# The Planck Lensing Potential

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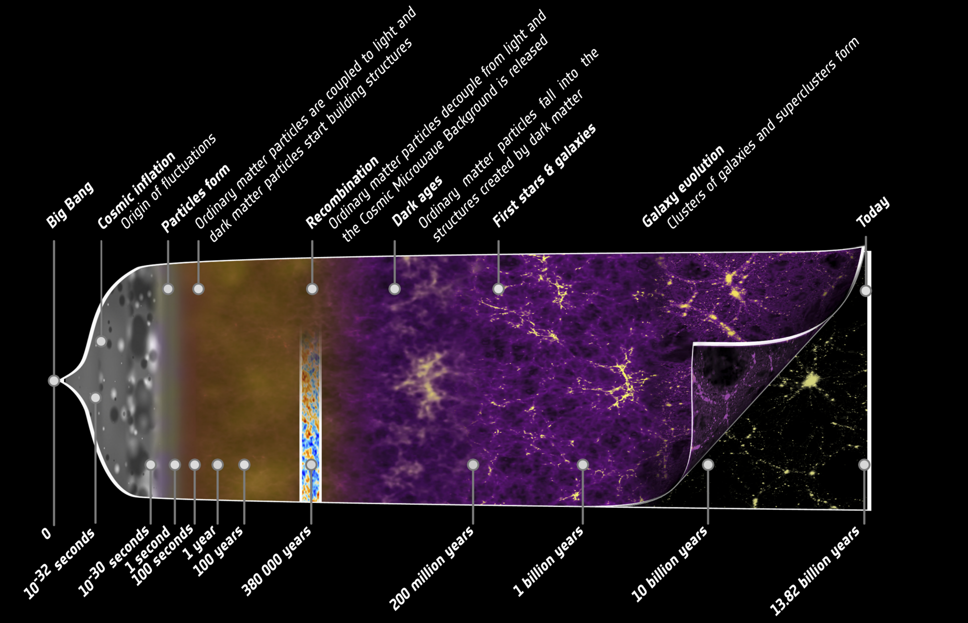
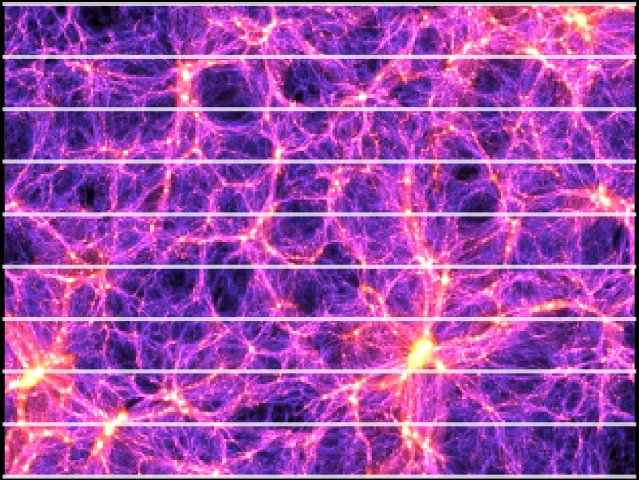
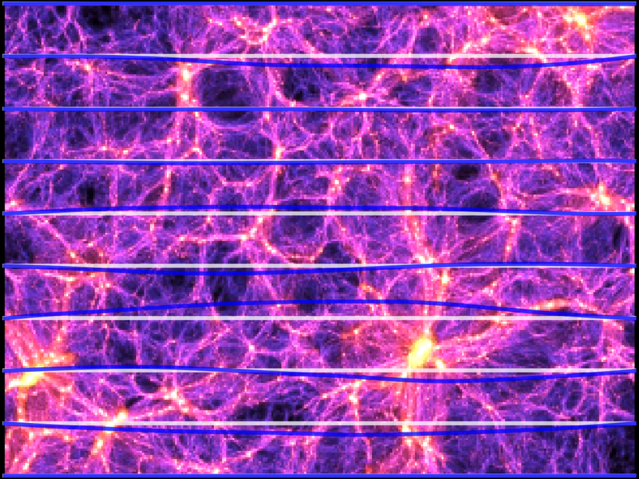
On behalf of the Planck Collaboration

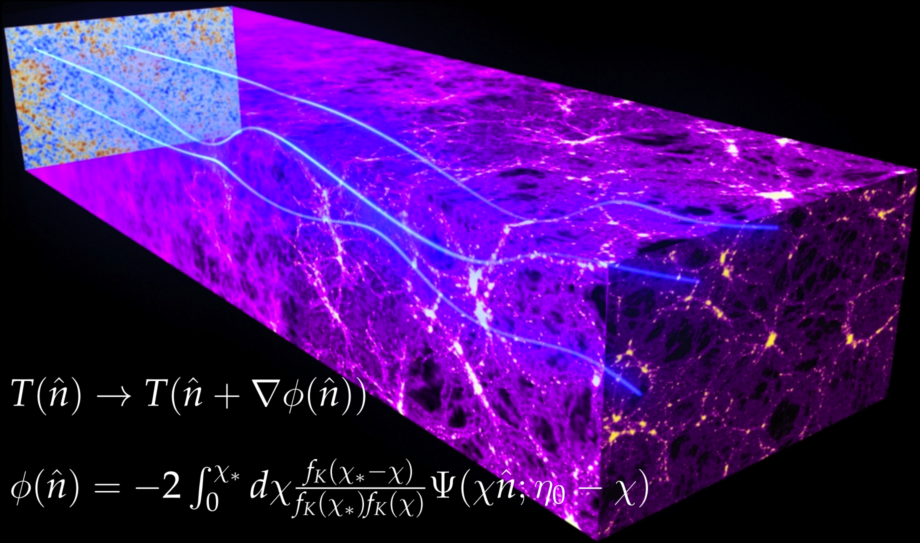
Observations and Theoretical
Challenges in Primordial Cosmology
Monday April 22nd, 2013



Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years







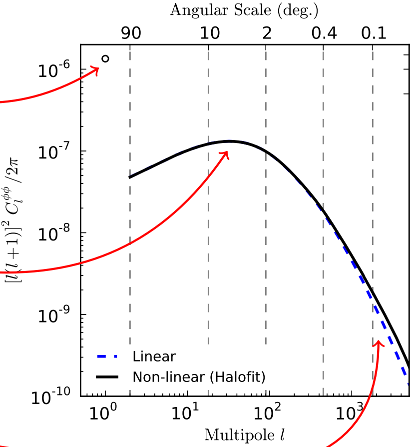
$$T(\hat{n}) \to T(\hat{n} + \nabla\phi(\hat{n}))$$

$$\phi(\hat{n}) = -2\int_0^{\chi_*} d\chi \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi\hat{n}; \eta_0 - \chi)$$

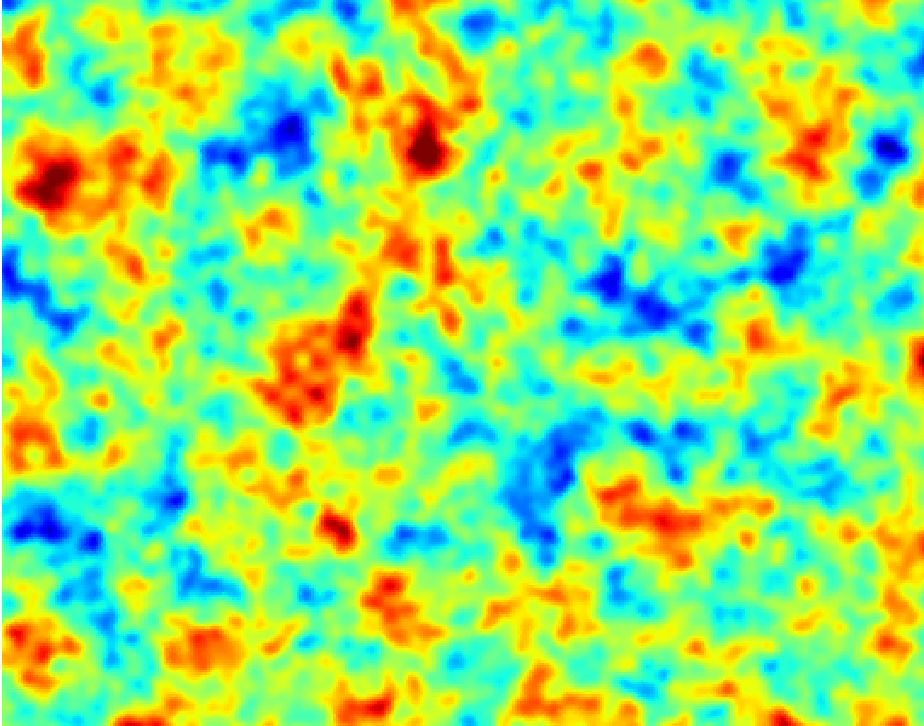
# LENSING POWER SPECTRUM

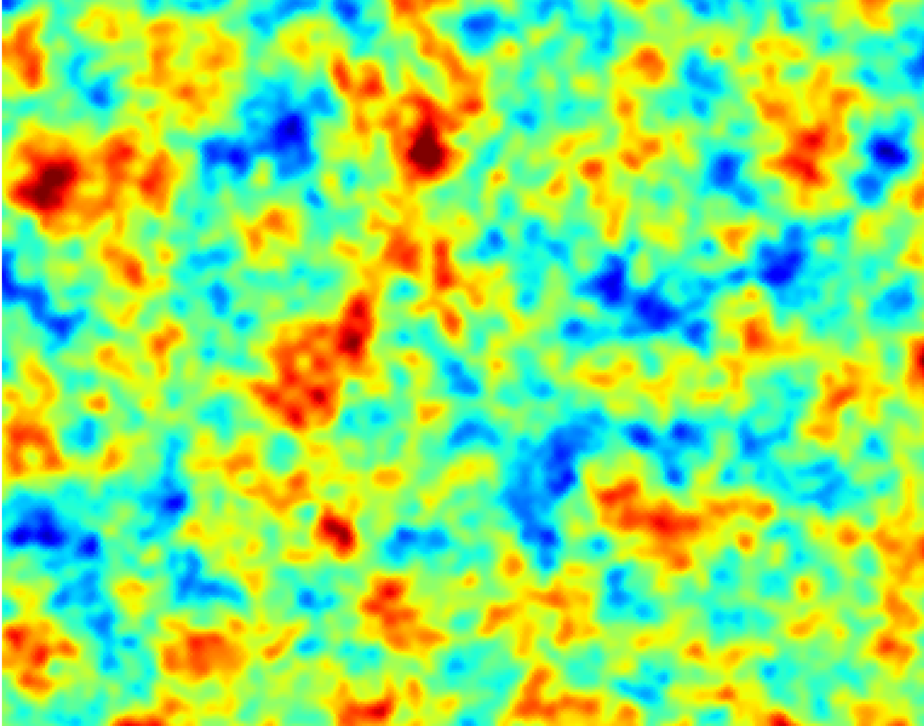
More details: Lewis and Challinor (astro-ph/0601594).

- Velocity dipole, with $v/c \approx 0.00123$ has deflection RMS of $\langle|\nabla\phi|^2\rangle^{1/2} = 3'$.
- Large-scale structure in the linear regime. Coherent over $\frac{300\text{Mpc}}{7000\text{Mpc}} \approx 2^o$. Deflection per "structure" of $\sim 0.3'$ so RMS of $\langle|\nabla\phi|^2\rangle^{1/2} \approx \sqrt{50} \times 0.3' = 2.4'$.
- Power spectrum corrections from non-linearity, although Gaussian still a good approximation.



