Ruđer Bošković Institute

Exploring the interstellar medium and magnetic fields of the Milky Way at low-radio frequencies

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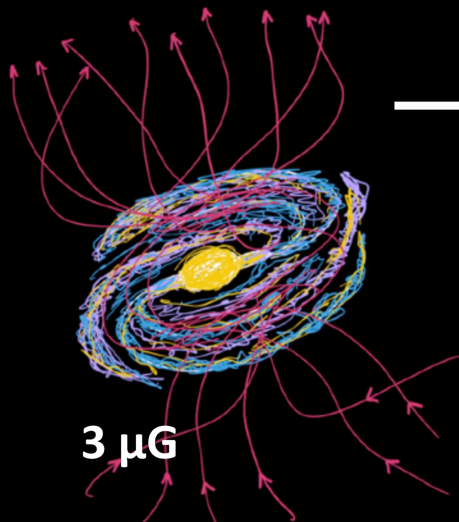
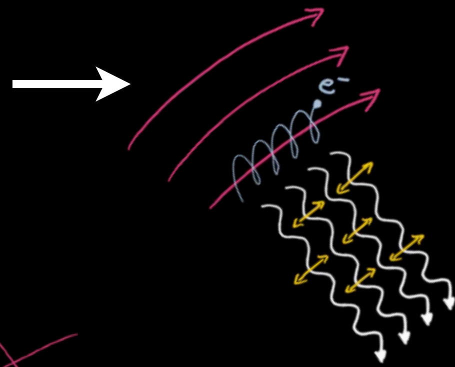


3 μG

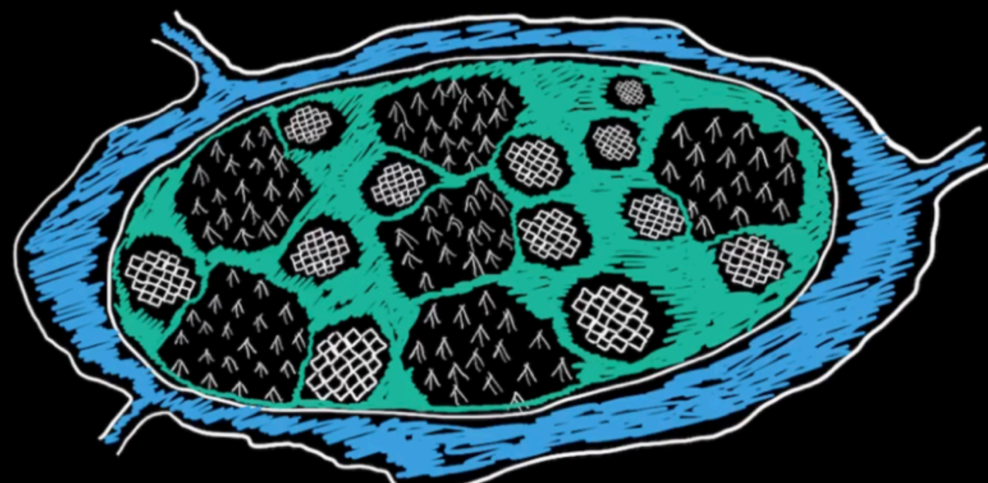


synchrotron emission

$$I_\nu \sim n_{CR} B_\perp^{\frac{p+1}{2}} \nu^{-\frac{p+3}{2}}$$

Faraday rotation

$$\Delta\theta = \lambda^2 \left(\text{const.} \int_0^d n_e \mathbf{B} \cdot \mathrm{d}\mathbf{l} \right)$$



The Low Frequency Array (LOFAR)

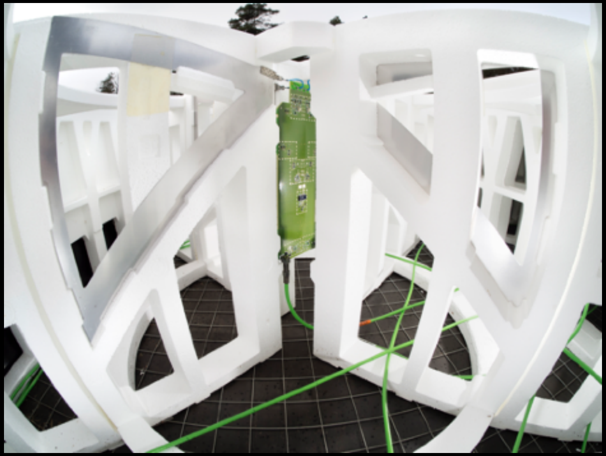
van Haarlem et al. 2013

10 - 240 MHz

LOFAR

Low Frequency Array

HBA: High Band Antenna
100-250 MHz



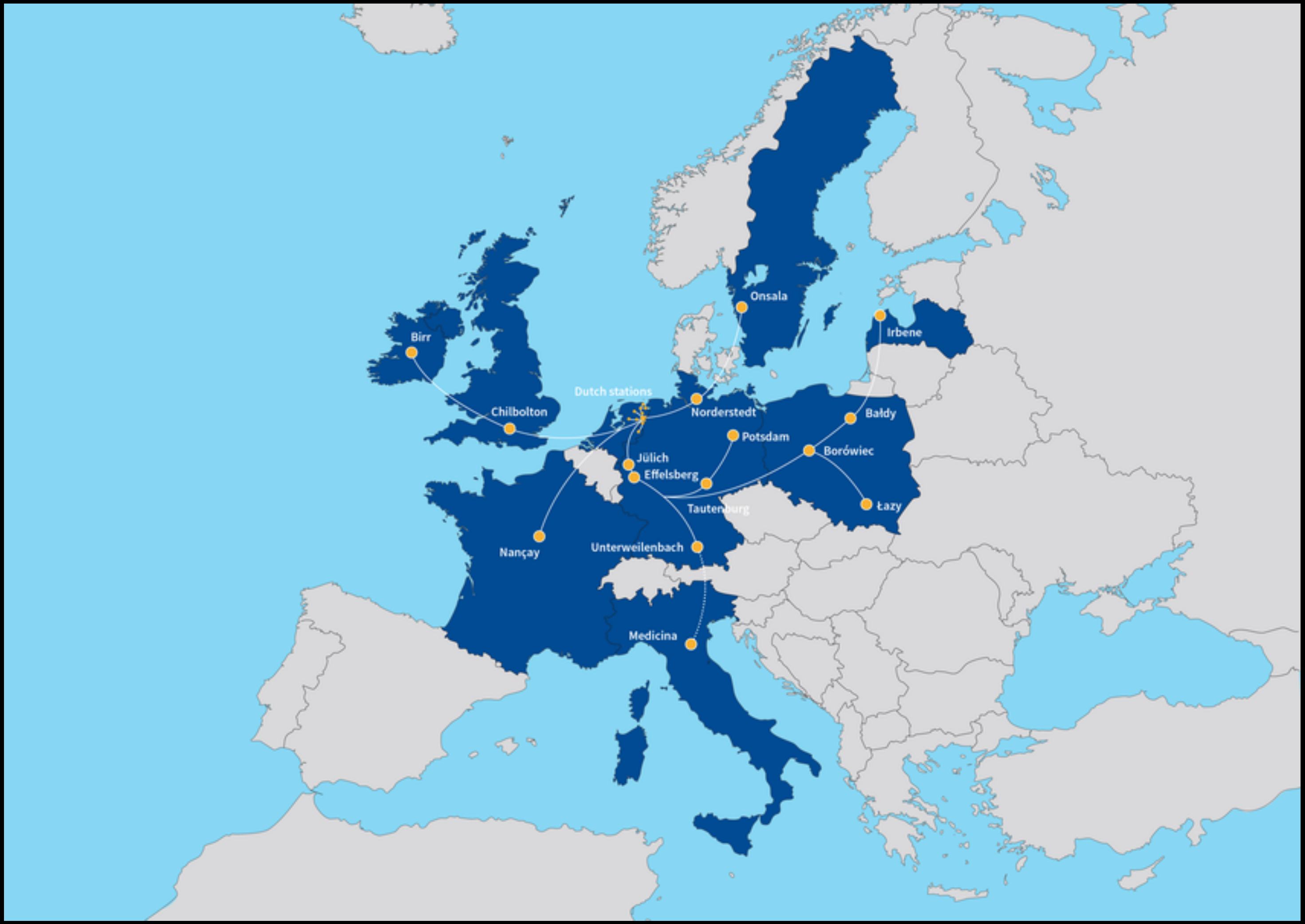
LBA: Low Band Antenna
10-80 MHz

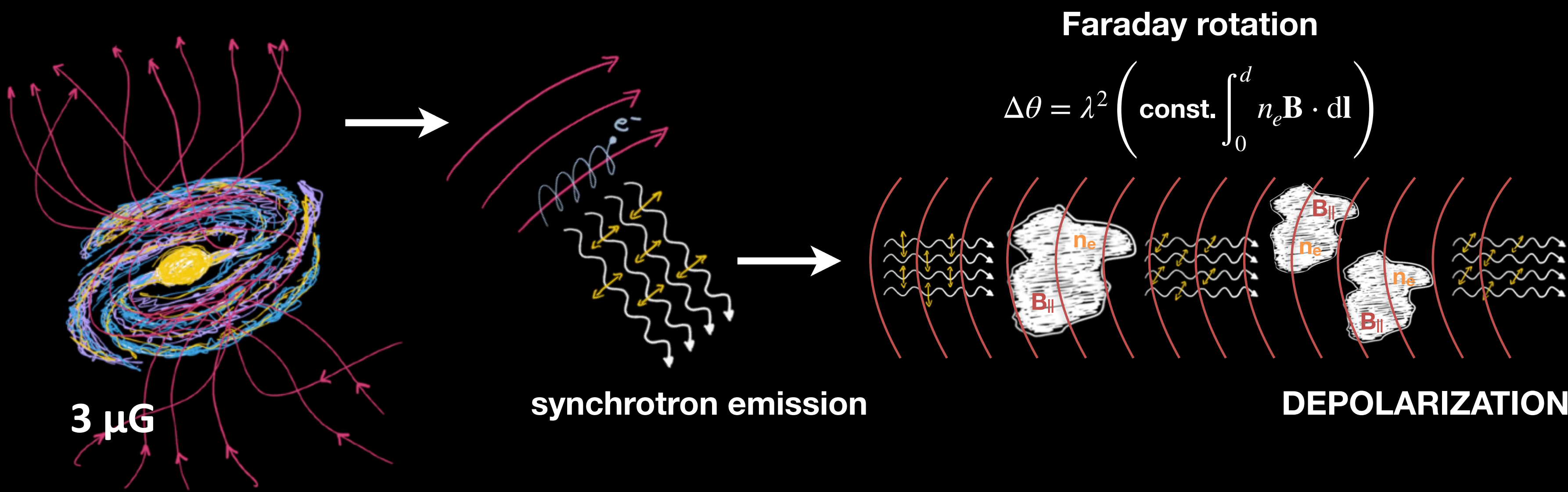
LOFAR

Low Frequency Array

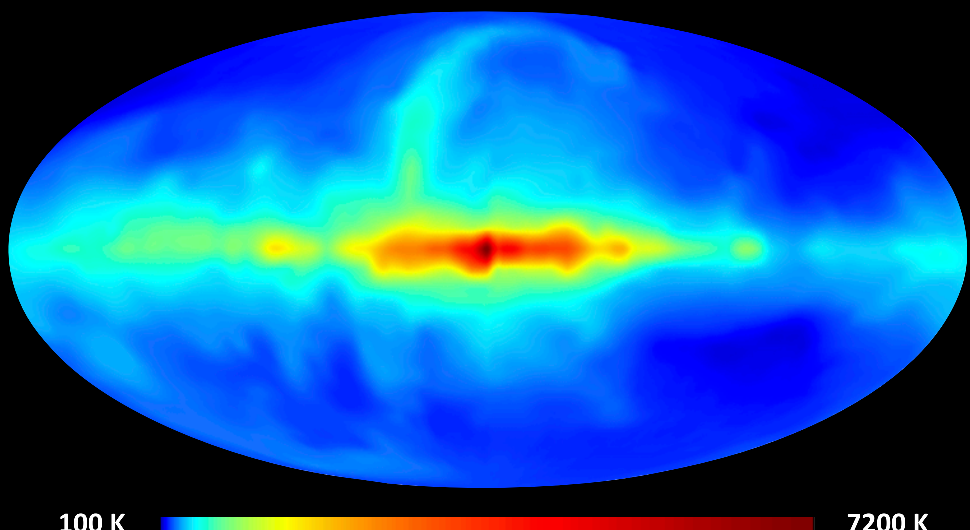
LOFAR

Low Frequency Array

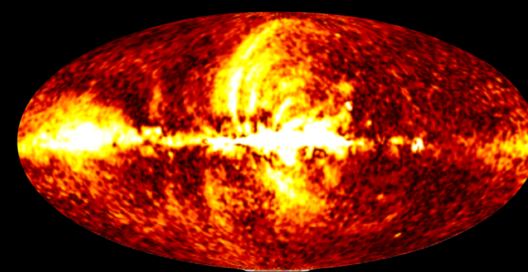




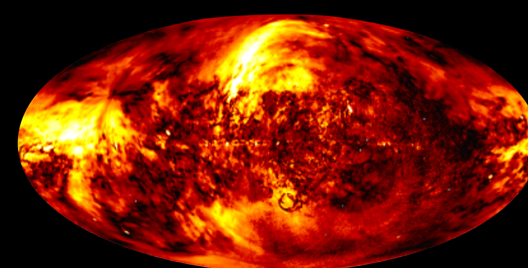
150 MHZ



Landecker & Wielebinski 1970



Polarized intensity @ 22.8 GHz

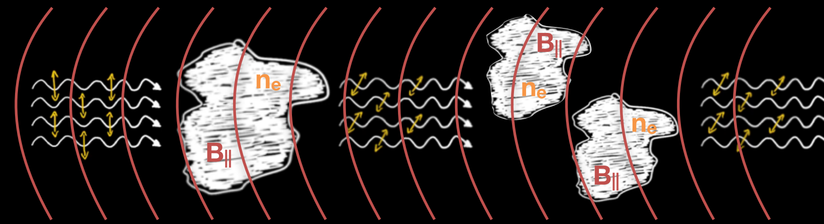


Polarized intensity @ 1.4 GHz

LINEAR POLARIZATION
Stokes Q, U

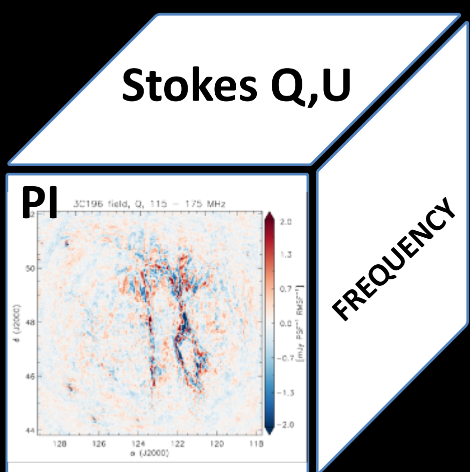
$$Q = PI\cos\theta$$
$$U = PI\sin\theta$$

$$PI = \sqrt{Q^2 + U^2}$$
$$\theta = \frac{1}{2}\tan^{-1}\frac{U}{Q}$$



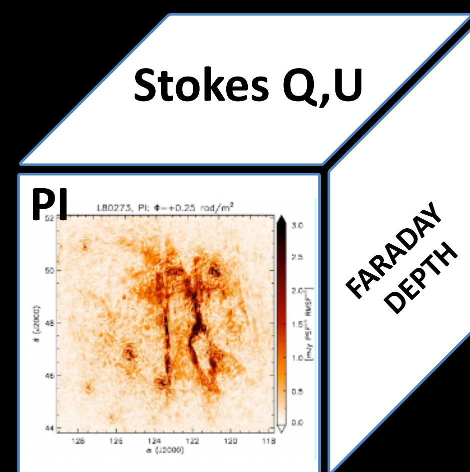
$$\theta = \theta_0 + \lambda^2 \left(\text{const.} \int_0^d n_e \mathbf{B} \cdot d\mathbf{l} \right)$$

