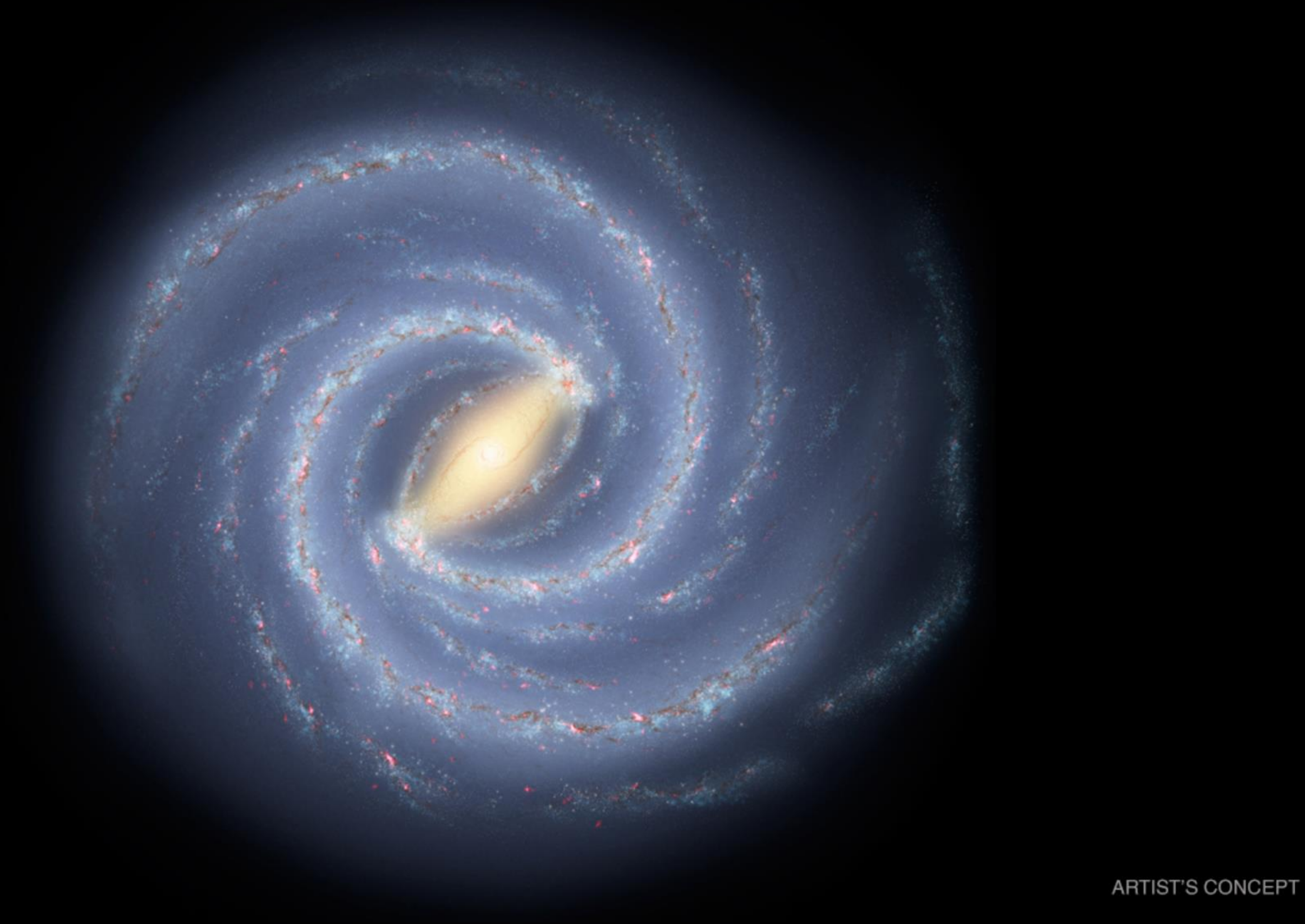
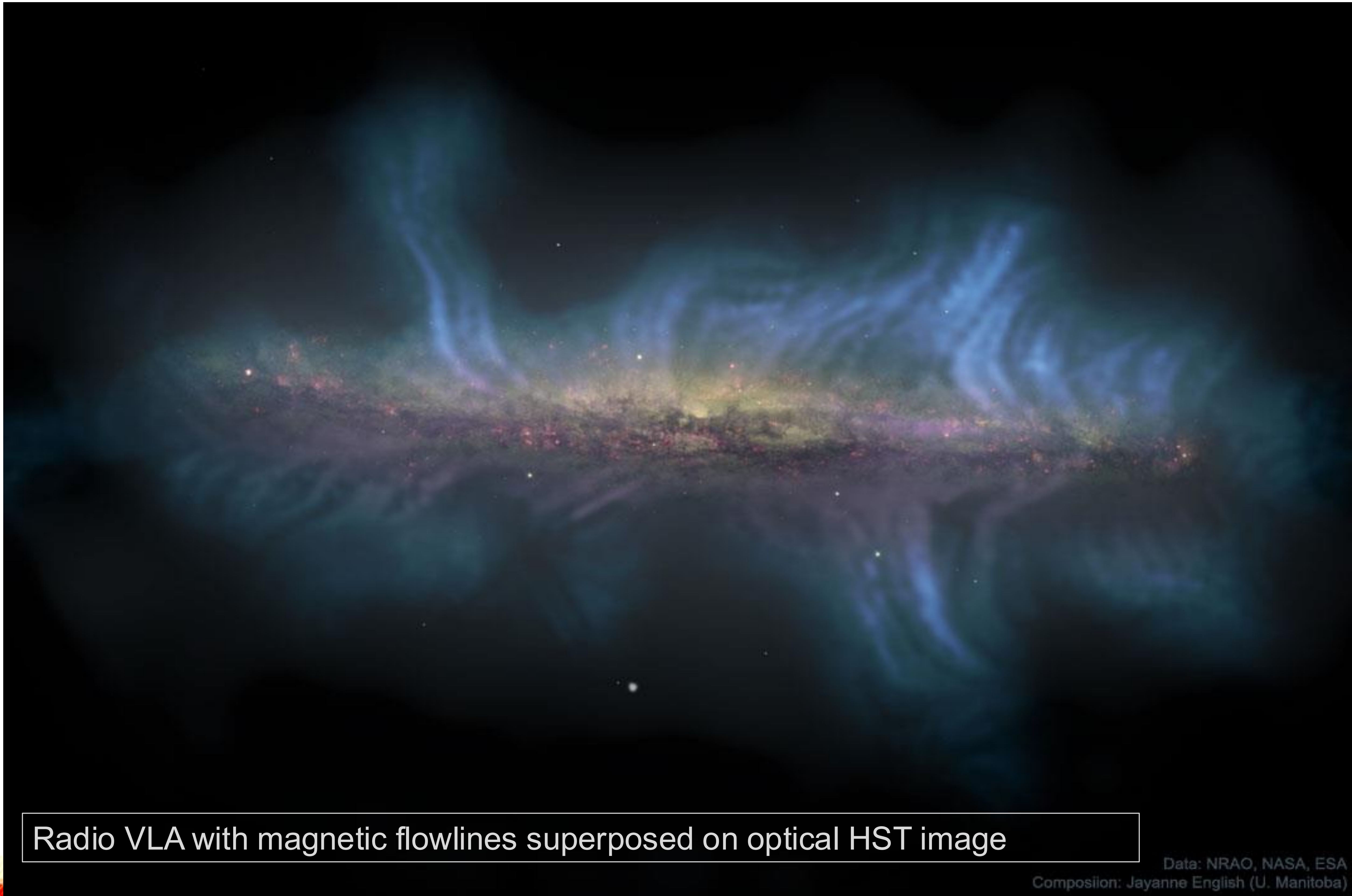
Magnetic Fields in the Milky Way

Marijke Haverkorn (Radboud University)

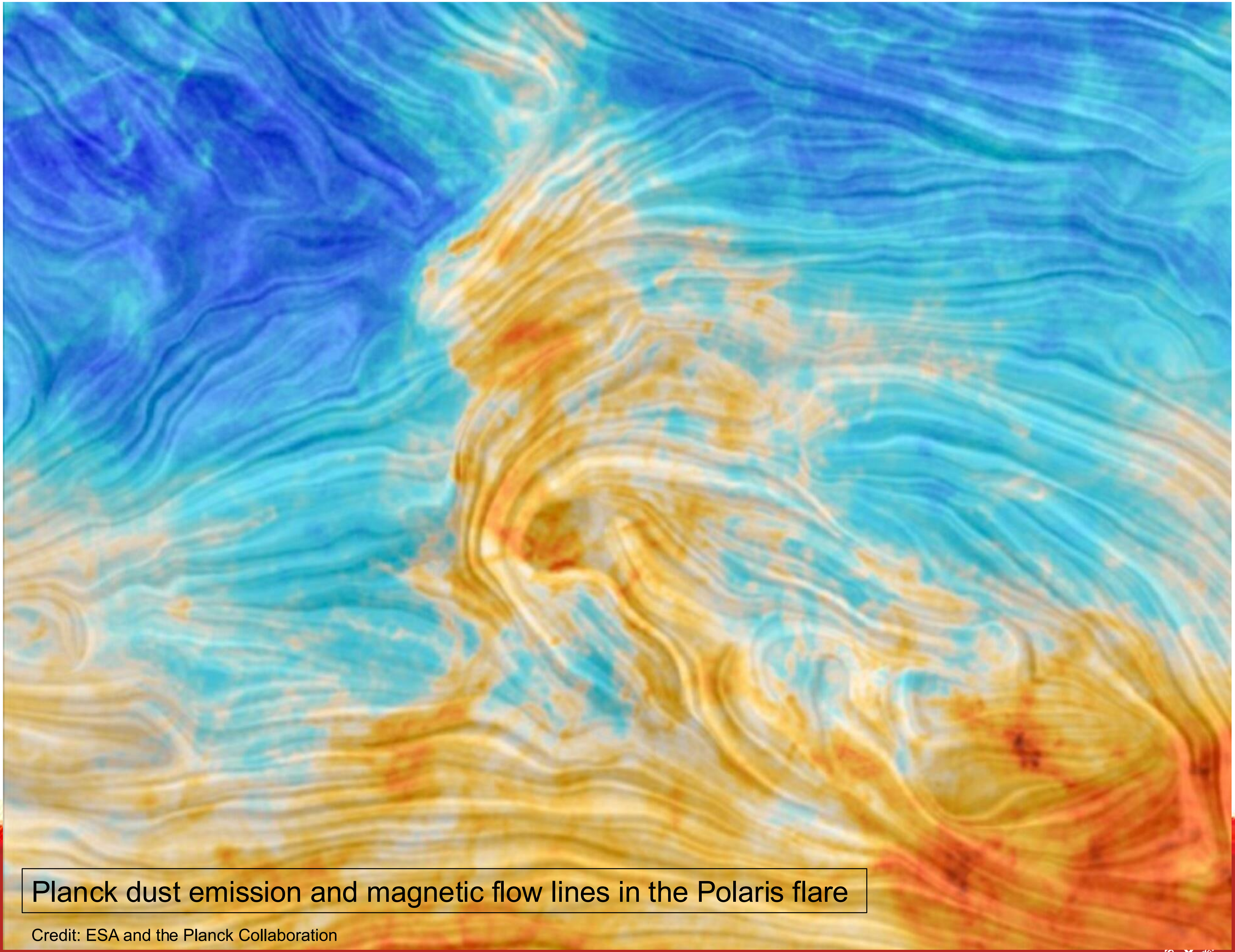


Credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

NASA, ESA, Hubble, Sofia



Radboud Universiteit



Planck dust emission and magnetic flow lines in the Polaris flare

Credit: ESA and the Planck Collaboration

Content

1. Setting the scene: the Interstellar Medium
2. The role of magnetic fields in the Interstellar Medium
3. Origin and maintenance of Galactic magnetic fields
4. Detection of Galactic magnetic fields
5. Strength and structure of the Galactic magnetic field

Interstellar gas phases

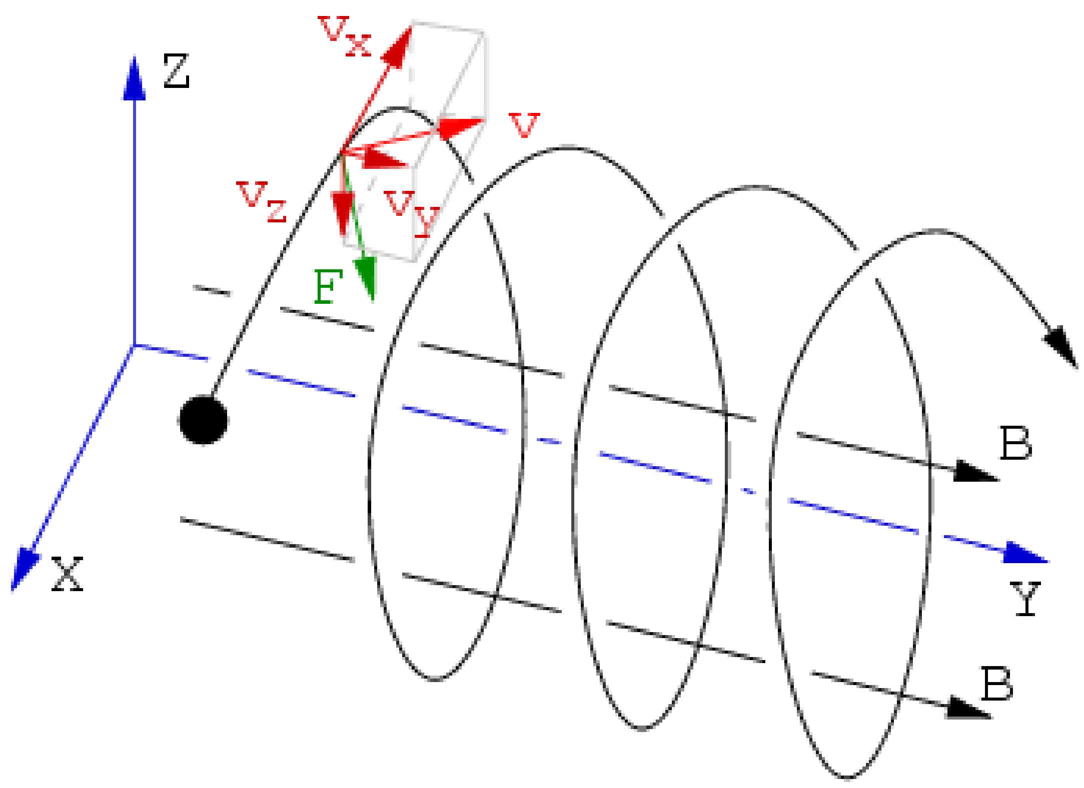
	Molecular	Cold atomic	Warm atomic	Warm ionized	Hot ionized
T [K]	10 – 20	50 – 100	$10^3 – 10^4$	~ 10^4	~ 10^6
n_H [cm^{-3}]	$10^2 – 10^6$	20 – 50	1 – 2	0.1 – 0.5	0.003 – 0.01
n_e/n_H	<< 1	$(0.3 – 1)10^{-3}$	0.01 – 0.05	~ 1	~ 1
p_{th}/k	1000 – $2\text{x}10^6$	1000 – 5000	2000 – 20000	1000 – 5000	3000 – 10000
B [μG]	> 5	~ 5	~ 5	~ 5	~ 5

$p_B/k \sim 7000$ cm^{-3} K

Content

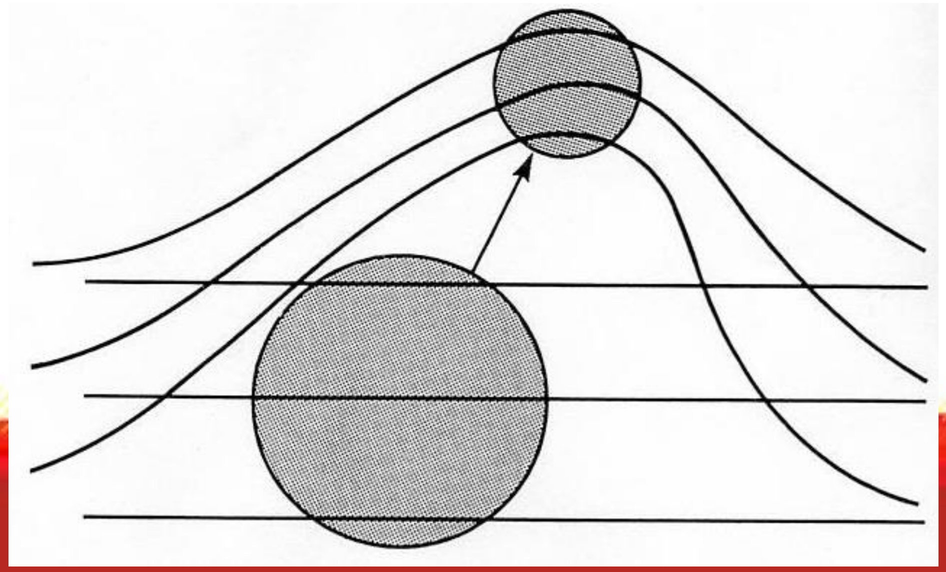
Role of Galactic magnetic field:

Magnetic fields and (ionized) matter are connected.



The Lorentz force couples ions to magnetic fields…

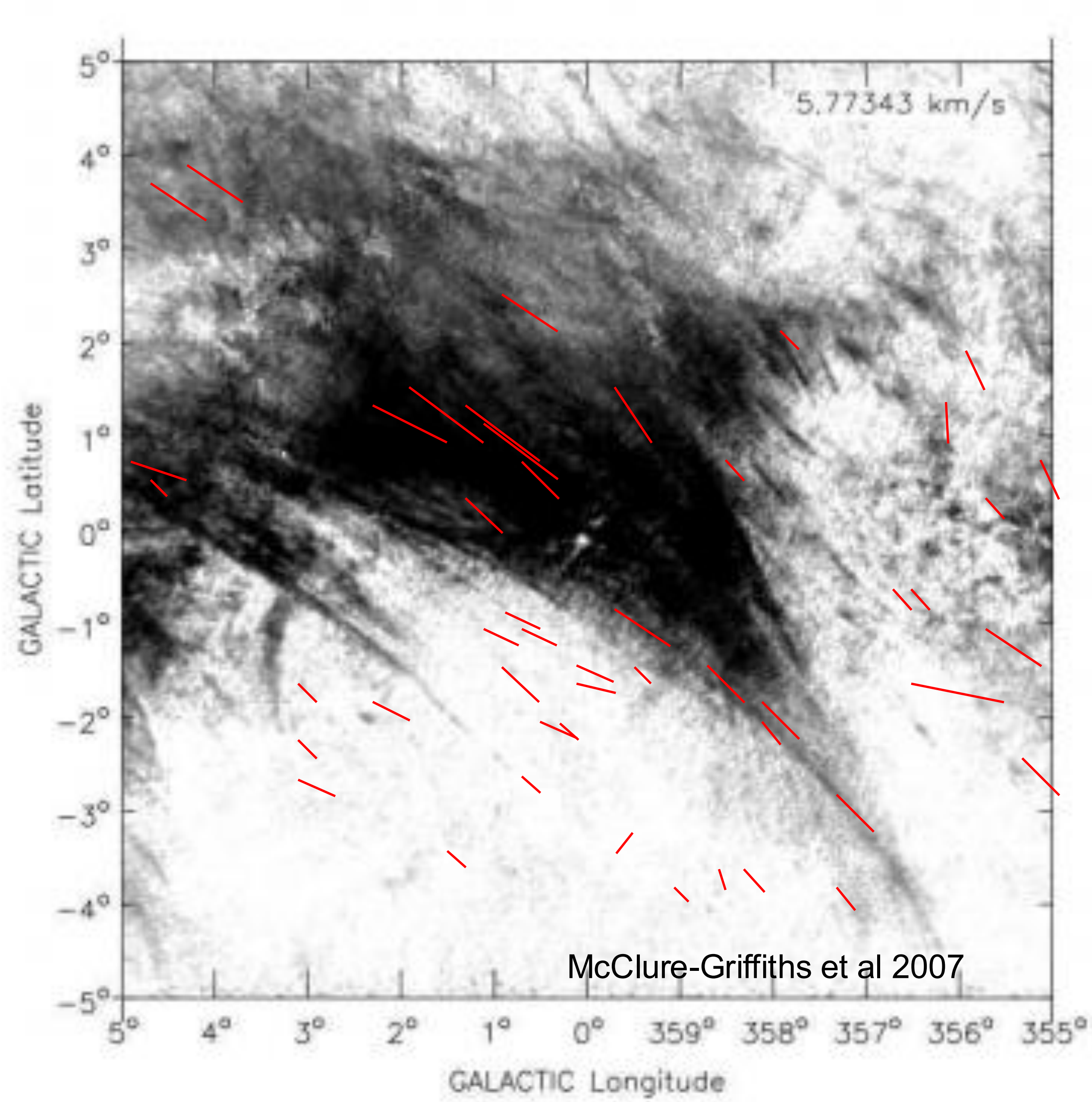
…causing flux freezing of magnetic field into plasma.



Role of Galactic magnetic field: drive gas dynamics

Filaments in clouds of atomic hydrogen…

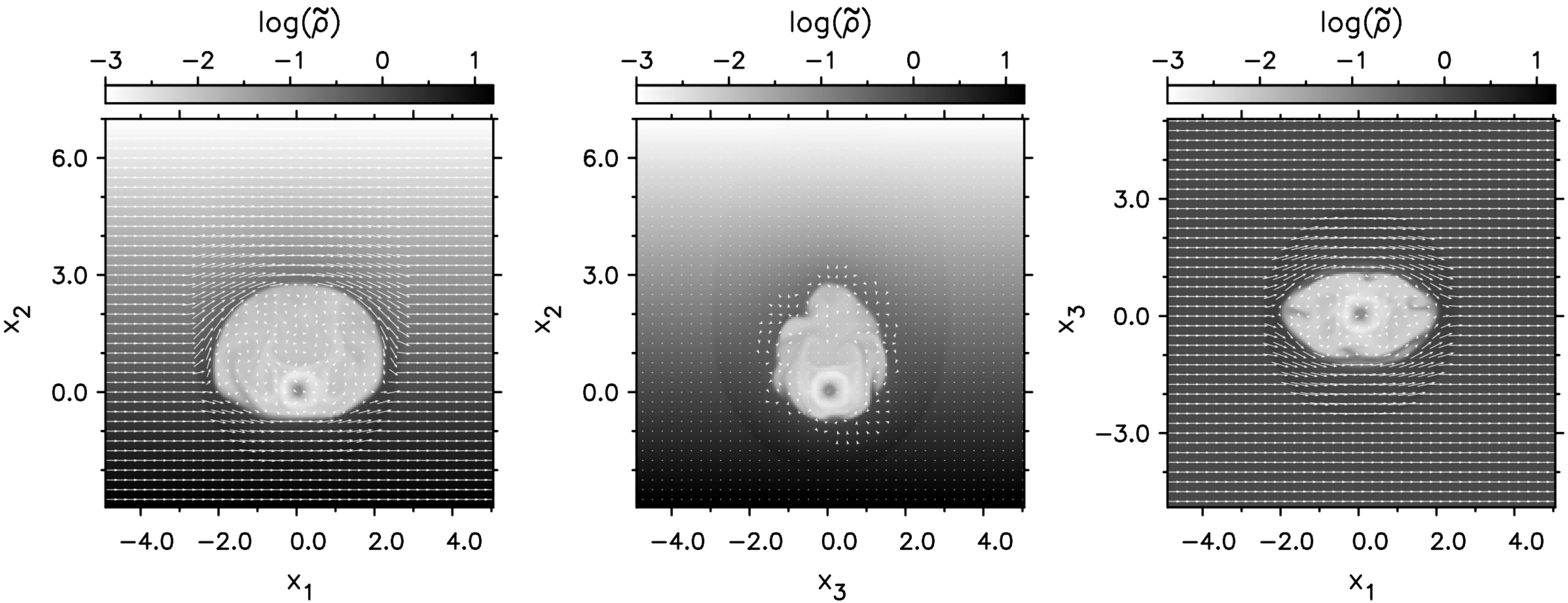
… are shaped by magnetic fields



teit

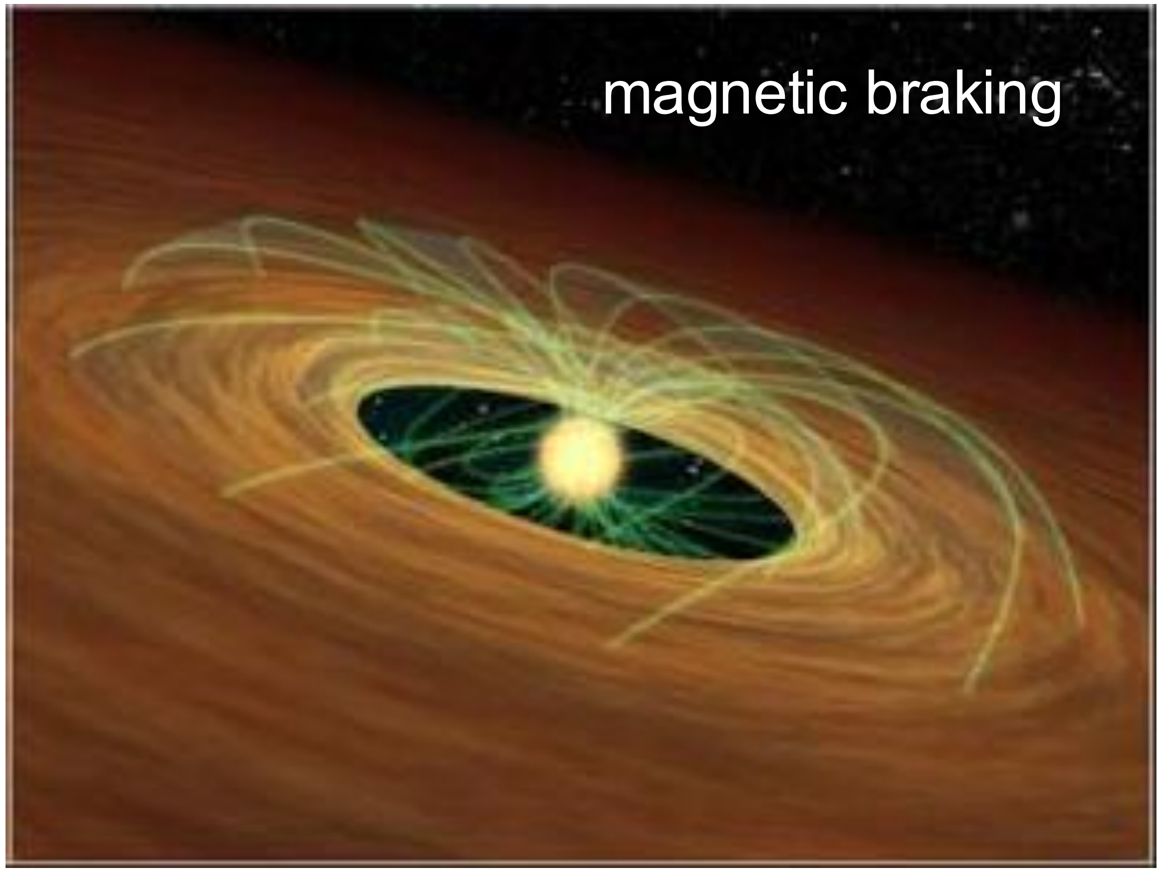
Role of Galactic magnetic field: drive gas dynamics

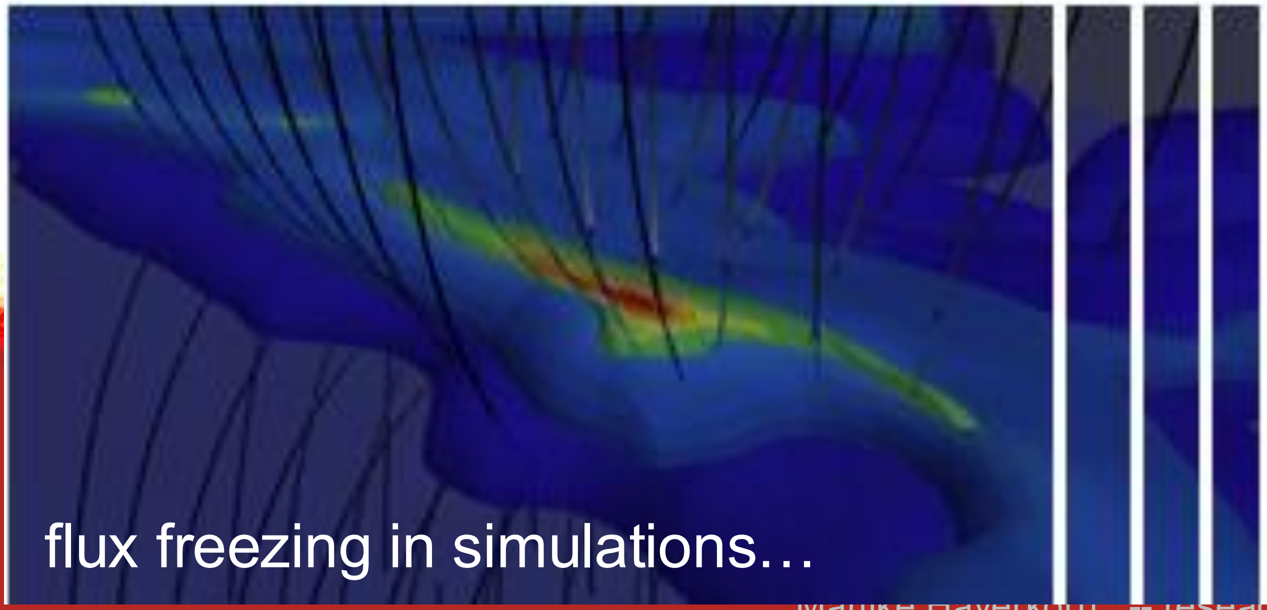
E.g. evolution of supernova remnants

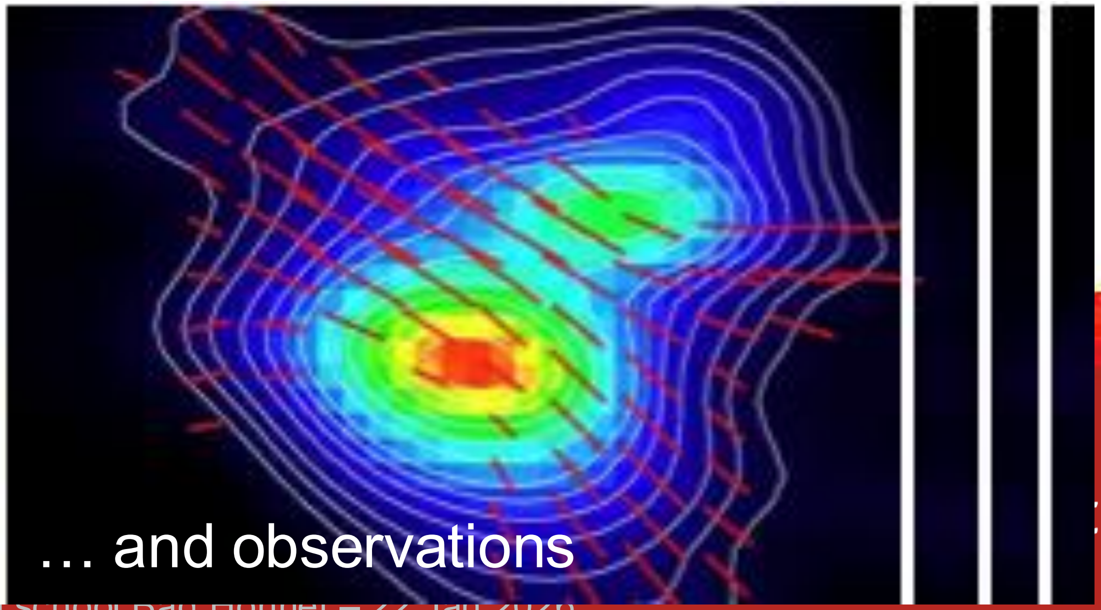


Stil et al (2009)

