Optimal joint reconstruction with the CMB

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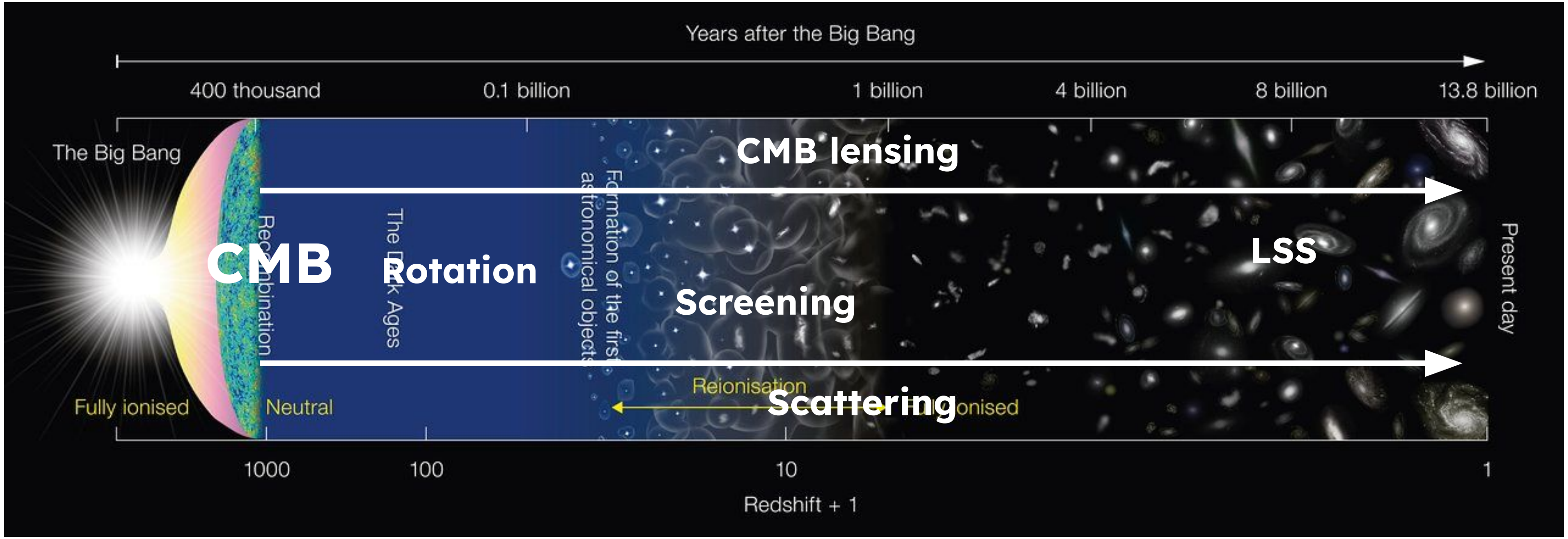
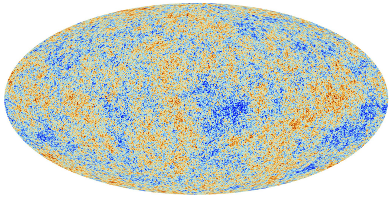
CMB history



Adapted from NAOJ

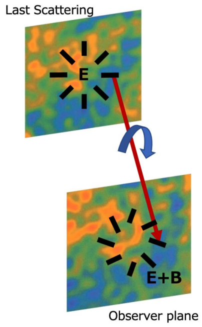
The observed CMB

Emission



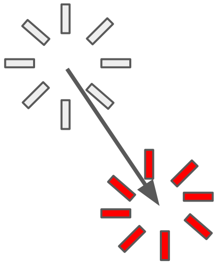
ESA and the Planck Collaboration

Early time rotation



Toshiya Namikawa

Lensing



Observer

Source Component

Model CMB

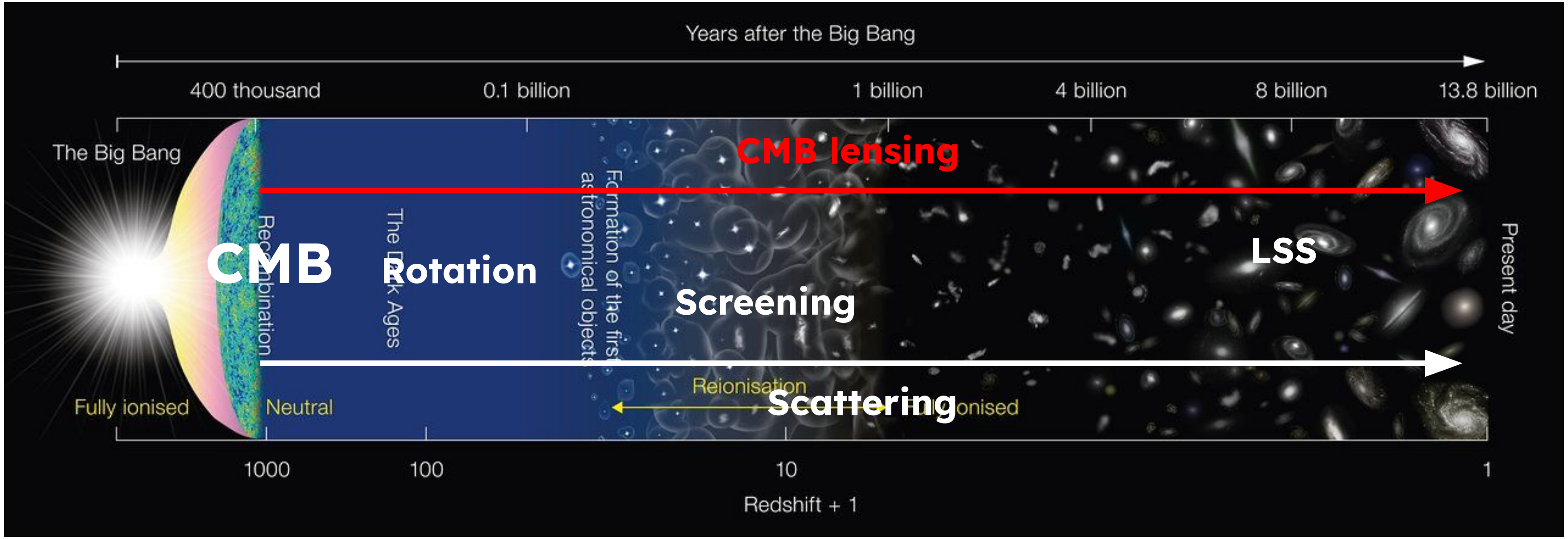
$$X^{\mathrm{dat}} = \mathcal{B} O_1 O_2 ... O_N X^{\mathrm{prim}} + \mathcal{B} f + n$$

Chain of operators (assume disjoint)

"Stuff"

