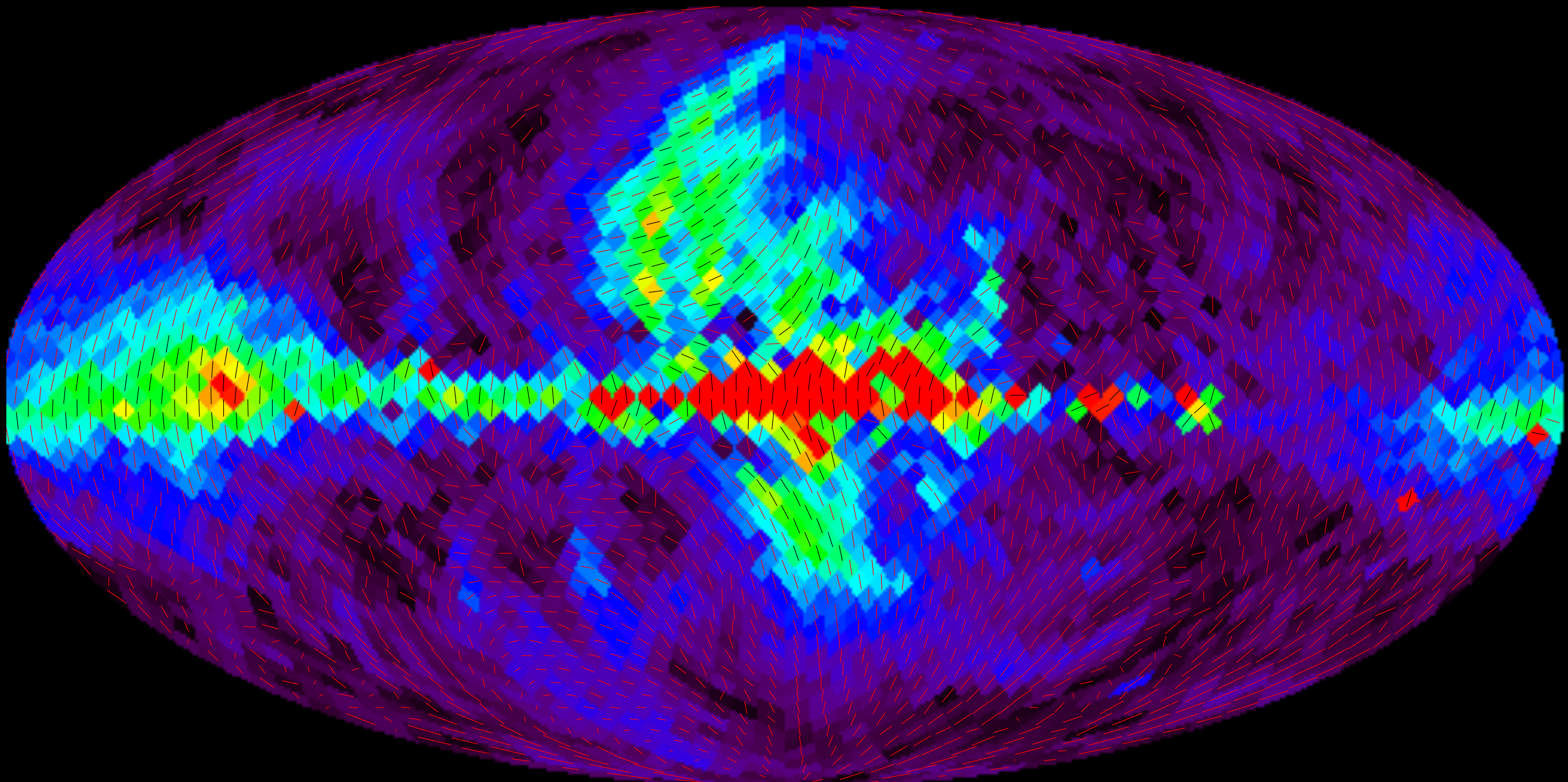
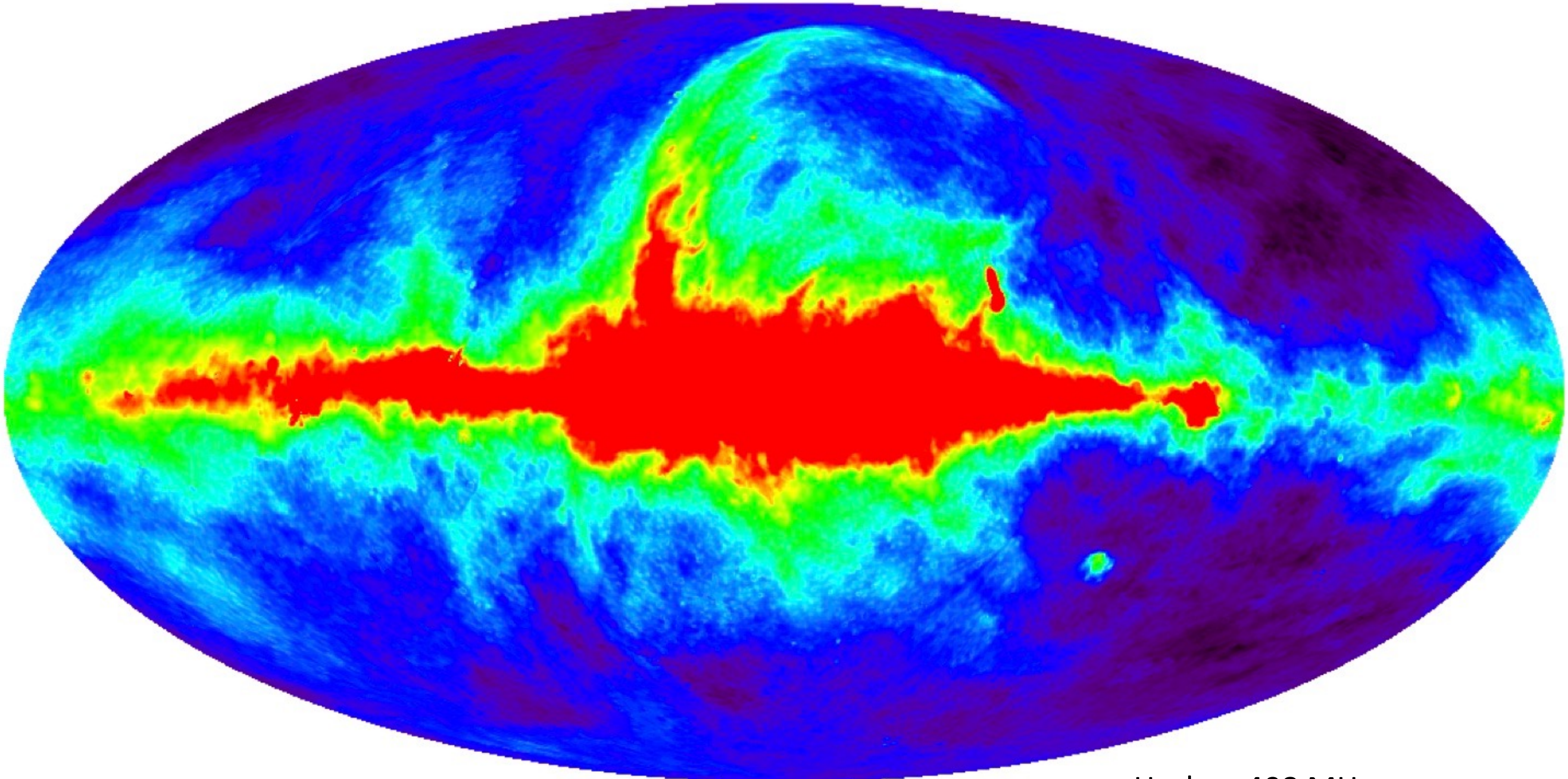
Synchrotron Polarization As a Test of the Radio Background



