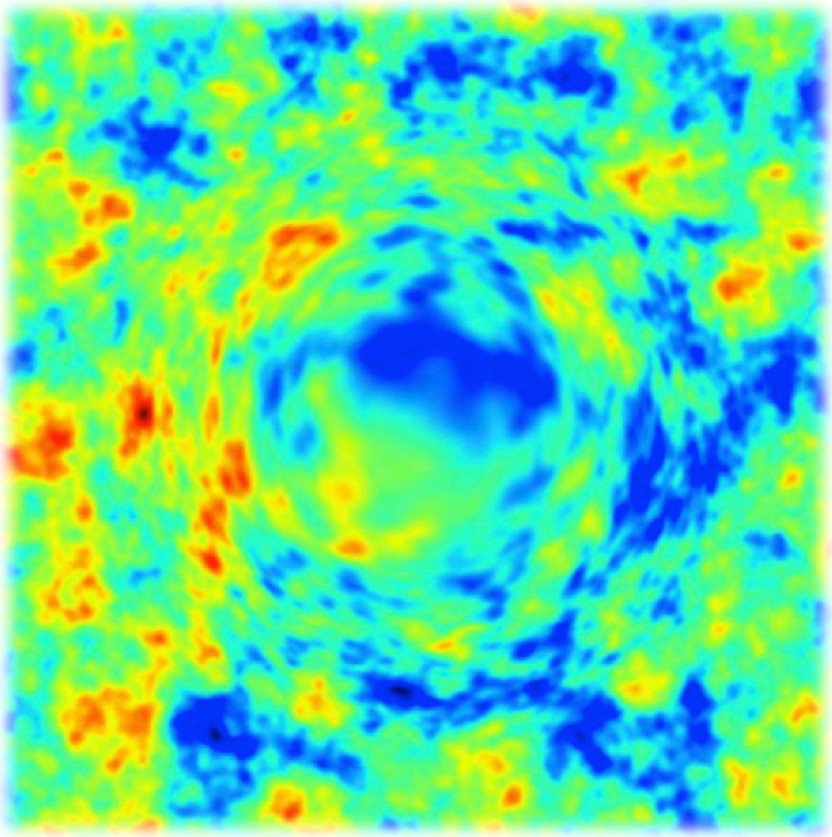
CMB Lensing: Present and Future



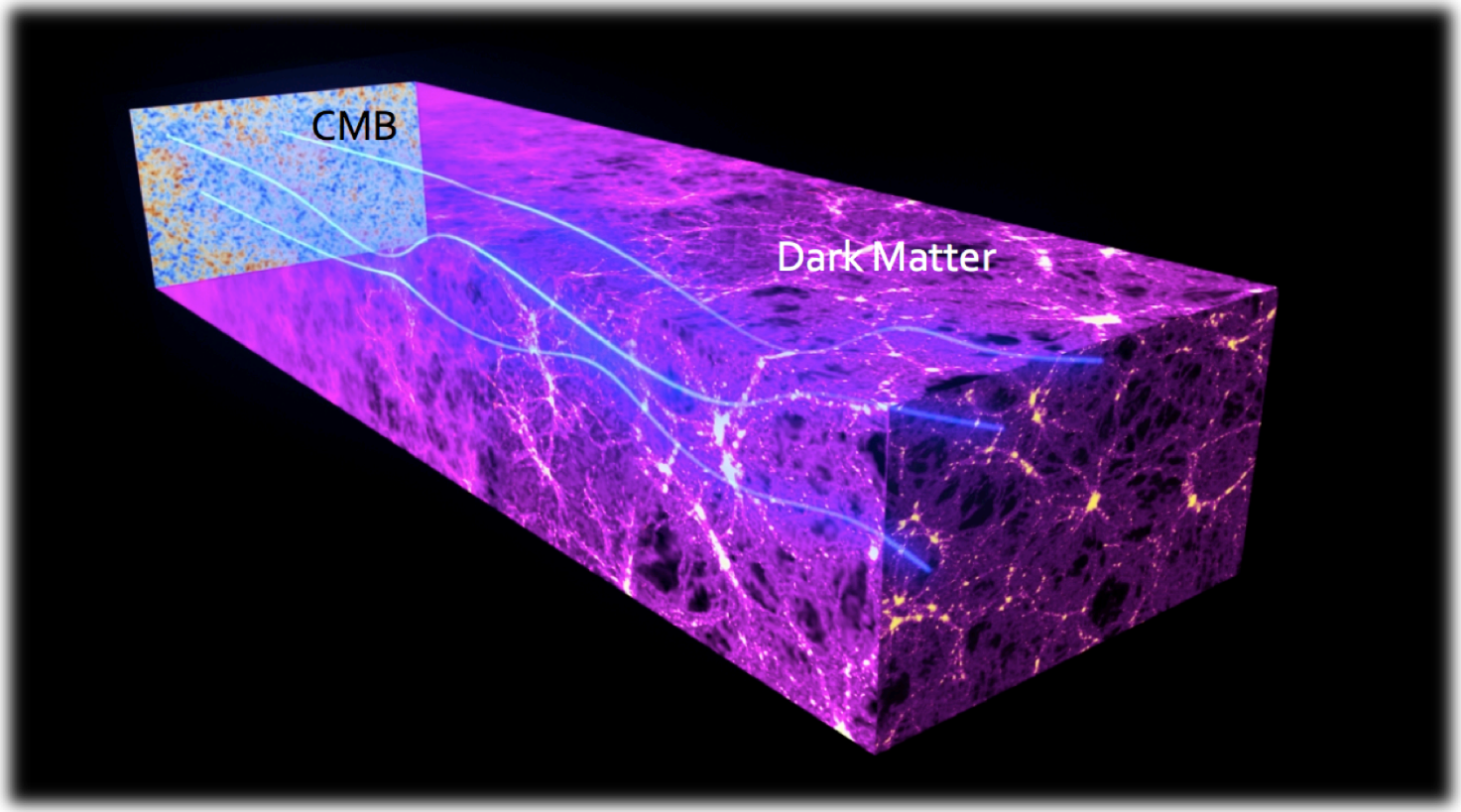
Blake D. Sherwin
LBNL
ACT / POLARBEAR / Simons Observatory / CMB Stage-IV Collaborations

Outline

- Introduction to CMB lensing and lensing reconstruction
- CMB lensing power spectra: probing neutrino mass and structure growth
- CMB lensing B-modes as noise for inflationary cosmology

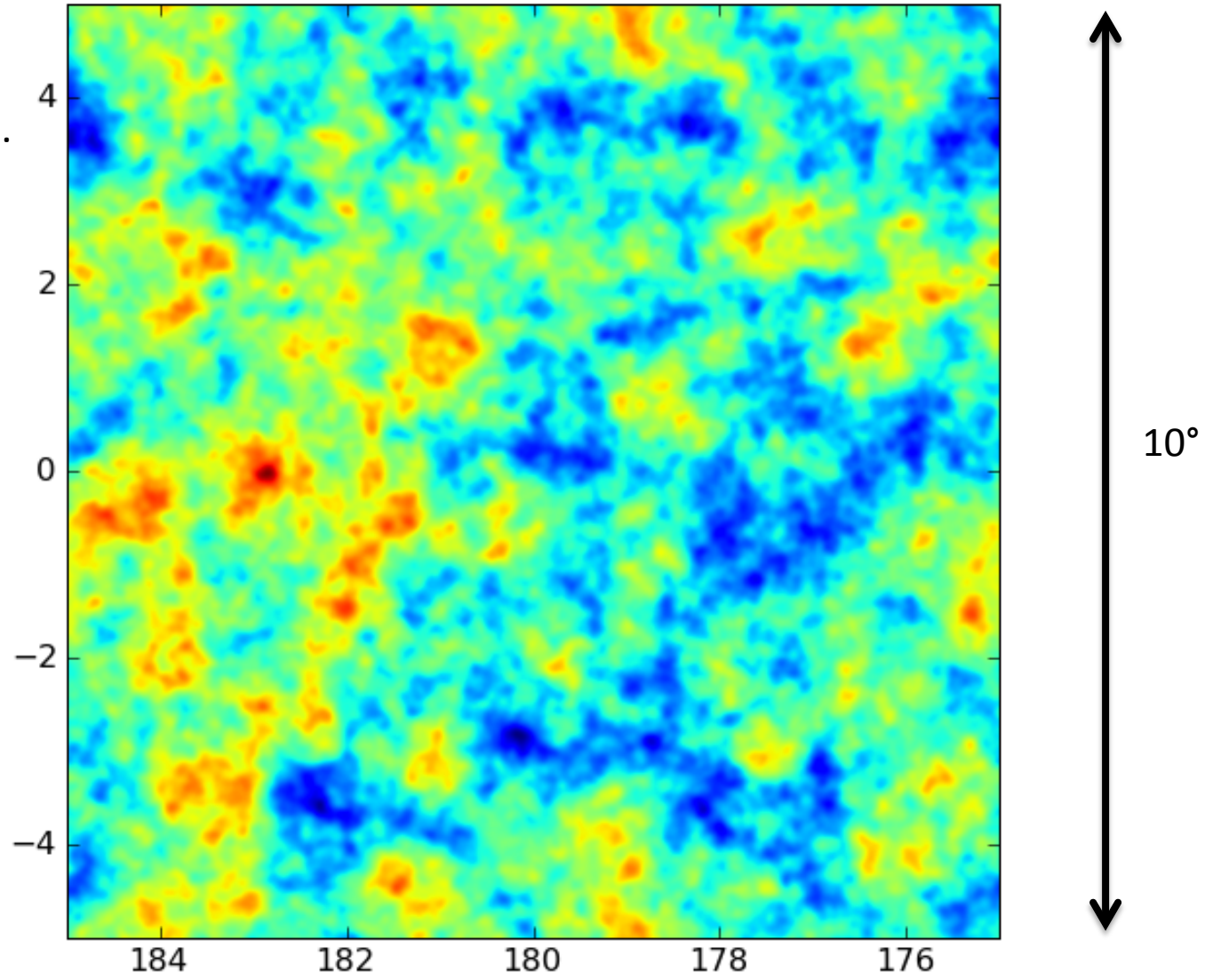
Gravitational Lensing of the CMB

- CMB: most distant radiation source. Affected by travel:
- Distribution of mass deflects / lenses CMB passing through



Unlensed CMB

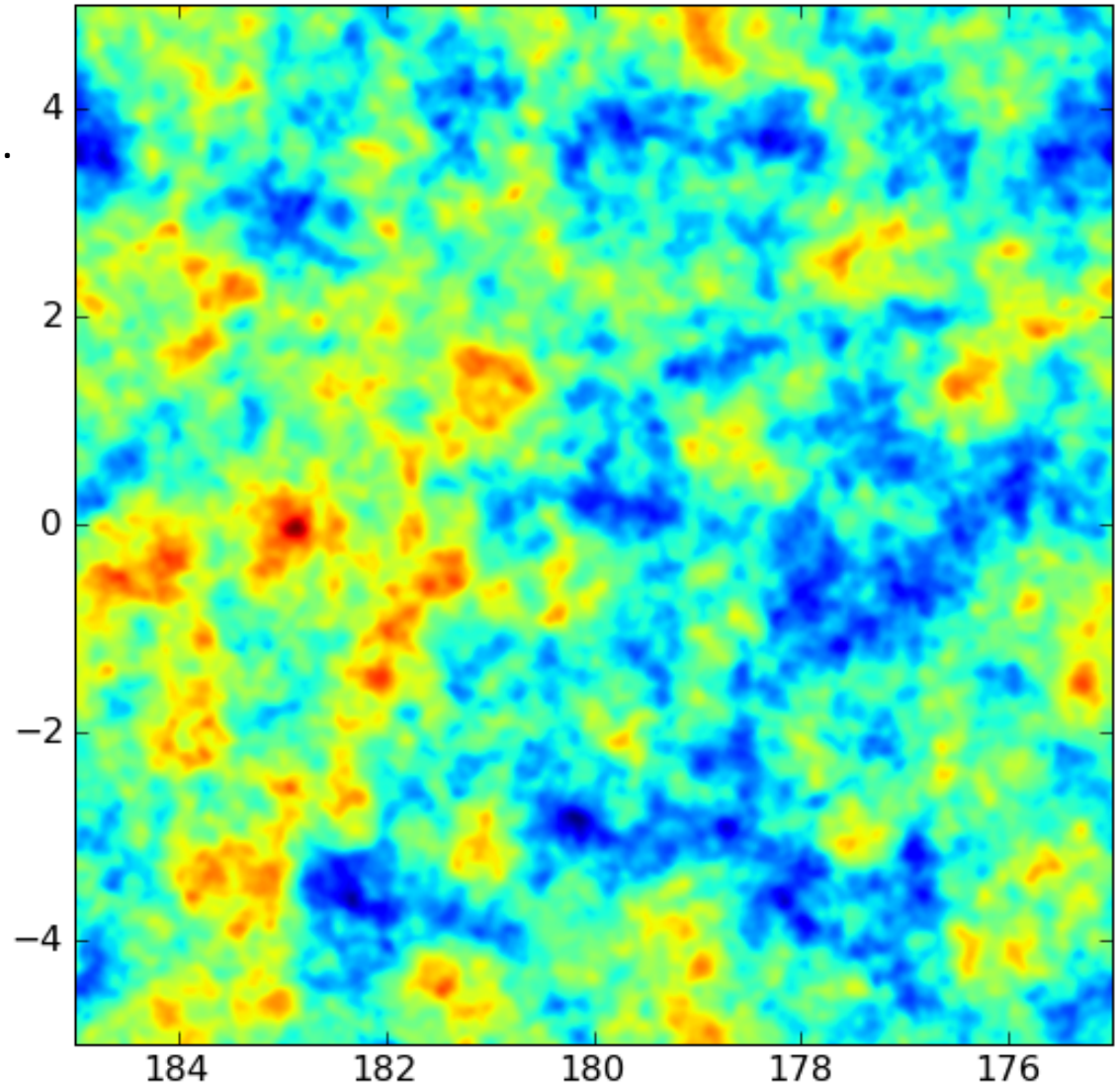
CMB Temp.



