Systematics diagnostics and self-calibration of CMB B-mode with distortion fields

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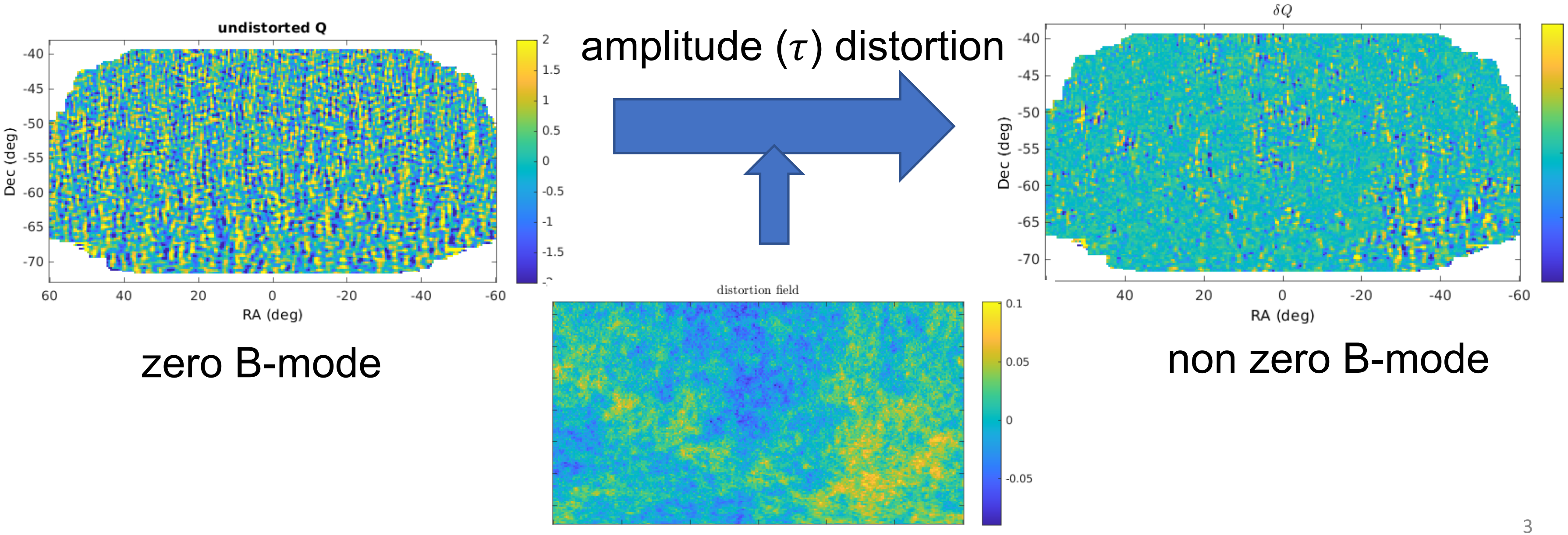
One-minute slide: Systematics diagnostics with distortion fields

- We study spatially varying distortion effects along the line-of-sight direction $\hat{n}$
- EB and TB quadratic estimators can be used to reconstruct the distortion fields
- The distortion field estimators can both serve as systematics checks and potentially detect interesting physics beyond the standard model.
  - physical effects: gravitational lensing, patchy reionization, cosmic birefringence
  - systematics: T to P leakage, gain/beam mismatch, detector rotation etc.
- The quadratic estimators are more sensitive than the BB power spectra in detecting the distortion fields in BK.
- We performed idealistic forecasts, showing that these methods will be helpful in identifying and mitigating systematic effects for future space missions such as LiteBIRD

How can we be sure the B-mode is of primordial origin?

- There are many possible sources of non-primordial B-mode.
- We focus on “line-of-sight”, or map based distortions that would generate non-primordial B-mode and leaves distinct signatures in $\langle EB \rangle$ or $\langle TB \rangle$.



Distortions in CMB along the line-of-sight can be modeled using 11 fields

- Expanding the CMB T,Q,U fields around the direction $\hat{n}$ and consider the leading order terms.

$$\delta[Q \pm iU](n) = [\tau \pm i2\omega](n)[Q_0 \pm iU_0](n) + [f_1 \pm if_2](n)[Q_0 \mp iU_0](n) + \sigma\vec{p}(n) \cdot \nabla[Q_0 \pm iU_0](n)$$
$$+ [\gamma_1 \pm i\gamma_2](n)T_0(n) + \sigma[d_1 \pm id_2](n)[\partial_1 \pm i\partial_2]T_0(n) + \sigma^2 q(n)[\partial_1 \pm i\partial_2]^2 T_0(n)$$

- $\tau(n)$: scalar field of modulation in **amplitude**
- $\omega(n)$: scalar field of **polarization rotation**
- $f_1 \pm if_2(n)$: spin ± 4 field coupling two **spin** states
- $\gamma_1 \pm i\gamma_2(n)$: spin ± 2 field of **monopole T to P** leakage
- $d_1 \pm id_2(n)$: spin ± 1 field of **dipole T to P** leakage
- $\boldsymbol{p}(n)$: change in **photon direction**
    - decompose into gradient and curl part of $\boldsymbol{p} = \nabla\Phi + \nabla \times \Omega$
    - $p_1 = \nabla \times \Omega$ and $p_2 = \nabla\Phi$
- $q(n)$: scalar field of **quadrupole T to P** leakage.

