UNIVERSITY OF CAMBRIDGE

HARVARD UNIVERSITY

New Approaches to Small-Scale **Lensing** of the **Cosmic Microwave Background** (CMB)

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CMB-S4 meeting

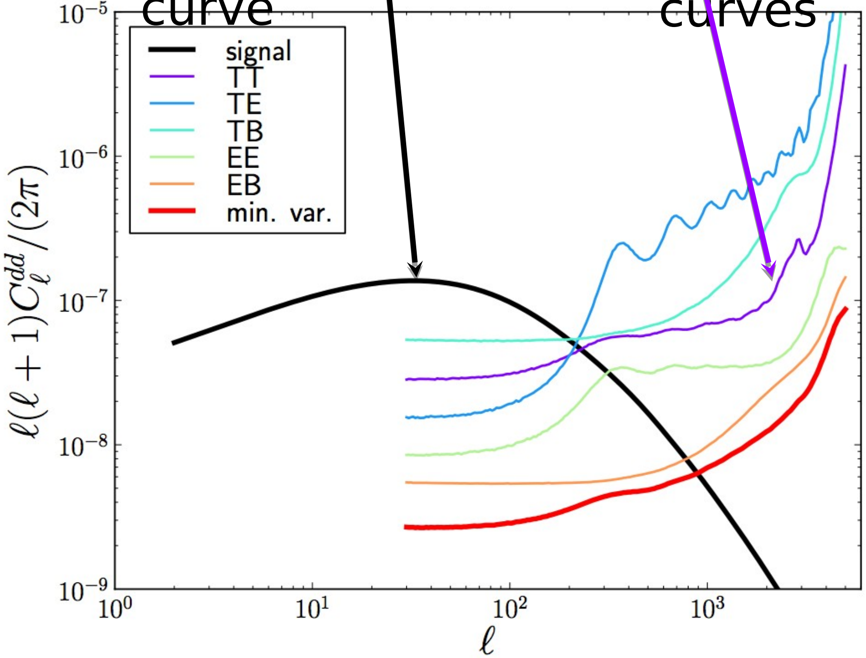
Outline

1. **Motivation**
2. Lensing reconstruction methods
   a. Quadratic estimator (QE)
   b. Gradient-inversion (GI)
3. Caveats and next steps
4. Summary

Small-scale puzzle

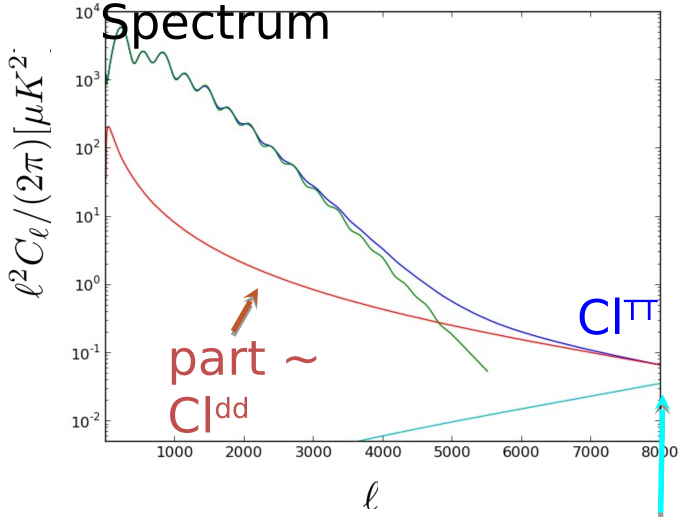
Lens signal curve

Noise curves



CMB Temperature Power Spectrum

)17)



~S4 error

- A puzzle: quadratic estimator noise gets large – seemingly cannot probe tiny CMB lenses / scales
- But with low enough noise, can read off tiny lenses from small-scale power spectrum.

Why go to small scales?

- Dark matter models (axions, warm dark matter, fuzzy dark matter)
- Cross-correlations with galaxy surveys (DESI, eBOSS, *Euclid*)
- Modeling of the one-halo term (assembly bias, baryonic physics, galaxy formation)

Will have measurements from ultra-deep survey LAT that we need to take full advantage of!

