

LOFAR Annual Meeting 2026

The Galactic ISM seen by LOFAR

What have we learned and what comes next?

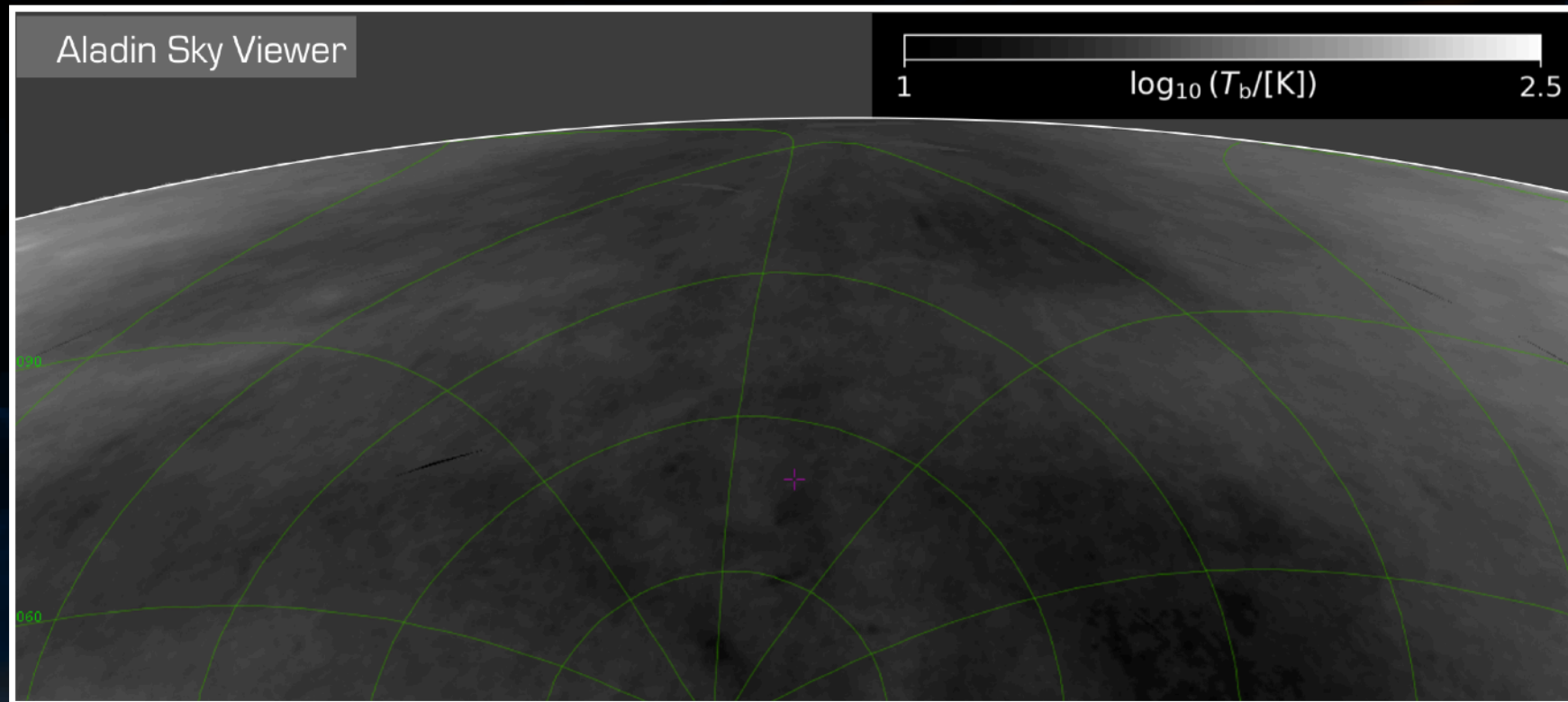
Andrea Bracco

In collaboration with:

V. Jelić, A. Erceg, L. Turić, I. Šnidarić, M. Haverkorn, L. Ceraj, J. Berat, M. Padovani, D. Galli, M.-A. Miville-Deschênes, F. Boulanger, J. Dickey, the LoTSS team + the Global Magneto-Ionic Medium Survey (GMIMS) team ...

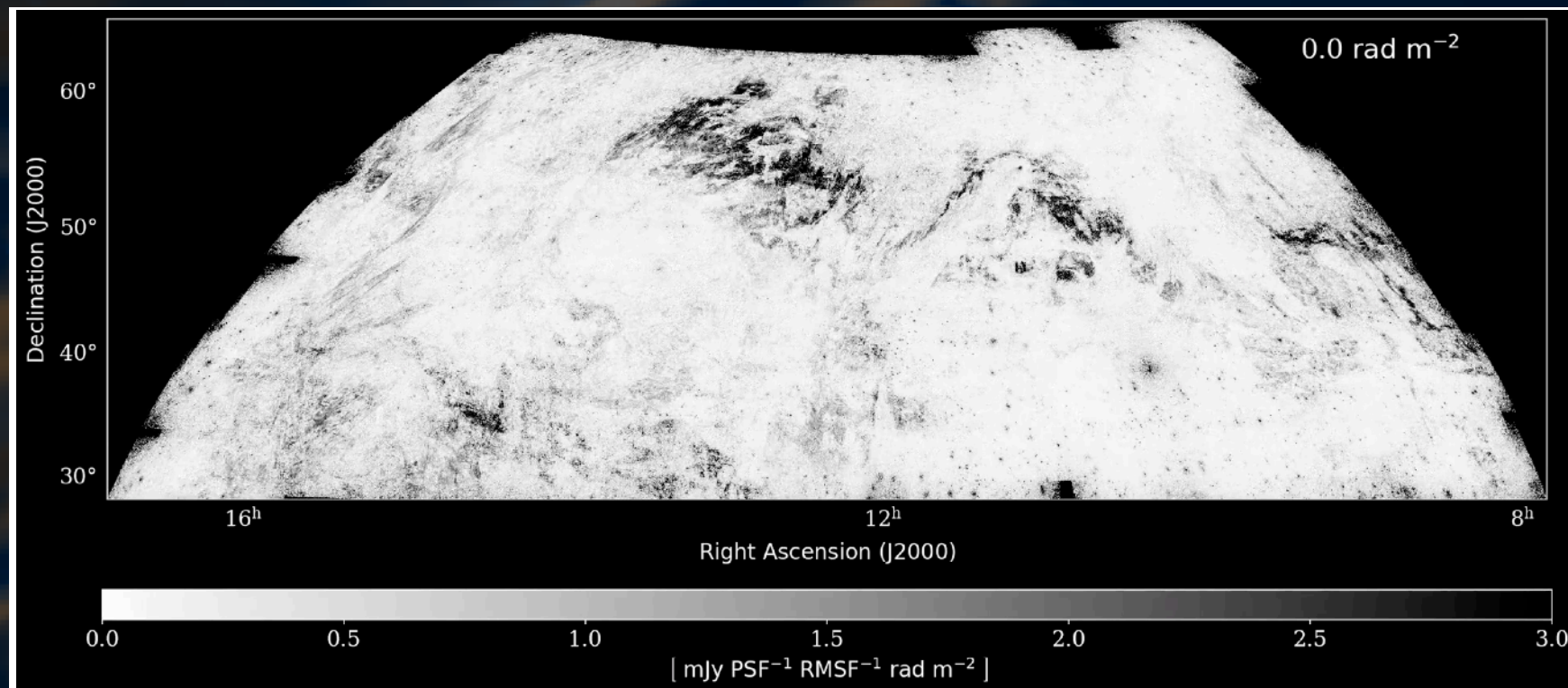
Motivation 1: how do we understand these new data ?

Total intensity ~ 408 MHz



[Remazeilles+2015]

Polarized intensity ~ 150 MHz

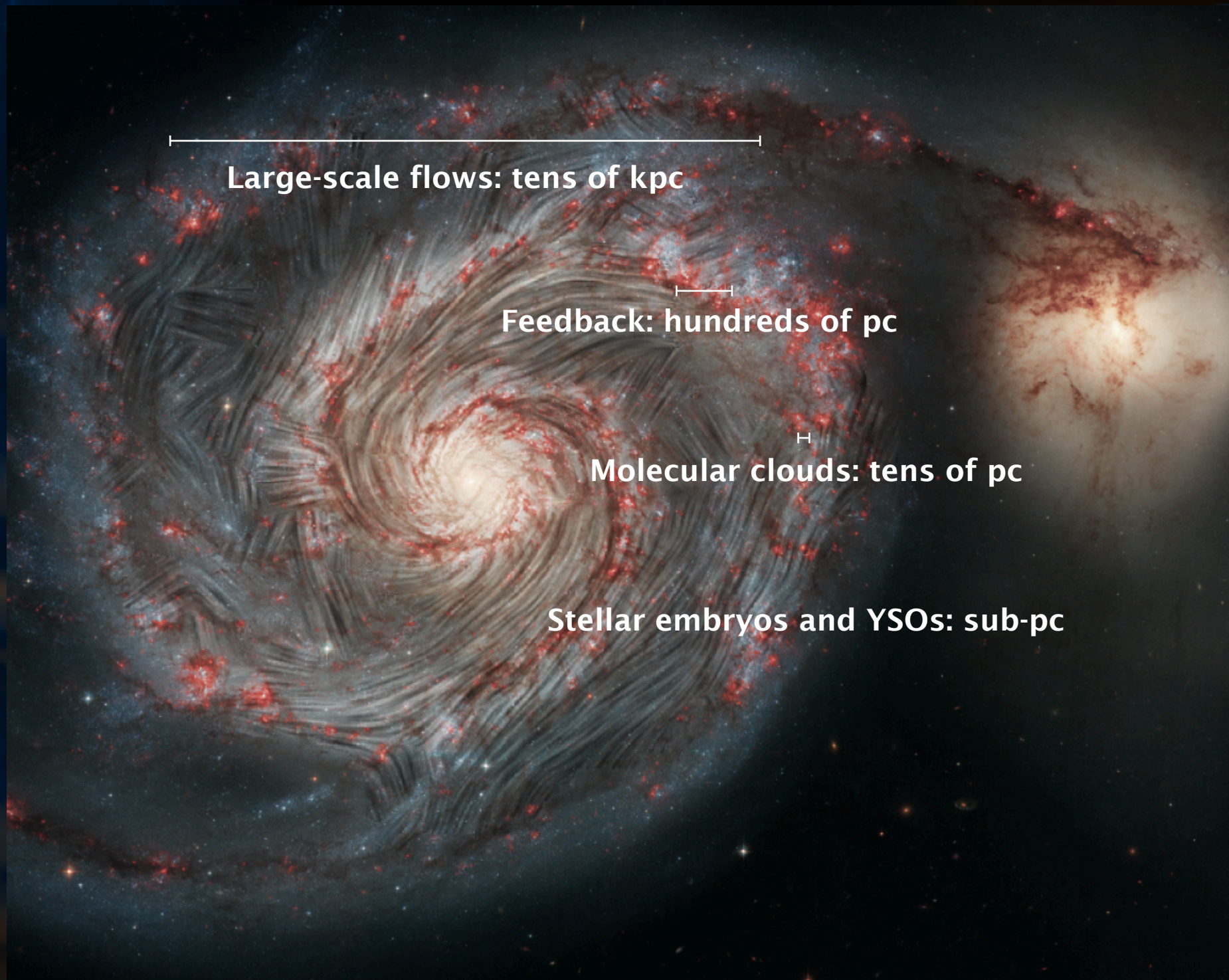


[Erceg+2022]

Large amount of unexpected linear polarization observed in the Galaxy with LOFAR

Motivation 2: magnetic fields and star formation

Messier 51 (M51) galaxy - The Whirlpool galaxy - Hubble Space Telescope SOFIA 154um (Borlaff+2021)



- **Big problem:**
Milky-Way type of galaxies
are inefficient in forming
stars

- **Ingredients:**

MAGNETIC FIELD vs MATTER

FEEDBACK & IONIZATION
(photons, shocks, cosmic rays)

TURBULENT and MULTIPHASE

HIM ($\sim 10^6$ K) ($\sim 10^{-2}$ cm $^{-3}$)
WIM ($\sim 10^4$ K) ($\sim 10^{-1}$ cm $^{-3}$)
WNM ($\sim 10^3$ K) ($\sim 10^0$ cm $^{-3}$)
CNM ($< 10^2$ K) ($> 10^2$ cm $^{-3}$)

MULTISCALE

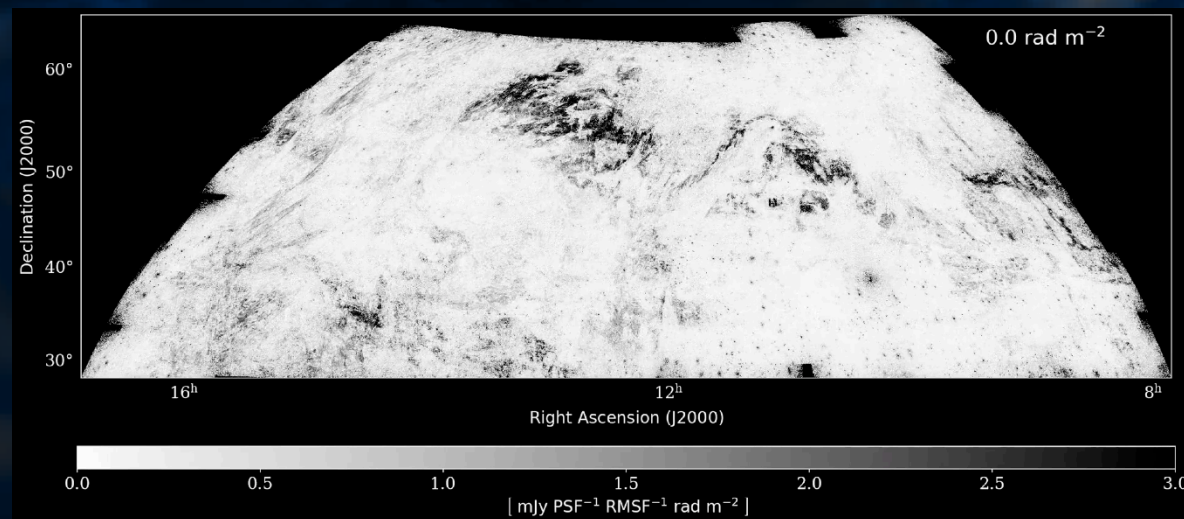
GALACTIC LABORATORY

Credits: NASA, ESA, S. Beckwith (STScI) and the Hubble Heritage Team (STScI/AURA)

