

Study of the interstellar medium through the low frequency radio observation of pulsars using LOFAR and NenuFAR

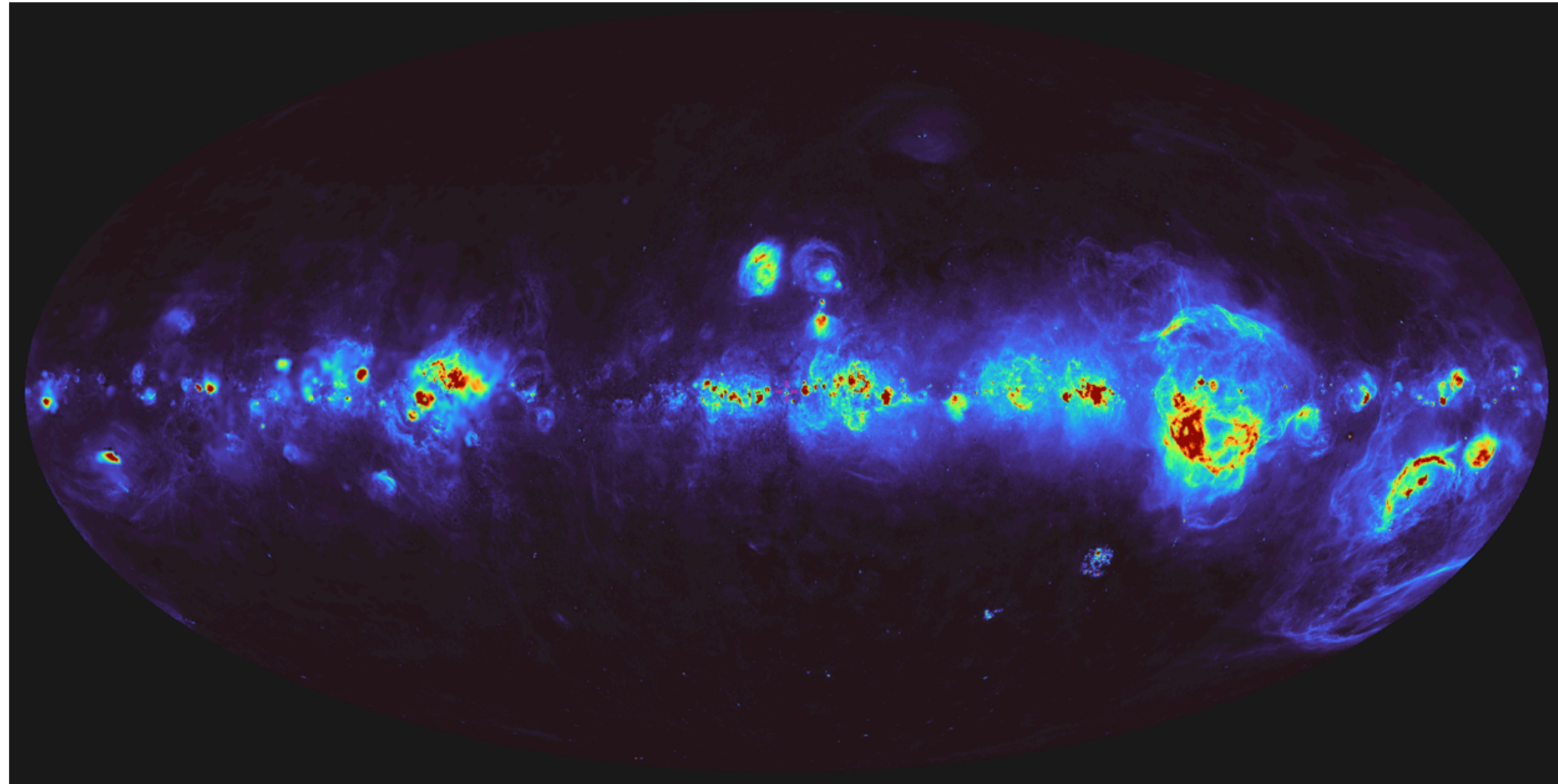
LOFAR Annual Meeting 2026,
8–12 June 2026,

Pauline NOE

*PhD student supervised by
G. Theureau and J.-M. Grießmeier
in collaboration with C. Tiburzi*