CMB Temperature (Unlensed)



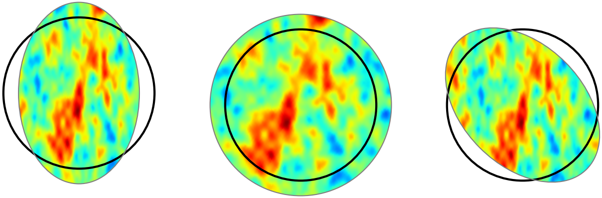


CMB Temperature (Lensed)

# CMB Lens Reconstruction

- We want to reconstruct the lensing potential $\phi(\hat{n})$.
- How to get the large-scale lenses: start by decomposing the lensing potential into convergence and shear modes:

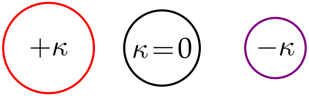
$$-\nabla_{ij}\phi = \begin{bmatrix} \kappa + \gamma_+ & \gamma_- - \omega \\ \gamma_- + \omega & \kappa - \gamma_+ \end{bmatrix}.$$



$\gamma_+$ $\kappa$ $\gamma_-$

# CMB Lens Reconstruction

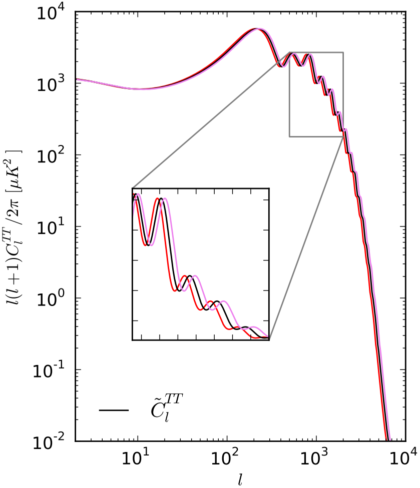
- Consider taking the power spectrum of a small patch with uniform $\kappa$.




- To first order in $\kappa$ we have $C_l^{TT} = \tilde{C}_l^{TT} + \kappa \Delta_l^{\kappa}$, where

$$\Delta_l^{\kappa} = \left[ l \frac{\partial \tilde{C}_l^{TT}}{\partial l} + 2\tilde{C}_l^{TT} \right]$$

- Look for $\Delta_l^{\kappa}$ in (localized) estimates of power spectrum, stitch together to get $\kappa(\hat{n})$.



# Quadratic CMB Lens Reconstruction

Suppose lenses are fixed, then CMB is still Gaussian, but becomes statistically anisotropic. Averaging over CMB realizations have

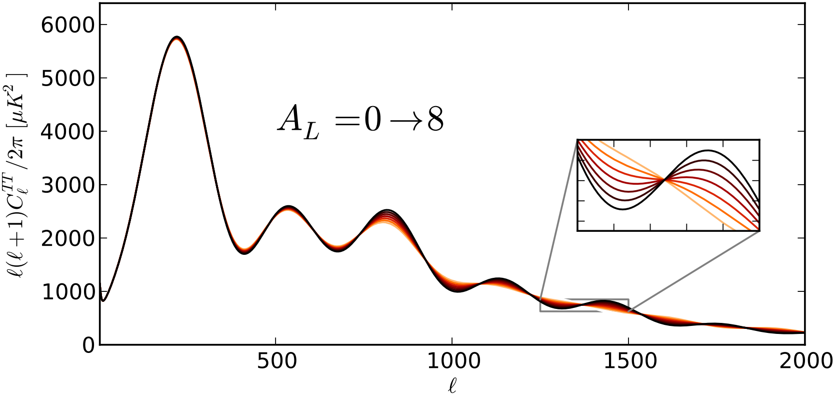
$$\frac{\partial\langle T(\vec{l}_1)T(\vec{l}_2)\rangle_{\rm CMB}}{\partial\phi(\vec{l})} = \Delta^{\phi}(\vec{l}_1,\vec{l}_2) = \frac{1}{2\pi}\vec{l}\cdot\left[\vec{l}_1\tilde{C}^{TT}_{l_1} + \vec{l}_2\tilde{C}^{TT}_{l_2}\right] + \mathcal{O}(\phi^2)$$

where $\vec{l} = \vec{l}_1 + \vec{l}_2$. As for $\kappa$, write down usual estimator as

$$\hat{\phi}(\vec{l}) = N^{\phi\phi}_l \int \frac{d^2\vec{l}_1}{2\pi}\hat{T}(\vec{l}_1)\hat{T}(\vec{l}_2)\Delta^{\phi}(\vec{l}_1,\vec{l}_2){\rm Var}^{-1}(T(\vec{l}_1)T(\vec{l}_2))\frac{1}{2}.$$

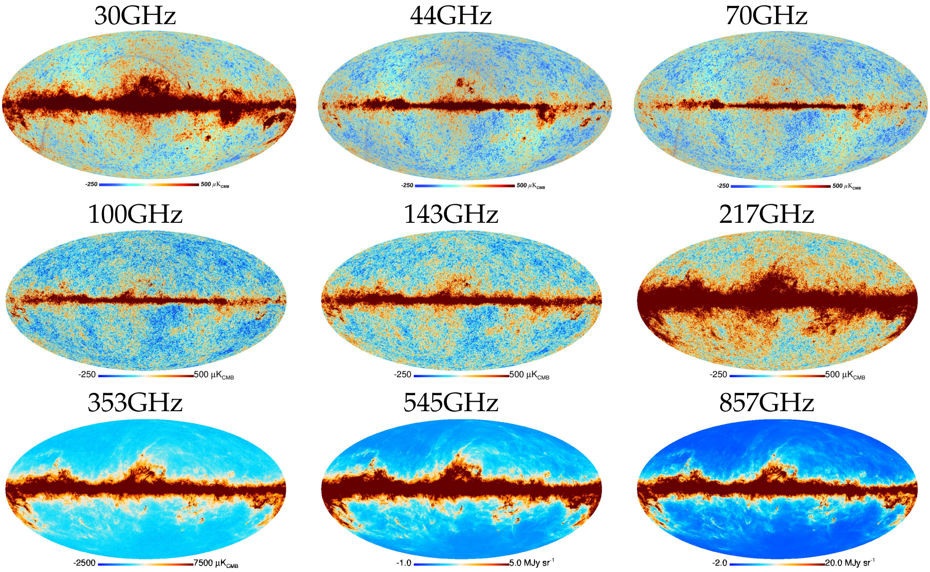
This is the minimum-variance quadratic estimator of Hu 2001 (astro-ph/0105424).