$T(\hat{\mathbf{n}})_{\text{unlensed}}$

Lensed CMB

CMB Temp.



10°

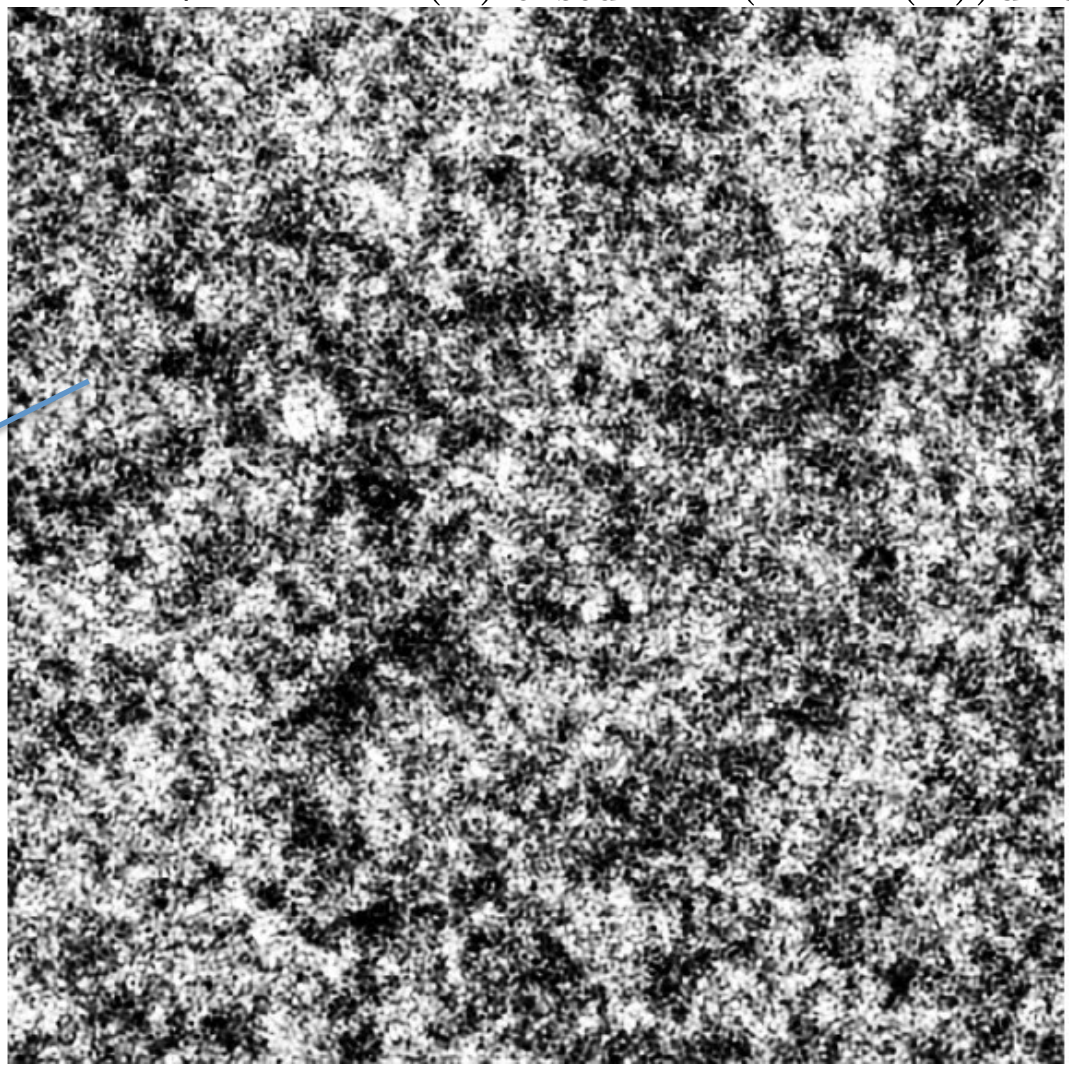
$$T(\hat{\mathbf{n}})_{\text{lensed}} = T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))_{\text{unlensed}}$$

Observable: Lensing Deflection $\mathbf{d}(\hat{\mathbf{n}})$

remaps the CMB temperature: $T(\hat{\mathbf{n}})_{\rm lensed} = T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))_{\rm unlensed}$

$|\mathbf{d}(\hat{\mathbf{n}})|_{\rm filt}$

small ~3 arcminute deflections, coherent on degree scales



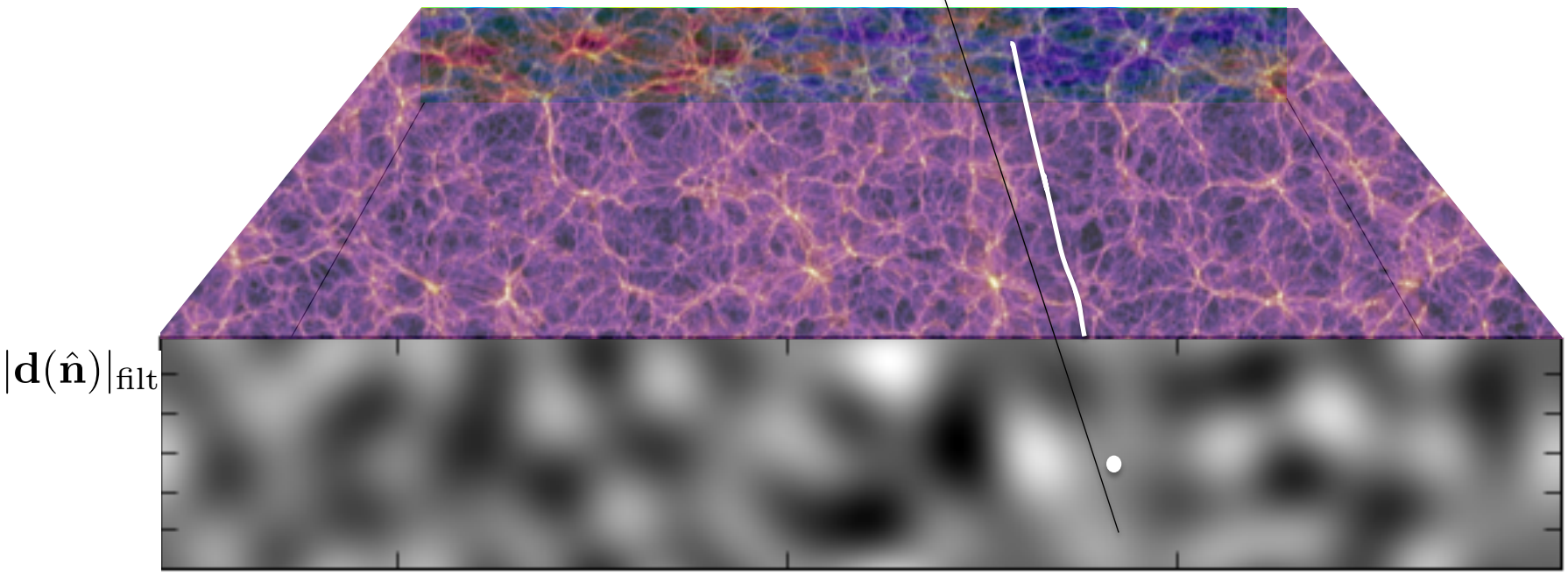
10°

I will usually plot the gradient filtered magnitude of the deflection $|\mathbf{d}(\hat{\mathbf{n}})|_{\rm filt}$ – i.e. the lensing convergence (N.B. lensing estimates both shear and convergence).

Probes Mass Projected Back to the CMB

- Amount of lensing deflection depends on the projected (dark) matter density in that direction – mainly at z~0.5-3

$$\underset{\text{lensing}}{\nabla \cdot d(\hat{\mathbf{n}})} = \int_0^{r_{\rm CMB}} \overset{\text{geometry}}{dr W(r)} \underset{\text{density}}{\delta(\hat{\mathbf{n}}, r)}$$



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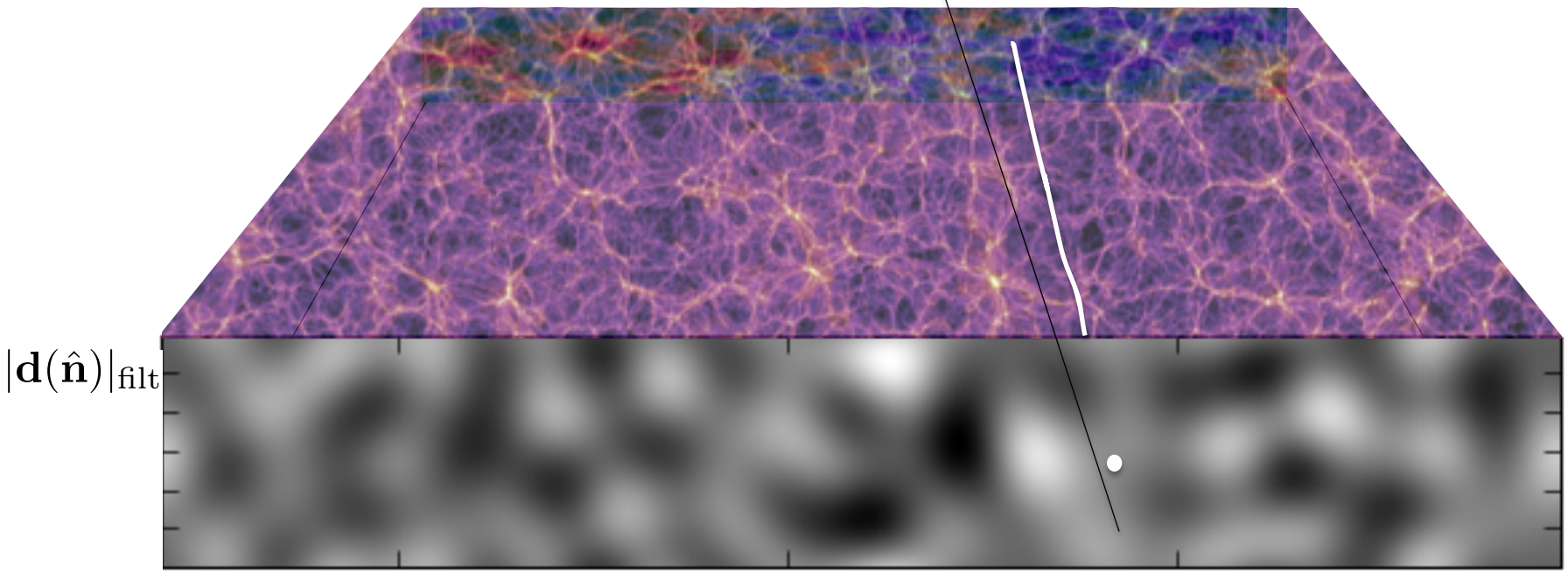
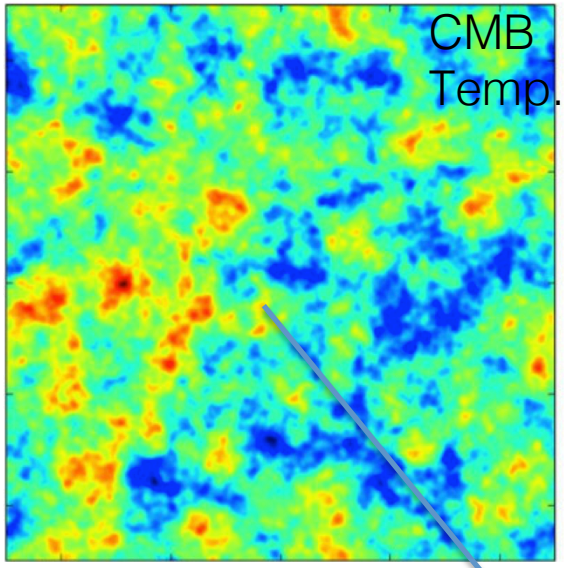


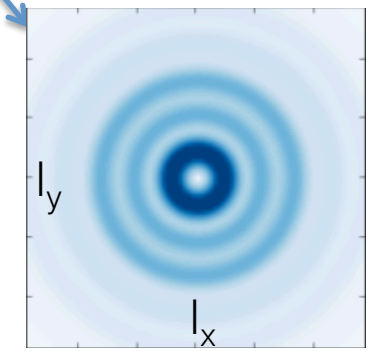
- How to measure: look for new lensing-induced correlations in T:

$$\hat{d}(\mathbf{L}) \sim \int d^2\mathbf{l}\, T(\mathbf{l}) T^*(\mathbf{l}-\mathbf{L})$$

CMB Lensing Measurement: An Approximate Picture



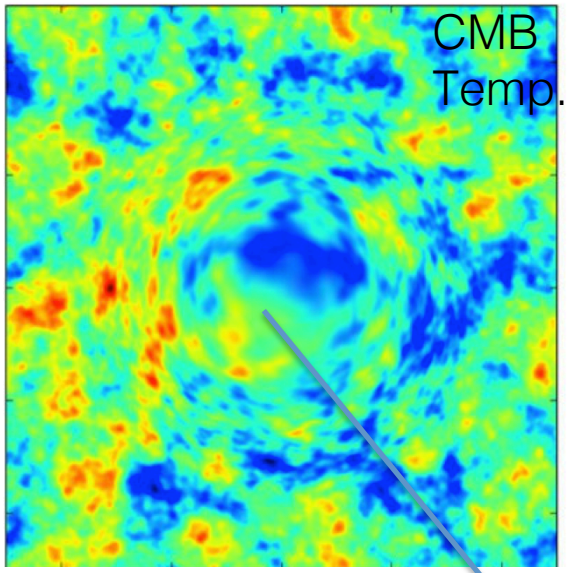
d: lensing deflection field

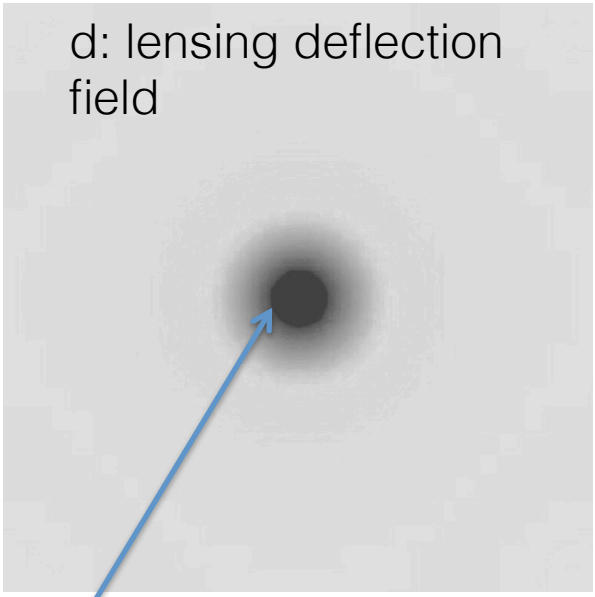


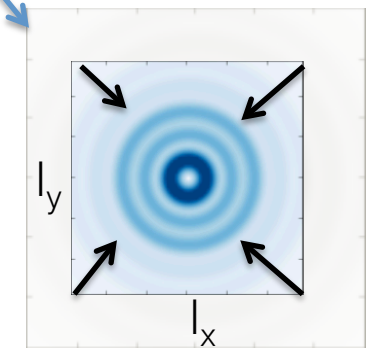
local 2D power spectrum

[Bucher++ 2012]

