Cosmological constraints and instrumental systematics studies using line-of-sight distortion fields with BICEP/*Keck* and beyond

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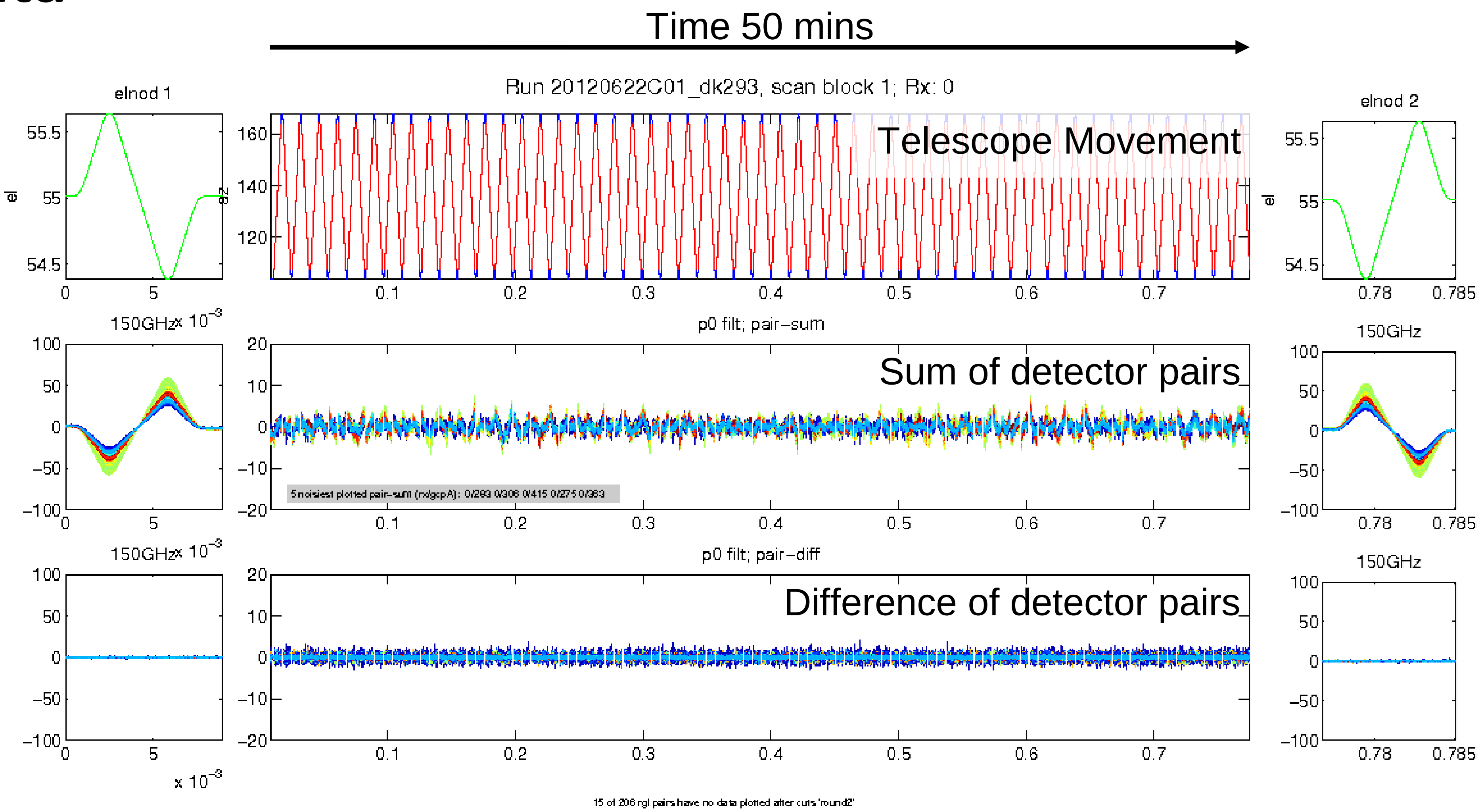
with Eric Yang & the BICEP/*Keck* collaboration

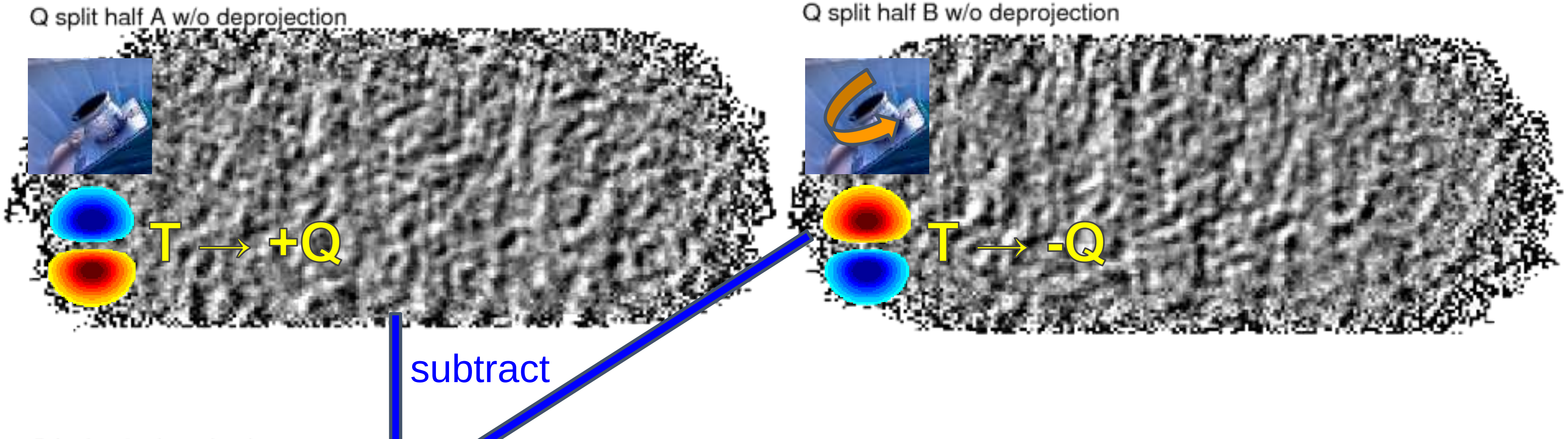
Raw Data

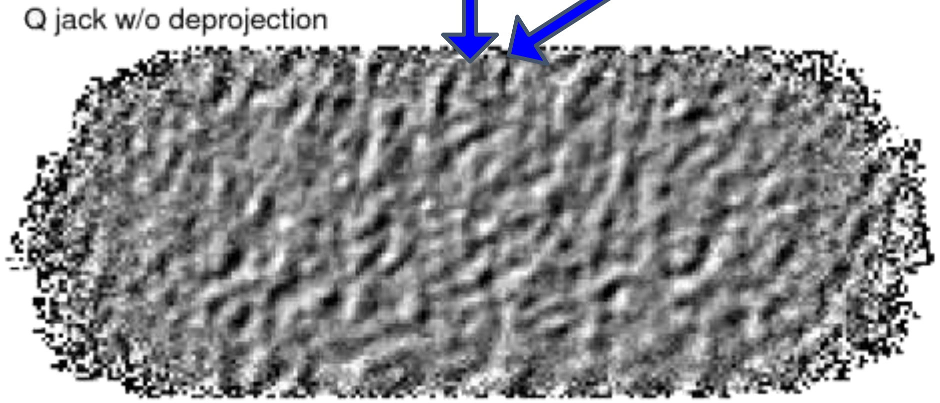


- ➢ Cover the whole field in 60 such scans then start over at new boresight rotation
- ➢ Scanning modulated the CMB signal to freqs < 4 Hz

Jackknife: Sensitive Test of Systematics

Maps using just half the boresight rotation angles:



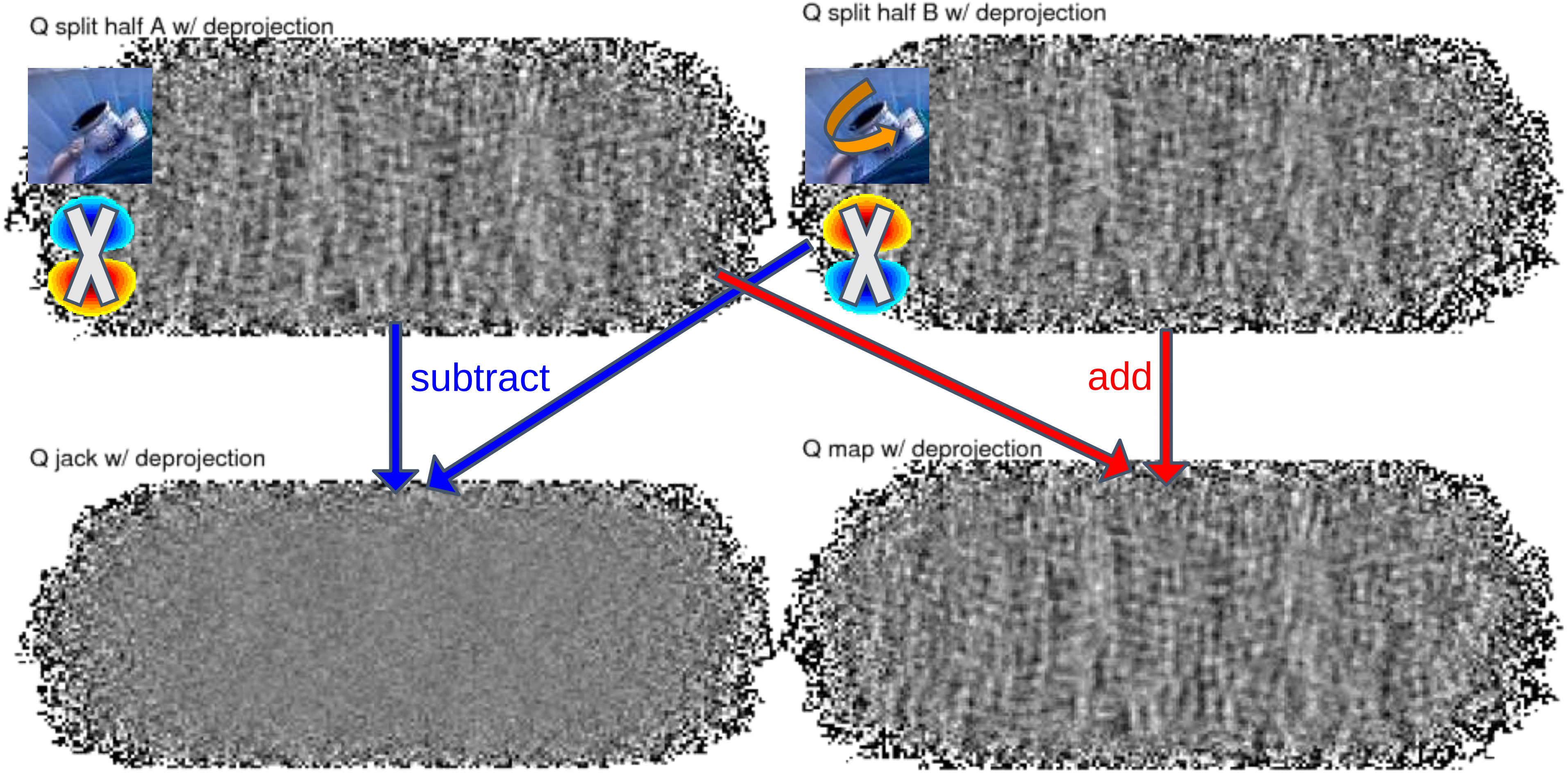


“Jackknife”:

- ➢ Difference the two halves instead of adding them
- ➢ Real signal cancels
- ➢ Systematic enhanced!

Systematics Removal: Deprojection

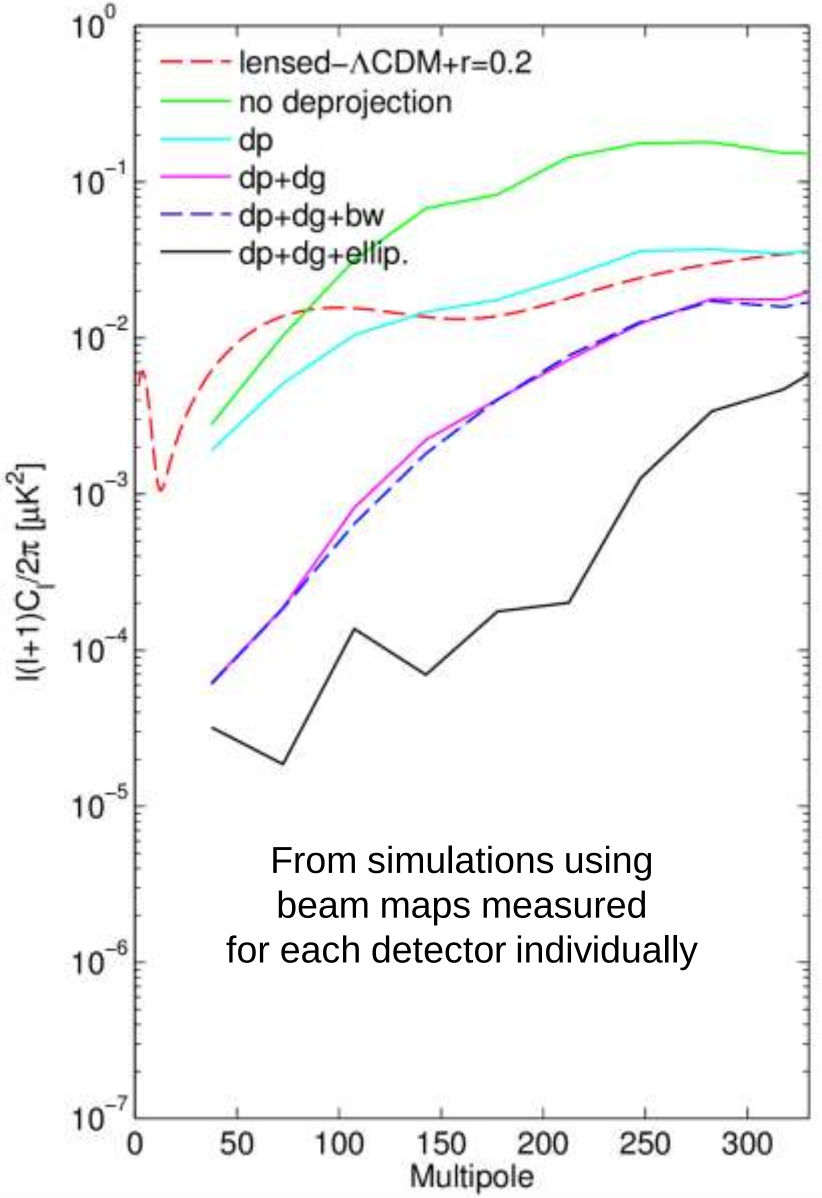
Maps using just half the boresight rotation angles:



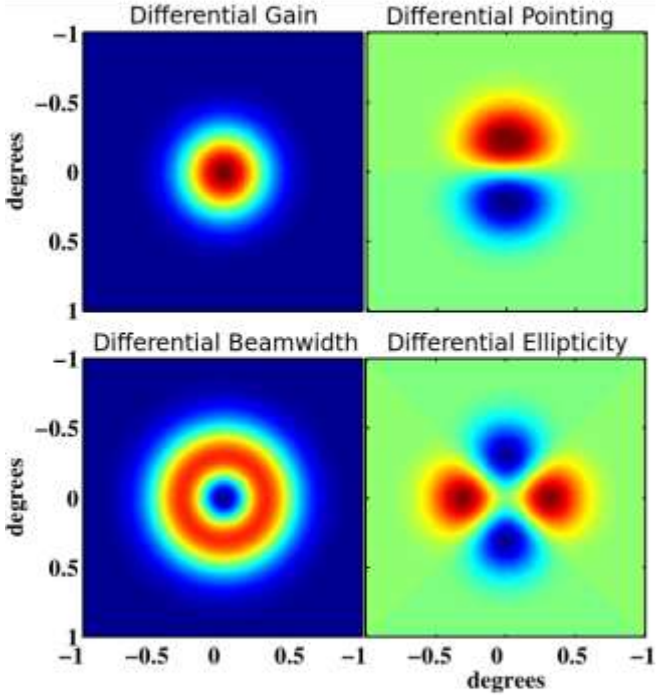
"Deprojection":

