Non-Gaussian deflections in CMB lensing reconstruction

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work with

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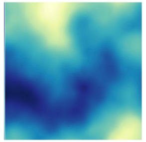
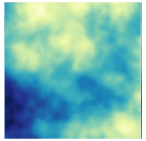
Resolving lenses with

ACT/Planck



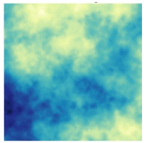
~40σ

Simons Observatory



~130σ

CMB-S4



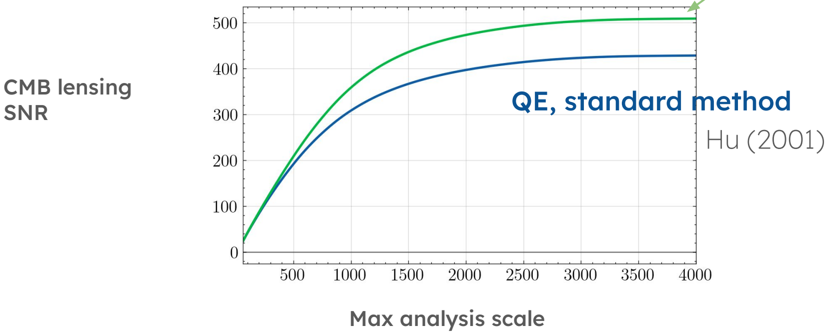
~400σ

Adapted from **Sebastian Belkner**

and new optimal **MAP, Bayesian methods**

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

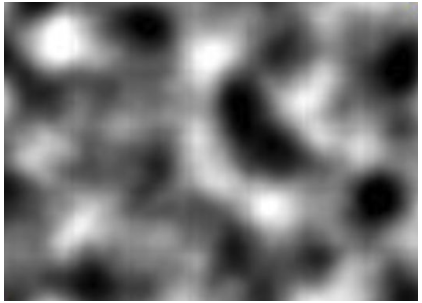
Polarization will be key



See Sayan's talk

CMB gravitational lensing gives you a

clean projected mass map of a non-Gaussian clumpy universe



Primordial non-Gaussianity

Neutrino masses

Going beyond GR/LCDM through growth of structure?

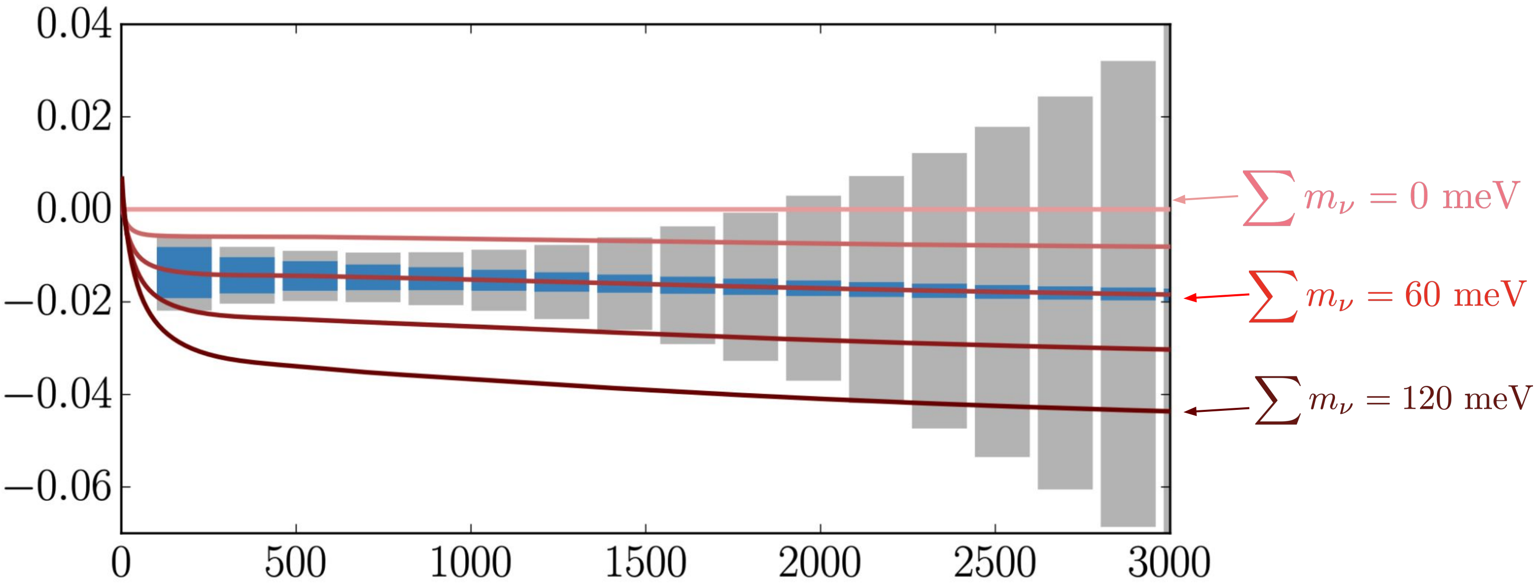
Exploring the dark sector

See David’s talk

See Blake’s talk

Detecting sum of neutrino masses

Fractional difference in power of projected mass fluctuations



Scale

CMB-S4 Science book

CMB-S4 ~ 4σ detection

Impact of a non-zero CMB lensing bispectrum

Consider the observed CMB four point function

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

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

CMB lensing bispectrum

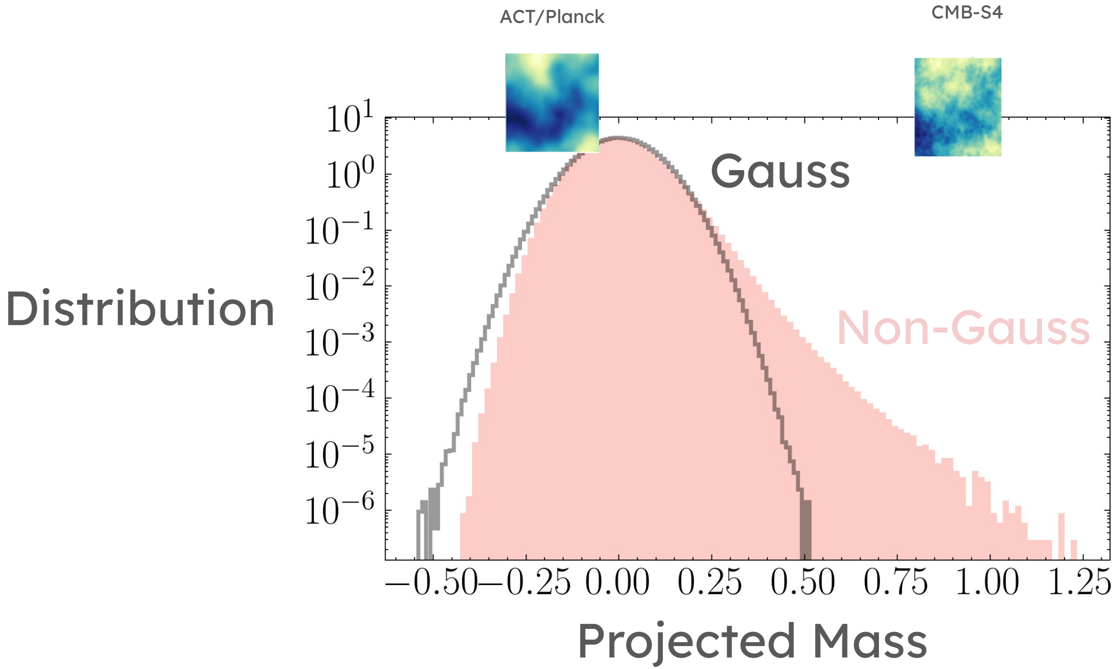
Bohm, Schmittfull, Sherwin (2016)
Fabbian, Lewis, Beck (2019)

$$\widehat{C_L^{\kappa\kappa}} \propto \left[C_L^{\hat\kappa\hat\kappa} - \left(B^{\rm gaussCMB} + B^{\kappa^2} + B^{\rm foregrounds} + B^{\kappa,\rm nG} + \ldots \right) \right]$$

Is $B^{\kappa,\rm nG}$ important?

*here we treat as bias, but could be also a signal

What is the impact of non-linearities on CMB lensing power spectrum **estimates**?



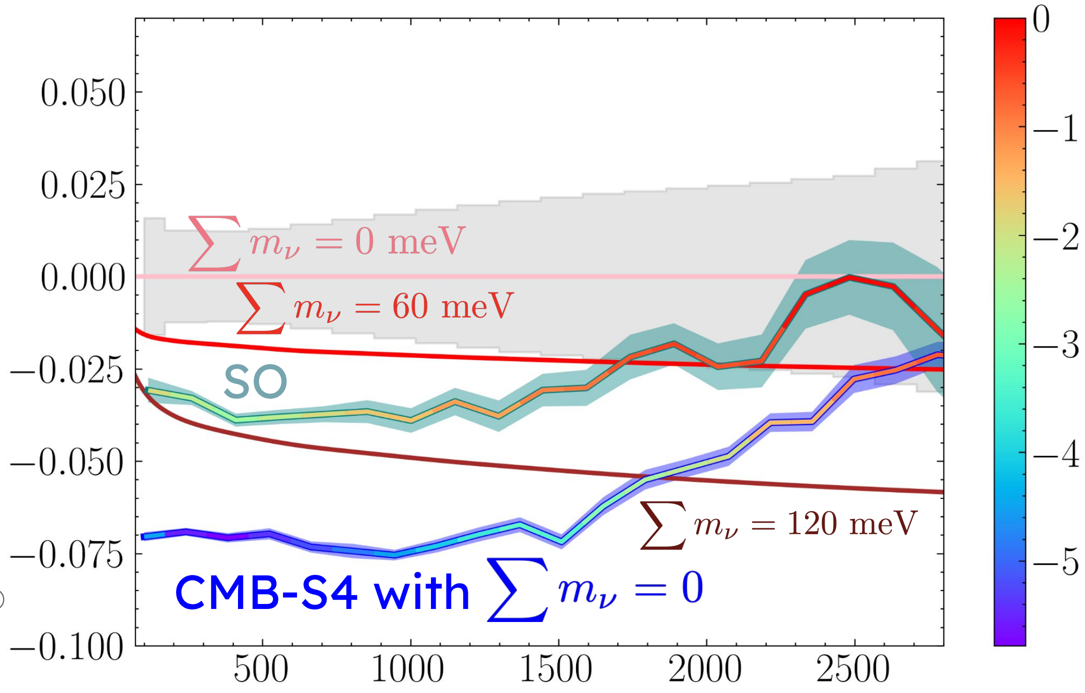
Non-zero **signal** bispectrum $\langle \kappa\kappa\kappa \rangle$ from **large-scale structure** and **post-Born** propagates into the CMB lensing spectra

