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Interstellar Magnetic Fields

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Canada

by $q = \eta v_K / c_s$, where ηv_K is the reduction of Keplerian velocity due to the RPG and c_s is the sound speed) also strongly affects clumping. We present local two-dimensional hybrid numerical simulations of aerodynamically coupled particles and gas in the midplane of PPDs. Magnetic fields and particle self-gravity are ignored. We explore three different RPG values appropriate for typical PPDs: $q = 0.025, 0.05$ and 0.1. For each q value, we consider four different particle size distributions ranging from sub-millimeter to meter sizes and run simulations

Results from a fully time dependent three-dimensional gasdynamic model of the interaction of the solar wind with the local interstellar medium are presented. Both subsonic and supersonic interstellar winds are considered, while the mediating effects of interstellar neutrals, magnetic fields, and cosmic rays are ignored. In accord with solar minimum observations by Ulysses, the solar wind properties are assumed to depend on heliolatitude. Two large, long-lived polar coronal holes, one in the northern and the other in the southern hemisphere, are assumed to produce a hot, low-density, high-speed wind which bounds a cooler, higher-density, low-speed ecliptic wind. The solar wind boundary conditions for the simulation are drawn directly from published Ulysses data [Phillips et al., 1995, 1996]. Results from these calculations are compared to simulations which adopt isotropic solar wind

I. INTRODUCTION

The problems discussed in this paper are motivated by the desire to understand the detailed mechanisms which trigger the formation of stars in normal spiral galaxies. Central to our discussion are two fundamental ideas: (i) spiral galactic shocks and (ii) the two-phase model of the interstellar medium. Within this context, we concentrate on the roles played by gravitational and thermal mechanisms. We avoid the vexing problem of the magnetic-field geometry by ignoring at the very outset the effects of the interstellar magnetic field. We do this not because we feel these effects to be unimportant, but because we wish to keep the present discussion as simple as possible.

a) Basic Concepts

Why do we care?

SKA Key Science Project: **Cosmic Magnetism**

Understanding the Universe is impossible without understanding magnetic fields. They fill intracluster and interstellar space, affect the evolution of galaxies and galaxy clusters, contribute significantly to the total pressure of the interstellar gas, are essential for the onset of star formation, and control the density and distribution of cosmic rays in the interstellar medium.

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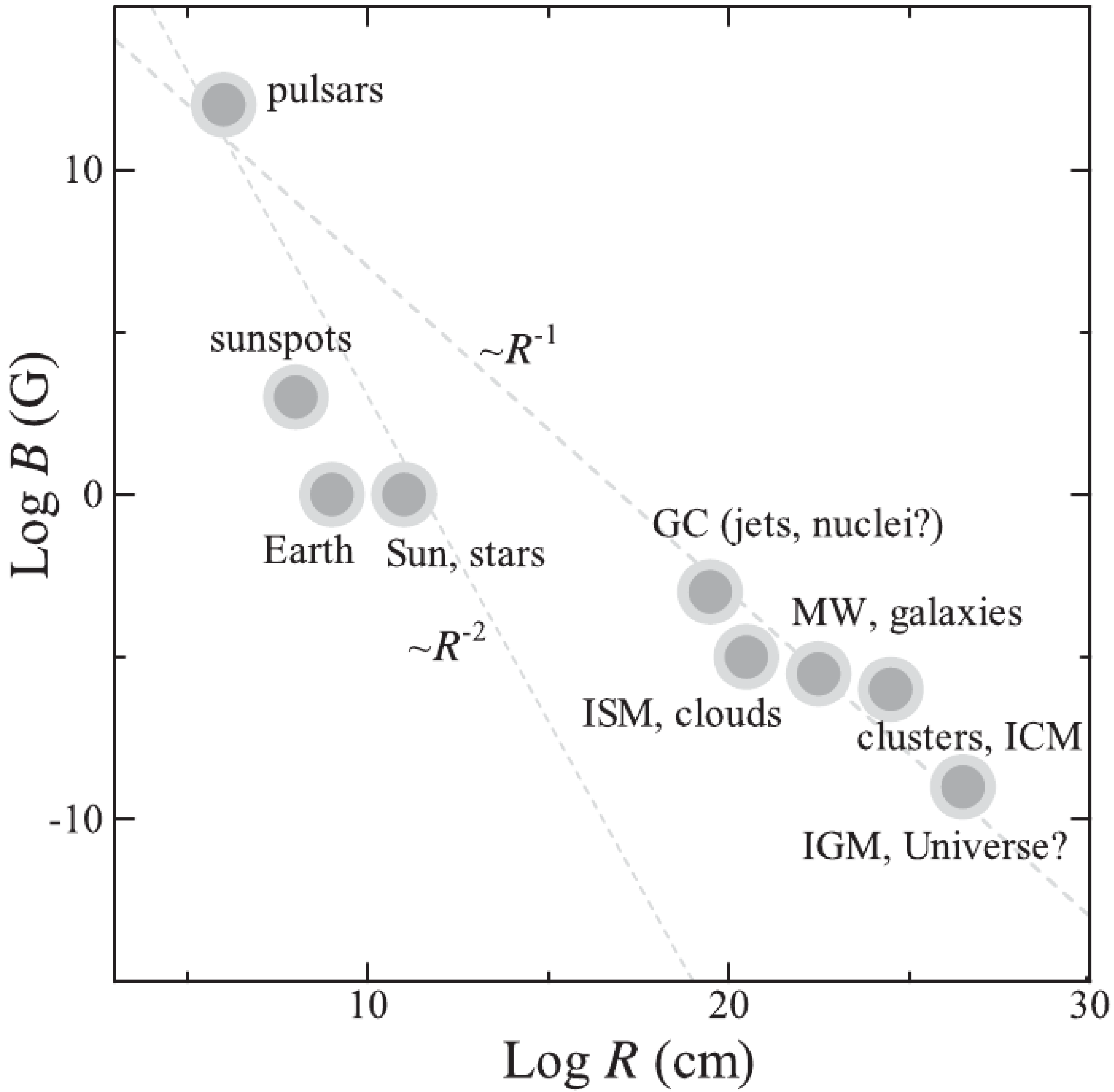
- Magnetic fields can be found everywhere.
- Magnetic fields affect everything.
- Magnetism is one of Nature's fundamental forces, BUT its origin and evolution in the Universe are still poorly understood.

Why do we care?



Overview

Why do we care?

Manifestation of interstellar magnetic fields.

- Starlight Polarization
- Thermal Dust Polarization
- Zeeman Splitting
- Radio Polarimetry

Interstellar Magnetic Fields

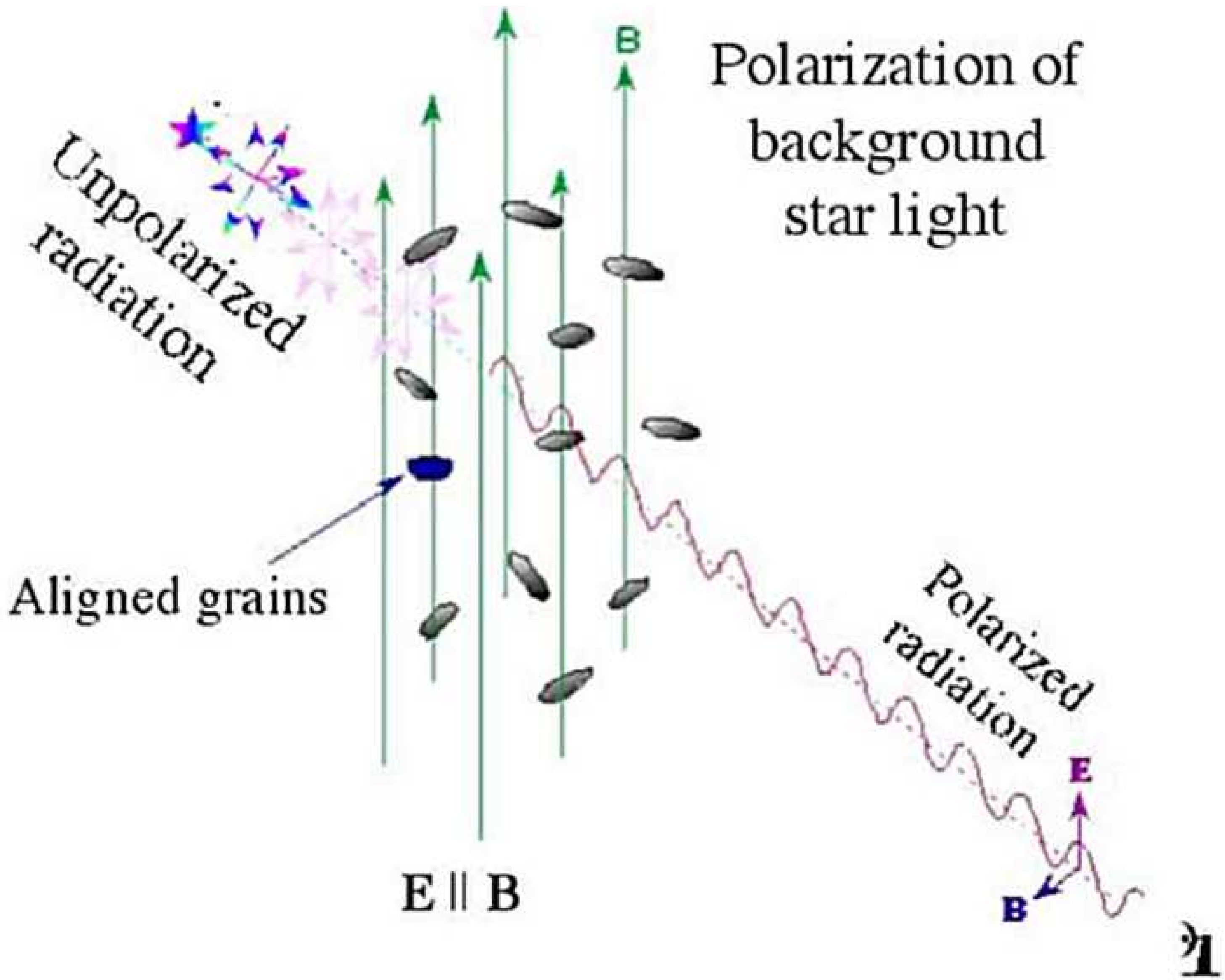
- Nearby Galaxies
- The Milky Way

Summary

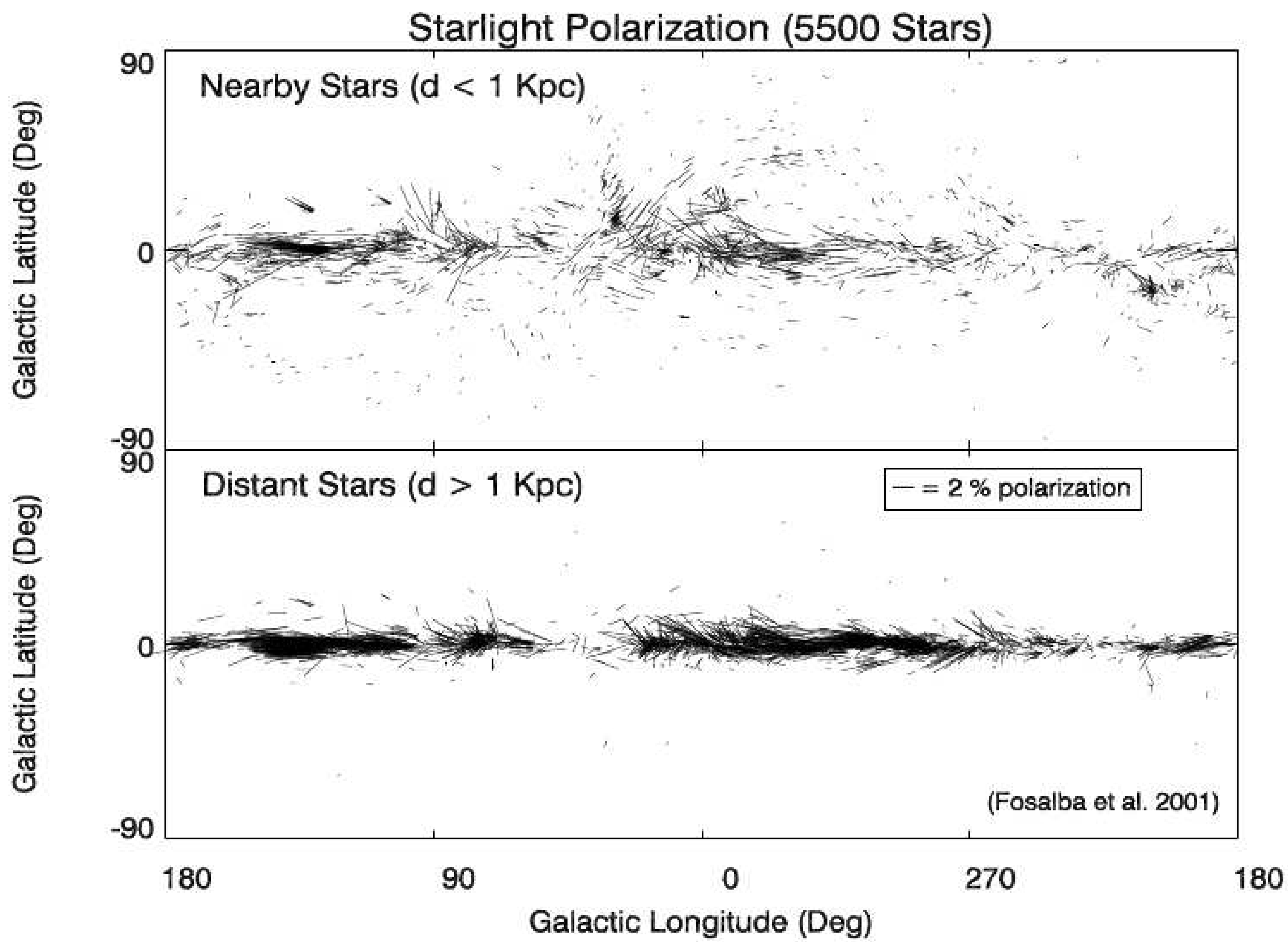
Observing Magnetic Fields

- Starlight Polarization
  - dust grains align with magnetic field lines
  - selective absorption by dust grains

