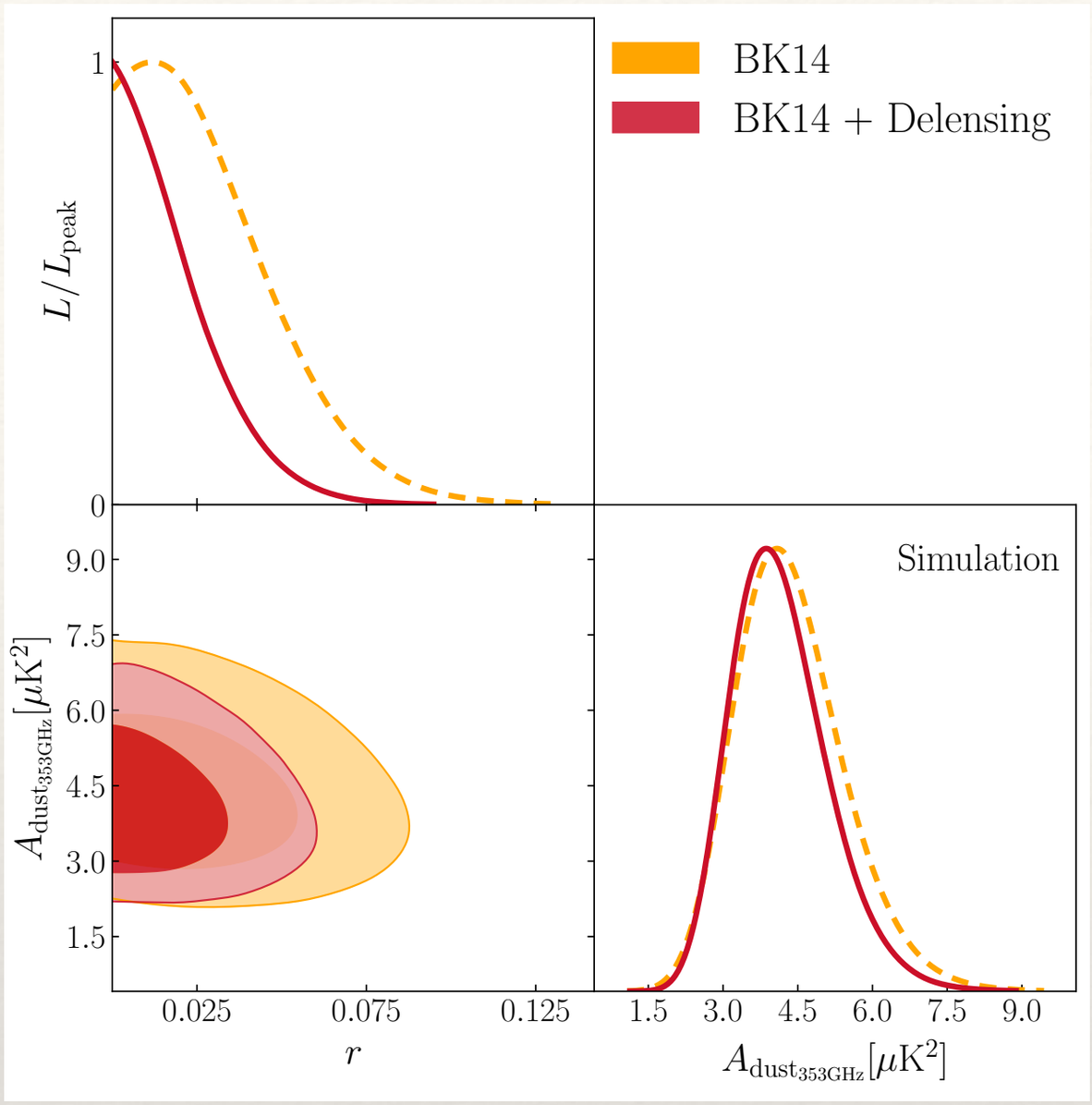

B-mode Delensing: current status and future ~~prospects~~ worries

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University of Chicago
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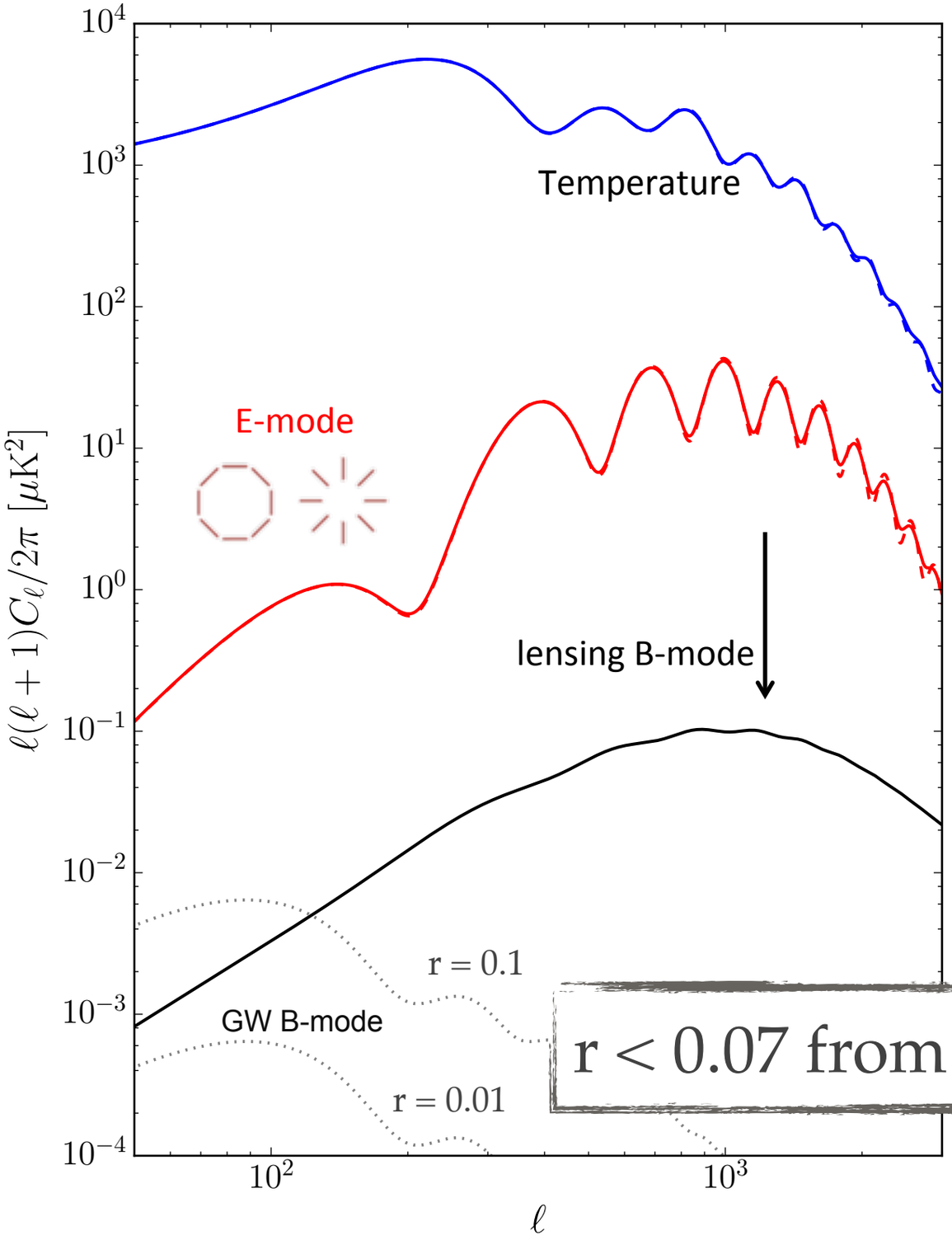
Jan 14, 2019
BCCP Lensing Workshop

Outline

- Where are we in terms of delensing the CMB?
- BICEP/Keck + SPT/Planck delensing example
- Future prospects

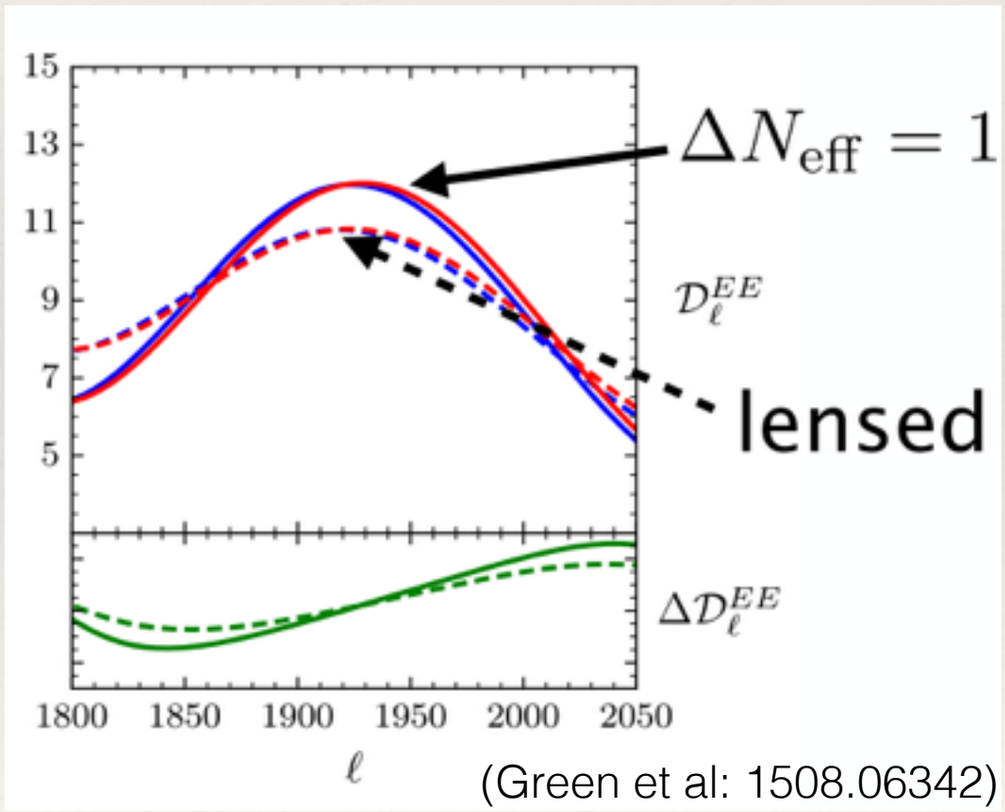
photo by Amy Lowitz

Why delens? i.e. are the effect of lensing limiting our parameter constraints?



