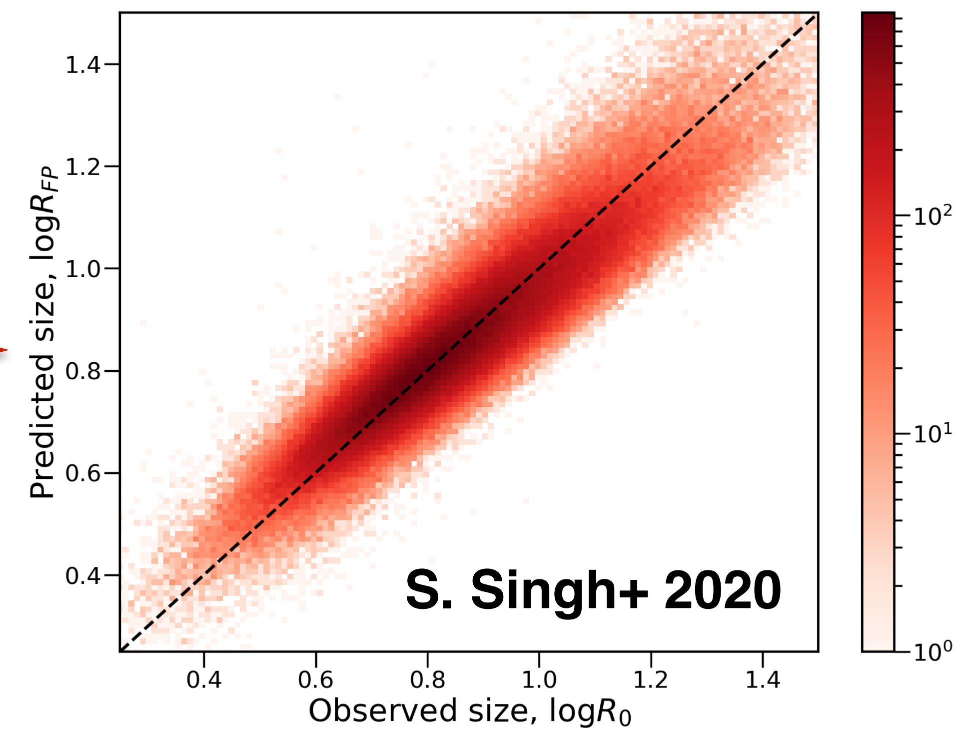
$$\log R_0 = a \log \sigma_0 + b \log I_0 + c$$

Size — Velocity dispersion — Surface brightness

The galaxy sizes can be used to measure

- Weak gravitational lensing
- Galaxy velocities
- Galaxy distances
- Galaxy Physics

contribute to the scatter



Fundamental Plane of galaxies
A New Probe

Cosmology with Fundamental plane

- Probes weak lensing convergence
  - Up to factor of 2 improvement in lensing measurements.
- Dependence on galaxy distances.
  - Photometric redshift calibration using lensing cross correlations.
  - Redshift distance relation with spectroscopic galaxy samples
- Galaxy velocities: Cross correlations with galaxies
- Size dependent selection biases in galaxy clustering. (S. Singh+ 2020)

Fundamental Plane of galaxies
A New Probe

Cosmology with Fundamental plane

Challenges

- Dependence on galaxy properties, density field and observational systematics.

Joachimi, S. Singh+ 2015; S. Singh+ 2020

- Need detailed study of galaxy sizes in cosmological volume simulations

- Generalized size predictor over a wider population of galaxies.

Summary

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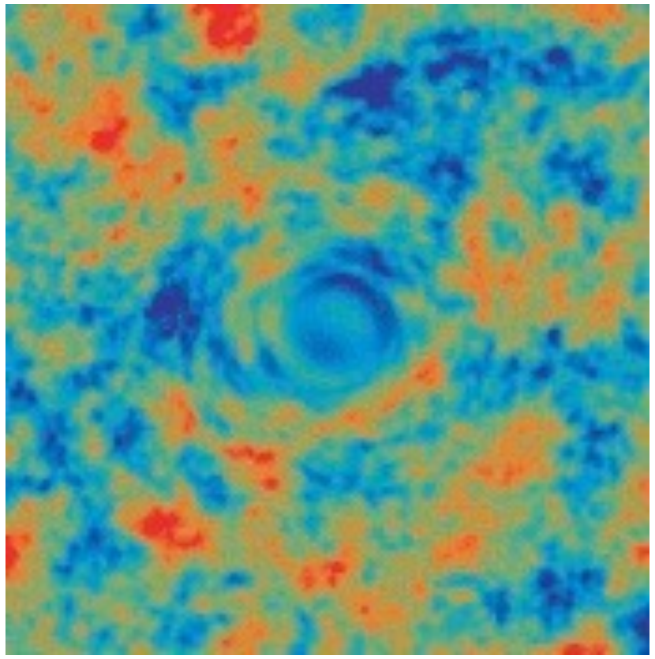
- Upcoming cosmological surveys will map the LSS and its growth at percent level precision.

Dark energy Gravity Inflation Neutrinos Dark matter Galaxy physics

- With improved Statistical precision, we will be well within the systematics dominated regime.
- Synergies between different probes will reduce the impact of systematics and improve the constraints on fundamental physics.
- Galaxy sizes provide new ways to probe weak lensing, photometric redshifts.
- Full optimal analysis presents interesting computational and theoretical challenges that need to be solved.

Back up Slides

CMB lensing



Hu&Okamoto 2001

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

Convergence

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

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

Galaxy-Lensing Cross correlations

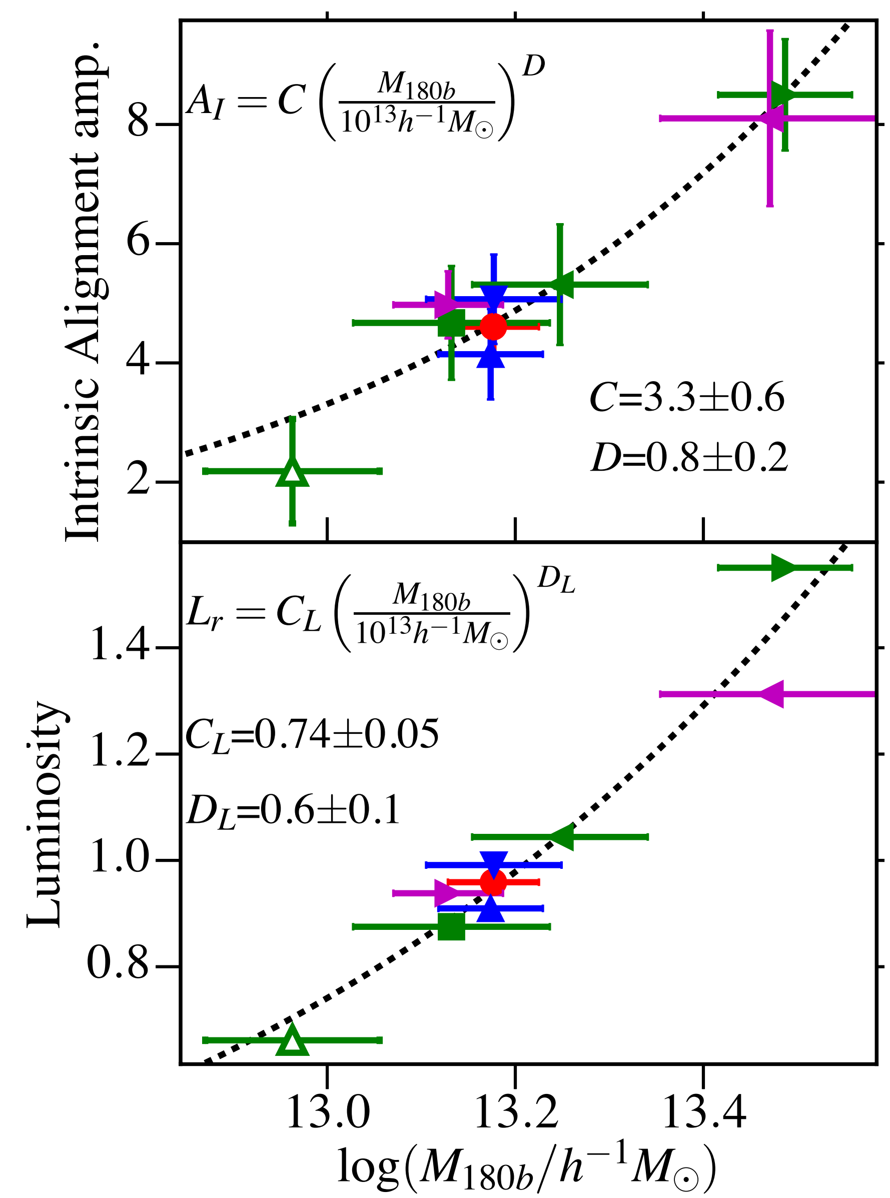
- Robust to additive lensing systematics.
- Direct probe of galaxy-matter cross correlations
- Combined with clustering, provides matter-matter correlation function.

