Modelling Polarized Foregrounds

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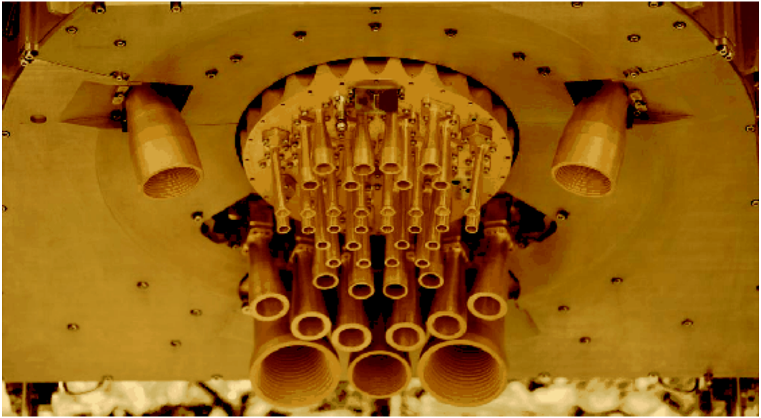
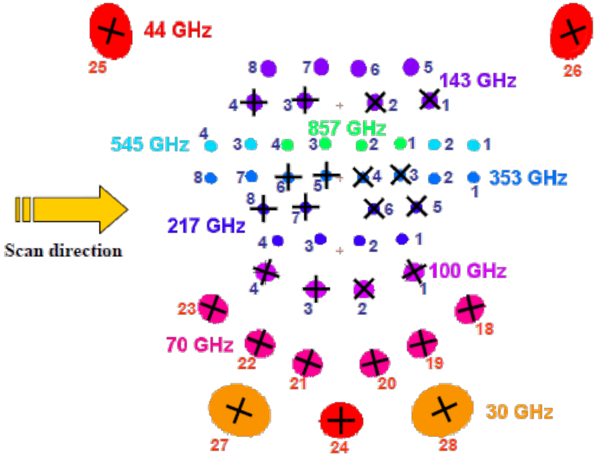
14 November 2019

Planck before Launch

Planck Focal Plane

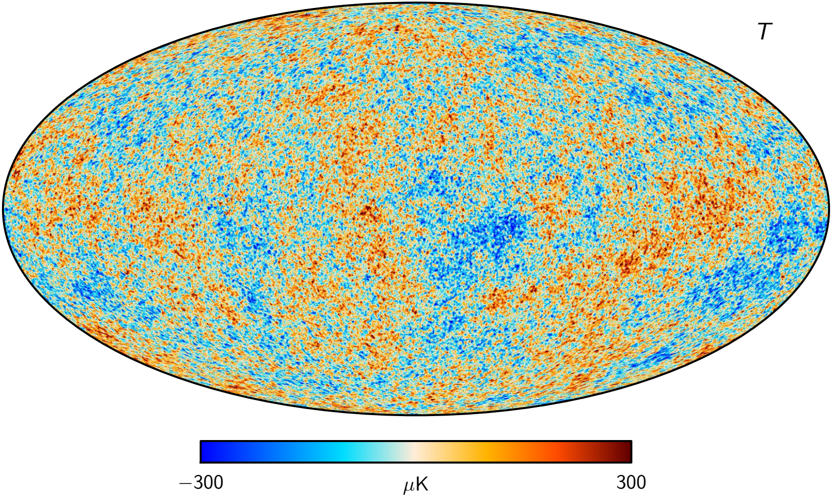


Planck Focal Plane Schematics



Planck 2018 CMB Maps

○ Intensity T ○ Polarization Q ○ Polarization U ○



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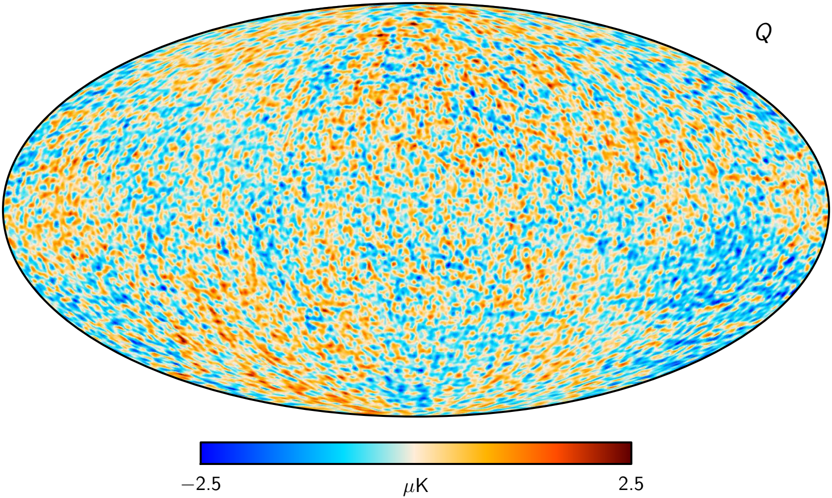

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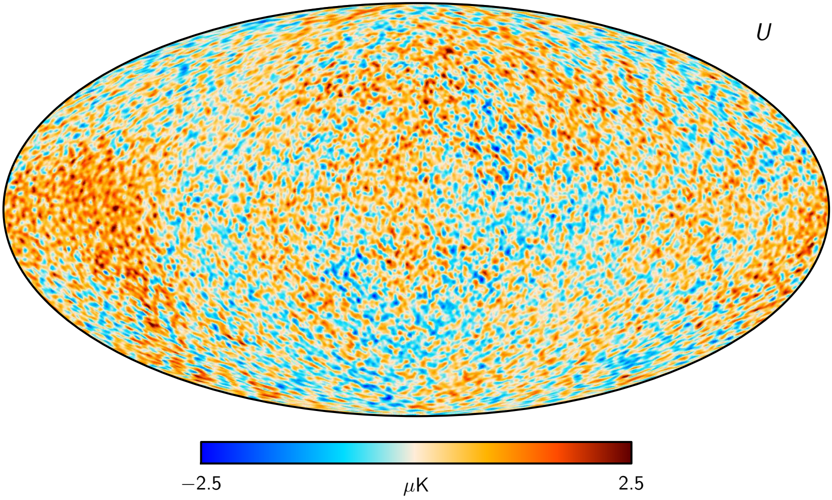
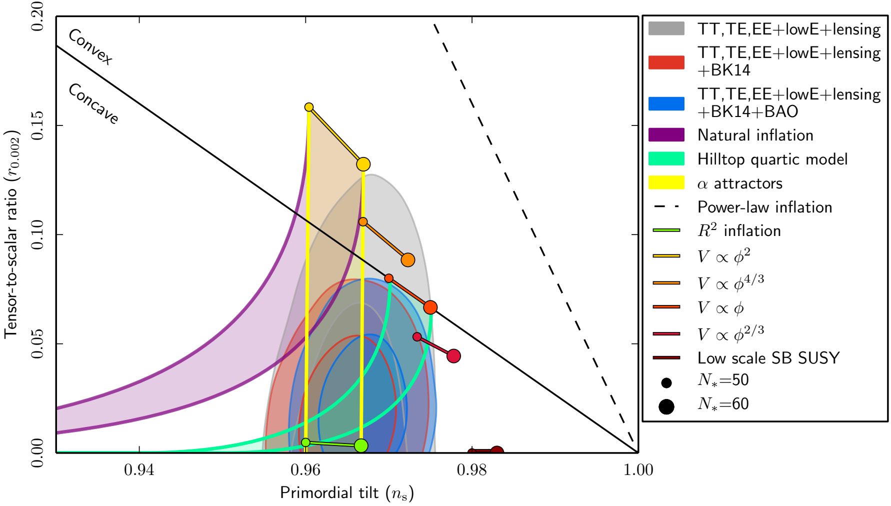
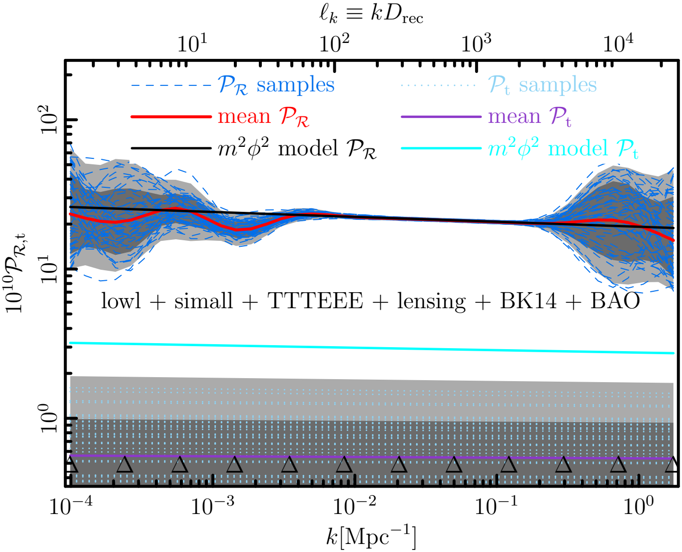


