

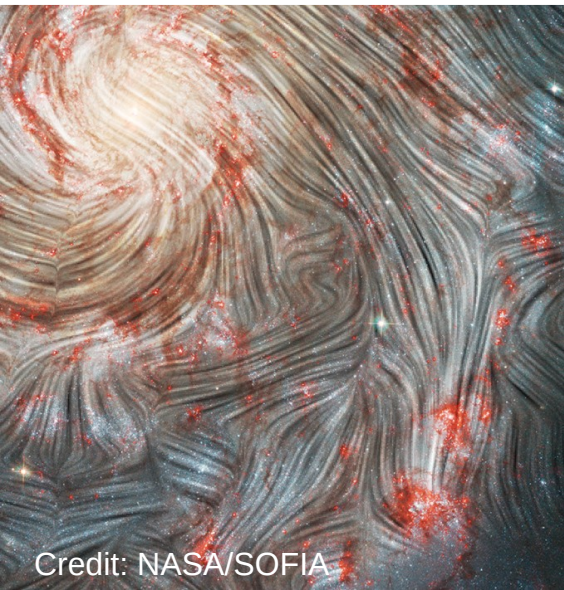


CHALMERS

 Vetenskapsrådet

*Knut and Alice
Wallenberg
Foundation*

Galactic magnetism in 3D



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With: D. Blinov, C. Dickinson, P. Hopkins, V. Pavlidou, T. Pearson,
V. Pelgrims, S. Ponnada, A. Ramaprakash, A. Readhead, R.
Skalidis, K. Tassis, S. Kumar

Magnetism and the SKA

Enabling science across scales:

Galaxy clusters, filaments and large-scale-structure, AGN jets, radio galaxies, Milky Way, molecular clouds...

19 chapters in the 2015 SKA science book

See also Heald et al (2020)

Cosmic Magnetism Science Working Group

The Cosmic Magnetism Science Working Group is focused on defining the role of magnetic fields in the physical processes that determine the structure and evolution of the Universe. SKA observations will establish the origin and evolution of magnetic fields throughout the cosmos.

Magnetic fields are a major agent of energetic processes in various cosmic objects, from star forming regions and stellar remnants, through galaxies, including our own Milky Way, to the large-scale structure of the Universe. Magnetism has long been recognized as a crucial element in these processes, but new technology is required to make the observational progress needed for a full understanding of how they unfold in practice.

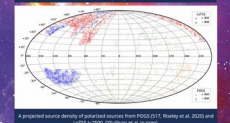
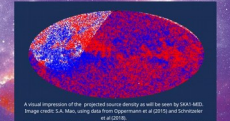
Radio astronomy provides the most effective probes of cosmic magnetism. The SKA's revolutionary capability promises to take our study of magnetic fields to a new level of precision, and expand our horizon to discover objects that are inaccessible in sufficient detail today. Specifically, its unrivalled sensitivity and resolving power, combined with wide frequency coverage, makes the SKA ideal for probing magnetism across the Universe through the study of polarized synchrotron emission and its Faraday rotation, and Zeeman splitting (for more details see Heald et al. 2020).

A dense Faraday Rotation Measure (RM) Grid

The SKA will produce a Faraday RM Grid, comprising polarimetric detections of 2-3 million radio galaxies, a factor two better than POSSUM. In addition to understanding the nature of the polarized sources themselves, the SKA's RM Grid will be used to probe a wide range of extended, intervening foreground sources, including:

- Milky Way and sources within (HII regions, SNRs, HVCs, magars, ...)
- Magellanic Clouds
- Nearby galaxies
- Galaxy Clusters
- Radio Galaxies
- Cosmic Web

The extremely high density of background RMs will enable the study of individual objects as well as statistical investigations of source classes. SKA1-LOW will complement the SKA1-MID RM Grid. Despite the low density of polarized sources detected to date at low with respect to mid frequencies, the 100x better precision in RM will permit very high-accuracy magnetic field measurements in some sources



Right: EBH5 H2 21cm brightness temperature (blue) and Faraday magnetic field observations at 333 GHz (orange) pattern of a 64 deg² field at mid Galactic latitude. This figure highlights the crucial correspondence of morphological structures that also correlate with the plane of the highly orientated of the magnetic field (Bracco et al. 2020).



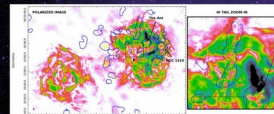
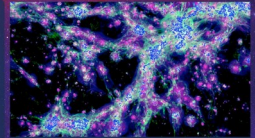
What is the role of magnetic fields in the evolution of cosmic objects?

The unmatched surface brightness sensitivity and angular resolution of the SKA will permit the imaging and detailed study of the diffuse magnetized media in the Milky Way and in nearby galaxies. This will allow us to uncover the role of magnetic fields in the star formation process. Combined with the detailed view of the magnetized medium in galaxy clusters and in the cosmic web, the SKA will probe magnetic fields from the smallest to largest scales and determine the mechanisms that shaped and amplified magnetic fields.



What is the structure of the Universe on the largest scales?

Our standard cosmology predicts that the majority of baryonic matter in the Universe exists as a cosmic web of diffuse, magnetized plasma. However, the distribution and properties of this extremely diffuse material are not yet well understood. Recent low frequency observations of SKA precursors and pathfinders, as LOFAR and MWA, proved to be very useful in detecting and constraining magnetic fields in the large-scale structure of the Universe, both through diffuse synchrotron emission and Faraday rotation of background radio sources. Understanding the cosmic web will allow us to address longstanding questions of modern astrophysics such as the thermal and dynamical evolution of galaxy clusters, the origin of the ultra-high energy cosmic rays, magneto-genesis and evolution of magnetic fields, and the inflationary theory of cosmology.



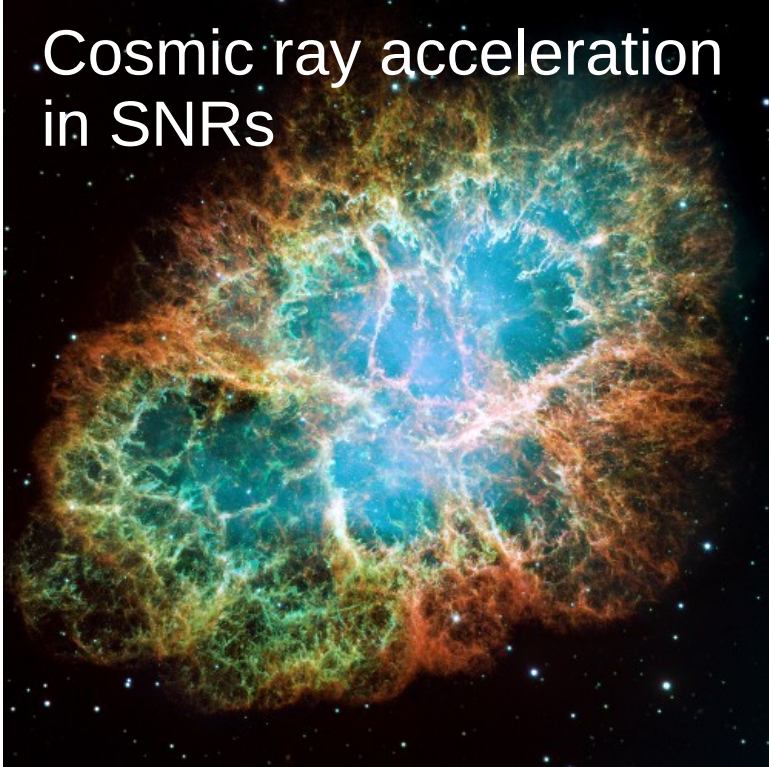
How do active galaxies influence their environments?

Radio galaxies are the ubiquitous background sources that are the backbone of the RM Grid, and they are also interesting to study as individual objects. The interface between radio galaxy lobes and their surrounding medium is a unique laboratory for various physical effects, and imparts complex structure on the observed polarization from the radio galaxies. The SKA will provide an unprecedented view of the complicated radio galaxy lobe structure, and allow the study of foreground sources through their effect on the radio galaxy emission.

Left: Polarized image of a 1.2 GHz field (displayed vertically) in the northern lobe of Hercules A. It is an 80 arcmin patch and shows complex polarization structure. The right image shows the same region of the galaxy image that would be seen with the SKA. The SKA will provide an unprecedented view of the complicated radio galaxy lobe structure, and allow the study of foreground sources through their effect on the radio galaxy emission.

Magnetic fields are everywhere in the Universe

Cosmic ray acceleration
in SNRs



Launching of powerful jets in
AGN



Galactic magnetic fields are 'special'

Local mean ISM energy densities

Magnetic $\sim 1 \text{ eV cm}^{-3}$

Thermal (hot gas) $\sim 1 \text{ eV cm}^{-3}$

Kinetic (turbulent) $\sim 1 \text{ eV cm}^{-3}$

Photons (CMB, stars) $\sim 1 \text{ eV cm}^{-3}$

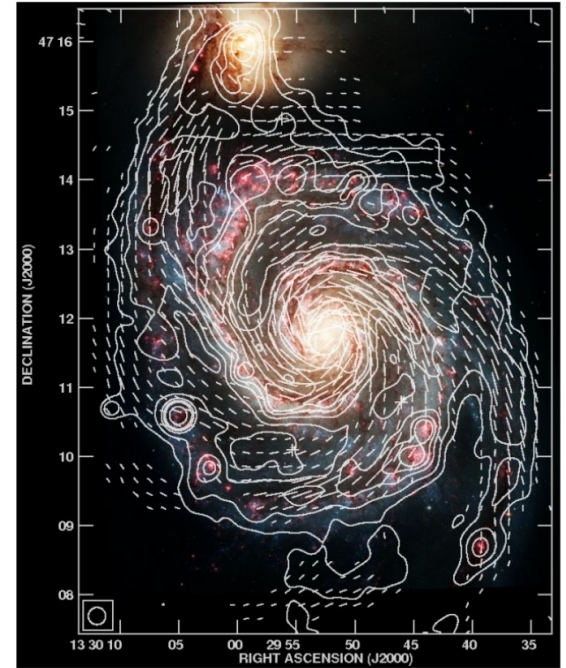
Cosmic rays $\sim 1 \text{ eV cm}^{-3}$

(e.g. Rand & Kulkarni 1989, Boulares & Cox 1990, Heiles 1995, Cummings+ 2016)

B fields:

Shape ISM structure

Alter kinematics & dynamics



Magnetic field of M51
(Fletcher+2011)

A lot remains unknown

Galaxy evolution

- How do magnetic fields affect star formation?

