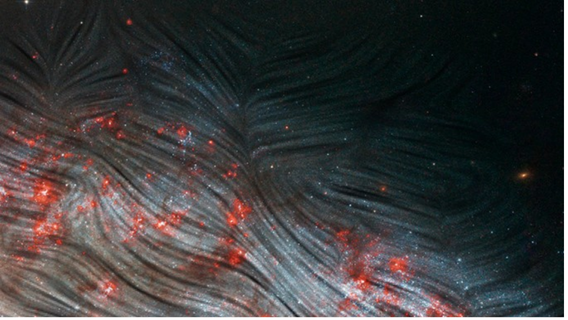
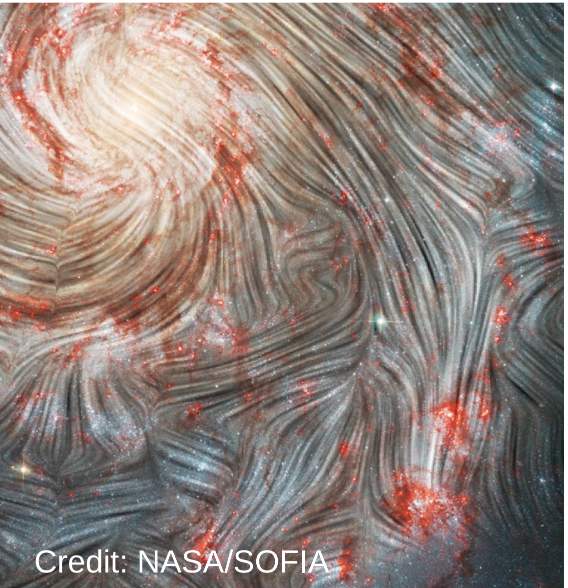


CHALMERS Vetenskapsrådet Knut and Alice Wallenberg Foundation

Galactic magnetism in 3D


Credit: NASA/SOFIA

Gina Panopoulou

Assistant professor
Chalmers University of Technology

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

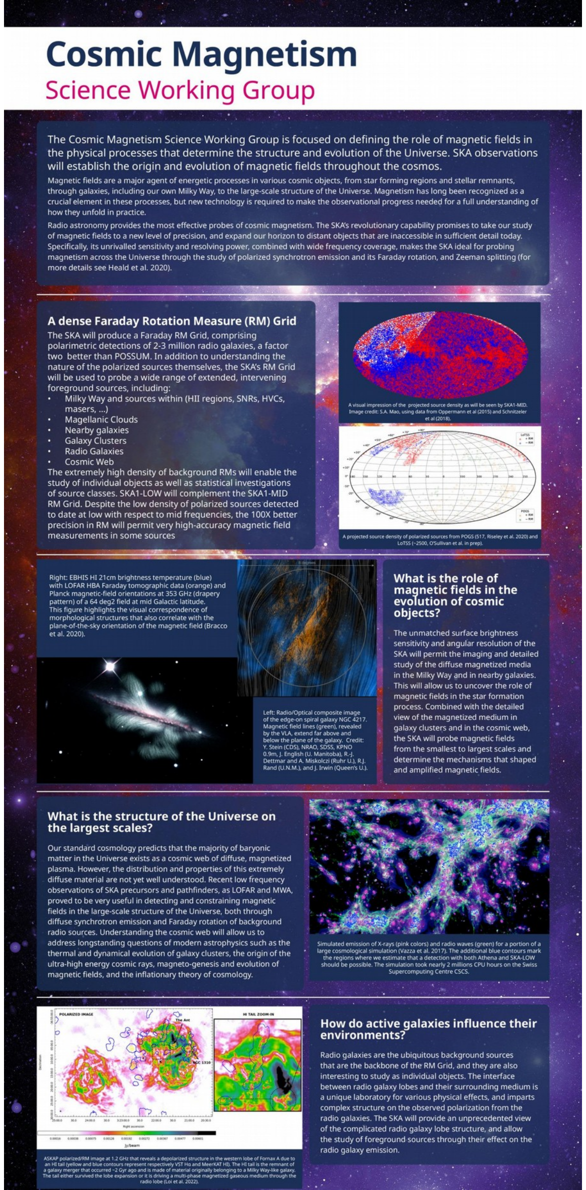
Magnetism and the SKA

Enabling science across scales:

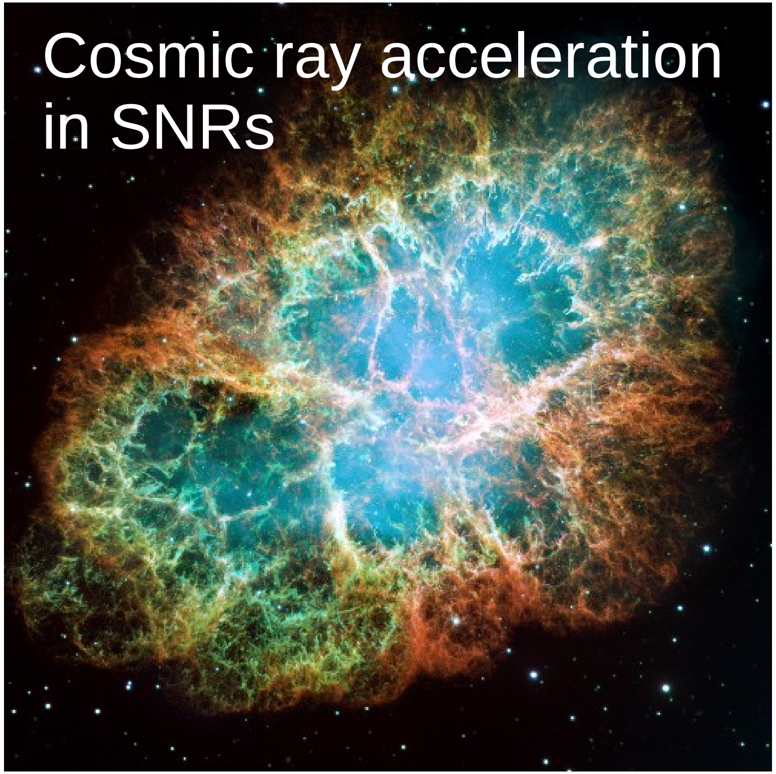
Galaxy clusters, filaments and large-scale-structure, AGN jets, radio galaxies, Milky Way, molecular clouds...

19 chapters in the 2015 SKA science book

See also Heald et al (2020)



Magnetic fields are everywhere in the Universe



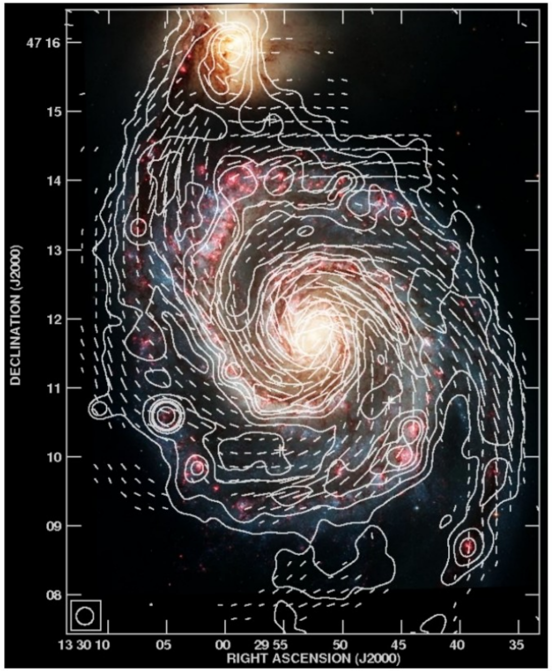
Galactic magnetic fields are `special’

Local mean ISM energy densities

Magnetic ~ 1 eV cm^{-3}
Thermal (hot gas) ~ 1 eV cm^{-3}
Kinetic (turbulent) ~ 1 eV cm^{-3}
Photons (CMB, stars) ~ 1 eV cm^{-3}
Cosmic rays ~ 1 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)

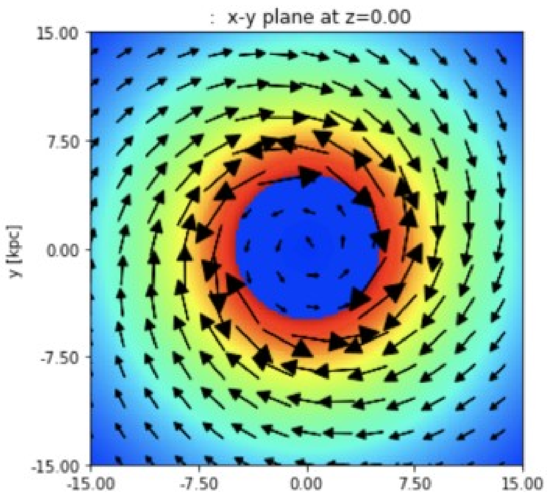
Abazajian+(2016), Jelic + (2010)

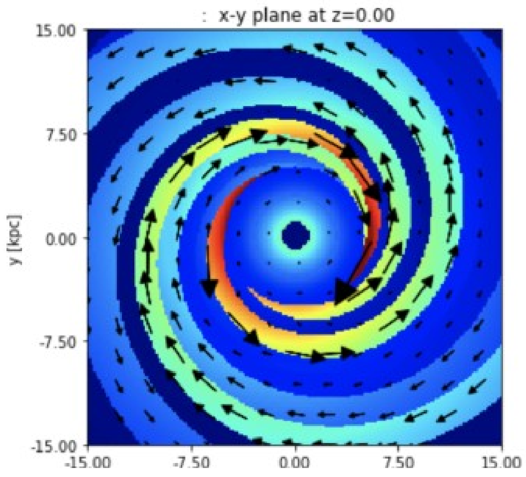
- Origin of Ultra-High energy cosmic rays

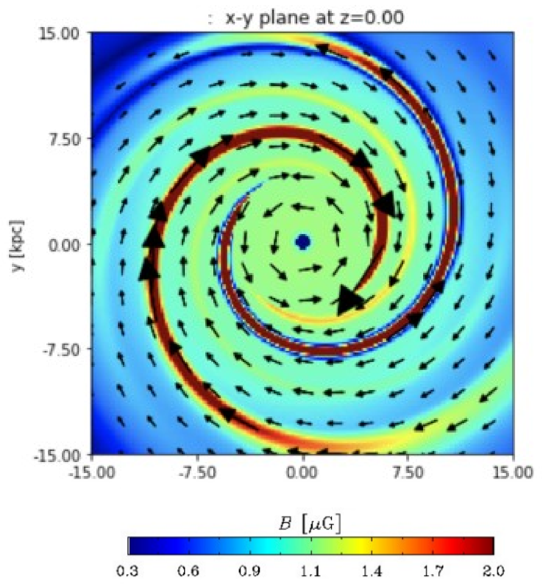
Unger & Farrar (2024)

Need accurate knowledge of the Galaxy’s magnetic field!

