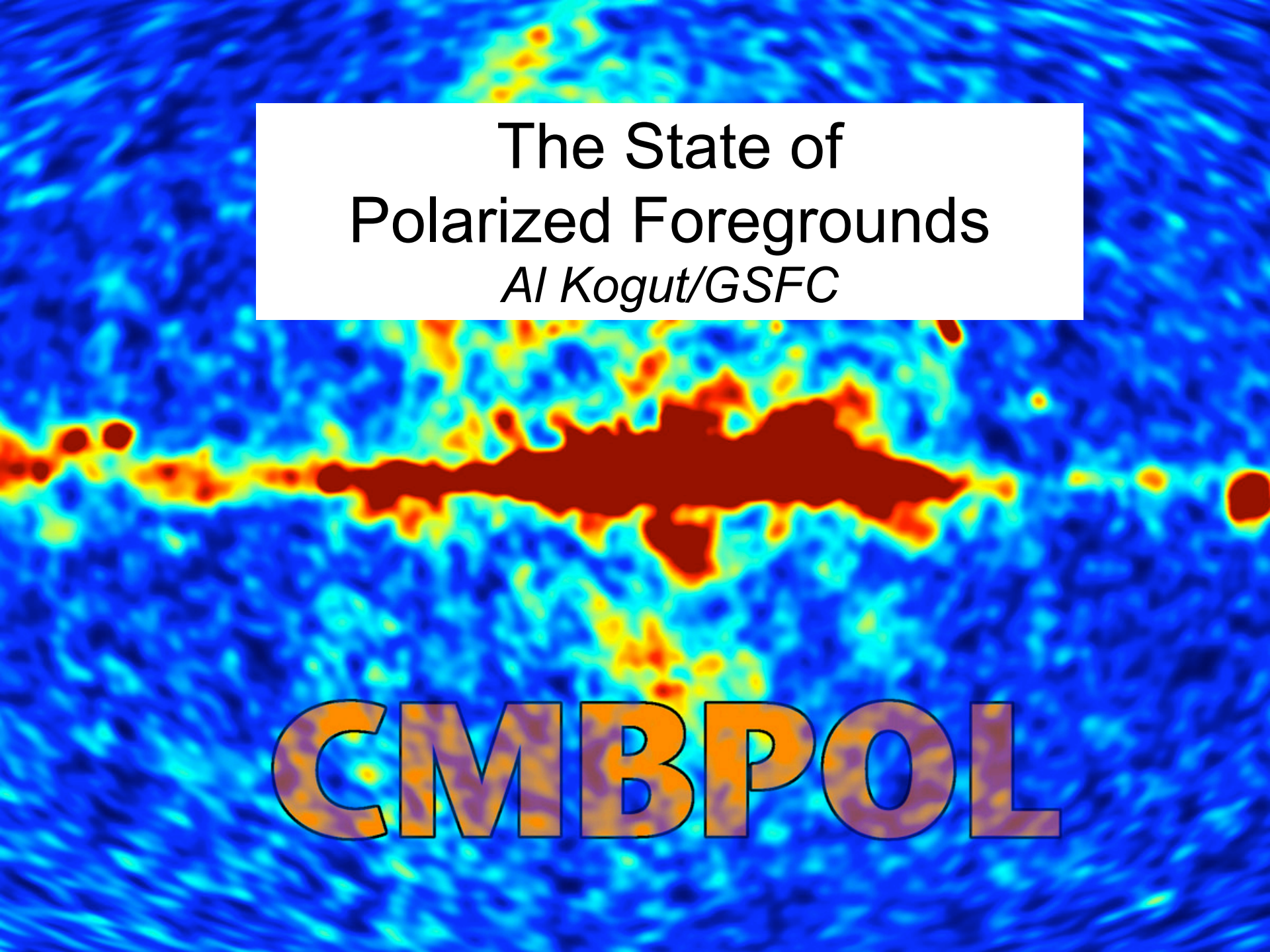
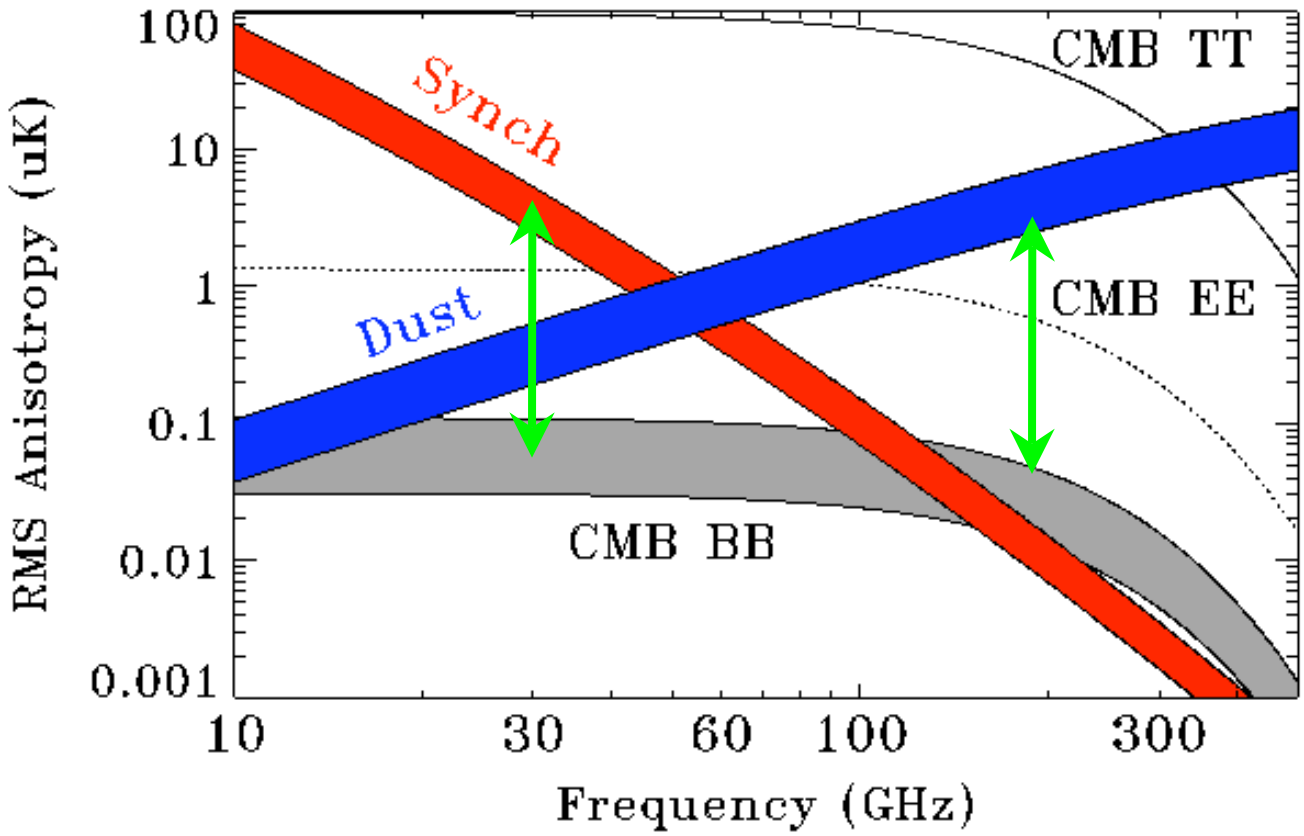
The State of Polarized Foregrounds

