Polar-**A**reas **S**tellar **I**maging in **P**olarization
High **A**ccuracy **E**xperiment

3D Tomography of Galactic Dust Polarization

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Nordita, Stockholm, 21 July 2017

PASIPHAE Collaboration

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IUCAA

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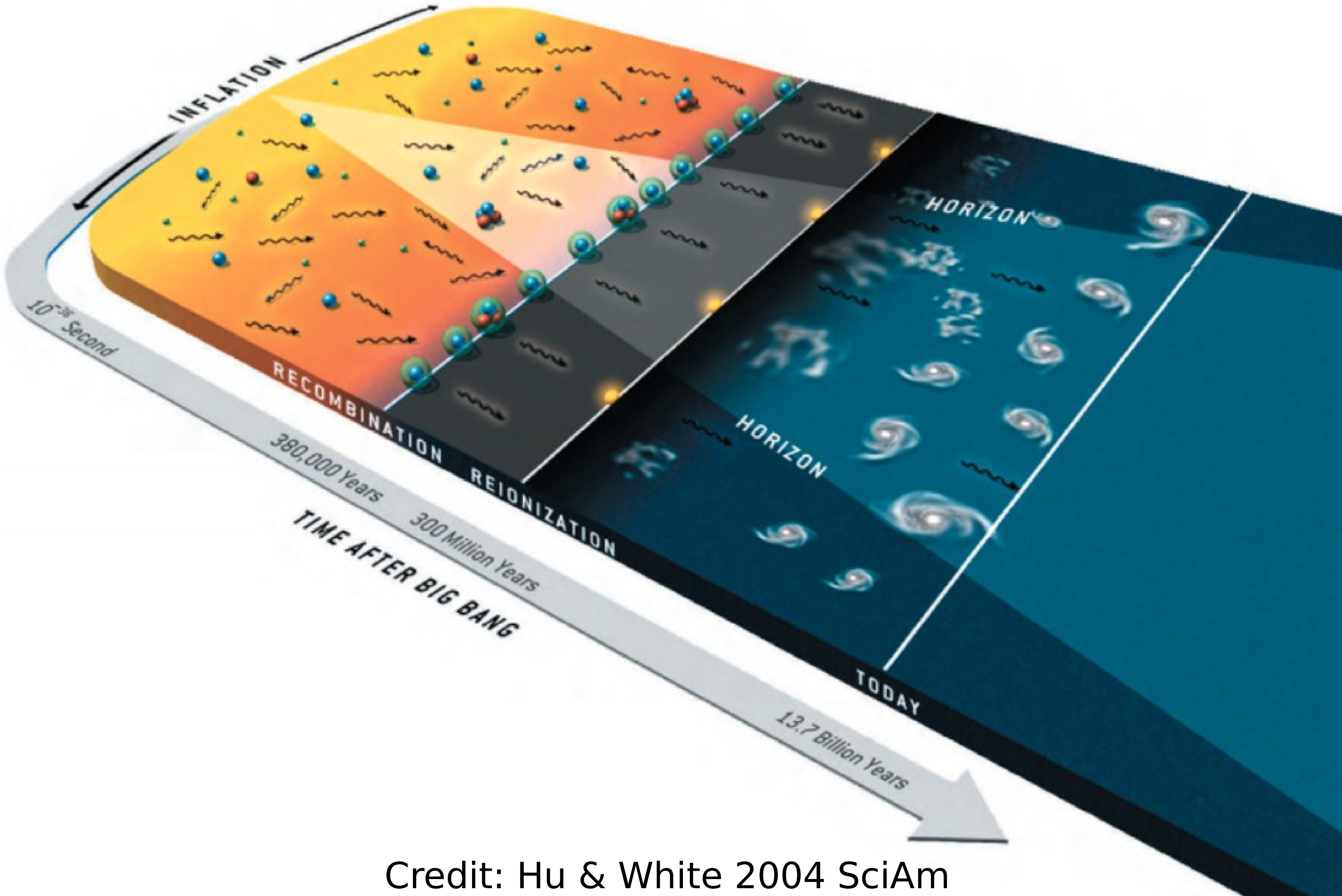
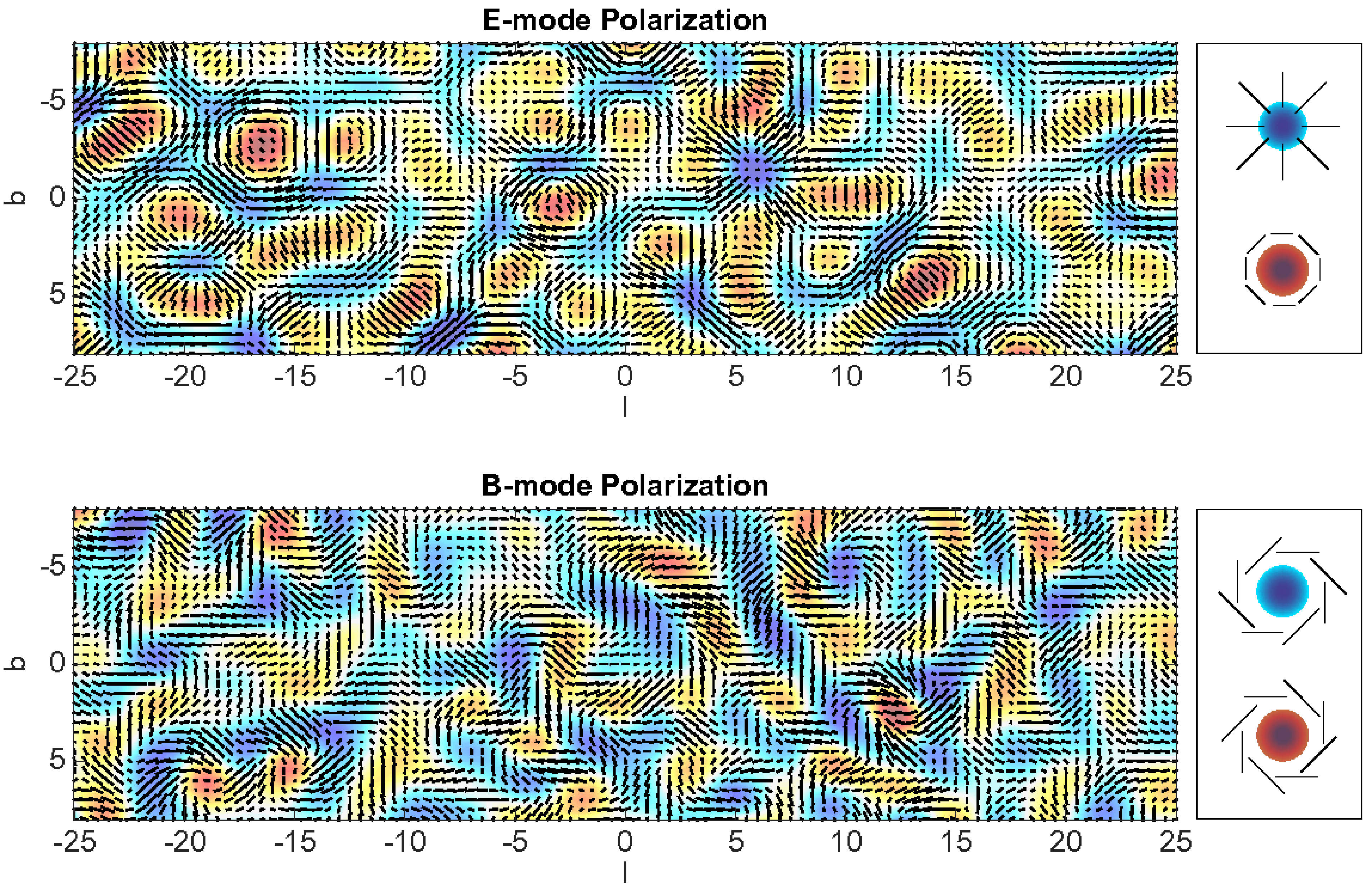
Goal: CMB Polarization