Hennebelle & Inutsuka (2019)

- How do magnetic fields emerge and evolve over time?

Beck (2019)

- How do cosmic rays propagate in the ISM?

Zweibel (2017)

Milky Way as a foreground

- Search for cosmological signatures (CMB B modes, EOR)

Abazajian+(2016), Jelic + (2010)

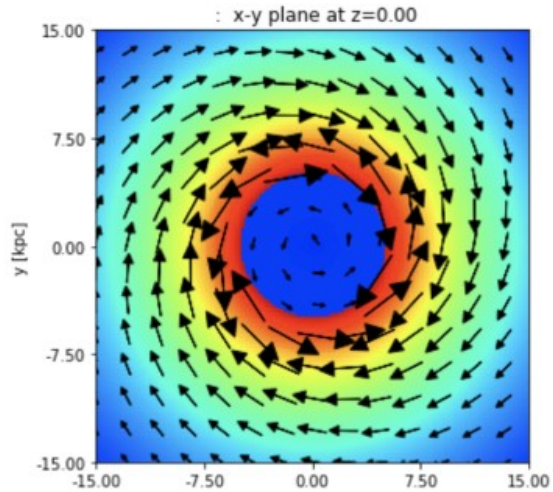
- Origin of Ultra-High energy cosmic rays

Unger & Farrar (2024)

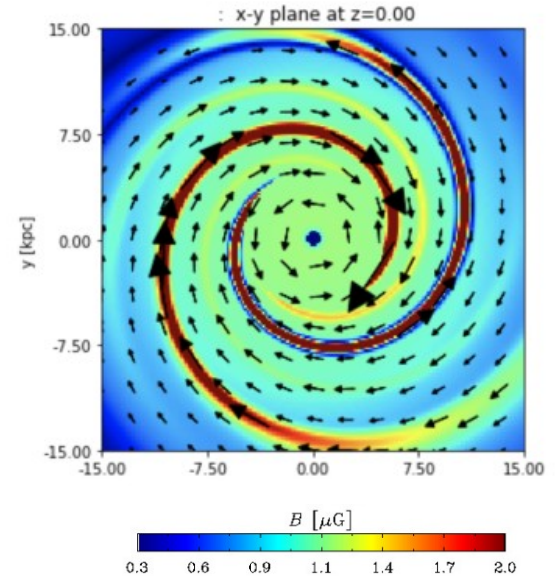
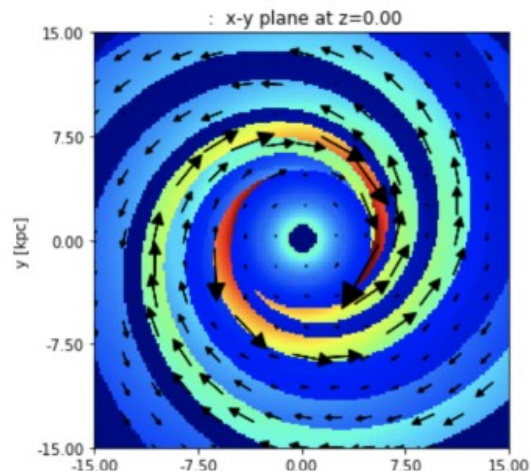


Need accurate knowledge of the Galaxy's magnetic field!

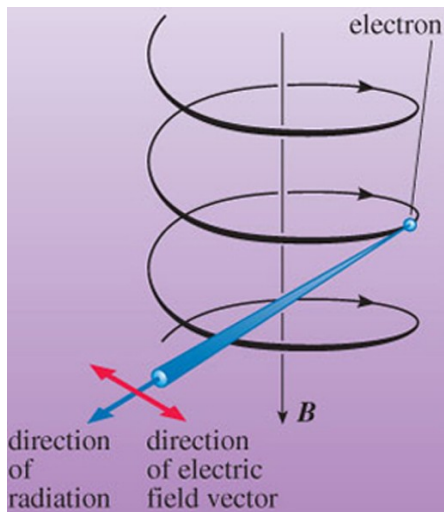
Galactic magnetic field models need work...



Jaffe 2019



How can we map magnetic field geometry?



Synchrotron emission

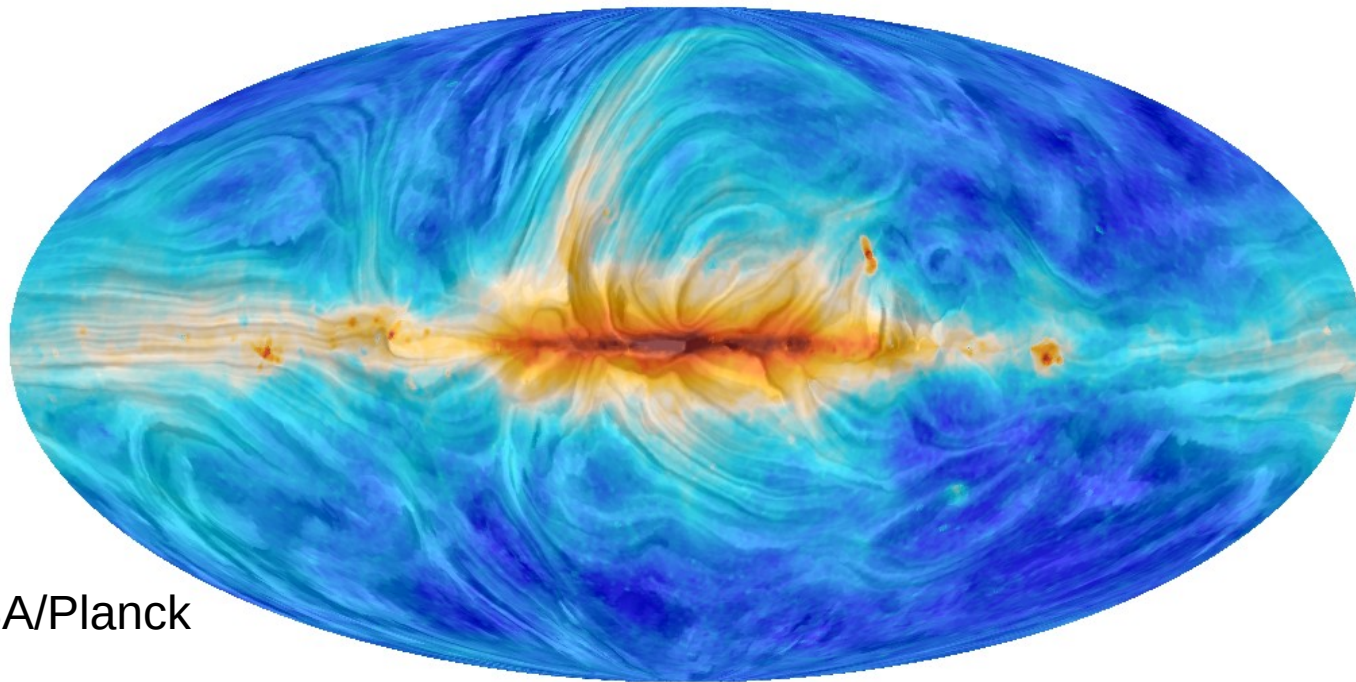
$$P_s \propto \int n_{CR} B_{pos}^2 dl$$

Density of cosmic-ray electrons

Plane-of-sky component of B

Integral along line of sight

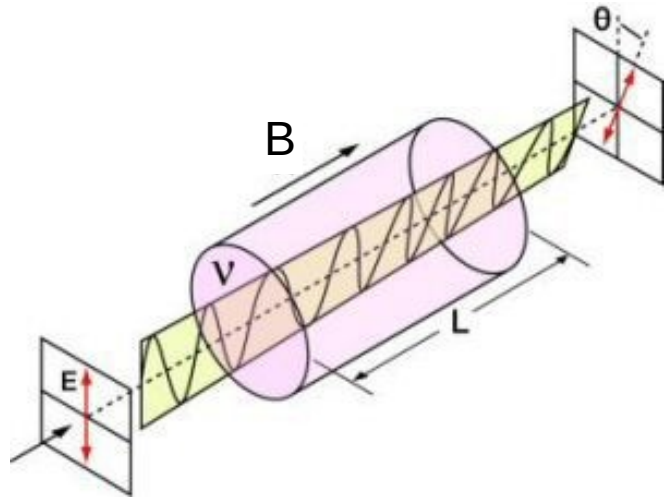
The magnetic field as seen from synchrotron emission



ESA/Planck

Light from cosmic ray electrons in our galaxy observed at ~ 30 GHz. Magnetic field lines are superimposed.

How can we map magnetic field geometry?



Faraday rotation

$$\Delta\theta \propto \lambda^2 \int n_e B_{los} dl$$

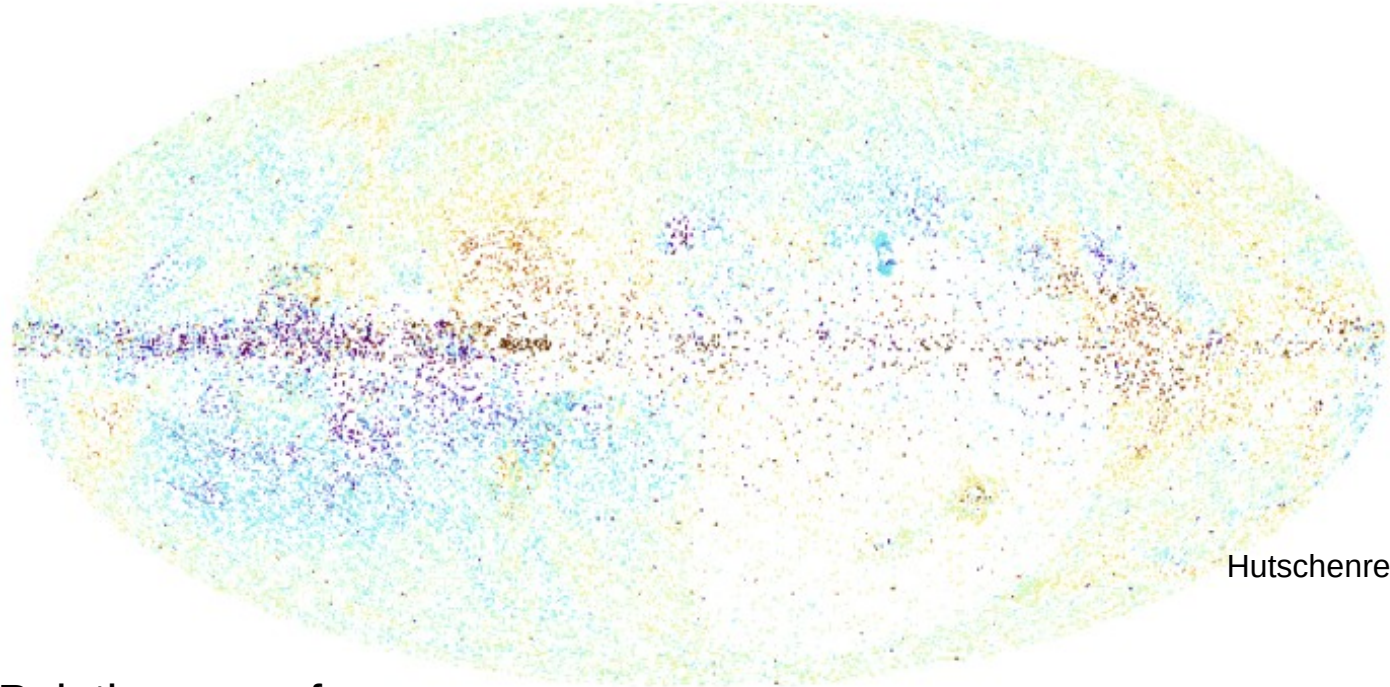
Density of
thermal
electrons

Line-of-sight
component of B

Faraday rotation towards extragalactic sources

Now:
55,000 extragal.
sources
~1000 pulsars
with RM (Han et al
2018)

