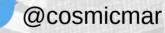
A 2020s Vision of CMB Lensing

Marius Millea

BERKELEY CENTER for COSMOLOGICAL PHYSICS

C @marius311

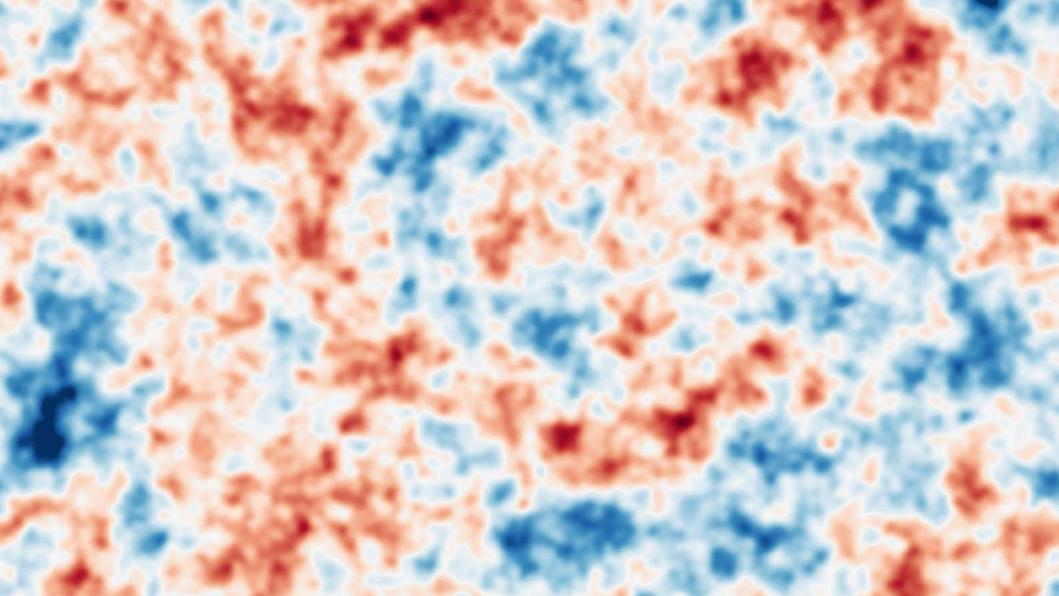


With: SPT Collaboration, Ethan Anderes, Ben Wandelt, Uros Seljak

Cosmology from Home 2020

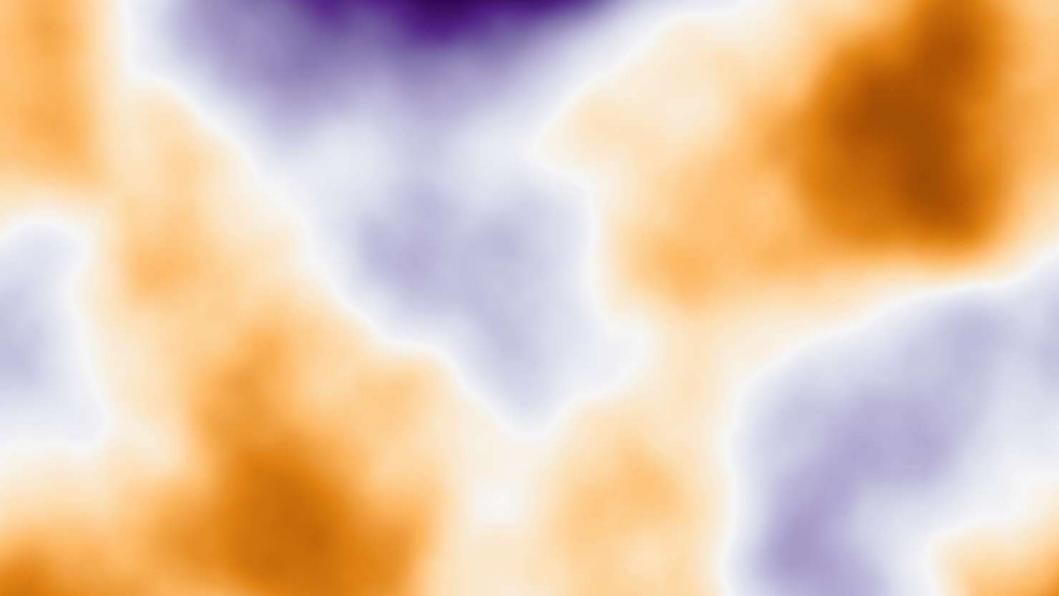
Main points

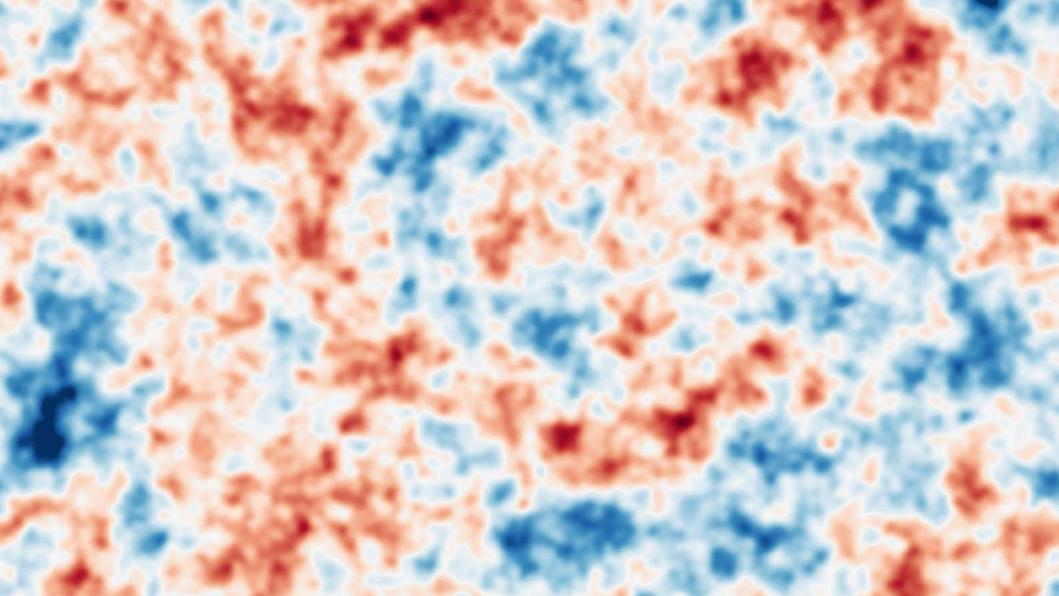
- CMB lensing now plays a role in nearly all aspects of CMB observations
- Techniques to analyze lensing are at a (necessary) watershed moment, requiring more sophistication
- I want to teach you how these work so you can do it yourself or you can understand the CMB data products that you may be interacting with in the future

