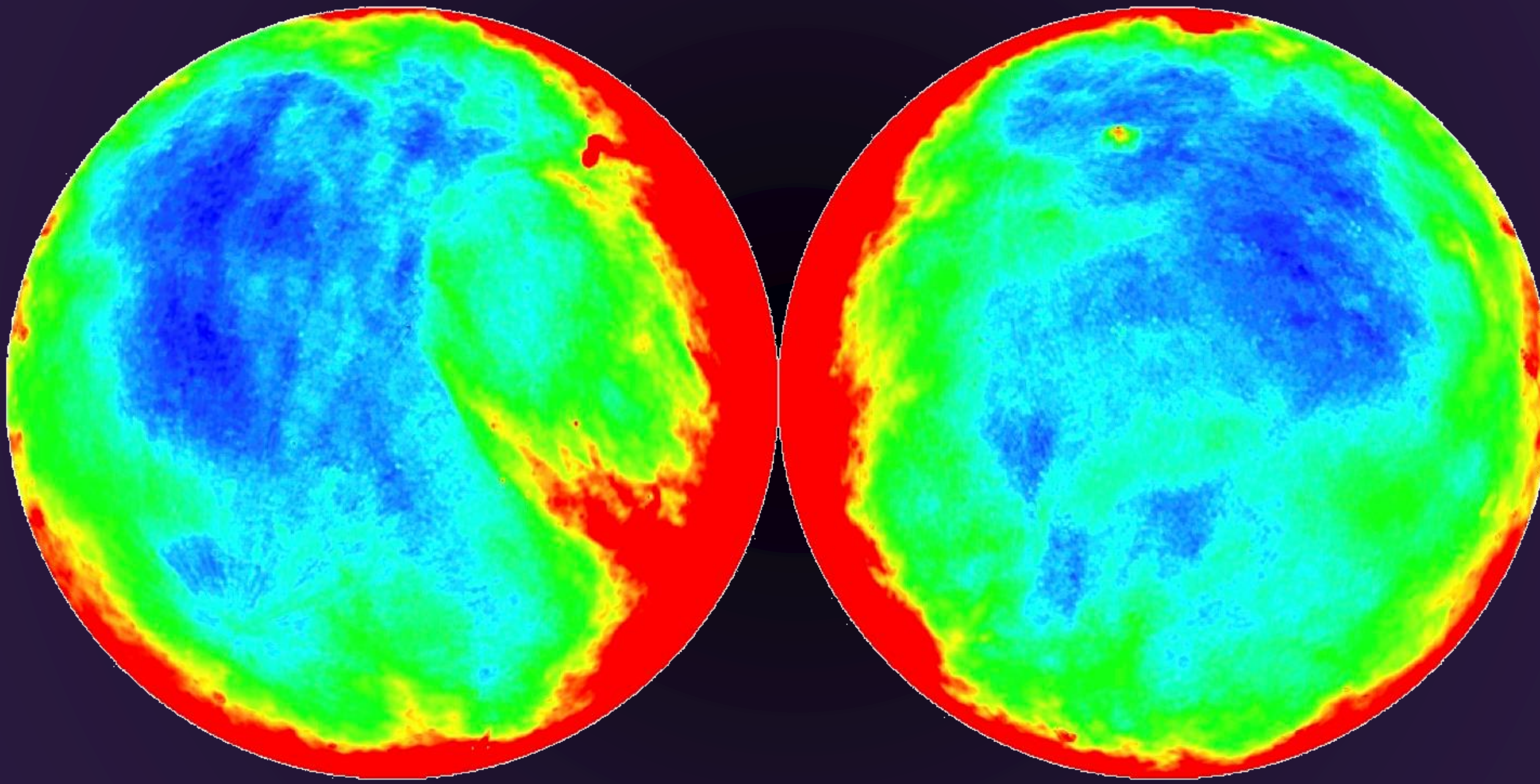
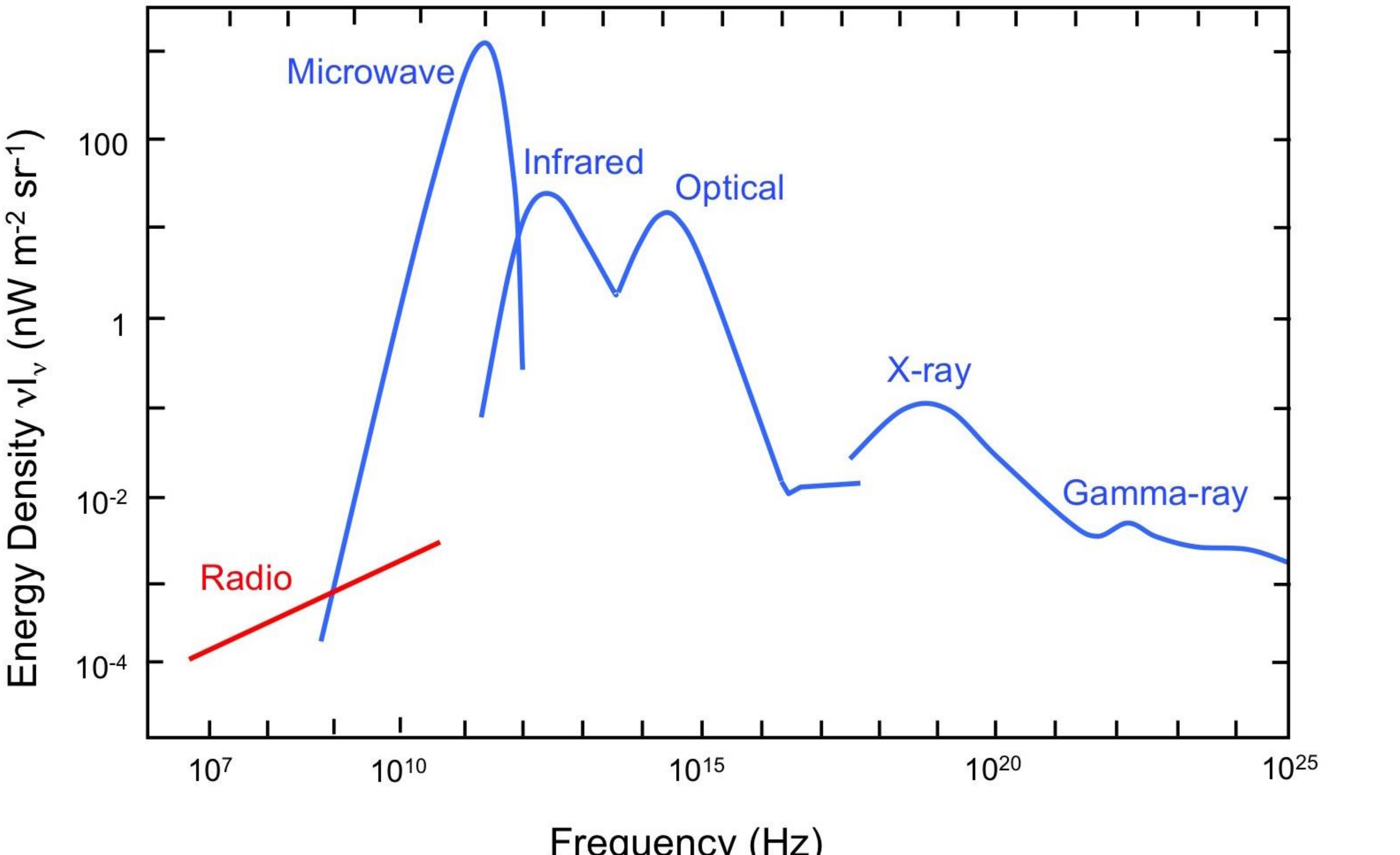
The Extragalactic Radio Background

Challenges and Opportunities

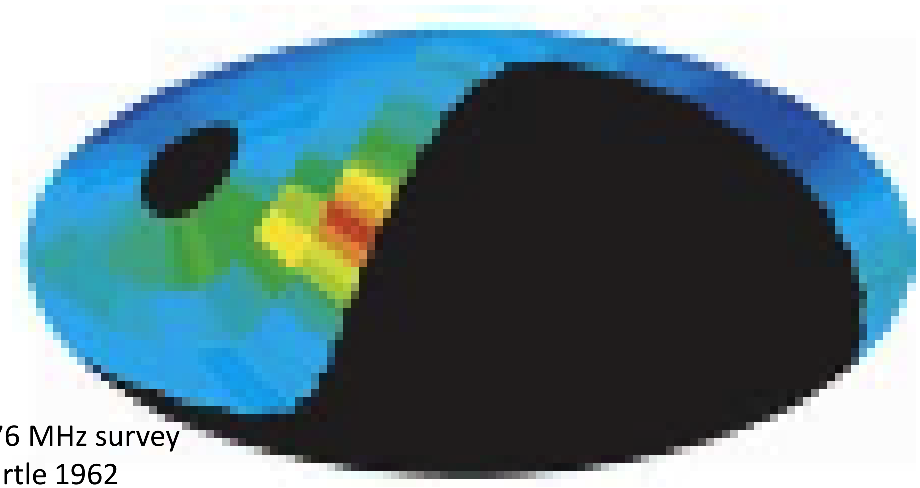


Al Kogut
Goddard Space Flight Center

Extragalactic Backgrounds



Early Background Estimates



176 MHz survey
Turtle 1962

T_{ex} From Spectral Index Variations

T_{ex} = 30—80 K at 176 MHz

= 3—6 K at 408 MHz

Assumes extragalactic component has different spectral index than galaxy

3D modeling of full-sky surveys

Fit 408 MHz survey:

Thin disk + thick disk + spiral arms

\+

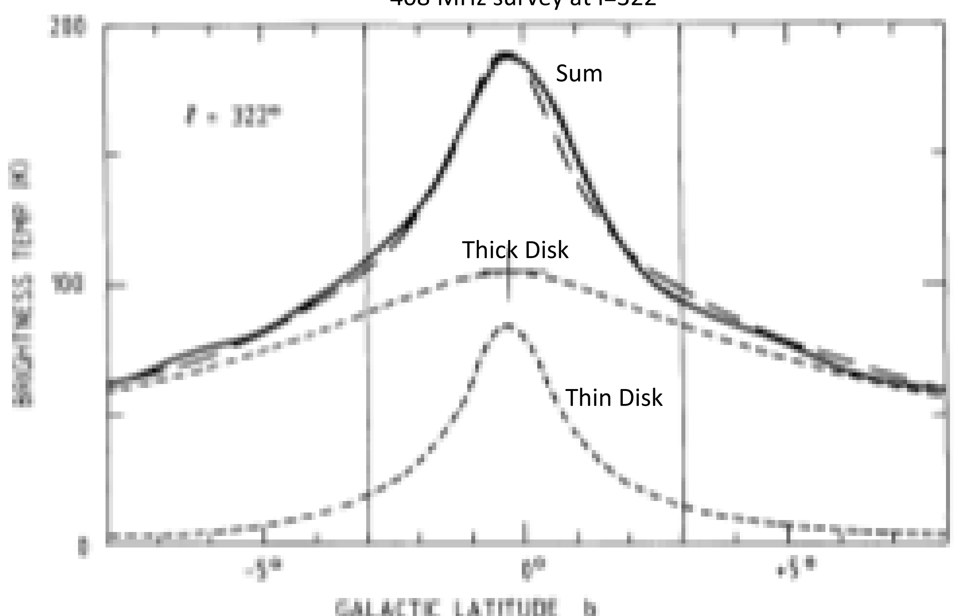
Extragalactic component

T_{ex} = 6 K at 408 MHz

(assumed value, not fit)

