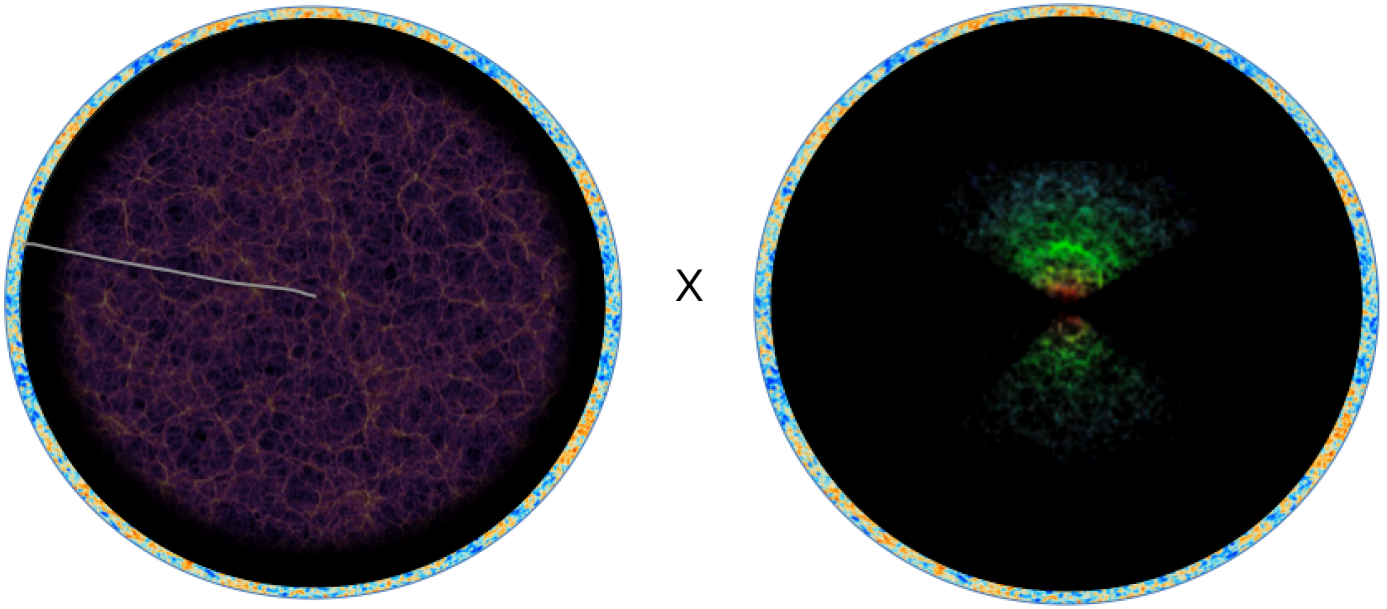
CMB Lensing Combined with Large Scale Structure: Overview / Science Case



Blake D. Sherwin

Einstein Fellow, LBNL

Outline

I. Brief Introduction: CMB lensing + LSS as probes of growth of structure

II. Combining weak lensing and CMB lensing

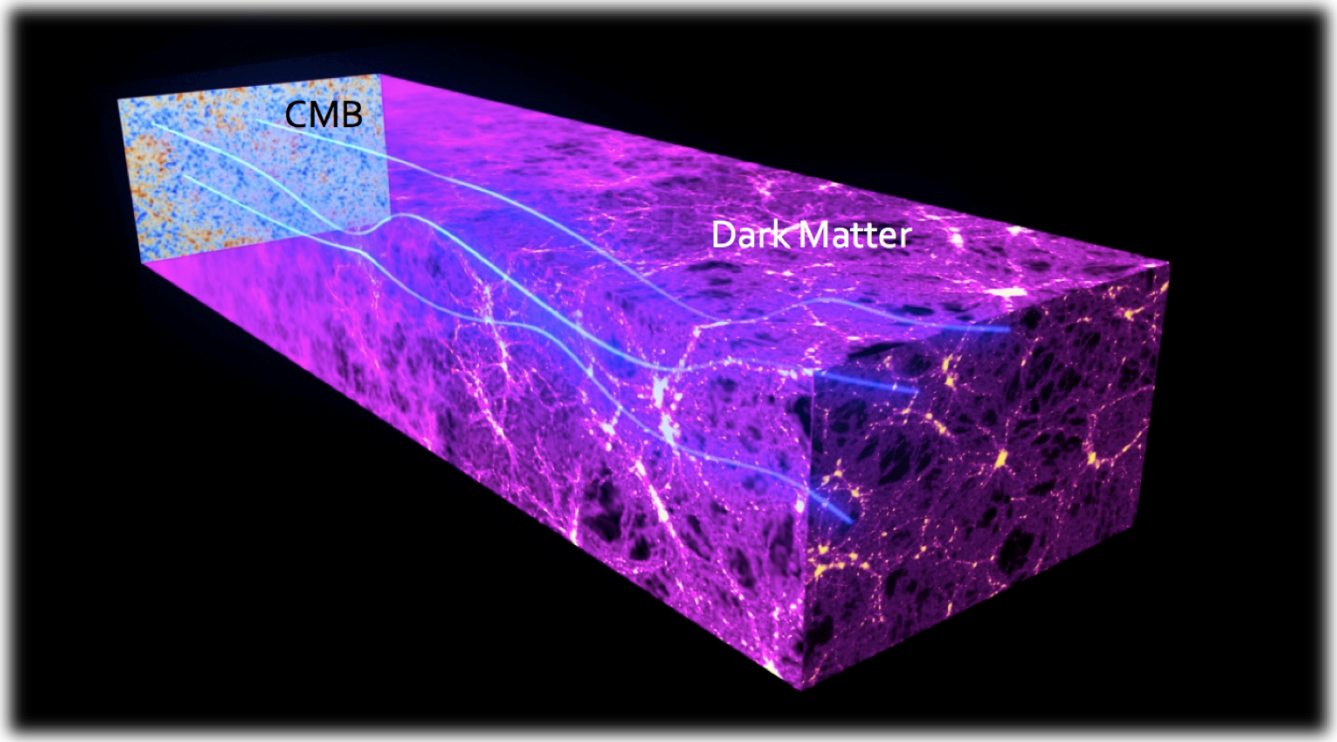
III. Combining galaxy clustering and CMB lensing

IV. High-z LSS cross-correlations, challenges and outlook

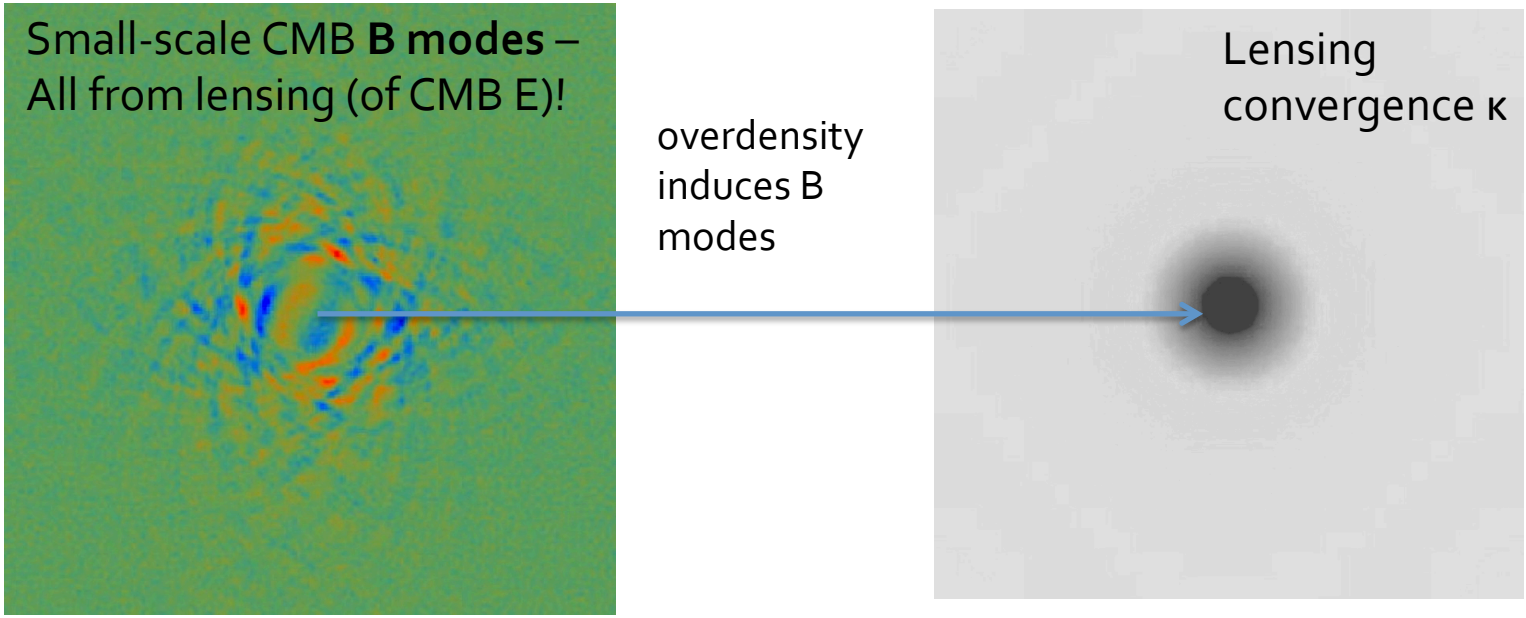
CMB Lensing

- Distribution of mass deflects / weakly lenses CMB passing through, described by lensing convergence κ

$$T(\hat{\mathbf{n}})_{\text{lensed}} = T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))_{\text{unlensed}} \qquad \kappa = \nabla \cdot \mathbf{d}/2$$



