Delensing: *T* science; *T* and *P* issues

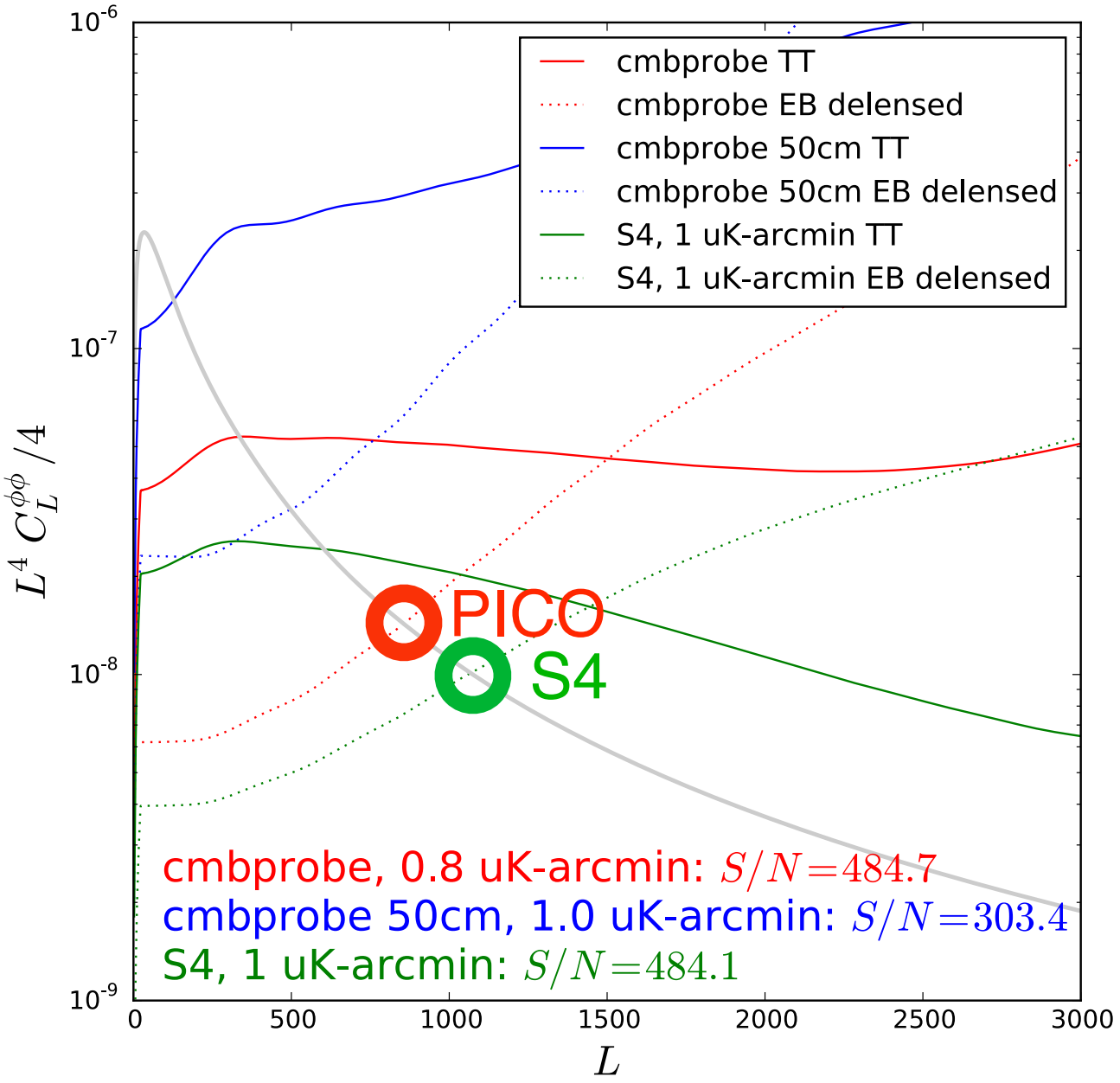
Alex van Engelen (CITA / U. Toronto)

- Susan Clark, Dan Green, D.W. Han, Colin Hill, Mat Madhavacheril, Joel Meyers, Neelima Sehgal, Blake Sherwin

- Lensing maps can come from:
  - CMB temperature - $\kappa(TT)$
  - Polarization - $\kappa(EB)$
  - External tracers
    -

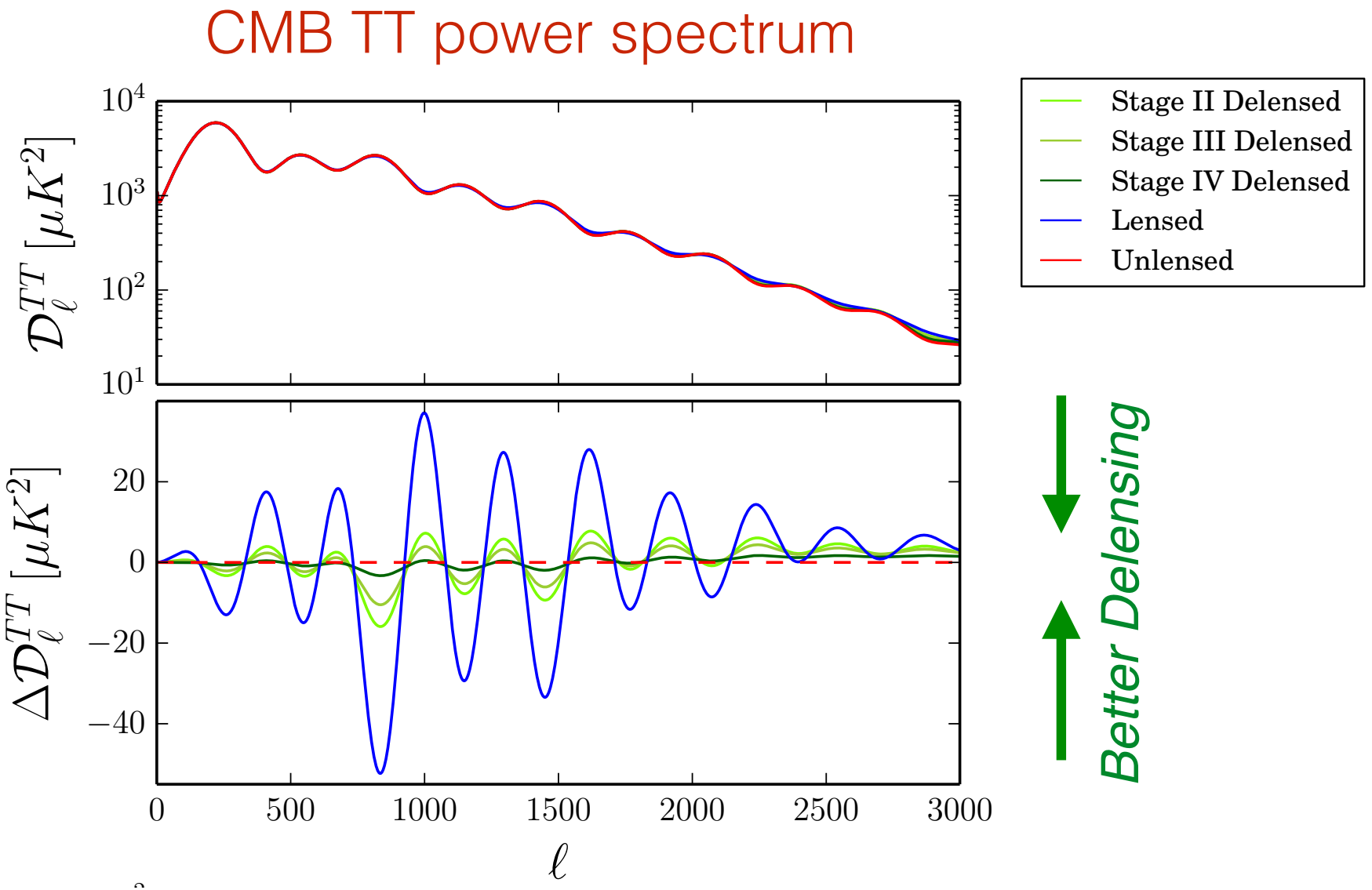
- Lensing maps can come from:
  - CMB temperature - $\kappa(TT)$
    - Today (Planck)
  - Polarization - $\kappa(EB)$
    - Future (S4 / PICO)
  - External tracers
    - Today (Planck CIB / Herschel CIB)
    -

Lensing map noise - from space!



- Polarization lensing will dominate for PICO
- Temperature: extragalactic foregrounds
- Polarization: galactic foregrounds

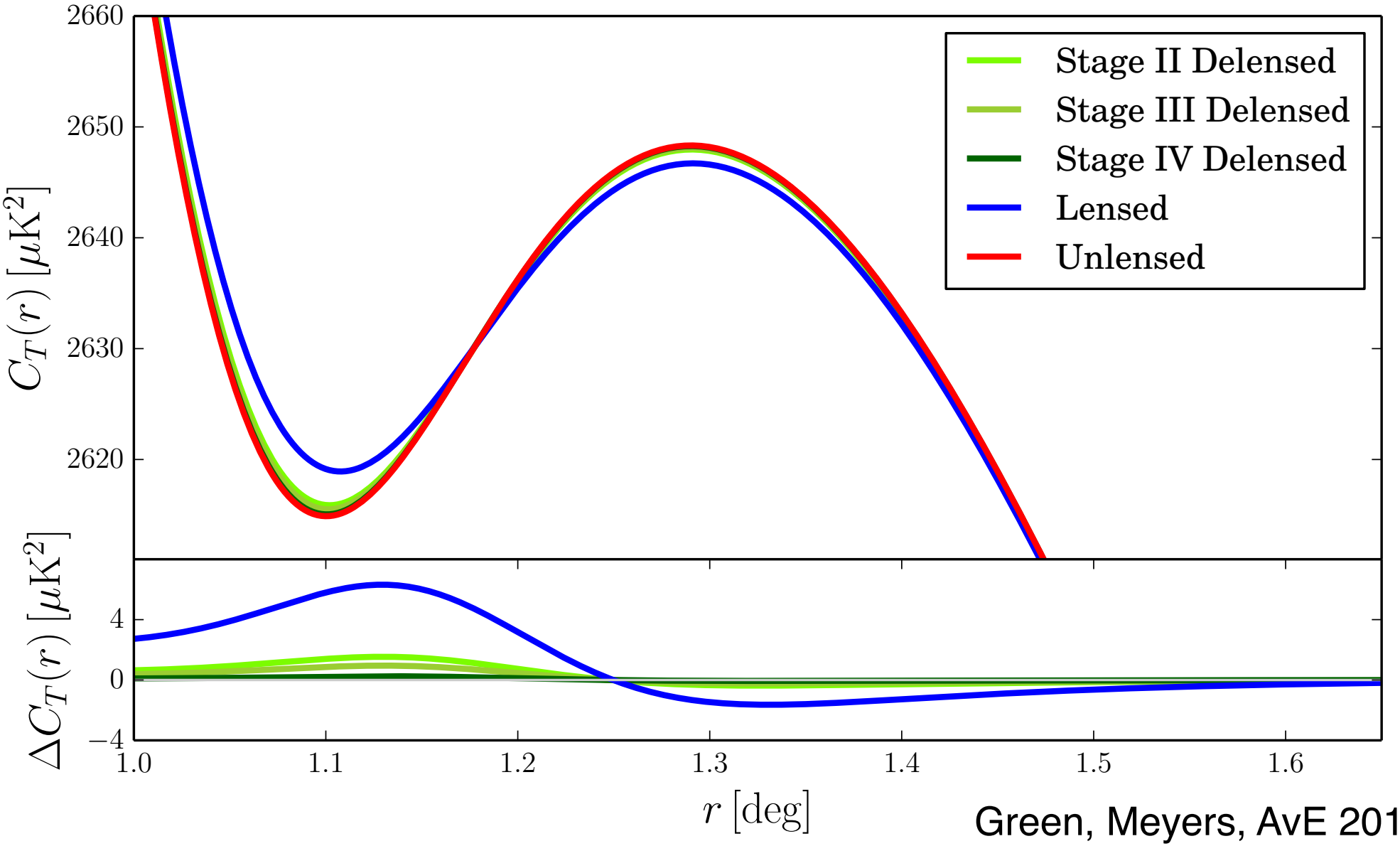
"Delensing beyond the B modes"



Green, Meyers, AvE 2016

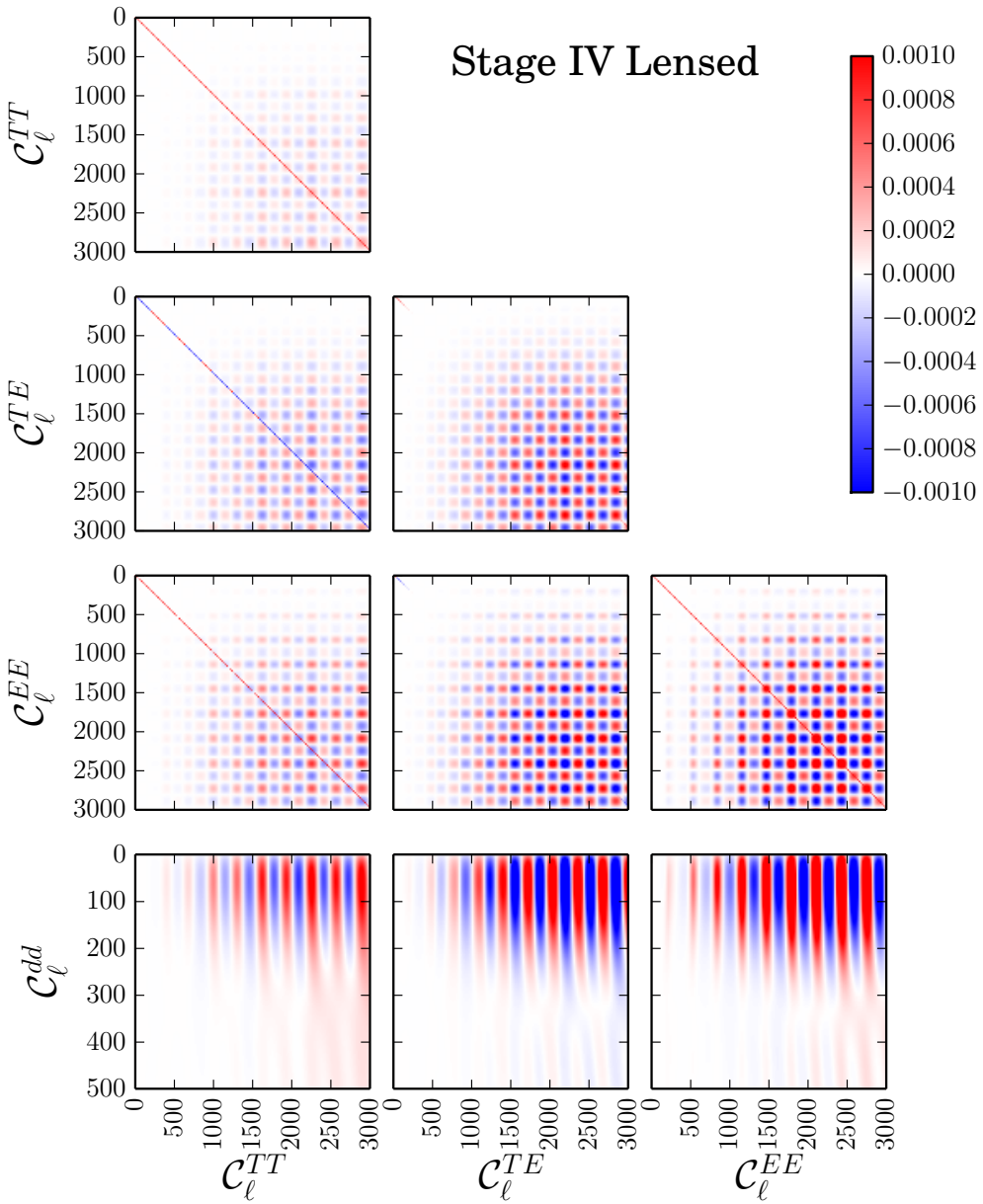
"Delensing beyond the B modes"