Planck 2018 Constraints on Inflation



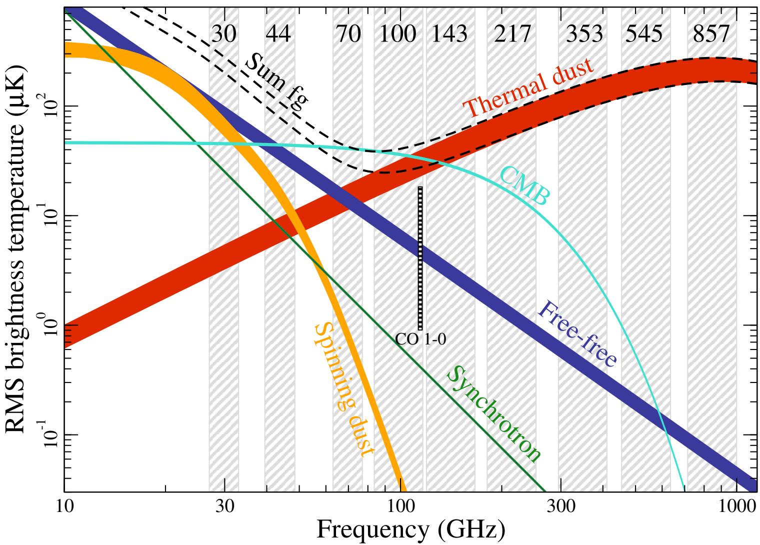
Primordial Scalar Fluctuations are now Nailed



The target now is B-modes!

CMB vs. Astrophysical Foregrounds

○ Intensity ○ Polarization ○ Atmospheric Transmission ○



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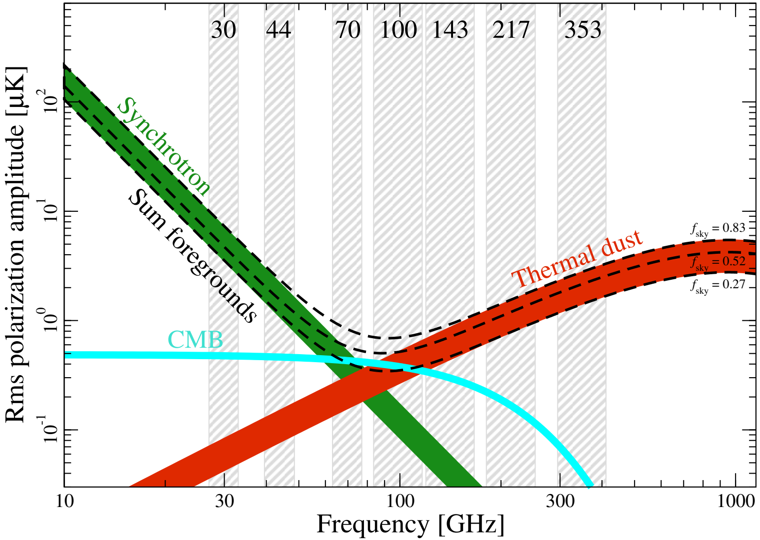
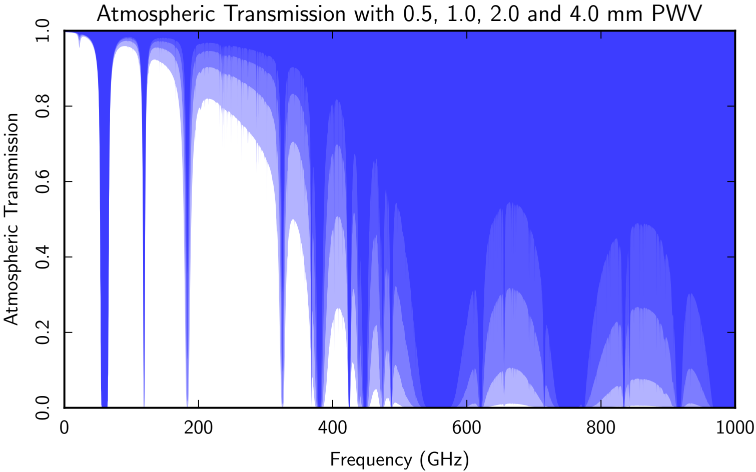
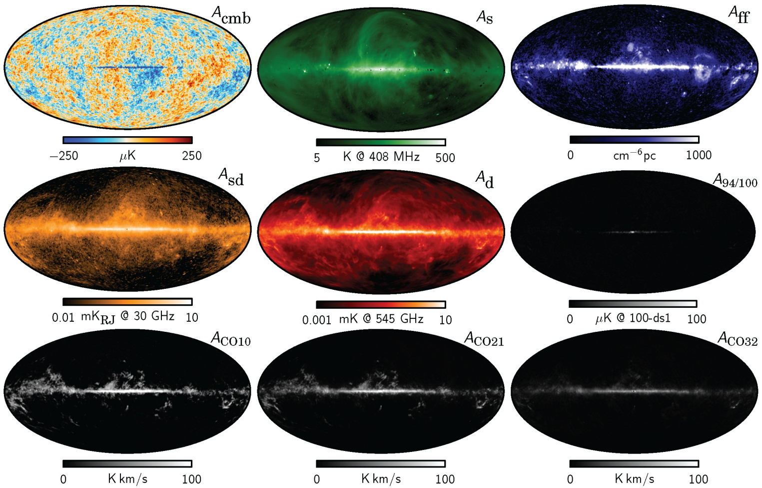


CMB vs. Astrophysical Foregrounds

◦ Intensity ◦ Polarization ◦ Atmospheric Transmission ◦



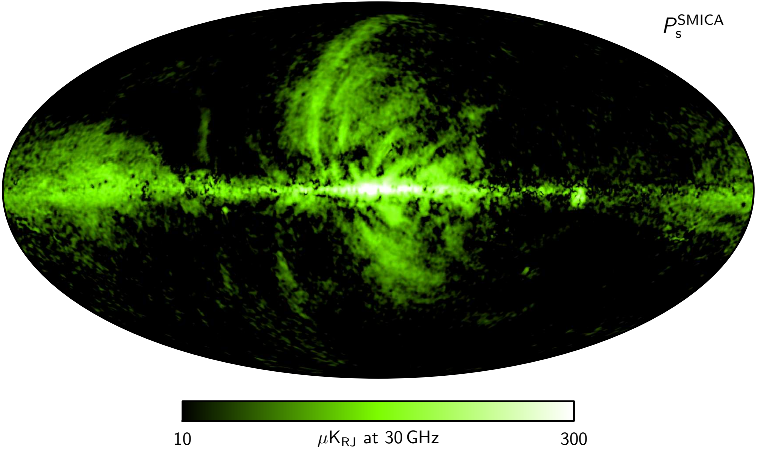
Temperature Component Maps



Polarization Component Maps

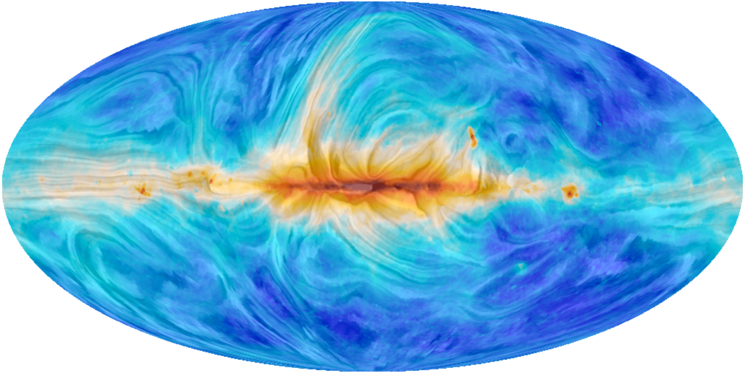
- Two main foregrounds, synchrotron emission and thermal dust
- Amplitude of CMB polarization is less than foregrounds
- Dust emission is highly polarized (polarization fraction is up to 20%)

Synchrotron Polarization Amplitude



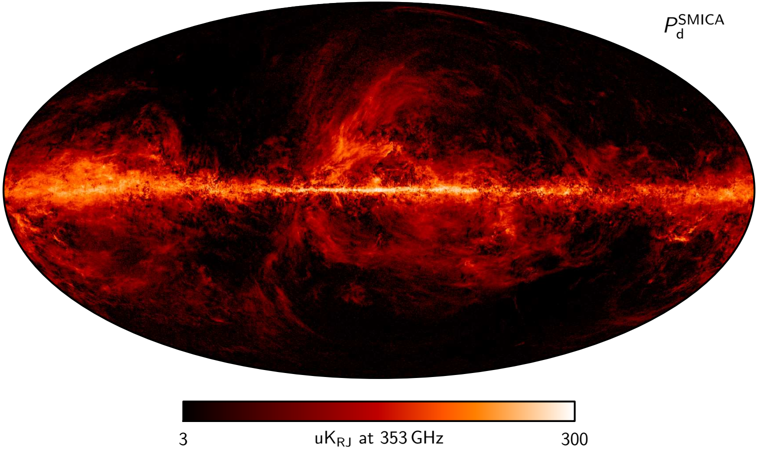
$P = \sqrt{Q^2 + U^2}$, SMICA component at 30GHz, smoothed to $40'$

Polarization Direction and Total Intensity



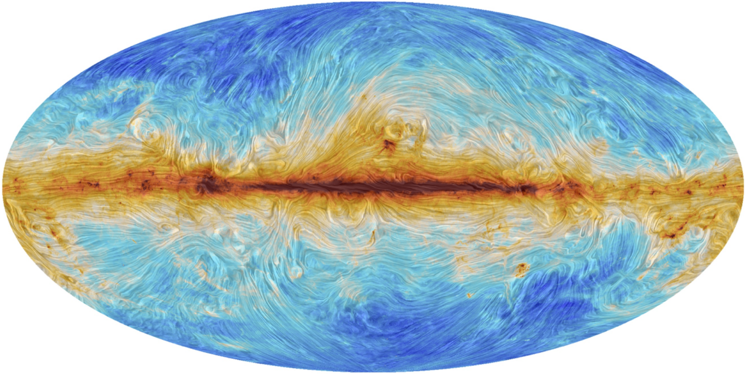
The colours represent intensity. The “drapery” pattern indicates the orientation of magnetic field projected on the plane of the sky, orthogonal to the observed polarization.