Starlight Polarization



Starlight Polarization

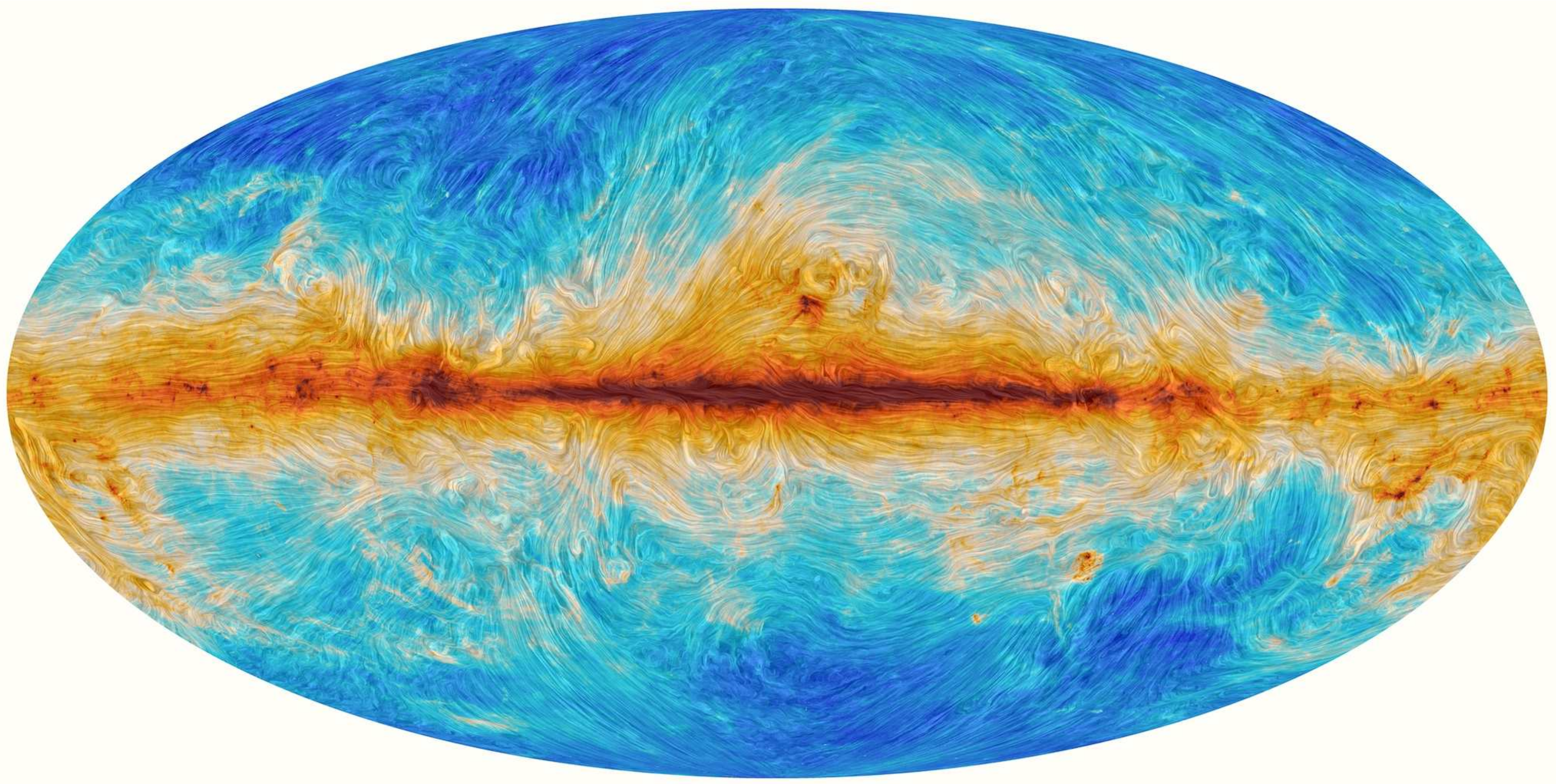


Fossalba et al., 2002

Observing Magnetic Fields

- Starlight Polarization
  - dust grains align with magnetic field lines
  - selective absorption by dust grains
- Polarization of thermal dust emission.

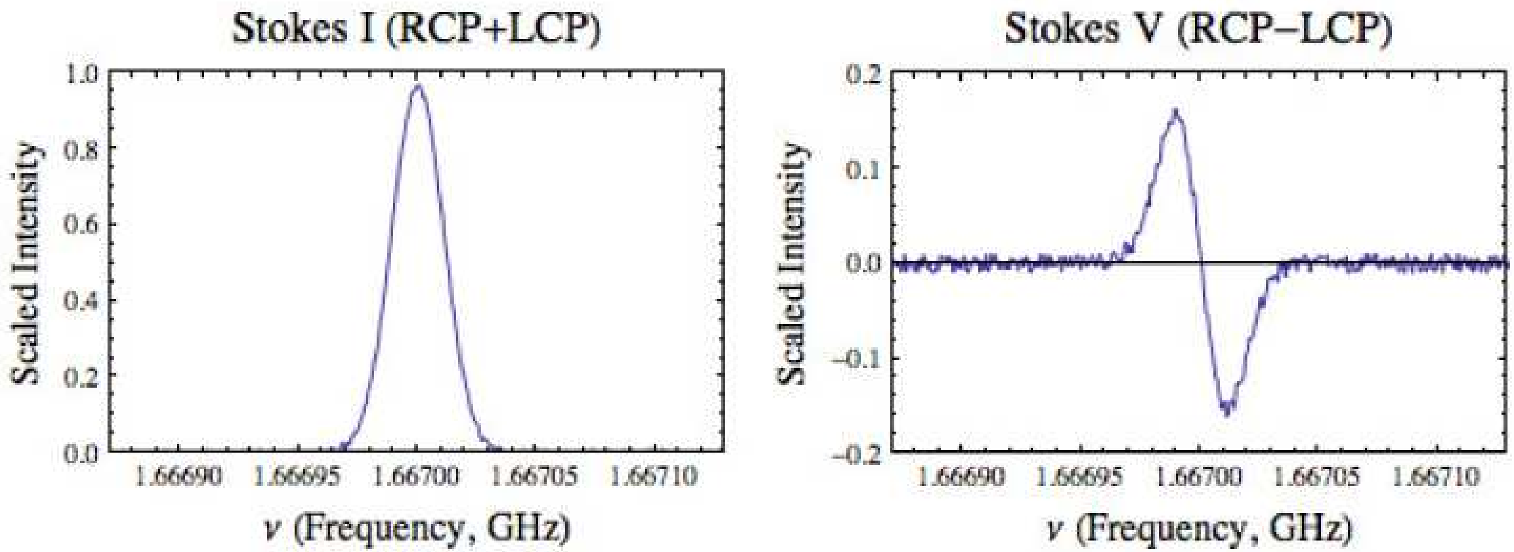
Thermal Dust Polarization



ⒸPlanck Collaboration

Observing Magnetic Fields

- Starlight Polarization
  - dust grains align with magnetic field lines
  - selective absorption by dust grains
- Polarization of thermal dust emission.
- Zeeman Splitting
  - strong magnetic fields are splitting emission lines in subcomponents
  - distance between these components depends on magnetic field strength



$$\Delta\nu \sim \mathrm{B}_{\|}$$

- observes neutral component $\Rightarrow$ complement to synchrotron and RM studies which probe the ionized component of the ISM
- can be observed in absorption and emission
- targets: atomic clouds, molecular clouds, masers
- Milky Way and nearby galaxies

Observing Magnetic Fields

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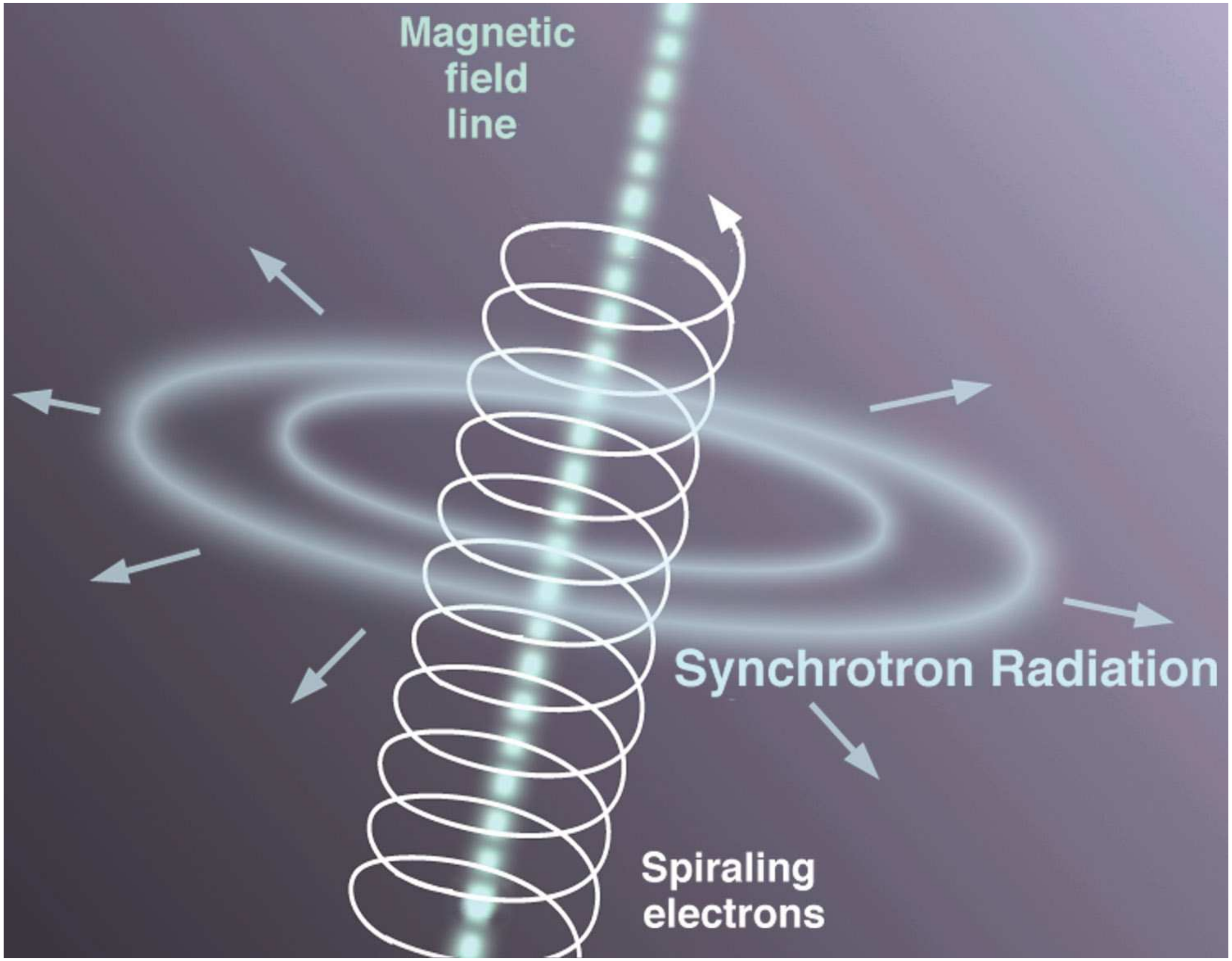
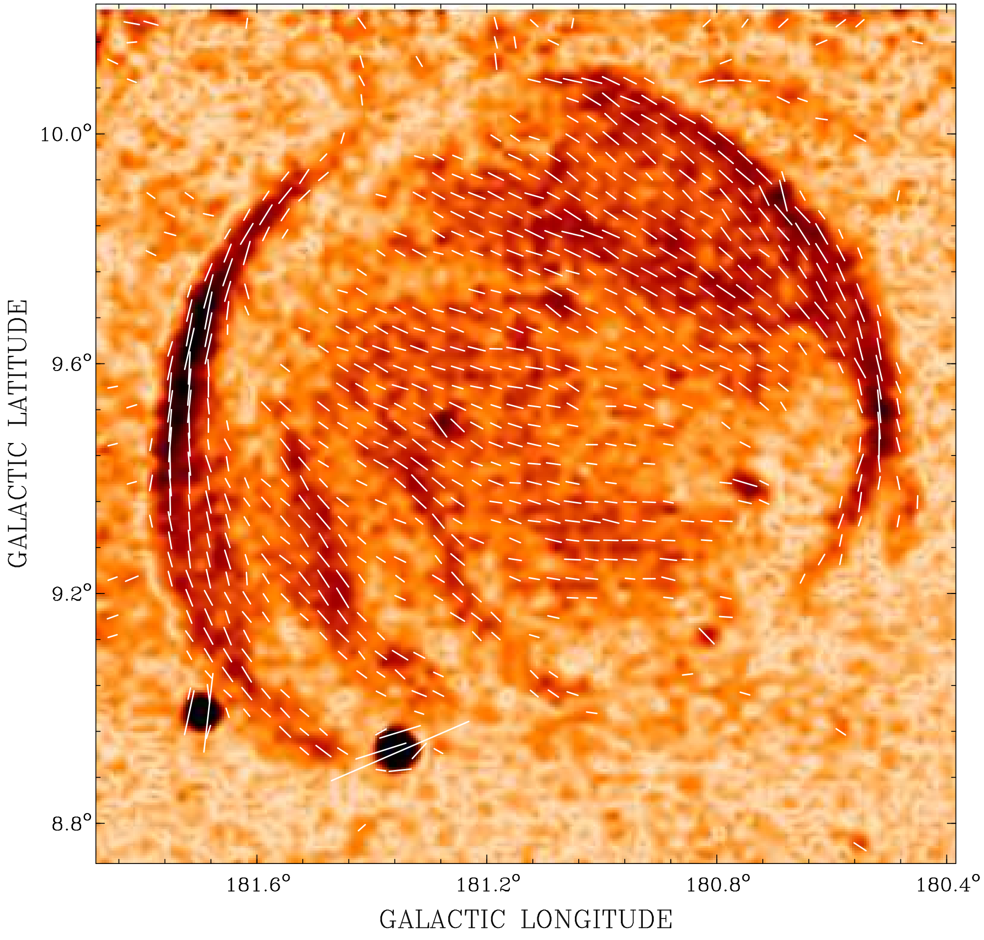
- Radio Polarimetry
  - Synchrotron emission
  - Faraday rotation