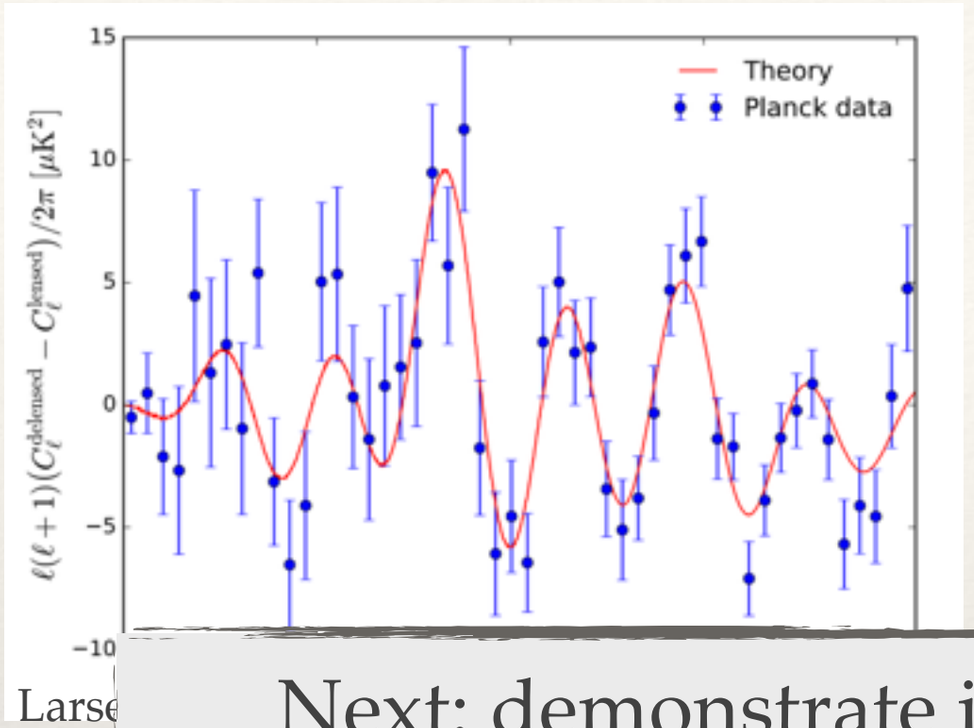
r < 0.07 from BK15

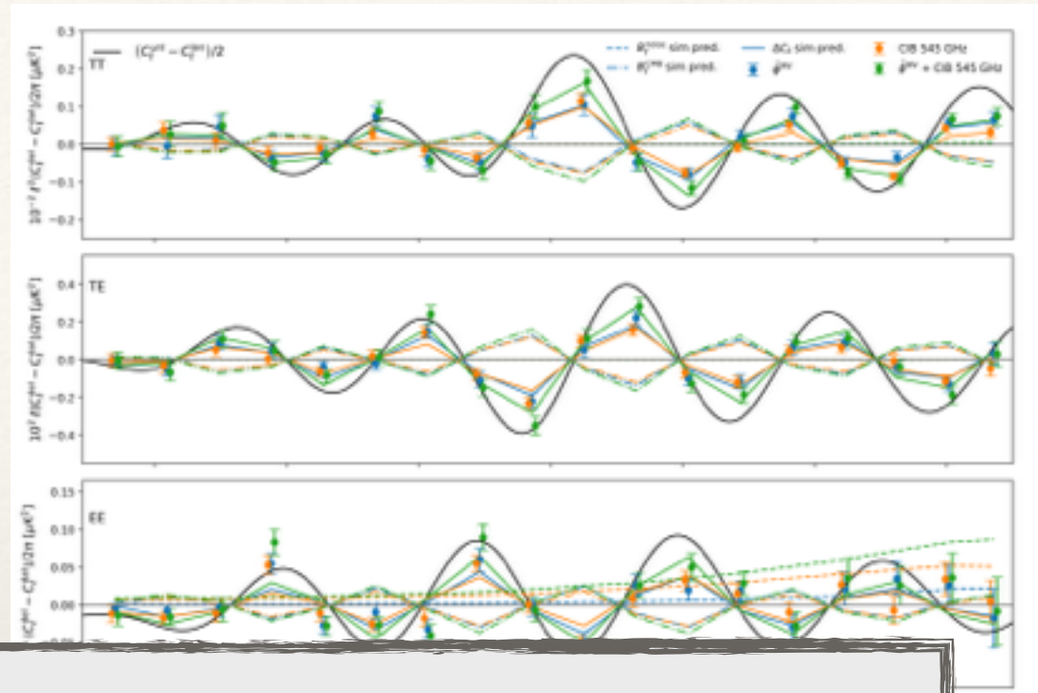
- For primordial gravitational wave r (in ~2-3 years)
  - cosmic strings, modified gravity, etc.
- For N_{eff} (in ~5+? years)



(Green et al: 1508.06342)

