Science and Technology Facilities Council

The University of Manchester

Paving the Way Towards a Robust B-mode Measurement

Joel Williams - christopher.williams-4@manchester.ac.uk

Overview

1. B-mode contamination from cosmology
   A. The example of cosmic polarization rotation
   B. Introduce the idea of QEs using the example of CPR
   C. B-mode contamination from cosmic polarisation rotation
2. Blind systematics cleaning using QEs
   A. Detailed Case study of differential gain
   B. The important lessons from this case study
   C. The power of this technique for robust *r* recovery

Instrument Systematics
and Cosmological Effects

↓

Distortions in CMB maps

↓ ⇡ QE reconstruction

Off-Diagonal Correlations

$\left(\left\langle a^{X}_{lm} a^{X'}_{l'm'} \right\rangle \neq 0 \text{ for } l \neq l'\right)$

Cosmic Polarization Rotation

$$\underbrace{{}_{\pm}X(\hat{\mathbf{n}})}_{(Q \pm iU)(\hat{\mathbf{n}})} = {}_{\pm}\tilde{X}(\hat{\mathbf{n}})e^{\pm i2\alpha(\hat{\mathbf{n}})}$$

Carroll et. al. (1990)

Cosmic Polarization Rotation

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Cosmological Birefringence

$$\mathscr{L}_{CS} = -g_{\phi\gamma\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\alpha(\hat{\mathbf{n}}) = \frac{g_{\phi\gamma\gamma}}{2}\int d\eta \left(\frac{\partial}{\partial\eta} + \hat{\mathbf{n}}\cdot\nabla\right)\phi(\eta,\hat{\mathbf{n}})$$

Carroll et. al. (1990)

Primordial Magnetic Fields

Faraday rotation

$$\alpha(\hat{\mathbf{n}}) = \frac{3c^2}{16\pi^2 e}\nu^{-2}\int \dot{\tau}\,\mathbf{B}\cdot d\mathbf{l}$$

Pogosian et. al. (2011)

CPR Quadratic Estimator

$$\hat{\alpha}_{LM} = -2N_L \sum_{ll'} \frac{\tilde{C}_{l'}^{EE}}{C_l^{BB} C_{l'}^{EE}} \sum_{mm'} B_{lm}(E_{l'm'})^* \xi_{lml'm'}^{LM} P_E$$

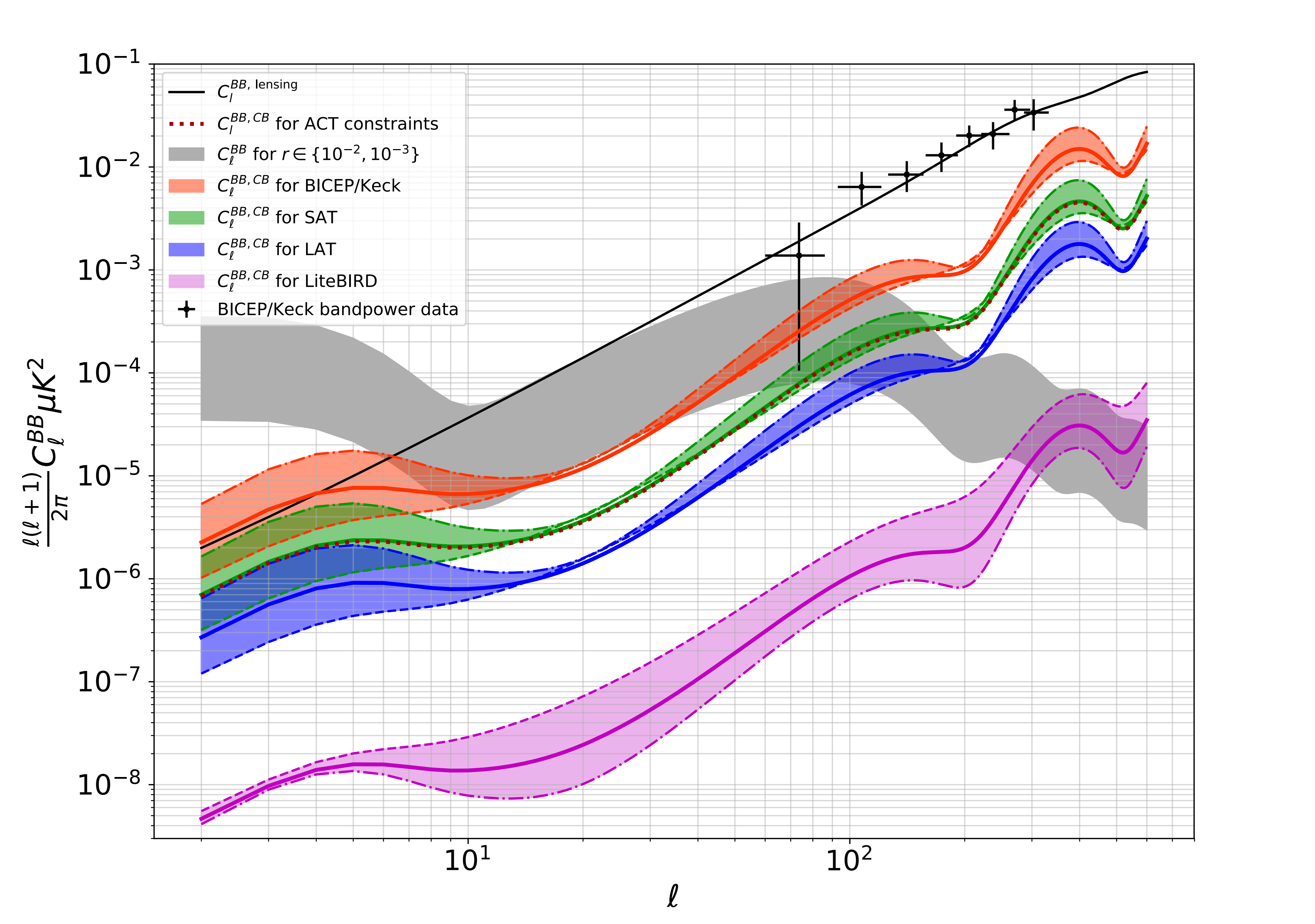
$$N_L = \left[4 \sum_{ll'} \sqrt{\frac{(2l+1)(2l'+1)}{4\pi}} \frac{(\tilde{C}_{l'}^{EE} H_{ll'}^{L})^2}{C_l^{BB} C_{l'}^{EE}} \right]^{-1}$$

