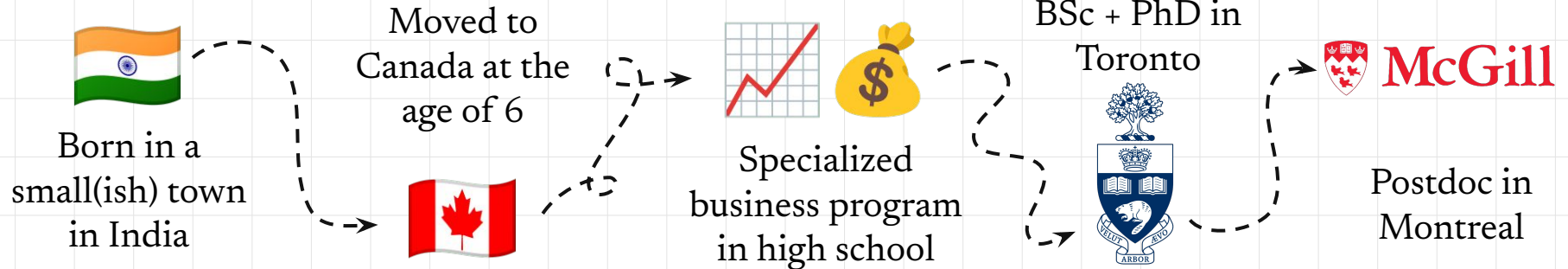




Ayush Pandhi



Polarimetry

CRASIES Summer School

05/27/2026

Ayush Pandhi, TSI Fellow



McGill



Trotter
Space Institute
at McGill



Why is Magnetism Important?

Magnetic fields are everywhere! They play a key role in astrophysical processes on various scales:

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- **Effect the evolution of planets (indicator of life/habitability)**

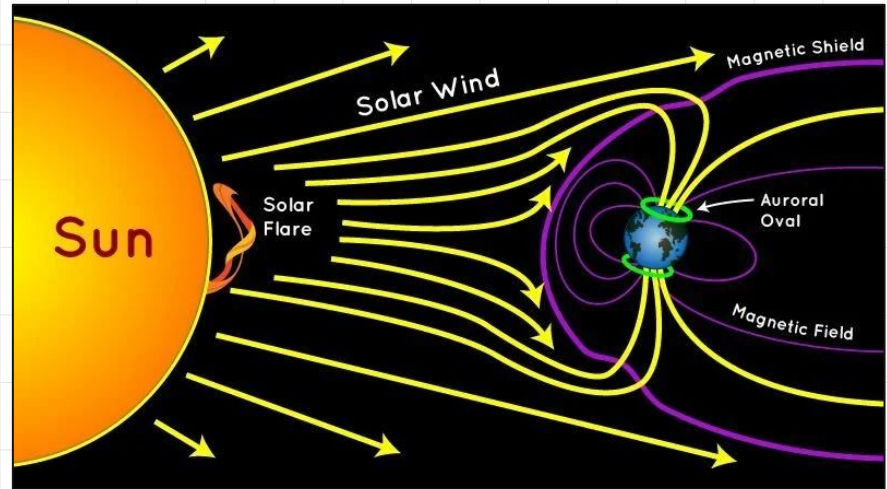


Image credit: NASA

Why is Magnetism Important?

Magnetic fields are everywhere! They play a key role in astrophysical processes on various scales:

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- **High-energy emission from compact objects**

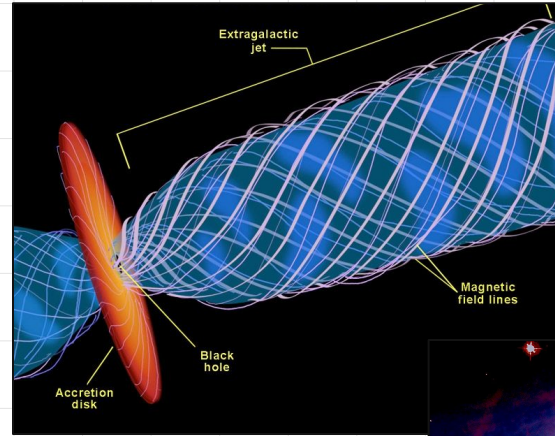


Image credits: NASA/Chandra



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- **Regulate protoplanetary disks and jets**

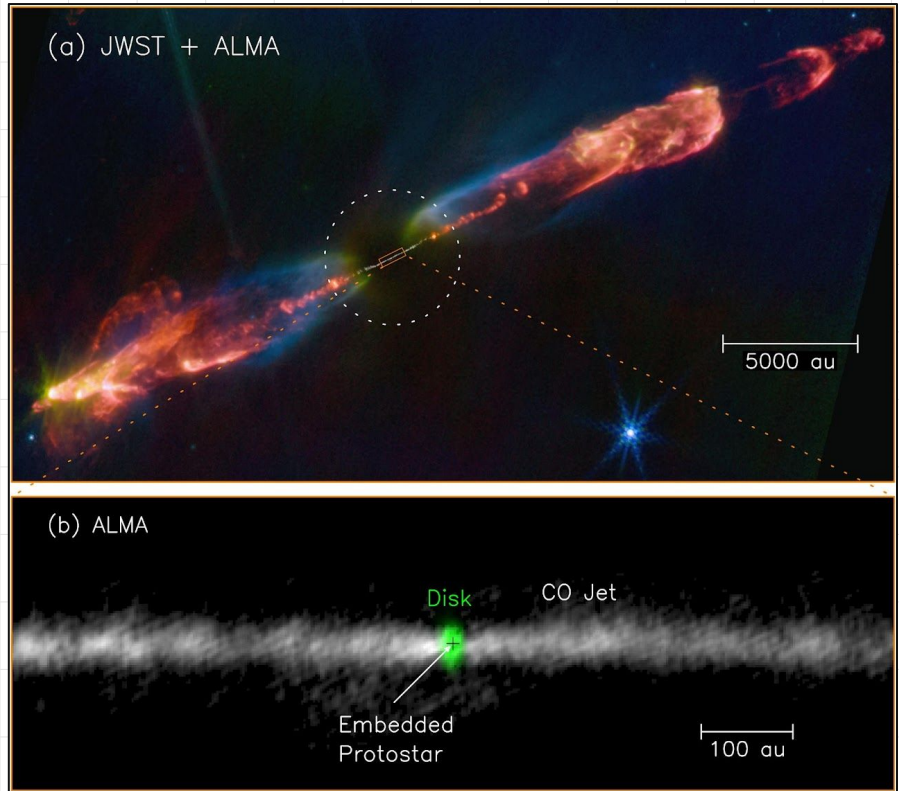


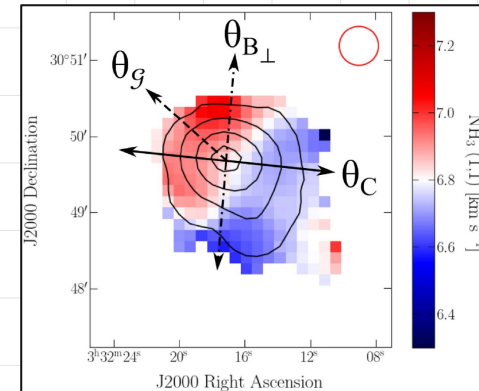
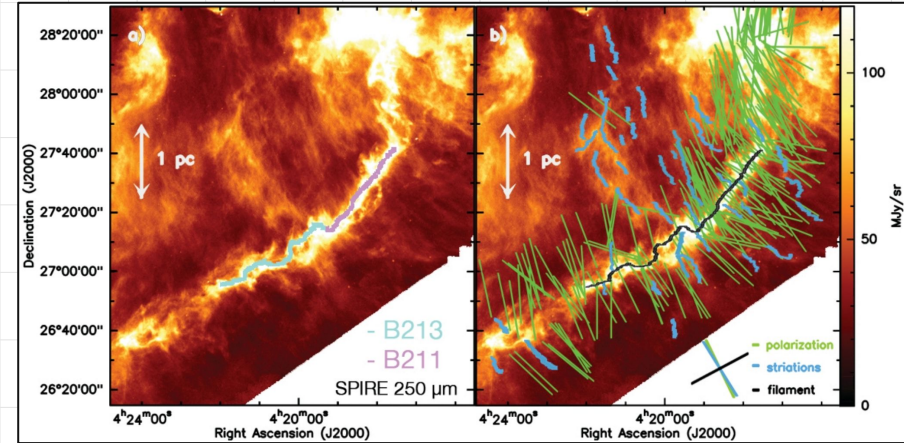
Image credits: NASA/JWST & ALMA

Why is Magnetism Important?