Fourier basis (like Q/U to E/B)

$$[D_1 \pm D_2](\mathbf{l}) = (\pm)^s \int \mathbf{d}\hat{\mathbf{n}}[D_1(\hat{\mathbf{n}}) \pm iD_2(\hat{\mathbf{n}})]e^{\mp is\phi_l} e^{-il\cdot\hat{\mathbf{n}}}$$

Distortion fields mix the E and B modes

- In the flat sky limit, assuming zero primordial and lensing B-mode, the leading order is
- For $\tau, \omega, f_1, f_2, p_1, p_2$

$$B(\mathbf{L}) = \int \frac{d^2\mathbf{l}_1}{(2\pi)^2} D(\mathbf{l}_1) E_0(\mathbf{l}_2) W_D^B(\mathbf{l}_1, \mathbf{l}_2)$$

- For $d_1, d_2, \gamma_1, \gamma_2, q$

$$B(\mathbf{L}) = \int \frac{d^2\mathbf{l}_1}{(2\pi)^2} D(\mathbf{l}_1) T(\mathbf{l}_2) W_D^B(\mathbf{l}_1, \mathbf{l}_2)$$

where E_0 is the undistorted E mode, and $l_1 + l_2 = L$

- Different weights W_D^B for different distortion fields.

Minimal variance quadratic estimators for the distortion fields

- For EB quadratic estimators, correlating two Fourier modes in E and B and averaging over CMB realizations, we have

$$\langle E(\mathbf{l_1})B(\mathbf{l_2})\rangle_{\rm CMB} = f^D_{EB}(\mathbf{l_1},\mathbf{l_2})D(\mathbf{l_1}+\mathbf{l_2})$$

With different $f(l_1, l_2)$ for different fields

$$\text{Ex. } f^{\tau}_{EB} = C^{EE}_{l_1}\sin 2(\phi_{l_1}-\phi_{l_2})$$

- We can construct an estimator $\widehat{D}$ with linear combinations of $E(\mathbf{l_1})B(\mathbf{l_2})$ that minimizes $\langle|\hat{D}_{EB}-D|^2\rangle_{\rm CMB}$

- We than derive the minimal variance estimator

$$\hat{D}_{EB}(\mathbf{L}) = A(\mathbf{L})\int\frac{d^2\mathbf{l}_1}{(2\pi)^2}E(\mathbf{l}_1)B(\mathbf{l}_2)\frac{f^D_{EB}(\mathbf{l}_1,\mathbf{l}_2)}{2C^{EE}_{\ell_1}C^{BB}_{\ell_2}}$$

Full table of f_{XB}^{D} and W_{D}^{X} weights

$$B(\mathbf{L}) = \int \frac{d^2\mathbf{l}_1}{(2\pi)^2} D(\mathbf{l}_1) E_0(\mathbf{l}_2) W_D^B(\mathbf{l}_1, \mathbf{l}_2)$$

$$\hat{D}_{EB}(\mathbf{L}) = A(\mathbf{L}) \int \frac{d^2\mathbf{l}_1}{(2\pi)^2} E(\mathbf{l}_1) B(\mathbf{l}_2) \frac{f_{EB}^D(\mathbf{l}_1, \mathbf{l}_2)}{2C_{\ell_1}^{EE} C_{\ell_2}^{BB}}$$