- ➢ From well-known temperature sky form a prediction of the leakage and remove it
- ➢ Cleans up maps even without cancellation from boresight rotation

Systematics Removal: Deprojection



Technique developed to remove
all types of leakage induced by differences
of detector pair beam shapes

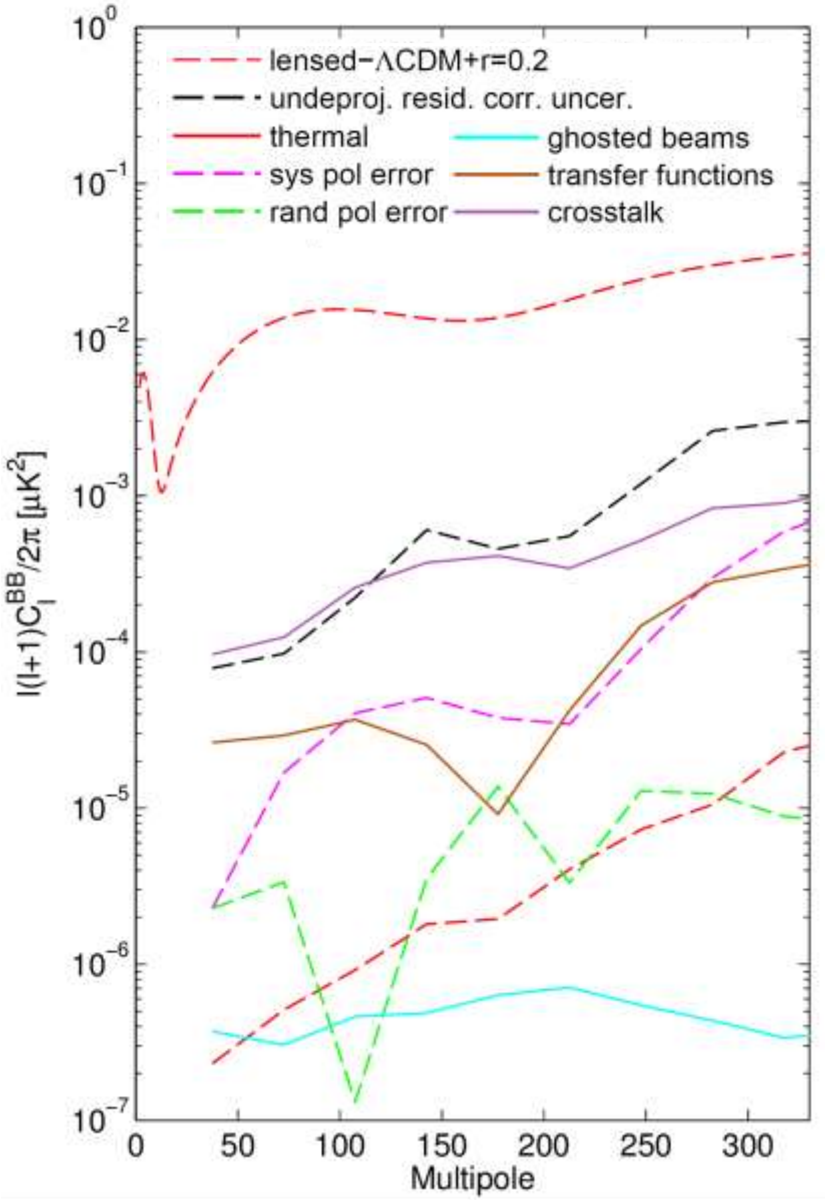


Use the Planck 143 GHz map to form template of the leakage

Deproject diff gain and pointing (& subtract diff ellipticity)

See talks by Clara and Kirit

Systematics beyond Beam imperfections



Other systematic effects investigated and simulated [BICEP/Keck III 2015]

Table of jackknife tests and corresponding PTE values [BICEP/Keck XV 2021]

Table 11. Jackknife PTE values from χ and χ^2 tests.

	2016		2017		2018	
	χ	χ^2	χ	χ^2	χ	χ^2
Band Power	1-5/1-9					
Deck jackknife						
EE	0.501/0.383	0.754/0.719	0.982/0.992	0.050/0.108	0.022/0.172	0.122/0.092
BB	0.936/0.998	0.443/0.226	0.731/0.419	0.848/0.563	0.567/0.924	0.130/0.152
EB	0.319/0.283	0.840/0.866	0.263/0.589	0.932/0.838	0.265/0.307	0.832/0.868
Scan dir jackknife						
EE	0.277/0.112	0.956/0.275	0.449/0.453	0.066/0.070	0.198/0.437	0.804/0.459
BB	0.764/0.872	0.525/0.196	0.283/0.433	0.162/0.407	0.168/0.172	0.012/0.030
EB	0.904/0.431	0.697/0.591	0.076/0.228	0.517/0.816	0.838/0.527	0.806/0.798
Temporal split jackknife						
EE	0.998/0.996	0.084/0.257	0.028/0.068	0.277/0.295	0.146/0.467	0.395/0.152
BB	0.098/0.200	0.261/0.255	0.263/0.531	0.331/0.317	0.826/0.946	0.822/0.719
EB	0.958/0.772	0.461/0.713	0.956/0.936	0.020/0.044	0.070/0.034	0.497/0.499
Tile jackknife						
EE	0.257/0.150	0.429/0.623	0.403/0.529	0.559/0.248	0.002/0.004	0.004/0.018
BB	0.527/0.713	0.323/0.495	0.952/0.852	0.455/0.816	0.697/0.862	0.705/0.371
EB	0.707/0.493	0.776/0.872	0.381/0.633	0.517/0.311	0.946/0.984	0.146/0.257
Azimuth jackknife						
EE	0.575/0.866	0.140/0.259	0.776/0.727	0.916/0.962	0.834/0.545	0.695/0.687
BB	0.014/0.126	0.082/0.068	0.178/0.425	0.435/0.667	0.487/0.279	0.860/0.665
EB	0.357/0.415	0.846/0.212	0.487/0.068	0.904/0.363	0.876/0.998	0.164/0.040
Mux col jackknife						
EE	0.309/0.429	0.335/0.363	0.731/0.745	0.232/0.625	0.681/0.946	0.894/0.778
BB	0.665/0.182	0.960/0.423	0.116/0.070	0.840/0.950	0.210/0.657	0.573/0.108
EB	0.451/0.681	0.944/0.992	0.335/0.339	0.423/0.415	0.248/0.353	0.988/0.924
Alt deck jackknife						
EE	0.982/0.996	0.220/0.166	0.972/0.954	0.172/0.405	0.056/0.182	0.102/0.214
BB	0.062/0.635	0.307/0.170	0.251/0.236	0.050/0.100	0.054/0.467	0.152/0.042
EB	0.198/0.192	0.477/0.790	0.411/0.731	0.238/0.118	0.667/0.429	0.513/0.814
Mux row jackknife						
EE	0.776/0.796	0.144/0.068	0.914/0.824	0.345/0.447	0.741/0.359	0.707/0.719
BB	0.822/0.725	0.539/0.631	0.425/0.631	0.561/0.800	0.515/0.673	0.890/0.583
EB	0.850/0.471	0.060/0.166	0.677/0.573	0.383/0.677	0.367/0.601	0.870/0.844
Tile and deck jackknife						
EE	0.631/0.421	0.788/0.878	0.439/0.427	0.888/0.920	0.886/0.926	0.715/0.902
BB	0.902/0.904	0.531/0.477	0.601/0.786	0.441/0.407	0.411/0.567	0.349/0.695
EB	0.311/0.461	0.429/0.569	0.842/0.709	0.204/0.377	0.896/0.944	0.733/0.485
Focal plane inner or outer jackknife						
EE	0.355/0.635	0.822/0.311	0.204/0.224	0.579/0.633	0.174/0.120	0.208/0.327
BB	0.800/0.922	0.711/0.555	0.663/0.928	0.617/0.295	0.148/0.194	0.204/0.283
EB	0.483/0.760	0.303/0.373	0.836/0.974	0.711/0.549	0.132/0.130	0.880/0.635
Tile top or bottom jackknife						
EE	0.942/0.641	0.064/0.010	0.768/0.960	0.505/0.397	0.910/0.679	0.204/0.463
BB	0.974/0.764	0.124/0.012	0.224/0.703	0.046/0.090	0.226/0.705	0.774/0.503
EB	0.353/0.717	0.675/0.593	0.786/0.932	0.411/0.451	0.136/0.345	0.148/0.174
Tile inner or outer jackknife						
EE	0.745/0.665	0.397/0.798	0.828/0.870	0.756/0.930	0.002/0.012	0.014/0.124
BB	0.337/0.667	0.224/0.421	0.196/0.667	0.956/0.818	0.810/0.924	0.076/0.138
EB	0.820/0.900	0.840/0.922	0.216/0.405	0.583/0.756	0.321/0.545	0.321/0.635
Moon jackknife						
EE	0.218/0.709	0.485/0.487	0.860/0.882	0.780/0.878	0.904/0.683	0.104/0.160
BB	0.976/0.824	0.255/0.607	0.996/0.946	0.108/0.246	0.206/0.164	0.142/0.385
EB	0.487/0.900	0.778/0.693	0.088/0.128	0.583/0.463	0.840/0.912	0.701/0.064
A and B offset best and worst jackknife						
EE	0.860/0.794	0.723/0.924	0.571/0.661	0.315/0.537	0.860/0.625	0.908/0.565
BB	0.453/0.561	0.022/0.044	0.970/0.972	0.194/0.293	0.860/0.942	0.814/0.780
EB	0.435/0.455	0.259/0.549	0.806/0.760	0.421/0.285	0.806/0.623	0.776/0.551