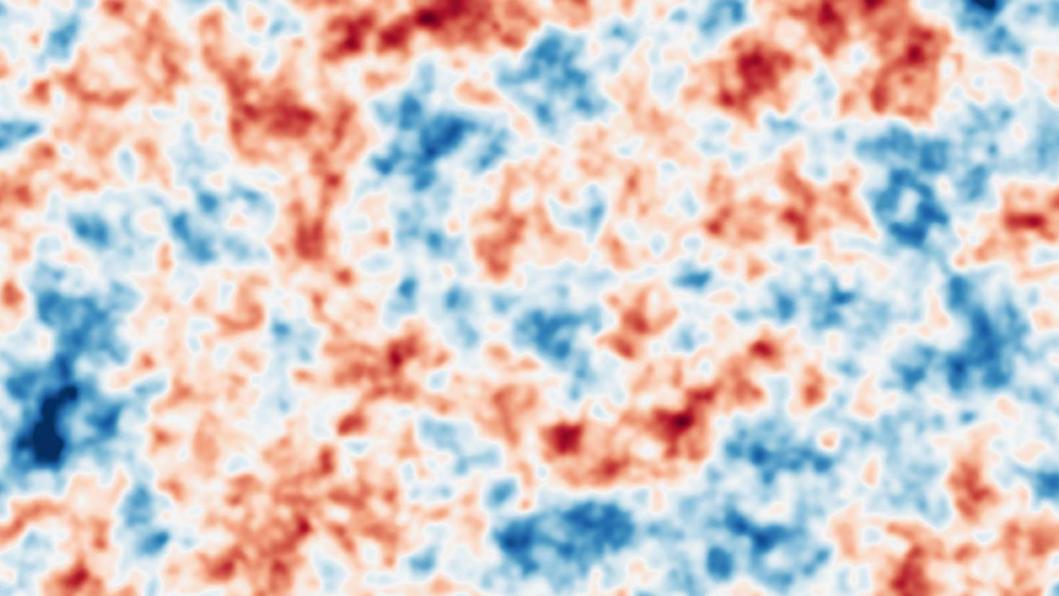


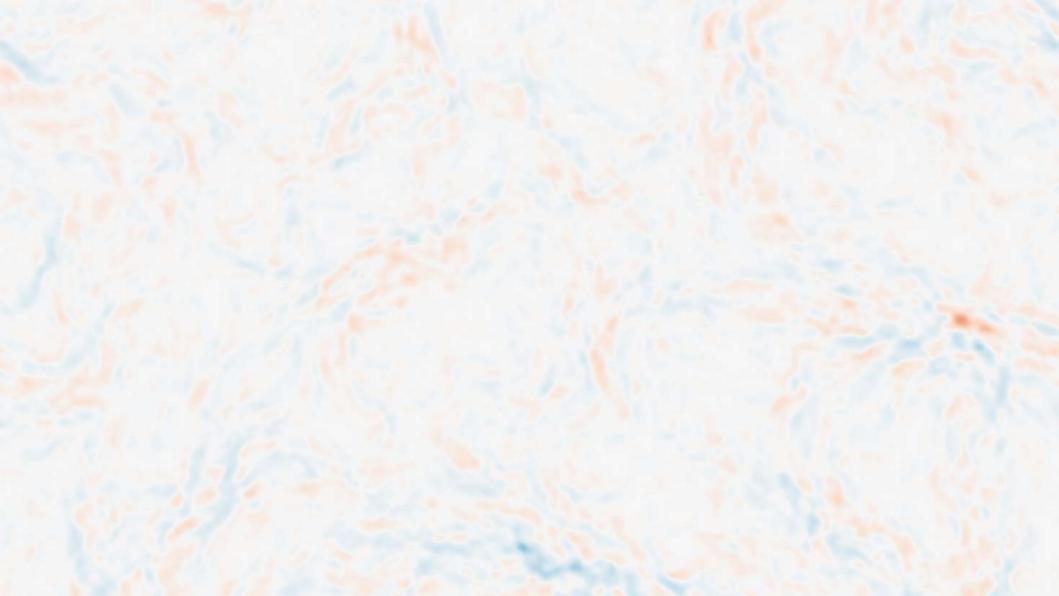
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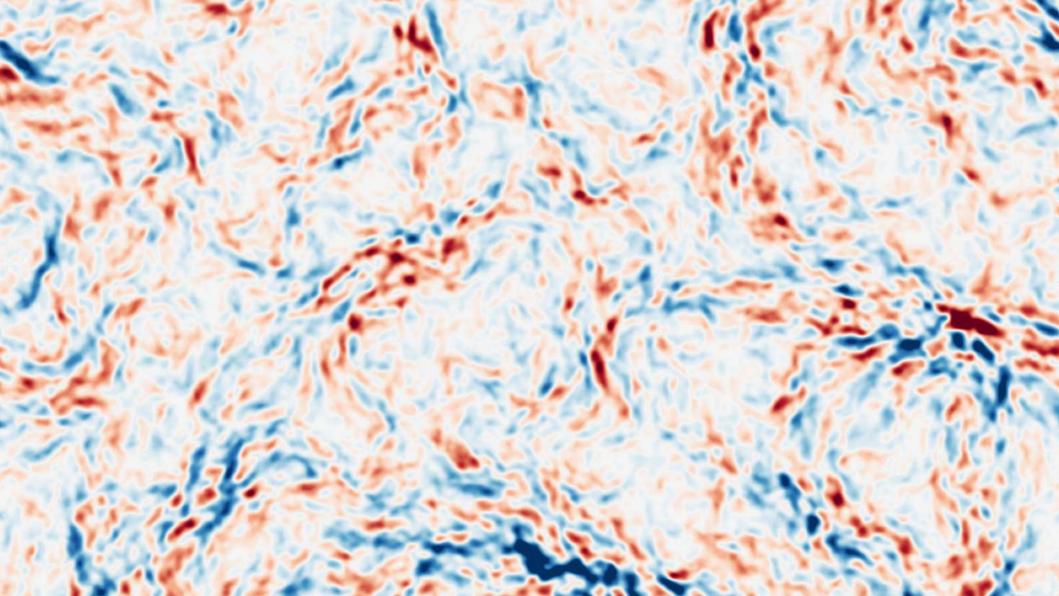
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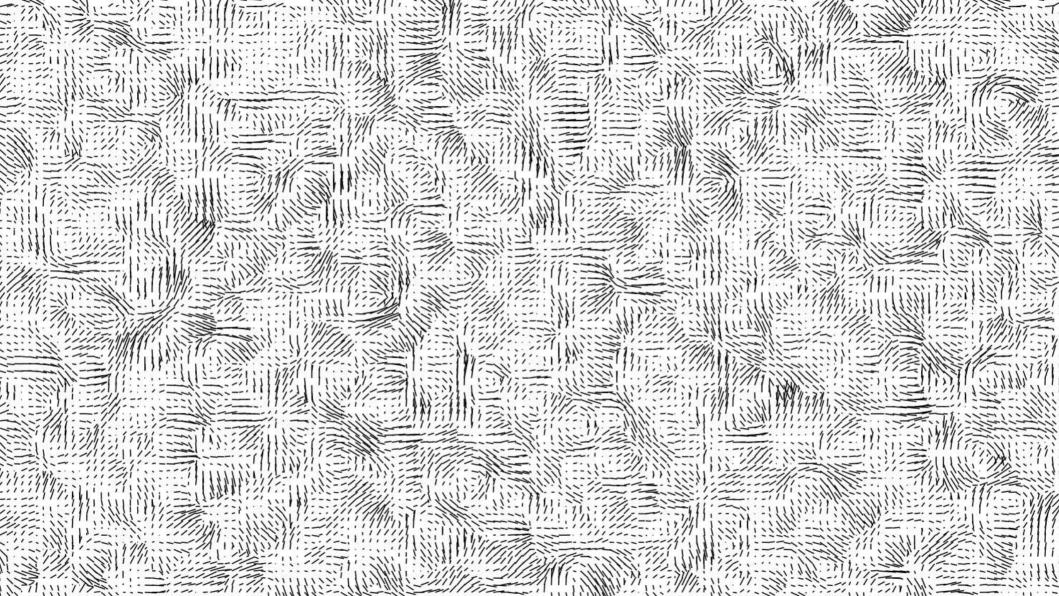