Dust Polarization Amplitude



$P = \sqrt{Q^2 + U^2}$, SMICA component at 353GHz, smoothed to $12'$

Polarization Direction and Total Intensity



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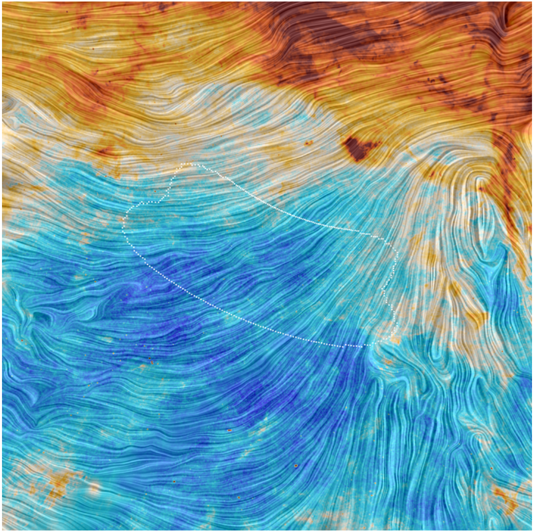
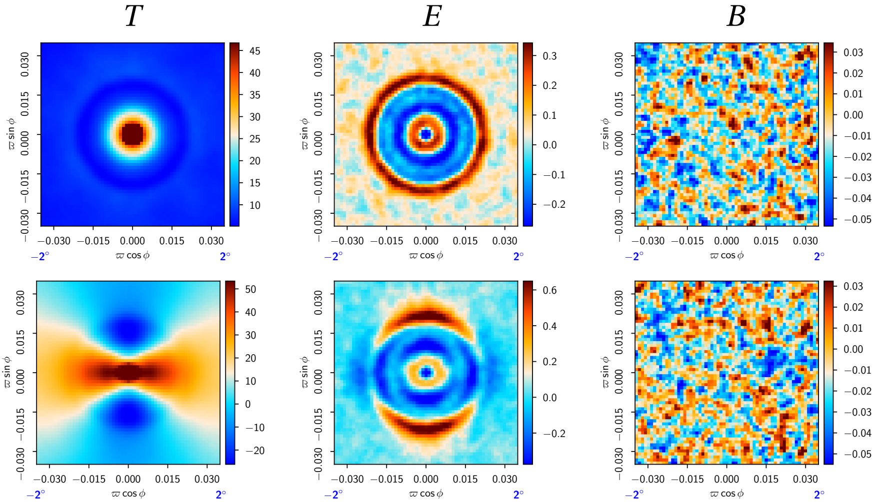
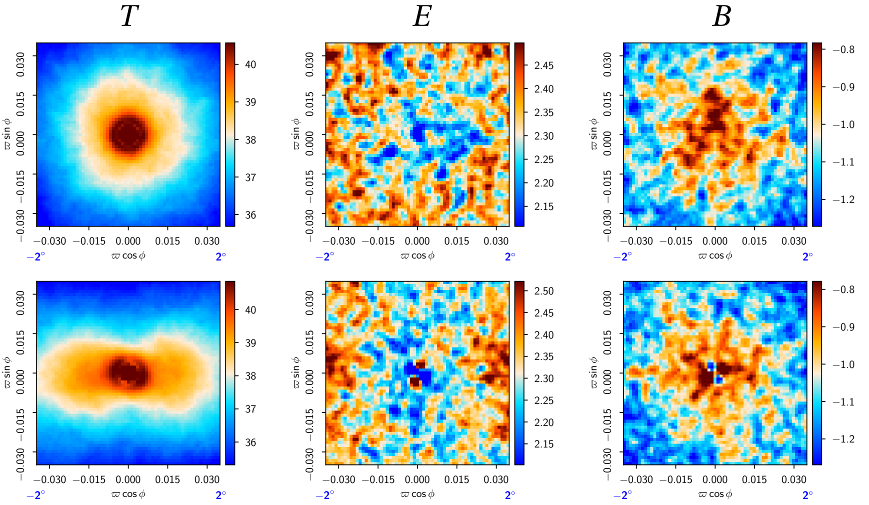
Planck View of BICEP2 Field



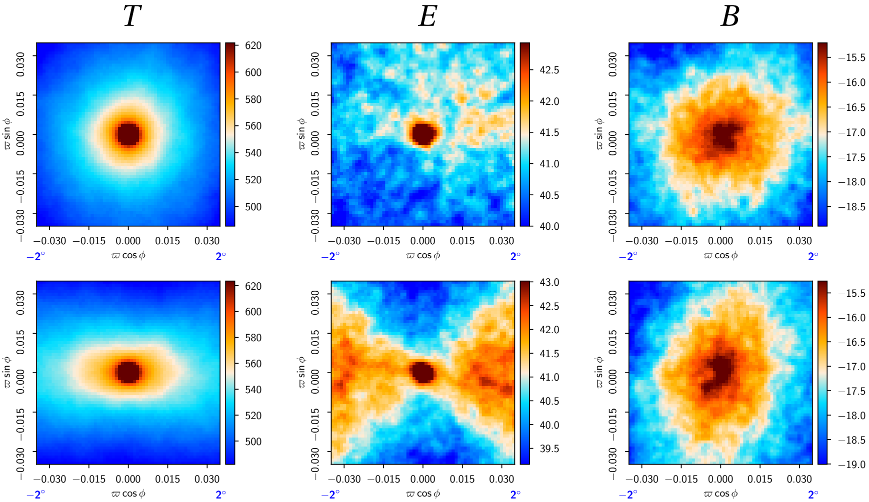
CMB Emission Stacks



30GHz Emission Stacks



353GHz Emission Stacks



Modelling Polarized Dust Emission

Polarized Dust Emission

Polarization is caused by magnetic field alignment:

$$\begin{aligned} I &= \int S_\nu e^{-\tau_\nu} d\tau_\nu \left[1 - p_0\left(\cos^2\gamma - \frac{2}{3}\right)\right] \\ \left\{ \begin{array}{c} Q \\ U \end{array} \right\} &= \int S_\nu e^{-\tau_\nu} d\tau_\nu \left\{ \begin{array}{c} \cos 2\psi \\ \sin 2\psi \end{array} \right\} p_0 \cos^2\gamma \end{aligned}$$

(p_0 is intrinsic polarization fraction ~ 0.21)

For a single layer, P/I determines magnetic field orientation:

$$\frac{I-P}{I+P} = 1 - \frac{6p_0}{2p_0+3}\cos^2\gamma$$

Polarization Fraction Tensor

Transform polarization tensor into polarization fraction tensor:

$$\begin{bmatrix} i+q & u \\ u & i-q \end{bmatrix} = \ln \begin{bmatrix} I+Q & U \\ U & I-Q \end{bmatrix}$$