Measuring CMB Lensing Convergence: An Approximate Picture

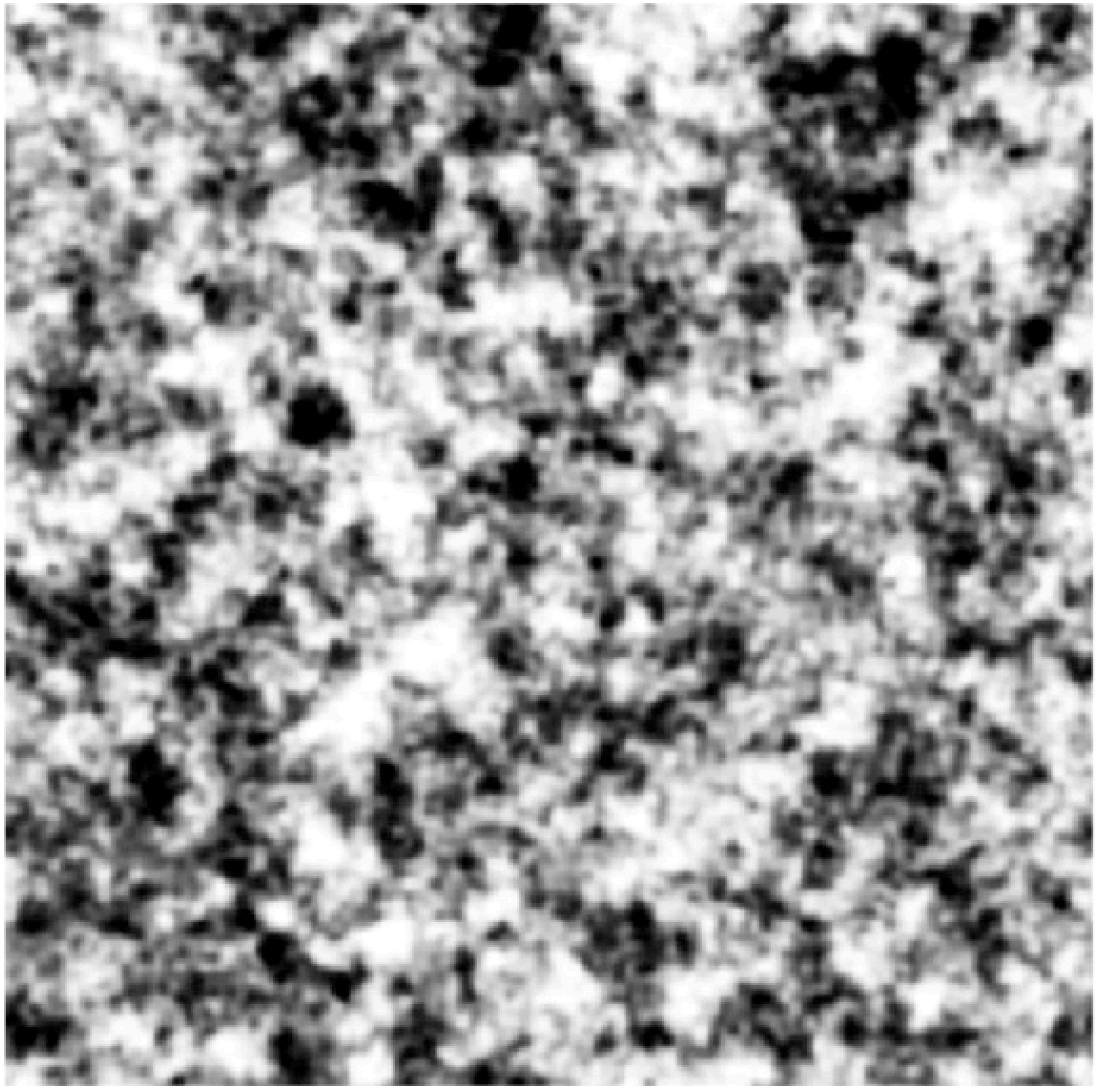


[Hu, Okamoto 2002]

look for lensing-induced correlations of E and B (delens, iterate, for higher signal-to-noise)

CMB Lensing Convergence Measurement

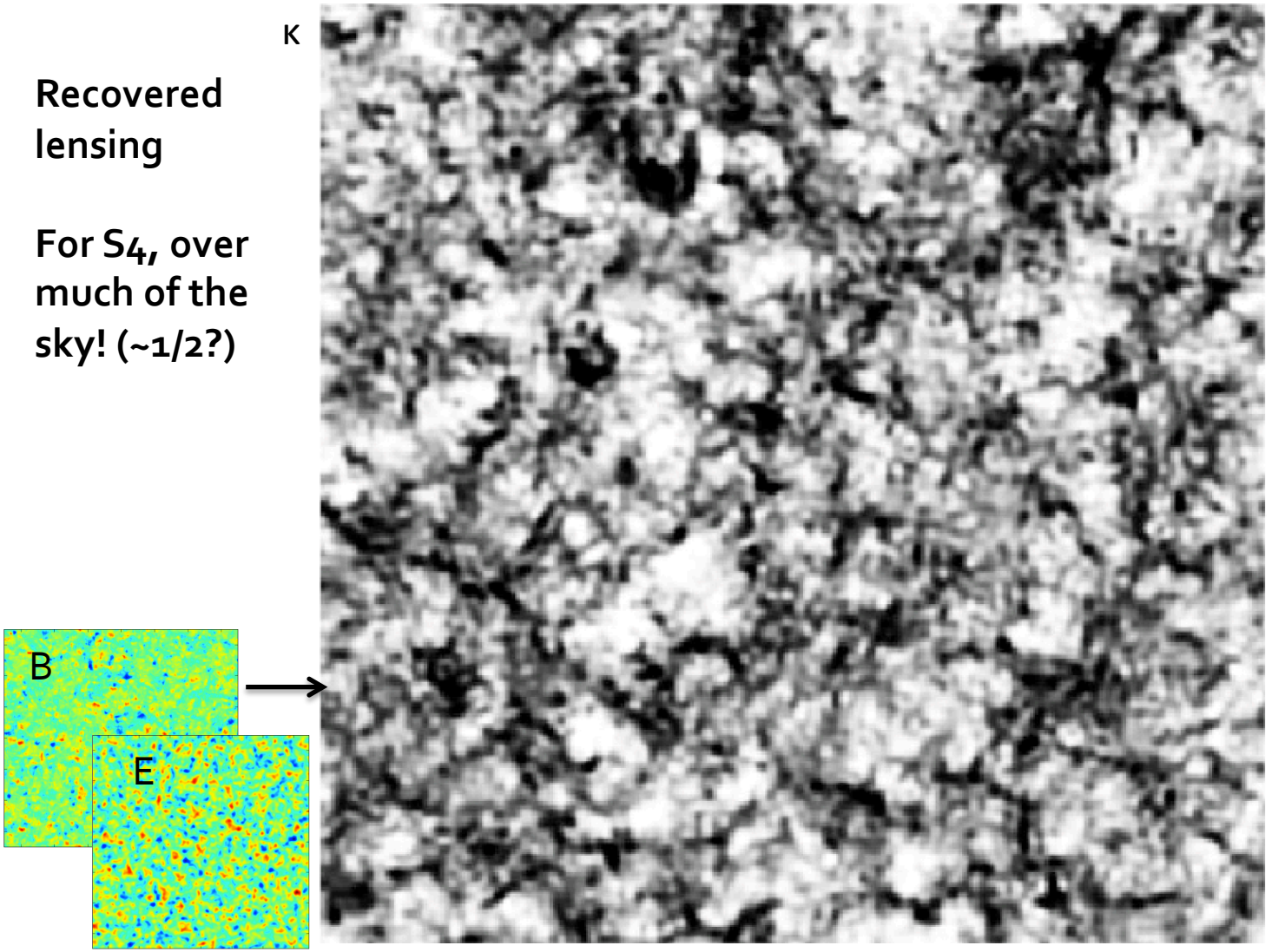
True Lensing: (Simulation input, 1uK' CMB noise)