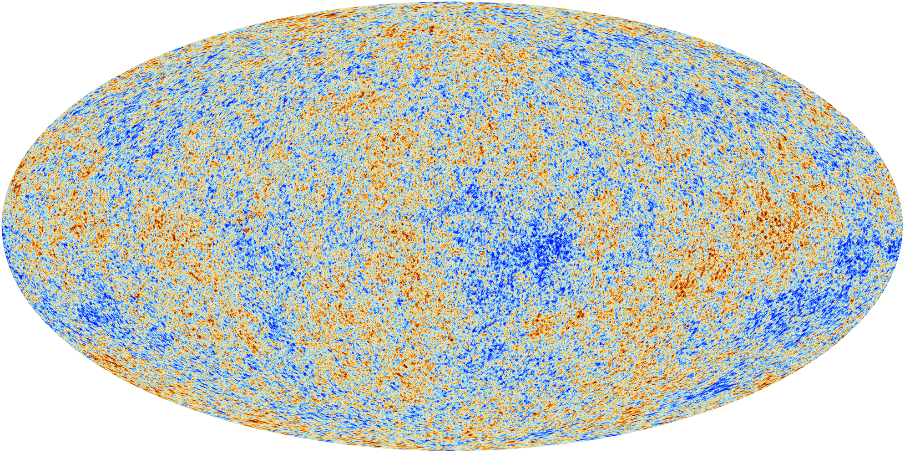
# Lensing Effect on the Power Spectrum

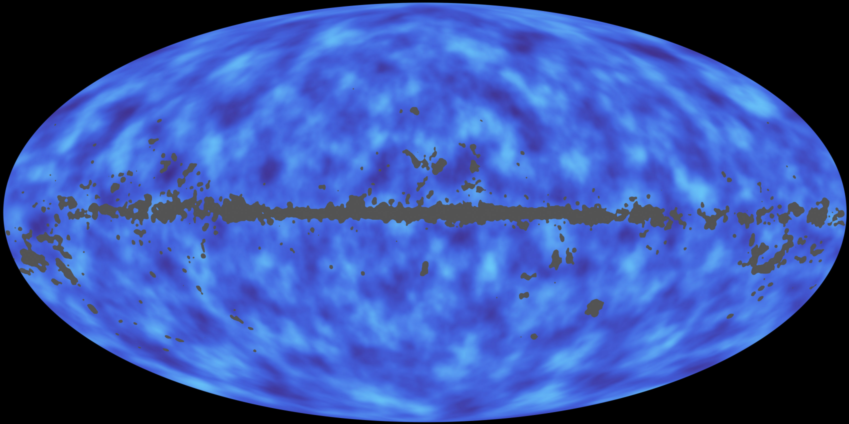


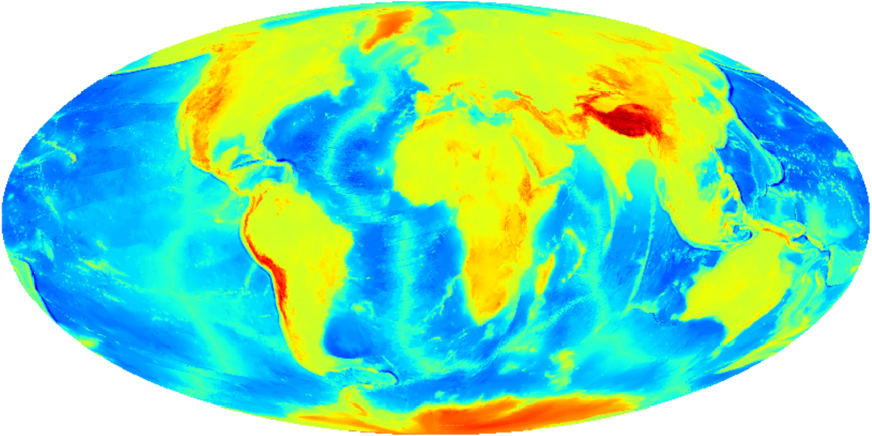

At second order, lensing smooths the accoustic peaks of the power spectrum. For interest, sometimes parameterize as $A_L$.

