LARGE-SCALE B-MODE POLARIZED FOREGROUNDS

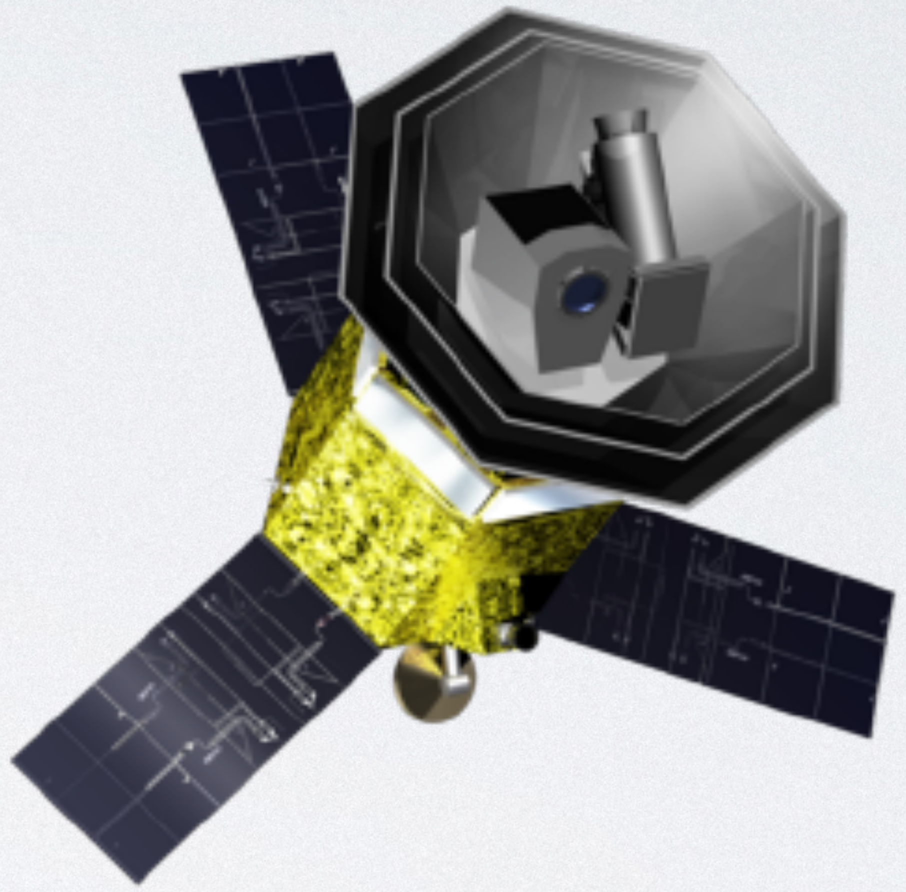
Andrei Frolov, SFU
frolov@sfu.ca

COSMOLOGY 2023 in Miramare, 29 August 2023

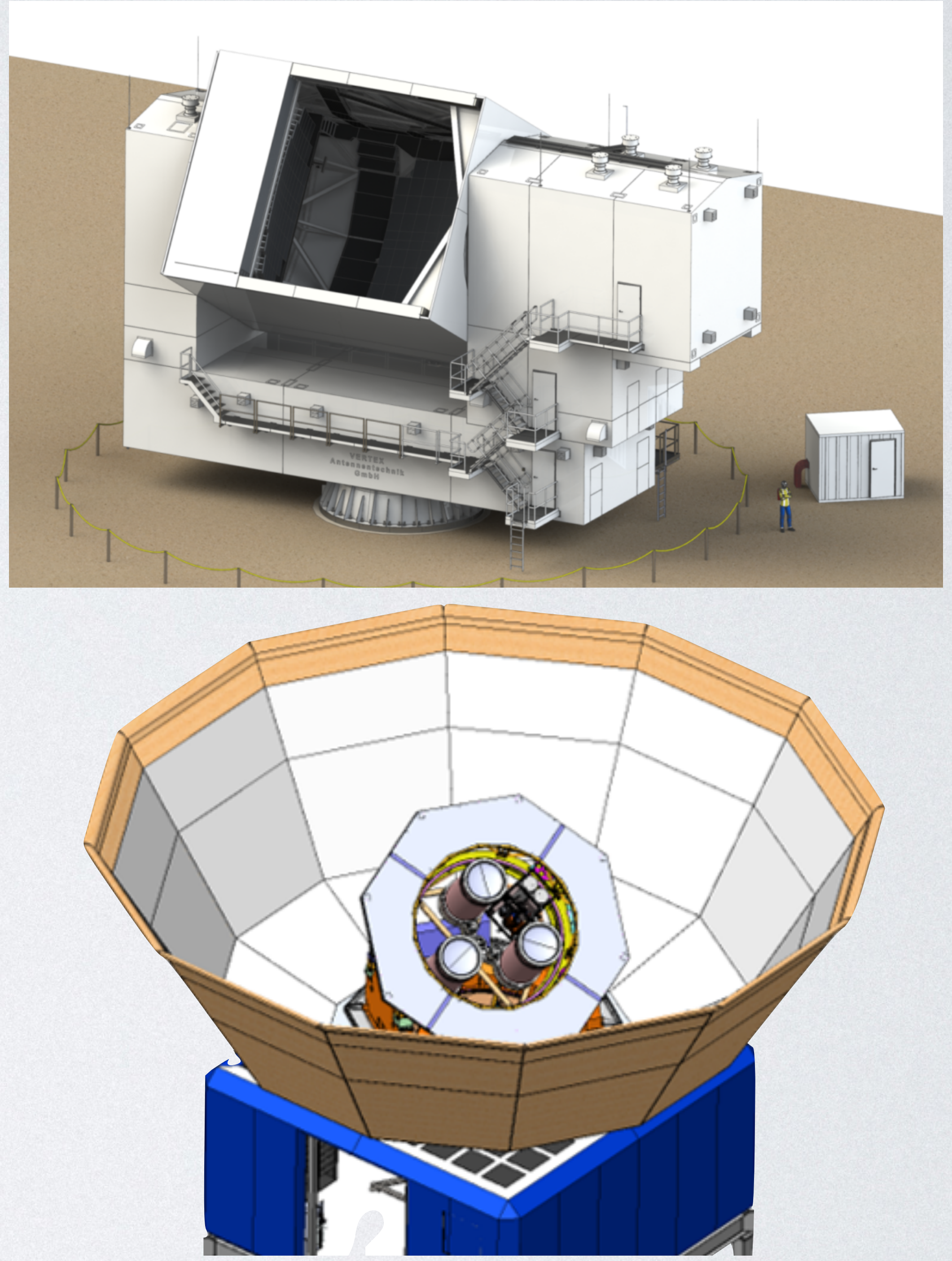
PAST AND FUTURE CMB EXPERIMENTS

Planck (done!)

Simons Observatory (happening now)

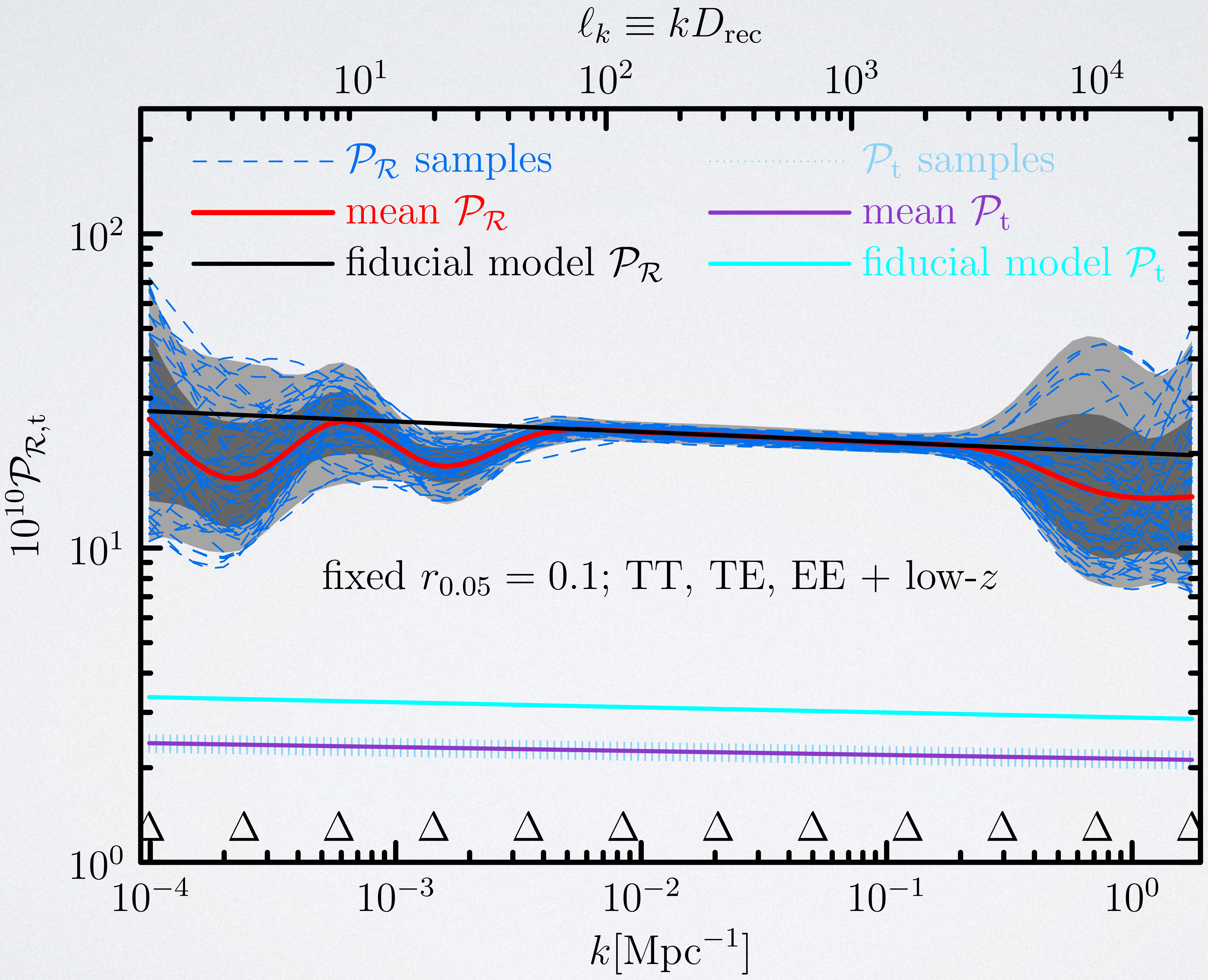


LiteBIRD (space based)



CMB-S4

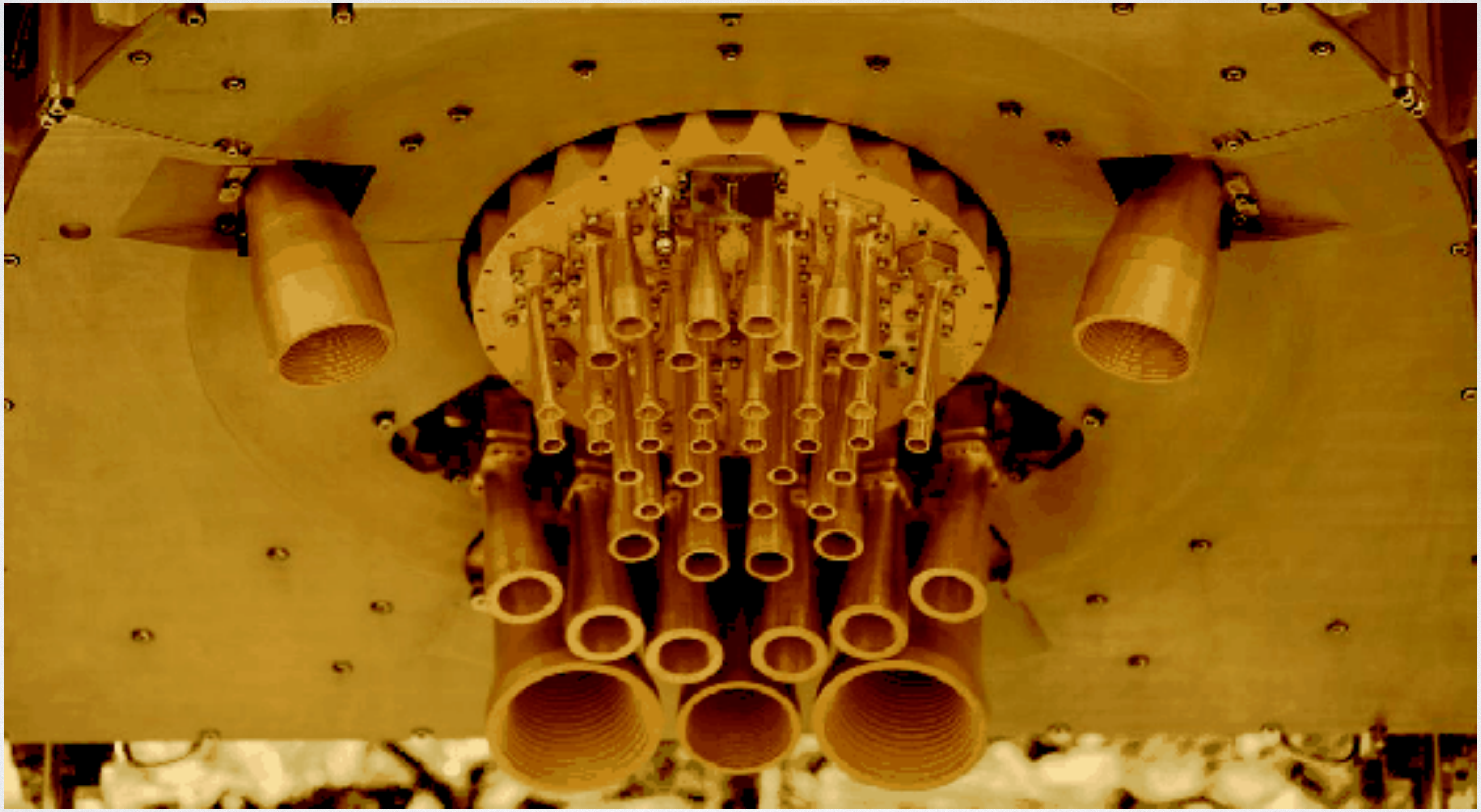
T AND E MODES ARE NOW NAILED!



