Controlling Beam Systematics in Next Generation CMB Experiments

CMB systematics and calibration focus workshop
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Nialh McCallum – nialh.mccallum@manchester.ac.uk

In collaboration with -
Daniel Thomas – dan.b.thomas1@gmail.com
Michael Brown – m.l.brown@manchester.ac.uk

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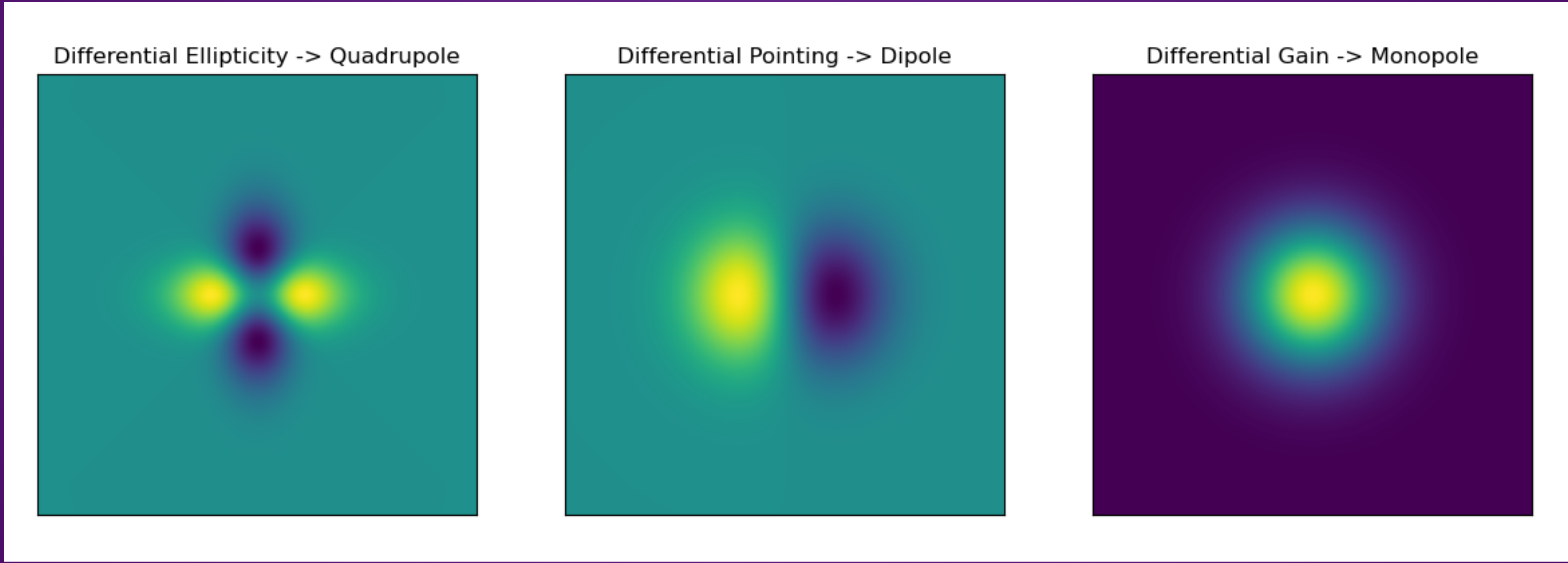
Common Beam Systematics

- Beam Ellipticity/Asymmetries
- Sidelobes (Ground pickup, sun, satellites?!?)
- Differential Systematics T->P Leakage/P->P Mixing
- Interaction with Half Wave Plate Systematics

Differential Beam Systematics



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Mitigation of Beam Systematics

1. Scan Strategy Design – crossing angle coverage metric
2. Instrument Rotation Capability – building in specific angles
3. Analytic Calculation – spin characterisation of systematics
4. Map making - Inclusion of additional spins to remove systematics

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Metric for evaluating crossing angle coverage

For a set of crossing angles ψ_j scan strategy in a pixel can be expressed

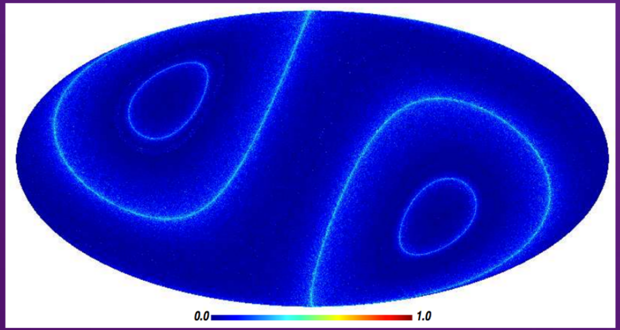
$$\tilde{h}_n = \frac{1}{N_{hits}} \sum \{\cos(n\psi_j) + i\sin(n\psi_j)\}$$