Synchrotron Radiation

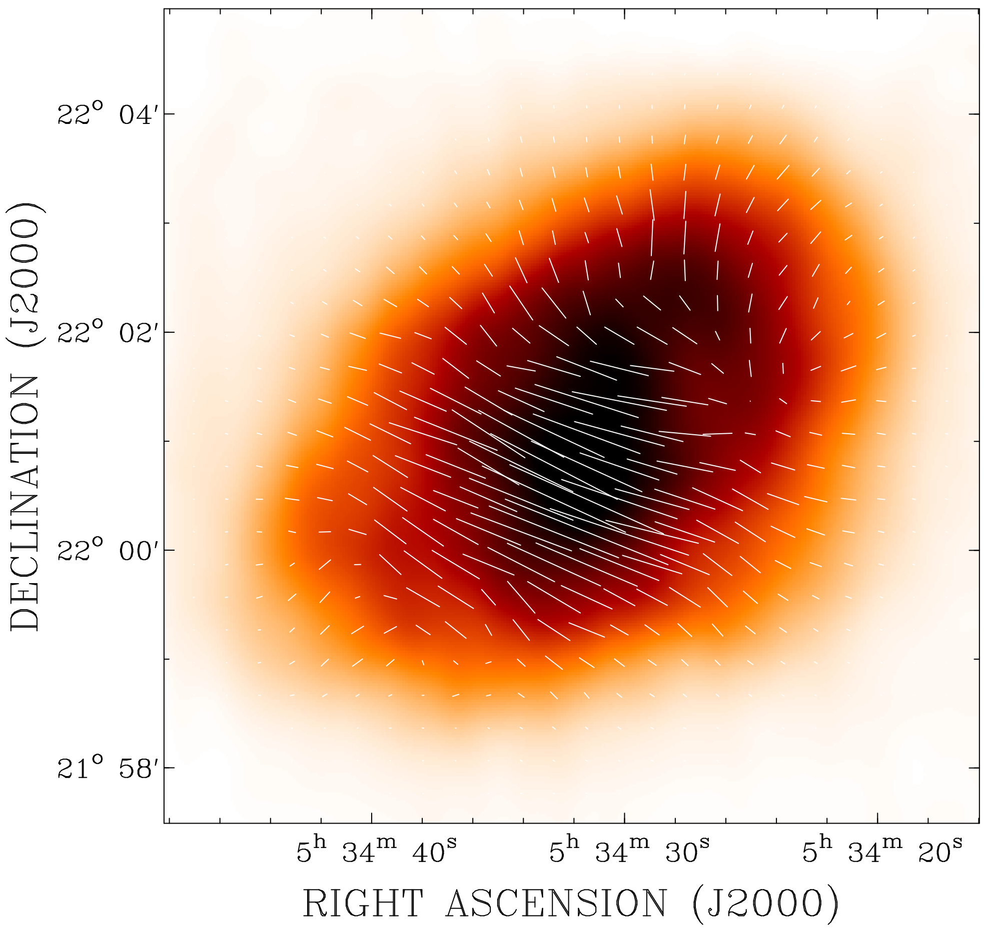


Detecting Magnetic Fields

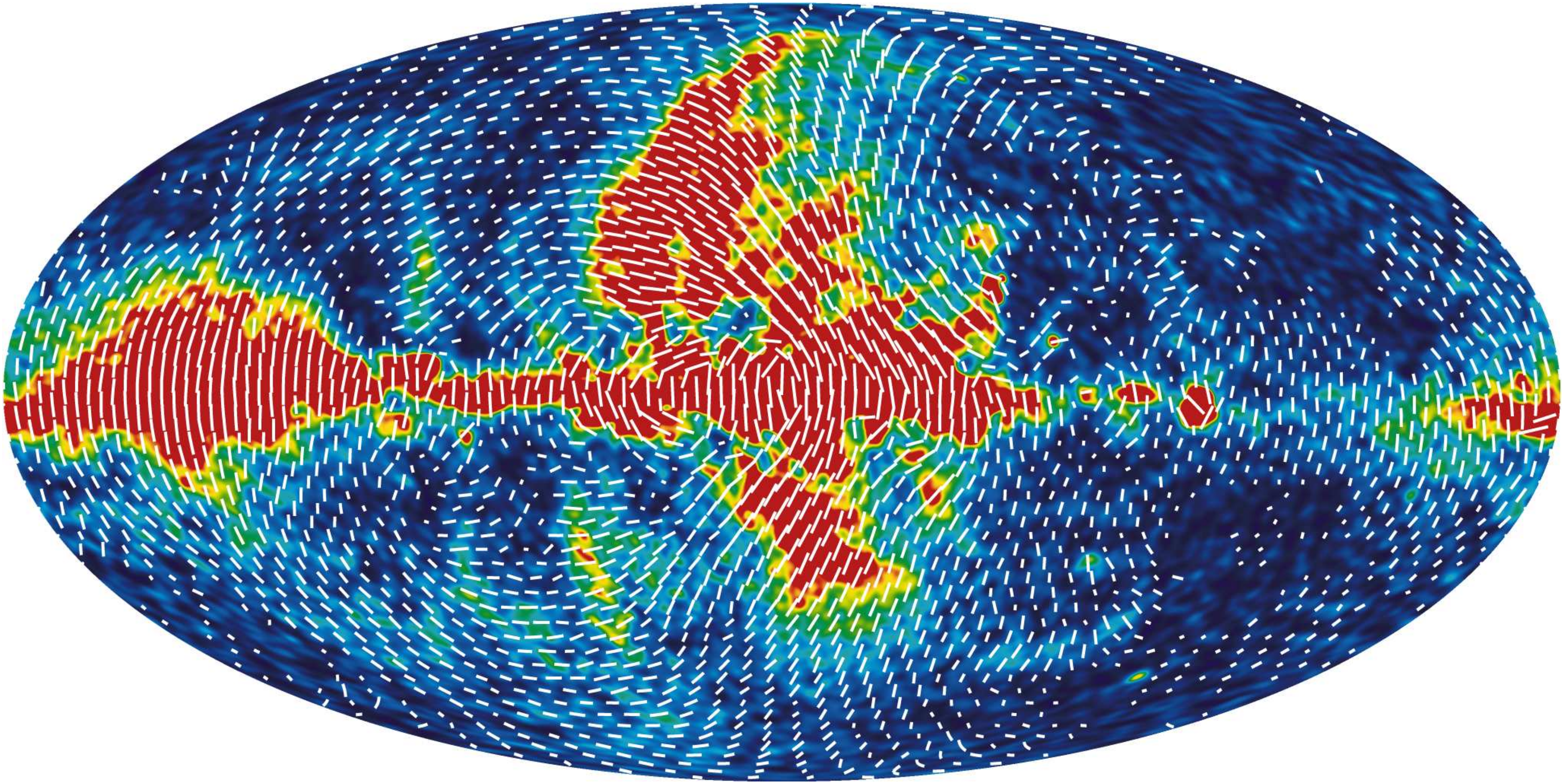
Kothes et al., 2017



Reich et al., 2002

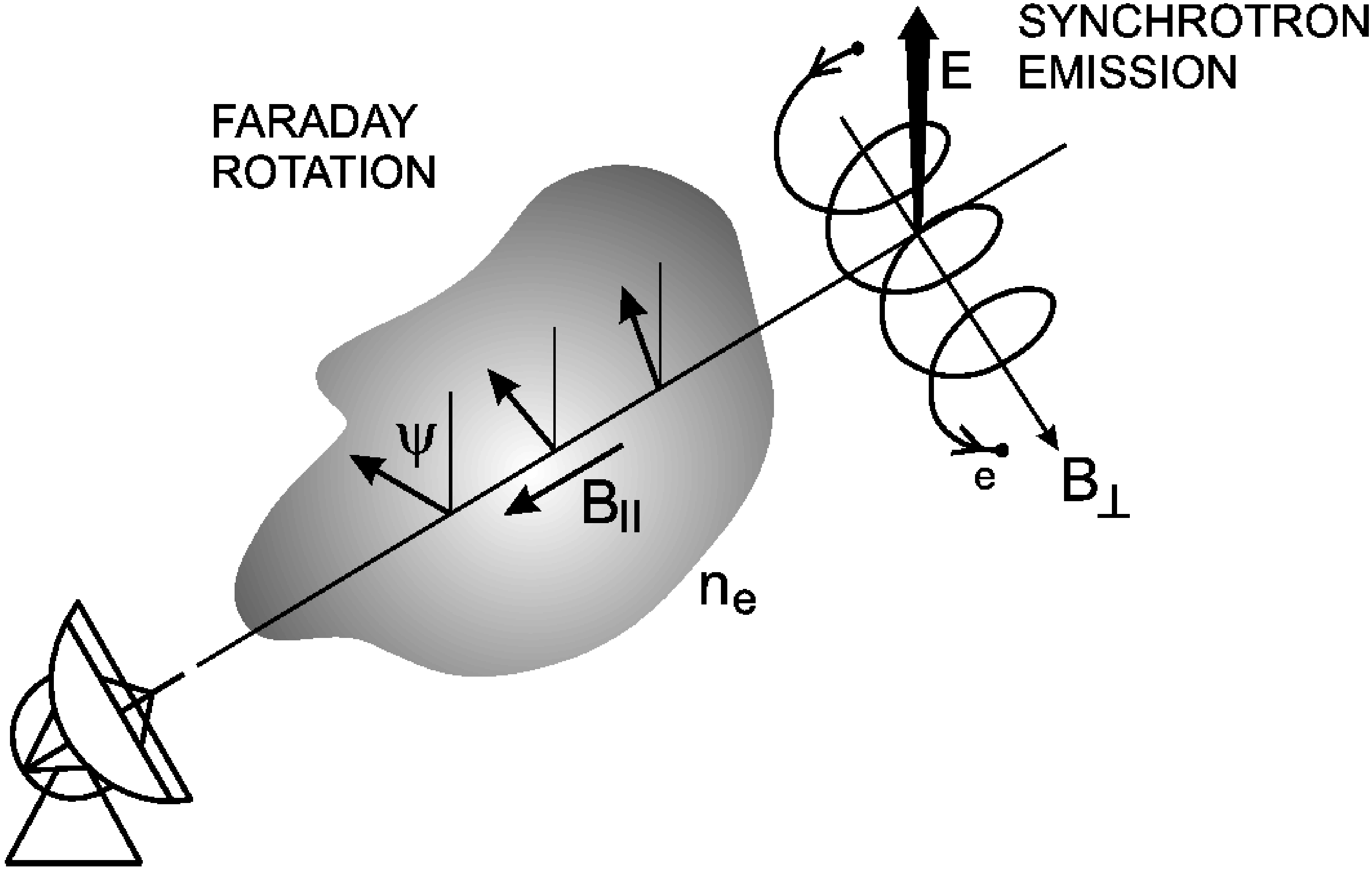


WMAP at 23 GHz



Ruiz-Granados et al, 2010

Mapping Magnetic Fields



Faraday Rotation

$$\Delta\phi = \frac{e^3\lambda^2}{2\pi m^2 c^4} \int_s n_e \, \vec{B} \cdot d\vec{s} = RM \, \lambda^2$$

Rotation Measure: $RM \propto \int_s B_{||} n_e ds$

$\Delta\phi$: angle rotation

e: electron charge

m: electron mass

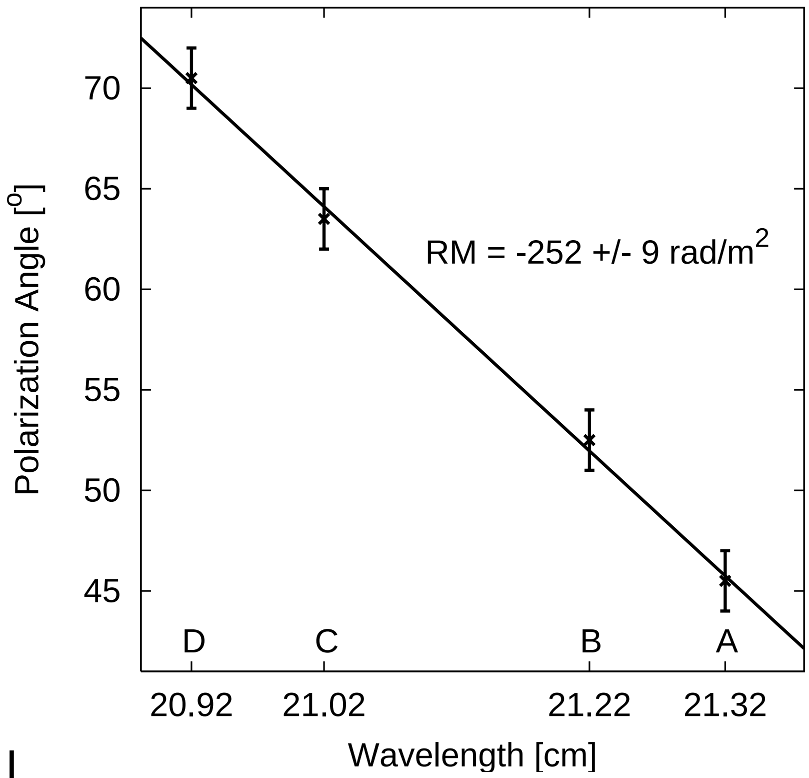
c: vacuum speed of light

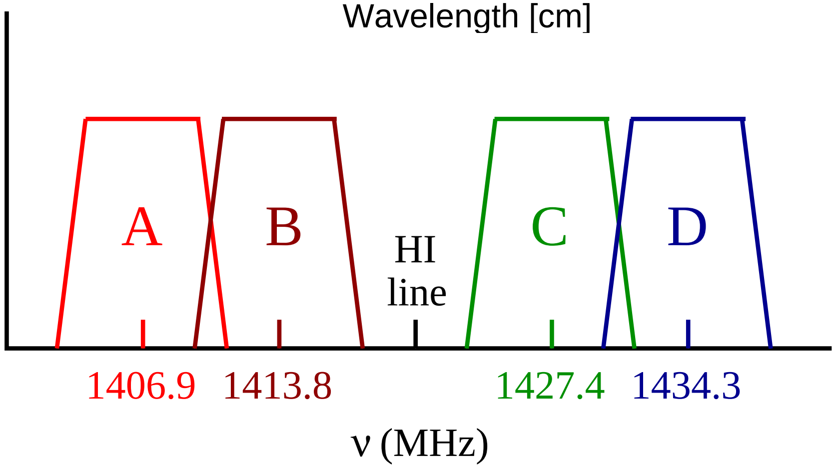
s: pathlength along the line of sight

n_e: electron density

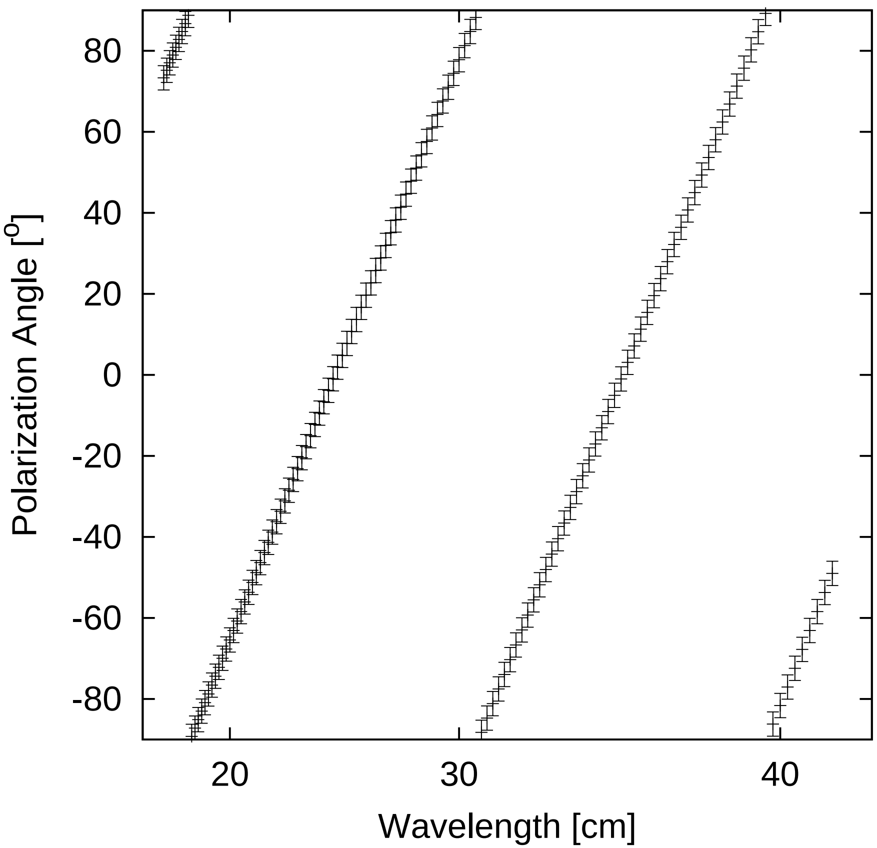
λ: wavelength

Faraday Rotation





Rotation Measure Synthesis



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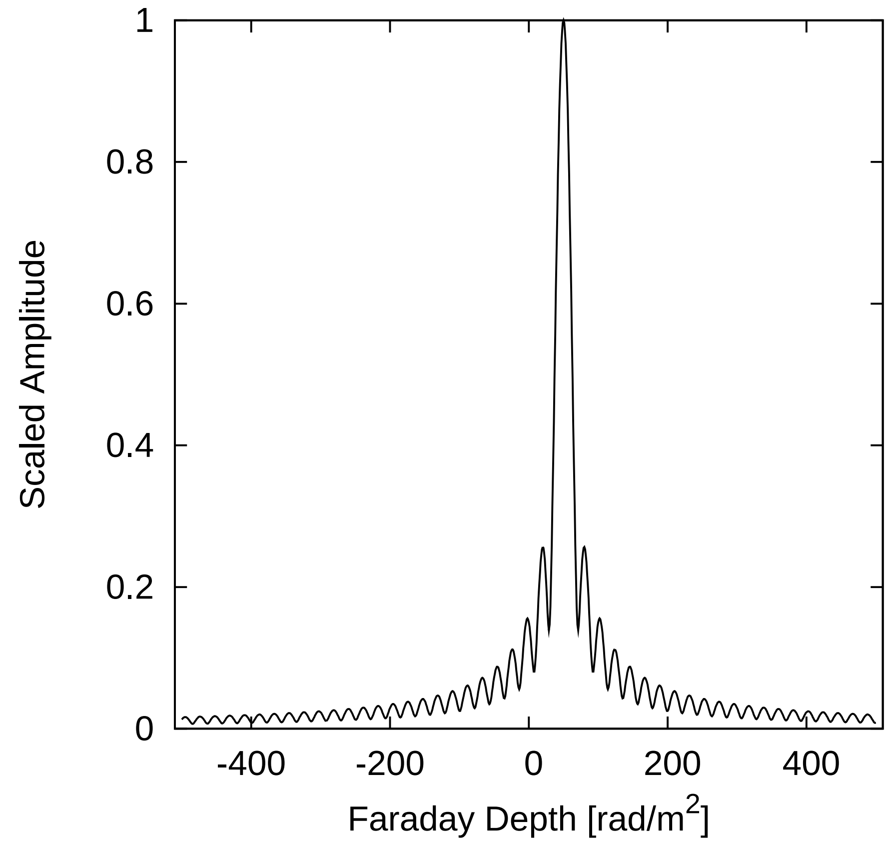