Galactic magnetic field models need work...

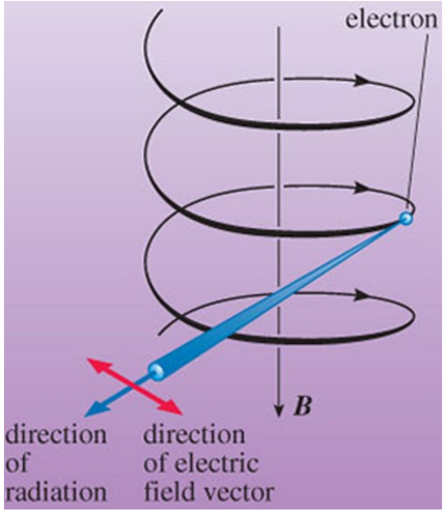






Jaffe 2019

How can we map magnetic field geometry?



Synchrotron emission

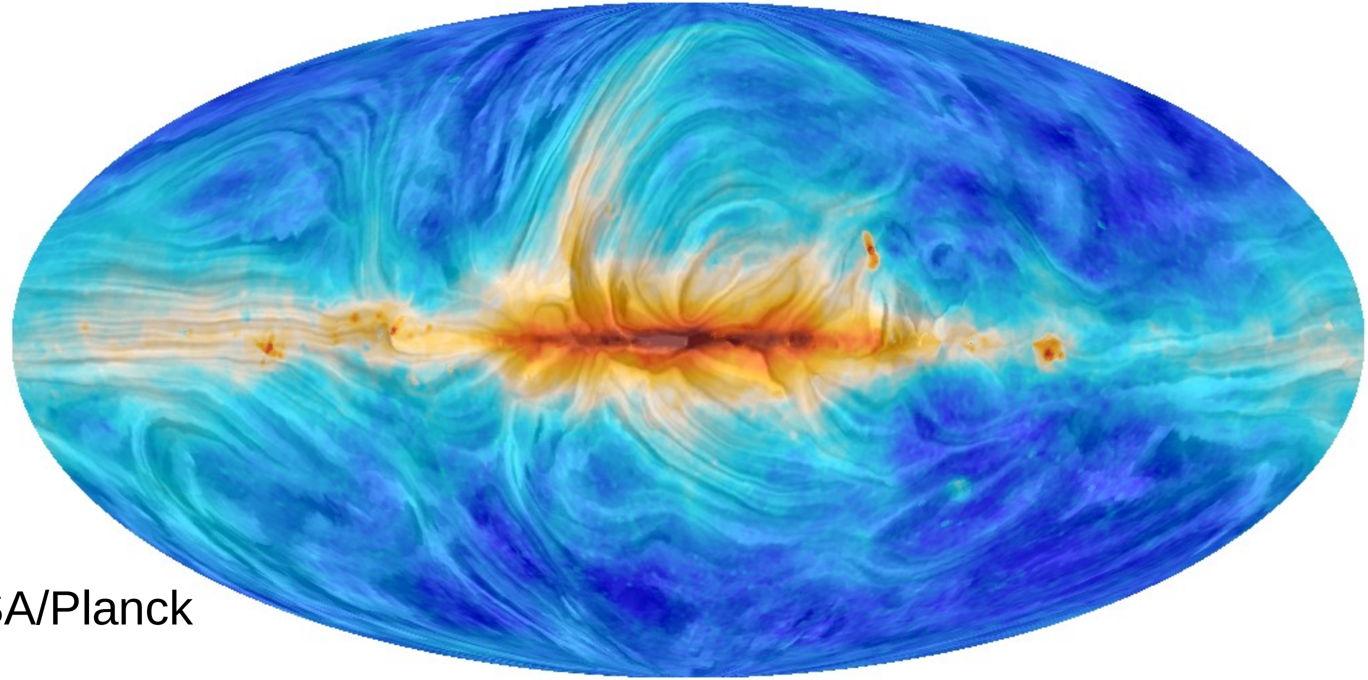
$$P_s \propto \int n_{CR} B_{pos}^2 \, dl$$

Integral along line of sight

Plane-of-sky component of B

Density of cosmic-ray electrons

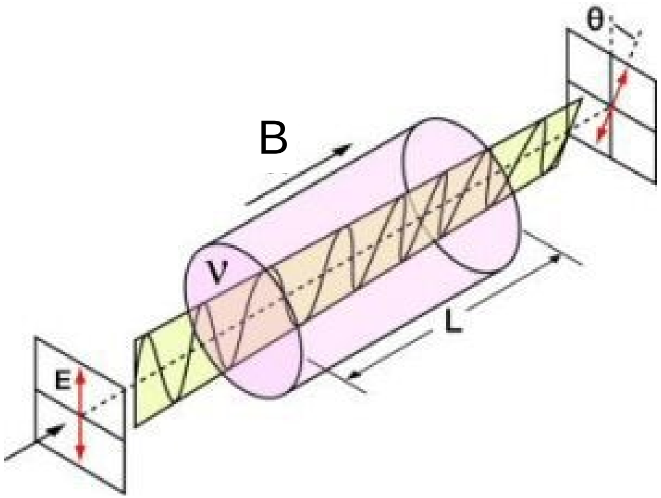
The magnetic field as seen from synchrotron emission



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

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

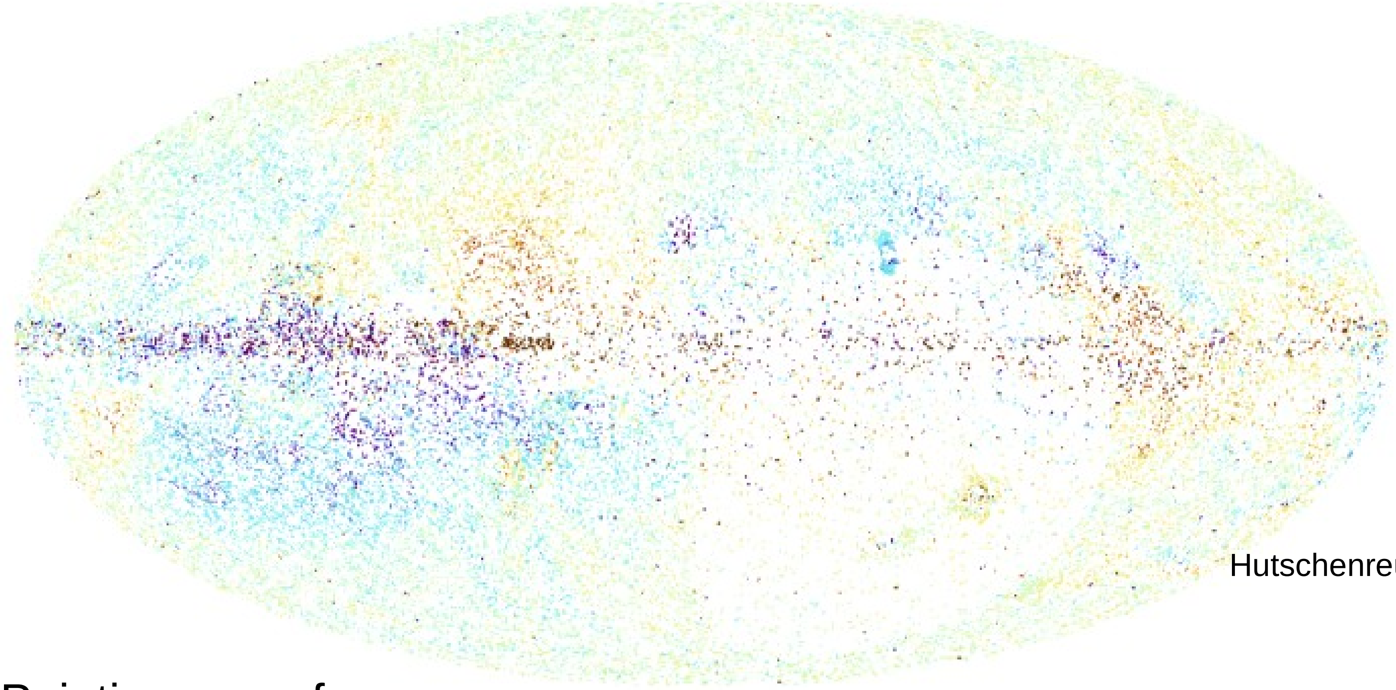
Density of thermal electrons

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)