New layer of instrumental systematic control: Are our maps statistically isotropic?

Basis of 11 map-level distortion fields:

$$
\begin{aligned}
\delta[Q \pm iU](\vec{n}) = \; & + [\tau(\vec{n}) \pm 2i\omega(\vec{n})]\,[\tilde{Q} \pm i\tilde{U}](\vec{n}) \\
& + [f_1(\vec{n}) \pm i f_2(\vec{n})]\,[\tilde{Q} \mp i\tilde{U}](\vec{n}) \\
& + [\gamma_1(\vec{n}) \pm i\gamma_2(\vec{n})]\, T(\vec{n}) \\
& + \vec{p}(\vec{n}) \cdot \nabla[\tilde{Q} \pm i\tilde{U}](\vec{n}) \\
& + [d_1(\vec{n}) \pm i d_2(\vec{n})]\,[\partial_1 \pm i\partial_2]\, T(\vec{n}) \\
& + q(\vec{n})[\partial_1 \pm i\partial_2]^2\, T(\vec{n})
\end{aligned}
$$

[Hu et al. 2003]

Basis of 11 map-level distortion fields

field	instrumental systematics
τ	detector gain miscalibration
ω	detector polarization angle miscalibration
p_1, p_2	detector beam center miscalibration
γ_1, γ_2	A/B detector gain mismatch
d_1, d_2	A/B detector differential pointing
q	A/B detector differential beamwidth
f_1, f_2	gain miscalibration coupled with deck angle rotation

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

Cosmological map distortions

Patchy reionization

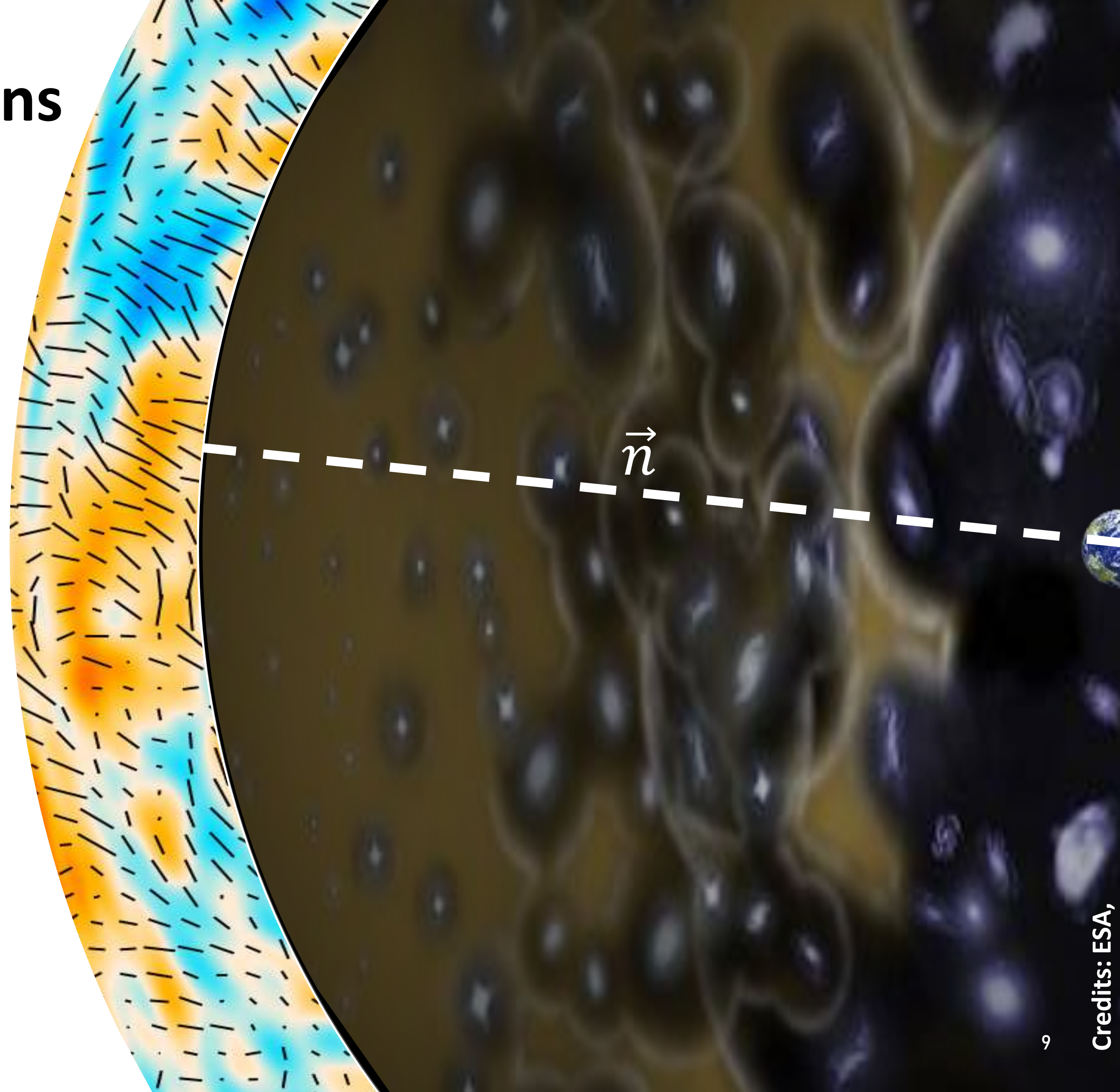
$$\Delta Q \pm iU = \tau\,(Q \pm iU)$$

↓

crinkly-surface model

[Glusevic et al. 2013]

$$C_L^{\tau\tau} = \left(\frac{A^\tau}{10^4}\right)\frac{4\pi}{L_c^2}\,e^{-L^2/L_c^2}$$

