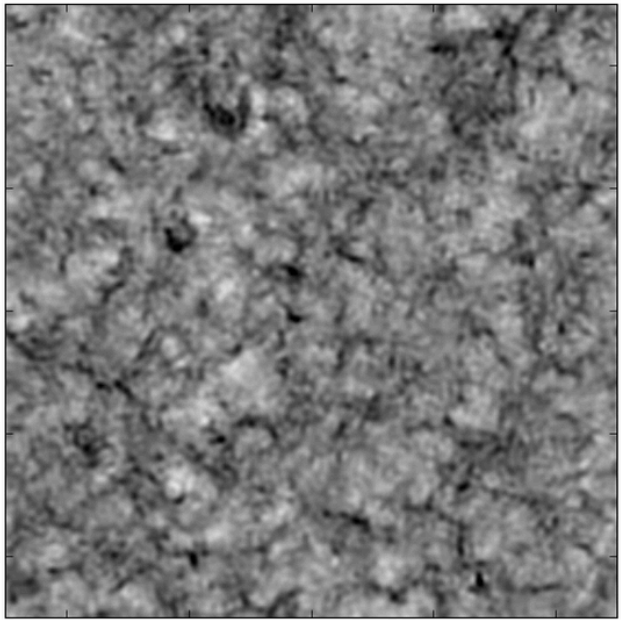
CMB Lensing Measurements, Present and Future



Blake D. Sherwin
(UC Berkeley, Department of Physics / Miller Institute for Basic Research in Science)

with Chang Feng, Alex van Engelen, David Spergel et al.
ACTPol and POLARBEAR collaborations

Introduction to CMB Lensing

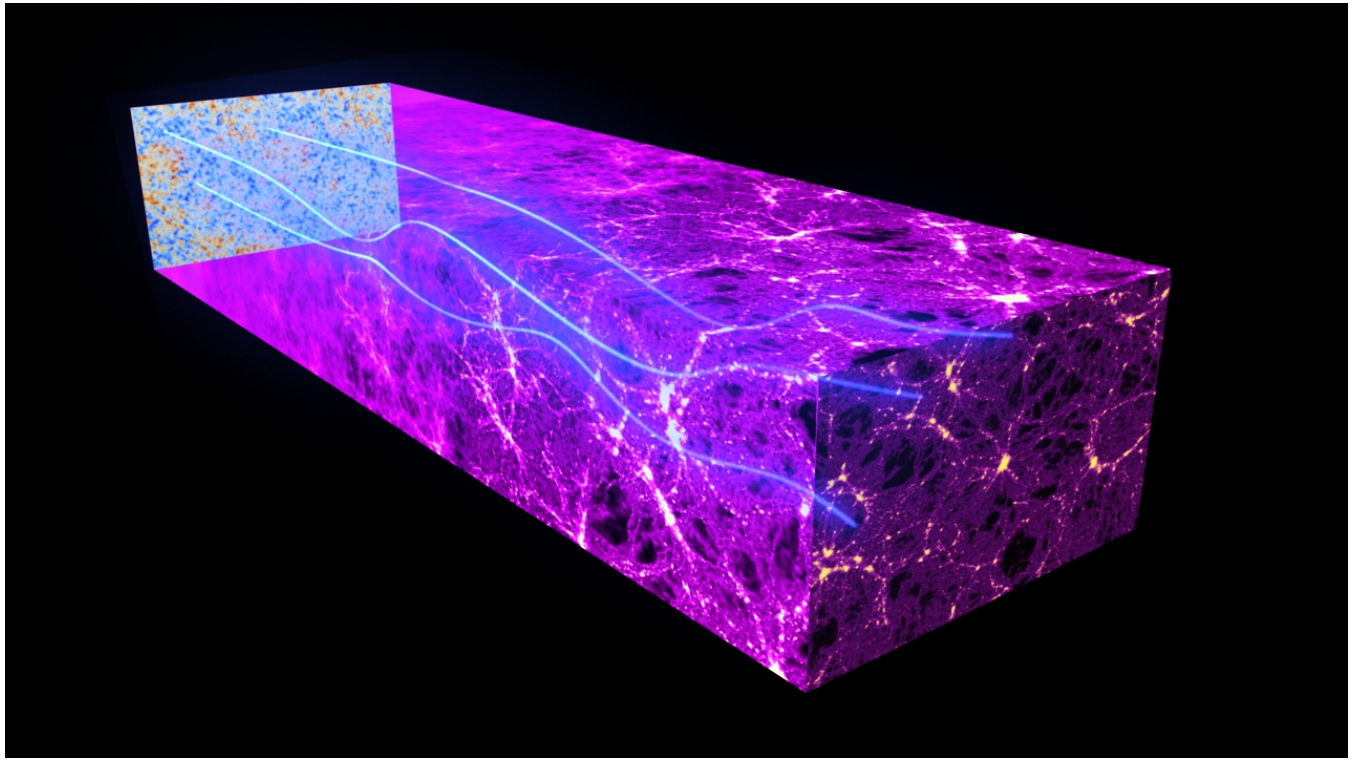
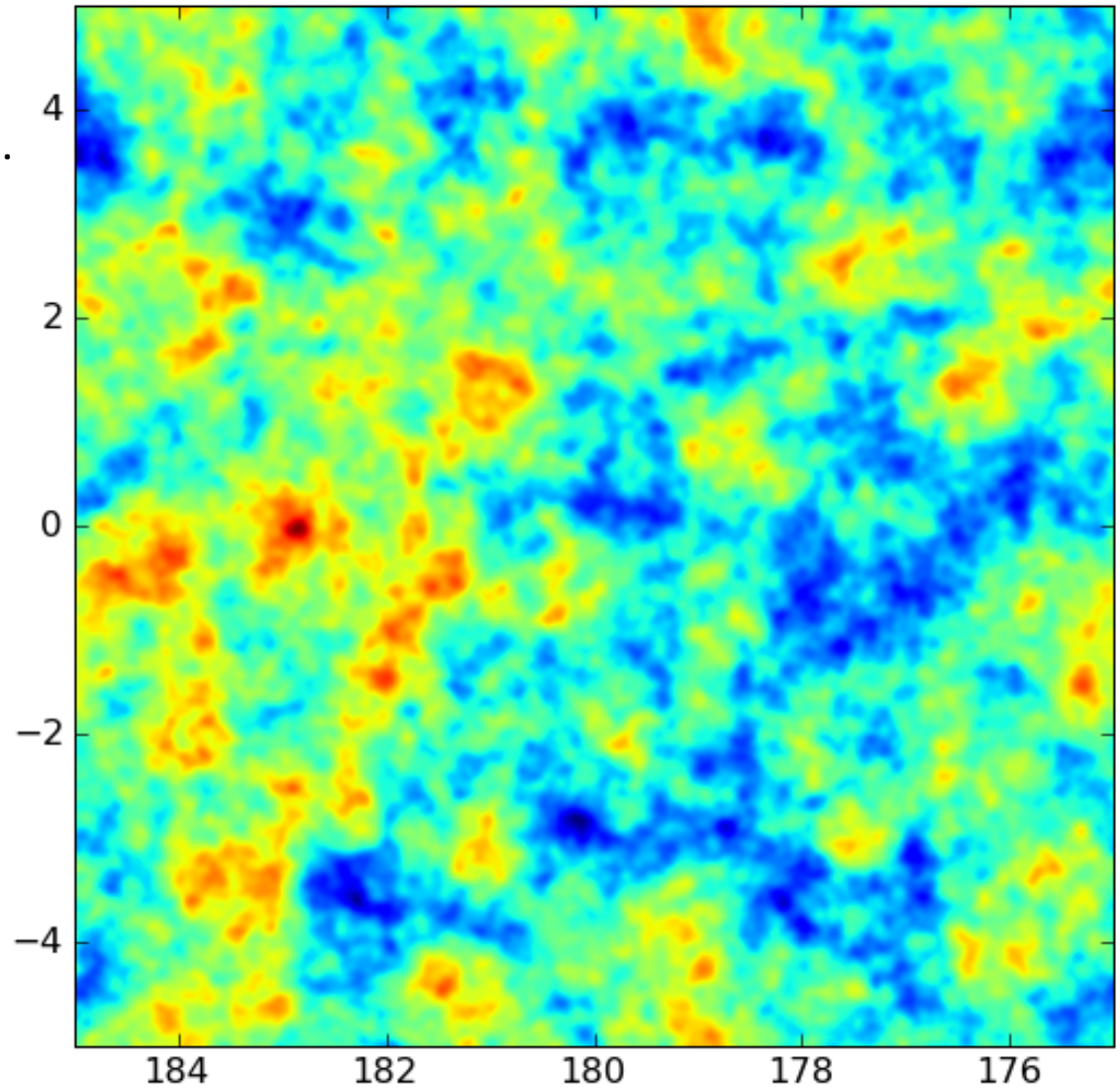


Image Credit: ESA

- Cosmic Microwave Background (CMB) photons are gravitationally lensed by the large scale mass distribution
- Many small deflections remap the observed CMB