CMB T correlation function



Green, Meyers, AvE 2016

Power spectrum covariances

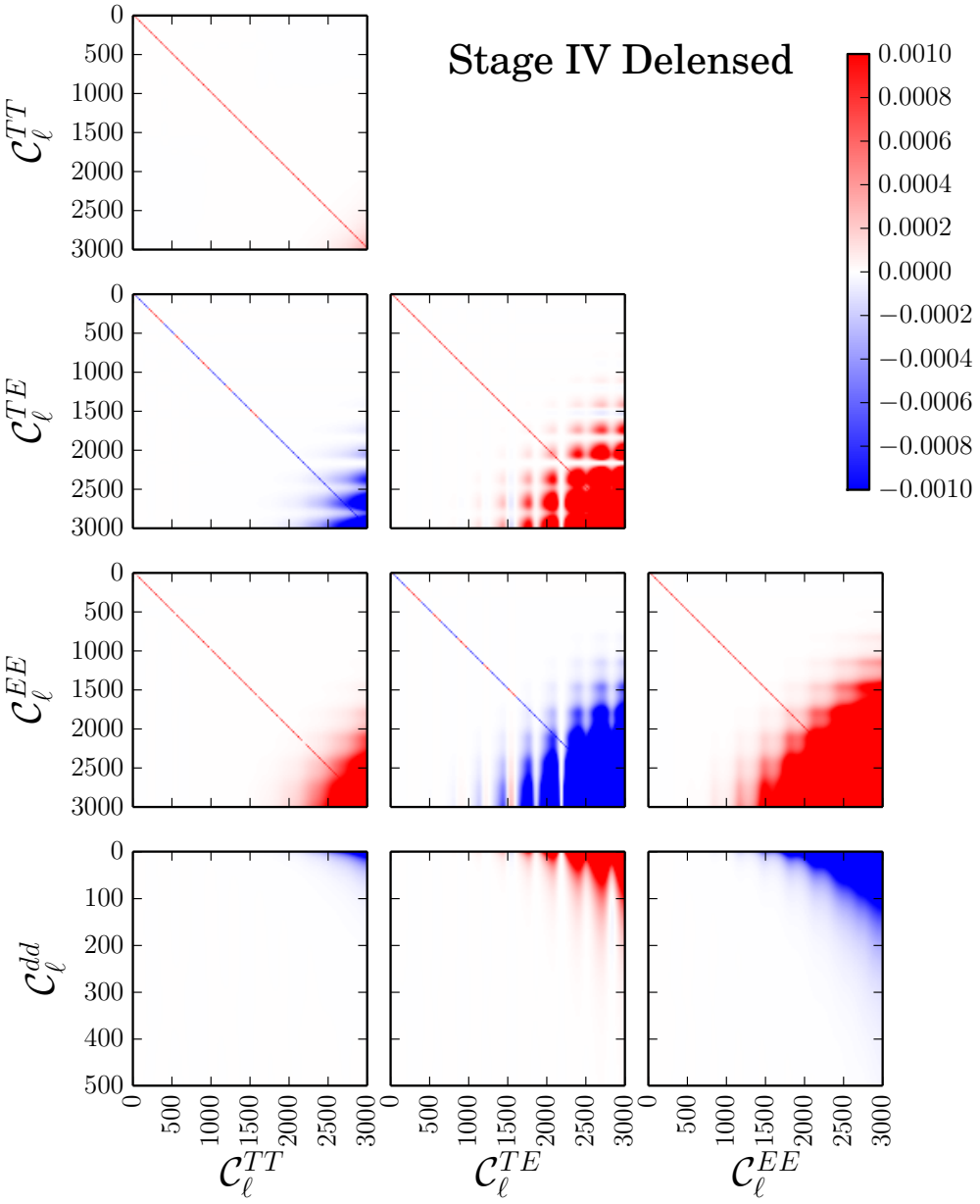


$$\mathrm{Cov}(C_\ell^{\mathrm{d},XY},\, C_{\ell'}^{\mathrm{d},WZ}) = \frac{f_{\mathrm{sky}}}{2\ell+1}\left[C_\ell^{\mathrm{d},XW}C_\ell^{\mathrm{d},YZ} + C_\ell^{\mathrm{d},XZ}C_\ell^{\mathrm{d},YW}\right]\delta_{\ell\,\ell'} + f_{\mathrm{sky}}\sum_L\left[\frac{\partial C_\ell^{\mathrm{d},XY}}{\partial C_L^{\phi\phi}}\mathrm{Cov}_{L\,L'}^{\phi\phi,\phi\phi}\frac{\partial C_{\ell'}^{\mathrm{d},WZ}}{\partial C_{L'}^{\phi\phi}}\right],$$

Green, Meyers, AvE 2016

See also:
Benoit-Levy, Smith, Hu 2012
Peloton, Schmittfull, Lewis, Carron, Zahn 2016
Motloch, Hu, and Benoit-Levy 2016

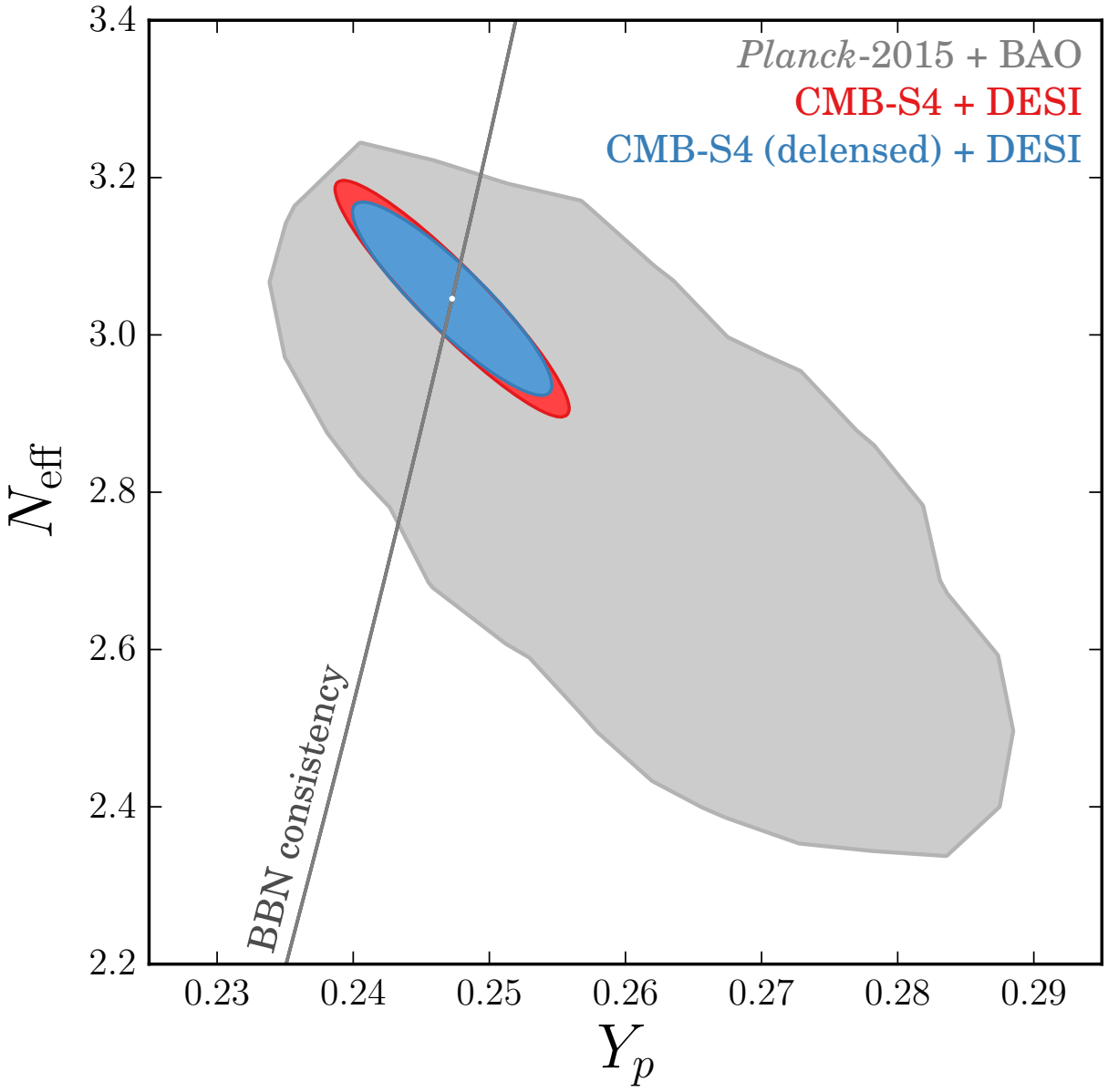
Power spectrum covariances



Delensing removes covariances

Green, Meyers, AvE 2016

Cosmology - N_{eff}



- Break degeneracy between N_{eff} (damping + phase shift) and Yp

Green, Meyers, AvE 2016
CMB-S4 science book

Delensing - possible issues

$B_{templ} \sim E_{obs} \bigstar \kappa(E_{obs} B_{obs})$

$B_{del} = B_{obs} - B_{templ}$

$\langle B_{del} B_{del} \rangle \sim \langle (B - EEB)^2 \rangle$

$\sim \langle BB \rangle - 2\langle EBEB \rangle + \ldots$

Bias if $\langle EBEB \rangle \neq 0$

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1. Biases even for GRF
2. Correlations from Dust

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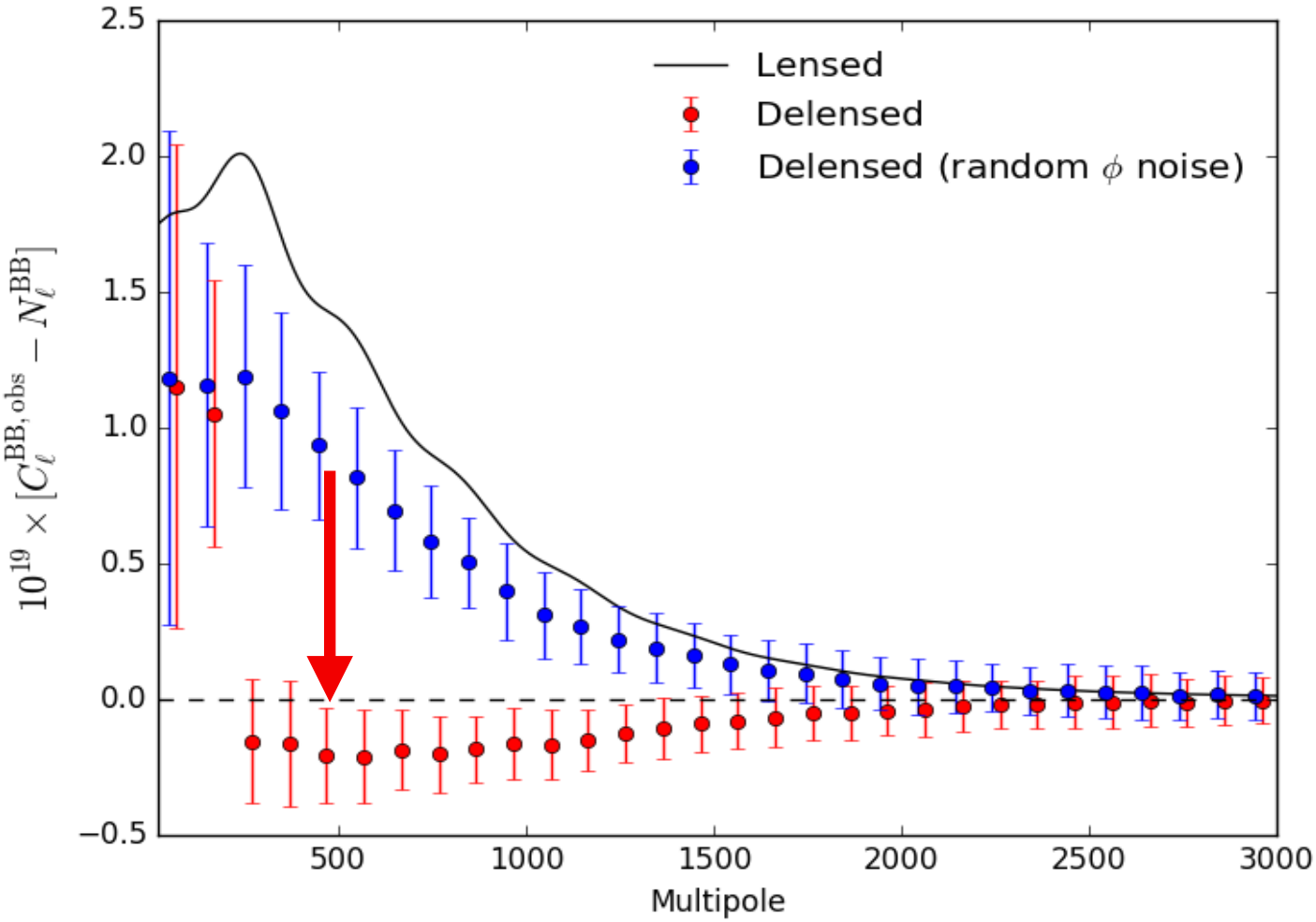
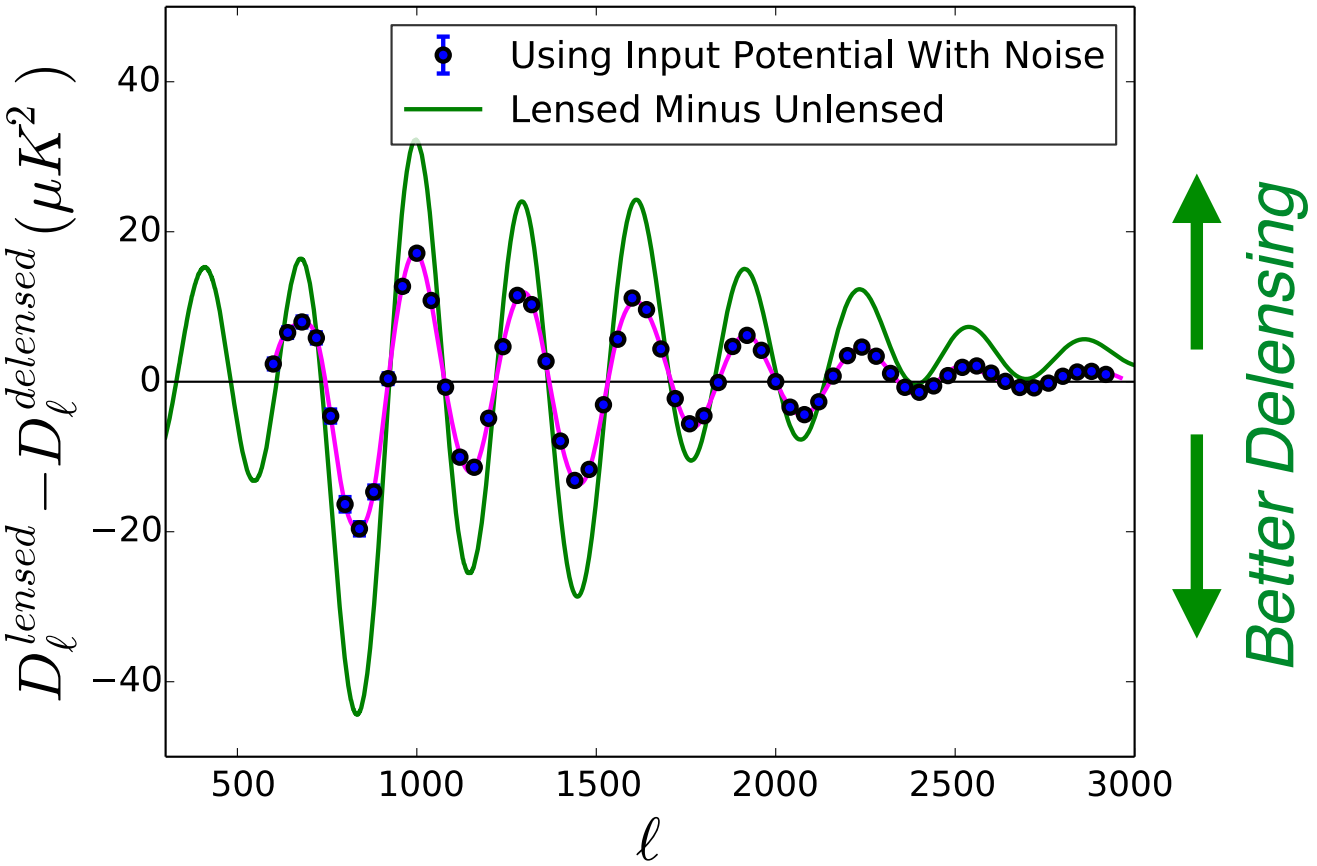
Using same lensed B modes for reconstruction that you are delensing