  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 and dark matter physics.

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



S. Singh+ 2015

Galaxy-lensing estimator

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

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.

Galaxy-Lensing cross correlations

Model

Galaxy Shear $\gamma_t = \frac{\Delta\Sigma(r_p)}{\Sigma_{\rm crit}}$

$$\Delta\Sigma_{gm}(r_p) = \Upsilon_{gm}(r_p) + \left(\frac{r_0}{r_p}\right)^2 \Delta\Sigma_{gm}(r_0)$$

Baldauf+ 2010

Measured using galaxy shear

Remove non-linear information that we cannot model

S. Singh+ 2020, 1811.06499

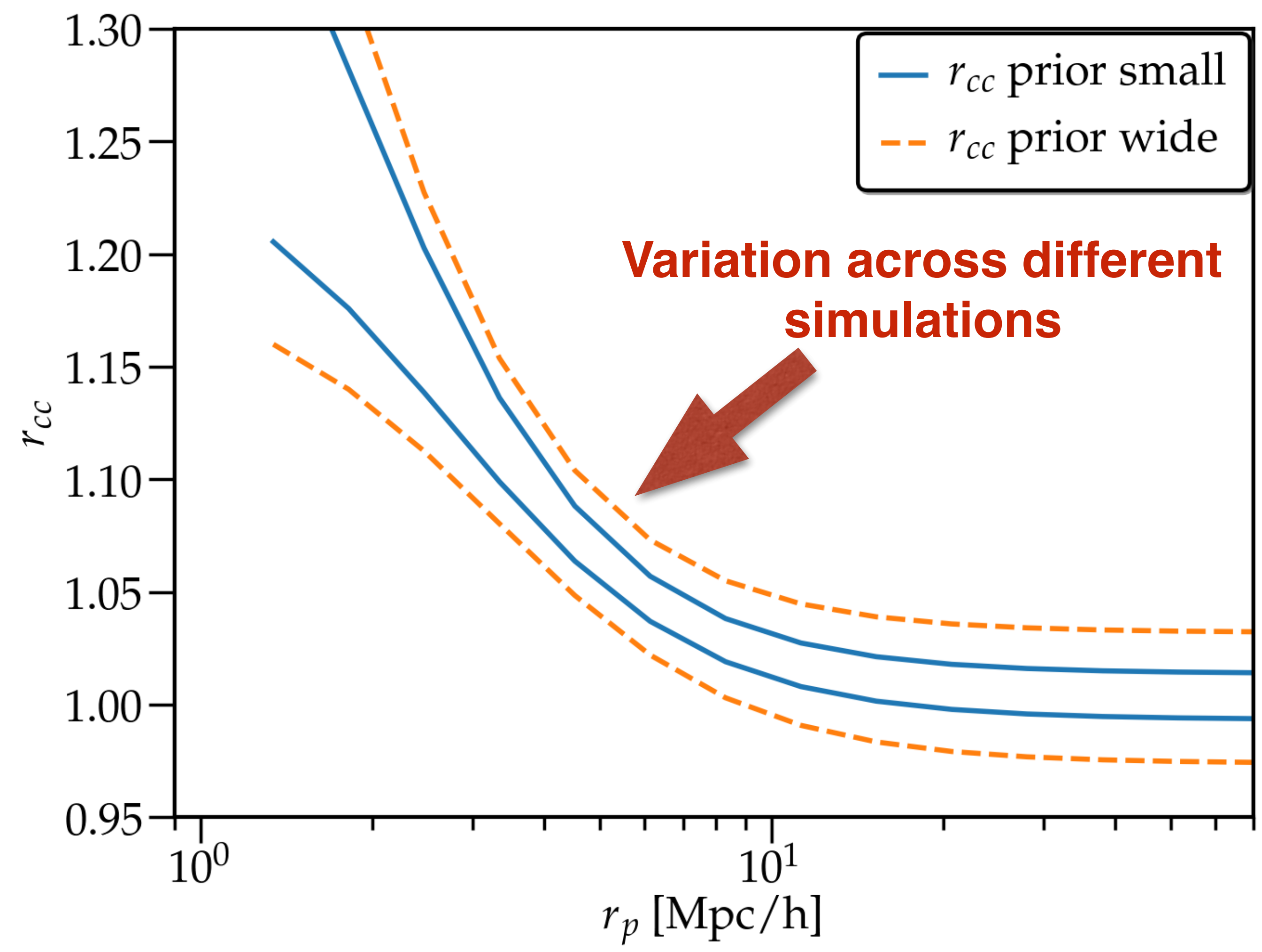
X

Galaxy-Lensing cross correlations

Model