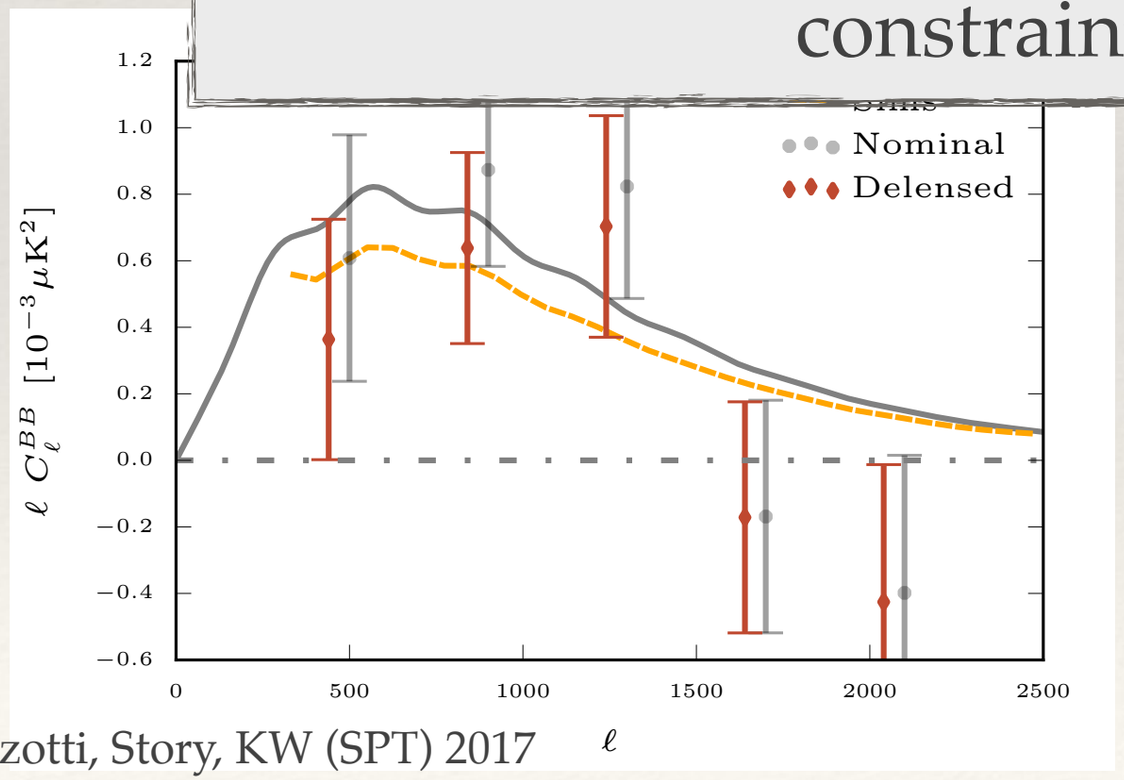
Delensing: demonstrations on data



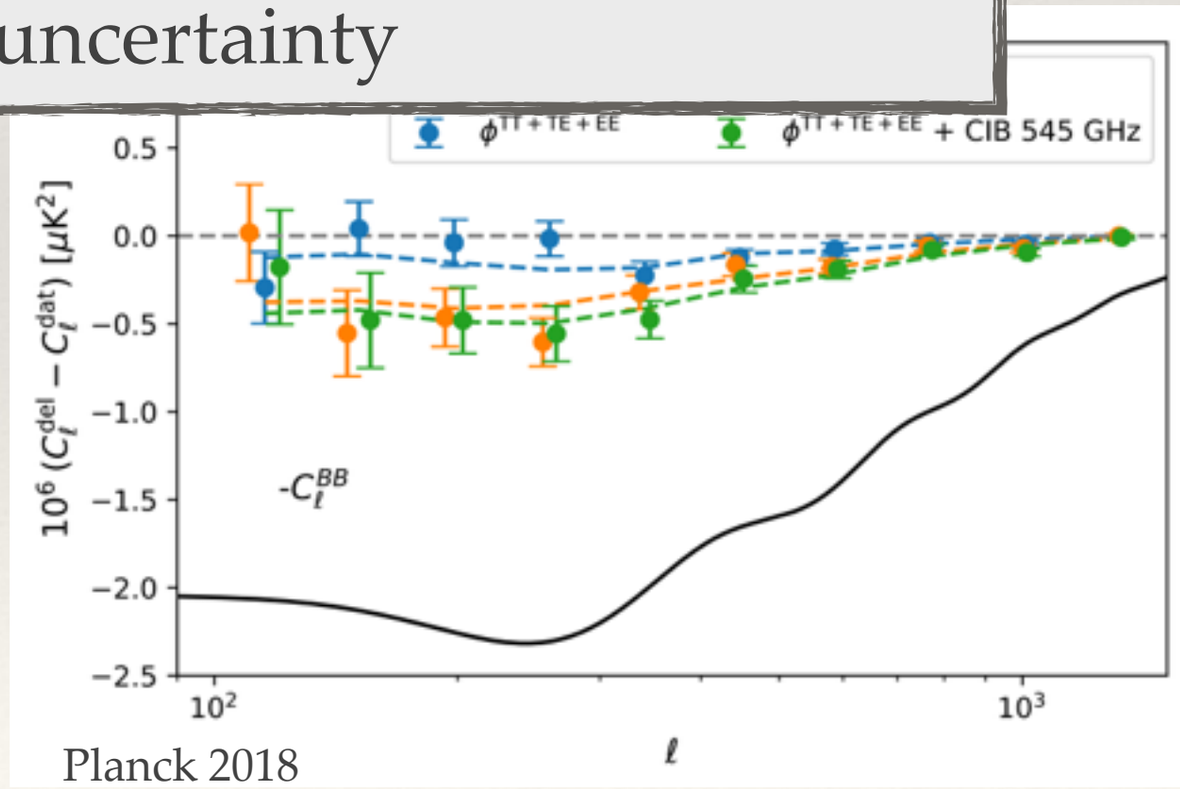


Larse

Next: demonstrate improvement on parameter constraint uncertainty

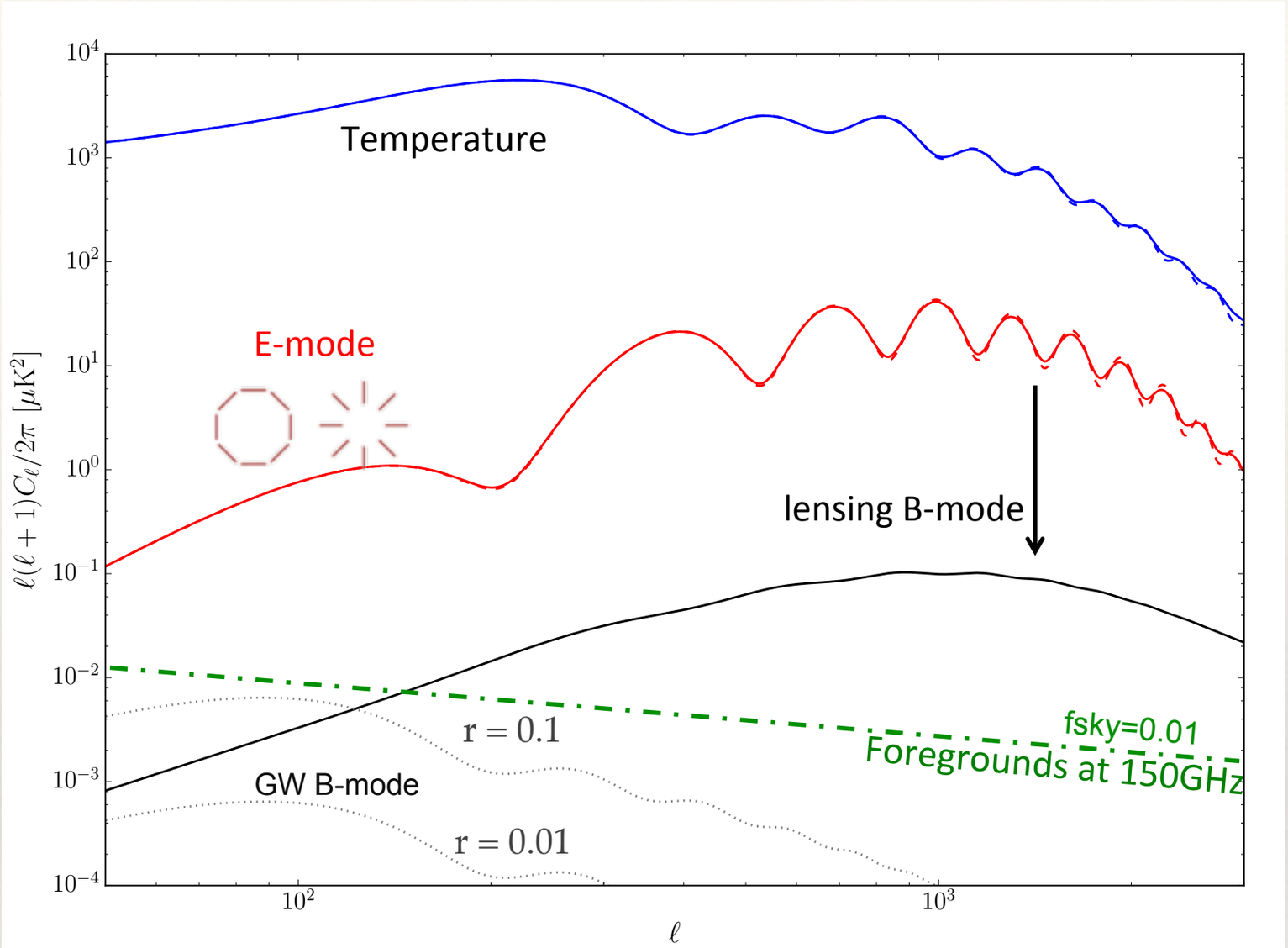


Manzotti, Story, KW (SPT) 2017



Planck 2018

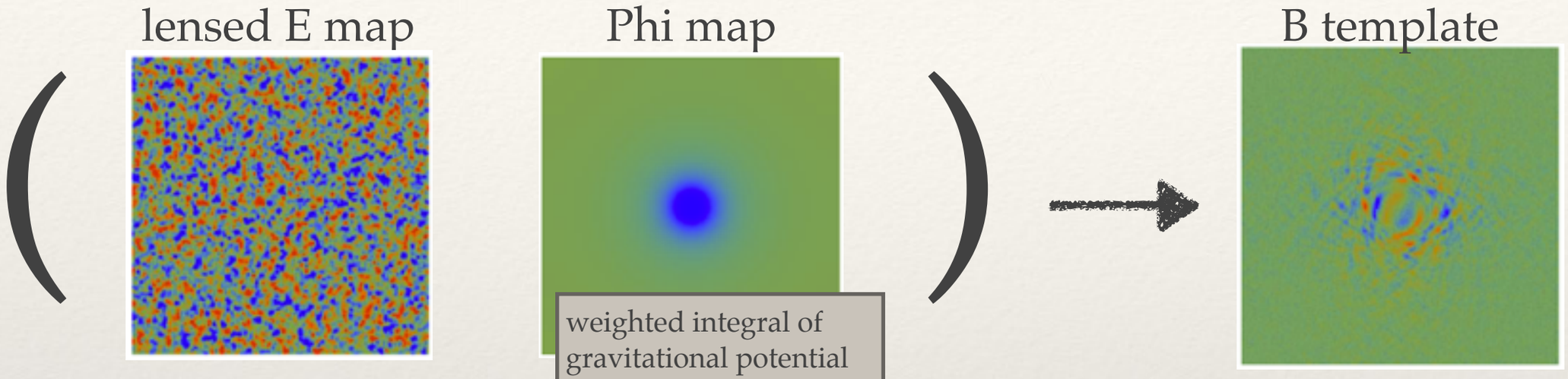
Delensing for r : a BICEP/Keck example



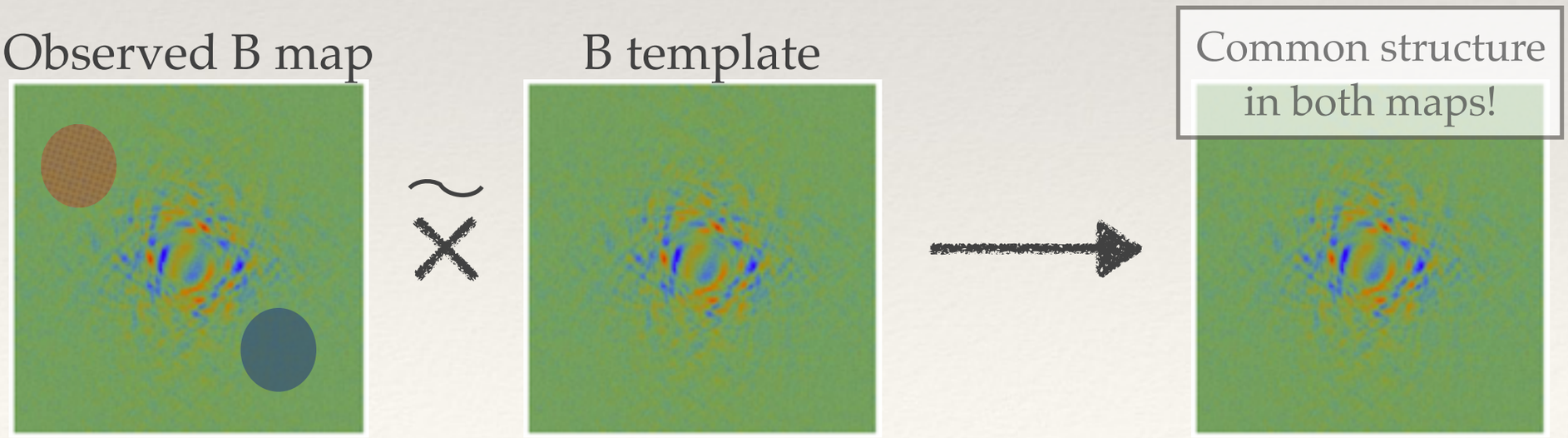
- We can fit lensing model + r simultaneously, but limited by sample variance of lensing
- **Delensing** B-modes: using the ***realization-specific*** lensing B-mode sky to reduce lensing sample variance
- Especially important if observing a small sky patch