Namikawa 2017

see also Teng+2010

T: Ideal delensing

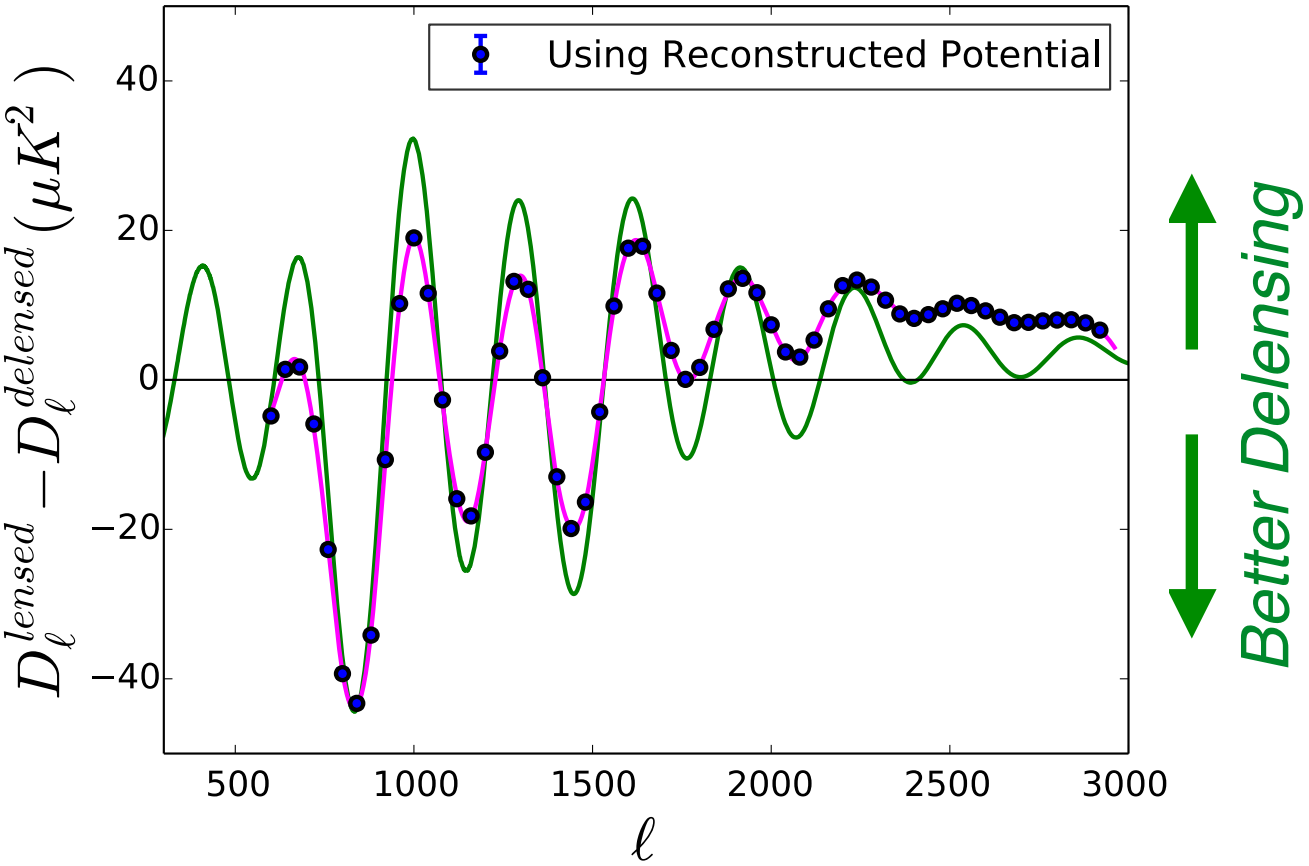


Better Delensing

- Uncorrelated noise

Sehgal, Madhavacheril, Sherwin, AvE 2017

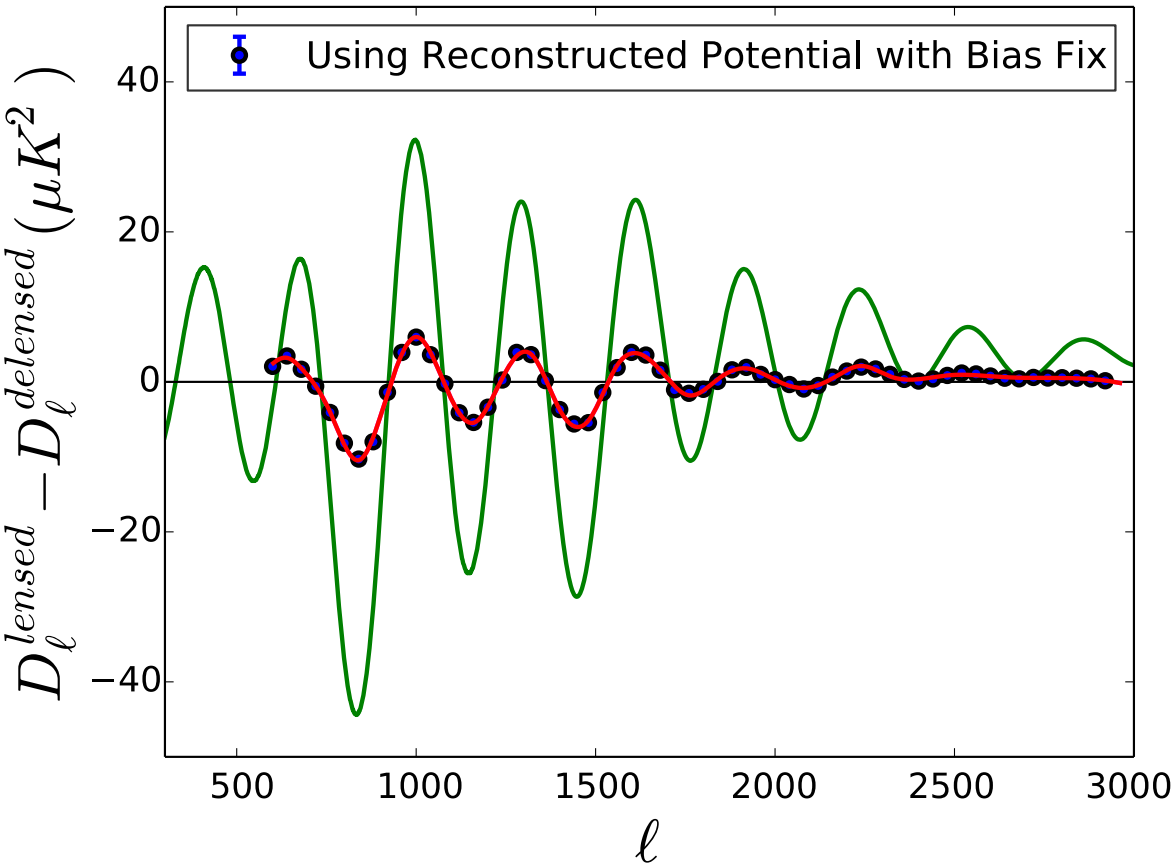
T: Using reconstructed lenses

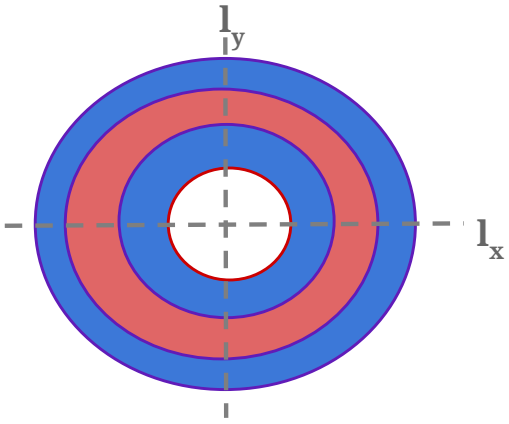


- Uncorrelated noise

Sehgal, Madhavacheril, Sherwin, AvE 2017

Mitigation method (a)

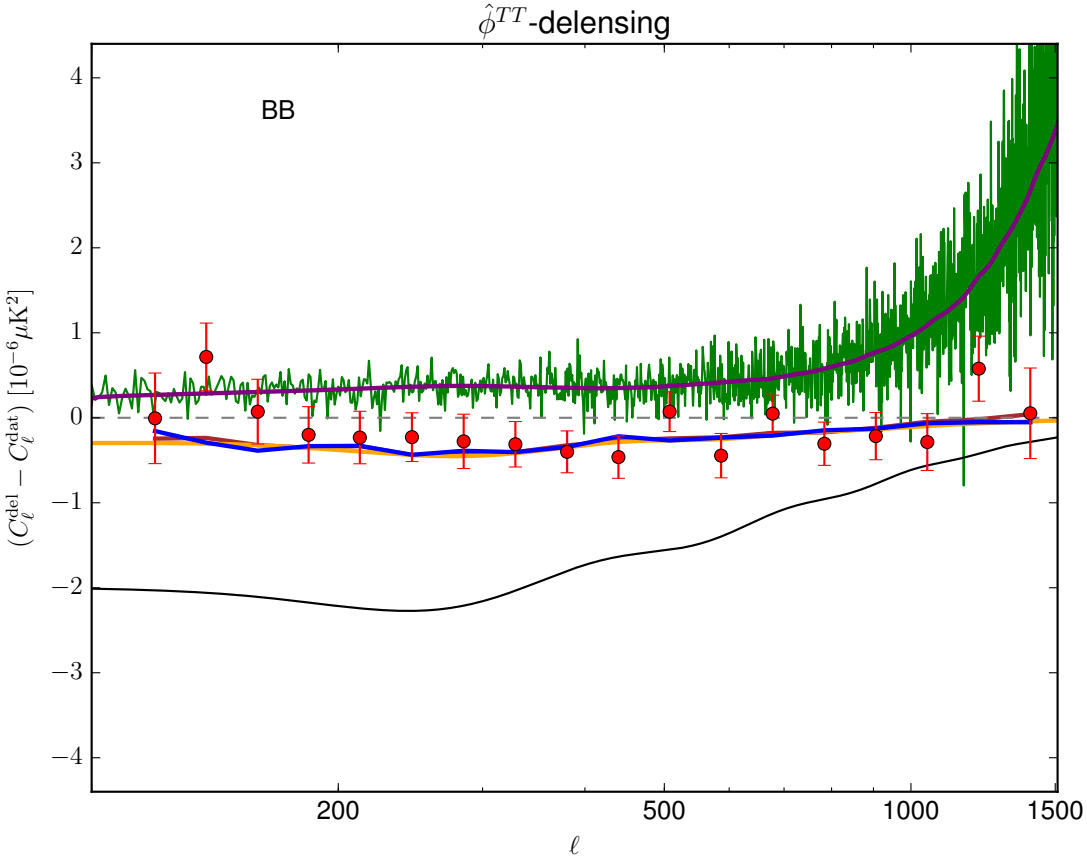




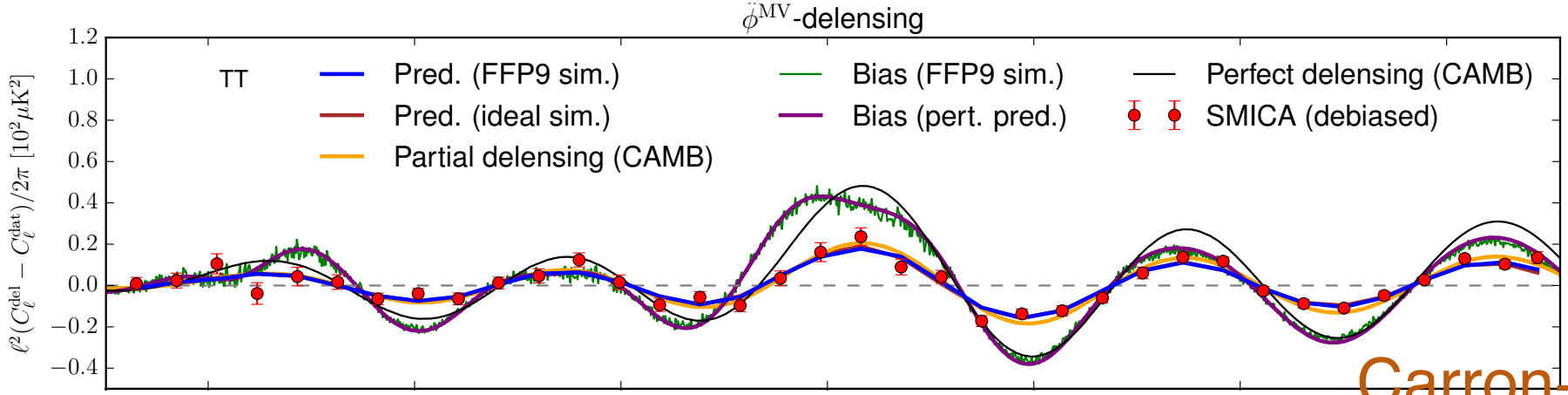
- Delens ~10 disjoint annuli separately

Sehgal, Madhavacheril, Sherwin, AvE 2017

Mitigation method (b)



- Get bias from simulations
- *Planck*: 20σ TT, 4σ BB (Carron+16)
- Response to sim/data mismatch



Carron+2016

Mitigation method (c)

Namikawa 2017

$$\langle B_{del} B_{del} \rangle \sim \langle (B - EEB)^2 \rangle$$
$$\sim \langle BB \rangle - \underbrace{2\langle EBEB \rangle}_{N^{(4)}} + \underbrace{\langle EBEBEE \rangle}_{N^{(6)}}$$

Calculate 4pt and 6pt directly from realization of map

Delensing - possible issues

$B_{templ} \sim E_{obs} \bigstar \kappa(E_{obs}B_{obs})$

$B_{del} = B_{obs} - B_{templ}$

$\langle B_{del}B_{del}\rangle \sim \langle(B - EEB)^2\rangle$

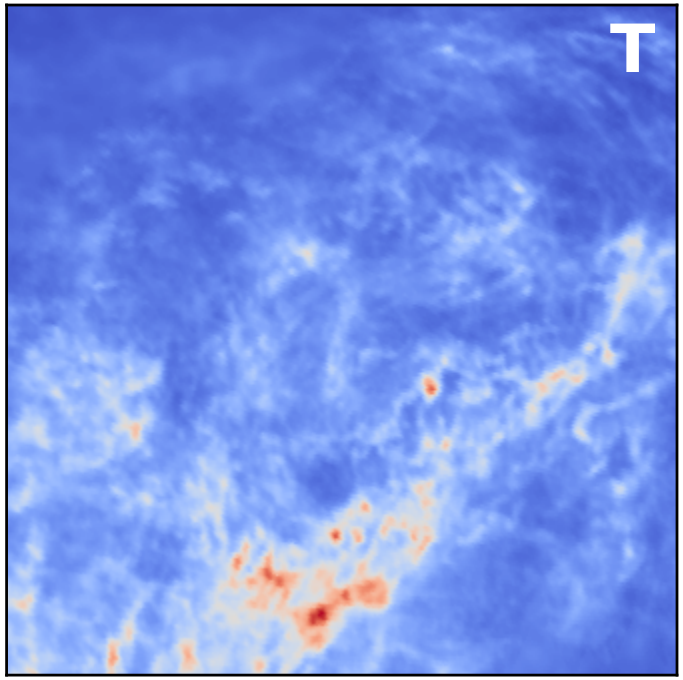
$\sim \langle BB\rangle - 2\langle EBEB\rangle + \ldots$

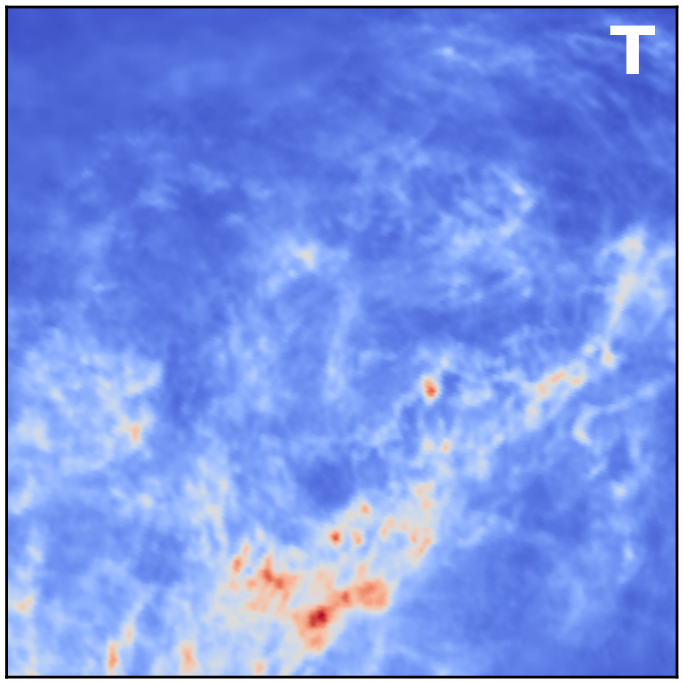
Bias if $\langle EBEB\rangle \neq 0$

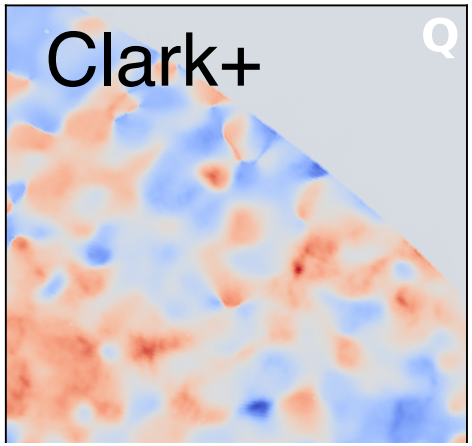
(sim. for TTTT)

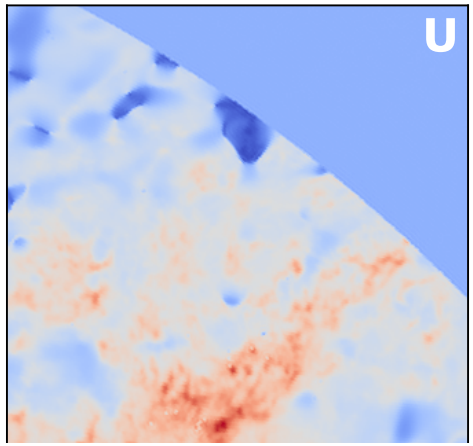
1. Biases even for GRF
2. Correlations from Dust