SKA MID:
3 million extragal.
sources!
SKA Phase 1 ~
10,000 pulsars
(Xue+2017)



Hutschenreuter+ 2022

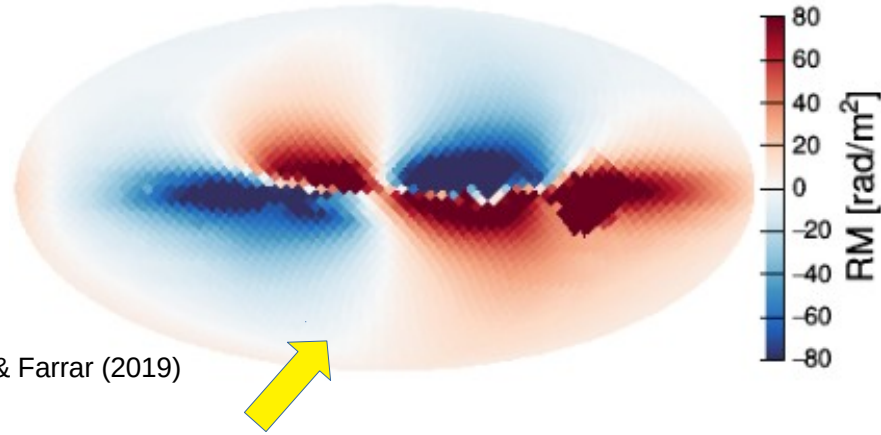
Pointing away from
observer



Pointing towards
observer

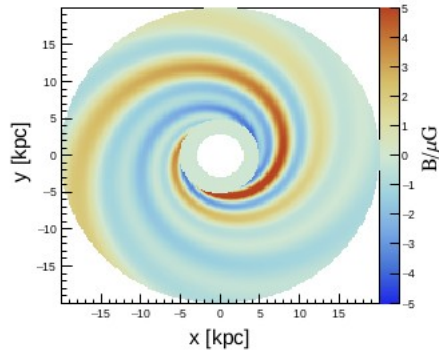
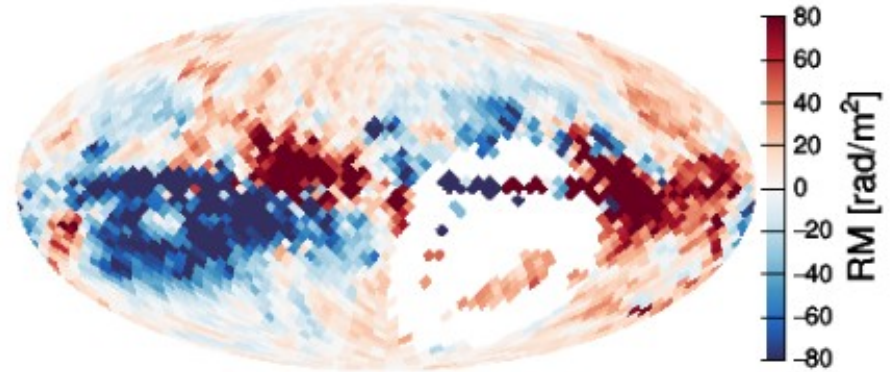
Models are constrained by 2D data

Model RM



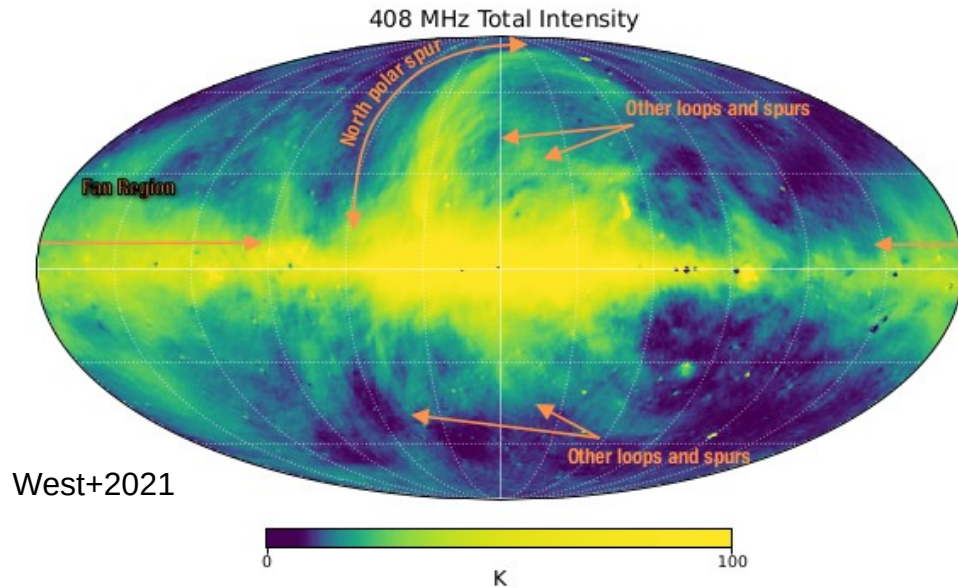
Unger & Farrar (2019)

Observed RM

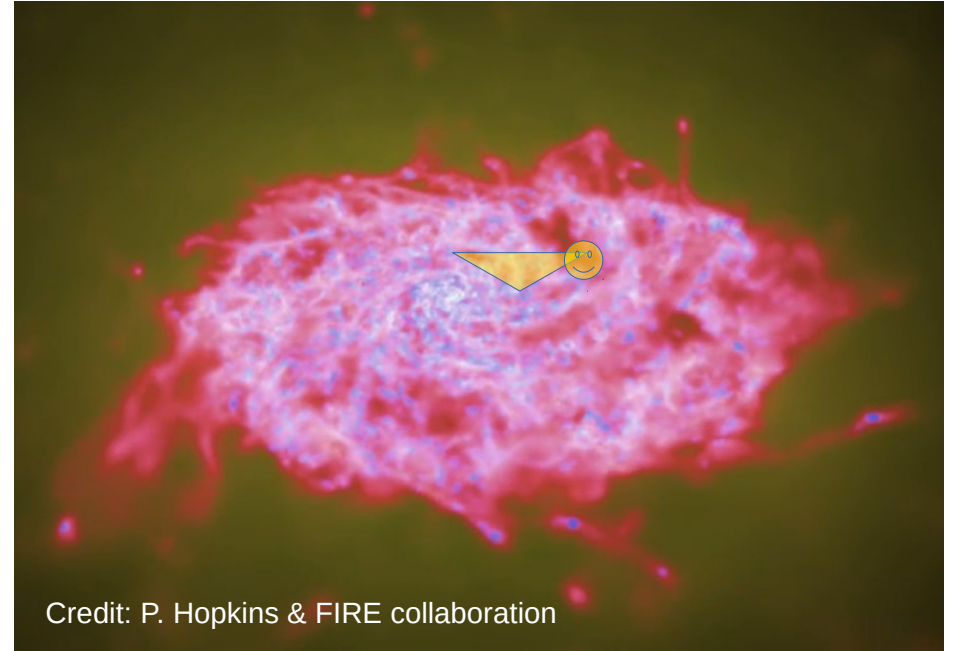


Mostly 2D data → degeneracies in 3D Galactic magnetic field models

How to tell what is near vs far?