Unlensed CMB

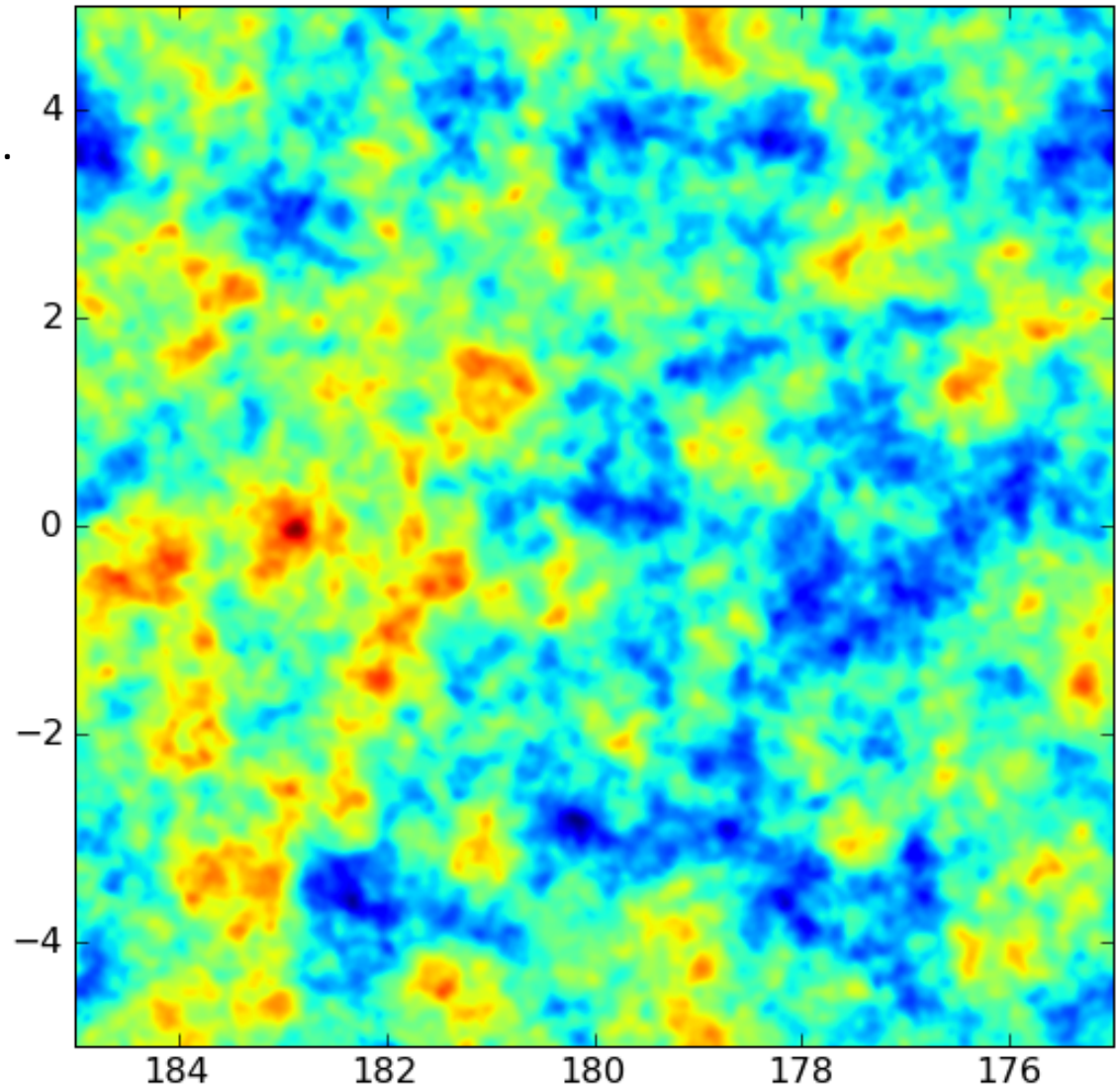
CMB Temp.



10°

Lensed CMB

CMB Temp.



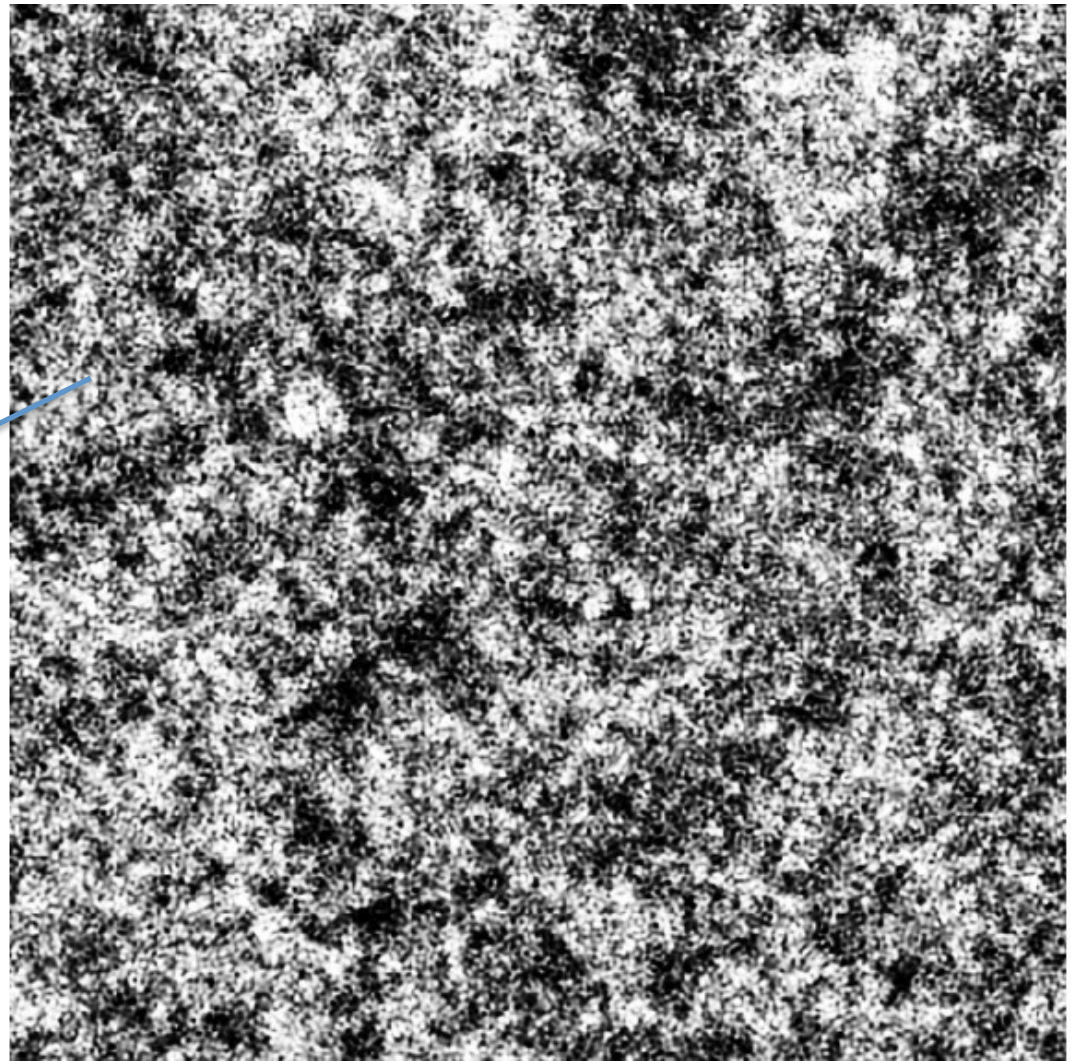
10°

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

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

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

small ~3 arcminute deflections, coherent on degree scales



10°

In this talk, I will plot the magnitude of the deflection $|\mathbf{d}(\hat{\mathbf{n}})|_{\rm filt}$
(actually, the gradient high-pass-filtered magnitude a.k.a. lensing convergence)

Lensing Deflection Field Measures Mass

- Amount of lensing deflection depends on the projected (dark) matter density in that direction, from redshift 0.5-3

$$|\mathbf{d}(\hat{\mathbf{n}})|_{\rm filt} = \int dz W(z) \delta(\hat{\mathbf{n}}, z)$$

δ: fractional matter overdensity $\delta = (\rho - \bar{\rho})/\bar{\rho}$
$W(z)$: geometric projection kernel

- Measurement of projected matter distribution will help address some of the most important questions in cosmology

NAS Decadal Survey: Key Questions

Cosmology and Fundamental Physics	CFP 1	How did the universe begin?
	CFP 2	Why is the universe accelerating?
	CFP 3	What is dark matter?
	CFP 4	What are the properties of neutrinos?

will explain in this talk

Talk Outline

- Progress in CMB temperature lensing measurements and constraints on parameters, e.g. neutrino mass
- CMB polarization lensing: why it is important, e.g. for delensing, and early measurements
- CMB polarization lensing: cosmological constraints from upcoming experiments

Lensing Reconstruction (How to Measure Lensing)

- **Lensing changes CMB statistics**, correlates formerly independent modes:

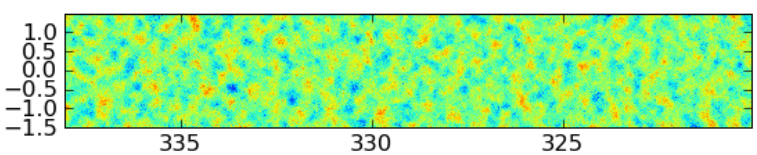
$$\langle T(\mathbf{l})T^*(\mathbf{l}-\mathbf{L})\rangle_{\rm CMB} \propto d(\mathbf{L})$$

$$\langle E(\mathbf{l})B^*(\mathbf{l}-\mathbf{L})\rangle_{\rm CMB} \propto d(\mathbf{L})$$

- Use this statistics-change: estimate CMB lensing deflection by measuring lensing-induced mode-correlations:

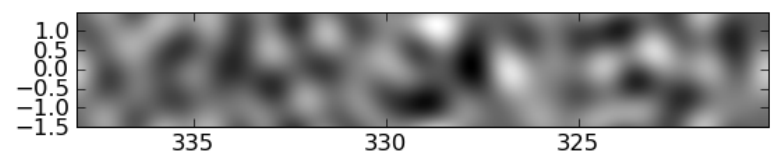
$$d(\mathbf{L}) = \int \frac{d^2\mathbf{l}}{(2\pi)^2} g^{TT}(\mathbf{l},\mathbf{L})T(\mathbf{l})T^*(\mathbf{l}-\mathbf{L})$$