Role of Galactic magnetic field: enable *and* slow down star formation





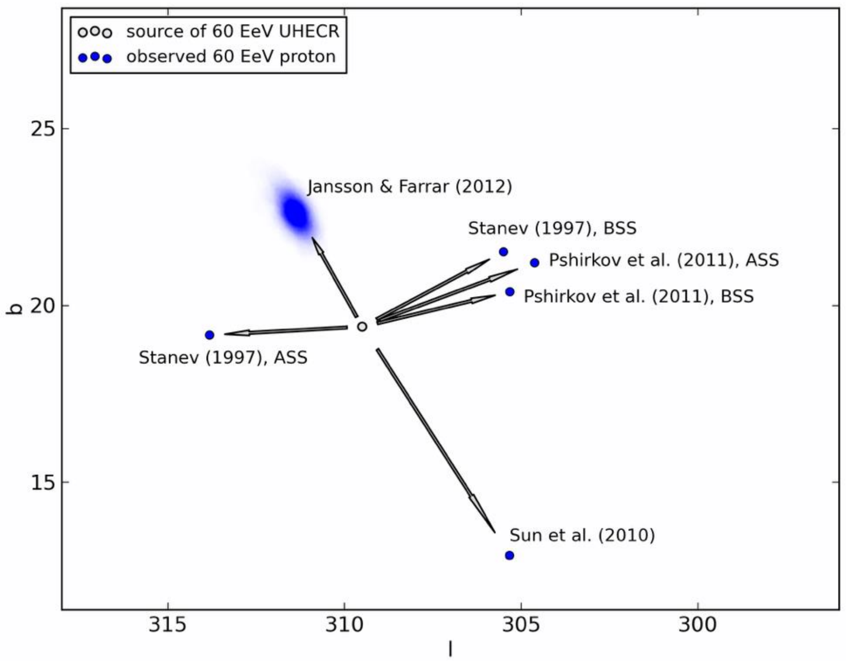


Role of Galactic magnetic field:
Drive acceleration and propagation of cosmic rays

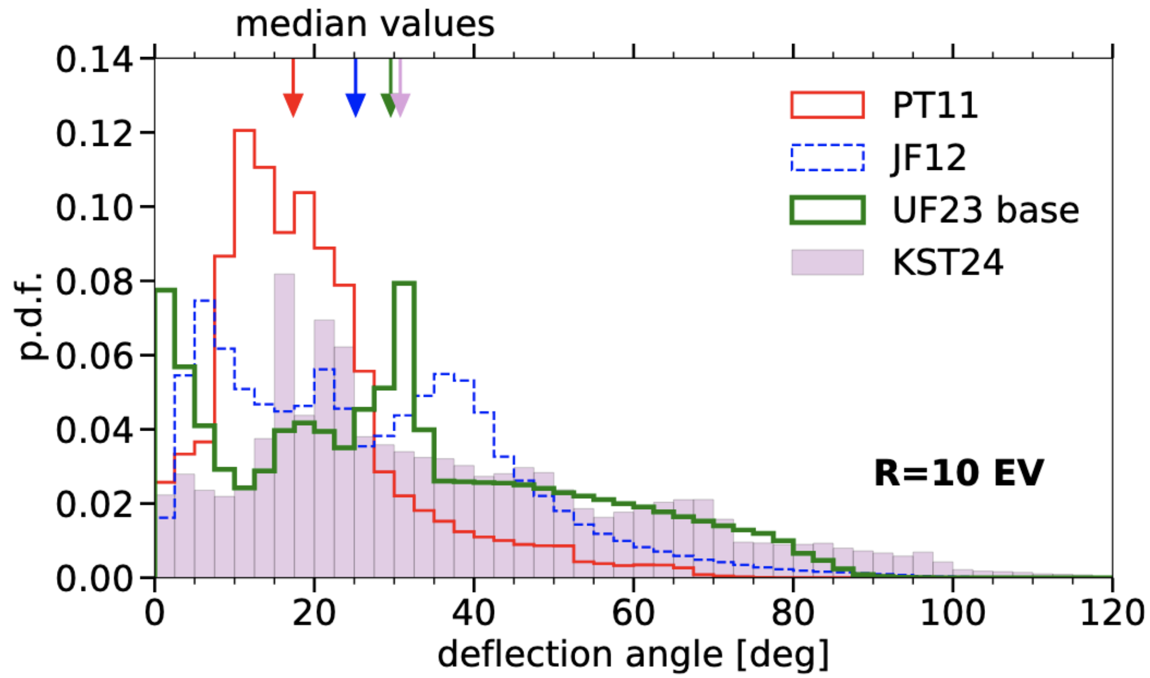
Farrar et al (2015)

20 Ultra-High Energy Cosmic Rays (UHECRs) propagating through a Galactic magnetic field.

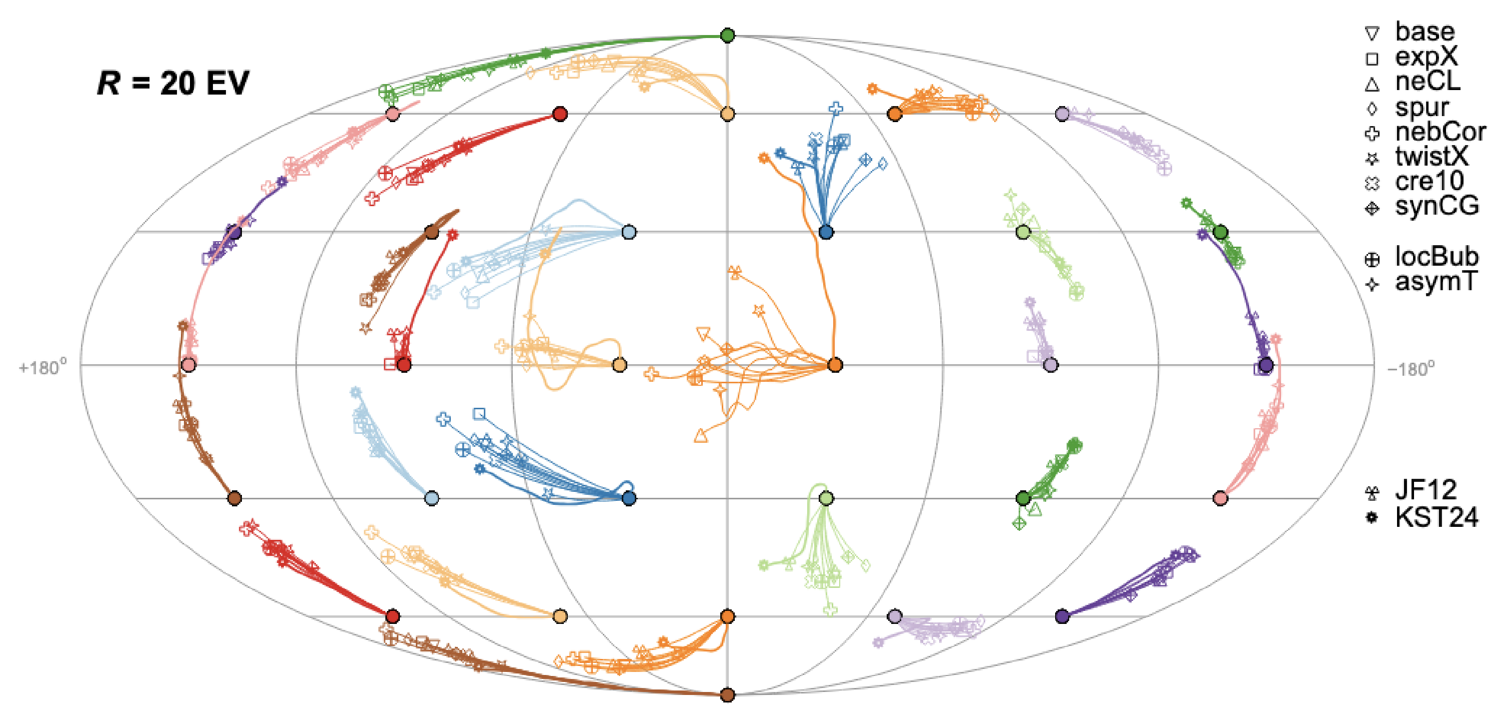
Galactic magnetic fields:
deflect Ultra-High Energy Cosmic Rays



Farrar et al (2015)



Bister (2025)



Unger & Farrar (2024)

Content

1. Setting the scene: the Interstellar Medium
2. The role of magnetic fields in the Interstellar Medium
3. Origin and maintenance of Galactic magnetic fields
4. Detection of Galactic magnetic fields
5. Strength and structure of the Galactic magnetic field

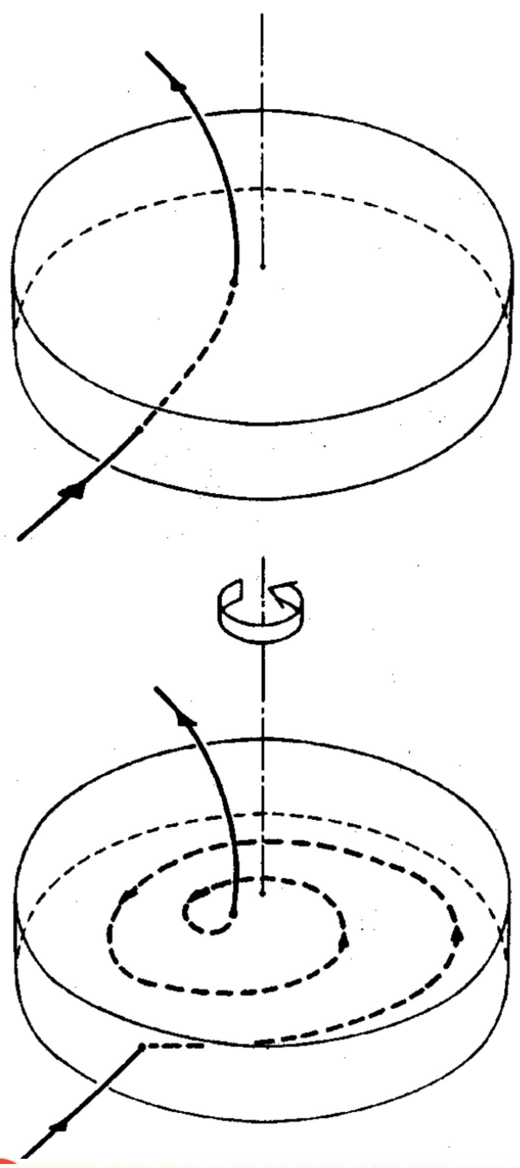
Origin and maintenance of galactic magnetic fields

Created by primordial magnetic fields:
- Possibly cosmological (in phase transitions? in inflation?)
- Some battery mechanism in interstellar plasma?
- Plasma instabilities?

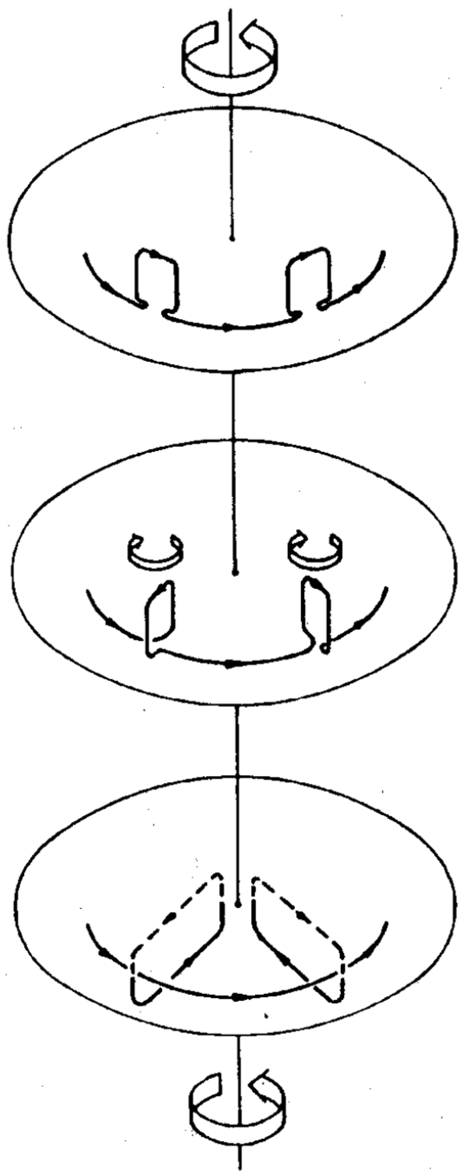
Amplified and maintained by dynamo action:
- Mean-field dynamo
- Turbulent dynamo

Mean-field (α-ω) dynamo

(B) Differential rotation:
B_ϕ produced from B_r

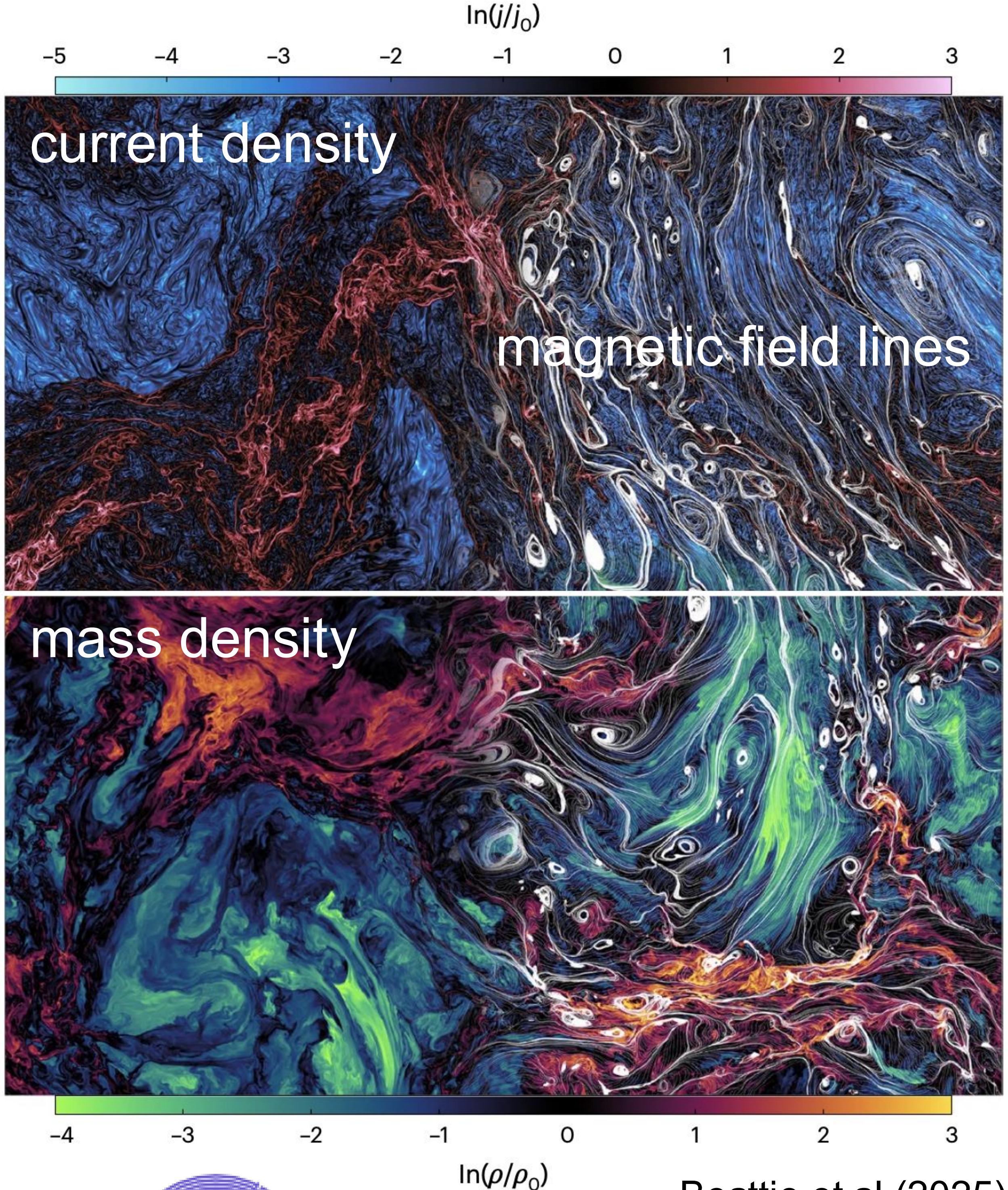


(C) Helical turbulence:
B_r produced from B_ϕ



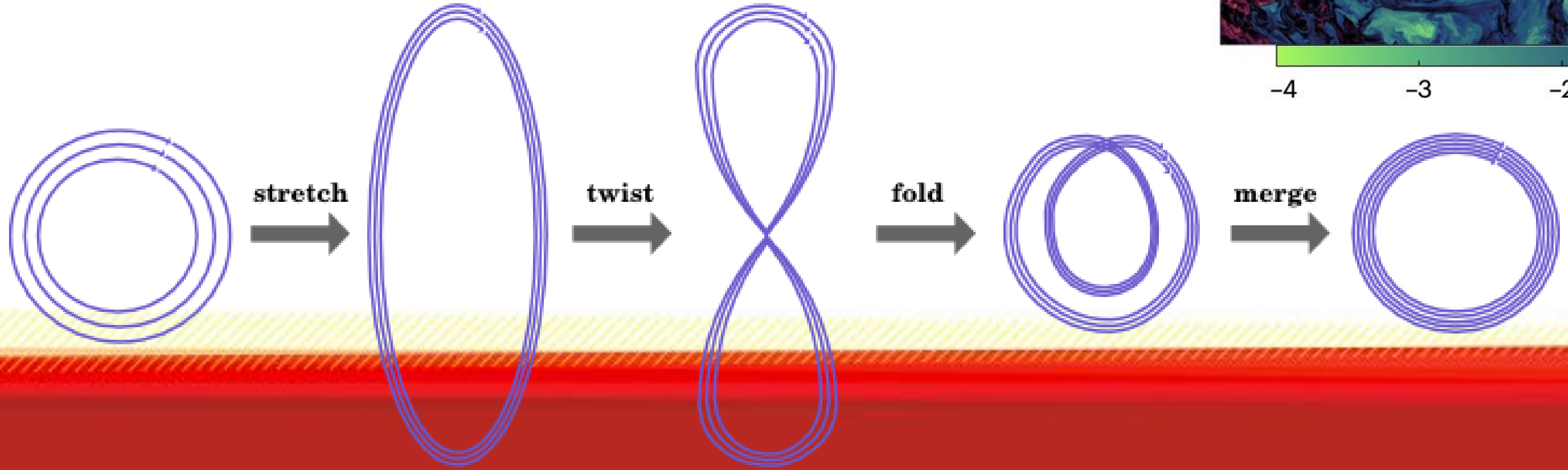
Slide credit Anvar Shukurov

Turbulent dynamo



Beattie et al (2025)

Image credit Jennifer Schober



Radboud Universiteit

Content

1. Setting the scene: the Interstellar Medium
2. The role of magnetic fields in the Interstellar Medium
3. Origin and maintenance of Galactic magnetic fields
4. Detection of Galactic magnetic fields
5. Strength and structure of the Galactic magnetic field

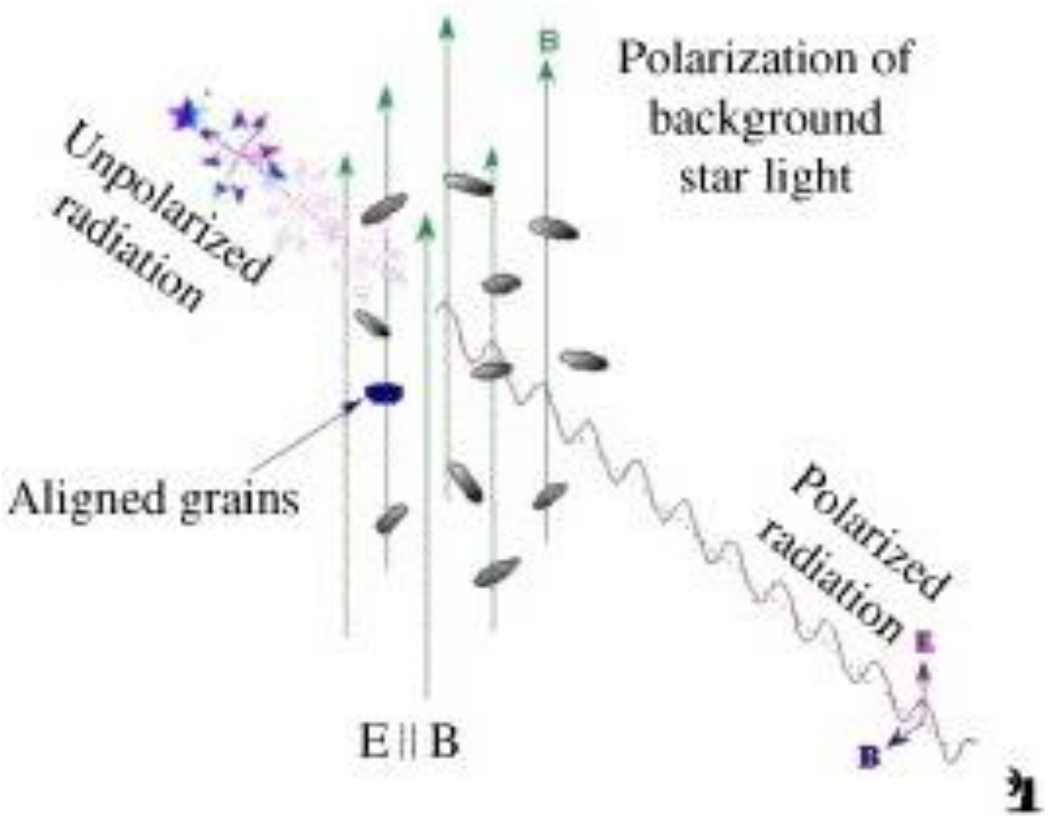
Detection methods:

PROCESS:	PROBES FIELD COMPONENT:	IN COMPONENT:	AT SPECTRAL REGION:
linear polarization due to dust absorption	direction of $B_{\perp}$	dust	Optical/near infrared
polarized dust emission	direction of $B_{\perp}$	dust	Far infrared/submm
synchrotron emission	strength of $B_{\perp}$	cosmic rays	Radio
synchrotron linear polarization	$B_{coherent}/B_{total}$	cosmic rays	Radio
Faraday rotation (linear polarization)	strength of $B_{//}$	ionized gas	Radio
Zeeman effect	strength of $B_{//}$	cold gas, stars	Radio
Masers (linear/circular polarization)	strength of B; angle between B and line of sight	specific non-equilibrium conditions	Radio
Davis-Chandrasekhar-Fermi (DCF)	strength of $B_{coherent}$	dust	Optical/near infrared

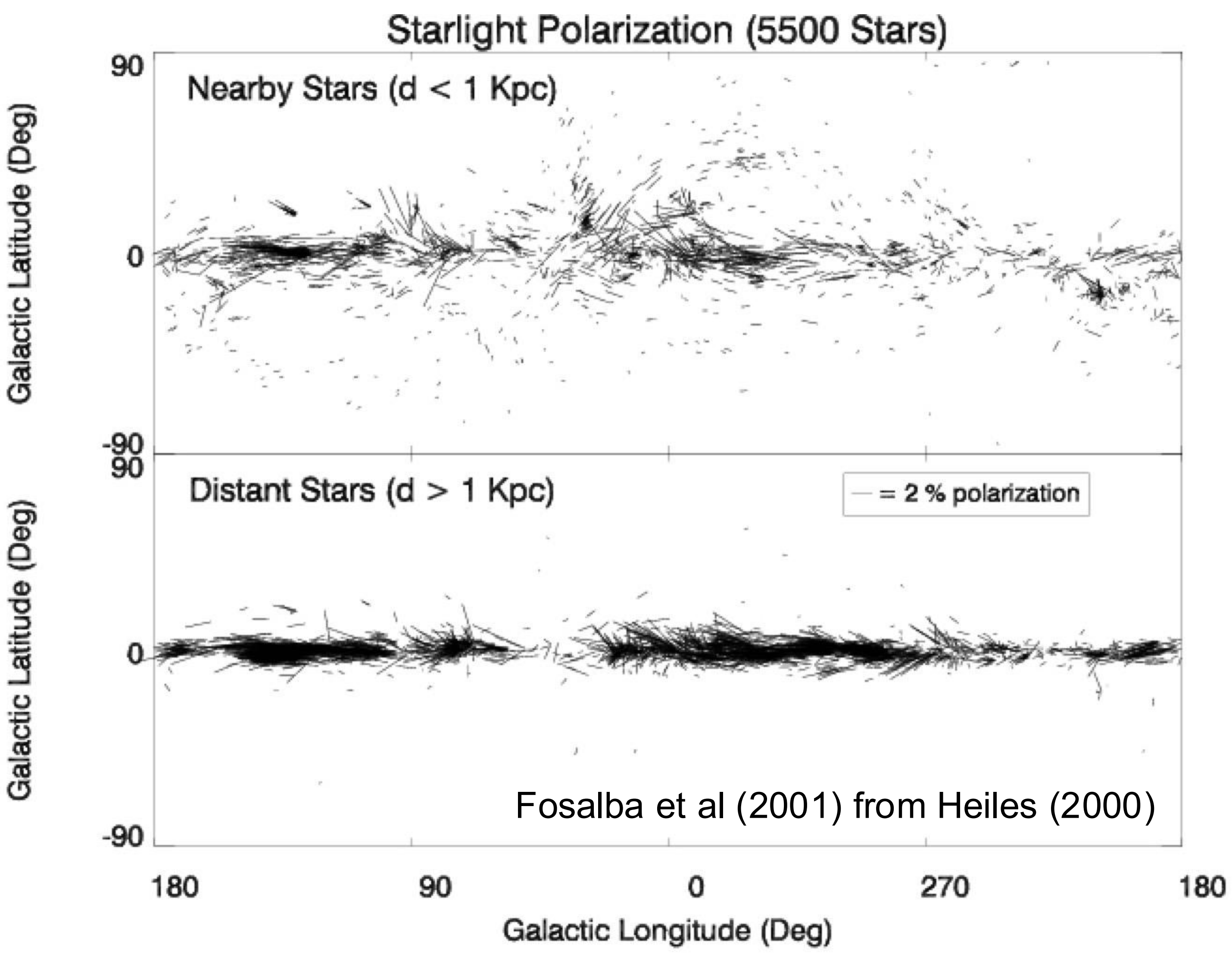
Detection methods:

PROCESS:	PROBES FIELD COMPONENT:	IN COMPONENT:	AT SPECTRAL REGION:
linear polarization due to dust absorption	direction of $B_\perp$	dust	Optical/near infrared
polarized dust emission	direction of $B_\perp$	dust	Far infrared/submm
synchrotron emission	strength of $B_\perp$	cosmic rays	Radio
synchrotron linear polarization	$B_{coherent}/B_{total}$	cosmic rays	Radio
Faraday rotation (linear polarization)	strength of $B_{//}$	ionized gas	Radio
Zeeman effect	strength of $B_{//}$	cold gas, stars	Radio
Masers (linear/circular polarization)	strength of B; angle between B and line of sight	specific non-equilibrium conditions	Radio
Davis-Chandrasekhar-Fermi (DCF)	strength of $B_{coherent}$	dust	Optical/near infrared

Measuring galactic magnetic fields:
1. Polarization due to dust absorption



Lazarian (2007)