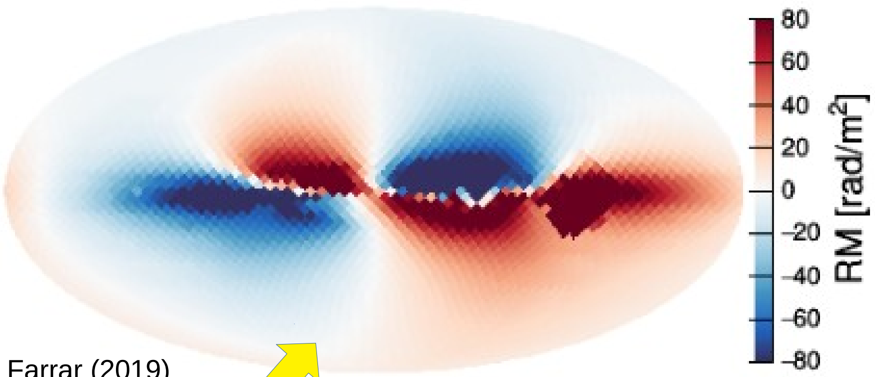
Hutschenreuter+ 2022

Pointing away from observer

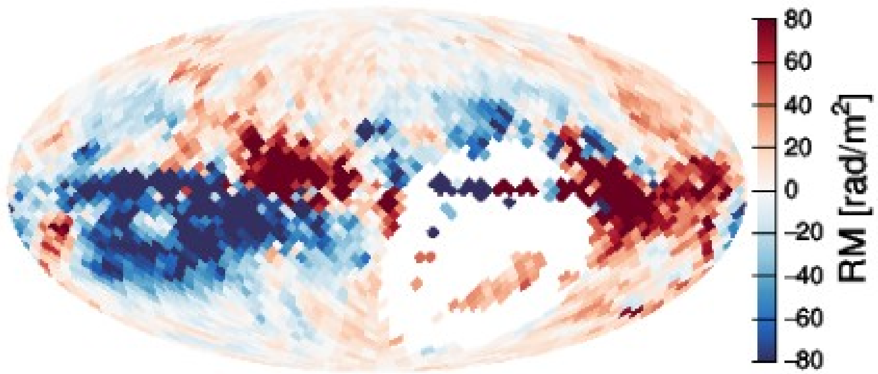
Pointing towards observer

Models are constrained by 2D data

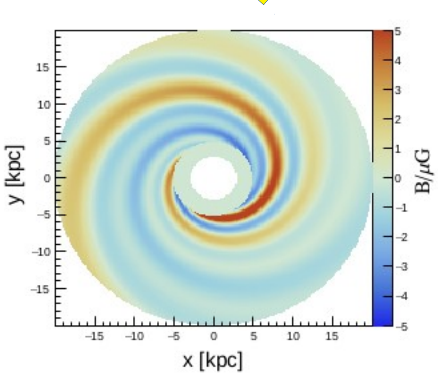
Model RM



Observed RM

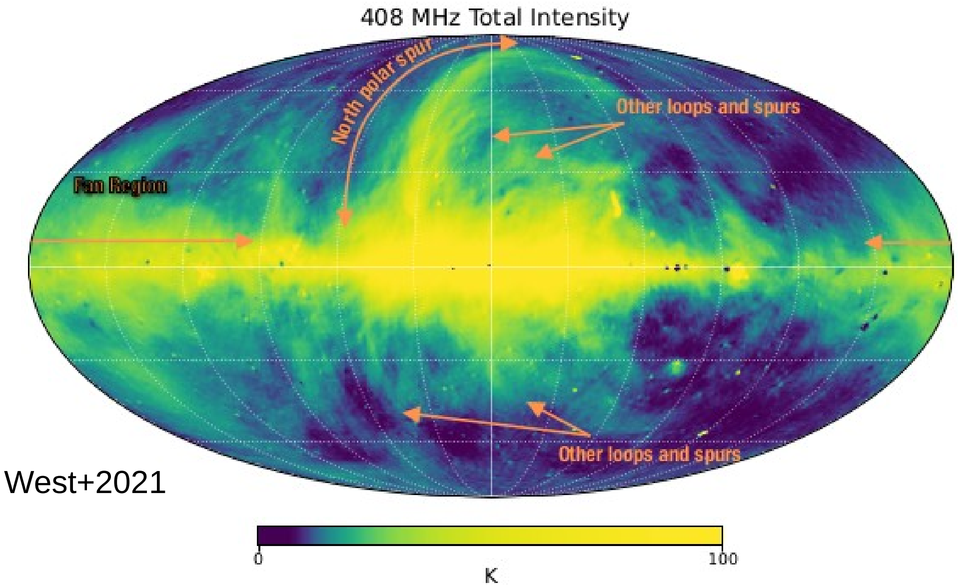


Unger& Farrar (2019)



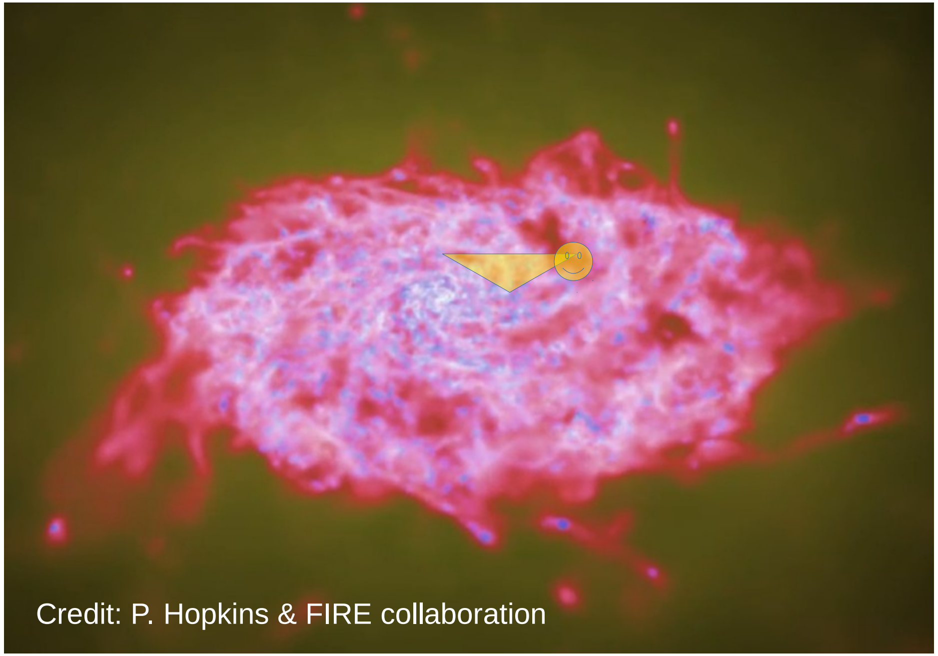
Mostly 2D data → degeneracies in 3D Galactic magnetic field models

How to tell what is near vs far?



West+2021

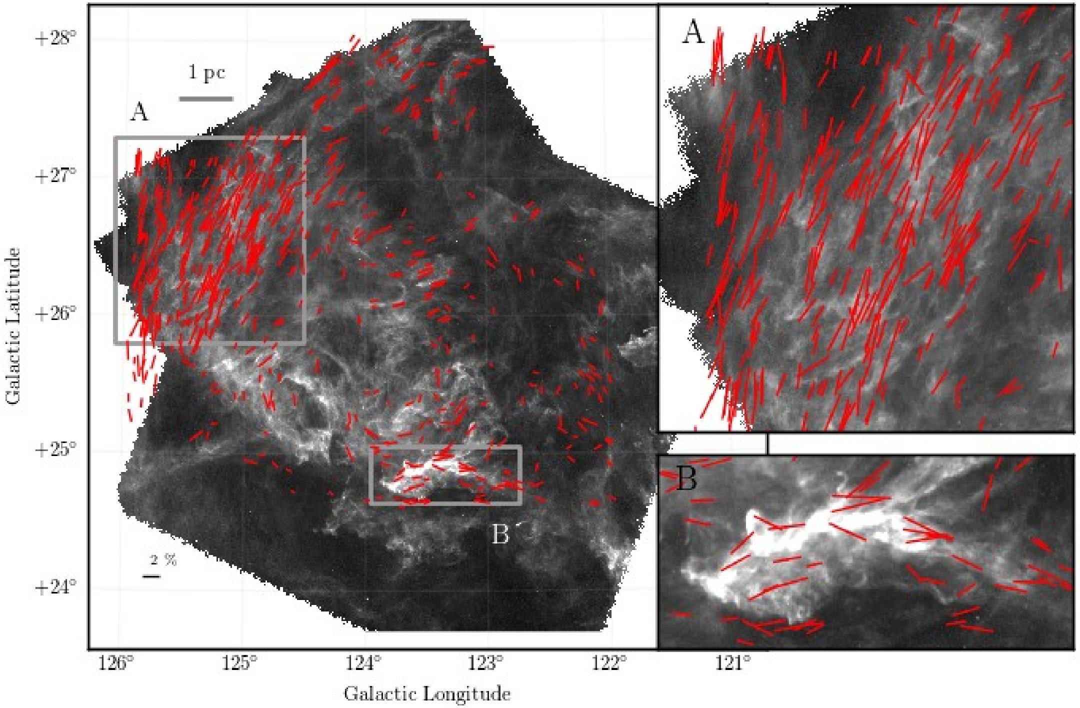
Simulation of MW-type galaxy



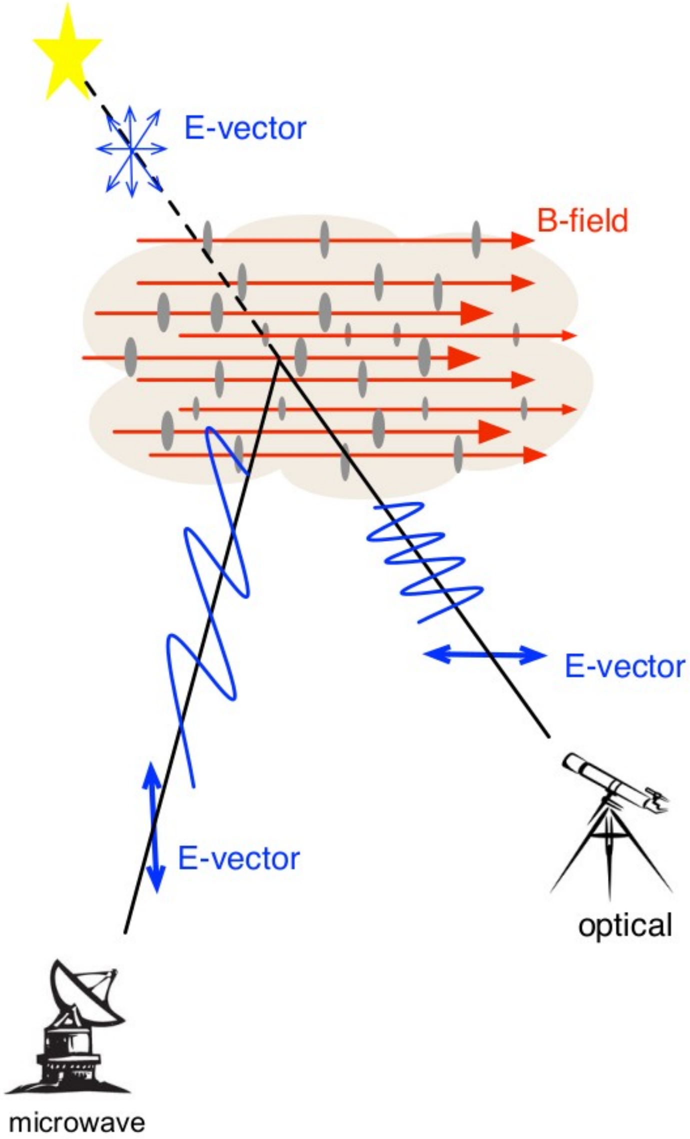
http://www.tapir.caltech.edu/~phopkins/Site/animations/Movies_m12i/gas.html