Ionized Interstellar Medium



Full-sky H α Milky Way Map

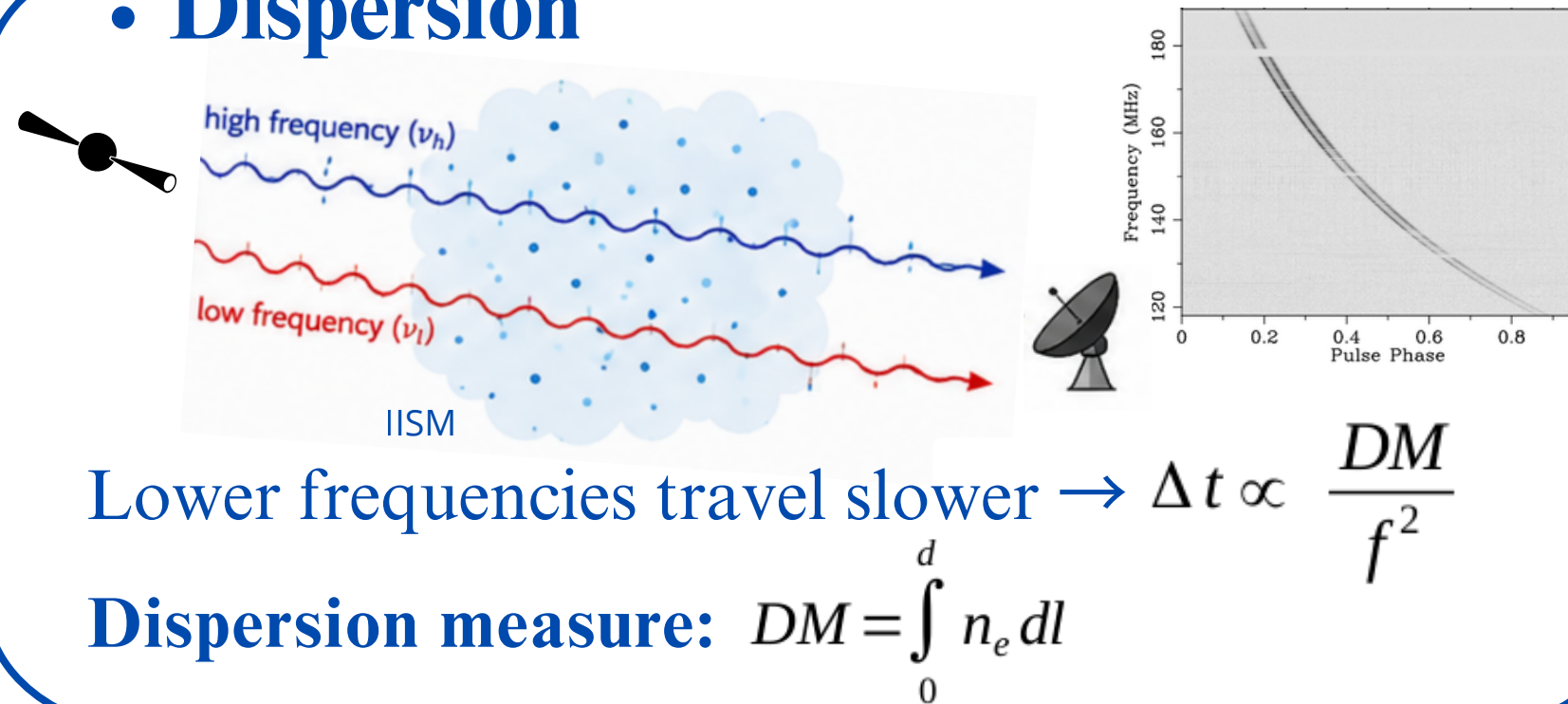
Finkbeiner, 2003

Mollweide projection produced with hips2fits, provided by CDS.

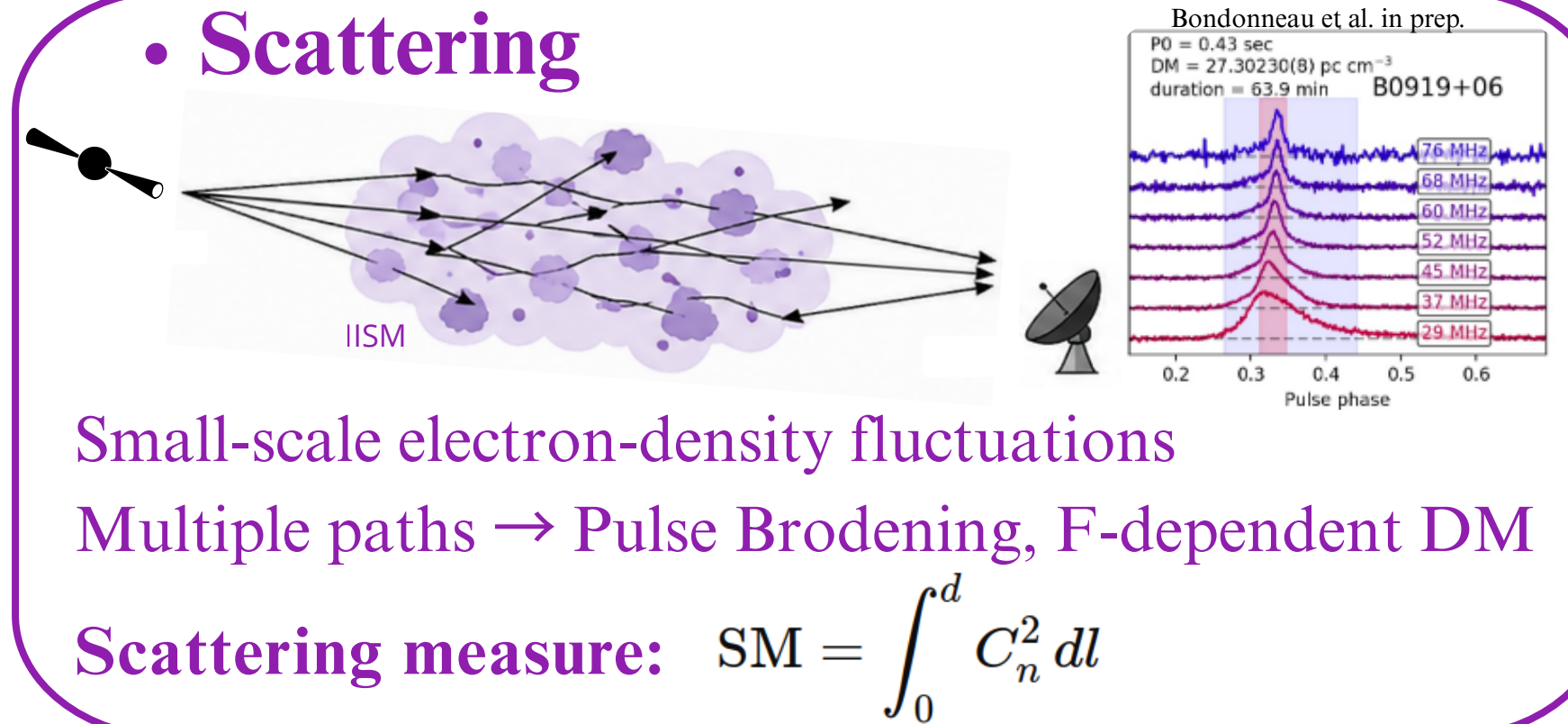
- **Milky Way is filled with ionized gas structures**
- **turbulent plasma, magnetic fields, and electron density fluctuations over many spatial scales**
- **Pulsar timing** = precise probe of the turbulence in the IISM

