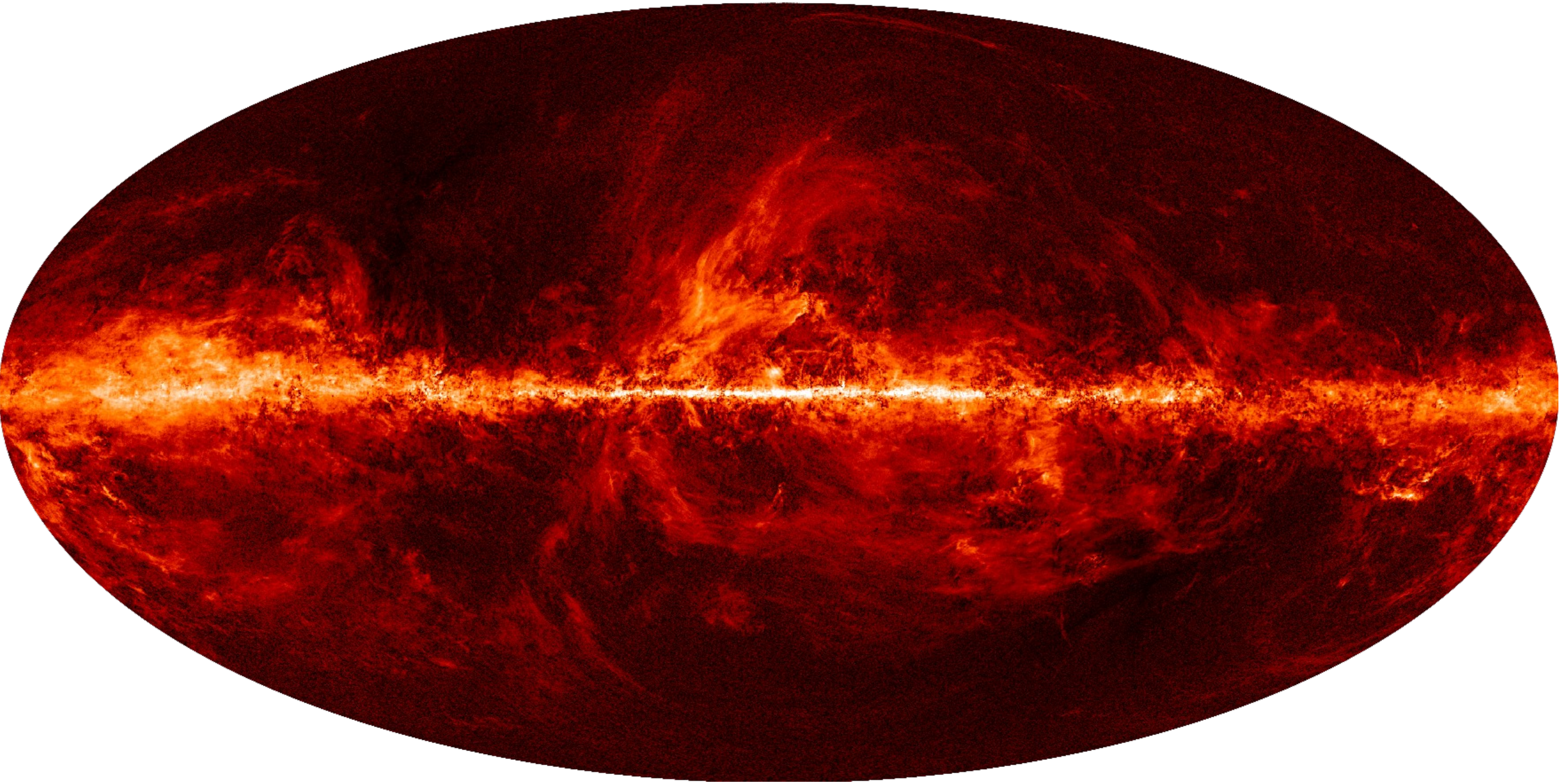
The Milky Way in Circular Polarization - a forecast