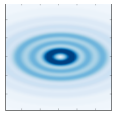
CMB Lensing Measurement: An Approximate Picture







local 2D power spectrum

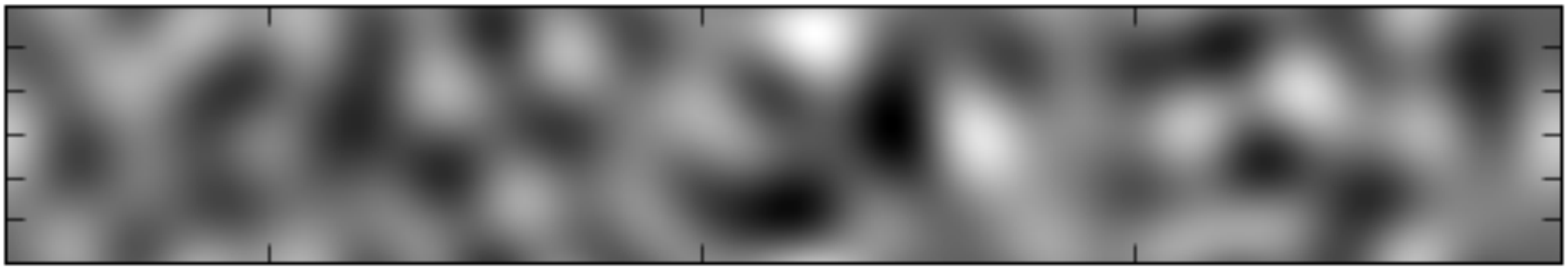
Infer lensing from "stretching" of the local CMB power spectrum  (+ shearing)

N.B. polarization much better!

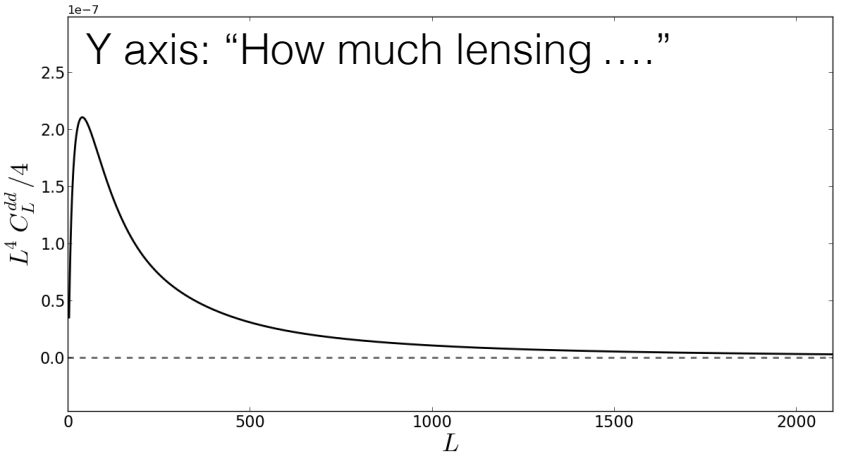
[Bucher++ 2012]

First CMB-only Lensing Map and Lensing Power Spectrum

ACT CMB Lensing Dark Matter Map



- Describe statistically with lensing power spectrum C_l^{dd}
- Probes any physics that affects structure growth



X axis: “for a lens of this angular scale?”

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- Introduction to CMB lensing and lensing reconstruction
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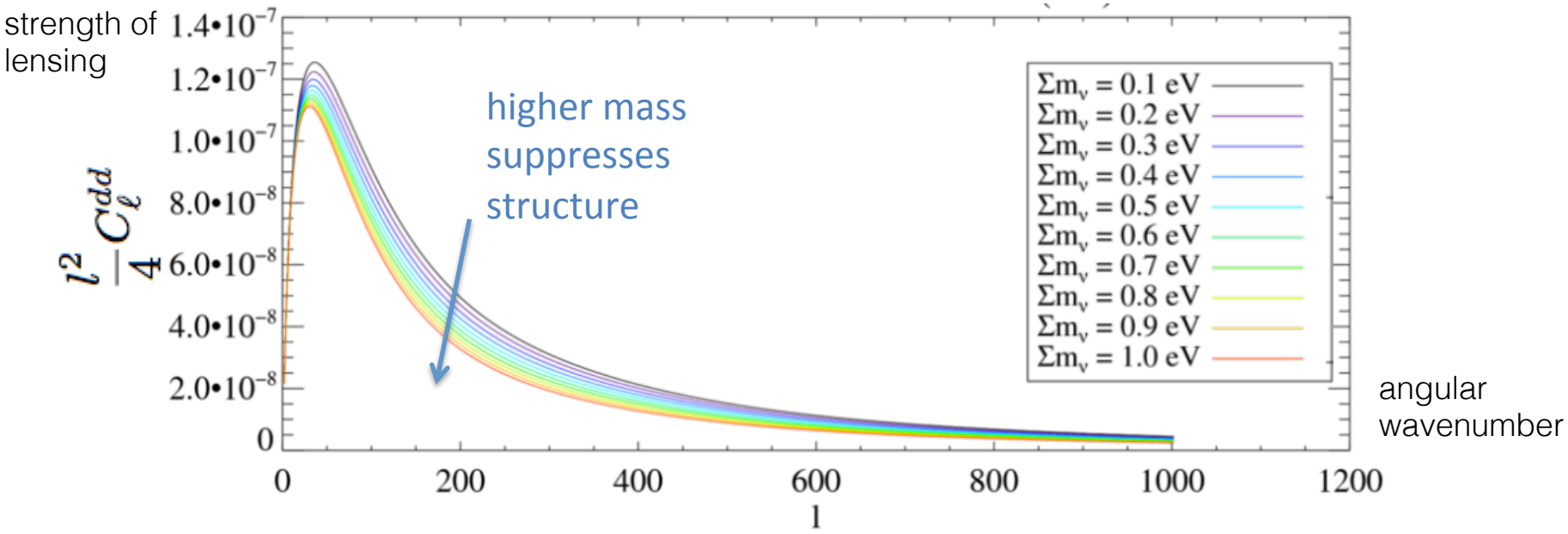
Example: Measuring the Unknown Neutrino Mass

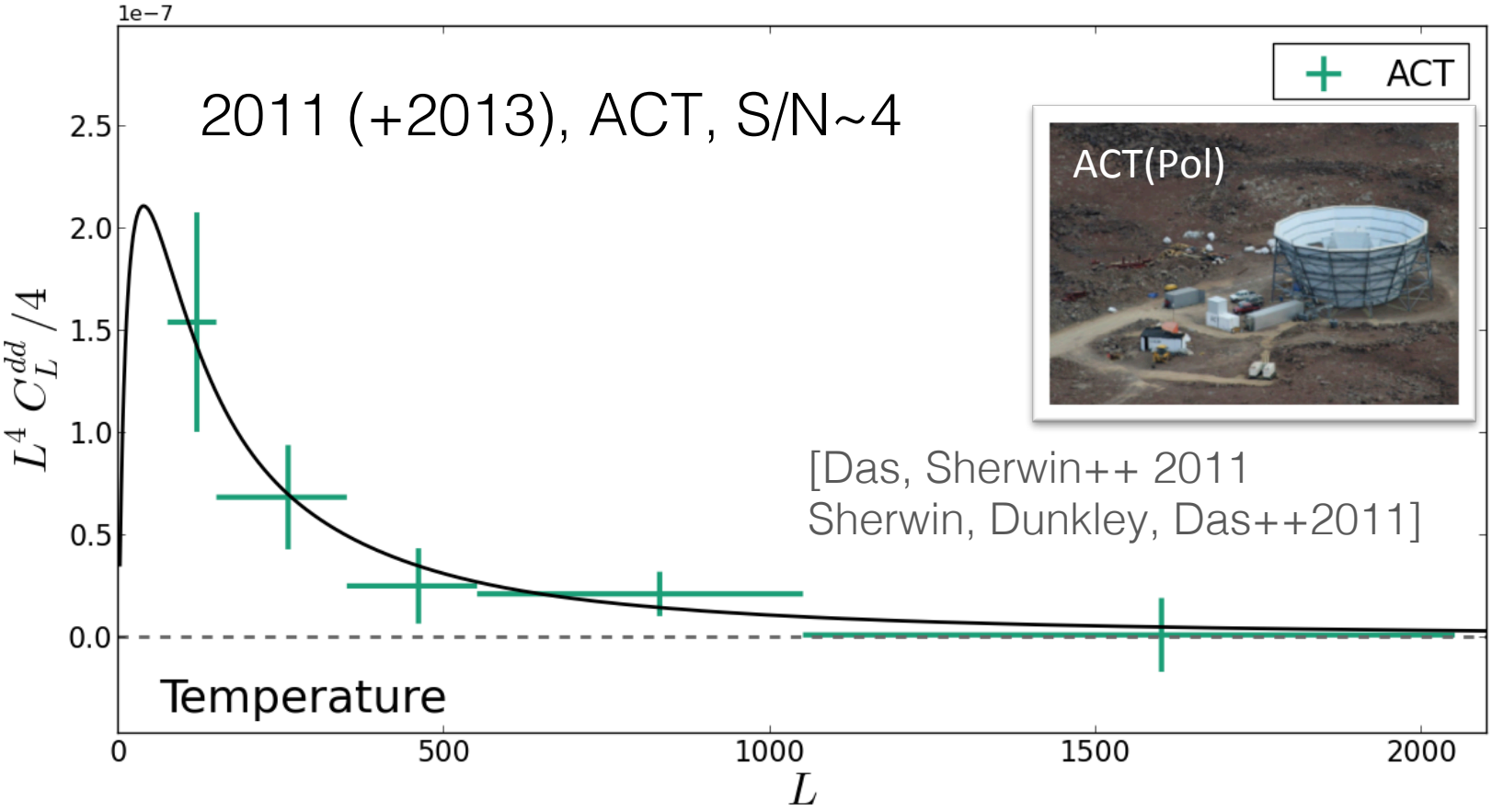
- Neutrino masses (unknown!) suppress small structure and lensing d, and its power spectrum C_l^{dd} – measure!



- Also: early dark energy, geometric degeneracy breaking

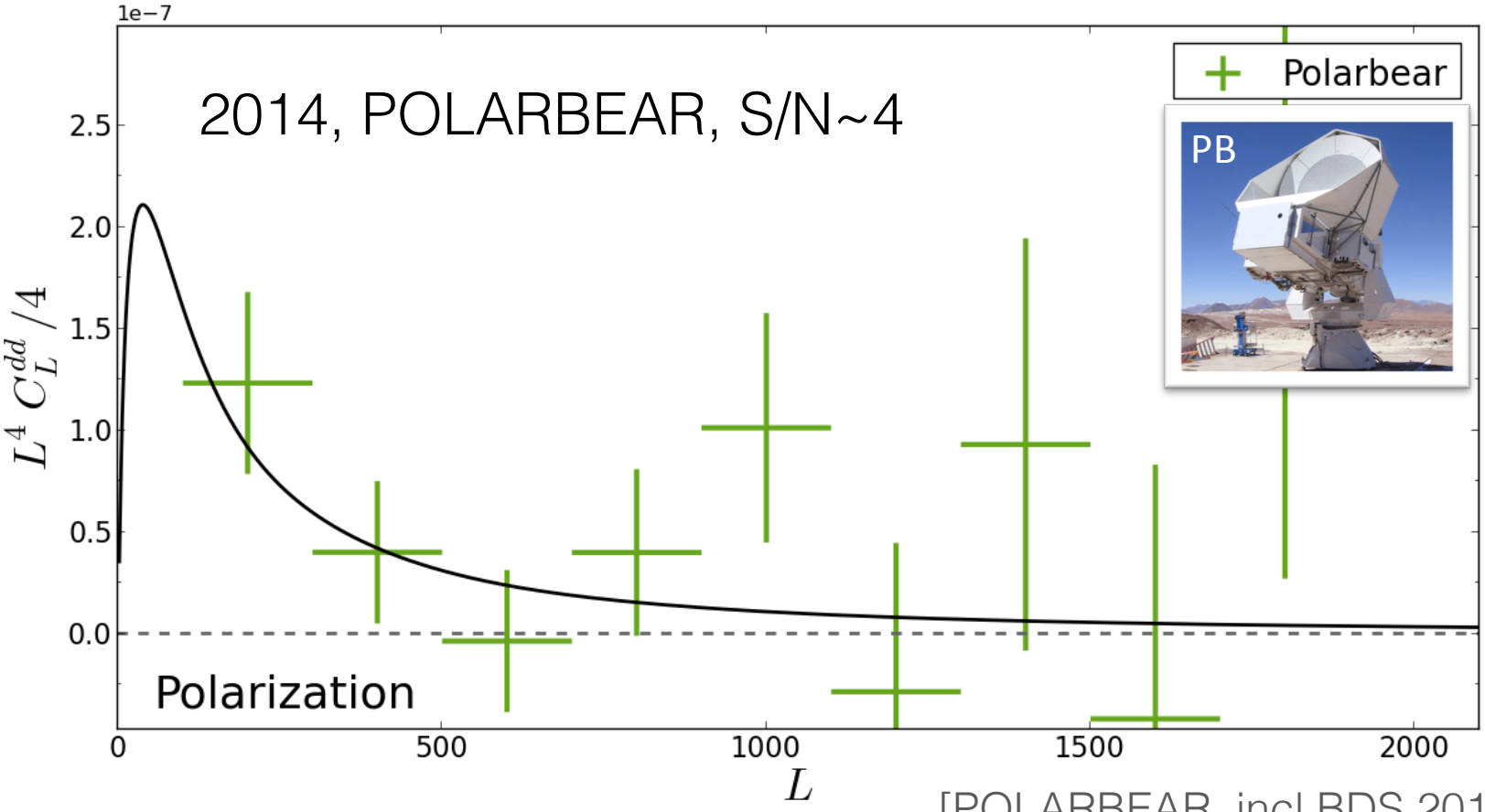
[Sherwin++ 2011, van Engelen++ 2012, Planck 2013]

Lensing Power Spectrum Measurements: Temperature



- ACT: first measurement of CMB lensing power spectrum. Challenging to extract signal under noise and foregrounds.