Extracting these to probe standard model and beyond

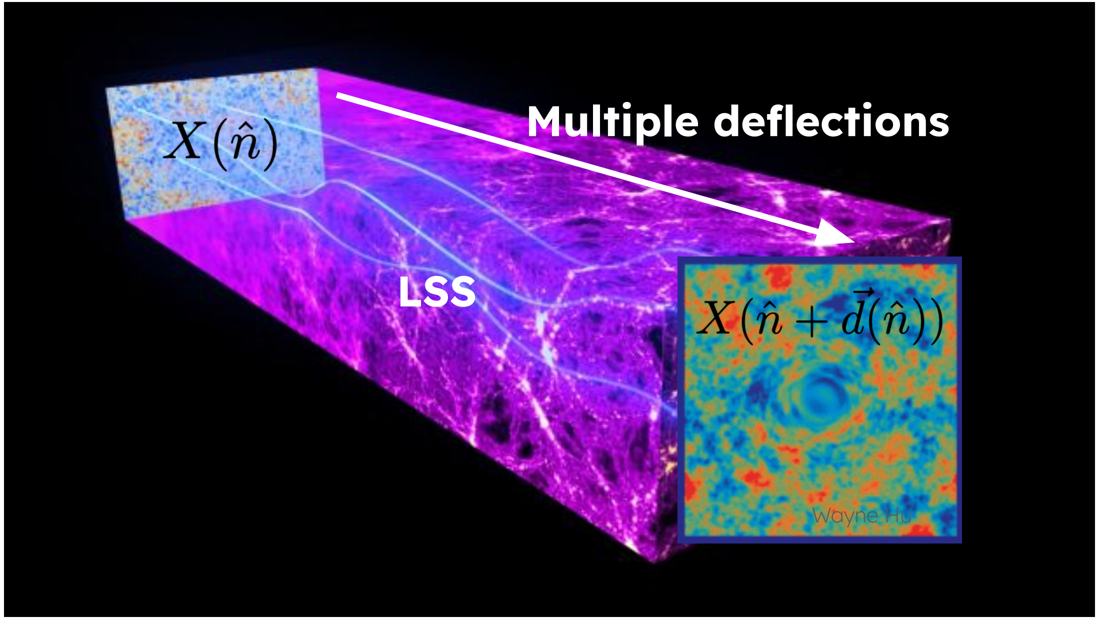
CMB history



Observer

Adapted from NAOJ

CMB lensing

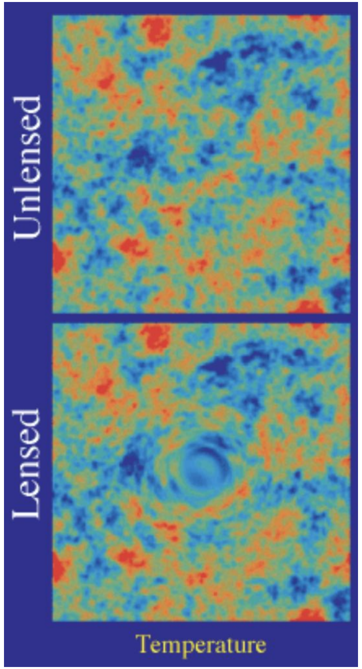


ESA and the Planck Collaboration

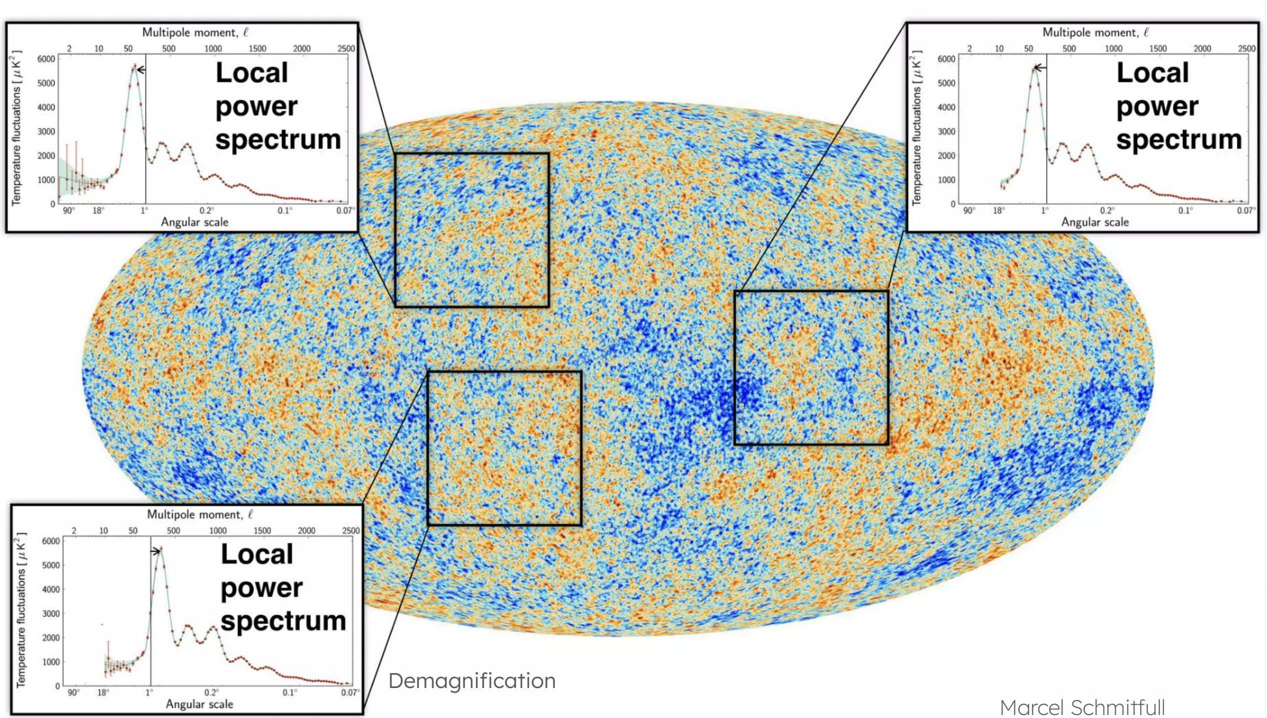
$$\vec{\nabla} \cdot \vec{d} \sim \kappa \sim \sum_i W_i \delta_i^m$$

- Measure of projected mass fluctuations from source
- Clean and robust cosmological probe

Standard CMB lensing reconstruction



Wayne Hu



Marcel Schmittfull

Large lens modulates small scale CMB power spectrum ->
look at shifts in the power spectrum to reconstruct the lens ~ $T_{\rm CMB} T_{\rm CMB}$

The QE CMB lensing estimator

$$\ln \mathcal{L} \supset -\frac{1}{2} X^{\mathrm{dat}} \cdot \mathrm{Cov}_{\kappa}^{-1} \mathrm{X}^{\mathrm{dat}} - \frac{1}{2} \mathrm{det} \mathrm{Cov}_{\kappa}$$

Hirata, Seljak (2003)
Hanson, Lewis, Challinor (2009)

Anisotropic CMB Covariance

$$\mathrm{Cov}_{\kappa} = \mathcal{B} D_{\kappa} C^{\mathrm{unl}} D_{\kappa}^{\dagger} \mathcal{B}^{\dagger} + N$$

Isotropic primordial CMB

The QE CMB lensing estimator

$$\ln \mathcal{L} \supset -\frac{1}{2} X^{\mathrm{dat}} \cdot \mathrm{Cov}_{\kappa}^{-1} \mathrm{X}^{\mathrm{dat}} - \frac{1}{2} \mathrm{det} \mathrm{Cov}_{\kappa}$$

Maximize

$$\hat{\kappa}_{\mathrm{QE}} \sim \bar{X}^{\mathrm{dat}} \bar{X}^{\mathrm{dat,WF}} \times \mathrm{Norm}$$

Inverse variance filtered map

"Best" unlensed map

First step of a Newton iteration starting from no lensing

MAP CMB lensing estimator

$$\ln p \supset -\frac{1}{2}X^{\rm dat} \cdot {\rm Cov}_{\kappa}^{-1}{\rm X}^{\rm dat} - \frac{1}{2}{\rm det}{\rm Cov}_{\kappa} + \ln {\rm p}_{\rm prior}$$

Hirata, Seljak (2003)
Millea, Anderes, Wandlet (2020)
Carron, Lewis (2017)

See Louis' talk

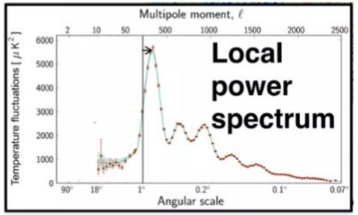
Maximize

$$\hat{\kappa}_{\rm MAP} \sim \bar{X}^{\rm dat}_{\hat{\kappa}_{\rm MAP}} \bar{X}^{\rm WF}_{\hat{\kappa}_{\rm MAP}} \times {\rm Norm}$$

Inverse variance filtered map

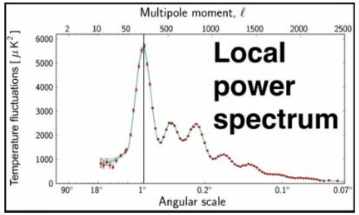
"Best" unlensed map

MAP Optimal CMB lensing estimator

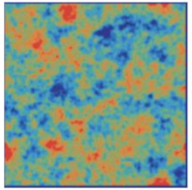


Remove some lensing

...



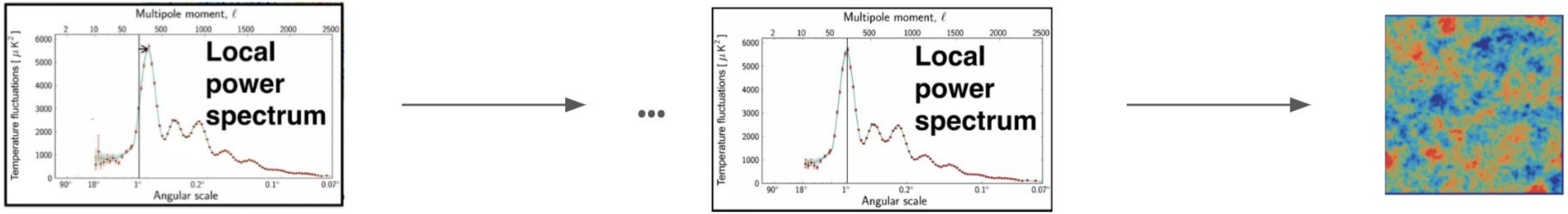
Remove some lensing



Remove lensing until convergence

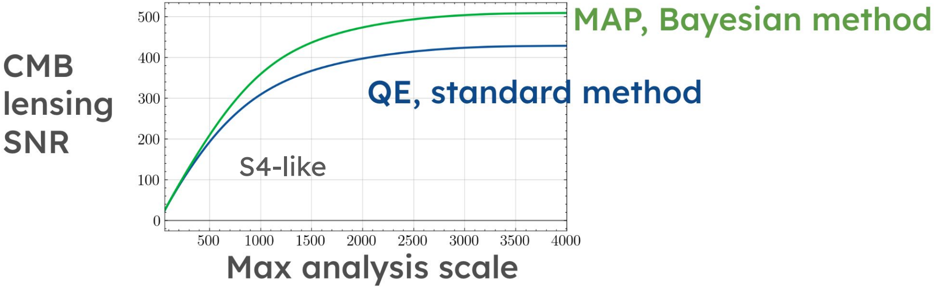
This is more complicated, less transparent, and more computationally intensive wrt QE

Why then?