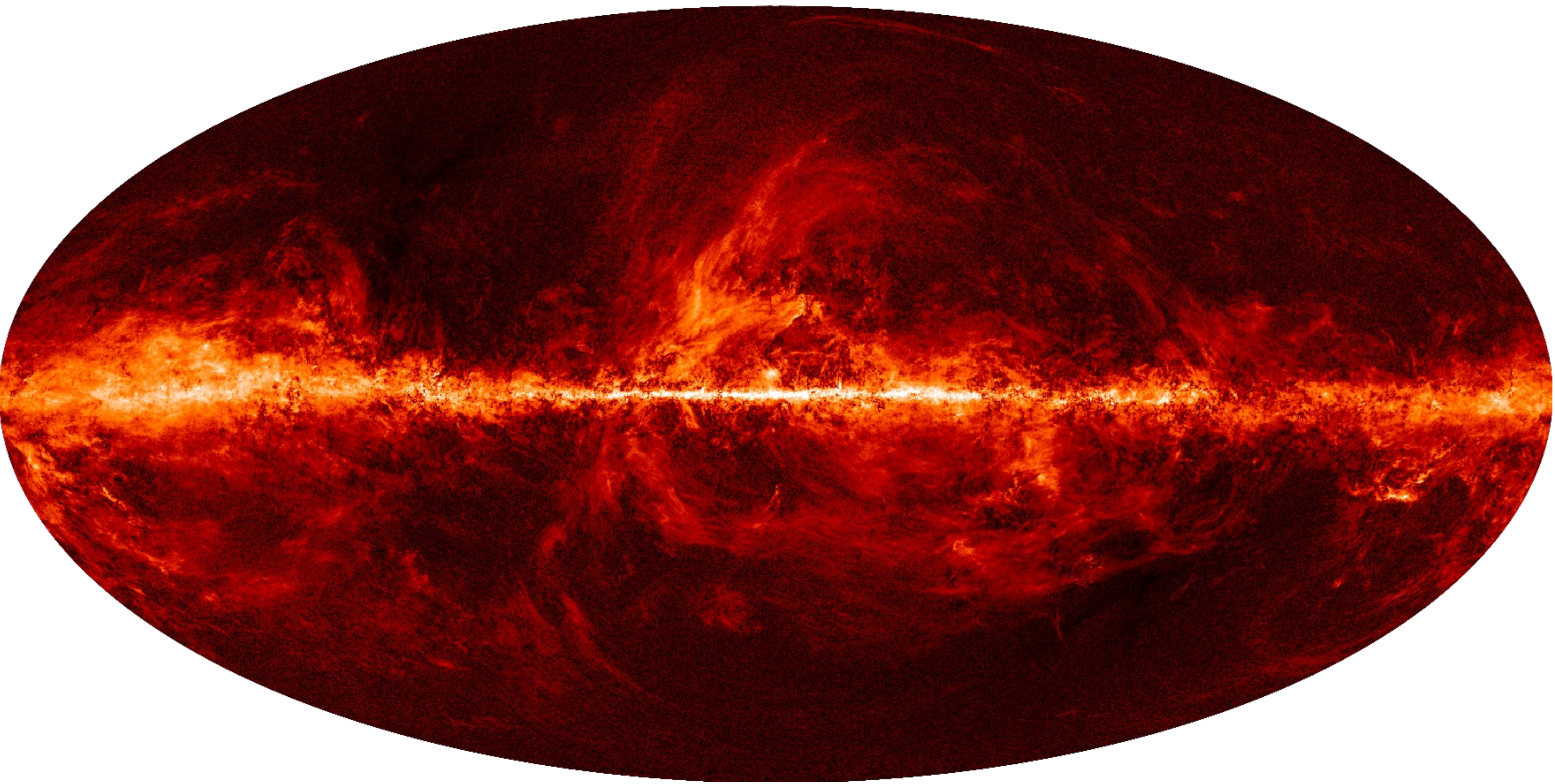
Torsten Enßlin – MPI f. Astrophysics

& Sebastian Hutschenreuter, Niels Oppermann, Valentina Vacca



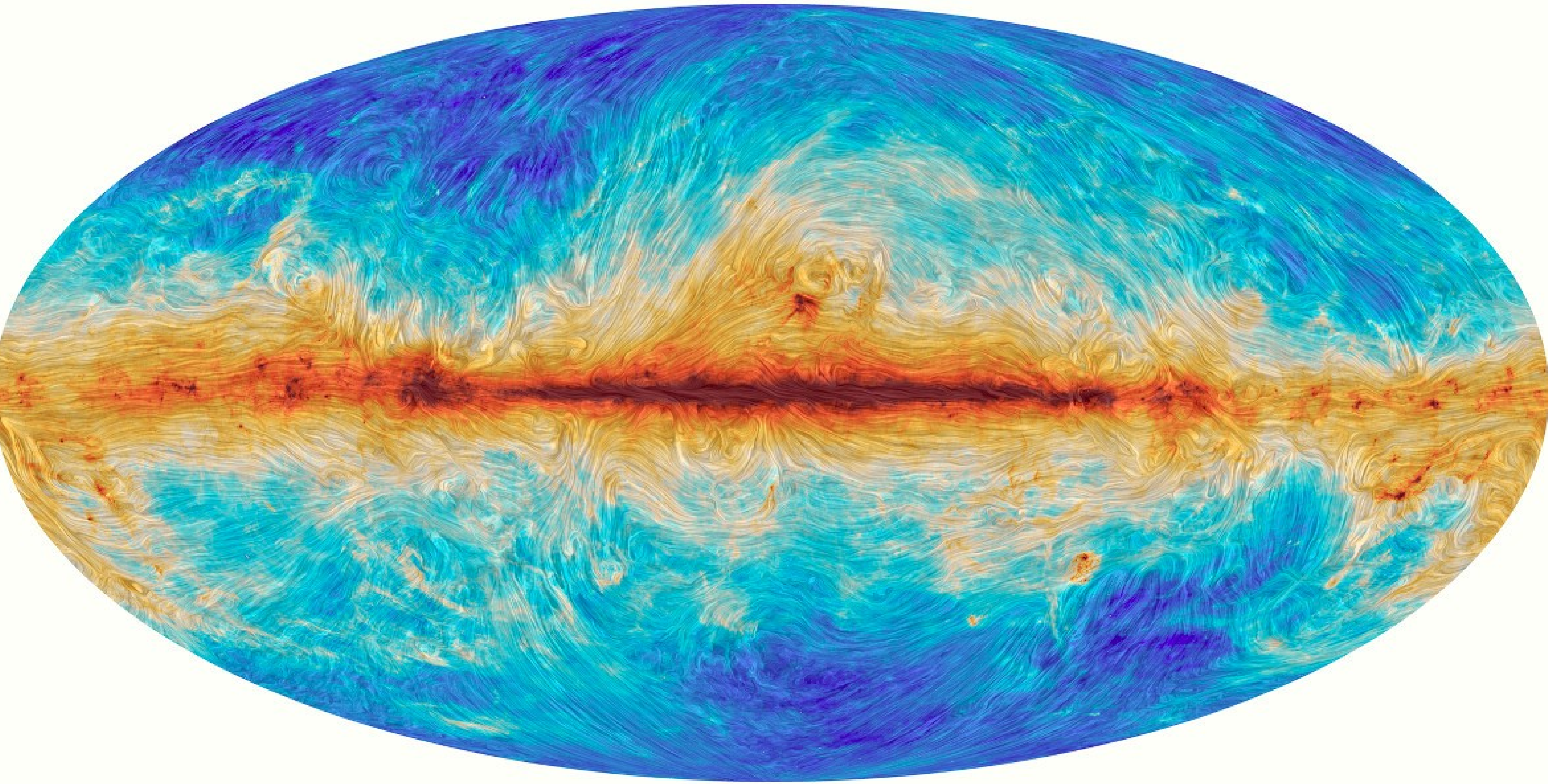
Polarized Dust Emission

Planck Mission



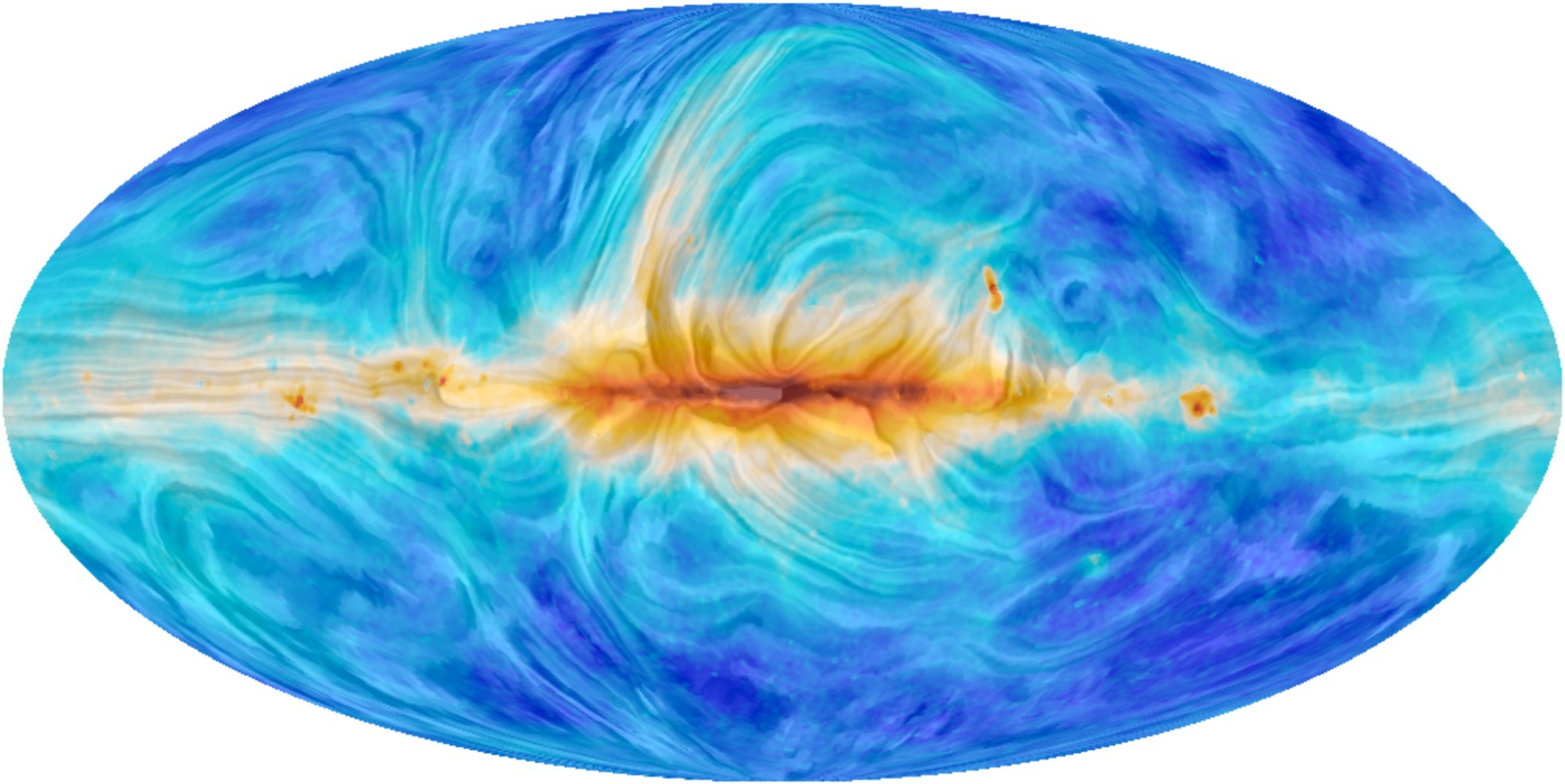
Dust Intensity & Polarization

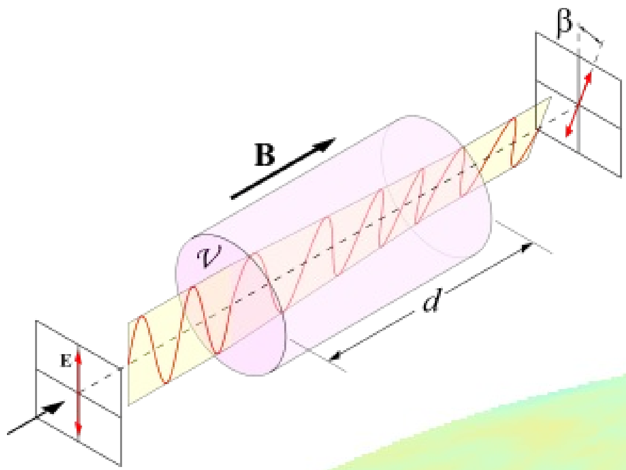
Planck Mission



Synchrotron Emission