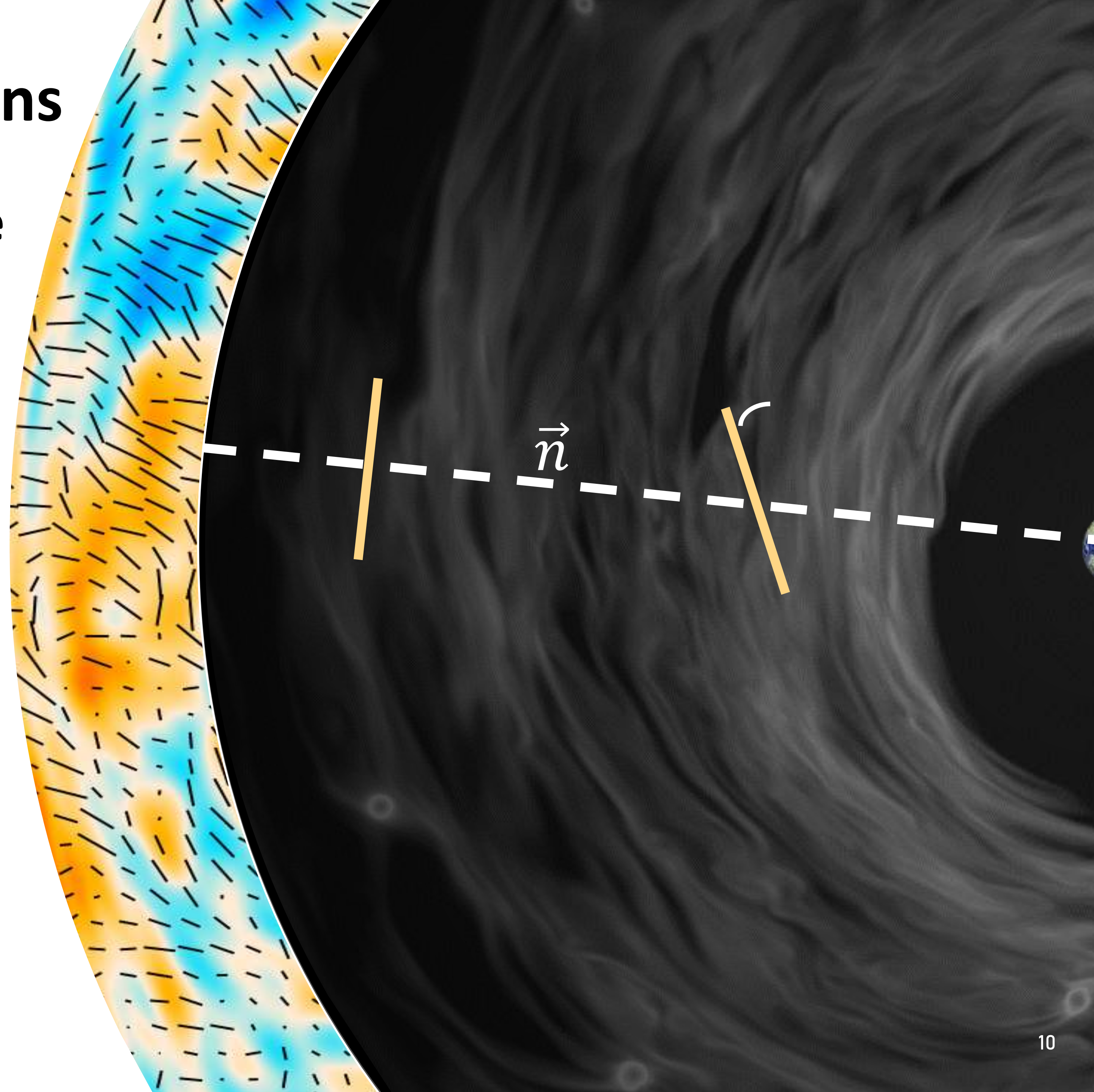


Cosmological map distortions

Anisotropic cosmic birefringence

$$\Delta Q \pm iU = \pm 2i\omega\,(Q \pm iU)$$

- photon-axion coupling, $g_{a\gamma}$
  [Carroll et al. 1990]
- primordial magnetic fields
  [Yadav et al. 2012]



Credits: Hongping Deng et al.

Cosmological map distortions

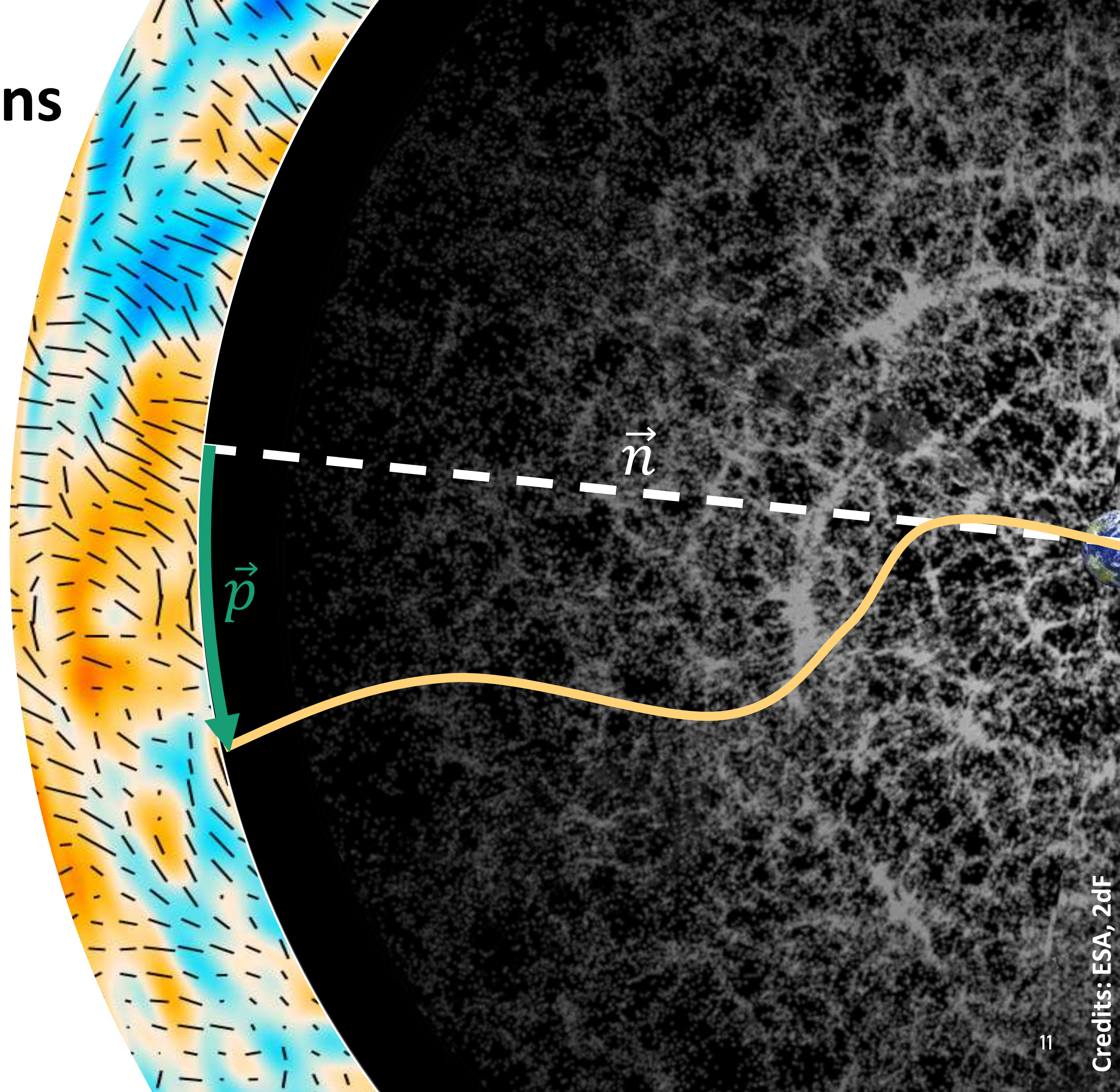
CMB lensing

$$\Delta Q \pm iU = \vec{p} \cdot \nabla(Q \pm iU)$$

↓

gradient lensing deflection

$$\vec{p}(\vec{n}) = -2 \int d\chi \frac{\chi_* - \chi}{\chi \chi_*} \nabla\Psi$$



