Title: Probing cosmic inflation: WMAP and beyond

Date: Feb 13, 2007 11:00 AM

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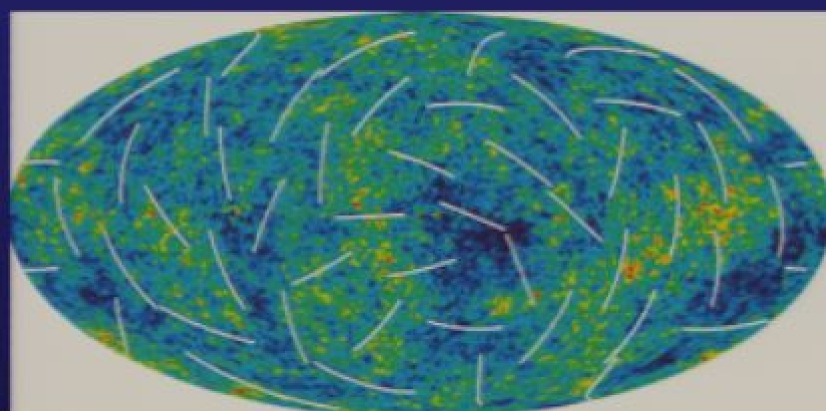
Abstract: Current measurements from WMAP and other cosmological probes are consistent with a simple inflationary model. Such models predict a background of gravitational waves which may soon be observable in the polarized component of the Cosmic Microwave Background.
However, WMAP has observed significant levels of polarized radiation from our galaxy, due to both synchrotron radiation and thermal dust emission.
A better understanding of this radiation will be vital if we are to correctly remove it and confidently detect an inflationary signal.
As well as discussing the observational case for inflation, I will review the physical origins of the polarized galactic emission, present a simple model for the galactic magnetic field, and discuss current and future directions for improving upon our galactic models.

Probing cosmic inflation: WMAP and beyond



Joanna Dunkley (Princeton University)
WMAP science team

Perimeter Institute, February 13th

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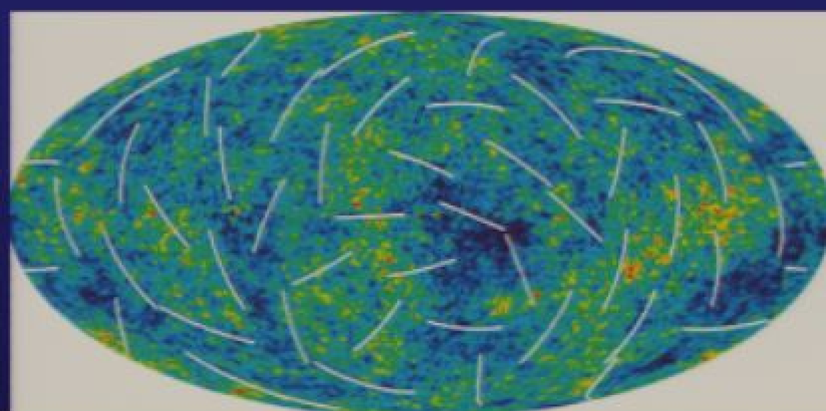

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Inflation

Inflationary paradigm - an extension of the standard big bang model

- Effective field theory, posits that the universe underwent a period of exponential expansion driven by the potential of an inflaton field.
- Expansion lasted for > 60 e-folds.
- Stretches tiny volume to a region much larger than the observed universe.

  - Developed to address flatness, horizon and monopole problem
  - Also provides mechanism for seeding cosmic structure

Inflationary Triumphs

- Nearly Scale Invariant Fluctuations (COBE)
- Flat (TOCO, Boomerang,...,WMAP)
- Adiabatic (Boomerang, CBI, ...,WMAP I)
- Superhorizon Fluctuations (WMAP I)
- Gaussian (WMAP I, WMAP II)
- $n < 1$ (~WMAP II)
- ***Gravitational Waves** (TBD)*

Inflation predicts gravitational waves

Slowly rolling single field

- Quantum fluctuations of inflaton field inside horizon
- Imprints scalar and tensor perturbations
- Tensor perturbations propagate as waves, uncoupled to density

$$r(k) \equiv \Delta^2_T(k) / \Delta^2_S(k) = 16\varepsilon_*$$

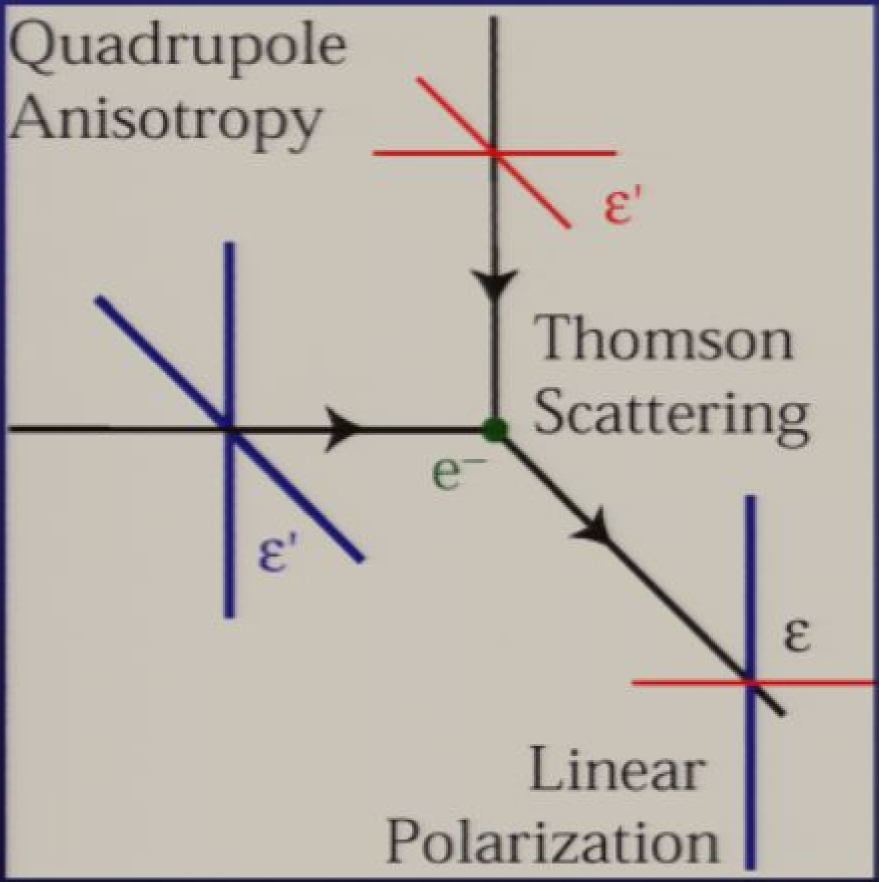
$$\varepsilon_* = \frac{{M_{Pl}}^2}{2}\left(\frac{V'(\phi)}{V(\phi)}\right)^2$$

- *Ratio r tells us energy scale of inflation*

e.g. If $V(\phi) \sim \phi^2$, $N = 60 \Rightarrow r = 0.13$

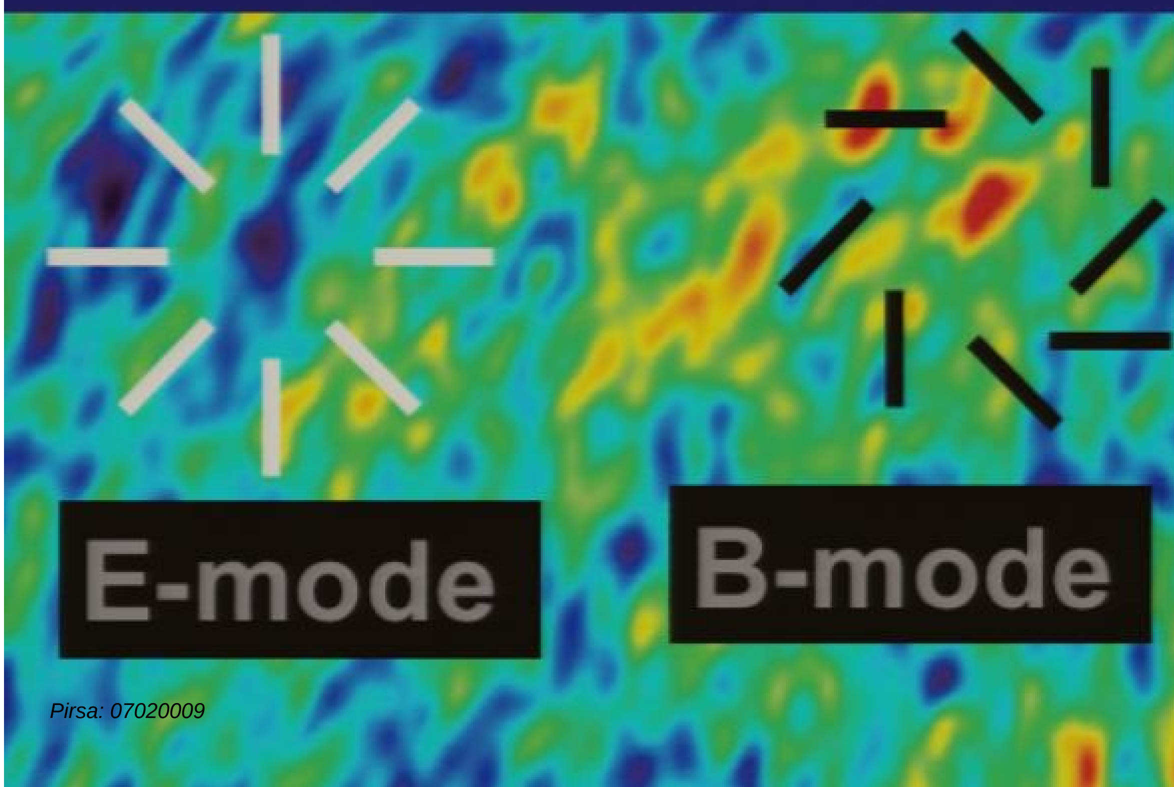
How do we detect gravitational waves?

- Polarization of the Cosmic Microwave Background
- Thomson scattering generates polarization, if…
  - Temperature **quadrupole** exists around an electron
- Generated at recombination by
  1. shear viscosity of photon-baryon fluid
  2. ***gravitational waves***



Polarized E and B modes

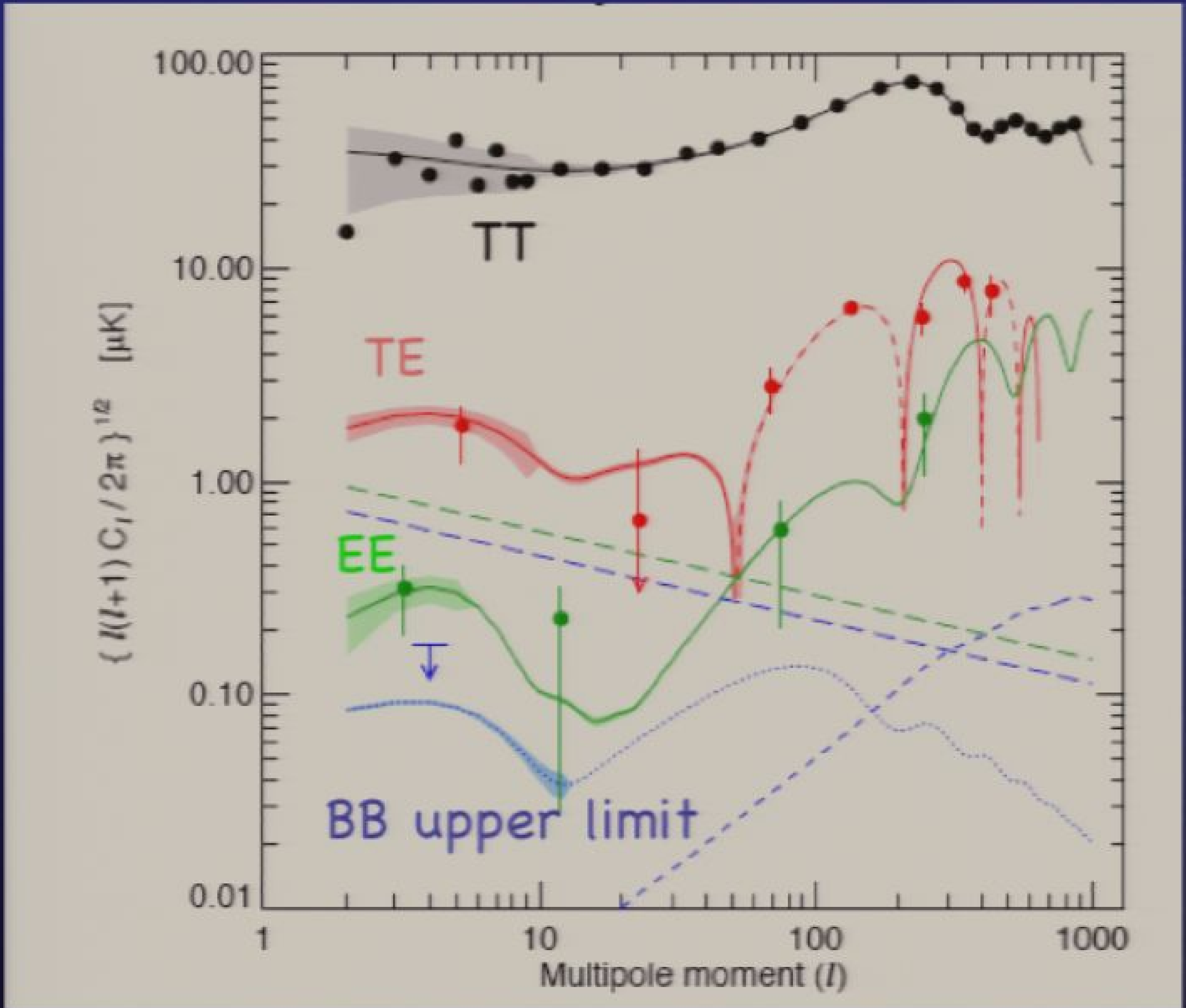
- Measure polarization with Q and U Stokes vectors
- Can decompose into a divergence-like "E-mode" and a vorticity-like "B-mode".
- Scalar perturbations are curl-free, so produce no B-modes
  - *So… B-mode detection = grav waves = inflation*



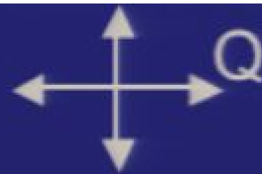
$$\Theta(\hat{n}) = \sum_{l} \sum_{m=-l}^{l} a^{T}{}_{lm} Y_{lm}(\hat{n})$$

$$(Q \pm iU)(\hat{n}) = \sum_{l} \sum_{m=-l}^{l} (a^{E}{}_{lm} \pm i a^{B}{}_{lm})\, {}_{\pm 2}Y_{lm}(\hat{n})$$

WMAP 3yr measurements

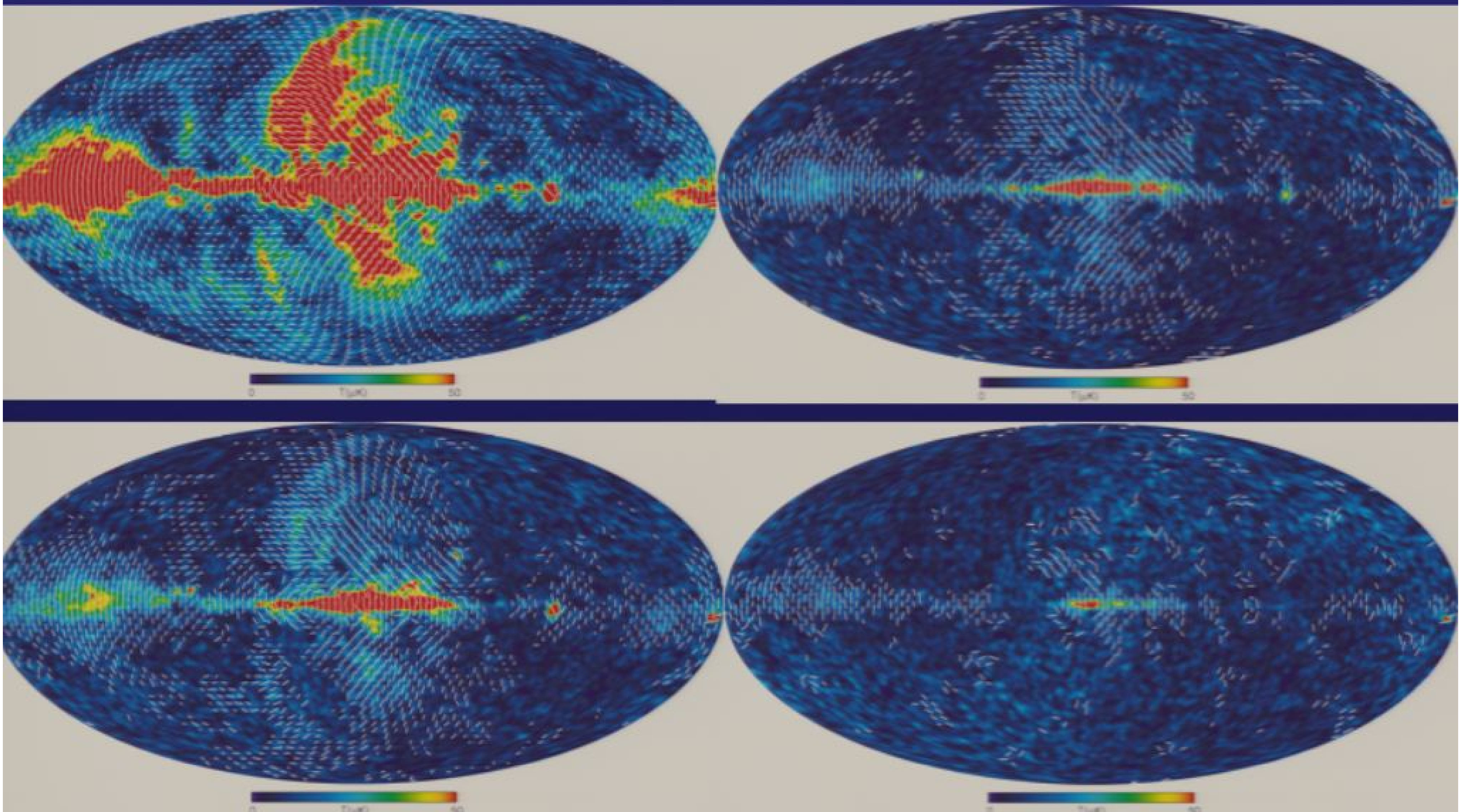


Now for the real data…



K Band (23 GHz)

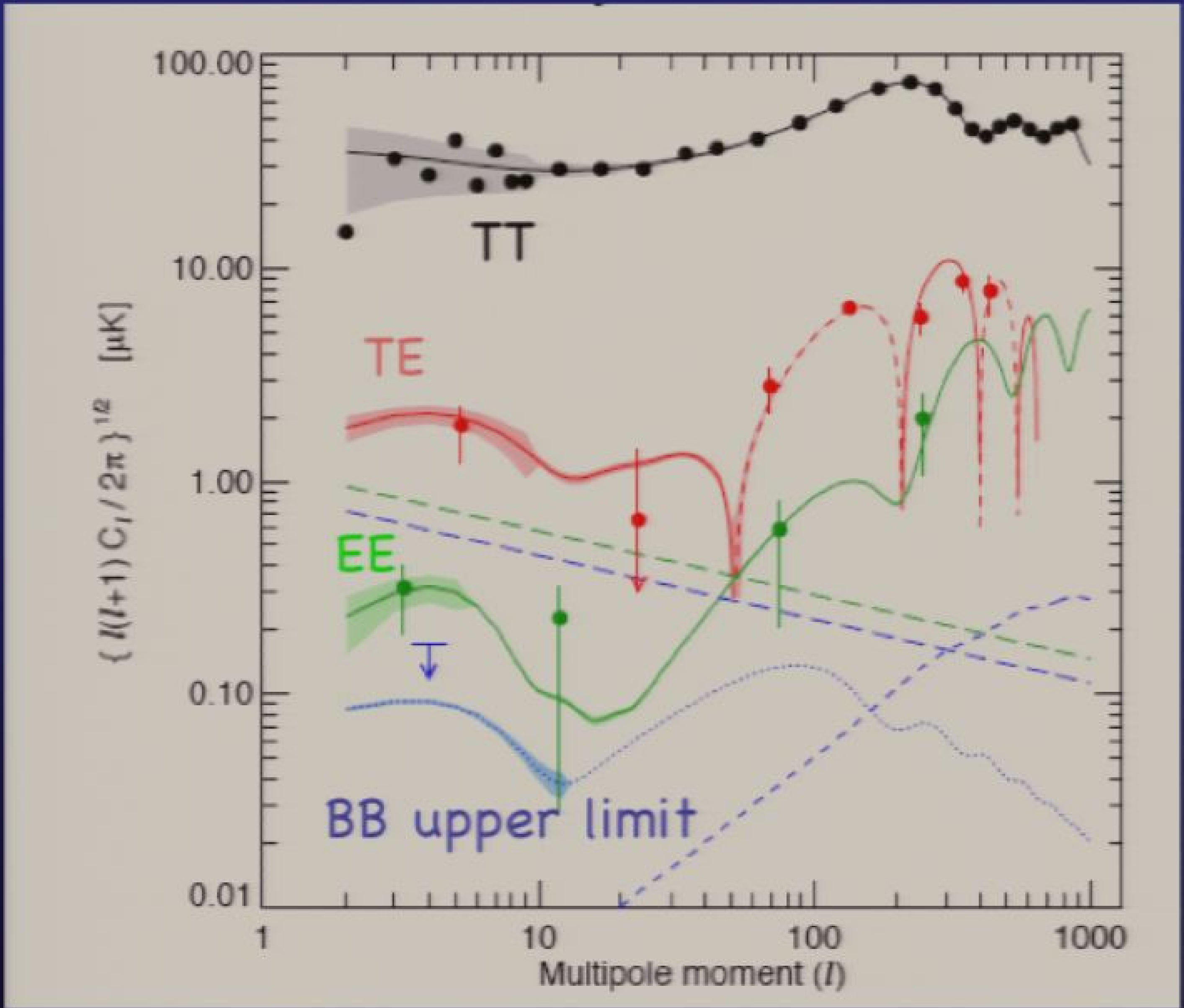
Q Band (41 GHz)