Palmeirim+ (2012)

Magnetic fields are everywhere! They play a key role in astrophysical processes on various scales:

- Effect the evolution of planets (indicator of life/habitability)
- High-energy emission from compact objects
- Regulate protoplanetary disks and jets
- **Shape the collapse of molecular clouds/star forming regions**



Pandhi+ (2023)

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- Effect the evolution of planets (indicator of life/habitability)
- High-energy emission from compact objects
- Regulate protoplanetary disks and jets
- Shape the collapse of molecular clouds/star forming regions
- **Affect gas dynamics, turbulence and cosmic ray propagation on galaxy (and cluster) scales**

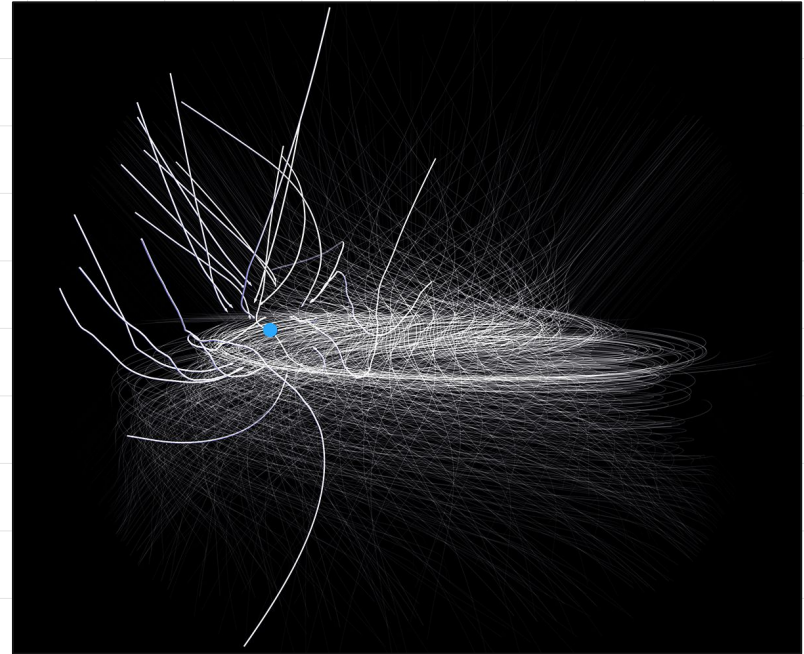


Image credit: NASA/Glennys Farrar

Observing Magnetic Fields

Magnetic field at a given point is a 3D vector, we observe projected components:

- Line-of-sight versus plane-of-sky magnetic field
 - Or physical components such as poloidal versus toroidal or ordered versus random
- Strength versus orientation



Image credit: Rainer Beck

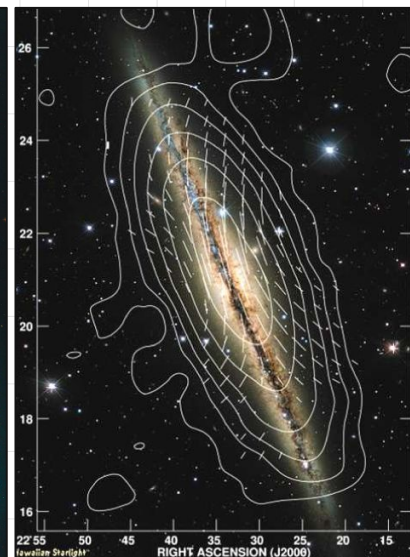


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Think of it like the velocity of a star: we observe radial velocity + proper motion and can translate that into galactocentric coordinates

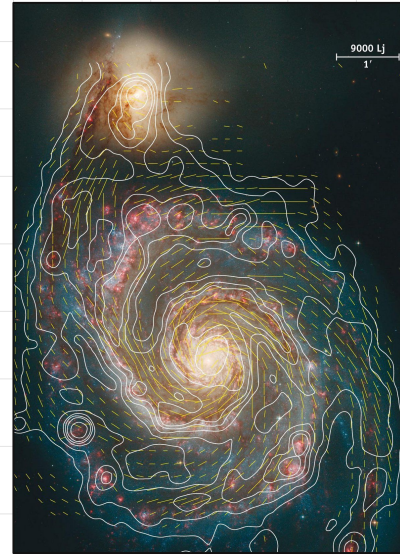


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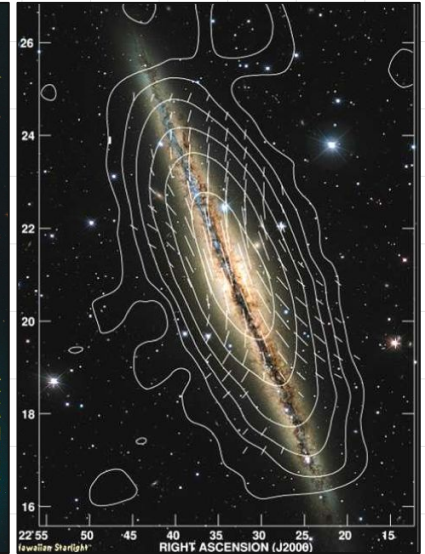


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Magnetic fields themselves are invisible; need to measure their influence on electromagnetic emission



Image credit: Rainer Beck

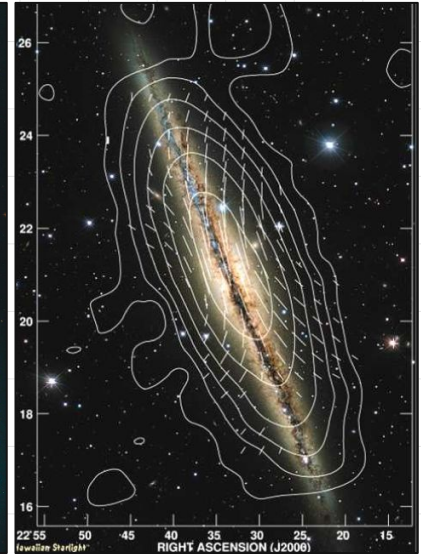


Image credit: Marita Krause

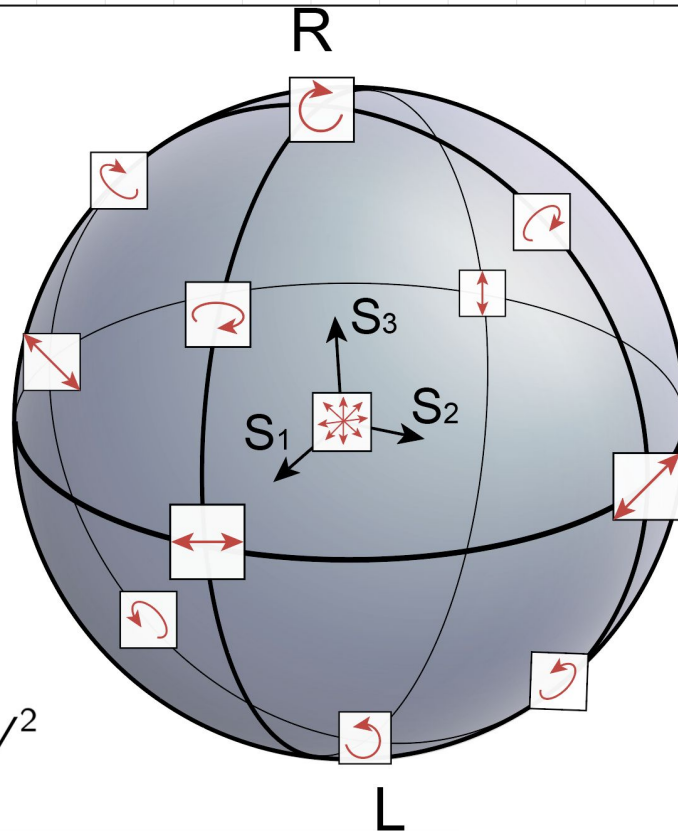
Radio Polarimetry Basics

$$S_0 = I = E_x^2 + E_y^2$$

$$S_1 = Q = E_x^2 - E_y^2$$

$$S_2 = U = 2E_x E_y \cos \delta$$

$$S_3 = V = 2E_x E_y \sin \delta$$



$$\text{radius} = I^2 \geq Q^2 + U^2 + V^2$$

Image credit: Greg Gbur

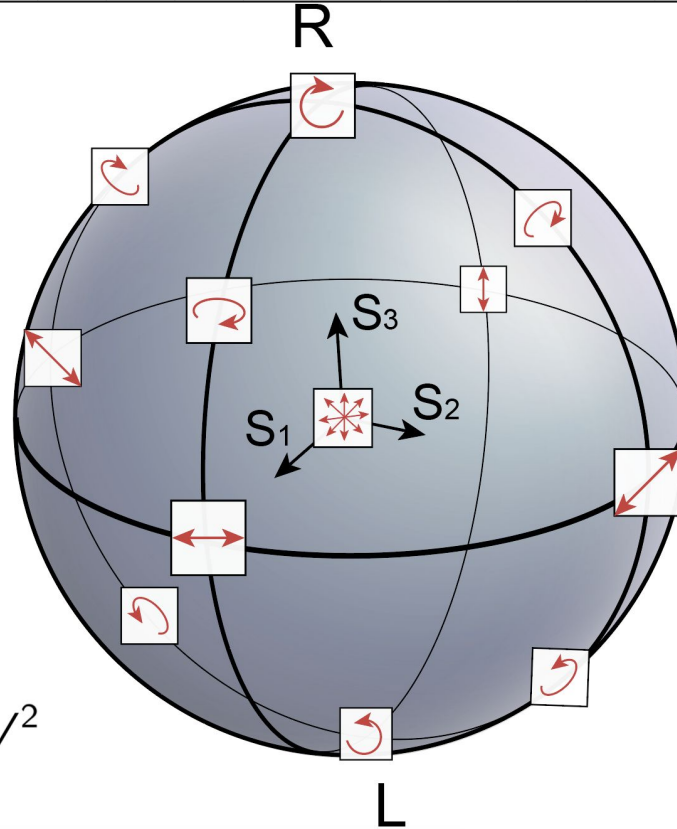
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$$\text{radius} = I^2 \geq Q^2 + U^2 + V^2$$

Image credit: Greg Gbur

Linear pol fraction:

$$L/I = [Q^2 + U^2]^{1/2}/I$$

Circular pol fraction:

$$|V|/I$$

Total pol fraction:

$$P/I = [Q^2 + U^2 + V^2]^{1/2}/I$$

Linear pol angle:

$$PA = 0.5 \tan^{-1}(U/Q)$$

Ellipticity angle:

$$EA = 0.5 \tan^{-1}(V/L)$$

Piecing Together Magnetic Fields

Tracer	$B_{\parallel}$	$B_{\perp}$	Orientation	Strength	2D or 3D?	Where?