[Hu, Okamoto 2002]



CMB temperature / polarization maps

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

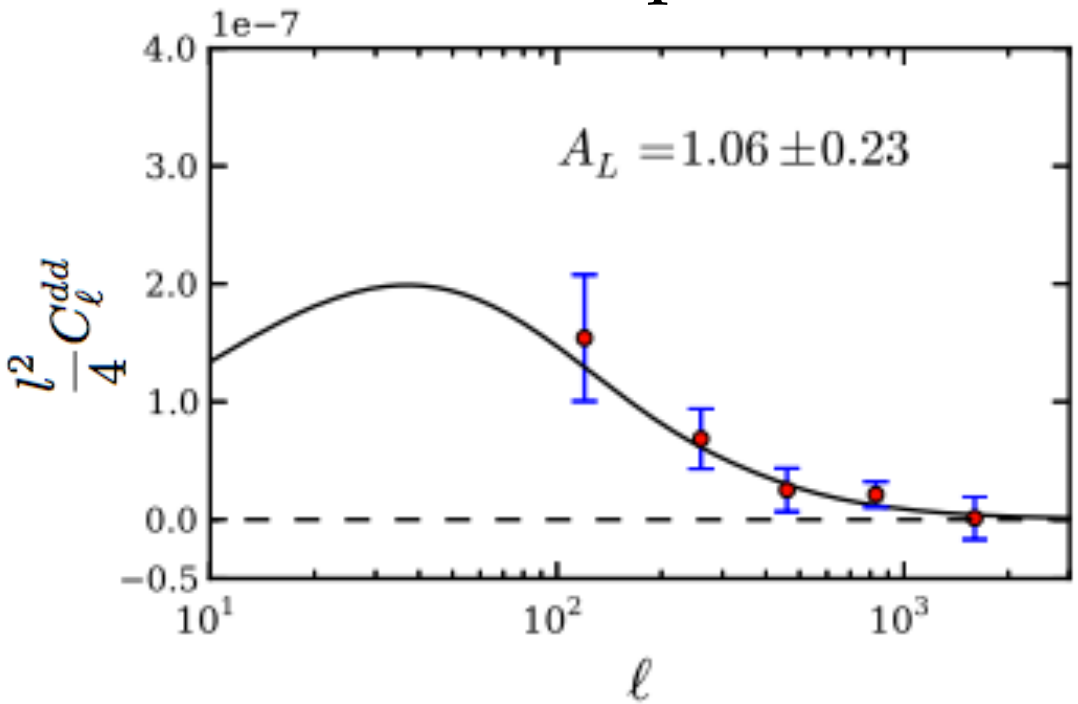


CMB lensing Map

C_ℓ^{dd} lensing power spectrum

C_ℓ^{dq} lensing cross-correlations

CMB Lensing Power Spectrum: First Detection in Temperature with ACT



[Das, Sherwin et al. 2011]
[Sherwin, Das et al. 2011]

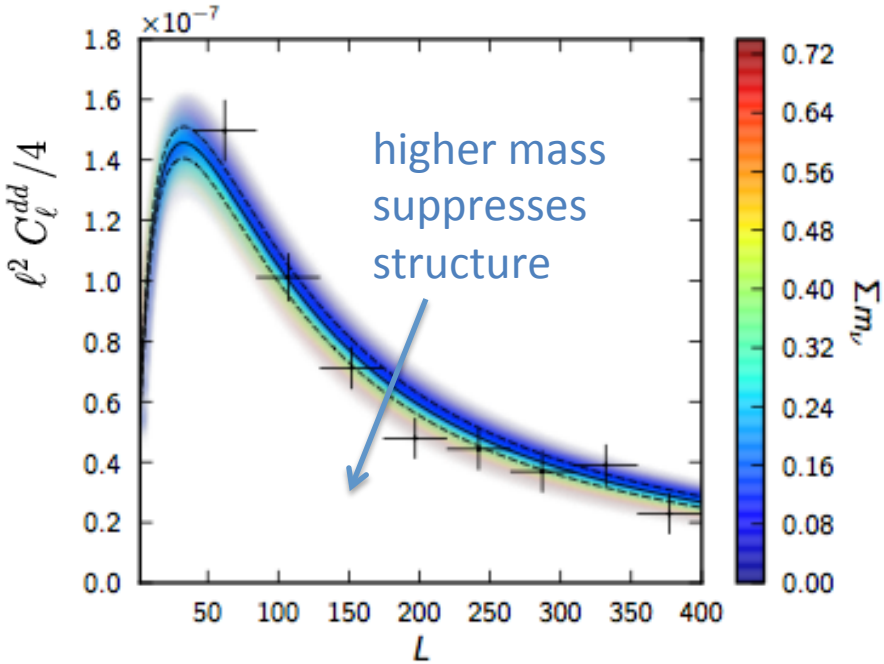
4 sigma (2011)
(4.6 sigma, update)

- Consistent with LCDM prediction - direct gravitational probe of mass/dark matter at high redshifts (z~0.3-3)
- Early cosmological constraints on dark energy density
- With Planck lensing at >25 sigma, has become precise probe!

[Planck Collaboration 2013, van Engelen et al. 2012]

Rapid Progress and New Applications: Constraints on Neutrino Masses

- Can measure sum of neutrino masses with lensing
- Massive neutrinos suppress growth of structure on small scales relative to large scales (by up to 5%/0.1eV)
- Lensing power spectrum reflects suppression of growth



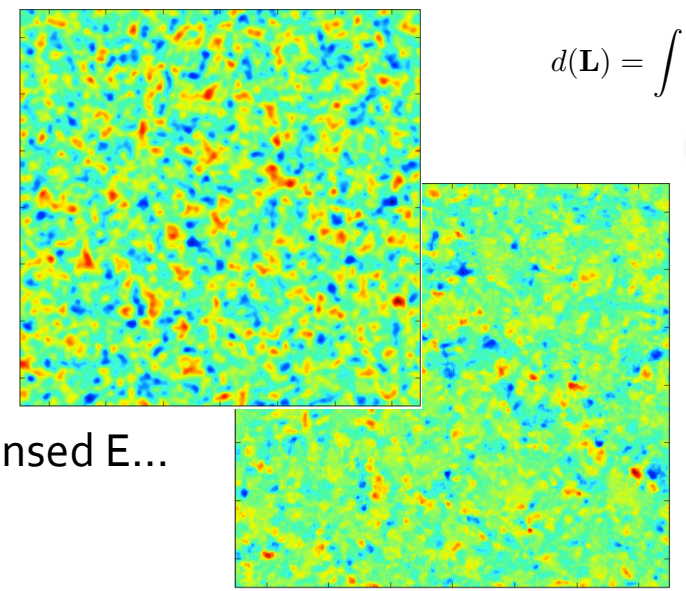
[Planck Collaboration 2013]

Constraint with Planck CMB lensing: $\sum m_\nu < 0.85\,\mathrm{eV}, \quad (95\%;\ \textit{Planck}+\mathrm{WP}+\mathrm{highL}),$

Polarization Lensing Measurements: Motivation and Early Results from POLARBEAR and ACTPol

Differences Between Temp. and Pol. Lensing

- Lensing remaps polarization, converts E to B
- Because we know all B on small scales is from lensing, and B cosmic variance doesn't contribute, polarization estimators are much more powerful below ~8uK' noise



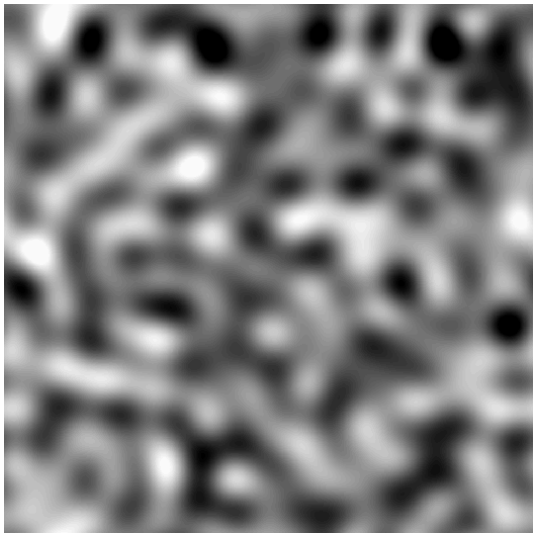
lensed E…

and B mode maps

$$d(\mathbf{L}) = \int \frac{d^2\mathbf{l}}{(2\pi)^2} g^{EB}(\mathbf{l},\mathbf{L}) E^*(\mathbf{l}) B(\mathbf{l}-\mathbf{L})$$

reconstruction with **polarization lensing** pipeline: **high resolution / correlation**

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



estimate of lensing deflection with **Polarization**

Differences Between Temp. and Pol. Lensing

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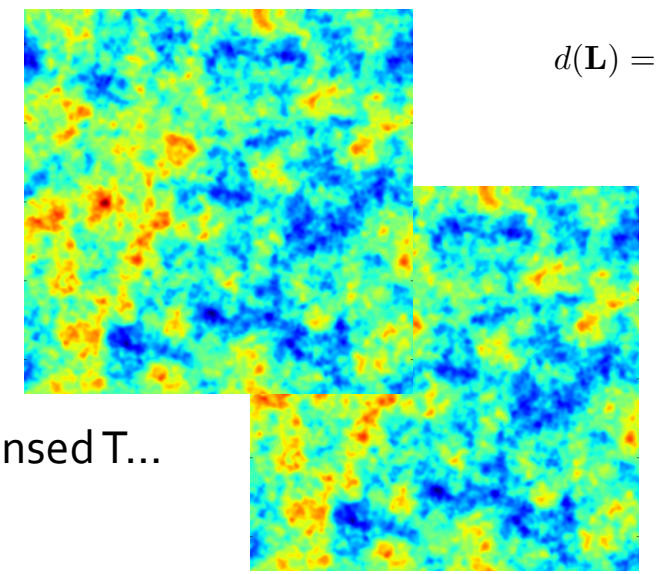


