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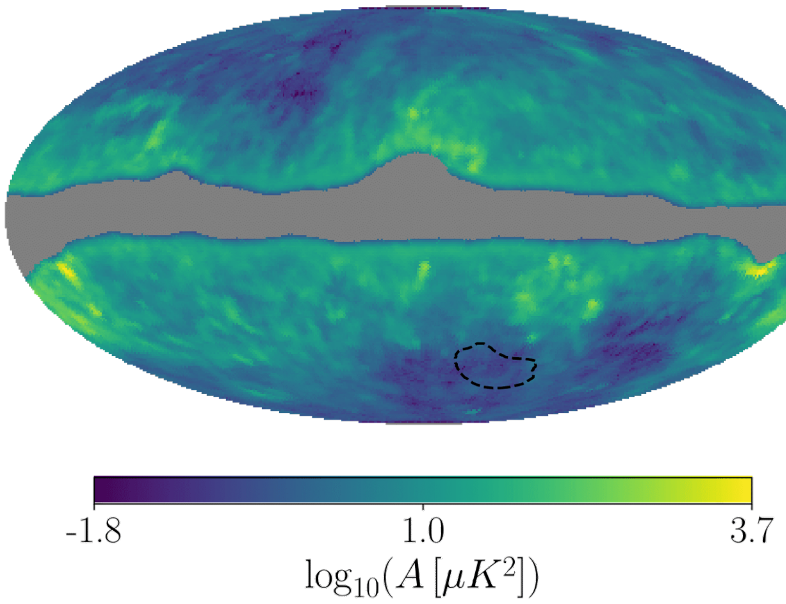

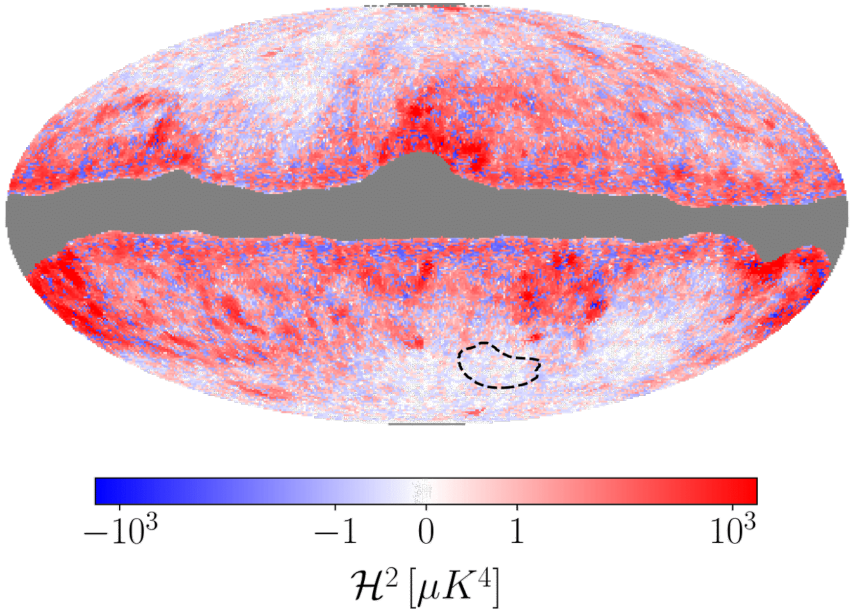

Detection and Removal of CMB B-mode Dust Foregrounds with Signatures of Statistical Anisotropy

OLIVER PHILCOX (PRINCETON)

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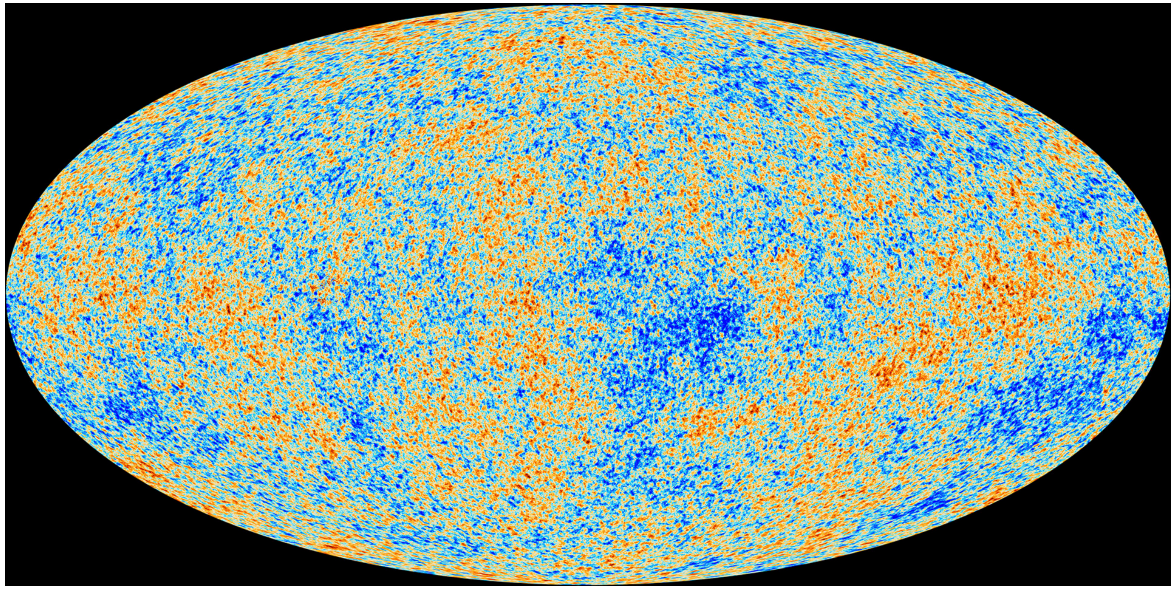
DECEMBER 6, 2019 - GRAVITY GROUP

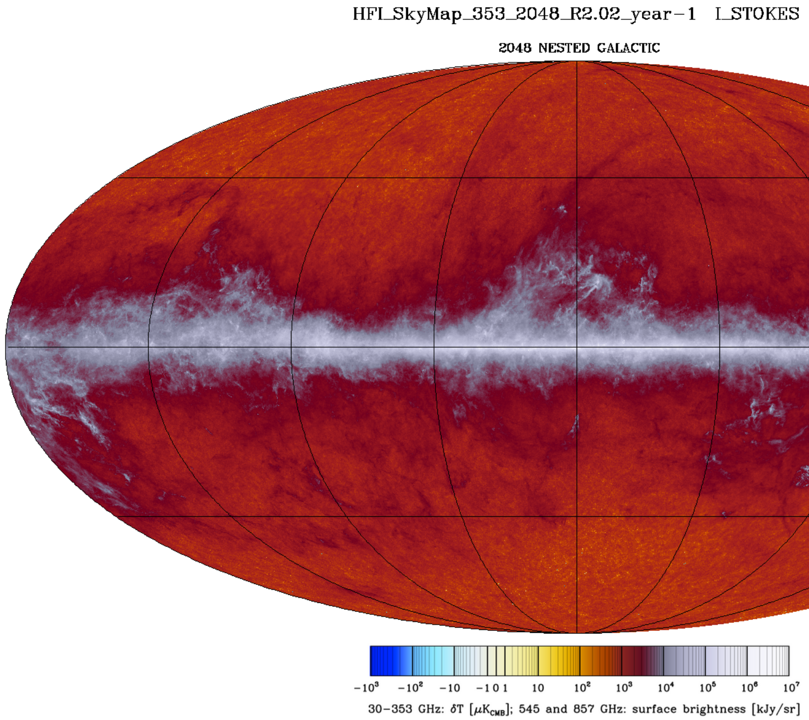
Outline

1. **Introduction to B-modes & Polarized Dust**
2. Detecting dust with anisotropy
3. How can this be used?
    1. Null Tests
    2. Dedusting

The Cosmic Microwave Background



Cleaned



Raw

[Planck Data Release 2]

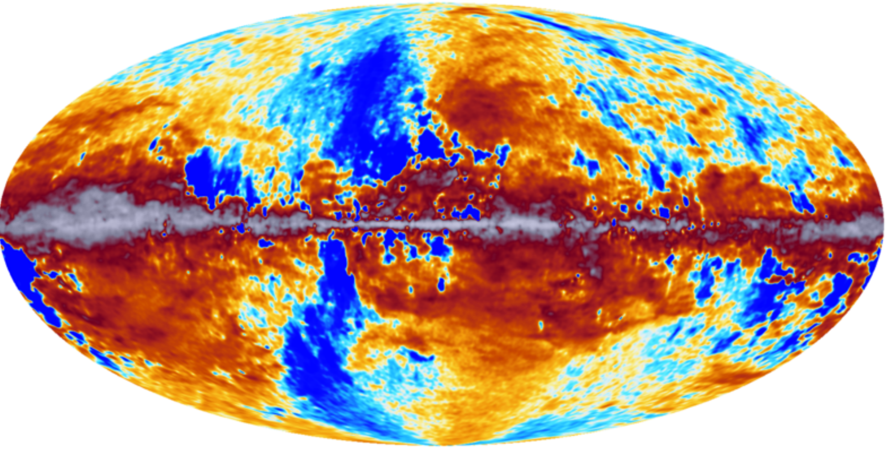
Polarized CMB

Observed
Q and **U** modes
(Stokes maps)

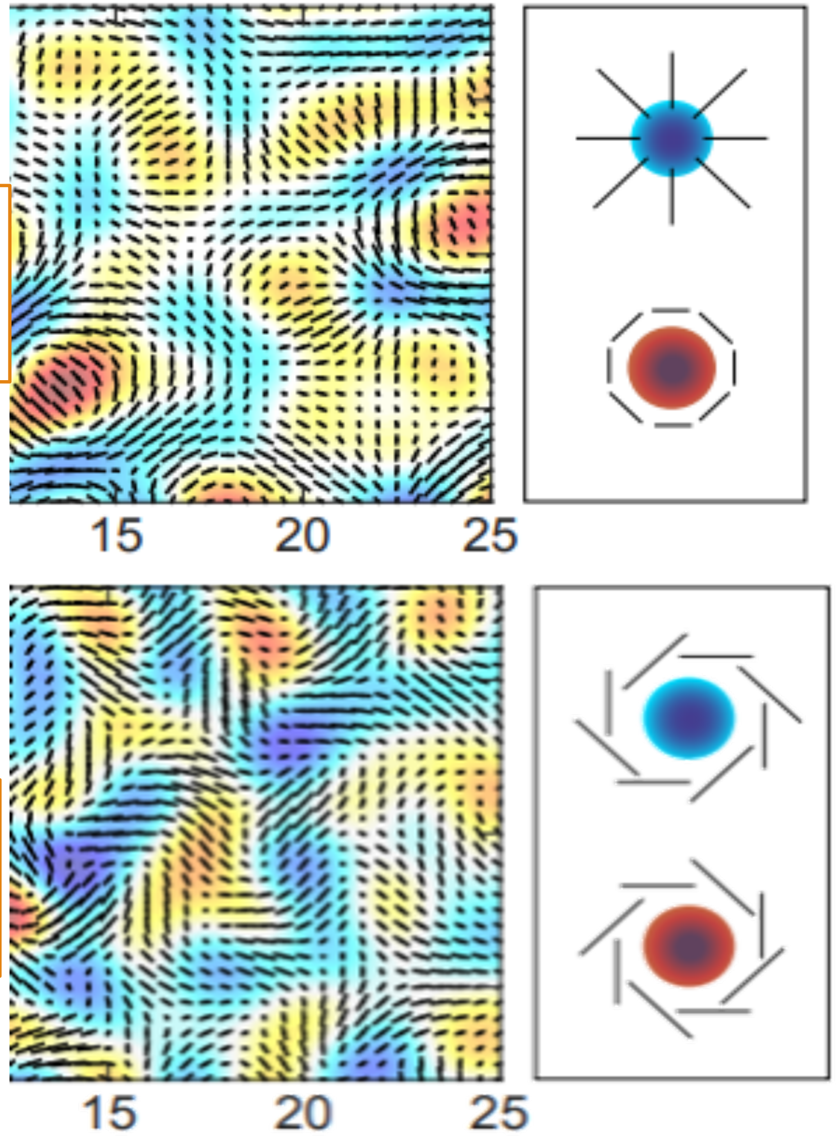
Spherical Harmonic Transforms

E-modes
(Grad)

B-modes
(Curl)