Gluscevic et. al. (2009)
Kamionkowski (2009)

CPR as a B-mode contaminant

$$\delta C_l^{BB} = \frac{1}{\pi}\sum_L C_L^{\alpha\alpha}(2L+1)\sum_{l'}(2l'+1)\tilde{C}_{l'}^{EE}(\underbrace{H_{ll'}^L}_{\text{Geometric Term}})^2 P_O + \mathcal{T}_B(B\to B)$$

Pogosian et. al. (2019)



Williams et. al. (2020)

Instrument Systematics → Distortions in CMB maps → Off-Diagonal Correlations

$$ {}_{\pm}X(\hat{\mathbf{n}}) = {}_{\pm}\tilde{X}(\hat{\mathbf{n}}) + {}_{\pm}\delta X(\hat{\mathbf{n}}) $$

Map level distortions from systematics

Yadav et. al. (2010)

Instrument Systematics → Distortions in CMB maps → Off-Diagonal Correlations

$$_{\pm}X(\hat{\mathbf{n}}) = {}_{\pm}\tilde{X}(\hat{\mathbf{n}}) + {}_{\pm}\delta X(\hat{\mathbf{n}})$$

For T to P leakage
from differential gain

$$_{\pm}\delta X(\hat{\mathbf{n}}) = (\gamma^{Q} \pm i\gamma^{U})(\hat{\mathbf{n}})\tilde{T}(\hat{\mathbf{n}})$$

Yadav et. al. (2010)

Instrument Systematics → Distortions in CMB maps → Off-Diagonal Correlations

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Yadav et. al. (2010)

$$(\gamma^Q \pm i\gamma^U)(\hat{\mathbf{n}}) = \frac{1}{2}\overbrace{\tilde{h}_{\pm 2}}^{\text{Scan Strategy}}(\hat{\mathbf{n}})\underbrace{(\delta g_1 \mp i\delta g_2)}_{\text{Differential detector gain}}$$

Williams, McCallum, et. al. (2020) in prep.

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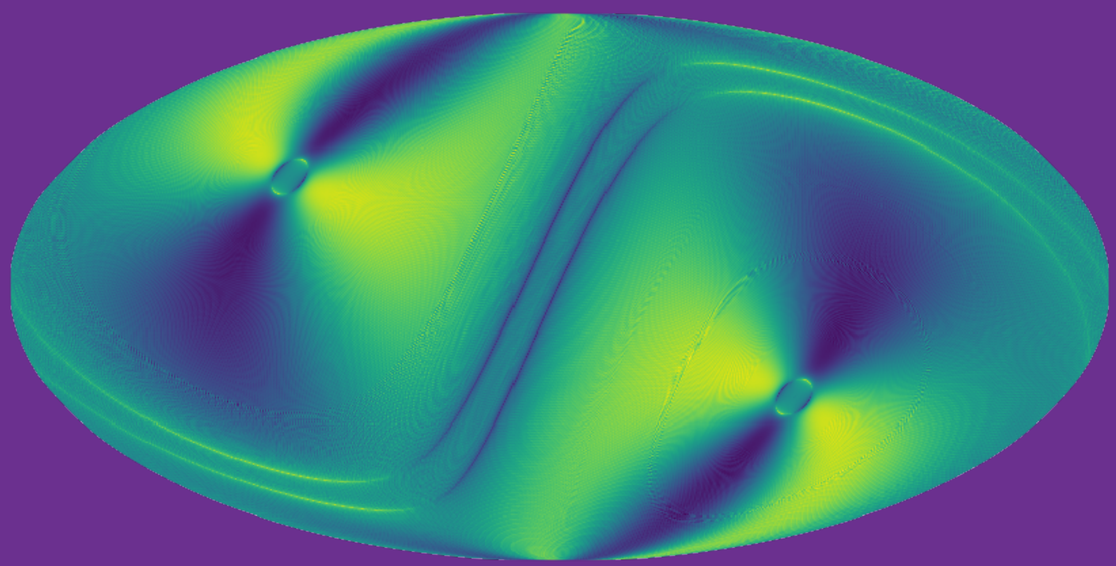
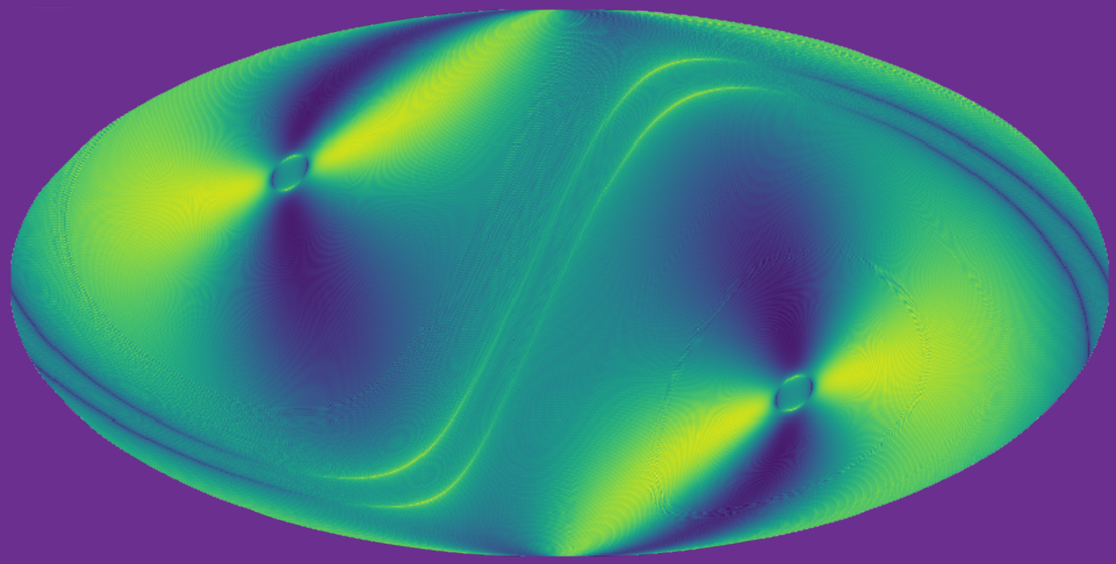
$\gamma^Q(\hat{\mathbf{n}})$



$\gamma^U(\hat{\mathbf{n}})$



Williams, McCallum, et. al. (2020) in prep.