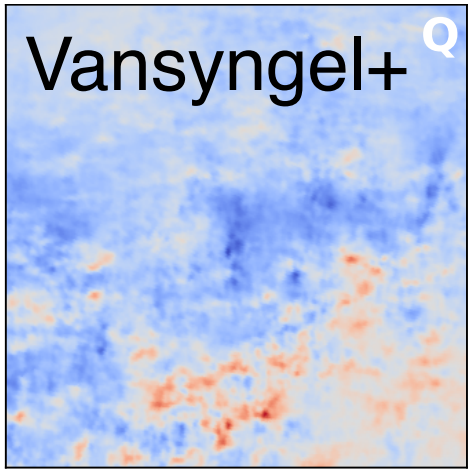
$\langle B_{long}B_{templ}\rangle$

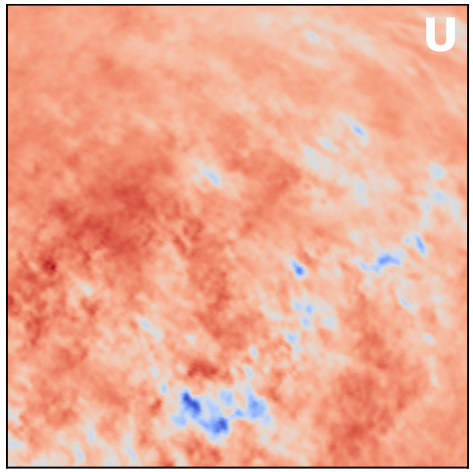

T


T


Clark+
Q


U


Vansyngel+
Q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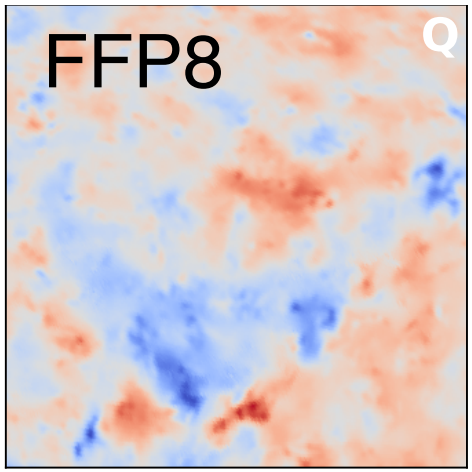
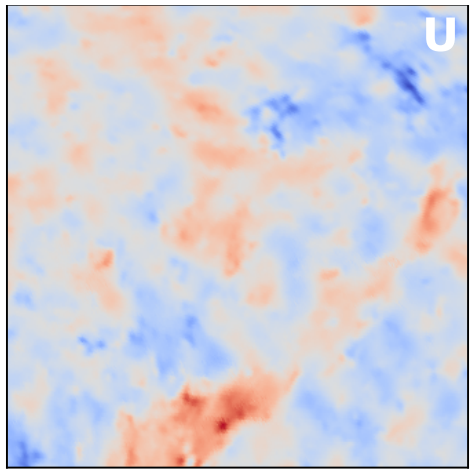
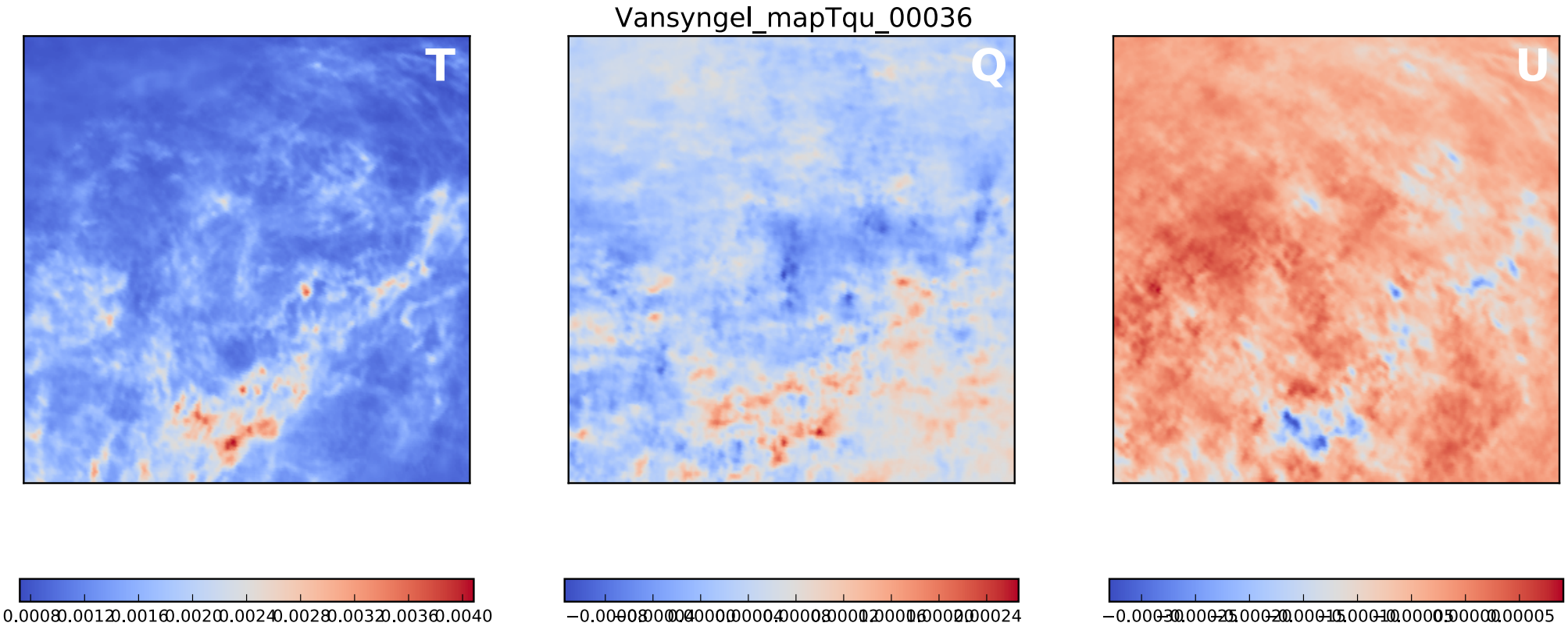

FFP8
Q

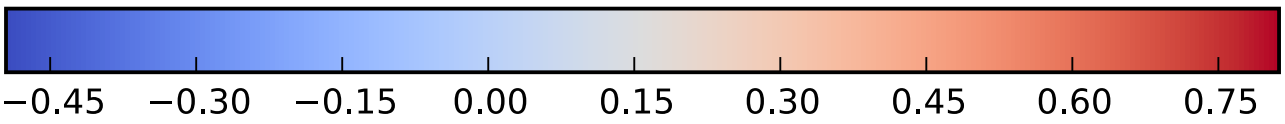

U

$$[T_{\mathrm{dust}}, Q_{\mathrm{dust}}, U_{\mathrm{dust}}]$$

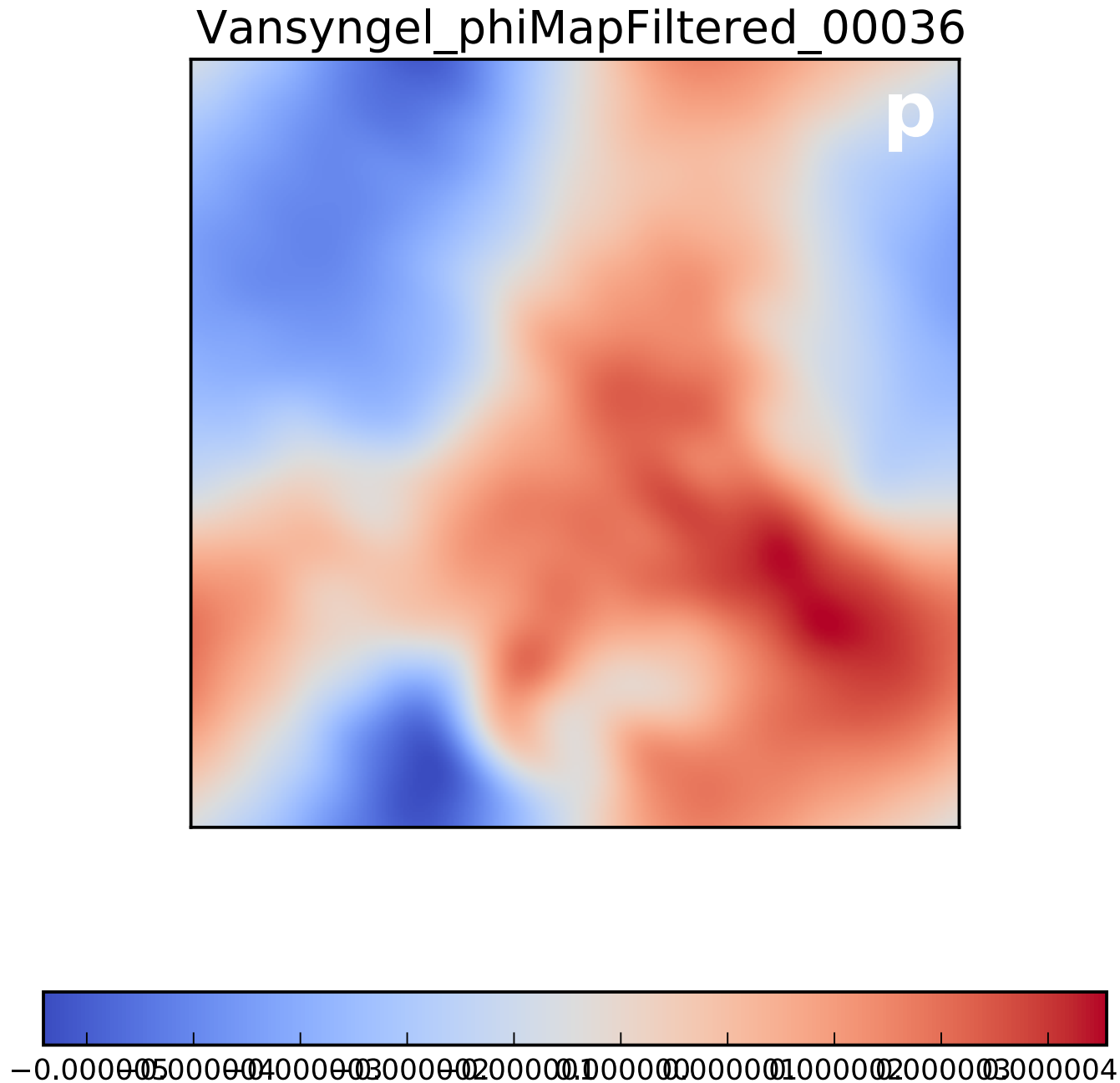


$$\kappa(E_{\rm dust}, B_{\rm dust})$$

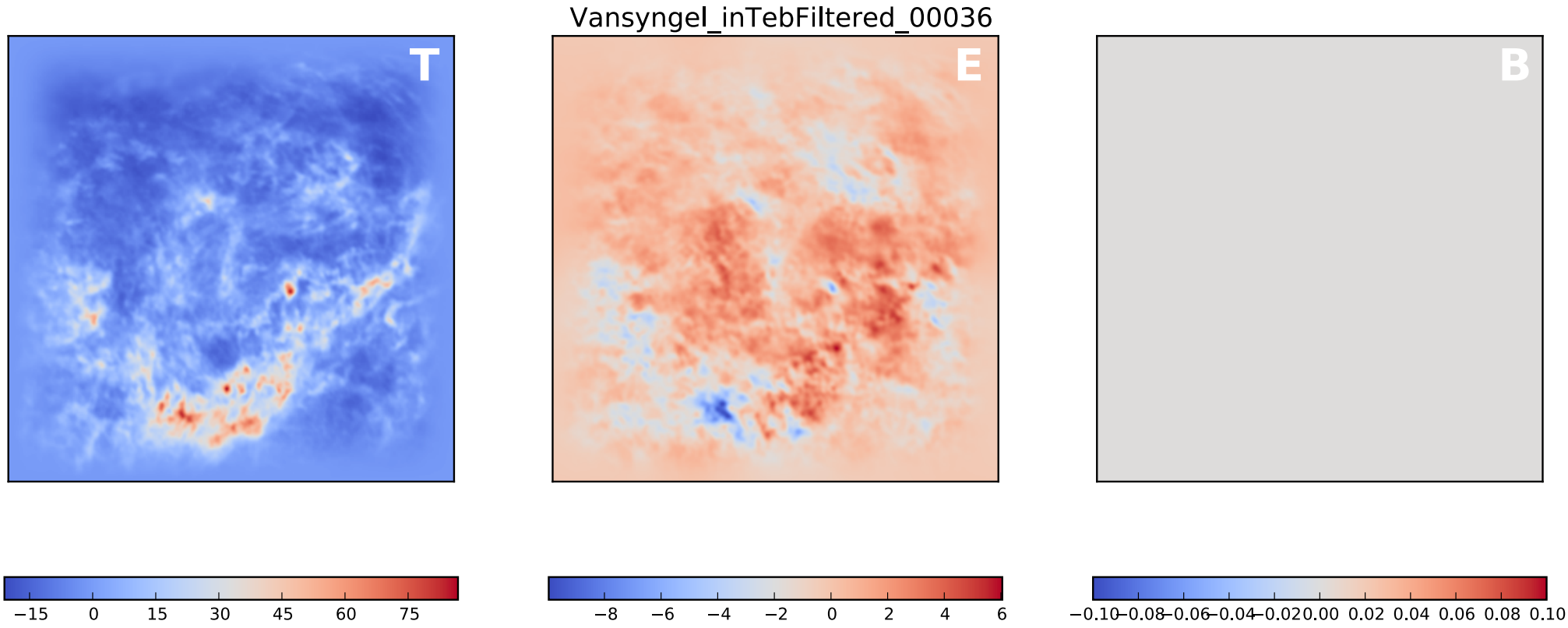
Vansyngel_kappaMap_00036



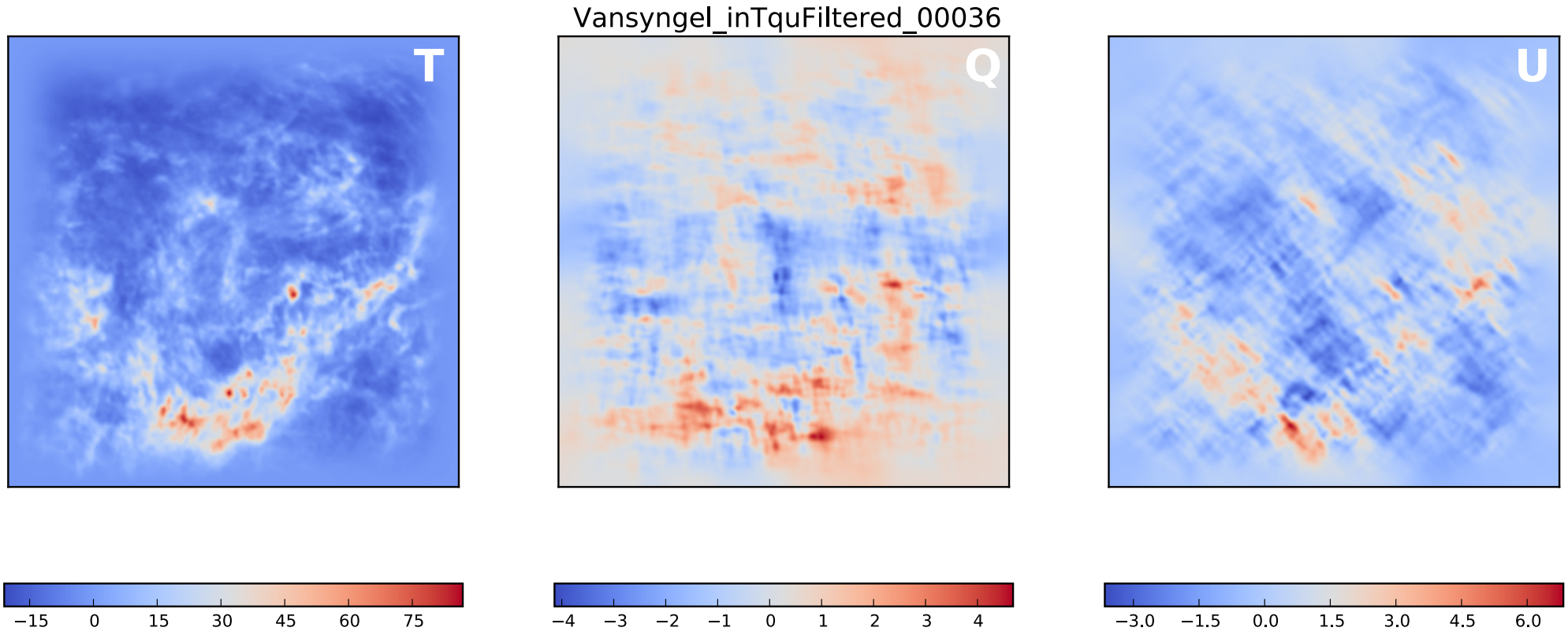
$$\phi(E_{\mathrm{dust}}, B_{\mathrm{dust}})$$



