Delensing: Updates from the South Pole Telescope and the BICEP/Keck Array

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B-mode from Space
Max Planck Institute for Astrophysics


BICEP/Keck Collaboration
Kavli Institute
for Cosmological Physics
AT THE UNIVERSITY OF CHICAGO
Berkeley
University of California


Inaugural South Pole Observatory Collaboration Meeting Oct 2019


South Pole Telescope Collaboration
NIST
BERKELEY LAB
UCDAVIS
UNIVERSITY OF CALIFORNIA
UNIVERSITY OF TORONTO
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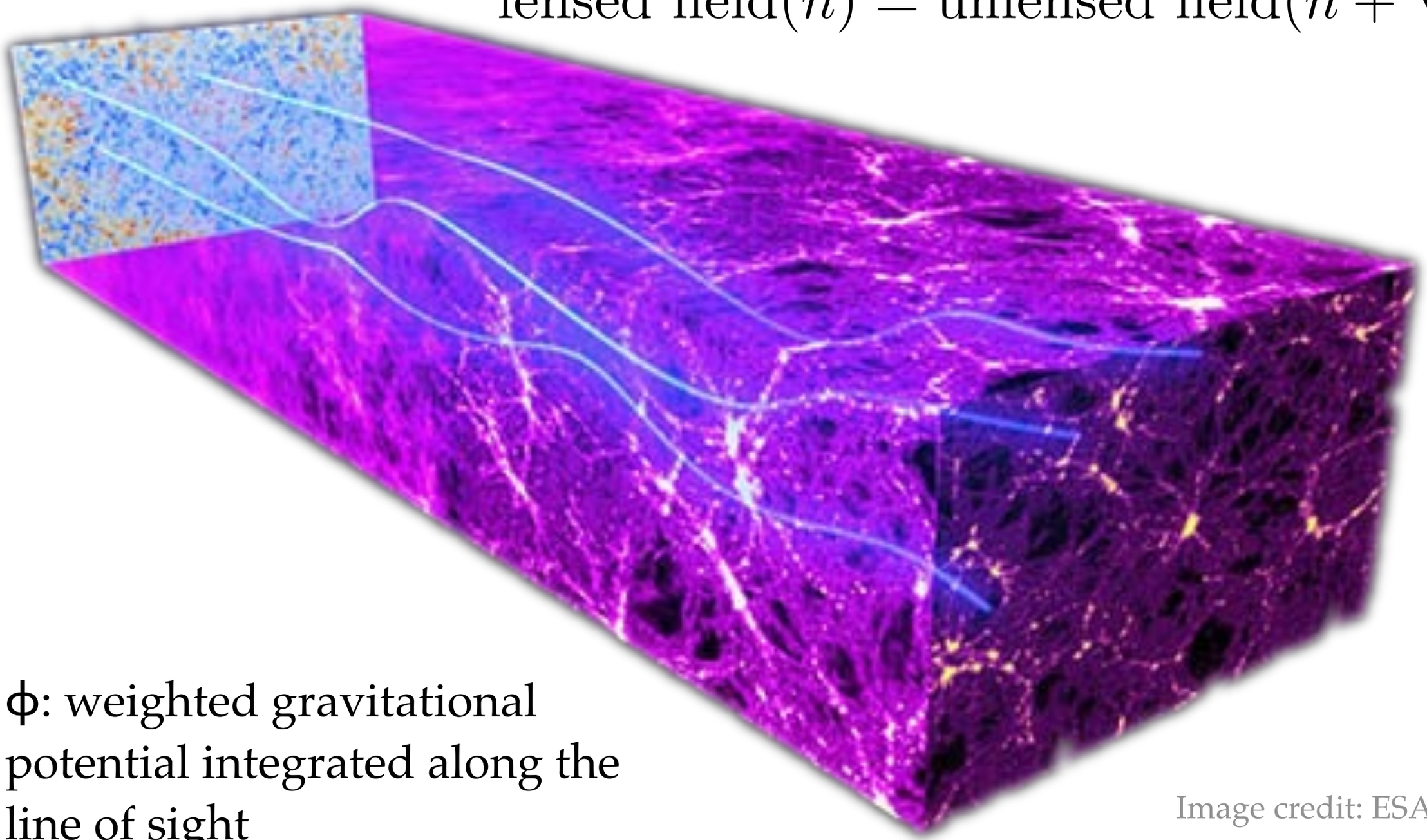
U.S. DEPARTMENT OF ENERGY

CMB lensing

$$\text{lensed field}(\hat{n}) = \text{unlensed field}(\hat{n} + \nabla\phi)$$



ϕ: weighted gravitational potential integrated along the line of sight

Image credit: ESA

$\mathrm{T}(\hat{n})\ (\pm 350\mu K)$

$\mathrm{E}(\hat{n})\ (\pm 25\mu K)$

$\mathrm{B}(\hat{n})\ (\pm 2.5\mu K)$

(no primordial B-modes)

unlensed

$\mathrm{T}(\hat{n})\ (\pm 350\mu K)$

$\mathrm{E}(\hat{n})\ (\pm 25\mu K)$

$\mathrm{B}(\hat{n})\ (\pm 2.5\mu K)$

(no primordial B-modes)

lensed

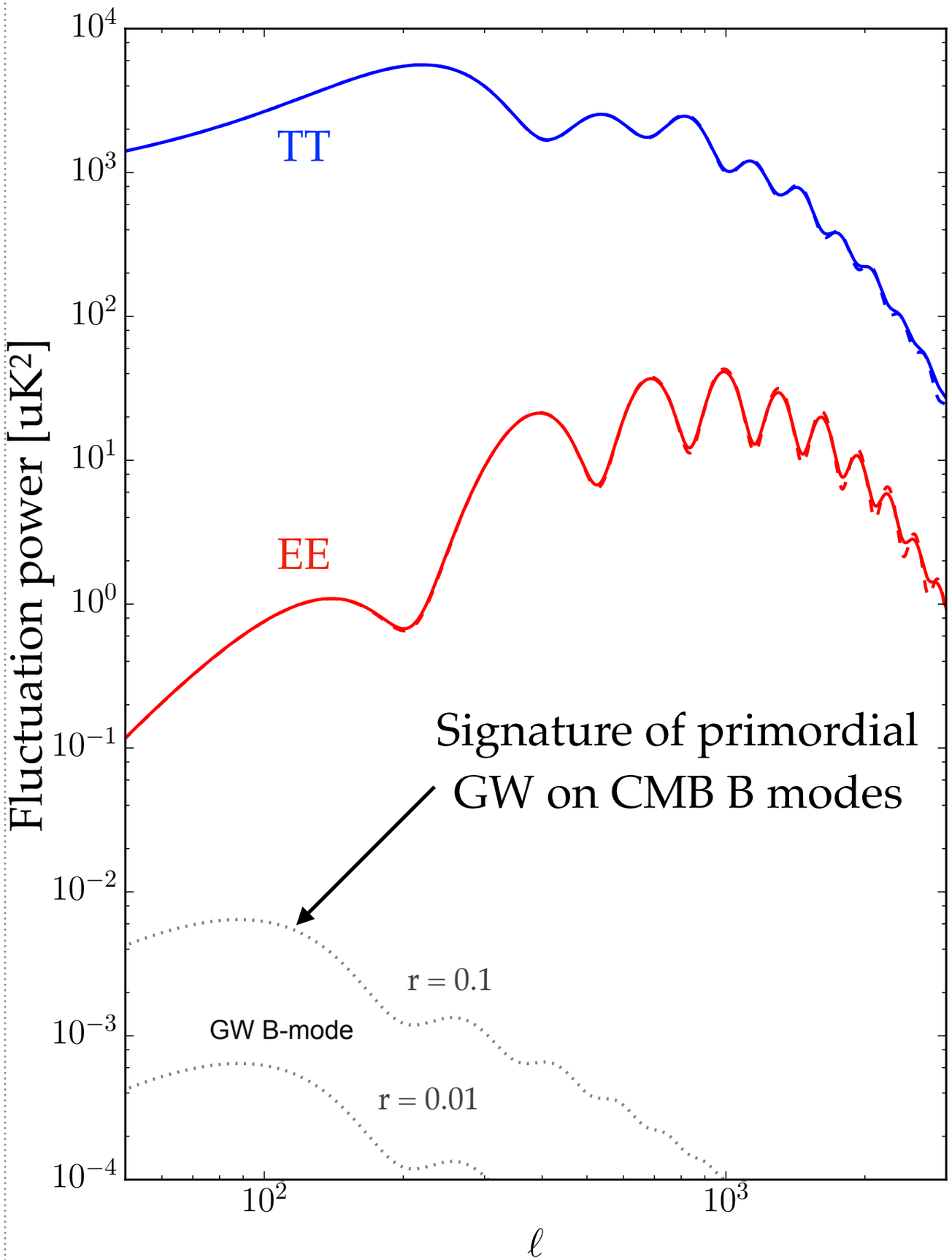
$\mathrm{T}(\hat{n})\ (\pm 350\mu K)$

$\mathrm{E}(\hat{n})\ (\pm 25\mu K)$

$\mathrm{B}(\hat{n})\ (\pm 2.5\mu K)$

$r = 0.1$

lensed



Lensing generates B modes which limit constraints on r

- Sample variance from lensing B modes limits how low constraints on *r* can be.
- Need **delensing** to remove the lensing B-mode contribution to the uncertainty to the *r* measurement.