CMB Lensing Convergence Measurement

Recovered lensing

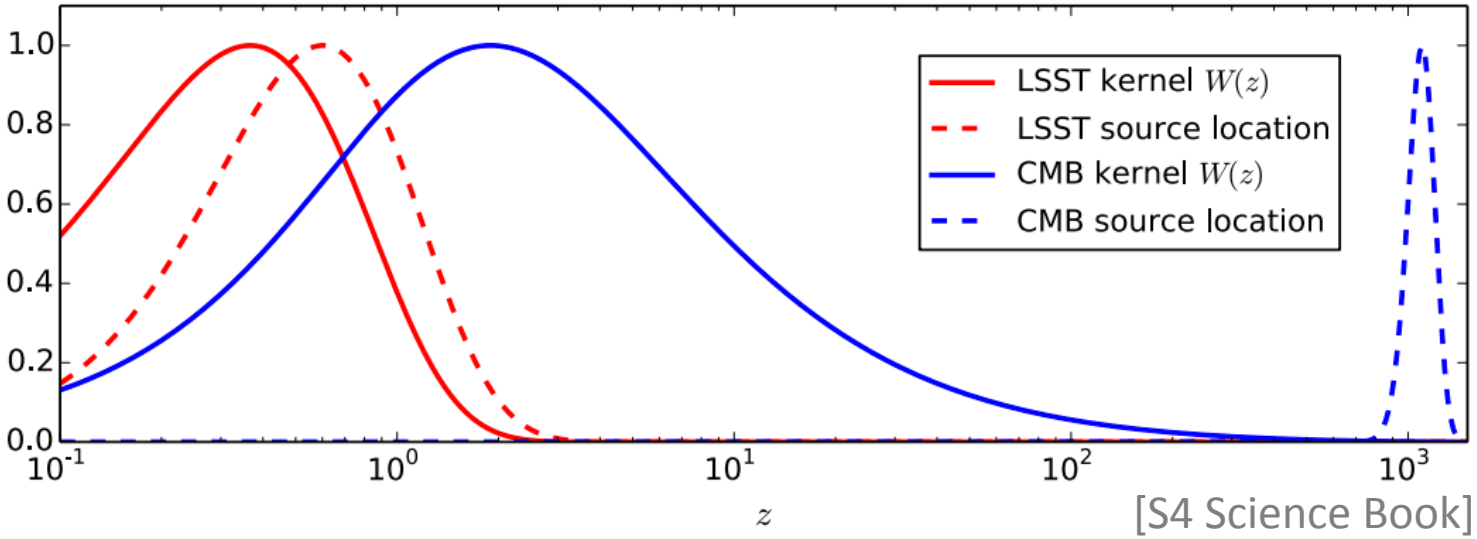
For S4, over much of the sky! (~1/2?)



[pipeline: Sherwin++ in prep. 2016]

Properties of Future / S4 CMB Lensing Maps

- Lensing maps probe matter density, projected over a wide redshift range peaking at z~2:

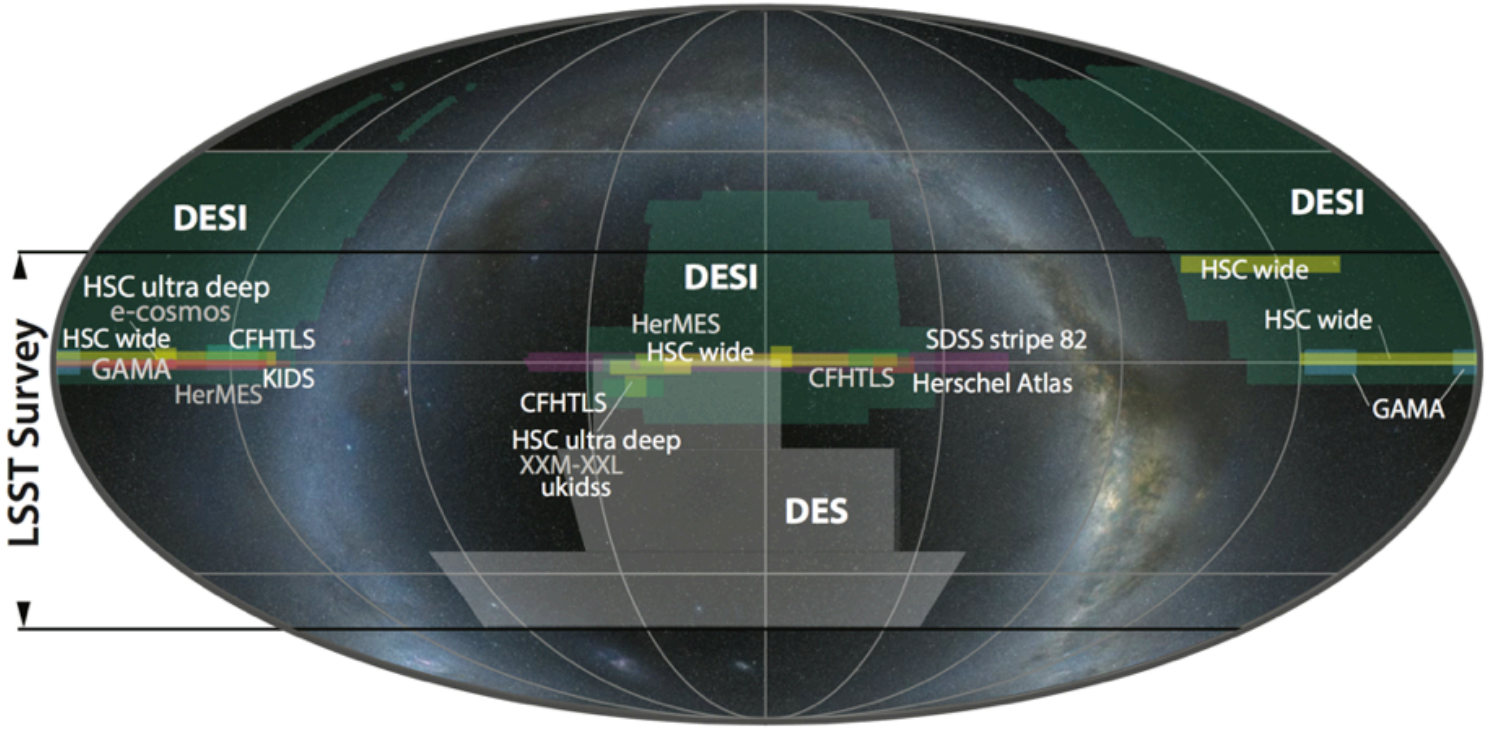


[S4 Science Book]

- Noisier than future WL, but signal is larger (wide z-range)
- Information clean: mainly on linear or quasi-linear scales
- Estimation robust: source redshift / properties / PSF … understood

What science can we target with CMB lensing + LSS?

- CMB S_4 (wide survey – half sky?) could target overlap with lots of upcoming and future surveys:



- Wide range of applications: Astrophysics at high-z, modified gravity, non-Gaussianity, r via delensing…

What science can we target with CMB lensing + LSS?

- **Focus: how can CMB + LSS help in measuring amplitude of structure as a function of redshift?**

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\rho_M\delta = 0,$$

components that don't cluster but
contribute energy suppress structure growth

  - Dark energy: structure amplitude vs. redshift probes w
  - Neutrinos: suppression of structure amplitude probes mass (+ can break degeneracies with w)

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I. Combining CMB Lensing and Galaxy Lensing

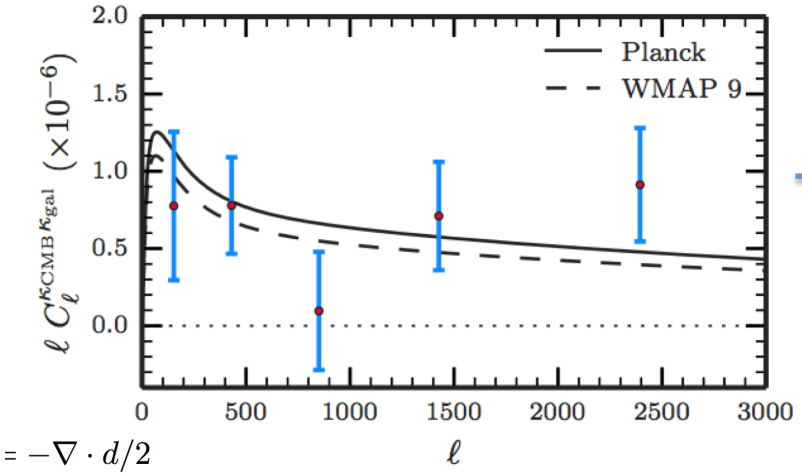
	CMB	Galaxy Lensing
Systematics / Limitations	**Fairly robust – though astrophysical biases** (see later - multifrequency data can help a lot)	Photo-z, shear measurement, baryonic effects, intrinsic alightment (hard problem - multiplicative biases?)
Probes z-dependence	No: one broad bin at high-z (0.5-3)	**Yes: multiple redshifts out to low-z**

- trace common structure, hope to gain some of the advantages of both by correlating or combining the fields

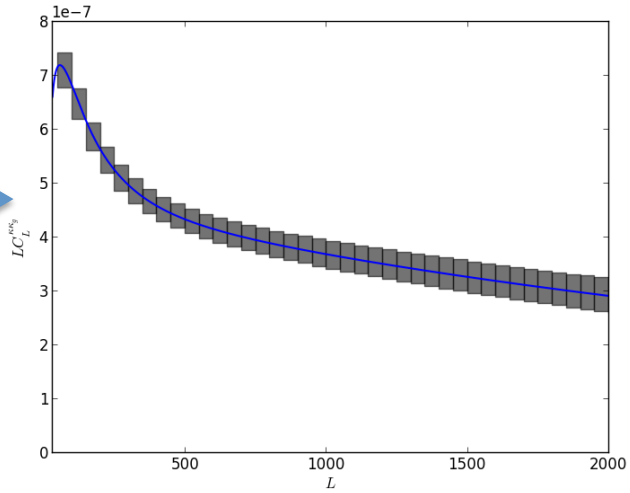
Weak Lensing x CMB Lensing

- Huge increase in precision driven by advances in CMB + LSS:

2015 – ACT x CFHT 4 sigma



2021 – AdvACT x LSST ~ 100 sigma



2025:

S4xLSST:
~400 sigma

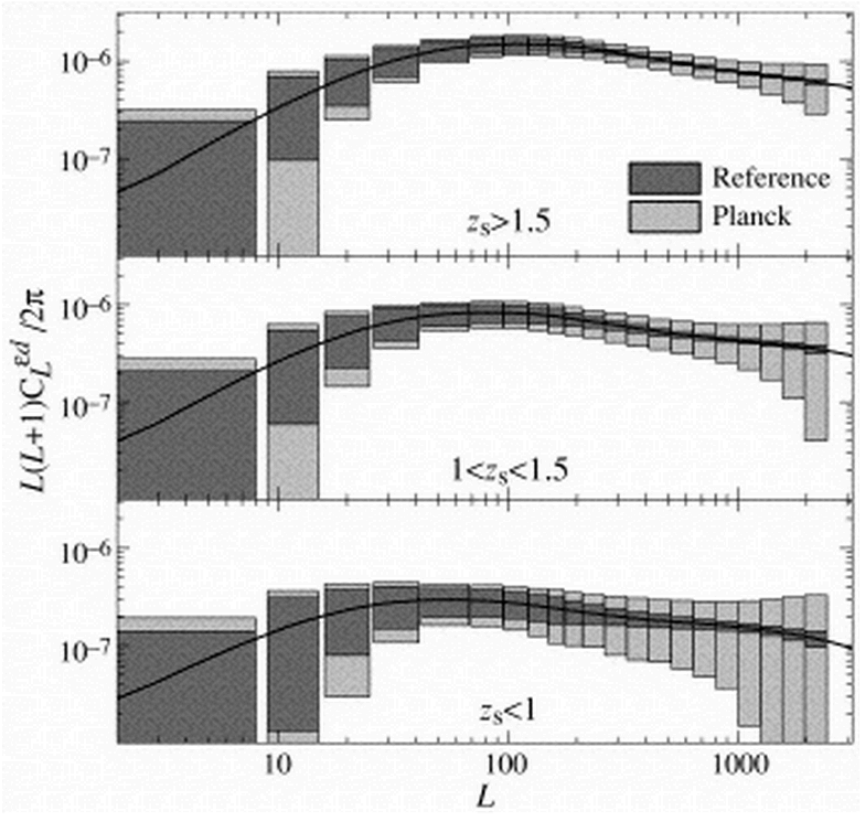
[Hand, Leauthaud, Das, Sherwin+15]
[also Kirk++15, Baxter++16,
Liu, Hill++2015, Harnois-Deraps++2016,
Miyatake++2016…]

- Many systematics disappear in cross-correlation

CMB Lensing x Weak Lensing Tomography

- CMB Lensing: a high-z anchor for DE studies tracking growth(z)
- Amplitude precision: S4 Lensing 0.2%, Planck Primordial 2% (from tau)!

Amplitude of structure vs. z (example)

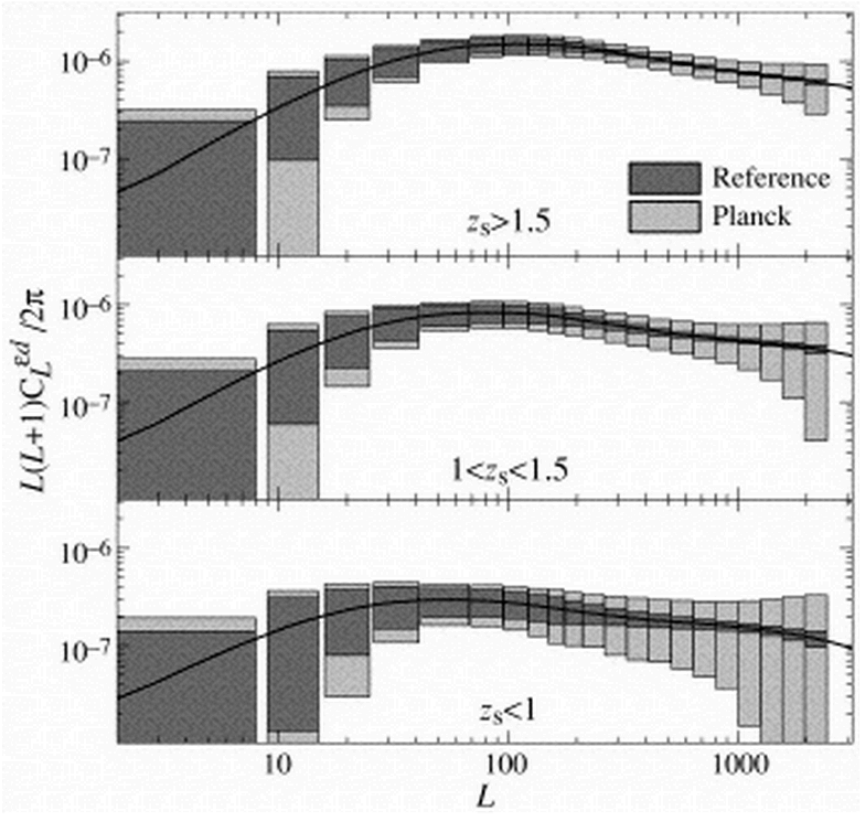


[Hu/Okamoto 2002]

CMB Lensing x Weak Lensing Tomography

- CMB Lensing: a high-z anchor for DE studies tracking growth(z)
- Amplitude precision: S4 Lensing 0.2%, Planck Primordial 2% (from tau)!
- [Neutrino mass without tau? Signal ~10 x smaller.]

Amplitude of structure vs. z (example)



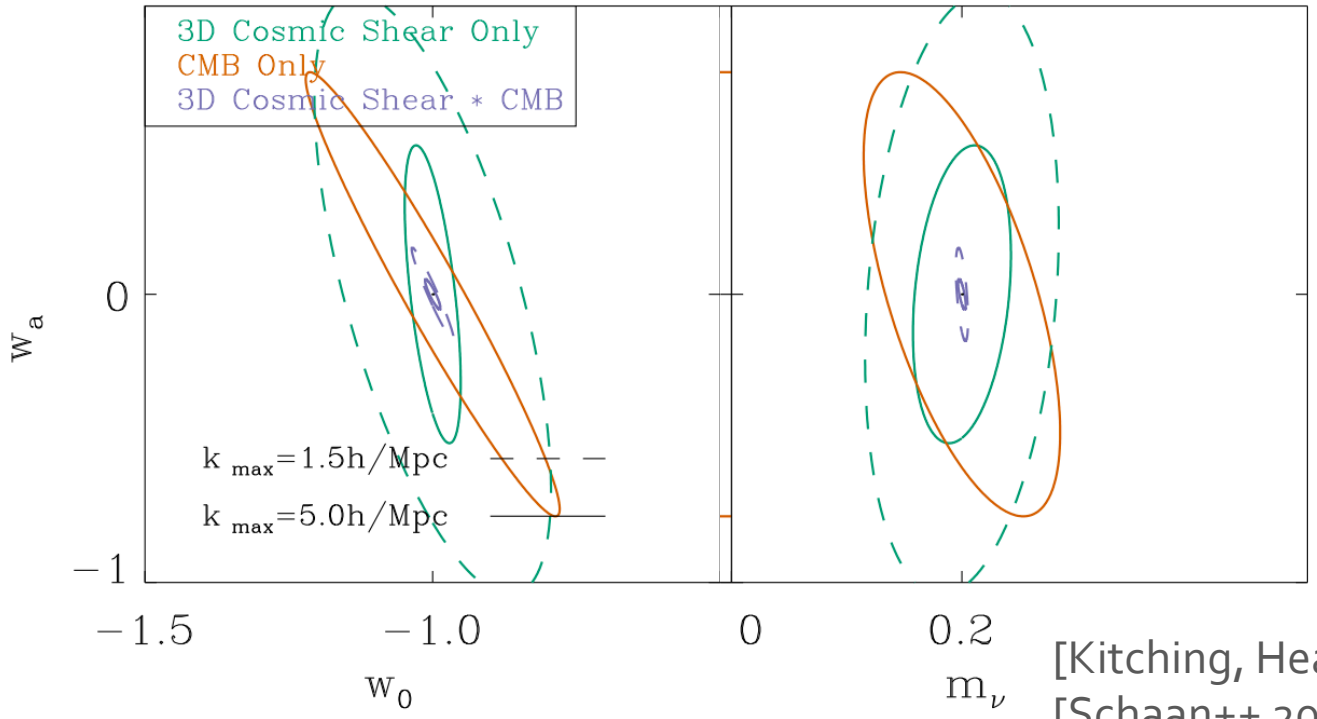
[Hu/Okamoto 2002]

CMB Lensing As a Weak Lensing Bias Calibrator

$$\hat{\kappa} = (1+m)\kappa_{\rm true} \qquad \frac{C_l^{\kappa_{\rm CMB}\kappa_{\rm opt}}}{C_l^{\kappa_{\rm CMB}\kappa_{\rm CMB}}} \propto (1+m) \qquad \frac{C_l^{\kappa_{\rm opt} g}}{C_l^{\kappa_{\rm CMB} g}} \propto (1+m)$$

- Future combinations for systematics calibration are very promising for dark energy and neutrino mass (see also E. Schaan's talk):

Core x Euclid Weak Lensing [S4 similar]



[Kitching, Heavens, Das 2014]
[Schaan++ 2016]
[Liu++2016]