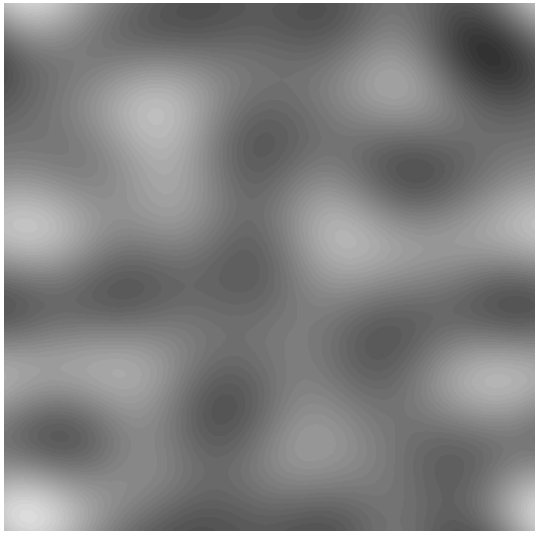
lensed T…

maps

$$d(\mathbf{L}) = \int \frac{d^2\mathbf{l}}{(2\pi)^2} g^{TT}(\mathbf{l},\mathbf{L}) T(\mathbf{l}) T^*(\mathbf{l}-\mathbf{L})$$

reconstruction with **temperature lensing** pipeline: **low resolution / correlation**

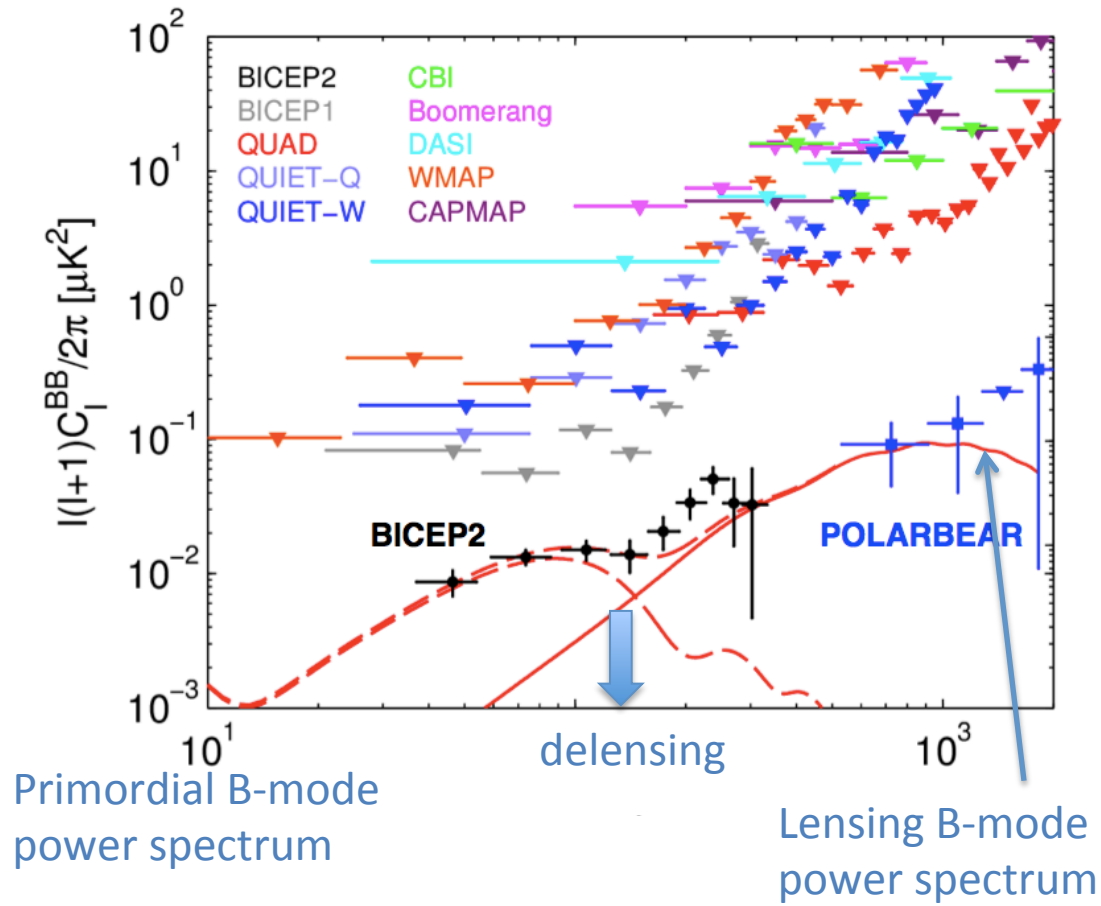
$|\mathbf{d}(\hat{\mathbf{n}})|_{\mathrm{filt}}$



estimate of lensing deflection with **Temperature**

Application of Polarization Lensing: Delensing The CMB

- Primordial B-mode polarization is a key observable for understanding the early universe
- Lensing B-mode **will** be limiting noise (either will limit n_T or will limit constraint on r)
- Idea: if know lensing, d, subtract off lensing B mode ~ E d i.e., delens

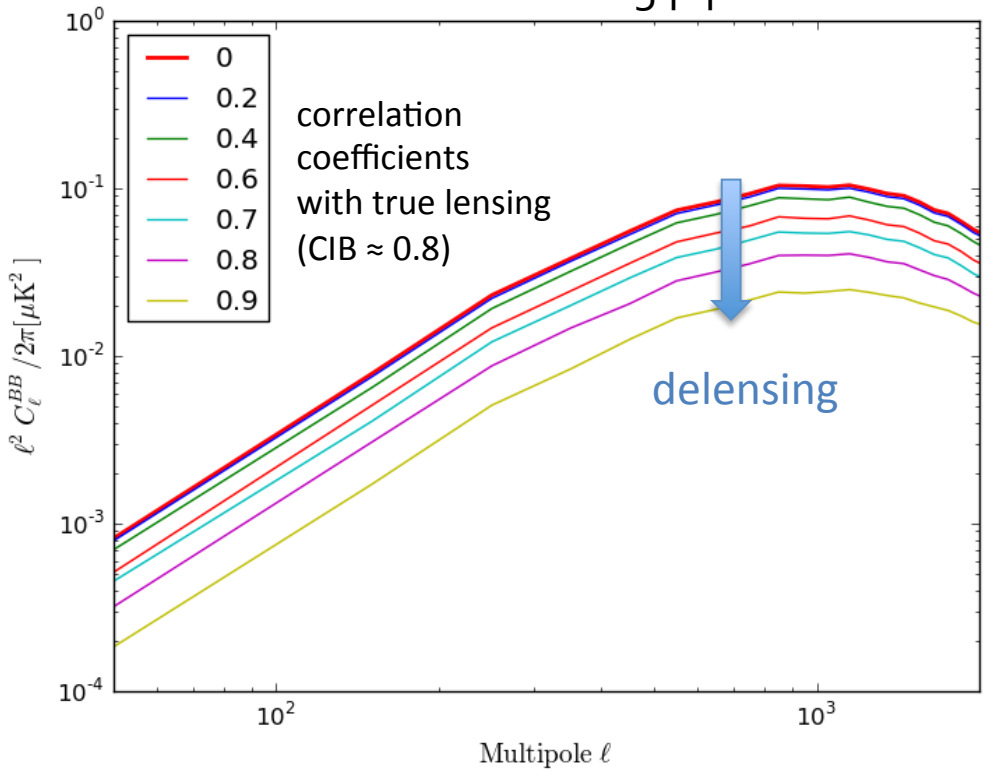


[POLARBEAR Collaboration 2014 incl. BDS, BICEP2 Collaboration 2014]

Delensing with CMB Polarization

- The B-mode power removed depends on the correlation of "delensing field" with true lensing, ~ r^2 (at l=10-1000)
- Polarization lensing is best due to highest correlation, though some large scale structure fields also work well (e.g., CIB)
- Ongoing work on improving methods, combining CMB + LSS delensing fields, demonstrating with data

simulated delensing pipeline



[Sherwin 2014 in prep.]