See Mathew's and Antony's talks

Pratten, Lewis (2016)

Impact of LSS non-Gaussianity of CMB lensing

Fractional difference in power of projected mass fluctuations



Bias per mode (sigma unit)

Use realistic simulations (credit G. Fabbian)

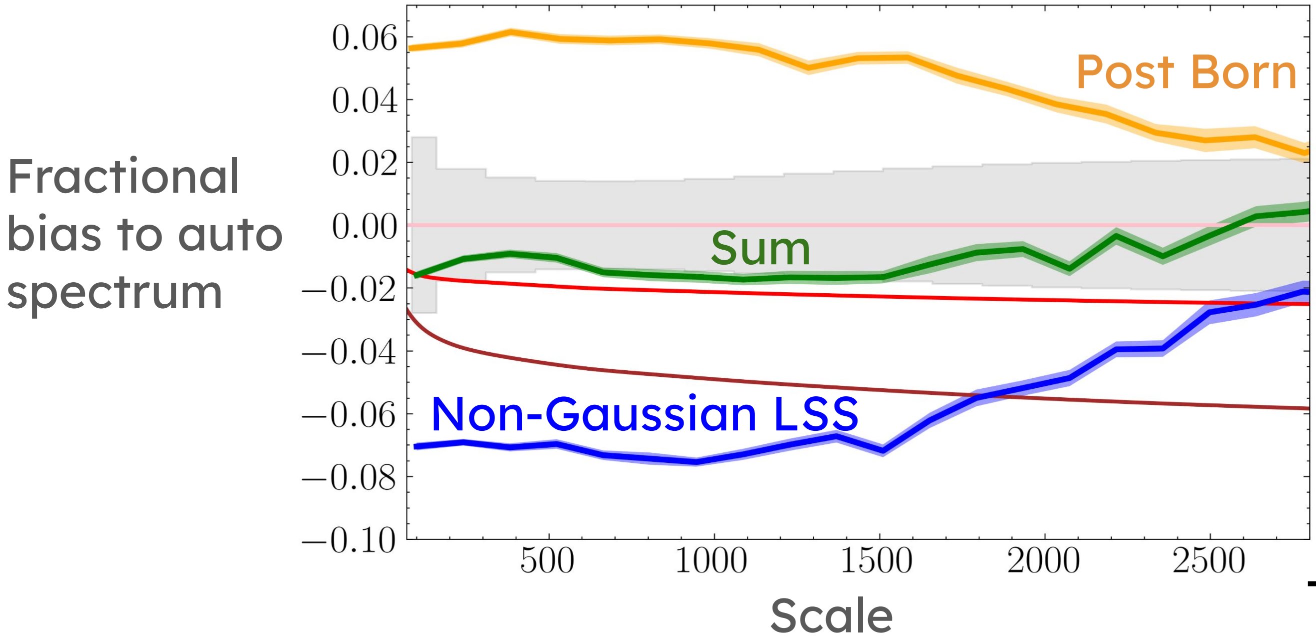
Bohm, Schmittfull, Sherwin (2016)
Fabbian, Lewis, Beck (2019)

Temperature only

Is there a way to mitigate this?

Especially relevant for cross-correlations.

CMB lensing auto-spectrum

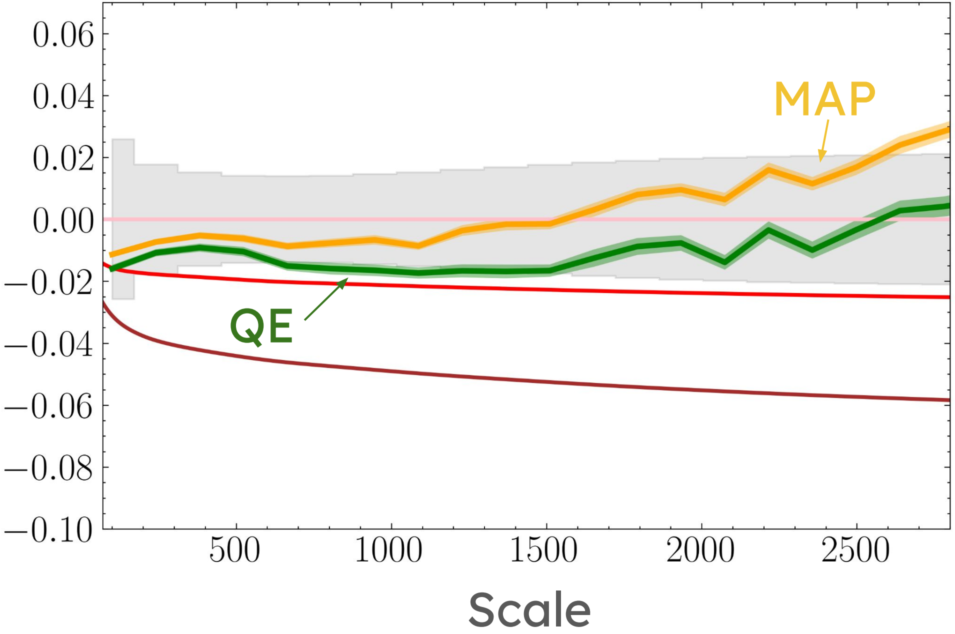


Bohm, Schmittfull, Sherwin (2016)
Bohm, Sherwin, et al. (2018)
Beck, Fabbian, Errard (2018)
Fabbian, Lewis, Beck (2019)

Temperature only

Impact of non-Gaussian deflections

Fractional bias to auto spectrum



Temperature only

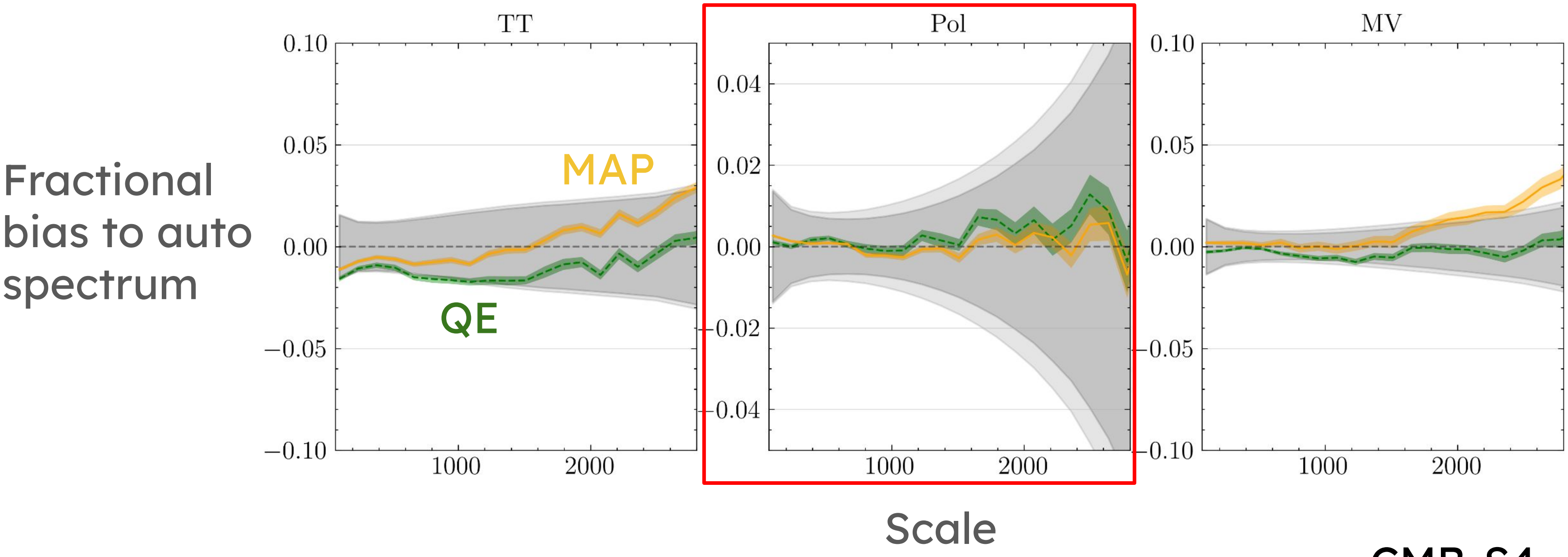
Sir D.Lensalot

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

Belkner, Carron, et al. (2023)

Mitigation with polarization

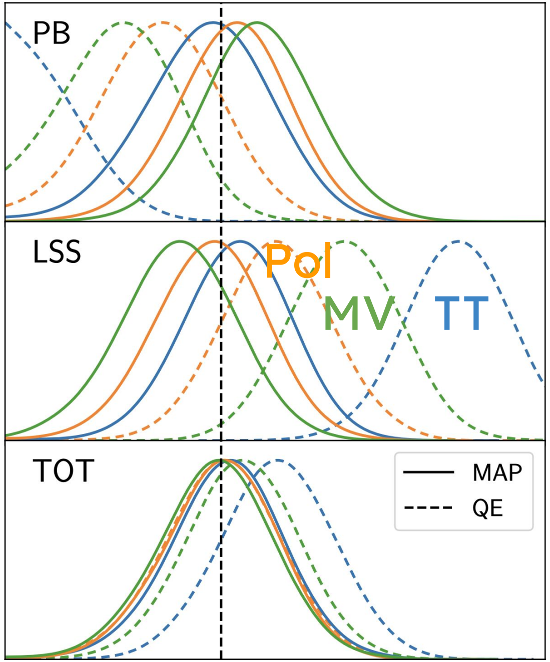
Works well for both QE and MAP



CMB-S4

Beck, Fabbian, Errard (2018)
Fabbian, Lewis, Beck (2019)

Impact of non-Gaussian deflections



Sum of neutrino masses

Relevant for high redshift sources

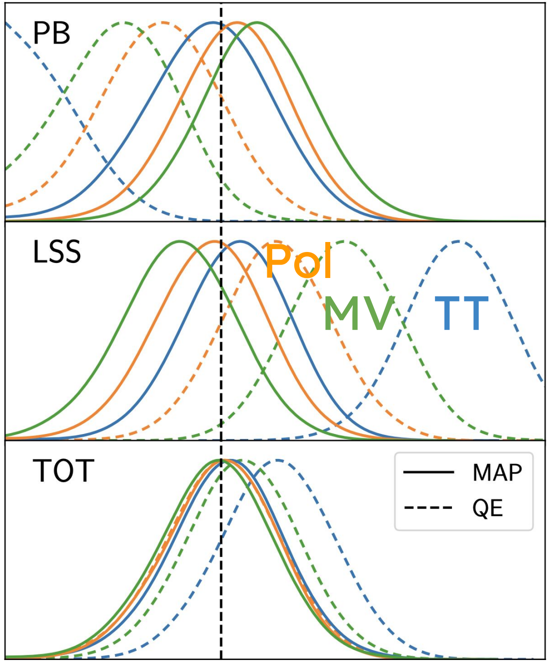
Relevant for CMB lensing cross-correlations

Nice cancellation for **CMB lensing auto-correlation**

(credit Louis Legrand)

Impact of non-Gaussian deflections

Do we need to get rid off temperature, or limit number of modes used?

