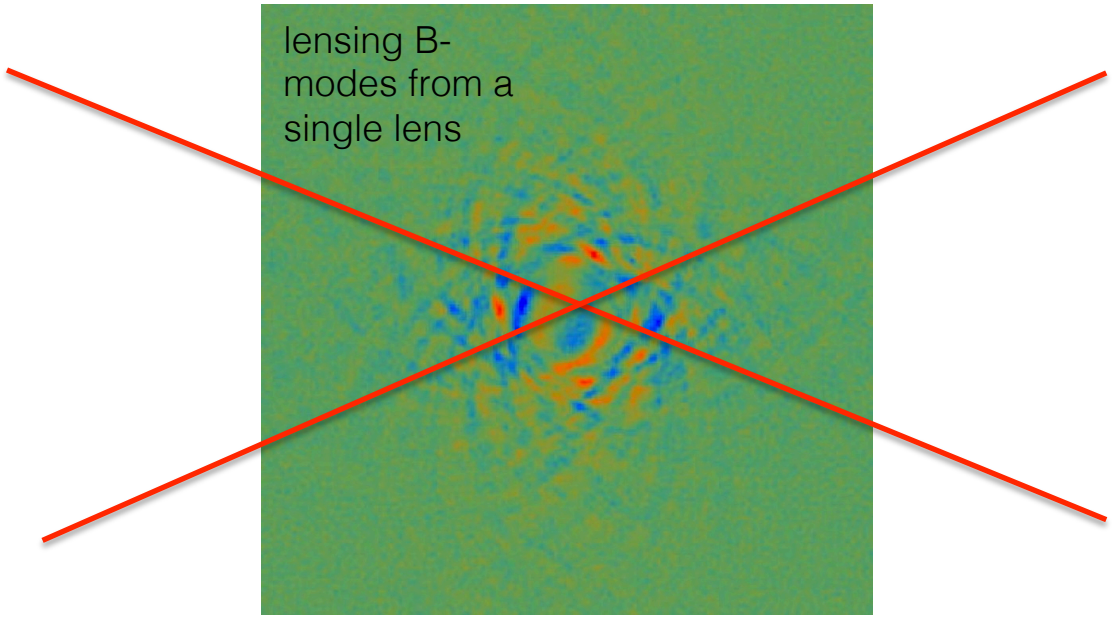
Delensing: New Methods and Challenges for Simons Observatory and LiteBIRD



Blake Sherwin

Department of Applied Mathematics and Theoretical Physics / Kavli Institute for Cosmology

University of Cambridge

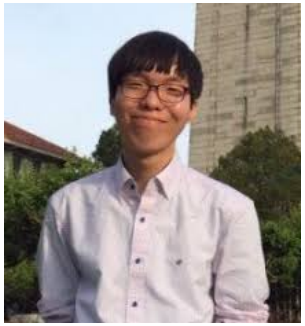
Science & Technology Facilities Council | UK Research and Innovation

erc European Research Council Established by the European Commission

Outline

- Part 1: Introduction and motivation
- Part 2: The Simons Observatory delensing pipeline
- Part 3: Comments on LiteBIRD delensing

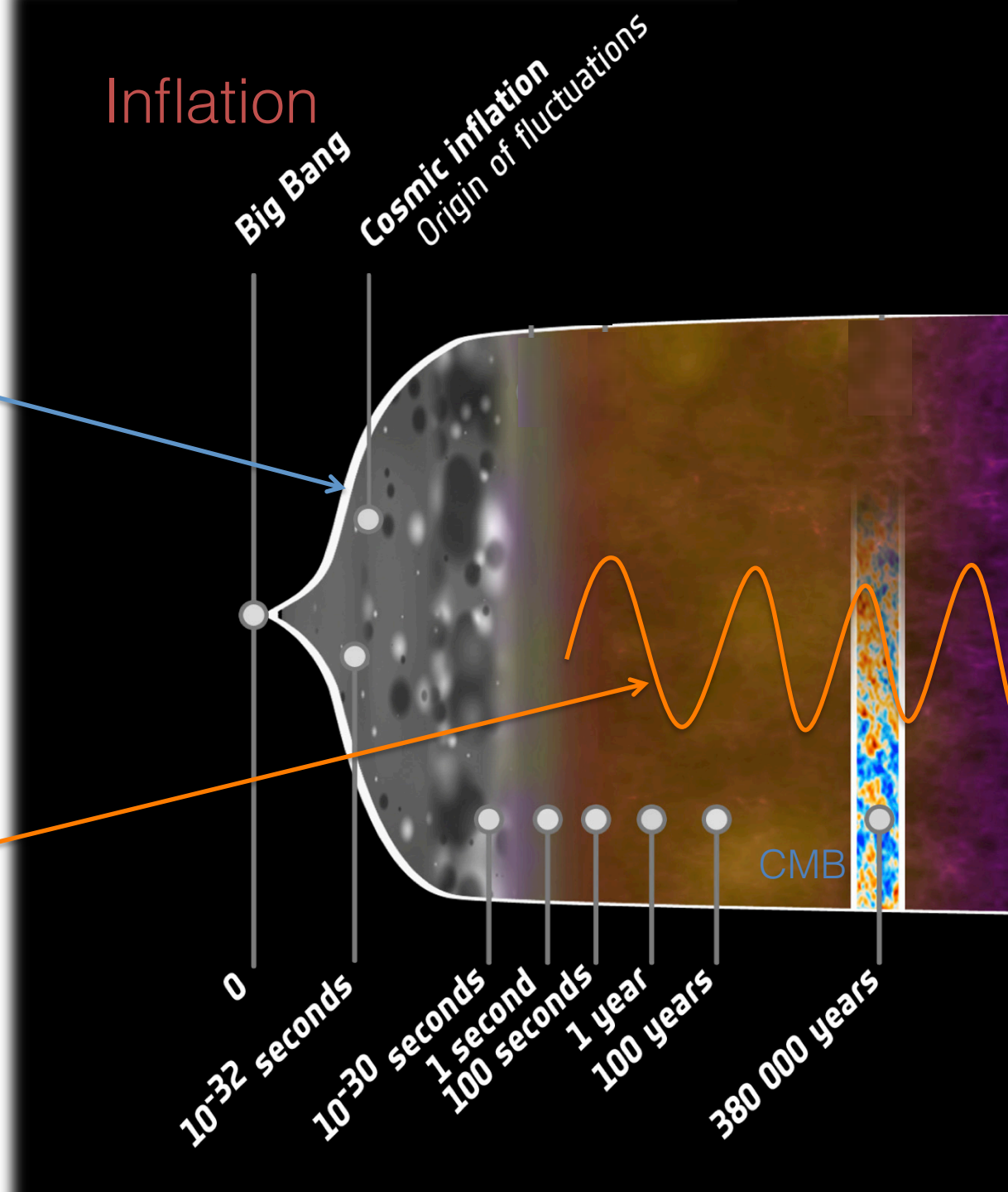




With Toshiya Namikawa, Anton Baleato, Byeonghee Yu, et al.

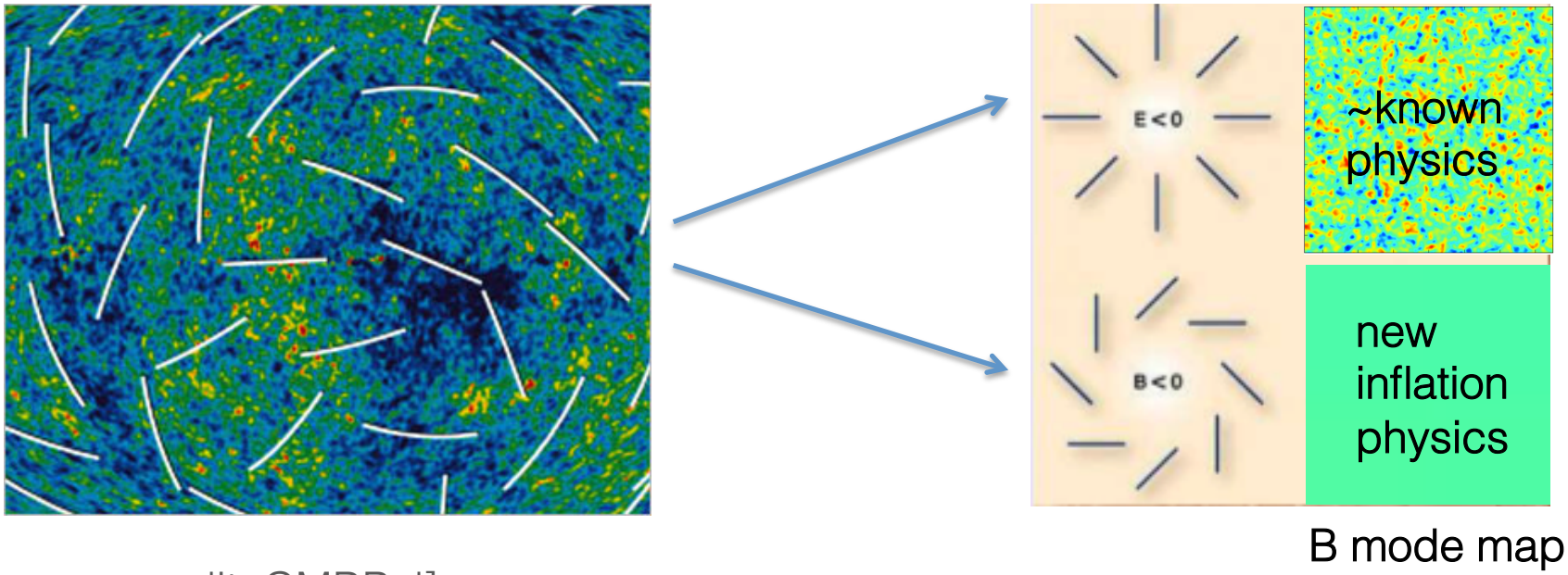
- Inflation: initial accelerated cosmic expansion.

