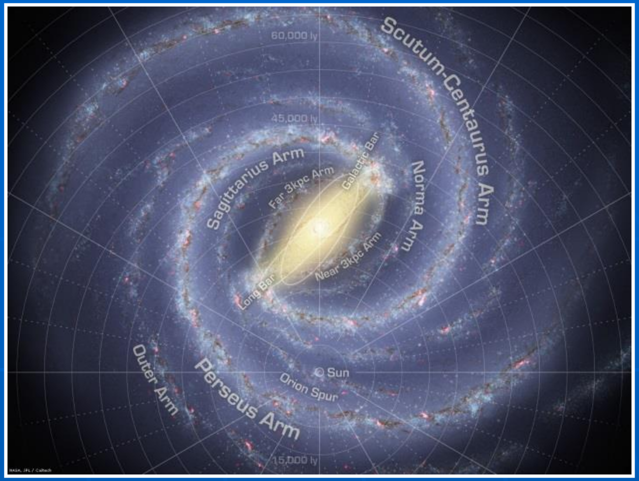
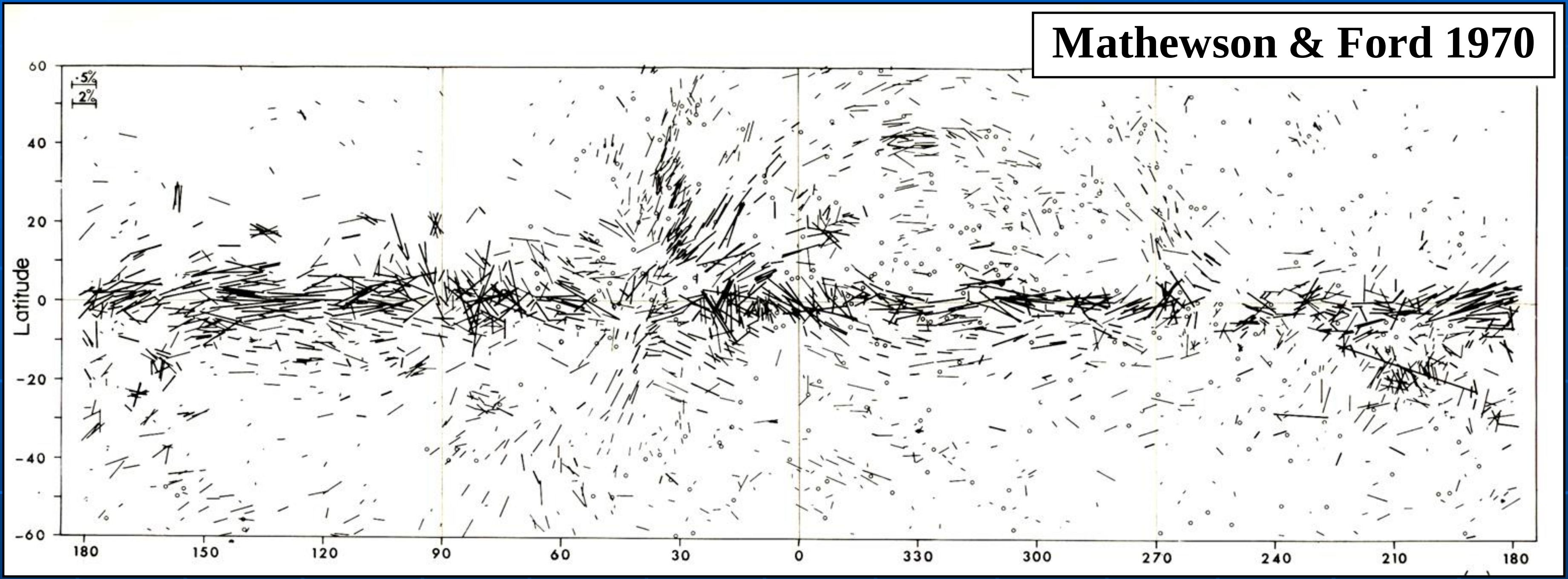




# Lecture 5:

# Magnetic Fields in the Milky Way

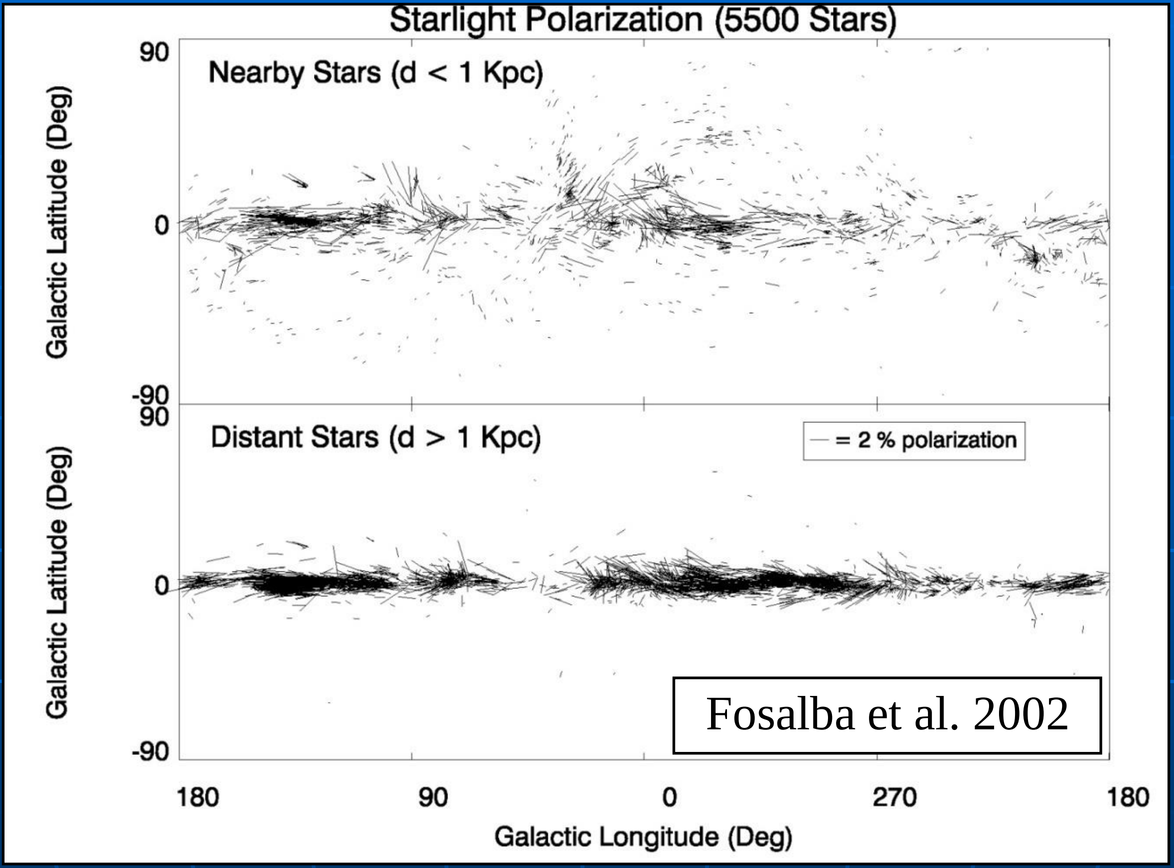
Rainer Beck, MPIfR Bonn

# Starlight polarization ($B_{\perp}$)



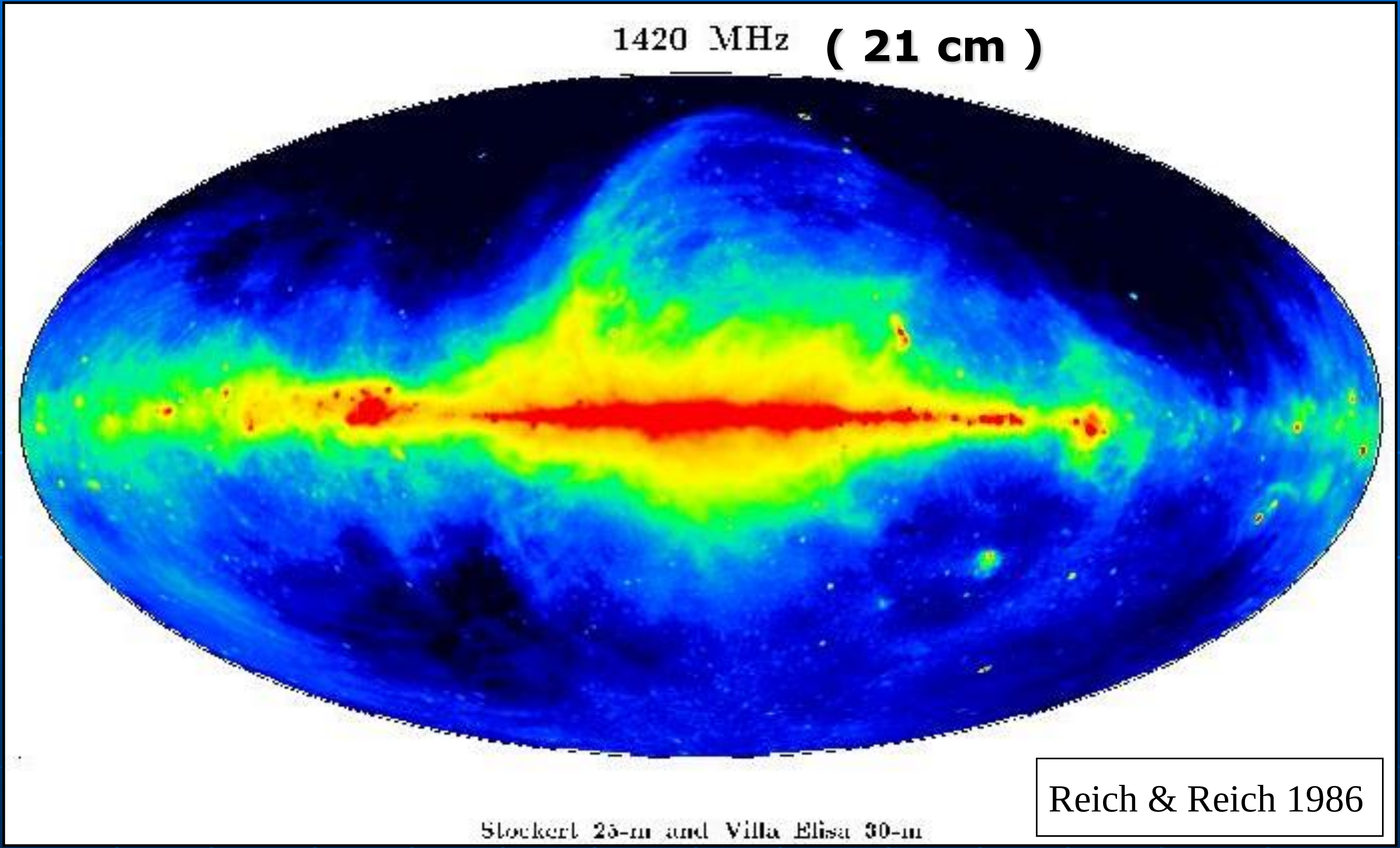

Large-scale ordered field, directed towards $l \approx 77°$, pitch angle ≈7°

# Starlight polarization ($B_\perp$)




Large-scale ordered field along the plane beyond 1kpc, more turbulent local field

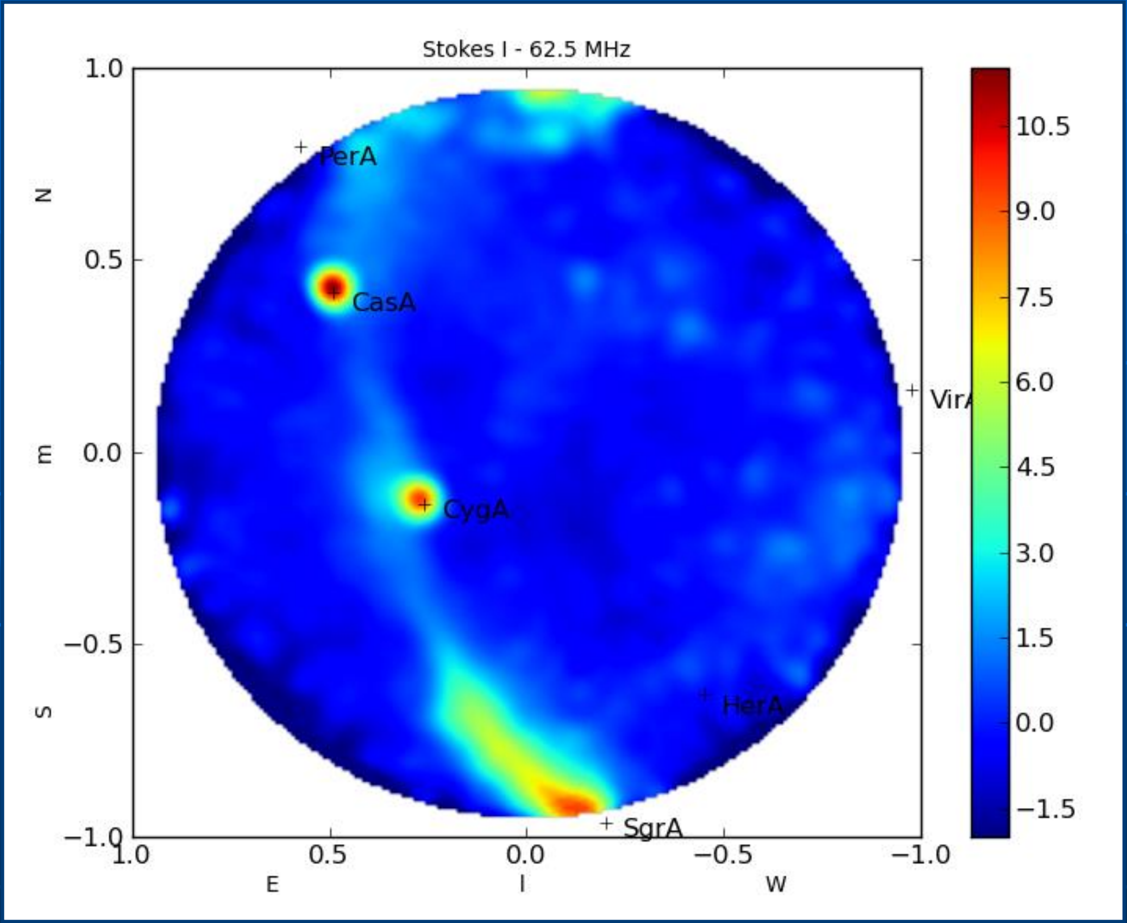
# The Milky Way in synchrotron light




More than 10 years of work !

