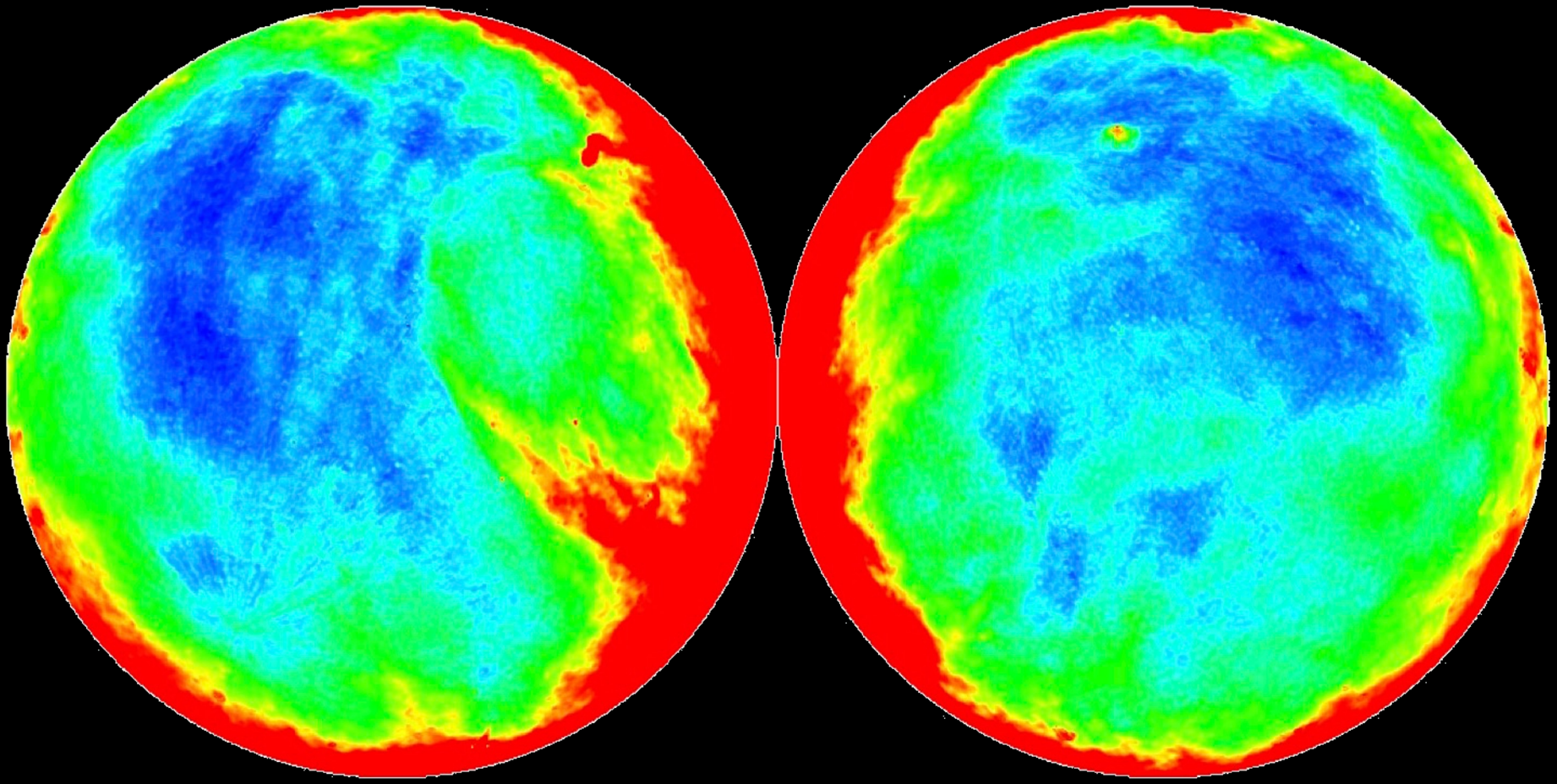
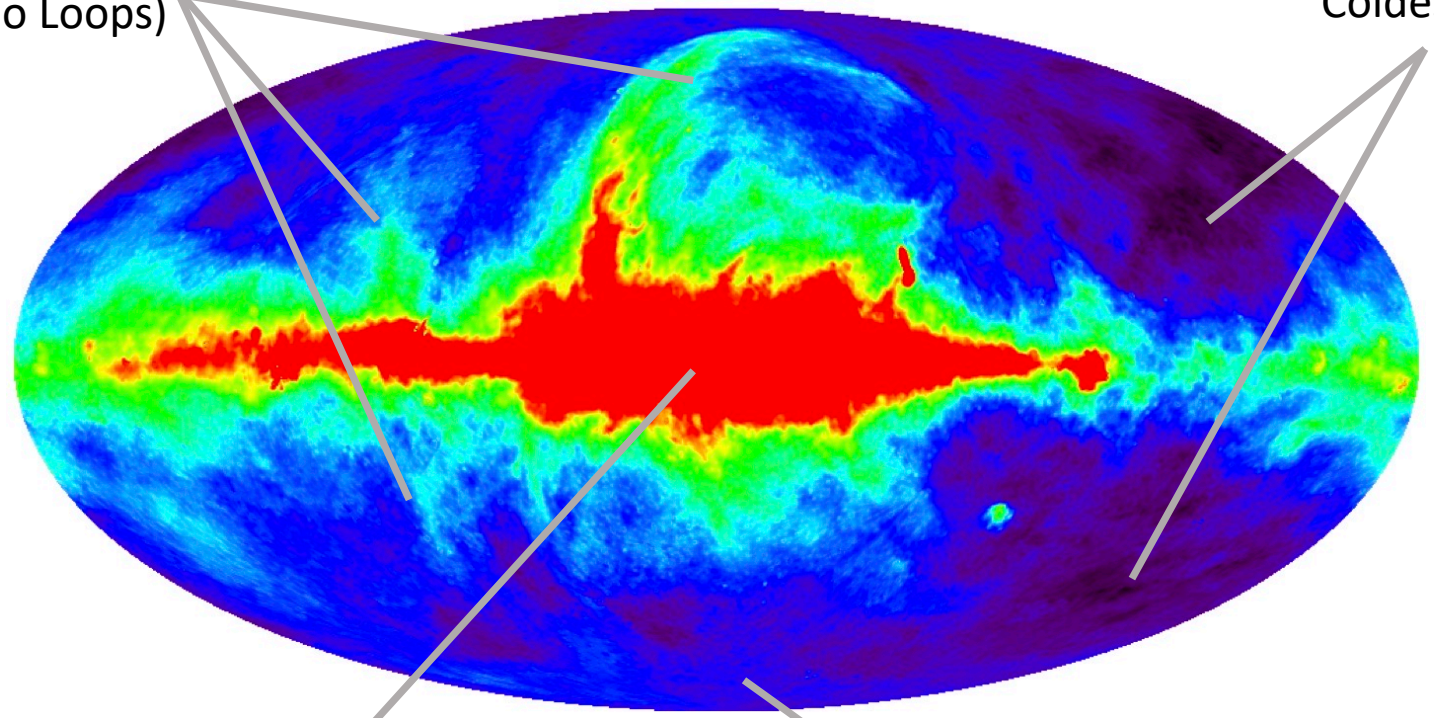
The Curious Case of the Radio Sky



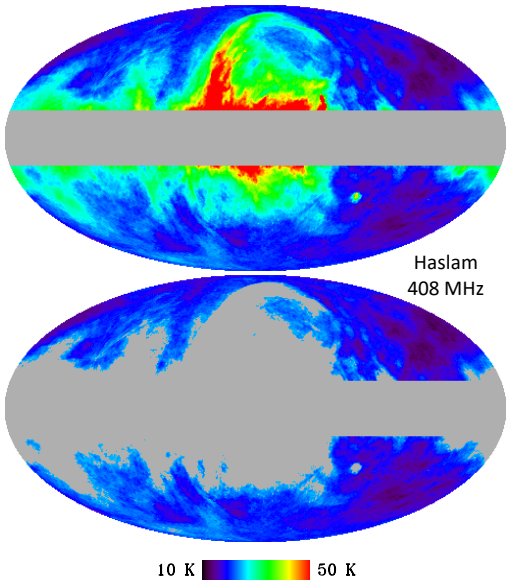
Al Kogut
Goddard Space Flight Center

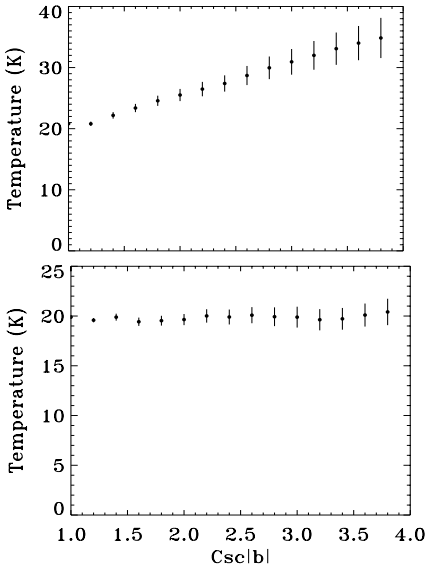
The Odd Structure of the Radio Sky



Haslam 408 MHz
(Mollweide Projection)

Anomalous High-Latitude Radio Emission





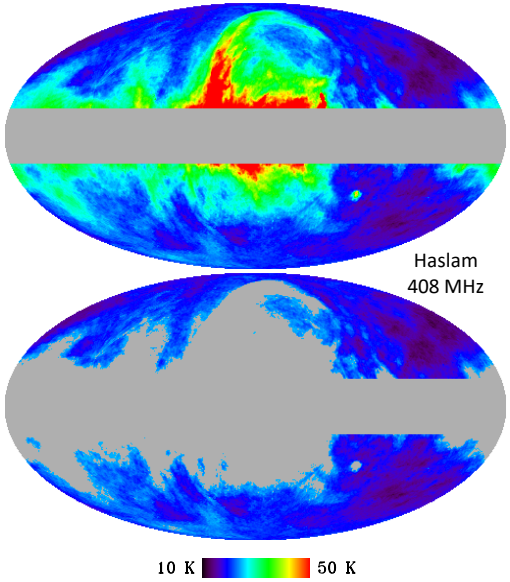
Radio dominated by few distinct structures

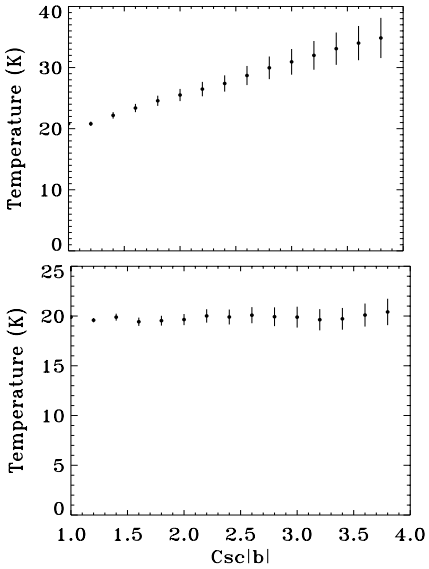
High-latitude emission has poor csc|b| dependence

Polar cap brightness well above cosecant model

Coldest spots not at the poles

Anomalous High-Latitude Radio Emission





Radio dominated by few distinct structures

High-latitude emission has poor csc|b| dependence

Polar cap brightness well above cosecant model

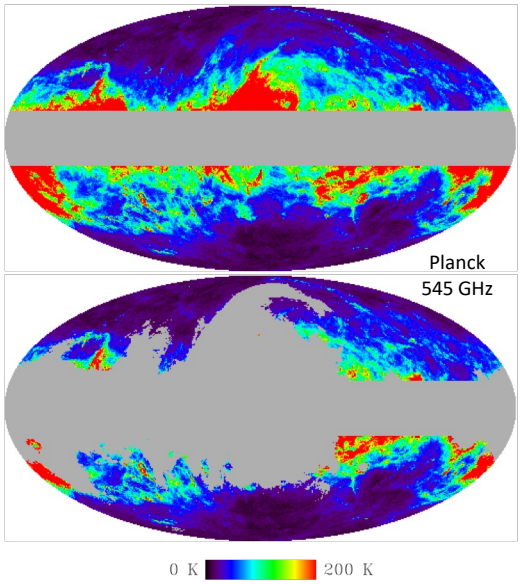
Coldest spots not at the poles

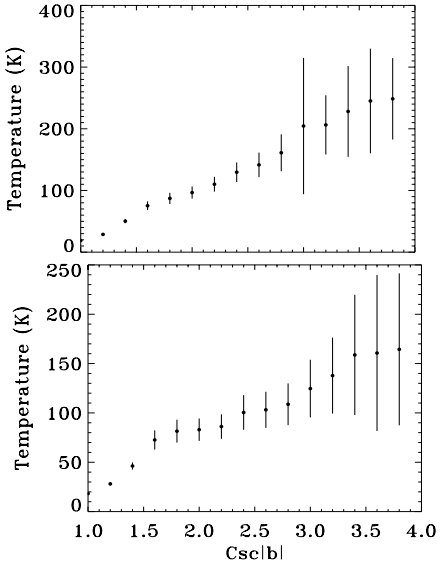
Compare to (e.g.) thermal dust

Dust follows plane-parallel slab

High-latitude emission with csc|b| dependence

Polar cap brightness in agreement with cosecant model





This Is Not News...

Westerhout & Oort 1951: "This residual [from the Bolton & Westerfold 100 MHz map] shows up immediately in a much too high temperature at high latitudes as well as in the hemisphere opposite to the center."

The question is ... Where does it come from?

Westerhout & Oort 1951: "This excess is still unexplained; the possibility that it may be due to a background of distant extra-galactic nebulae cannot be ruled out".

Baldwin 1957: Proposes model with spherical halo and no extragalactic sources

Baldwin 1967: "Alternatively one may argue that the rather uniform temperatures at high latitudes point to the complete absence of a halo. In this case the extragalactic radiation would be very considerable".