T to P Quadratic Estimators

$$\hat{\gamma}^B_{LM} = N^{\gamma^B}_L \sum_{ll'} \frac{\tilde{C}^{TT}_{l'}}{C^{TT}_{l'} C^{BB}_l} \sum_{mm'} B_{lm}(T_{l'm'})^* {}_+I^{Ll'l}_{Mm'm} P_E$$

$$N^{\gamma^B}_L = \left[\sum_{ll'} \frac{(H^L_{l'l})^2}{(2L+1)} \frac{(\tilde{C}^{TT}_{l'} P_E)^2}{C^{BB}_l C^{TT}_{l'}} \right]^{-1}$$

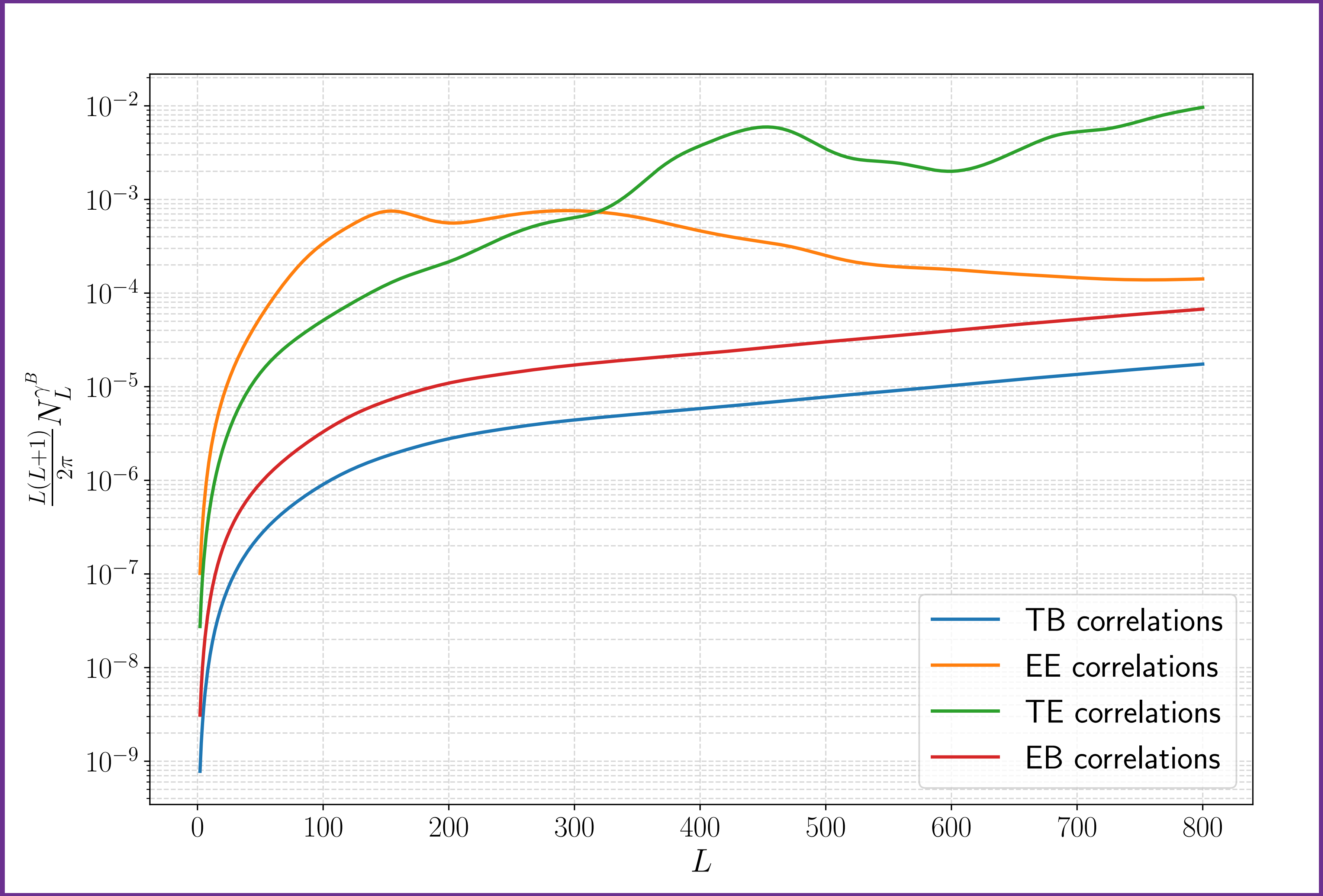
$$\hat{\gamma}^E_{LM} = -\, i N^{\gamma^E}_L \sum_{ll'} \frac{\tilde{C}^{TT}_{l'}}{C^{TT}_{l'} C^{BB}_l} \sum_{mm'} B_{lm}(T_{l'm'})^* {}_+I^{Ll'l}_{Mm'm} P_O$$

$$N^{\gamma^E}_L = \left[\sum_{ll'} \frac{(H^L_{l'l})^2}{(2L+1)} \frac{(\tilde{C}^{TT}_{l'} P_O)^2}{C^{BB}_l C^{TT}_{l'}} \right]^{-1}$$

Which correlations should you use?