The LOFAR contribution to Galactic ISM studies

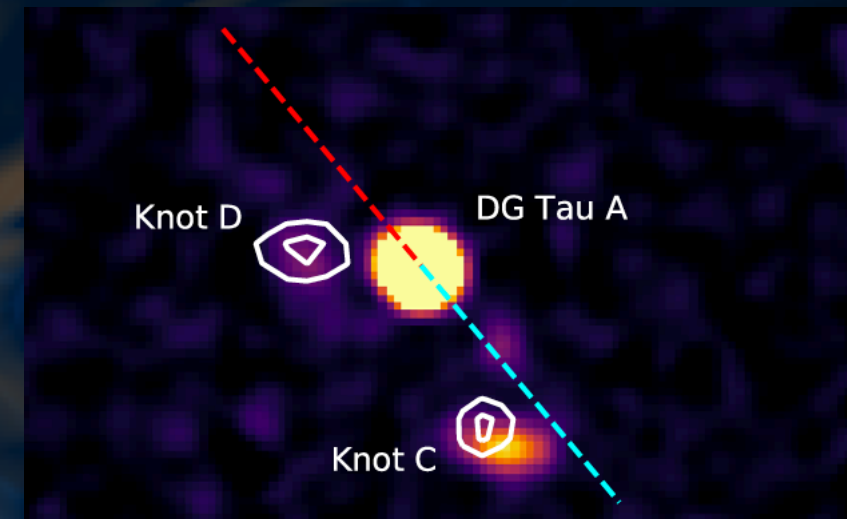
“sub-grid” physics in external galaxies

Phase transition
in the magnetized ISM



[e.g.,
Zaroubi+2015,
Jelić+2018,
Bracco+2020,
Turić+2021,
Padovani+2021,
Bracco+2022,
Erceg+2022, 2024a, 2024b,
Berat+2026]

Non-thermal processes in
Young stellar objects

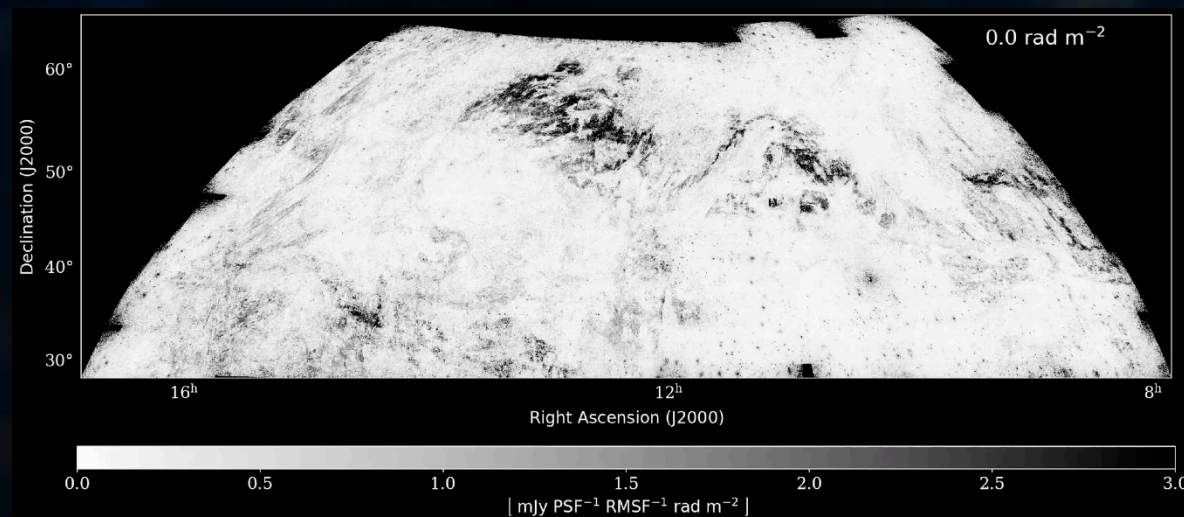


[e.g.,
Feeney-Johansson+2019, 2021
Bracco+2025]

The LOFAR contribution to Galactic ISM studies

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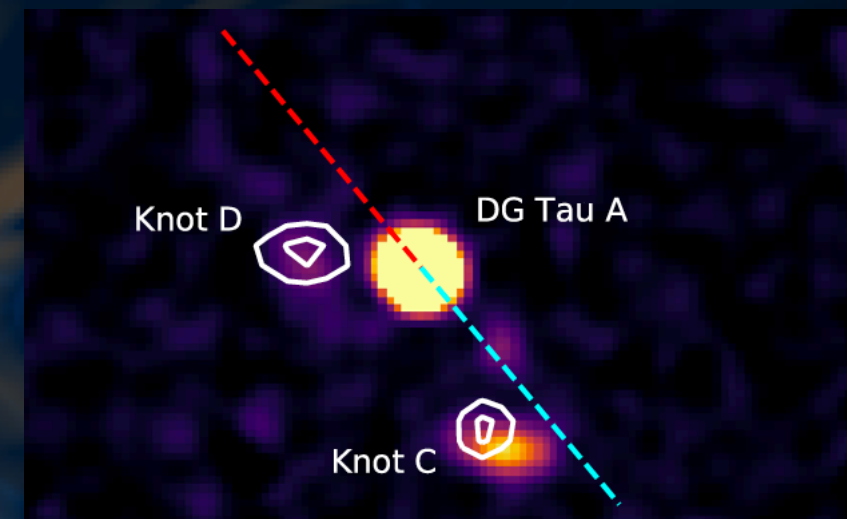
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Berat+2026]

- * HBA: Polarized Emission
- * HBA: Depolarization

Non-thermal processes in Young stellar objects



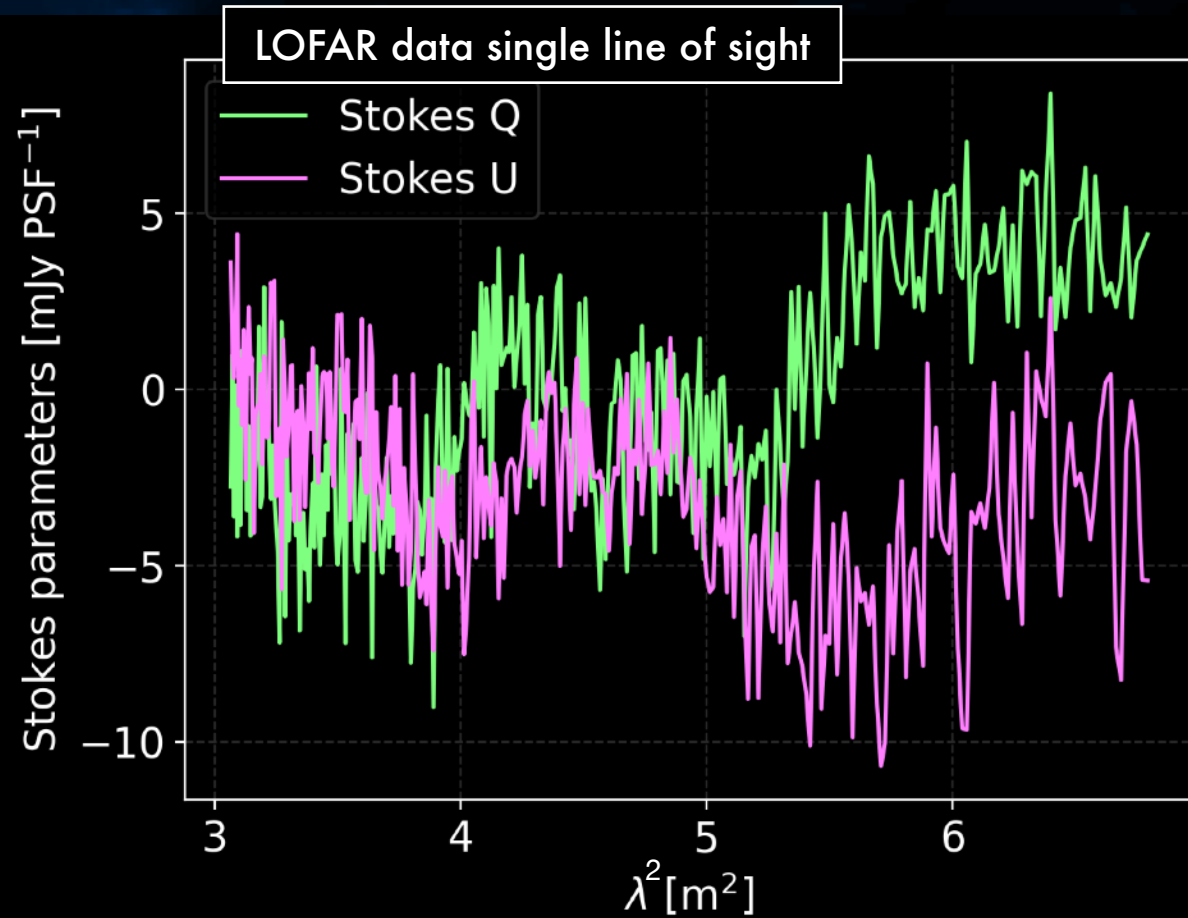
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A little reminder: Faraday tomography

Radio observables (Stokes I,Q,U) :

$$P(\lambda^2) = Q(\lambda^2) + iU(\lambda^2) = P_0 e^{2i(\psi_0 + RM\lambda^2)}$$

$$\psi_{\text{pol}} = 0.5 \arctan(U/Q) = \psi_0 + RM\lambda^2 \propto \psi_0 + \lambda^2 \int n_e \vec{B} \cdot d\vec{l}$$



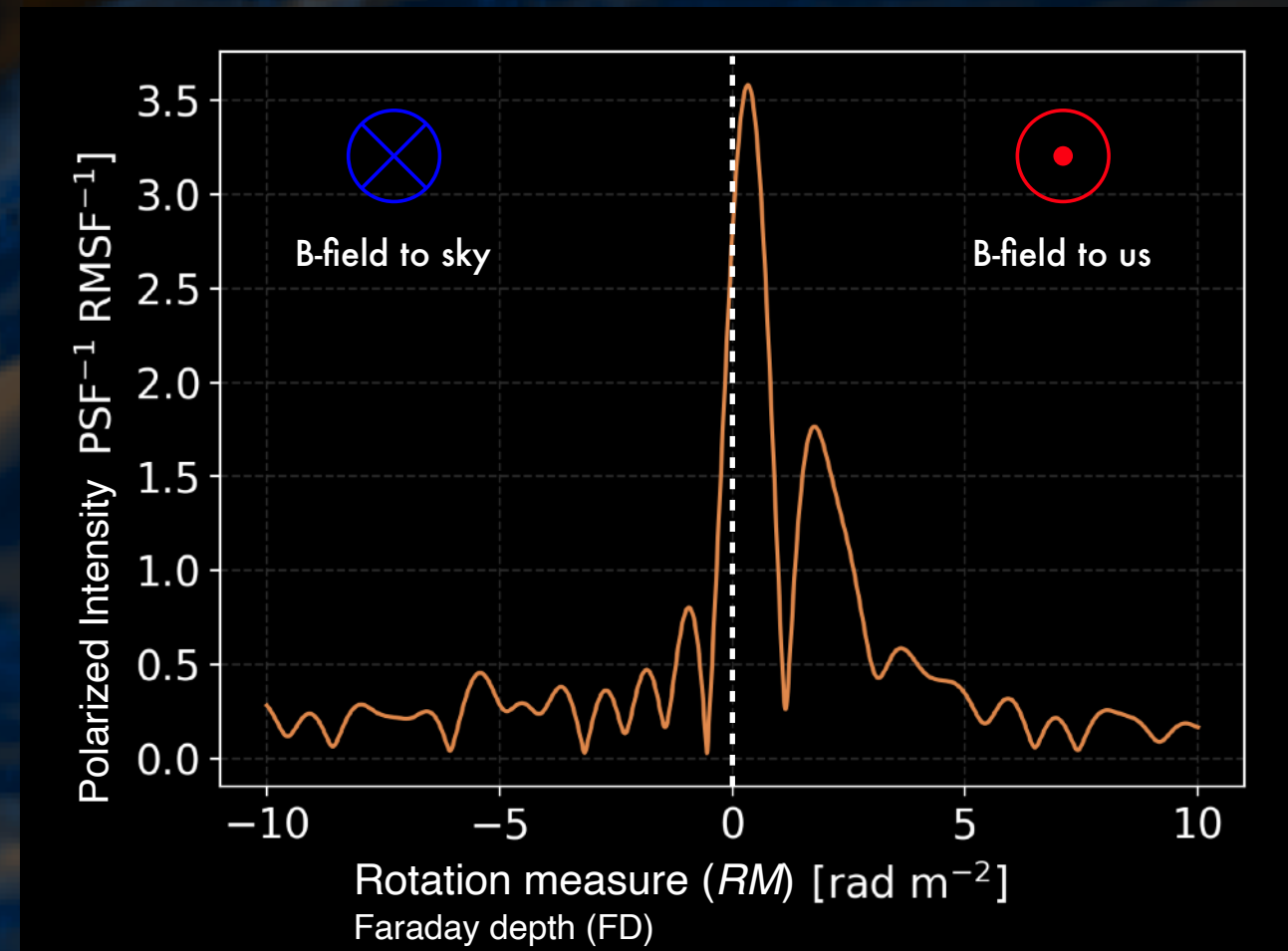
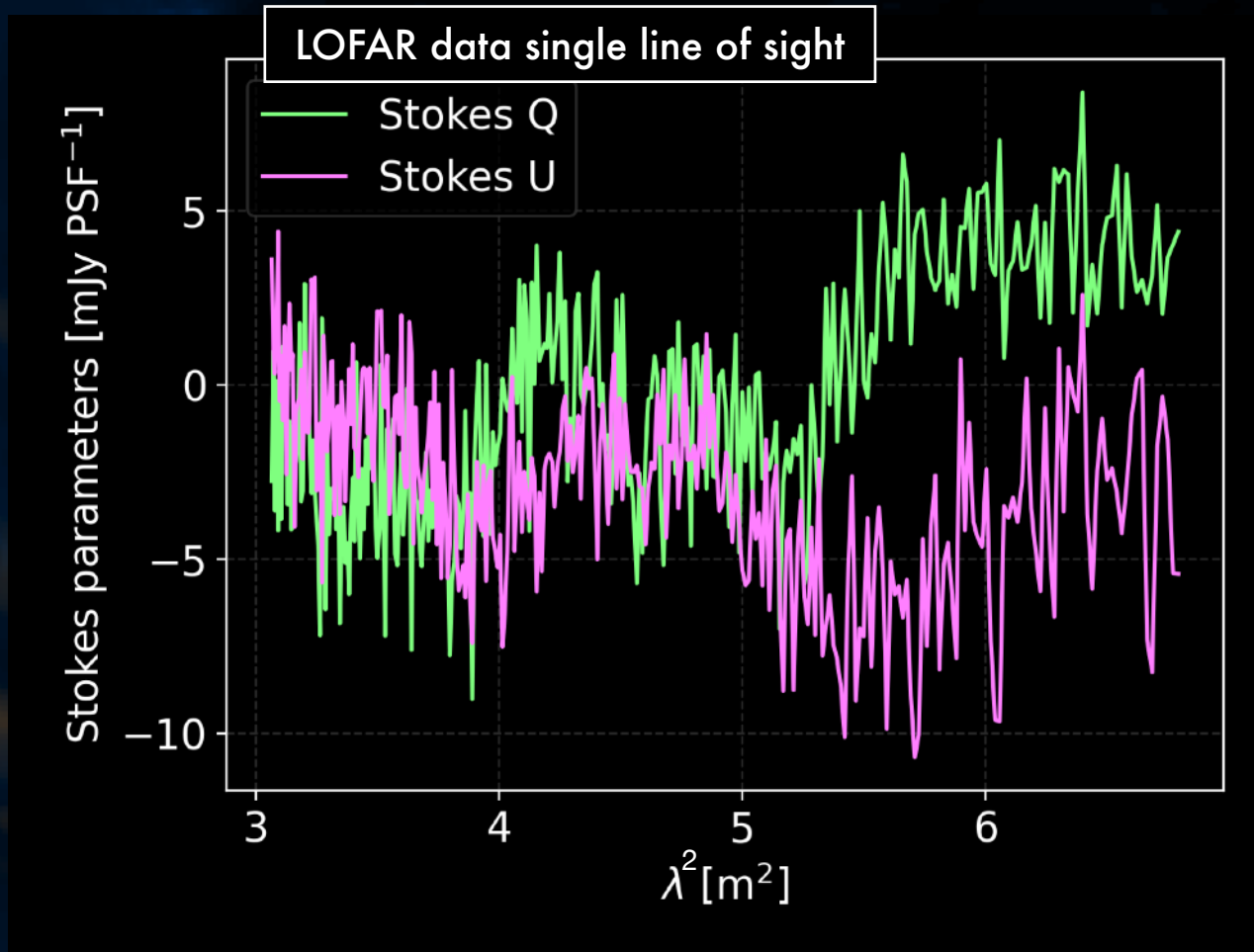
[Jelić+2015]