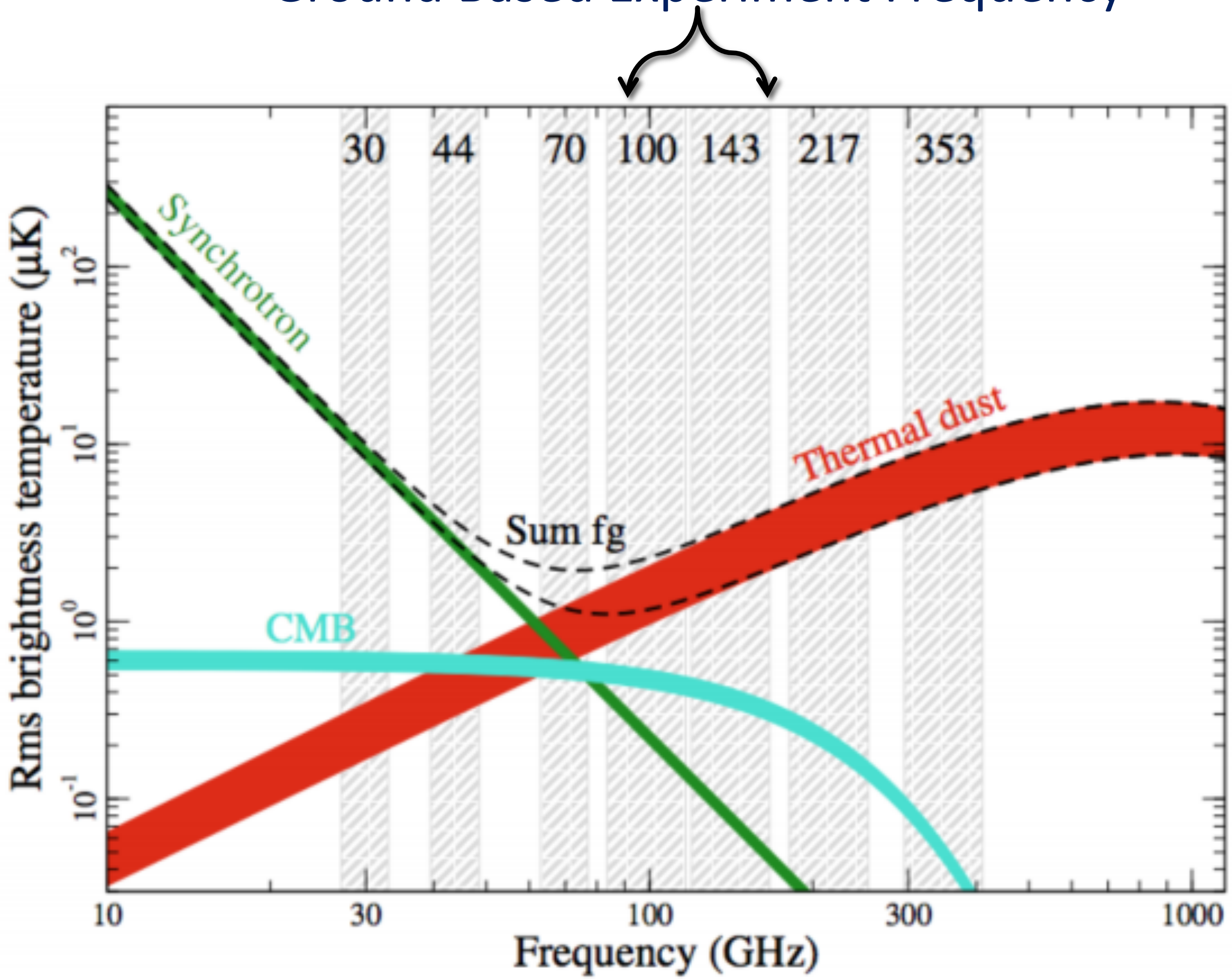
Planck DR2 353 GHz Q-map



[Kamionkowski & Kovetz 2016]

What Generates CMB Polarization?

Ground Based Experiment Frequency



[Dickinson, 2016]

- Scattering from electrons at recombination ($z \sim 1100$)
- Weak lensing from large-scale structure
- **Foregrounds**
  - Synchrotron Radiation ($\nu < 100$ GHz)
  - **Thermal Dust Emission** ($\nu > 100$ GHz)

The Search for Inflation

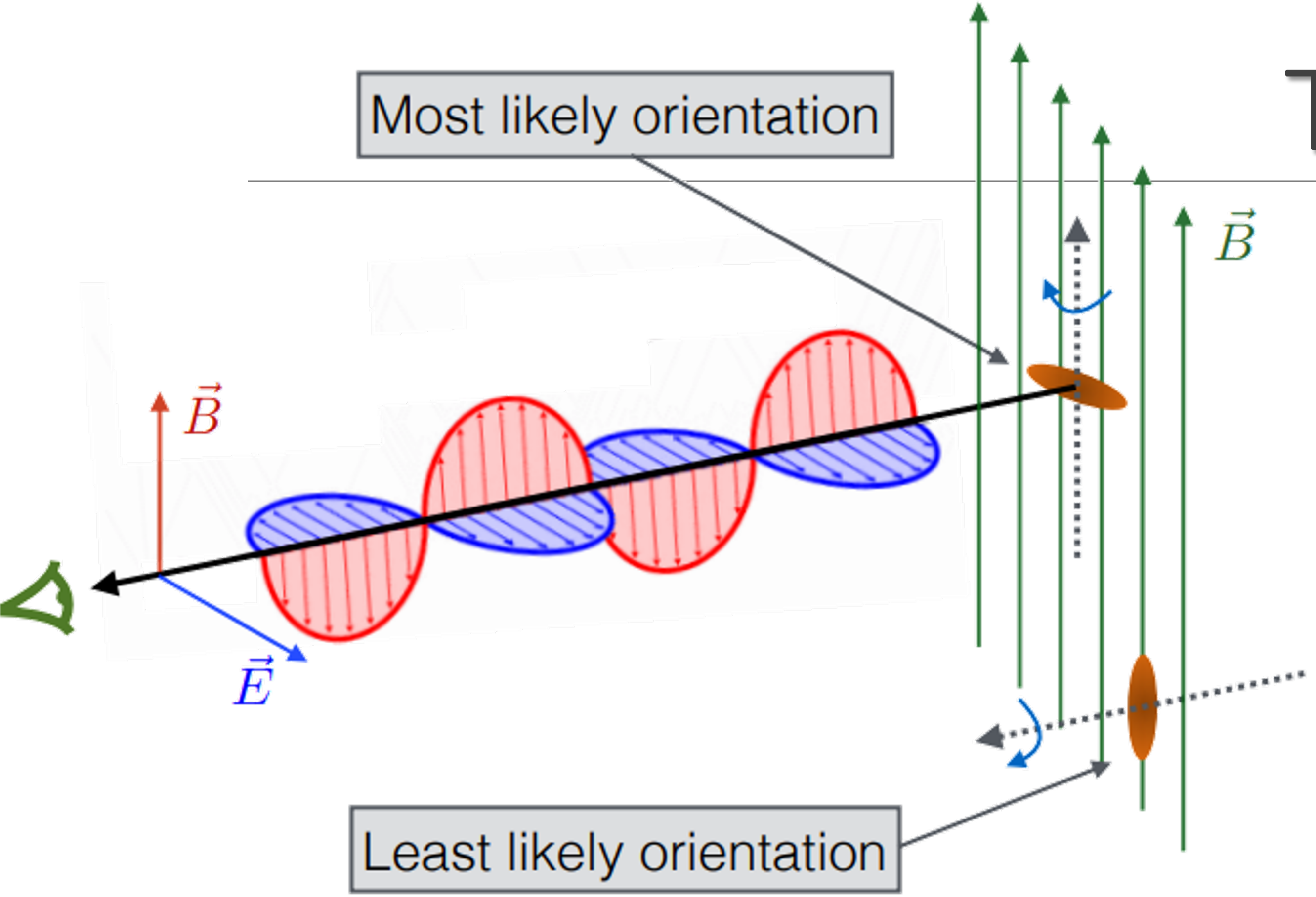
Primordial gravitational wave discovery heralds 'whole new era' in physics

Gravitational waves could help unite general relativity and quantum mechanics to reveal a 'theory of everything'

[The Guardian, 17 March, 2014]

- Inflation predicts gravitational waves with $\lambda \sim \text{ Mpc}$
- Search for these in the CMB?
  - Best to look in clean **B-modes**
- BICEP2 (2014) – ‘Discovery of IGWs’
  - Later showed to be **residual dust**…

Thermal Dust Emission



[Credit: Levrier 2015]

- ❑Asymmetric dust grains in the interstellar medium radiate through thermal emission
- ❑Alignment with the Galactic magnetic field induces polarization
- ❑This depends on the shape, composition and size of the grains
- ❑On few-degree scales we expect the polarization direction to be roughly **coherent**

Dust Subtraction

Standard Approach:

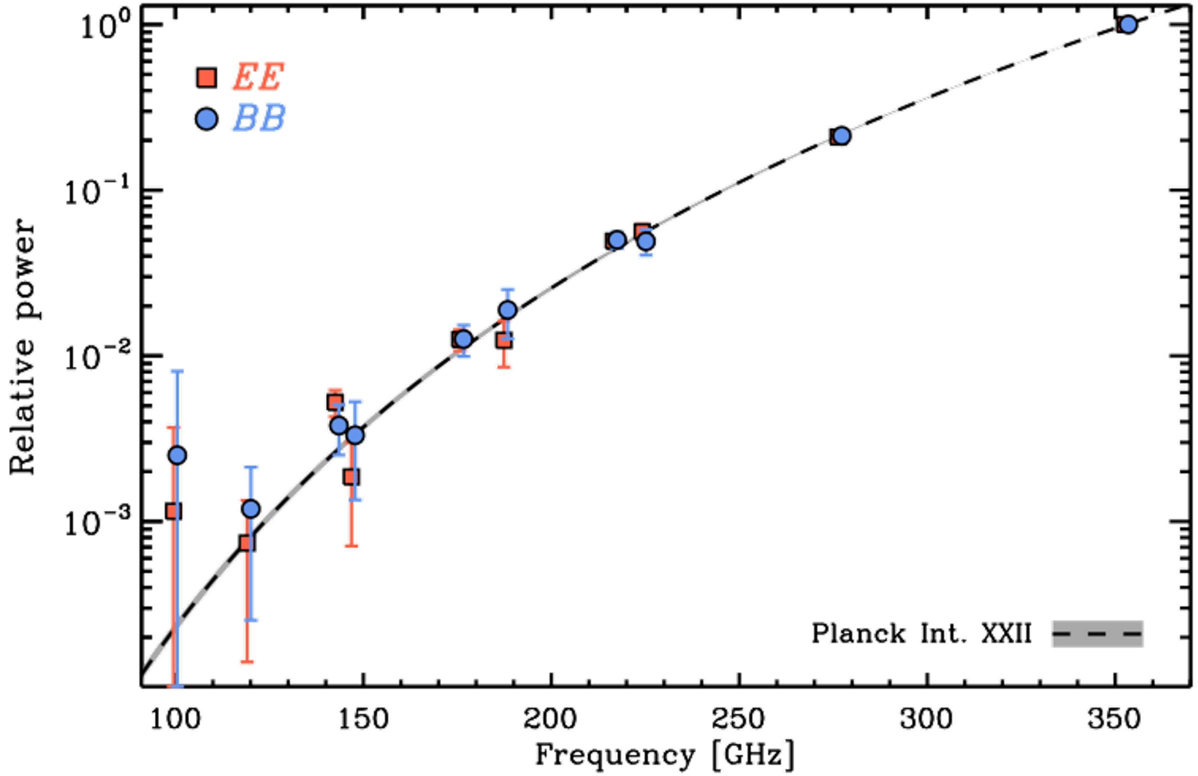
1. Assume a dust frequency dependence
2. Use multi-frequency data to remove dust

But:

- ☐ Multi-temperature dust?
- ☐ Decorrelation?
- ☐ Harder to apply from the ground

Can we develop a single-frequency approach?

Dust Frequency Dependence



[Planck Int. XXII & XXX]

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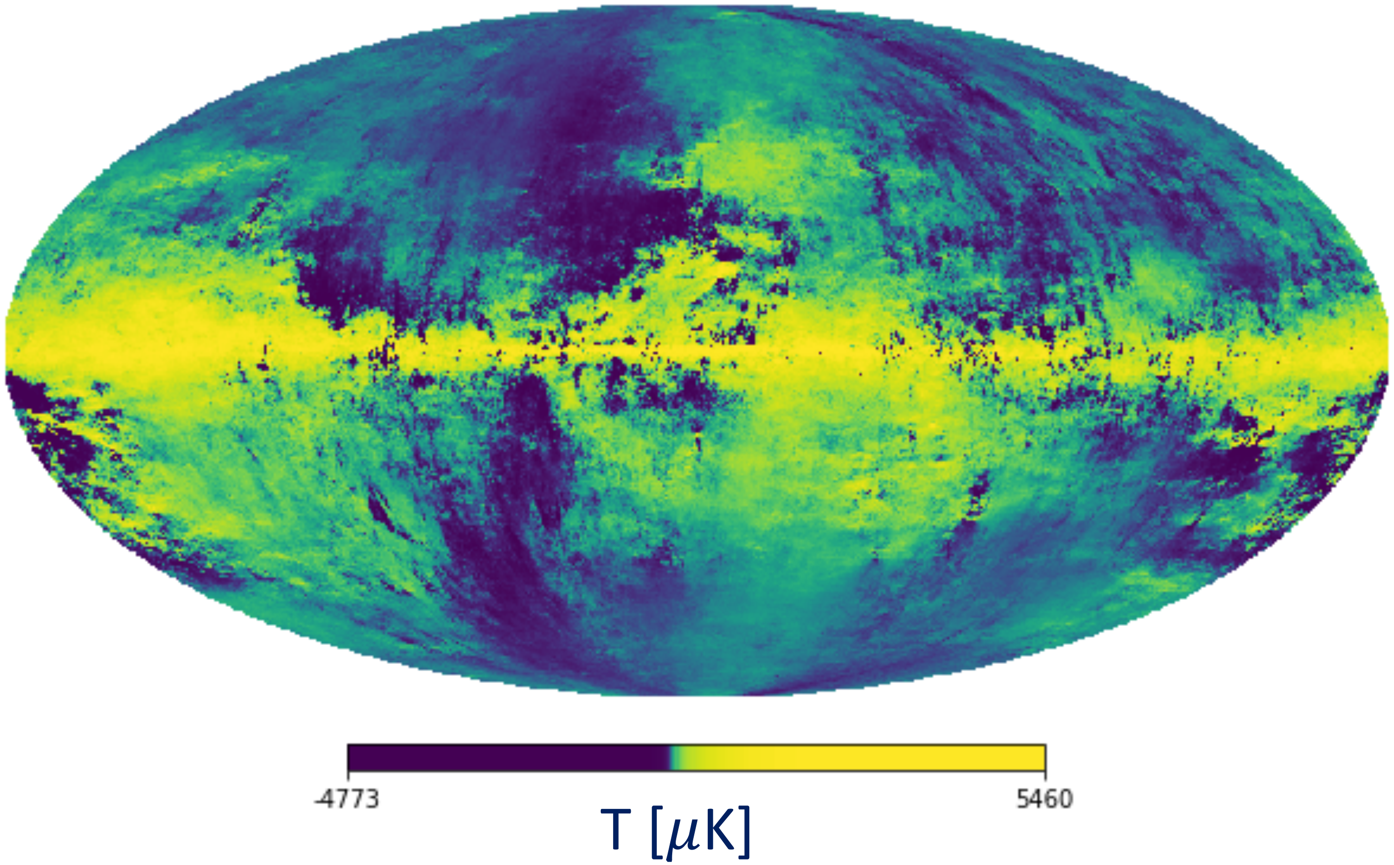
Aims & Simulations