Propagation Effects

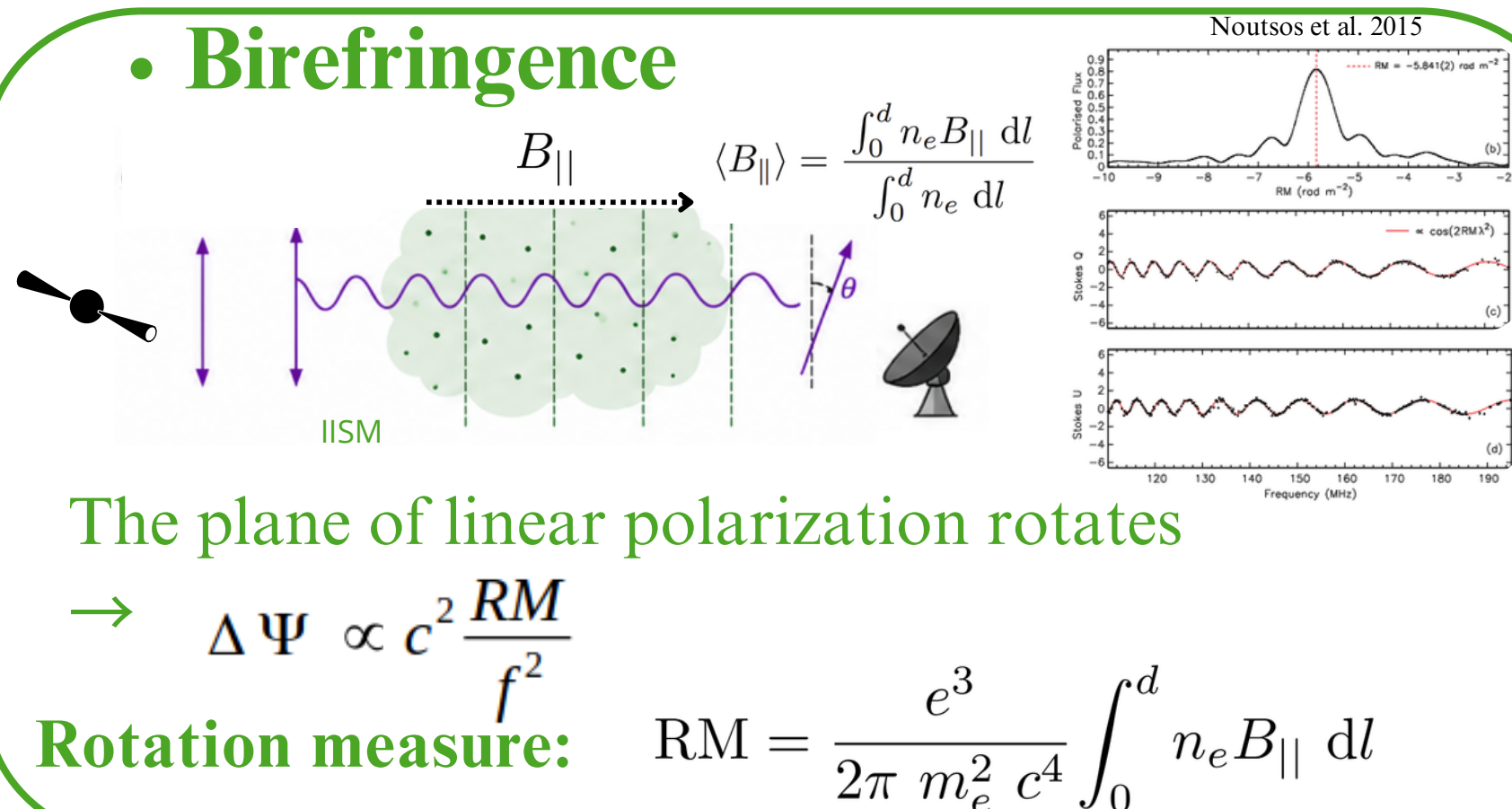
• Dispersion



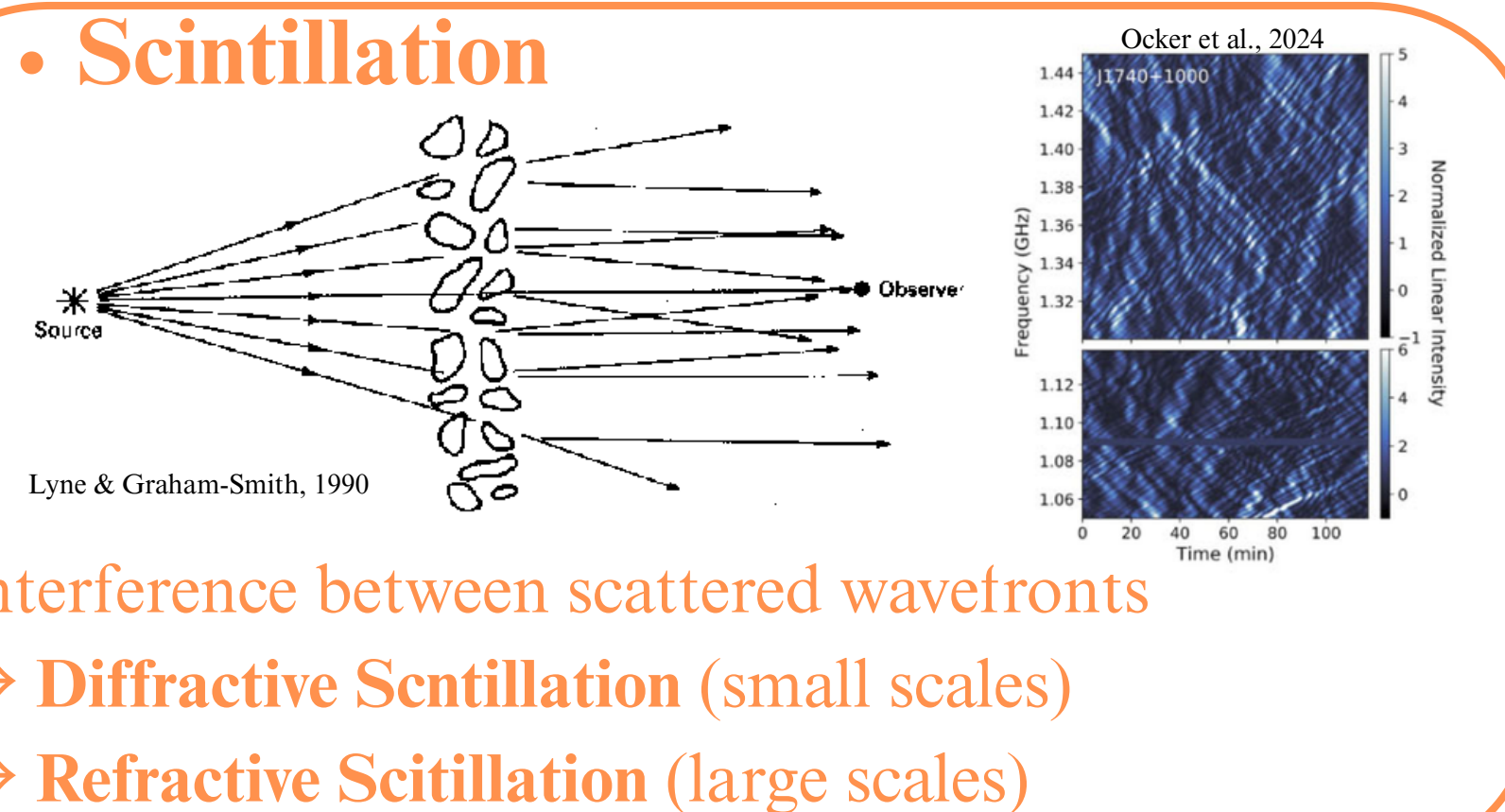
• Scattering