- Many models make detectable inflationary gravity waves, find to gain more insight



CMB B-mode Polarization: Reminder

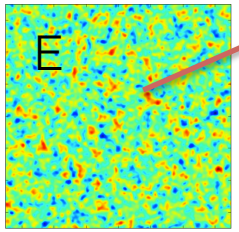
- Any polarization map can be decomposed into E and B mode fields
- B-mode: contains signals from inflation, if there

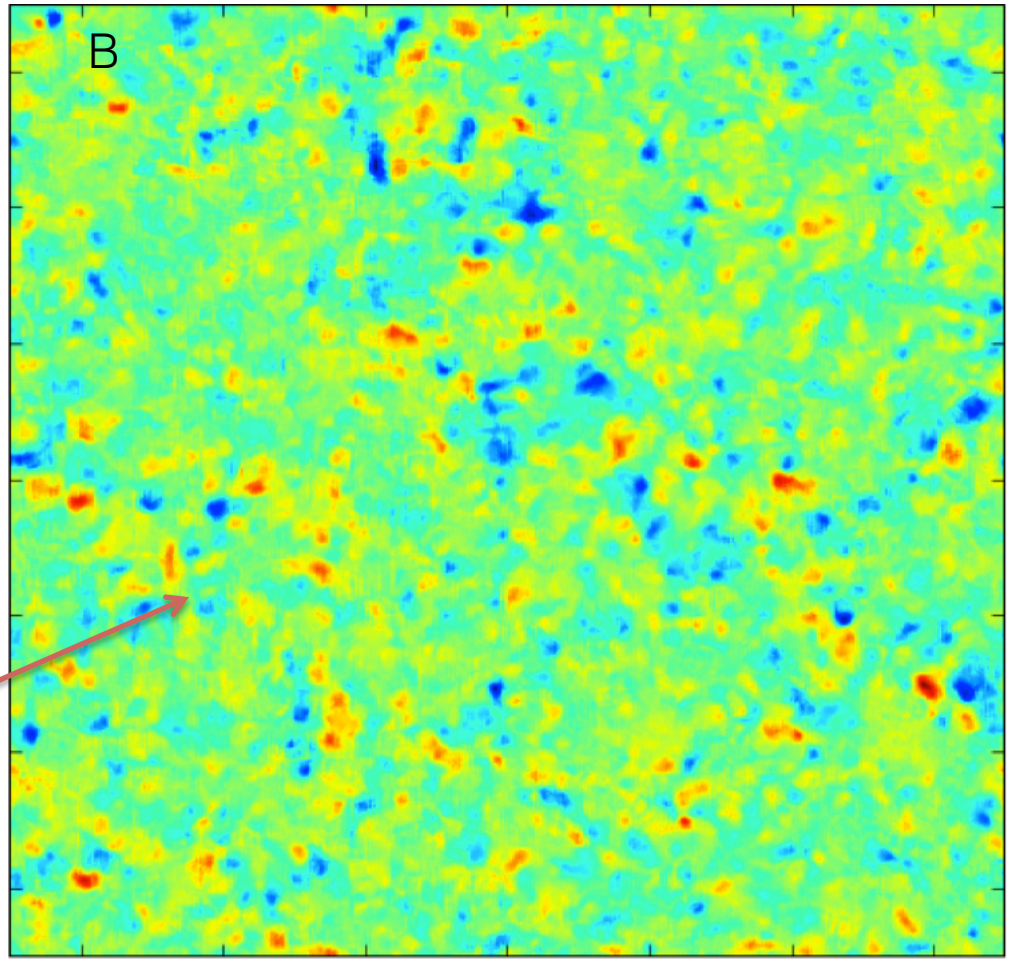


[Image credit: CMBPol]

Problem for CMB B-mode Searches: Lensing B-Mode Polarization

Gravitational lensing converts E- to B-polarization





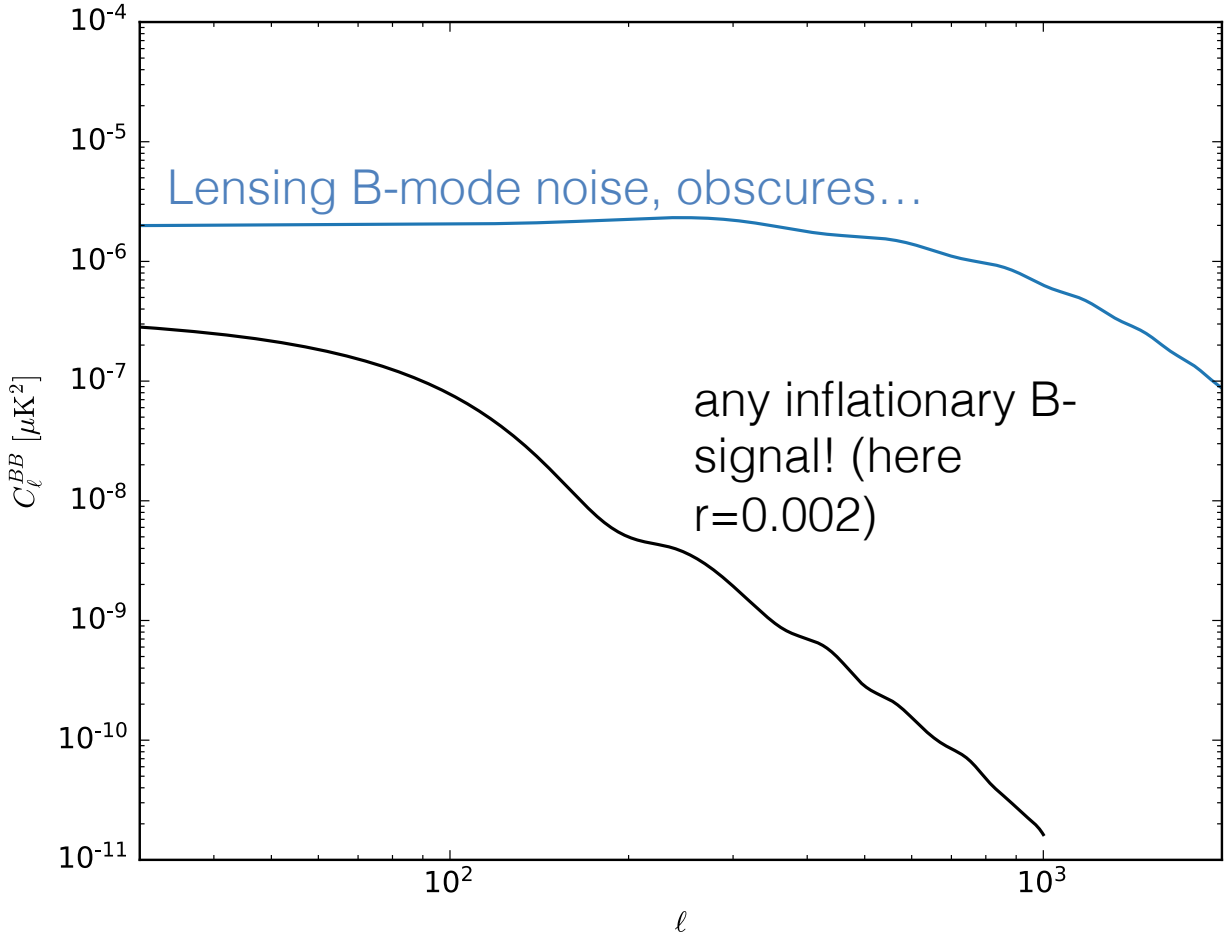
10°

$$B^{lens}(\mathbf{L}) \sim \int d\mathbf{l}\, W(\mathbf{l},\mathbf{L}) E(\mathbf{l}) d(\mathbf{L}-\mathbf{l})$$

W: geometric kernel

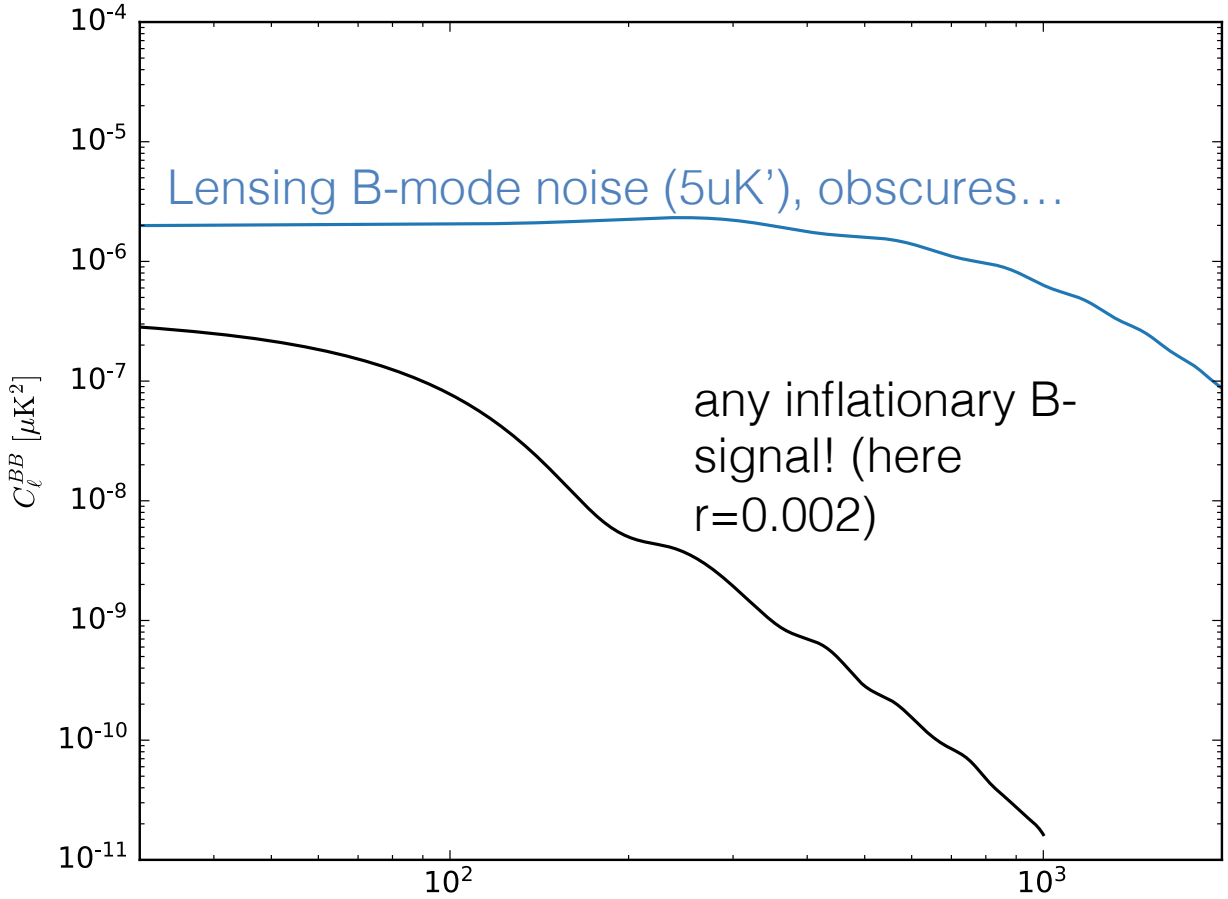
Lensed CMB B-Polarization: Noise for Inflation-B