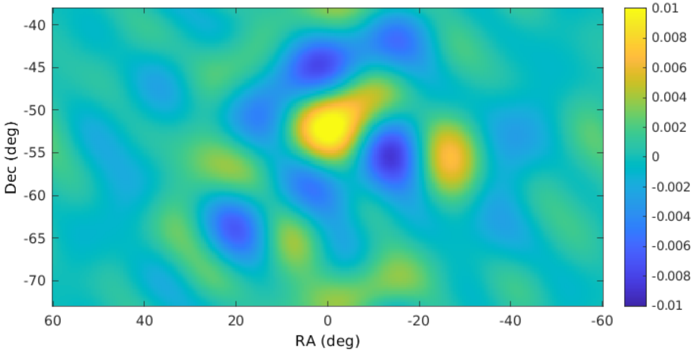
$\mathcal{D}$	$f_{EB}^{\mathcal{D}}(\mathbf{l}_1, \mathbf{l}_2)$	$f_{TB}^{\mathcal{D}}(\mathbf{l}_1, \mathbf{l}_2)$	$W_{\mathcal{D}}^{B}(\mathbf{l}_1, \mathbf{l}_2)$	$W_{\mathcal{D}}^{E}(\mathbf{l}_1, \mathbf{l}_2)$
a	$\tilde{C}_{l_1}^{EE} \sin 2(\varphi_{\mathbf{l}_1} - \varphi_{\mathbf{l}_2})$	$\tilde{C}_{l_1}^{TE} \sin 2(\varphi_{\mathbf{l}_1} - \varphi_{\mathbf{l}_2})$	$\sin[2(\varphi_{\mathbf{l}_2} - \varphi_{\mathbf{L}})]$	$\cos[2(\varphi_{\mathbf{l}_2} - \varphi_{\mathbf{L}})]$
ω	$2\tilde{C}_{l_1}^{EE} \cos 2(\varphi_{\mathbf{l}_1} - \varphi_{\mathbf{l}_2})$	$2\tilde{C}_{l_1}^{TE} \cos 2(\varphi_{\mathbf{l}_1} - \varphi_{\mathbf{l}_2})$	$2\cos[2(\varphi_{\mathbf{l}_2} - \varphi_{\mathbf{L}})]$	$-2\sin[2(\varphi_{\mathbf{l}_2} - \varphi_{\mathbf{L}})]$
γ_1	$\tilde{C}_{l_1}^{TE} \sin 2(\varphi_{\mathbf{L}} - \varphi_{\mathbf{l}_2})$	$\tilde{C}_{l_1}^{TT} \sin 2(\varphi_{\mathbf{L}} - \varphi_{\mathbf{l}_2})$	$\sin[2(\varphi_{\mathbf{l}_1} - \varphi_{\mathbf{L}})]\,,$	$\cos[2(\varphi_{\mathbf{l}_1} - \varphi_{\mathbf{L}})]$
γ_2	$\tilde{C}_{l_1}^{TE} \cos 2(\varphi_{\mathbf{L}} - \varphi_{\mathbf{l}_2})$	$\tilde{C}_{l_1}^{TT} \cos 2(\varphi_{\mathbf{L}} - \varphi_{\mathbf{l}_2})$	$\cos[2(\varphi_{\mathbf{l}_1} - \varphi_{\mathbf{L}})]\,,$	$-\sin[2(\varphi_{\mathbf{l}_1} - \varphi_{\mathbf{L}})]$
f_1	$\tilde{C}_{l_1}^{EE} \sin 2(2\varphi_{\mathbf{L}} - \varphi_{\mathbf{l}_1} - \varphi_{\mathbf{l}_2})$	$\tilde{C}_{l_1}^{TE} \sin 2(2\varphi_{\mathbf{L}} - \varphi_{\mathbf{l}_1} - \varphi_{\mathbf{l}_2})$	$\sin[2(2\varphi_{\mathbf{l}_1} - \varphi_{\mathbf{l}_2} - \varphi_{\mathbf{L}})]$	$\cos[2(2\varphi_{\mathbf{l}_1} - \varphi_{\mathbf{l}_2} - \varphi_{\mathbf{L}})]$
f_2	$\tilde{C}_{l_1}^{EE} \cos 2(2\varphi_{\mathbf{L}} - \varphi_{\mathbf{l}_1} - \varphi_{\mathbf{l}_2})$	$\tilde{C}_{l_1}^{TE} \cos 2(2\varphi_{\mathbf{L}} - \varphi_{\mathbf{l}_1} - \varphi_{\mathbf{l}_2})$	$\cos 2(2\varphi_{\mathbf{l}_1} - \varphi_{\mathbf{l}_2} - \varphi_{\mathbf{L}})$	$-\sin 2(2\varphi_{\mathbf{l}_1} - \varphi_{\mathbf{l}_2} - \varphi_{\mathbf{L}})$
d_1	$\tilde{C}_{l_1}^{TE}(l_1\sigma) \cos(\varphi_{\mathbf{L}} + \varphi_{\mathbf{l}_1} - 2\varphi_{\mathbf{l}_2})$	$\tilde{C}_{l_1}^{TT}(l_1\sigma) \cos(\varphi_{\mathbf{L}} + \varphi_{\mathbf{l}_1} - 2\varphi_{\mathbf{l}_2})$	$-(\mathbf{l}_2\sigma) \cos[\varphi_{\mathbf{l}_1} + \varphi_{\mathbf{l}_2} - 2\varphi_{l}]$	$-(\mathbf{l}_2\sigma) \sin[\varphi_{\mathbf{l}_1} + \varphi_{\mathbf{l}_2} - 2\varphi_{L}]$
d_2	$-\tilde{C}_{l_1}^{TE}(l_1\sigma) \sin(\varphi_{\mathbf{L}} + \varphi_{\mathbf{l}_1} - 2\varphi_{\mathbf{l}_2})$	$-\tilde{C}_{l_1}^{TT}(l_1\sigma) \sin(\varphi_{\mathbf{L}} + \varphi_{\mathbf{l}_1} - 2\varphi_{\mathbf{l}_2})$	$(l_2\sigma) \sin[\varphi_{\mathbf{l}_1} + \varphi_{\mathbf{l}_2} - 2\varphi_{\mathbf{L}}]$	$(l_2\sigma) \cos[\varphi_{\mathbf{l}_1} + \varphi_{\mathbf{l}_2} - 2\varphi_{\mathbf{L}}]$
q	$-\tilde{C}_{l_1}^{TE}(l_1\sigma)^2 \sin 2(\varphi_{\mathbf{l}_1} - \varphi_{\mathbf{l}_2})$	$-\tilde{C}_{l_1}^{TT}(l_1\sigma)^2 \sin 2(\varphi_{\mathbf{l}_1} - \varphi_{\mathbf{l}_2})$	$-(l_2\sigma)^2 \sin[2(\varphi_{\mathbf{l}_2} - \varphi_{\mathbf{L}})]$	$-(l_2\sigma)^2 \cos[2(\varphi_{\mathbf{l}_2} - \varphi_{\mathbf{L}})]$
p_1	$-\tilde{C}_{l_1}^{EE}\sigma(\mathbf{l}_1 \times \hat{\mathbf{L}}) \sin 2(\varphi_{\mathbf{l}_1} - \varphi_{\mathbf{l}_2})$	$-\tilde{C}_{l_1}^{TT}\sigma(\mathbf{l}_1 \times \hat{\mathbf{L}}) \sin 2(\varphi_{\mathbf{l}_1} - \varphi_{\mathbf{l}_2})$	$\sigma(\mathbf{l}_2 \times \hat{\mathbf{l}}_1) \cdot \hat{\mathbf{z}} \sin[2(\varphi_{\mathbf{l}_2} - \varphi_{\mathbf{L}})]$	$\sigma(\mathbf{l}_2 \cdot \hat{\mathbf{l}}_1) \sin[2(\varphi_{\mathbf{l}_2} - \varphi_{\mathbf{L}})]$
p_2	$-\tilde{C}_{l_1}^{EE}\sigma(\mathbf{l}_1 \cdot \hat{\mathbf{L}}) \sin 2(\varphi_{\mathbf{l}_1} - \varphi_{\mathbf{l}_2})$	$-\tilde{C}_{l_1}^{TT}\sigma(\mathbf{l}_1 \cdot \hat{\mathbf{L}}) \sin 2(\varphi_{\mathbf{l}_1} - \varphi_{\mathbf{l}_2})$	$\sigma(\mathbf{l}_2 \cdot \hat{\mathbf{l}}_1) \sin[2(\varphi_{\mathbf{l}_2} - \varphi_{\mathbf{L}})]$	$\sigma(\mathbf{l}_2 \times \hat{\mathbf{l}}_1) \cdot \hat{\mathbf{z}} \sin[2(\varphi_{\mathbf{l}_2} - \varphi_{\mathbf{L}})]$