Ka Band (33 GHz)

V Band (61 GHz)

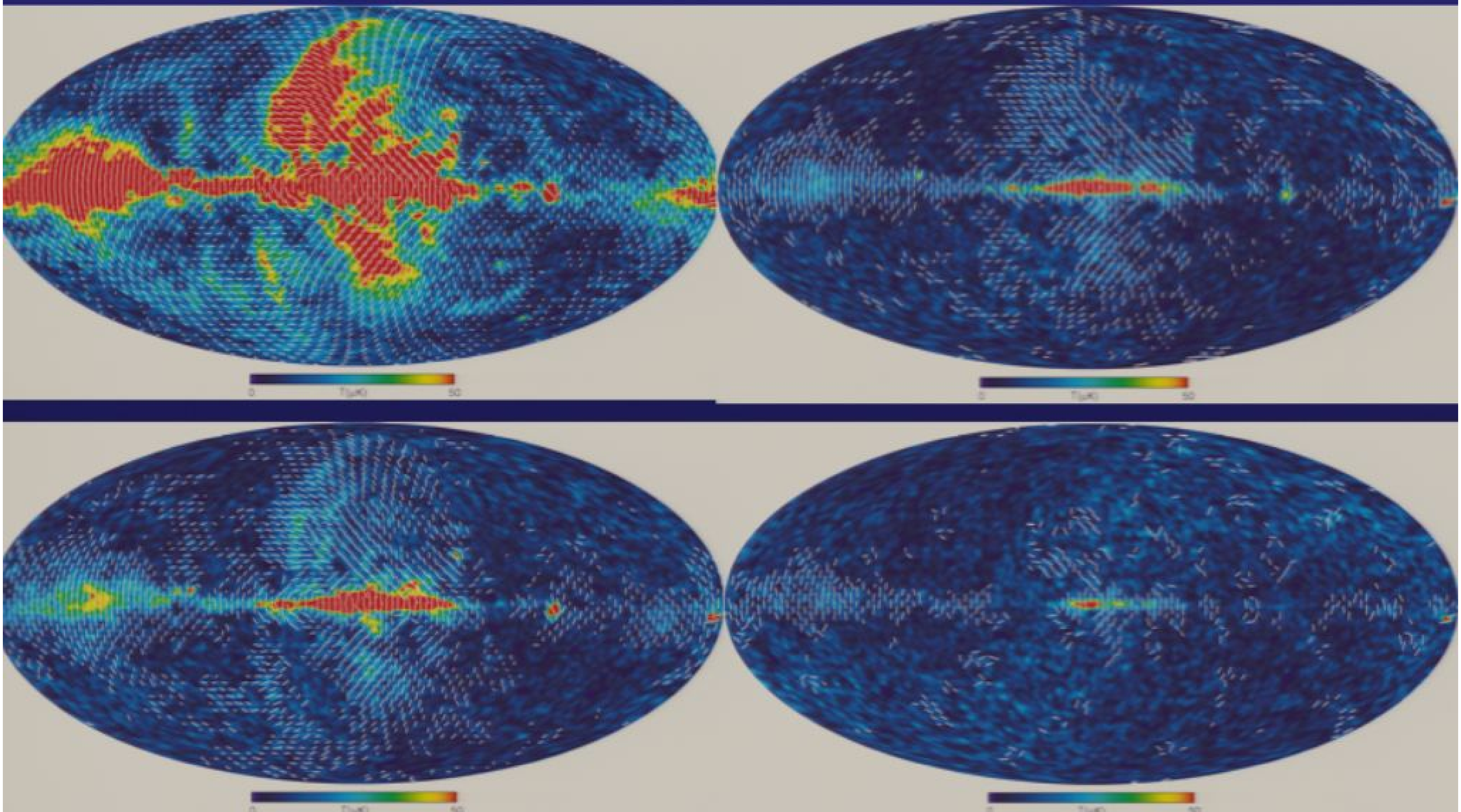
WMAP 3yr measurements



Now for the real data… Q

K Band (23 GHz)

Q Band (41 GHz)



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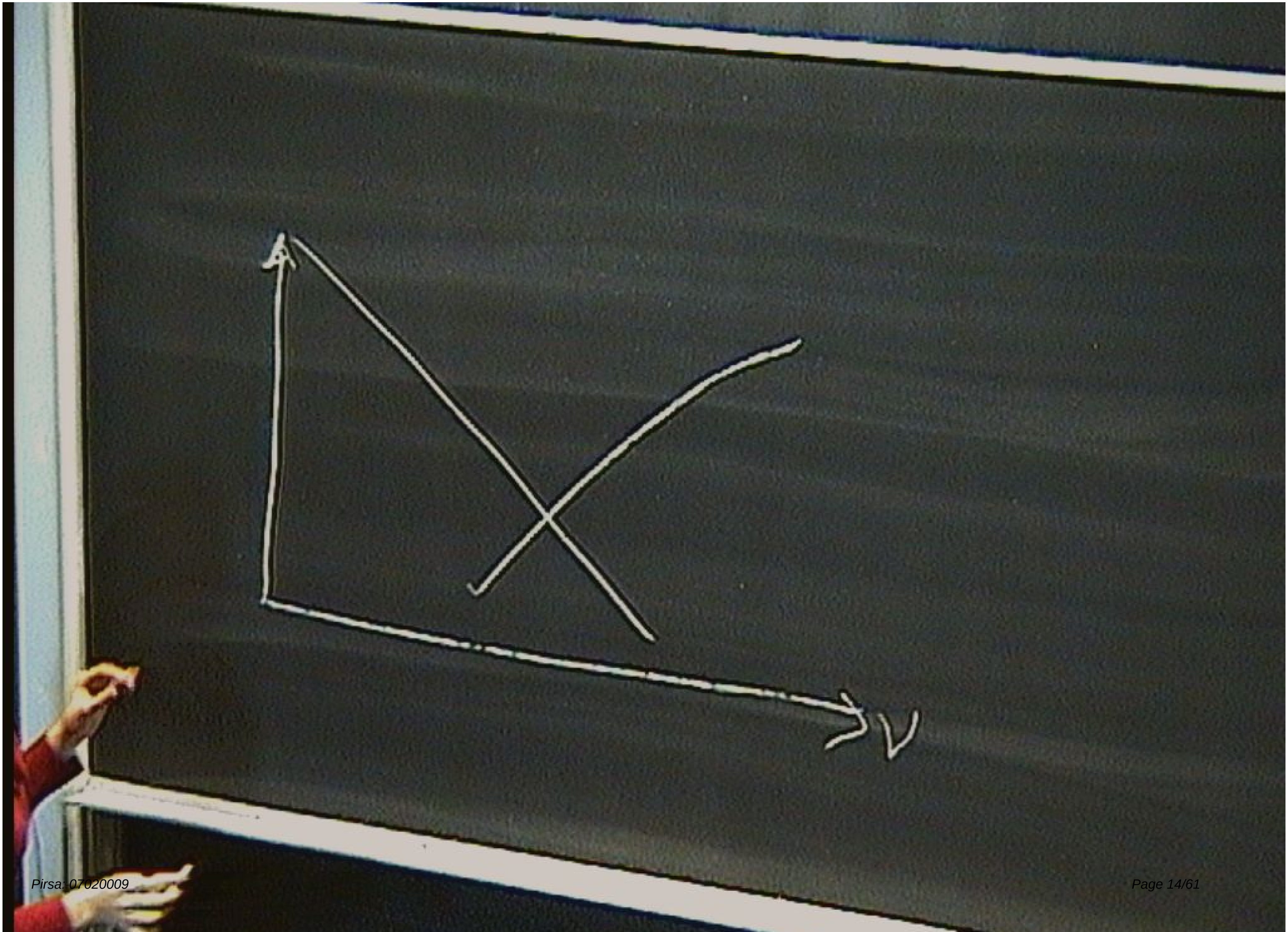
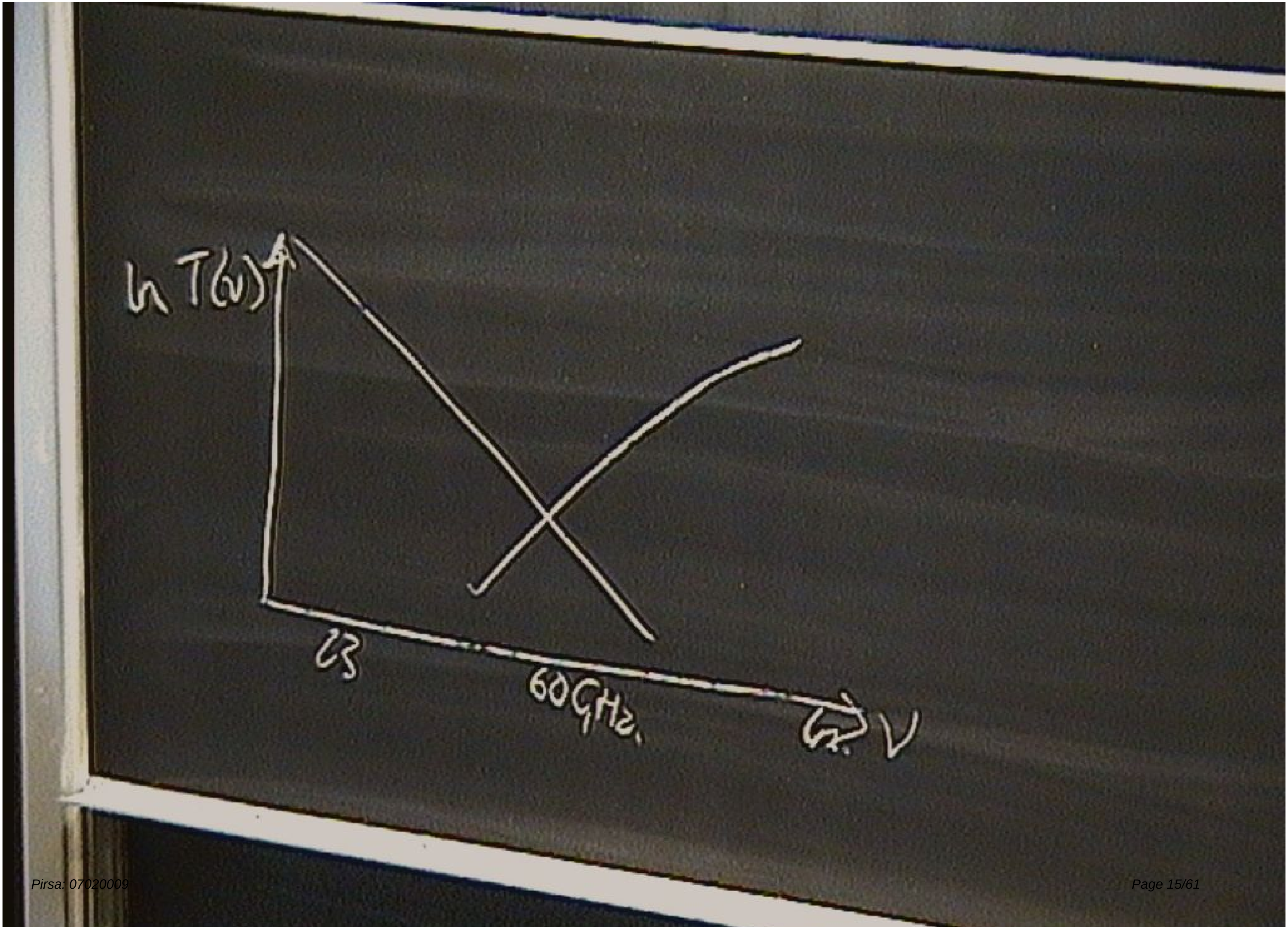
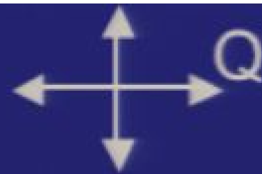


ν


ln T(ν)
23
60GHz
ν

Now for the real data…



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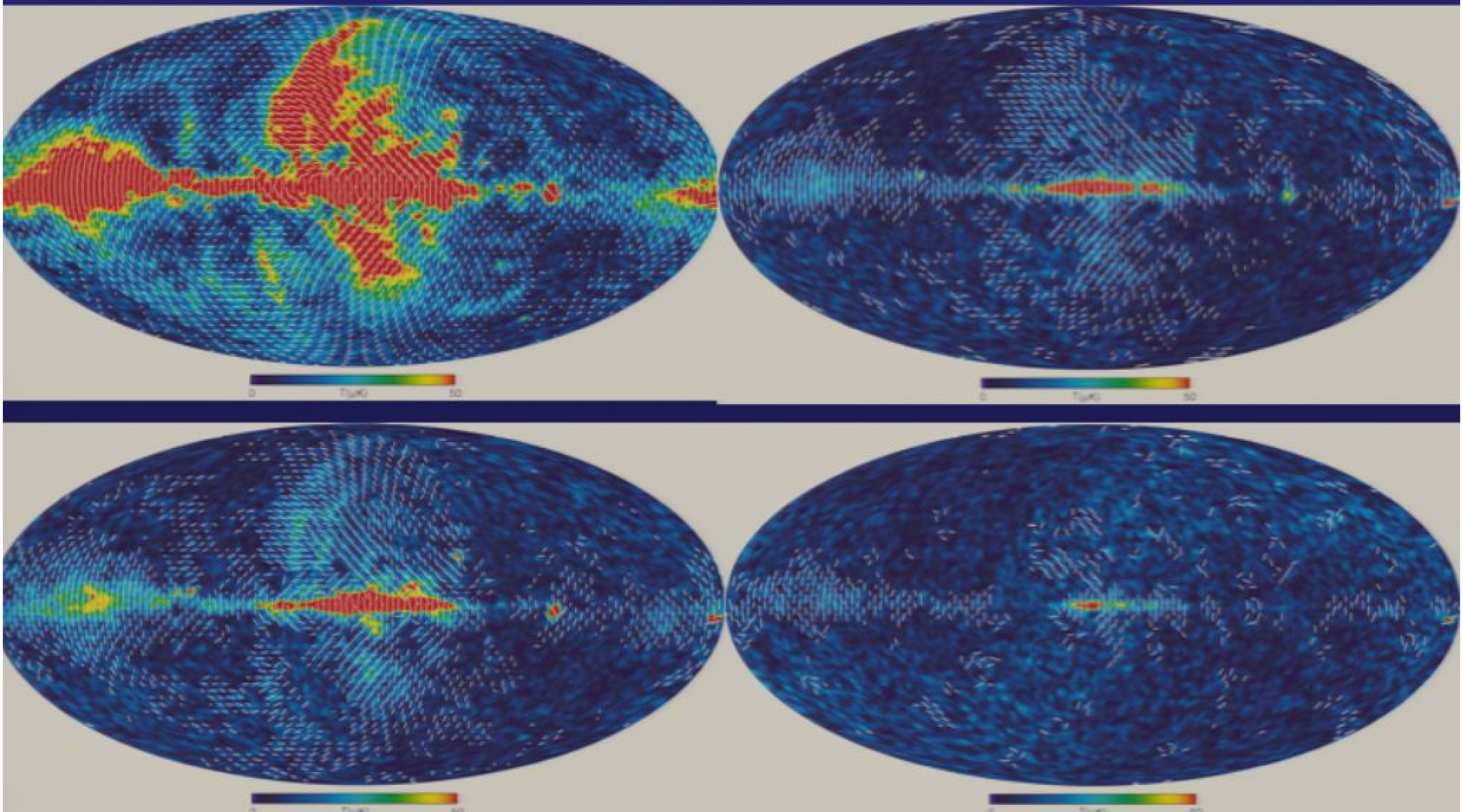