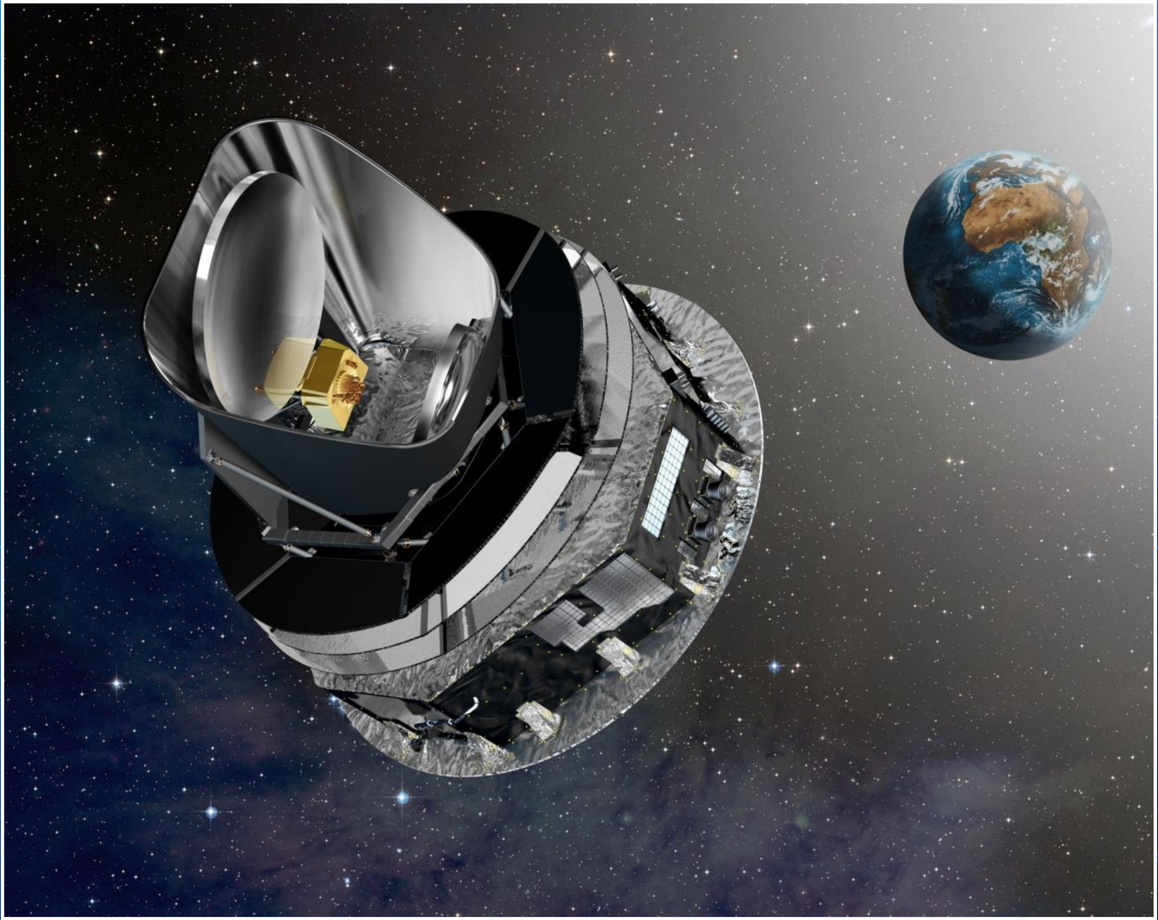
# The Milky Way in synchrotron light: Effelsberg LOFAR station

(J. Köhler & J. Anderson)

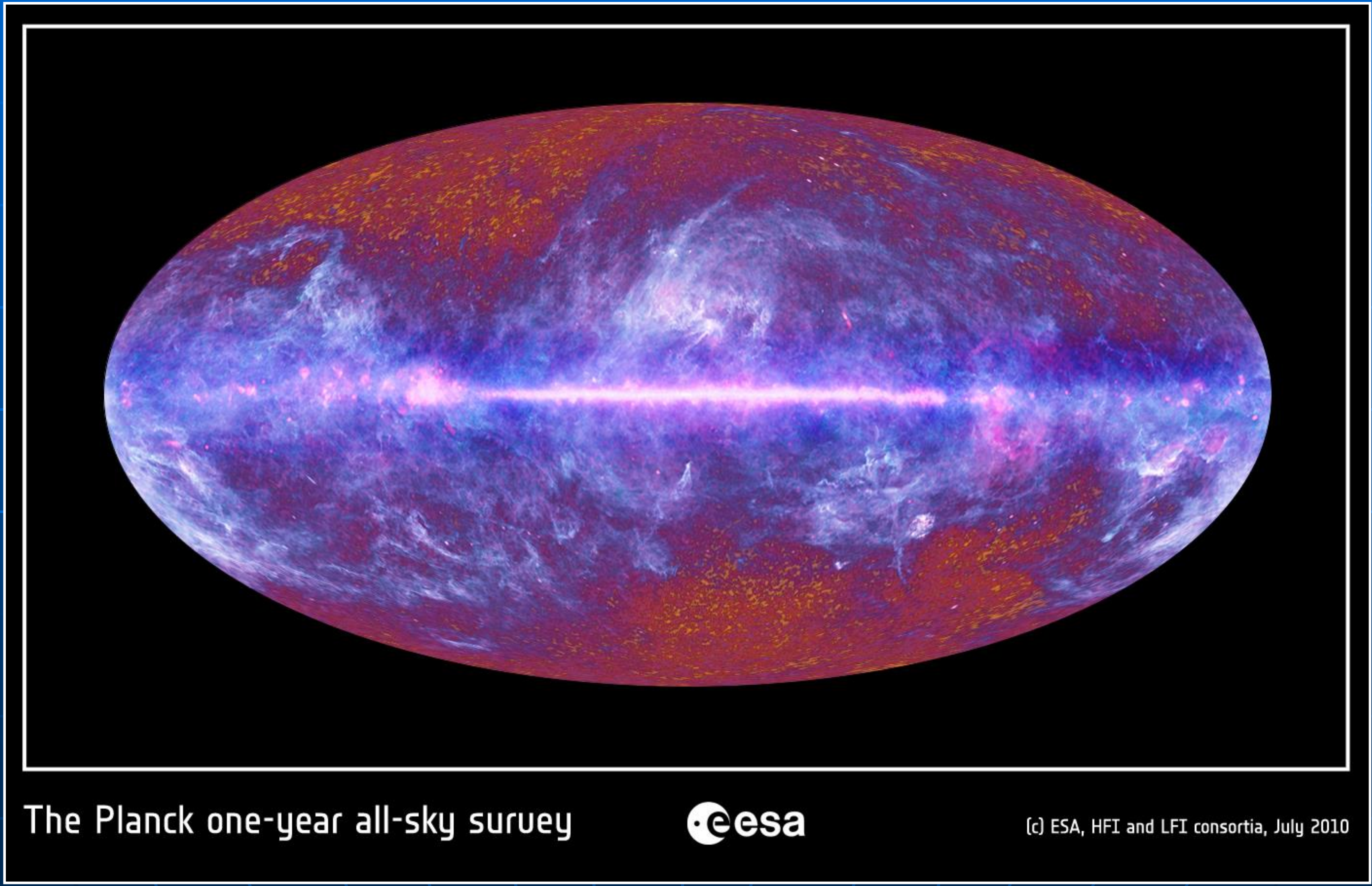



- Data set from Transient Buffer Board
- Single channel at 62.5 MHz with 200 kHz bandwidth
- **1.3 sec integration time**