Remove lensing until you get an unlensed CMB

Reduce noise



True for SPT too, generally not very beneficial for S3

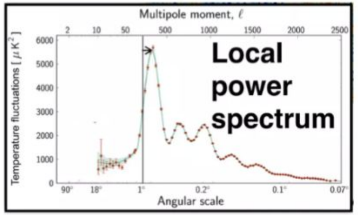
Large-scale squeezed limit Noise

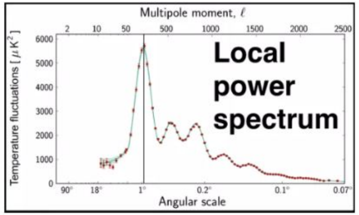
(e.g. Challinor et al. 2017, Carron and Lewis 2024)

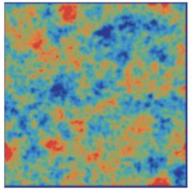
$$(S/N)\_L \sim \sum_l (2l+1) \frac{C_l^{EE} C_l^{EE}}{C_l^{tot,EE} C_l^{tot,BB}}$$

Remove lensing from here

Why then?



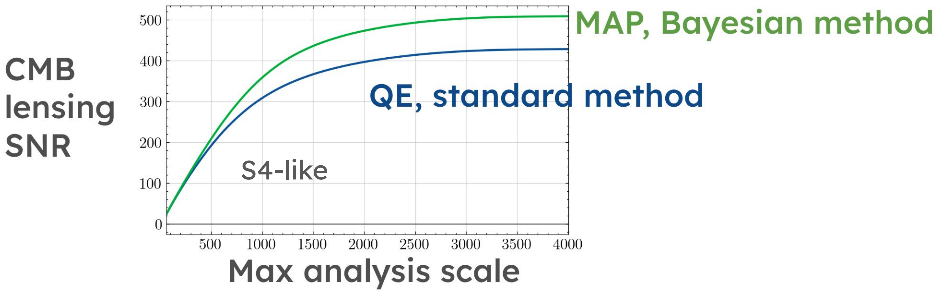


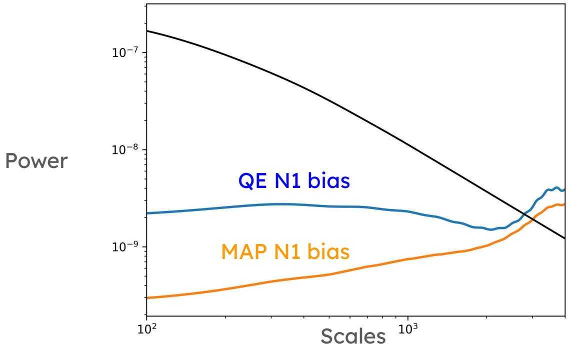


Remove lensing until you get an unlensed CMB

Reduce noise

Reduce biases





True for SPT too, generally not very beneficial for S3

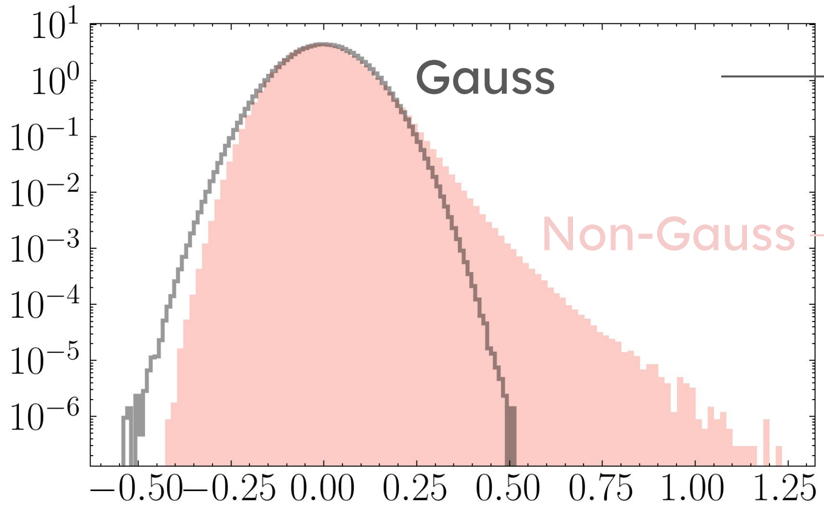
Might benefit even S3

work with

Sebastian Belkner, Louis Legrand, Julien Carron, Giulio Fabbian

True CMB lensing field non-Gaussian

Distribution

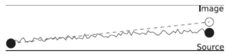


Projected CMB lensing mass

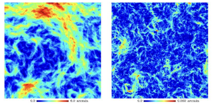
Current surveys can assume this

CMB-S4 and SO?

Due LSS non-Gaussianity and Post-Born effects



Credit S. Dodelson

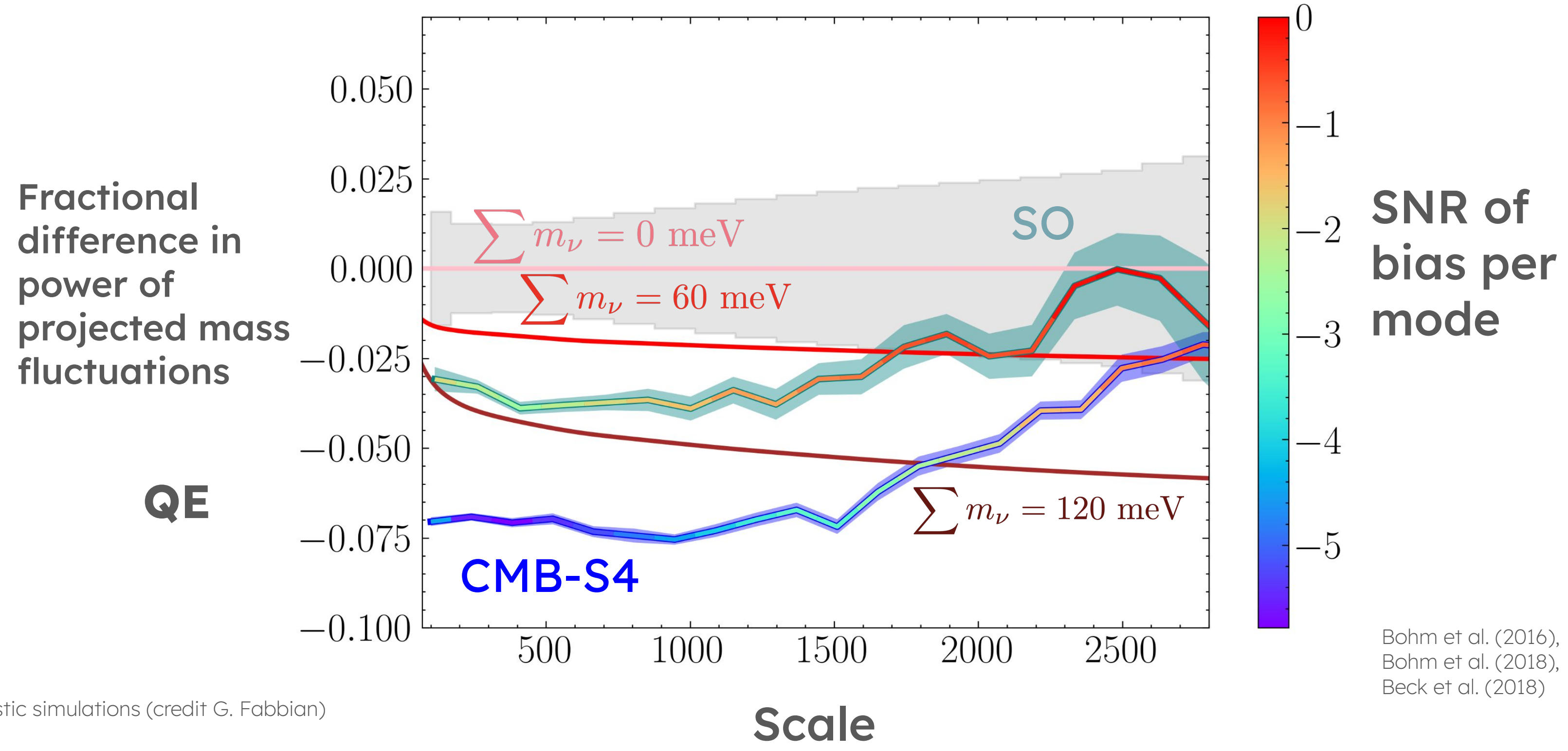


Pratten, Lewis (2016)