Planck Mission



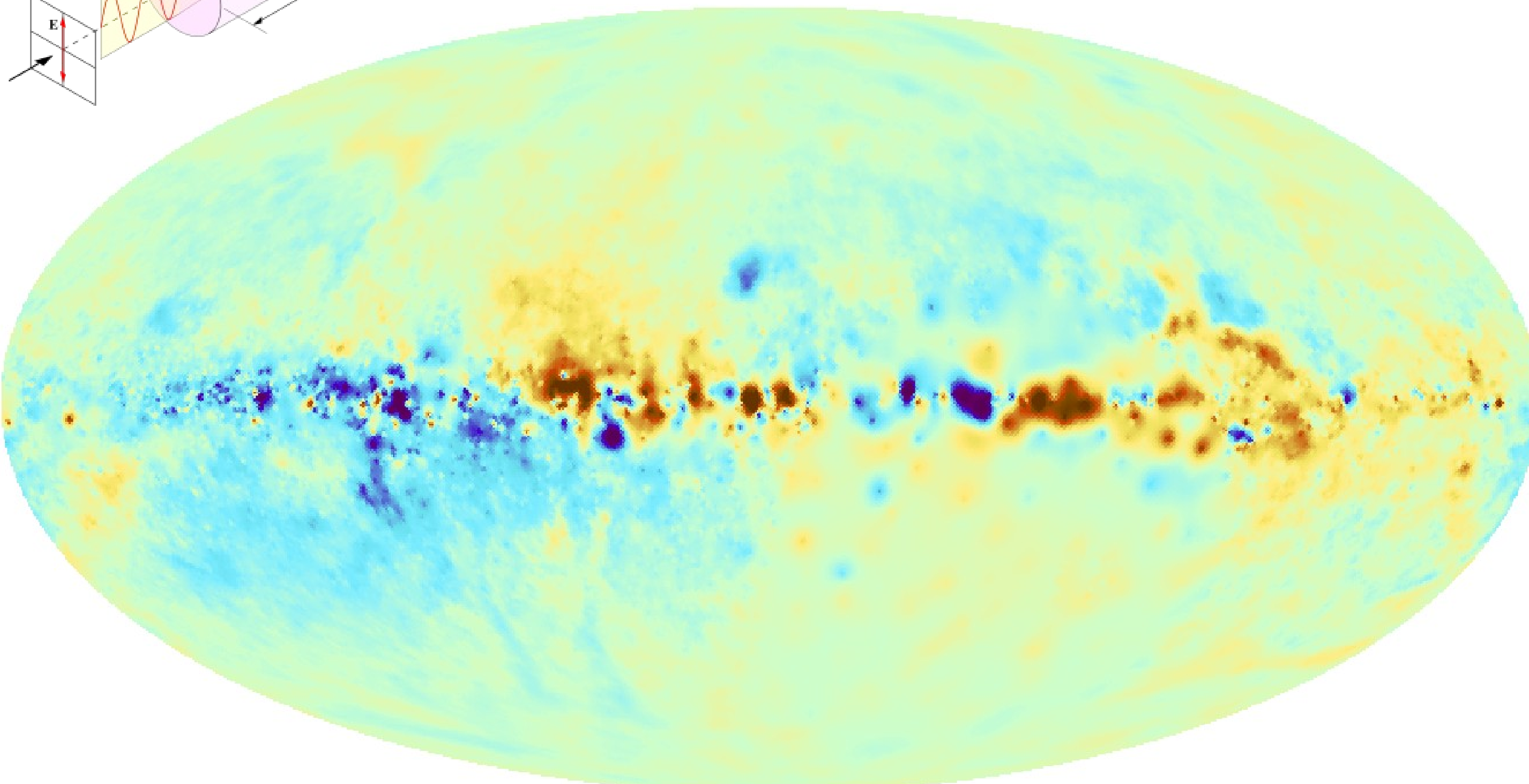


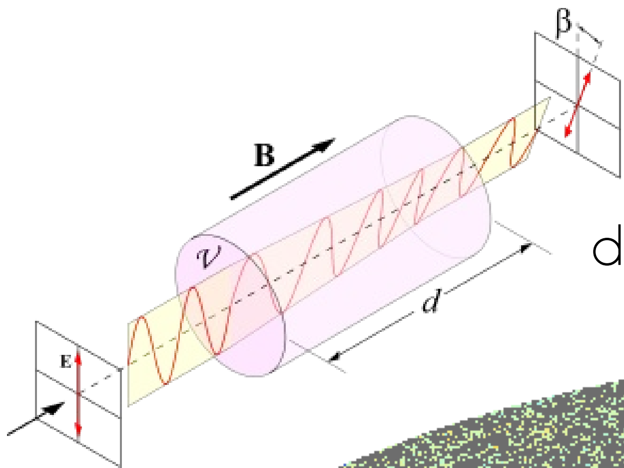
Faraday Sky

Oppermann et al. (2012)

Faraday depth:

$$\phi(z) \propto \int_0^z dz\, n_\mathrm{e}\, B_z$$



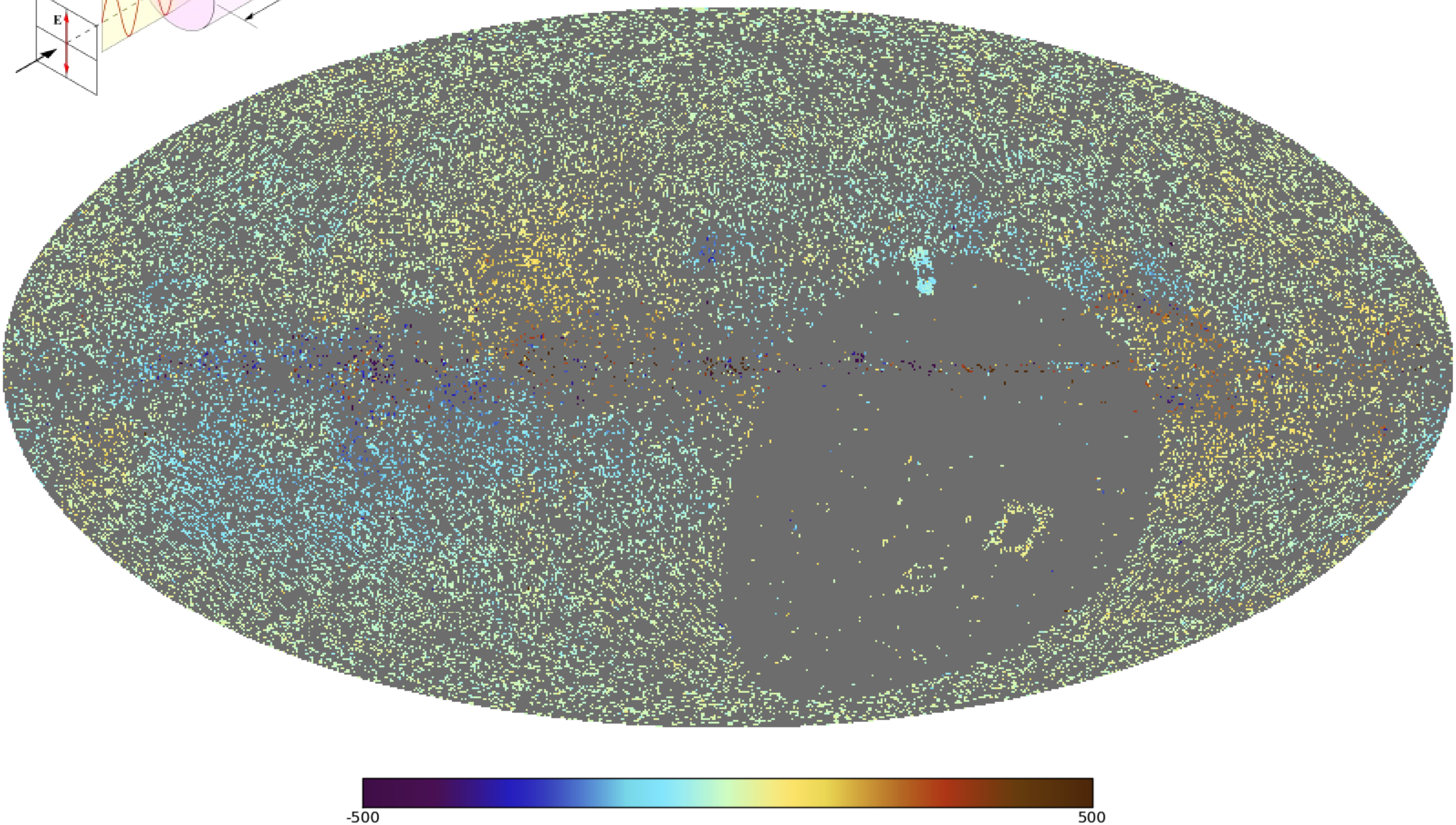


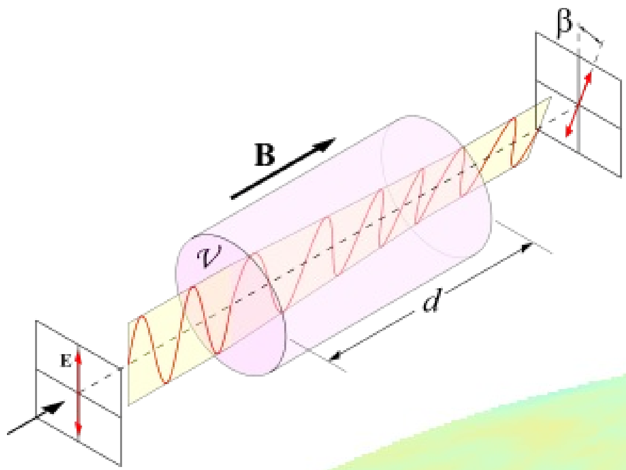
Faraday Sky

data from Taylor et al. (2009) & others

Faraday depth:

$$\phi(z) \propto \int_0^z dz\, n_\mathrm{e}\, B_z$$





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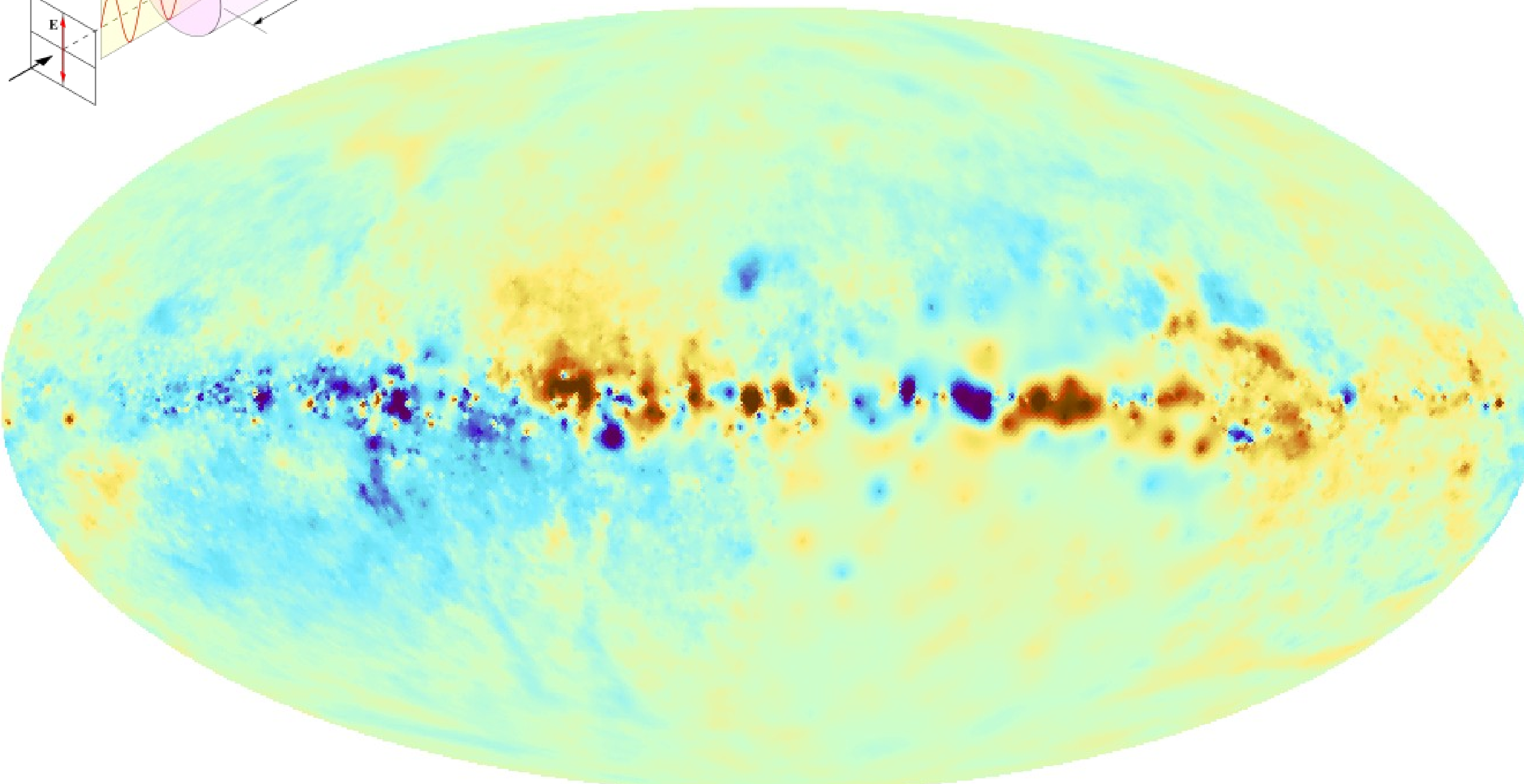
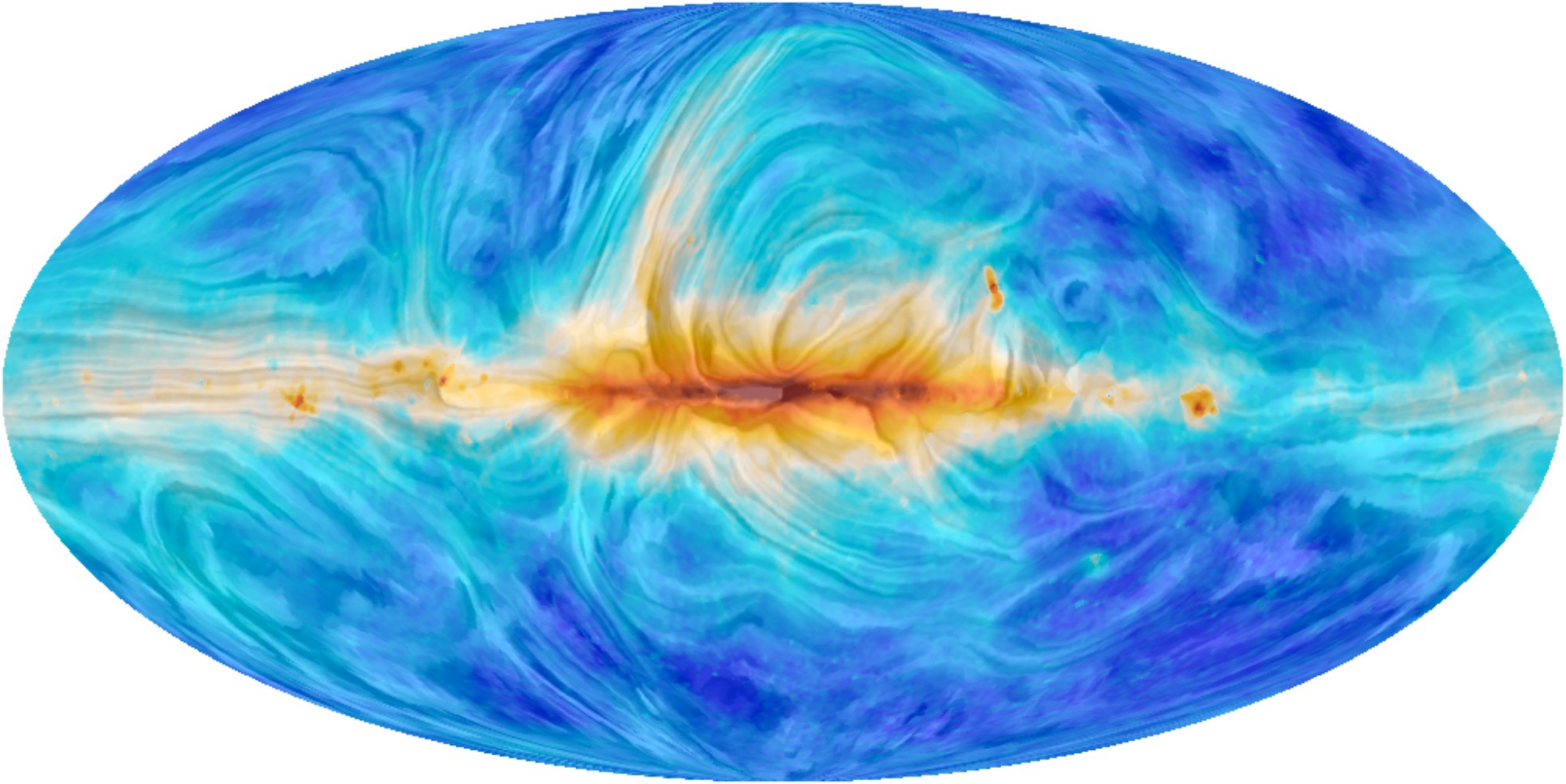


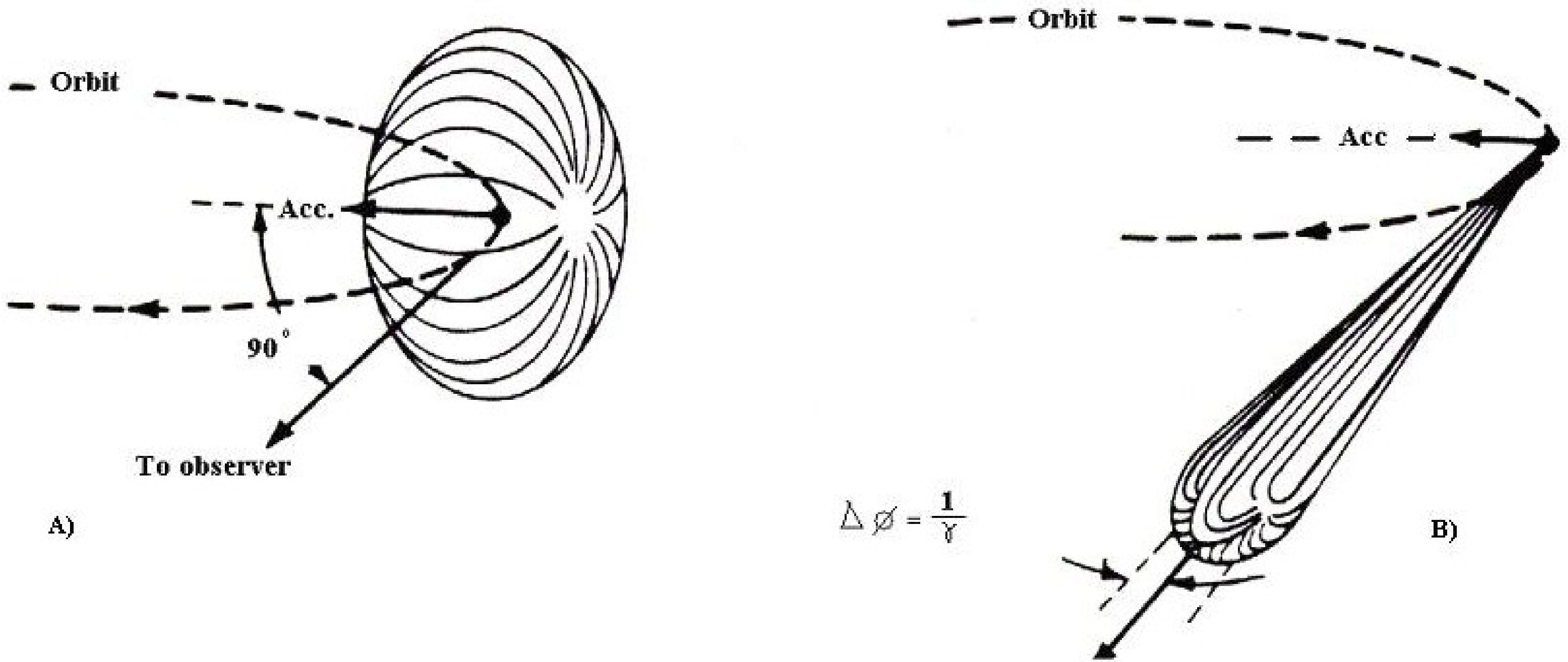
Synchrotron Emission

Planck Mission



Synctrotron emission

en.wikipedia.org/wiki/Synchrotron_radiation



Circular Polarisation Sky

Emissivities from Pandya et al. (2016)