Vansyngel+ Dust Simulations – Q map



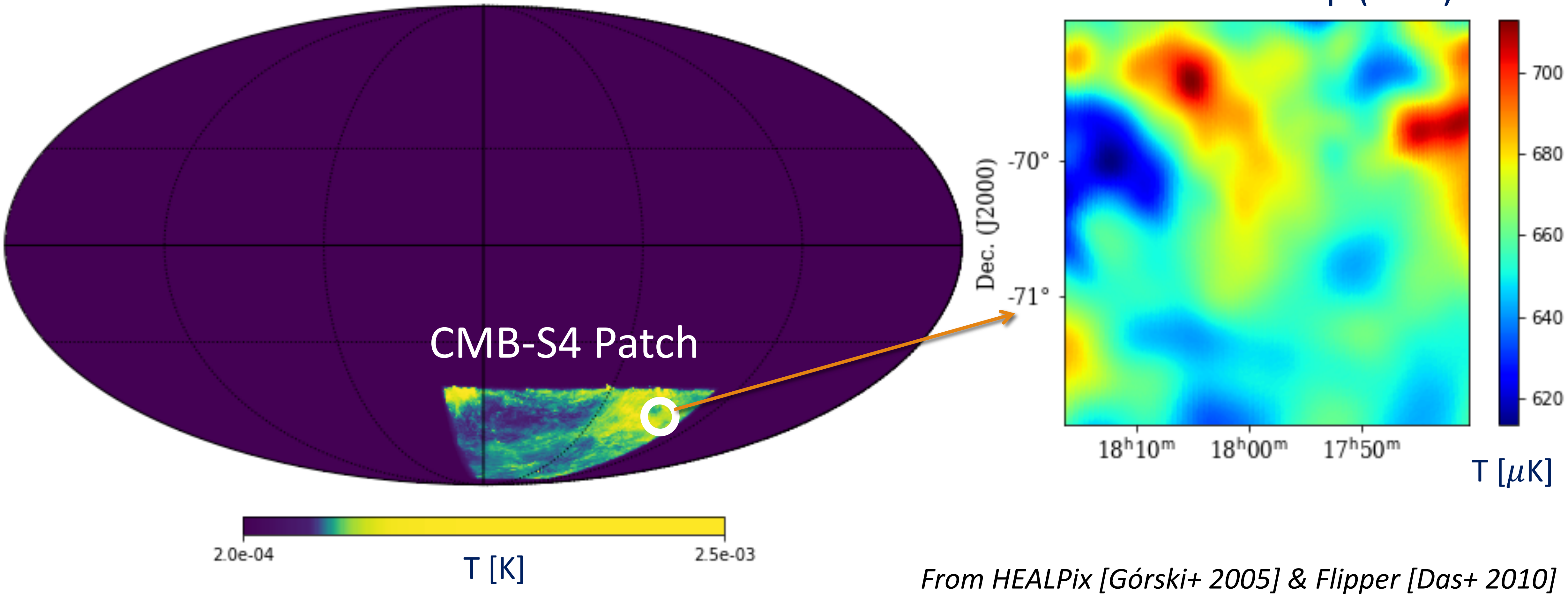
[Vansyngel+ 2017]

- Detect & characterise **dust anisotropy**
- Apply this to the **CMB-S4** experiment (mid-2020s)
- Dust data is full-sky simulations of Vansyngel+ (2017)

Splitting Up the Sky

CMB Thermal Dust Map at 353 GHz [Vansyngel+ 2017 Simulations]

3° cut-out map (‘tile’)



From HEALPix [Górski+ 2005] & Flipper [Das+ 2010]

Creating Mock Data

- ❑ Reduce frequency to 150 GHz [via modified blackbody frequency scalings]

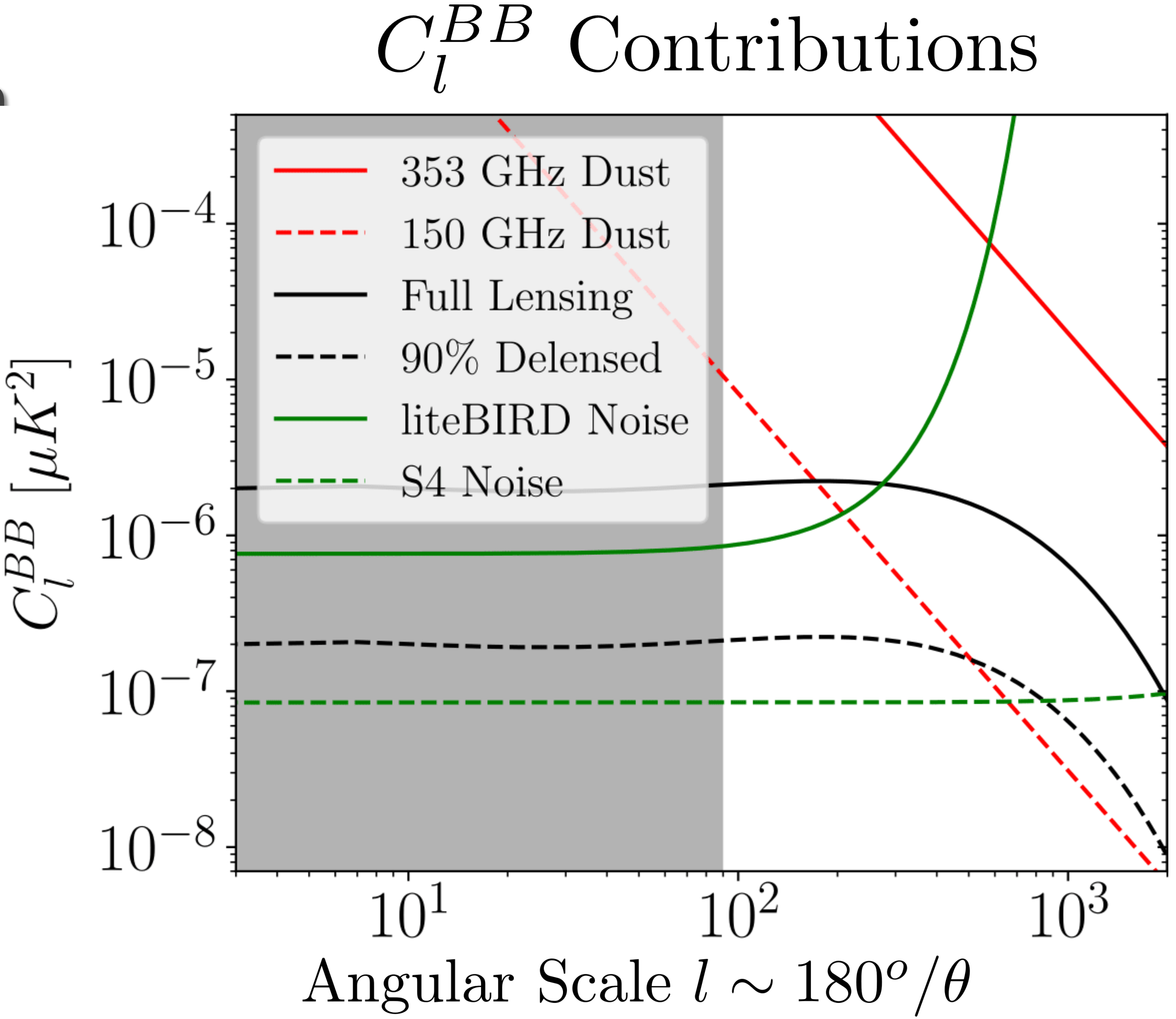
- ❑ Add weak lensing signal [computed from Planck FFP10 Simulations]

- ❑ Add instrument noise

$$C_l^{\text{noise}} = \Delta_{\text{P}}^2 \exp\left(\frac{l(l+1)\theta_{\text{FWHM}}^2}{8\ln 2}\right)$$

[using $\Delta_P = 1\mu K'$, $\theta_{\text{FWHM}} = 1.5'$ for CMB-S4]

[Philcox+ 2018b]



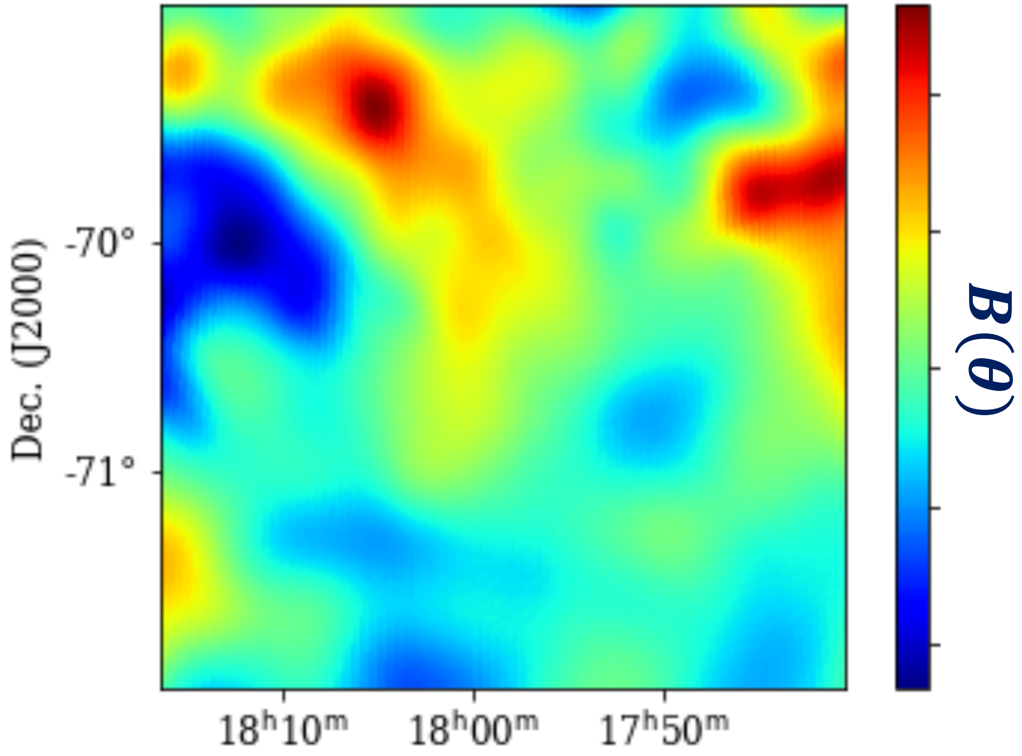
Hexadecapolar Anisotropy (I)

☐ Small regions of dust should show **hexadecapolar** anisotropy in 2D power spectra

$$\left|\tilde{B}(\vec{l})\right|^2 = Al^{-2.42}[1 - f_c \cos 4\phi_{\vec{l}} - f_s \sin 4\phi_{\vec{l}}]$$

[Kamionkowski & Kovetz, 2014]

3° B-mode Real-Space Map



Hexadecapolar Anisotropy (I)

- ☐ Small regions of dust should show **hexadecapolar** anisotropy in 2D power spectra

$$\left|\tilde{B}(\vec{l})\right|^2 = Al^{-2.42}[1 - f_c \cos 4\phi_{\vec{l}} - f_s \sin 4\phi_{\vec{l}}]$$

[Kamionkowski & Kovetz, 2014]

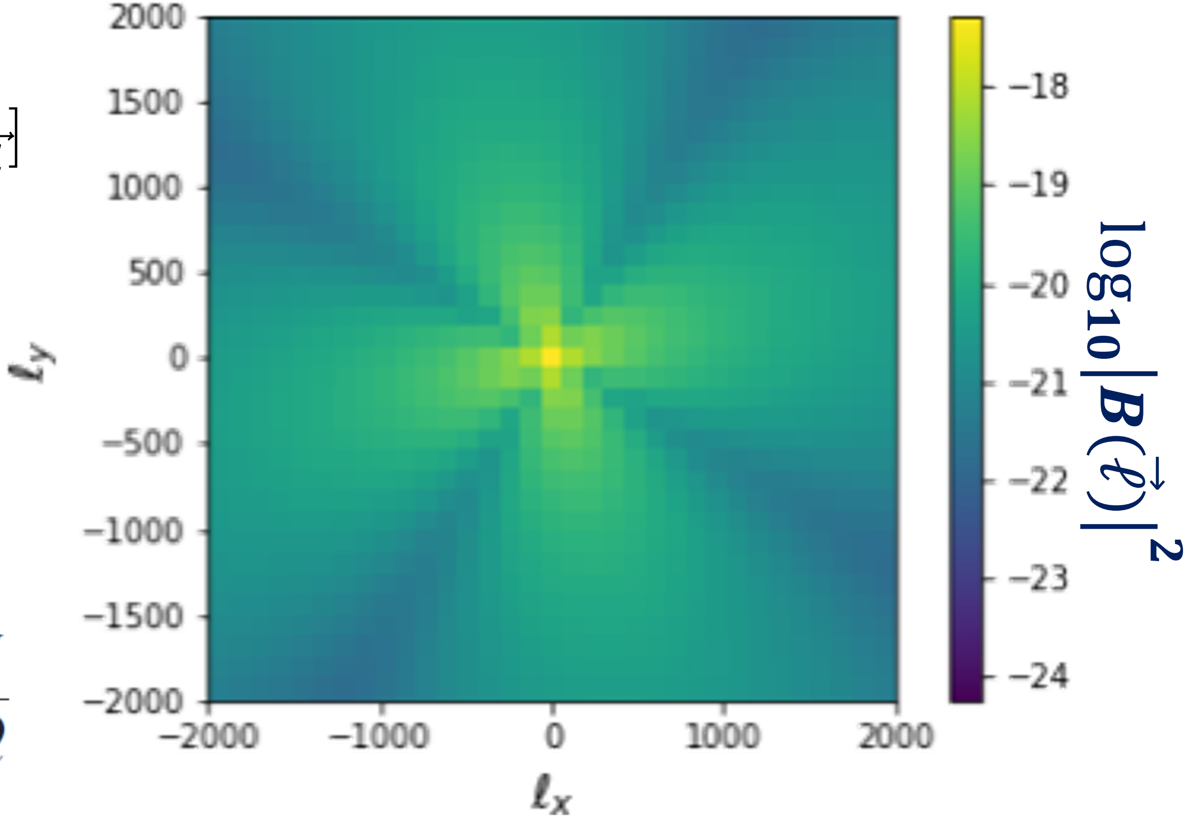
- ☐ IGWs do **not** have this structure.
- ☐ **Idealized** 2D power spectrum
- ☐ Define the **hexadecapole power** and **angle:**

$$H^2 = (Af_s)^2 + (Af_c)^2$$

$$\tan 4\alpha = \frac{Af_s}{Af_c}$$

$$2\alpha = \arctan \frac{U}{Q}$$

Idealized 2D B-mode Power



Hexadecapolar Anisotropy (II)

☐ Small regions of dust should show **hexadecapolar** anisotropy in 2D power spectra

$$\left|\tilde{B}(\vec{l})\right|^2 = Al^{-2.42}[1 - f_c \cos 4\phi_{\vec{l}} - f_s \sin 4\phi_{\vec{l}}]$$

[Kamionkowski & Kovetz, 2014]

☐ IGWs do **not** have this structure.