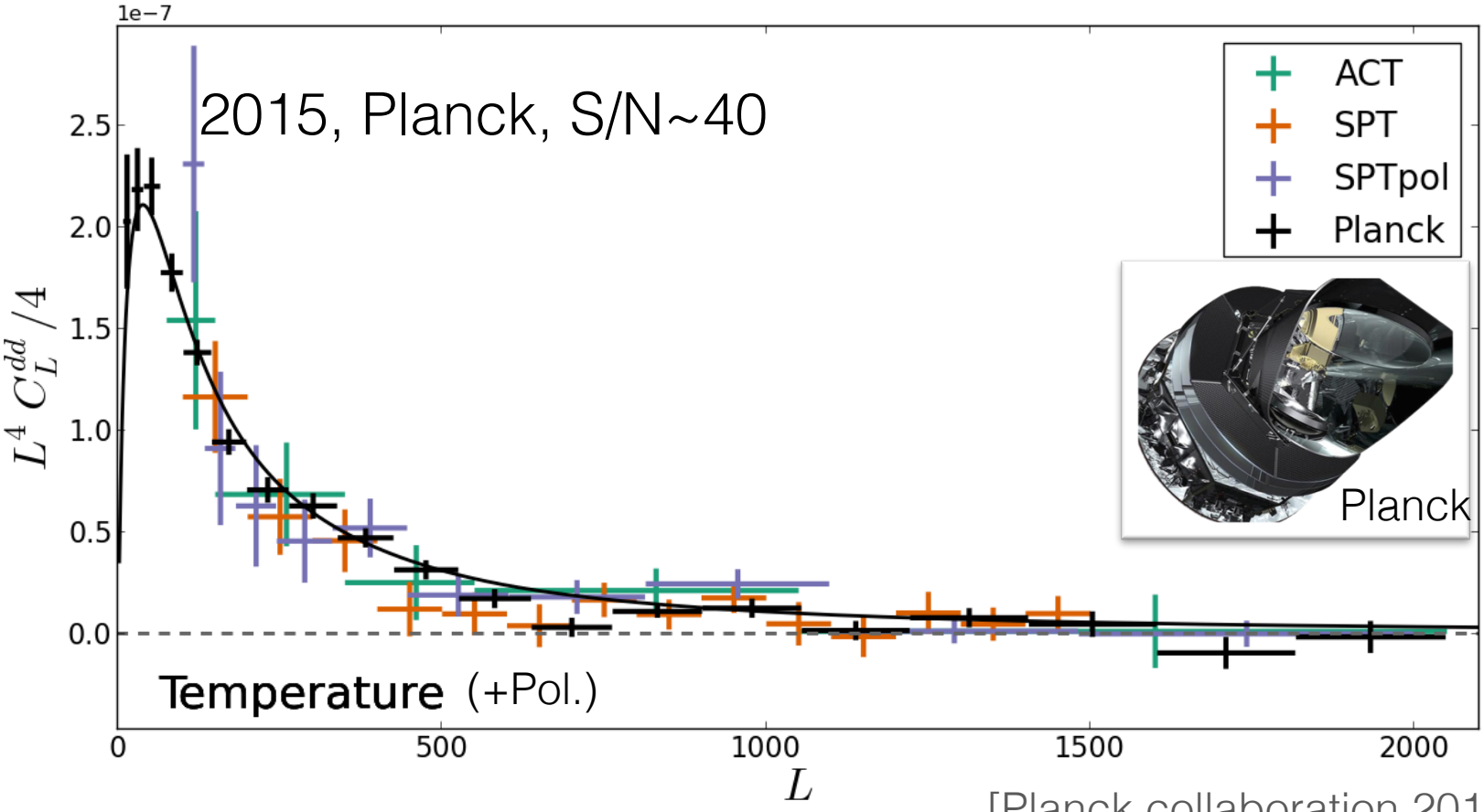
Lensing Power Spectrum Measurements: Polarization



[POLARBEAR, incl.BDS 2014a,b]

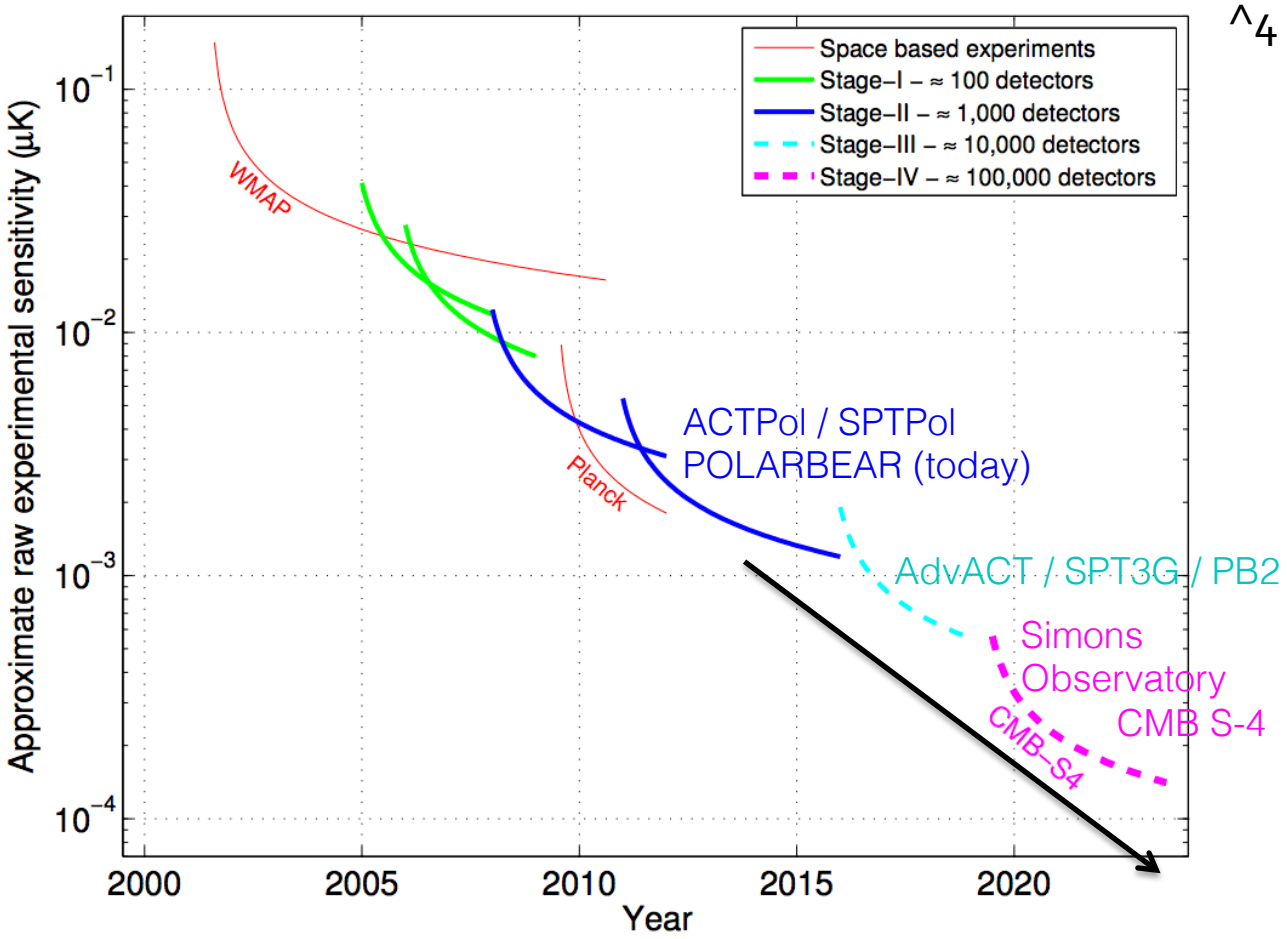
- First detection of important polarization lensing technique

Progress in CMB Lensing Power Spectrum Measurements 2011-now



[Planck collaboration 2015]

Timeline of CMB Experiments



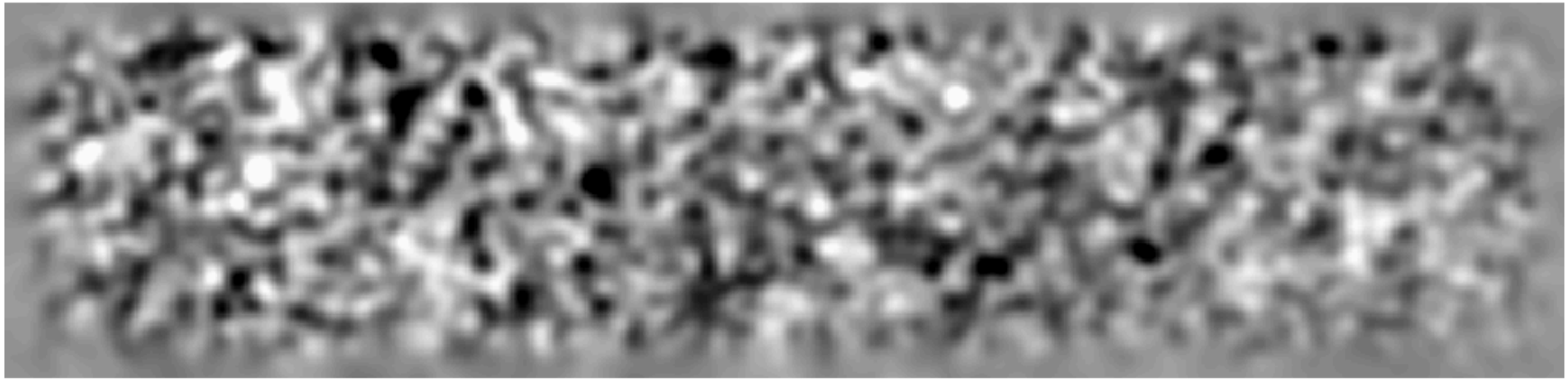
^4

Figure 6. *Plot illustrating the evolution of the raw sensitivity of CMB experiments, which scales as the total number of bolometers. Ground-based CMB experiments are classified into Stages with Stage II experiments having O(1000) detectors, Stage III experiments having O(10,000) detectors, and a Stage IV experiment (such as CMB-S4) having O(100,000) detectors.*

[Abazajian++ 2014]

Current Work: Preliminary ACTPol Lensing Results

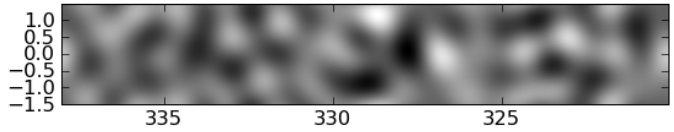
- A preliminary lensing map, reconstructed from temperature+polarization:



ACTPol CMB Lensing Convergence Map (51 degs. long)

[Sherwin et al. in prep.]