Ideal Scan $|\tilde{h}_n| = 0$

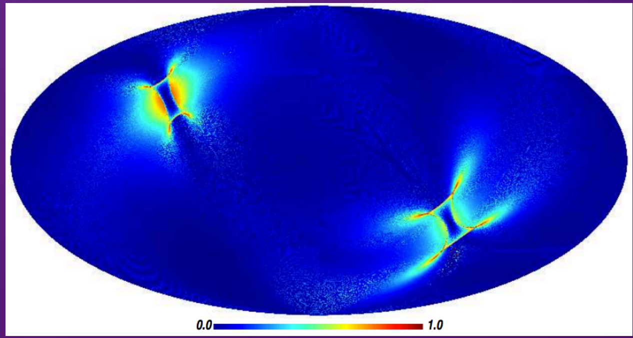
Worst case scenario $|\tilde{h}_n| = 1$

<u>Advantages</u>

- Directly appear in map making ($\tilde{h}_2, \tilde{h}_4$) and systematics (e.g. pointing error couples to $\tilde{h}_1, \tilde{h}_3$)
- Implemented as operator in TOAST



$|\tilde{h}_1|^2$ WMAP



$|\tilde{h}_1|^2$ Planck

See Wallis et al. - https://arxiv.org/abs/1604.02290 and McCallum et al. - https://arxiv.org/abs/2008.00011

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Instrument Rotation Metric

- Easy incorporation of the effect of boresight rotation, precession etc.
- Incorporates effect of sky rotation into metric
- i.e. Suitable for analysis of scans from ground, balloon, or space

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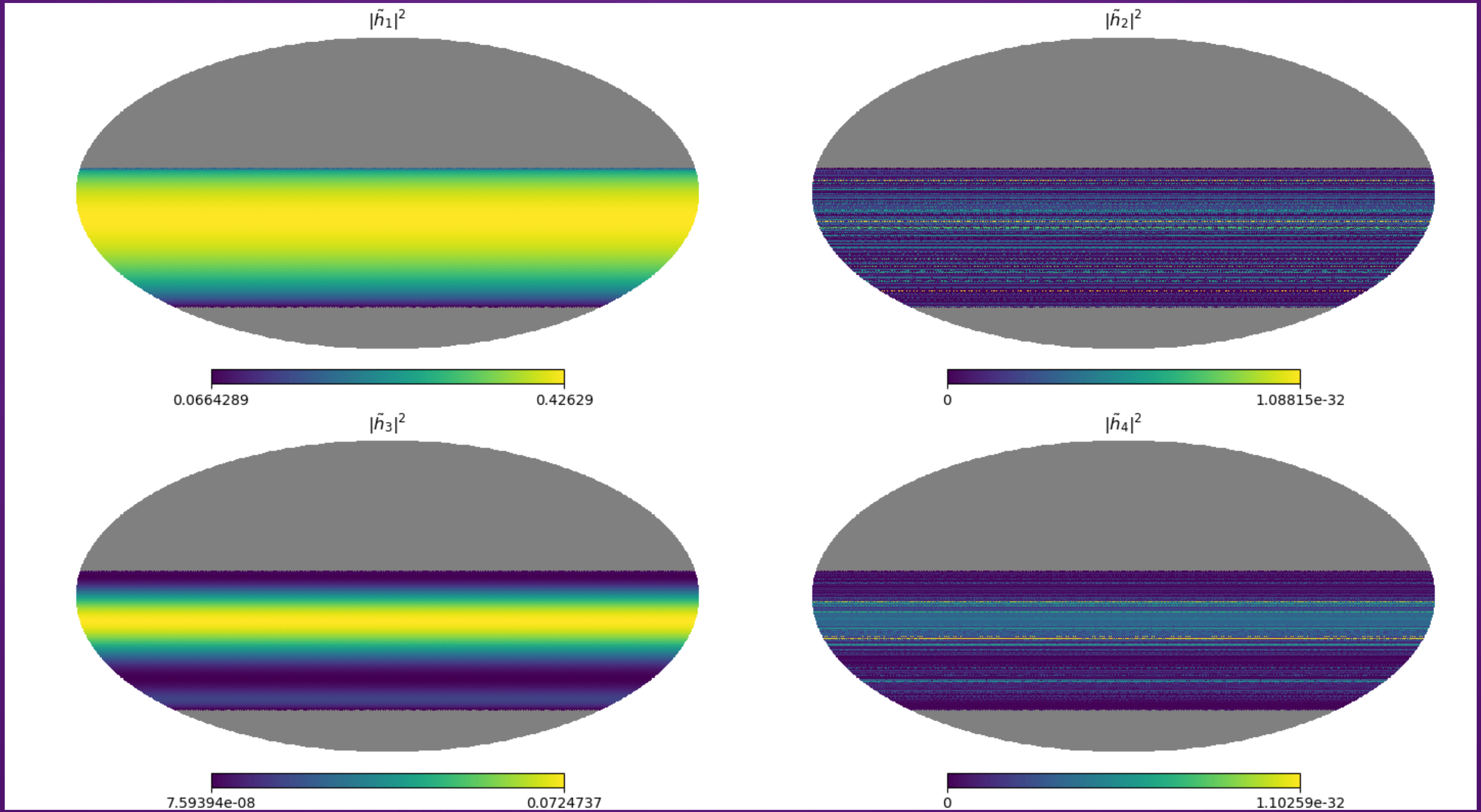
Boresight Rotation