$$\Upsilon_{gm} = r_{cc}^{\Upsilon} \sqrt{\Upsilon_{gg} \Upsilon_{mm}}$$

Galaxy physics
Learn from simulations

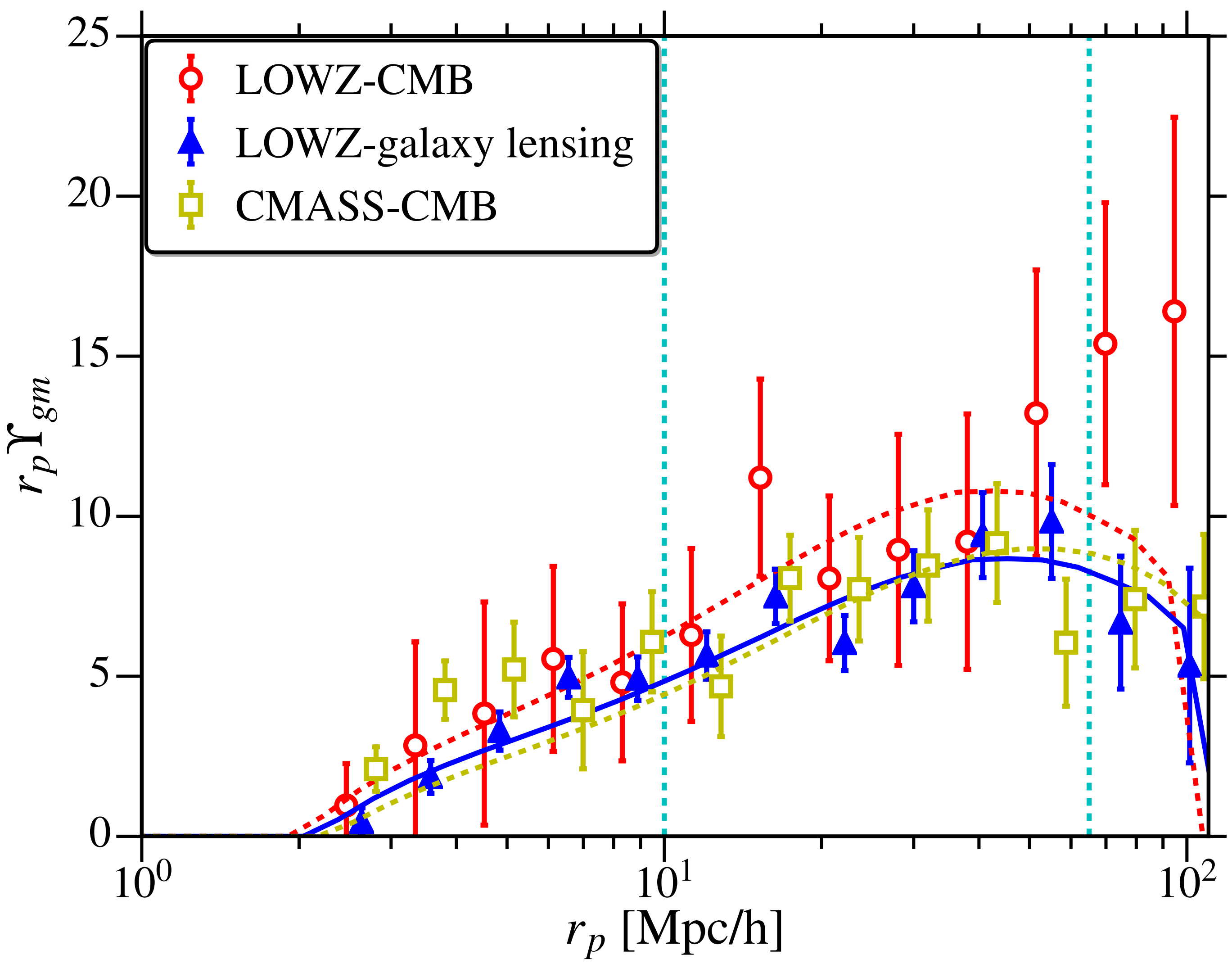


S. Singh+ 2020, 1811.06499

X

Measurements

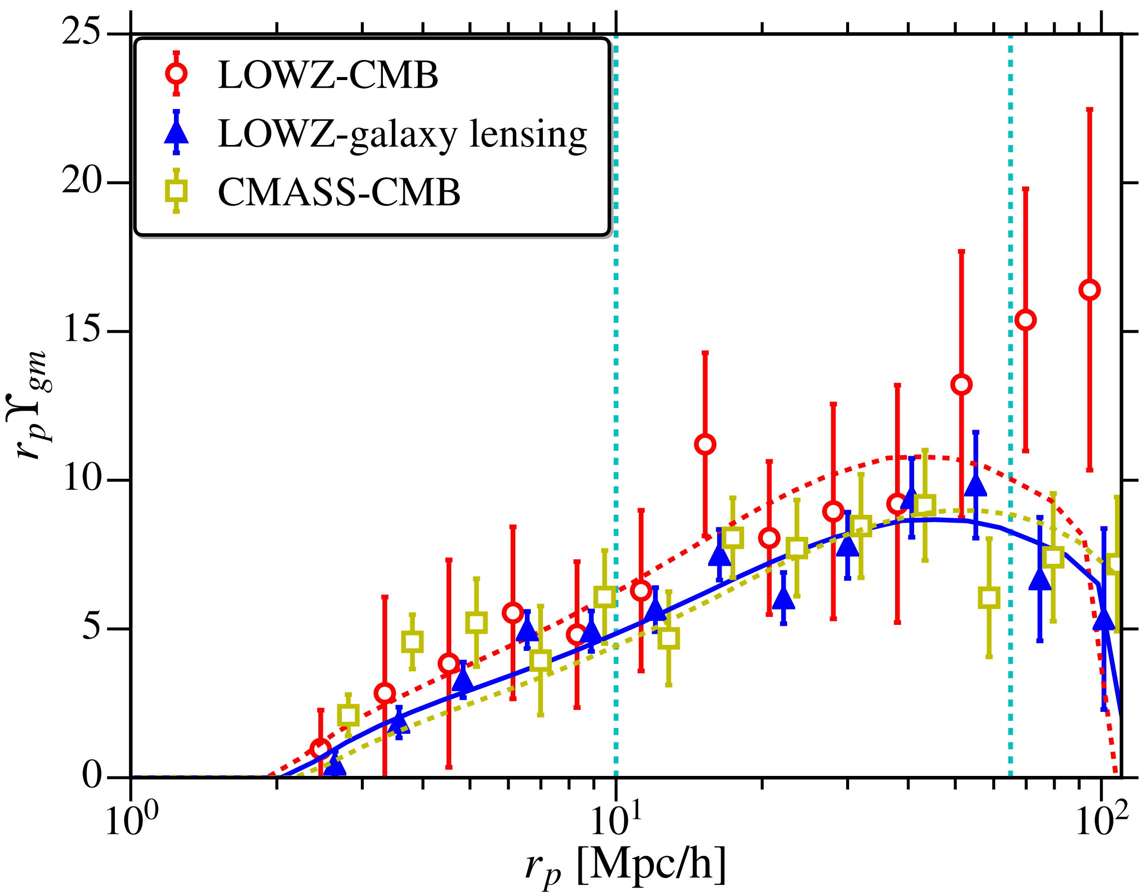
Galaxy-Lensing Cross correlations

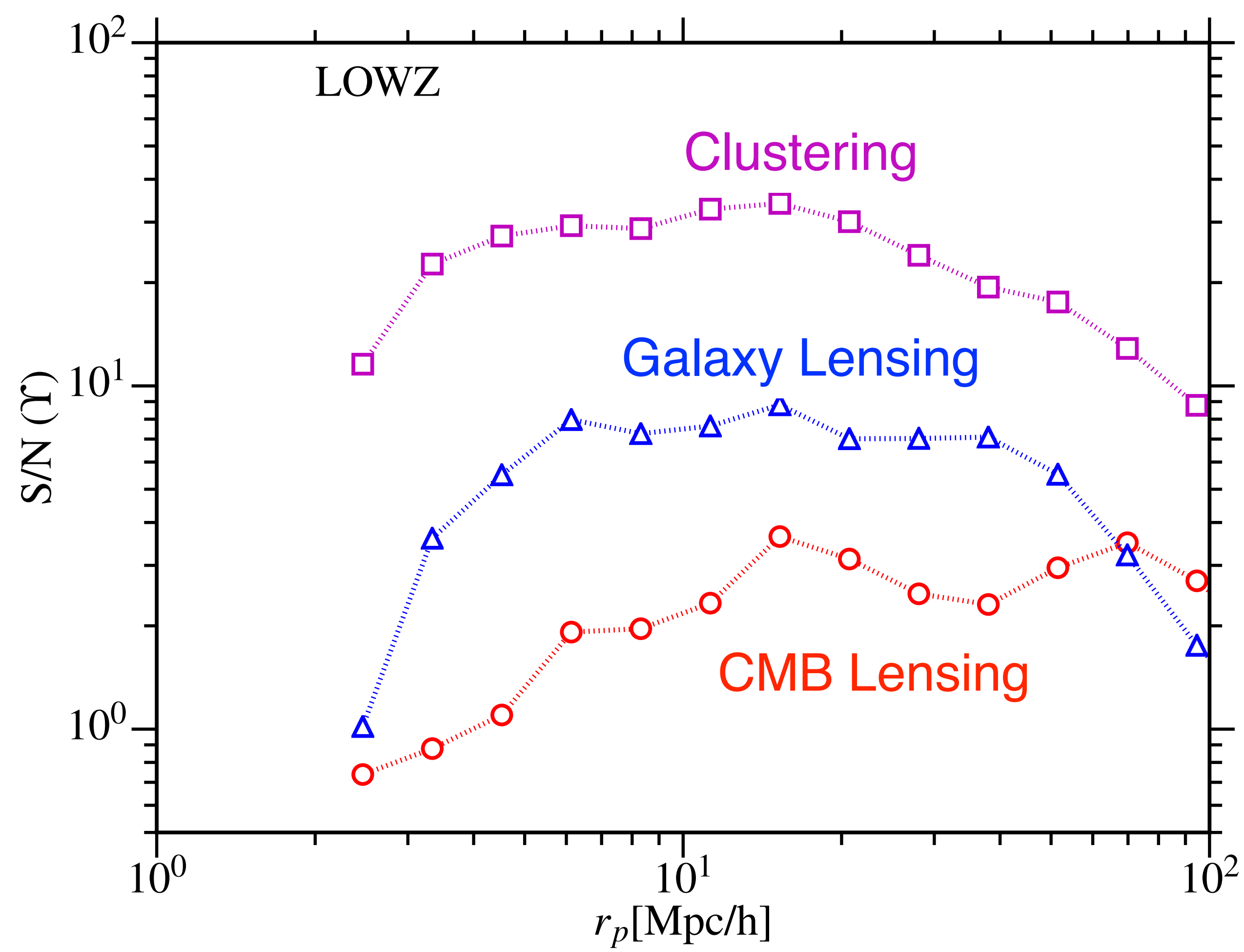


S. Singh+
2016b

Measurements

Galaxy-Lensing Cross correlations





S. Singh+
2016b

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Testing ΛCDM + GR

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 $\psi = \phi$

Constructing a null test,

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

Lensing

Velocities (RSD)

E_G Parameter

Lensing

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

Zhang+ 2007

Velocities (RSD)