Credits: ESA, 2dF

Reconstruction of Distortion Fields

The quadratic estimator

measured B map

filter function specific to each distortion field

$$\bar{D}_{\boldsymbol{L}}^{XB} = A_L^{D,XB} \int \frac{d^2 \boldsymbol{l}_1}{(2\pi)^2} X_{\boldsymbol{l}_1} B_{\boldsymbol{l}_2} \frac{f_{\boldsymbol{l}_1,\boldsymbol{l}_2}^{D,XB}}{C_{\boldsymbol{l}_1}^{XX} C_{\boldsymbol{l}_2}^{BB}}$$

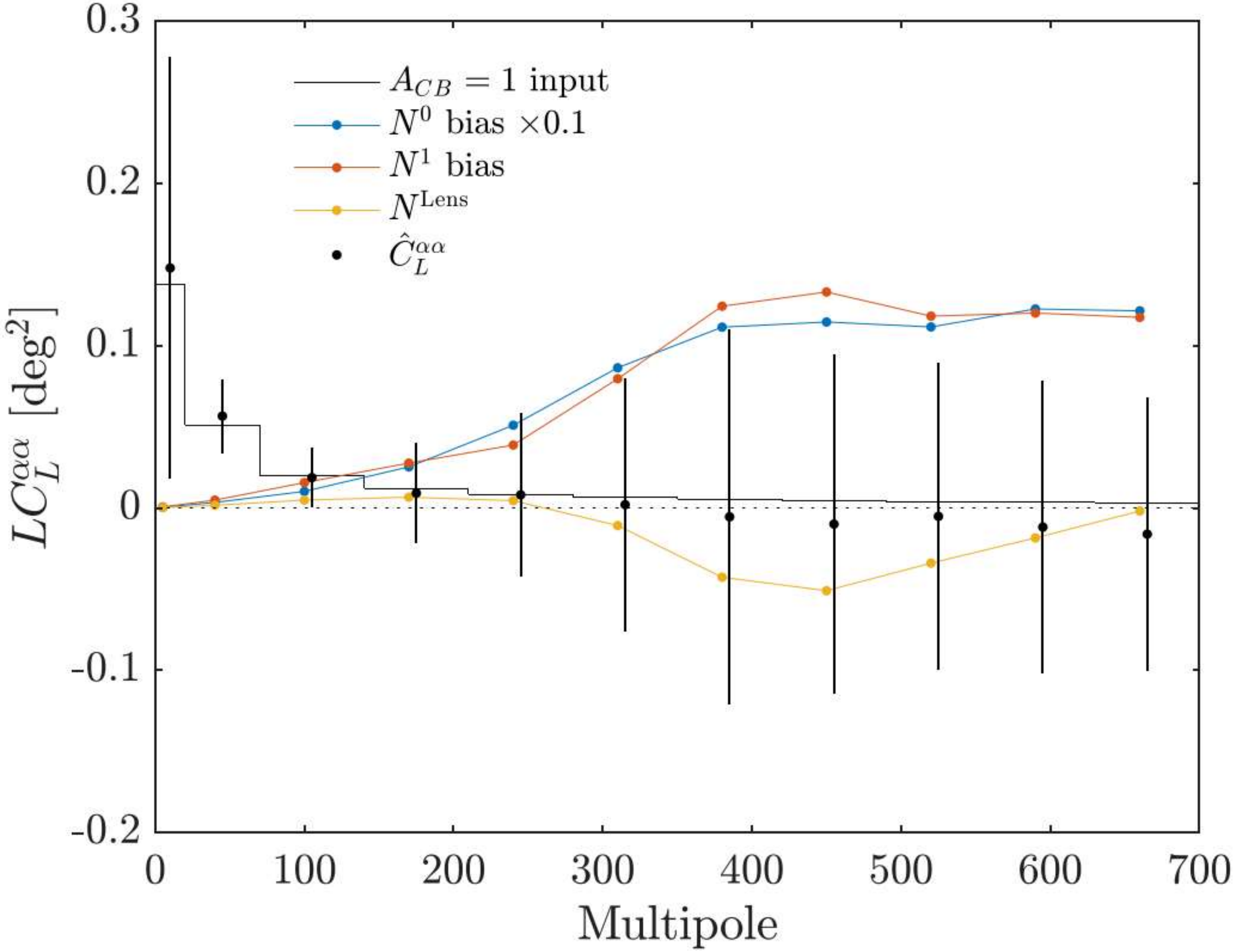
normalization

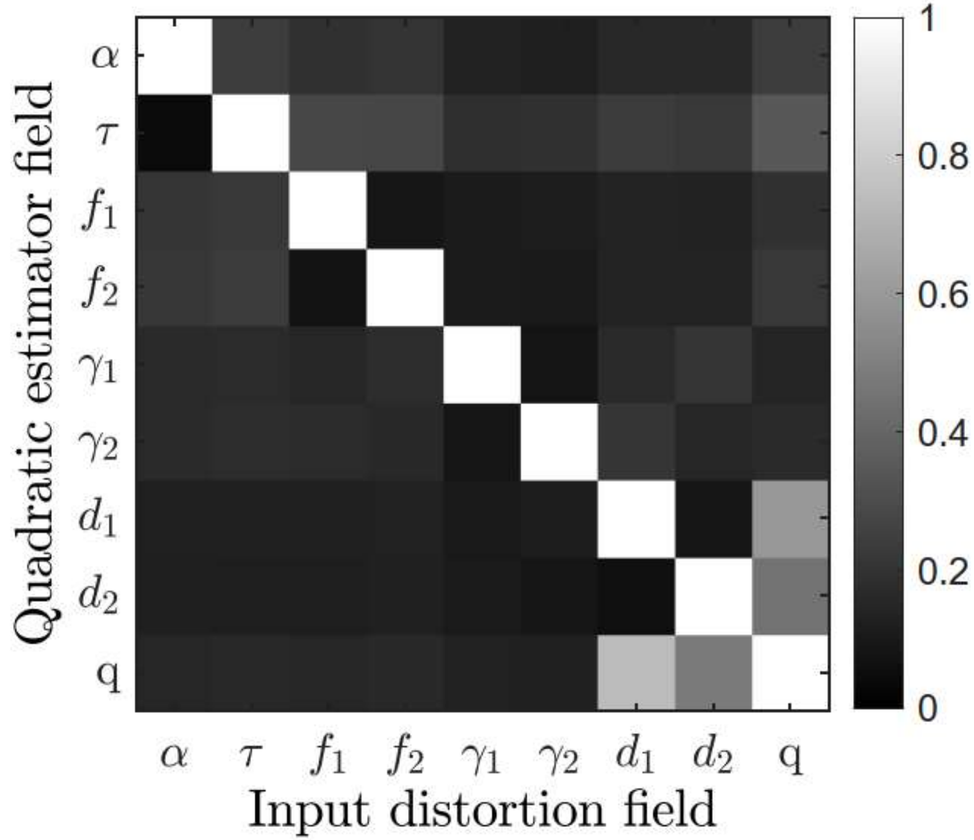