FARADAY DEPTH



RM synthesis

Burn et al. 1966
Brentjens & de Bruyn 2008



$$\mathbf{P}(\lambda^2) = \mathbf{Q}(\lambda^2) + i\,\mathbf{U}(\lambda^2)$$

$$F(\Phi) = \int_{-\infty}^{+\infty} W(\lambda^2) P(\lambda^2) e^{-i2\Phi\lambda^2} d\lambda^2$$

RM synthesis

Brentjens & de Bruyn 2008

$Q(\nu), U(\nu)$

$$\mathbf{P}(\lambda^2) = \mathbf{Q}(\lambda^2) + i\,\mathbf{U}(\lambda^2)$$

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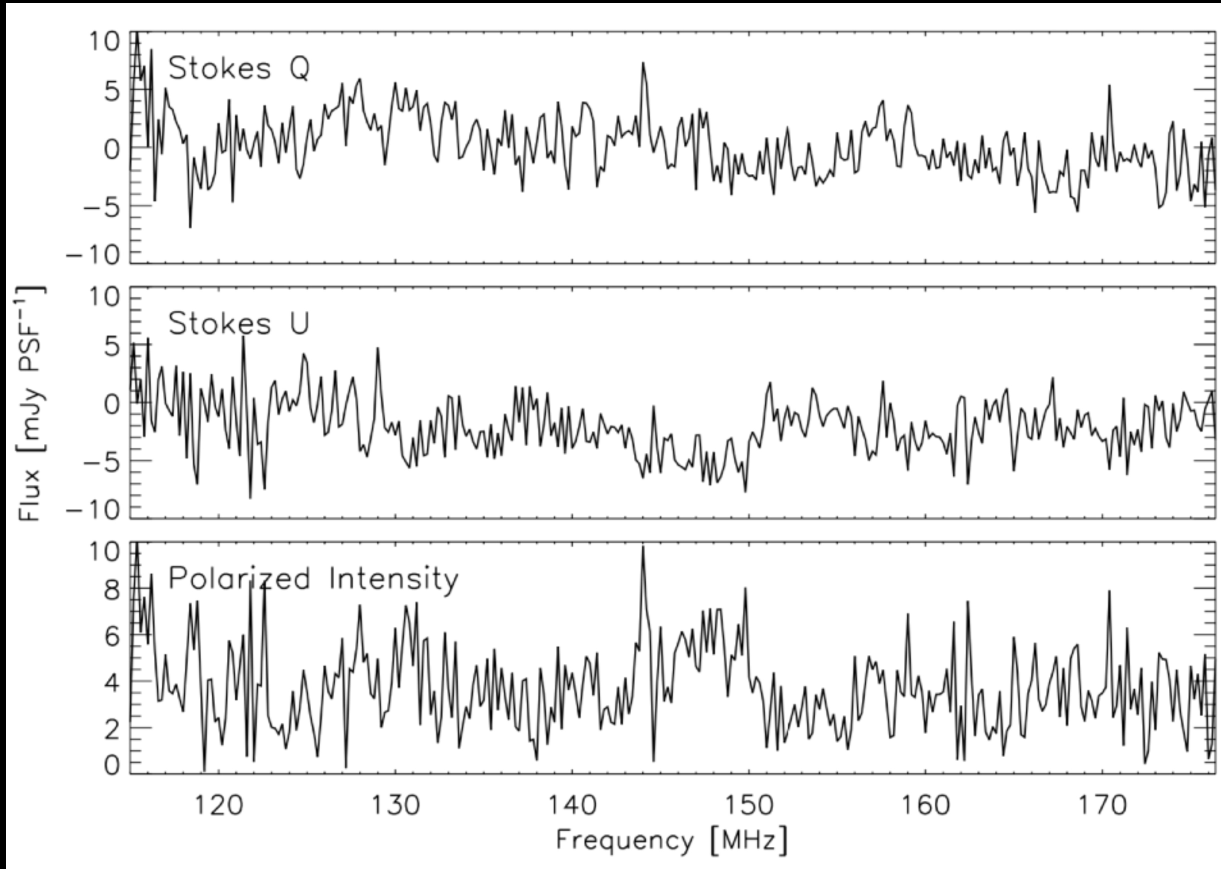
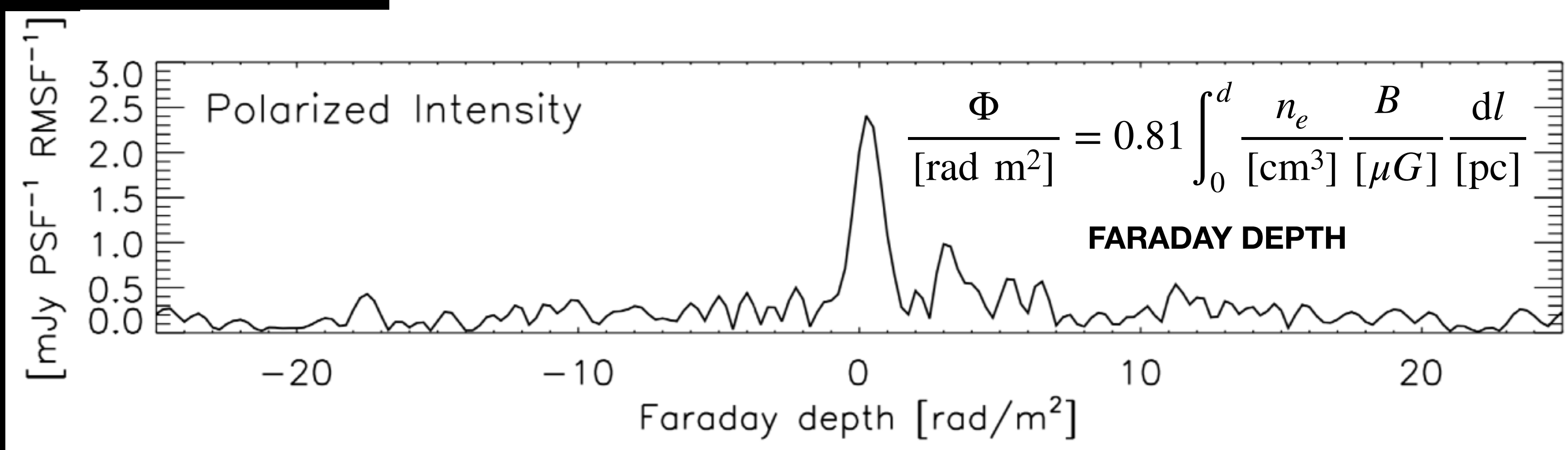
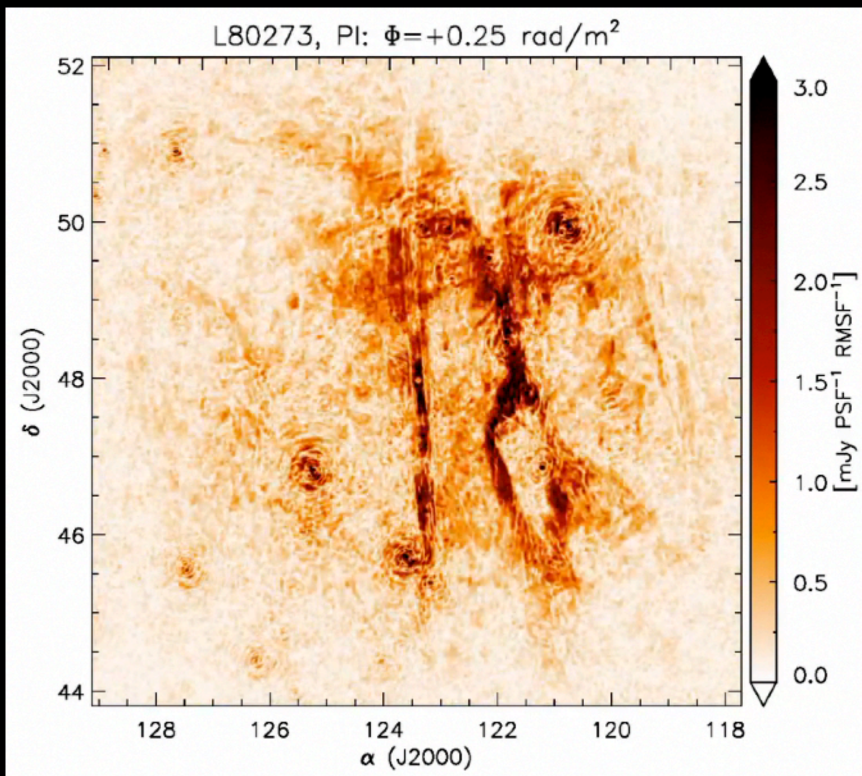
$Q(\Phi), U(\Phi)$

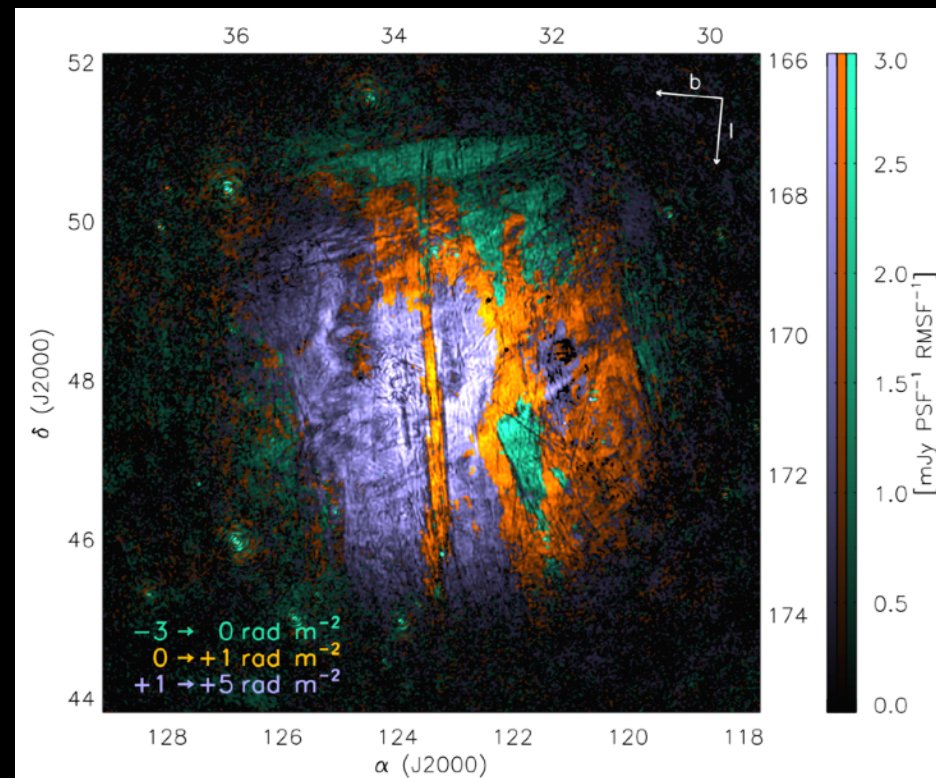




Faraday tomography

LOFAR-HBA observations
3C 196 field
6-8 h (115 - 175 MHz, 183 kHz)
$\delta\Phi = 1$ rad/m²





Jelić et al. 2015

RM synthesis

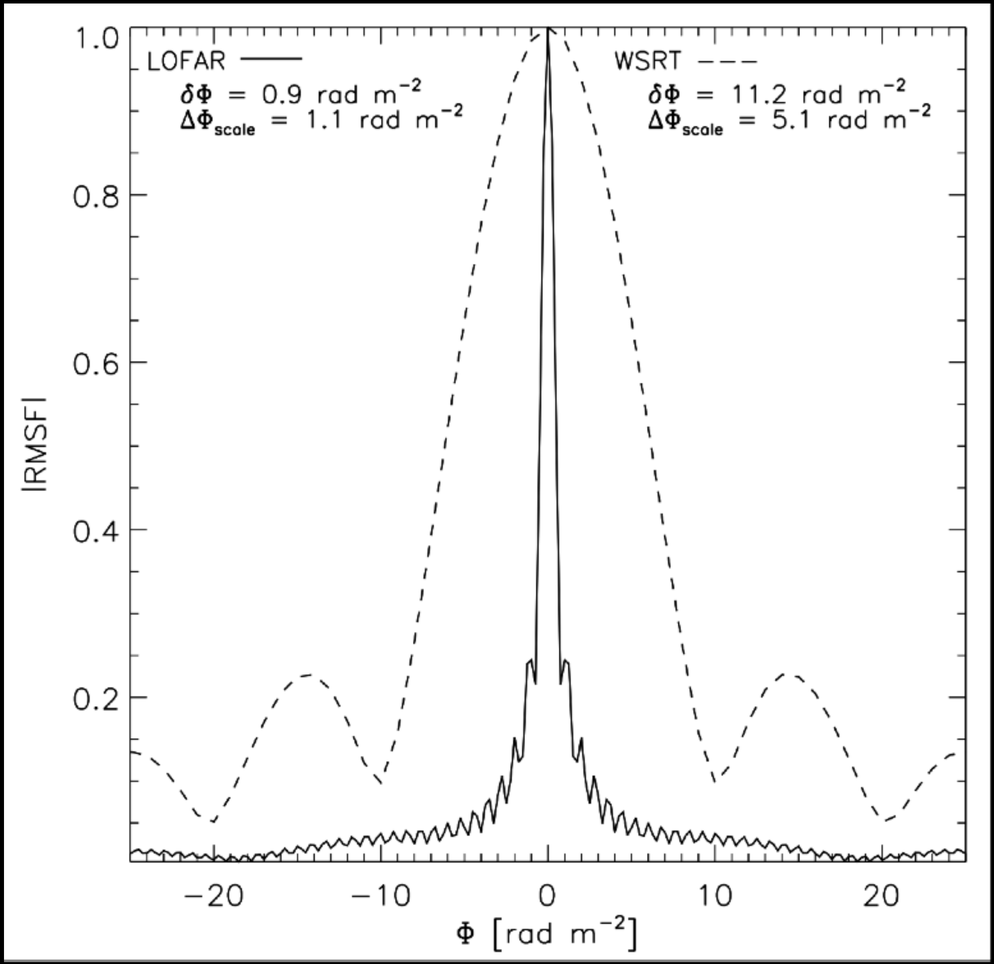
Brentjens & de Bruyn 2008

RESOLUTION IN FARADAY DEPTH $\delta\Phi \approx \frac{2\sqrt{3}}{\Delta\lambda^2}$

δΦ @ 150 MHz: 1 rad/m²
δΦ @ 350 MHz: 10 rad/m²
δΦ @ GHz: > 100 rad/m²

LARGEST SCALE IN FARADAY DEPTH $\Delta\Phi_{\text{scale}} \approx \frac{\pi}{\Delta\lambda^2_{\text{min}}}$