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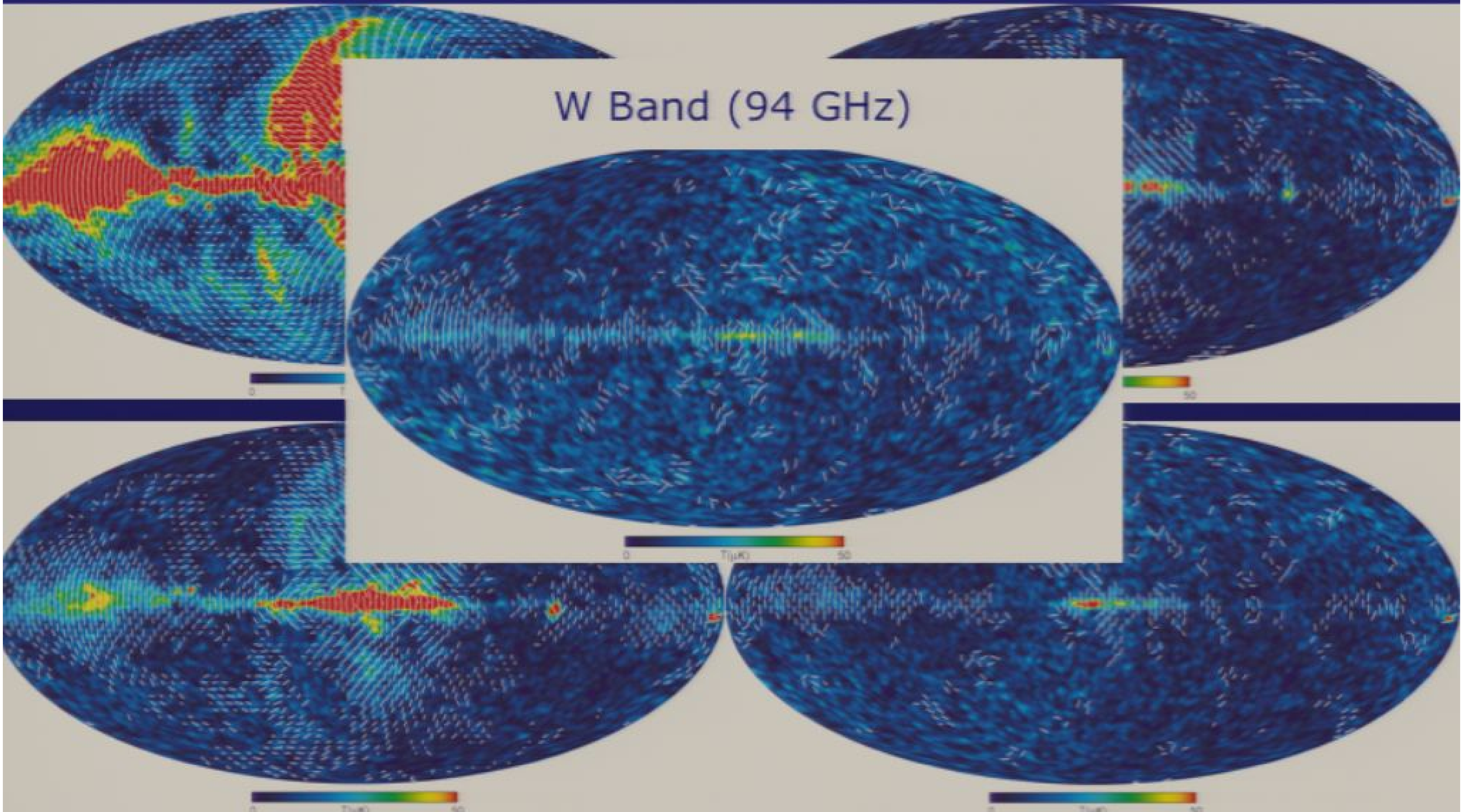
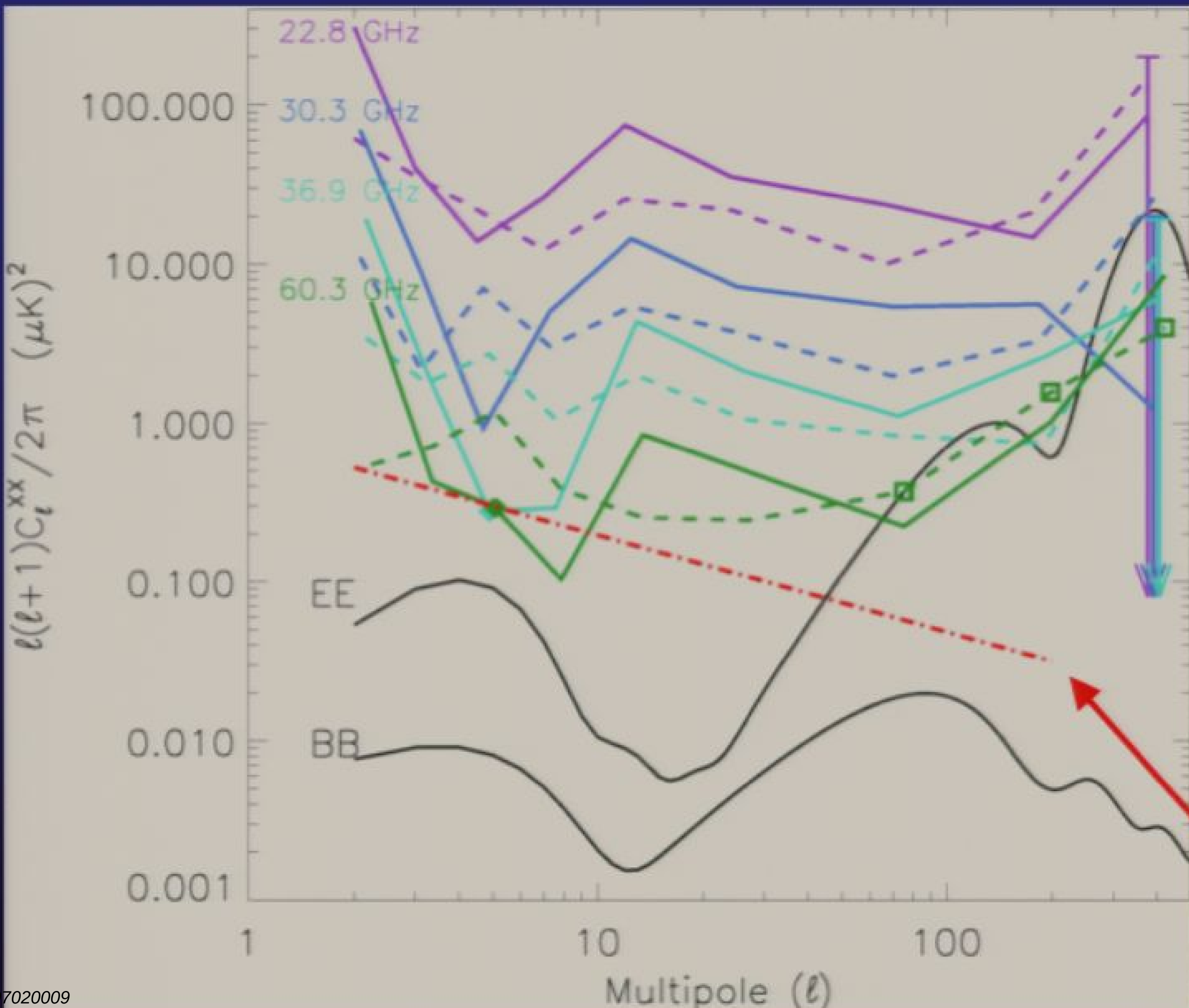


Ka Band (33 GHz)

V Band (61 GHz)

Galactic emission high even outside mask



K-band: 5μK

W-band: 0.6μK

E 0.3μK

B 0.1μK

tau=0.09
r=0.3

Rough fit to BB FG in 60GHz

WMAP 3yr template cleaning worked well

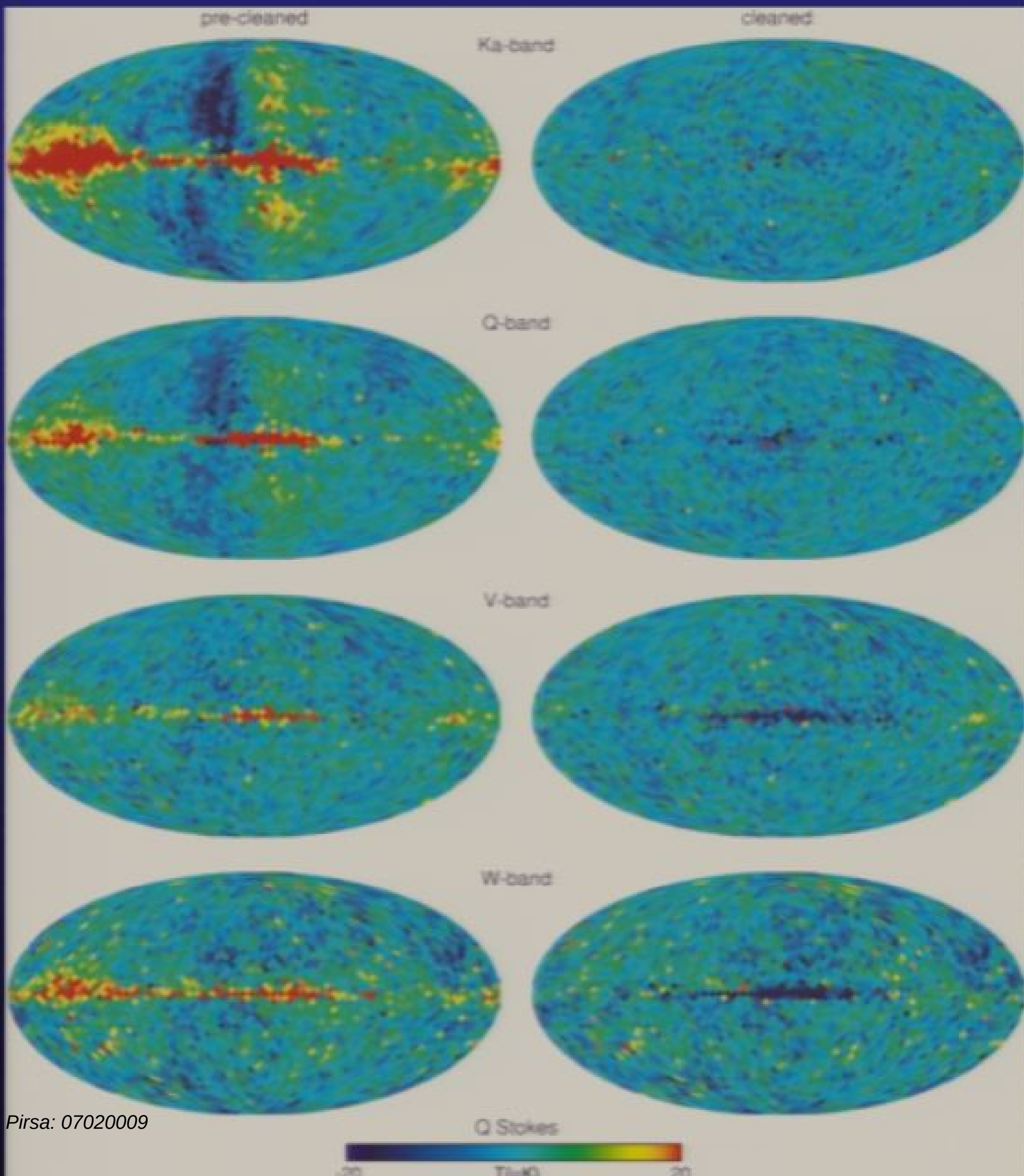


TABLE 4
COMPARISON OF χ^2 BETWEEN PRE-CLEANED AND CLEANED MAPS

Band	χ^2/ν Pre-cleaned	χ^2/ν Cleaned	ν	$\Delta\chi^2$
Ka	10.65	1.20	6144	58061
Q	3.91	1.09	6144	17326
V	1.36	1.19	6144	1045
W	1.38	1.58	6144	-1229
Ka	2.142	1.096	4534	4743
Q	1.289	1.018	4534	1229
V	1.048	1.016	4534	145
W	1.061	1.050	4534	50

The top half of the table compares χ^2/ν for the full-sky pre-cleaned map to χ^2/ν for full-sky cleaned map. The bottom half makes a similar comparison for the region outside the P06 mask.

- Synchrotron template = K band with a spectral index
- Dust template = FDS intensity map, index = 2
- Cleaned Q and V maps have reduced chi-squared of ~1.02 per DOF=4534 (outside P06)

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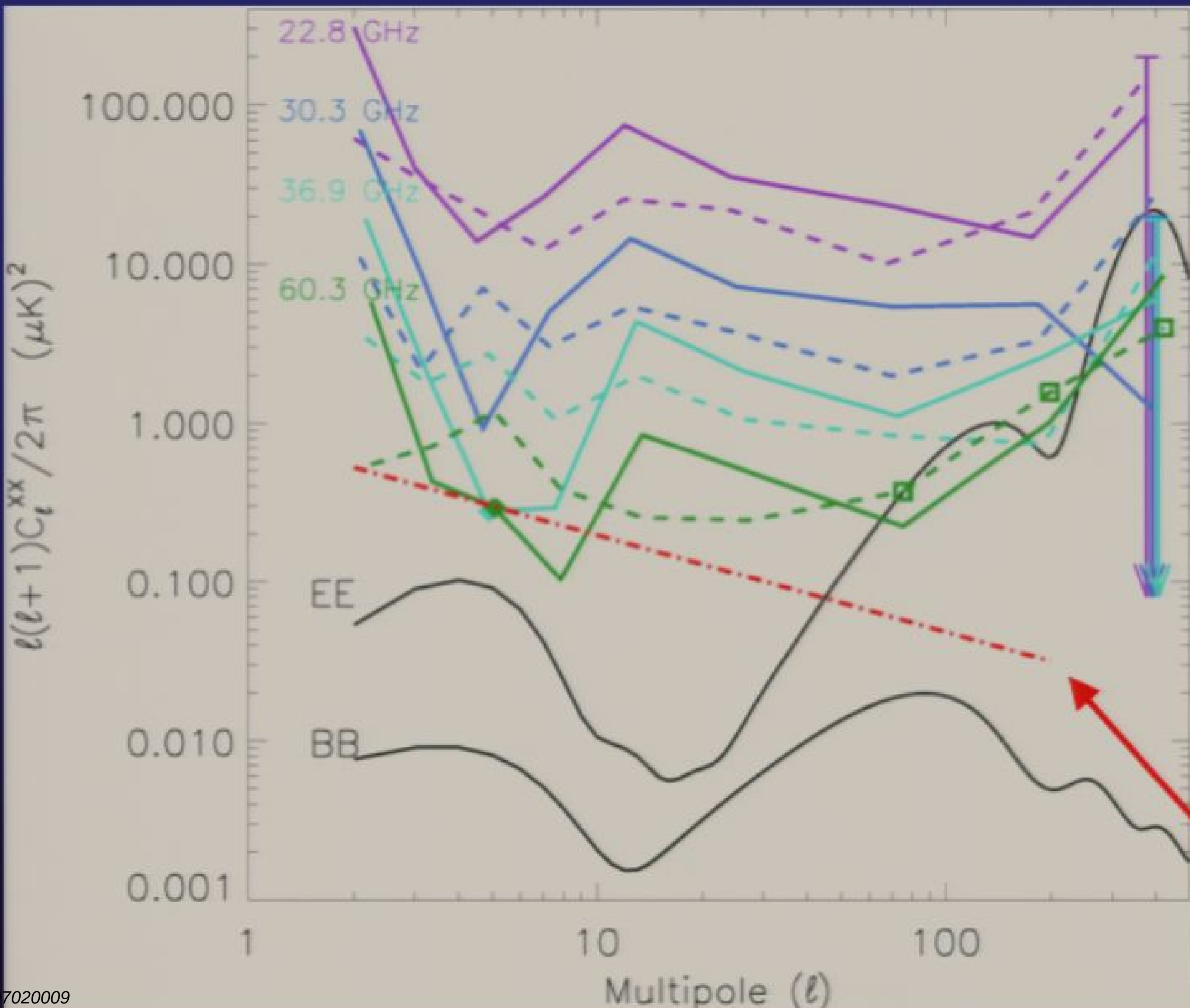

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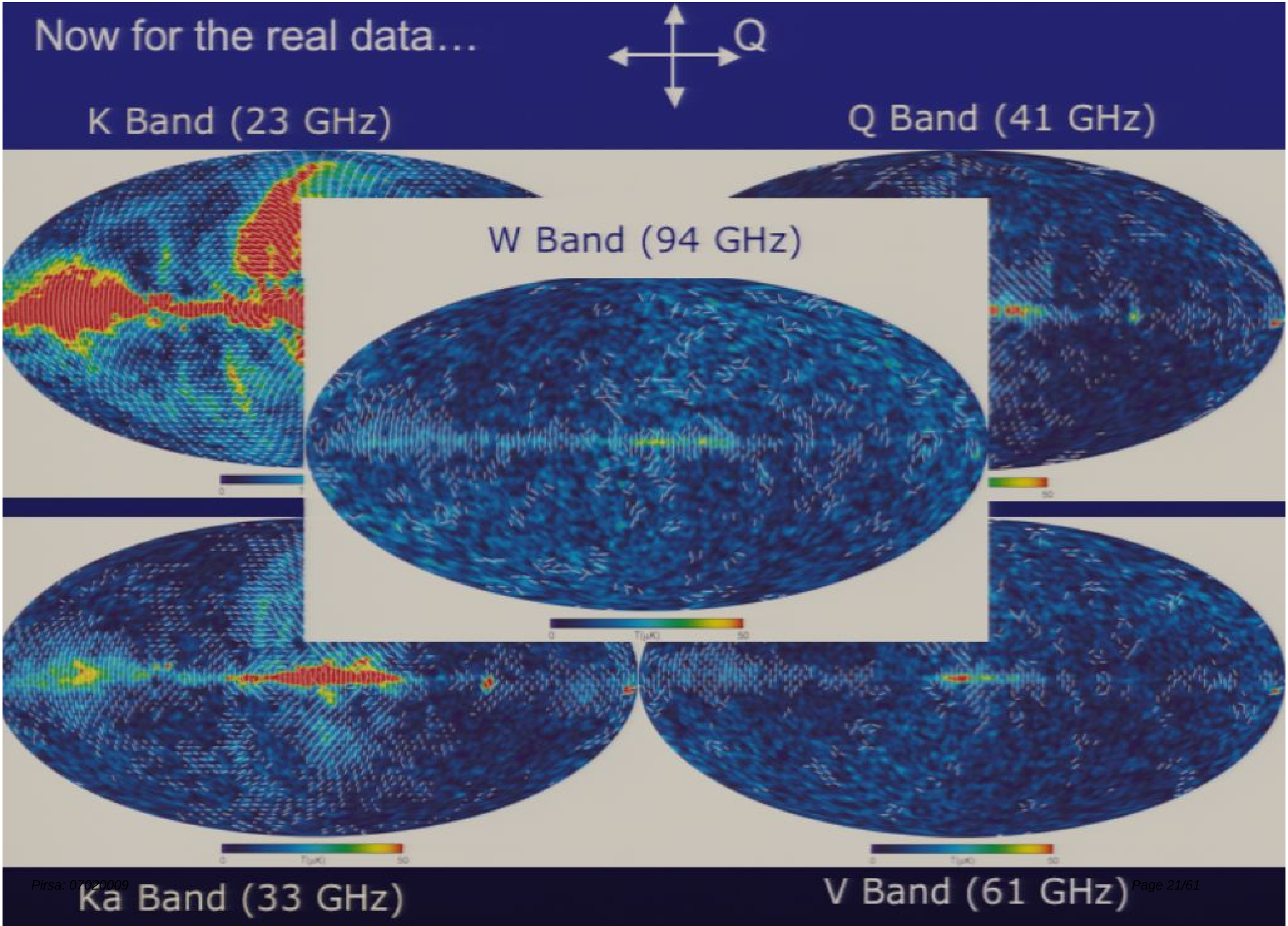
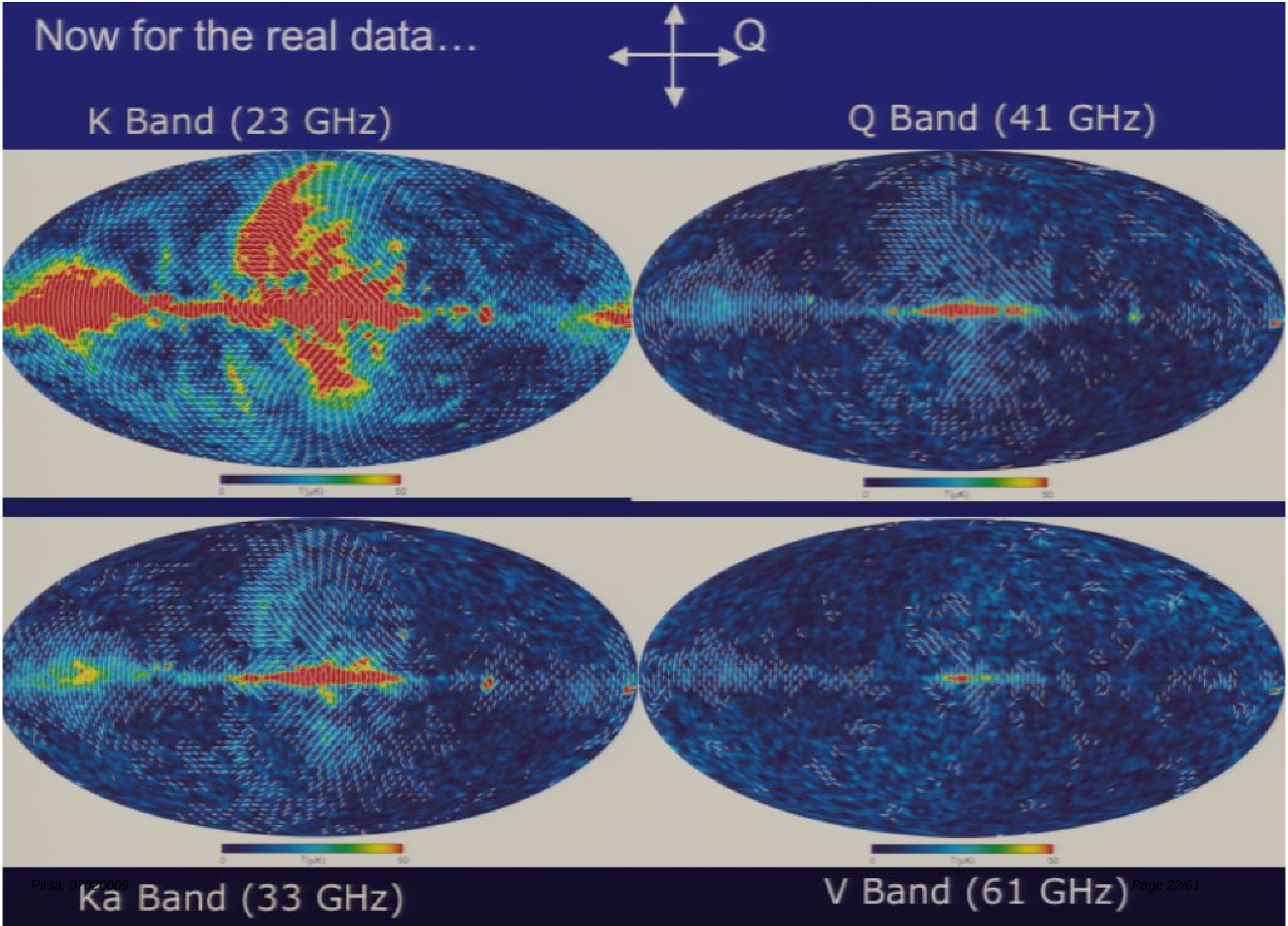