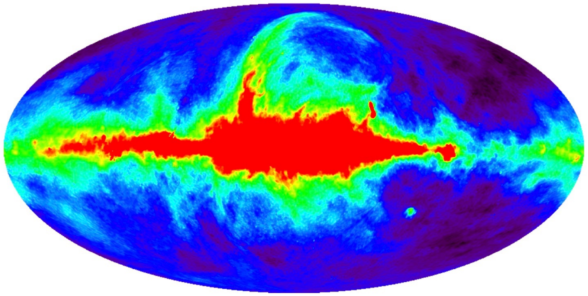
Al Kogut
Goddard Space Flight Center

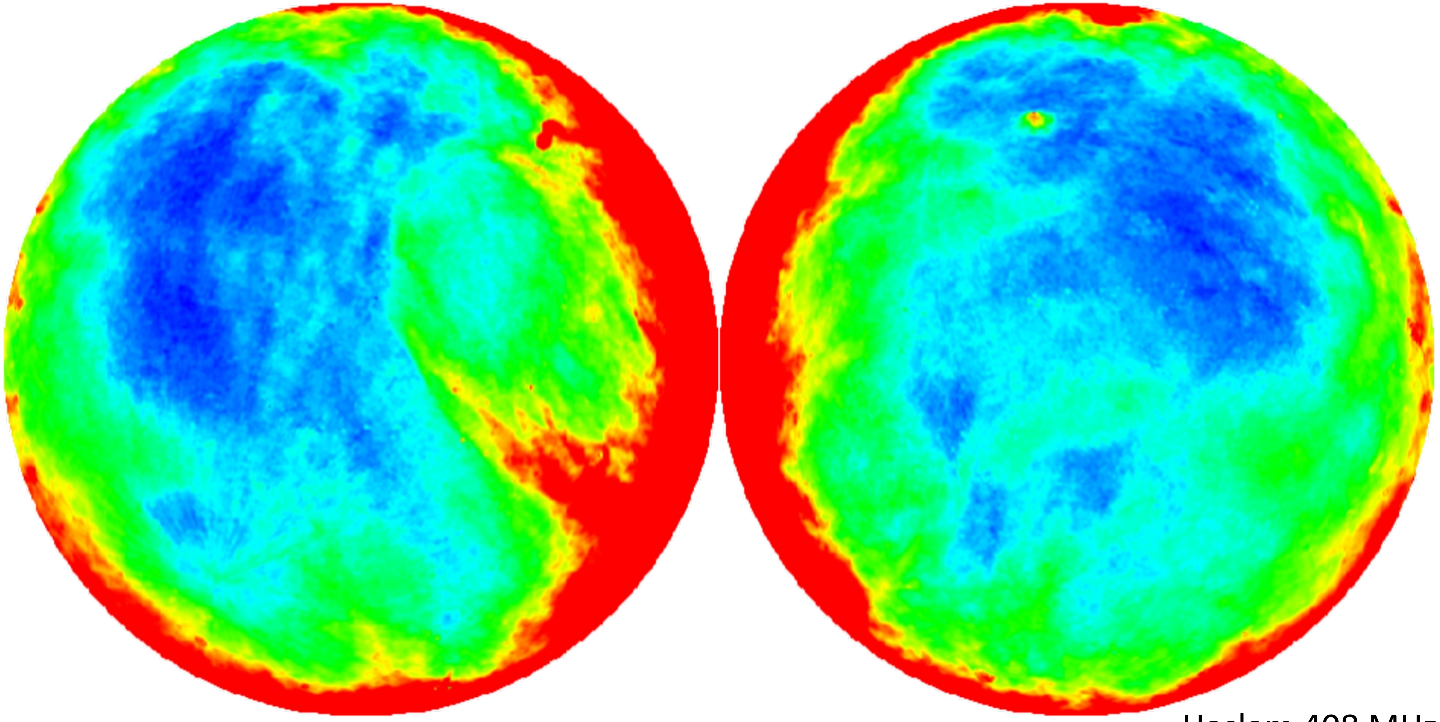
Visualizing the Radio Monopole



Haslam 408 MHz
(Mollweide Projection)

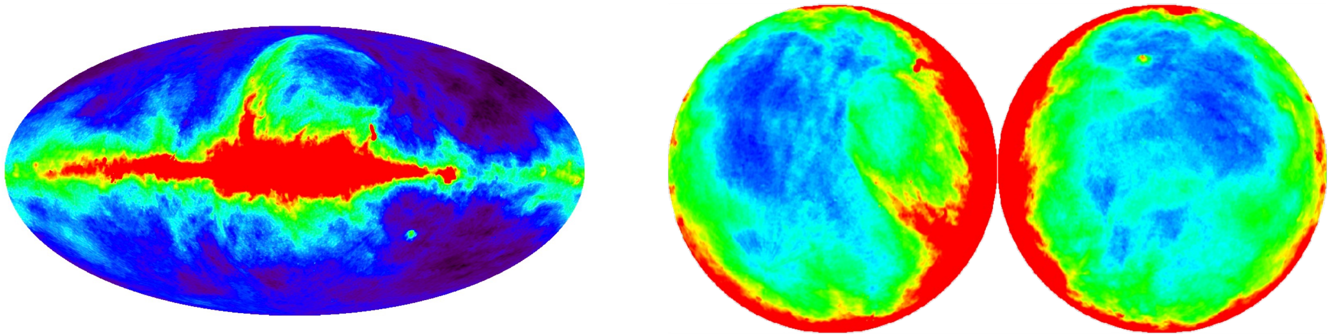
Visualizing the Radio Monopole

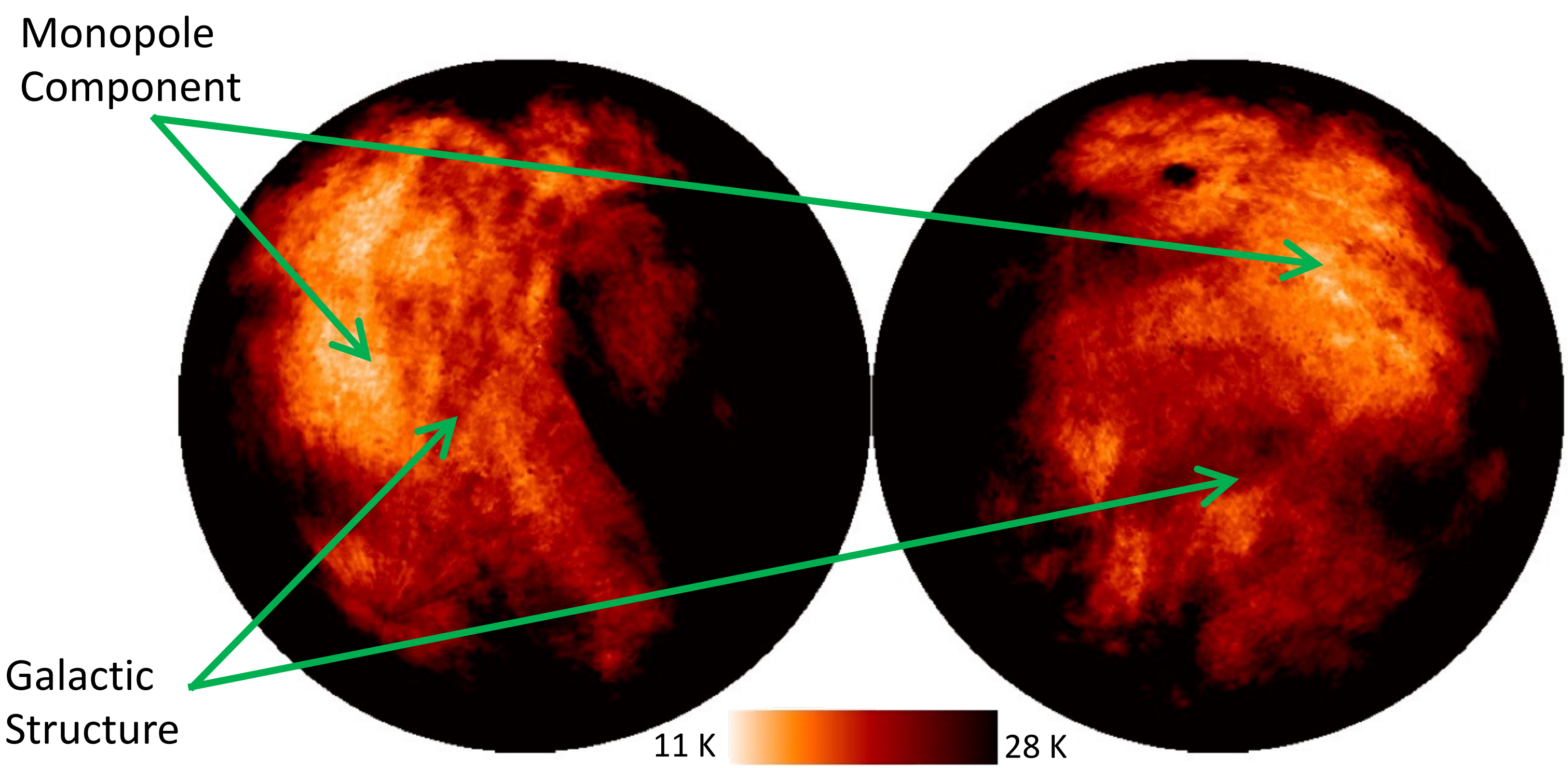




Haslam 408 MHz
(Polar Stereographic Projection)