measured T or E map

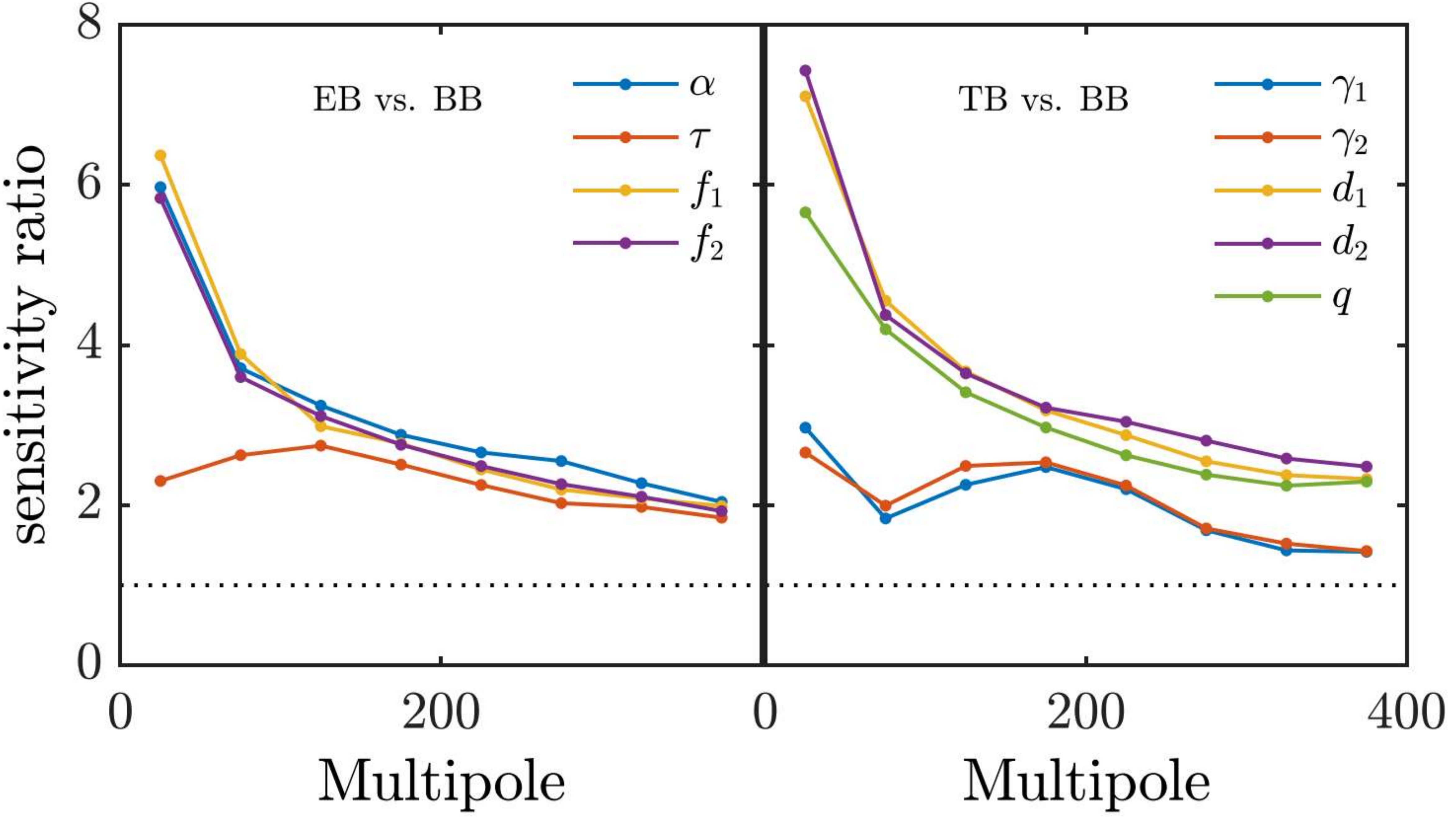
$$\left\langle \left| \hat{D}_{\boldsymbol{L}} \right|^2 \right\rangle = \hat{C}_{\boldsymbol{L}}^{DD} + \hat{N}_{\boldsymbol{L}}^{DD}$$

bias terms: $N_L^{(0)}$, $N_L^{(1)}$, N_L^{lens}

Reconstruction of Distortion Fields



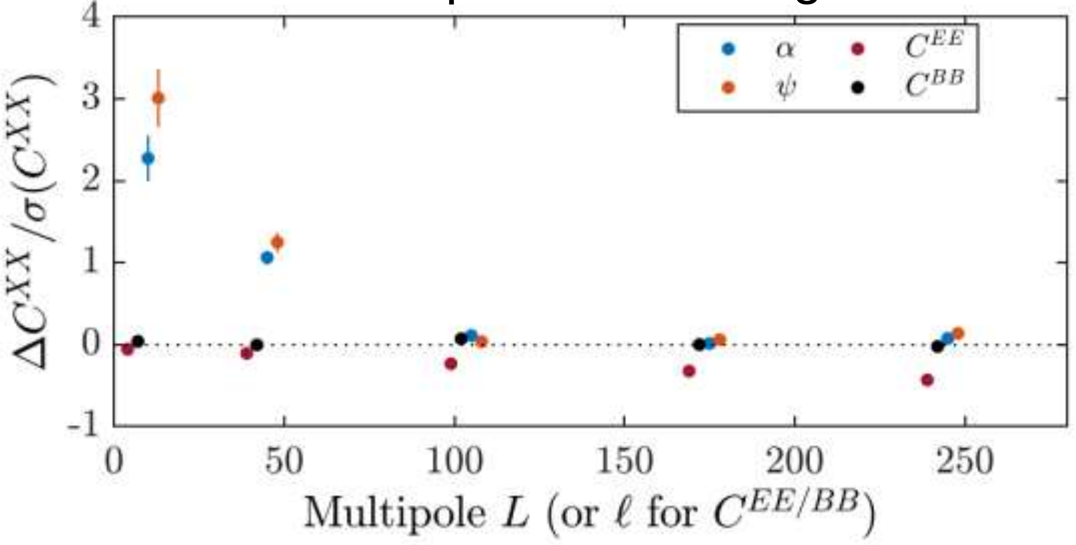




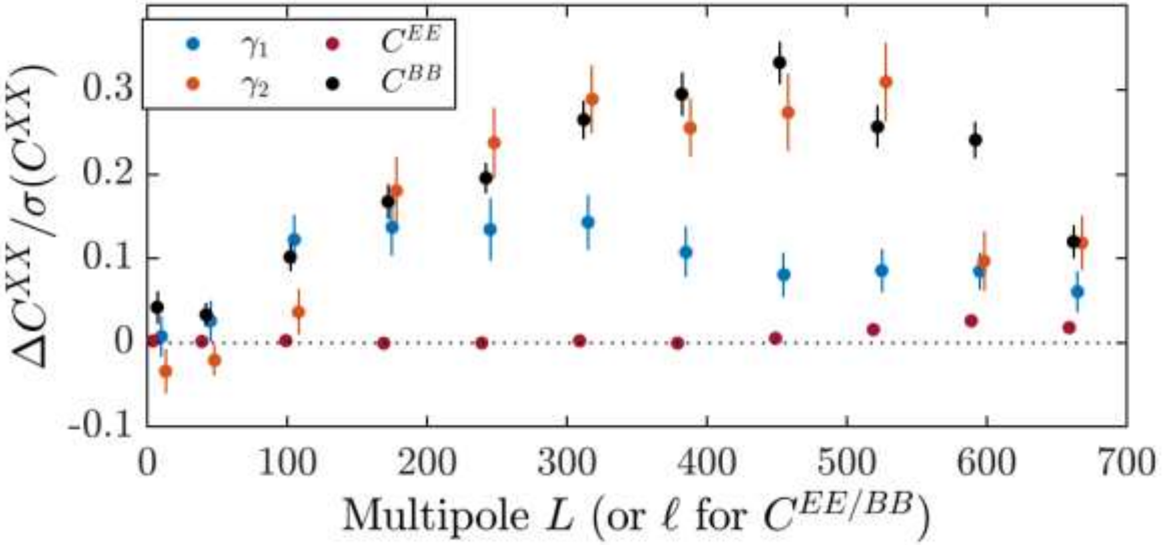
EB vs. BB
TB vs. BB
α
τ
f_1
f_2
γ_1
γ_2
d_1
d_2
q
sensitivity ratio
Multipole
Multipole
0
2
4
6
8
0
200
0
200
400