- 180-degree rotation (SO-LAT): zeros $\tilde{h}_1$, $\tilde{h}_3$; no effect on $\tilde{h}_2$, $\tilde{h}_4$
- 90-degree rotation (SO-SAT): zeros $\tilde{h}_2$; strong effect on $\tilde{h}_1$, $\tilde{h}_3$; no effect on $\tilde{h}_4$
- 45-degree zeros $\tilde{h}_4$; works well for all
- Intuitively we are heading towards ideal scan
  - i.e. Scans repeated at 8 distinct deck angles in 45-degree steps (e.g. 0, 45, 90, 135, 180, 225, 270, 315) would zero $\tilde{h}_1$, $\tilde{h}_2$, $\tilde{h}_3$, and $\tilde{h}_4$.
  - Bicep already considered this and utilized the 45-degree deck angle separations in their design

Deck angles of [0, 45, 90, 135]



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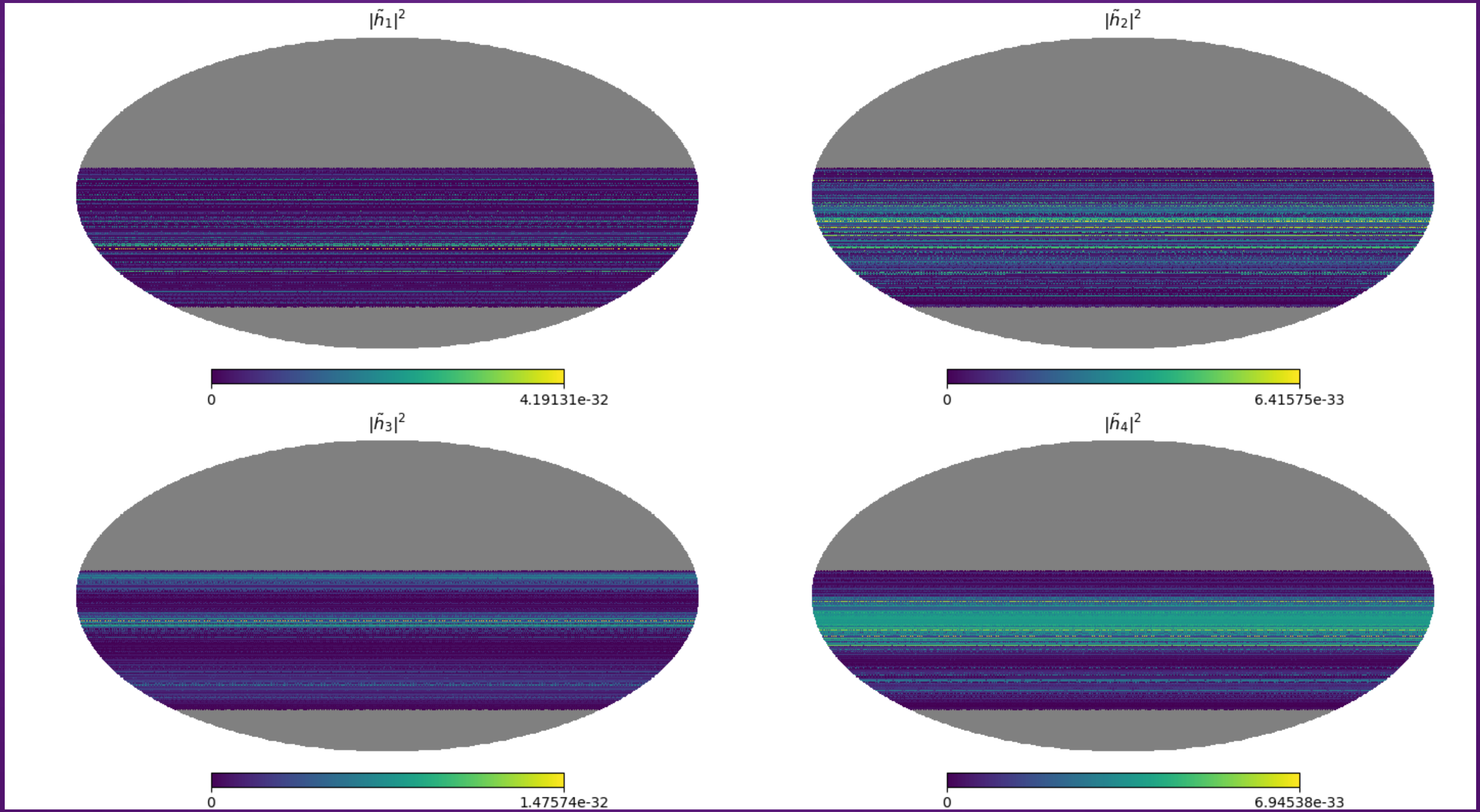
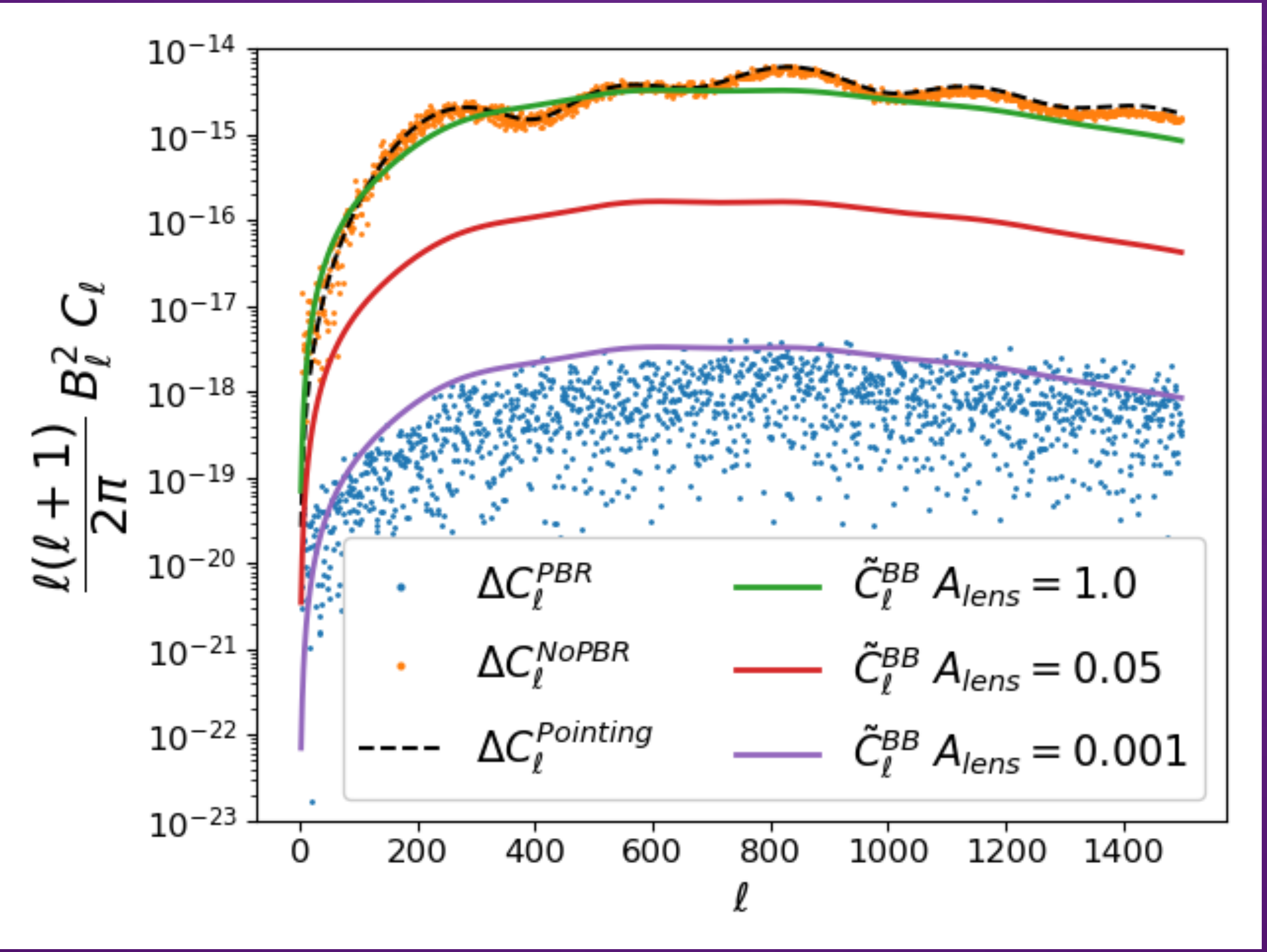
Deck angles of [0, 45, 90, 135, 180, 225, 270, 315]