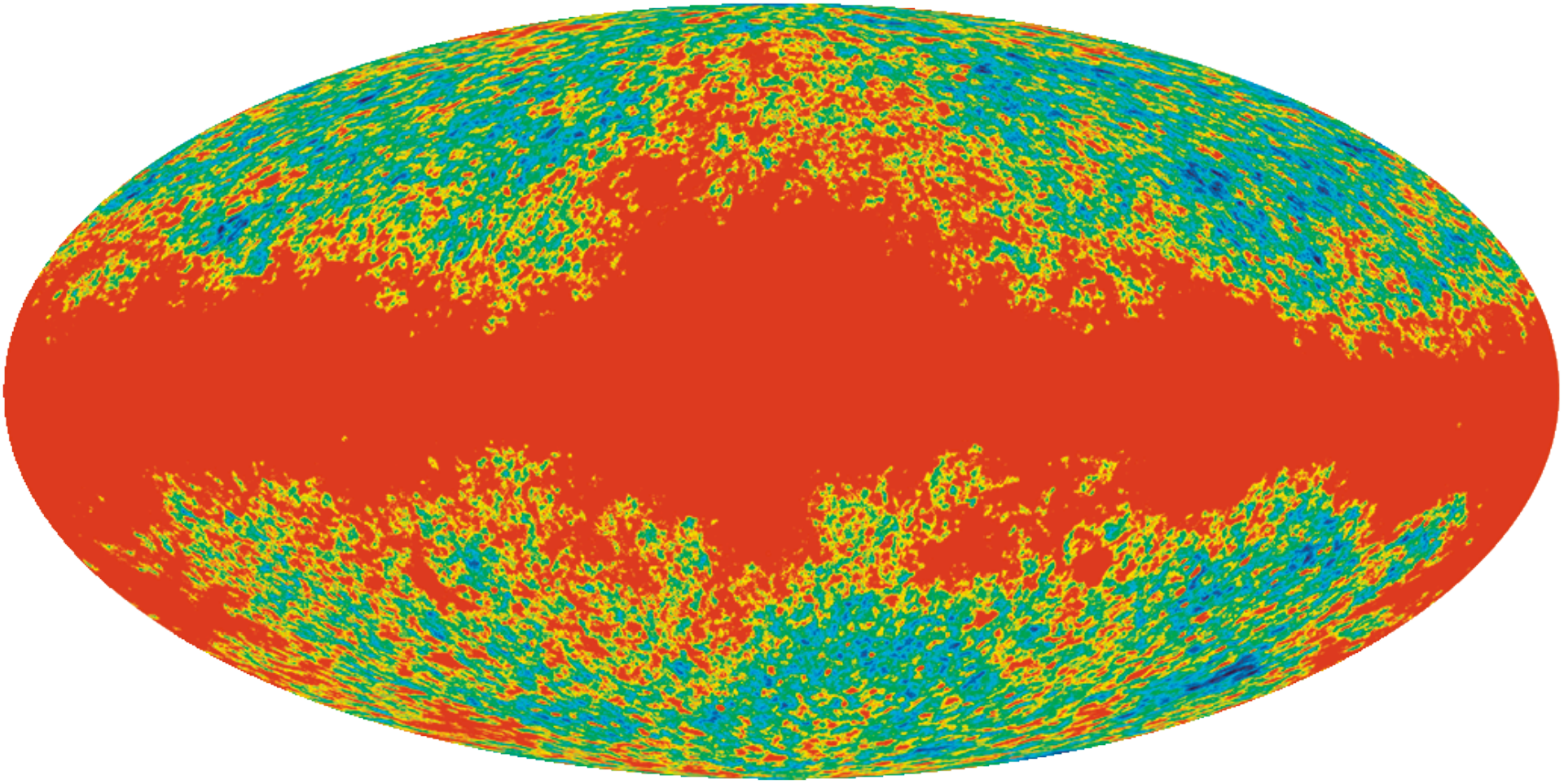
Al Kogut/GSFC



The Problem In A Nutshell

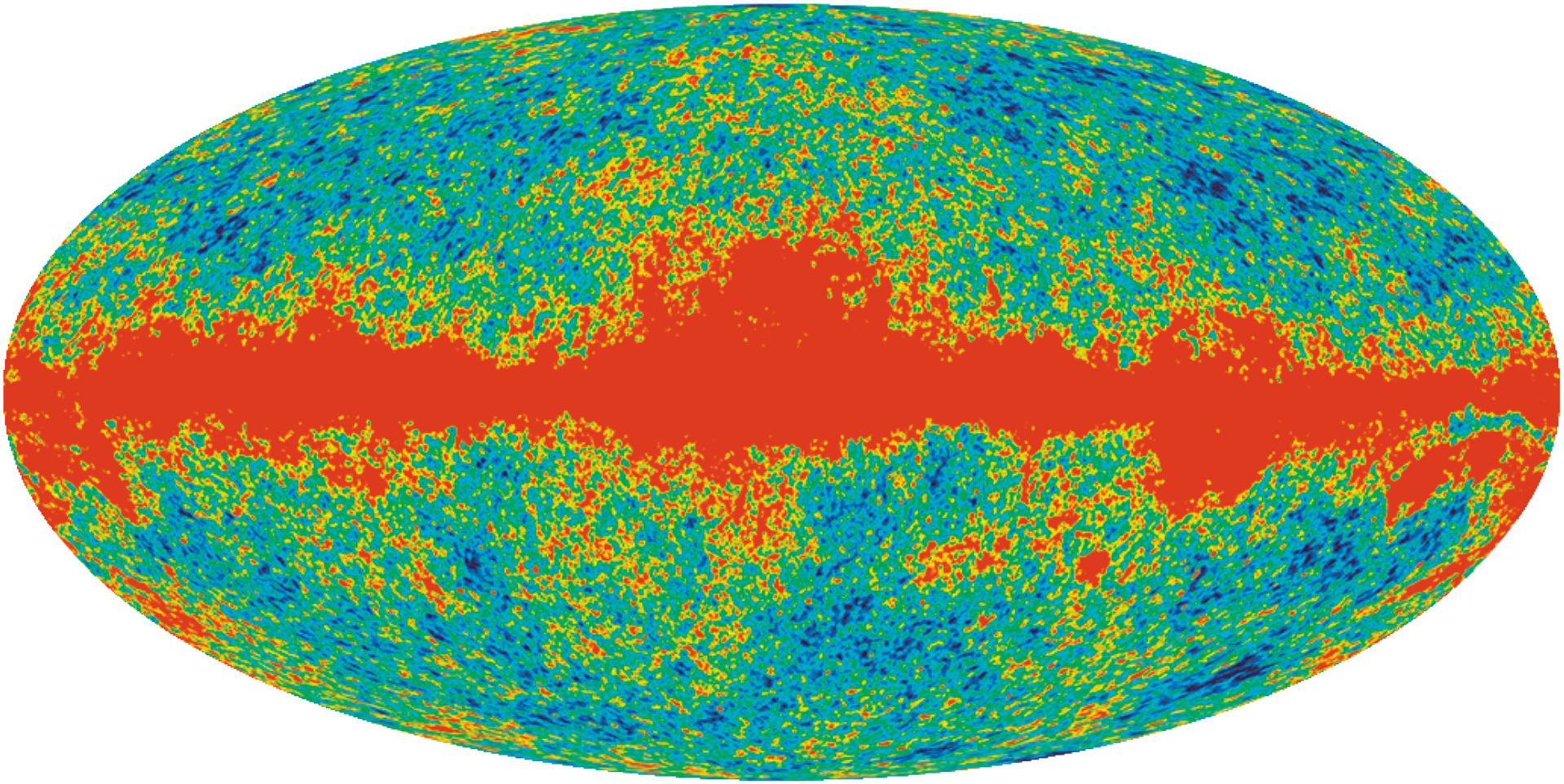


Galactic foregrounds are 2 orders of magnitude brighter than primordial B-mode polarization from 30 to 200 GHz