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

Reyes+ 2010

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

E_G Parameter

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

Zhang+ 2007

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

Reyes+ 2010

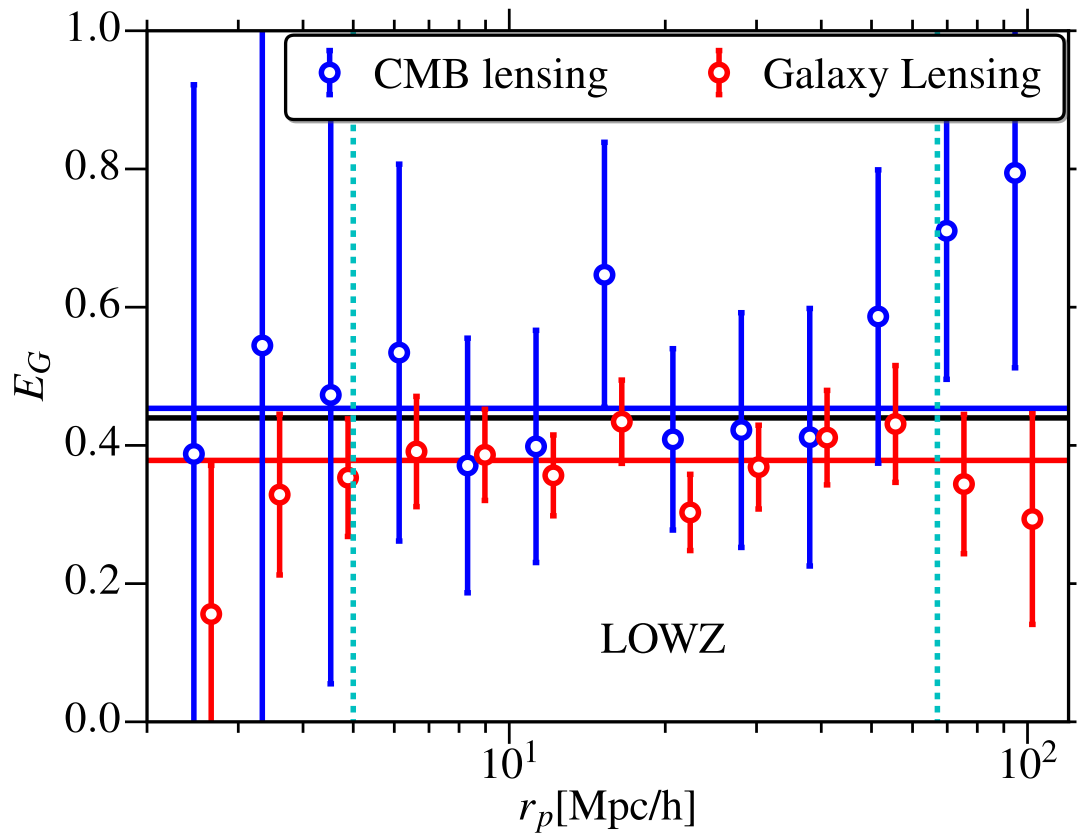
See also, Pullen+ 2015, Leonard+ 2015

Problems

- Non-linear galaxy bias and galaxy-matter cross-correlation.
- Residual linear RSD in galaxy clustering — Baldauf+ 2010

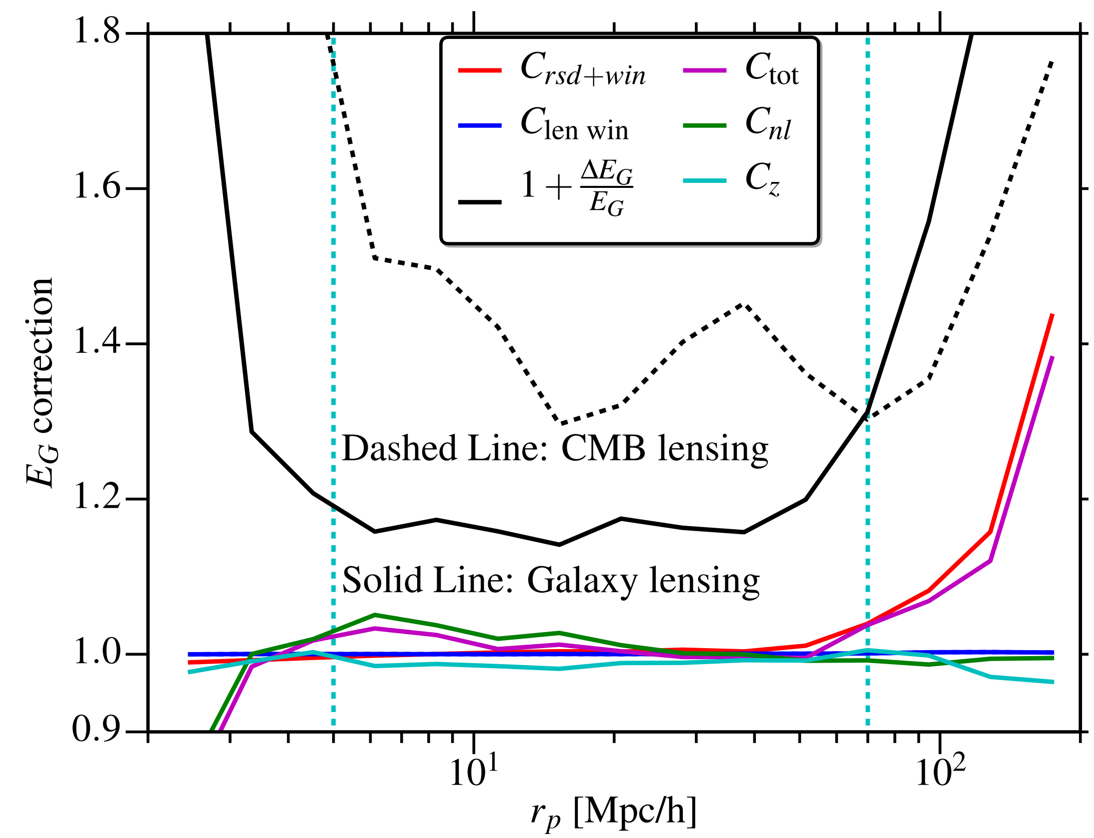
Need to compute corrections from simulations and/or theory.