Many thanks to Paddy Leahy for pointing out these papers

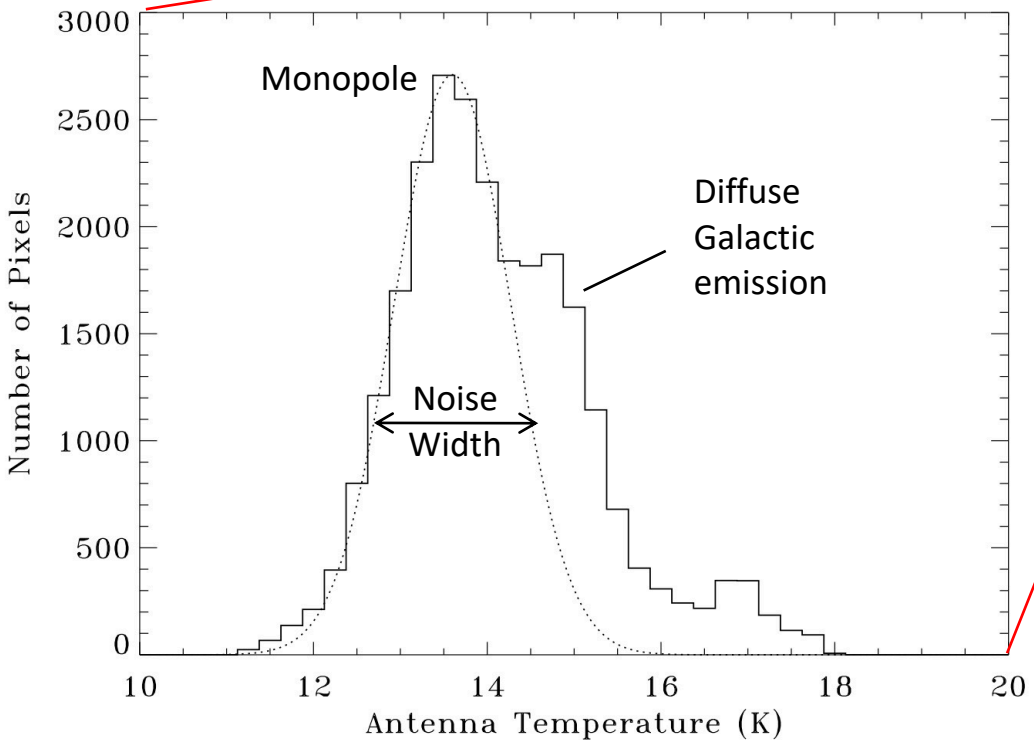
Simple Background Estimate

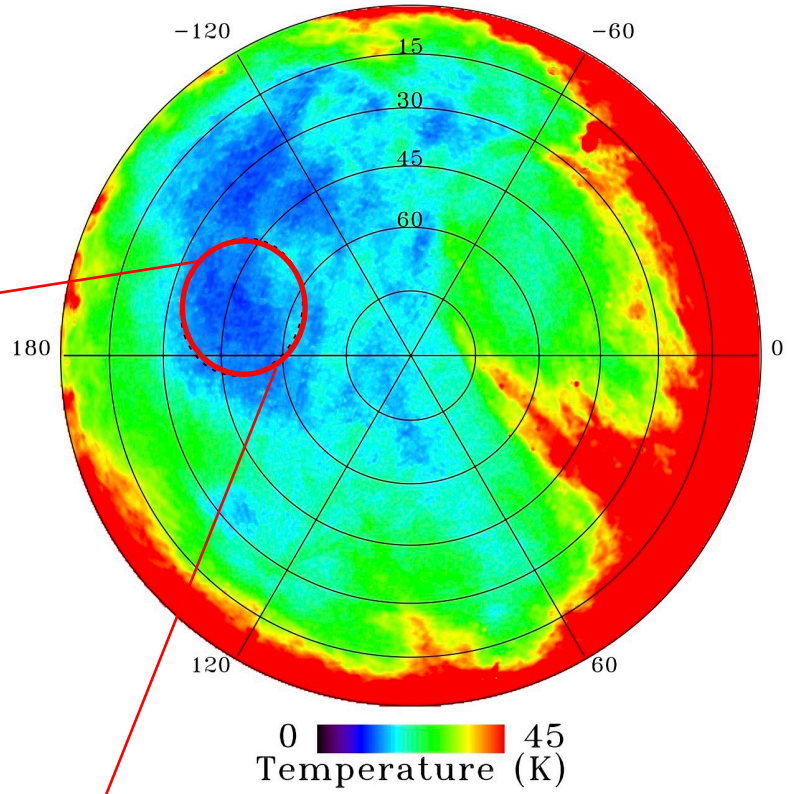
Recall that 408 MHz survey has pixel noise ~ 1 K

Histogram of coldest patch has

- Peak at 13.6 K
- Gaussian width 0.65 K

Beware of bias: Coldest pixels include downward noise fluctuations

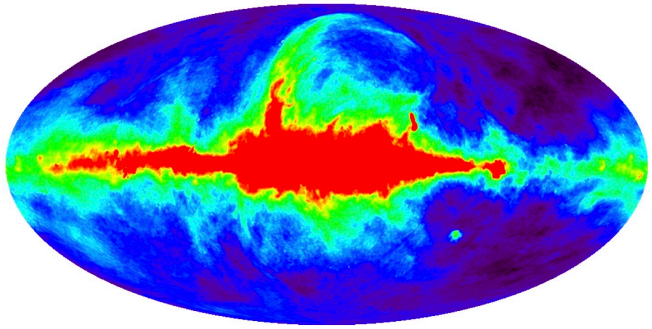




Subtract CMB 2.7 K to get

T_{BG} ~ 11 K at 408 MHz

The Advent Of Precision Data



Haslam et al 1982 408 MHz survey

Problem: Surveys from 50's to 80's not intended for precise modeling

Calibration errors 5—20%

Zero level errors of many K

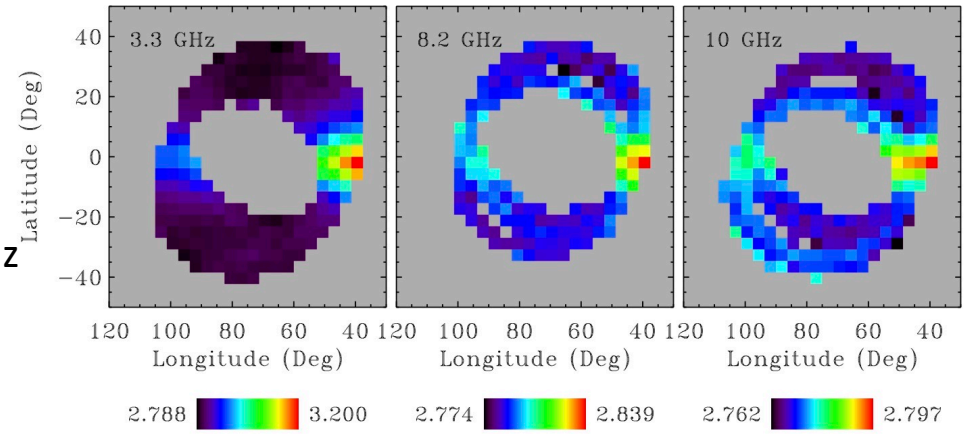
Not a problem for bright structures, but difficult to nail down monopole component

ARCADE-2 Balloon Flight

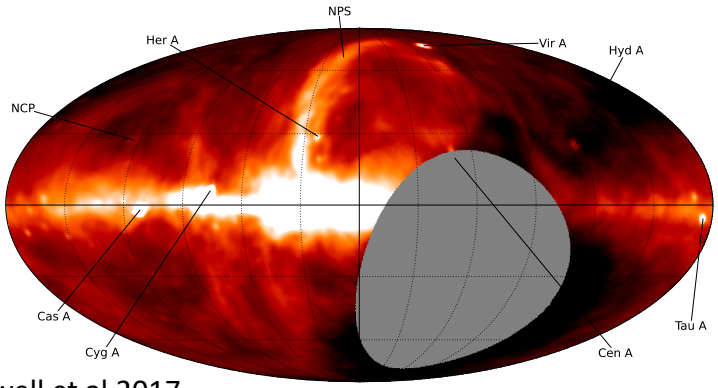
Gain error < 0.03%

Zero level error < 10 mK

Limited sky coverage at 3—90 GHz



Kogut et al 2010



Dowell et al 2017

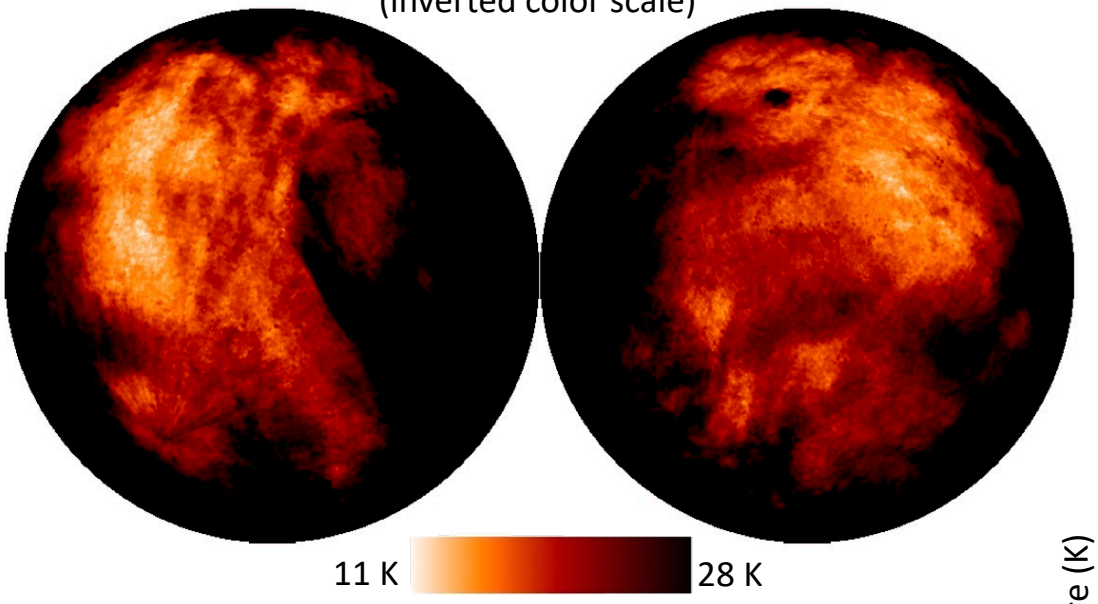
Long Wavelength Array Sky Maps

Nearly full-sky coverage 35—80 MHz

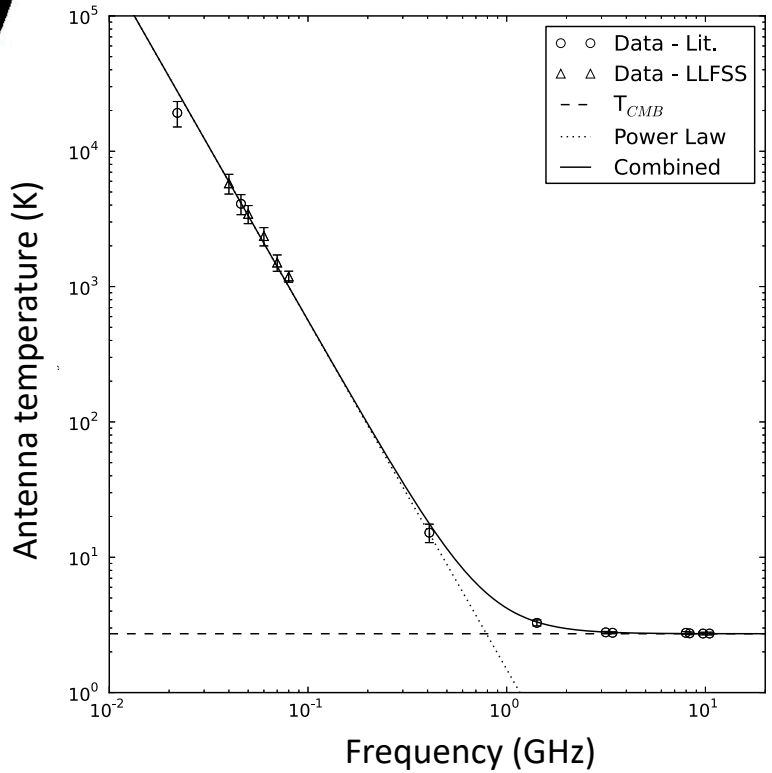
Signal-to-noise ratio > 200 at high latitude