$[T_{\rm dust}, E_{\rm dust}, B_{\rm dust}]$ filtered

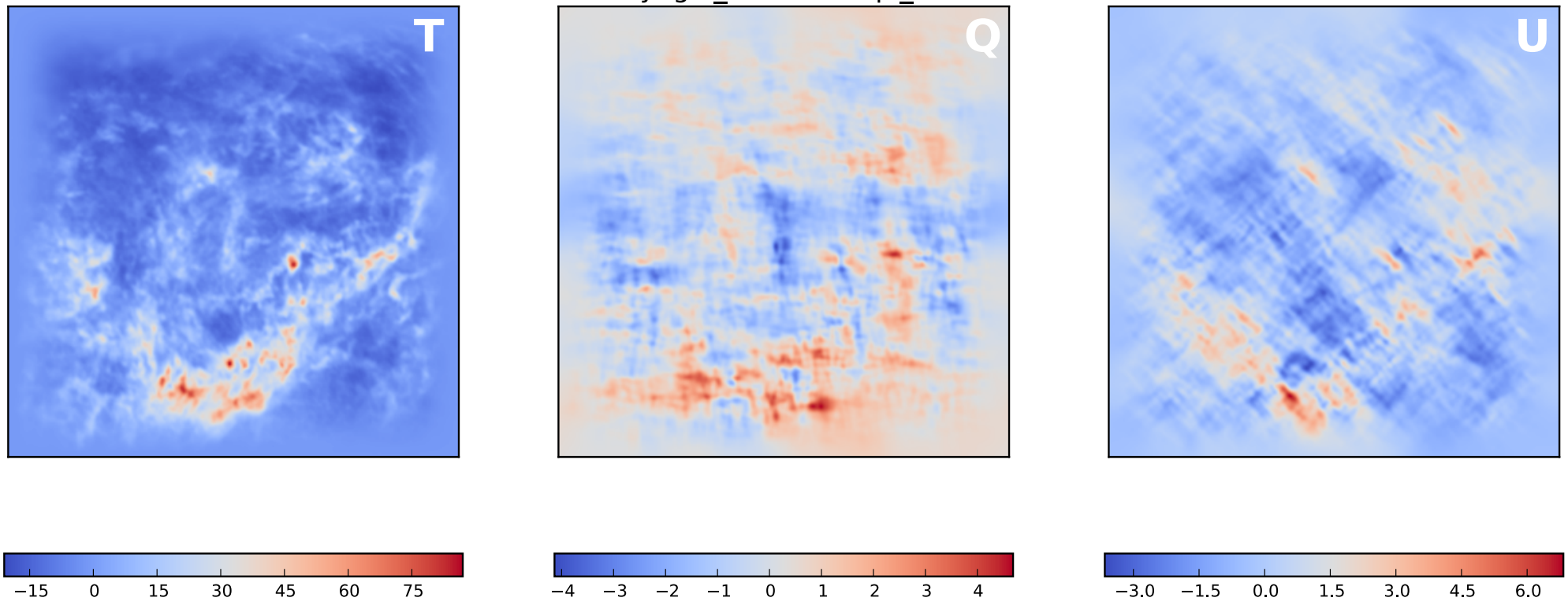


$[T_{\rm dust}, Q_{\rm dust}, U_{\rm dust}]$ filtered



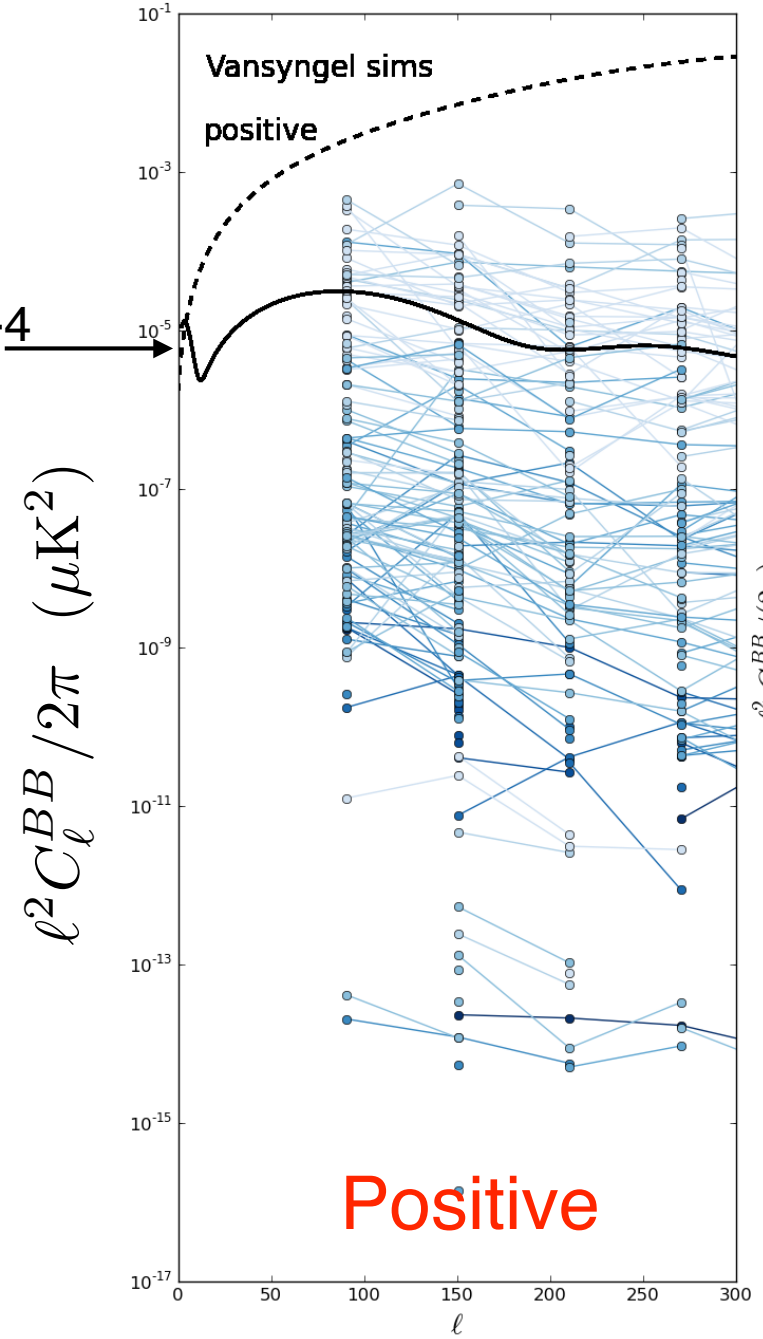
$[T_{\rm dust}, Q_{\rm dust}, U_{\rm dust}]$ filtered lensed with $\phi(E_{\rm dust} B_{\rm dust})$

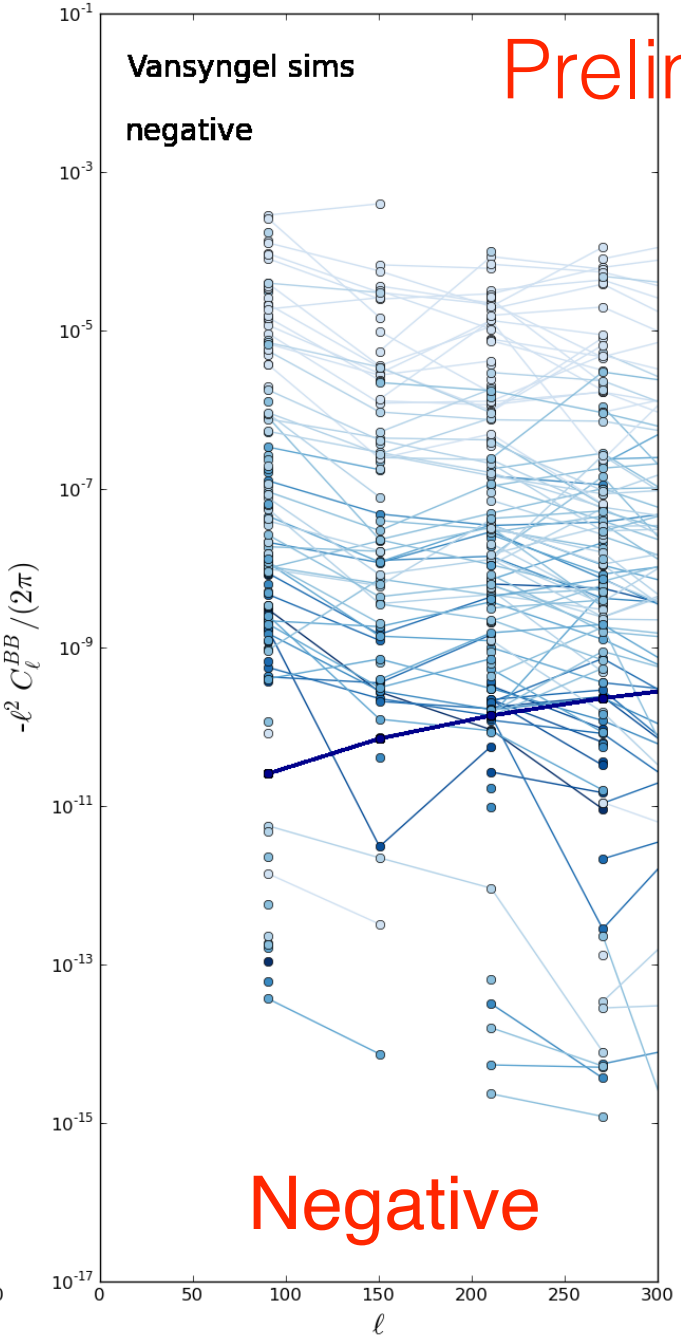
Vansyngel_delensedTqu_00036



$\langle B_{\rm dust} B_{\rm template} \rangle$

r=5x10^{-4}





Preliminary

Clark sims: no bias seen (preliminary)

See also poster by Dominic Beck

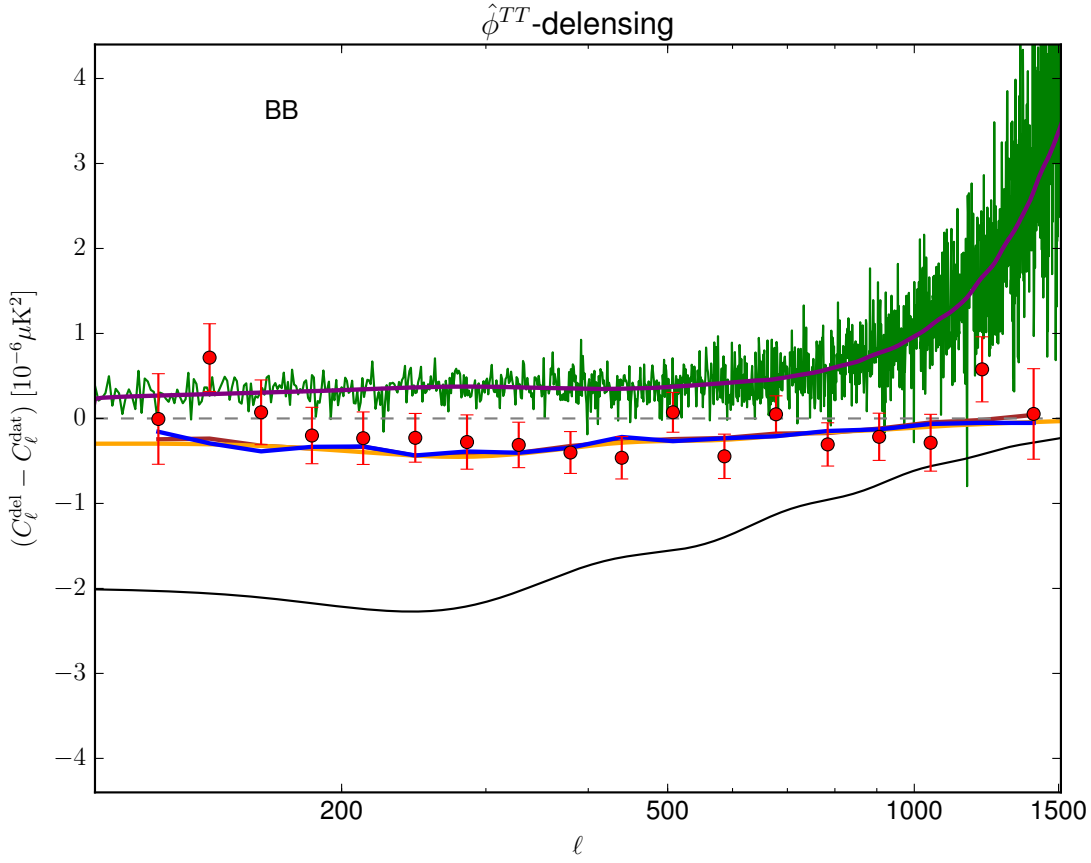
Summary

- *T* delensing
- Biases for *T* and *P* delensing arise when using same modes to reconstruct κ that you are trying to delens.
  - 3 methods to mitigate
- Polarized Dust NG on small scales??? No evidence for impact at leading order in Vansyngel simulations

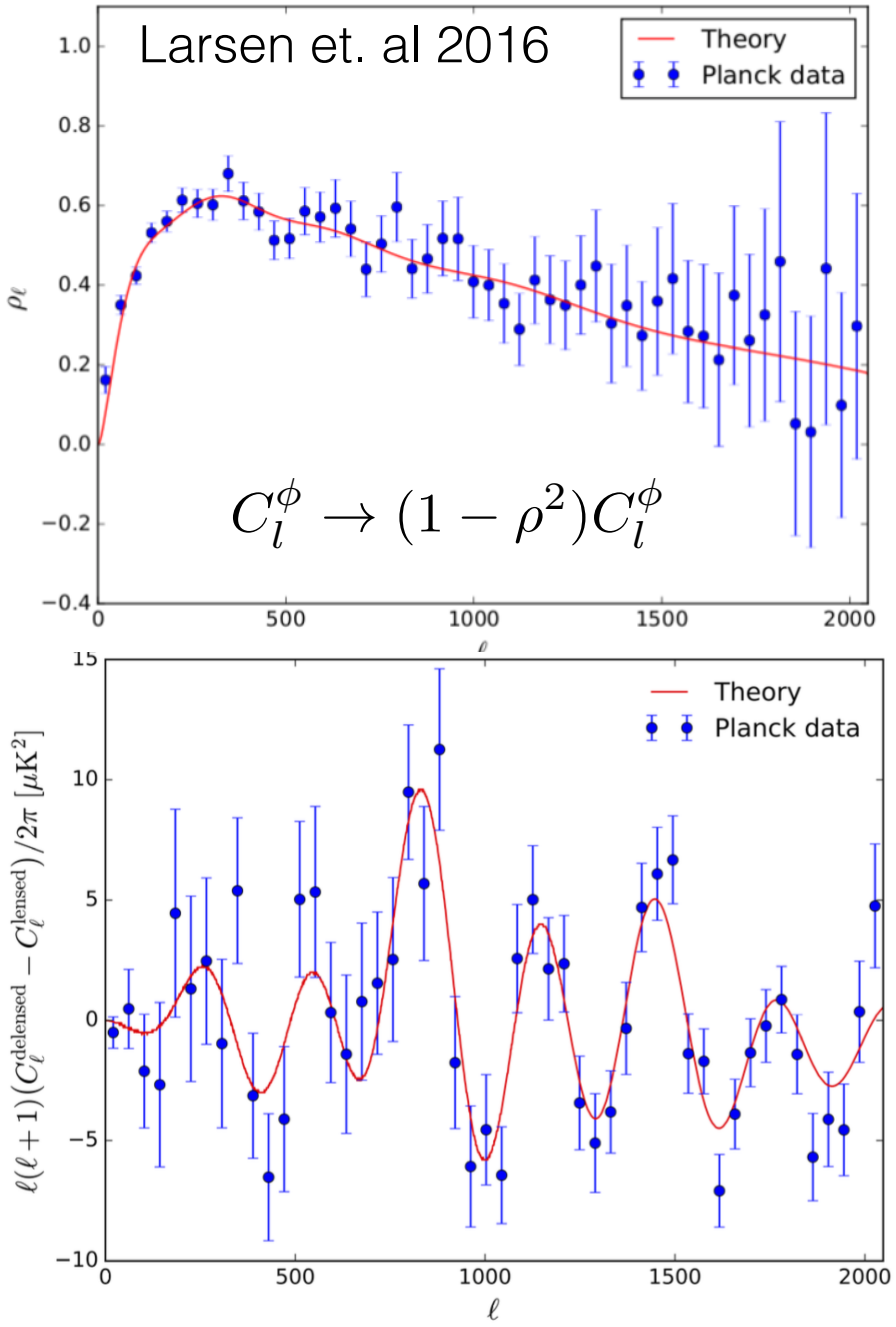
Extra slides…..