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[Jelić+2015]

Faraday tomography ('Fourier transform')

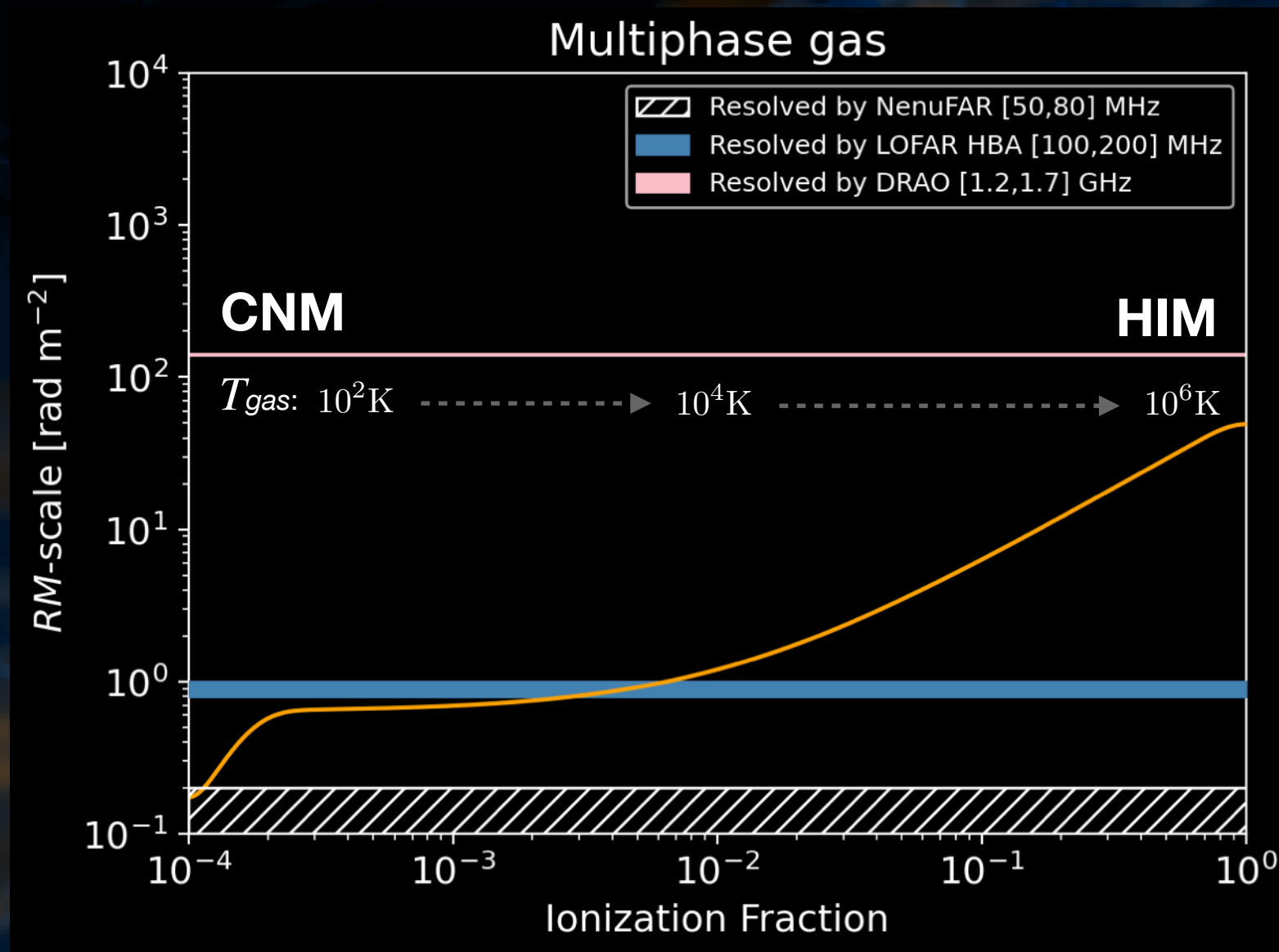
[Brentjens & de Bruyn 2005]

Why Phase transition? Why LOFAR?

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- A limited frequency sampling limits both small and large scales in the RM space

Expected RM-scale curve as a function of ISM gas phase

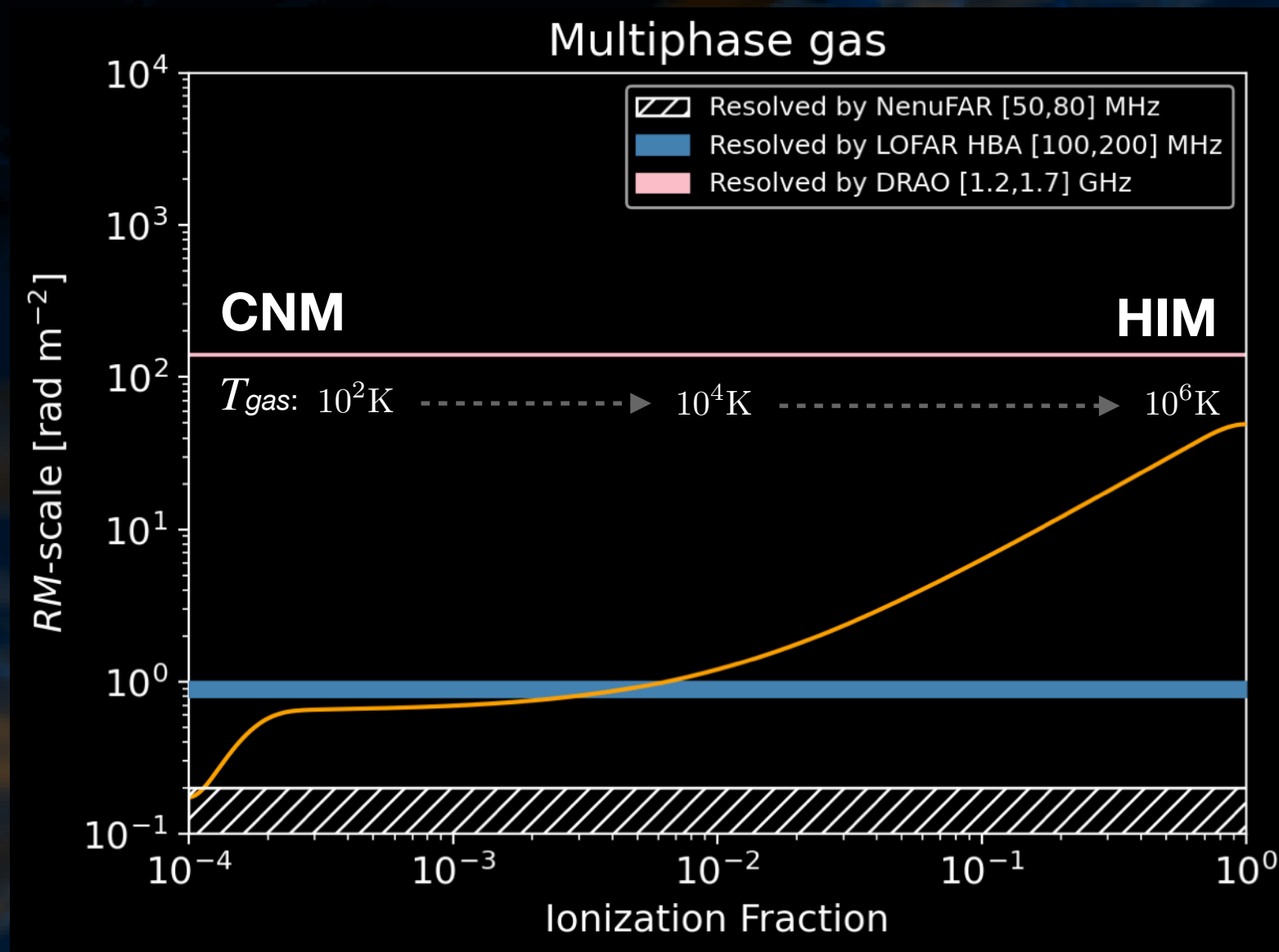


[Sun+AB+2026, upcoming in AASKAII]

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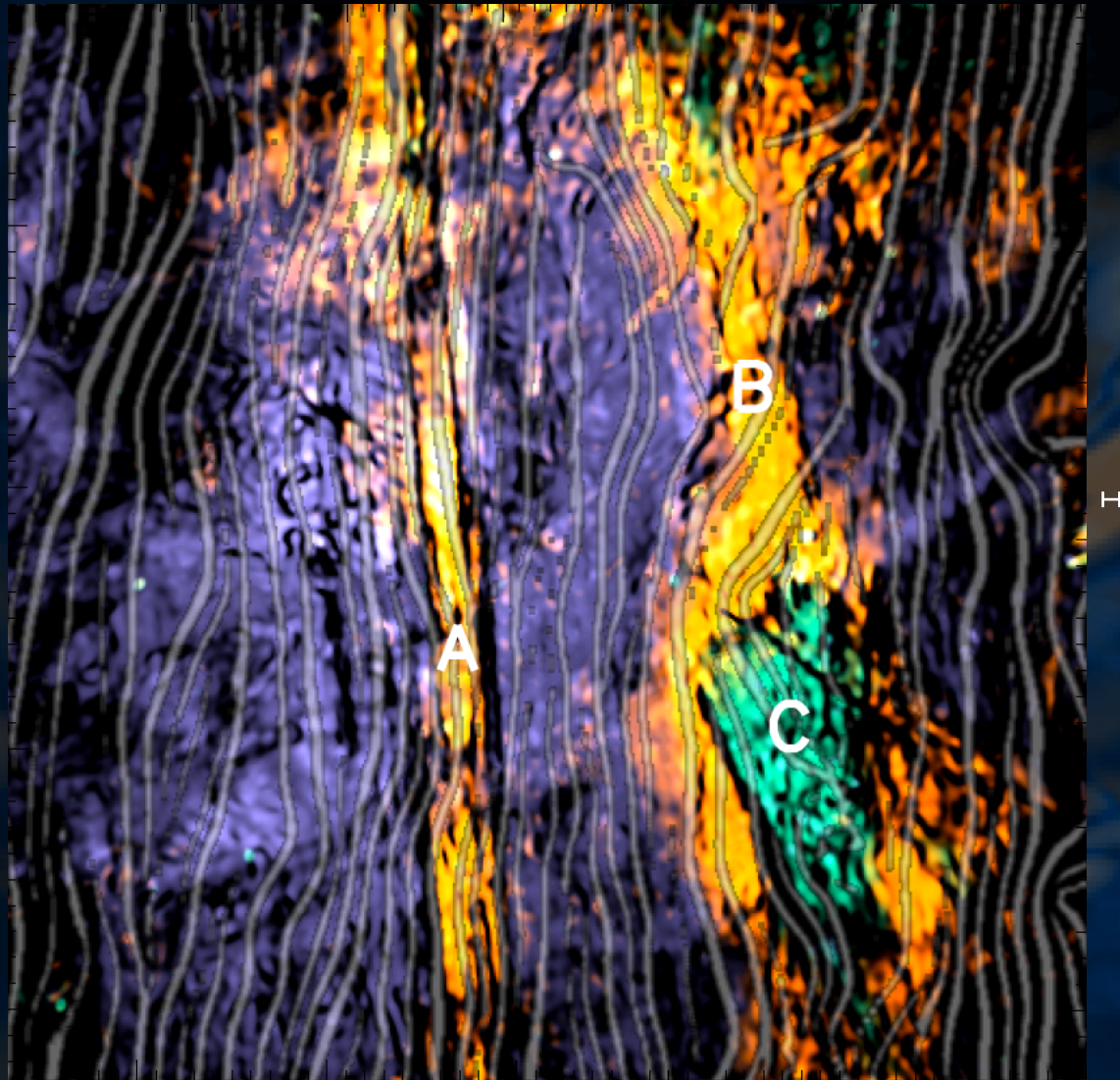
[Sun+AB+2026, upcoming in AASKAII]