Blue: neutral gas
pink: warm ionized gas

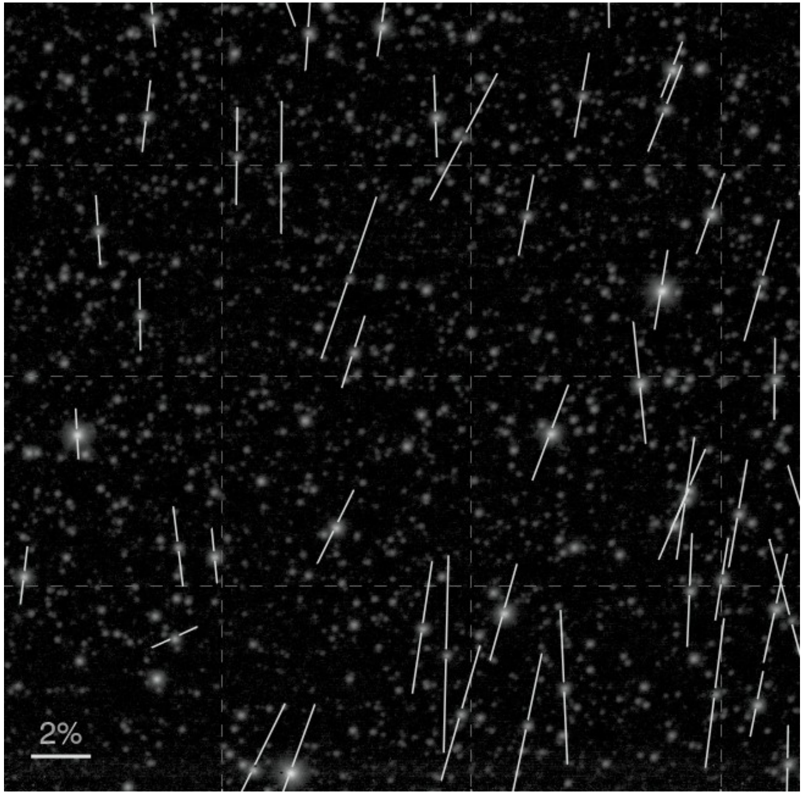
Stellar polarimetry to the rescue



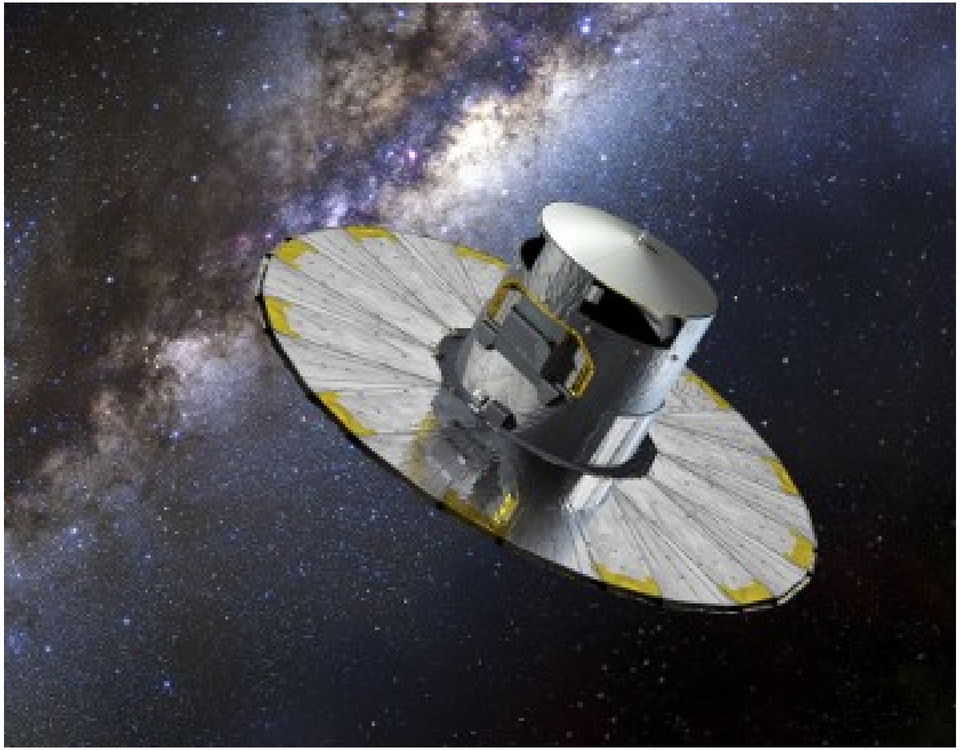
Panopoulou+2016



For each star, we now have its distance

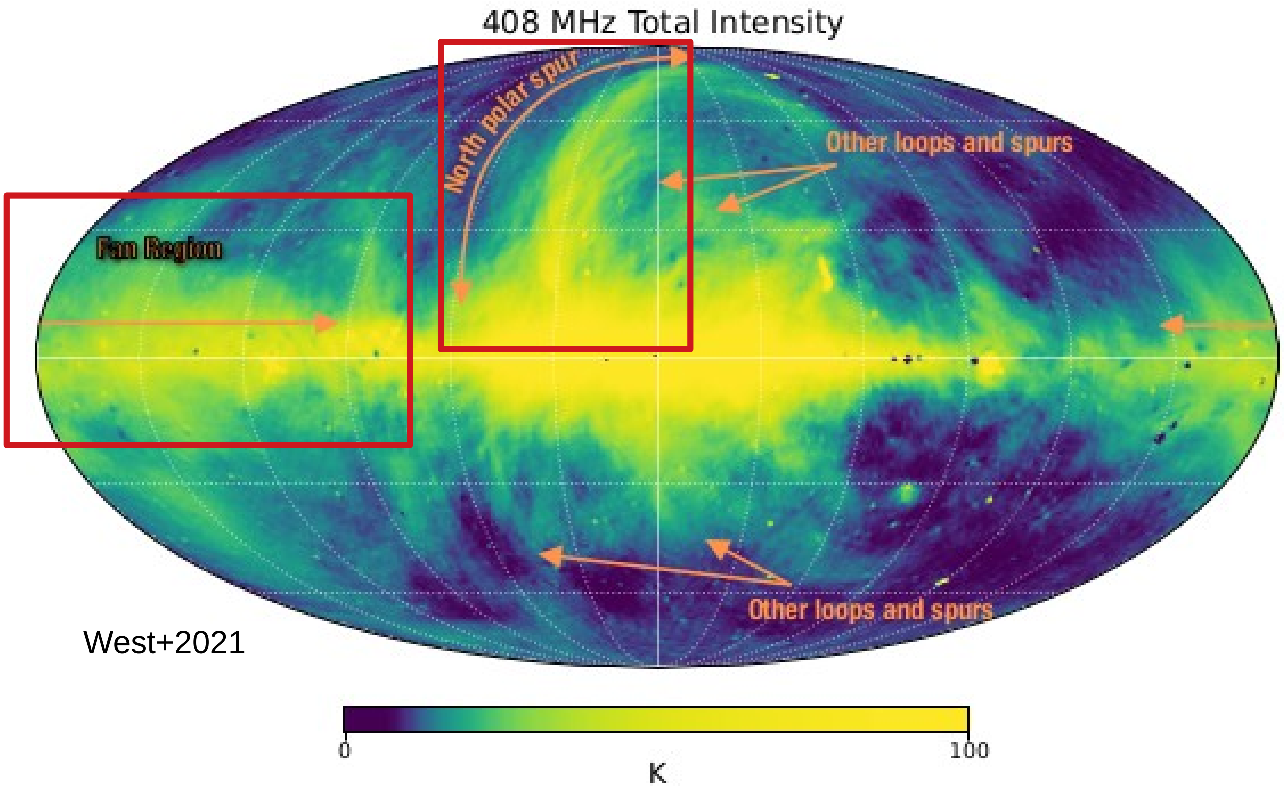


Clemens+2012



ESA's Gaia satellite delivers distances to billions of stars

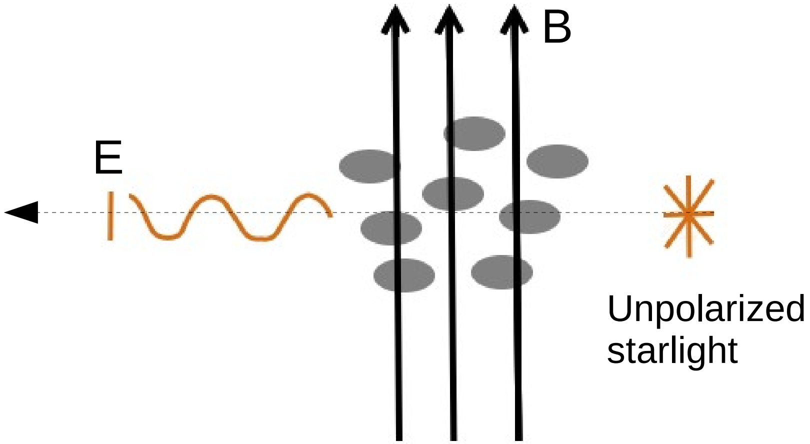
Determining the distance to radio features