e.g. Planck lensing 2018,
Manzotti, Story, **KW** (SPT, 1701.04396),
Polarbear (1909.13832)

How does lensing enter 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

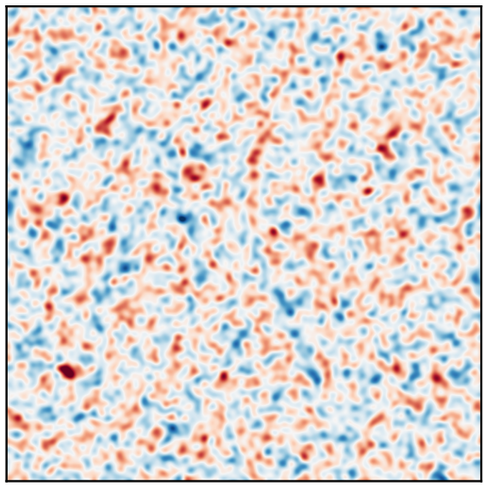
Noise variance becoming comparable/lower than lensing variance at 90/150 GHz

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

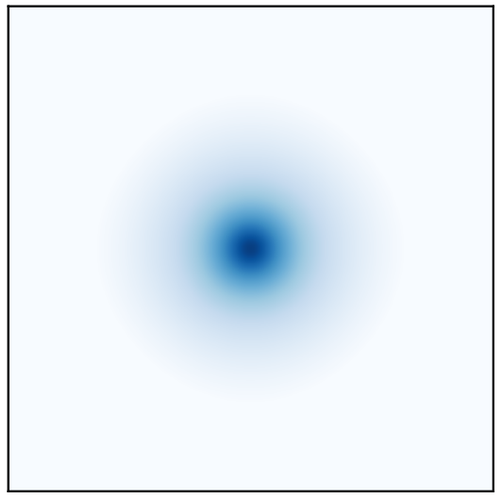
Delensing: the idea

1. Use φ to lens E-mode map to get expected lensing B template

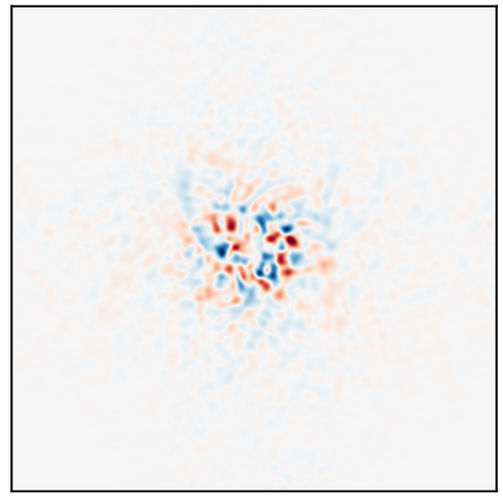
E map



φ map

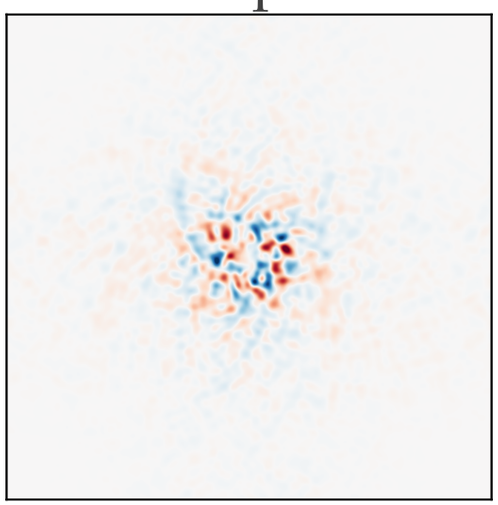


B template

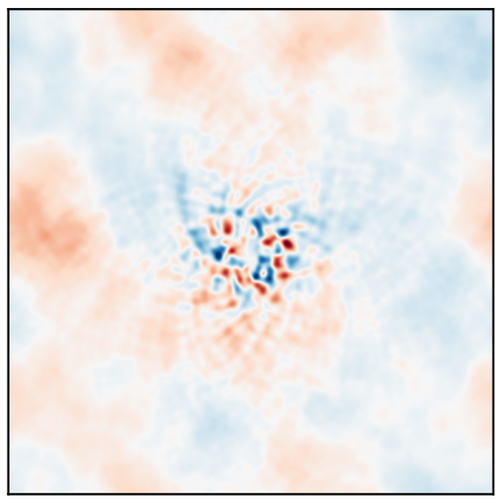


2. From lensing B template, one can then measure its auto- and cross-spectra

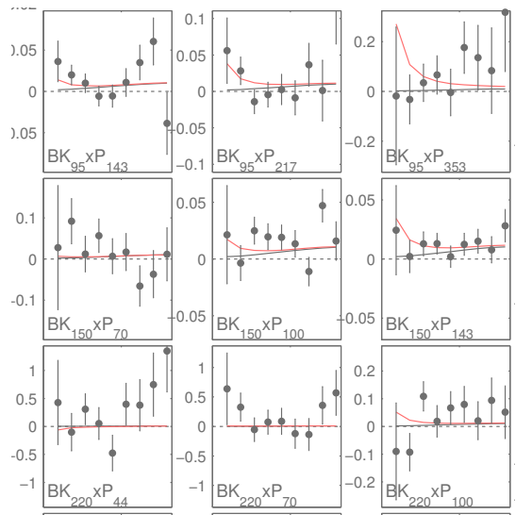
B template



Observed B



Spectra



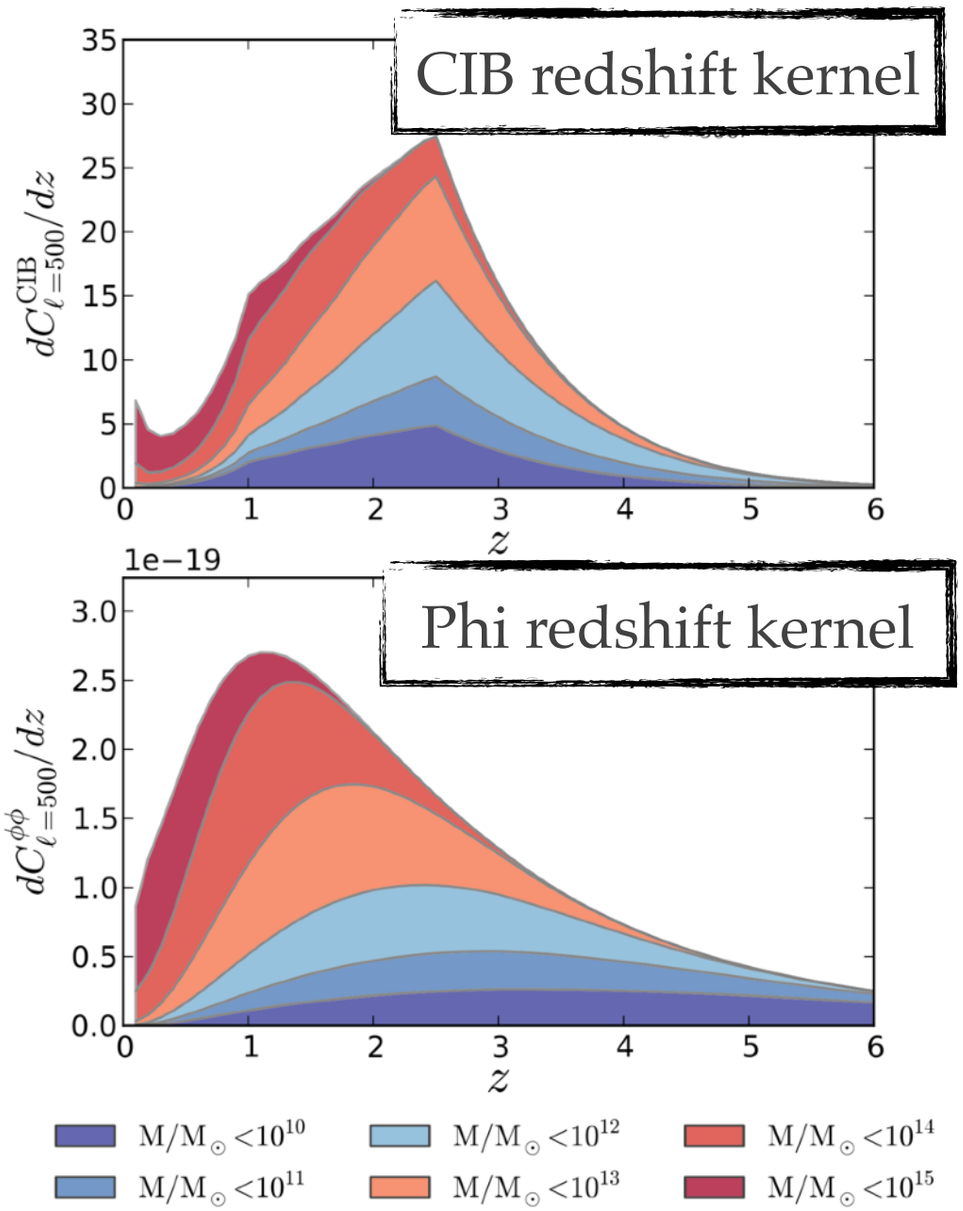
CIB as a φ tracer

- Can reconstruct φ from CMB, but S/N is not great currently. (Will get better!)

- Cosmic infrared background (CIB) from dusty star-forming dusty galaxies with redshift distribution peaked between z~1 and 2.

- CMB lensing potential's redshift kernel peaks between $1 < z < 3$

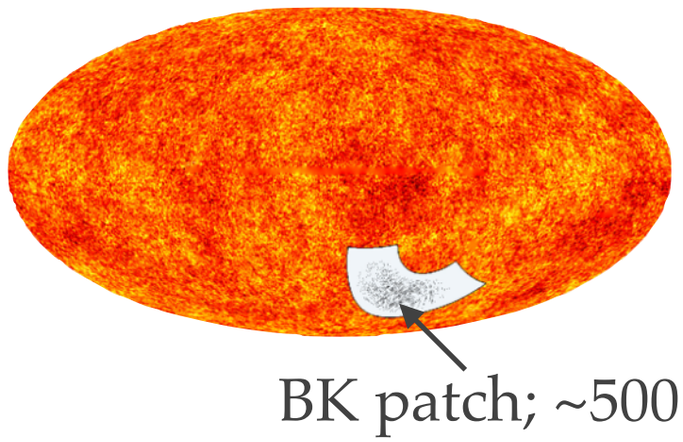
- Cross-correlation can be as high as ~80%