The lower the frequency the finer the resolution in RM-space (**Ionospheric warning < 100 MHz!**)

Multiphase and Magnetized Emission with LOFAR

- LOFAR HBA emission (colors)
- B-field in neutral gas with Planck (drapery)

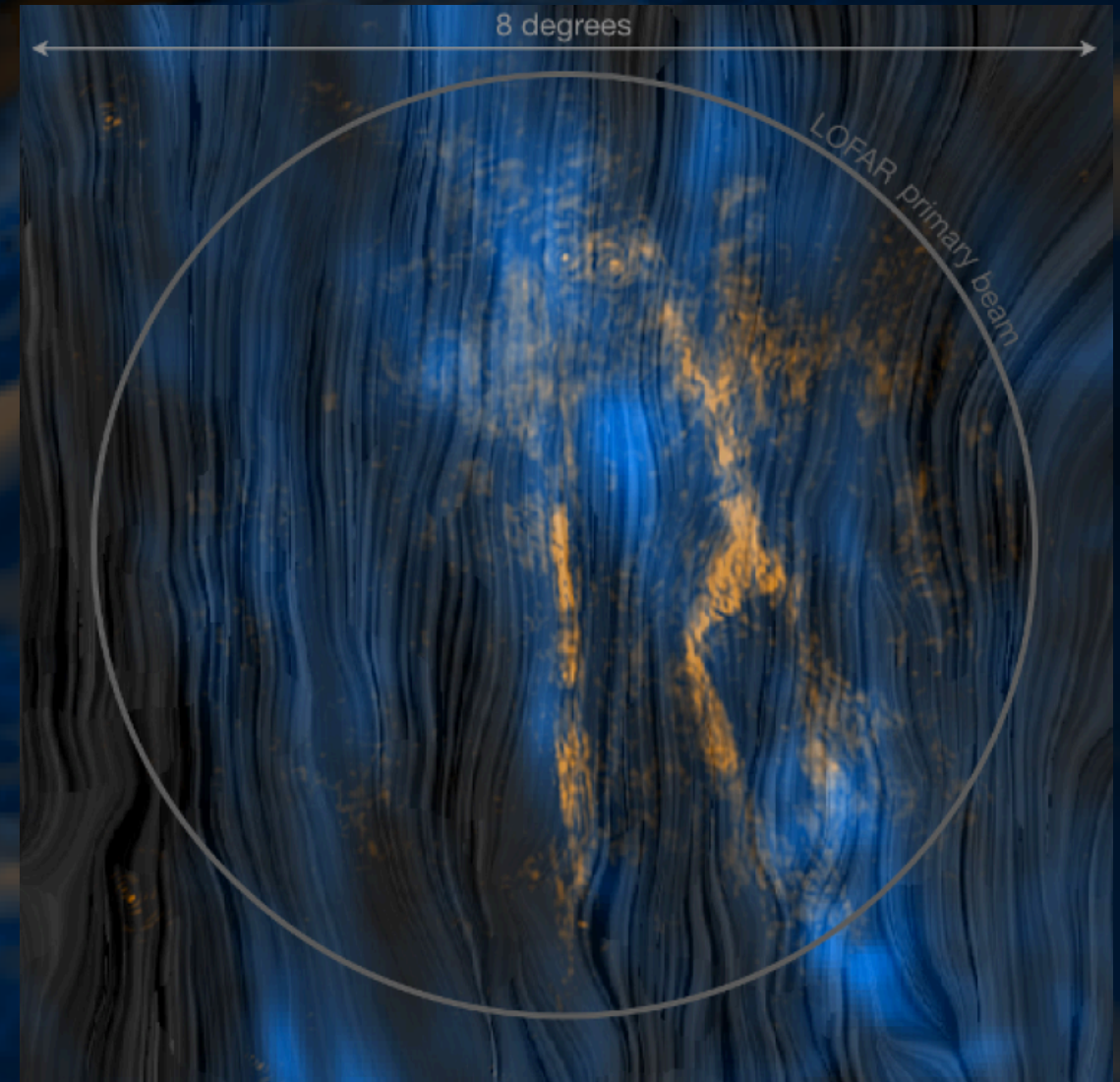
3C196 field



(Zaroubi+2015)

- LOFAR HBA emission in orange
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- Hi at 21 cm in blue

3C196 field

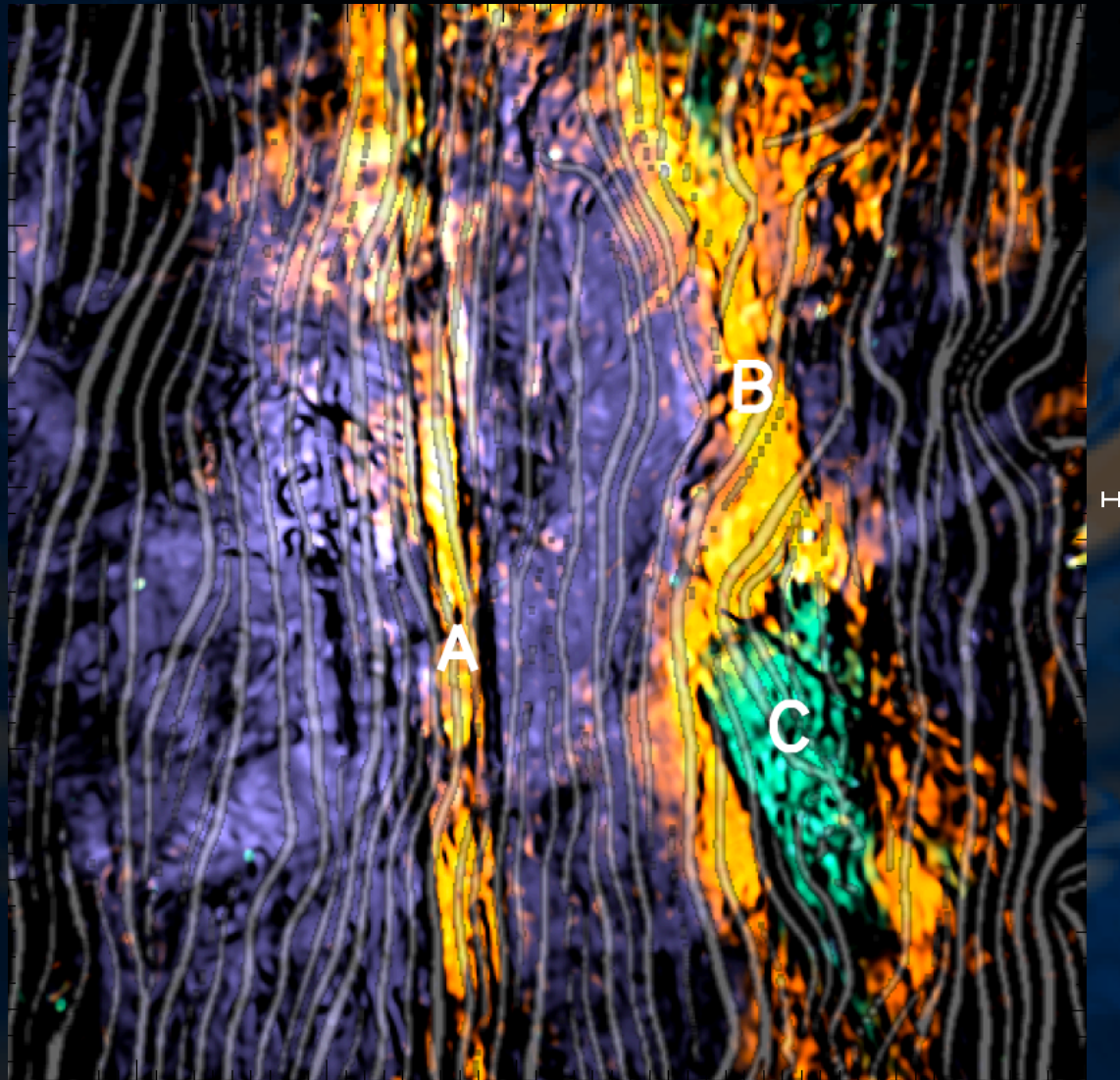


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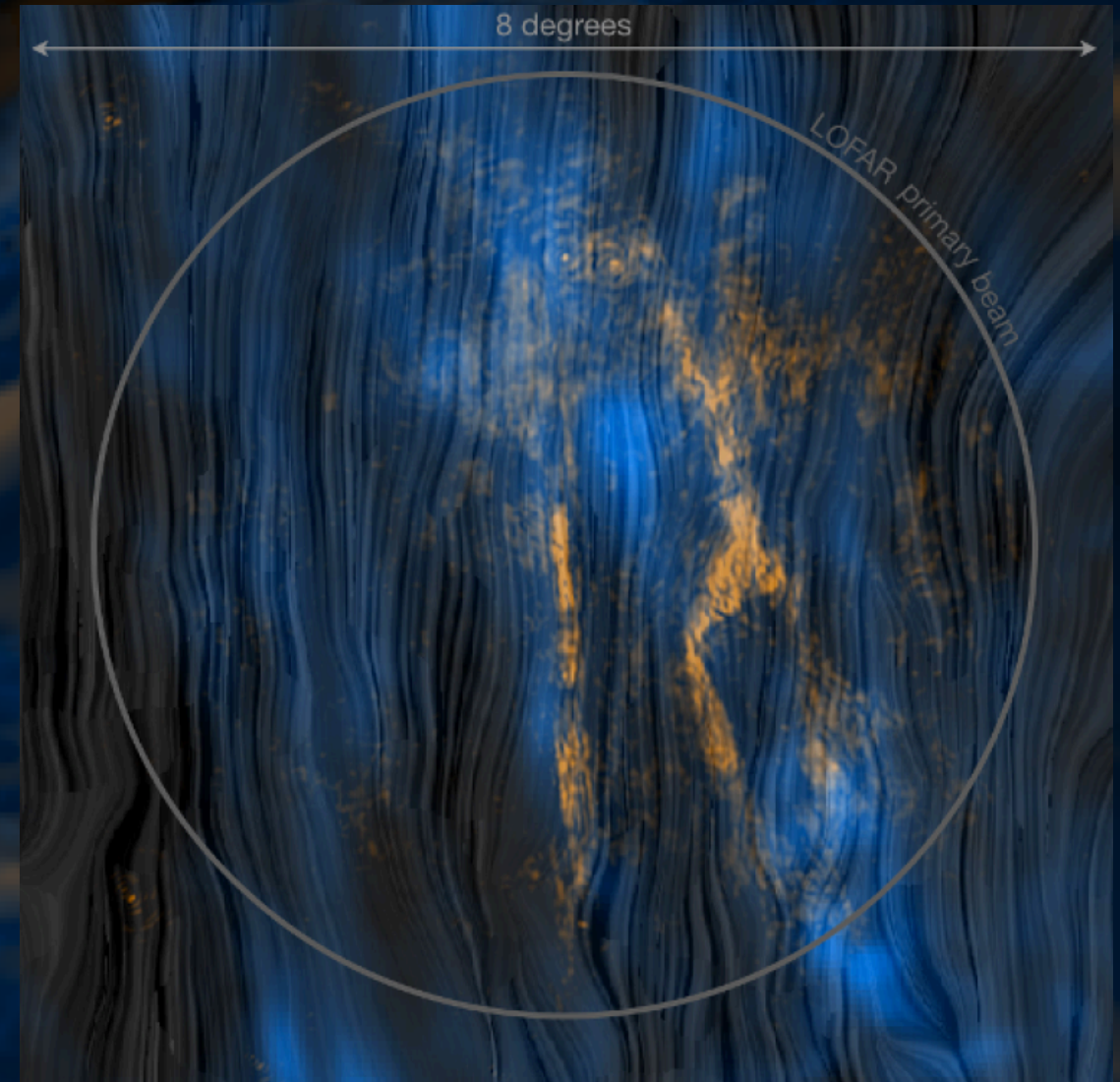
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(Bracco+2020)

Results

In intermediate latitude/diffuse fields CNM ($\sim 100\text{K}$ gas) is responsible for the observed correlation