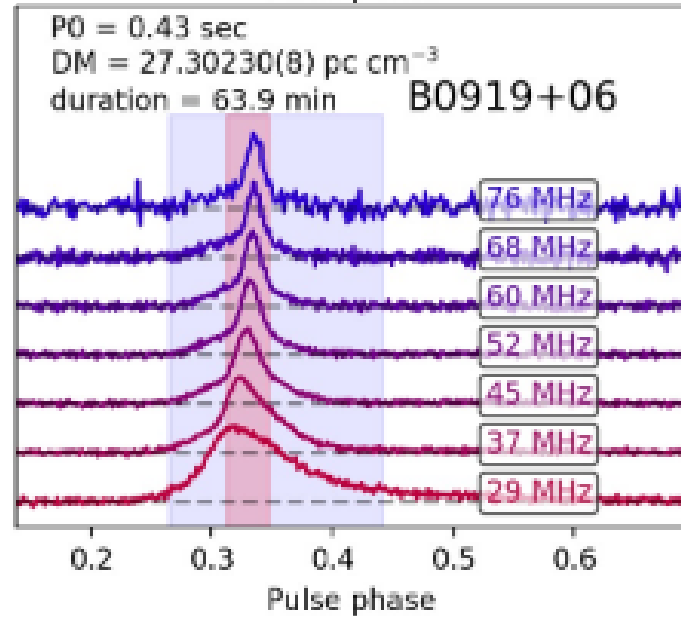
• Birefringence



• Scintillation

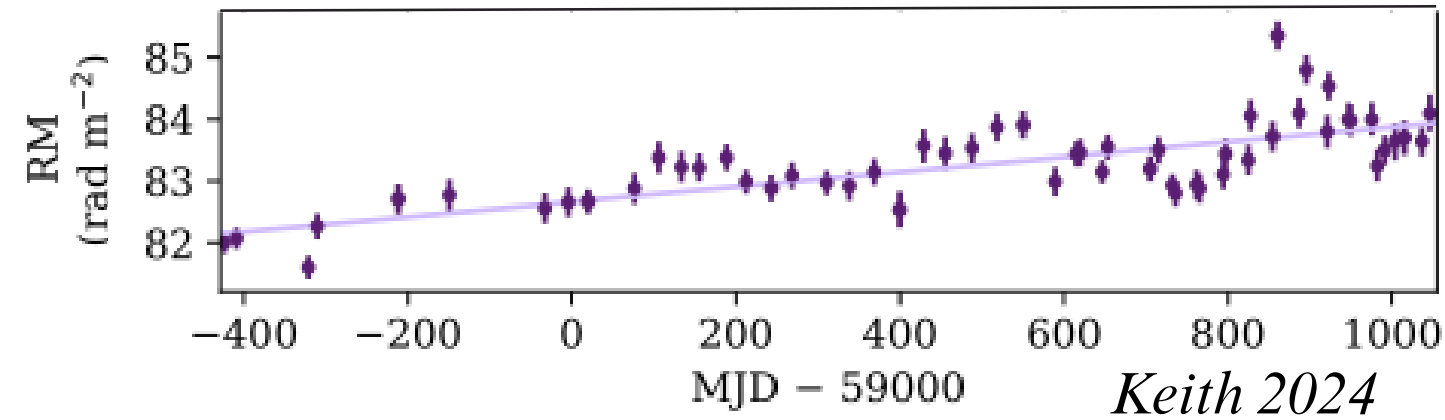


Bondonneau et al. in prep.