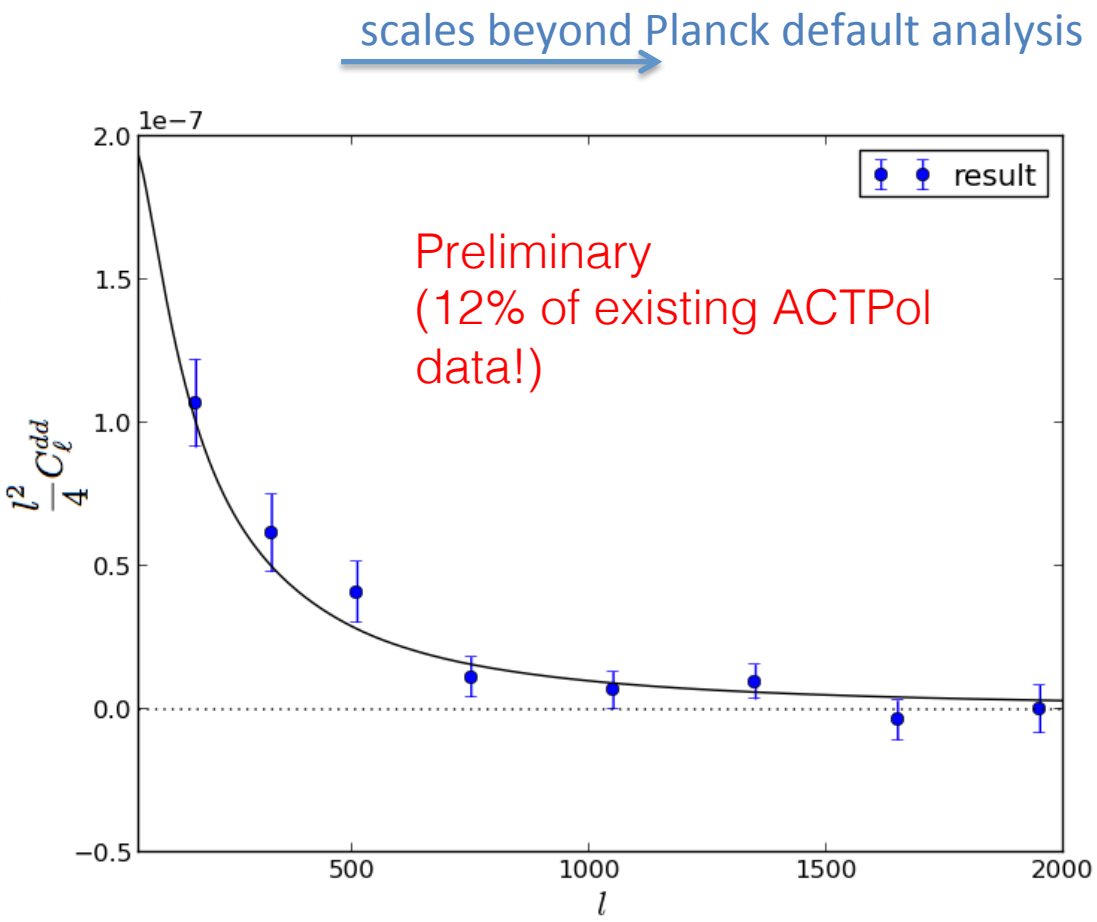
compare older ACT lensing maps



- Power spectrum bias subtraction: estimate corrections from data

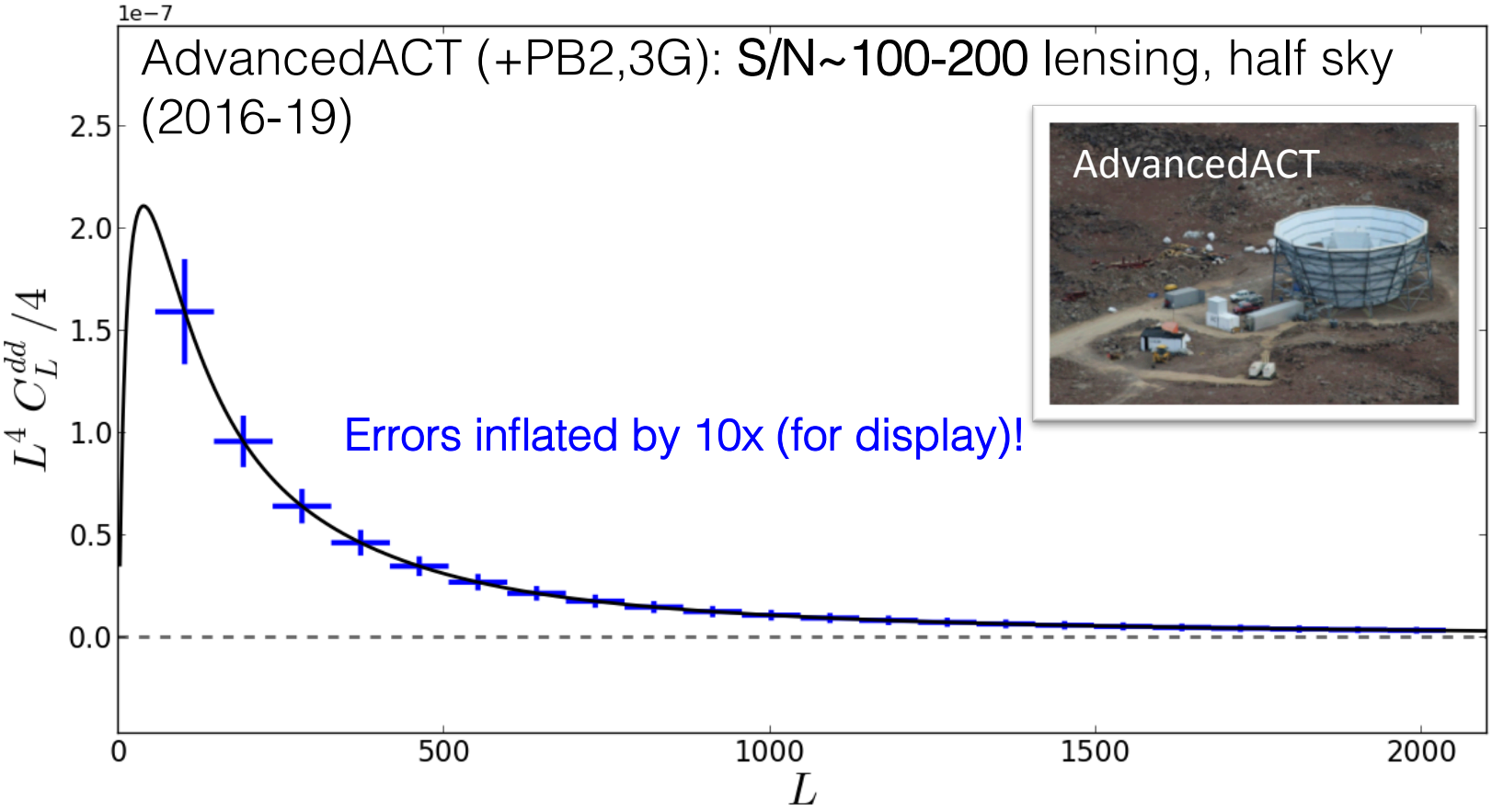
Current Work: Preliminary ACTPol Lensing Results

- ACTPol lensing power spectrum (preliminary, 12% of data analyzed!)
- Currently finalizing analysis, systematic testing (curl?).



[Sherwin et al. in prep.]

The Future: Stage-III and CMB Stage-IV Precision Lensing Power Spectra



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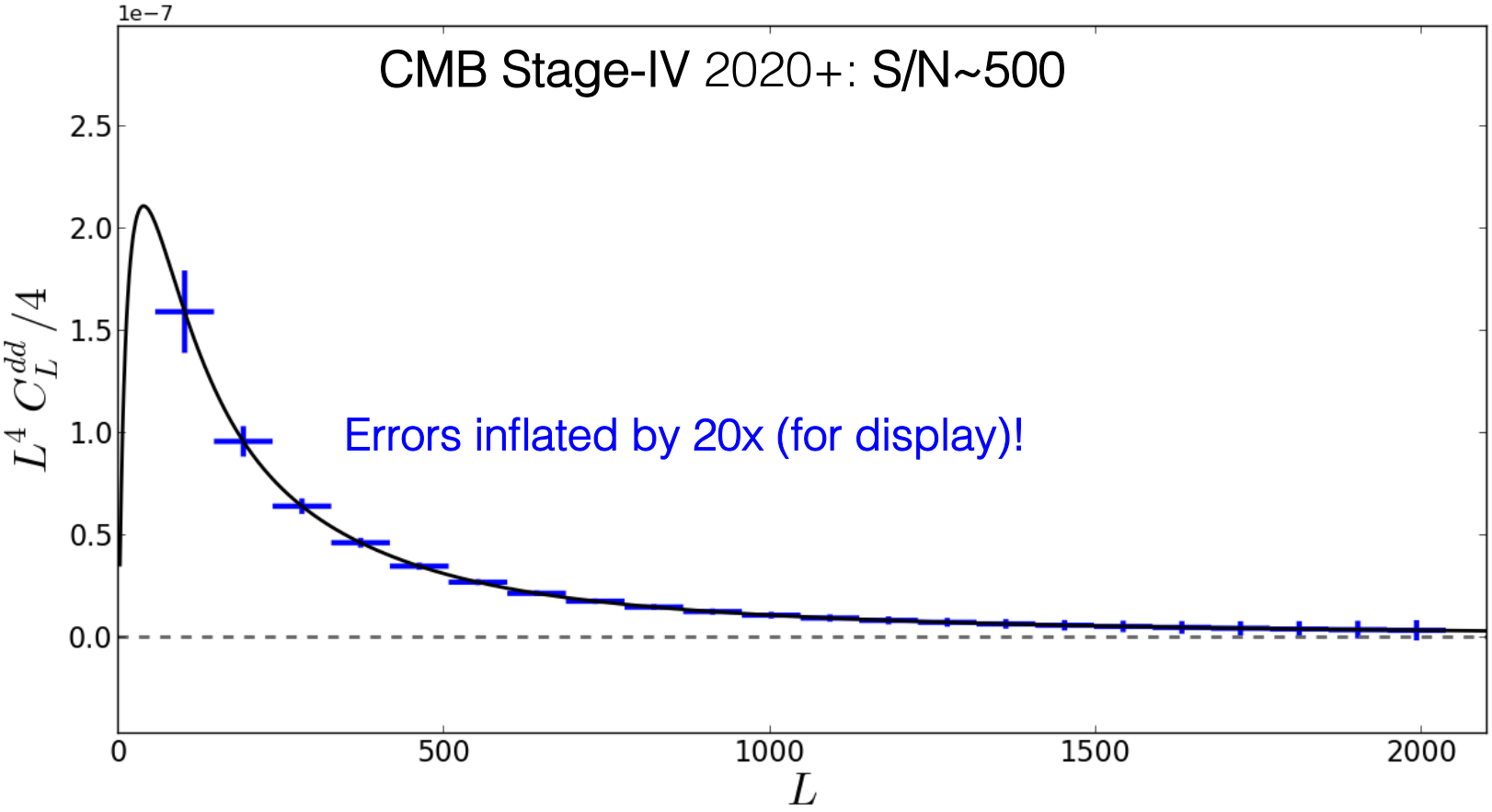
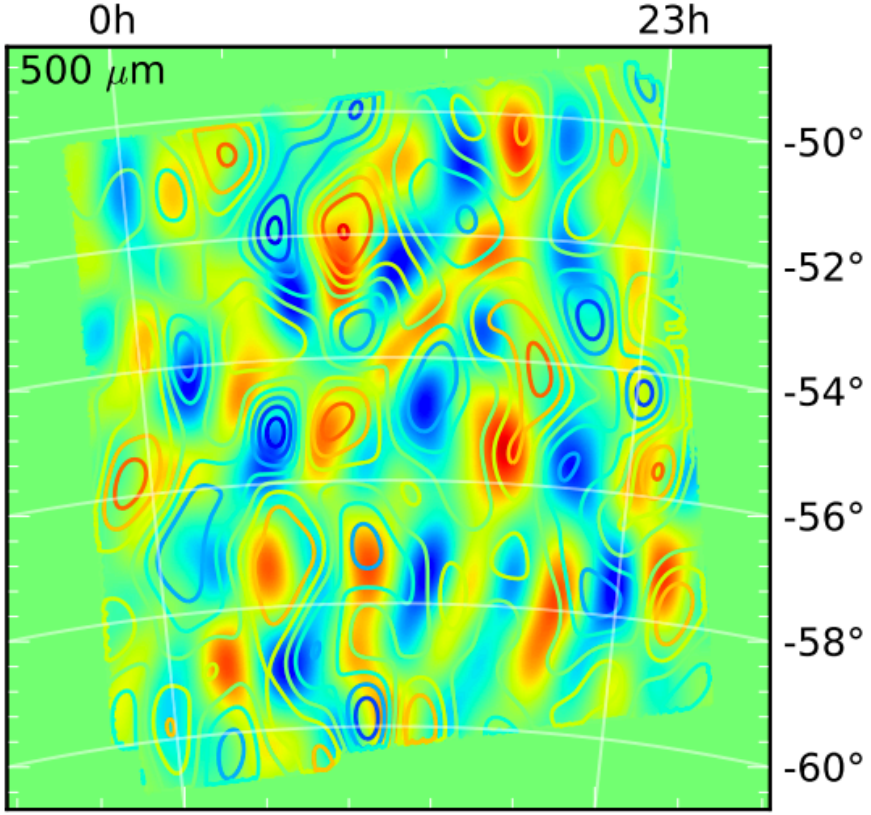


- Neutrino mass constraint near min. (>60 meV)!: $\sigma(\sum m_\nu) \sim 50$ meV (AdvancedACT, SPT3G, PB2…)
  $\sigma(\sum m_\nu) \sim 15$ meV (CMB S4)

Aside: Great Potential for Cross-correlation Science

- Half-sky lensing maps to high z (see $3x10^{13}M_{\odot}$ halos to z>2)
- Lots of overlap with other surveys (DES / DESI / LSST…);

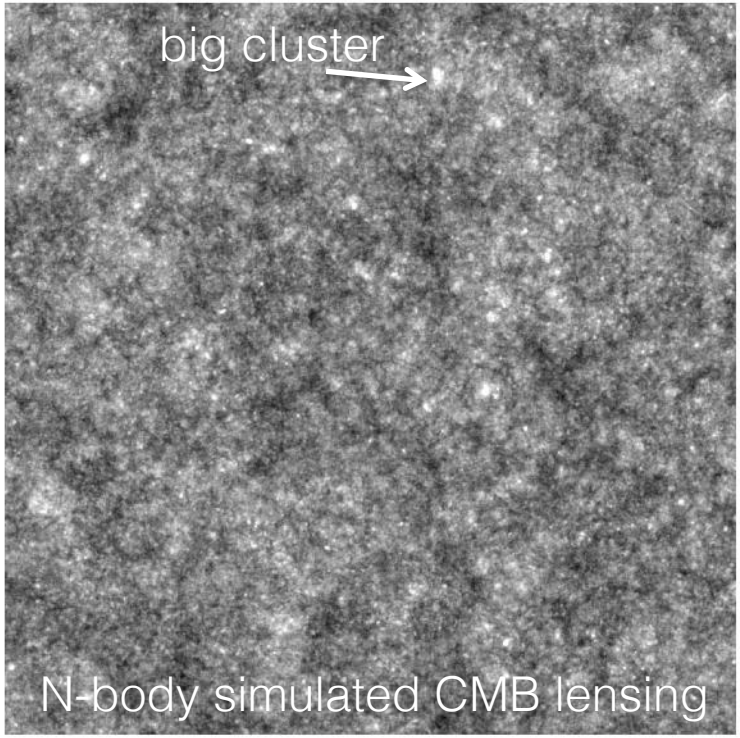
Galaxies (color) trace lensing (contours):

