Robust CMB Lensing

(for your high-resolution ground-based experiment)

Mathew Madhavacheril

(@ Princeton)

with Amanda Macinnis, Omar Darwish, DW Han, **Colin Hill, Sigurd Naess**, Neelima Sehgal, **Blake Sherwin, Kendrick Smith**, Alexander van Engelen

$$C_\ell^{gg}$$
$$C_\ell^{\kappa g}$$
$$C_\ell^{\kappa\kappa}$$

Joint probes

A channel for robust beyond LCDM exploration

g = shear and/or clustering

k = CMB lensing

$$C_\ell^{gg}$$
$$C_\ell^{\kappa g}$$
$$C_\ell^{\kappa\kappa}$$

g = shear

Multiplicative bias calibration

(e.g. Schaan et. al. 2016)

g = redmagic clustering

alternative S8 independent of source photo-zs

(e.g. DES Y1 results)

g = gold sample clustering

primordial non-Gaussianity from sample variance cancellation

(e.g. Schmittfull, Seljak 2017)

$$C_\ell^{gg}$$
$$C_\ell^{\kappa g}$$
$$C_\ell^{\kappa\kappa}$$

→

Currently limited by CMB foregrounds

(but can be mitigated both in the short and long term)

$$C_\ell^{gg}$$

$$C_\ell^{\kappa g}$$

$$C_\ell^{\kappa\kappa}$$

→

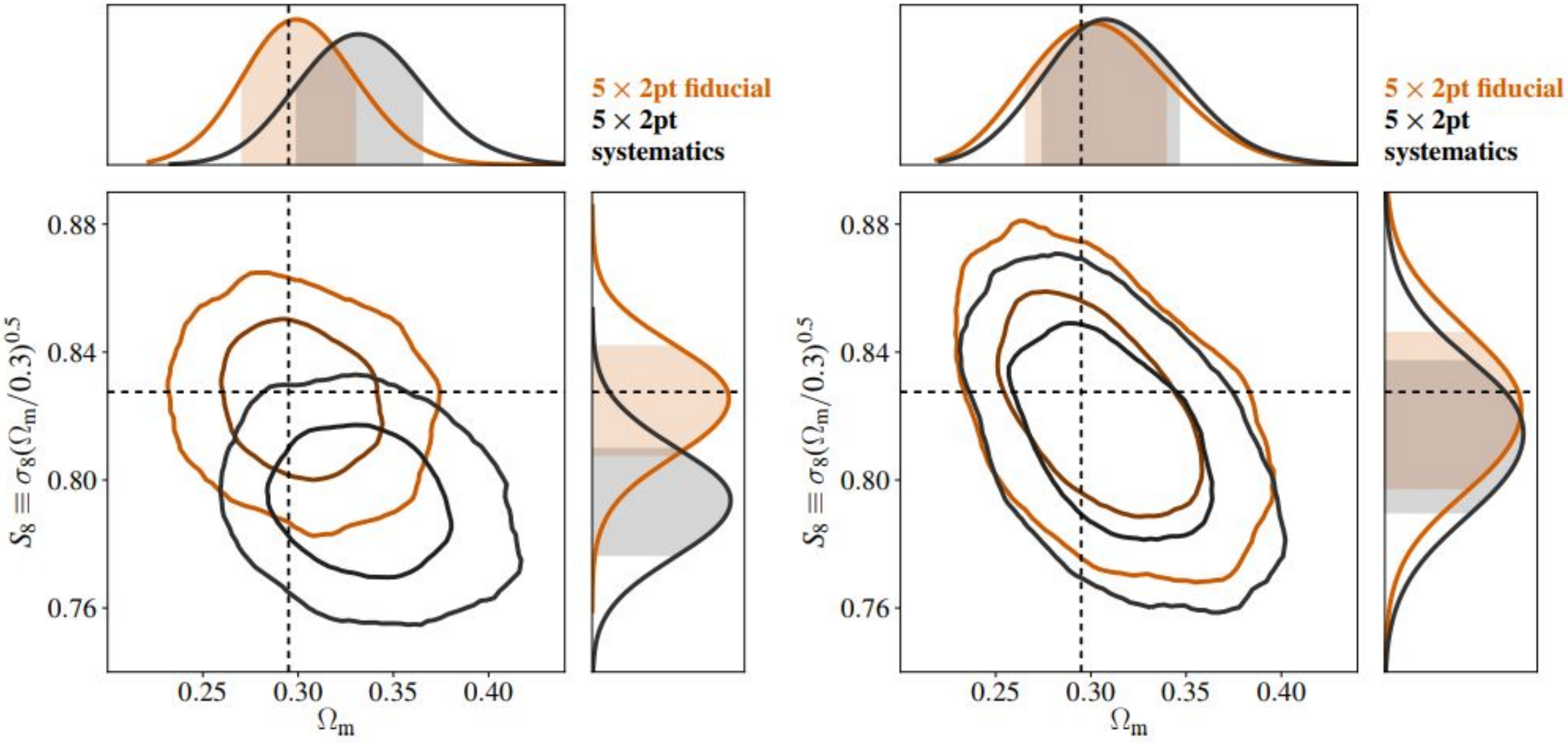
Large noise biases need to be subtracted

(instrument/atmospheric noise dependent -- can we simulate these?)