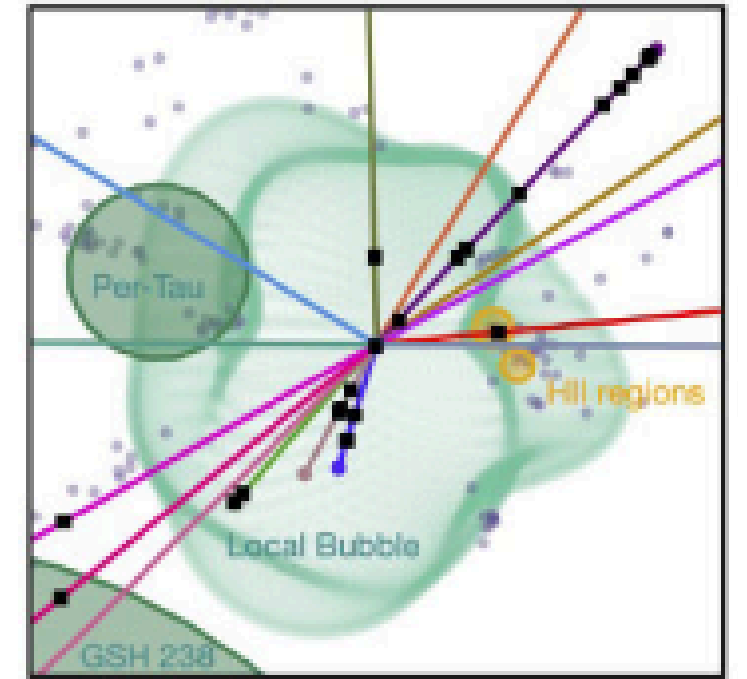
Pulse broadening

Probes to study the IISM



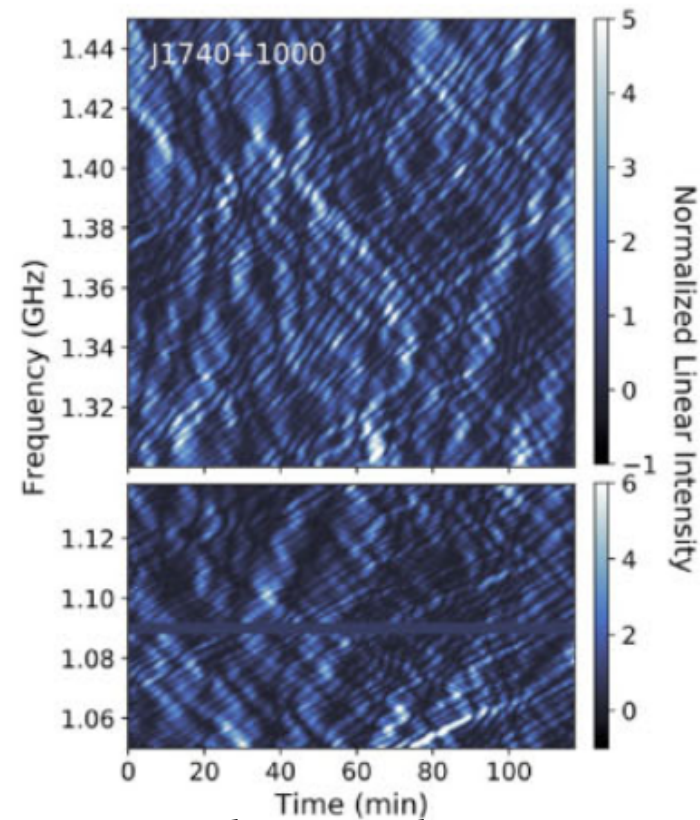
RM(t), RISS, $\tau(t)$, DM(t)

Ocker et al. 2024



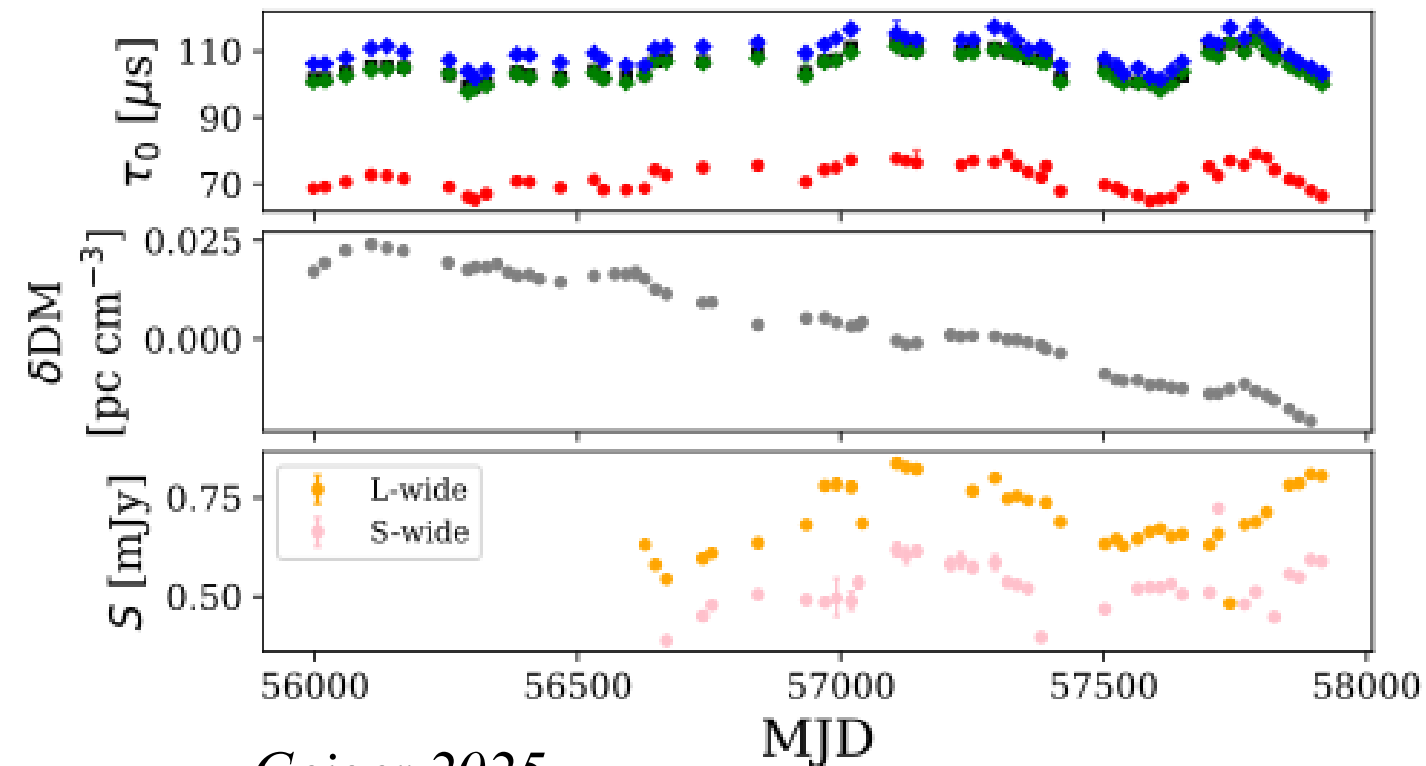
SM(r), DM(r)