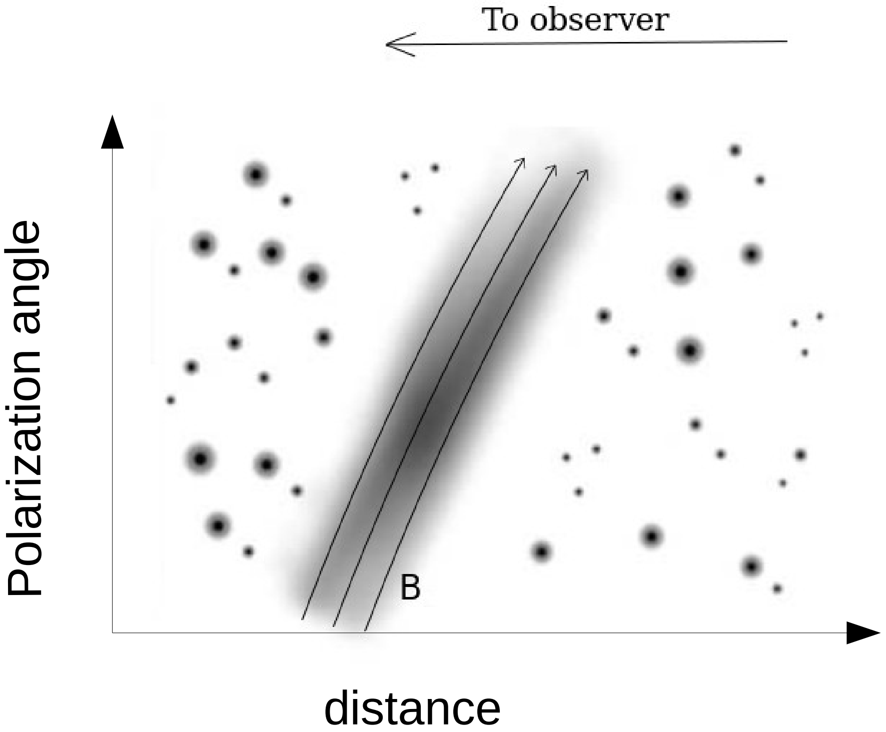


West+2021

Constraining distances to synchrotron-emitting structures

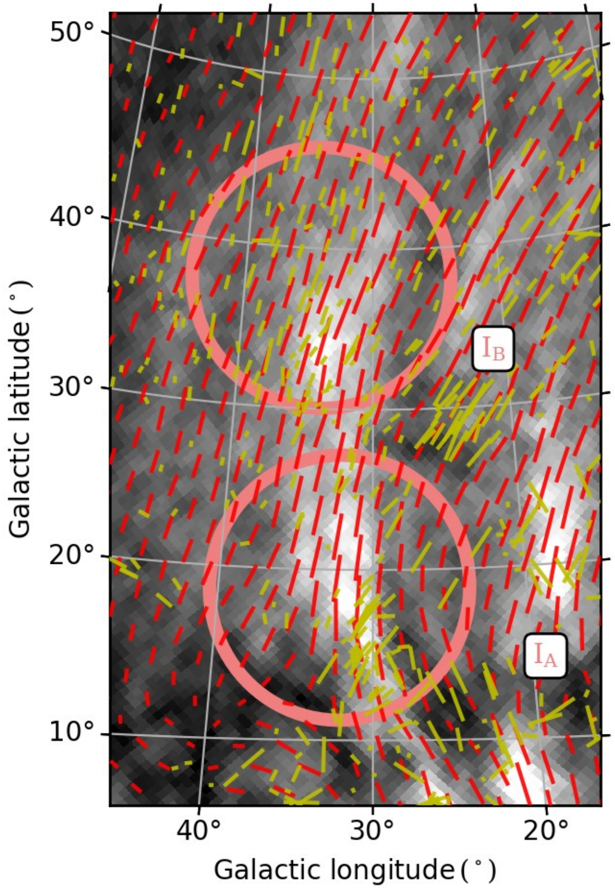
Magnetically aligned dust polarizes background starlight





Review on grain alignment:
Andersson et al. 2015

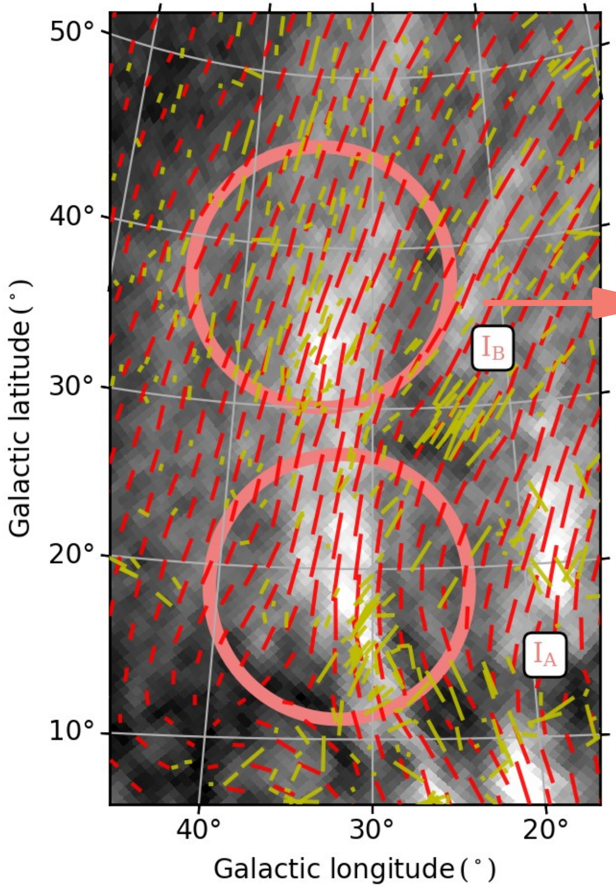
Polarimetry towards the North Polar Spur