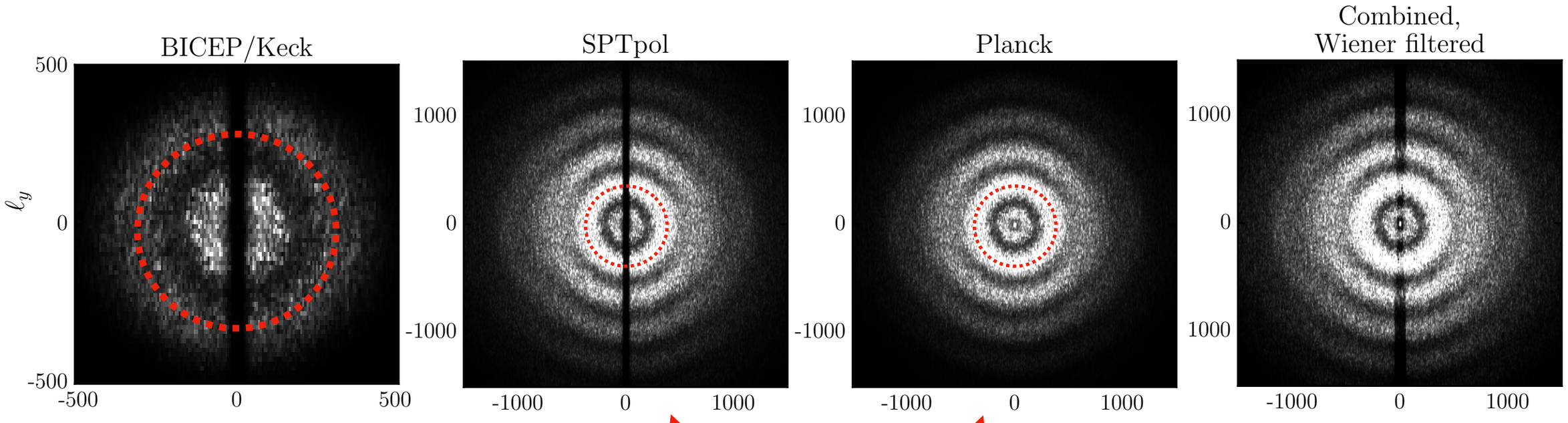
Planck 2013 XVIII

Lensing template inputs: Q/U maps for E modes

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



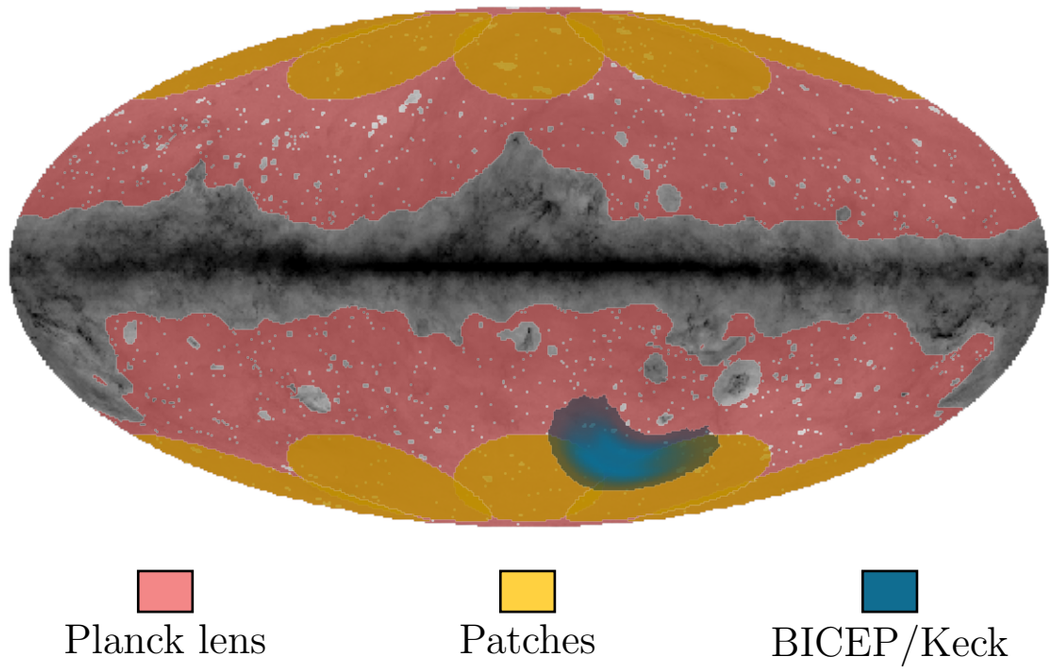
E mode 2D angular power spectra

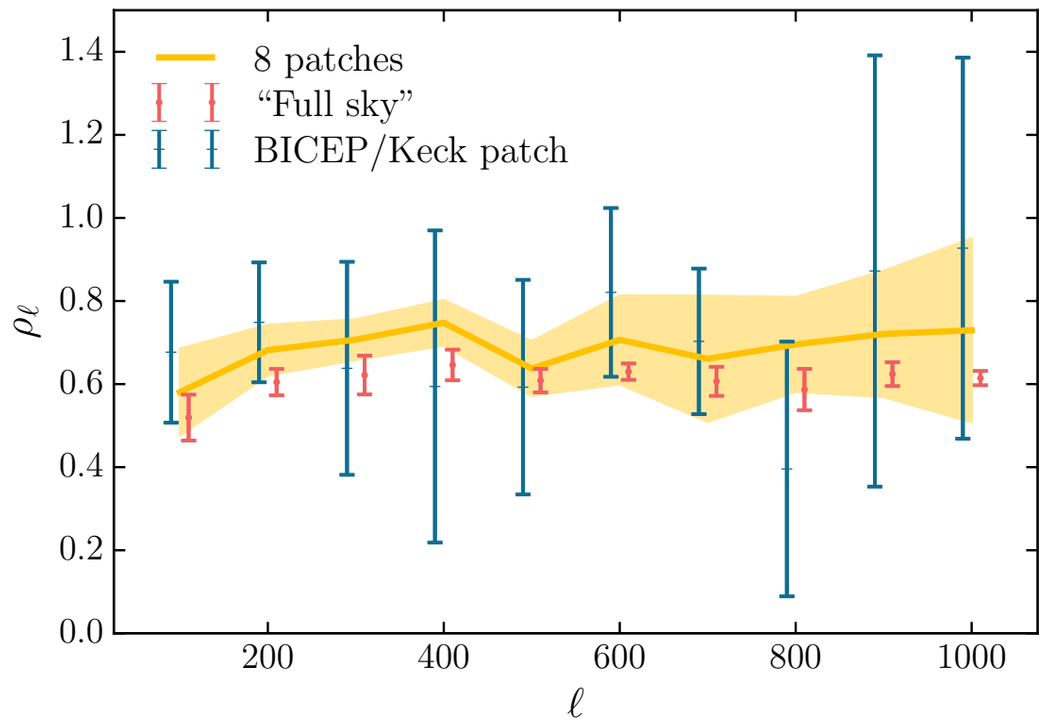


Cover broader multipole range than BK

Lensing template inputs: CIB

- CIB map: *Planck*
- Need CIB auto-spectrum and CIBxφ for filtering and generating simulated realizations.
- 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 underlying φ and adding Gaussian noise with the auto-spectra and cross-spectra with φ distribution drawn from the covariance of the spectra measured from the 8 patches.