Starlight Polarization

Wavelength regime: IR – UV

- A fraction of dust grains are elongated with their short axes aligned with the local magnetic field
- Background (unpolarized) light absorbed preferentially along the long axes
- Resulting light is polarized parallel to the intervening magnetic field

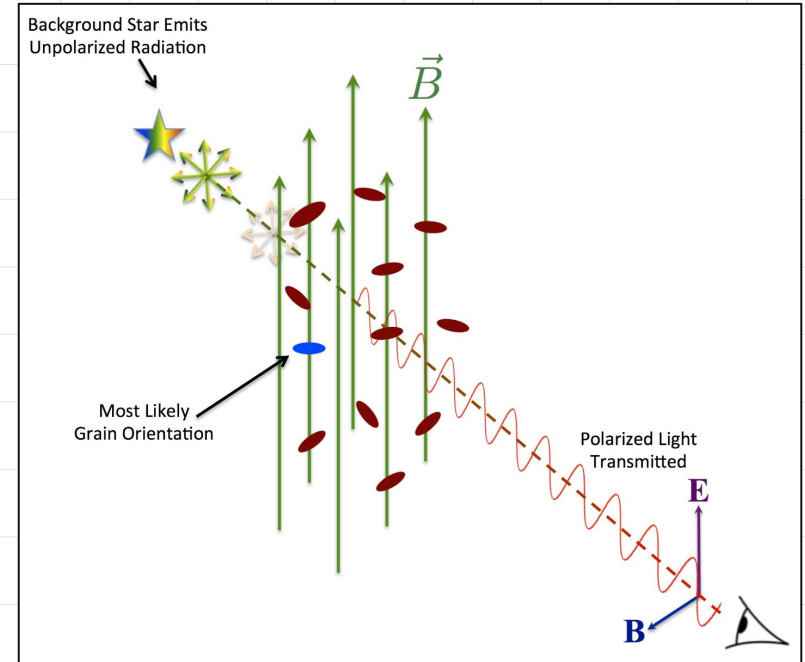


Image credit: B-G Anderson

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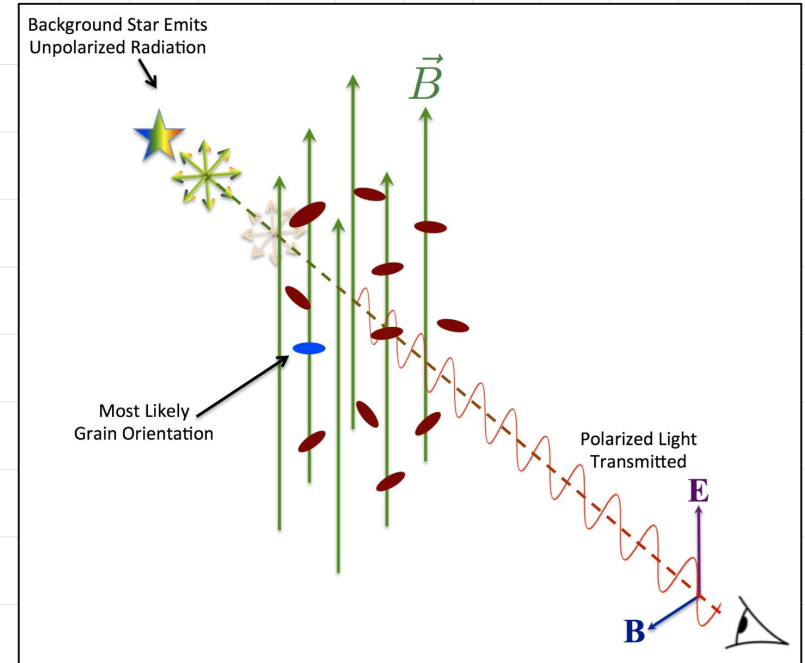


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What magnetic field components can we learn about with starlight polarization? Limiting factor?

⇒ **2D $B_{\perp}$ orientation (with some 3D information), limited to very local volume (~1-2 kpcs)**

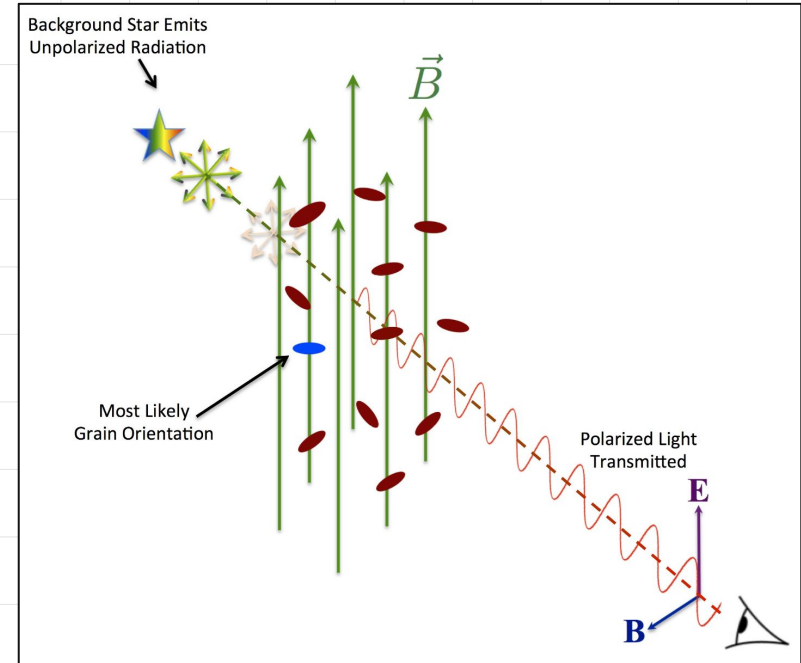
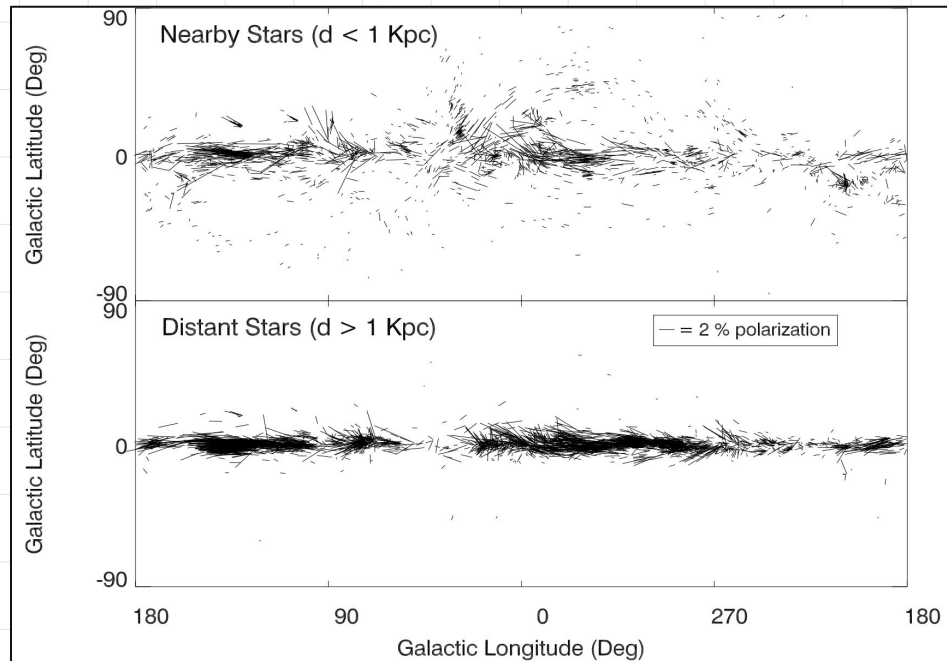
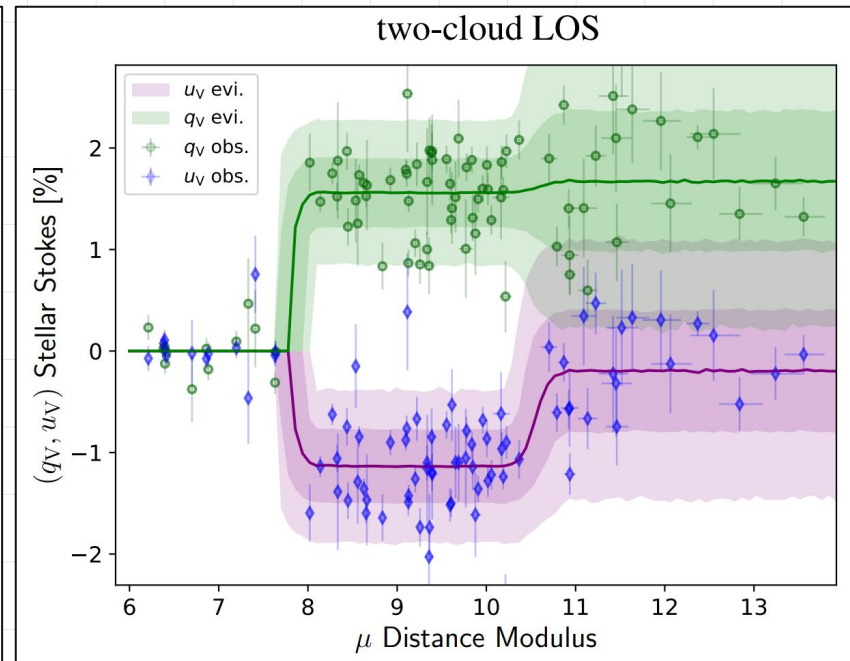