***LiteBIRD*-like instrument**

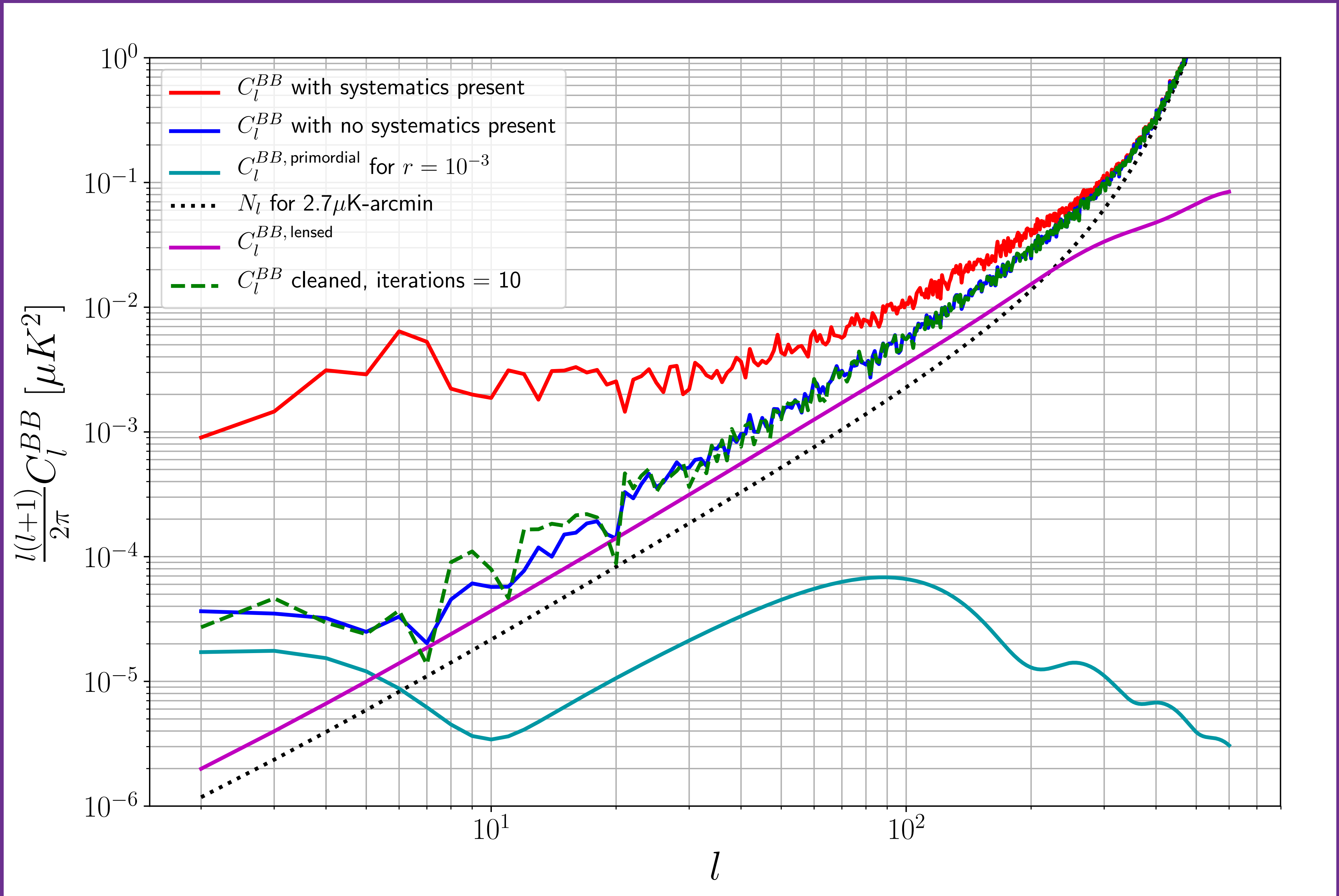
$$w_{TT}^{-1} = 2.7\mu\text{K arcmin}$$
$$\theta_{FWHM} = 30 \text{ arcmin}$$



You have to test to see which is best for each systematic!

Can you clean the B-mode?

$$_{\pm}\tilde{X}(\hat{\mathbf{n}}) = {}_{\pm}X(\hat{\mathbf{n}}) - (\hat{\gamma}^{Q} \pm i\hat{\gamma}^{U})(\hat{\mathbf{n}})T(\hat{\mathbf{n}})$$