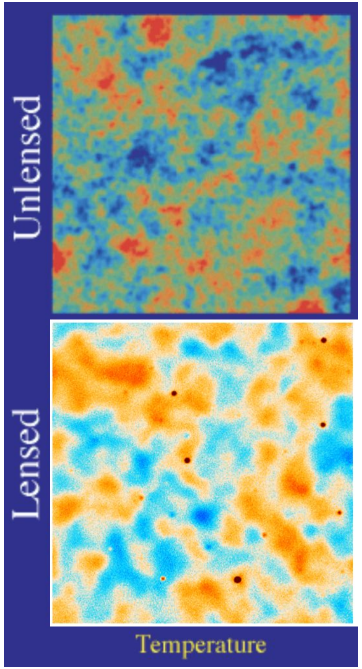


Sum of neutrino masses

Temperature useful for:

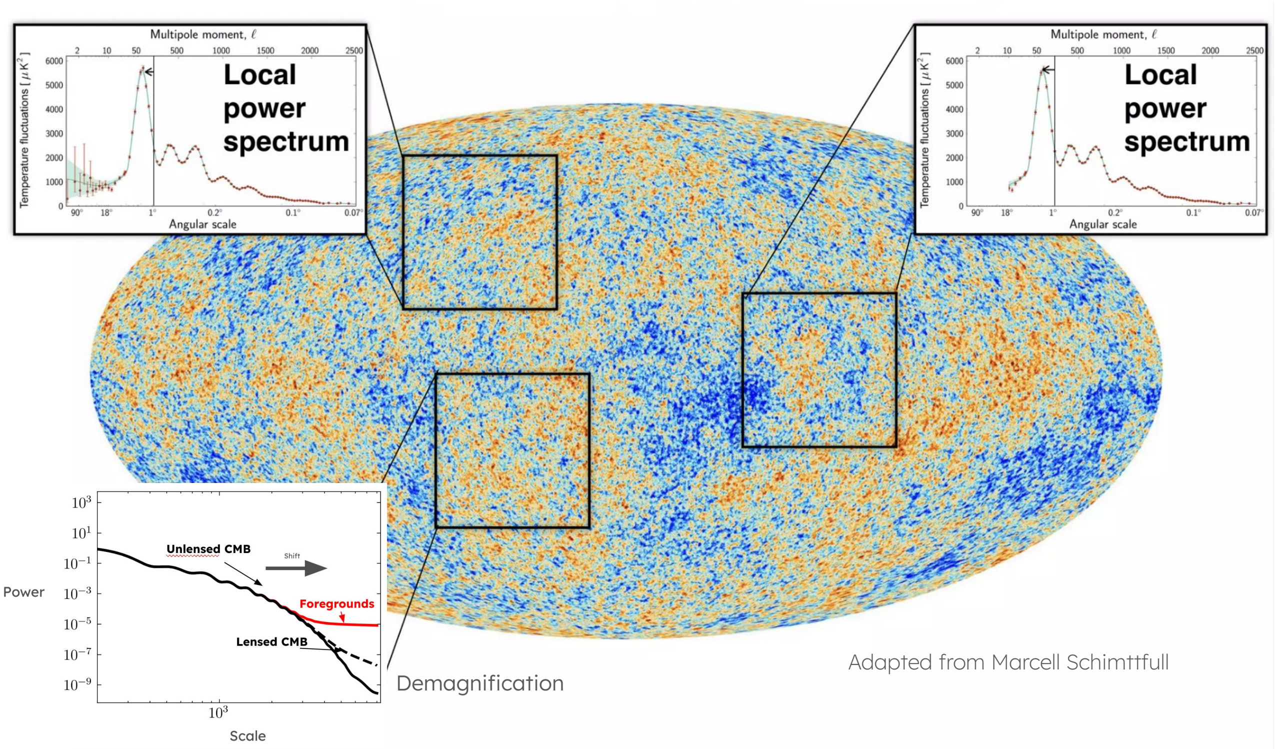
- SO
- delensing
- cross-correlations SNR when going on smaller scales
- check consistency between TT and Pol

Foreground geometric deprojection



Adapted from Wayne Hu and ACT

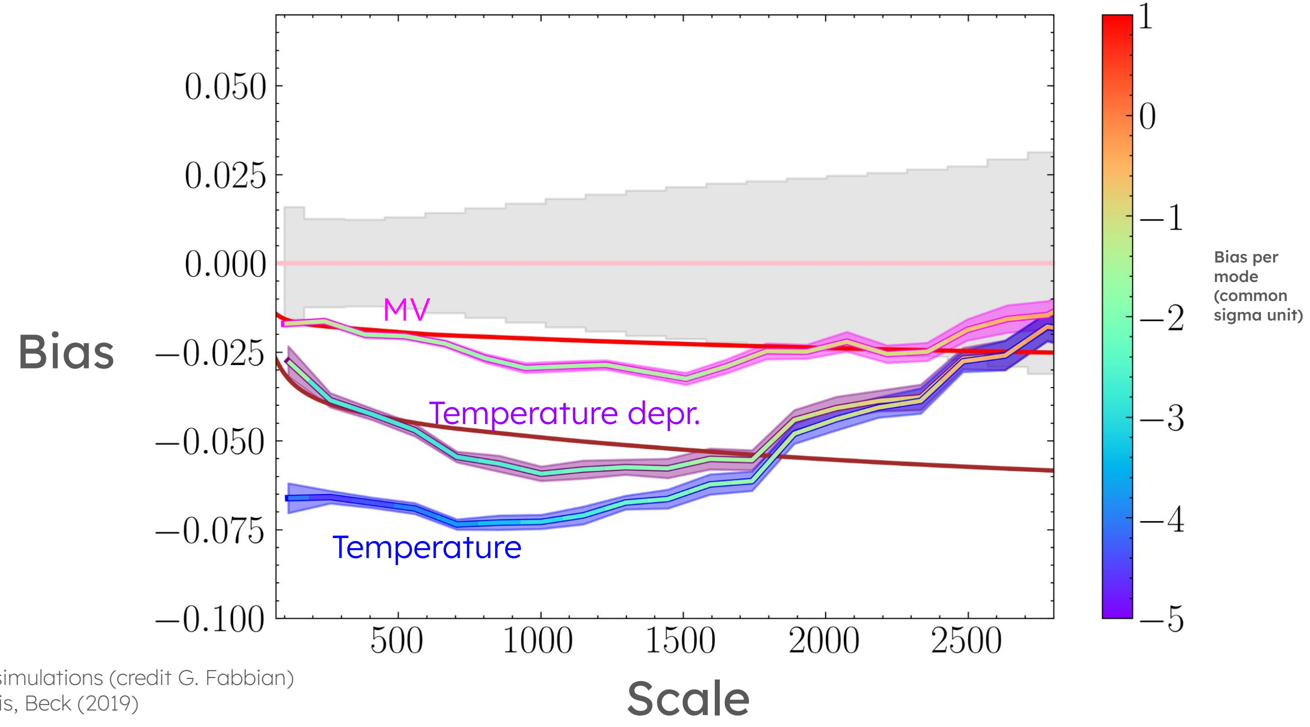
As seen from current ground based surveys



Adapted from Marcell Schimttfull

Contamination makes CMB lensing estimator thinks there is an underdensity!
Reconstructs fake lens -> remove part of this from your total lens estimate

Foreground deprojection on CMB lensing non-Gaussianity



See Julien's talk for generalizations of foregrounds deprj.

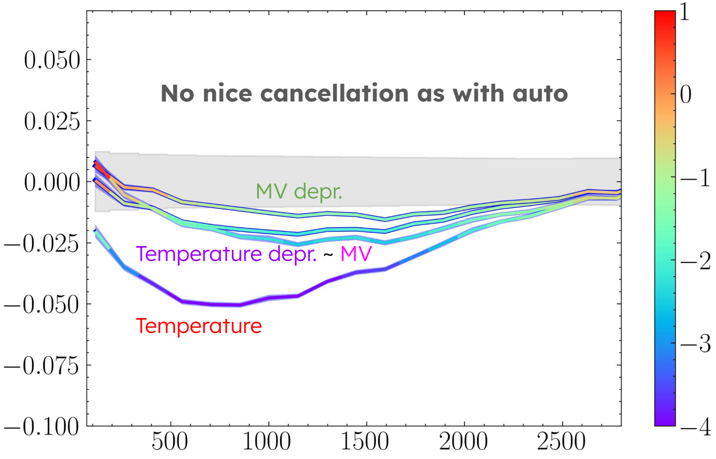
Polarization ~ shear (and bigger lenses wrt T) -> robust to biases

Use realistic simulations (credit G. Fabbian)
Fabbian, Lewis, Beck (2019)

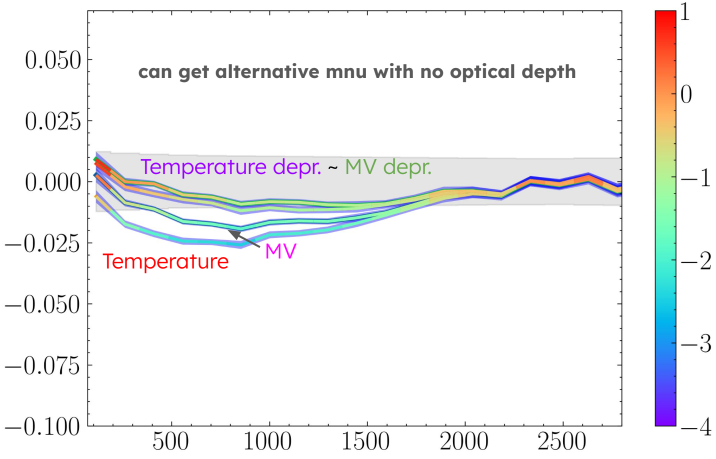
Cross-correlations with galaxies

(galaxy map generated by **Mathew Robertson**)