Image credit: B-G Anderson

Starlight Polarization



Fosalba+ (2002)



Pelgrims+ (2023)

Piecing Together Magnetic Fields

Tracer	$B_{\parallel}$	$B_{\perp}$	Orientation	Strength	2D or 3D?	Where?
Starlight	✗	✓	✓	✗	3D(ish)	< 1-2 kpc

Dust Polarization

Wavelength regime: sub-mm – IR

- Dust heated by absorbed light, re-emits as thermal radiation at longer wavelengths
- Thermal radiation is preferentially polarized along the long axes of the dust grains
- Resulting radiation is polarized perpendicular to the local magnetic field

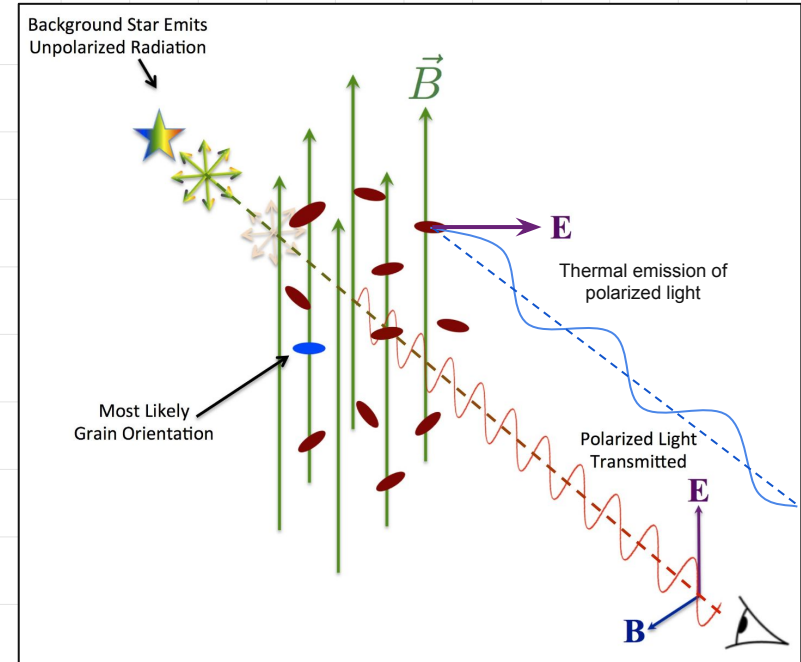


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⇒ **2D $B_{\perp}$ orientation only (no depth information)**