Now for the real data…
Q
K Band (23 GHz)
Q Band (41 GHz)
W Band (94 GHz)
Ka Band (33 GHz)
V Band (61 GHz)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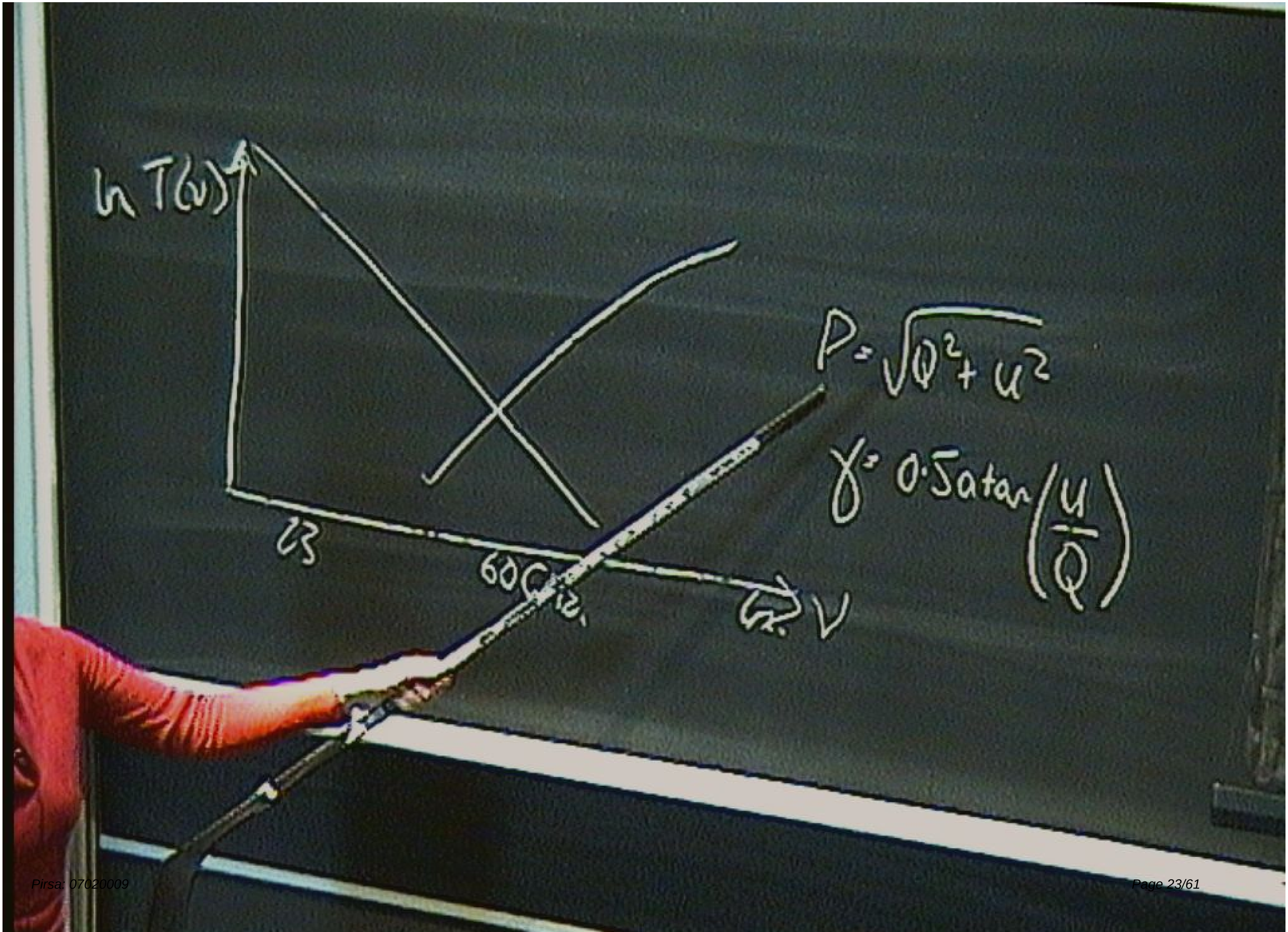
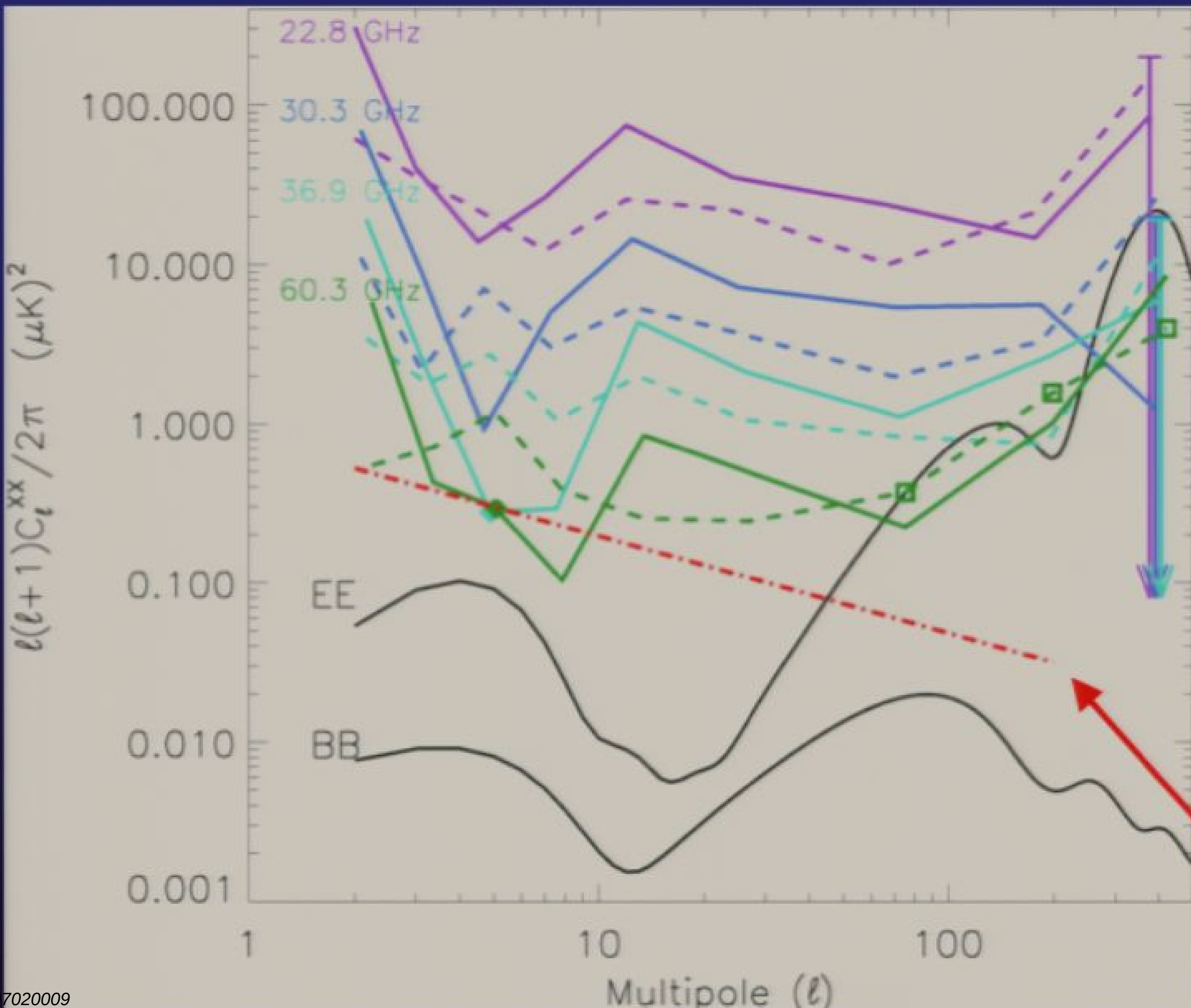
V Band (61 GHz)


ln T(v)
23
60
V
P = √(Q² + u²)
γ = 0.5 atan(u/Q)

Galactic emission high even outside mask



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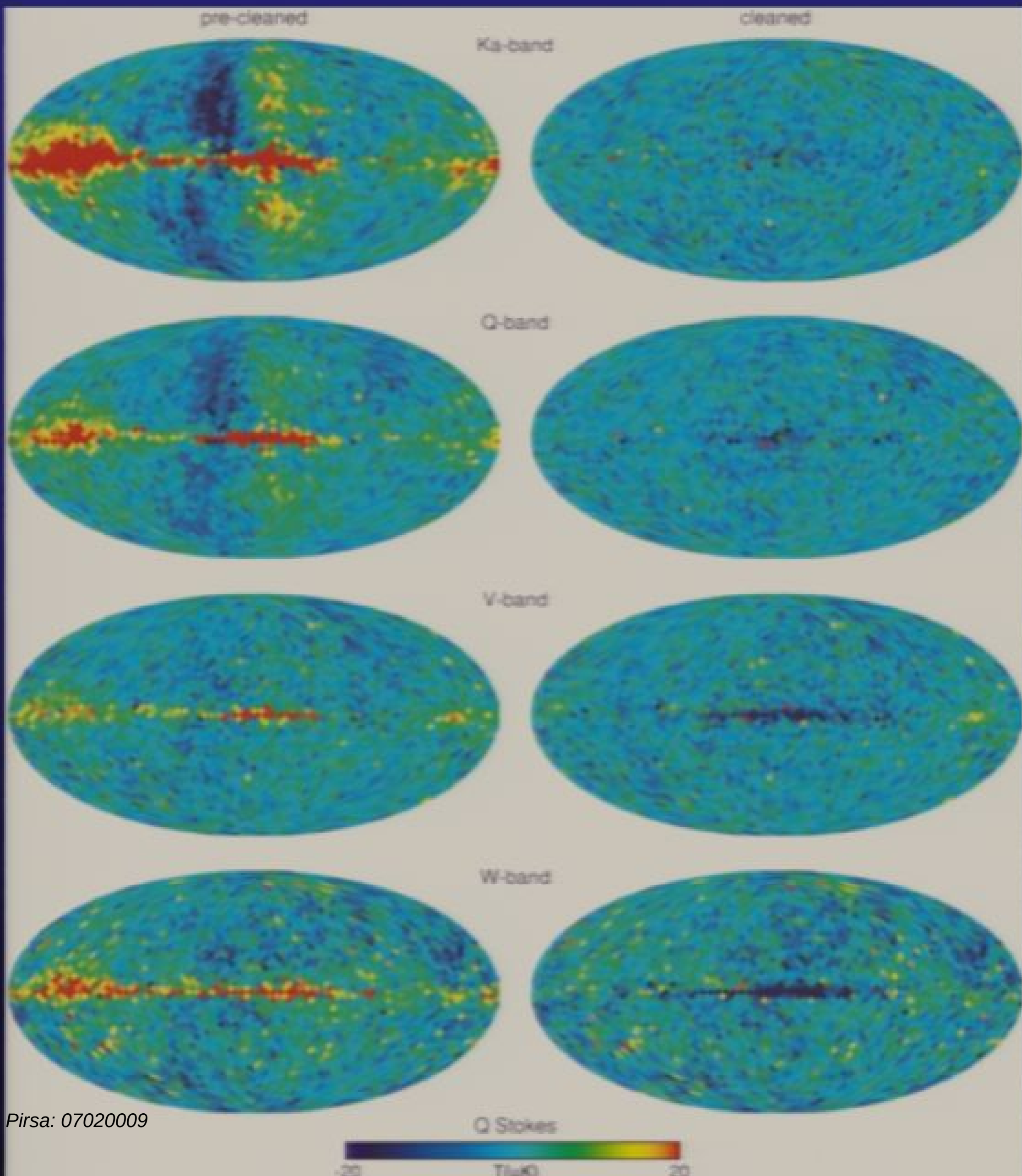

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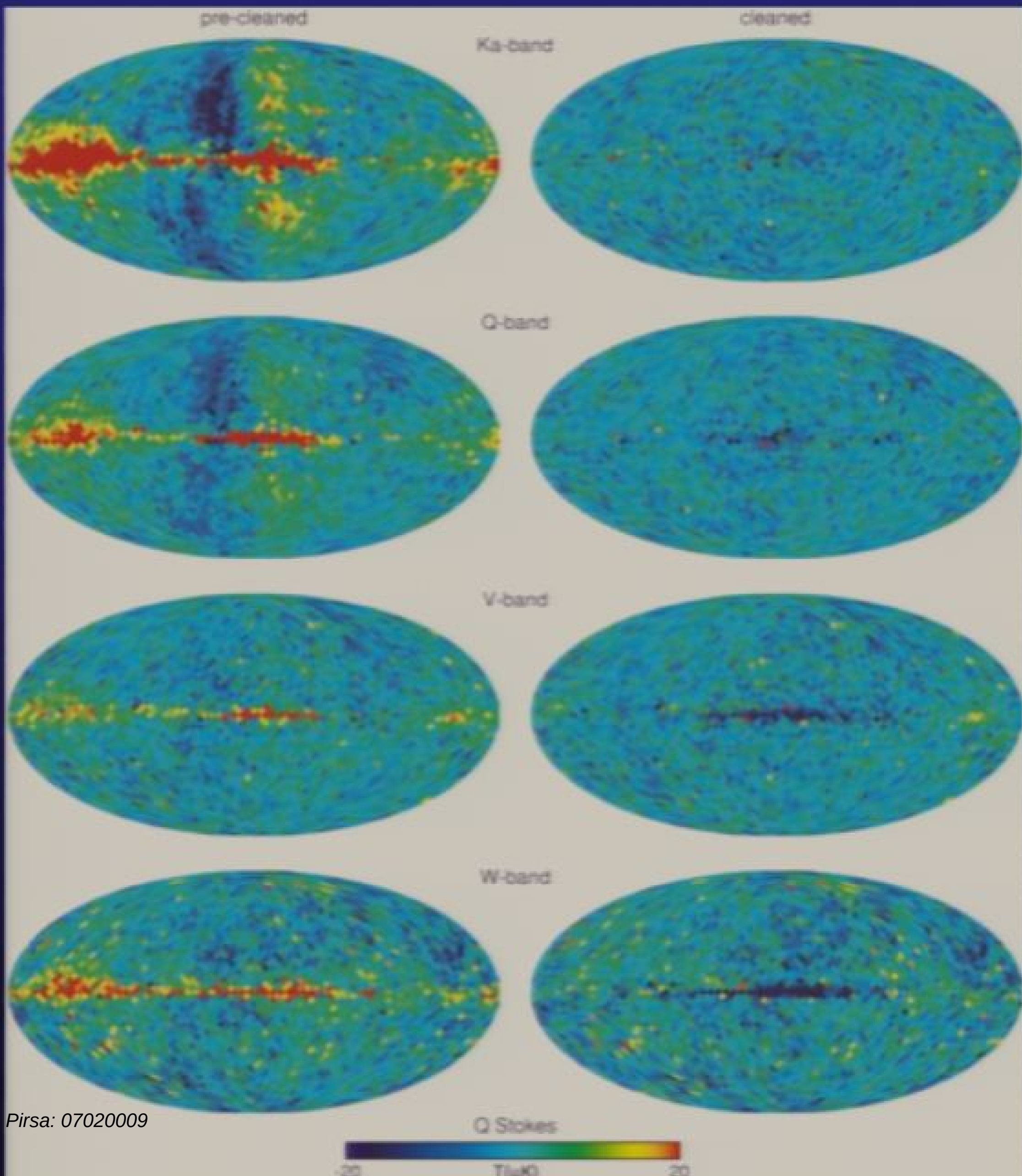

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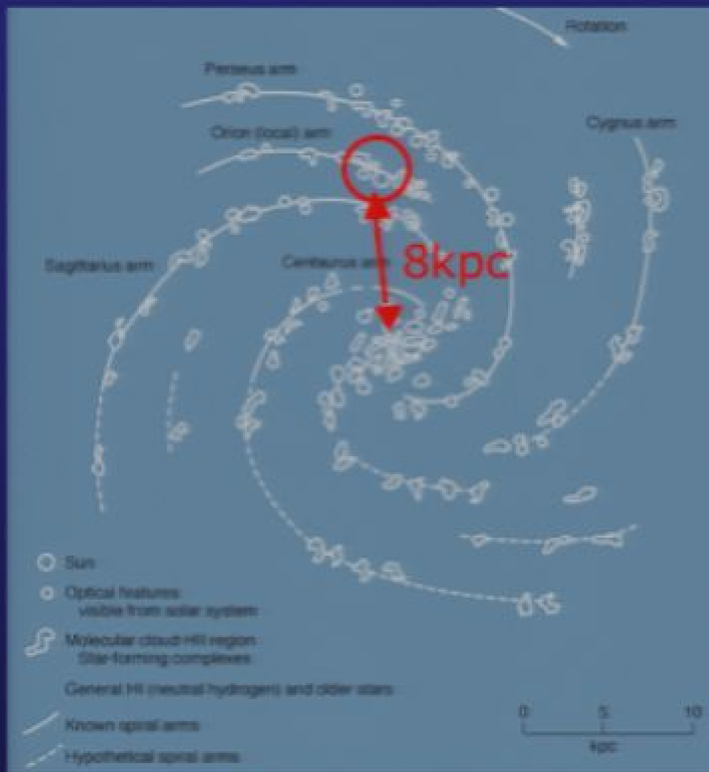
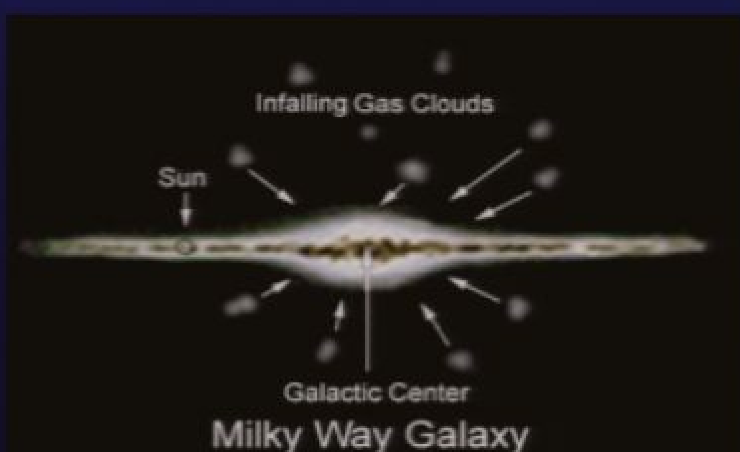
The polarized microwave galaxy





What do we care about?