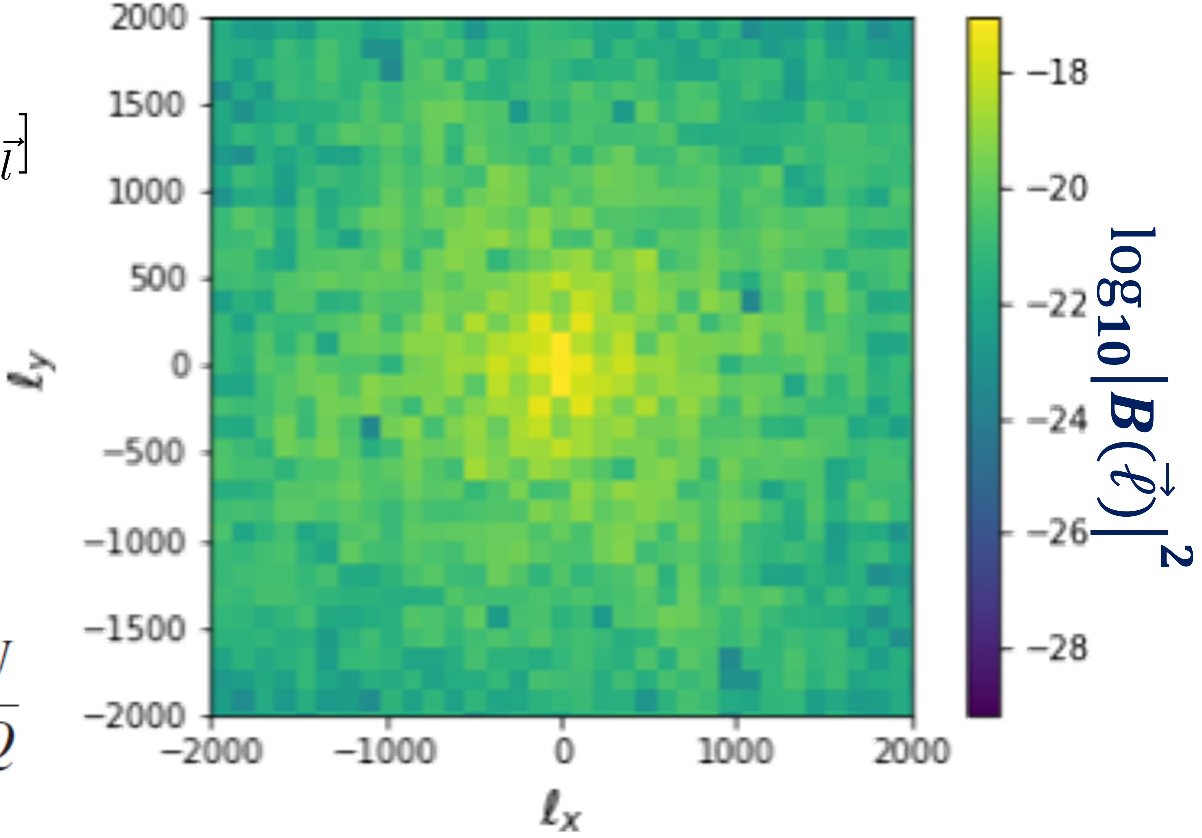
☐ **True** 2D power spectrum

☐ Define the **hexadecapole power** and **angle:**

$$\boxed{\begin{aligned} H^2 &= (Af_s)^2 + (Af_c)^2 \\ \tan 4\alpha &= \frac{Af_s}{Af_c} \end{aligned}}$$

$$2\alpha = \arctan \frac{U}{Q}$$

True 2D B-mode Power



Statistical Estimators

$$\widehat{A} = \frac{\sum_{\vec{l}} \mathcal{B}^2(\vec{l})\Lambda_l^2 / C_l^{\mathrm{fid}}}{\sum_{\vec{l}} \Lambda_l^2}$$

$$\widehat{Af_c} = \frac{\sum_{\vec{l}} \boxed{\mathcal{B}^2(\vec{l})\Lambda_l^2 \cos 4\phi_{\vec{l}}} / C_l^{\mathrm{fid}}}{\sum_{\vec{l}} (\Lambda_l \cos 4\phi_{\vec{l}})^2}$$

$$\widehat{Af_s} = \frac{\sum_{\vec{l}} \boxed{\mathcal{B}^2(\vec{l})\Lambda_l^2 \sin 4\phi_{\vec{l}}} / C_l^{\mathrm{fid}}}{\sum_{\vec{l}} (\Lambda_l \sin 4\phi_{\vec{l}})^2}$$

[cf. Kamionkowski & Kovetz, 2014]

Dust B-mode power:

$$\mathcal{B}^2(\vec{l}) = |B(\vec{l})|^2 - (C_l^{\mathrm{lens}} + C_l^{\mathrm{noise}})$$

Signal-to-noise ratio:

$$\Lambda_l = \frac{AC_l^{\mathrm{fid}}}{AC_l^{\mathrm{fid}} + C_l^{\mathrm{noise}} + C_l^{\mathrm{lens}}}$$

Fiducial slope: [Planck Int. XXX, 2014]

$$C_l^{\mathrm{fid}} = l^{-2.42}$$

Dealing with Bias (I)

- The hexadecapole power statistic, $H^2 = (Af_s)^2 + (Af_c)^2$ is intrinsically biased.
  - Even an ***isotropic*** dust map will have $H^2 > 0$

- To remove bias we must use **Monte Carlo simulations**
  - These are computed from the same power spectra in each tile as the data.
  - **But,** they are *isotropic* by construction

- Create a ***debiased*** hexadecapole statistic:

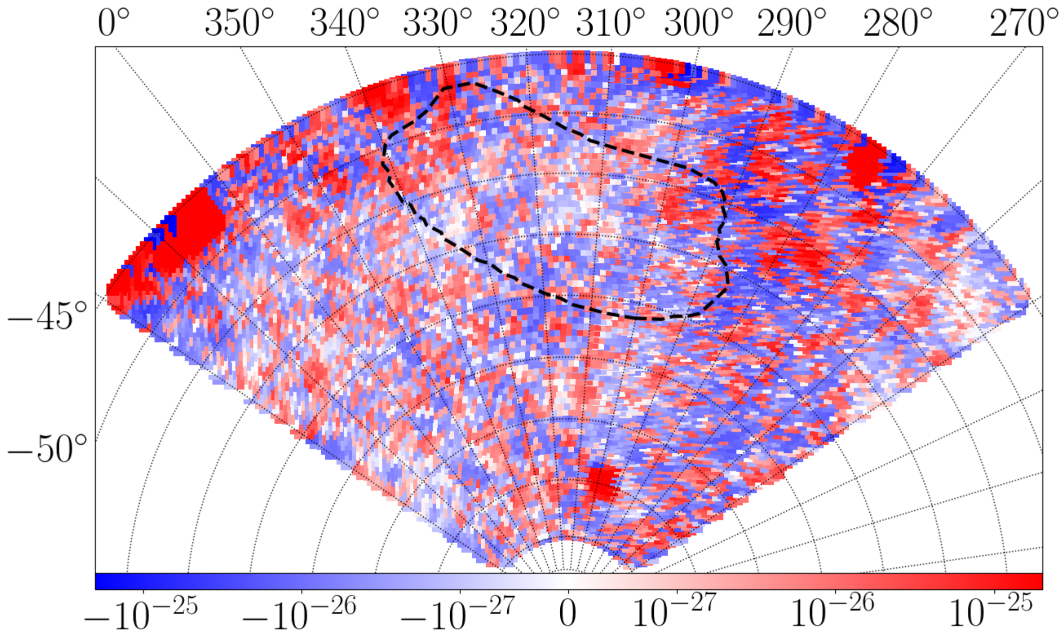
$$\boxed{\mathcal{H}^2 = H^2 - H^2_{\text{bias, iso}}}$$

Dealing with Bias (II)

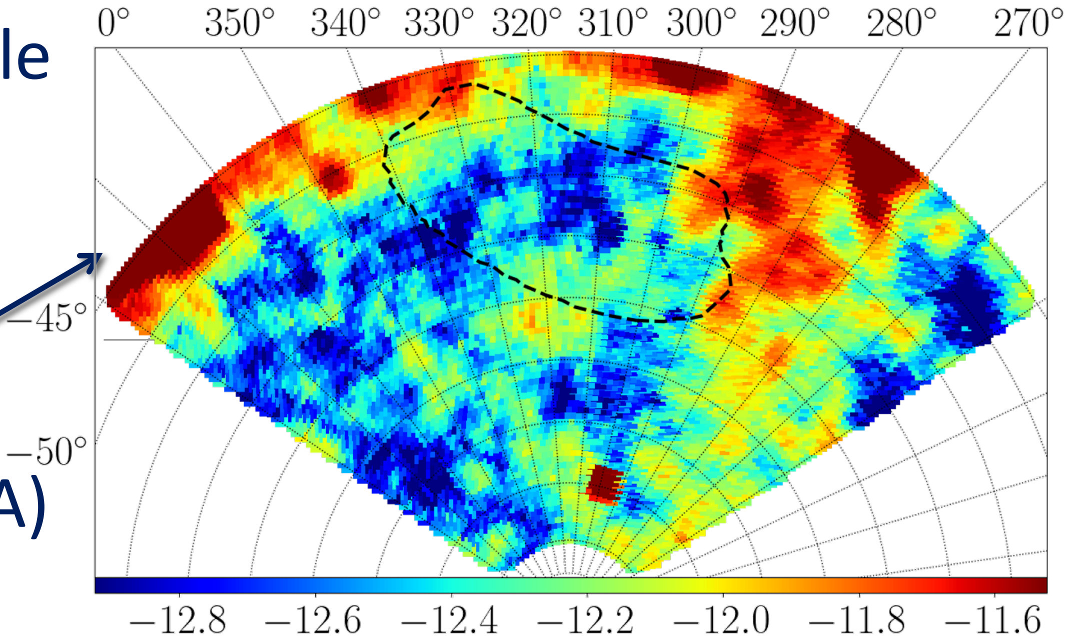
- Use **'realization dependent debiasing'** combining data and simulations via cross-correlations
- Remove bias in each tile using 500 MC simulations:

$$H^2_{\mathrm{bias,iso}} = \begin{cases} 4\langle H^2\rangle_{\mathrm{DS}} - \langle H^2\rangle_{\mathrm{SS}} & \text{(Data)} \\ \langle H^2\rangle_{\mathrm{SS}} & \text{(MC Simulations)} \end{cases}$$

- **Also:**
  - Remove small residual 'lensing bias' using a patch with only noise + lensing present
  - Remove pixellation biases by tile rotations

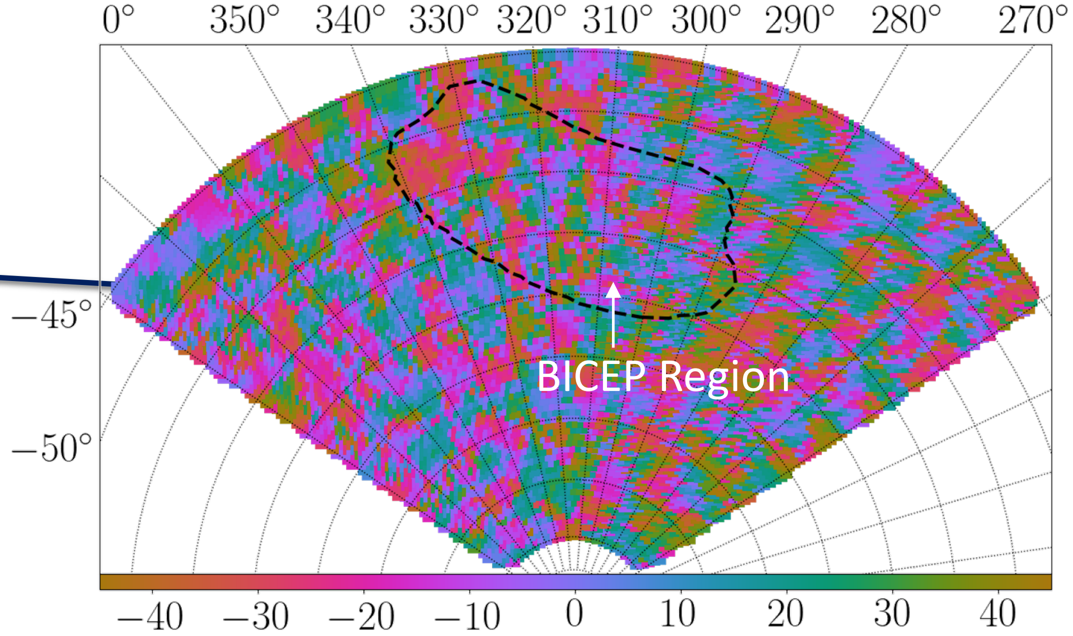


Hexadecapole Power ($\mathcal{H}^2$)



Monopole Amplitude (A)