CMB-S4



SO



Bias per mode (common sigma unit)

Bias

Scale

Scale

Preliminary

What happens when combining multiple bins? (e.g. for Euclid)

Conclusions

- Control over biases for new generation of CMB lensing analyses is crucial
- **Mitigation can be achieved** in a variety of ways, **without sacrificing temperature** useful information -> explore mitigation techniques
  - can also theoretically model
  - use simple lognormal simulations
- Cross-correlations studies will play a big role -> study impact on joint analysis in several bins
- Will be interesting to exploit the bispectrum/nG, and/or enhance this with external probes (cleaning)

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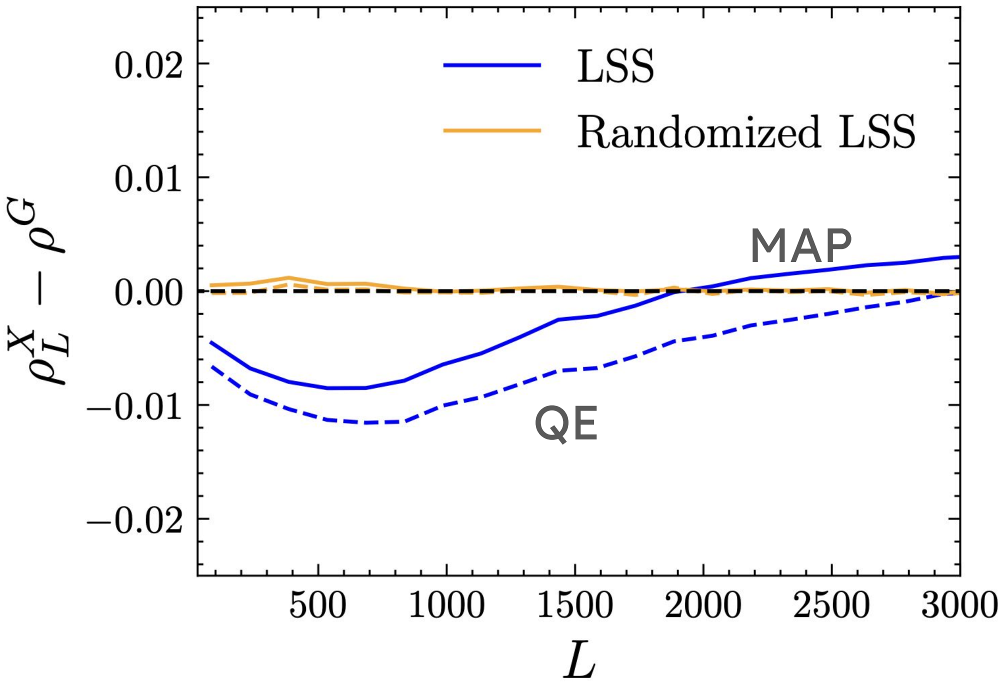
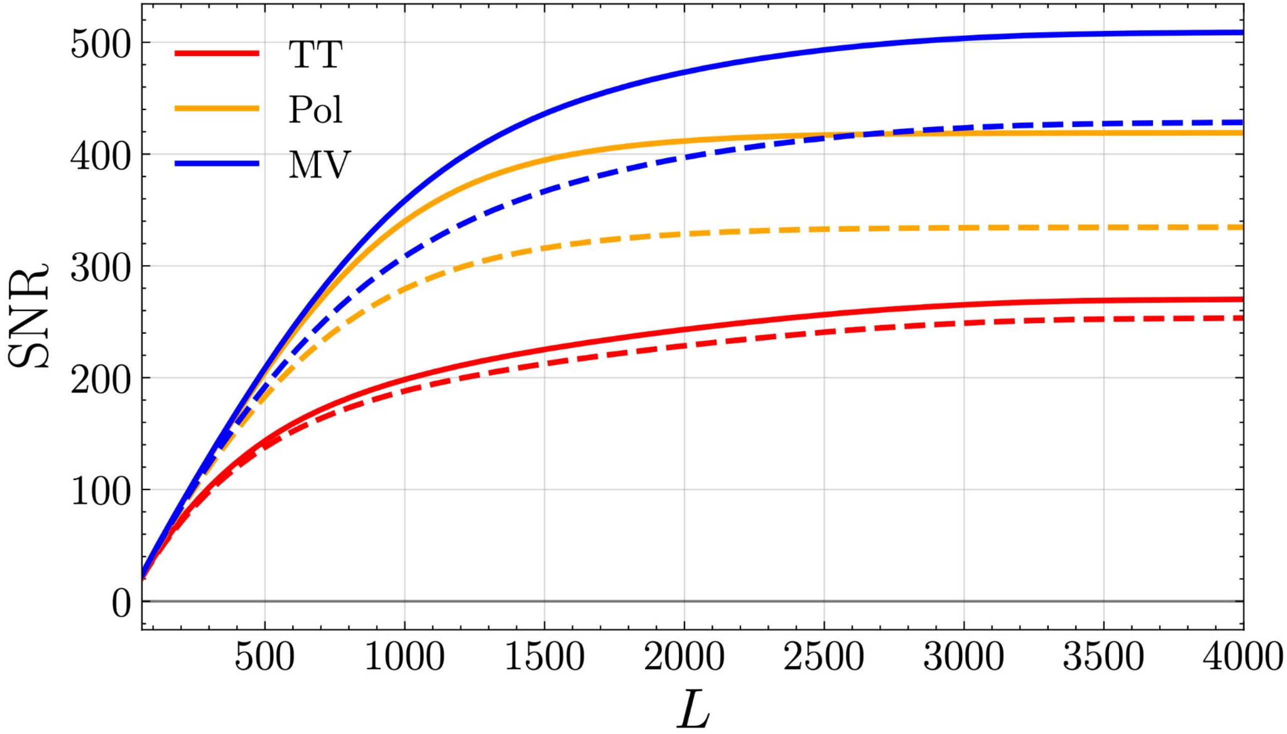
Extras