$$V = \alpha_V \int dl\, n_{\mathrm{rel}} B_{||}\, B_{\perp}^{3/2} \qquad \alpha_V = -\frac{0.342 \cdot \mathrm{e}^{9/2}}{\pi\, \sqrt{2\pi}\, \nu^{3/2}\, m_{\mathrm{e}} c^{7/2} (\gamma_{\mathrm{min}}^{-2} - \gamma_{\mathrm{max}}^{-2})}$$

$$I = \alpha_I \int dl\, n_{\mathrm{rel}} B_{\perp}^{2} \qquad \alpha_I = \frac{\mathrm{e}^4}{6\pi m_{\mathrm{e}}^2 c^3 \nu\, (\gamma_{\mathrm{min}}^{-2} - \gamma_{\mathrm{max}}^{-2})}$$

$$\phi = \alpha_\phi \int dl\, n_{\mathrm{th}} B_{||} \qquad \alpha_\phi = \frac{e^3}{2\pi m_e^2 c^4}$$

$$d = \phi\, I = \alpha_\phi \alpha_I \int dl \int dl'\, n_{\mathrm{th}}(l)\, n_{\mathrm{rel}}(l')\, B_{||}(l)\, B_{\perp}^2(l')$$

$$\frac{V}{d} = \frac{\alpha_V}{\alpha_\phi \alpha_I}\, \frac{\int dl\, n_{\mathrm{rel}} B_{||}\, B_{\perp}^{3/2}}{\left(\int dl\, n_{\mathrm{th}} B_{||}\right) \left(\int dl\, n_{\mathrm{rel}} B_{\perp}^2\right)}$$

Model

$$\overline{B}^2(n) = \langle \vec{B}^2 \rangle_{(\vec{B}|n)}, \qquad \langle f(x,y) \rangle_{(x|y)} = \int dx\, \mathcal{P}(x|y)\, f(x,y)$$

$$\overline{B}^2(n) = \frac{B_0^2}{n_{\mathrm{th0}}^{\beta_{\mathrm{th}}} n_{\mathrm{rel0}}^{\beta_{\mathrm{rel}}}} n_{\mathrm{th}}^{\beta_{\mathrm{th}}} n_{\mathrm{rel}}^{\beta_{\mathrm{rel}}} = B_0^2\, x_{\mathrm{th}}^{\beta_{\mathrm{th}}} x_{\mathrm{rel}}^{\beta_{\mathrm{rel}}}$$

$$\text{with } \beta_{\mathrm{th}} = 0 \text{ and } \beta_{\mathrm{rel}} = 1$$

$$\begin{aligned} M_{ij}(\vec{x},\vec{y}) &= \langle B_i(\vec{x})\, B_j(\vec{y}) \rangle_{(\vec{B})} = M_{ij}(\vec{r}) \\ &= M_{\mathrm{N}}(r)\, \delta_{ij} + (M_{\mathrm{L}}(r) - M_{\mathrm{N}}(r))\ \hat{r}_i \hat{r}_j, \end{aligned}$$

$$M(\vec{r})|_{\vec{r}=(r,0,0)} = \begin{pmatrix} M_{\mathrm{L}} & 0 & 0 \\ 0 & M_{\mathrm{N}} & 0 \\ 0 & 0 & M_{\mathrm{N}} \end{pmatrix} (r)$$

Correlations

$$\lambda_{\mathrm{L}} = \int dr\, M_{\mathrm{L}}(r)/M_{\mathrm{L}}(0)$$

$$\lambda_{\mathrm{N}} = \int dr\, M_{\mathrm{N}}^2(r)/M_{\mathrm{N}}^2(0)$$

$$\begin{aligned}
\langle \phi^2 \rangle_{(\vec{B}|n)} &= \alpha_\phi^2 \int_0^\infty dl \int_0^\infty dl'\, n_{\mathrm{th}}(l)\, n_{\mathrm{th}}(l') \langle B_{||}(l)\, B_{||}(l') \rangle_{(\vec{B}|n)} \\
&\approx \alpha_\phi^2 \int_0^\infty dl \int_{-\infty}^\infty dr\, n_{\mathrm{th}}(l)\, n_{\mathrm{th}}(l+r)\, M_{\mathrm{L}}(r) \\
&\approx \frac{1}{3}\alpha_\phi^2 \lambda_{\mathrm{L}} \int_0^\infty dl\, n_{\mathrm{th}}^2\, \overline{B}^2(n).
\end{aligned}$$

$$\langle B_i B_j B_k B_l \rangle_{(\vec{B})} = M_{ij} M_{kl} + M_{ik} M_{jl} + M_{il} M_{jk}$$

Estimator

$\epsilon^2 = \langle \left[V - \overline{V}(d) \right]^2 \rangle_{(\vec{B}|n)}$ quadratic error expectation

$\overline{V}(d) = v\, d$ linear estimator

$$
\begin{aligned}
\frac{d\epsilon^2}{dv} &= -2\langle [V - v\, d]\ d\rangle_{(\vec{B}|n)} \\
&= 2\left[v\langle d^2\rangle_{(\vec{B}|n)} - \langle V\, d\rangle_{(\vec{B}|n)} \right] = 0.
\end{aligned}
$$

$\overline{V} = \langle V\, d\rangle_{(\vec{B}|n)} \langle d^2\rangle^{-1}_{(\vec{B}|n)} d$ optimal linear estimator

$$
\begin{aligned}
\langle d^2\rangle_{(\vec{B}|n)} &= \langle \phi^2 I^2\rangle_{(\vec{B}|n)} \\
\langle V\, d\rangle_{(\vec{B}|n)} &= \langle V\, \phi\, I\rangle_{(\vec{B}|n)}
\end{aligned}
$$

Calculation

$$\begin{aligned}
\langle d^2\rangle_{(\vec{B}|n)} &= \alpha_\phi^2\alpha_I^2\int dl_1\ldots\int dl_4\, n_{\rm th1}\, n_{\rm th2}\, n_{\rm rel3}\, n_{\rm rel4}\langle B_{||1}B_{||2}B_{\perp 3}^2B_{\perp 4}^2\rangle_{(B|n)}\\
&= \alpha_\phi^2\alpha_I^2\int dl_1\ldots\int dl_4\, n_{\rm th1}\, n_{\rm th2}\, n_{\rm rel3}\, n_{\rm rel4} M_{\rm L12}\ \left[M_{\rm N33}\, M_{\rm N44}+2\, M_{\rm N34}^2\right]\\
&\approx \frac{1}{27}\,\lambda_{\rm L}\alpha_\phi^2\alpha_I^2\ \left[\int dl\, n_{\rm th}^2\overline{B}^2\right]\left[\left(\int dl\, n_{\rm rel}\,\overline{B}^2\right)^2+2\lambda_{\rm N}\int dl\, n_{\rm rel}^2\,\overline{B}^4\right]
\end{aligned}$$

$$\begin{aligned}
\langle V\, d\rangle_{(\vec{B}|n)} &= \alpha_V\alpha_\phi\alpha_I\int dl_1\ldots\int dl_3\, n_{\rm th1}\, n_{\rm rel2}\, n_{\rm rel3}\langle B_{||1}B_{||2}B_{\perp 2}^{\frac{3}{2}}B_{\perp 3}^2\rangle_{(B|n)}\\
&\approx \alpha_V\alpha_\phi\alpha_I\int dl_1\ldots\int dl_3\, n_{\rm th1}\, n_{\rm rel2}\, n_{\rm rel3}\left\langle B_{||1}B_{||2}\ \left(\frac{1}{4}B_{\perp 0}^{\frac{3}{2}}+\frac{3}{4}\,B_{\perp 0}^{-\frac{1}{2}}\,B_{\perp 2}^2\right)B_{\perp 3}^2\right\rangle_{(B|n)}\\
&= \alpha_V\alpha_\phi\alpha_I\int dl_1\ldots\int dl_3\, n_{\rm th1}\, n_{\rm rel2}\, n_{\rm rel3}\frac{B_{\perp 0}^{-\frac{1}{2}}}{4}\,M_{\rm L12}\left(B_{\perp 0}^2M_{\rm N33}+\,+3\,\left[M_{\rm N22}\,M_{\rm N33}+2\,M_{\rm N23}^2\right]\right)\\
&\approx \frac{B_{\perp 0}^{-\frac{1}{2}}}{36}\,\lambda_{\rm L}\alpha_V\alpha_\phi\alpha_I\left[B_{\perp 0}^2\left(\int\ dl\, n_{\rm th}n_{\rm rel}\,\overline{B}^2\right)\left(\int\ dl\, n_{\rm rel}\,\overline{B}^2\right)+\left(\int dl\, n_{\rm th}\, n_{\rm rel}\,\overline{B}^4\right)\left(\int dl\, n_{\rm rel}\,\overline{B}^2\right)\right.\\
&\quad\left.+2\lambda_{\rm N}\int dl\, n_{\rm th}\, n_{\rm rel}^2\,\overline{B}^6\right]
\end{aligned}$$