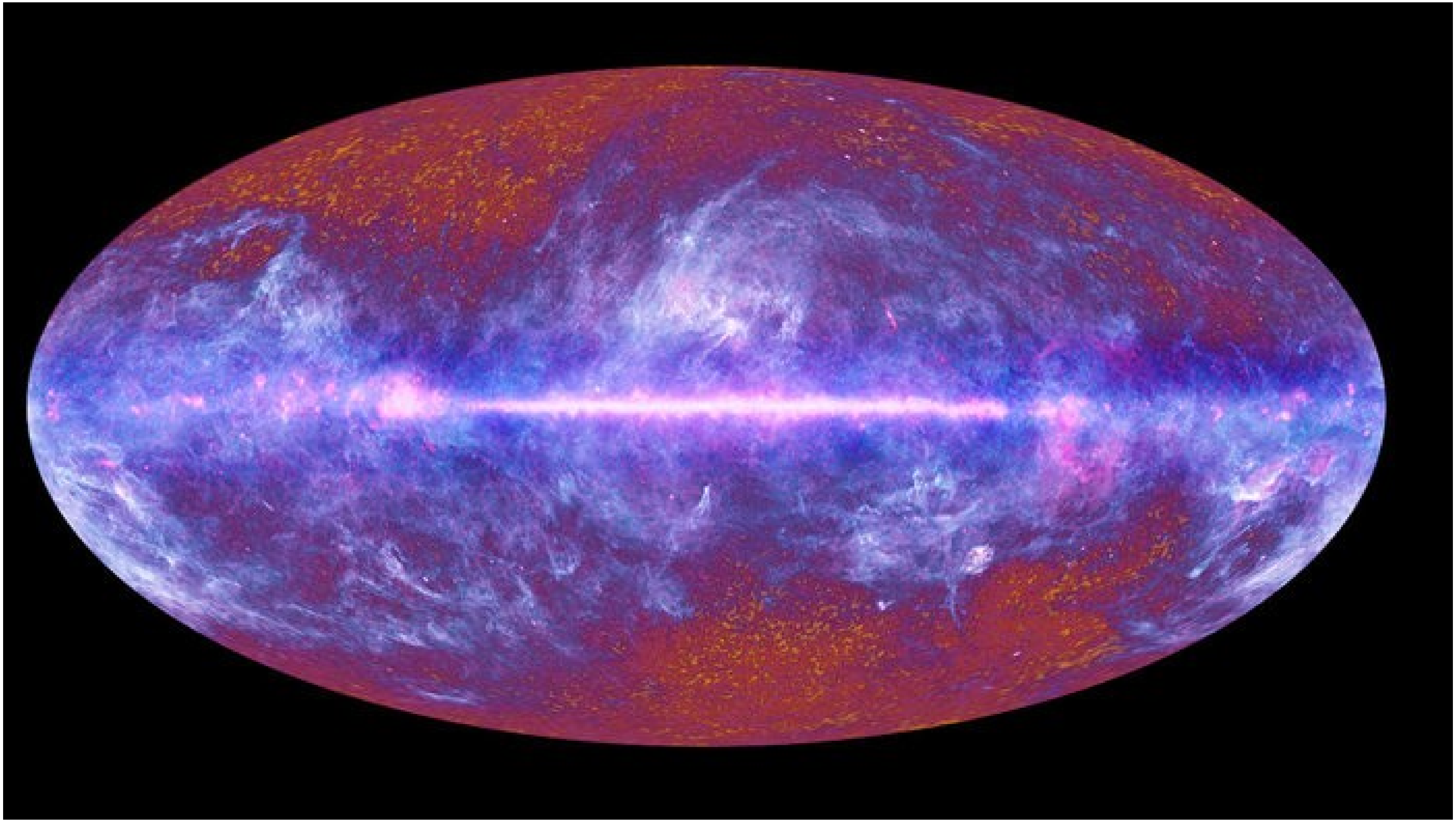


Credit: Hu & White 2004 SciAm

Goal: CMB Polarization

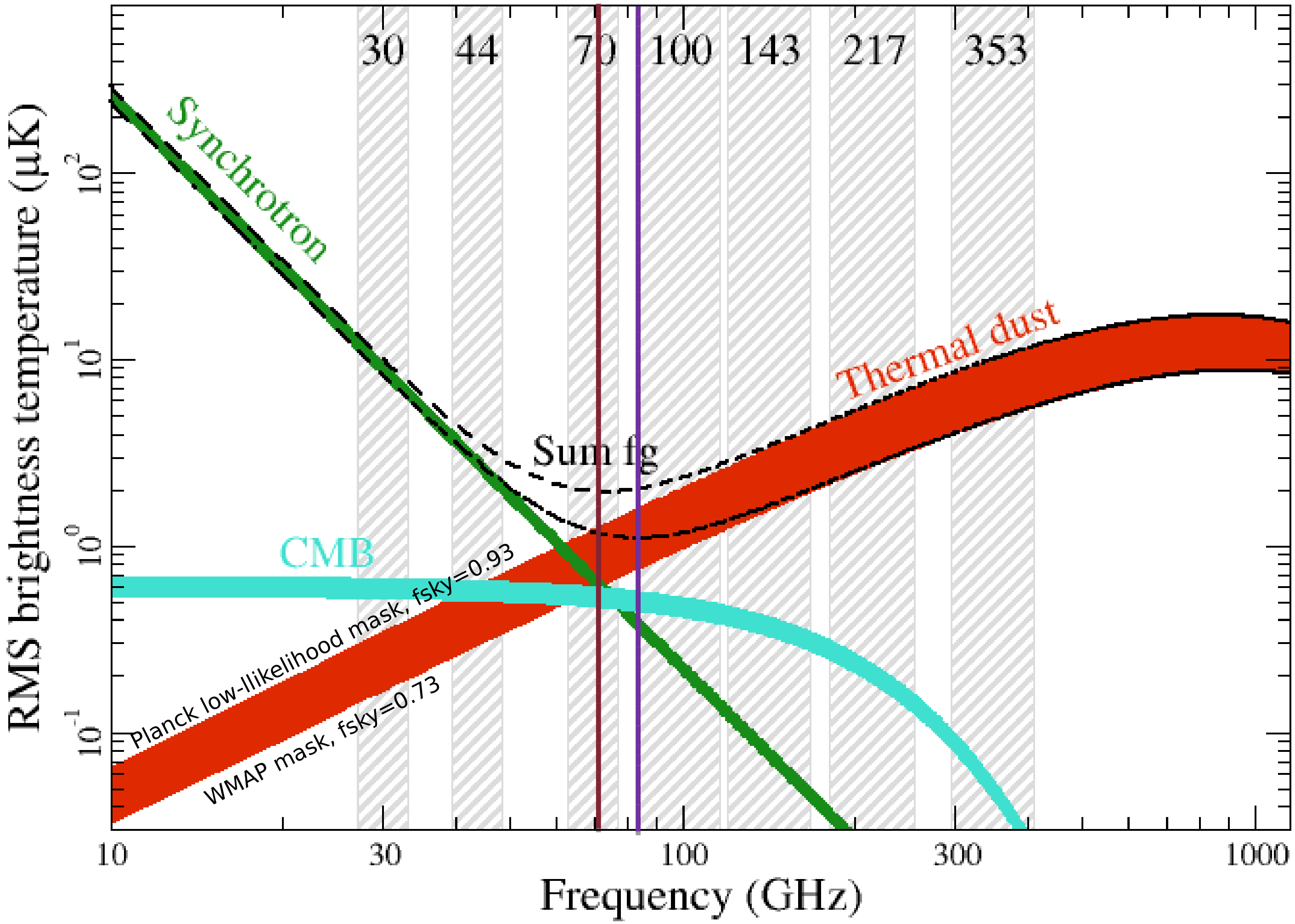


Problem: Foregrounds



ESA/ LFI & HFI Consortia

Polarization Foregrounds at a Glance



Polarization foreground minimum between **70 and 85 GHz** for sky fractions between 73 and 93% at **40 arcmin** resolution

Bayesian Component Separation

- We adopt a parametric Bayesian approach for diffuse component separation
- We assume that the data may be written as the sum of signal and noise,

$$\mathbf{d}_\nu = \mathbf{s}_\nu + \mathbf{n}_\nu$$

where the signal may be written on the following form

$$\mathbf{s}_\nu(\theta) = s_\nu(\mathbf{a}_i, \beta_i, g_\nu, \mathbf{m}_\nu, \Delta_\nu)$$

$$= g_\nu \sum_{i=1}^{N_{\mathrm{comp}}} \mathbf{F}_\nu^i(\beta_i, \Delta_\nu)\mathbf{a}_i + \mathbf{T}_\nu \mathbf{m}_\nu$$

Calibration

Spectral index

Bandpass

Signal amplitude

Monopole/dipole

- The posterior distribution reads

$$P(\theta|\mathbf{d}) = \frac{P(\mathbf{d}|\theta)P(\theta)}{P(\mathbf{d})} \propto \mathcal{L}(\theta)P(\theta)$$

Likelihood

Prior

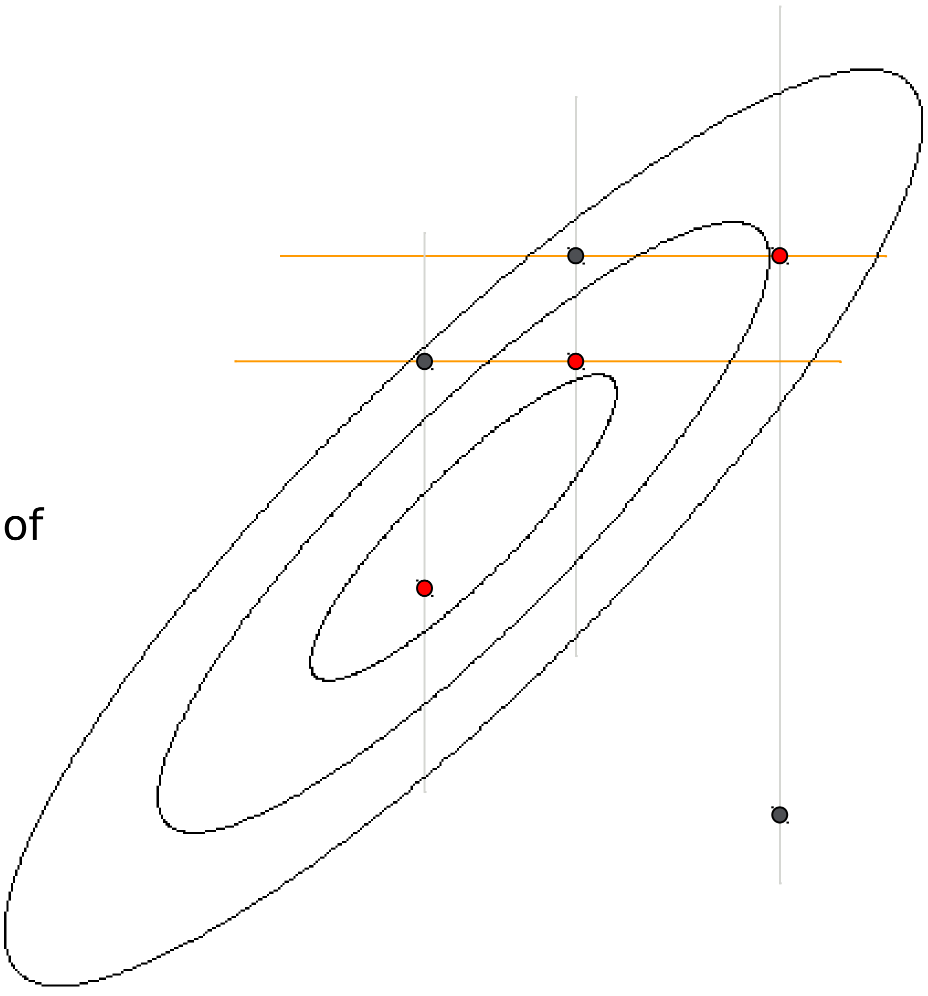
- The noise is very nearly Gaussian distributed, and the likelihood is given by

$$\mathcal{L}(\mathbf{a}_i, \beta_i, g_\nu, \mathbf{m}_\nu, \Delta_\nu) \propto e^{-\frac{1}{2}\sum_\nu [\mathbf{d}_\nu - \mathbf{s}_\nu(\theta)]^t \mathbf{N}^{-1} [\mathbf{d}_\nu - \mathbf{s}_\nu(\theta)]}$$