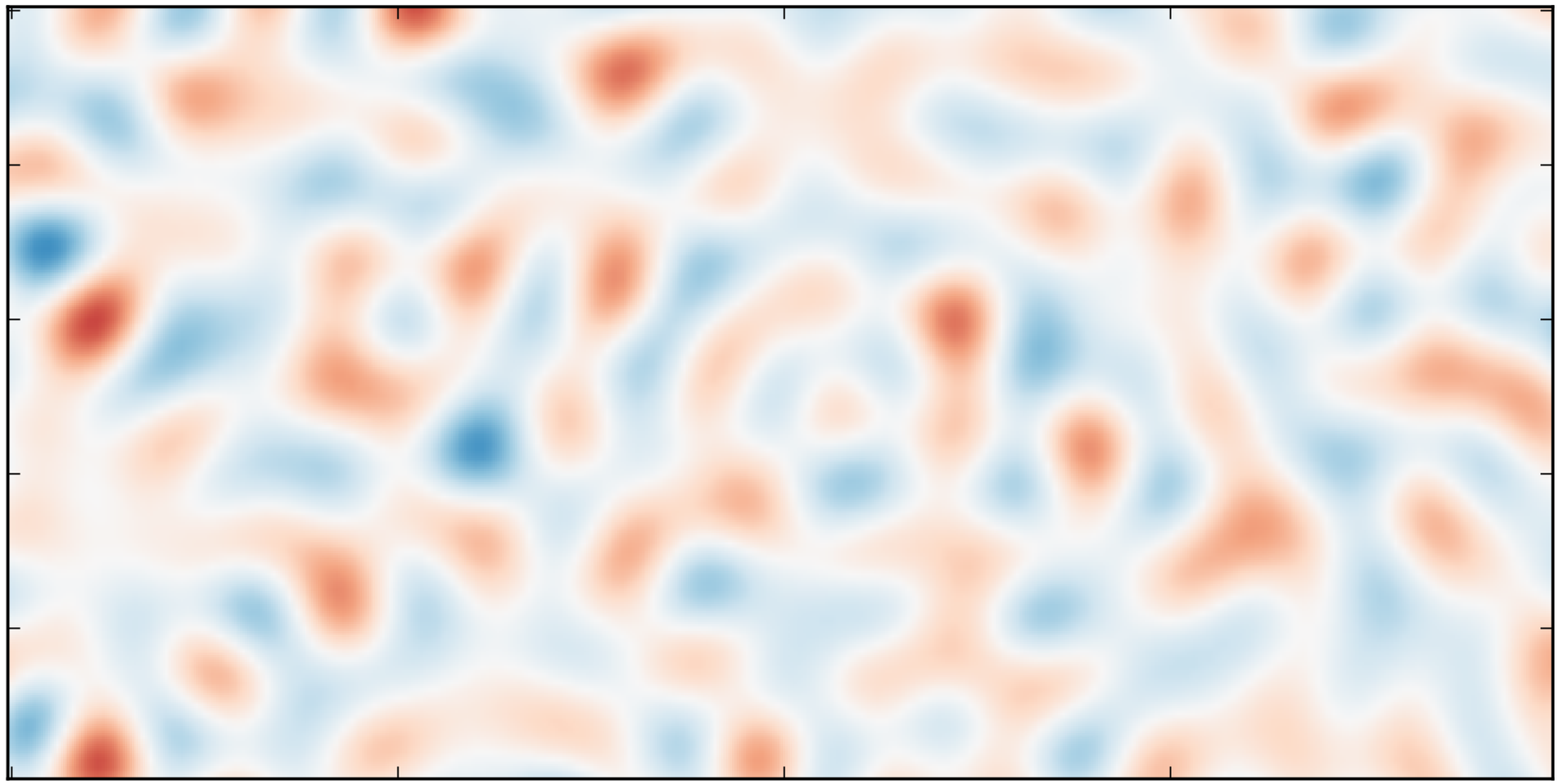




Making the lensing template: undeflection-and-difference

$\pm 0.35 \mu K$

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

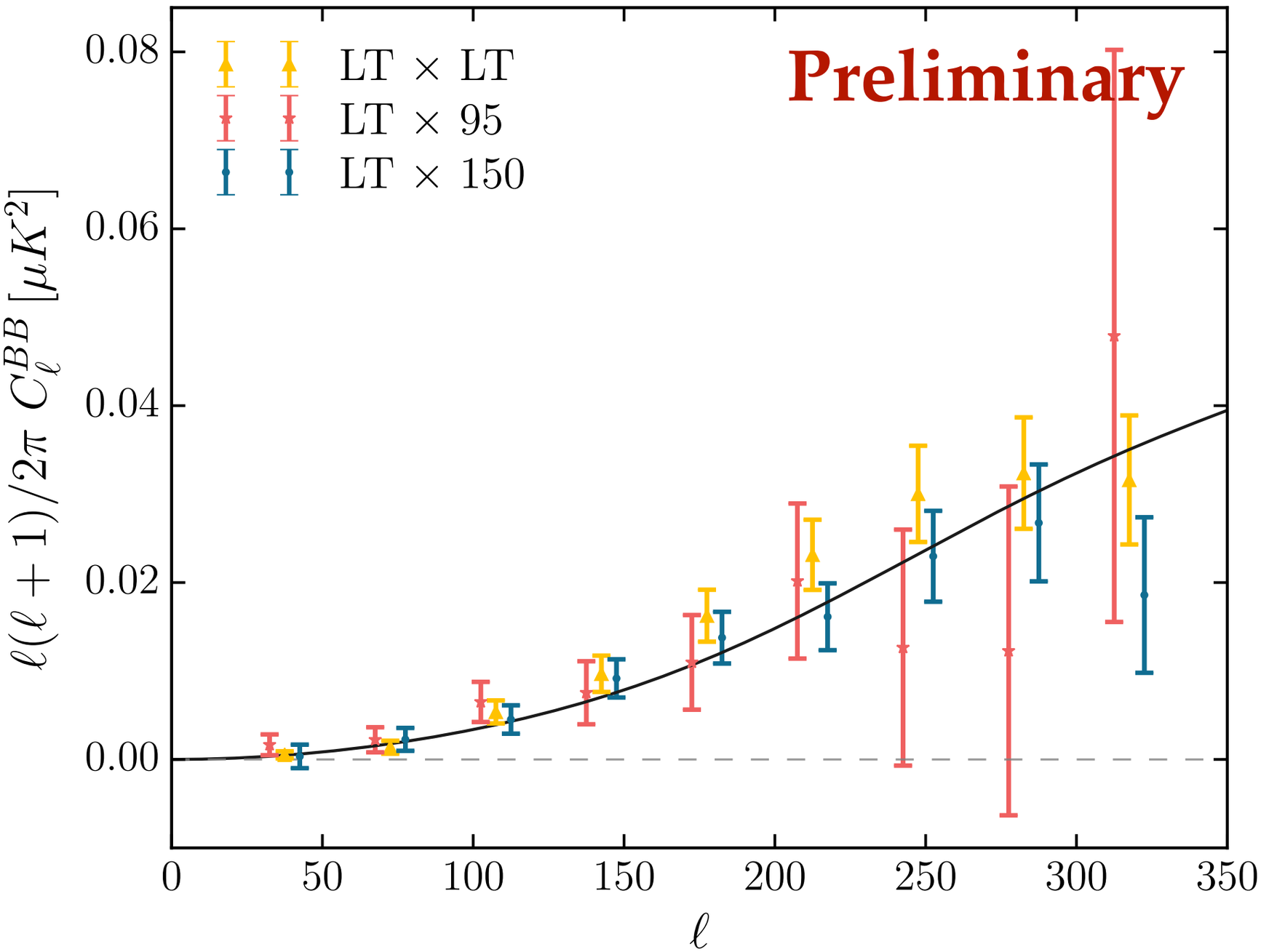


Sim

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

Same for U map

Form auto- and cross-spectra of the lensing template



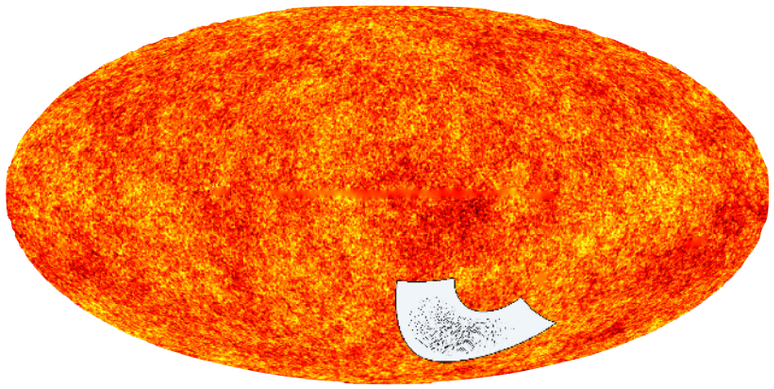