Amplitude of Post Born corrections

Credit **G. Fabbian**

Impact of LSS non-Gaussianity only

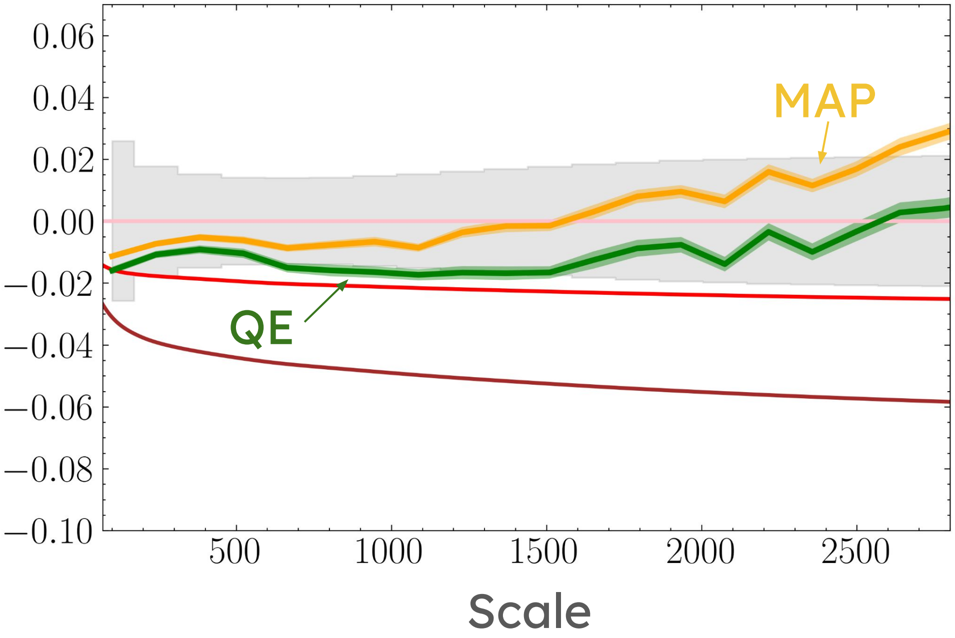


Bohm et al. (2016), Bohm et al. (2018), Beck et al. (2018)

Use realistic simulations (credit G. Fabbian)

Impact of non-Gaussian deflections

Fractional bias to auto spectrum



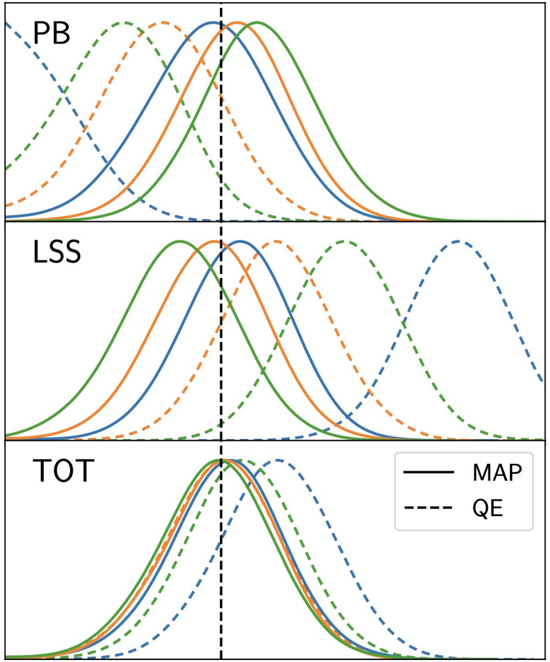
Temperature only

Sir D.Lensalot

Using **delensalot** code (credit **Sebastian Belkner** and Julien Carron)

Impact of non-Gaussian deflections

MAP estimator
more robust wrt QE



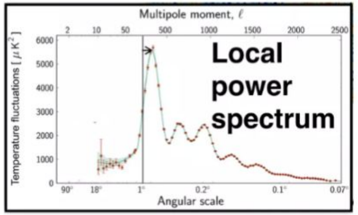
Sum of neutrino masses

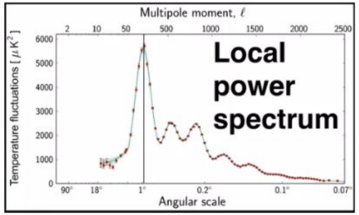
Important for CMB lensing cross-correlations (motivation for MAP maps)

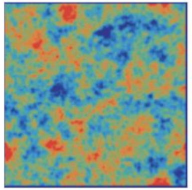
Nice cancellation for CMB lensing auto-correlation

Louis Legrand

Why then?

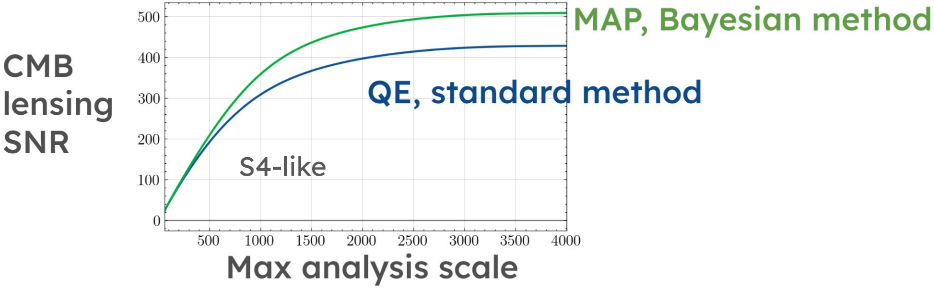




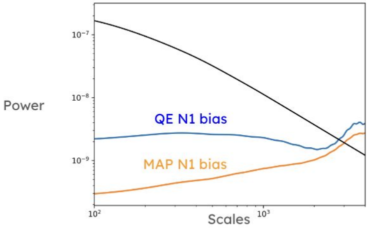


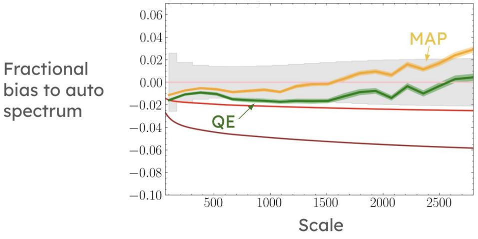
Remove lensing until you get an unlensed CMB