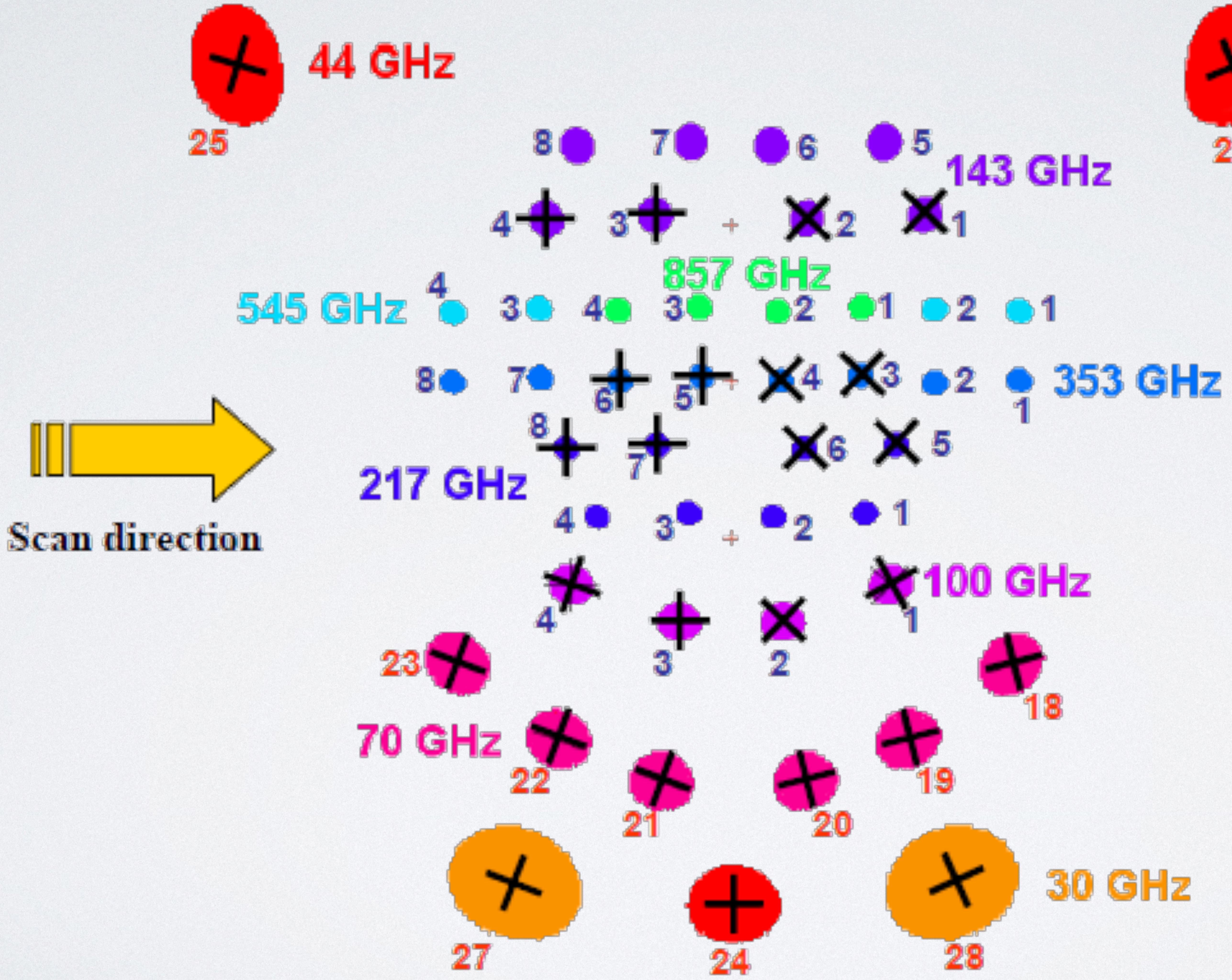
NEXT TARGET: B-MODES

primordial gravitational waves, large scale lensing…

PLANCK FOCAL PLANE



PLANCK FOCAL PLANE



30 GHz

44 GHz

70 GHz

100 GHz

143 GHz

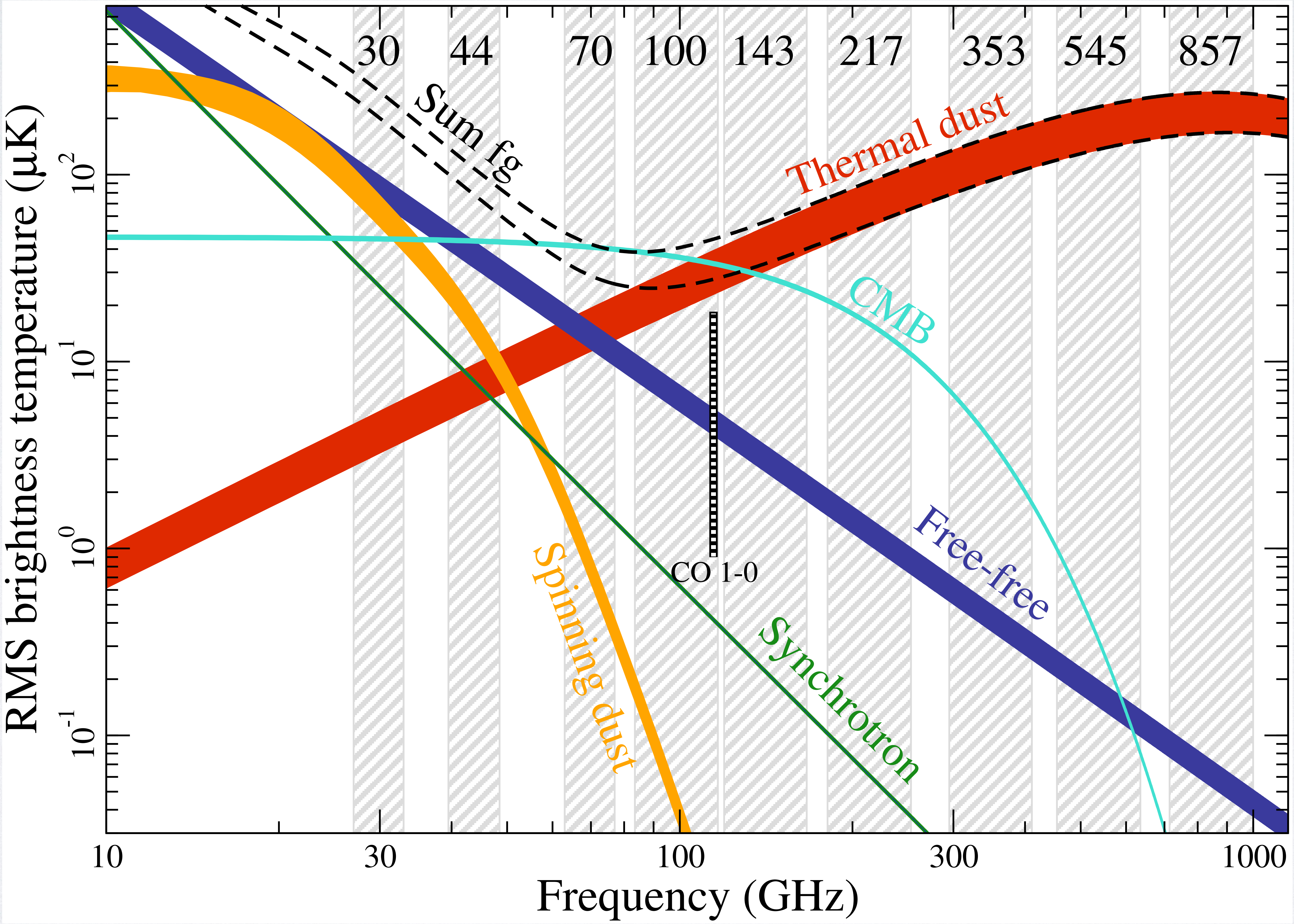
217 GHz

353 GHz

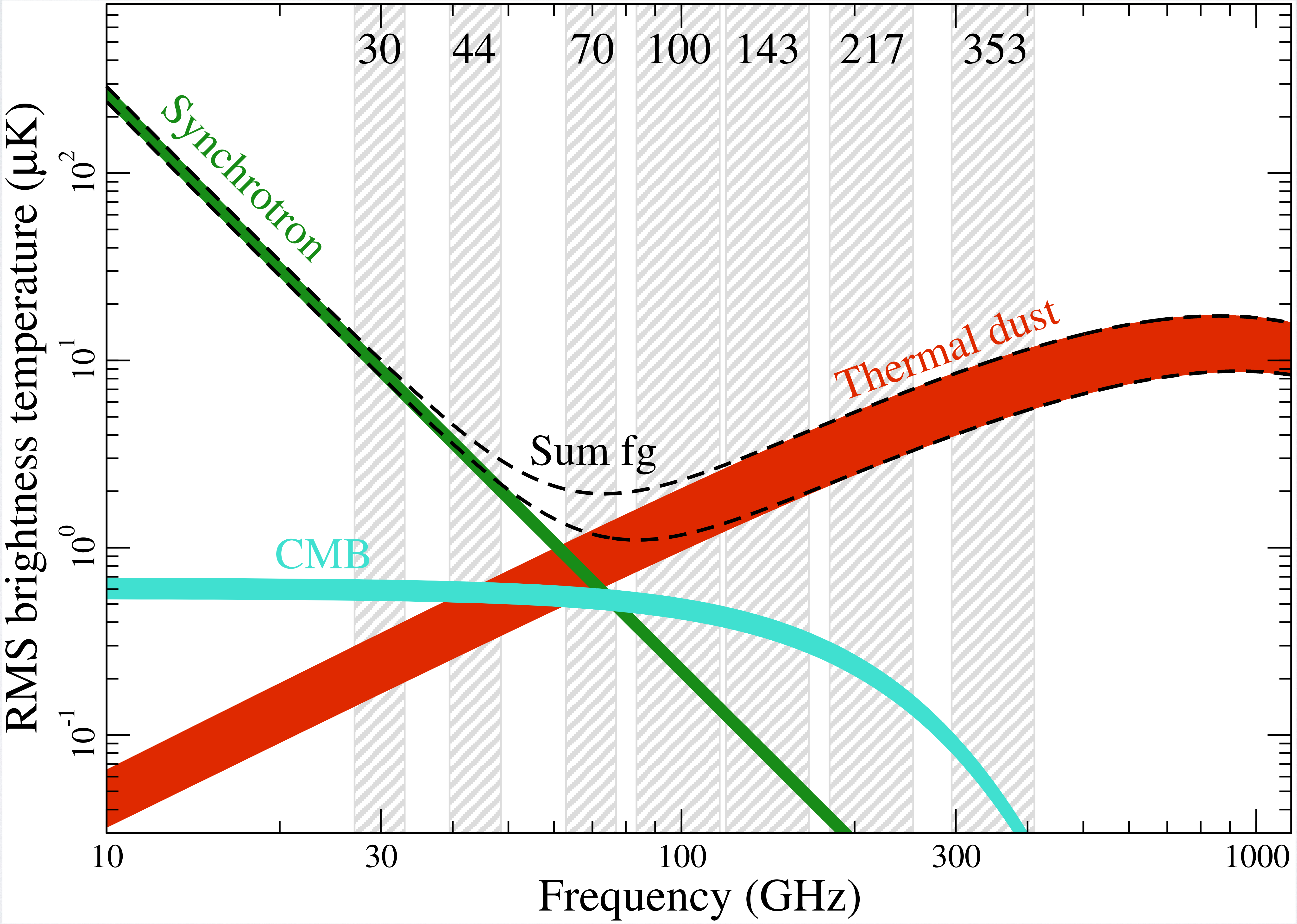
545 GHz

857 GHz

INTENSITY FOREGROUNDS



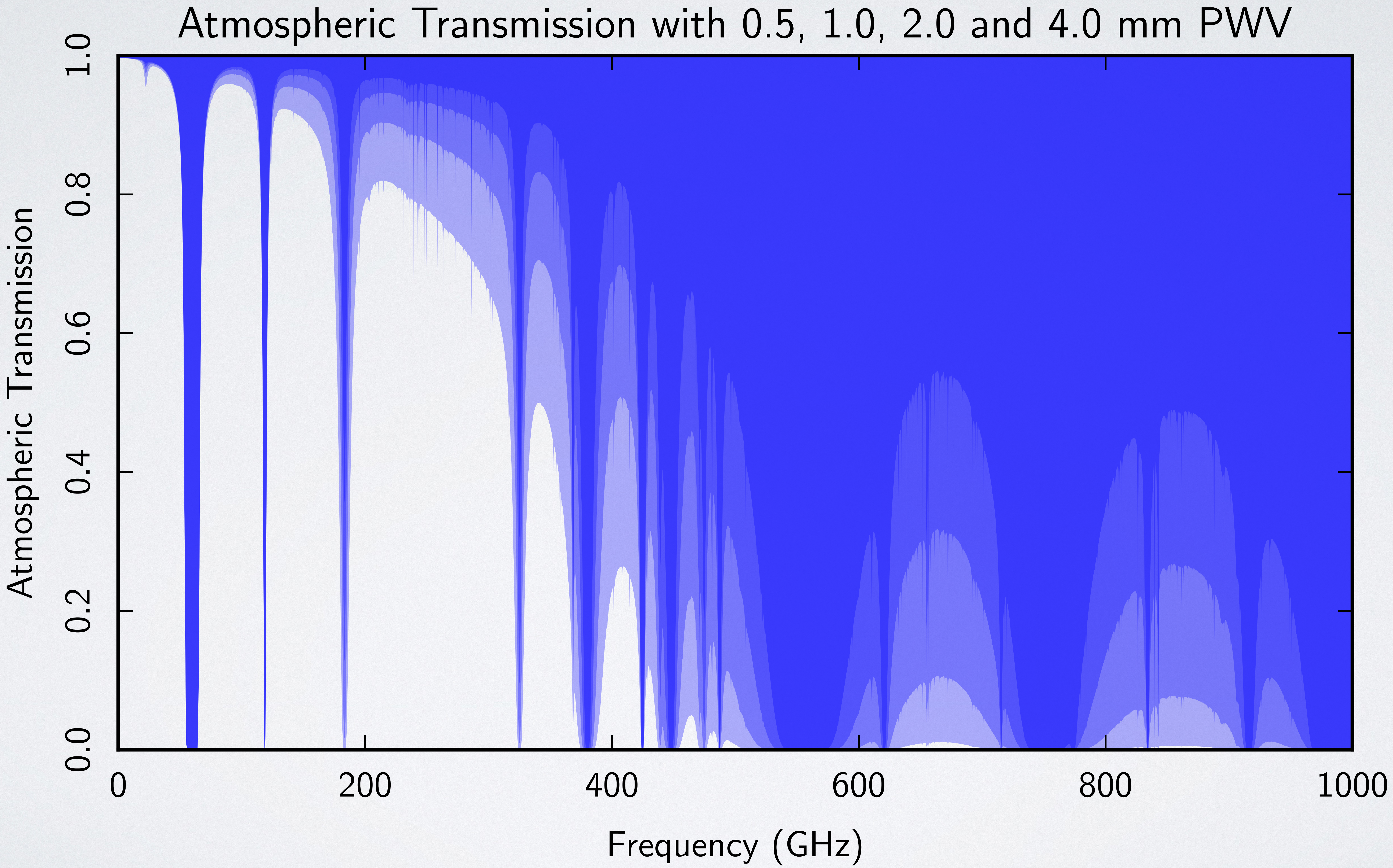
POLARIZED FOREGROUNDS



POLARIZED FOREGROUNDS

- two main foregrounds - synchrotron and thermal dust
- both are *strongly* polarized, with abundant B-mode content
- synchrotron is power law, dominant at *low frequency*
- thermal dust is modified black body, dominant at *high frequency*
- primordial B-modes are *sub-dominant* at all frequencies

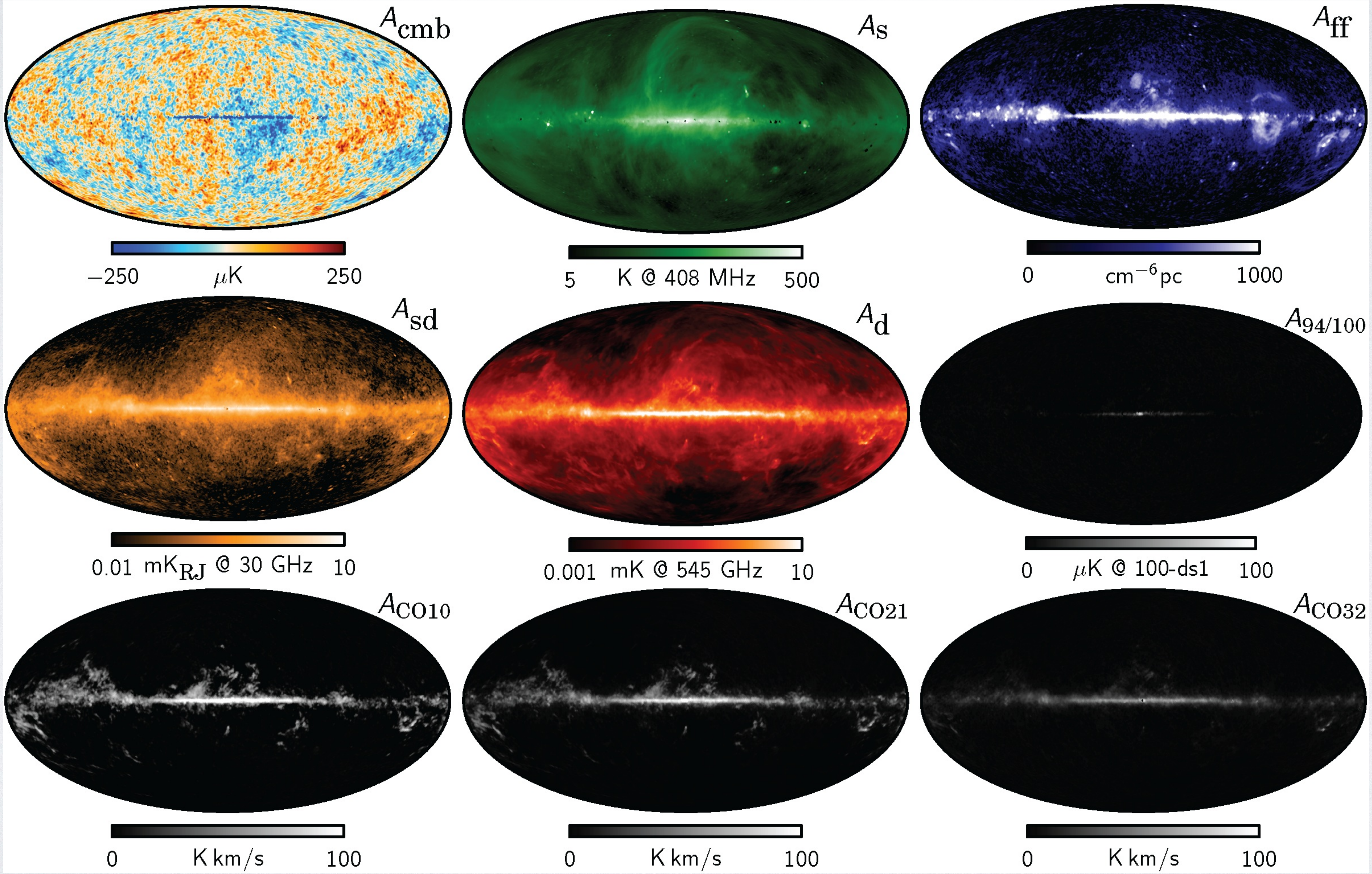
ADDITIONAL COMPLICATION - WATER!