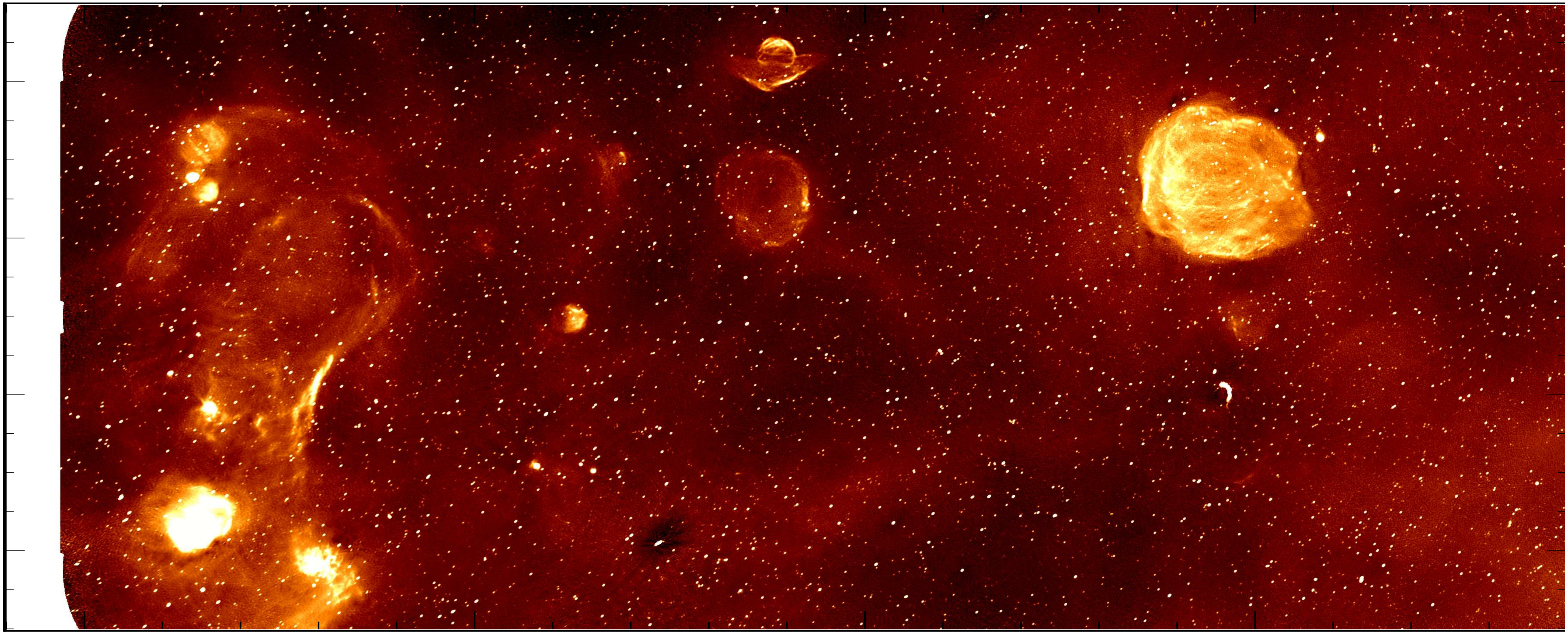
Typical value found for the Outer Galaxy:
$RM \approx -200$ rad/m^2

- 1420 MHz (21 cm): $\Delta\phi \approx 500^\circ$
- 4850 MHz (6 cm): $\Delta\phi \approx 40^\circ$
- 32 GHz (9 mm): $\Delta\phi \approx 1^\circ$

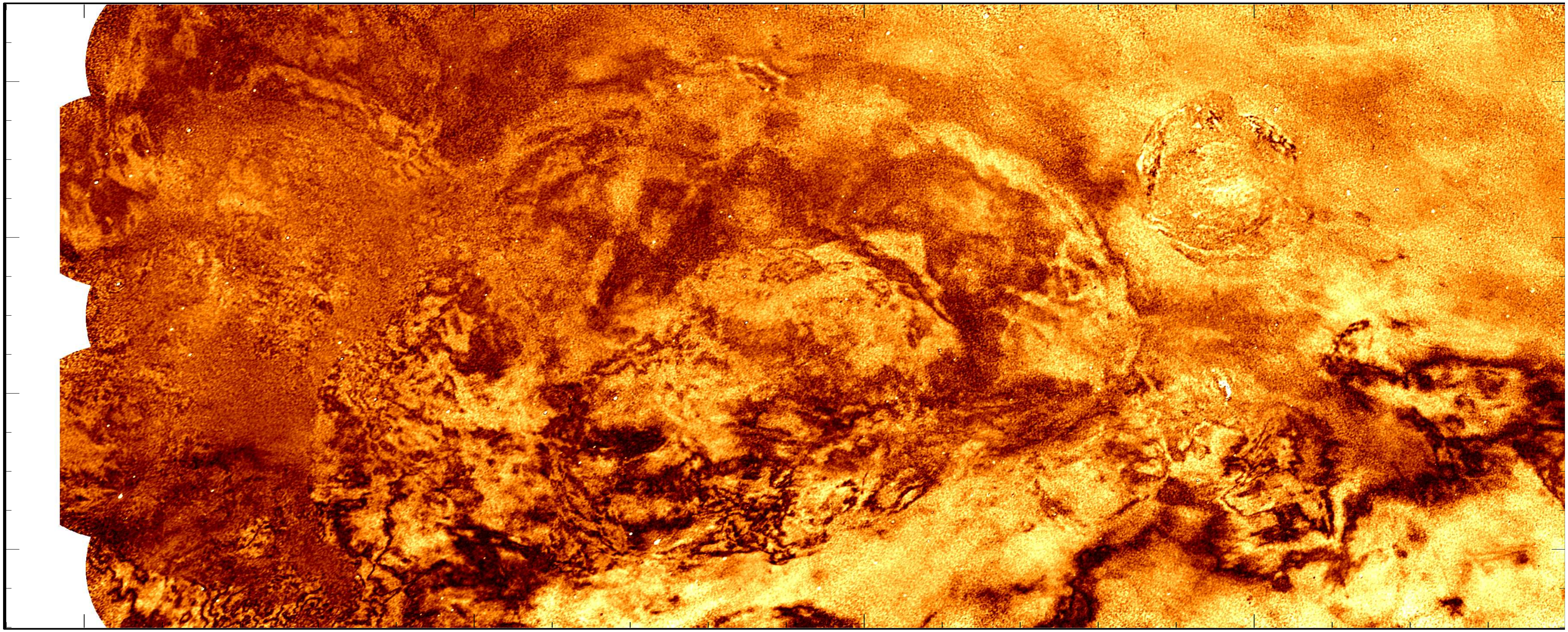
Typical value found for the Inner Galaxy:
$RM \approx \pm$ several 100s rad/m^2

Towards the Galactic Centre:
$RM \gtrsim 1000$ rad/m^2 have been found.