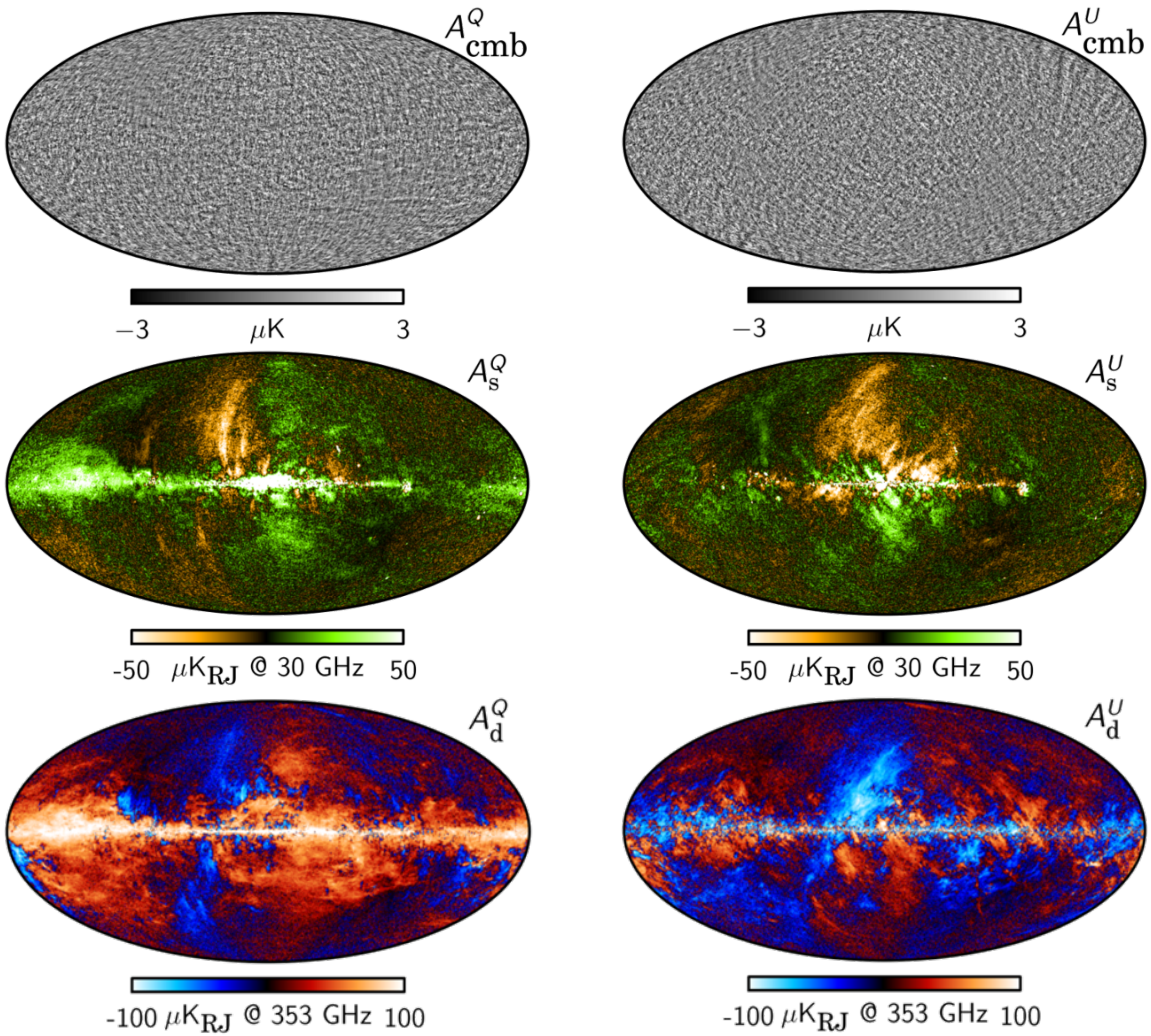
Bayesian Component Separation

- The posterior contains millions of correlated and non-Gaussian parameters. How is it possible to map out this distribution?
- Answer: Gibbs sampling
  - Rather than sampling from or maximizing the full joint distribution, iterate over conditionals
- We apply this to our problem in terms of the following Gibbs chain:

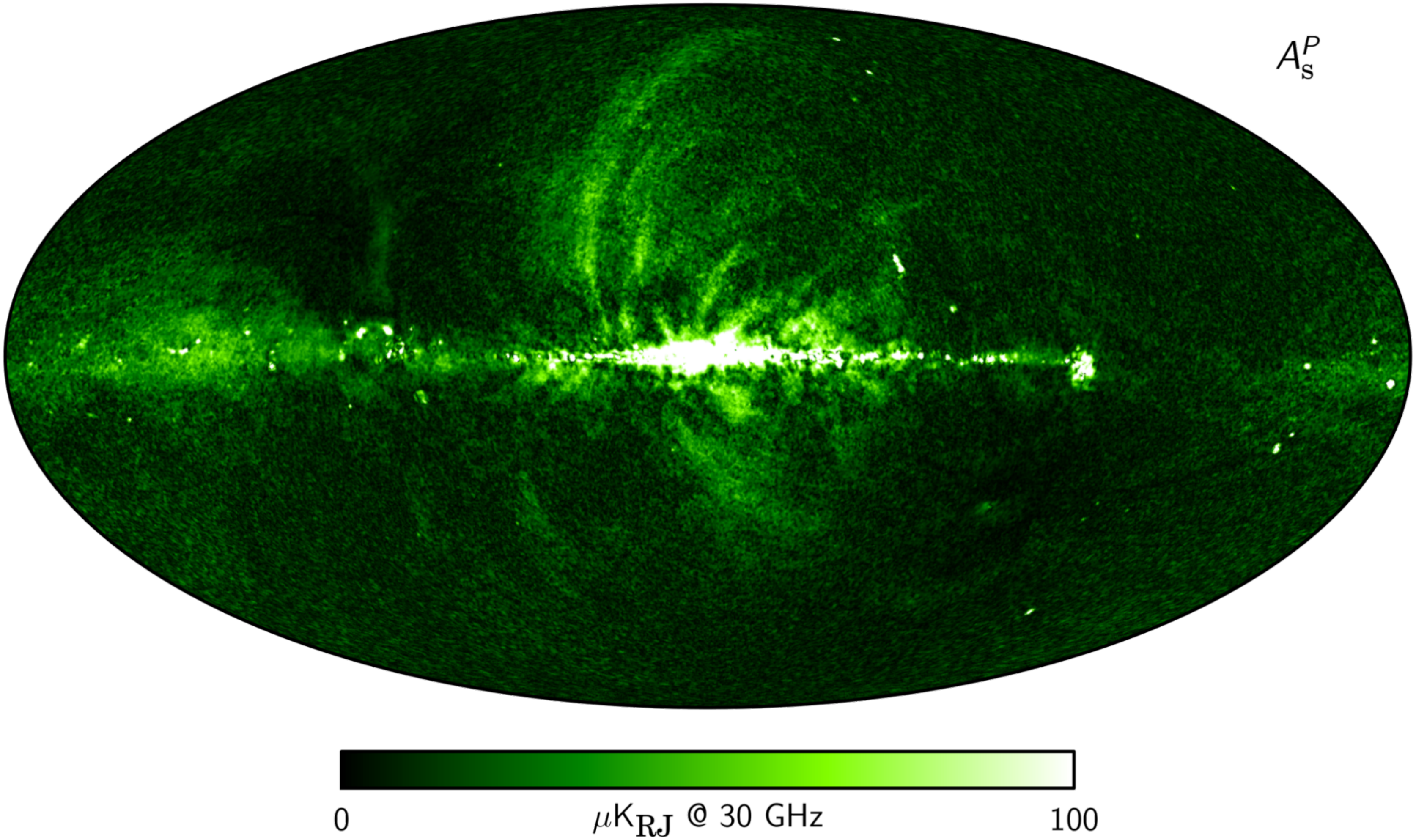
$$
\begin{aligned}
\mathbf{a}_i &\leftarrow P(\mathbf{a}_i|\beta_i, g_\nu, \mathbf{m}_\nu, \Delta_\nu, C_\ell) \\
\beta_i &\leftarrow P(\beta_i|\mathbf{a}_i, g_\nu, \mathbf{m}_\nu, \Delta_\nu, C_\ell) \\
g_\nu &\leftarrow P(g\nu|\mathbf{a}_i, \beta_i, \mathbf{m}_\nu, \Delta_\nu, C_\ell) \\
\mathbf{m}_\nu &\leftarrow P(m_\nu|\mathbf{a}_i, \beta_i, g_\nu, \Delta_\nu, C_\ell) \\
\Delta\nu &\leftarrow P(\Delta_\nu|\mathbf{a}_i, \beta_i, g_\nu, \mathbf{m}_\nu, C_\ell) \\
C_\ell &\leftarrow P(C_\ell|\mathbf{a}_i, \beta_i, g_\nu, \mathbf{m}_\nu, \Delta_\nu)
\end{aligned}
$$