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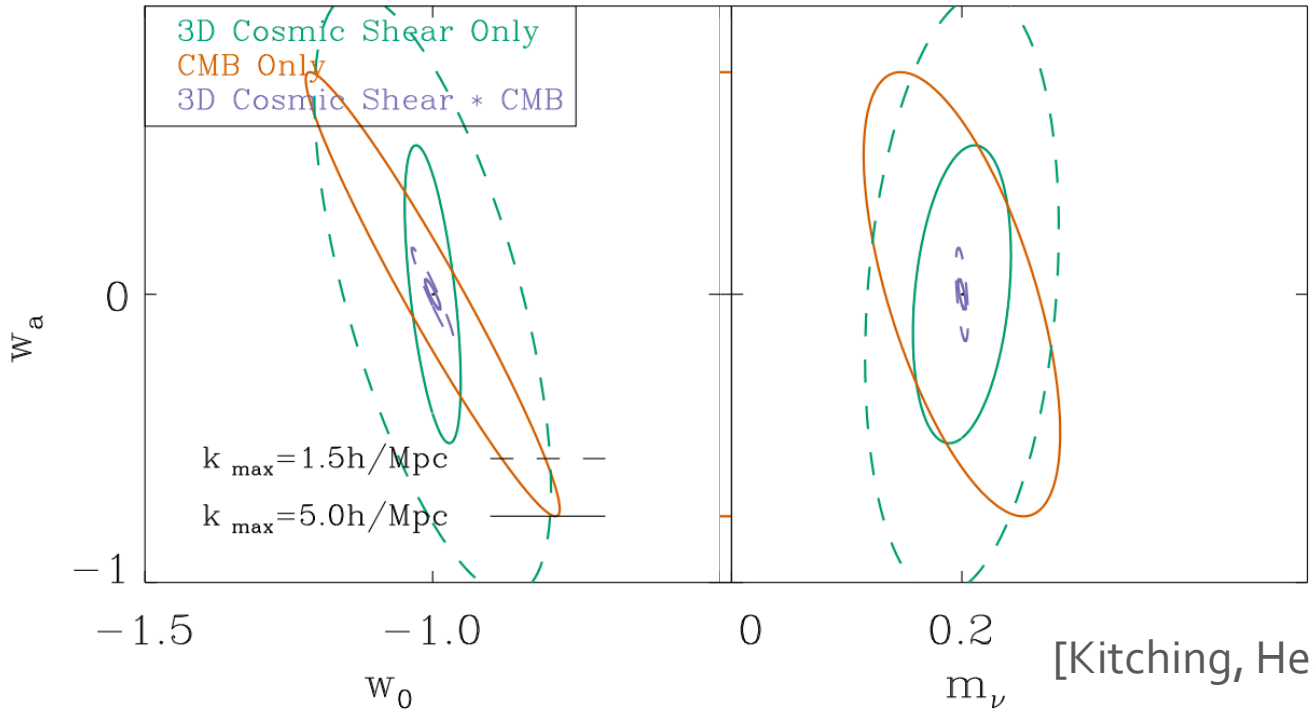

Big improvements if minimal datasets, lots of model freedom. Otherwise, moderate improvements or cross-checks.

[Kitching, Heavens, Das 2014]

- Dark energy FoM: joint analysis, factor of 2 improvement

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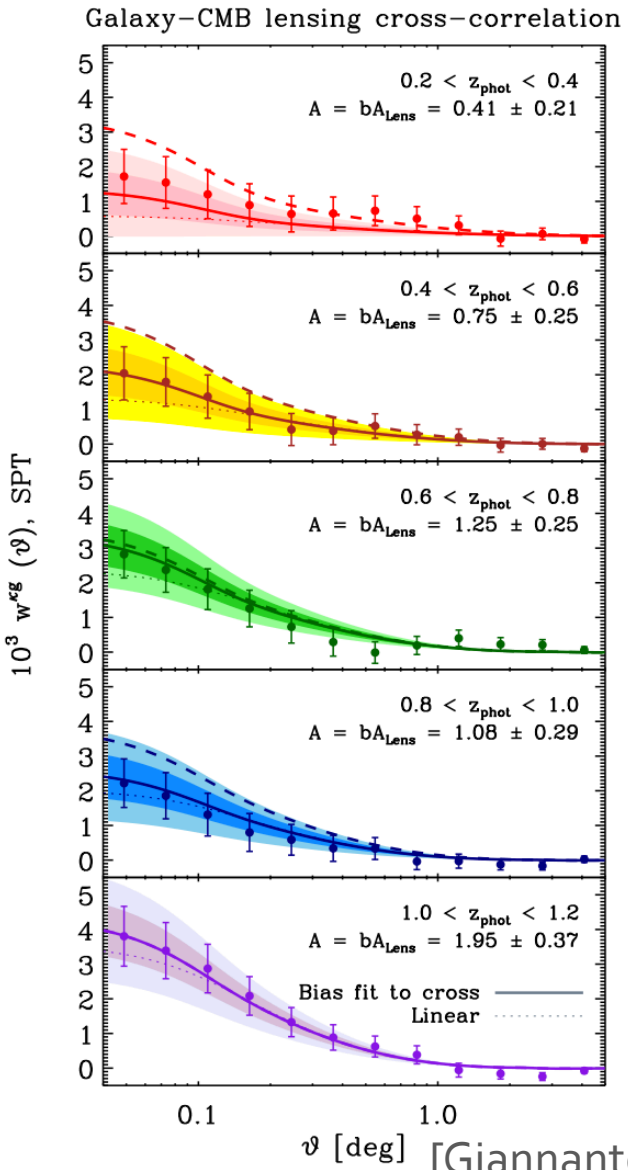
III. Galaxies x CMB Lensing

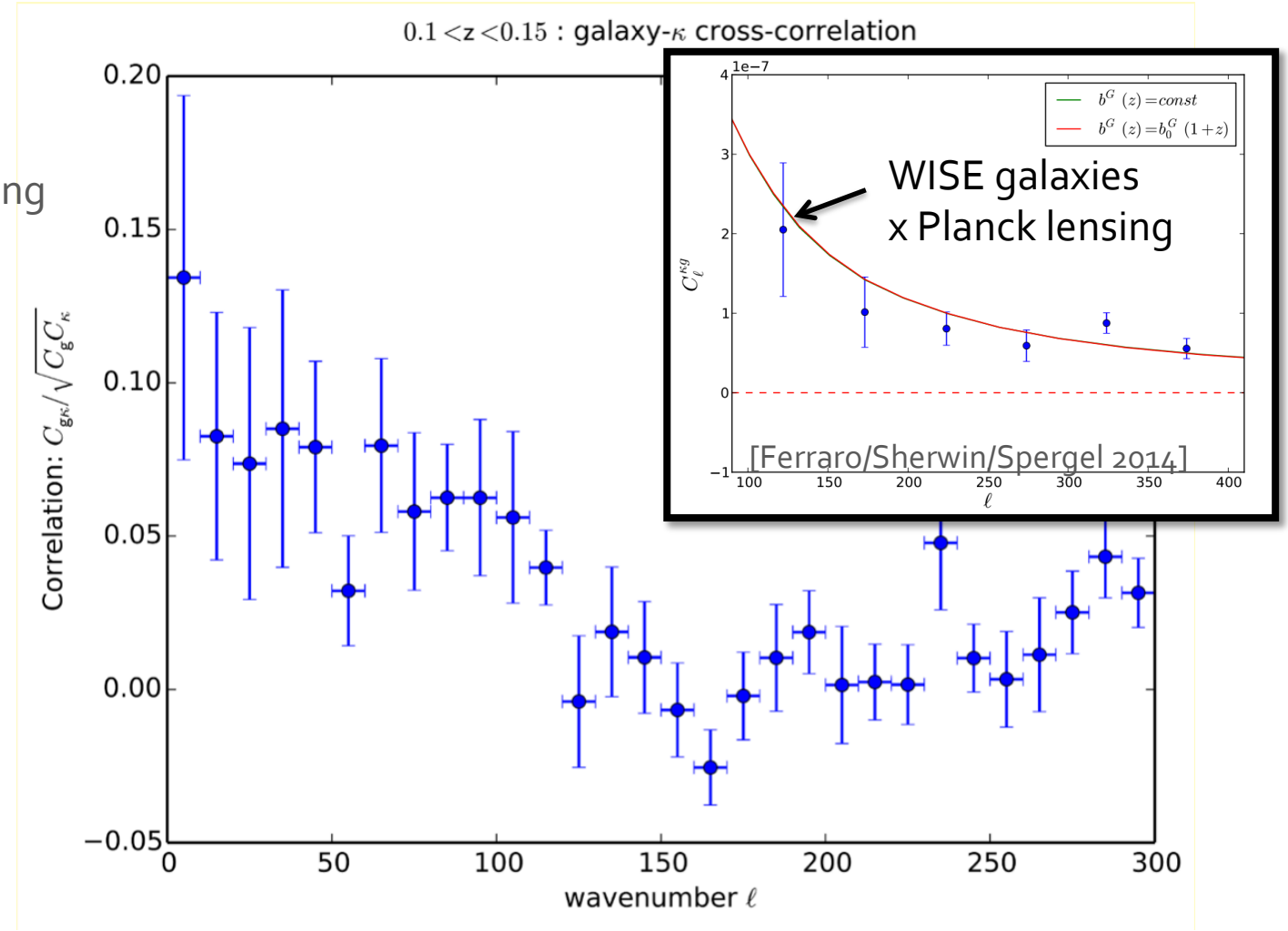
- Galaxy clustering C_l^{gg} at z: structure amplitude degenerate with bias, $b(z)^2\,\sigma(z)^2$
- Galaxy cross-correlation C_l^{kg} depends differently on bias ($b\sigma^2$ vs $b^2\sigma^2$), "cancel" (linear) bias to get matter power vs. z!