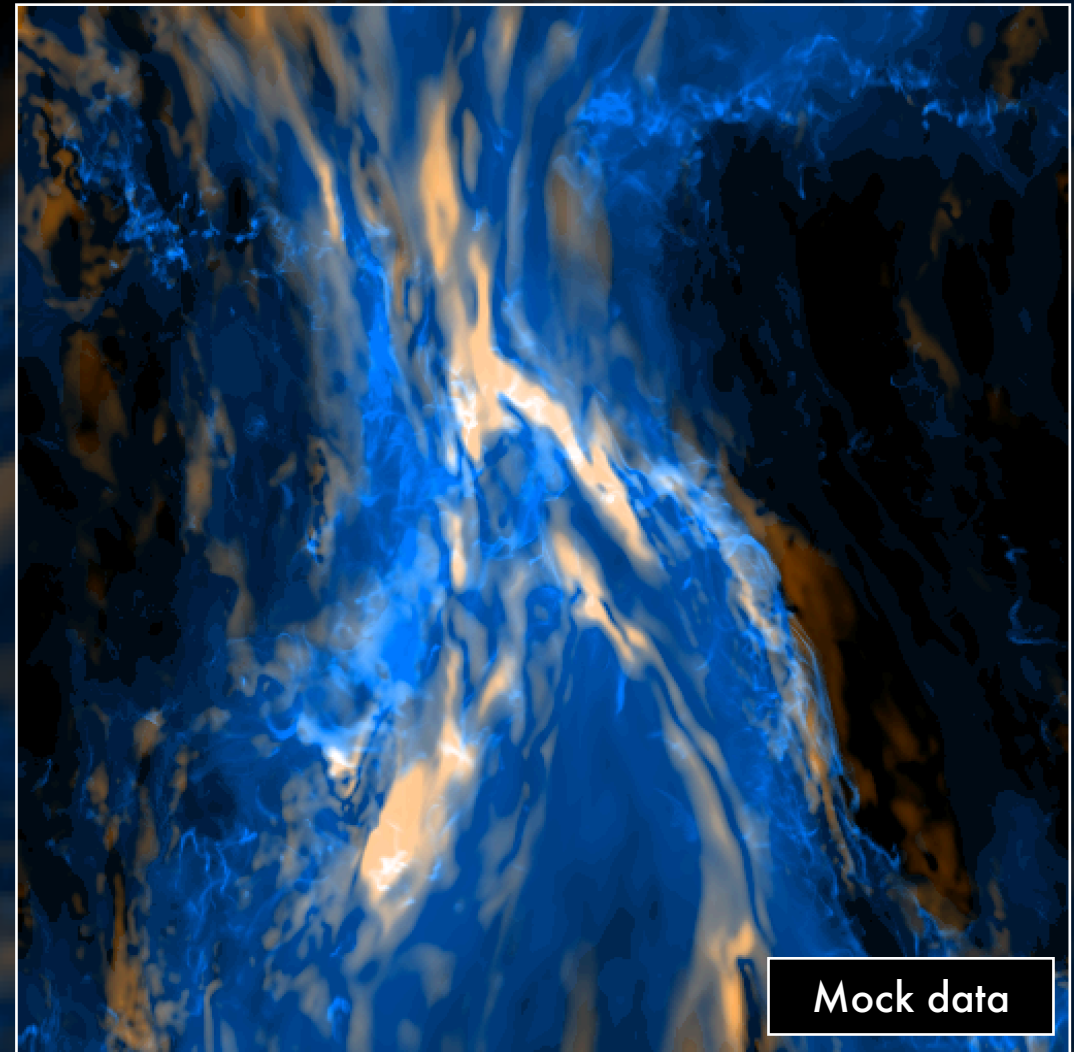
Multiphase and Magnetized Emission with LOFAR

* Large datasets and complex dynamics require modelling:
Post-processing numerical simulations of the multiphase ISM: ionization, cosmic rays (SKA Data Challenge #3)

Blue: HI including 100K and 6000K gas



[Bonaldi+2025]

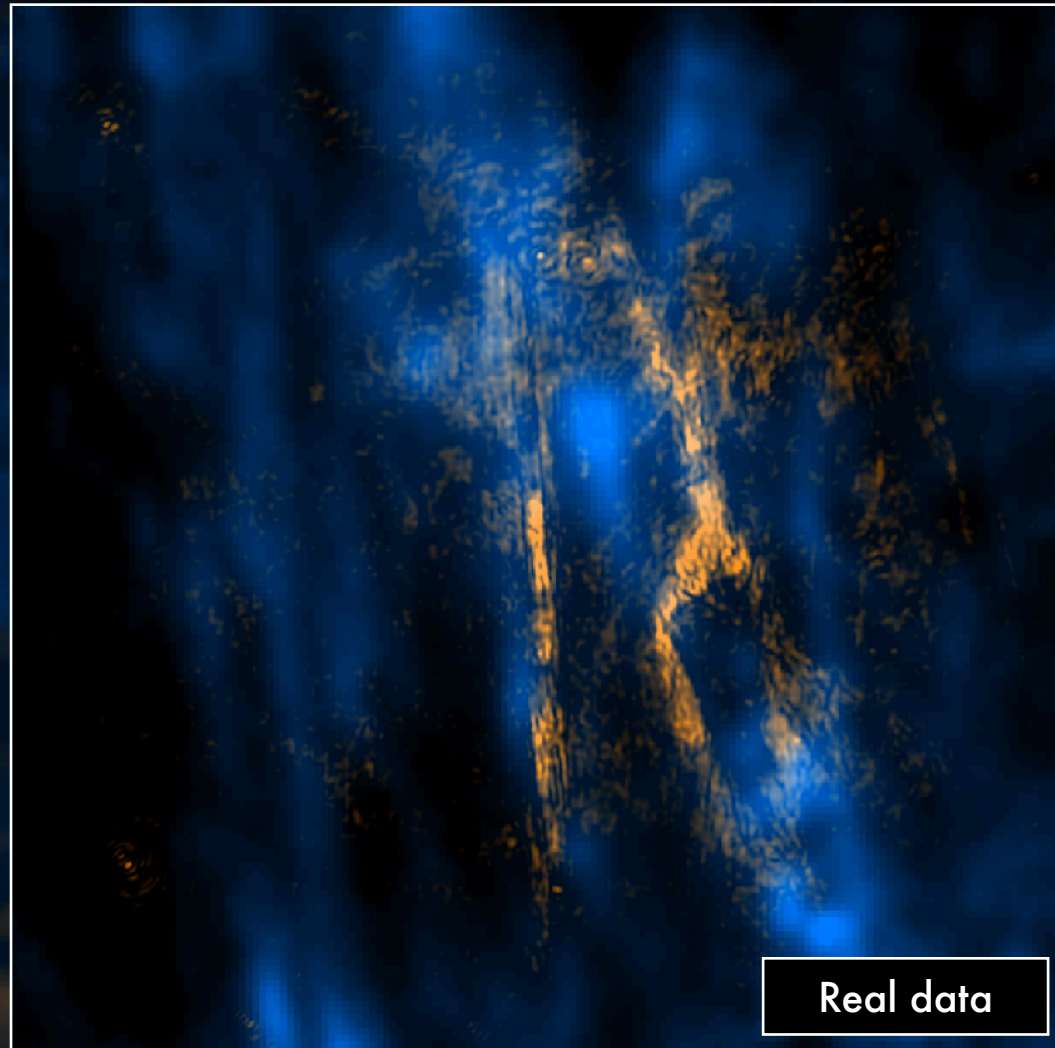


[Padovani+2021, Bracco+2022]

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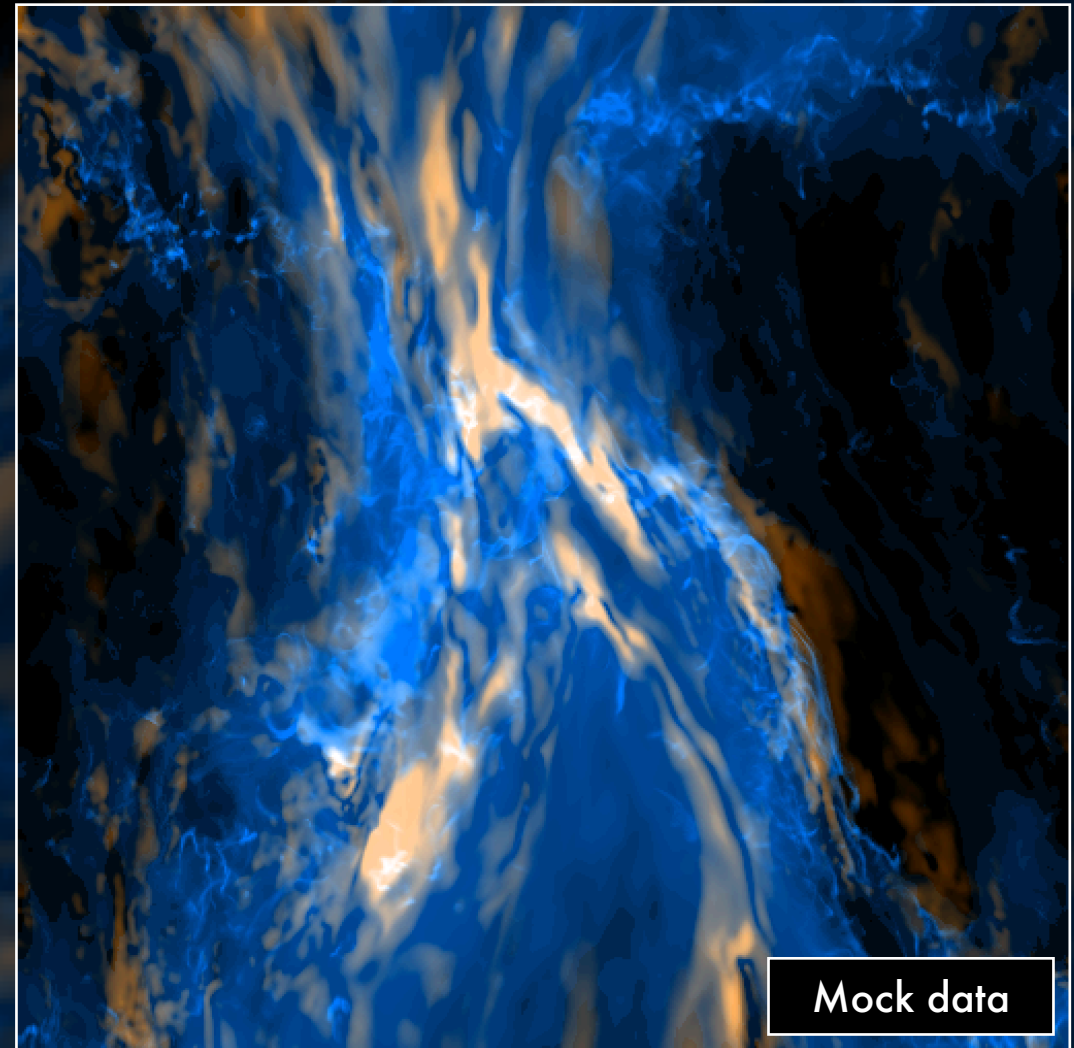
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Real data

[Bracco+2020]



Mock data

[Padovani+2021, Bracco+2022]

Results

From comparison with simulations WNM (~6000K gas) is responsible for the observed correlation
Confirmed statistically on different MHD simulations (Berat+2026)

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[Bracco+2020]



[Padovani+2021, Bracco+2022]

Open question: what physical ingredients are we missing ?

