The Galactic Magnetic Fields:
Progress over the last 30 years

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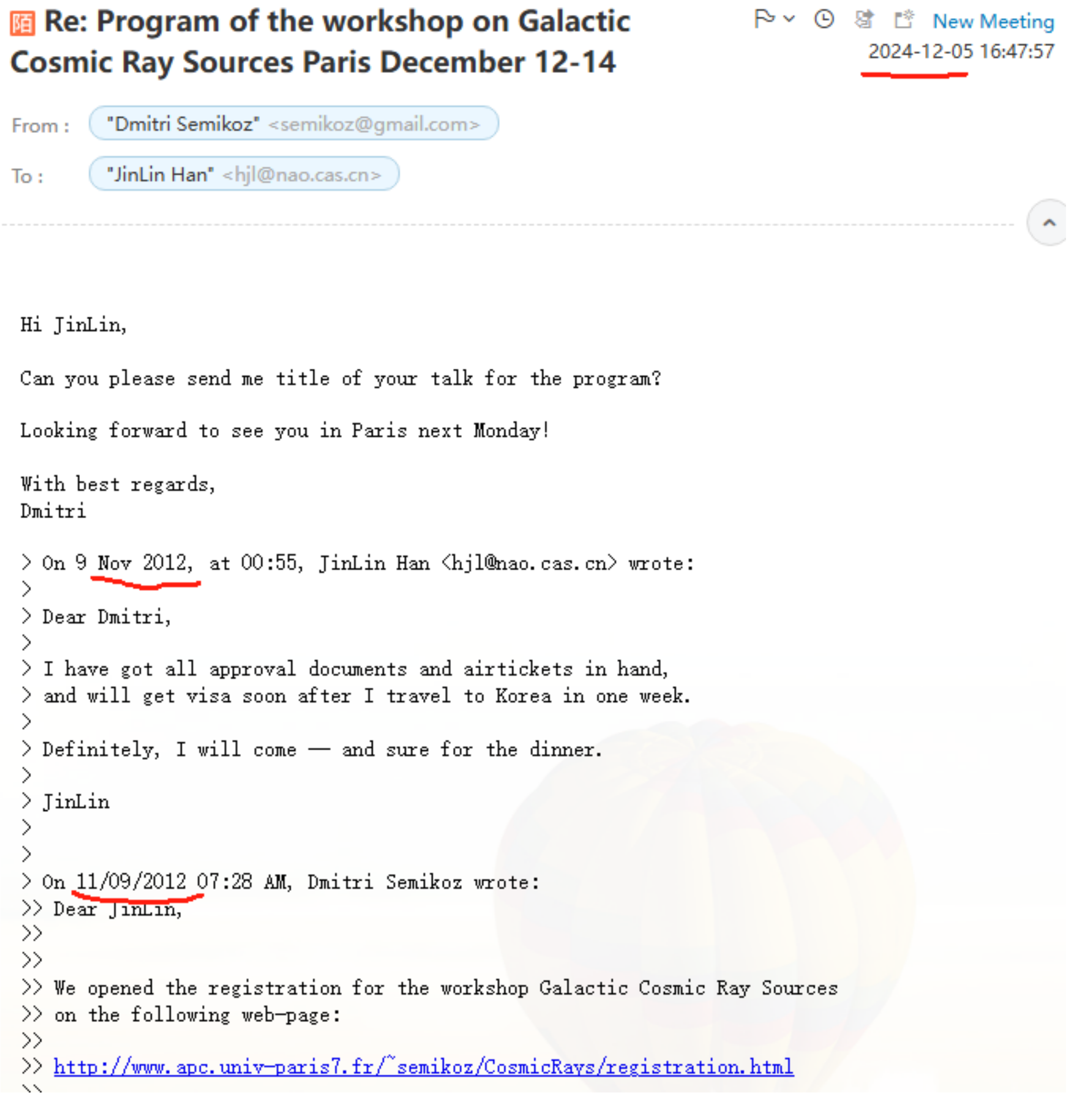

Re: Program of the workshop on Galactic Cosmic Ray Sources Paris December 12-14

2024-12-05 16:47:57

From : "Dmitri Semikoz" <semikoz@gmail.com>

To : "JinLin Han" <hjl@nao.cas.cn>

Hi JinLin,

Can you please send me title of your talk for the program?

Looking forward to see you in Paris next Monday!

With best regards,
Dmitri

> On 9 Nov 2012, at 00:55, JinLin Han <hjl@nao.cas.cn> wrote:
>
> Dear Dmitri,
>
> I have got all approval documents and airtickets in hand,
> and will get visa soon after I travel to Korea in one week.
>
> Definitely, I will come — and sure for the dinner.
>
> JinLin
>
>
> On 11/09/2012 07:28 AM, Dmitri Semikoz wrote:
>> Dear JinLin,
>>
>>
>> We opened the registration for the workshop Galactic Cosmic Ray Sources
>> on the following web-page:
>>
>> http://www.apc.univ-paris7.fr/~semikoz/CosmicRays/registration.html

Sincerely thank Dmitri Semikoz and other organizers to invite me here.

International Symposium of Cosmic Magnetic Fields

2025.10.12-16

NAOC-headquarter, Beijing, China

Topics

- Magnetic fields of
- Magnetic fields on
- Magnetic fields in
- Magnetic fields in
  propagation
- Magnetic fields in
- Magnetic fields in
  processes
- Magnetic fields in

Welcome to Beijing, China !

The Galactic Magnetic Fields: Progress over the last 30 years

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The Milky Way：
an edge-on spiral galaxy with a bar

Courtesy： R. Hurt 2008

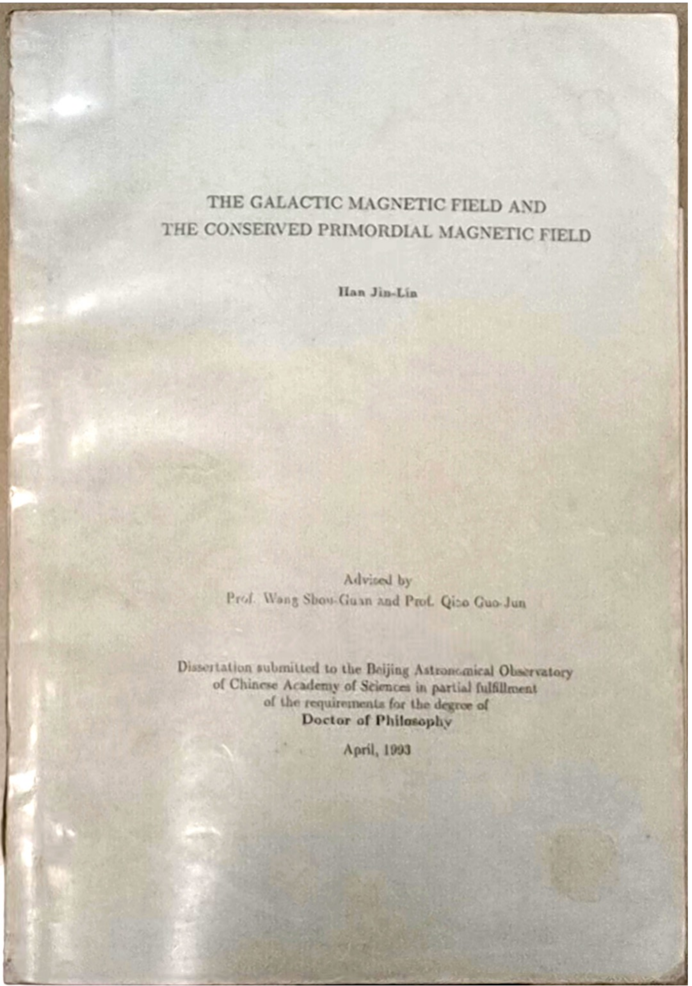
Over Last 30 years, a lot of progresses on understanding the Milky Way

- WMAP and Planck measured the full sky polarization at n*10GHz & m*100GHz
- Gaia measured billion stars, position, color, spectra ...
- BeSSeL projects measured many key points for spiral structures

- So many telescopes get capbility to measure polarization
- So many polarization surveys done for the Galactic plane
- So many radio sources get the Faraday rotation meaured
- So many pulsars discovered ...

==> Much better understanding on the structure of the Milky Way.

Started from my PhD phase (1989-1993) on magnetic field structure of the Milky Way



THE GALACTIC MAGNETIC FIELD AND
THE CONSERVED PRIMORDIAL MAGNETIC FIELD

Han Jin-Lin

Advised by
Prof. Wang Shou-Guan and Prof. Qiao Guo-Jun

Dissertation submitted to the Beijing Astronomical Observatory
of Chinese Academy of Sciences in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

April, 1993

THE LOCAL MAGNETIC FIELD IN OUR GALAXY*

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United Laboratory for Optical Astronomy, Chinese Academy of Sciences and Department of Geophysics, Beijing University, Beijing 100875, China

Abstract. The pitch angles of the local magnetic field in our Galaxy, previously derived from Rotation Measures (RMs) of pulsars by many authors, are not consistent with each other and with the pitch angles of the local spiral arms. That may be due to the fact that the used pulsar samples are located in different arms in which the directions of the magnetic fields are different. In this paper 2-D and 3-D models for the local magnetic field based on spiral arms are proposed for fitting the RMs of 129 nearby pulsars. In our models the amplitude of the uniform field changes sinusoidally to avoid abrupt reversals, and the directions are parallel or anti-parallel. The best-fitting 2-D model shows that in the Orion arm the strength of the regular field component is $2.4 \pm 0.3 \mu G$, with its direction towards $l = 73^o \pm 3^o$. There is a direction reversal in Sagittarius-Carina arm beginning at $D_{rev} = 0.3 Kpc$. The half "wavelength" of the sinusoidal variation is about $1.7 \pm 0.4 Kpc$. The best fitting 3-D model shows that the scale height is only about 0.16 Kpc, which means that the local uniform field is confined in the galactic plane. The strongest regular field in this 3-D model is about $2.8 \pm 0.3 \mu G$. The results from both, the 2-D model as well as the 3-D model, show that the orientation of the field is in excellent agreement with the spiral arms.

Key words: The Galaxy, Magnetic Field, Rotation Measure, Pulsars

1. Introduction

There are extensive studies of magnetic fields in spiral galaxies during the recent years. The general conclusion is that the regular fields have their strength at about several μG, and that the magnetic field lines follow more or less the spiral arms (e.g. Wielebinski, 1990; Beck, 1991).

In our Galaxy the existence of the magnetic field was deduced from the discovery of the linear polarization of starlight (Hall, 1949; Hiltner, 1949). The conclusion from reanalysing the data of stellar optical polarization is that the magnetic field is aligned with the galactic plane and in the direction of $l = 45^o$ in the vicinity of the Sun, but beyond a circle of 600 pc it is directed toward $l = 70^o$ (Ellis and Aron, 1978). Simard-Normandin and Kronberg (1989) analysed the RMs of extragalactic radio sources and found that the local field point towards $l = 76^o$ with reversals at the neighbouring arms. Sofue and Fujimoto (1983) found the bisymmetric magnetic field configuration could fit the RMs of extragalactic radio sources well. Inoue and Tabara (1981) concluded from a study of RMs of extragalactic sources and pulsars and optical polarization of starlight that $B_{reg} = 1.6 \pm 0.4 \mu G$ and $l_B = 100 \pm 10^o$ for the local field. There have been many attempts to derive the local or global magnetic field in our Galaxy from RMs of pulsars since the pioneering work of Manchester (1974). Because the pulsars have no intrinsic Faraday rotation, $\langle n_e \rangle$ along the line-of-sight can be estimated from Dispersion Measures (DMs). Pulsars are located

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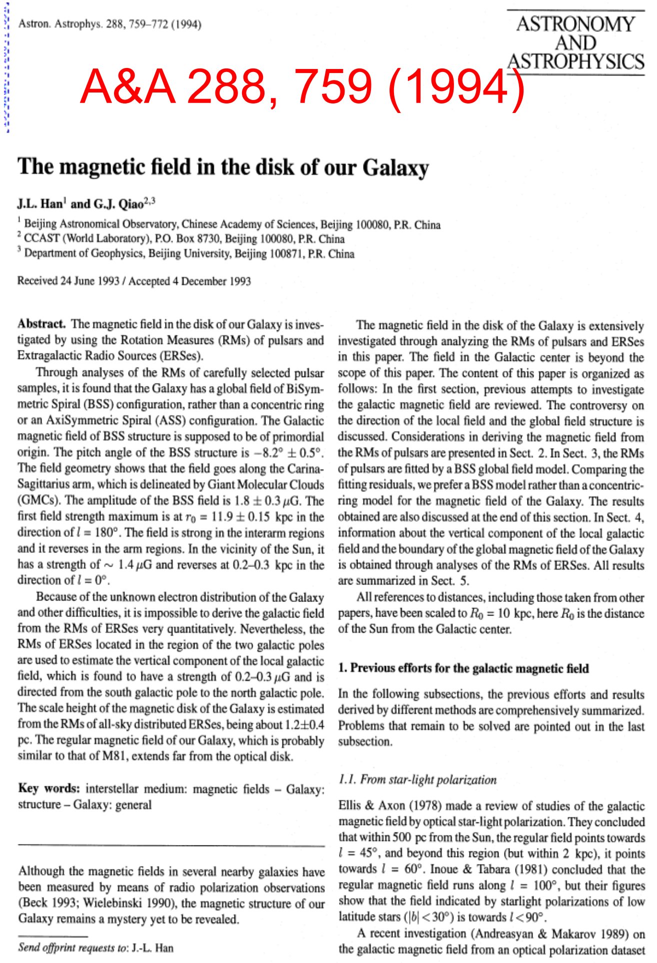
* The project was supported by NSF of China

Krause et al. (eds.), The Cosmic Dynamo, 279–281.

IAU Symp. No. 157, 279 (1993)



Astron. Astrophys. 288, 759–772 (1994)

ASTRONOMY
AND
ASTROPHYSICS

A&A 288, 759 (1994)

The magnetic field in the disk of our Galaxy

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Abstract. The magnetic field in the disk of our Galaxy is investigated by using the Rotation Measures (RMs) of pulsars and Extragalactic Radio Sources (ERSes).

Through analyses of the RMs of carefully selected pulsar samples, it is found that the Galaxy has a global field of BiSymmetric Spiral (BSS) configuration, rather than a concentric ring or an AxiSymmetric Spiral (ASS) configuration. The Galactic magnetic field of BSS structure is supposed to be of primordial origin. The pitch angle of the BSS structure is $-8.2° \pm 0.5°$. The field geometry shows that the field goes along the Carina-Sagittarius arm, which is delineated by Giant Molecular Clouds (GMCs). The amplitude of the BSS field is $1.8 \pm 0.3\,\mu$G. The first field strength maximum is at $r_0 = 11.9 \pm 0.15$ kpc in the direction of $l = 180°$. The field is strong in the interarm regions and it reverses in the arm regions. In the vicinity of the Sun, it has a strength of $\sim 1.4\,\mu$G and reverses at 0.2–0.3 kpc in the direction of $l = 0°$.

Because of the unknown electron distribution of the Galaxy and other difficulties, it is impossible to derive the galactic field from the RMs of ERSes very quantitatively. Nevertheless, the RMs of ERSes located in the region of the two galactic poles are used to estimate the vertical component of the local galactic field, which is found to have a strength of 0.2–0.3 μG and is directed from the south galactic pole to the north galactic pole. The scale height of the magnetic disk of the Galaxy is estimated from the RMs of all-sky distributed ERSes, being about 1.2±0.4 pc. The regular magnetic field of our Galaxy, which is probably similar to that of M81, extends far from the optical disk.

Key words: interstellar medium: magnetic fields – Galaxy: structure – Galaxy: general

Although the magnetic fields in several nearby galaxies have been measured by means of radio polarization observations (Beck 1993; Wielebinski 1990), the magnetic structure of our Galaxy remains a mystery yet to be revealed.

The magnetic field in the disk of the Galaxy is extensively investigated through analyzing the RMs of pulsars and ERSes in this paper. The field in the Galactic center is beyond the scope of this paper. The content of this paper is organized as follows: In the first section, previous attempts to investigate the galactic magnetic field are reviewed. The controversy on the direction of the local field and the global field structure is discussed. Considerations in deriving the magnetic field from the RMs of pulsars are presented in Sect. 2. In Sect. 3, the RMs of pulsars are fitted by a BSS global field model. Comparing the fitting residuals, we prefer a BSS model rather than a concentric-ring model for the magnetic field of the Galaxy. The results obtained are also discussed at the end of this section. In Sect. 4, information about the vertical component of the local galactic field and the boundary of the global magnetic field of the Galaxy is obtained through analyses of the RMs of ERSes. All results are summarized in Sect. 5.

All references to distances, including those taken from other papers, have been scaled to $R_0 = 10$ kpc, here R_0 is the distance of the Sun from the Galactic center.

1. Previous efforts for the galactic magnetic field

In the following subsections, the previous efforts and results derived by different methods are comprehensively summarized. Problems that remain to be solved are pointed out in the last subsection.

1.1. From star-light polarization

Ellis & Axon (1978) made a review of studies of the galactic magnetic field by optical star-light polarization. They concluded that within 500 pc from the Sun, the regular field points towards $l = 45°$, and beyond this region (but within 2 kpc), it points towards $l = 60°$. Inoue & Tabara (1981) concluded that the regular magnetic field runs along $l = 100°$, but their figures show that the field indicated by starlight polarizations of low latitude stars ($|b| < 30°$) is towards $l < 90°$.

A recent investigation (Andreasyan & Makarov 1989) on the galactic magnetic field from an optical polarization dataset

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Send offprint requests to: J.-L. Han

Observational B-tracers: What info out?

1. Zeeman splitting: *parallel field, in situ (masers, clouds)*

$\Delta\nu \propto B_{//}$ ------ maser regions & coulds

2. Polarization of starlight: *perpendicular field in 2 or 3 kpc*

orientation // $B_{\perp}$ ------------- stars

3. Polarization at infrared, mm, submm: *perpendicular field*

orientation // $B_{\perp}$ ------------- clouds or regions

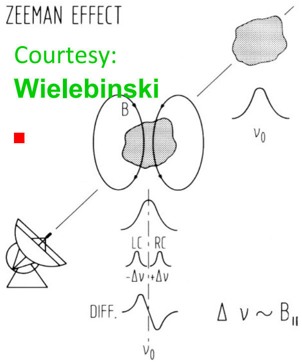
4. Synchrotron radiation: *vertical field structures (added)*

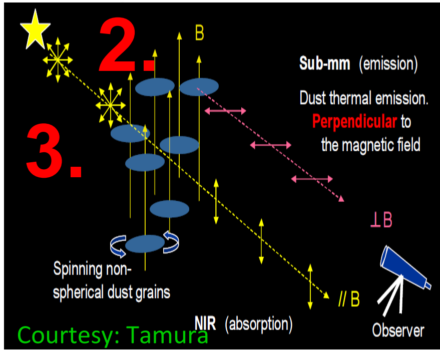
total intensity $S \propto B_{\perp}^{2/7}$, $p\% \propto B_{\perp u}^{2} / B_{\perp t}^{2}$

5. Faraday rotation: *parallel field, integrated (the halo & disk)*

$RM \propto \int n_e B_{//} ds$ ------ pulsars + EGSes

1.





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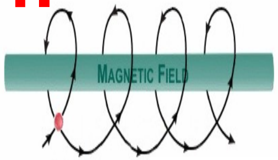

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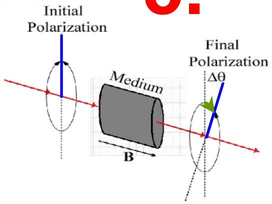
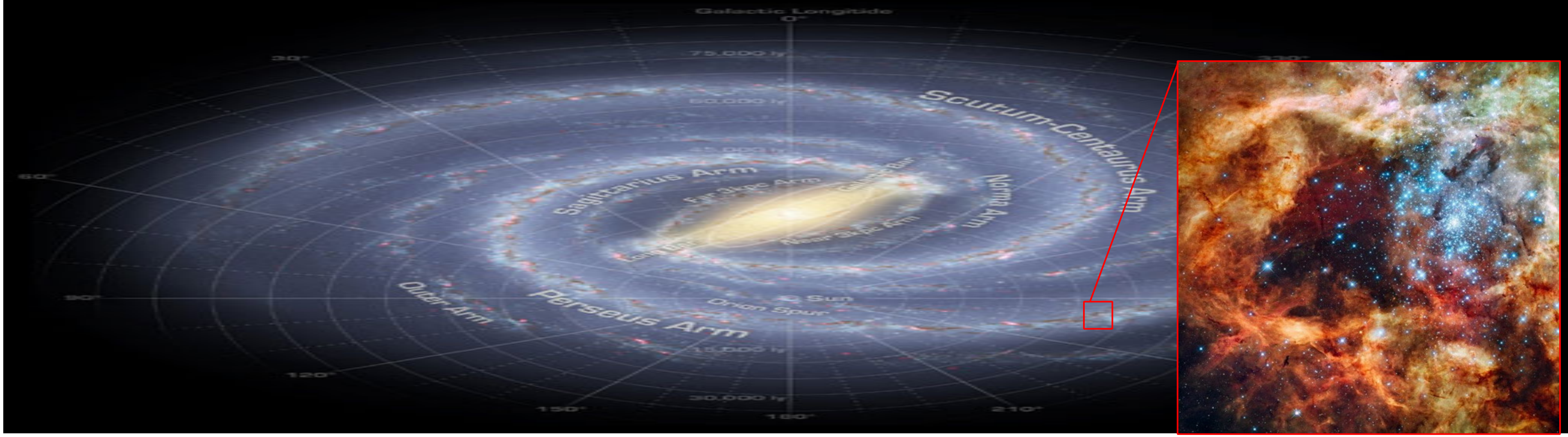
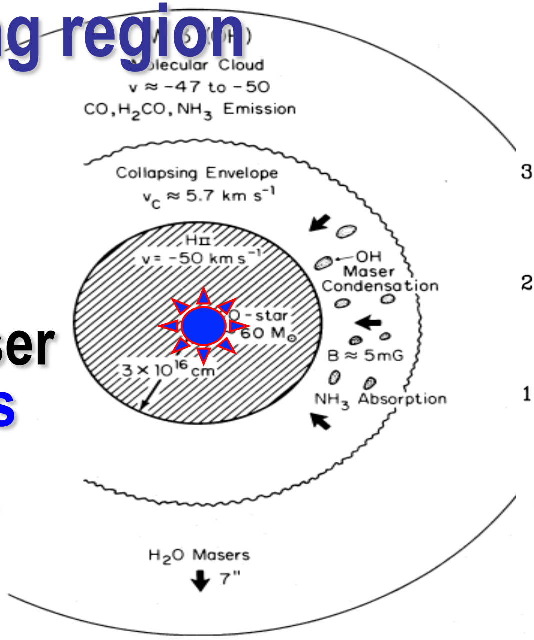


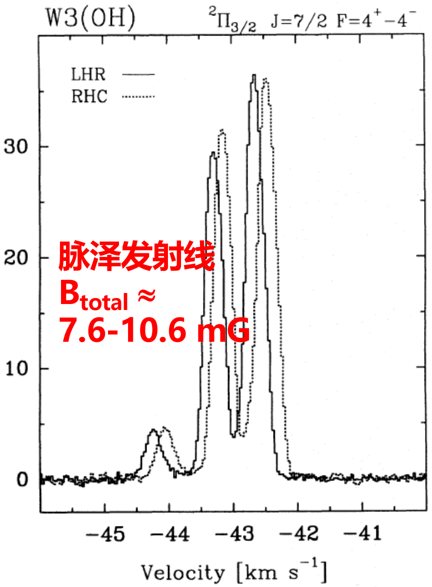


Maser spots near the star-forming region as B-field tracers

Han & Zhang (2007, A&A 464, 609)

- Collect Zeeman splitting data of maser spots in **HII and star formation regions**
- Spots in one region always have the same field orientation!



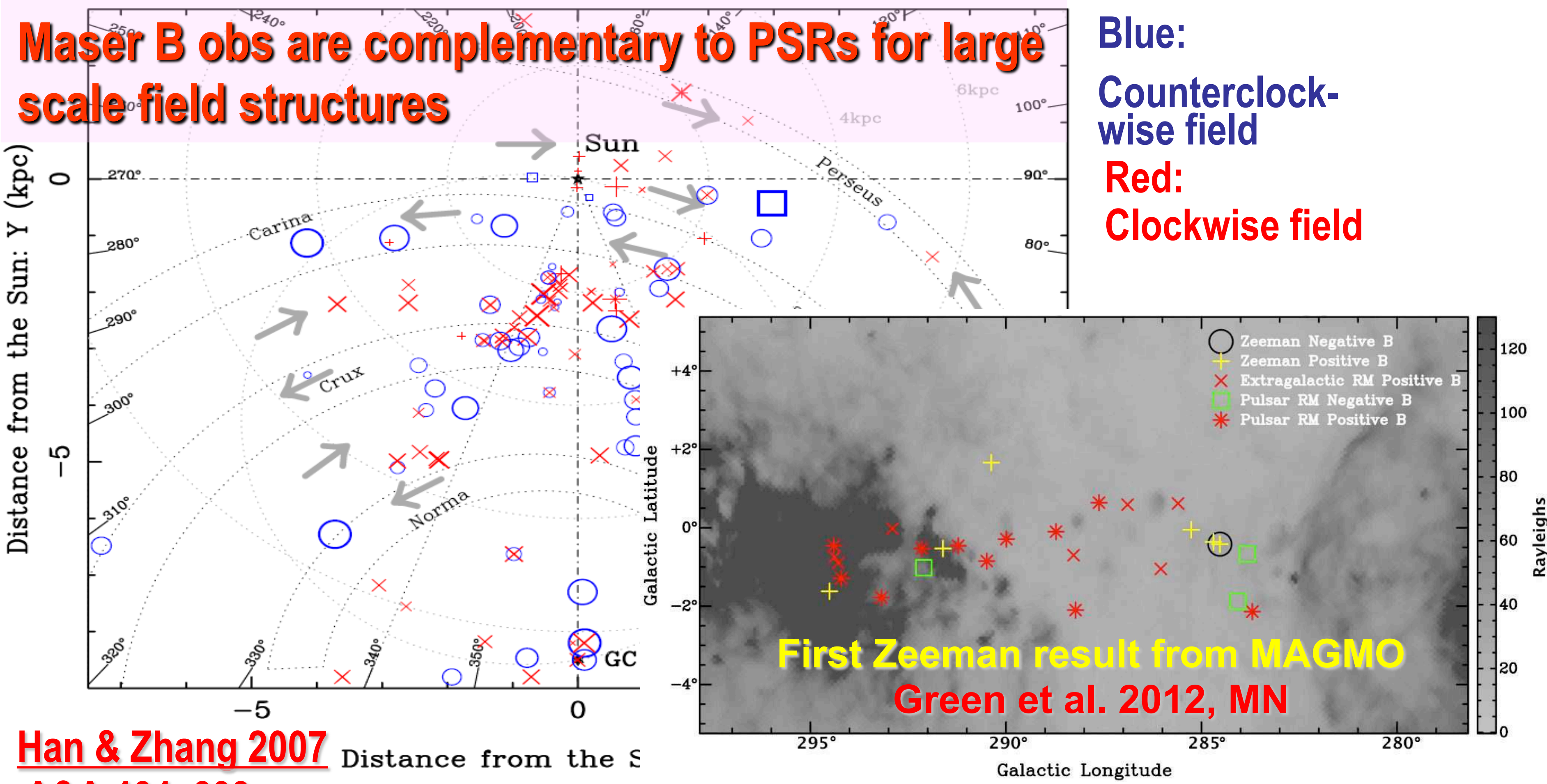


脉泽发射线

$B_{total} \approx$ 7.6-10.6 mG

The Galactic distribution of Zeeman data

In situ AU-scale-B directions coherent in many kpc scale!



Maser B obs are complementary to PSRs for large scale field structures

Blue:

Counterclockwise field

Red:

Clockwise field

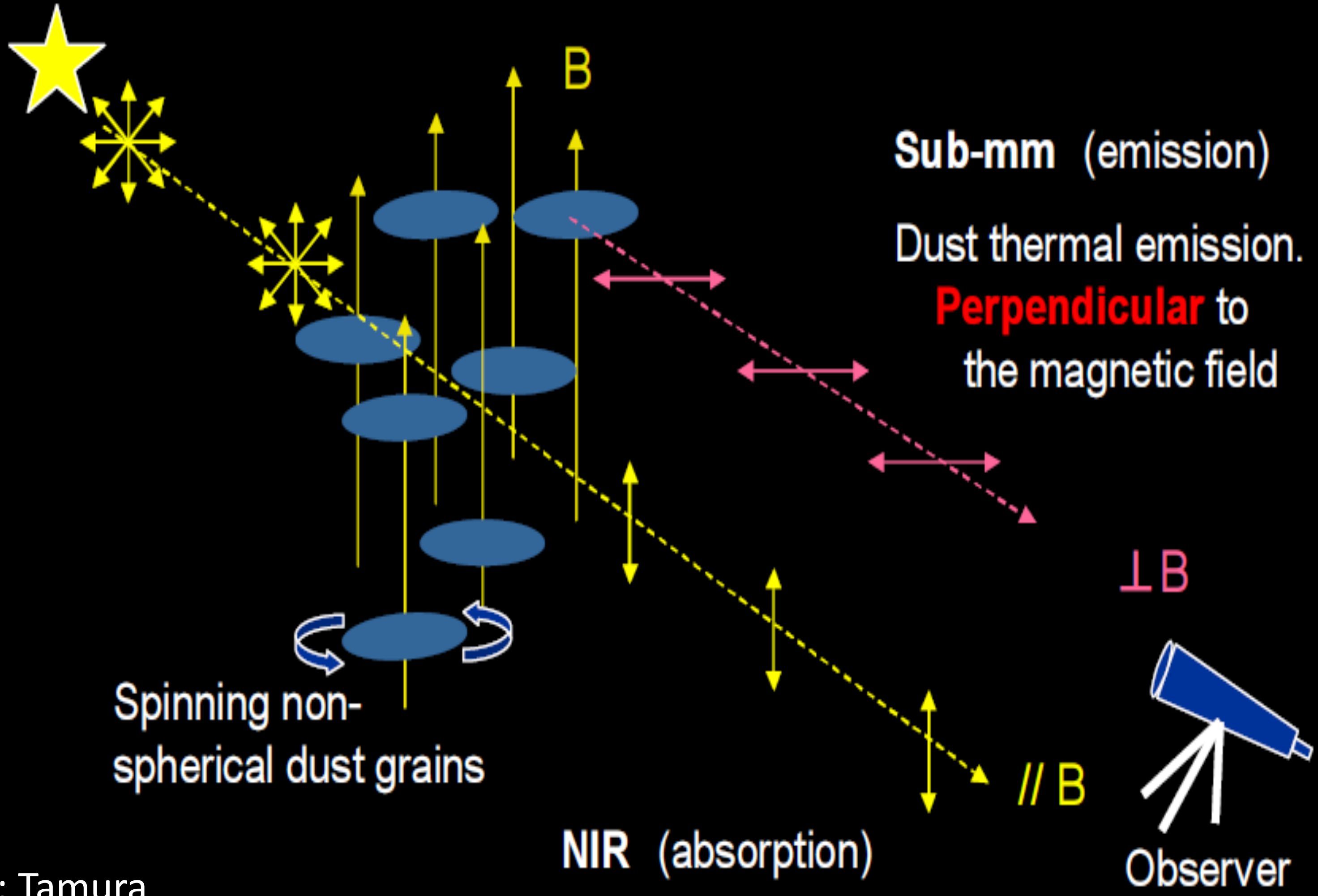
First Zeeman result from MAGMO

Green et al. 2012, MN

Han & Zhang 2007

A&A 464, 609

Magnetic Fields due to dusts: emission or scattering/absorption



Sub-mm (emission)

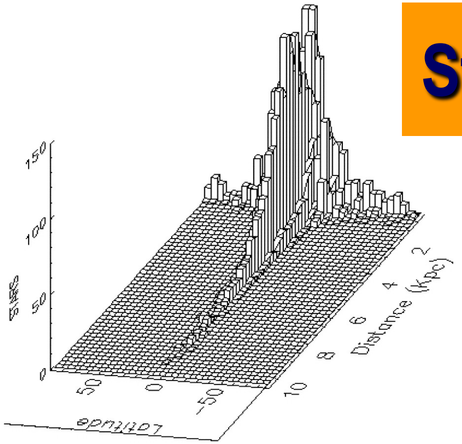
Dust thermal emission. **Perpendicular** to the magnetic field

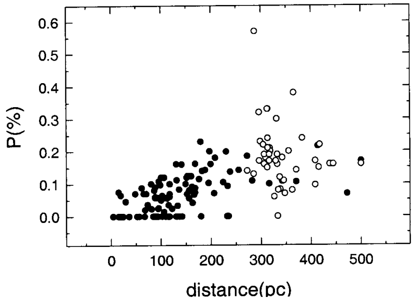
NIR (absorption)

Courtesy: Tamura

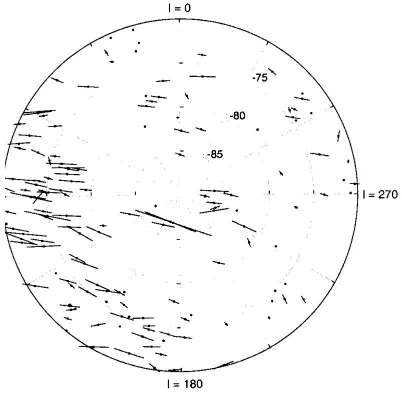
Starlight polarization: *local field // arm*

- 9000 stars have polarization measured
- mostly nearby (1~2kpc)
- polarization percentage increases with distance

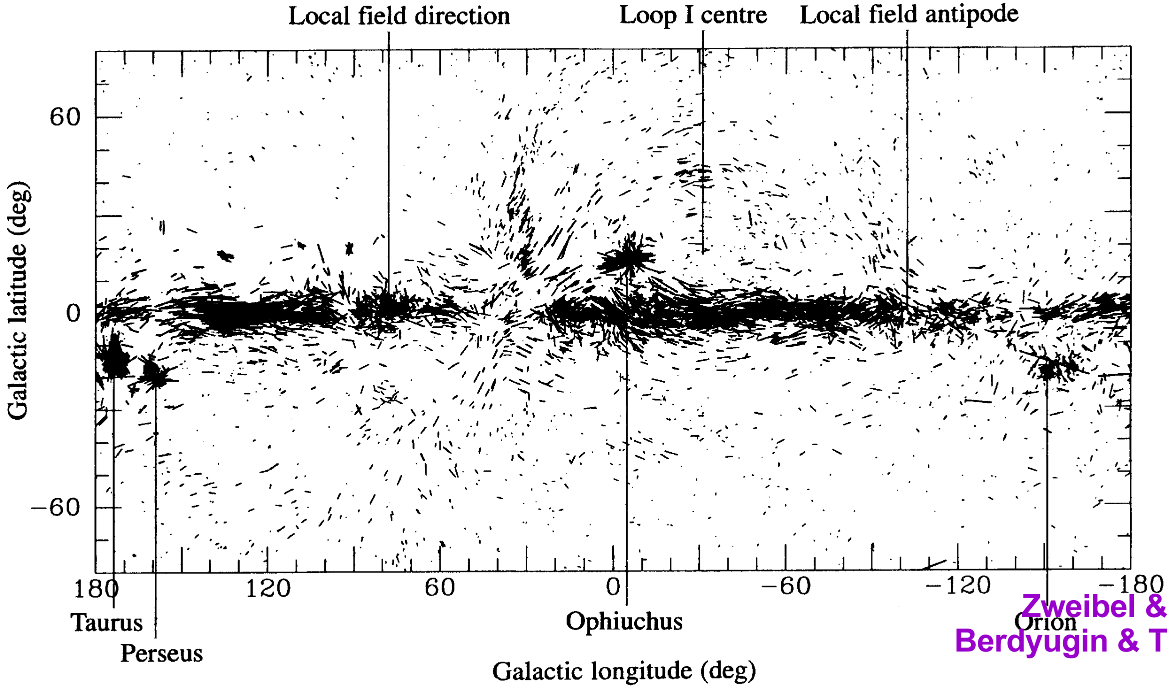




Polarization vs. distance dependence in the SGP area.
w data are plotted with open circles



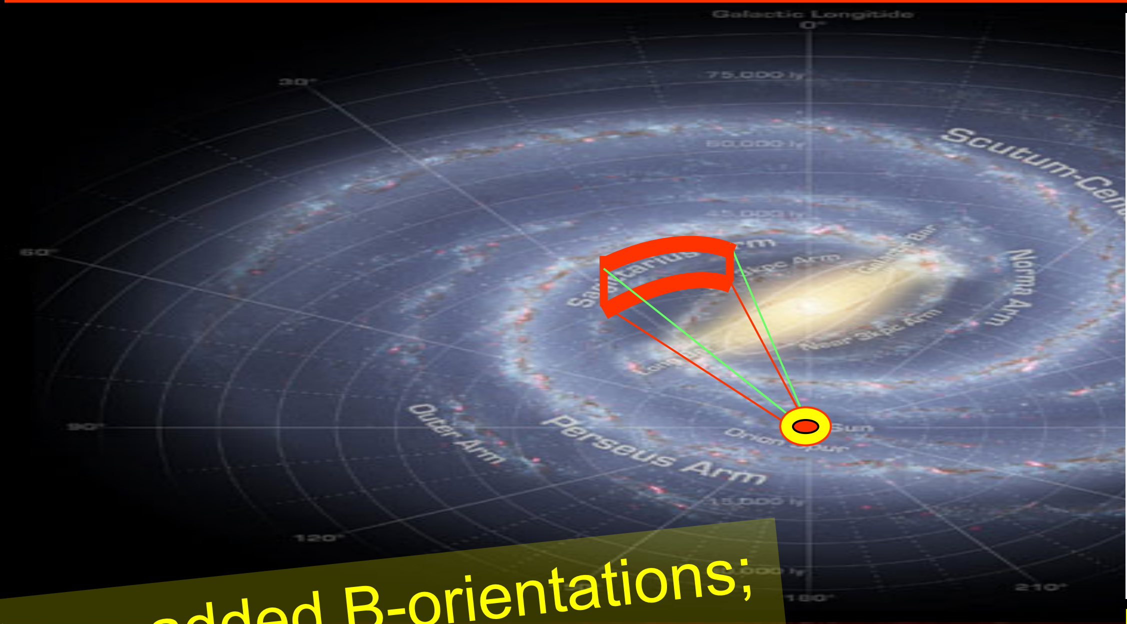
. Polarizations of the stars around the SGP. The length
bar gives the amount of polarization, its direction gives
ection of the polarization plane

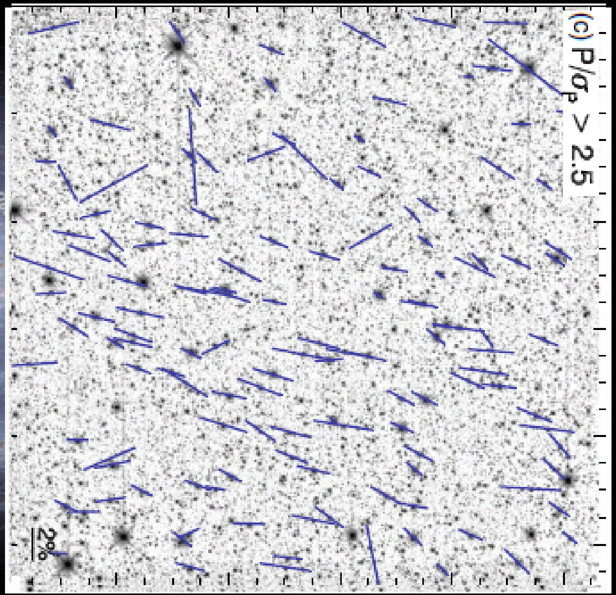


Zweibel & Heiles 1997, Nature 385,131
Berdyugin & Teerikorpi 2001, A&A 368,635

GALACTIC PLANE INFRARED POLARIZATION SURVEY (GPIPS):

Clemens et al. 2012 ApJS: 0.5 million stars; 18<l<56^{O} & |b|<1^{O}





data has been released

Only co-added B-orientations;
no strength, no direction!