Fidelity of the reconstruction

Difference in the cross-correlation coefficient with the input simulation

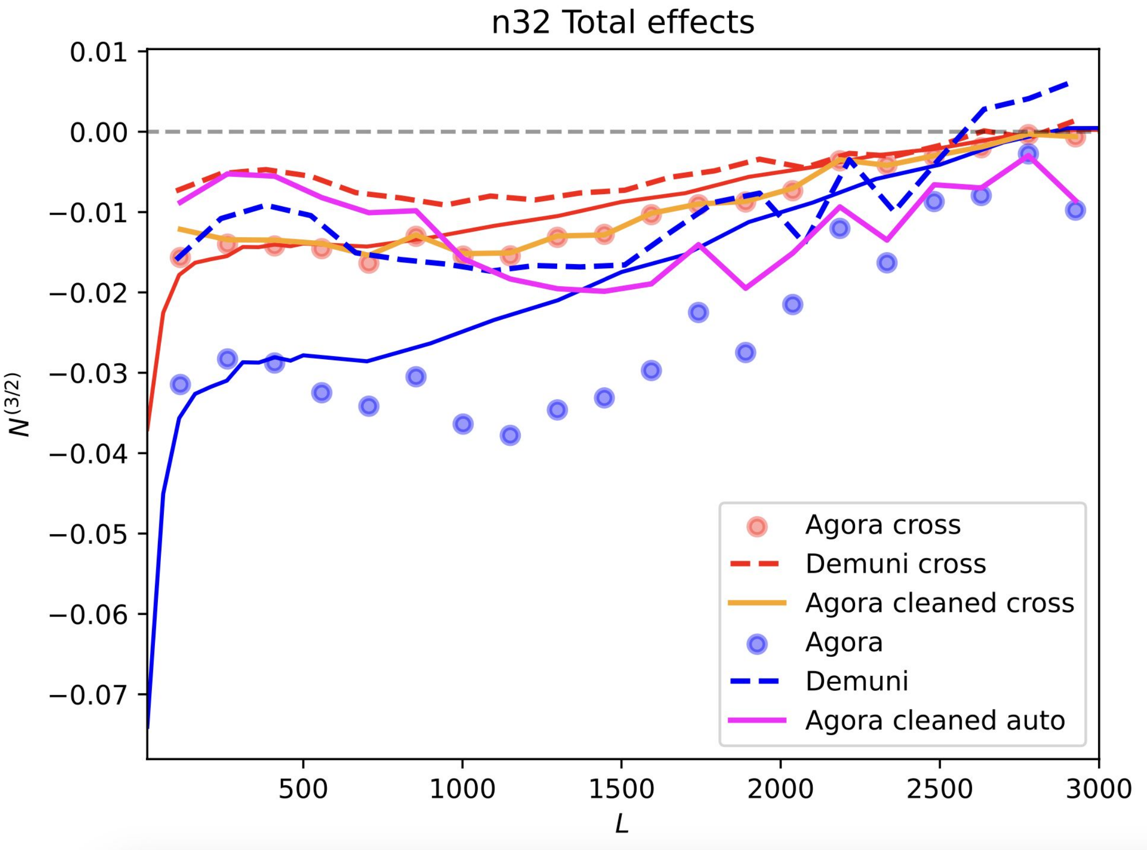


SNR



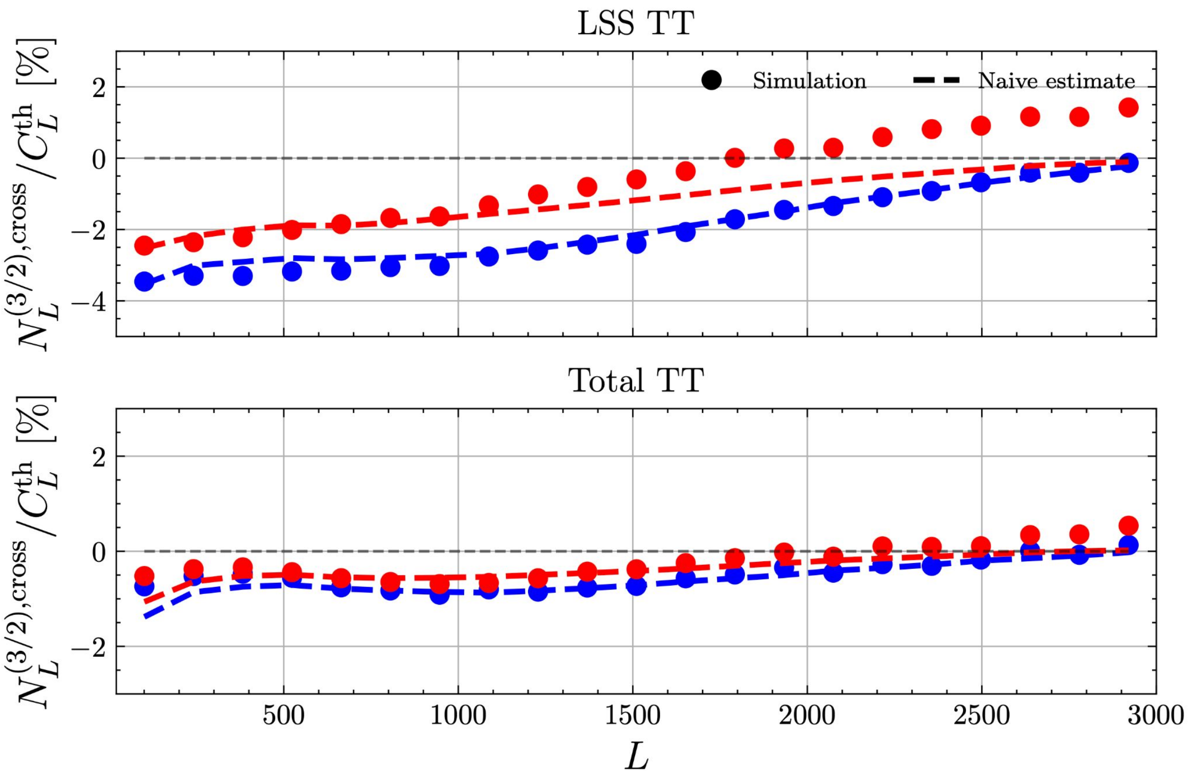
TT
Pol
MV
SNR
0
100
200
300
400
500
500
1000
1500
2000
2500
3000
3500
4000
L

Cleaning a projected mass map



Use CIB from Agora

Theory



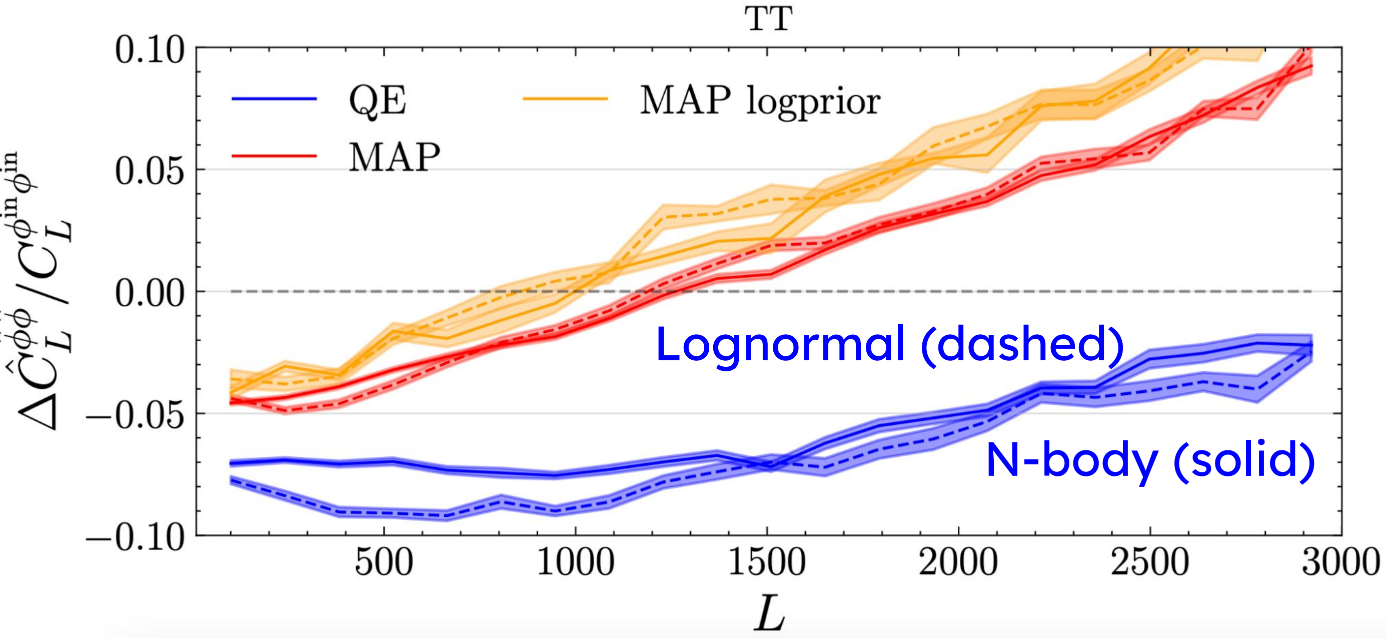
MAP

QE

Using GM bispectrum fit for LSS.