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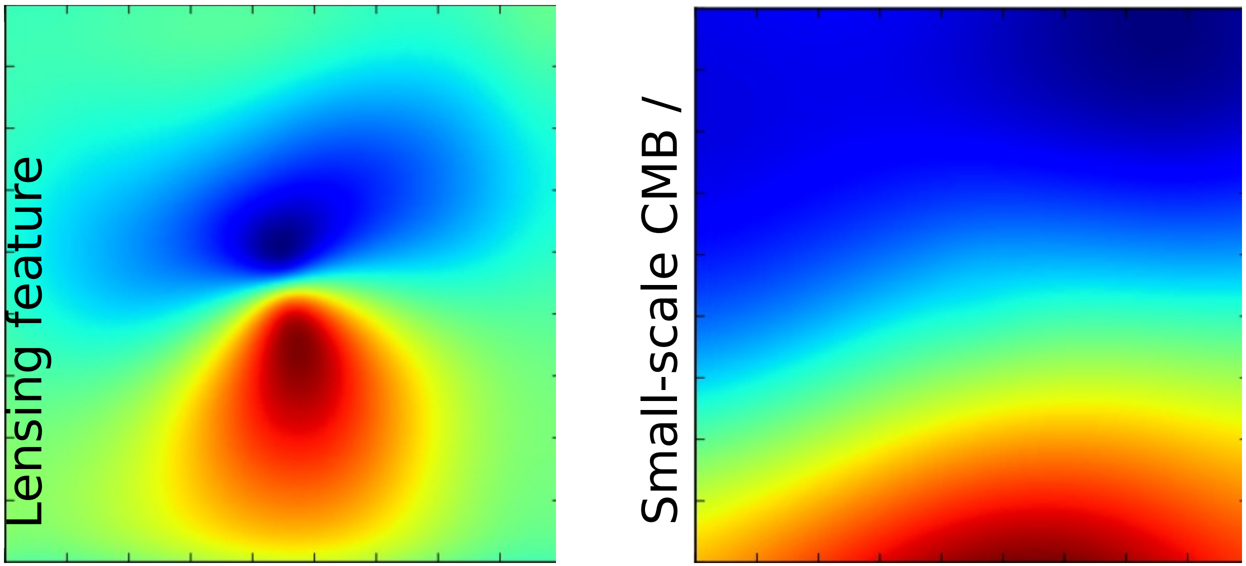
Gradient Inversion Lensing Estimation

Small-scale CMB only: Lensing feature



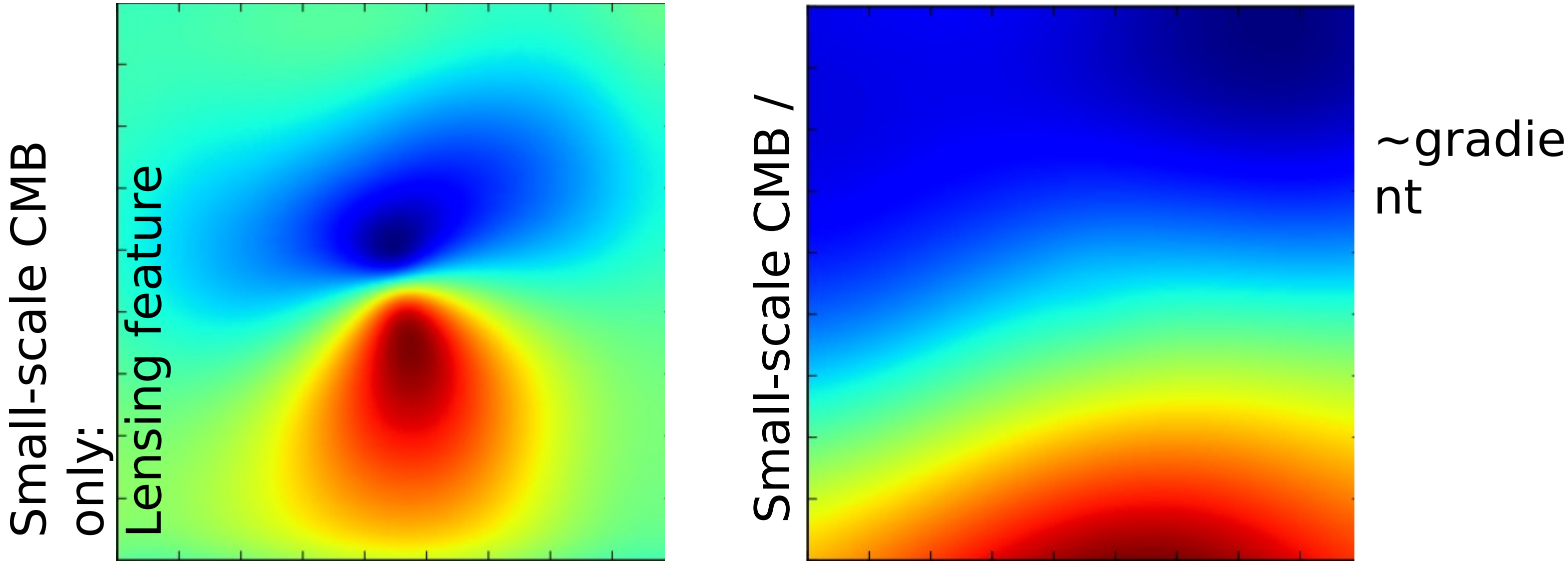
Small-scale CMB / ~gradient

- On small scales, CMB gradient ∇T is effectively constant. Lensing expansion:

$$T(\mathbf{x}) = T^u(\mathbf{x}+\mathbf{d}) \approx \cancel{T^u(\mathbf{x})} + \mathbf{d}(\mathbf{x}) \cdot \nabla T^u + \cdots$$

~~Noise Foregrounds~~

Gradient Inversion Lensing Estimation



- Suggests simple “gradient inversion” estimator:

$$\hat{d}^{GI}(\mathbf{L}) = \frac{T(\mathbf{L})}{\hat{\mathbf{n}}_{\mathbf{L}} \cdot \nabla T^u}$$