Connecting delensing to σ(r)

BICEP/Keck likelihood analysis framework:

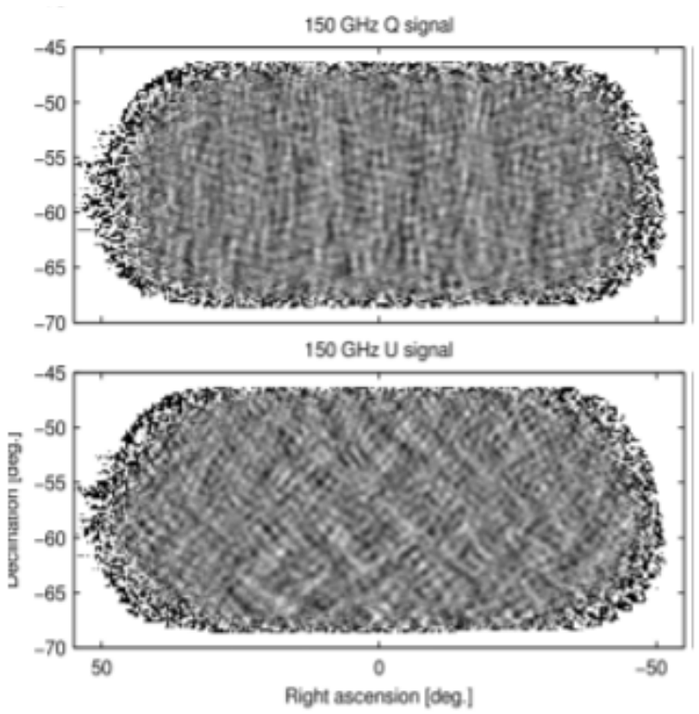
how is delensing incorporated

BICEP/Keck likelihood input (+ delensing)

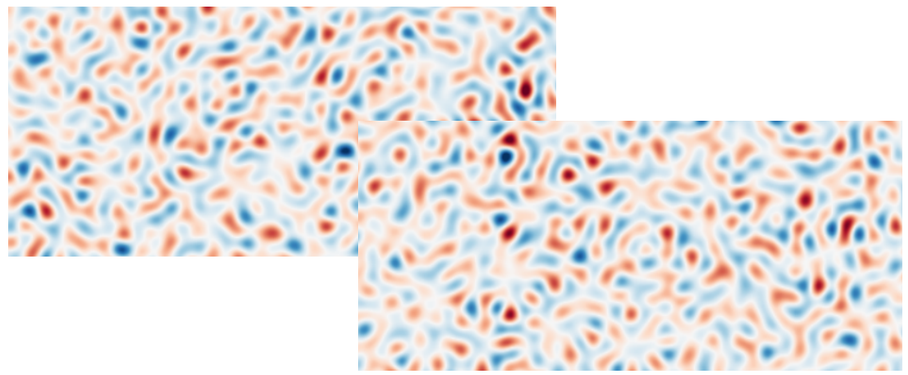
- Input maps to multicomponent analysis that extracts constraints on *r*



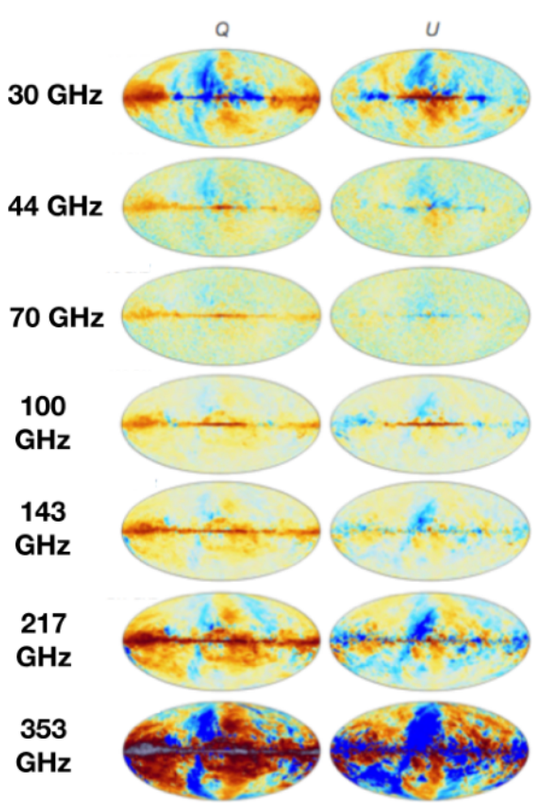
Maps from BICEP/Keck (95/150GHz)