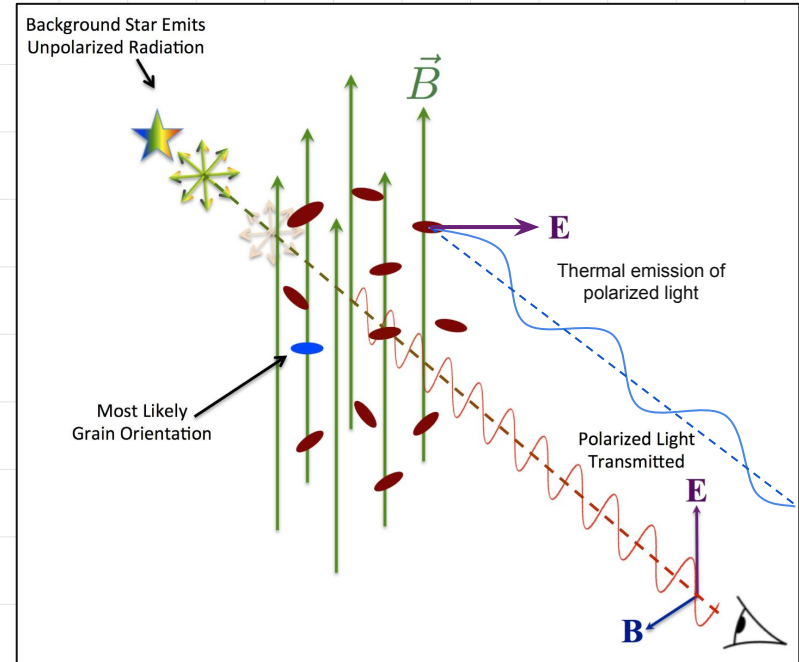


Image credit: B-G Anderson

Dust Polarization

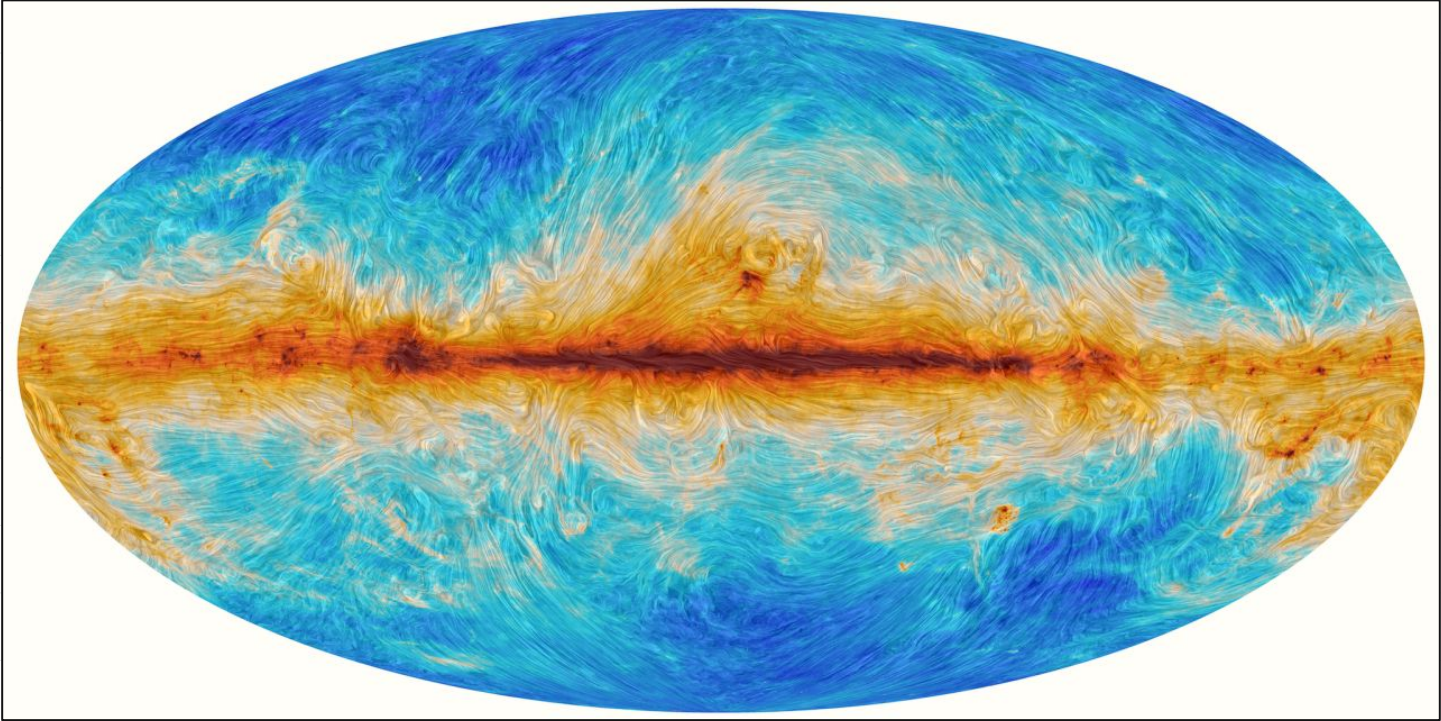


Image credit: ESA/Planck Collaboration

Dust Polarization

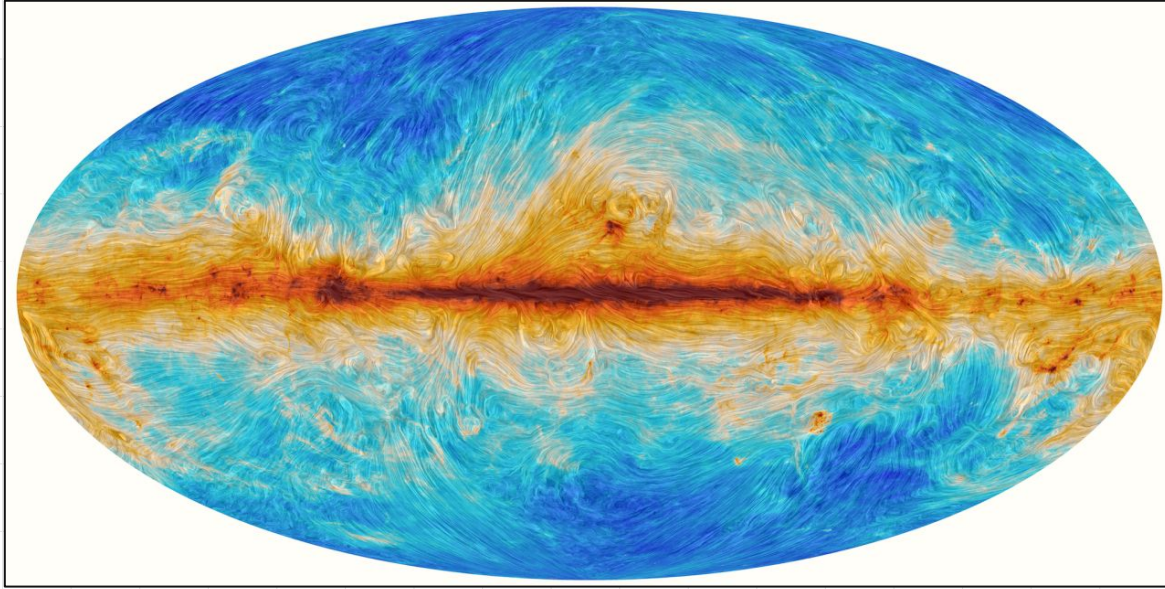


Image credit: ESA/Planck Collaboration

Why don't these look similar?

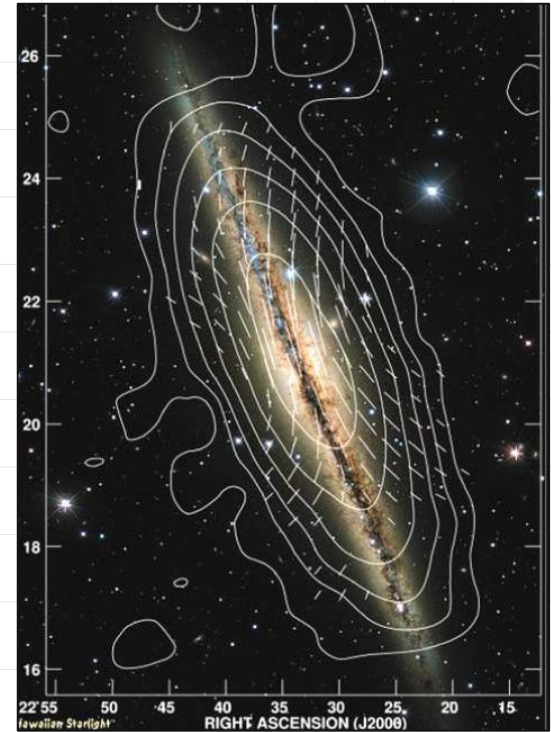


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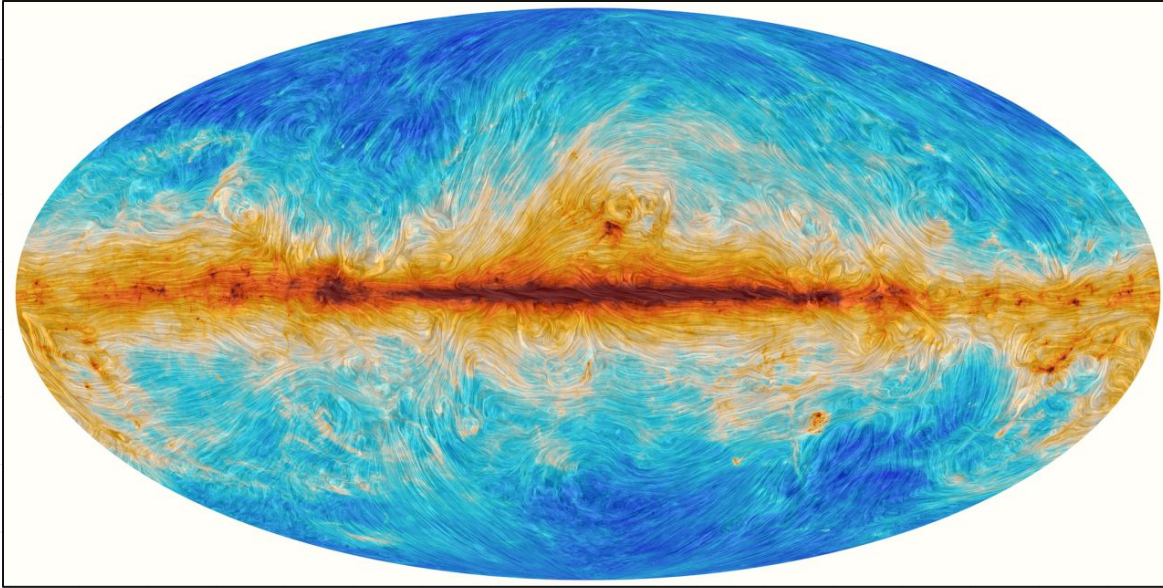
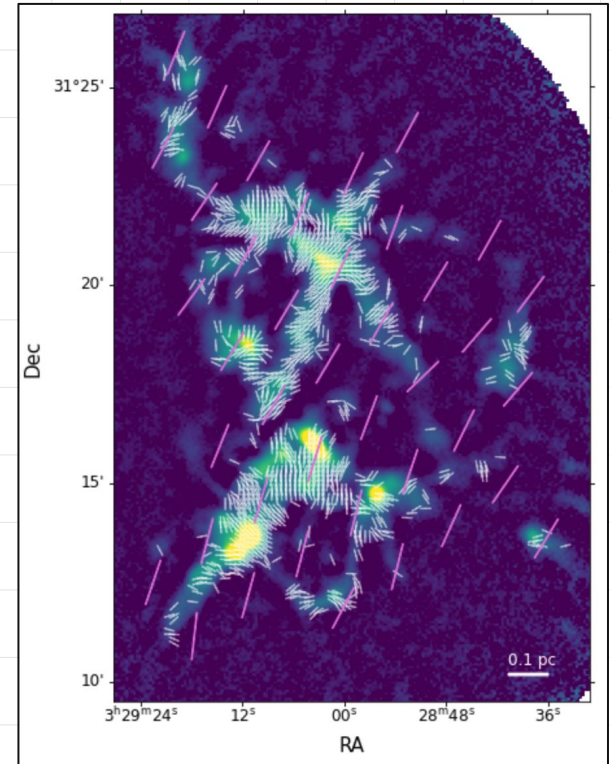


Image credit: ESA/Planck Collaboration



Yin, Pandhi+ (2026)

Piecing Together Magnetic Fields

Tracer	$B_{\parallel}$	$B_{\perp}$	Orientation	Strength	2D or 3D?	Where?
Starlight	✗	✓	✓	✗	3D(ish)	< 1-2 kpc
Dust	✗	✓	✓	✗	2D	ISM, galaxies

Synchrotron Emission

Wavelength regime: radio

- Electrons gyrating in magnetic field emit polarized radio emission perpendicular to the local magnetic field