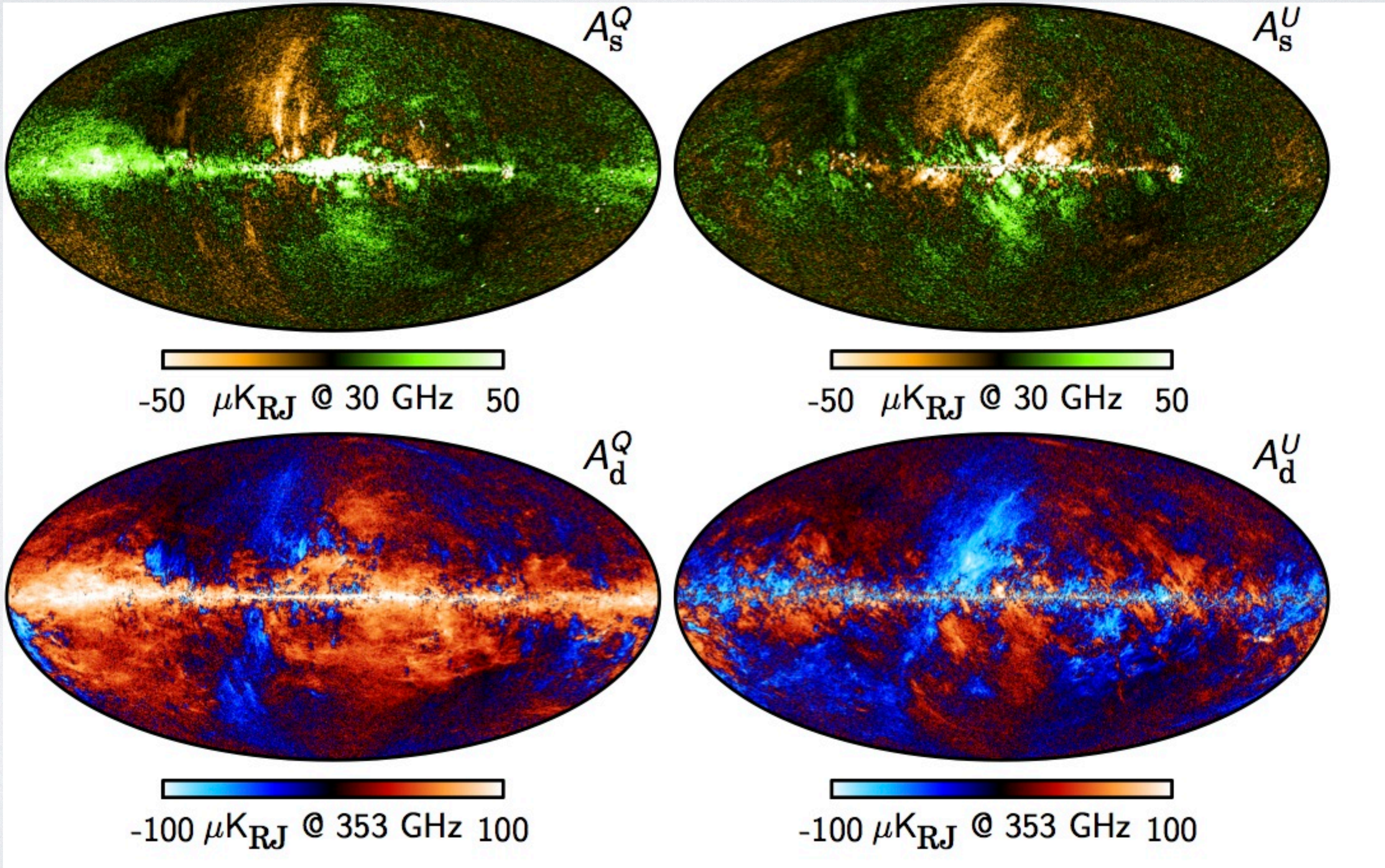
COMPONENT SEPARATION

- different components have different frequency dependence!
- two basic strategies: fit component spectra (Gibbs samplers), or construct minimal variance linear combination (ILC, BLUE, etc.)
- Planck used 4 pipelines (Commander, NILC, SEVEM, SMICA)
- spatial and morphological information not fully exploited yet…

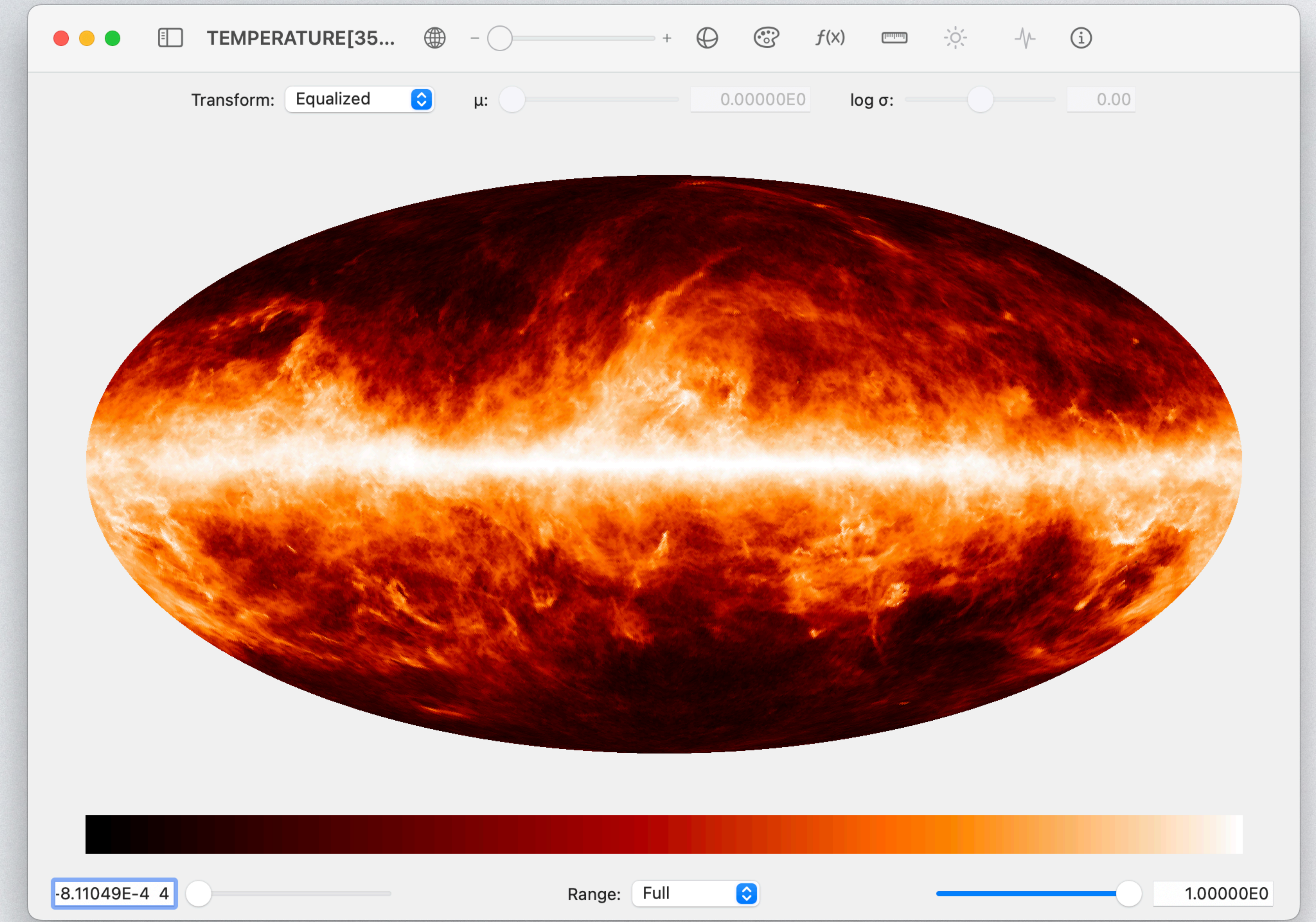
INTENSITY COMPONENTS

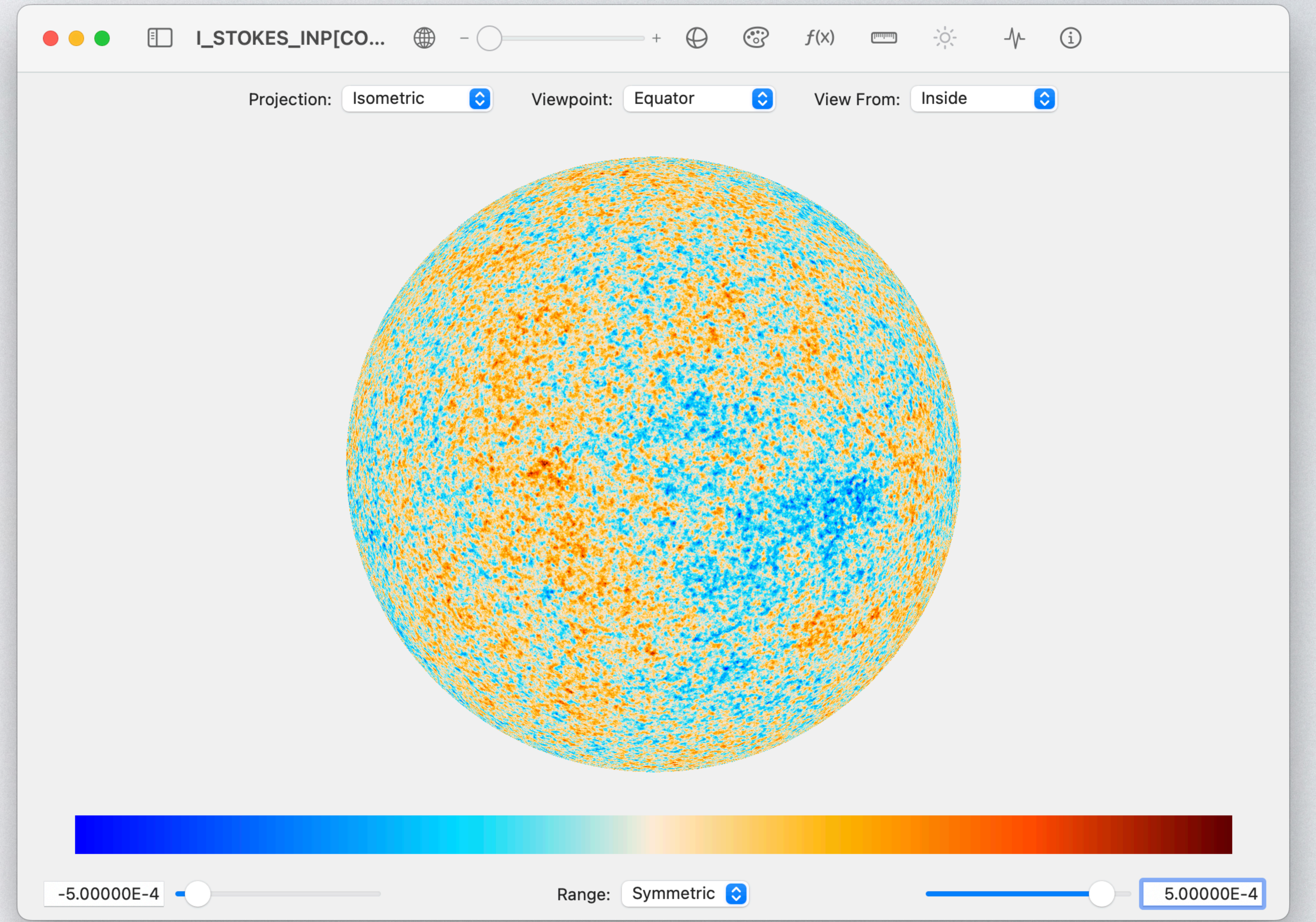


POLARIZED COMPONENTS



QUICK ASIDE - HEALPIX VIEWER





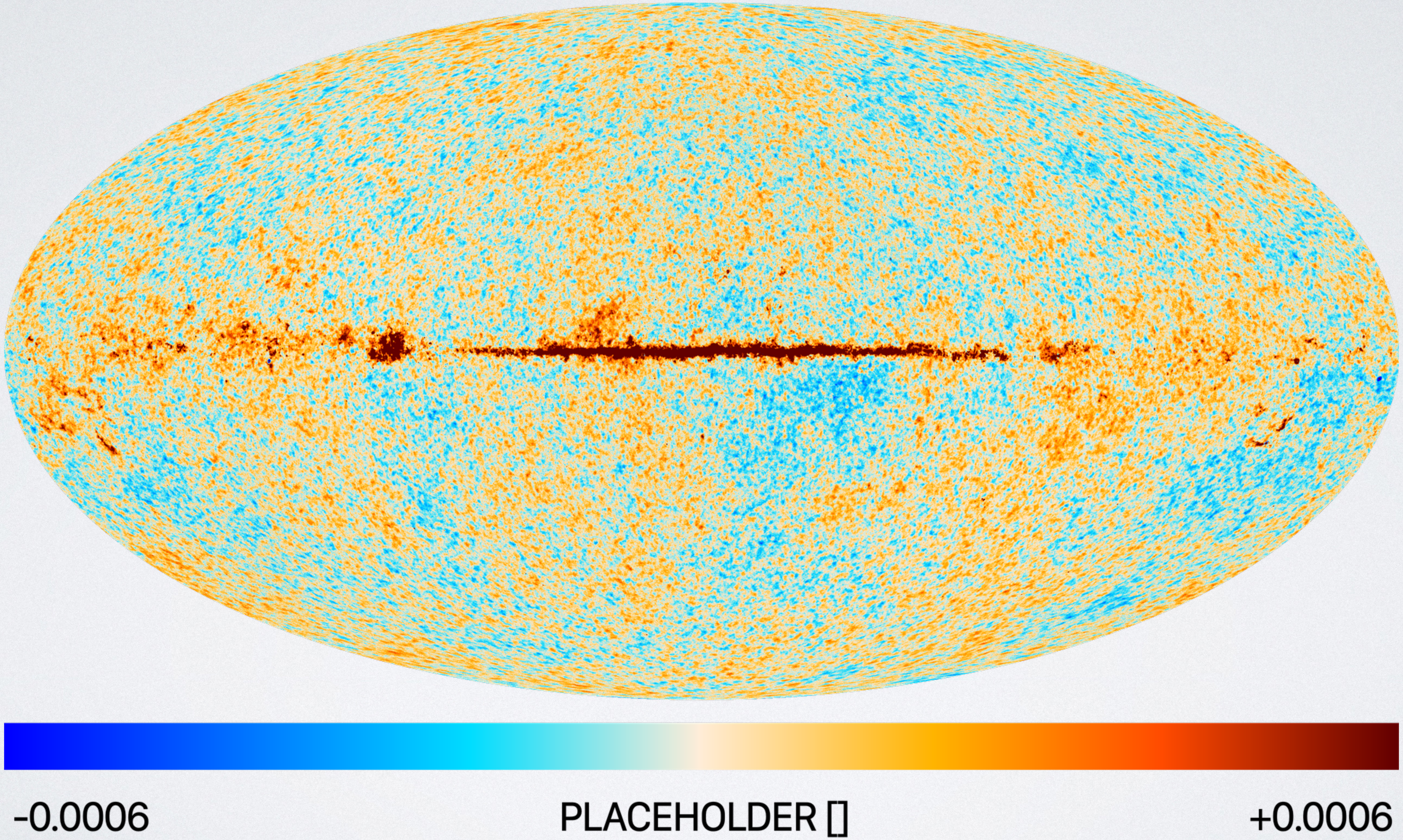
https://github.com/andrei-v-frolov/healpix-viewer