3. More mitigation methods

- Model this bias using simulations (Carron+2016)

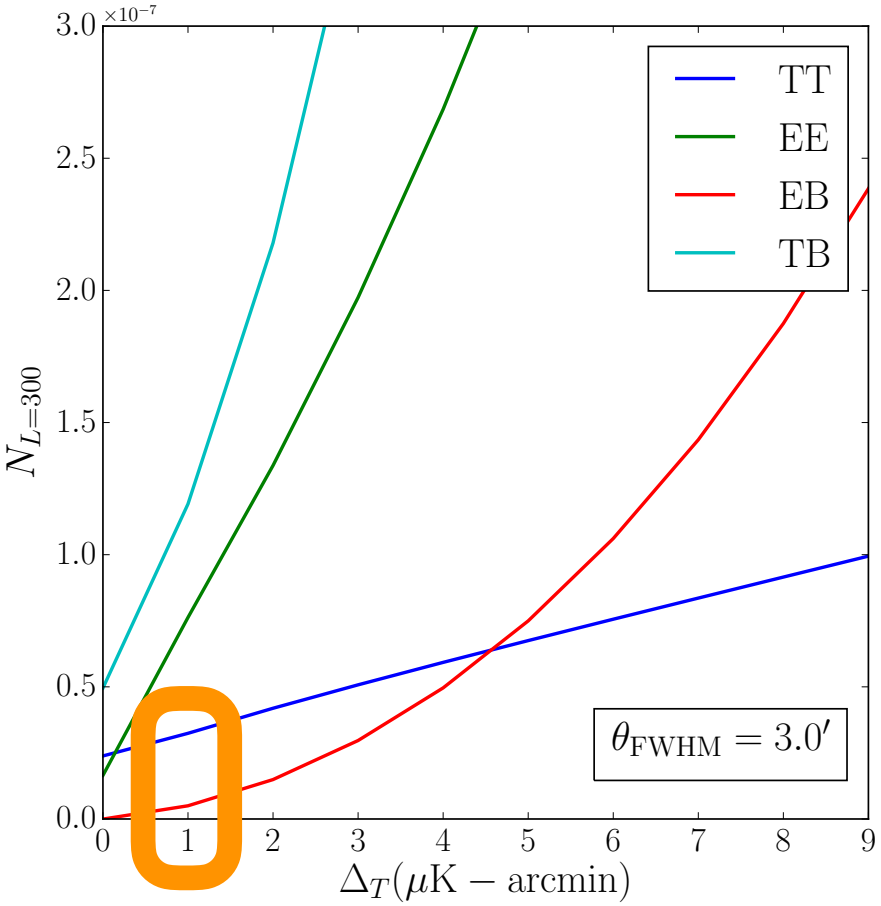


Demonstration with *Planck* CIB



Outline

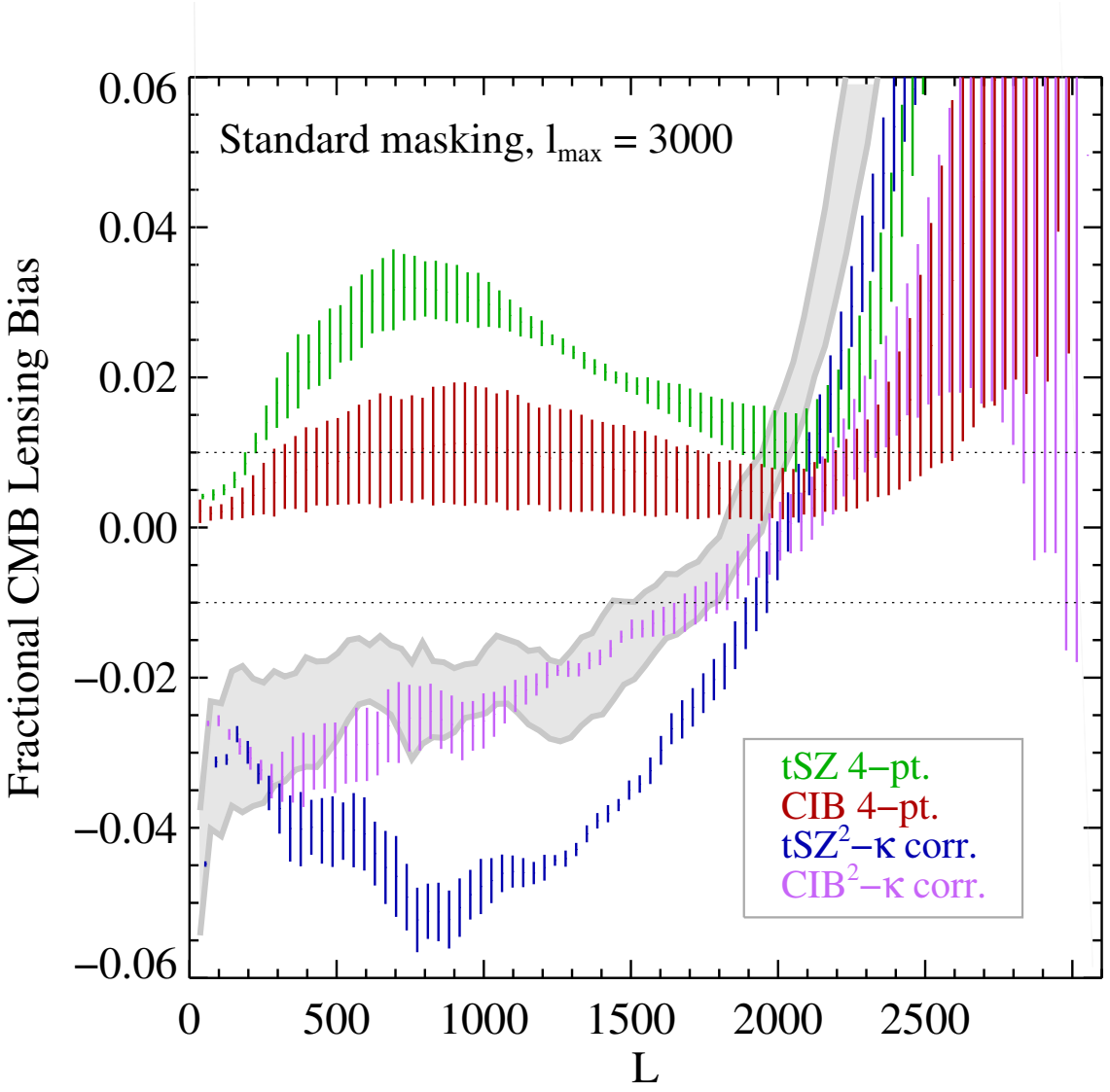
Lensing noise vs. instrumental noise



- P lensing will dominate for S4
- T: extragalactic foregrounds
- P: galactic foregrounds

CMB-S4 science book

Foregrounds in CMB temperature-based lensing



tSZ-tSZ-tSZ-tSZ

CIB-CIB-CIB-CIB

tSZ-tSZ-κ

CIB-CIB-κ

- Biases of several percent at one frequency
  - Here 20 uK-amin noise(!)
- Spectral cleaning (not kSZ - Hill&Ferraro 17)
- Spatial cleaning
- Also, impact of κ non-Gaussianity (Boehm +16)

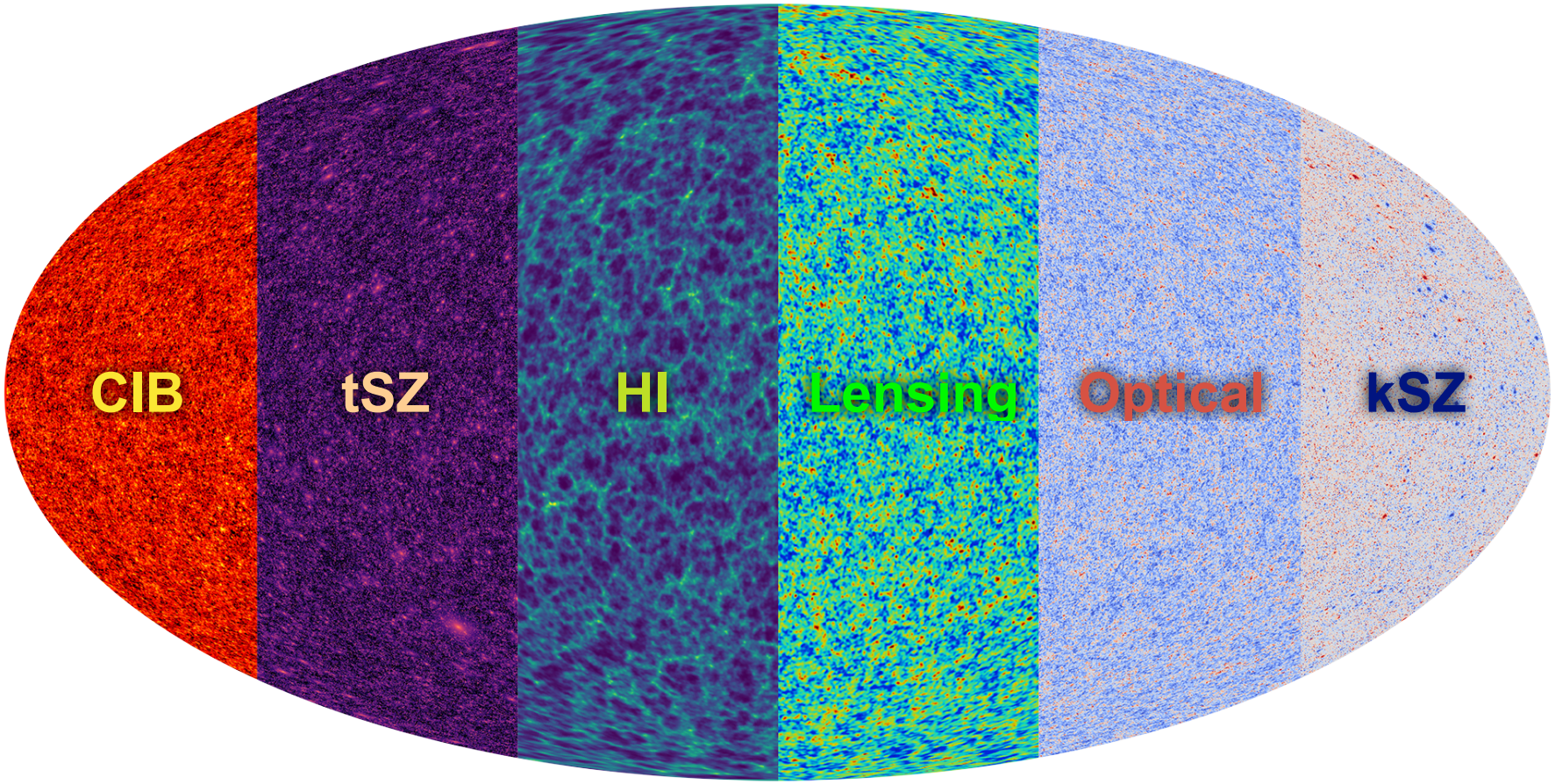
van Engelen, Bhattacharya, Sehgal, Holder, Zahn, Nagai 2014

- CIB/tSZ/kSZ/κ bi/trispectra are measurable and interesting
- Is bias-hardening feasible?
- Is spectral cleaning feasible? tSZ/CIB bispectrum/trispectrum residuals — comparable to kSZ?

To-do for TT lensing — test both spectral and spatial cleaning with full end-to-end simulation analysis

CITA peak-patch simulation

Alvarez, Stein, Bond, Battaglia, van Engelen, Pham, +++



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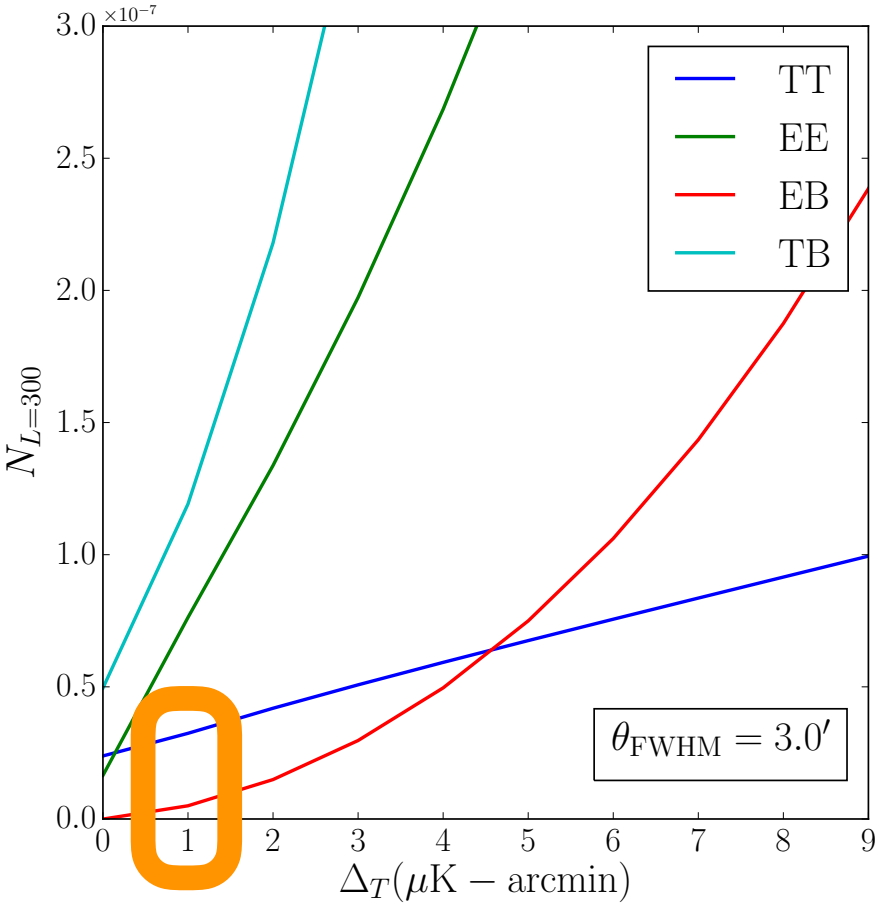

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CMB-S4 science book

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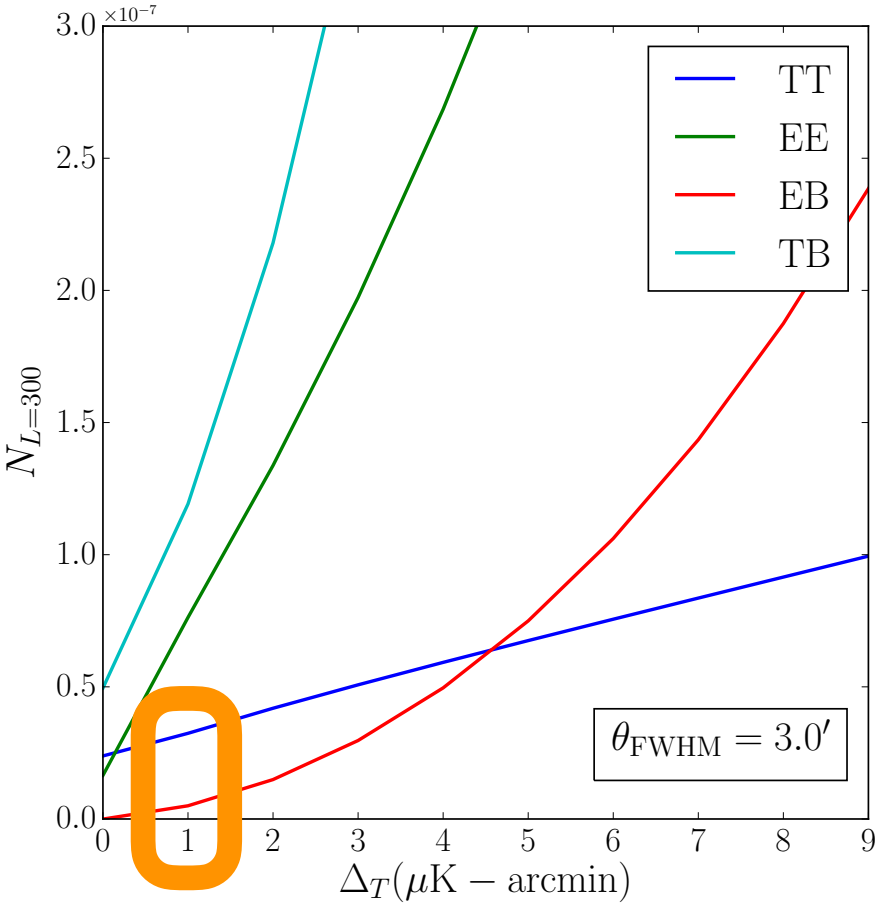

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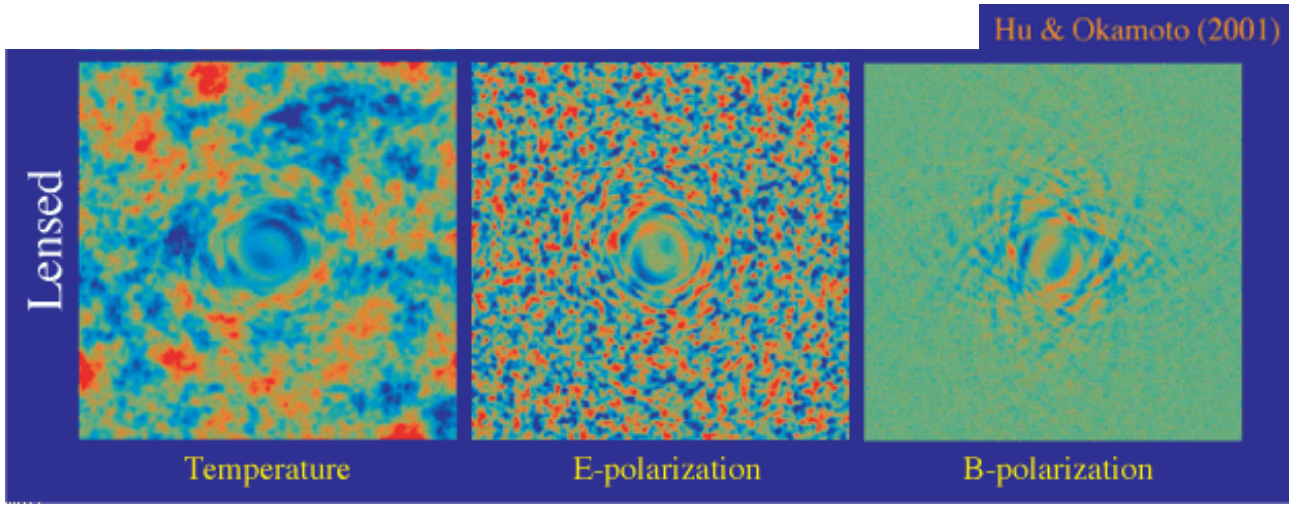
CMB-S4 science book