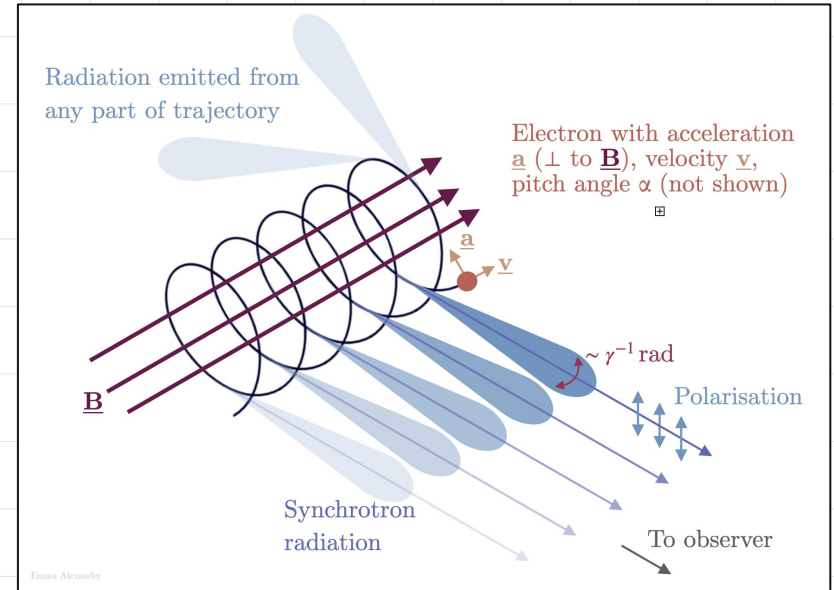


Image credit: Emma Alexander

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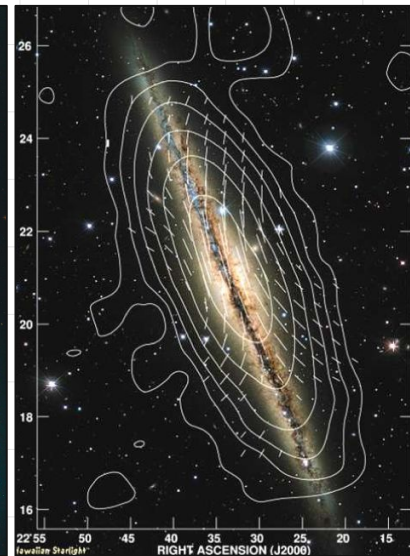


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- Total intensity from synchrotron emission:

$$I \propto N(E) B_{\perp}^{1+\alpha} \nu^{-\alpha} L$$



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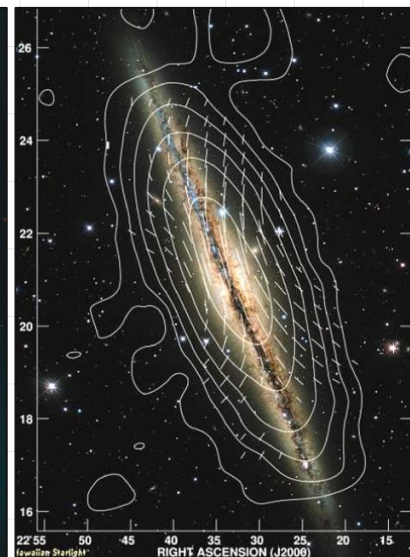


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- Assuming energy densities of cosmic rays and magnetic field are in equipartition, you can directly relate I and $B_{\perp}$

⇒ **Estimate of magnetic field strength**

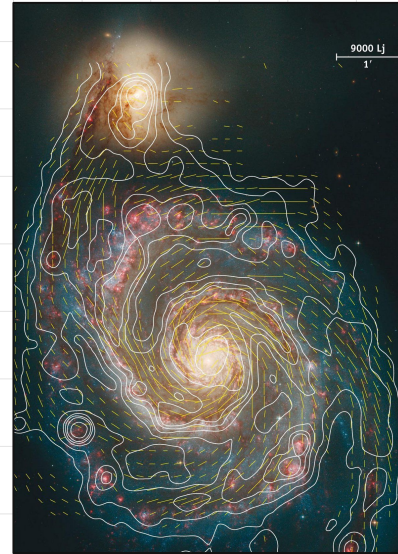


Image credit: Rainer Beck

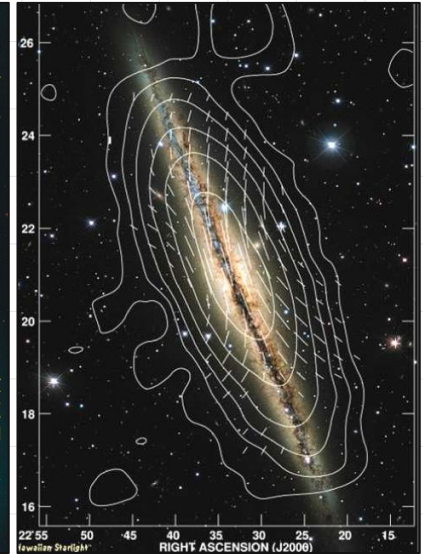


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Synchrotron Emission

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Is equipartition a good assumption?

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- Assuming energy densities of cosmic rays and magnetic field are in equipartition, you can directly relate I and $B_{\perp}$

⇒ **(Often biased)** Estimate of magnetic field strength

Is equipartition a good assumption?

- $L >$ diffusion length of cosmic ray electrons (~ 100 s of pc)
- Time scales $>$ acceleration time of cosmic ray electrons ($\sim$ Myrs)
- No strong inhomogeneities in B over the observed volume
- Overestimation of magnetic field strengths in simulated observations (Dacunha+ 2025)

Piecing Together Magnetic Fields

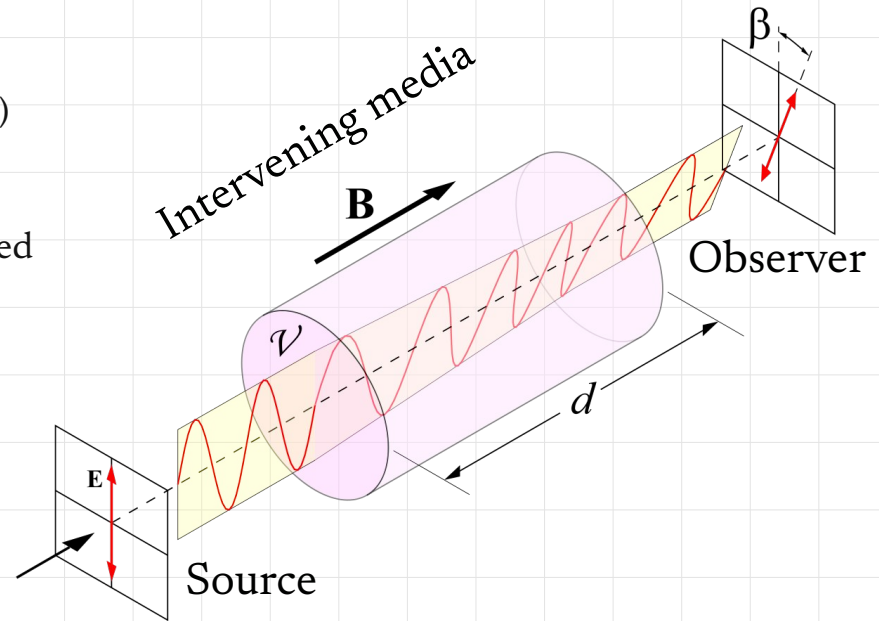
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Dust	✗	✓	✓	✗	2D	ISM, galaxies
Synchrotron	✗	✓	✓	⚠	2D	ISM, SNRs, AGN, galaxy clusters

Faraday Rotation

Wavelength regime: radio

- PA of (background) linearly polarized emission is rotated when it propagates through a (foreground) magnetized plasma
- PA rotation amplified at low frequencies; quantified by rotation measure (RM):

$$\text{RM} \propto n_e B_{\parallel} L$$



Faraday Rotation

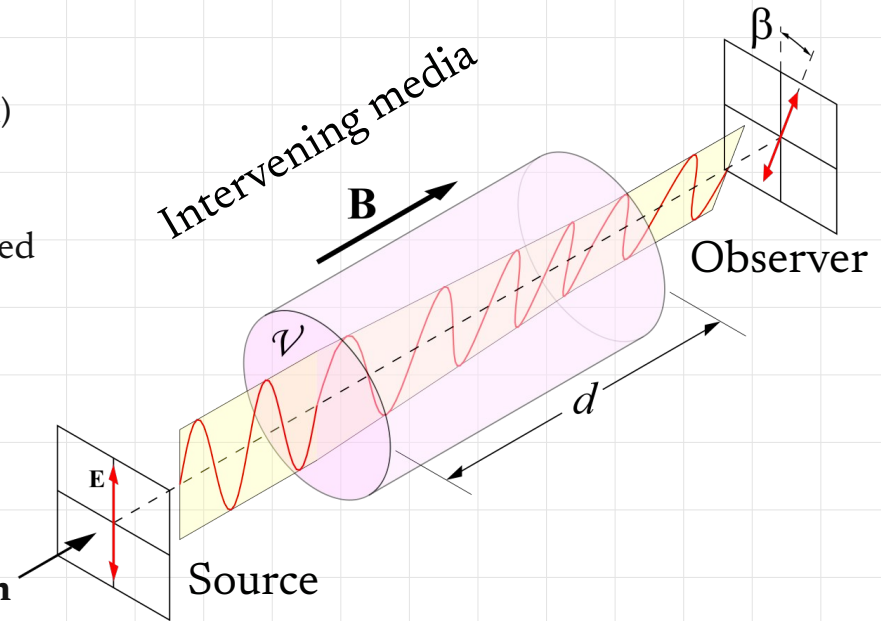
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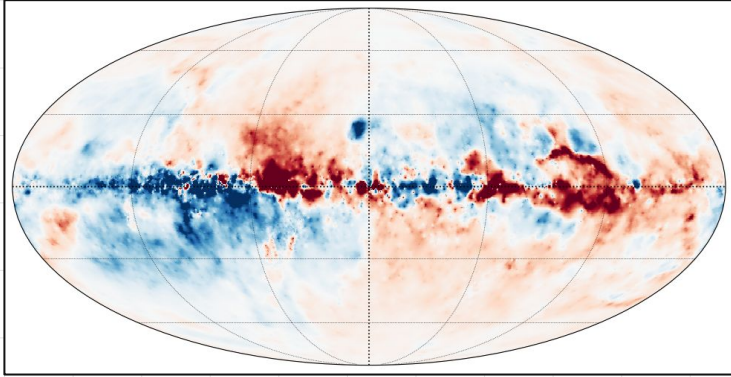
$$\text{RM} \propto n_e B_{\parallel} L$$