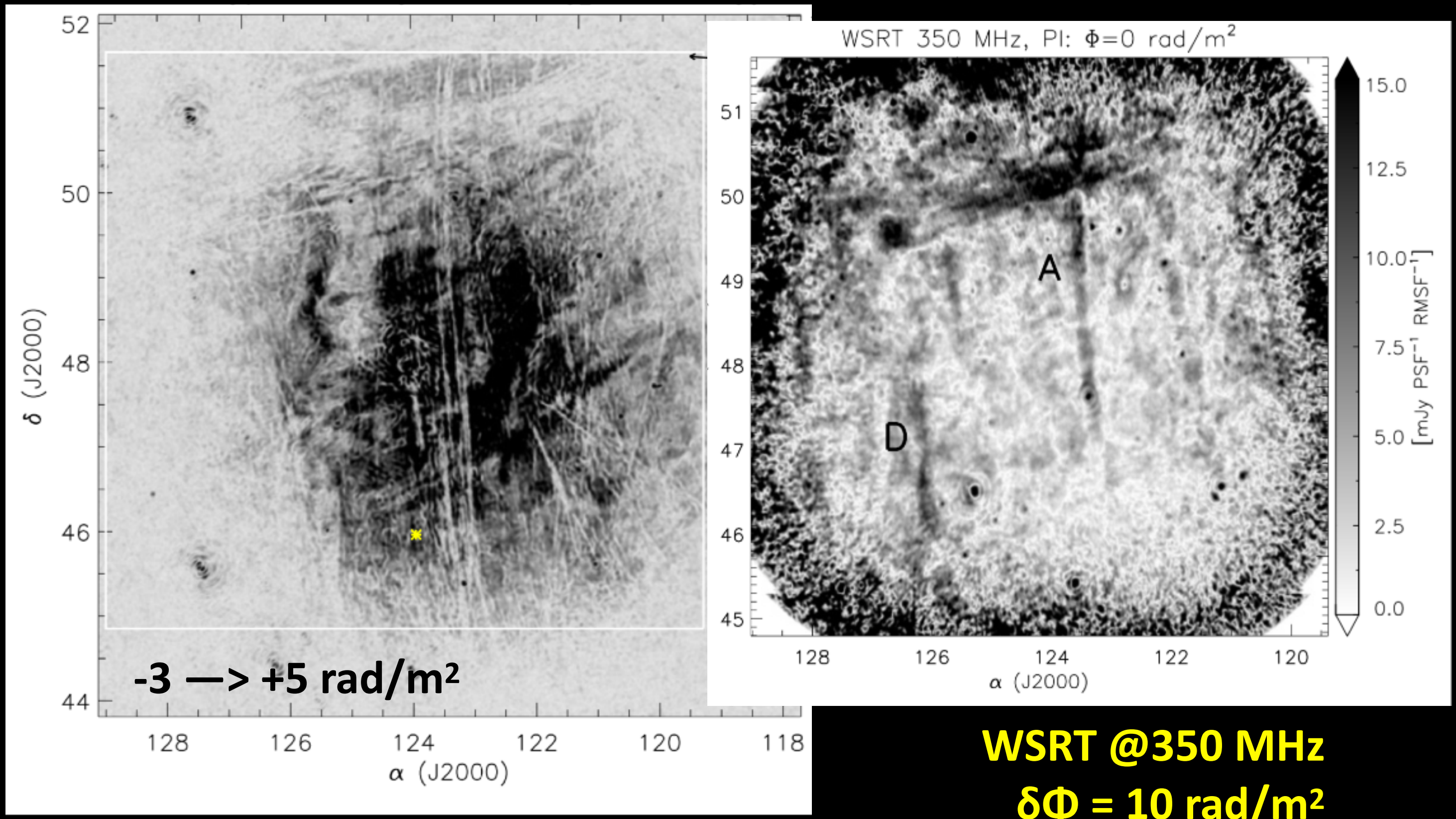
$\lambda^2\Delta\Phi \ll 1$	**FARADAY THIN STRUCTURE**
$\lambda^2\Delta\Phi \gg 1$	**FARADAY THICK STRUCTURE**



- Faraday thickness is frequency dependant, to resolve Faraday thick structure $\lambda^2_{\text{min}} \ll \Delta\lambda$
- observations at low-radio frequencies is sensitive to Faraday rotation caused by small column density medium

3C 196 field

LOFAR @ 145 MHz
$\delta\Phi = 1\ rad/m^2$

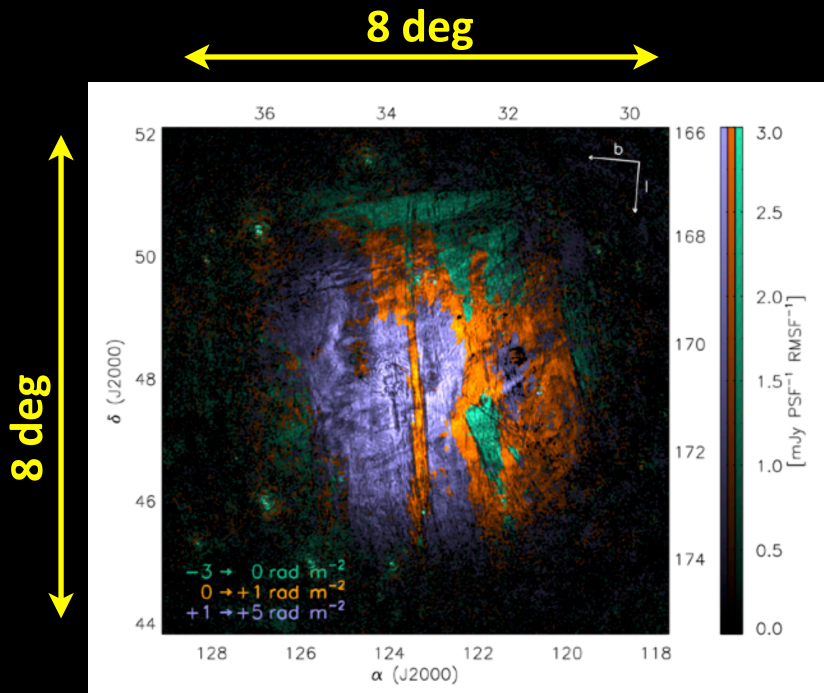


WSRT @350 MHz
$\delta\Phi = 10\ rad/m^2$

- comparable angular resolution (~3 arcmin)
- different resolution in Faraday depth (~1 rad/m^2 vs. ~10 rad/m^2)

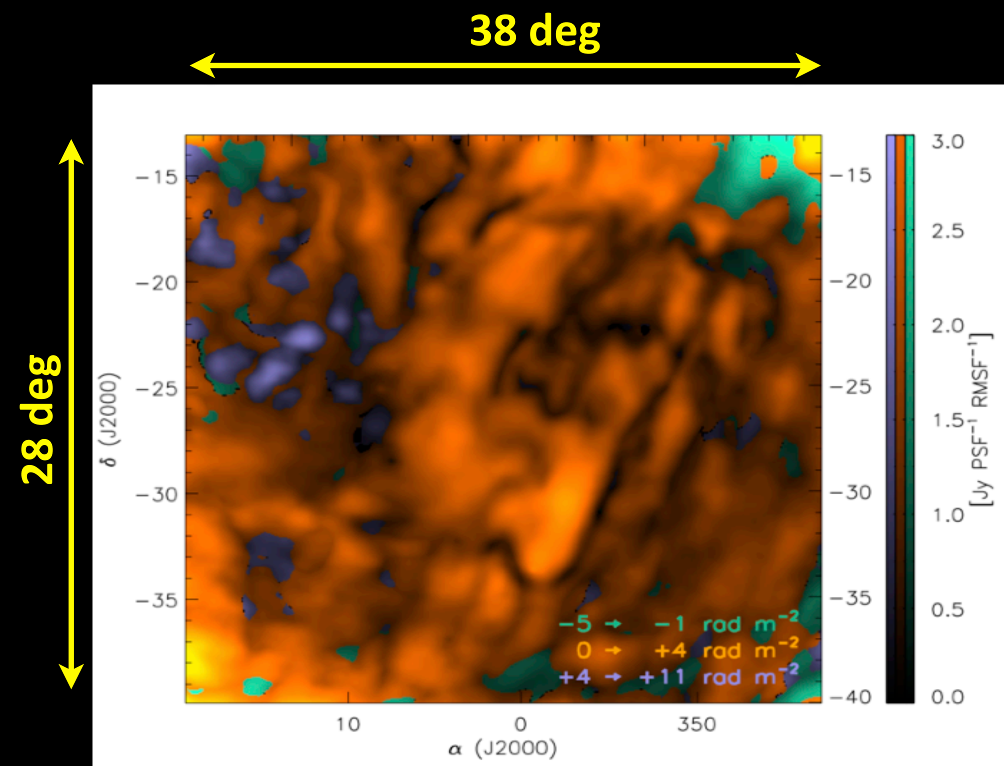
Faraday thin structure @ 350 MHz is Faraday thick @ 150 MHz

Jelić et al. 2015



Jelic et al. 2015

LOFAR observations

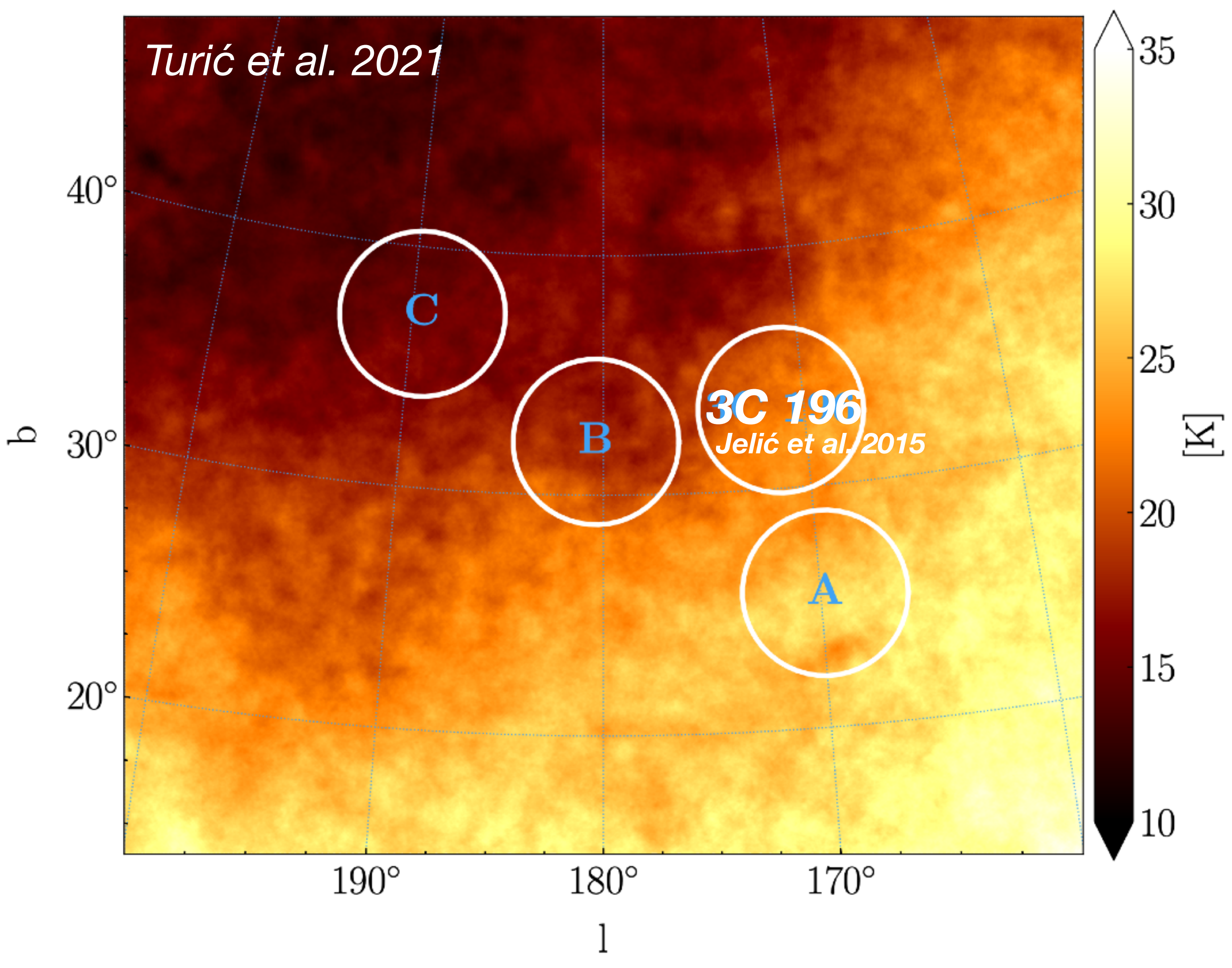


Lenc et al. 2016

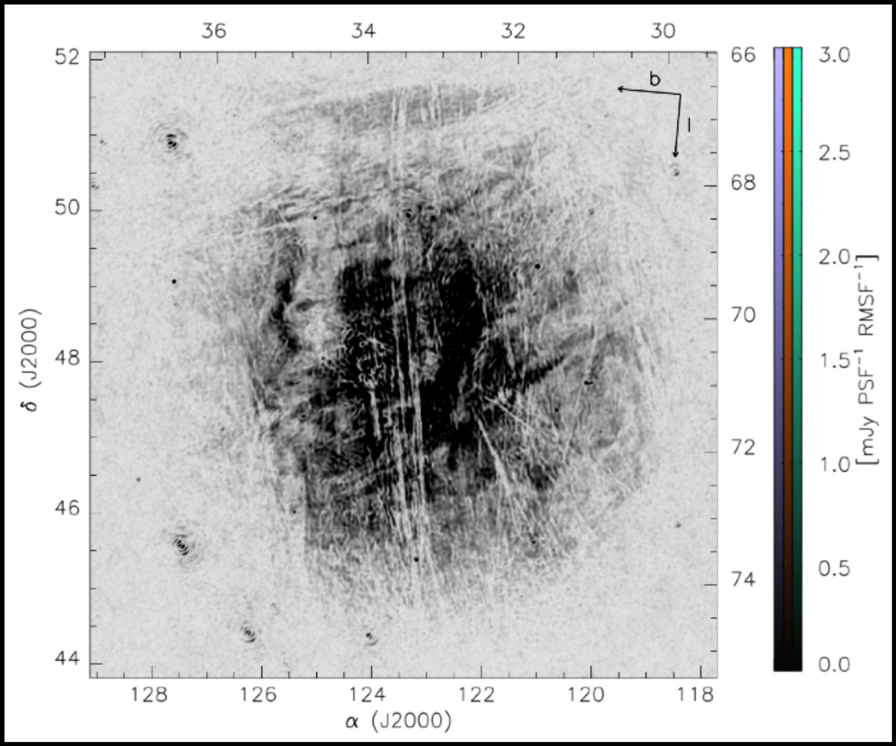
MWA observations

- comparable resolution in Faraday depth (~1rad/m^2)
- different angular resolution (~3 arcmin vs. 1 deg)