Polarization at mm, sub-mm, infrared

Working toward measure B-field of galactic scale

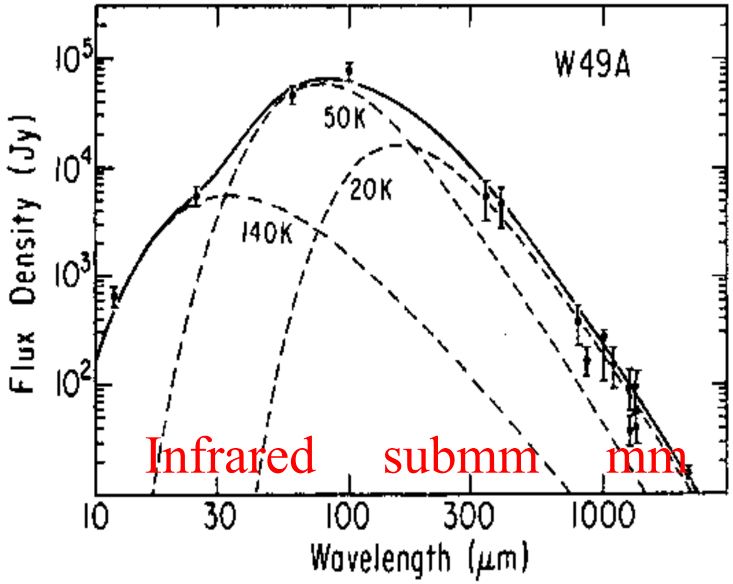
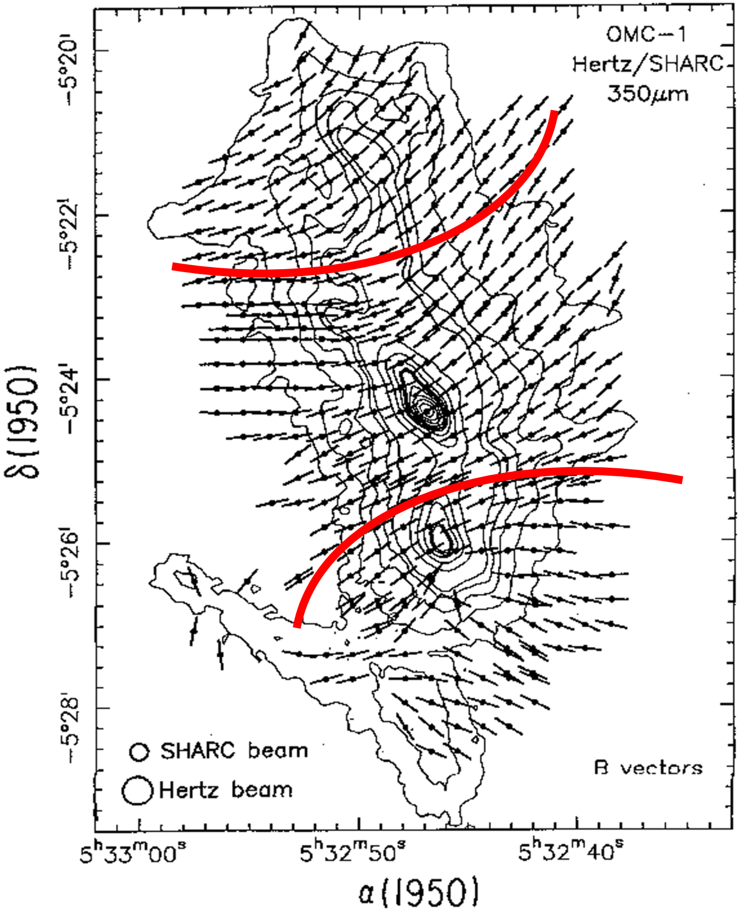


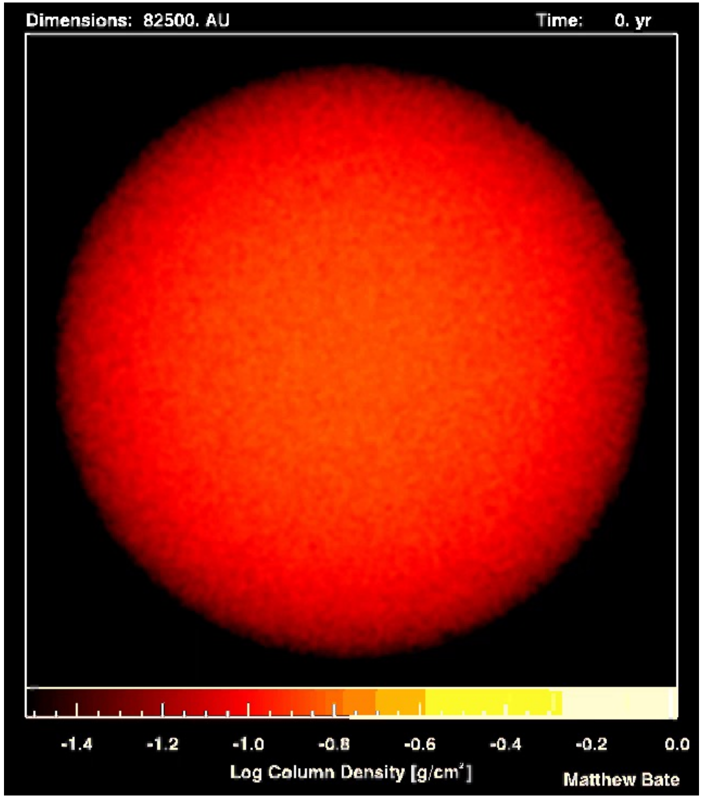
FIG. 2.—Total flux spectrum and derived temperature components of the molecular cloud W49A. Adapted from Sievers et al. 1991. (Area sampled includes warm component in core.)

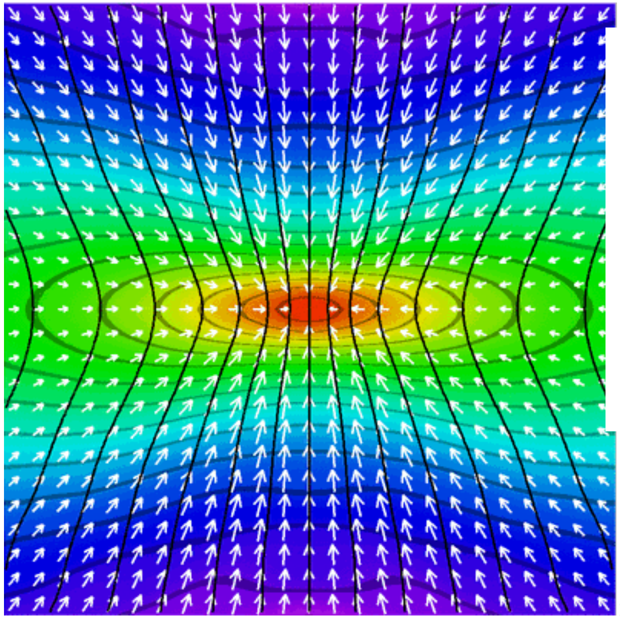


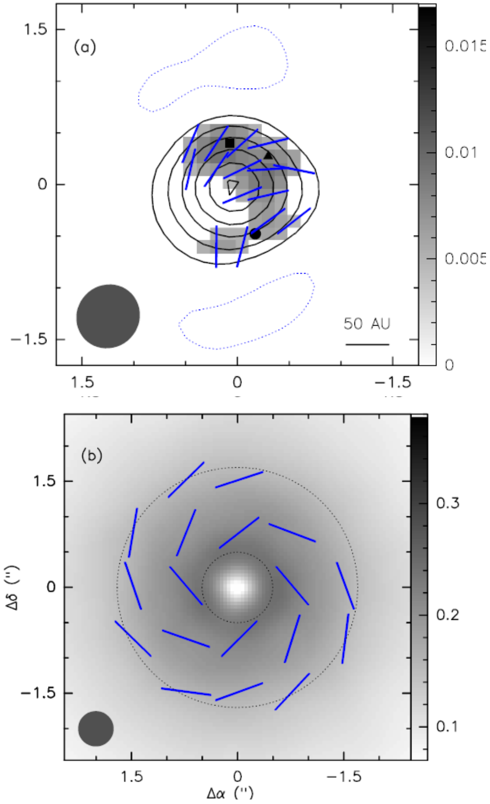
or map. Same data as in Fig. 12 but with vectors rotated 90° to show the inferred direction of the magnetic field. All vect
contours show flux densities measured at the same wavelength, 350 μm, with the photometer SHARC (Lis et al. 1998).

- Thermal emission (of dusts)
- Preferentially aligned by B

Hildebrand et al. PASP 112, 1215







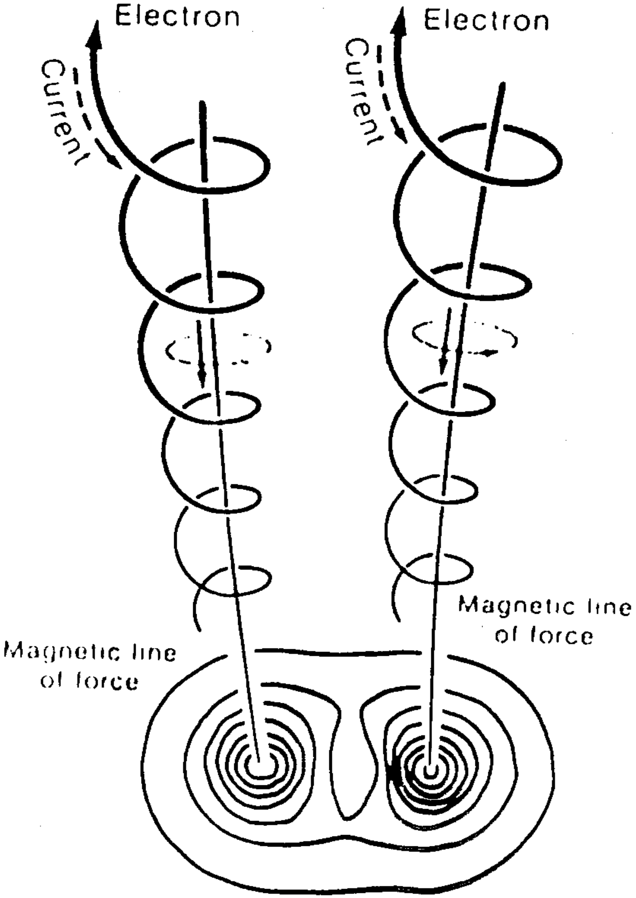
Origin of magnetic fields in stars and planets?

New observations show:

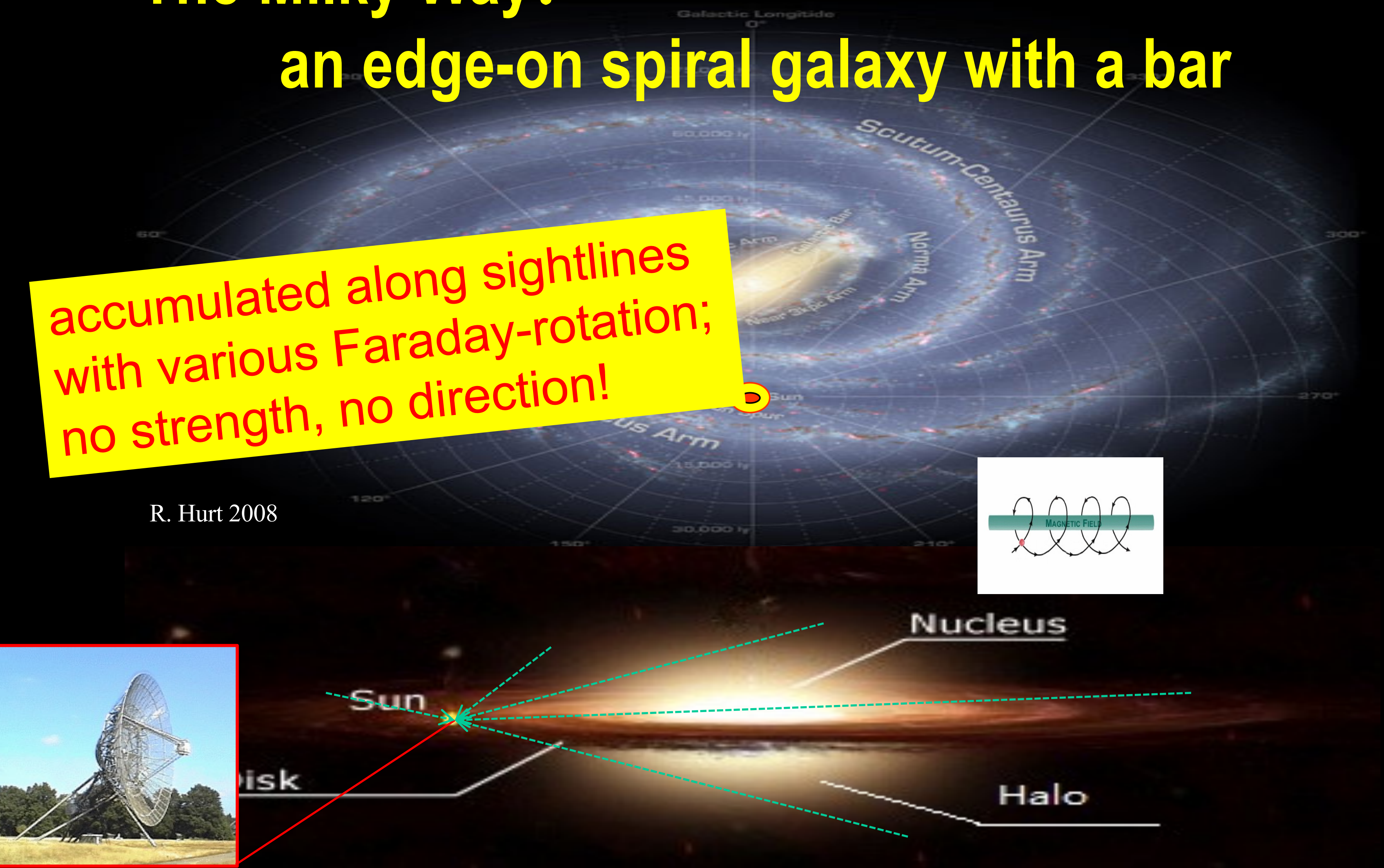
preserved from clouds during star forming !

ALMA Obs.
e.g. Rao et al.
2014, ApJ 780, L6

Synchrotron emission



The Milky Way:
an edge-on spiral galaxy with a bar

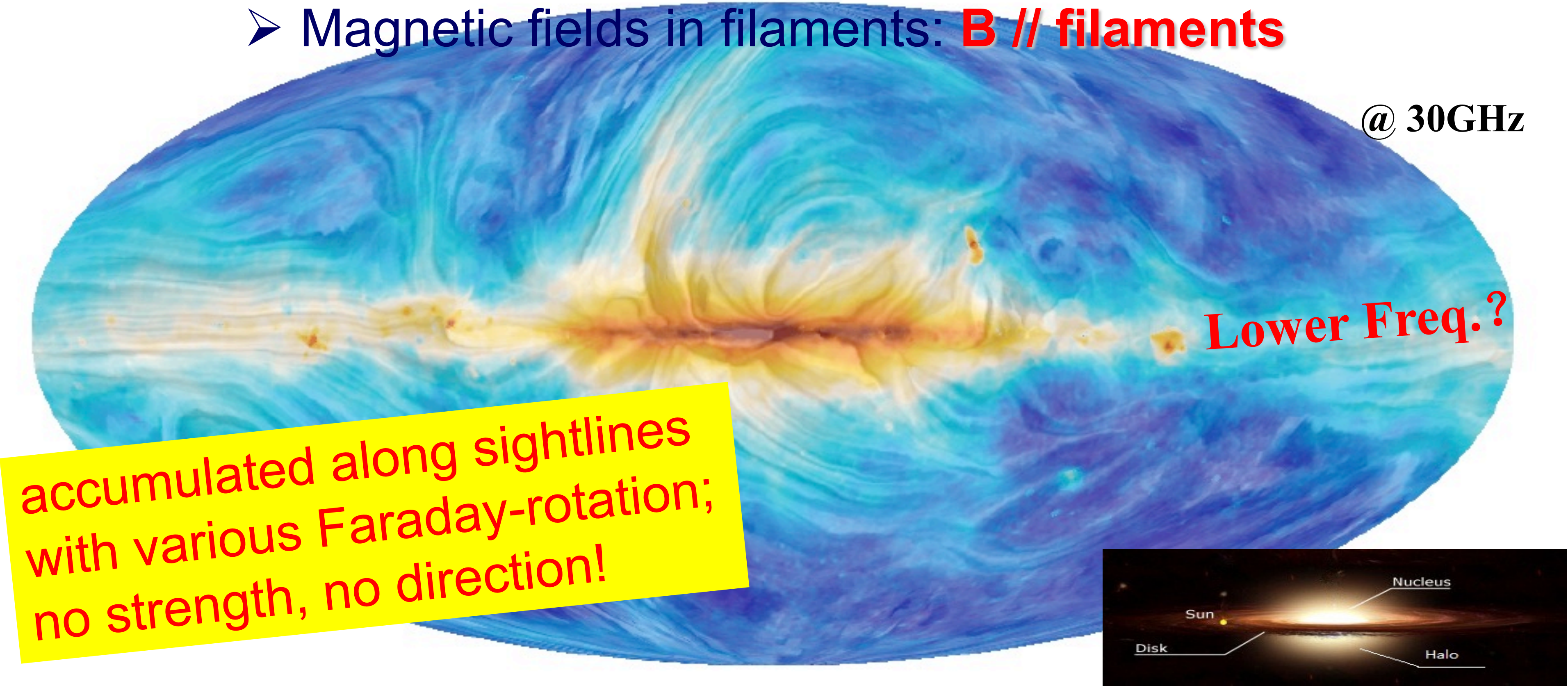


accumulated along sightlines with various Faraday-rotation; no strength, no direction!

R. Hurt 2008

Planck 2015：Best all-sky synchrotron

- ➢ Magnetic fields in the disk: **B // Galactic Plane**
- ➢ Magnetic fields in filaments: **B // filaments**

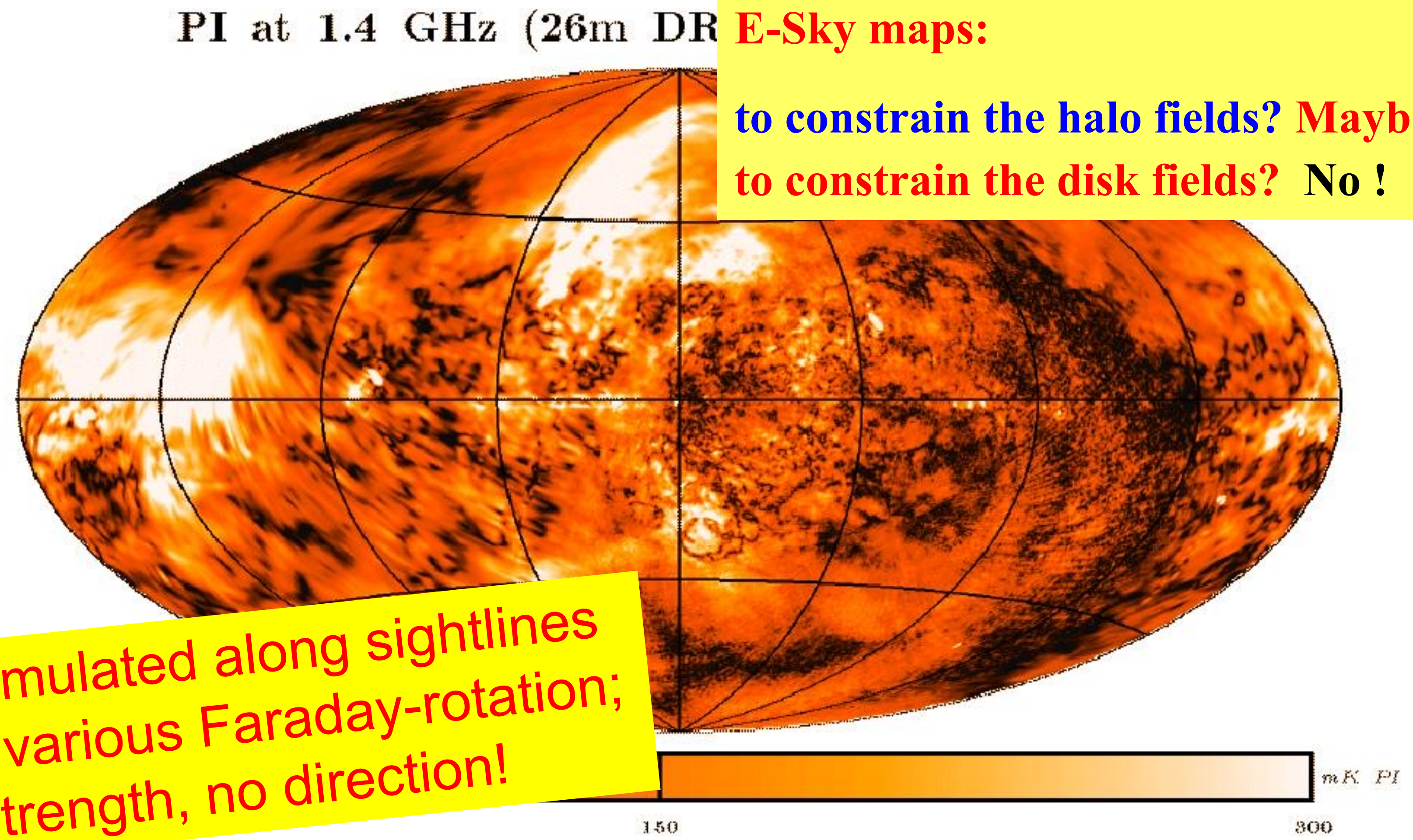


@ 30GHz

Lower Freq.?

accumulated along sightlines with various Faraday-rotation; no strength, no direction!

Fig. 20. All-sky view of the magnetic field and total intensity of synchrotron emission measured by *Planck*. The colours represent intensity. The "drapery" pattern, produced using the line integral convolution (LIC, Cabral & Leedom 1993), indicates the orientation of magnetic field projected on the plane of the sky, orthogonal to the observed polarization. Where the field varies significantly along the line of sight, the orientation pattern is irregular and difficult to interpret.



E-Sky maps:

to constrain the halo fields? Maybe.

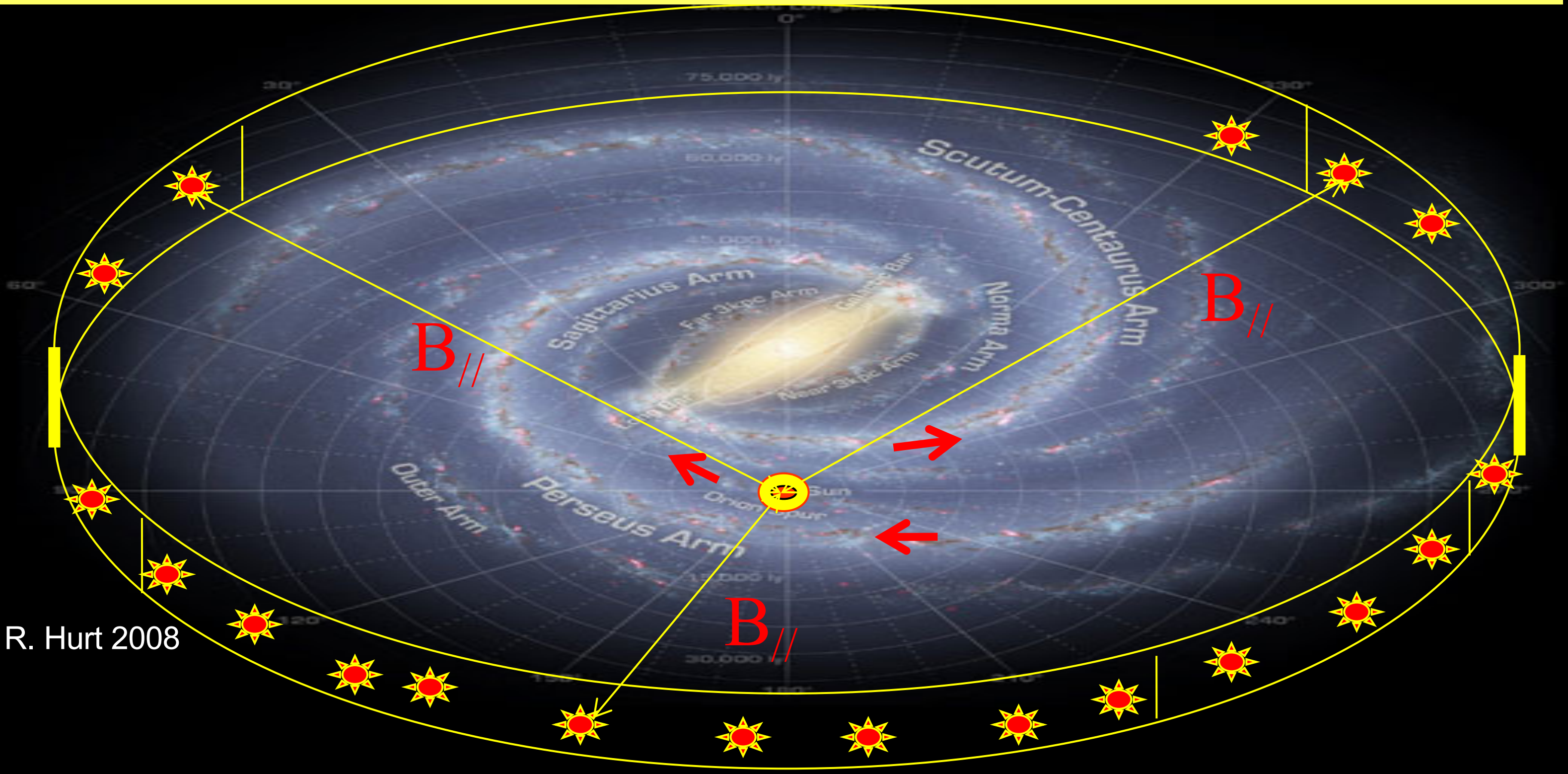
to constrain the disk fields? No !

accumulated along sightlines with various Faraday-rotation; no strength, no direction!

21cm DRAO+Villa Elisa all-sky polarization survey

(Wolleben et al. 2004)

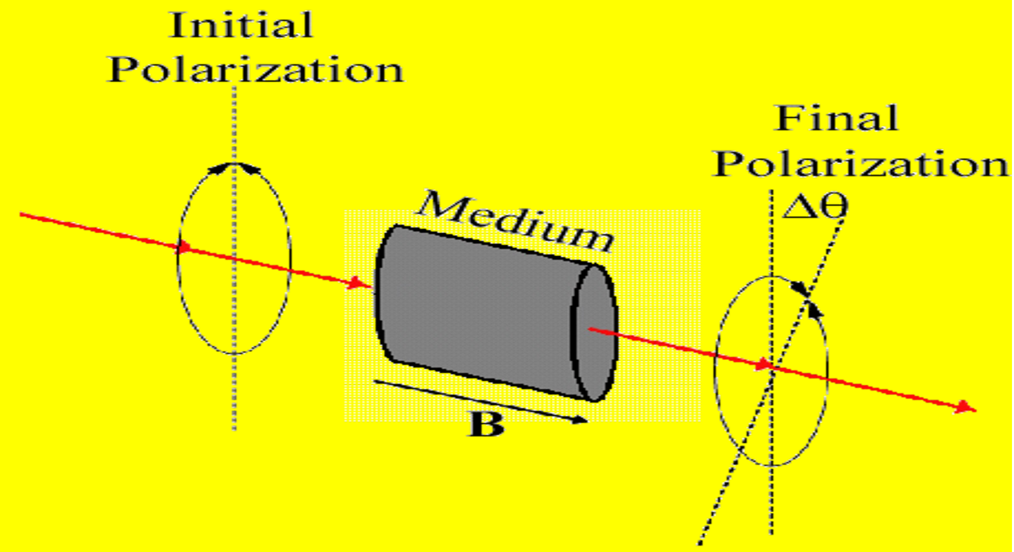
RMs of background sources: Integration but helps



R. Hurt 2008

$$RM = \frac{e^3}{2\pi m_e^2 c^4} \int_{Sun}^{source} [\frac{\lambda(l)}{\lambda_{obs}}]^2 n_e(l) \mathbf{B(l)} \bullet \mathbf{dl}$$

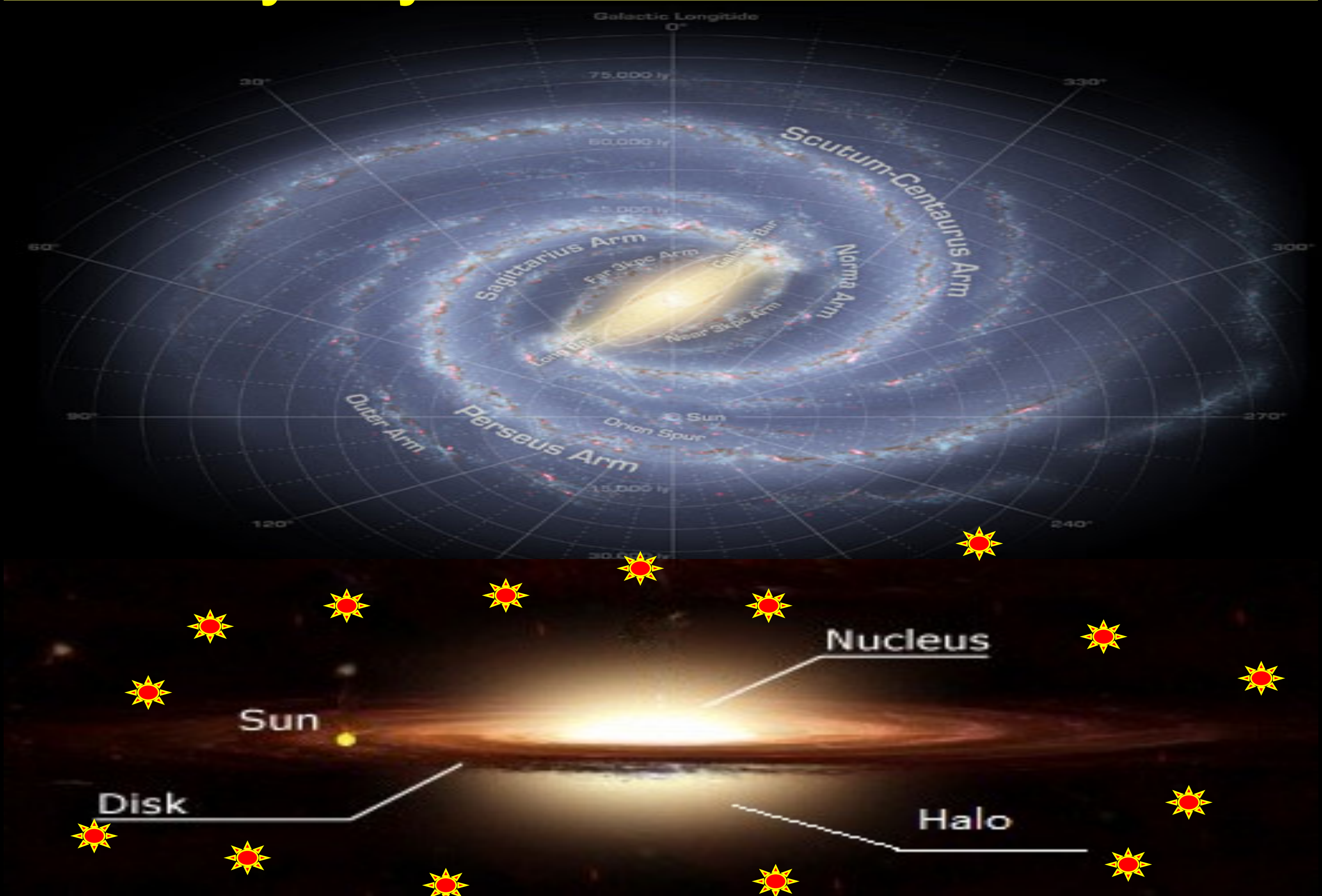
Faraday Rotation in the interstellar medium



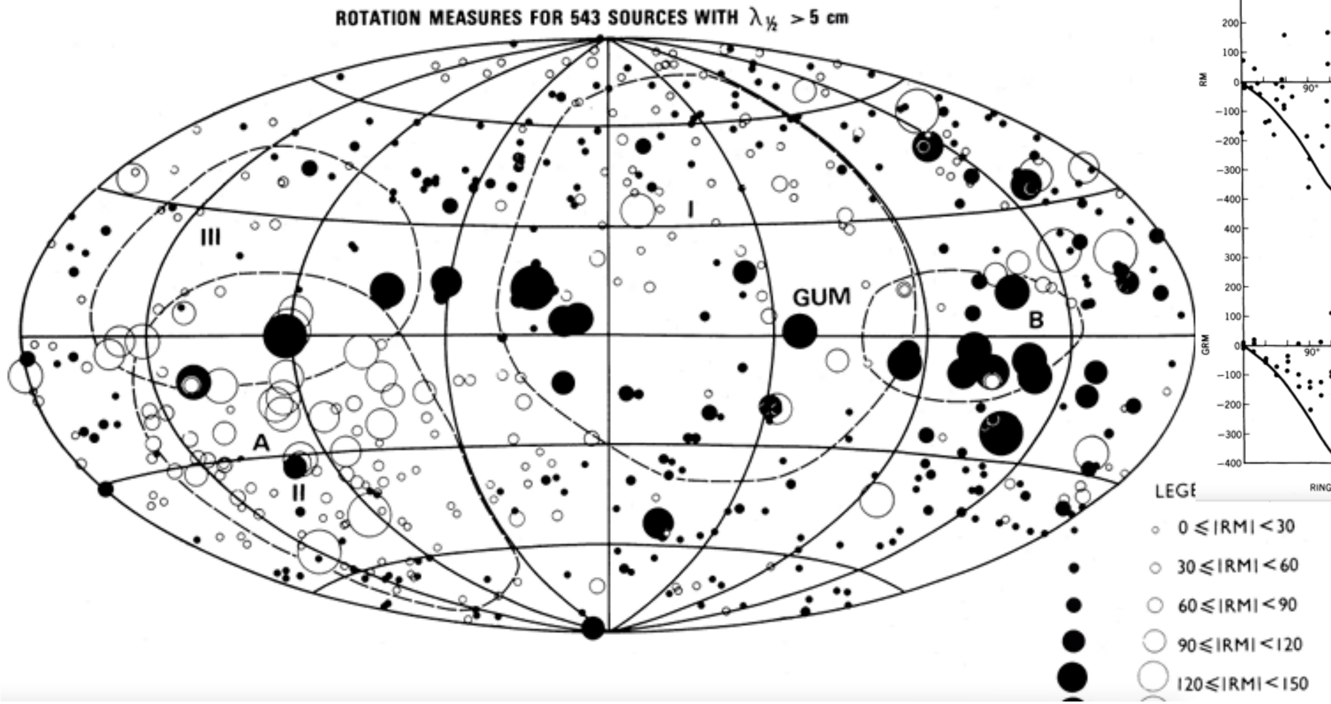
$$RM = \frac{PA_{\lambda 1} - PA_{\lambda 2}}{\lambda_1^2 - \lambda_2^2}$$

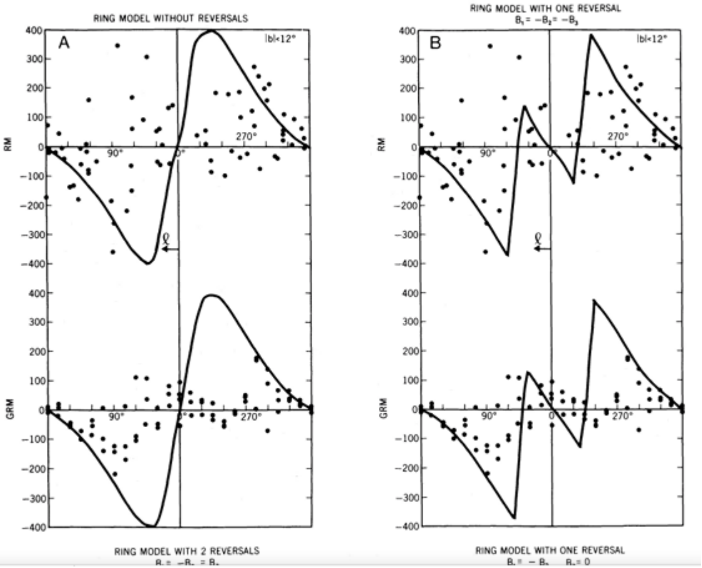
$$RM = \frac{e^3}{2\pi m_e^2 c^4} \int_{\mathrm{PSR}}^{\mathrm{Sun}} \left[\frac{\lambda(l)}{\lambda_{obs}}\right]^2 n_e(l)\,\mathbf{B(l)} \bullet \mathbf{dl} = 0.820 \left\langle B_{\|} \right\rangle \int_0^{Dist} n_e\, dl$$

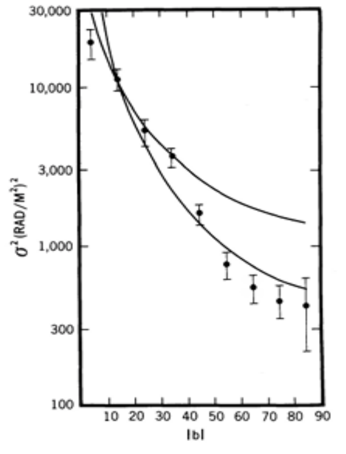
RMs of extragalactic sources: Integration of Ne*B//



Faraday Rotation distribution in Sky





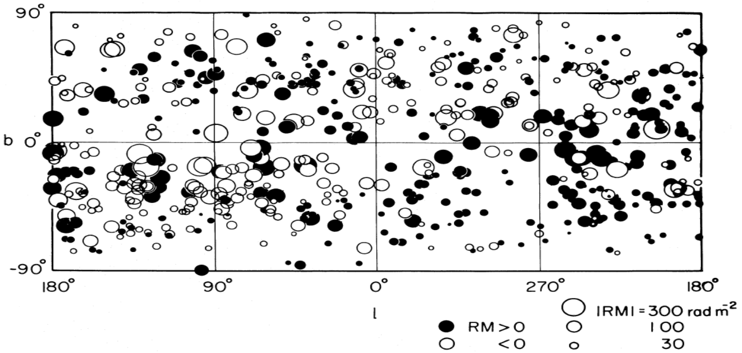


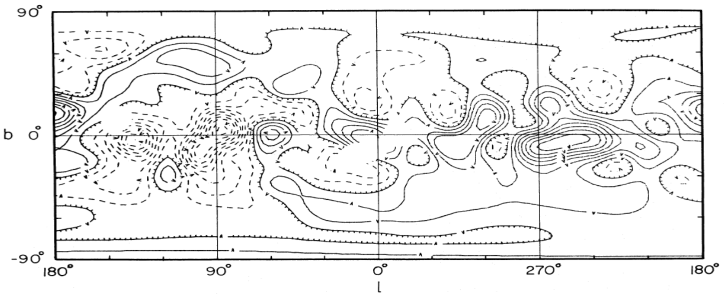
10.—The variance of the distribution of RMs

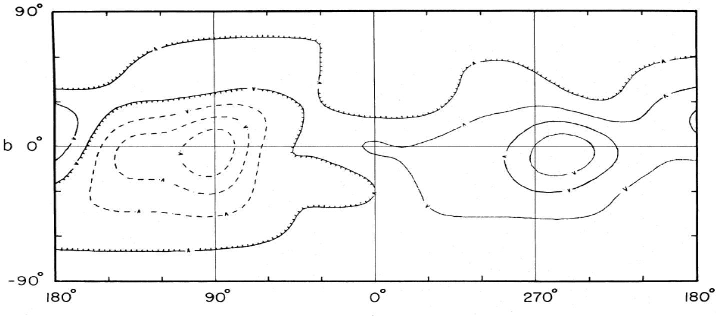
- ➢ got the RM sky distribution
- ➢ infered the BSS B-structure in the disk
- ➢ got scale height from sigma_RM(|b|)

M. Simard-Normandin & P.P. Kronberg (1980, ApJ 242, 74)

Faraday Rotation Sky

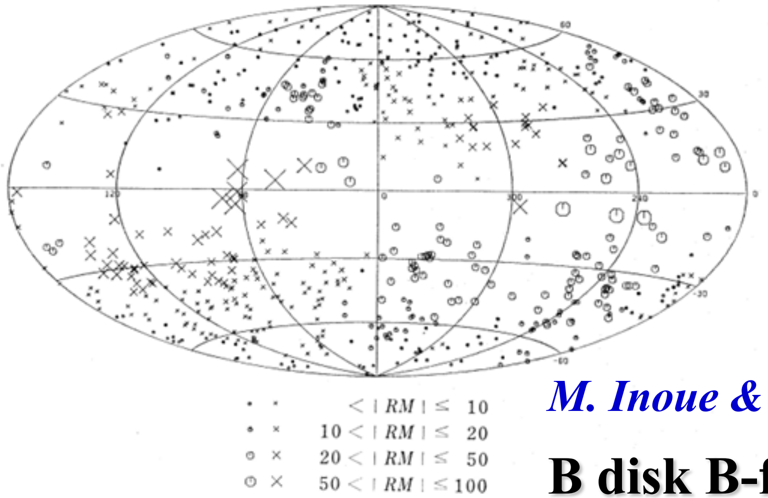


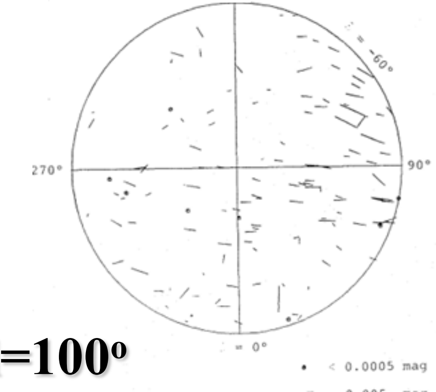




Sofue & Fujimoto (1983):

BiSymmetric Spiral for disk B-field!