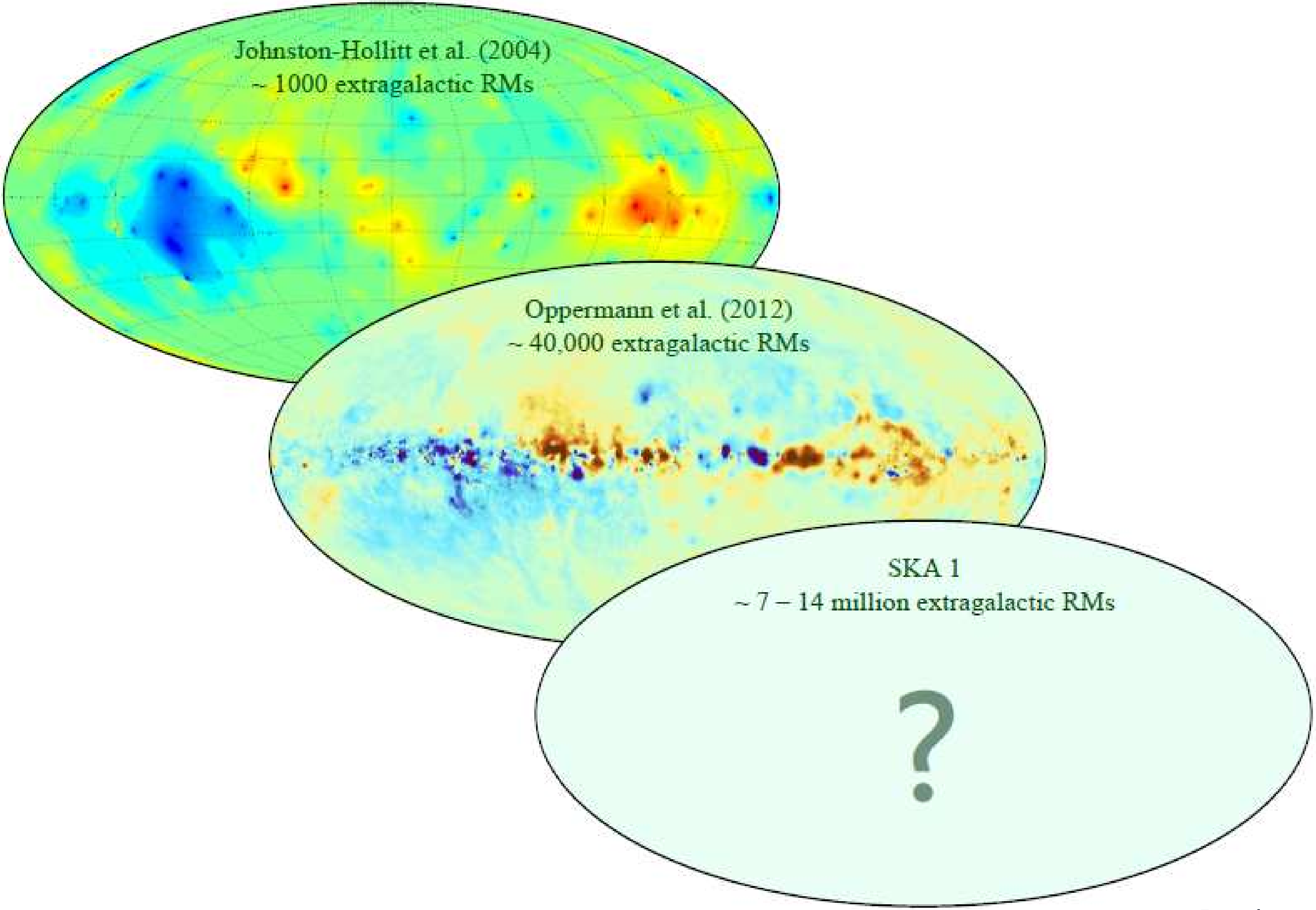
Widefield Polarimetry

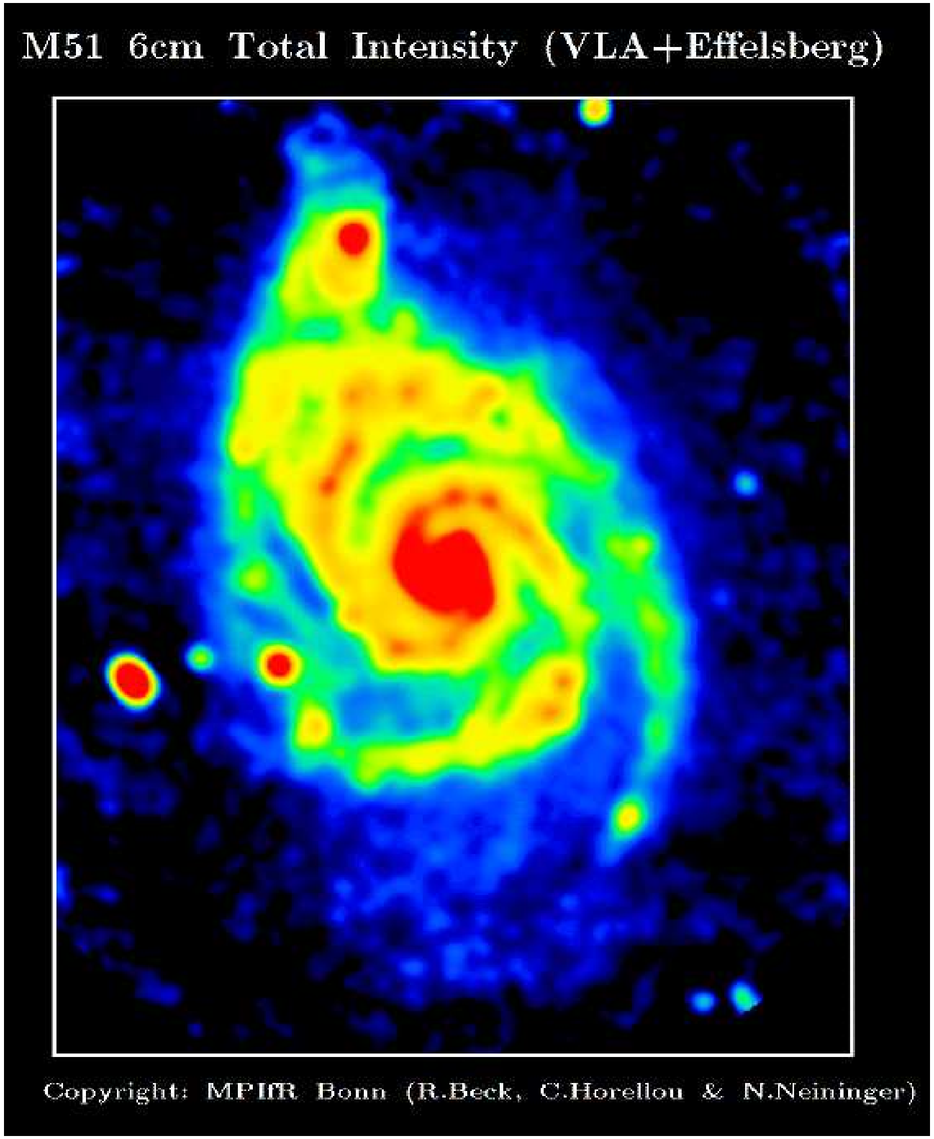


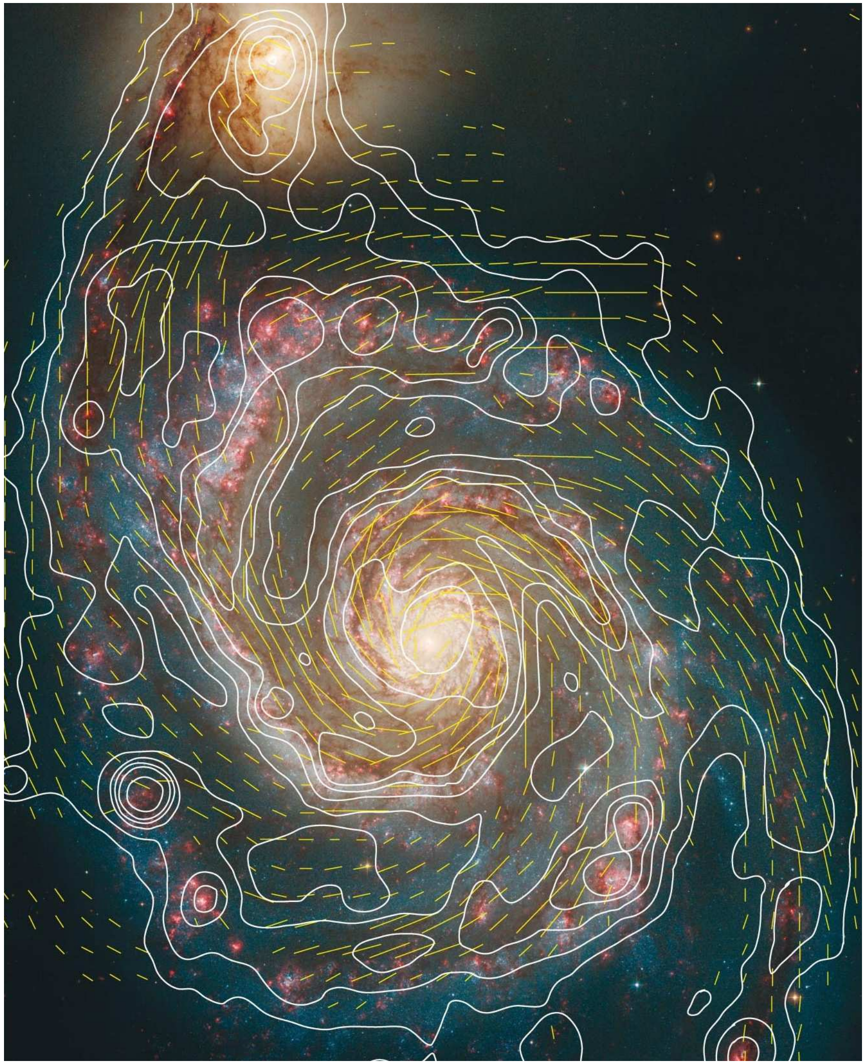
Widefield Polarimetry



Mapping Rotation Measures

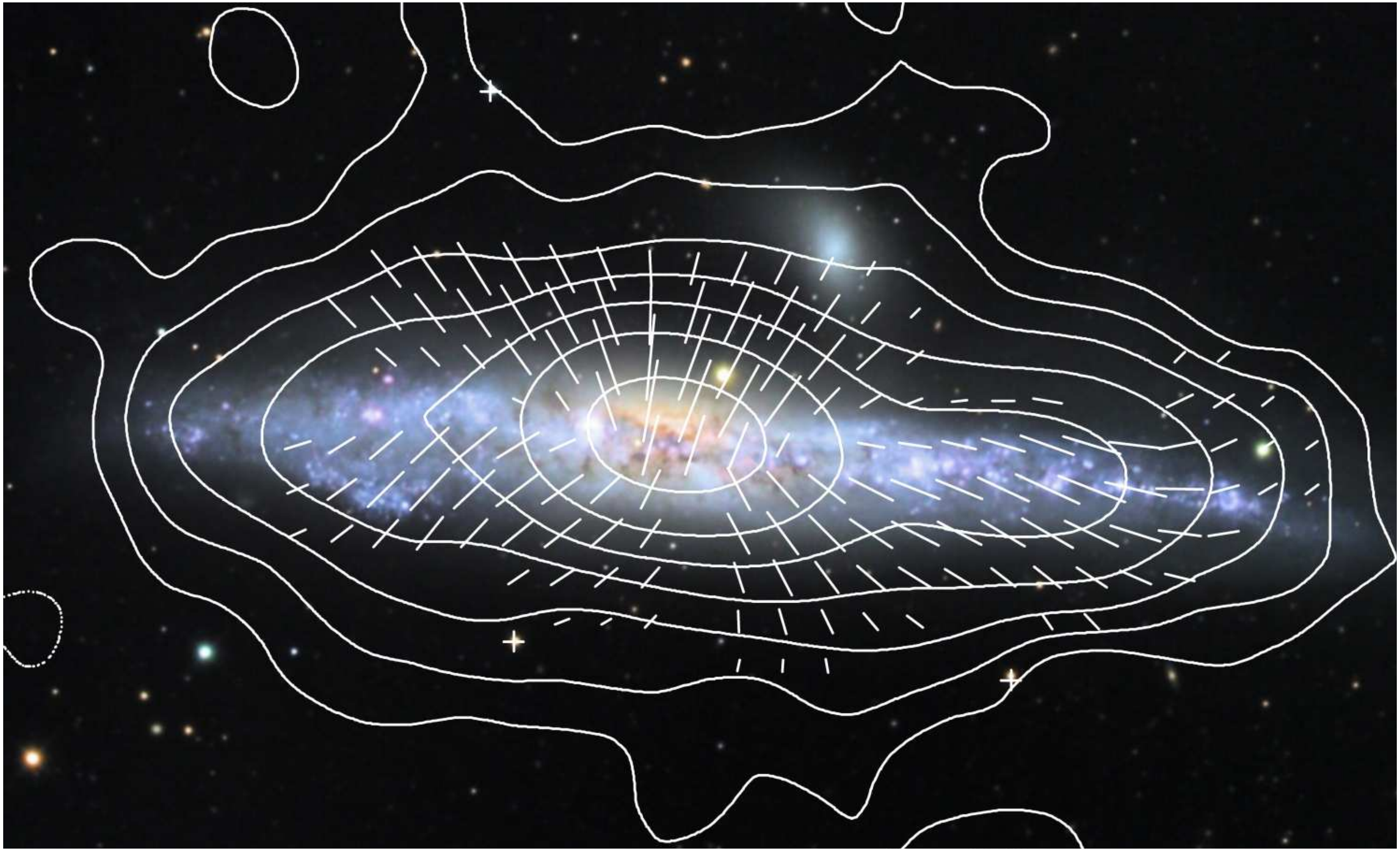






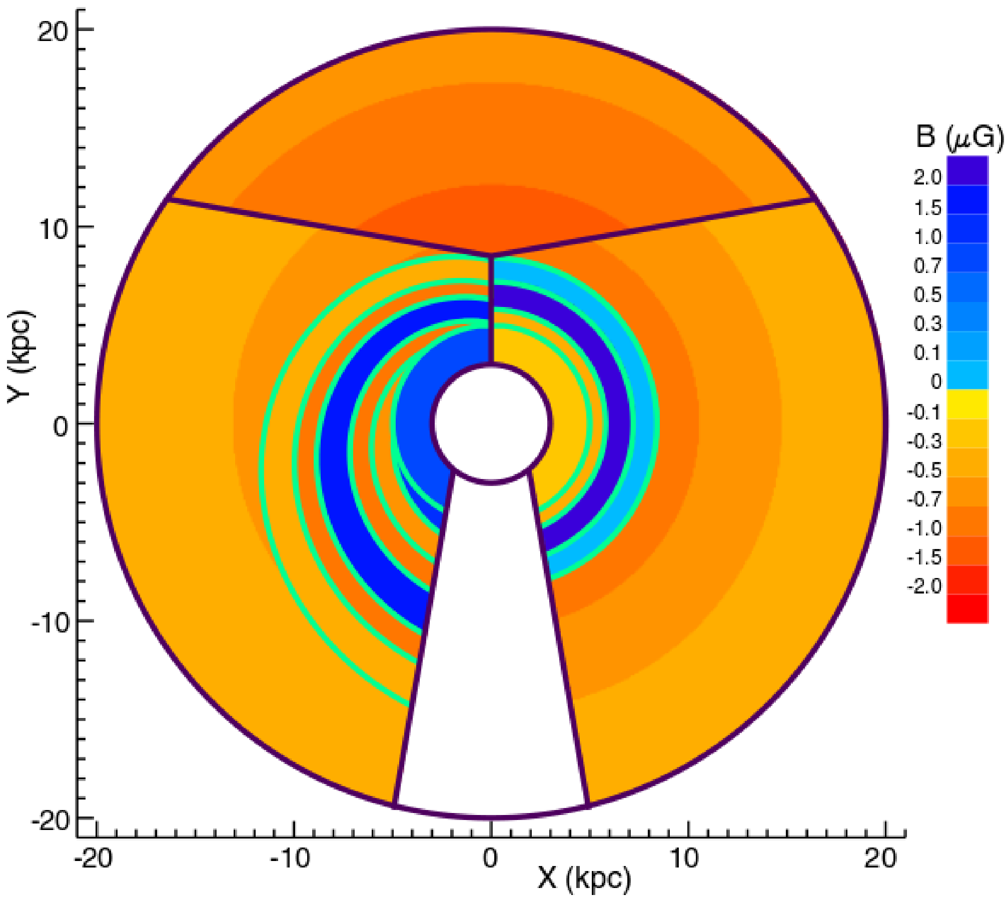
Fletcher et al., 2011

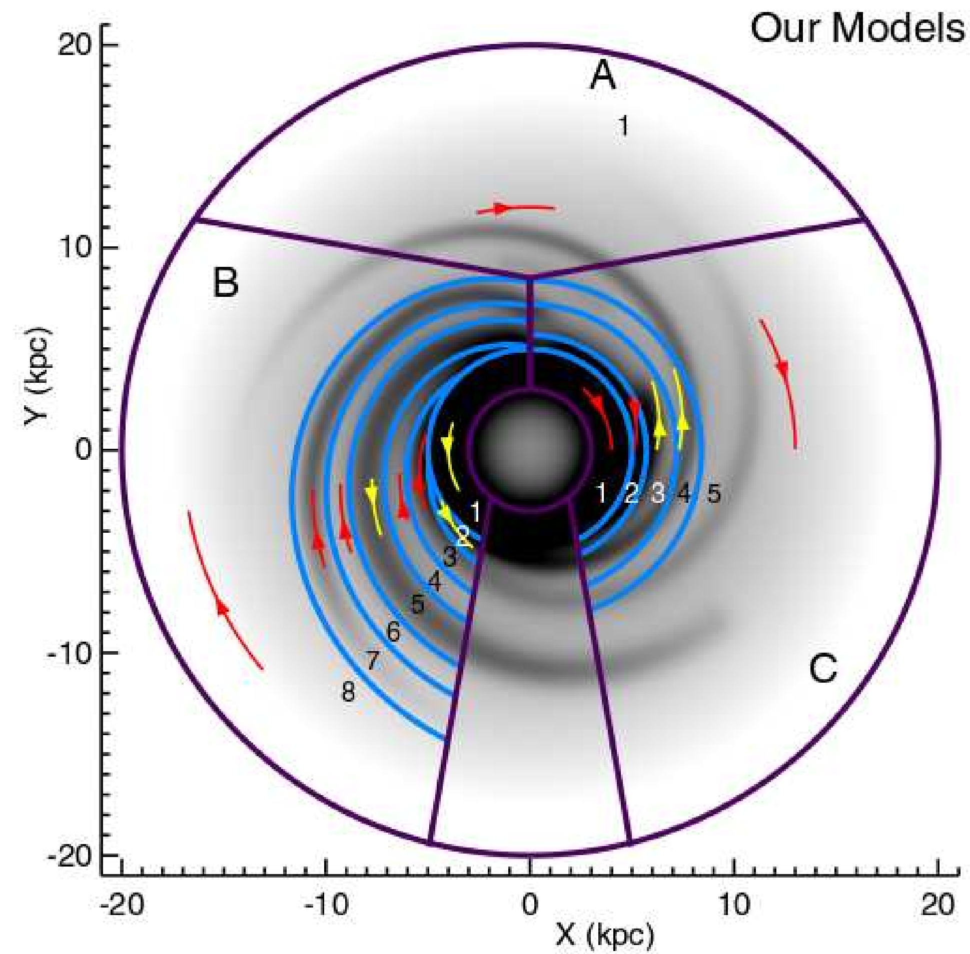
Nearby Galaxies



Krause, 2009

The Milky Way Galaxy

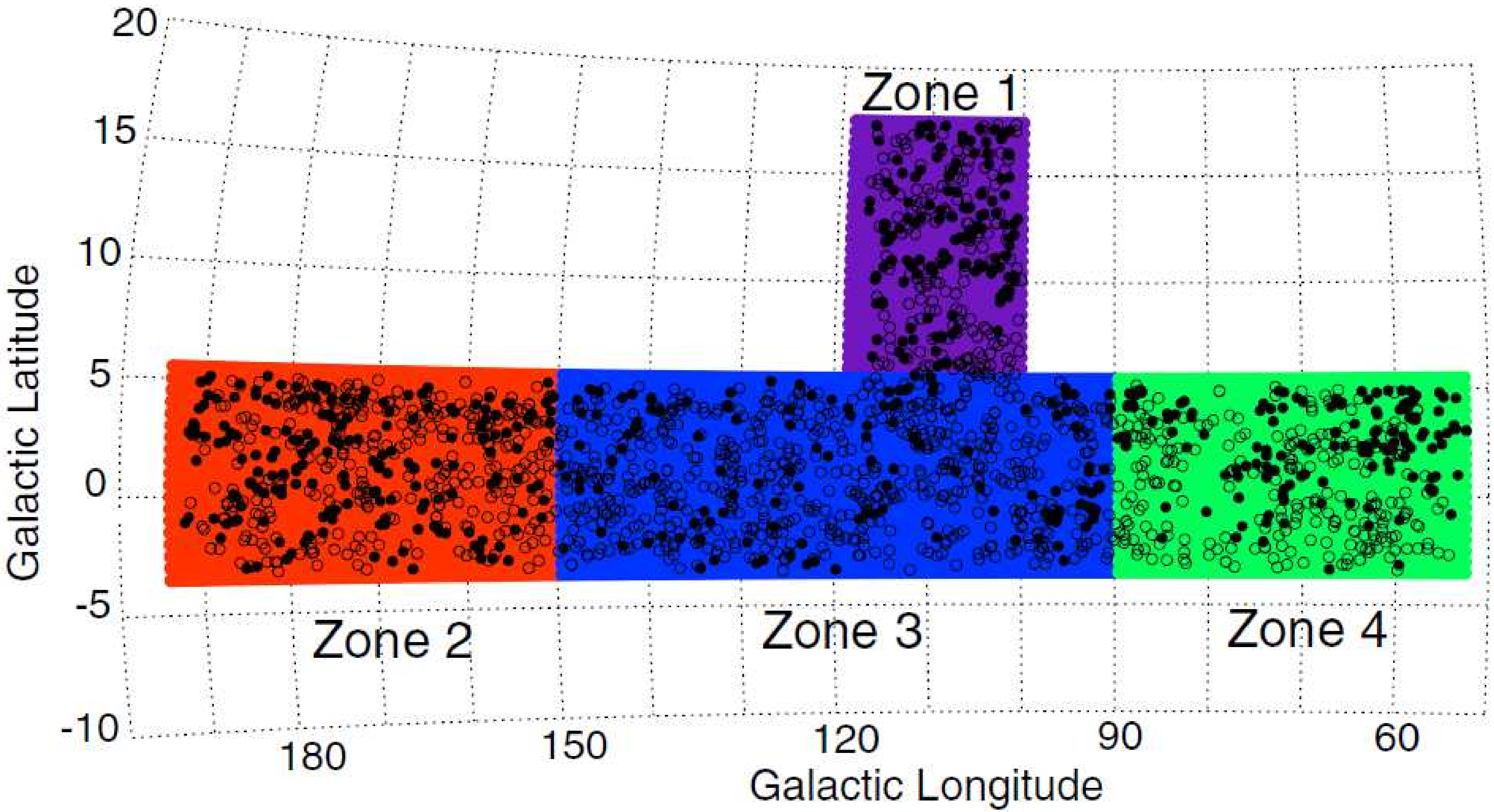




Van Eck et al., 2011 ⇒ Sun et al, 2008 ⇒ Jansson & Farrar, 2012

RMs in the CGPS

Foster et al., 2013



The Warm Neutral Medium

The MIM and WNM can be linked by two observables: rotation measure (RM) and atomic hydrogen column density (N_{HI}).