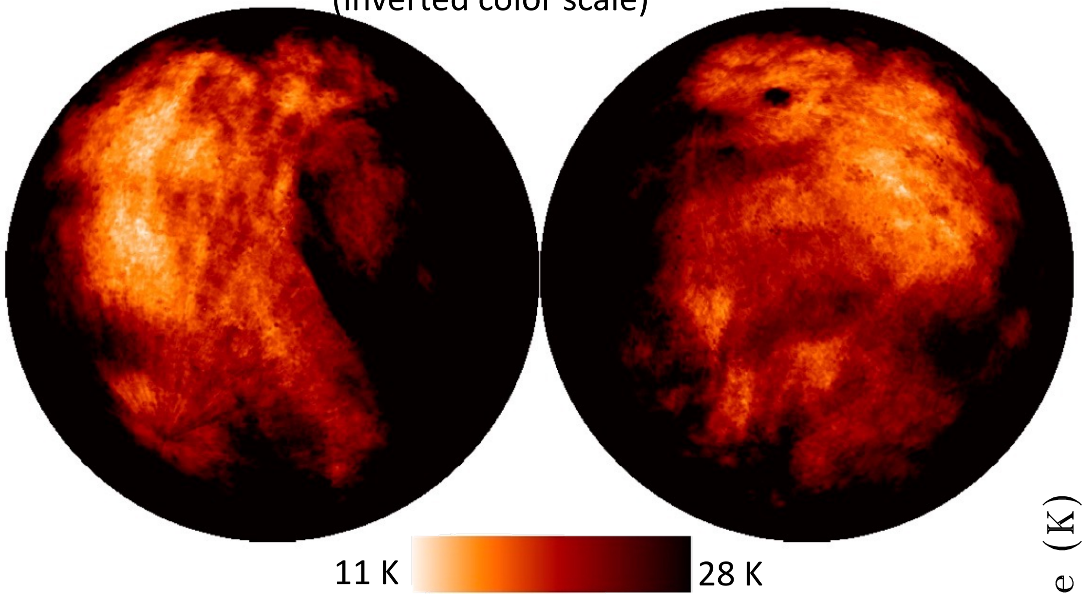
Visualizing the Radio Monopole



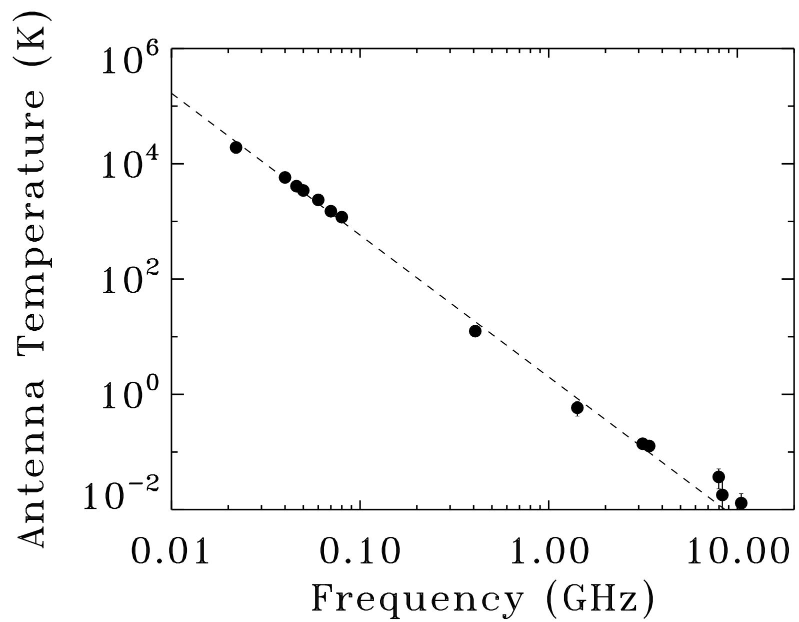


Radio (Synchrotron) Background

Polar projection of 408 MHz survey
(inverted color scale)



Radio morphology shows bright monopole component screened by spatially-variable Galactic component



Power-law frequency dependence of monopole

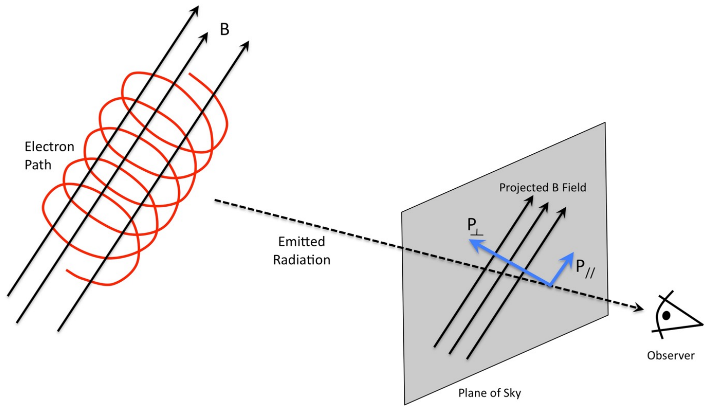
$T_A \sim \nu^{\beta}$

$\beta = -2.58 \pm 0.05$

strongly suggestive of synchrotron emission

Fixsen et al 2011
Dowell & Taylor 2018

Synchrotron Polarization



A power-law distribution of ultra-relativistic electrons

$$N(E) = \kappa E^{-p}$$

has synchrotron emissivity per unit volume

$$\epsilon \propto \kappa B^{(p+1)/2} \;\; \Gamma\left(\frac{p}{4}+\frac{19}{12}\right)\Gamma\left(\frac{p}{4}-\frac{1}{12}\right)$$

with power-law frequency dependence

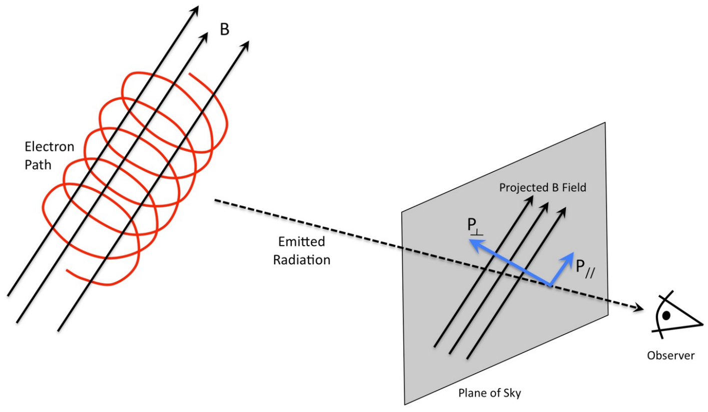
$$T_A(\nu) \propto \nu^{\beta} \qquad \beta = -(p+3)/2$$

and fractional polarization

$$f = \frac{p+1}{p+7/3}$$

Measured value β=-2.6 predicts f = 0.7

Synchrotron Polarization



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$$\epsilon \propto \kappa B^{(p+1)/2} \ \Gamma\left(\frac{p}{4} + \frac{19}{12}\right) \Gamma\left(\frac{p}{4} - \frac{1}{12}\right)$$

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$$T_A(\nu) \propto \nu^\beta \qquad \beta = -(p+3)/2$$