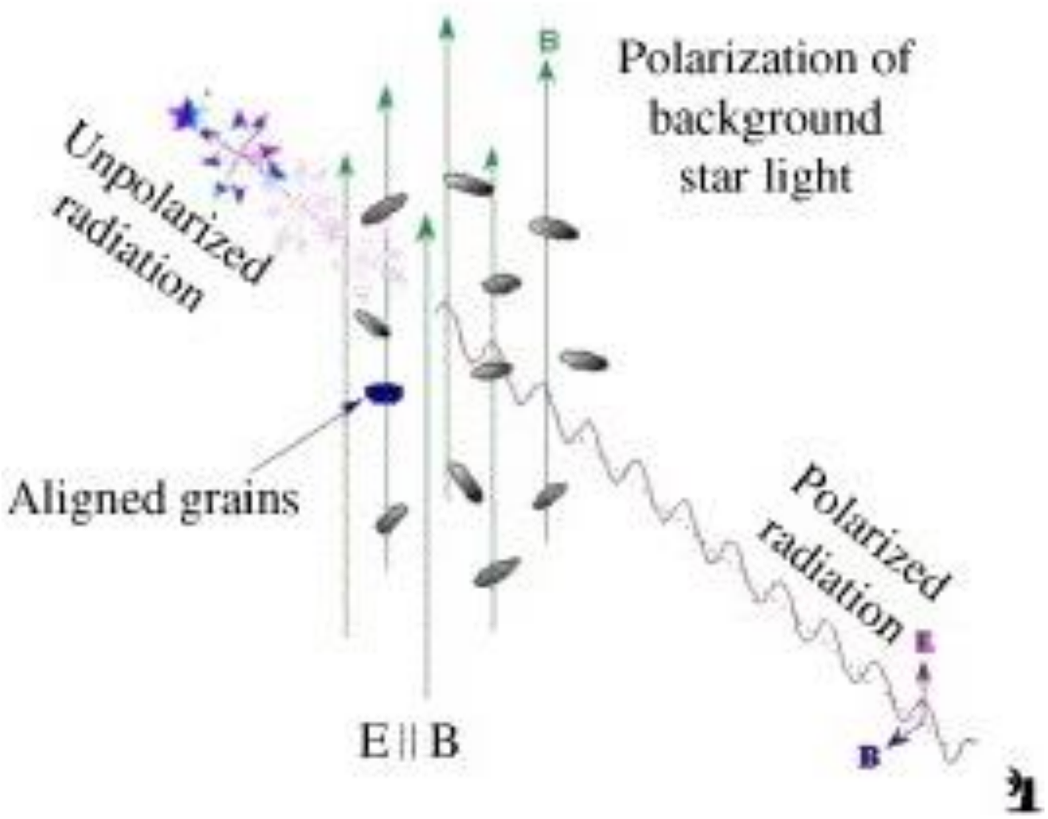
Fosalba et al (2001) from Heiles (2000)

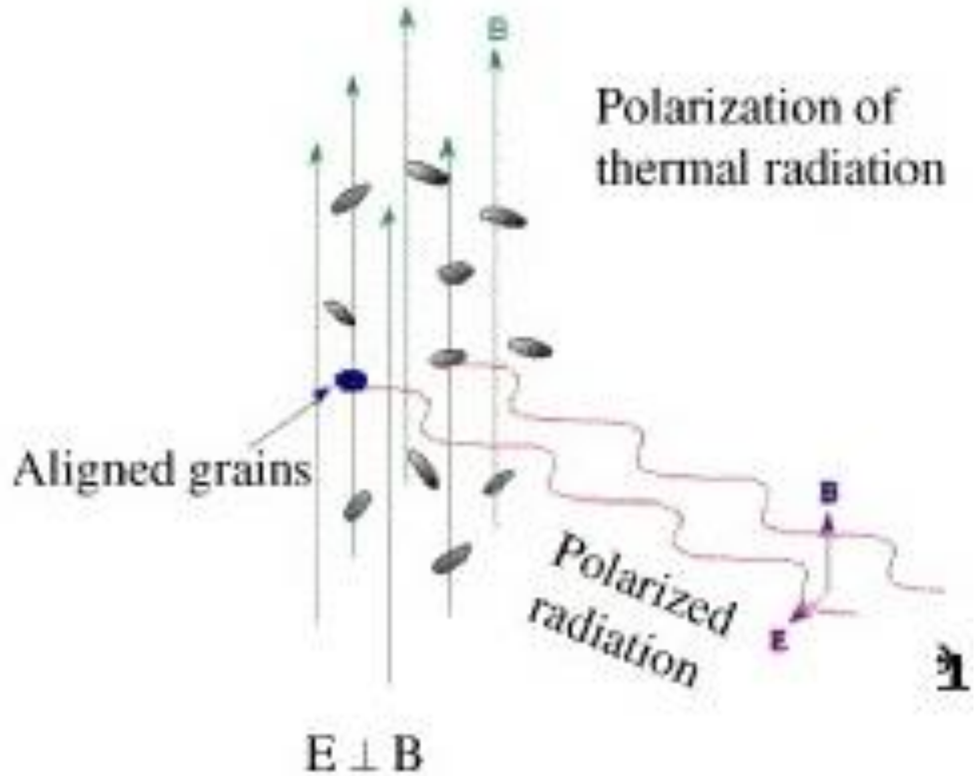
Detection methods:

PROCESS:	**PROBES FIELD COMPONENT:**	**IN COMPONENT:**	**AT SPECTRAL REGION:**
linear polarization due to dust absorption	direction of $B_\perp$	dust	Optical/near infrared
polarized dust emission	direction of $B_\perp$	dust	Far infrared/submm
synchrotron emission	strength of $B_\perp$	cosmic rays	Radio
synchrotron linear polarization	$B_{coherent}/B_{total}$	cosmic rays	Radio
Faraday rotation (linear polarization)	strength of $B_{//}$	ionized gas	Radio
Zeeman effect	strength of $B_{//}$	cold gas, stars	Radio
Masers (linear/circular polarization)	strength of B; angle between B and line of sight	specific non-equilibrium conditions	Radio
Davis-Chandrasekhar-Fermi (DCF)	strength of $B_{coherent}$	dust	Optical/near infrared

Radboud Universiteit

Measuring galactic magnetic fields:
2. Polarized dust emission

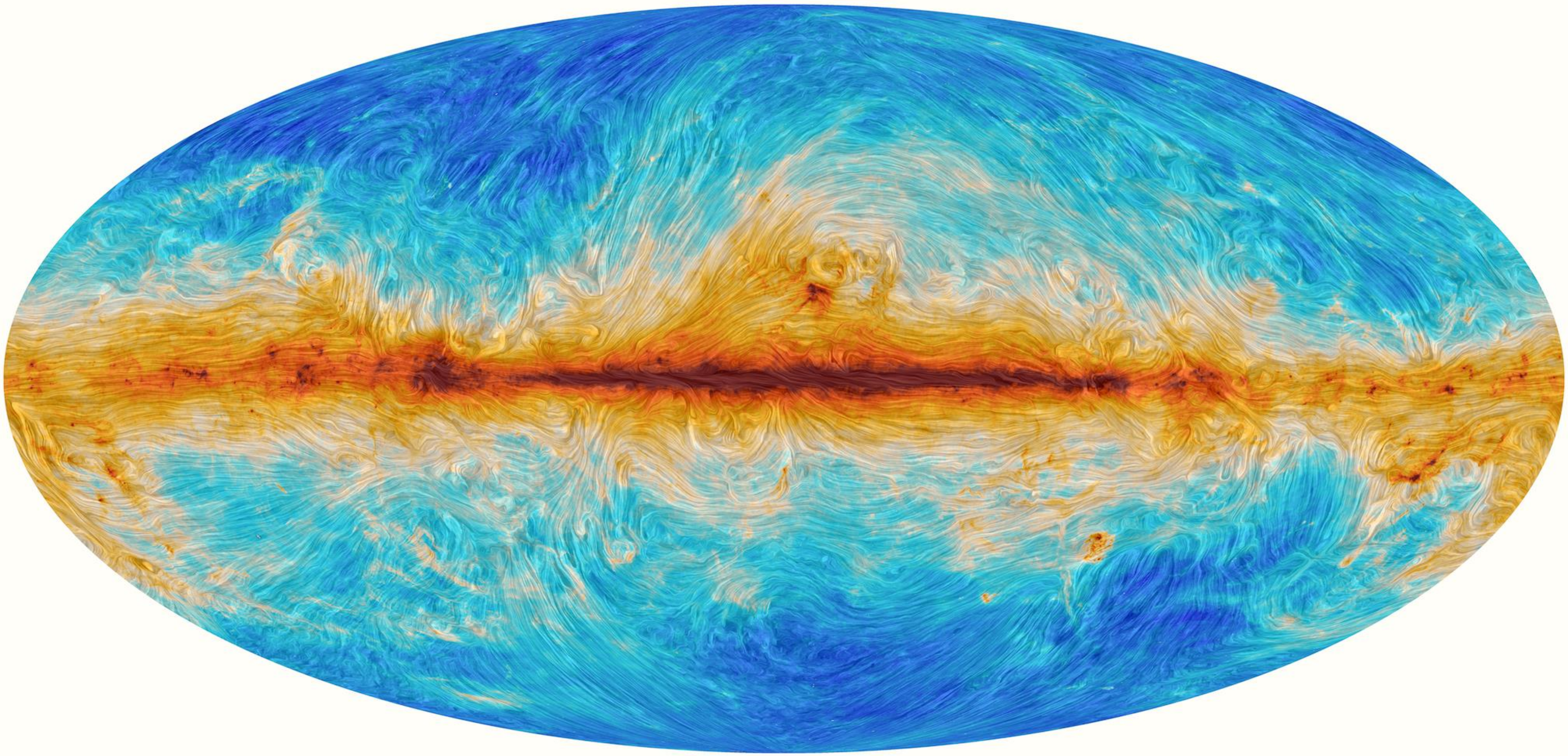




Lazarian (2007)

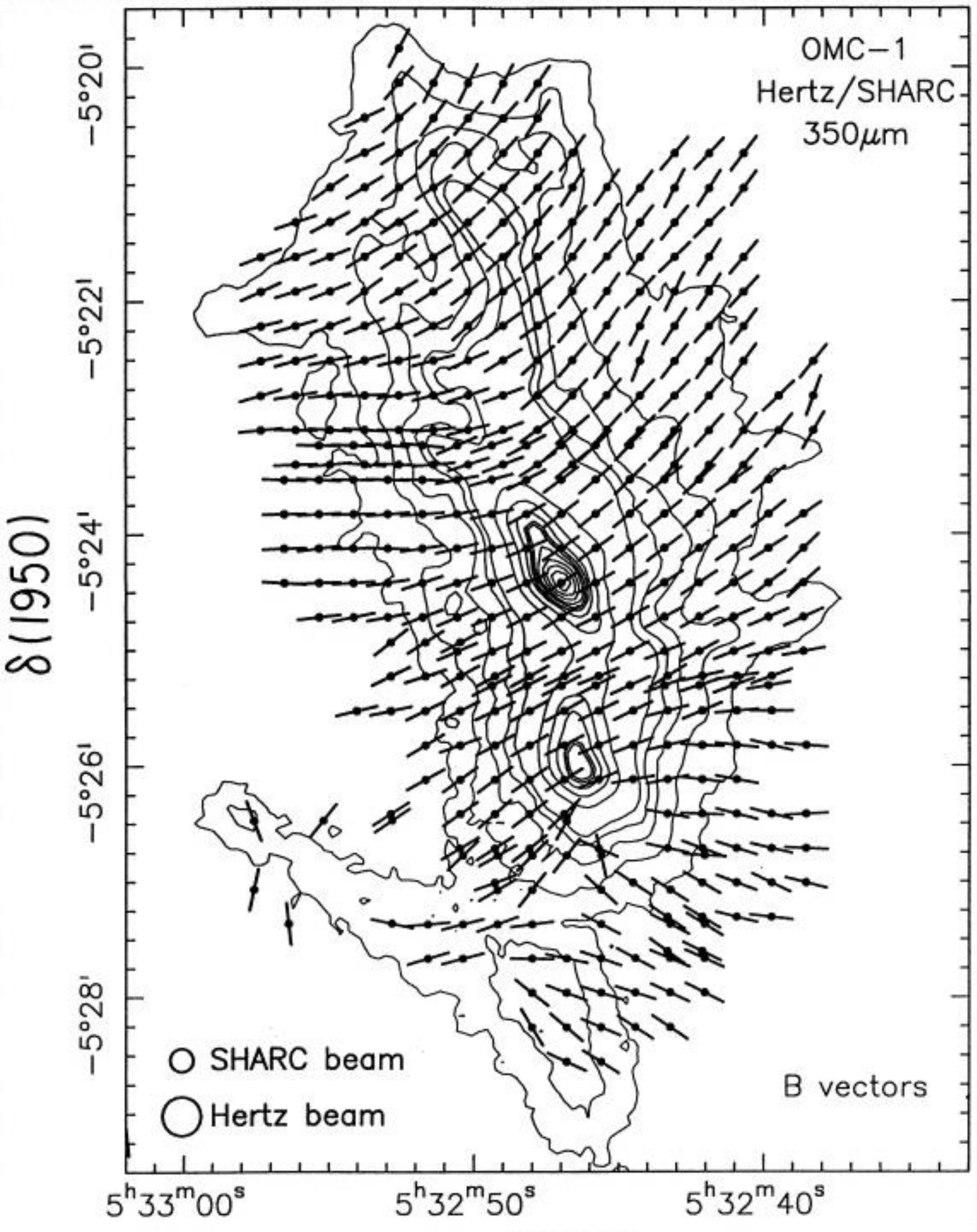
Radboud Universiteit

Measuring galactic magnetic fields:
2. Polarized dust emission



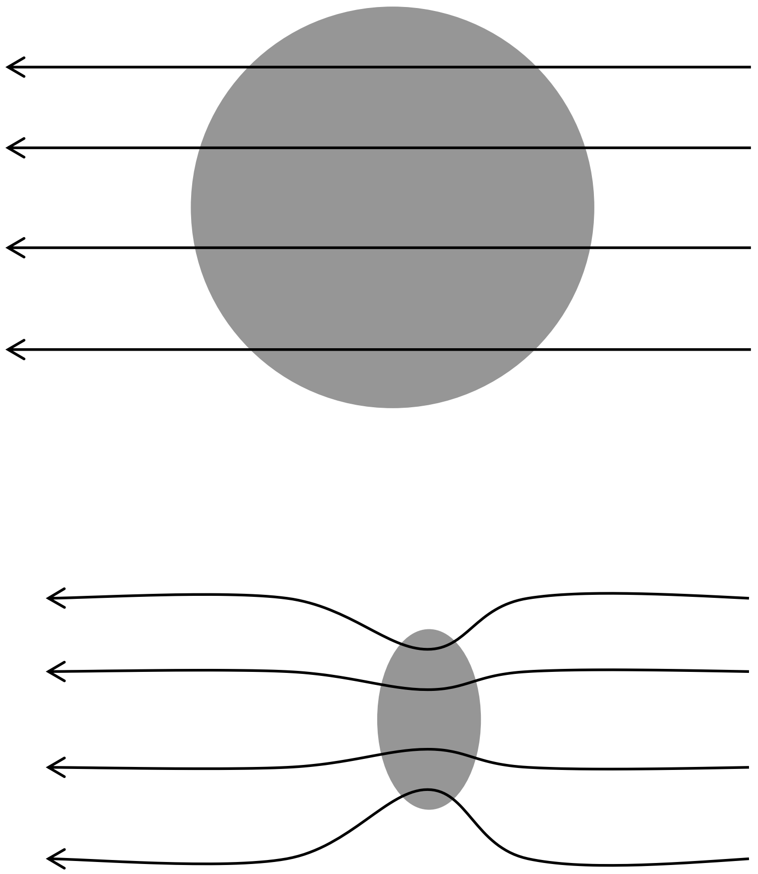
Credit: ESA/Planck collaboration /M.-A. Miville-Deschênes/CNRS

Measuring galactic magnetic fields:
2. Polarized dust emission



Hildebrand et al 2000

Example:
'Hourglass' shape.
Gravitational contraction bends magnetic fields



Radboud Universiteit

Detection methods:

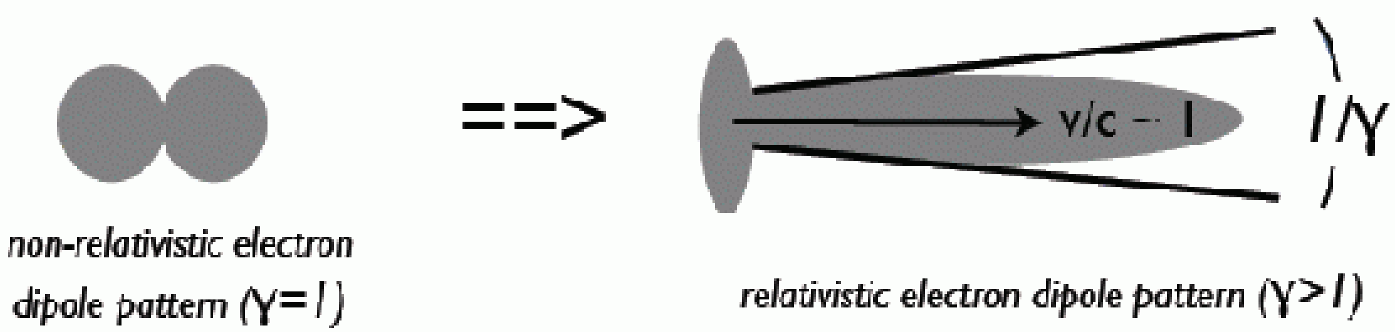
PROCESS:	PROBES FIELD COMPONENT:	IN COMPONENT:	AT SPECTRAL REGION:
linear polarization due to dust absorption	direction of $B_\perp$	dust	Optical/near infrared
polarized dust emission	direction of $B_\perp$	dust	Far infrared/submm
synchrotron emission	strength of $B_\perp$	cosmic rays	Radio
synchrotron linear polarization	$B_{coherent}/B_{total}$	cosmic rays	Radio
Faraday rotation (linear polarization)	strength of $B_{//}$	ionized gas	Radio
Zeeman effect	strength of $B_{//}$	cold gas, stars	Radio
Masers (linear/circular polarization)	strength of B; angle between B and line of sight	specific non-equilibrium conditions	Radio
Davis-Chandrasekhar-Fermi (DCF)	strength of $B_{coherent}$	dust	Optical/near infrared

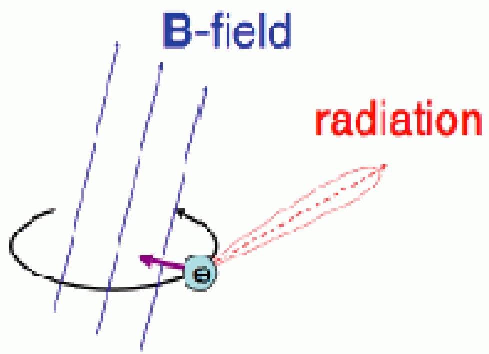
Measuring galactic magnetic fields:
3. Synchrotron emission

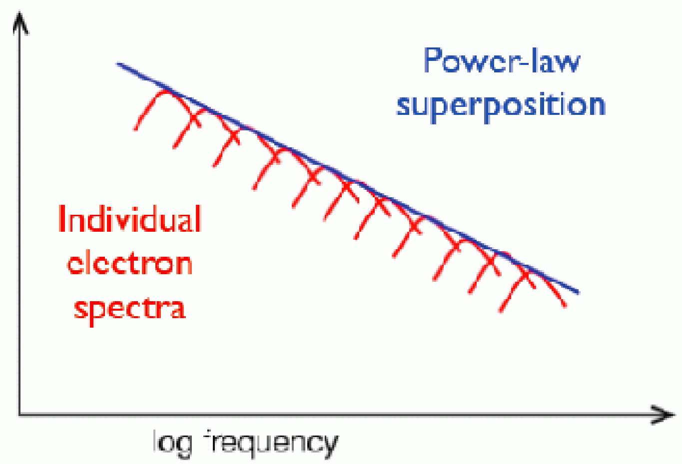
Synchrotron emission is caused by acceleration of relativistic cosmic ray electrons in a magnetic field.

Total synchrotron intensity is given by $$I_\nu \propto N_0 B_\perp^{\frac{\gamma+1}{2}} \nu^{-\frac{(\gamma-1)}{2}}$$

for a cosmic-ray electron distribution $$N(E)dE = N_0 E^{-\gamma} dE$$





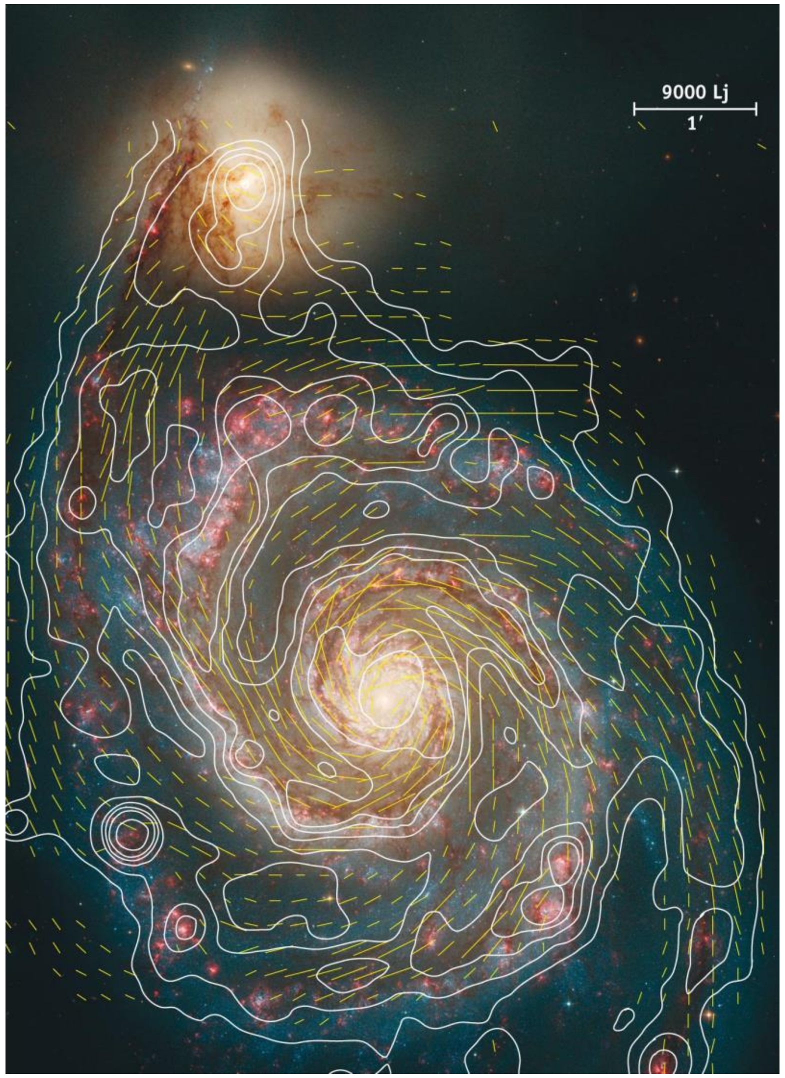


Measuring galactic magnetic fields:
3. Synchrotron emission

Assuming equipartition between magnetic and cosmic ray energy:

$$B_{eq} \propto \frac{(S_\nu \nu^n)^{2/7}\ D^2}{V}$$

where S_ν = flux density;
D = distance;
V = volume of emitting gas



Fletcher, Beck, SuW & Hubble heritage team

BUT: (Beck et al 2003)

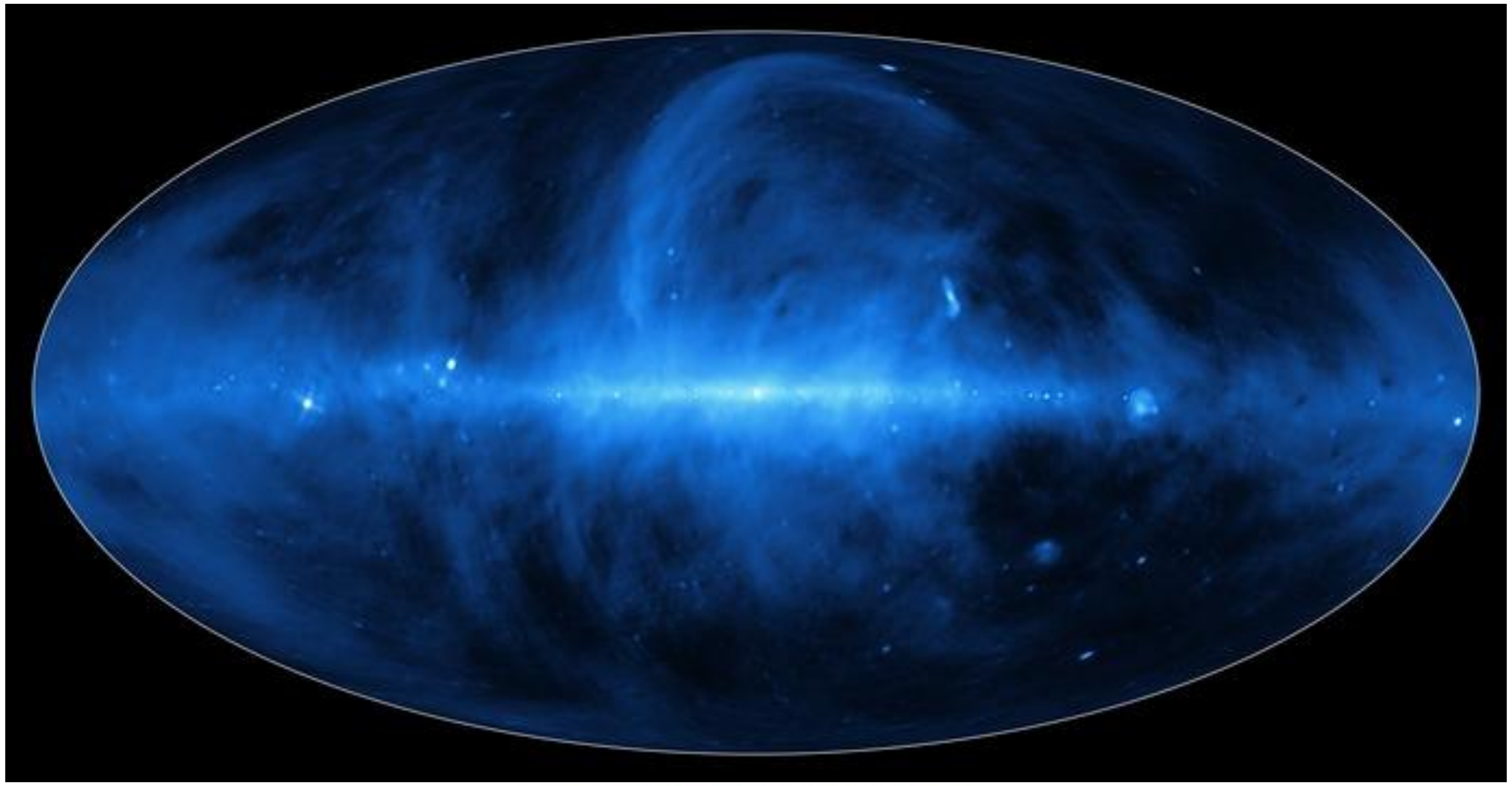
If anisotropy in **B**: B_{reg} overestimated

If **B** correlated with n_{CR}: B_{reg} and B_{tot} overestimated

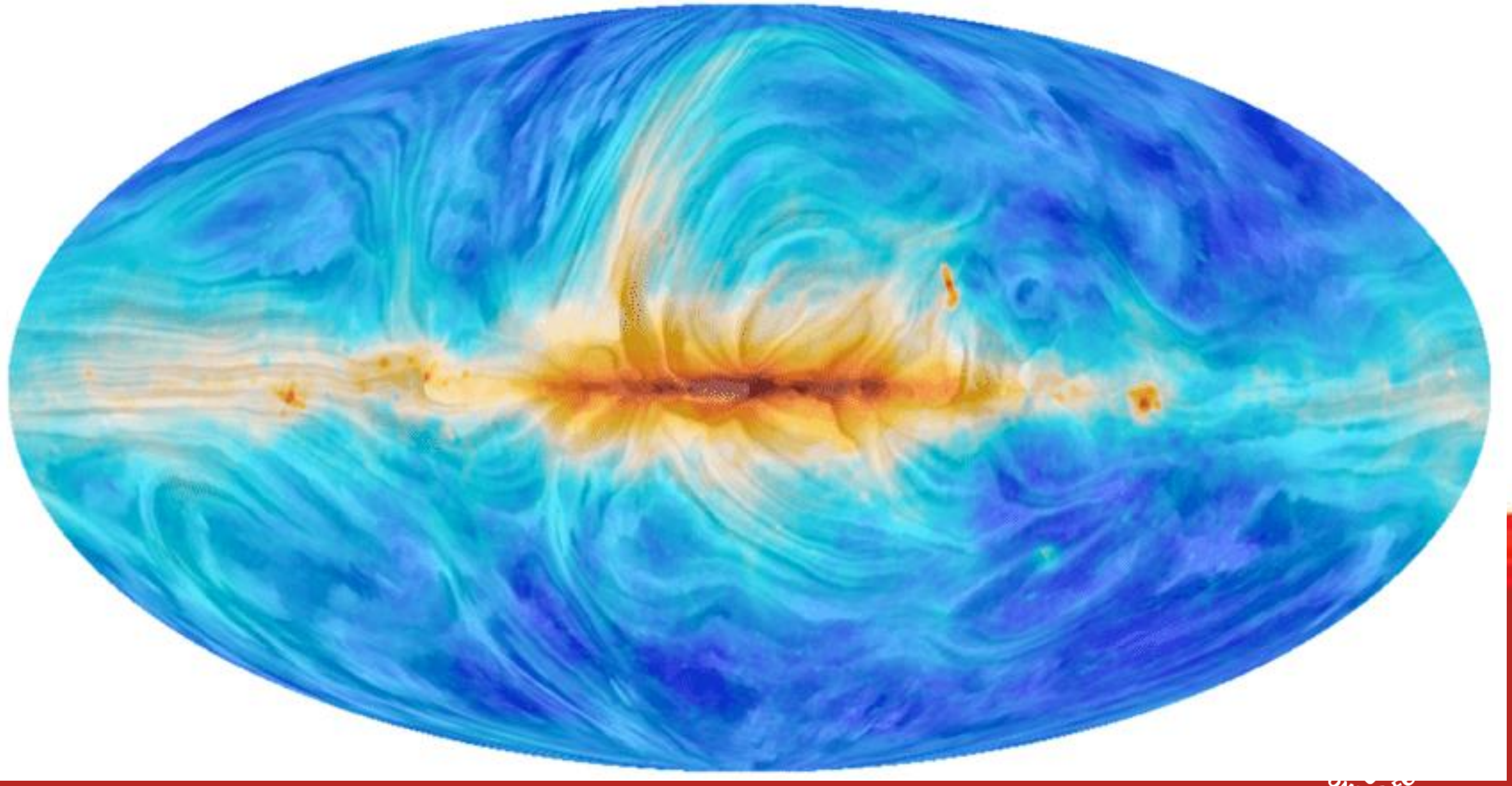
Measuring galactic magnetic fields:
3. Synchrotron emission

Credit: ESA/Planck collaboration /M.-A. Miville-Deschênes/CNRS

Total intensity (Stokes I)



Linear polarization (Stokes Q,U)



Detection methods:

PROCESS:	PROBES FIELD COMPONENT:	IN COMPONENT:	AT SPECTRAL REGION:
linear polarization due to dust absorption	direction of $B_\perp$	dust	Optical/near infrared
polarized dust emission	direction of $B_\perp$	dust	Far infrared/submm
synchrotron emission	strength of $B_\perp$	cosmic rays	Radio
synchrotron linear polarization	$B_{coherent}/B_{total}$	cosmic rays	Radio
Faraday rotation (linear polarization)	strength of $B_{//}$	ionized gas	Radio
Zeeman effect	strength of $B_{//}$	cold gas, stars	Radio
Masers (linear/circular polarization)	strength of B; angle between B and line of sight	specific non-equilibrium conditions	Radio
Davis-Chandrasekhar-Fermi (DCF)	strength of $B_{coherent}$	dust	Optical/near infrared

Measuring galactic magnetic fields:
4. Synchrotron polarization

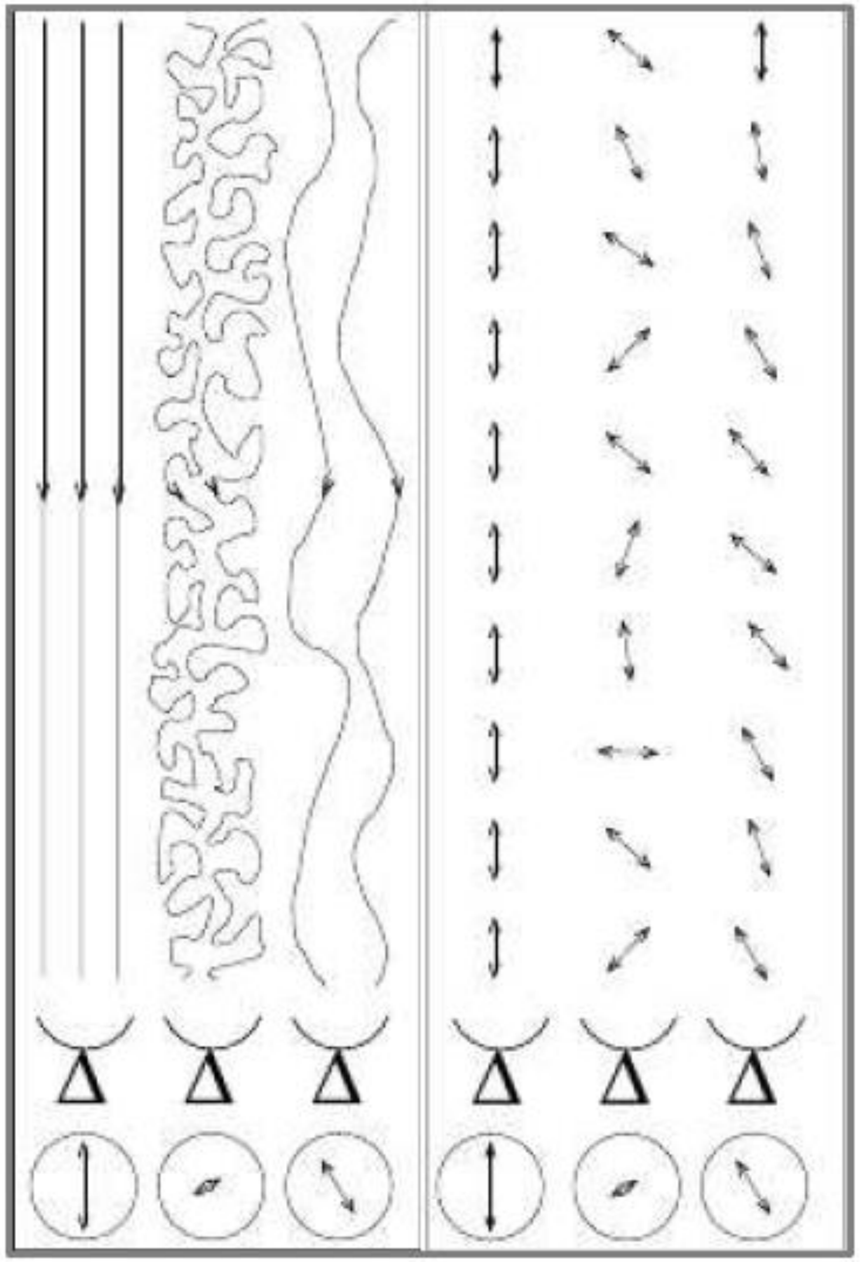
Polarization degree (for γ = *5/2*):

$$\Pi = \frac{\gamma + 1}{\gamma + \frac{7}{3}} \approx 72\%$$

Observed degree of polarization

$$p \leq p_{\max} \qquad p \propto \frac{B^2_{\perp,reg}}{B^2_{\perp,tot}}$$

Measures the strength of the regular field in the plane of the sky.



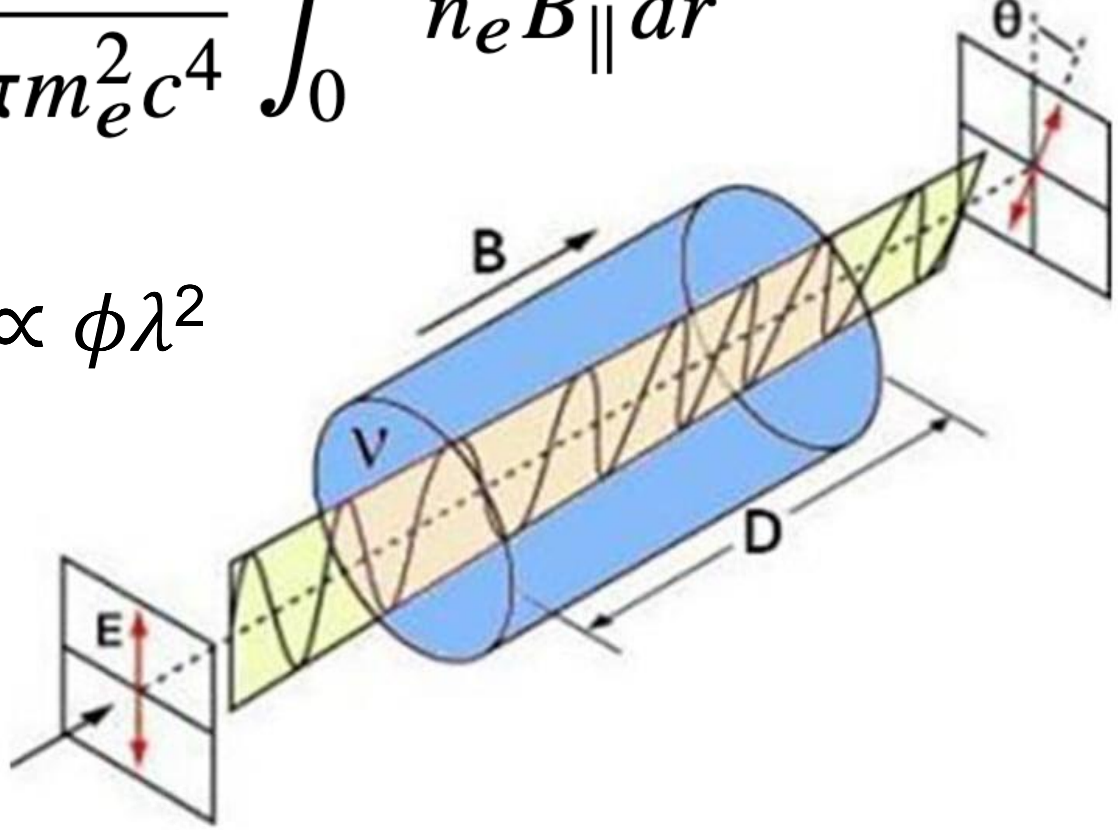
Detection methods:

PROCESS:	PROBES FIELD COMPONENT:	IN COMPONENT:	AT SPECTRAL REGION:
linear polarization due to dust absorption	direction of $B_{\perp}$	dust	Optical/near infrared
polarized dust emission	direction of $B_{\perp}$	dust	Far infrared/submm
synchrotron emission	strength of $B_{\perp}$	cosmic rays	Radio
synchrotron linear polarization	$B_{coherent}/B_{total}$	cosmic rays	Radio
Faraday rotation (linear polarization)	strength of $B_{//}$	ionized gas	Radio
Zeeman effect	strength of $B_{//}$	cold gas, stars	Radio
Masers (linear/circular polarization)	strength of B; angle between B and line of sight	specific non-equilibrium conditions	Radio
Davis-Chandrasekhar-Fermi (DCF)	strength of $B_{coherent}$	dust	Optical/near infrared

Measuring galactic magnetic fields:
4. Faraday rotation

Faraday depth: $\phi\ [\mathrm{rad\,m^{-2}}] = \frac{e^3}{2\pi m_e^2 c^4} \int_0^r n_e B_\parallel dr'$

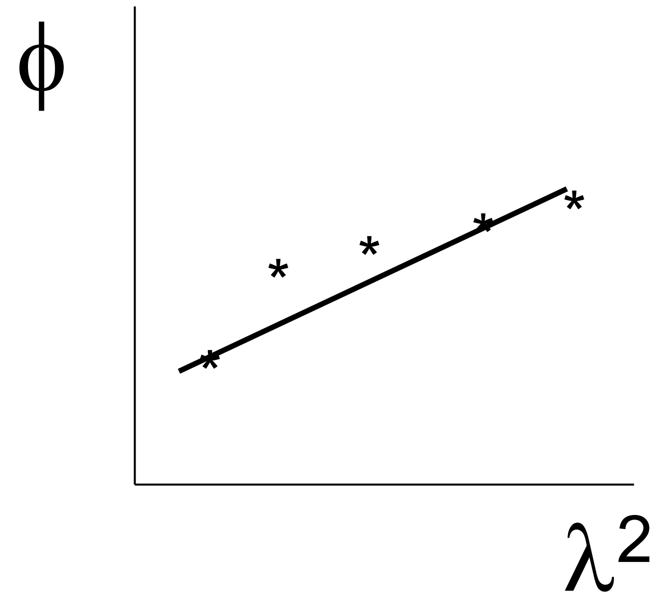
Polarization angle rotation: $\Delta\theta \propto \phi\lambda^2$



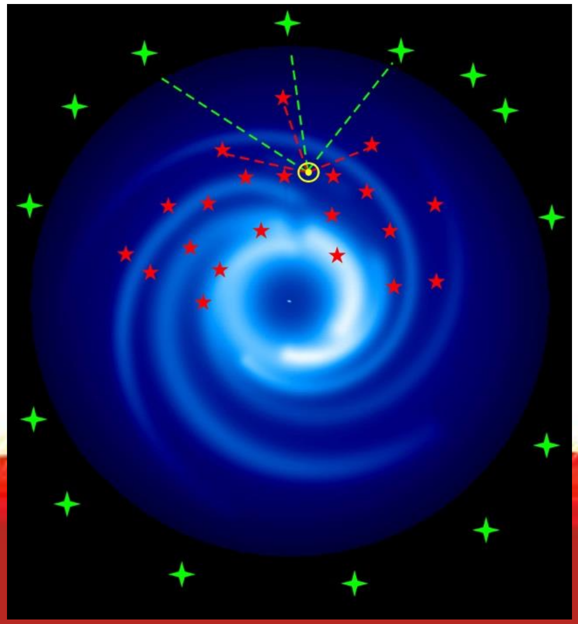
Measuring galactic magnetic fields:
4. Faraday rotation

Faraday depth: $$\phi\ [\mathrm{rad\ m^{-2}}] = \frac{e^3}{2\pi m_e^2 c^4}\int_0^r n_e B_{\parallel} dr'$$

Polarization angle rotation: $\Delta\theta \propto \phi\lambda^2$



Source can be
- pulsars
- polarized extragalactic point sources
- diffuse synchrotron emission

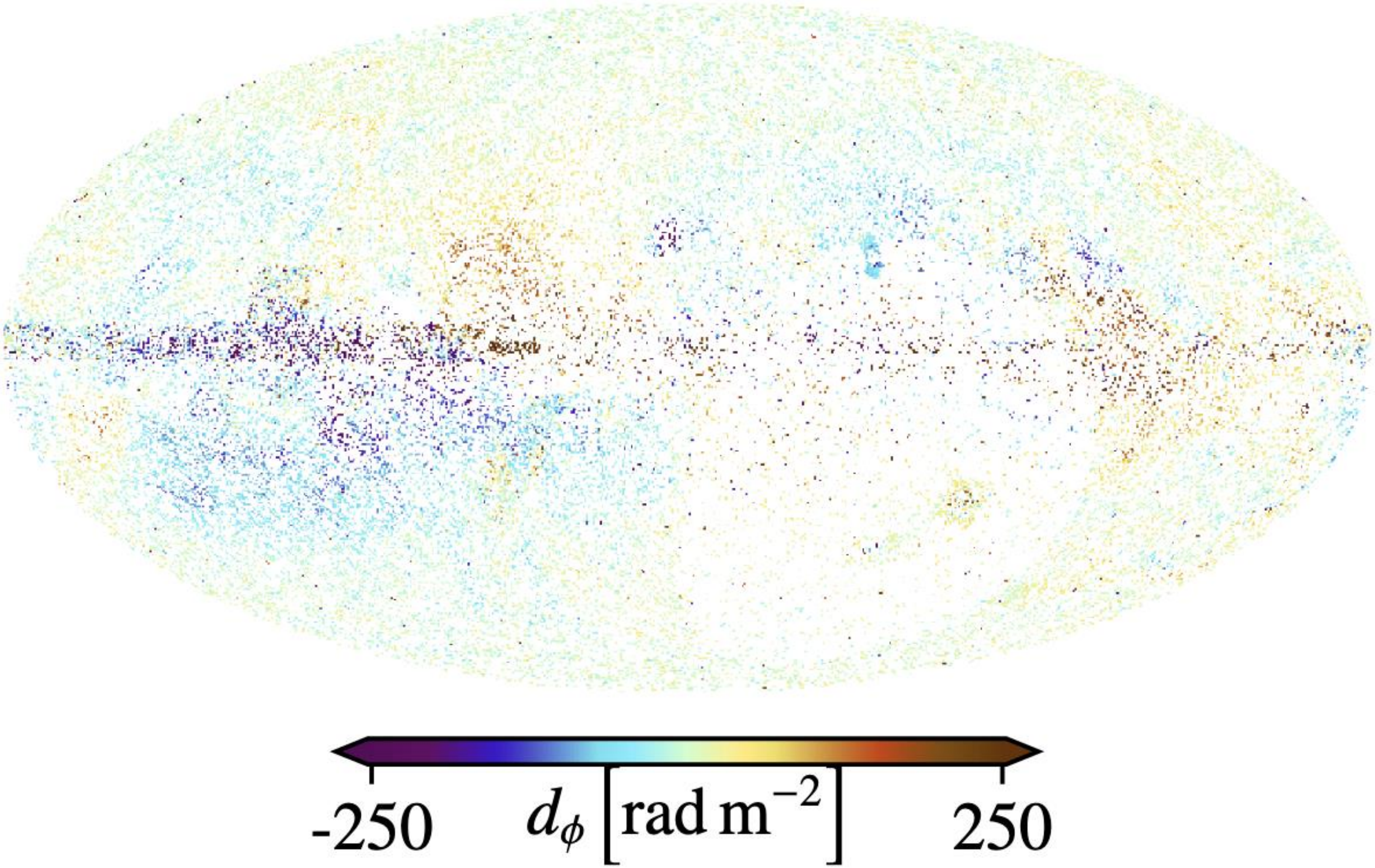


Radboud Universiteit

Measuring galactic magnetic fields:
4. Faraday rotation

Extragalactic 'point' sources:

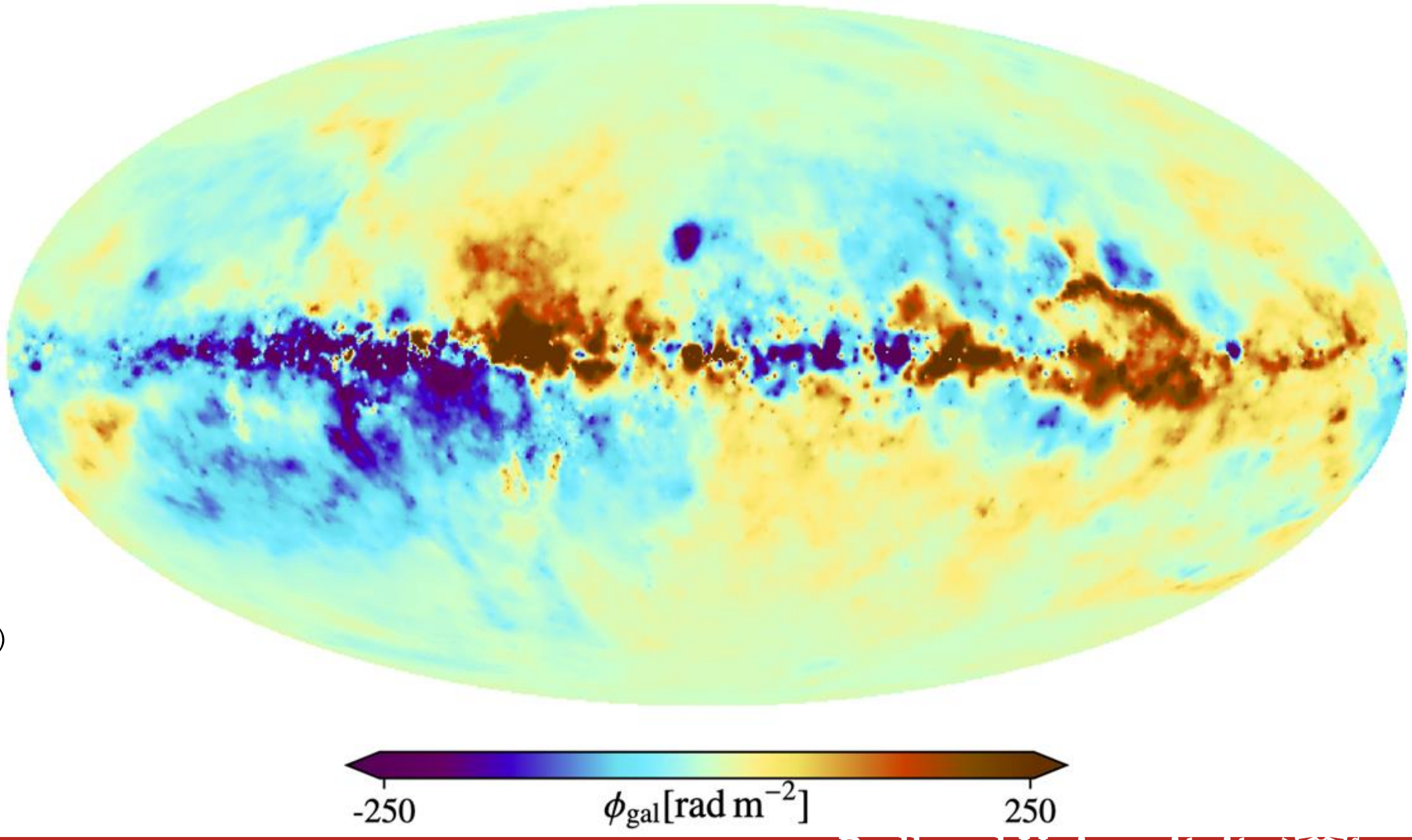
RM Grid



Hutschenreuter et al (2020)

Measuring galactic magnetic fields:
4. Faraday rotation

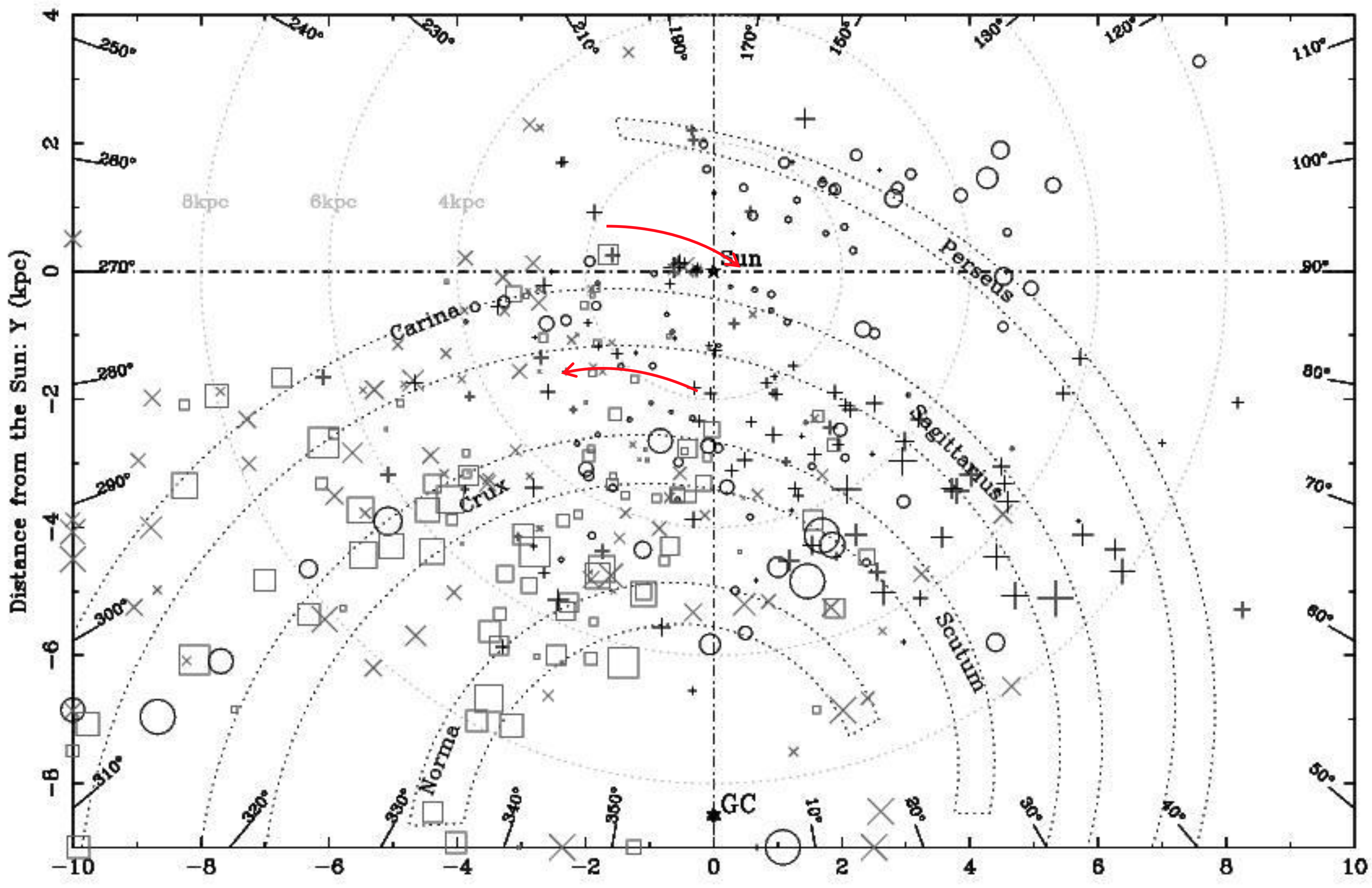
Extragalactic 'point' sources:



Hutschenreuter et al (2022)

Measuring galactic magnetic fields:
4. Faraday rotation

Pulsars:



Han et al 2006

REMINDER

$$RM = 0.81 \int n_e B \cdot ds$$

Radboud Universiteit

Measuring galactic magnetic fields:
4. Faraday rotation

Pulsars:

- ☺ at known distances: 3D sampling of the Galaxy
- ☺ additional info about n_e in dispersion measure: $DM = \int n_e \, ds$
- ☺ no intrinsic Faraday rotation
- ☹ large distance uncertainties
- ☹ mostly in or near Galactic plane

Extragalactic sources:

- ☺ evenly distributed over the sky
- ☺ many many sources (abt 36000 now) --> "RM grid"
- ☹ intrinsic Faraday rotation RM_{int} ~ 5-10 rad m^{-2}

Measuring galactic magnetic fields:
4. Faraday rotation

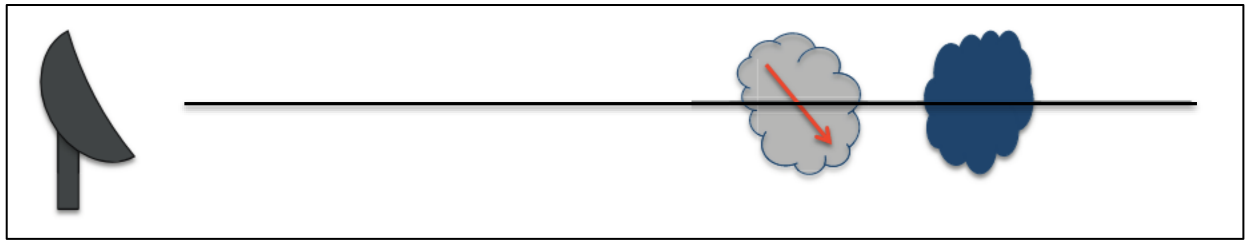
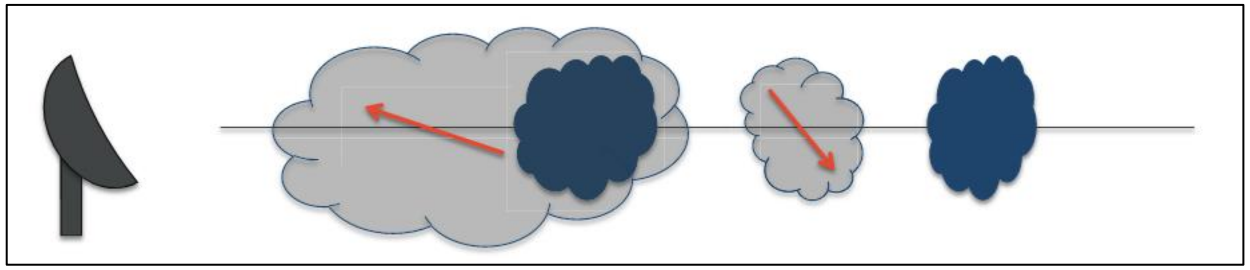
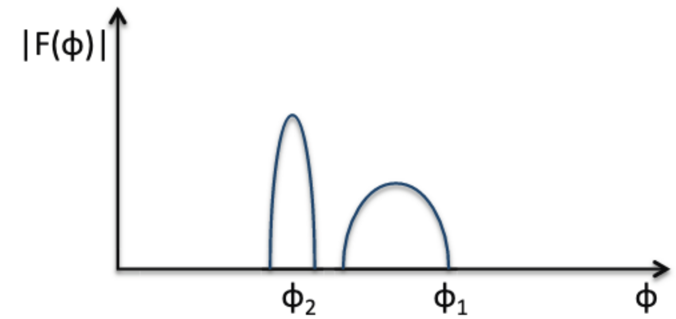


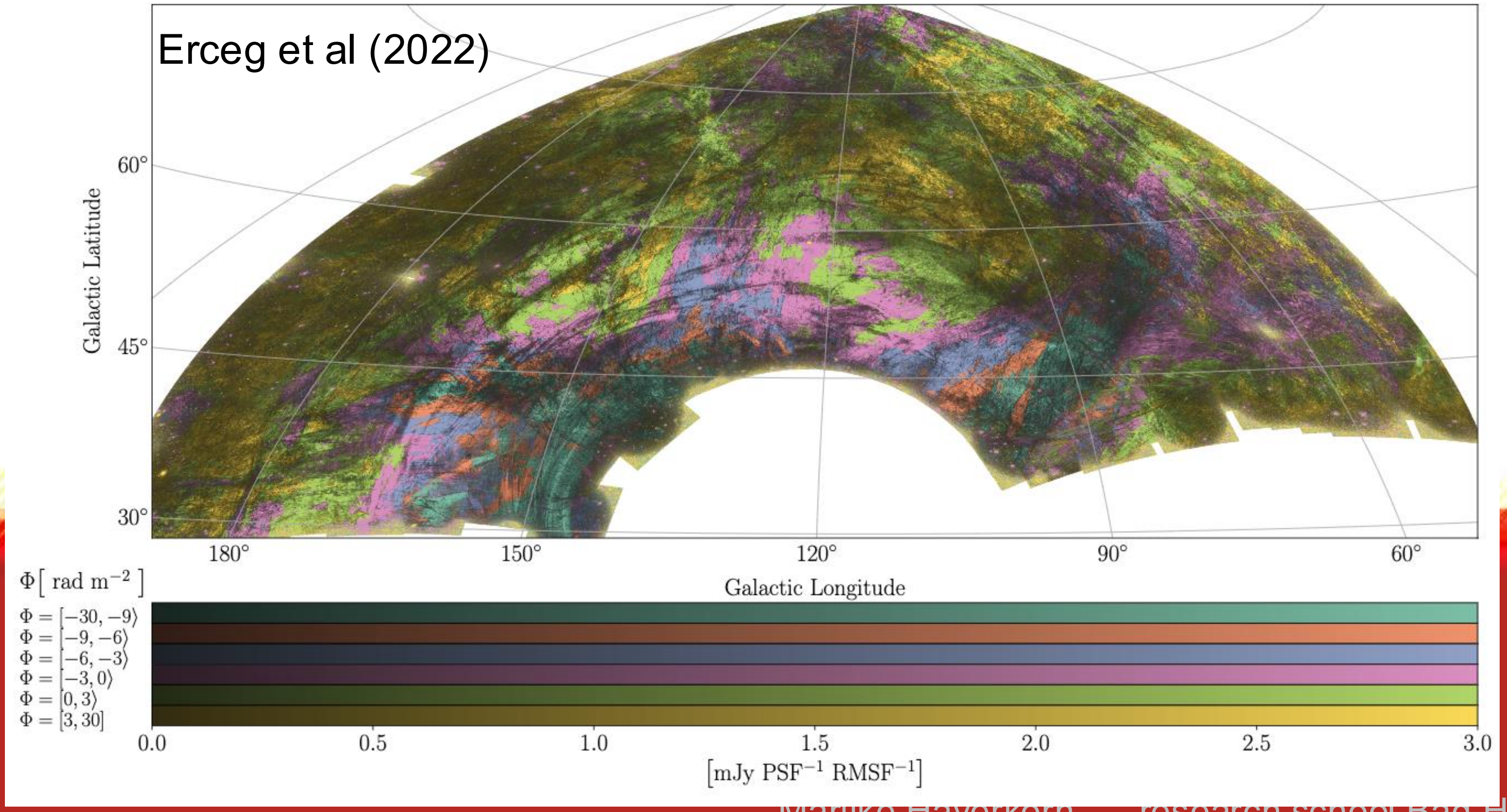
Image credit Marta Alves, in Ferrière (2016)



$$\mathrm{RM} = \phi = \frac{d\theta}{d\lambda^2} = \frac{\Delta\theta}{\Delta\lambda^2}$$