(Yadav et al. 2009)

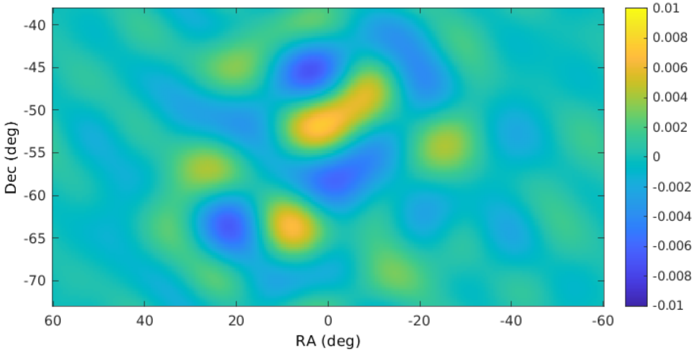
Example of an input and reconstructed distortion field with 3 years BICEP3 noise level

- map depth $\approx 3\mu K$-arcmin with effective area of ≈ 600 square degree.
- Scale independent input polarization rotation spectra $\frac{L(L+1)}{2\pi} C_L^{DD} = 1{\times}10^{-4}$
- $\omega(n)$ input and reconstruction filtered to $\ell = 20 - 40$

Reconstruction

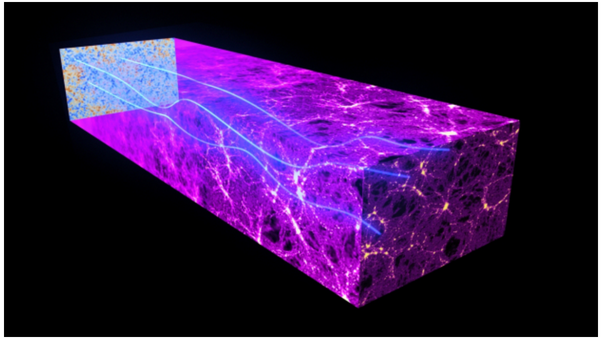


Input

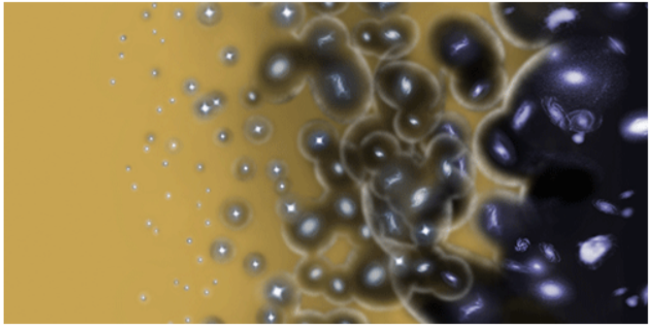


Physical processes can give rise to certain distortions

Fields	Physical process
$p_2(n)$	Gradient part of lensing
$p_1(n)$	Curl part of lensing
$\omega(n)$	Massless pseudoscalar field that couples to the electromagnetic term. Primordial magnetic field with Faraday rotation.
$\tau(n)$	Patchy reionization



(ESA and Planck)



(ESA/C. Carreau)

Instrumental systematics can generate all kinds of distortions

Fields	Instrumental systematics (in a BK-like experiment)
τ	detector gain miscalibration
ω	detector rotation miscalibration
$p_{1/2}$	detector beam center miscalibration
$\gamma_{1/2}$	A/B detector gain mismatch
$d_{1/2}$	A/B detector differential pointing
q	A/B detector differential beamwidth
$f_{1/2}$	gain miscalibration coupled with deck angle rotation (in a BK-like experiment)

- Different detectors have different coverage on the final map which can create a spatially varying distortion effect.

What to do if there is a detection of the distortion field?

- For known and existing cosmological effects (lensing p_2):
  - Self calibrate by removing the modes from distortion fields (delensing)
  - In practice, it is more effective to build the template with lensing potential and E mode derived from large aperture telescope instead of doing an entire self-calibration process.
- For conjectured cosmological signal (ω, τ)
  - Control systematics better (Ex. more aggressive data cuts) and see if the significance is reduced.
  - If not, try to detect it with other experiments as well → Discovery !!
- For fields with only systematics origin ($d_{1/2}$, q, $f_{1/2}$, $\gamma_{1/2}$)
  - As null tests: in many cases distortion field analysis is more sensitive to systematics than BB
  - It is possible to remove the spurious modes with a “delensing”-like procedure, but it would likely complicate the analysis

Bicep/Keck Array matrix pipeline allows rapid simulation generation with various distortion field inputs

- Existing observation matrix can generate simulations rapidly
  - includes all the filtering operations.
  - generates different distortion/CMB realizations Q^{in}, U^{in} and multiply with observation matrix.