Exploiting Symmetries

Differential Pointing example using ground-based Chile observatory -



$$\Delta^P = \frac{1}{4}\tilde{h}_1(\rho_1\, e^{i\,\chi_1} + \rho_2\, e^{i\,(\chi_2-\pi/4)})\,\eth I(\Omega) + \frac{1}{4}\tilde{h}_3(\rho_1\, e^{-i\,\chi_1} + \rho_2\, e^{-i\,(\chi_2+3\pi/4)})\bar{\eth} I(\Omega)$$

- Boresight Rotation of 180°
- $\tilde{h}_1$ and $\tilde{h}_3$ --> 0

Beam FWHM 7arcmin
Pointing offset 0.1arcmin
(Just T->P Leakage)

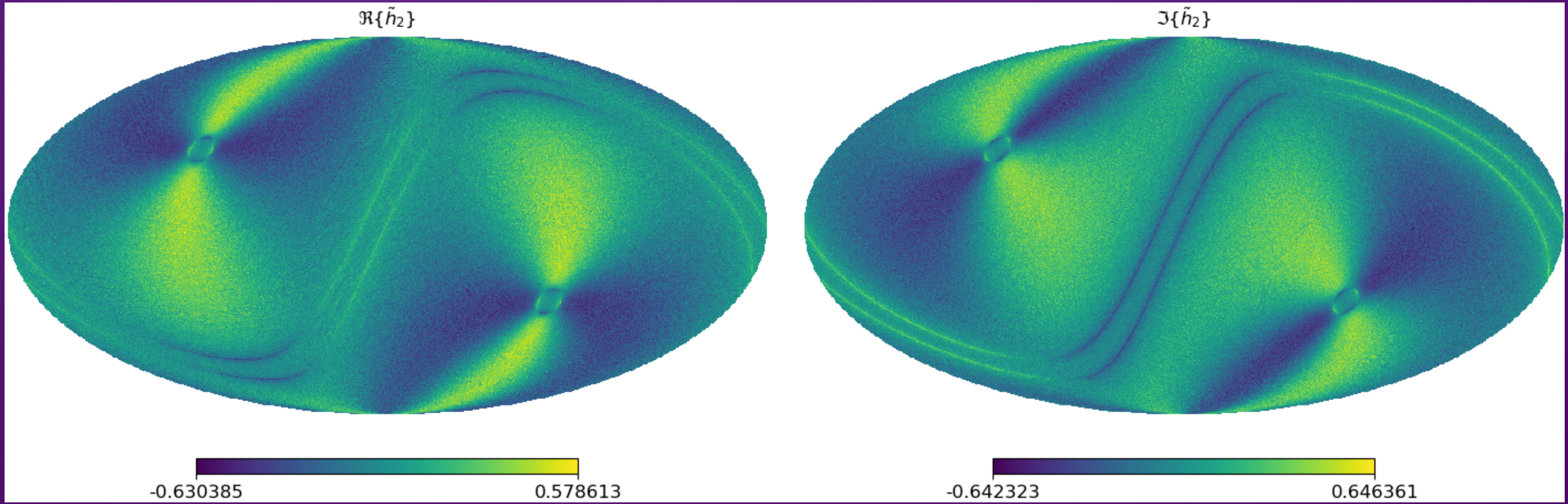
See Thomas et al. - https://arxiv.org/abs/1905.12647

Spin characterisation of systematics

$$\tilde{h}_n(\theta,\phi) = \frac{1}{N_{\text{hits}}(\theta,\phi)} \sum_j \left(\cos\left(n\varphi_j(\theta,\phi)\right) + i\sin\left(n\varphi_j(\theta,\phi)\right)\right)$$

$${}_k\tilde{S}^d(\theta,\phi) = \sum_{k'=-\infty}^{\infty} \tilde{h}_{k-k'}(\theta,\phi)\,{}_{k'}\tilde{S}(\theta,\phi)$$

EPIC Satellite Scan Example $\tilde{h}_2$ Field -



See McCallum et al. - https://arxiv.org/abs/2008.00011

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Propagating to Pseudo Power Spectra

$$ {}_2\tilde{S}^d_{\ell m} = {}_2\tilde{P}_{\ell m} + {}_2\tilde{\Delta}_{\ell m} $$

