Improved r constraint with delensing: systematics considerations

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CMB systematics and calibration focus workshop
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Outline

- Overview of methods and results from the first demonstration of improved r constraint on data with delensing

- Quantification of potential biases and degradation to $\sigma(r)$: CIB-ϕ correlation, polarization calibration, CIB modeling

- Systematics checks on Galactic foregrounds

- Outlook

How does lensing degrade the r estimate?

Lensing, foreground, (PGW B-modes)

Instrument noise

$$\sigma(r)^{*} \propto C_\ell^{\mathrm{BB}} + N_\ell$$

Delensing for r = reduce the sample variance contributed by lensing when measuring r

*assuming diagonal covariance & brutally simplified

$$\sigma(r) \propto \sum_\ell \sqrt{\frac{1}{\#\ \mathrm{of\ modes}}} \left(\frac{C_\ell^{BB} + N_\ell}{\partial C_\ell^{BB}/\partial r} \right)$$

Why now for BICEP/Keck?

Contributions to σ(r): $C_\ell^{\mathrm{BB,fg}} + C_\ell^{\mathrm{BB,lens}} + N_\ell$

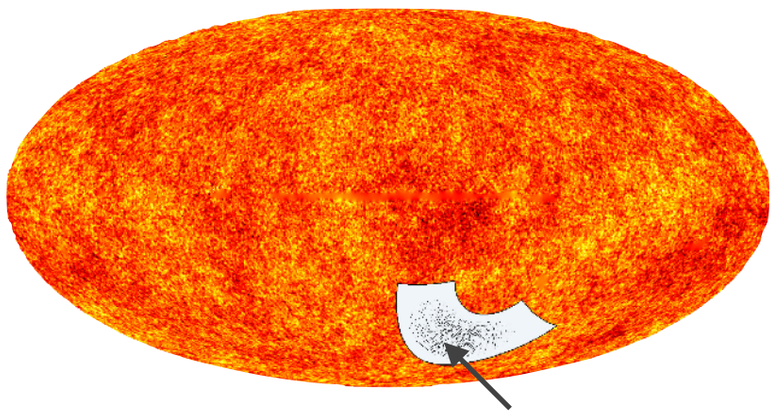
For current BICEP/Keck data set:

Foregrounds becoming sample-variance limited

Noise variance becoming comparable/lower than lensing variance at 90/150 GHz

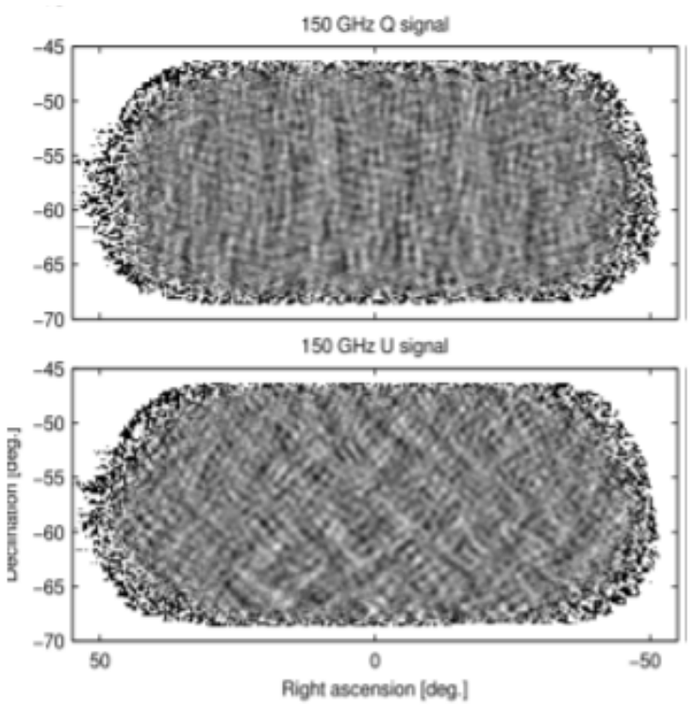
In regime where delensing can begin to improve $\sigma(r)$

Reminder of the BICEP/Keck r analysis: input maps

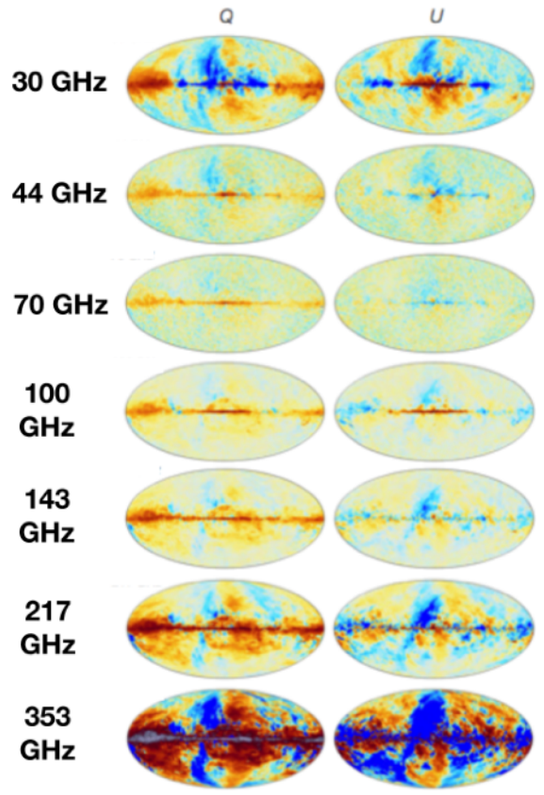


BK/SPTpol patch; ~500 deg^2

Maps from BICEP/Keck (95/150GHz)



Maps from Planck/WMAP



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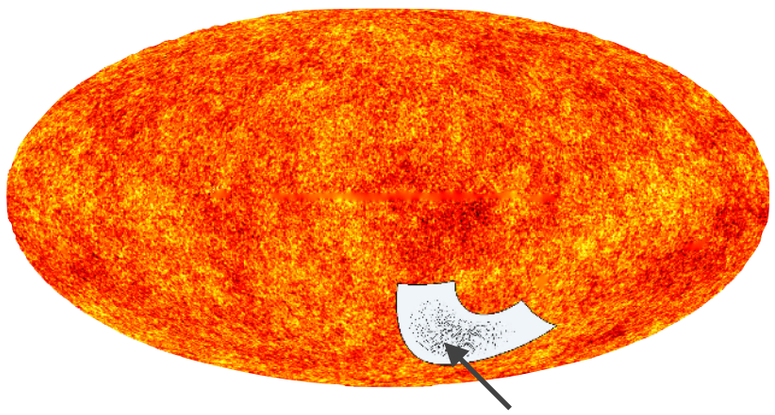
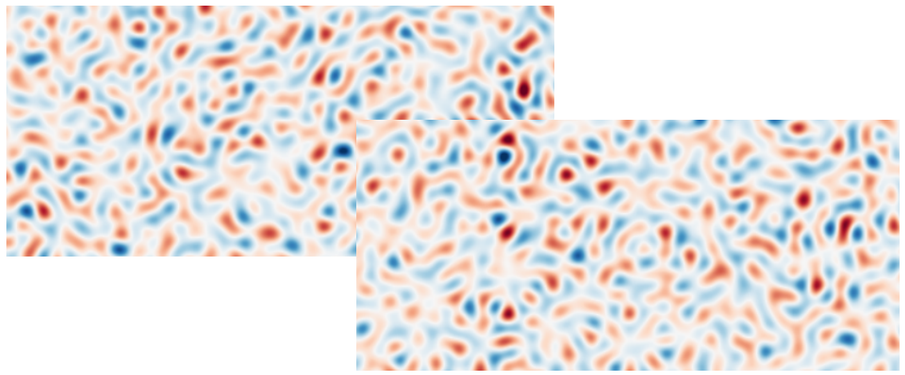