Systematic simulations

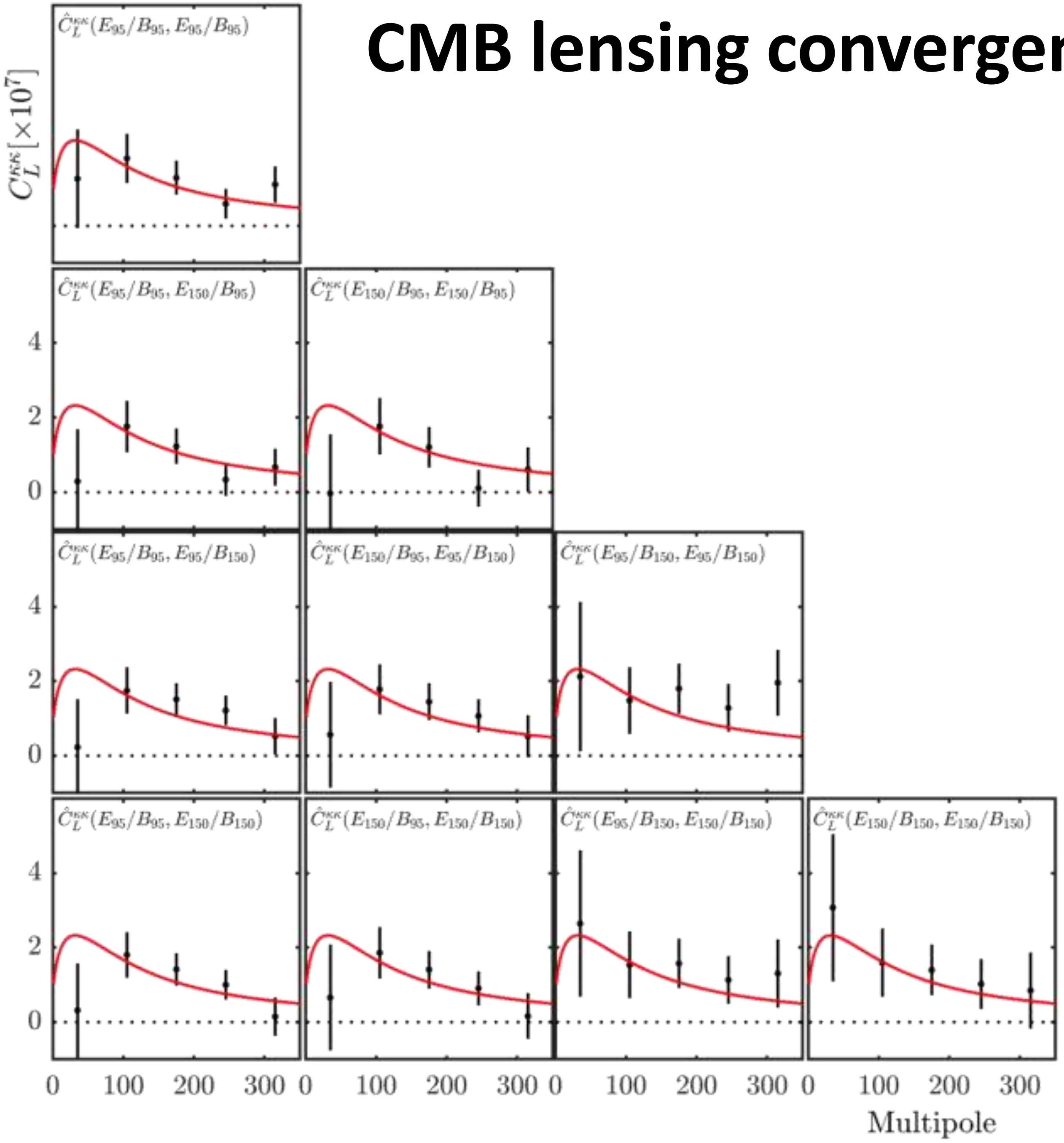
10 % random polarization angle rotation



10 % hour to hour differential gain fluctuation



CMB lensing convergence



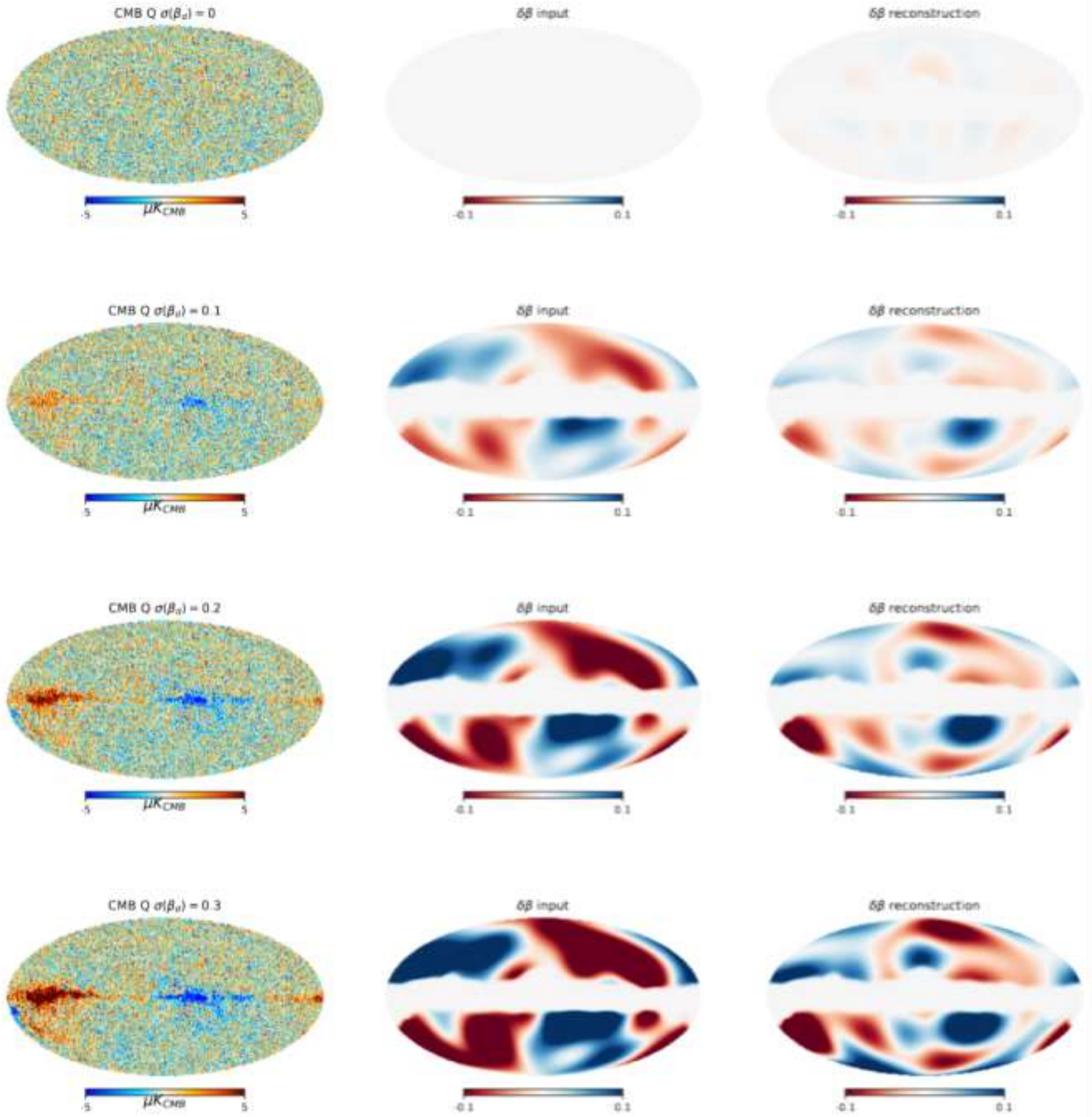
$A_L^{\phi\phi} = 1.15 \pm 0.36$ (BK14 EBEB)
$A_L^{\phi\phi} = ?.?? \pm 0.20$ (BK18 EBEB)
$A_L^{\phi\phi} = 1.03 \pm 0.09$ (BK18 BB)

Beyond BICEP/*Keck*

Measure the "distortion" caused by a varying dust SED in a component-separated CMB map

F. Bianchini

K. Wu



Conclusions

- We use TB and EB quadratic estimators to reconstruct spatially varying distortion fields in BK 95 GHz and 150 GHz maps
- Distortion fields can be used for instrumental systematics identification and perform measurements of patchy reionization, anisotropic cosmic birefringence or lensing
- Distortion fields can be more sensitive to certain types of instrumental systematics than traditional EE and BB jackknifes and have been already a useful tool to identify spurious instrumental systematics in ongoing data analysis
- Could be potentially used for systematics mitigation in the future