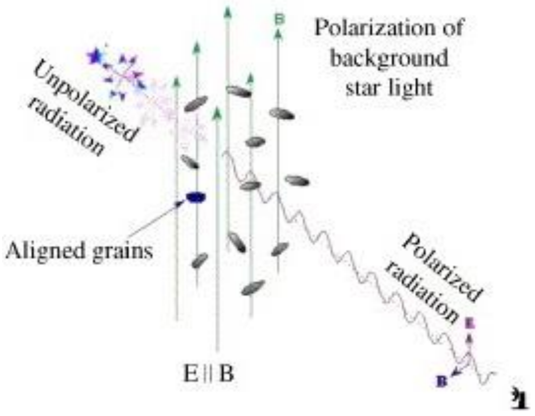
$$\tilde{F}(\phi) = K \int_{-\infty}^{+\infty} \tilde{P}(\lambda^2) e^{-2i\phi(\lambda^2-\lambda_0^2)}\, d\lambda^2$$

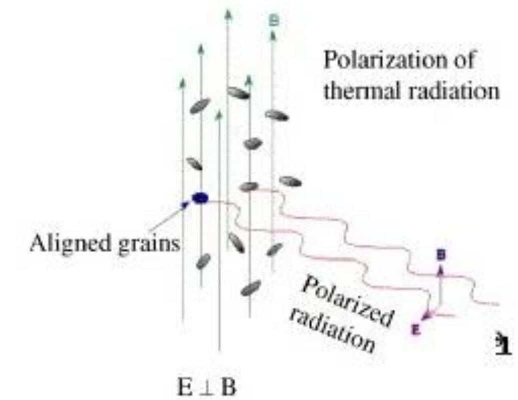


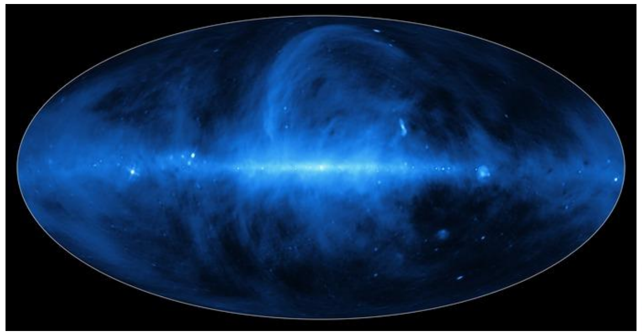
Erceg et al (2022)

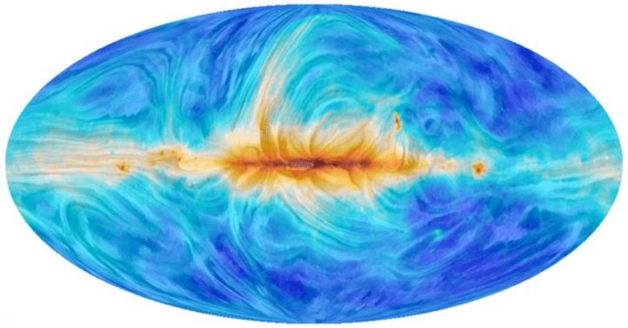
Detection methods:

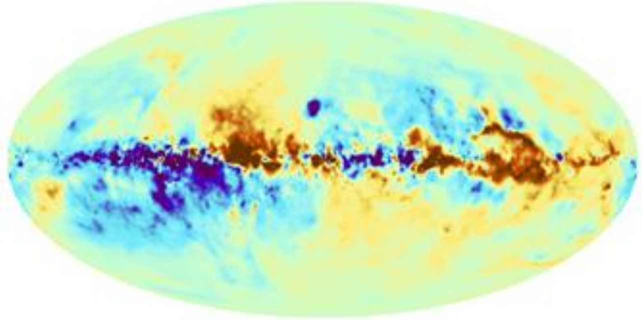
PROCESS:	IN COMPONENT:
linear polarization due to dust absorption	dust
polarized dust emission	dust
synchrotron emission	cosmic rays
synchrotron linear polarization	cosmic rays
Faraday rotation (linear polarization)	ionized gas









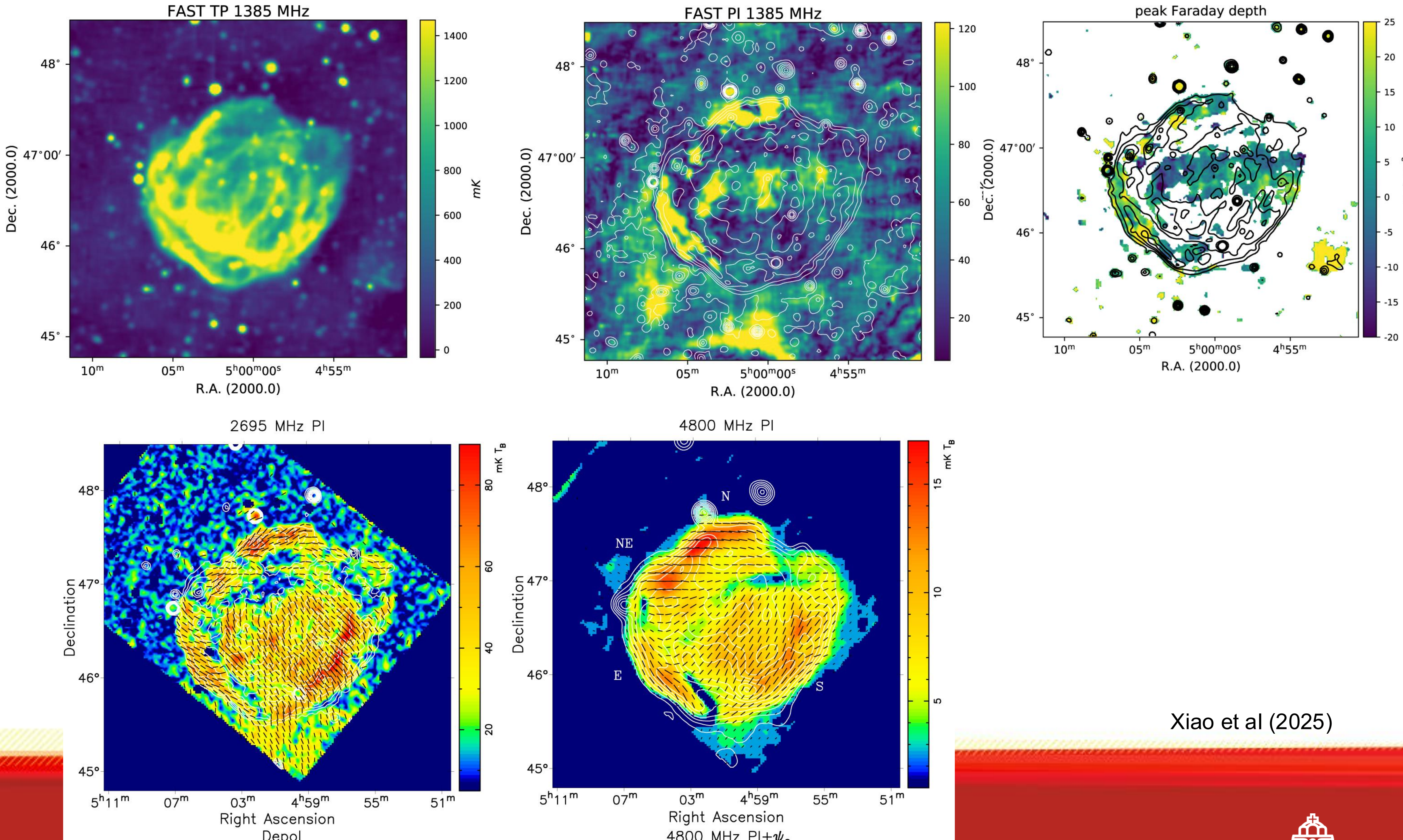


How would you search for magnetic fields in:

PROCESS:	IN COMPONENT:
linear polarization due to dust absorption	dust
polarized dust emission	dust
synchrotron emission	cosmic rays
synchrotron linear polarization	cosmic rays
Faraday rotation (linear polarization)	ionized gas

A supernova remnant?

Magnetic fields in supernova remnants



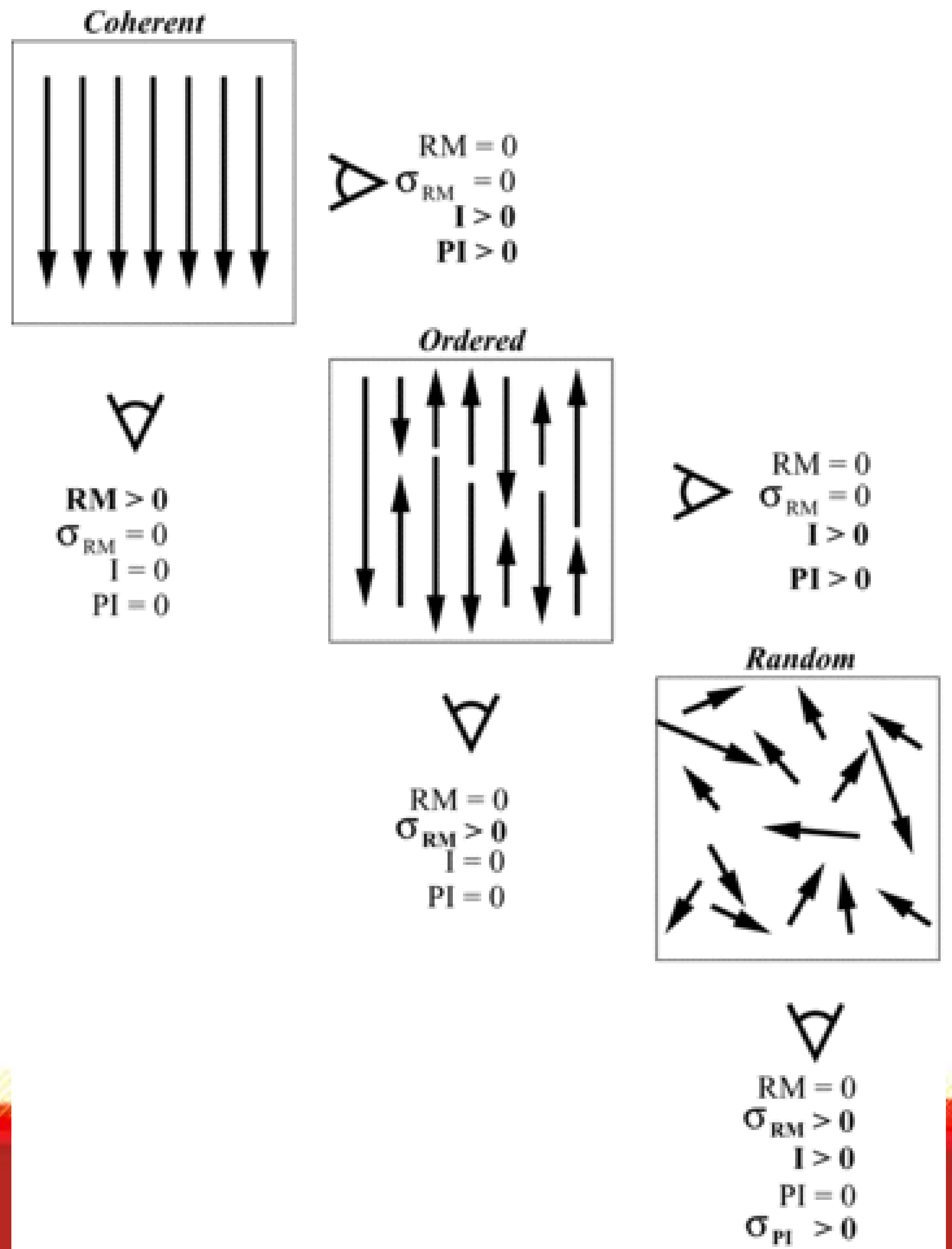
Xiao et al (2025)

Content

Typical strengths of cosmic magnetic fields:

OBJECT	FIELD STRENGTH [Gauss = 10^{-4} T]
Magnetars	$10^{15} – 10^{16}$
Pulsars	$10^{11} – 10^{13}$
Magnetic A-stars	10^{4}
Sunspot	2.5×10^{3}
Sun	10
Earth	0.6
Supernova remnant	$10^{-4} – 10^{-5}$
Intracluster medium	$10^{-5} – 10^{-6}$
Interstellar medium	5×10^{-6}
Solar Wind at 1 AU	2×10^{-6}
Intergalactic medium	$< 10^{-9}$ (random component) $< 10^{-11}$ (uniform component)

Interstellar magnetic field configurations

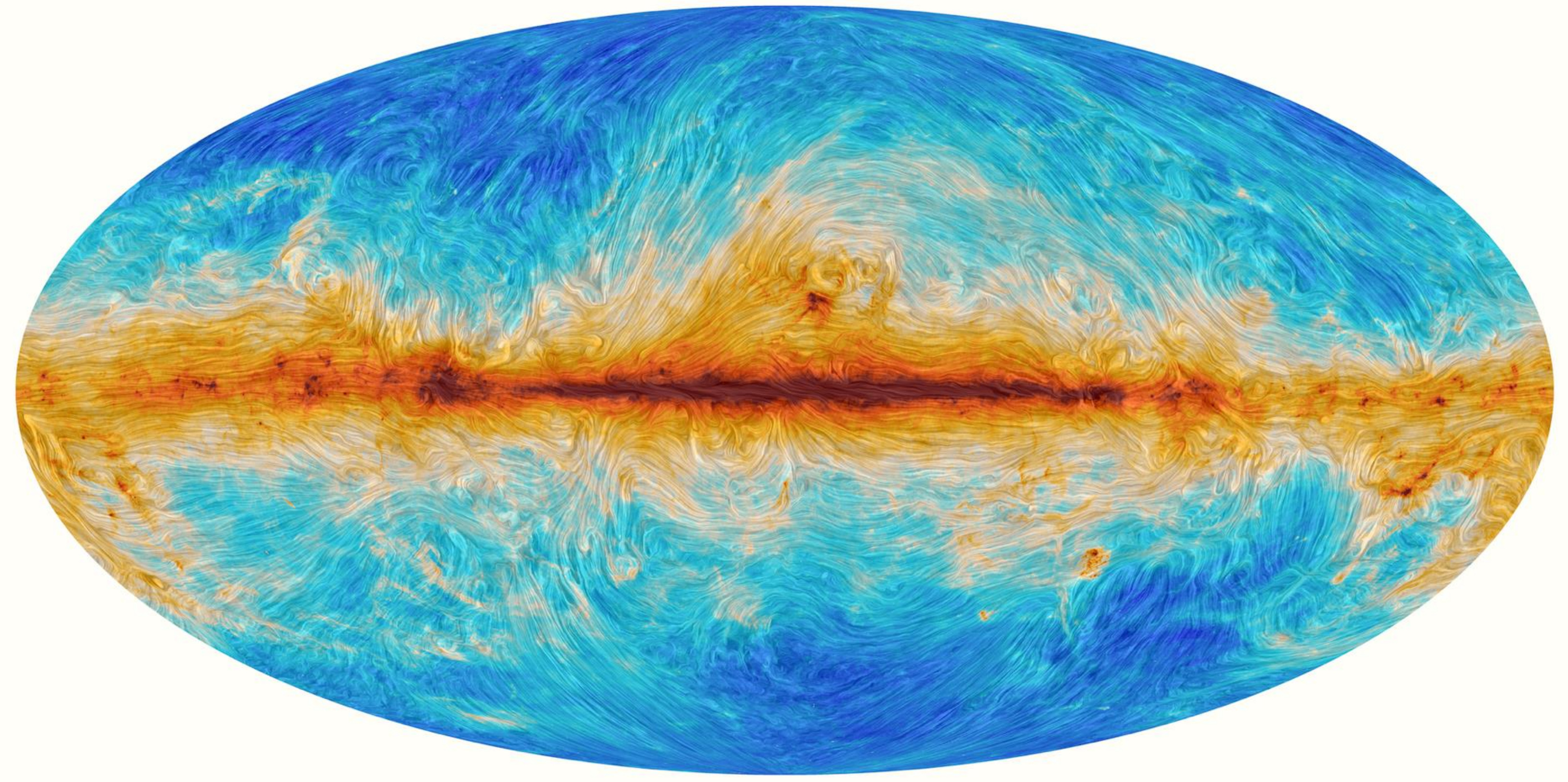


Anisotropic random

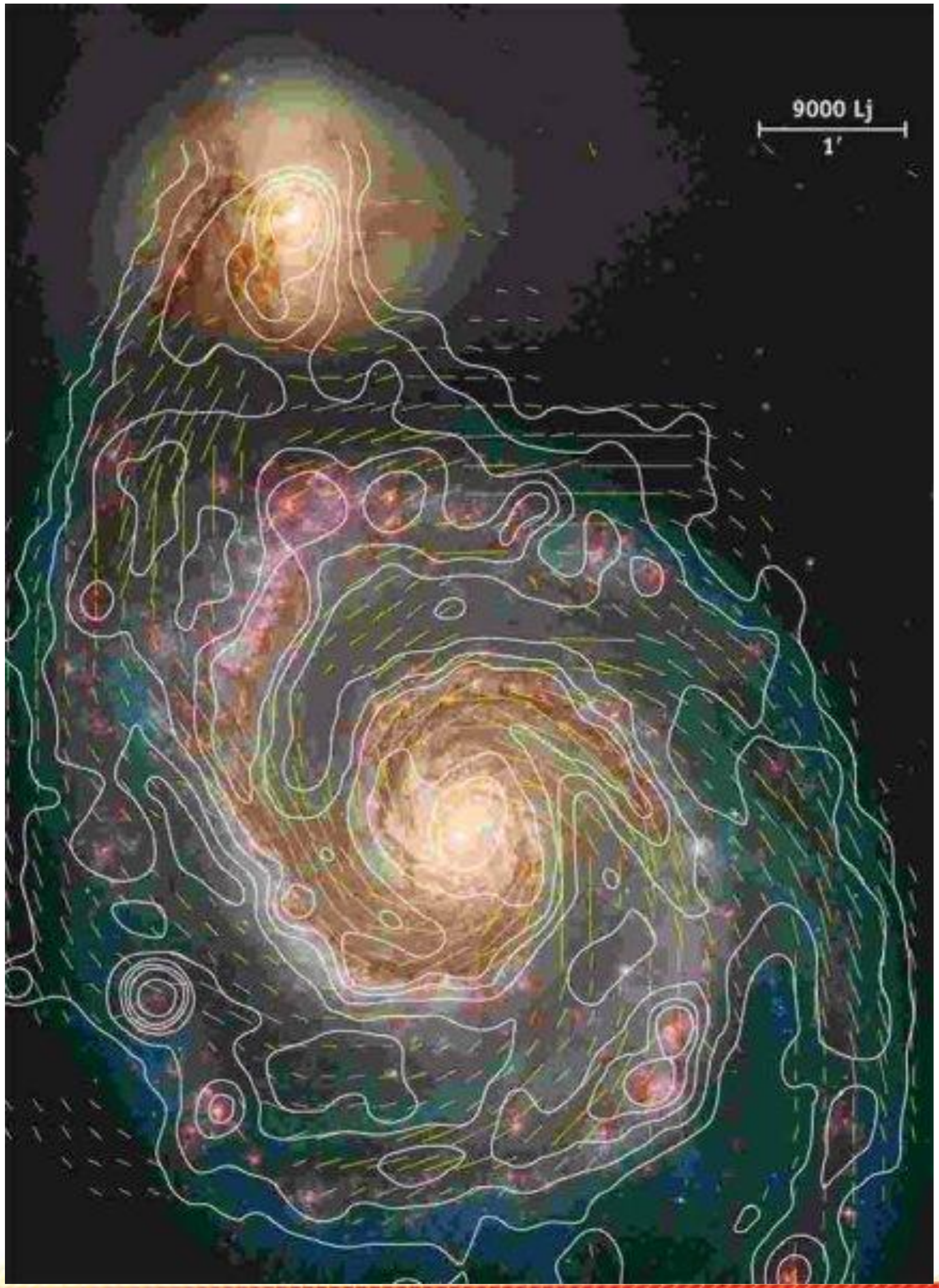
vs

Isotropic random

Large-scale, coherent Galactic magnetic field



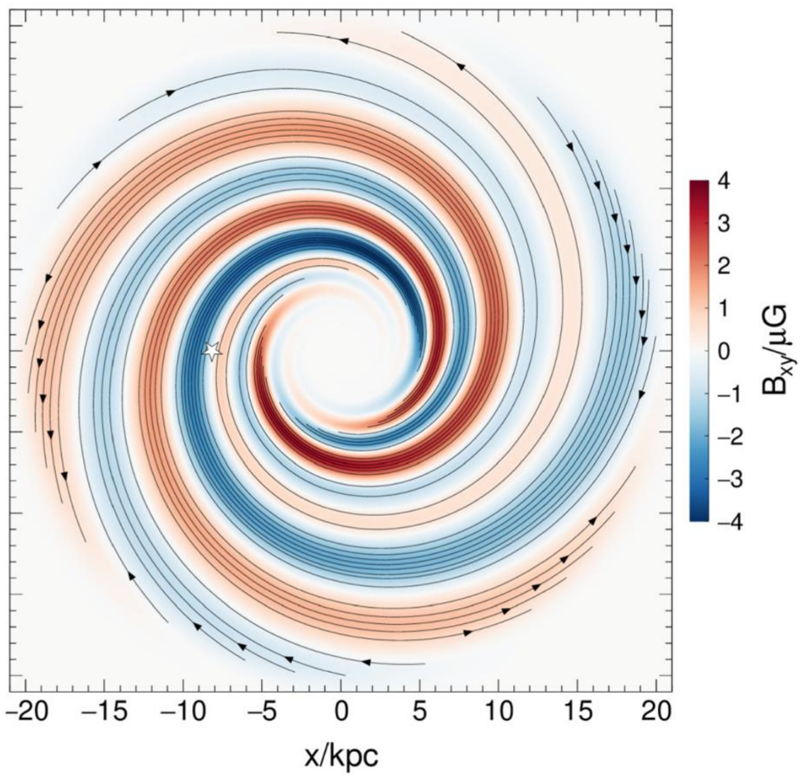
Credit: ESA/Planck collaboration /M.-A. Miville-Deschênes/CNRS



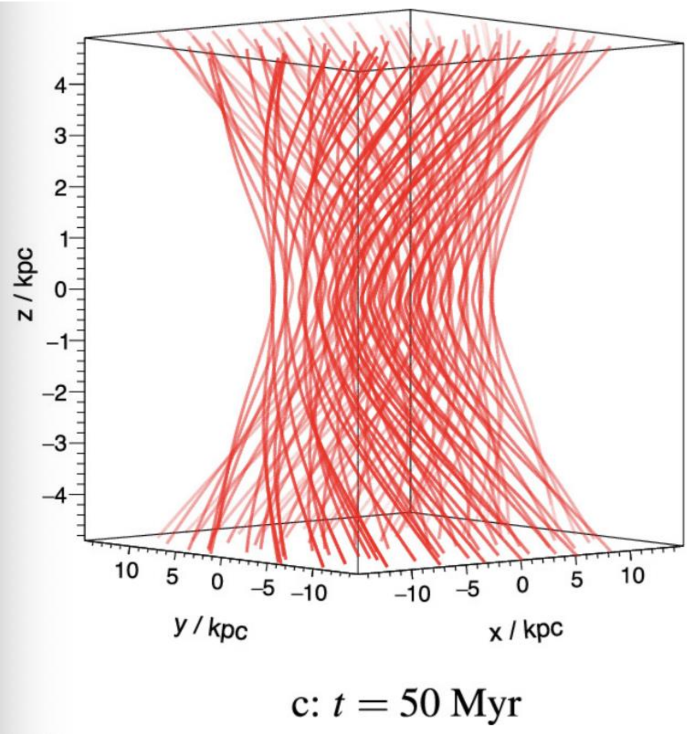
Credit: A. Fletcher MPIfR Bonn/Hubble Heritage Team

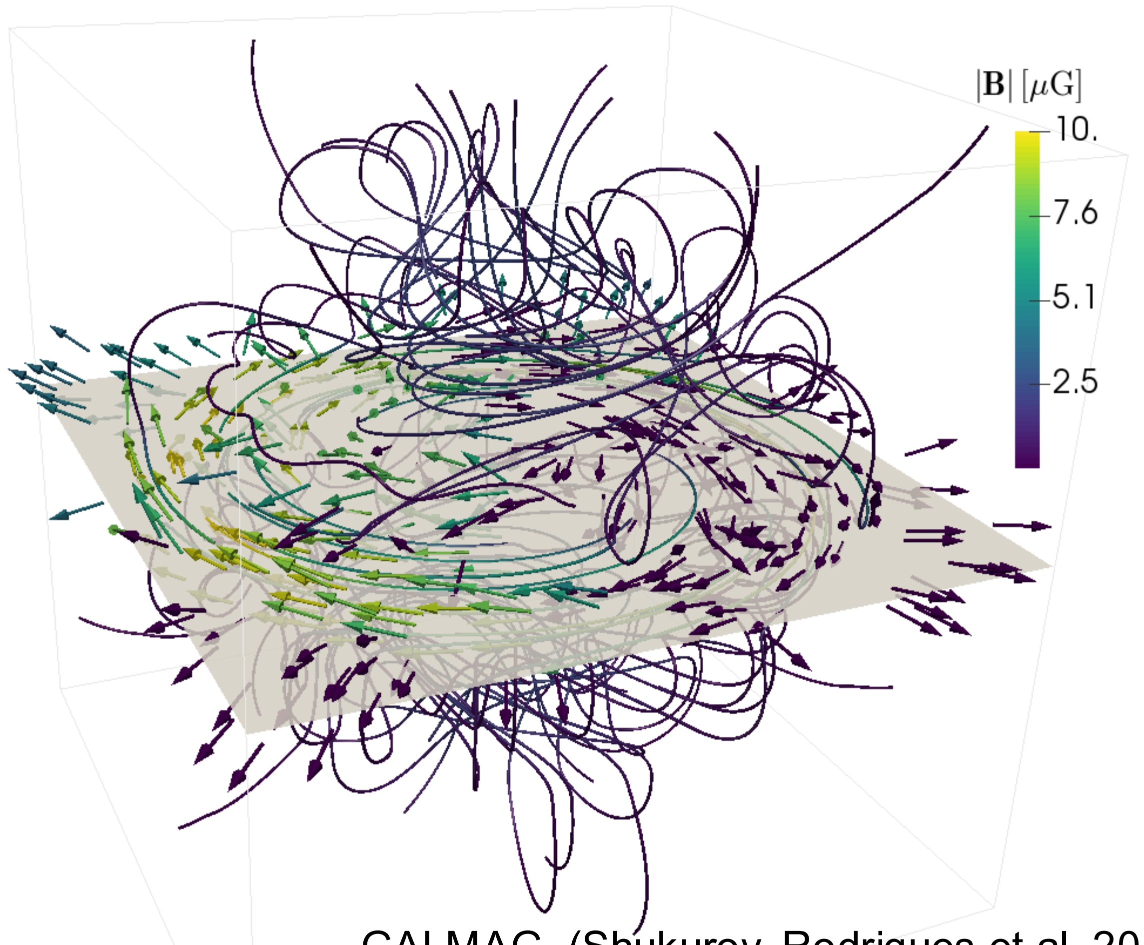
Global Galactic magnetic field models

Heuristic models vs dynamo theory based models



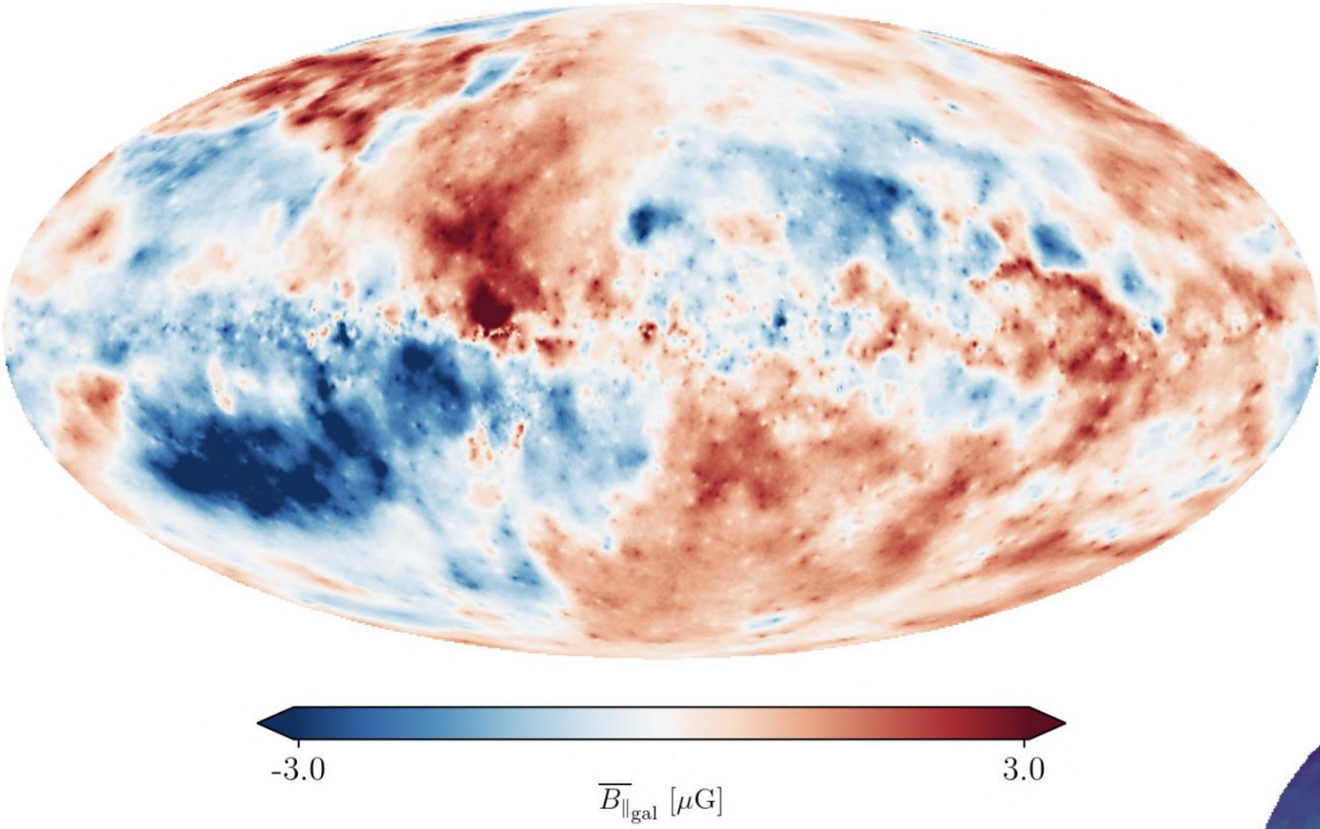
Unger & Farrar (2024)