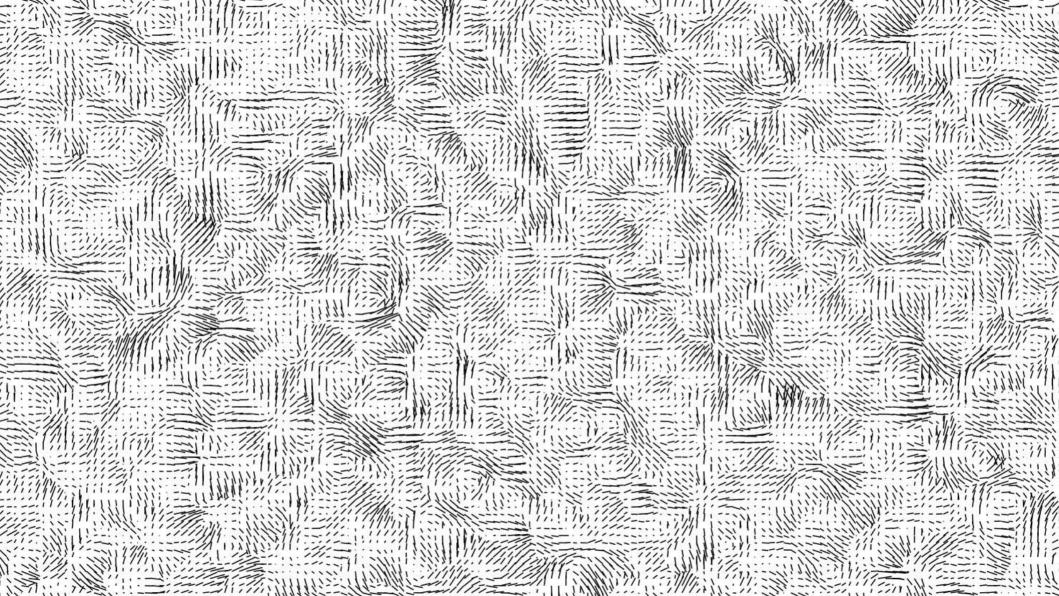


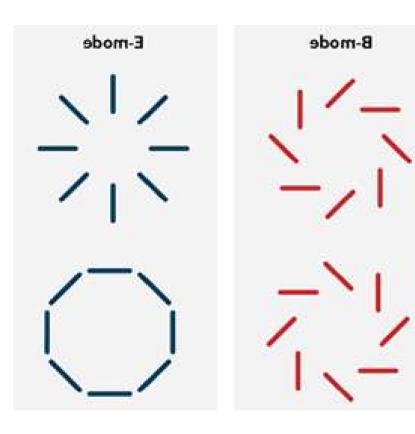






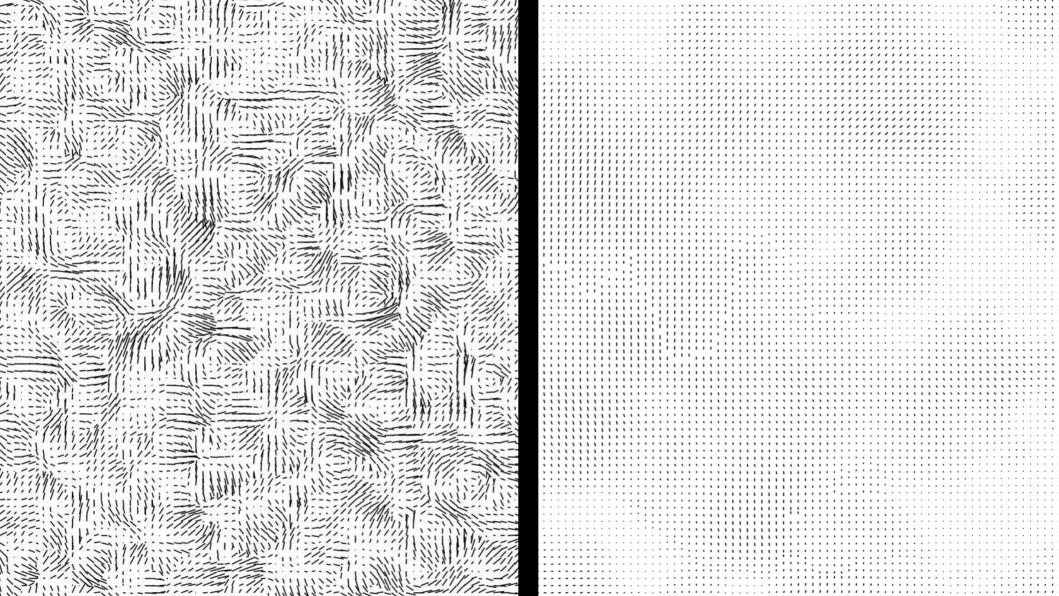


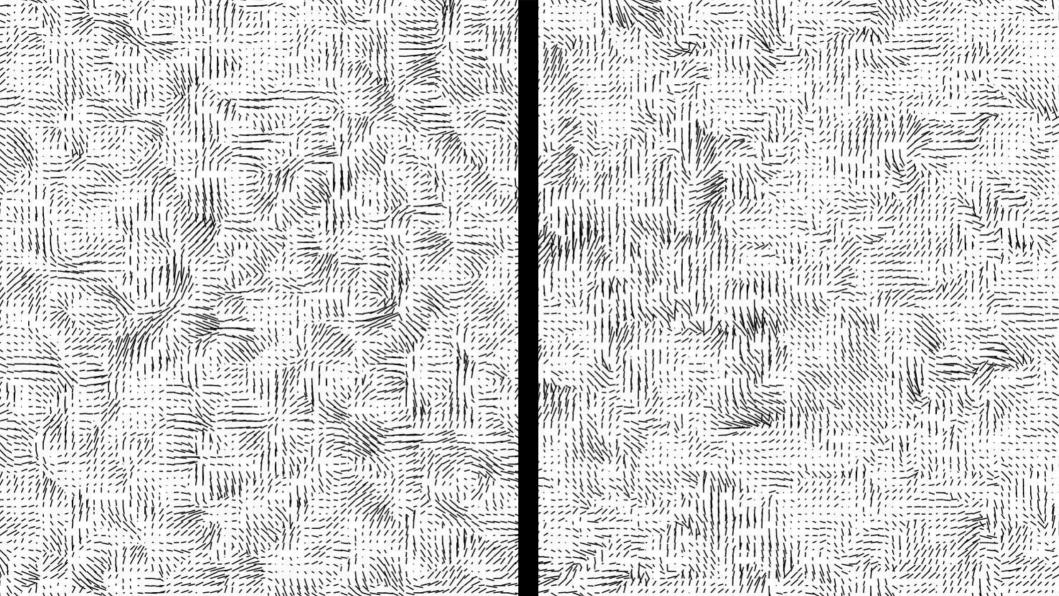


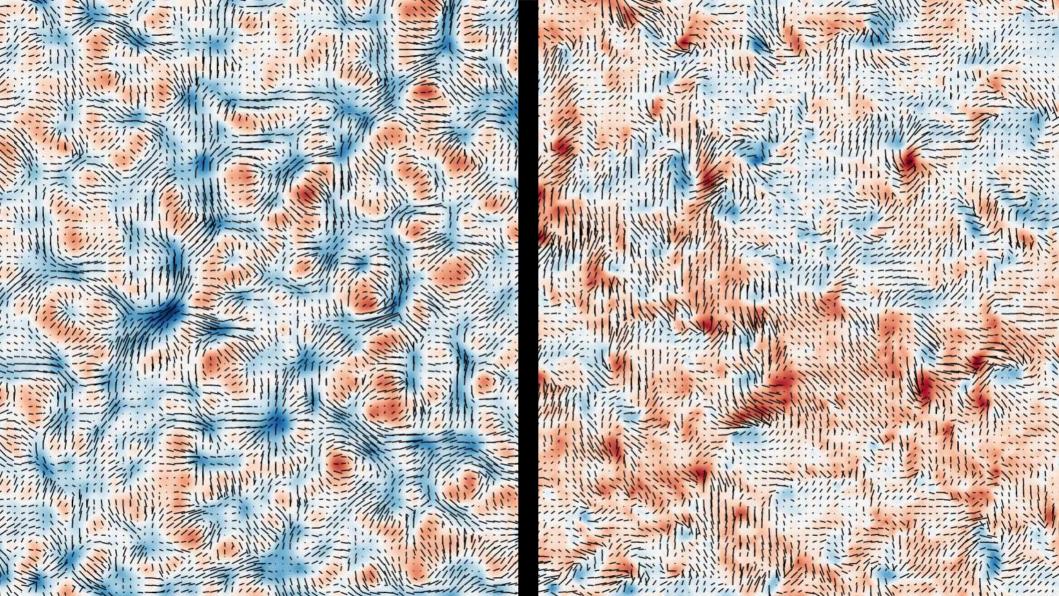


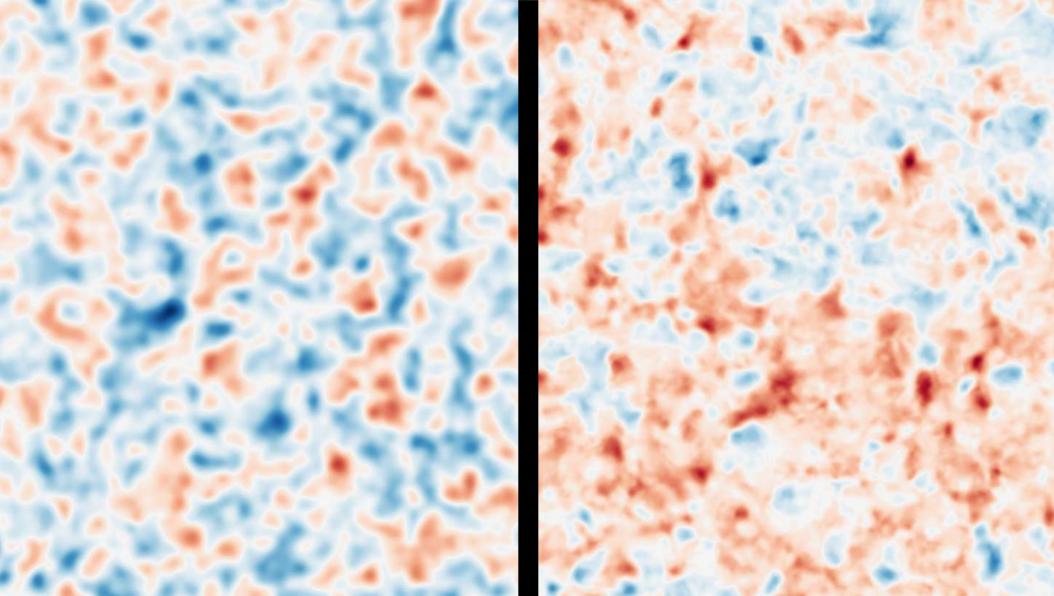
Sheared (lensed) E mode



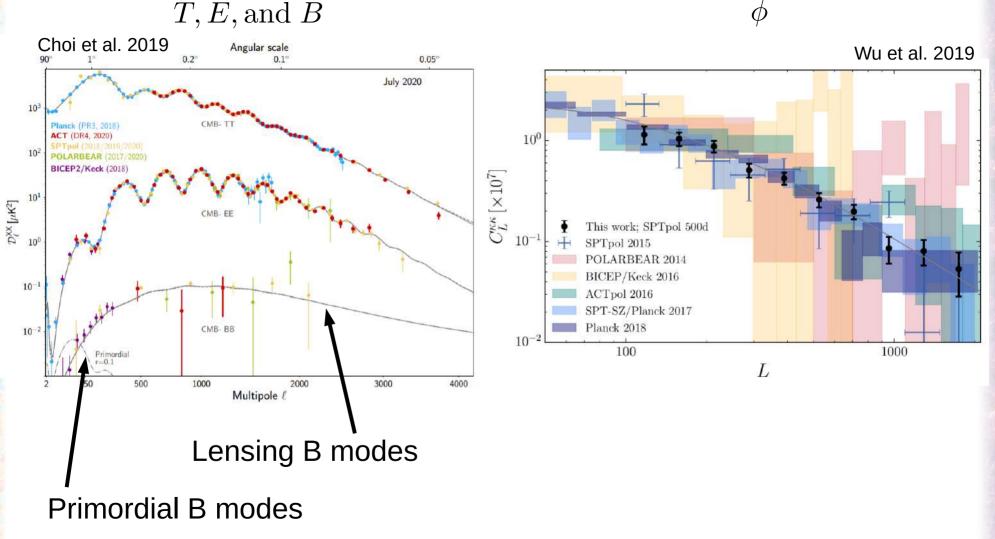


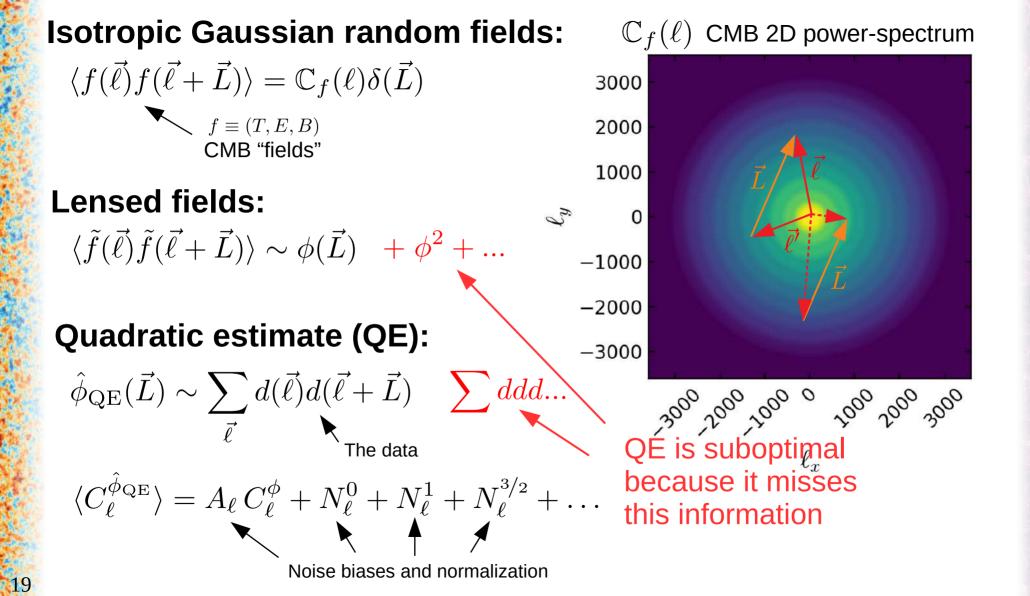




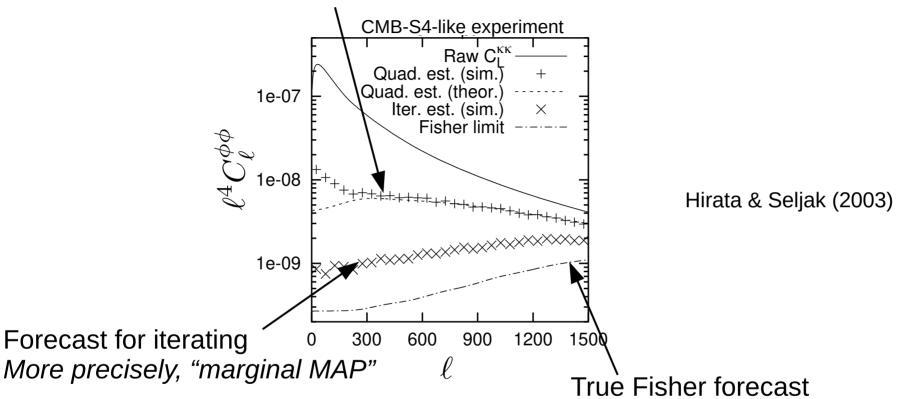


T, E, and B





Quadratic estimate noise spectrum



- These are forecasts or highly simplified analyses
- Almost 20 years later, we are finally asking: How do we do this to real data?

Towards optimality...

- **DeepCMB** (Caldeira et al. 2018)
 - Achieves noise levels comparable to the iterative-forecast