BK/SPTpol patch; ~500 deg²

+ lensing template



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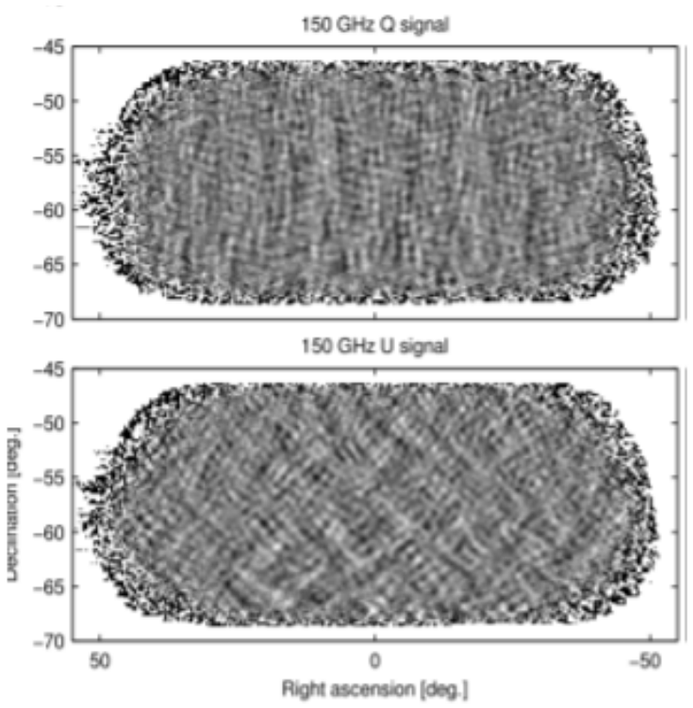
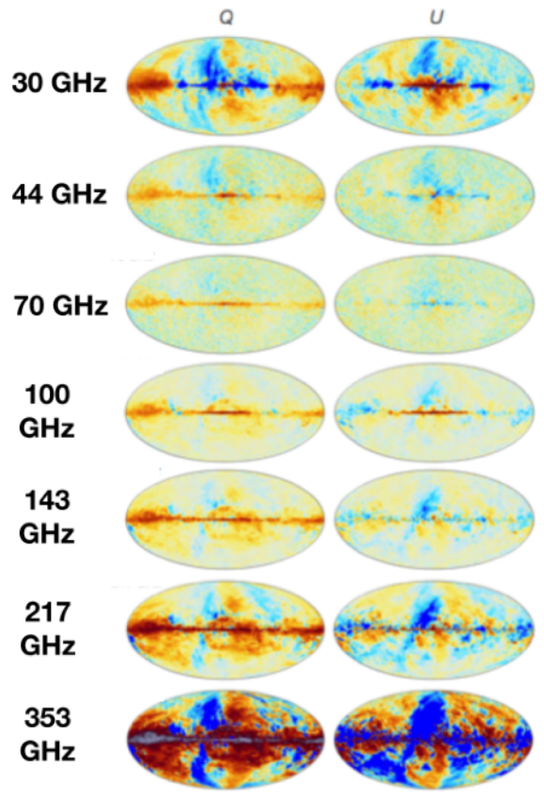
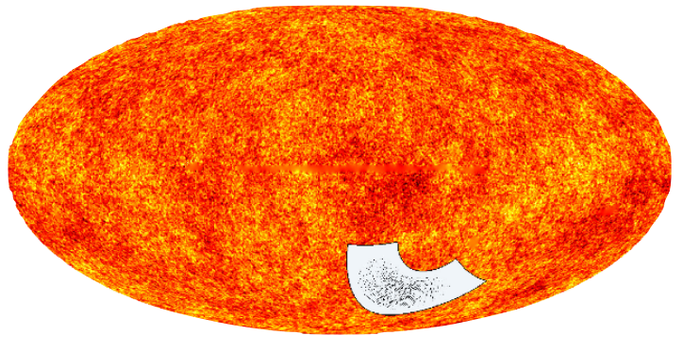


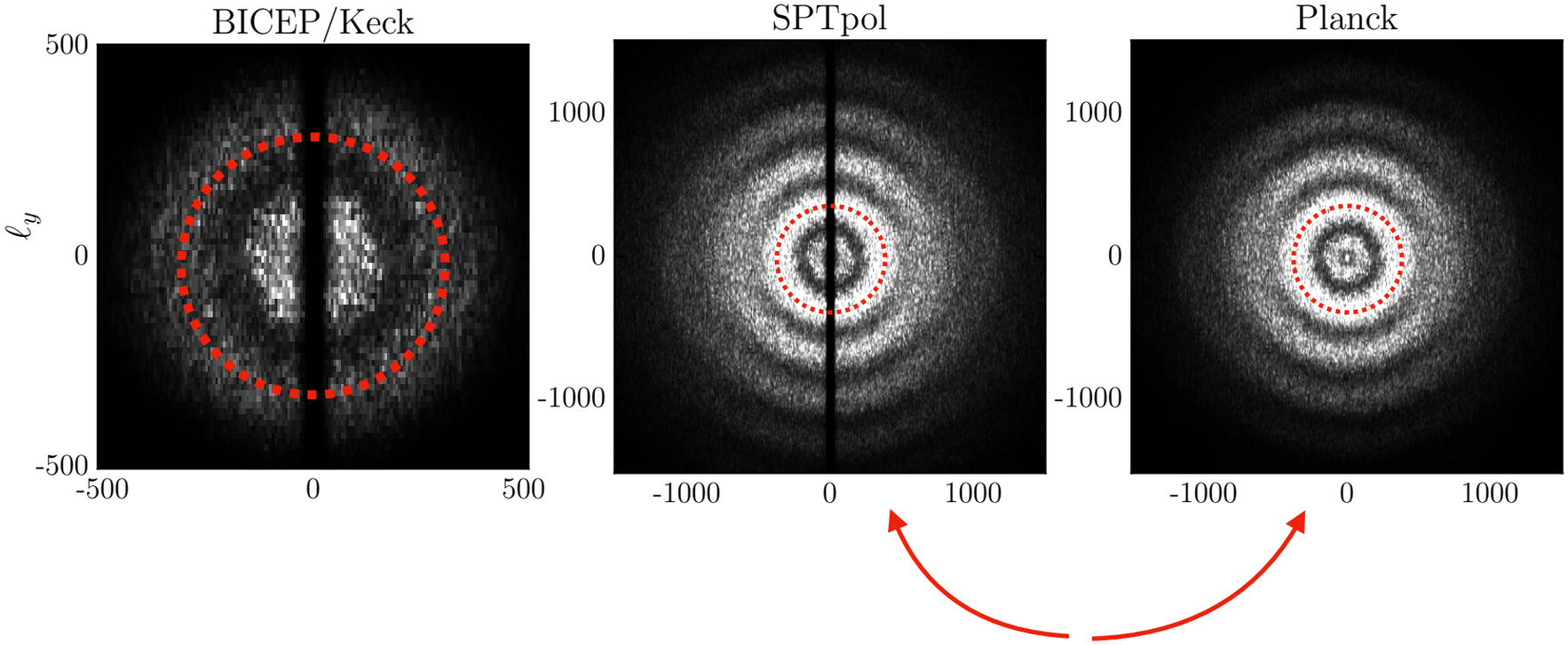


Lensing template inputs: Q/U maps for E modes

E modes: combine Q/U maps from BICEP/Keck 150GHz, SPTpol 150GHz, and *Planck* 143GHz



E mode 2D angular power spectra (signal simulation)



Cover broader multipole range than BK;
SPTpol contributes most S/N to the final lensing template.