Foreground biases

(focus on tSZ for cross-corr)

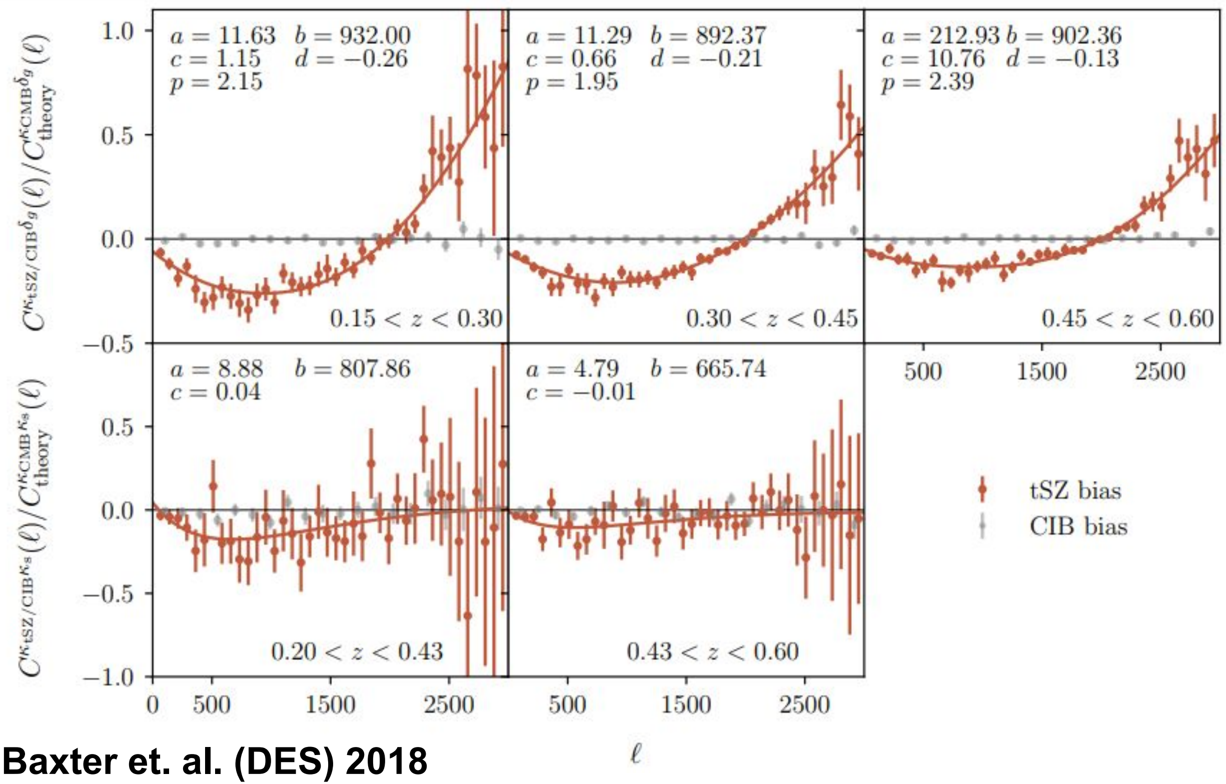
Baxter++ (SPT-DES) 2018



We are "systematics limited" **now**.