Reduce noise

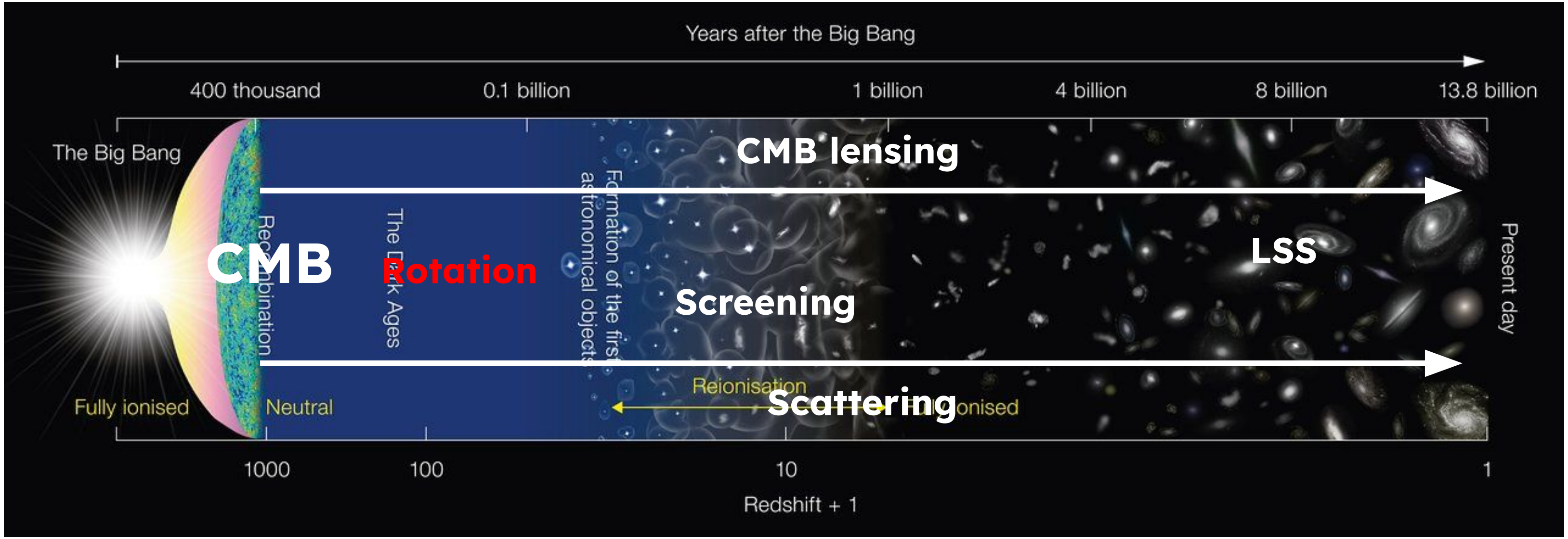


Reduce biases





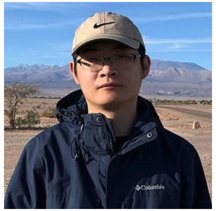
CMB history



Observer

Adapted from NAOJ

includes

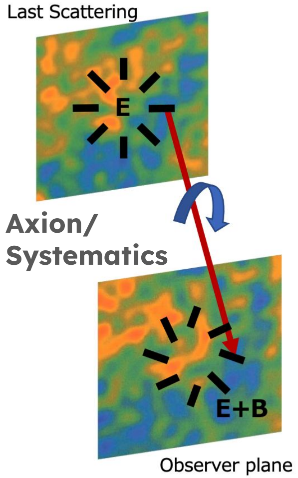


Sebastian Belkner, Yilun Guan, Hongbo Cai

Anisotropic CMB rotation

$$\mathcal{L} \supset h(\chi) F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Extra field rotating CMB polarization

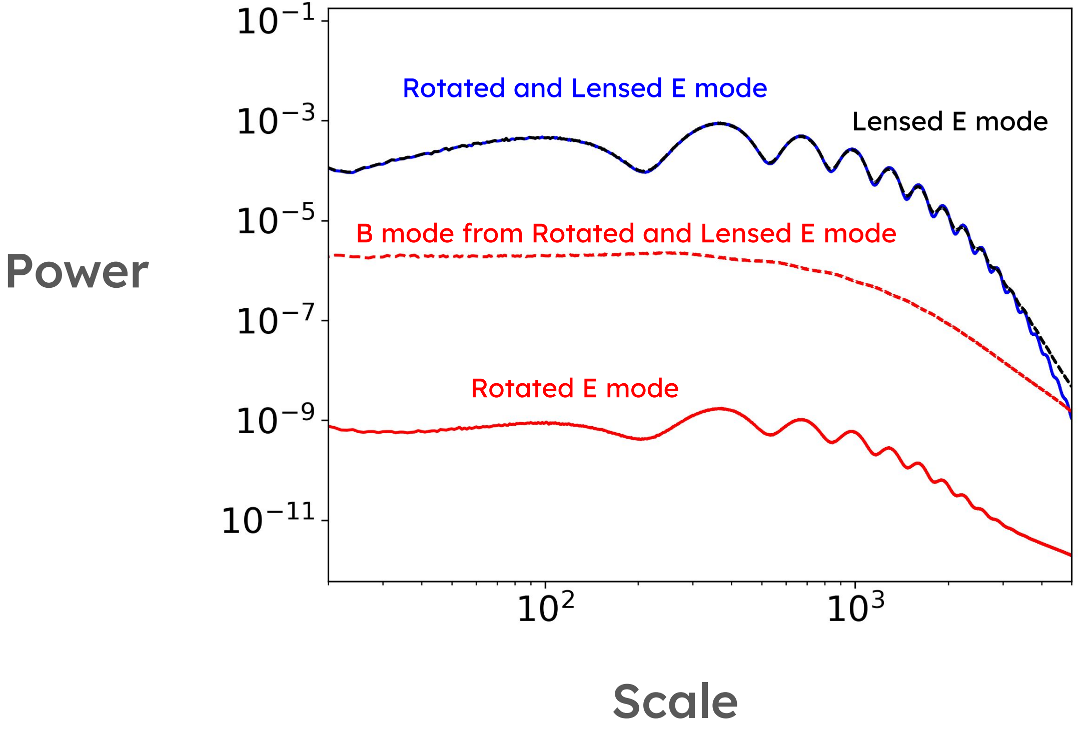


Toshiya Namikawa

$C_L^{\alpha\alpha}$ ~ proxy for a coupling

- Can be a measure of some axion-like particle
- Hint of parity-violating physics
- Difficult measurement