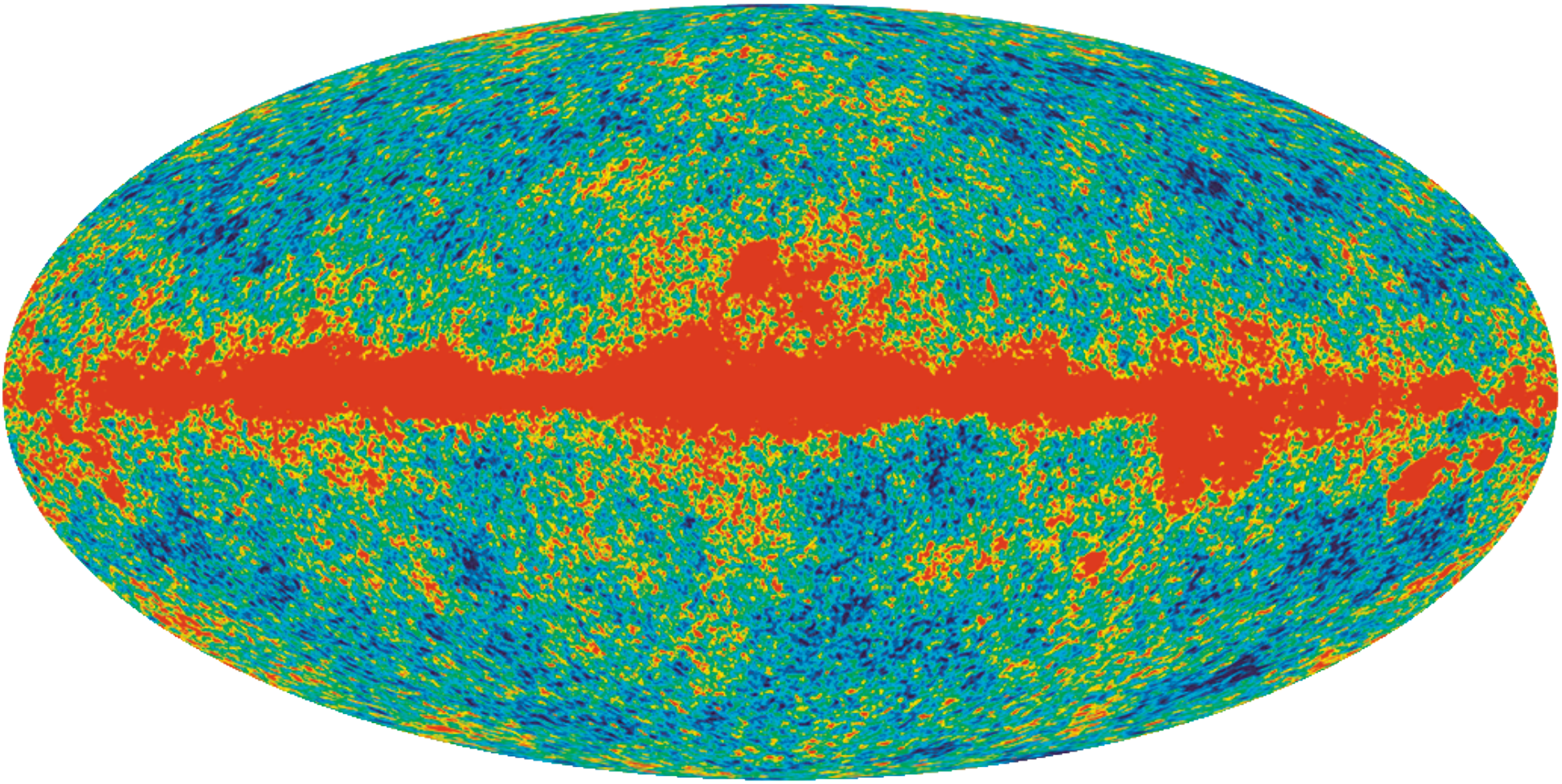
WMAP 5-yr 22 GHz

Intensity



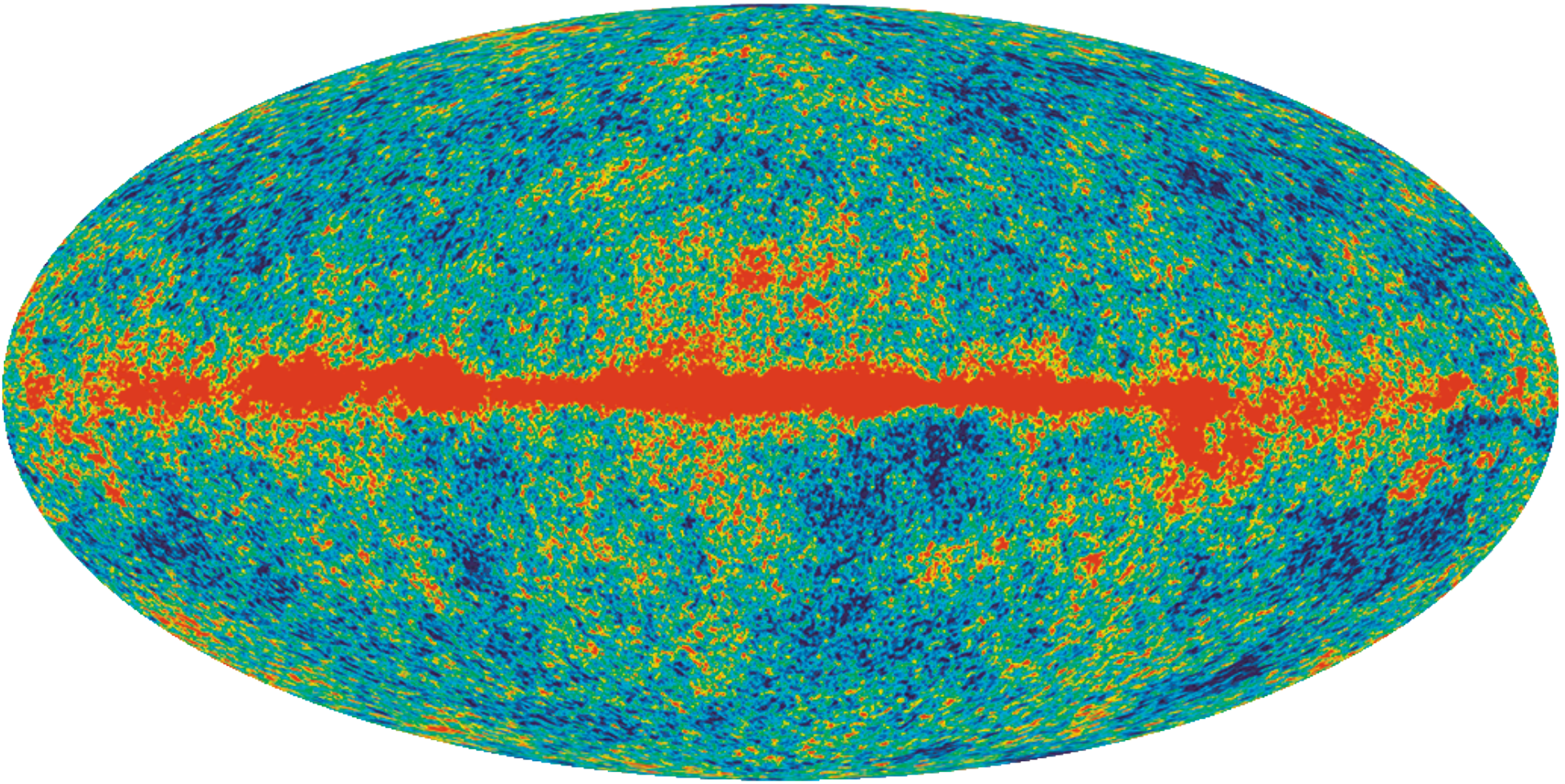
WMAP 5-yr 33 GHz

Intensity



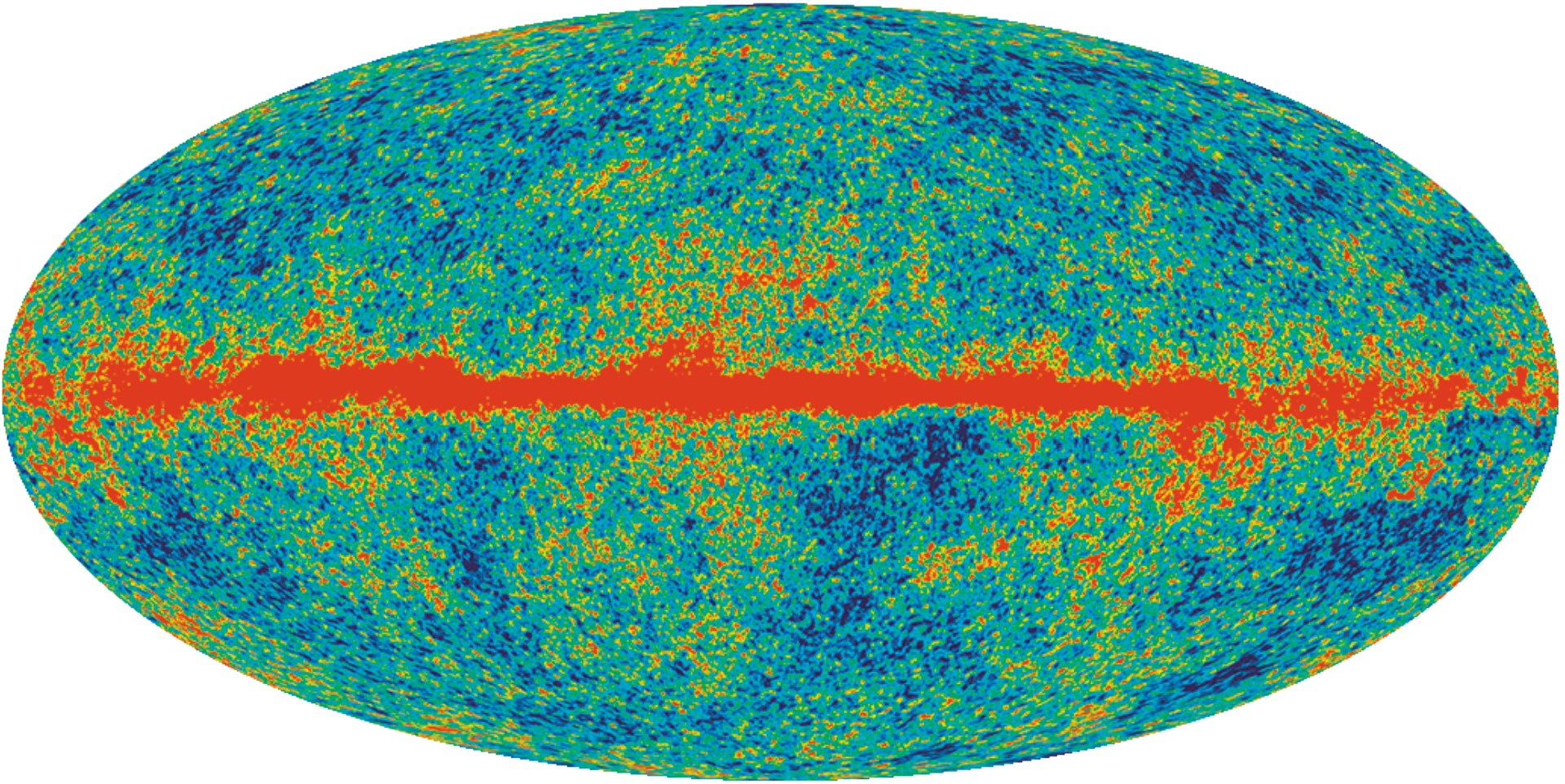
WMAP 5-yr 41 GHz

Intensity



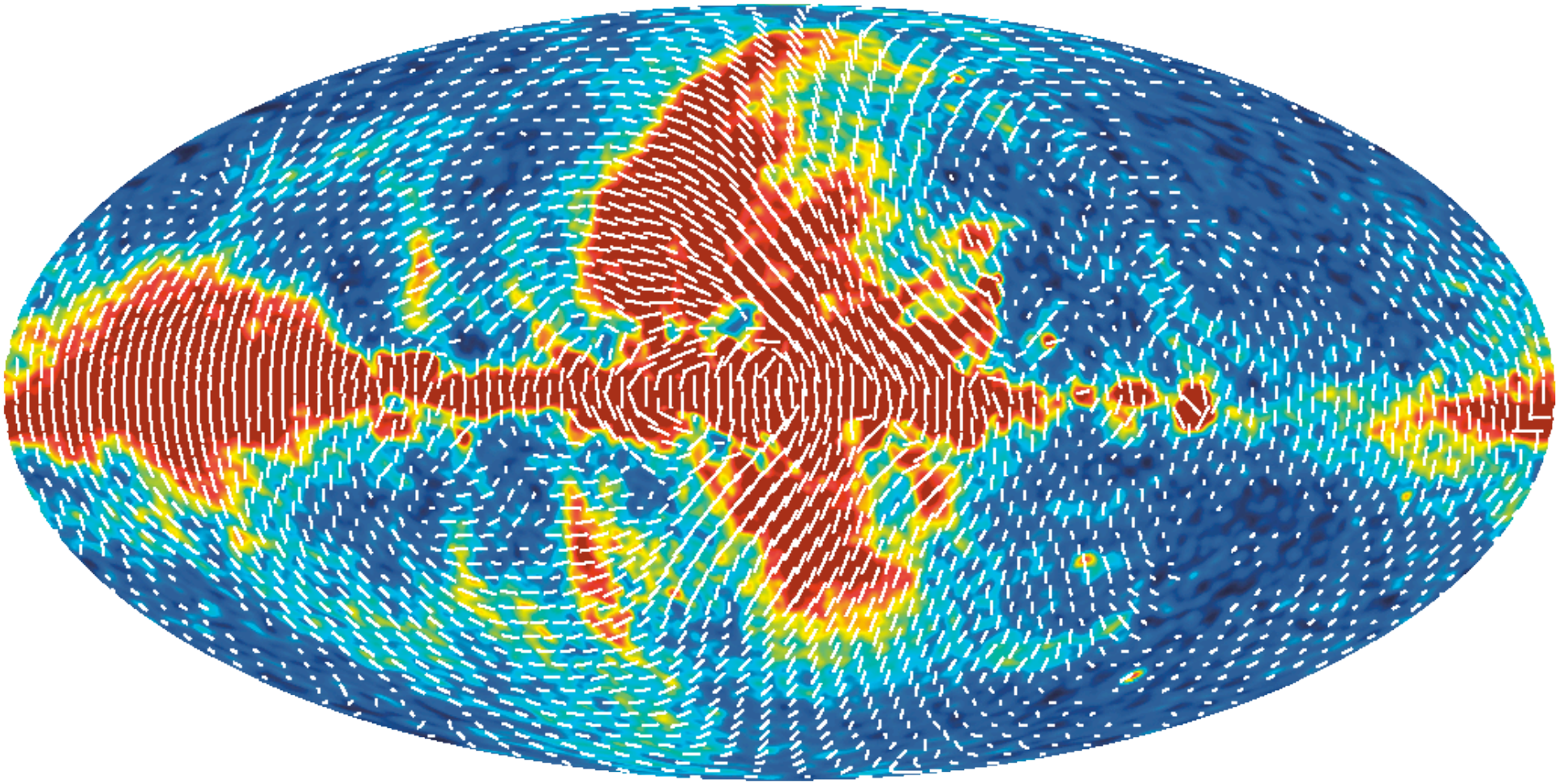
WMAP 5-yr 61 GHz

Intensity



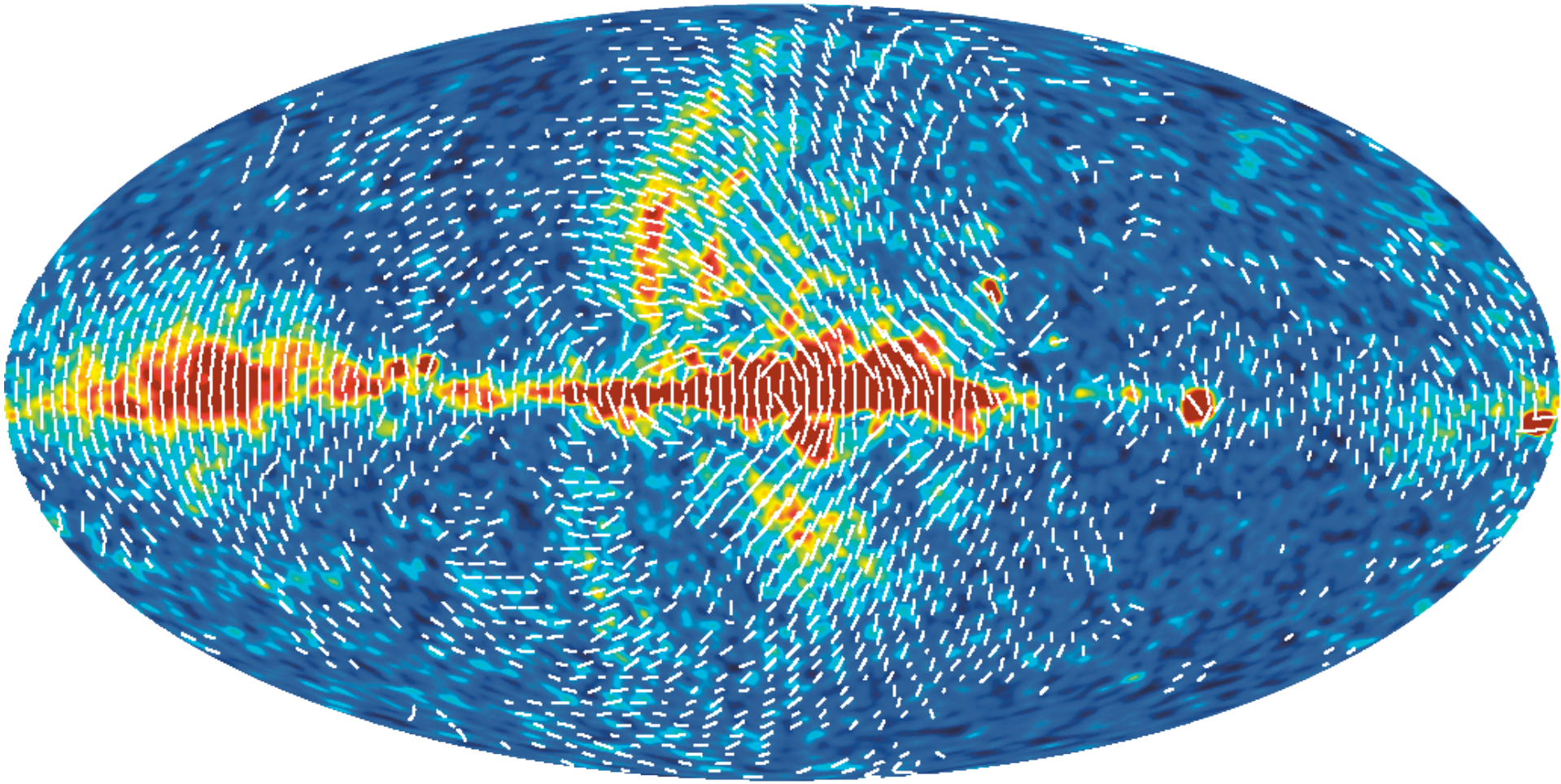
WMAP 5-yr 93 GHz

Intensity



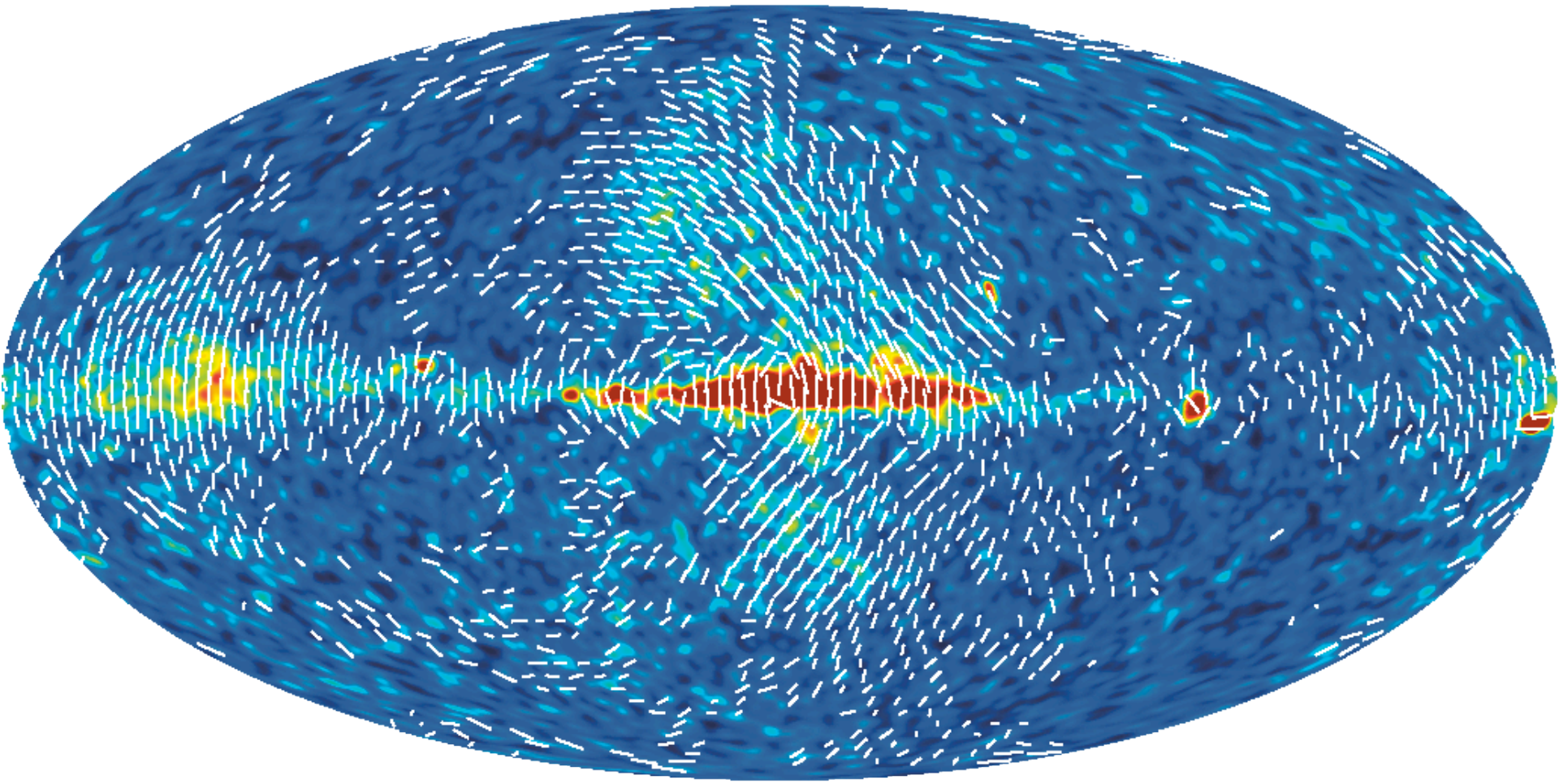
WMAP 5-yr 22 GHz

Polarization



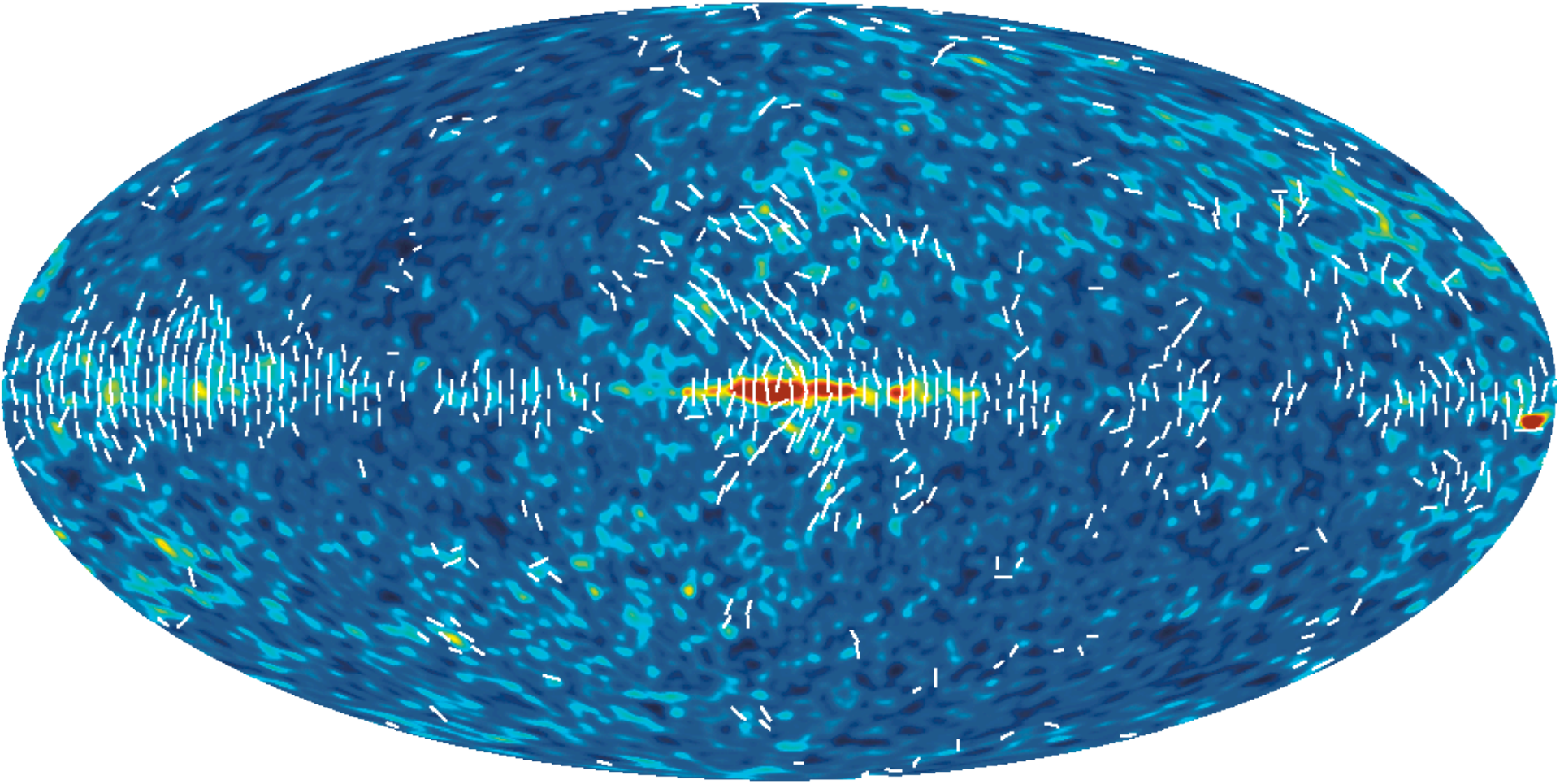
WMAP 5-yr 33 GHz

Polarization