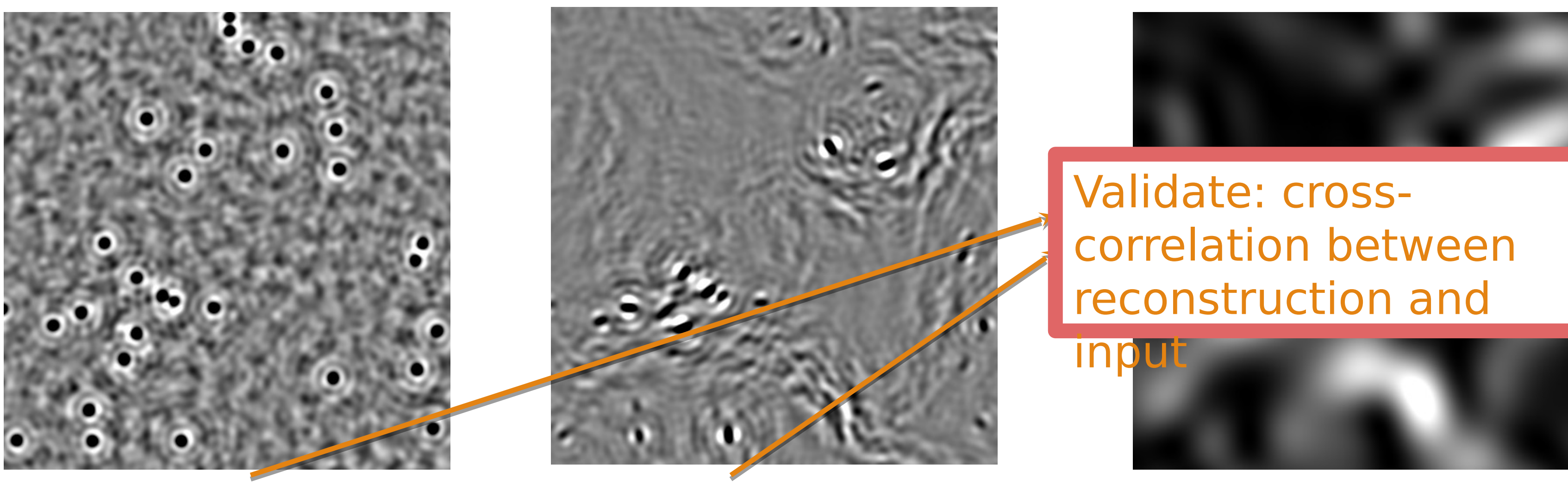
Not limited by cosmic variance;
SNR ~ local gradient

- Quadratic estimator: divides out <grad²> – extra error!

$$\hat{d}^{QE}(\mathbf{L}) = \hat{d}^{GI}(\mathbf{L}) \frac{(\hat{\mathbf{n}}_{\mathbf{L}} \cdot \nabla T^u)^2}{\langle (\hat{\mathbf{n}}_{\mathbf{L}} \cdot \nabla T^u)^2 \rangle}$$

Simulation: GI Lensing Maps and Spectra

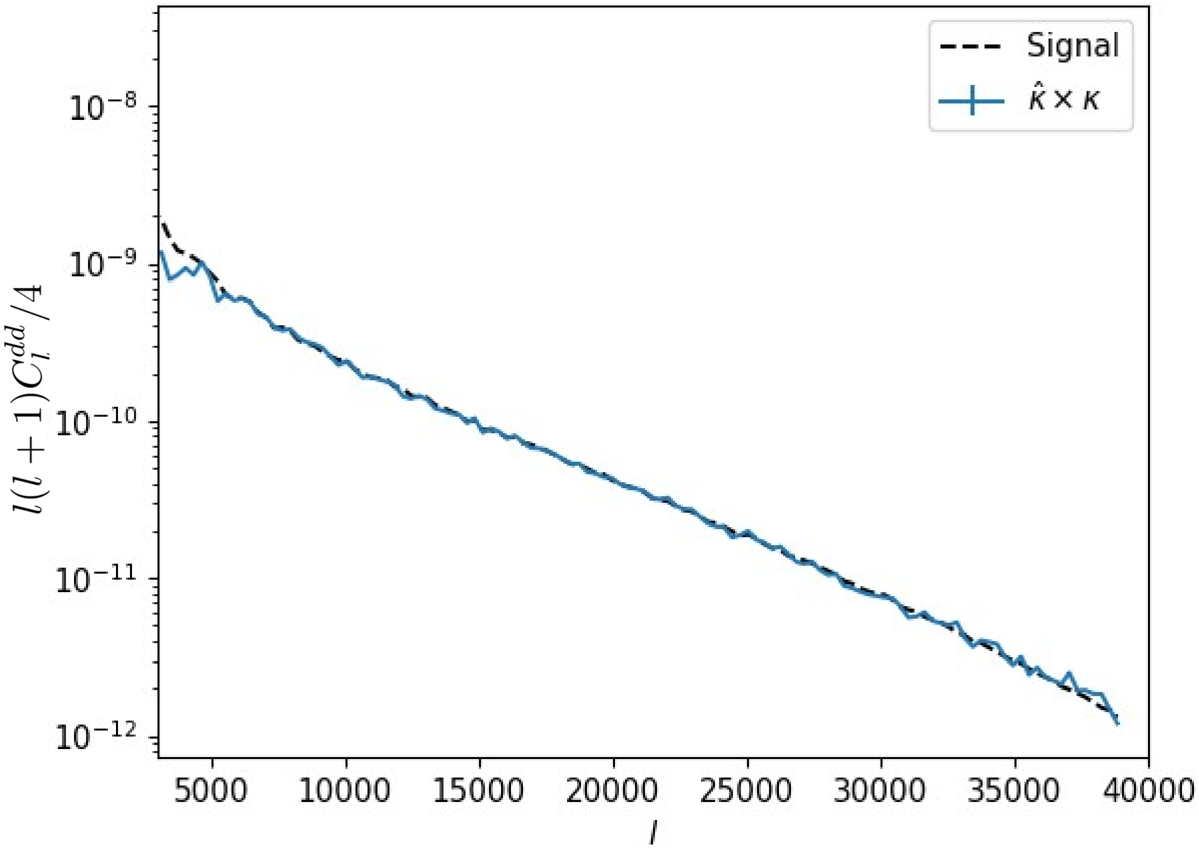
Expected noise is gradient-magnitude-dependent