Faraday tomography

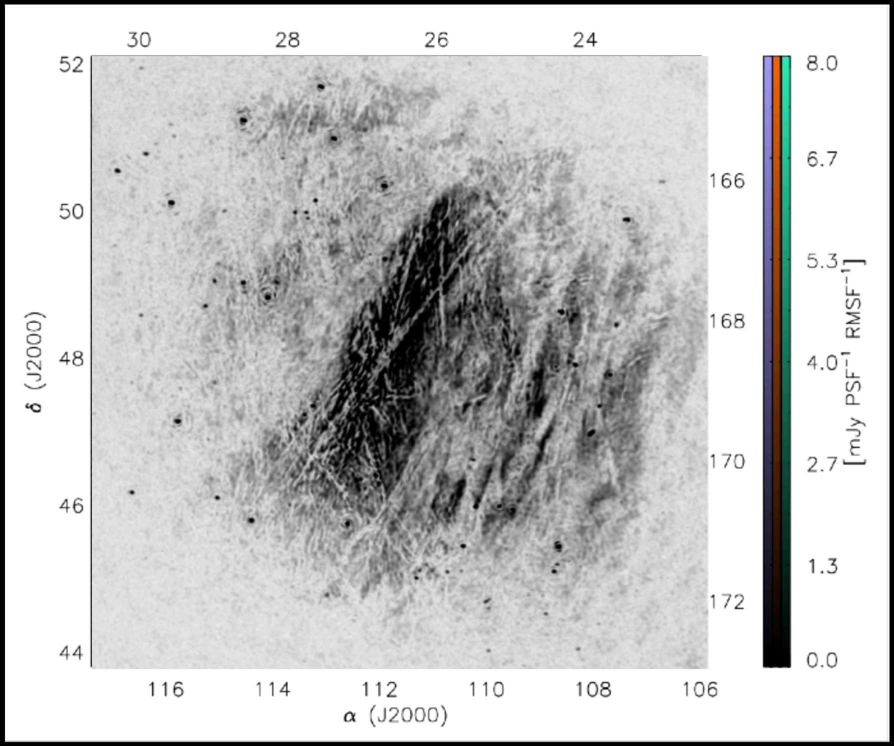


3C 196 field



Jelić et al. 2015

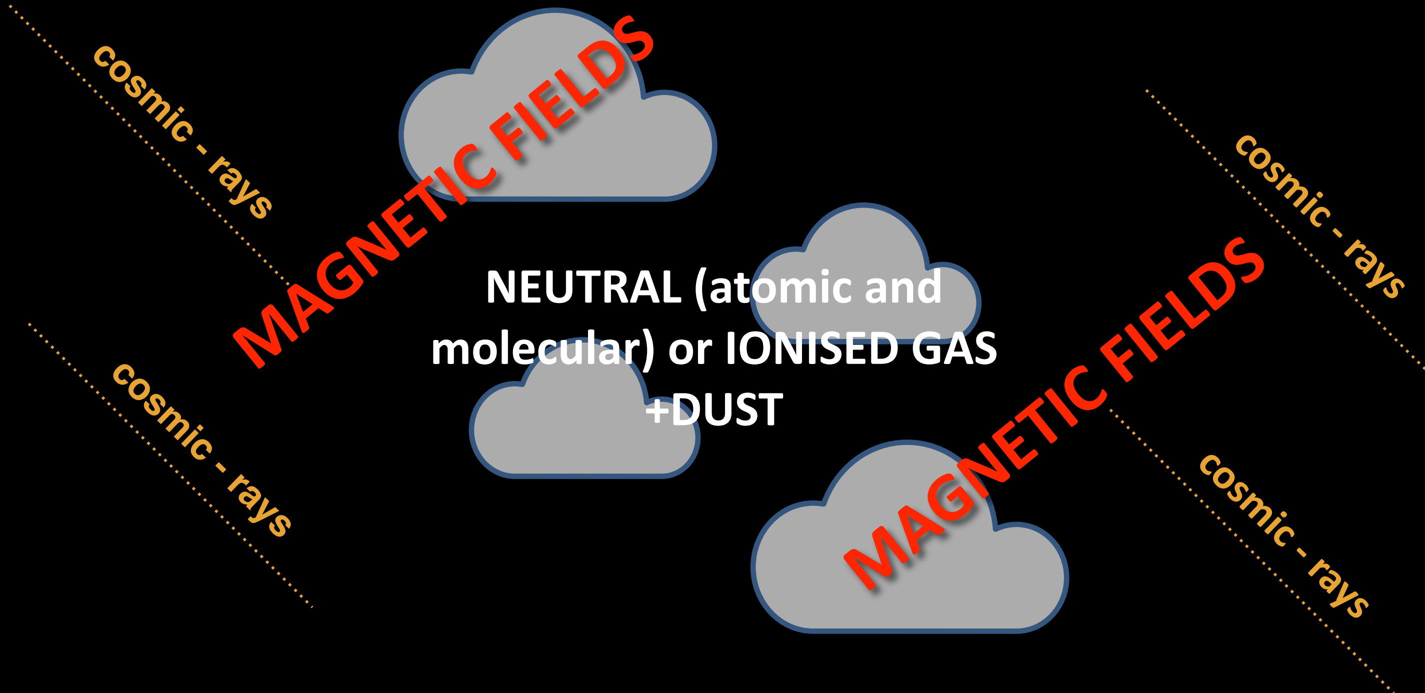
Field A



Truić et al. 2021

- **brightness of the emission is 1-10K, only a few percent of intrinsically polarized emission**

Where along the line-of-sight does depolarization happen ?
From where does the observed emission originate from ?
What drives the morphology of observed emission ?



INTERSTELLAR MEDIUM (ISM)

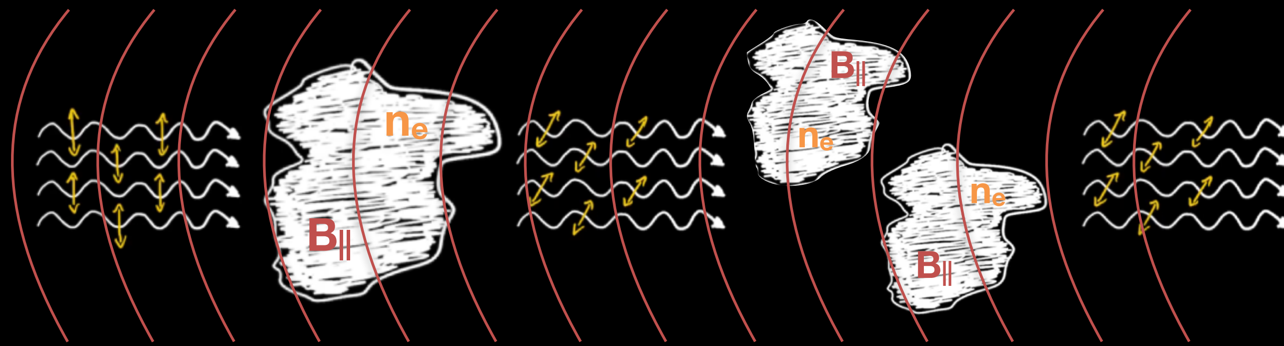
Hot Ionised Medium (HIM) $T \sim 10^6$ K; $n \sim 10^{-2}$ cm^{-3}

Warm Ionised Medium (WIM) $T \sim 5 \times 10^3$ K; $n \sim 0.5 - 2$ cm^{-3}

Warm Neutral Medium (WNM) $T \sim 5 \times 10^3$ K; $n \sim 0.5 - 2$ cm^{-3}

Cold Neutral Medium (CNM) $T \sim 10^2$ K; $n \sim 10^2$ cm^{-3}

Molecular Clouds $T \sim 10$ K; $n \sim 10^3$ cm^{-3}



	CNM	WNM	WIM	HIM
T [K]	80	5 000	8 000	10^6
n_H [cm^{-3}]	30	0.4	0.2	0.005
n_e [cm^{-3}]	0.02	0.01	0.2	0.006
L [pc]	10	30	30	100
$B_{\|\|}$ = 1 μG	0.2 rad m^{-2}	0.25 rad m^{-2}	**5 rad m^{-2}**	0.5 rad m^{-2}

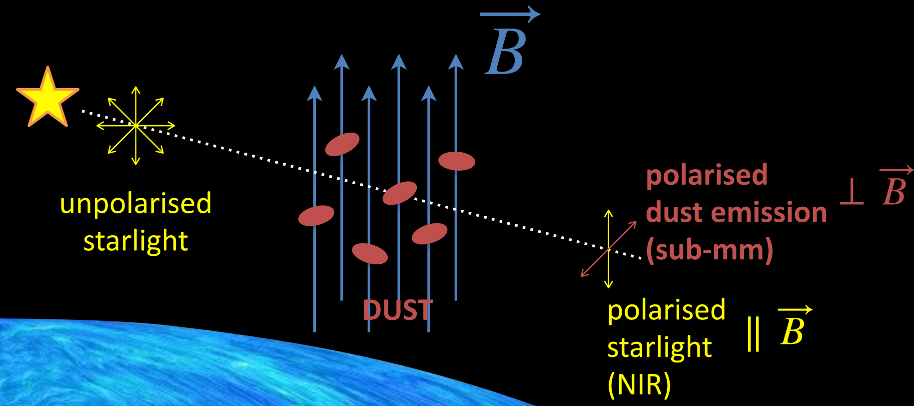
Ferrière 2020

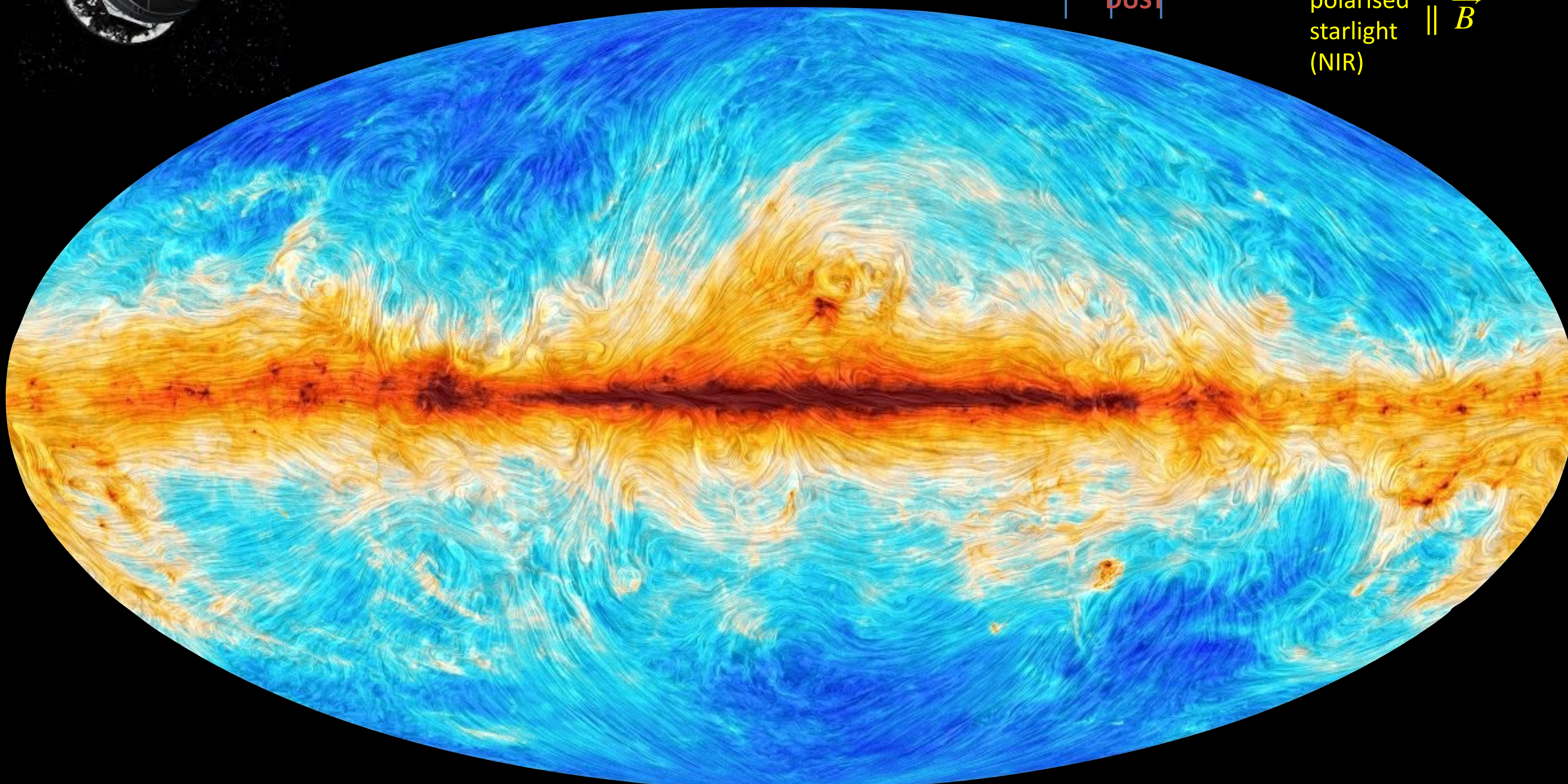
MULTI-TRACERS ANALYSIS + SIMULATIONS

Zaroubi et al. 2015, Kalberla & Kerp 2016, Van Eck et al. 2017, Jelić et al. 2018, Bracco et al. 2020, Turić et al. 2021

Padovani et al. 2021, Bracco et al. 2022

Dust polarized emission



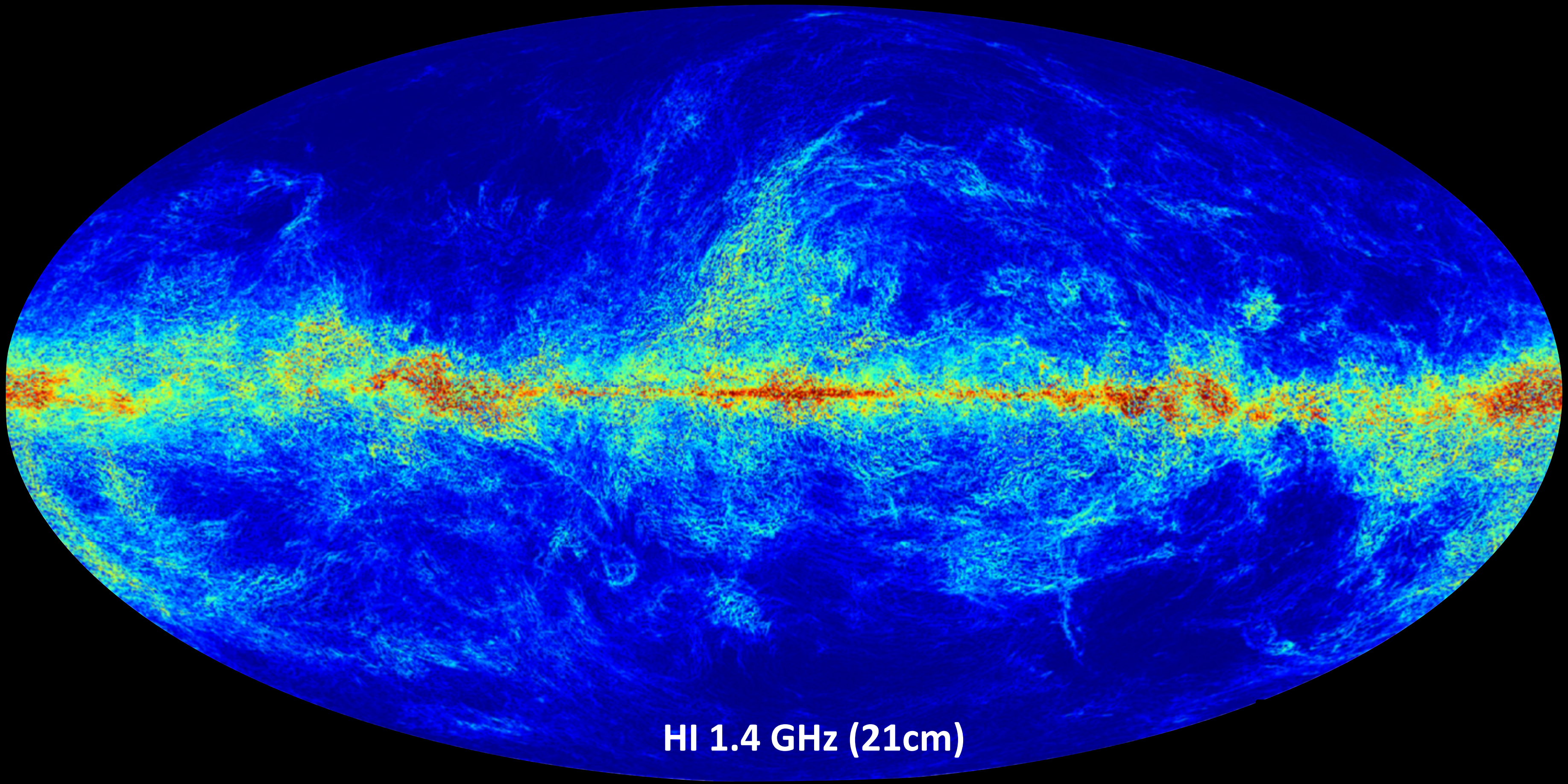


Planck map @ 343 GHz

Planck Collaboration I and XIX 2015

HI emission (GASS, GALFA-HI i EBHIS)