and fractional polarization

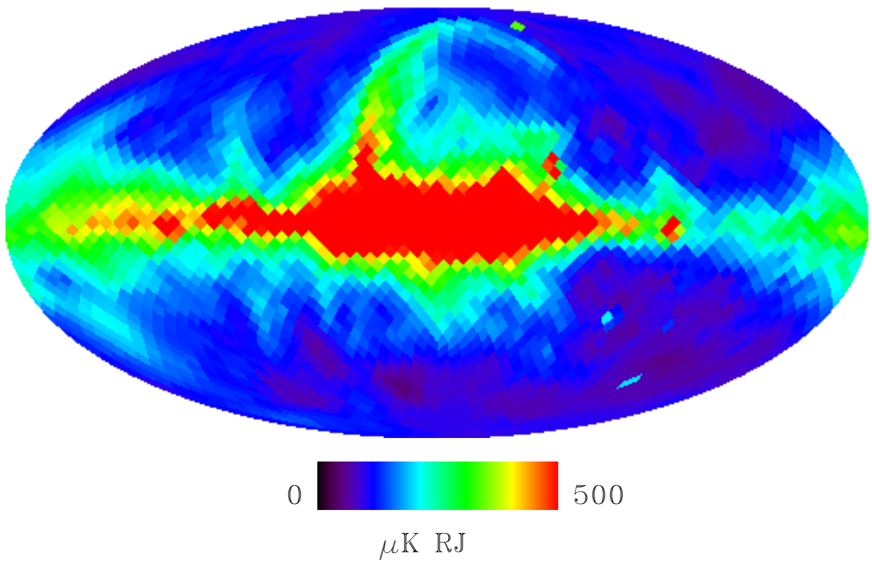
$$f = \frac{p+1}{p+7/3}$$

Measured value β=-2.6 predicts f = 0.7

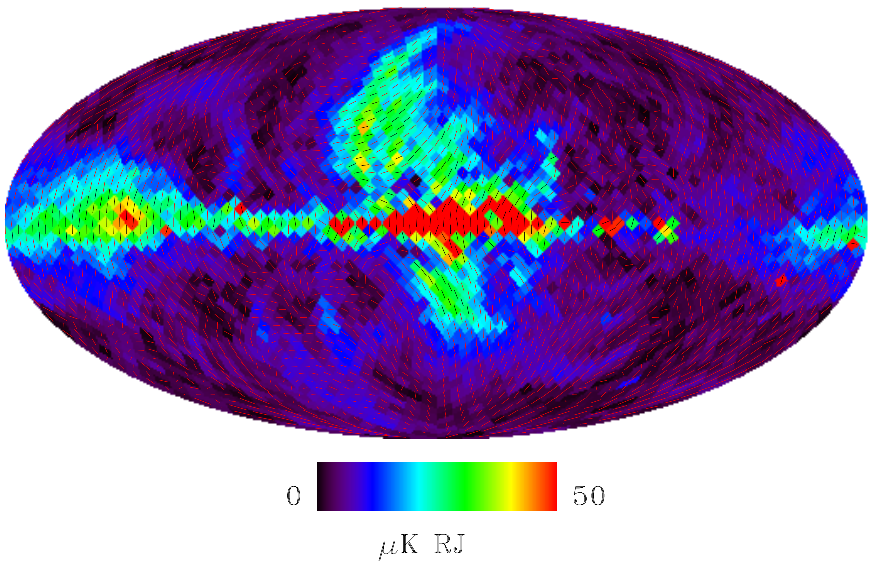
THIS IS NOT OBSERVED

Observed Synchrotron Emission

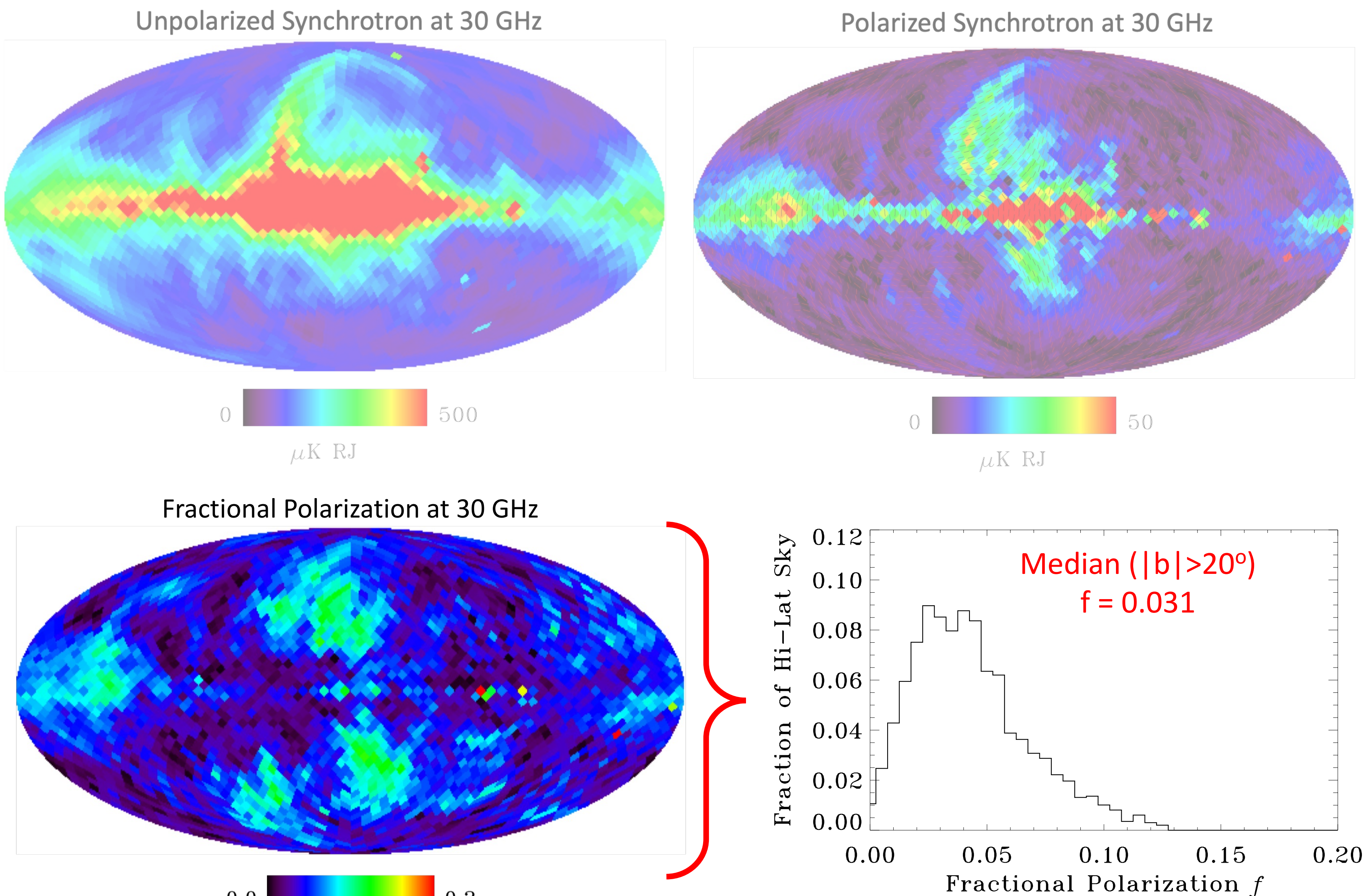
Unpolarized Synchrotron at 30 GHz



Polarized Synchrotron at 30 GHz

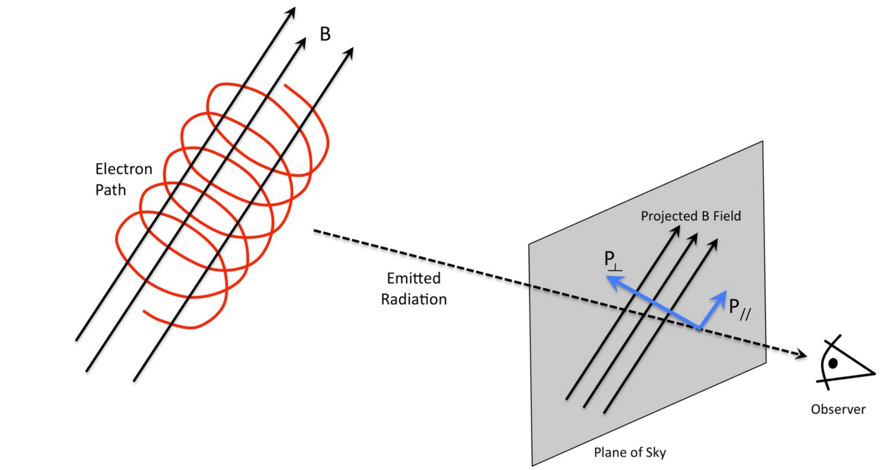


Observed Synchrotron Emission



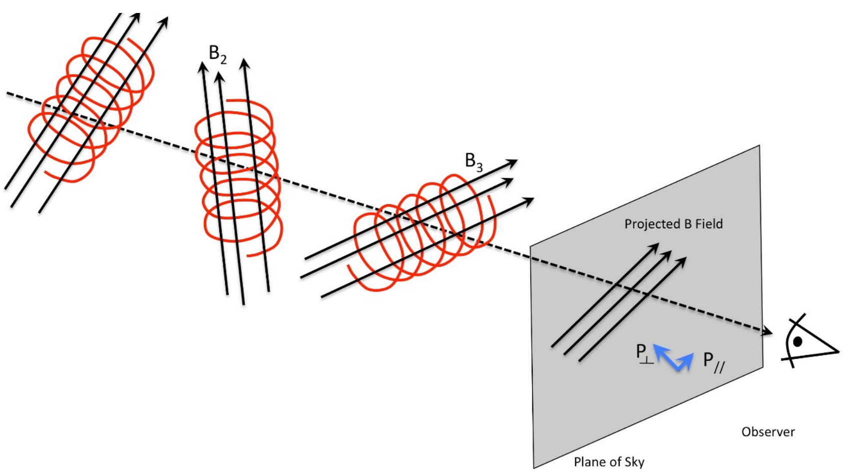
Synchrotron Depolarization I

Observed <f>=0.03 not even close to single-domain value f=0.7
Can multiple domains explain the observed depolarization?



Single Magnetic Domain

$$f \sim 0.7$$



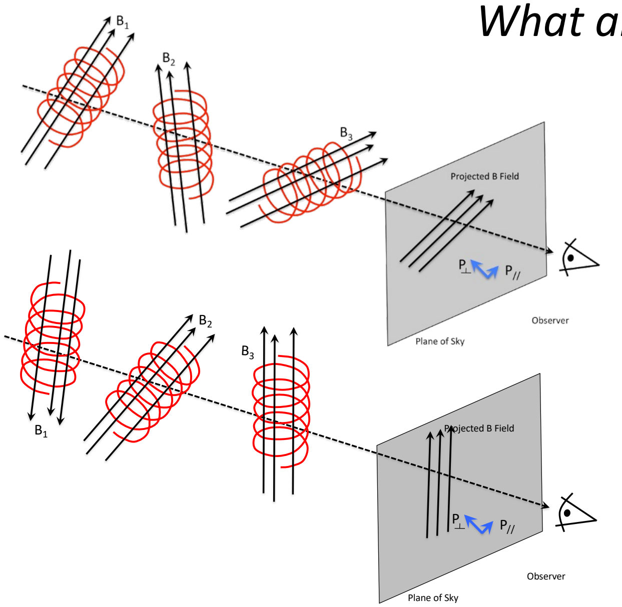
N Uncorrelated Domains
Intensities add, polarizations cancel

$$f \sim \frac{0.7}{\sqrt{N}}$$

Naive calculation: f=0.03 requires N > 500 independent domains on typical line of sight

Synchrotron Depolarization II

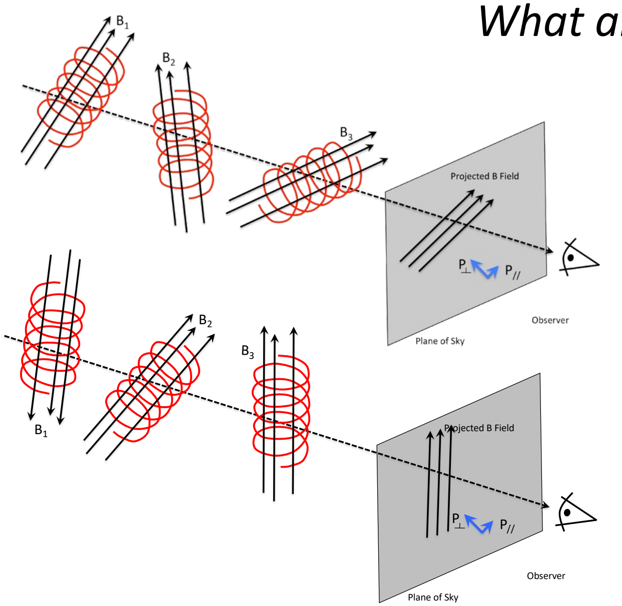
What about polarization angles?