E_G Measurements



S. Singh+ 2018

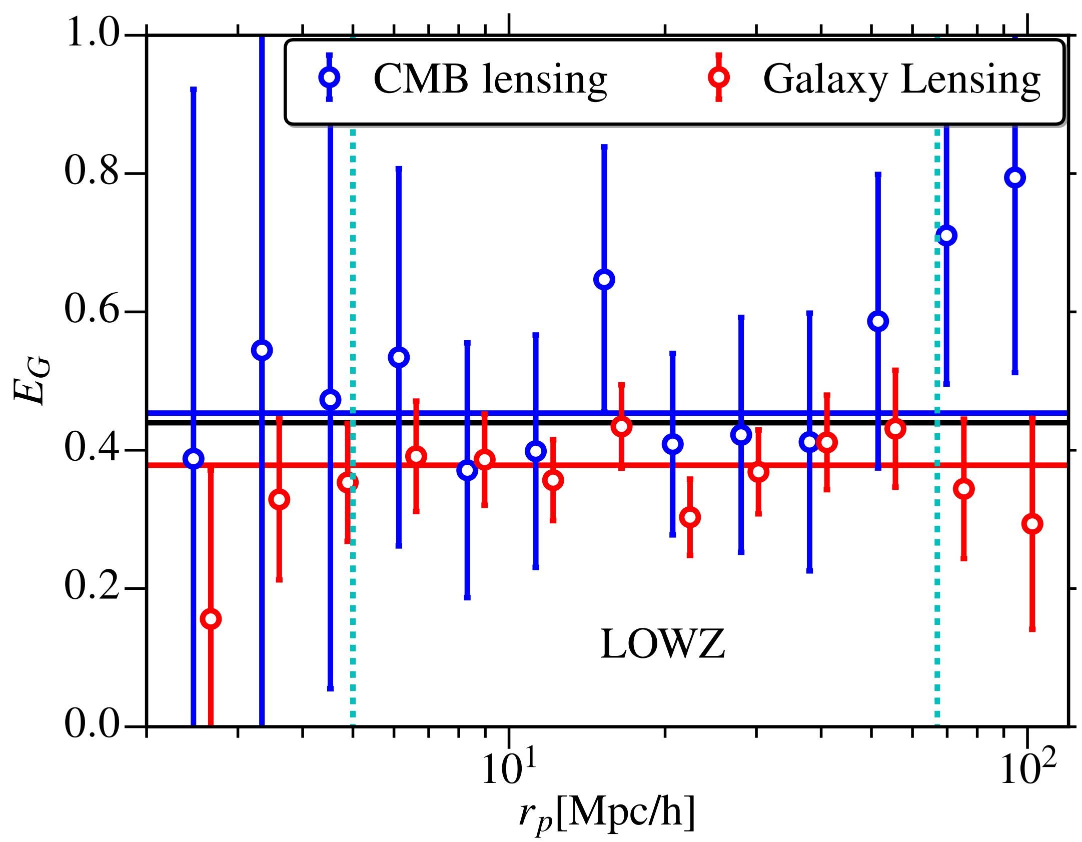
Corrections applied



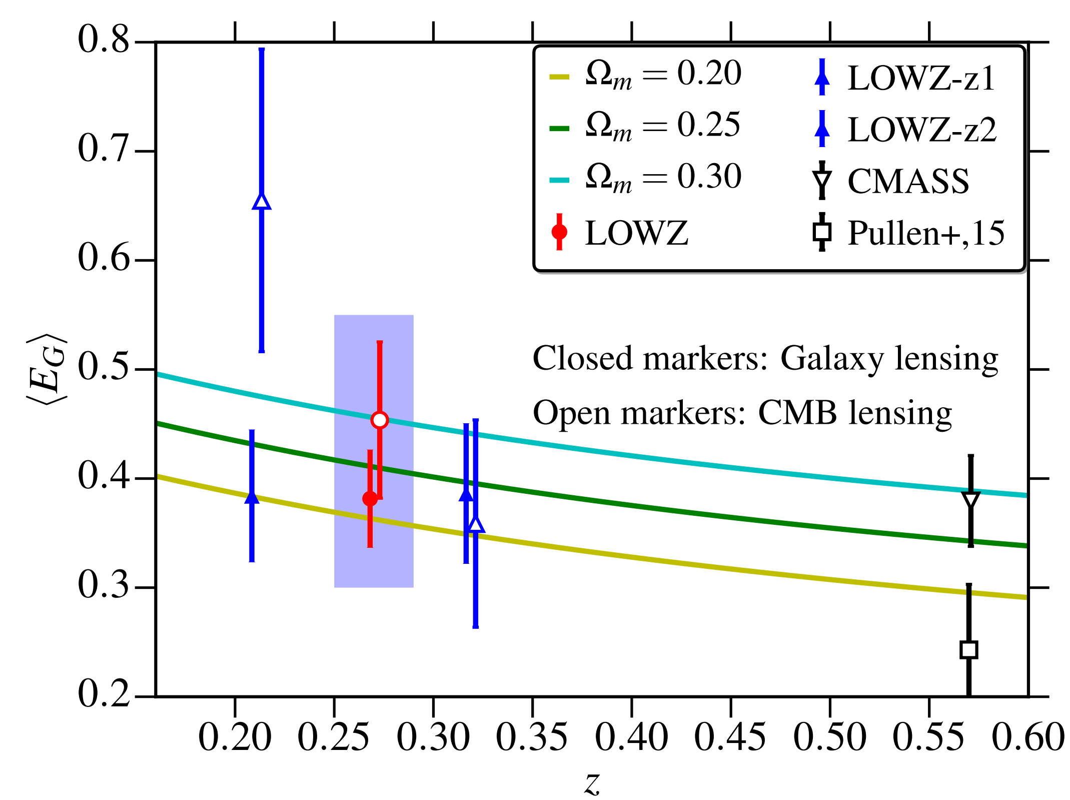
See also: Reyes et al. 2010, Blake et al. 2016, Pullen et al. 2016, Alam et al. 2016

E_G Measurements

Measurement as function of scale



Measurement at different redshifts



~10% constraints on E_G at multiple redshifts.

Consistent with Planck ΛCDM predictions

S. Singh+, 2018

More 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.**

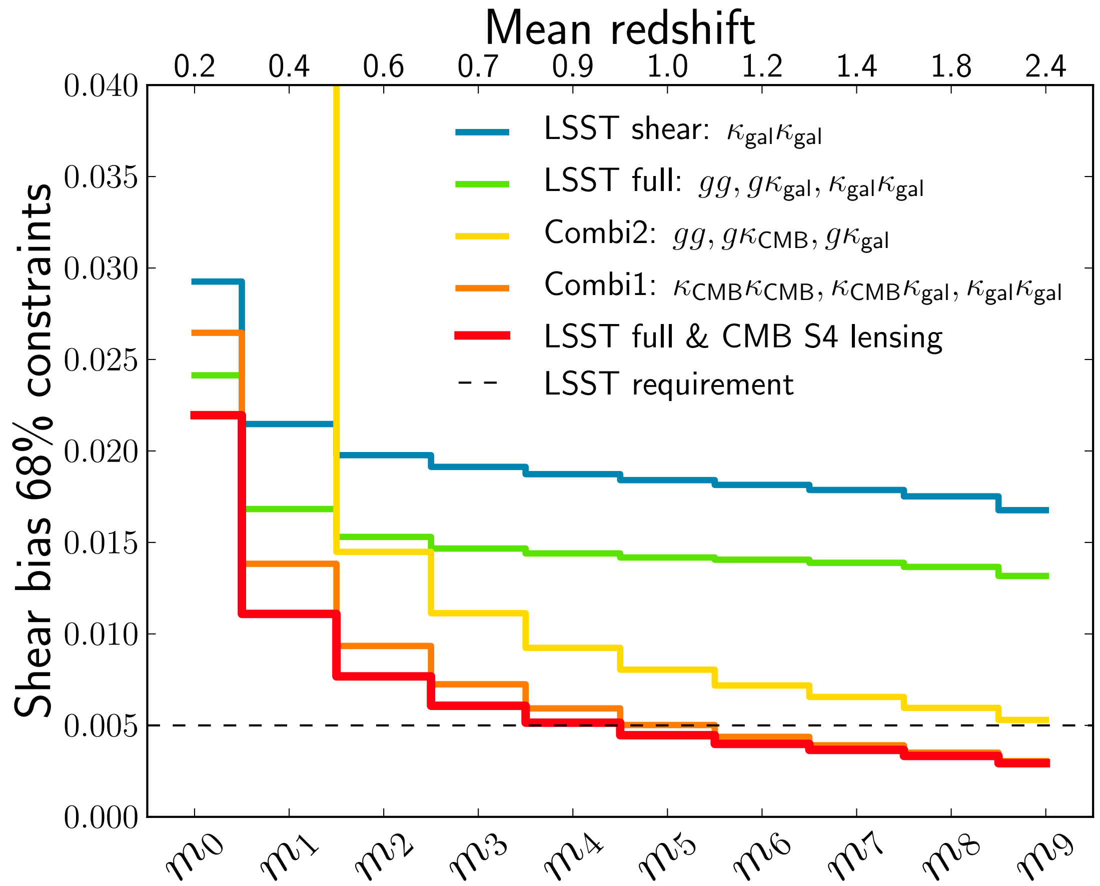
Constraining lensing Systematics

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

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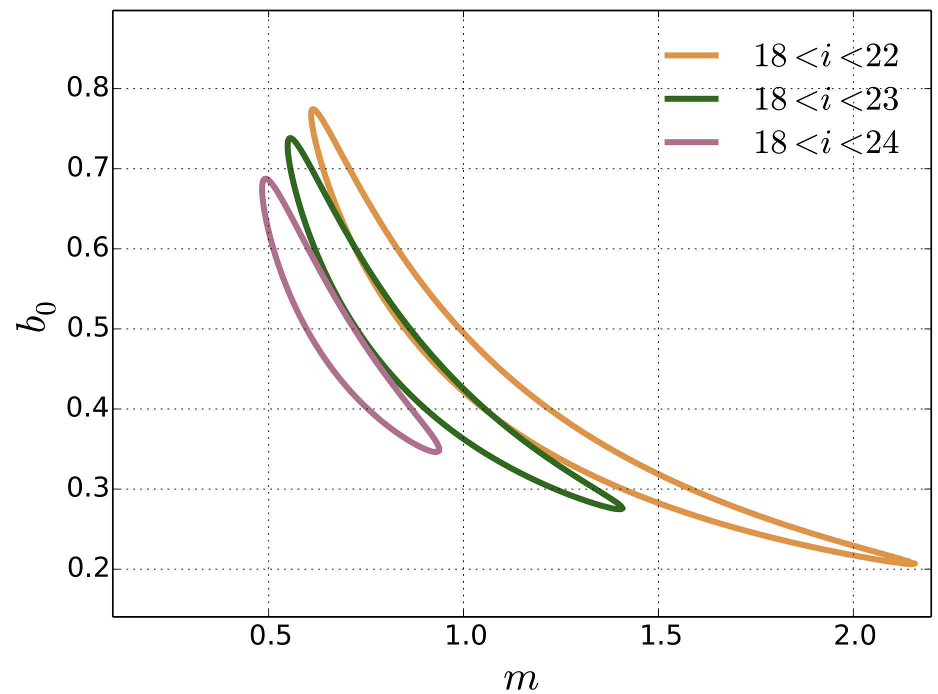
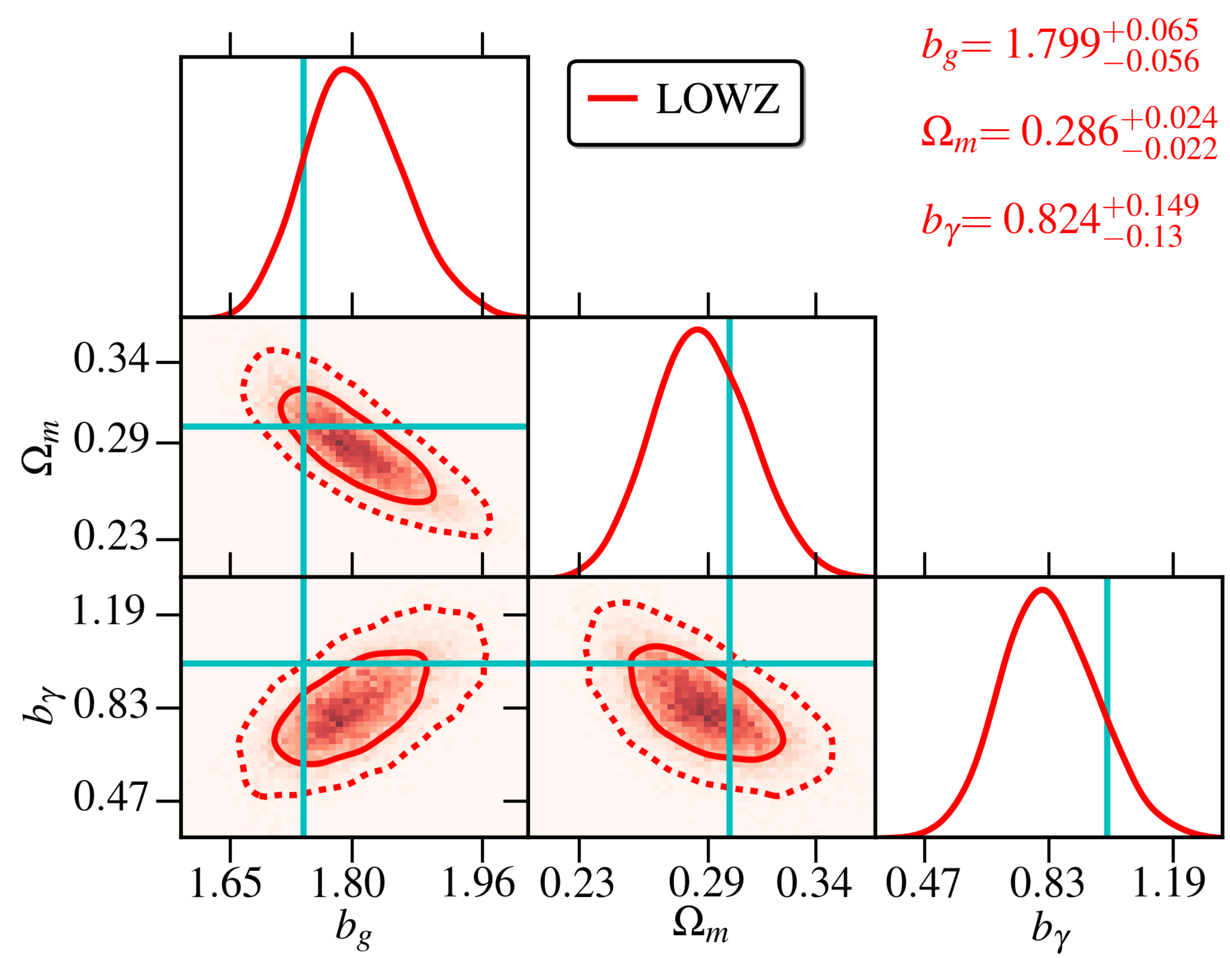
Constraining lensing Systematics