Download on the
Mac App Store

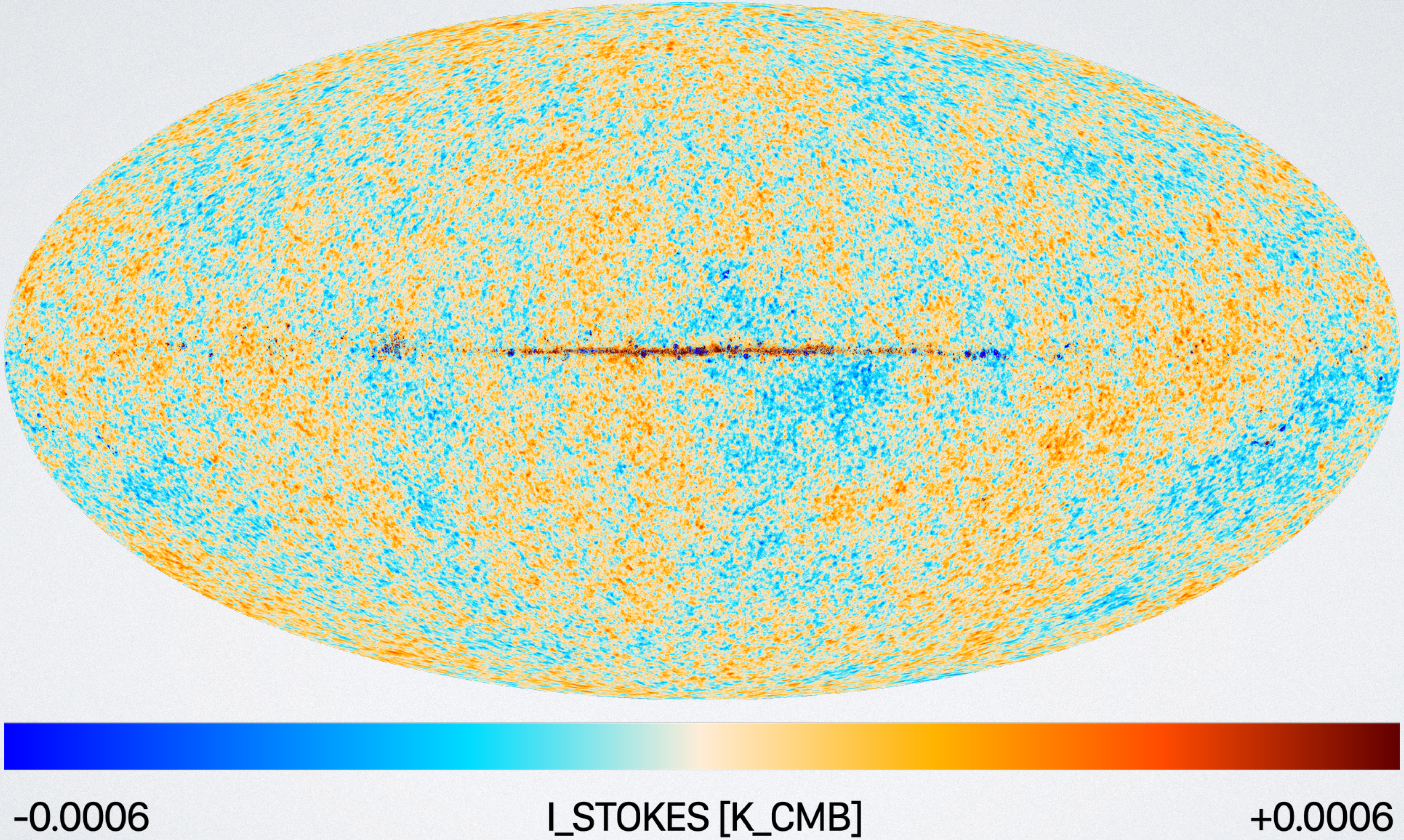
COMPONENT SEPARATION ON GPU

- Gibbs samplers are massively parallel - perfect fit for GPU…
- I coded up simplified (3 component, no beams) Commander model
- uses Barzilai-Borwein optimizer, can be extended with spatial priors
- takes 30ms to separate three nside=2048 maps on M1 laptop…
- this means you can do component separation in *real time* now!

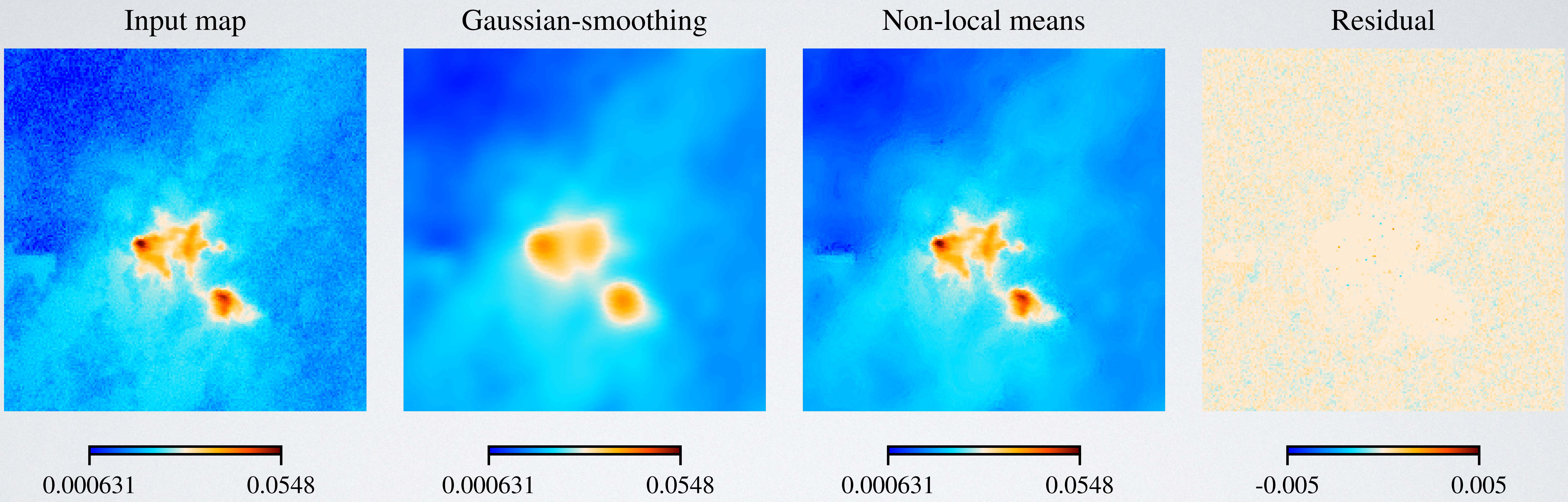
QUICK AND DIRTY (REAL TIME)



COMMANDER 2018 (HOURS)



QUICK ASIDE II - NON-LOCAL MEANS



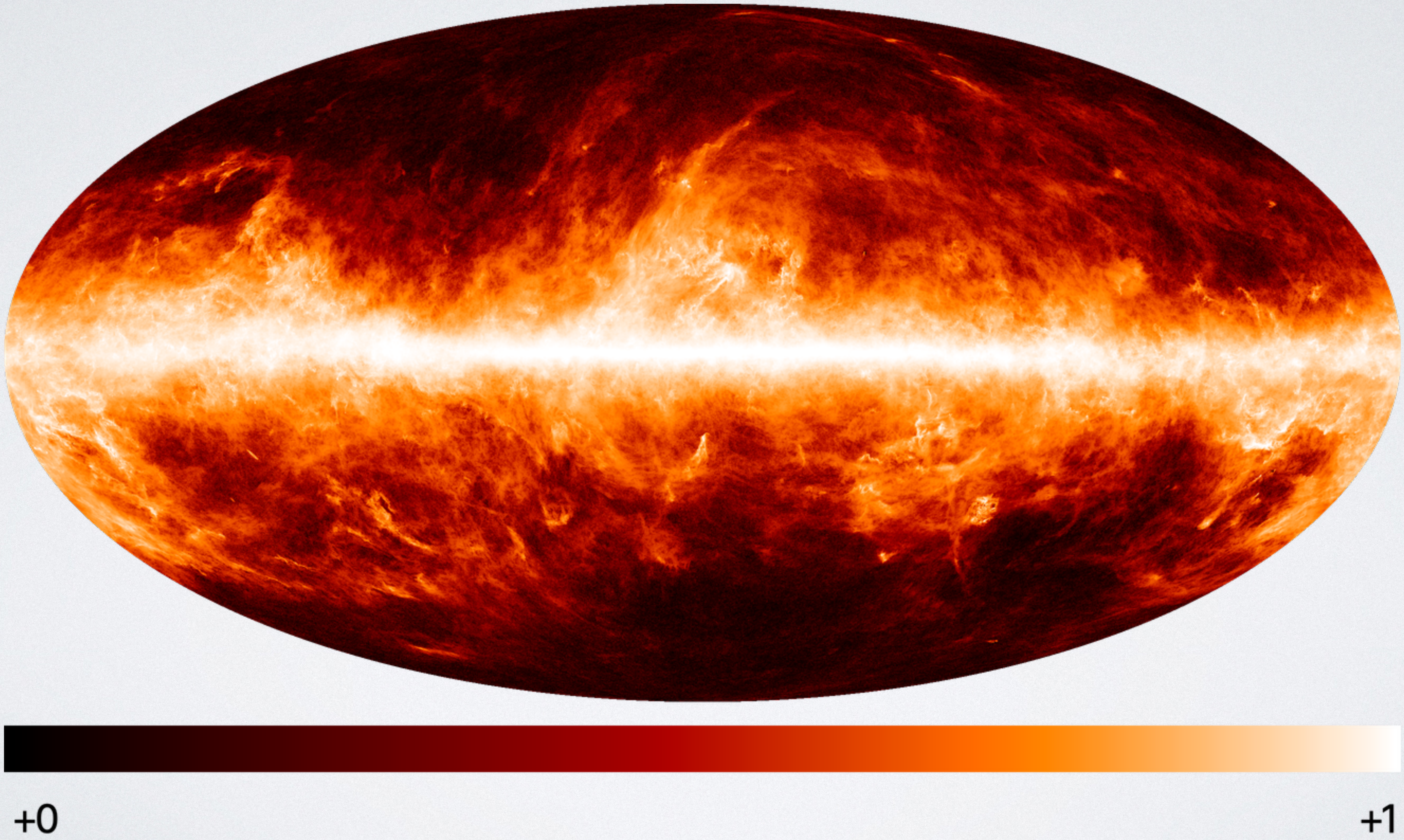
average smarter, not harder: average *similar* pixels, not *nearby* ones!