Multiple magnetic domains along each line of sight should reduce fractional polarization, but increase scatter in polarization direction from one line of sight to another

Synchrotron Depolarization II

What about polarization angles?



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Synchrotron Depolarization II

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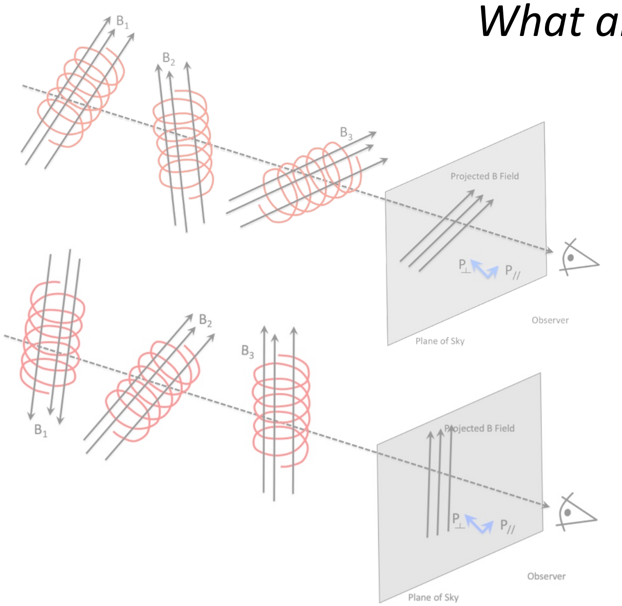

Multiple magnetic domains along each line of sight should reduce fractional polarization, but increase scatter in polarization direction from one line of sight to another

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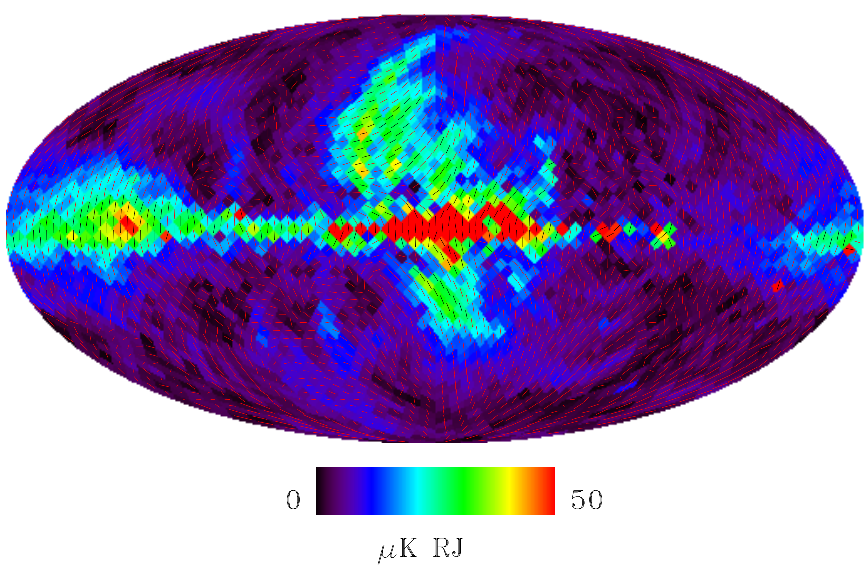
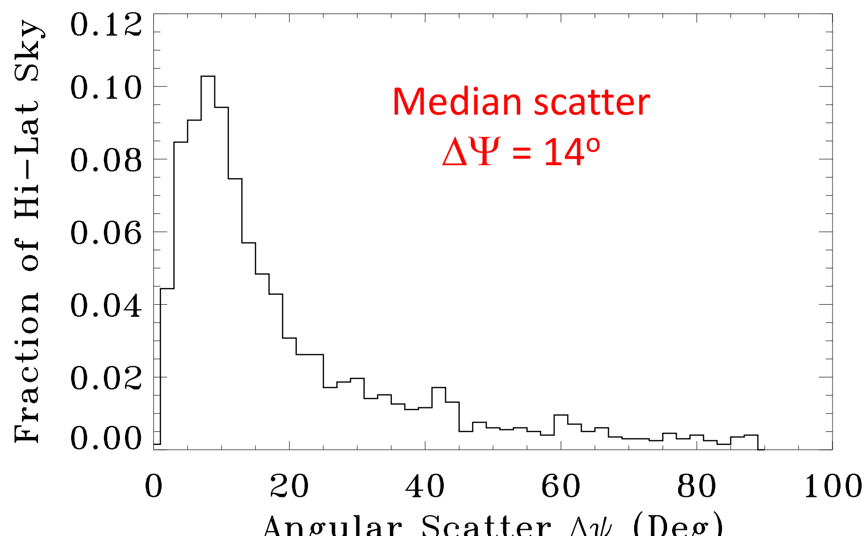
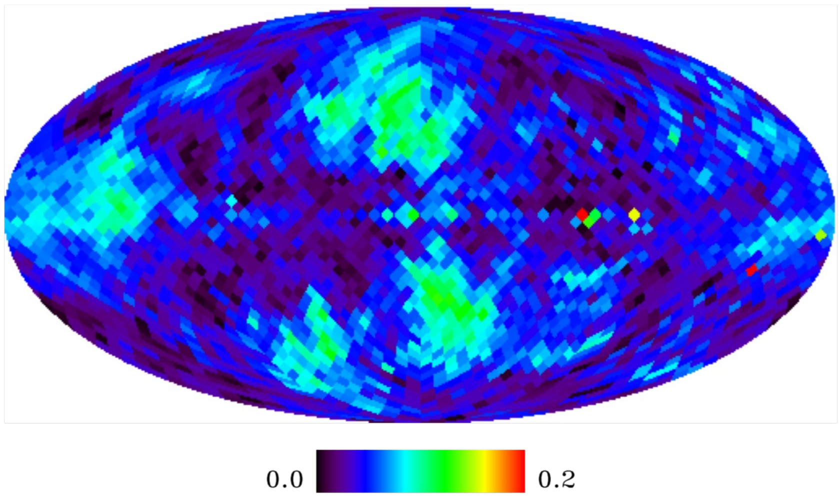




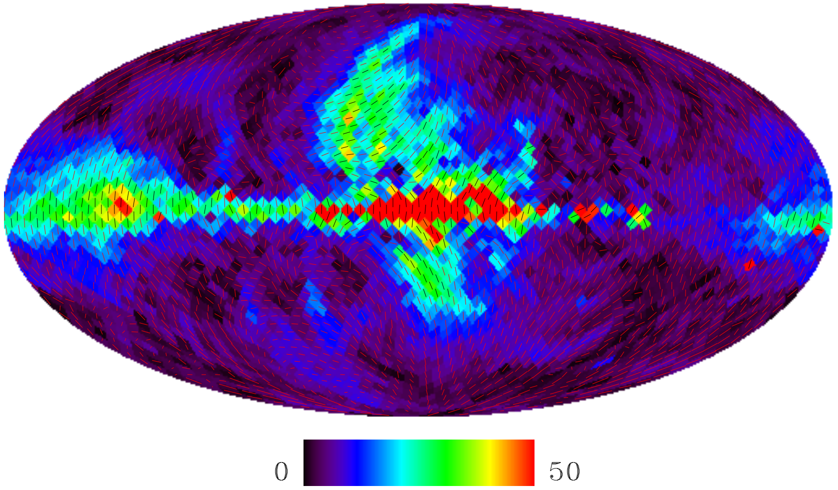
The Problem

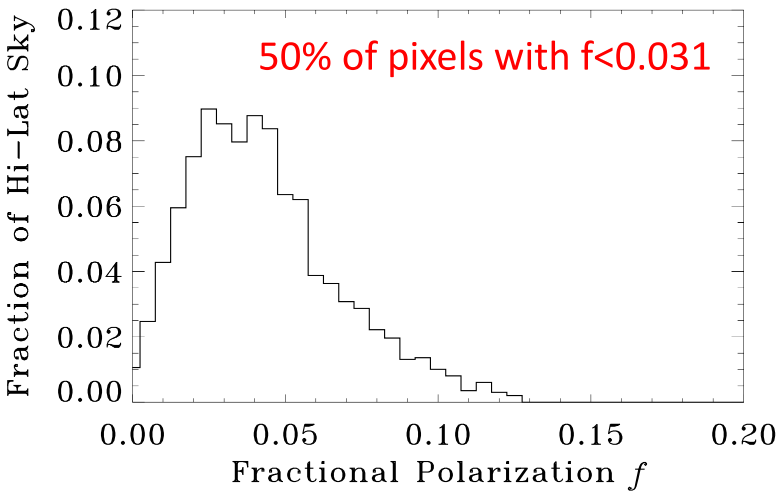
Synchrotron sky is strikingly de-polarized, but polarization direction is highly aligned
Can we reconcile this with Galactic magnetic field?