Modelling with lognormal simulations

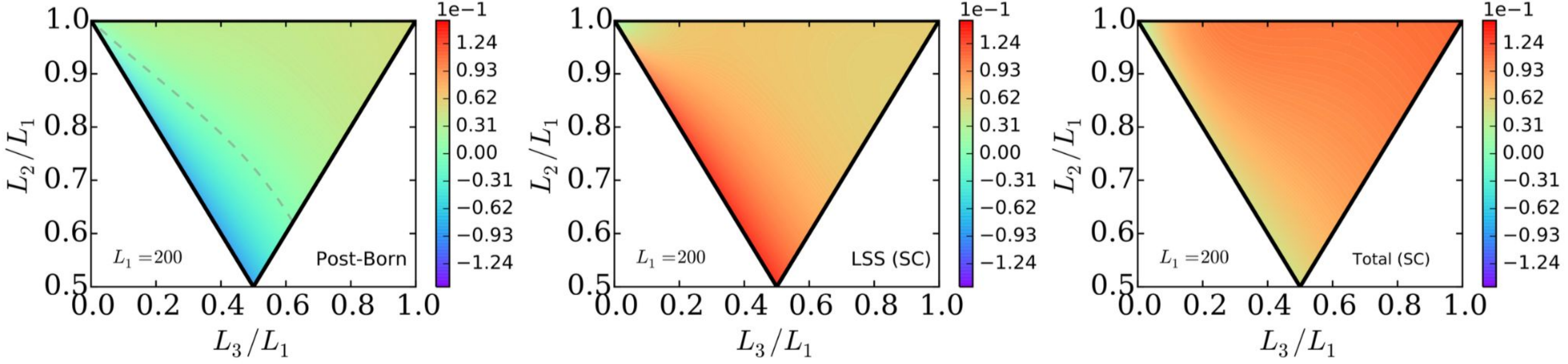
Fractional bias to auto spectrum



Scale

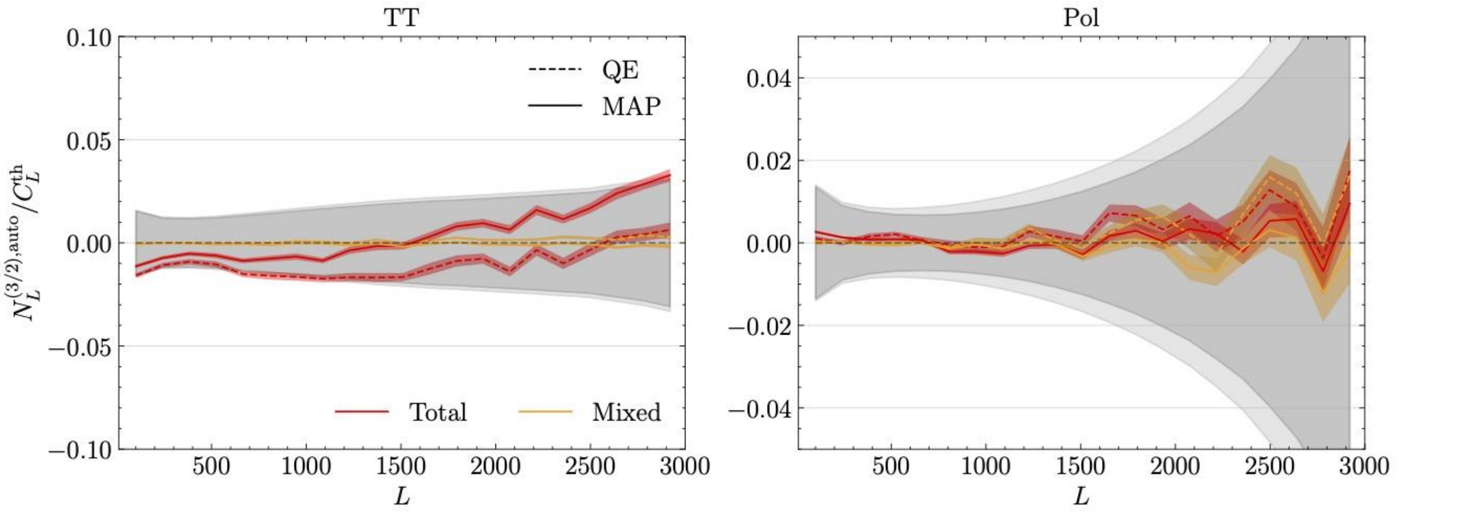
CMB-S4

CMB lensing Bispectrum

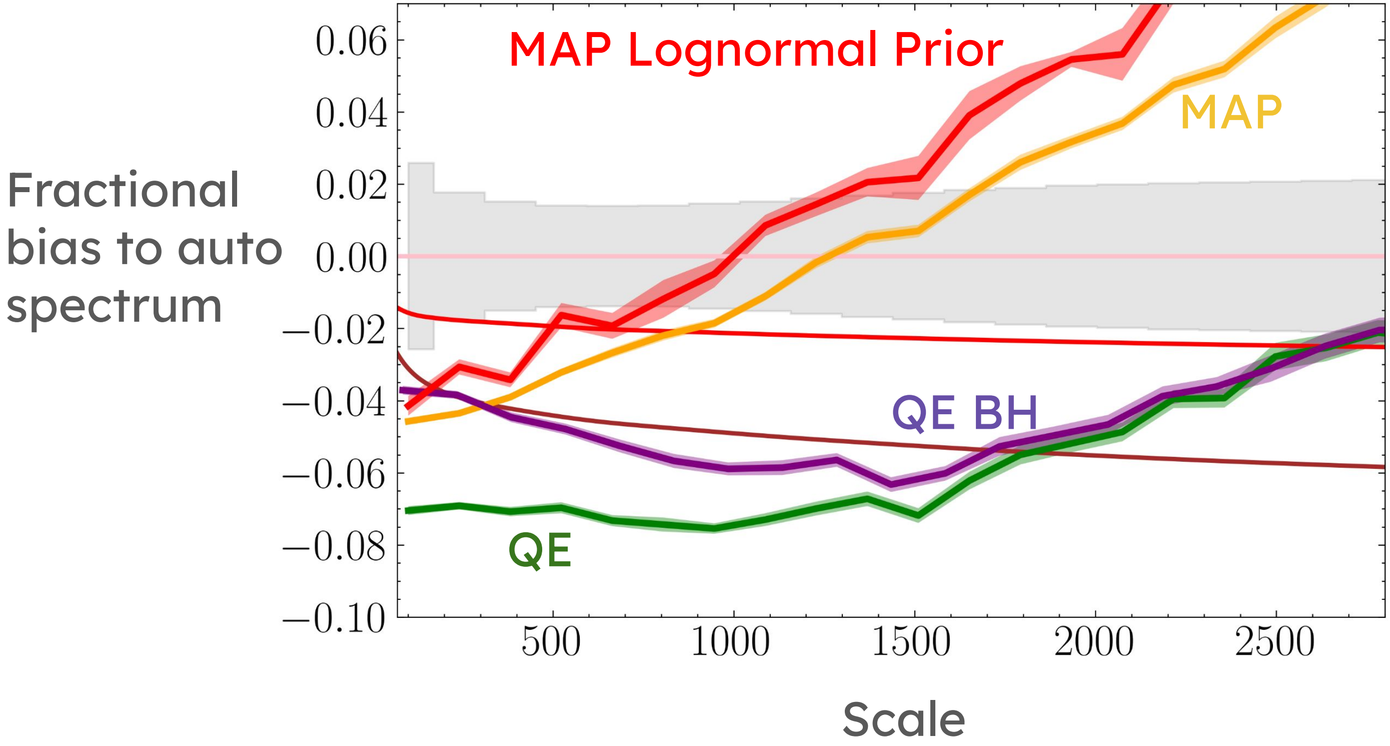


Pratten, Lewis (2016)

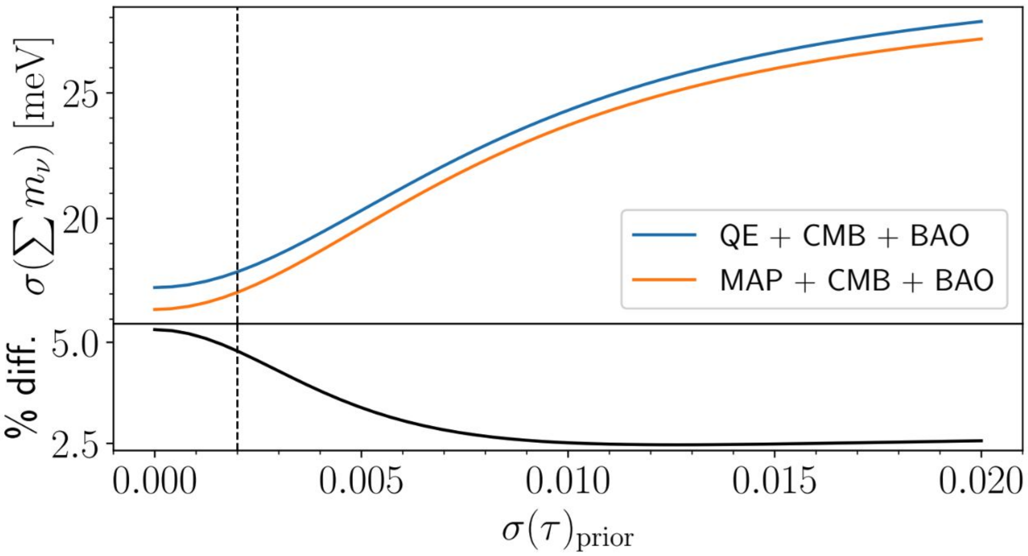
Joint Potential-Curl reconstruction



Alternative estimators, LSS Case



Impact of tau prior



Credits Louis Legrand

Bias Hardening MAP

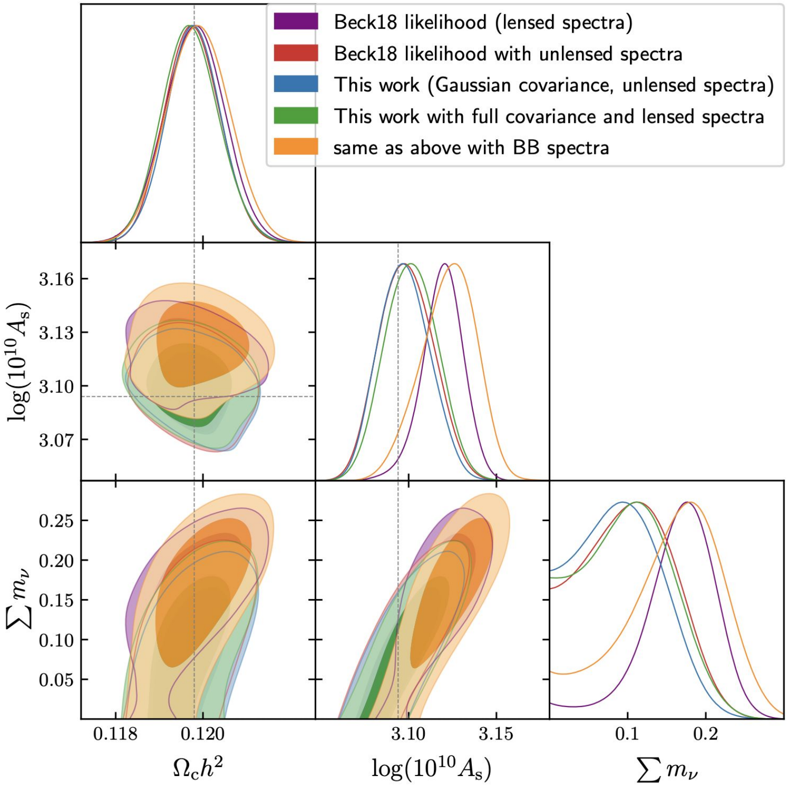
The log-likelihood becomes then

$$\mathcal{L} \equiv \ln L(X^{\rm dat}|\vec{\alpha}, S^2) = -\frac{1}{2} X^{\rm dat} \cdot {\rm Cov}^{-1}_{\vec{\alpha},S^2} X^{\rm dat} - \frac{1}{2} \det {\rm Cov}_{\vec{\alpha},S^2} \ . \quad (4)$$

In the end we have something of the form

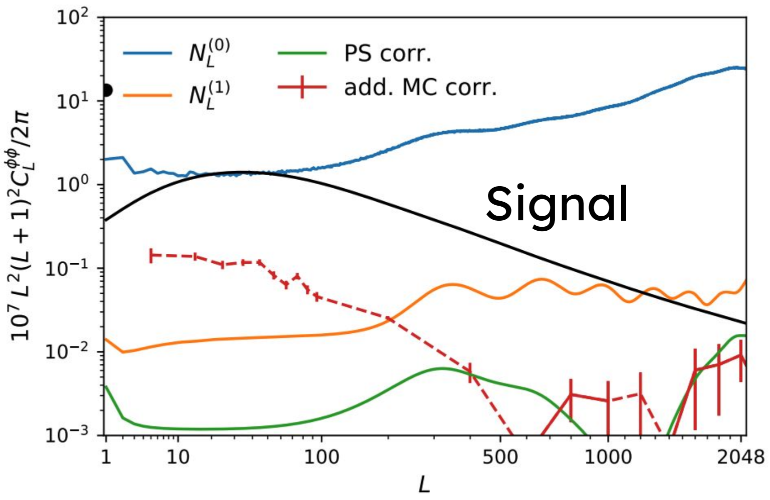
$$\begin{bmatrix} \hat{\phi} \\ \widehat{S^2} \end{bmatrix} = \begin{bmatrix} \frac{1}{C^{\phi\phi}_{\vec{L}}} \frac{1}{1-\rho^2_{\vec{L}}} & \frac{1}{C^{\phi S^2}_{\vec{L}}} \frac{\rho^2_{\vec{L}}}{1-\rho^2_{\vec{L}}} \\ \frac{1}{C^{\phi S^2}_{\vec{L}}} \frac{\rho^2_{\vec{L}}}{1-\rho^2_{\vec{L}}} & \frac{1}{C^{S^2 S^2}_{\vec{L}}} \frac{1}{1-\rho^2_{\vec{L}}} \end{bmatrix}^{-1} \begin{bmatrix} \frac{\delta \mathcal{L}}{\delta \phi}\Big|_{\phi=\hat{\phi}, S^2=\widehat{S^2}} \\ \frac{\delta \mathcal{L}}{\delta S^2}\Big|_{\phi=\hat{\phi}, S^2=\widehat{S^2}} \end{bmatrix}$$

Comparing likelihoods



Biases to CMB lensing studies

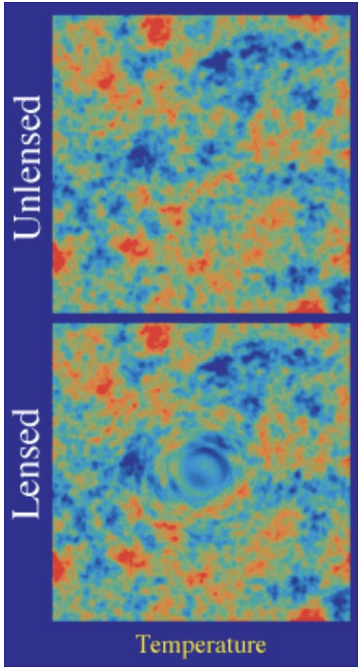
- Gaussian bias
- Foregrounds bias
- Noise bias
- Mask bias
- Beam bias
- kappa^2 bias
- .....