arXiv:2306.00211

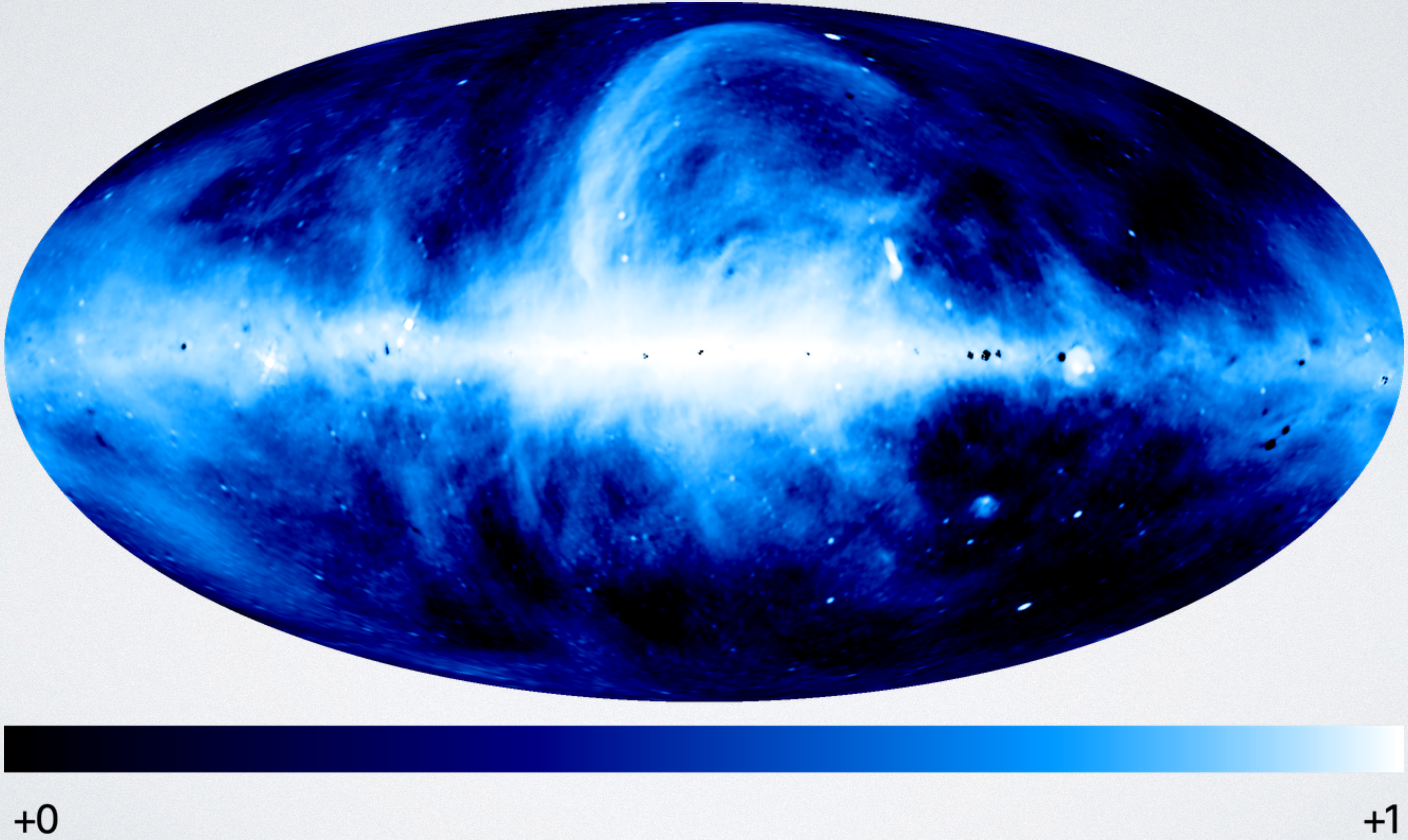
BACK TO FOREGROUNDS…

modelling large-scale polarized emission

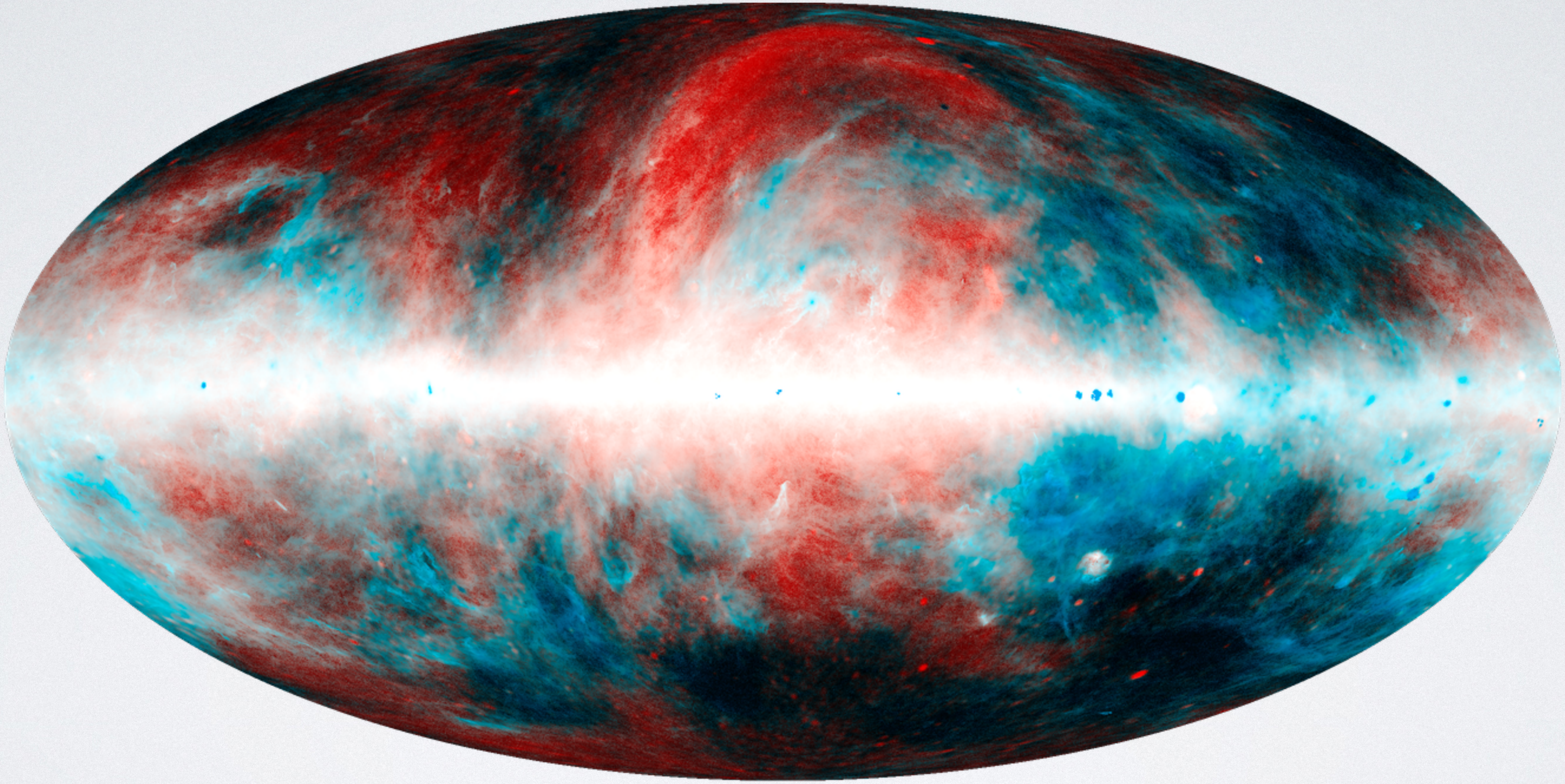
THERMAL DUST EMISSION



SYNCHROTRON EMISSION



DUST AND SYNCHROTRON



the intensity of two polarized foregrounds is not quite correlated!

SHORT SUMMARY

- thermal dust is ~20K black body, modified by ~2.6 power law
- intensity traces dust distribution (complicated, but optically thin), polarization fraction traces magnetic field configuration (simple)
- synchrotron is -3.1 power law, extremely polarized
- intensity traces electron distribution (complicated, optically thick), polarization fraction traces magnetic field (averaged, not so simple)

POLARIZED DUST EMISSION

- polarization is caused by grain alignment due to magnetic field:

$$I = \int S_\nu e^{-\tau_\nu} d\tau_\nu \left[1 - p_0 \left(\cos^2\gamma - \frac{2}{3} \right) \right]$$

$$\begin{Bmatrix} Q \\ U \end{Bmatrix} = \int S_\nu e^{-\tau_\nu} d\tau_\nu \begin{Bmatrix} \cos 2\psi \\ \sin 2\psi \end{Bmatrix} p_0 \cos^2\gamma$$

p_0 is intrinsic polarization fraction ~0.21, γ and ψ are angles of magnetic field

POLARIZED DUST EMISSION

- geometric factors in emission integral from magnetic field orientation:

$$\mathfrak{p} \equiv \frac{B_\phi^2 + B_\theta^2}{B^2} = \cos^2\gamma$$

$$\mathfrak{q} \equiv \frac{B_\phi^2 - B_\theta^2}{B^2} = \cos^2\gamma \cos 2\psi$$

$$\mathfrak{u} \equiv -\frac{2B_\phi B_\theta}{B^2} = \cos^2\gamma \sin 2\psi$$

MAGNETIC FIELD MODEL

- split magnetic field into large-scale and random components:

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

- dust samples magnetic field, giving *average* geometric factors

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

- all complexity is in dust column density distribution, fit large-scale $\bar{\mathbf{B}}$!

EXPANDING TO LINEAR ORDER...

- intensity and polarization split into large-scale and random parts:

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

$$Q = s_\nu p_0 \left[\mathfrak{q}[\bar{\mathbf{B}}] + \left.\frac{\partial \mathfrak{q}}{\partial \mathbf{B}}\right|_{\bar{\mathbf{B}}} \langle \delta \mathbf{B} \rangle + \ldots \right]$$

$$U = s_\nu p_0 \left[\mathfrak{u}[\bar{\mathbf{B}}] + \left.\frac{\partial \mathfrak{u}}{\partial \mathbf{B}}\right|_{\bar{\mathbf{B}}} \langle \delta \mathbf{B} \rangle + \ldots \right]$$

ESTIMATORS OF MAGNETIC FIELD

- estimator of dust column depth: $I + P = s_\nu\left(1 + \frac{2}{3}p_0\right) + O(\delta B^2)$
- estimators of magnetic field geometry:

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

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

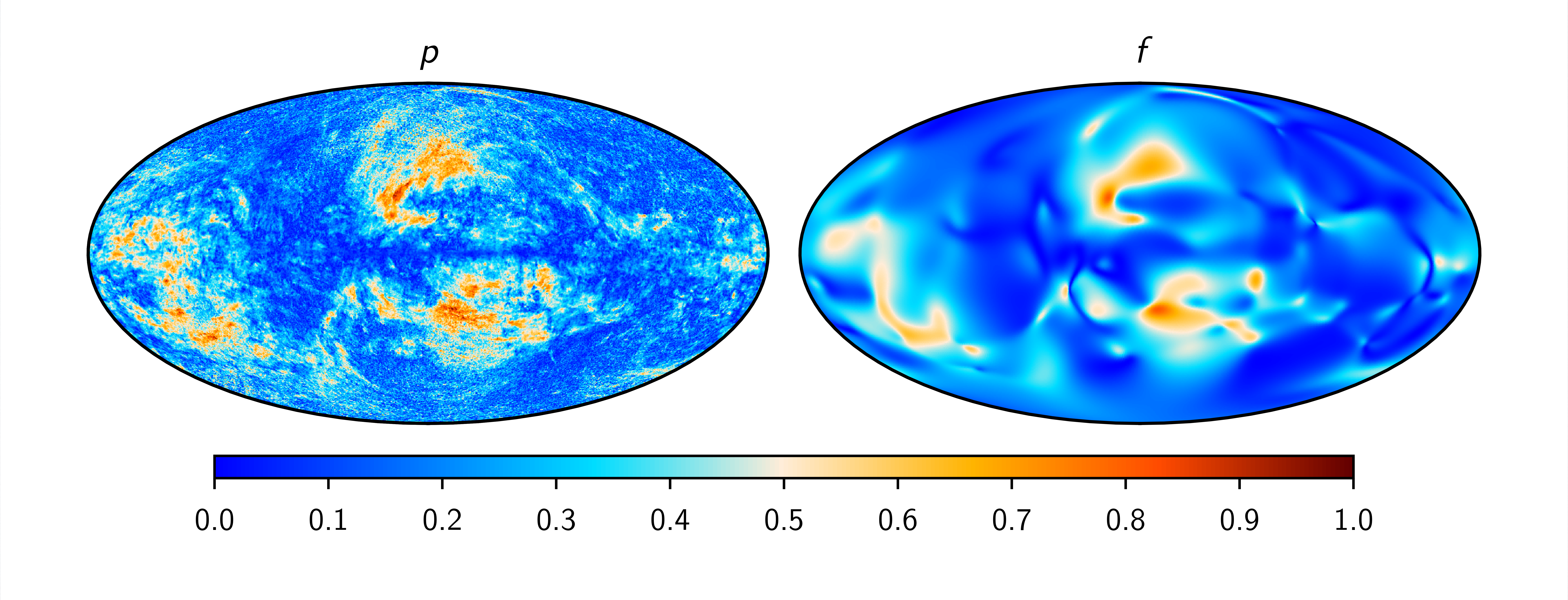
MAGNETIC FIELD RECONSTRUCTION

- one can fit large-scale (smooth) magnetic field optimizing

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

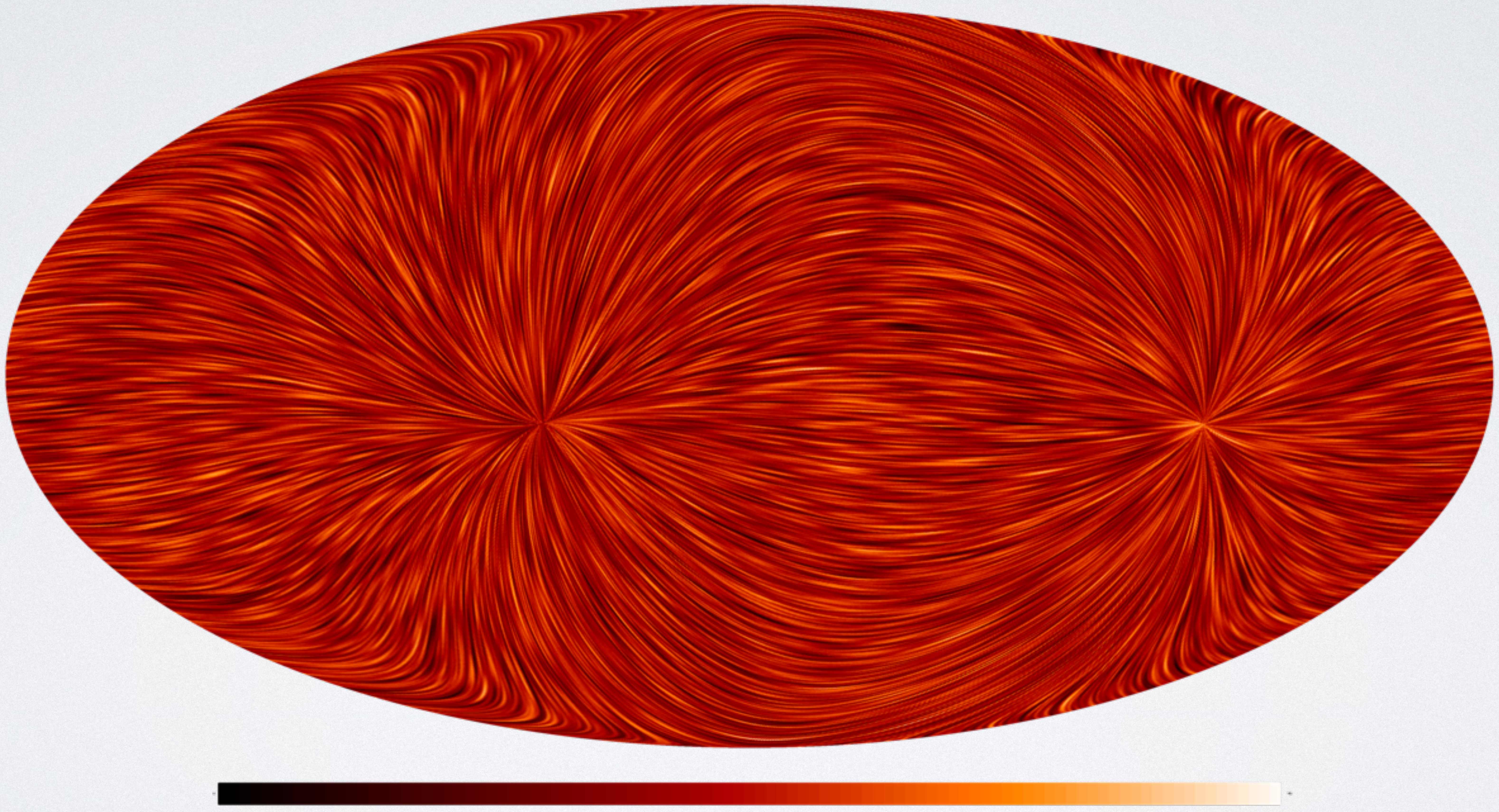
- optimization problem is large, use L-BFGS-B optimizer and wait…
- this seems a bit simple-minded, but it works! but why?…
- looks like dust does not have too much averaging along line of sight, samples magnetic field mostly from a single layer…

MAGNETIC FIELD RECONSTRUCTION



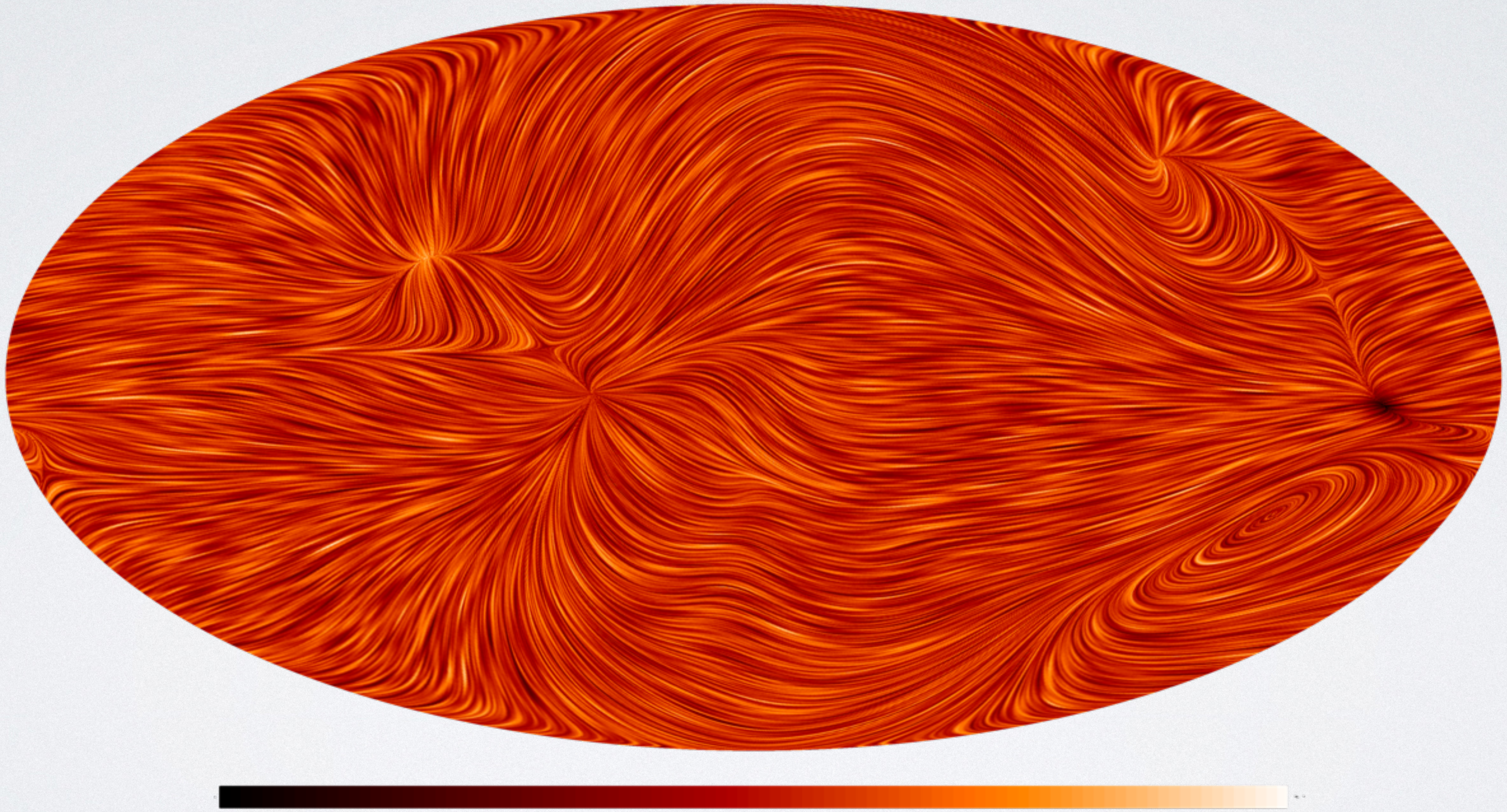
polarization fraction in 353 GHz dust map versus reconstruction with $\ell_{max} = 15$