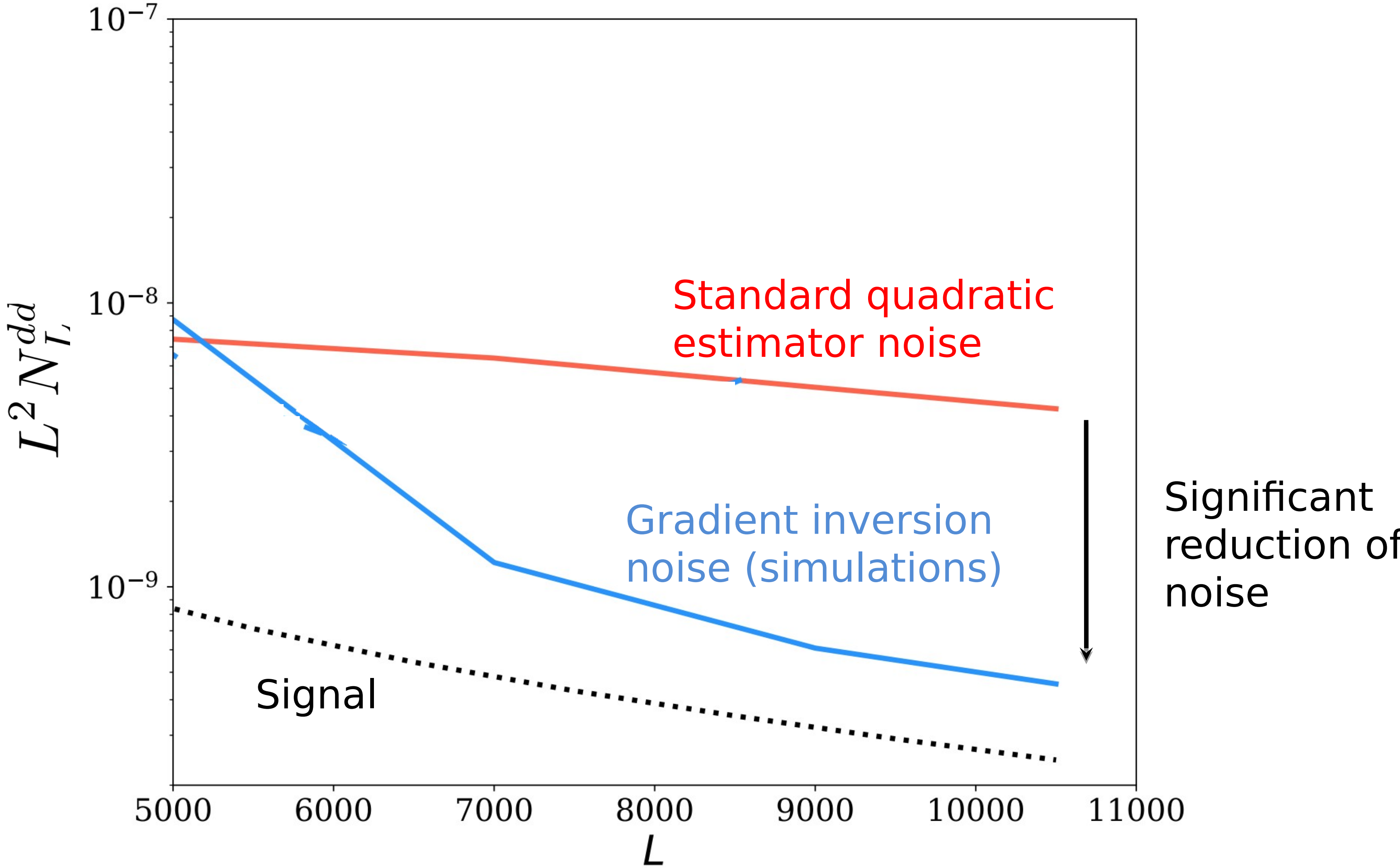
Reconstruction on ultra-small scales (L>5000) for S4: GI does well in large gradient regions