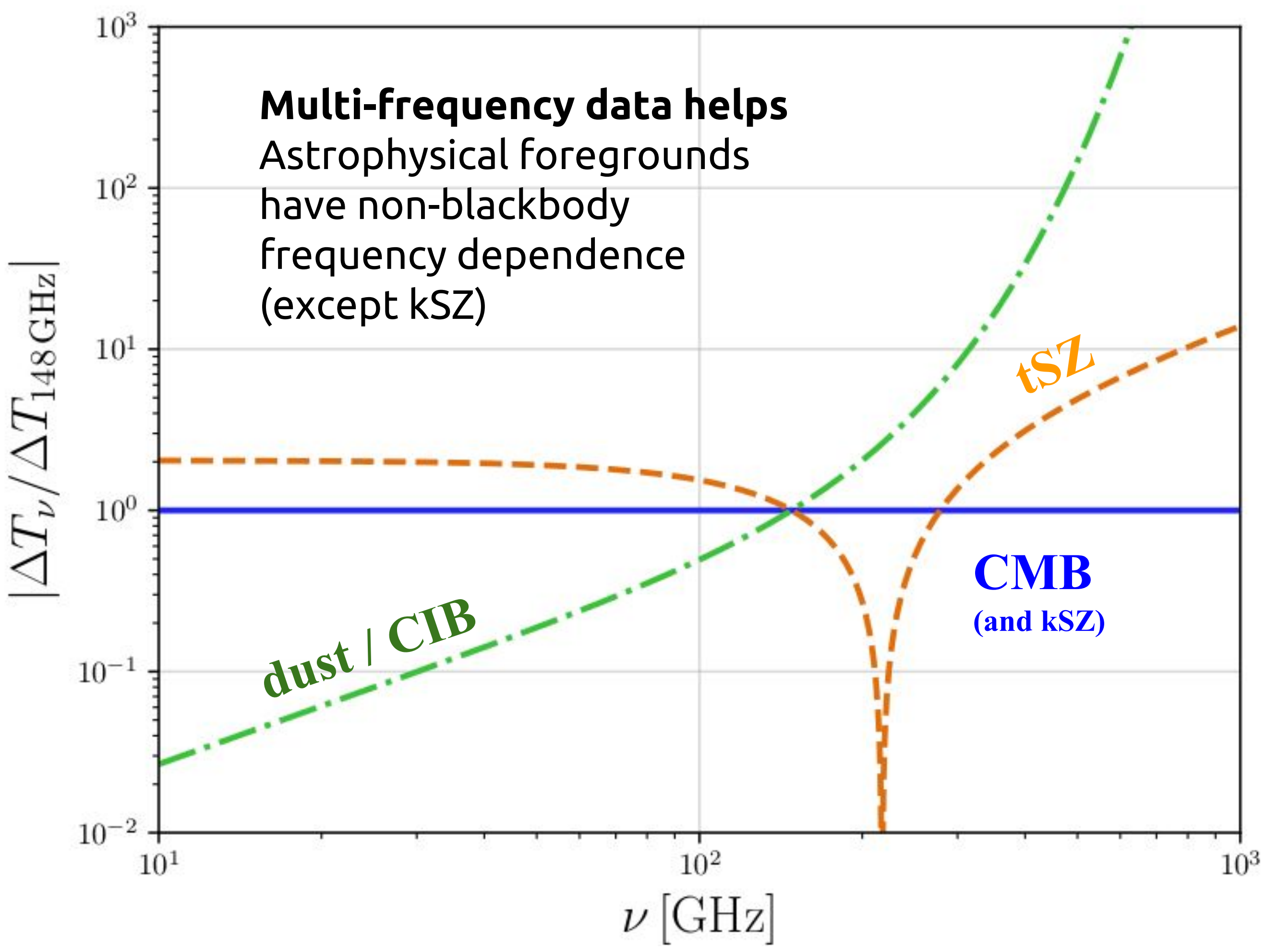
Factor of almost 2x reduction in constraints if not mitigated.

Foreground biases - now primarily from tSZ



Baxter et. al. (DES) 2018

~ 20% at large scales from tSZ


Multi-frequency data helps
Astrophysical foregrounds
have non-blackbody
frequency dependence
(except kSZ)
tSZ
CMB
(and kSZ)
dust / CIB
$|\Delta T_\nu / \Delta T_{148\,\mathrm{GHz}}|$
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{1}
10^{2}
10^{3}
ν [GHz]

Status of multi-frequency analysis

- Planck measured the sky at 9 frequencies from 30-857 GHz (relatively low res, high noise)

- ACT and SPT have been using single frequencies (150 GHz)
  - severely limits ability to avoid foreground biases in cross-correlations

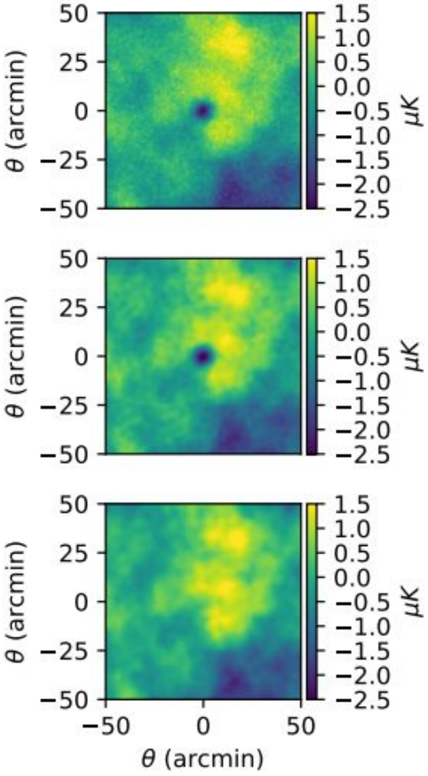
- High-resolution multi-frequency data from ground-based experiments only beginning to be utilized