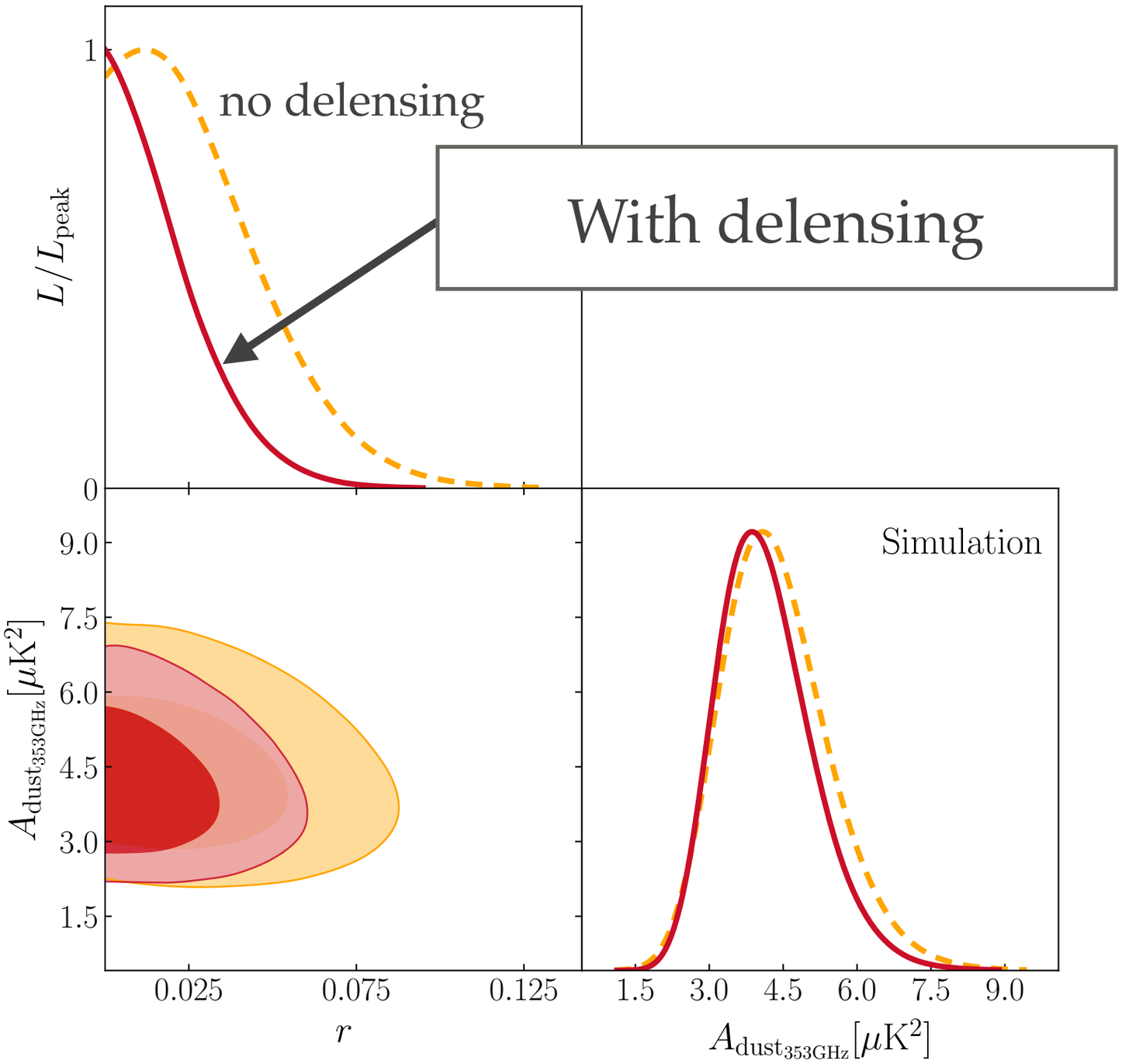
+ lensing template



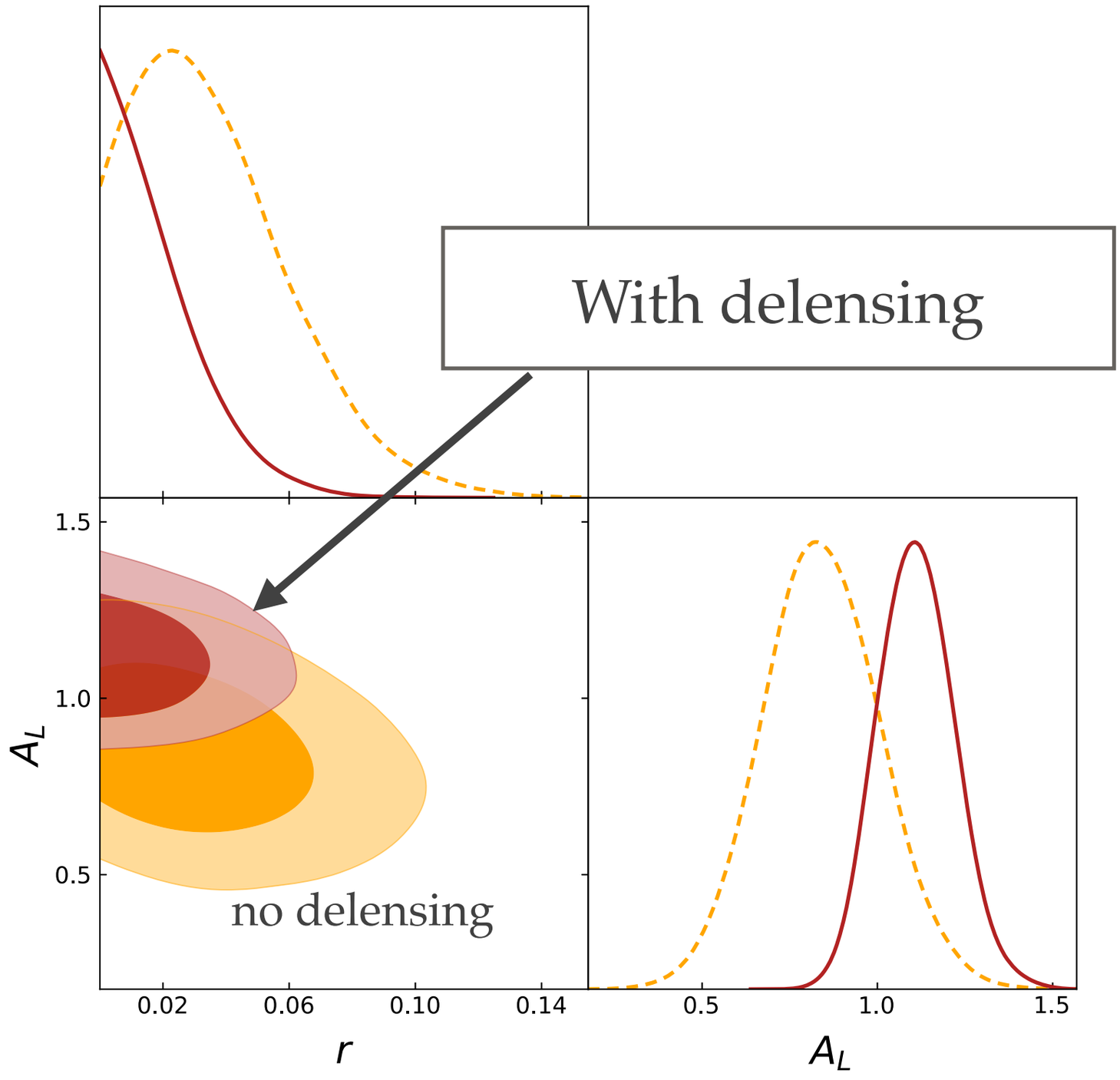
Maps from Planck/WMAP



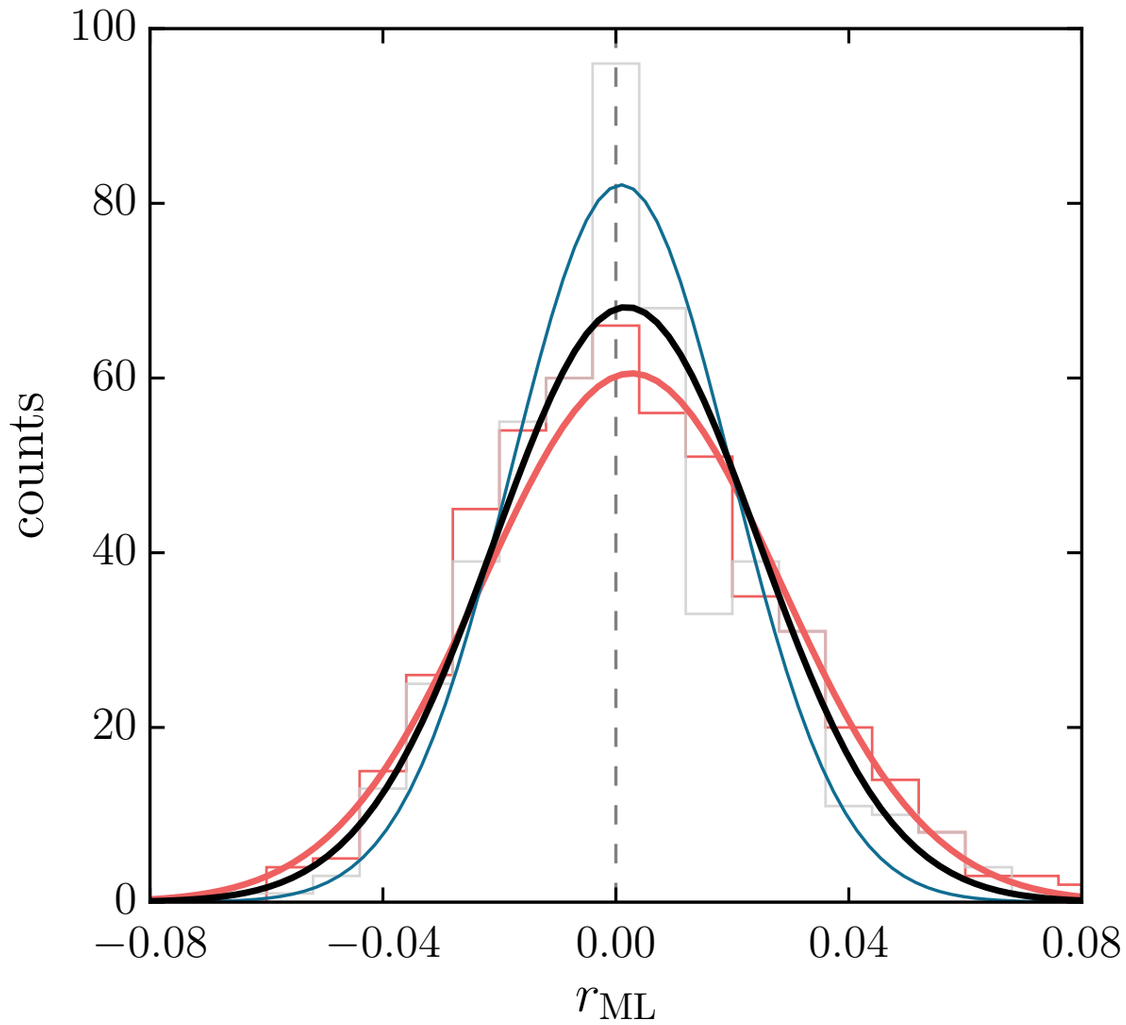
Posterior distribution with delensing (sim)