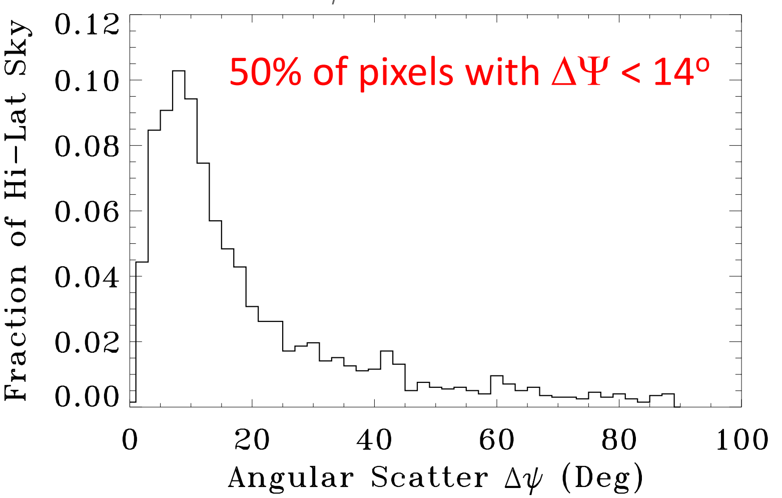
Fractional Polarization P/I



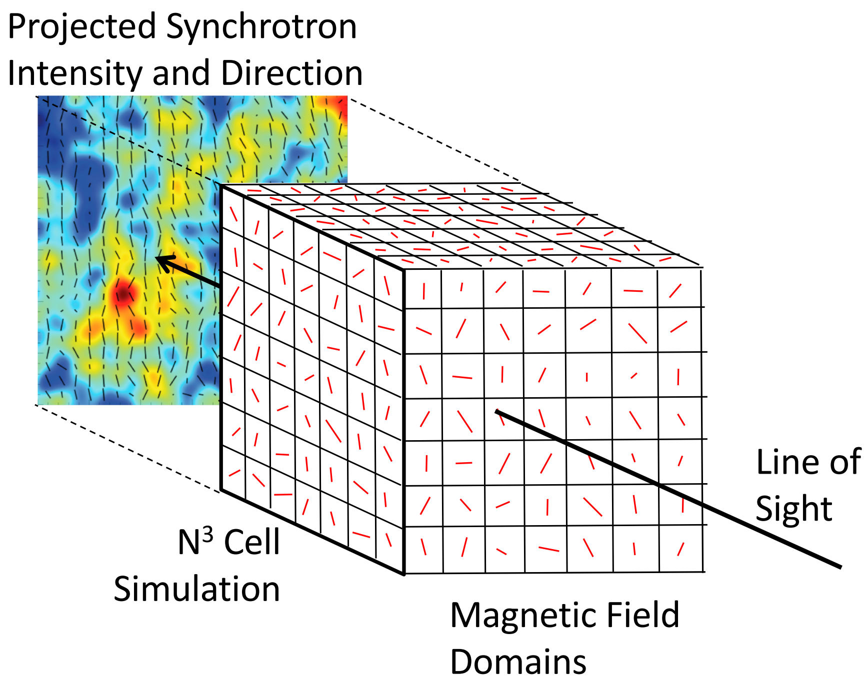
Polarized Intensity and Direction







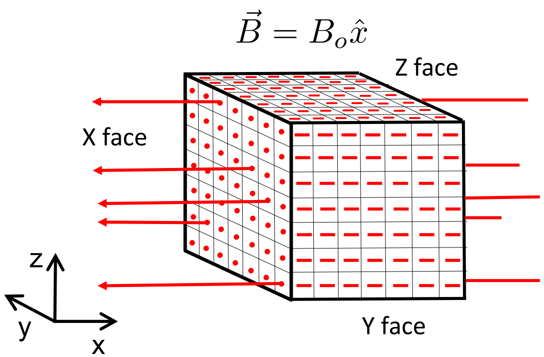
Test: Magnetohydrodynamic Simulations



- Generate turbulent magnetic field realization
- Calculate synchrotron amplitude and orientation within each cell
- Sum intensity and polarization along each projected line of sight
- Compare to Planck data

Can magnetic field turbulence reproduce the observed depolarization with the alignment of polarization directions?

Magnetohydrodynamic Simulations



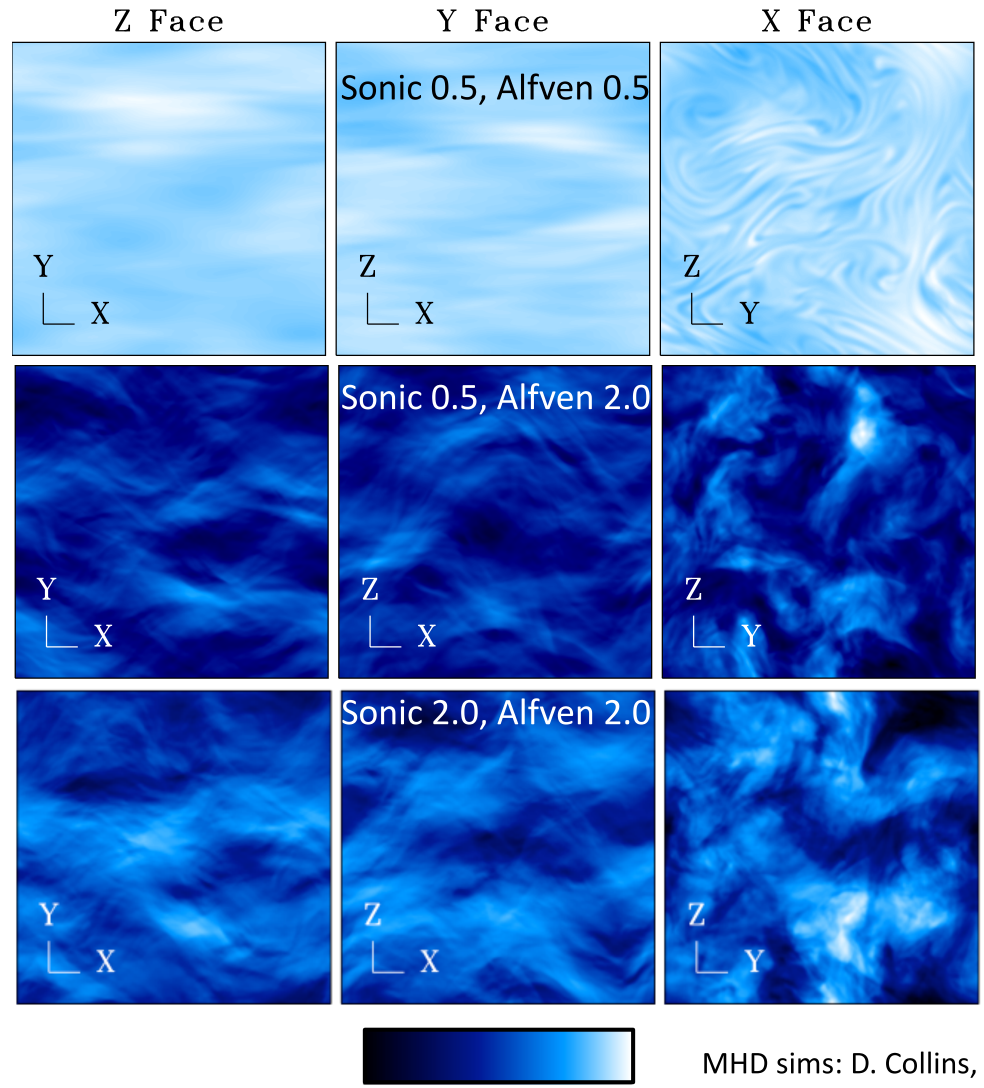
Enzo code: Seed cube with uniform field in x

Add kinetic energy on large scales

Cascade energy to progressively smaller scales

Vary sonic and Alfven Mach numbers
- Sonic: Ratio of kinetic to thermal energy
- Alfven: Ratio of kinetic to magnetic energy