(includes 2.7 K CMB)

408 MHz survey at l=322

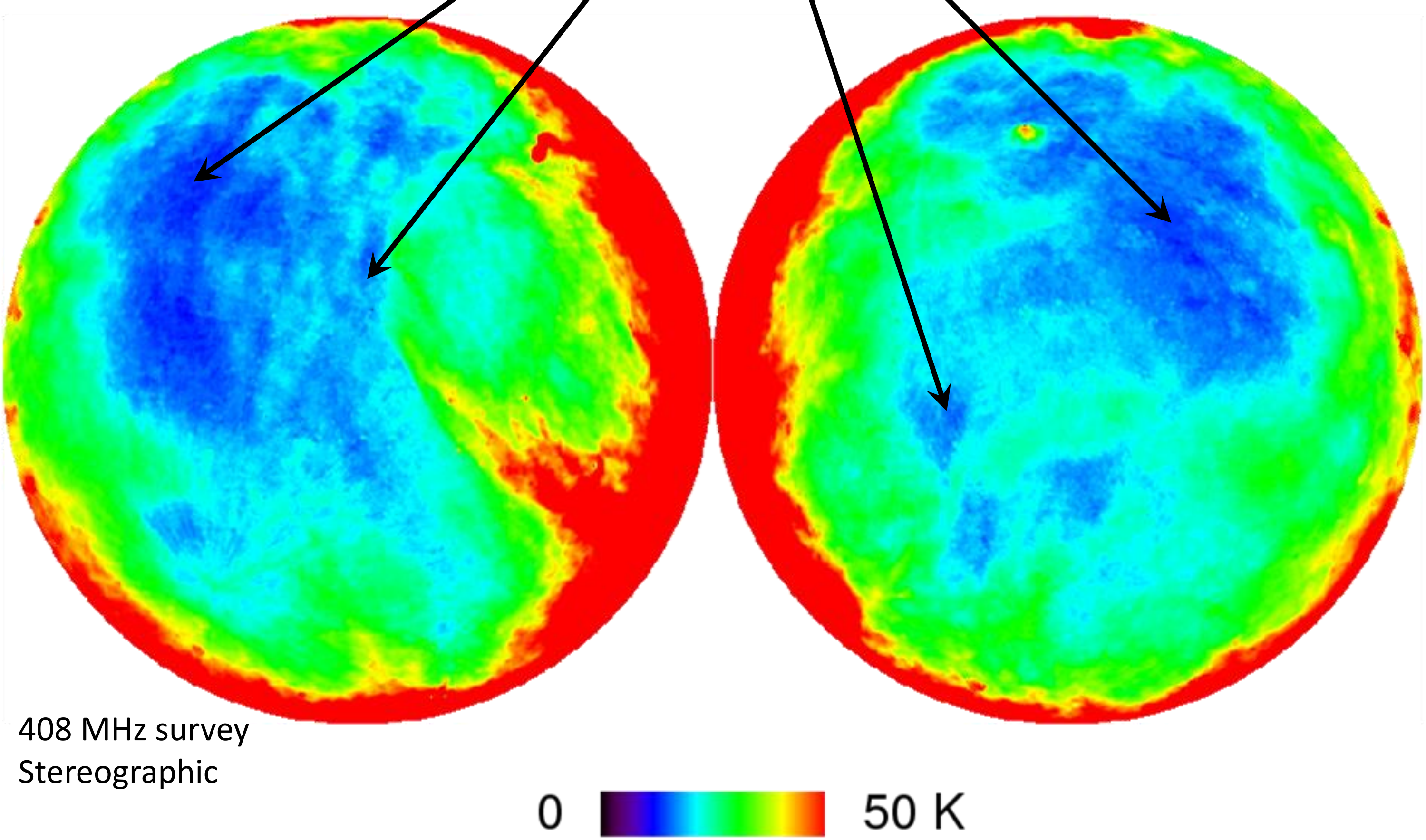


Phillips et al 1981
Beuermann et al 1985

Monopole Component of the Radio Sky

Coldest pixels ~ 11 K across much of radio sky

Consistent with isotropic source
Point sources contribute ~ 2—3 K
Where does the rest come from?



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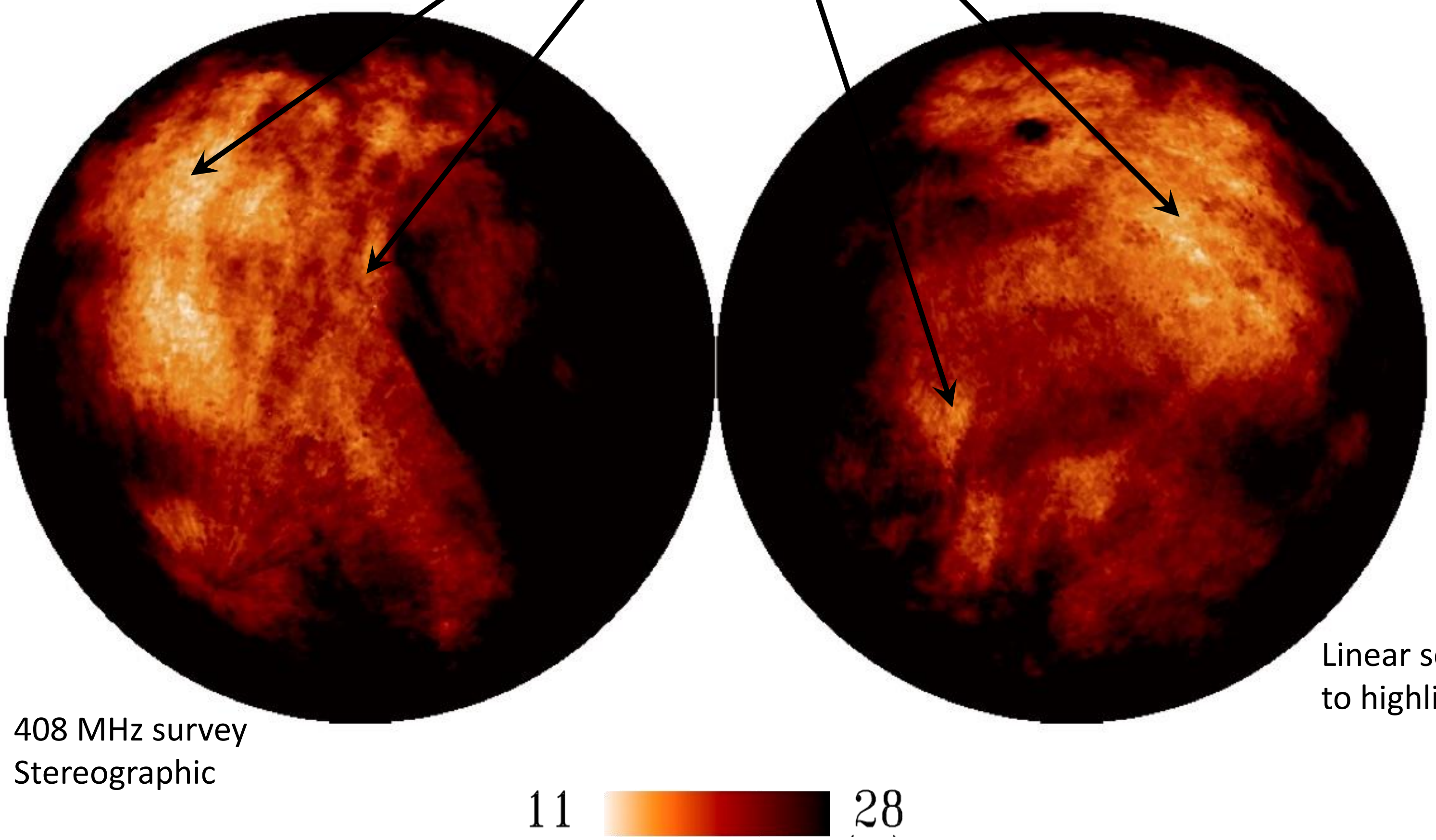


Linear scale chosen
to highlight isotropic component

408 MHz survey
Stereographic

Simple Background Estimate

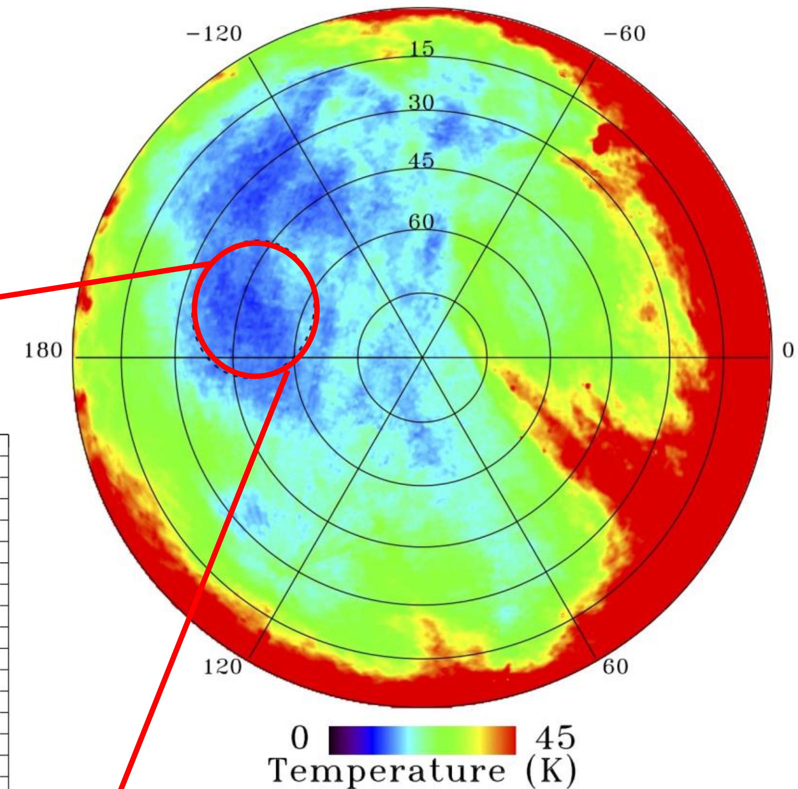
Recall that 408 MHz survey has pixel noise ~ 1 K