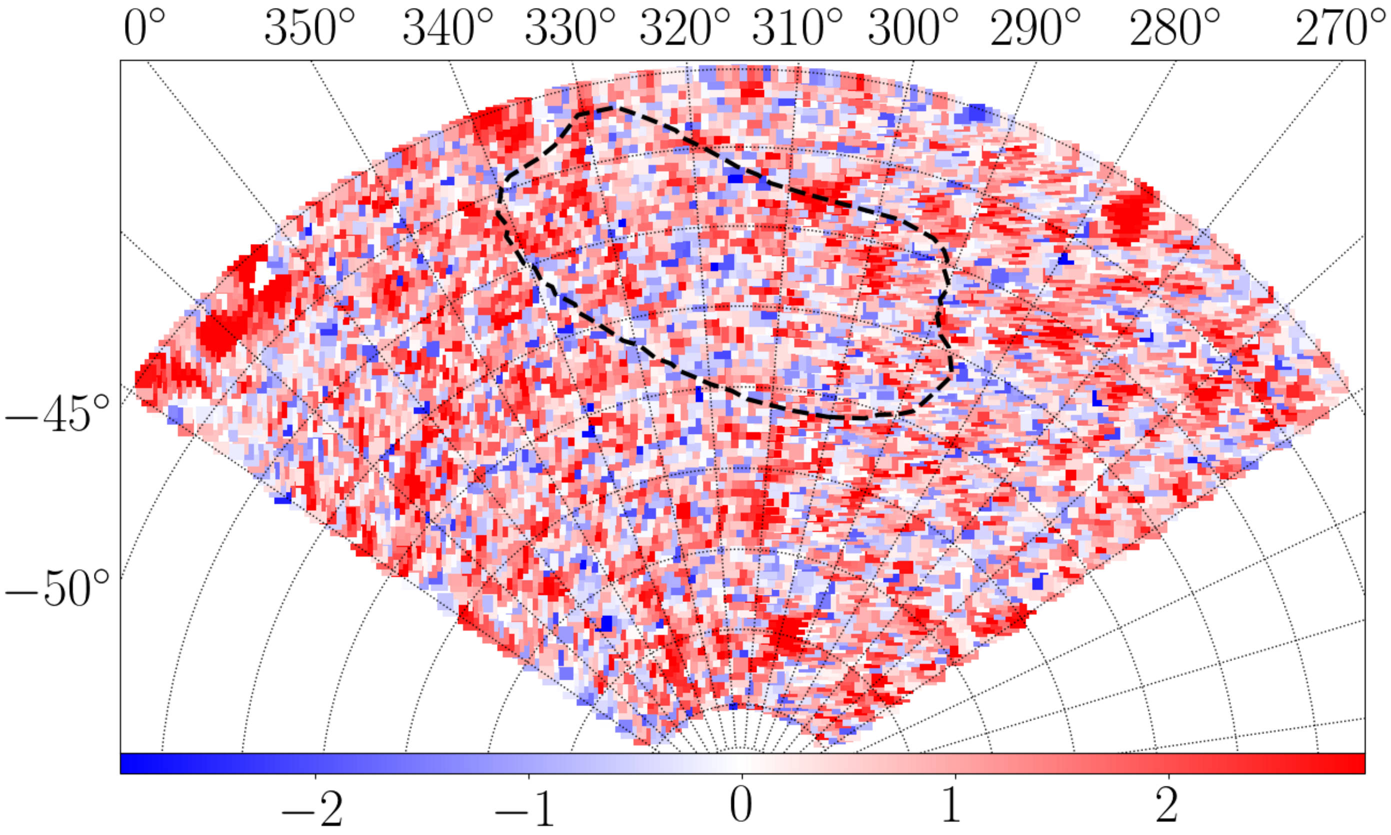
Anisotropy Angle, α



[Philcox+ 2018b]

Anisotropy Probability

- ☐ Convert the hexadecapole power to a (Gaussian) **anisotropy likelihood**
- ☐ Only weak detection significances on this scale



Probability of Anisotropy (σ)

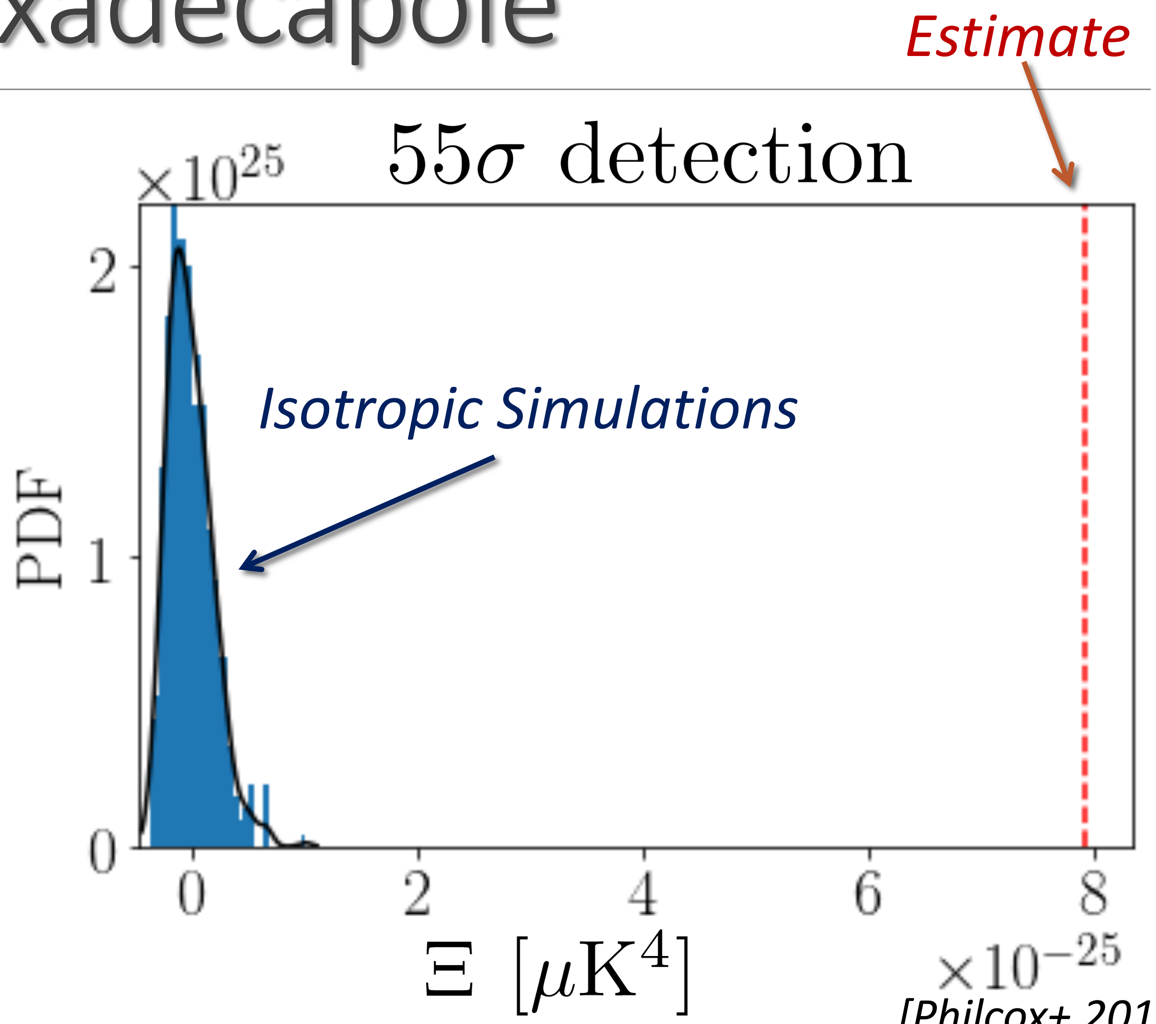
[Philcox+ 2018b]

Patch Averaged Hexadecapole

- ☐ Define average hexadecapole

$$\Xi = \langle \mathcal{H}^2 \rangle_{\text{patch}}$$

- ☐ Compute Ξ for data and MC simulations
- ☐ **A 55σ detection of anisotropy**



[Philcox+ 2018b]

IGW Contamination

- ☐ If inflationary gravitational waves were present, would we mistake them for dust?

- ☐ Using a full-sky realisation of IGWs with current constraints:

  [Using Planck FFP10 Simulations with BICEP2/Keck collaboration limits]

$$\mathcal{S}^{r=0.1}_{\text{tensor bias}} = -0.04 \pm 0.58$$

  - ☐ **No significant detection of hexadecapole anisotropy from IGWs**

[Philcox+ 2018b]

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A Null Test for Dust: Motivation

Scenario:

- ☐ We think our experiment has detected inflationary gravitational waves at a tensor-to-scalar ratio $r = r_0$

  ($r \lesssim 0.07$; BICEP2 Collaboration 2016)

- ☐ Are these true IGWs or just a detection of poorly-subtracted dust?

- ☐ **Test if we can detect dust at this level**

A Null Test for Dust: Application

- ☐ Artificially reduce the dust level in the simulation by some factor.

$$r_{\mathrm{eff}}(f_{\mathrm{dust}}) = \frac{\langle A_{80} \rangle}{C_{80}^{\mathrm{tensor}}(r=1)} f_{\mathrm{dust}}^2$$

- ☐ Can we still detect dust?