B-mode power



Lensed CMB B-Polarization: Noise for Inflation-B

B-mode power

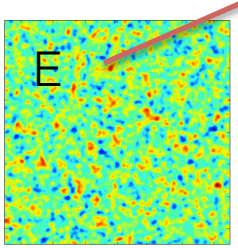


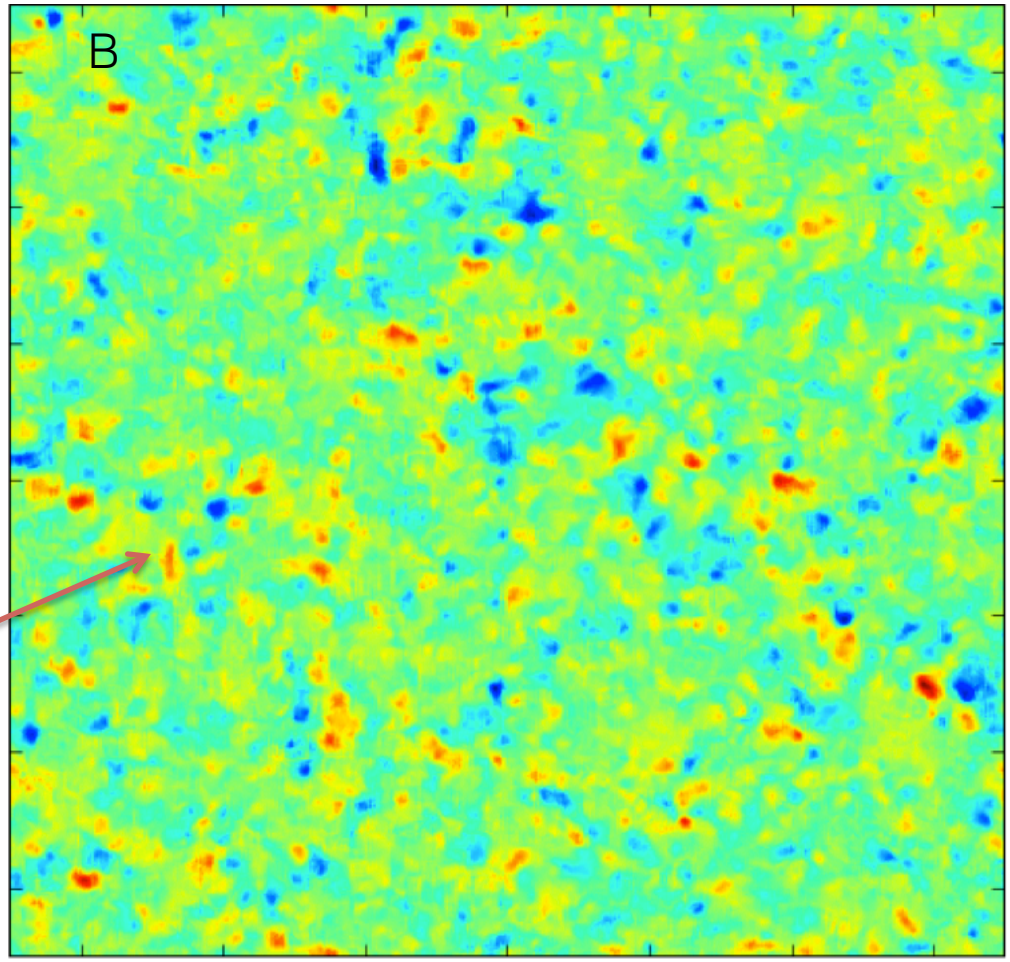
- Mean "problem": must know / subtract mean lensing power
- Error problem: lensing adds additional cosmic variance

  $\sigma(r) \sim (N_l^{BB} + C_l^{BB,lens})$. ~x 2 error for Simons Observatory, ~10 for S4

Delensing the CMB: Lensing Removal

Gravitational lensing converts E- to B-polarization

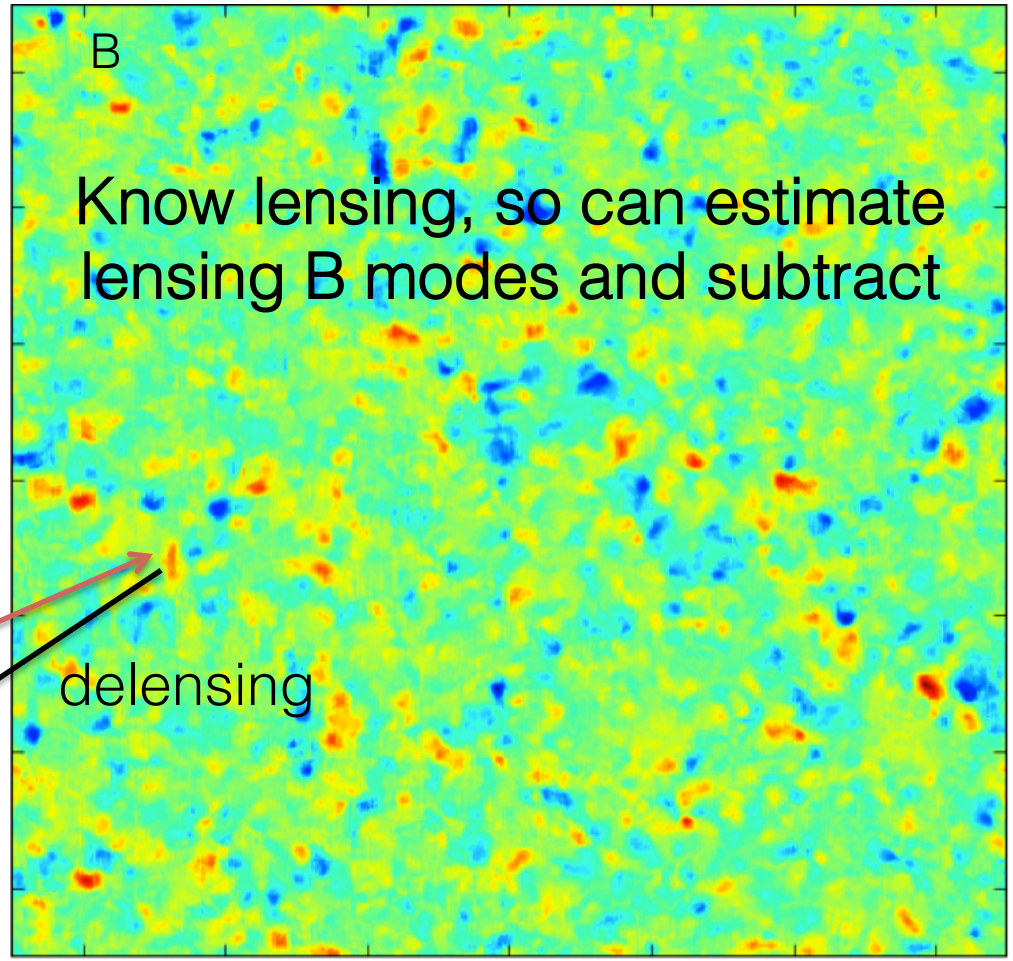




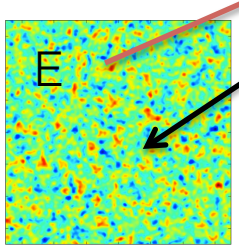
10°

$$B^{lens}(\mathbf{L}) \sim \int d\mathbf{l}\, W(\mathbf{l},\mathbf{L}) E(\mathbf{l}) d(\mathbf{L}-\mathbf{l})$$

Delensing the CMB: Lensing Removal



Gravitational lensing converts E- to B- polarization



S/N weighted estimate of lensing d

Linearized version:

$$B^{data} - \hat{B}^{lens} \sim B^{data} - \int d\mathbf{l}\, W(\mathbf{l},\mathbf{L}) E(\mathbf{l}) \hat{d}^{filt}(\mathbf{L}-\mathbf{l})$$

Delensing Performance

$$\sigma(r) \sim \langle C_l^{BB,\mathrm{lens}} + N_l^{BB} \rangle_{l<100}$$

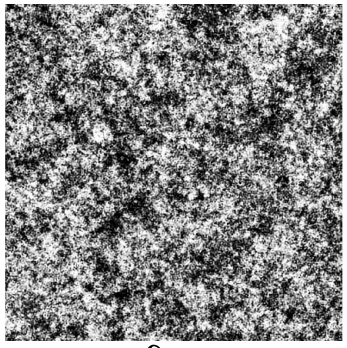
$C_l^{BB,res}$

- Error reduction depends on residual lensing B-mode
- Find that delensing reduces B-mode power by a factor $(1 - \rho^2)$

  [ρ : correlation coefficient of lensing estimate with true lensing field]

- Need good tracers! Lensing L~200-800 most important.

To Delens, Need To Measure Good Maps of CMB Lensing - How?



CMB lensing is a probe of the projected mass distribution

$$\nabla \cdot \mathbf{d} \sim \int dz W(z)\delta(z)$$

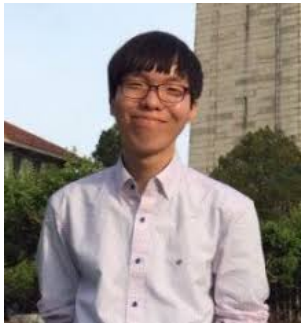
Standard “Internal” case:

1) Reconstruct lensing $\hat{d}$ from changes in background CMB

Outline

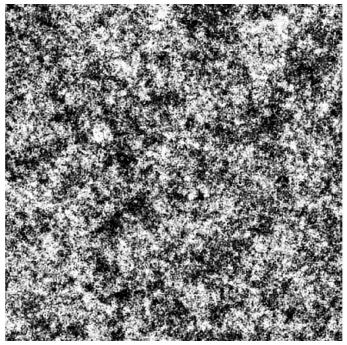
- Part 1: Introduction and motivation
- Part 2: The Simons Observatory delensing pipeline
- Part 3: Comments on LiteBIRD delensing





With Toshiya Namikawa, Anton Baleato, Byeonghee Yu, et al.

To Delens Simons Observatory, Need To Measure Good Maps of CMB Lensing - How?



CMB lensing is a probe of the projected mass distribution

$$\nabla \cdot \mathbf{d} \sim \int dz W(z) \delta(z)$$

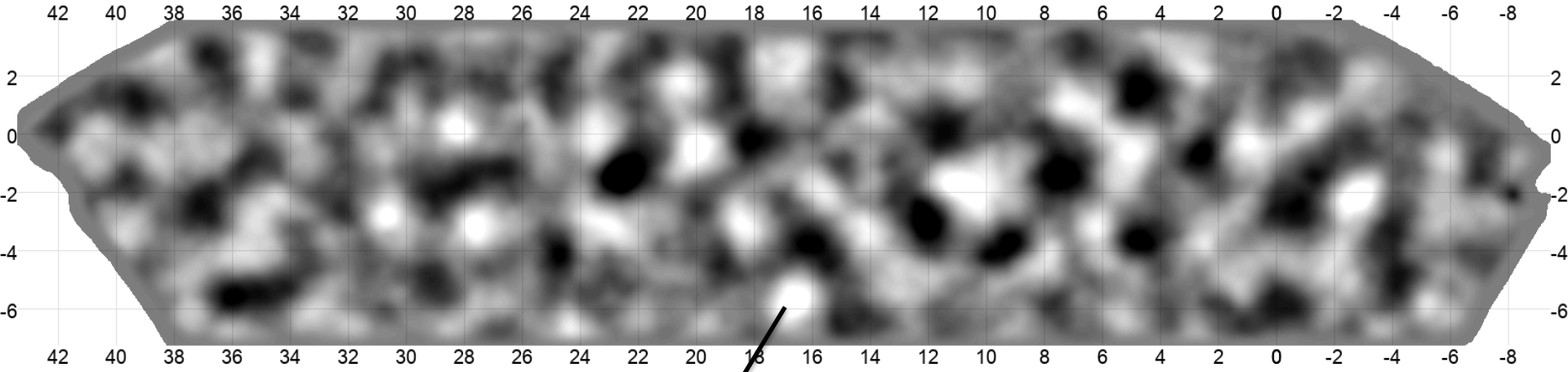
1) Reconstruct lensing from changes in background CMB. Problem for SO: only improves constraints by ~25%

2) Estimate lensing from highly correlated Large Scale Structure tracers of lensing, e.g. CIB or galaxies.