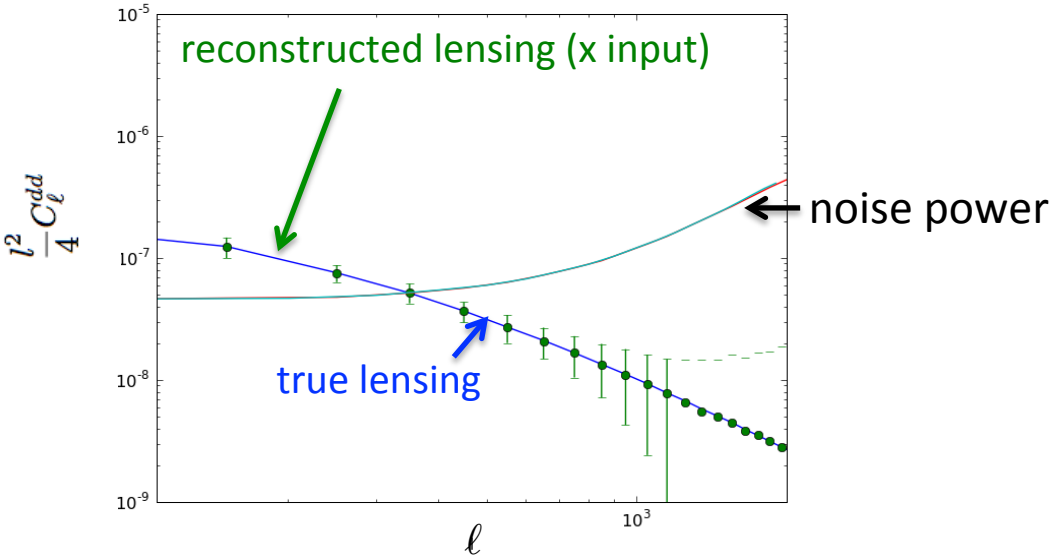
[Smith et al. 2010]

Polarization Lensing Reconstruction: Pipelines

- Polarization lensing pipeline (near-optimal) developed for two high-resolution CMB telescopes:
  [Pearson, Sherwin, Lewis 2014]

- POLARBEAR, so far, measured polarization to great depth, ~5uK' over ~30 sq. deg

- ACTPol, so far, measured ~200 sq. deg. of polarization at ~12uK'



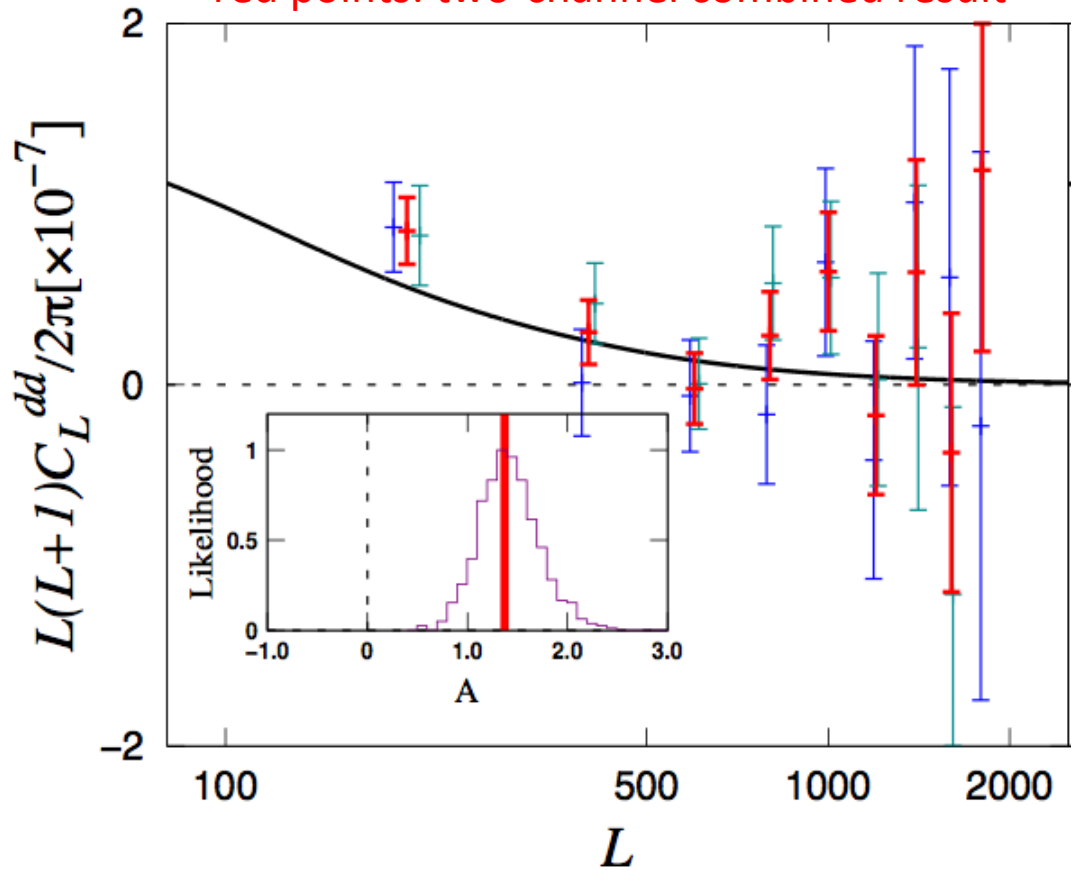
POLARBEAR telescope

ACTPol telescope

Lensing Power Spectrum: Detection in Polarization with POLARBEAR

- 4.2 sigma result, first CMB-only detection of pol. Lensing – and lensing B-modes
- Novel measurement: proof of concept
- Blind analysis; passes a number of null tests and systematic checks; signal seen in two channels on three maps

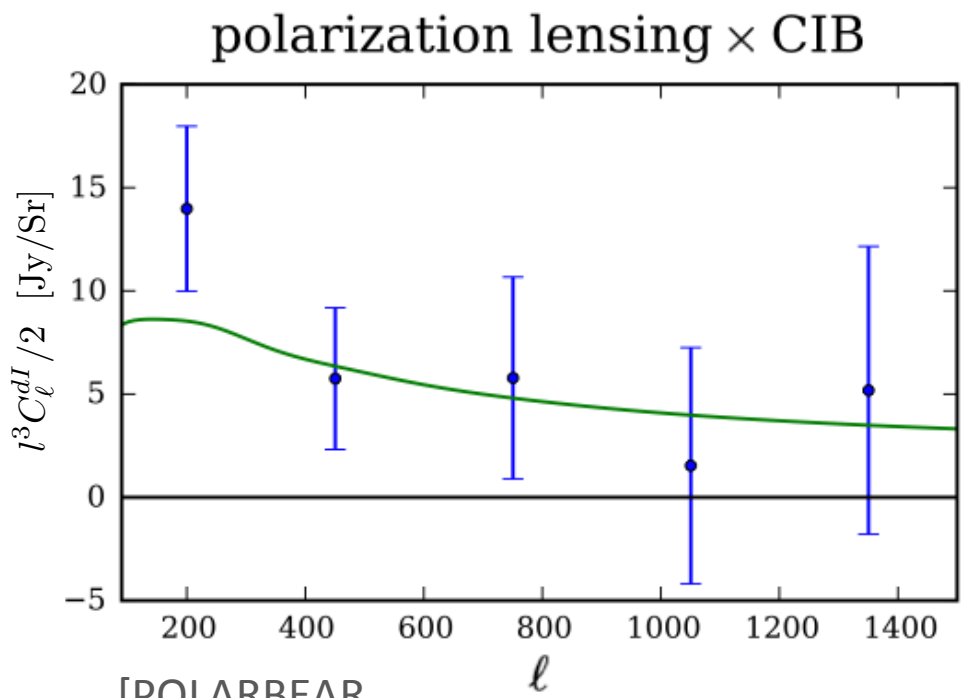
red points: two-channel combined result



[POLARBEAR Collaboration 2013, incl. BDS]

Lensing Cross-correlations: POLARBEAR Lensing x Infrared Background (CIB)

- 4 sigma detection: early measurement of polarization lensing / B-modes (with Hanson et al. 2013)
- Robust: systematics don't correlate!
- Blind analysis; passes numerous null-tests and systematic checks

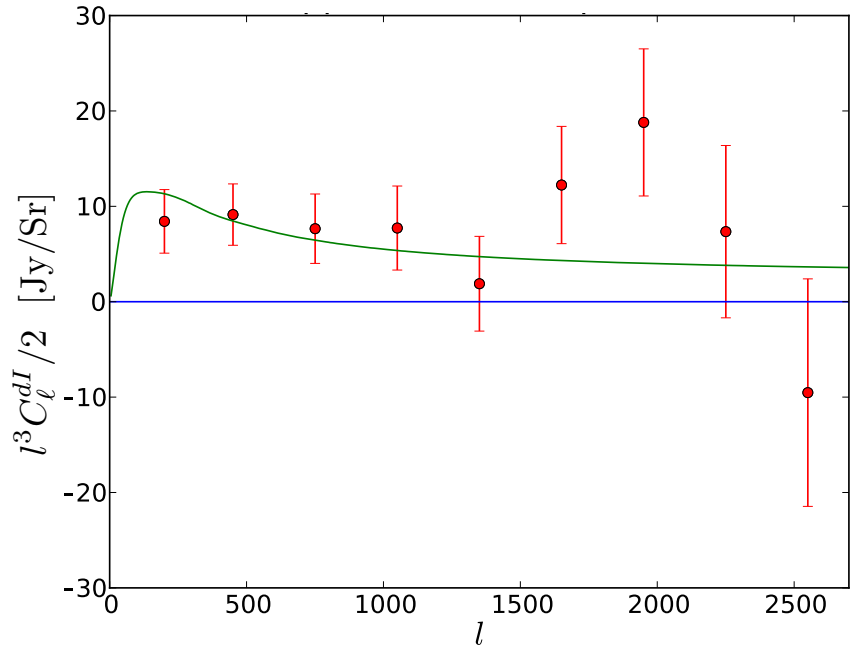


[POLARBEAR Collaboration 2013, incl. BDS (corr. auth.)]

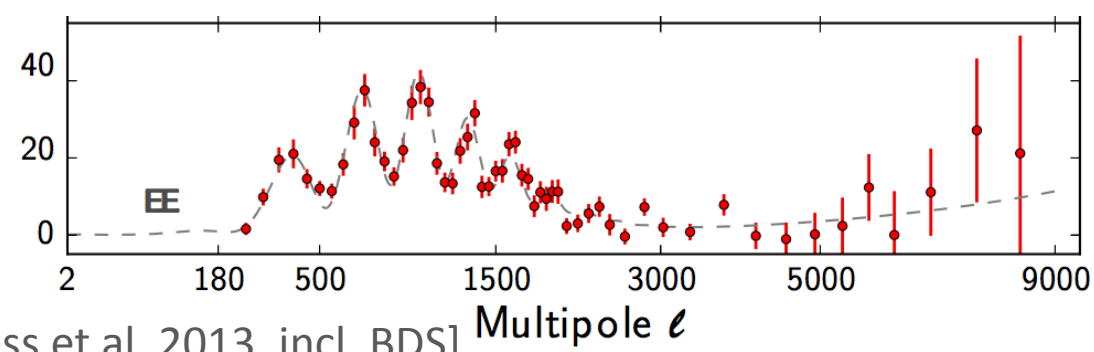
Polarization Lensing Measurements with ACTPol

- 5 sigma polarization-only lensing with ACTPol, with only first 3 months of data
- Soon: higher (~10+ sigma) S/N cross and auto power spectra
- (See also: high S/N EE power spectrum)

preliminary



[Van Engelen, Sherwin, Sehgal et al. in prep.]