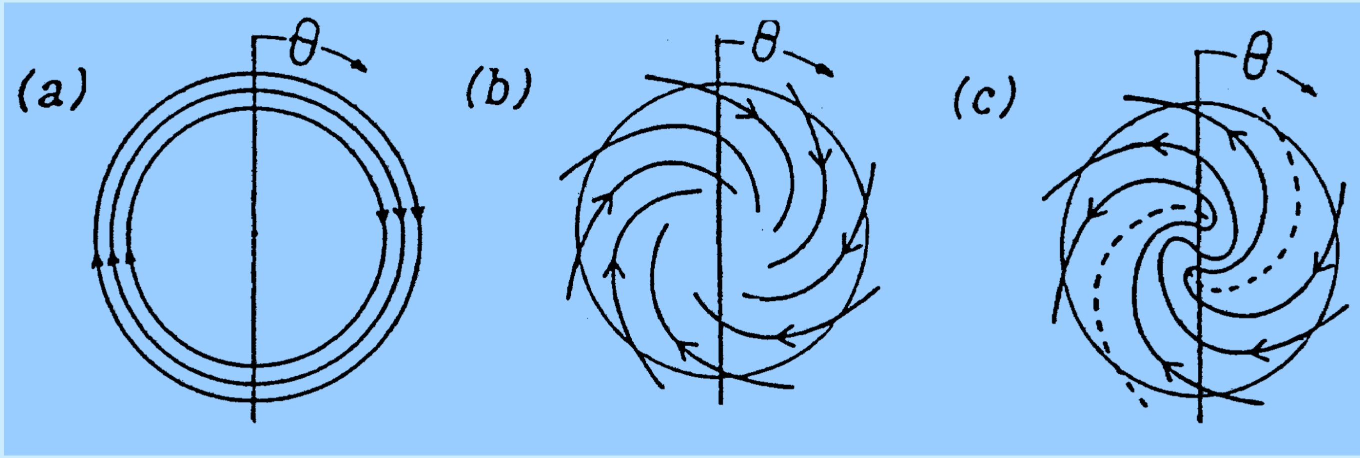


M. Inoue & H. Tabara (1981, PASJ 33, 603):

B disk B-field in 2 kpc! B=1.5uG to l=100°

3 proposed models for B-field structure in the Galactic disk

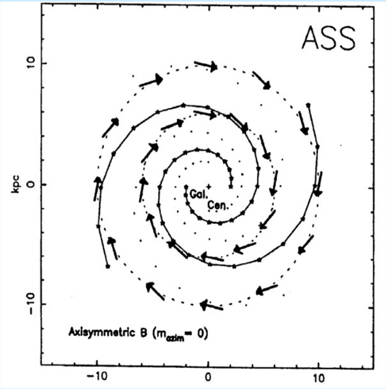
Concentric Rings Rings model	Axi-symmetric spiral (ASS)	Bi-Symmetric Spiral (BSS)



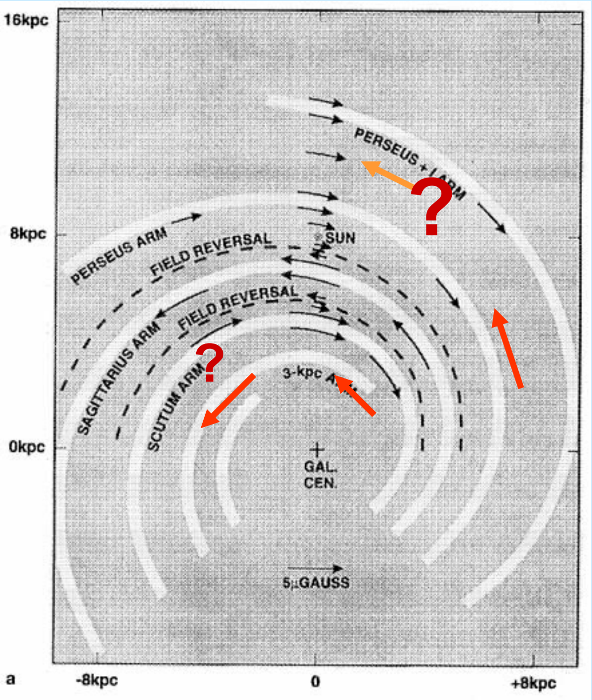
How to judge?

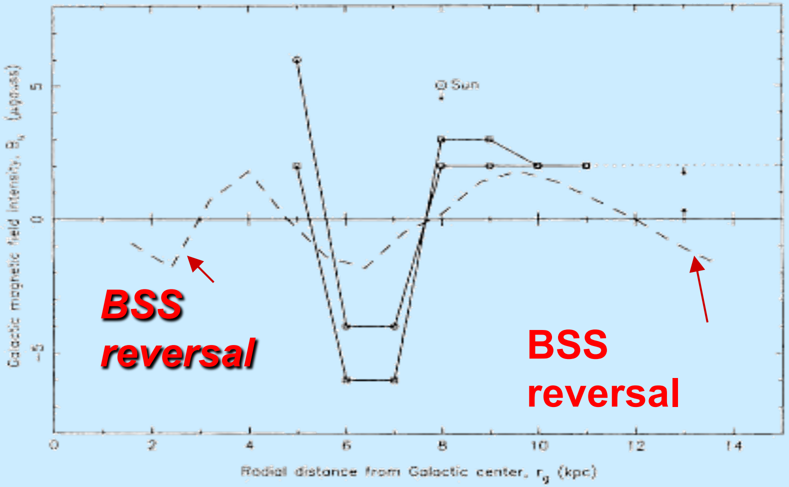
= > More data!

Axi-Symmetric Spiral (ASS) model by J.P. Vallee



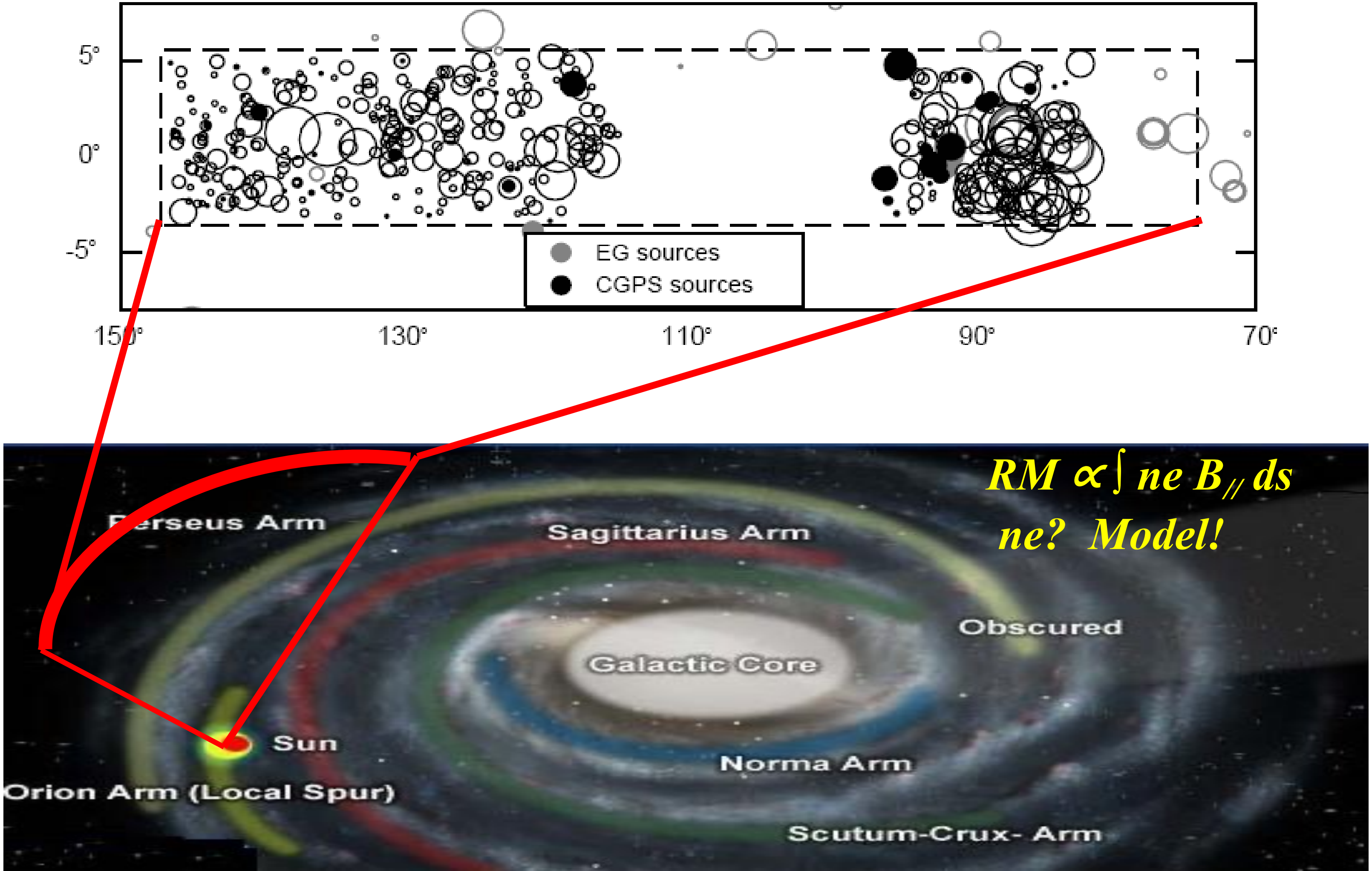
- Main Problem: fields go across the arms
- Newly: *one **radius** range for reversed **fields***
- Not consistent with field reversals near
  - -- Perseus arm??
  - -- the Norma arm !!





RMs from Canadian Galactic plane Survey

Brown et al. 2003

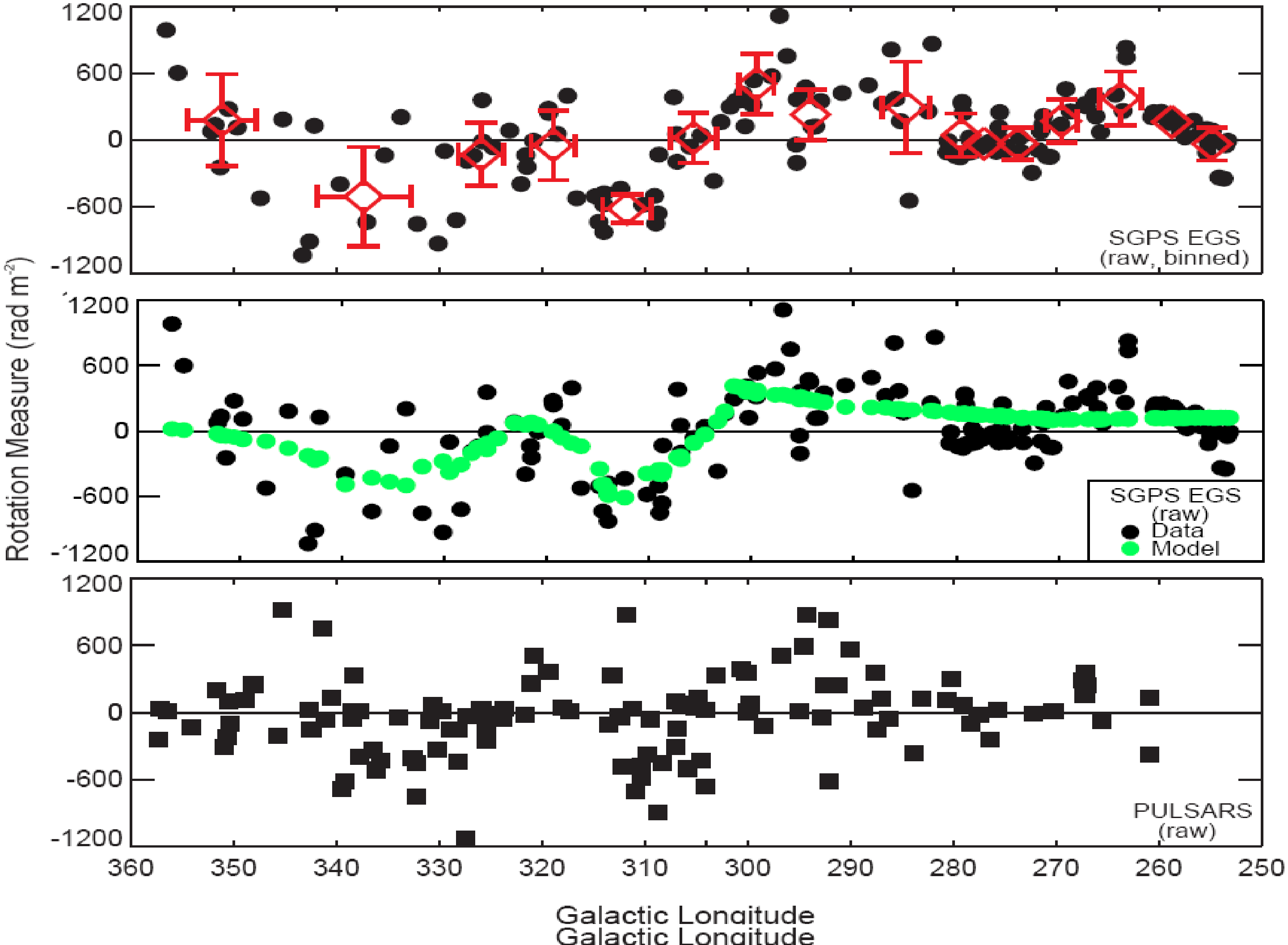


$RM \propto \int ne\, B_{//}\, ds$

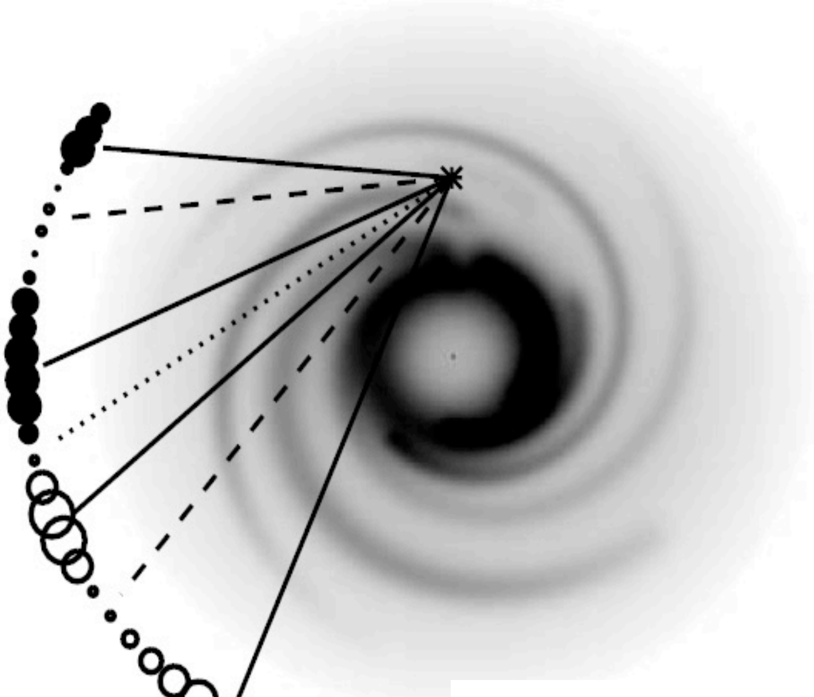
ne? Model!

RMs from the southern Galactic plane

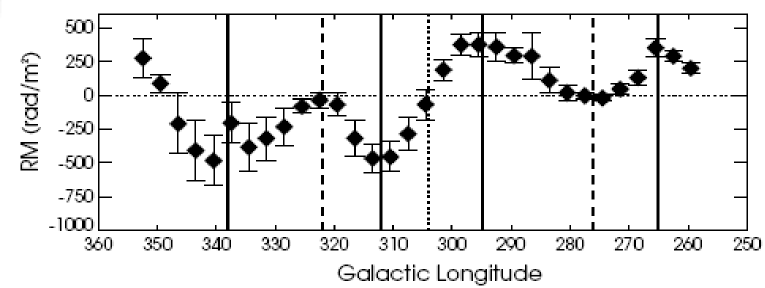
Brown et al. 2007



RMs from extragalactic RM sources near the Galactic plane: Magnetic Structure -- Yes!



... if we have radio sources inside our Milky Way with somehow known distances, it would be much better ...



Haverkorn et al. 2006, AN

Pulsars: Best probes for Galactic Ne and B-field

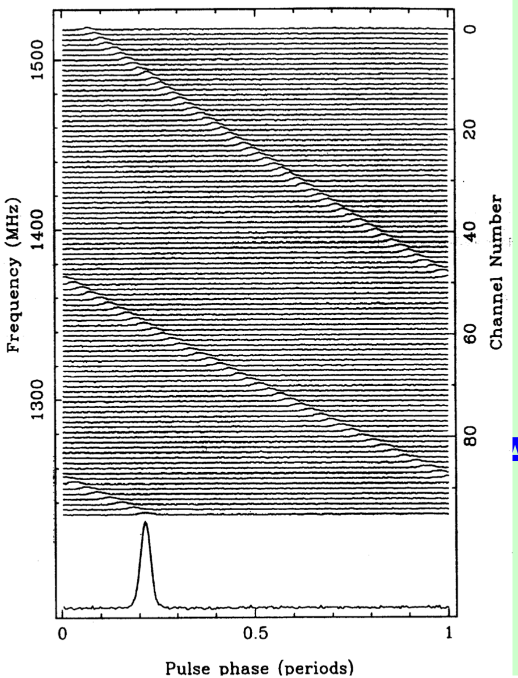
- **Polarized + no intrinsic RM: Faraday rotation:**

$$RM = \frac{e^3}{2\pi m_e^2 c^4}\int_{\mathrm{PSR}}^{\mathrm{Sun}}\left[\frac{\lambda(l)}{\lambda_{obs}}\right]^2 n_e(l)\,\mathbf{B(l)}\bullet\mathbf{dl} = 0.820\langle B_{\|}\rangle \underline{\int_0^{Dist} n_e dl}$$

<B> to us:
RM>0

- ***n*$_e$: can be measured:**

$$DM = \underline{\int_0^{Dist} n_e dl}$$

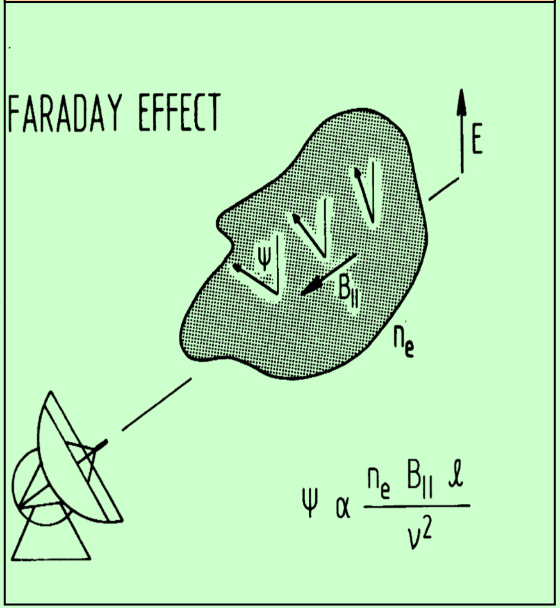


<== the delay tells DM

$$\Delta t = 8.3\times 10^3\, DM\,\frac{\Delta\nu}{\nu_{MHz}^3}\,\mathrm{sec}$$

the rotation of position angles tells RM value ==>

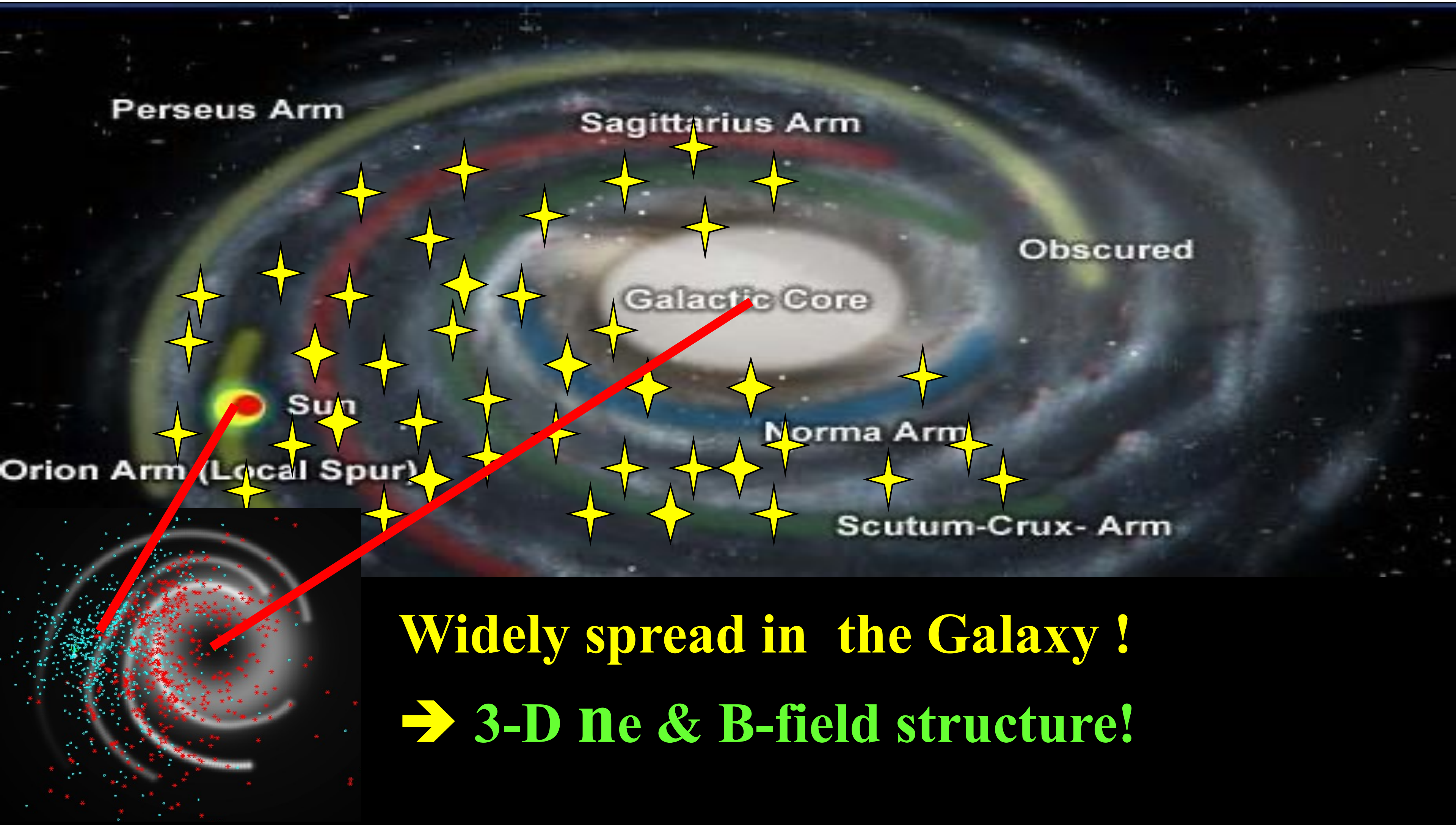
$$RM = \frac{PA_{\lambda 1} - PA_{\lambda 2}}{\lambda_1^2 - \lambda_2^2}$$



Average field strength can be directly derived

$$\boxed{\langle B_{||}\rangle = 1.232\,\frac{RM}{DM}\,\mu G}$$

Pulsars: Best probes for Galactic Ne and B-field



Widely spread in the Galaxy !

→ 3-D ne & B-field structure!

Pulsar RMs and the B-field in the disk

(R.J. Rand & S.R. Kulkarni, 1989, ApJ 343, 760)

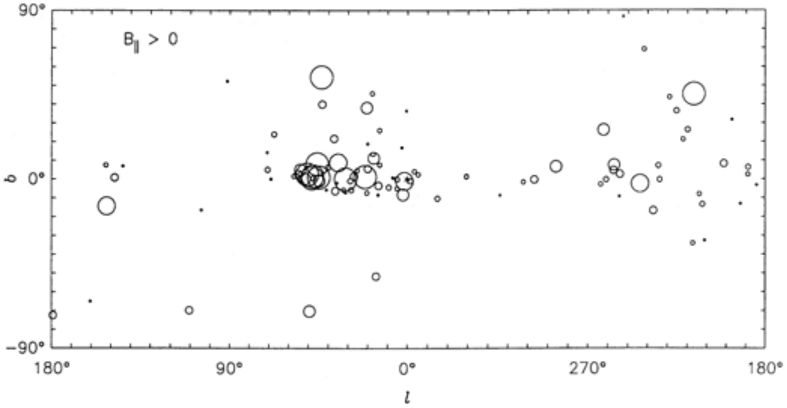


FIG. 2a

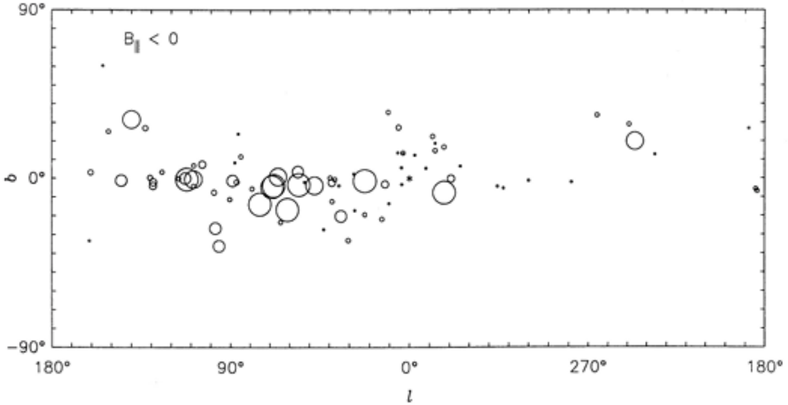
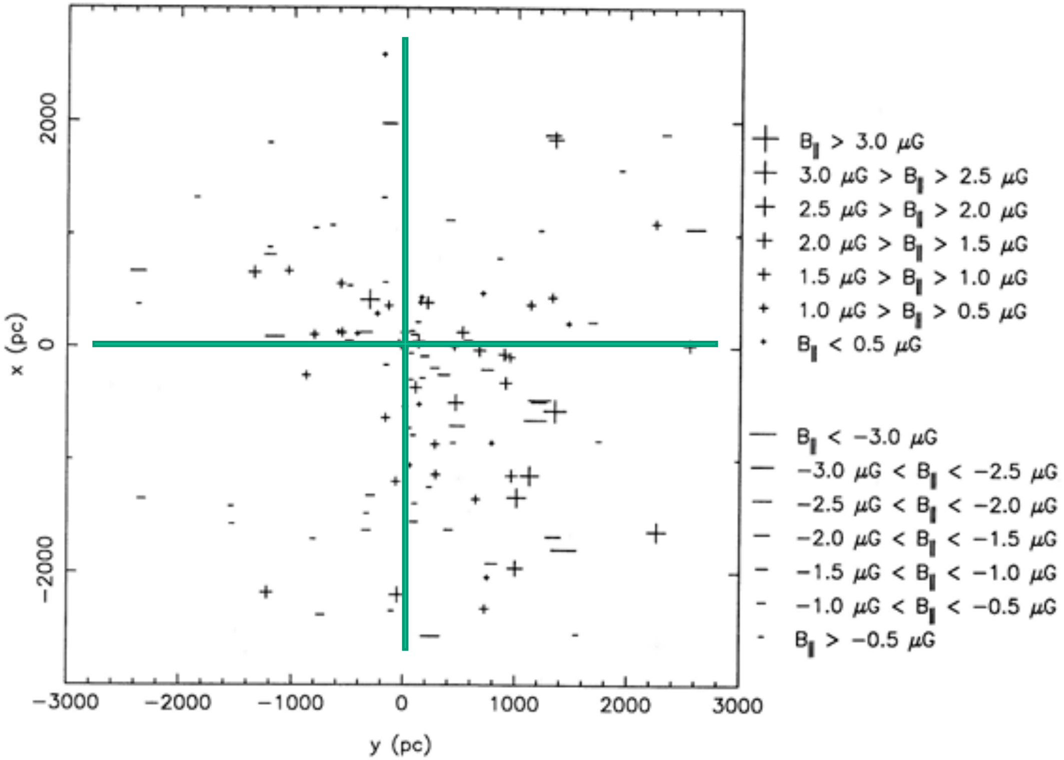


FIG. 2b

FIG. 2.—View of $B_\parallel$'s in Galactic coordinates for pulsars with distances less than 3 kpc. (a) positive $B_\parallel$'s; (b) negative $B_\parallel$'s.



Pulsar RMs and the B-field in the disk

(R.J. Rand & S.R. Kulkarni, 1989, ApJ 343, 760)

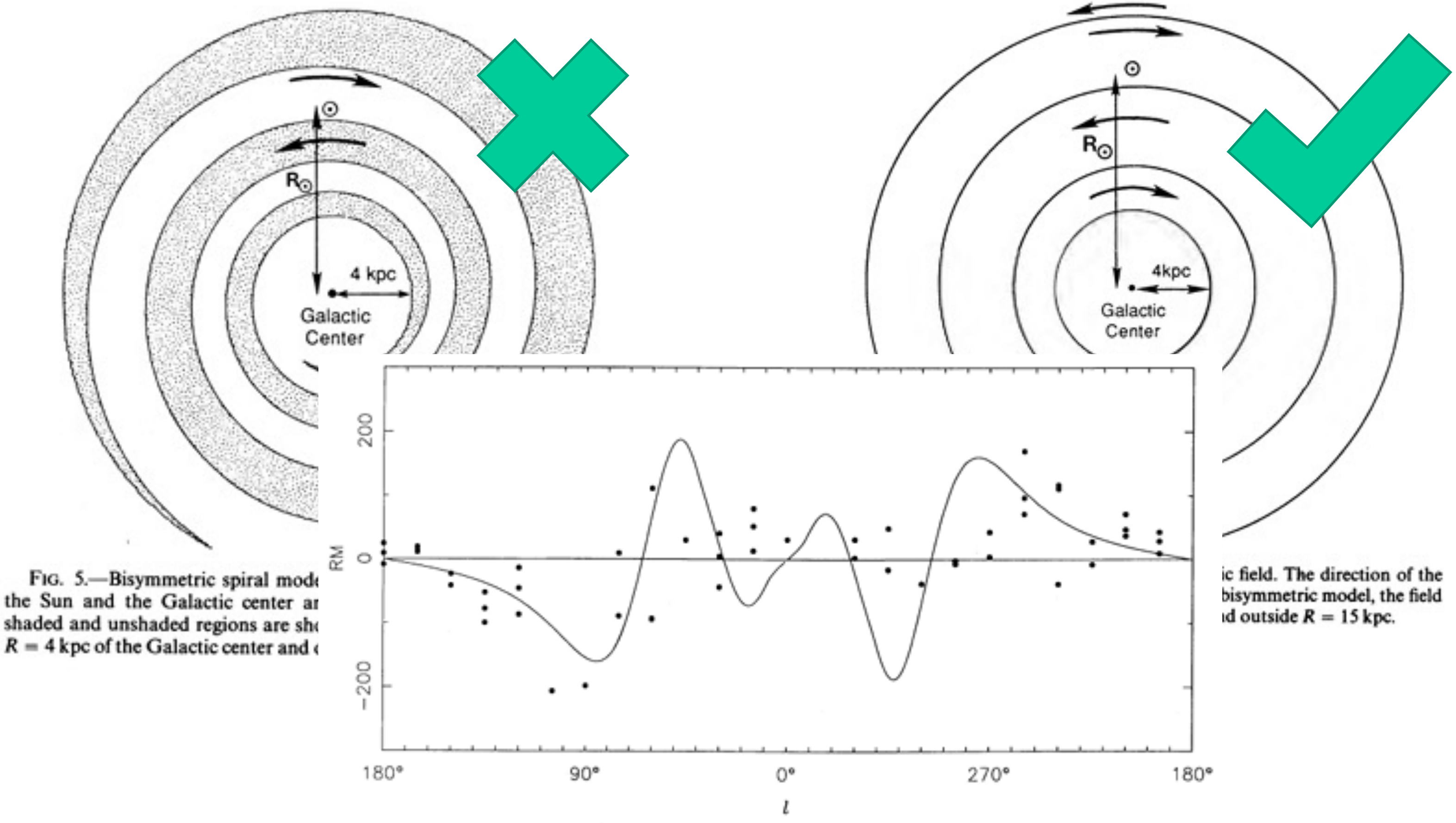


FIG. 5.—Bisymmetric spiral mod
the Sun and the Galactic center ar
shaded and unshaded regions are sho
R = 4 kpc of the Galactic center and

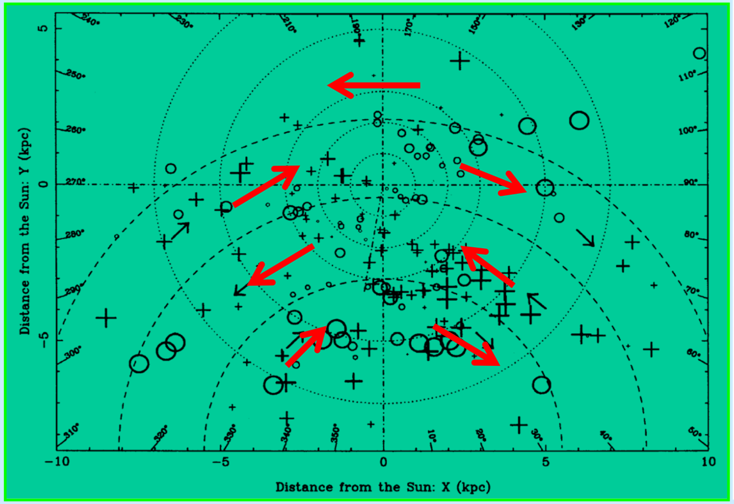
ic field. The direction of the
bisymmetric model, the field
ıd outside R = 15 kpc.

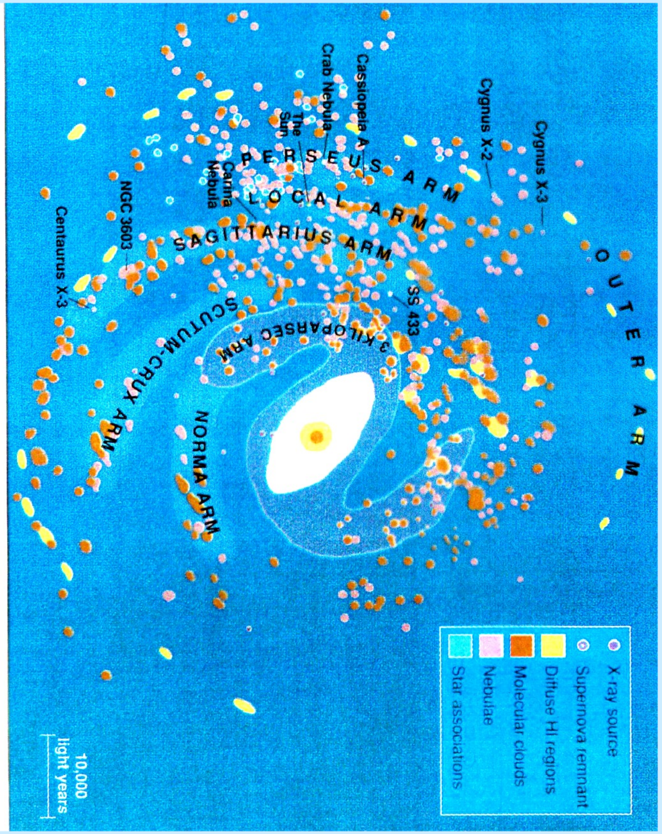
Ring model:

by R. Rand & S. Kulkarni (1989)
R. Rand & A.Lyne(1994)

Concentric rings of reversed fields

- Selection effect problem
- Field lines go across the arms
- Formula mistakes for the BSS modeling, then introduce it



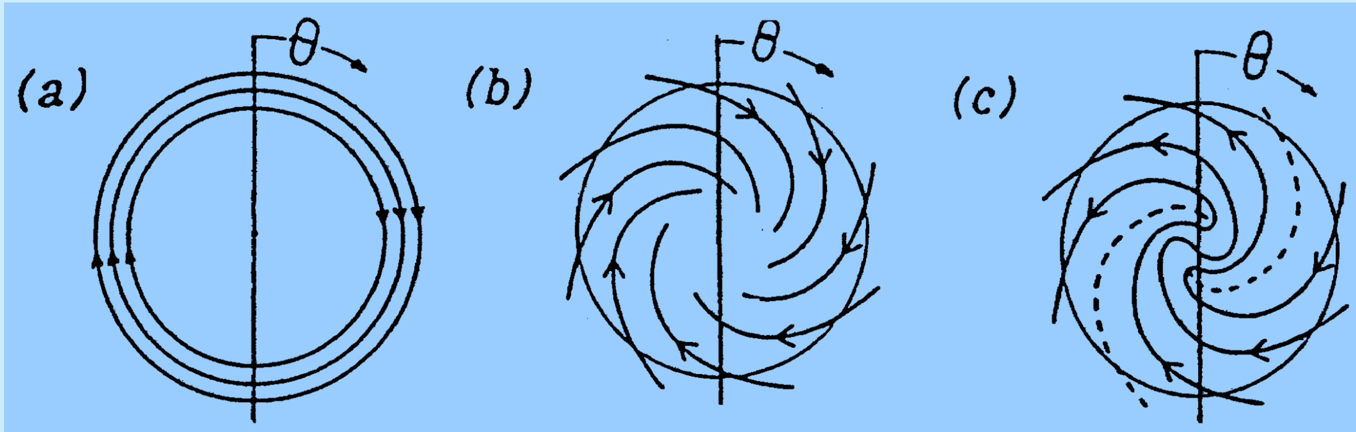


3 proposed models for
B-field structure in the Galactic disk

Concentric Rings
Rings model

Axi-symmetric spiral (ASS)

Bi-Symmetric Spiral (BSS)



How to judge?

= > More data!

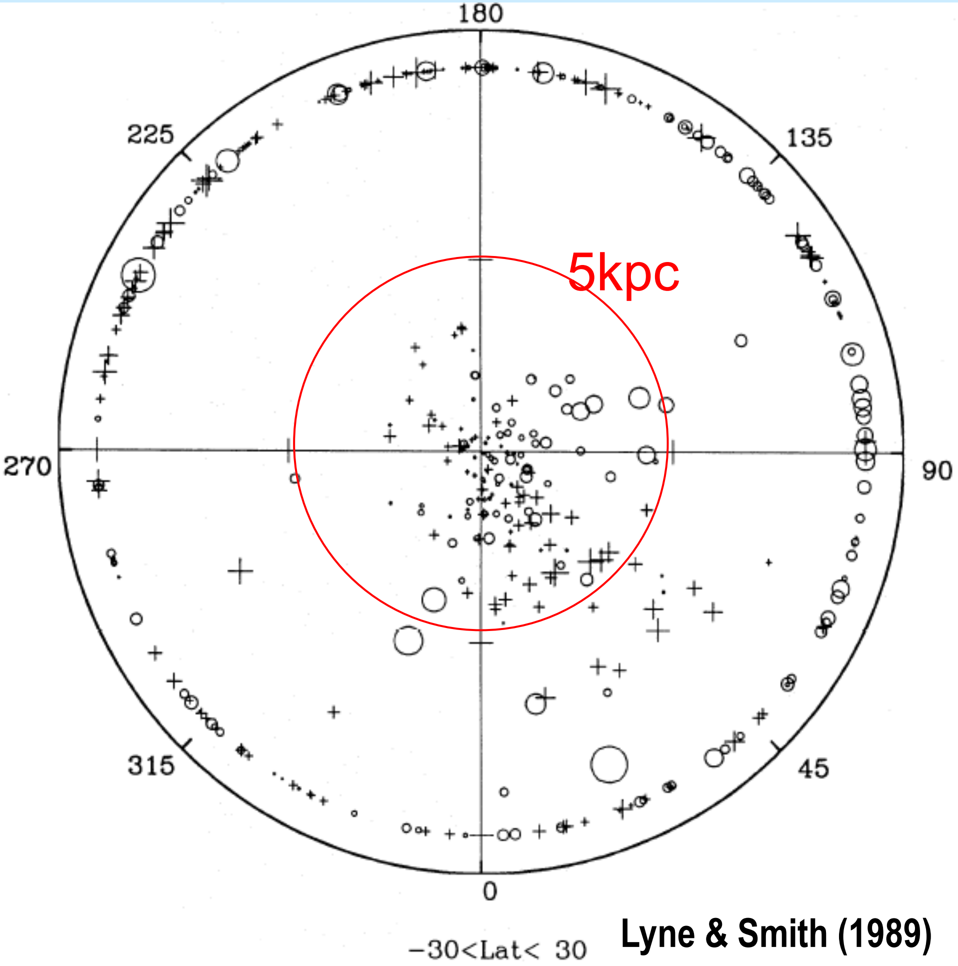
Large-scale: How *large* is the "large" here?

RMs of 185 pulsars

> ~ 3kpc?!