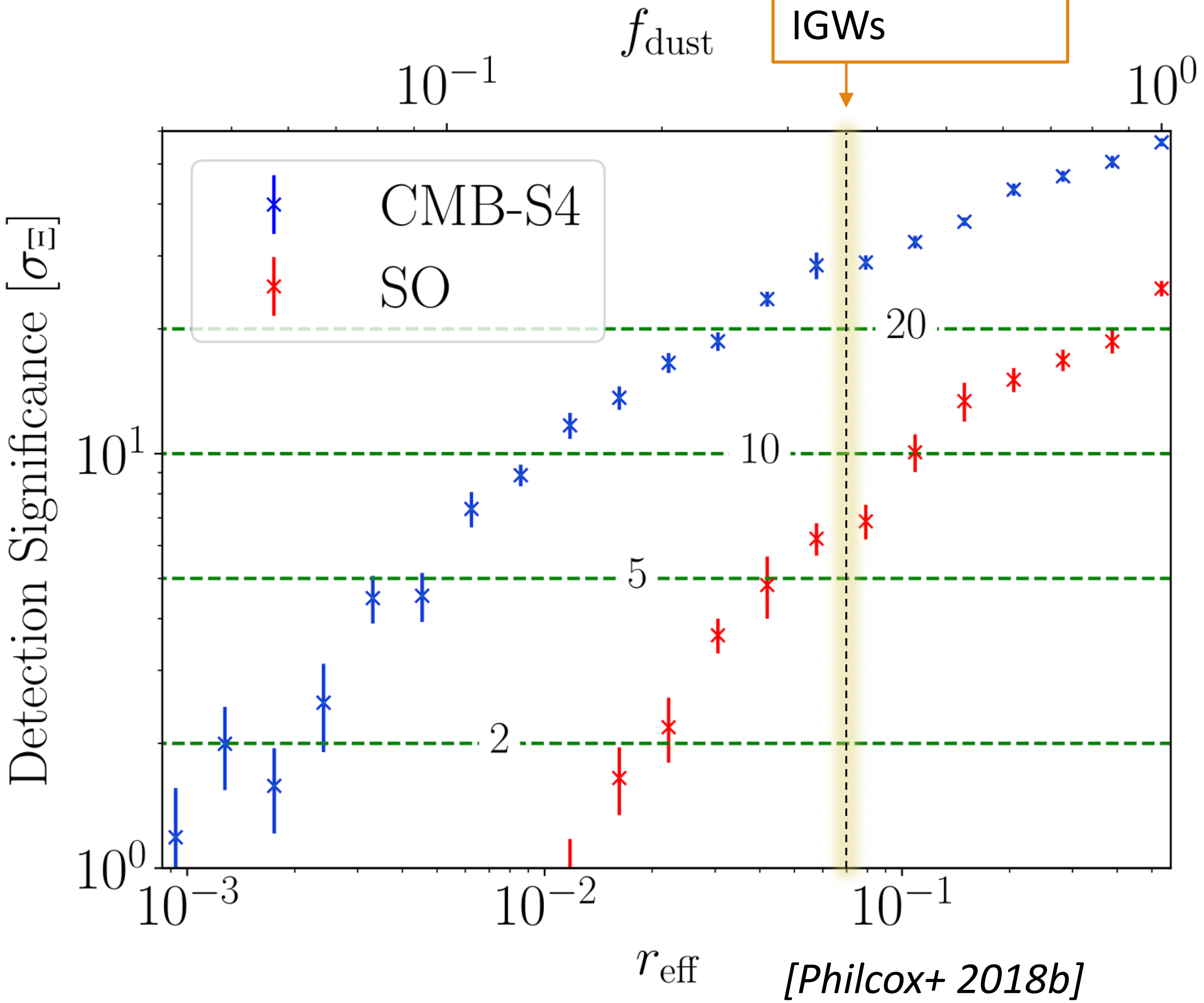
CMB S4:
55σ detection

2σ limit:
$r_{\mathrm{eff}} = 0.001$

Simons Observatory (SO):
25σ detection

2σ limit:
$r_{\mathrm{eff}} = 0.02$

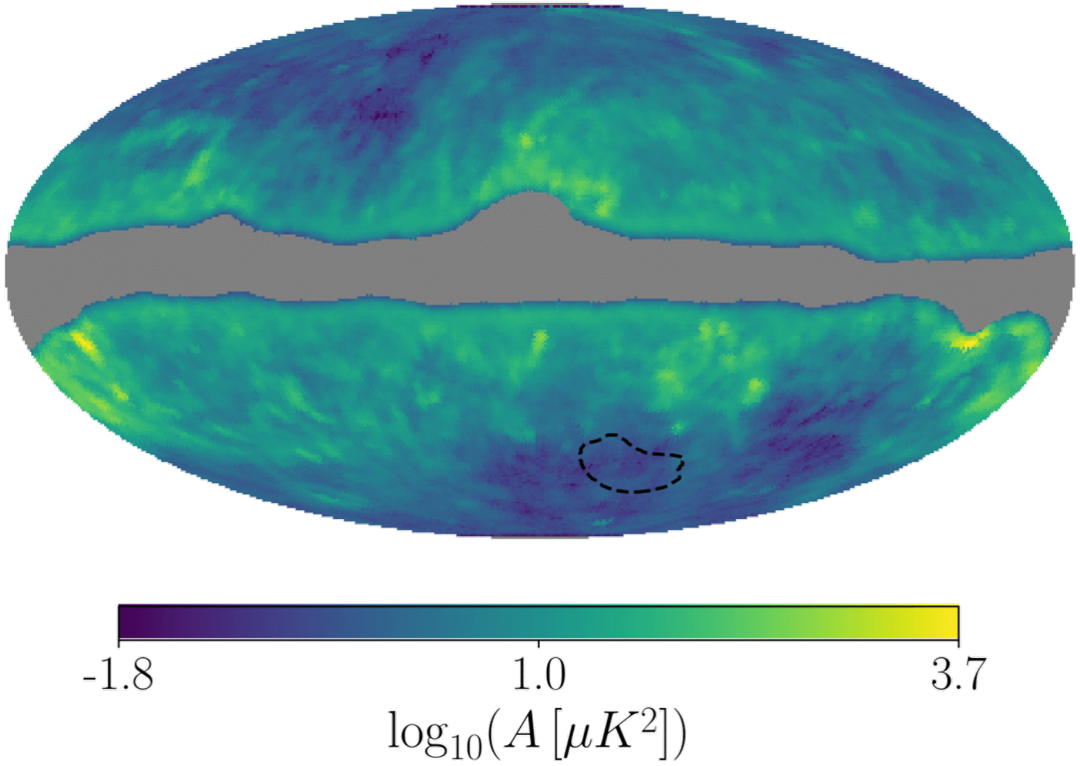
Current upper bound on IGWs



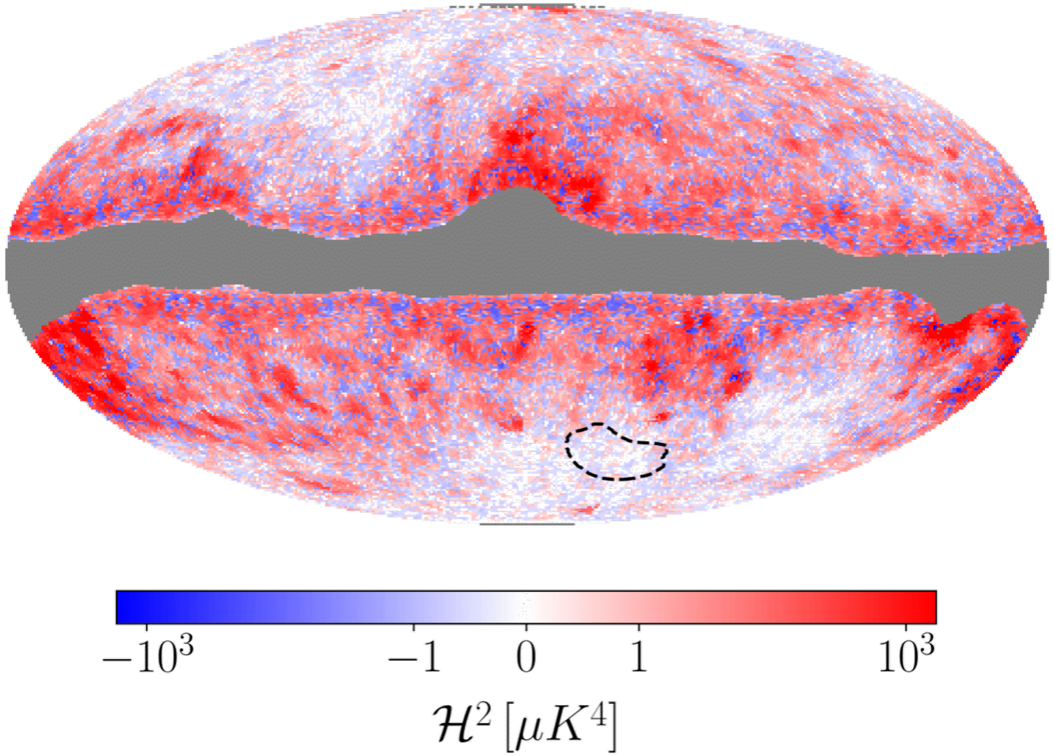
[Philcox+ 2018b]

Full Sky Correlations

Monopole Amplitude A

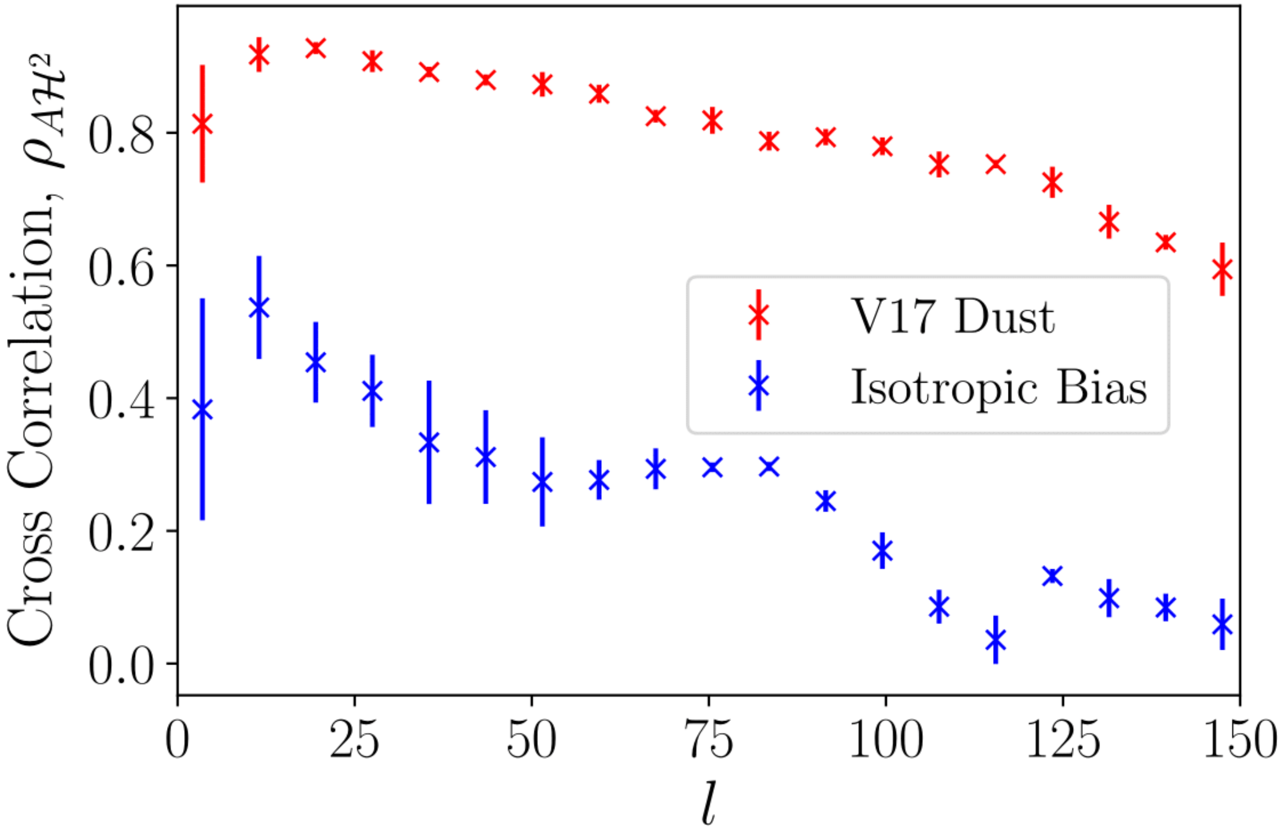


Hexadecapole Amplitude $\mathcal{H}^2$



Using Planck GAL80 Mask + CMB-S4 [Abazaijan+ 2016] Noise Parameters with HEALPix [Górski+ 2005] for visualisation

Full Sky Correlation Coefficient



Power Spectra Estimated with POLSPICE (Chon+ 2004)

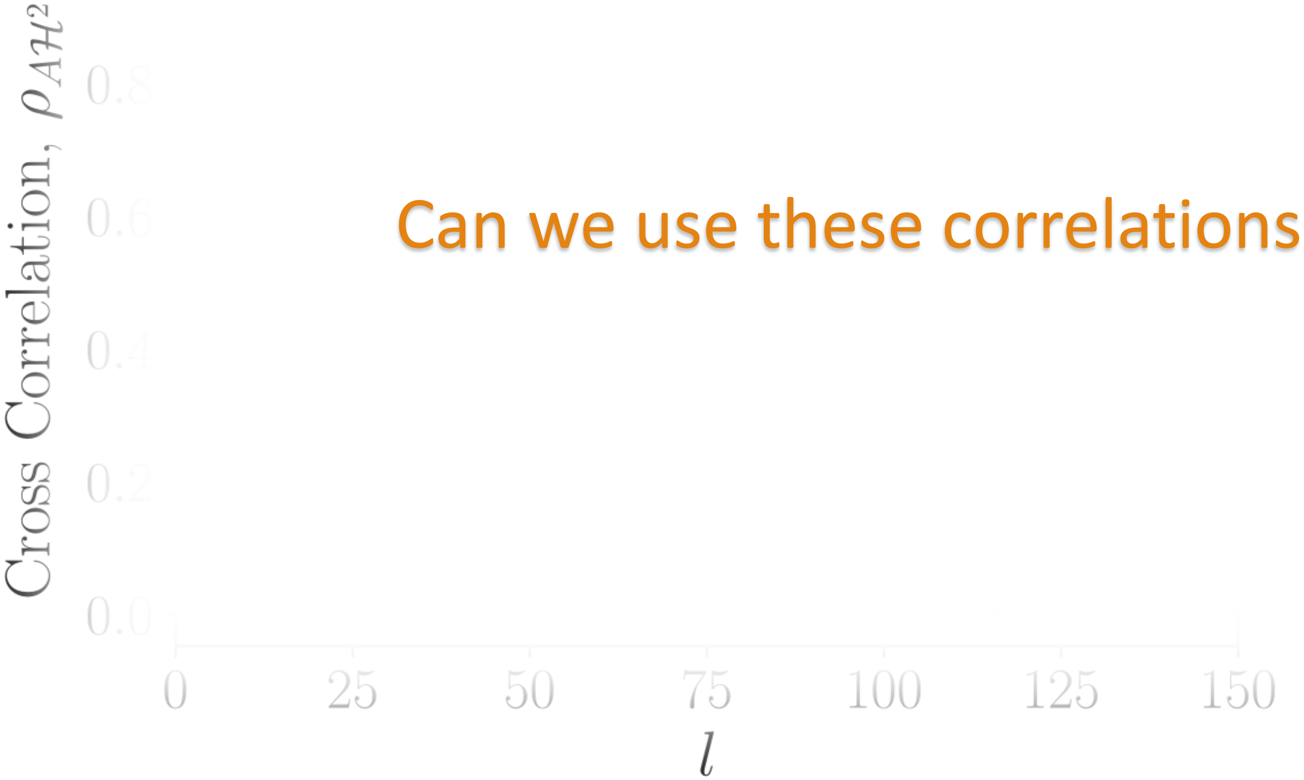
- ☐ Compute the correlation function between **monopole** and **hexadecapole**:

$$\rho_{A\mathcal{H}^2}(l) = \frac{C_l^{A\mathcal{H}^2}}{\sqrt{C_l^A C_l^{\mathcal{H}^2}}}$$

- ☐ Very strong correlations on large angular scales!

[Philcox+ 2018b]

Full Sky Correlation Coefficient



pole:

Can we use these correlations to reconstruct the dust?

[Philcox+ 2018b]

Power Spectra Estimated with POLSPICE (Chon+ 2004)

Dedusting Techniques (I)

❑Using the anisotropy angle we can reconstruct Q, U maps:

$$\widehat{U}(\boldsymbol{r}) \propto I(\boldsymbol{r})R(\boldsymbol{r})\sin(2\alpha(\boldsymbol{r})),$$

$$\widehat{Q}(\boldsymbol{r}) \propto I(\boldsymbol{r})R(\boldsymbol{r})\cos(2\alpha(\boldsymbol{r})).$$

Intensity Map

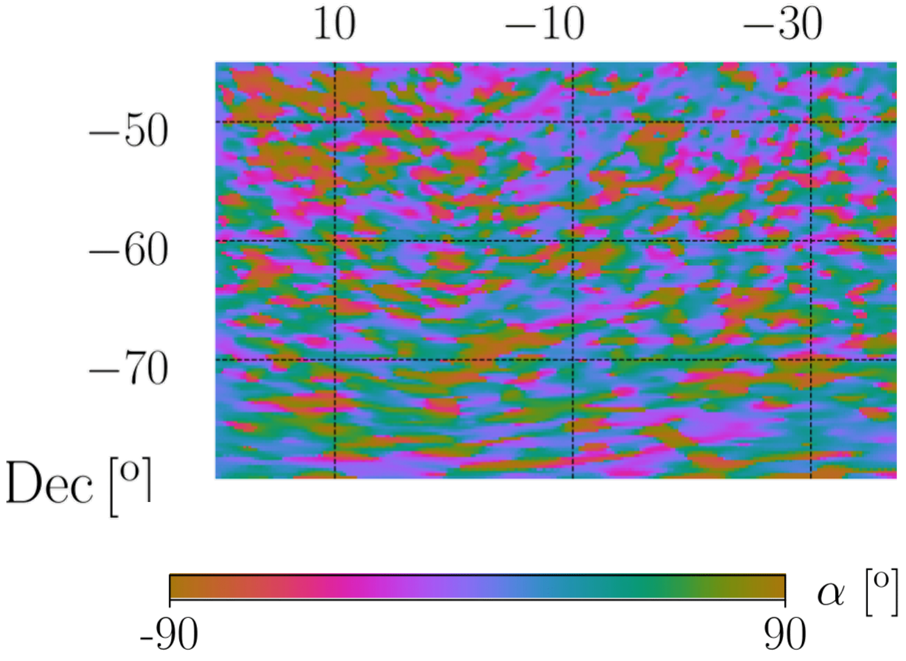
Angle Map

with anisotropy fraction proxy

$$R(\boldsymbol{r}) = \left(\frac{\mathcal{H}^2(\boldsymbol{r})}{\langle I^4\rangle_{\text{tile}}(\boldsymbol{r})}\right)^{1/4}$$