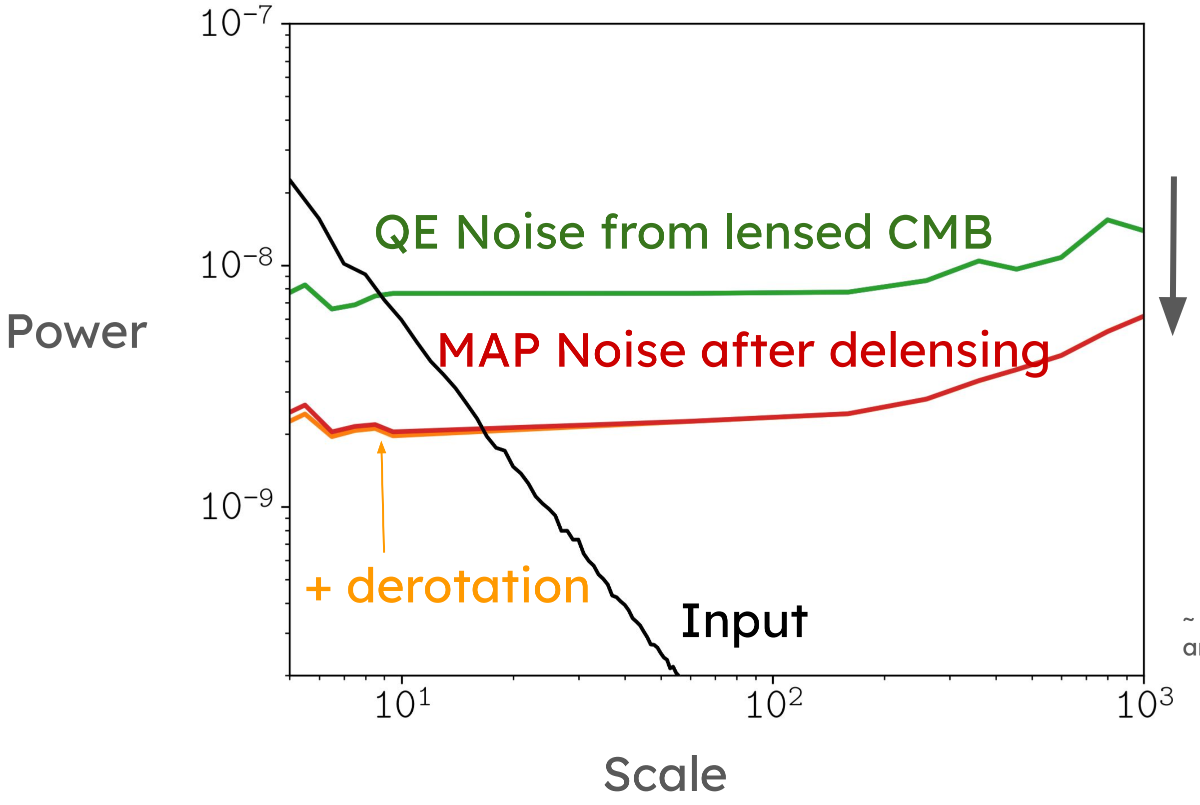
CMB power spectrum



Large-scale squeezed limit Noise

$$\sim \sum_l (2l+1) \frac{C_l^{EE} C_l^{EE}}{C_l^{tot,EE} C_l^{tot,BB}}$$

Rotation estimator



CMB-S4 -like levels

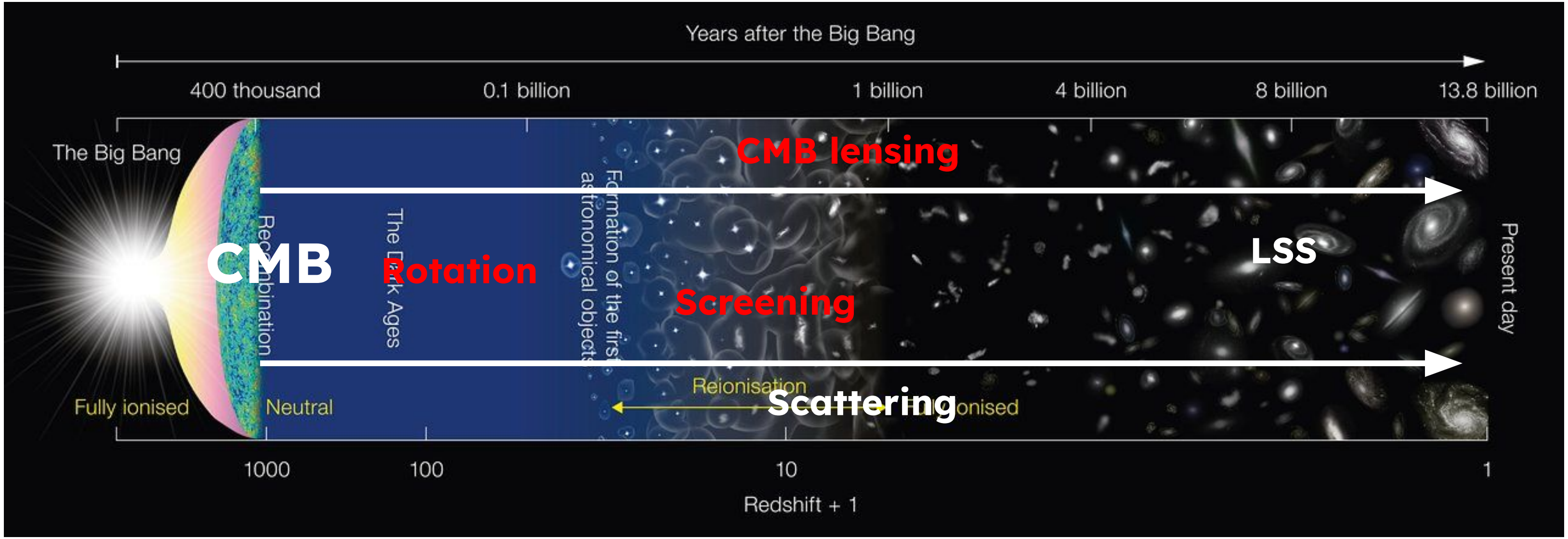
3x reduction in noise

+ reduction in N1 biases too (can already benefit current surveys)

~ scale invariant spectrum with amplitude 10^{-7}

jointmap code

CMB history



Observer

Adapted from NAOJ

Joint MAP estimator

Posterior

$$\ln p(X^{\rm dat}|\xi_1,\xi_2,\xi_3,\dots) = -\frac{1}{2}X^{\rm dat}\cdot {\rm Cov}^{-1}_{\xi_1,\xi_2,\xi_3,\dots}X^{\rm dat} + -\frac{1}{2}\det {\rm Cov}_{\xi_1,\xi_2,\xi_3,\dots} + {\rm const} \quad ,$$

Look at variations in the CMB covariance to give

Estimator

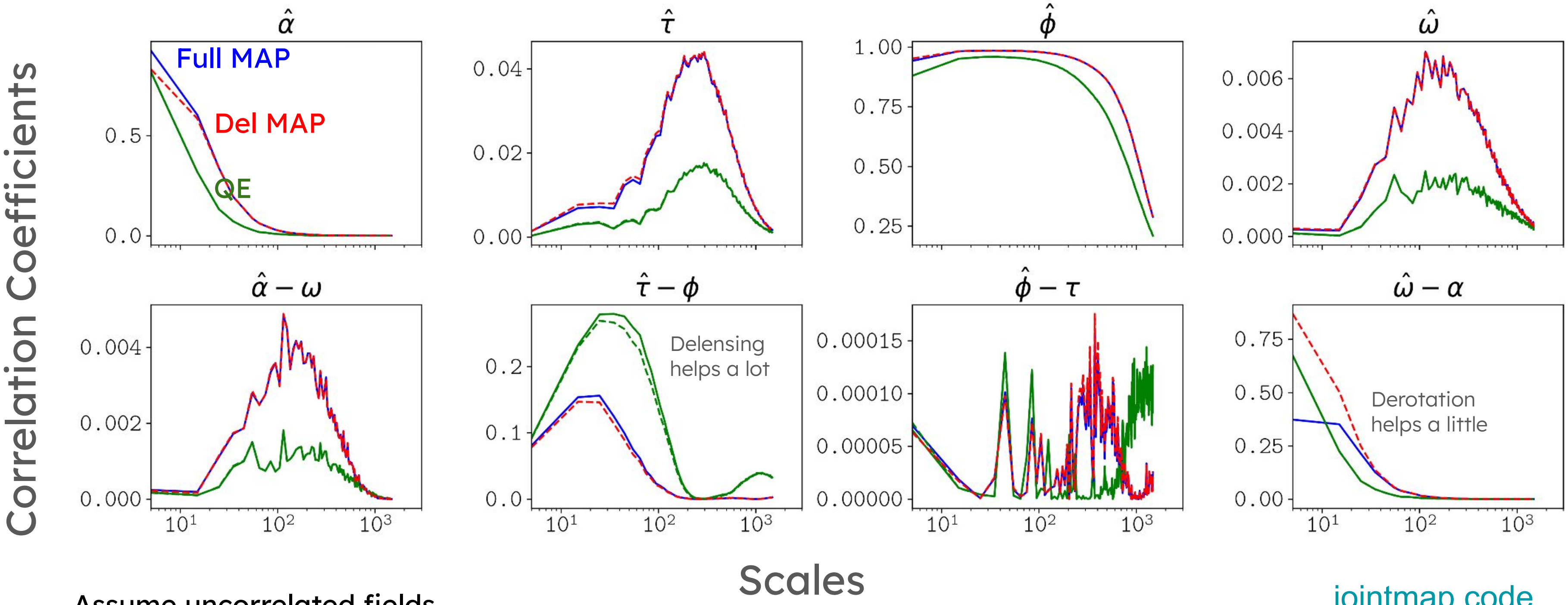
$$g_{\rm QD}(\hat{n}) = -\left(\overline{X}^{d}\right)\left(K_{j-1}\frac{\delta O_j}{\delta \xi_j}W_{j+1}X^{\rm WF}\right)(\hat{n})$$

Inverse variance filtered map

“Best” un-operated map

Likelihood approach flexible (e.g. can add other non-distorting sources of anisotropies, allow for splitting of the data, forward model certain systematics)

Joint MAP estimator



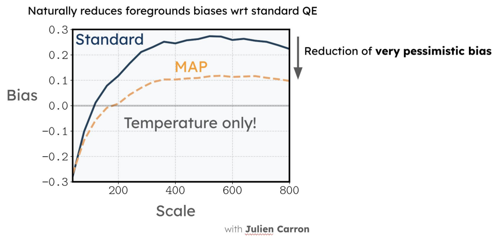
Assume uncorrelated fields.

jointmap code

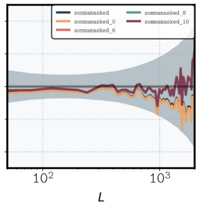
Going forward

- Can we remove rotation bias for curl estimator by including **temperature information?**

- Temperature is still beneficial, even for CMB-S4, for a variety of reasons (including cross-correlations, consistency checks, …).
    - Deal with the scattered CMB and foregrounds.



MAP gradient cleaning



Conclusions

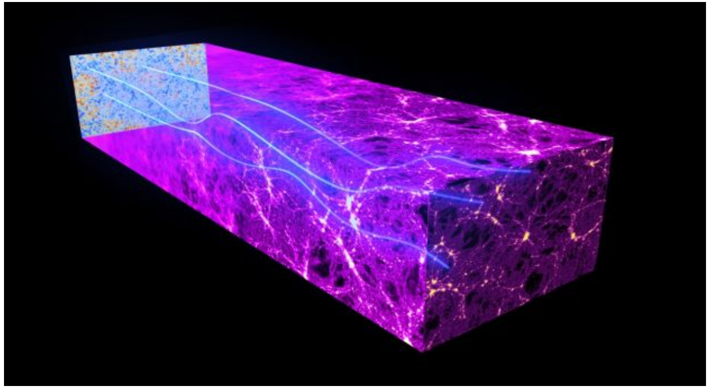
- Distorted CMB is rich in features
  - ACT, SPT, SO, CMB-S4, should consider joint distortion analyses
- MAP estimators can deal with this (in principle can also include certain instrumental effects)
  - It reduces noises
  - It reduces biases
- MAP estimators can already be applied to current data (no need to wait)
  - Potential application e.g. for lensing, delensed cosmic birefringence
- If interested in PMFs, X-rays, SBI, please let’s chat! **o.darwish@pm.me**