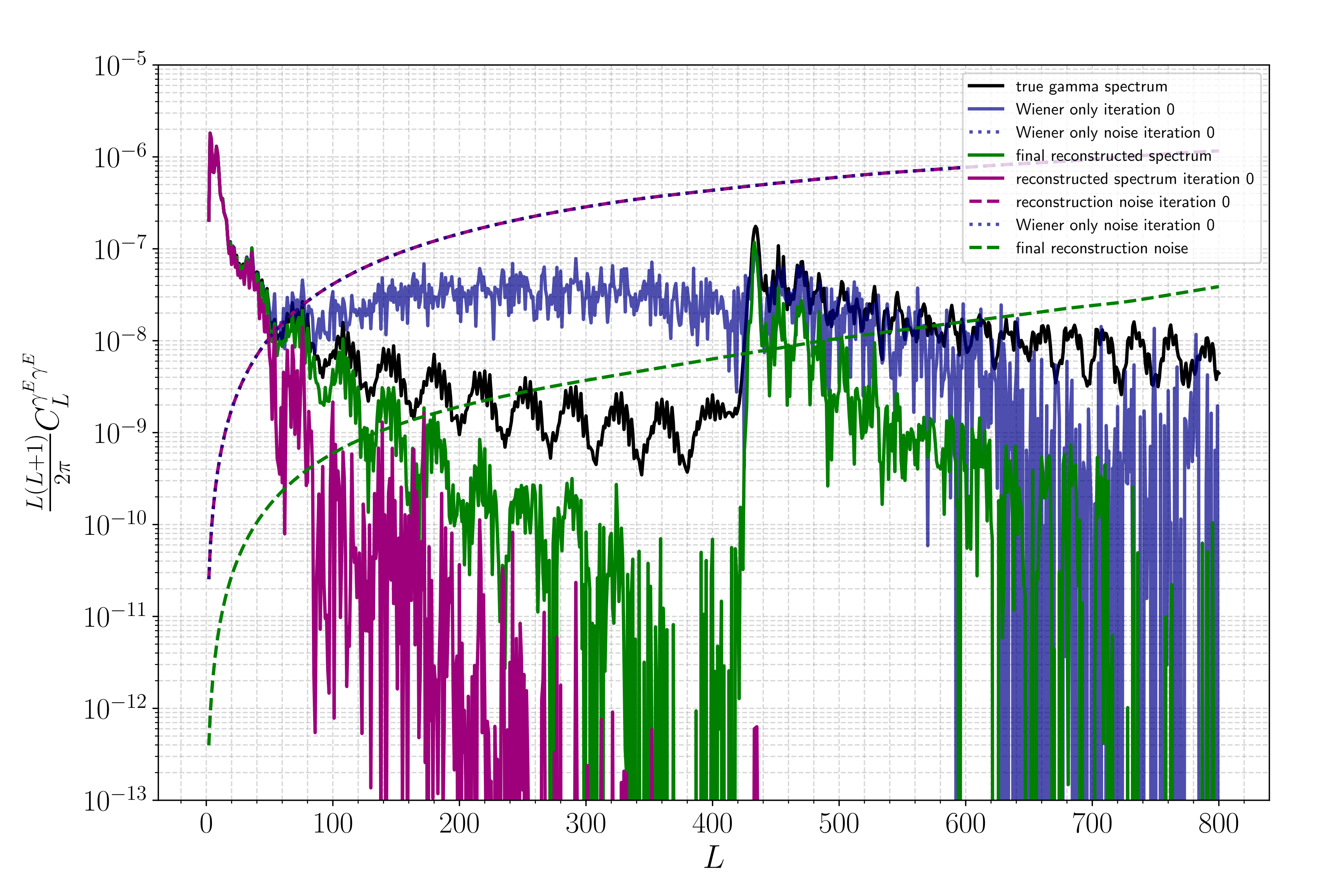


***LiteBIRD*-like instrument**

$w_{TT}^{-1} = 2.7\mu$K arcmin

$\theta_{FWHM} = 30$ arcmin

What filtering should you use?



Wiener Filter:

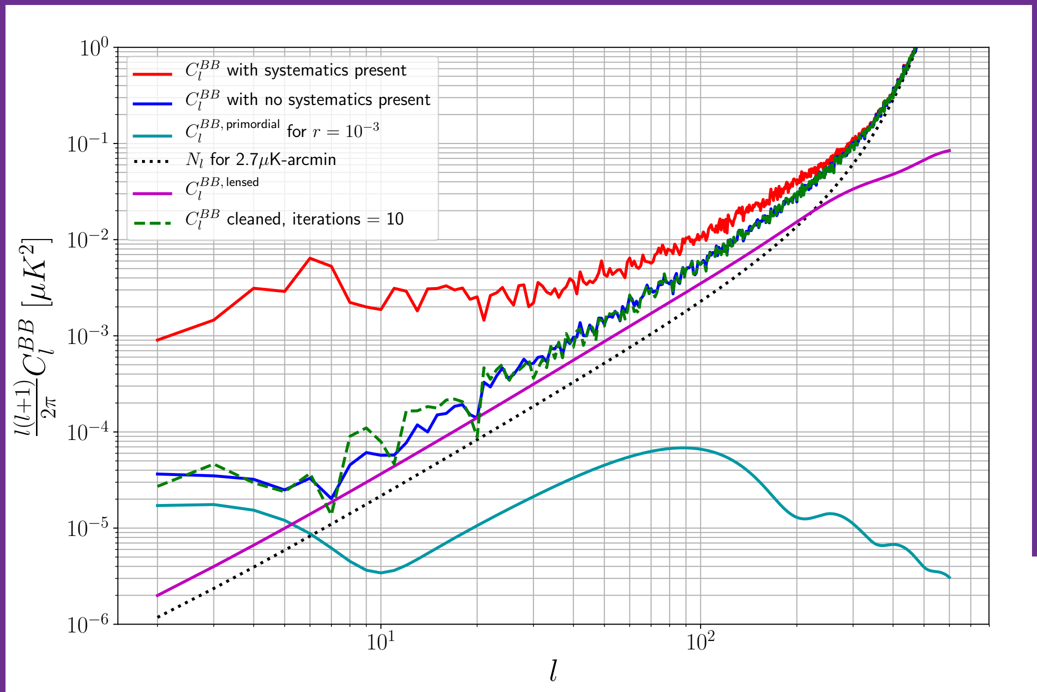
$$f_L^{\gamma^E} = \frac{\hat{C}_L^{\gamma^E\gamma^E} - N_L^{\gamma^E}}{\hat{C}_L^{\gamma^E\gamma^E}}$$

Gaussian Filter:

$$f_L^{\gamma^E} = A\exp\left(-\left[\frac{\hat{C}_L^{\gamma^E\gamma^E}}{\hat{C}_L^{\gamma^E\gamma^E} - N_L^{\gamma^E}}\right]^2\right)$$

The optimum filter is not always the best filter!