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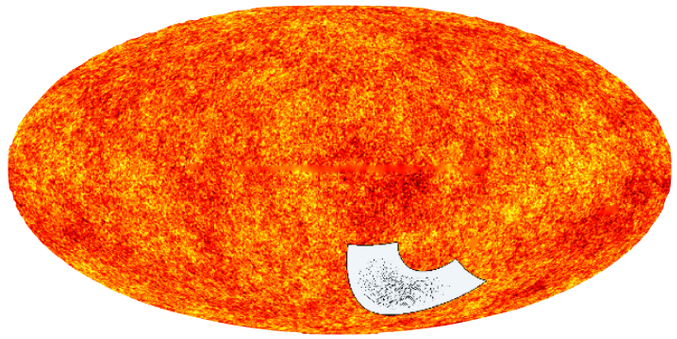

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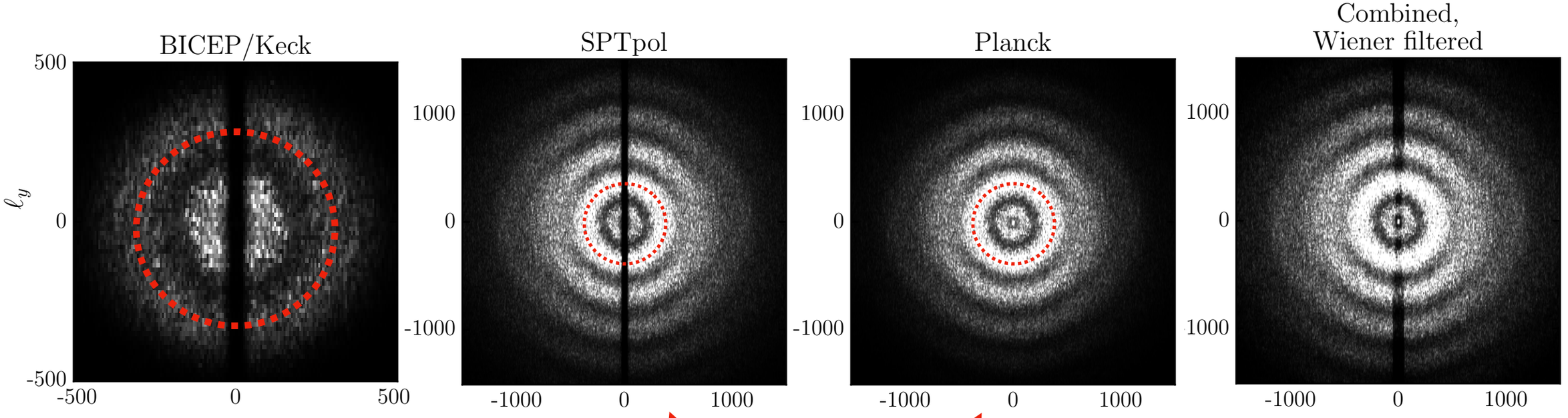
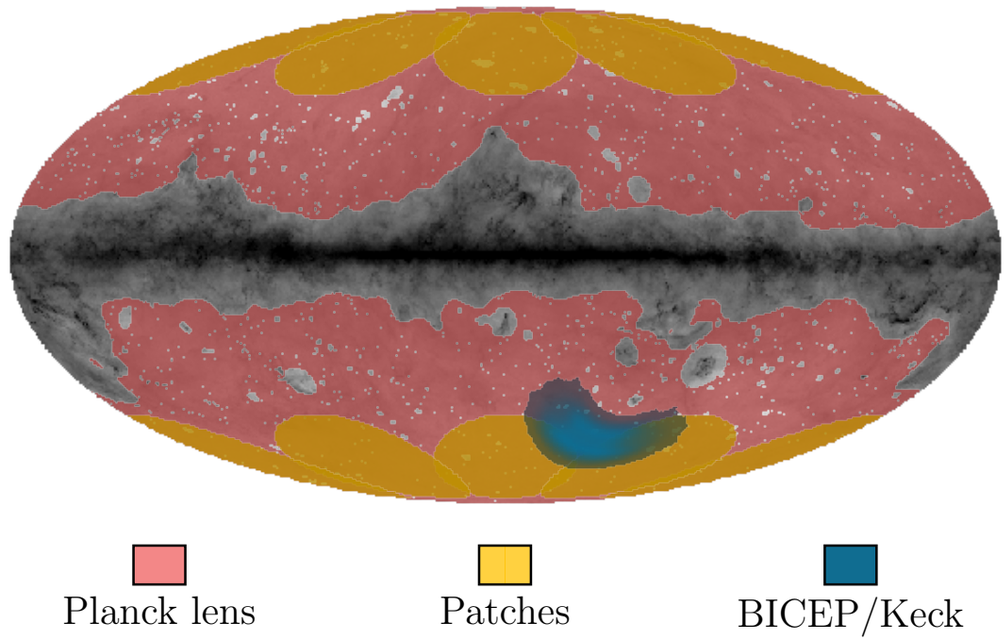
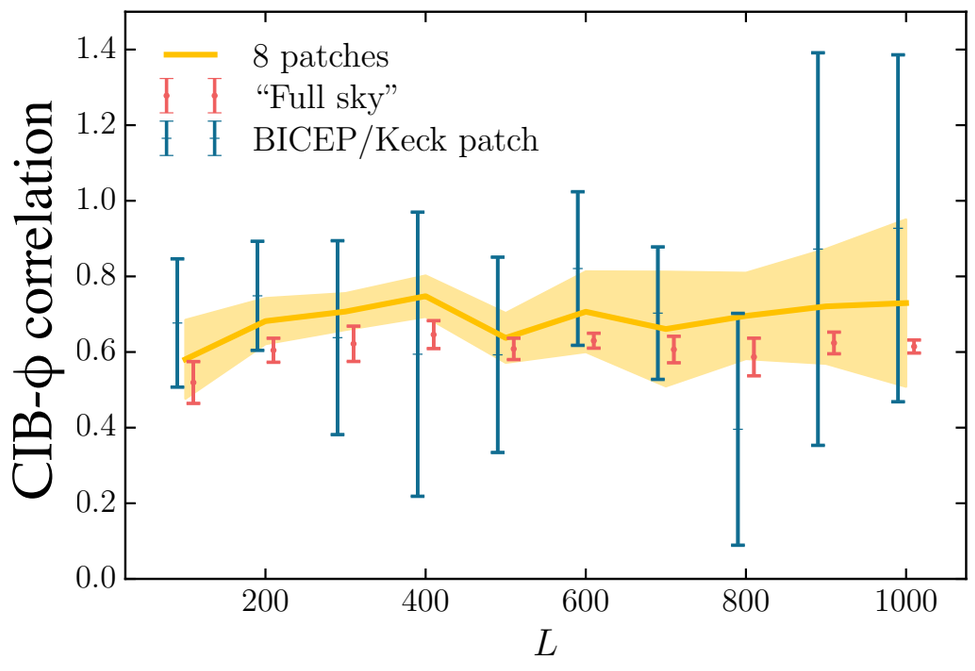


Cover broader multipole range than BK;
SPTpol contributes most S/N to the final lensing template.