- *Magnetic field*
- Energetic electrons
  - Injection in star-forming regions
  - Diffusion of electrons along field lines
- Dust

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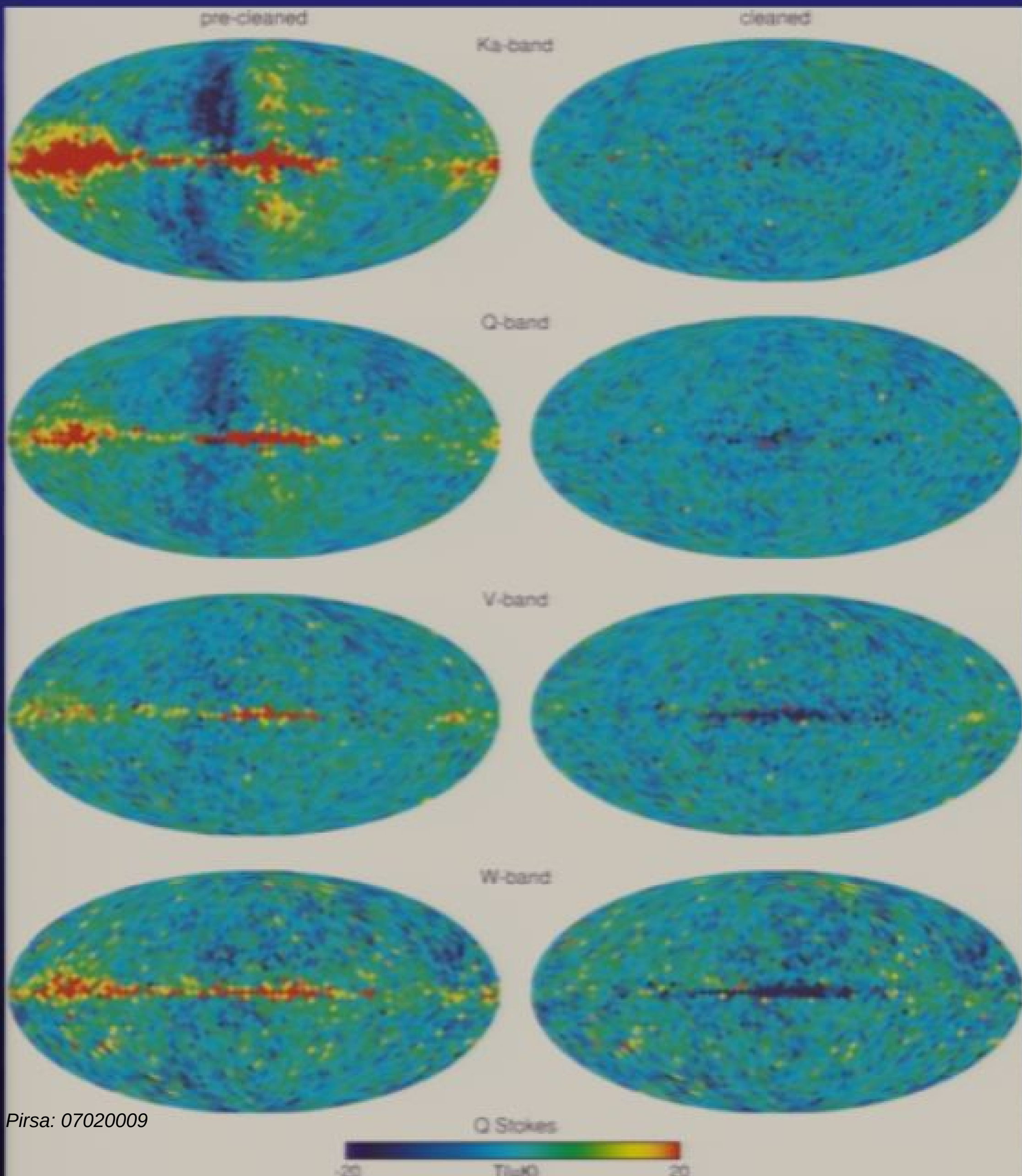

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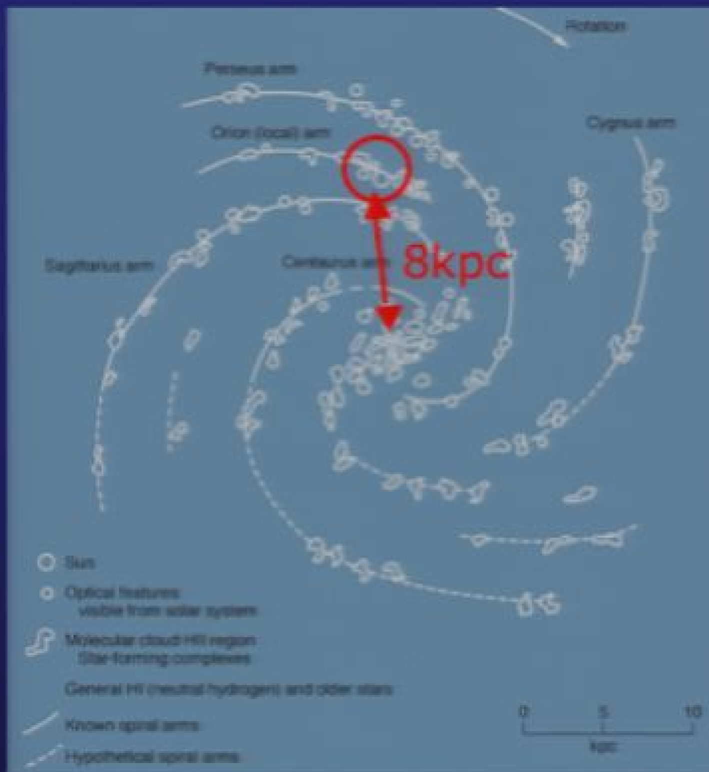

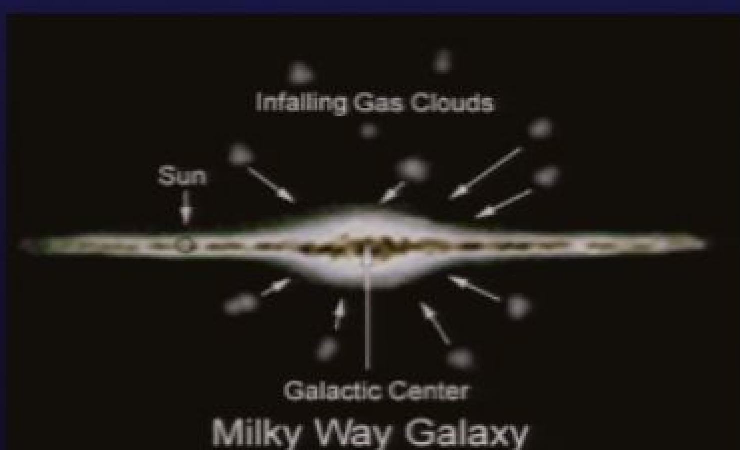

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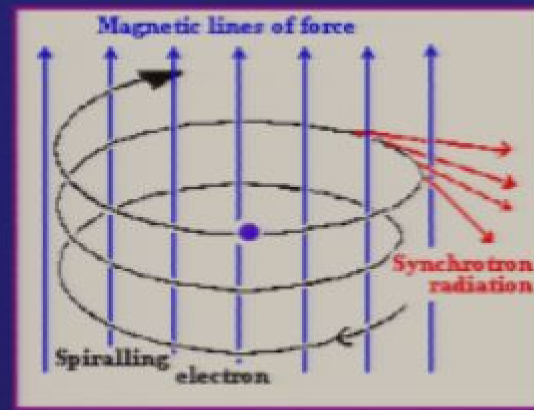
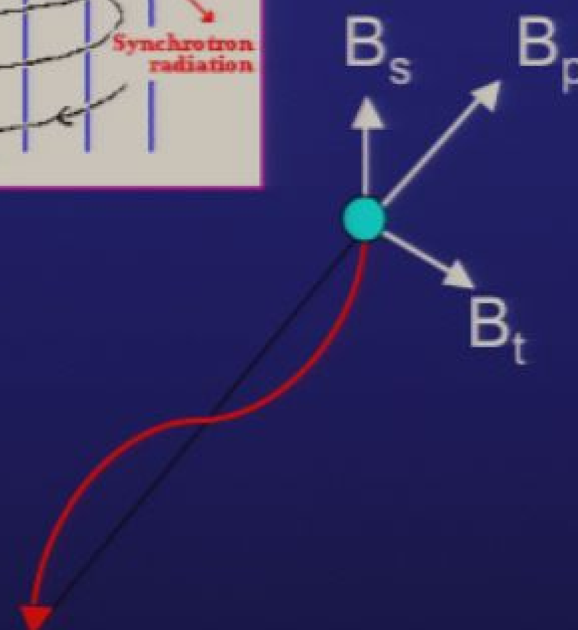
Synchrotron radiation

Relativistic electrons spiraling in magnetic fields





$$I(\mathbf{x}) \propto n_e(\mathbf{x})[B_s(\mathbf{x})^2 + B_t(\mathbf{x})^2]$$

$$Q(\mathbf{x}) \propto n_e(\mathbf{x})\Pi_s[B_s(\mathbf{x})^2 - B_t(\mathbf{x})^2]$$

$$U(\mathbf{x}) \propto n_e(\mathbf{x})\Pi_s[2B_s(\mathbf{x})B_t(\mathbf{x})]$$

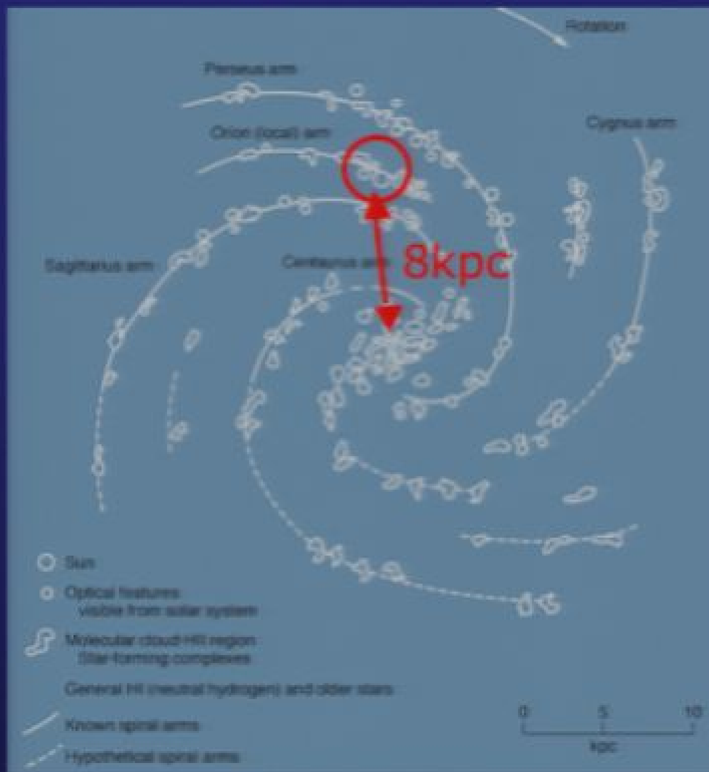
Spectrum of radiation depends on energy distribution of electrons:

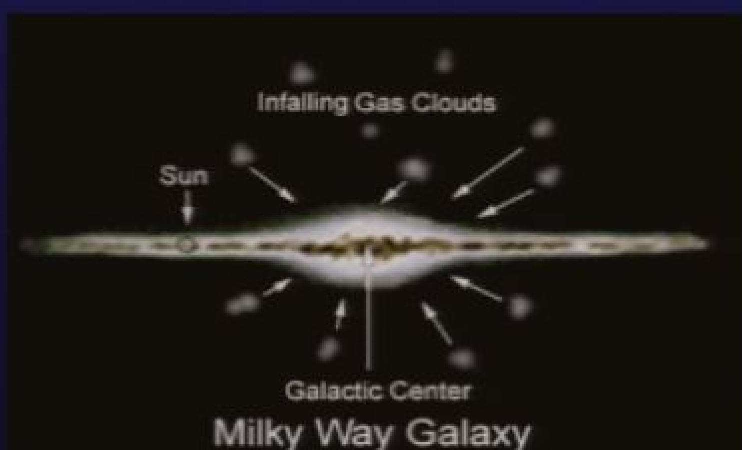
$$n(E) \propto E^{-p}$$

$$I(\nu) \propto \nu^{-\frac{p+3}{2}}$$

Radiation is polarized perpendicular to B-field

The polarized microwave galaxy





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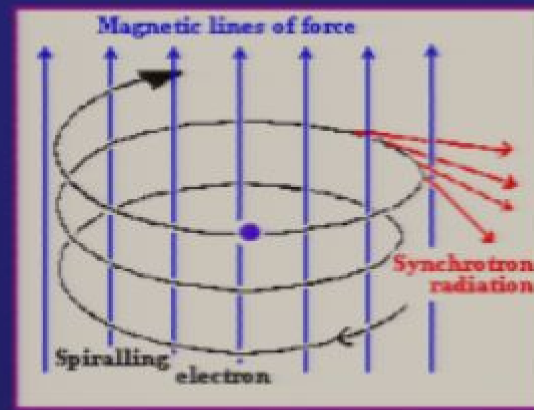

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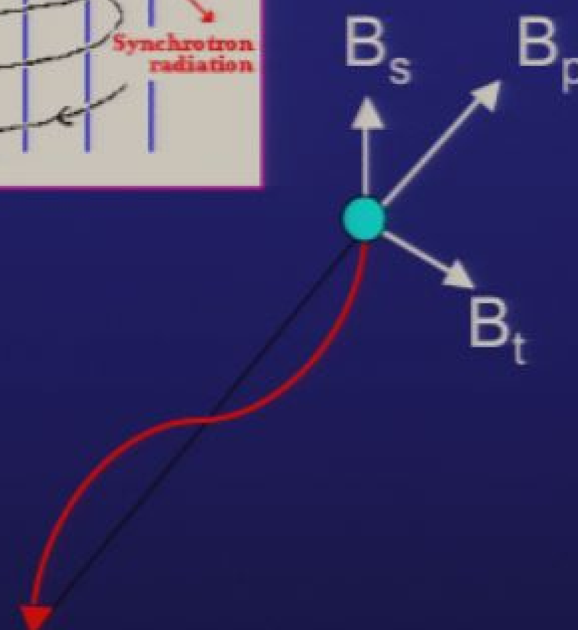

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Radiation is polarized perpendicular to B-field

Diffusion through the galaxy

- We look at integrated line of sight

$$I(\hat{n}) \propto \int_x dx\, n_e(x,\hat{n})[B_s(x,\hat{n})^2 + B_t(x,\hat{n})^2]$$

$$Q(\hat{n}) \propto \Pi_s \int_x dx\, n_e(x,\hat{n})[B_s(x,\hat{n})^2 - B_t(x,\hat{n})^2]$$

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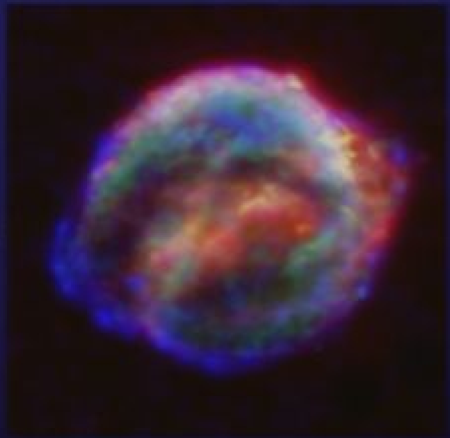
$$\tan 2\gamma(\hat{n}) = \frac{U(\hat{n})}{Q(\hat{n})}$$

- How do the electrons get there?
  - injected in supernovae, diffuse along B-field lines.

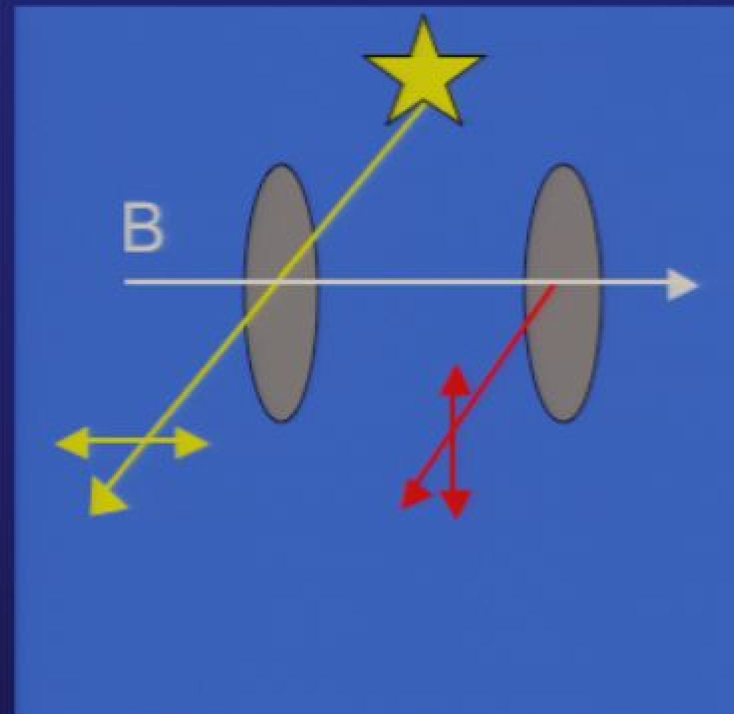


$$\frac{dN}{dt} - D\nabla^2 N - \frac{\partial}{\partial E}\left(\frac{\partial E}{\partial t} N\right) = A(E,r,t)$$

So we understand the physics, but we don't know electron injection rate, diffusion rate, and location of injection, or B-field...

Thermal dust emission

- Grains align with B-field
- Index: $T(\nu) \propto \nu^2$
- Fractional polarization depends on B-field and asymmetry of dust grains
- Use starlight to trace directions



$$I(\hat{n}) \propto \int_x dx \rho_d(x,\hat{n})$$

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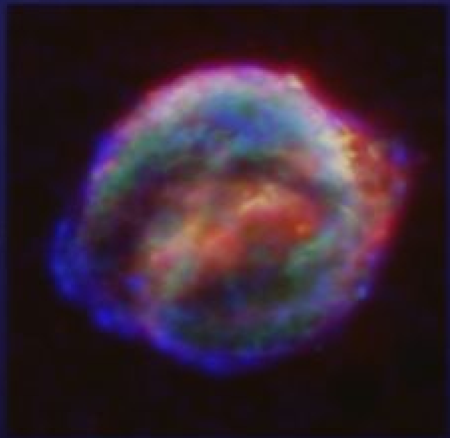

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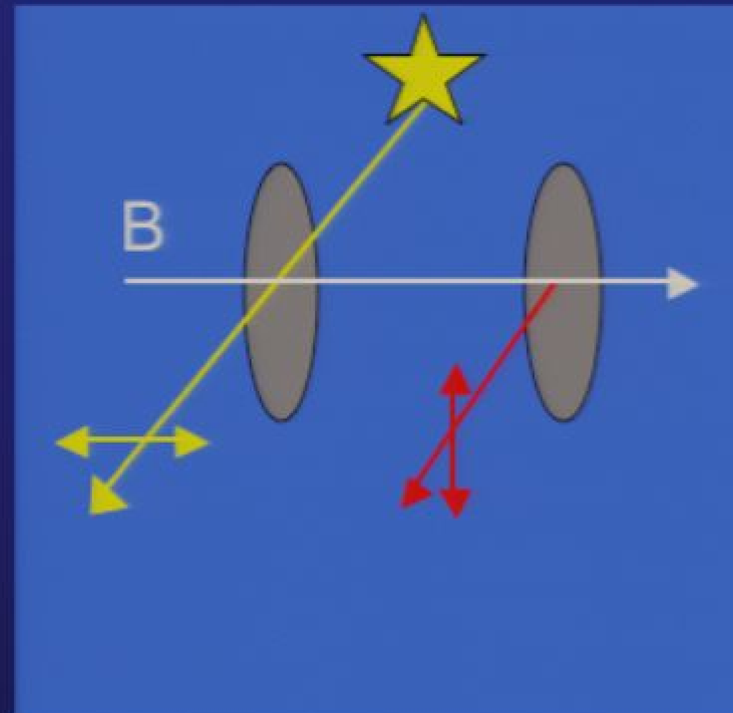
- Index: $T(\nu) \propto \nu^2$
- Fractional polarization depends on B-field and asymmetry of dust grains
- Use starlight to trace directions