- HI filaments follow orientation of the magnetic field



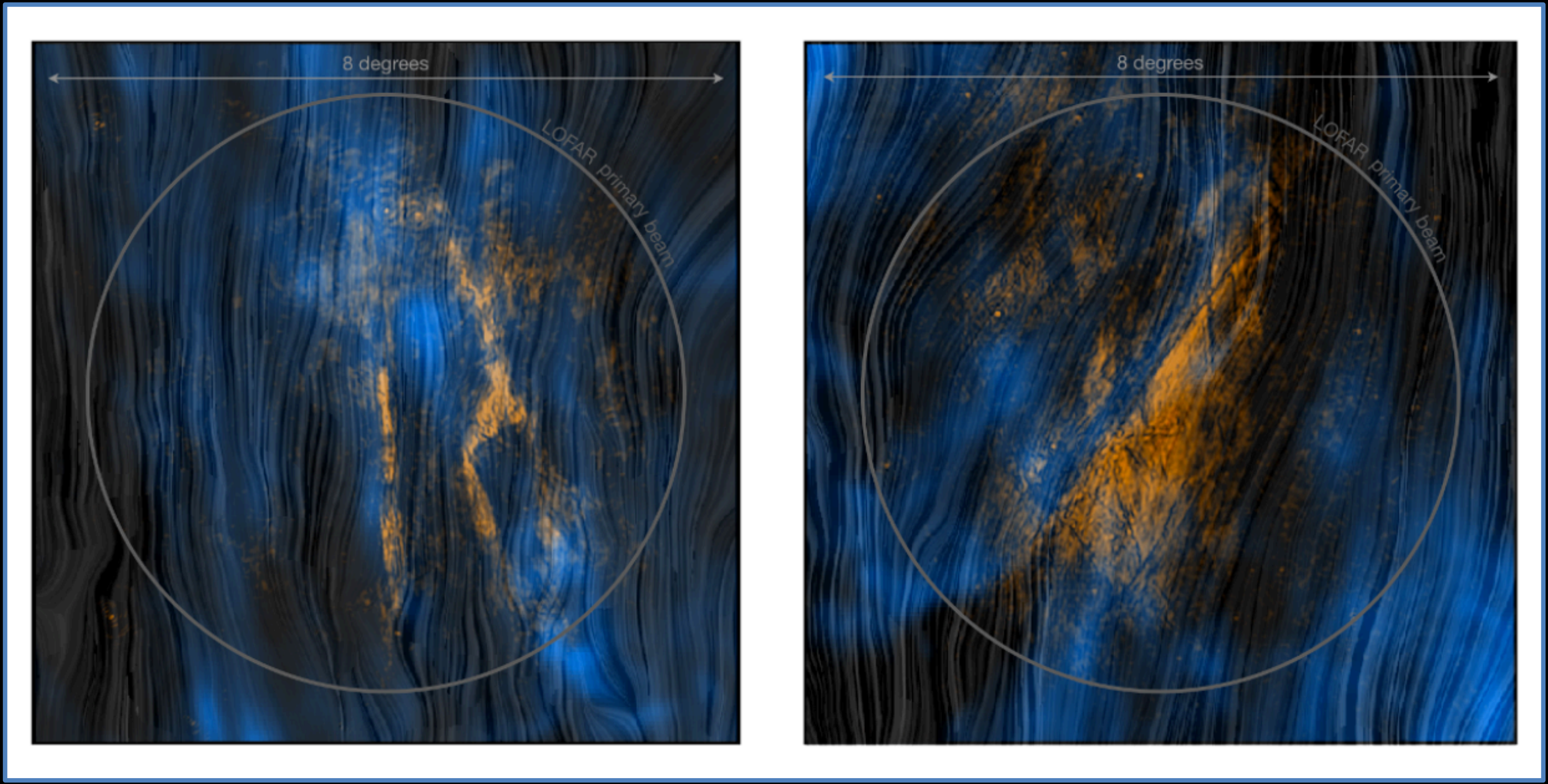
Clark et al. 2014; Kalberla et al. 2016

3C 196 field

LOFAR 0 rad/m², EBHIS -5 km/s

Field A

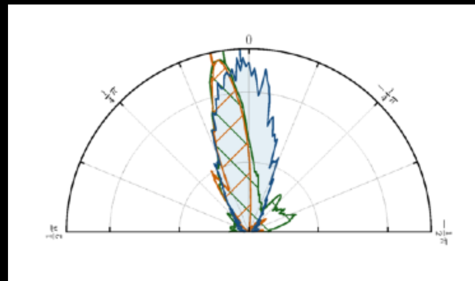
LOFAR -1.25 rad/m², EBHIS +1.4 km/s



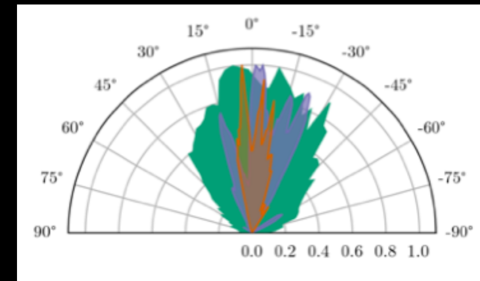
Zaroubi, Jelić et al. 2015, Kalberla & Kerp 2016,
Bracco et al. 2020

- observed correlation between Faraday structures, magnetic field probed by polarised dust emission and neutral hydrogen (mostly CNM and LNM)

3C 196 field



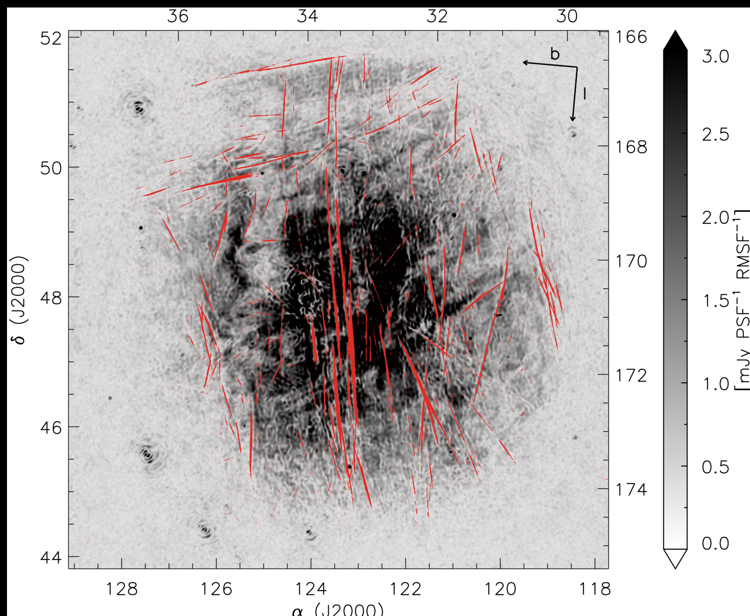
Field A



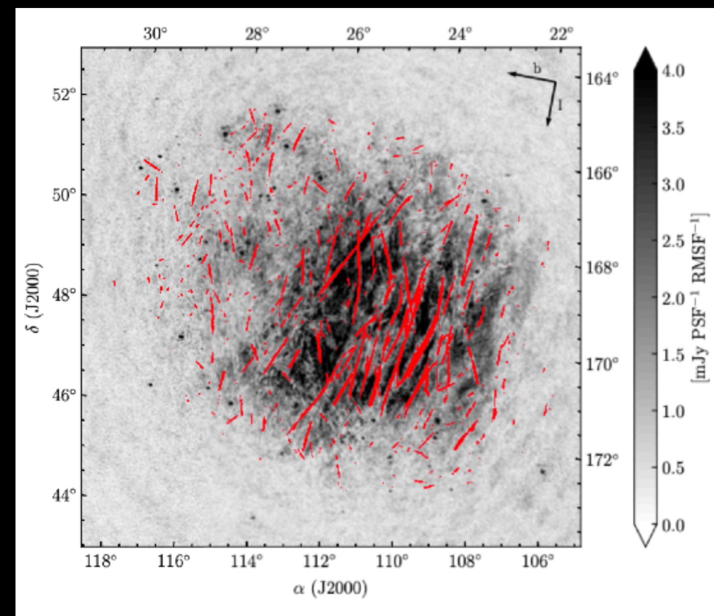
LOFAR data

EBHIS data

Planck data



Jelić et al. 2018



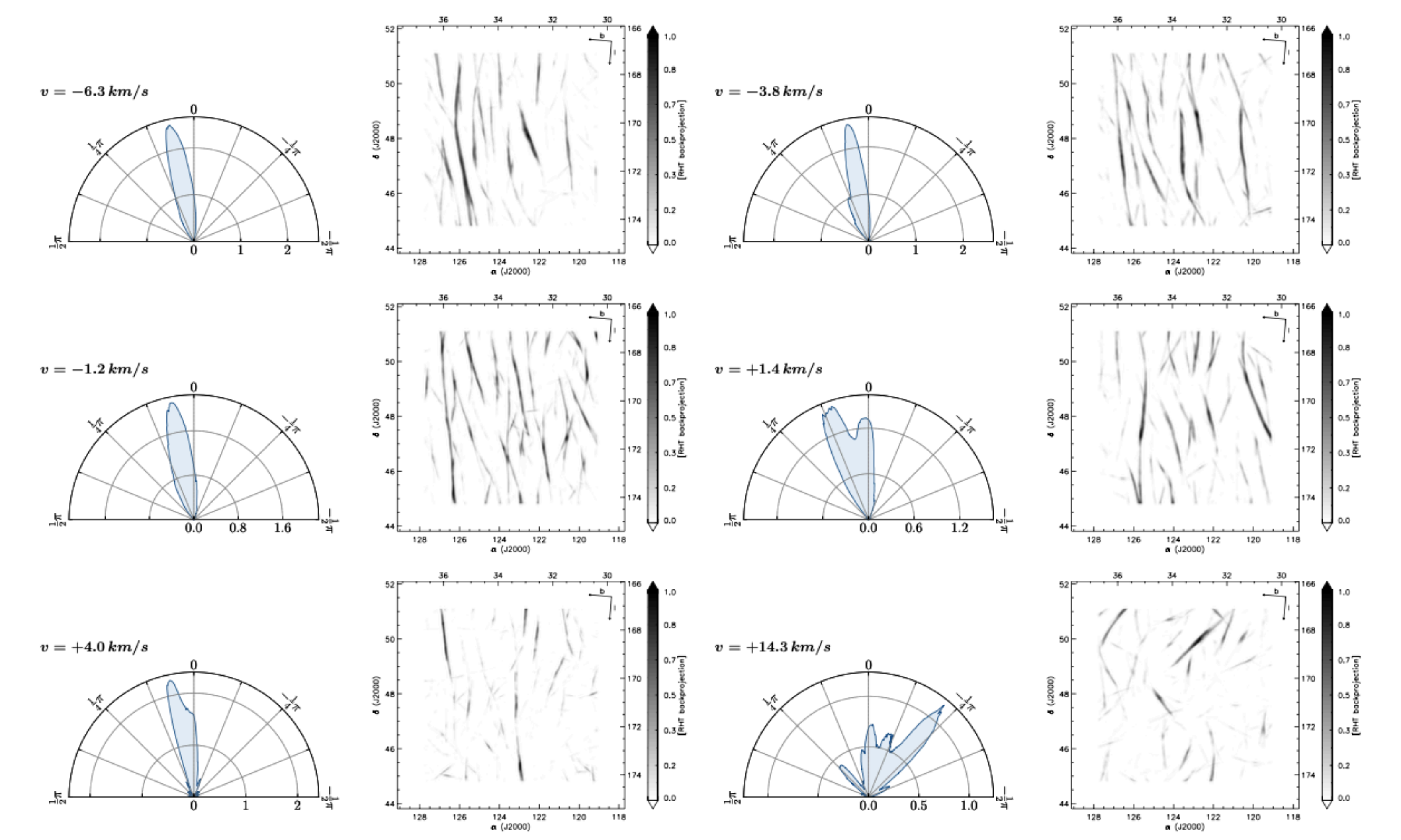
Turić et al. 2021

- analysis of straight depolarisation canals using Rolling Hough Transform (**RHT**, *Clark et al. 2014*)

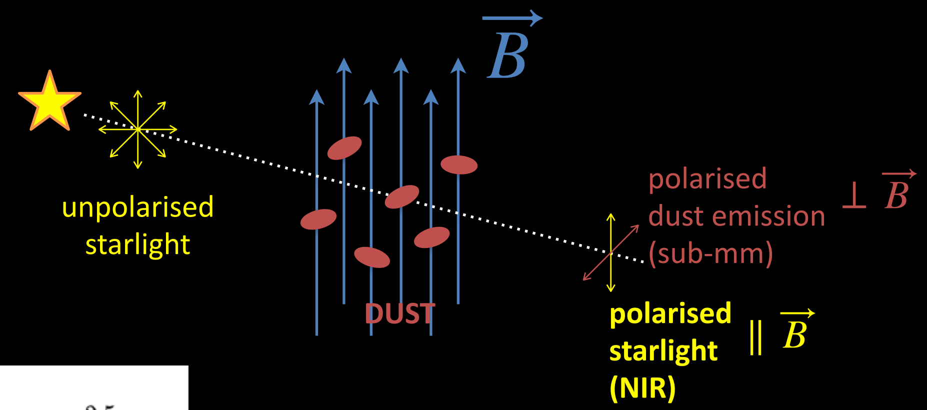
- *an alignment between three tracers of the local interstellar medium, driven by a very ordered local magnetic field in the plane-of-the-sky*

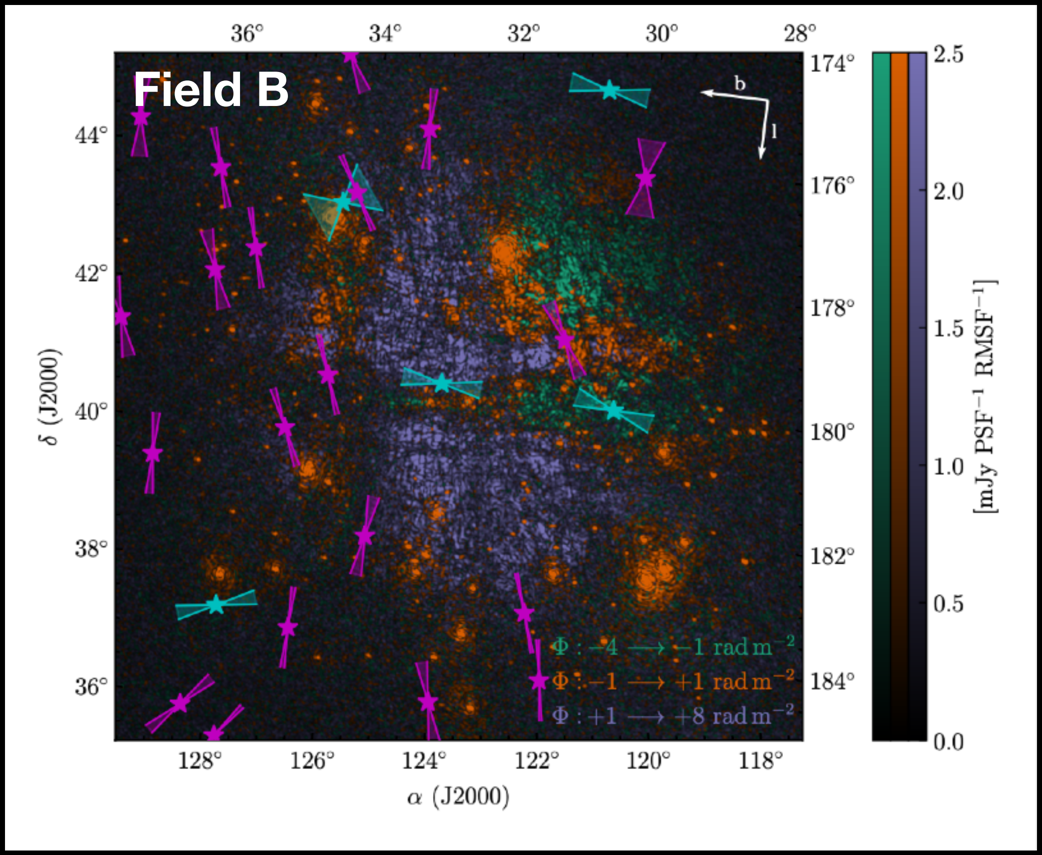
3C 196 field: HI filaments (EBHIS data)