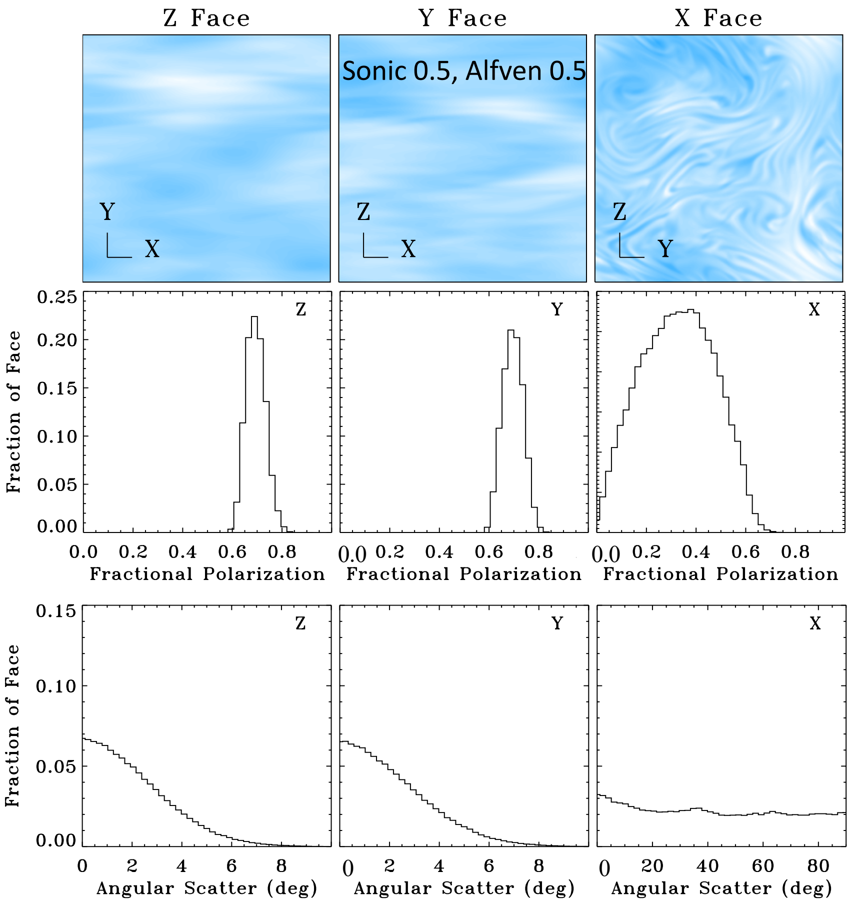
Projected B field through cube faces



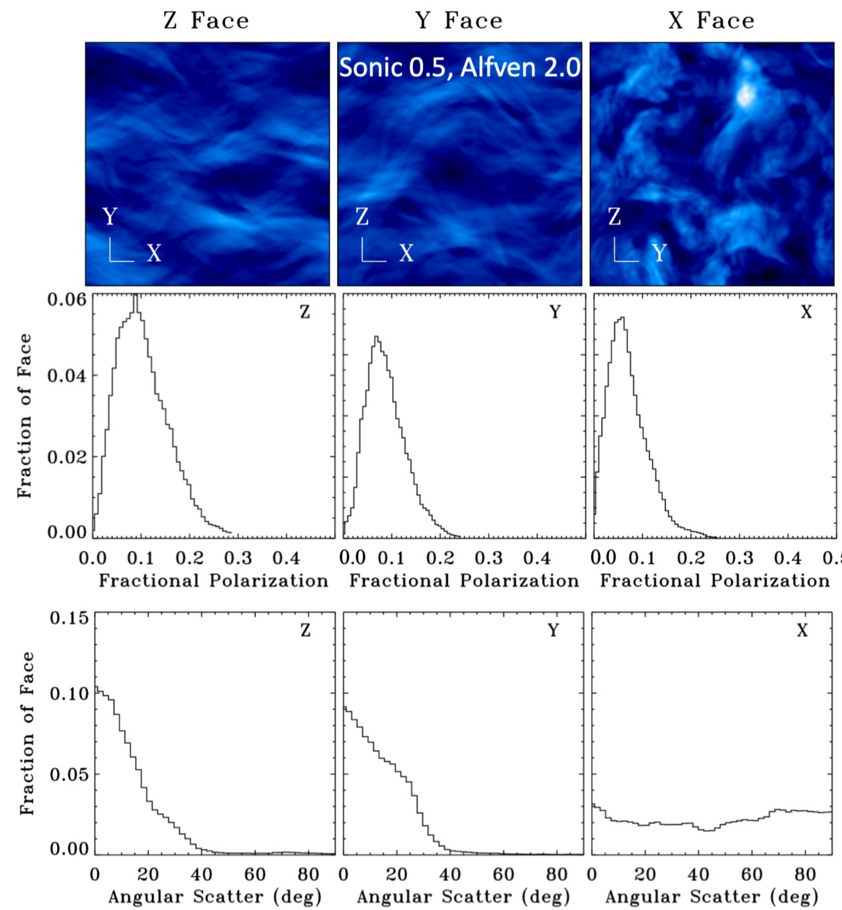
MHD sims: D. Collins, FSU

MHD Results

Highly Ordered



Less Ordered



Confirm expected pattern:
Depolarization is accompanied by increased scatter in polarization direction

MHD Sims vs Synchrotron Sky

	Mach Number	Fractional Polarization		Angular Scatter	
$\mathcal{M}$	$\mathcal{M}_{\mathrm{A}}$	Perpendicular	Parallel	Perpendicular	Parallel
0.5	0.5	0.68	0.33	1.6	40.0
0.5	2.0	0.09	0.06	11.0	49.0
1.0	0.5	0.69	0.34	1.7	43.0
1.0	2.0	0.13	0.10	10.0	40.0
2.0	2.0	0.23	0.17	9.0	38.0
3.0	2.0	0.21	0.17	9.5	42.0
Planck Sky $\|b\| > 20^\circ$		$\boxed{0.031}$		$\boxed{14.1}$	

MHD Sims vs Synchrotron Sky

Mach Number			Fractional Polarization		Angular Scatter	
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0.5	0.5		0.68	0.33	1.6	40.0
0.5	2.0	"Best" Match	0.09	0.06	11.0	49.0
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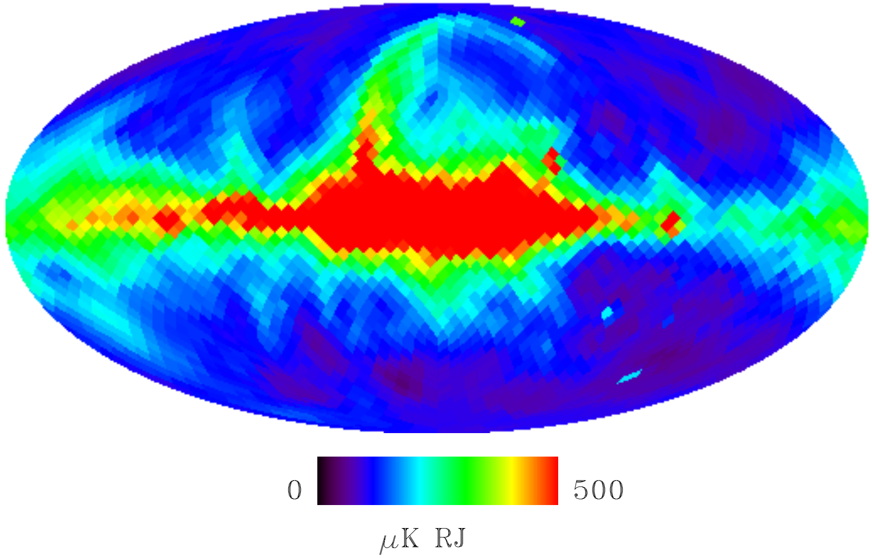
3.0	2.0		0.21	0.17	9.5	42.0
Planck Sky $\lvert b \rvert > 20^\circ$			0.031		14.1	

None of the simulations reproduced the observed pattern of low fractional polarization with highly aligned directions

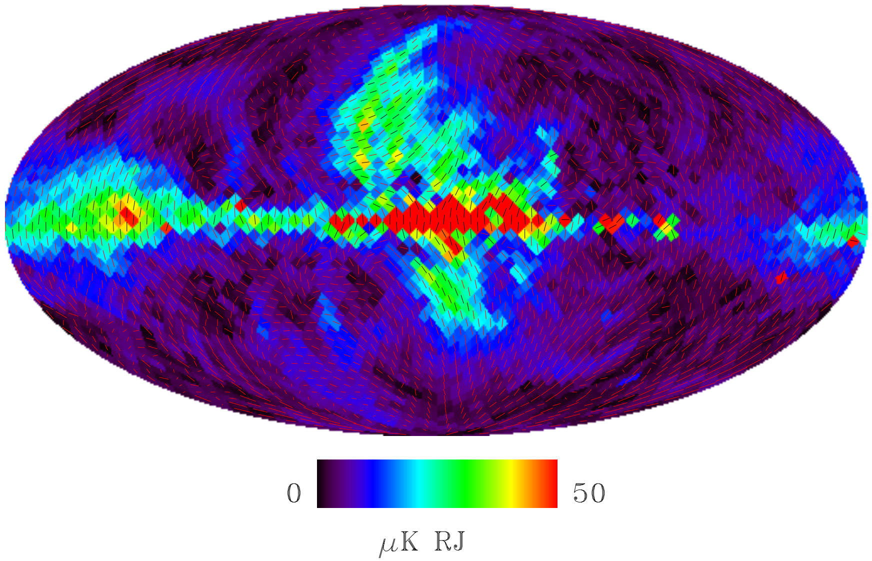
Is there an escape hatch?