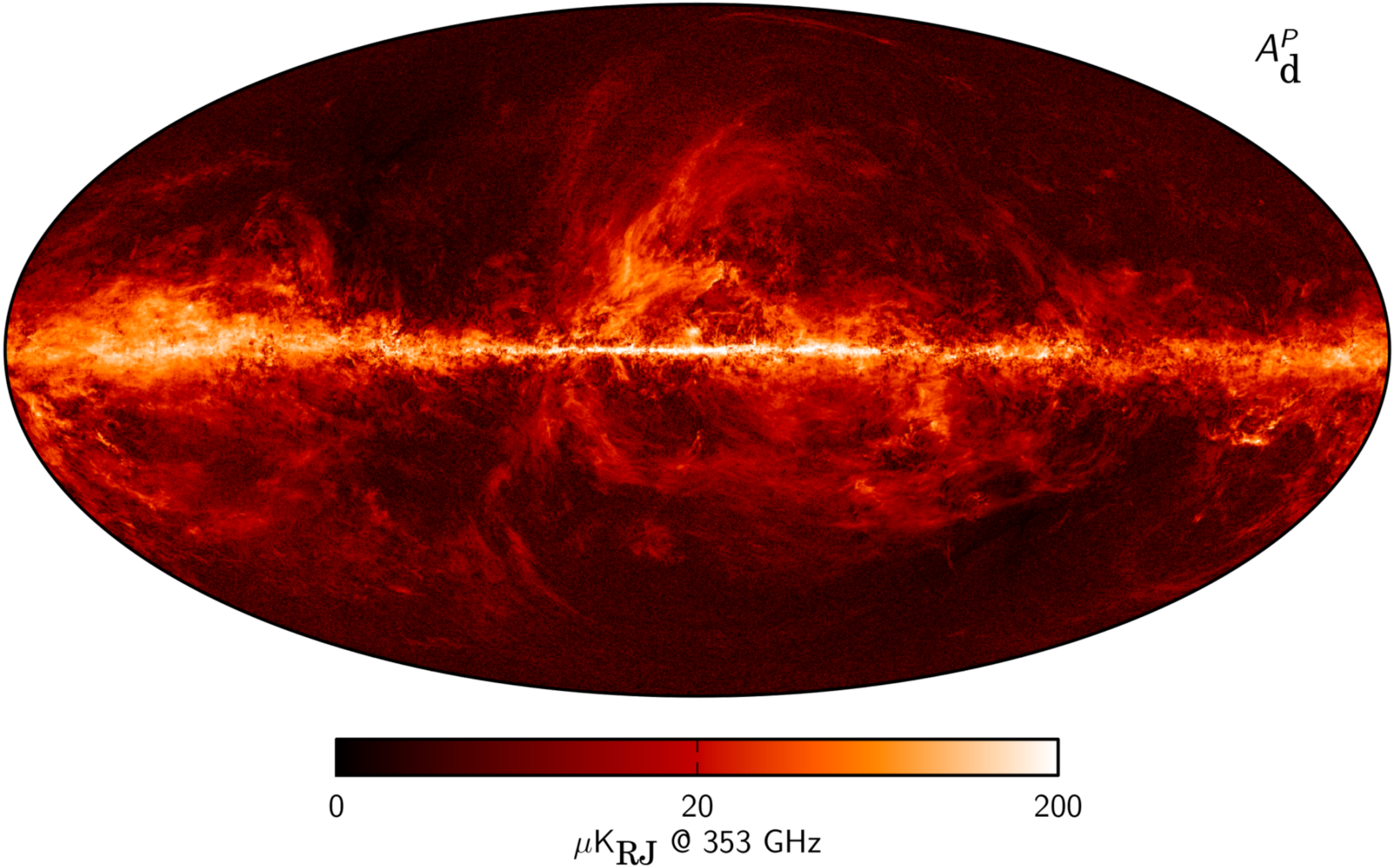
Polarization Sky Model



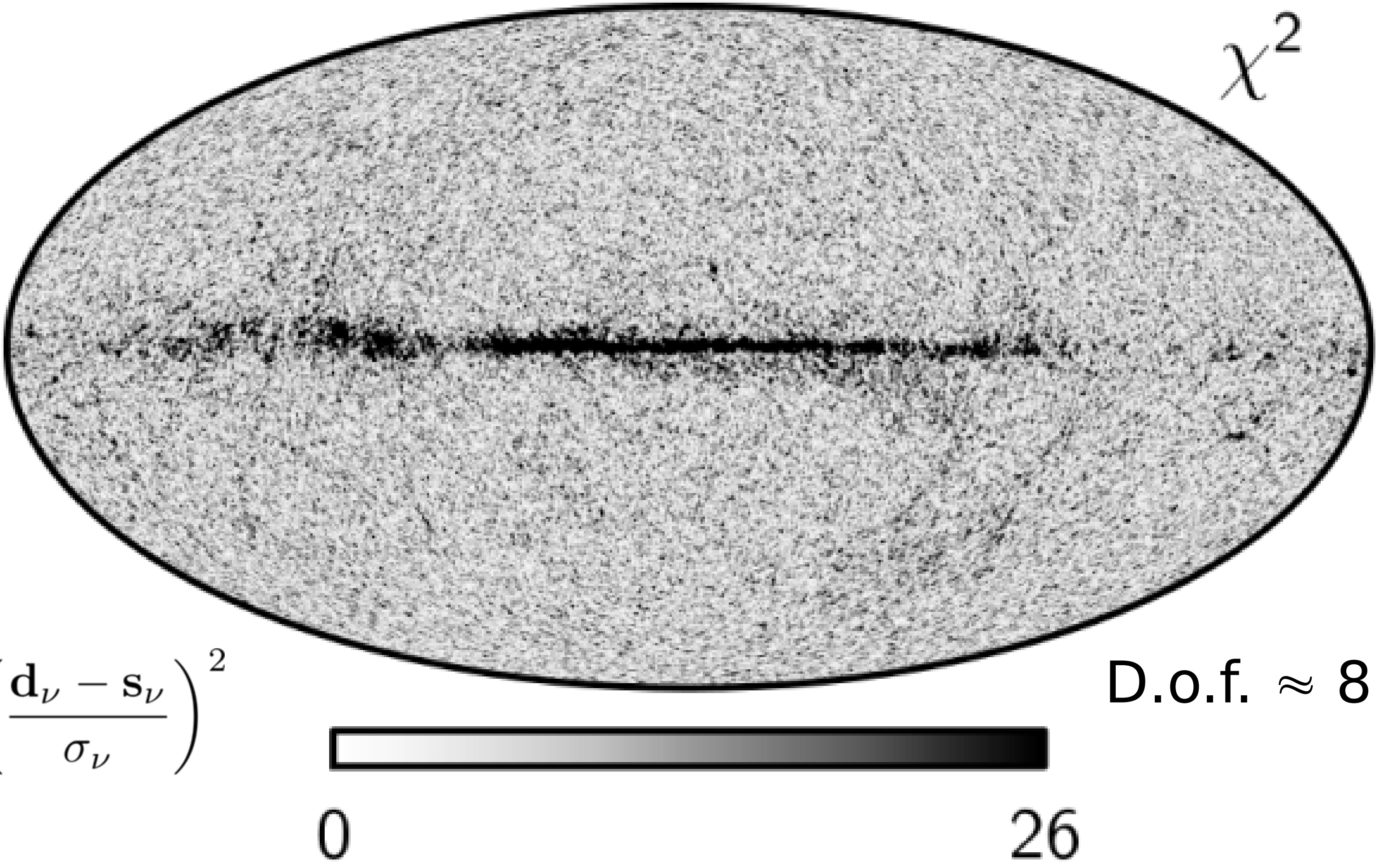
Polarized Synchrotron at 30 GHz



Polarized Thermal Dust at 353 GHz



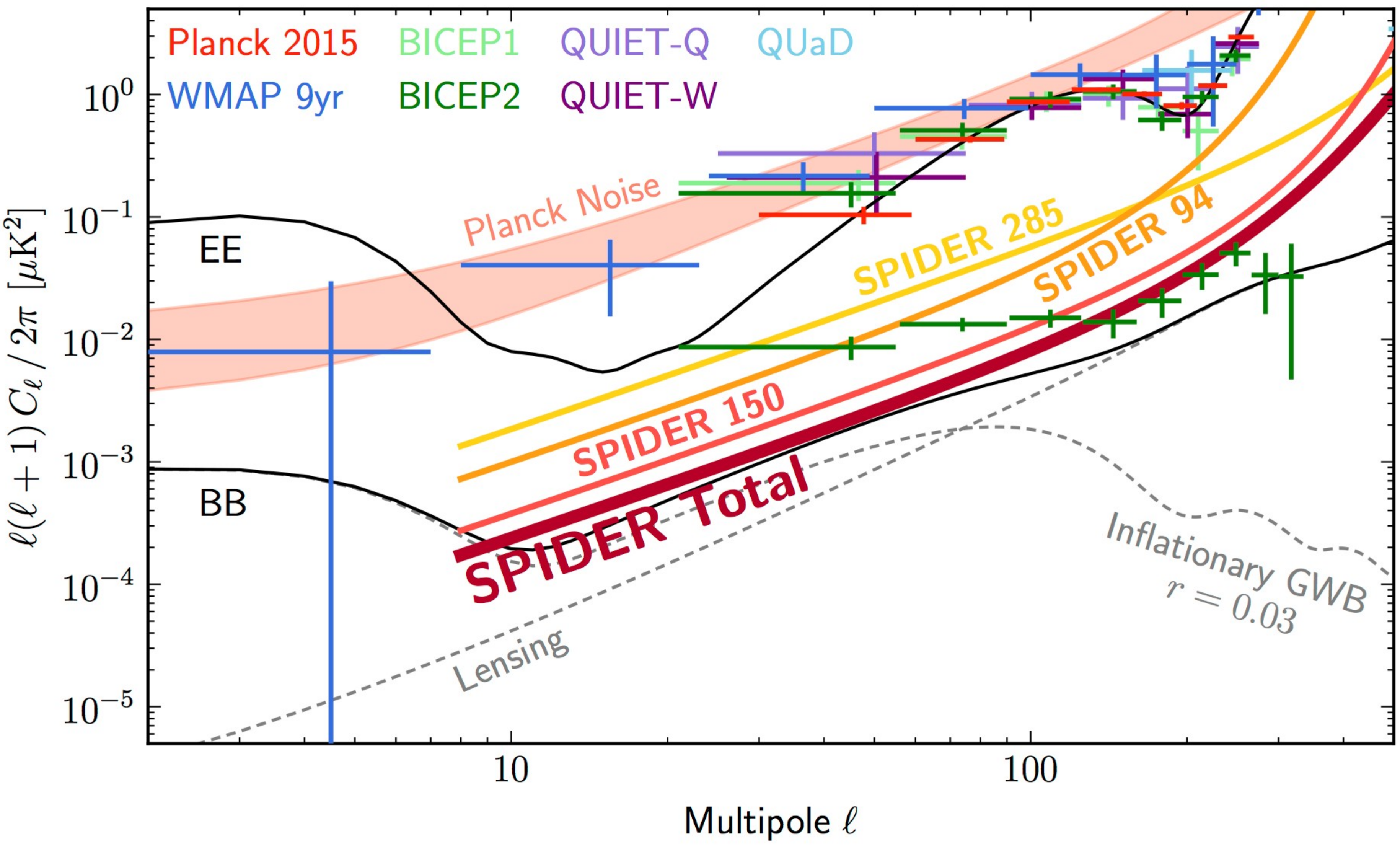
Goodness of Fit



$$\chi^2 = \sum_{\nu} \left(\frac{\mathbf{d}_\nu - \mathbf{s}_\nu}{\sigma_\nu} \right)^2$$