Visualising The High-Latitude Excess

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

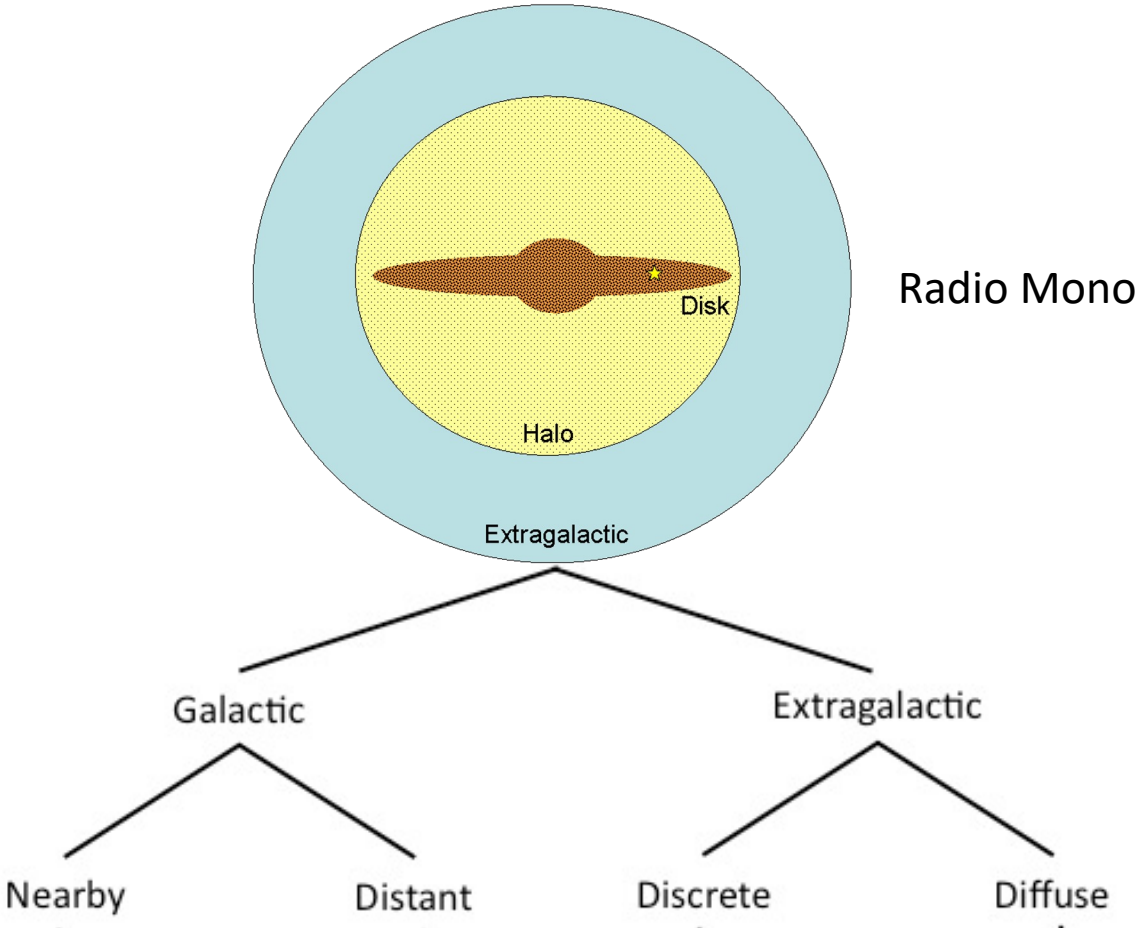
$T_A \sim \nu^{\beta}$

$\beta = -2.58 +/- 0.05$

strongly suggestive of synchrotron emission

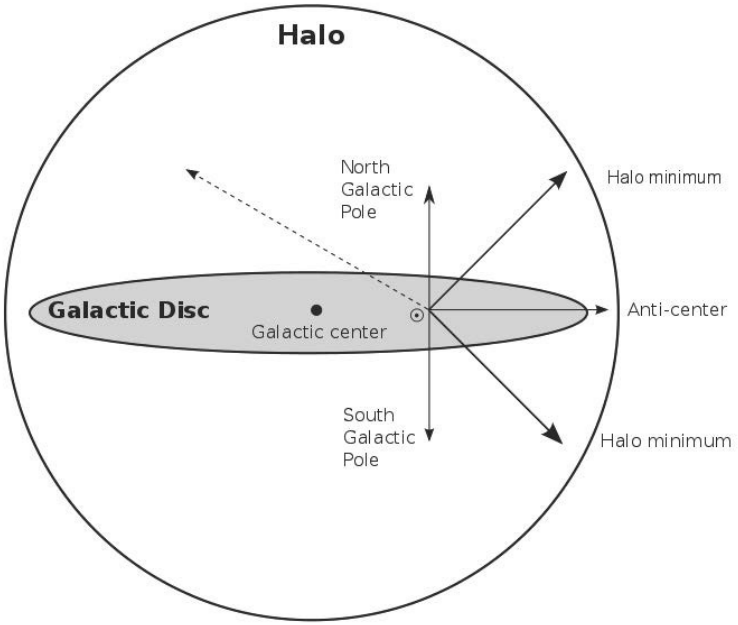
Fixsen et al 2011
Dowell & Taylor 2018

Where To Put The Radio Monopole?



Radio Monopole is ...

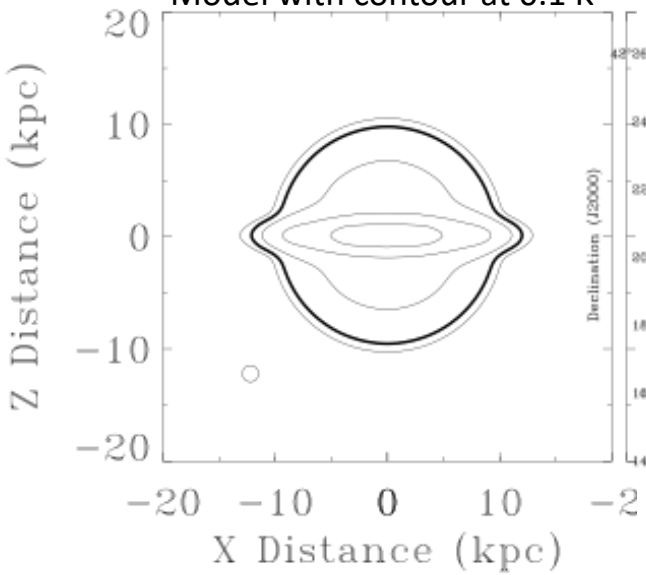
A Galactic Halo?



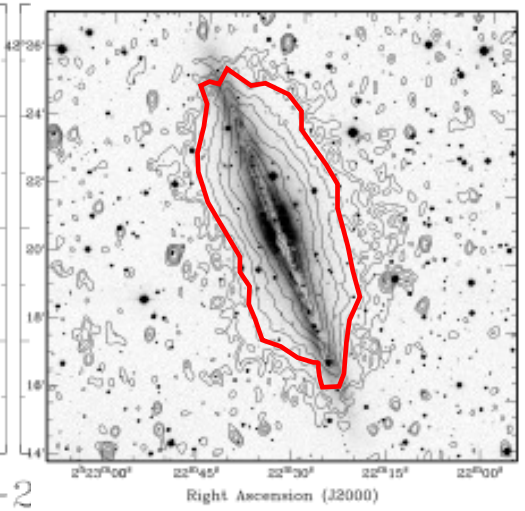
Subrahmanyan & Cowsik 2013

Model radio sky as disk + halo + anisotropic pieces
Halo diameter 28 kpc extends beyond solar circle
Explains why coldest patches are not at poles

Model with contour at 0.1 K



Data with contour at 0.1 K

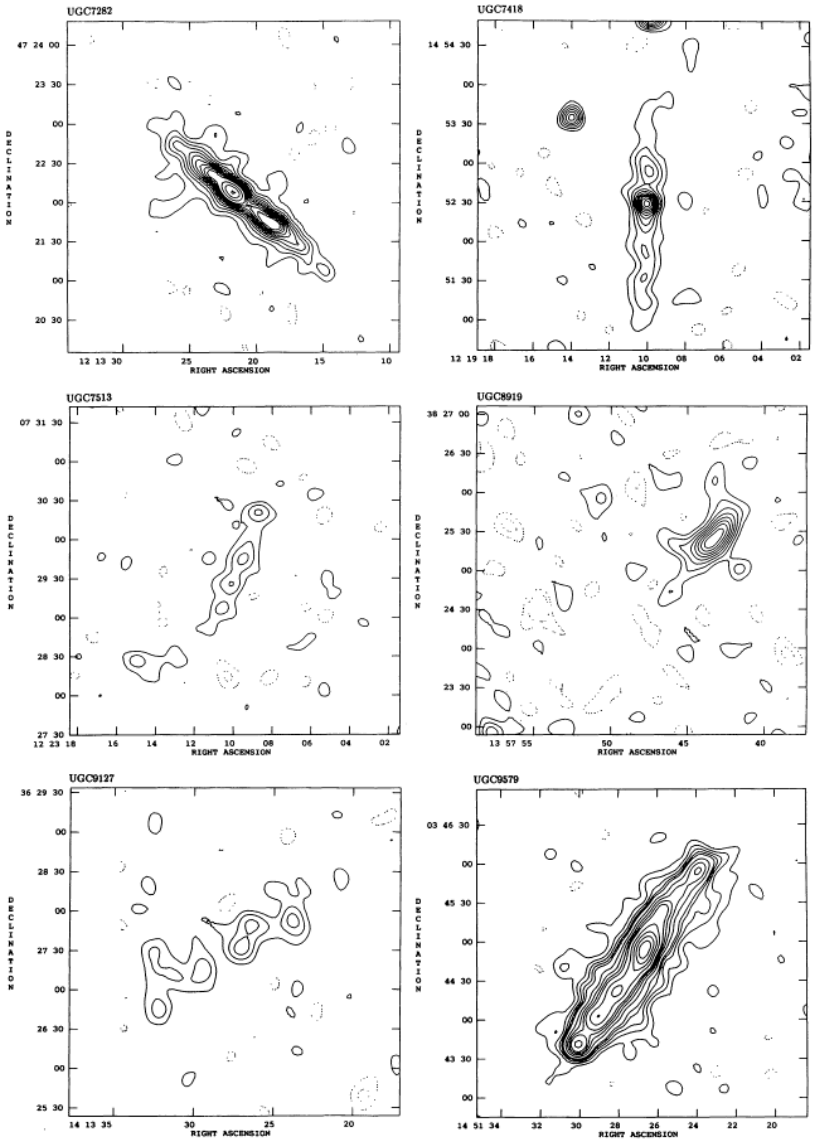


NGC 0891, Oosterloo et al 2007

Problem ...

Implies detectable halo
Not seen in survey of edge-on spirals

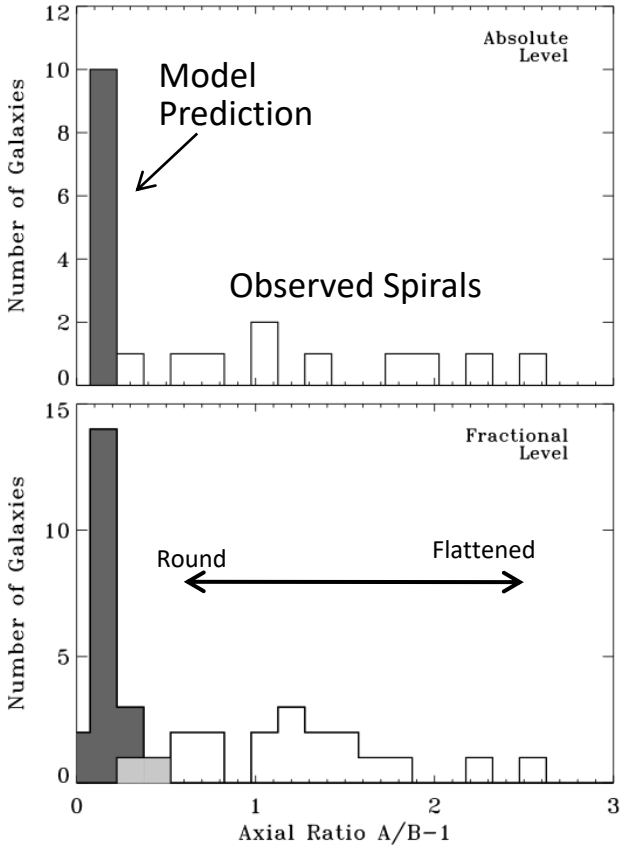
Where Have All The Halos Gone?



Radio Properties of Typical Spirals

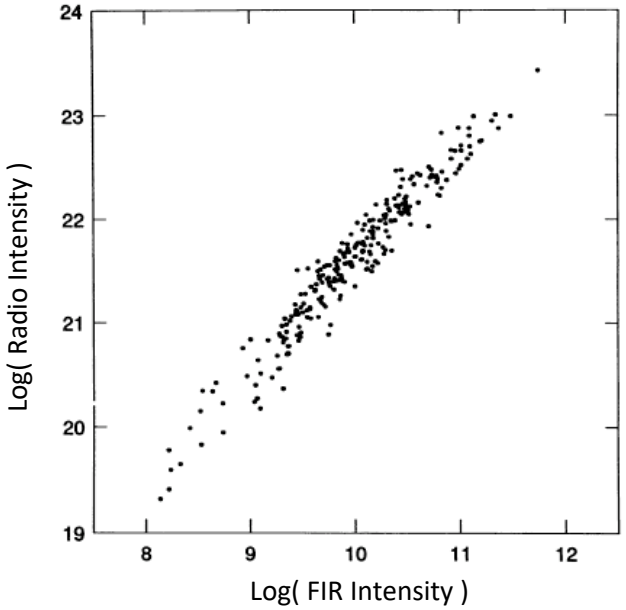
- Little or no extended emission
- Few cases of isolated spurs
- Halo contribution < 10% of disc

Axial Ratio Test: Compare Data to Model



Singal et al 2015

Diffuse Galactic Origin?



Condon 1992, ARAA, 30, 575

Remarkably tight correlation exists between radio and far-IR emission

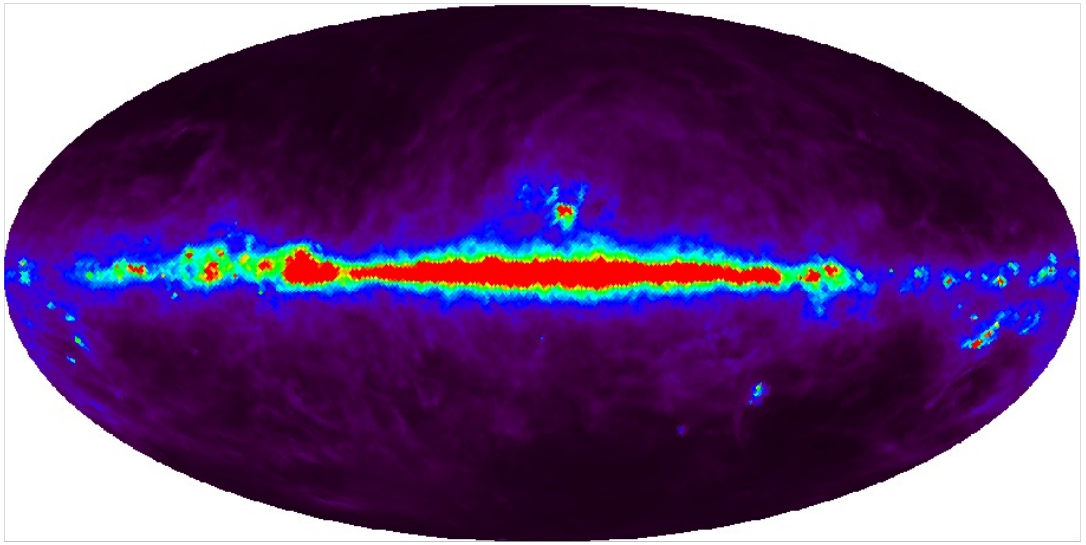
If high-latitude Galaxy is bright in radio, it should also be bright in the far-IR

But it's not …

Two tests:

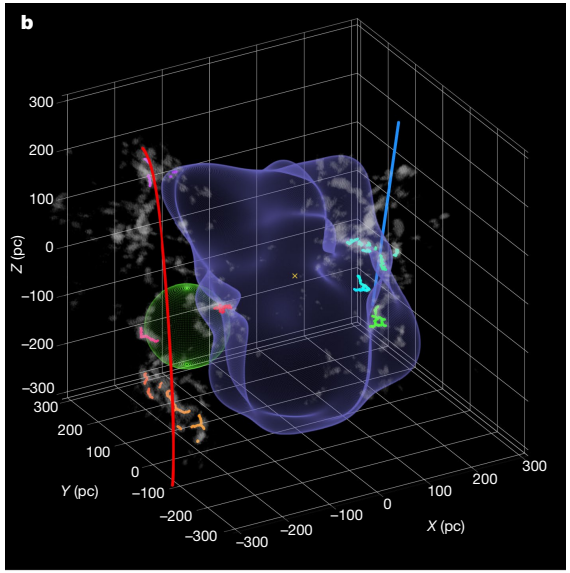
- DIRBE x canonical Radio/FIR ratio
- Scale observed radio/FIR to |b|=90

Obtain T ~ 5K at 408 MHz: Too Small!