Jelić et al. 2018



- magnetic field is **coherent** over some parts of the line-of-sight, supported by observations of HI filaments which are aligned to each other over the wide range of velocities (*Jelić et al. 2018*)
- magnetic field is **tangled** along the line-of-sight, supported by different orientation of HI filaments at different velocities (*Clark 2018, 2019*)

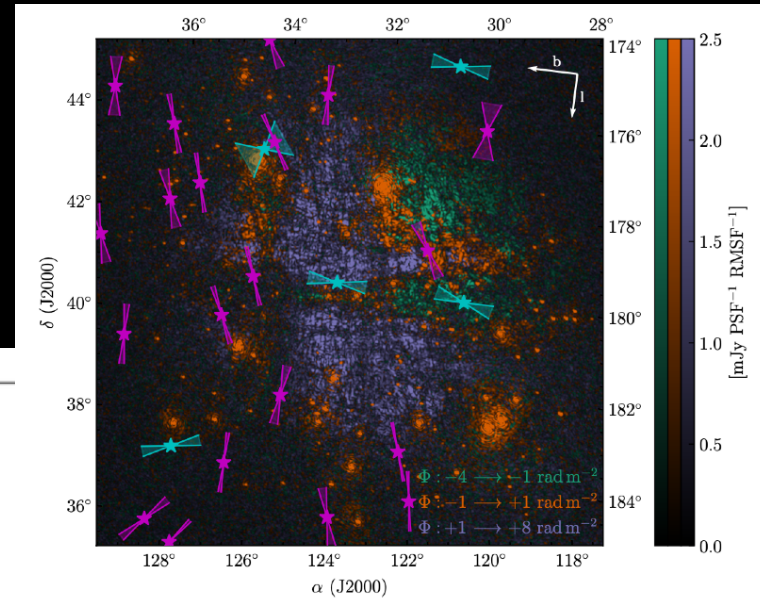


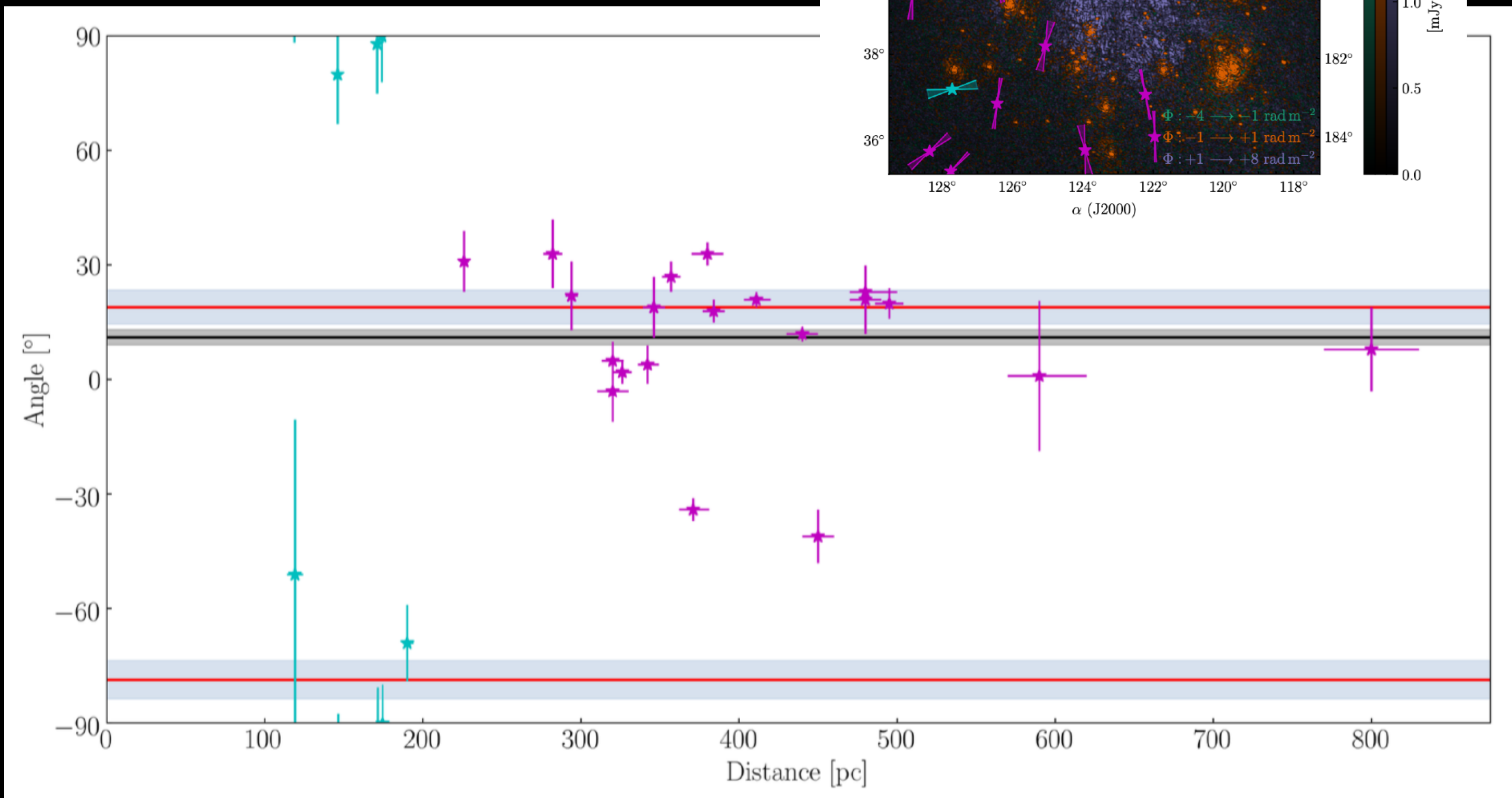


Turić et al. 2021

- available starlight polarization data (*Heiles 2000; Berdyugin, A. et al. 2001; Berdyugin, A. & Teerikorpi, P. 2002; Bailey et al. 2010; Berdyugin, A. et al. 2014*) with their distances from the Bailer-Jones catalogue (*Bailer-Jones et al. 2018*), which is based on Gaia Data Release 2 (*Gaia Collaboration et al. 2018*)

- polarized synchrotron emission observed at different Faraday depths originates from different distances:
    - 100 - 200 pc (-4 —> 0 rad/m^2)
    - 250 - 800 pc (0 —> +8 rad/m^2)

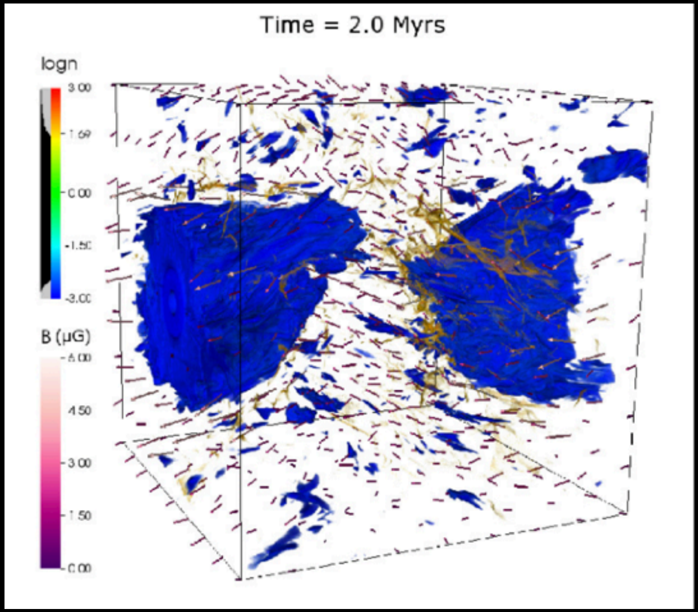




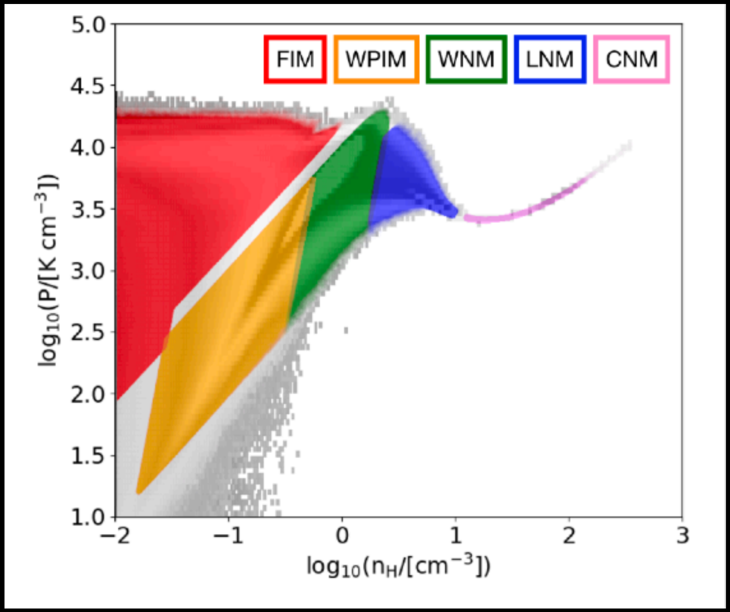
Turić et al. 2021

Synthetic observations of the multiphase interstellar medium

- based on *Ntormousi, et al. 2017* MHD simulations of colliding super-shells
- polarized emission from synchrotron radiation based on *Padovani et al. 2021,* assuming uniform distribution of cosmic-ray electrons, with variable energy spectral index
- analytical approach for ionization steady state, based on *Wolfire 2003, Bellomi et al. 2020*

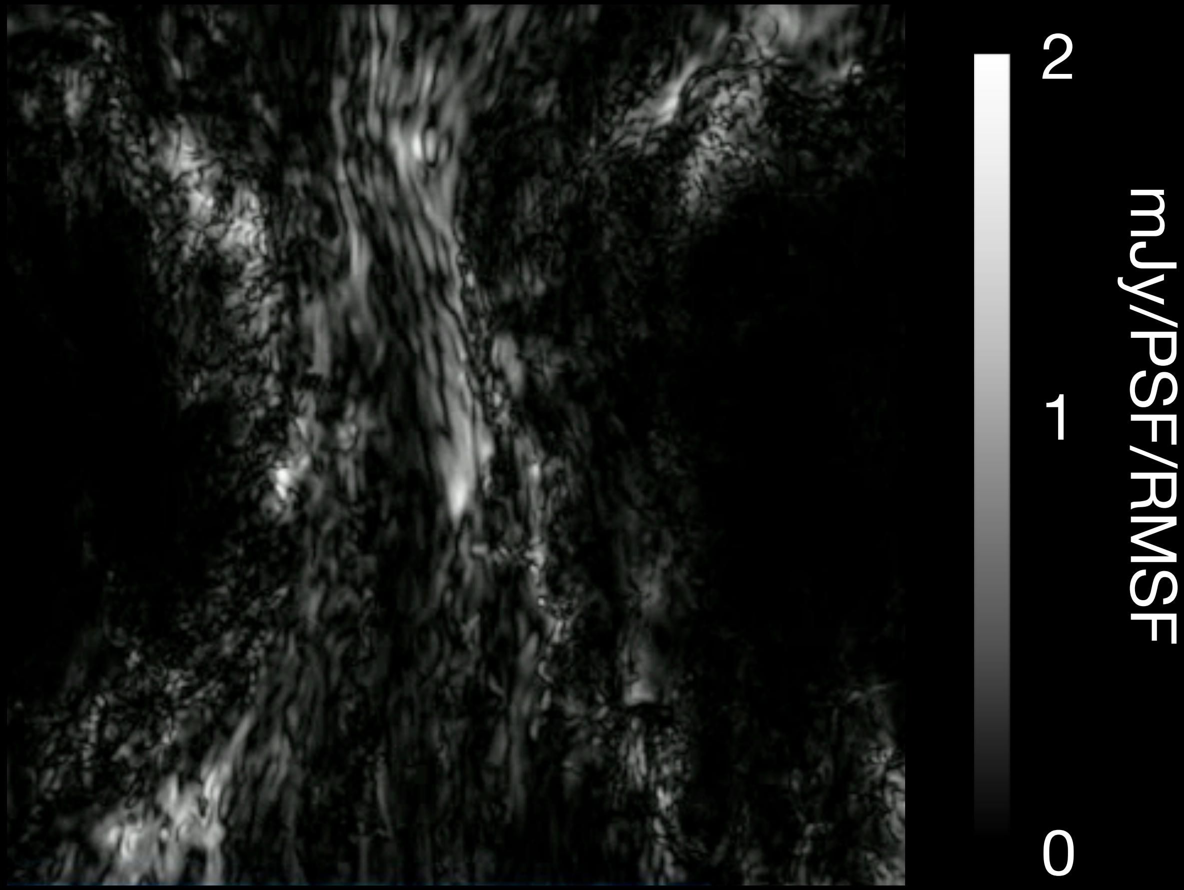


Ntormousi, et al. 2017



Bracco et al. 2022

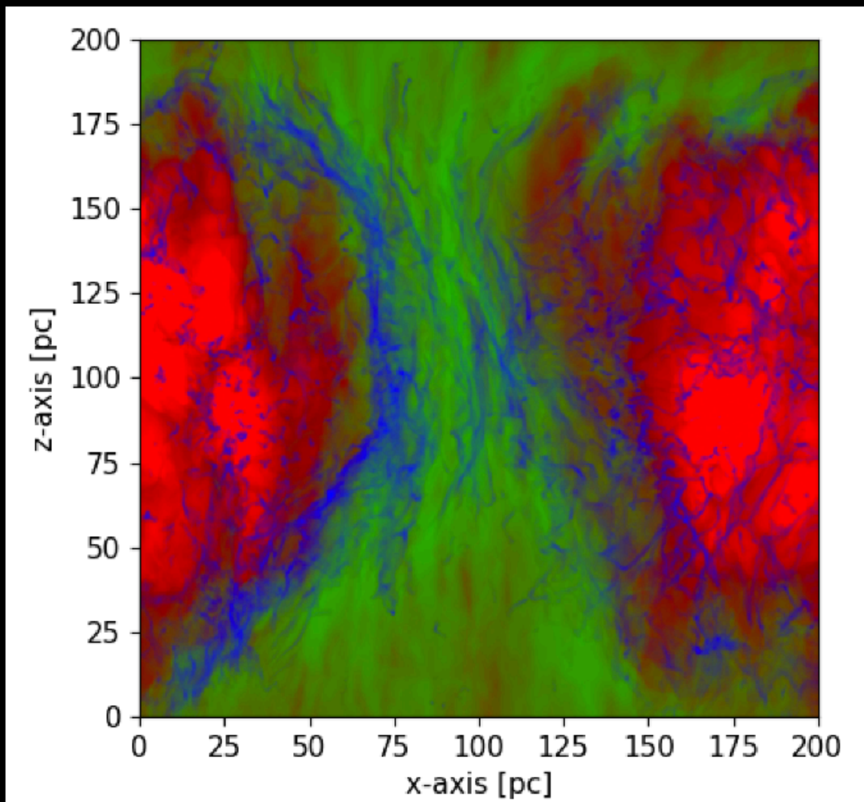
Synthetic observations of the multiphase interstellar medium