[Sherwin, Schmittfull 2015]

Illustration: ACTPol Lensing (500 / 2100 sq. degs.) vs. Large-scale Structure

ACT lensing mass map (potential), one 500 deg^2 field

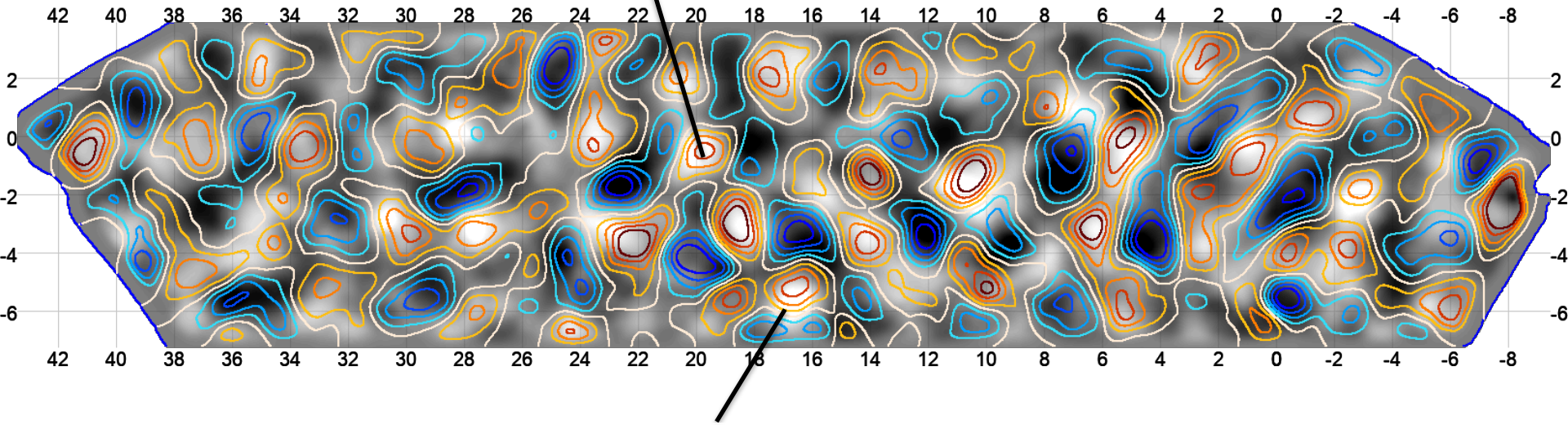


Color scale: strength of lensing
[light = more lensing / matter]

[Omar Darwish ++ in prep.]

Illustration: ACTPol Lensing vs. Large-scale Structure (Planck CIB)

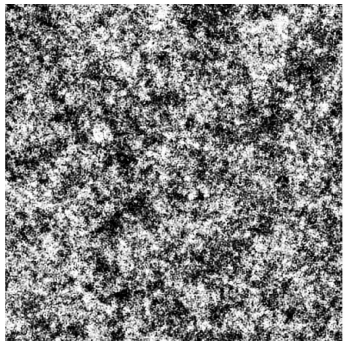
Orange/blue contours: cosmic infrared background (galaxy emission)
[orange = more galaxies]



Grey color scale: strength of lensing
[light = more lensing / matter]

[Omar Darwish ++ in prep.]

To Delens Simons Observatory, Need To Measure Good Maps of CMB Lensing - How?



CMB lensing is a probe of the projected mass distribution

$$\nabla \cdot \mathbf{d} \sim \int dz W(z)\delta(z)$$

1) Reconstruct lensing from changes in background CMB. Problem for SO: only improves constraints by ~25%

2) Estimate lensing from Large Scale Structure tracers of lensing, e.g. **CIB, galaxies.** Can show:

CIB-lensing cross

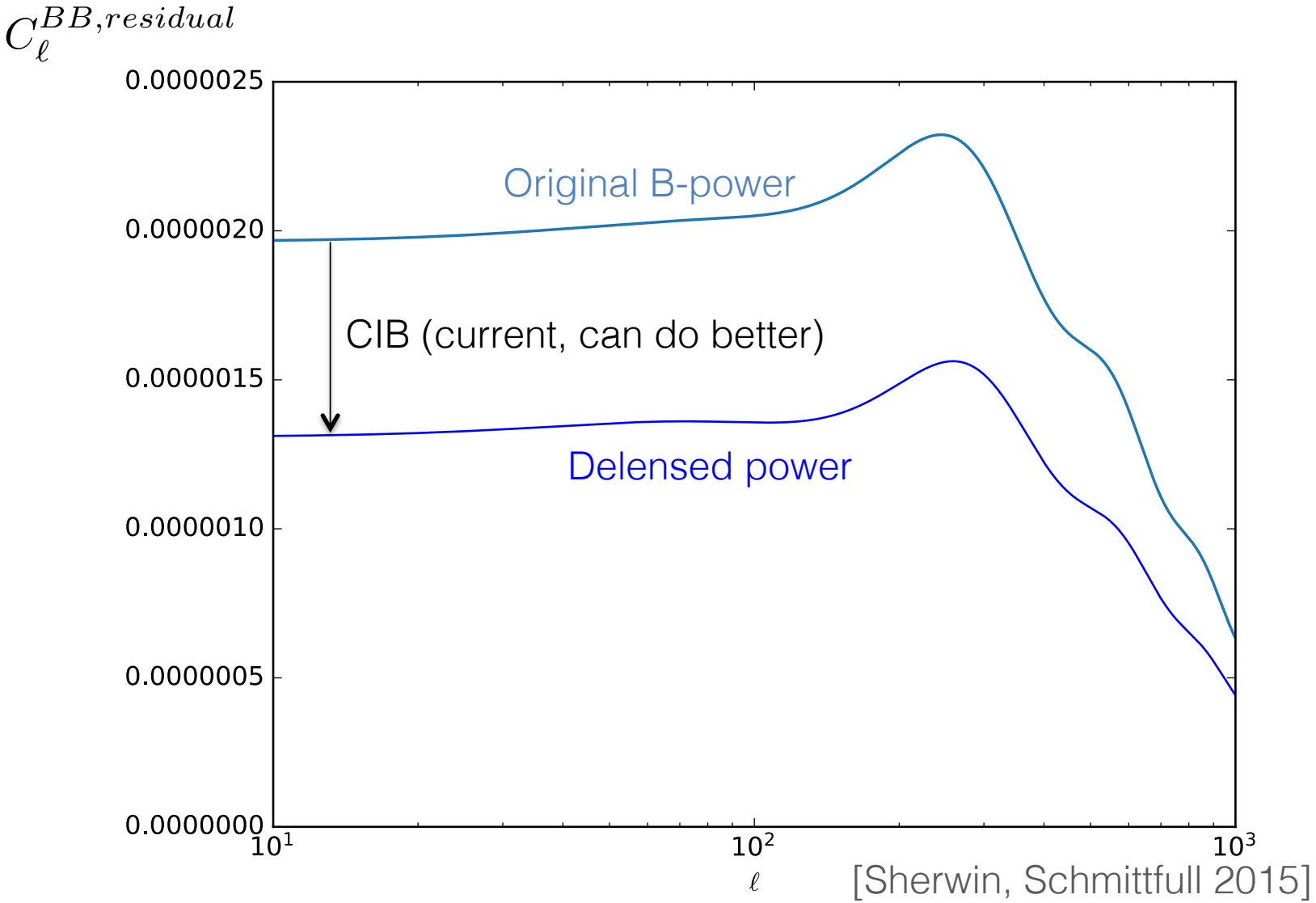
$$\hat{d}^I(\mathbf{l}) = \frac{C_l^{dI}}{C_l^{dd}} \times I(\mathbf{l})$$

CIB map

Lensing power

[Sherwin, Schmittfull 2015]

CIB Delensing for Simons Observatory

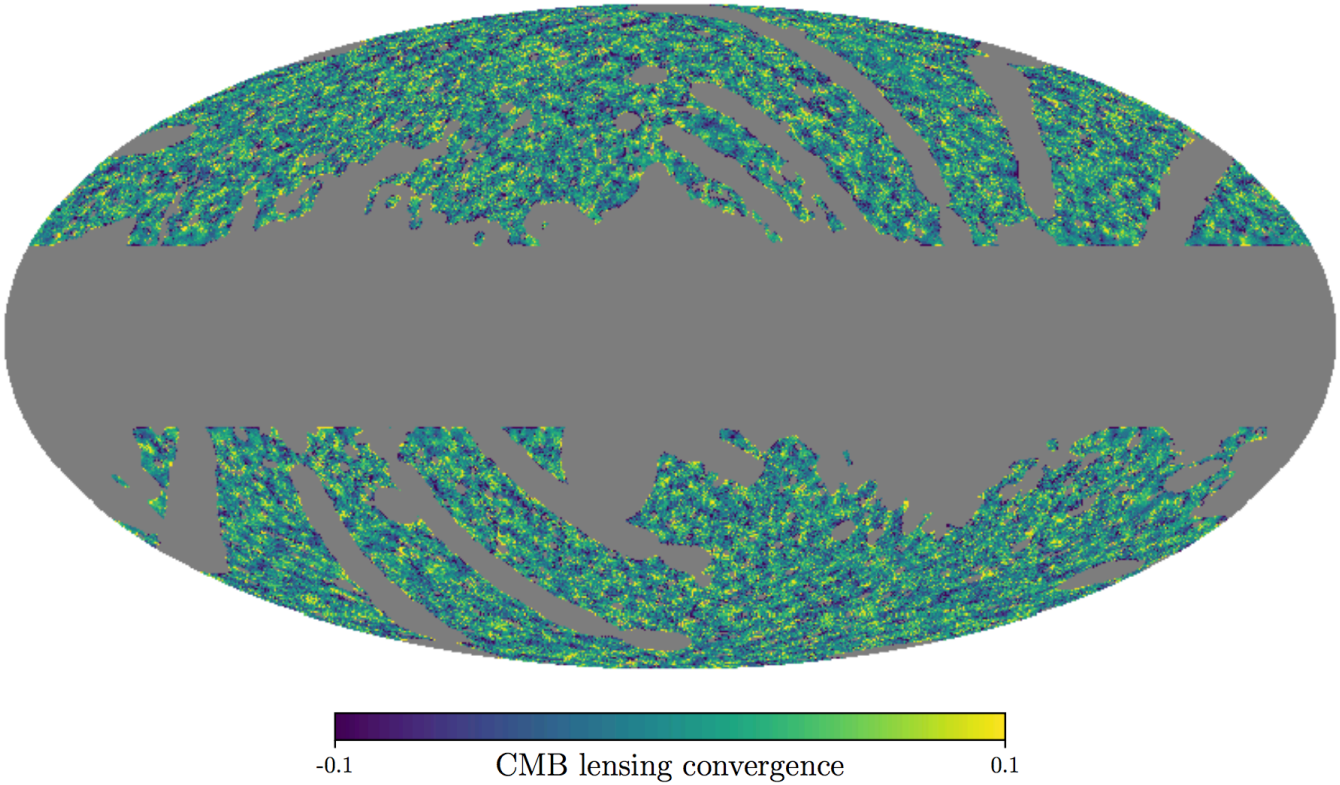


[Sherwin, Schmittfull 2015]