Lensing template inputs: CIB for ϕ tracer

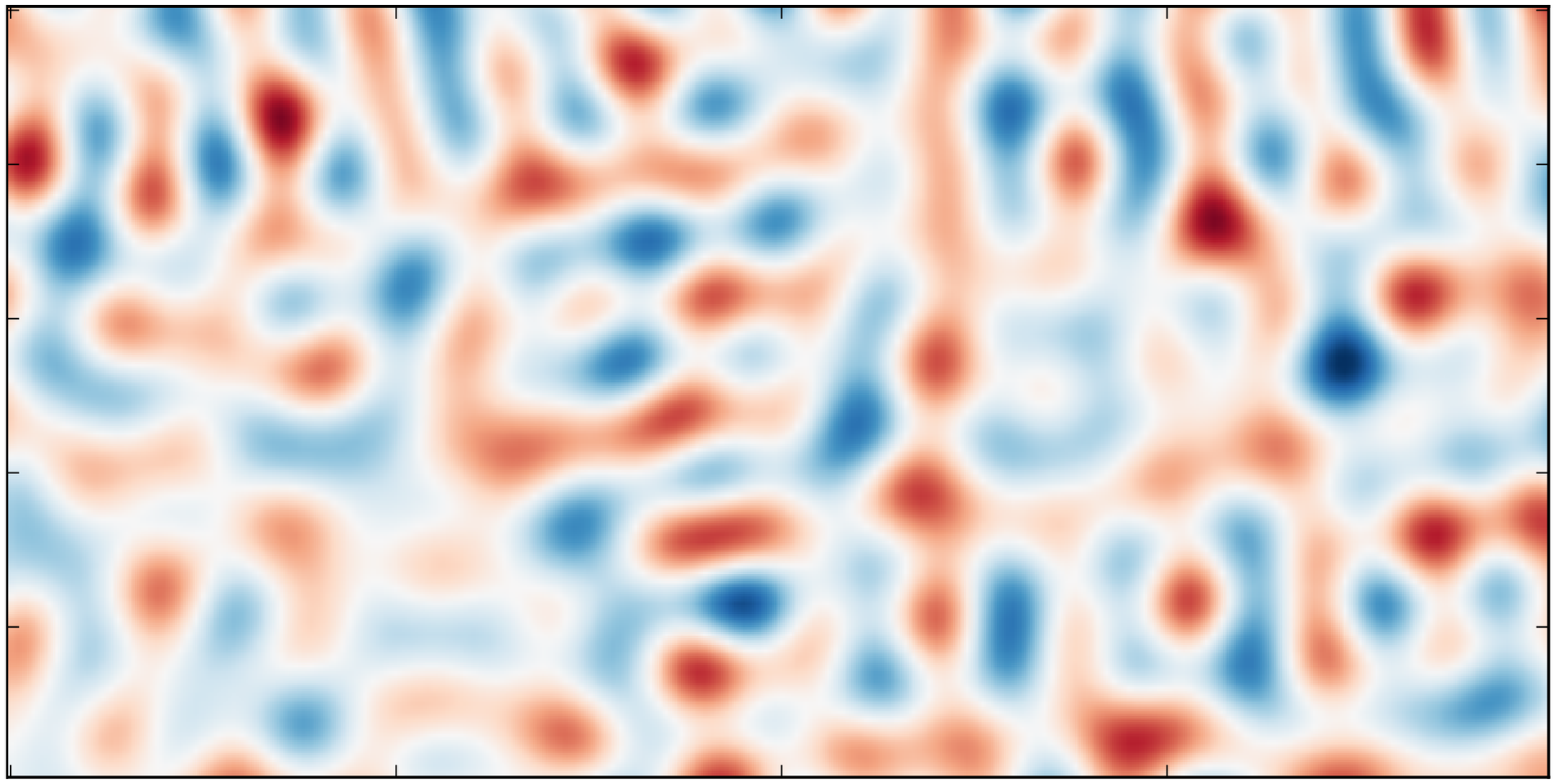
- CIB map: Planck GNILC
- Need CIB auto-spectrum and CIBxϕ for filtering and generating simulated CIB realizations.
  - CIBxϕ measure with Planck ϕ reconstruction.
- Use high Galactic latitude areas to estimate the CIB auto-spectrum and CIBxϕ to ensure similar levels of dust contamination.
- Generate CIB realizations by rescaling the simulated ϕ and adding Gaussian noise given the CIB auto-spectra and CIBxϕ; distribution drawn from the covariance of the spectra measured from the 8 patches.





Making the lensing template: undeflect-and-difference

$\pm 3.5 \mu K$



Sim

1) Lensed Q map; 2) Undeflected Q map; 3) Lensed-Undeflected Q map

Same for U map

Making the lensing template: undeflect-and-difference

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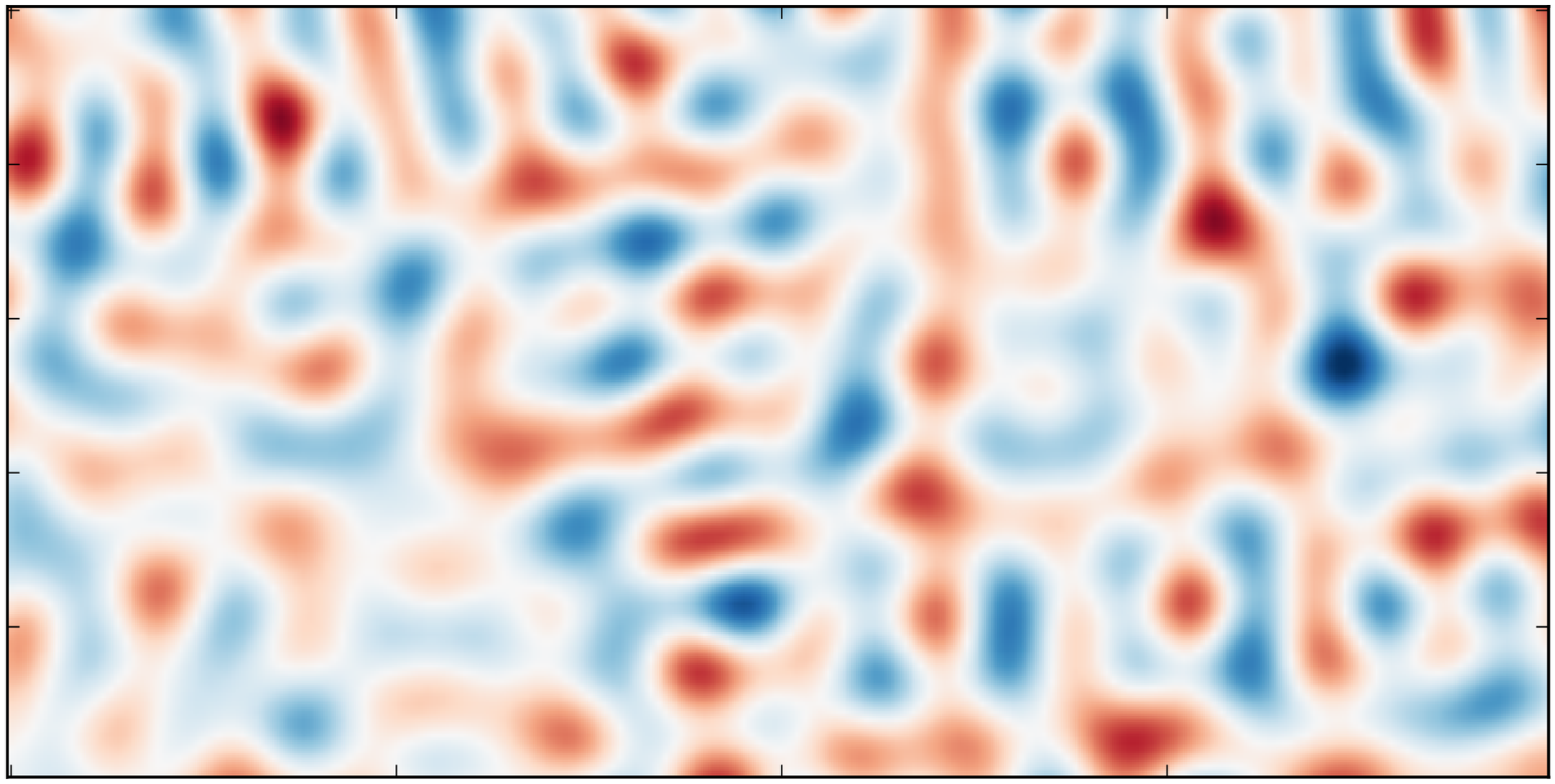
Undeflect by $-\nabla\hat{\phi}$