[Naess et al. 2013, incl. BDS]

Upcoming Cosmological Constraints from CMB Polarization Lensing Experiments

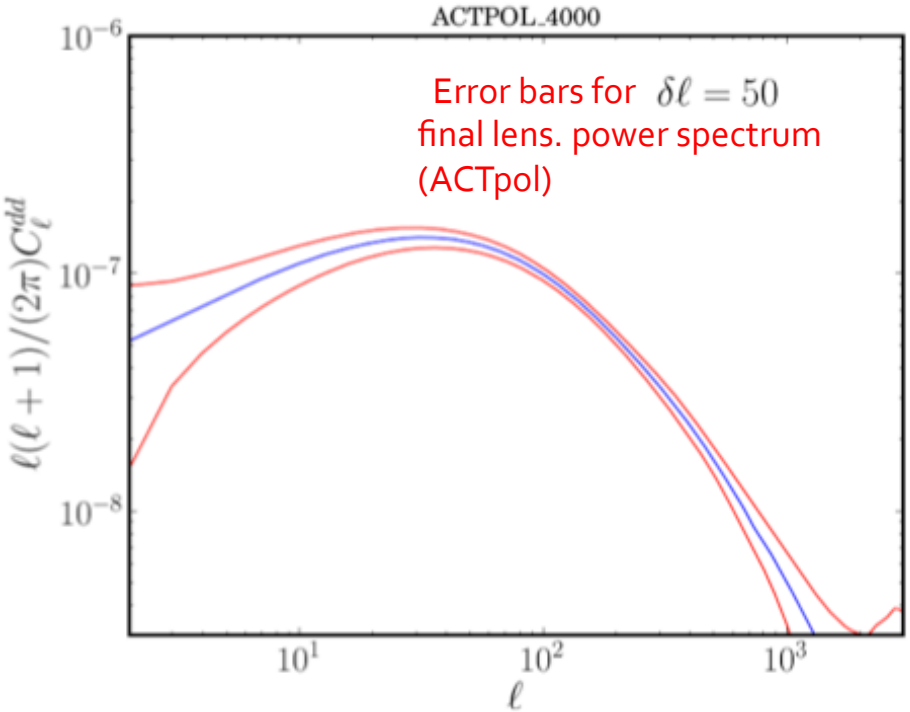
Upcoming Polarization Lensing Science with ACTPol-wide / PB-II…

ACTPol, POLARBEAR-II, SPTPol and similar experiments will soon measure the lensing signal at ~50+ sigma and hence

- Measure neutrino masses, with e.g., ACTPol + Planck, to <0.1eV.

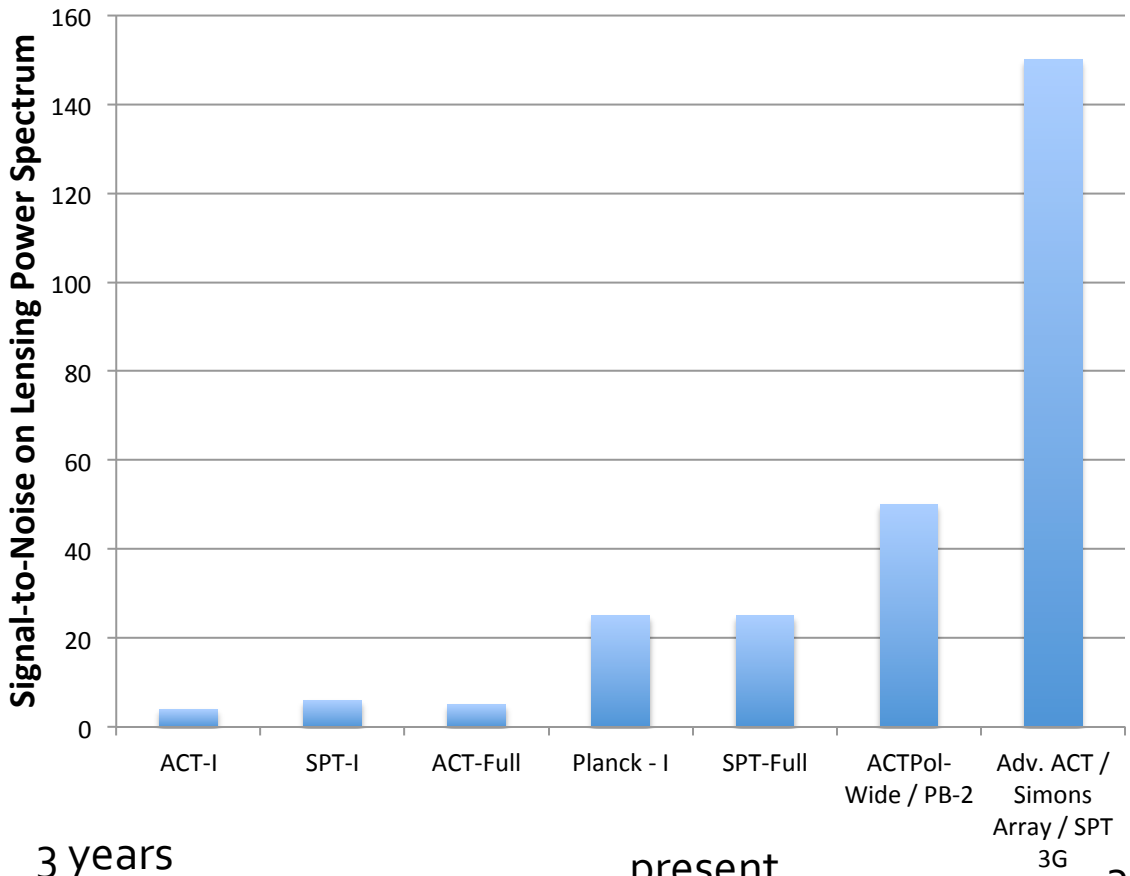
- Via cross-correlations: calibrate astrophysical and systematic biases in galaxy and weak lensing surveys; constrain neutrino masses + DE

[e.g. Hand, Das, Leautheaud, Sherwin et al. 2013]



AdvancedACT, Simons Array, SPT 3G, CMB S4…

- Progress expected to continue with upcoming experiments
- AdvancedACT/ S.A./ SPT3G – 2015 onwards can measure lensing at >>100 sigma, neutrino mass to within ~0.02eV
- Exciting prospects, but lots of work to do!



3 years ago

present day

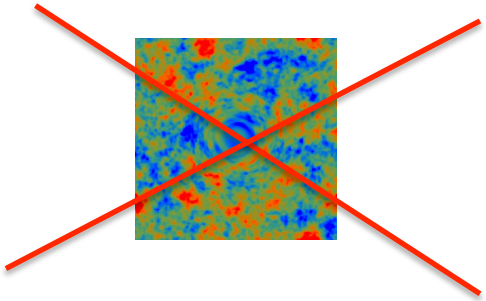
3 years from now

Summary

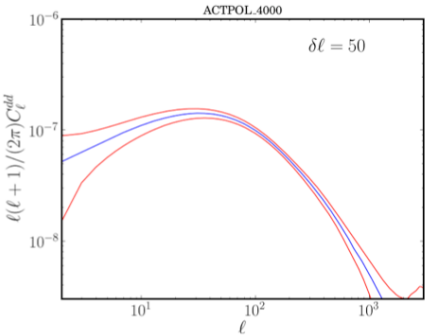
- Rapid progress in CMB temperature lensing measurements (e.g. ACT to Planck) has made lensing a powerful probe of fundamental physics, e.g. neutrino mass

$$d \rightarrow m_\nu$$

- Recently: first measurements of polarization lensing (with SPTPol, POLARBEAR, ACTPol) – this technique allows for much higher accuracy. Allows delensing to study primordial B!