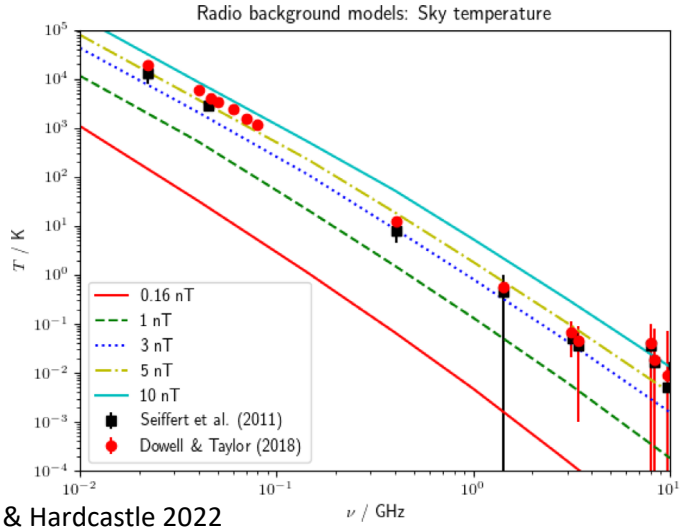


DIRBE 100 μm absolute map

Local Bubble Origin?



Zucker et al. 2022



Krause & Hardcastle 2022

Solar system is near the center of a bubble of ionized gas from recent supernovae

Could synchrotron radiation within the bubble create a signifincant monopole?

Simulate emission with measured cosmic ray energy distribution and a turbulent (Kolmogorov) magnetic field

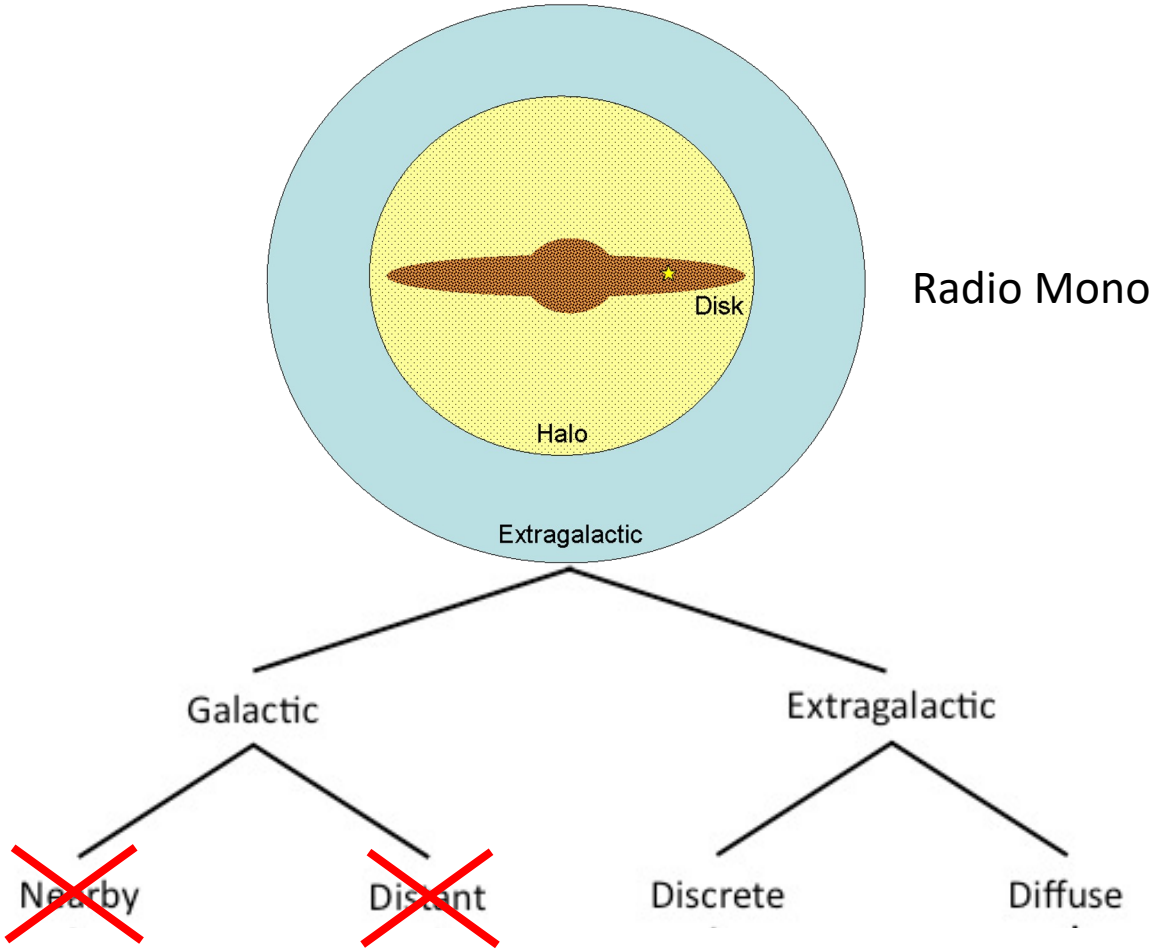
Best fit requires magnetic field 30—50 nG

- Field strength well in excess of equipartition
- Synchrotron spectrum has too much curvature
- Problem with fractional polarization

Expected contribution to observed monopole is at the few-percent level

Where To Put The Radio Monopole?

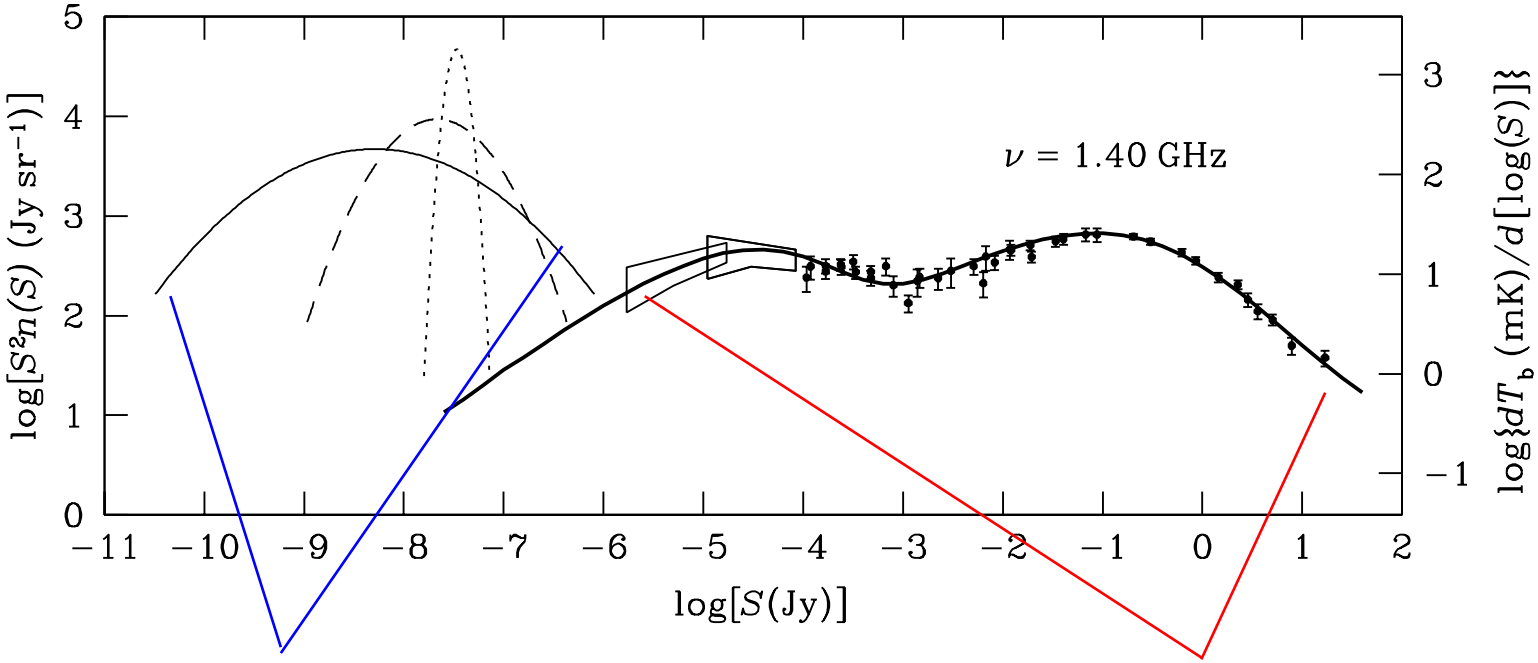
Where To Put The Radio Monopole?



Radio Monopole is ...

Discrete Extragalactic Origin?

Simplest solution: monopole component as integrated emission from discrete sources



Possible populations
to make up the difference

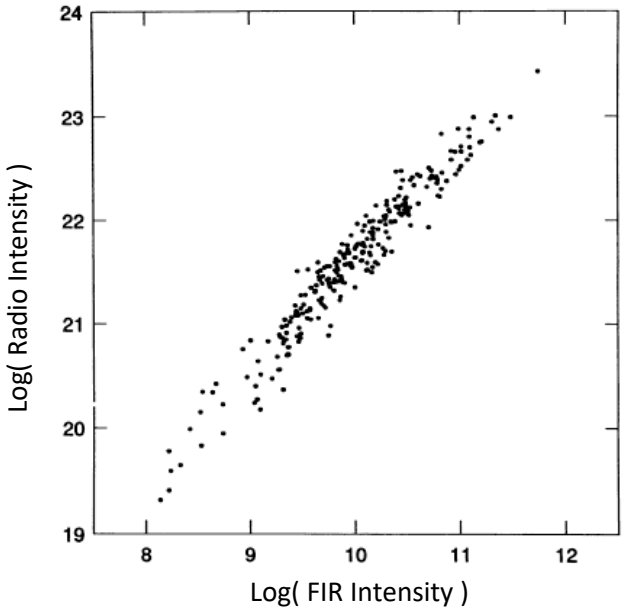
Known sources:
20% of radio monopole

Problem: Required faint populations exceed density of galaxies in Hubble UDF by factor of 100

Condon et al. 2012

Discrete Extragalactic Origin?

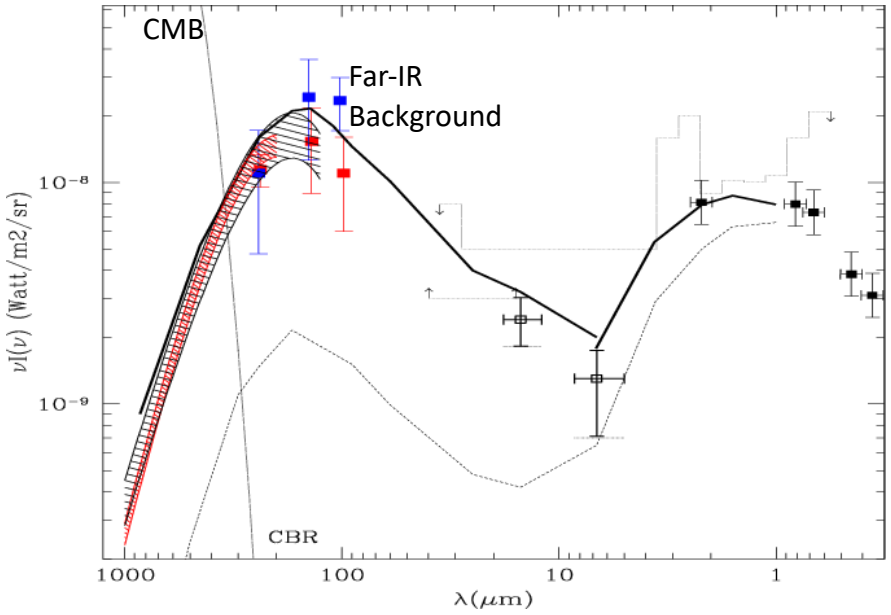
Radio/FIR correlation provides independent check on extragalactic origin



Condon 1992, ARAA, 30, 575

Tight correlation between radio and IR emission

Use observed far-IR background to predict integrated radio emission from same galaxies



Predict T_R ~ 1—2 K at 408 MHz

- Consistent with radio source counts
- Too small to make up observed background

Dwek & Barker 2002, APJ, 575, 7

Franceschini et al 2001

Diffuse Extragalactic Origin?

Could monopole be integrated emission from sources of low surface brightness?