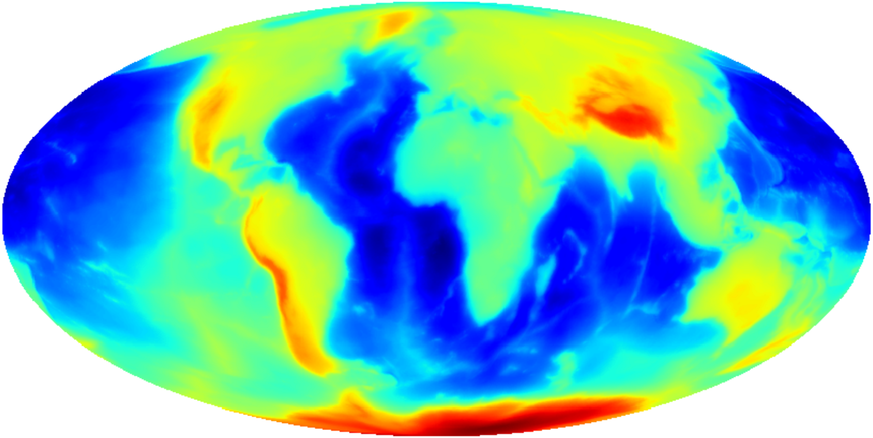
# Planck Sky Maps

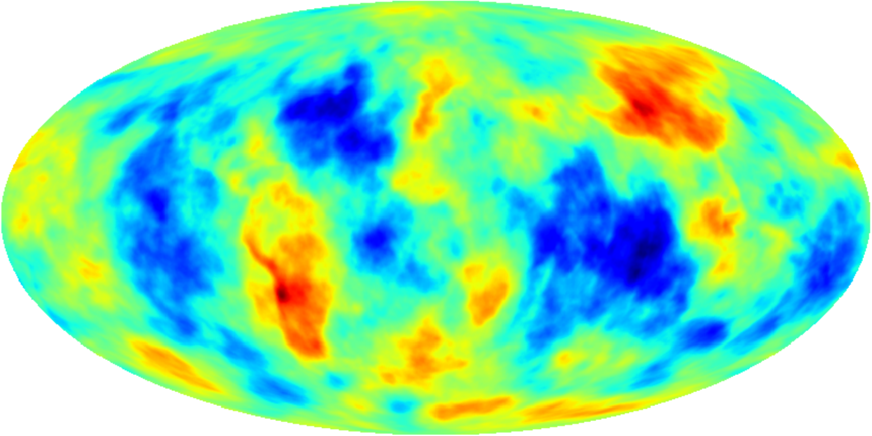




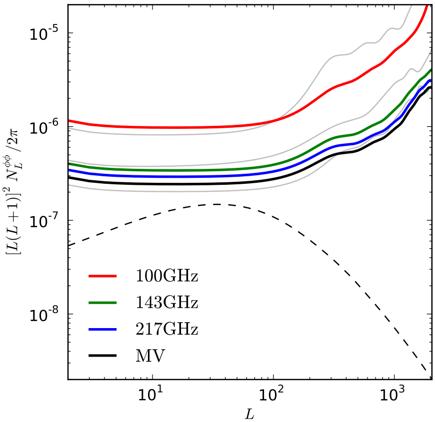


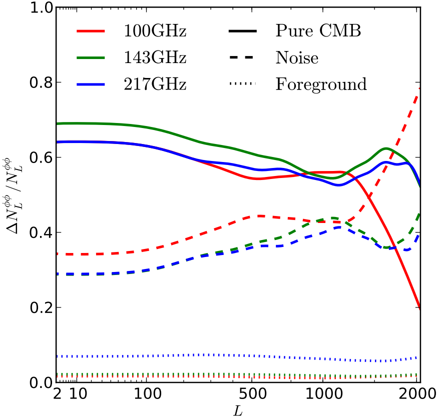


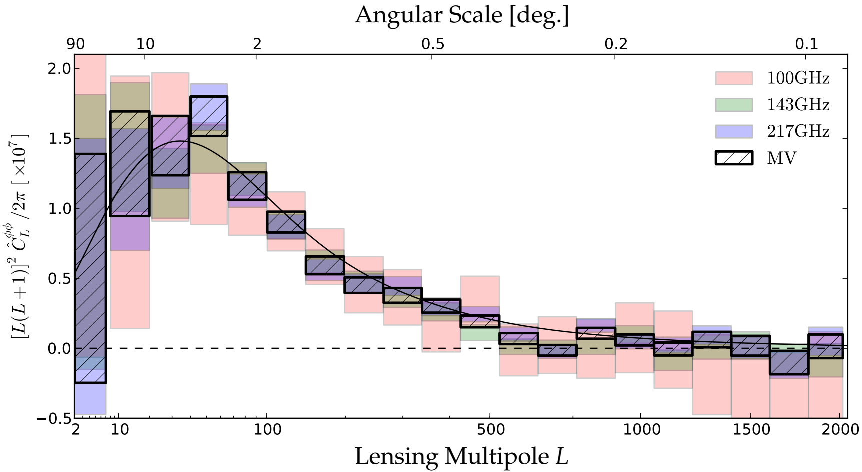




# Noise Levels / Noise Budget





Angular Scale [deg.]
90
10
2
0.5
0.2
0.1
100GHz
143GHz
217GHz
MV
$[L(L+1)]^2 \hat{C}_L^{\phi\phi} / 2\pi \, [\times 10^7]$
2.0
1.5
1.0
0.5
0.0
−0.5
2
10
100
500
1000
1500
2000
Lensing Multipole $L$

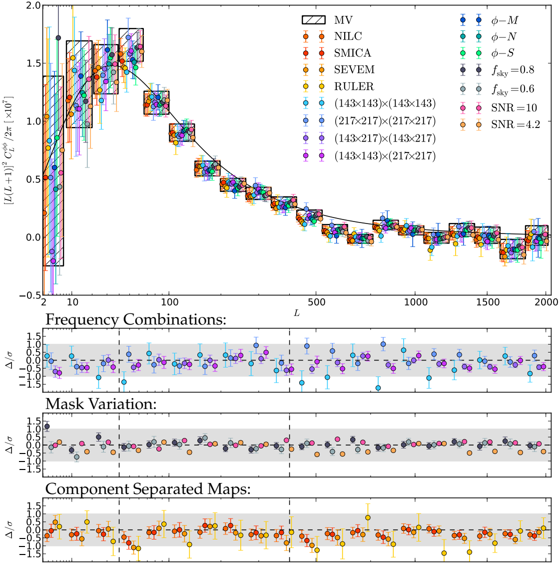
# TECHNICAL DETAILS:

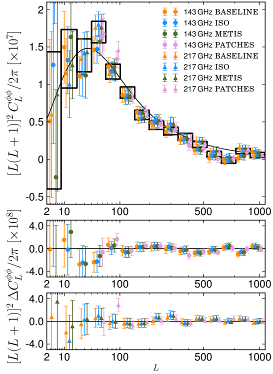
- Point source shot-noise correction.
- Frequency- and map- cross-estimators.
- Bias-hardened estimators for both instrumental and foreground contamination (Namikawa et. al. arxiv:1209.0091).
- Phase-dependent $N^{(0)}$ bias correction, motivated by likelihood:

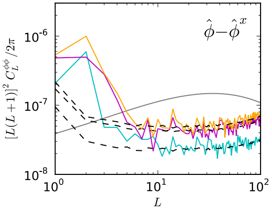
$$\Delta C^{\phi\phi}_{L,x}\Big|_{\rm N0} = \Big\langle - C^{\widetilde{\phi\phi}}_{L,x}\left[\bar{T}^{(1)}_{\rm MC}, \bar{T}^{(2)}_{\rm MC'}, \bar{T}^{(3)}_{\rm MC'}, \bar{T}^{(4)}_{\rm MC}\right] + C^{\widetilde{\phi\phi}}_{L,x}\left[\bar{T}^{(1)}_{\rm MC}, \bar{T}^{(2)}, \bar{T}^{(3)}_{\rm MC}, \bar{T}^{(4)}\right] + C^{\widetilde{\phi\phi}}_{L,x}\left[\bar{T}^{(1)}_{\rm MC}, \bar{T}^{(2)}, \bar{T}^{(3)}, \bar{T}^{(4)}_{\rm MC}\right] + C^{\widetilde{\phi\phi}}_{L,x}\left[\bar{T}^{(1)}, \bar{T}^{(2)}_{\rm MC}, \bar{T}^{(3)}, \bar{T}^{(4)}_{\rm MC}\right] + C^{\widetilde{\phi\phi}}_{L,x}\left[\bar{T}^{(1)}, \bar{T}^{(2)}_{\rm MC}, \bar{T}^{(3)}_{\rm MC}, \bar{T}^{(4)}\right] - C^{\widetilde{\phi\phi}}_{L,x}\left[\bar{T}^{(1)}_{\rm MC}, \bar{T}^{(2)}_{\rm MC'}, \bar{T}^{(3)}_{\rm MC}, \bar{T}^{(4)}_{\rm MC'}\right]\Big\rangle_{\rm MC,MC'}, \quad (17)$$