- Work has begun on higher precision CMB (polarization) lensing surveys, which will become one of our most powerful tools for cosmology



Bonus slides…

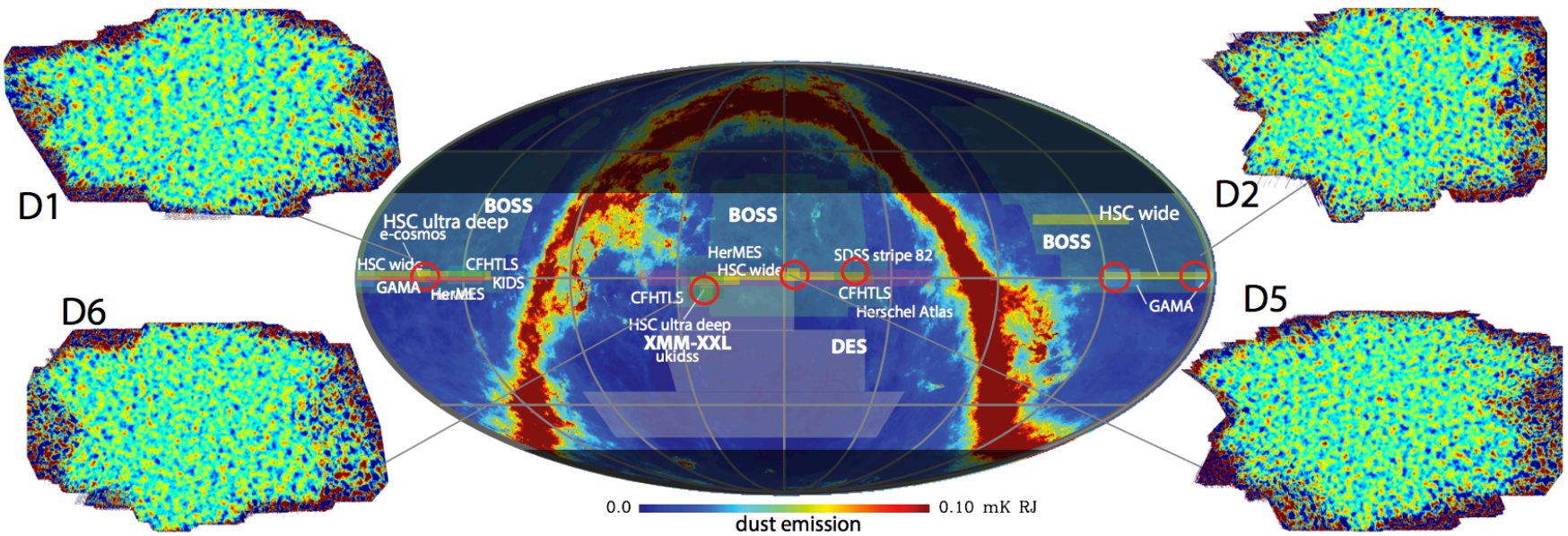
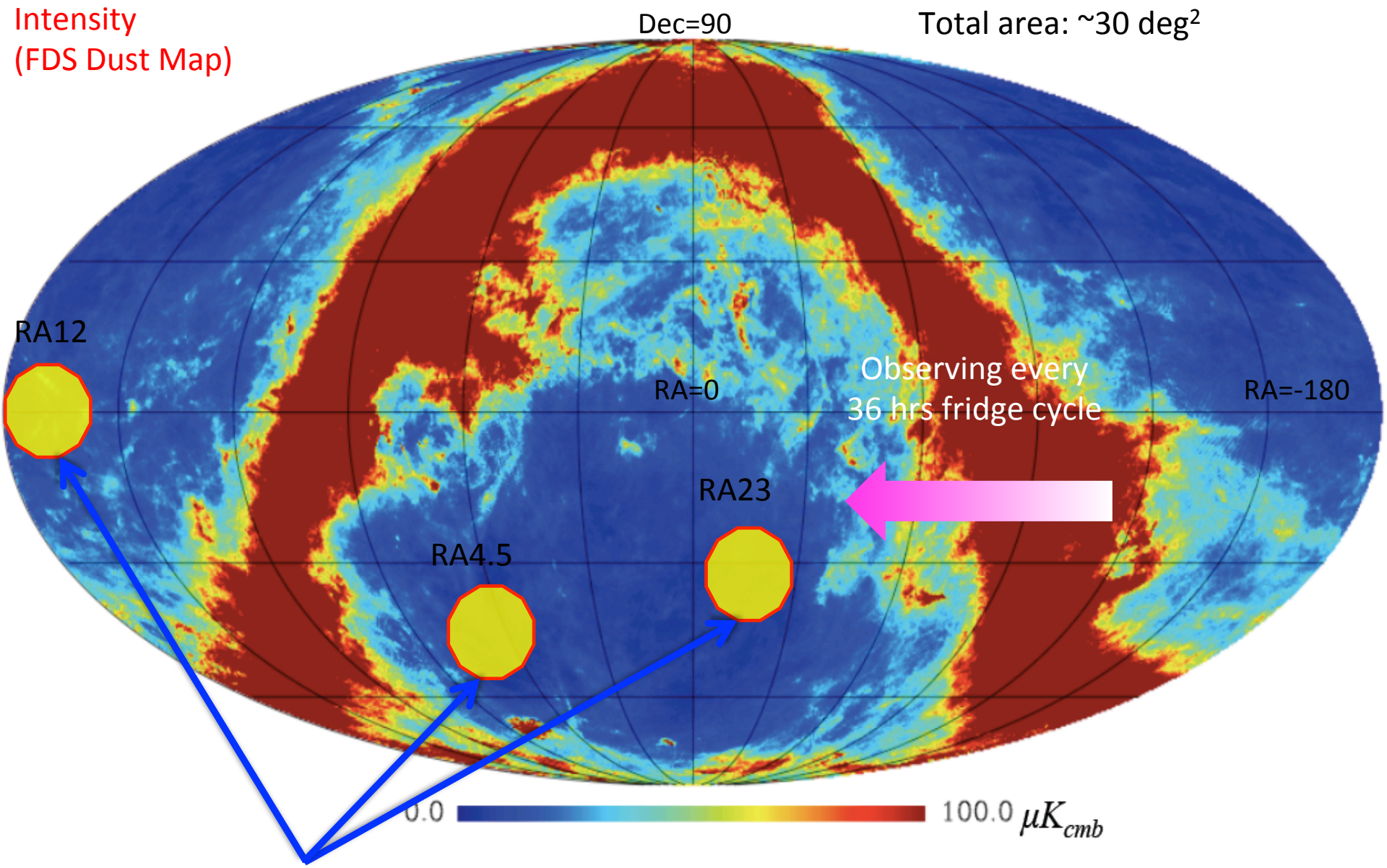


FIG. 1.— ACTPol maps and overlapping surveys. The maps have been filtered to emphasize $\ell > 300$. The power spectra are obtained with only the high S/N region of each map. Going from left to right across the equator, the red circles indicate patches D1, D6, D5, D4, D3, D2 (the first ACTPol season focused on D1, D2, D5, and D6). More than half the sky, as indicated by the light colored area, is accessible to ACTPol. Overlapping surveys include SDSS (SDSS 2014), BOSS(BOSS 2014), CFHTLS (CFHTLS 2014; Hand et al. 2013), XMM-XXL (XMM-XXL 2014), Herschel (HerMES & HeLMS, Oliver et al. (2012); Viero et al. (2014)), HSC (Subaru 2014), DES (DES 2014), GAMA (Driver et al. 2009), and KiDS (de Jong et al. 2013).

Observations in 2012 & 2013



select low dust regions

~3,300 hrs

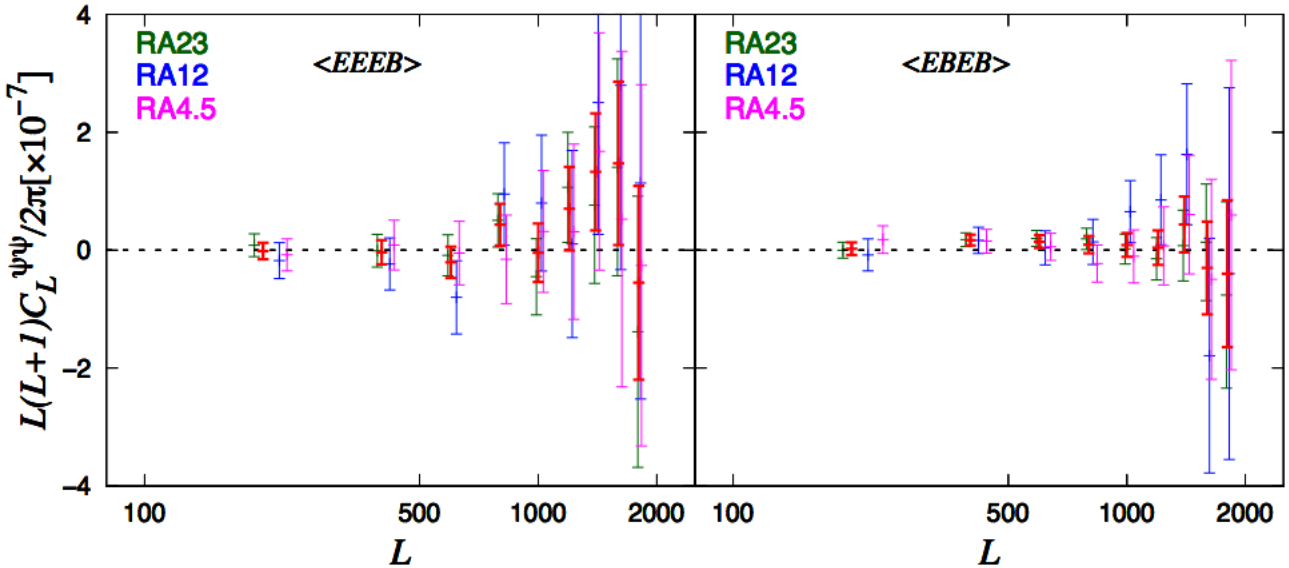


FIG. 2: Curl null power spectra for each of the three patches for the $\langle EEEB \rangle$ and $\langle EBEB \rangle$ estimators. The patch-combined curl null power spectra are shown in red for the two lensing estimators. All the curl null power spectra are consistent with zero.