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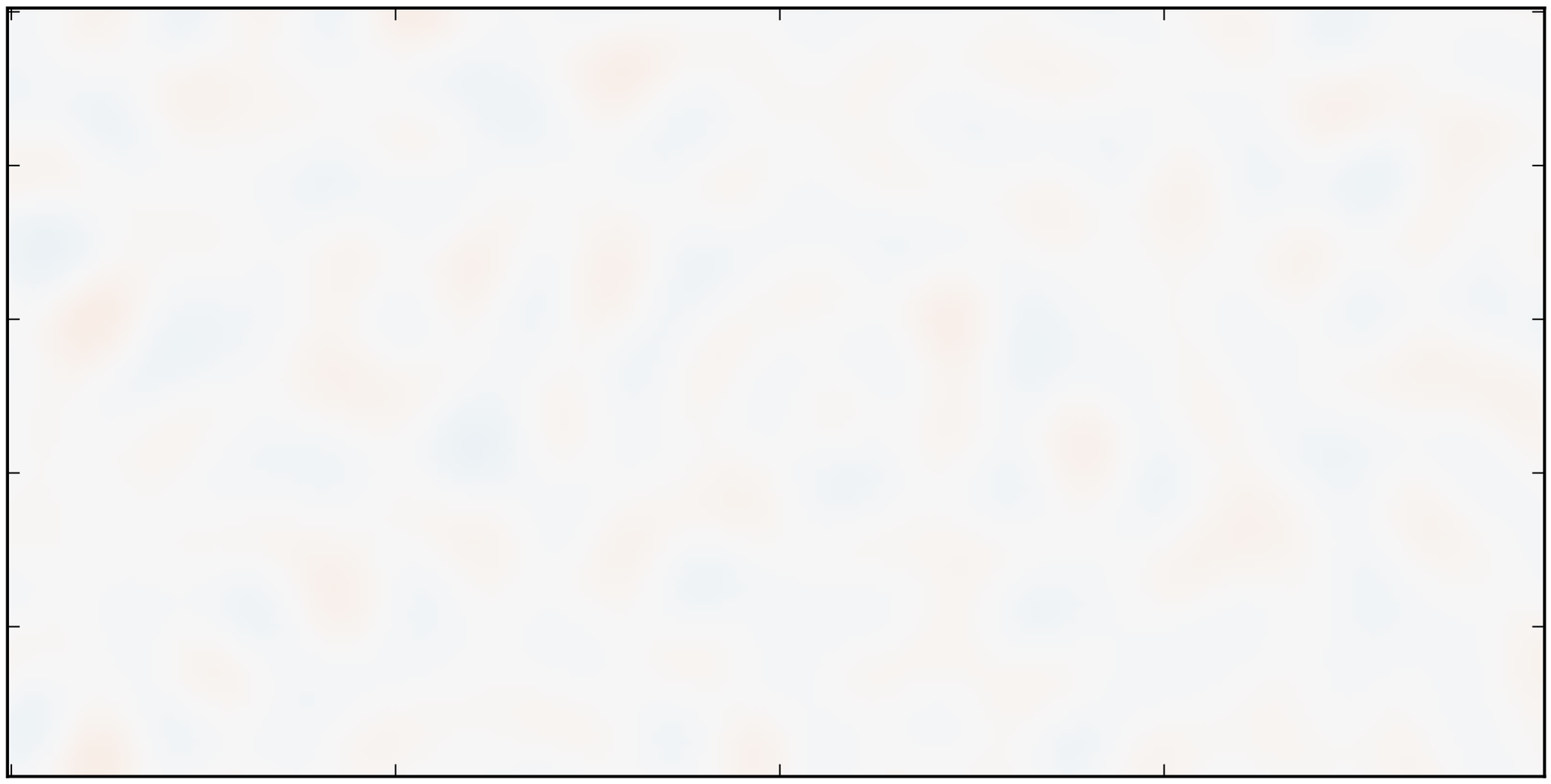

Sim

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Making the lensing template: undeflect-and-difference

$\pm 0.35 \mu K$

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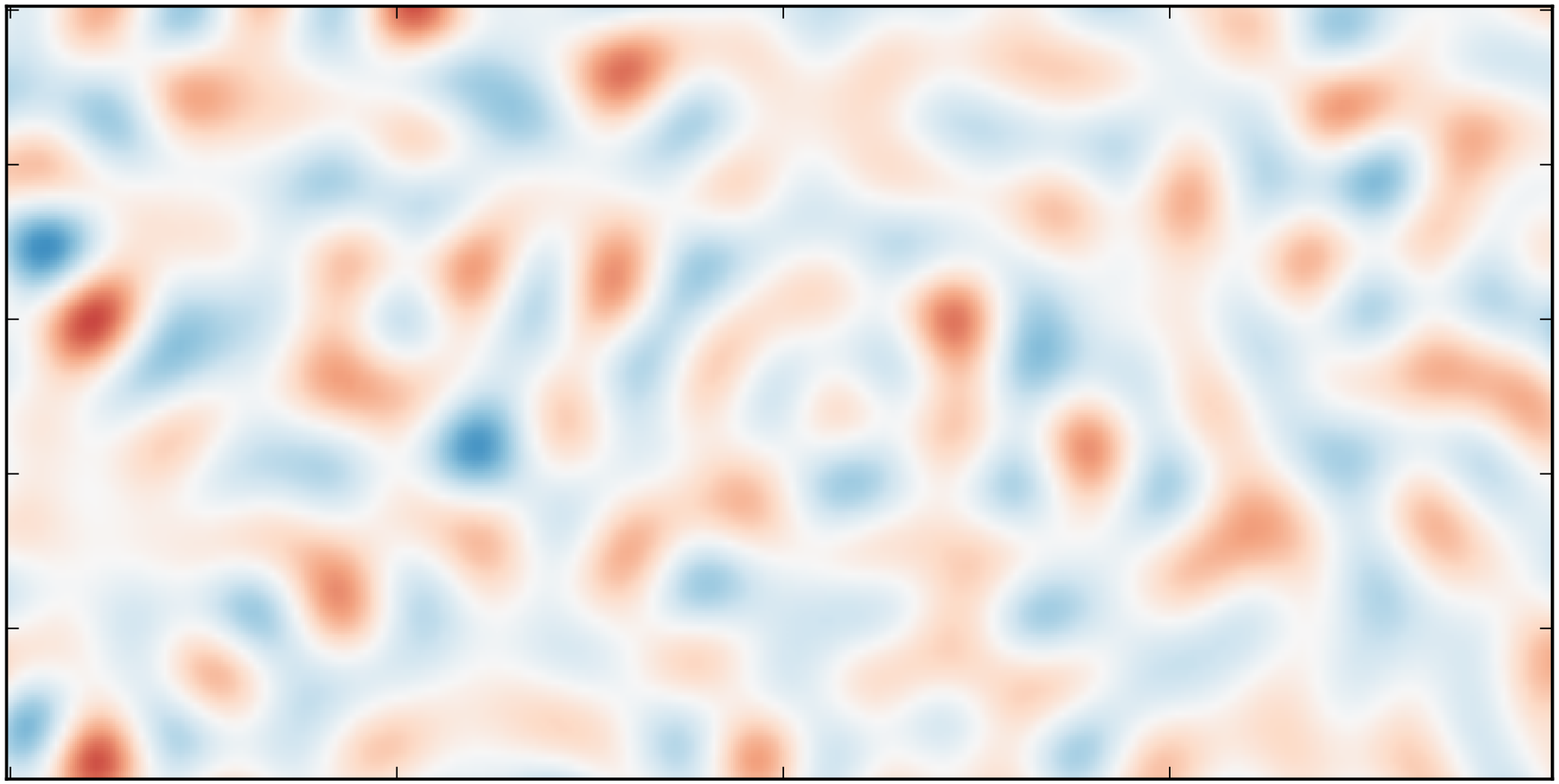