MM, Hill, 2018

Planck 143 GHz

Planck SMICA

LGMCA



Single frequency

“Standard cleaning”

effectively inverse noise coadd of all frequencies where noise includes empirical foregrounds

“Constrained cleaning”

minimize noise under the constraint that tSZ-like frequency dependence is nulled

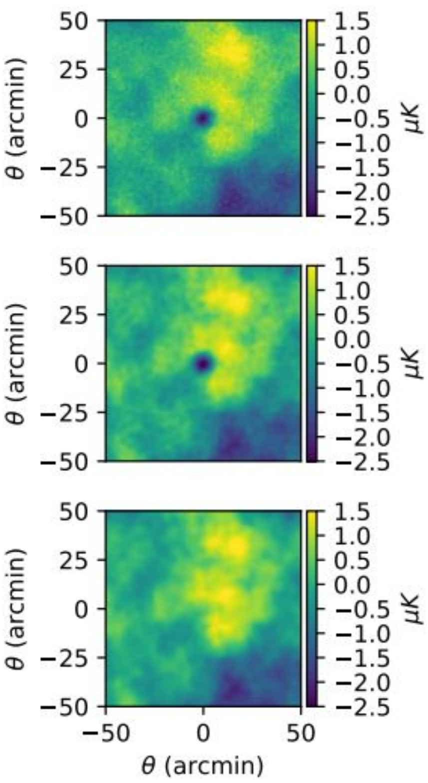
Note of caution on “multi-frequency foreground cleaning”

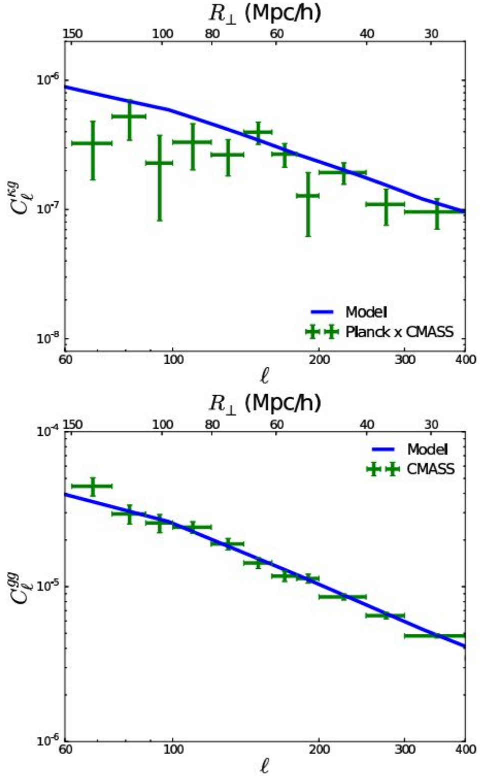
MM, Hill, 2018

Planck 143 GHz

Planck SMICA

LGMCA





Pullen++ 2015
CMASS lenses
Planck CMB source

Planck SMICA used in Planck lensing map

~2 sigma low cross-correlations with Planck lensing

Planck x CFHT, Liu 2015
Planck x DES, Giannantonio 2015
Planck x WISE, Hill et. al.

Can insufficient foreground cleaning explain cross-correlation tensions?

Problem: constrained cleaning blows up noise on small scales

Solution: “gradient cleaning”

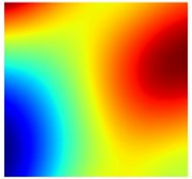
MM, Hill (PRD) 2018

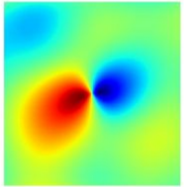
(Also see alternatives like CMB lensing shear in Emmanuel’s talk)

Gradient cleaning
Motivation: small-scale cluster lensing limit

Large-scale gradient Small-scale dipole

$$\hat{\kappa} \propto \vec{\nabla} \cdot \left[\left[\vec{\nabla} T \right]_{\rm low} \left[T(\vec{\theta}) \right]_{\rm high} \right]$$