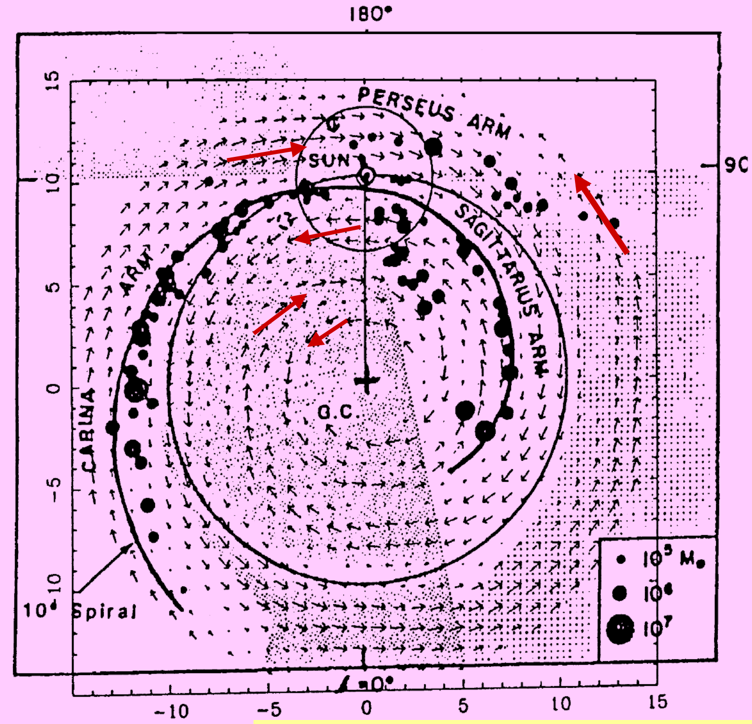
Arm-seperation: 1 or 2 kpc!

Data distribution: Selection effect!



Lyne & Smith (1989)

Bi-Symmetric Spiral Model



Proposed from *RMs of Extragalactic Radio Sources:*

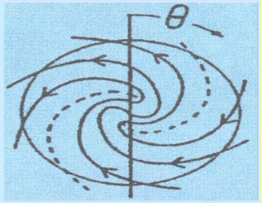
Simard-Normandin & Kronberg (1980)
Sofue & Fujimoto (1983)

Confirmed by *Pulsar RMs:*

Han & Qiao (1994)
Indrani & Deshpande (1998)
Han, Manchester, Qiao (1999)
Han,Manchester, Lyne, Qiao(2002)

Supported by *starlight polarization*

Heiles (1996)



The best match to all evidence

field reversals & pitch angle – 8° ±2°

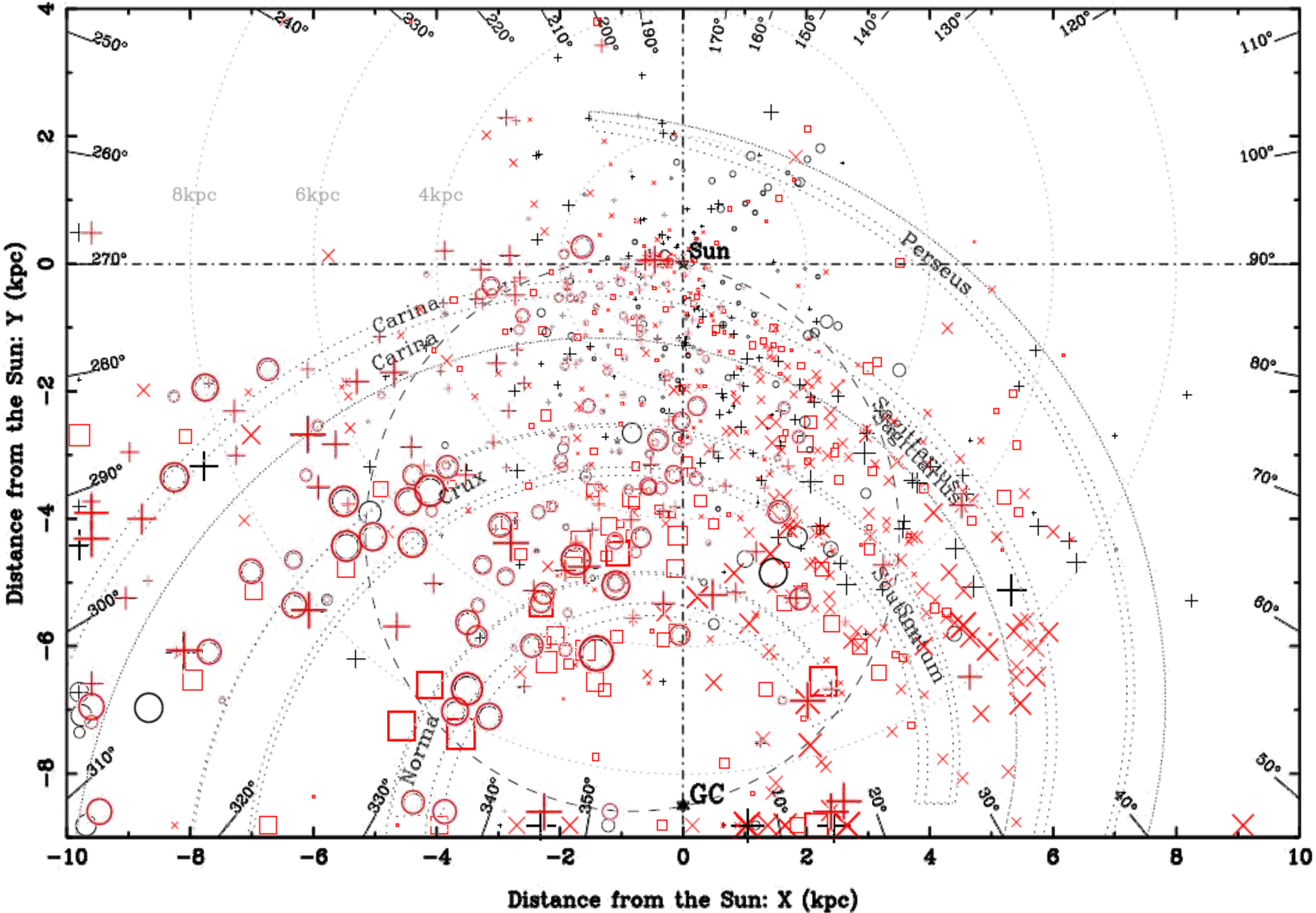
(the field stronger in interarm region?)

We took the baton for 2 decades for pulsar RMs

Authors	No. of RMs	No. New RMs
Hamilton & Lyne (1987)	**163**	**119**
Rand & Lyne (2004):	**27**	**27**
Qiao et al. (1995)	**48**	**33**
Van Ommen et al. (1997)	24	**2**
Han et al. (1999)	**63**	**54**
Crawford (2001):	7	**7**
Mitra et al. (2003):	11	**11**
Weisberg et al. (2003)	36	**17**
Han et al. (2006):	**223**	**196**
Han et al. (2018):	**477**	**386**
Xu et al. (2022):	**134**	**134**
Wang et al. (2023)	**402**	**402**

Total No. of pulsar RM published: → ***1453***

Our measurements

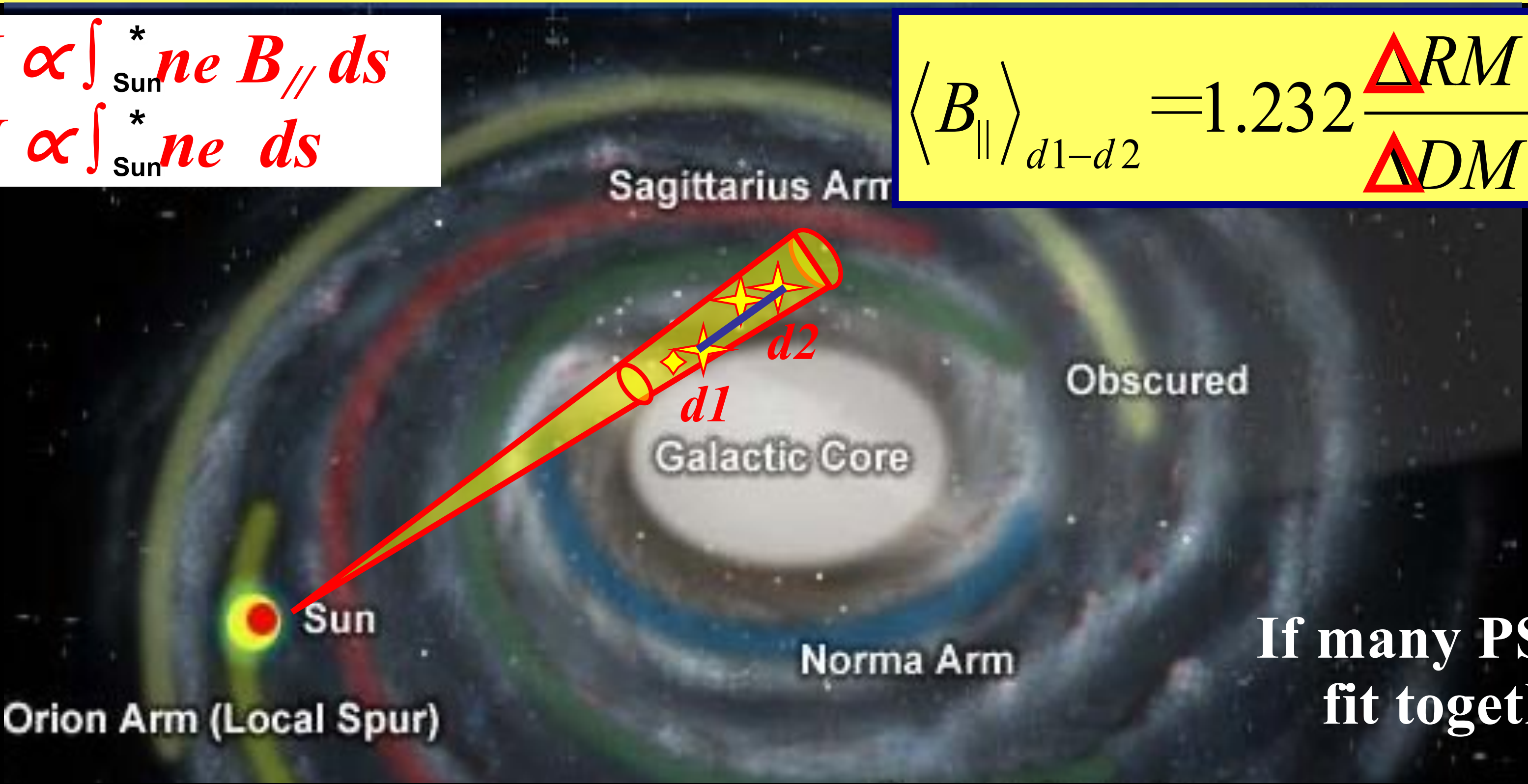


Paired pulsars probe the B-field in the between region

$$RM \propto \int_{Sun}^{*} ne\, B_{//}\, ds$$

$$DM \propto \int_{Sun}^{*} ne\, ds$$

$$\langle B_{\parallel} \rangle_{d1-d2} = 1.232 \frac{\Delta RM}{\Delta DM}\, \mu G$$



If many PSRs, fit together!

Analysis is not limited to *modeling B all the path*, but can *measure B in the region* between! *Significant improvement!*

No worry about foreground, much less sensitive on distances

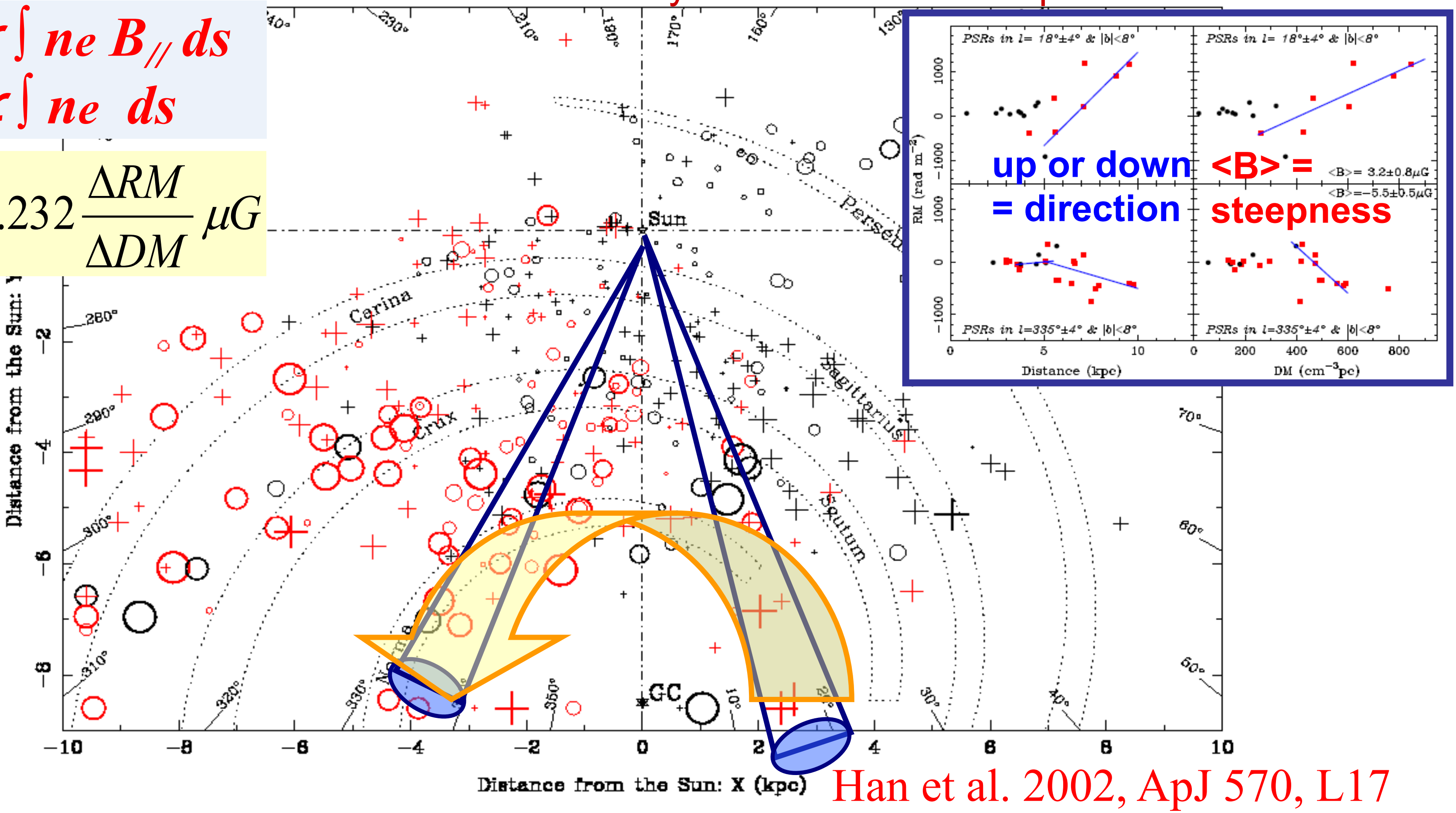
We got the B-field in the most inner arm: the Norma arm

red: new measurements by Parkes 64m telescope

$$RM \propto \int n_e B_{//} \, ds$$

$$DM \propto \int n_e \, ds$$

$$\langle B_{||} \rangle = 1.232 \frac{\Delta RM}{\Delta DM} \mu G$$



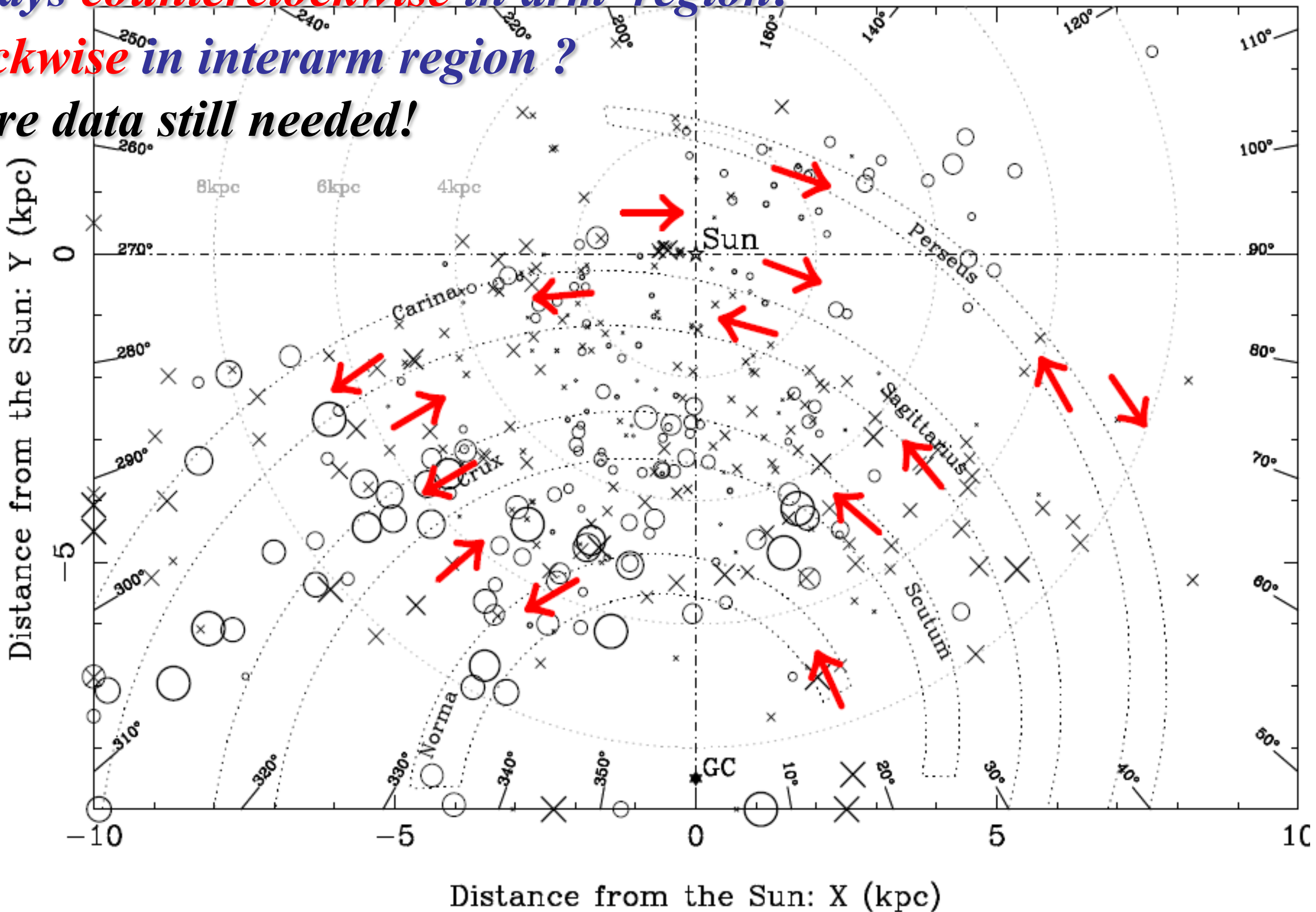
up or down = direction

<B> = steepness

Han et al. 2002, ApJ 570, L17

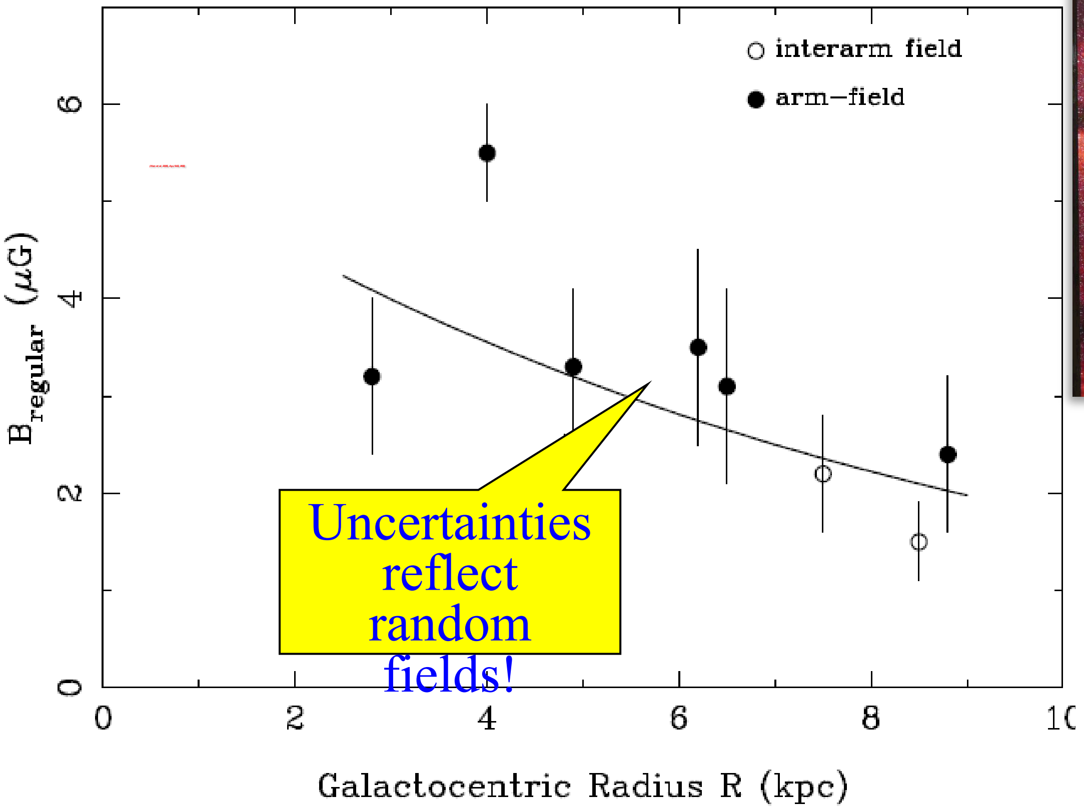
We measured magnetic fields in the Galactic disk by pulsar RM/DM *(Han et al. 2006, ApJ 642, 868)*

- *always counterclockwise in arm region!*
- *clockwise in interarm region ?*
- ***More data still needed!***

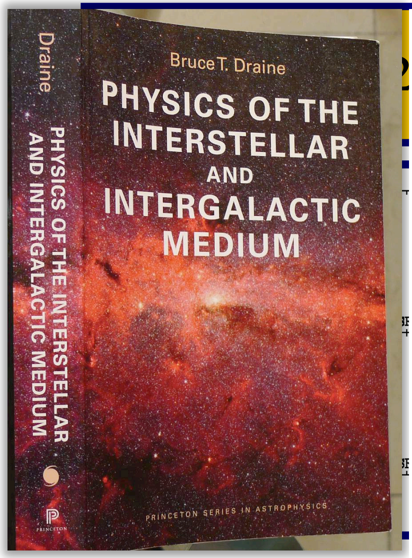


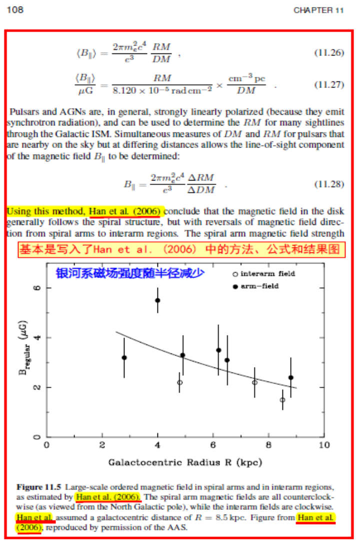
We measured radial dependence of regular field strength

(Han et al. 2006, ApJ 642, 868)



Uncertainties reflect random fields!





108 CHAPTER 11

$$\langle B_\parallel \rangle = \frac{2\pi m_e^2 c^4}{e^3} \frac{RM}{DM} \,, \qquad (11.26)$$

$$\frac{\langle B_\parallel \rangle}{\mu\mathrm{G}} = \frac{RM}{8.120 \times 10^{-5}\,\mathrm{rad\,cm^{-2}}} \times \frac{\mathrm{cm^{-3}\,pc}}{DM} \,. \qquad (11.27)$$

Pulsars and AGNs are, in general, strongly linearly polarized (because they emit synchrotron radiation), and can be used to determine the RM for many sightlines through the Galactic ISM. Simultaneous measures of DM and RM for pulsars that are nearby on the sky but at differing distances allows the line-of-sight component of the magnetic field $B_\parallel$ to be determined:

$$B_\parallel = \frac{2\pi m_e^2 c^4}{e^3} \frac{\Delta RM}{\Delta DM} \,. \qquad (11.28)$$

Using this method, Han et al. (2006) conclude that the magnetic field in the disk generally follows the spiral structure, but with reversals of magnetic field direction from spiral arms to interarm regions. The spiral arm magnetic field strength

基本是写入了Han et al. （2006）中的方法、公式和结果图

Figure 11.5 Large-scale ordered magnetic field in spiral arms and in interarm regions, as estimated by Han et al. (2006). The spiral arm magnetic fields are all counterclockwise (as viewed from the North Galactic pole), while the interarm fields are clockwise. Han et al. assumed a galactocentric distance of $R = 8.5$ kpc. Figure from Han et al. (2006), reproduced by permission of the AAS.

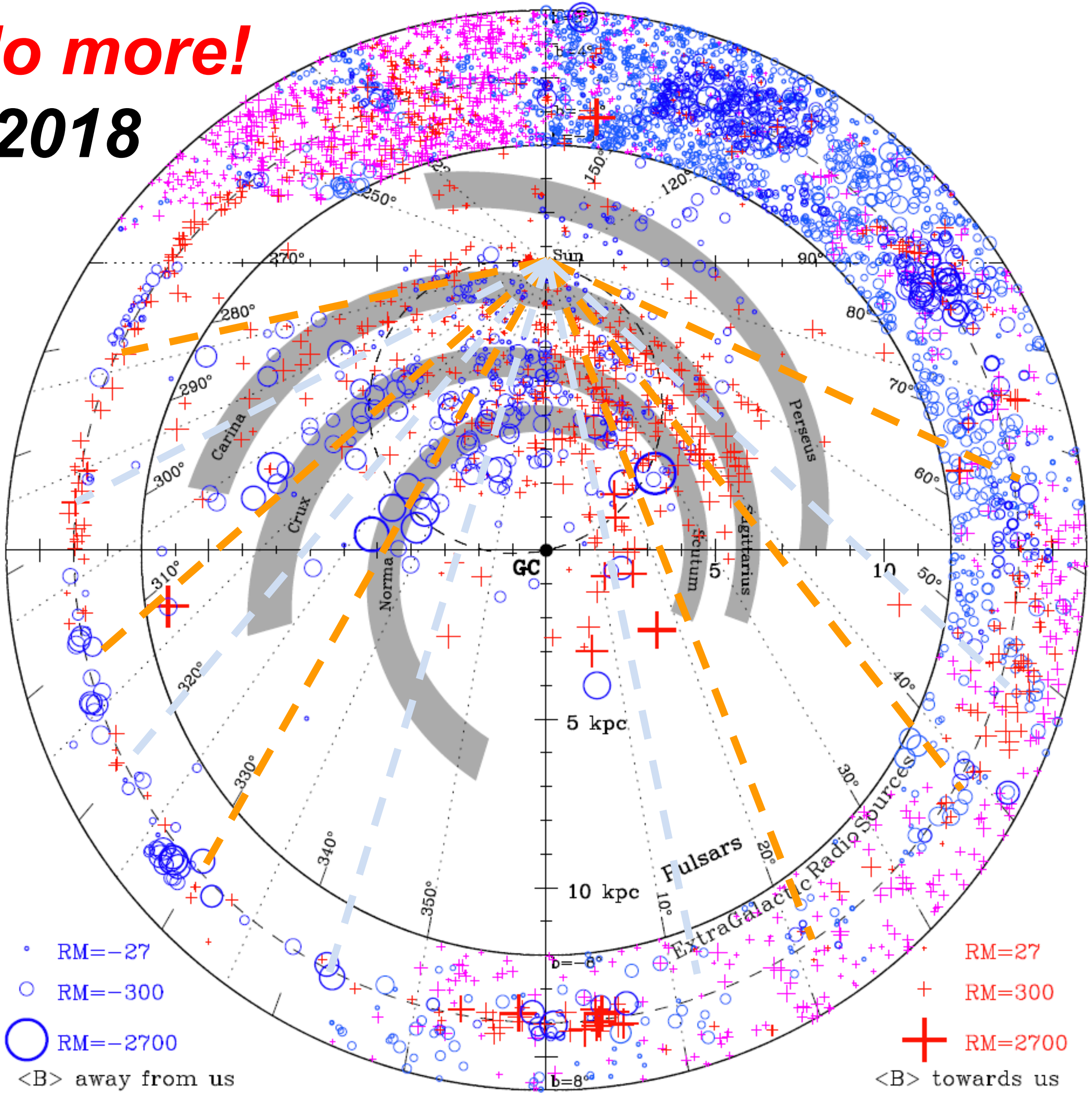
$$B_{\mathrm{regular}}(R) = B_0 \bullet \exp\left[\frac{-(R - R_\oplus)}{R_B}\right]$$

$$B_0 = 2.1 \pm 0.3\,\mu\mathrm{G}$$

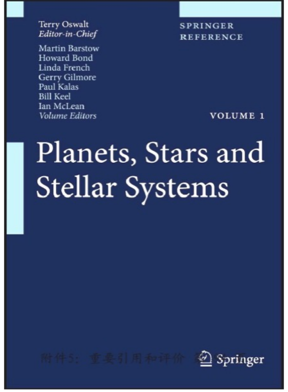
$$R_B = 8.5 \pm 4.7\,\mathrm{kpc}$$

No stop, do more!

Han et al. 2018



Han et al. 2018
ApJS 234, 11



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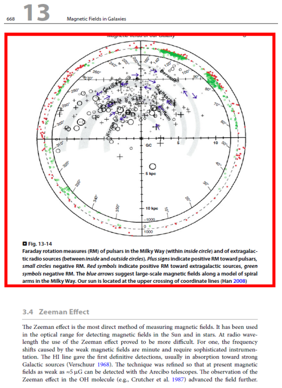
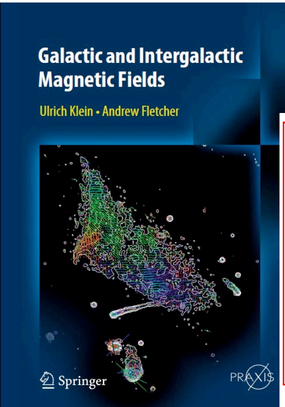


Fig. 13-14
Faraday rotation measures (RM) of pulsars in the Milky Way (within *inside circle*) and of extragalactic radio sources (between *inside* and *outside circles*). *Plus signs* indicate positive RM toward pulsars, *small circles* negative RM. *Red symbols* indicate positive RM toward extragalactic sources, *green symbols* negative RM. The *blue arrows* suggest large-scale magnetic fields along a model of spiral arms in the Milky Way. Our sun is located at the upper crossing of coordinate lines (Han 2008)

3.4 Zeeman Effect

The Zeeman effect is the most direct method of measuring magnetic fields. It has been used in the optical range for detecting magnetic fields in the Sun and in stars. At radio wavelength the use of the Zeeman effect proved to be more difficult. For one, the frequency shifts caused by the weak magnetic fields are minute and require sophisticated instrumentation. The HI line gave the first definitive detections, usually in absorption toward strong Galactic sources (Verschuur 1968). The technique was refined so that at present magnetic fields as weak as ≈5 μG can be detected with the Arecibo telescopes. The observation of the Zeeman effect in the OH molecule (e.g., Crutcher et al. 1987) advanced the field further.



Galactic and Intergalactic
Magnetic Fields

Ulrich Klein • Andrew Fletcher

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PRAXIS

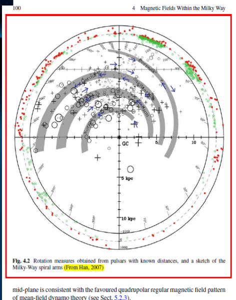
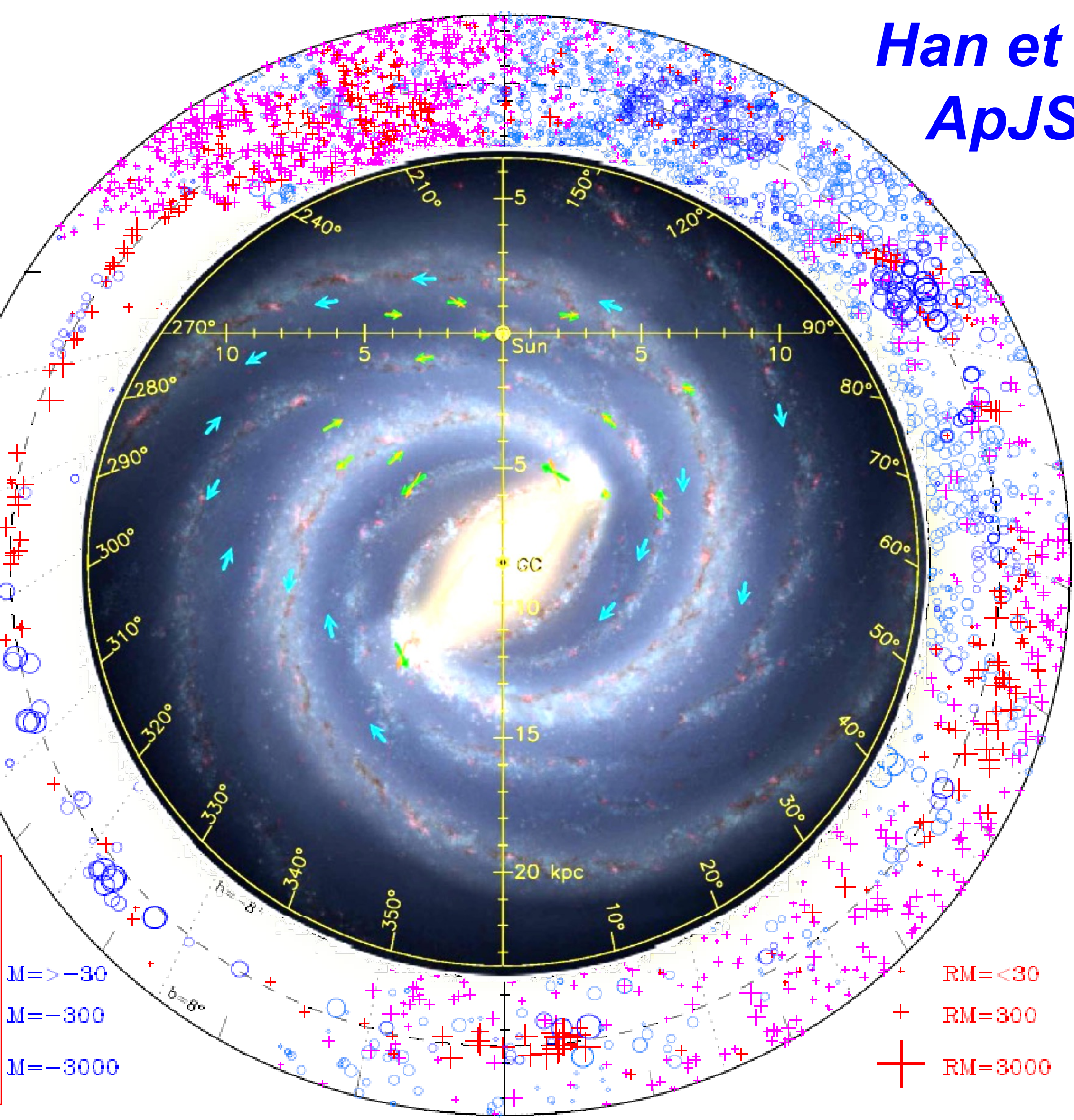
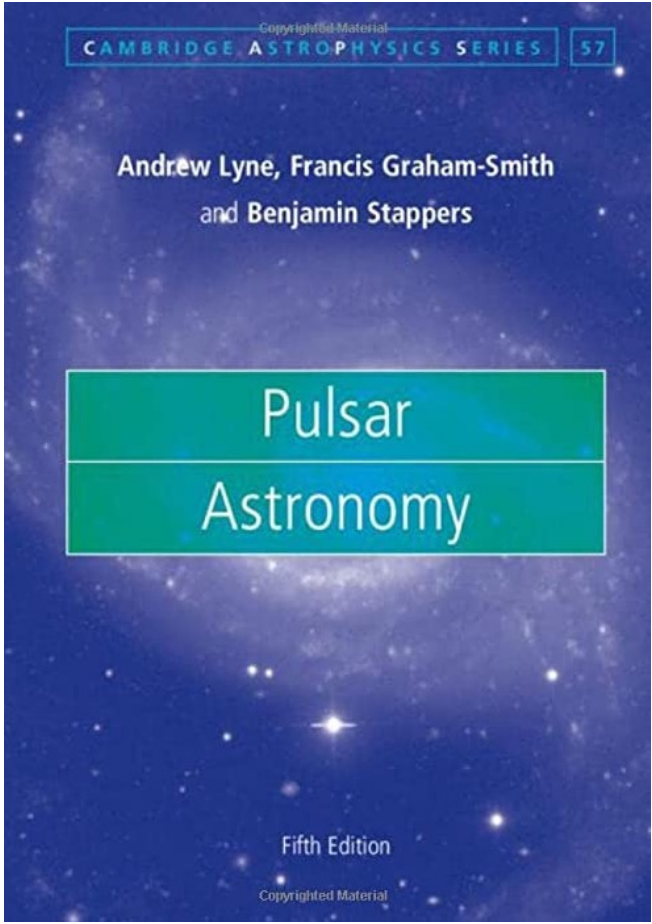


Fig. 4.2 Rotation measures obtained from pulsars with known distances, and a sketch of the Milky-Way spiral arms (From Han, 2007)

mid-plane is consistent with the favoured quadrupolar regular magnetic field pattern of mean-field dynamo theory (see Sect. 5.2.3).



Who understand us better?

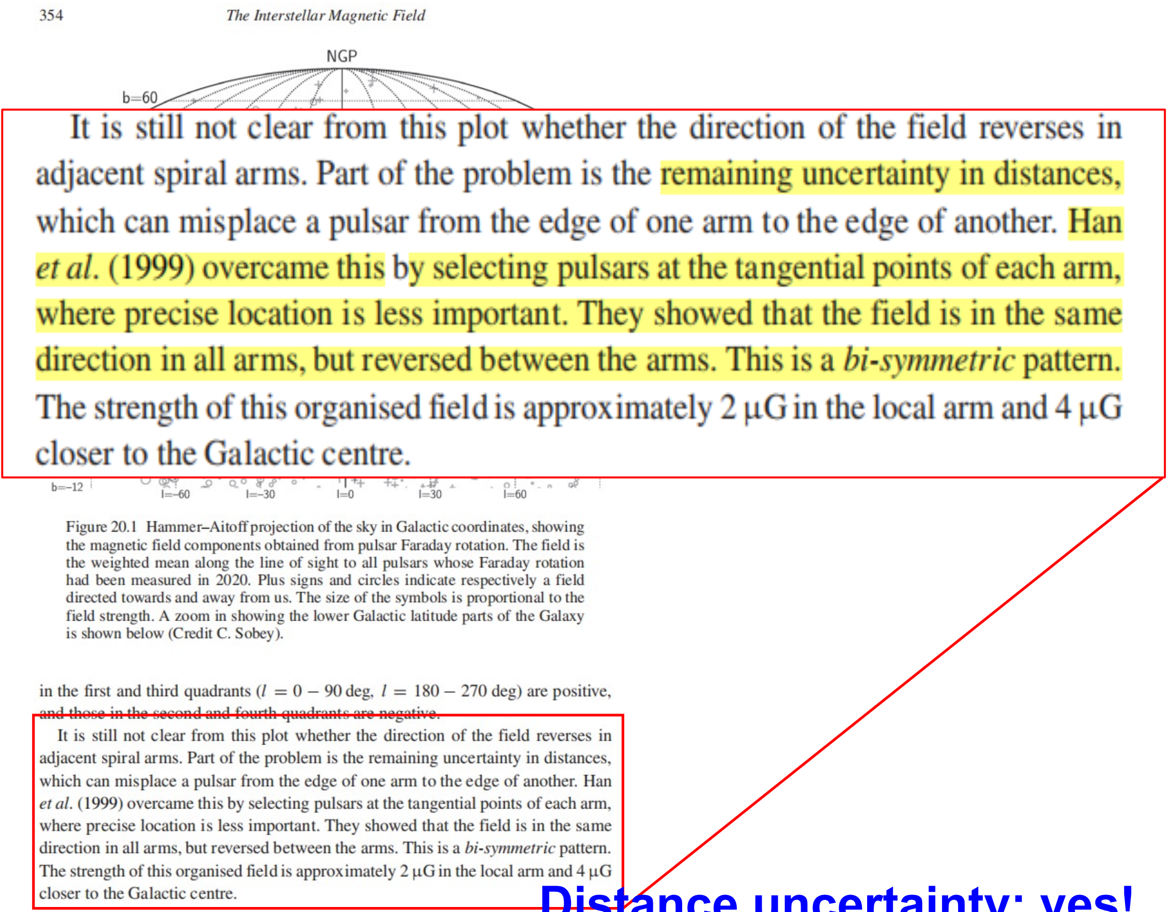


CAMBRIDGE ASTROPHYSICS SERIES 57

Andrew Lyne, Francis Graham-Smith
and Benjamin Stappers

Pulsar
Astronomy

Fifth Edition



It is still not clear from this plot whether the direction of the field reverses in adjacent spiral arms. Part of the problem is the remaining uncertainty in distances, which can misplace a pulsar from the edge of one arm to the edge of another. Han *et al.* (1999) overcame this by selecting pulsars at the tangential points of each arm, where precise location is less important. They showed that the field is in the same direction in all arms, but reversed between the arms. This is a *bi-symmetric* pattern. The strength of this organised field is approximately 2 μG in the local arm and 4 μG closer to the Galactic centre.