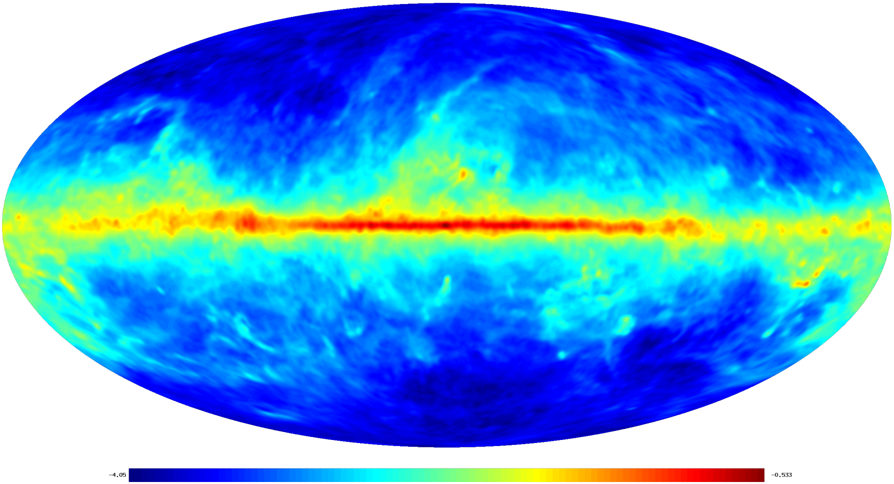
This is an invertible transformation on IQU maps:

$$i = \frac{1}{2}\ln\left(I^2 - P^2\right), \quad q = \frac{1}{2}\frac{Q}{P}\ln\frac{I+P}{I-P}, \quad u = \frac{1}{2}\frac{U}{P}\ln\frac{I+P}{I-P}$$

$$I = e^i \cosh p, \qquad Q = \frac{q}{p} e^i \sinh p, \qquad U = \frac{u}{p} e^i \sinh p$$

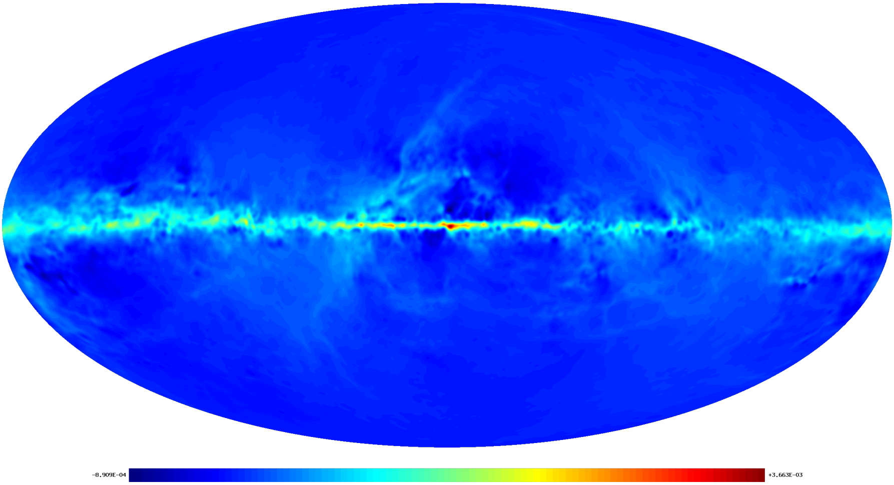
Polarization Fraction Tensor [Dust]

○ ln I ○ E ○ B ○ i ○ e ○ b ○



Polarization Fraction Tensor [Dust]

◦ In I ◦ E ◦ B ◦ i ◦ e ◦ b ◦



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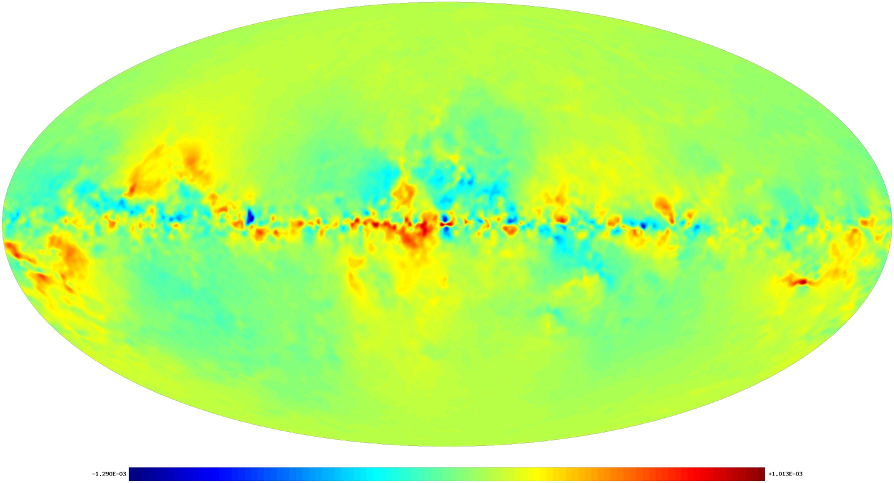

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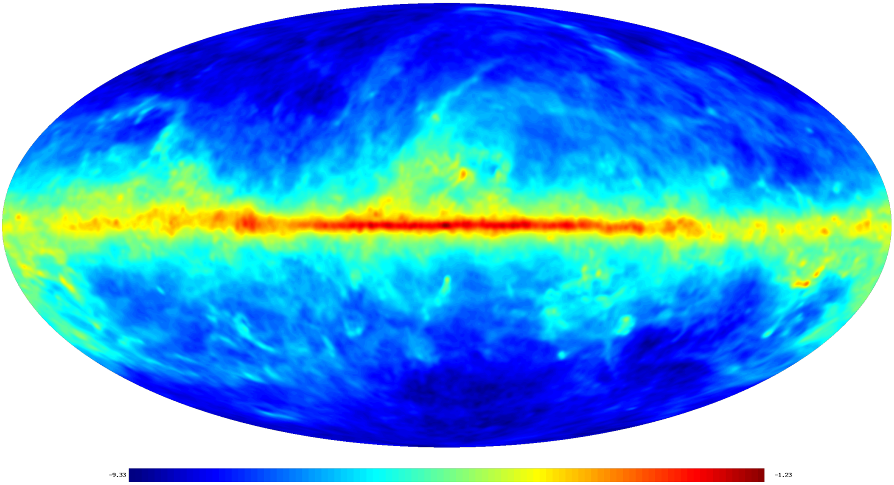

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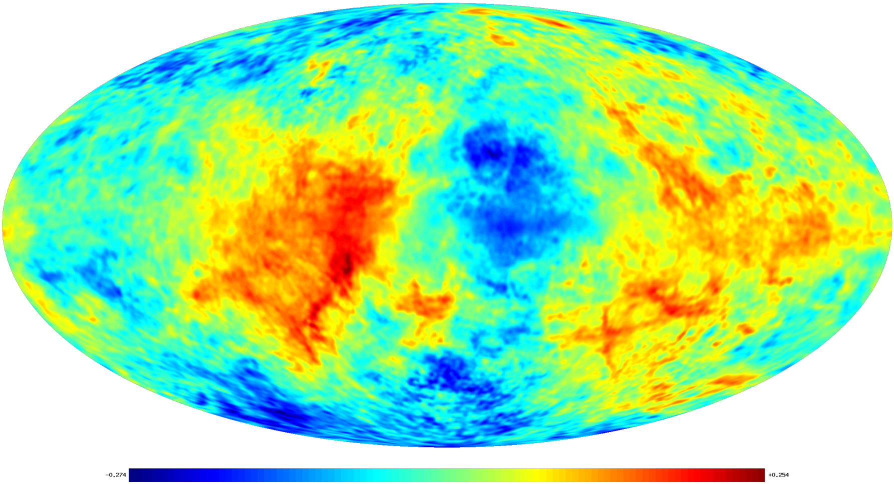

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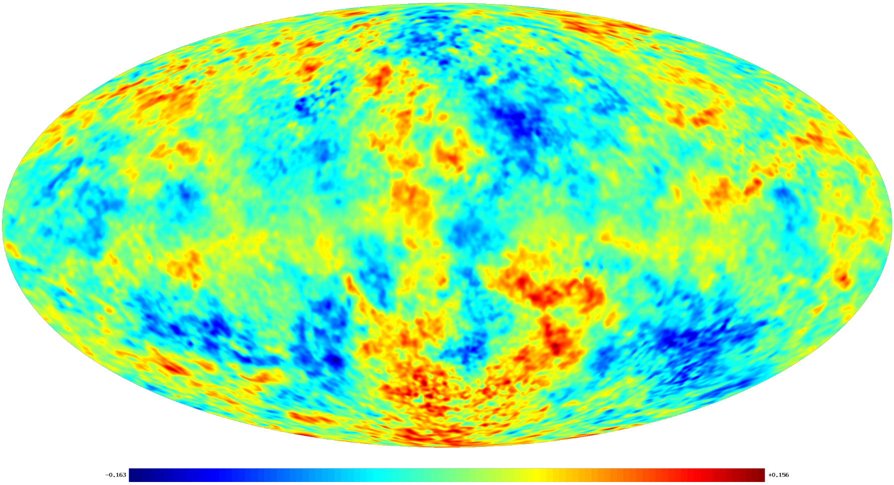
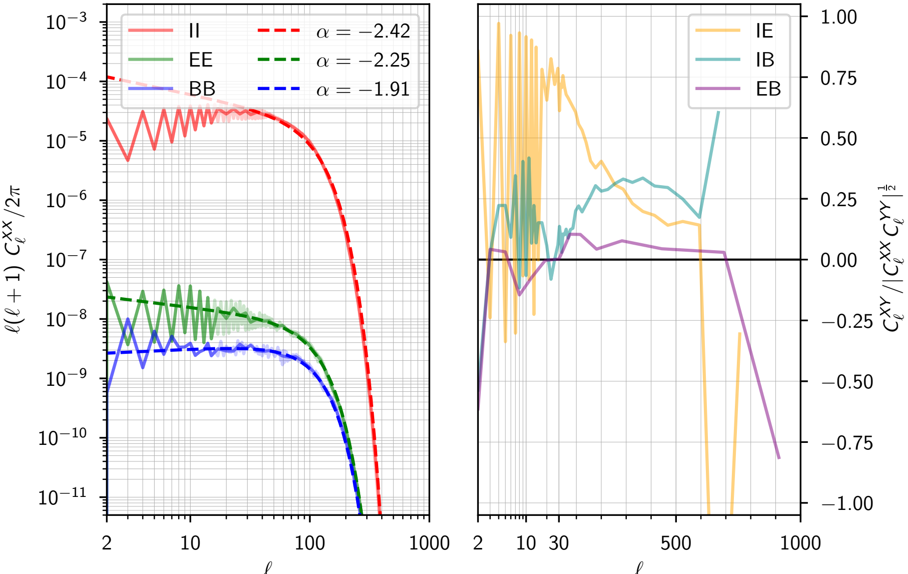


Parity-Violating Correlations Disappear!