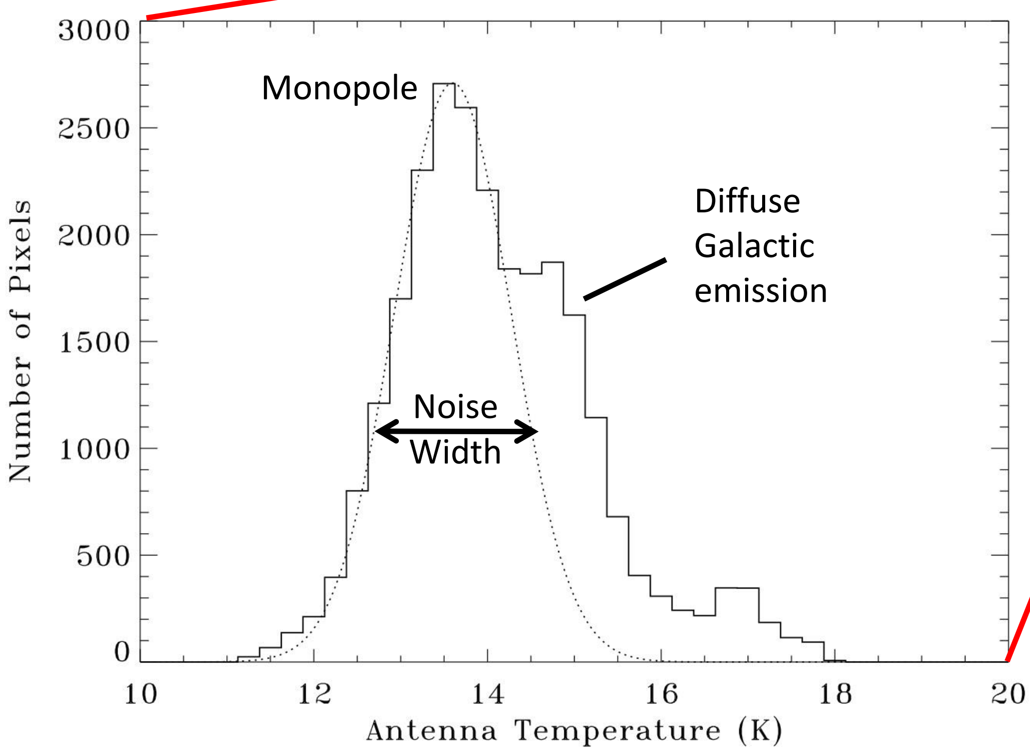
Histogram of coldest patch has

Peak at 13.6 K

Gaussian width 0.65 K

Beware of bias: Coldest pixels include downward noise fluctuations

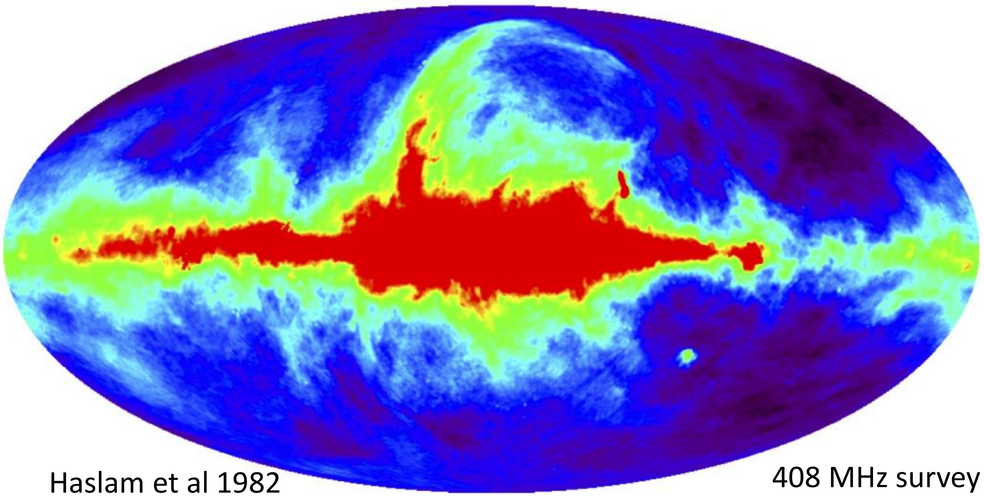




Subtract CMB 2.7 K to get

$\mathbf{T_{ex} \sim 11\ K}$

Advent of Precision Data



Haslam et al 1982

408 MHz survey

Problem: Surveys from 60's to 80's
not intended for background detection

Calibration errors 5—20%

Zero level errors of many K

Not a problem for bright structures,
but difficult to nail down fainter background

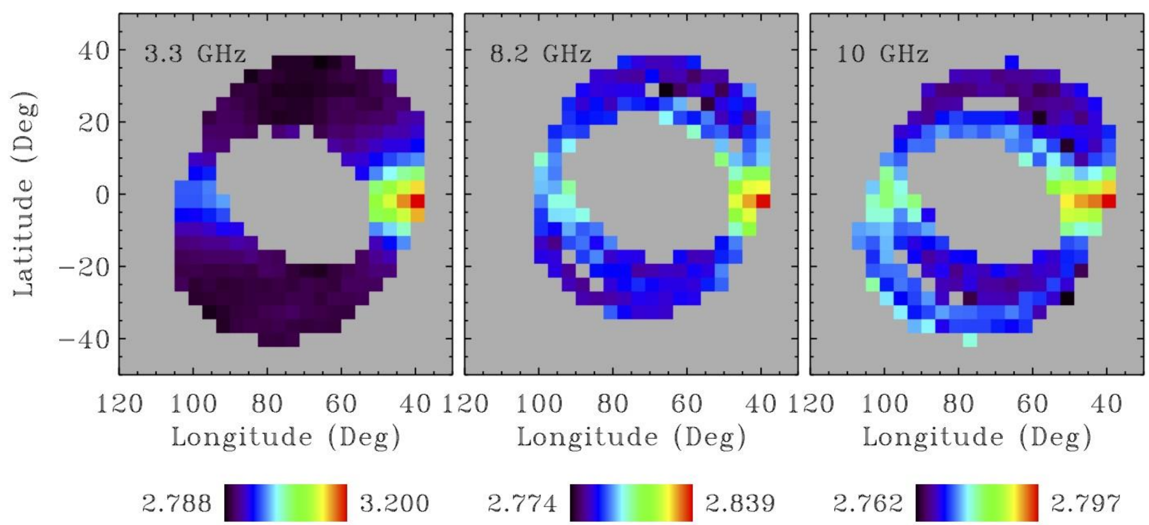
ARCADE-2 sky measurements

Compare sky to external calibrator

- at multiple frequencies
- using fully cryogenic instrument
- from a balloon platform