Recovering *r*



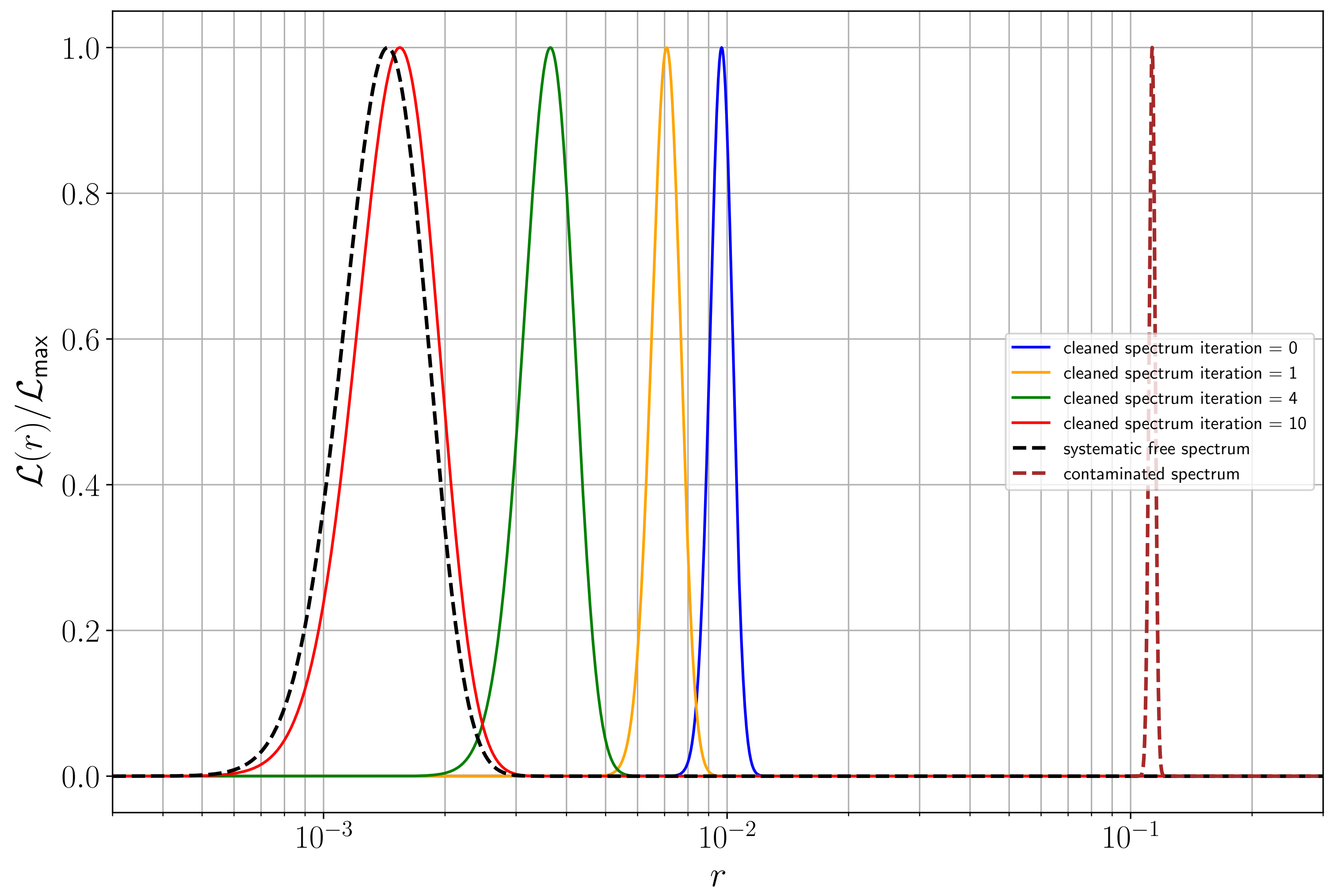
$$\ln \mathscr{L}(r) = A \sum_l (2l+1) \left[\frac{\widehat{C}_l^{BB}}{r\, C_l^{BB,GW} + C_l^{BB,L} + N_l^{BB}} + \ln\left(r\, C_l^{BB,GW} + C_l^{BB,L} + N_l^{BB} \right) - \frac{2l-1}{2l+1} \ln\left(\widehat{C}_l^{BB} \right) \right]$$

Hamimeche and Lewis (2008)