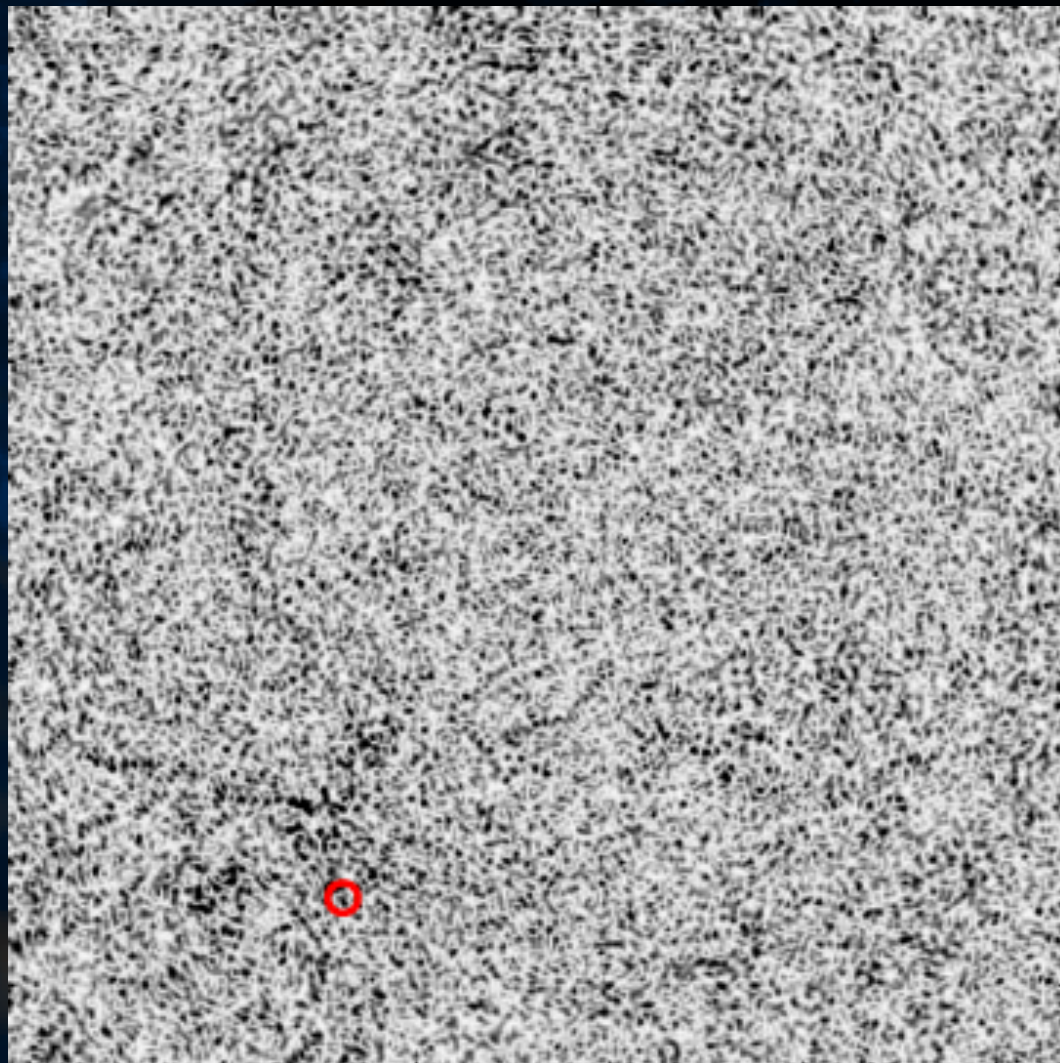
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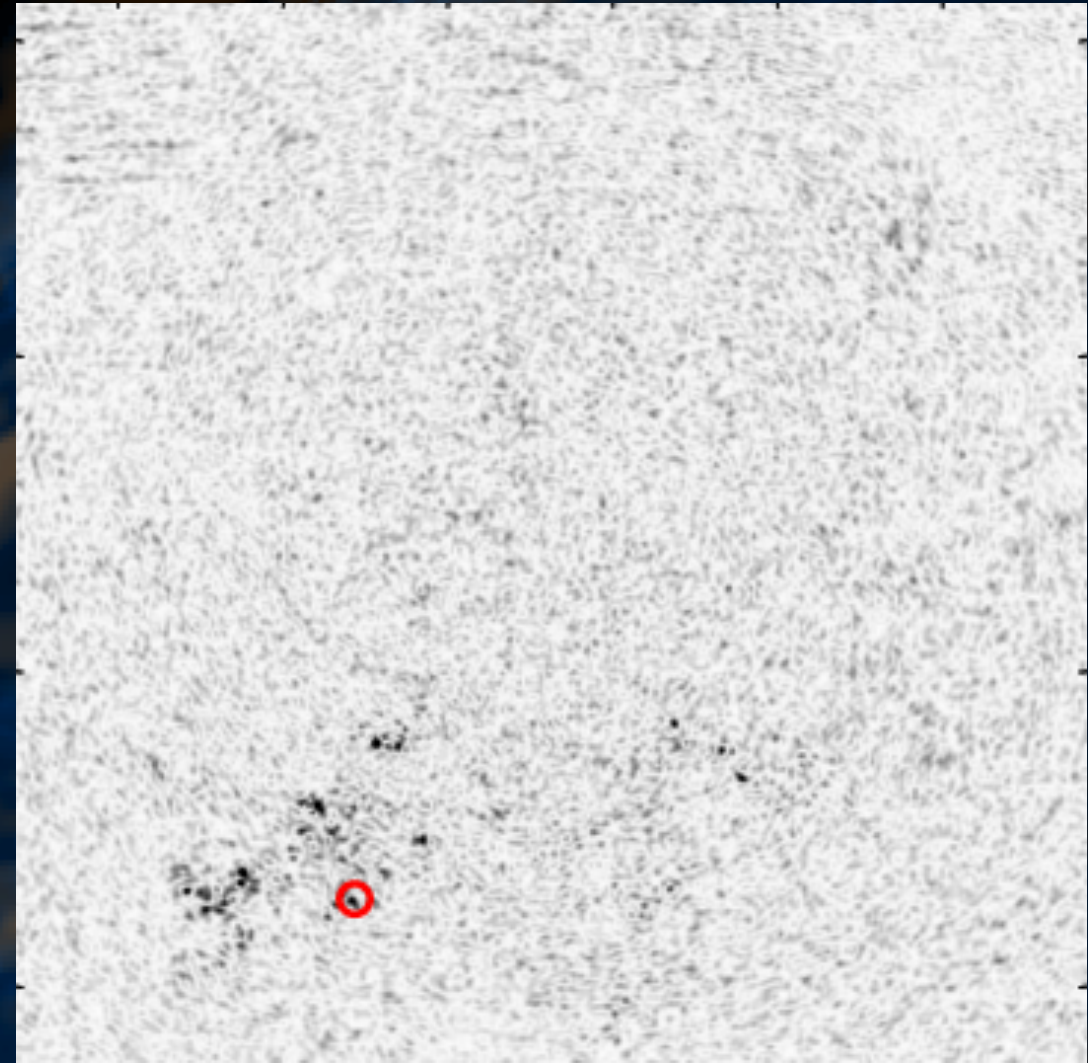
1) Polarized emission is ubiquitous, it may just be matter of sensitivity!

FD > 16 rad/m²



ELAIS field - 1 night

FD > 16 rad/m²

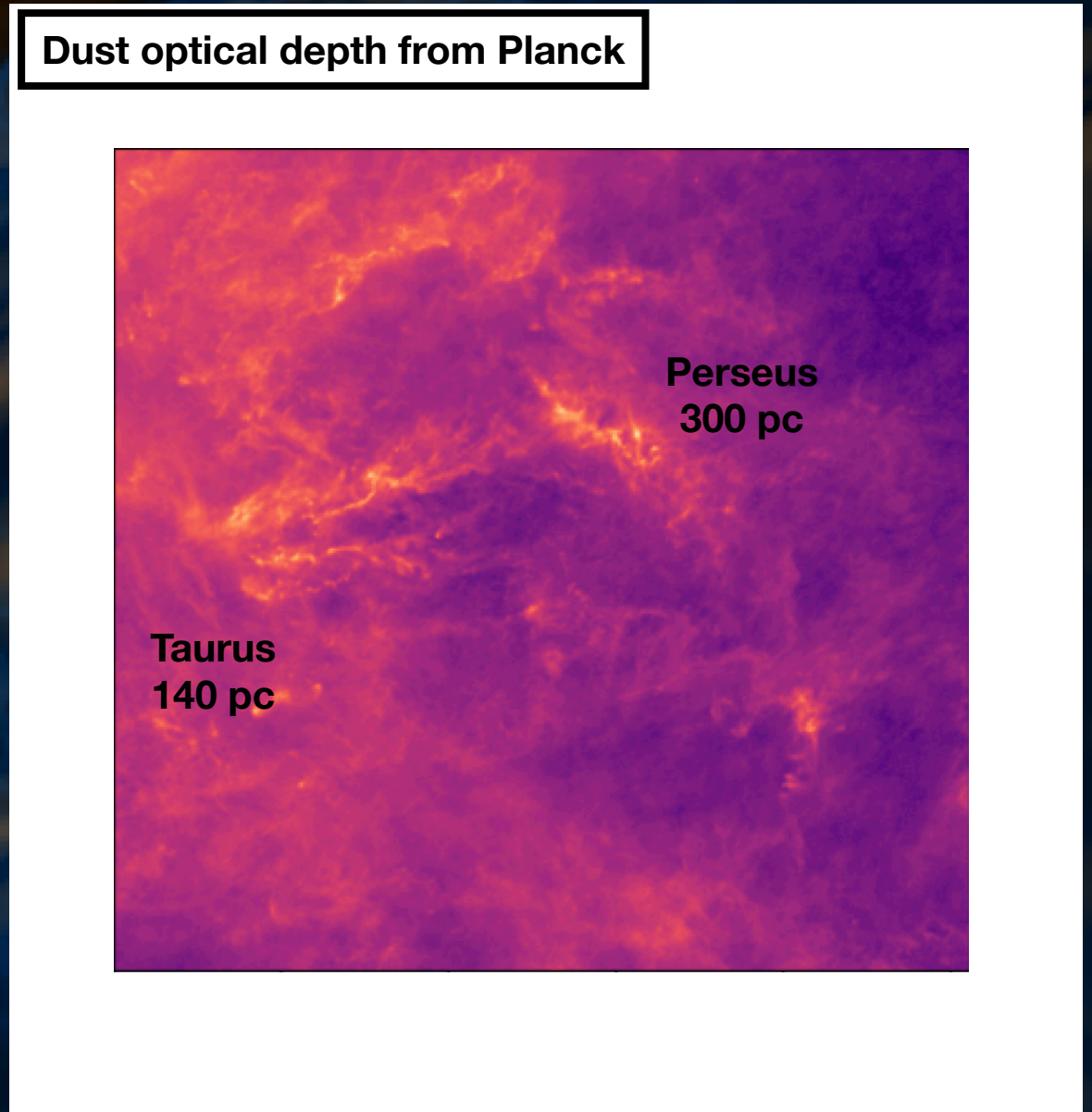
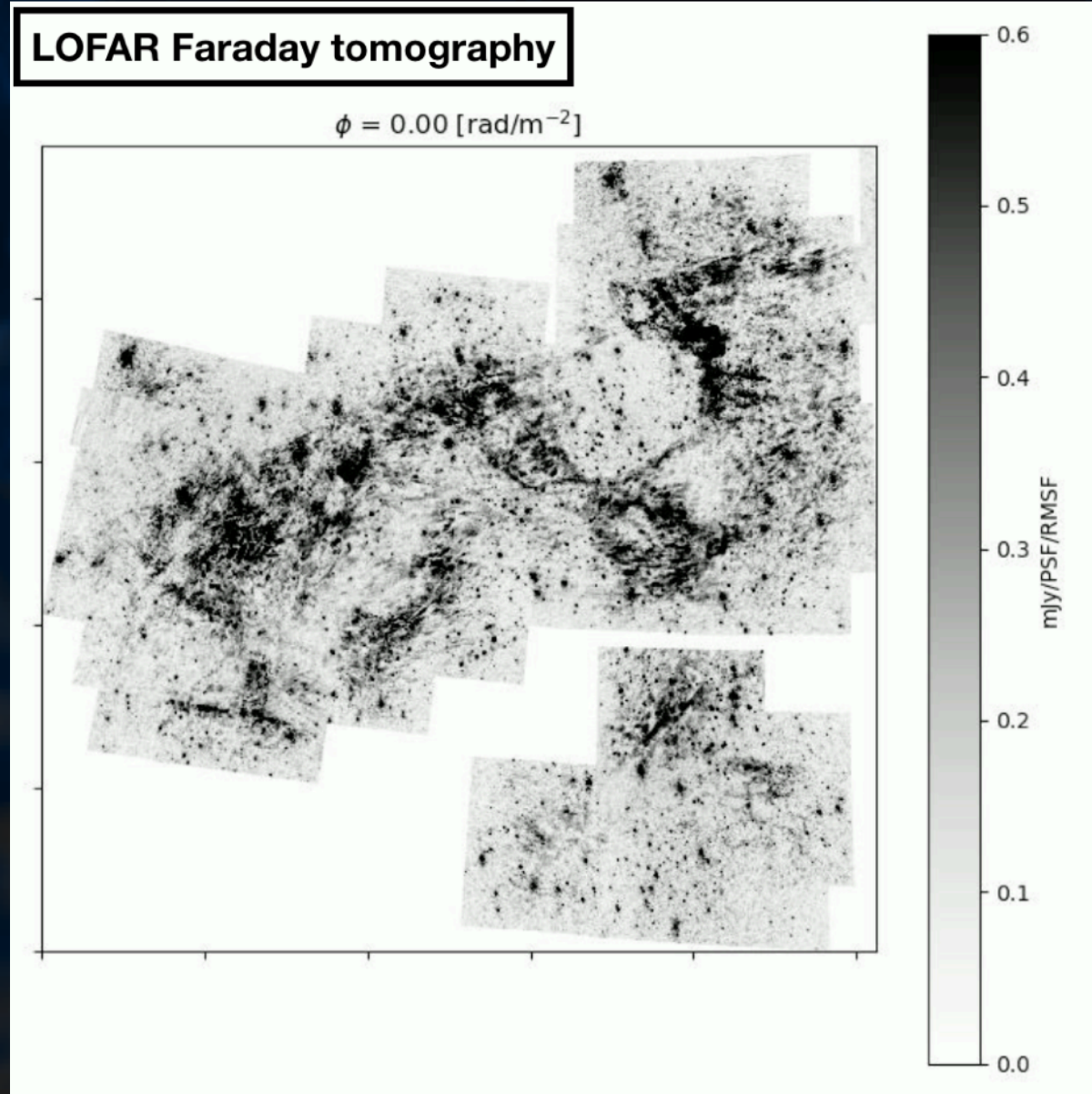


ELAIS field - 20 nights stacked

[Šnidarić+2022]

Multiphase and Magnetized Emission with LOFAR

- 1) Polarized emission is ubiquitous, it may just be matter of sensitivity!
- 2) We have first LoTSS data toward star-forming molecular clouds: Taurus and Perseus

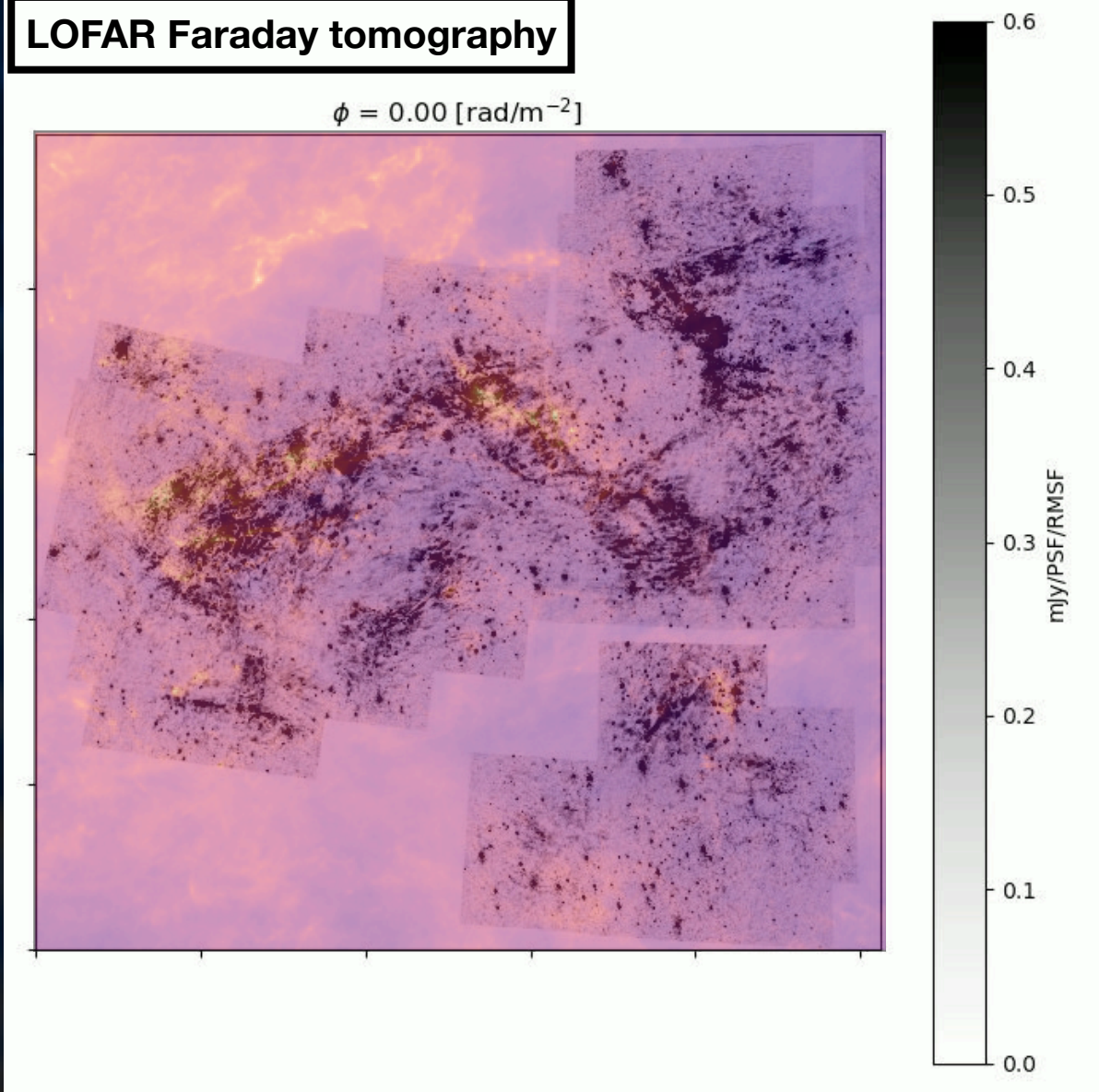


[Bracco+ in preparation]