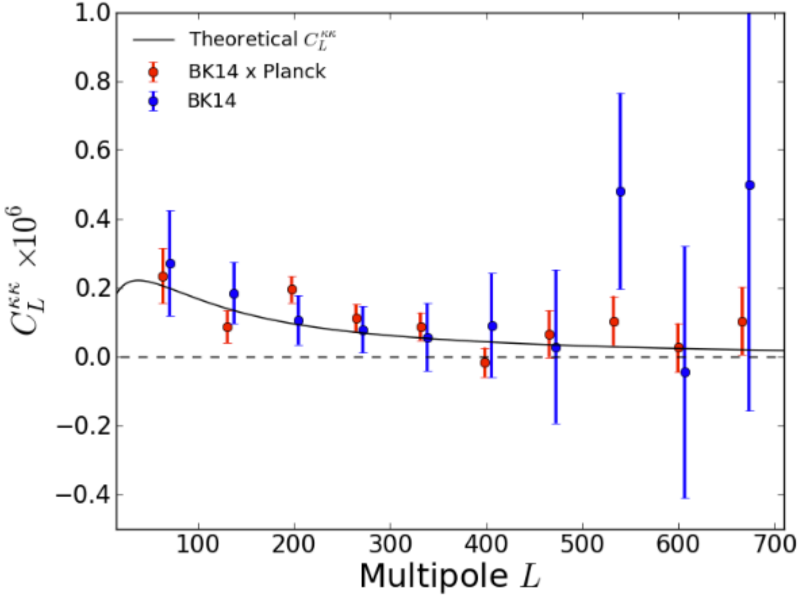
$$\begin{pmatrix} Q^{\rm obs} \\ U^{\rm obs} \end{pmatrix} = \mathcal{R} \begin{pmatrix} Q^{\rm in} \\ U^{\rm in} \end{pmatrix} + \begin{pmatrix} Q^{\rm noise} \\ U^{\rm noise} \end{pmatrix}$$

- E/B purification with purification matrix derived from observation matrix.
  - reduce reconstruction noise by removing E to B leakage.

$$\begin{pmatrix} Q^{\rm B} \\ U^{\rm B} \end{pmatrix} = \mathbf{\Pi_B} \begin{pmatrix} Q^{\rm obs} \\ U^{\rm obs} \end{pmatrix}$$

$p_2(n)$: Lensing analysis from BK collaboration

- Constraint from the published BK14 results:
  - $A_L^{\phi\phi} = 1.15 \pm 0.36$ from auto spectrum of the reconstructed lensing potential
  - $A_L^{\phi\phi} = 1.13 \pm 0.20$ from cross correlating with Planck lensing potential
- Preliminary results from 3 years of BICEP3 data:
  - $\sigma\left(A_L^{\phi\phi}\right) = 0.22$ from 95GHz auto spectra



(BK collaboration, 2016)

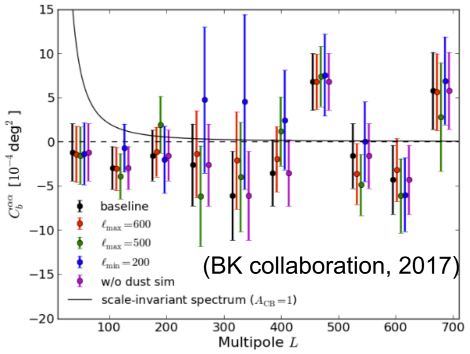
$\omega(n)$: Cosmic Birefringence constraint from BK collaboration

- Pseudo-scalar field and primordial magnetic field both predict a scale-invariant power spectrum at large scales.

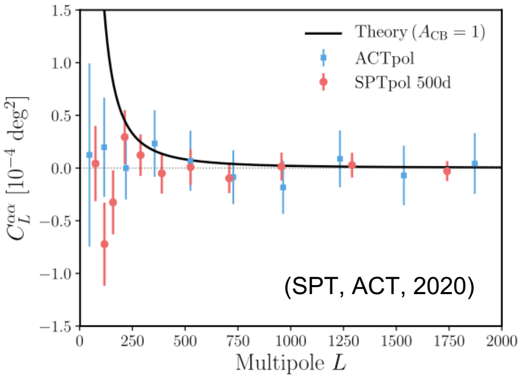
$$\frac{L(L+1)}{2\pi} C_L^{\alpha\alpha} = A_{CB} \times 10^{-4} [\text{rad}^2]$$

  - BK14: $A_{CB} \leq 0.33$ ($\sigma(A_{CB}) = 0.086$)
  - SPTpol: $A_{CB} \leq 0.10$ ($\sigma(A_{CB}) = 0.096$)
  - ACTpol: $A_{CB} \leq 0.10$

- Preliminary sensitivity from 3 years of BICEP3:
  - $\sigma(A_{CB}) = 0.013$
  - This is better than existing constraint by a factor of 2-3



(BK collaboration, 2017)



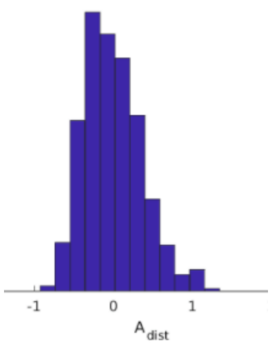
(SPT, ACT, 2020)

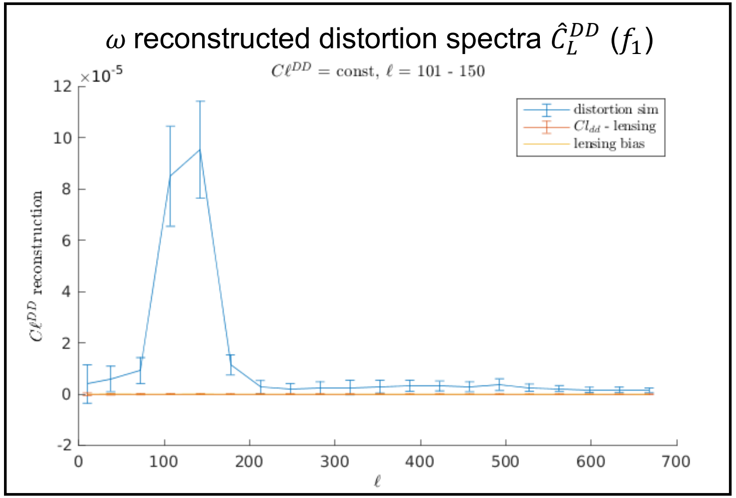
Sensitivity comparison of EB/TB quadratic estimator vs. B-mode power spectrum at detecting distortion fields