- Renormalizable likelihood code, so uncertainty in $C_\ell^{TT}$ or $B_\ell$ for lens reconstruction can be handled consistently with TT power spectrum analysis.

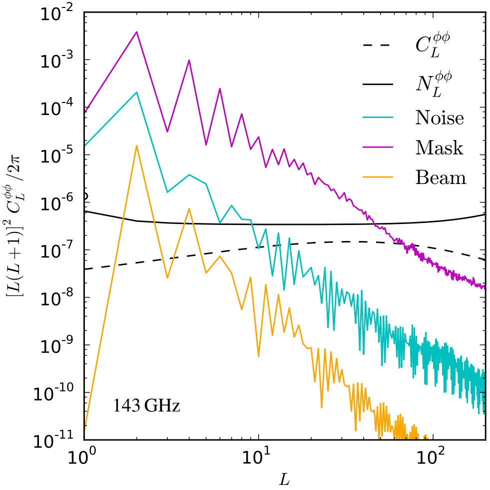
# Consistency Tests

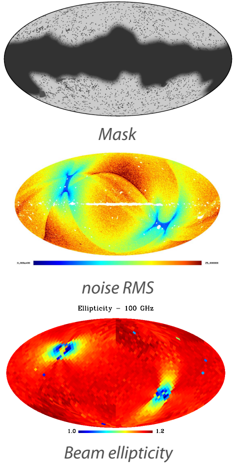


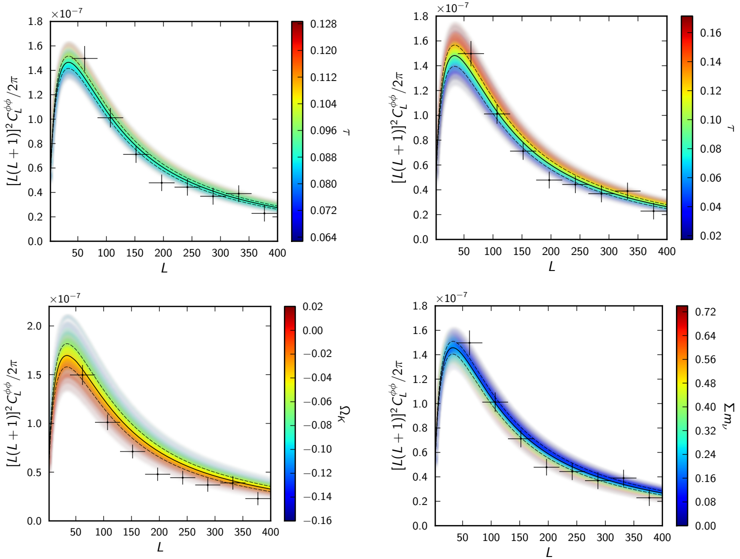



# LOW MULTIPOLES:



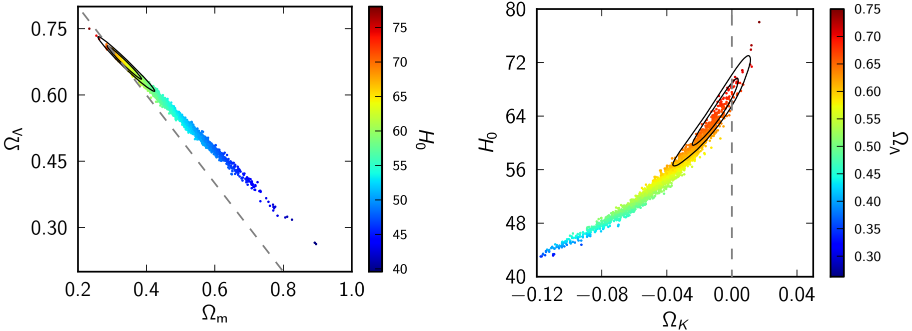




- "Mean-field" corrections are very large at low-$L$. We fail some detailed consistency tests at $L < 10$ (though not very badly!).



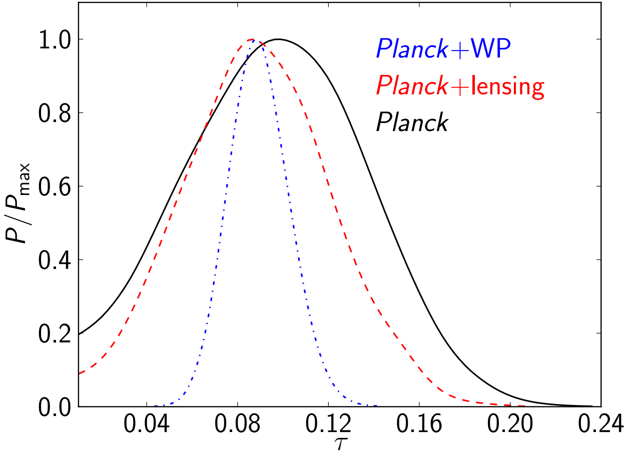

The lensing power spectrum provides a CMB lever arm on structure at intermediate redshifts.