Monopole Subtraction

Unpolarized Synchrotron at 30 GHz



Polarized Synchrotron at 30 GHz



Previous results assumed that the observed radio monopole is (mostly) Galactic.

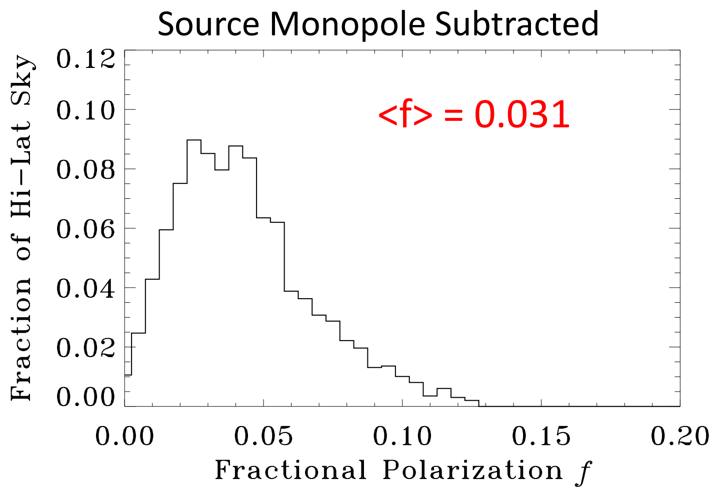
Unpolarized synchrotron intensity corrected for known radio source population, but the observed monopole is 4x brighter than the source contribution

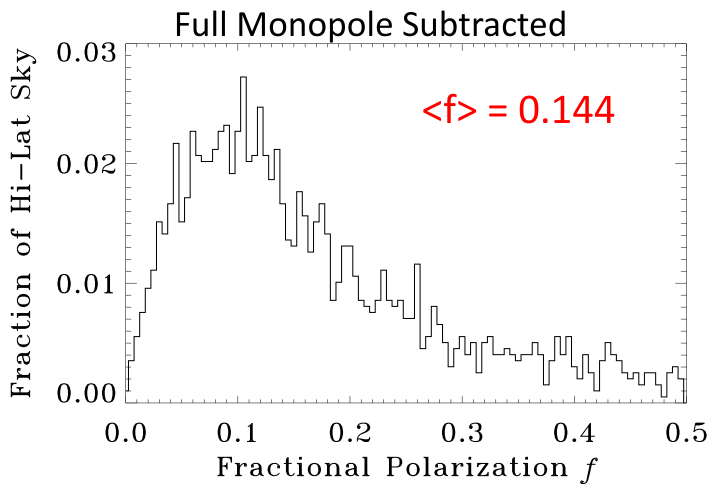
Fractional polarization is defined as $\dfrac{\text{Polarized Intensity}}{\text{Unpolarized Intensity}}$

Make denominator smaller, ratio f gets bigger but directions are unchanged

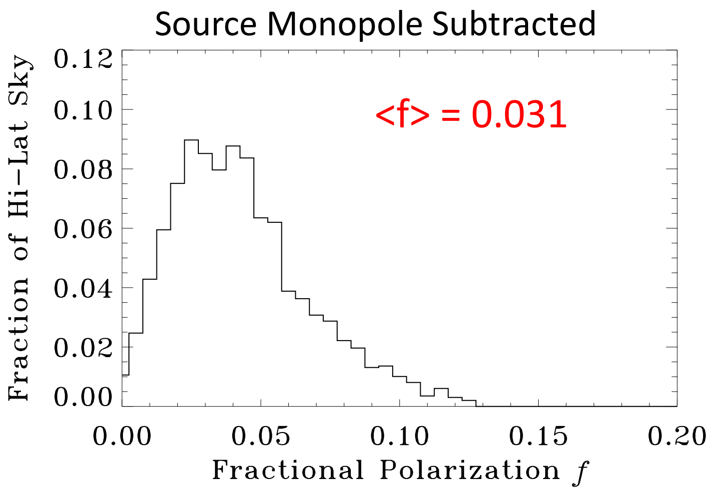
Suppose instead we subtract the full radio monopole from Galactic synchrotron models?

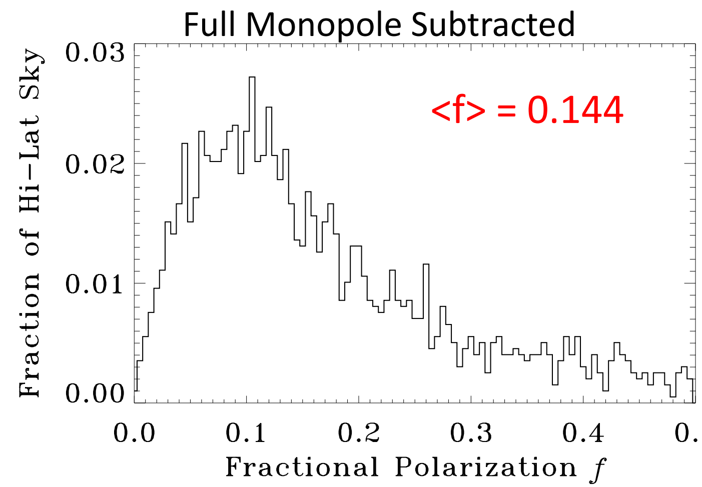
Monopole Subtraction





Monopole Subtraction





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1.0	2.0	Best Match	0.13	0.10	10.0	40.0
2.0	2.0		0.23	0.17	9.0	38.0
3.0	2.0		0.21	0.17	9.5	42.0
Planck Sky $\lvert b\rvert > 20^\circ$ (nominal)			0.031		14.1	
Planck Sky $\lvert b\rvert > 20^\circ$ (corrected)[a]			0.144		14.1	

[a] After removing monopole component

If full radio monopole is removed from Galactic synchrotron model, MHD simulations are in much closer agreement with observations

Future Directions

Extragalactic origin to observed monopole nearly eliminates tension between fractional polarization and polarization alignment.

Fuller exploration of MHD simulations:

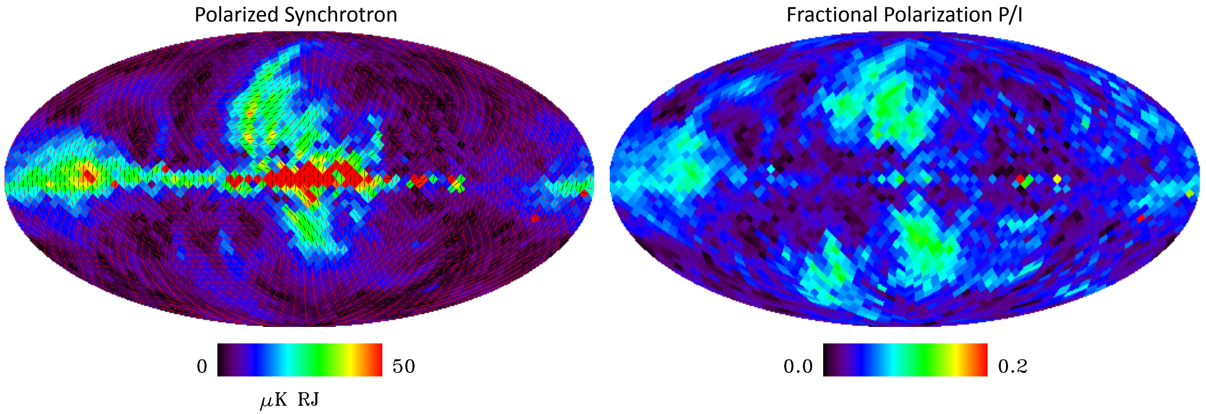
- Broader parameter space in sonic, Alfven Mach numbers
- Include global magnetic field orientation
- Include other field tracers (Faraday rotation maps, ...)

New observations to improve (unpolarized) component separation

- Include synchrotron spectral index uncertainty
- Maps at 3—20 GHz with absolute zero-level calibration (spectral index)
- Maps near 30 GHz with absolute zero-level calibration (30 GHz monopole)

Conclusions

Existing models of Galactic synchrotron emission fail to explain
the combination of low fractional polarization with highly aligned directions



Extragalactic origin to observed monopole nearly eliminates this tension

New maps at 3—30 GHz with absolute zero-level calibration
will help component separation by connecting CMB surveys
to synchrotron-dominated surveys at longer wavelength

Fractional polarization and angular alignment should be considered
in future models of Galactic synchrotron emission.

THANK YOU