Delensing: the idea

1. Use Phi tracer and lensed E map to get estimate of lensing B modes



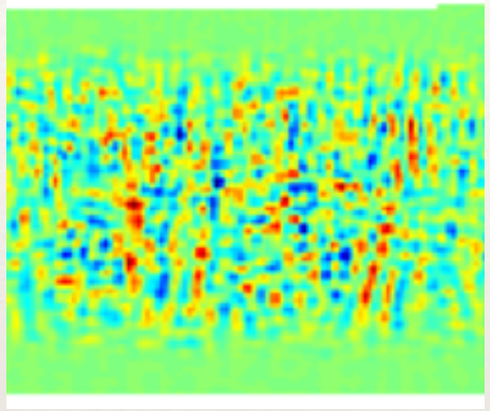
2. Cross-correlate the lensing B template with observed B mode map to quantify how much lensing B modes are in the observed map



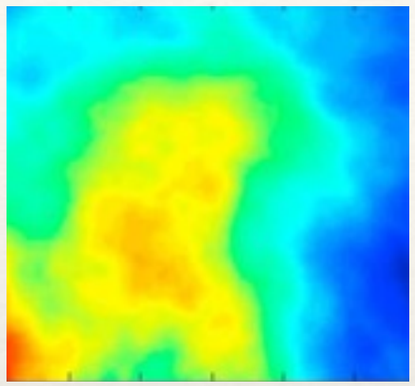
Lensing template construction

1. Undeflect by $-\nabla(\phi)$

Lensed Q/U map



ϕ map

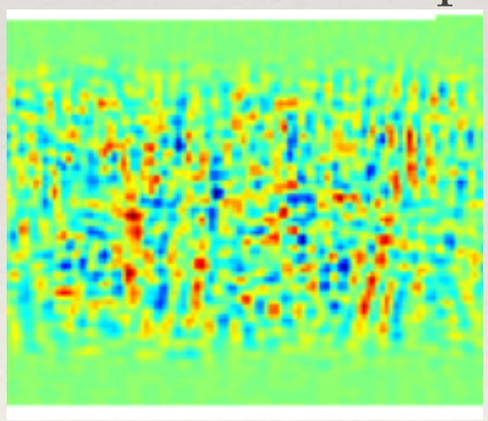


Q/U maps that has no lensing B-modes

(in ideal, noiseless case)

2. Difference the pre- and post-deflected map

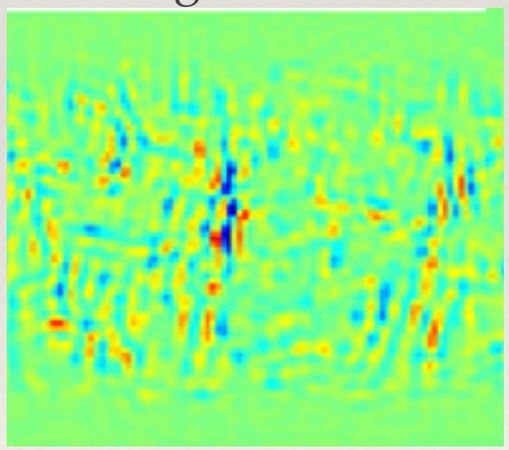
Lensed Q/U map



Q/U maps that has no lensing B-modes

(in ideal, noiseless case)

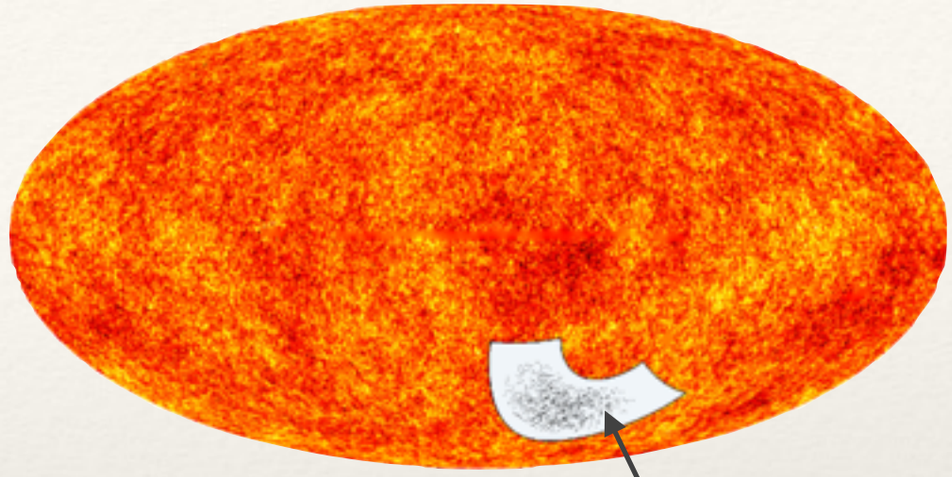
lensing template: Q/U maps that contain lensing E/B modes



Feed the Q/U map through a B-estimator to get the power spectra as inputs to the multicomponent analysis.

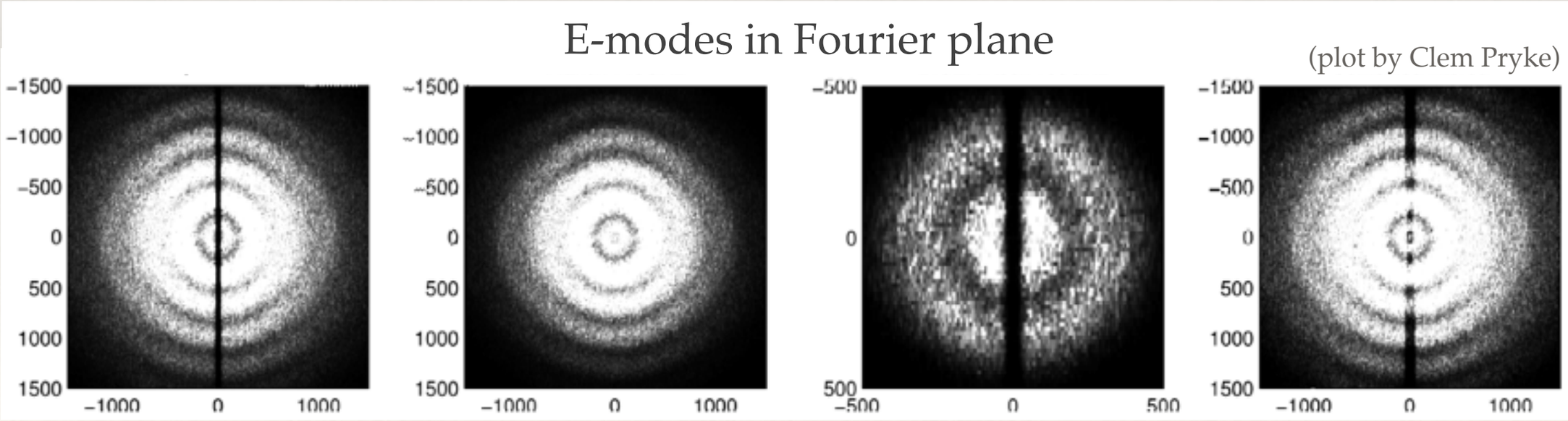
Inputs to BK lensing template

- Phi tracer: Planck's CIB map
- Q/U maps: combination of BICEP/Keck, SPTpol, and Planck maps



E-modes in Fourier plane

(plot by Clem Pryke)



SPTpol | Planck | BICEP/Keck (note different ell-range) | Combined

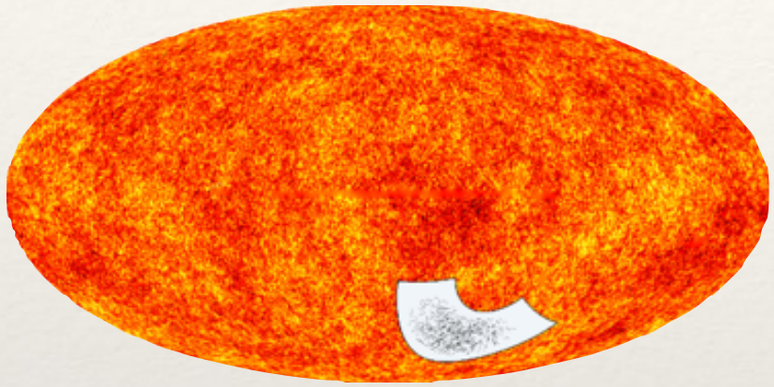
Connecting delensing to σ(r)