# Parameter Constraints



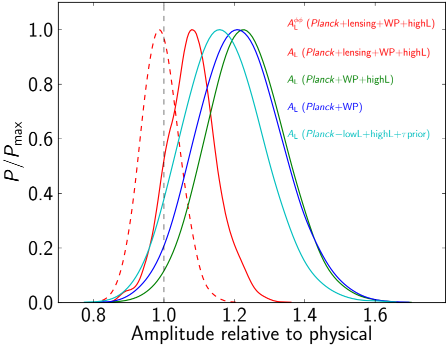

Lensing completely demolishes the CMB geometrical degeneracy (see also Sherwin et. al. 2011, van Engelen et. al. 2012 for ACT and SPT results).

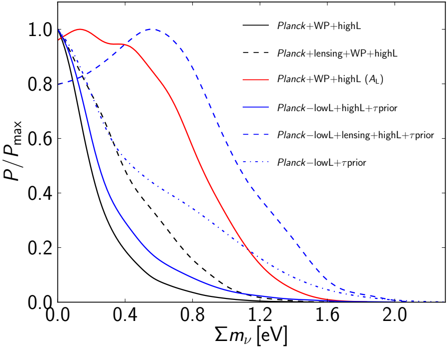
# Parameter Constraints




With Planck, lensing also helps to break the $A_s e^{-\tau}$ degeneracy in the primary CMB.

# PARAMETER CONSTRAINTS




Note: TT lensing power spectrum prefers high lensing amplitude relative to theory, leading to some counter-intuitive results. Something to watch.

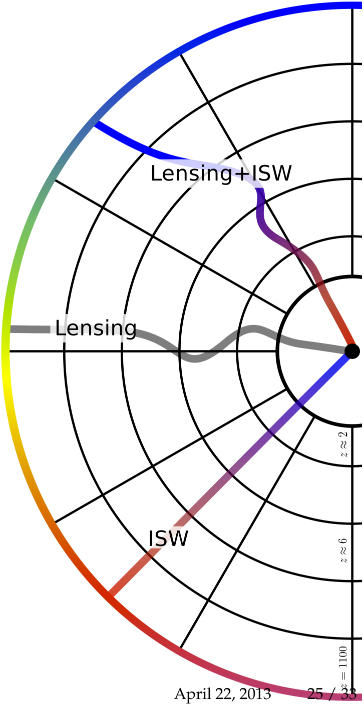
# Lensing-ISW Correlation

- We measure an amplitude for the lensing-ISW bispectrum of

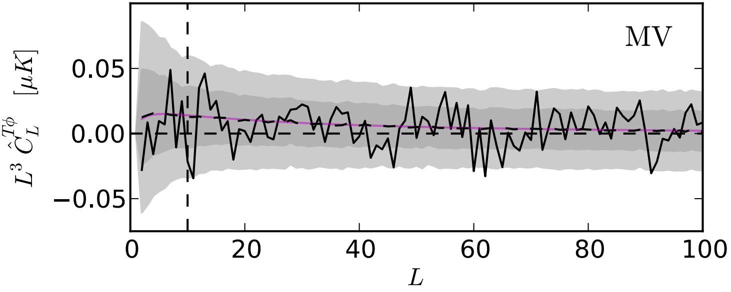
$$\hat{A}^{T\phi} = 0.78 \pm 0.32.$$

- Consistent with the ΛCDM expectation of $\hat{A}^{T\phi} = 1$ and discrepant with zero at $\sim 2.4\sigma$.
- Provides a bias for estimates of $f_{NL}^{\text{loc}}$

$$\hat{f}_{NL}^{\text{loc}} = 9.8 \pm 5.8 \quad \text{(ignore lensing)}$$
$$\hat{f}_{NL}^{\text{loc}} = 2.7 \pm 5.8 \quad \text{(debiased)}$$



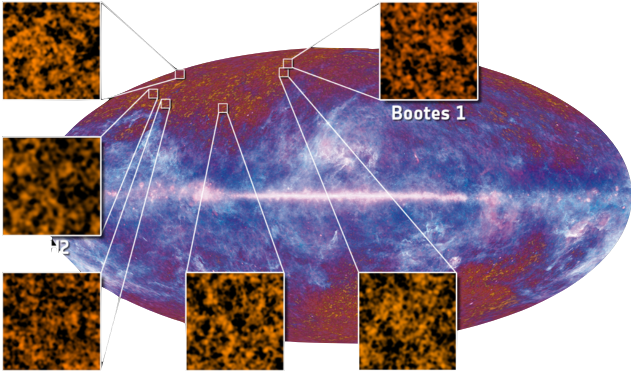
# Lensing-ISW Correlation




- Lensing-ISW bispectrum has associated cross-spectrum $C_L^{T\phi}$.
- Potentially a (semi-) independent low-$L$ probe; striking odd/even differences, though not significant.

| | Lensing-ISW Amplitudes | | |
|---|---|---|---|
| | $\hat{A}^{T\phi}$ (all L) | $\hat{A}^{T\phi}$ (even L) | $\hat{A}^{T\phi}$ (odd L) |
| 100 GHz . . . . | $0.93 \pm 0.52$ | $0.45 \pm 0.72$ | $1.44 \pm 0.73$ |
| 143 GHz . . . . | $0.81 \pm 0.36$ | $0.27 \pm 0.48$ | $1.37 \pm 0.52$ |
| 217 GHz . . . . | $0.87 \pm 0.35$ | $0.54 \pm 0.49$ | $1.22 \pm 0.49$ |
| MV . . . . . . . . . | $0.78 \pm 0.32$ | $0.25 \pm 0.45$ | $1.32 \pm 0.46$ |

# CIB-Lensing Correlation

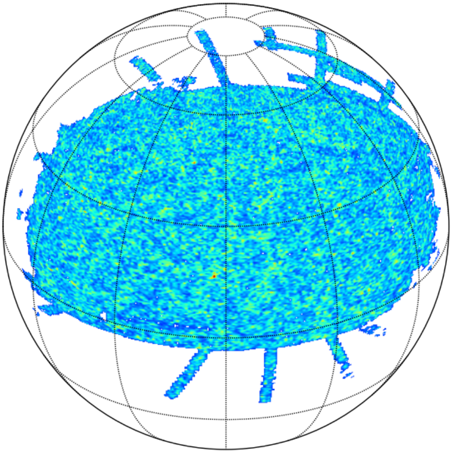



The high-frequency Planck maps trace Cosmic Infrared Background (CIB) fluctuations, primarily sourced by star formation at high-redshift; strong correlations with lensing (Song et. al.).