[Hadzhiyska et al. 2019]

Successful Validation: reconstruction x input correlation

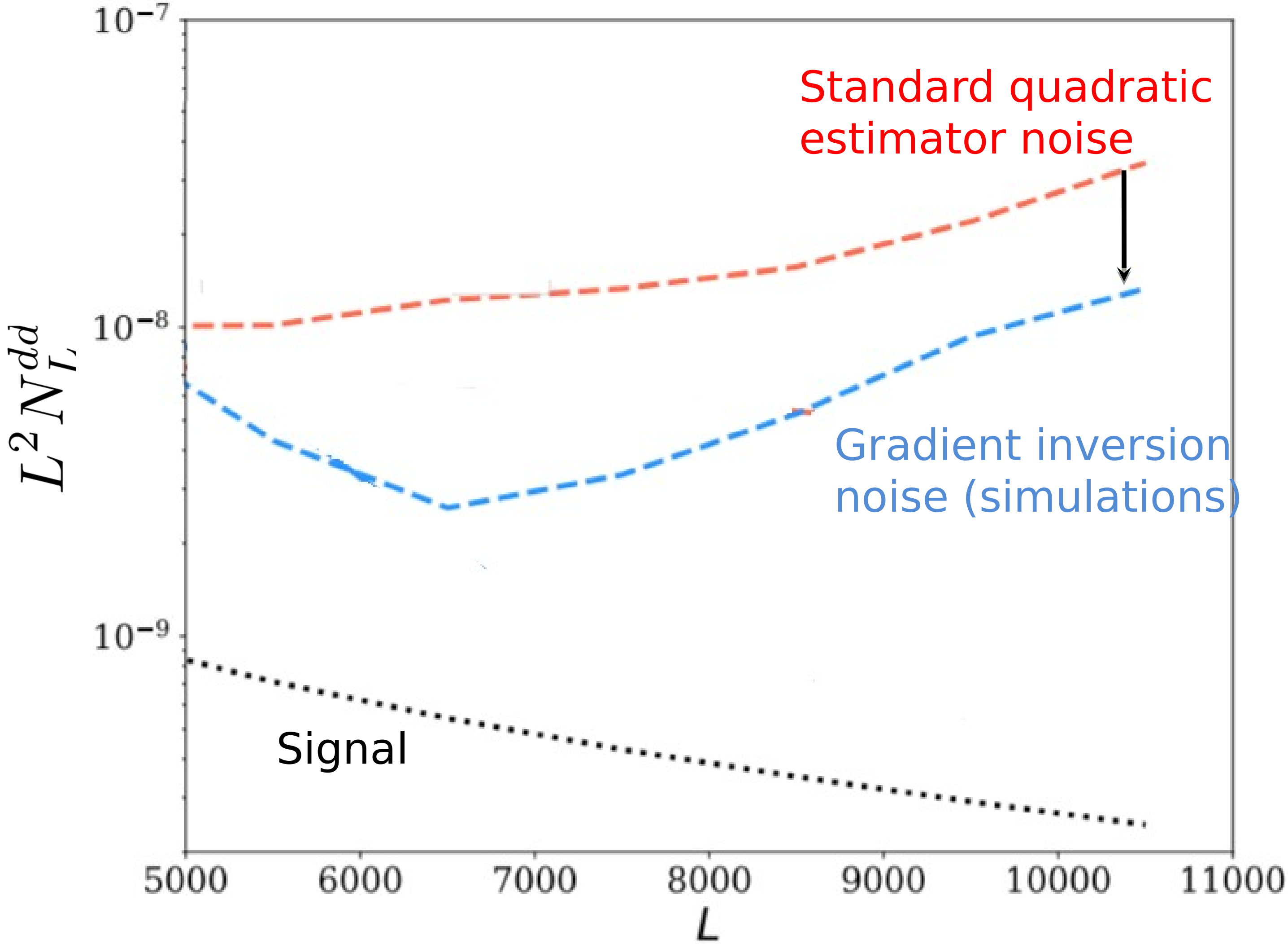


Significant Improvements Possible?
Ultra-low noise errors (0.1 uK')



- Error on the measurements smaller for GI compared with QE

Significant Improvements Possible?
CMB-S4 wide noise errors (1 uK')



- Error on the measurements even smaller for GI compared with QE

Significant Improvements Possible?
Signal-to-noise ratio

- Estimate the signal-to-noise ratio for the auto- and cross-correlation of the convergence field:

$$\mathrm{SNR}^2 = \sum_{ij} C_L^{i\ \kappa\kappa} \widehat{\mathrm{Cov}}_{ij}^{-1} C_L^{j\ \kappa\kappa}$$

- Significant improvement compared to QE (on L>4000):

C_L^{dd} → Auto QE

SNR	UL	S4-like	SO-like
Auto QE	205	100	7
Auto GI	1515	360	30

Factor of 4 improvement!

Caveats and next steps

- Suggest that a better estimator exists on small scales!
    a. reachable with CMB-S4 LAT survey
- Foreground noise (CIB, tSZ, kSZ)
    a. proposed ideas for how to clean
    b. polarization does not suffer from that
- Optimal method: maximum likelihood estimator can bridge the gap on intermediate and small scales (in progress)

Multi-frequency approaches to cleaning are available!