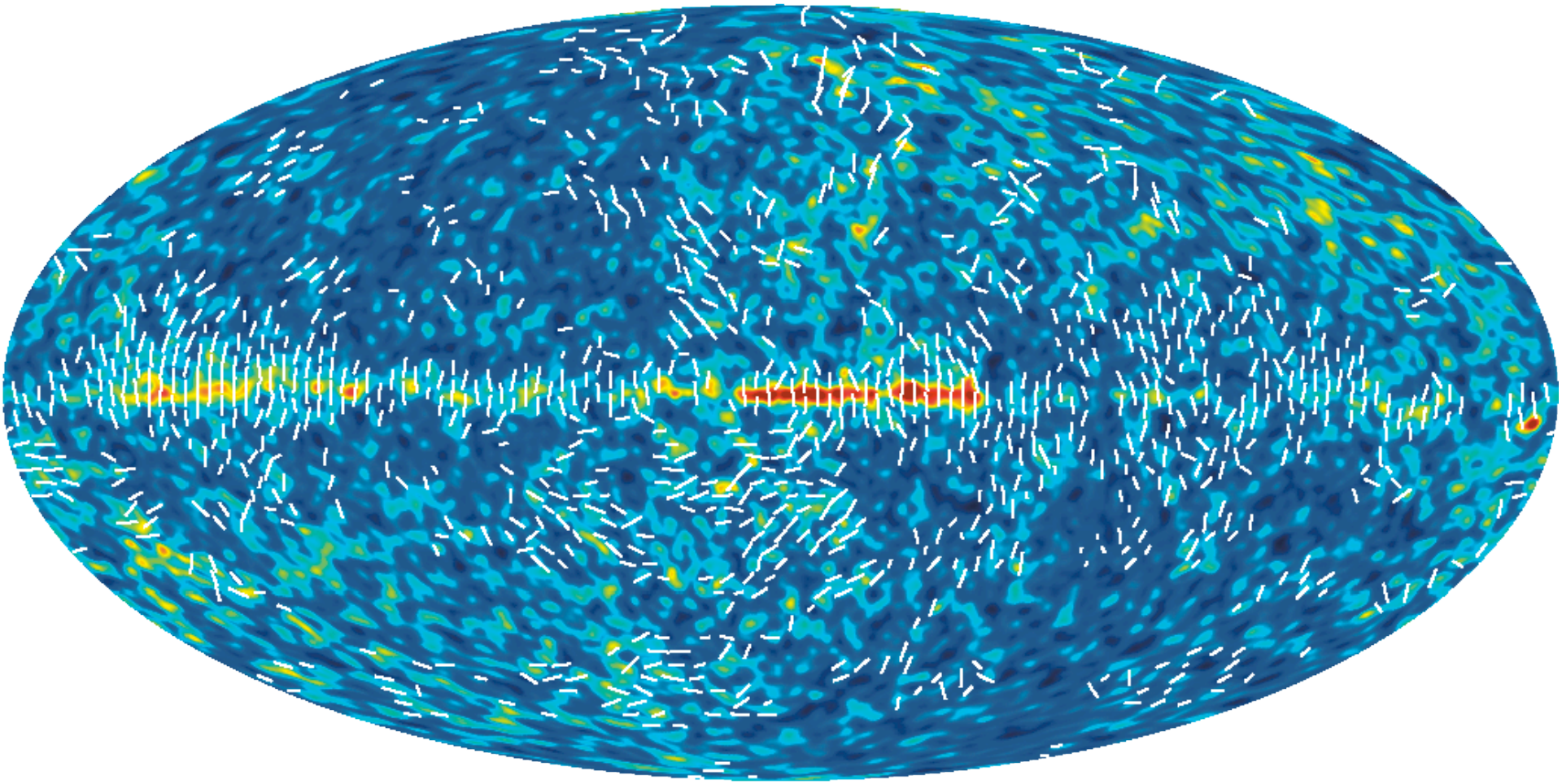
WMAP 5-yr 41 GHz

Polarization



WMAP 5-yr 61 GHz

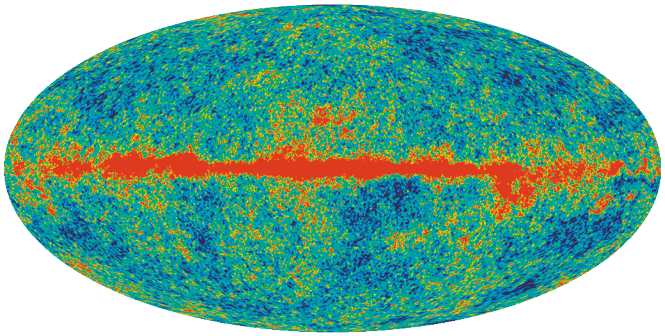
Polarization



WMAP 5-yr 93 GHz

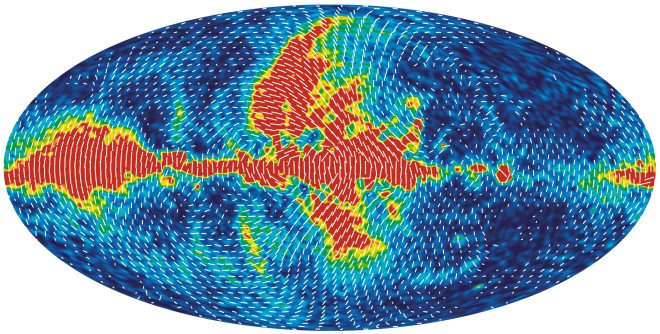
Polarization

This Time It's Different



Temperature Analysis: Signal-Dominated

- Mask brightest foregrounds in plane
- Light cleaning outside mask
- Templates, linear combination, …



Polarization Analysis: Foreground-Dominated

- Percent-level cleaning even at high latitude*
- More rigorous tests of methods
- Greater emphasis on astrophysics