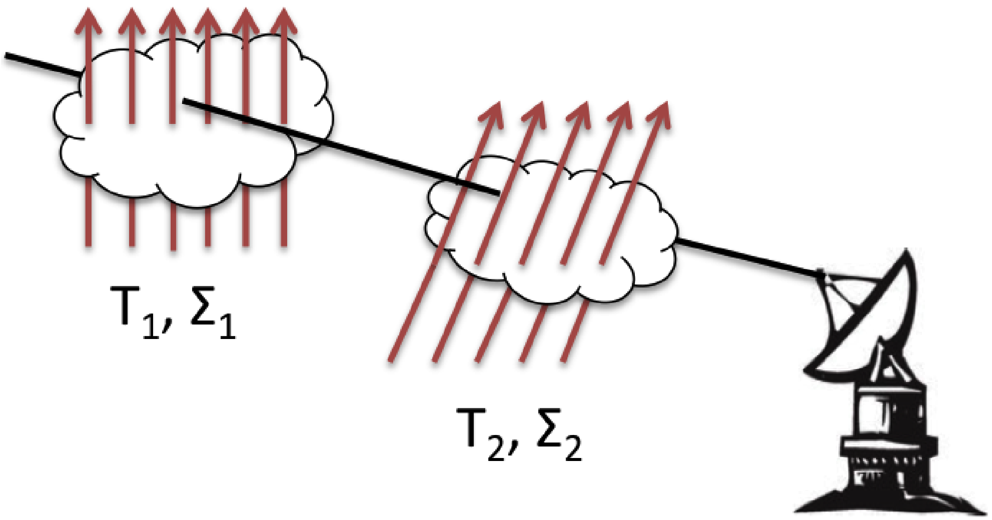
D.o.f. ≈ 8

SPIDER Sensitivity



Challenges of Modeling Dust

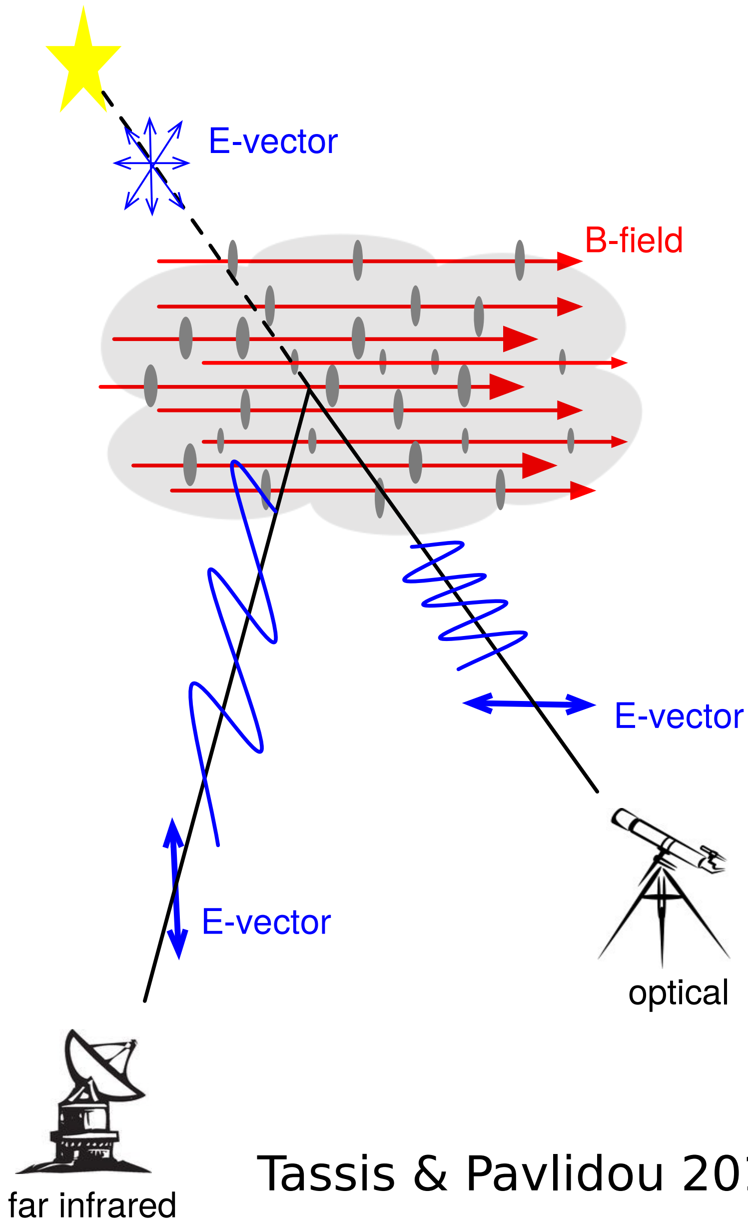
- Multiple clouds along the line of sight
- Clouds of different T may *dominate emission* at different frequencies
- Emission from each cloud can be modeled as a modified black body
- Total signal is the sum of emissions from different clouds along the l.o.s – not a true MBB



Tassis & Pavlidou 2015

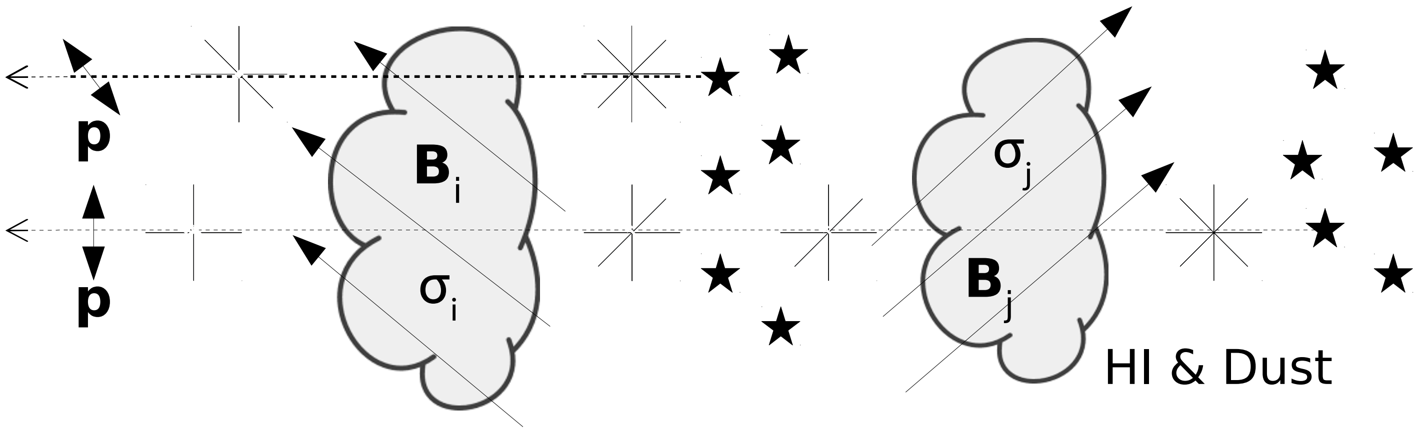
Optical Polorimetry of Starlight

- Dust absorption induces polarization of starlight through extinction
- Common origin with polarized dust emission
- Unique handle on 3D structure of the magnetic field within the dust clouds



Tassis & Pavlidou 2015

Tomography of Galactic B-Field

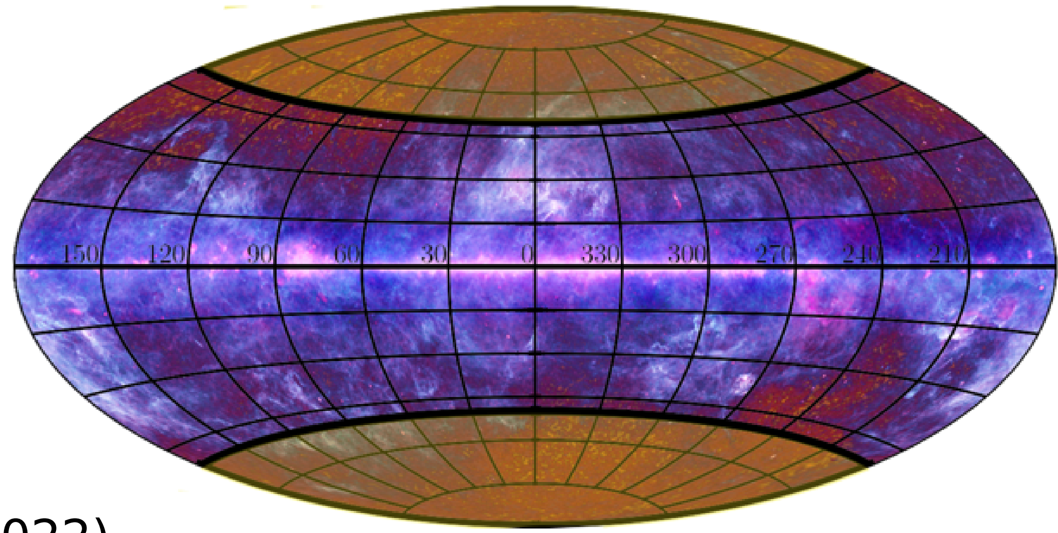


$$\boldsymbol{B}_i^{\perp} = \sqrt{4\pi\rho_i}\,\frac{\delta v_i}{\delta\theta_i}\left(\cos(\phi_i),\,\sin(\phi_i)\right)$$