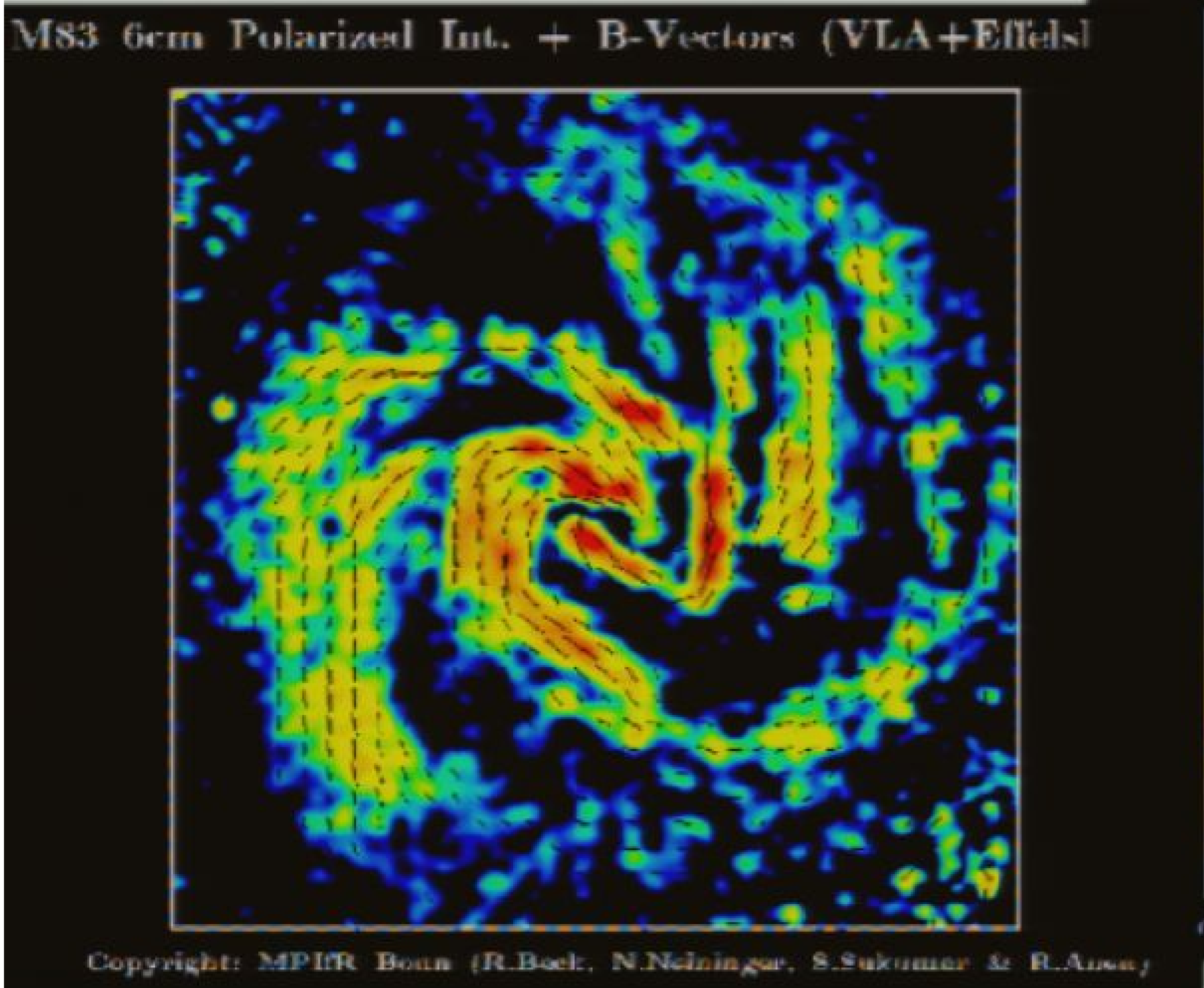


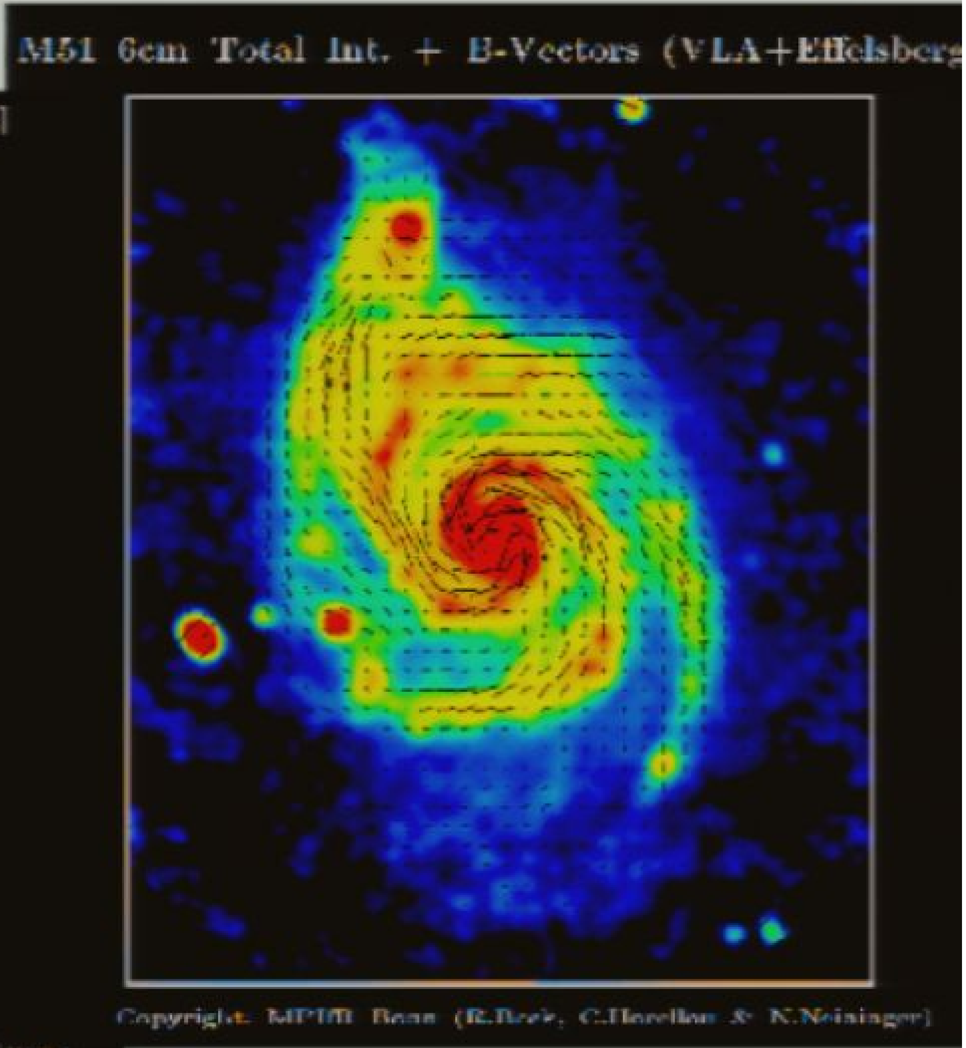
$$I(\hat{n}) \propto \int_x dx \rho_d(x,\hat{n})$$

$$Q(\hat{n}) \propto \int_x dx f_d(x,\hat{n}) \rho_d(x,\hat{n}) [B_s(x,\hat{n})^2 - B_t(x,\hat{n})^2]$$

$$U(\hat{n}) \propto \int_x dx f_d(x,\hat{n}) \rho_d(x,\hat{n}) [2B_s(x,\hat{n}) B_t(x,\hat{n})]$$

Magnetic Field Structure in external galaxies exhibit spiral structure





Wielebinski et al 2005, Beck et al 1996, Sofue et al 1986

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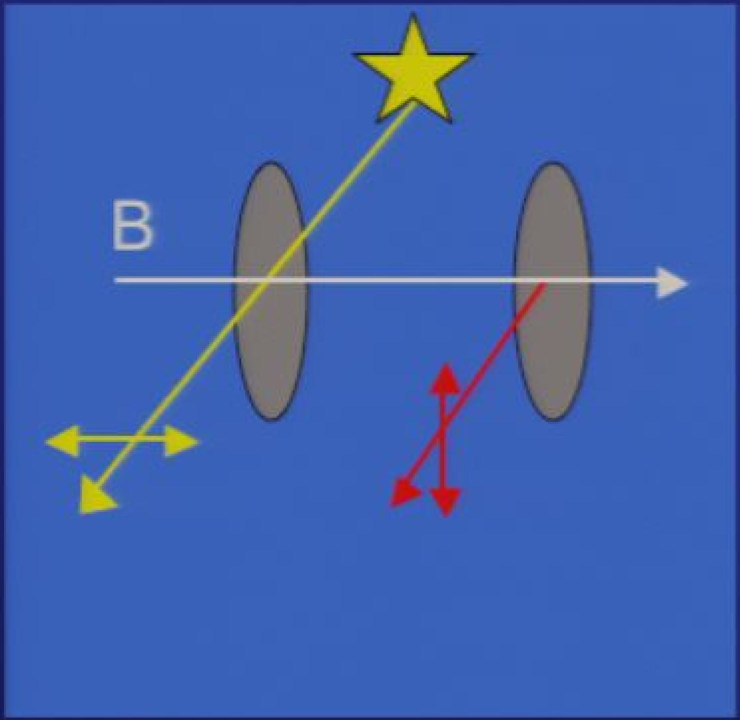

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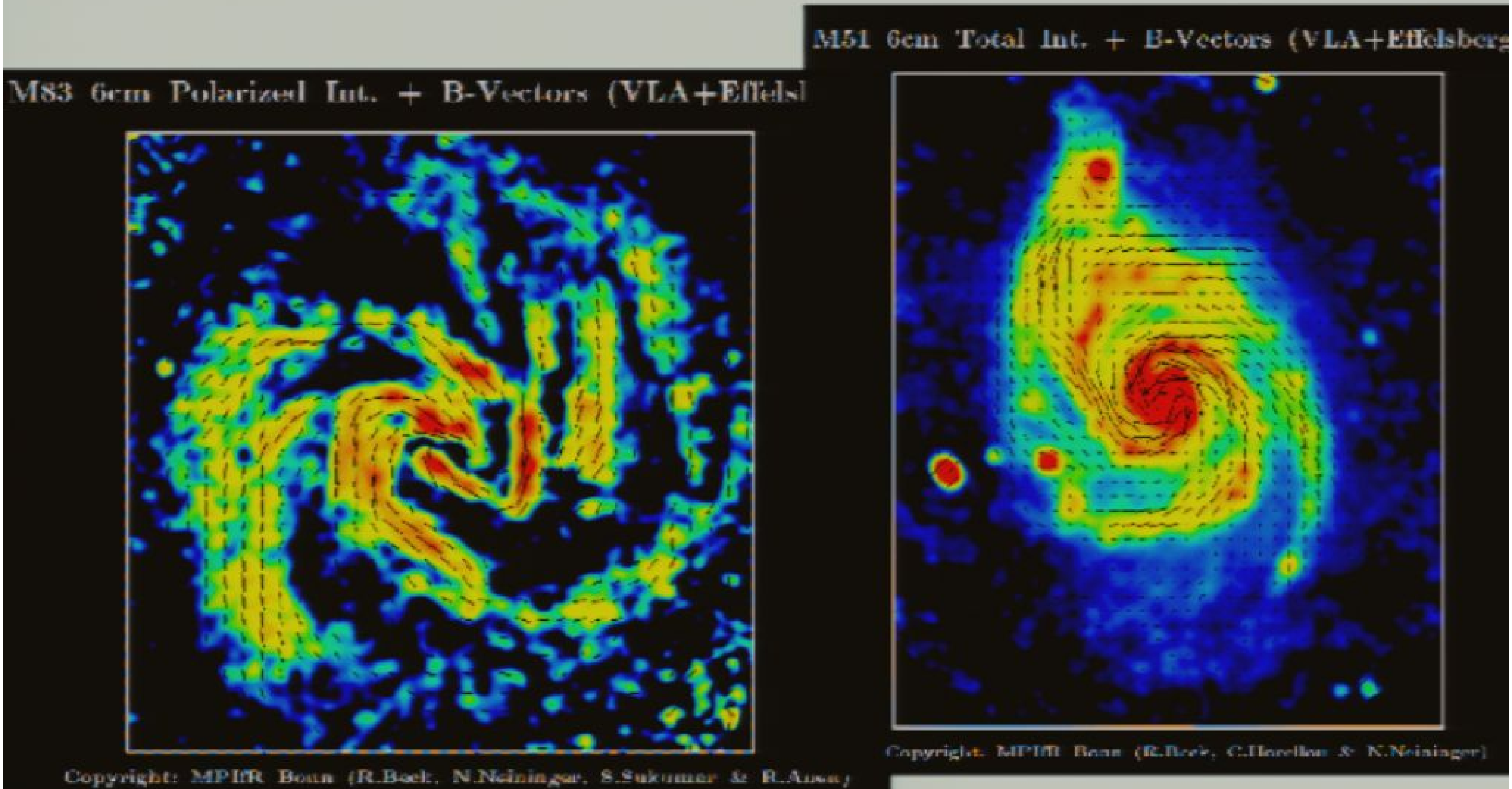

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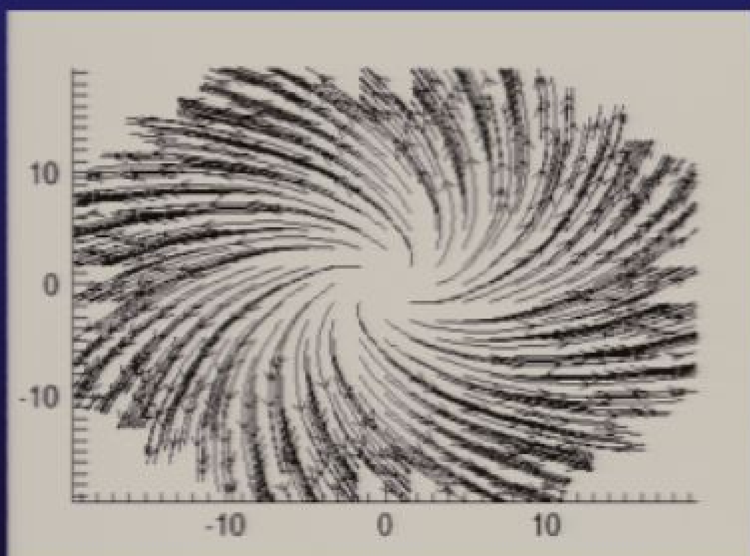
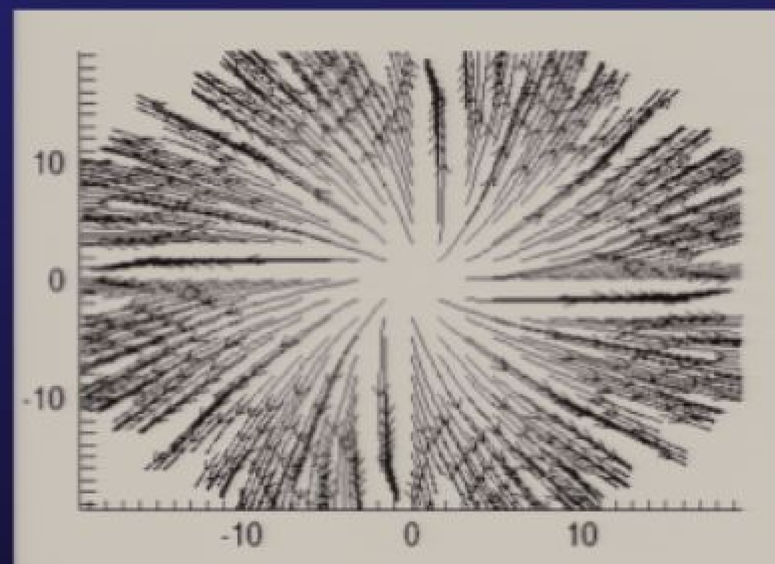
Coherent field model

$$\mathbf{B}(r,\phi,z) = B_0[\cos\psi(r)\cos\chi(z)\hat{r} + \sin\psi(r)\cos\chi(z)\hat{\phi} + \sin\chi(z)\hat{z}]$$

$$\psi(r) = \psi_0 + \psi_1 \ln(r/8\text{kpc})$$
$$\chi(z) = \chi_0 \tanh(x/1\text{kpc})$$

B_0 typically ~6μG





ψ_0 =35° Varying ψ_0 ψ_0 =10°

Complications: north/south symmetry, field reversals, varying opening angle

Coherent field model

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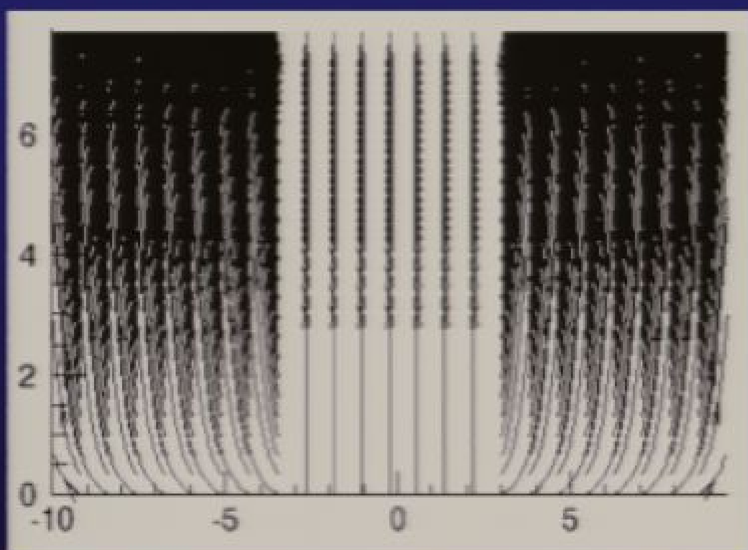

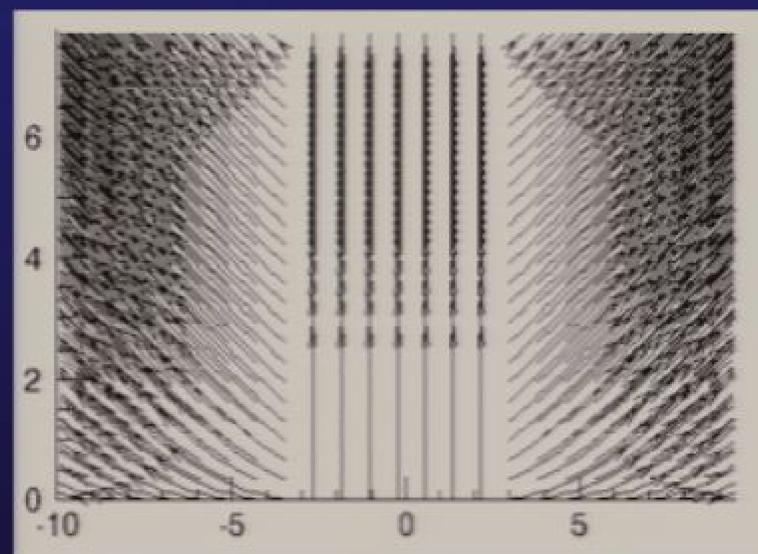

χ_0 =60°   Varying χ_0 χ_0 =25°

Complications: north/south symmetry, field reversals, varying opening angle

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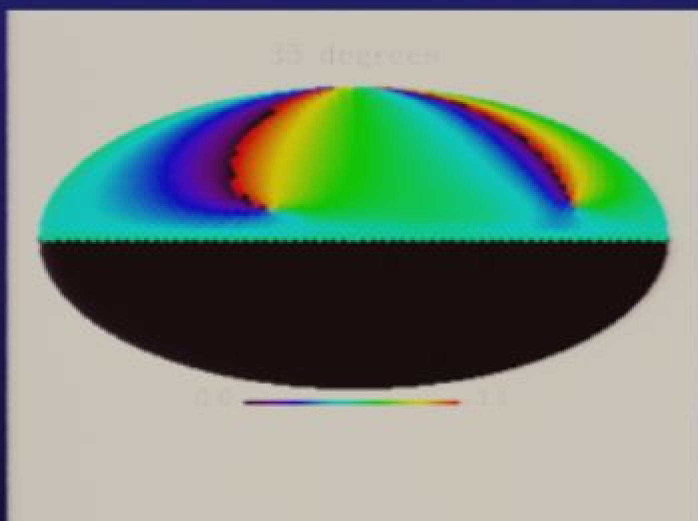
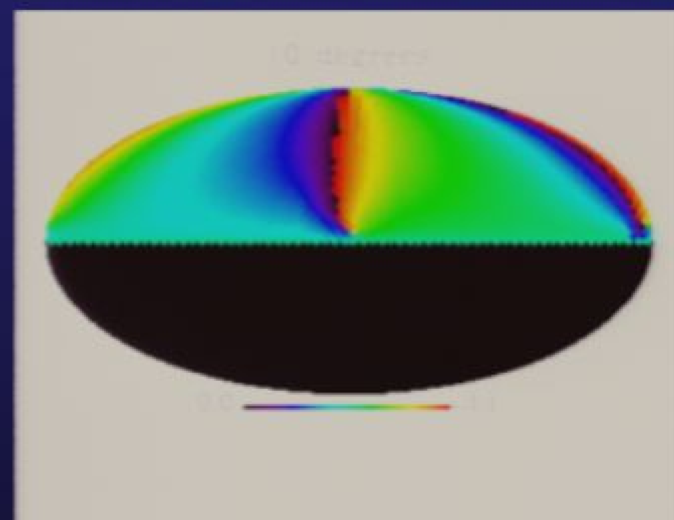
$$n = n_0 \exp(-r/h_r) \sec h^2(x/h_d)$$