◦ polarization ◦ polarization fraction ◦



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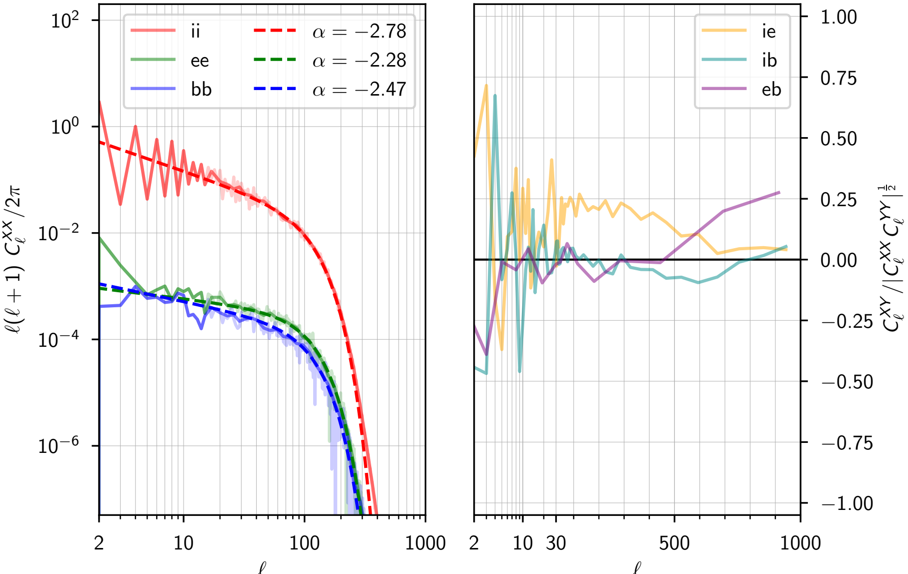


Geometric Factors in Emission Integral

$$\begin{aligned}
\mathfrak{p} \equiv \frac{B_\phi^2 + B_\theta^2}{B^2} &= \cos^2\gamma \\
\mathfrak{q} \equiv \frac{B_\phi^2 - B_\theta^2}{B^2} &= \cos^2\gamma \cos 2\psi \\
\mathfrak{u} \equiv -\frac{2B_\phi B_\theta}{B^2} &= \cos^2\gamma \sin 2\psi
\end{aligned}$$

These get averaged along the line of sight with weighting:

$$\langle X \rangle = \frac{1}{s_\nu} \int S_\nu e^{-\tau_\nu} d\tau_\nu X, \quad s_\nu = \int S_\nu e^{-\tau_\nu} d\tau_\nu$$

Magnetic Field Model

Split magnetic field into large-scale and random components:

$$\mathbf{B} = \bar{\mathbf{B}} + \delta\mathbf{B}$$

To first order, intensity and polarizations components are:

$$\begin{aligned}
I &= s_\nu\left(1+\tfrac{2}{3}p_0\right) - s_\nu p_0\left[\mathfrak{p}[\bar{\mathbf{B}}] + \left.\frac{\partial\mathfrak{p}}{\partial\mathbf{B}}\right|_{\bar{\mathbf{B}}}\langle\delta\mathbf{B}\rangle + \ldots\right] \\
Q &= s_\nu p_0\left[\mathfrak{q}[\bar{\mathbf{B}}] + \left.\frac{\partial\mathfrak{q}}{\partial\mathbf{B}}\right|_{\bar{\mathbf{B}}}\langle\delta\mathbf{B}\rangle + \ldots\right] \\
U &= s_\nu p_0\left[\mathfrak{u}[\bar{\mathbf{B}}] + \left.\frac{\partial\mathfrak{u}}{\partial\mathbf{B}}\right|_{\bar{\mathbf{B}}}\langle\delta\mathbf{B}\rangle + \ldots\right]
\end{aligned}$$

They split into large-scale pattern and random component!

Reconstruct Large-Scale Magnetic Field

Estimator of dust column depth:

$$I + P = s_\nu\left(1 + \tfrac{2}{3}p_0\right) + O(\delta B^2),$$

Estimators of magnetic field geometry:

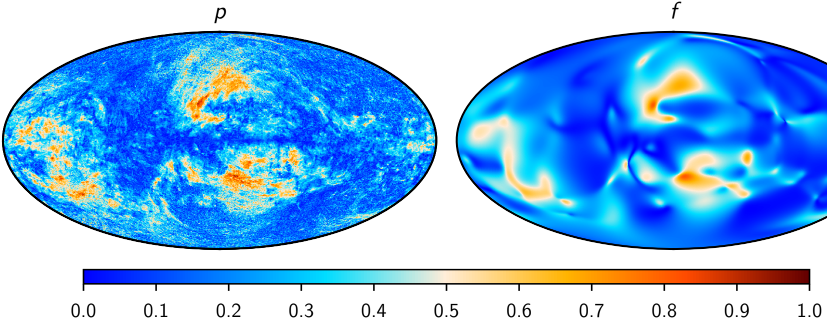
$$\tilde{q} \equiv \frac{Q}{I+P} = \frac{3p_0}{3+2p_0}\left[\mathfrak{q}[\bar{\mathbf{B}}] + \left.\frac{\partial \mathfrak{q}}{\partial \mathbf{B}}\right|_{\bar{\mathbf{B}}} \langle \delta \mathbf{B} \rangle + \ldots\right],$$

$$\tilde{u} \equiv \frac{U}{I+P} = \frac{3p_0}{3+2p_0}\left[\mathfrak{u}[\bar{\mathbf{B}}] + \left.\frac{\partial \mathfrak{u}}{\partial \mathbf{B}}\right|_{\bar{\mathbf{B}}} \langle \delta \mathbf{B} \rangle + \ldots\right].$$

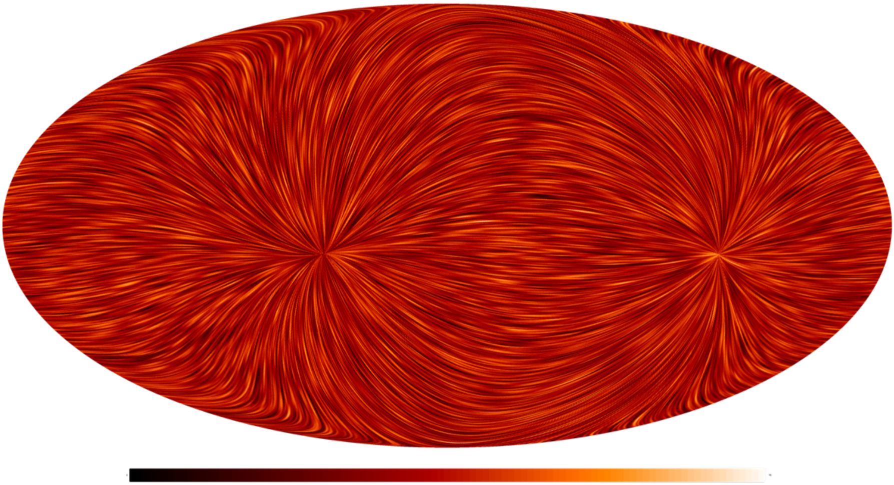
Reconstruct large-scale magnetic field using least square fit:

$$\chi^2_{\bar{\mathbf{B}}} = \left(\tilde{q} - \varepsilon\,\mathfrak{q}[\bar{\mathbf{B}}]\right)^2 + \left(\tilde{u} - \varepsilon\,\mathfrak{u}[\bar{\mathbf{B}}]\right)^2, \quad \varepsilon = \frac{3p_0}{3+2p_0}.$$