Figure 20.1 Hammer–Aitoff projection of the sky in Galactic coordinates, showing the magnetic field components obtained from pulsar Faraday rotation. The field is the weighted mean along the line of sight to all pulsars whose Faraday rotation had been measured in 2020. Plus signs and circles indicate respectively a field directed towards and away from us. The size of the symbols is proportional to the field strength. A zoom in showing the lower Galactic latitude parts of the Galaxy is shown below (Credit C. Sobey).

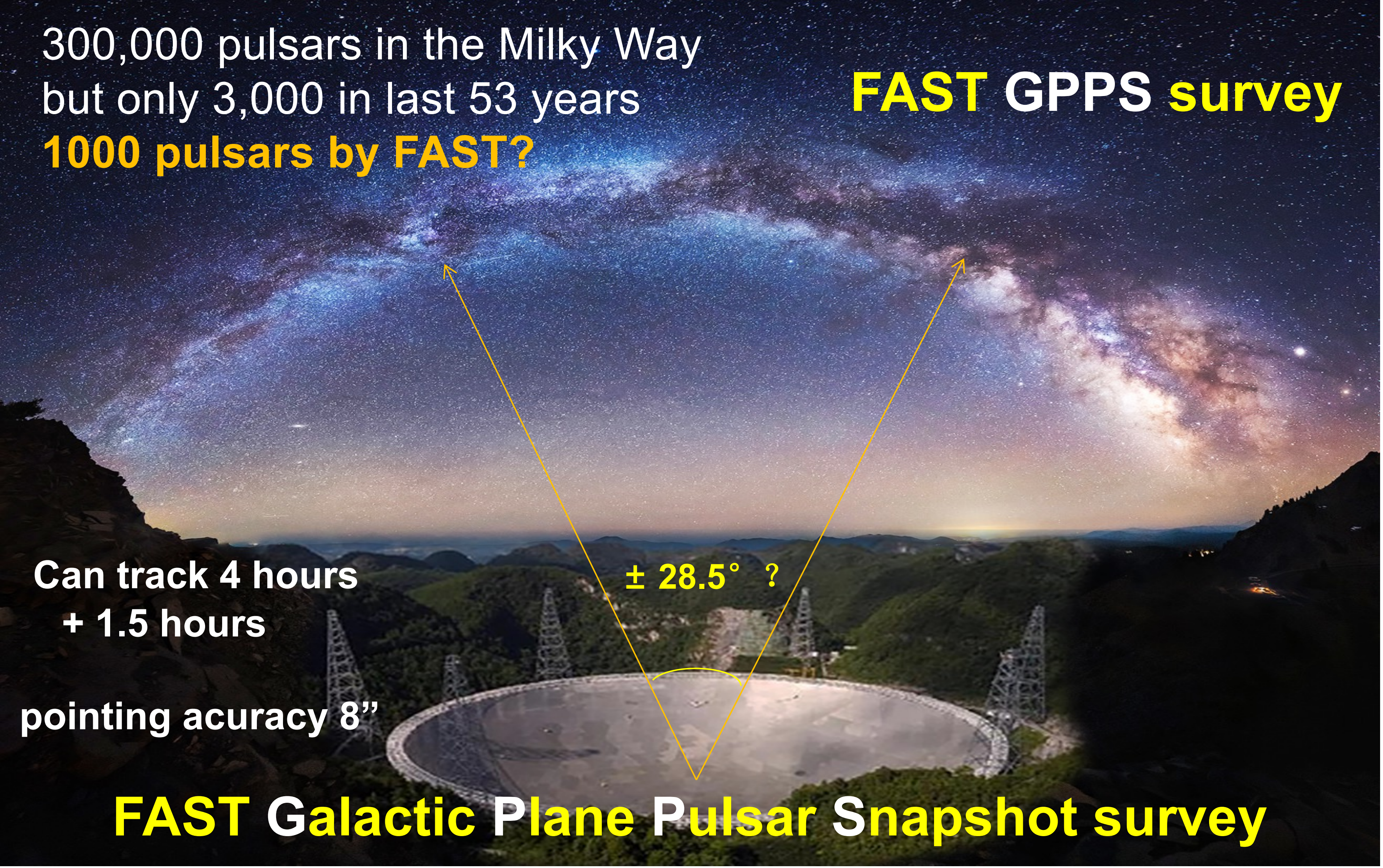
in the first and third quadrants ($l = 0 - 90$ deg, $l = 180 - 270$ deg) are positive, and those in the second and fourth quadrants are negative.

It is still not clear from this plot whether the direction of the field reverses in adjacent spiral arms. Part of the problem is the remaining uncertainty in distances, which can misplace a pulsar from the edge of one arm to the edge of another. Han *et al.* (1999) overcame this by selecting pulsars at the tangential points of each arm, where precise location is less important. They showed that the field is in the same direction in all arms, but reversed between the arms. This is a *bi-symmetric* pattern. The strength of this organised field is approximately 2 μG in the local arm and 4 μG closer to the Galactic centre.

Distance uncertainty: yes!
but collectively, fine!

FAST GPPS survey

300,000 pulsars in the Milky Way
but only 3,000 in last 53 years
1000 pulsars by FAST?

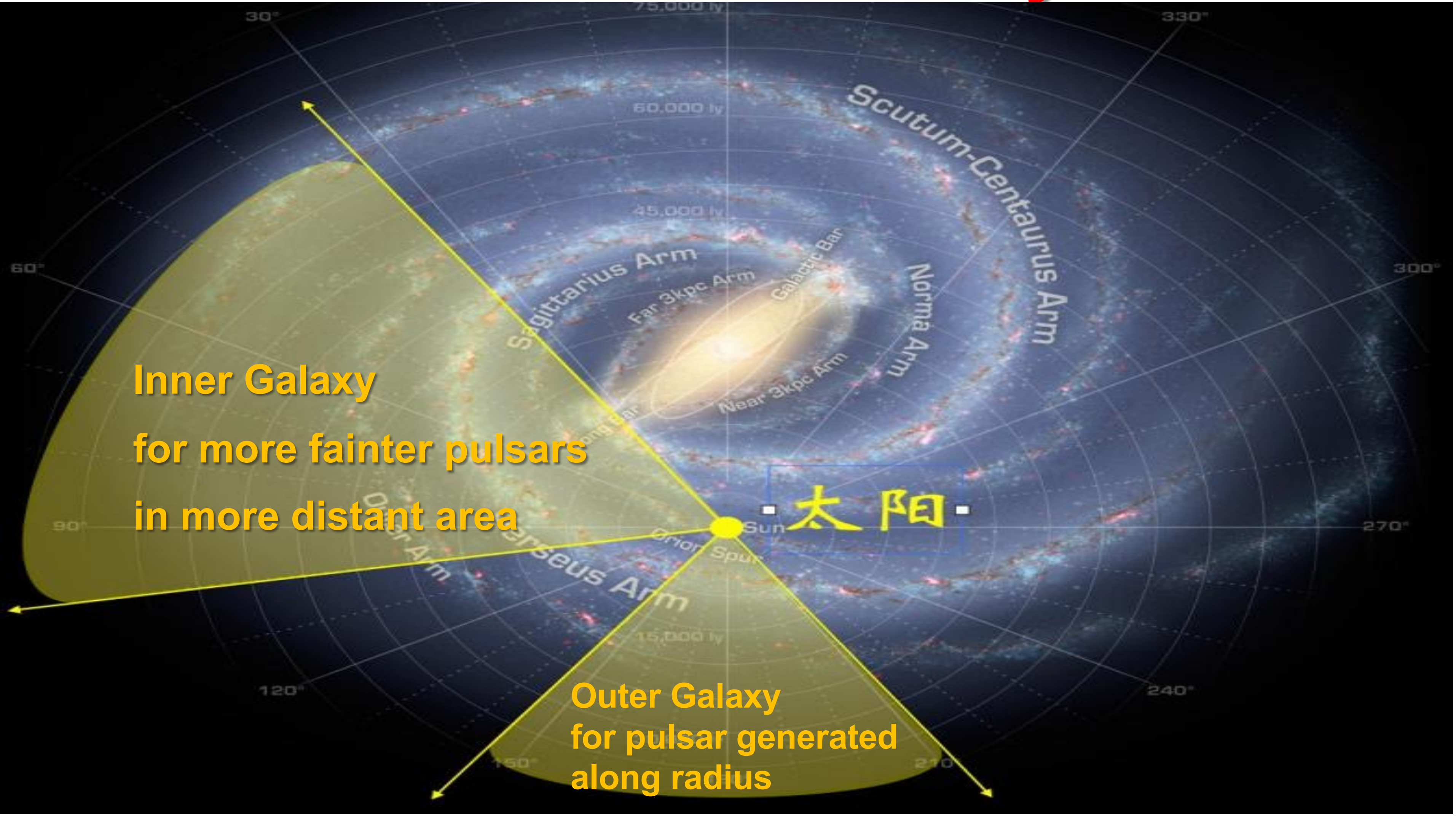


**Can track 4 hours
+ 1.5 hours**

pointing acuracy 8”

FAST Galactic Plane Pulsar Snapshot survey

FAST-GPPS：Survey area



Inner Galaxy

for more fainter pulsars

in more distant area

Outer Galaxy
for pulsar generated
along radius

751 pulsars on GPPS Web

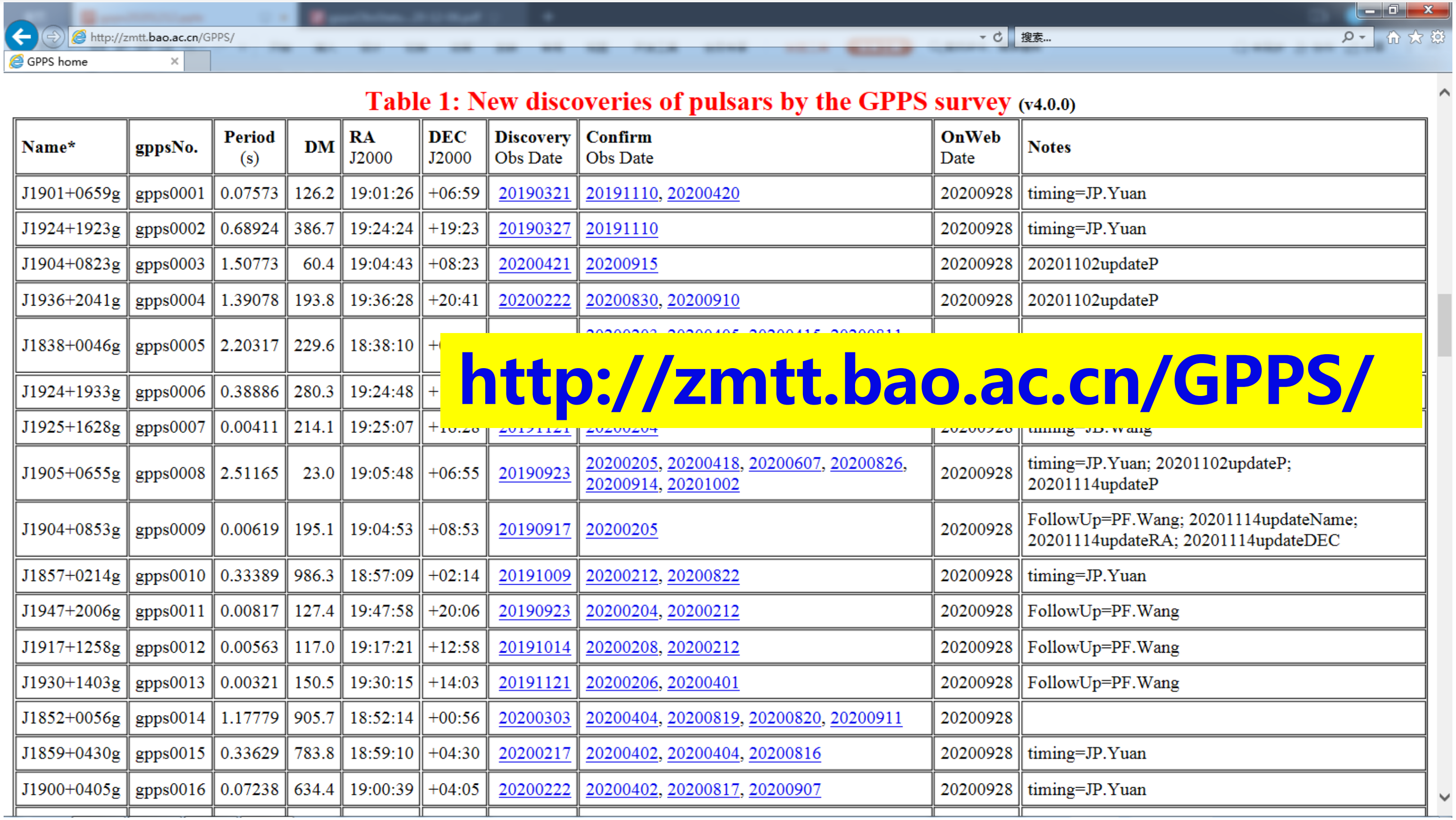


Table 1: New discoveries of pulsars by the GPPS survey (v4.0.0)

Name*	gppsNo.	Period (s)	DM	RA J2000	DEC J2000	Discovery Obs Date	Confirm Obs Date	OnWeb Date	Notes
J1901+0659g	gpps0001	0.07573	126.2	19:01:26	+06:59	20190321	20191110, 20200420	20200928	timing=JP.Yuan
J1924+1923g	gpps0002	0.68924	386.7	19:24:24	+19:23	20190327	20191110	20200928	timing=JP.Yuan
J1904+0823g	gpps0003	1.50773	60.4	19:04:43	+08:23	20200421	20200915	20200928	20201102updateP
J1936+2041g	gpps0004	1.39078	193.8	19:36:28	+20:41	20200222	20200830, 20200910	20200928	20201102updateP
J1838+0046g	gpps0005	2.20317	229.6	18:38:10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
J1924+1933g	gpps0006	0.38886	280.3	19:24:48	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
J1925+1628g	gpps0007	0.00411	214.1	19:25:07	+16:28	20191121	20200204	20200928	timing=JB.Wang
J1905+0655g	gpps0008	2.51165	23.0	19:05:48	+06:55	20190923	20200205, 20200418, 20200607, 20200826, 20200914, 20201002	20200928	timing=JP.Yuan; 20201102updateP; 20201114updateP
J1904+0853g	gpps0009	0.00619	195.1	19:04:53	+08:53	20190917	20200205	20200928	FollowUp=PF.Wang; 20201114updateName; 20201114updateRA; 20201114updateDEC
J1857+0214g	gpps0010	0.33389	986.3	18:57:09	+02:14	20191009	20200212, 20200822	20200928	timing=JP.Yuan
J1947+2006g	gpps0011	0.00817	127.4	19:47:58	+20:06	20190923	20200204, 20200212	20200928	FollowUp=PF.Wang
J1917+1258g	gpps0012	0.00563	117.0	19:17:21	+12:58	20191014	20200208, 20200212	20200928	FollowUp=PF.Wang
J1930+1403g	gpps0013	0.00321	150.5	19:30:15	+14:03	20191121	20200206, 20200401	20200928	FollowUp=PF.Wang
J1852+0056g	gpps0014	1.17779	905.7	18:52:14	+00:56	20200303	20200404, 20200819, 20200820, 20200911	20200928	
J1859+0430g	gpps0015	0.33629	783.8	18:59:10	+04:30	20200217	20200402, 20200404, 20200816	20200928	timing=JP.Yuan
J1900+0405g	gpps0016	0.07238	634.4	19:00:39	+04:05	20200222	20200402, 20200817, 20200907	20200928	timing=JP.Yuan

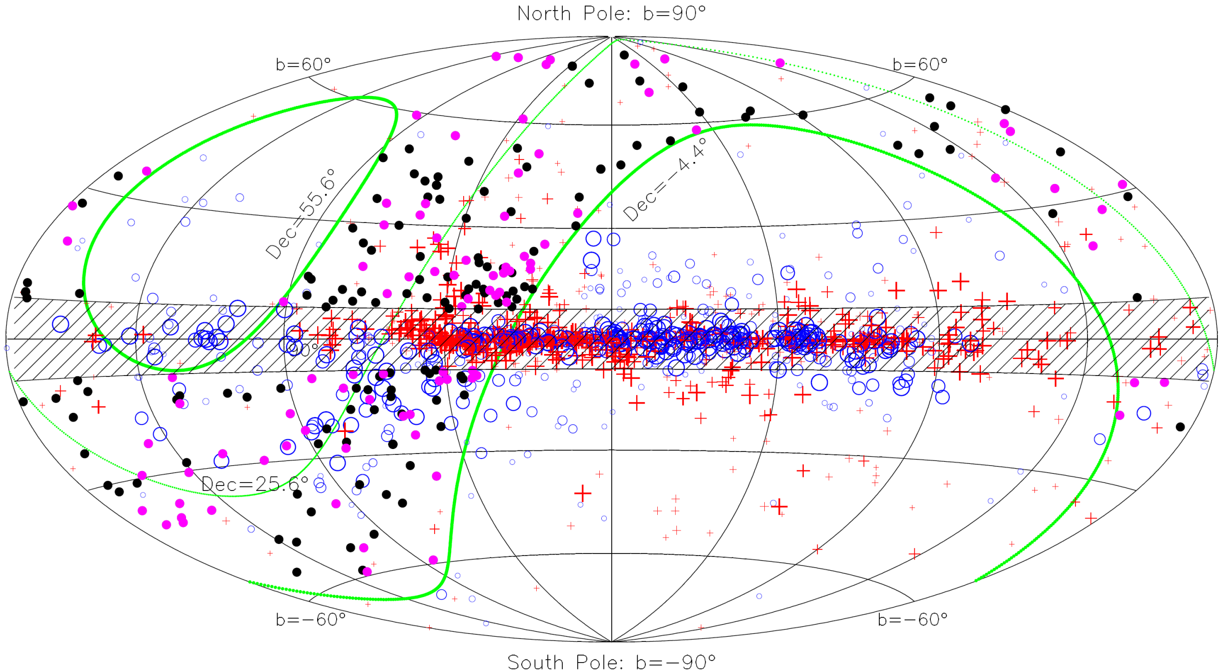
http://zmtt.bao.ac.cn/GPPS/

FAST pulsar polarization observation

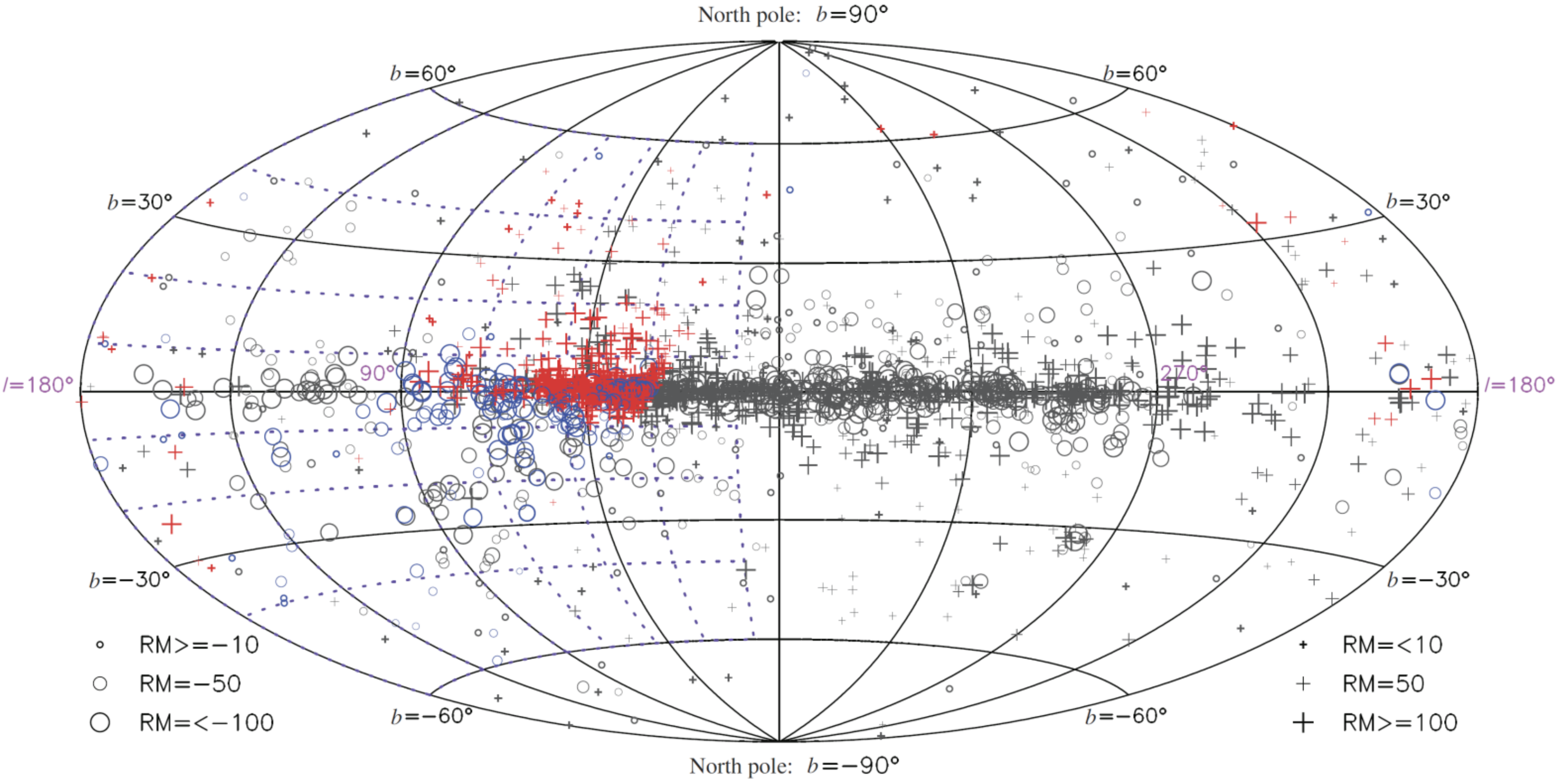
- **Total 3341 pulsars, 1453 of which have known RMs**
- **FAST can measure Faraday rotation for faint pulsars**
- **Two PI projects for halo pulsars: PT2020_0164、PT2021_0051**

  => 134 new RMs (Xu et al. 2022, doi: 10.1007/s11433-022-2033-2)
- **The Galactic plane pulsar snapshot (GPPS) survey: Polarization data**

  => 404 new RMs (Wang et al. 2023, doi: 10.1088/1674-4527/acea1f)



New RMs for 134 halo pulsars and 311 disk pulsars

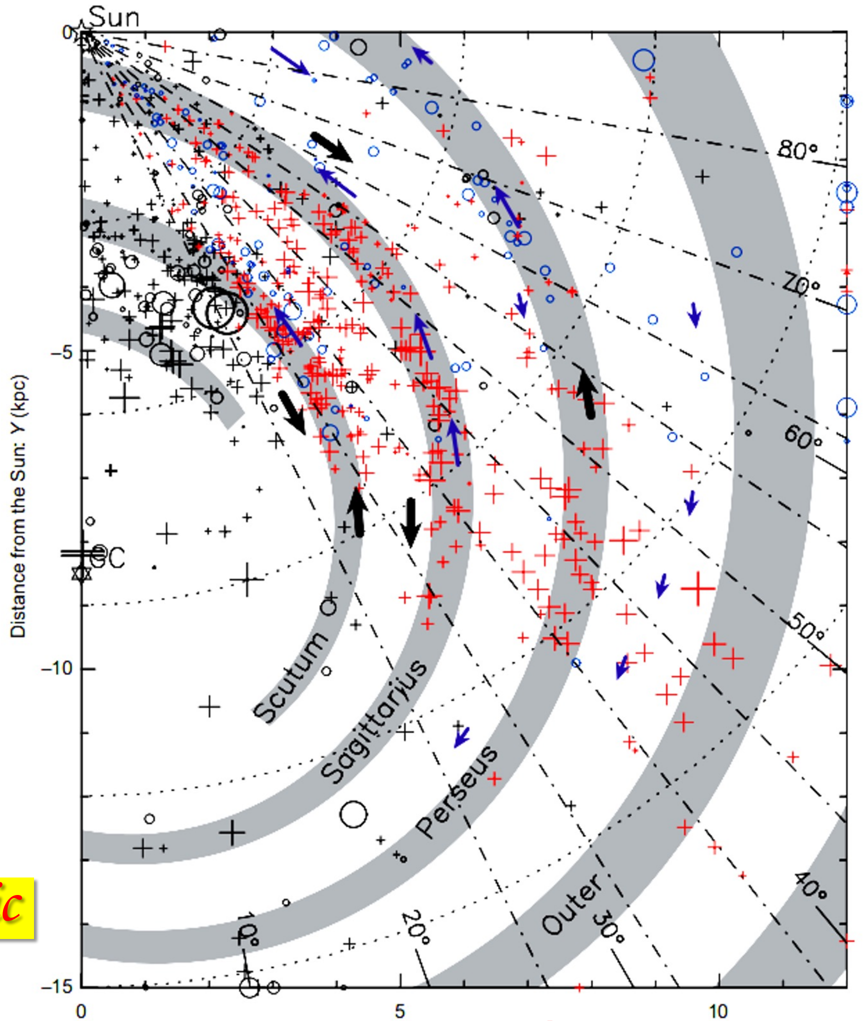


(Xu et al. 2022, doi: 10.1007/s11433-022-2033-2)

Magnetic fields in the first quadrant of the Galactic disk

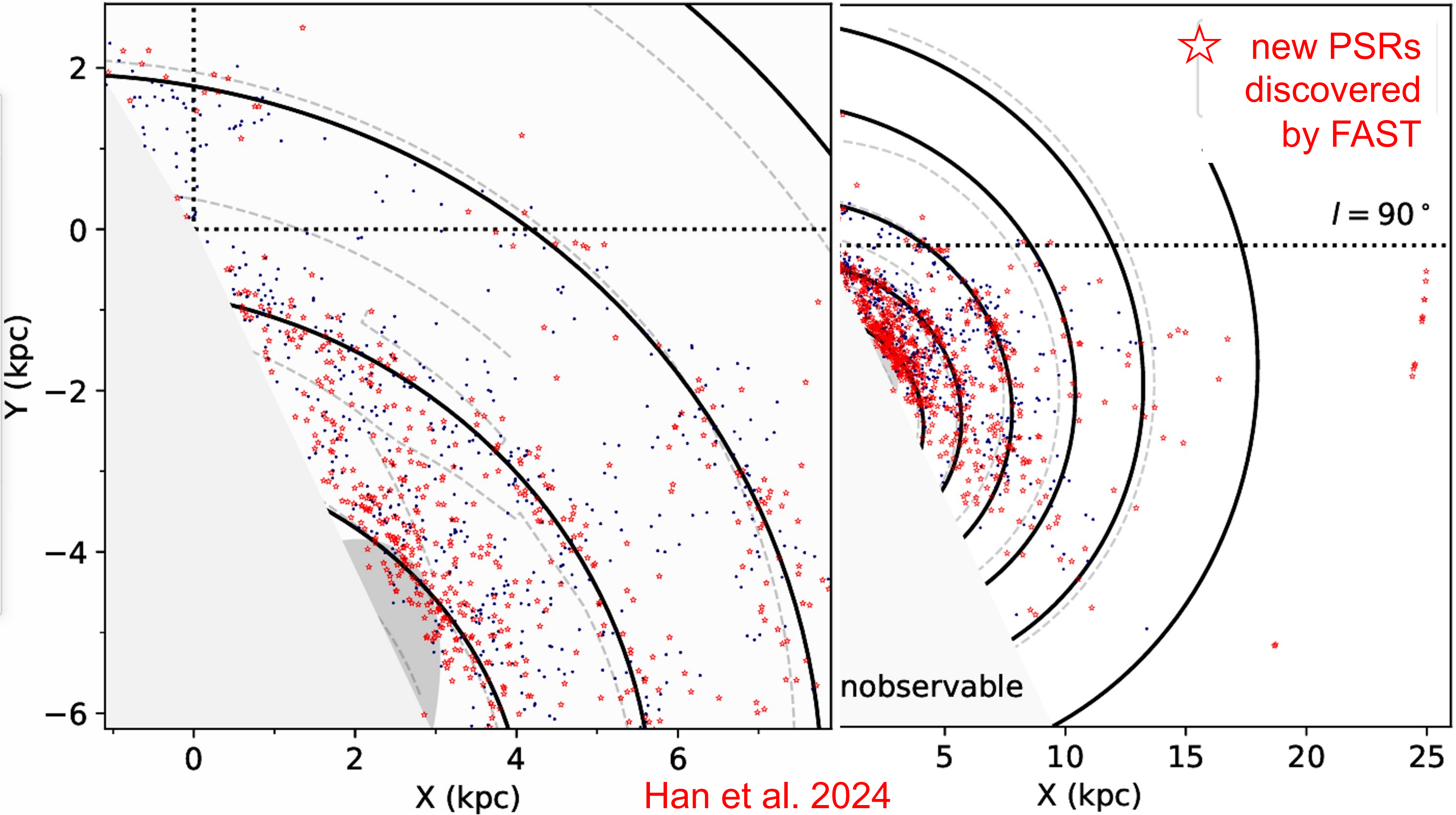
- **In FAST pulsar database (Wang et al. 2022) we determined RMs for 311 pulsars for the first time**
- **Large number of RMs in (26°<l<90°) increased by a factor of two compared to the previous work.**
- **Explore the fields in farther arms up to 15 kpc**

Without FAST,
it is very difficult to explore magnetic
fields in such wide areas



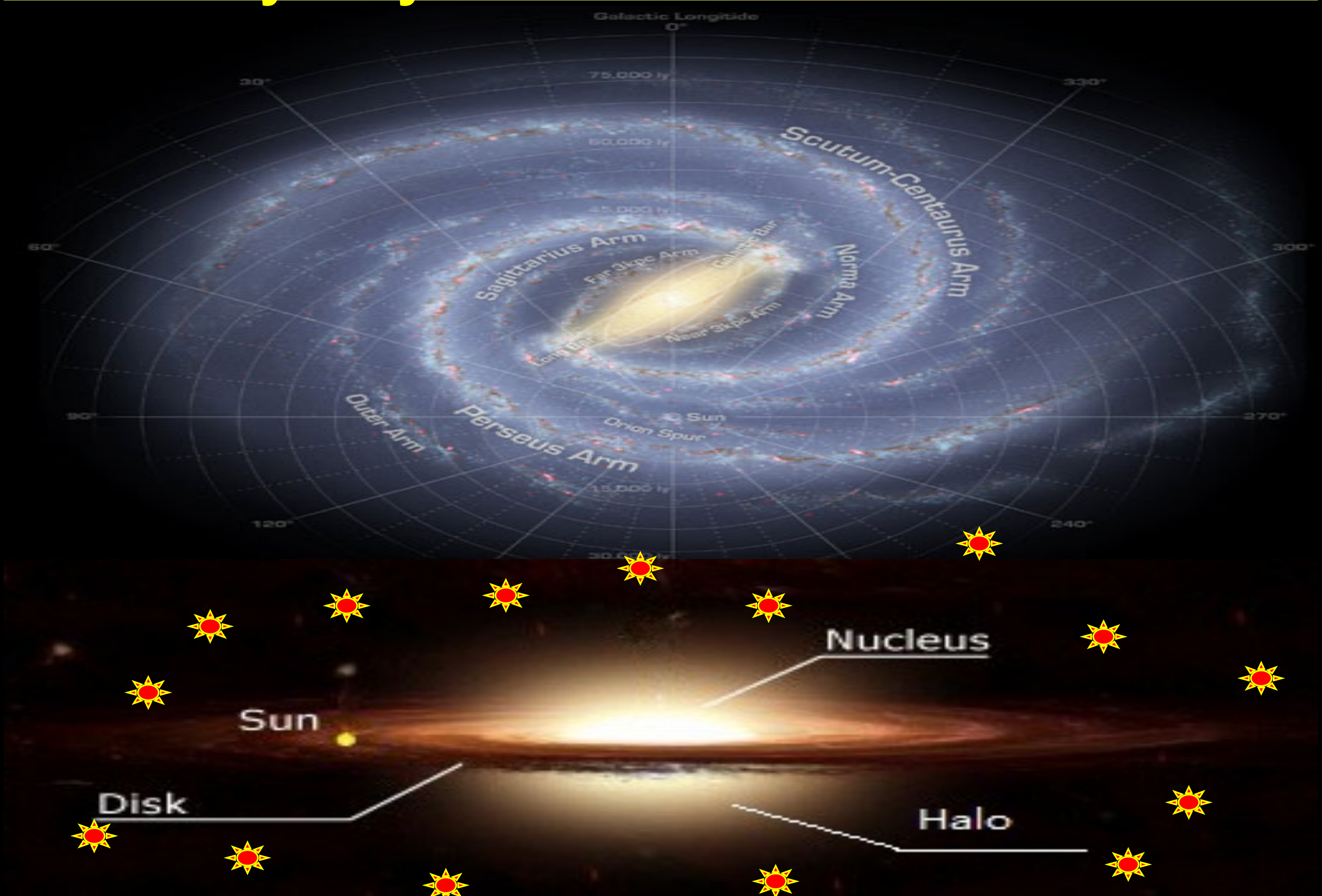
(Xu et al. 2022, doi: 10.1007/s11433-022-2033-2)

Where the FAST can measure in future?



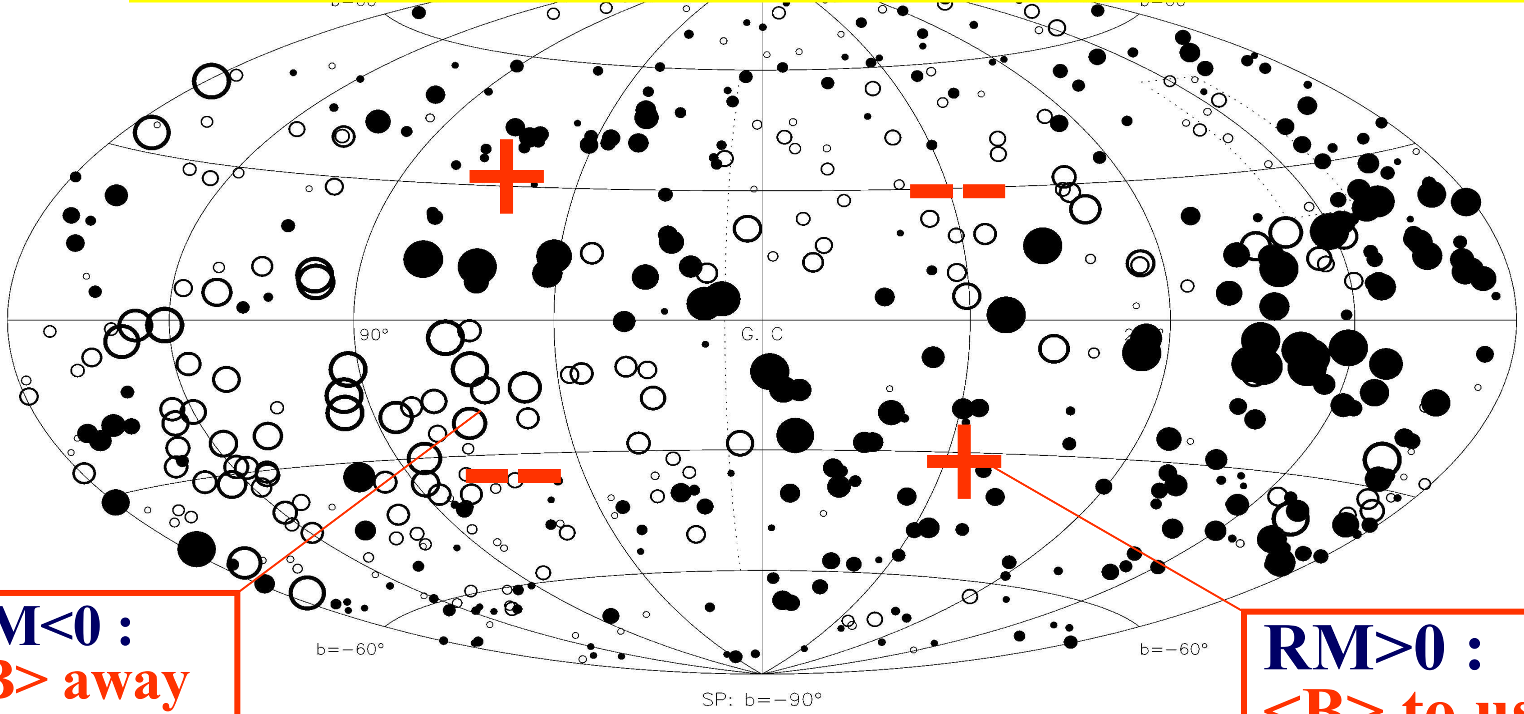
Han et al. 2024

RMs of extragalactic sources: Integration of Ne*$B_{//}$



RM Sky: Anti-symmetry!

$$RM = \frac{e^3}{2\pi m_e^2 c^4}\int_{\mathrm{PSR}}^{\mathrm{Sun}}[\frac{\lambda(l)}{\lambda_{obs}}]^2 n_e(l)\mathbf{B(l)}\bullet\mathbf{dl} = 0.820\langle B_\parallel\rangle\int_0^{Dist} n_e dl$$

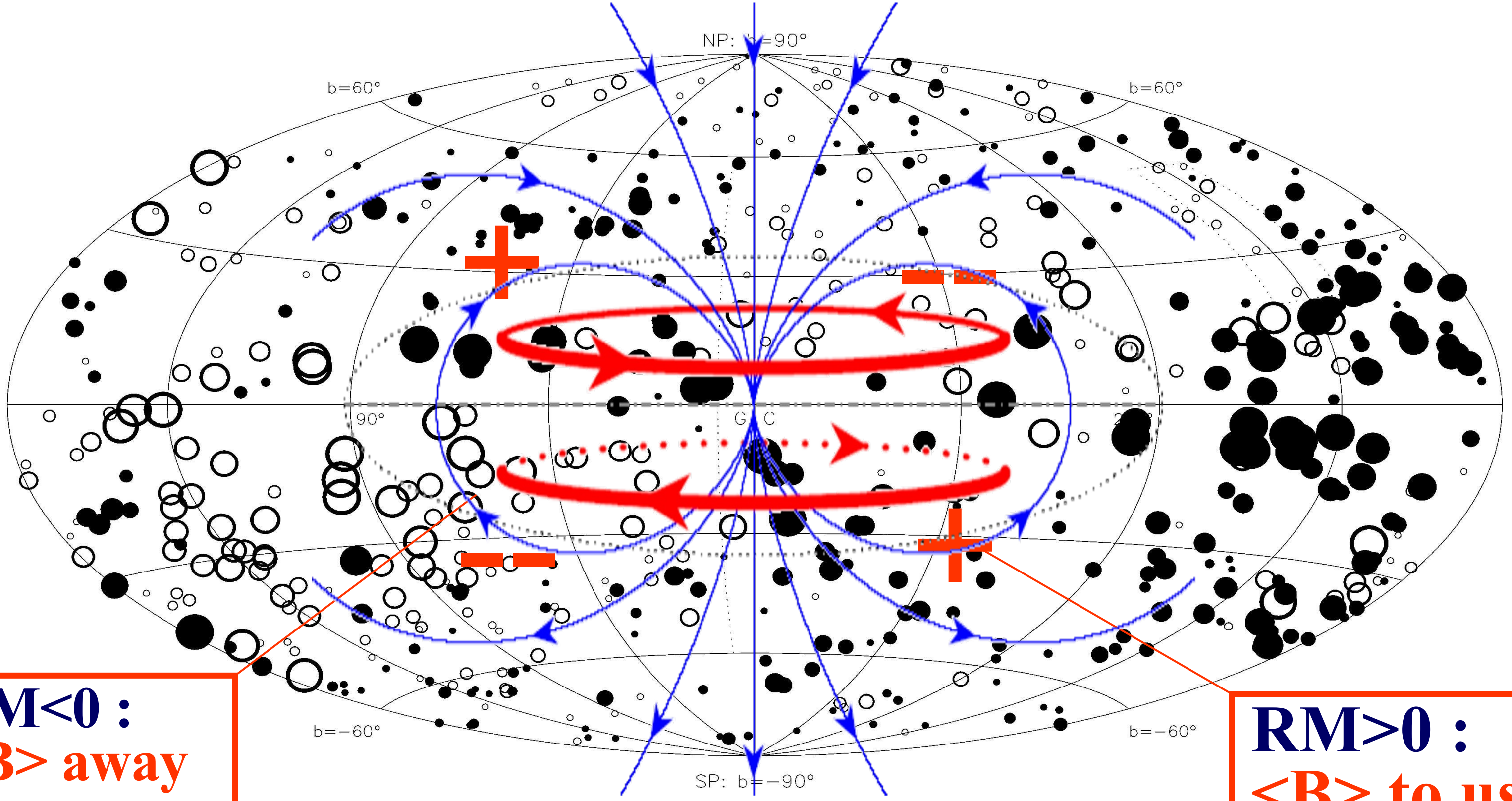


RM<0 :
<B> away from us

RM>0 :
<B> to us

RM Sky: Anti-symmetry!