- Stars at different distances act as lampposts
  - Stellar distances will be given by Gaia
- To model the magnetic field, we need, for each cloud:
  - Volume density ρ_i and velocity dispersion δv_i from HI surveys
  - Polarization angle Φ_i and dispersion $\delta\theta_i$ from PASIPHAE

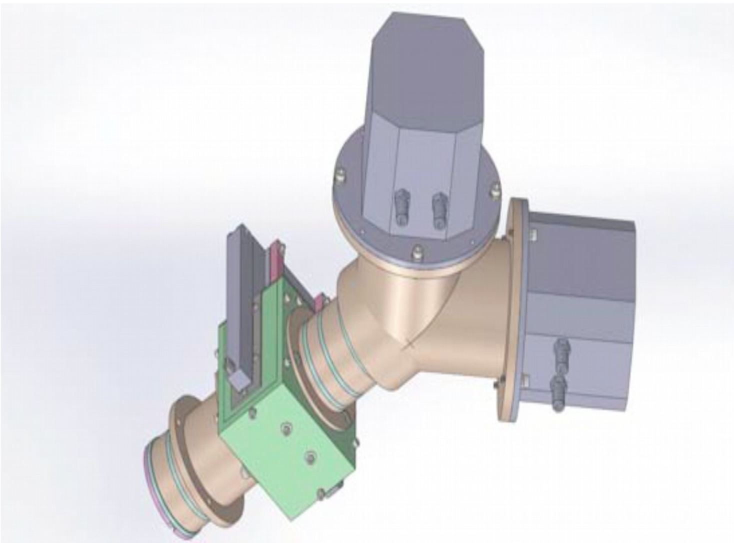
PASIPHAE Survey

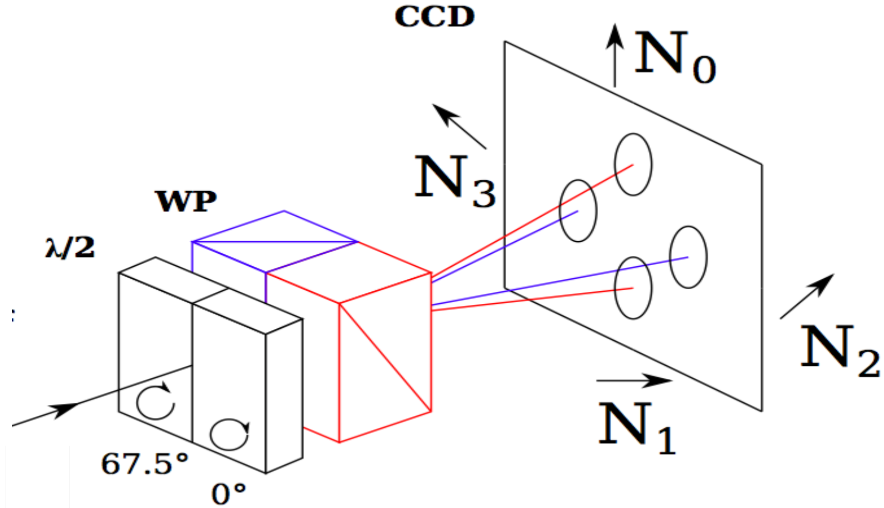
- Will measure polarization down to 0.3% at 3σ for all stars with Rmag < 16.5
- Survey will run concurrently in
- North (Skinas 1.3 m telescope) and south (South African Astronomical Observatory 1 m telescope) over 4 years (2019-2022)
- Will cover the sky at |b| ≥ 50⁰ over 9,000 sqdeg
- Will deliver over 10^6 confident polarization measurements



PASIPHAE

PASIPHAE's Design: WALOPs



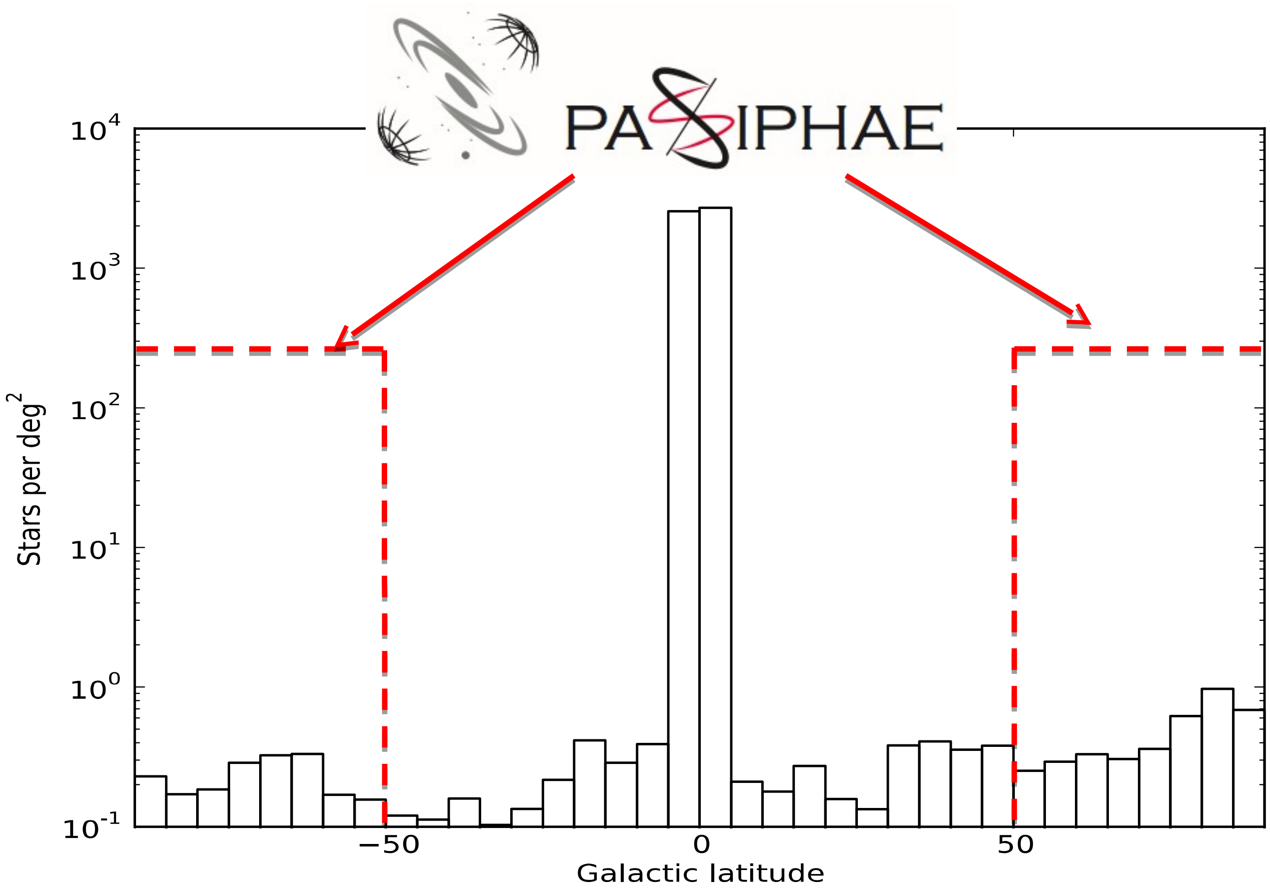


$$q = \frac{N_0 - N_1}{N_0 + N_1} \qquad u = \frac{N_2 - N_3}{N_2 + N_3}$$

For each point source:

- Split light in 4 linear polarization states differing by 22.5º
- Project each state in a different CCD
- Combine to obtain Stokes parameters
- Technology has successfully been tested with RoboPol, extended to wide FoV

PASIPHAE's Improvement



Stellar polarization measurements

PASIPHAE will increase the starlight polarization observations at high Galactic latitudes 1000 fold!

Dust Model with PASIPHAE

- Dust polarization signal is the sum of emissions from different clouds along the line of sight
- With the current dust model, Commander fits the dust amplitudes and spectral indices for each pixel separately ~ 50M parameters

$$\begin{pmatrix} Q(\nu) \\ U(\nu) \end{pmatrix} = \begin{pmatrix} a_p^Q(\hat{\boldsymbol{n}}) \\ a_p^U(\hat{\boldsymbol{n}}) \end{pmatrix} \cdot \left(\frac{\nu}{\nu_0}\right)^{\beta_p(\hat{\boldsymbol{n}})} \cdot B_\nu\left(T_d(\hat{\boldsymbol{n}})\right)\Big|_{p \in pixels}$$

- With the information from PASIPHAE about the polarization direction in each cloud, the fitting can be done with one parameter per cloud ~ 10^4 parameters

$$\begin{pmatrix} Q(\nu) \\ U(\nu) \end{pmatrix} = \sum_{i \in clouds} a_i N_H^i \begin{pmatrix} q_i(\hat{\boldsymbol{n}}) \\ u_i(\hat{\boldsymbol{n}}) \end{pmatrix} \cdot \left(\frac{\nu}{\nu_0}\right)^{\beta_i} \cdot B_\nu\left(T_d^i\right)$$

HI Surveys (N_H^i)