Reconstructed Polarization Fraction



Magnetic Field Lines



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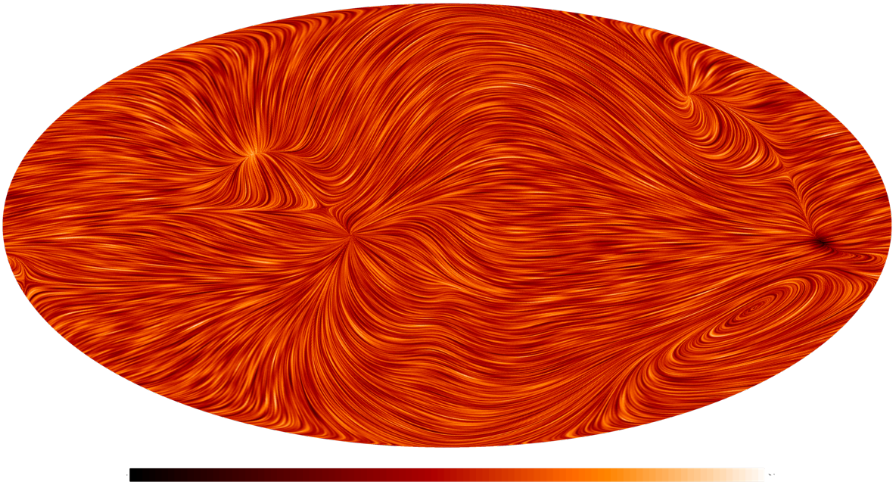
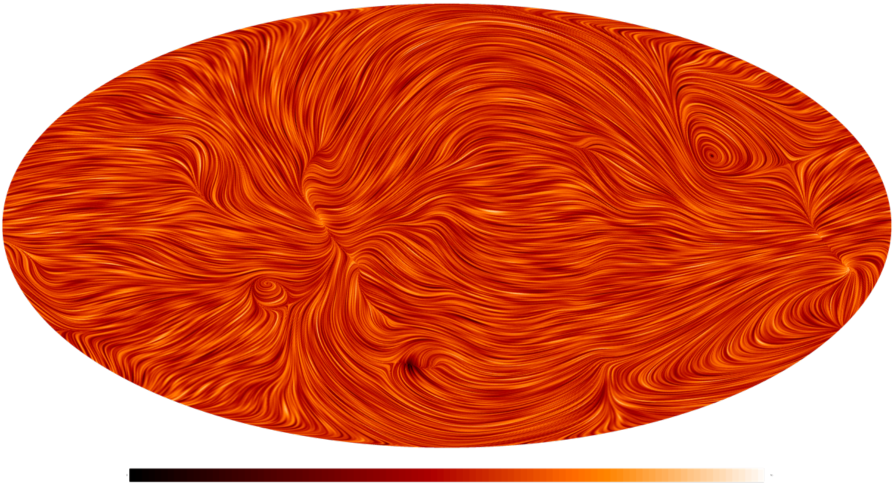


Magnetic Field Lines

$\circ\, \ell_{\text{max}} = 1 \circ \ell_{\text{max}} = 5 \circ \ell_{\text{max}} = 10 \circ \ell_{\text{max}} = 20 \circ$



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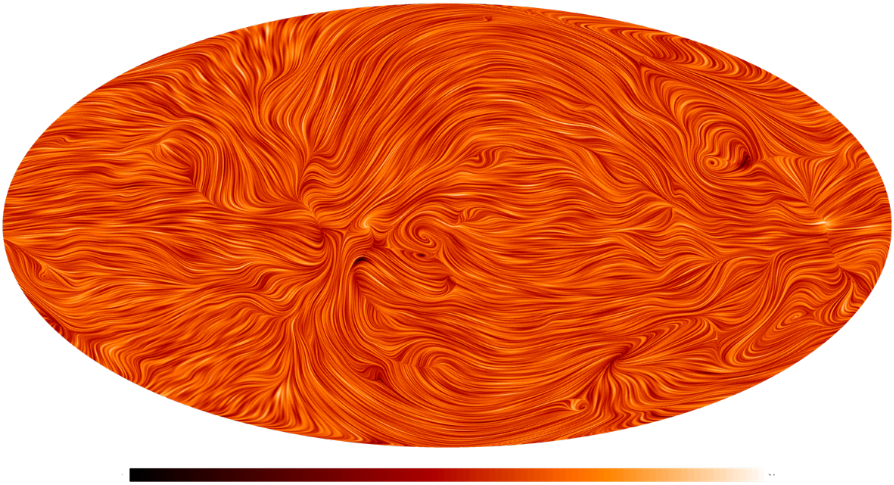
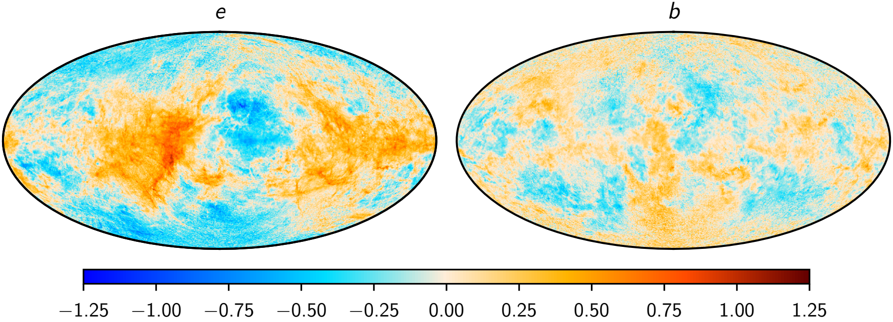


Reconstructed Polarization Fraction



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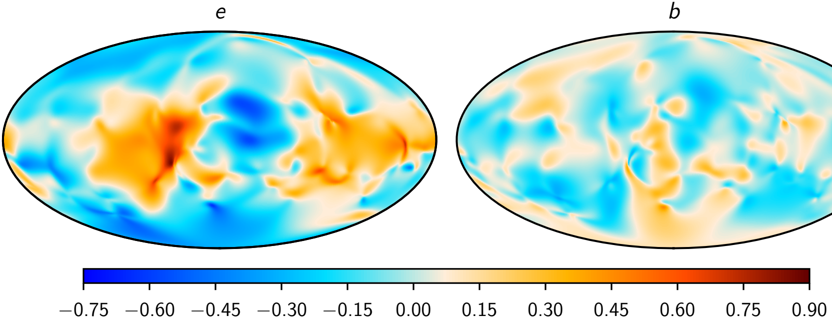

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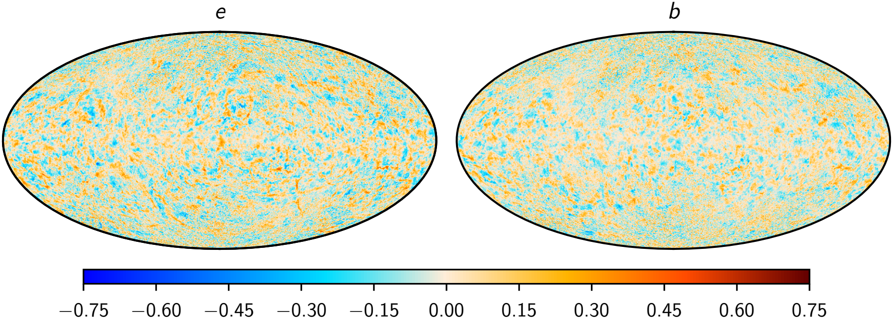
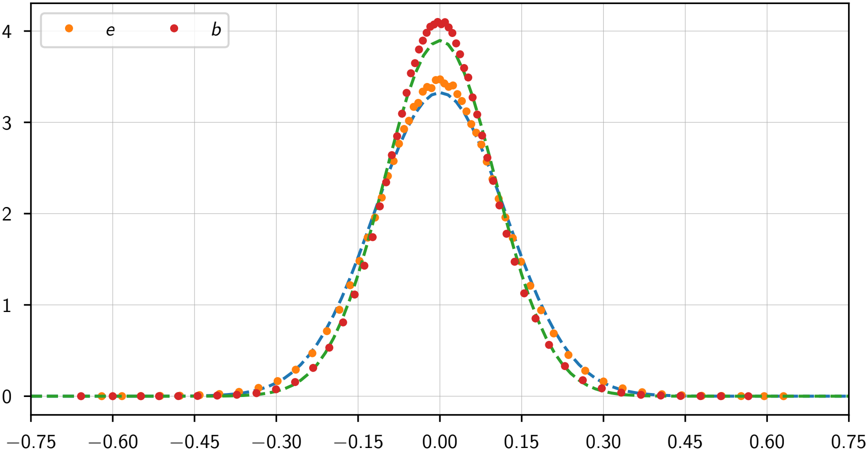