* A few small patches are pretty clean, though

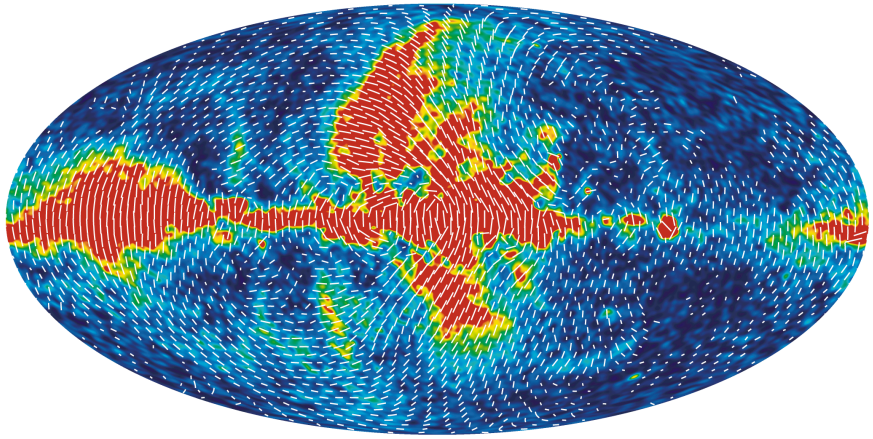
Synchrotron: Status and Issues

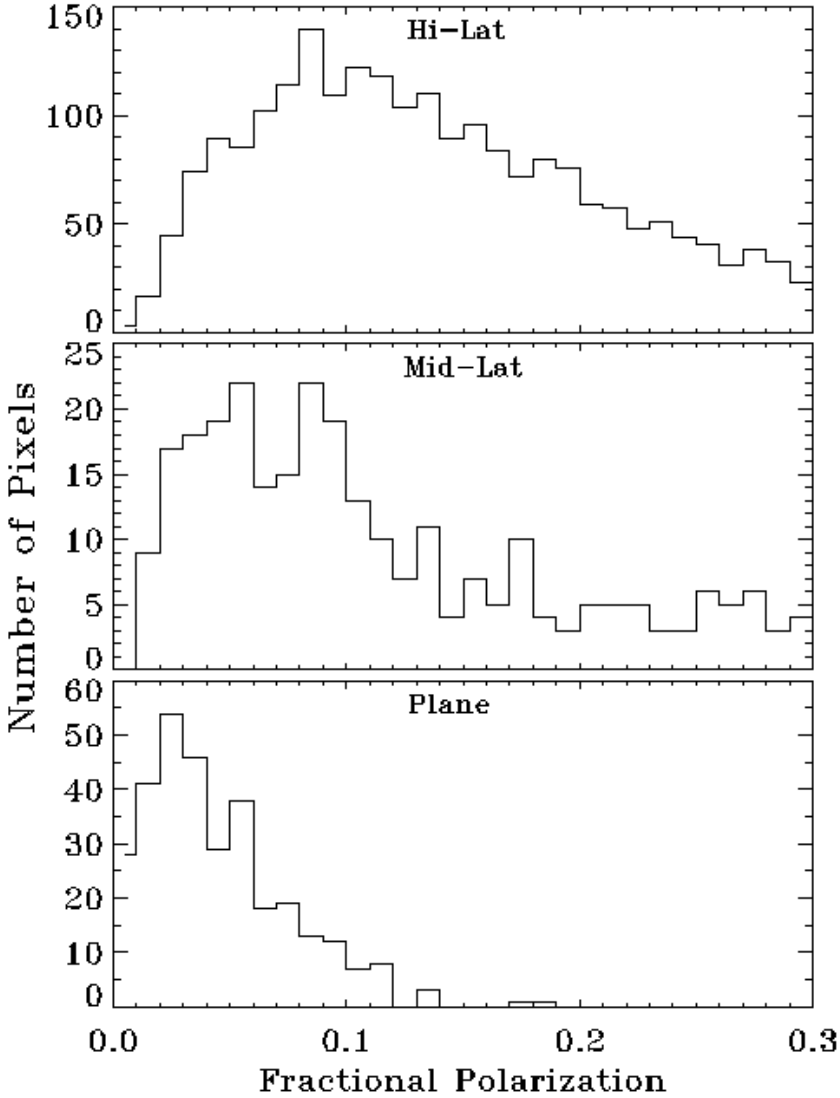
$$T_S^Q(\hat{n},\upsilon) = T_S^P(\hat{n},\upsilon_0)\cos 2\gamma(\hat{n})\left(\frac{\upsilon}{\upsilon_0}\right)^{\beta_S(\hat{n})+C(\hat{n})\log(\upsilon/\upsilon_0)}$$

$T_S^P(\hat{n},\upsilon_0)$	Morphology at reference frequency
$\gamma(\hat{n})$	Polarization angle (magnetic field)
$\beta_S(\hat{n})$	Spectral index
$C(\hat{n})$	Spectral curvature