- Generate distortion fields with flat C_L^{DD} in a narrow range of multipole ($\Delta\ell = 50$)
- Estimate amplitude $\hat{A}$ for null sims from $\hat{C}_L^{DD}$ and $\hat{C}_L^{BB}$
- $\sigma(\hat{A})^{-1}$ is proportional to the sensitivity (significance) of detecting the distortion

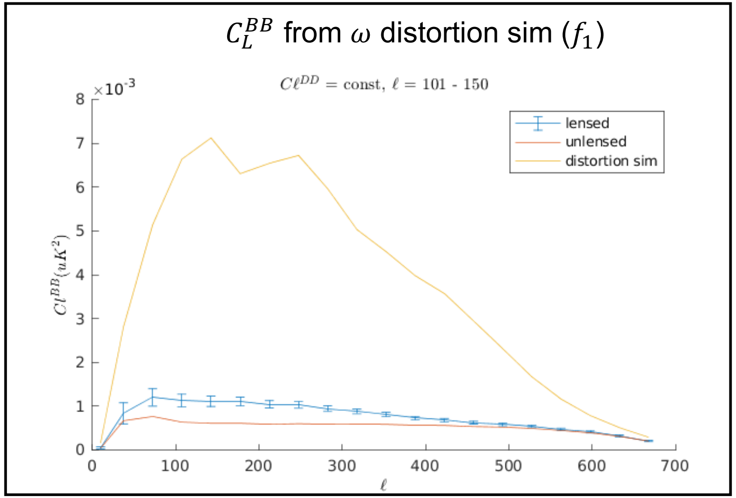
$$\hat{A}_{dist} = \frac{\sum_{b,b'} C_b \mathbf{Cov}_{bb'}^{-1} C_{b'}^{fid}}{\sum_{b,b'} C_b^{fid} \mathbf{Cov}_{bb'}^{-1} C_{b'}^{fid}} \Rightarrow \text{sensitivity ratio} = \frac{\sigma(A_{BB})}{\sigma(A_{EB/TB})}$$

$\sigma(A)$



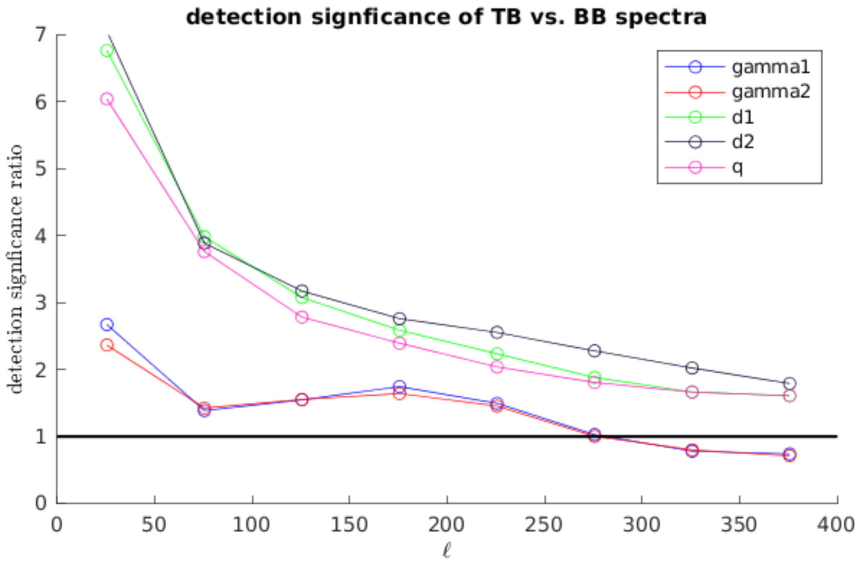


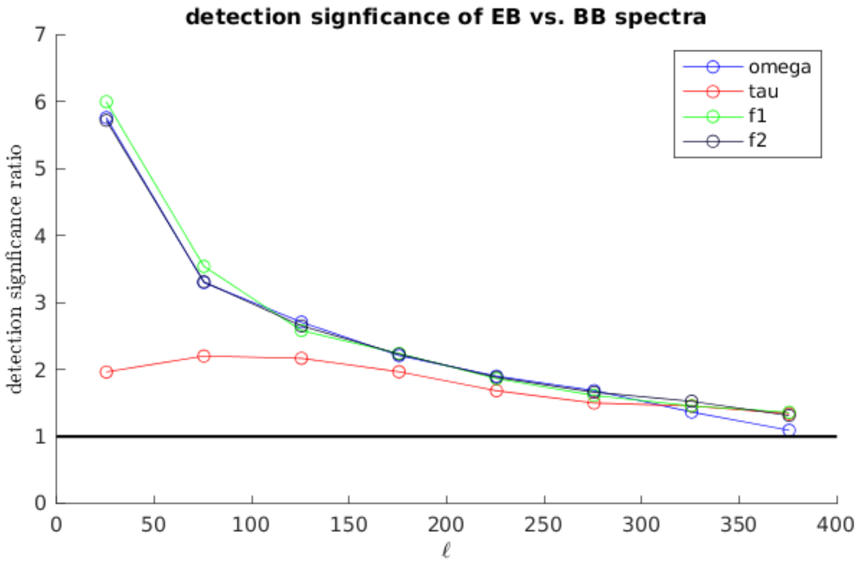
vs.