# PLANCK (2010 - ?)

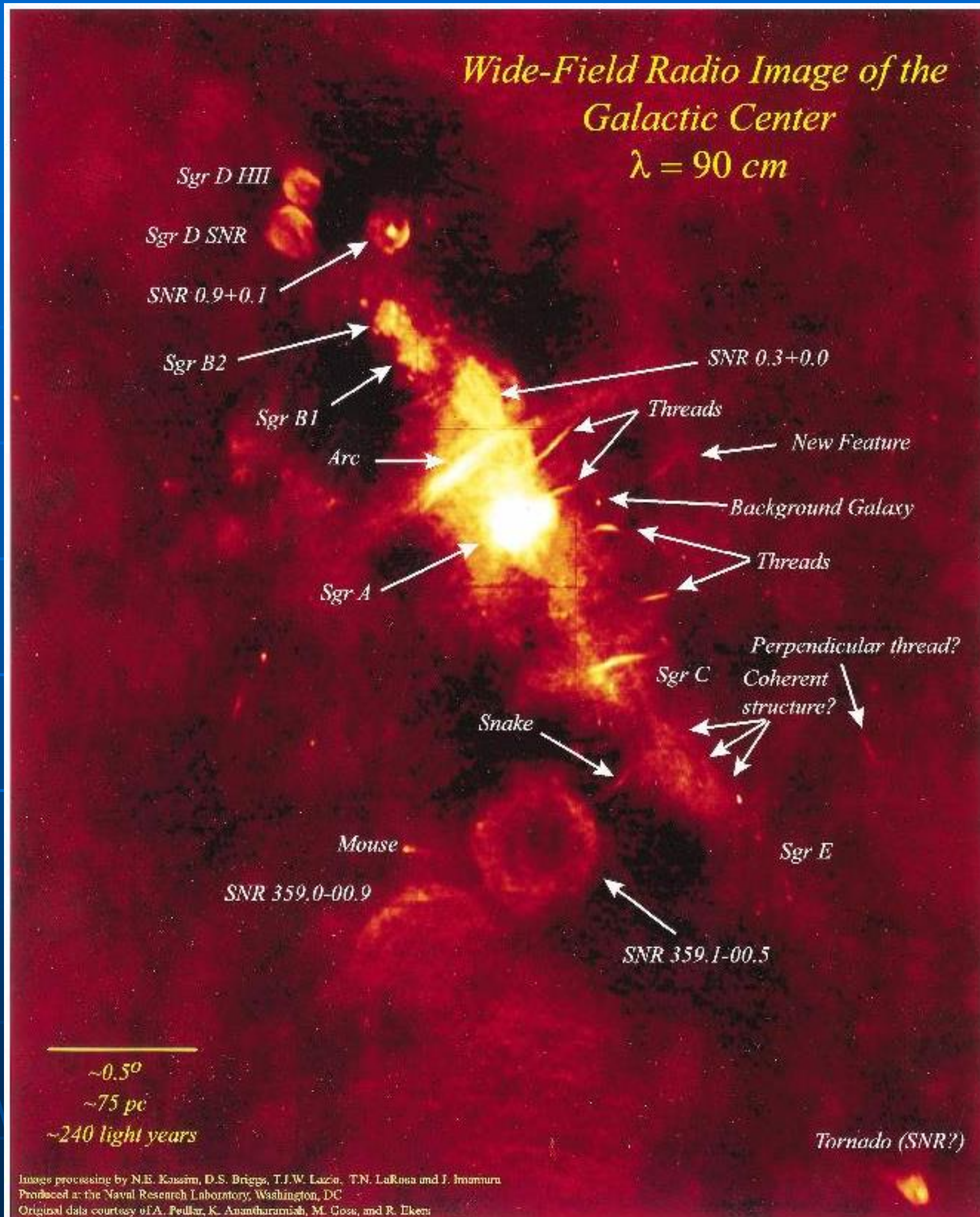


# PLANCK (30-857 GHz, 0.3mm-1cm)



# Central region of the Milky Way

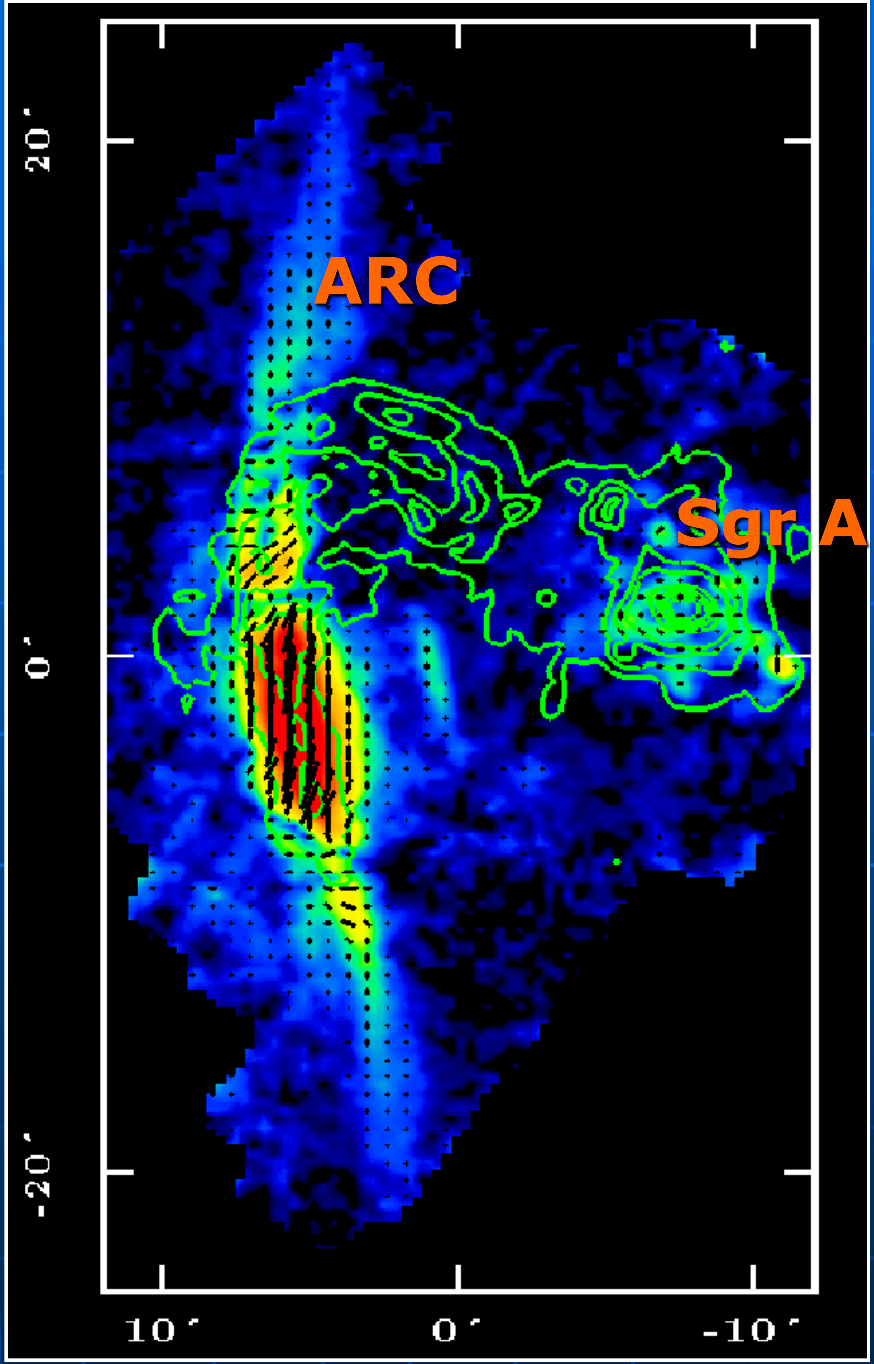
VLA 6 cm




Kassim et al., NRL/NRAO

# Central region

Effelsberg 9 mm
Total + pol. int.
(Reich, priv. comm.)

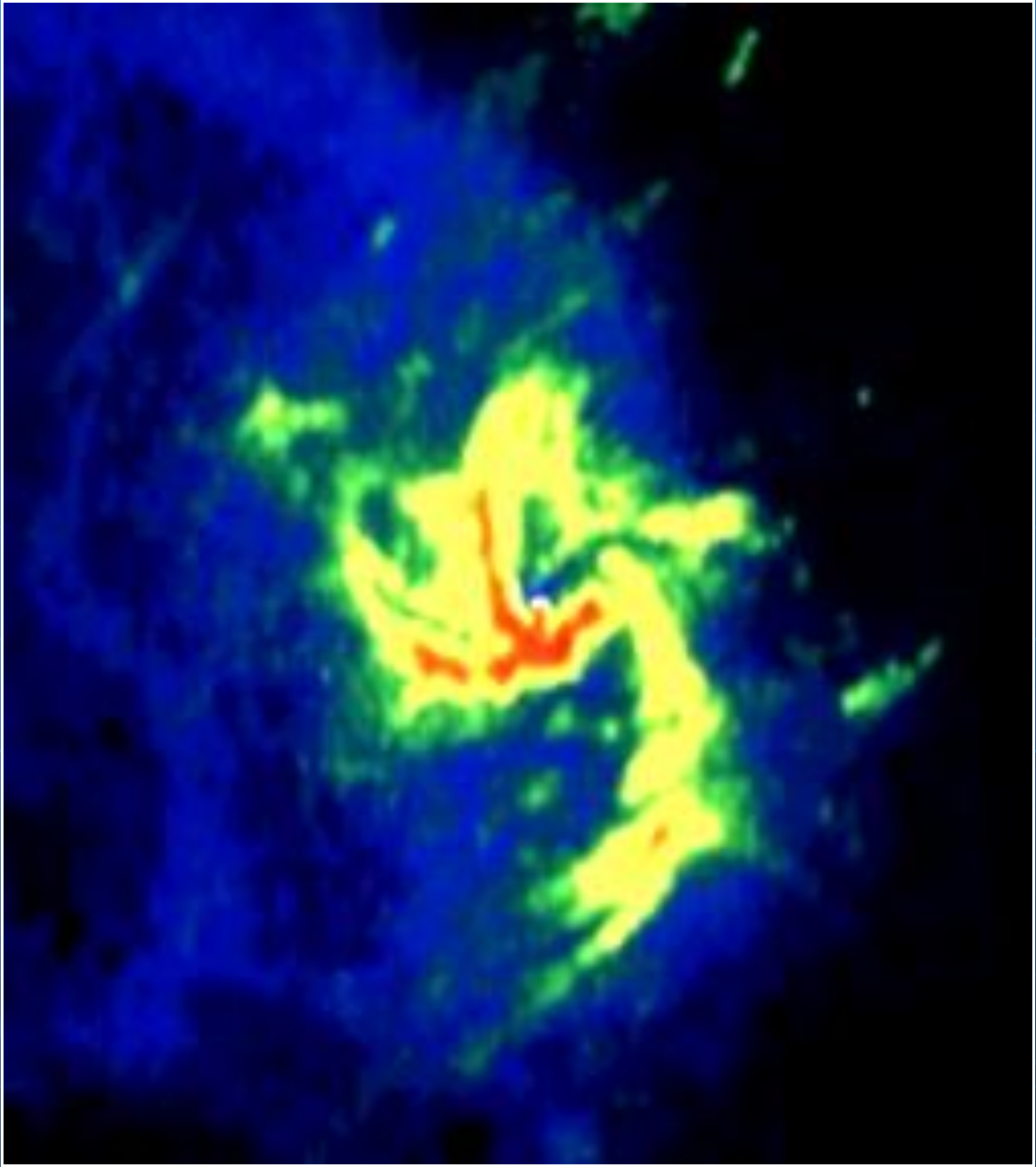



Percentage polarization up to ~60% :

Almost totally aligned field, perpendicular to plane

# Innermost region of the Milky Way

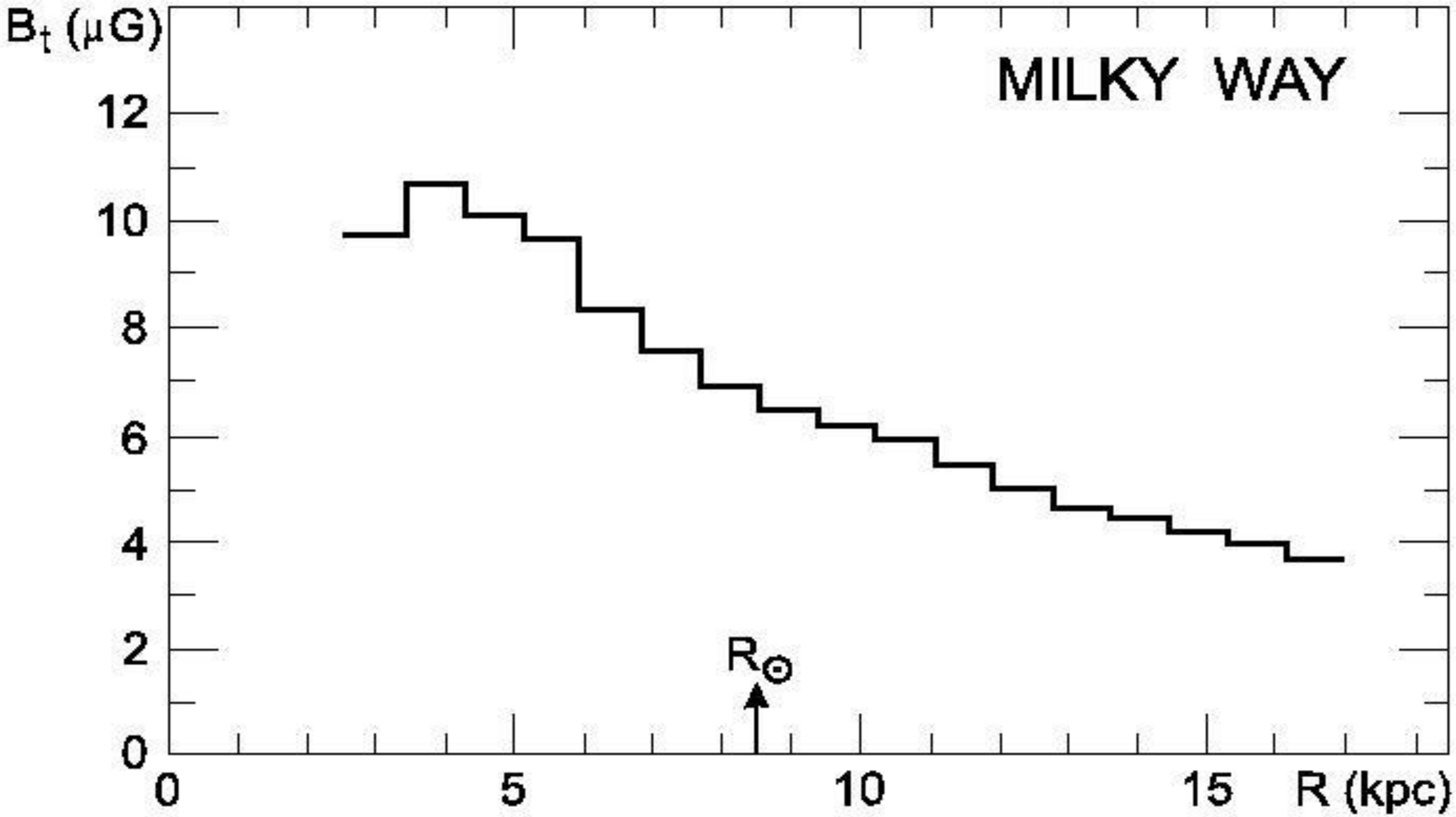
VLA 6 cm



W.M. Goss, NRAO

# Equipartition field in the Milky Way

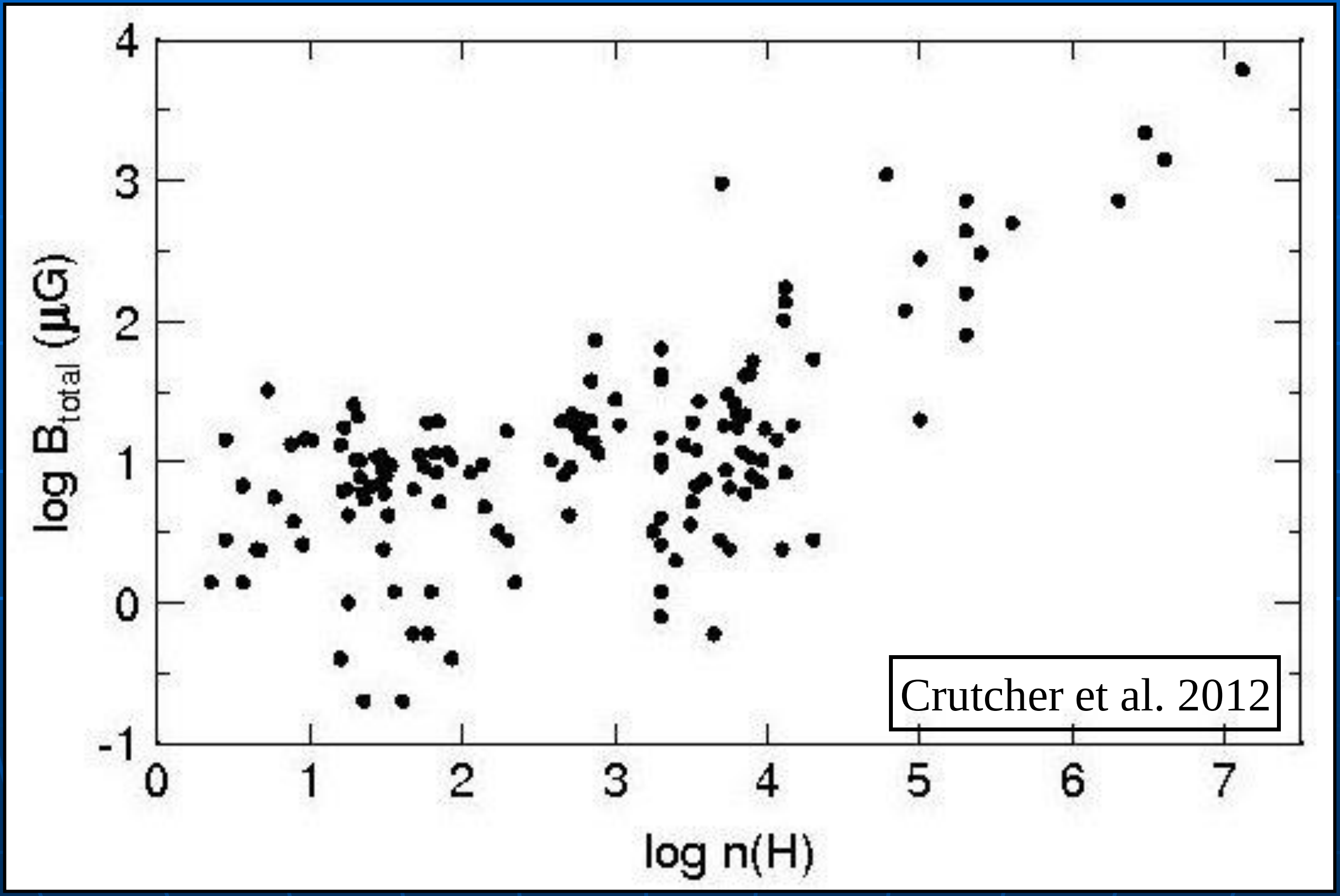
(Berkhuijsen, in Wielebinski & Beck 2005)