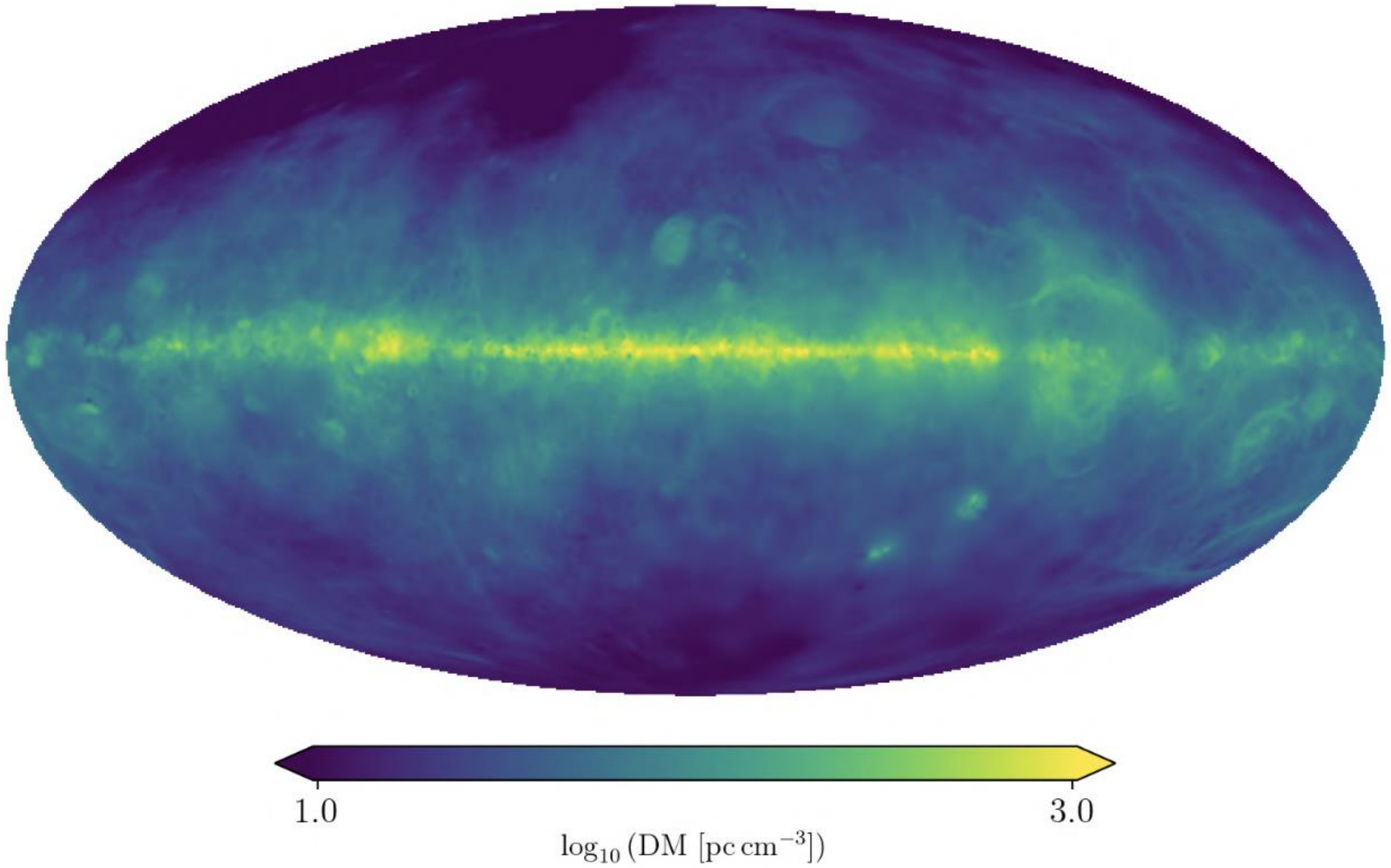


GALMAG (Shukurov, Rodrigues et al 2019)

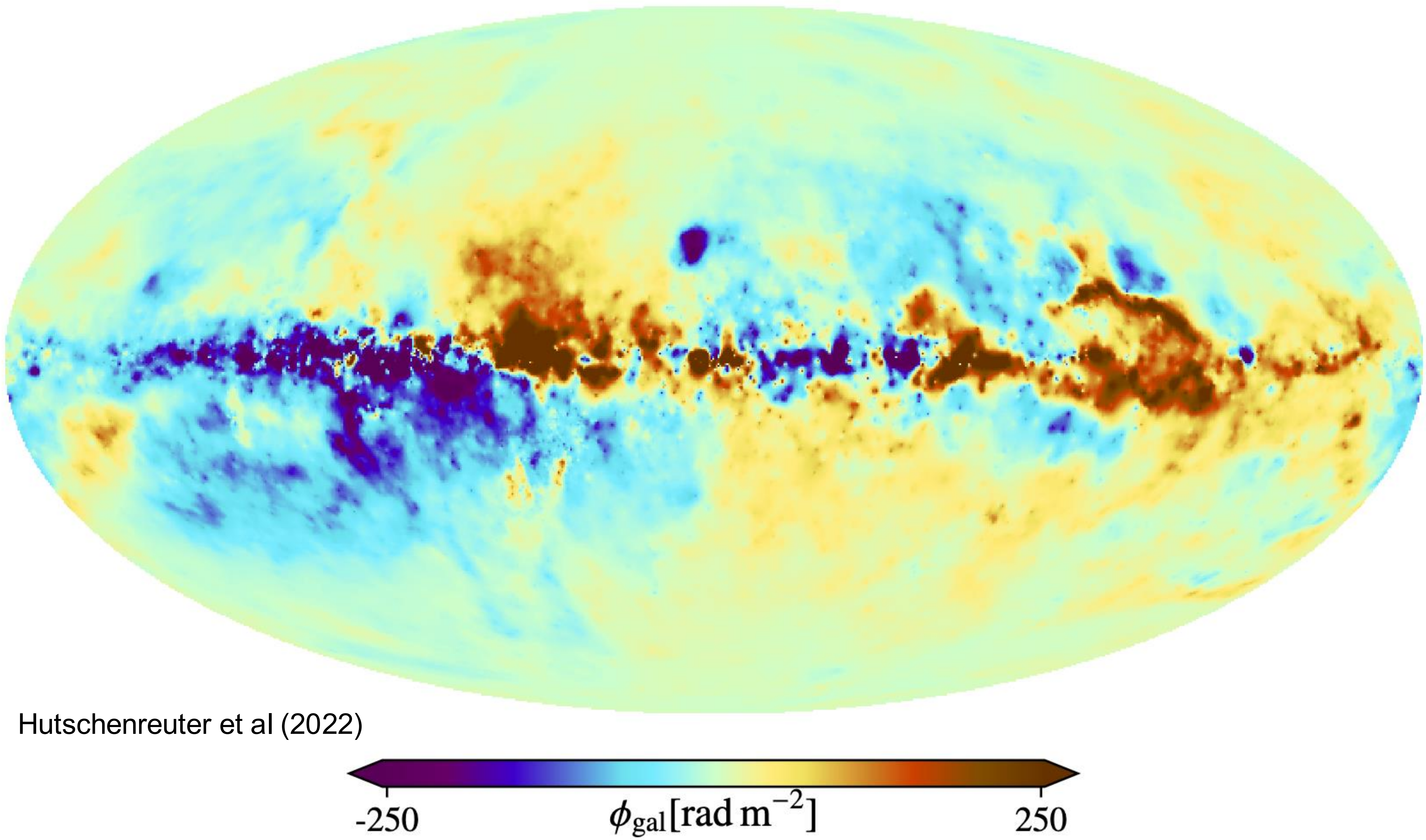
Next step: non-parametrized inference of magnetic fields



Hutschenreuter et al (2024)

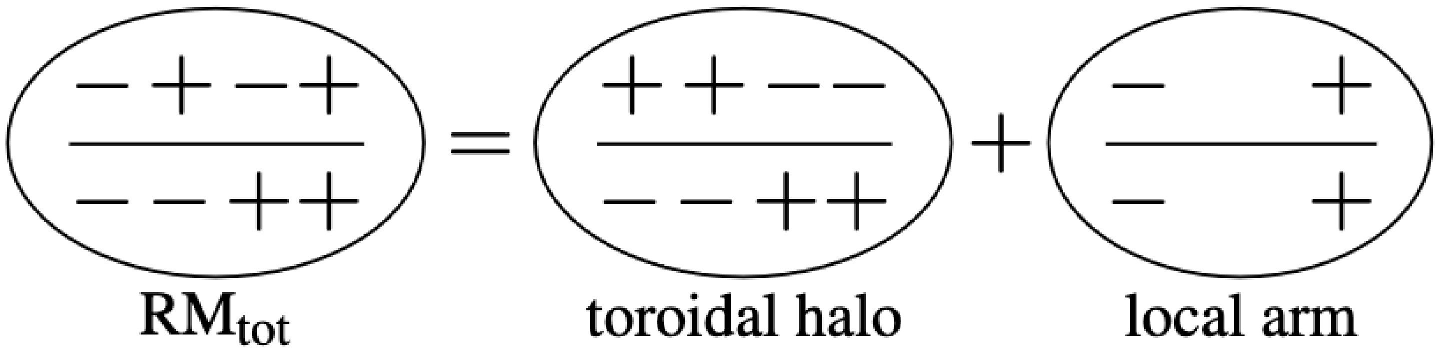


Coherent Galactic magnetic field: global variations over the sky

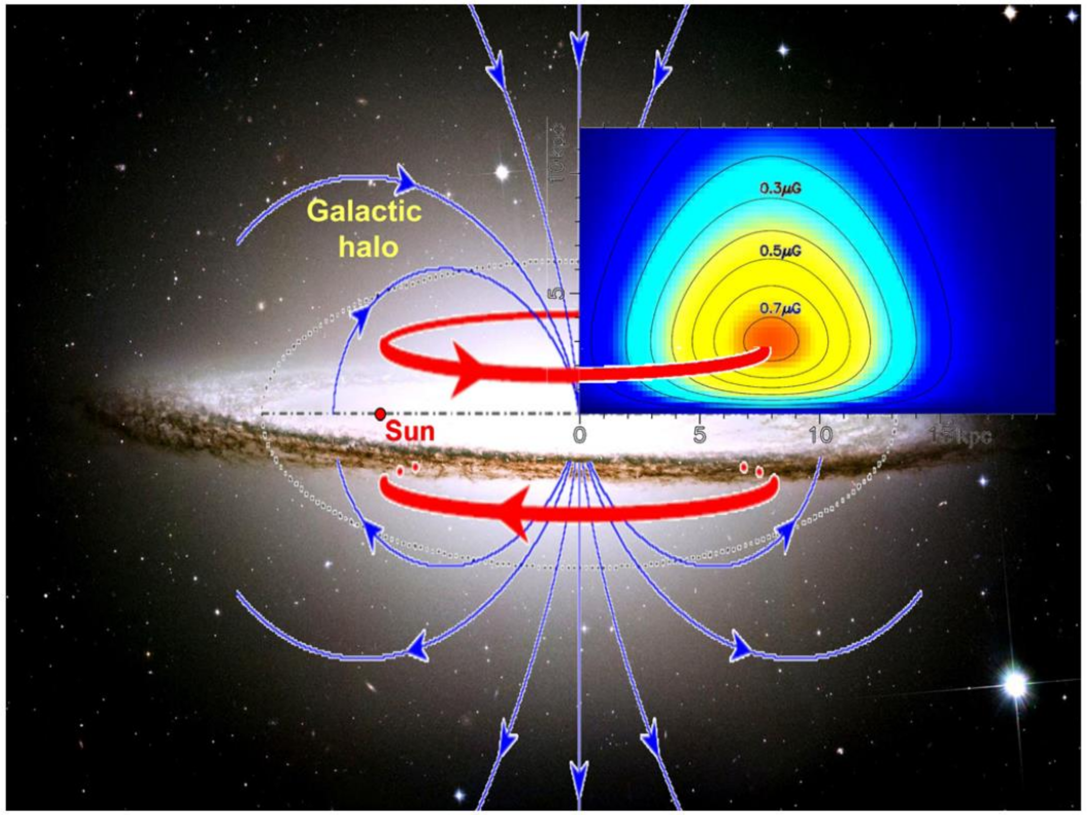


Hutschenreuter et al (2022)

Coherent Galactic magnetic field: Toroidal structure



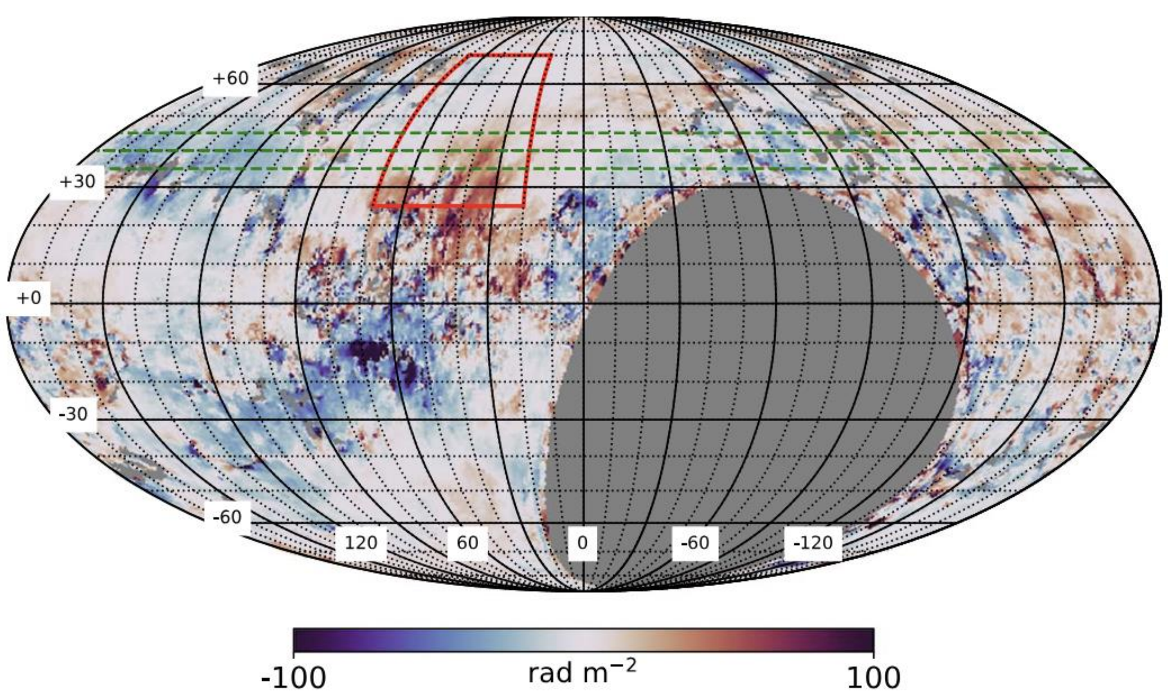
Unger & Farrar (2023)



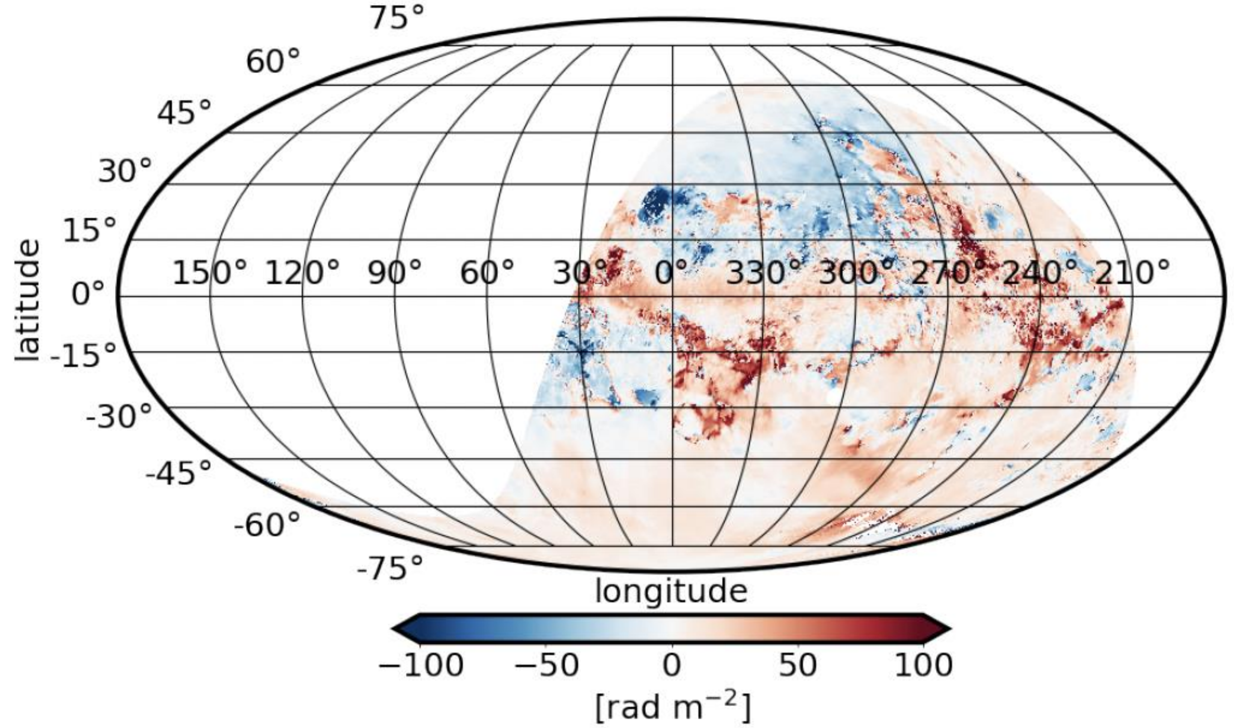
Xu & Han (2024)

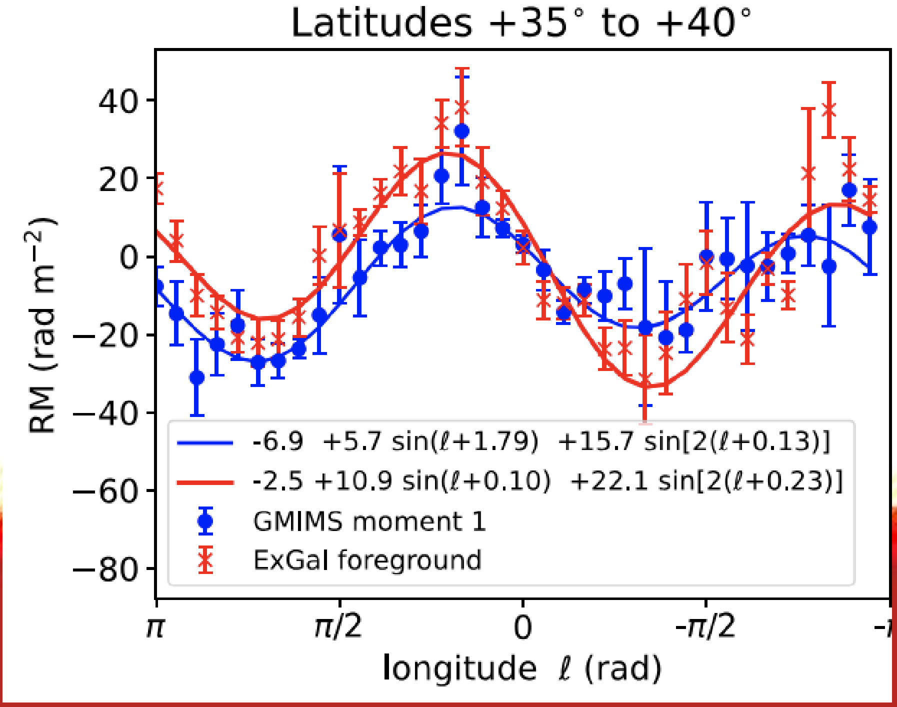
Coherent Galactic magnetic field: M0 dipole + M1 quadrupole?

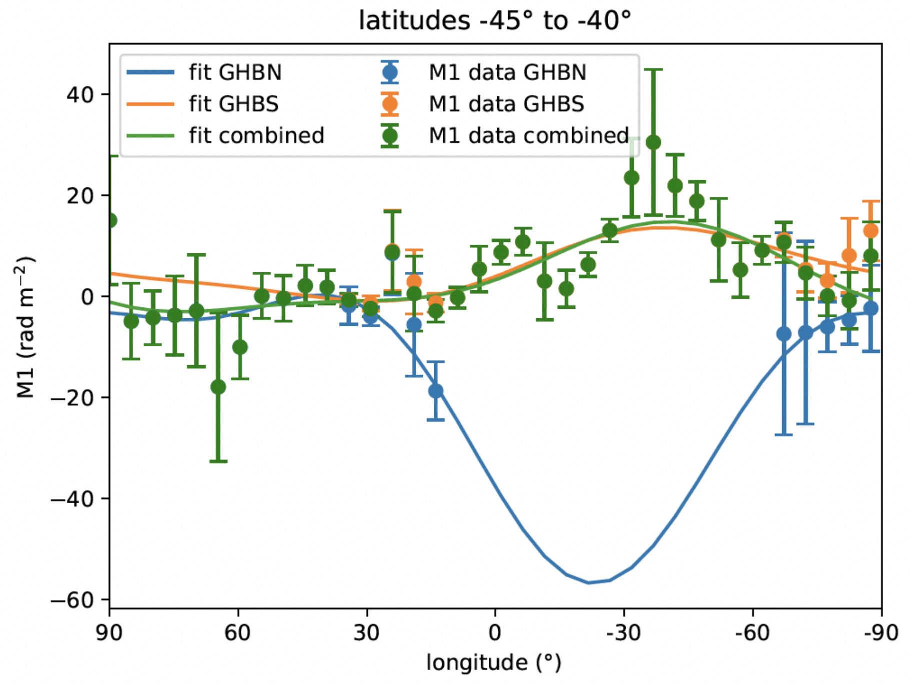
Dickey et al (2022)



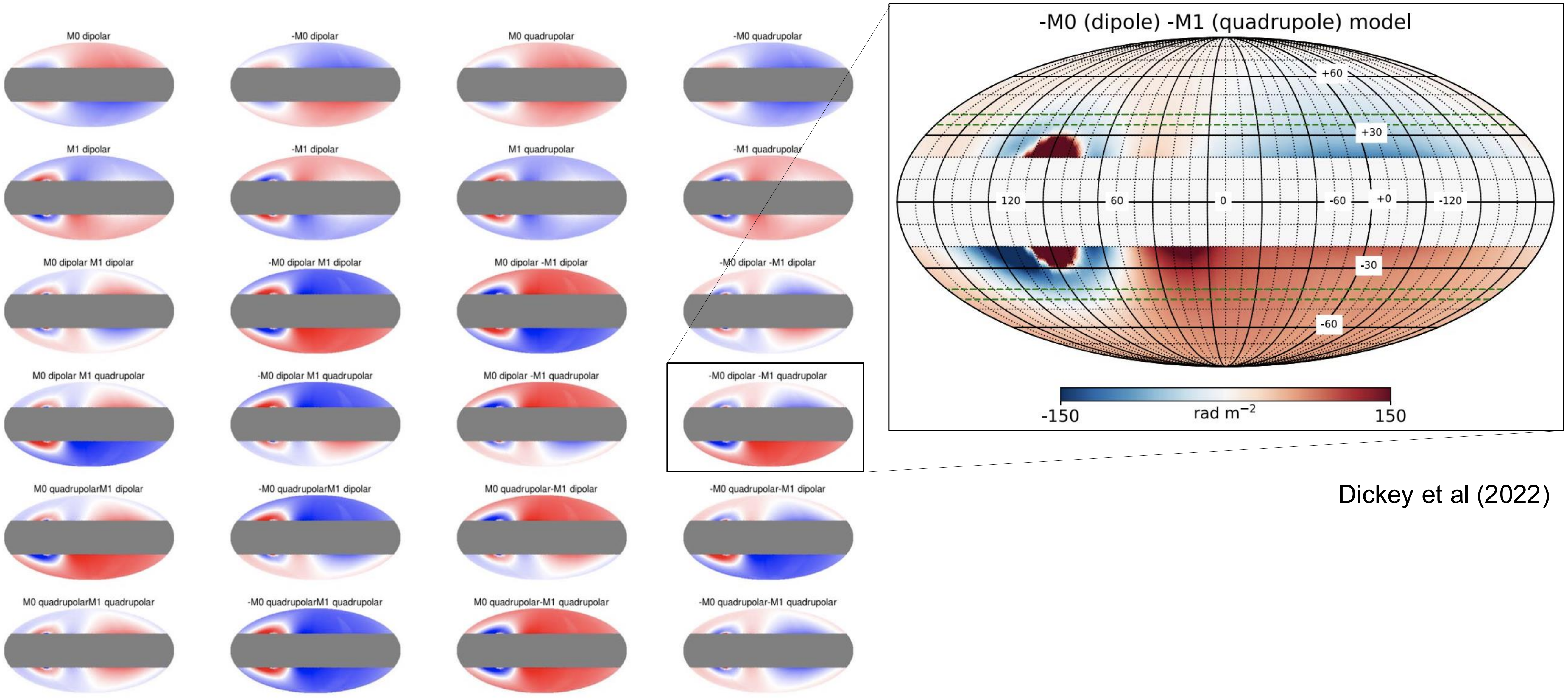
Caroline van Bergen, bachelor thesis Radboud University





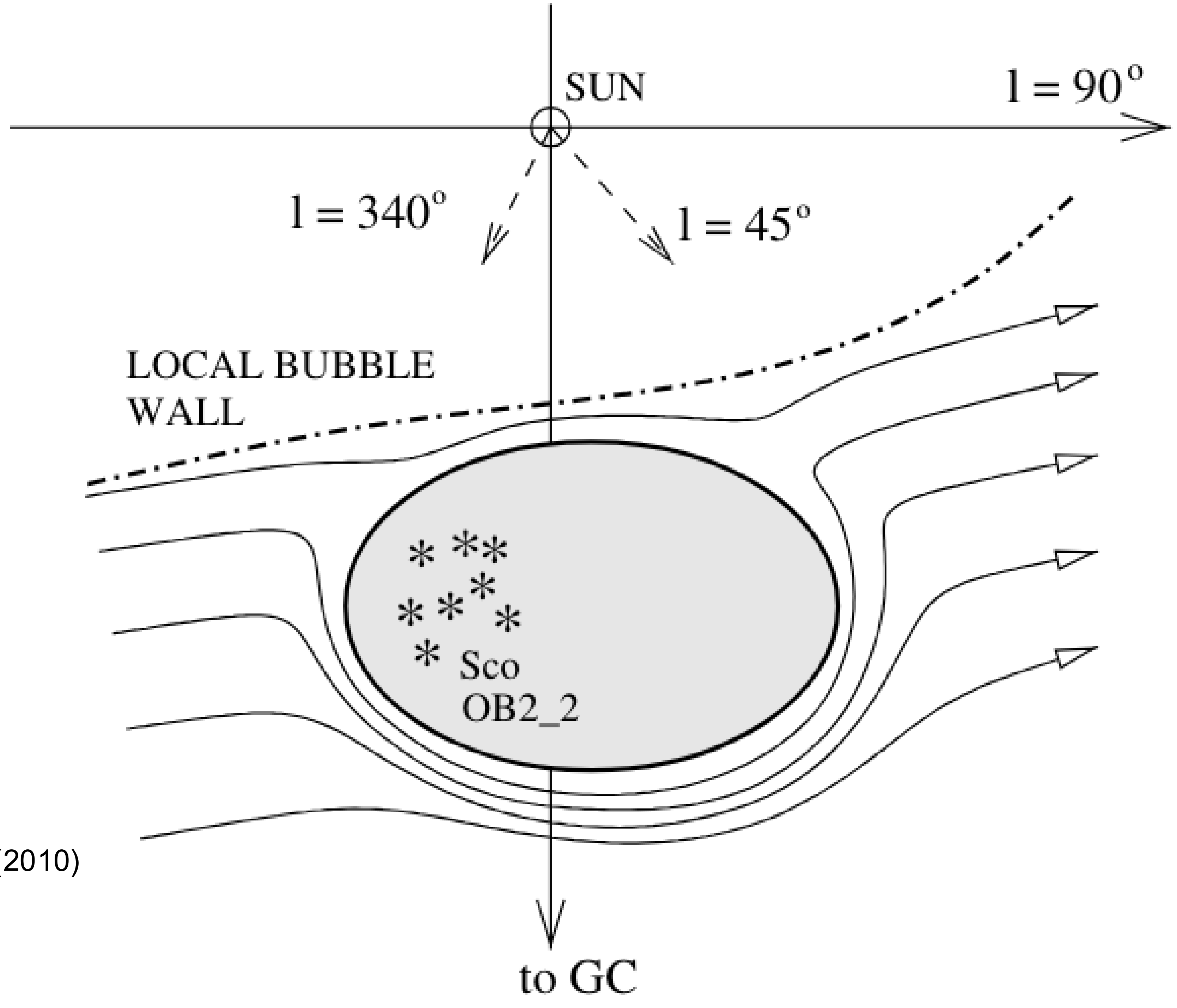


Coherent Galactic magnetic field: M0 dipole + M1 quadrupole?