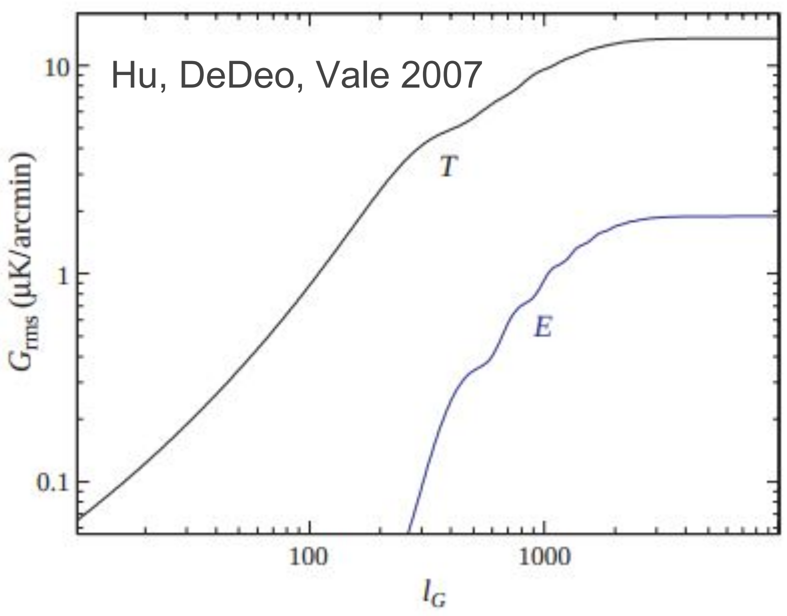




Hu, DeDeo, Vale 2007

Quadratic estimator picture in real space

CMB cluster lensing: eliminating tSZ bias



- Gradient needs to be measured well only up to L=2000
- Planck component separated temperature maps good enough for gradient map!

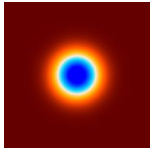
$$\kappa \approx \nabla.[T_L \nabla T_L] + \cancel{\nabla.[F \nabla T_L]}$$

- Doesn’t work for kSZ but additional low-pass filtering can help

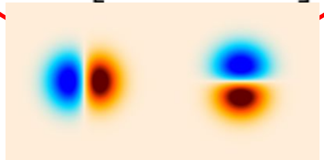
CMB cluster lensing: eliminating tSZ bias

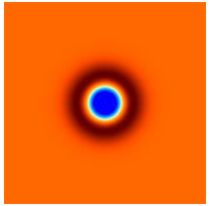
$$\kappa \approx \nabla . [T \nabla T]$$

$$T = T_L + F$$



$$\kappa \approx \nabla . [T_L \nabla T_L] + \nabla . [F \nabla F] + \nabla . [T_L \nabla F] + \nabla . [F \nabla T_L]$$





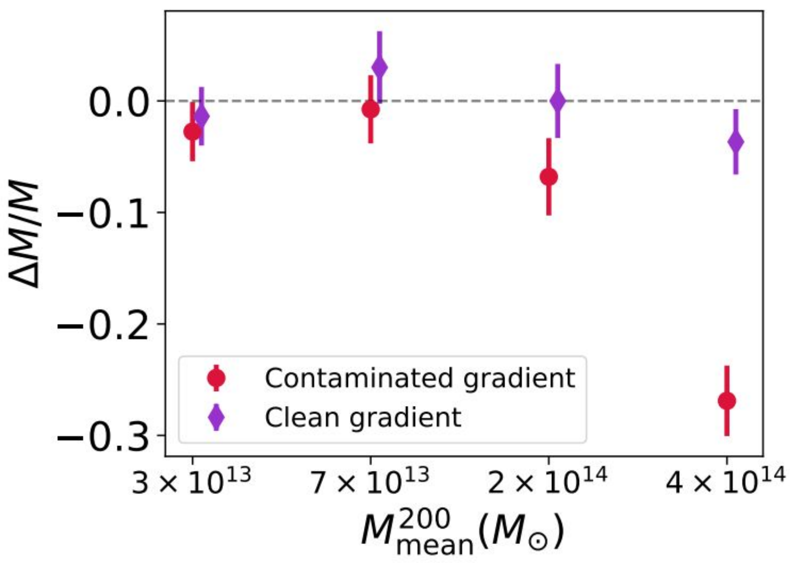
Bias originates from misestimated CMB gradient