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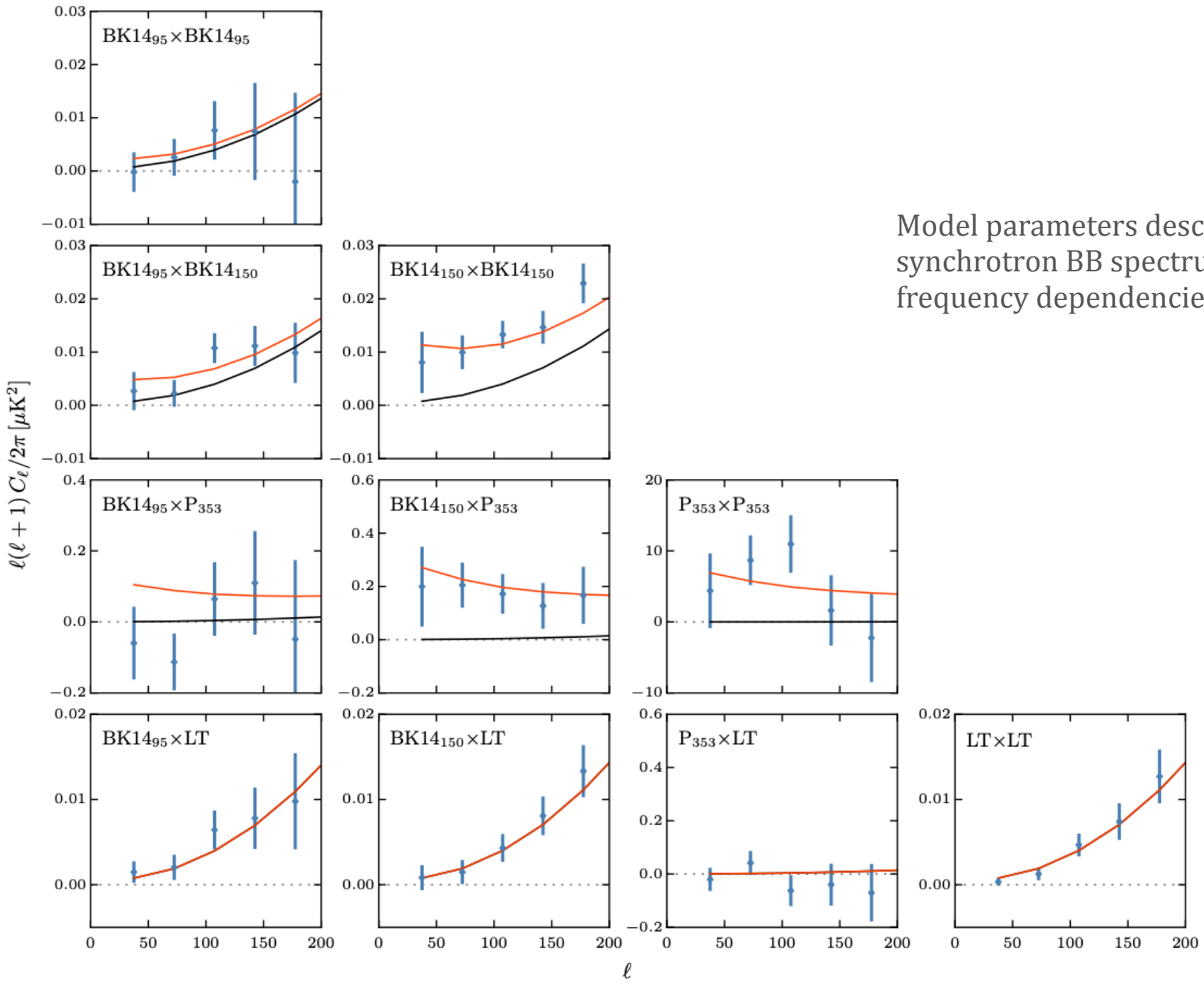
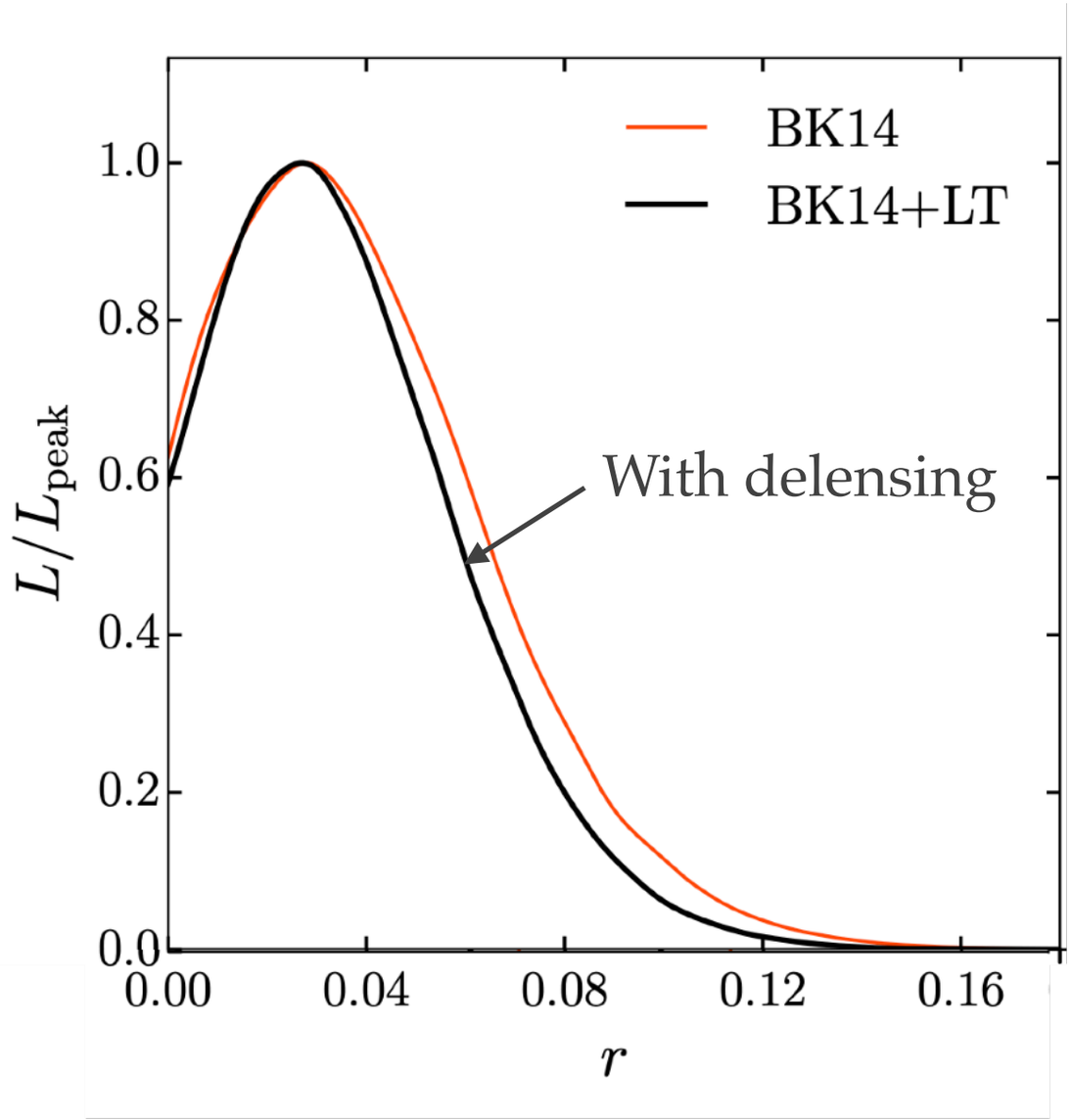
Reminder of the BICEP/Keck r analysis: spectra