Sensitivity comparison of EB/TB quadratic estimator vs. B-mode power spectrum at detecting distortion fields

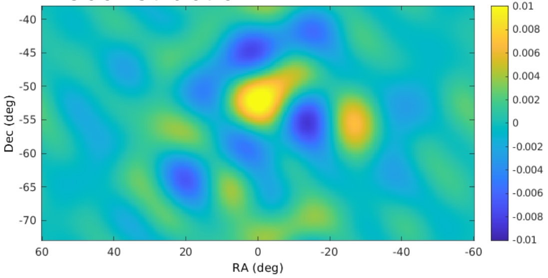
- Up to $\ell = 300 - 400$, quadratic estimator is more sensitive than BB power spectra
- Distortion fields will be detected in quadratic estimator before showing up as spurious B-mode





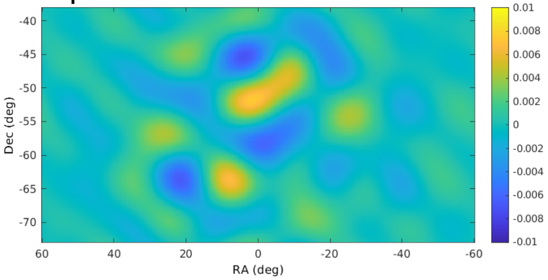
Distortion field estimators for space experiments

Reconstruction



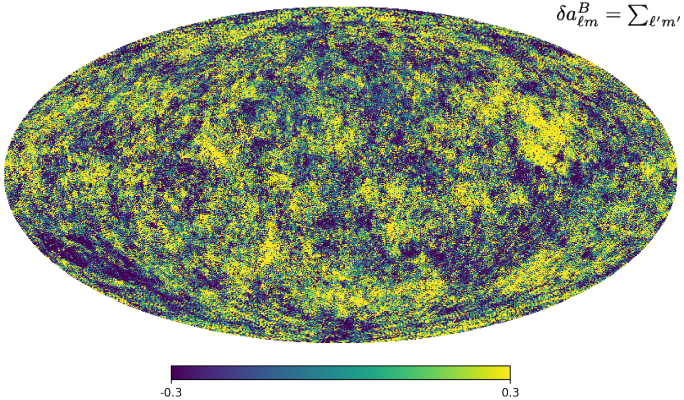
$$B(\mathbf{L}) = \int \frac{d^2\mathbf{l}_1}{(2\pi)^2} D(\mathbf{l}_1) E_0(\mathbf{l}_2) W_D^B(\mathbf{l}_1, \mathbf{l}_2)$$

Input



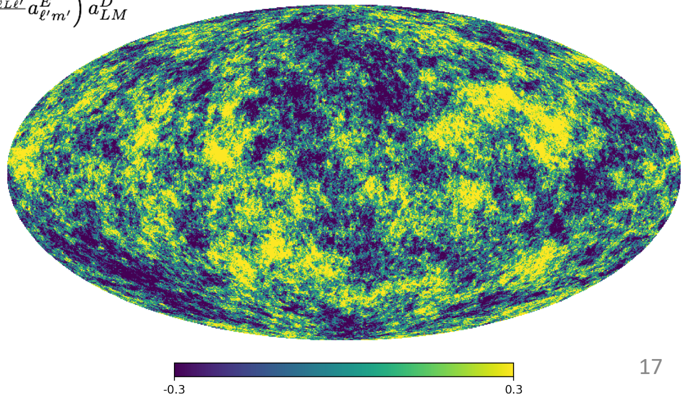
Generalization of the formalism to curved-sky (Beck et al. in prep.)

estimated a



$$\delta a^B_{\ell m} = \sum_{\ell' m'} \sum_{LM} (-1)^m \begin{pmatrix} \ell & \ell' & L \\ m & m' & -M \end{pmatrix} \left(\frac{{}_{+}F^D_{\ell L \ell'} - {}_{-}F^D_{\ell L \ell'}}{2i} a^E_{\ell' m'} \right) a^D_{LM}$$

input a



LiteBIRD forecasts for quadratic estimators vs. BB

Assumptions include

- Gaussian dust and synchrotron over 51% of the sky
- White noise between $\ell = 2 - 500$
- Flat $C_L^{DD} = A_D$ smoothed to 1 degree

$$C_L^{DD} = A_D \times \exp\left(-L(L+1)\frac{\theta^2}{8\ln 2}\right)$$

- Same sensitivity comparison method

C_b is either C_L^{DD} or B mode C_L^{BB}

$$\hat{A}_{dist} = \frac{\sum_{b,b'} C_b \mathbf{Cov}_{bb'}^{-1} C_{b'}^{fid}}{\sum_{b,b'} C_b^{fid} \mathbf{Cov}_{bb'}^{-1} C_{b'}^{fid}}$$