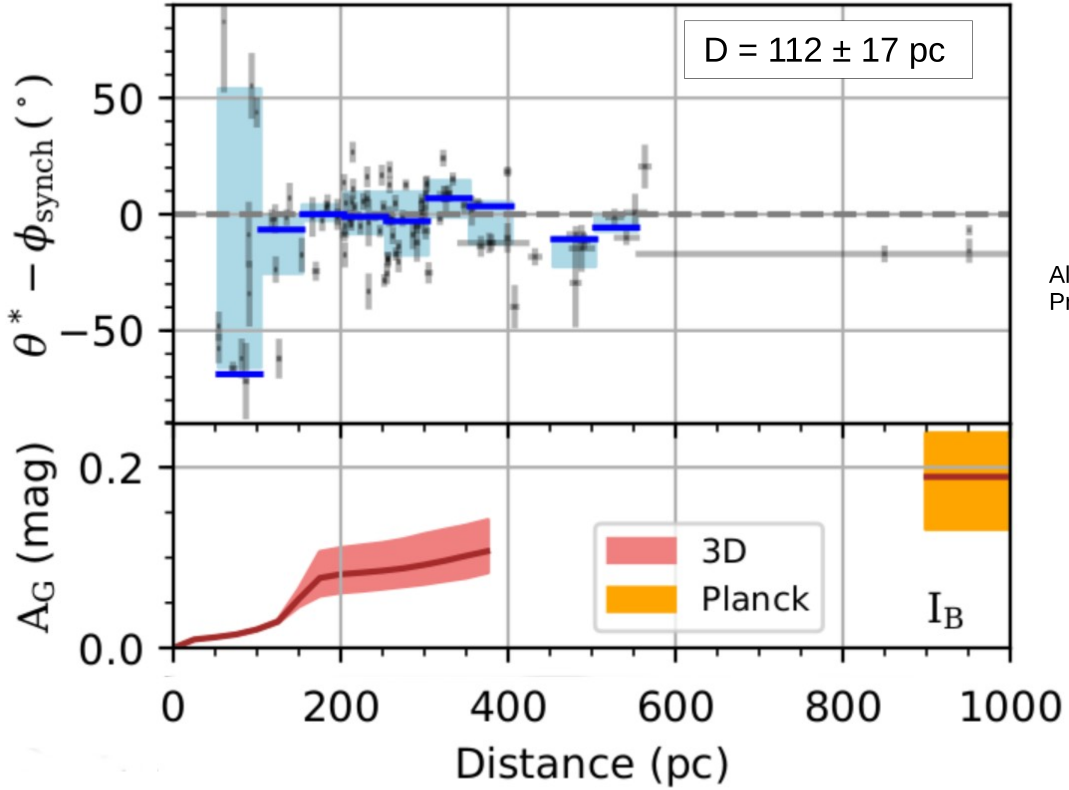


Panopoulou et al. 2021

*Synchrotron pol. Angles have been rotated by 90 deg to trace B field

Starlight traces same B field as synchrotron at ~100 pc



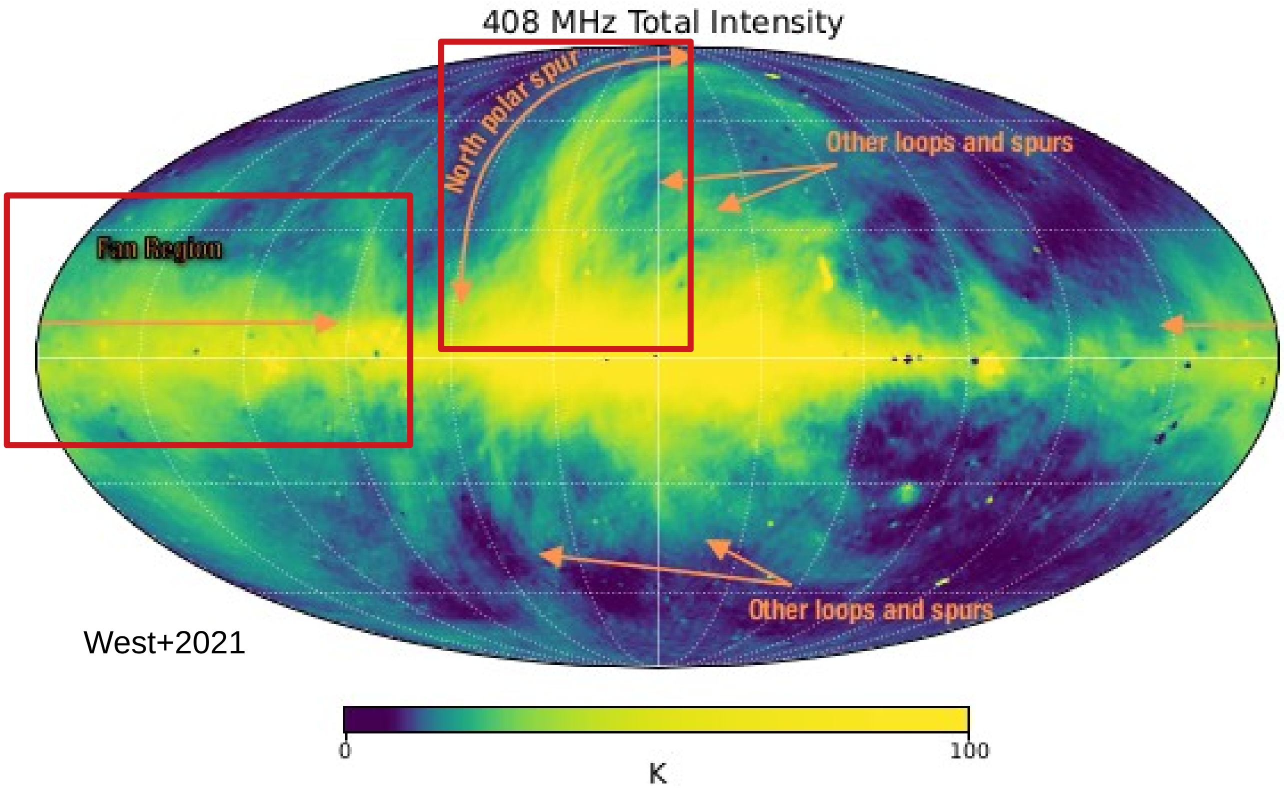


Alignment quantified by Projected Rayleigh Statistic

Panopoulou et al. 2021

*Synchrotron pol. Angles have been rotated by 90 deg to trace B field

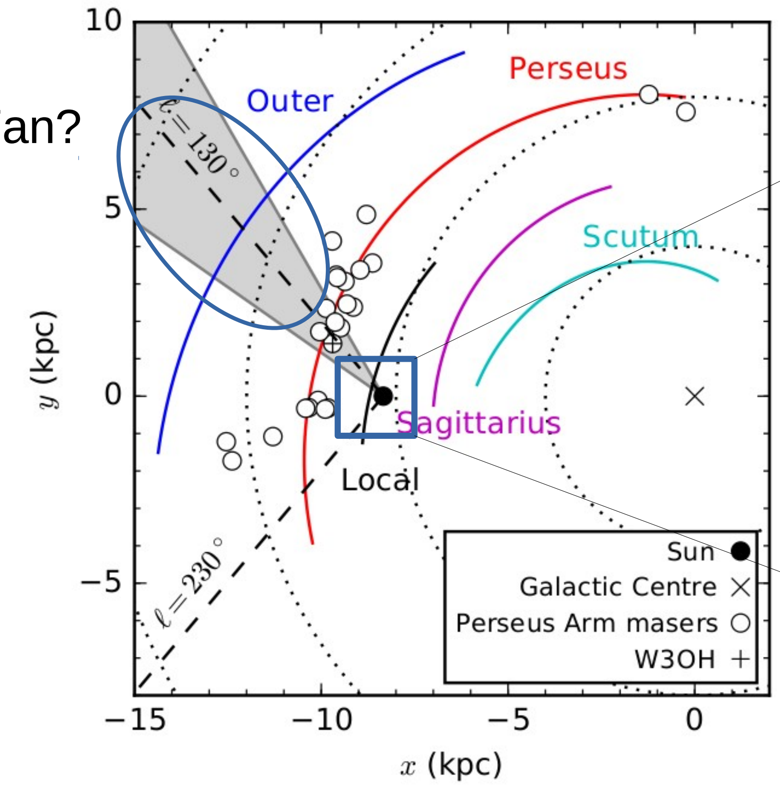
Determining the distance to radio features



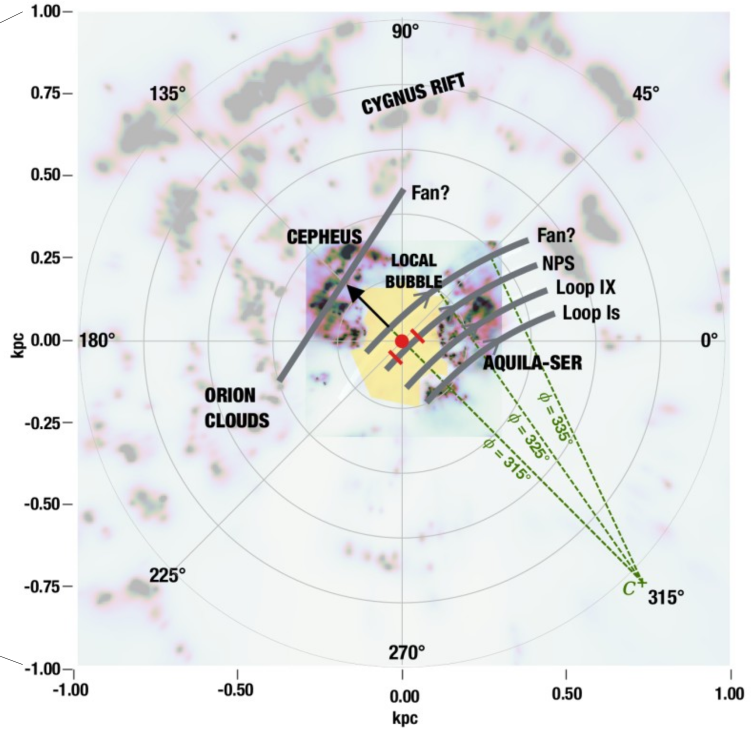
West+2021

Is the Fan distant or nearby?

Fan?

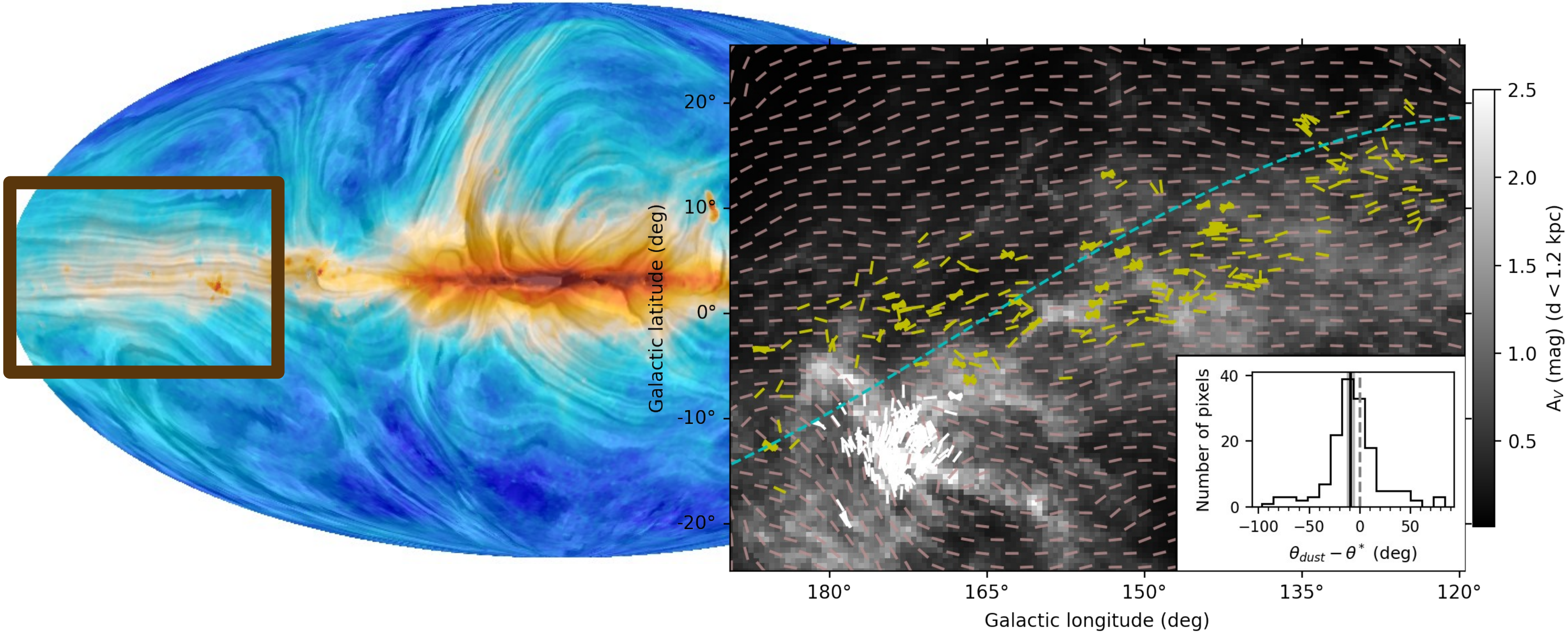


Hill+(2017)



West+(2021)

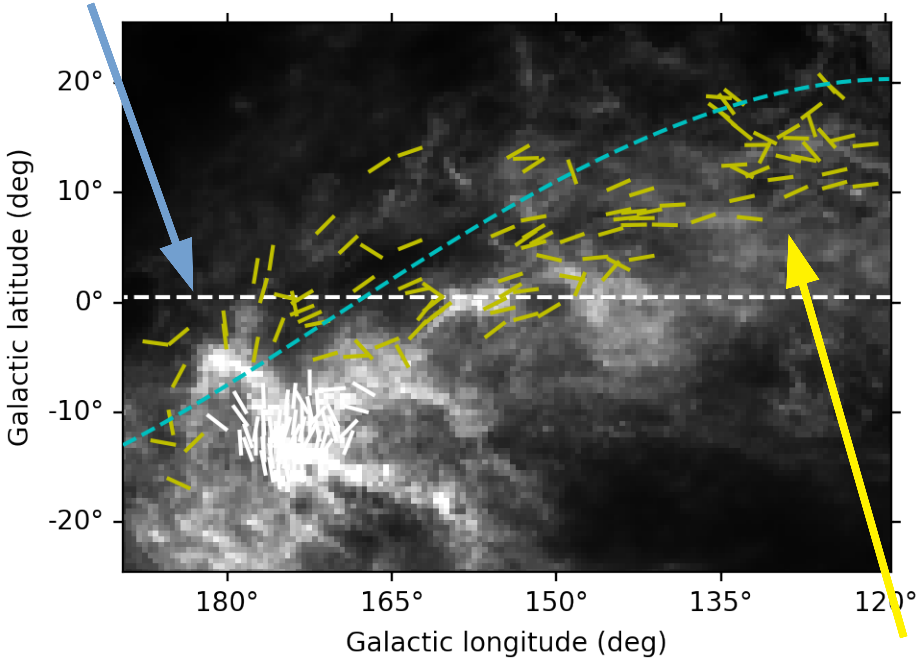
Magnetic field uniform from synchrotron & dust emission



Panopoulou+ subm.