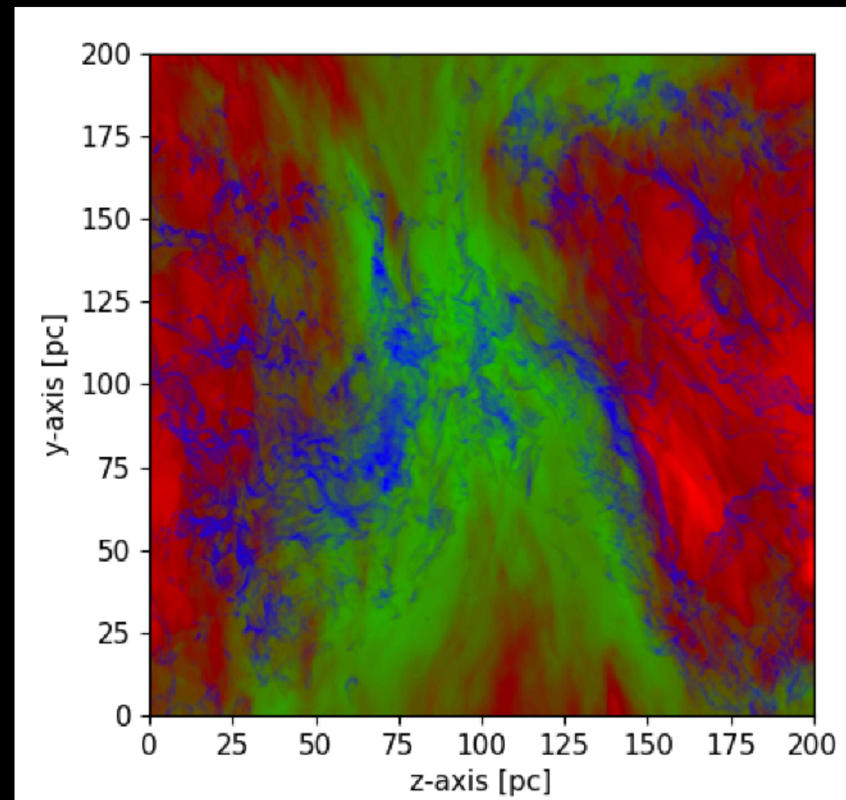


Bracco et al. 2022

Synthetic observations of the multiphase interstellar medium

- in the simulations we can distinguish warm/ionized to cold/neutral phases





Hot/fully ionized **Warm/partially ionized** **Cold/neutral**

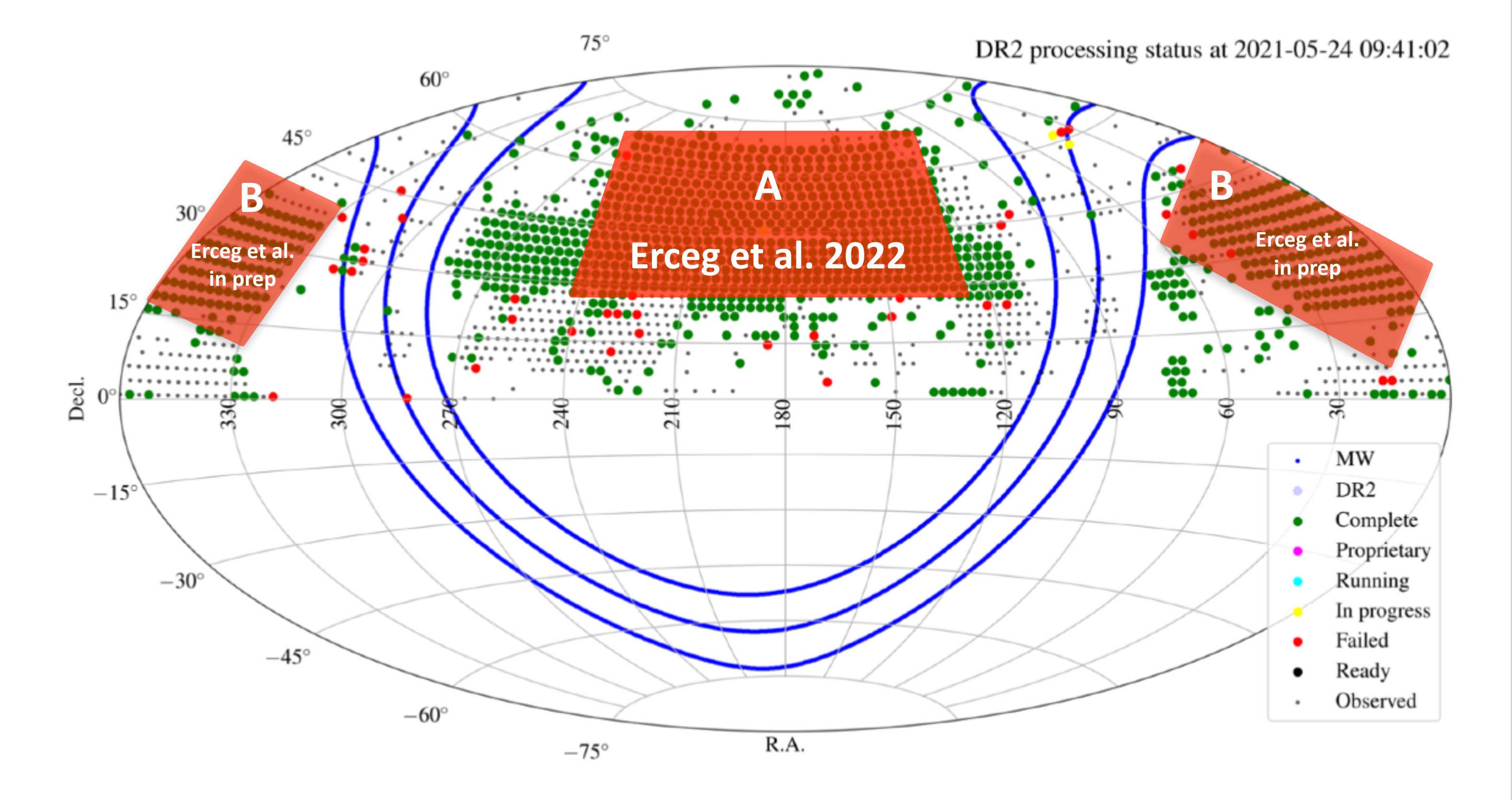
- strong correlation is found with warm/partially ionized, where is the cold gas in polarization ?

Bracco et al. 2022

LoTSS - LOFAR Two-metre Sky Survey

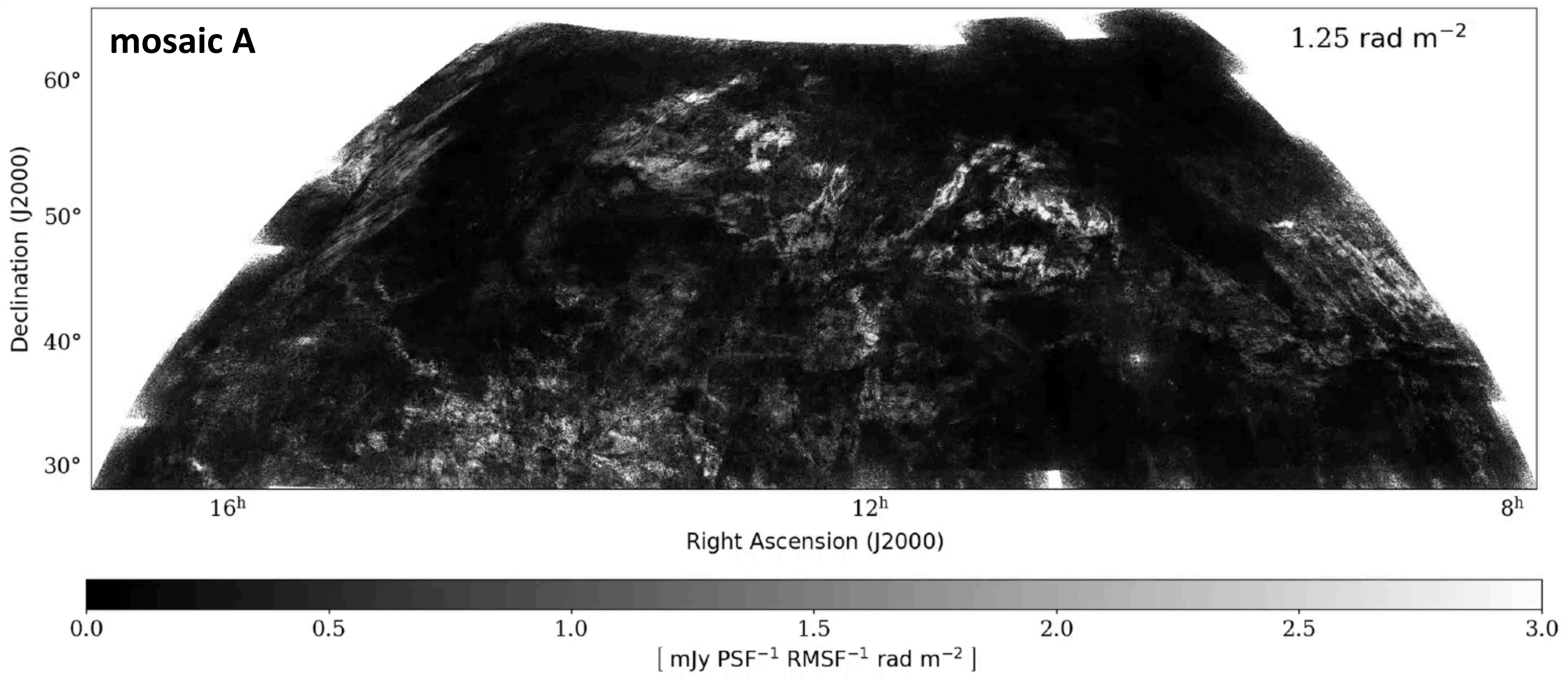
https://lofar-surveys.org

Shimwell et al. 2017, 2019, 2022

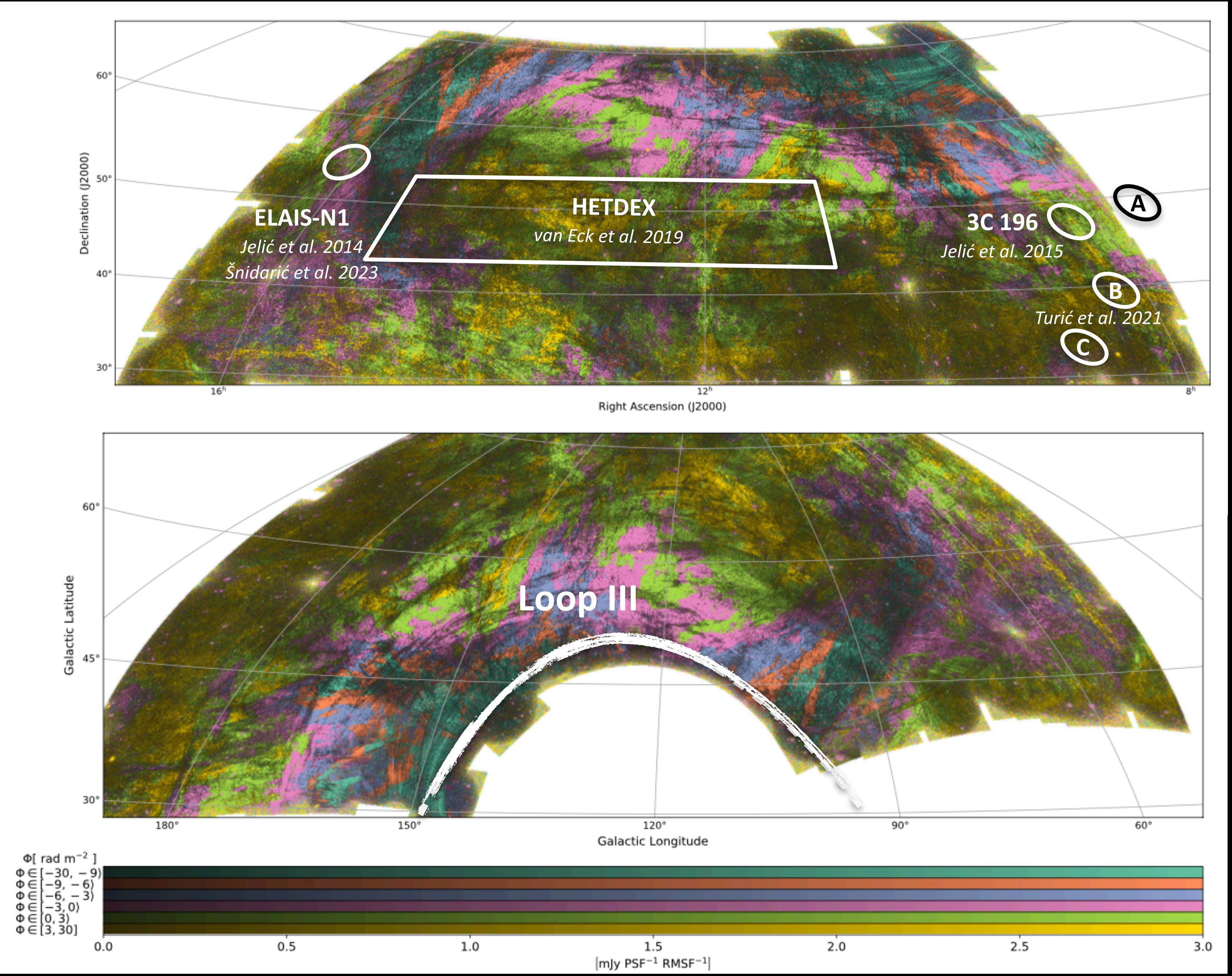


- LOFAR-HBA observations (120 - 168 MHz)
- mosaic A: 841 x 64 deg^2 fields towards outer Galaxy (3 100 deg^2)
- mosaic B: 198 x 64 deg^2 fields towards inner Galaxy (1 200 deg^2)

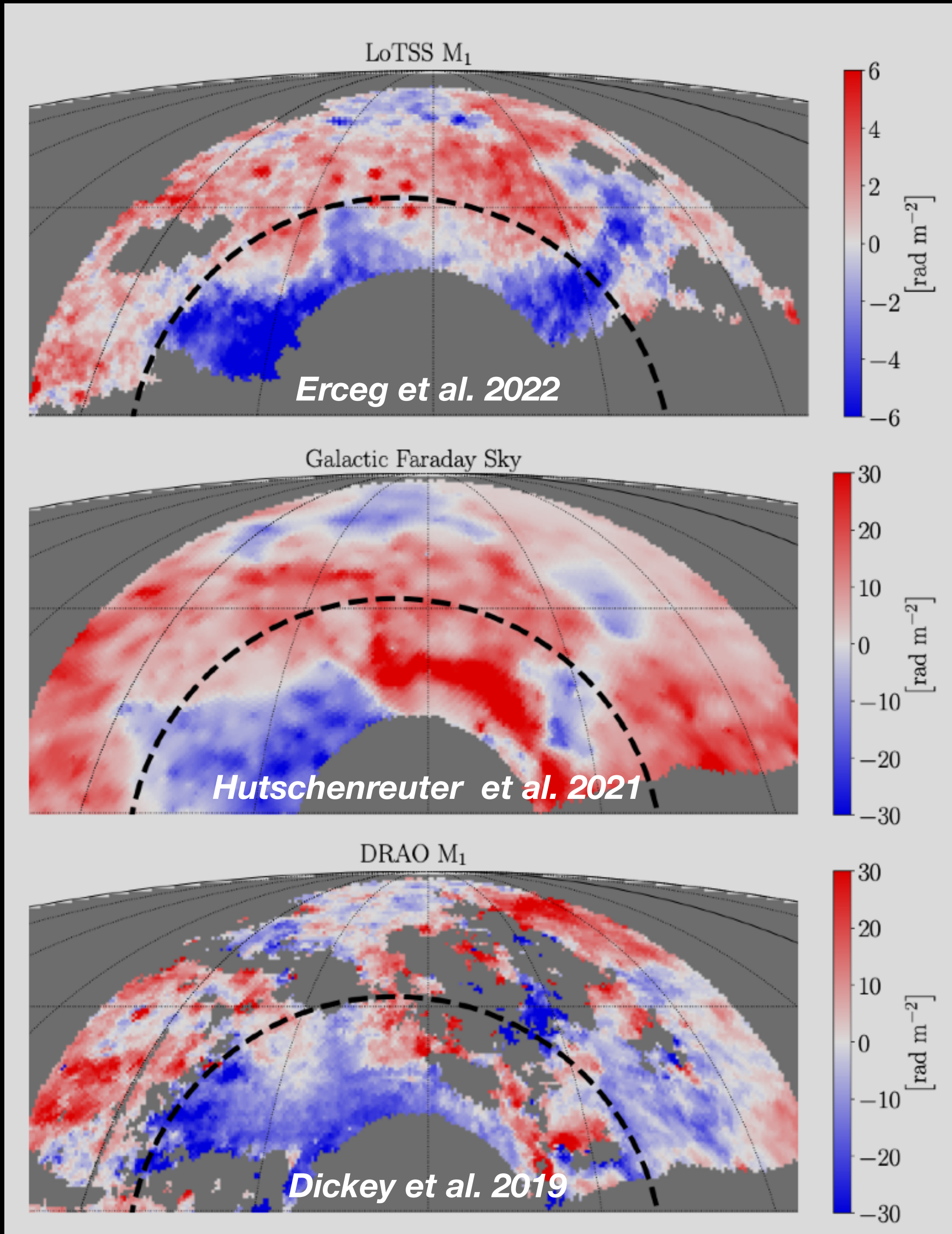
The intermediate Galactic latitude in the outer Galaxy