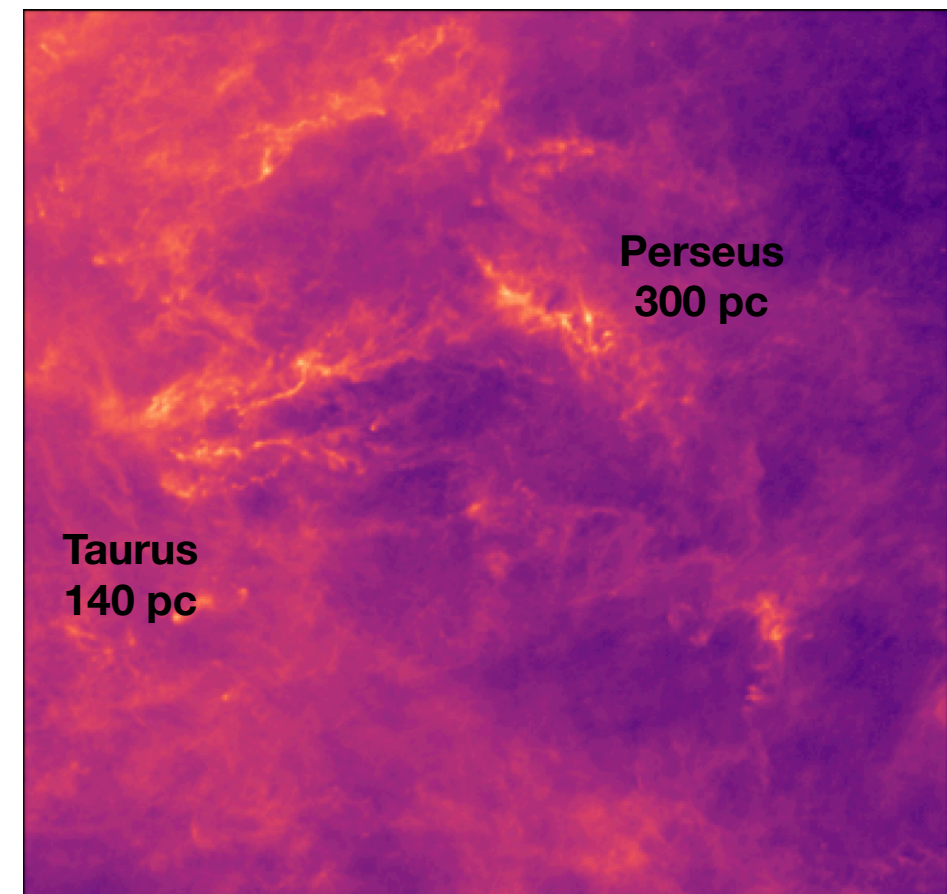
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LOFAR Faraday tomography

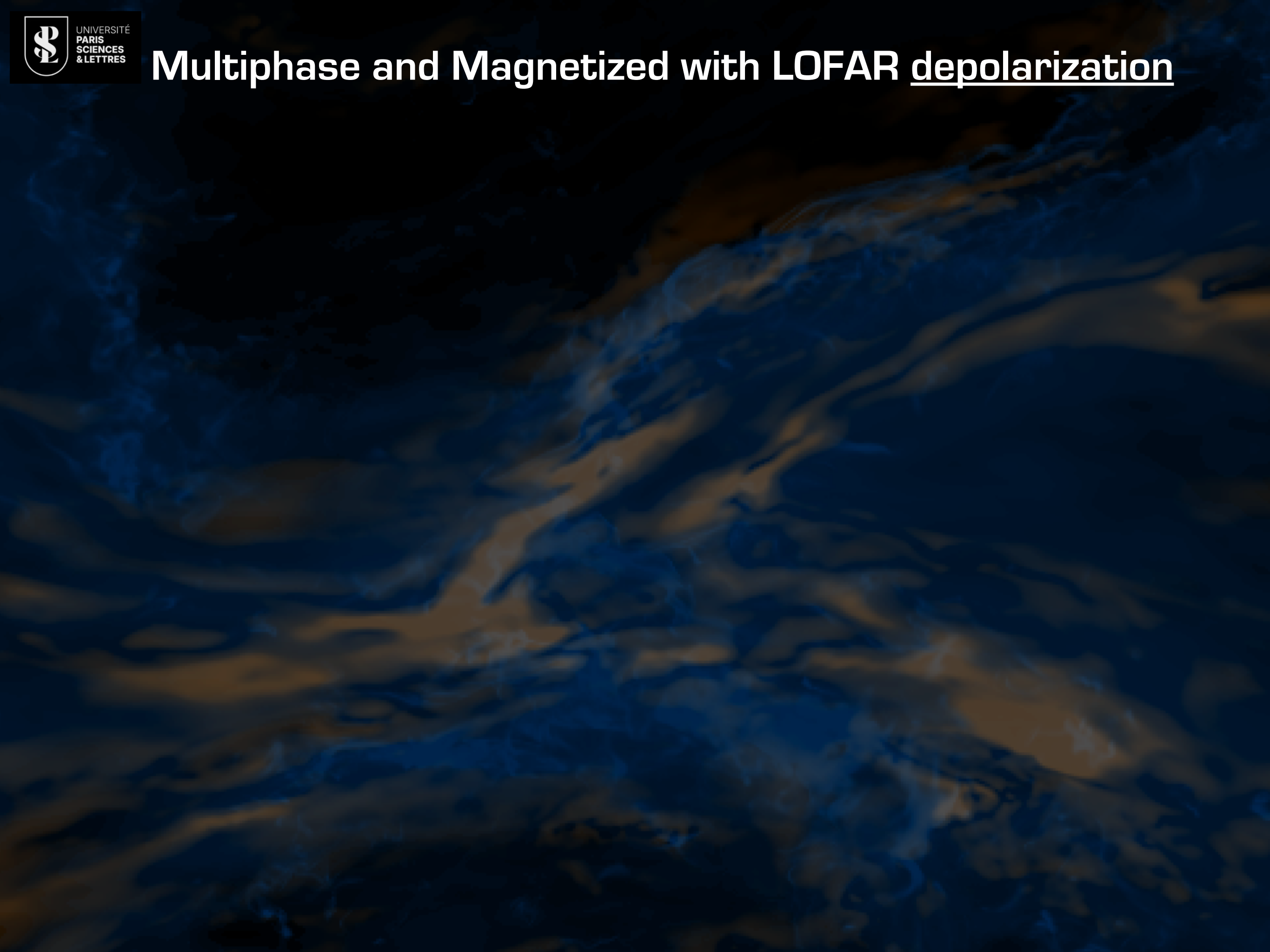


Dust optical depth from Planck

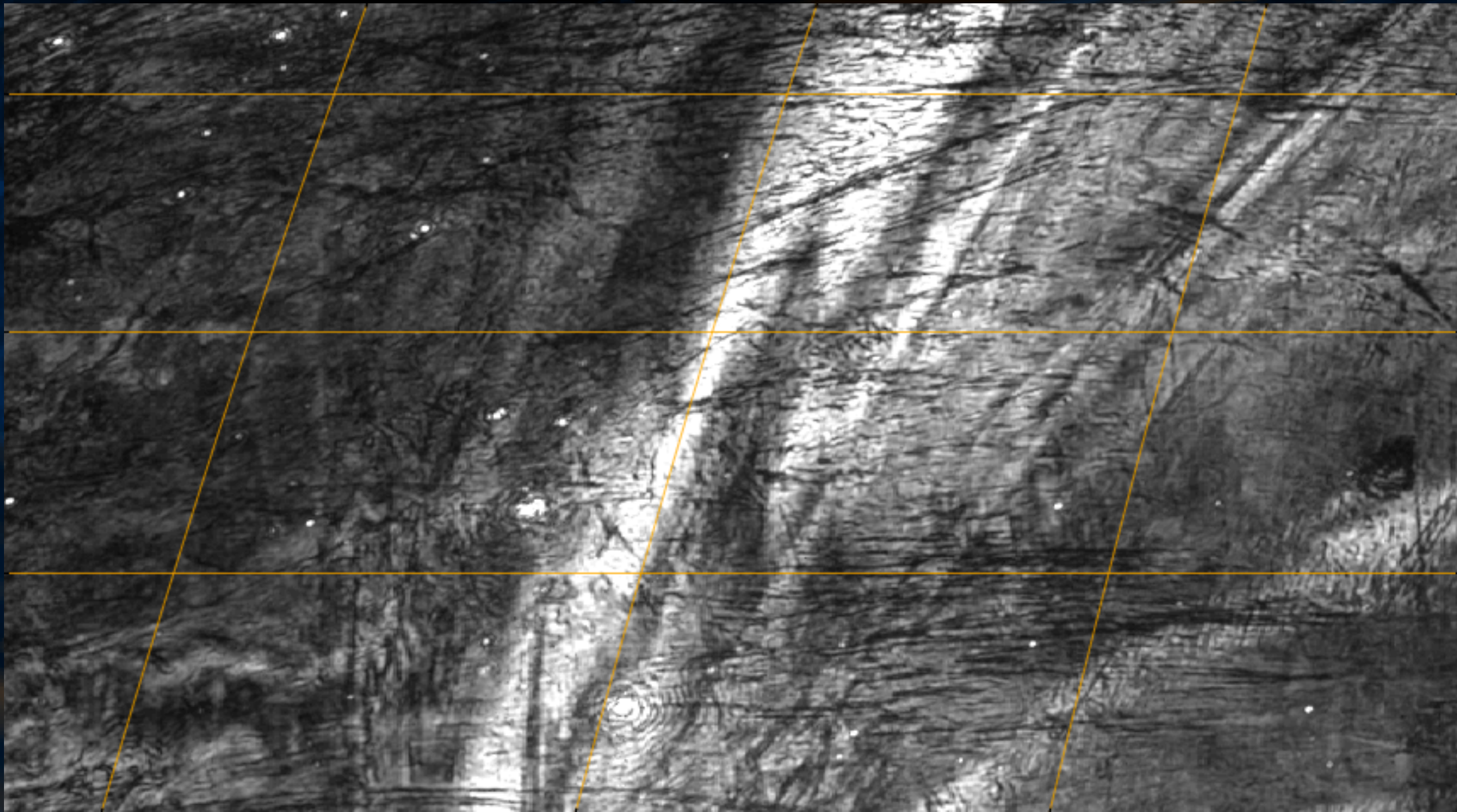


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Multiphase and Magnetized with LOFAR depolarization