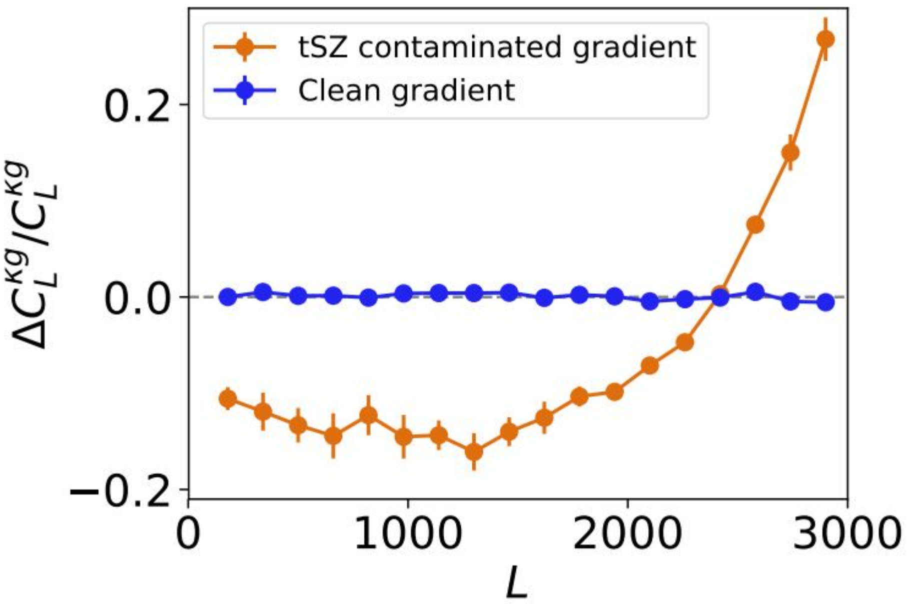
MM, Hill, 2018

Gradient cleaning strategy

- Use multi-frequency data (could be just Planck) with **constrained** cleaning to get gradient -- your gradient is effectively lower resolution now (expect some loss of S/N for large-scale lenses)
- Use single frequency or multi-frequency **standard cleaning** to get non-gradient
- Eliminates tSZ, CIB, Galactic foreground bias (but not kSZ)

MM, Hill, 2018





End-to-end simulations for tSZ demonstrate **gradient cleaning**
<5% loss in S/N when cleaning only gradient with **Planck** multi-frequency data but **<<1% bias** compared to 20% bias

Future / ongoing work

Near-term large-scale and cluster lensing

- Preparing gradient cleaned lensing maps for ACT x DES cross-correlation analyses
- End-to-end simulations of deprojection + gradient cleaning with tSZ, CIB, kSZ, dust and synchrotron for temperature + polarization
- Test gradient cleaning on anisotropic galactic foregrounds (might do better than shear?) and for delensing
- Effective kSZ bias when using gradient cleaning + polarization estimators?
- Shear estimators -- effect of maximum multipole (non-gaussianity biases)

Noise biases

$$C_\ell^{gg}$$

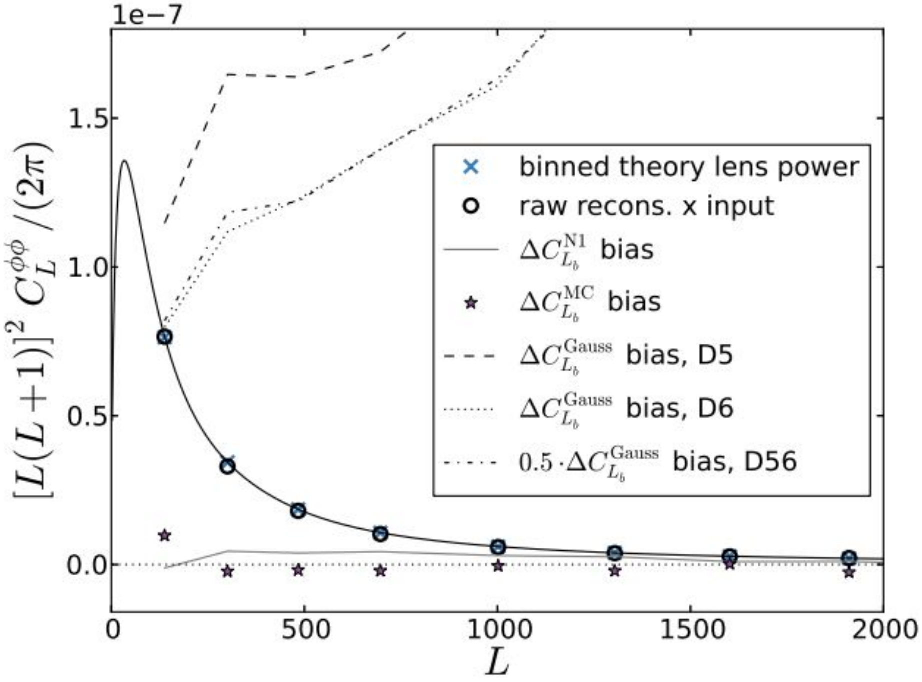
$$C_\ell^{\kappa g}$$

$$C_\ell^{\kappa\kappa}$$

→ Large noise biases need to be subtracted

(instrument/atmospheric noise dependent)

$$\langle TTTT \rangle \sim \langle \phi\phi \rangle \sim C_L^{\phi\phi}$$



Sherwin, van Engelen, Sehgal, MM ++ 2016

Large noise biases appear from chance CMB correlations and instrument noise correlated between each of 4 legs

Instrument noise part is subtracted off using simulations (but in a realization dependent way -- which adds robustness)

However...