Galaxy bias



Shear multiplicative bias

Liu+ 2016: CFHTLens+Planck



S. Singh+ 2016b

$$b_\gamma \equiv m$$

(assuming no systematics in CMB lensing)

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

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Cosmic Distance Ratio

$$\mathcal{R} = \frac{g\kappa_{\rm CMB}}{g\kappa_{gal}} = \frac{\Sigma_c(z_l, z_s)}{\Sigma_c(z_l, z_*)} \frac{\Sigma(z_l)}{\Sigma(z_l)}$$

Hu+ 2007b

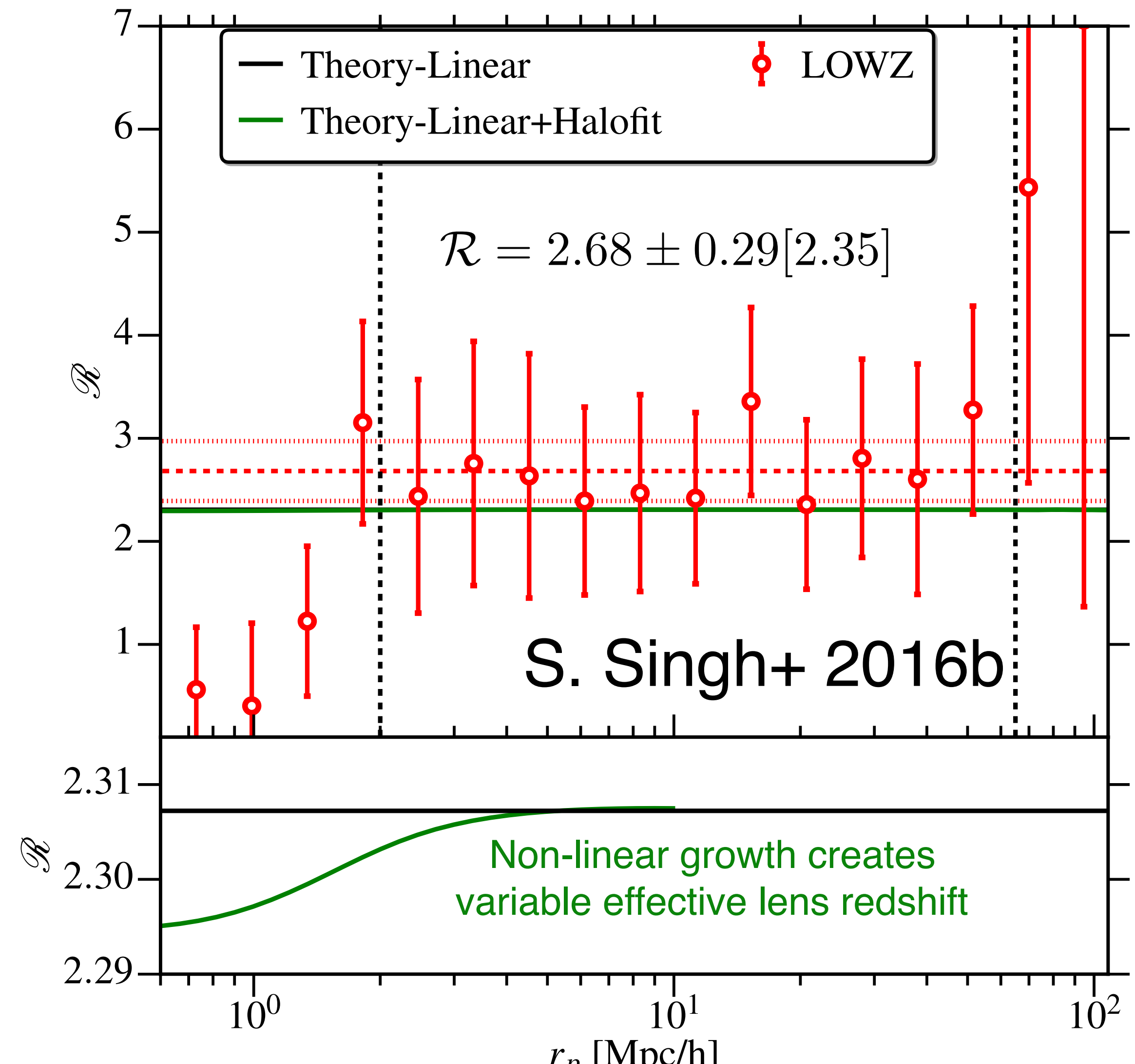
Geometric test, independent of power spectrum