MAGNETIC FIELD LINES



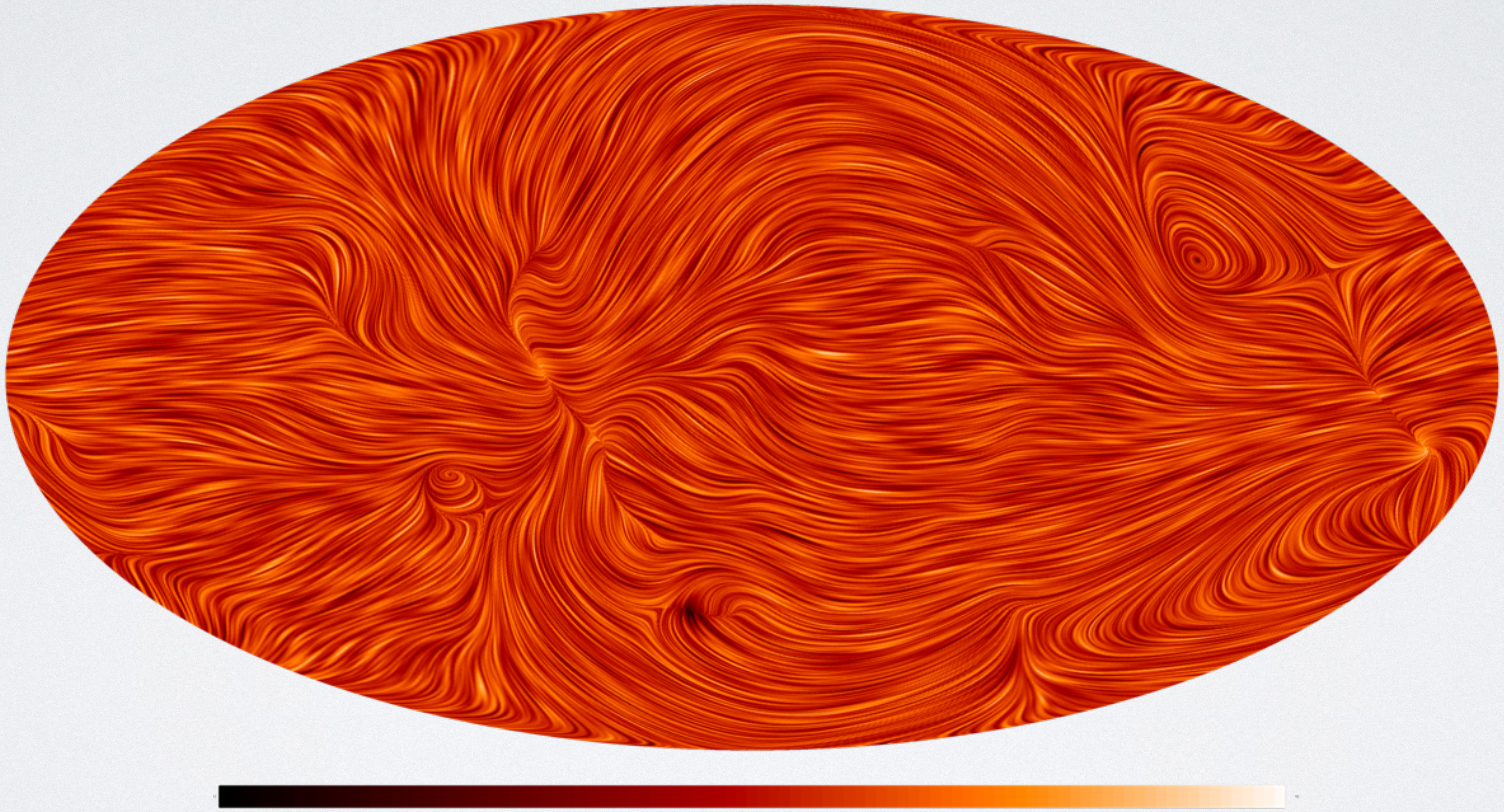
$\ell_{\mathrm{max}} = 1$

MAGNETIC FIELD LINES



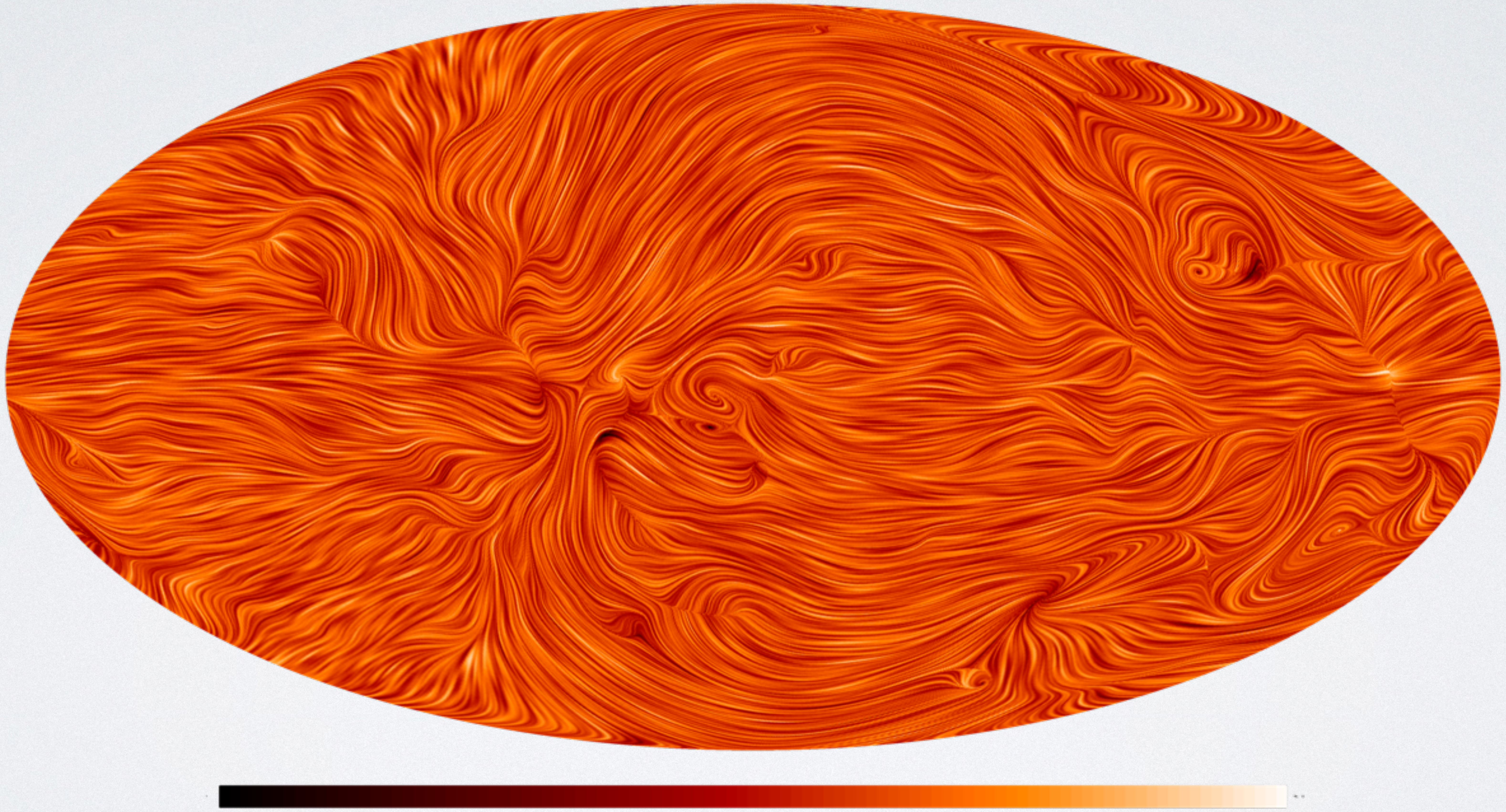
$\ell_{max} = 5$

MAGNETIC FIELD LINES



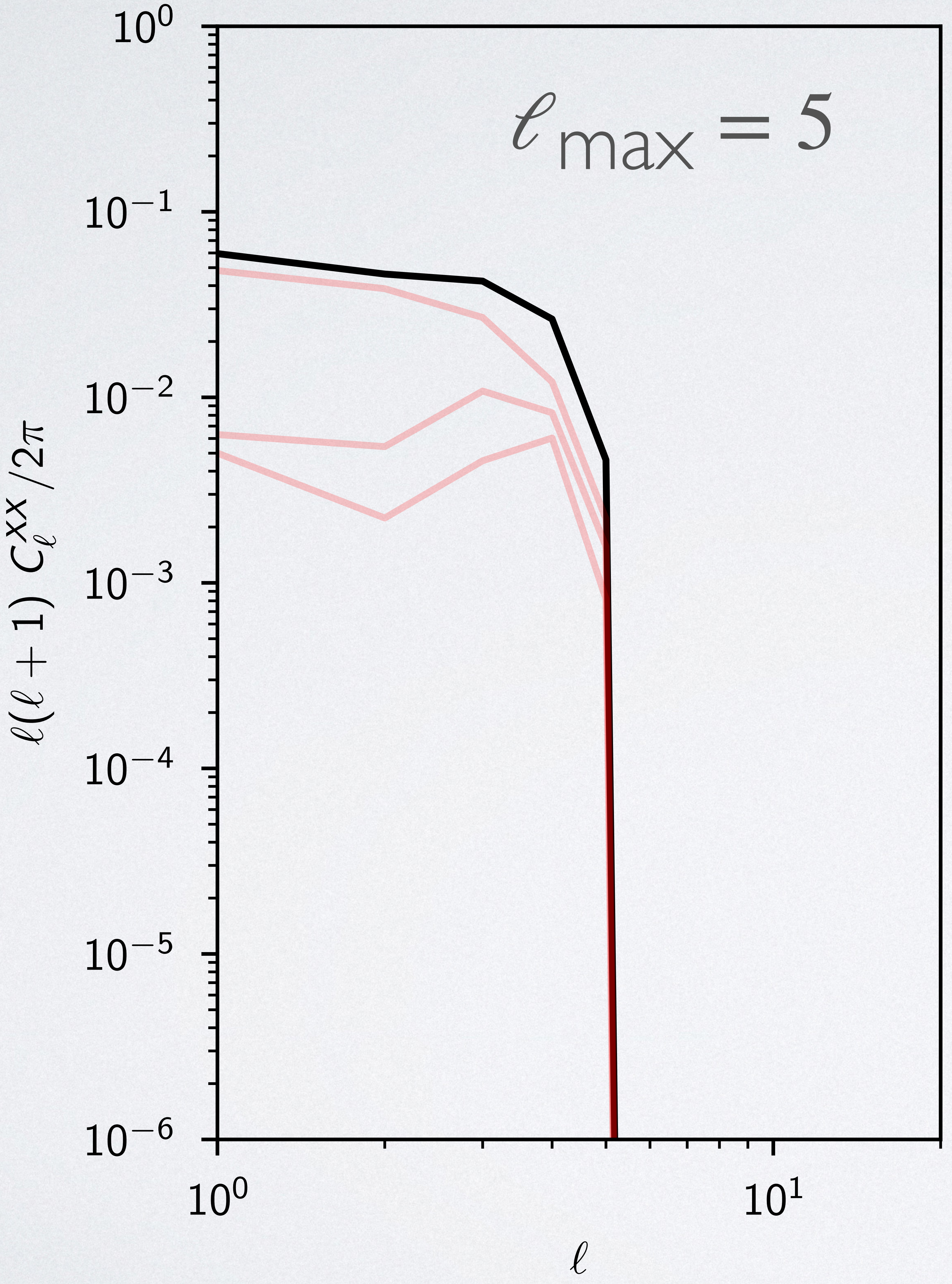
$\ell_{\max} = 10$

MAGNETIC FIELD LINES

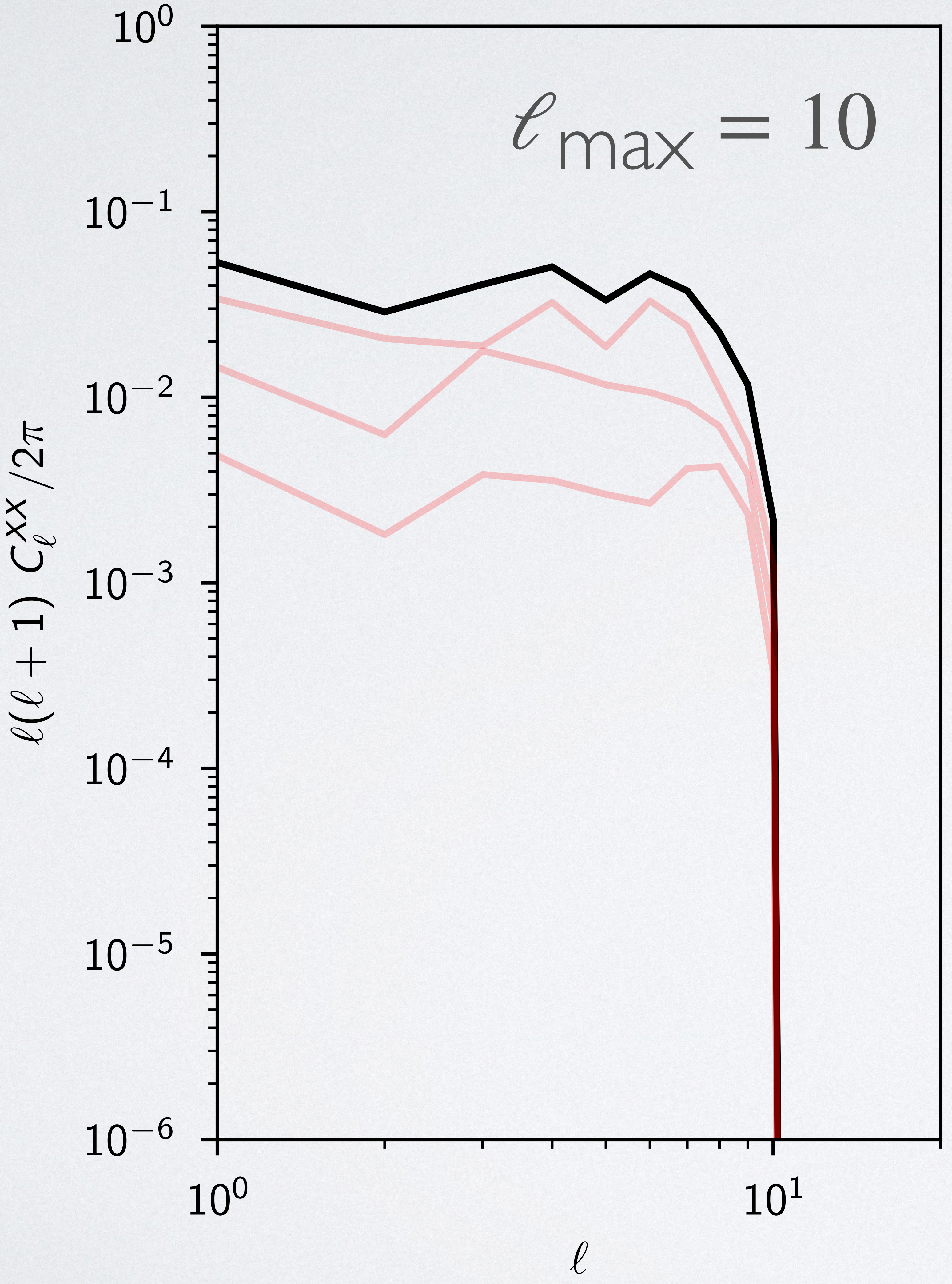


$\ell_{max} = 20$

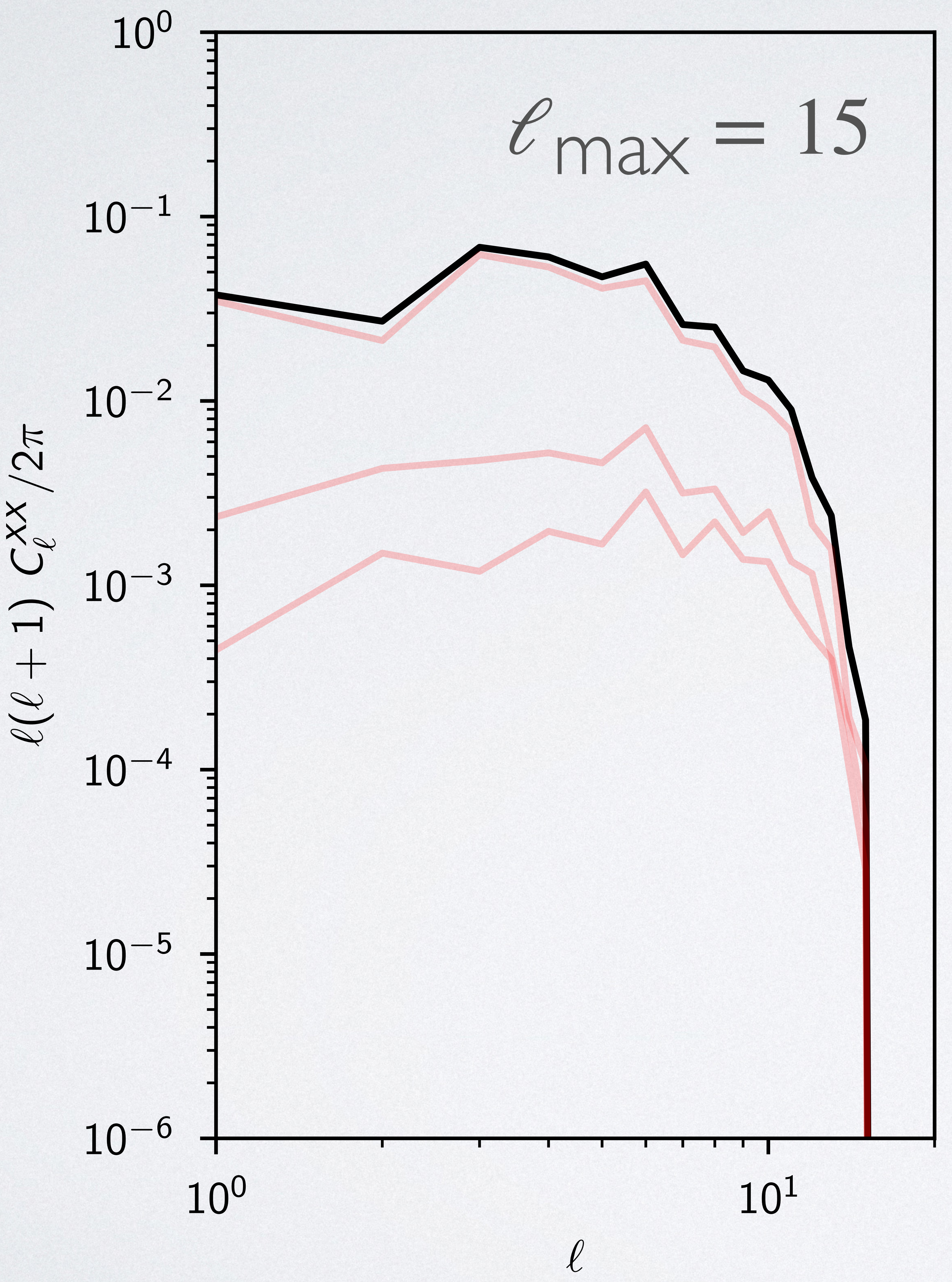