Problem: we don't want to depend on hard-to-simulate noise simulations to subtract biases

Solution: split lensing

MM, Smith, Naess, Sherwin in prep

Split-based lensing power

MM, Smith, Naess, Sherwin in prep

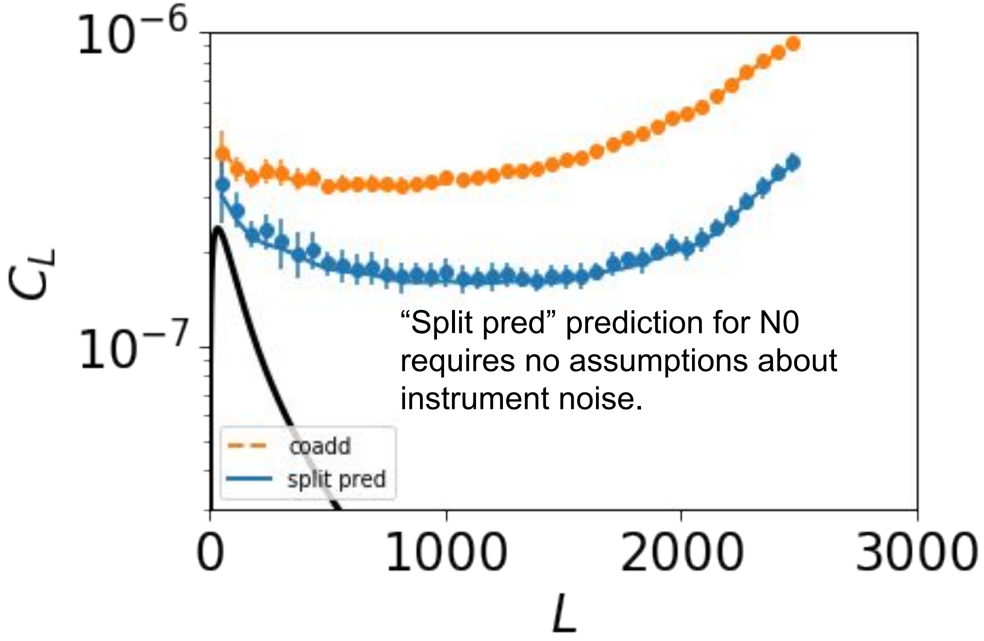
CMB mapmakers provide n (n=4 typically) split maps that have independent instrument noise.

Build “cross-only” estimator that does not repeat splits.

Naively, for noise split T_i

$$\hat{C}_{\phi\phi}^{\rm raw} \sim \sum_{i \neq j \neq k \neq l} \langle T_i T_j T_k T_l \rangle$$

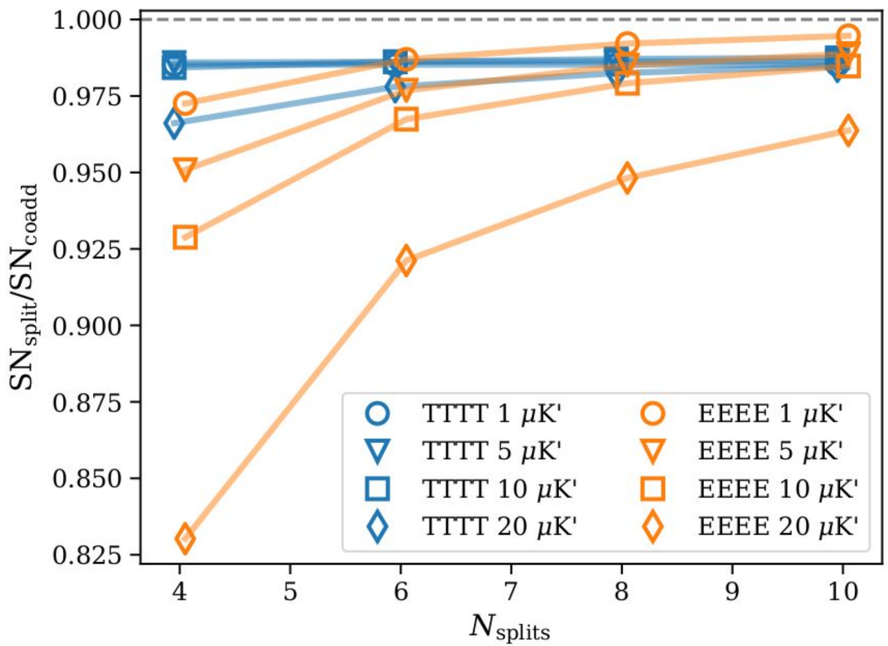
requires $O(n^4)$ evaluations, but we write down and use an estimator with $O(n^2)$ complexity.



“Split pred” prediction for N0 requires no assumptions about instrument noise.