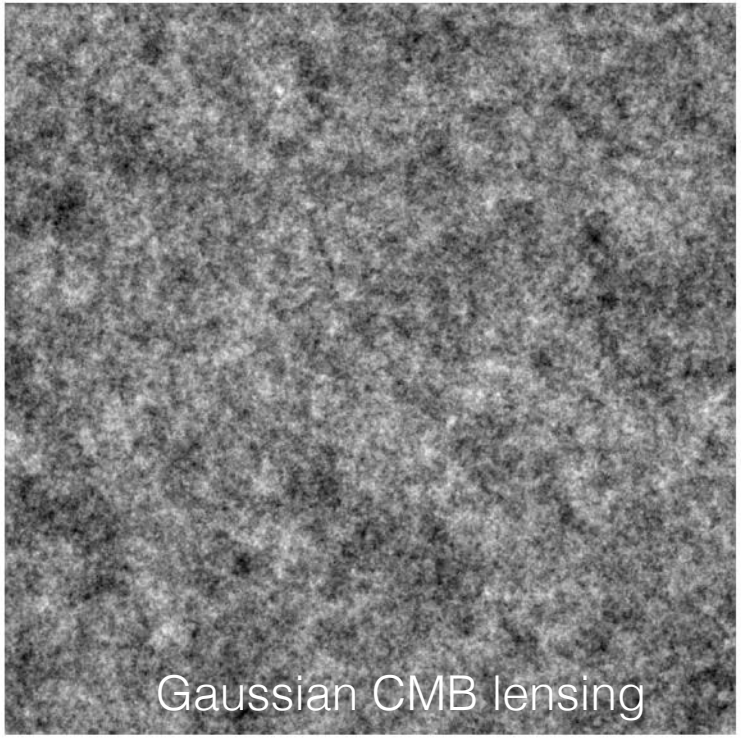


[Holder++ 2013]

CMB lensing correlated with
-Quasars [Sherwin++2012]
-Optical lensing [Hand, Leauthaud, Das, Sherwin++]
-Herschel [POLARBEAR, Sherwin corr. author., 2015]
-WISE [Ferraro, Sherwin, Spergel 2015]
-Planck CIB [v. Engelen, Sherwin+ 2015]
-Galaxy halos [Madhavacheril+ 2015]
-Radio Galaxies [Alllison, Lindsay, Sherwin++] …

Example Challenge: Higher Order Corrections





[Sherwin, Boehm, Liu, Hill in prep.]

- Structure formation non-linear -> many-sigma bias to CMB-S3/S4 temperature estimator, must be accounted for! [+Post-Born effects,..]
- Other challenges: dust foregrounds, bias subtraction, beams, …

[Boehm, Schmittfull, Sherwin 2016; Pratten and Lewis 2016; Namikawa++ 2016, Liu++ in prep.]

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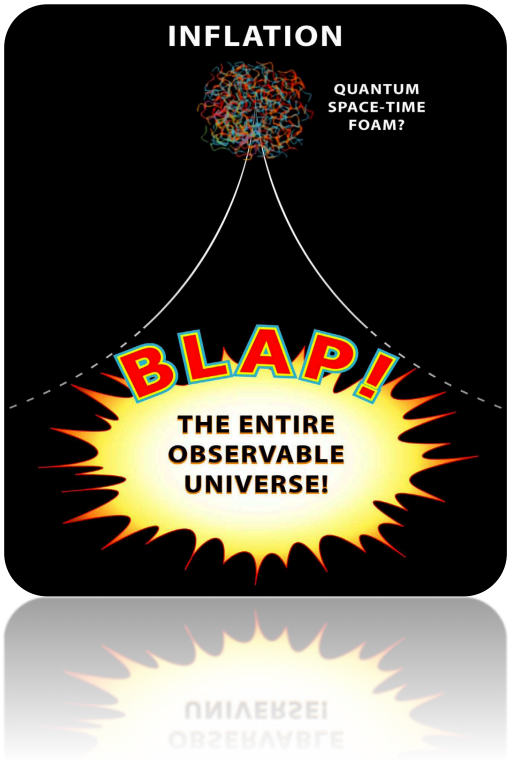
Constraining the Physics of Inflation with the CMB

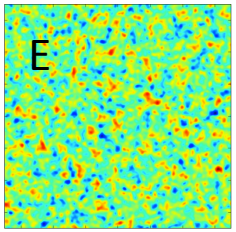
- Many models of inflation produce gravitational waves
- Strength would tell us the *energy scale of inflation.* Even improved upper limits interesting: could kill large-field inflation models
- These gravitational waves create characteristic CMB B-polarization

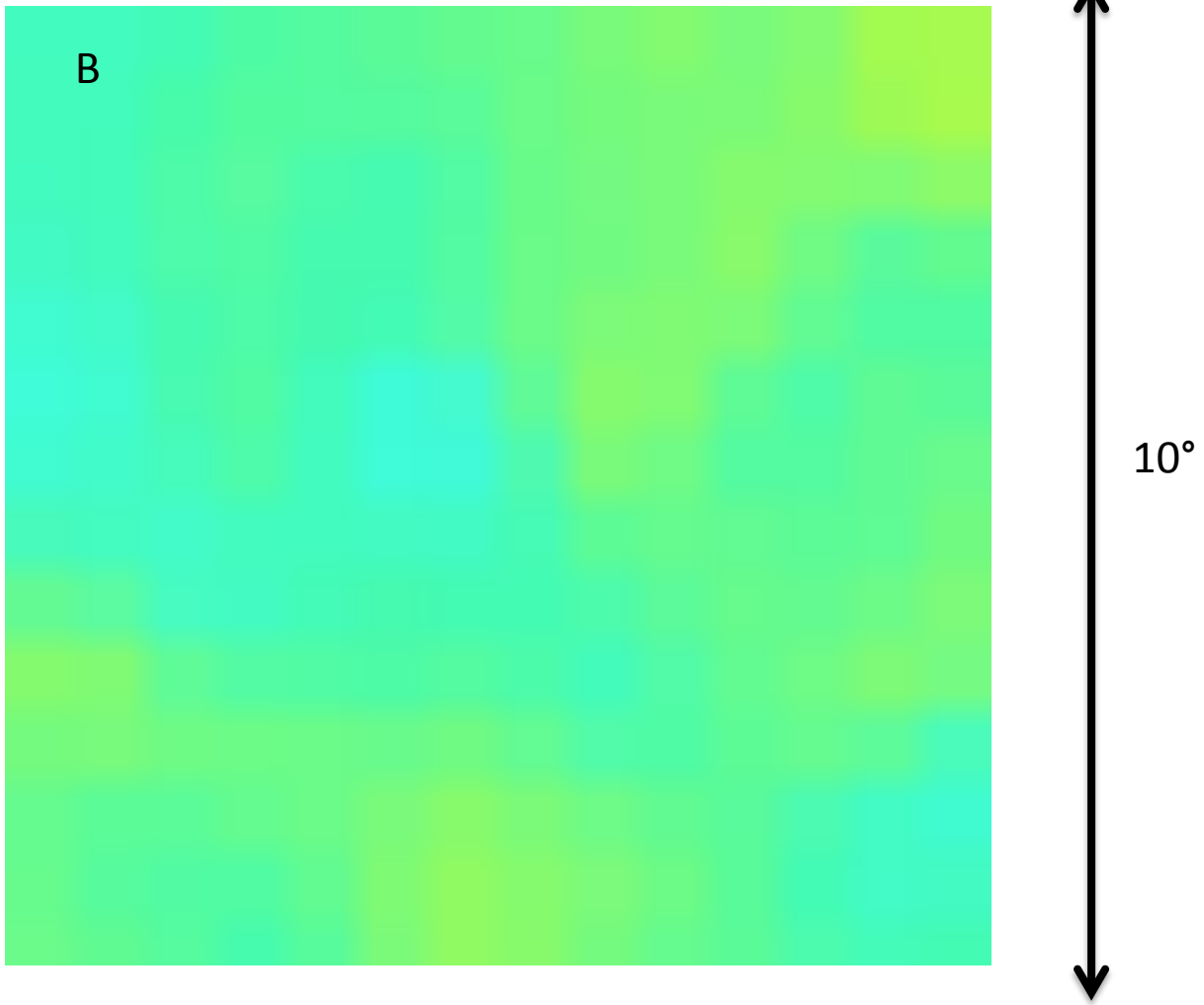


CMB B-polarization* with Small Inflationary Signal

See signal clearly as there is no background variance from scalar density perturbations

B-modes are a "null channel"

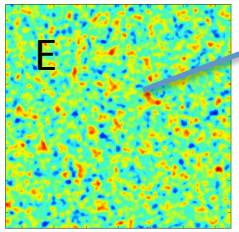


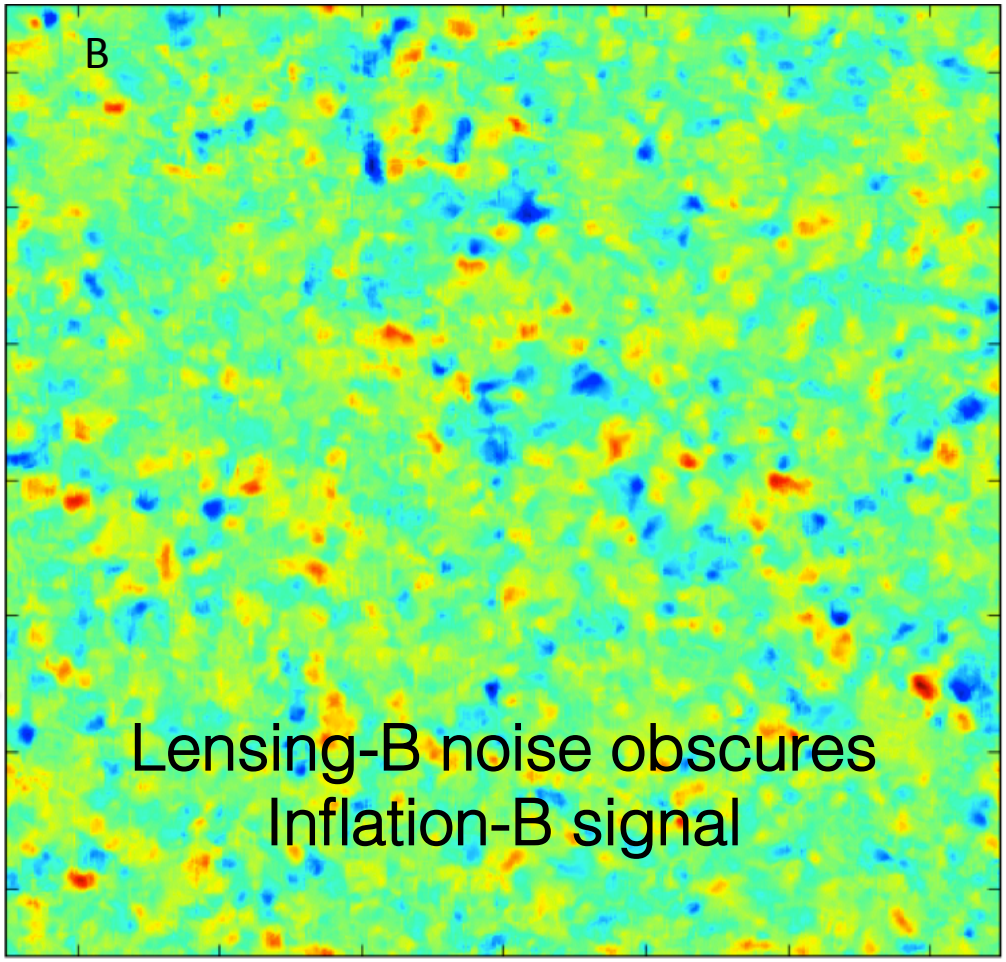


*ignoring lensing and dust for now

Lensed CMB B-Polarization

Gravitational lensing d converts E- to B- polarization



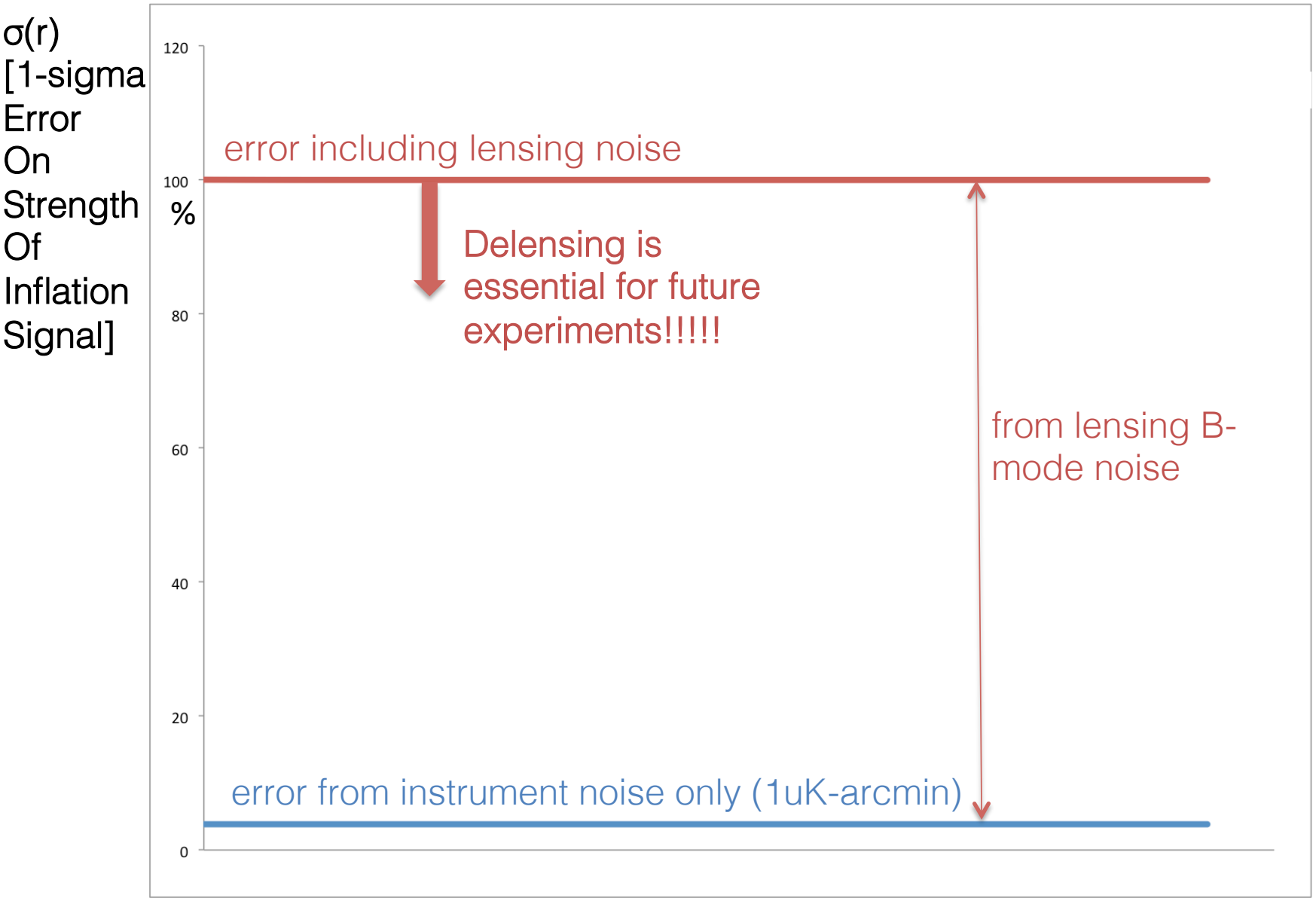


10°

$$B^{\rm lens}(\mathbf{l}) = \int \frac{d^2\mathbf{l}'}{(2\pi)^2} W(\mathbf{l},\mathbf{l}') E(\mathbf{l}') d(\mathbf{l}-\mathbf{l}')$$