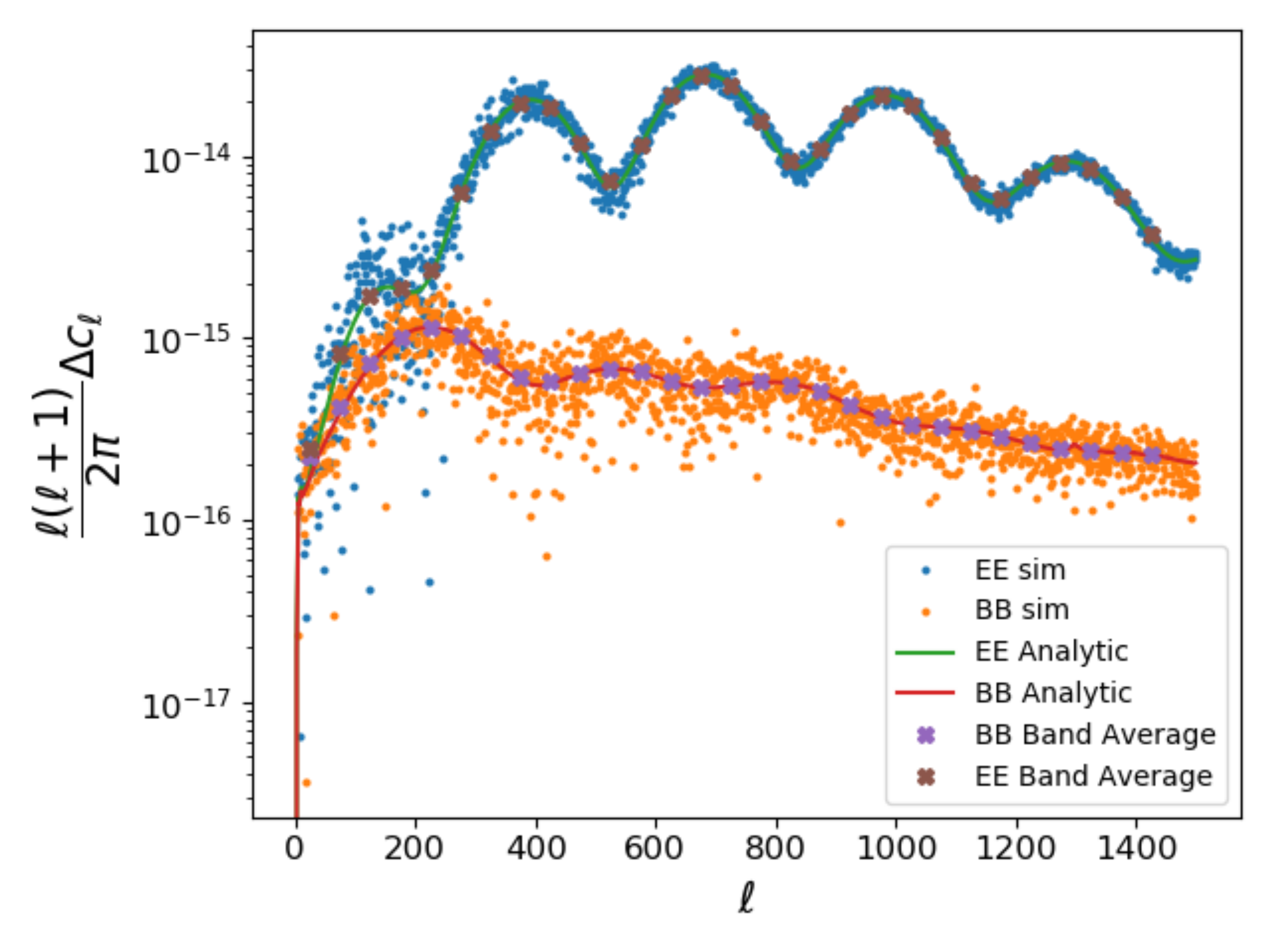
$$ \tilde{C}_\ell^{\hat{B}\hat{B}} = \tilde{C}_\ell^{\tilde{B}\tilde{B}} + \frac{1}{2\,(2\ell+1)} \sum_m \Big\{ \langle {}_2\tilde{\Delta}_{\ell m}\, {}_2\tilde{\Delta}^*_{\ell m} \rangle - (-1)^m\, \Re \langle {}_2\tilde{\Delta}_{\ell m}\, {}_2\tilde{\Delta}_{\ell -m} \rangle - 4 \Im \langle \tilde{B}_{lm}\, {}_2\tilde{\Delta}^*_{\ell m} \rangle \Big\} $$

$$ \tilde{C}_\ell^{\hat{E}\hat{E}} = \tilde{C}_\ell^{\tilde{E}\tilde{E}} + \frac{1}{2\,(2\ell+1)} \sum_m \Big\{ \langle {}_2\tilde{\Delta}_{\ell m}\, {}_2\tilde{\Delta}^*_{\ell m} \rangle + (-1)^m\, \Re \langle {}_2\tilde{\Delta}_{\ell m}\, {}_2\tilde{\Delta}_{\ell -m} \rangle + 4\, \Re \langle \tilde{E}_{\ell m}\, {}_2\tilde{\Delta}^*_{\ell m} \rangle \Big\} $$

See McCallum et al. - https://arxiv.org/abs/2008.00011

Demonstration - Differential Gain Systematic

Differential Gain example using an EPIC satellite scanning strategy -



$$
{}_2\tilde{\Delta}^g_{\ell m} = \sum_{\substack{l_1 m_1 \\ l_2 m_2}} \left(\frac{1}{2}\, {}_2h_{l_1 m_1} \left(\delta g_1 - i\,\delta g_2\right) \begin{pmatrix} \ell & l_1 & l_2 \\ 2 & -2 & 0 \end{pmatrix} I_{l_2 m_2} + \frac{1}{4}\, {}_0h_{l_1 m_1} \left(g_1^A + g_1^B + g_2^A + g_2^B\right) \begin{pmatrix} \ell & l_1 & l_2 \\ 2 & 0 & -2 \end{pmatrix} {}_2P_{l_2 m_2} \right.
$$
$$
\left. + \frac{1}{4}\, {}_4h_{l_1 m_1} \left(g_1^A + g_1^B - g_2^A - g_2^B\right) \begin{pmatrix} \ell & l_1 & l_2 \\ 2 & -4 & 2 \end{pmatrix} {}_{-2}P_{l_2 m_2} \right) (-1)^m \sqrt{\frac{(2\ell+1)(2l_1+1)(2l_2+1)}{4\pi}} \begin{pmatrix} \ell & l_1 & l_2 \\ -m & m_1 & m_2 \end{pmatrix}
$$

See McCallum et al. - https://arxiv.org/abs/2008.00011

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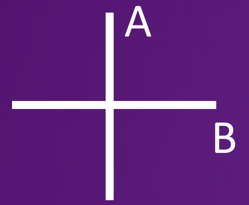
Map Making – Solving for Systematics

Gain Mismatch Example -



$$\frac{1}{2}\left[d^A - d^B\right] = \left[1 + \frac{g^A + g^B}{2}\right]\left[Q\cos\left(2\psi\right) + U\sin\left(2\psi\right)\right] + \frac{1}{2}\left[g^A - g^B\right] I$$