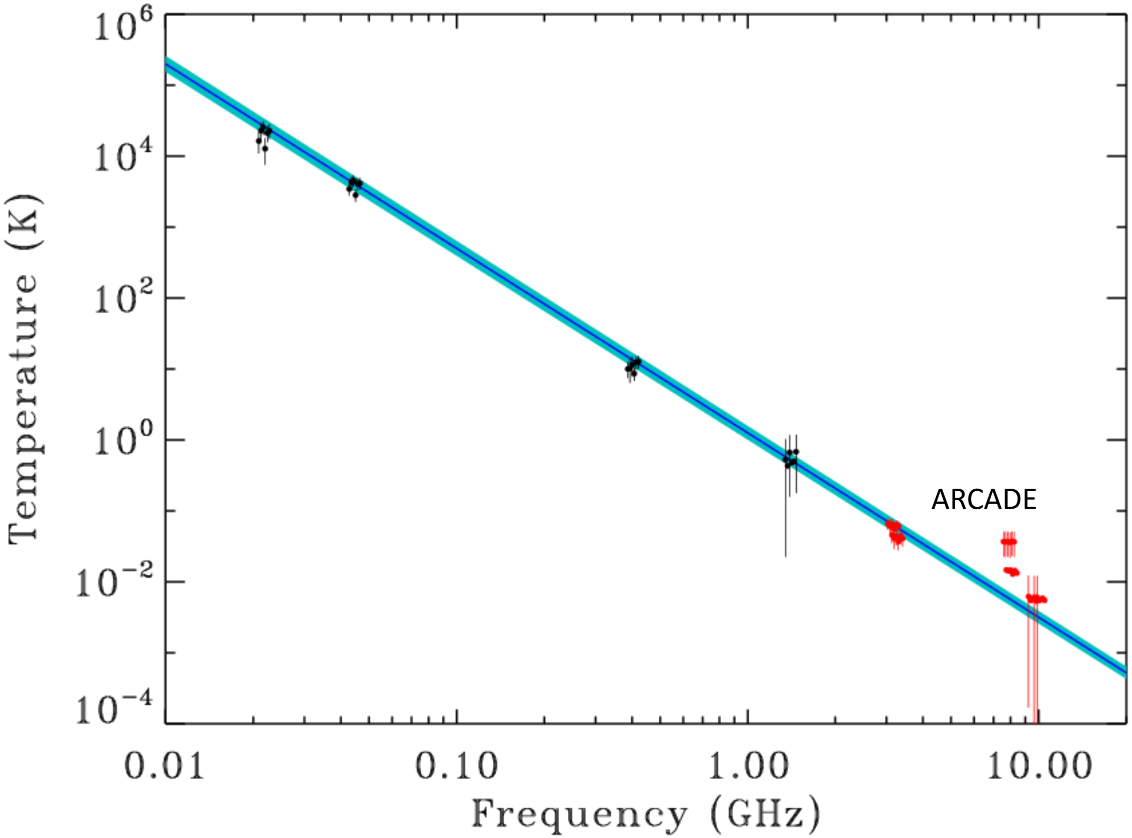
Gain error < 0.03%

Zero level error < 10 mK



Kogut et al 2010

ARCADE vs Low-Frequency Surveys



ARCADE + Low-freq

T_{ex} = 11.6 ±0.9 K

Low-freq alone

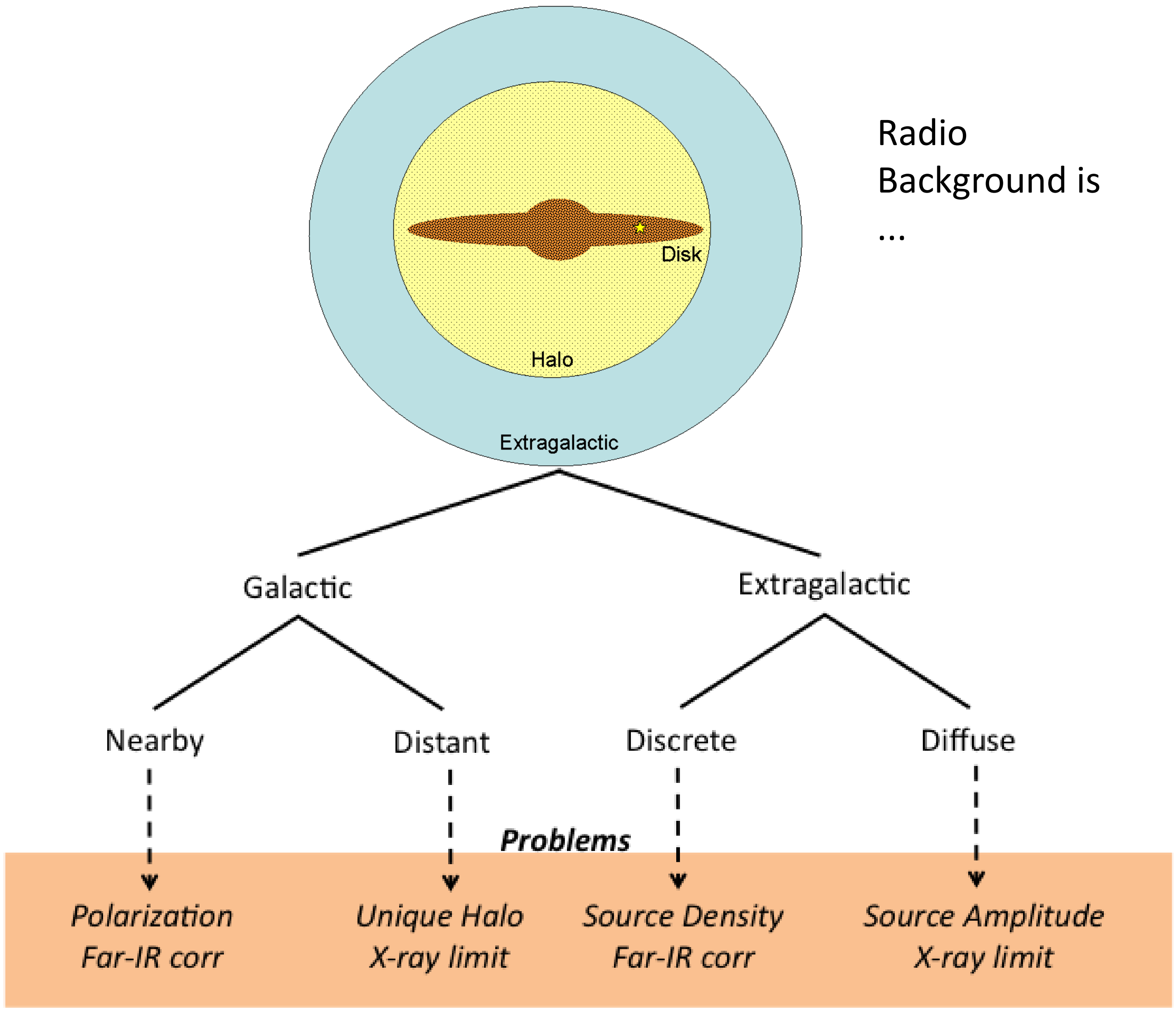
T_{ex} = 15 ± 5 K

Monopole component detected in all radio surveys
Not dependent on ARCADE data alone

Question: Where does it come from?

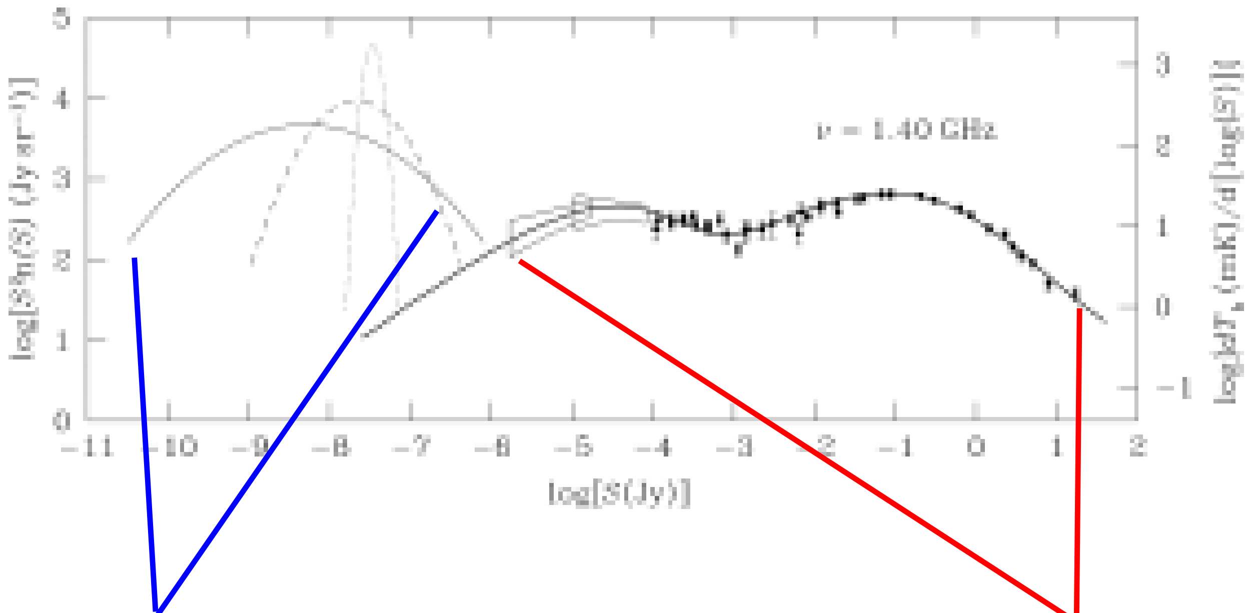
Origins and Issues

Radio Background is ...



Extragalactic Source Populations

Simplest solution: monopole component as integrated emission from discrete sources



Possible populations
to make up the difference

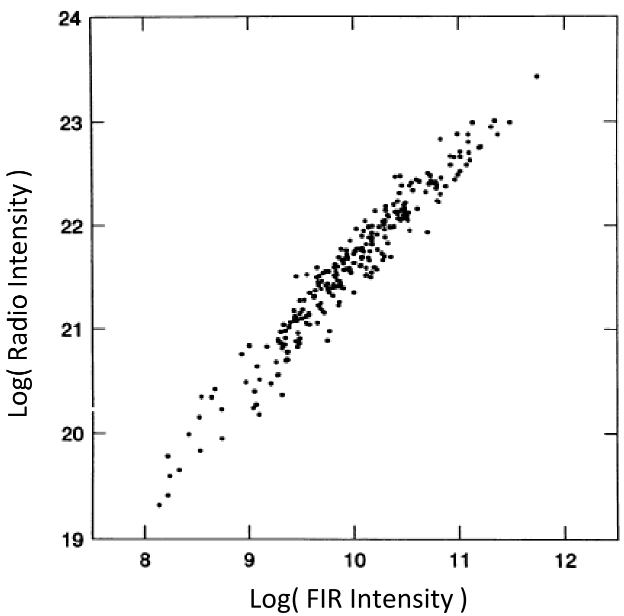
Known sources:
20% of radio monopole

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

Condon et al. 2012

Radio/Far-IR Correlation

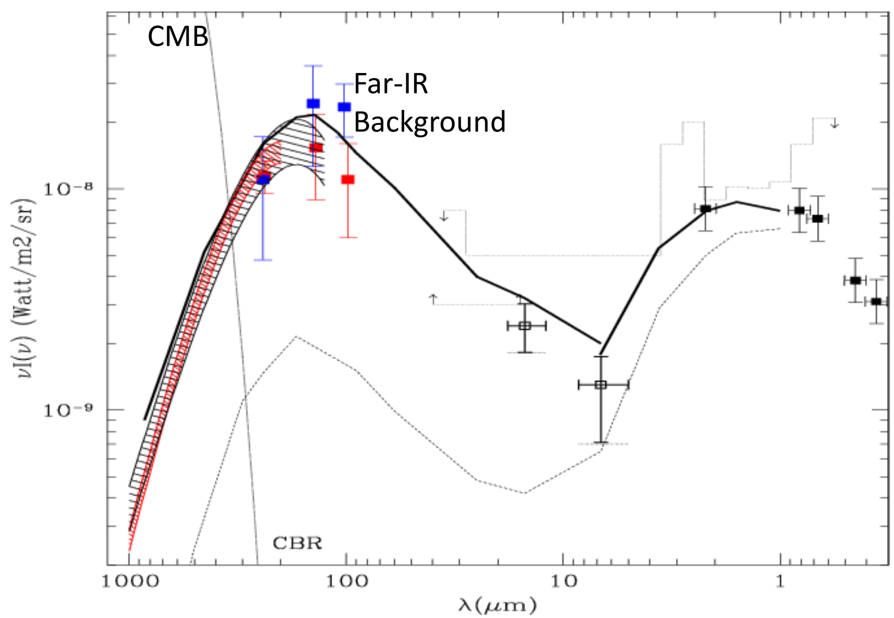
Independent Check on Extragalactic Origin



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 Emission

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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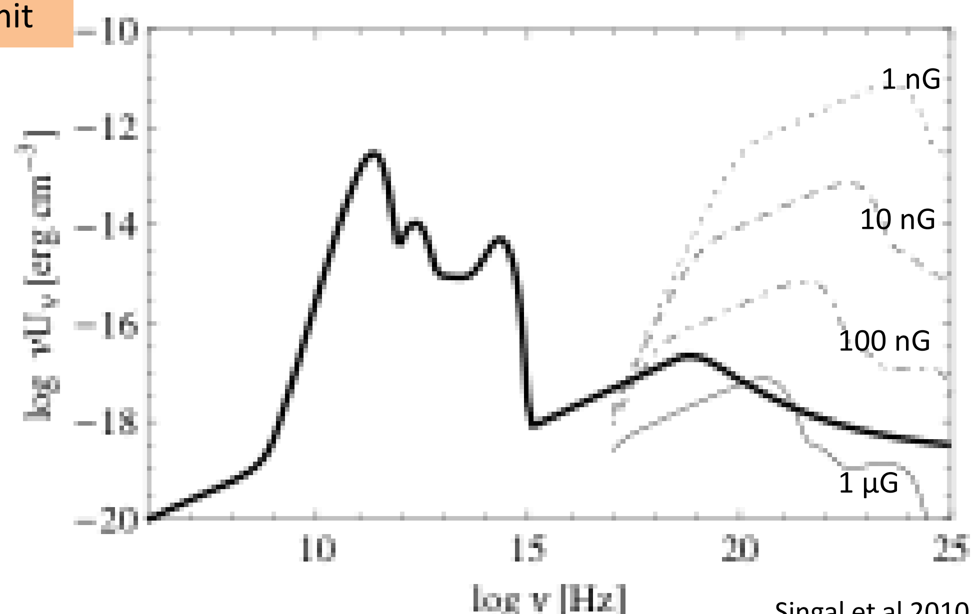
CMB sets lower limit