Parameters model superposition of emission along line of sight

Polarized Synchrotron: Status & Issues
Morphology





Large Angular Scales: WMAP 5-yr Data

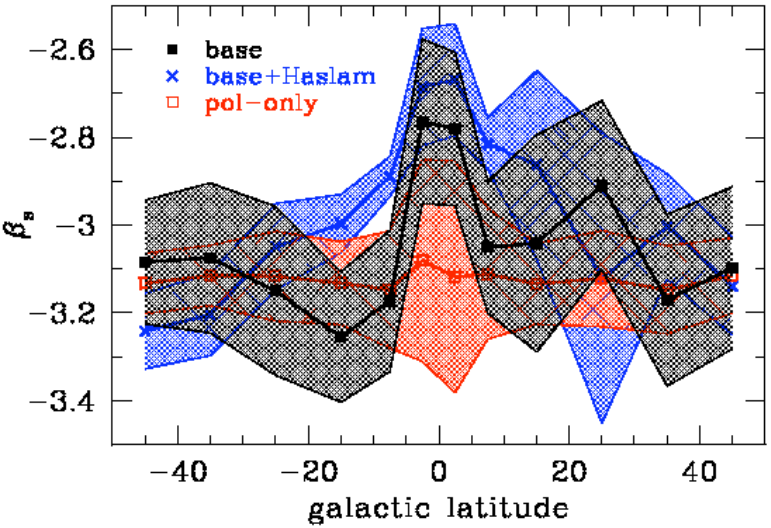
- Reasonable S/N ratio at 22 GHz
- 4° pixels: S/N > 3 over 90% of sky
- Measure power spectrum to l ~ 100

Fractional Polarization

- Few percent in plane, larger at high lat
- Depolarization via line-of-sight effects
- Confusion from unpolarized stuff

Kogut et al. 2007, ApJ, 665, 355

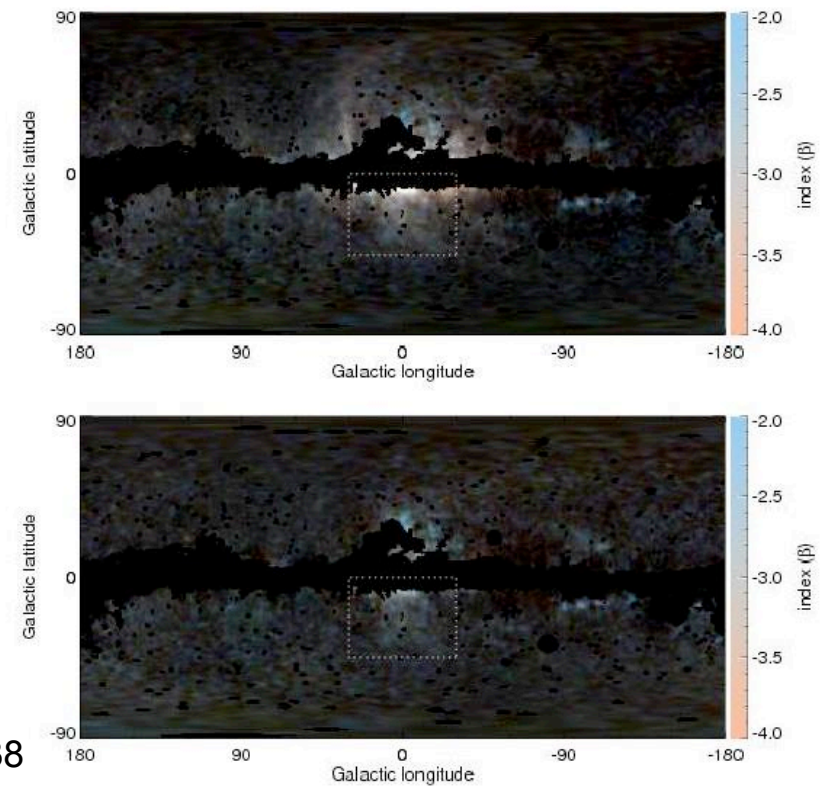
Polarized Synchrotron: Status & Issues
Spectral Index



Gold et al. 2008, arXiv:0803:0715

Just beginning to measure $\beta_S(\hat{n})$

- Flatter in plane, steeper at high lat
- Limited by S/N in polarization
- Limited by confusion in intensity



Room for Improvement:

- S/N in polarization
- Confusion: Multiple components along same line of sight
- Cosmic ray connection (GALPROP project)

Dobler & Finkbeiner 2007, arXiv:0712:1038

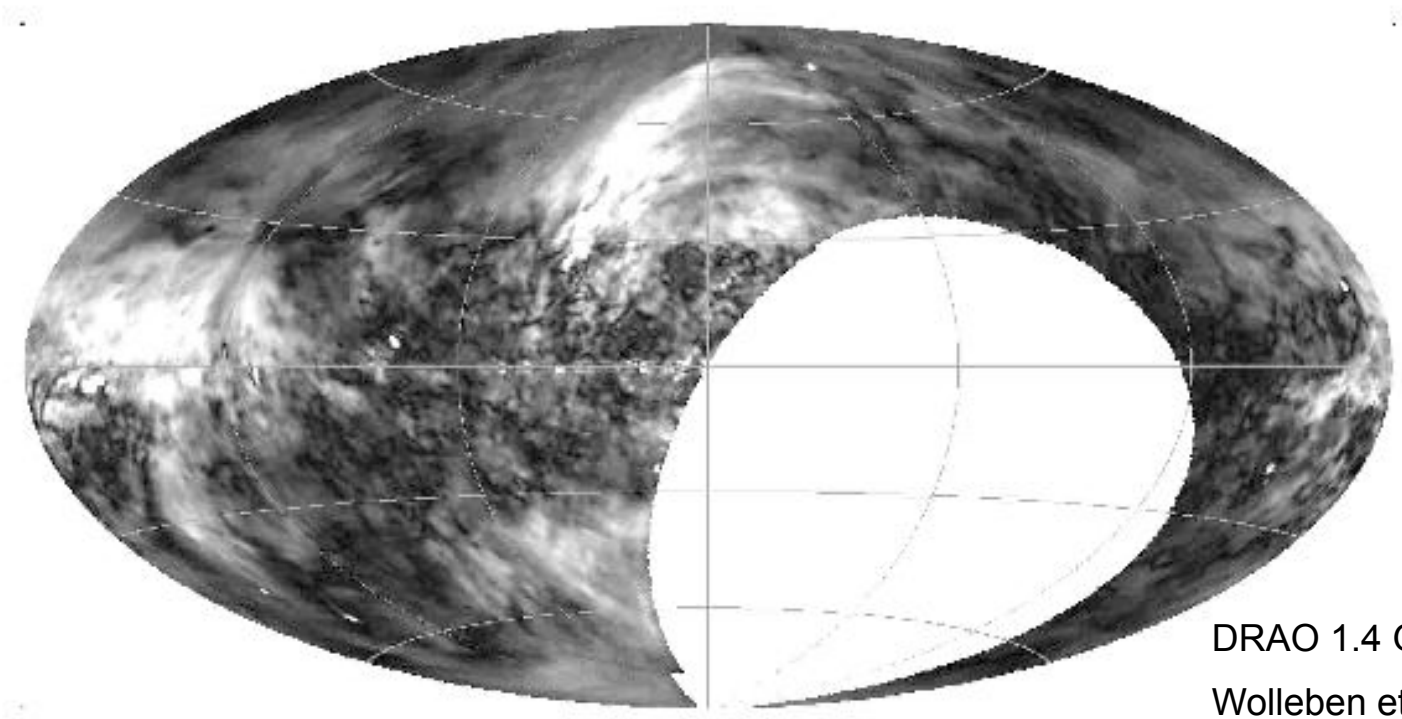
Polarized Synchrotron: Status & Issues

Small-Scale Features

- Interferometric maps at low frequencies
- Heavily contaminated by Faraday rotation
- Waiting for sensitive mm-wave survey

Spectral curvature

- No convincing detection yet
- Expected from cosmic ray data
- Curvature variation across sky?



DRAO 1.4 GHz polarization

Wolleben et al. 2005, A&A, 448, 411

Dust: Status and Issues

$$T_d^Q(\hat{n},\upsilon) = \sum_{i=1}^{k} w_i\, \varepsilon_i(\hat{n},\upsilon)\ \cos 2\gamma_d(\hat{n})\ \kappa_i \left(\frac{\upsilon}{\upsilon_0}\right)^{\beta_i} B_\upsilon(T_i(\hat{n}))$$

$T_i(\hat{n})$	Dust temperature
$\varepsilon_i(\hat{n},\upsilon)$	Fractional polarization
$\gamma_d(\hat{n})$	Polarization angle (magnetic field)
β_i	Spectral index
κ_i	Emissivity
w_i	Weight (normalization)

Admixture of species and emitting regions along line of sight

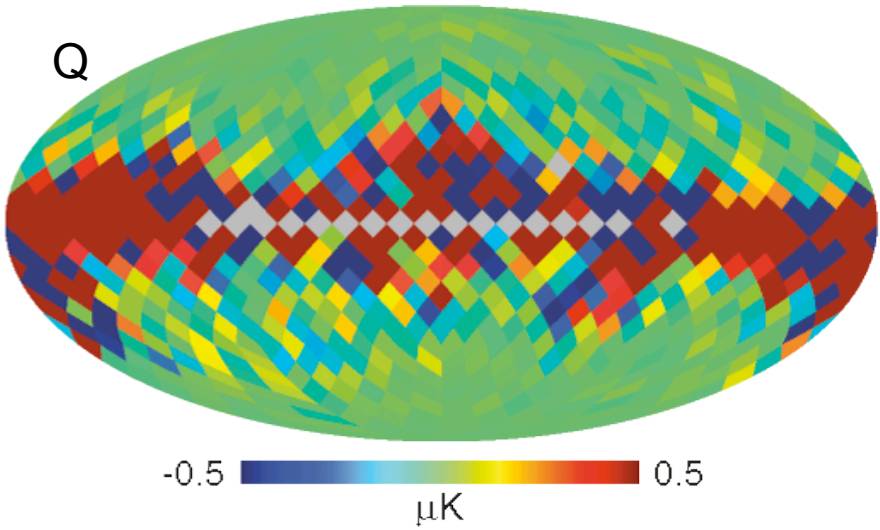
Polarized Dust: Status & Issues
Large-Scale Morphology