BICEP/Keck analysis framework:

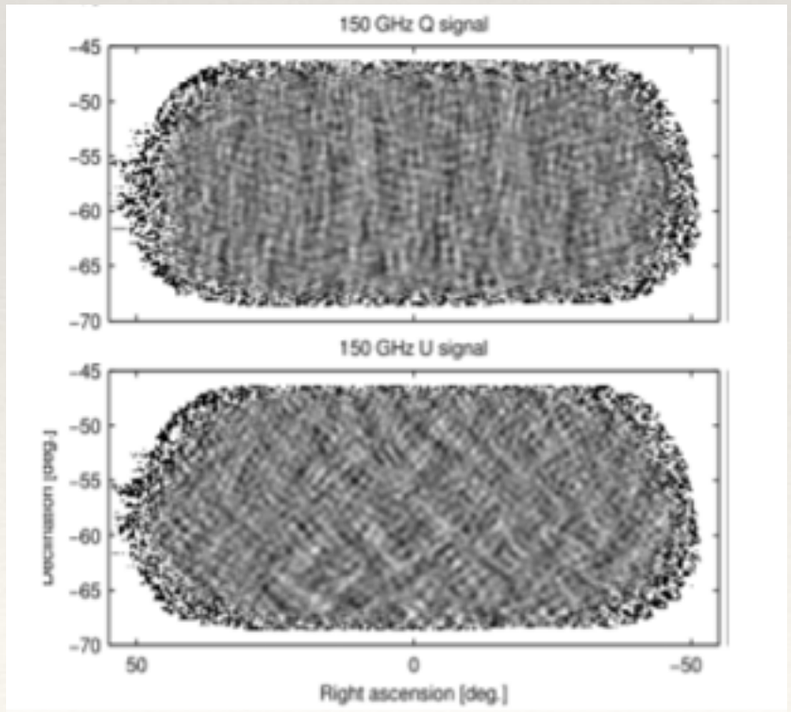
how is delensing incorporated

BK multicomponent analysis (no delensing)

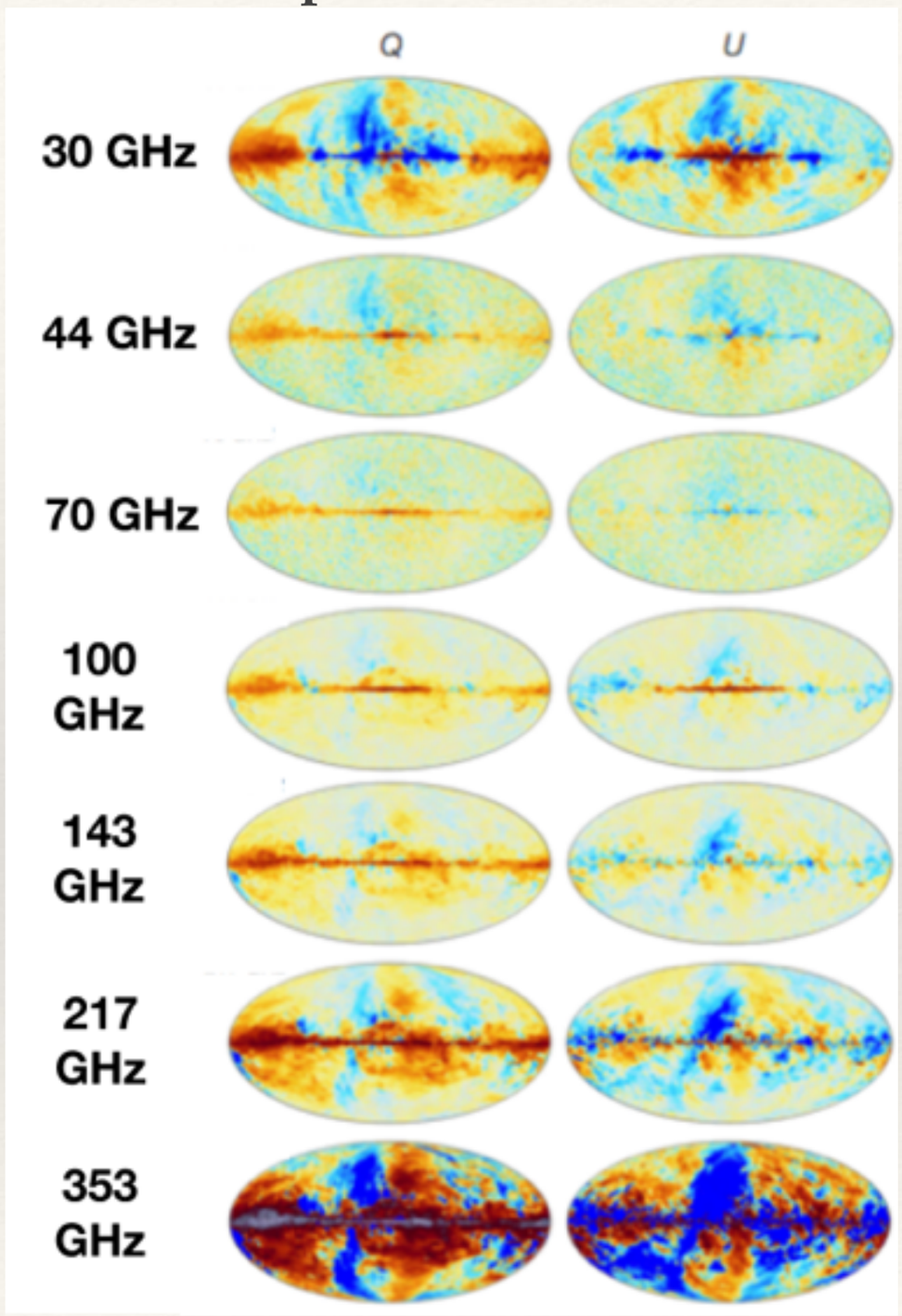
- Input maps to multicomponent analysis that extracts constraints on *r*



Maps from BICEP/Keck (95/150/220 GHz)



Maps from Planck



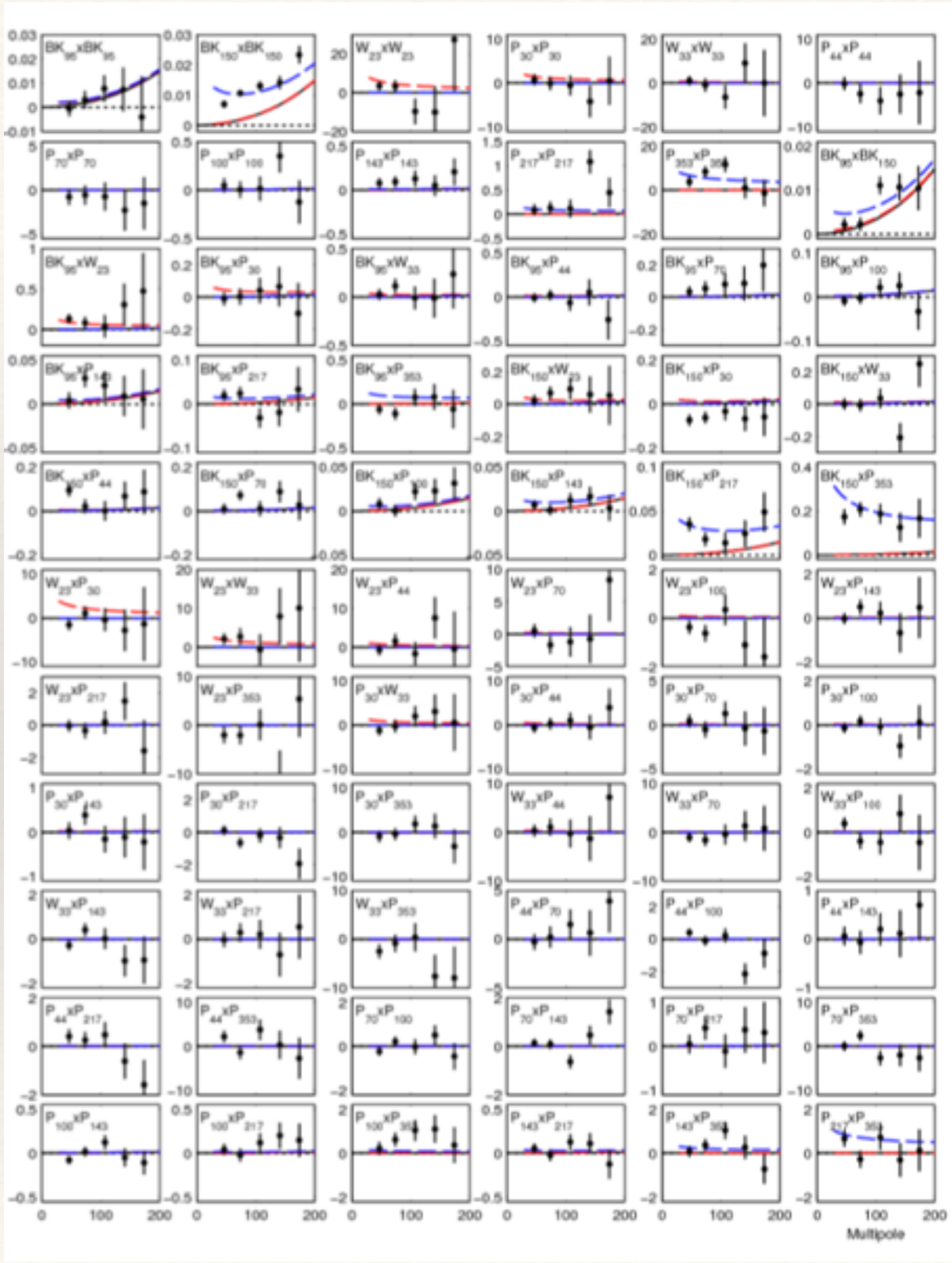
+ WMAP

BK multicomponent analysis (no delensing)