Model parameters describe *r*, lensing, dust and synchrotron BB spectrum amplitudes, shapes, frequency dependencies, and correlations.

r posterior with and without delensing



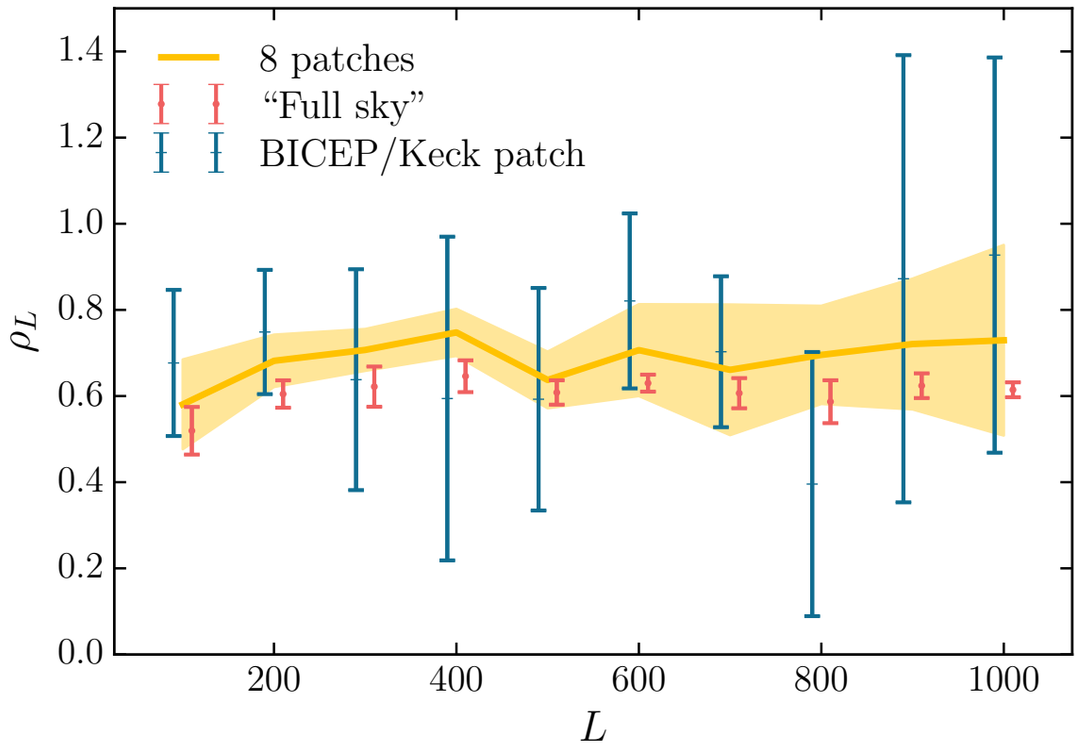
The 95% C.L. upper limit on r is reduced from r<0.090 to r<0.082.

Systematics considerations

- CIB-phi cross-correlation
- Polarization calibration
- CIB non-Gaussianity
- Galactic dust contamination in Q/U maps and in CIB map

Misestimation in CIB-ϕ correlation

- Analyze simulations generated with $0.5\sigma_{sp}$ shift in CIB-ϕ cross-power as if they were the baseline.
- End-to-end result shows a bias on r by 0.2σ.
- $0.5\sigma_{sp}$ shift is expected to be larger than what the ϕ field and the CIB map could have, given that ϕ comes from a component separated map.
- Future delensing with CIB combined with CMB-ϕ would have less contribution from CIB; smaller impact.
- Can marginalize over this uncertainty.



Biases in polarization calibration

Frequency [GHz]	*EE* first peaks SMICA %	Cosmology driven Camspec %	Cosmology driven Plik %	Combined residuals %
100	+2.4 ± 0.5	+1.3 ± 0.5	+1.0 ± 0.5	+0.7 ± 1.0
143	Ref.	−1.6 ± 0.5	−1.7 ± 0.5	−1.7 ± 1.0
217	+3.6 ± 0.5	+2.5 ± 0.5	+2.0 ± 0.5	+1.9 ± 1.0

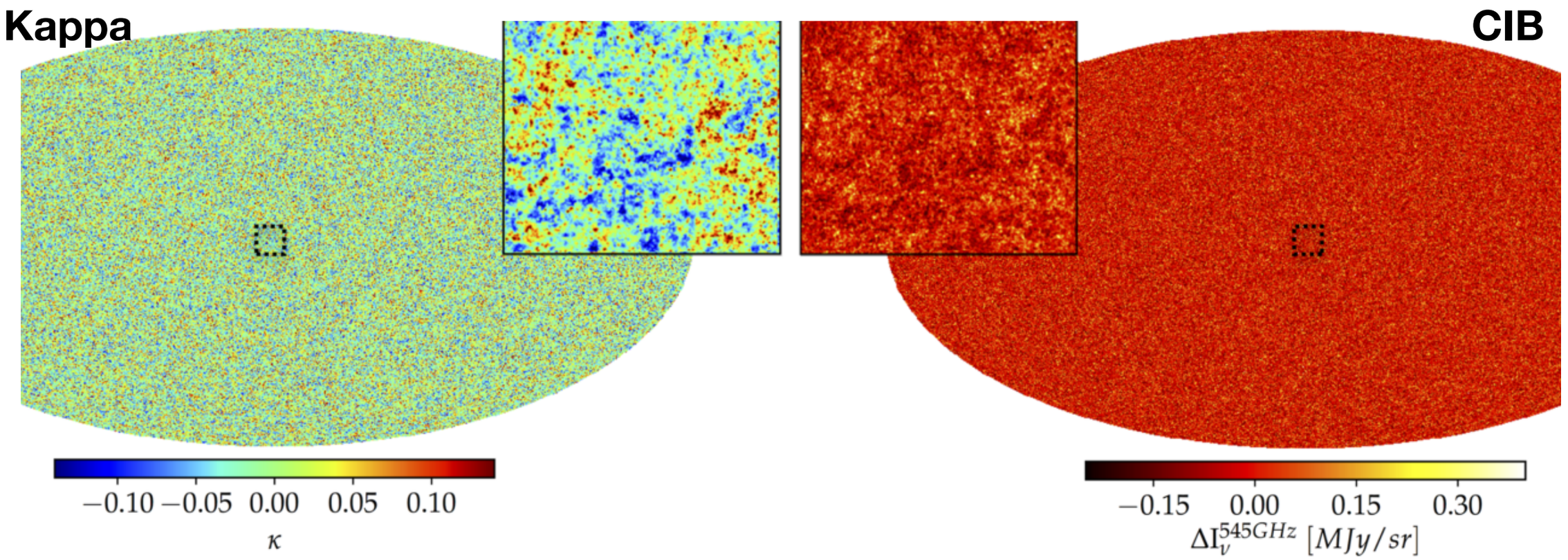
Table 9 of Planck 2018 III; 1807.06207

- Planck polarization maps could be biased at ~1.7%; SPTpol Q/U maps are calibrated off Planck maps.

- Simulate biased SPTpol Q/U maps and analyze as if it is unbiased; find negligible bias in *r*.