$\sim 10^3$ km DISS



Ocker et al. 2024

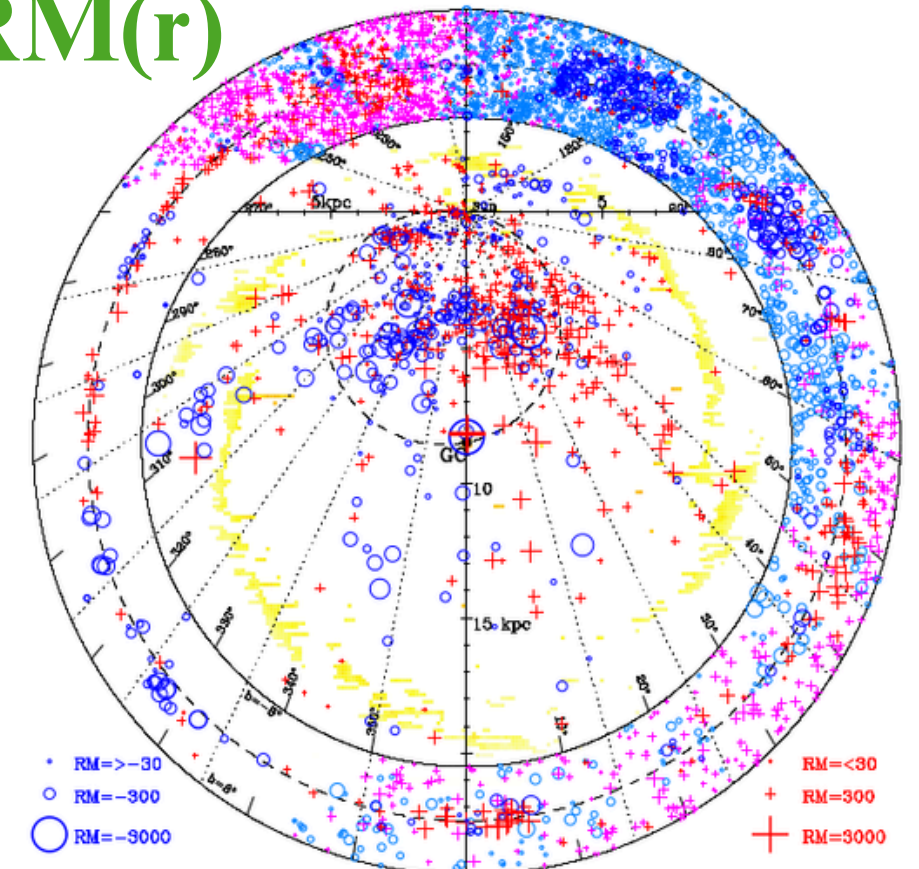
~ 0.01 au



Geiger 2025

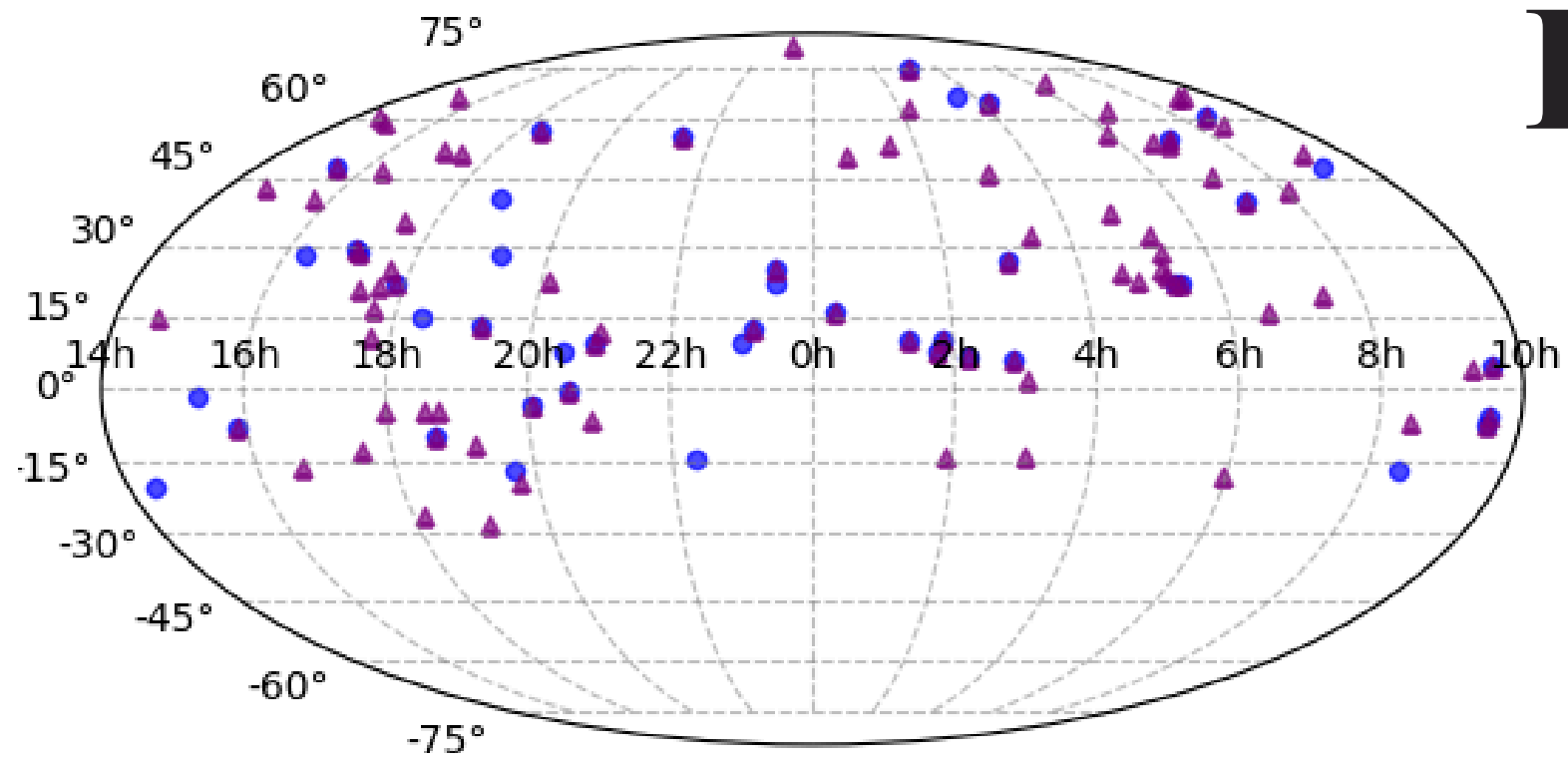
$\sim 10-100$ au

~ 100 pc -10 kpc RM(r)



Han 2018

Datasets



NenuFAR 10–85 MHz

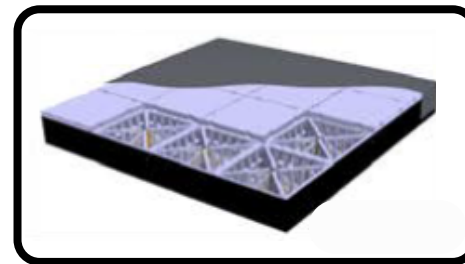


- Time Spand: **2019-Now**
- Cadence: **monthly**
- **~40 normal pulsars + few ms pulsars**

International LOFAR stations

LOFAR - FR606

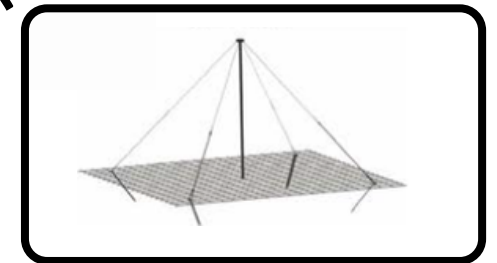
High Band Antennas (HBA)



110-190 MHz



Low Band Antennas (LBA)