Outliers omitted if significantly different from surroundings



RM<0 :
<B> away from us

RM>0 :
<B> to us

Anti-symmetric RM sky: halo B fields = A0 dynamo

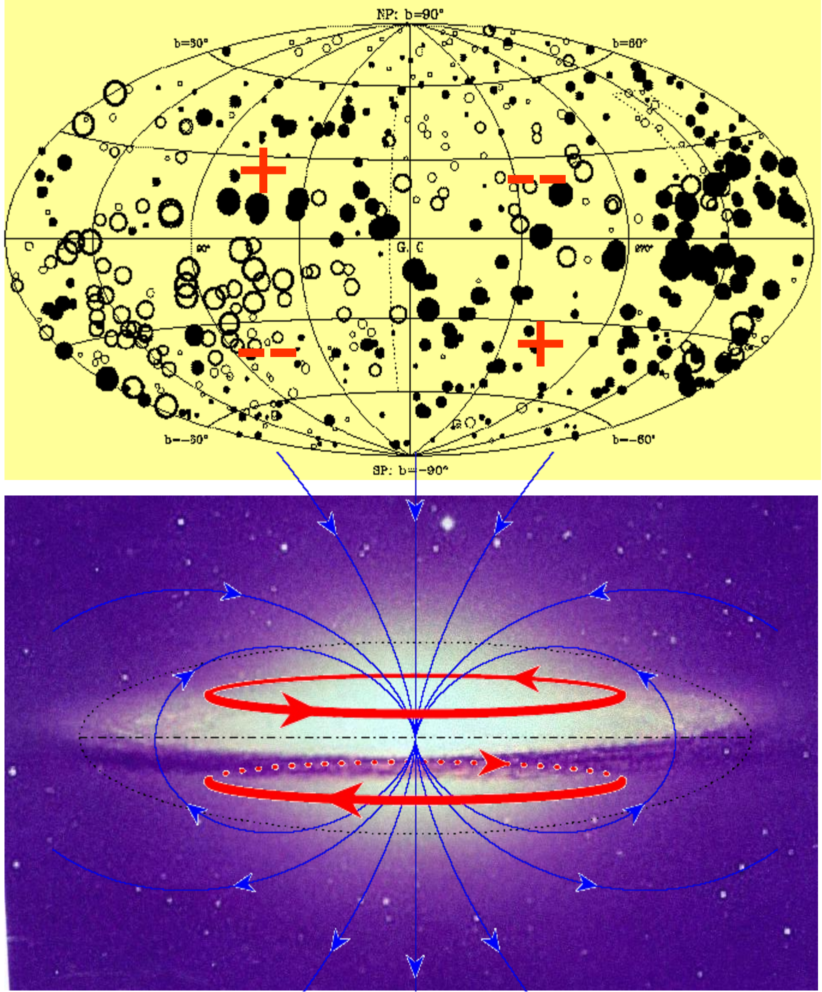
(Han et al. 1997, A&A322, 98)

Evidence for global scale B

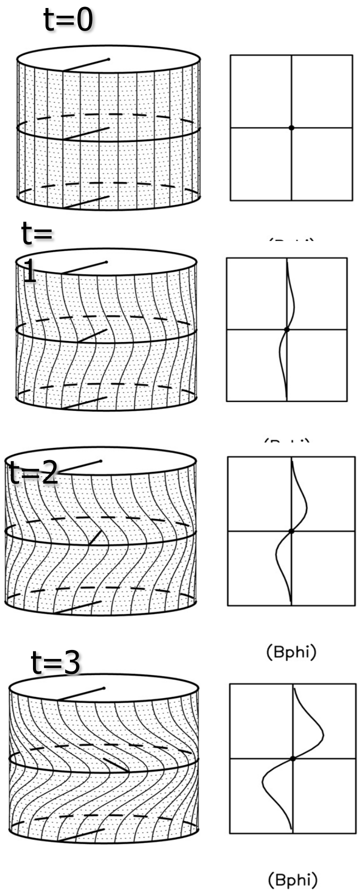
- High anti-symmetry to the Galactic coordinates
- Only in inner Galaxy
- nearby pulsars show it at higher latitudes

Implications

- Consistent with B-field configuration of A0 dynamo
- The first dynamo mode identified on galactic scales



Generation of toroidal fields in the halo

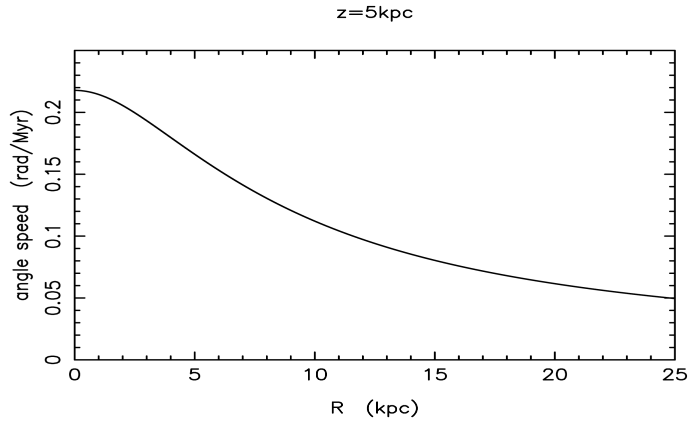


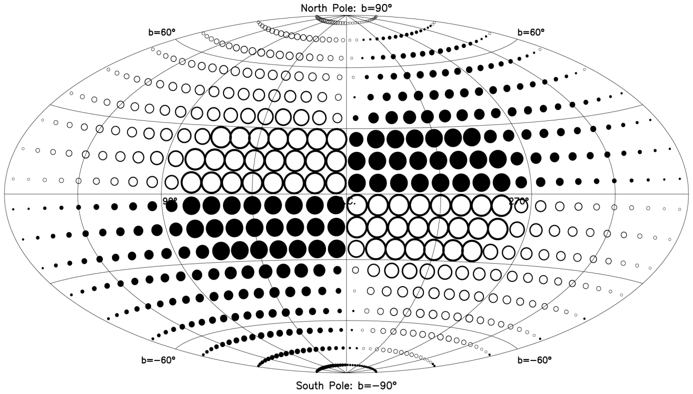
- **Angular velocity** $\omega = \sqrt{\frac{|g_R|}{R}}$

- **Radial shear works on** B_R

$$B_\varphi = B_R R \frac{\partial \omega}{\partial R} t$$

$$t = 1\,\mathrm{Myr}$$

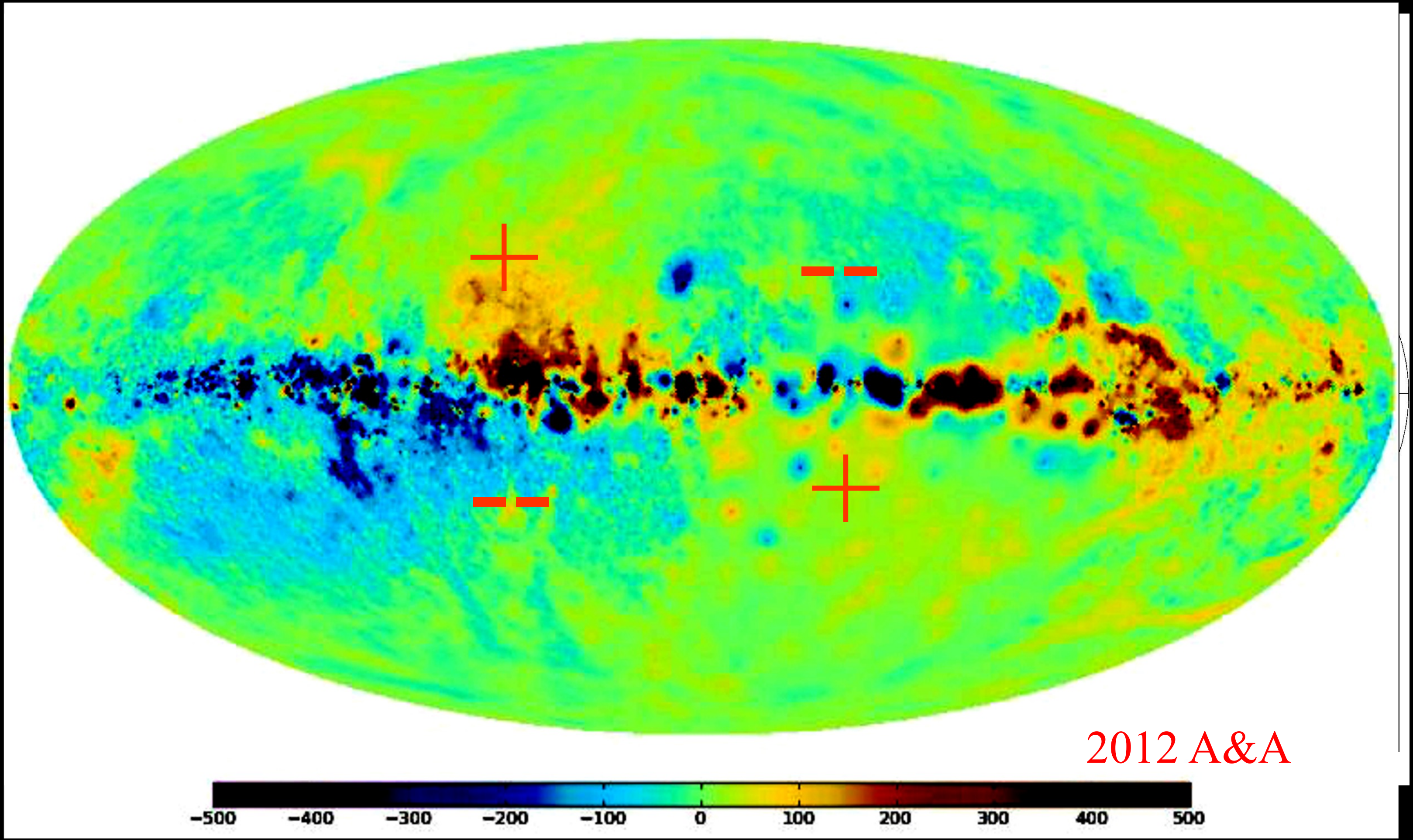




RM sky: Antisymmetry is confirmed!

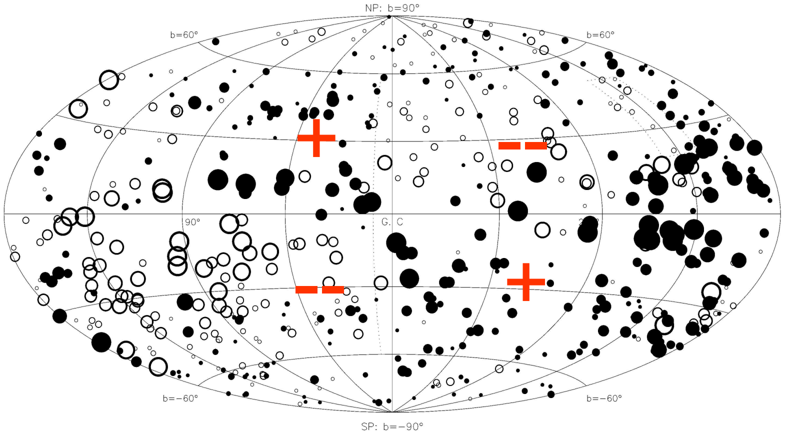
***Notice:** RM estimated from only 2 IFs of NVSS data*

***Individually:** cannot trust! **Collectively:** Ok!*

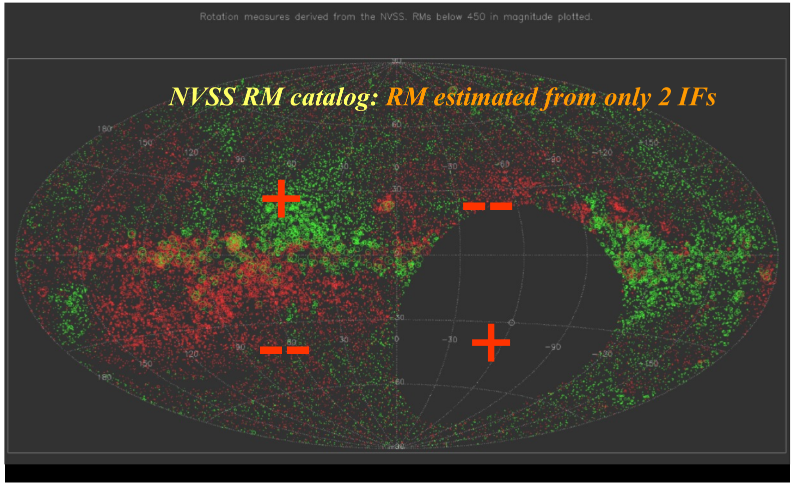


2012 A&A

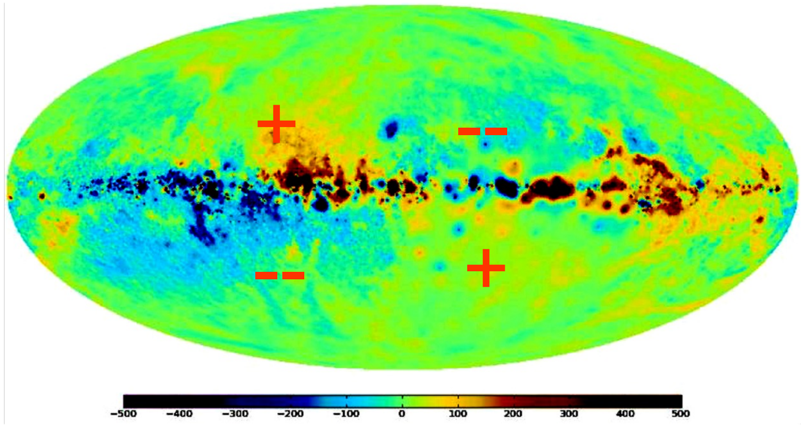
This has been confirmed again and again



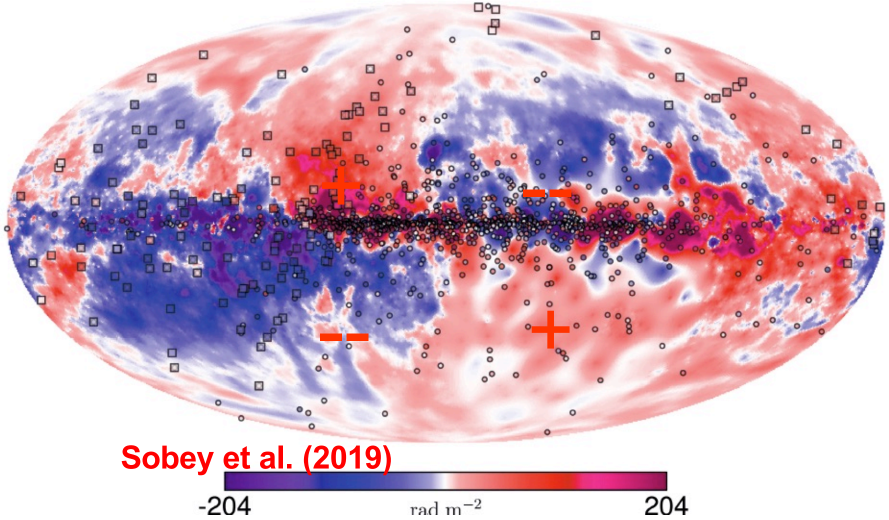
Han et al. (1997, 1999)



Taylor et al. (2009）

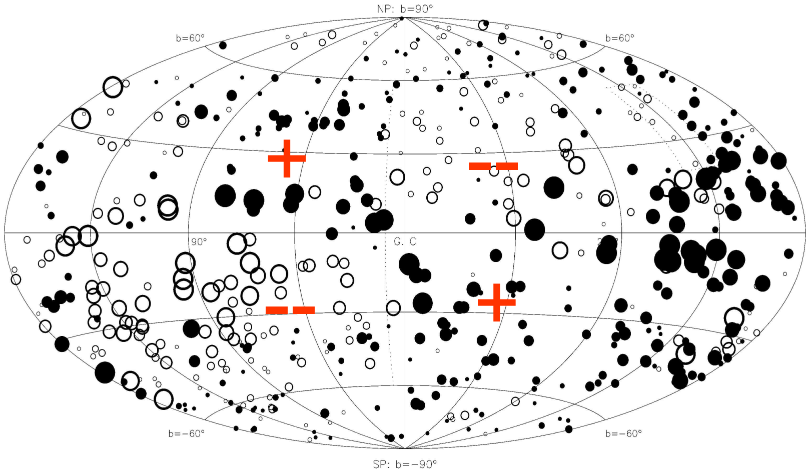


Oppermann et al. (2012)

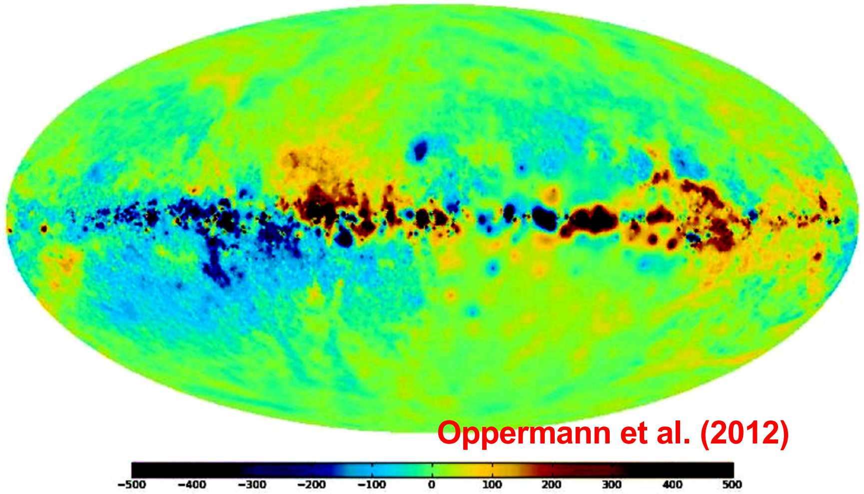


Sobey et al. (2019)

This has been confirmed again and again

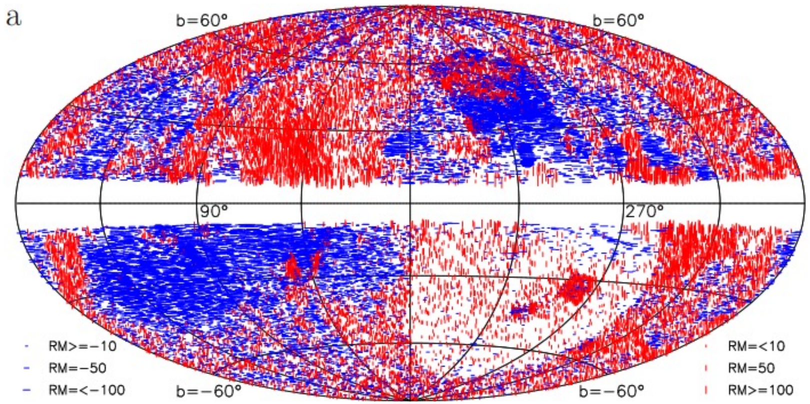


Han et al. (1997, 1999)

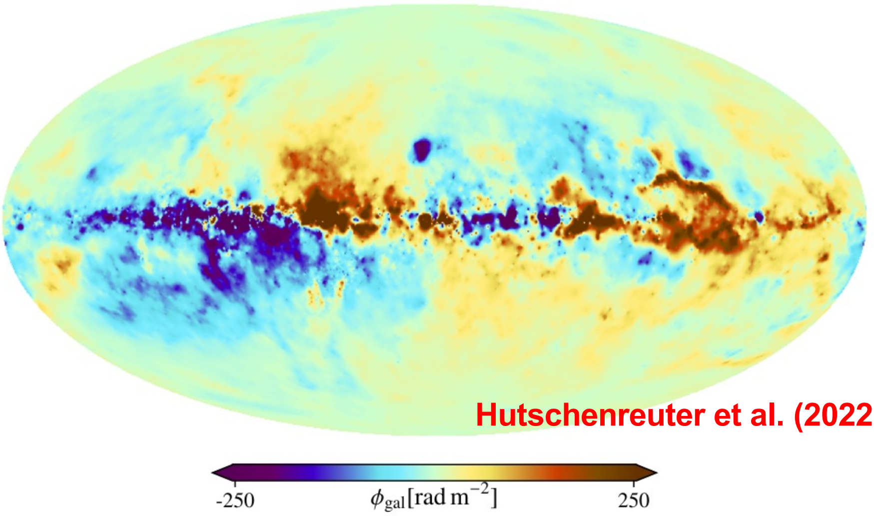


Oppermann et al. (2012)

A&A 657, A43 (2022)

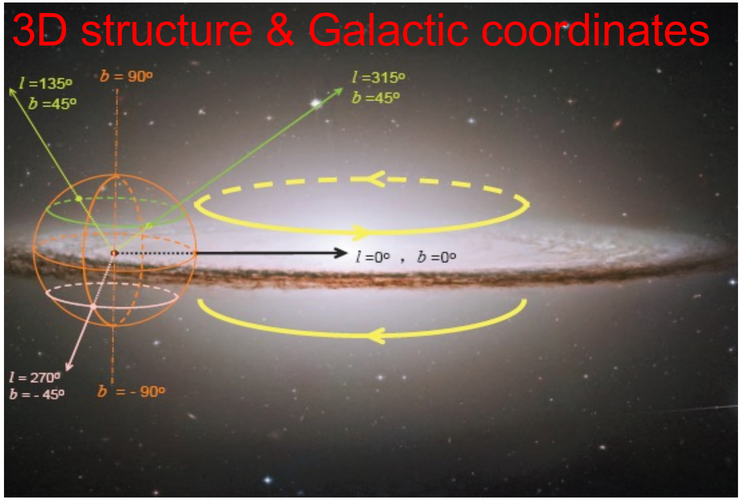


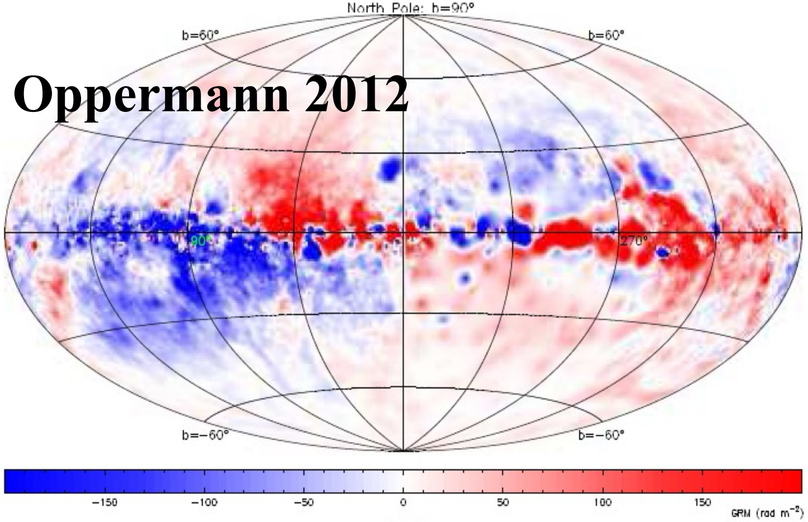
Xu & Han (2024)

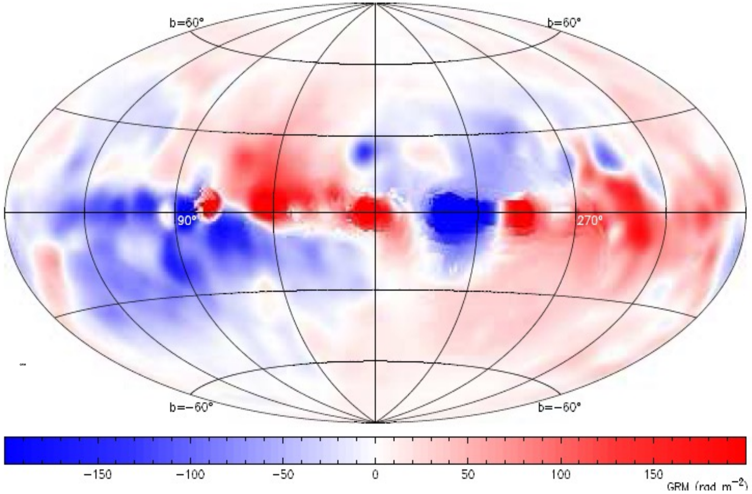


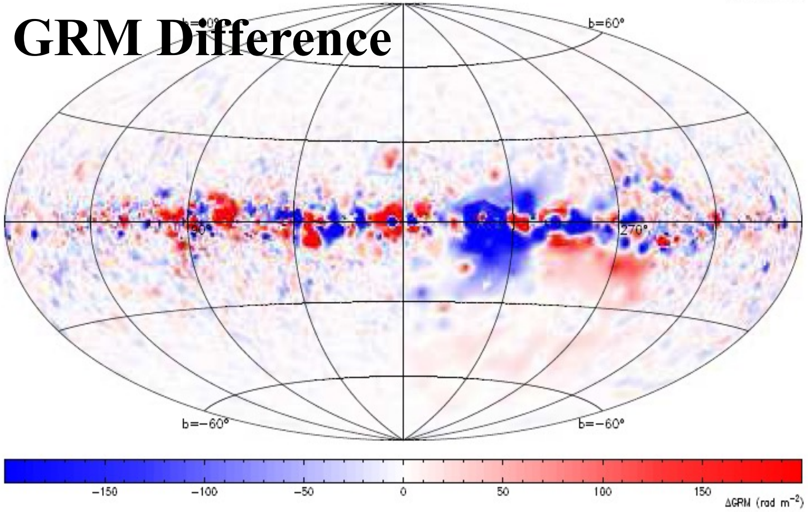
Hutschenreuter et al. (2022)

RM foreground from our Milky Way: GRM

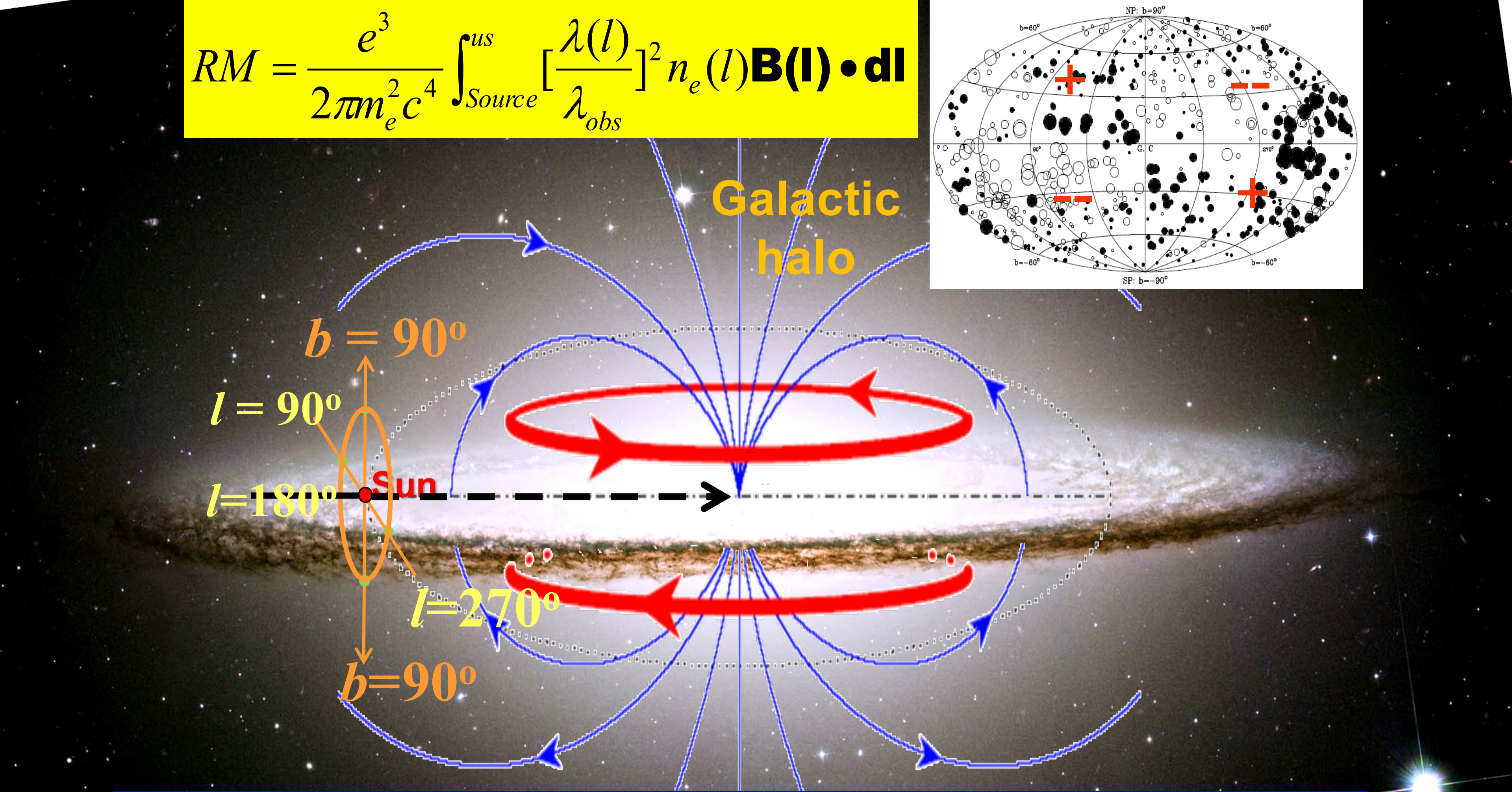



Oppermann 2012



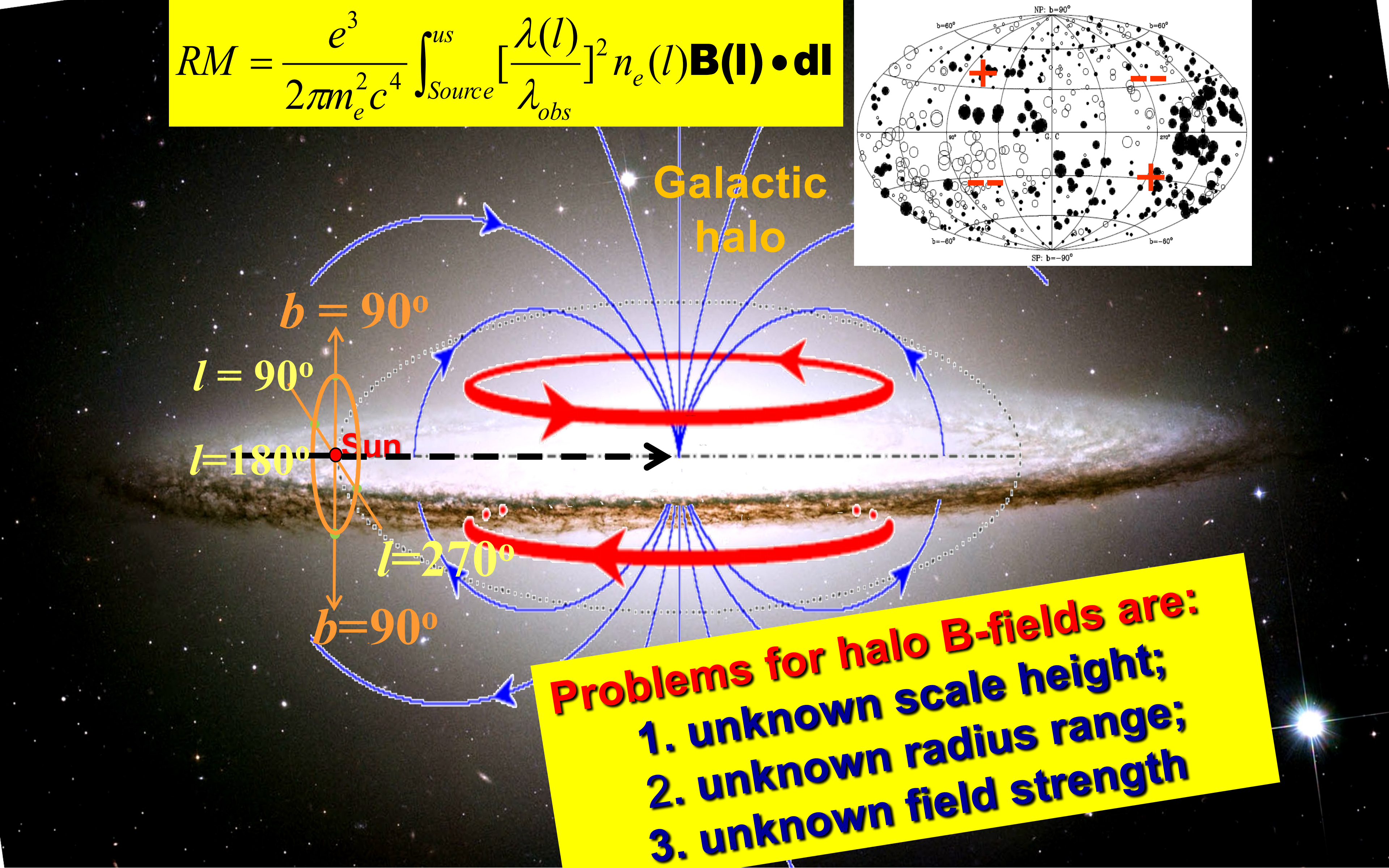

GRM Difference

$$RM = \frac{e^3}{2\pi m_e^2 c^4}\int_{Source}^{us}[\frac{\lambda(l)}{\lambda_{obs}}]^2 n_e(l)\,\mathbf{B(l)}\bullet\mathbf{dl}$$



This has been widely adopted in almost all models for the Galactic magnetic fields, with or without citations of Han et al. (1997, A&A 322, 98) and Han et al. (1998, MNRAS 306, 371)

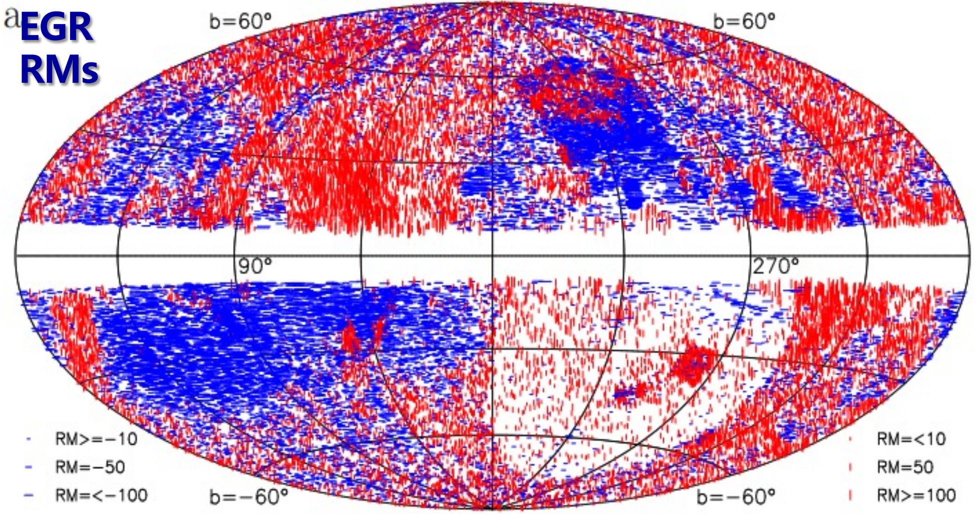
$$RM = \frac{e^3}{2\pi m_e^2 c^4}\int_{Source}^{us}\left[\frac{\lambda(l)}{\lambda_{obs}}\right]^2 n_e(l)\,\mathbf{B(l)}\bullet\mathbf{dl}$$

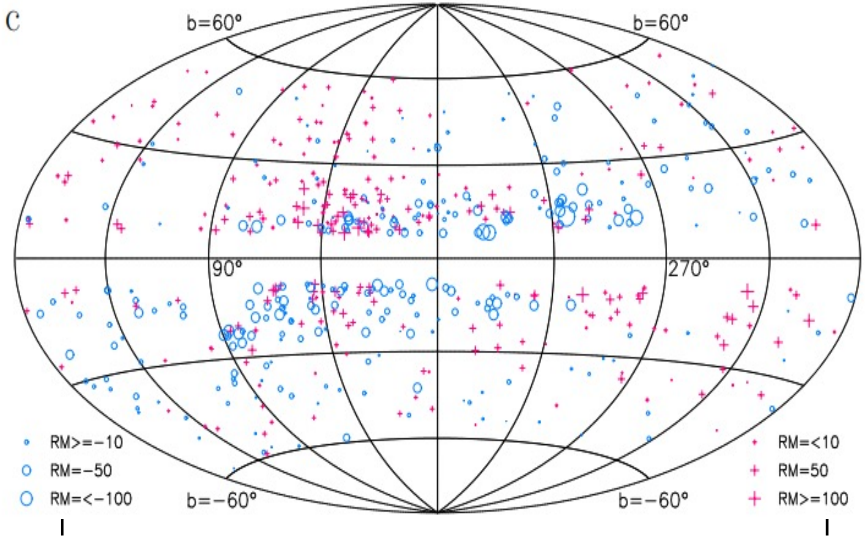


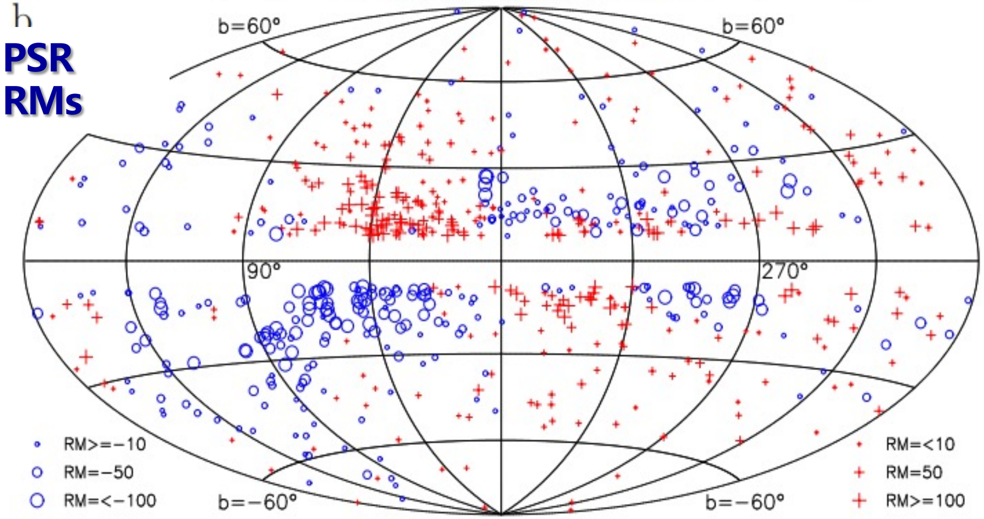
Problems for halo B-fields are:

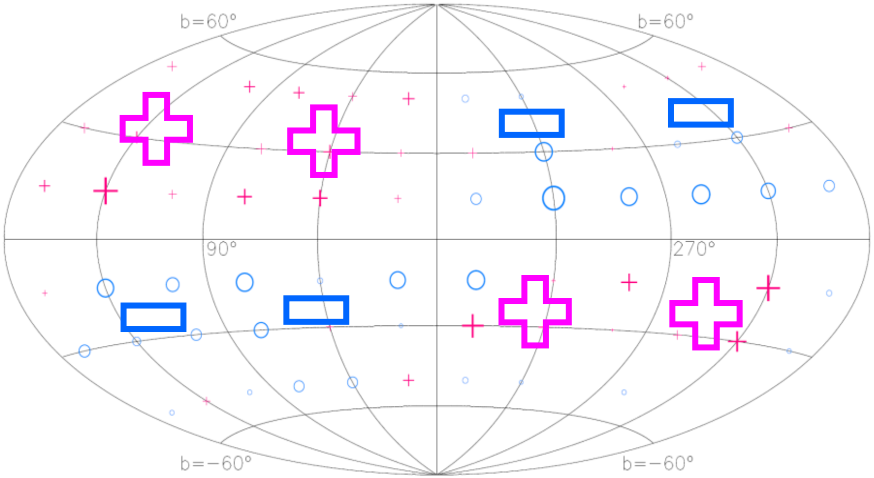
1. unknown scale height;
2. unknown radius range;
3. unknown field strength

Huge Magnetic Rings in the Galactic Halo



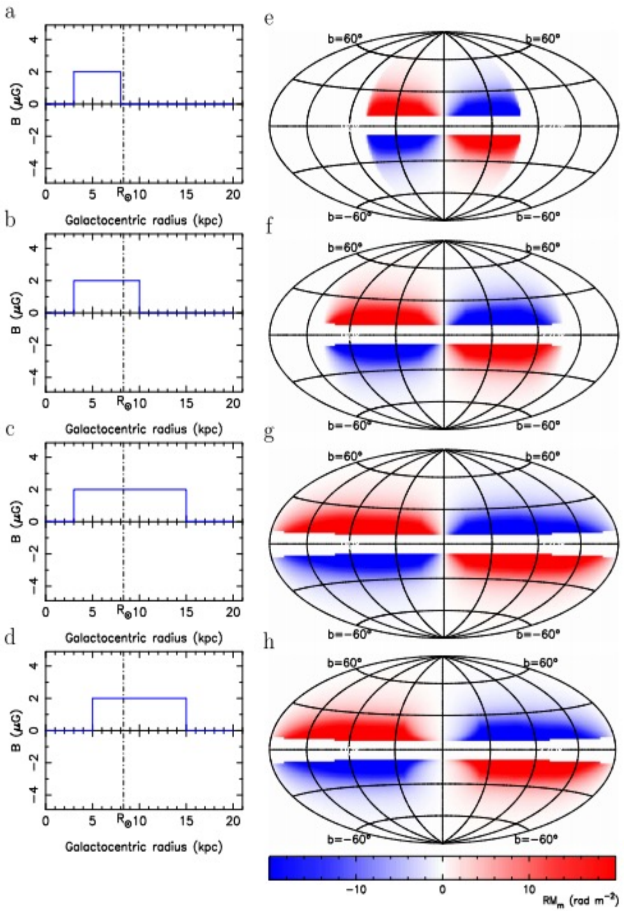


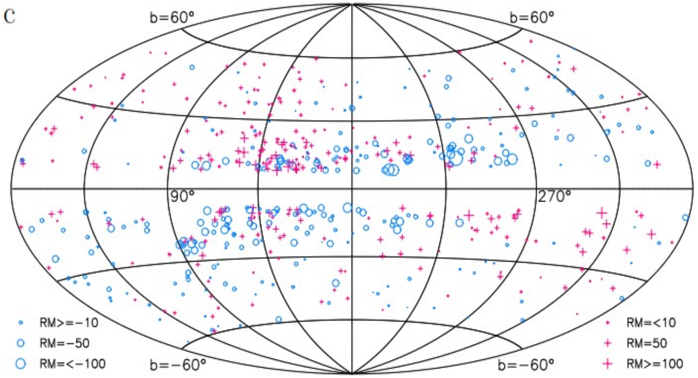


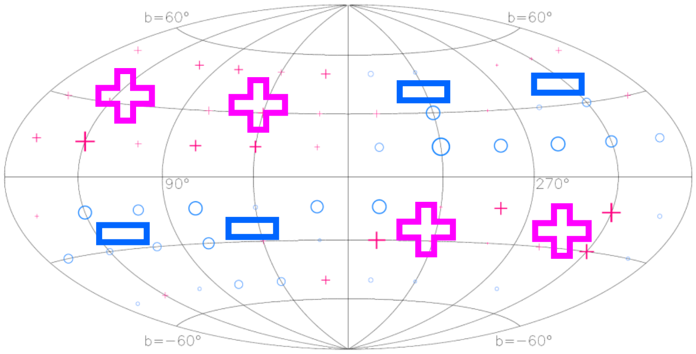


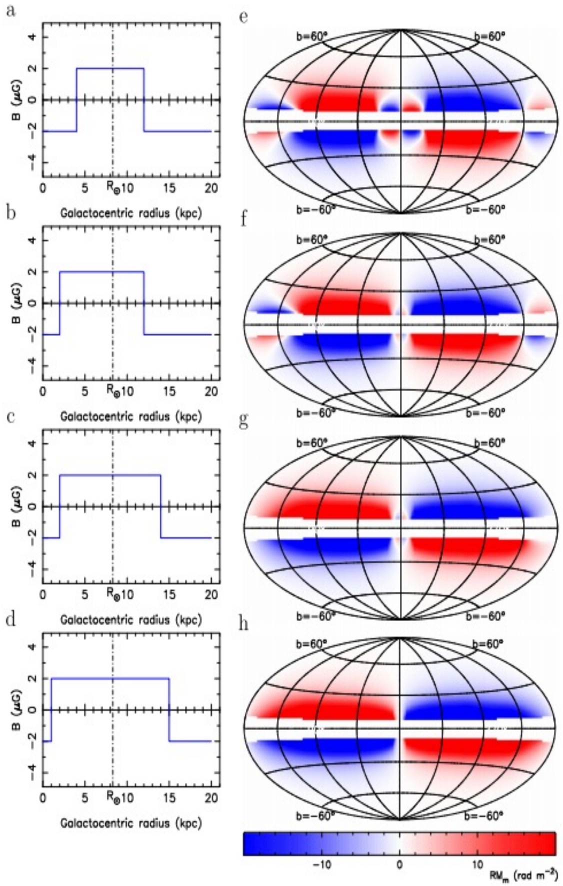
Xu & Han 2024, ApJ

How huge are the Magnetic Rings in the Galactic Halo?