Lensing template breaks r degeneracy with A_{lens}



How much do we improve σ(r)?



No delensing

Perfect delensing

This analysis

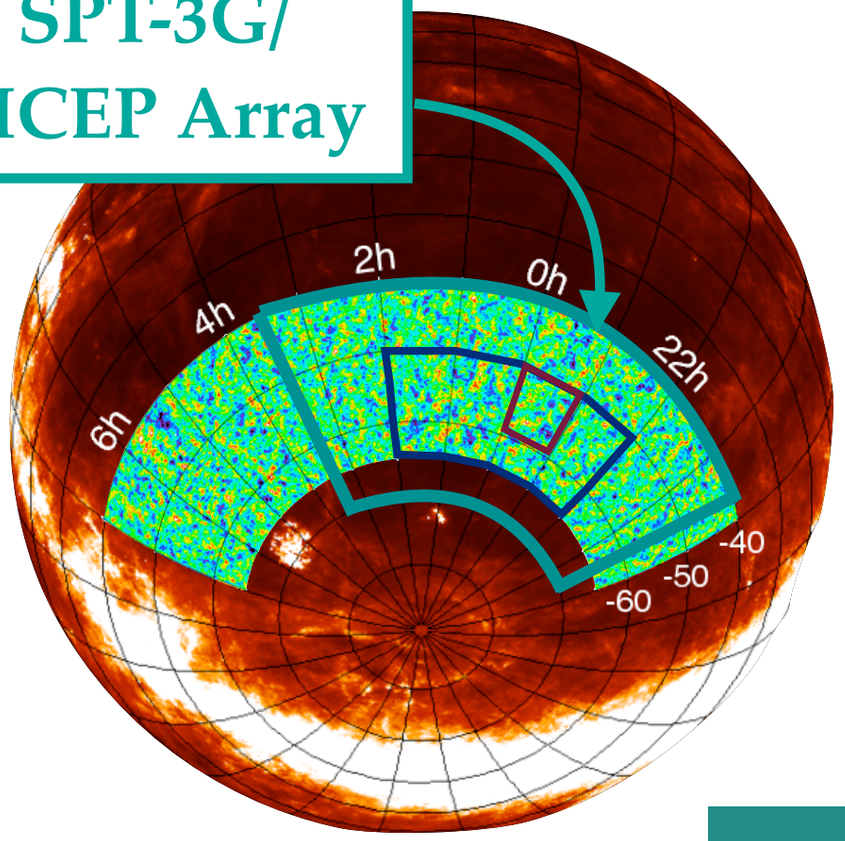
- With perfect φ map and E modes, adding a lensing template to the BK14 data set improves σ(r) from 0.026 to 0.019.
  - ~30% of Clbb variance is from lensing
- Using CIB φ tracer to form the lensing template, σ(r) improves by ~10% from BK14 to 0.023.
- When only one of the 3 input E modes are used, SPTpol improves σ(r) most, then is BK, then Planck.

Current limitation to delensing

- B mode variance is dominated by galactic foregrounds; even with perfect delensing we do not improve σ(*r*) very significantly.
- Need better φ tracer: CIB map we use has cross-correlation with underlying φ at 60-80%. CMB-derived φ from upcoming CMB experiments will do better!