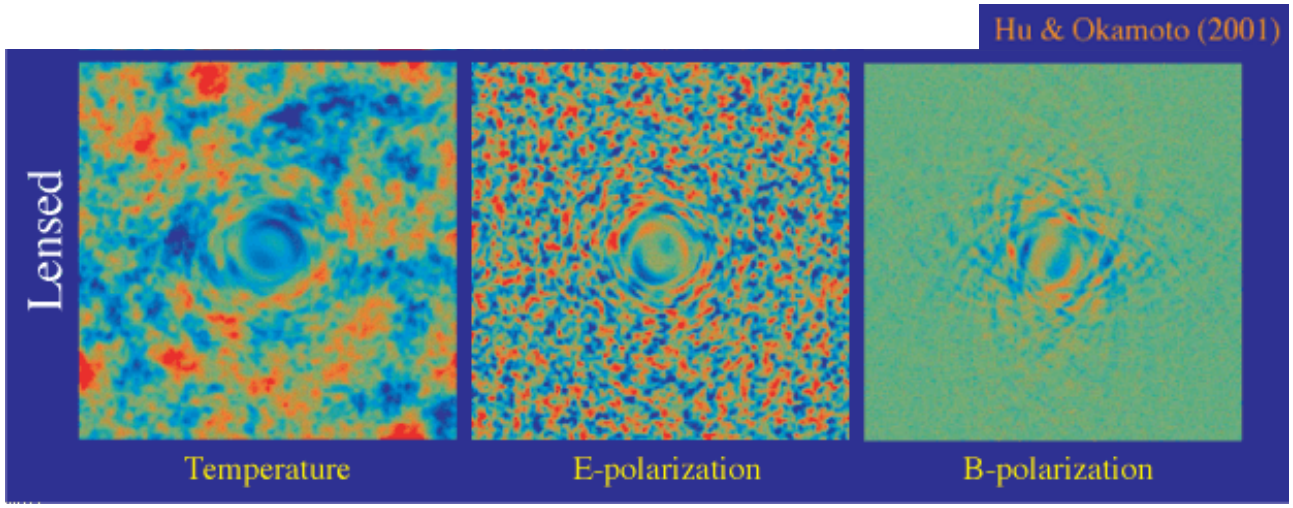
Lensing/Delensing



Slides courtesy Neelima Sehgal

Lensing/Delensing

We measure this



Slides courtesy Neelima Sehgal

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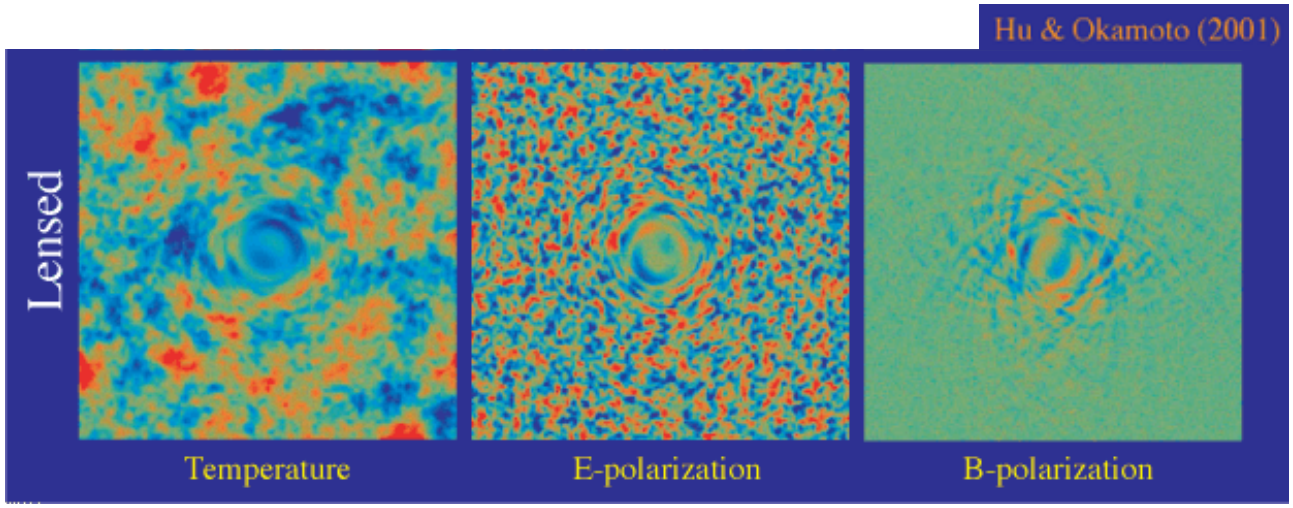

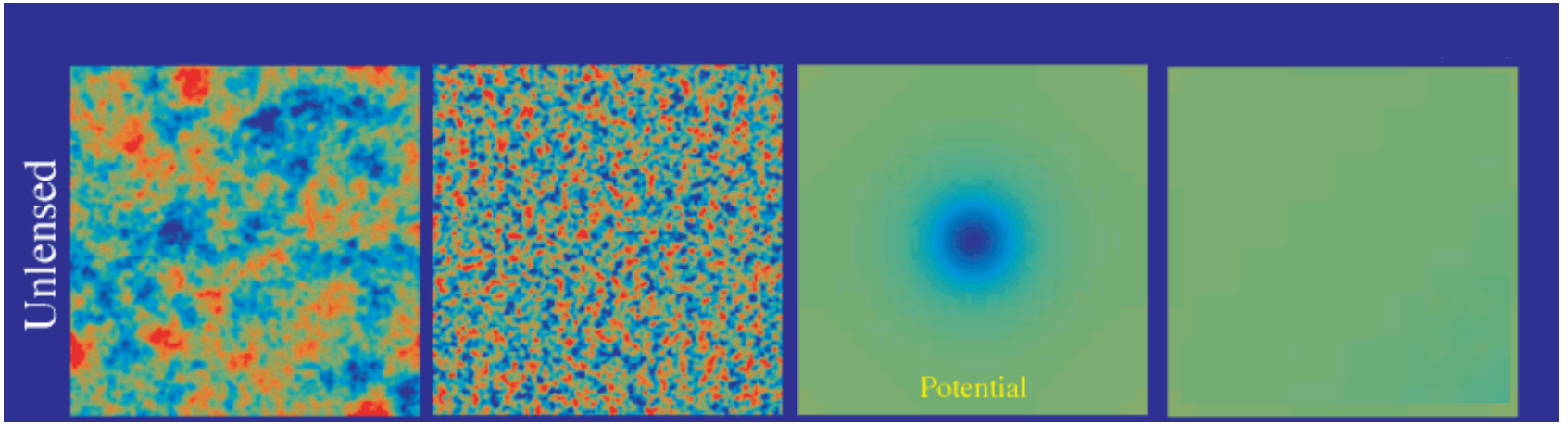

Slides courtesy Neelima Sehgal

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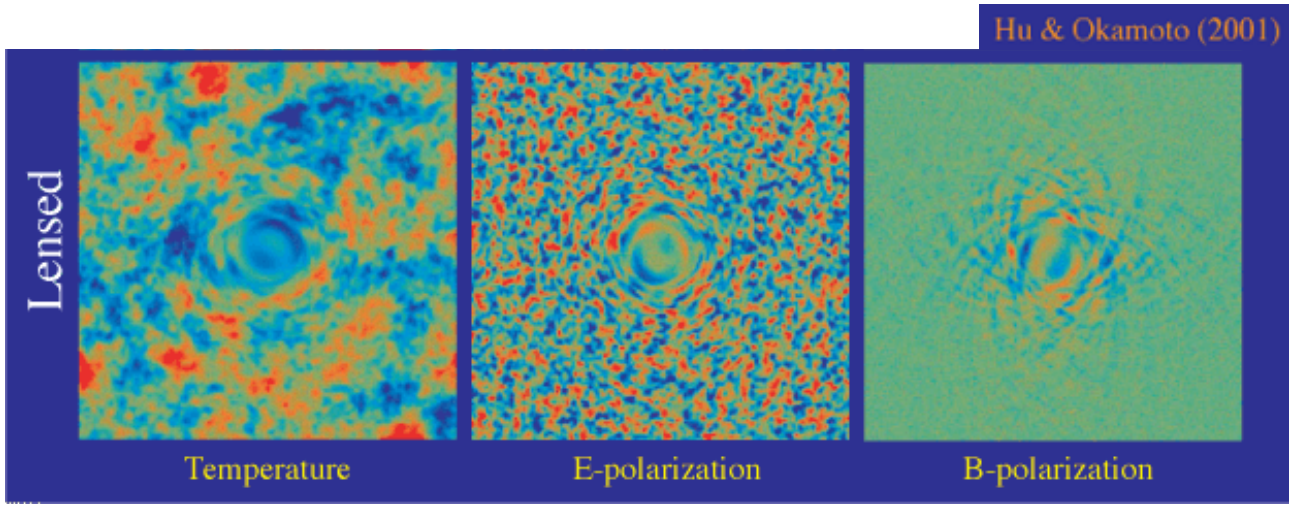
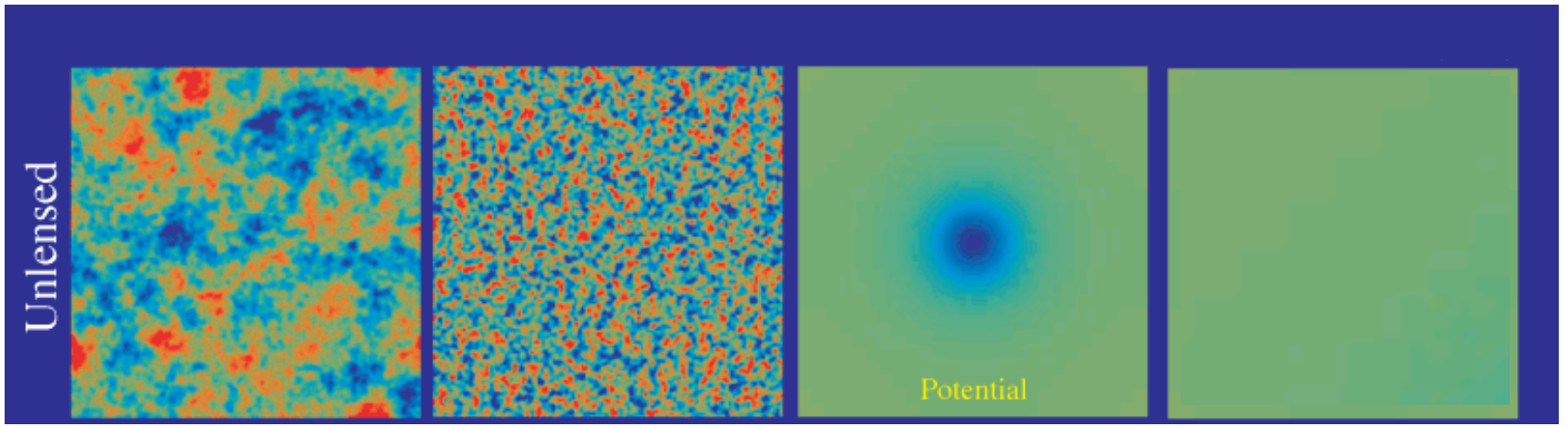


We want this



Slides courtesy Neelima Sehgal

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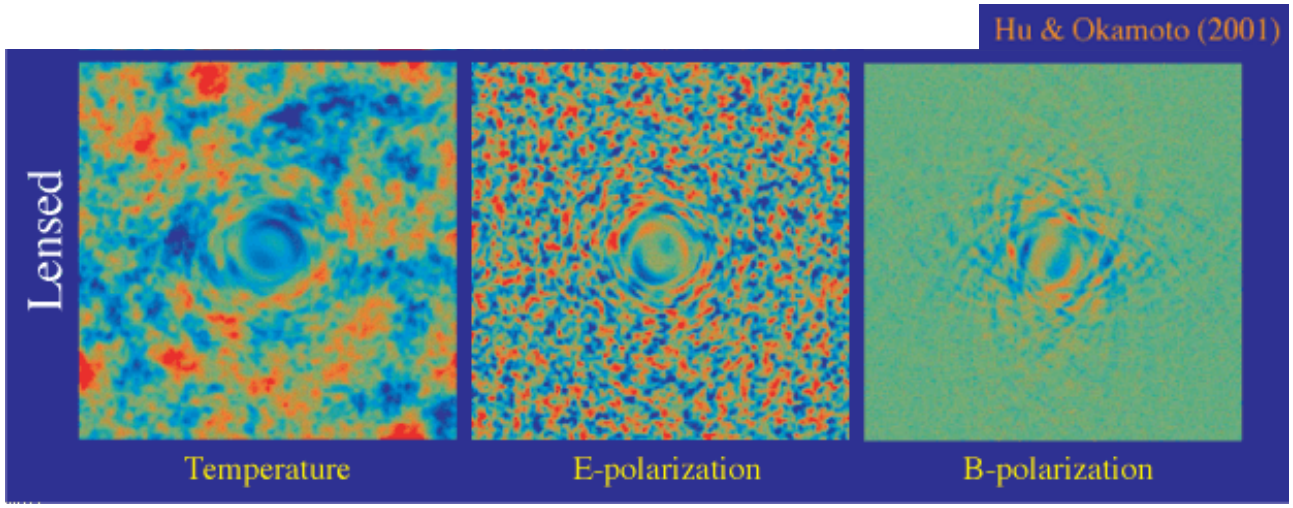

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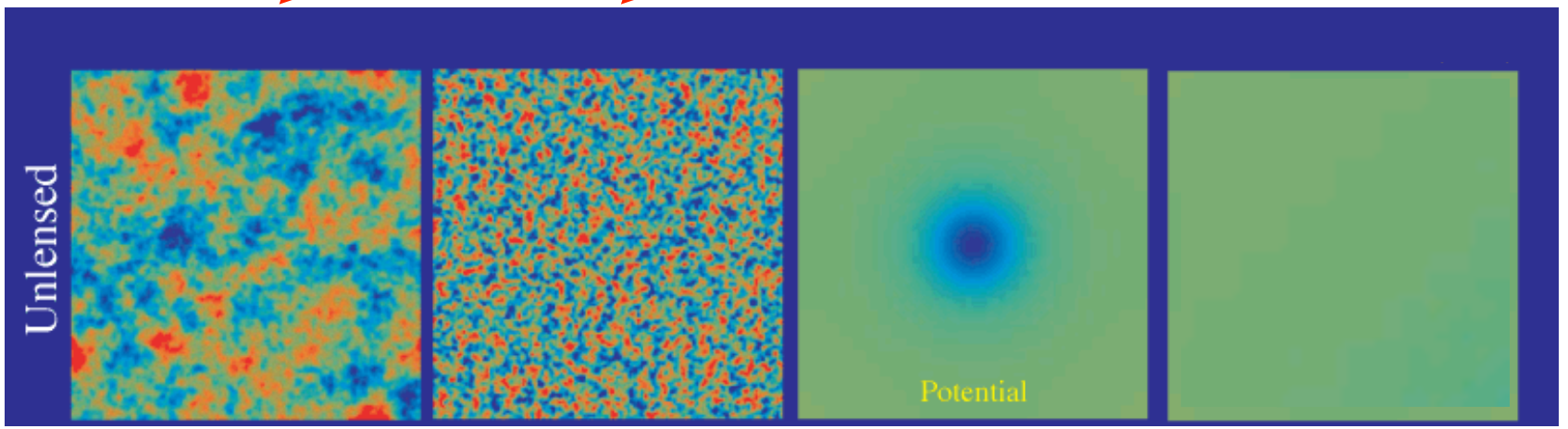
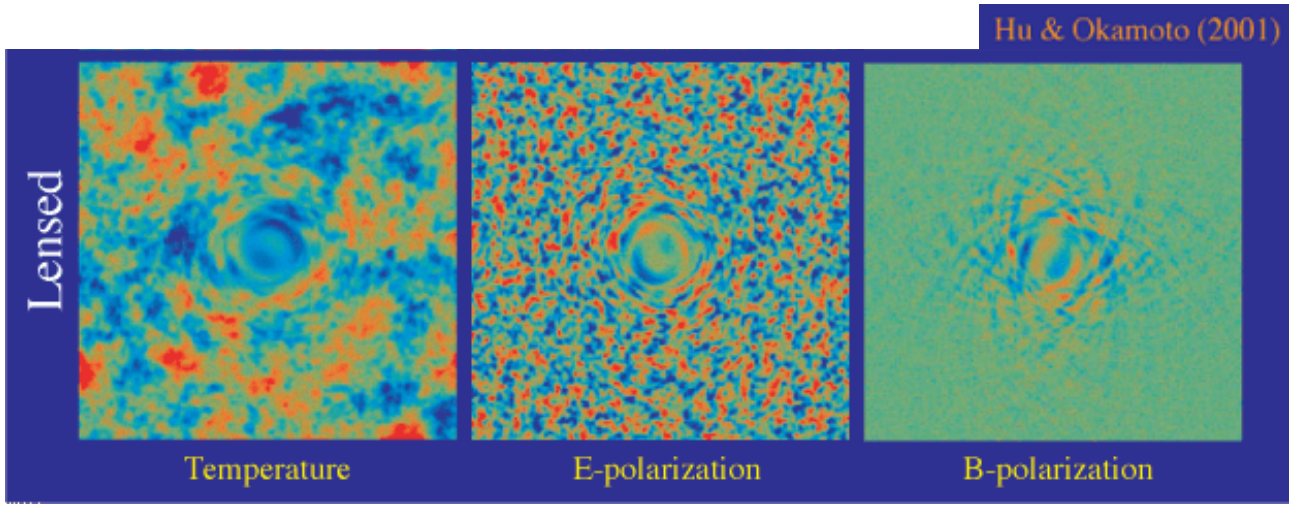