RECONSTRUCTED SPECTRUM



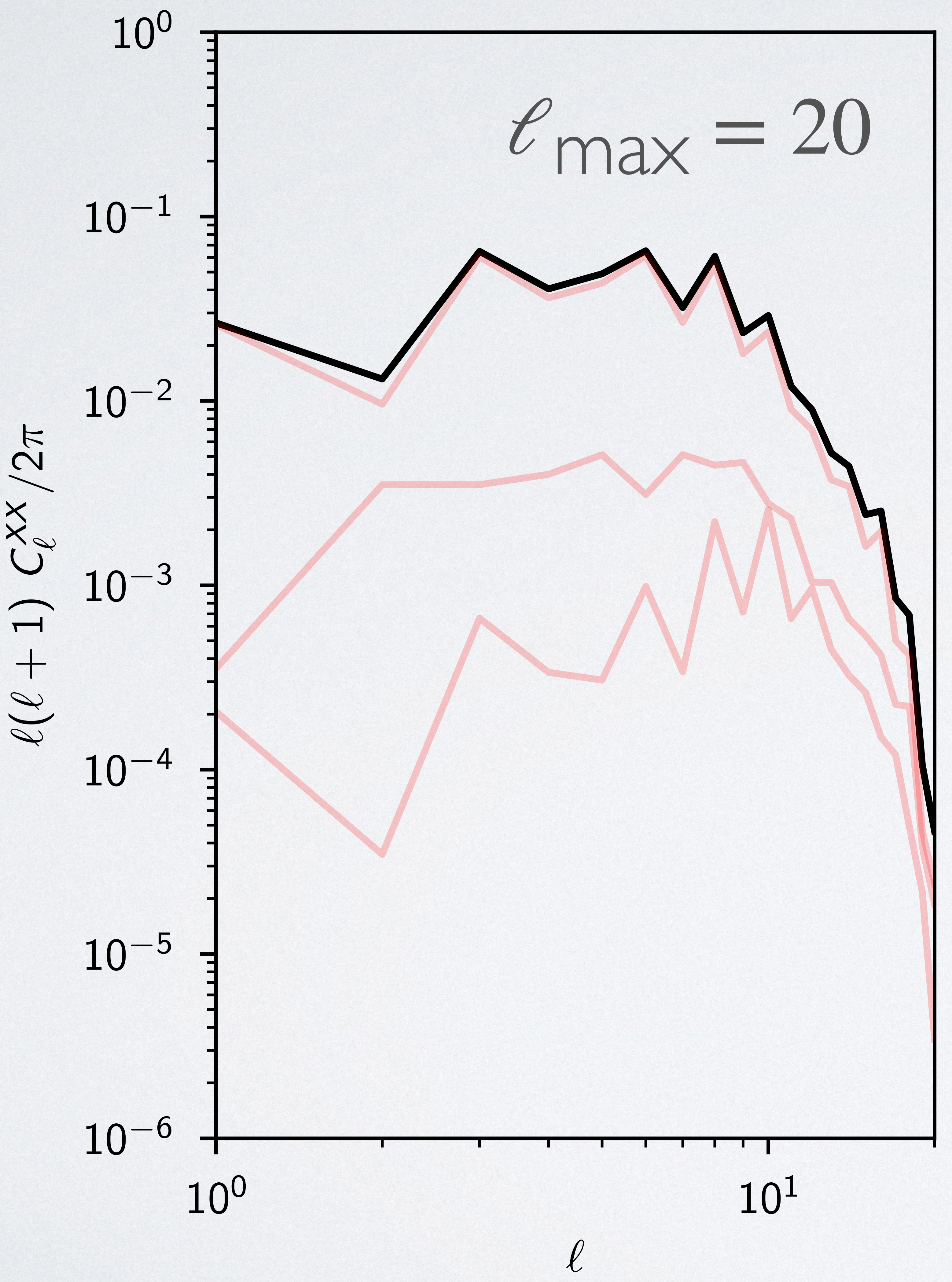
RECONSTRUCTED SPECTRUM



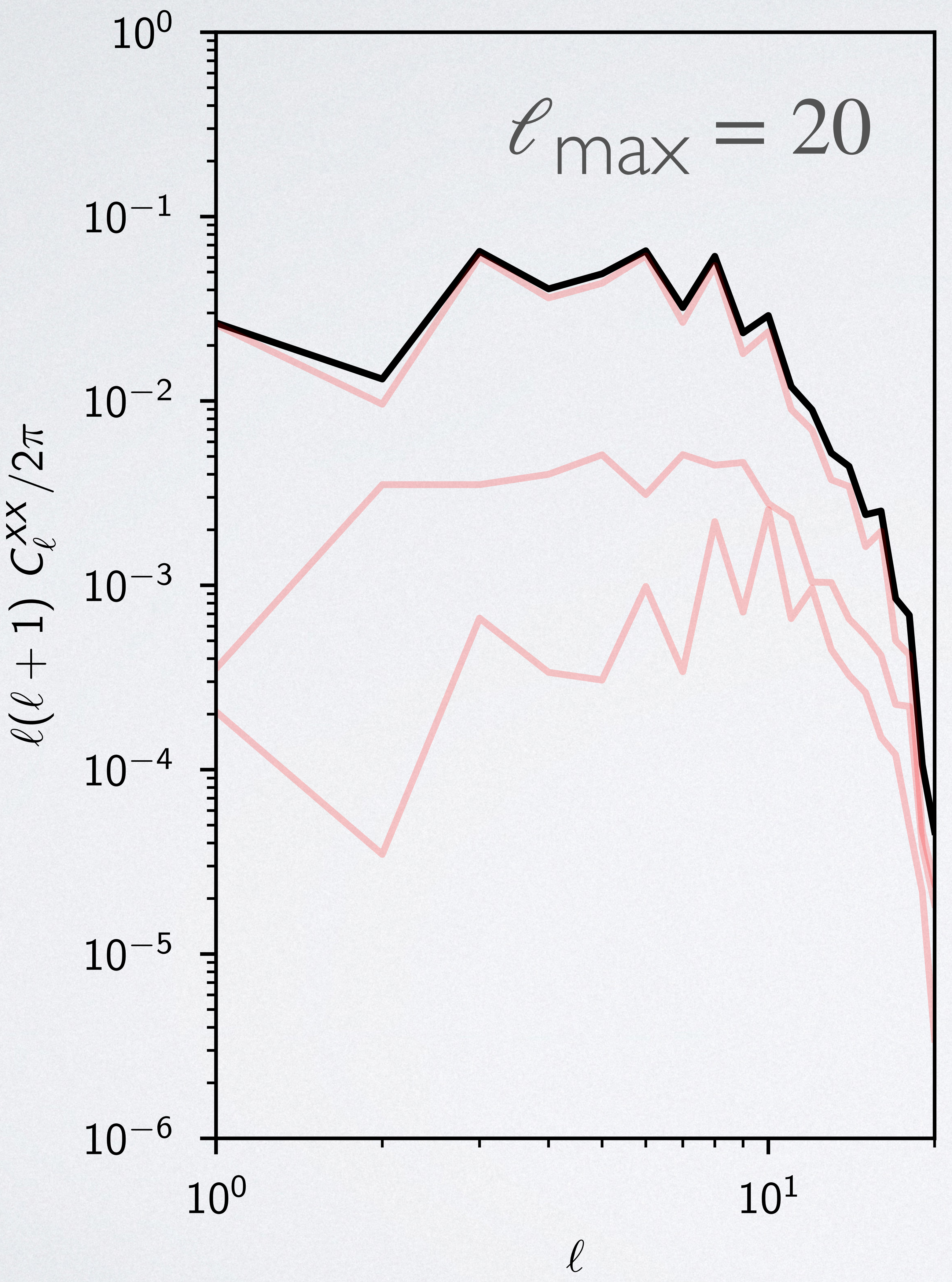
RECONSTRUCTED SPECTRUM



RECONSTRUCTED SPECTRUM



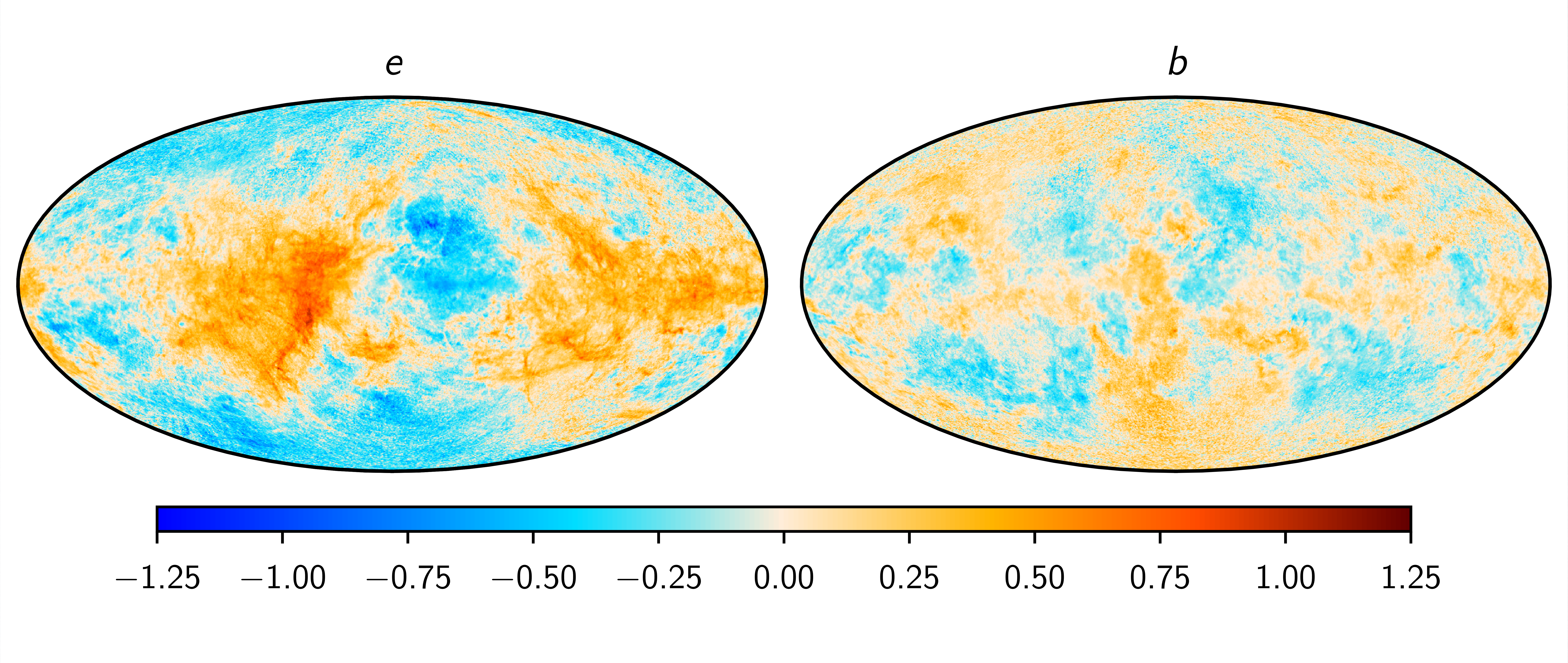
RECONSTRUCTED SPECTRUM



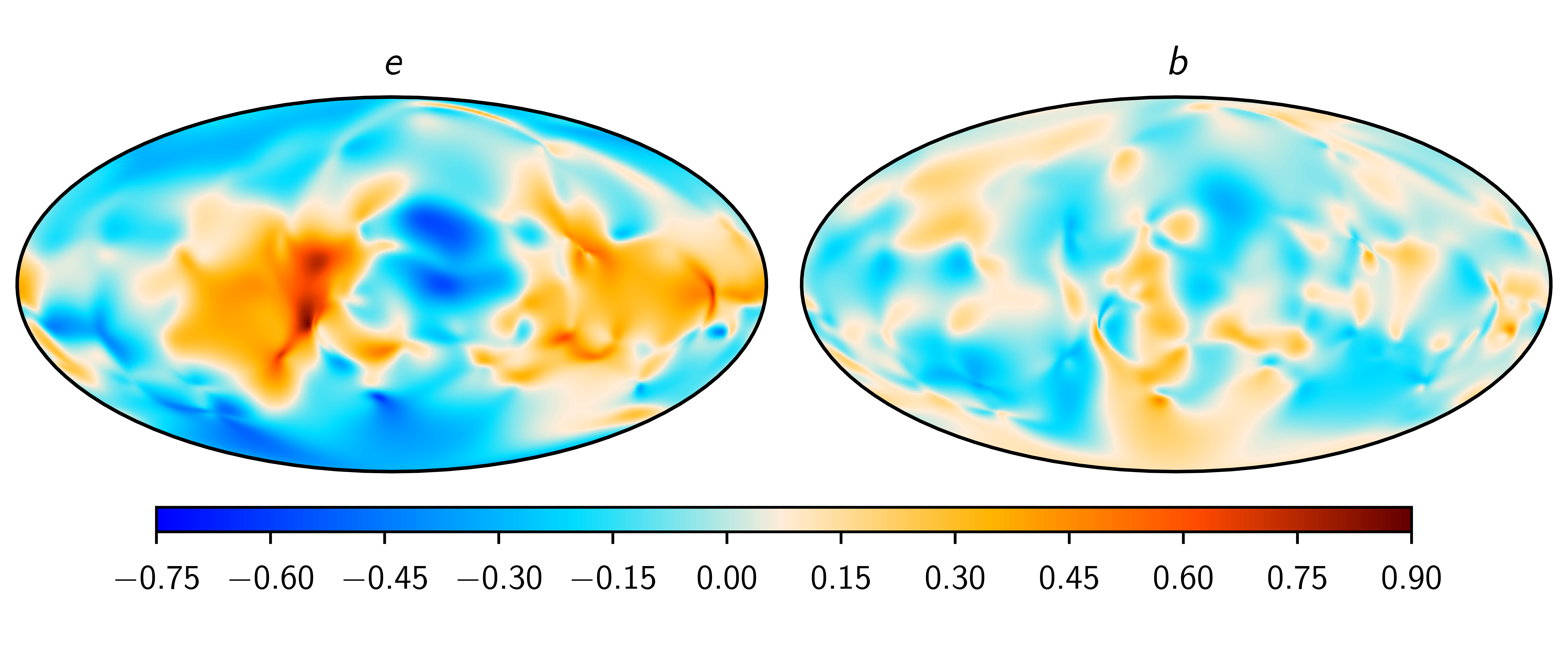
there seems to be a break at $\ell \sim 10$!

large scale (local) and turbulent components?