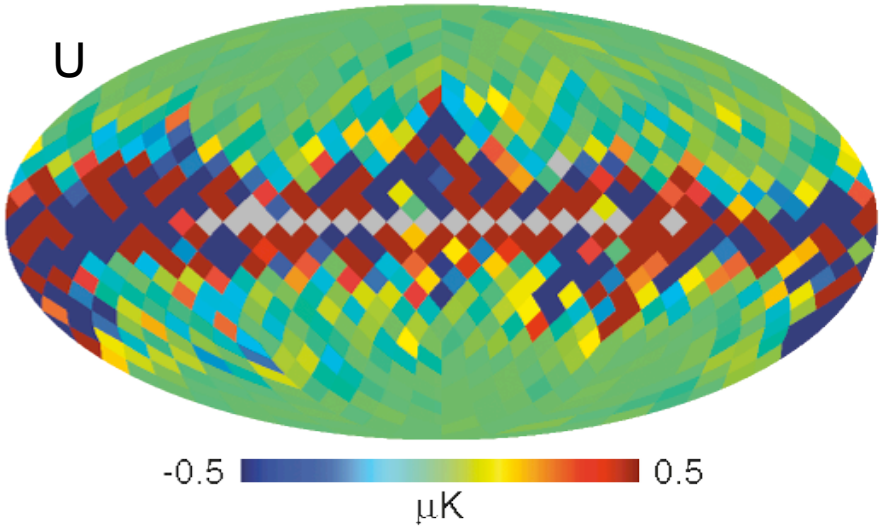
Large Angular Scales: WMAP 5-yr Data

- Low S/N at high latitude
- 4° pixels: S/N < 2 over 97% of sky

Fractional Polarization

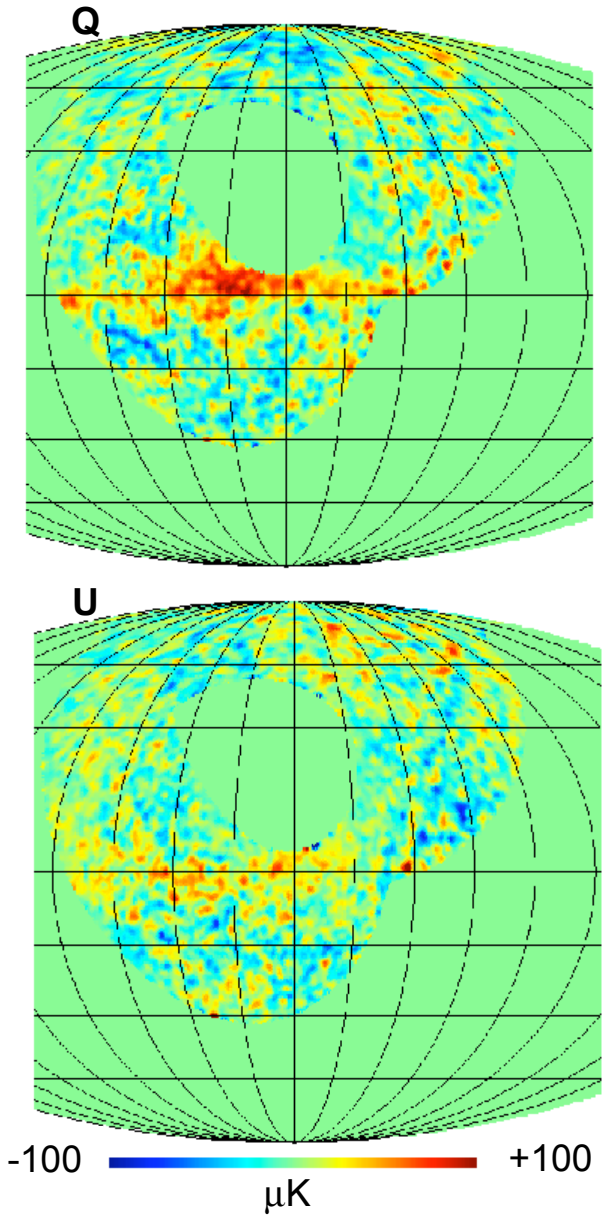
- Few percent in plane (depolarized)
- 2--4% at higher latitudes





Dunkley et al. 2008, arXiv:0803.0586

Polarized Dust: Status & Issues
Small-Scale Morphology



Ponthieu et al. 2005, A&A, 444, 327

Small Angular Scales: ARCHEOPS

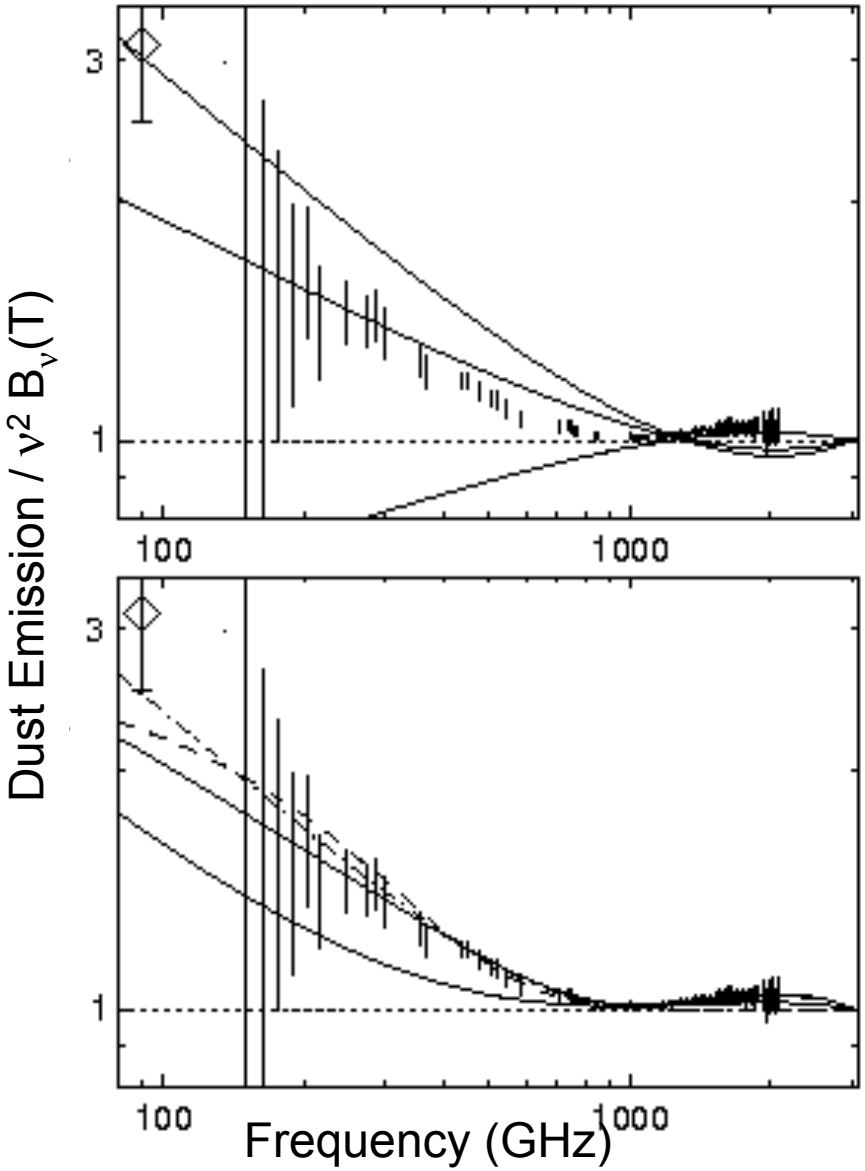
- Low S/N at high latitude
- Fractional polarization ~5% at 345 GHz

New Dust Measurements Coming Soon

- Planck HFI: 100, 143, 217, 353 GHz
- EBEX: 150, 250, 350, 450 GHz
- SPIDER: 100, 150, 220 GHz

… which brings up the question of spectra …

Polarized Dust: Status & Issues
Frequency Dependence: Stokes I



Finkbeiner, Davis, & Schlegel 1999, ApJ, 524, 867

FDS Model Based on COBE Data

Single Component

- $\langle T \rangle$ = 18.1 K , β=2.0
- β=2.2 is better for ν < 300 GHz

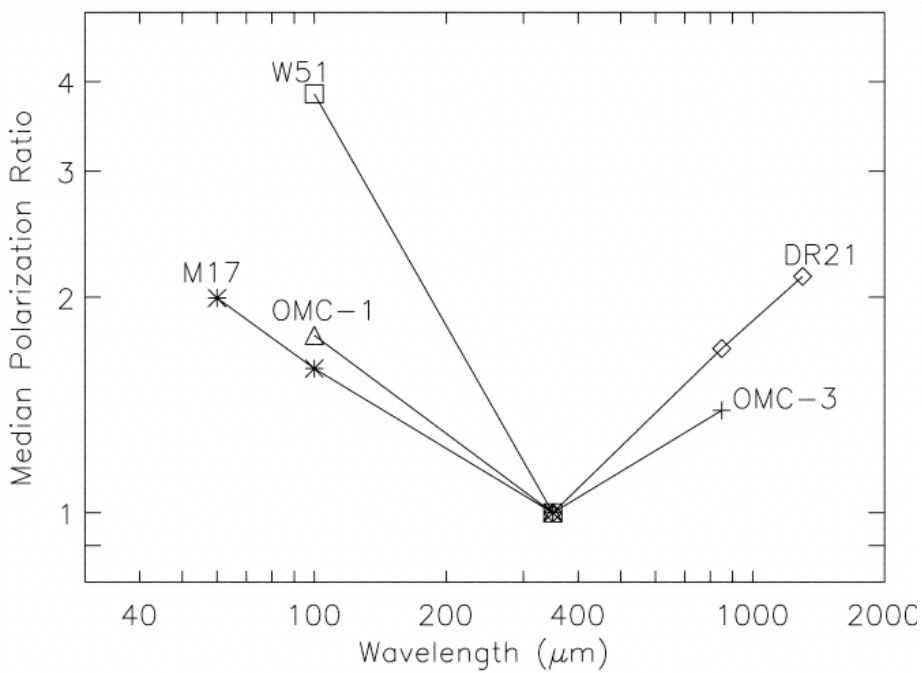
Two Components

- $\langle T_1 \rangle$ = 9.4 K , β_1=1.7
- $\langle T_2 \rangle$ = 16.2 K , β_2=2.7

But …

- χ^2/DOF = 1.85 for best model
- Clearly an approximation!