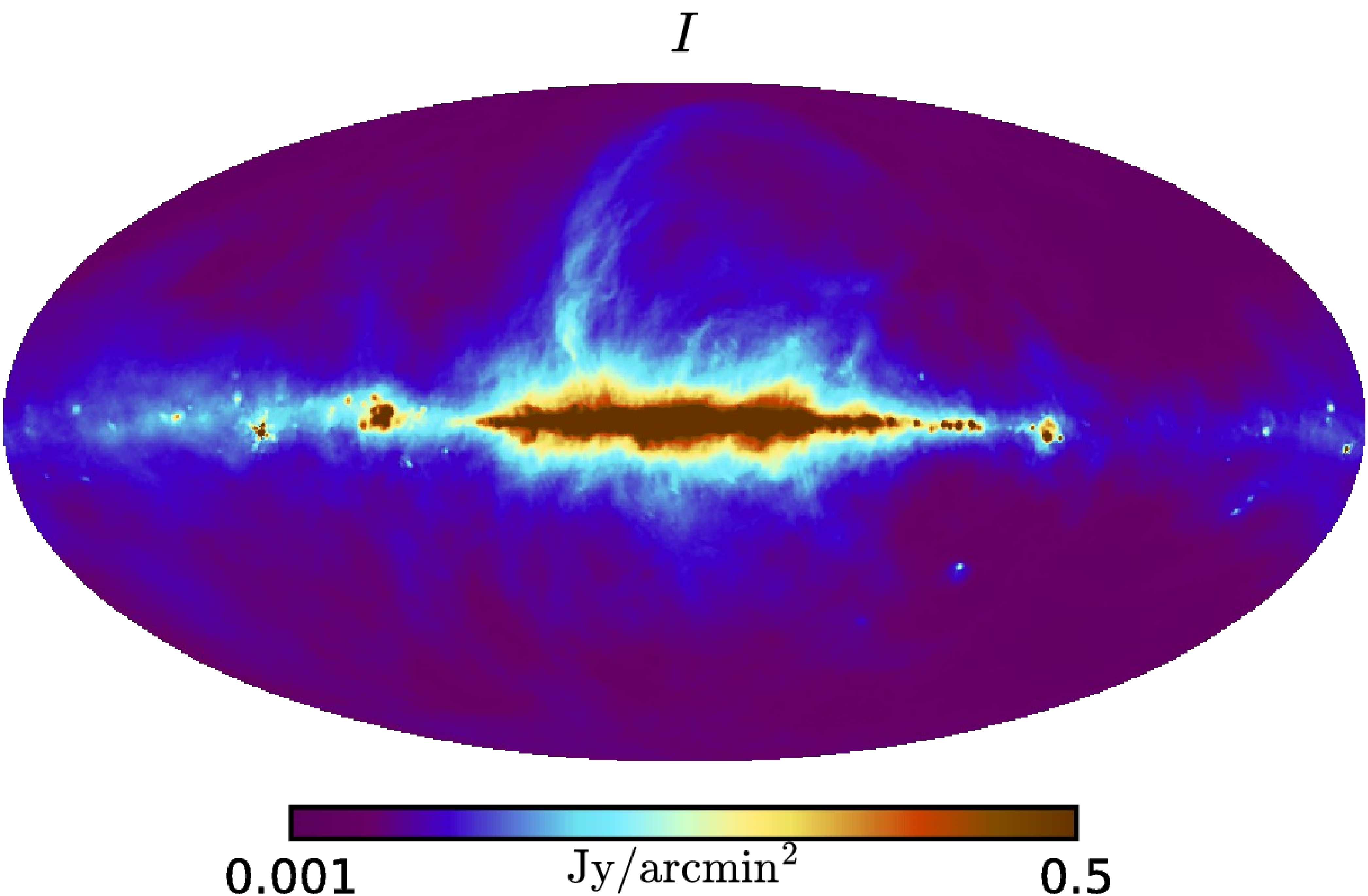
Result

$$\overline{V} = \alpha\,\sigma\,\phi\,I, \text{ with}$$

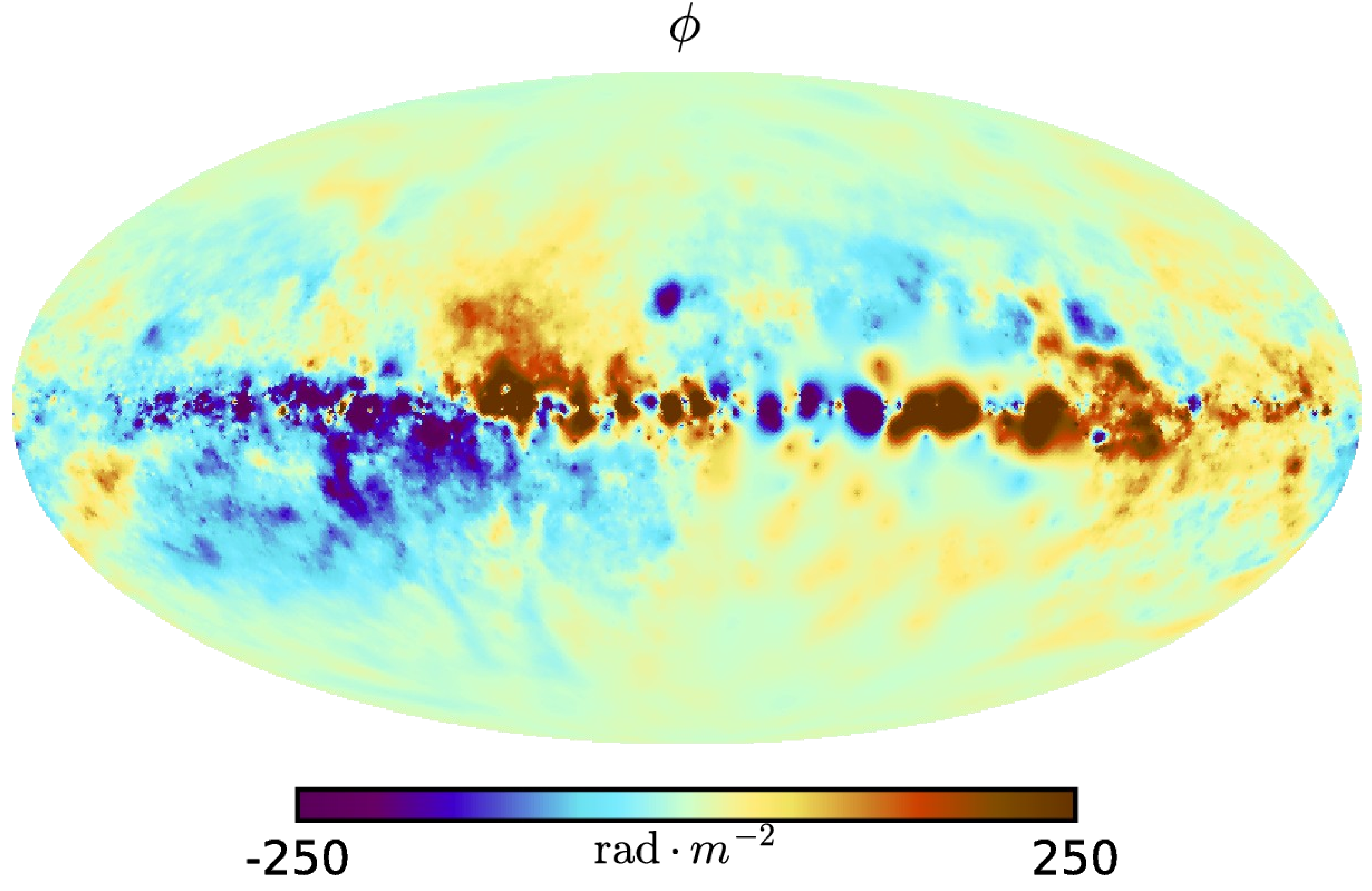
$$\alpha = \frac{3\,\alpha_V}{4\,\alpha_\phi\,\alpha_I\,B_{\perp 0}^{1/2}} \approx -4.269 \cdot \sqrt{\frac{m_\mathrm{e}^3\,c^7}{\mathrm{e}^5\,\nu\,B_0}}$$