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

Direction of B field from synchrotron

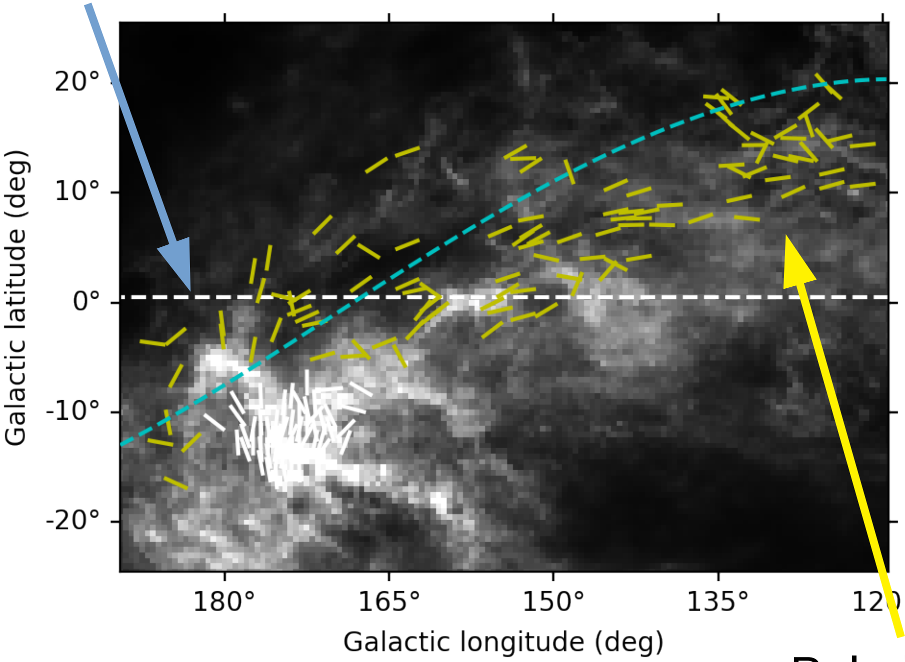


Polarization of nearby stars

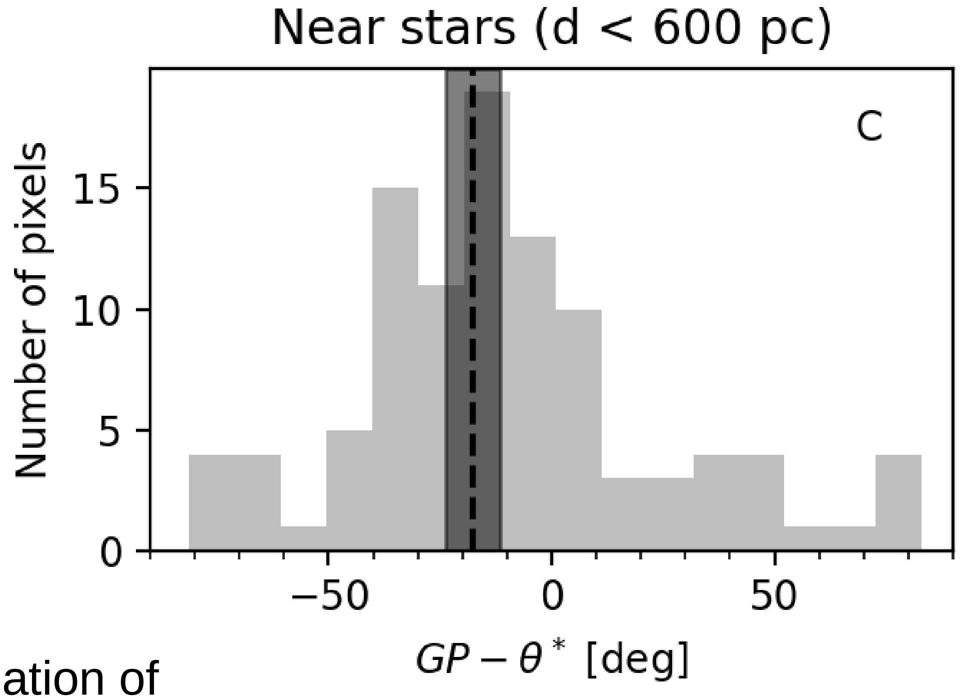
Panopoulou+ subm.

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

Direction of B field from synchrotron

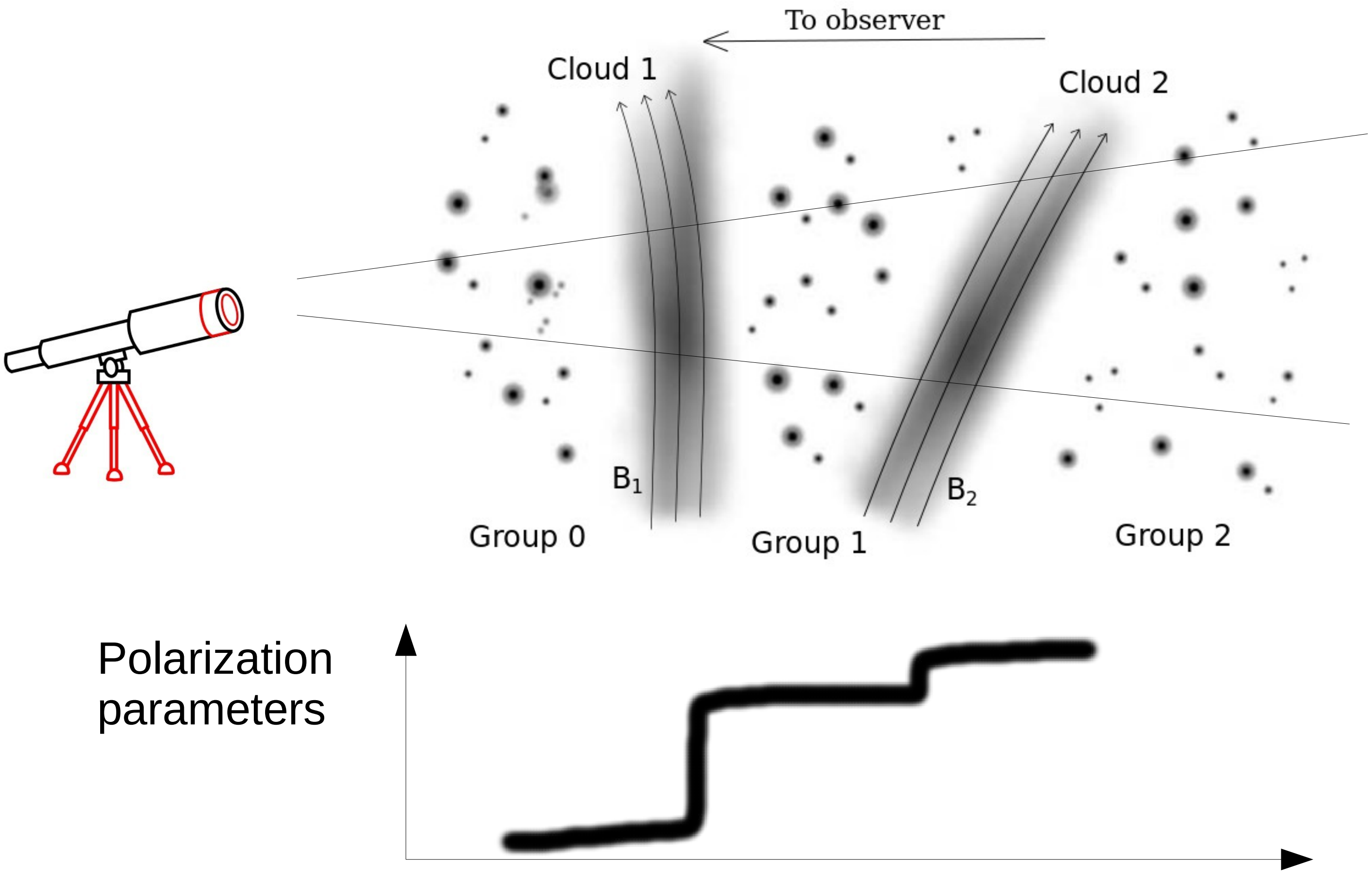


Polarization of nearby stars



Panopoulou+ subm.

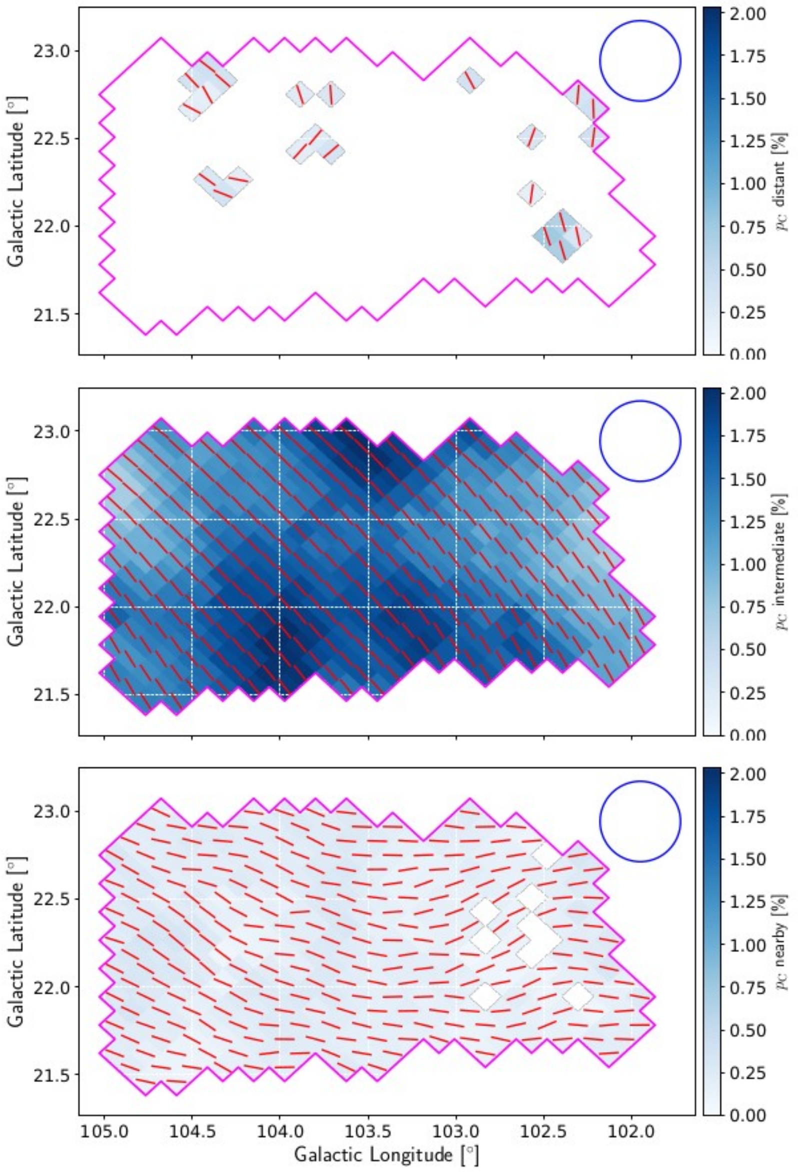
Tomographic mapping of the B field geometry