Problems

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

A good test for lensing systematics

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



See also Miyatake+ 2016

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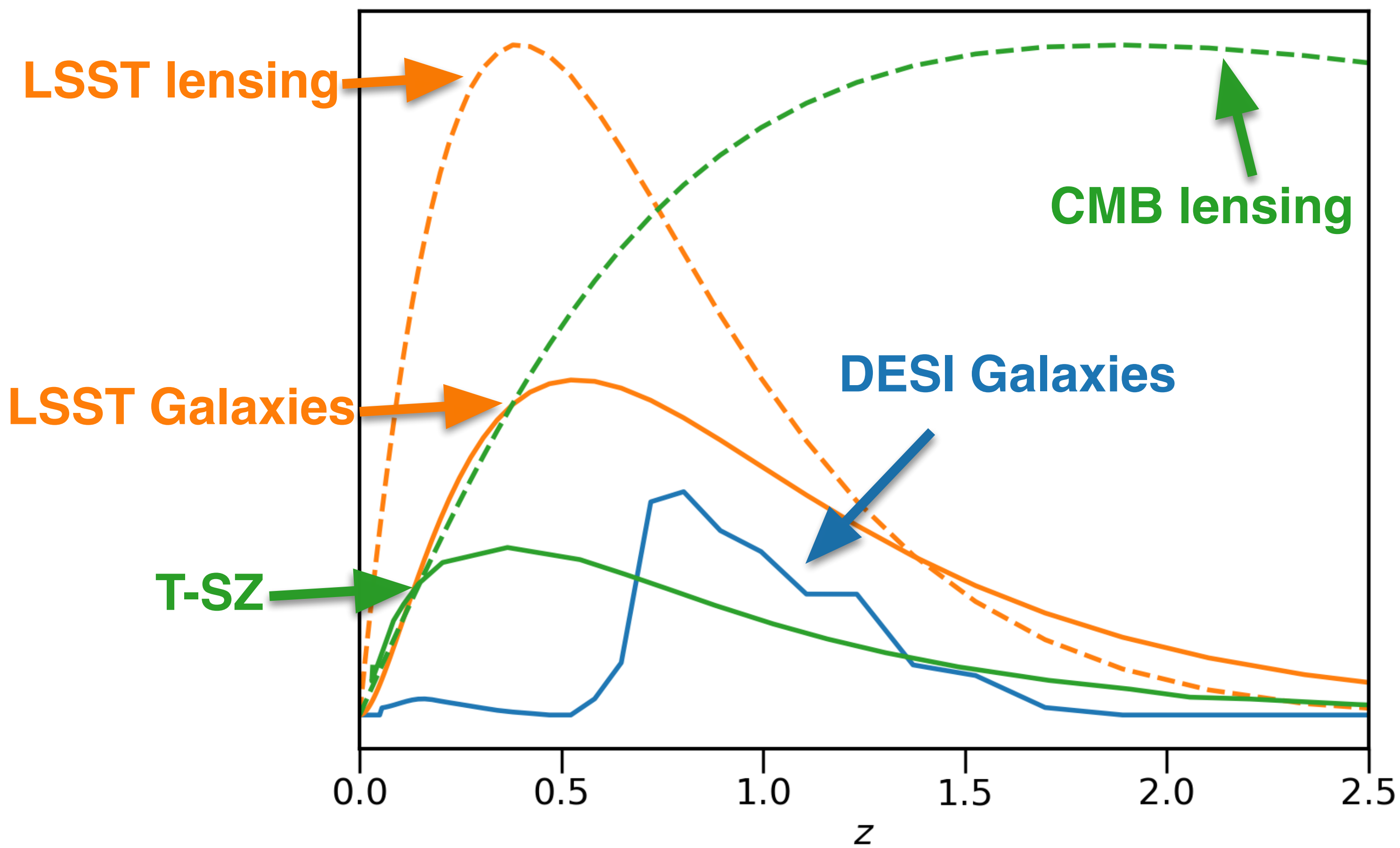
Next generation joint analysis

LSST+DESI+CMB experiments



Redshift overlap of different probes

(y-axis normalization is arbitrary, for clarity)

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Computational Challenges

The Inference Problem

$$P(\theta_{cosmo}|data) \propto \int d\theta_{nuisance} P(data|\theta_{cosmo}, \theta_{nuisance})$$

Accurate inference in high dimensional space, O(50) or more parameters

- Standard power spectrum analysis: model calculations scale as $N^2_{\rm Probe}$
- MCMC complexity scales exponentially with dimensions

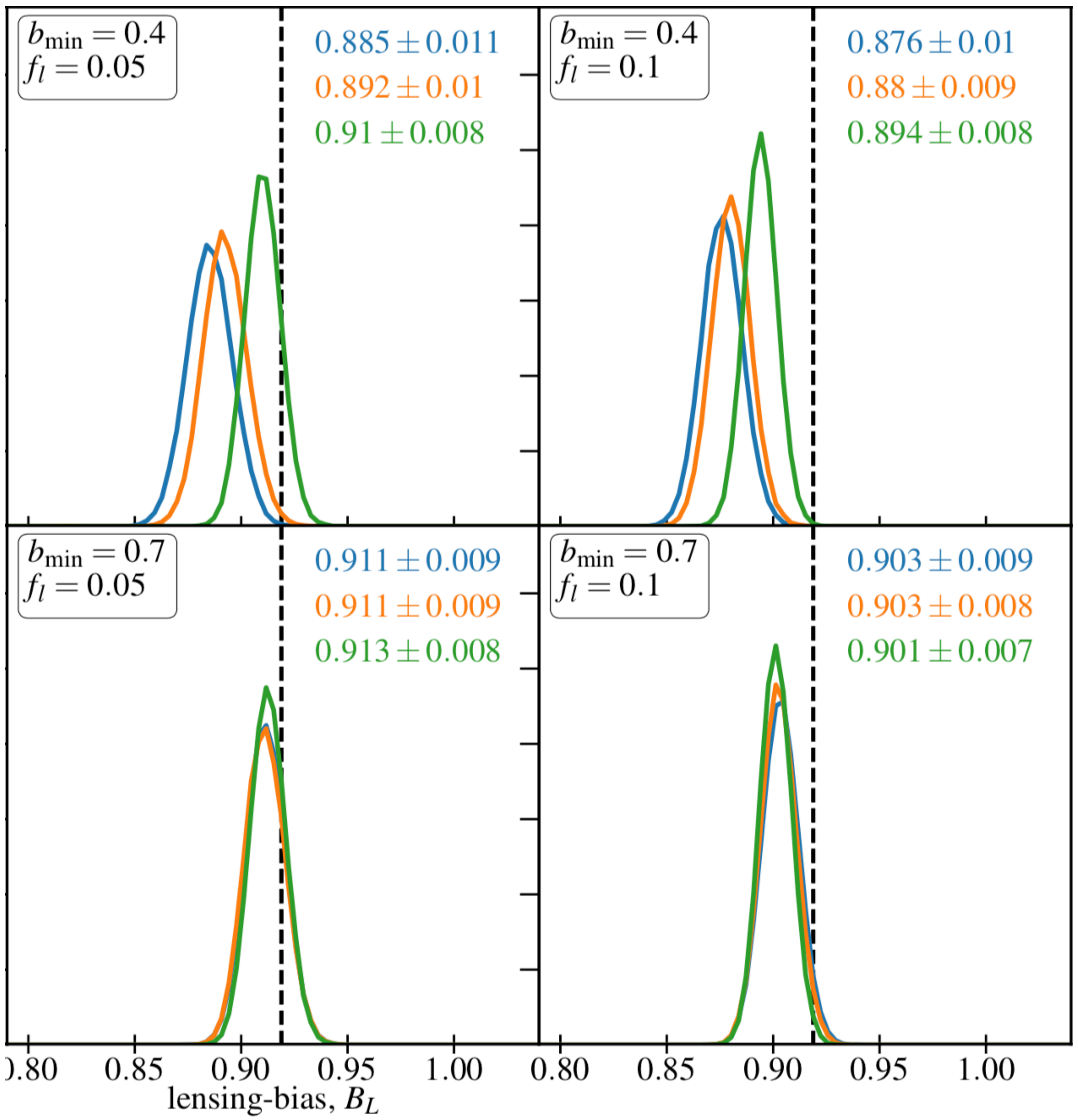
What we need

- Speeding up calculations.
- Differentiable models or emulators: Speeding up inference.
- Fast posterior estimations, e.g. Seljak & Yu 2019.

Challenges

Clustering photo-z

Galaxy bias and lensing calibration



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arXiv: 1803.08915

Challenges

Systematics/ Nuisance parameters

- Astrophysical
  - **Intrinsic alignments of galaxies**
  - Galaxy physics, e.g. S. Singh+ 2020
- Observational systematics
  - Selection function of galaxies
  - Blending, fiber collisions
  - Photometric redshift uncertainties

A biased and very incomplete list

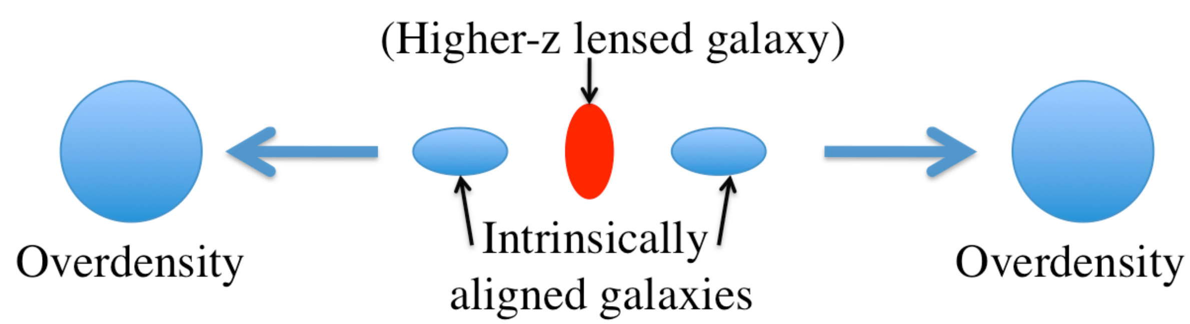
Data

- Need to understand estimators, selection effects. S. Singh+ 2017; S. Singh+ in prep
- Covariance Matrices

Modeling

- Accurate predictions on non-linear scales. e.g. S. Singh+ 2020
- Accurate and high precision emulators.
- Modeling baryonic physics
- Speed