Hexadecapole Strength

❑Use these to compute **approximation** for B-mode map from dust


Hexadecapole Angle Map

[Philcox+ 2018b]

Dedusting Techniques (II)

- Scaling is found via *cross-correlations* with the data

$$a_c(l) = C_l^{\widehat{B}B} / C_l^{\widehat{B}\widehat{B}}$$

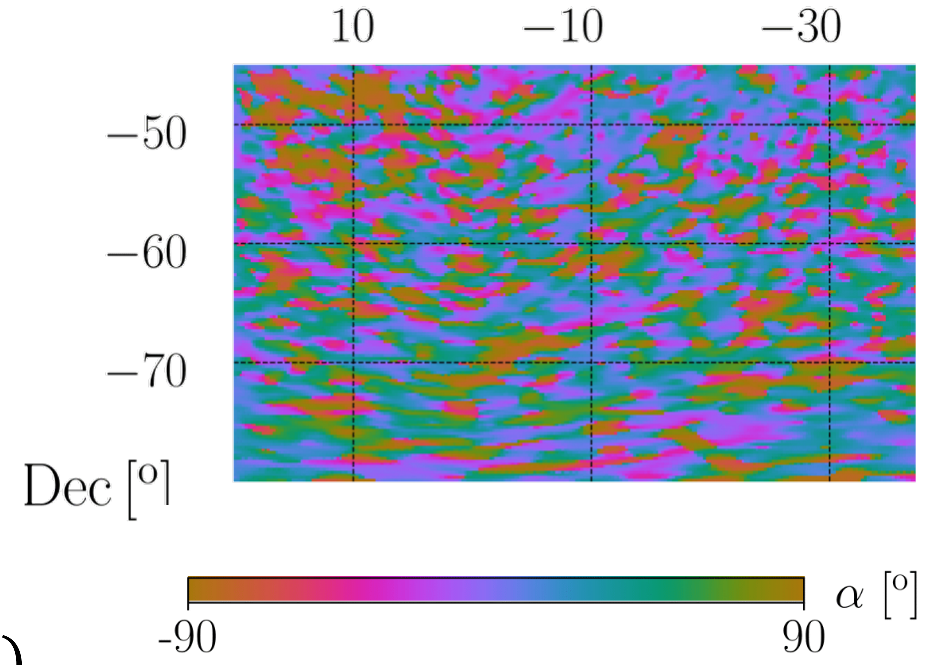
Scaling Factor

Model x Data Power Spectrum

Model x Model Power Spectrum

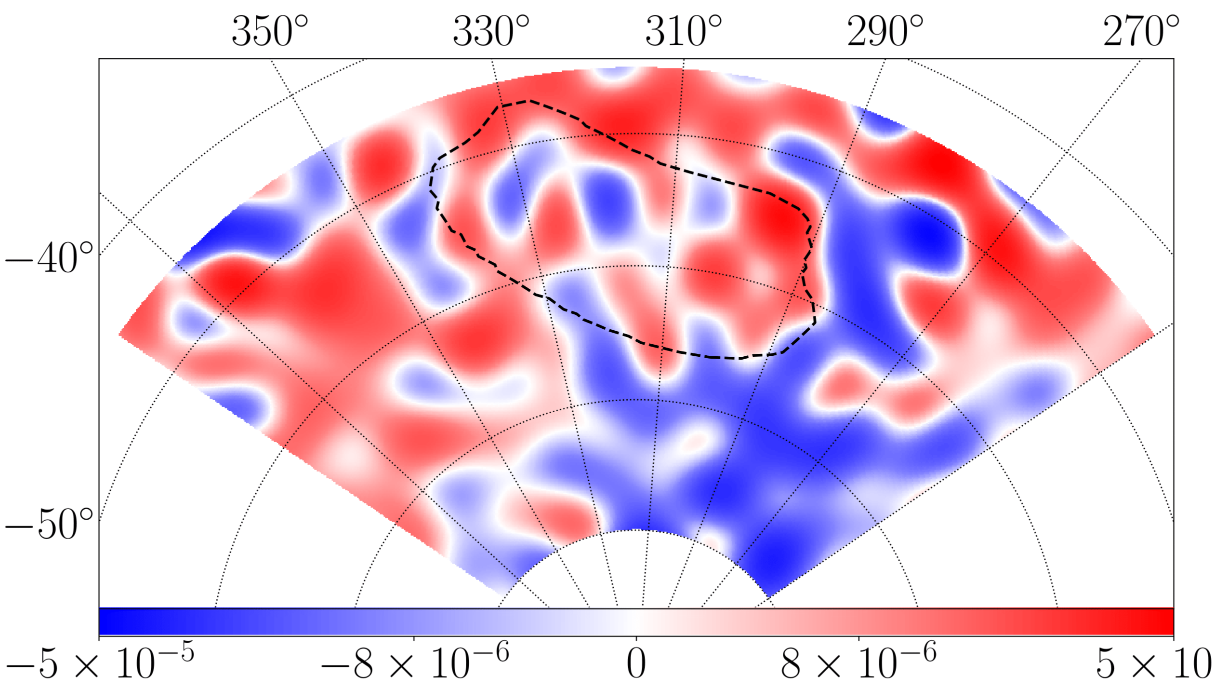
- Cross-correlations are also used to avoid information loss in conversion from $4\alpha(\boldsymbol{r}) \rightarrow 2\alpha(\boldsymbol{r})$ polarization angles

Hexadecapole Angle Map

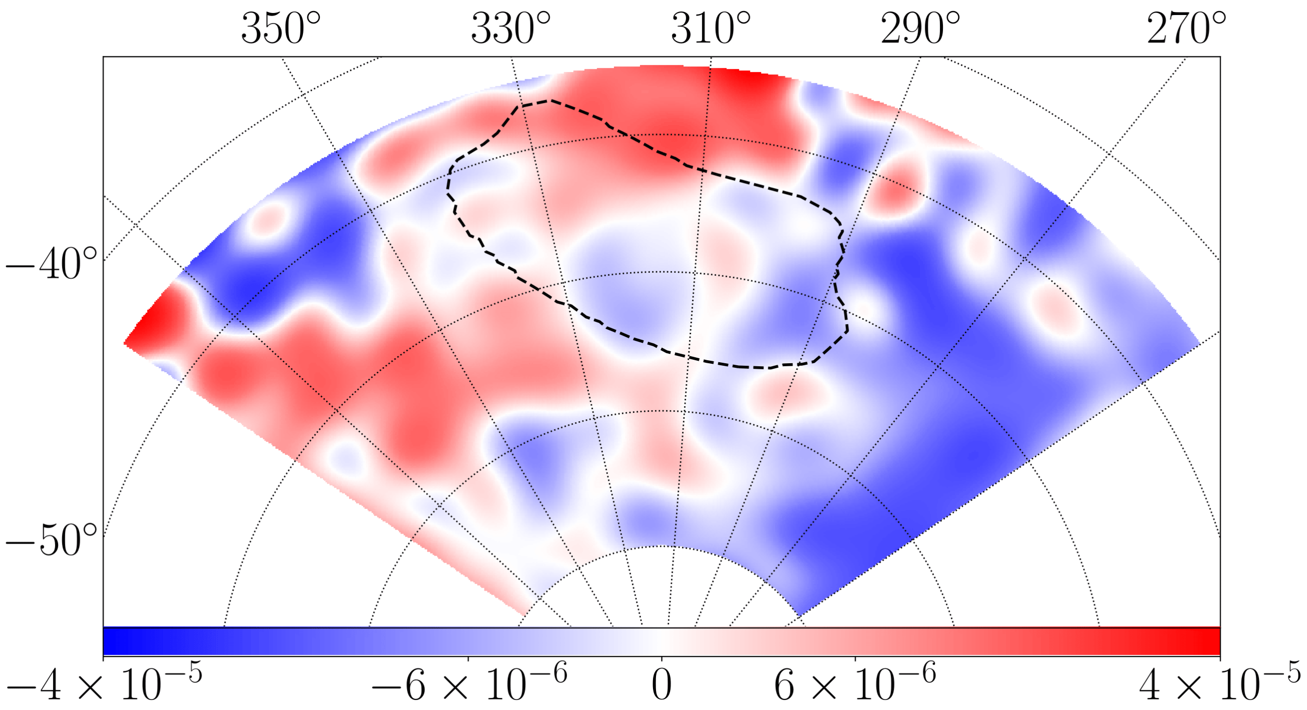


[Philcox+ 2018b]

Dedusting in Practice



Estimated B-mode Map

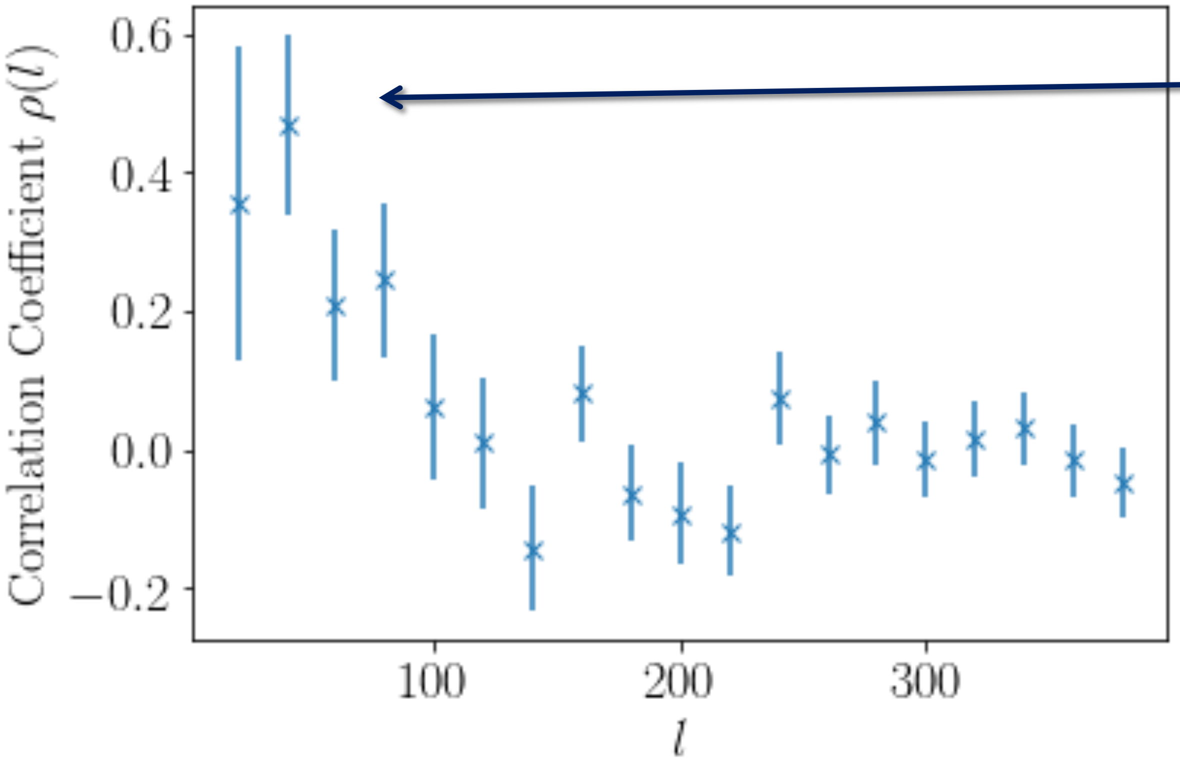


True B-mode Map

[Philcox+ 2018b]

Dedusting Correlations

Correlation of estimated & true B-mode power:



Correlation is significantly non-zero at low l!

[Philcox+ 2018b]

Summary

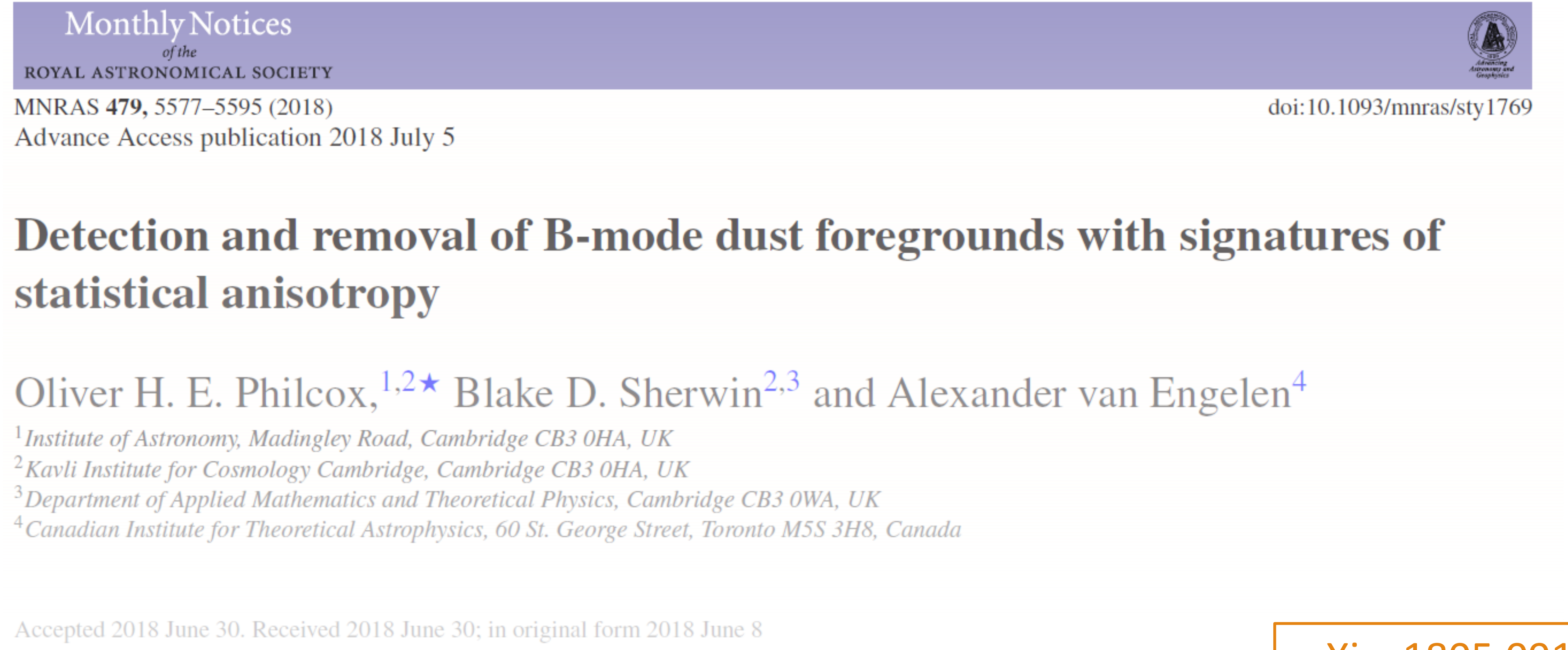
- ☐ Hexadecapolar anisotropy is **detectable** in futuristic CMB-experiments