$$RM = 0.81\, B_{\|} \int n_e\, dl$$

$$N_{HI} = 1.82 \times 10^{18} \int T_B\, dv = \int n_{HI}\, dl$$

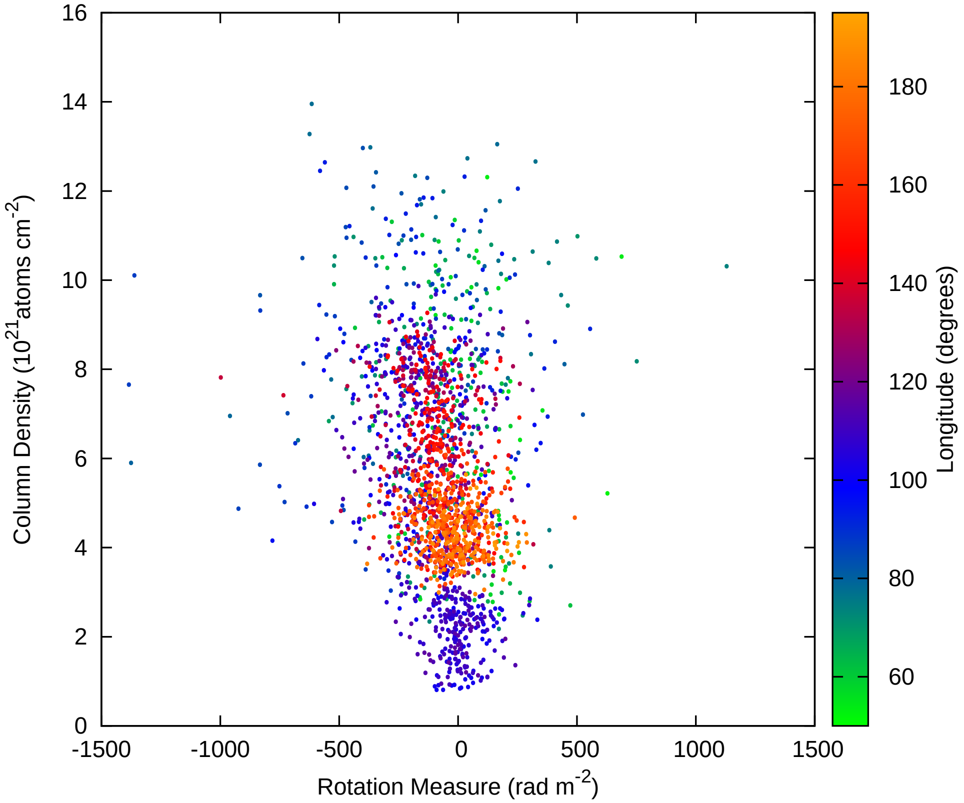
The ratio $\frac{RM}{N_{HI}}$ is then related to the ionization fraction χ_e

$$\chi_e = \frac{n_e}{n_p + n_{HI}} \simeq \frac{1}{1 + \frac{n_{HI}}{n_e}}$$

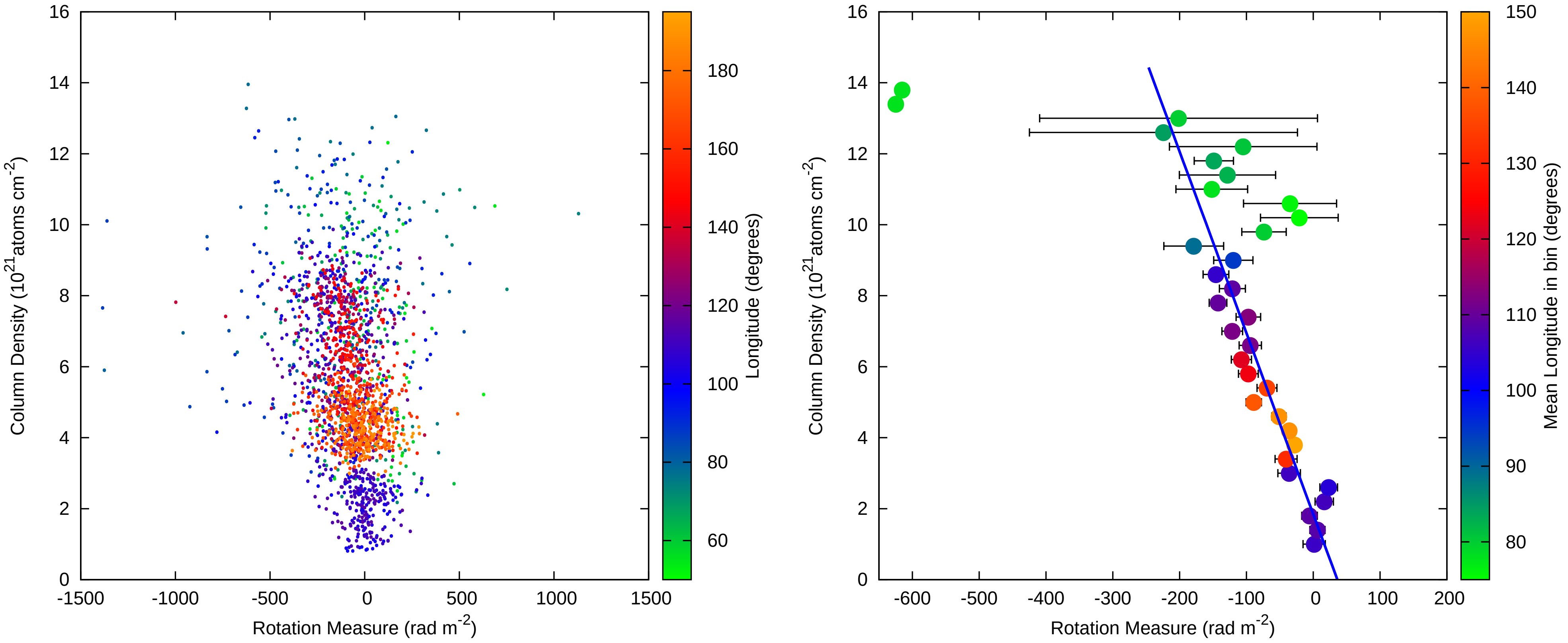
by

$$\frac{RM}{N_{HI}} \simeq 2.632 \times 10^2 B_{\|} \left(\frac{1}{\chi_e} - 1\right)^{-1}$$

RMs and N_{HI}

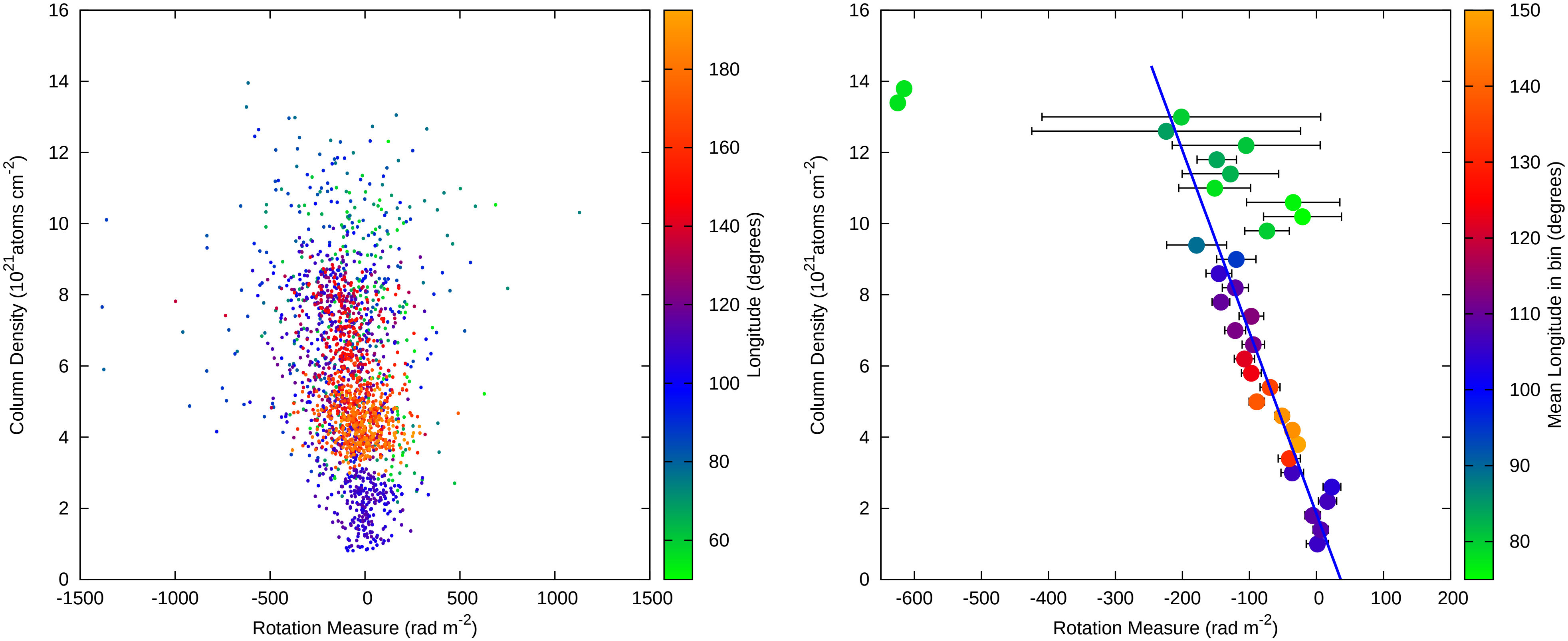


RMs and N_{HI}



Column Density (10^{21} atoms cm^{-2})
Rotation Measure (rad m^{-2})
Longitude (degrees)
Column Density (10^{21} atoms cm^{-2})
Rotation Measure (rad m^{-2})
Mean Longitude in bin (degrees)

RMs and N_{HI}



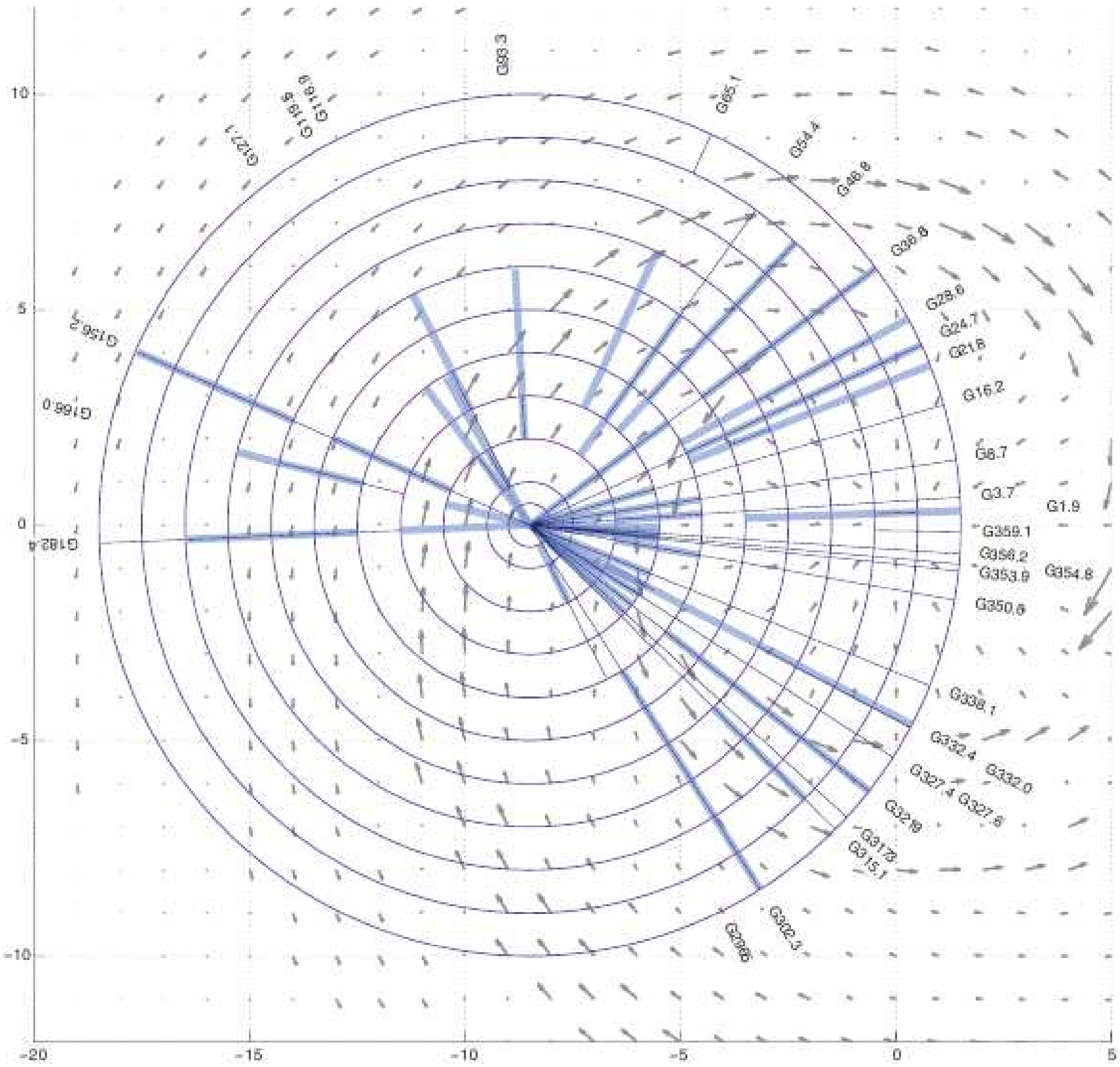
$$\frac{RM}{N_{HI}} = -21.8 \pm 1.5 \text{ rad m}^{-2}/10^{21} \text{ atoms cm}^{-2}$$

RMs and N_{HI}

- $\frac{RM}{N_{HI}} = -21.8 \pm 1.5$ rad m^{-2}/10^{21} atoms cm^{-2}
- within 100 pc of the sun: $\chi_e \approx 0.08$ (Jenkins, 2013)
  $\Rightarrow B_{\|} = -0.95 \pm 0.06$ μG
- agrees with $B_{\|} = -1.2 \pm 0.5$ μG (Van Eck et al., 2011)
  $\Rightarrow \chi_e \approx 0.07$
- The large-scale magnetic field is tied to the warm neutral medium.