LoTTS Survey DR2: *Erceg et al. 2022*



LoTSS Survey DR2: *Erceg et al. 2022*

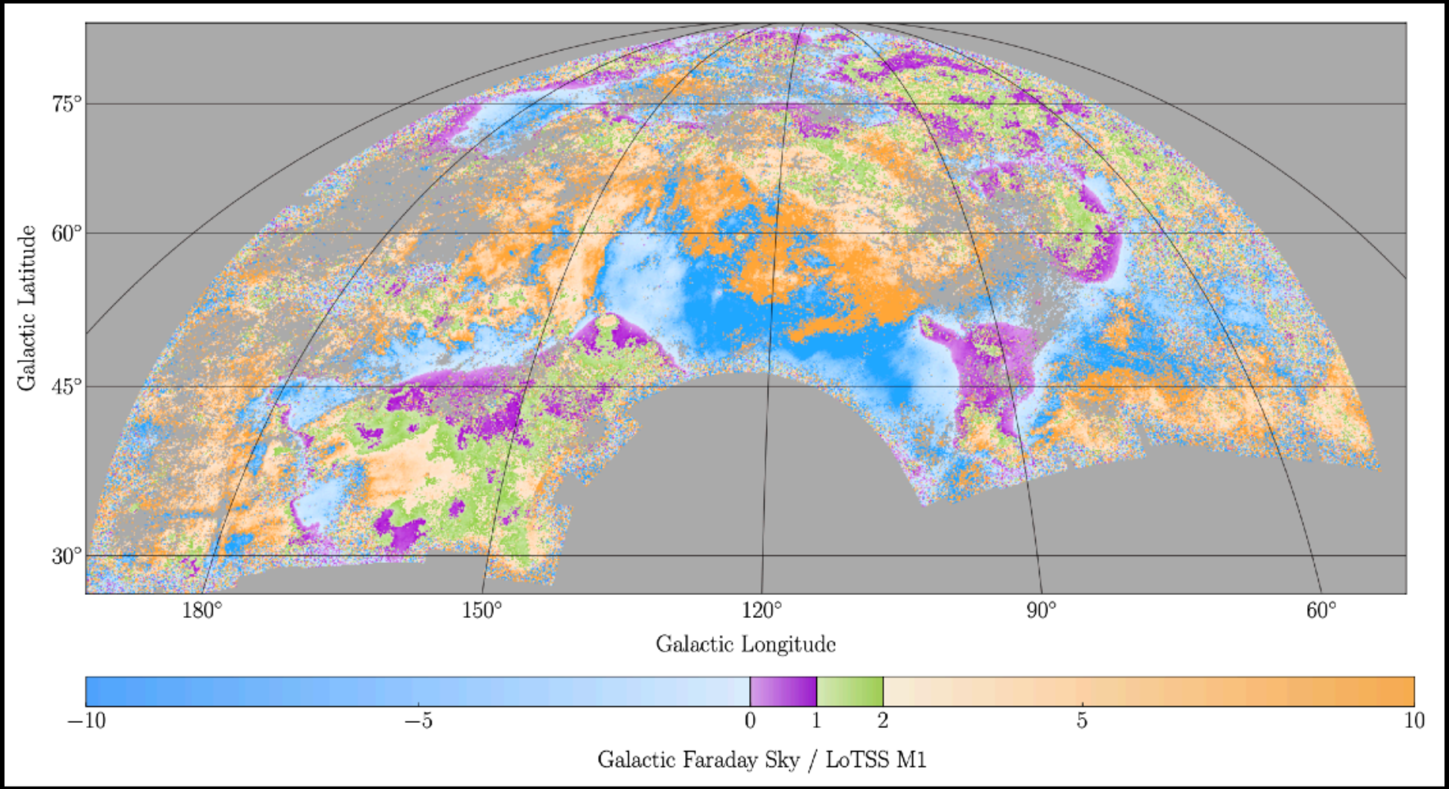


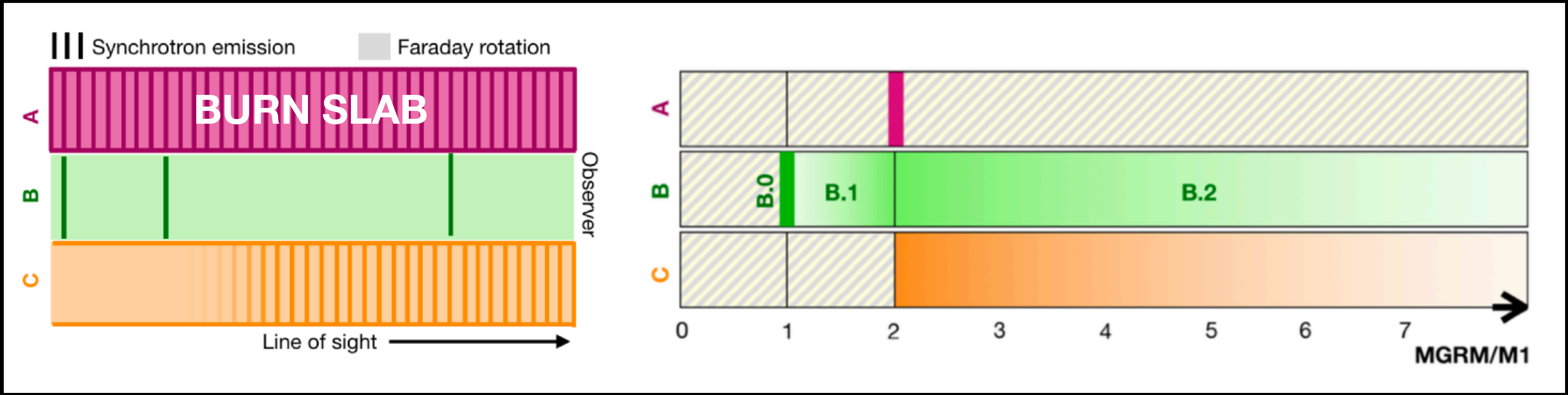
M1 - First Faraday moment - intensity weighted mean Faraday depth

Galactic Faraday Sky - the total RM produced by the Galaxy, reconstructed using extragalactic sources

- a correlation between the LoTSS M1 and the Galactic Faraday Sky
- a lack of correlation between the LoTTS M1 and DRAO GMIMS M1 - a result of frequency-dependent Faraday depth resolution and depolarisation

Erceg et al. 2022



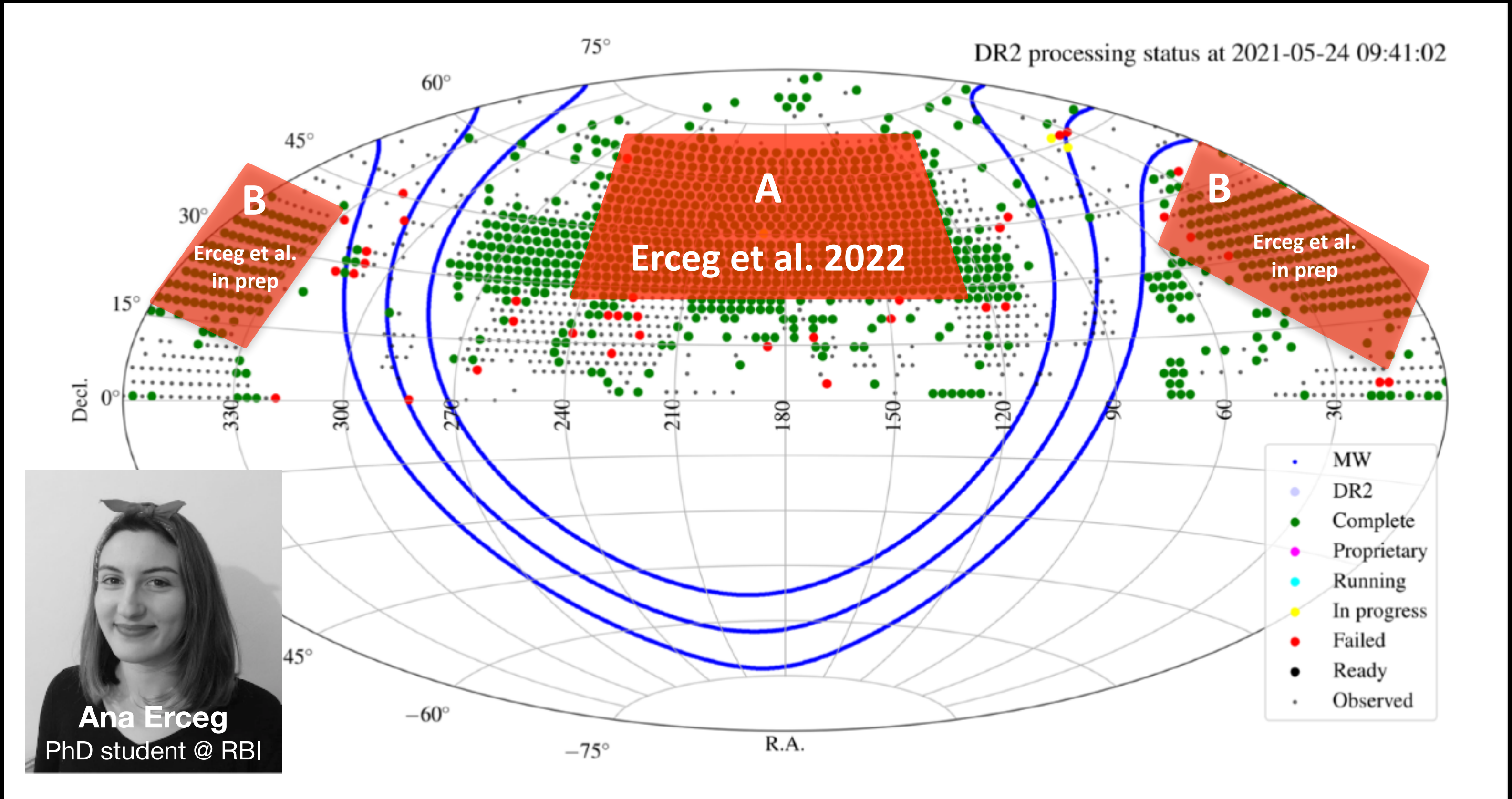


Erceg et al. 2022

LoTSS - LOFAR Two-metre Sky Survey

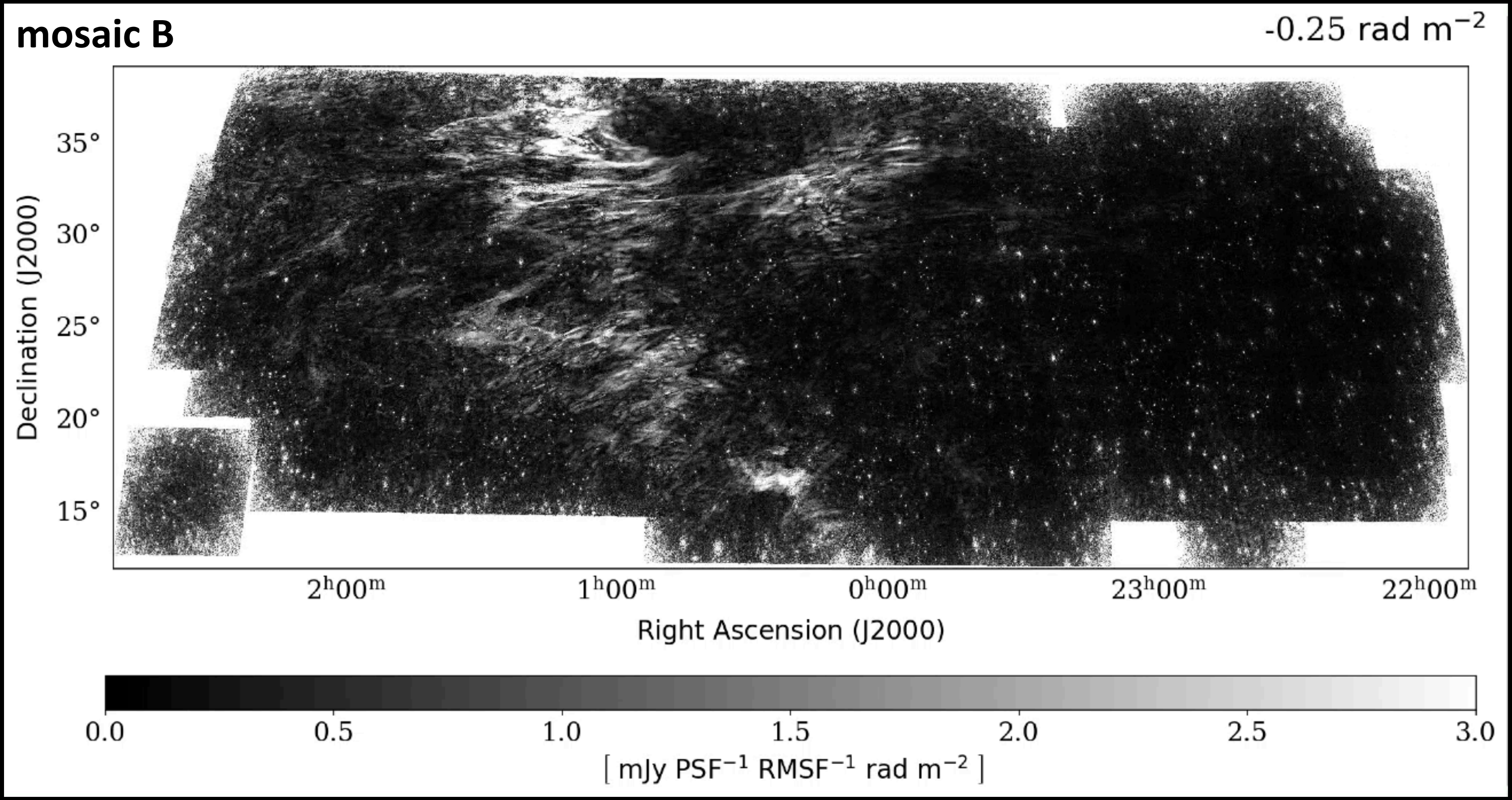
https://lofar-surveys.org

Shimwell et al. 2017, 2019, 2022



- LOFAR-HBA observations (120 - 168 MHz)
- mosaic A: 841 x 64 deg² fields towards outer Galaxy (3 100 deg²)
- mosaic B: 198 x 64 deg² fields towards inner Galaxy (1 200 deg²)

The intermediate Galactic latitude in the inner Galaxy



LoTTS Survey DR2: *Erceg et al. in prep.*

- LOFAR (115 - 175 MHZ) is an excellent instrument to do Faraday tomography of the local ISM and constrain its physical properties

- morphology of the observed polarized emission is very rich, with the brightness temperature up to tens of K, including a discovery of many filamentary structures and linear depolarization canals

- based on multi-frequency/multi-tracers analysis we found an alignment between three distinct tracers of the local ISM, the ordered magnetic field plays a crucial role in confining different interstellar medium phases

- the spatial distribution of the LOFAR polarization as a function of the distance can be studied by using the state-of-the-art starlight extinction and polarization data