- Short radio transients (pulsars, FRBs) also give us dispersion measure ($\text{DM} \propto n_e L$)

⇒ **Ratio of RM/DM provides average $B_{\parallel}$ orientation and strength in intervening plasma**

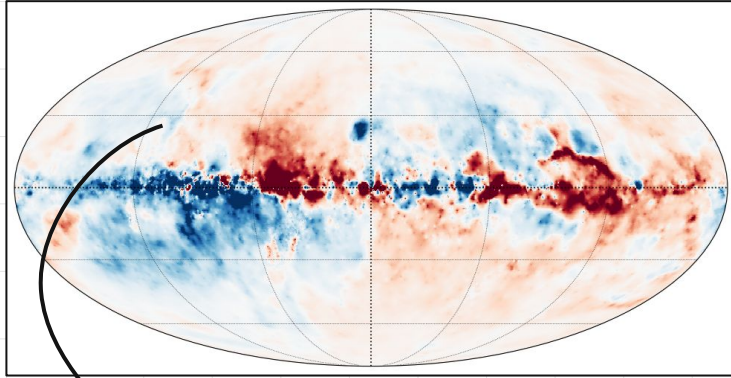


Faraday Rotation

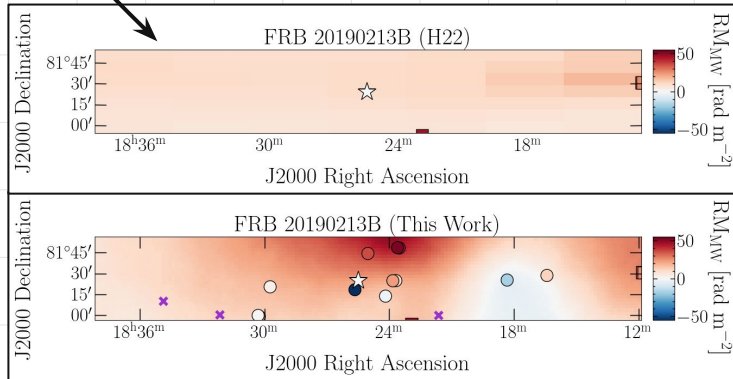


Recreated from Hutschenreuter+ (2022)

Faraday Rotation

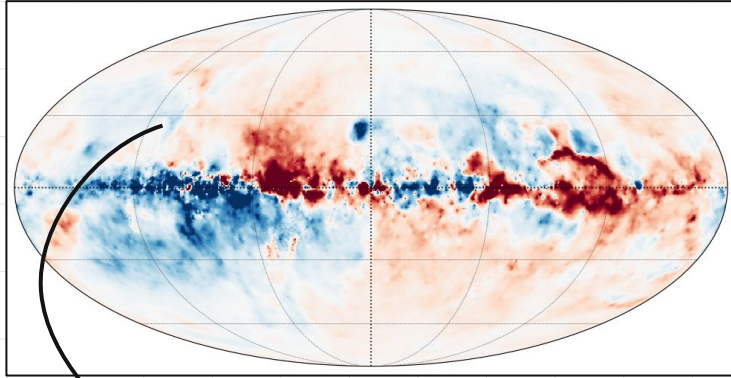


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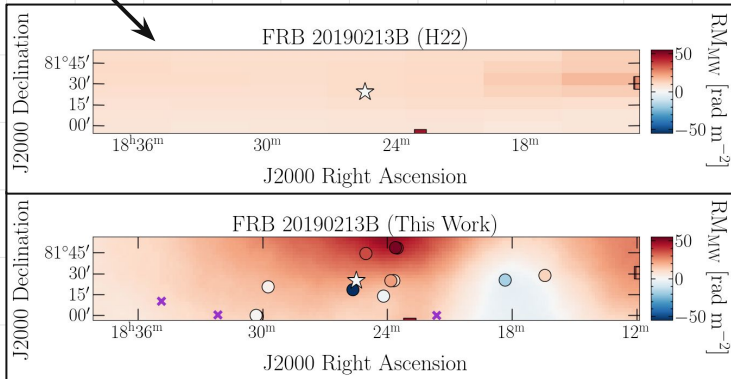


Pandhi+ (2026); Khadir, Pandhi+ (2025)

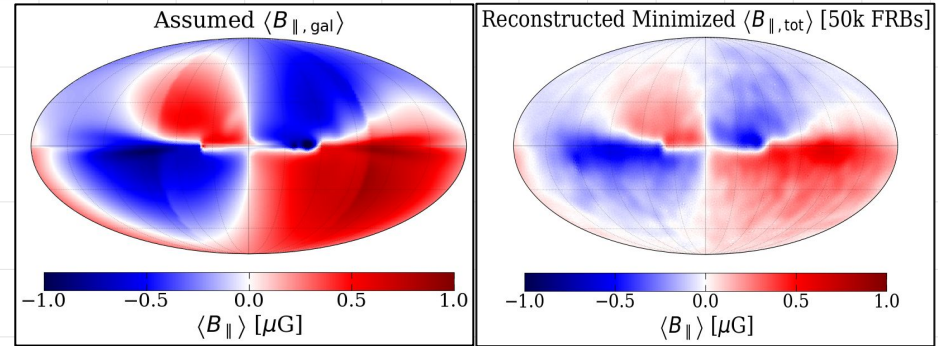
Faraday Rotation



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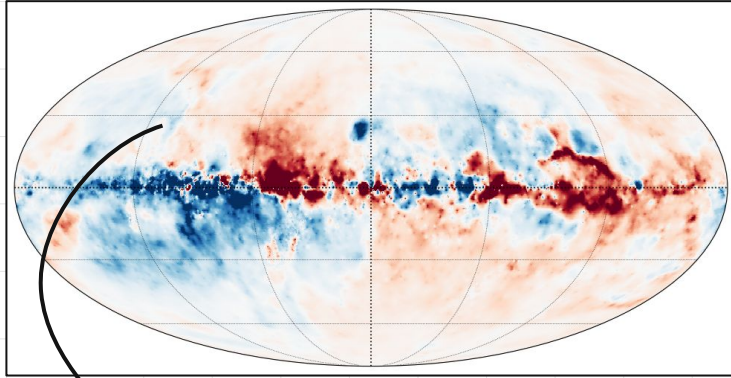


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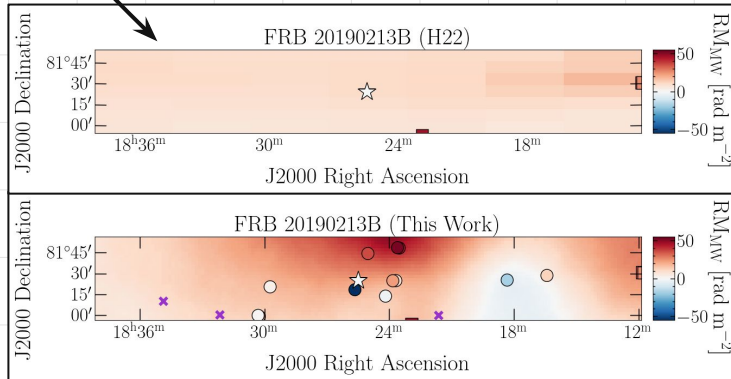


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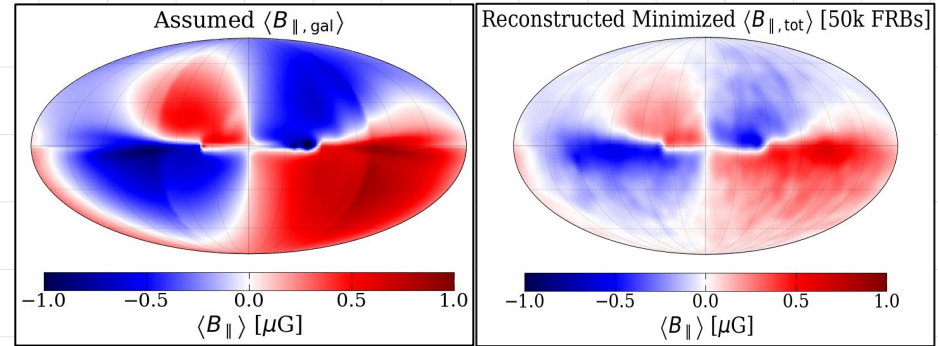
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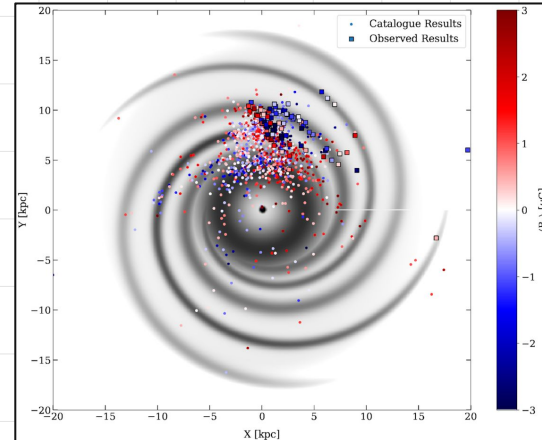
Recreated from Hutschenreuter+ (2022)



Pandhi+ (2026); Khadir, Pandhi+ (2025)



Pandhi+ (2022)



Also see Curtin+
(2025)!