 - Challenges in extracting cosmological parameters
- Gradient inversion (Horowitz et al. 2018, Hadzhiyska et al. 2018)
 - Simple, but only optimal in the asymptotic limit of small scales
- **Optimal filtering** (Mirmelstein et al. 2019)
 - A way to more optimally filter a QE ϕ map before taking its power spectrum
 - May be useful mainly in the short term

Bayesian methods

- Guaranteed to be optimal, but computationally hard

Bayesian Lensing

Cosmological parameters or theory spectra

Notation: $x^2/\mathbb{C} \equiv x^{\dagger}\mathbb{C}^{-1}x$

Data model: $d = \mathbb{L}(\phi)f + n$

Priors:

$$f \sim \text{Gaussian}(0, \mathbb{C}_f(\theta))$$
 $n \sim \text{Gaussian}(0, \mathbb{C}_n$
 $\phi \sim \text{Gaussian}(0, \mathbb{C}_{\phi}(\theta))$ $\theta \sim \text{Uniform}$

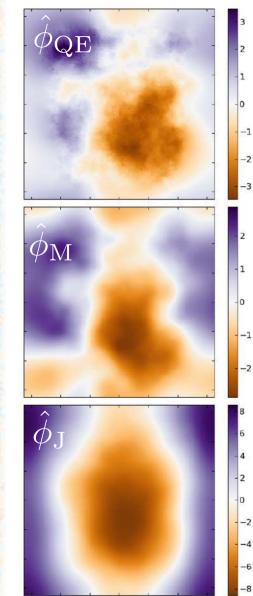
"Joint" posterior (MM,Anderes,Wandelt 2018, 2020):

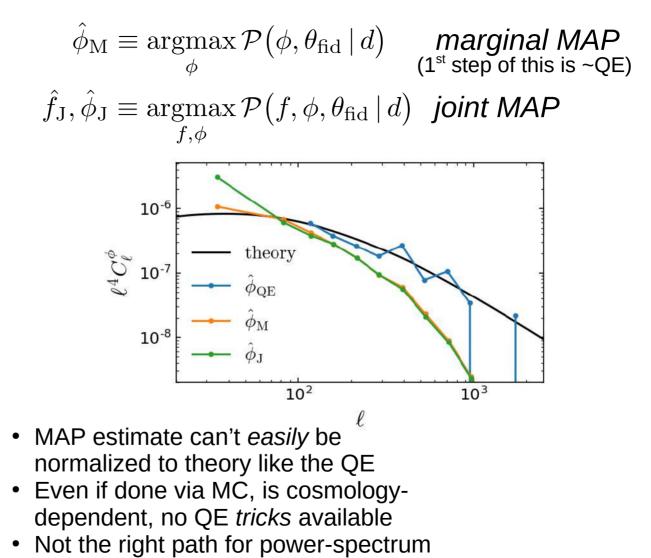
$$\mathcal{P}(f,\phi,\theta \,|\, d) = \frac{\exp\left\{-\frac{(d - \mathbb{L}(\phi)f)^2}{2\,\mathbb{C}_n}\right\}}{\det \mathbb{C}_n^{1/2}} \frac{\exp\left\{-\frac{f^2}{2\,\mathbb{C}_f(\theta)}\right\}}{\det \mathbb{C}_f(\theta)^{1/2}} \frac{\exp\left\{-\frac{\phi^2}{2\,\mathbb{C}_\phi(\theta)}\right\}}{\det \mathbb{C}_\phi(\theta)^{1/2}}$$

"Marginal" posterior (Hirata&Seljak 2003; Carron&Lewis 2018):

$$\mathcal{P}(\phi, \theta \,|\, d) = \frac{\exp\left\{-\frac{d^2}{2\,\mathbb{C}_d(\phi, \theta)}\right\}}{\det\,\mathbb{C}_d(\phi, \theta)^{1/2}} \frac{\exp\left\{-\frac{\phi^2}{2\,\mathbb{C}_\phi(\theta)}\right\}}{\det\,\mathbb{C}_\phi(\theta)^{1/2}}$$

where $\mathbb{C}_d(\phi, \theta) \equiv \mathbb{L}(\phi)\mathbb{C}_f(\theta)\mathbb{L}(\phi)^{\dagger} + \mathbb{C}_n$





or parameter estimation

"Joint" posterior (MM, Anderes, Wandelt 2018, 2020):

$$\mathcal{P}(\tilde{f},\phi,\theta \,|\, d) = \frac{\exp\left\{-\frac{(d-\tilde{f}_{-})^2}{2\mathbb{C}_n}\right\}}{\det \mathbb{C}_n^{1/2}} \frac{\exp\left\{\frac{(\mathbb{L}(\phi)^{-1}\tilde{f})^2}{2\mathbb{C}_f(\theta)}\right\}}{\det \mathbb{C}_f(\theta)^{1/2}} \frac{\exp\left\{-\frac{\phi^2}{2\mathbb{C}_\phi(\theta)}\right\}}{\det \mathbb{C}_\phi(\theta)^{1/2}} \frac{1}{\det \mathbb{L}(\phi)}$$