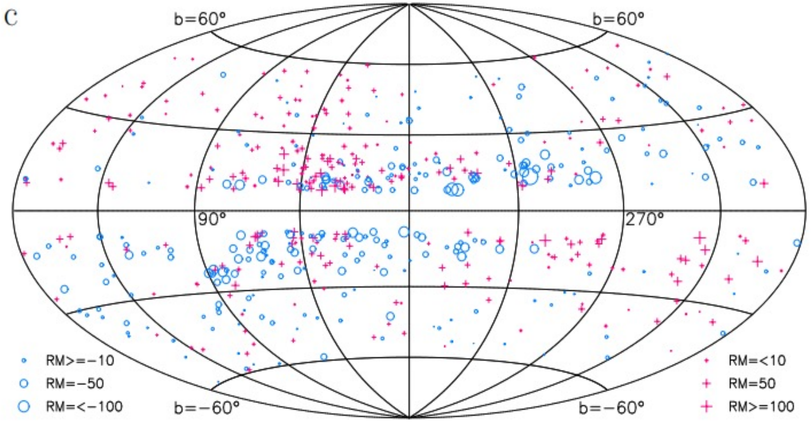


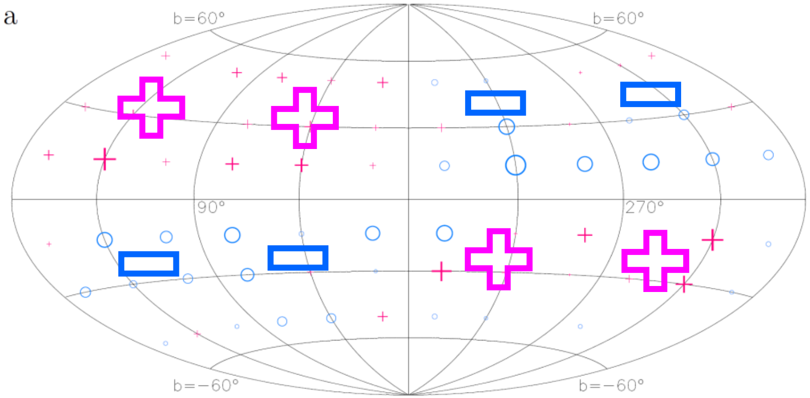




Xu & Han 2024, ApJ

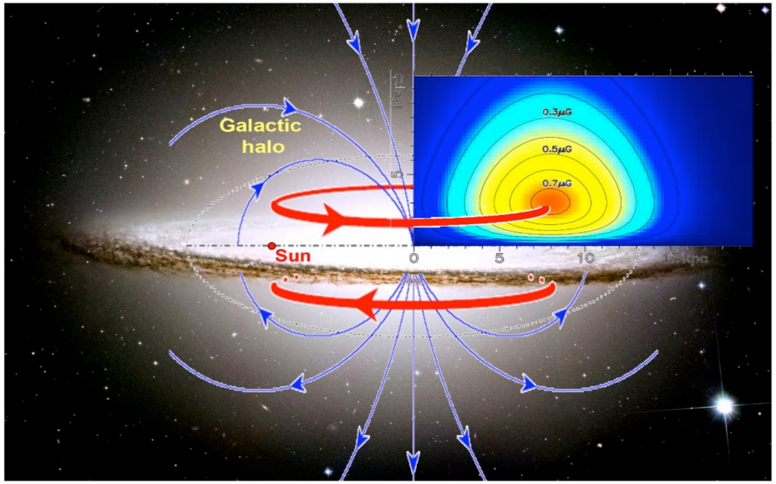
Huge Magnetic Rings in the Galactic Halo





Simply comparing to all simulations of B-field structure and n_e distribution models, we conclude that:

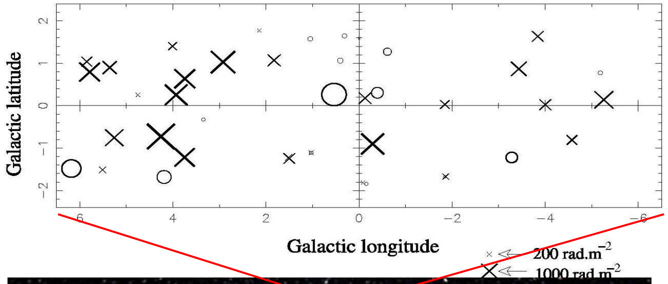
Rings must start from R~1kpc and must extend to R > 15kpc!

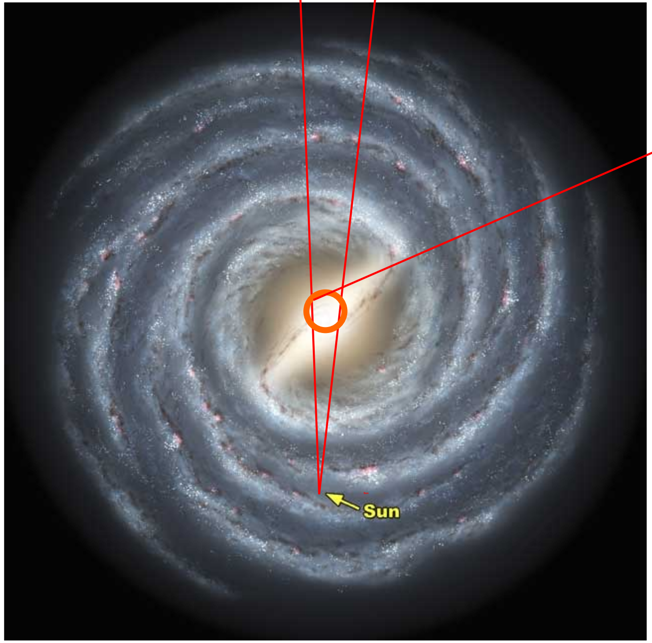


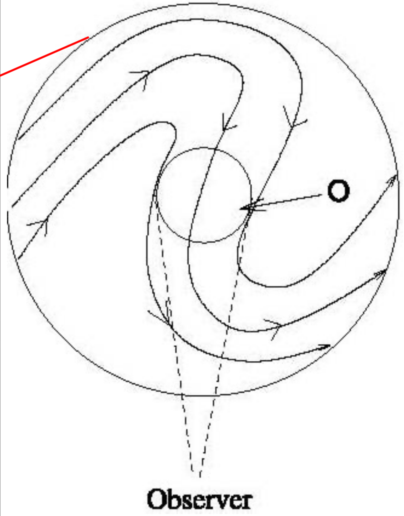
Xu & Han 2024, ApJ

RMs of background radio sources in the GC region

(Roy et al. 2008)







What's Wrong here?

Ou, It is just right!

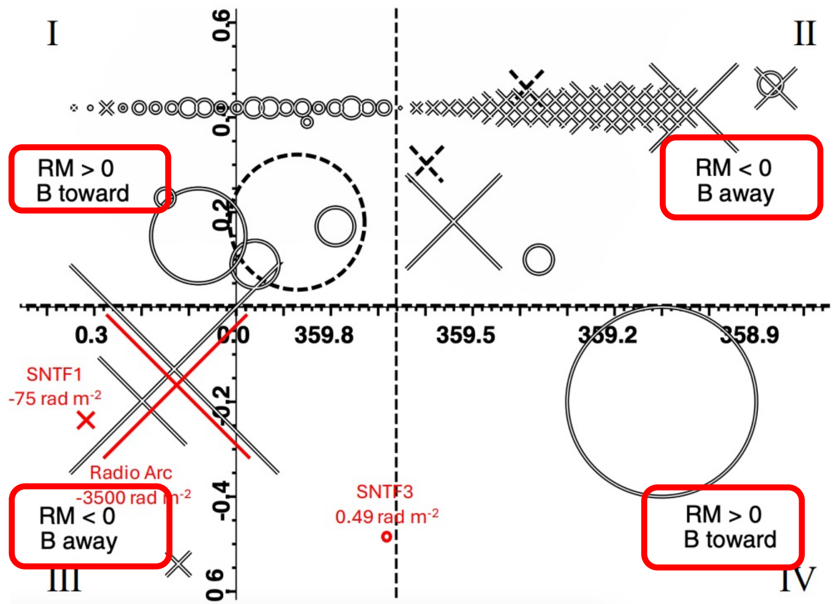


Figure 9. The large-scale RM distribution observed towards the GC. In this figure the extent of the GC in the plane of the sky has been split into four quadrants (labeled I – IV in the figure). Circles represent positive RM values and crosses represent negative RM values, with the size of each symbol scaled by RM magnitude. Black circles and crosses represent the RM values collated previously by Law et al. (2011). Red circles and crosses represent new RM values studied in this and other recent radio polarimetric studies of the GC (Paré et al. 2019, 2021).

D. M. Pare et al. 2024

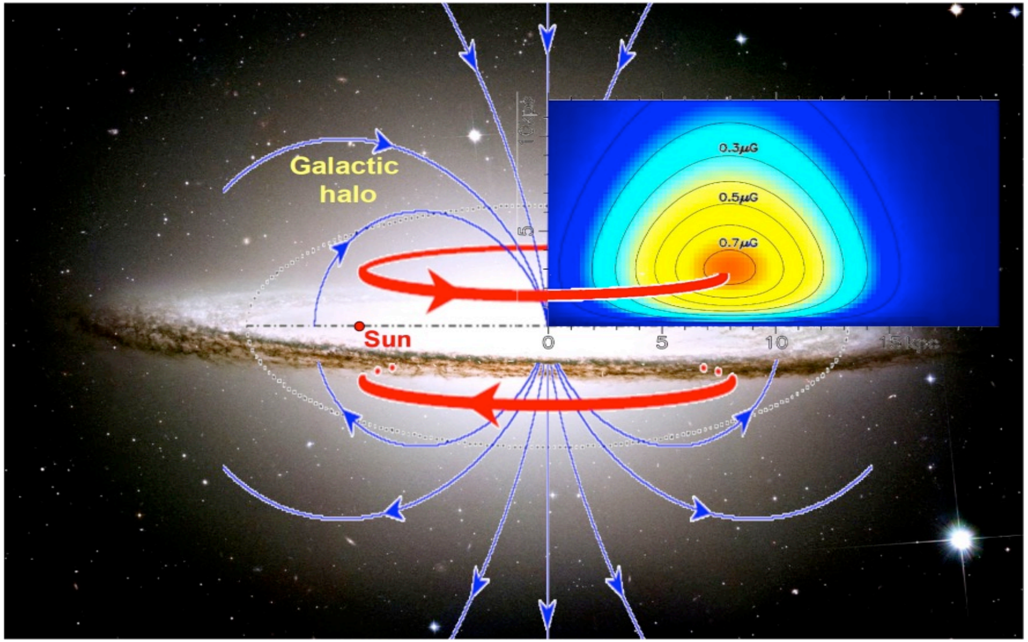
https://arxiv.org/pdf/2408.16745

RMs of background radio sources in the GC region

What’s Wrong here?

Ou, It is just right!

Rings must start from R~0.1kpc and must extend to R > 15kpc!



14

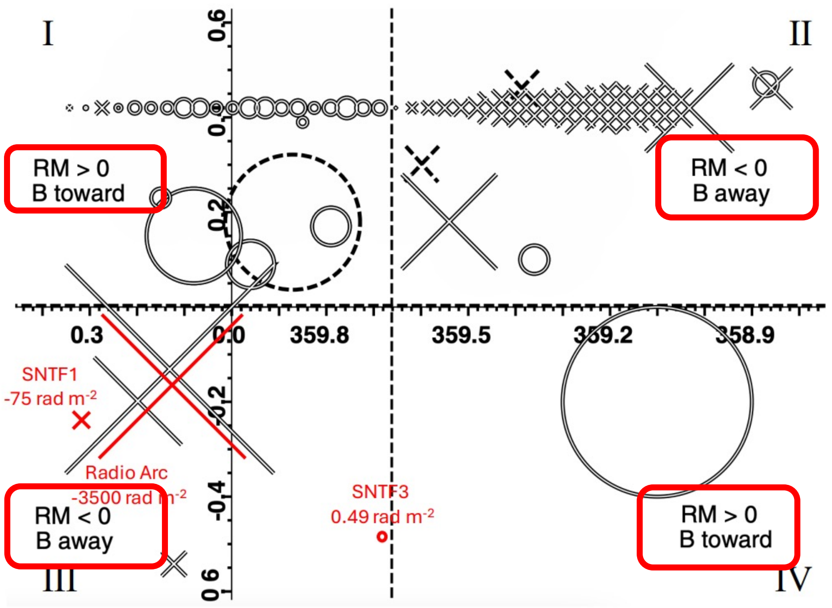
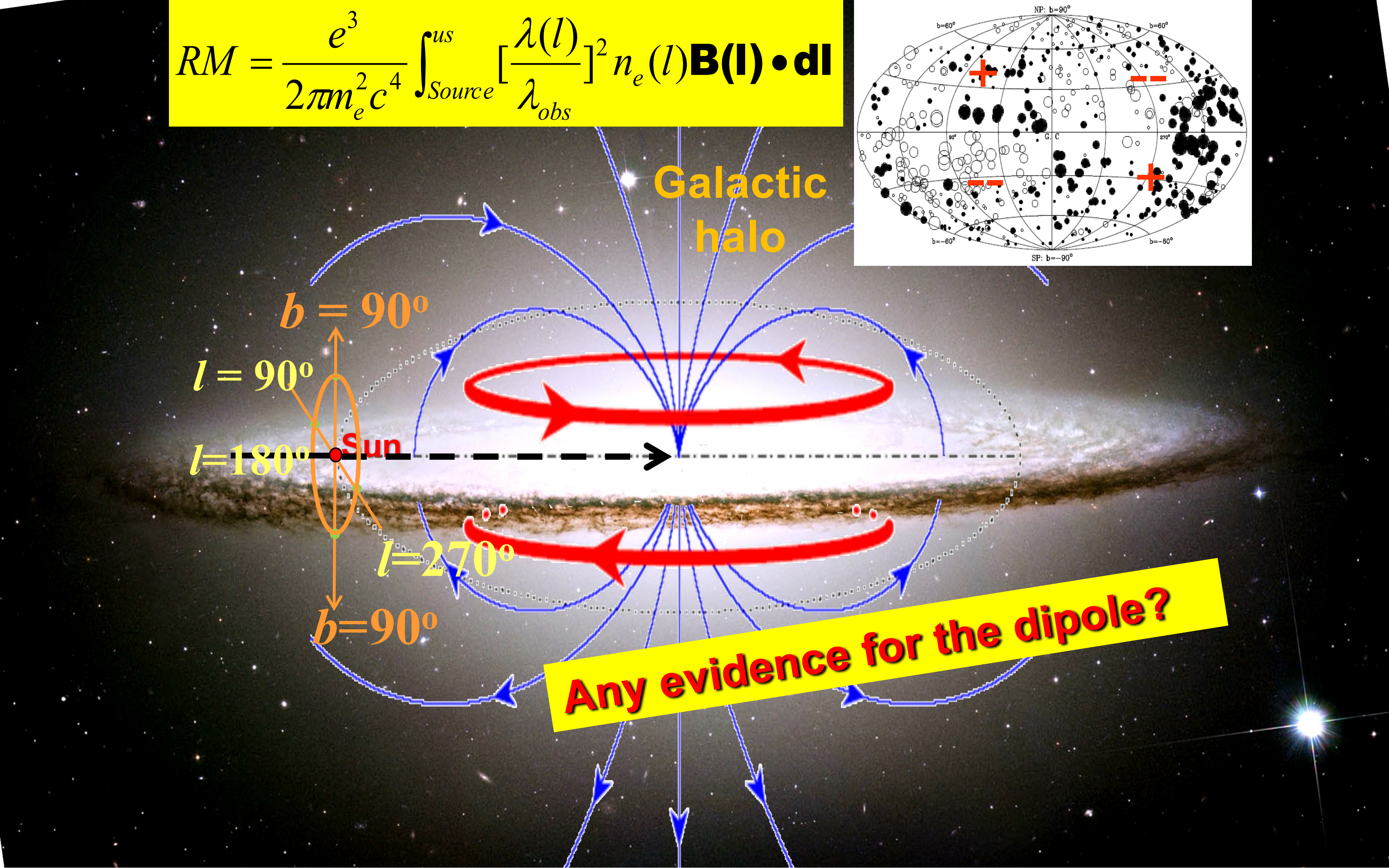


Figure 9. The large-scale RM distribution observed towards the GC. In this figure the extent of the GC in the plane of the sky has been split into four quadrants (labeled I – IV in the figure). Circles represent positive RM values and crosses represent negative RM values, with the size of each symbol scaled by RM magnitude. Black circles and crosses represent the RM values collated previously by Law et al. (2011). Red circles and crosses represent new RM values studied in this and other recent radio polarimetric studies of the GC (Paré et al. 2019, 2021).

D. M. Pare et al. 2024

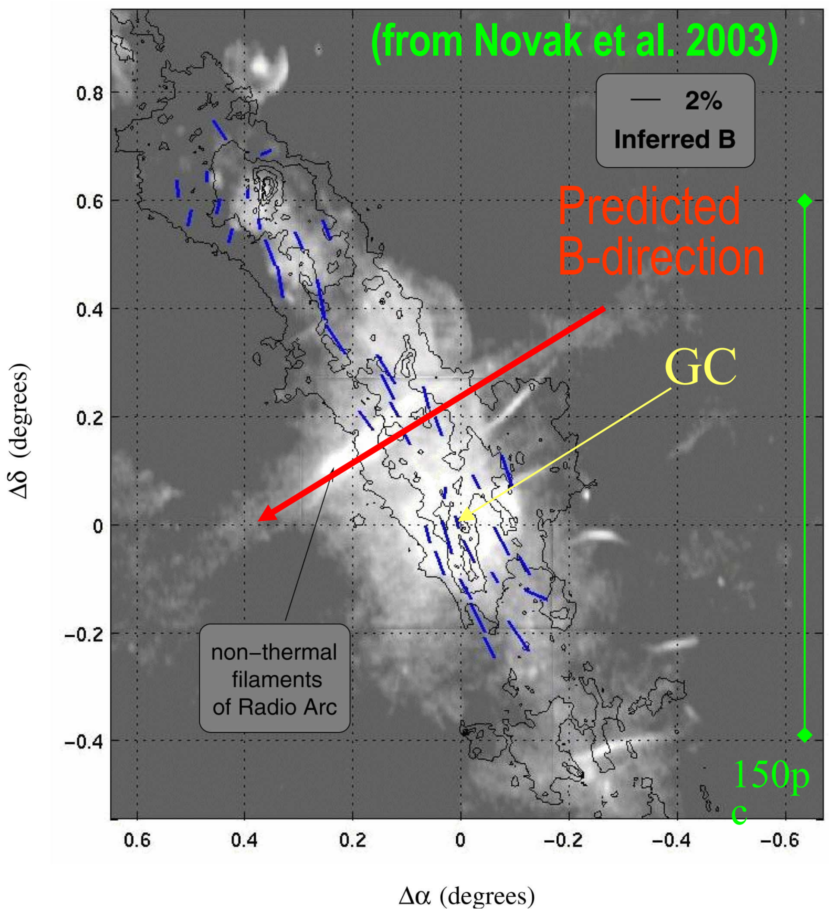
https://arxiv.org/pdf/2408.16745

$$RM = \frac{e^3}{2\pi m_e^2 c^4}\int_{Source}^{us}[\frac{\lambda(l)}{\lambda_{obs}}]^2 n_e(l)\mathbf{B(l)}\bullet\mathbf{dl}$$



Any evidence for the dipole?

Poloidal & Toroidal fields near GC



Toroidal fields

(Novak et al. 2003, 2000)

- **permeated in the *central molecular zone (400pc*50pc)***
- sub-mm obs of p%
- toroidal field directions *determined by averaged RMs of plumes or SNR!*

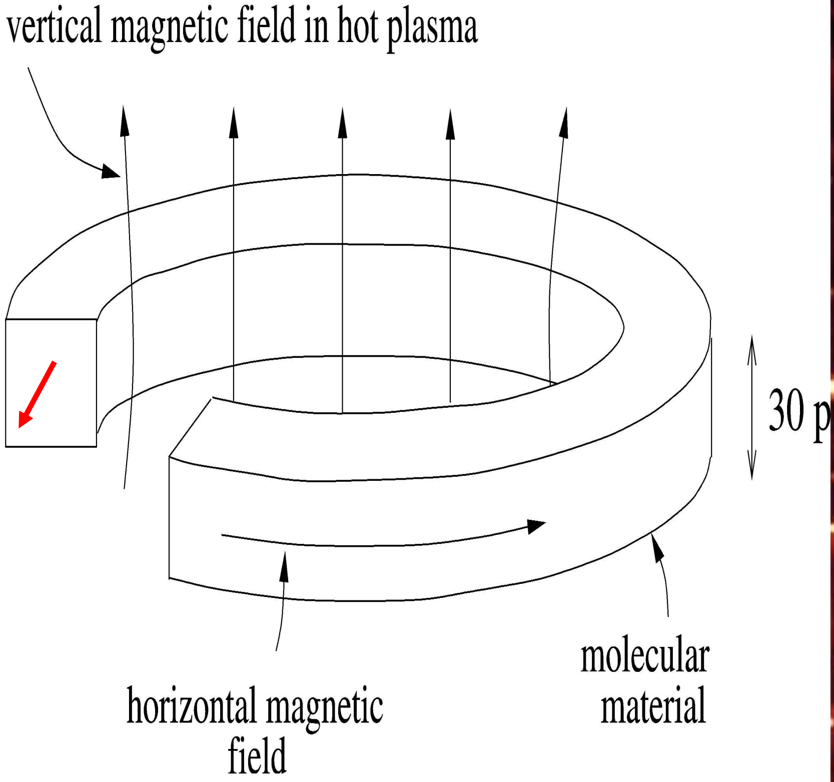
Poloidal field

filaments Unique to GC

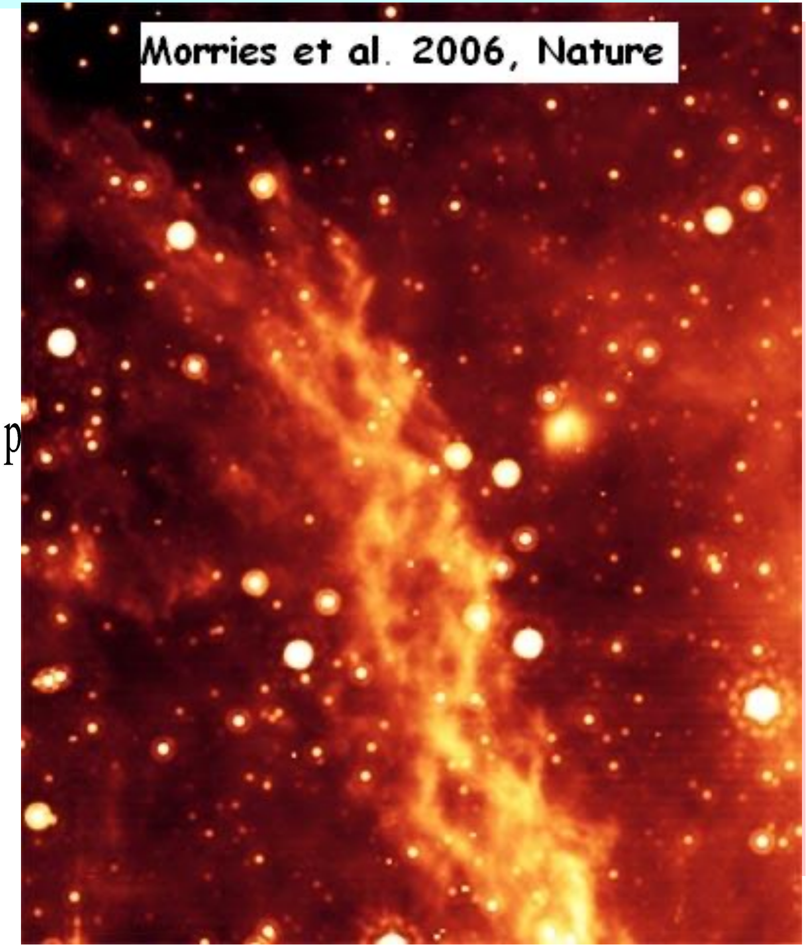
--- dipolar geometry!

(Morris 1994; Lang et al.1999)

Magnetic fields in our Galaxy: **near GC**



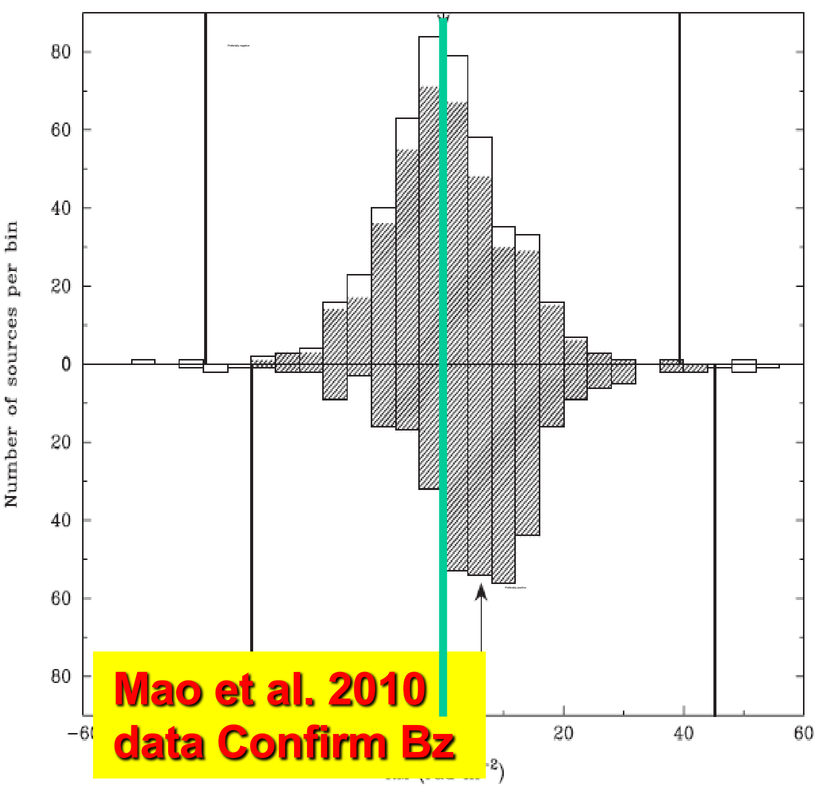
(from B.D.C. Chandran 2000)



Morries et al. 2006, Nature

Local vertical components: from *poloidal field?*

North Galactic Pole

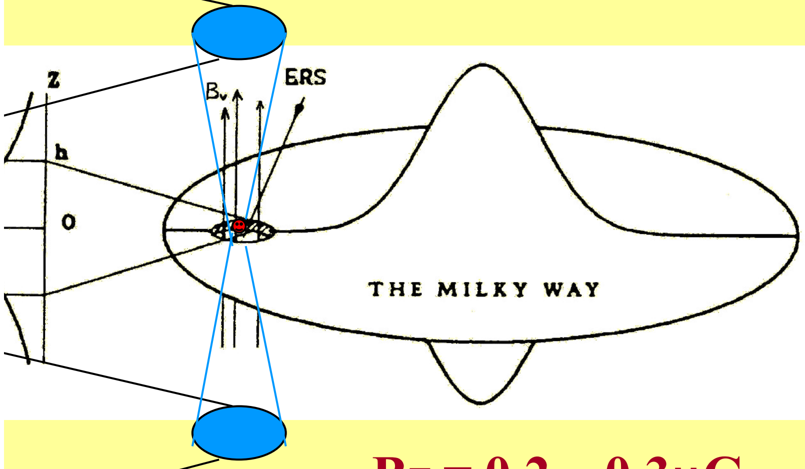


Mao et al. 2010 data Confirm Bz

South Galactic Pole

Beck (2001, SSRv 99, 243):

Unique measurement of Vertical B-component



$Bz = 0.2 \sim 0.3\mu G$

pointing from SGP to NGP

ect of the NPS discounted already!)

(see Han & Qiao 1994; Han et al. 1999)

The Galactic Magnetic Fields:
Progress over the last 30 years

- Large-scale B-fields in our Galaxy: much better knowledge and much better understanding
- In the Galactic disk, we striggled for 30 years: B-field along the spiral arms, reverse directions in the arm and interarm regions.
- In the Galactic halo: huge magnetic toruses with reversed directions in the upper and lower, from 0.1kpc to 15 kpc.

More details could be described by more data!

Take the model from Appendix of Xu & Han (2024, ApJ, 966, 240)

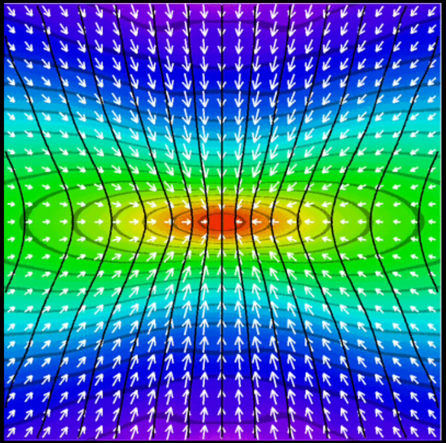
Thanks for your attension !

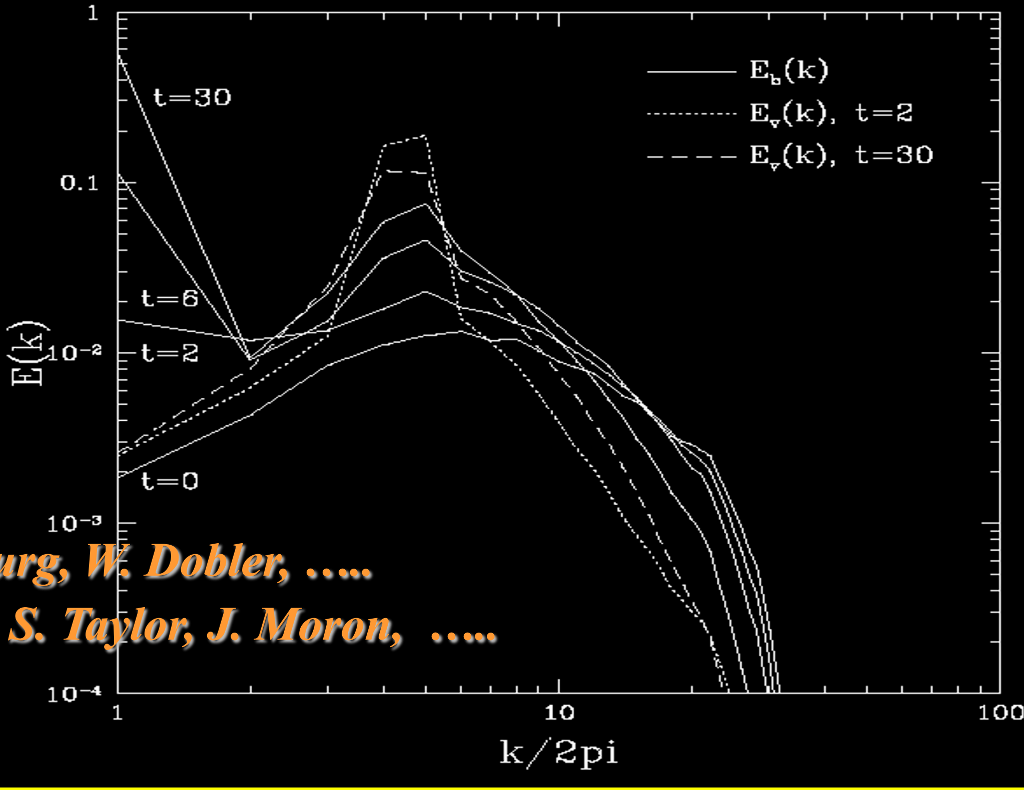
The FAST-GPPS Survey

Many Simulations of dynamos

---- check spatial B-energy spectrum & its evolution

e.g. Magnetic energy distribution on different spatial scales (k=1/λ)





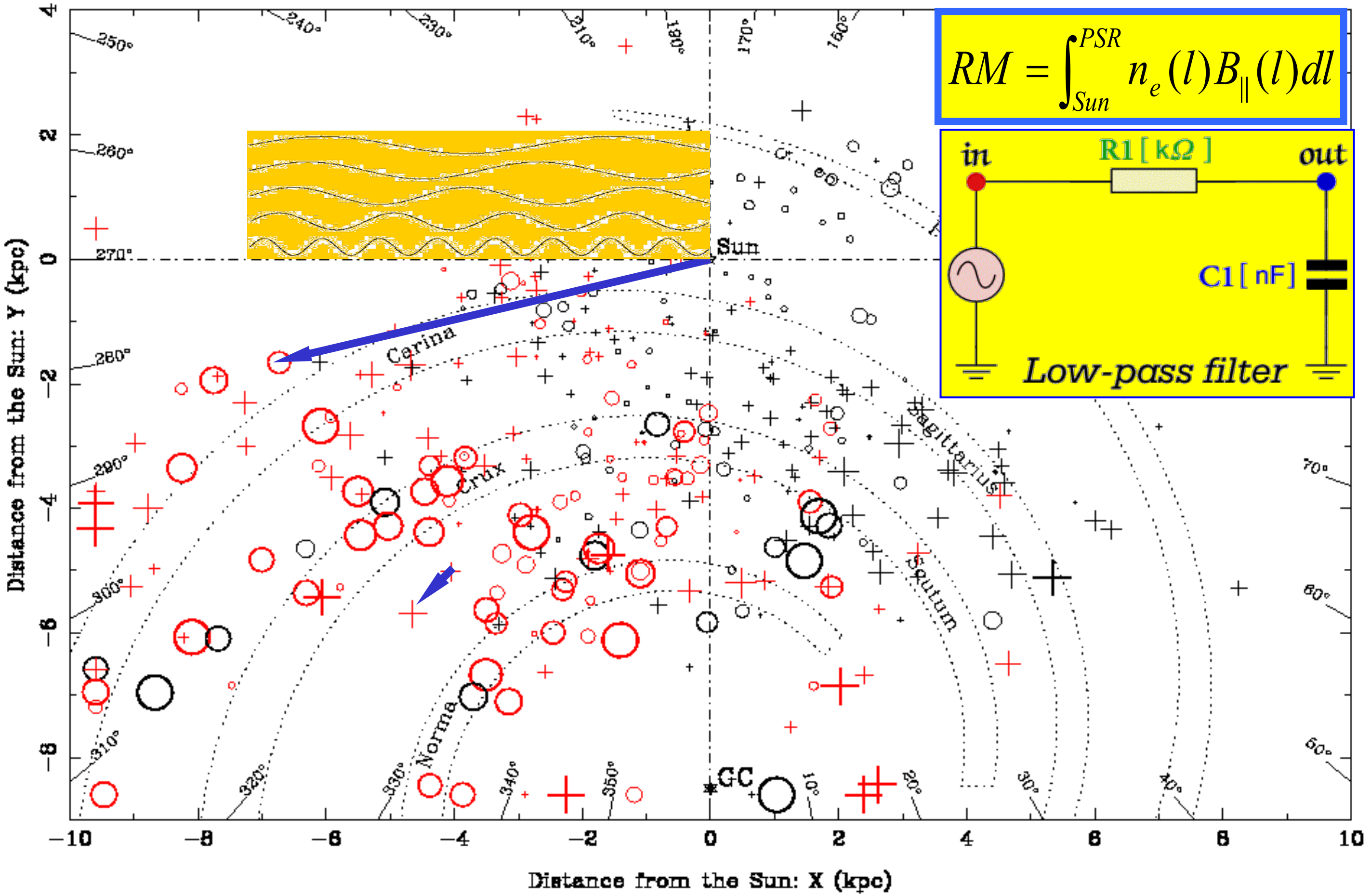
Many papers by

- *N.E. L. Haugen, A. Brandenburg, W. Dobler, …..*
- *A. Schekochihin, S.C. Cowley, S. Taylor, J. Moron, …..*
- *E. Blackman, J. Maron …..*
- *Others …..*

No measurements of the B-energy spectrum !