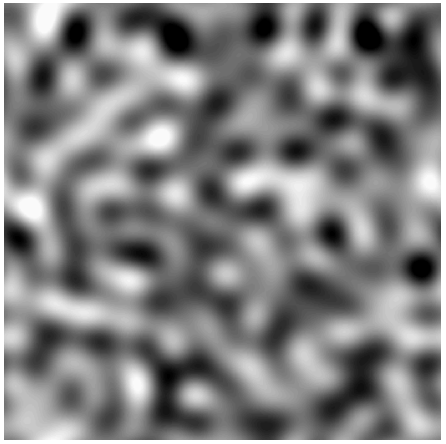
kernel E-mode lensing

Future: CMB Stage-IV Error Budget for Measuring Inflationary Grav. Wave Signal



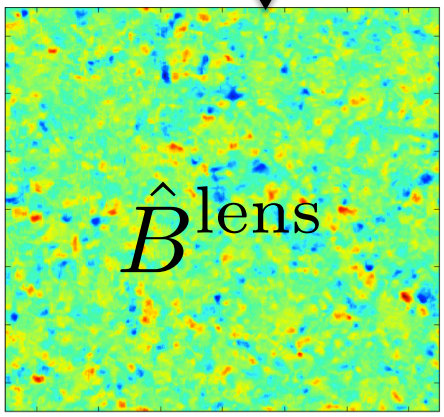
Delensing The CMB

- How to reduce lensing noise?
- Delensing: undo lensing deflection (construct $B_{lensing}$ map from measured lensing d and subtract)
- Want to demonstrate!



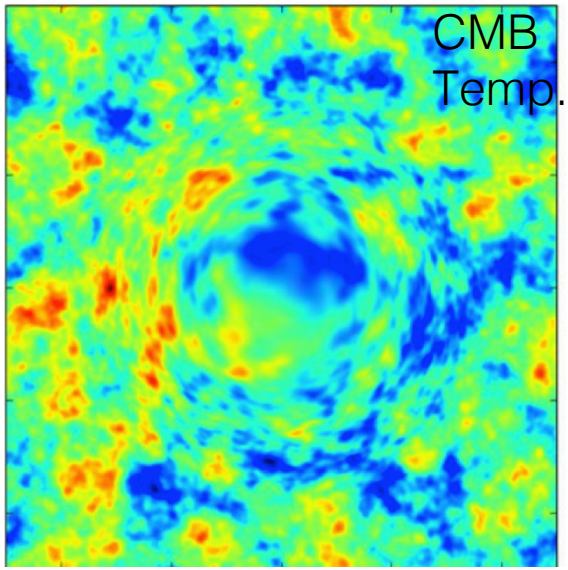
lensing estimate d

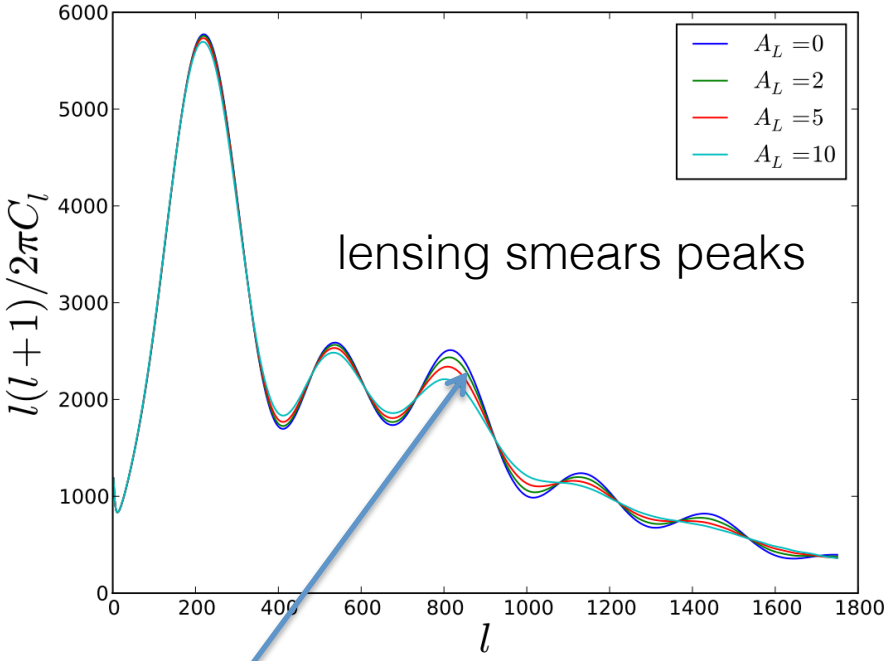
subtract

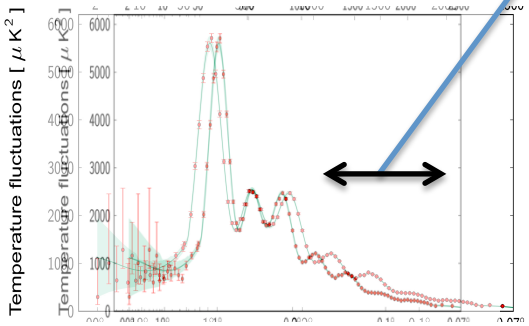


estimate of lensing B (from d+E)

Aside: Lensing Effect on CMB Temperature Power Spectra

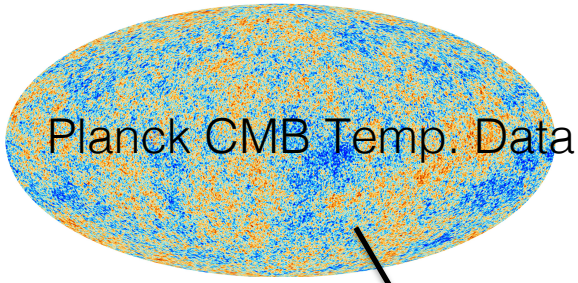




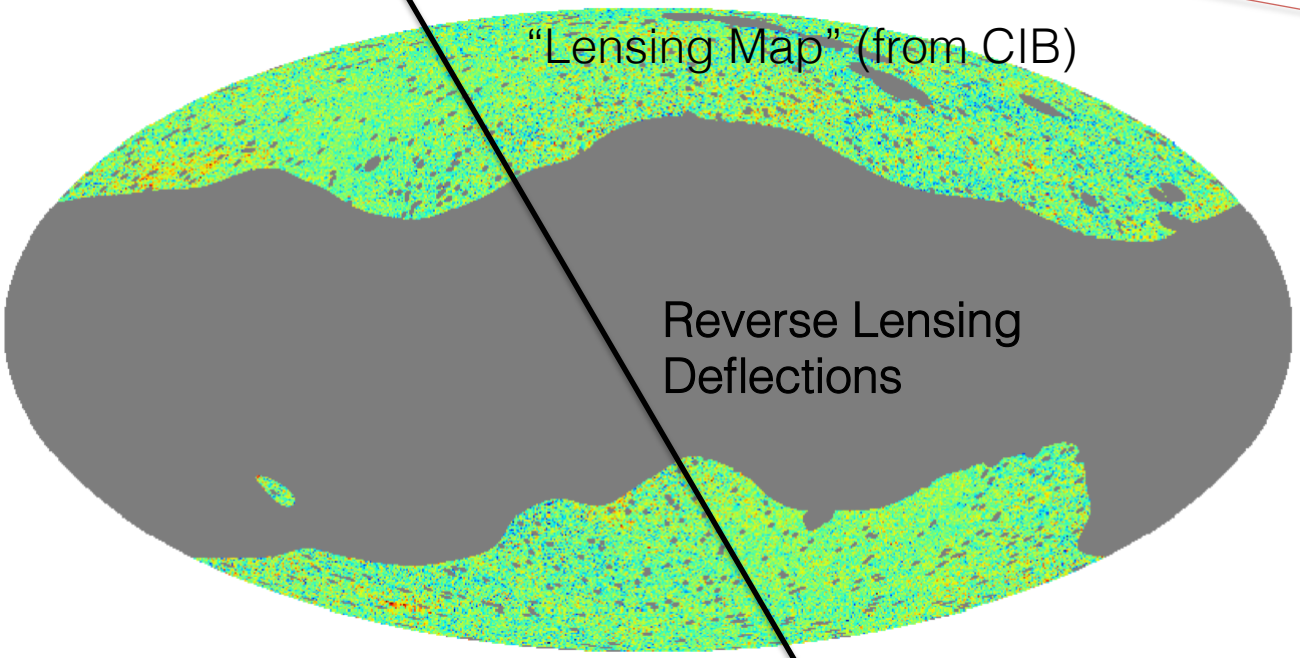


effect arises from averaging of magnified and demagnified regions

Demonstrating Delensing with (Temp.) Data

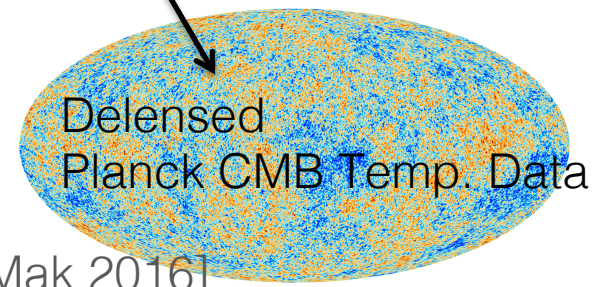


Planck CMB Temp. Data



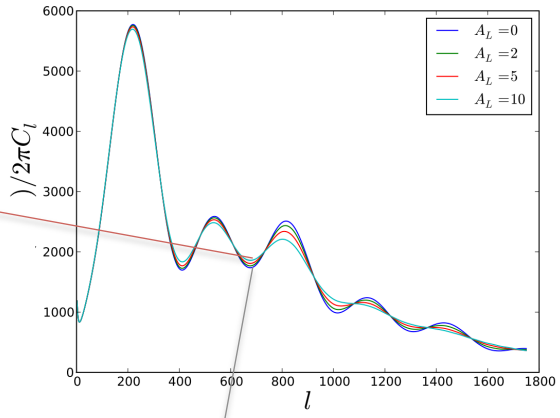
"Lensing Map" (from CIB)

Reverse Lensing Deflections



Delensed Planck CMB Temp. Data

Measure power before…



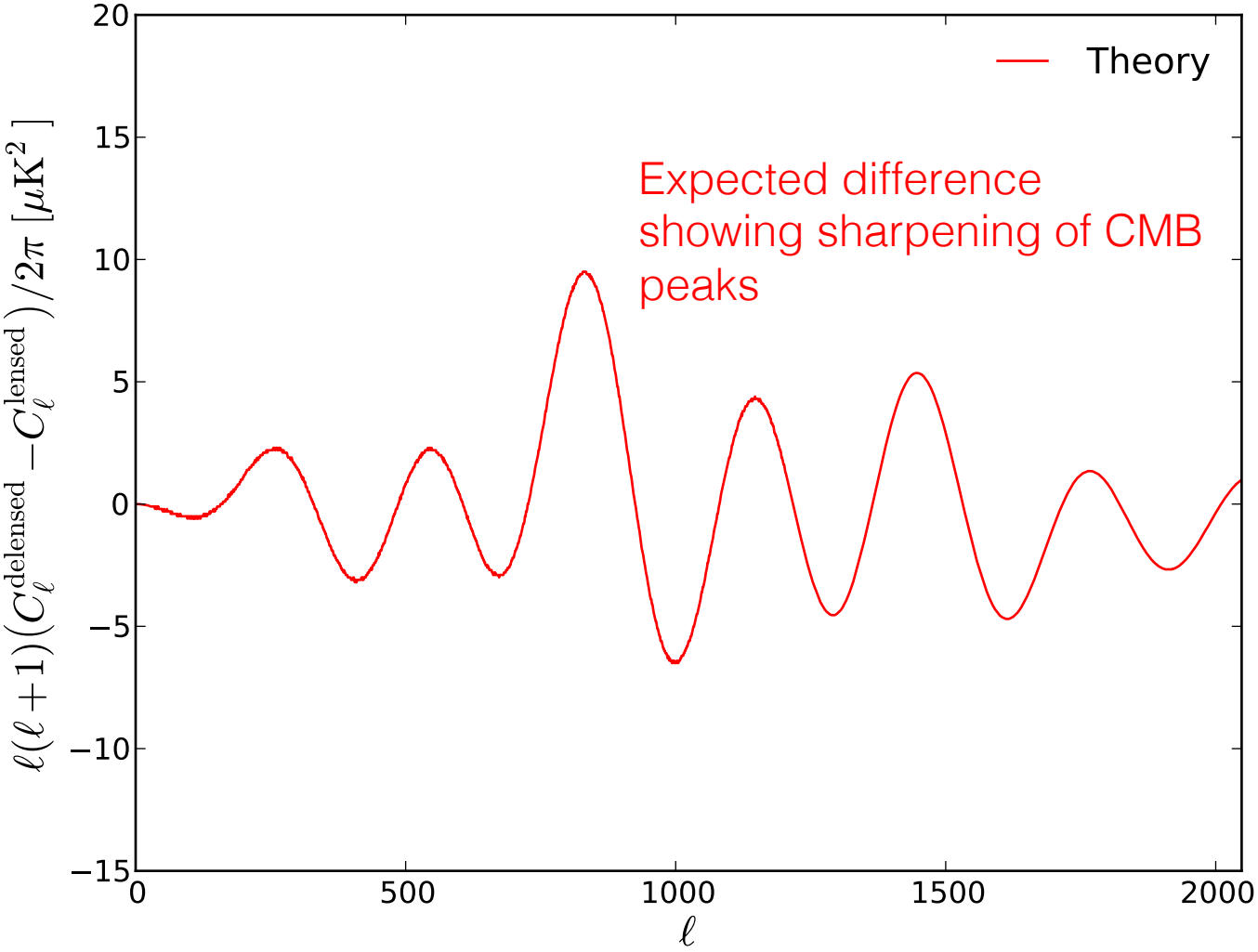
+ measure power after delensing

Take difference!