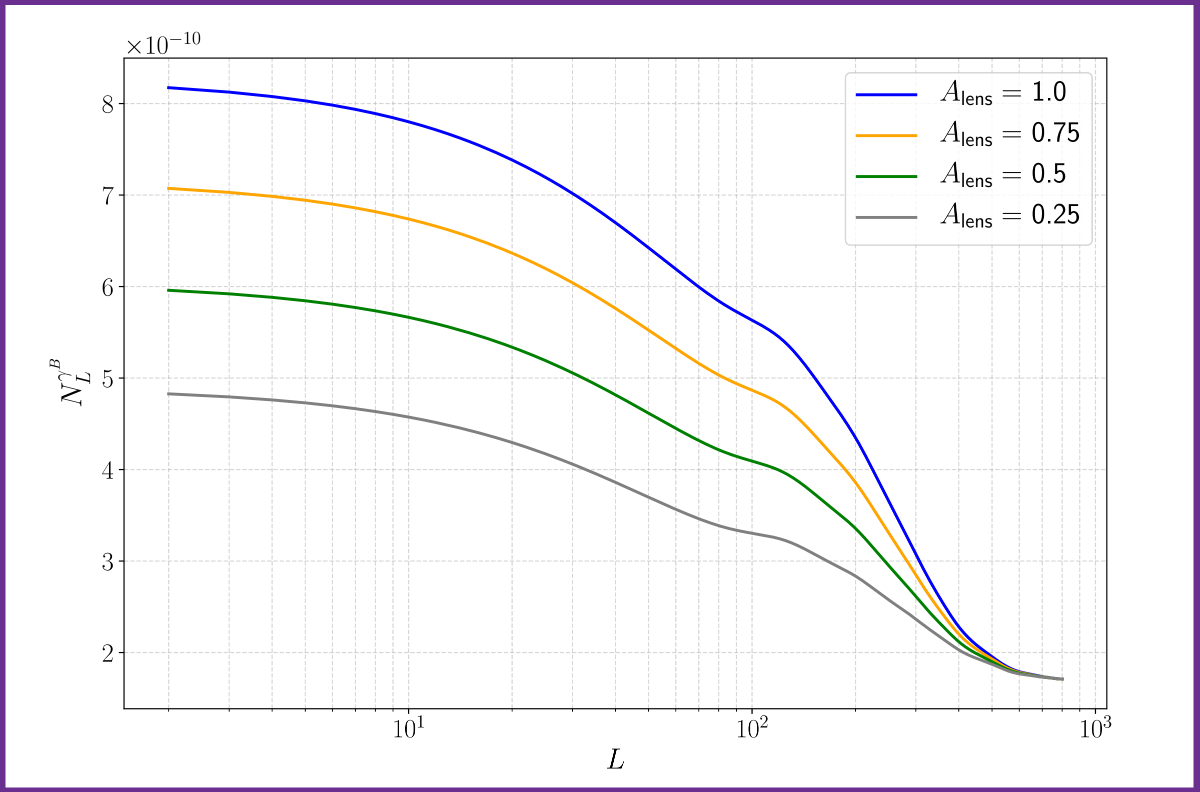
Single realisation

Injected $r = 10^{-3}$

~2 orders of magnitude bias reduction



Recovering *r*



Delensing

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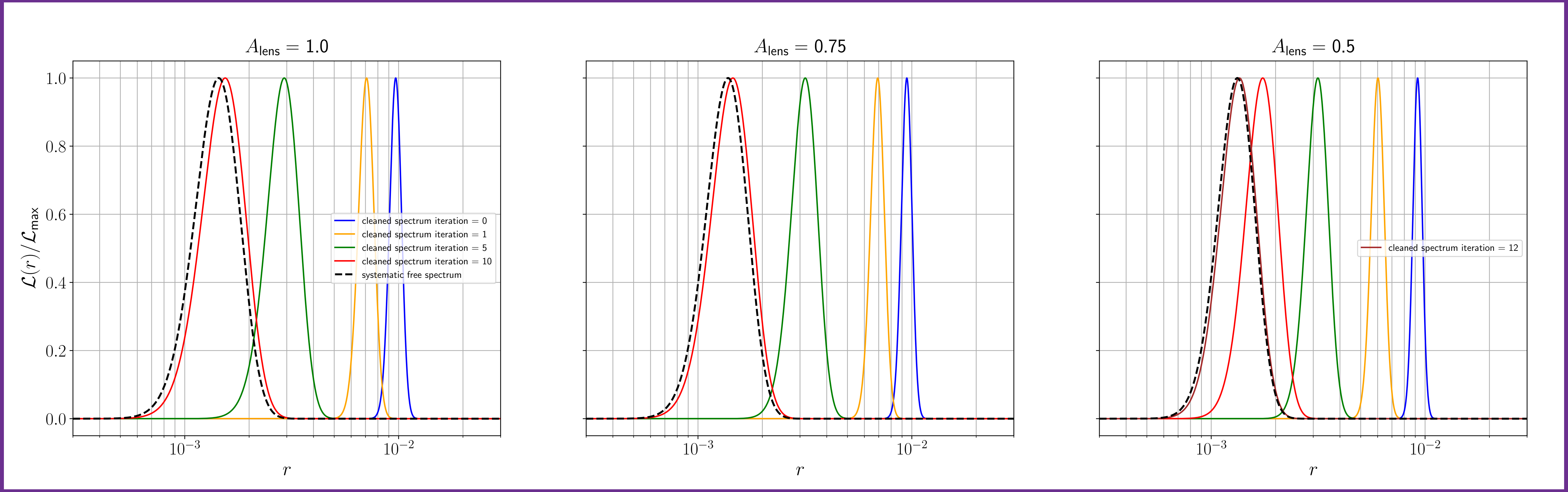
Reduced observed B-mode power

↓

Reduced reconstruction noise

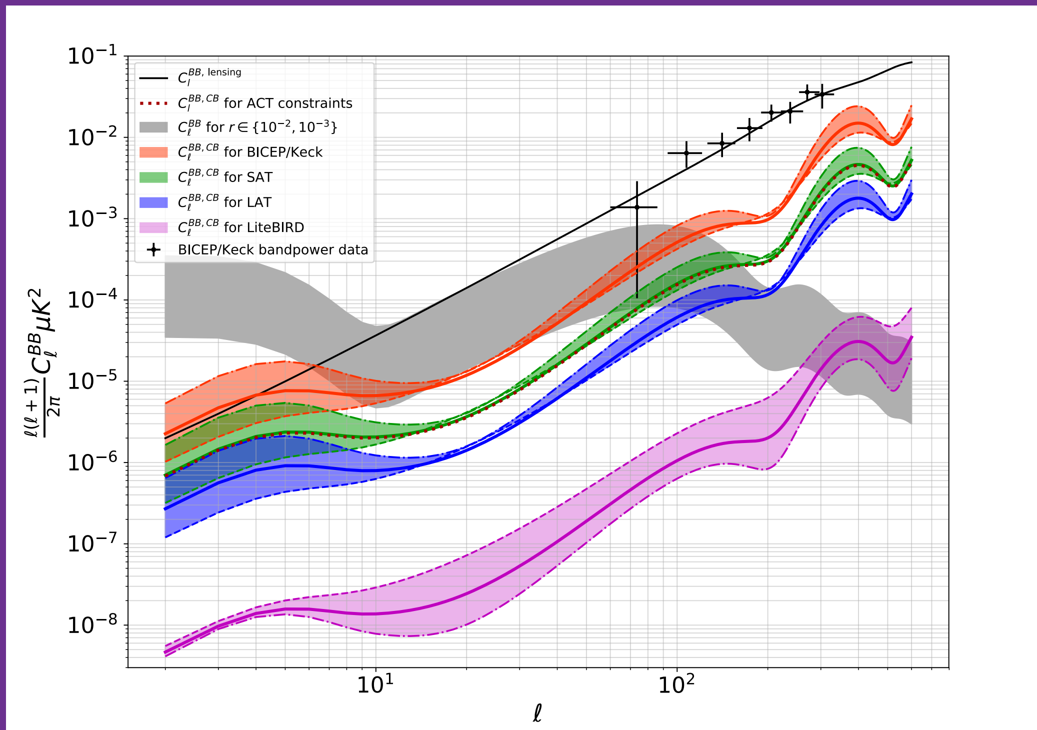


Why should you care?