$\chi_0 = 60^o$ Varying χ_0 $\chi_0 = 25^o$

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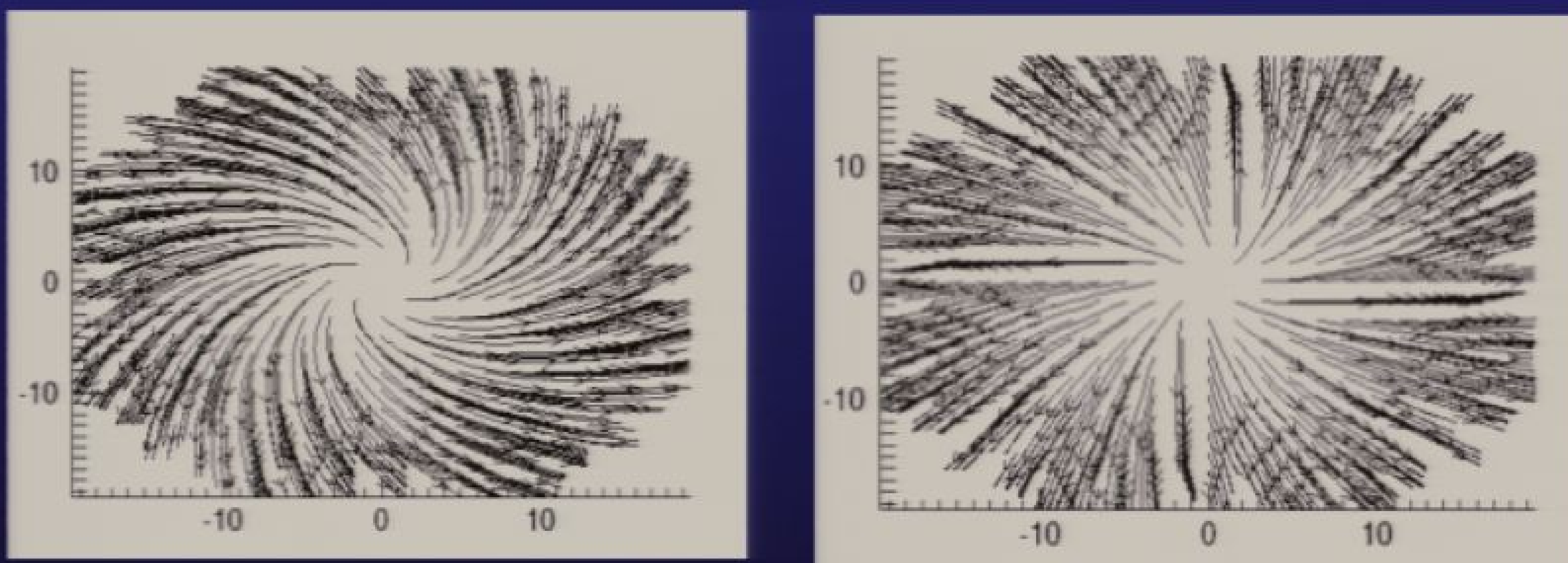
B_0 *typically* $\sim 6\mu G$



$\psi_0 = 35^o$ Varying ψ_0 $\psi_0 = 10^o$

Complications: north/south symmetry, field reversals, varying opening angle

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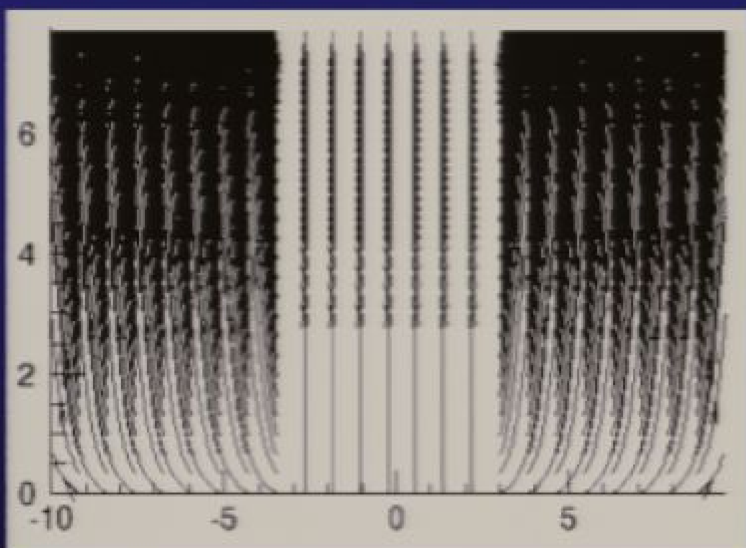

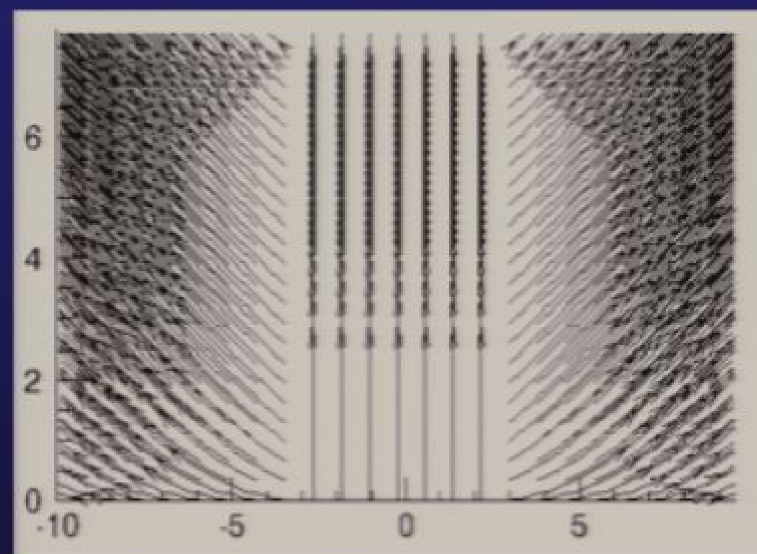

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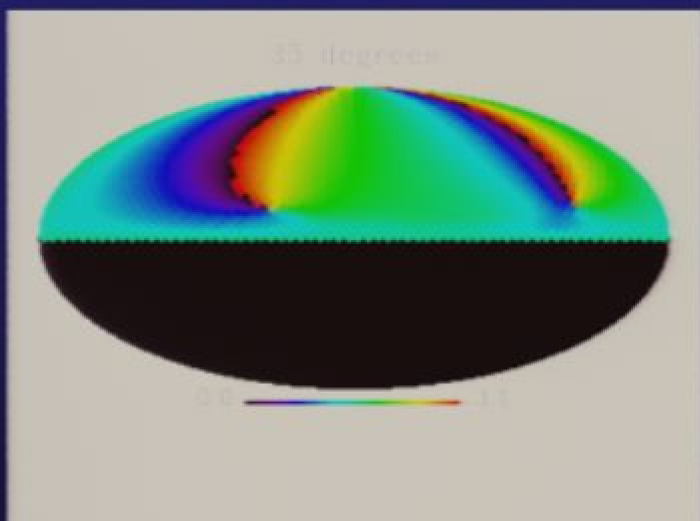
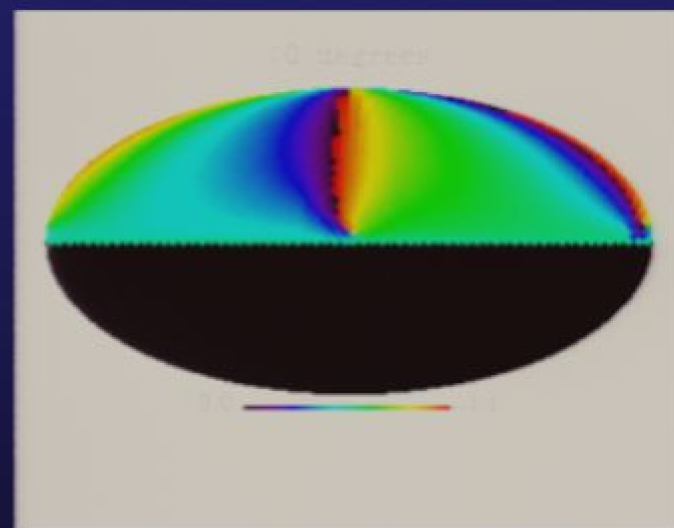
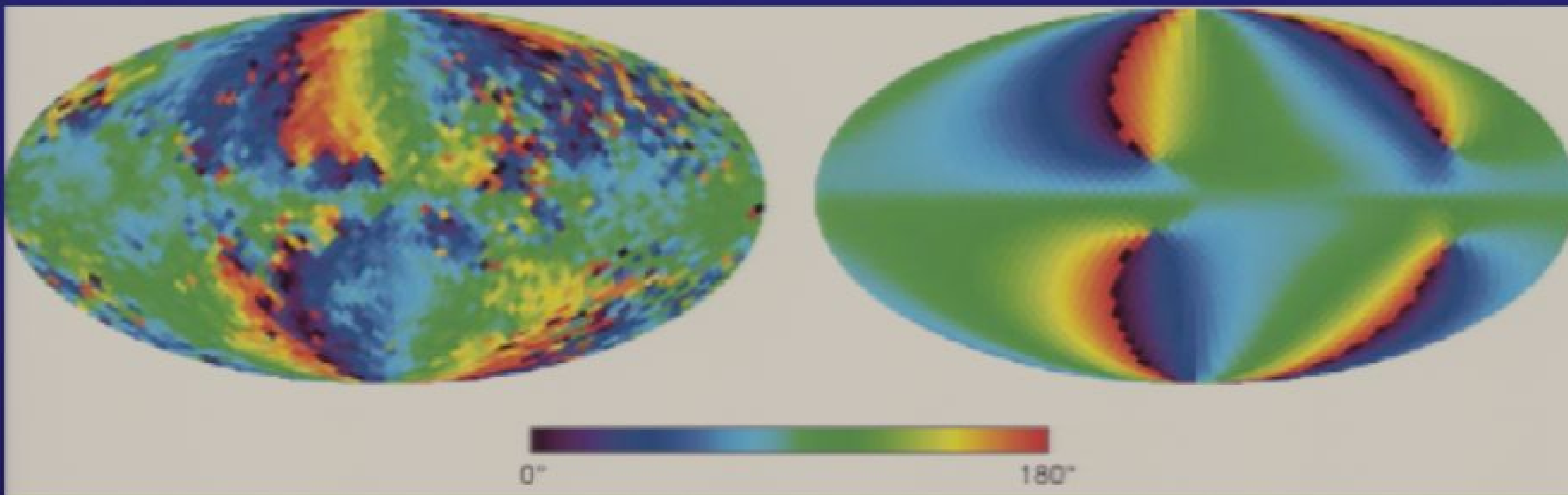




Effect on polarization directions

Complications: north/south symmetry, field reversals, varying opening angle

Fits global structure well



- Best-fit opening angle 35°
- $r=\cos[2(\gamma_{model}-\gamma_{data})]=0.76$
- Pulsar measurements indicate 8° (Beck 2001, Han 2006), mainly from plane
- Could be North polar spur confusion (Beck)

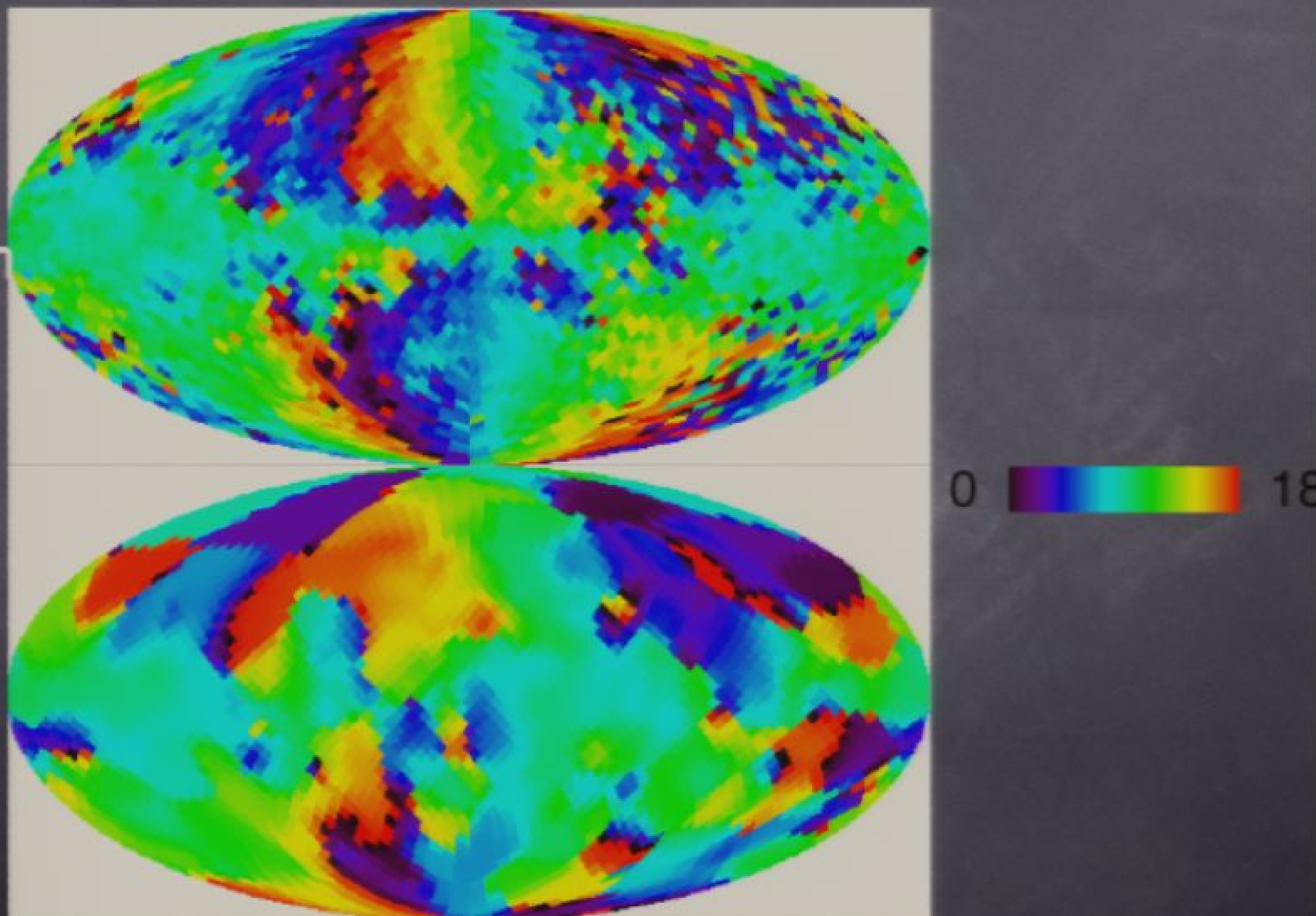
$$\tan 2\gamma(\hat{n}) = \frac{U(\hat{n})}{Q(\hat{n})}$$

Dust directions in qualitative agreement with synchrotron (different dust and electron spatial distributions)

T-B: synch; Star Light; Interpolated Map

K polarization directions

Optical Dust (rotated 90 degrees)



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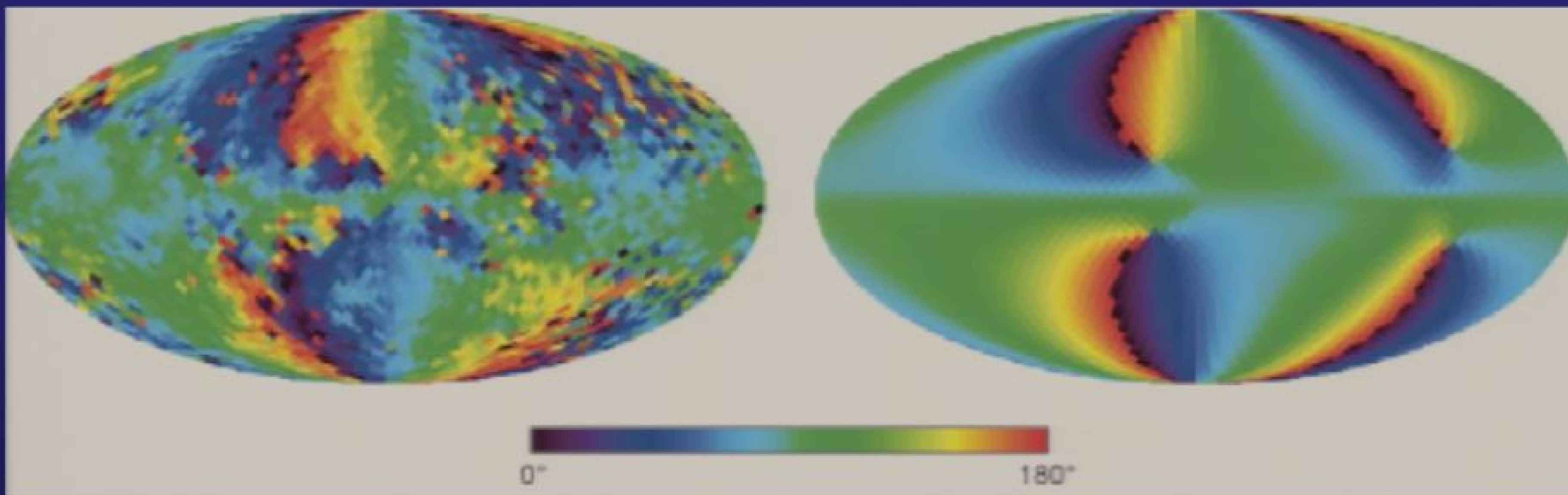

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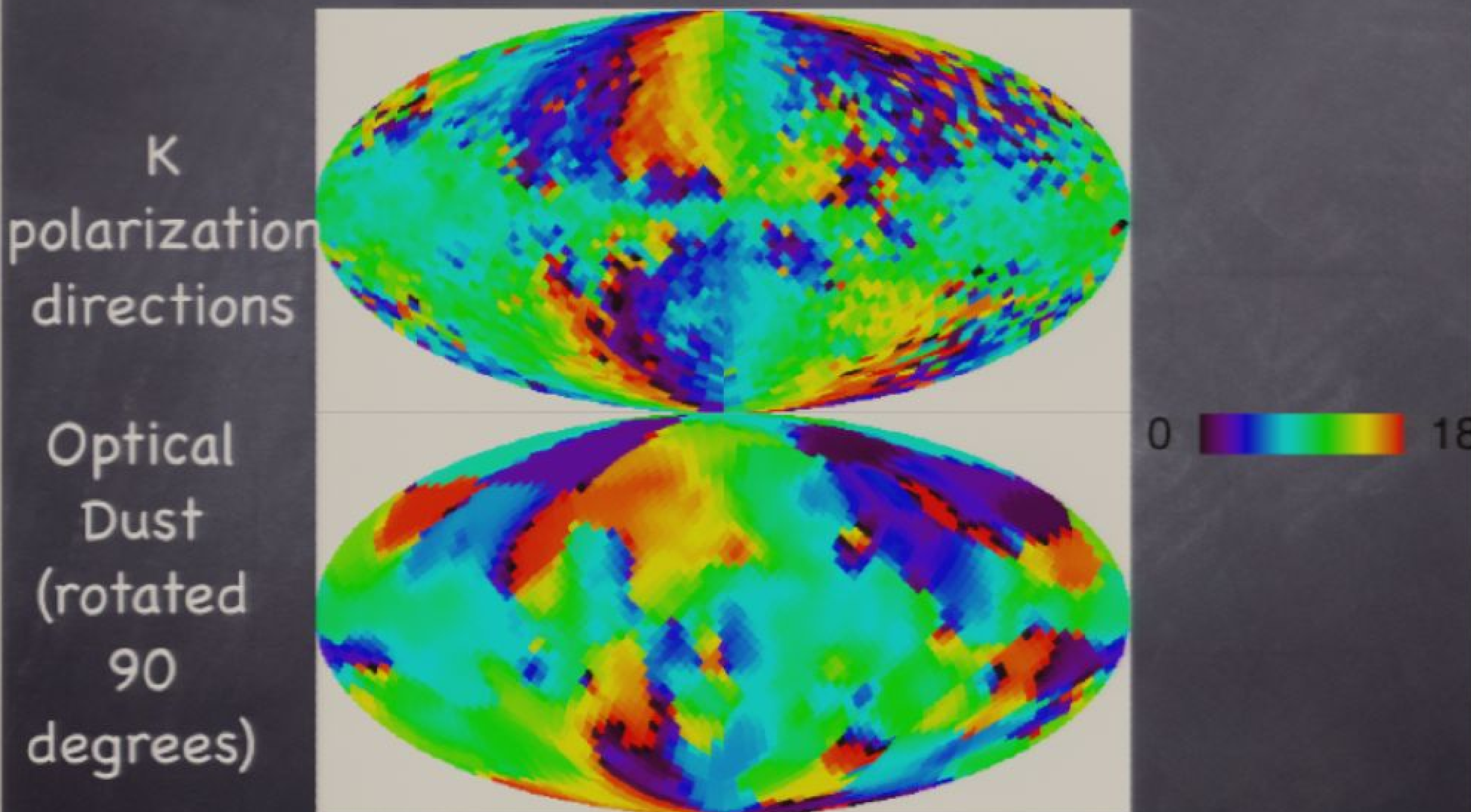
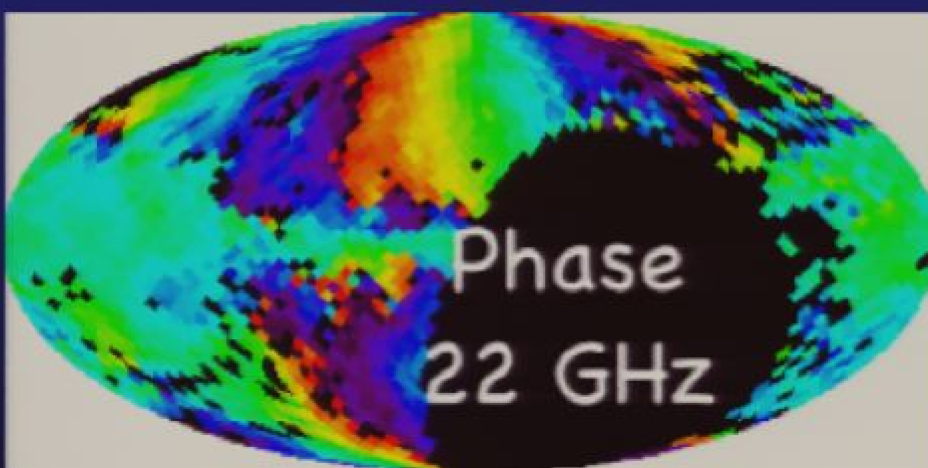