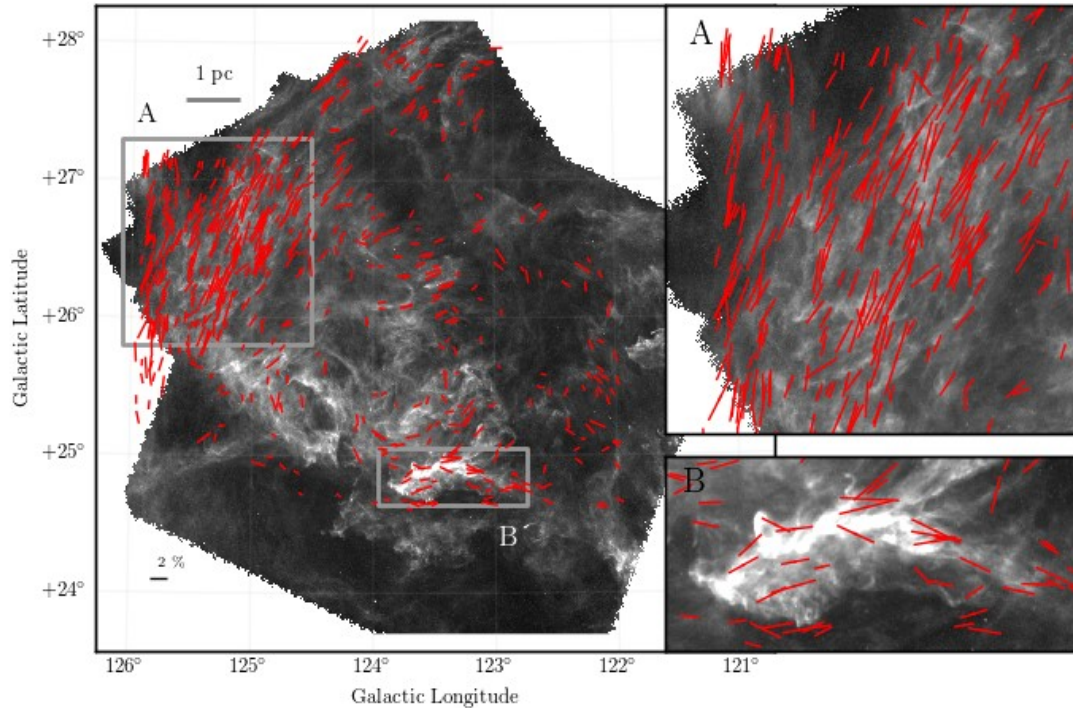
Simulation of MW-type galaxy



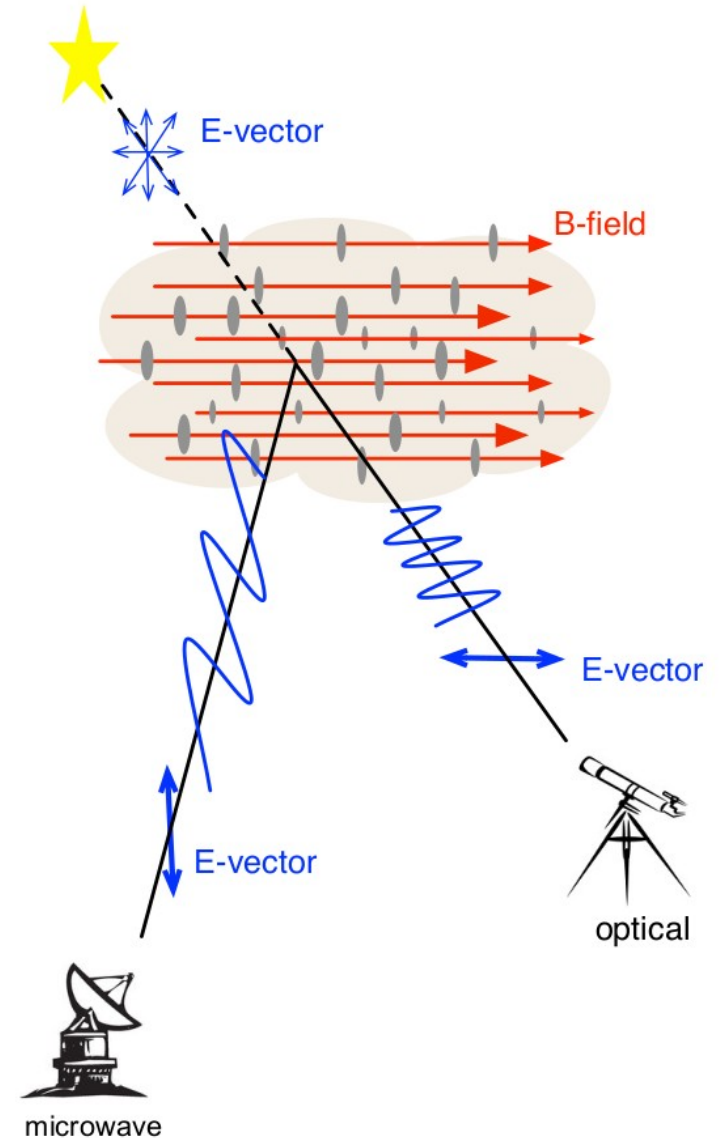
http://www.tapir.caltech.edu/~phopkins/Site/animations/Movies_m12i/gas.html