Multi-tracer Delensing for Simons Observatory

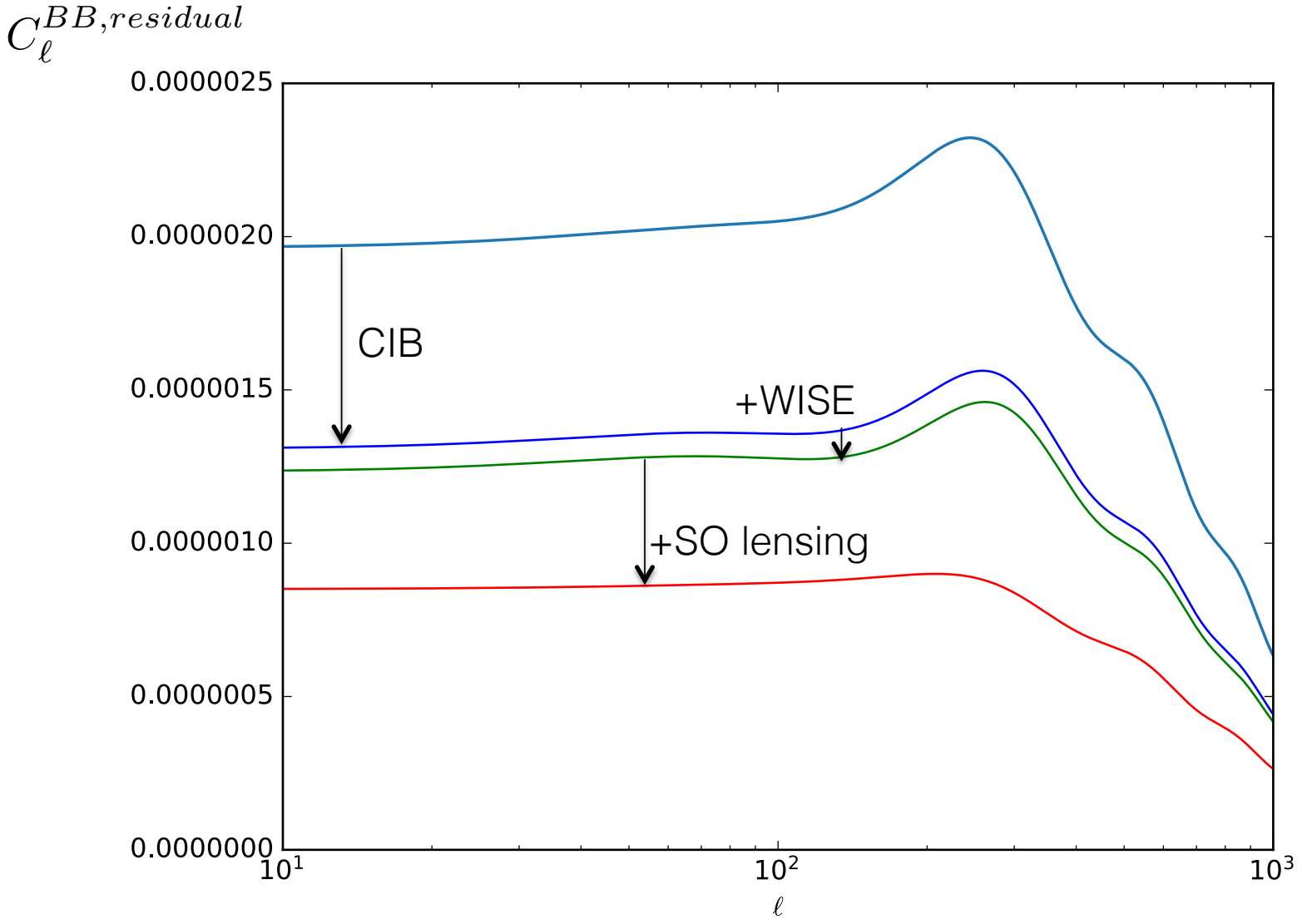
- Can co-add SO lensing map with different large scale structure tracers to delens [Yu, Hill, Sherwin 2017]

Example delensing map made from coadd of Planck lensing + CIB + WISE galaxies



- "Multitracer" delensing can greatly improve delensing performance: now coadd SO lensing + DES/LSST + CIB + …

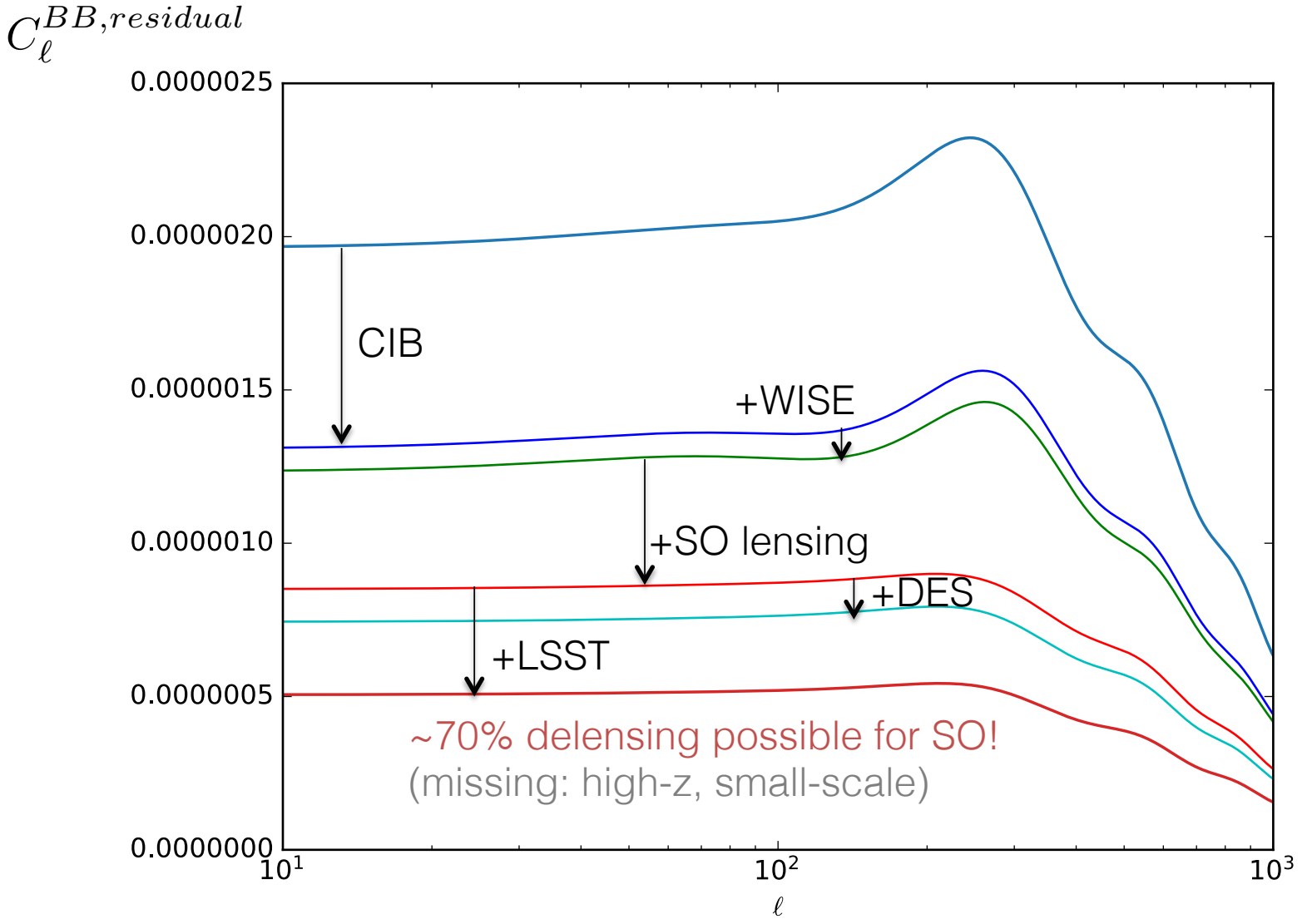
Multi-tracer Delensing for Simons Observatory



$$I(\mathbf{l}) = \sum c_i(\mathbf{l}) I_i(\mathbf{l})$$

$$c_i = (C_l^{I_i I_j})^{-1} C_l^{dI_j}$$

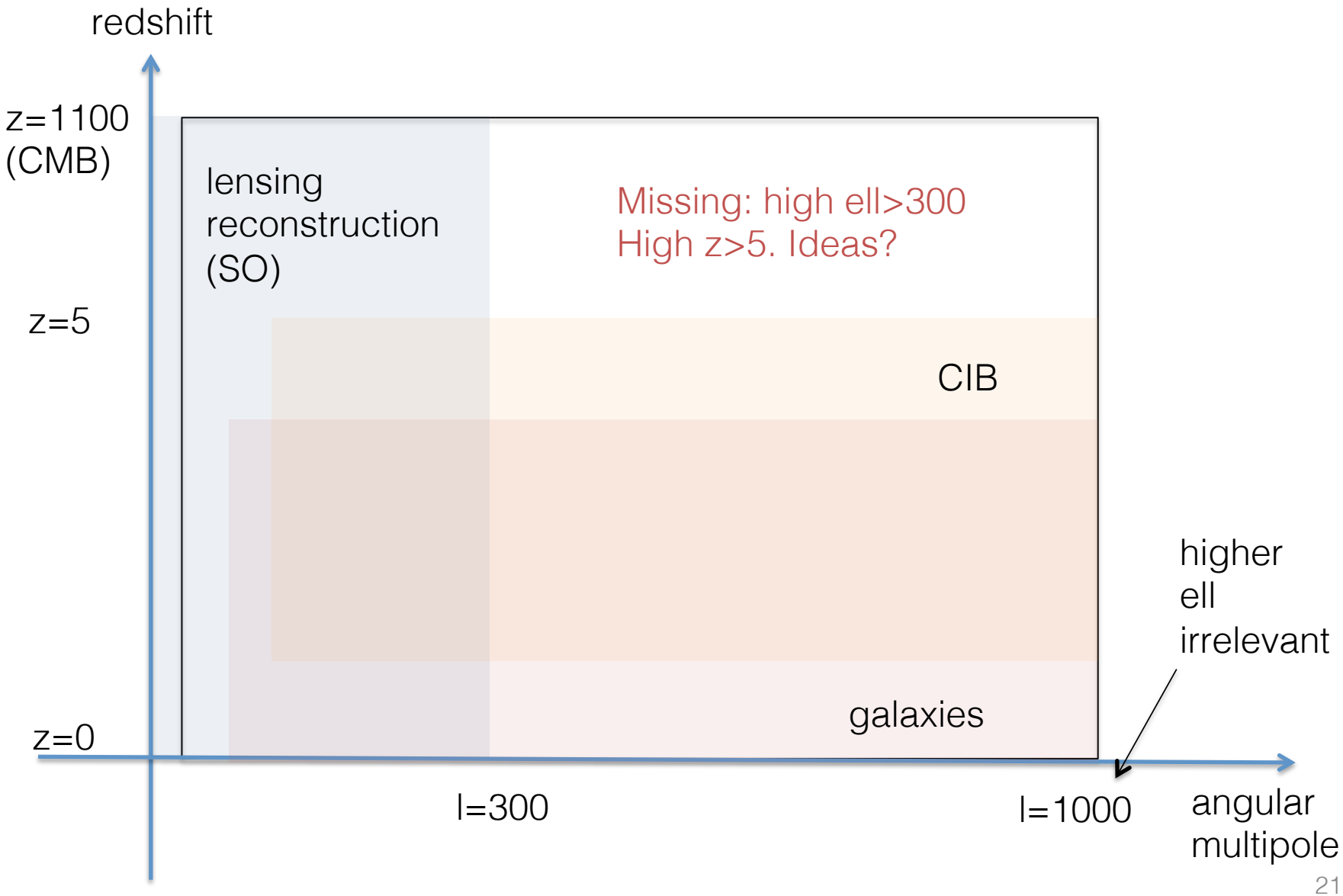
Multi-tracer Delensing for Simons Observatory



$$I(\mathbf{l}) = \sum c_i(\mathbf{l}) I_i(\mathbf{l})$$

$$c_i = (C_l^{I_i I_j})^{-1} C_l^{dI_j}$$

Aside: What structures are we missing?