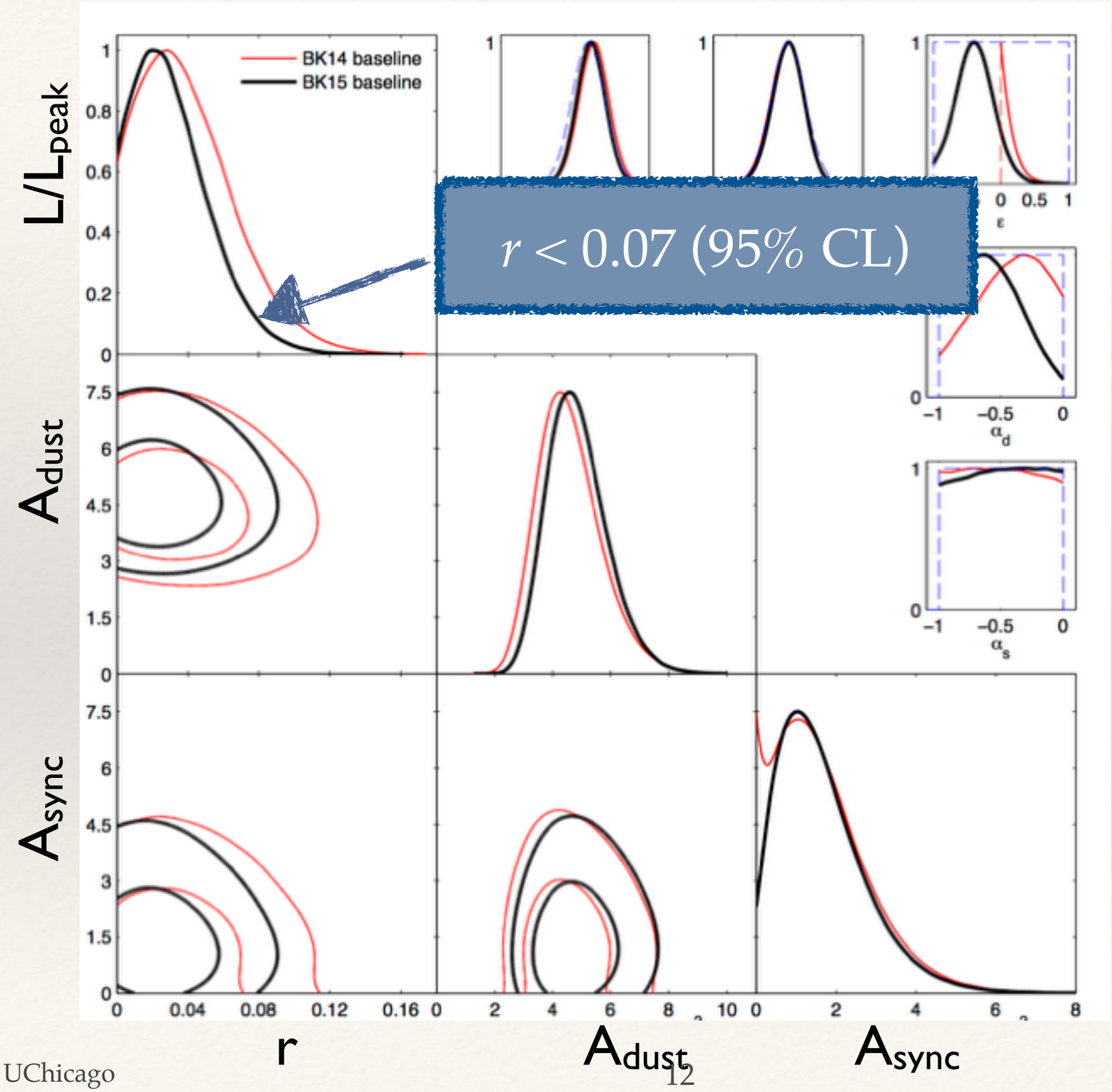
- Take the auto- and cross-spectra of the BICEP/Keck and WMAP/Planck maps
- To calculate the likelihood, compare the data bandpowers against the model expectation values of lensing BB, *r*, and 7 parameter foreground model:

  $A_{\rm dust}, \alpha_{\rm dust}, \beta_{\rm dust}, A_{\rm sync}, \alpha_{\rm sync}, \beta_{\rm sync}$

  dust/sync correlation



BK15 constraints



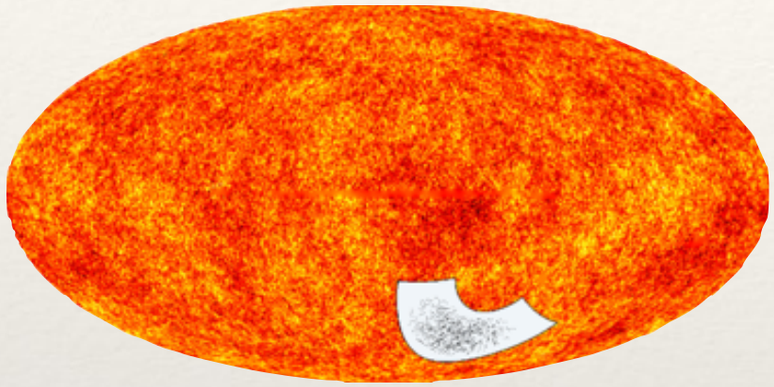
$r < 0.07$ (95% CL)

Allow Dust/ Sync correlation

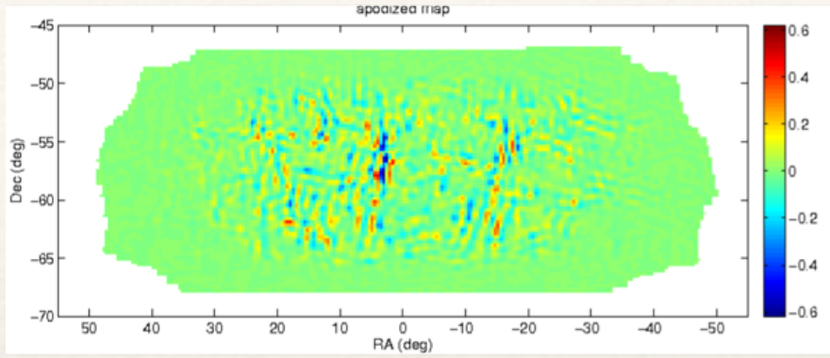
Allow generous variation in spatial spectral indices of dust & sync

BK multicomponent analysis (+ delensing)

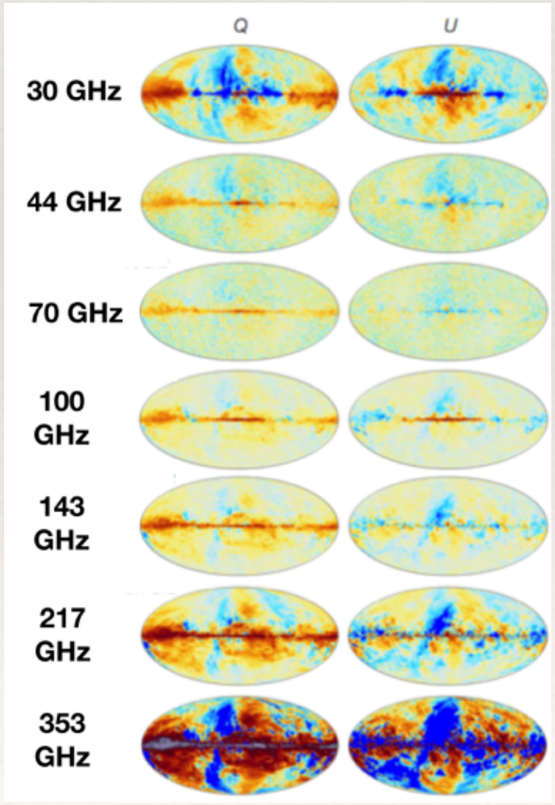
- Input maps to multicomponent analysis that extracts constraints on *r*