## Consistent with estimates from γ rays

(Strong et al. 2000)

# Field strengths in Milky Way clouds
(Zeeman effect)




Average field strength in low-density clouds: **≈6 μG (0.6 nT)**
(1 NanoTesla = 10 MicroGauss)

# Zeeman data of Galactic gas clouds

(Crutcher et al. 2009, 2012)

- Average total field strength in the diffuse ISM is ≈ 6 μG
- B is approximately constant at gas densities below about $10^3$ $cm^{-3}$, then increases steeply ($\propto \rho^{0.5}$)
- Mass/magnetic flux ratios are subcritical at low ISM densities and become slightly supercritical in dense molecular clouds, allowing cloud collapse
- Magnetic fields are dynamically significant and possibly crucial to understanding the physics of star formation

# Star Formation Rate is LOW

**Basu 2012**

A key issue on the large scale

Total molecular ($H_2$) gas mass $$M_{tot} \approx 10^9 \, M_{sun}$$

Dynamical time (for gravity-driven fragmentation and collapse)
Avg. $n$ = 100 cm$^{-3}$

$$t_d \approx \frac{1}{2} \frac{1}{\sqrt{G\rho}} \approx 3 \times 10^6 \text{ yr}$$

Implied star formation rate (SFR)

$$\dot{M}_{SF} \approx M_{tot} / t_d \approx 300 \, M_{sun} / \text{yr}$$

BUT, observed Galactic SFR is

$$\dot{M}_{SF,obs} \approx 1 - 5 \, M_{sun} / \text{yr}$$

e.g. Williams and McKee (1987), Misiriotis et al. (2006), Robitaille & Whitney (2010), and many others

# Cloud collapse

- Cloud cores need to be stabilized (because star formation is much less efficient than expected from purely gravitational collapse of molecular clouds):
  Magnetic field or turbulent pressure ?
- Magnetic fields help to transport angular momentum of rotating molecular clouds outwards
- Needed: Ambipolar diffusion (slipping of neutral gas with respect to ionized gas and magnetic fields)

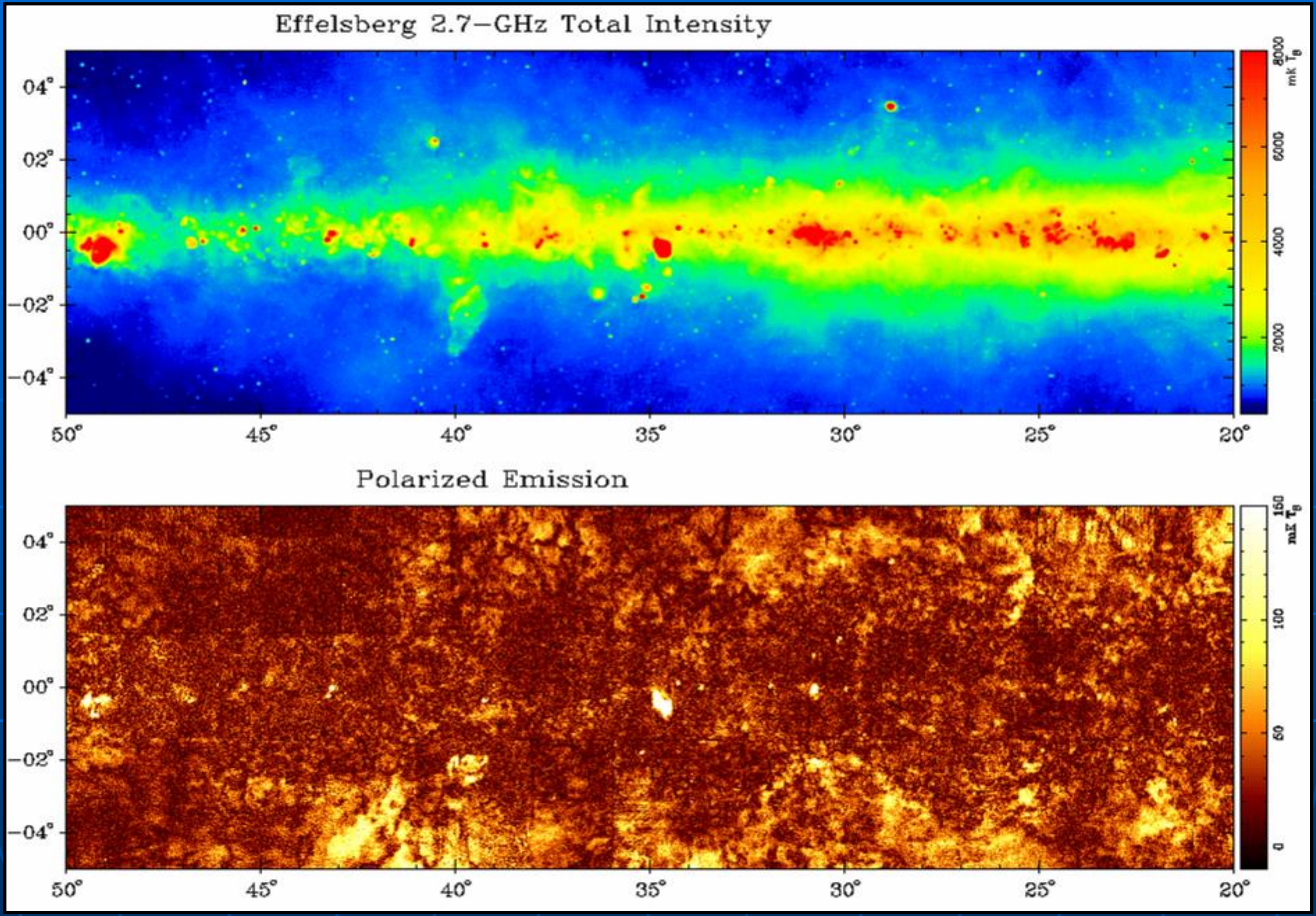
# Ambipolar diffusion

Test of ambipolar diffusion model:

- Measure the ratio of mass to magnetic flux ($M/\Phi$)
- Large (supercritical) $M/\Phi$: collapse
- Compare $M/\Phi$ in cloud core and envelope: Ambipolar diffusion predicts that $M/\Phi$ is larger in core than in envelope
- Observations: $M/\Phi$ is **smaller** in core than in envelope – weak magnetic field, hence cloud support by turbulence ? (Crutcher et al. 2009)

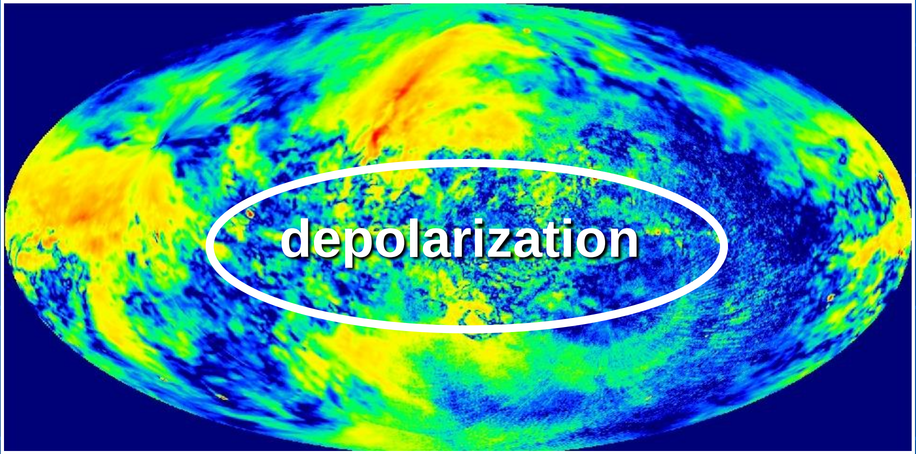
# Synchrotron polarization

- Small-scale and large-scale field structures can be measured
- Fields in SNRs, HII regions and planetary nebulae can be measured

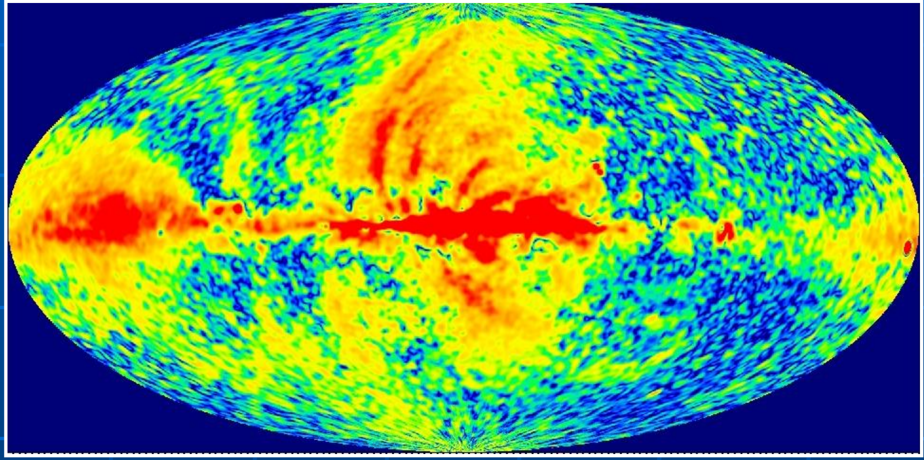



Anticorrelation of I and PI along Galactic latitude:
Magnetic fields near the Galactic plane are turbulent
(Reich et al. 1990, Duncan et al. 1999)