Early SO Delensing Pipeline: Technical Details

- Linearized delensing B-mode template (better control)

S/N weighted estimate of lensing d

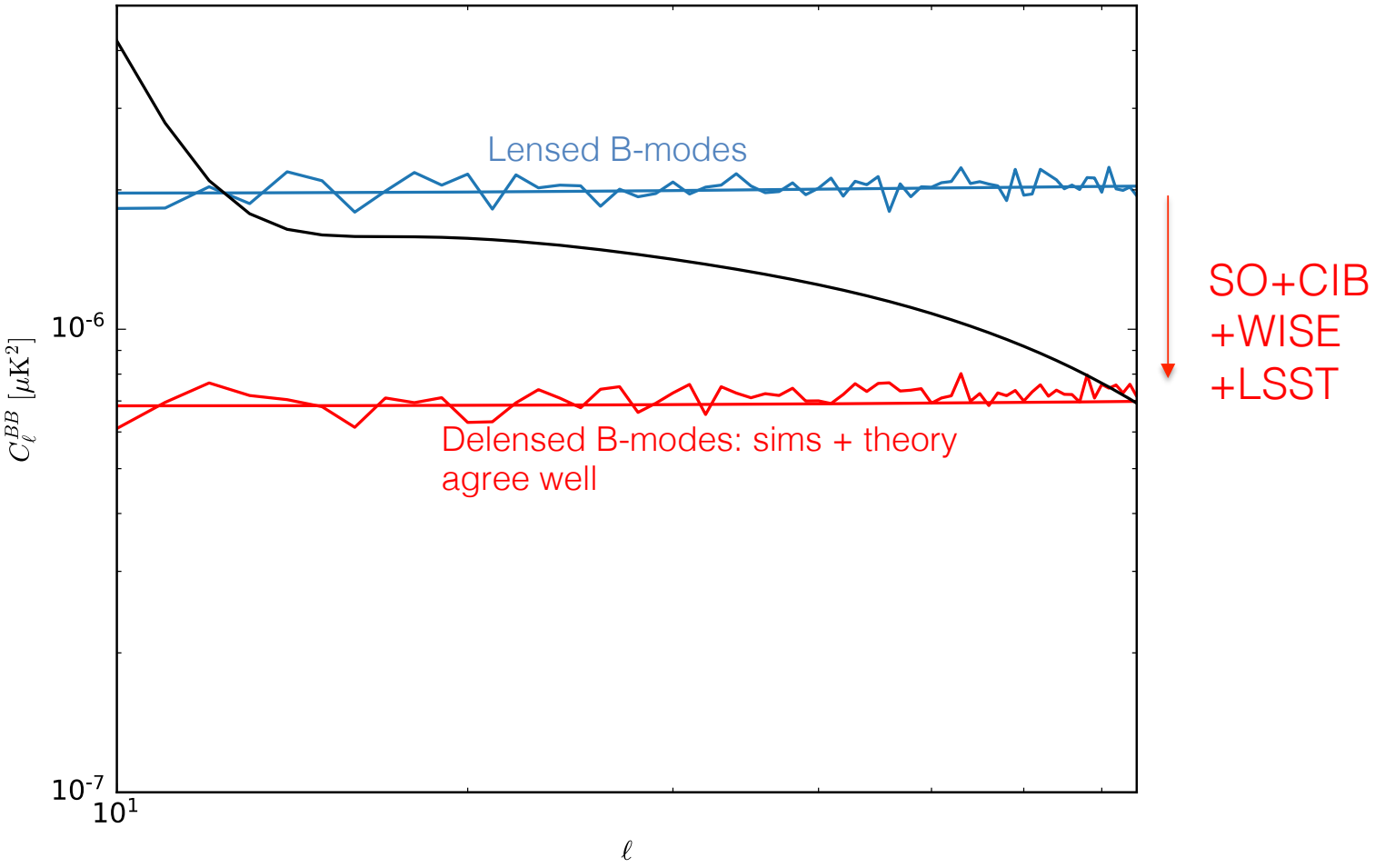
$$B^{data} - \hat{B}^{lens} \sim B^{data} - \int d\mathbf{l}\, W(\mathbf{l}, \mathbf{L}) E(\mathbf{l}) \hat{d}^{filt}(\mathbf{L} - \mathbf{l})$$

Not full non-linear remapping

- Curved sky construction
- Mask / inhomogeneity treatment: full Wiener filtering

Early SO Delensing Pipeline: Test on Simulations

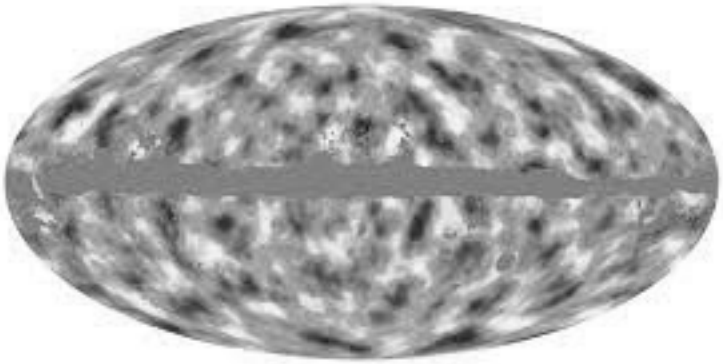
- Polarization simulation: multitracer delensing demonstration with SO (preliminary). Performs as expected!



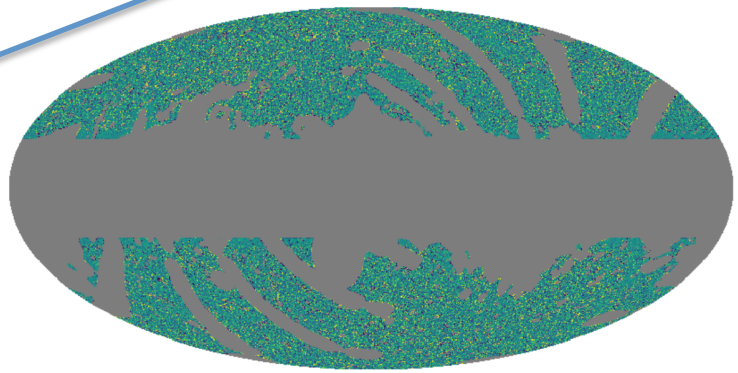
Why I think this will work I: LSS modeling required?

- Tracer calibration and delensing residual depend only on measurable spectra

$$I(\mathbf{l}) = \sum c_i(\mathbf{l}) I_i(\mathbf{l}) \qquad c_i = (C_l^{I_i I_j})^{-1} C_l^{d I_j}$$



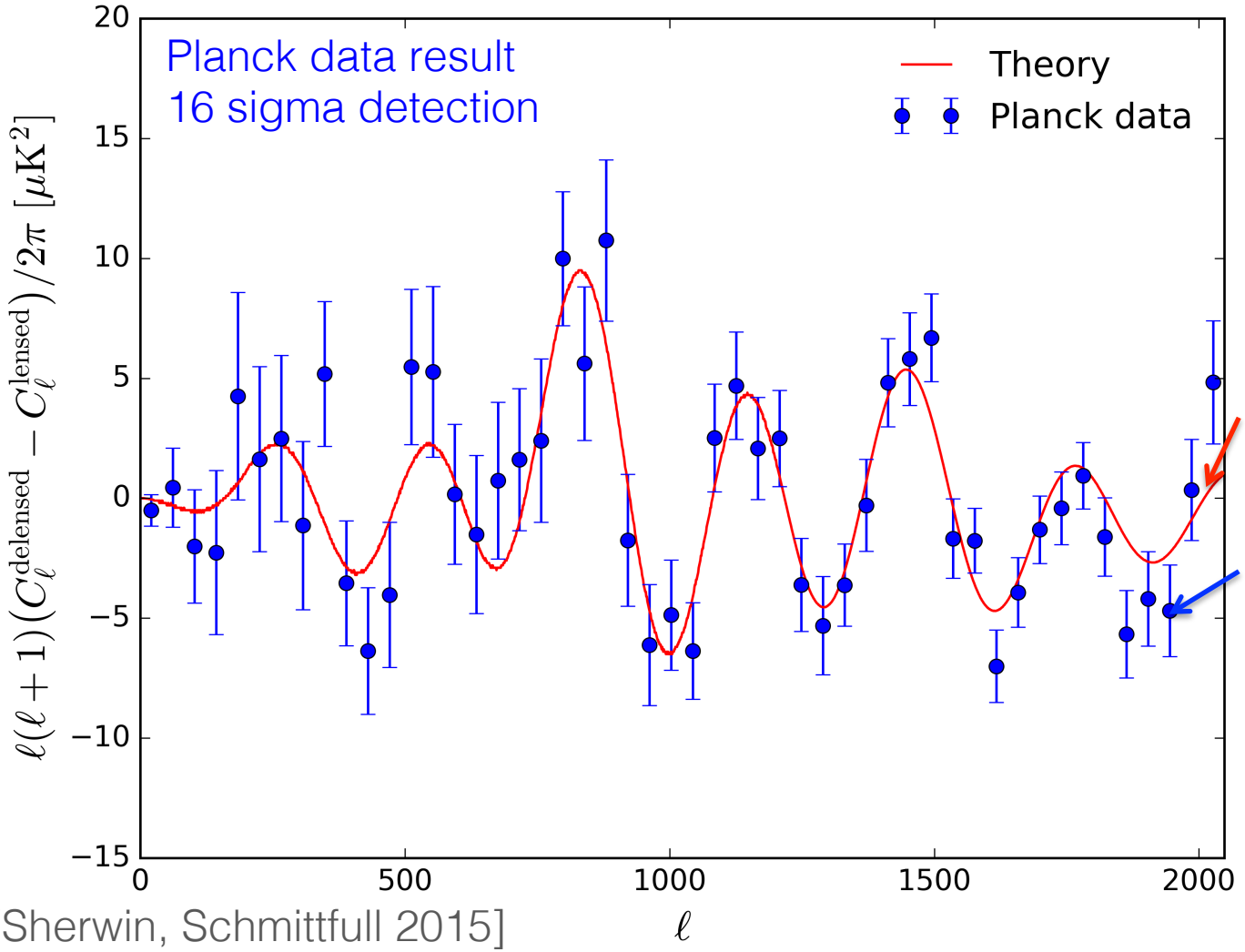
Noisy-ish lensing map (low S/N per mode)



High S/N but mis-scaled LSS map

- Cross-spectra (assuming isotropy) can have high S/N -> can calibrate LSS map, modeling not needed for small sky fractions

Why I think this will work II: Data demonstration of CIB delensing (of Temp.)