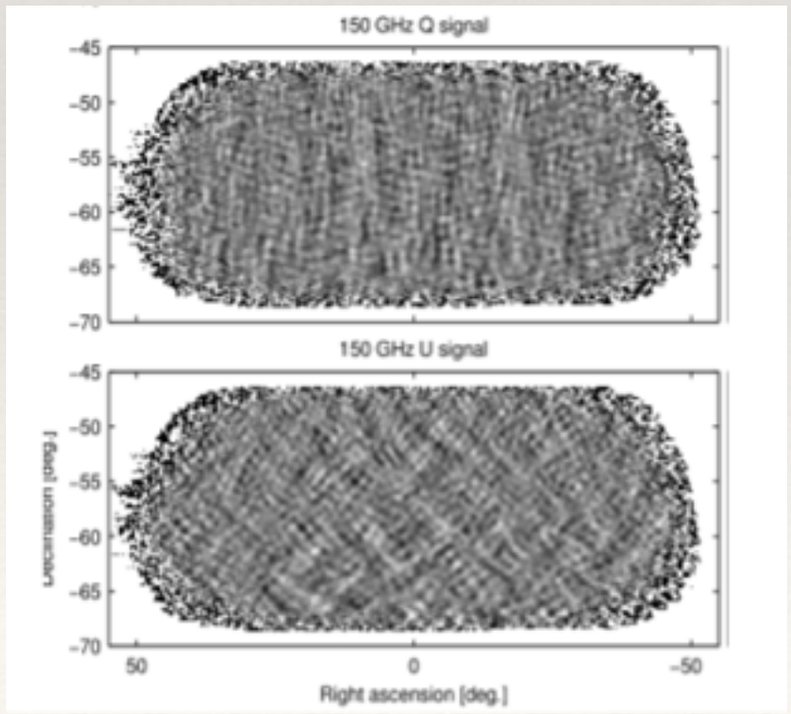
+ lensing template



Maps from Planck

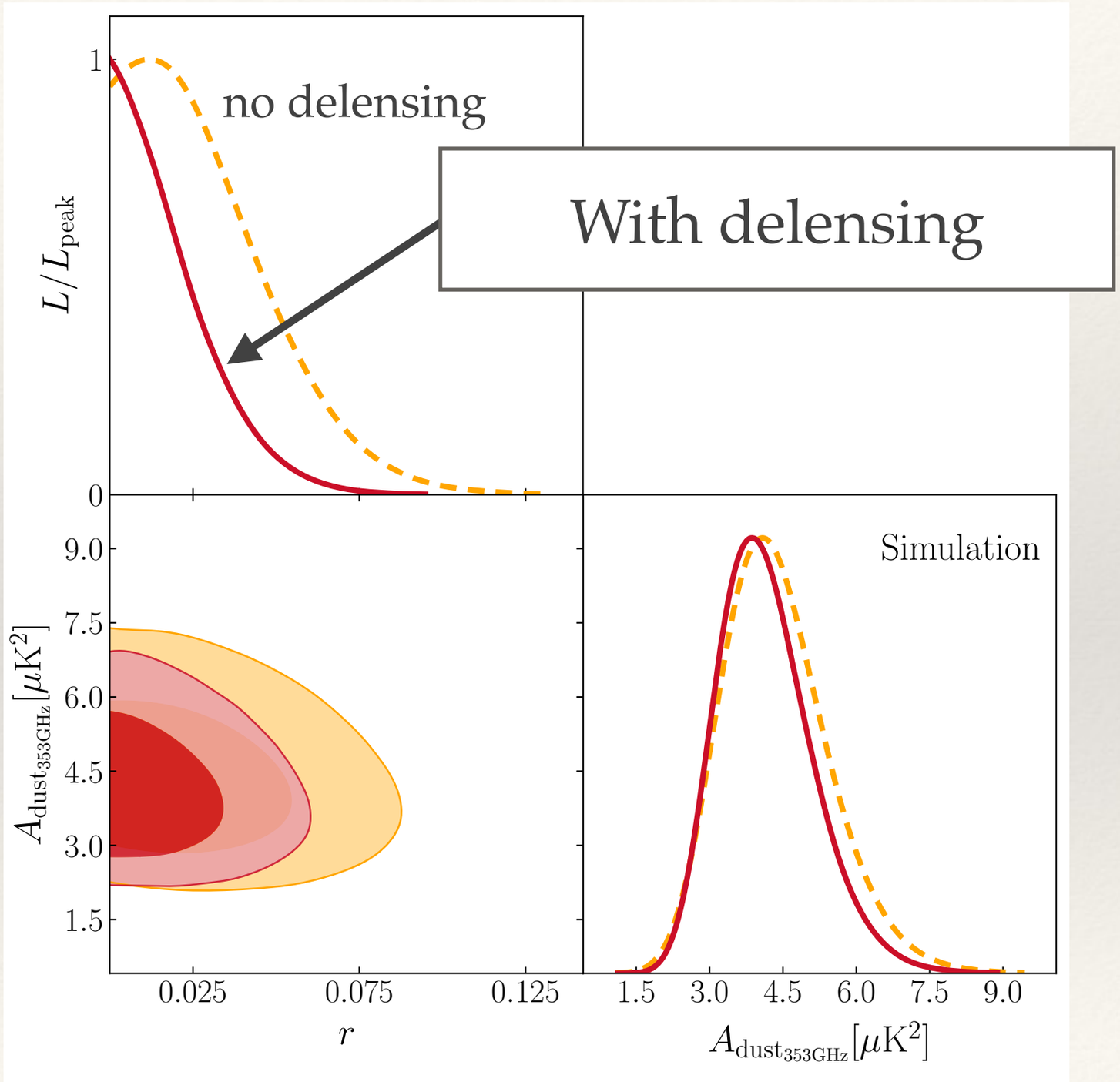


Maps from BICEP/Keck (95/150/220 GHz)

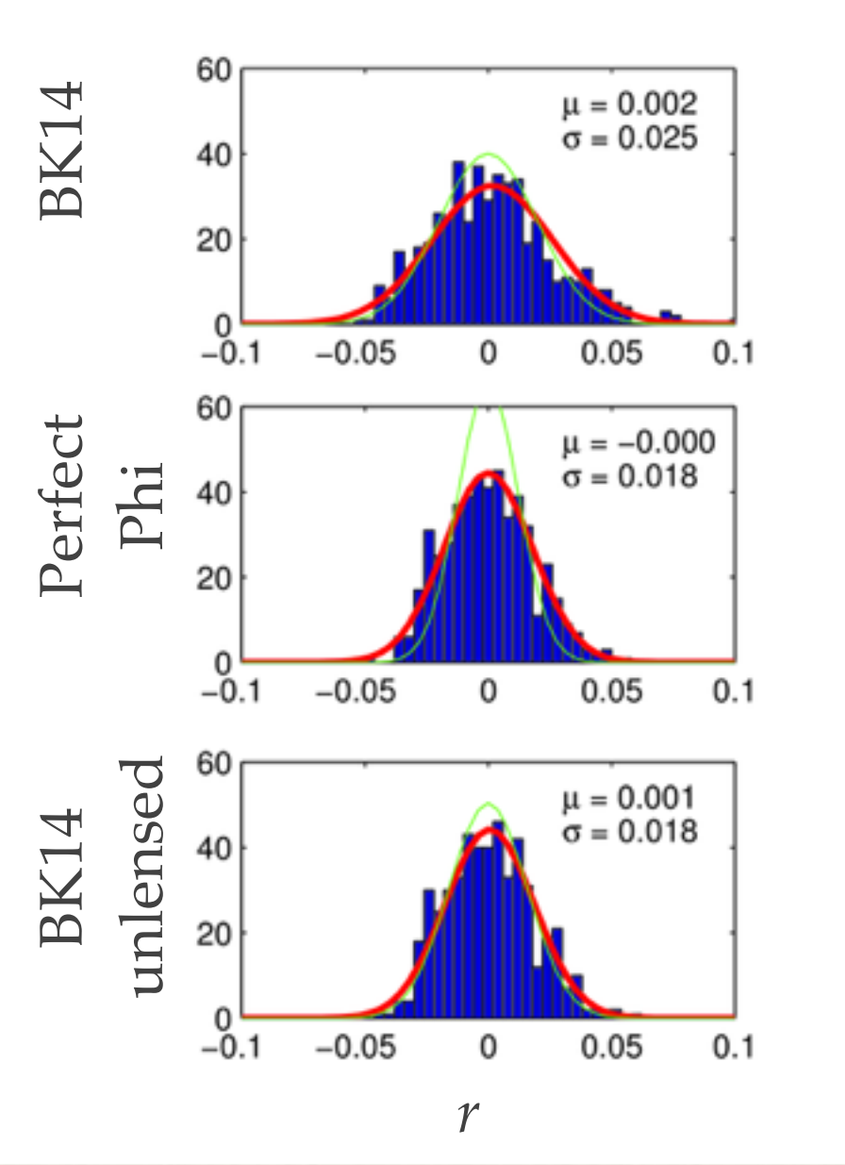


Lensing template as input in multicomponent analysis

The covariance matrix that enters the likelihood has information of the covariance between the lensing BB spectrum and the observed BB spectrum —> reducing σ(r).



How much do we improve σ(r)?



- With perfect ϕ map (no decorrelation, no noise), adding a lensing template to the BK14 data set improves σ(r) from 0.025 to 0.018
- Using CIB phi tracer to form the lensing template, σ(r) improves by ~10% from BK14

Checks/tests

- How much do we bias the lensing template (and therefore r)
  - if the polarization calibration is off?
  - if the bandpasses between BK/SPT/Planck for Q/U combination are differently sensitive to galactic dust?
  - if the CIB-phi correlation is misestimated?
  - if the CIB map is contaminated by dust?
  - if the Q/U map is contaminated by dust?