Random Residual is Quite Gaussian

◦ 1-point PDF ◦ Tails ◦ Local non-Gaussianity corrected ◦



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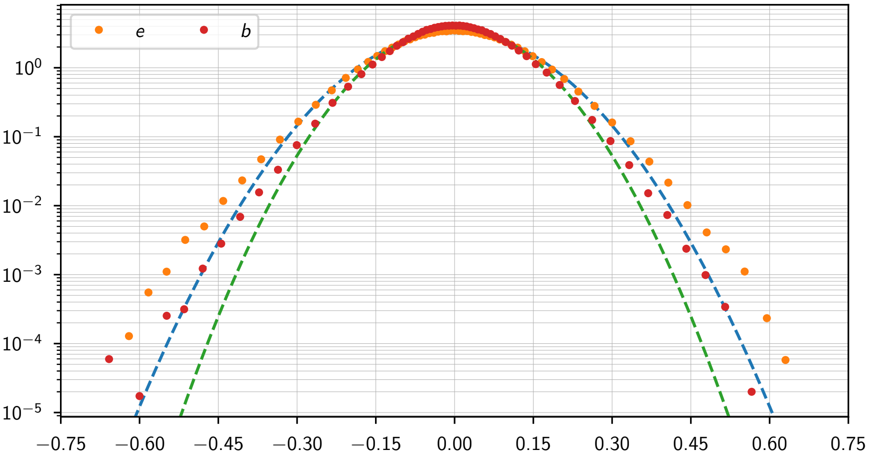

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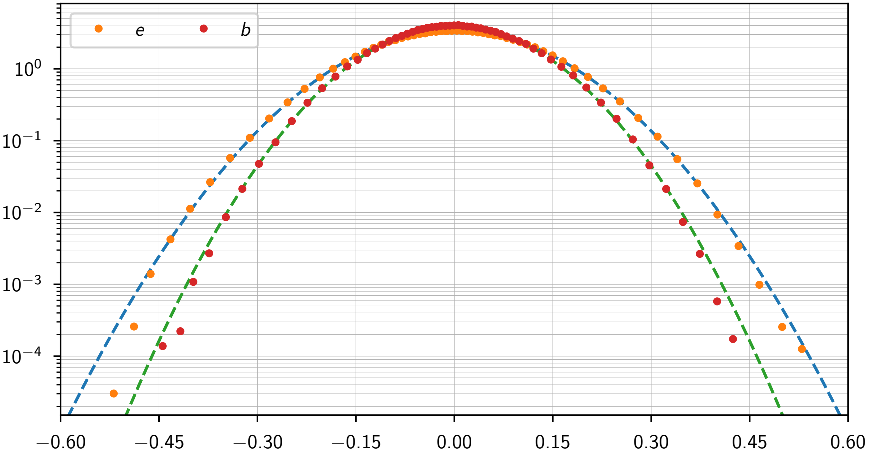
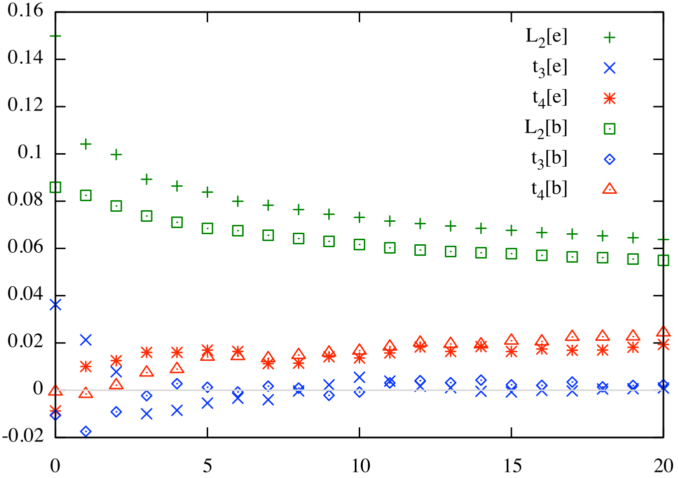


Where to Stop?



Polarized Dust Emission is Actually Very Simple!

Model It!

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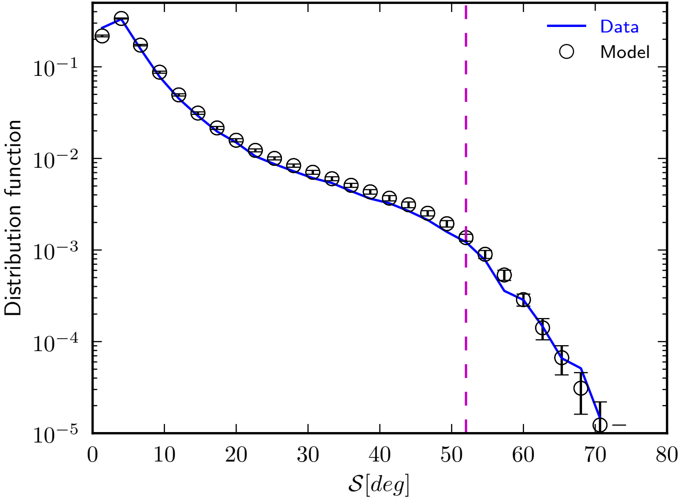
Model It!

Random Realizations Reproduce Sky Statistics



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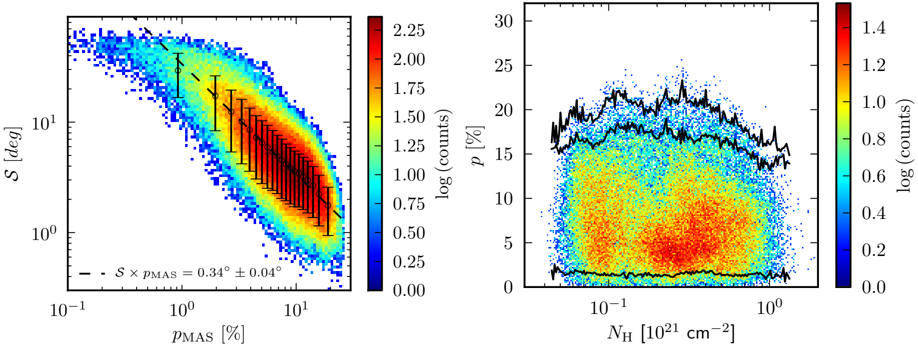

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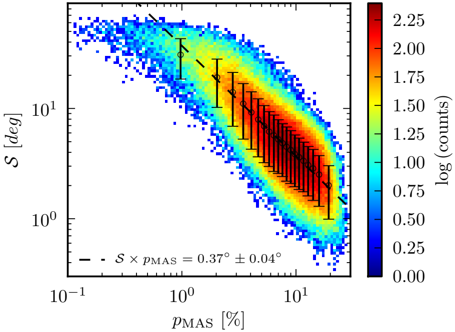
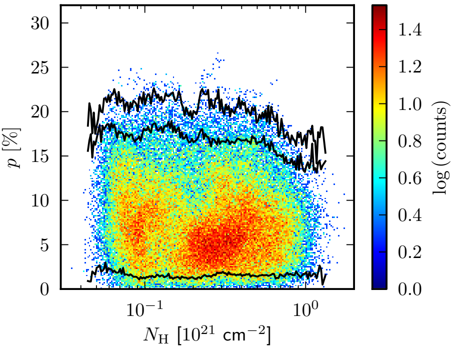
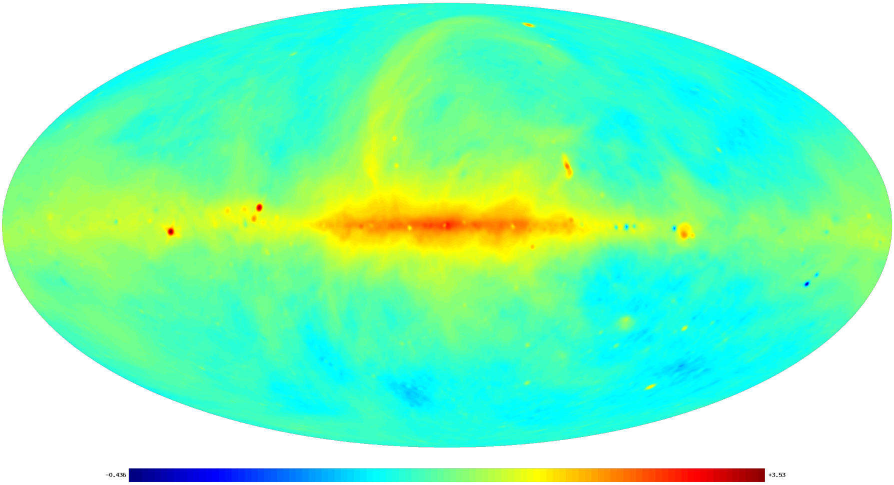




Modelling Synchrotron Emission

Polarization Fraction Tensor [Synchrotron]