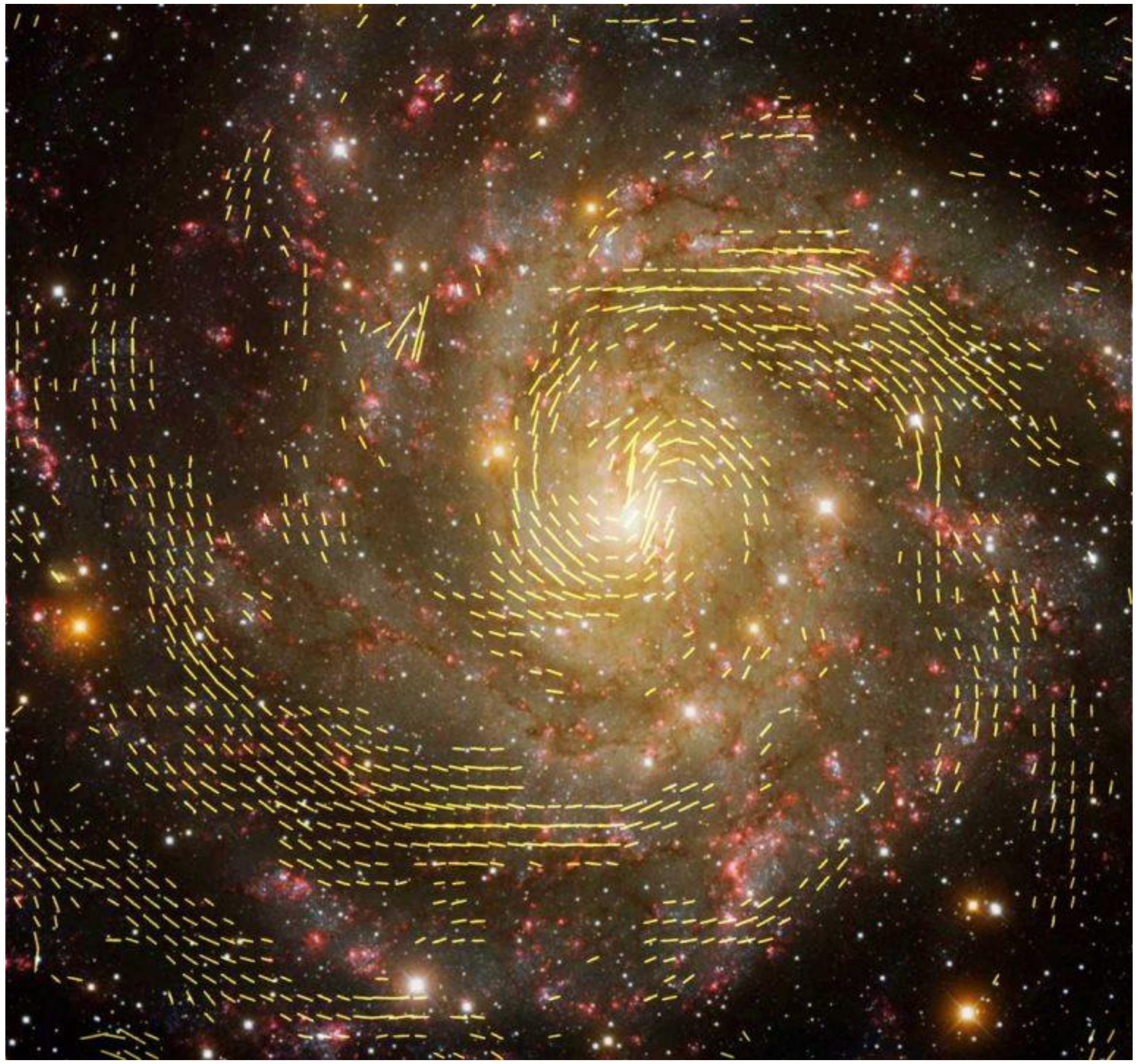
Dickey et al (2022)

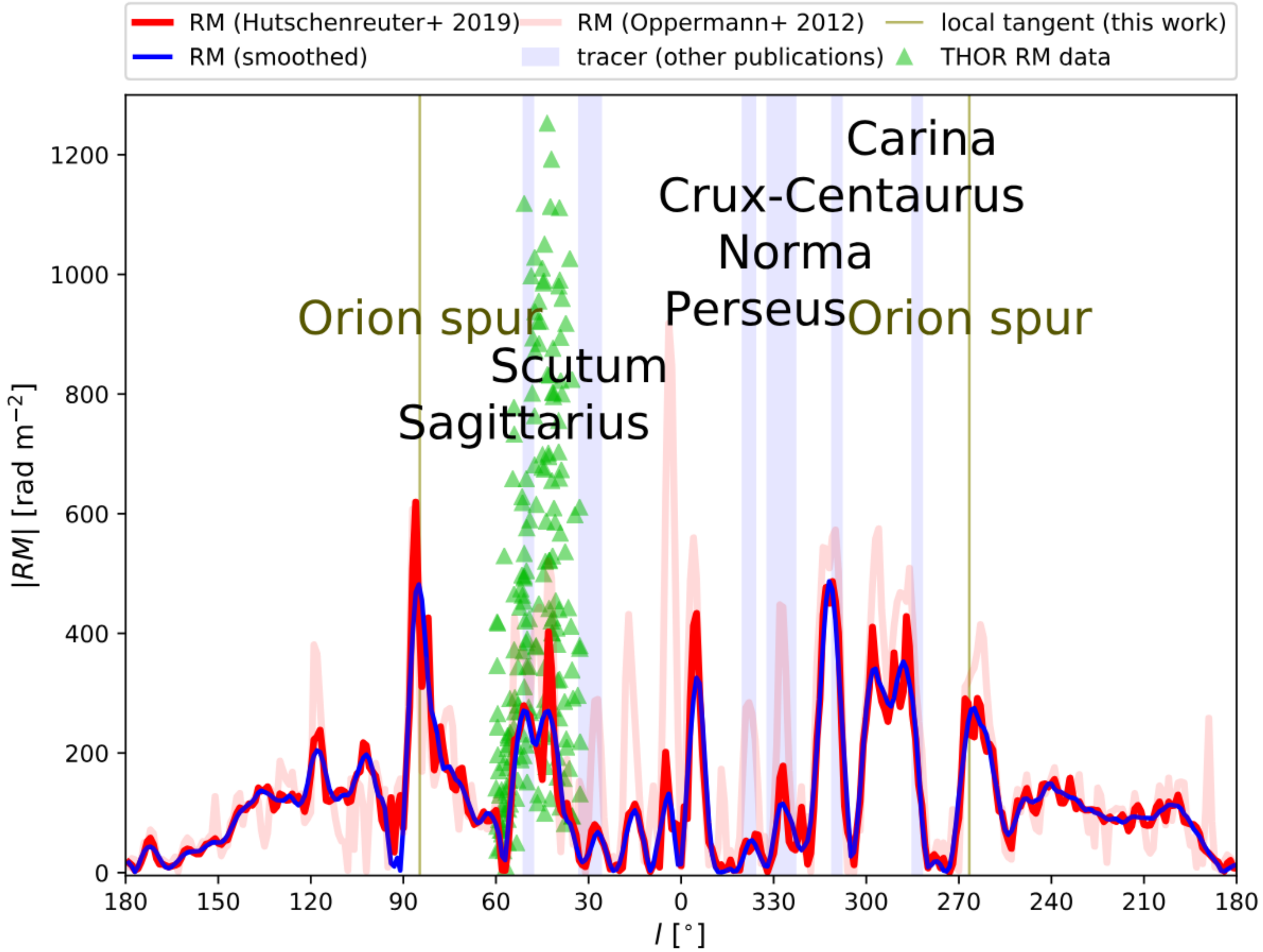
Coherent Galactic magnetic field: Or just an in-your-face foreground structure?



Wolleben et al (2010)

Magnetic arms in between spiral arms?

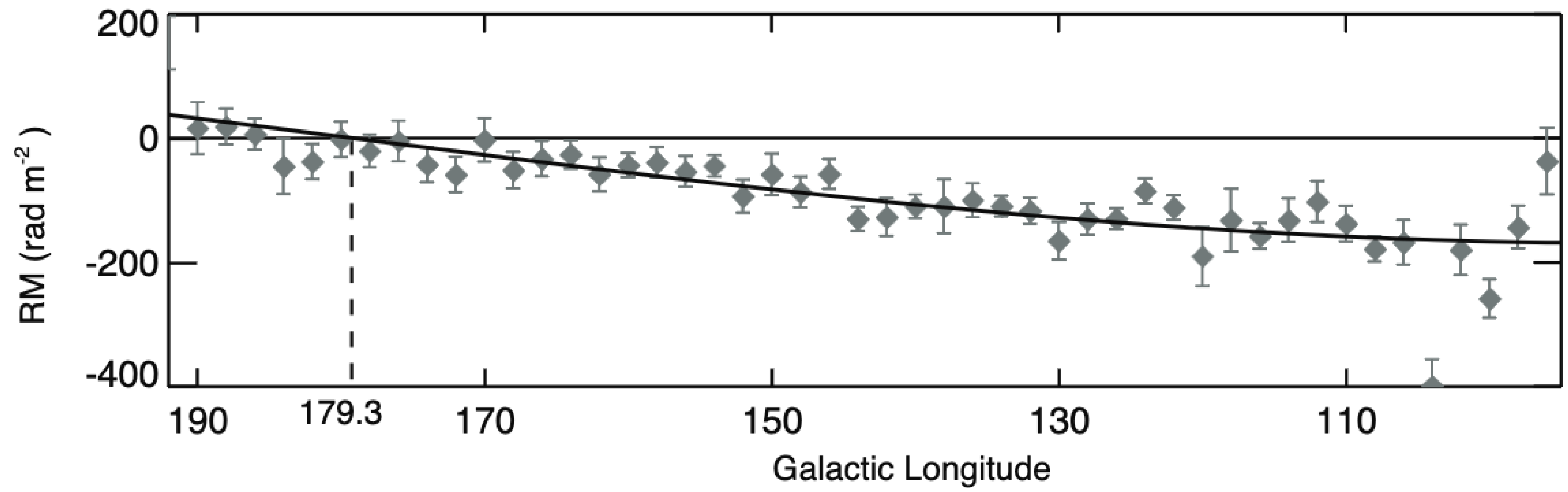




Reissl et al (2020), Shanahan et al (2019)

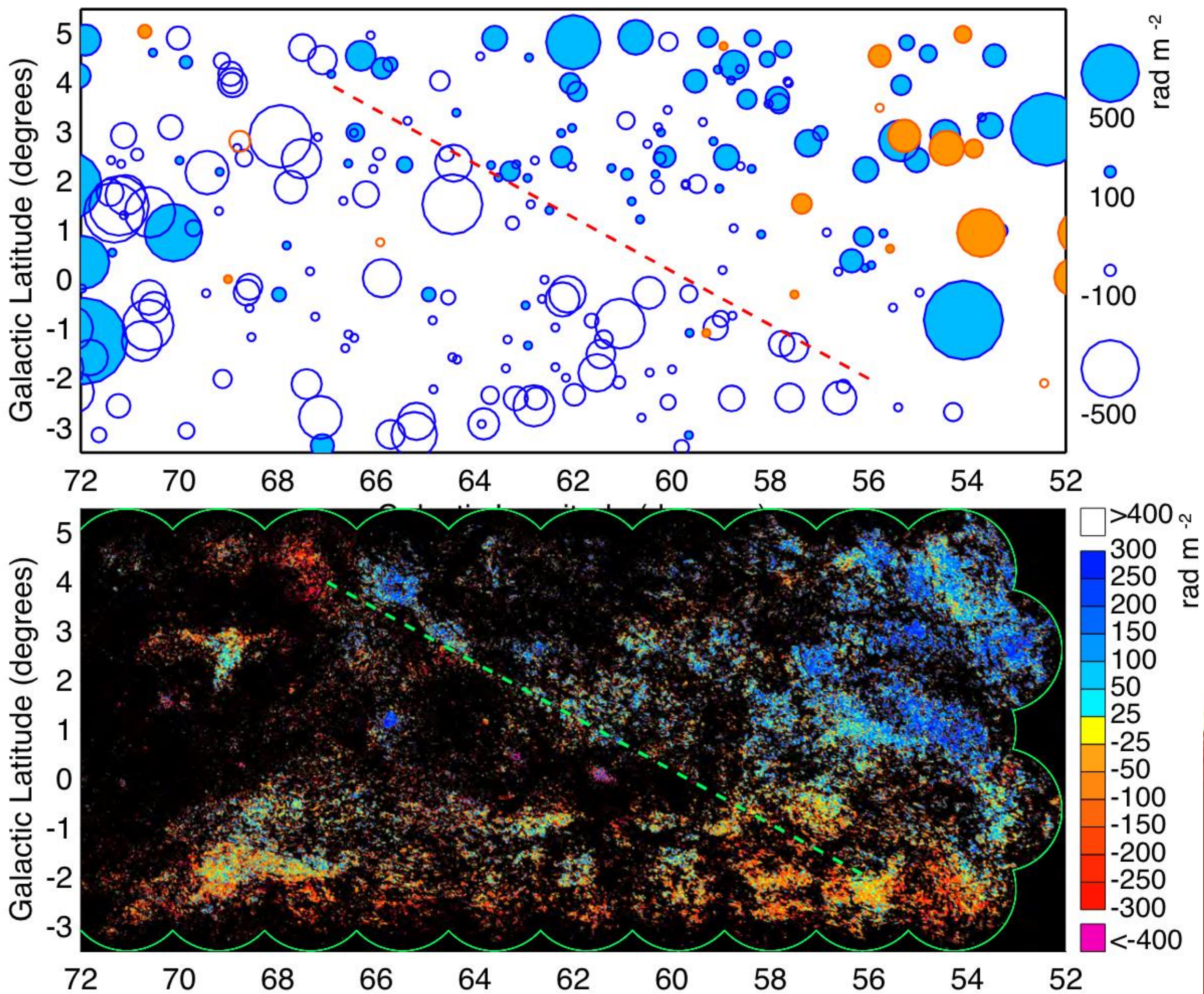
Image credit: R. Beck, MPIfR; NRAO/AUI/NSF; graphics: U. Klein, AIfA; Background image: T.A. Rector, University of Alaska Anchorage and H. Schweiker, WIYN; NOAO/AURA/NSF.

Deviations from ‘simple’ spiral arms

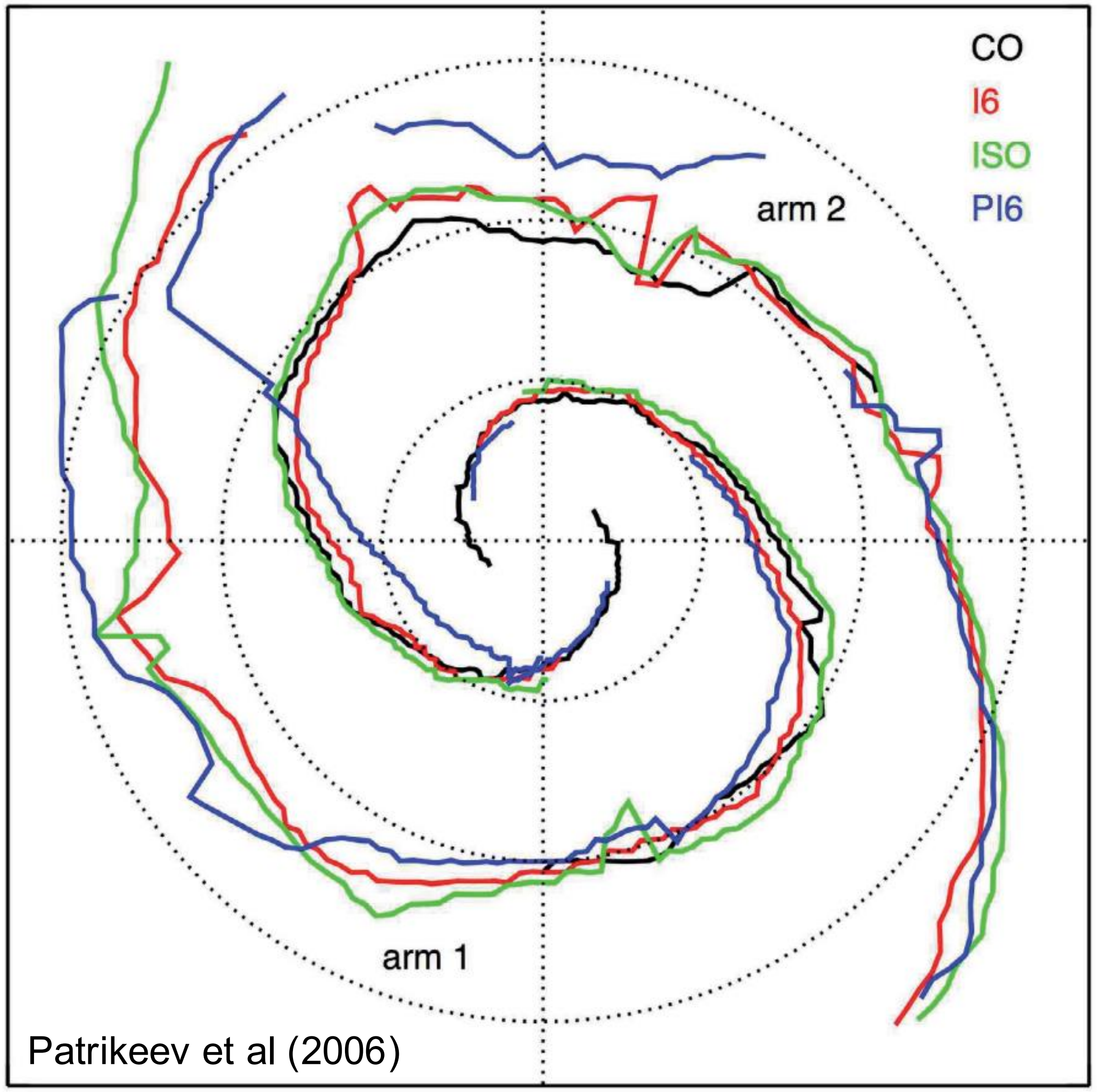


Rae & Brown (2010)

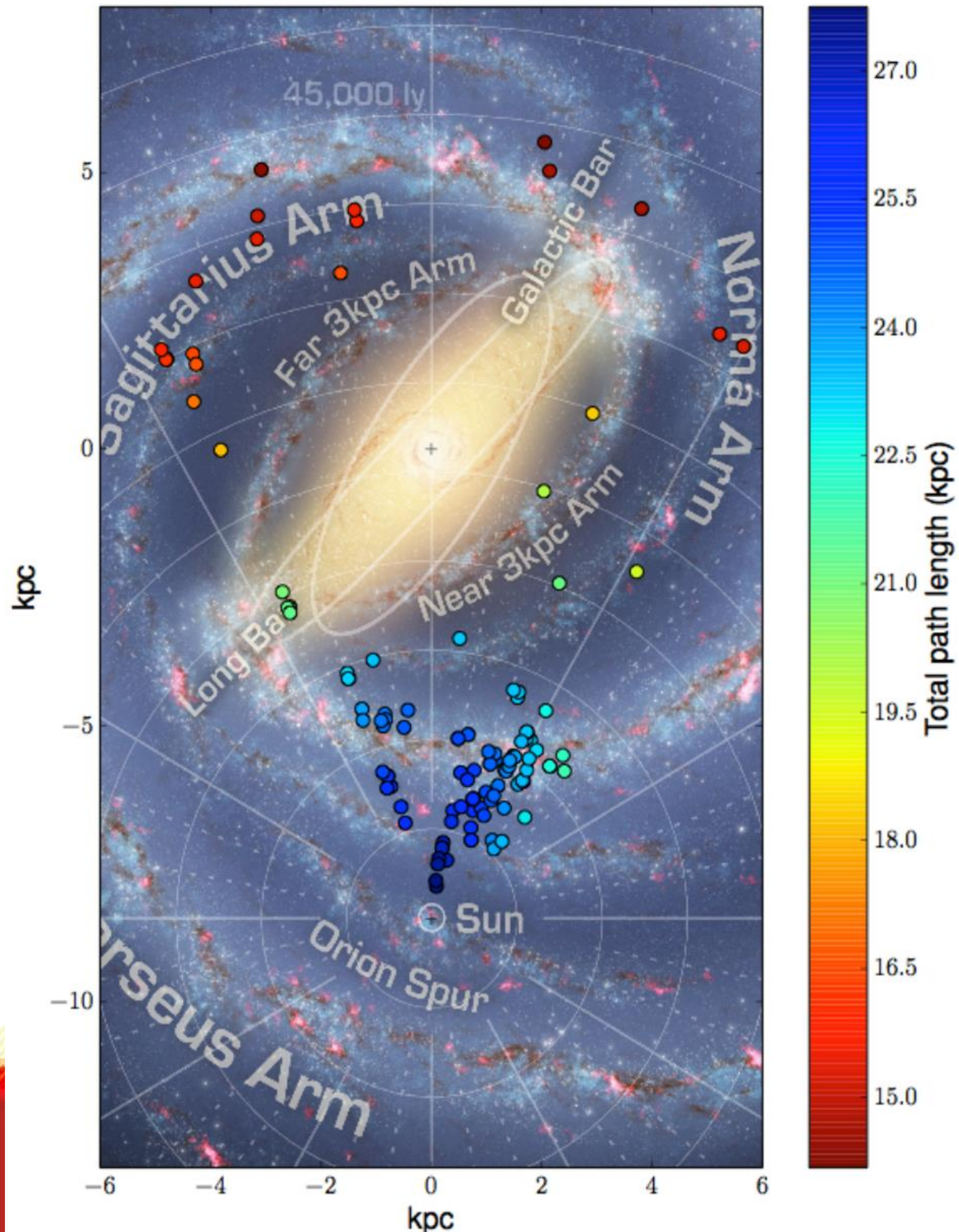
Ordog et al (2017)

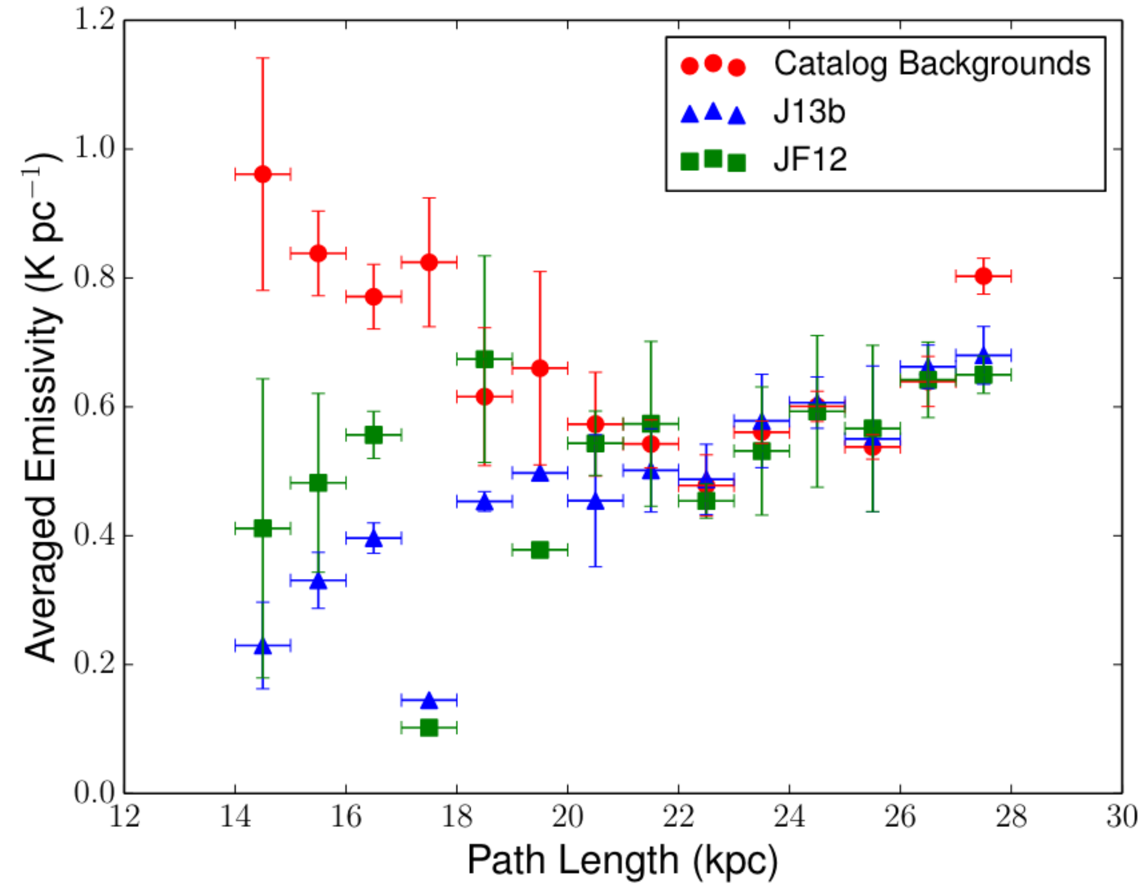


Coherent Galactic magnetic field: deviations



Deviations from 'simple' spiral arms

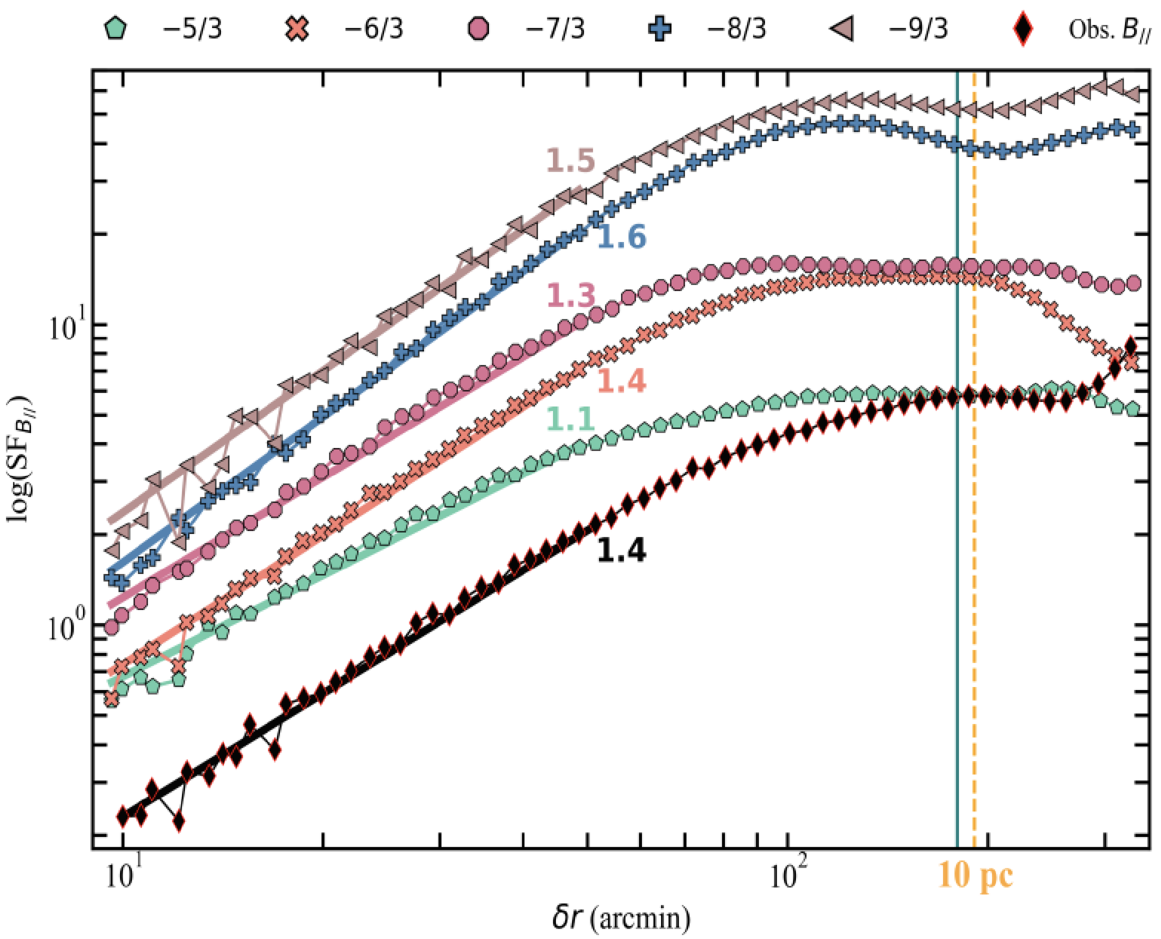




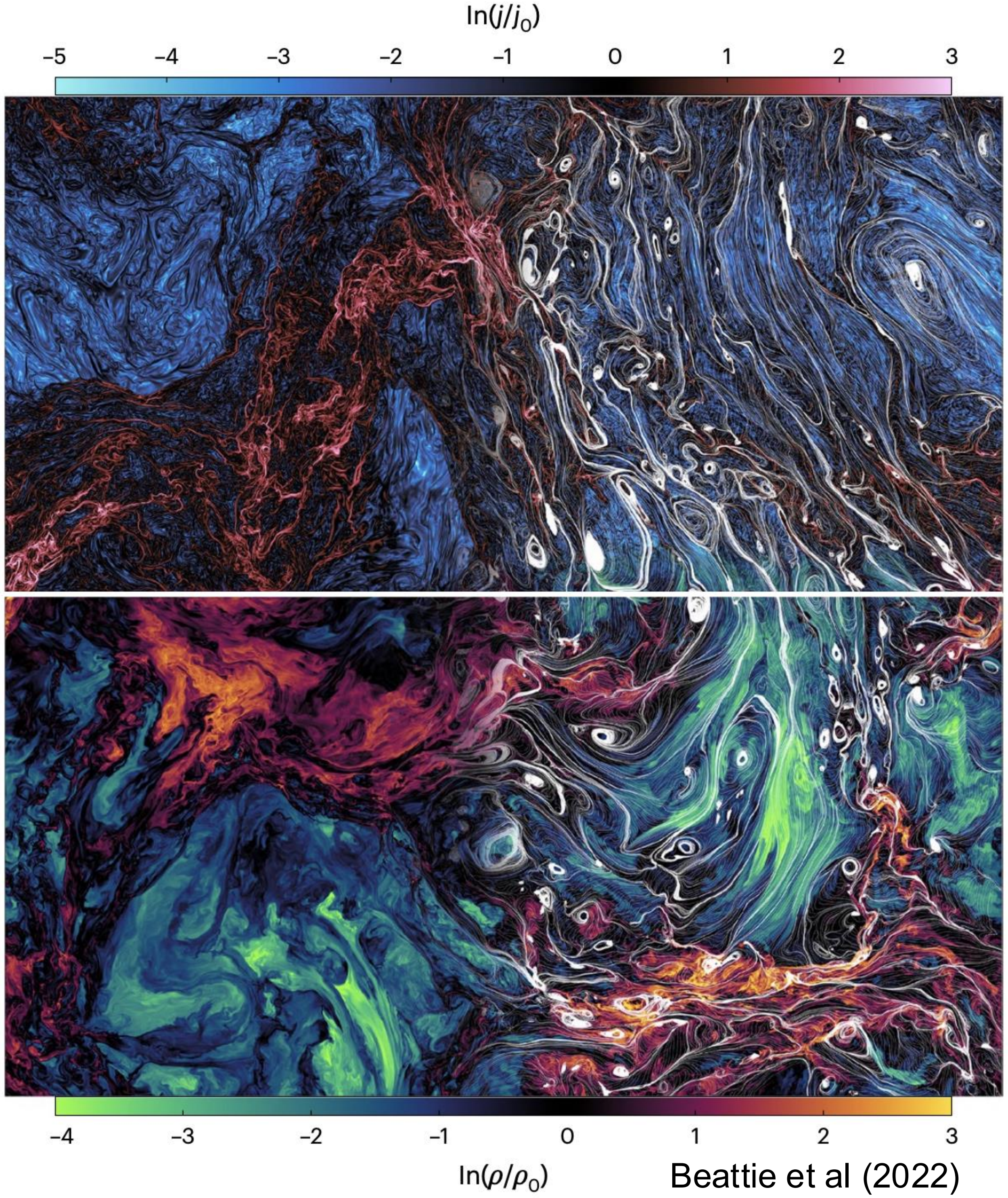
Polderman et al (2019),
AL-Zetoun et al (in prep)