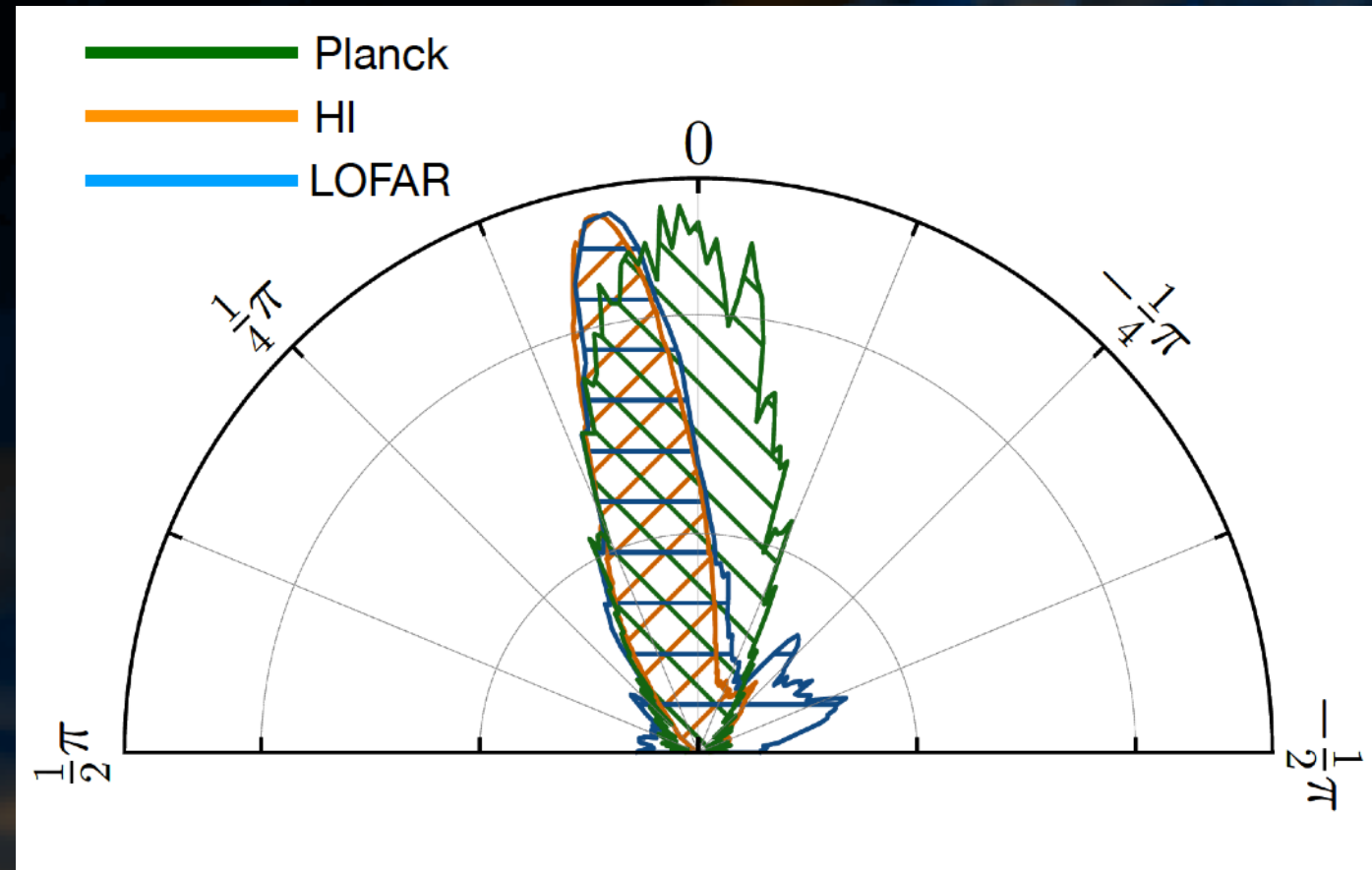
Multiphase and Magnetized with LOFAR depolarization



(Erceg+2022)

Depolarization canals are sharp, well aligned, and regular

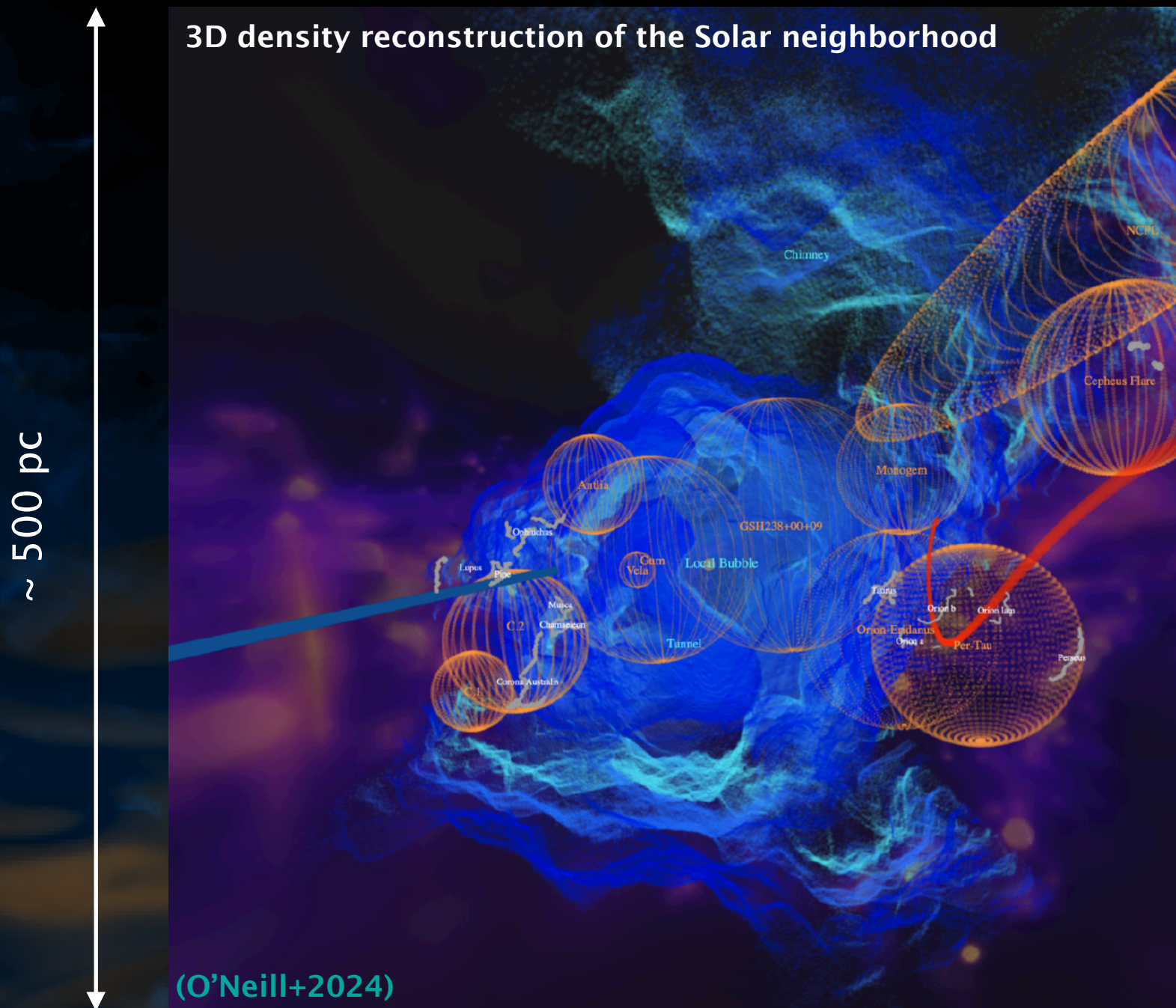
Multiphase and Magnetized with LOFAR depolarization



(Jelić+2018)

Aligned with tracers of the partially neutral and magnetized ISM and starlight polarization;
We can trace their distances (Turić+2021, Erceg+2024a)

Multiphase and Magnetized with LOFAR depolarization



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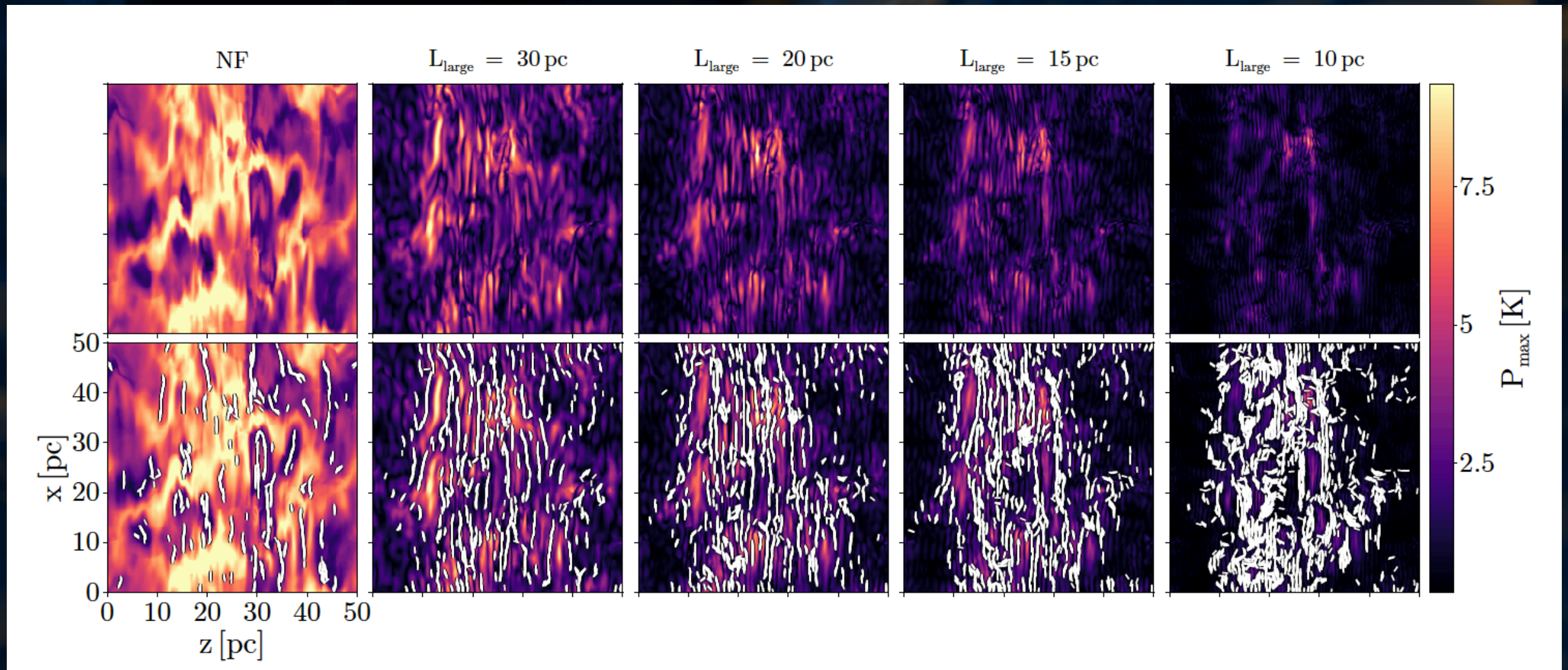
Some canals may be located at the edge of the *Local Bubble* (**Erceg+2024b, Boulanger+2024**)

Why such depolarization canals with LOFAR?

... sharp, well aligned, and regular ...

Why such depolarization canals with LOFAR?

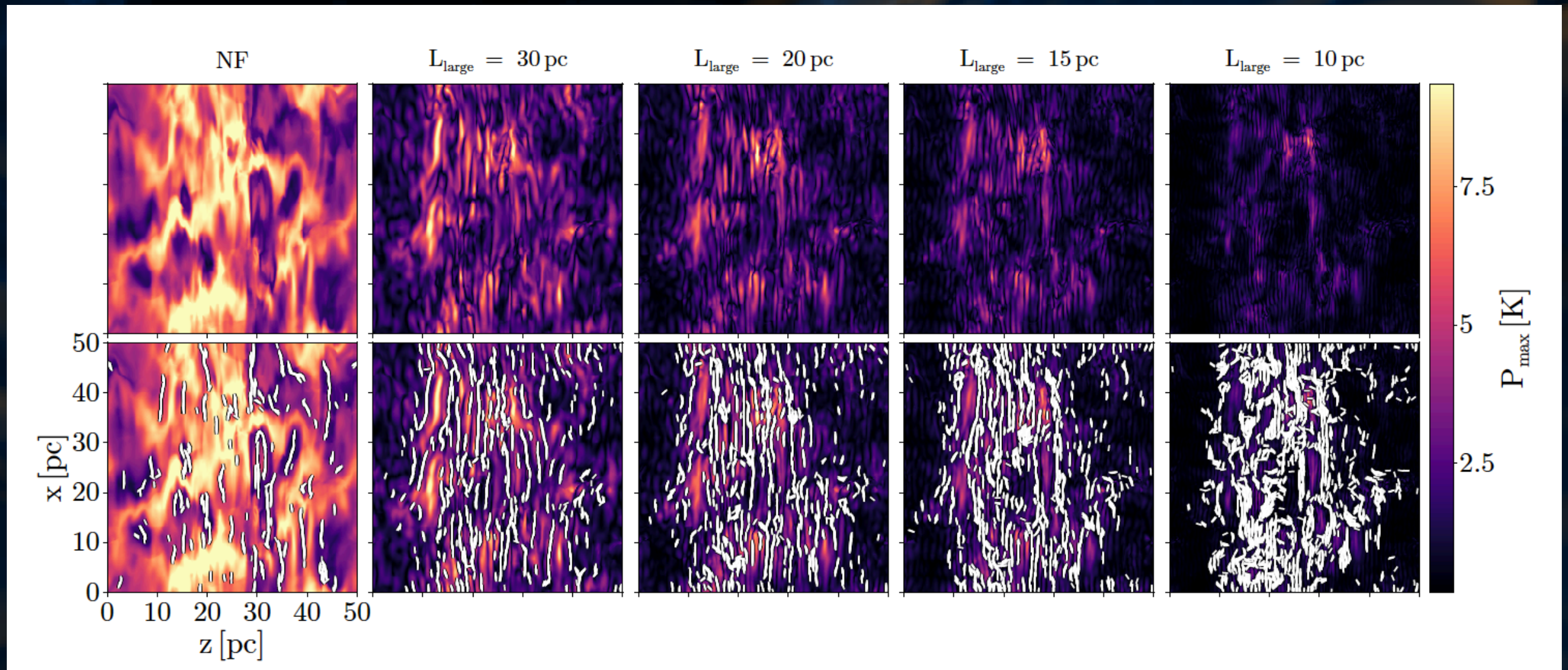
Testing the effect of spatial filtering with mock data from 50-pc MHD multiphase gas simulations. Vertical mean B field



(Berat+ in preparation)

Why such depolarization canals with LOFAR?

Testing the effect of spatial filtering with mock data from 50-pc MHD multiphase gas simulations.
Vertical mean B field



(Berat+ in preparation)

Preliminary results:

Interferometry may select specific magnetic structures in the diffuse synchrotron emission

Conclusions

- LOFAR is a precious instrument for Galactic ISM studies: “sub-grid” physics in extragalactic environments — from YSOs to the diffuse ISM.
- The broadband sensitivity at low frequency revealed a NEW sky in polarization with Faraday tomography — constraining Galactic foreground (e.g., rotation measure grids).
- Observations are challenging the state-of-the-art understanding of cold gas formation in the ISM, which is key for the emergence of molecular clouds (H₂) and star formation.
- LOFAR depolarization canals are UNIQUE structures that have proven to be useful probes of the magnetized and multiphase ISM. We now understand their possible origin.
- Multifrequency studies are ongoing to explore the link between magnetic fields and multiphase gas — LOFAR + GMIMS (DRAO+CHIME, up to the GHz range).
- Bright future with LOFAR2.0 and the SKA over the full sky