Instead of maximizing, *marginalize:*

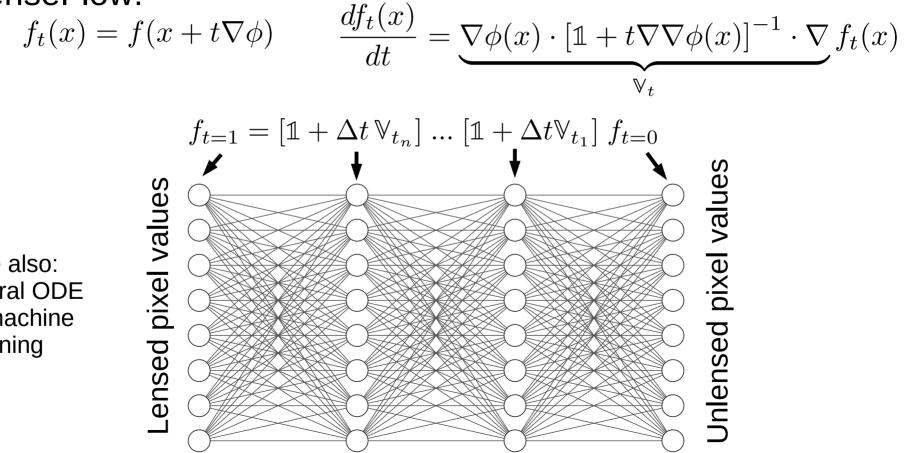
$$\mathcal{P}(\theta \,|\, d) = \int \mathrm{d}f \mathrm{d}\phi \, \mathcal{P}(f, \phi, \theta \,|\, d)$$

This is guaranteed to be "optimal," ie represent all the information that we can extract.

This ~million dimensional marginalization done with Hamiltonian Monte Carlo.

Traditional lensing: $f(x) = f(x + \nabla \phi) \approx f(x) + \nabla f(x) \nabla \phi(x) + \dots$

LenseFlow:

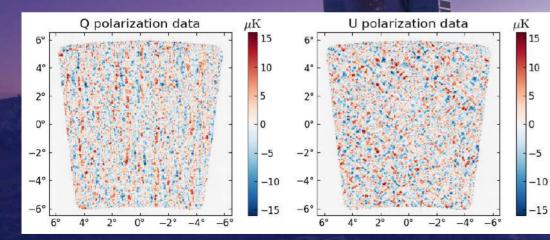


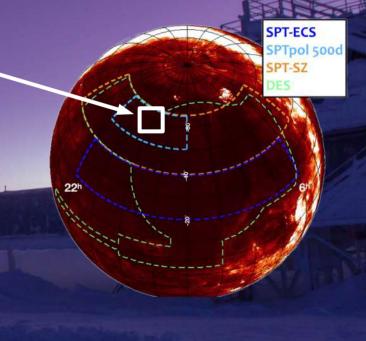
See also: neural ODE in machine learning

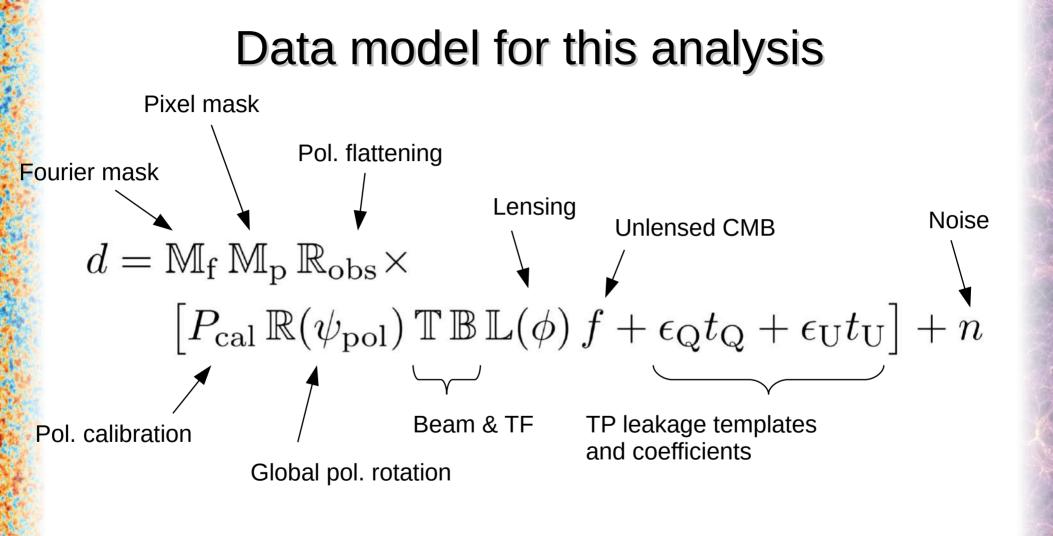
Upcoming South Pole Telescope Analysis

With Cail Daley, Jody Ti-Lin Chou, SPT collaboration

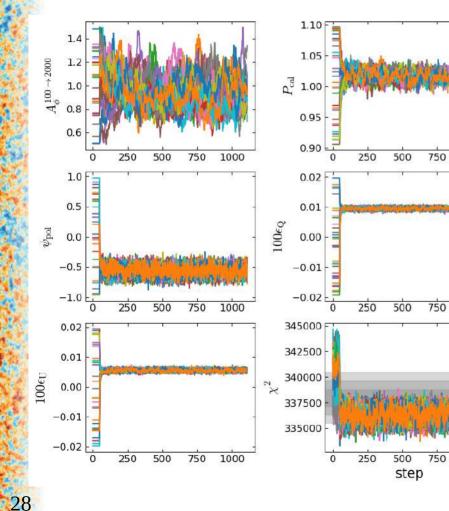
Deepest 100deg² polarization measurements to-date at the angular scales most relevant for lensing.