Blue: neutral gas
pink: warm ionized gas

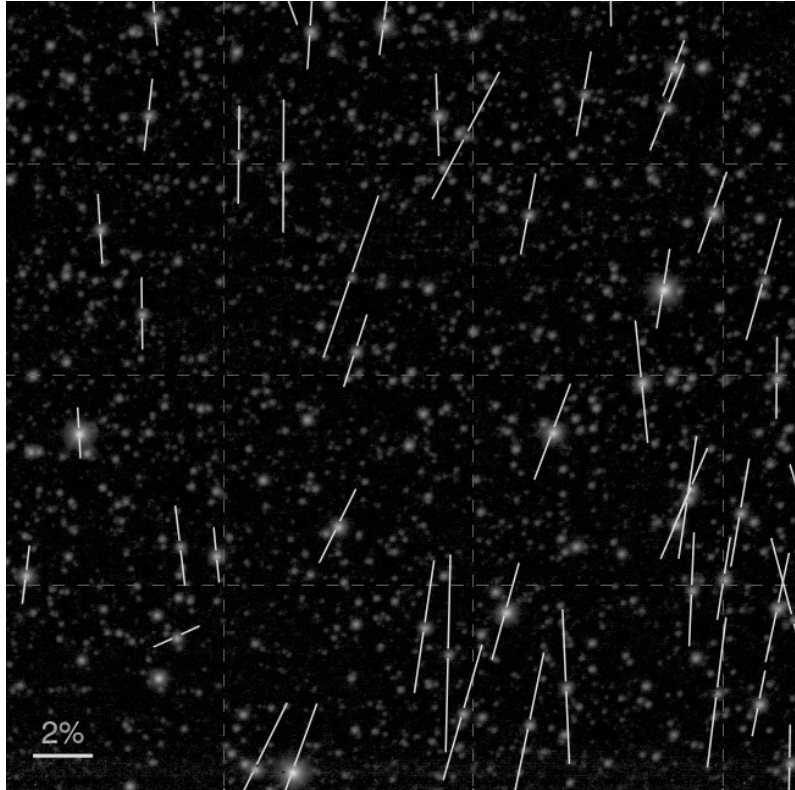
Stellar polarimetry to the rescue



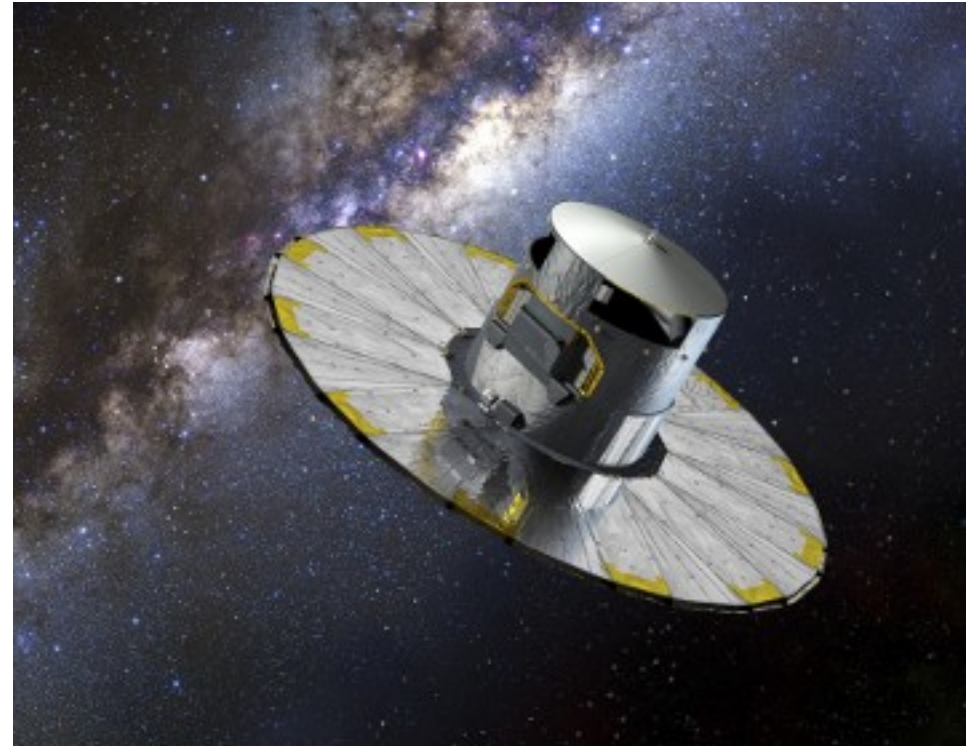
Panopoulou+2016



For each star, we now have its distance

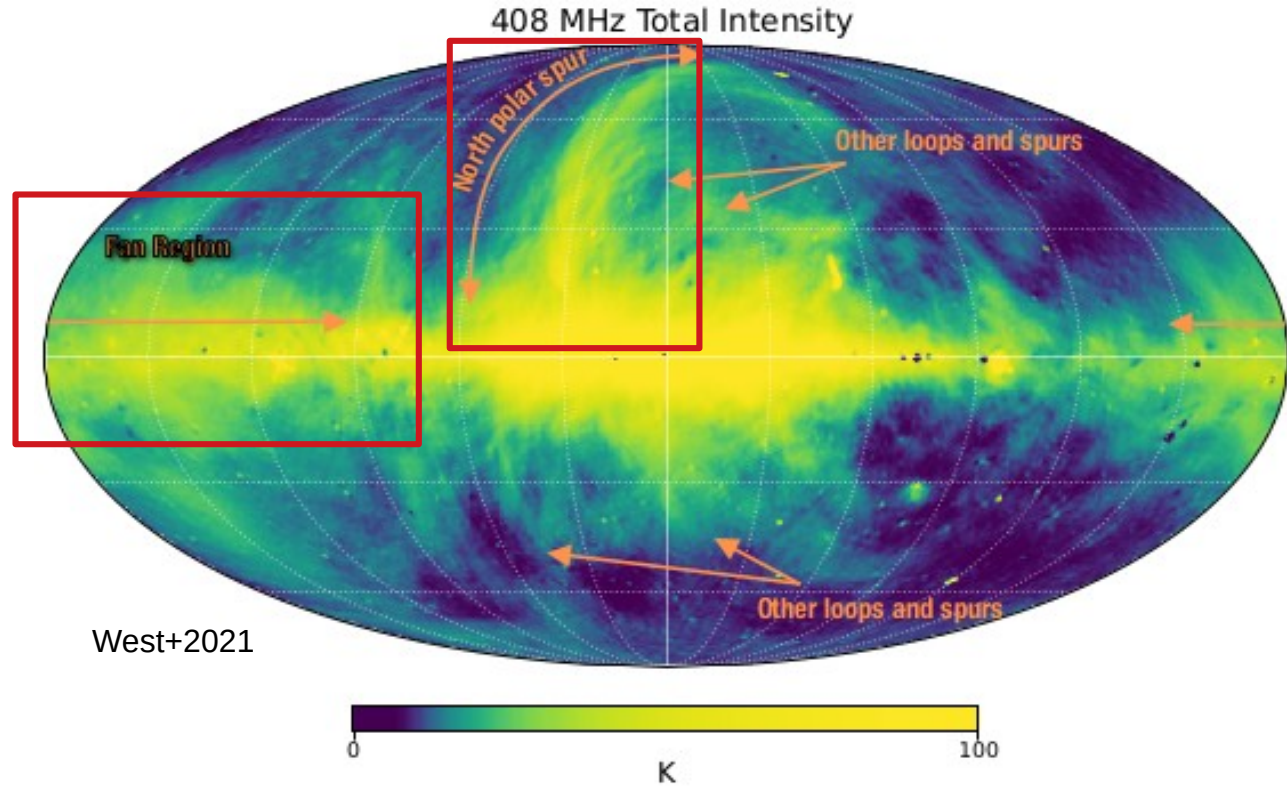


Clemens+2012



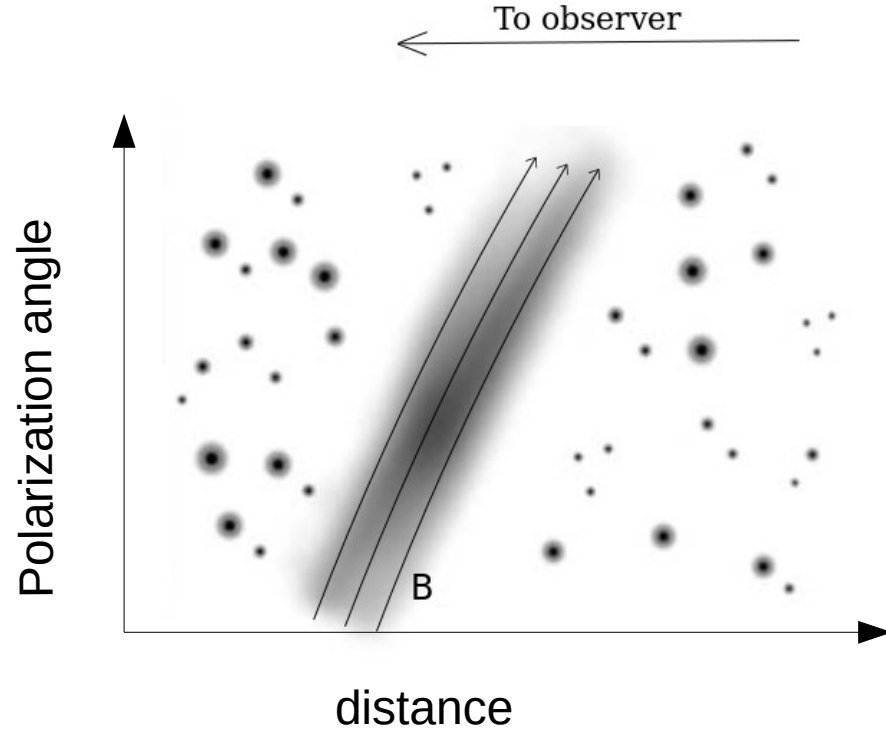
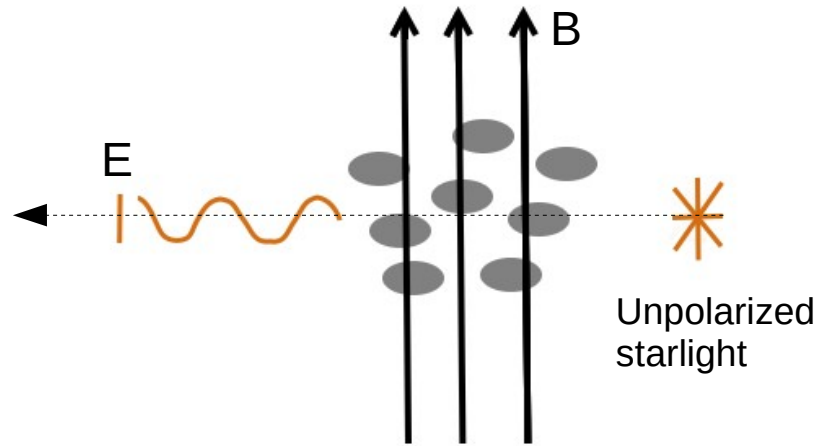
ESA's Gaia satellite delivers distances to billions of stars

Determining the distance to radio features

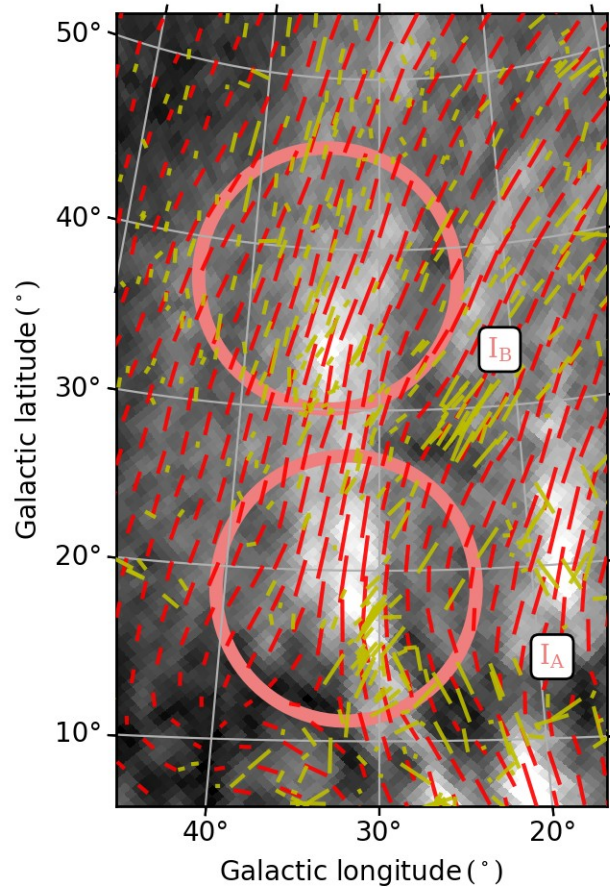


Constraining distances to synchrotron-emitting structures

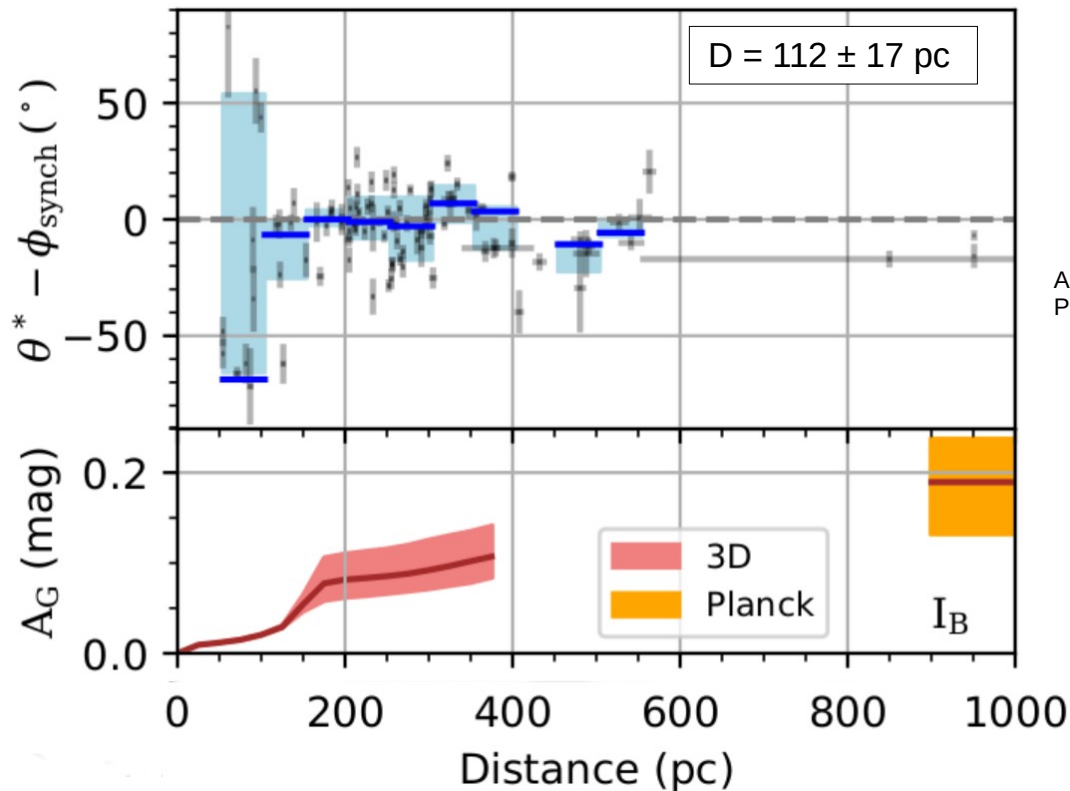
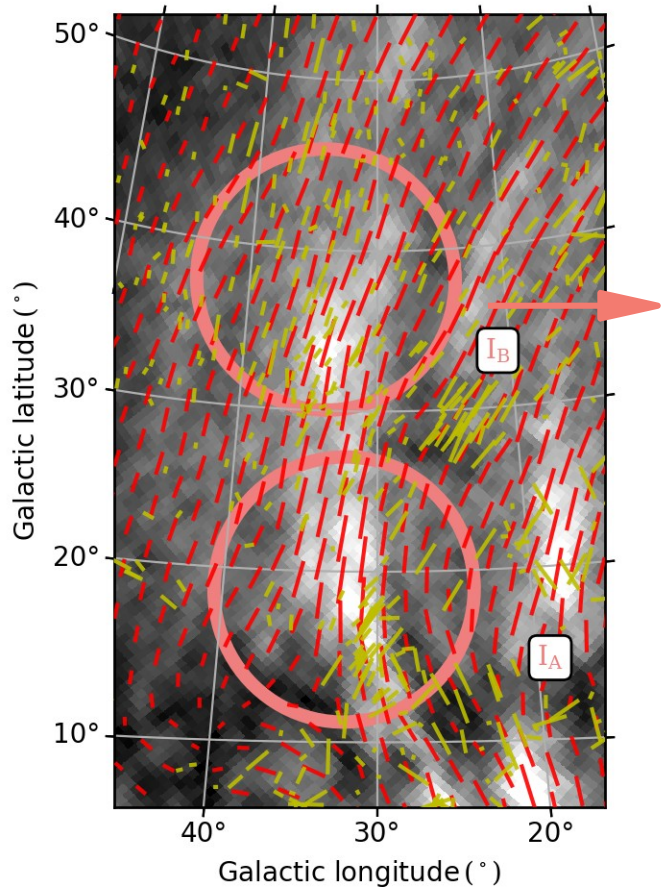
Magnetically aligned dust polarizes background starlight