Has a blackbody frequency dependence, but is not correlated with the CMB gradient.

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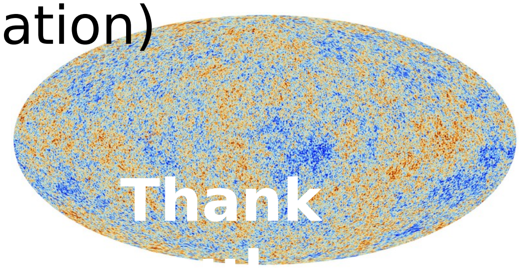
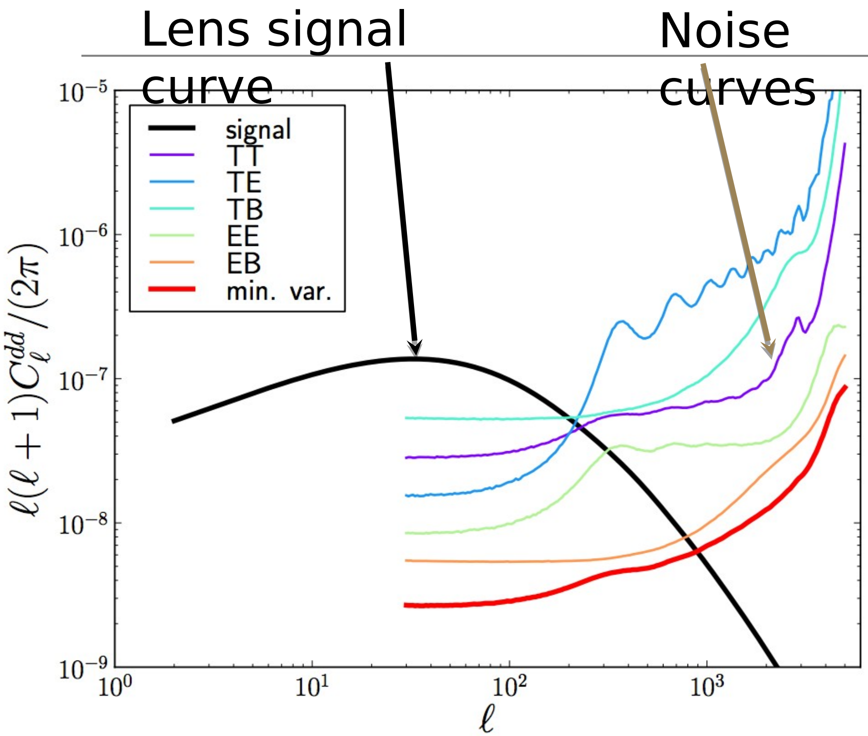
Summary
arXiv:1905.04217

1. There is lots of unexplored lensing potential on small scales
2. Advantages of small-scale lensing:
    a. axion physics, warm dark matter (WDM)
    b. cross-correlations with galaxies, polarization
    c. assembly bias (one-halo term)
3. Proposed a new estimator for very small scales
4. There are some caveats that can be overcome (foreground cleaning, polarization)



Backup Slides

Small-scale puzzle



Noise for CMB-S4 (Schaan et al. 2017)

- A puzzle: quadratic estimator noise gets large – seemingly cannot probe tiny CMB lenses / scales

Lensing Measurement with the Quadratic Estimator

Lensing changes known homogeneous statistics: introduces new correlations

$$\langle T(\mathbf{l})T^*(\mathbf{l}-\mathbf{L})\rangle \sim d(\mathbf{L})$$

T: temperature (Fourier mode)
l: wavenumber

So: measure lensing by looking for these correlations with a Quadratic Estimator in the CMB fields:

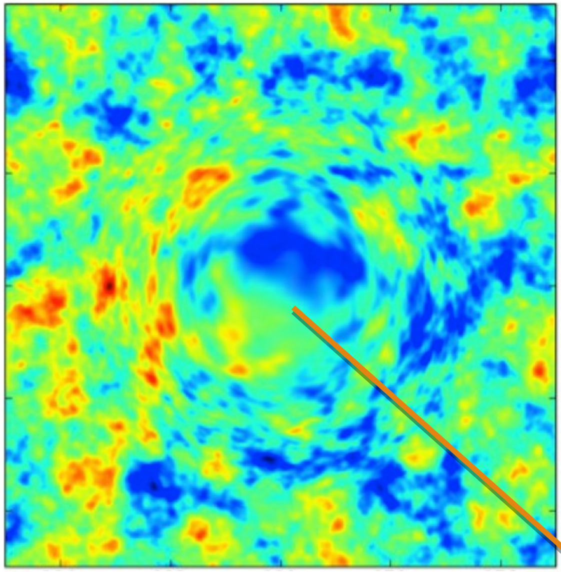
$$\hat{d}(\mathbf{L}) \sim \int d^2\mathbf{l}\; T(\mathbf{l})T^*(\mathbf{l}-\mathbf{L})$$