$$\text{sensitivity ratio} = \frac{\sigma(A_{BB})}{\sigma(A_{EB/TB})}$$

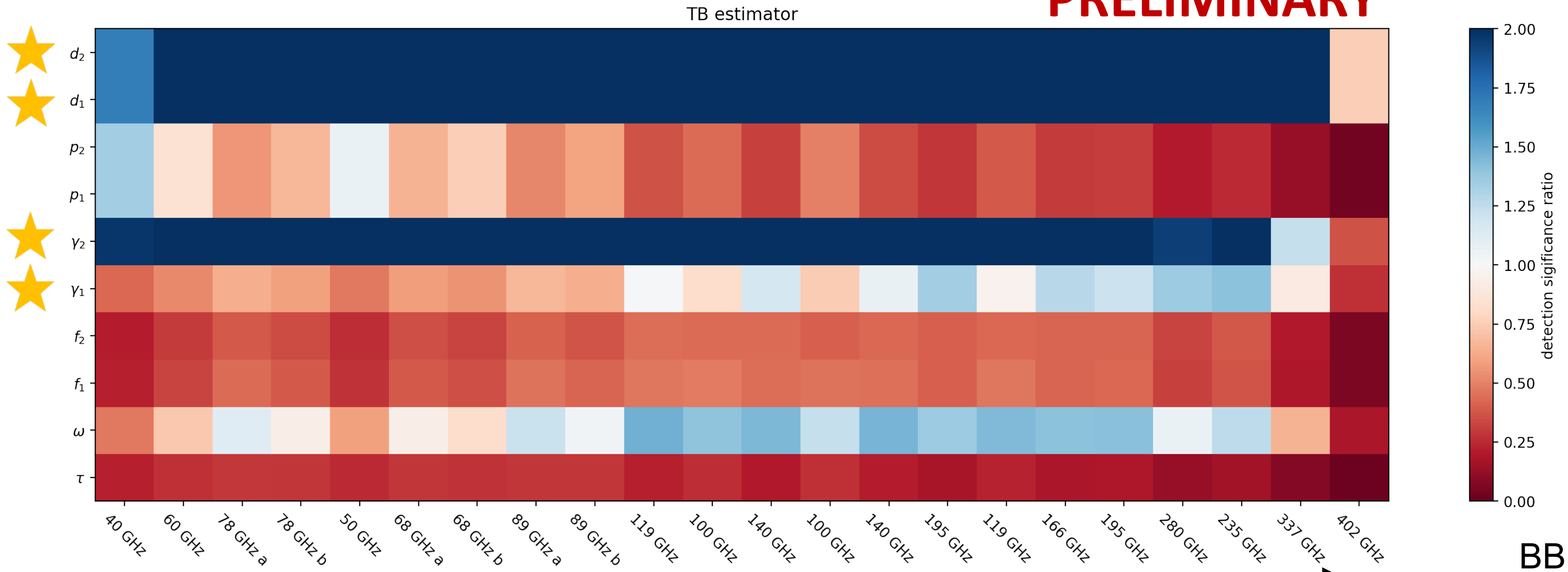
LiteBIRD forecasts for TB estimators’ sensitivity vs. BB

Assumptions include

- Gaussian dust and synchrotron over 51% of the sky
- White noise between $\ell = 2 - 500$
- Flat $C_L^{DD} = A_D$ smoothed to 1 degree

PRELIMINARY

TB better



BB better

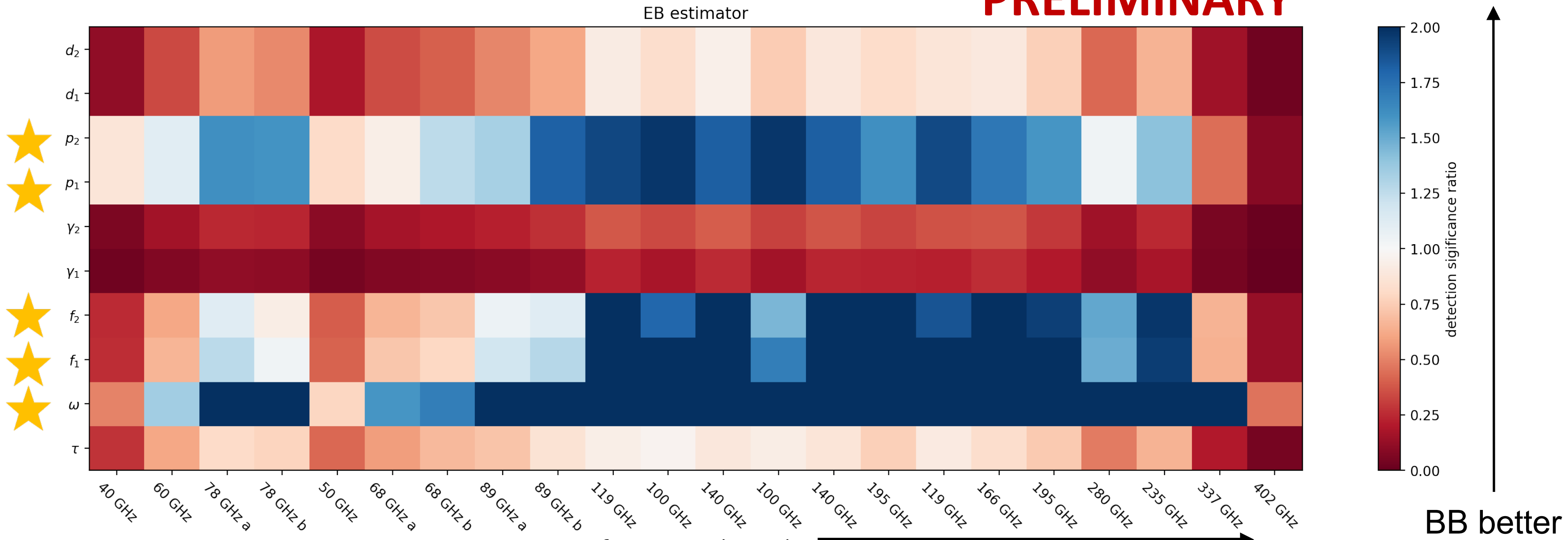
increasing resolution

LiteBIRD forecasts for EB estimators’ sensitivity vs. BB

Assumptions include

- Gaussian dust and synchrotron over 51% of the sky
- White noise between $\ell = 2 - 500$
- Flat $C_L^{DD} = A_D$ smoothed to 1 degree

PRELIMINARY



One-minute slide:
Systematics diagnostics on distortion fields

- We study spatially varying distortion effects along the line-of-sight direction $\hat{n}$
- EB and TB quadratic estimators can be used to reconstruct the distortion fields from the signature EB and TB correlations of the different distortion fields.
- The distortion field estimators can both serve as systematics checks and potentially detect interesting physics beyond the standard model.
  - physical effects: lensing, patchy reionization, cosmic birefringence
  - systematics: T to P leakage, gain mismatch, detector rotation etc.
- We demonstrated with realistic BK simulation pipeline that the quadratic estimators are more sensitive than the BB power spectra in detecting the distortion fields.
- We performed idealistic forecasts, showing that these methods will be helpful in identifying and mitigating systematic effects for future space missions such as LiteBIRD

Thank you!