Intrinsic alignments of galaxy shapes



Galaxy Shapes are aligned with the matter distribution

Biases the weak lensing measurements using galaxy shear

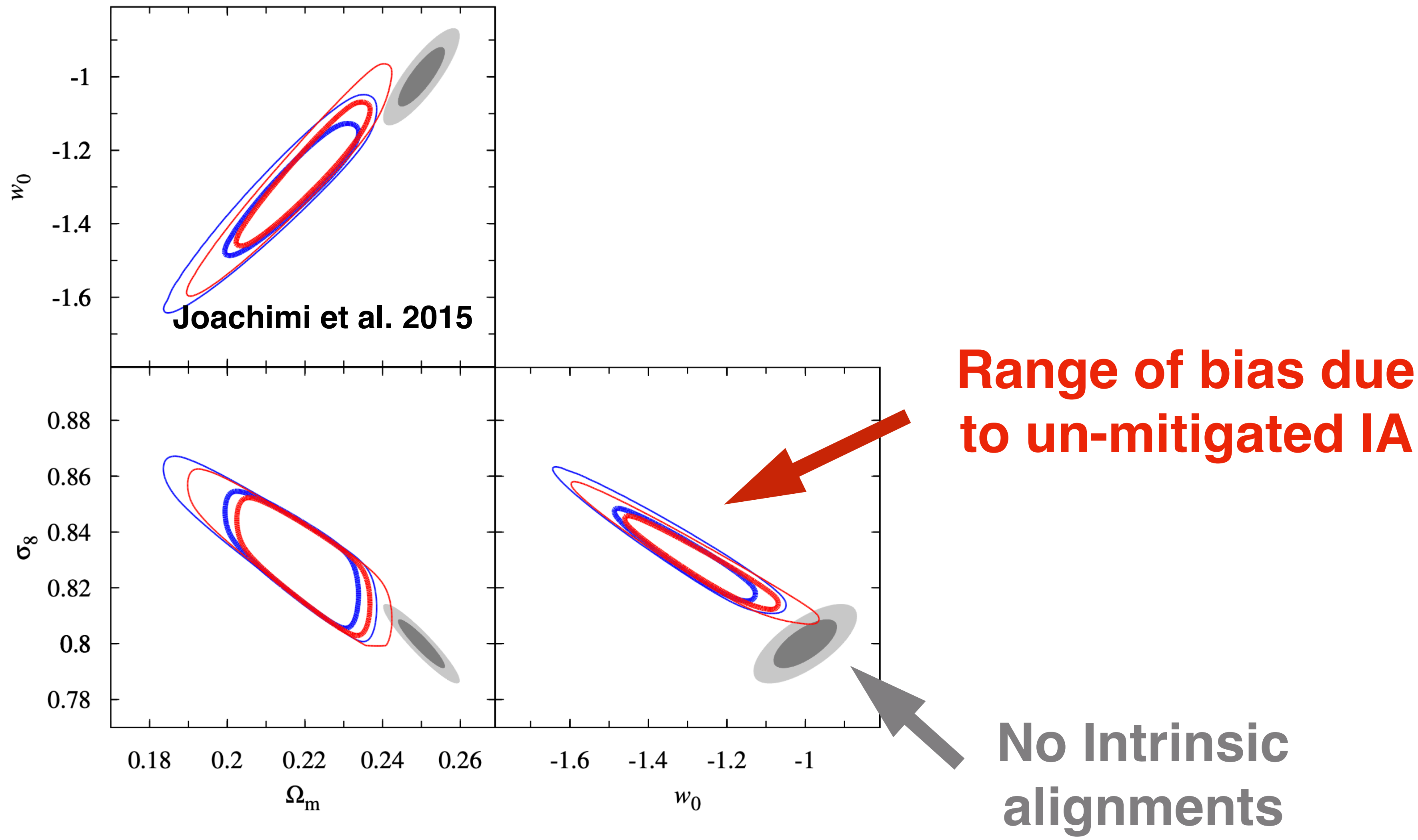
Can bias galaxy clustering measurements

(Hirata 2009, S. Singh+ 2020)

Intrinsic alignments of galaxy shapes

Biases the weak lensing measurements using galaxy shear

Can bias redshift space measurements



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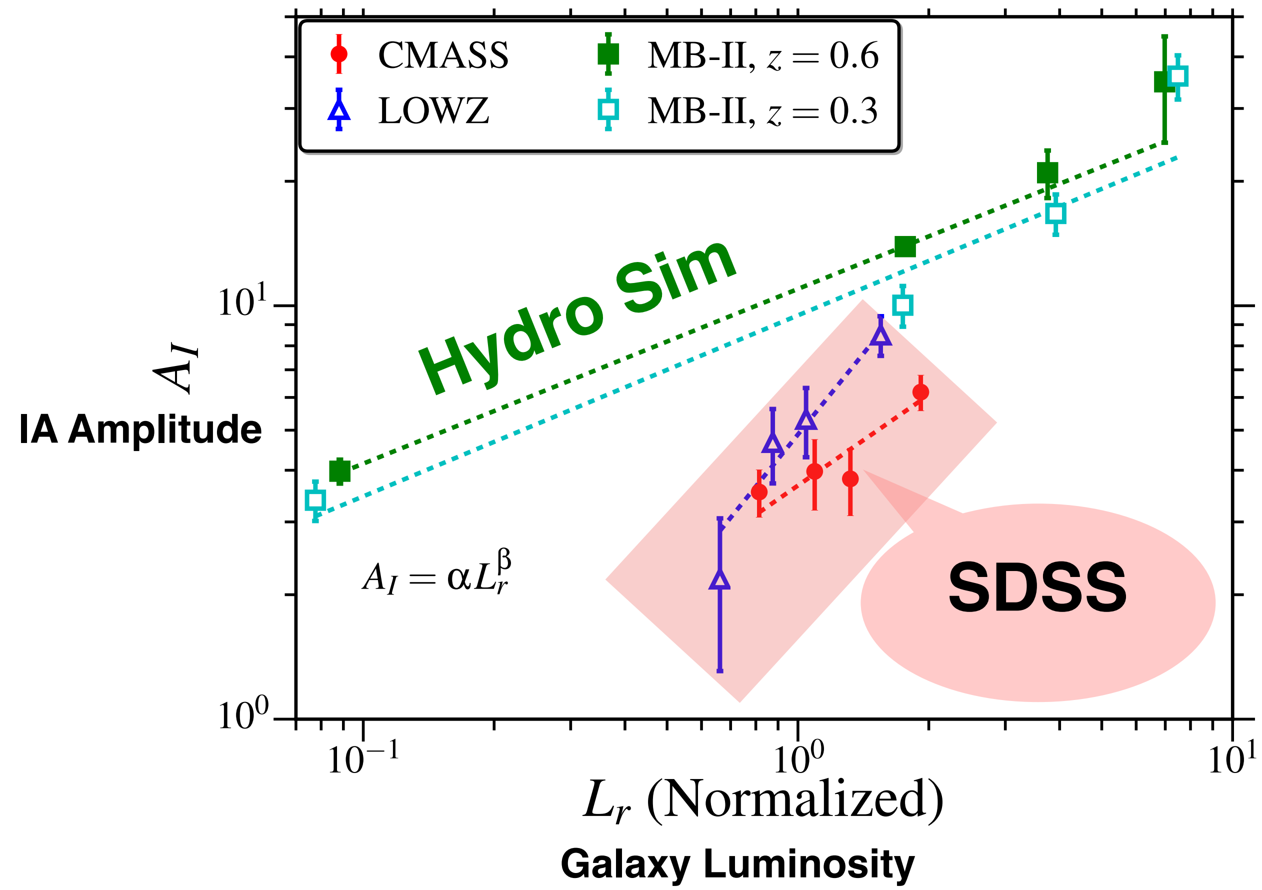
Intrinsic alignments of galaxy shapes

State of the art

- Detections in red, elliptical galaxies
- No detection for spiral galaxies
- Multiple studies in simulations
- Simulations do not agree, among themselves and with data



S. Singh+ 2015, 2016a
Tenneti, S. Singh+ 2015

Need better measurements

Intrinsic alignments of galaxy shapes

Next Decade

Extremely important for weak lensing and redshift space distortions science

- High precision measurements over a broader population of galaxies. **DESI+LSST**
  - Wider redshift and luminosity coverage.
  - Measurements for spiral galaxies.

- New mitigation strategies for weak lensing analysis.
  - Cross correlations.
  - Splitting samples based on expected IA.

- New mitigation strategies for redshift space distortions analysis (S. Singh+, 2020).
- New probes of galaxy physics (DESI+LSST+SZ)
  - E.g. Galaxies are more aligned with dark matter than gas inside halos.

Martin & SS, in prep