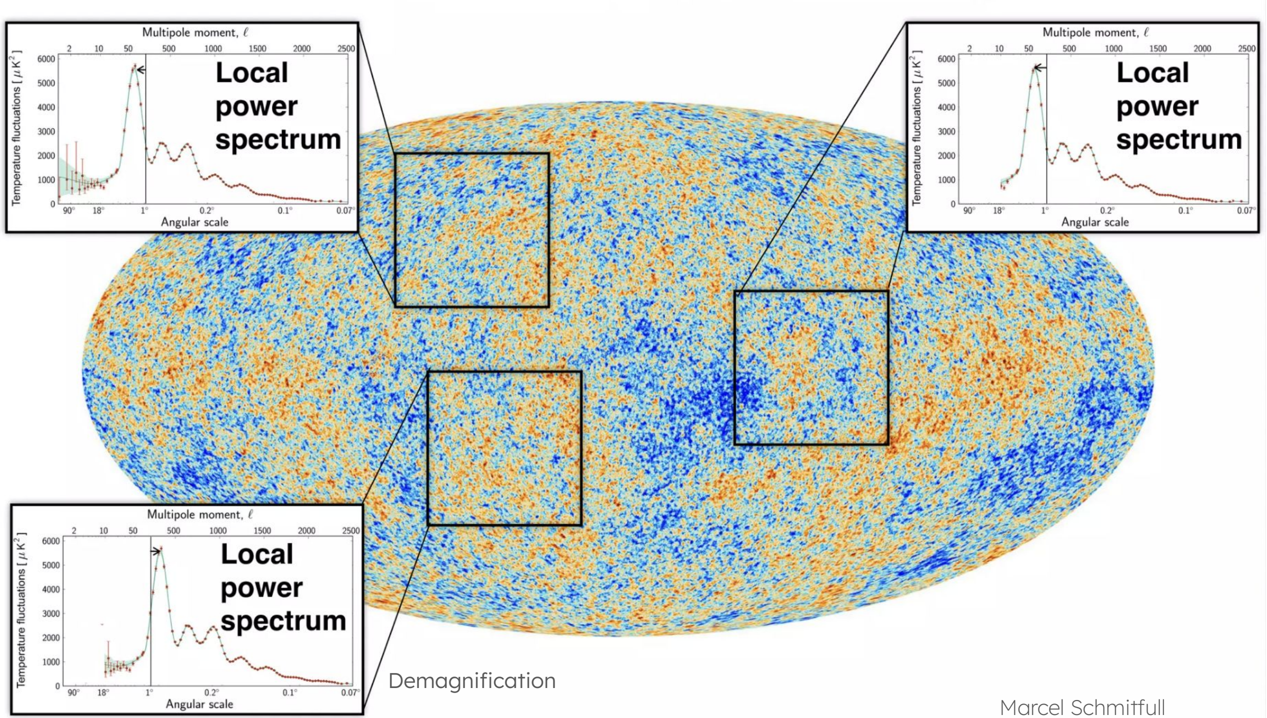
Carron & Planck Collaboration (2020)

$$\langle \hat{\kappa}\hat{\kappa} \rangle \sim \langle T_{\rm obs} \times T_{\rm obs} T^{'}_{\rm obs} \times T^{'}_{\rm obs} \rangle$$

QE CMB lensing reconstruction



Wayne Hu



Marcel Schmittfull

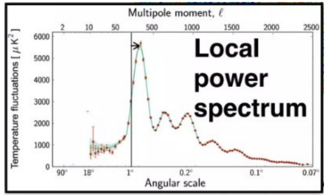
Large lens modulates small scale CMB power spectrum ->
look at shifts in the power spectrum to reconstruct the lens ~ $T_{\rm CMB} T_{\rm CMB}$

In particular

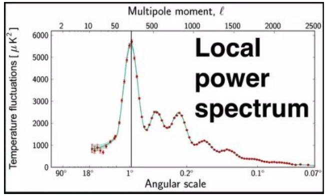
the QE CMB lensing estimator

by construction does not look for $\kappa^2, \ldots$

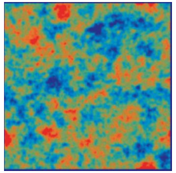
while optimal MAP methods can include all of the information
by iterating the QE procedure several times



→ ...



→



CMB lensing power spectrum

Lens estimate

$$\hat{\kappa}(\vec{L}) \sim T_{\rm obs} \times T_{\rm obs}$$

gives a raw auto-spectrum

$$\langle \hat{\kappa}\hat{\kappa} \rangle \sim \langle T_{\rm obs} \times T_{\rm obs} T^{'}_{\rm obs} \times T^{'}_{\rm obs} \rangle$$

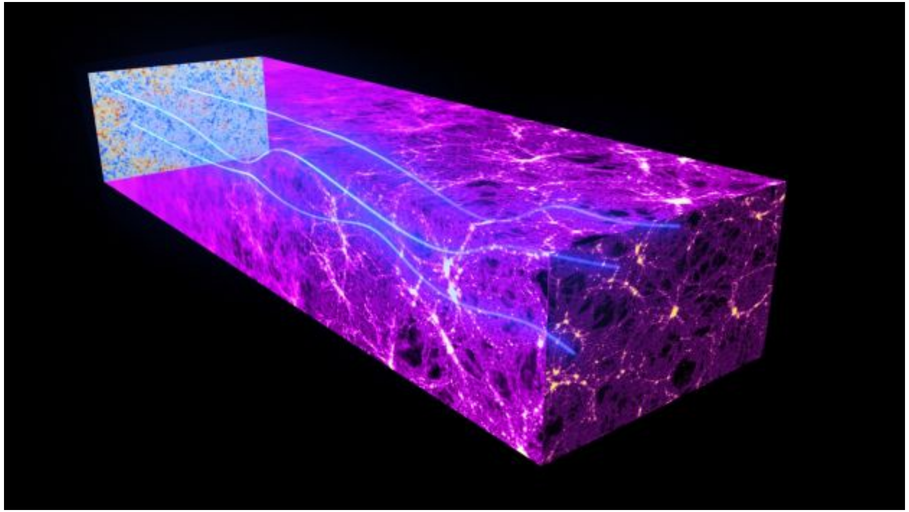
$$\supset C_L^{\kappa\kappa} + \langle T^{\rm u}_{\rm CMB} T^{\rm u}_{\rm CMB} T^{\rm u}_{\rm CMB} T^{\rm u}_{\rm CMB} \rangle + ... + \langle T_{\rm f} T_{\rm f} T_{\rm f} T_{\rm f} \rangle + ...$$

Signal

Chance (Gaussian) CMB fluctuations

Dominant foreground power

Beyond Gaussian mass map

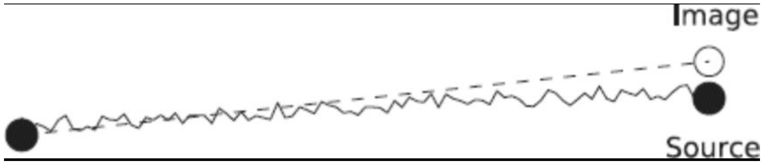


ESA and the Planck Collaboration

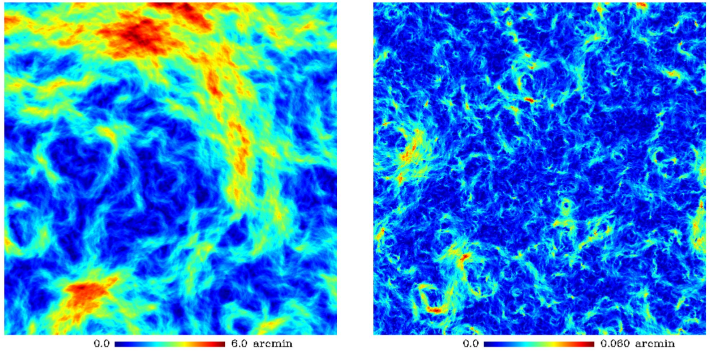
Projected non-Gaussian large scale structure

See Mathew's and Antony's talk

Is single deflection approximation good enough?



Credit S. Dodelson



Amplitude of Post Born corrections

Credit G. Fabbian

See Mathew's and Antony's talk

Pratten, Lewis (2016)

Use QE CMB lensing estimator

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

Maximize

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

First step of a Newton iteration starting from no lensing

The QE CMB lensing estimator

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

by construction misses info in $\phi^2,\ \ldots.$

but also $XXX,\ XXXX,\ \ldots$

MAP CMB lensing estimator

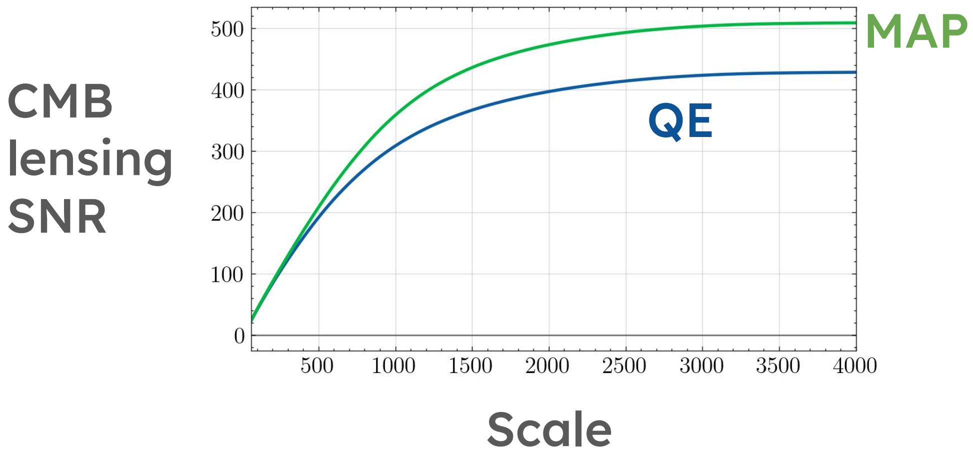
$$\ln p \supset -\frac{1}{2}X^{\rm dat}\cdot {\rm Cov}_{\kappa}^{-1}{\rm X}^{\rm dat} - \frac{1}{2}{\rm detCov}_{\kappa} + \ln {\rm p}_{\rm prior}$$

⇓ **Maximize**

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

Carron, Lewis (2017)