Separation of primordial CMB and mass map from Lensing analysis

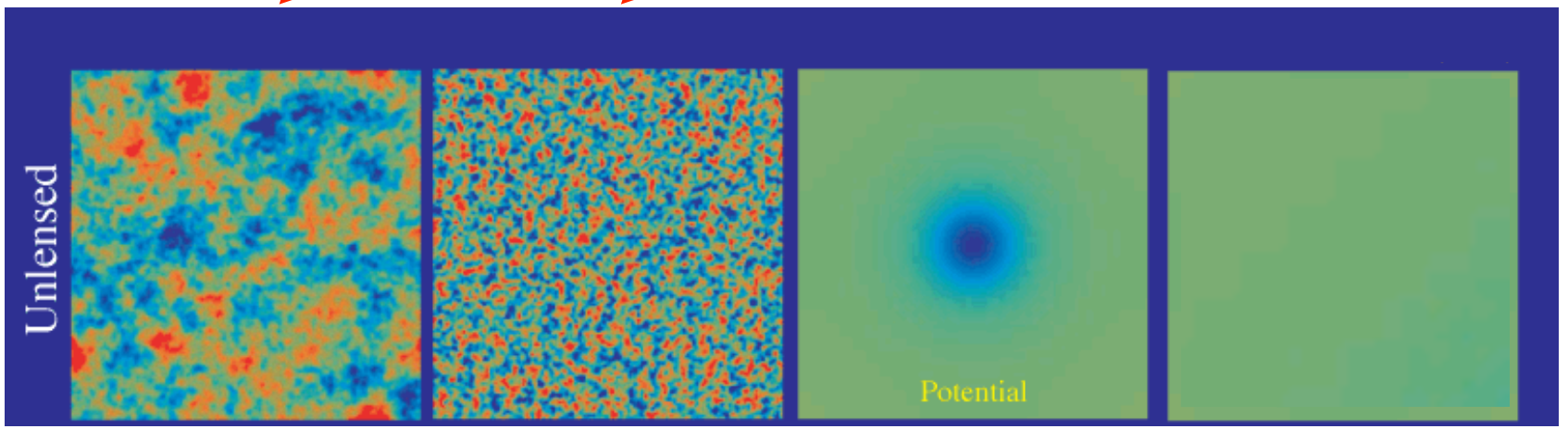
Slides courtesy Neelima Sehgal

Lensing/Delensing

We measure this



We want this



Neff constraints

$\sum m_\nu$ w constraints

Slides courtesy Neelima Sehgal

Areas of Lensing

Slides courtesy Neelima Sehgal

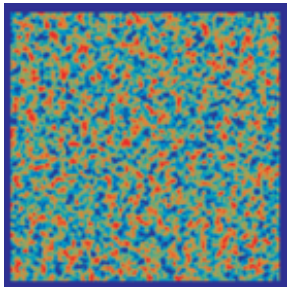
Areas of Lensing

- Delensing —> r, Neff

Slides courtesy Neelima Sehgal

Areas of Lensing

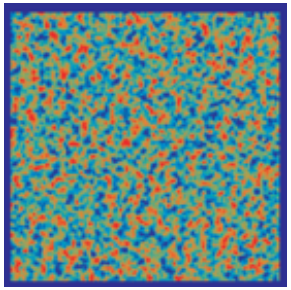
- Delensing —> r, Neff



Slides courtesy Neelima Sehgal

Areas of Lensing

- Delensing —> r, Neff

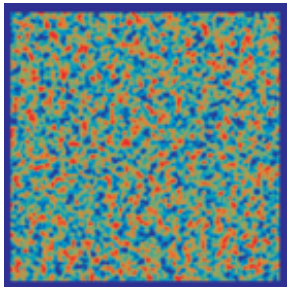


- Large-scale lensing —> $\sum m_\nu$, w, dm

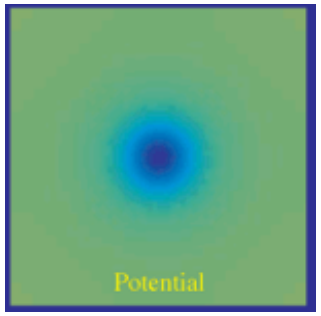
Slides courtesy Neelima Sehgal

Areas of Lensing

- Delensing —> r, Neff



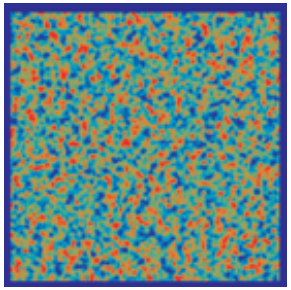
- Large-scale lensing —> $\sum m_\nu$, w, dm



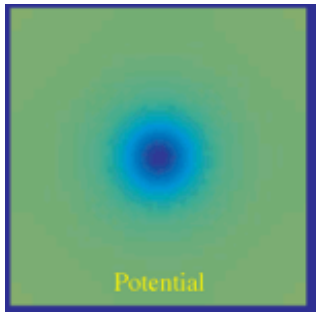
- Small-scale lensing —> w, $\sum m_\nu$

Slides courtesy Neelima Sehgal

Areas of Lensing

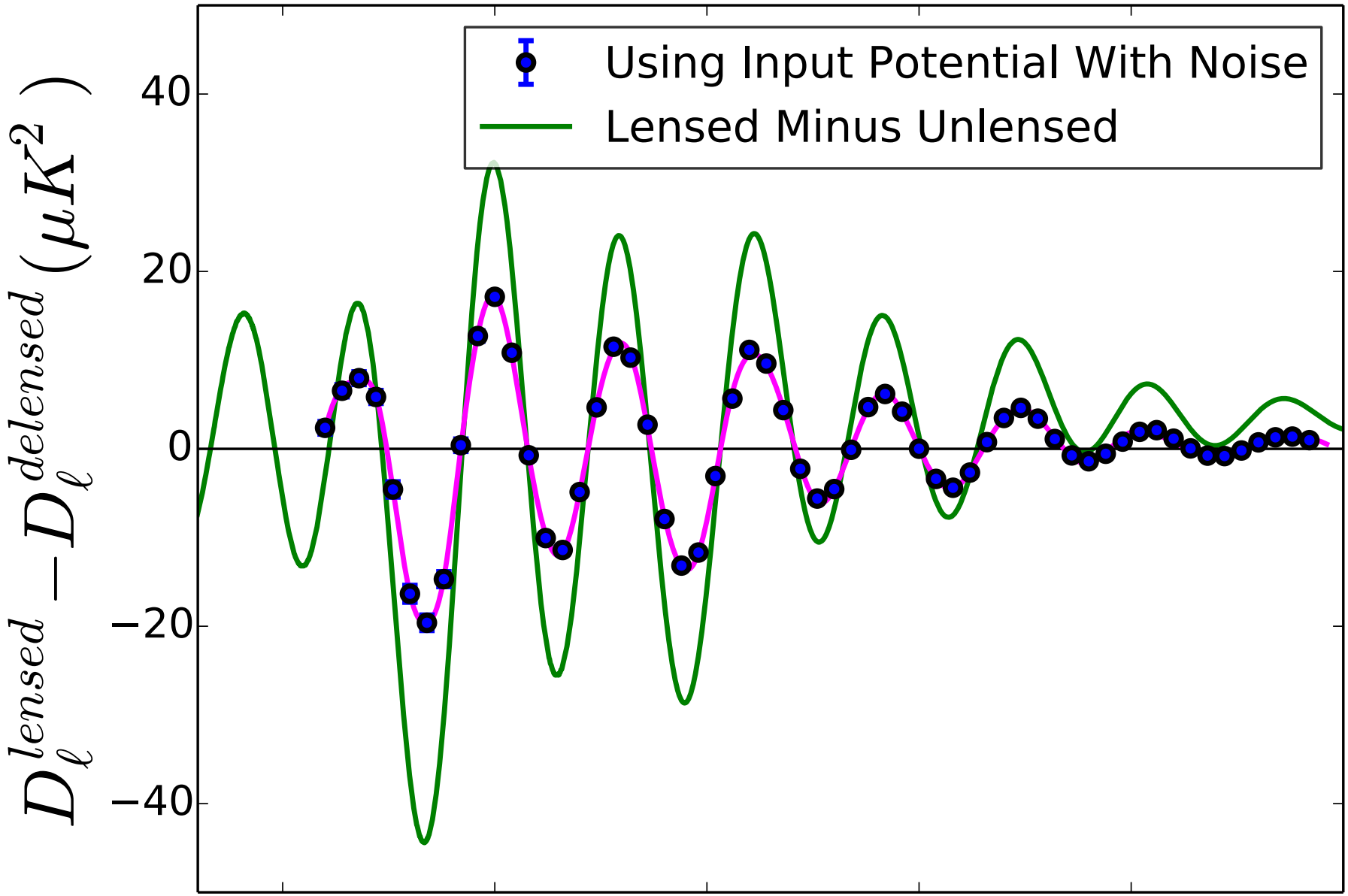


- Delensing —> r, Neff
- Large-scale lensing —> $\sum m_\nu$, w, dm
- Small-scale lensing —> w, $\sum m_\nu$
- Cross-correlation between CMB lens and other data sets —> w, $\sum m_\nu$



Slides courtesy Neelima Sehgal

1. Ideal delensing



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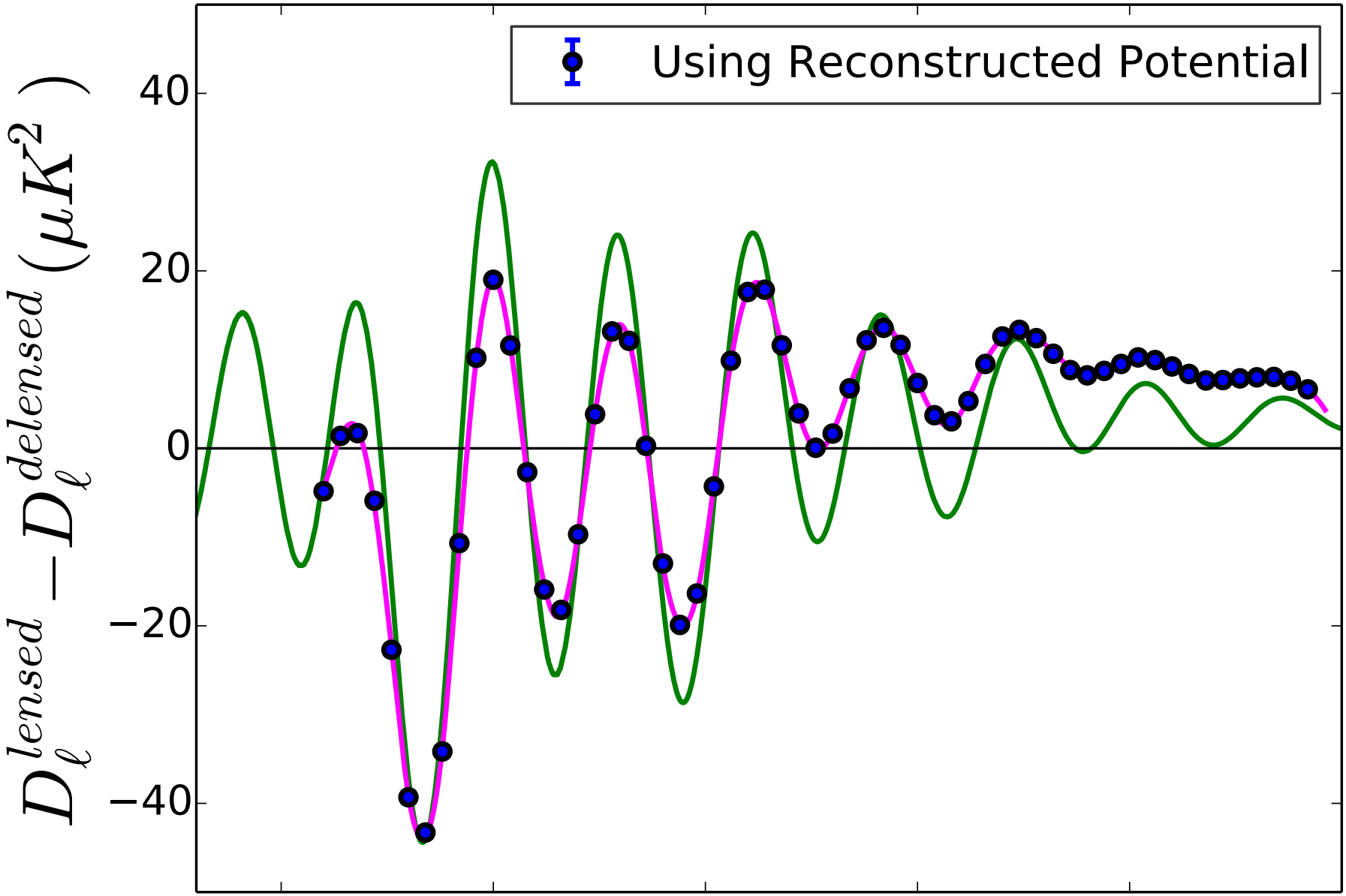
2. Using reconstructed lenses



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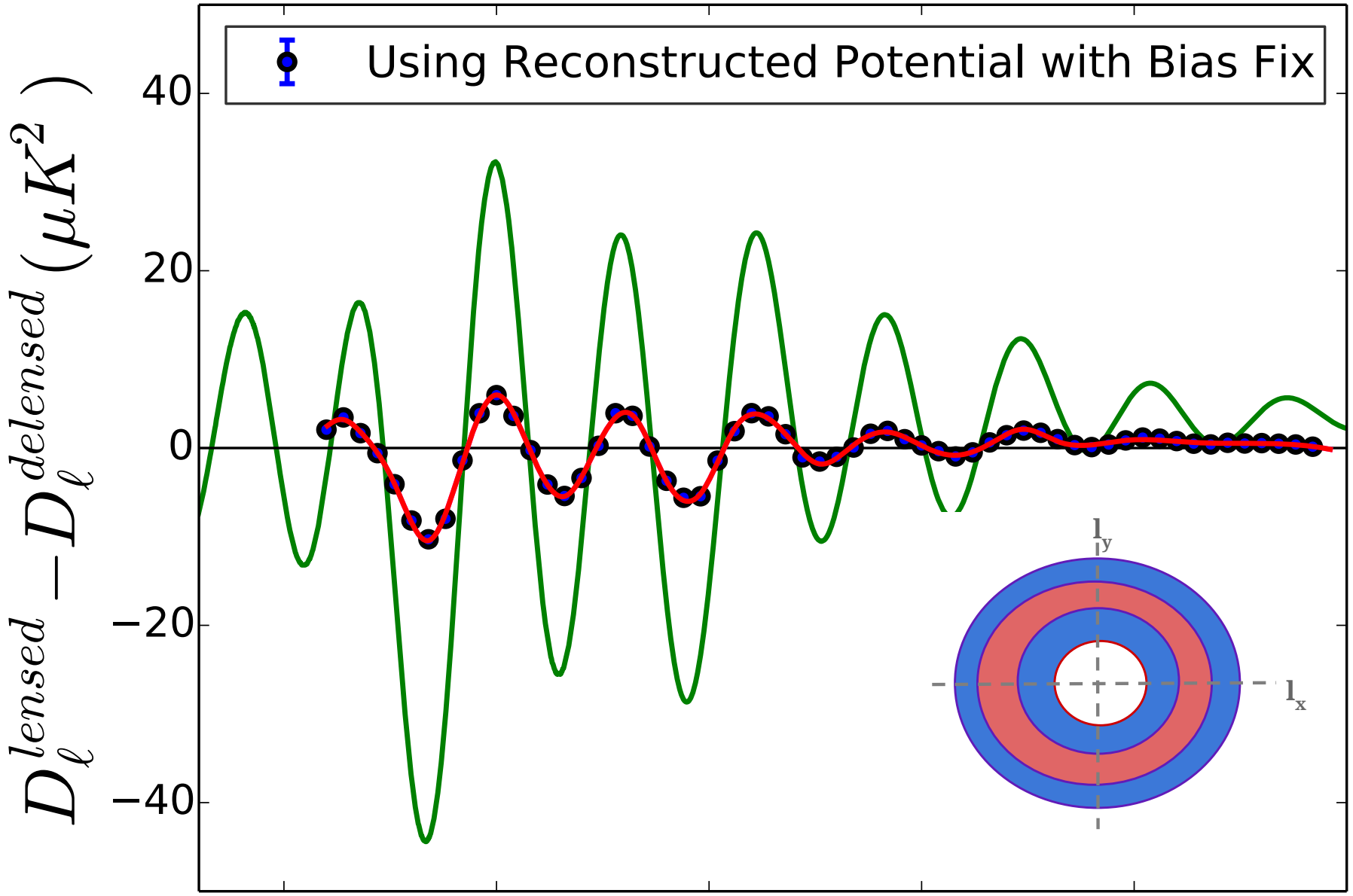
3. One mitigation method



Sehgal, Madhavacheril, Sherwin, AvE 2017

Targets

- κκ autospectrum
- Delensing

<κκ> ~ <EBEB> or <TTTT>

$B_{templ} \sim E \bigstar \kappa(EB)$

Bias if $\langle B_{low} B_{templ} \rangle \sim \langle EBEB \rangle \neq 0$

Targets

- κκ autospectrum
- Delensing

<κκ> ~ <EBEB> or <TTTT>

Non-Gaussianity of dust polarization on small scales?

$B_{templ} \sim E \bigstar \kappa(EB)$

$B_{del} = B_{obs} - B_{templ}$

Bias if $\langle B_{low} B_{templ} \rangle \sim \langle EBEB \rangle \neq 0$