[Giannantonio++ 2016]

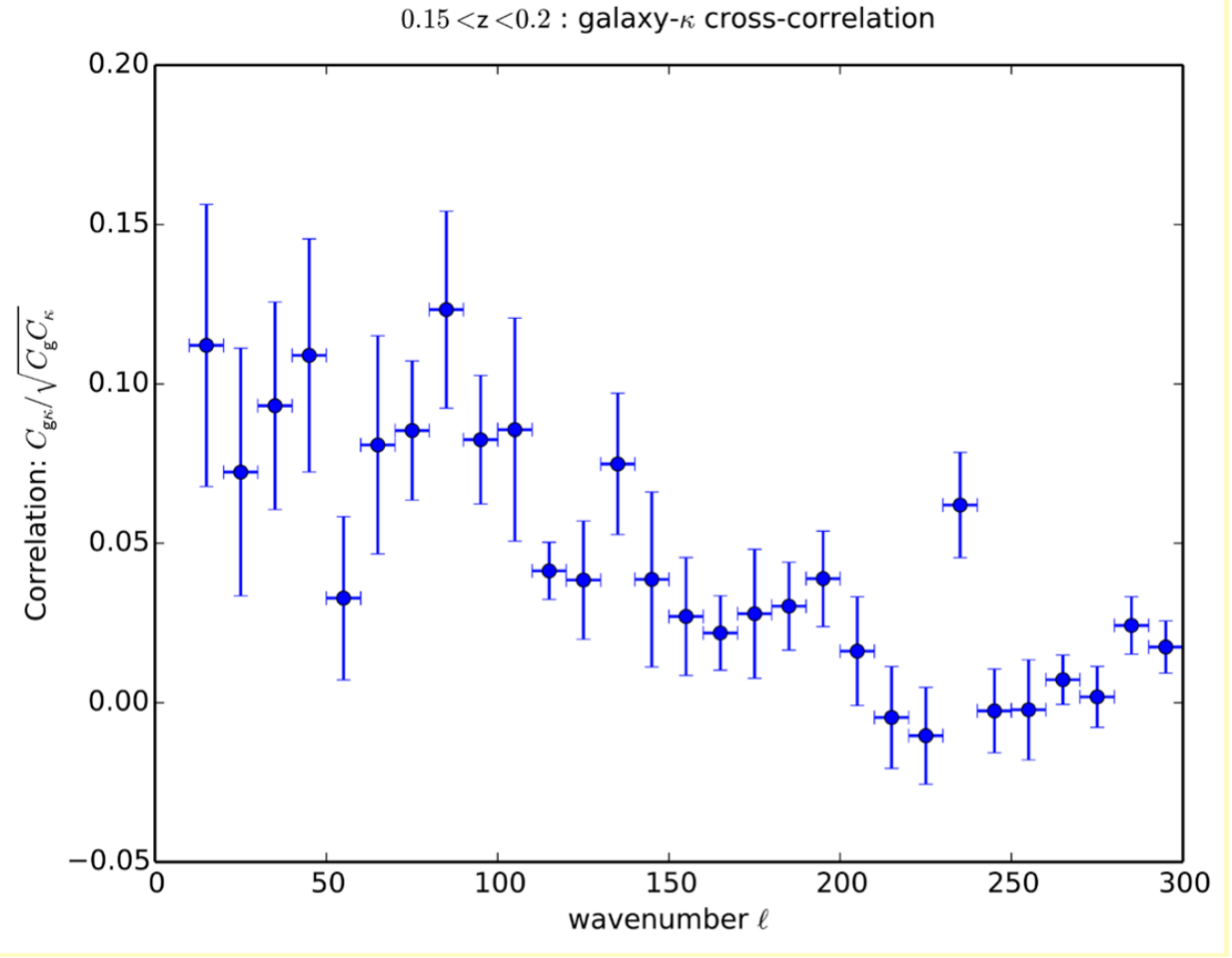
Galaxy Correlation Tomography

WISE
x
Planck Lensing

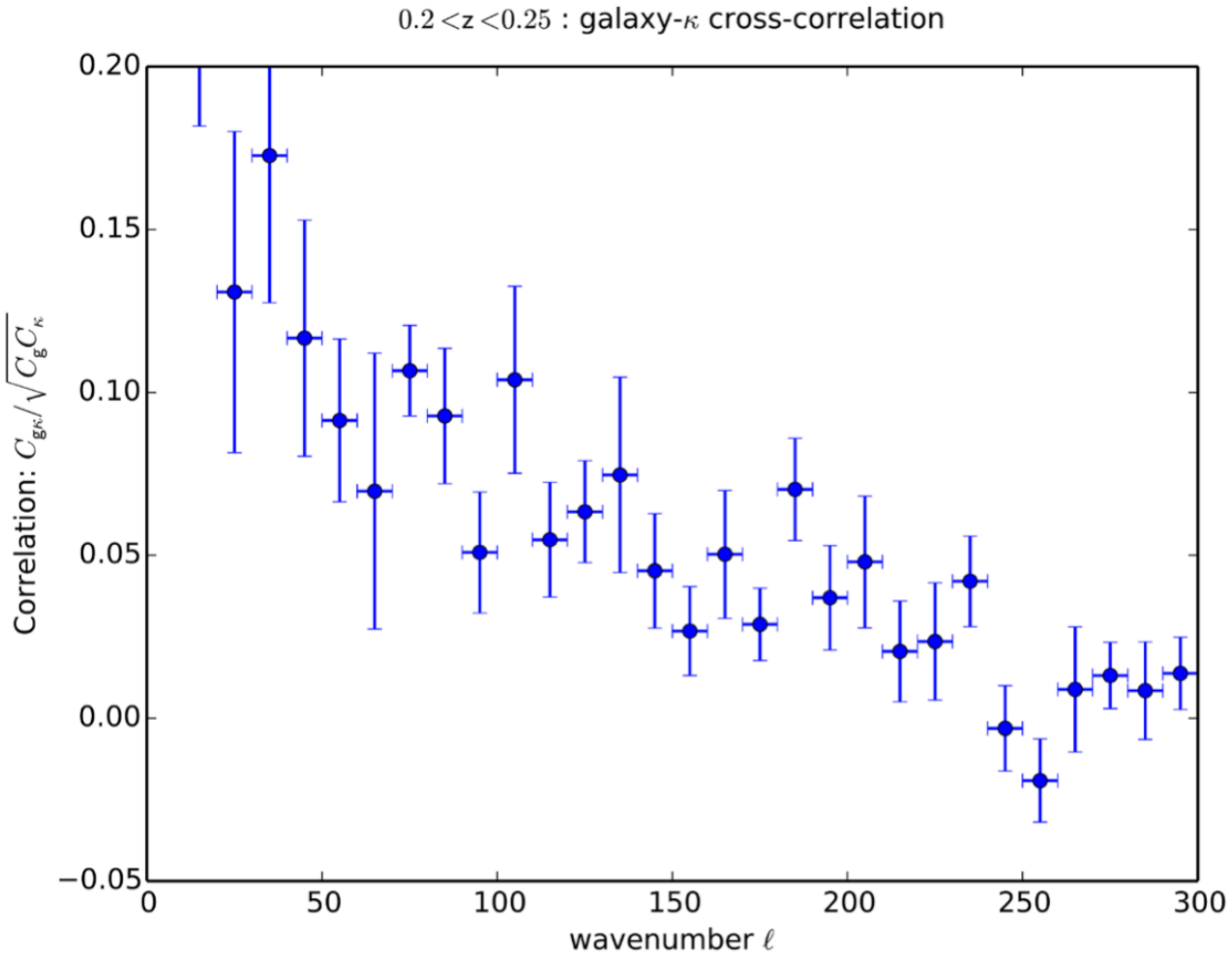


[Figure credit: John Peacock]