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

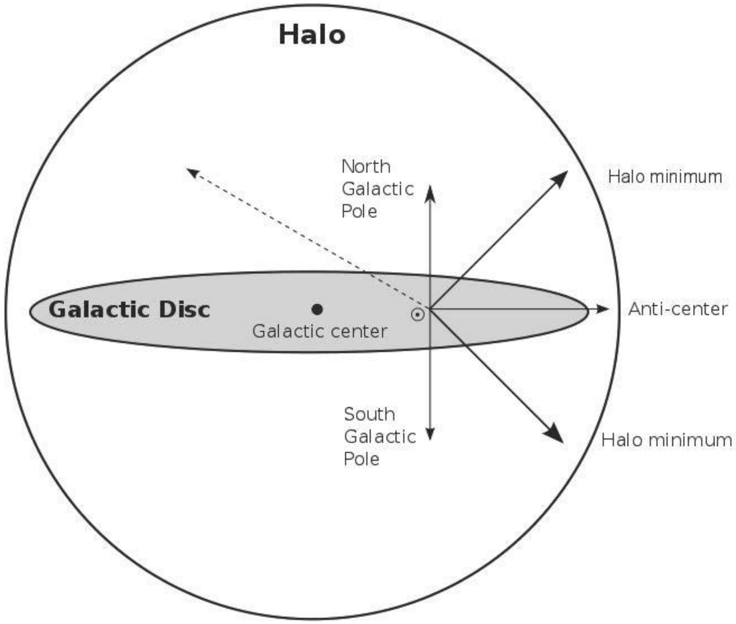
B > 1 μG

Conflicts with B < 0.2 μG for IGM



Singal et al 2010

Galactic Halo



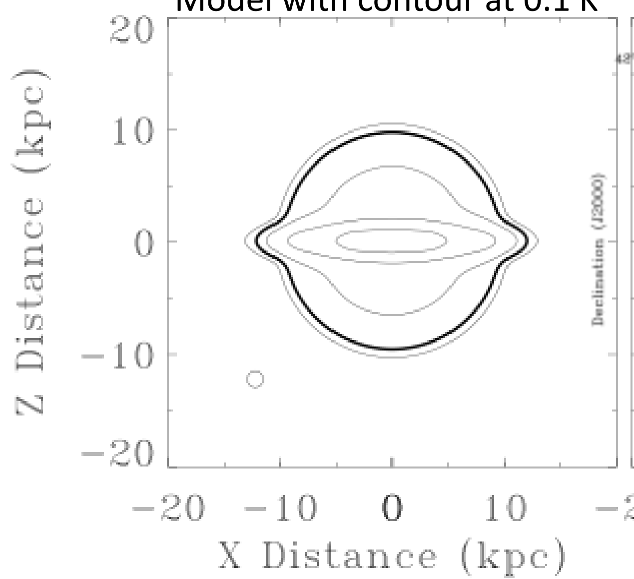
Subrahmanyan & Cowsik 2013

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

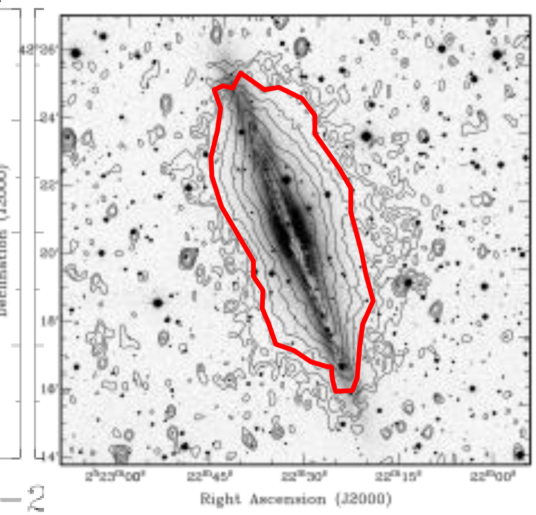
Problem ...

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

Model with contour at 0.1 K

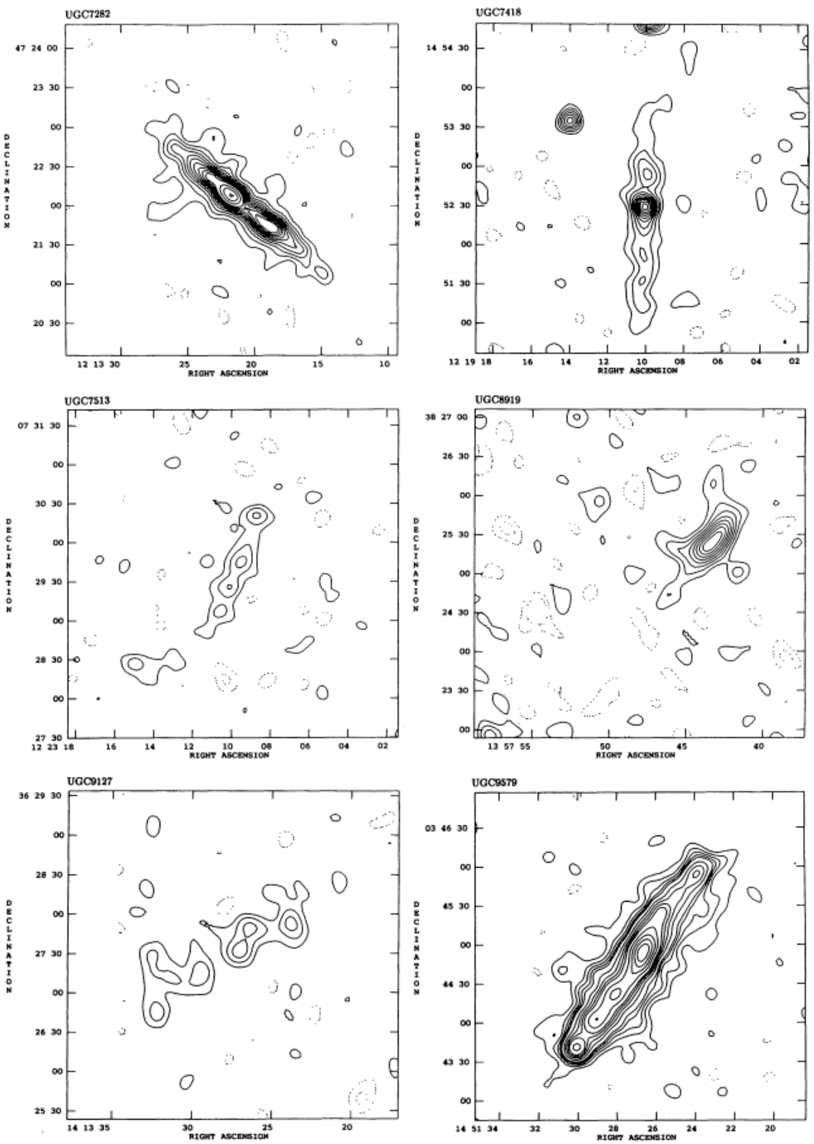


Data with contour at 0.1 K



NGC 0891, Oosterloo et al 2007

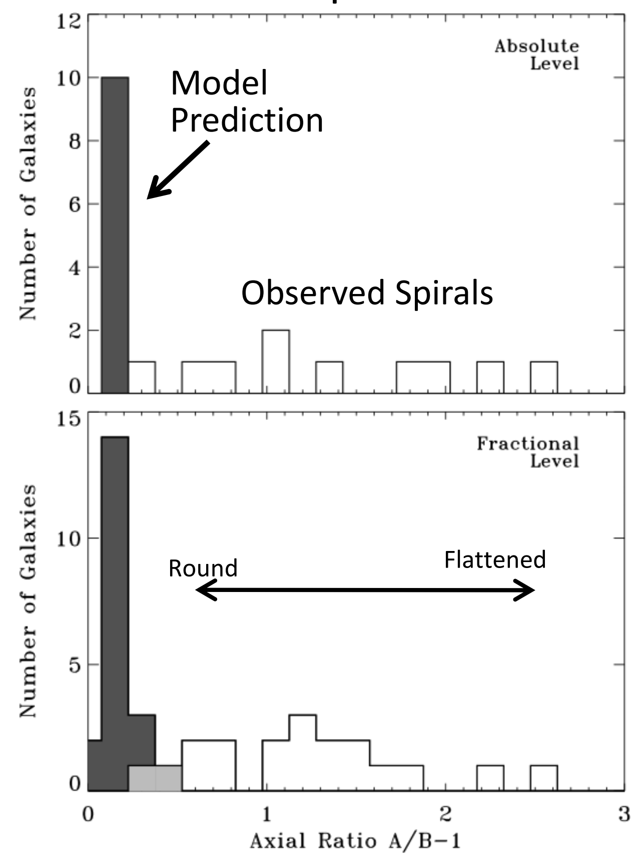
Where Are The Radio Halos?



Radio Properties of Typical Spirals

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

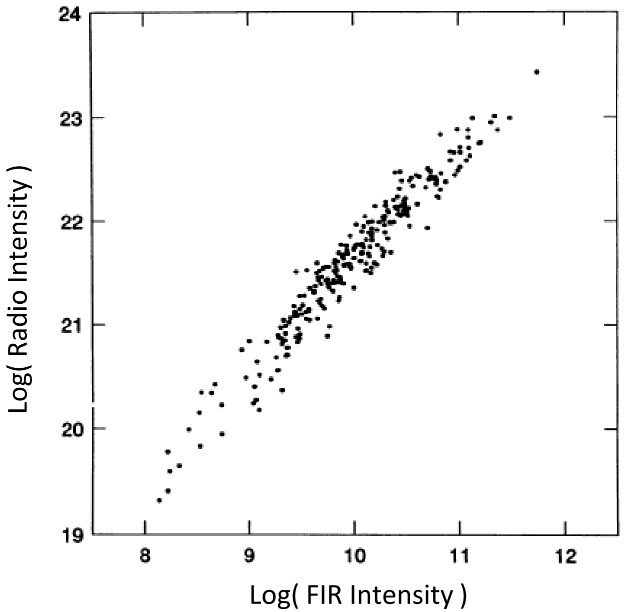
Axial Ratio Test: Compare Data to Model



Singal et al 2015

Radio/Far-IR Correlation I

Local (Galactic) Origin



Condon 1992, ARAA, 30, 575

Remarkably tight correlation exists between radio and far-IR emission

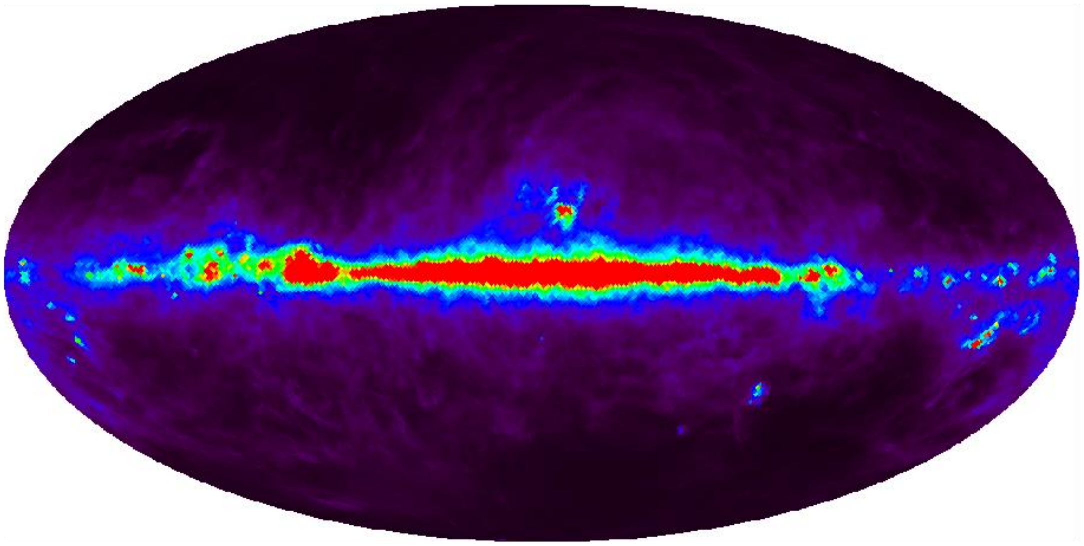
If high-latitude Galaxy is bright in radio, it should also be bright in the far-IR