SPT-3G lensing

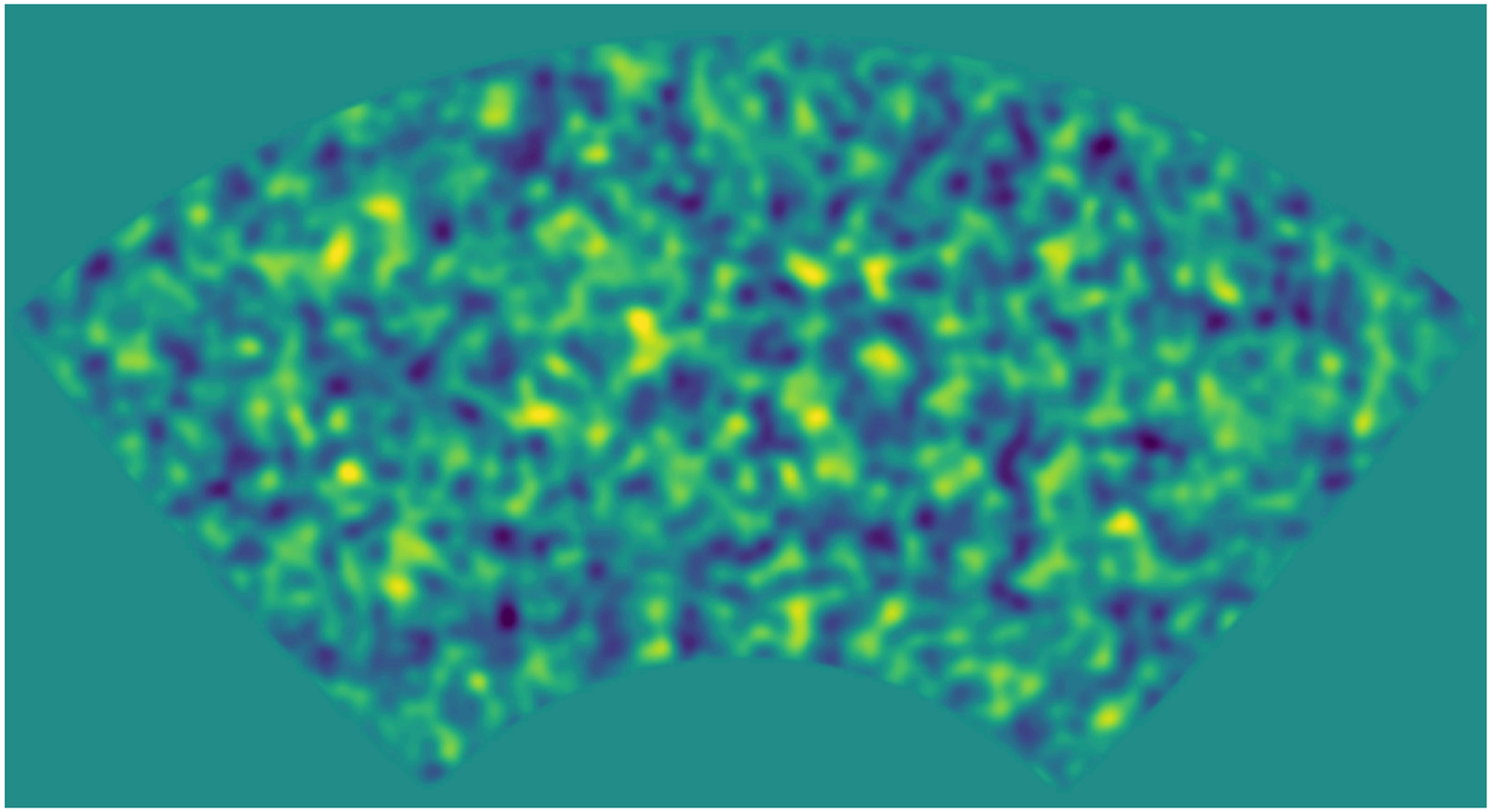
SPT-3G/ BICEP Array



SPT-3G lensing

Zhaodi Pan
UChicago

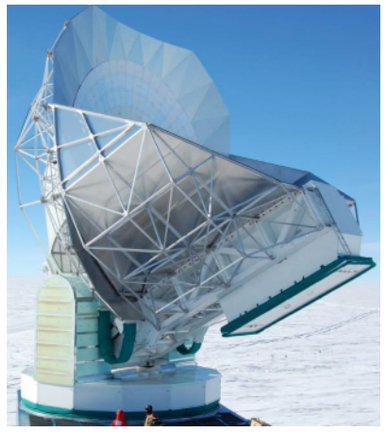
MV reconstruction on 1500 sq. deg. SPT3G footprint, 2018 noise level (simulation)

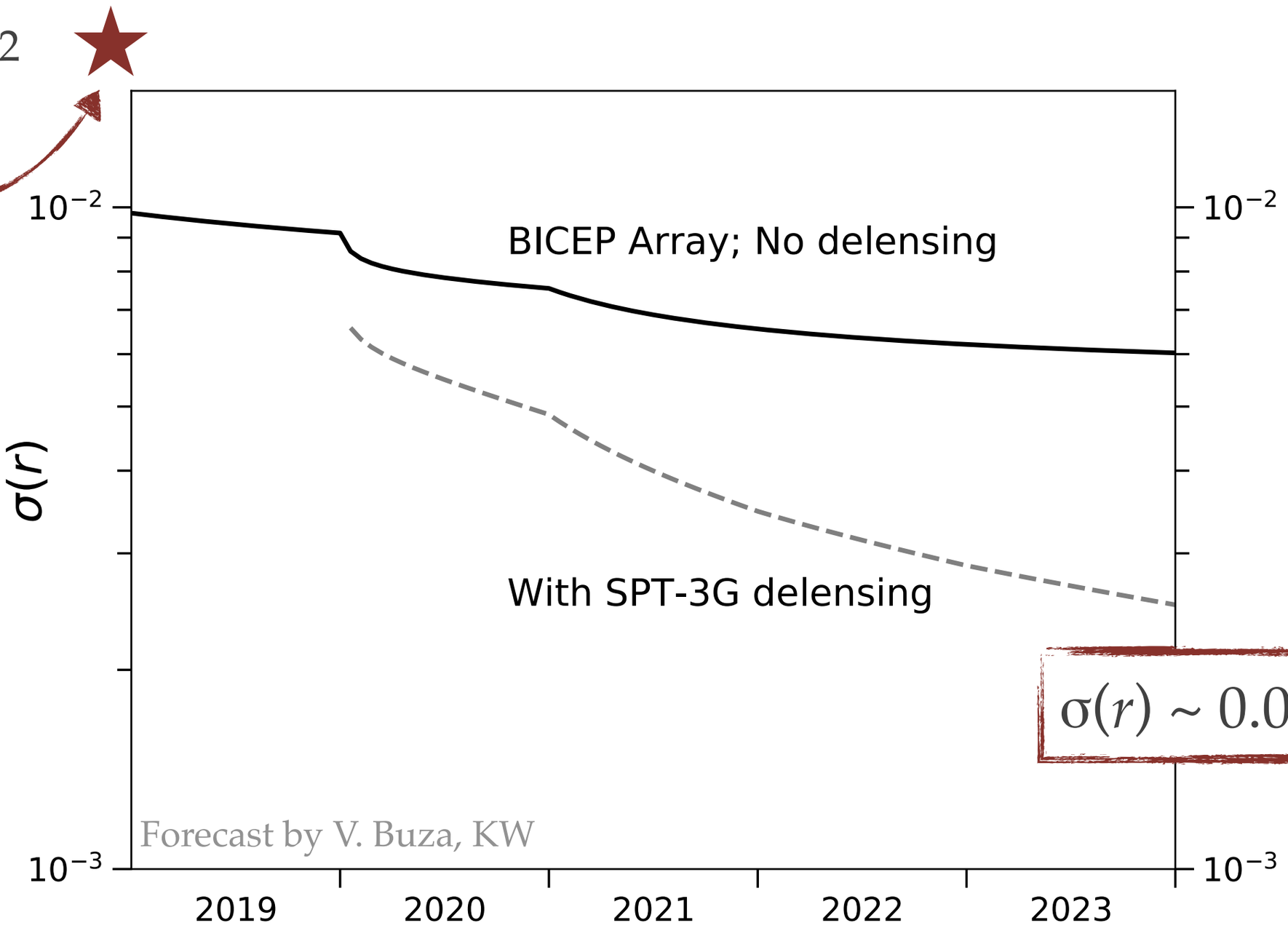


Delensing BICEP/Keck B-mode maps using SPT-3G φ to improve r constraint

Current $\sigma(r) = 0.02$
(BK15)

BICEP Array





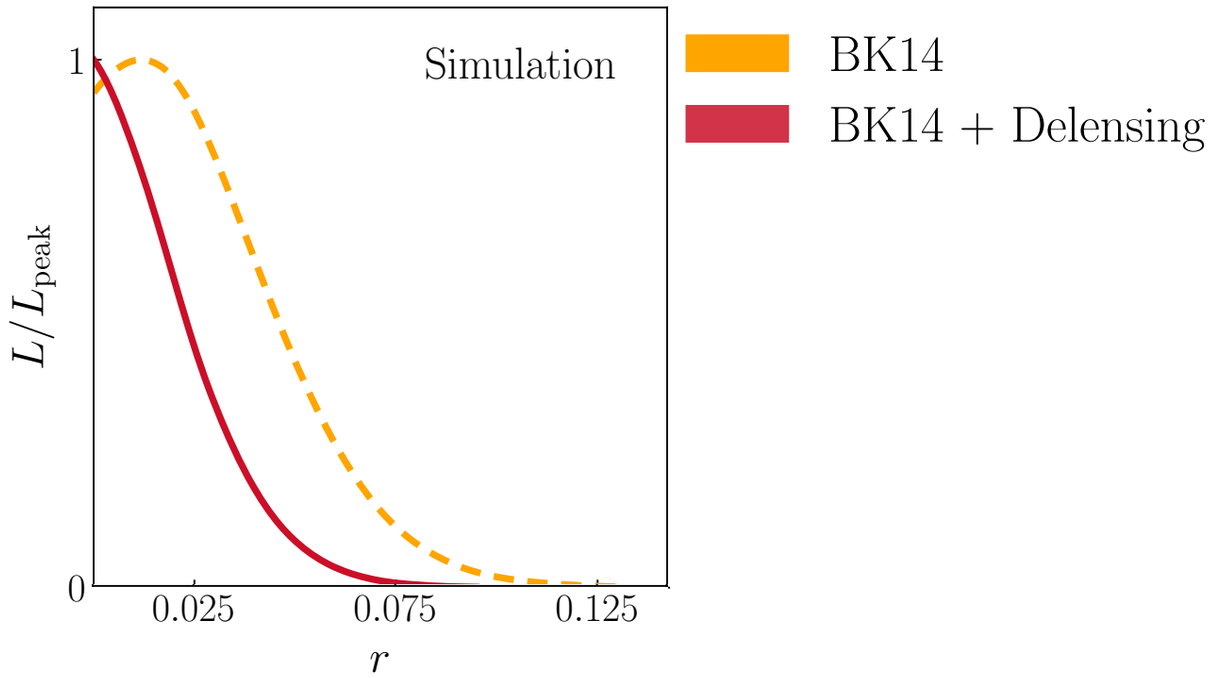
Summary

- Add lensing template to the BK14 analysis.

- Use CIB as φ tracer and combined BK, SPTpol, and Planck maps for E modes.

- Delensing of BICEP/Keck maps currently improves σ(*r*) by 10%.

- Delensing BICEP Array B-mode maps with SPT-3G φ map improves σ(*r*) by > 2x.



Extras