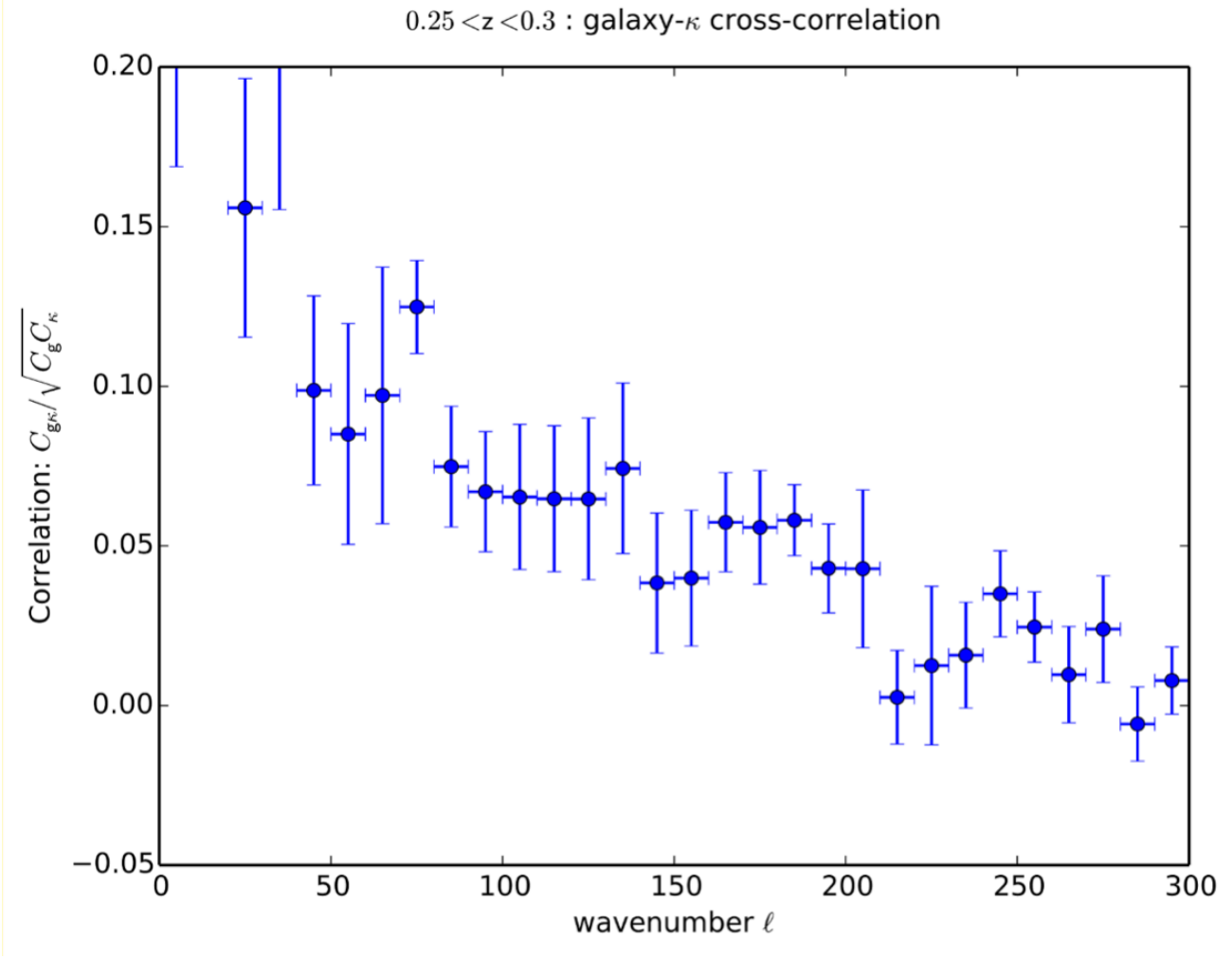
Galaxy Correlation Tomography



Galaxy Correlation Tomography



Galaxy Correlation Tomography



Galaxy – CMB Lensing Cross-correlations: Neutrino Masses

- To some extent, breaks degeneracies of neutrino mass and dark energy
- Comparable significance to S4 lensing alone [~400 sigma LSST/S4, 500 S4]
- $C_l^{gg} + C_l^{kg}$: independent channel for neutrino mass – confirm detection?

Combination of LSST galaxies and S4 CMB lensing

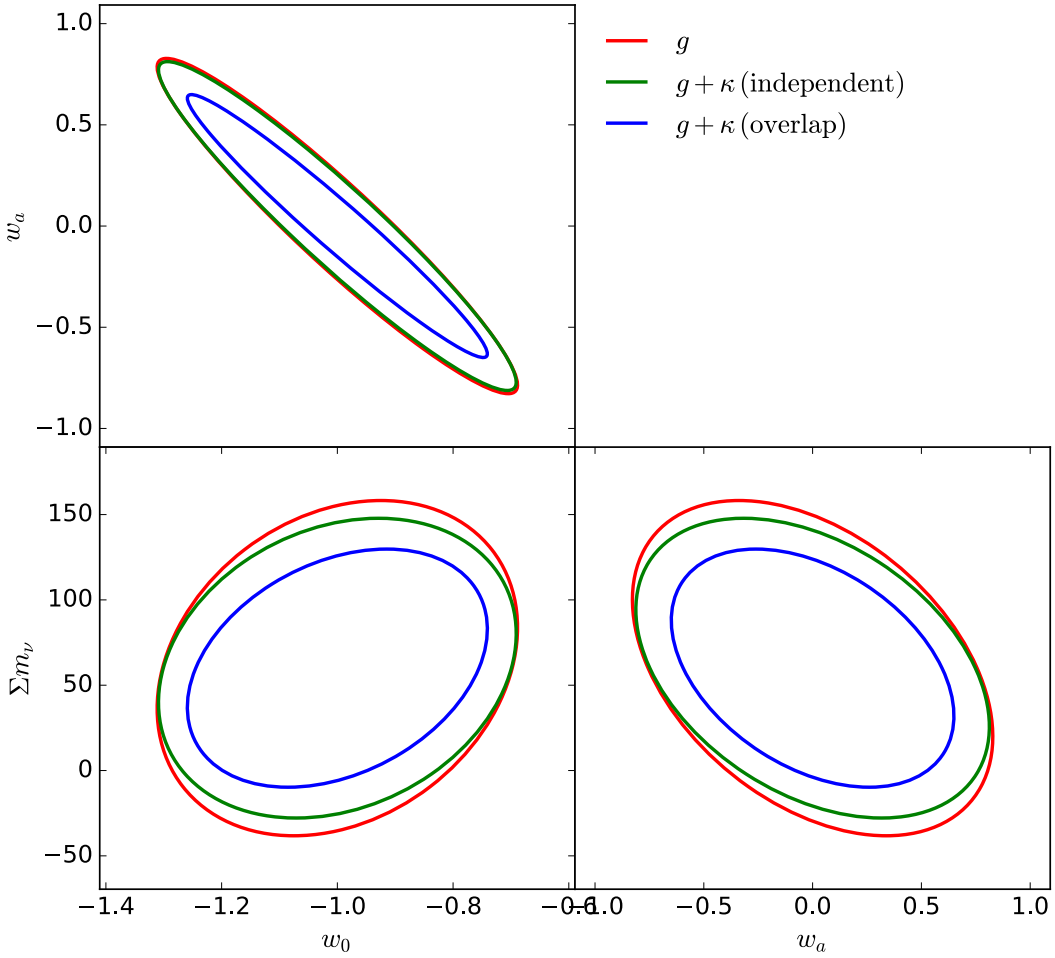


Figure credit: David Alonso

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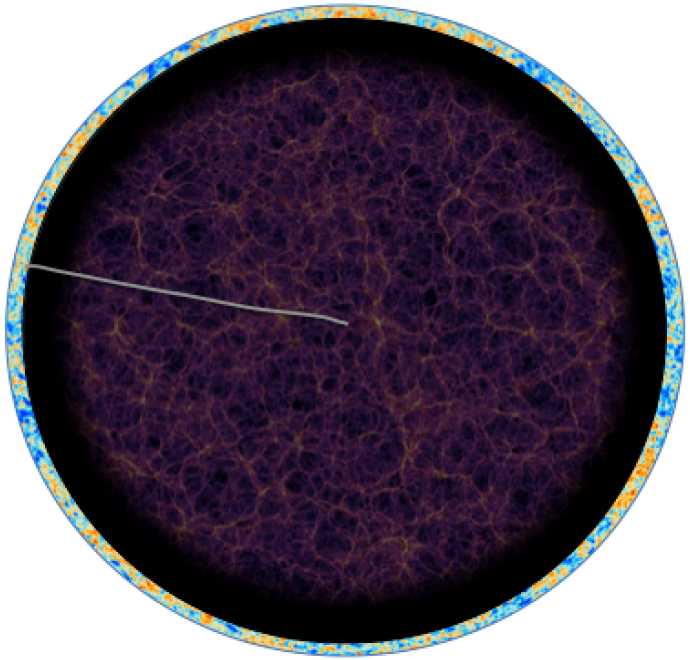
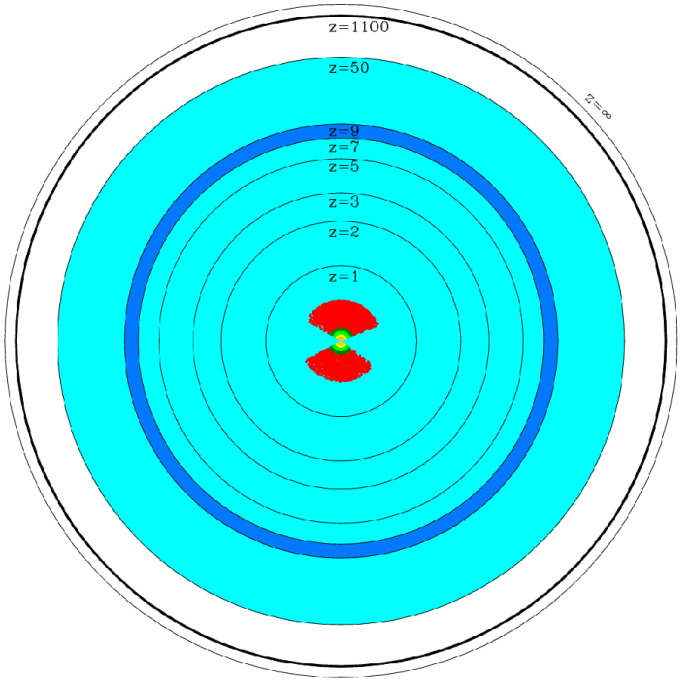
IV: High-Redshift Cross-correlations

- CMB x 21cm?
  - intensity mapping: excellent redshift overlap, but foreground filtering removes radial k = 0, destroys CMB lensing correlation