30-90 MHz

- Time Spand: **2012-Now**
- Cadence: **weekly**
- **100 pulsars**

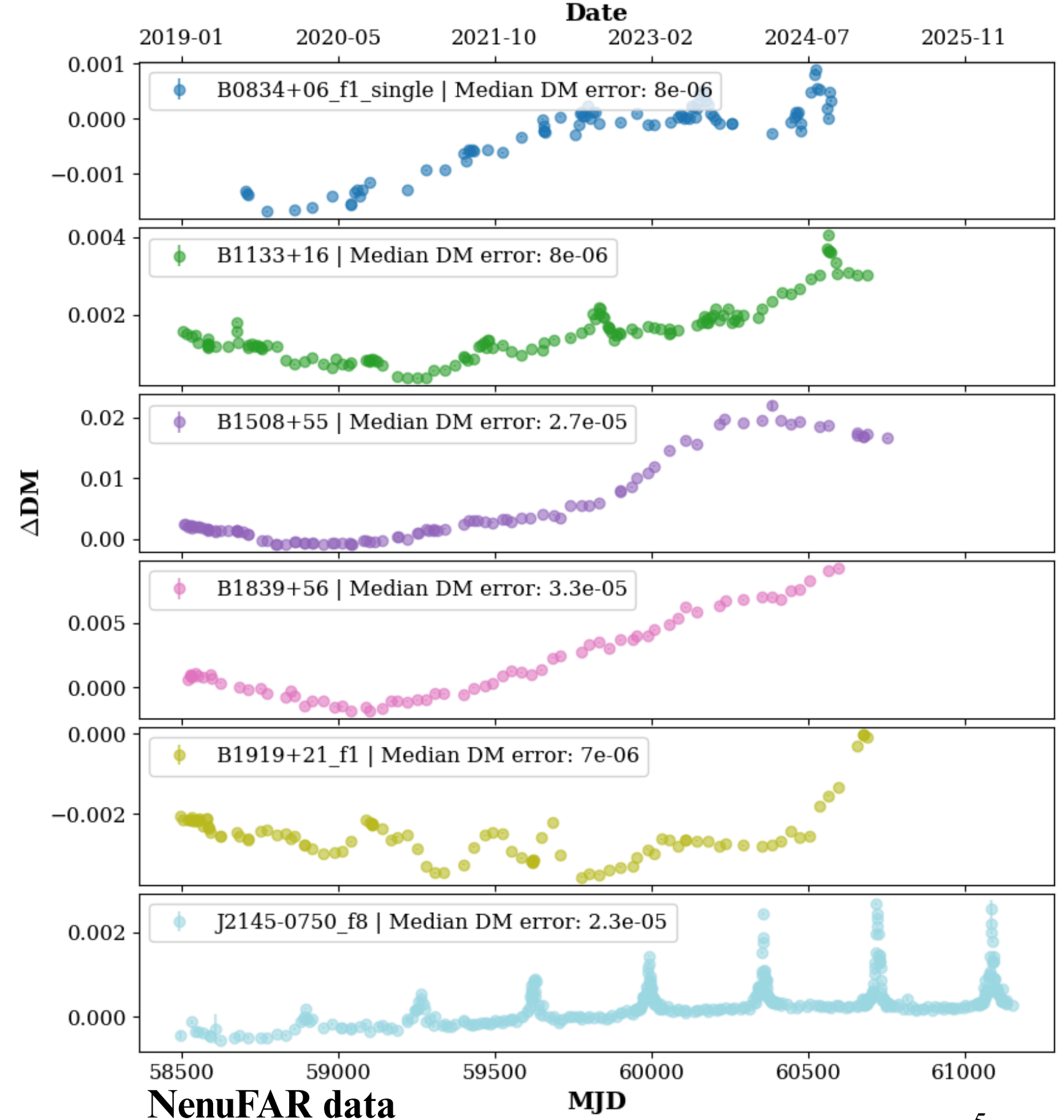
Probing the plasma content

- **Dispersion** → direct measurements of n_e fluctuations across the LOS
- **Dispersion measure** of the pulsar:

$$DM = \int_0^d n_e dl$$