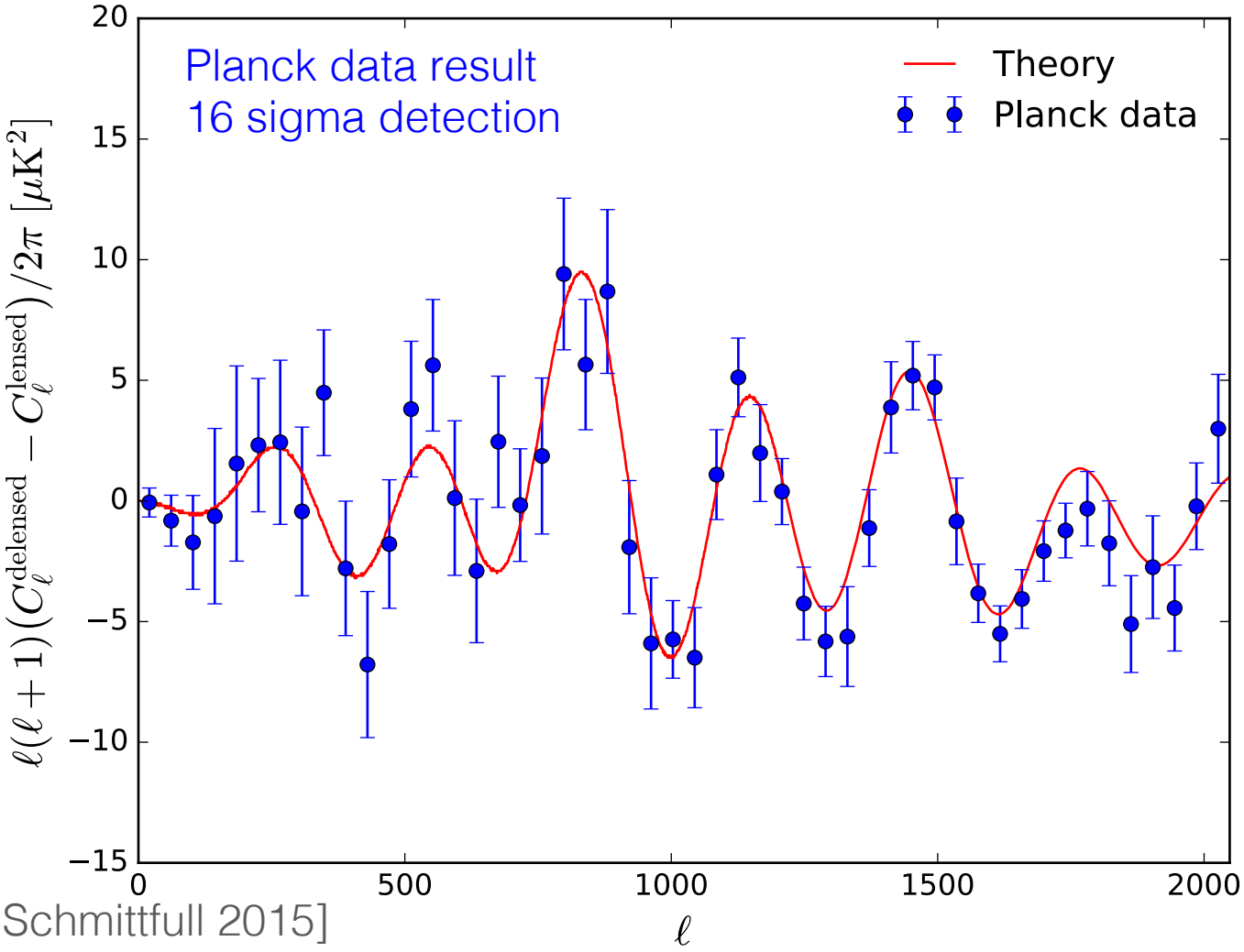
[Sherwin, Schmittfull 2015]

[Larsen, Challinor, Sherwin, Mak 2016]

Demonstrating Delensing: Difference of Lensed and Delensed Temp. Spectra



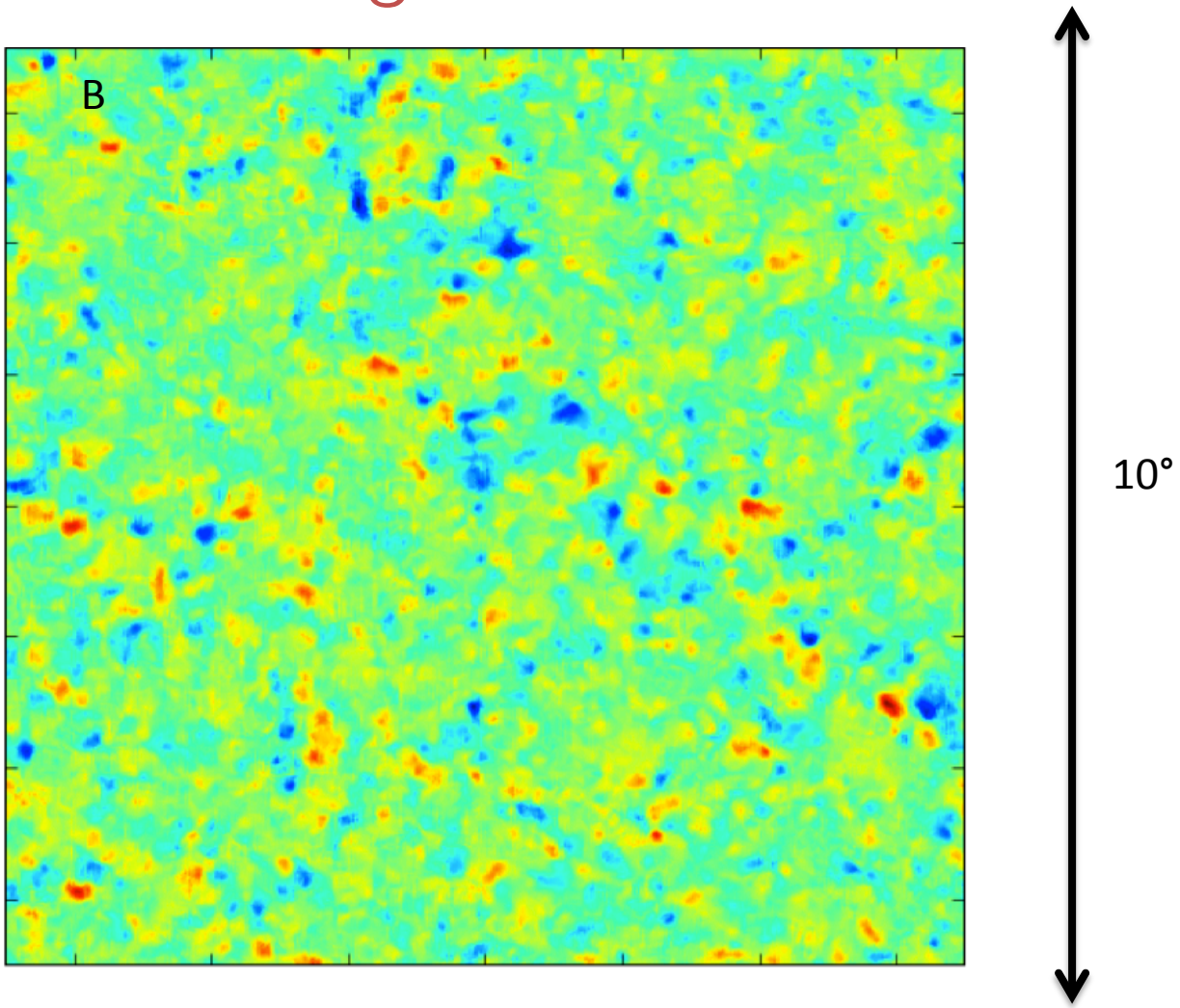
First Demonstration of Delensing in Data
(Difference of Lensed and Delensed Temp. Spectra – Peaks Show Successful Delensing)



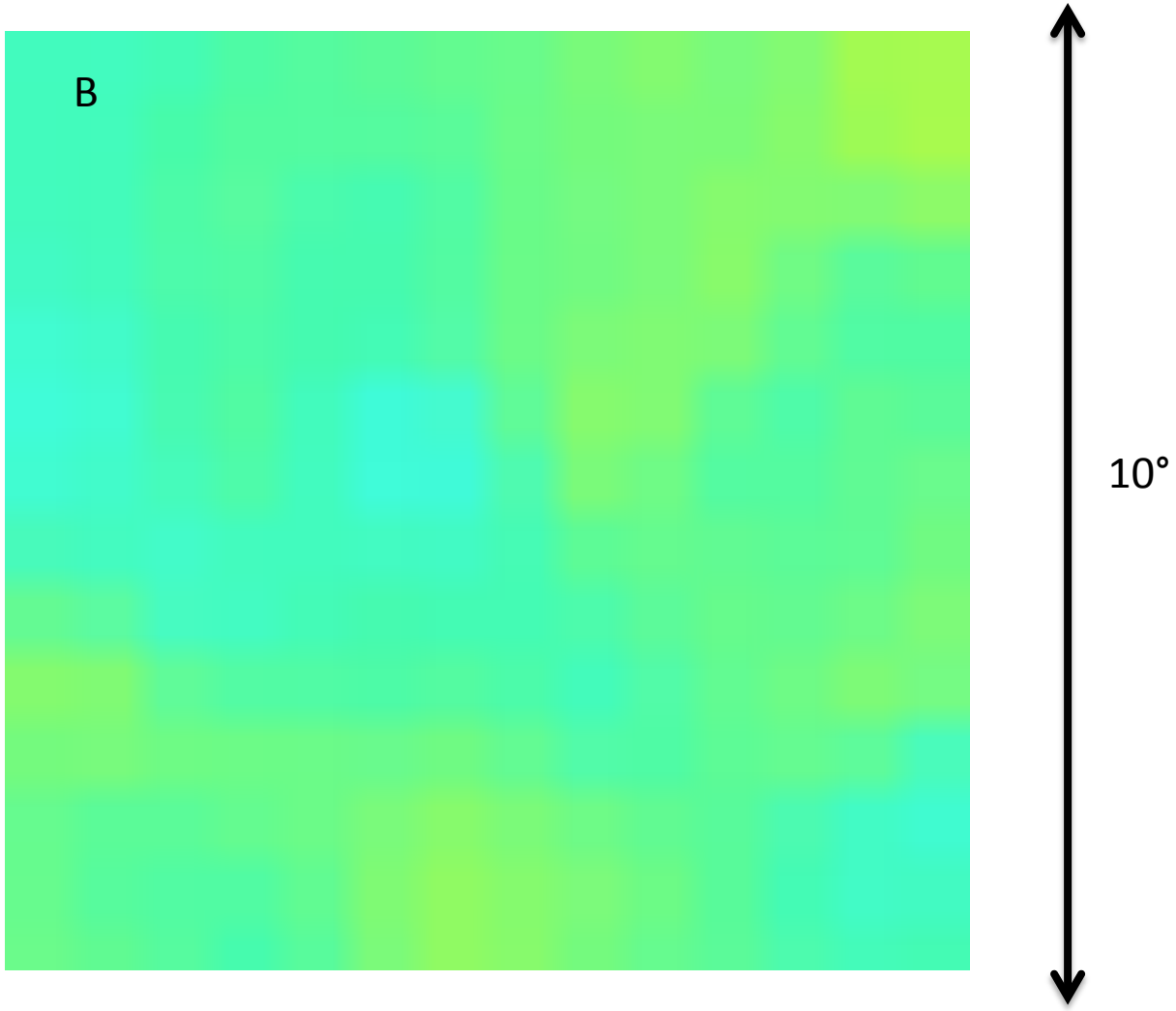
[Sherwin, Schmittfull 2015]

[Larsen, Challinor, Sherwin, Mak 2016]

Future B Mode Map – Lensing-Dominated



Delensed B Map – Inflation Signal?



Summary

- CMB lensing directly probes high-z mass
- Measurements have already progressed rapidly, but with CMB Stage-III / Stage-IV they will be much more powerful still!
- These lensing measurements will allow us to
  - measure neutrino masses
  - enable remarkably powerful probes of inflation via delensing
  - constrain astrophysics via cross-correlation