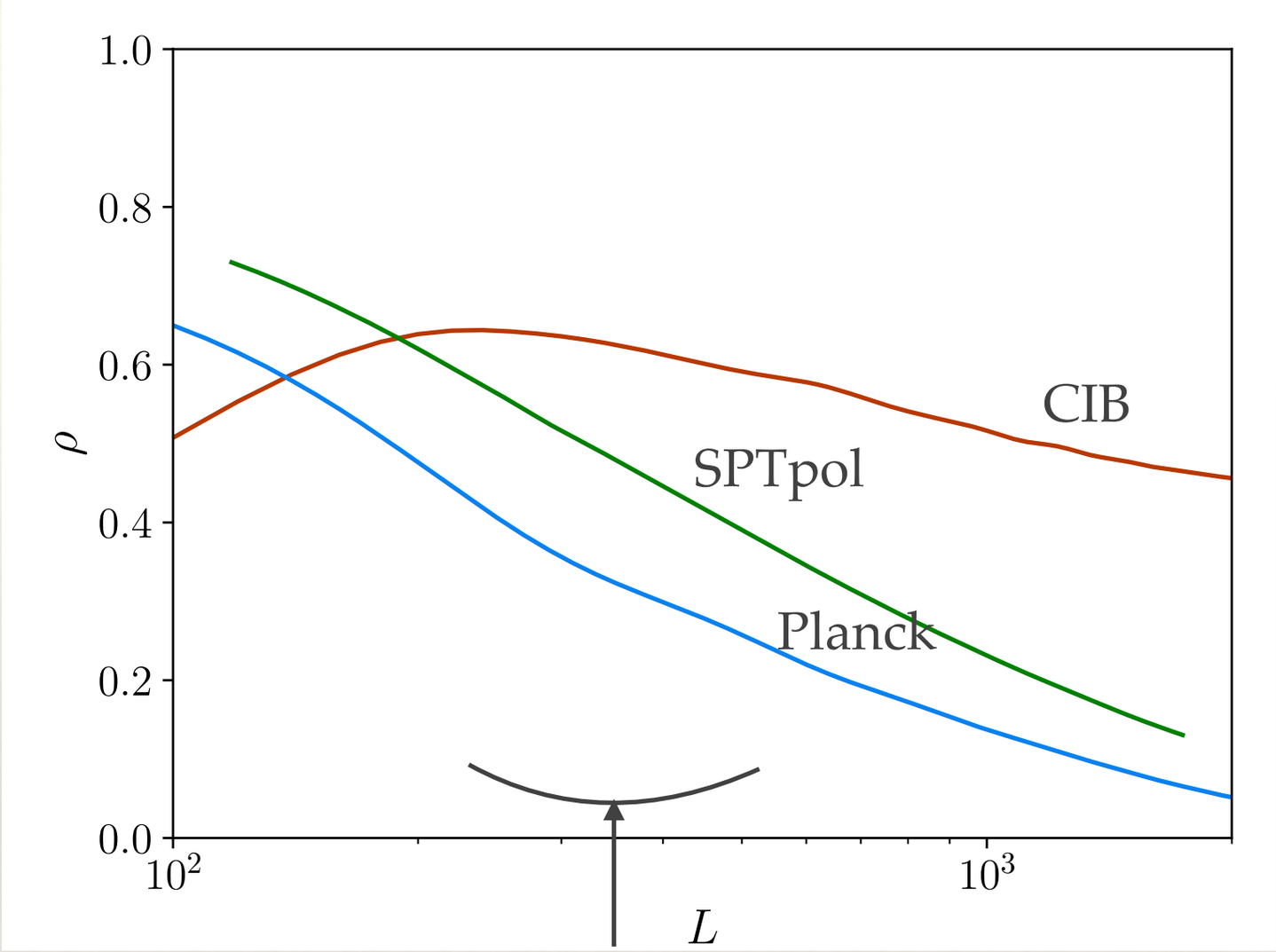
Delensing efficiency

Cross-correlation of tracer and ϕ-field

$$\rho_\ell = \frac{C_l^{\text{tracer-}\phi}}{\sqrt{C_l^{\text{tracer-tracer}} C_l^{\phi\phi}}}$$

For CMB reconstructed ϕ

$$\rho_\ell = \sqrt{\frac{C_\ell^{\phi\phi}}{C_\ell^{\phi\phi} + N_\ell^{\phi\phi}}}$$



~scales of lenses that source most lensing B-modes

- In the limit that the E-mode noise is small, the correlation between the ϕ tracer and the underlying phi field determines how well the lensing B-modes are estimated —> delensing efficiency

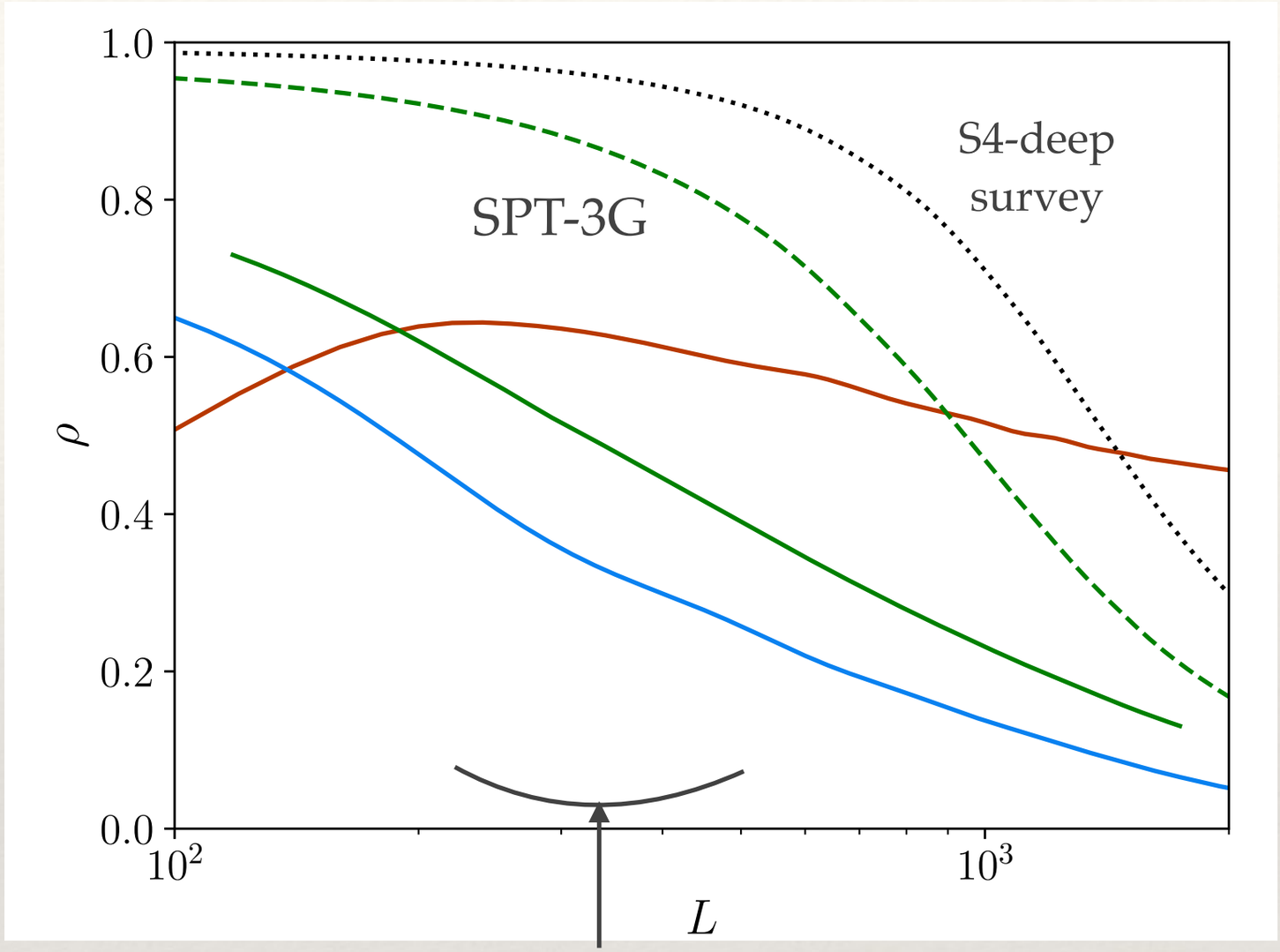
Forecasts (SPT-3G / CMB-S4)

Cross-correlation of tracer and ϕ-field

$$\rho_\ell = \frac{C_l^{\text{tracer-}\phi}}{\sqrt{C_l^{\text{tracer-tracer}} C_l^{\phi\phi}}}$$

For CMB reconstructed ϕ

$$\rho_\ell = \sqrt{\frac{C_\ell^{\phi\phi}}{C_\ell^{\phi\phi} + N_\ell^{\phi\phi}}}$$



~scales of lenses that source most lensing B-modes

CMB reconstructed ϕ will soon be the best lensing potential tracer for B-mode delensing

For future experiments

- Biases:
  - Need to control biases from using CMB phi for delensing (e.g. Carron+ 2017, Namikawa 2017, Sehgal+2017, Teng+2011)
  - Non-Gaussian foregrounds (galactic and extragalactic) biasing the CMB phi reconstruction used for delensing (e.g. van Engelen, etc.)
  - Higher-order lensing/post-Born effects (e.g. Boehm+ 2018)
- Covariances
  - to what precision will we need to model the covariance amongst delensed bandpowers (or covariance between lensing templates and CMB spectra)?
- Effects from mis-modeling of beam, noise, boundary/source masks…
- How do the above translate/accumulate for iterative approaches or for sampling?

Summary

- Delensing improves constraints on parameters like r and N_{eff}.
- For BICEP/Keck, we have incorporated delensing into a likelihood analysis for r.
- B mode variance is currently dominated by galactic foregrounds; even with perfect delensing we do not improve σ(r) very significantly. For BK14, σ(r) is reduced by ~10% after delensing using CIB as ϕ tracer.
- CIB map we use has cross-correlation with underlying ϕ at 60-80%; CMB ϕ from next generation CMB experiments will have correlation > 90% for large angular scales.
- Much work have been done to understand and characterize potential biases in high S/N regime lensing/delensing. Non-Gaussian polarized dust foregrounds small scales maybe is the most uncertain known unknown…

photo by Amy Lowitz