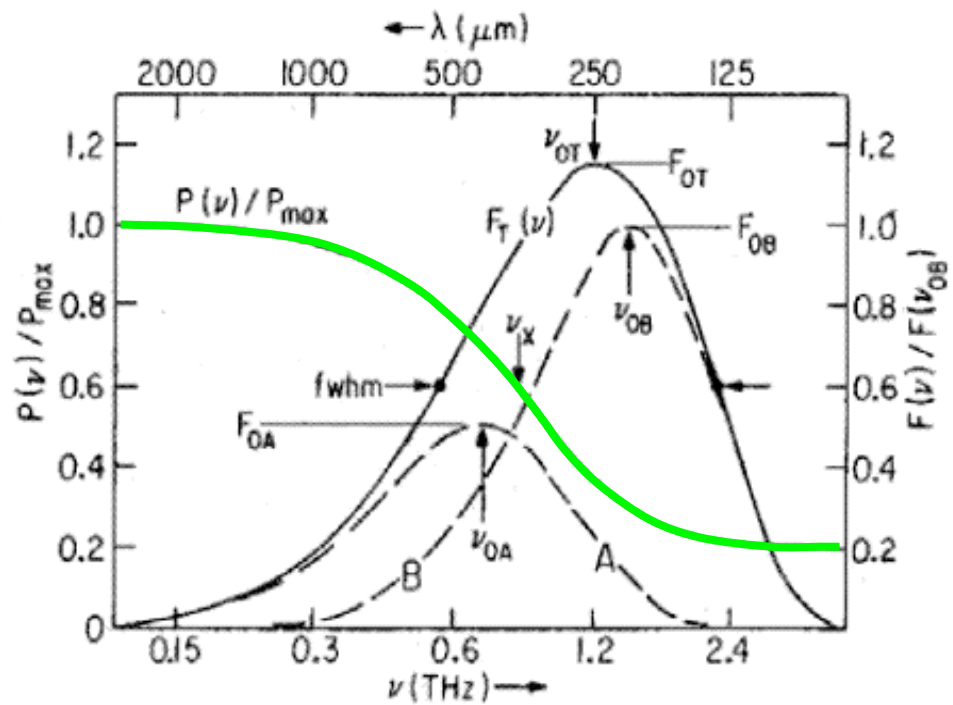
Polarized Dust: Status & Issues
Frequency Dependence: Fractional Polarization



Vaillancourt 2002, ApJ, 142, 53

Molecular Clouds: Minimum near 350 GHz

- Different (local) environments
- Different dust species



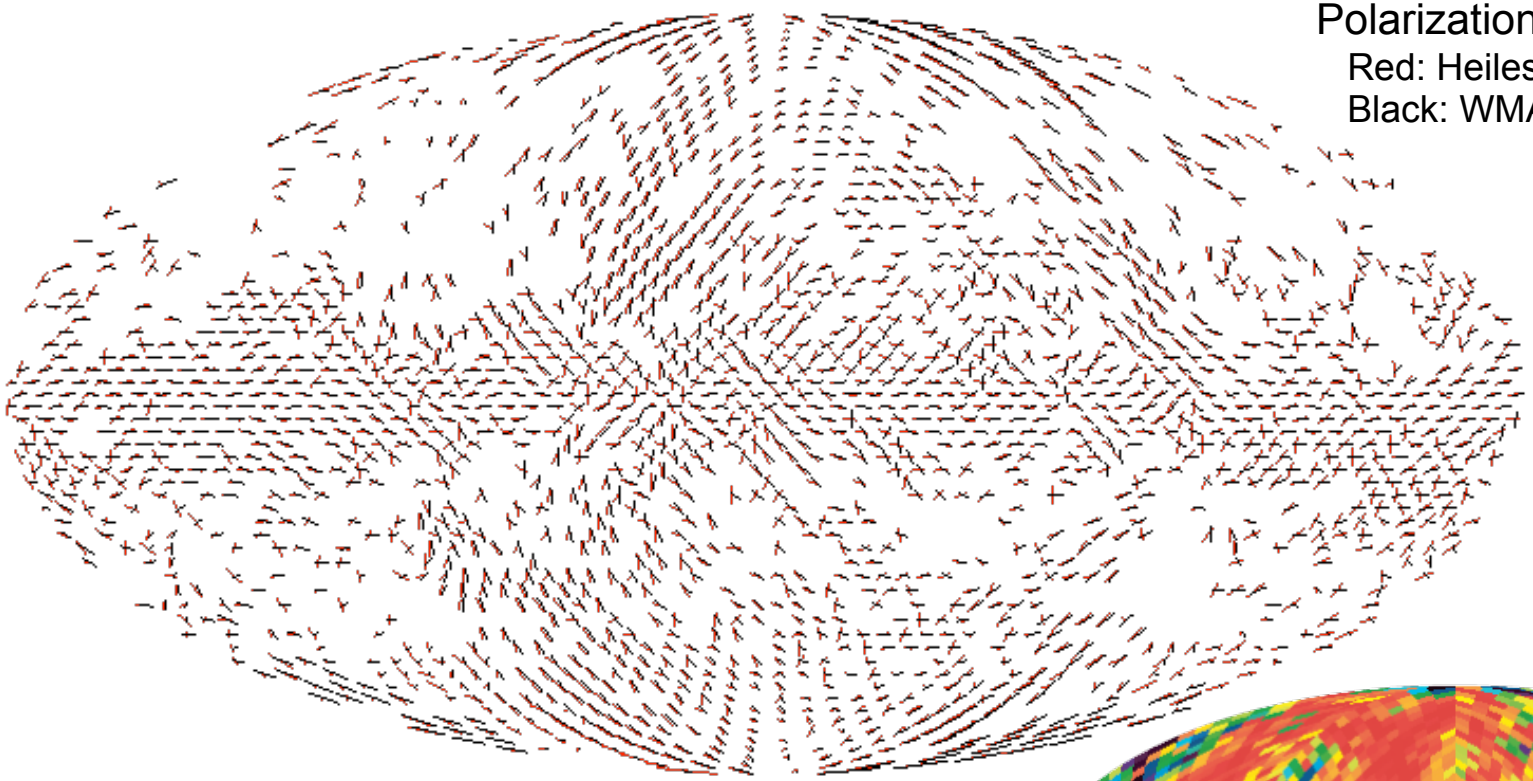
Diffuse Cirrus: Monotonic change

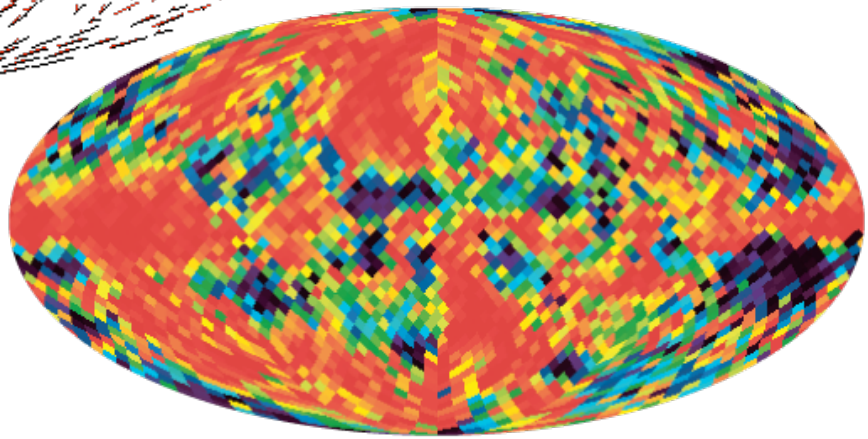
- Same environment, different species

Hildebrand & Kirby 2004, ASP Conf Series 309, 515

Polarized Dust: Status & Issues
Polarization Angle

Polarization Angle $\gamma(\hat{n})$
Red: Heiles dust absorption
Black: WMAP synchrotron





Dust $\gamma(\hat{n})$ *mostly* traces synchrotron

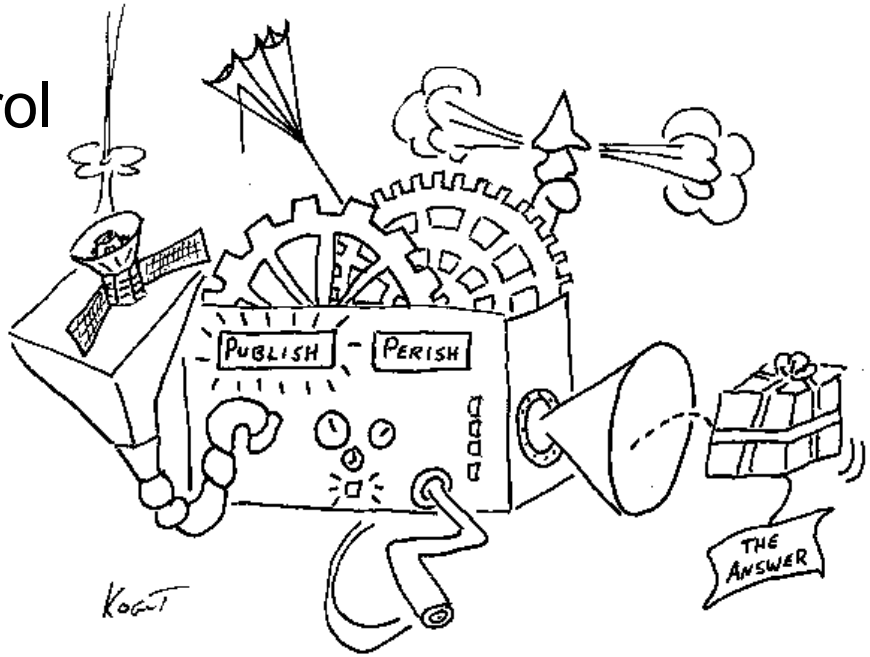
Differences are real & significant

Heiles 2000, AJ, 119, 923
Page et al. 2007, ApJS, 170, 335, 327
Kogut et al. 2007, ApJ, 665, 355

Foreground Status

Cleaning "machinery" under control

- Algorithms exist and work as advertised
- Multiple methods, multiple sims



Astrophysics not quite there yet

- Just starting to map polarized foregrounds
- Considerable uncertainty in fitted parameters
- Biggest need is more data!

A Look Into Al's Crystal Ball

Desired Outcome

Strong statement that the foreground problem, while not solved, is under control, and that anticipated new measurements, including a CMB polarization satellite, will allow detection of primordial B modes to a cosmologically interesting level even after foreground correction.

Questions for Discussion

1. Where are new observations most needed?

- What bands, with what sensitivity?
- Detailed maps of foreground morphology
- Better measurement of spectral behavior
- Limits on unwanted line-of-sight effects

Connection with detailed astrophysical models

- Synchrotron emission $\leftrightarrow$ Charged particle propagation
- Dust emission $\leftrightarrow$ Physical properties of dust grains

Questions for Discussion

2. How much can we simplify?

- Worst case parameter scenario: 8+ parameters per pixel
  - Synch: T(n), γ(n), β(n) plus global curvature too
  - Dust: T(n), ε(n) for 2 species plus γ(n) plus global β1 and β2
  - Plus more to account for line-of-sight effects?

Simulations will be very useful here!

Questions for Discussion

3. How will we know what is good enough?

- Balance number of channels vs cost
- Principal component analysis, χ^2

Simulations will be very useful here as well!