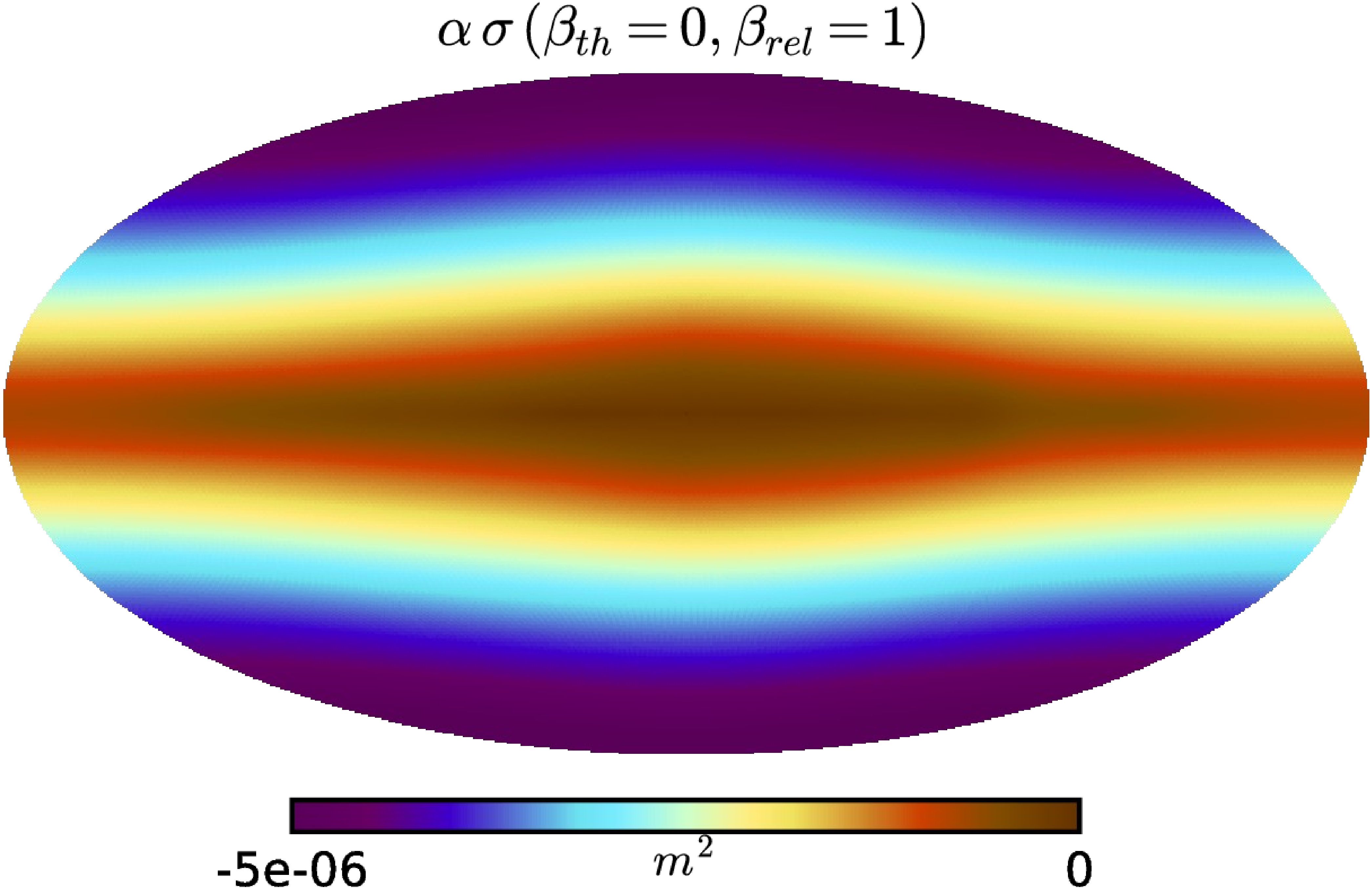
$$\approx \text{-}2.189 \cdot 10^{18} \left(\frac{\nu}{408\,\mathrm{MHz}}\right)^{-12} \left(\frac{B_0}{6\,\mu\mathrm{G}}\right)^{-12}$$

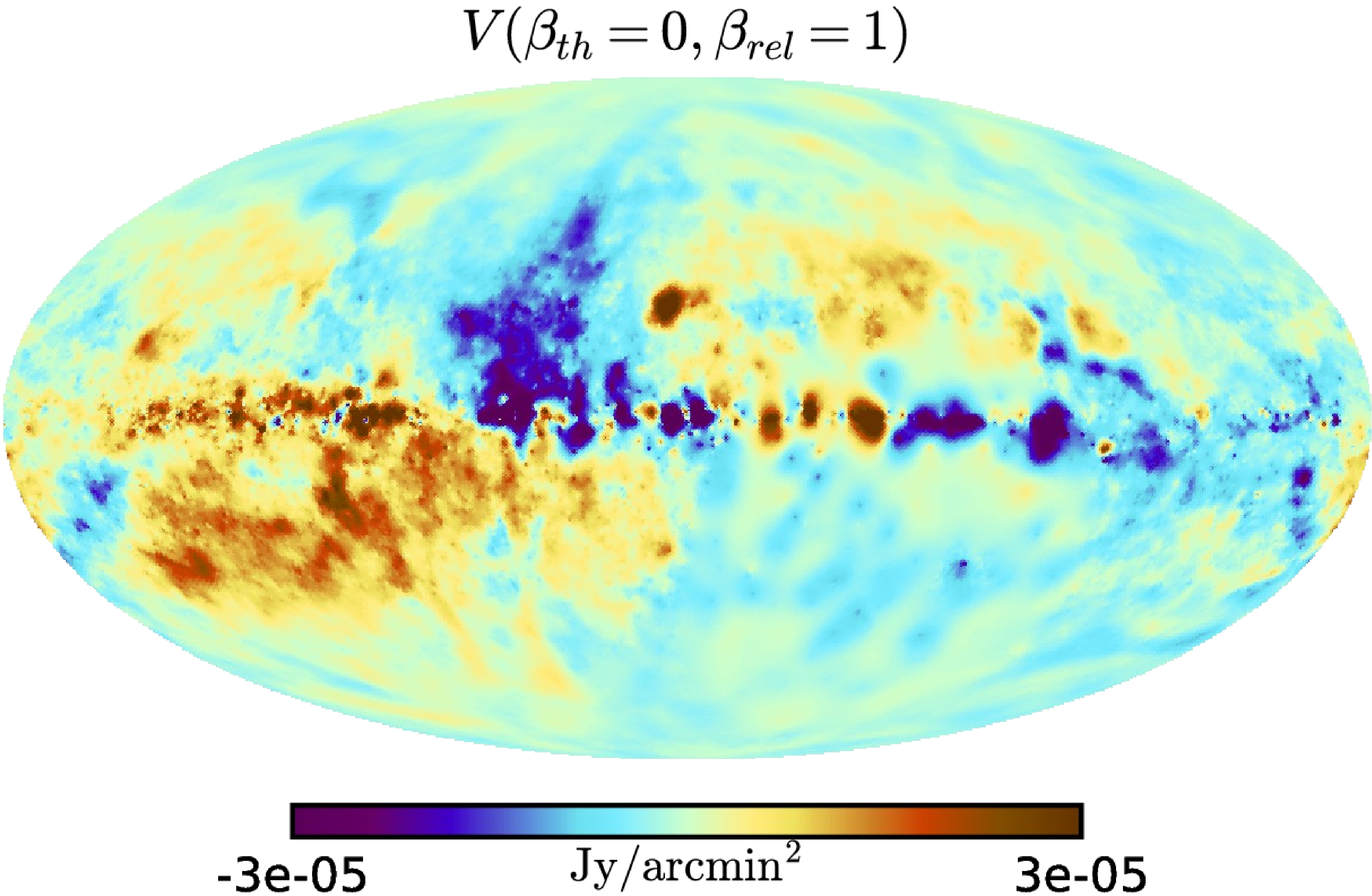
$$\sigma \approx \frac{\int\; dl\, n_\mathrm{th} n_\mathrm{rel}\, \left(\frac{2}{3} B_0^2\, \overline{B}^2 + \overline{B}^4\right) \frac{2}{3} B_0^2\, \overline{B}^2 + \overline{B}^4\Big)\Big] + 2\lambda_\mathrm{N} \int dl\, n_\mathrm{th}\, n_\mathrm{rel}^2\, \overline{B}^6}{\left(\int dl\, n_\mathrm{th}^2 \overline{B}^2\right) \left(\int dl\, n_\mathrm{rel}\, \overline{B}^2\right)\; n_\mathrm{rel}\, \overline{B}^2\Big)^2 + 2\lambda_\mathrm{N} \int dl\, n_\mathrm{rel}^2\, \overline{B}^4\Big]}$$