Theory prediction for Delensed – Lensed temperature power

Actual result from data (agrees well!)

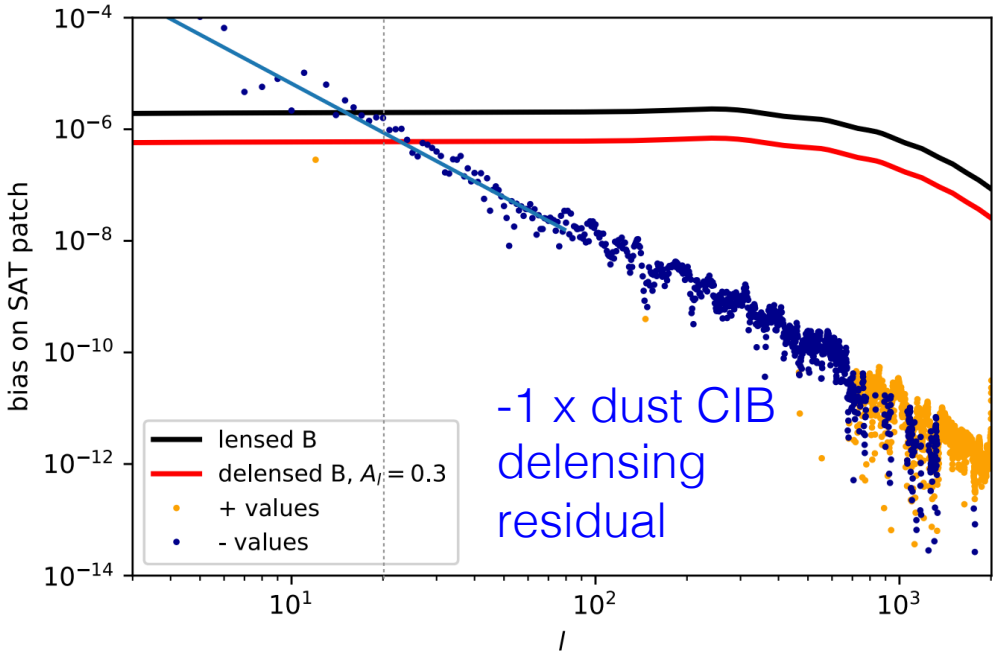
[Sherwin, Schmittfull 2015]

[Larsen, Challinor, Sherwin, Mak 2016] [Polarbear 2019, Manzotti++2017, Carron++ 2017…]

Why this might not work: Correlated foreground propagation,…

- Lensing foregrounds correlated with B foregrounds can give biases, e.g., <(B-Ed) x (B-Ed)>, cross terms involving <BEd>

fgs.??? fgs.??? fgs.???



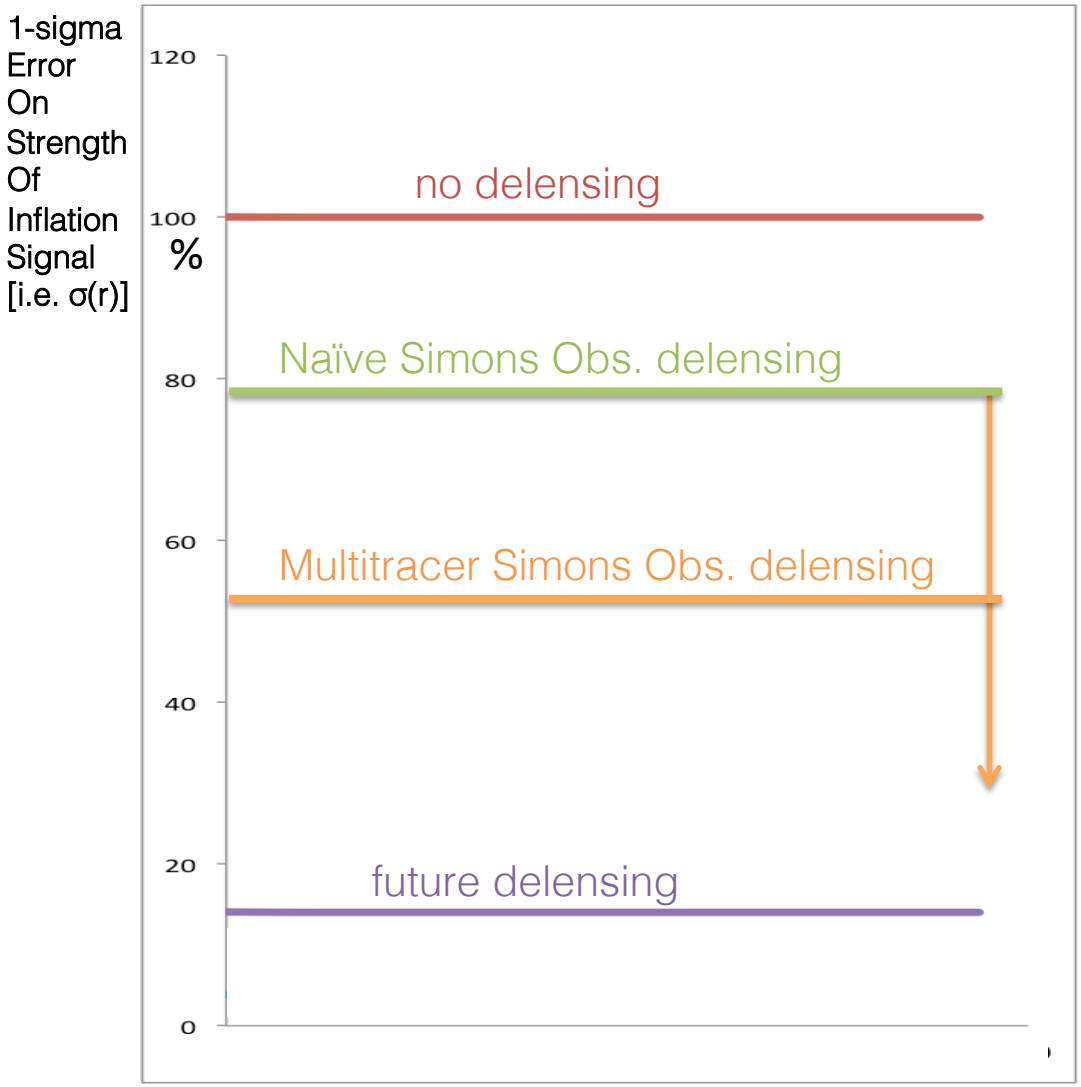
CIB delensing dust residuals appear small for SO/S4, but non-negligible at large scales

[Baleato, Challinor, Sherwin, Namikawa prep.]

- Other challenges: likelihood and integration with foreground cleaning,…

Outlook for SO Delensing

- Lots still to figure out and test
- Target: ~1.7x improvement in SO r constraints
- Potentially final results σ(r)~0.002X instead of 0.004 with delensing!

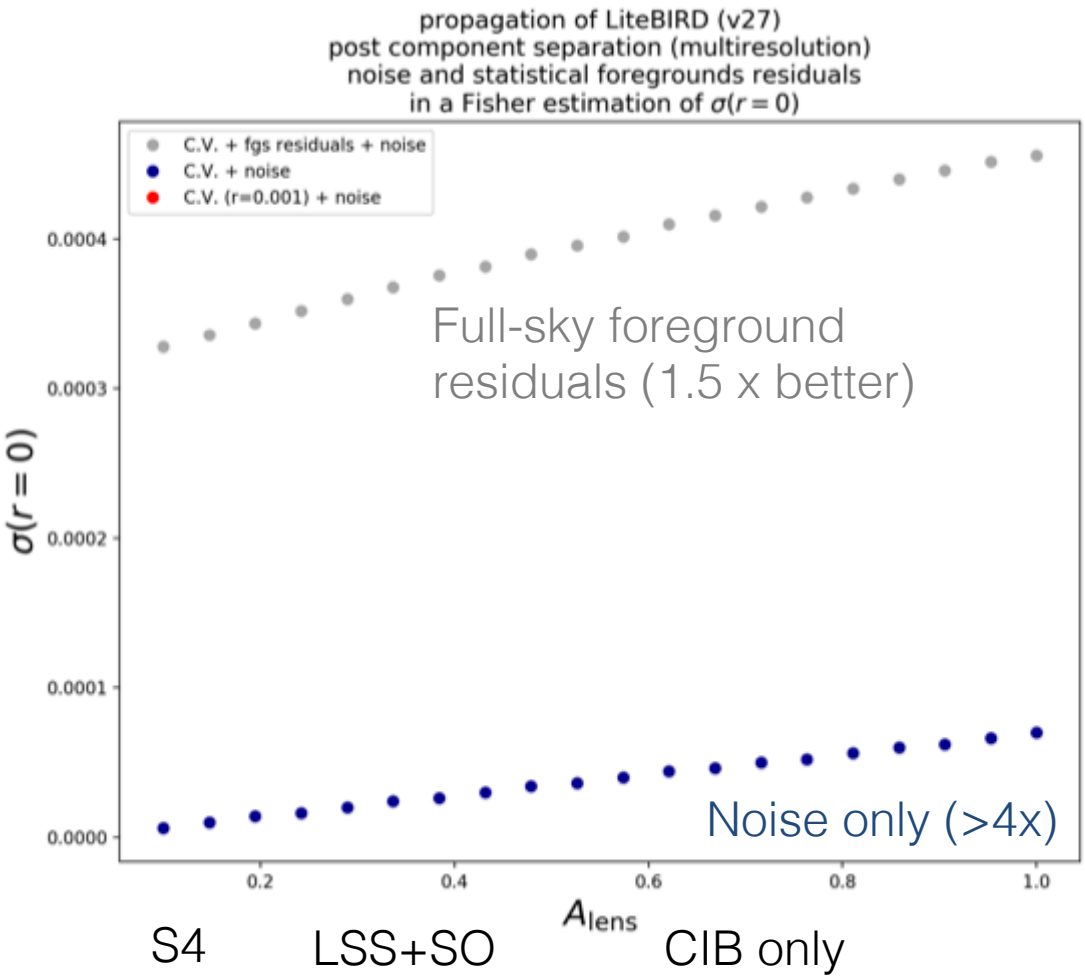


Outline

- Part 1: Introduction and motivation
- Part 2: The Simons Observatory delensing pipeline
- Part 3: Comments on LiteBIRD delensing

LiteBIRD Delensing: Performance and Foregrounds

Forecasts
with
J. Errard
(2018+
just updated)



- Strongly cleaning-dependent: currently 1.5 – 4+ x improvement. Could some areas give better performance?