Polarimetry towards the North Polar Spur

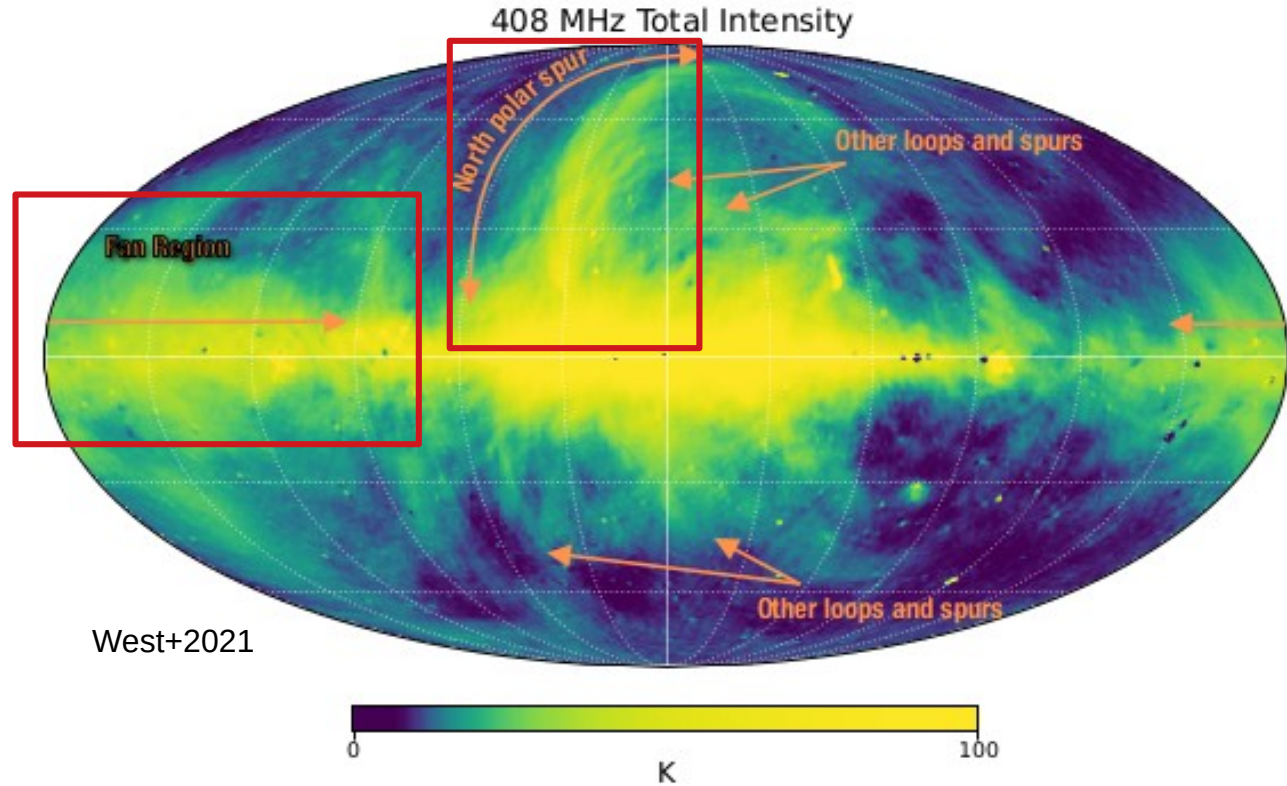


Starlight traces same B field as synchrotron at ~ 100 pc

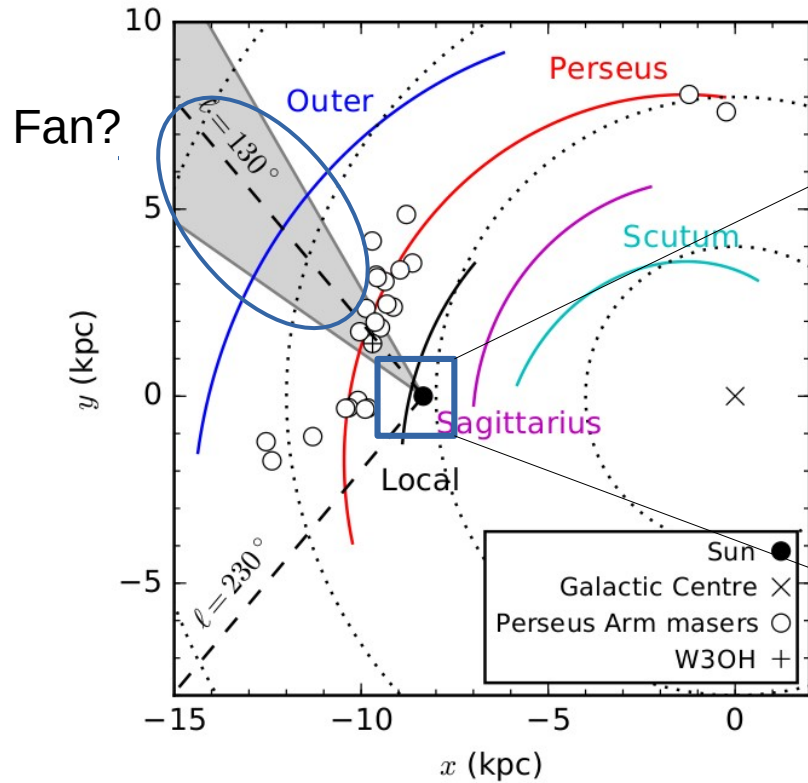


Alignment quantified by Projected Rayleigh Statistic

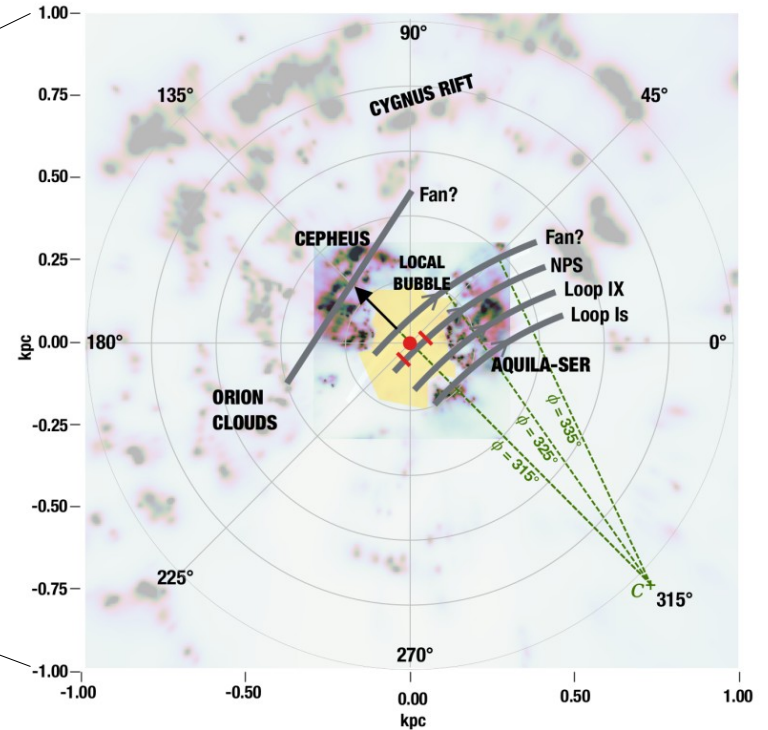
Determining the distance to radio features



Is the Fan distant or nearby?

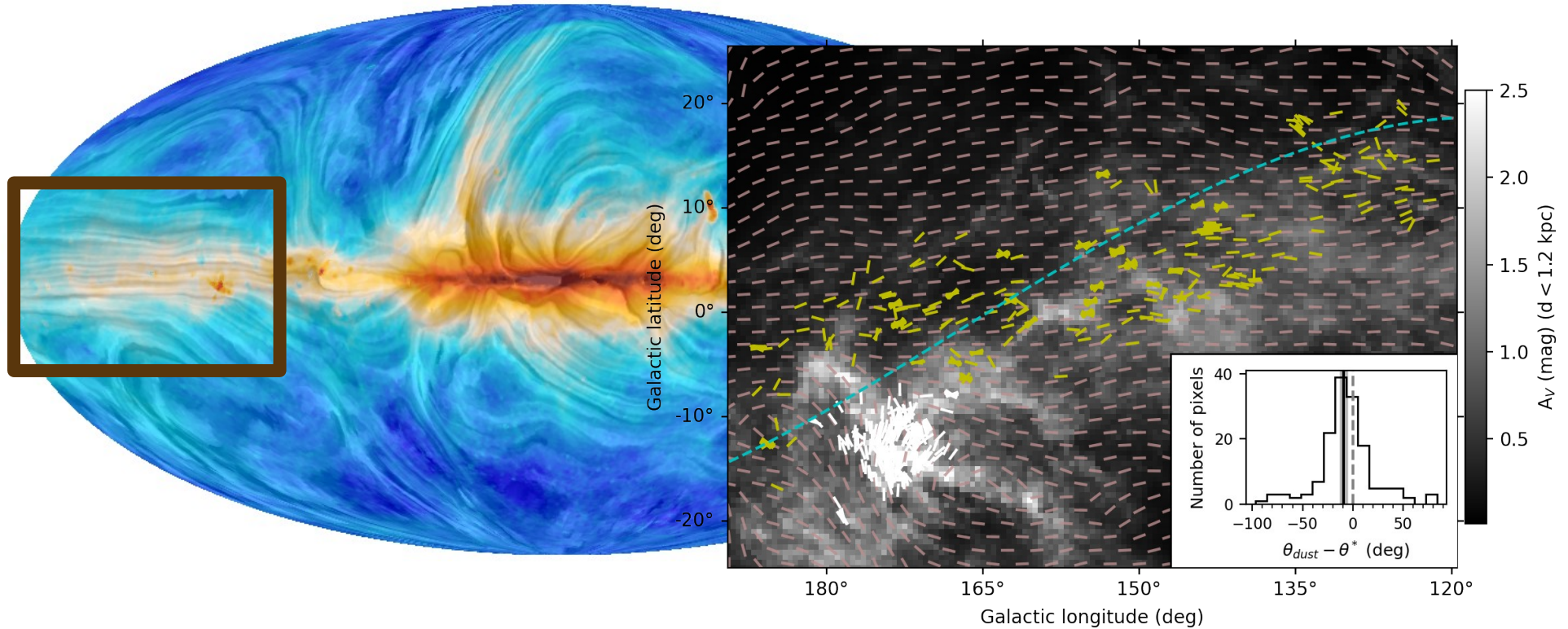


Hill+(2017)