○ In I ○ E ○ B ○ i ○ e ○ b ○



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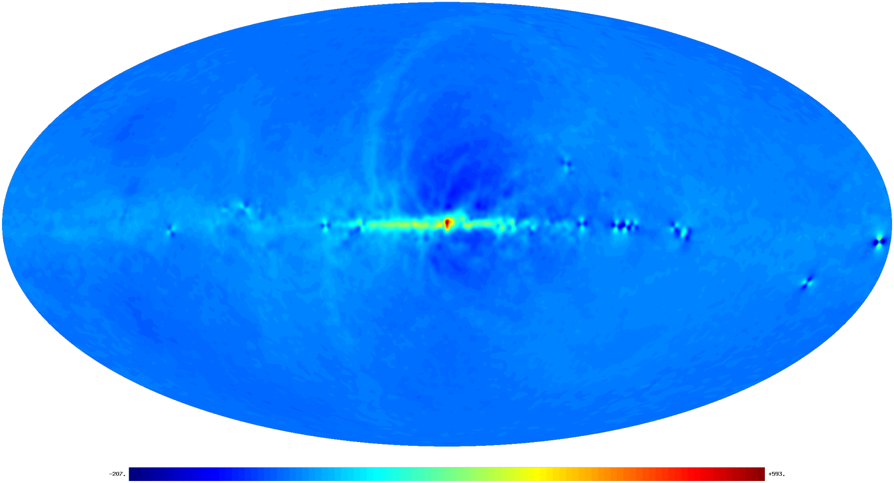
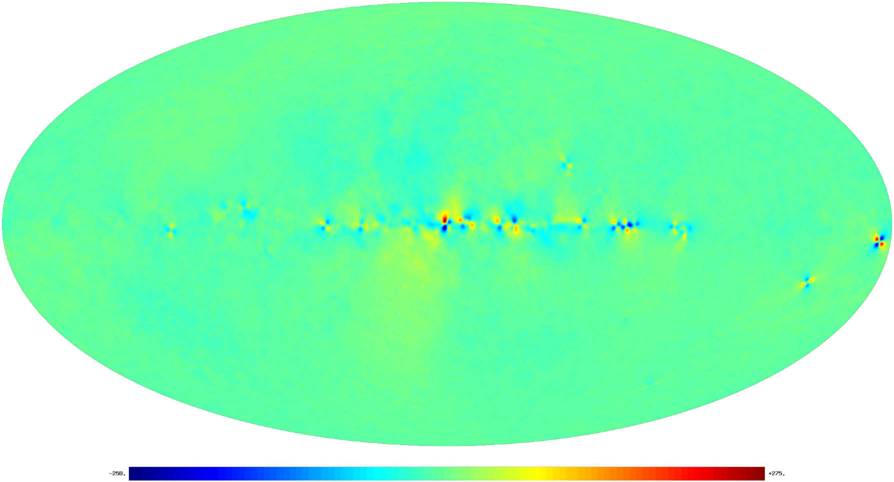


Polarization Fraction Tensor [Synchrotron]

○ ln I ○ E ○ B ○ i ○ e ○ b ○



Polarization Fraction Tensor [Synchrotron]

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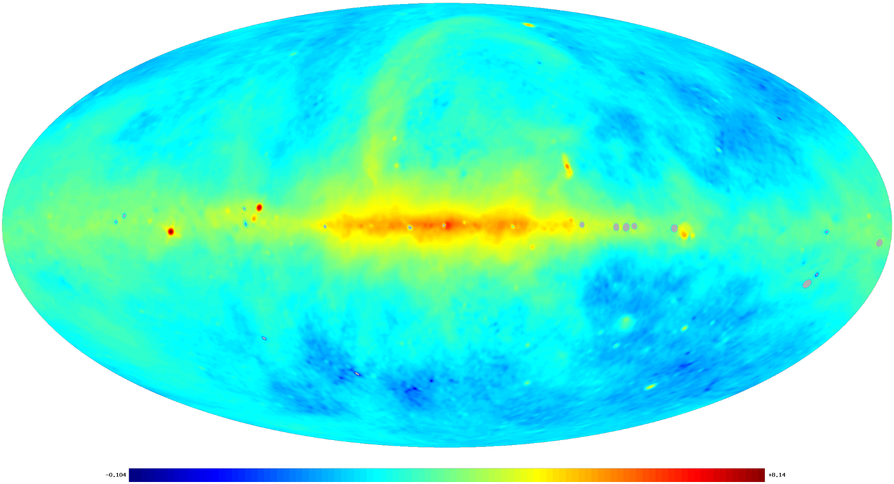

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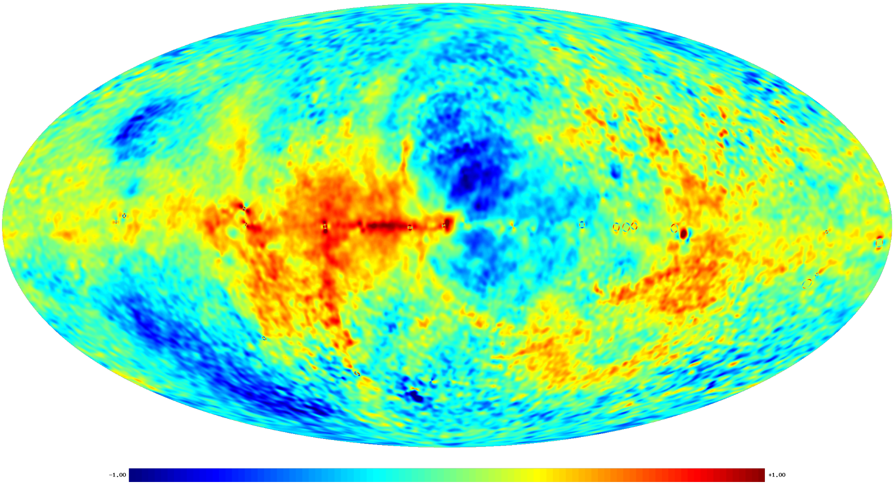

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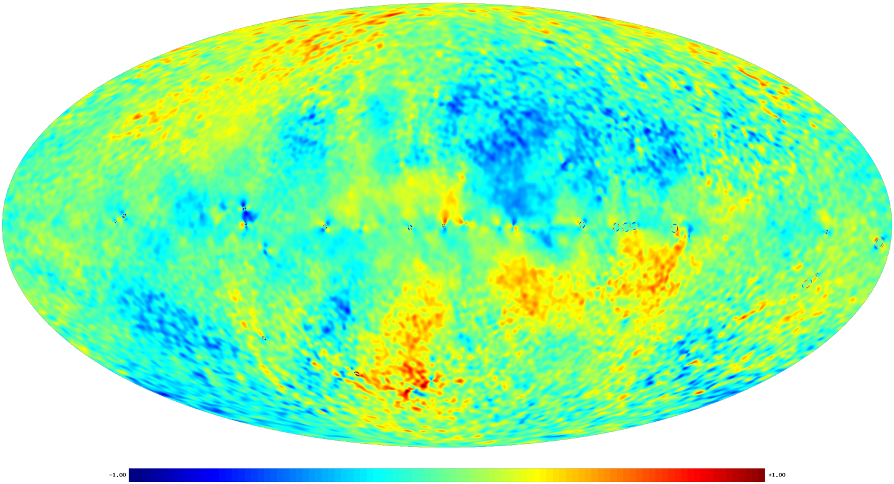

Synchrotron Polarization

Rybicki & Lightman (1979)

$$P_\perp(\omega) = \frac{\sqrt{3}}{4\pi}\frac{q^3 B_\perp}{mc^2}[F(x)+G(x)]$$

$$P_\parallel(\omega) = \frac{\sqrt{3}}{4\pi}\frac{q^3 B_\perp}{mc^2}[F(x)-G(x)]$$

$$F(x)=x\int_x^\infty K_{\frac{5}{3}}(\xi)d\xi, \quad G(x)=xK_{\frac{2}{3}}(x), \quad x=\frac{\omega}{\omega_c}$$

$$\omega_c=\frac{3}{2}\frac{qB_\perp}{mc}\gamma^2$$

Synchrotron Polarization

Rybicki & Lightman (1979)

$$N(\gamma)d\gamma \propto \gamma^{-p}d\gamma$$

$$P \propto \frac{q^3 B_\perp}{mc^2}\left(\frac{qB_\perp}{mc\omega}\right)^{\frac{1}{2}(p-1)}$$

$$\Pi(\omega) = \frac{P_\perp(\omega) - P_\parallel(\omega)}{P_\perp(\omega) + P_\parallel(\omega)} = \frac{G(x)}{F(x)} \quad \longrightarrow \quad \Pi = \frac{p+1}{p+\frac{7}{3}}$$

But polarization fraction varies on the sky!

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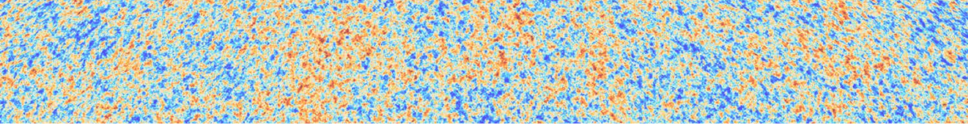
$$\Pi(\omega) = \frac{P_\perp(\omega) - P_\parallel(\omega)}{P_\perp(\omega) + P_\parallel(\omega)} = \frac{G(x)}{F(x)} \quad \longrightarrow \quad \Pi = \frac{p+1}{p+\frac{7}{3}}$$

But polarization fraction varies on the sky!



What are we looking at here?

Spatial dependence of spectral index?

And why is it correlated to magnetic features?

– The End –