Simple Binned Map Making

Observed Spin-2 Signal (Just T->P Leakage)

$$\begin{pmatrix} Q \\ U \end{pmatrix} = \begin{pmatrix} \langle \cos^2(2\psi_j)\rangle & \langle \cos(2\psi_j)\sin(2\psi_j)\rangle \\ \langle \sin(2\psi_j)\cos(2\psi_j)\rangle & \langle \sin^2(2\psi_j)\rangle \end{pmatrix}^{-1} \begin{pmatrix} \langle d_j \cos(2\psi_j)\rangle \\ \langle d_j \sin(2\psi_j)\rangle \end{pmatrix}$$

$$\Rightarrow$$

$${}_2\tilde{S}^d(\theta,\phi) = \tilde{h}_0(\theta,\phi)P(\theta,\phi) + \frac{1}{2}\tilde{h}_2(\theta,\phi)(g^A - g^B)\, I(\theta,\phi)$$

$$\begin{pmatrix} I \\ Q \\ U \end{pmatrix} = \begin{pmatrix} 1 & \langle \cos(2\psi_j)\rangle & \langle \sin(2\psi_j)\rangle \\ \langle \cos(2\psi_j)\rangle & \langle \cos^2(2\psi_j)\rangle & \langle \cos(2\psi_j)\sin(2\psi_j)\rangle \\ \langle \sin(2\psi_j)\rangle & \langle \sin(2\psi_j)\cos(2\psi_j)\rangle & \langle \sin^2(2\psi_j)\rangle \end{pmatrix}^{-1} \begin{pmatrix} \langle d_j\rangle \\ \langle d_j \cos(2\psi_j)\rangle \\ \langle d_j \sin(2\psi_j)\rangle \end{pmatrix}$$

$$\Rightarrow$$

$${}_2\tilde{S}^d(\theta,\phi) = \tilde{h}_0(\theta,\phi)P(\theta,\phi) + \frac{1}{2}\tilde{h}_2$$ [redacted] $$I(\theta,\phi)$$

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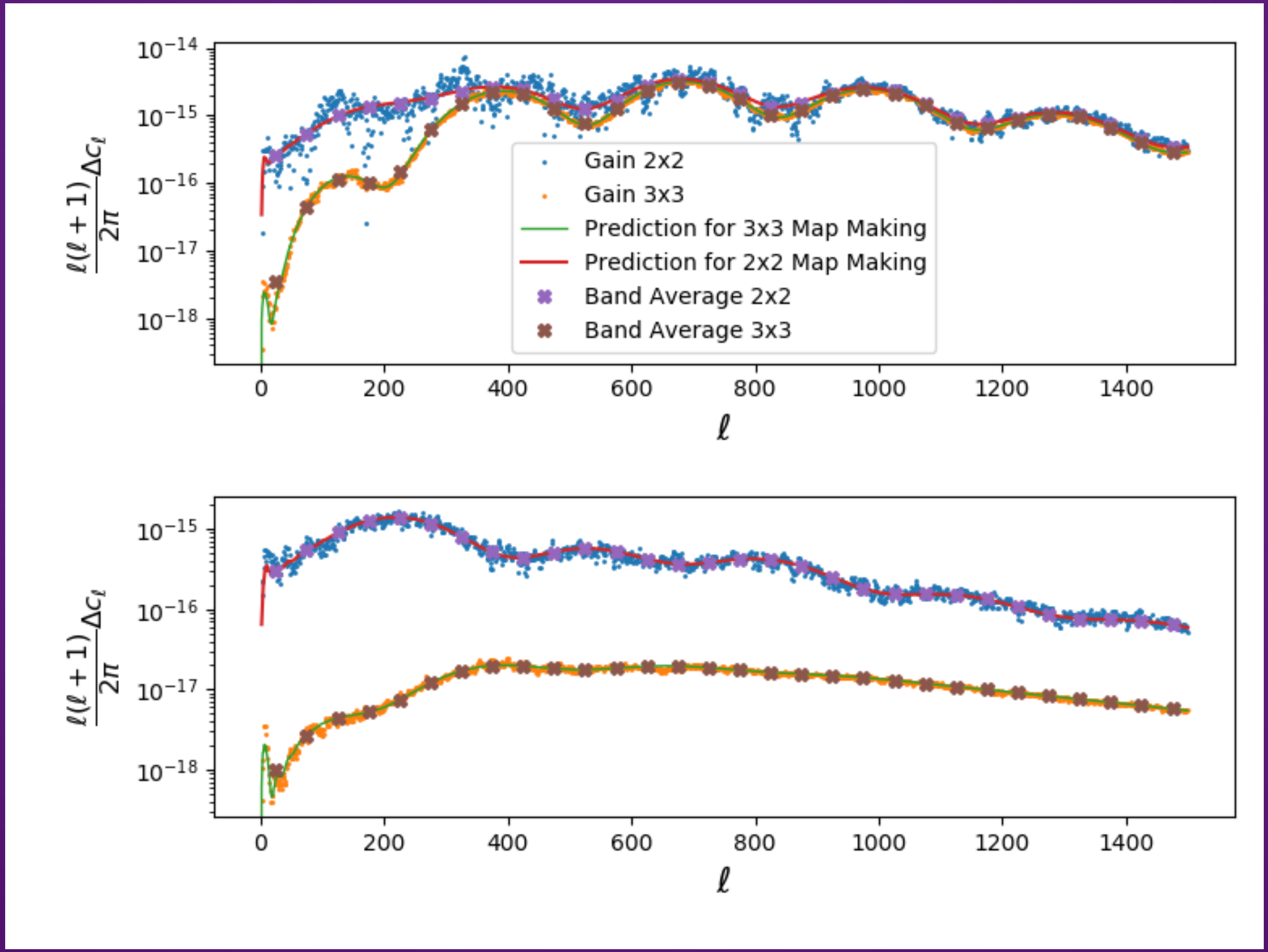
Map Making – Solving for Systematics