# All-sky surveys in polarized intensity ($B_\perp$)



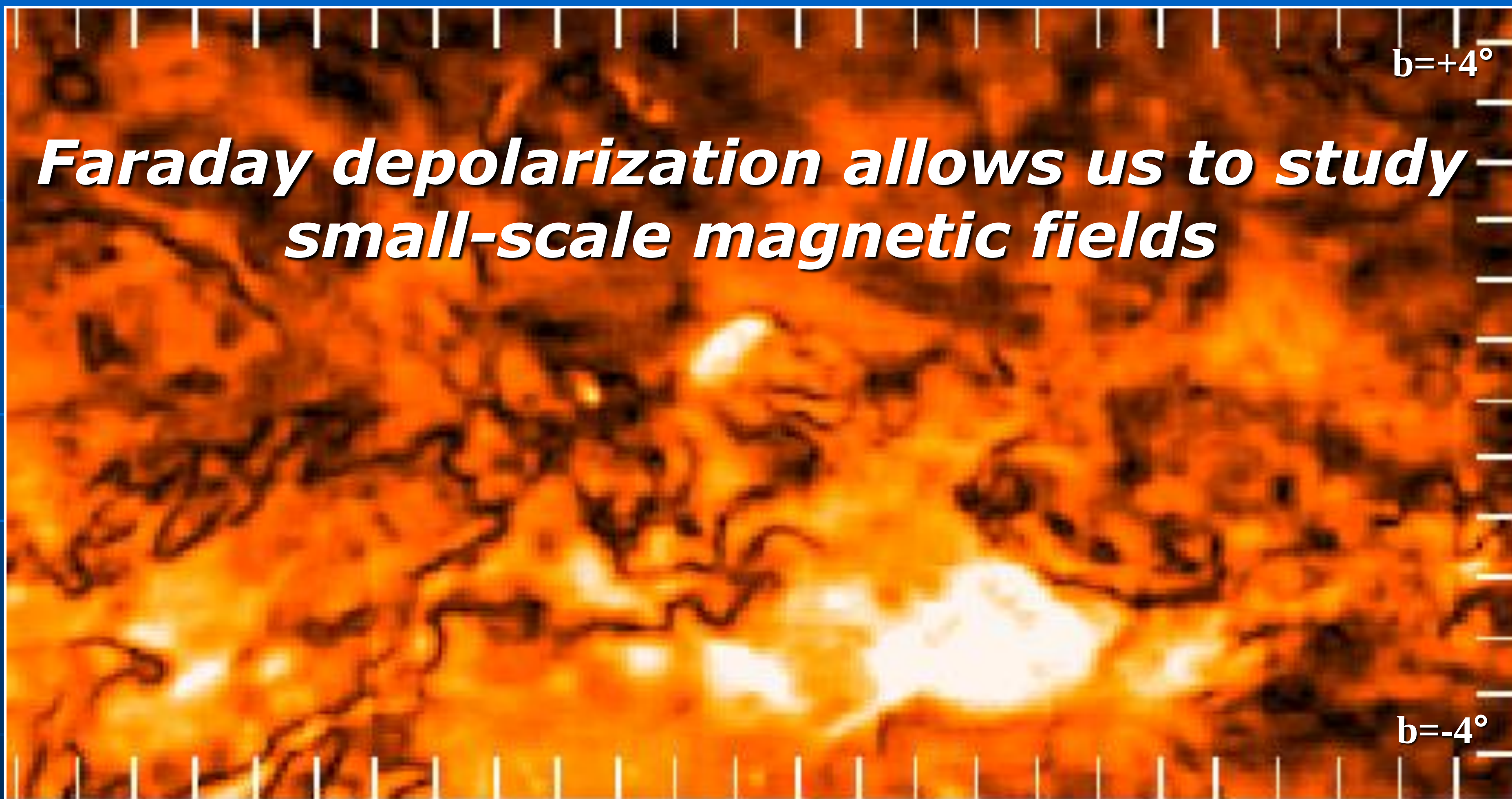

1.4 GHz DRAO (Wolleben et al. 2006)
+ Villa Elisa (Testori et al. 2008)



22.8 GHz WMAP (Page et al. 2007)

Strong Faraday depolarization by turbulent fields around the Galactic plane

# Synchrotron Emission from the Milky Way
(Perseus - Auriga)



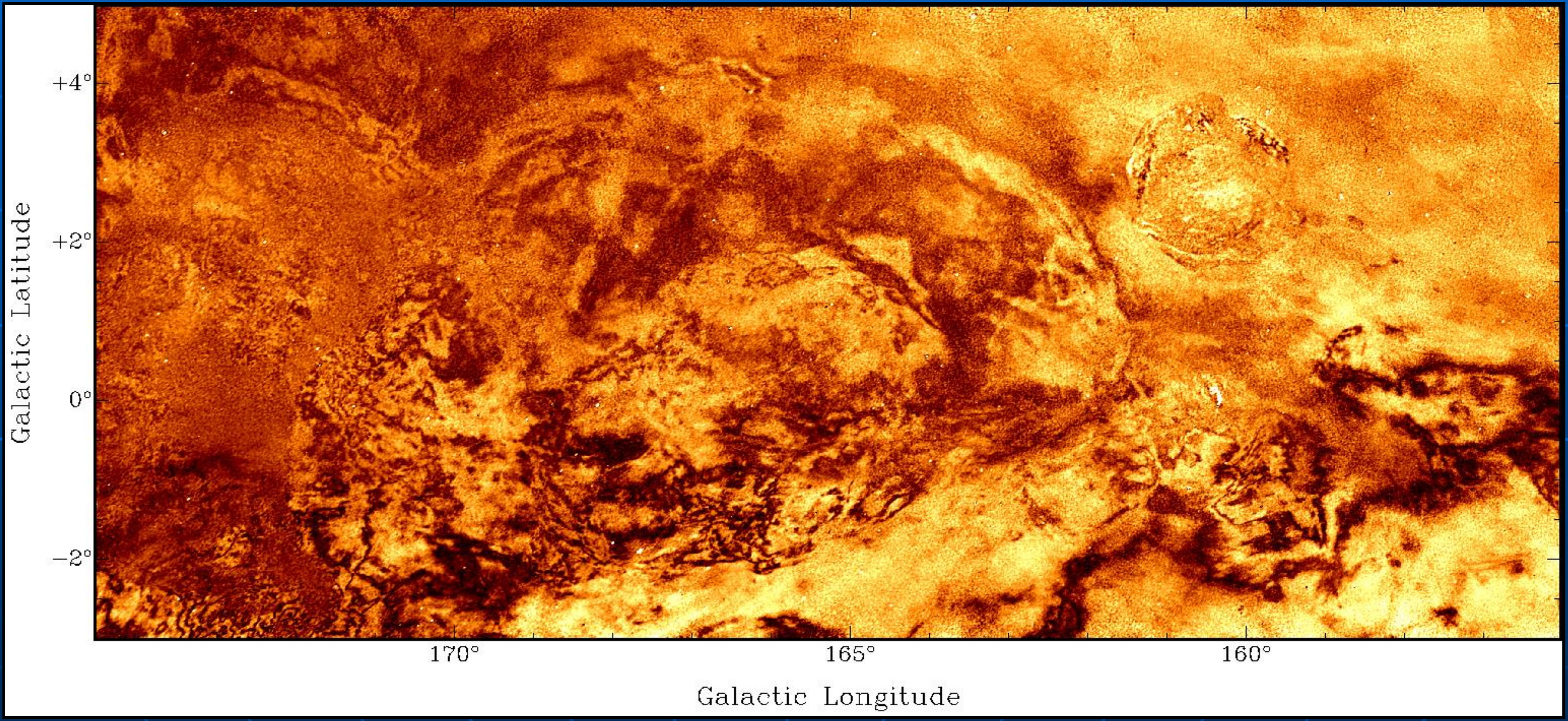

l=166° l=150°

Polarized emission
Total emission

Effelsberg 21 cm (Reich et al. 2003)

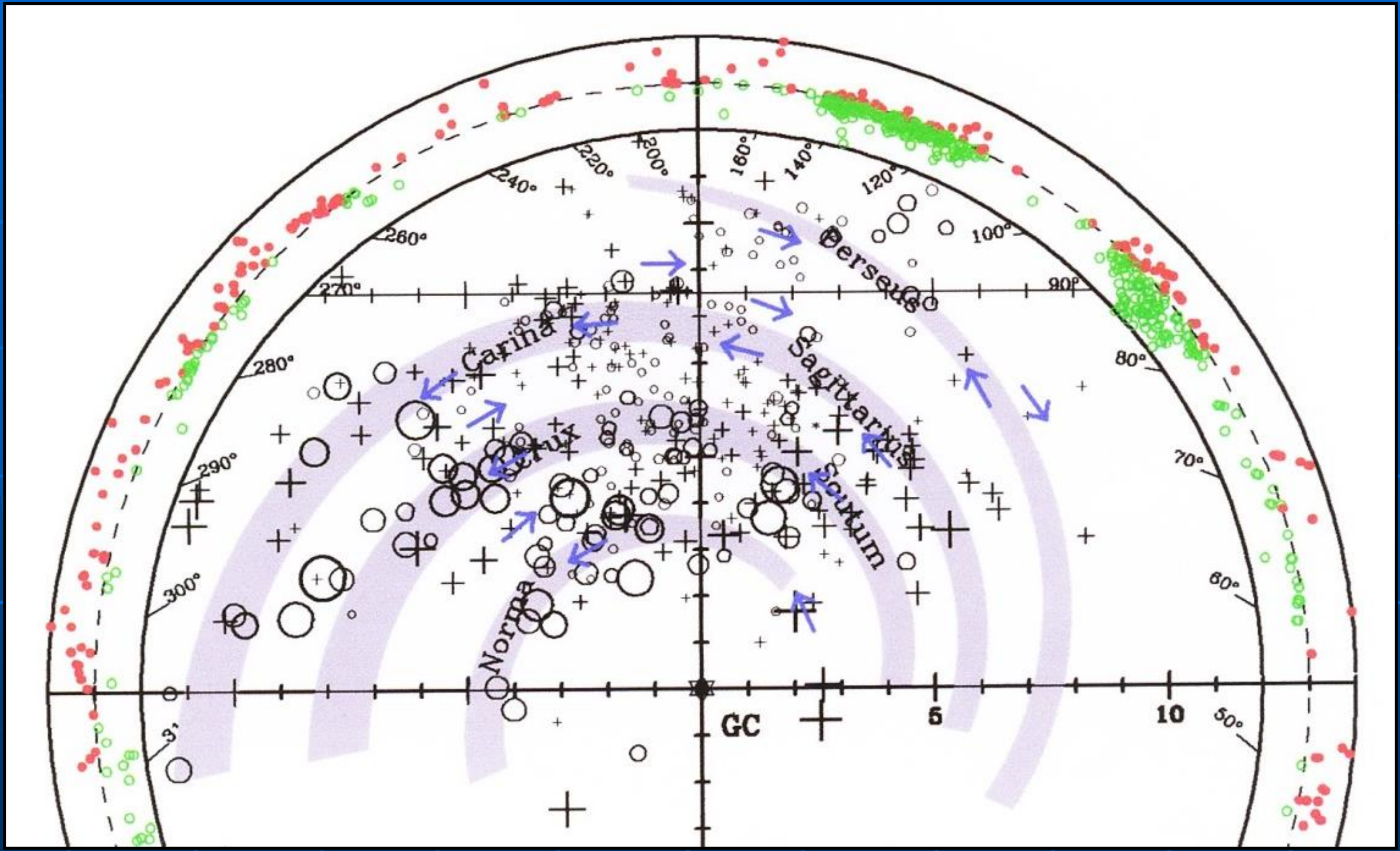
# Higher resolution:
# Canadian Galactic Plane Survey
(21 cm, DRAO+Effelsberg)

Landecker et al. 2010




Depolarization canals : Signatures of MHD turbulence
(Fletcher & Shukurov 2006)

# Pulsar RMs in the Milky Way

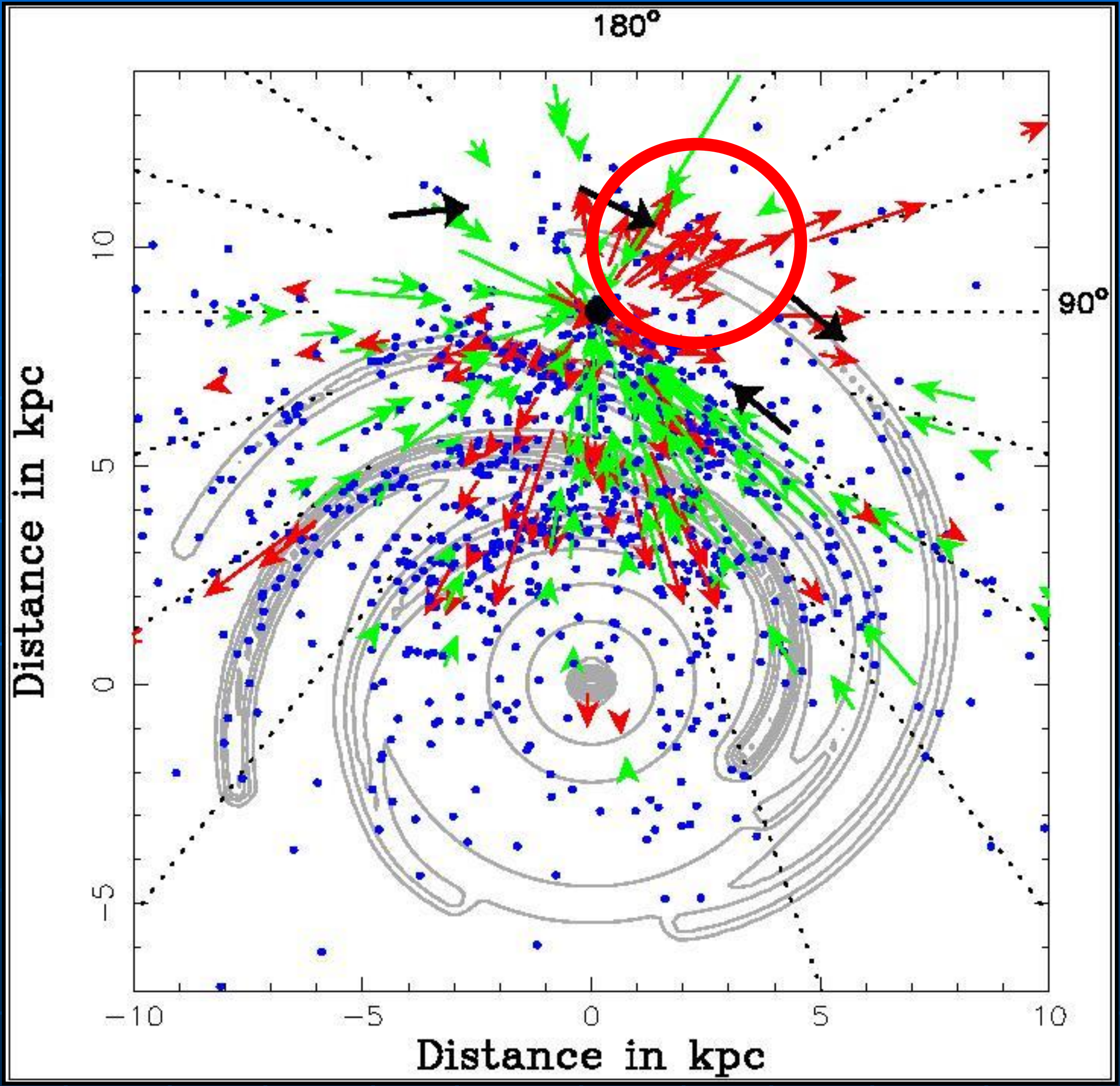



Han et al. 2007

- Many field reversals of the large-scale field ?
- Problem: pulsar distances are uncertain