Radboud Universiteit

Small-scale turbulent magnetic fields

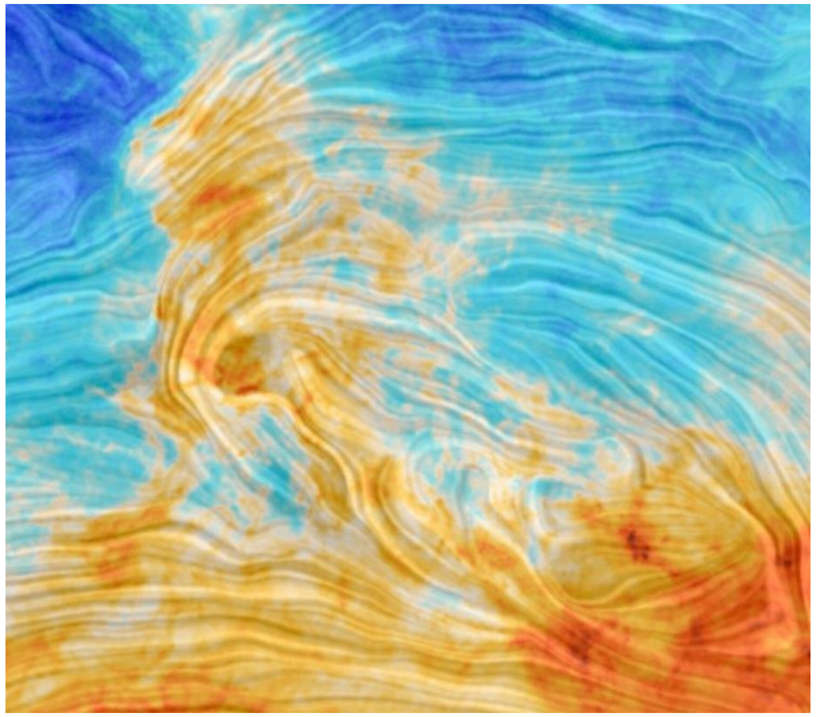


Raycheva et al (2022)

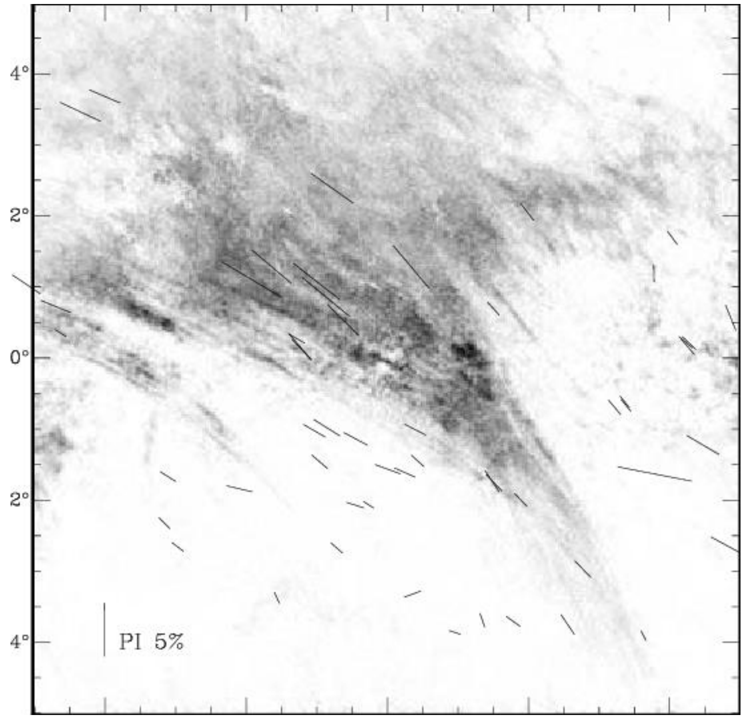


Beattie et al (2022)

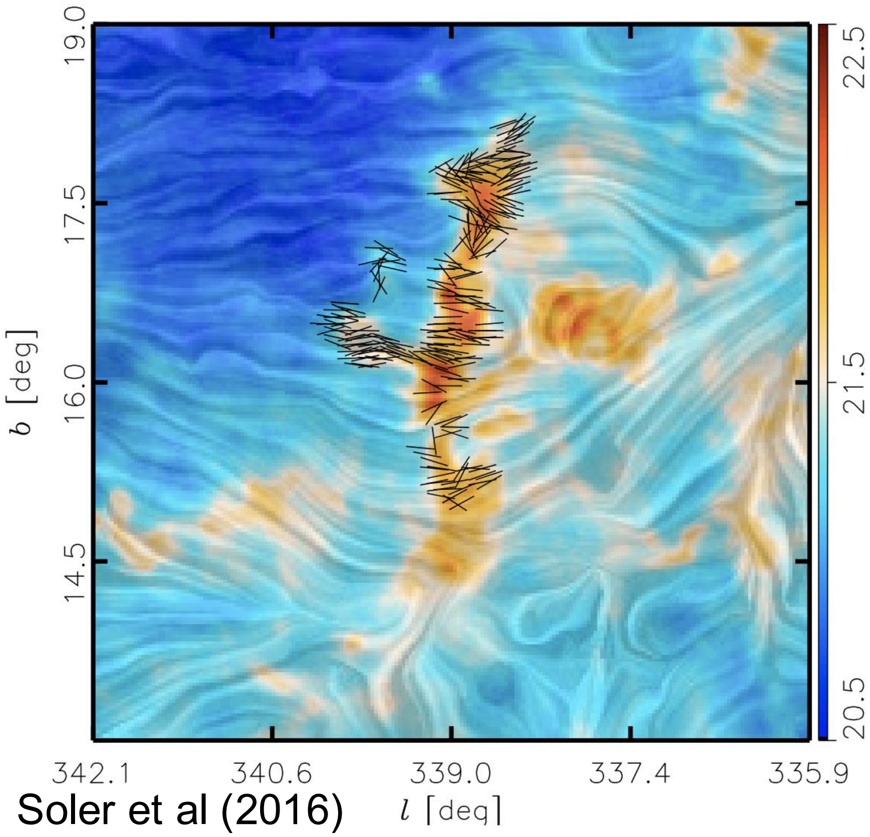
Small-scale structure correlates with the ISM



Credit: ESA and the Planck Collaboration

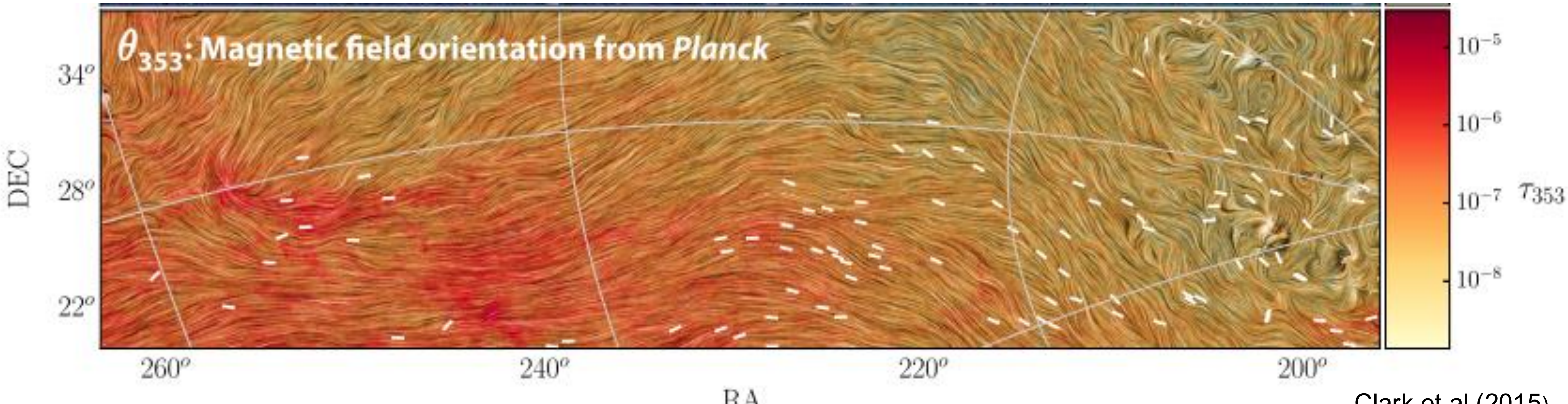


McClure-Griffiths et al (2005)

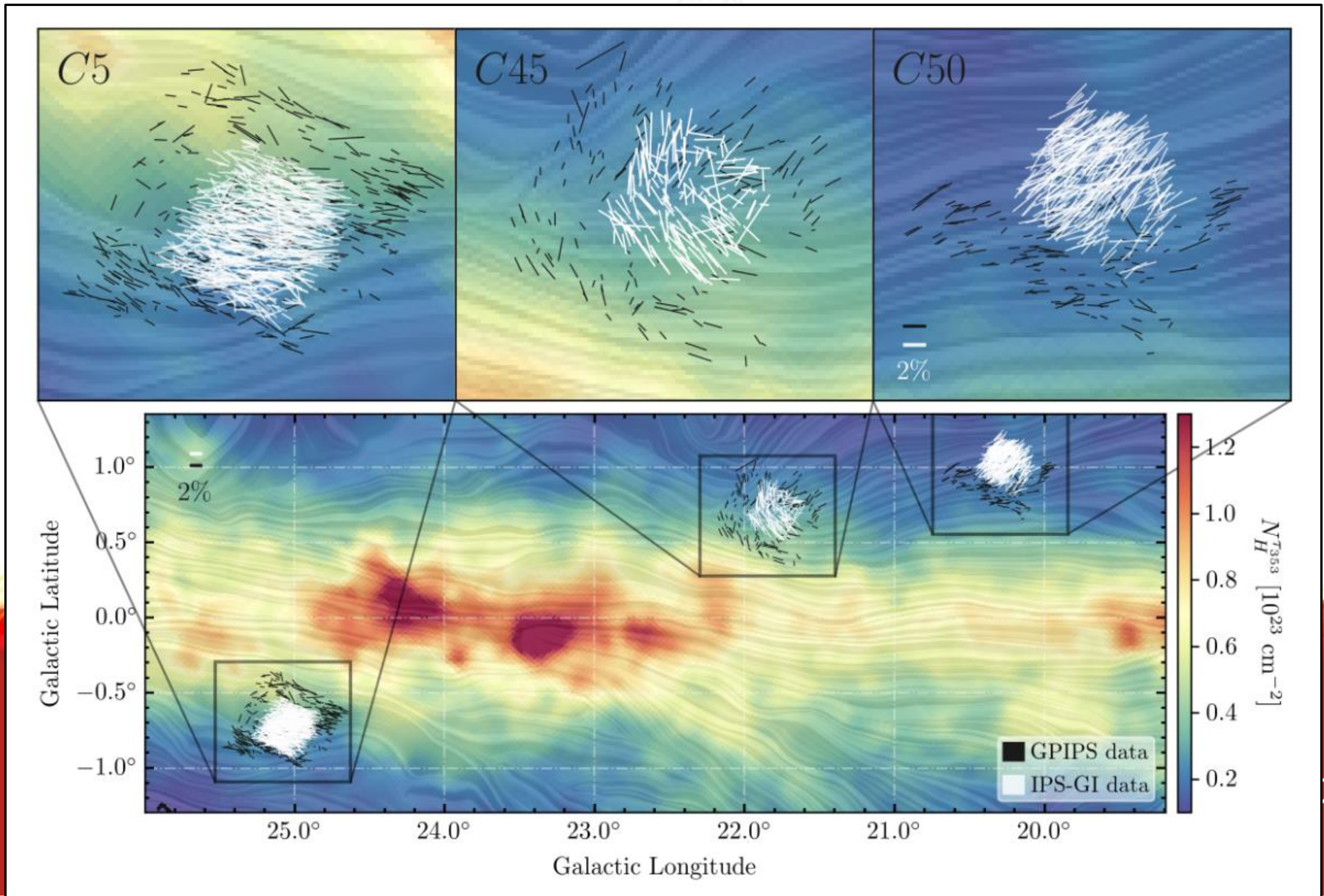


Soler et al (2016)

Magnetic field correlations: starlight polarization with dust polarization

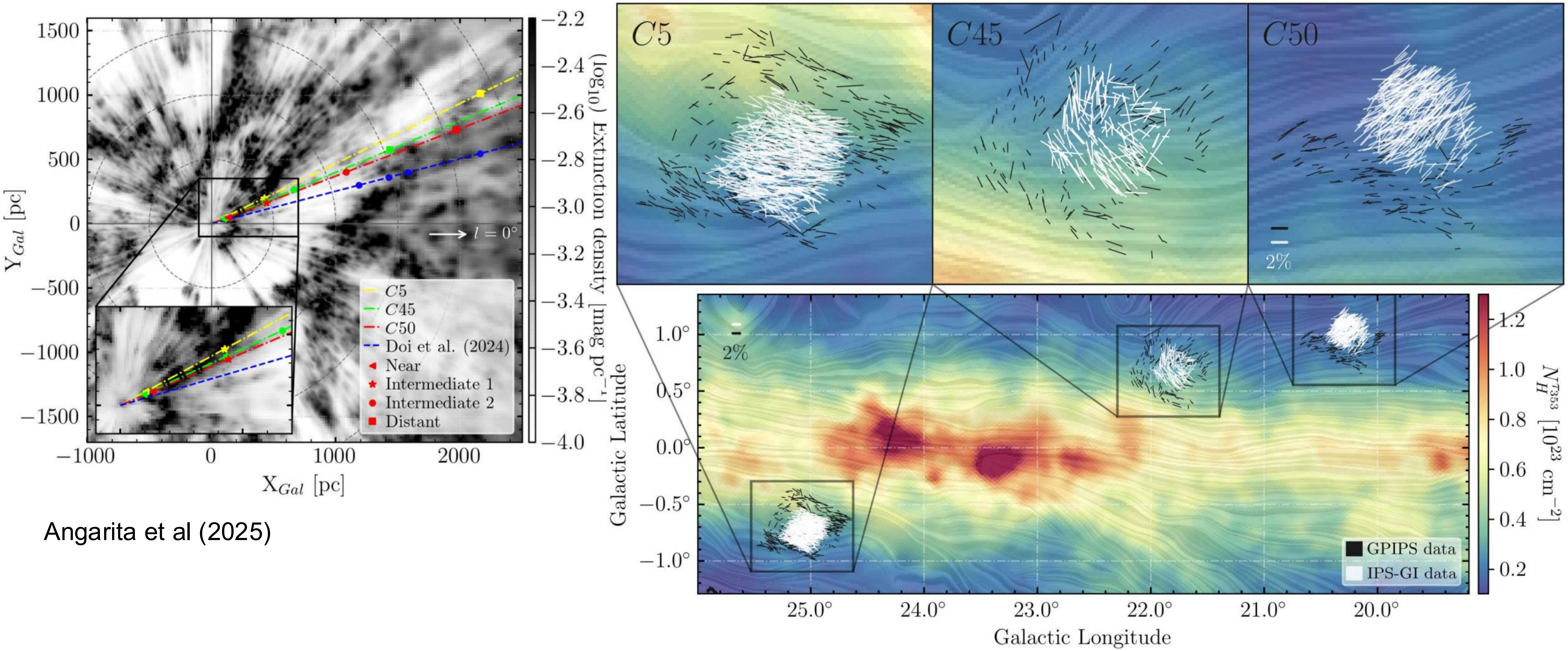


Clark et al (2015)



Angarita et al (2025)

Optical/near-infrared starlight polarization gives interstellar magnetic field in 3 spatial dimensions



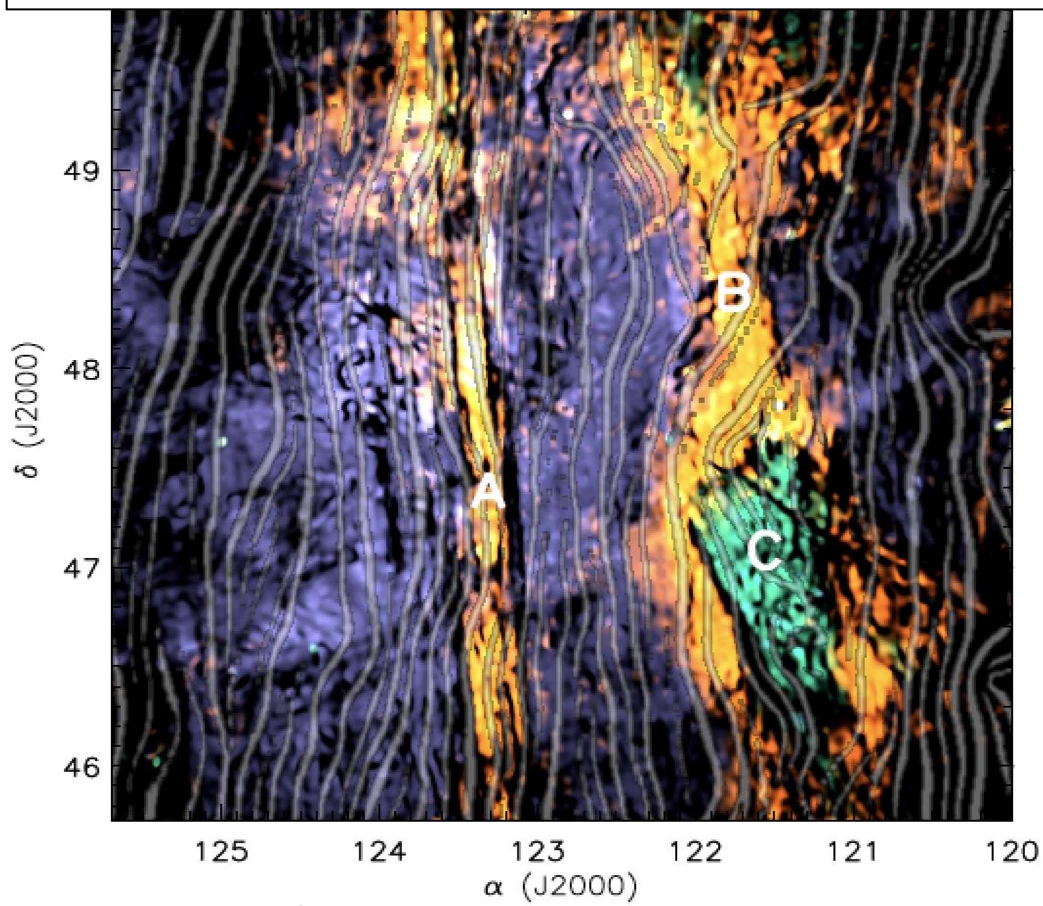
Angarita et al (2025)

Magnetic field correlations: starlight polarization with with neutral gas filaments

Clark et al (2015)

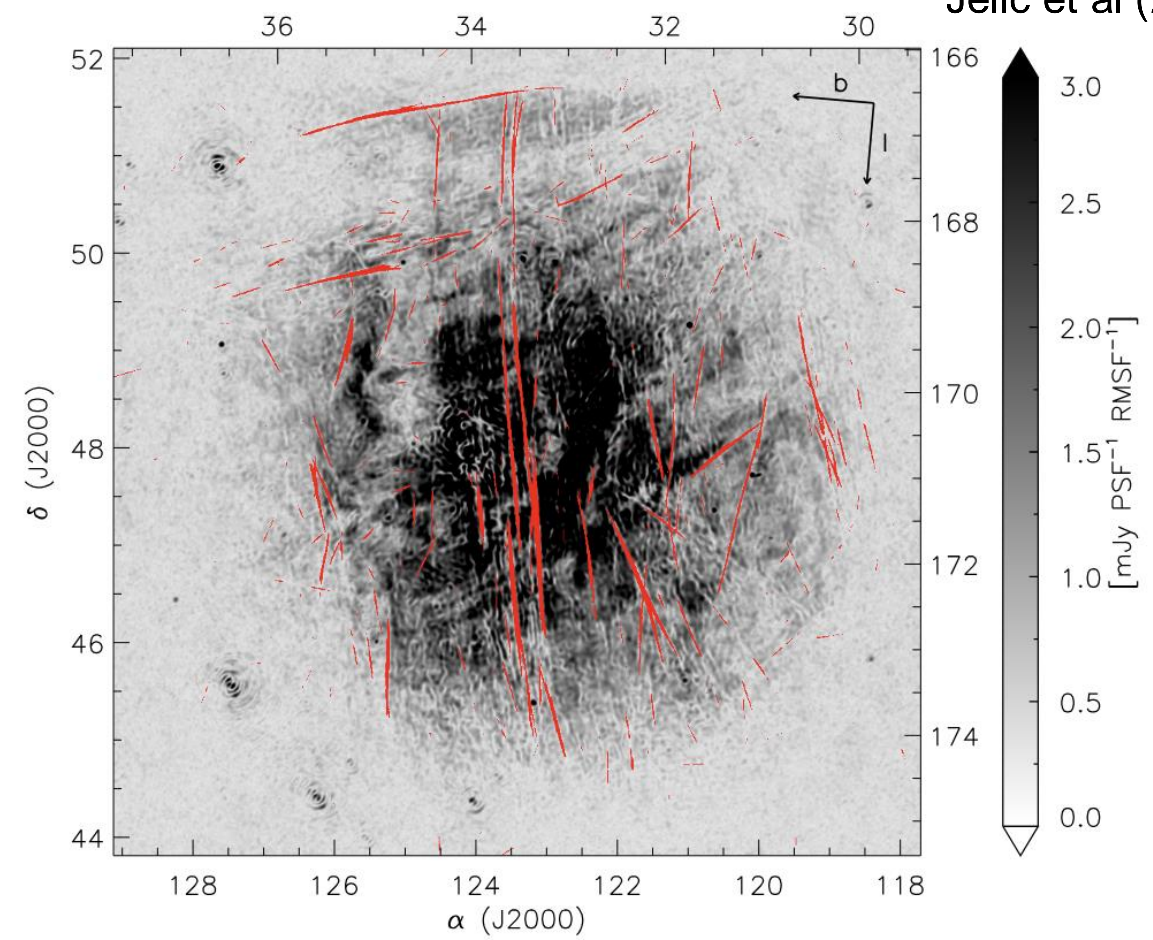
Magnetic field correlations: dust polarization with LOFAR Faraday depth filaments

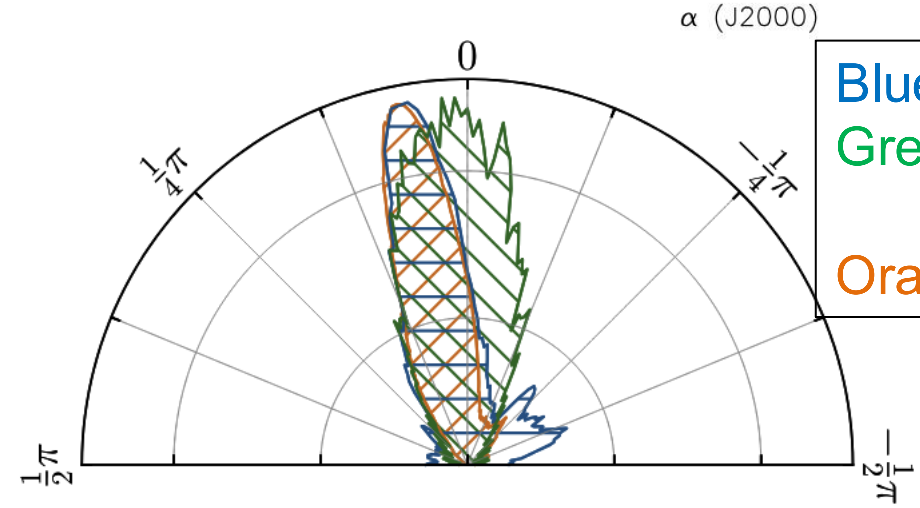
Color: LOFAR Faraday depth
Grey: magnetic field from dust polarization



Zaroubi et al (2015)

Jelić et al (2018)

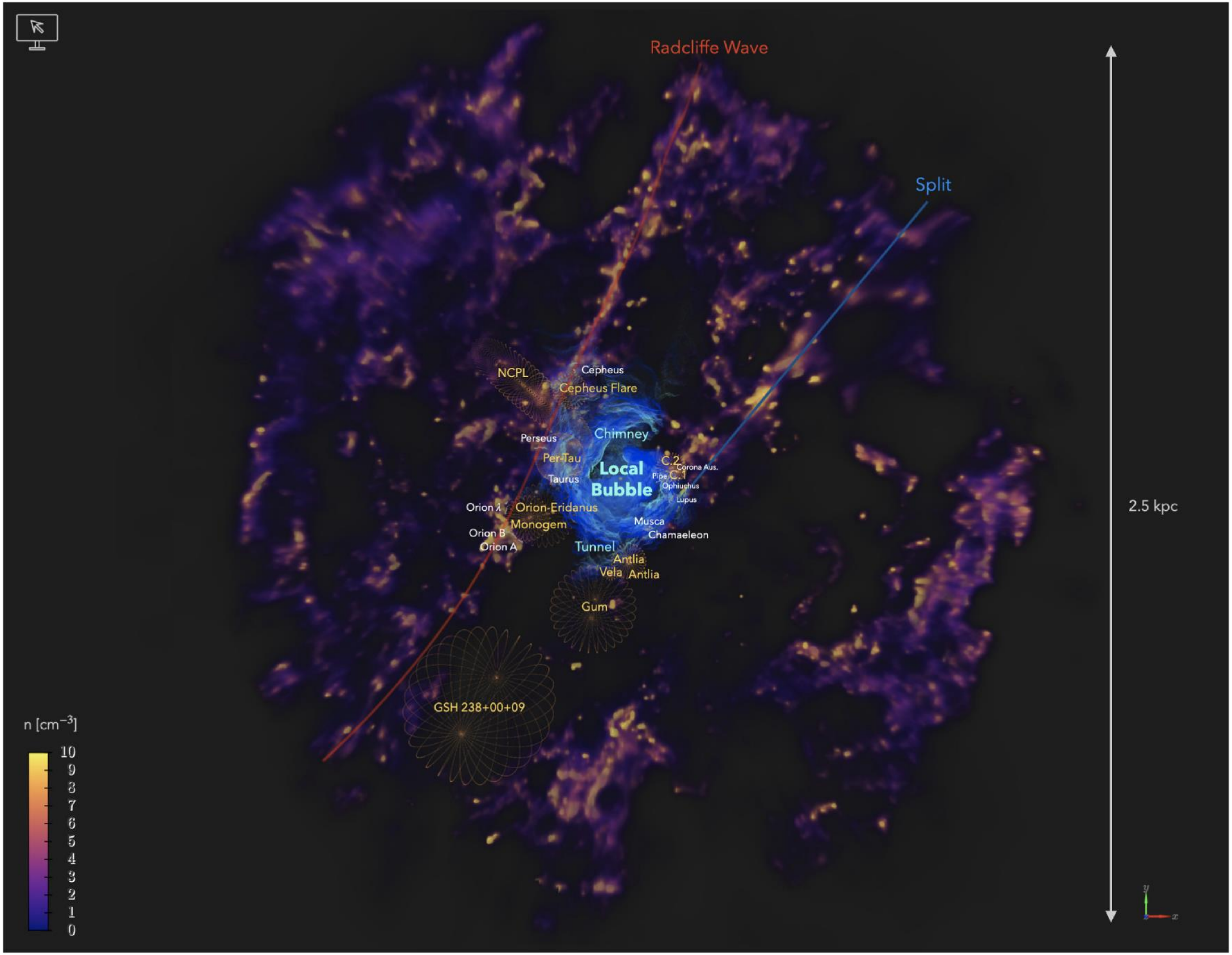




Blue: LOFAR Faraday depth
Green: magnetic field from dust polarization
Orange: HI filaments

Tracing the Local Bubble

O'Neill et al (2024)



Conclusions

Energy densities of thermal gas, turbulent gas, cosmic rays and interstellar magnetic field are comparable → all components are dynamically important and give feedback on each other.

Interstellar magnetic field important in driving gas dynamics, influencing star formation, dictating cosmic-ray propagation and diffusion, etc.

Magnetic fields are created (by some mechanism) in the early Universe, and are **amplified and maintained** by a dynamo process.

Large-scale Galactic magnetic field runs along spiral arms but also has a poloidal component; models get more complex, but cannot include observed deviations from spiral structure.

Small-scale interstellar magnetic field is intermittent, anisotropic turbulent; field orientations often **correlate** with dust and hydrogen gas filaments.