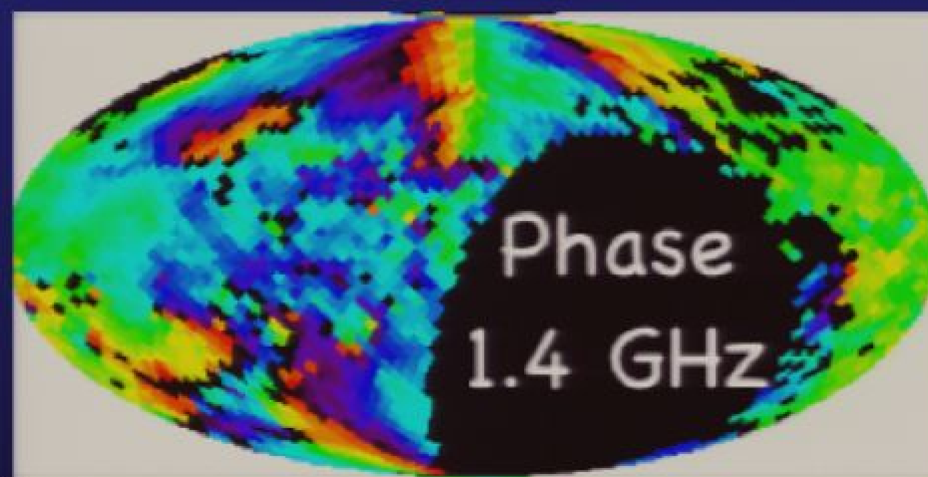
Faraday rotation

Different handed polarizations propagate at different speeds

$$\Delta\theta \propto 1/\nu^2 \int \mathrm{d}r n_e B_p \approx 420^\circ / \nu^2$$

DRAO survey





From rotation measures should be able to test if galactic field is symmetric. *(in progress...)*

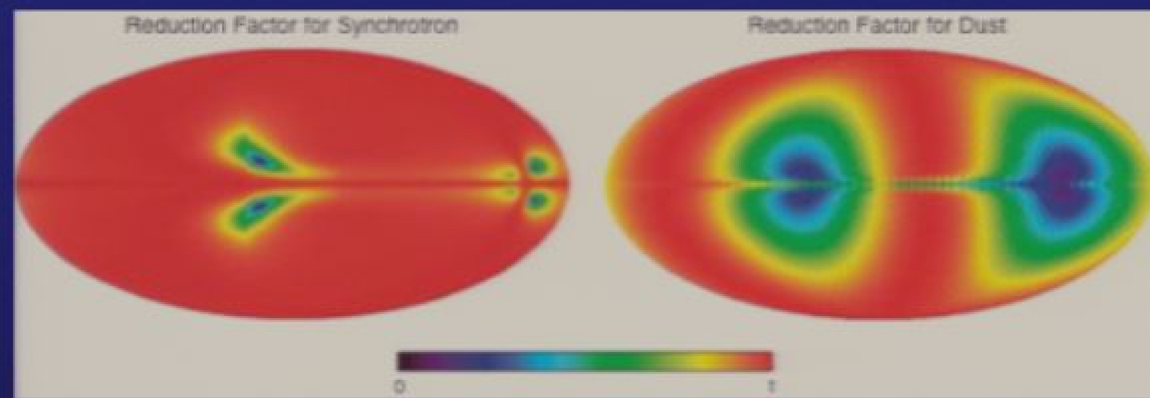
Is it all coherent?

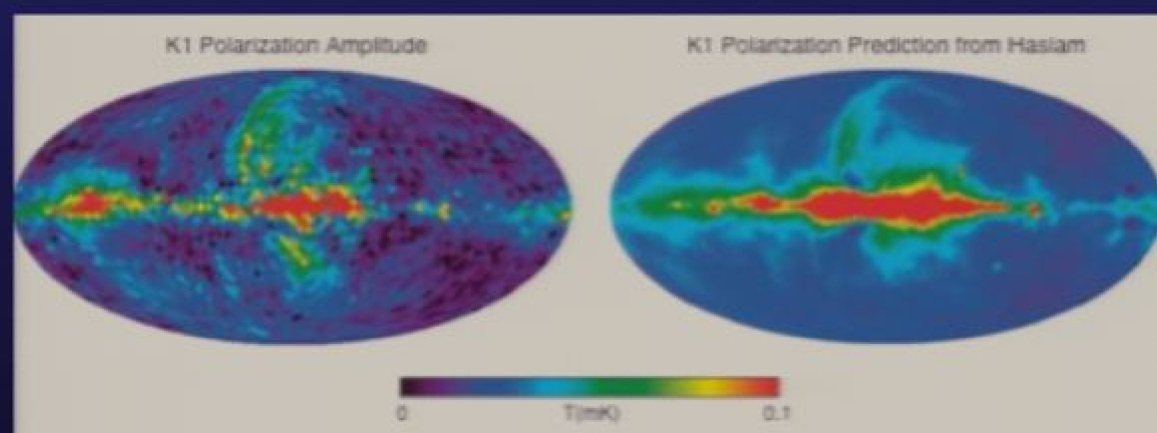
- Can predict polarized K-band signal if perfectly coherent

$$P(\hat{n}) = \Pi_s g_{sync} I(\hat{n})$$

- Incoherent field reduces net polarization
- Need 50% reduction to fit Haslam data:

  Must be large amount of small-scale turbulent field





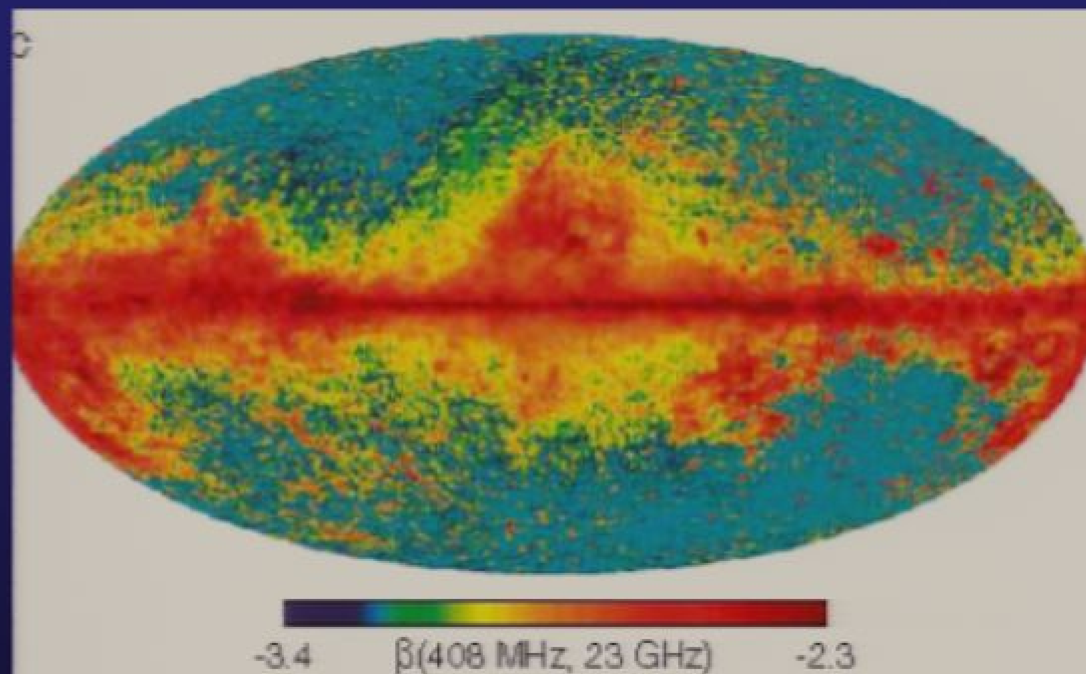
$$g_{sync}(\hat{n}) = \frac{\sqrt{Q^2(\hat{n}) + U^2(\hat{n})}}{\Pi_s I(\hat{n})}$$

Tracking down the electrons

- Spatial variation of synchrotron spectral index tells us about electron injection and diffusion
- Index is *still* a source of uncertainty, due to possible spinning dust confusion

-->Polarization helps!

-->A single index (β=-3.3) fits the WMAP 3yr pol data well, away from plane



Bennett et al 2003 (WMAP1)

What new astrophysics can we learn?

WMAP in conjunction with radio surveys and optical starlight:

- What is the coherent field?
  - Polarization directions and rotation measures (RMs) between WMAP and lower frequency surveys
- What is the turbulent field?
  - fractional polarization.
  - starlight correlation.
  - Is it connected to star-forming regions
- Where are the electrons injected and with what energy distribution?
  - synchrotron spectral index measurements
- How do they cool and diffuse?
- How much do dust grains align with B-field?
- **Is there any emission from spinning dust?
  - combining temperature and polarization measurements at low frequency

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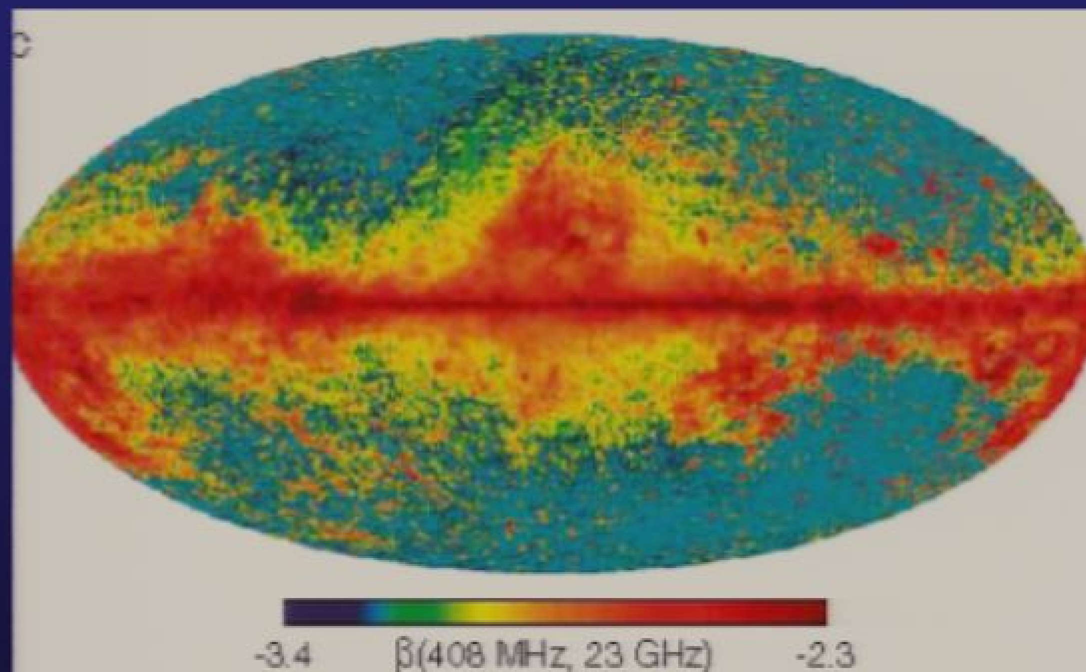

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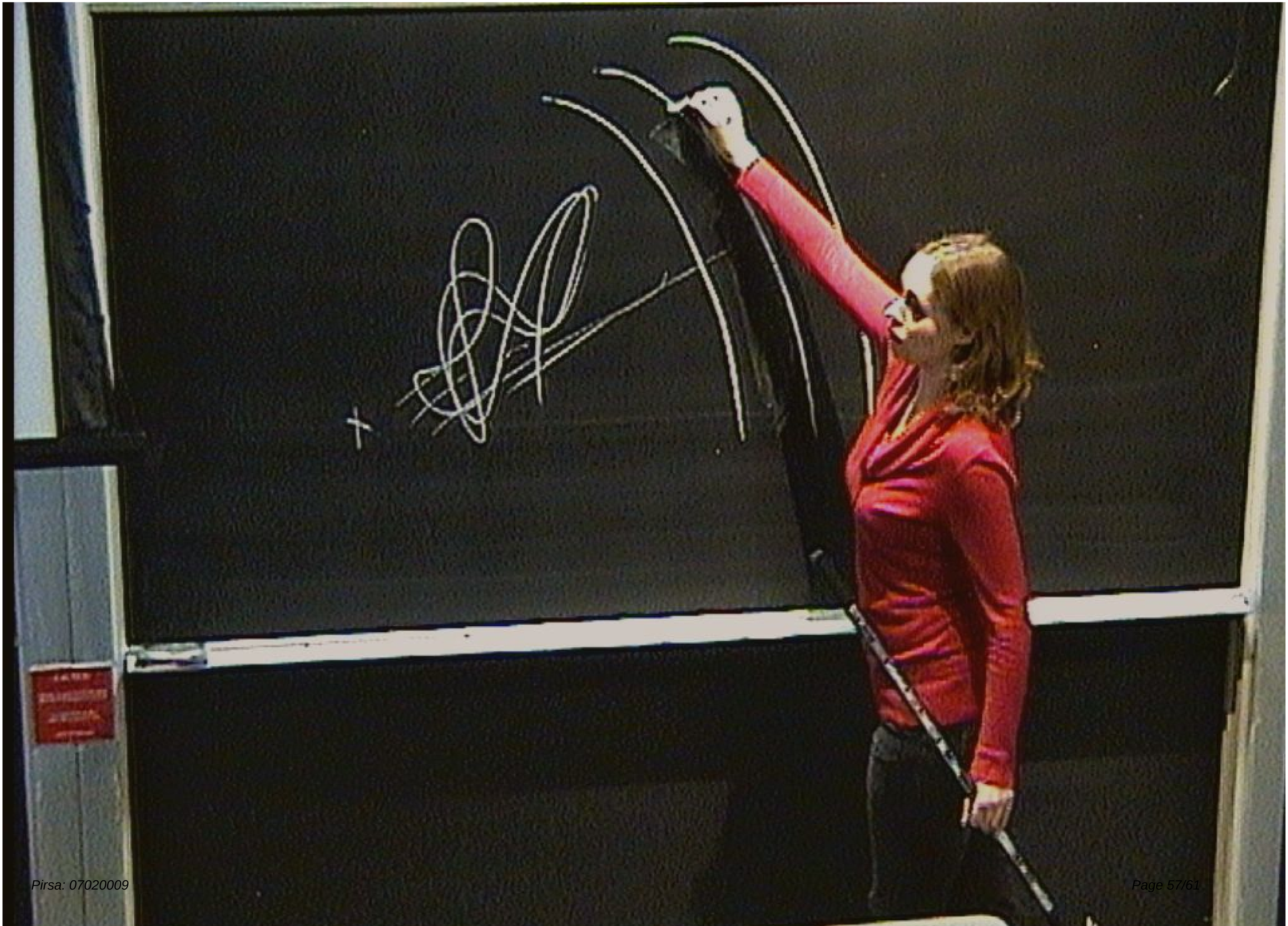
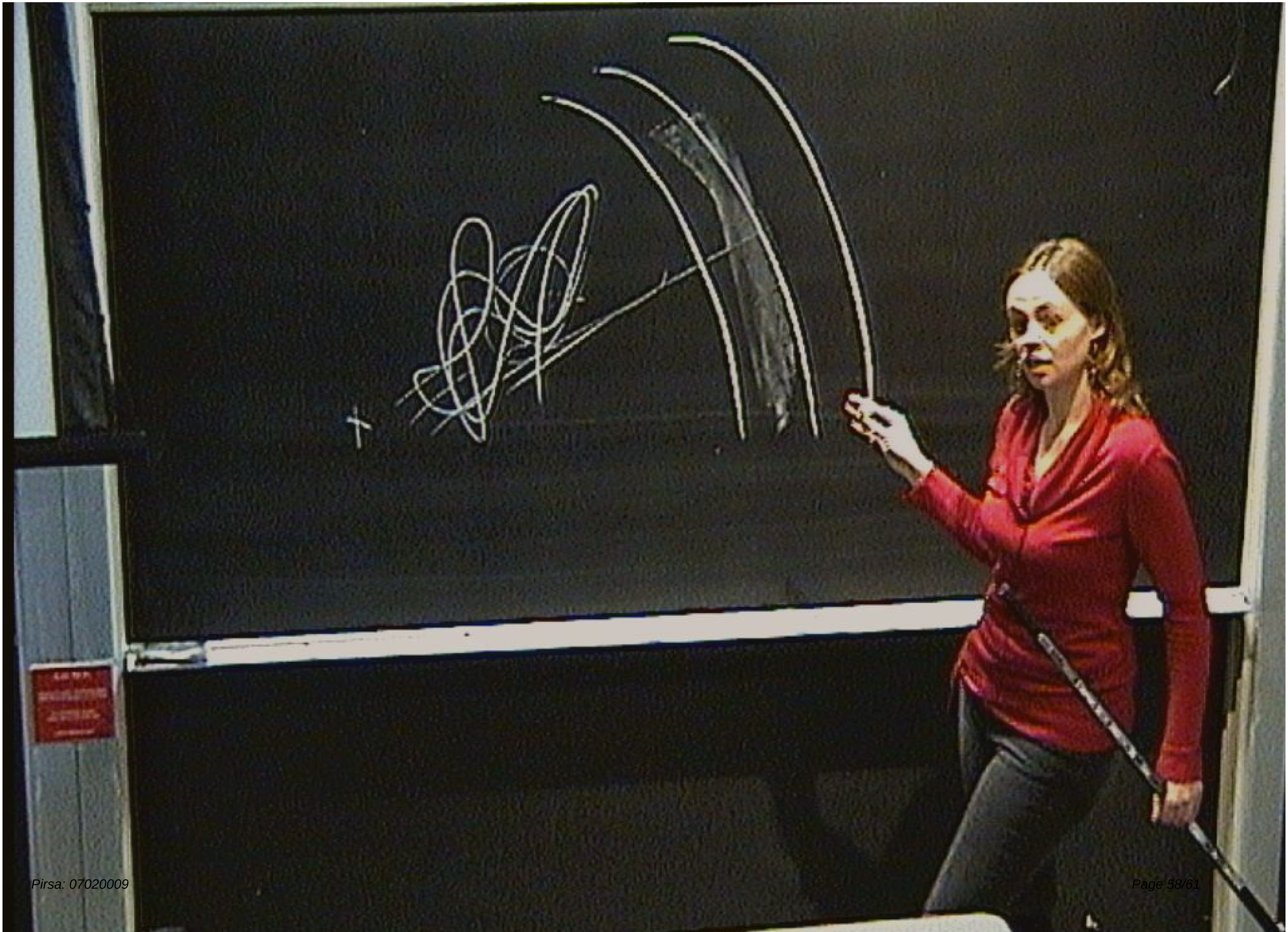
How will we apply our knowledge?

- Model informs us on the simplest way to characterize polarized emission
  - spatial and frequency variation of indices
  - polarization directions and fractions
  - expect consistent integrated temp and pol?

- Identify regions with low Galactic polarization

- Understand where we can safely include lower frequency measurements





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Summary

Convincing evidence for inflation will come with a detection of primordial gravitational waves. Understanding the polarized emission from our galaxy is vital if we are to succeed in this task.

- The CMB and other cosmological datasets have so far passed tests for inflation. The polarized CMB B-mode is the next goal.
- Polarized galactic emission dominates the CMB signal at all frequencies.
- Microwave data provides a new way to measure the galactic B-field, without contamination by Faraday rotation. A partially coherent spiral model fits the data well.
- An improved understanding of the magnetic field, cosmic ray electrons and dust in the Milky Way will be crucial if we are to really test inflation.