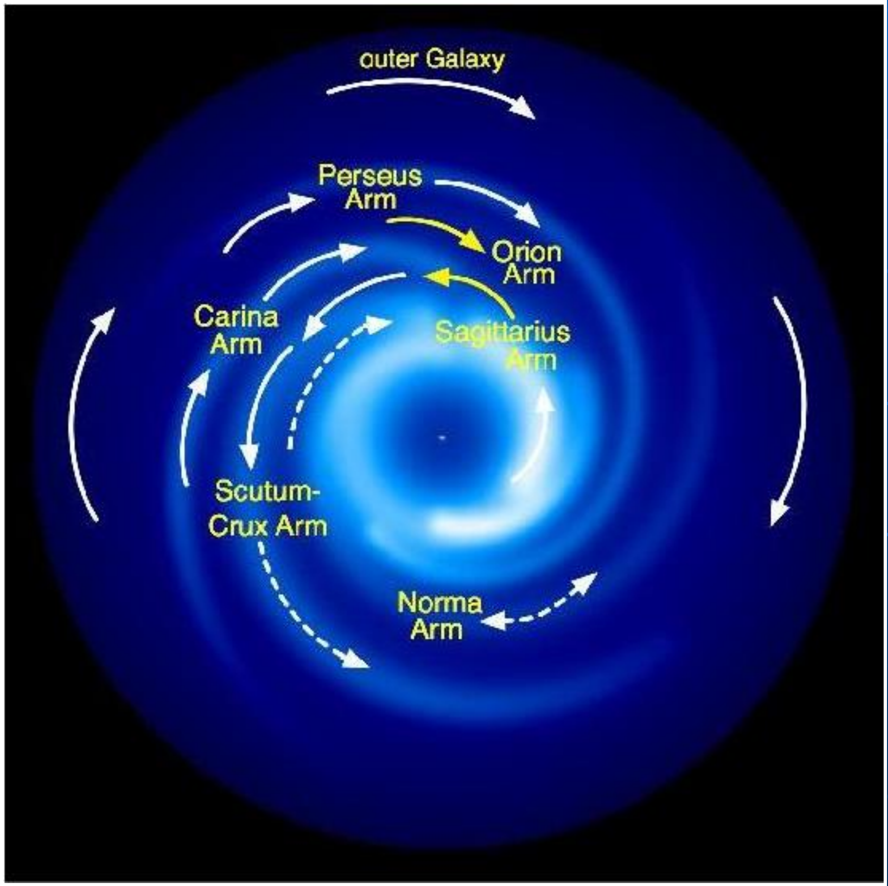
# Pulsar RMs in the Milky Way

Mitra et al. 2004




Strong RM deviations around HII regions

# The large-scale magnetic field in the Milky Way
## (from pulsar RM data)
(Han et al. 2006, Brown et al. 2007, 2010, Noutsos et al. 2008)






- Local field is clockwise
- Field in Sagittarius arm is counter-clockwise
  → ***reversal*** between arms
- **The overall field structure is not known yet**

*Large-scale field reversals are rare in spiral galaxies:*

*Is our Milky Way special ?*

# Origin of the reversals in the Milky Way

- Signature of turbulent fields (**not** large-scale)
- Relics of field reversals from the protogalactic phase
- Higher dynamo modes
- Disturbance by major interaction

# Are geomagnetic reversals triggered by reversals of the Galactic magnetic field ?

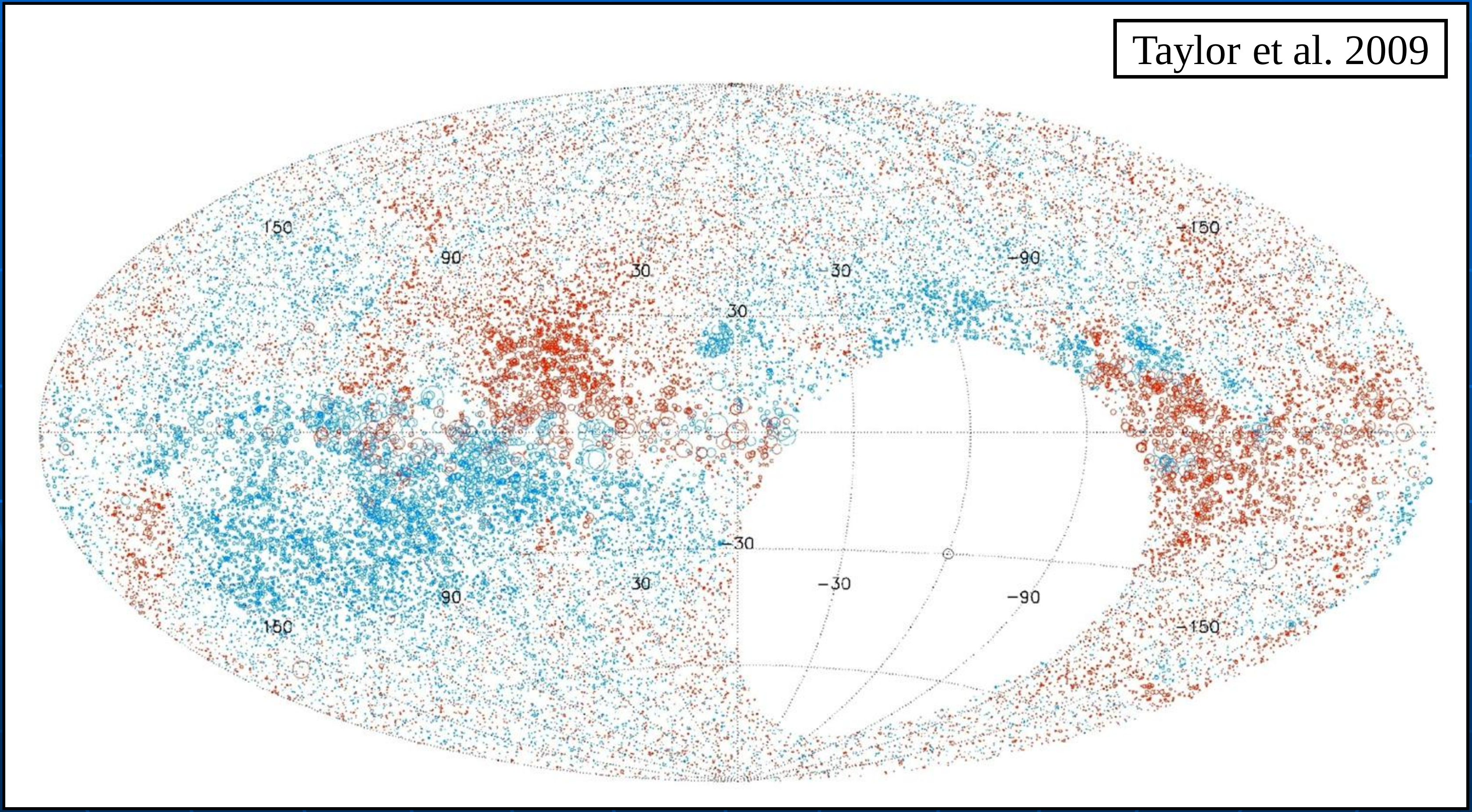
**No !**

- Geomagnetic field: Quiet periods of ≈ 50 Myr without reversals (superchrons), followed by turbulent periods with reversals every 0.2-1 Myr
- Last superchrons: 100, 280, 450 Myr ago
- Superchrons: passages of the solar system through interarm regions with regular magnetic fields? (Wendler 2004)
- However: Solar system is near to corotation radius (7.8 kpc) (Mishurov & Zenina 1999)
- Relative velocity to spiral arm pattern: ≈ 4 km/s
- Time between spiral arm passages: ≈ 3 Gyr !
- *How could the heliosphere connect the Galactic to the geomagnetic field ?*

# RMs of background sources ($B_\parallel$)

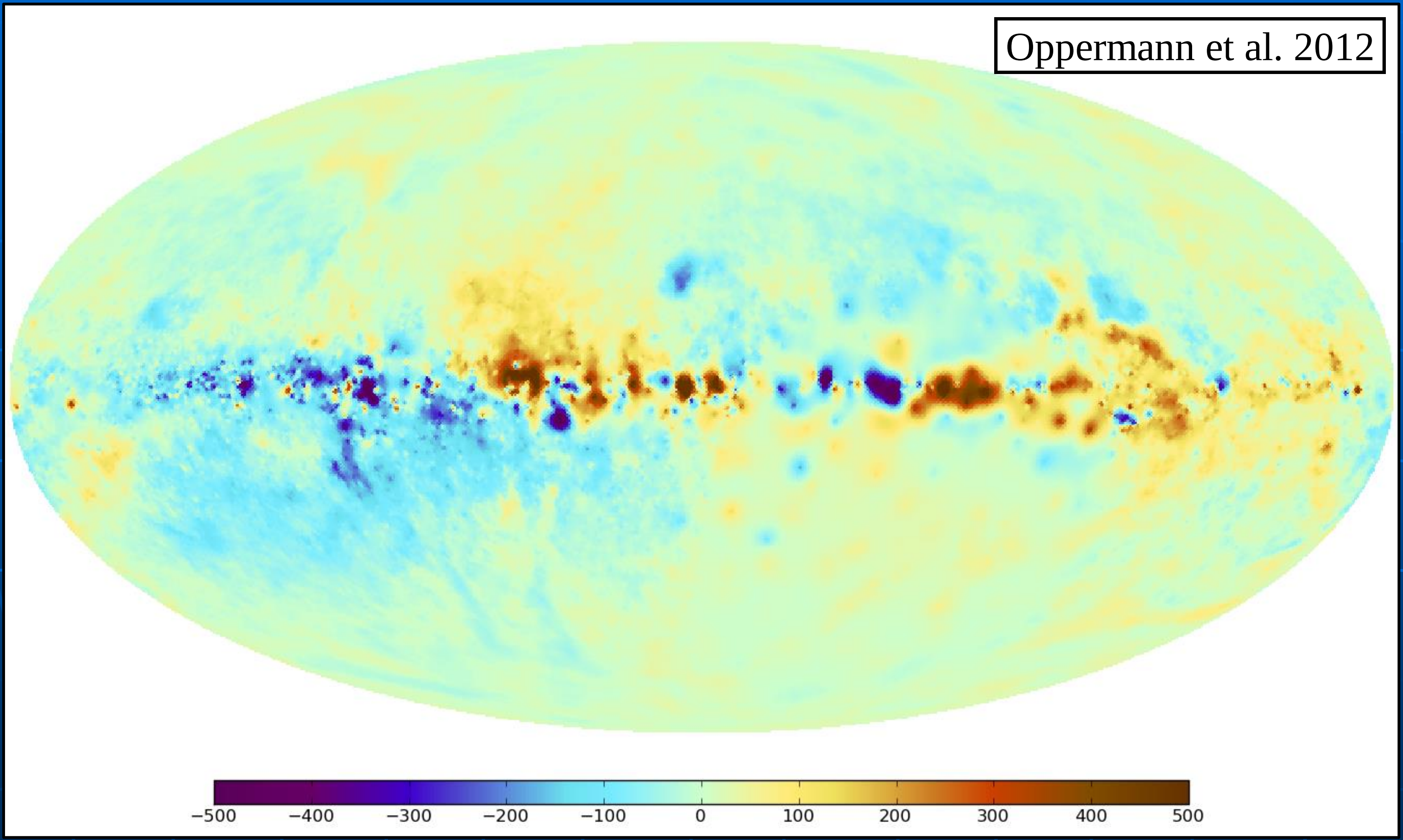
(VLA NVSS 21cm)

≈37.000 sources (≈1 source per deg$^2$)



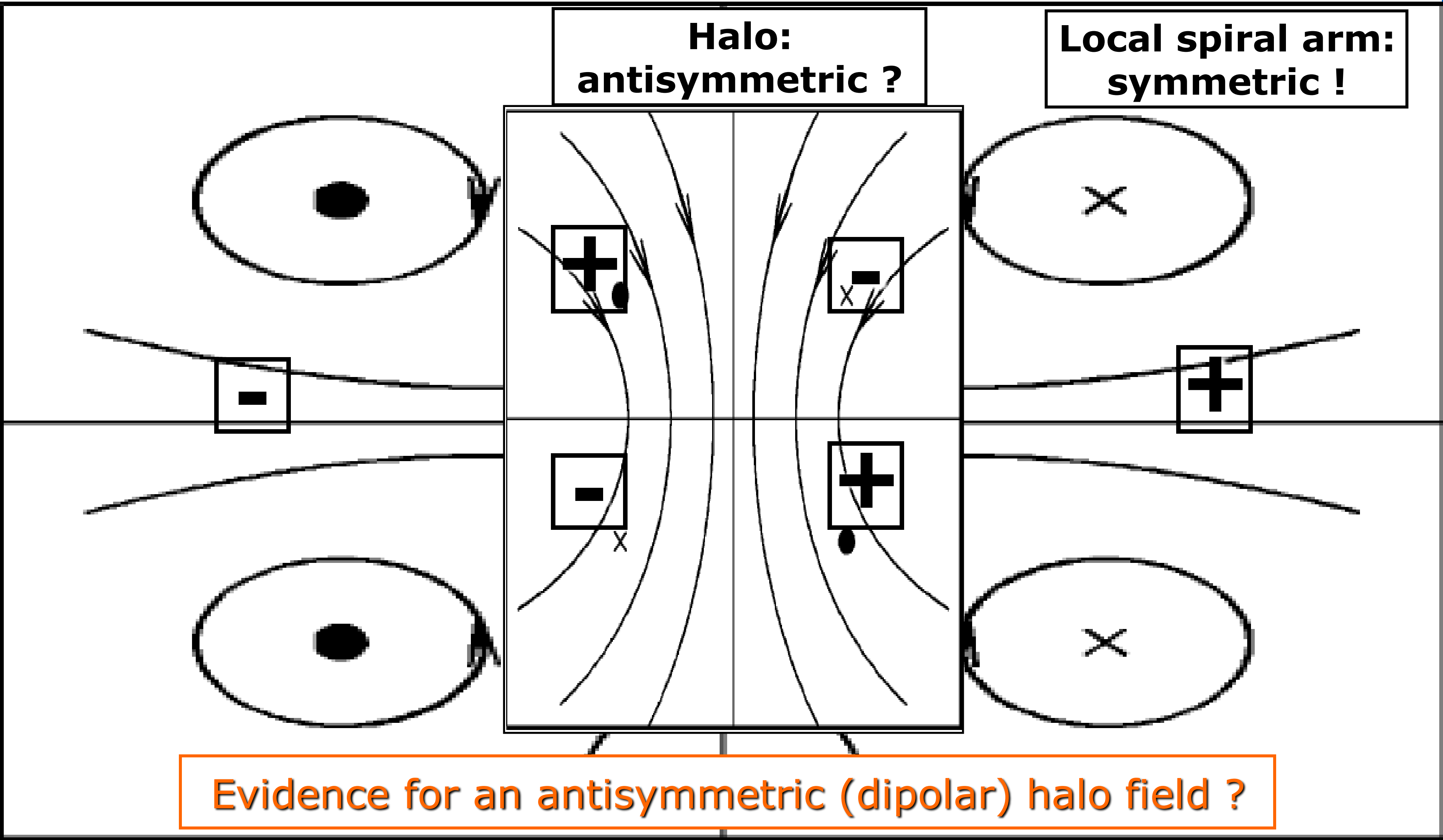

Large-scale field symmetry

# The RM Sky (41330 sources)




*Evidence for an antisymmetric (dipolar) halo field ?*

# Dynamo modes of the Milky Way




Evidence for an antisymmetric (dipolar) halo field ?