Constraint from radio vs X-ray backgrounds

Radio emission from ultra-relativistic electrons

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

$$I_\nu \sim \kappa_e \; B^{(p+1)/2} \; \nu^{-(p-1)/2}$$

X-ray emission from inverse Compton scattering of CMB photons from **same** electrons

$$I_\nu \sim \kappa_e \; \kappa_\gamma \, f(p)$$

Singal et al 2010

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Frequency dependence sets p

Knobs to set amplitude

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CMB sets lower limit

Singal et al 2010

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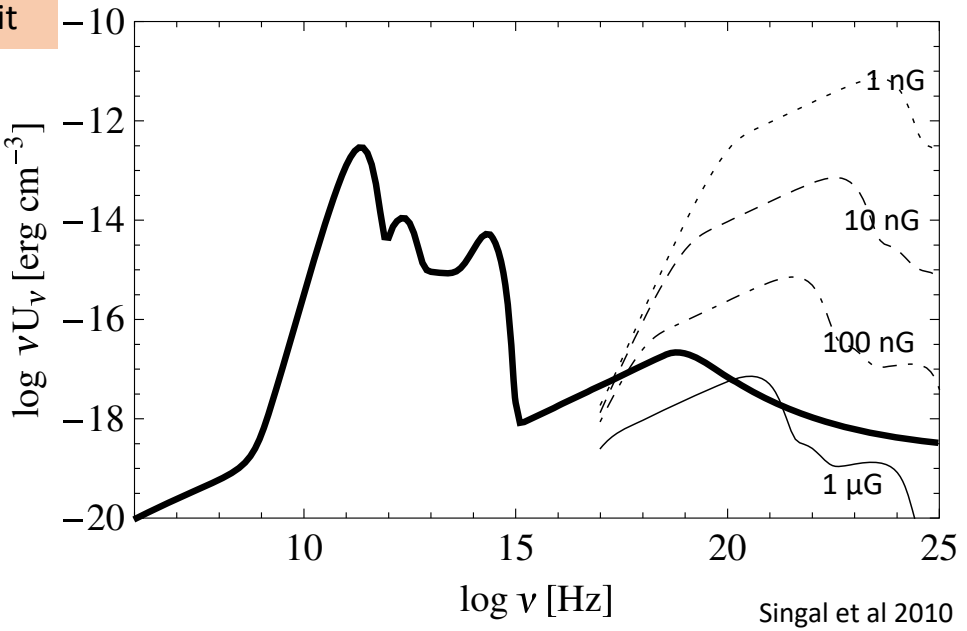
CMB sets lower limit

Large magnetic field B required to avoid over-producing X-rays

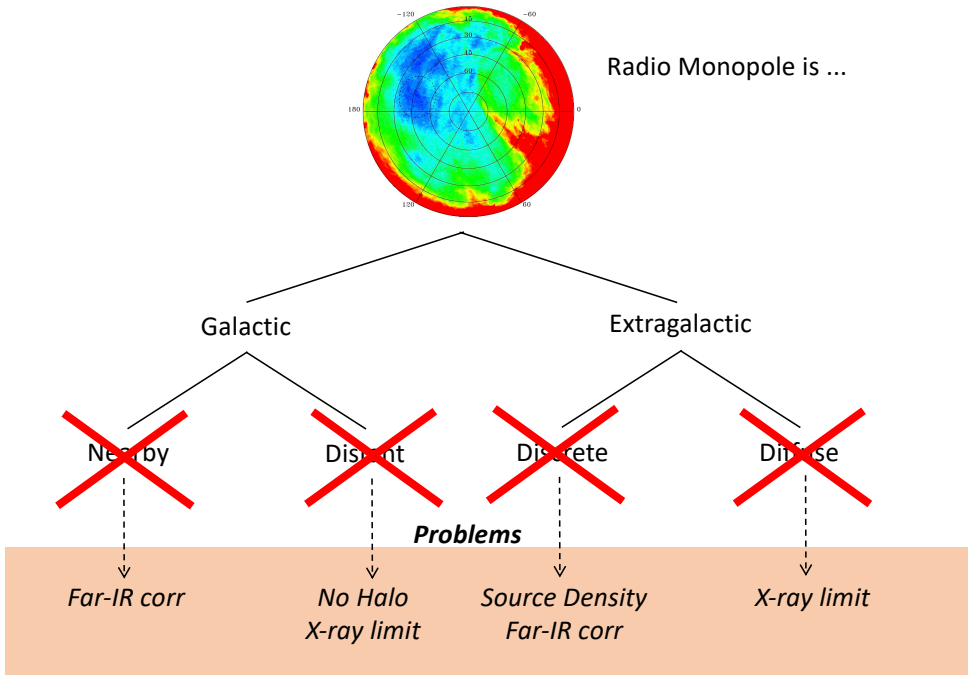
B > 1 μG

Conflicts with B < 0.2 μG for IGM

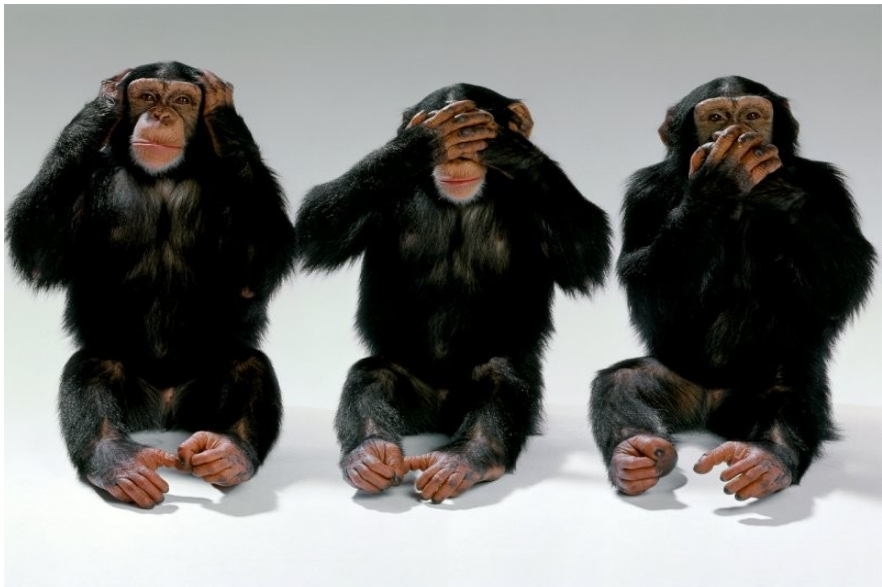


Singal et al 2010

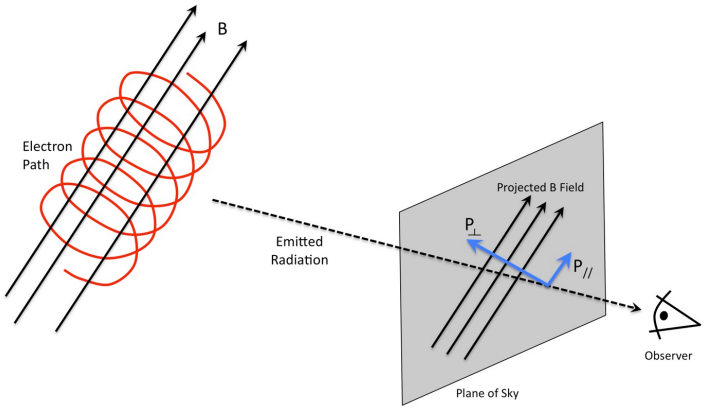
NOW what?



Having efficiently ruled out a number of "most plausible" origins, what comes next?



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

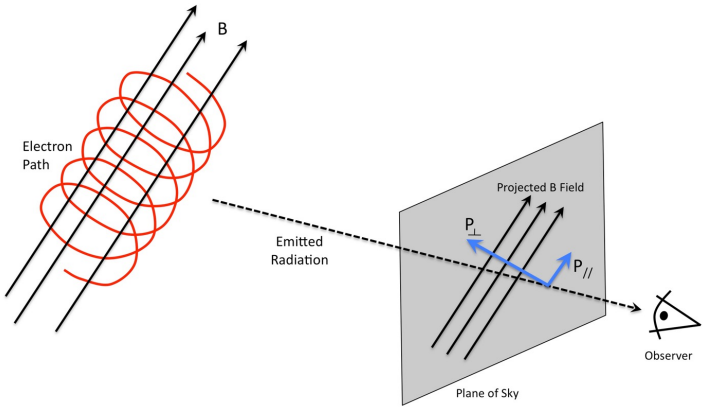
$$T_A(\nu) \propto \nu^{\beta} \qquad \beta = -(p+3)/2$$

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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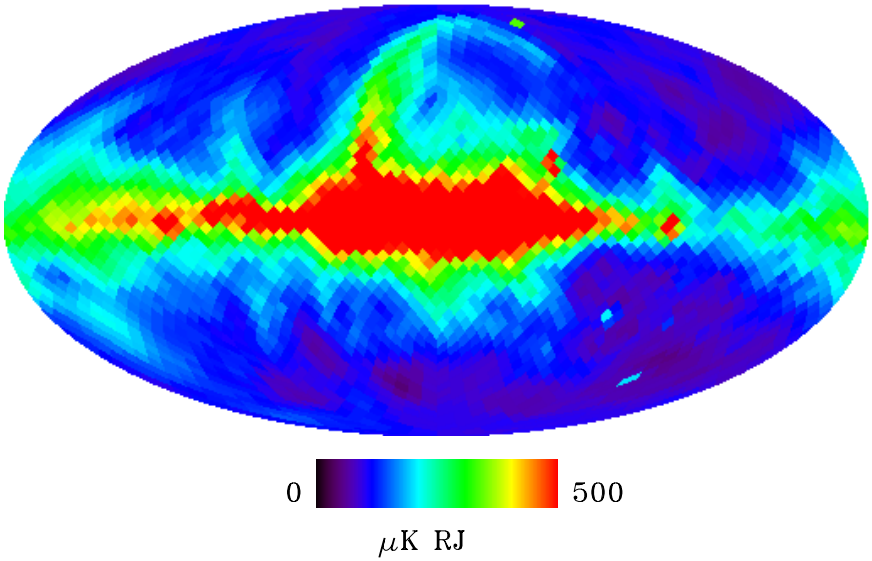
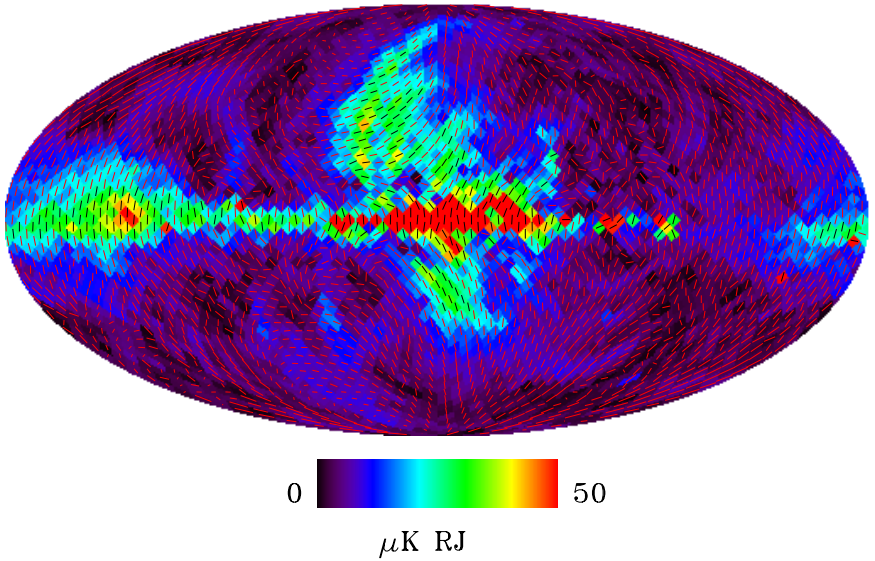
THIS IS NOT OBSERVED