But it's not …

Two tests:

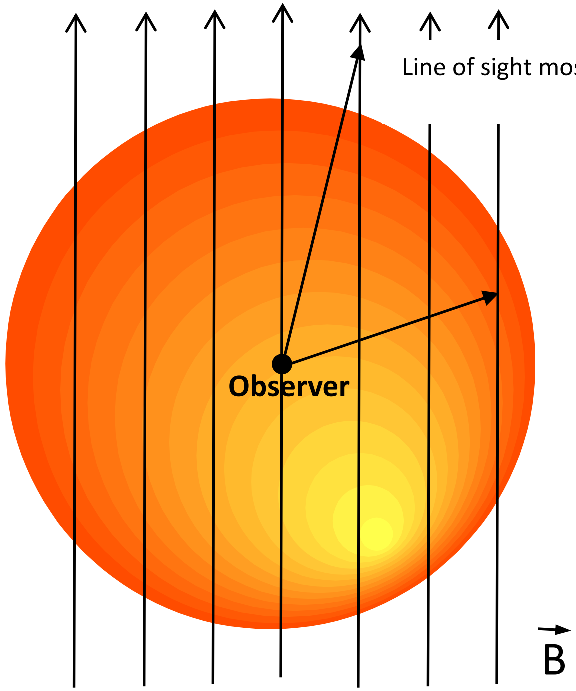
- DIRBE x canonical Radio/FIR ratio
- Scale observed radio/FIR to |b|=90

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

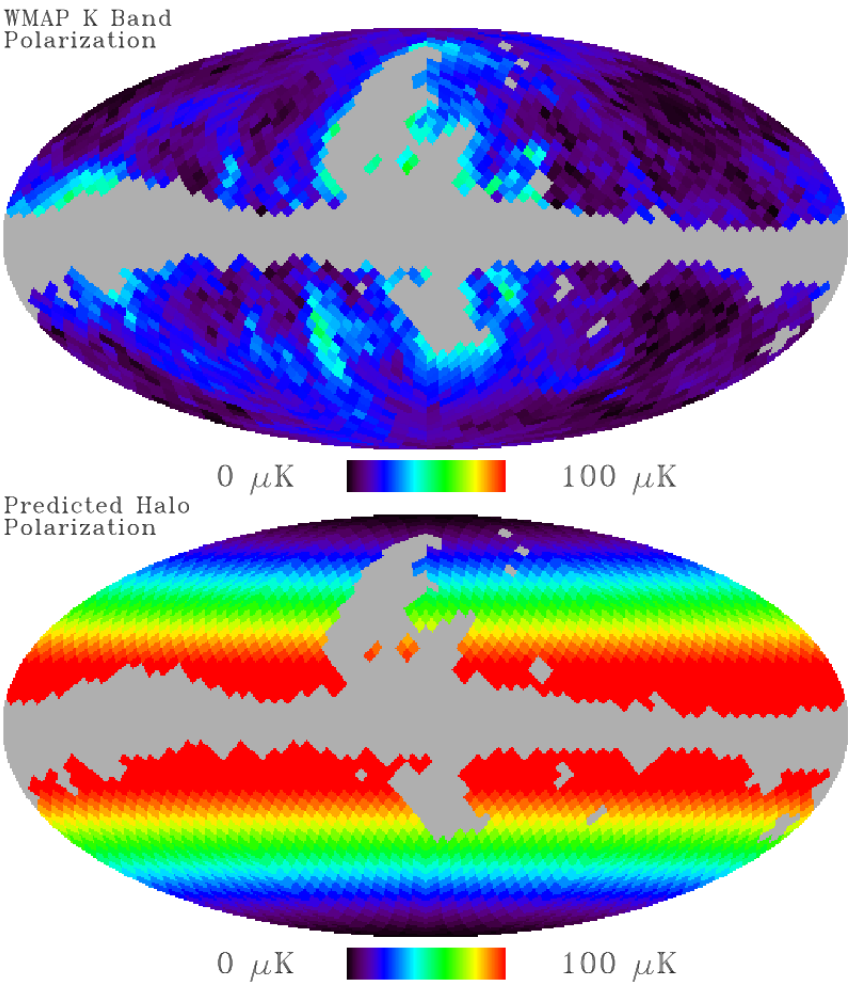


DIRBE 100 μm absolute map

Local (Nearby) Origin



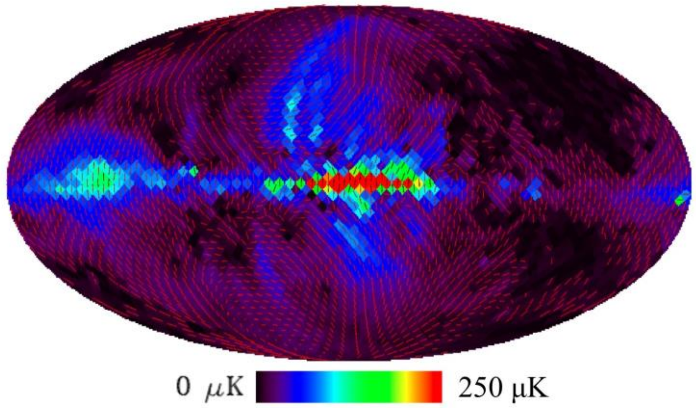
Polarized synchrotron $\propto B_\perp$



If we were inside spherical bubble with uniform field …

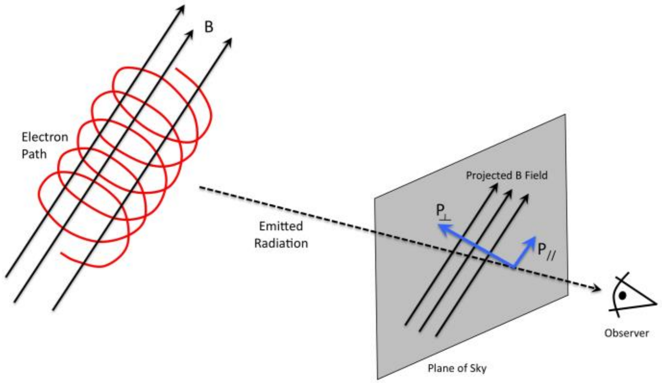
- Predicted amplitude ~ 400 μK at 23 GHz
- Typical polarization fraction f~0.25
- Expect polarized quadrupole ~ 100 μK (not seen)

Depolarization



The observed radio sky is strikingly depolarized

Although synchroton emission is inherently highly polarized (fractional polarization p ~ 0.7), half the synchrotron sky shows $p < 0.05$.



Crude estimate:

Simulate turbulent magnetic field

Intensities add, polarizations cancel

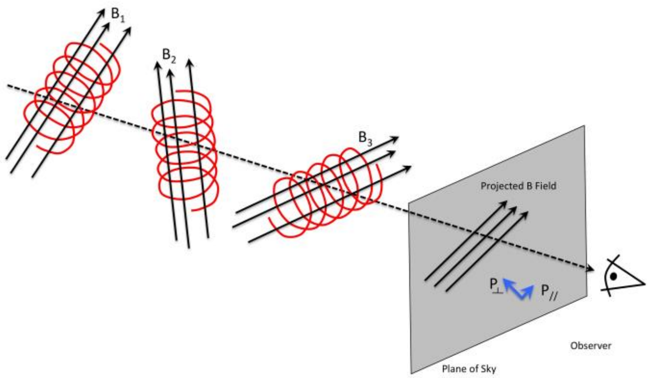
How many independent cells needed to depolarize?

Problem:

Simulations show $>10^4$ cells required

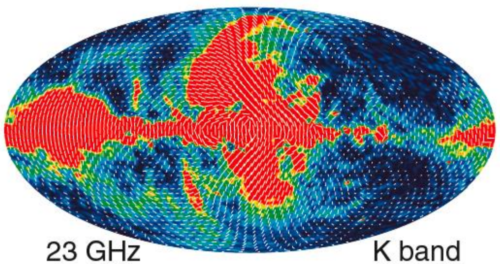
Mean cell diameter <0.05 pc

Ratio of turbulent/mean field too high!



Fractional Polarization

In which we play with the denominator ...



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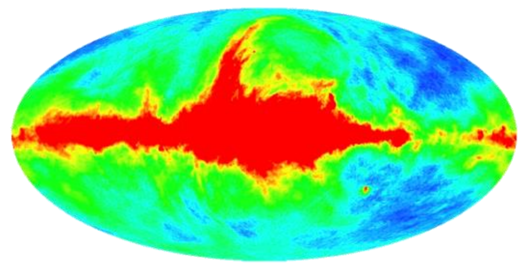

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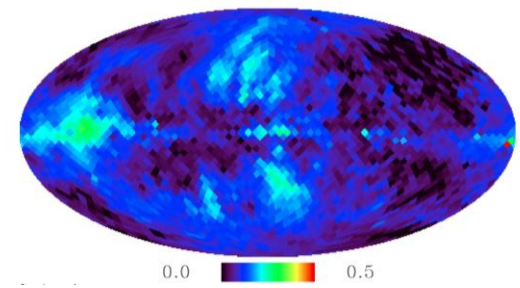


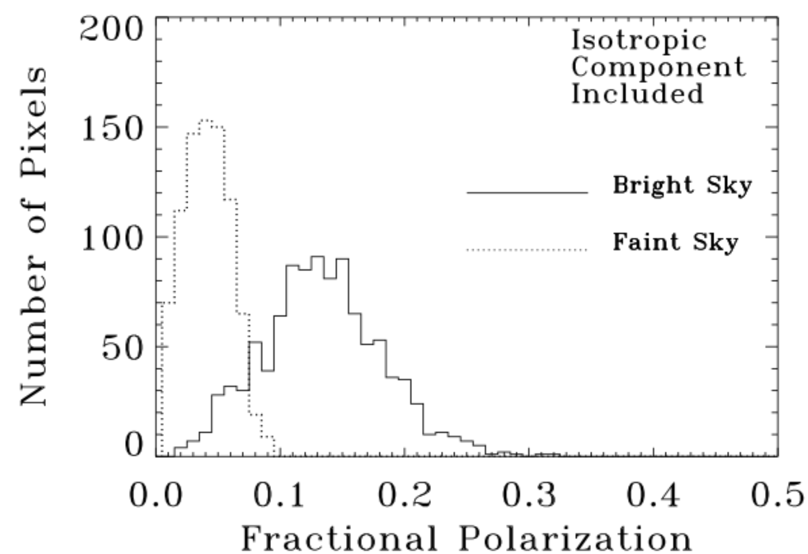
Polarized Intensity

Unpolarized Intensity

Fractional Polarization

Two problems:

- Faintest 50% of sky is depolarized
- Bright features more polarized than dim

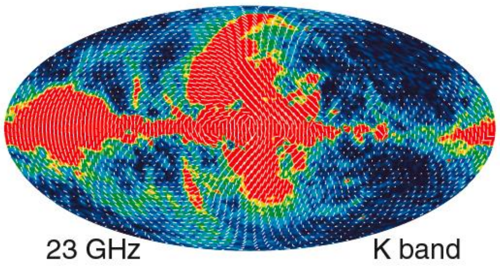


Suppose we remove the isotropic part
from the denominator of this equation ...