$$\sim \mathrm{FT}[T\nabla T]$$

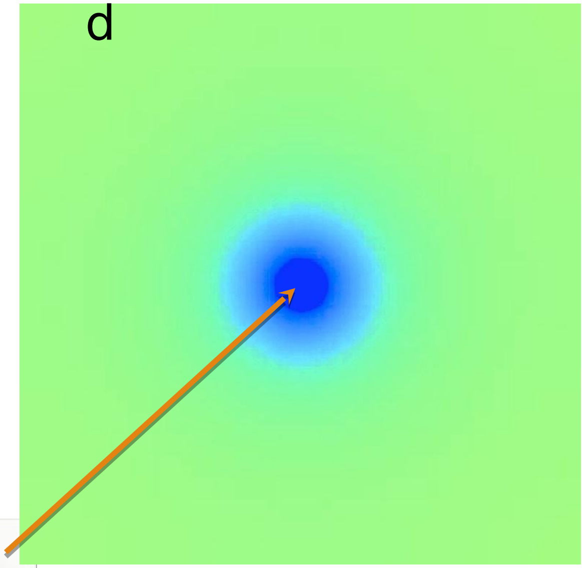
[Zaldarriaga, Seljak 1997, Hu, Okamoto 2002]

CMB Lensing Measurement: An Approximate Picture

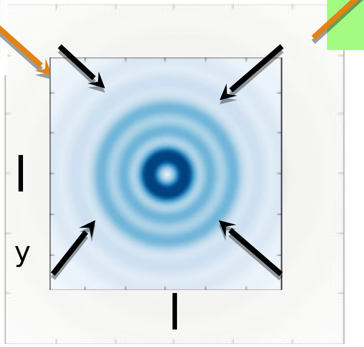
CMB temperature



Lensing deflection
d



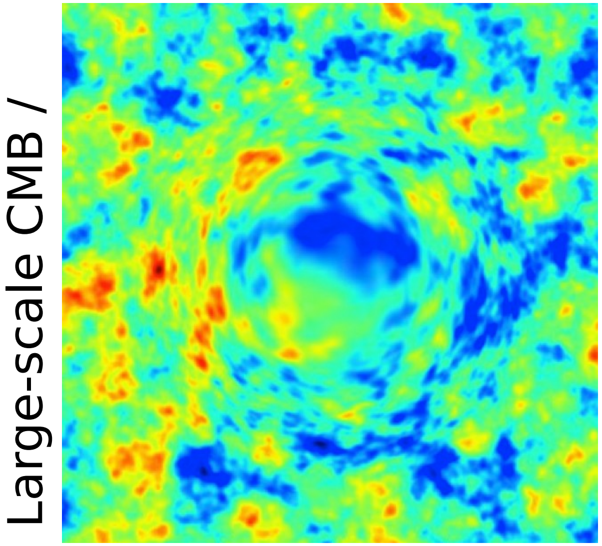
local 2D power spectrum

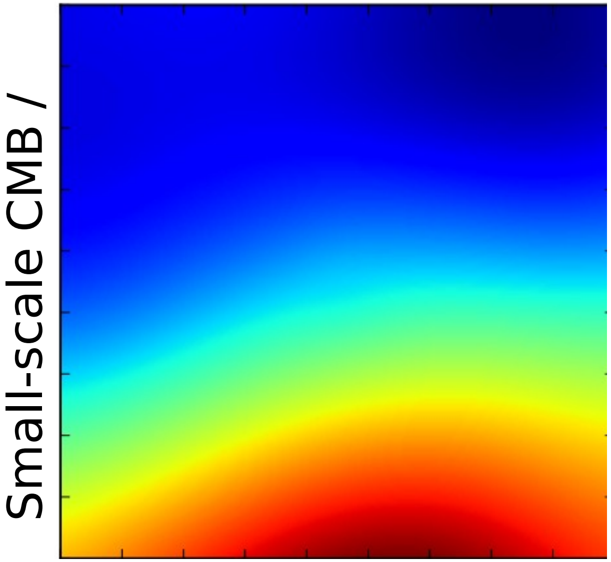


Infer lensing from "stretching" of the local CMB power spectrum
(+ shearing)

[Bucher et al. 2012]

The Simplicity of Small-scale CMB





~gradient

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Noise
Foregrounds

Gradient Inversion Lensing Estimation

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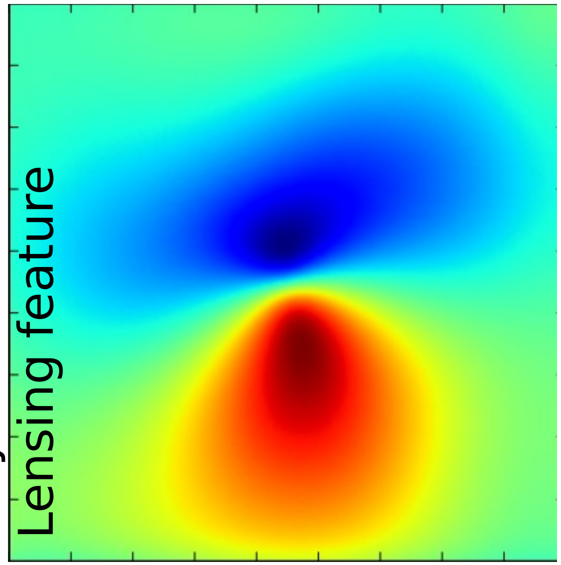