CMB lensing in the presence of a bispectrum

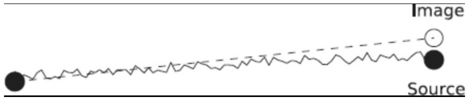
$$C_L^{\hat{\kappa}\hat{\kappa}} \sim \langle T_{\rm CMB} T_{\rm CMB} T_{\rm CMB} T_{\rm CMB} \rangle \supset \langle \langle T_{\rm CMB} T_{\rm CMB} \rangle \langle T_{\rm CMB} T_{\rm CMB} \rangle \rangle$$

$$\langle \sim \kappa(\vec{L}) \quad \sim \kappa(\vec{l}_1)\kappa(\vec{l}_3)$$

CMB lensing bispectrum

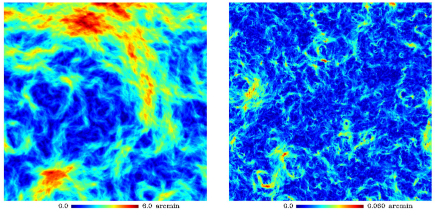


ESA and the Planck Collaboration



Bohm, Schmittfull, Sherwin (2016)
Fabbian, Lewis, Beck (2019)

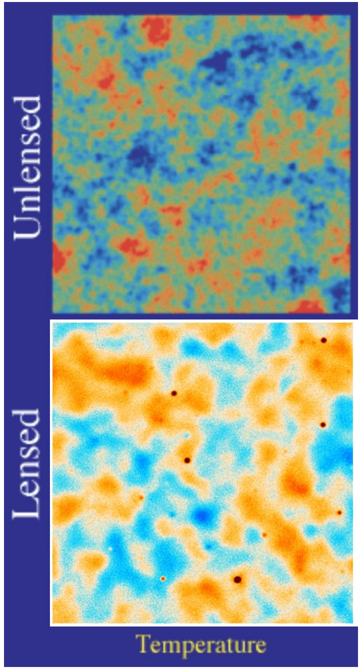
Credit S. Dodelson

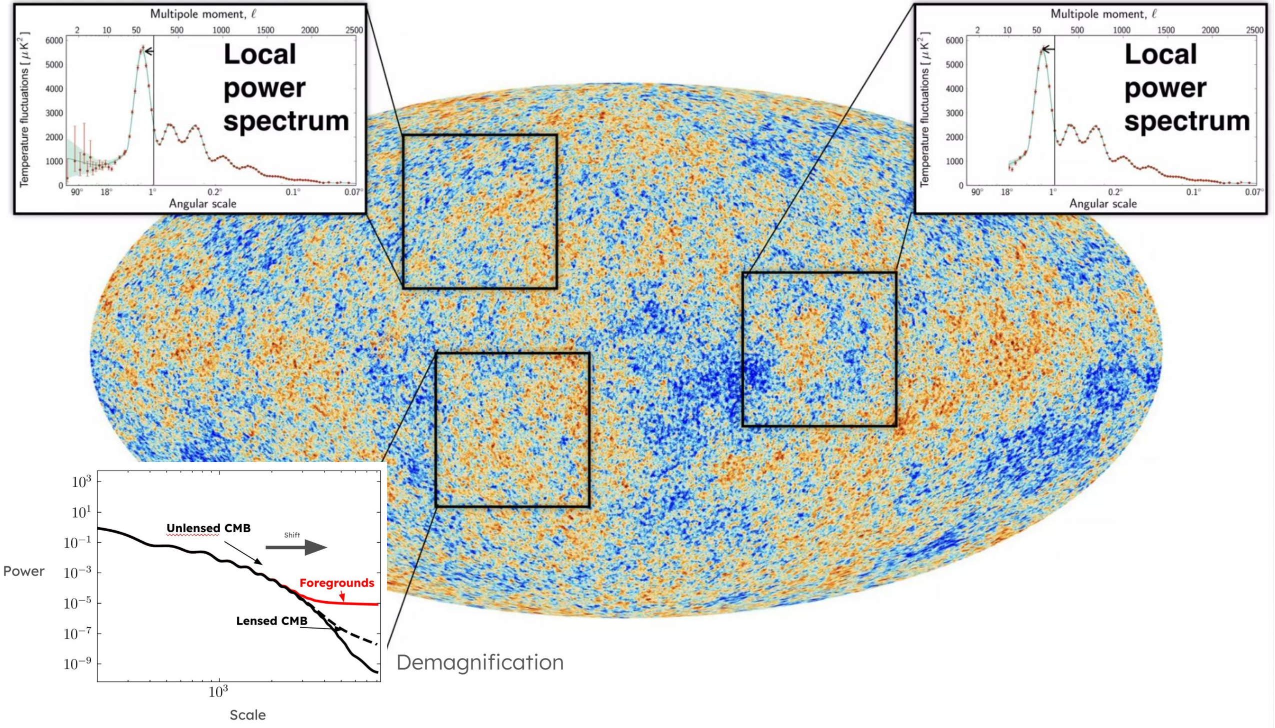


Amplitude of Post Born corrections

Credit G. Fabbian

Foreground geometric deprojection



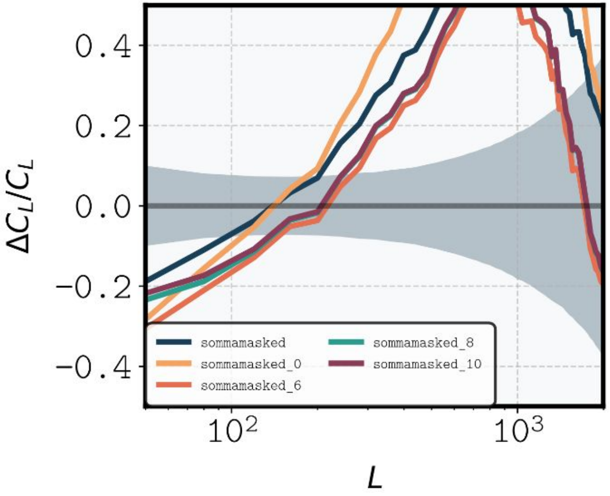


Contamination makes CMB lensing estimator thinks there is an underdensity!

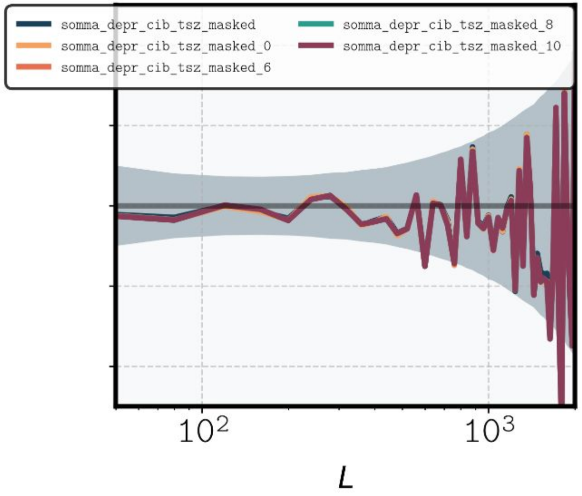
Reconstructs fake lens $T_{\mathrm{f}}T_{\mathrm{f}}$ -> remove part of this from your total lens estimate

Working with Websky simulations

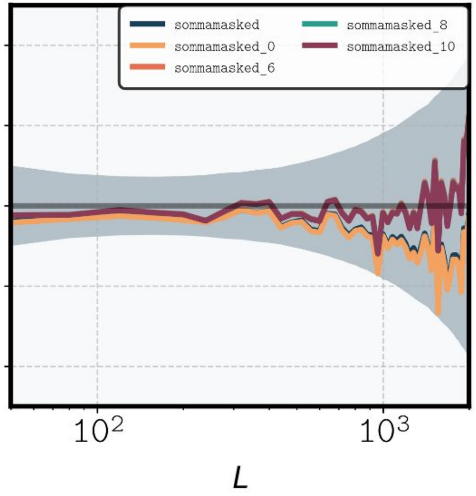
ILC only



Depr ILC



Symmetrised ILC



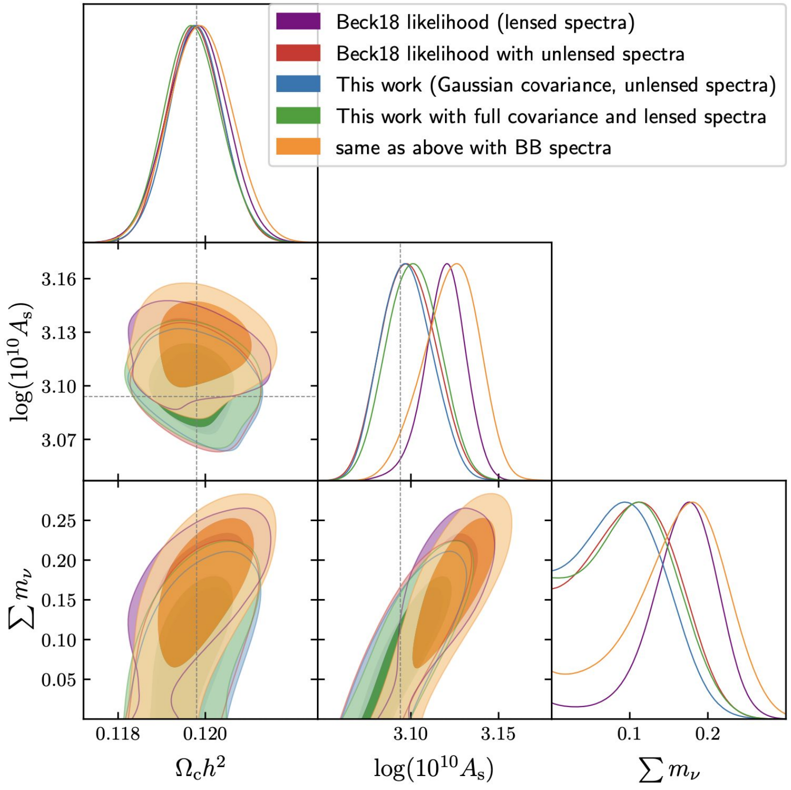
Bonus point: easily get symmetrised estimator.