Fractional Polarization

In which we play with the denominator ...

Remove isotropic component *Increase fractional polarization*



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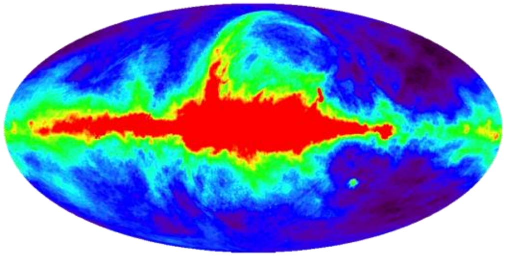

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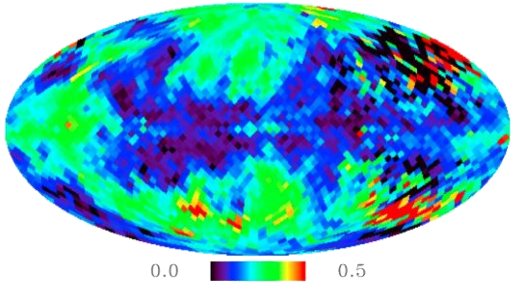


Polarized Intensity

Unpolarized Intensity

Biggest effect on dimmest regions

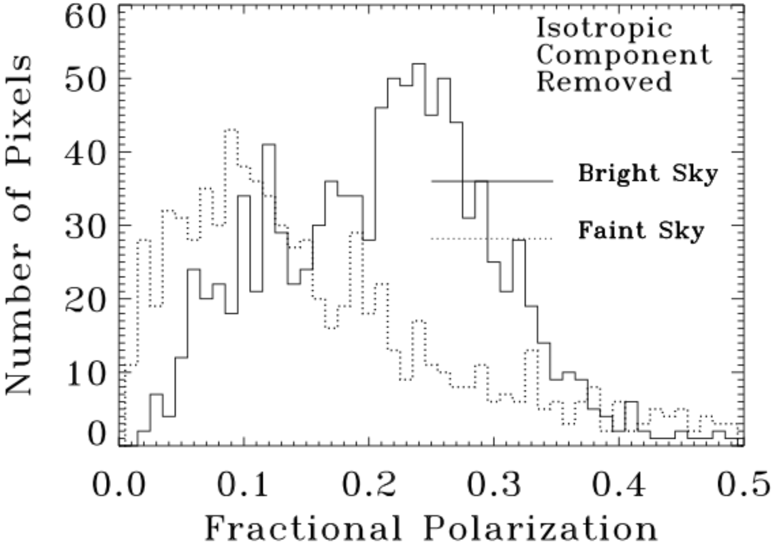
Fractional Polarization

Biggest effect on dimmest regions

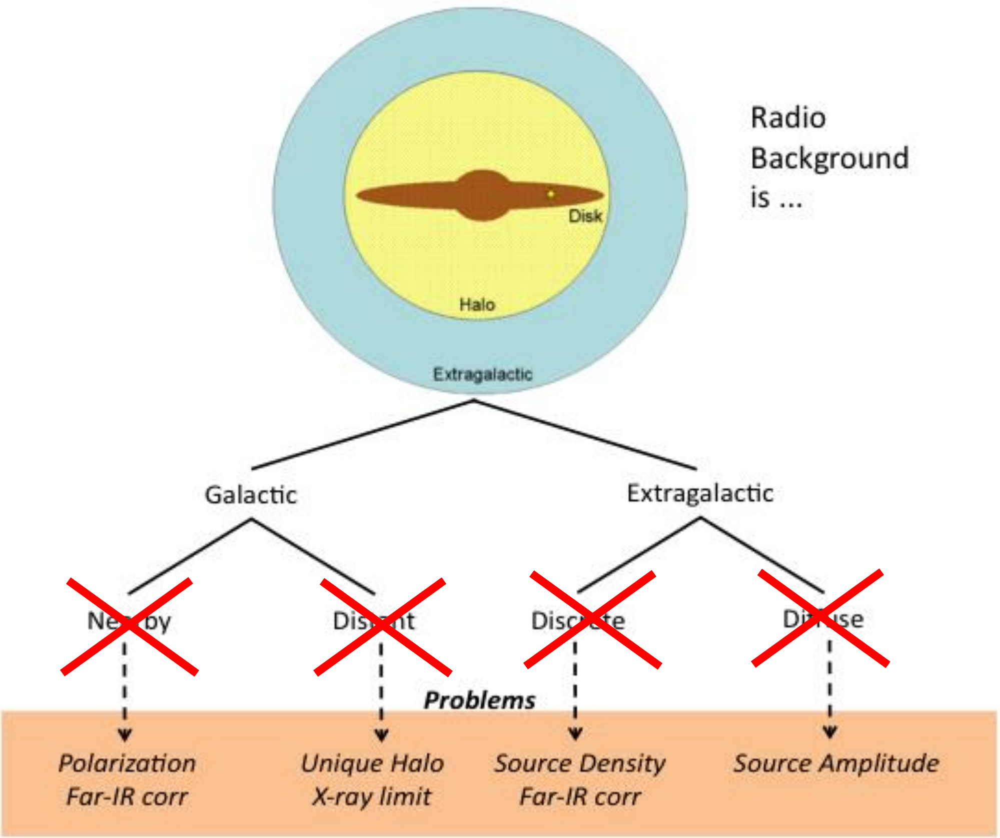
Problem solved?

- Fractional polarization now 10%—30%
- Broad overlap between bright/dim regions

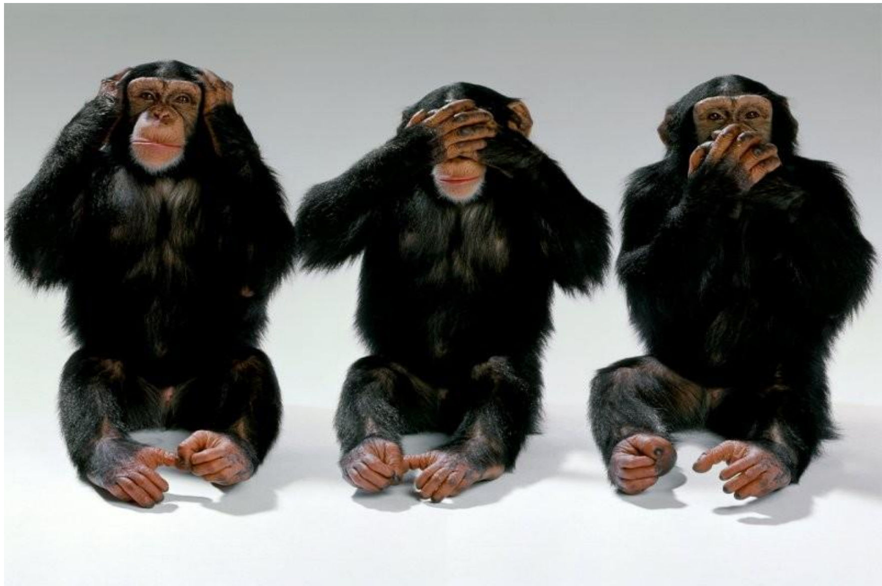
Suppose we remove the isotropic part from the denominator of this equation ...



NOW what?



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



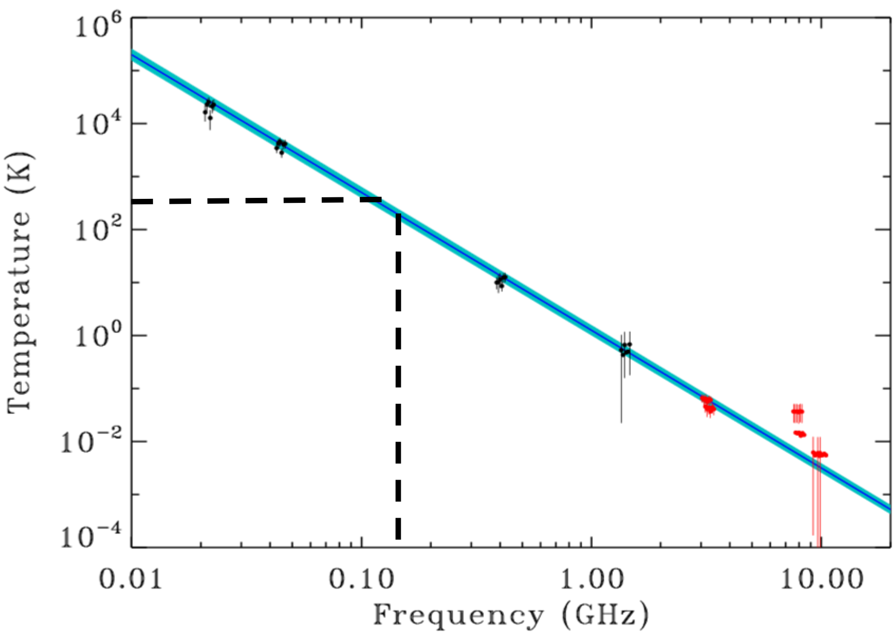
Future Directions

Frequency	Background Temperature	Zero Level	Gain	Absolute Uncertainty	Fractional Uncertainty
22 MHz	22,000 K	5000 K	5%	5100 K	23%
45 MHz	3400	250	10%	420	12%
408 MHz	11	0.9	10%	1.4	13%
1420 MHz	0.43	0.5	5%	0.5	116%
3.15 GHz	0.056	0.003	0.01%	0.003	5%

Low-frequency surveys have substantial uncertainty
Dominated by zero-level errors

ARCADE has small errors, but limited coverage

Synchrotron polarization not well mapped in faintest parts of sky



Solution 1: Map sky at frequency where sky temperature matches ground temperature

ν ~ 120 MHz

T_{sky} ~ 300 K

Don't need great angular resolution

Solution 2: Map sky at frequency where zero level is already well established

ν ~ 3.15 GHz (ARCADE)

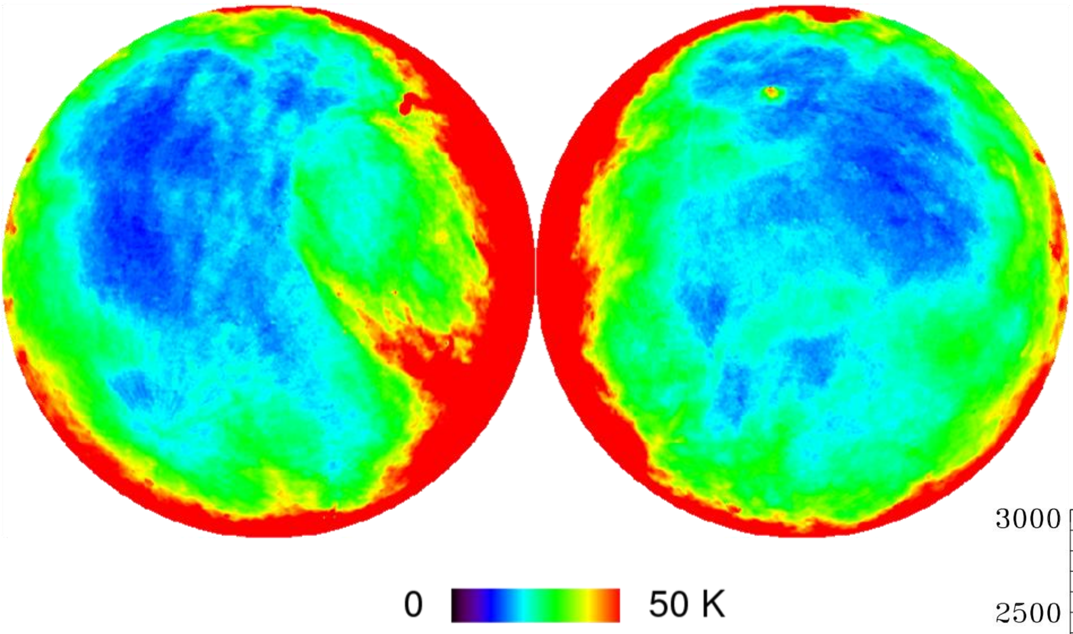
Improve ARCADE resolution & sky coverage

Solution 3: Nail down synchrotron amplitude and polarization

Faraday rotation → Frequencies > 5 GHz

CBASS, PIXIE, ...