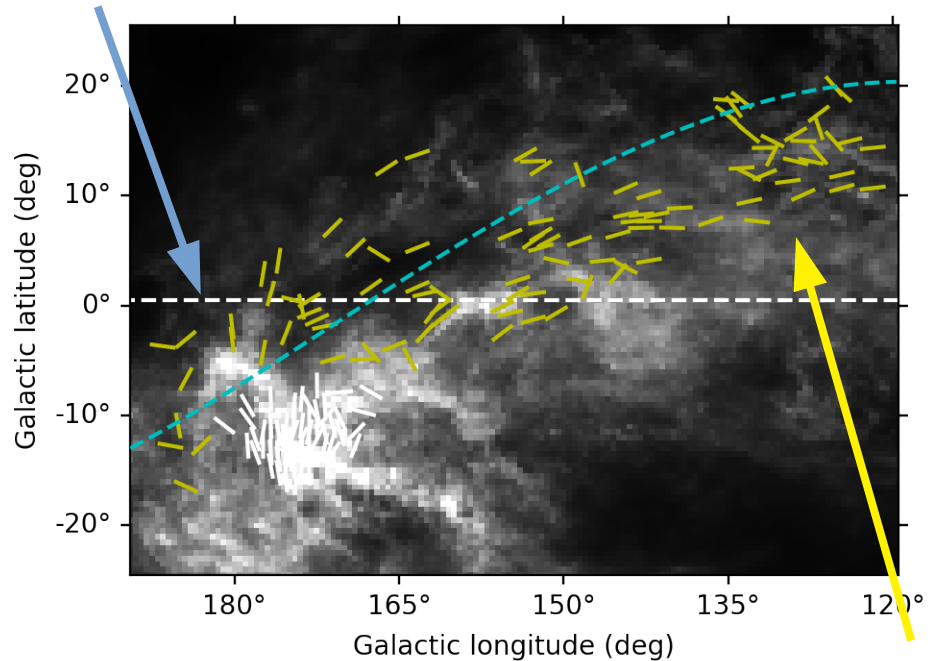
West+(2021)

Magnetic field uniform from synchrotron & dust emission



But polarization of nearby stars does not follow Fan region trend...

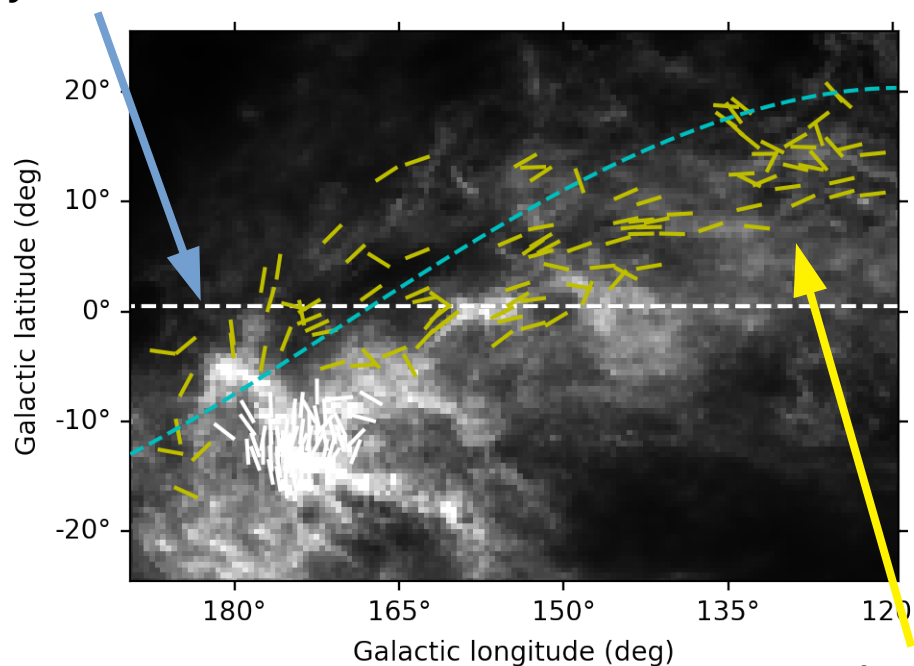
Direction of B field
from synchrotron



Polarization of
nearby stars

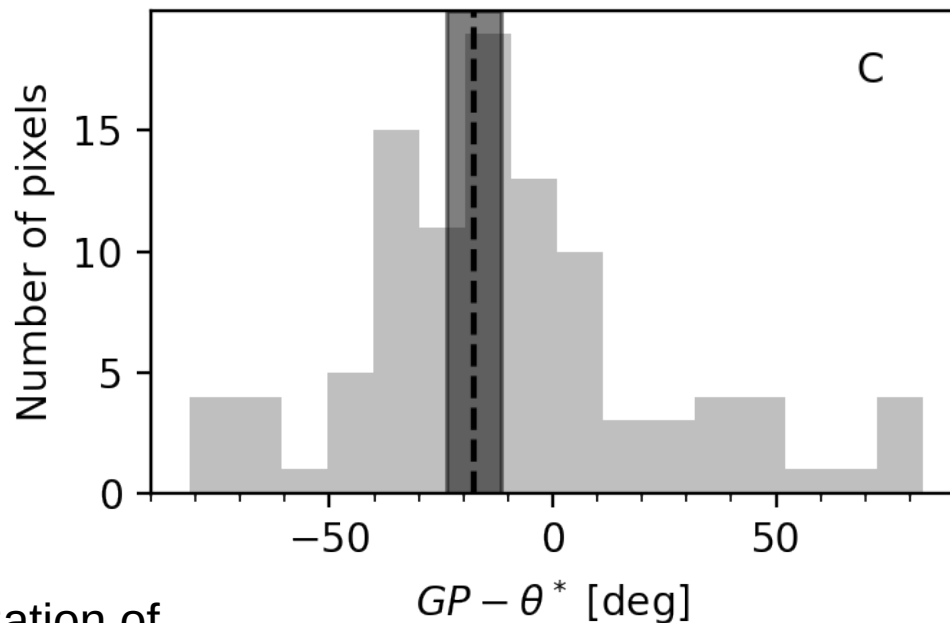
But polarization of nearby stars does not follow Fan region trend...

Direction of B field from synchrotron



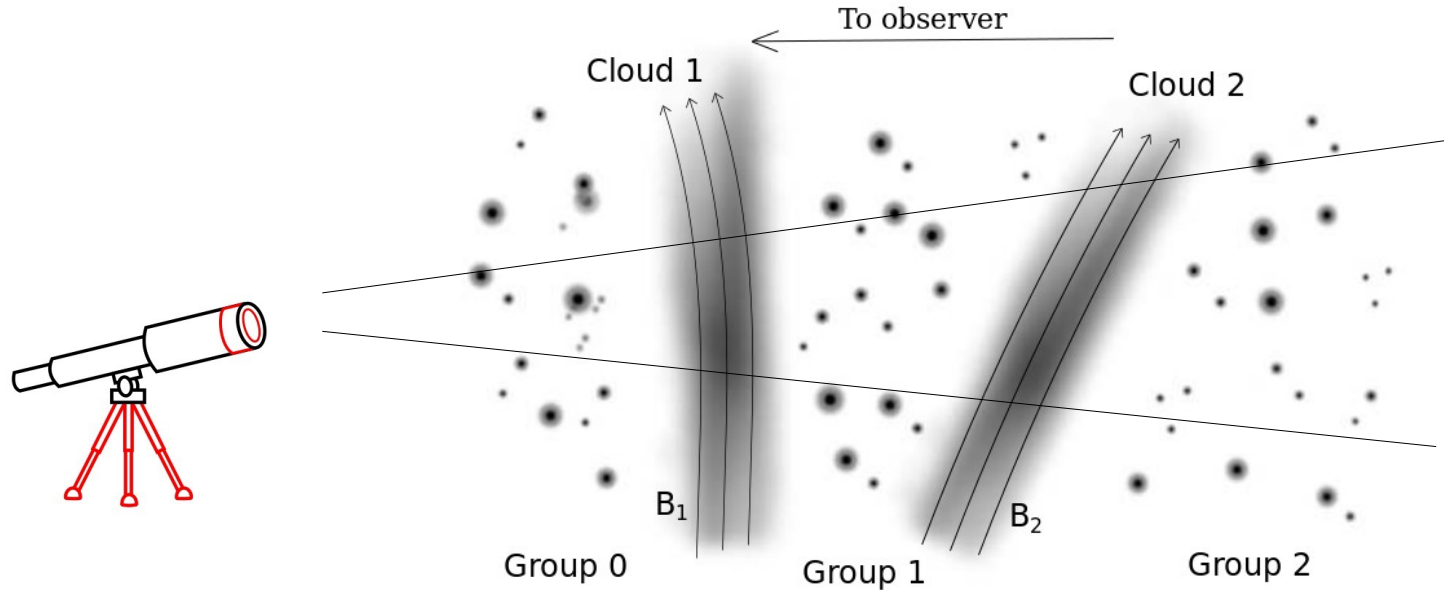
Polarization of nearby stars

Near stars ($d < 600$ pc)



Panopoulou+ subm.