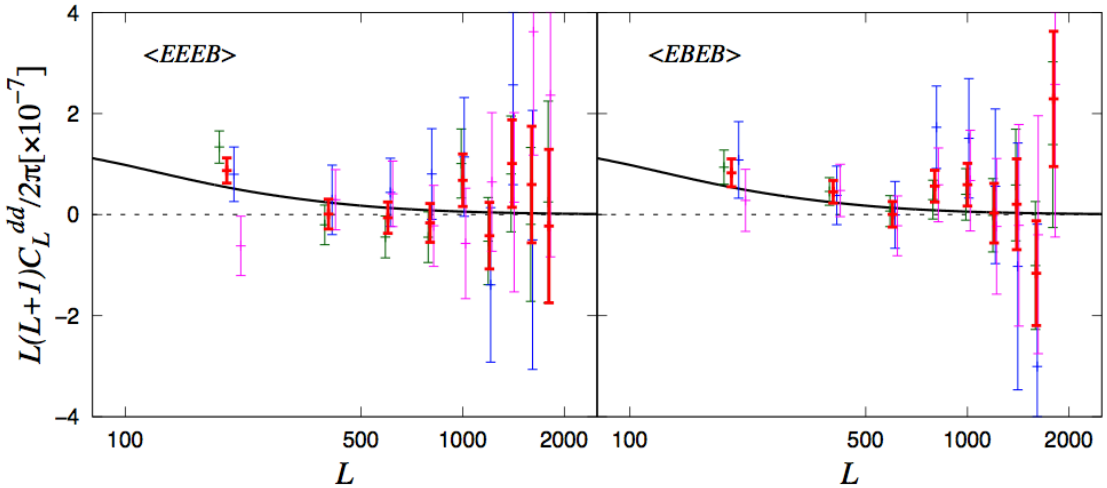


FIG. 3: Polarization lensing power spectra for each lensing estimator. Measured polarization lensing power spectra for each of POLARBEAR's three patches, for both lensing estimators $\langle EEEB\rangle$ (left) and $\langle EBEB\rangle$ (right). The lensing signal predicted by the ΛCDM model is shown as the solid black curve. The measured lensing power spectra are shown for each patch in dark green (RA23), blue (RA12) and magenta (RA4.5), respectively and are offset in L slightly for clarity. The patch-combined lensing power spectrum is shown in red.

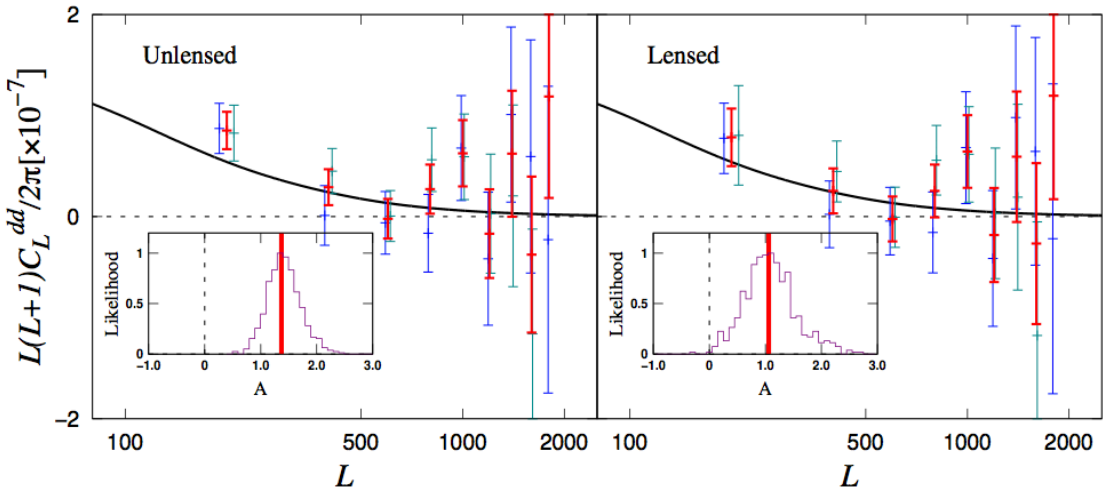


FIG. 4: Polarization lensing power spectra. Polarization lensing power spectra co-added from the three patches and two estimators are shown in red. The lensing signal predicted by the ΛCDM model is shown as the solid black curve. The polarization lensing power spectrum $\langle EEEB\rangle$ is in blue and $\langle EBEB\rangle$ dark green. *Left:* A 4.2σ rejection of the null hypothesis of no lensing. These data indicate a lensing amplitude $\mathcal{A} = 1.37 \pm 0.30 \pm 0.13$ normalized to the fiducial ΛCDM value. *Right:* The same data, assuming the existence of gravitational lensing to calculate error bars–including sample variance and including the covariance between $\langle EEEB\rangle$ and $\langle EBEB\rangle$. In this case, the lensing amplitude is measured as $\mathcal{A} = 1.06 \pm 0.47^{+0.32}_{-0.27}$, corresponding to 53% uncertainty on the amplitude of the C_L^{dd} power spectrum (26% uncertainty on the amplitude of matter fluctuations). The histograms of the amplitudes $\mathcal{A}$ from 500 unlensed and lensed simulations are shown in the inset boxes.

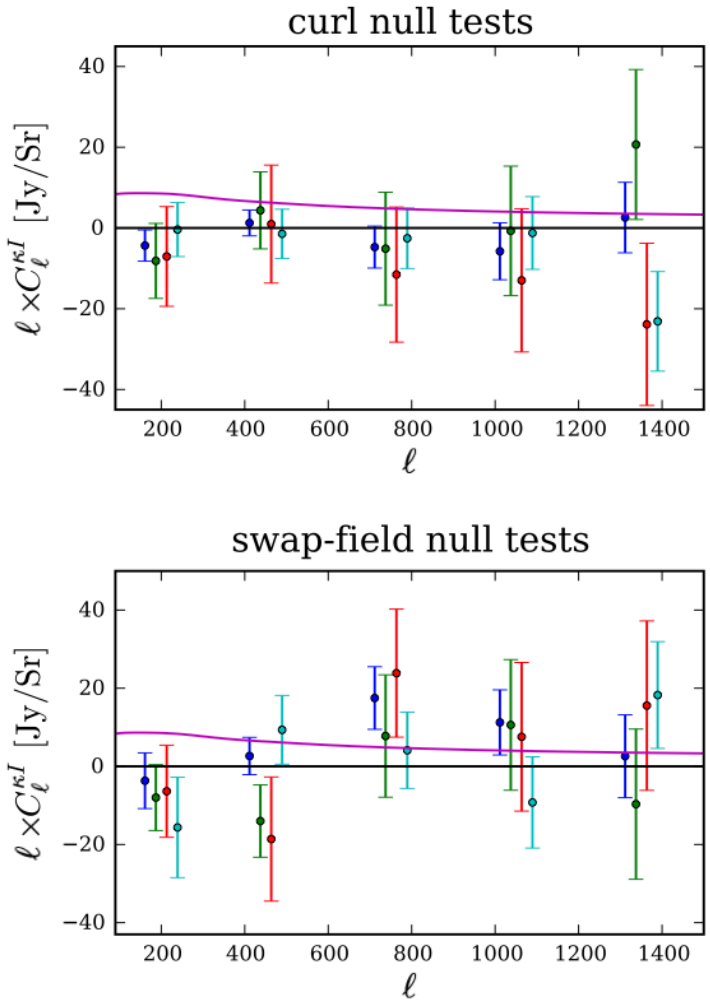


FIG. 2: **Upper panel**: Curl null tests for all four combinations of estimator / map – EB/RA23 (dark blue), EE/RA23 (green), EE/RA12 (red), EB/RA12 (cyan). In this figure, curl null test values and errors have been scaled down by a factor of two for the EE estimator, for ease of plotting (PTEs are unaffected). **Lower panel**: Swap-field null tests. Note that the four sets of points are not entirely statistically independent. The null tests are consistent with zero and thus provide no evidence for any systematic errors.

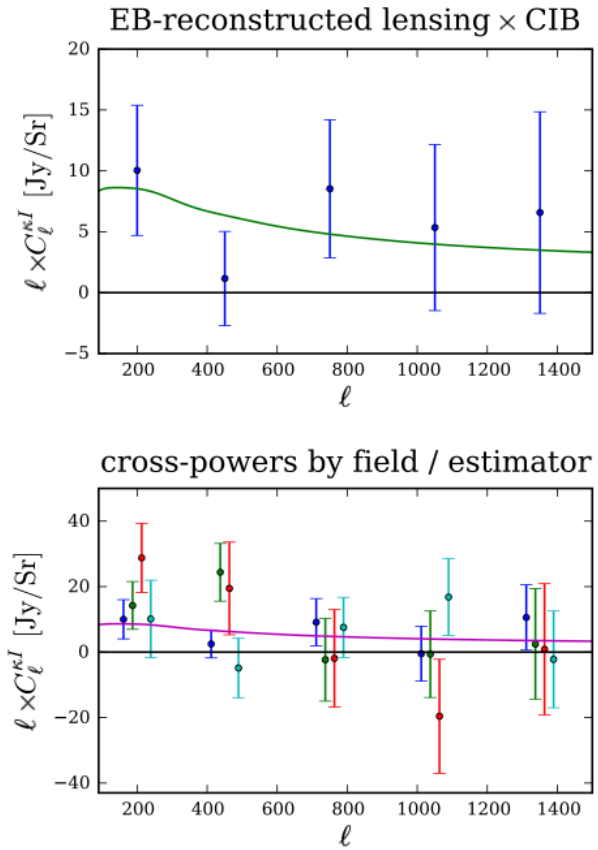


FIG. 1: Cross-power spectra of CMB polarization lensing and the 500μm *Herschel* CIB flux. **Top panel**: the minimum variance combination of all polarization lensing measurements cross-correlated with the *Herschel* maps; this result corresponds to 4.0σ evidence for gravitational lensing of CMB polarization. **Middle panel**: the cross power of EB-reconstructed lensing with the *Herschel* maps; constructed from the EB estimator applied to both POLARBEAR maps, this result corresponds to 2.3σ evidence for lensing B-modes. **Bottom panel**: all four combinations of the two lensing estimators (EE, EB) applied to two different POLARBEAR maps (RA23, RA12) and cross-correlated with *Herschel* - EB/RA23 (dark blue), EE/RA23 (green), EE/RA12 (red), EB/RA12 (cyan), listing from left to right for each bandpower. The fiducial theory curve for the lensing – CIB cross-spectrum [16] is also shown (solid line).