- This method offers a way to blindly clean experiments
- This offers a way to diagnose issues with your experiment
- This method is complimentary to other methods
- You can use this to check your instrument behaves as expected
- This method can be applied long after data taking has finished

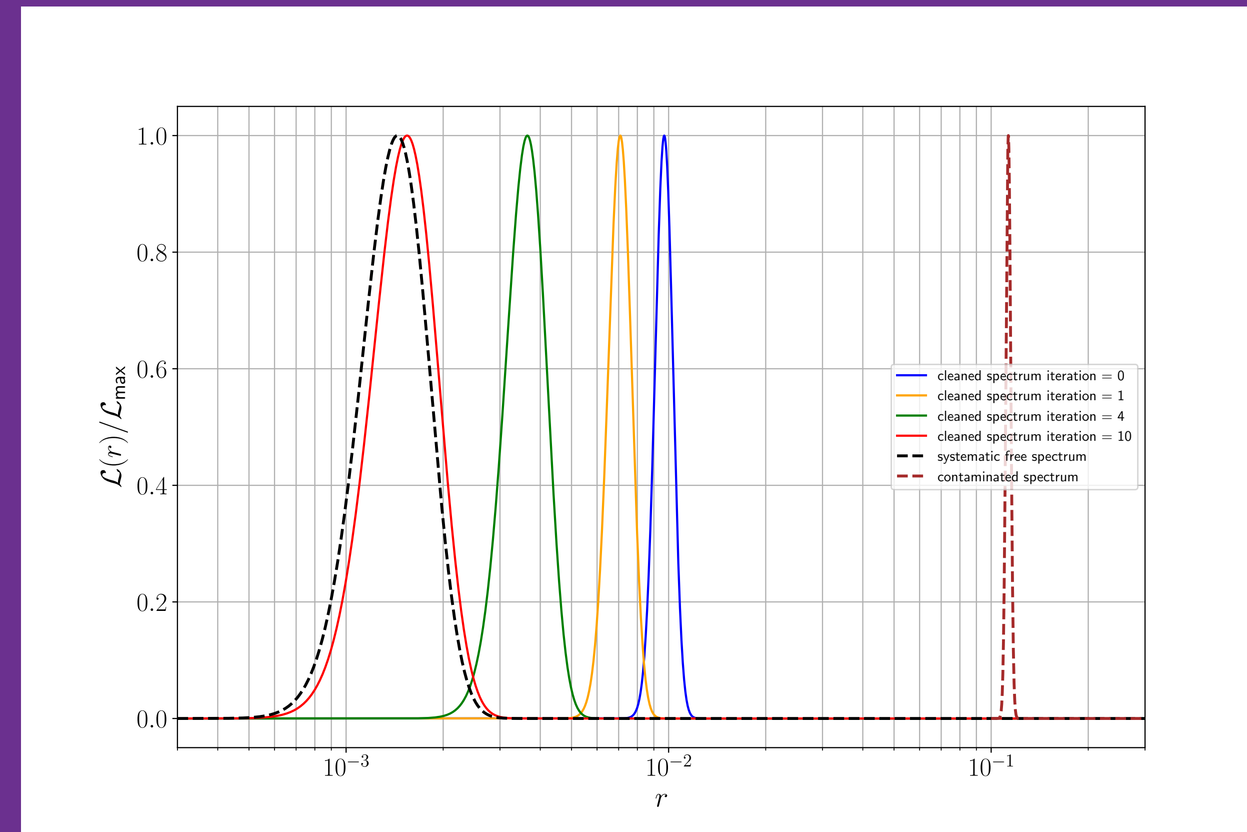
1 Minute summary slide

CPR contamination

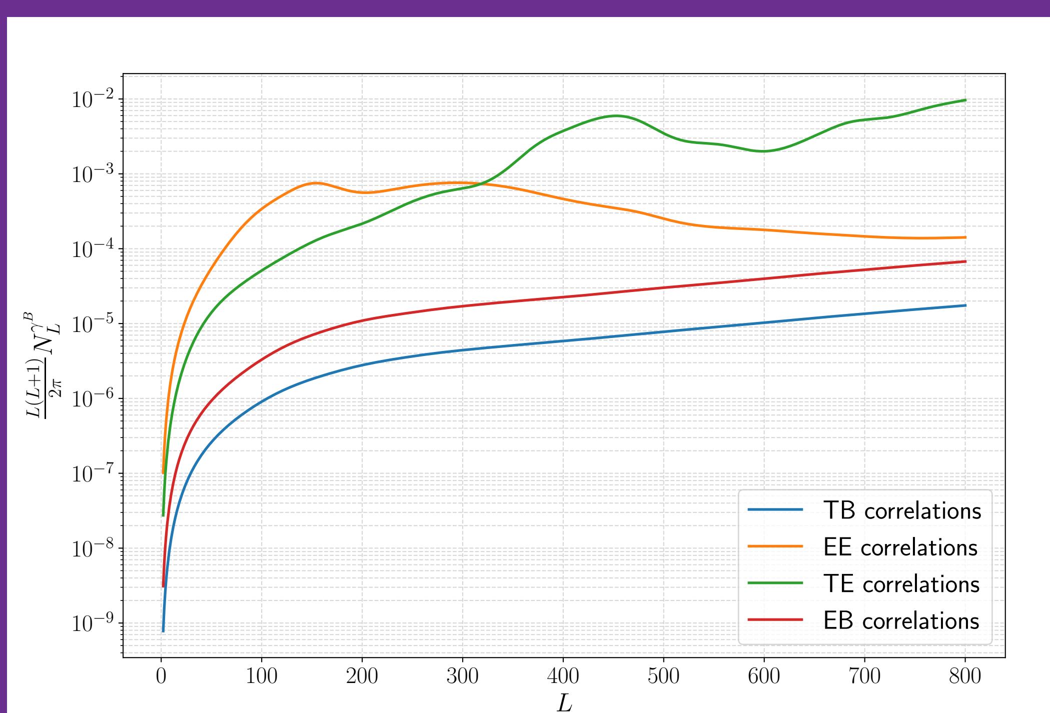


Williams et. al. (2020)

Effect of QE systematics cleaning on r



Choice of correlations



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Gaussian Filter:

$$F_L^{\gamma^B} = \exp\left(-\left[\frac{\hat{C}_L^{\gamma^B\gamma^B}}{\hat{C}_L^{\gamma^B\gamma^B} - N_L^{\gamma^B}}\right]^2\right)$$

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Any Questions?