$$\vec{g} = \vec{g}_{AB,CD} + \vec{g}_{CD,AB} \to \mathcal{R} = \mathcal{R}_{AB,CD} + \mathcal{R}_{AB,CD} \to A_L \sim \mathcal{R}^{-1}$$

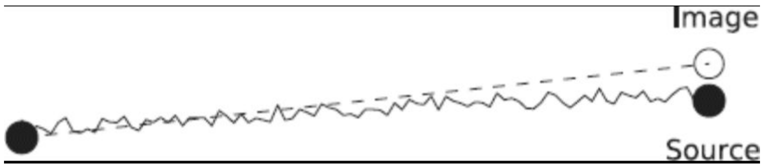
vs original paper, where you need to invert a matrix for minimum variance weights
(applies for TE I think too)

$$w_\alpha = \frac{\sum_\beta \left(\mathbf{N}^{-1}\right)_{\alpha\beta}}{\sum_{\alpha,\beta} \left(\mathbf{N}^{-1}\right)_{\alpha\beta}}$$

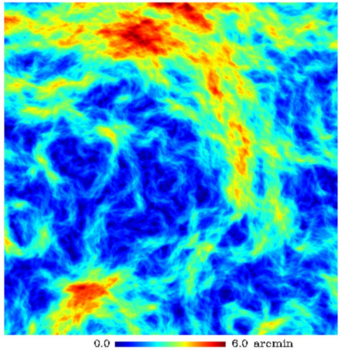
Comparing likelihoods

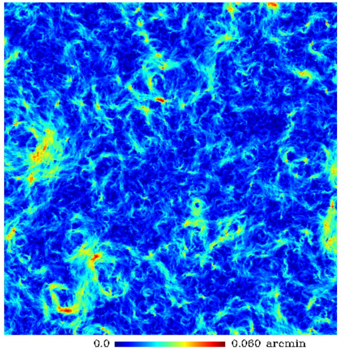


Due LSS non-Gaussianity and Post-Born effects



Credit S. Dodelson



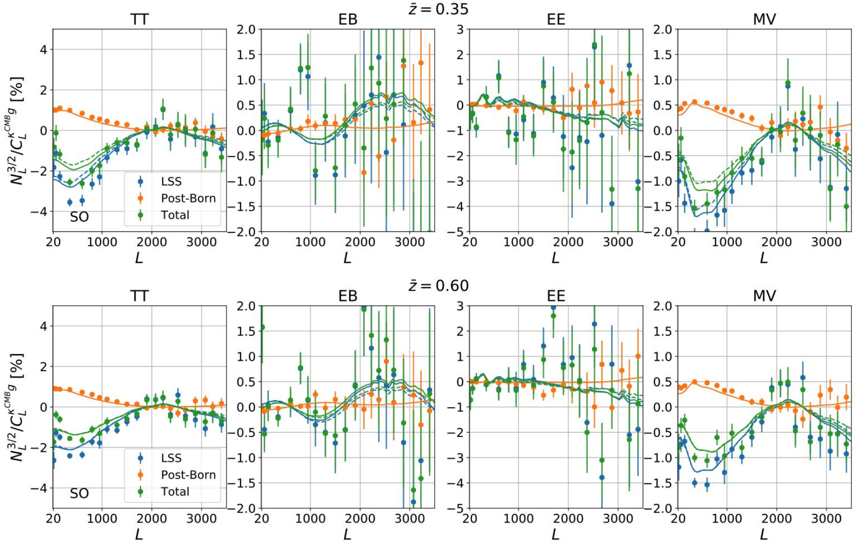


Credit **G. Fabbian**

Pratten, Lewis (2016)

Amplitude of Post Born corrections

Cross-correlations with QE



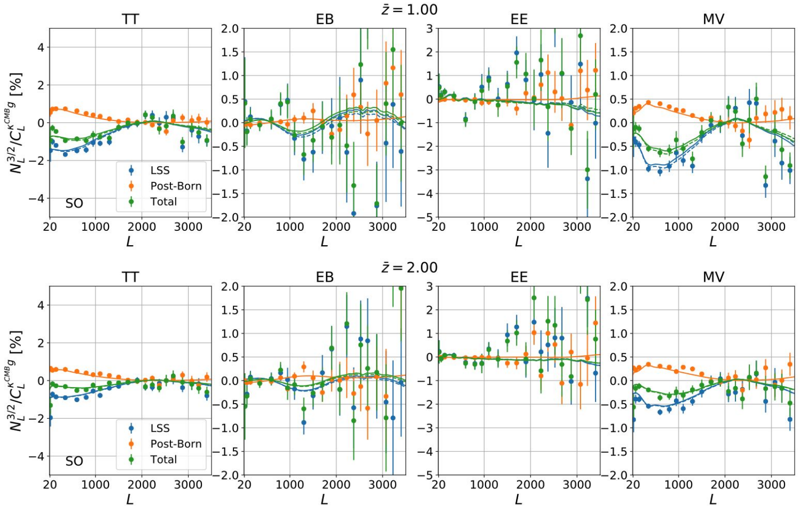


Figure 12: Fractional $N_L^{(3/2)}$ bias for the cross-correlation power spectrum between the reconstructed CMB lensing potential of SO and galaxy density at different redshift bins. The redshift increases moving from top to bottom. Theoretical predictions using GM fitting formulae for the matter bispectrum are shown as solid lines while those based on SC fitting formulae are shown as dashed lines. Different contributions to the $N_L^{(3/2)}$ signal are shown in different colours. The error bars accounts for the sample variance of CMB alone.

Cross-correlations with QE

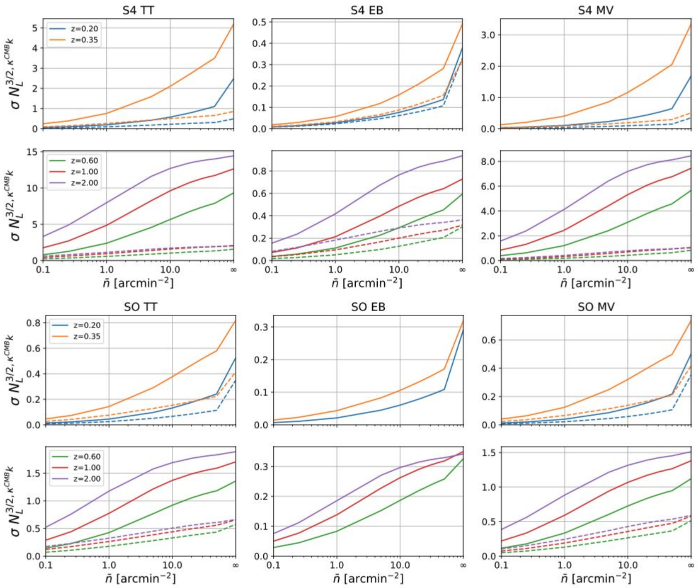


Figure 15: Detection significance of $N_L^{(3/2)}$ measured in simulations for cross-correlation between the reconstructed CMB lensing and galaxy lensing as a function of the shot noise in an LSS survey (solid). Results for S4 (SO) are shown in the upper (lower) panels. LSST/Euclid-like surveys have $\bar{n} \approx 3$, depending on the bin thickness. Different reconstruction channels are shown from left to right, while different redshift bins are shown in different colours. The dashed lines show the detection significance σ of the residual $N_L^{(3/2)}$ bias after subtraction of the analytical prediction of this work (using GM fitting formulae gives consistent results).