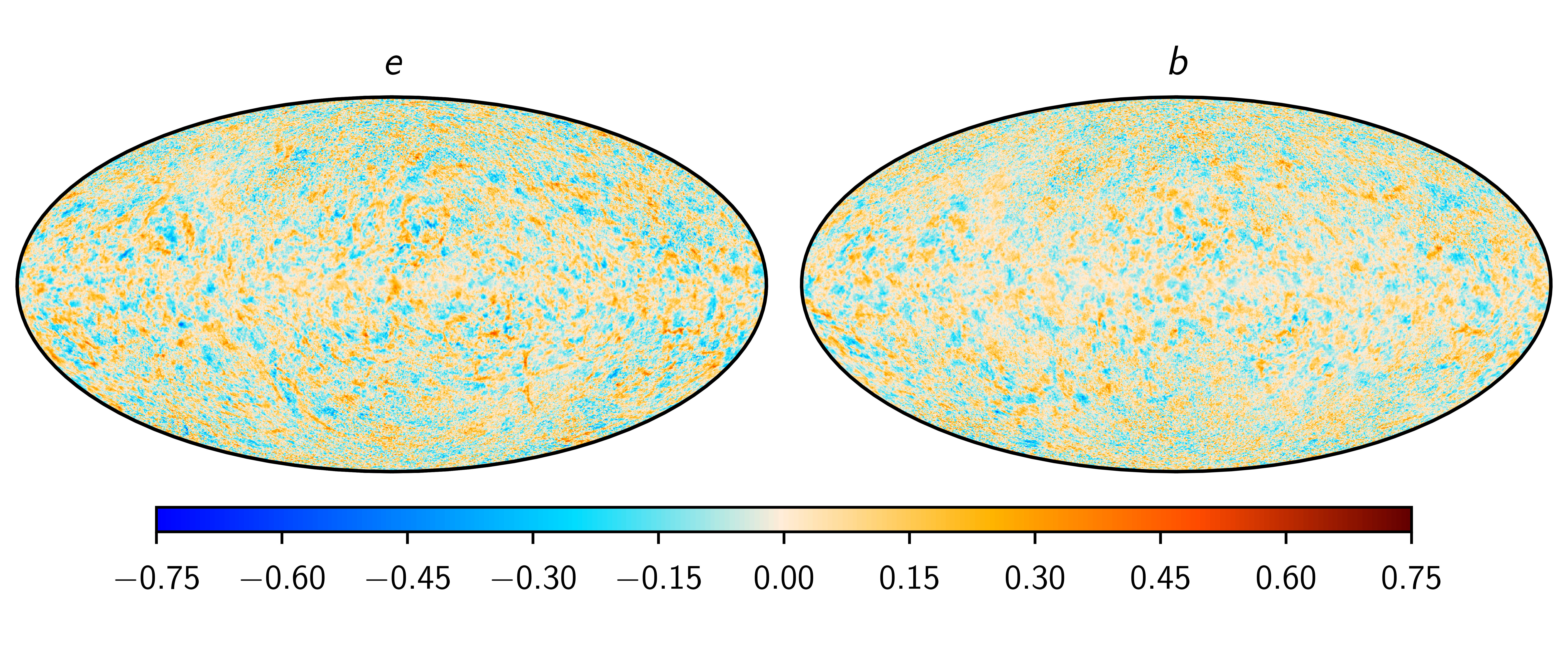
DUST POLARIZATION FRACTION



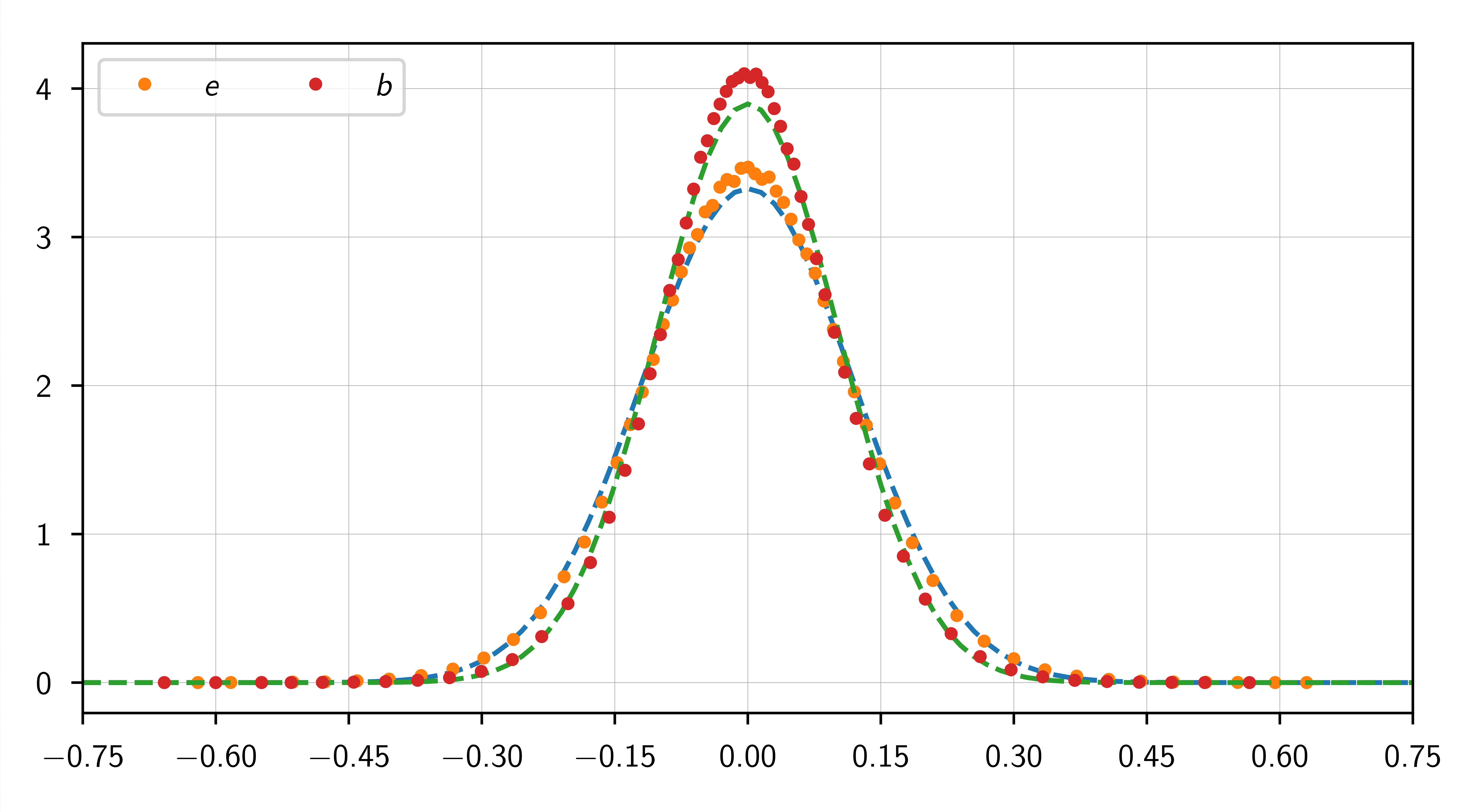
LARGE SCALE COMPONENT



TURBULENT COMPONENT



RANDOM PART IS QUITE GAUSSIAN!



DUST POLARIZATION IS SIMPLE!

large-scale spatial template common to all frequency channels, can be extracted (and reliably subtracted), residual is Gaussian!

SYNCHROTRON IS NOT SO SIMPLE…

- synchrotron polarization also depends on magnetic field, but sampled by electron density, and it does depend on field magnitude…
- polarization fraction is reduced by averaging along the line of sight, getting explicit reconstruction is more complicated…
- logarithmic variables are still the best to describe map statistics

POLARIZATION FRACTION TENSOR

- transform polarization tensor into polarization fraction tensor:

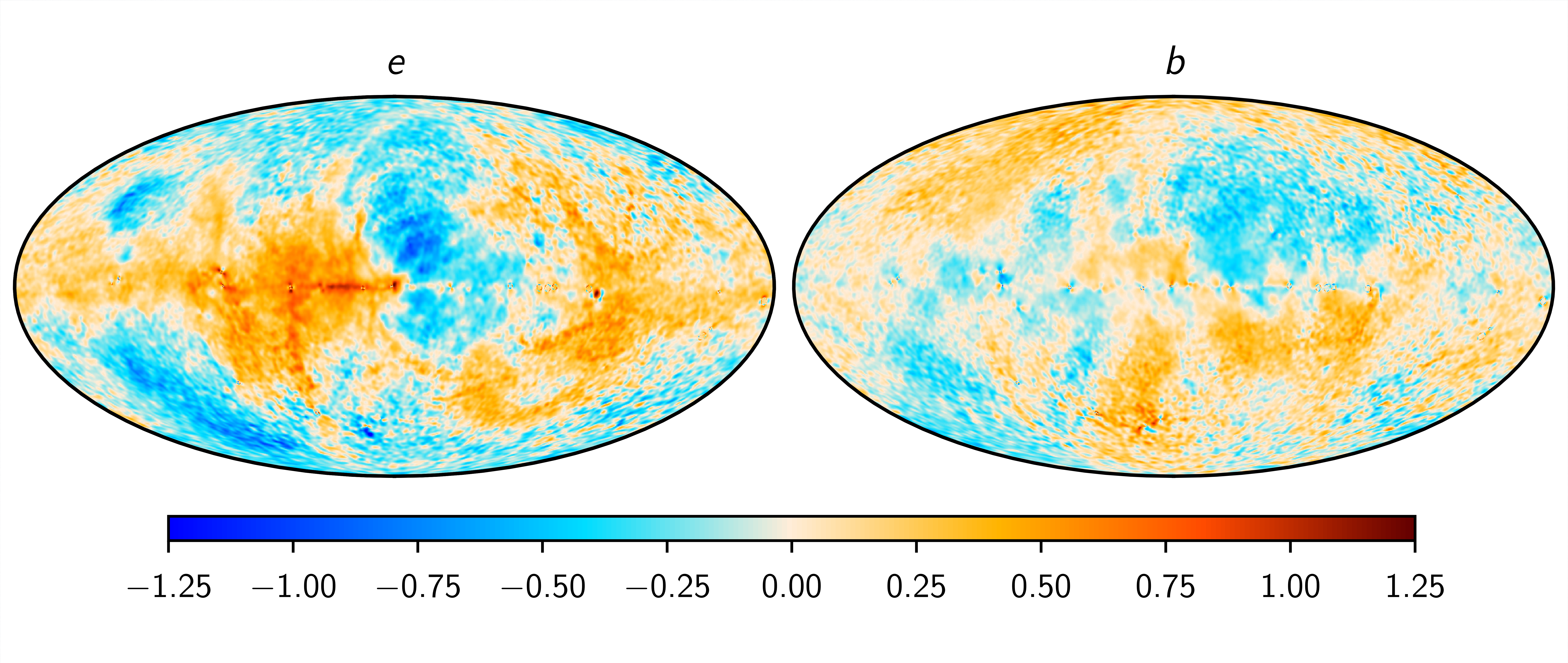
$$\begin{bmatrix} i+q & u \\ u & i-q \end{bmatrix} = \ln \begin{bmatrix} I+Q & U \\ U & I-Q \end{bmatrix}$$

- this is an invertible transformation on IQU maps:

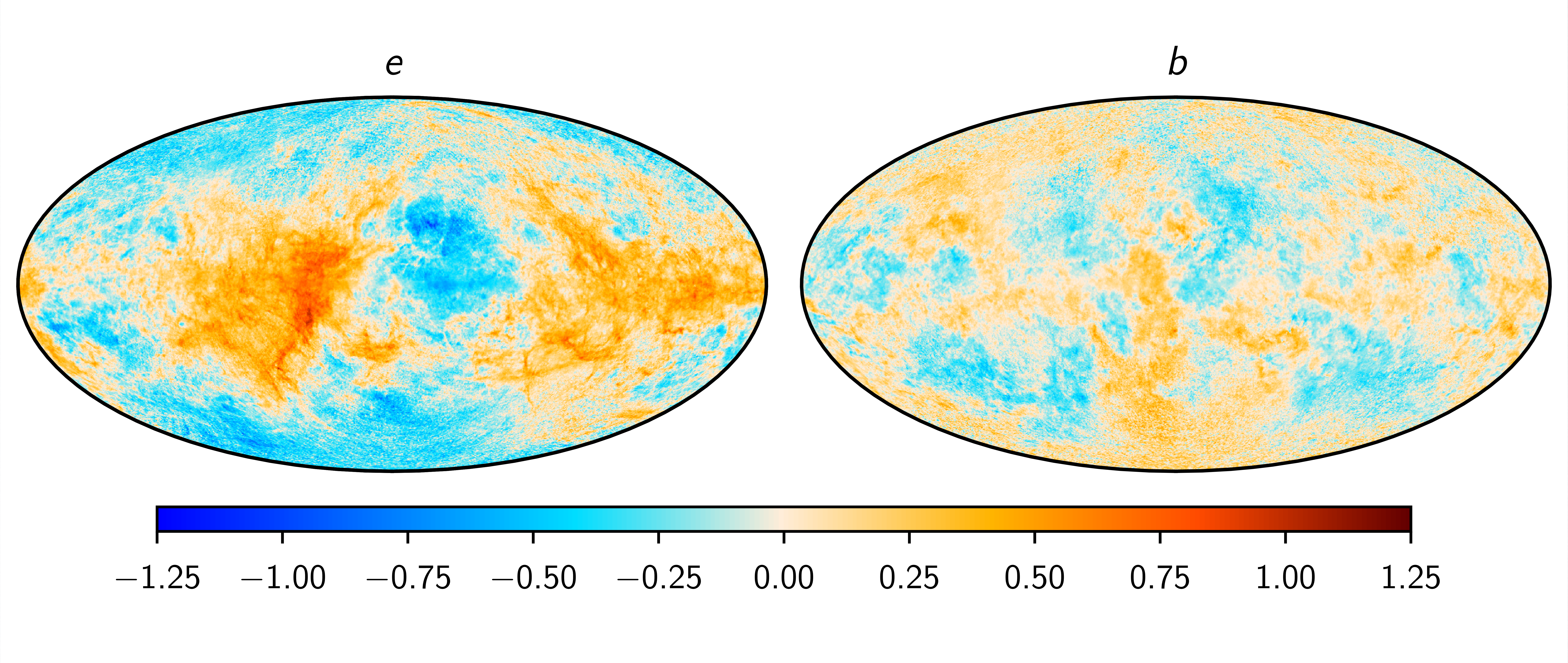
$$i = \frac{1}{2} \ln \left(I^2 - P^2 \right), \qquad q = \frac{1}{2} \frac{Q}{P} \ln \frac{I+P}{I-P}, \qquad u = \frac{1}{2} \frac{U}{P} \ln \frac{I+P}{I-P}$$

- useful for defining likelihoods and priors, also reconstruction…

SYNC POLARIZATION FRACTION



DUST POLARIZATION FRACTION



SHORT SUMMARY

- dust polarization is actually fairly simple on large scales!
- synchrotron is more complicated, not entirely correlated to dust
- additional data could be rolled in (Faraday rotation in particular)
- I am working on GPU algorithms for visualization, data clean-up, and component separation… still in progress, but it's fun!

THANKS!