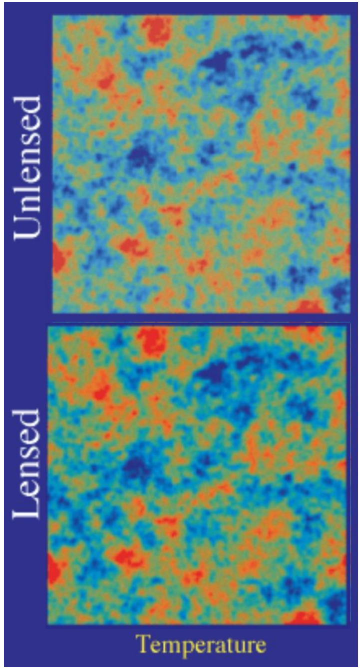
MAP CMB lensing estimator

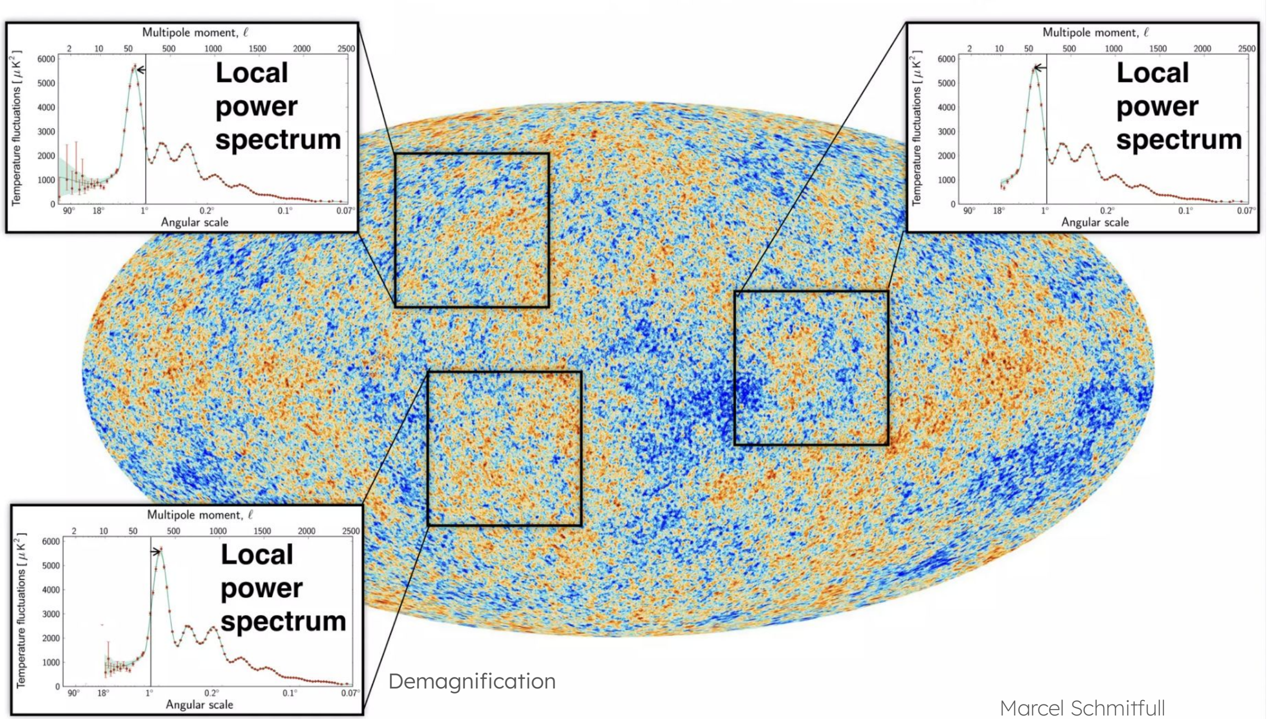


$$\hat{\kappa}_{\mathrm{MAP}} \sim \bar{X}^{\mathrm{dat}}_{\hat{\kappa}_{\mathrm{MAP}}} \bar{X}^{\mathrm{dat}}_{\hat{\kappa}_{\mathrm{MAP}}} \times \mathrm{Norm}$$

Carron, Lewis (2017)

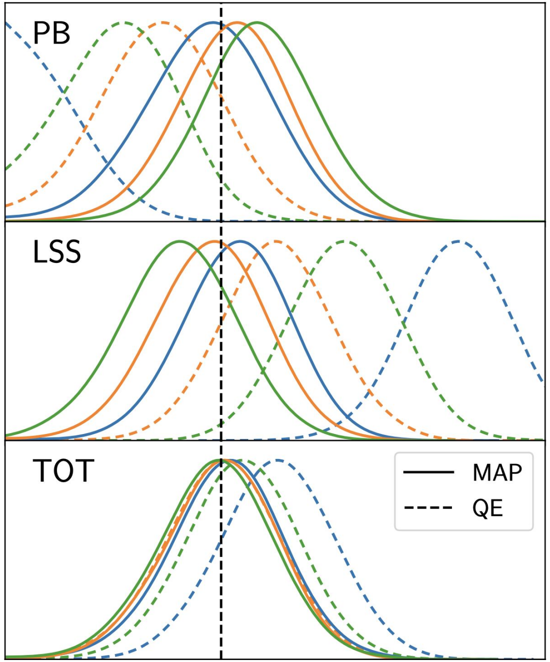
QE CMB lensing reconstruction





Chance CMB Gaussian fluctuation makes CMB lensing estimator think there is a lens.
Reconstructs noise fake lens.

Impact of non-Gaussian deflections

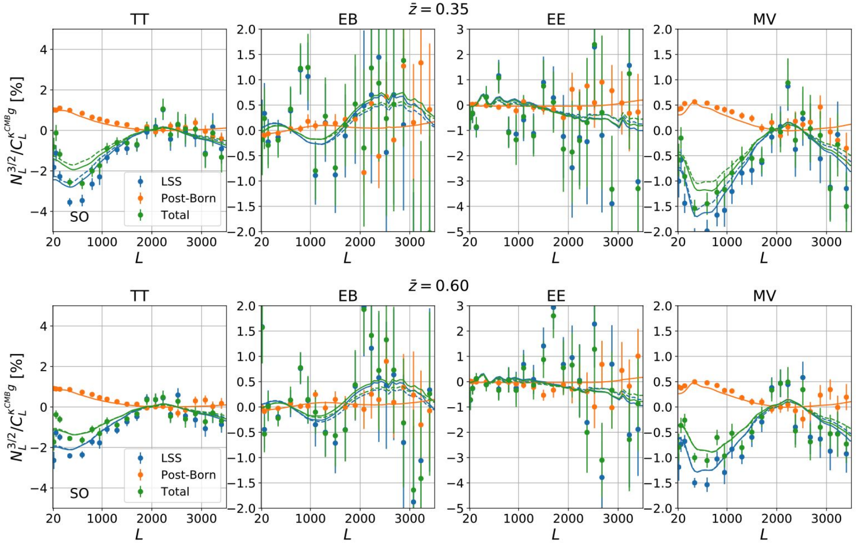


Sum of neutrino mass

Important for CMB lensing cross-correlations

Nice cancellation for CMB lensing auto-correlation

Cross-correlations with QE



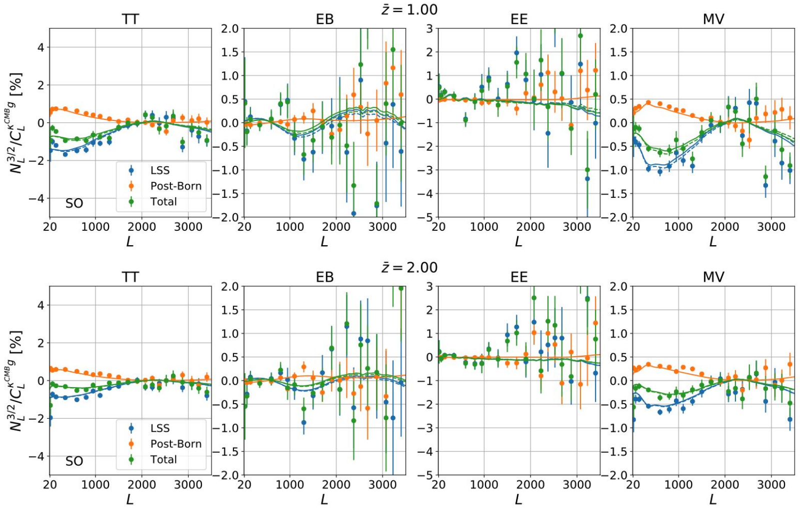


Figure 12: Fractional $N_L^{(3/2)}$ bias for the cross-correlation power spectrum between the reconstructed CMB lensing potential of SO and galaxy density at different redshift bins. The redshift increases moving from top to bottom. Theoretical predictions using GM fitting formulae for the matter bispectrum 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

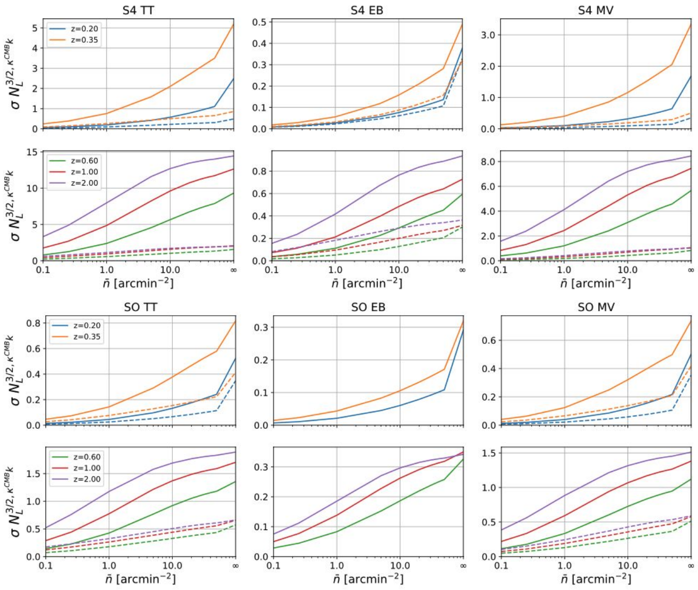


Figure 15: Detection significance of $N_L^{(3/2)}$ measured in simulations for cross-correlation between the reconstructed CMB lensing and galaxy lensing as a function of the shot noise in an LSS survey (solid). Results for S4 (SO) are shown in the upper (lower) panels. LSST/Euclid-like surveys have $\bar{n} \approx 3$, 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).