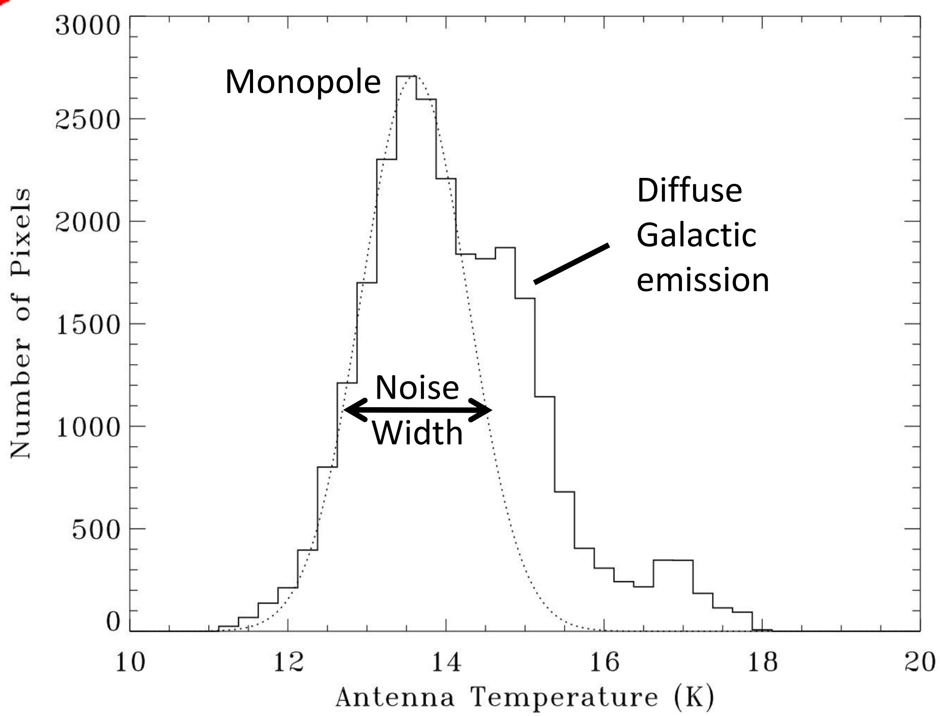
Parting Thoughts



Radio sky contains significant monopole

- Amplitude ~ 11K at 408 MHz
- Spectral index -2.6

What is it??

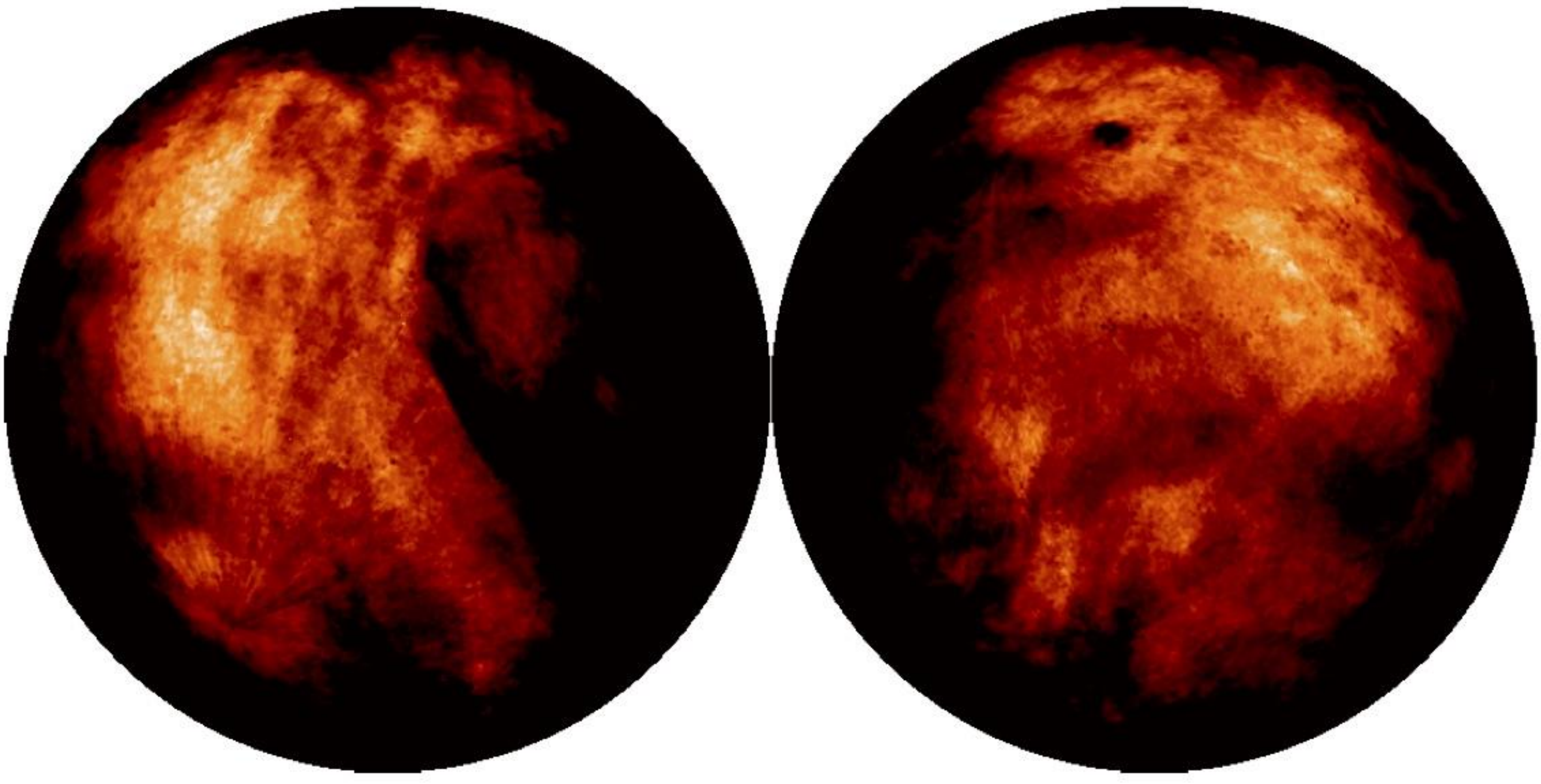


Looking for a (synchrotron) source that's

- Isotropic
- Depolarized
- Uncorrelated with far-IR / other tracers

But not unique to Milky Way

There are more things in heaven and Earth, Horatio,
Than are dreamt of in your philosophy
Shakespeare (Hamlet)



Measurement Uncertainty

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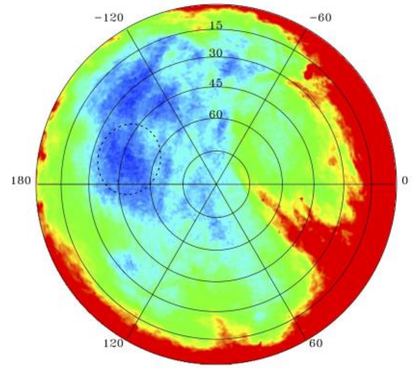
Origins and Issues



Radio Background is …

Galactic

- Nearby → *Polarization*, *Far-IR corr*
- Distant → *Unique Halo*, *X-ray limit*

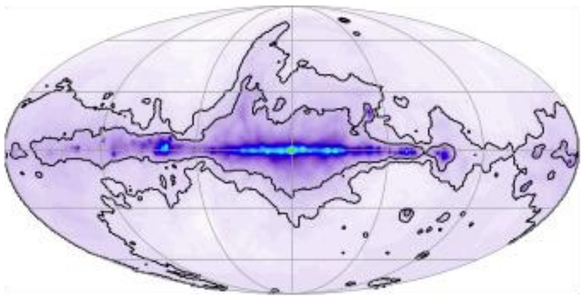
Extragalactic

- Discrete → *Source Density*, *Far-IR corr*
- Diffuse → *Source Amplitude*, *X-ray limit*

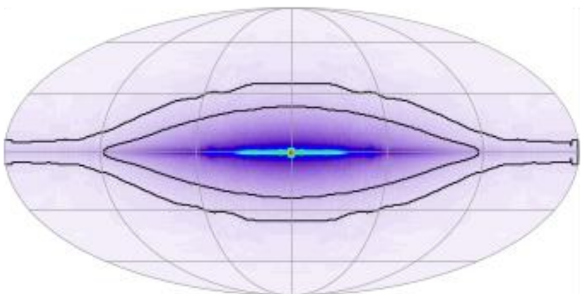
Problems

Polarization	*Unique Halo*	*Source Density*	*Source Amplitude*
Far-IR corr	*X-ray limit*	*Far-IR corr*	*X-ray limit*

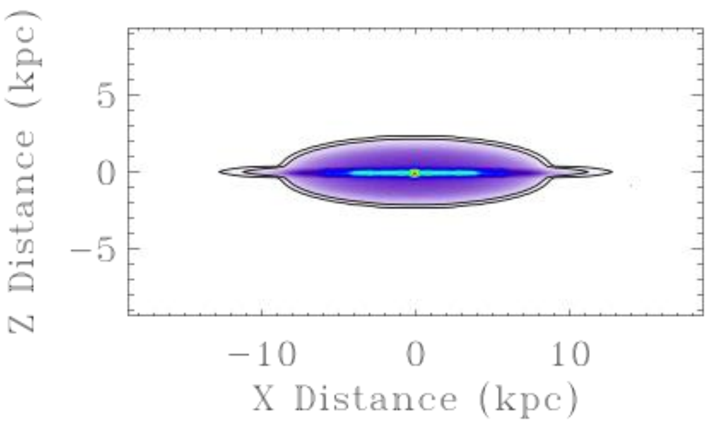
Radio Halo Model



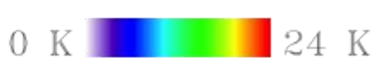
Anisotropic Galactic sources



Simplified source distribution
(viewed from Solar circle)



Simplified source distribution
(viewed by external observer)



Singal et al 2015