Tomographic mapping of the B field geometry



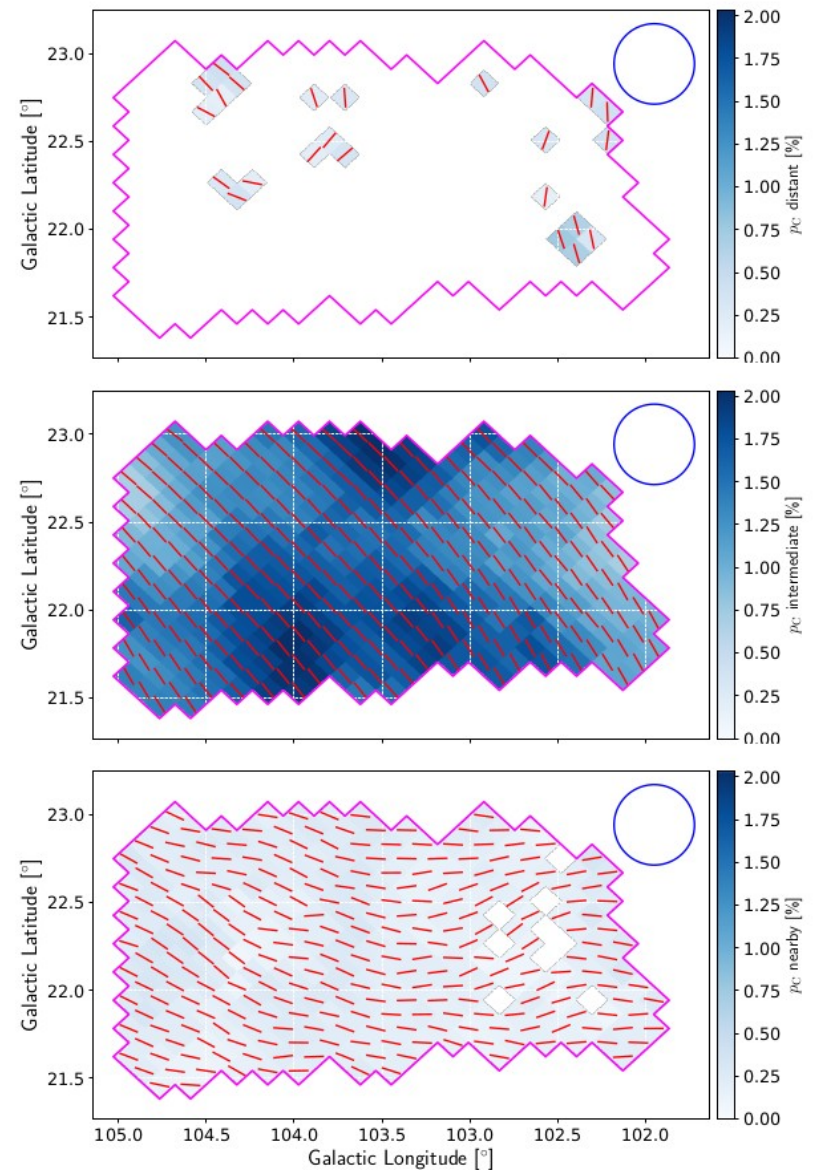
Polarization parameters



First application:
Panopoulou+ 2019
Automated Bayesian
methodology:
Pelgrims+ 2023

Distance from Earth

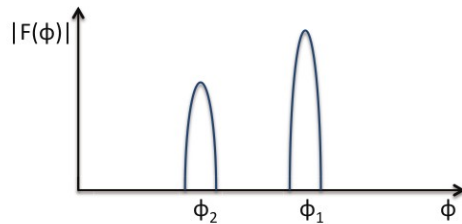
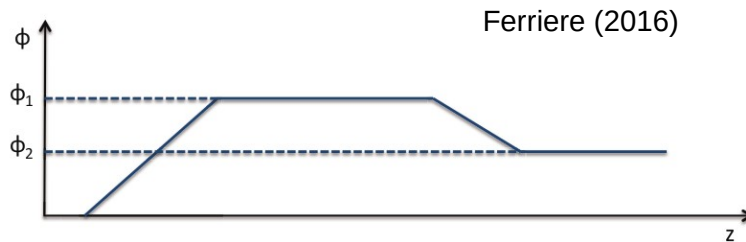
First tomographic map of the B field orientation



Pelgrims+2024

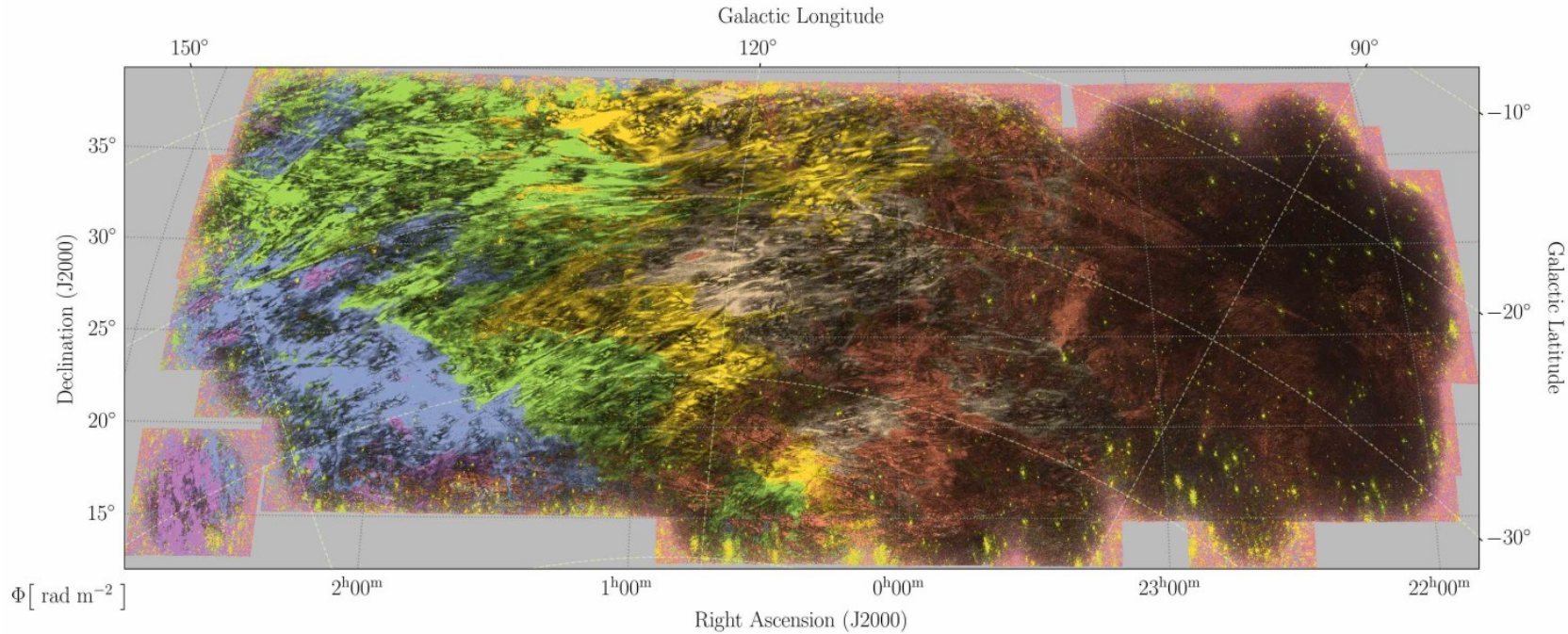
The path to full 3D reconstruction

Dissecting the line-of-sight B field with Faraday tomography



See also: Jelic+ 2020, Erceg+ 2022, 2024...

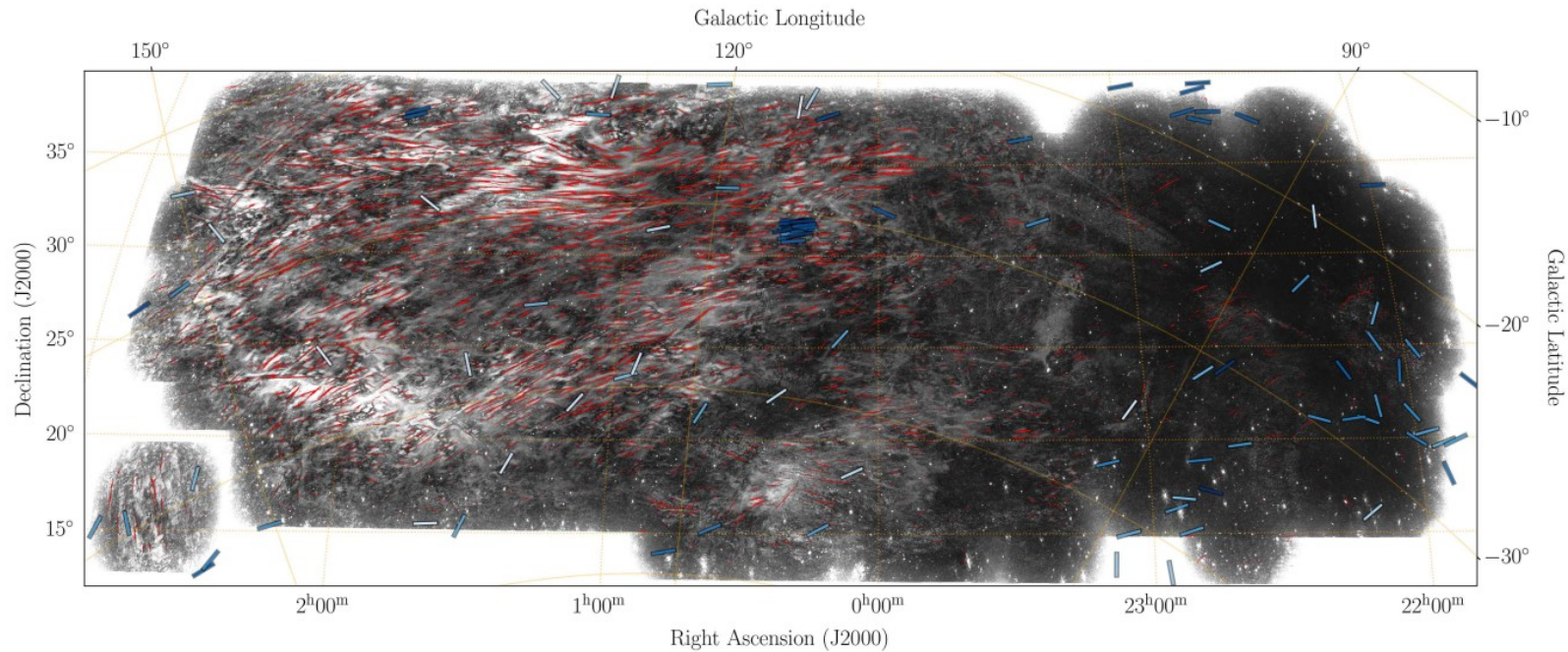
Imprint of 3D magnetic field clearest at low frequencies



$\Phi = [-50, -4)$
 $\Phi = [-4, -2)$
 $\Phi = [-2, 0)$
 $\Phi = [0, 2)$
 $\Phi = [2, 4)$
 $\Phi = [4, 50)$

Erceg+2024

Starlight polarimetry anchors the distance



Erceg+2024

Summary

- Mapping 3D geometry of B field important for many open questions (galaxy evolution, cosmic ray physics, CMB/EOR cosmology)
- Stellar polarimetry + Gaia distances are a powerful probe of 3D magnetized ISM
- New constraints on distance and origin of radio loops & Fan region
- Tomographic mapping of magnetic field orientation is a reality
- SKA RMs and Faraday tomography will pave path towards 3d reconstruction of B field in Milky Way