CMB Lensing



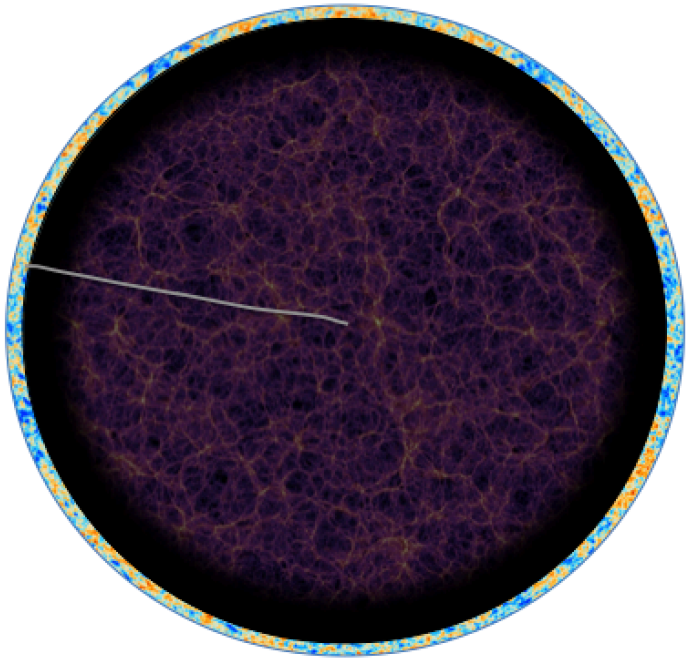
21cm

High-Redshift Cross-correlations

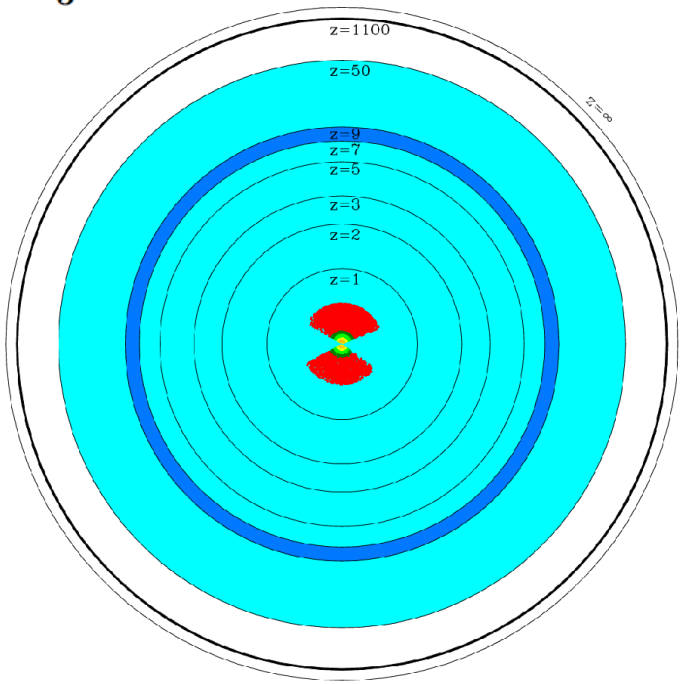
- CMB x 21cm?
  - intensity mapping: excellent redshift overlap, but foreground filtering removes radial k = 0, destroys CMB lensing correlation
  - potential solution – get large scale modes from small scale power?

$$\xi_S(r) \approx \xi_{S0}(r) + (\frac{68}{21}\xi_{S0}(r) + \frac{1}{3}r\xi'_{S0}(r))\delta_L$$

[Sherwin/Zaldarriaga 2012]



CMB Lensing



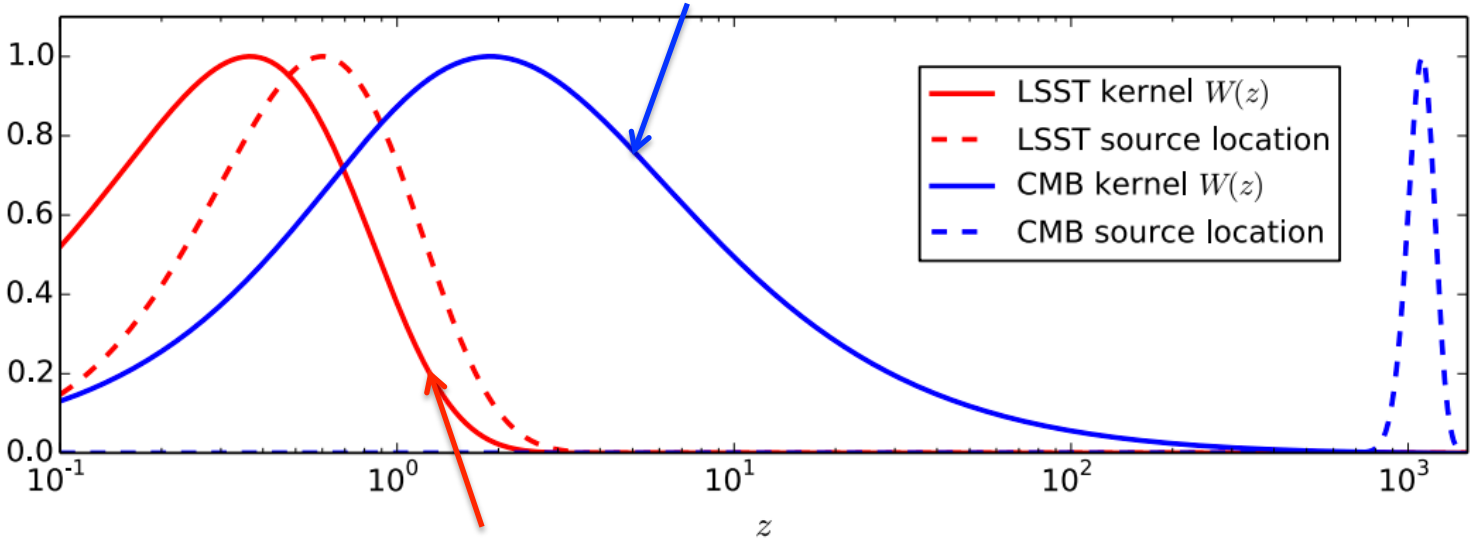
21cm

High-Redshift Cross-correlations

[van Engelen, Sherwin++2015, Holder+2013, Doux++ 2016, Hill/Spergel 2014, Sherwin+2012…]

- Lots of high-z cross-correlations (x CIB, Ly-a, tSZ, QSOs…)
- Note: adding high-z structure could boost low-z cross-correlation S/N, by reducing sample variance

If you nail down the structure here…



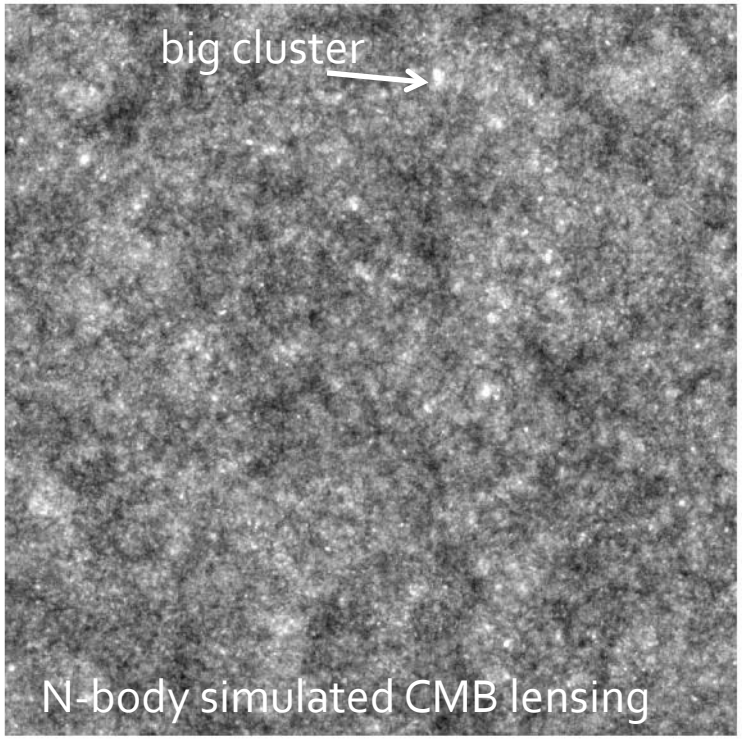
you may have less uncorrelated "noise" for your cross-correlation here

[Sherwin/Schmittfull 2015, Simard++ 2015]

CMB Lensing Systematics

- Multiplicative and additive biases from bi/trispectra of foregrounds (+lensing itself)
- Typical picture: when nothing is done, ~few percent effect.
- Multifrequency data and estimator "hardening" should make these unobservable

Fairly robust (esp. cross-corrs.)



[Sherwin++ in prep. 2016b]
[Liu, Hill, Sherwin++ 2016]
[van Engelen++ 2013, Osborne++2013]

Summary:
Science Case for CMB Lensing + LSS

- CMB lensing provides high-z anchor for structure growth. Combinations allow tracking of amplitude of structure across z to probe dark energy

- Cross-correlations probe systematic and astrophysical biases, break degeneracies (esp. for free models)

- Low systematic, different, competitive s/n observable – cross-checks on, e.g. neutrino mass detection

- Many high-z cross-correlations also interesting, may help low-z cross-correlations

Questions

- What are the most promising future survey targets for cross-correlation?
- How much do we gain from survey overlap/cross-correlations vs. just degeneracy breaking in each case? How much is overlap worth?
- In future surveys, can we get neutrino physics with tomography alone?
- What is the most interesting target for high-z astrophysics?
- Is more effort on propagating CMB lensing systematics needed?
- Are there parameters we should be targeting more [running? curvature?]