Observed Synchrotron Emission

Unpolarized Synchrotron at 30 GHz

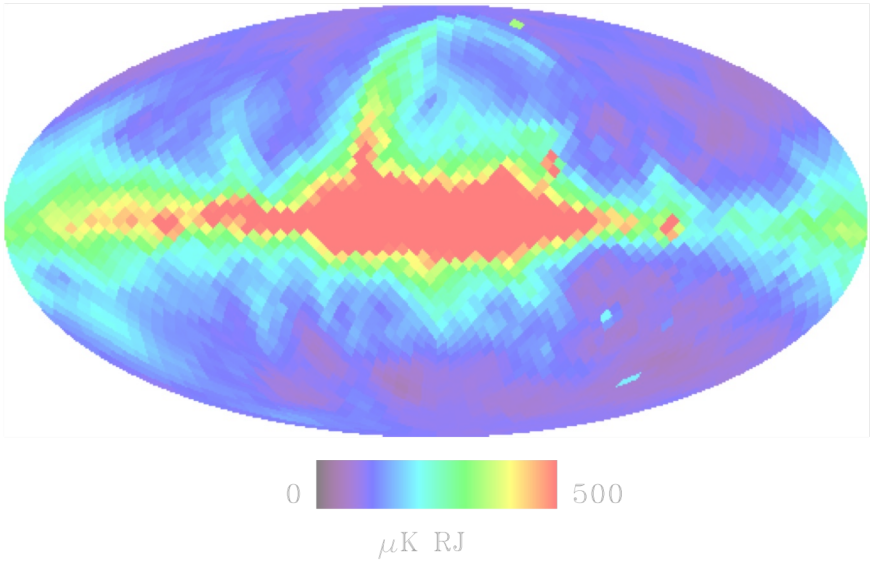


Polarized Synchrotron at 30 GHz

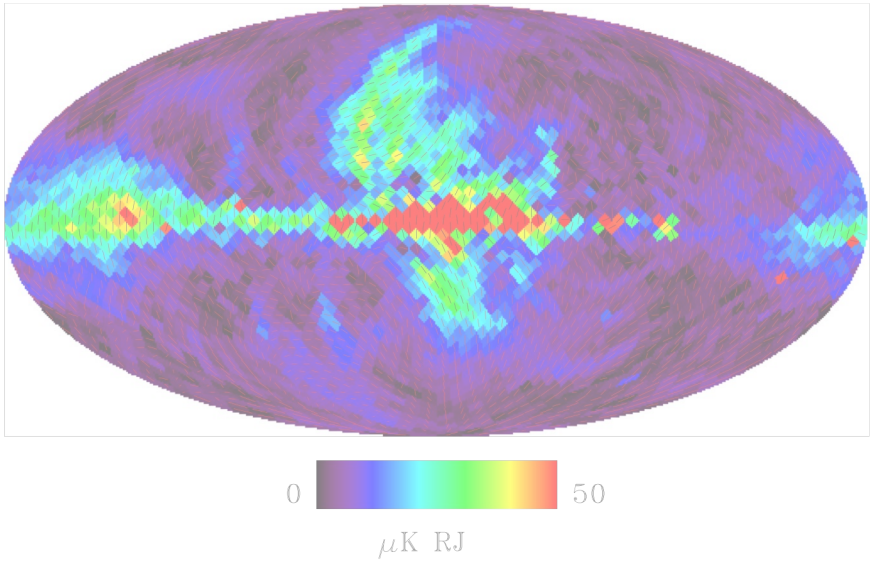


Observed Synchrotron Emission

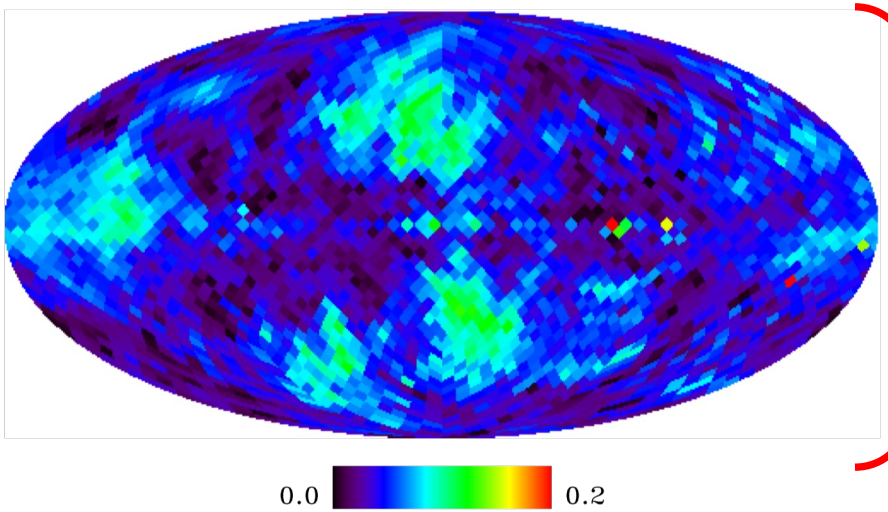
Unpolarized Synchrotron at 30 GHz

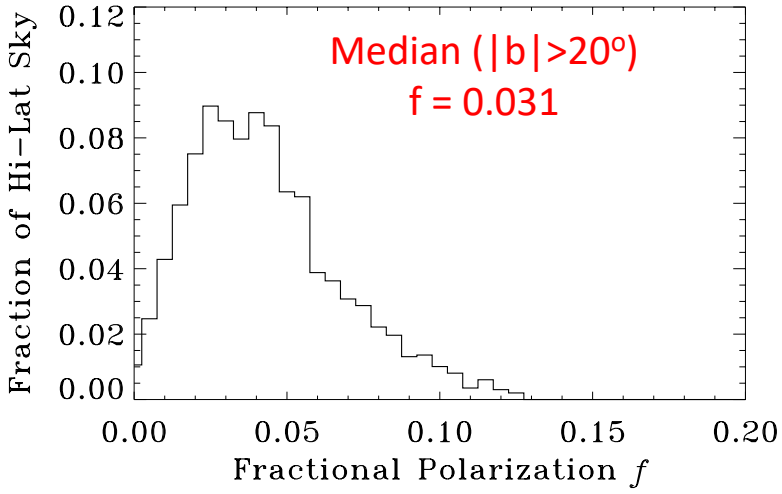


Polarized Synchrotron at 30 GHz



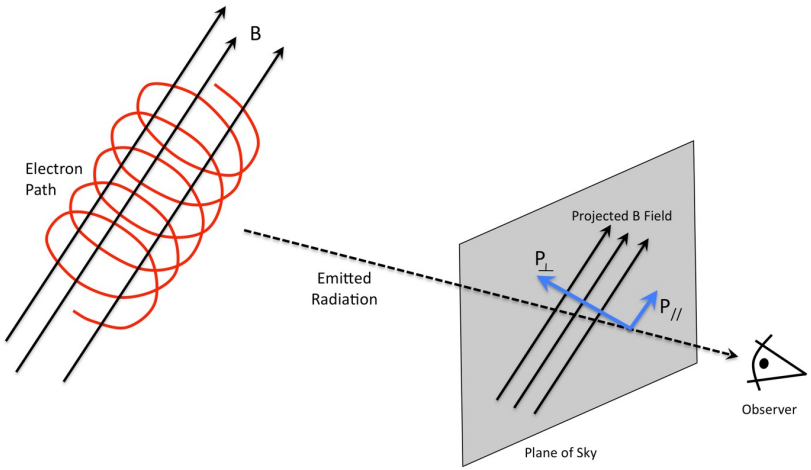
Fractional Polarization at 30 GHz





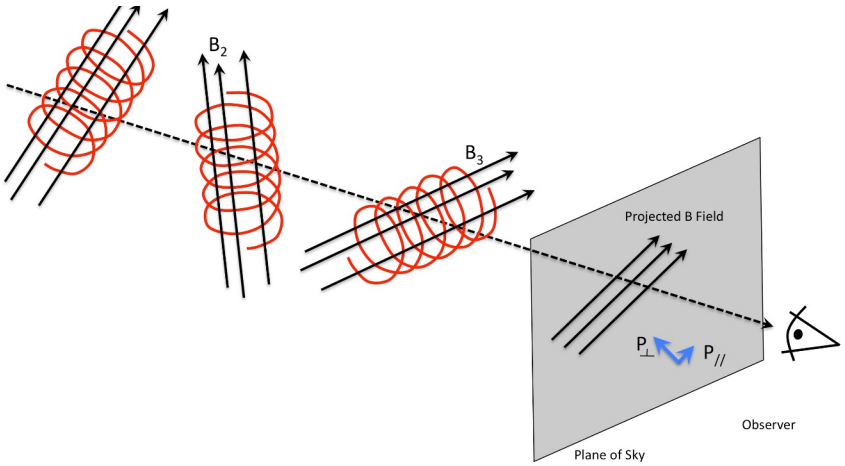
Synchrotron Depolarization I

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



Single Magnetic Domain

$$f \sim 0.7$$



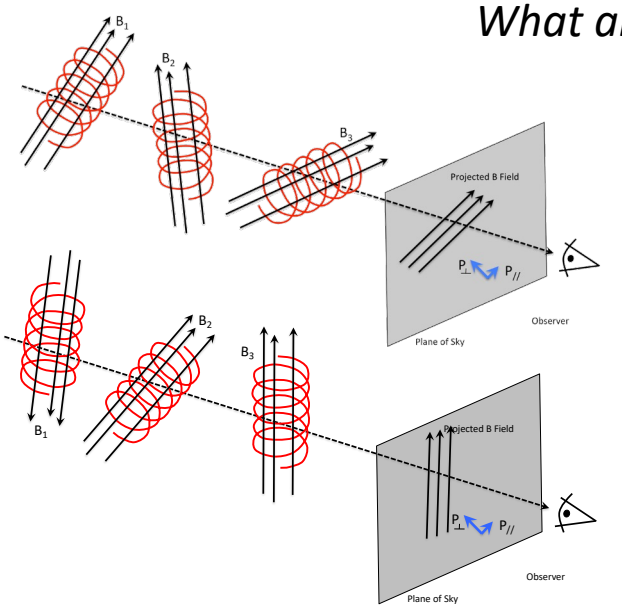
N Uncorrelated Domains
Intensities add, polarizations cancel

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

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

Synchrotron Depolarization II

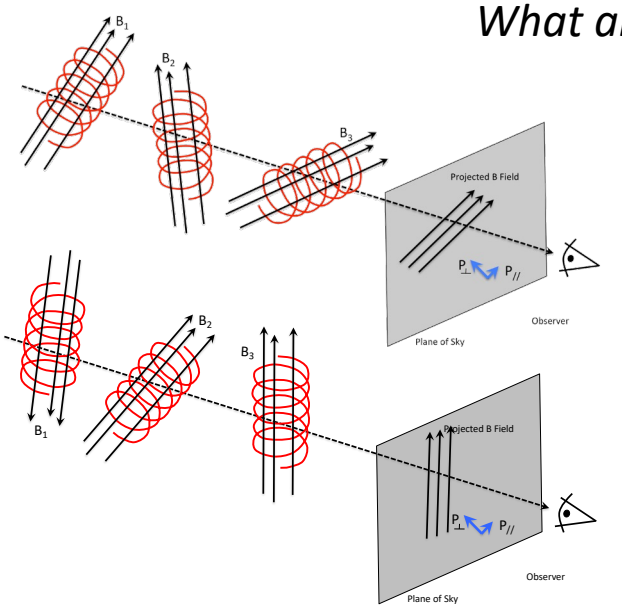
What about polarization angles?



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?



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

THIS IS NOT OBSERVED

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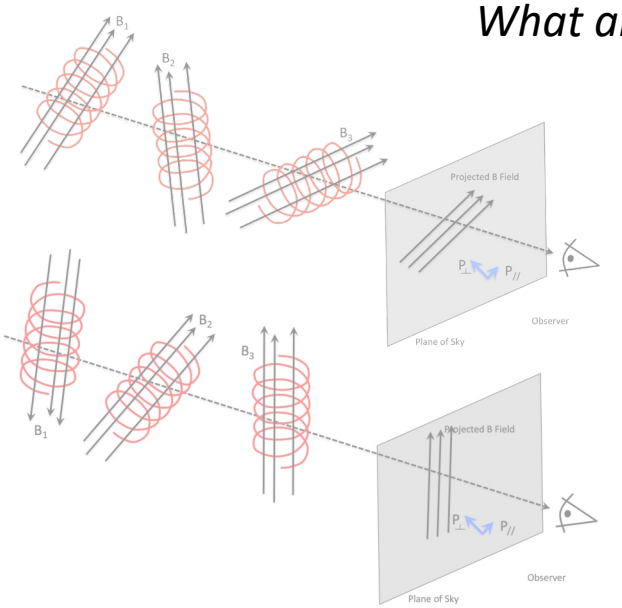

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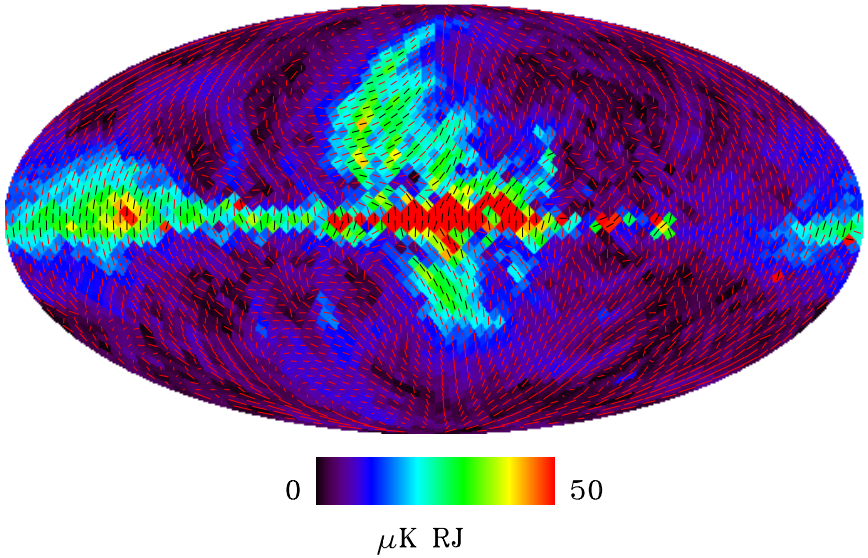
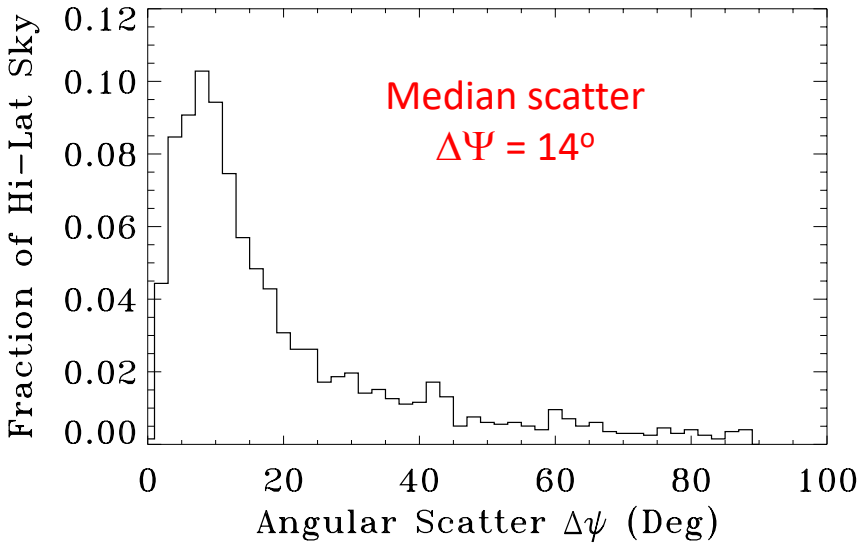
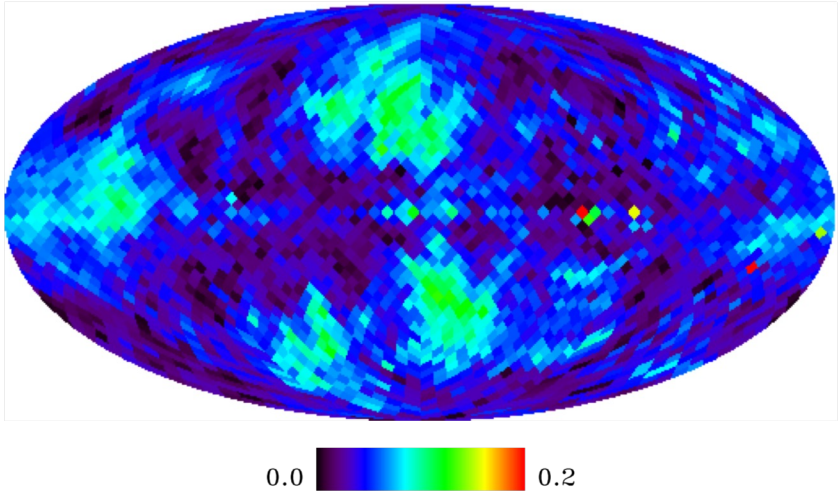




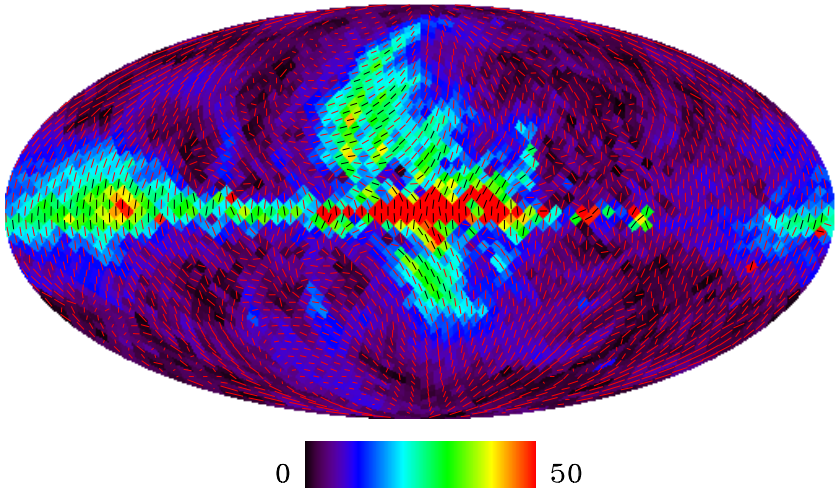
The Problem

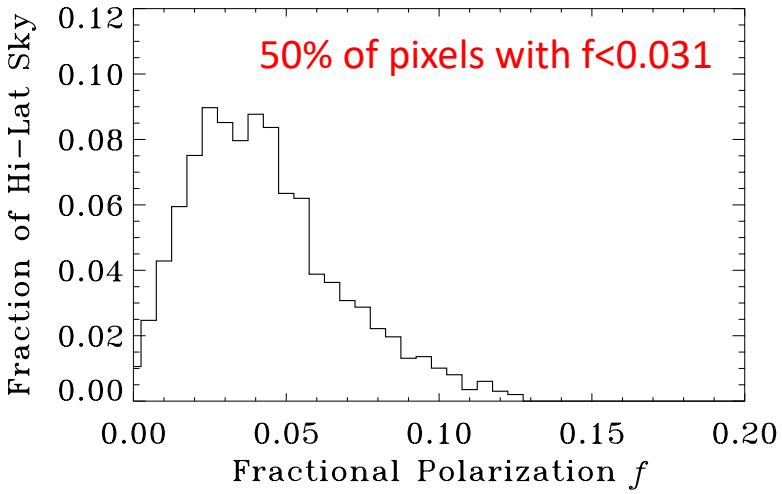
Synchrotron sky is strikingly de-polarized, but polarization direction is highly aligned
Can we reconcile this with Galactic magnetic field?