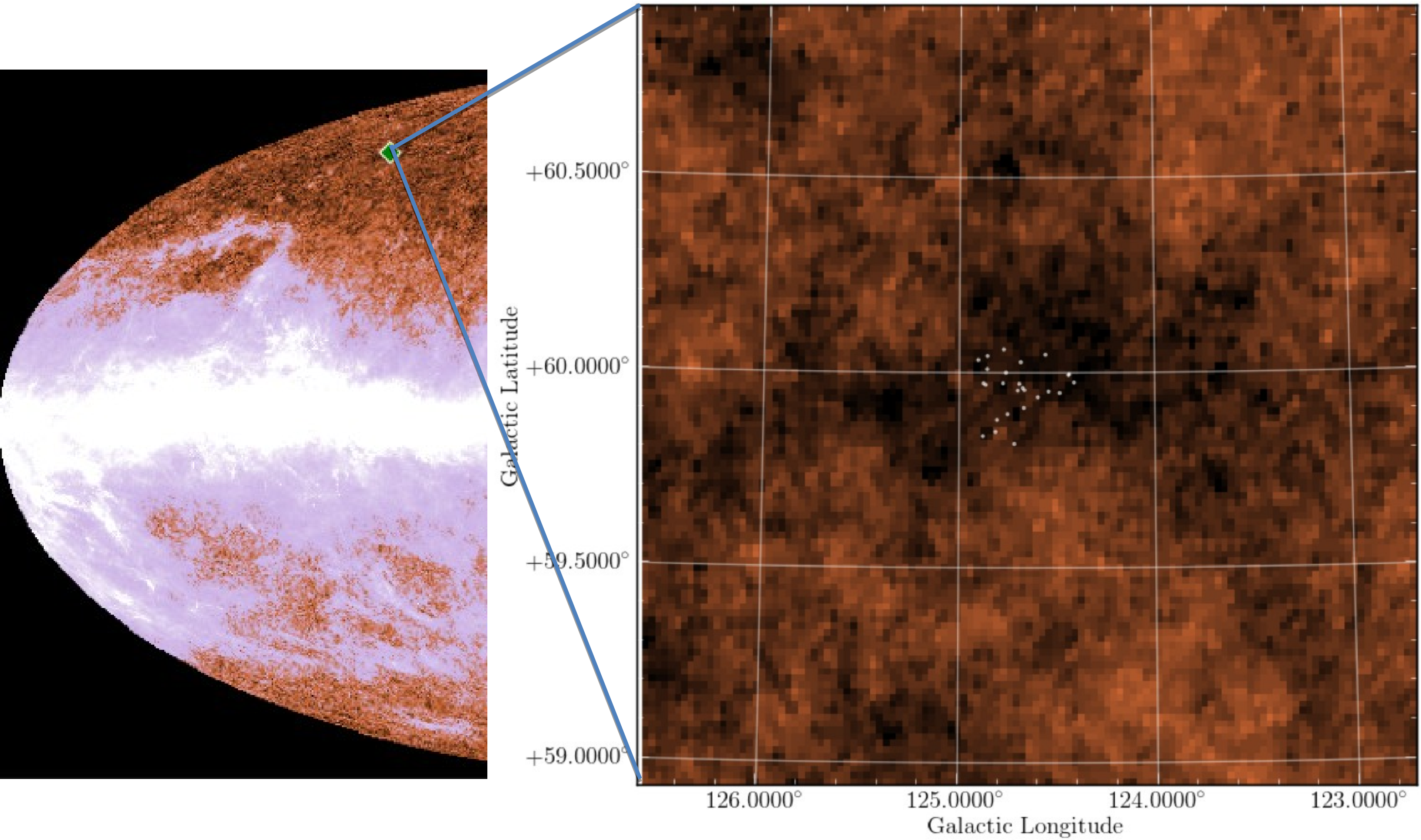
PASIPHAE ($q_i(\hat{\boldsymbol{n}})$, $u_i(\hat{\boldsymbol{n}})$)

Commander (a_i, β_i, T_d^i)

Summary

- Commander, a Gibbs sampling method with parametric foreground models, is a very powerful component sepatration software
- High sensitivity CMB experiments like Spider require a more accurate forground emission model
- Information about the polarization properties of individual dust clouds from PASIPHAE can be utilized to construct a simpler and more realistic dust polarization model
  - Would such a simplistic model be enough to capture the complexities of the physical signal to a full extend?
  - If not, the model can be used as a prior for a more rigorous parametric fitting

Is Starlight Polarized Enough at High |b|?

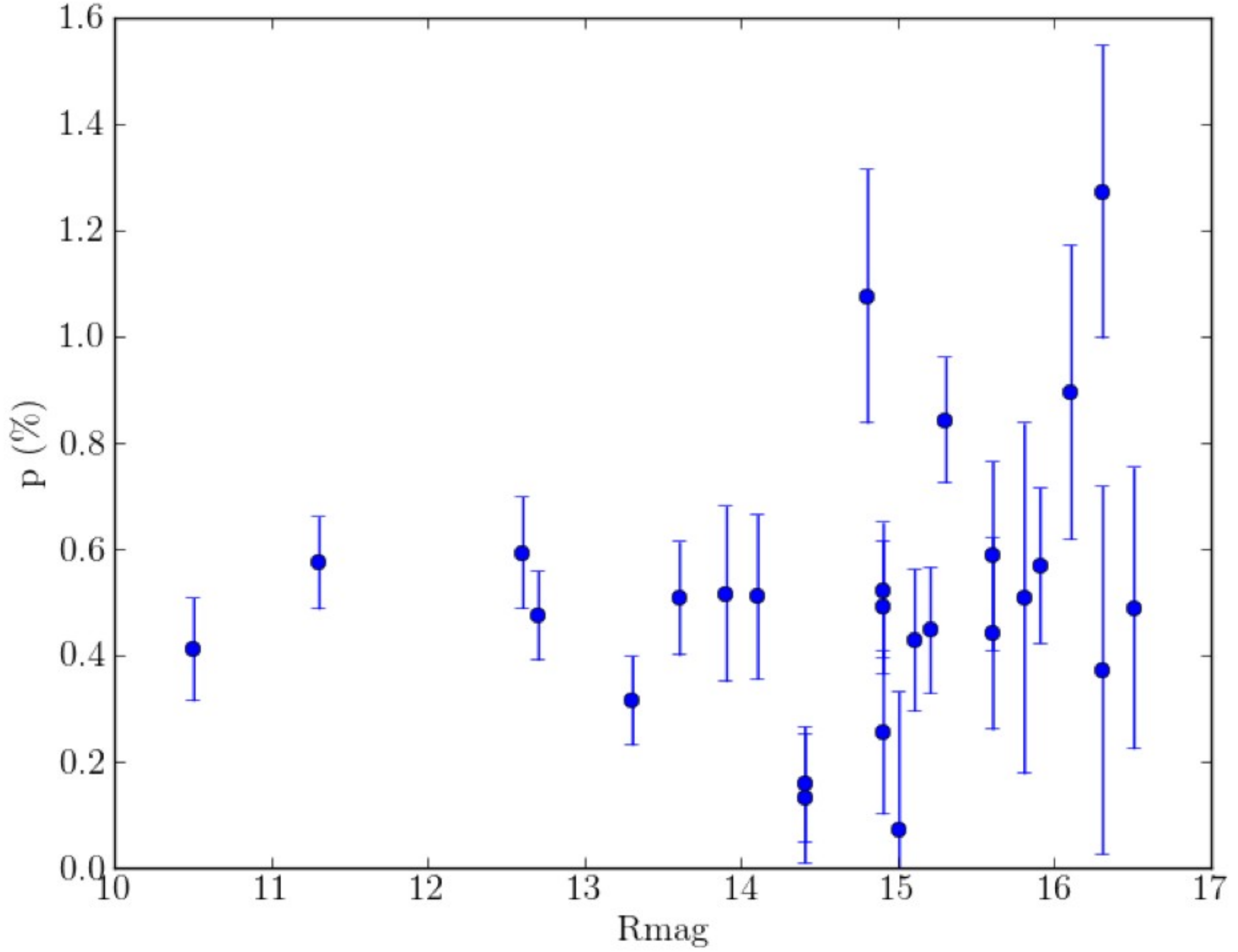


Go to the “darkest” spot - in dust emission according to Planck - of the northern sky and measure starlight polarization with RoboPol

Is Starlight Polarized Enough at High |b|?

YES!