# Magnetic field model for the Milky Way

The Milky Way is similar to external galaxies – except for 1-2 reversals

Jansson & Farrar 2012

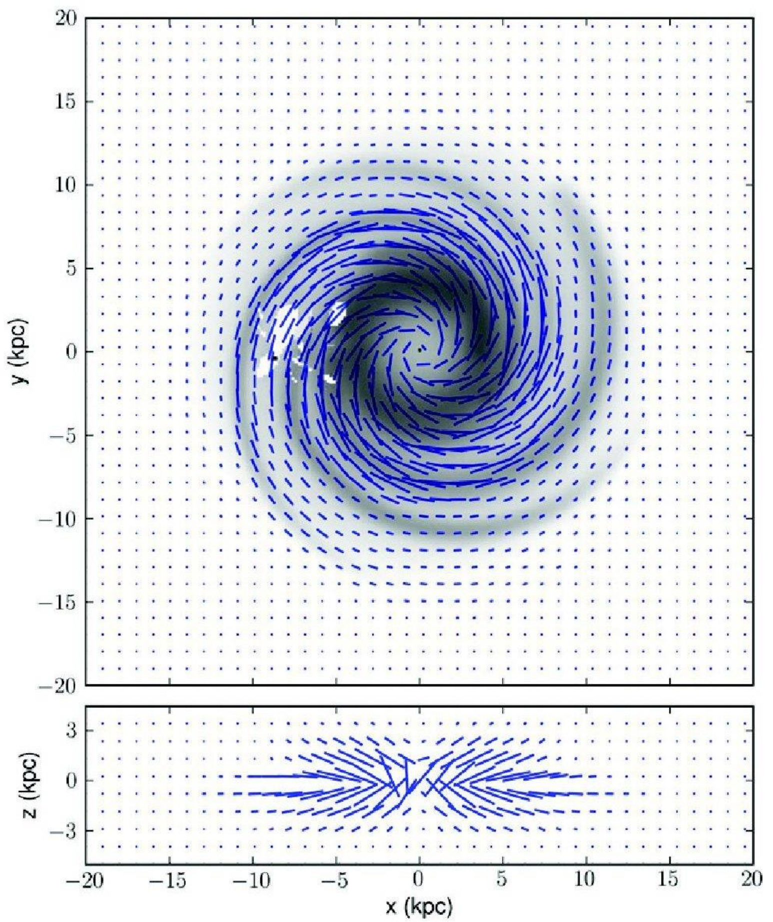
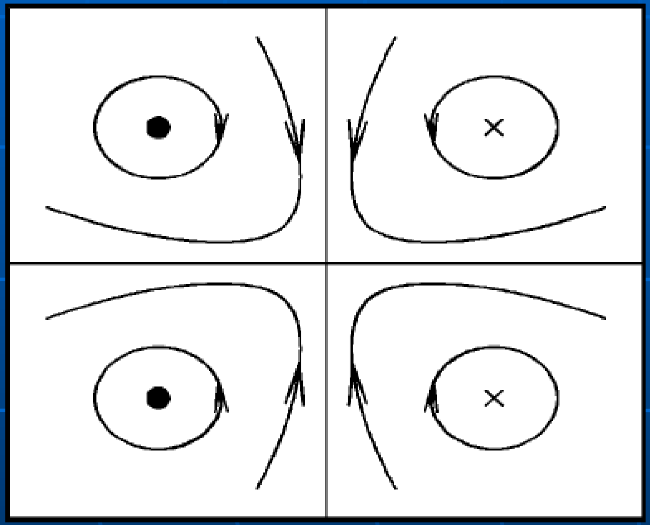



**Figure 9.** Milky Way as seen (in polarization) by an extragalactic observer, face-on (above) and edge-on (below). Plotted "bars" (sometimes referred to as "vectors") are the would-be-observed polarization angles, rotated 90° to line up with the magnetic field orientation. Lengths of bars are proportional to polarization intensity. Faraday depolarization and beam depolarization are neglected. The face-on plot is overlaid on the NE2001 thermal electron distribution.

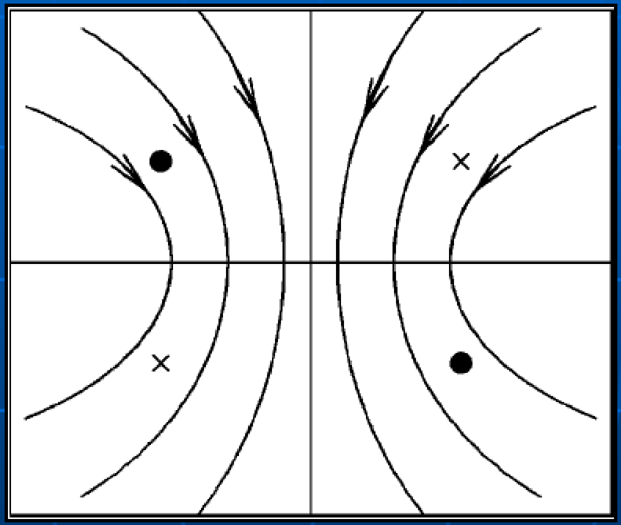
# Regular magnetic fields in the Galactic halo ?

Quadrupolar (symmetric)

Dipolar (antisymmetric)



Galactic plane

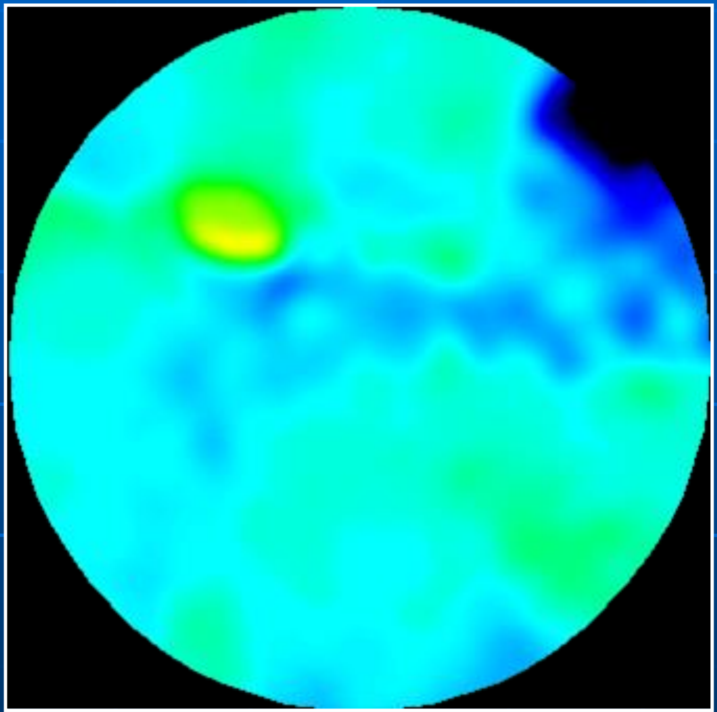


Dynamo
(thin disk)

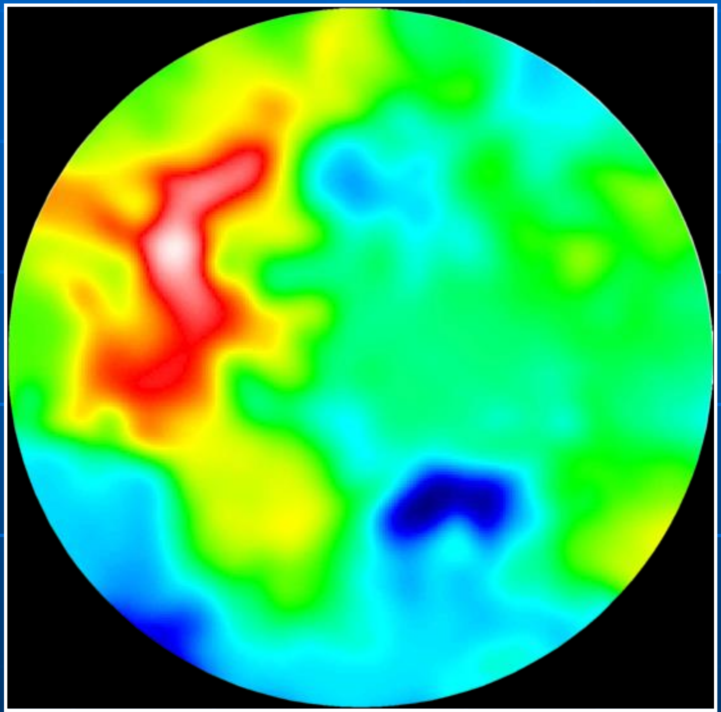
Dynamo
(thick disk)
or primordial field

# Faraday RMs of extragalactic sources

Mao et al. 2010



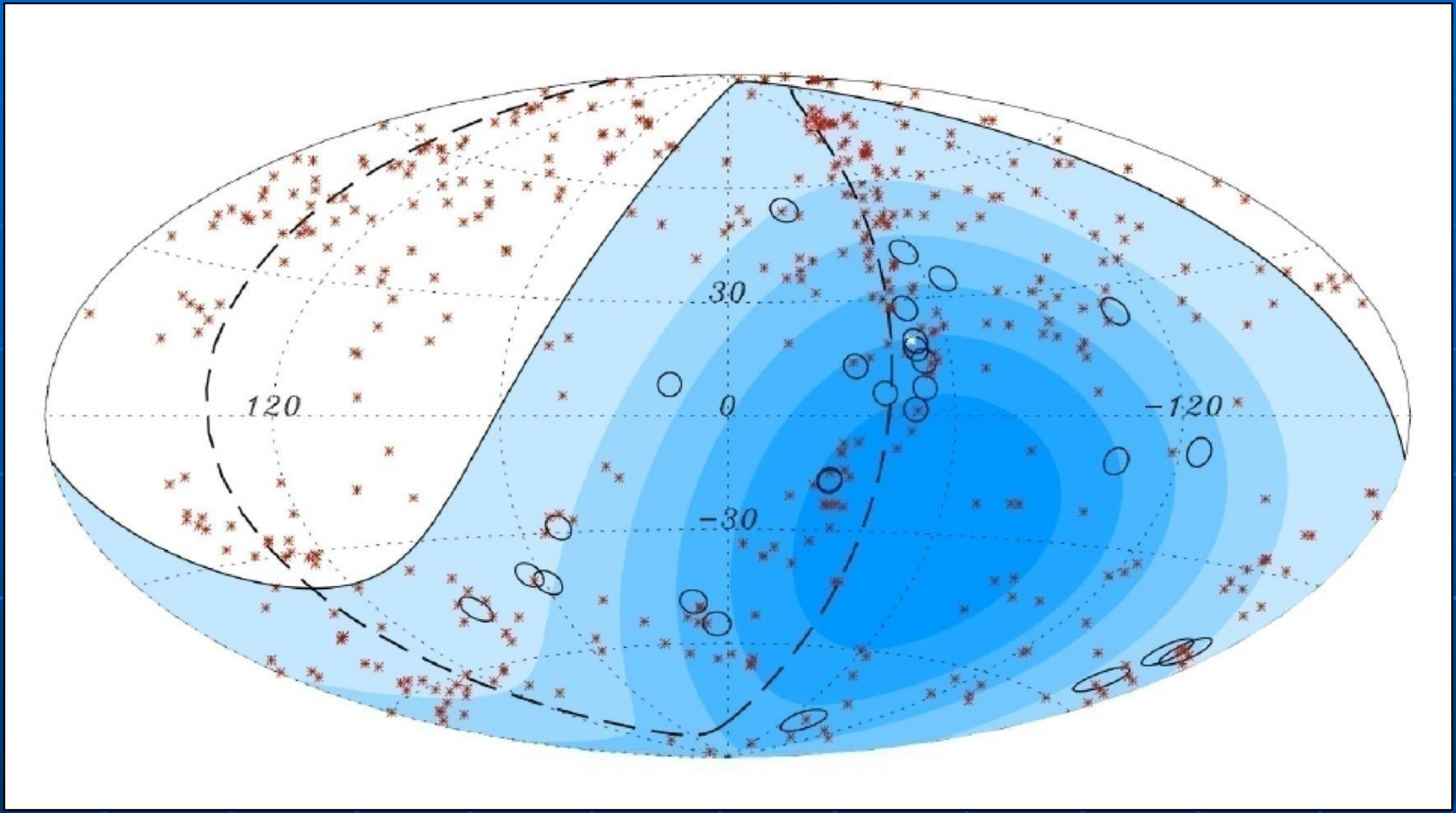
North Galactic Pole



South Galactic Pole

Weak vertical field (≈ 0.3μG) only towards the south:
**No** significant large-scale vertical field !