LiteBIRD Delensing: Challenges and Solutions?

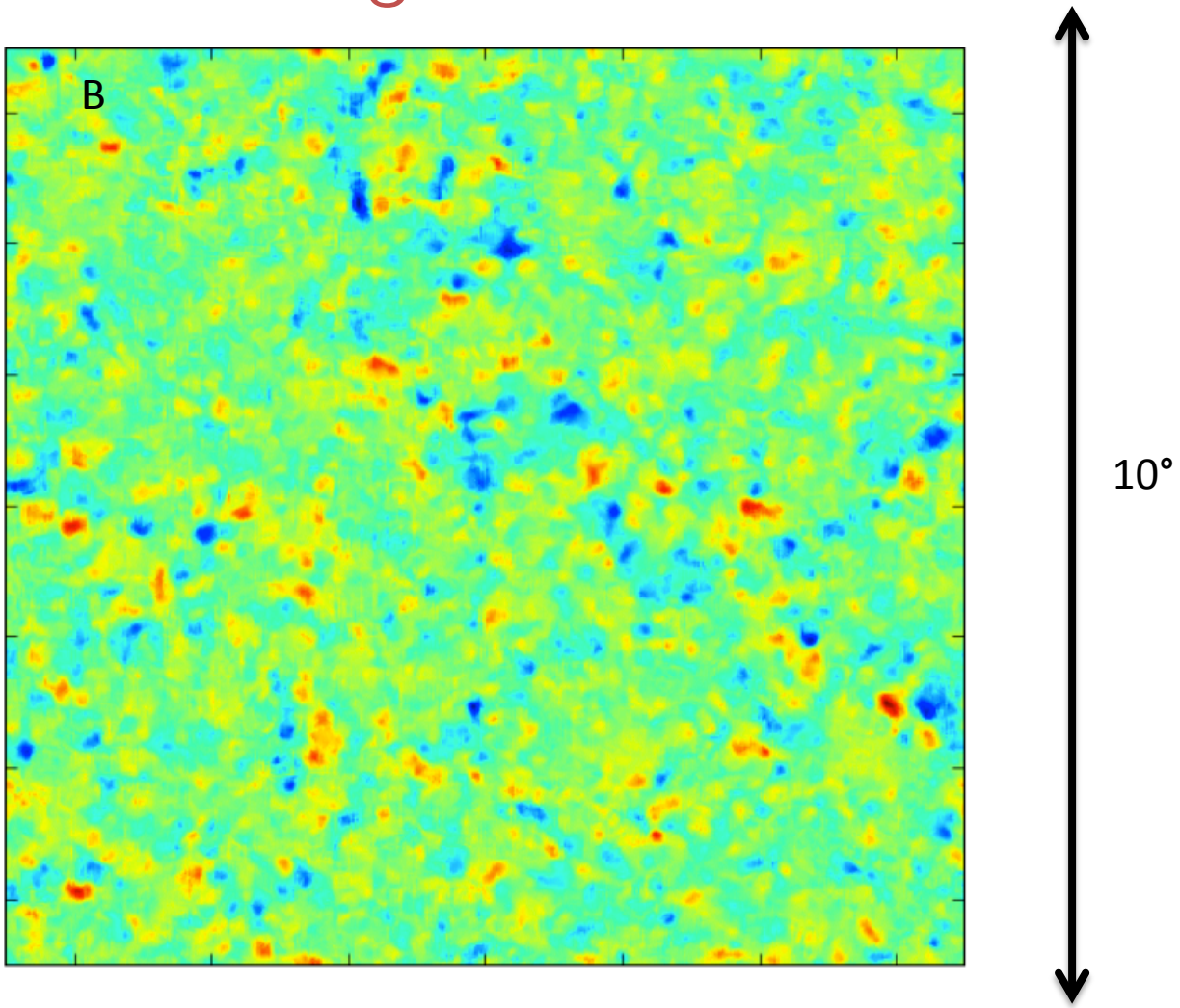
- Astrophysical uncertainty: more limiting than SO if we use CIB only.
- Foreground delensing biases: may become quite significant at low ell.
- Harder problem!

LiteBIRD Delensing: Challenges and Solutions?

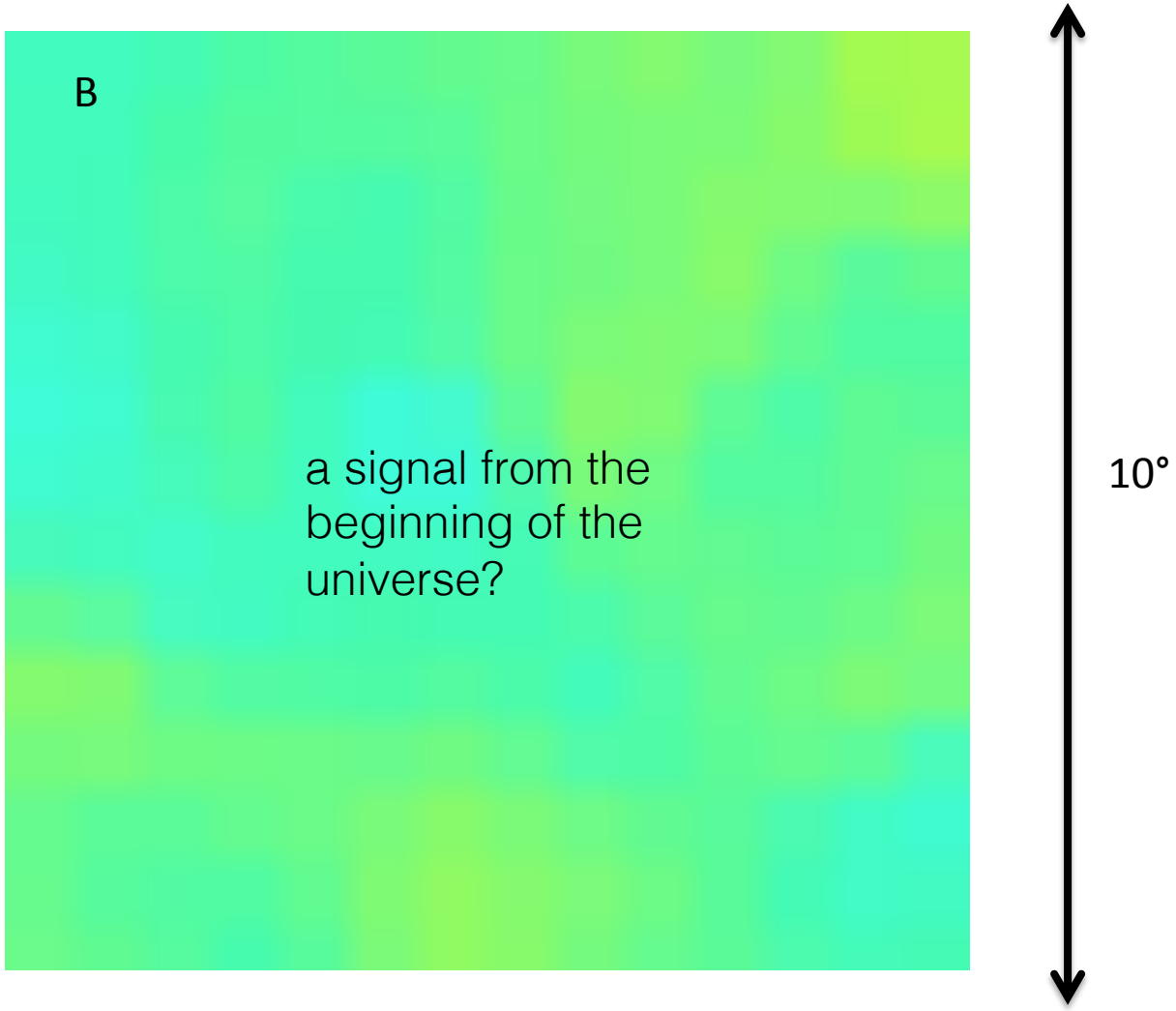
- Astrophysical uncertainty: more limiting than SO if we use CIB only.
- Foreground delensing biases: may become quite significant at low ell.
- Harder problem!

- Solutions: reduce systematics with new LSS methods and more extensive ground-based CMB. Work ongoing now!

Future B Mode Map – Lensing-Dominated

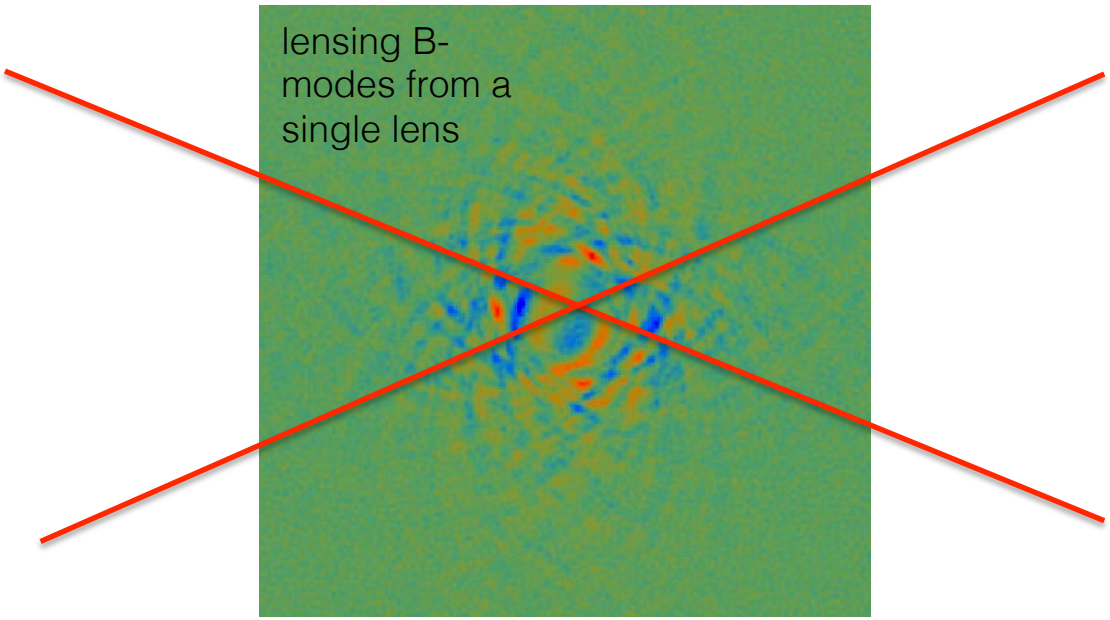


Delensed B Map – Inflation Signal?



Conclusions

- Delensing becoming crucial for inflationary B-mode search
- New multi-tracer LSS delensing methods could nearly double Simons Observatory performance; implemented in a new pipeline
- LiteBIRD delensing: potential and challenges, work ongoing!



On what scales do we need lensing information?

- Lenses at L ~200-800 most important for delensing

- So: L~200-800 lenses most important for delensing

How much does each lensing scale contribute to lensing B?