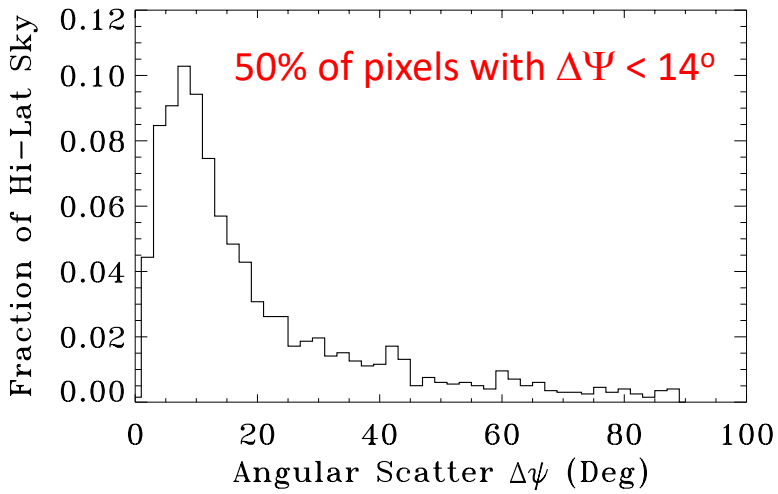
Fractional Polarization P/I



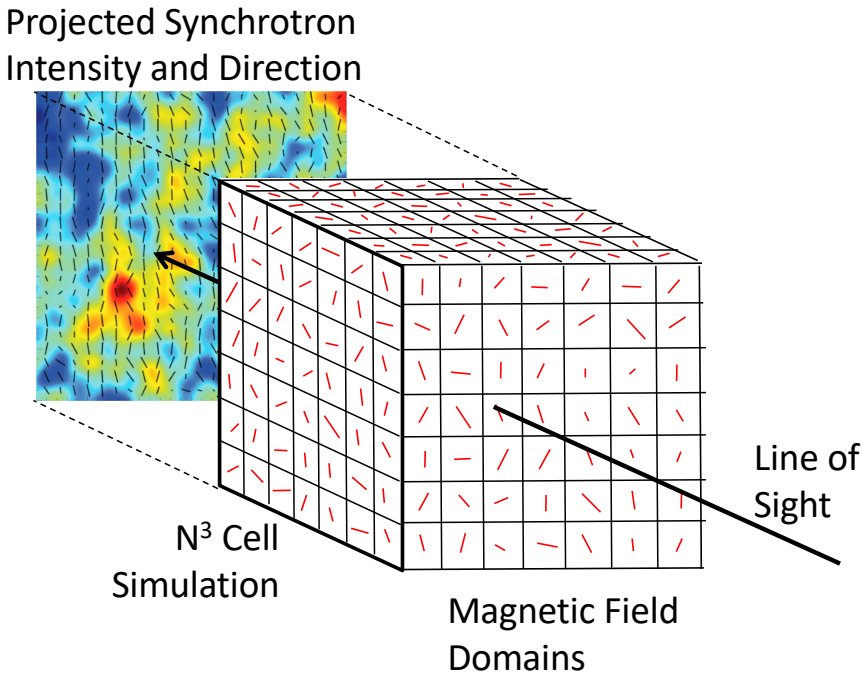
Polarized Intensity and Direction







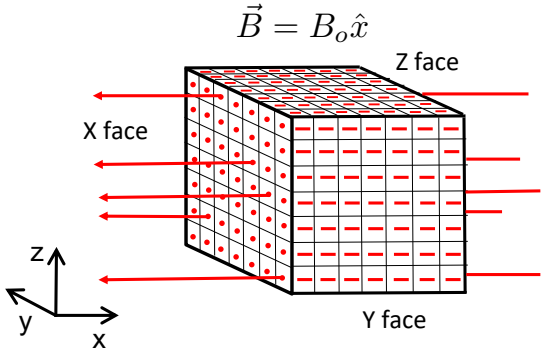
Test: Magnetohydrodynamic Simulations



- 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



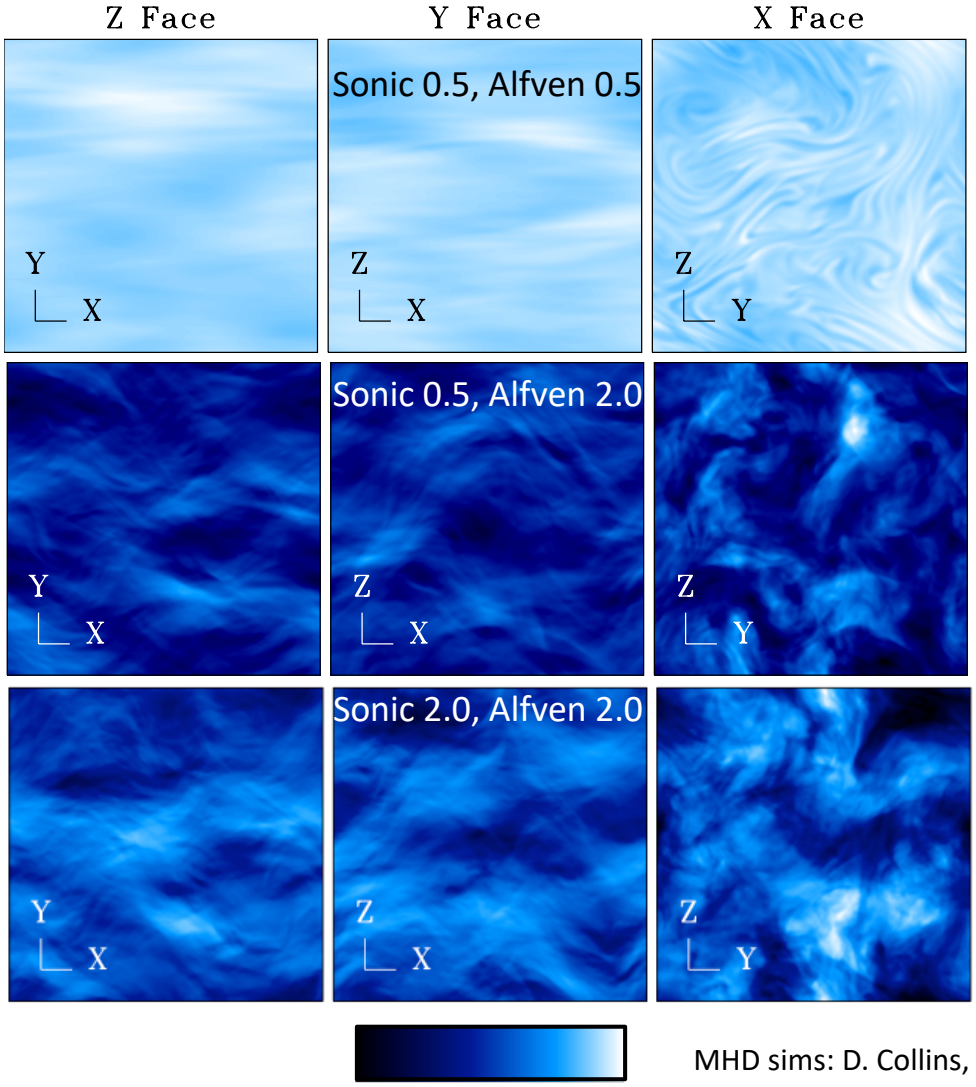
Enzo code: Seed cube with uniform field in x

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

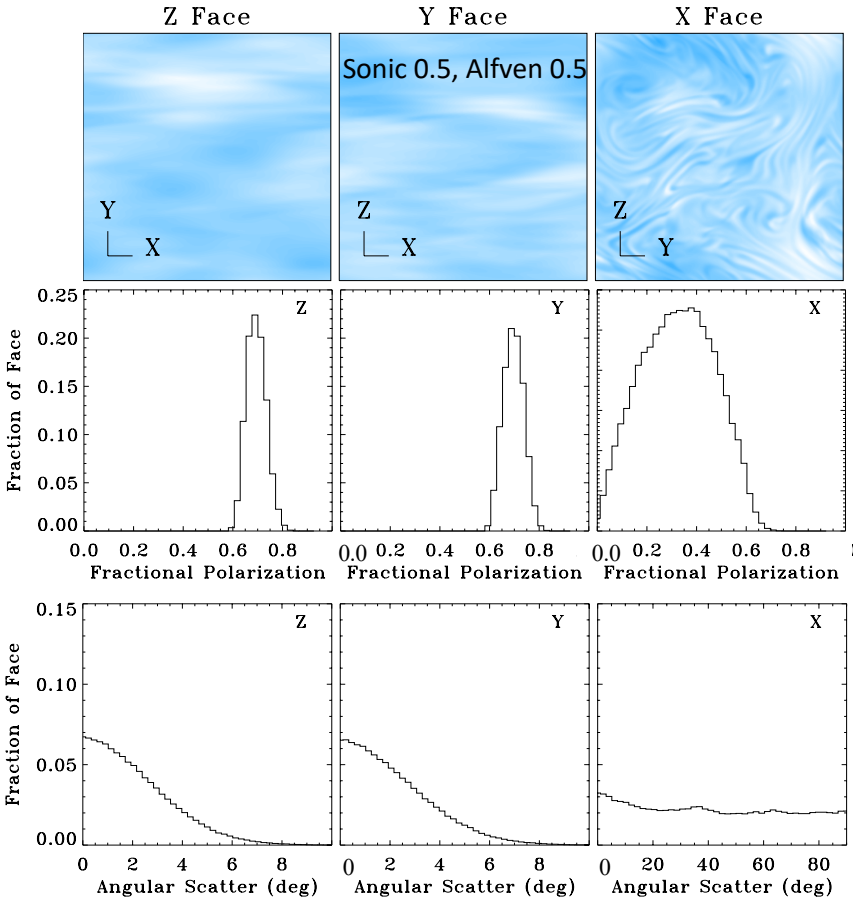
Projected B field through cube faces



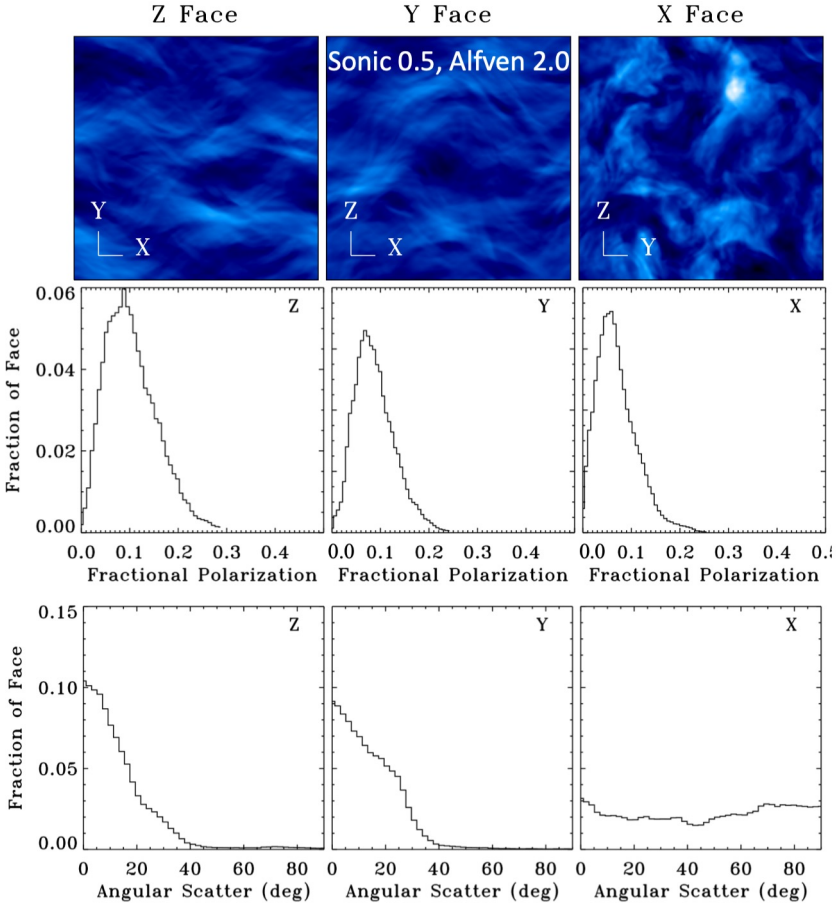
MHD sims: D. Collins, FSU

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	
$\mathcal{M}$	$\mathcal{M}_{\rm A}$	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 $\lvert b\rvert > 20^\circ$		0.031		14.1	

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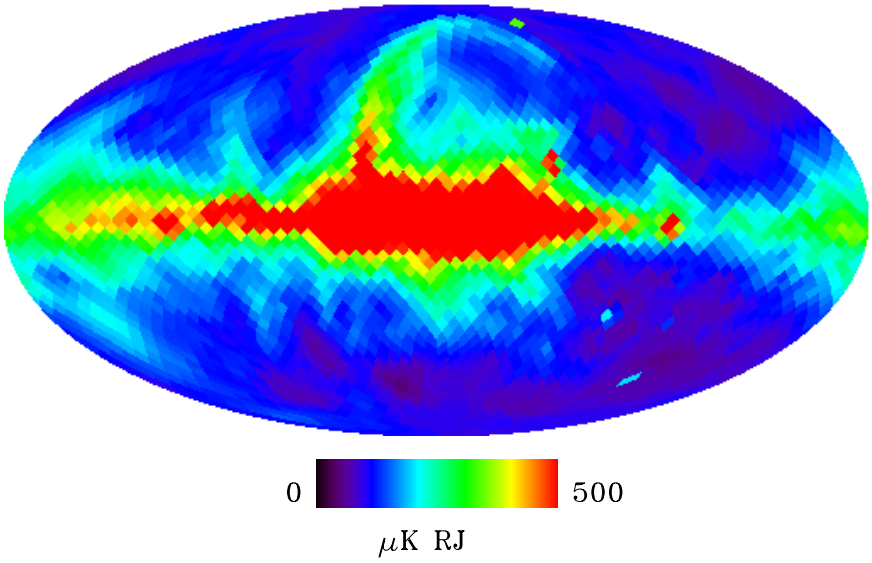
Planck Sky $\lvert b\rvert > 20^\circ$			0.031		14.1	