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

Distance from Earth

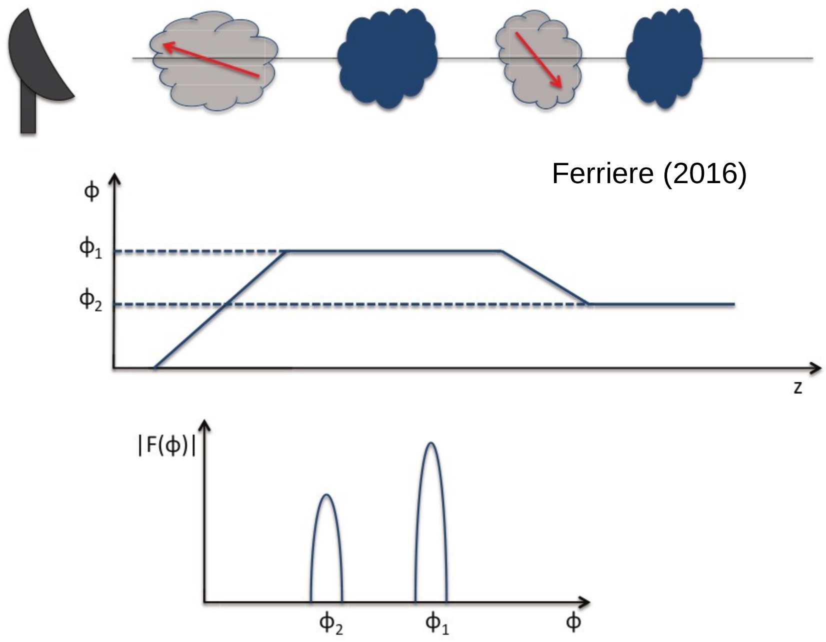
First tomographic map of the B field orientation



Pelgrims+2024

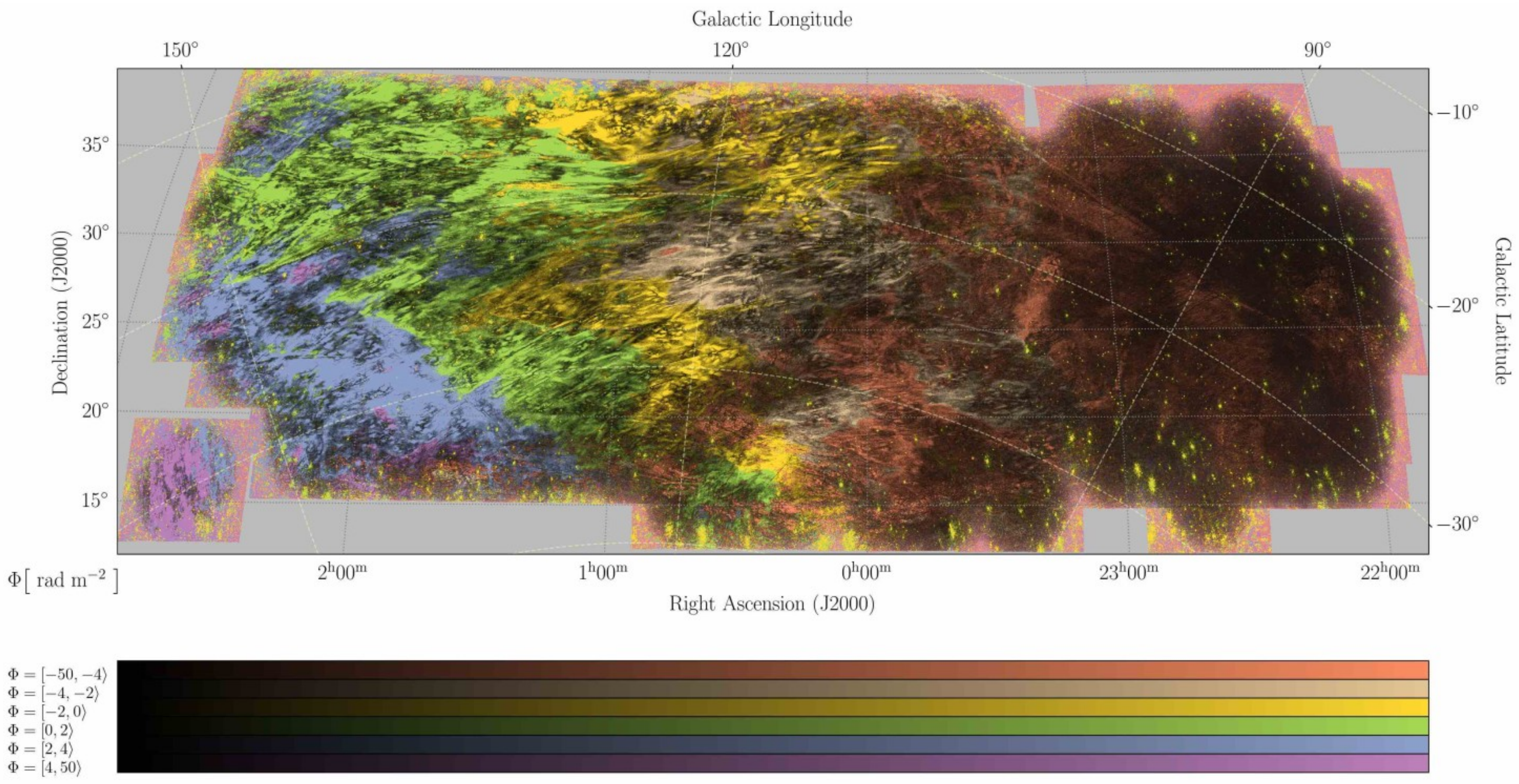
The path to full 3D reconstruction

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



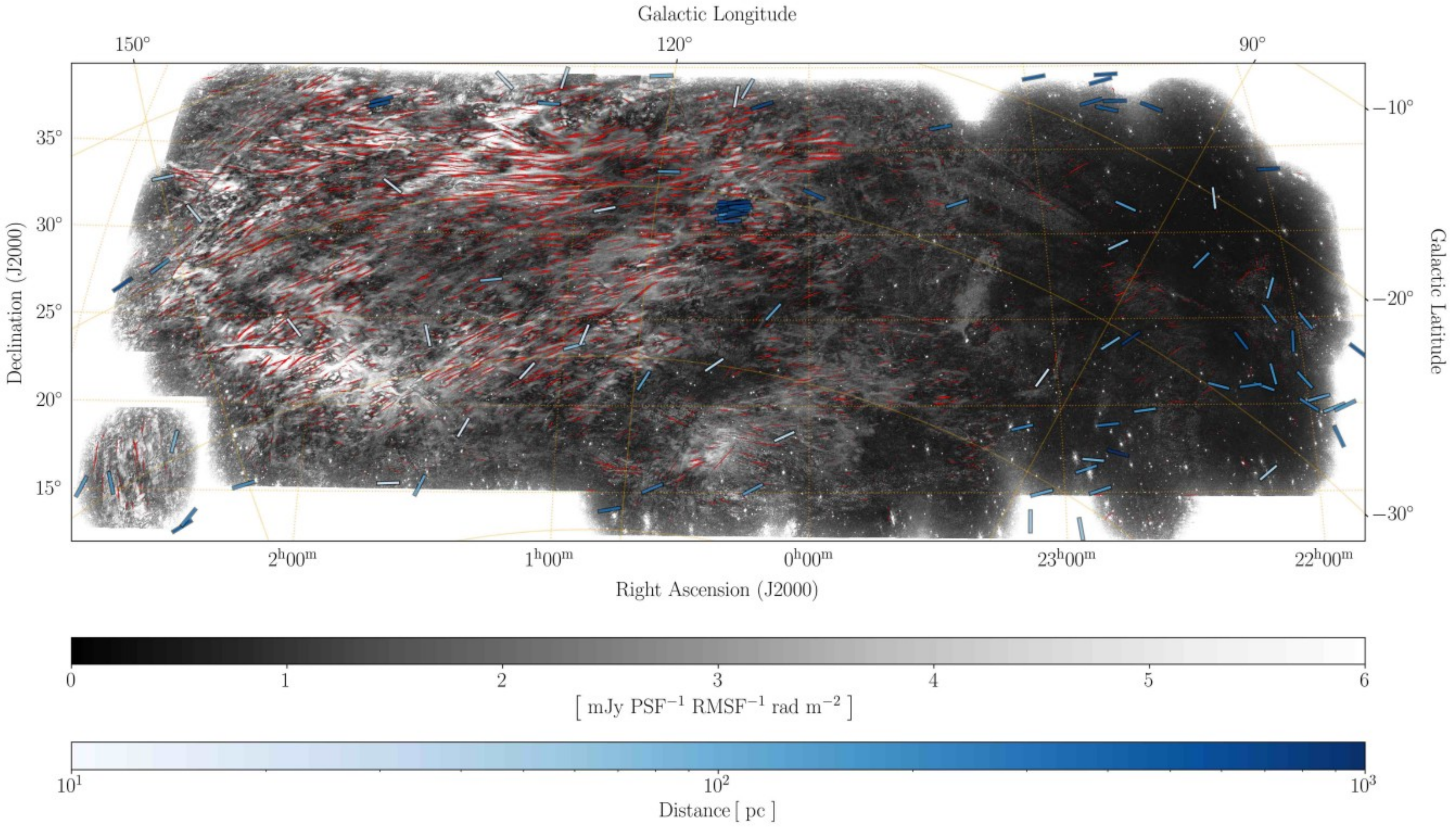
See also: Jelic+ 2020, Erceg+ 2022, 2024...

Imprint of 3D magnetic field clearest at low frequencies



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