Related: See Silvia Galli talk on CMB polarization self-calibration

CIB non-Gaussianity



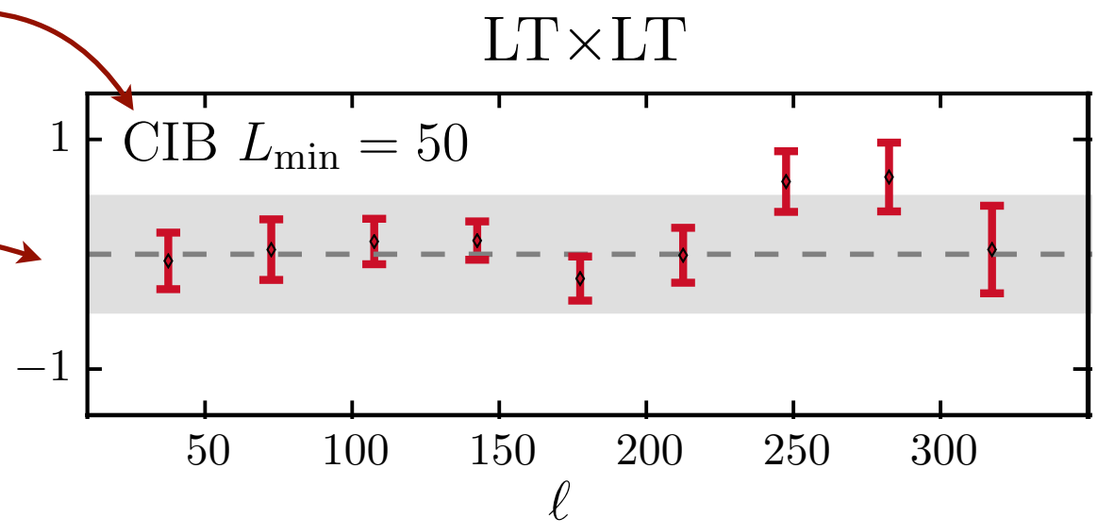
Websky sims

- Model CIB signal (part that correlates with ϕ) and noise (part that does not correlate with ϕ) to be both Gaussian;
- Compare lensing template bandpower variance given Gaussian vs non-Gaussian ϕ simulations (from Websky); find no statistically distinguishable difference between the two.
- Artificially increase the lensing template bandpower variance in the covariance matrix and find negligible difference in σ(r).

Galactic dust in Q/U and CIB maps

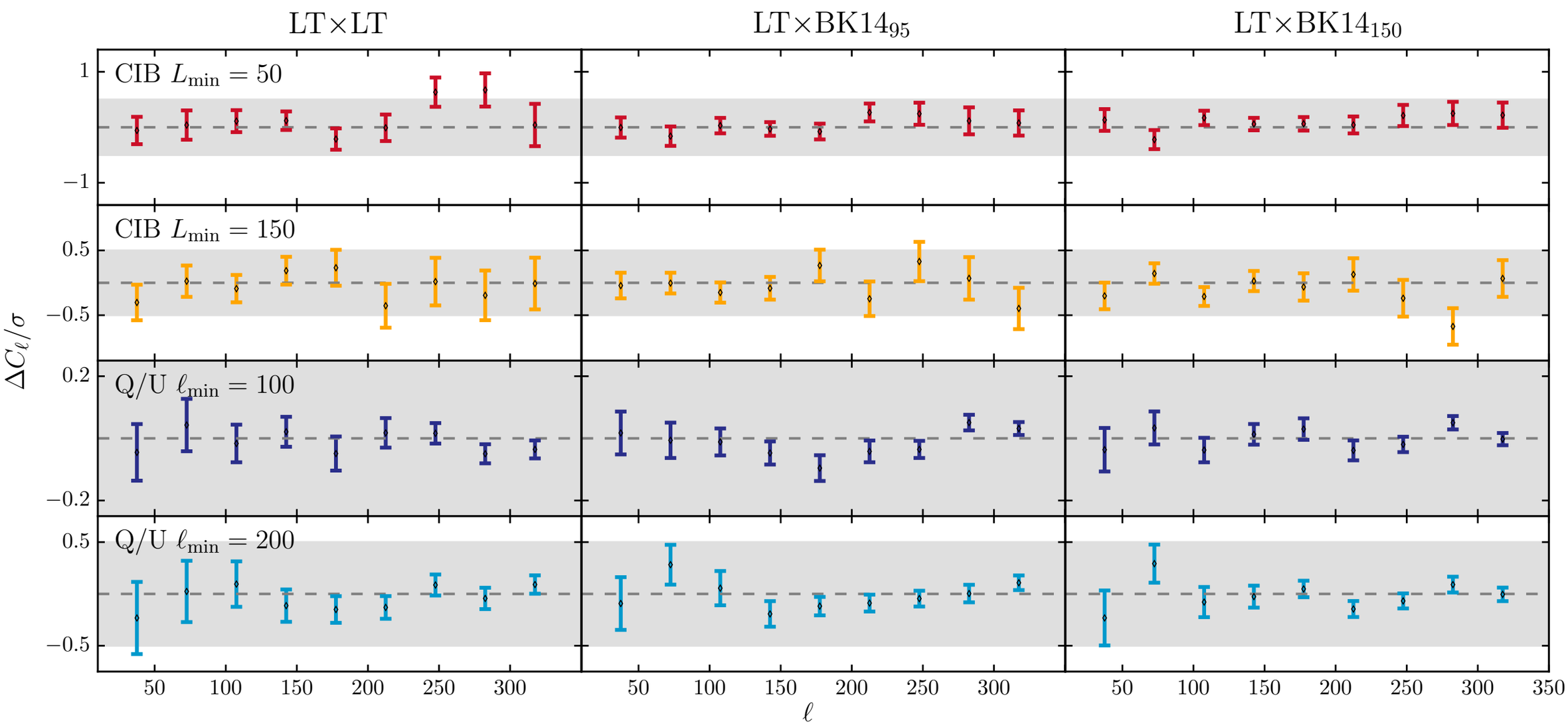
Analysis change vs baseline

Differenced-bandpowers scaled by 1-σ bandpower uncertainty



- Unmodelled non-Gaussian Galactic dust fluctuations could exist in Q/U maps and in CIB map
- Are they large enough to alter the lensing template auto- and cross-spectra beyond what is expected from noise?
- Test: cut out scales below L_{min} and form difference-spectra with baseline; Galactic dust dominates large angular scales and this test would be pick them out if they are large.

Galactic dust in Q/U and CIB maps



Outlook

Instrumental systematics

- Combine ϕ reconstructed from CMB with external tracers —> how do instrumental systematics bias ϕ reconstruction and subsequently the lensing template?

  - Mirmelstein et al. (arXiv 2011.13910) addresses instrumental effects on biases to ϕ power spectrum for a SO-like experiment configuration. (Session 6)

  - For each experimental set up, need to propagate instrumental biases in ϕ to the lensing template for B-mode delensing; in addition to potential instrumental biases to the E-mode map (e.g. Pcal example earlier).

  - Important for survey/instrument design — are there symmetries one can design in (e.g. in scan strategy, orientation of the camera/pixels) to reduce potential sources of biases.

(See also Blake Sherwin's talk in Session 10)

CMB-ϕ delensing: foregrounds

- Preliminary studies of biases on lensing templates with various galactic dust models (Vansyngel, amplitude-modulated dust, …) suggest that biases on r is small/can be mitigated. (cf. Beck et al. (2001.02641), CMB-S4 low-ell BB working group, SPT-3G/BK internal work)

- Small scale dust can have very unexpected non-Gaussianity. Further modeling and checks are needed to build confidence.

- Similarly for extragalactic foreground biases, esp. for TT reconstruction.

Summary slide

- We are just beginning to be lensing-limited in our r measurement (recent improved r constraint with delensing arXiv: 2011.08163).

- Reduce $\sigma(r)$ by ~10% for the "BK14" data set using a lensing template constructed Q/U maps of SPTpol, BICEP/Keck, and Planck and using a Planck CIB map as ϕ tracer.

- $\sigma(r)$ will become dominated by lensing sample variance in the next few years for BICEP/Keck. For this and also for future experiments, it will be increasingly important to quantify and mitigate delensing-related systematics.