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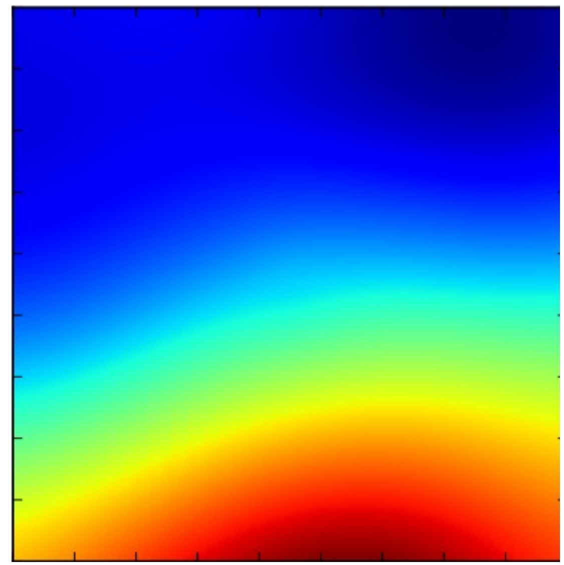


- Fourier transform with constant gradient:

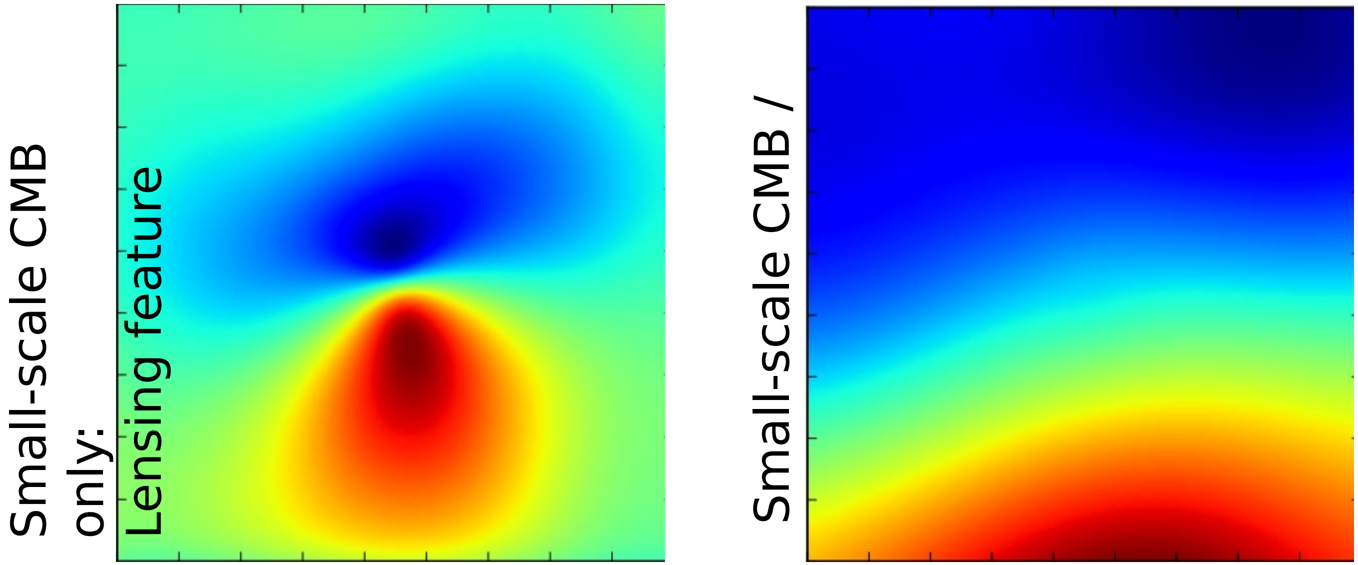
$$T(\mathbf{L}) = d(\mathbf{L}) \times |\nabla T^u|_{\hat{\mathbf{n}}_\mathbf{L}}$$

- Suggests simple “gradient inversion” estimator:

$$\hat{d}(\mathbf{L}) = \frac{T(\mathbf{L})}{|\nabla T^u|_{\hat{\mathbf{n}}_\mathbf{L}}}$$

[Horowitz et al. 2017, Zaldarriaga, Seljak 1997]

Gradient Inversion Lensing Estimation



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← Not limited by cosmic variance;
SNR ~ local gradient

GI Extension to Large Maps and Spectra

- Expected noise is direction and position dependent

$$N^{dd}(\mathbf{L}, \mathbf{x}) \sim \frac{N_L^{TT}}{|\nabla T^u(\mathbf{x})|^2_{\hat{\mathbf{n}}_\mathbf{L}}}$$

- Create inverse noise weight W = N^{-1} , allow gradient to slowly vary in final, continuous estimator:

$$d(\mathbf{L}) \sim FT\left[\frac{T(\mathbf{x})}{|\nabla T^u(\mathbf{x})|_{\hat{\mathbf{n}}_\mathbf{L}}} W(\mathbf{L}, \mathbf{x})\right]$$

[Hadzhiyska et al. 2019]