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

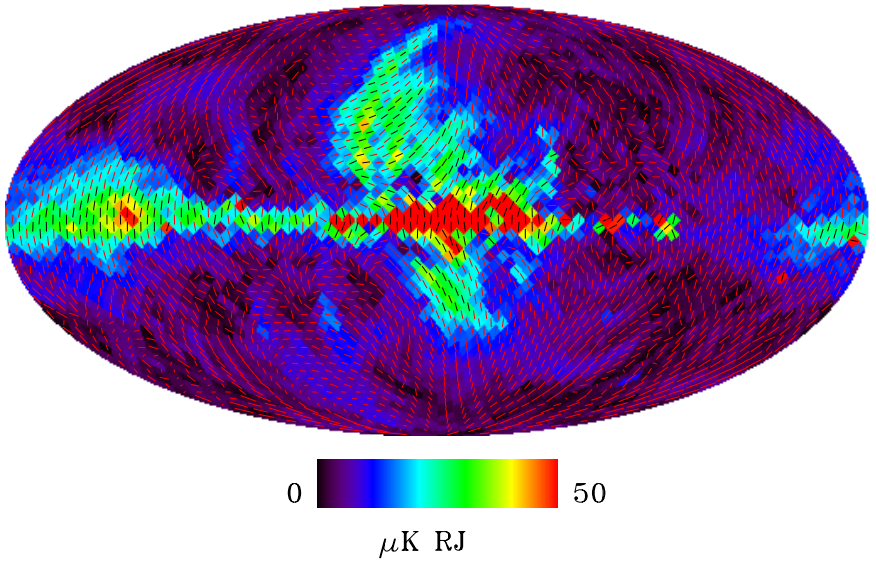
Is there an escape hatch?

Monopole Subtraction

Unpolarized Synchrotron at 30 GHz



Polarized Synchrotron at 30 GHz



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

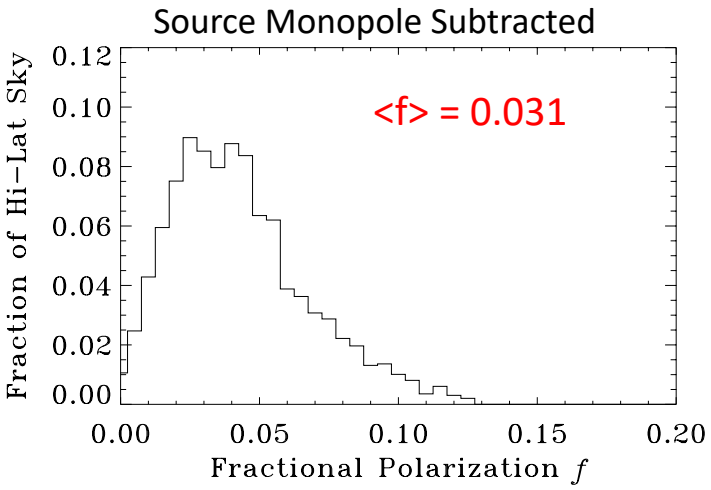
Unpolarized synchrotron intensity corrected for known radio source population, but the observed monopole is 4x brighter than the source contribution

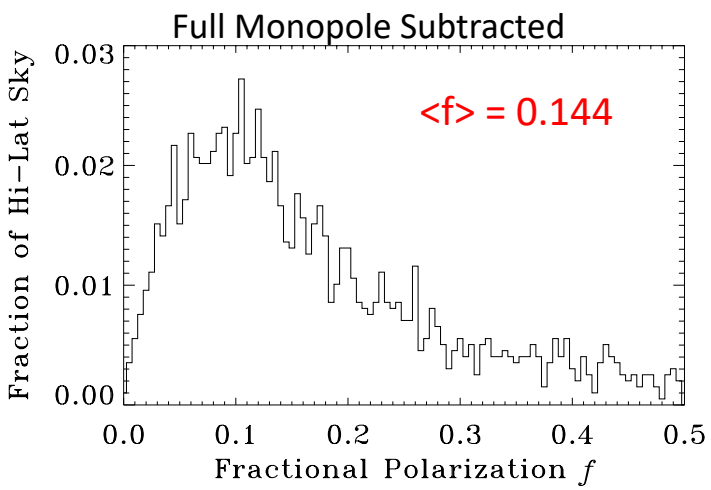
Fractional polarization is defined as $\frac{\text{Polarized Intensity}}{\text{Unpolarized Intensity}}$

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





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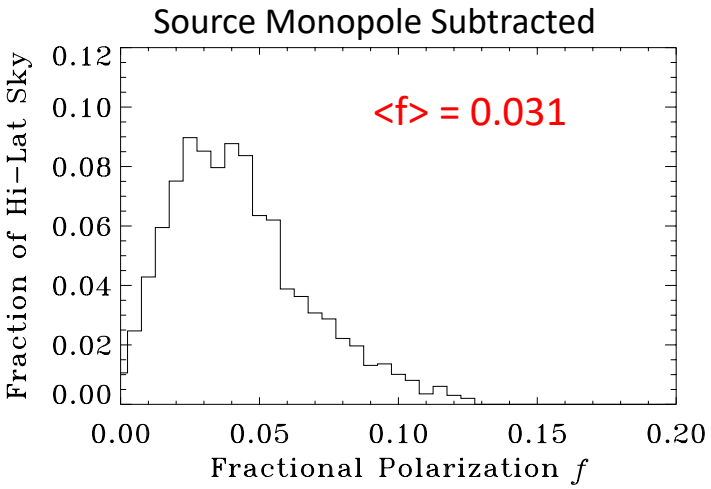

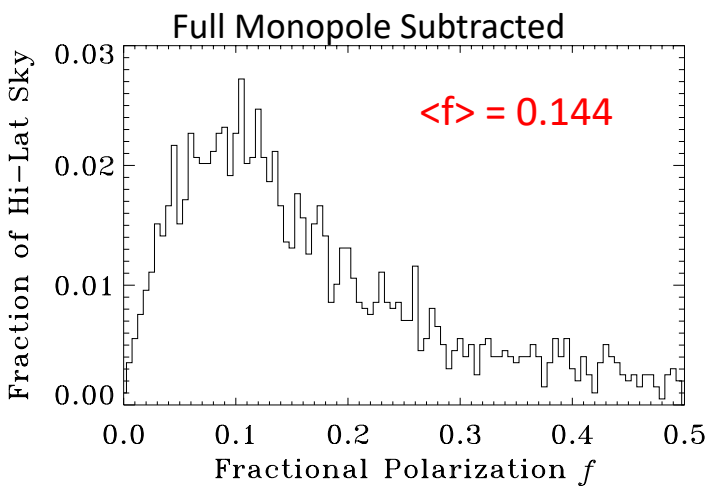

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2.0	2.0		0.23	0.17	9.0	38.0
3.0	2.0		0.21	0.17	9.5	42.0
Planck Sky $\|b\| > 20°$ (nominal)			0.031		14.1	
Planck Sky $\|b\| > 20°$ (corrected)[a]			0.144		14.1	

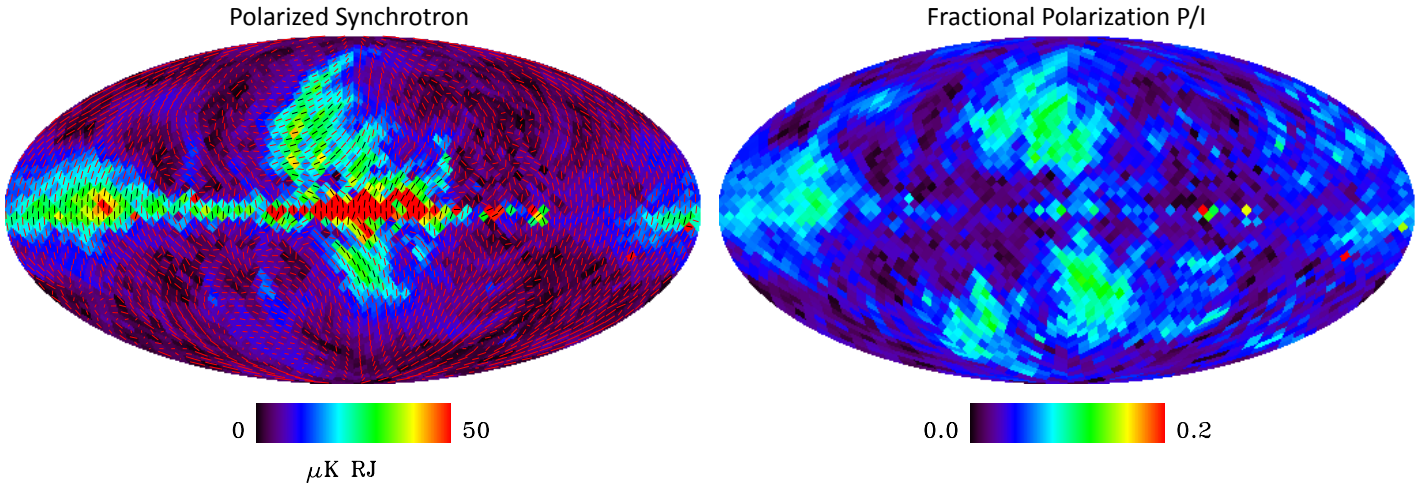
[a] After removing monopole component

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

65 Years of ... Not Much Progress?

Existence of the radio monoole first identified 65 years ago, with suggested origins ranging from local to Galactic halo to extragalactic sources.

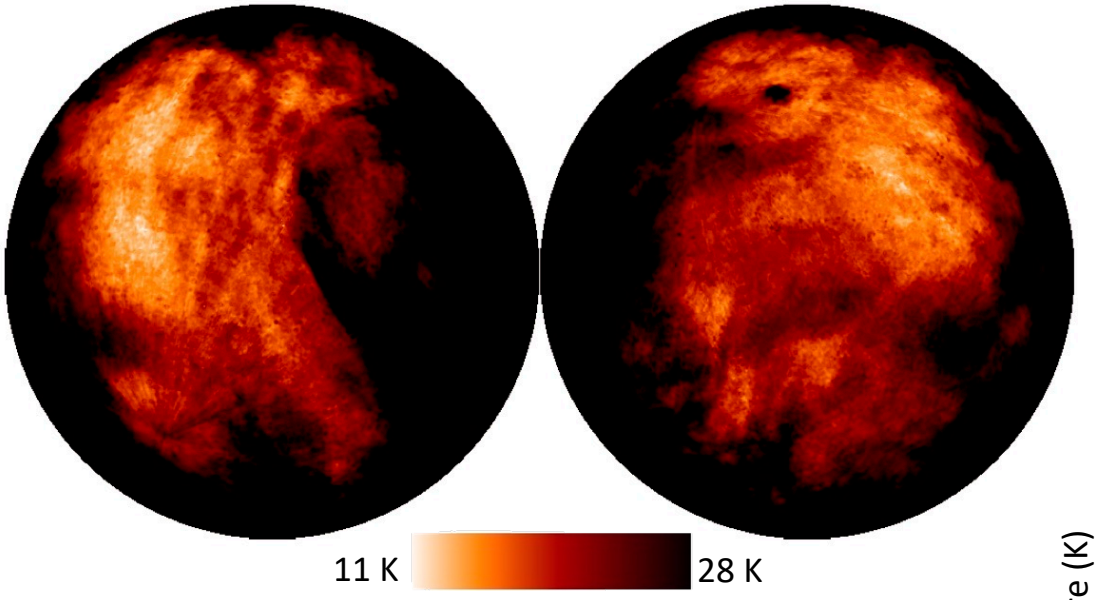
65 years later, still no consensus – what is wrong with our models?



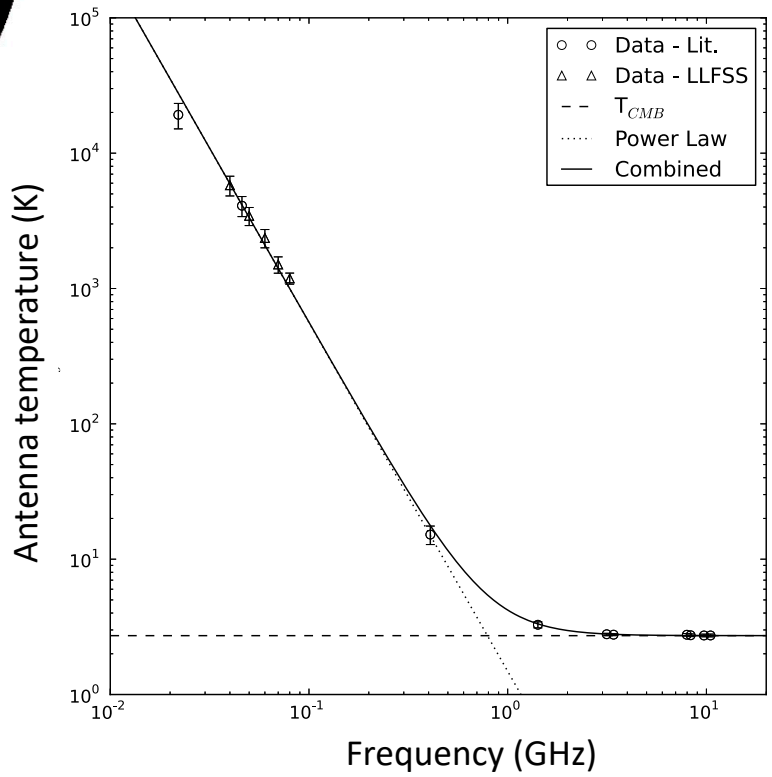
Current models of Galactic synchrotron emission can't explain combination of low fractional polarization and highly ordered polarization direction.

Extragalactic origin to observed monopole eliminates this tension but requires something new

Parting Thoughts



The other day upon the stair
I met a man who wasn't there
He wasn't there again today ...
I wish, I wish he'd go away!
-- William Hughes Mearns



THANK YOU