Pulsar RM distribution onto Galactic plane

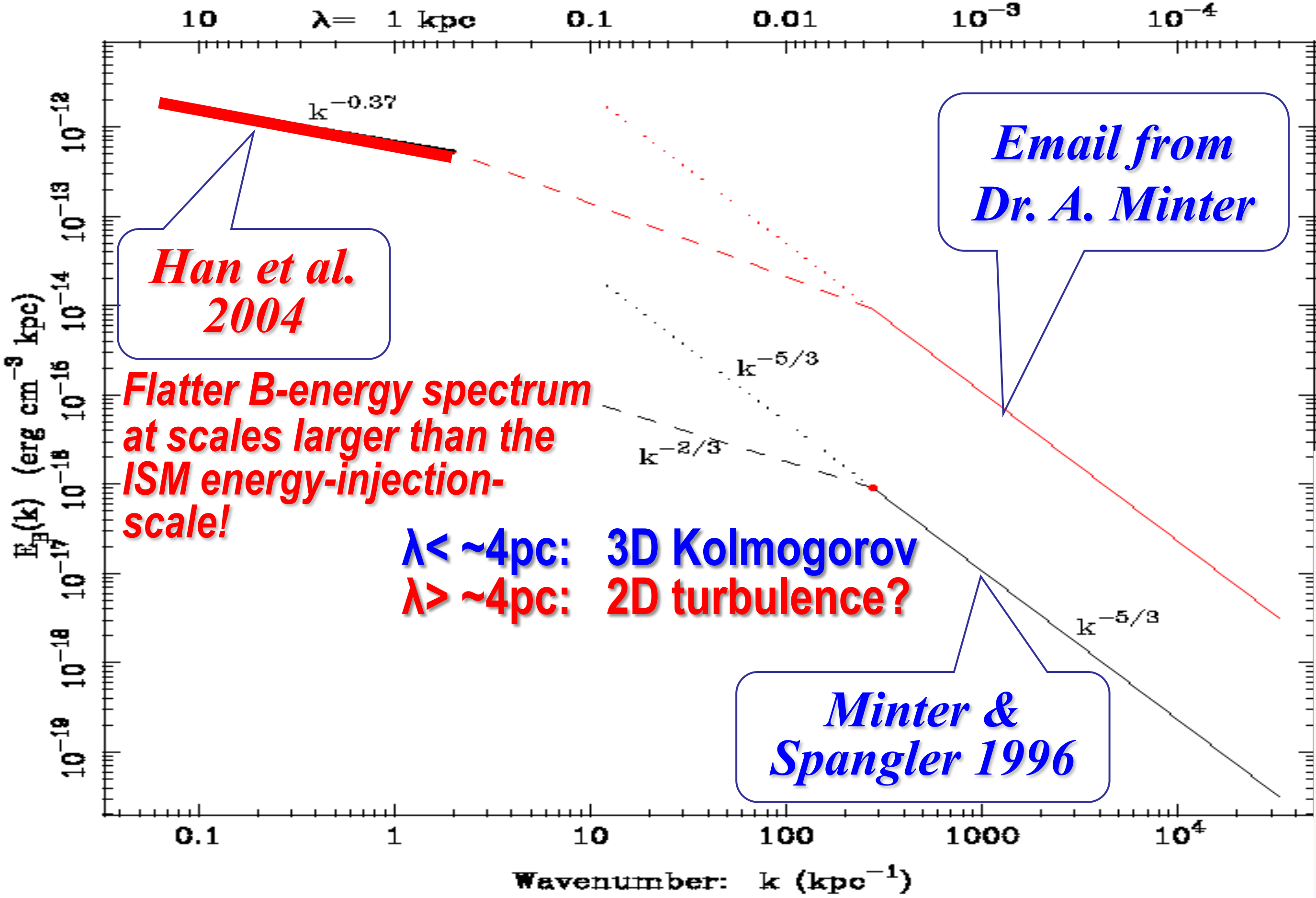
red: new measurements by Parkes 64m telescope



$$RM = \int_{Sun}^{PSR} n_e(l) B_{\parallel}(l)\, dl$$

Spatial magnetic energy spectrum of our Galaxy

(Han et al. 2004, ApJ 610, 820)



Han et al. 2004

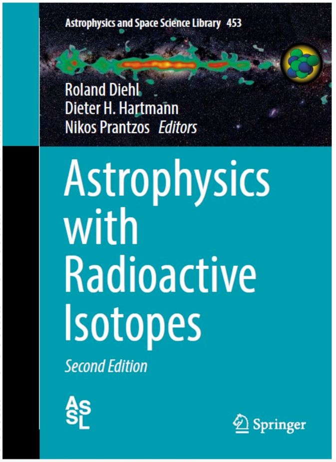
Flatter B-energy spectrum at scales larger than the ISM energy-injection-scale!

Email from Dr. A. Minter

λ< ~4pc: 3D Kolmogorov

λ> ~4pc: 2D turbulence?

Minter & Spangler 1996



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Second Edition

ASSL

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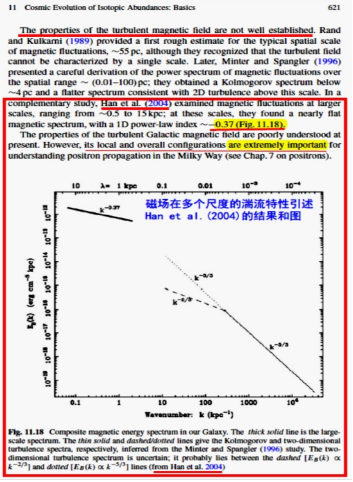


11 Cosmic Evolution of Isotopic Abundances: Basics 621

The properties of the turbulent magnetic field are not well established. Rand and Kulkarni (1989) provided a first rough estimate for the typical spatial scale of magnetic fluctuations, ~55 pc, although they recognized that the turbulent field cannot be characterized by a single scale. Later, Minter and Spangler (1996) presented a careful derivation of the power spectrum of magnetic fluctuations over the spatial range ~ (0.01–100) pc; they obtained a Kolmogorov spectrum below ~4 pc and a flatter spectrum consistent with 2D turbulence above this scale. In a complementary study, Han et al. (2004) examined magnetic fluctuations at larger scales, ranging from ~0.5 to 15 kpc; at these scales, they found a nearly flat magnetic spectrum, with a 1D power-law index ~−0.37 (Fig. 11.18).

The properties of the turbulent Galactic magnetic field are poorly understood at present. However, its local and overall configurations are extremely important for understanding positron propagation in the Milky Way (see Chap. 7 on positrons).

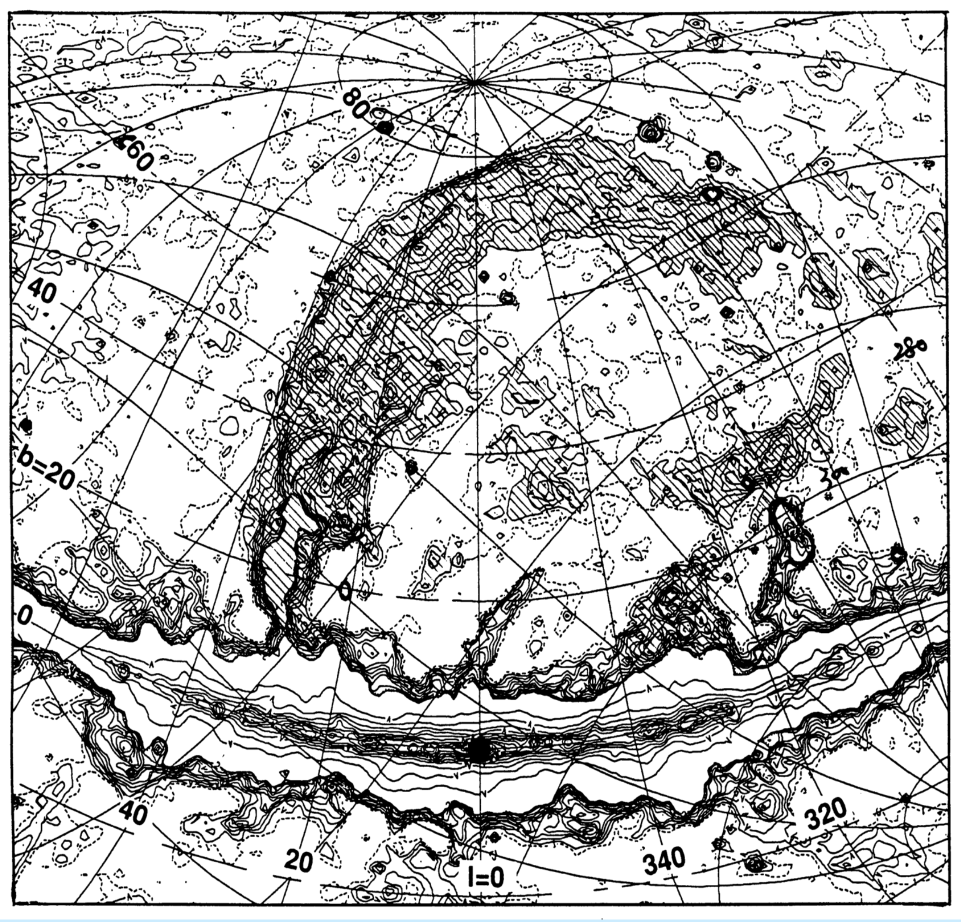
磁场在多个尺度的湍流特性引述
Han et al. (2004) 的结果和图

Fig. 11.18 Composite magnetic energy spectrum in our Galaxy. The *thick solid* line is the large-scale spectrum. The *thin solid* and *dashed/dotted* lines give the Kolmogorov and two-dimensional turbulence spectra, respectively, inferred from the Minter and Spangler (1996) study. The two-dimensional turbulence spectrum is uncertain; it probably lies between the *dashed* [$E_B(k) \propto k^{-2/3}$] and *dotted* [$E_B(k) \propto k^{-5/3}$] lines (from Han et al. 2004)

Effect of the North Polar Spur

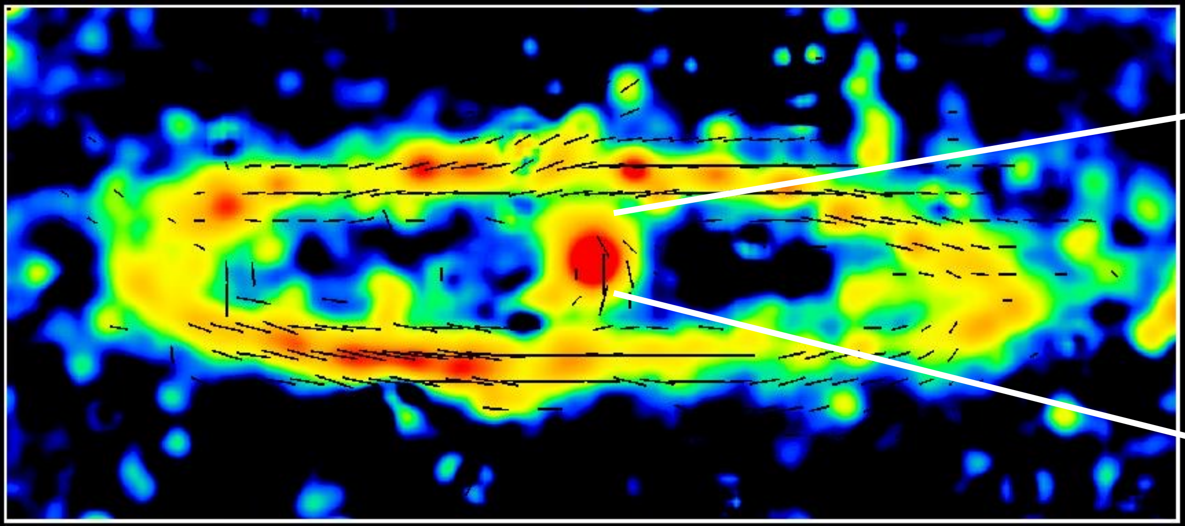
- How B-lines expended?
- What RM distribution expected?
- Ne enhanced?

NPS: RM?



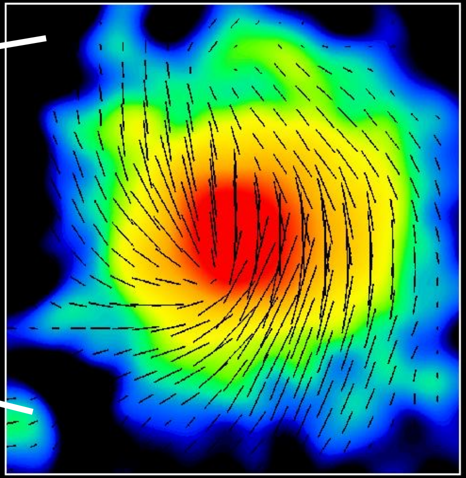
Magnetic fields in other Galaxies

M31 6cm Total Intensity + Magnetic Field (Effelsberg)



Copyright: MPIfR Bonn (R.Beck, E.M.Berkhuijsen & P.Hoernes)

M31 Center 3.6cm Total Int. + B-Vectors (Effelsberg)



Copyright: MPIfR Bonn (Rainer Beck & Christine Blesinger)

Organized B inside and outside of the circumnuclear “Ring” !

==> Ring B fields!

（From Rainer Beck talk）

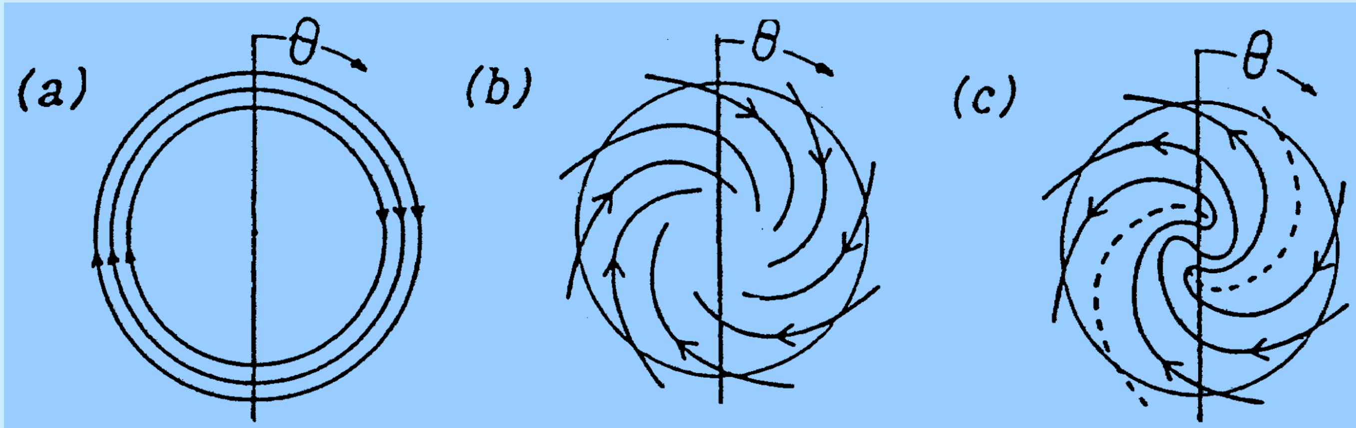
3 proposed models for

B-field structure in the Galactic disk

Concentric Rings
Rings model

Axi-symmetric
spiral (ASS)

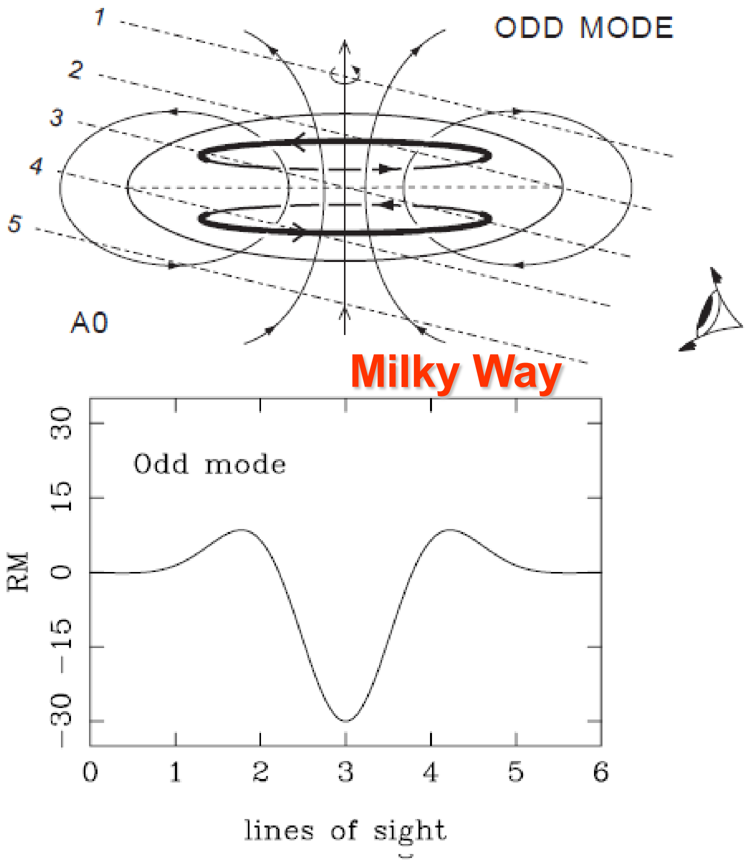
Bi-Symmetric Spiral
(BSS)



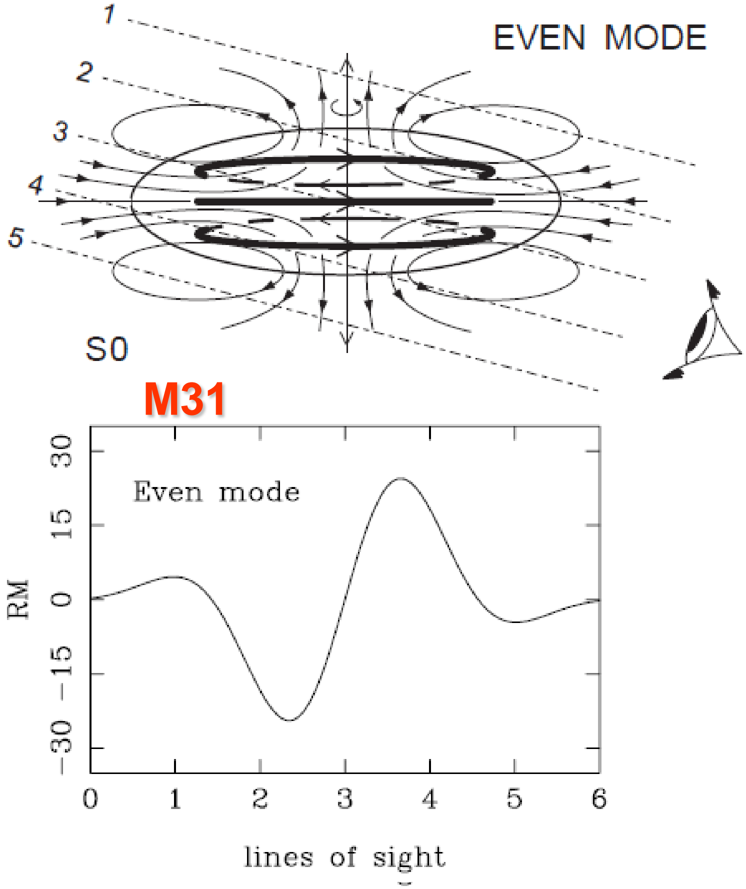
R. Wielebinski & F. Krause 1993， A&A Rev.

Han et al. 1998: A&A 355, 1117

RMs of background sources for B structure in M31

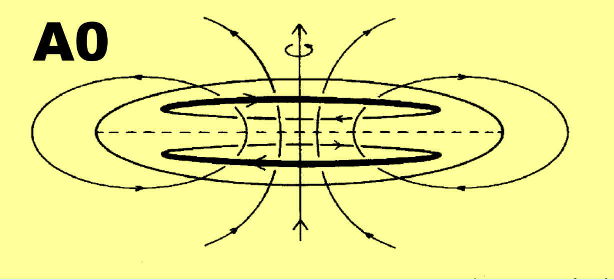


Milky Way

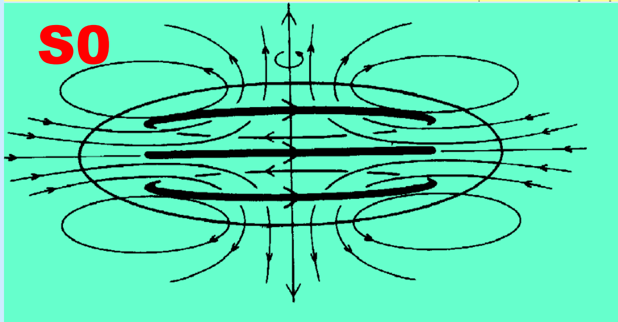


M31

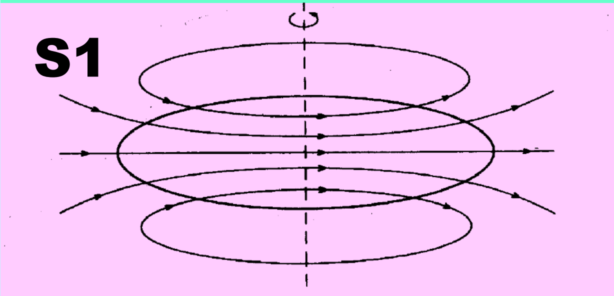
Basic Dynamos: 3 B-field Configurations



A0



S0

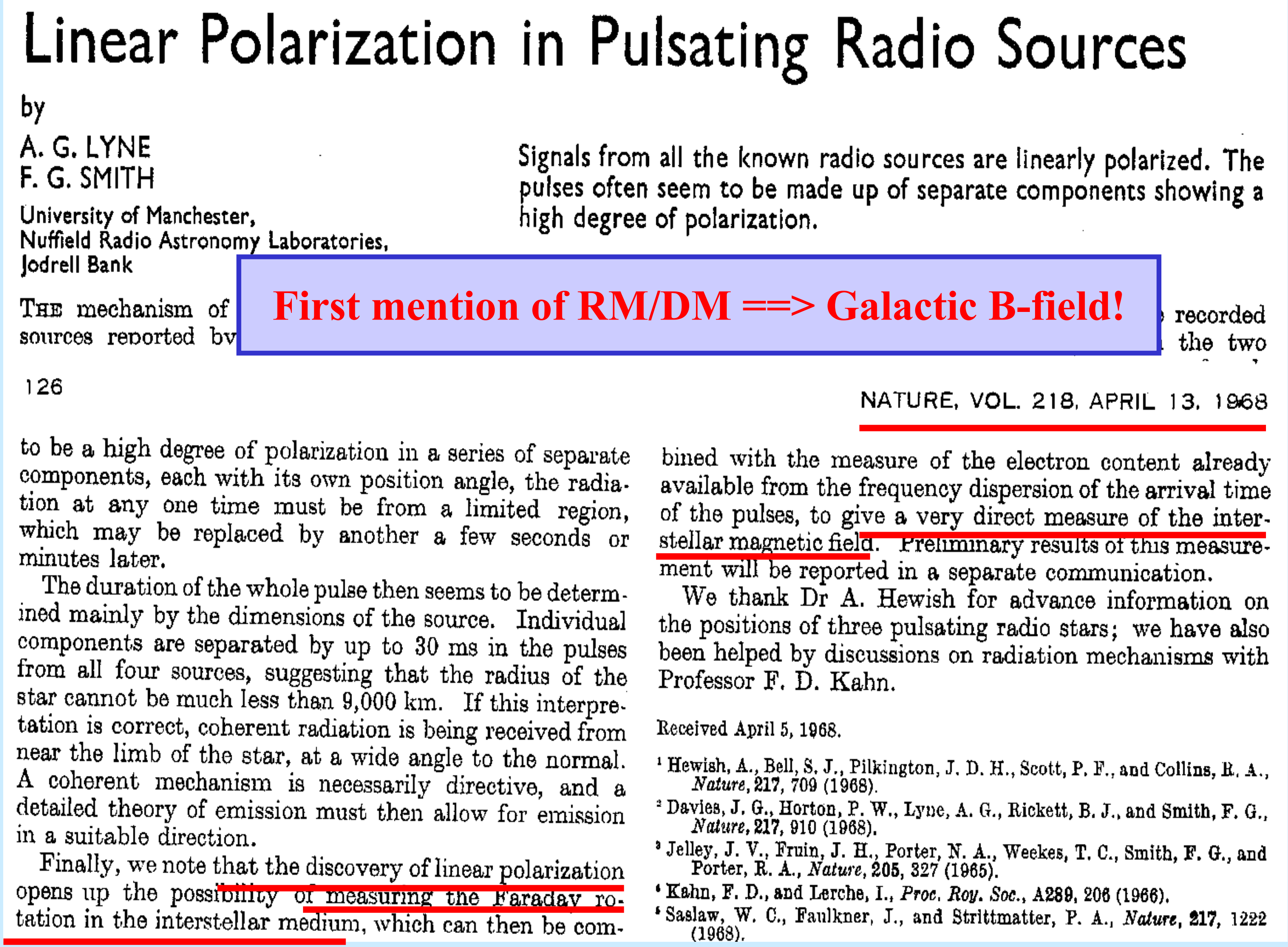


S1

M31: only 21 polarized bright background sources available !!

Han, Beck, Berkhuijsen (1998):

An even mode (S0) dynamo may operate in M31 !



Linear Polarization in Pulsating Radio Sources

by

A. G. LYNE
F. G. SMITH

University of Manchester,
Nuffield Radio Astronomy Laboratories,
Jodrell Bank

Signals from all the known radio sources are linearly polarized. The pulses often seem to be made up of separate components showing a high degree of polarization.

THE mechanism of … recorded
sources reported by … the two

First mention of RM/DM ==> Galactic B-field!

to be a high degree of polarization in a series of separate components, each with its own position angle, the radiation at any one time must be from a limited region, which may be replaced by another a few seconds or minutes later.

The duration of the whole pulse then seems to be determined mainly by the dimensions of the source. Individual components are separated by up to 30 ms in the pulses from all four sources, suggesting that the radius of the star cannot be much less than 9,000 km. If this interpretation is correct, coherent radiation is being received from near the limb of the star, at a wide angle to the normal. A coherent mechanism is necessarily directive, and a detailed theory of emission must then allow for emission in a suitable direction.

Finally, we note that the discovery of linear polarization opens up the possibility of measuring the Faraday rotation in the interstellar medium, which can then be combined with the measure of the electron content already available from the frequency dispersion of the arrival time of the pulses, to give a very direct measure of the interstellar magnetic field. Preliminary results of this measurement will be reported in a separate communication.

We thank Dr A. Hewish for advance information on the positions of three pulsating radio stars; we have also been helped by discussions on radiation mechanisms with Professor F. D. Kahn.

Received April 5, 1968.

[1] Hewish, A., Bell, S. J., Pilkington, J. D. H., Scott, P. F., and Collins, R. A., *Nature*, **217**, 709 (1968).

[2] Davies, J. G., Horton, P. W., Lyne, A. G., Rickett, B. J., and Smith, F. G., *Nature*, **217**, 910 (1968).

[3] Jelley, J. V., Fruin, J. H., Porter, N. A., Weekes, T. C., Smith, F. G., and Porter, R. A., *Nature*, **205**, 327 (1965).

[4] Kahn, F. D., and Lerche, I., *Proc. Roy. Soc.*, A**289**, 206 (1966).

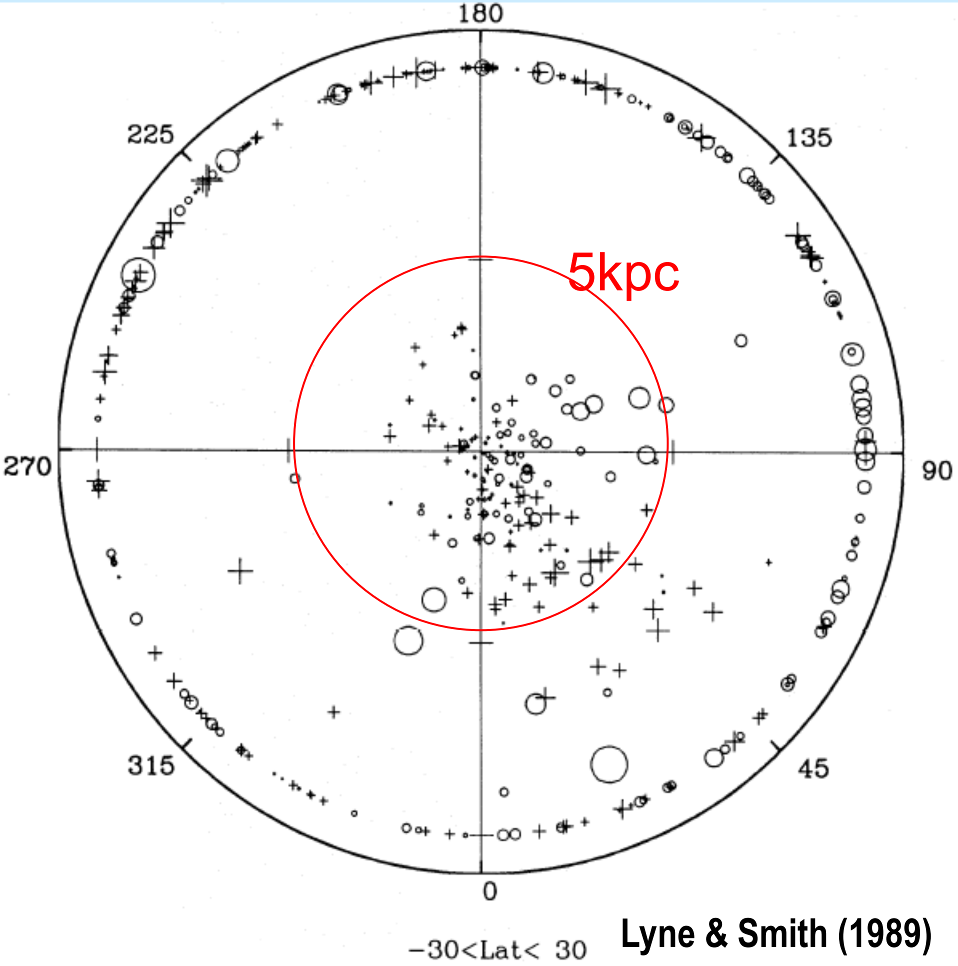
[5] Saslaw, W. C., Faulkner, J., and Strittmatter, P. A., *Nature*, **217**, 1222 (1968).

Large-scale: How *large* is the "large" here?

RMs of 185 pulsars

> ~ 3kpc?!

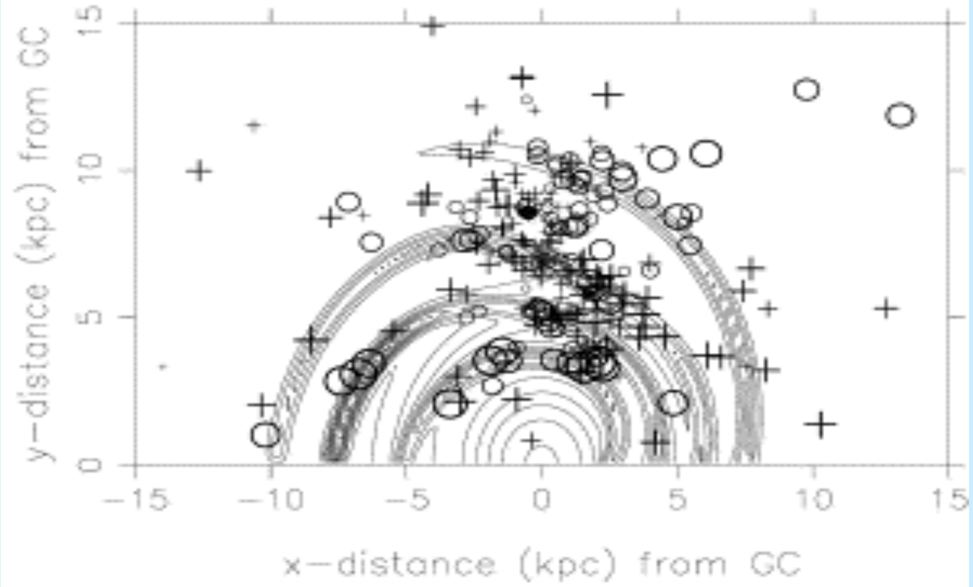
Arm-seperation: 1 or 2 kpc!

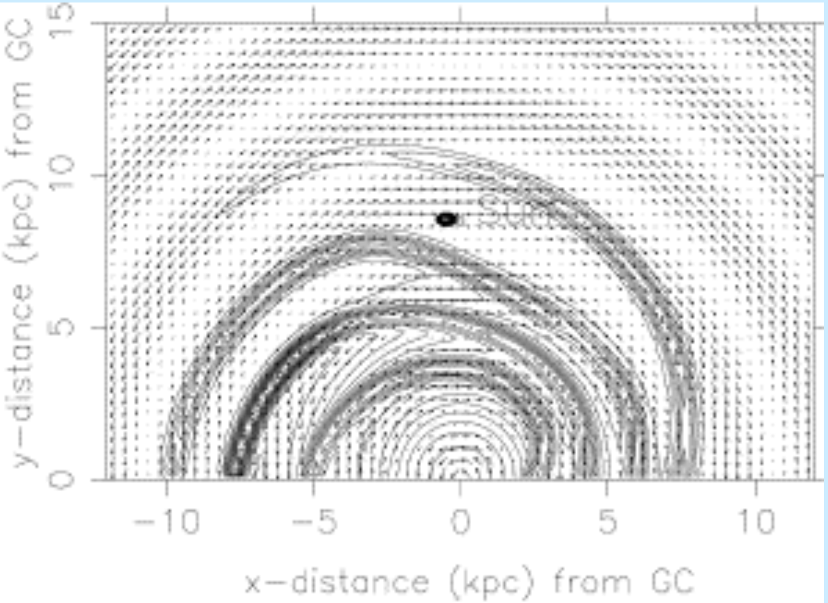


Lyne & Smith (1989)

Indrani & Deshpanda (1998):

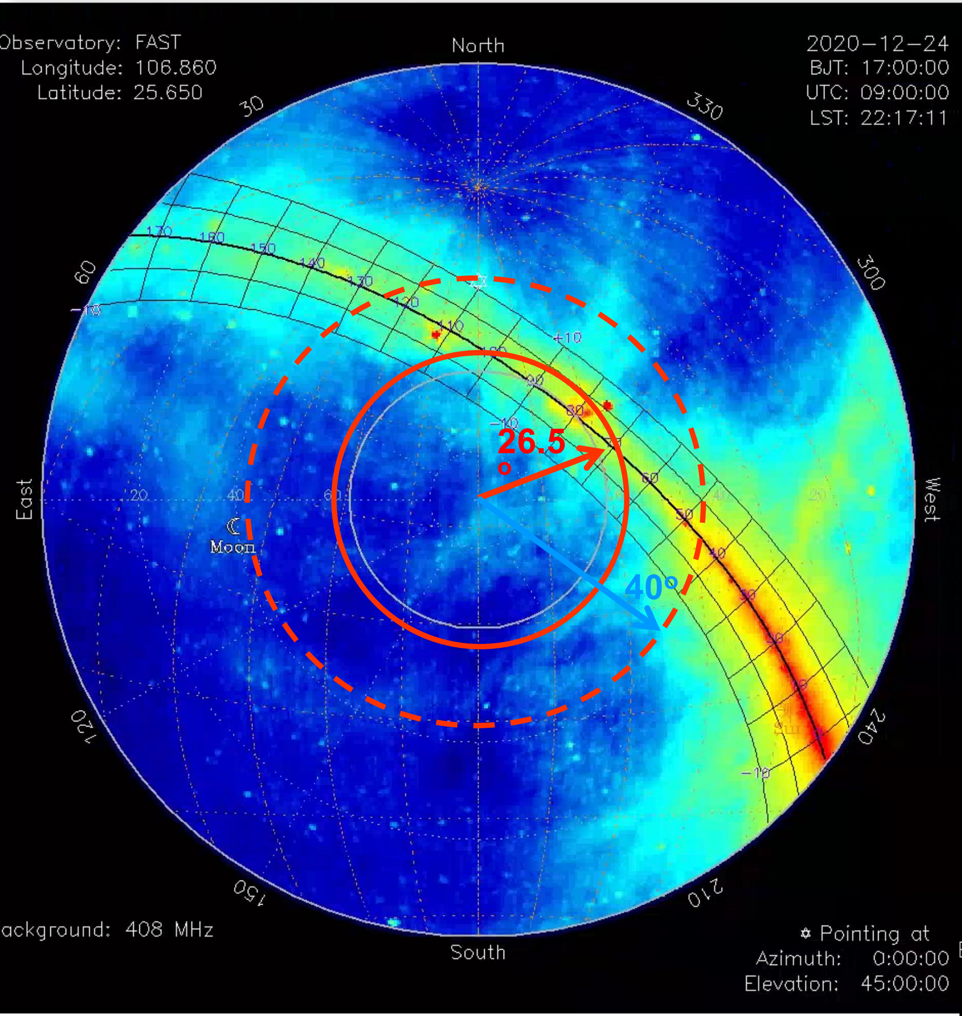
- *BSS model fit data best*
- *Formula of BSS field of Han & Qiao (1994) is correct ---*

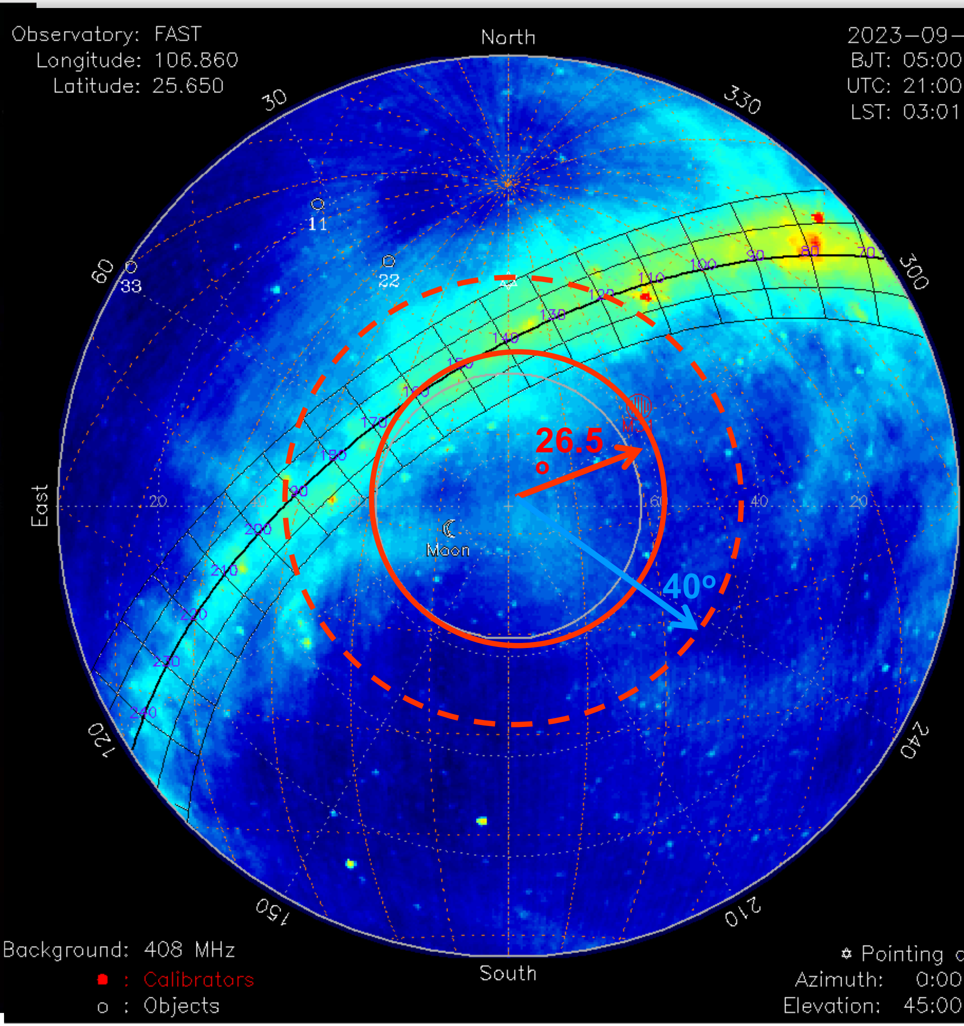




To guess large-scale B-field structure from limited data: **modeling & Verified by more data!**

The FAST-GPPS survey

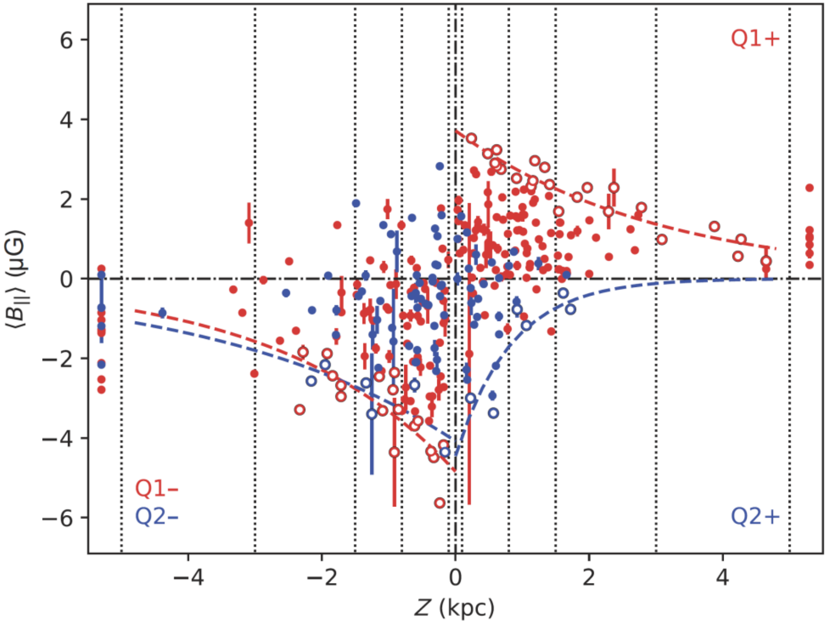




Magnetic fields in the Galactic halo

The scale height of the halo magnetic fields

$$\langle B_{\|} \rangle = 1.232 \frac{\mathrm{RM}}{\mathrm{DM}} = \frac{\int_0^D n_e \mathbf{B} \cdot \mathrm{d}l}{\int_0^D n_e \, \mathrm{d}l}$$



First quadrant Q1:
positive (negative) field values above (below) the Galactic plane

Second quadrant Q2:
all negative field values

$$\langle B_{\|} \rangle = \langle B_{\|} \rangle_0 \exp(-|Z|/H)$$

Lower limit of
the scale height of halo
magnetic field:
2.7±0.3 kpc

(Xu et al. 2022, doi: 10.1007/s11433-022-2033-2)