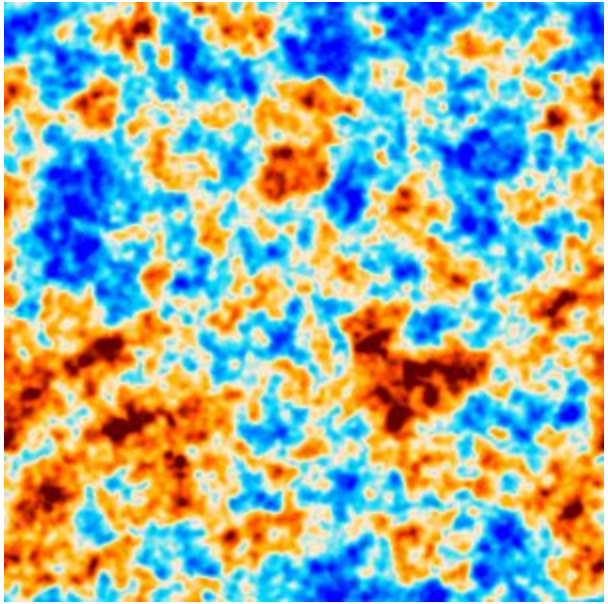
Split-based lensing power

MM, Smith, Naess, Sherwin in prep



Practically no hit in S/N because CMB maps are signal dominated over large ranges of ell

Conclusions



- CMB foregrounds currently limit cross-correlations
- Robust multi-frequency mitigation typically increases noise
- But “Gradient cleaning” approach allows zero bias, no hit in S/N

- CMB lensing autospectrum noise biases require difficult simulations of noise
- Split-based lensing approach circumvents this with no hit in S/N

Bonus material

Diagonal $\langle TT \rangle \sim C_\ell^{TT}$ — 2-point function

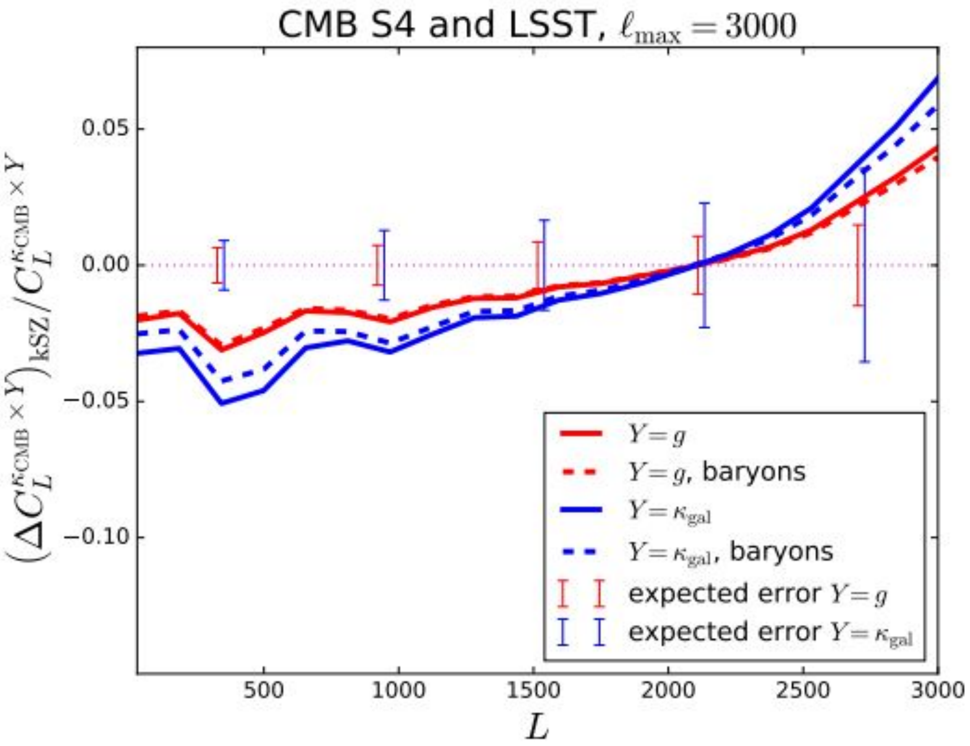
Off-diagonal $\langle TT \rangle \sim \phi$ — Lens reconstruction

$\langle TTTT \rangle \sim \langle \phi\phi \rangle \sim C_L^{\phi\phi}$ — 4-pt function

$\langle TT\delta_g \rangle \sim \langle \phi\delta_g \rangle \sim C_L^{\phi\delta_g}$ — Cross-correlation

Foreground biases **<ksz ksz g>**

- kSZ bias in temperature regardless of multi-frequency
- Some model uncertainty but >3% biases (for S4)



Simone Ferraro, Colin Hill 2017