# AUGER UHECR events (> 5 $10^{19}$ eV)



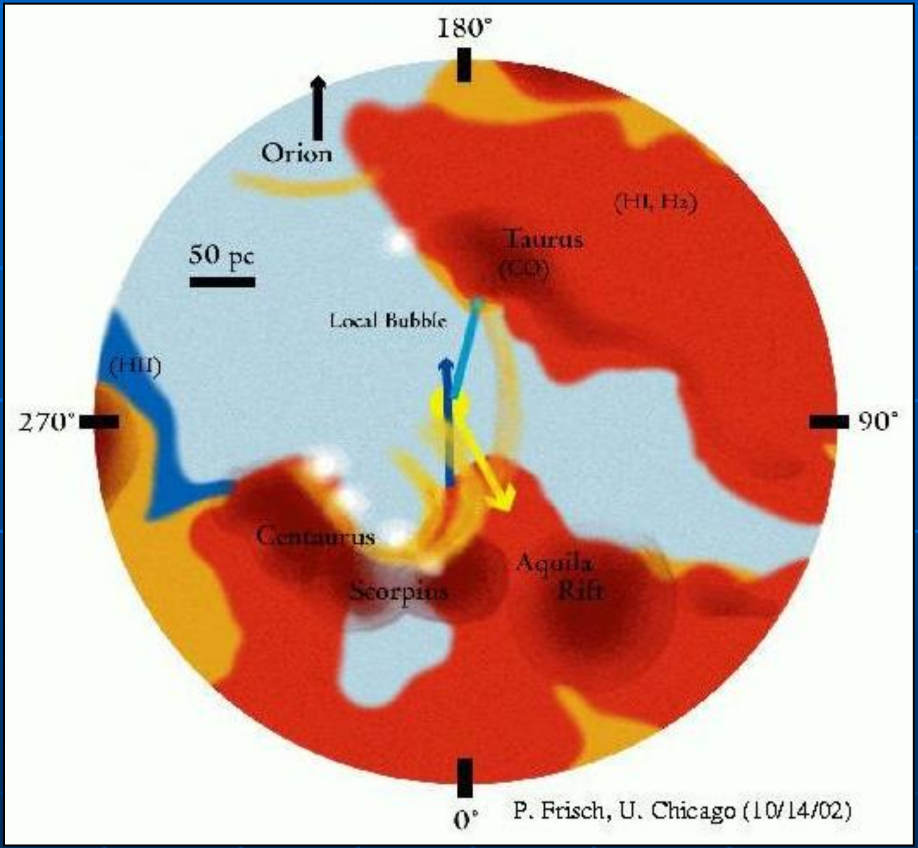

Localizing the UHECR sources requires
detailed knowledge about the Milky Way´s magnetic field

# The local environment

- Since 5-10 Myr the solar system passes through a low-density region generated by SNs, the Local Bubble

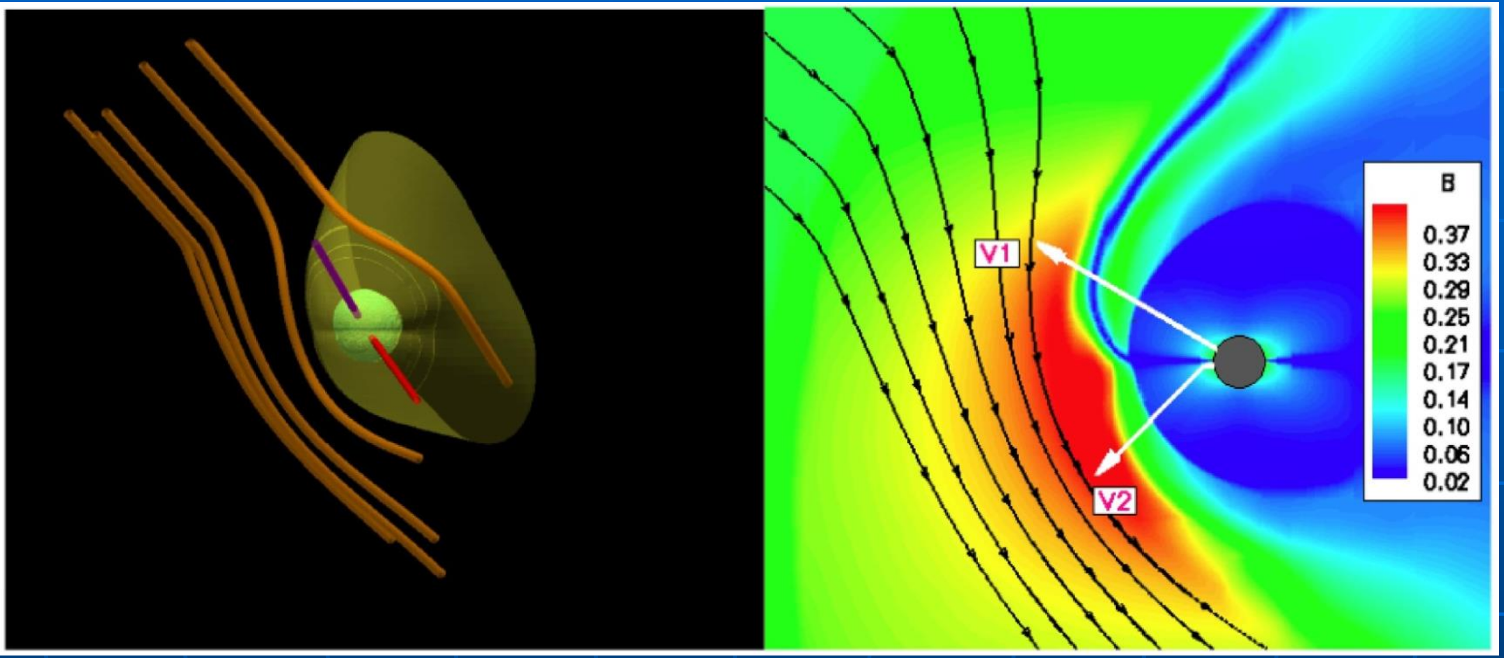
- A region of moderate density, the Local Interstellar Cloud, will be reached in ≈ 0.1 Myr

- Almost nothing is known about the local field



# The very local field

Opher et al. 2007




- Voyager: The very local field is strongly tilted with respect to the Galactic plane

  ⟶ The orientation of the very local field differs strongly from that of the large-scale Galactic magnetic field

# Summary:
# Magnetic fields in the Milky Way

- The ordered disk field has a spiral pattern with a pitch angle similar to that of the optical arms

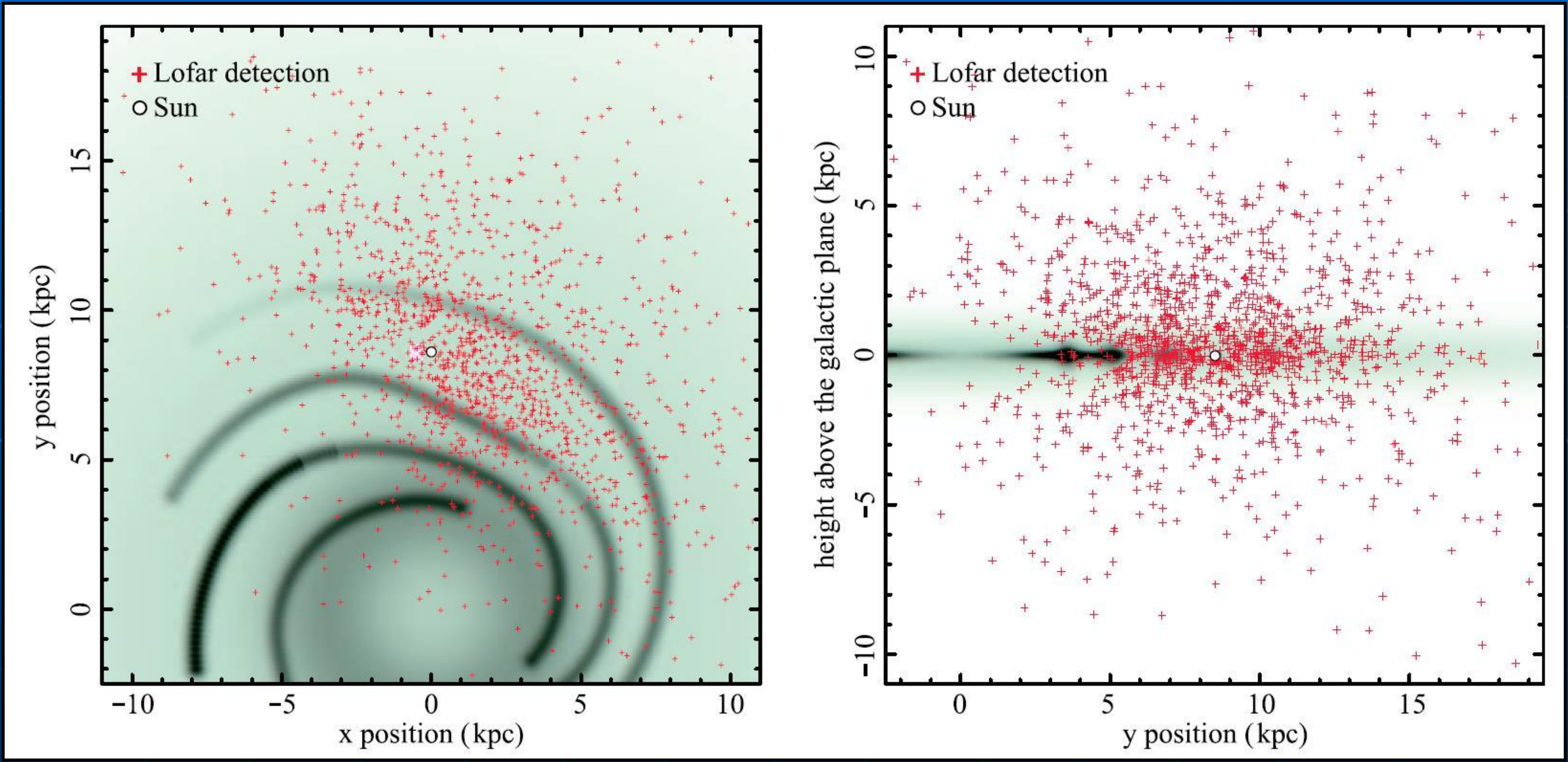
- The large-scale disk field has a large-scale reversal at 0.5-1 kpc inside the solar radius

- The overall structure of the large-scale disk field is not known yet

- The Milky Way has an extended magnetic halo, but nothing is known yet about its structure

# Simulation: LOFAR pulsar survey

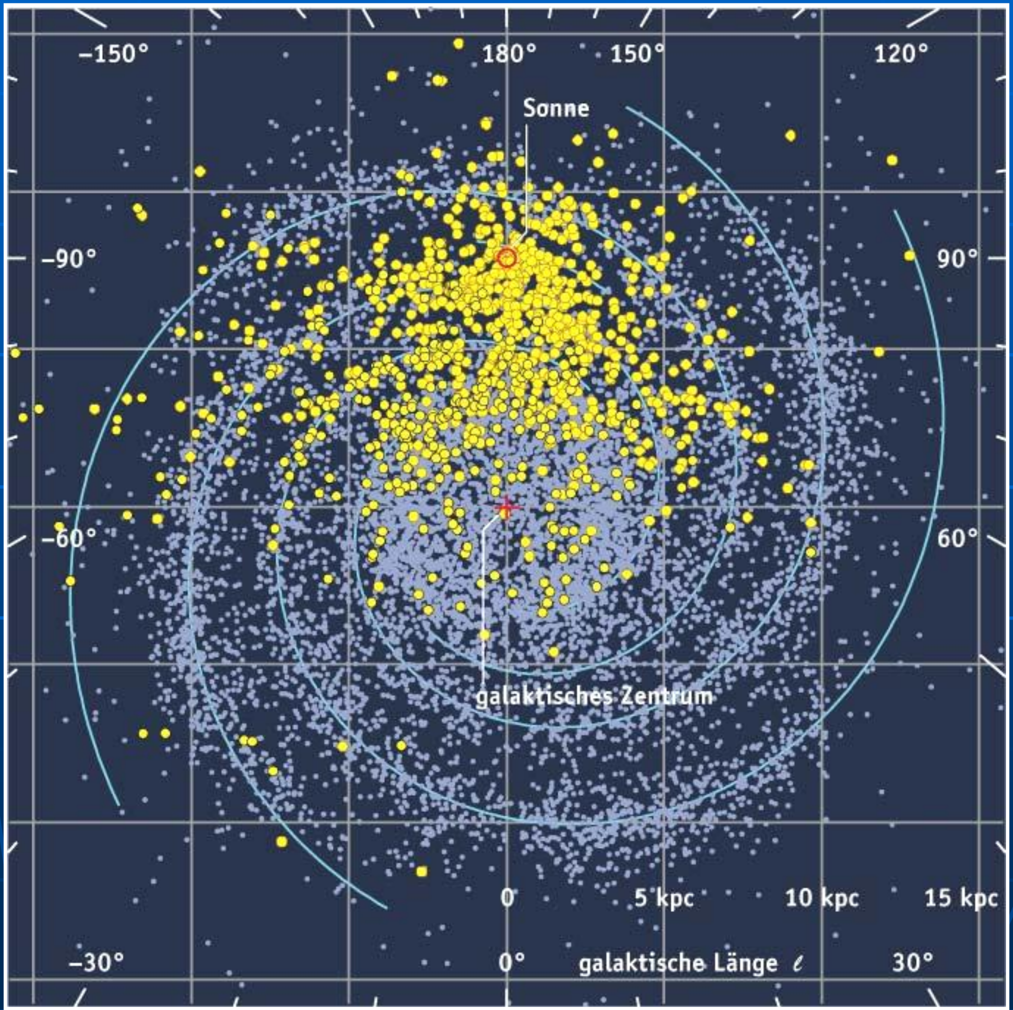
Pulsars detected with LOFAR will be mostly nearby (due to scattering)




Leeuwen & Stappers 2010

# Future survey of rotation measures of pulsars in the Milky Way with the SKA

Known pulsars and pulsars to be detected with the SKA (≈30000)




Cordes 2001