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Summary

- $\tilde{h}_n$ metric can incorporate the effect of instrument rotation and sky rotation together -> Suitable for analysis of scans from ground, balloon, or space
- Instrument rotation capability should be incorporated to exploit symmetries to suppress systematics
- Prior knowledge of the scan strategy can be used to analytically calculate systematics through their spin-characterization
- Inclusion of additional spins in map-making can remove systematic leakage

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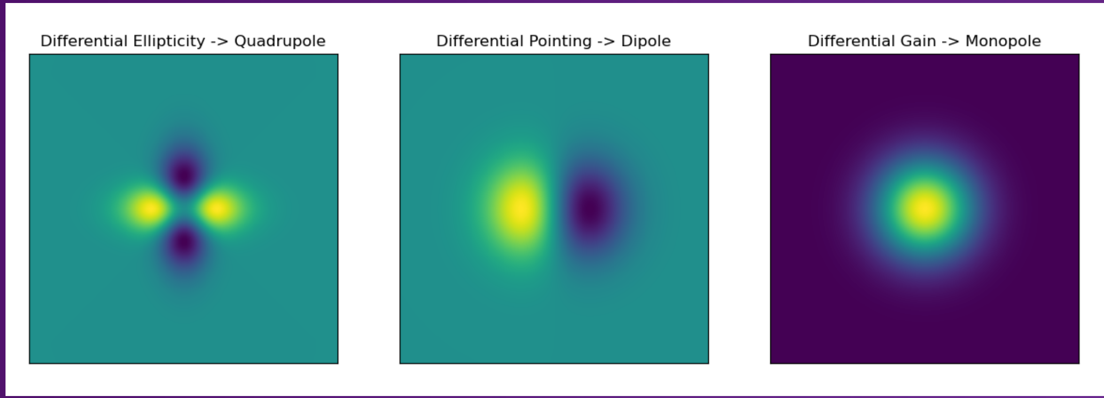
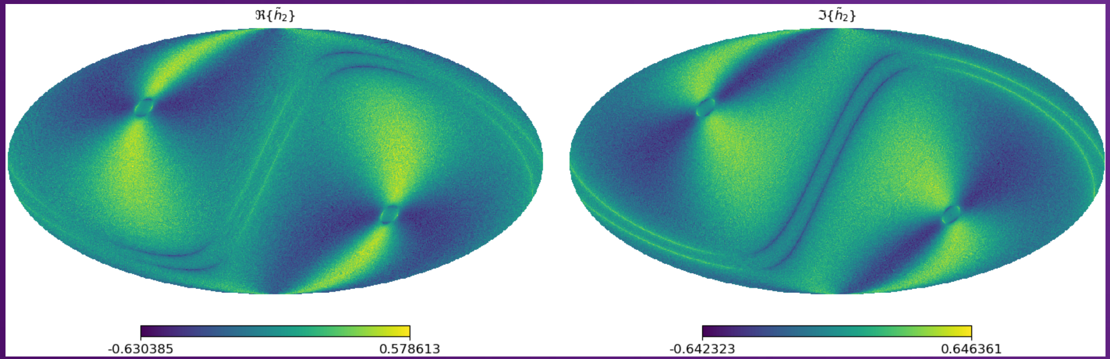
Controlling Beam Systematics in Next Generation CMB Experiments (1-minute slide)

UKRI Science and Technology Facilities Council





$$\tilde{h}_n = \frac{1}{N_{hits}} \sum \{\cos(n\psi_j) + i \sin(n\psi_j)\}$$

Beam Systematics

- Temperature to Polarisation Leakage
- Polarisation Mixing

Scan Strategy Design

- Suppression of systematics
- Analytic calculation of systematics

Instrument Rotation

- Specific angles can zero some systematics
- 8 distinct deck angles in 45-degree steps would zero $\tilde{h}_1$, $\tilde{h}_2$, $\tilde{h}_3$, and $\tilde{h}_4$ (e.g. 0, 45, 90, 135, 180, 225, 270, 315)

Map Making

-Inclusion of additional spins in map making to decouple systematics from polarisation

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