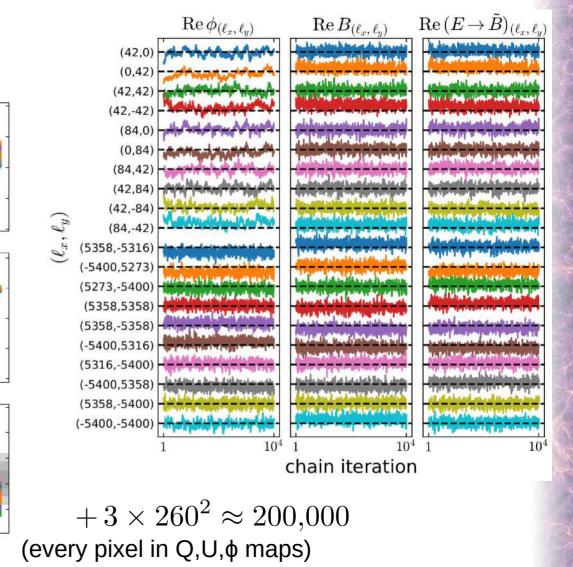






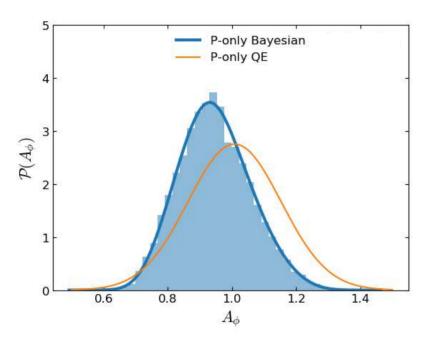
Trace of various quantities throughout the samples:





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$\begin{array}{l} \Delta A_{\mathrm{T} \to \mathrm{P}} \\ \Delta A_{\mathrm{pol.rot.}} \end{array}$	$\ll 0.001 < 0.001$	$\ll 0.001 < 0.001$	N/A N/A	2.00		} <mark>}</mark> \	- o rc+0.08		
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					$A_{\phi}^{100 \rightarrow 2000}$	$P_{ m cal}$	$\psi_{ m pol}$	$100\epsilon_{ m Q}$	$100\epsilon_{ m U}$

Comparison to QE



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Bayesian: 0.9459(75) ± 0.1123(50) QE: 1.01 ± 0.134

Preliminary

- 23% tighter error bars, in line with expectations from forecasts
- First time cosmological parameter extracted from optimal lensing reconstruction

Bayesian lensing paves the way for solving future problems in CMB analysis

Foreground contamination

SPTpol

Planck

For point sources in the 1-halo regime:

$$\mathcal{P}\left(S_{\text{pix}}\right) = \int_{-\infty}^{\infty} dt \exp\left\{itS_{\text{pix}} + \int_{0}^{S_{\text{cut}}} dS \frac{d\bar{N}}{dSd\Omega_{\text{pix}}} \left[\exp(itS) - 1\right]\right\}$$

work with Emmanuel Schaan

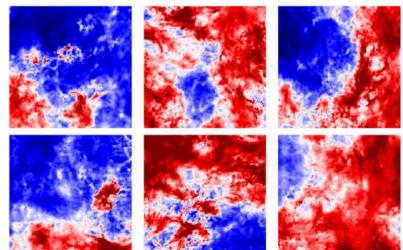
Machine learning models

Aylor et al. 2019

Generative neural network

 $\operatorname{Gaussian}(0,\mathbb{I}_{64})$

Prior distribution

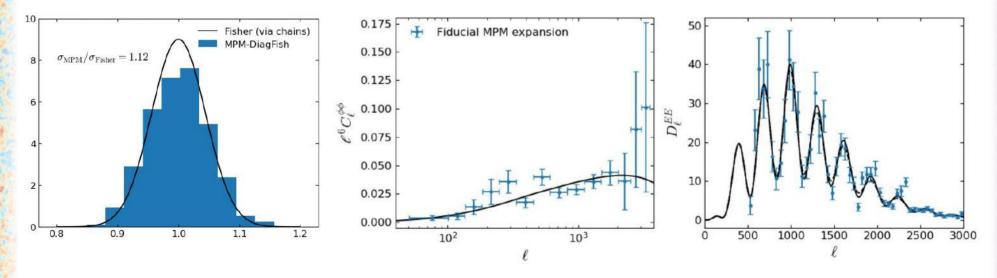


work with Ben Thorne, Lloyd Knox

Joint bandpower estimation MM, Seljak, in prep

 $\mathcal{P}(C_{\ell}^{\phi\phi}, C_{\ell}^{EE}, | d) = \int df d\phi \, \mathcal{P}(f, \phi, C_{\ell}^{\phi\phi}, C_{\ell}^{EE} | d)$

We have developed **approximations** to this integral. Using our ability to get the *exact* answer via sampling, we can **validate** these approximations given realistic data.



Conclusions

- Through the 2020s, all lensing analyses will eventually go beyond the QE
- The Bayesian solution is a promising way forward
- For exploring the Bayesian posterior, check out CMBLensing.jl

cosmicmar.com/CMBLensing.jl

CMBLensing.jl Search does CMBLensing.jl • Documentation • Installation Lensing a flat-sky map The Lensing Posterior MAP estimation Calling from Python Field Basics

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CMBLensing.jl

docs stable 🧐 launch binder build passing

CMBLensing.jl is a next-generation tool for analysis of the lensed Cosmic Microwave Background. It is written in Julia and transparently callable from Python.

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At its heart, CMBLensing.jl maximizes or samples the Bayesian posterior for the CMB lensing problem. It also contains tools to quickly manipulate and process CMB maps, set up modified posteriors, and take gradients using automatic differentiation.

Highlights

• Fully Nvidia GPU compatible (speedups over CPU are currently 3x-10x, depending on the problem size and hardware).