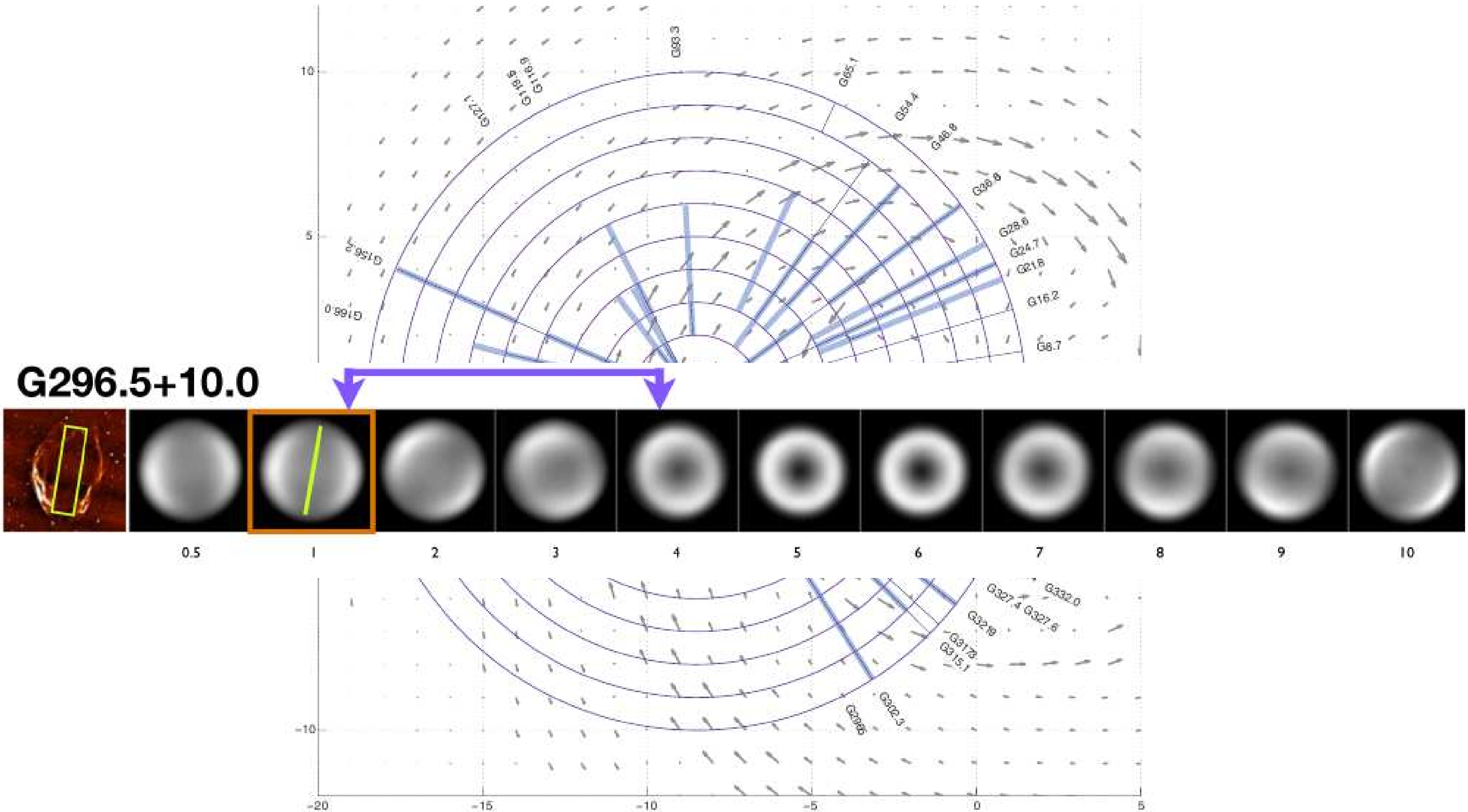
SNRs in the Milky Way Galaxy

West et al., 2016, A&A 587, A148:



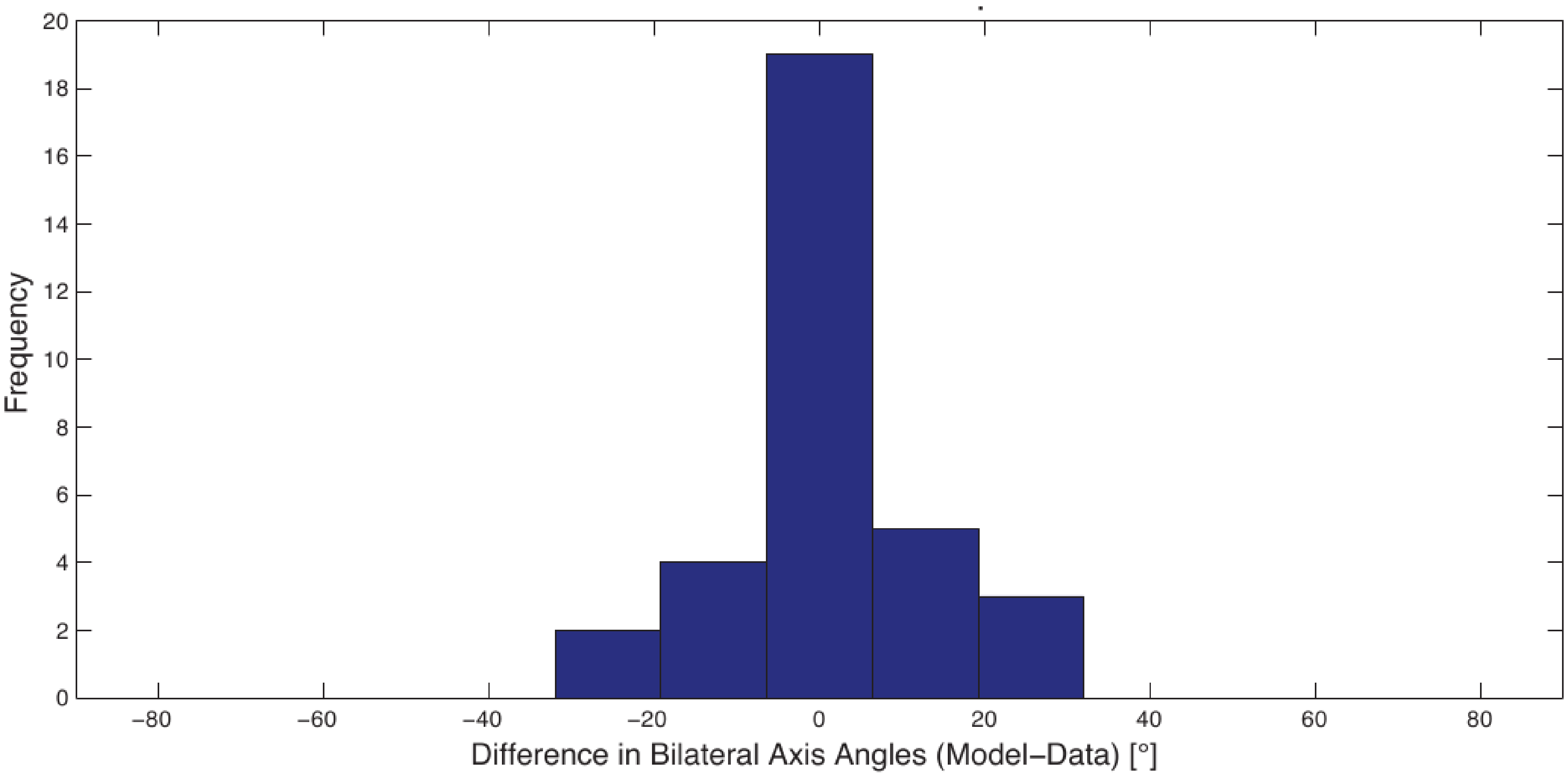
SNRs in the Milky Way Galaxy

West et al., 2016, A&A 587, A148:

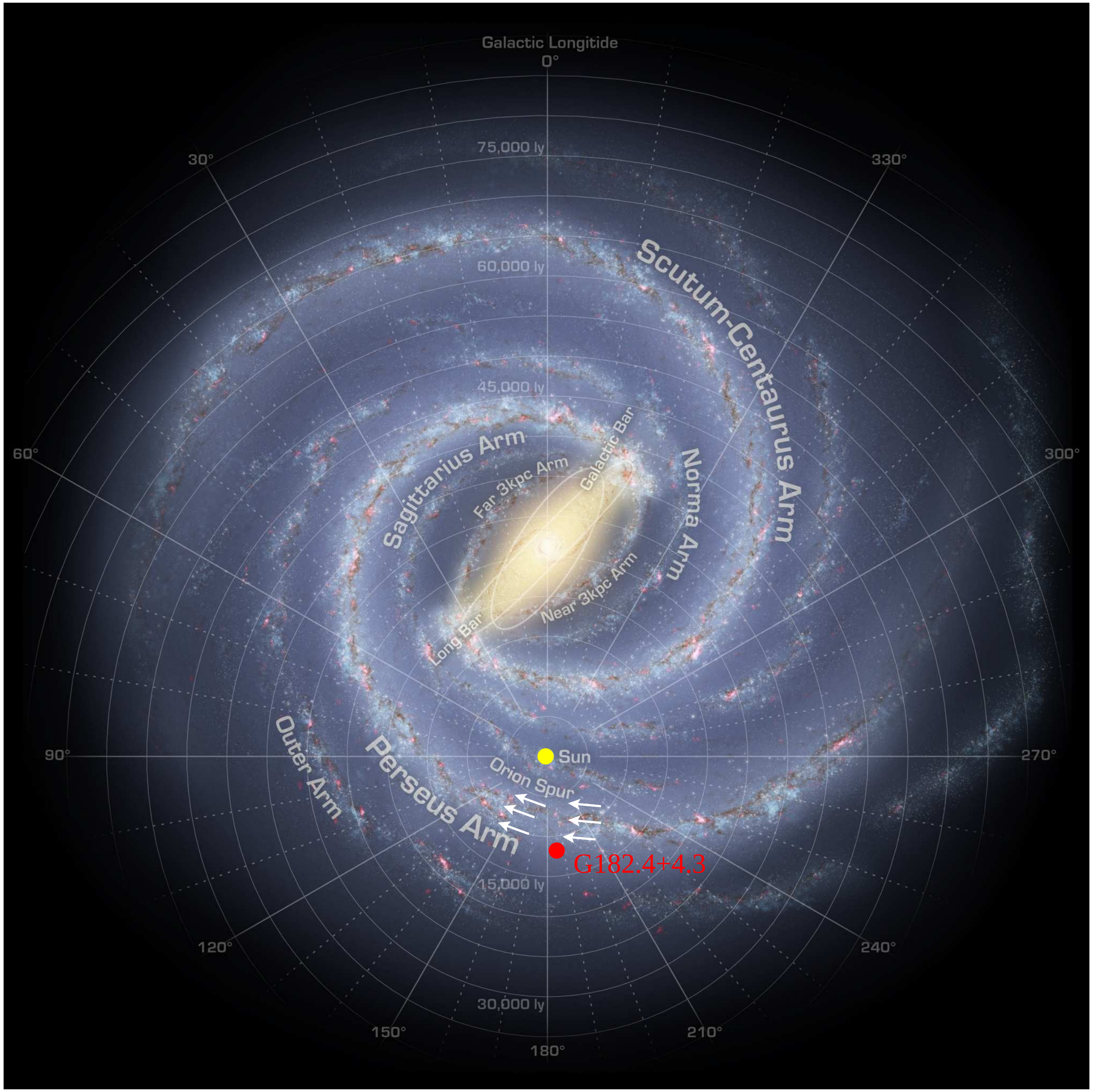


SNRs in the Milky Way Galaxy

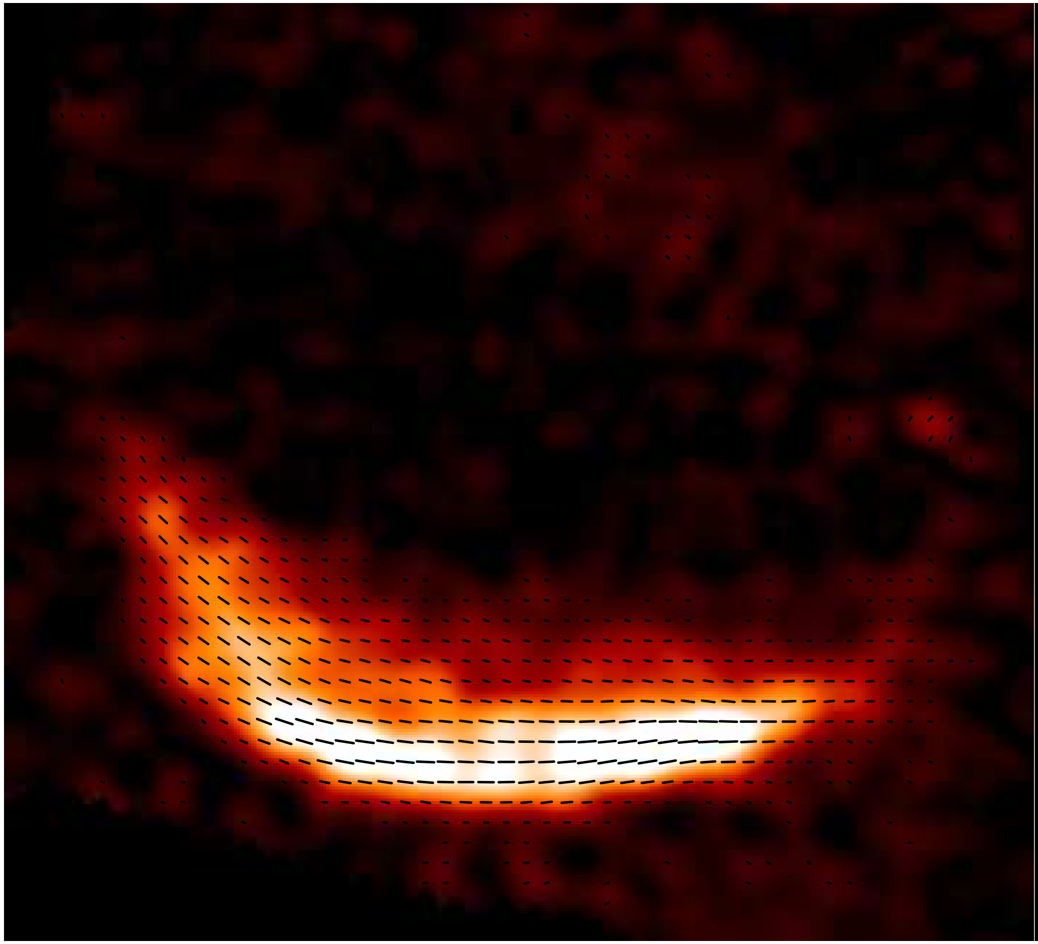
West et al., 2016, A&A 587, A148:



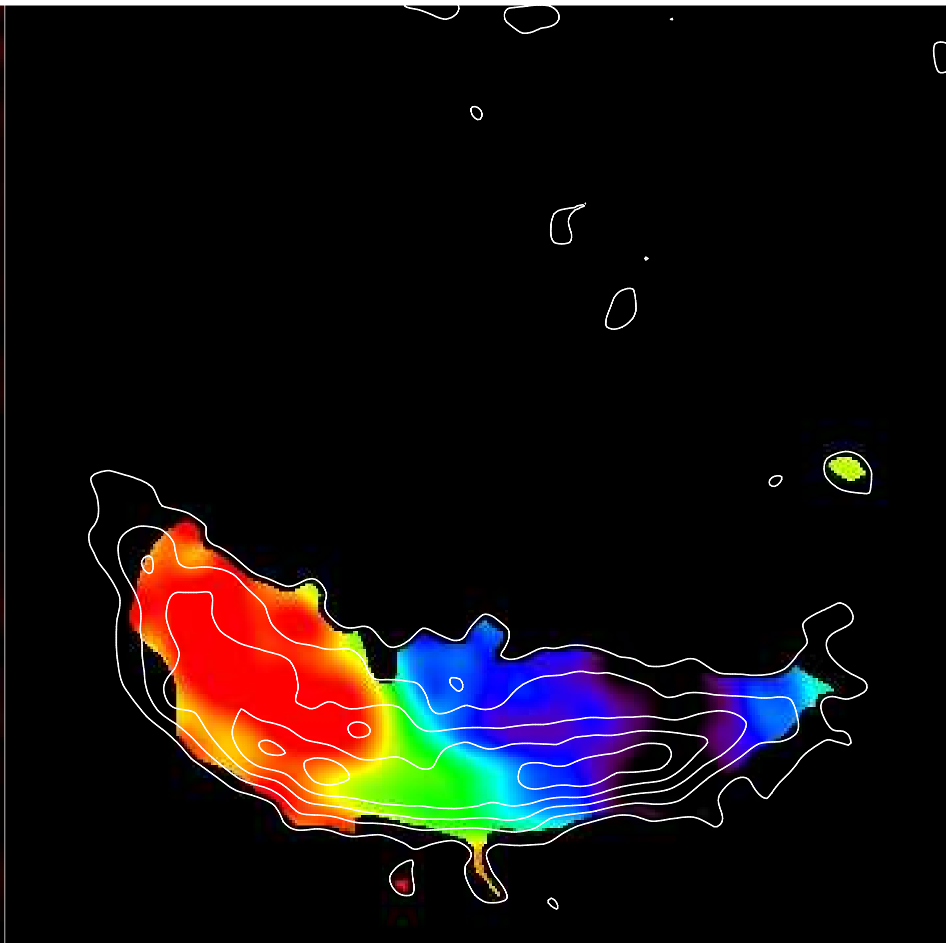
G182.4+4.3 in the Milky Way Galaxy



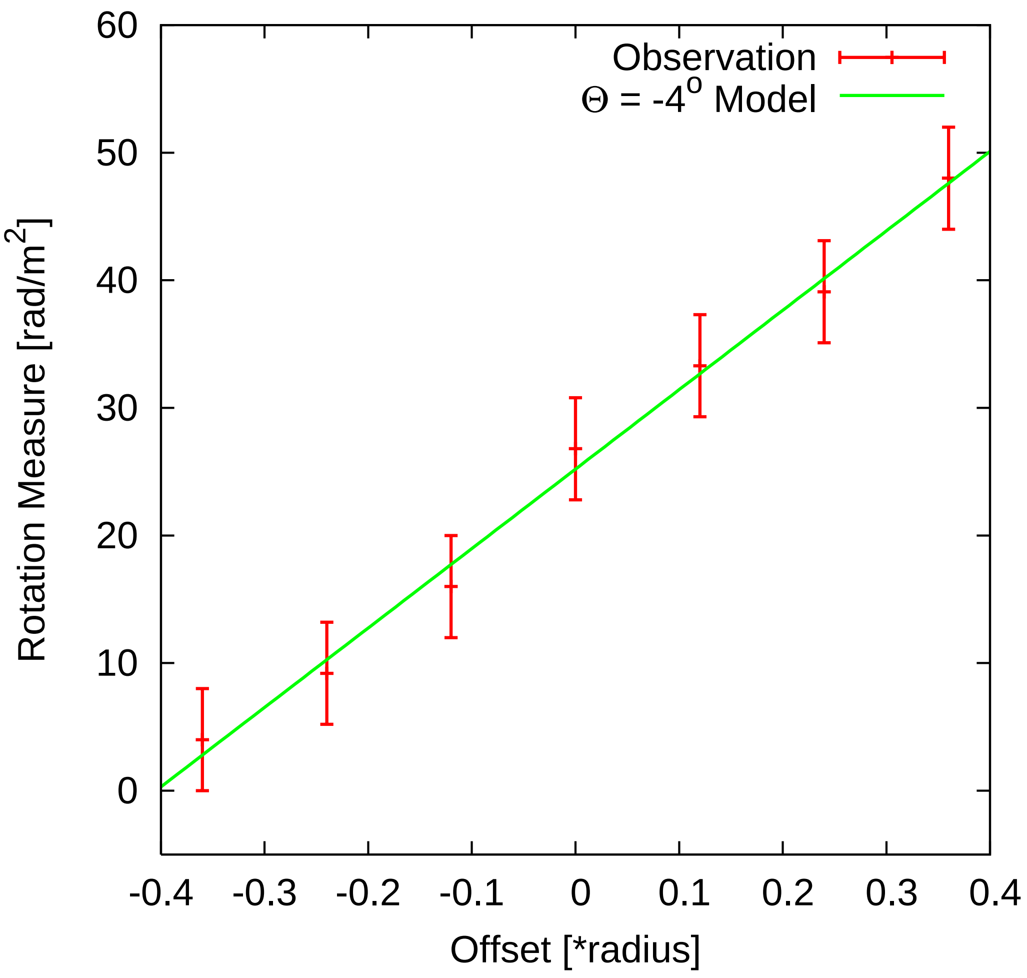
G182.4+4.3



G182.4+4.3 at 5 GHz (Effbg 100m)
B-vectors are overlaid.



RM map of G182.4+4.3
PI contours are overlaid.



Kothes & Brown, 2009

- The ambient B-field is pointing towards us from back left to front right.
- Neglecting foreground RM gives an upper limit for $|\Theta|$.
- We fit $\Theta \geq -4°$.
- If we assume that the foreground B-field is about $4\,\mu$G and has the same $|\Theta|$ as the SNR's ambient B-field, we find $\Theta = -2°$.
- This would indicate an azimuthal magnetic field for the outer Galaxy.

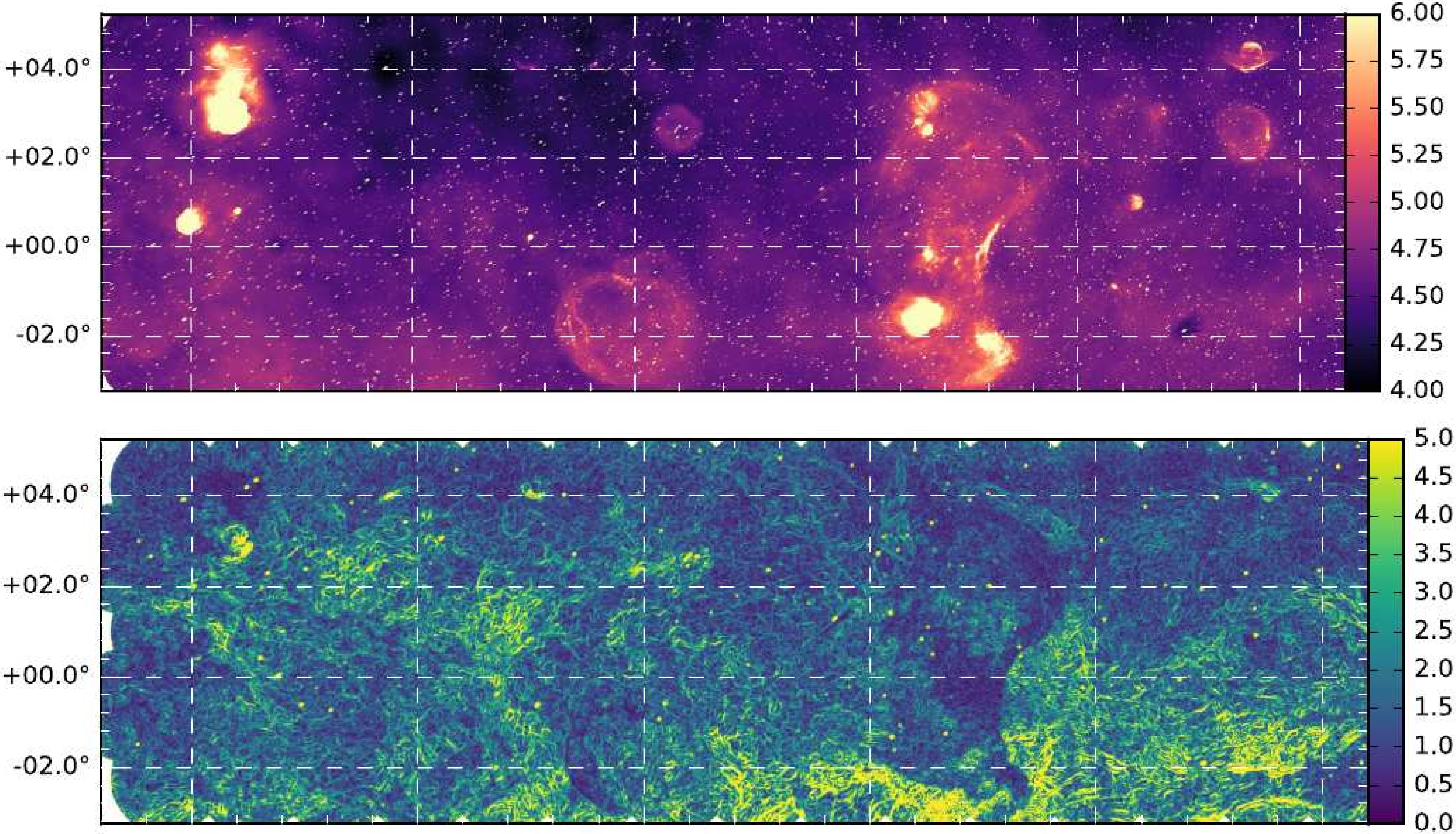
Gaensler et al., 2011:

$$|\nabla \boldsymbol{P}| = \sqrt{\left(\frac{\partial Q}{\partial x}\right)^2 + \left(\frac{\partial U}{\partial x}\right)^2 + \left(\frac{\partial Q}{\partial y}\right)^2 + \left(\frac{\partial U}{\partial y}\right)^2}$$

To characterize the so-called depolarization canals, which turned out to be indication of magnetic field turbulence.

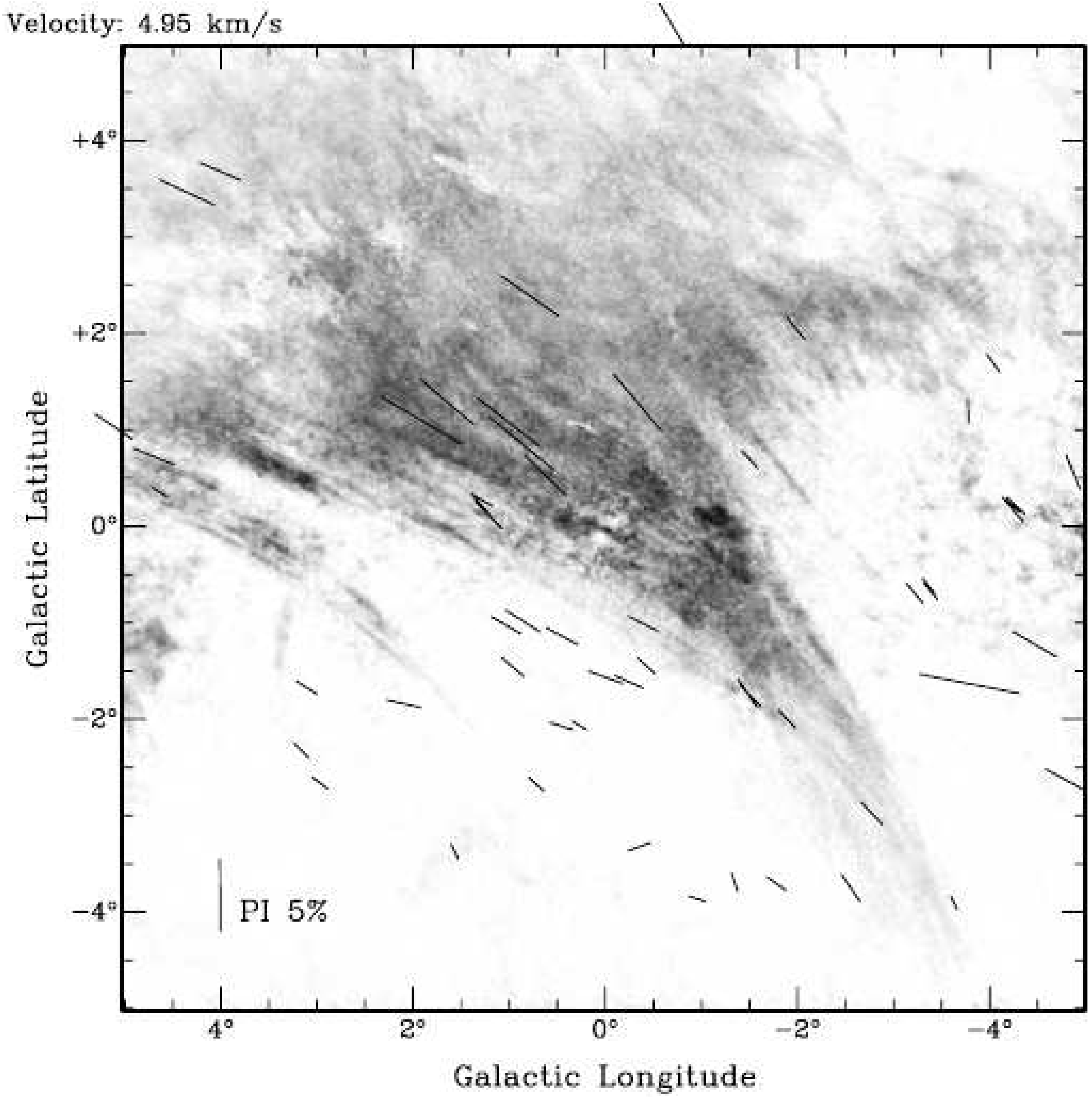
Polarisation Gradients

Herron et al., 2017:



Riegel-Crutcher Cloud

McClure-Griffiths et al., 2006:



Summary

- Radio Polarimetry is the best tool to study the Galactic Magnetic field.
- Synchrotron Emission reveals the Magnetic Field in the plane of the sky and Faraday rotation its line of sight component.
- The distribution of turbulence as studied with the polarization gradient method reveals a complex structure of magnetic turbulence in the plane of the Galaxy.
- The mean regular magnetic field of the Milky Way is about 1 – 2 μG a factor of 2 or 3 lower than the total magnetic field.
- The regular Milky Way magnetic field is tied to the WNM and generally follows spiral arms, but may get more circular towards the Outer Galaxy.