- ☐ Use this as a **null test** for dust
  - ☐ **55σ** detection for CMB S4 noise
  - ☐ $r_{\text{eff}} = \mathcal{O}(0.001)$ detected at **95% confidence**

- ☐ Possibility of single frequency '**dedusting**'

Future Work

- ☐ Include E-modes
- ☐ Use continuous angle distribution
  [Kamionkowski/Kovetz 2014]
- ☐ Combine with multi-frequency cleaning
- ☐ Apply to real data



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Advance Access publication 2018 July 5

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Detection and removal of B-mode dust foregrounds with signatures of statistical anisotropy

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arXiv: 1805.09177

Thanks for your attention

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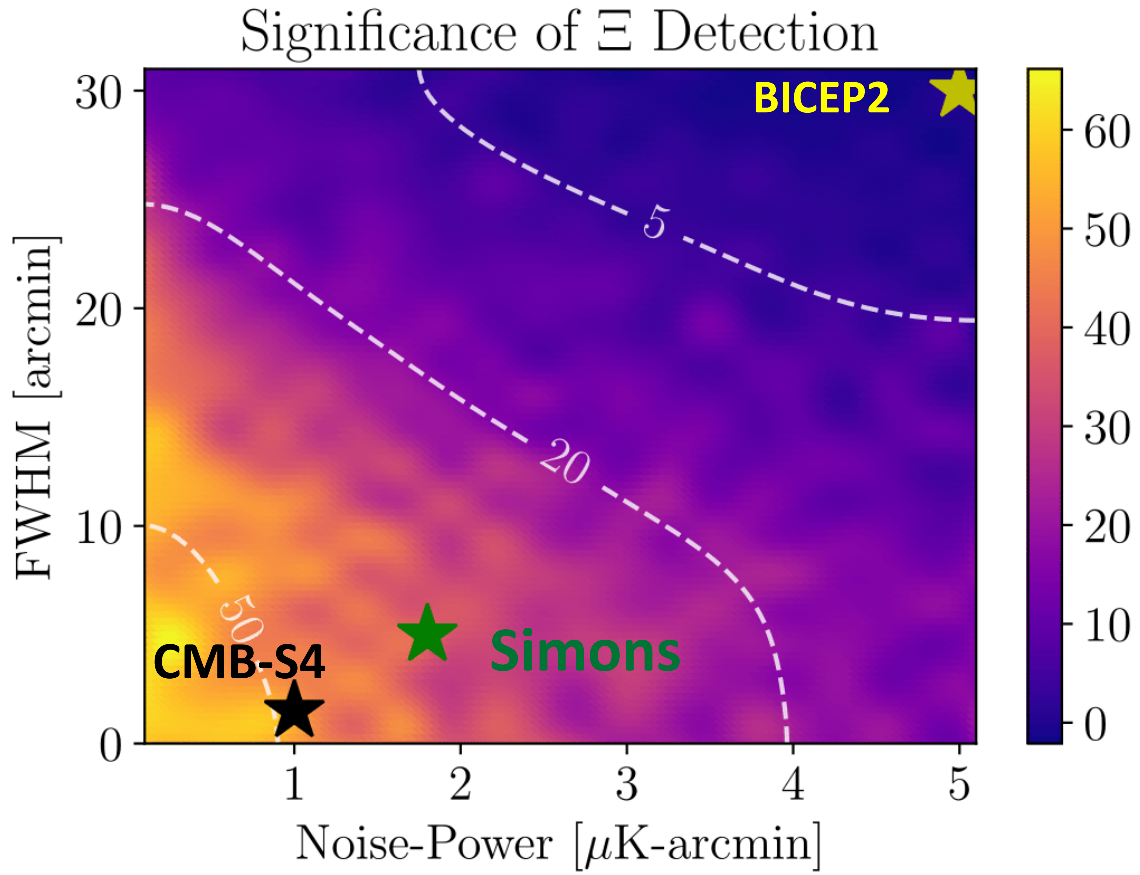
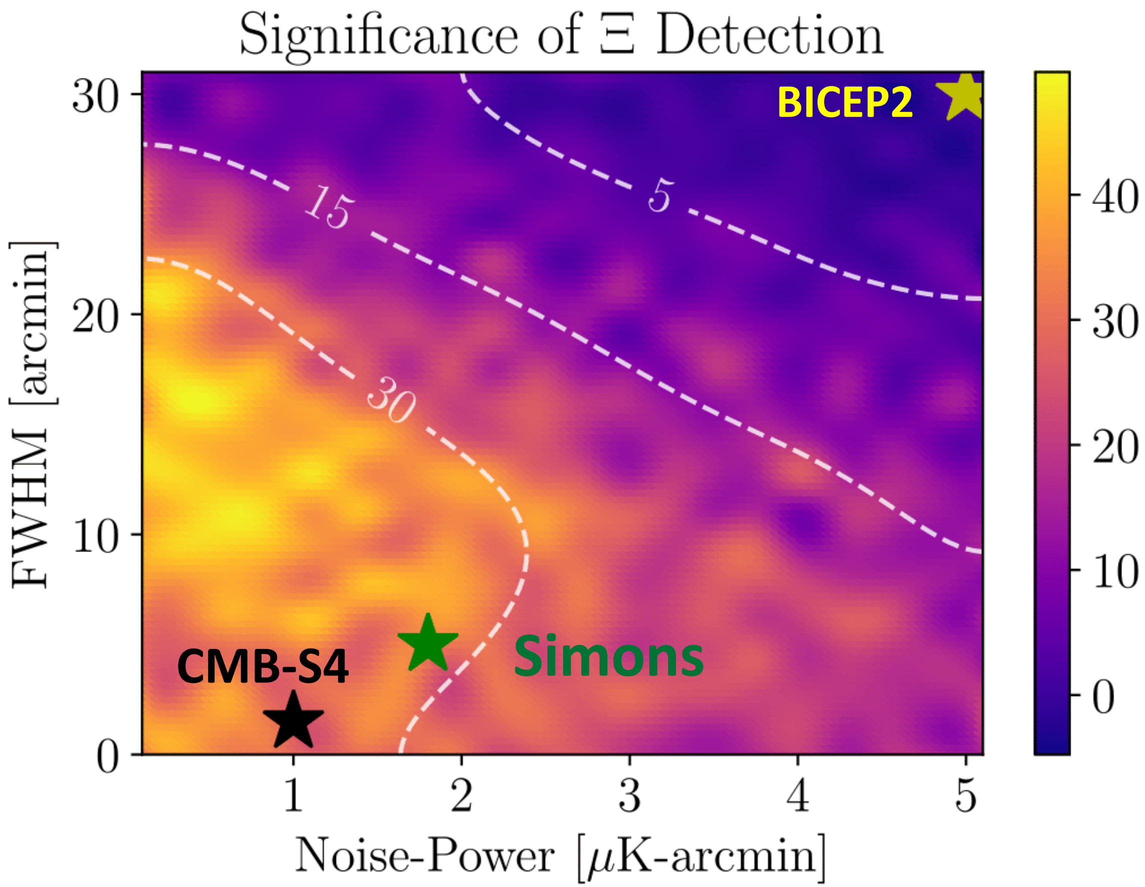
Noise Parameters

90% Delensing



No Delensing



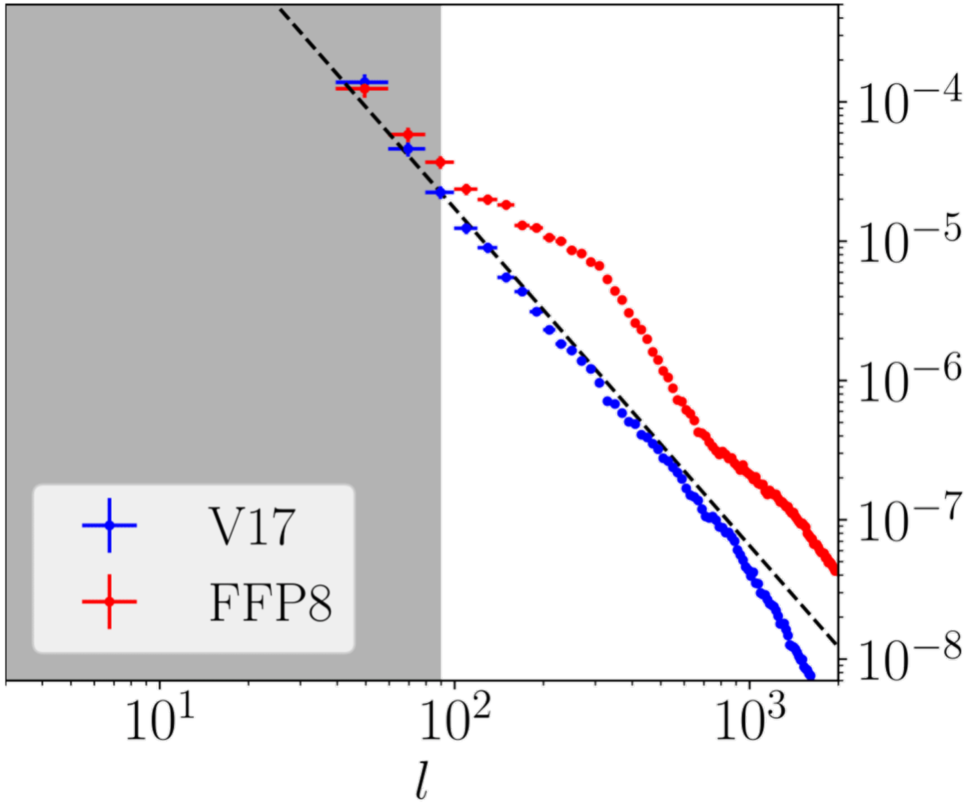
[Philcox+ 2018b]

FFP8 simulations

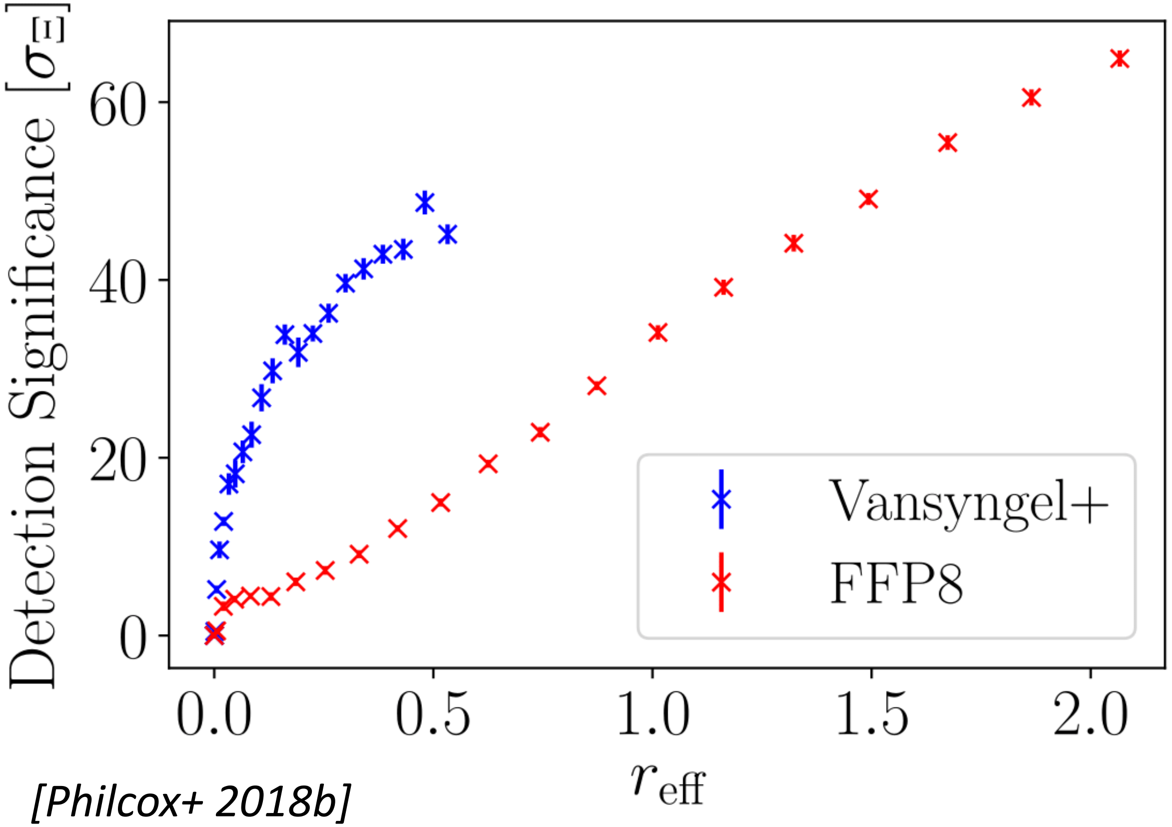
Differences may result from:

1. Older base-maps
2. Unphysical small-scale power
3. Different C_l^{BB} slope

$C_l^{BB}[\mu\mathrm{K}^2]$ Spectra



Null Tests



[Philcox+ 2018b]