Ng, Pandhi+ (2020)

Piecing Together Magnetic Fields

Tracer	$B_{\parallel}$	$B_{\perp}$	Orientation	Strength	2D or 3D?	Where?
Starlight	✗	✓	✓	✗	3D(ish)	< 1-2 kpc
Dust	✗	✓	✓	✗	2D	ISM, galaxies
Synchrotron	✗	✓	✓	⚠	2D	ISM, SNRs, AGN, galaxy clusters
Faraday rotation	✓	✗	✓ (avg)	✓ (avg)	3D(ish)	ISM, AGN, pulsars, FRBs

Zeeman Splitting

Wavelength regime: (mostly) radio

- Degeneracies in electron energy states for an atom broken in the presence of a magnetic field
- Spectral line splits into two with separation:
 $\Delta\nu = 2.8 (B/\mu\text{G}) \text{ Hz} \ll \text{linewidth}$

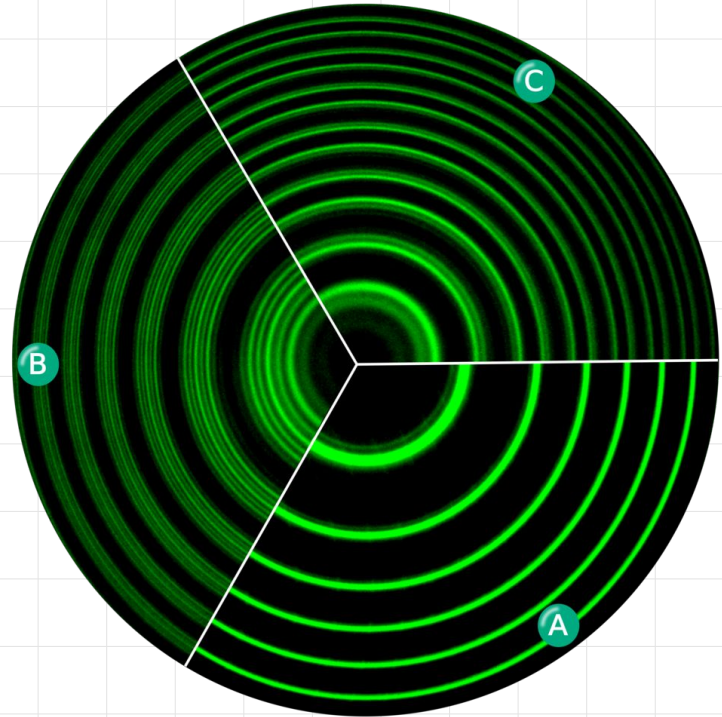


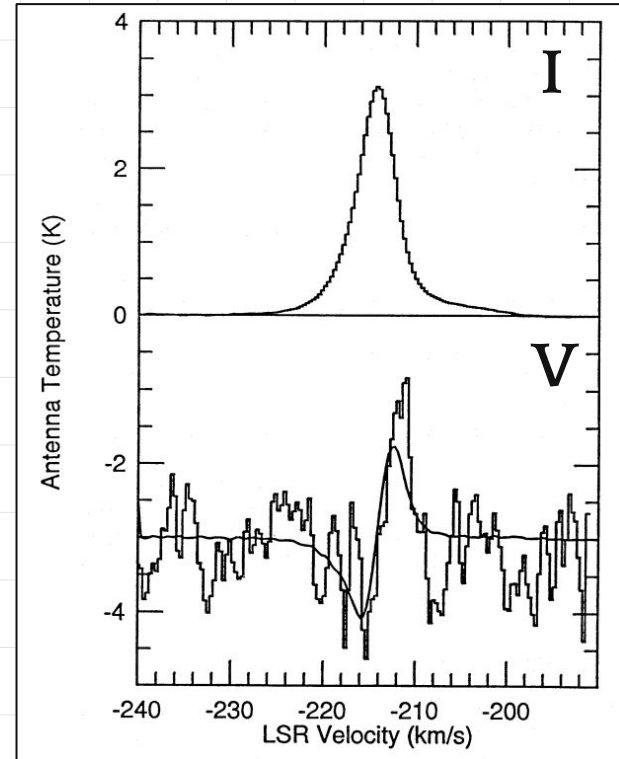
Image credit: Warren Leywon

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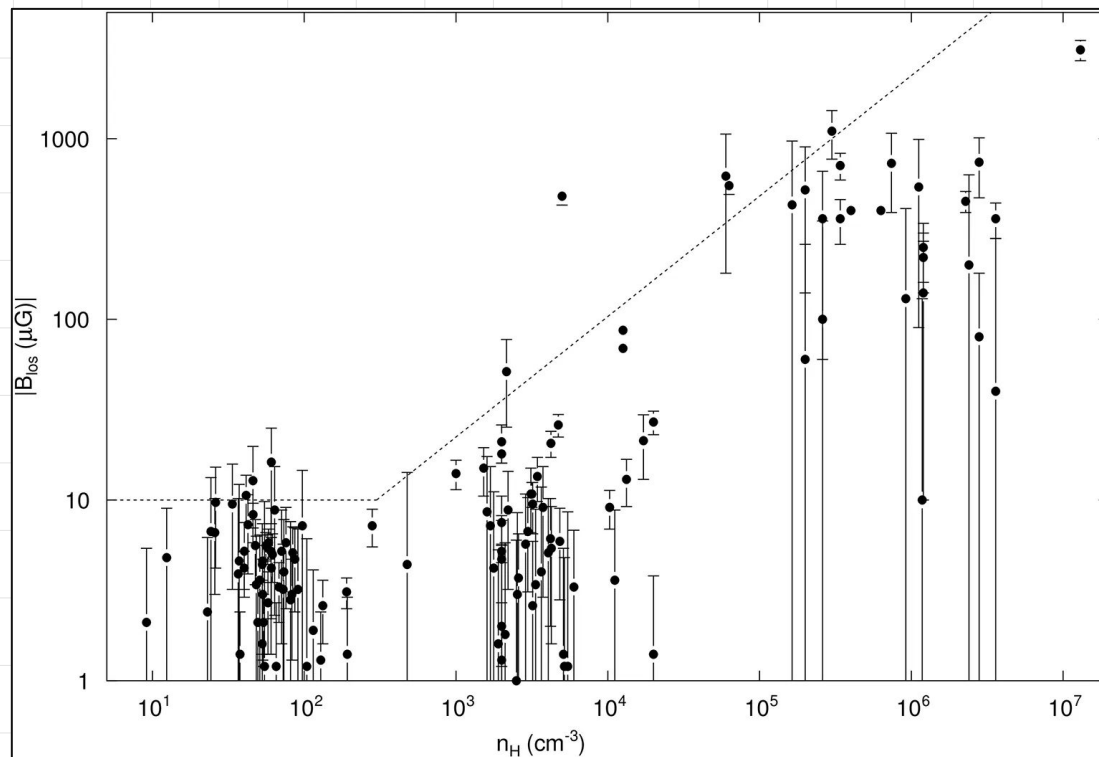
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- Spectral line splits into two with separation:
 $\Delta\nu = 2.8 (B/\mu\text{G}) \text{ Hz} \ll \text{linewidth}$
- Circular polarization of the split states diverge:
$$V(\nu) \propto B_{\parallel} (dI/d\nu)$$
- Very time intensive observations!

⇒ **Direct measurement of $B_{\parallel}$ strength but limited by spectral line emitters and observation time**



Kazes+ (1991)

Zeeman Splitting



Also some
extragalactic
detections (see
Robishaw+ 2008)!

Crutcher+ (2010); Crutcher & Kemball (2019)

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Faraday rotation	✓	✗	✓ (avg)	✓ (avg)	3D(ish)	ISM, AGN, pulsars, FRBs
Zeeman Effect	✓	✗	✓	✓	2D	Masers (ISM or galaxies)