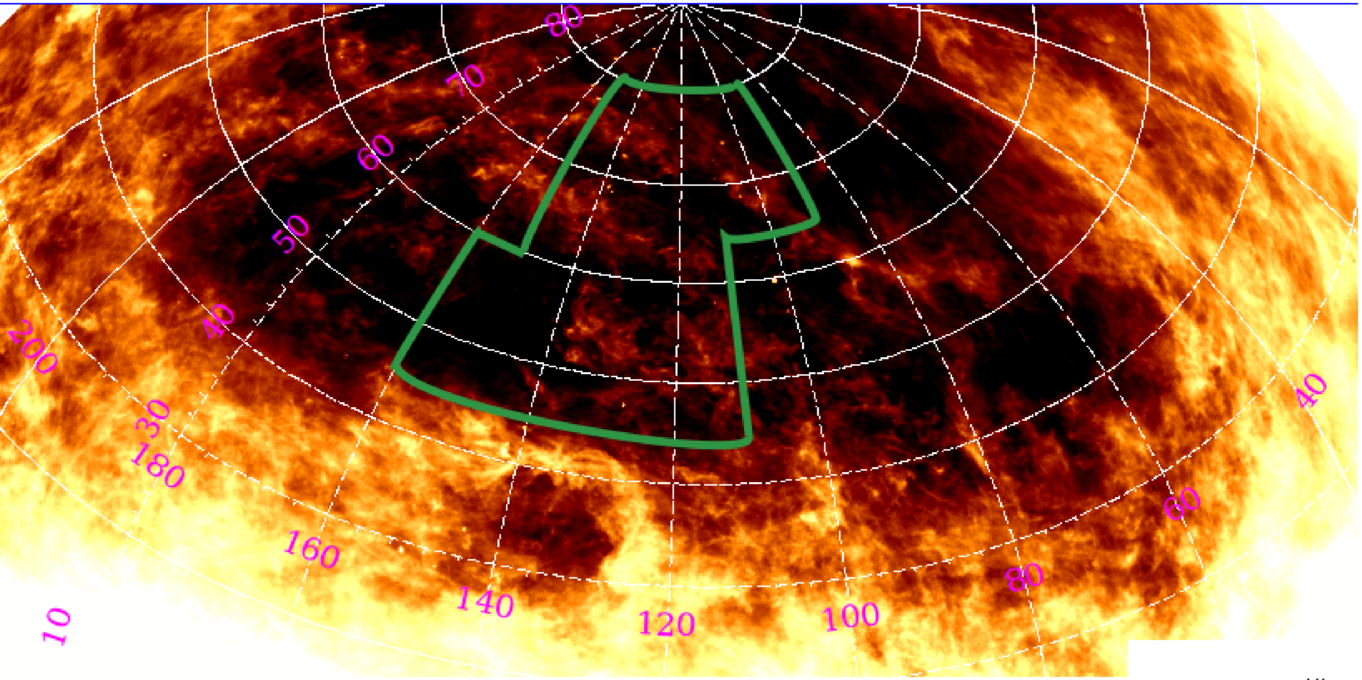
50% of stars polarized at > 0.4%

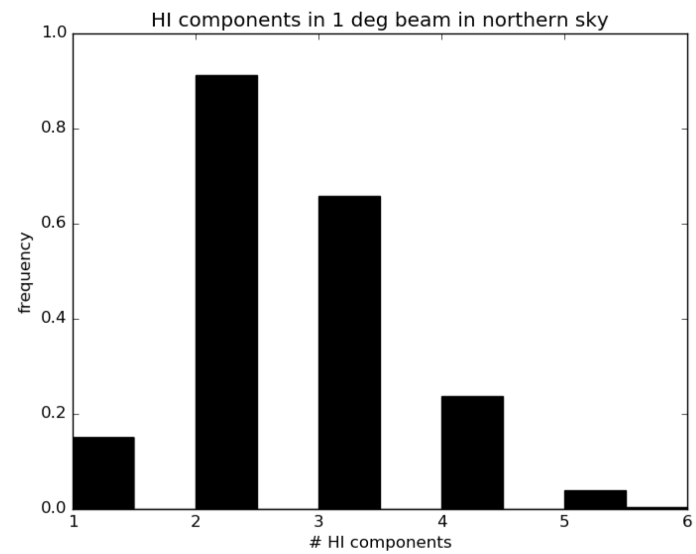


Panopoulou et al. in prep

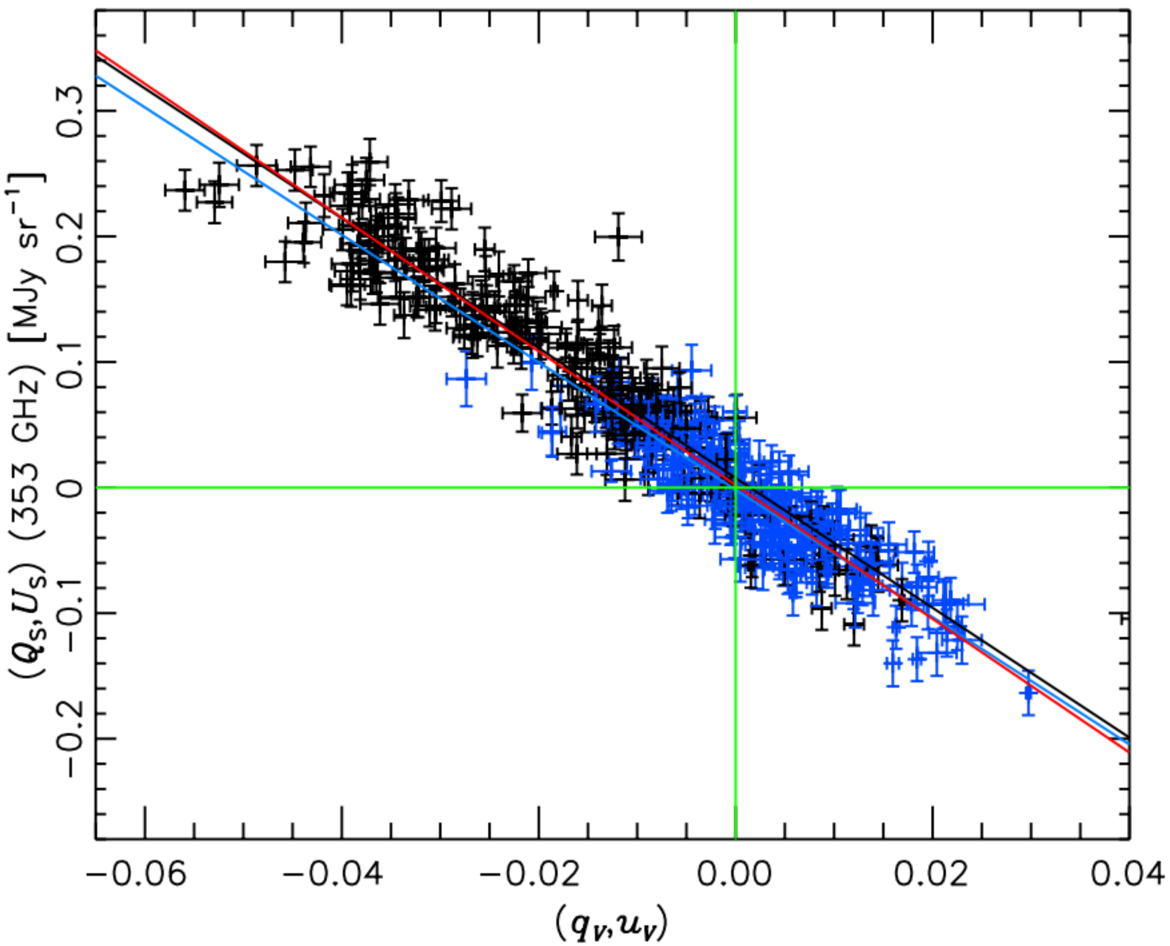
robopol

Q1: # of Clouds along the l.o.s.



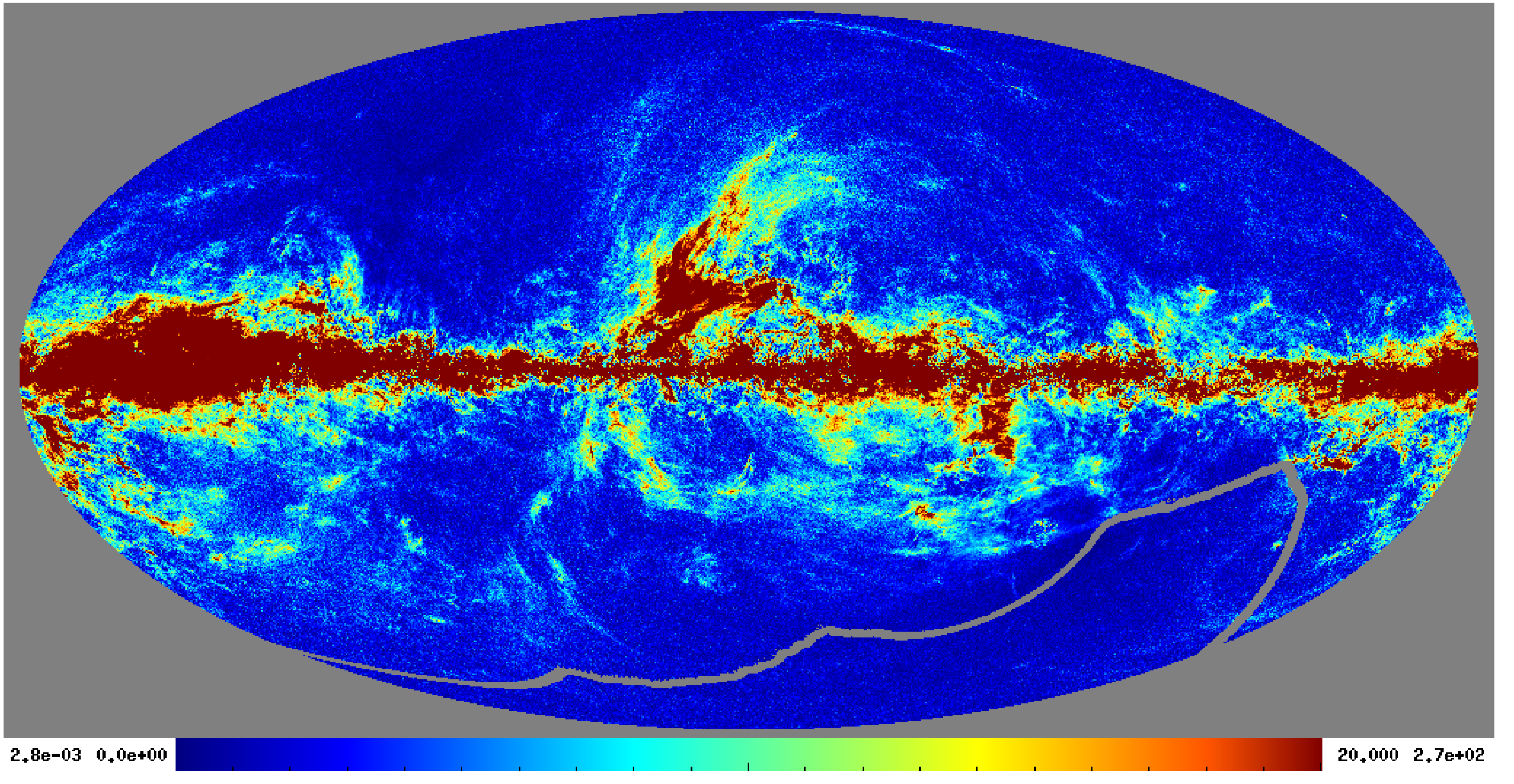


Q2: Dust Polarization & Stellar Polarization



Correlation of polarized intensity in emission with the degree of stellar polarization – *Planck* Intermediate Results XXI. 2015

SPIDER Sky Patch



SPIDER field on Planck Commander dust polarization amplitude map at 150 GHz