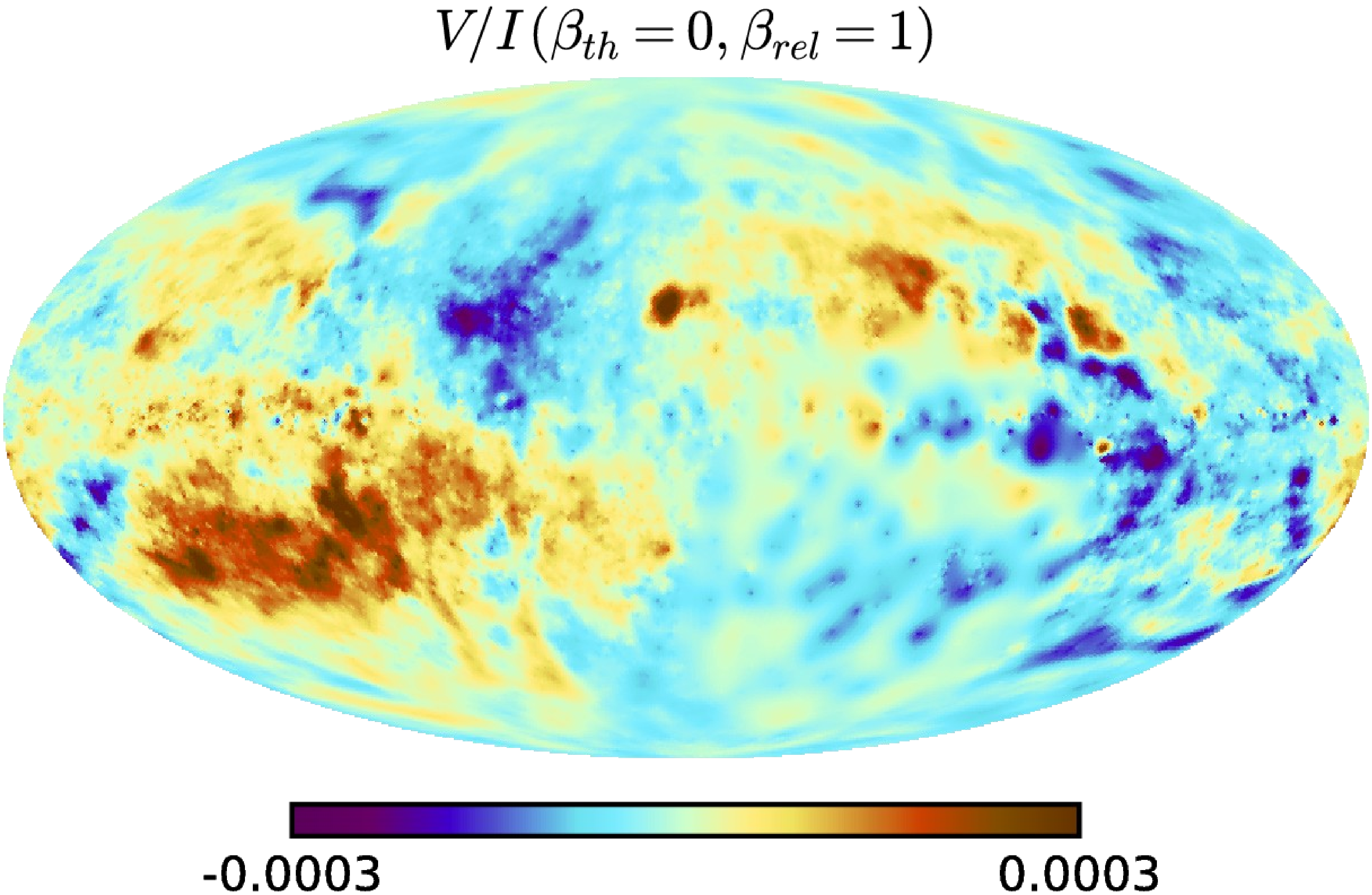


Haslam et al. (1982) & Remazeilles et al. (2015)

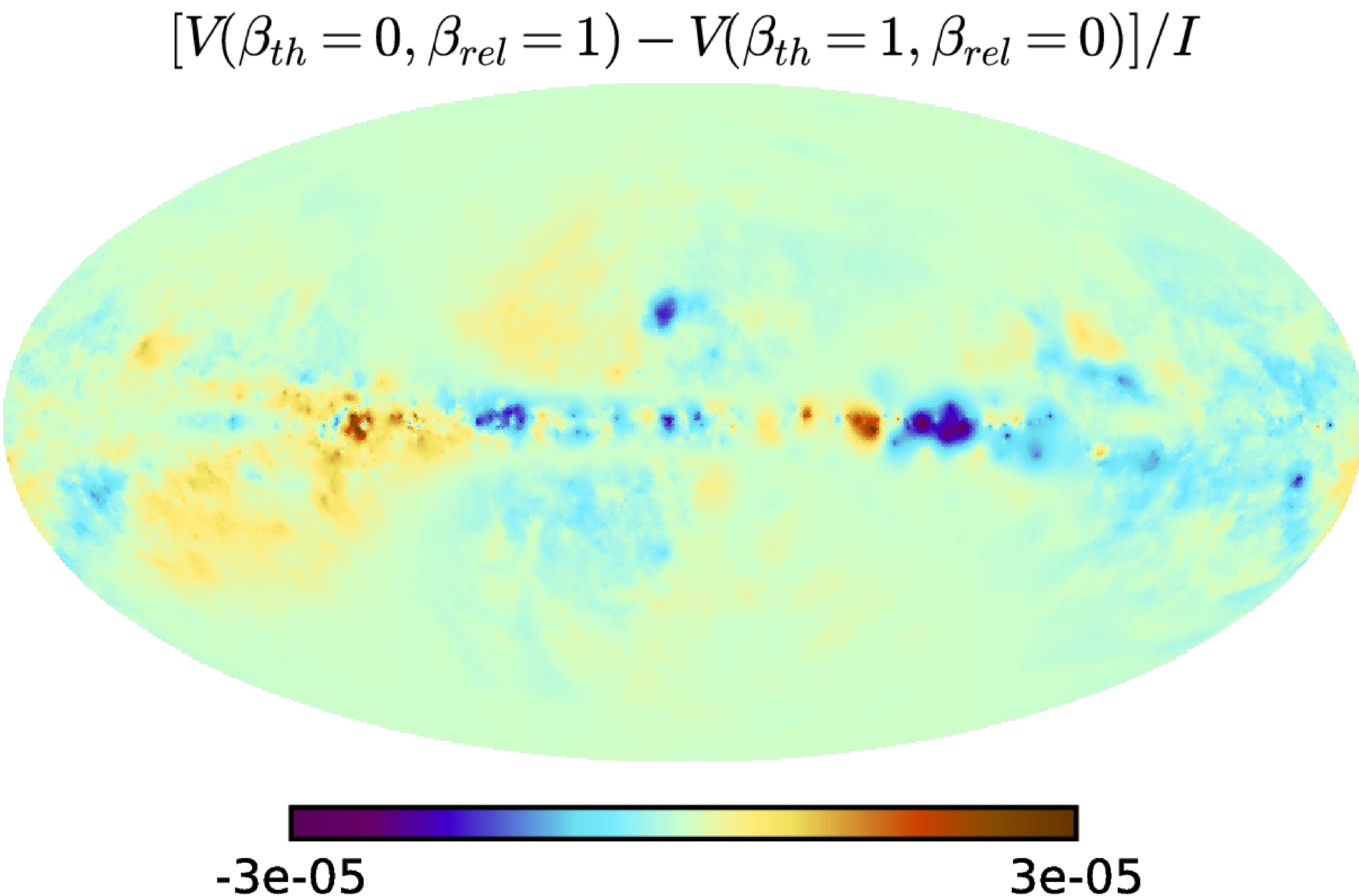

ϕ
-250
$\mathrm{rad} \cdot m^{-2}$
250


$\alpha\,\sigma\,(\beta_{th}=0,\,\beta_{rel}=1)$
-5e-06
m^2
0


$V(\beta_{th}=0, \beta_{rel}=1)$
-3e-05
Jy/arcmin^2
3e-05



$V/I\,(\beta_{th}=0, \beta_{rel}=1)$
-0.0003
0.0003


$[V(\beta_{th} = 0, \beta_{rel} = 1) - V(\beta_{th} = 1, \beta_{rel} = 0)]/I$
-3e-05
3e-05

The Galaxy in circular polarization: all-sky radio prediction, detection strategy, and the charge of the leptonic cosmic rays

Torsten A. Enßlin,[*] Sebastian Hutschenreuter,[*] Valentina Vacca,[†] and Niels Oppermann[‡]

The diffuse Galactic synchrotron emission should exhibit a low level of diffuse circular polarization (CP) due to the circular motions of the emitting relativistic electrons. This probes the Galactic magnetic field in a similar way as the product of total Galactic synchrotron intensity times Faraday depth. We use this to construct an all sky prediction of the so far unexplored Galactic CP from existing measurements. This map can be used to search for this CP signal in low frequency radio data even prior to imaging. If detected as predicted, it would confirm the expectation that relativistic electrons, and not positrons, are responsible for the Galactic radio emission. Furthermore, the strength of real to predicted circular polarization would provide statistical information on magnetic structures along the line-of-sights.

2017. PRD 96, Issue 4, id.043021
– arXiv:1706.08539

Conclusions

- Galactic magnetism is beautiful
- 3D structure becomes accessible via polarization
- **Circular Polarization is the next frontier**
- CP expectation map presented
- Detection is feasible with current / future telescopes if well calibrated
- CP allows test of
  - co-spatiallity of field components
  - charge of synchrotron emitting leptons


Thank you !