# External Correlations

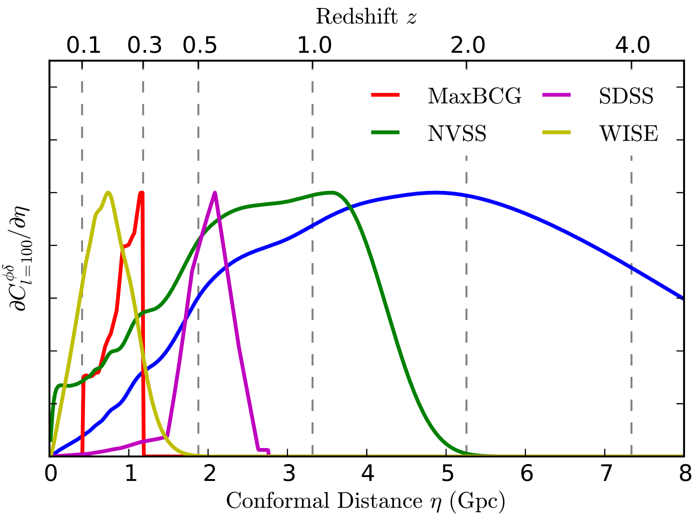
- The CMB lensing potential has significant correlations with other tracers of large-scale structure.
- Can observe by stack the lensing map at the position of catalog objects.
- Equivalently, pixelize into a fractional overdensity map $\delta(\hat{n})$ and take cross-spectrum

$$\hat{C}_L^{\delta\phi} = \frac{1}{2L+1} \sum_M \delta_{LM} \hat{\phi}^*_{LM}.$$



SDSS DR8-based
LRG Catalog
Ross, Ho et. al.

# External Correlations



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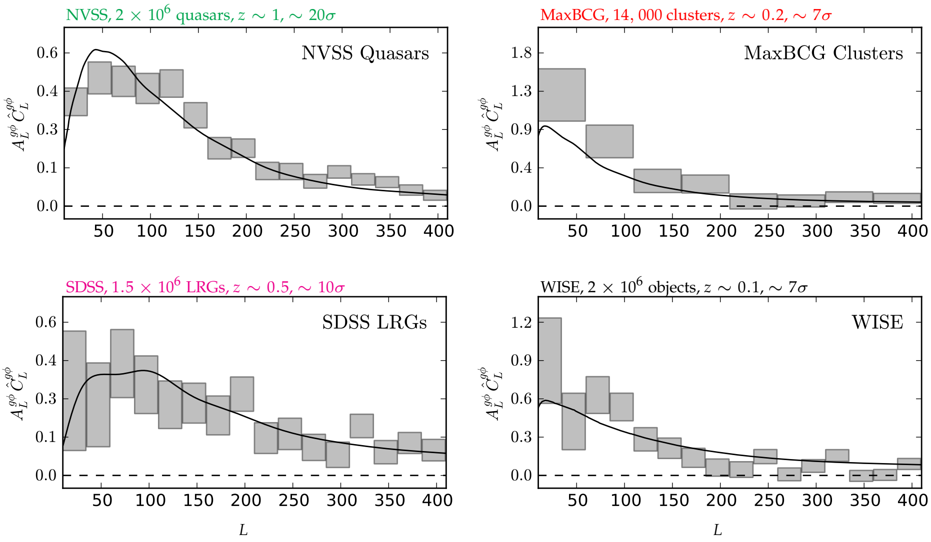


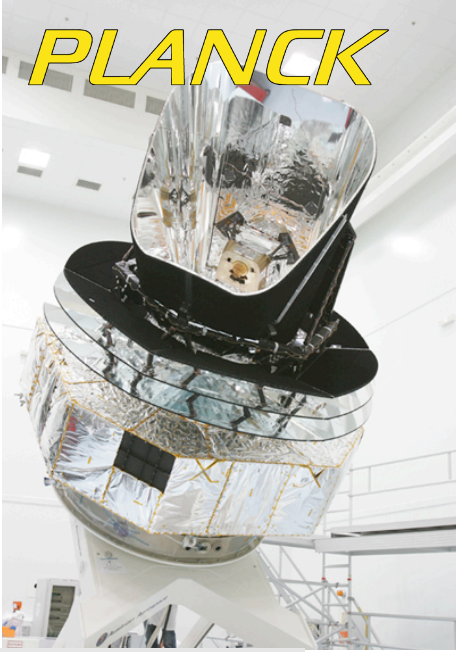
# LENSING IN THE 2013 RELEASE

Data processing papers

- I Overview of products and scientific results
- II The Low Frequency Instrument data processing
- III LFI systematic uncertainties
- IV Low Frequency Instrument beams and window functions
- V LFI calibration
- VI High Frequency Instrument data processing
- VII HFI time response and beams
- VIII HFI photometric calibration and mapmaking
- IX HFI spectral response
- X Energetic particle effects: characterization, removal, and simulation

Science papers

- XII Component separation
- XIII Galactic CO emission
- XIV Zodiacal emission
- XV CMB power spectra and likelihood
- XVI Cosmological parameters
- XVII Gravitational lensing by large-scale structure
- XVIII The gravitational lensing infrared background correlation
- XIX The integrated Sachs-Wolfe effect
- XX Cosmology from Sunyaev-Zeldovich cluster counts
- XXI Cosmology with the all-sky Planck Compton parameter y-map
- XXII Constraints on inflation
- XXIII Isotropy and statistics of the CMB
- XXIV Constraints on primordial non-Gaussianity
- XXV Searches for cosmic strings and other topological defects
- XXVI Background geometry and topology of the Universe
- XXVII Doppler boosting of the CMB
- XXVIII The Planck Catalogue of Compact Sources
- XXIX Planck catalogue of Sunyaev-Zeldovich sources




- Every high-resolution CMB experiment is now a lensing survey; in the past two years CMB lensing has moved from detection mode $\to$ precision cosmological probe.
- Planck is at the forefront of this push.
- Look forward to the full mission + polarization for a sub-3% measurement of $C_L^{\phi\phi}$.