- **Epoch-Wise** method models a DM value and a constant offset over each parsed ToA for an observing epoch (*see Iraci et al., 2024*):

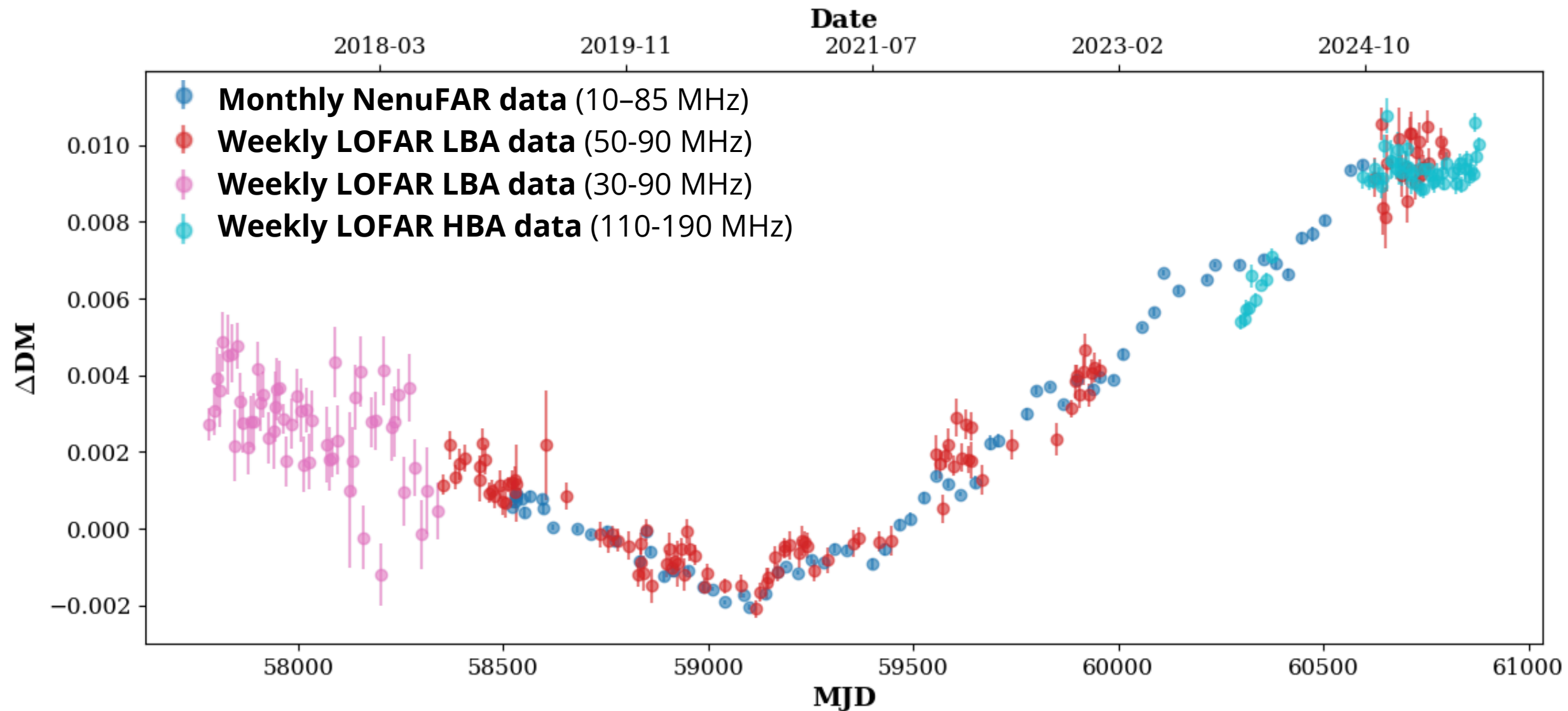
$$\Delta t = \frac{DM}{\nu^2} + C$$



Combining datasets

DM time series - Preliminary Result

J1840+5640

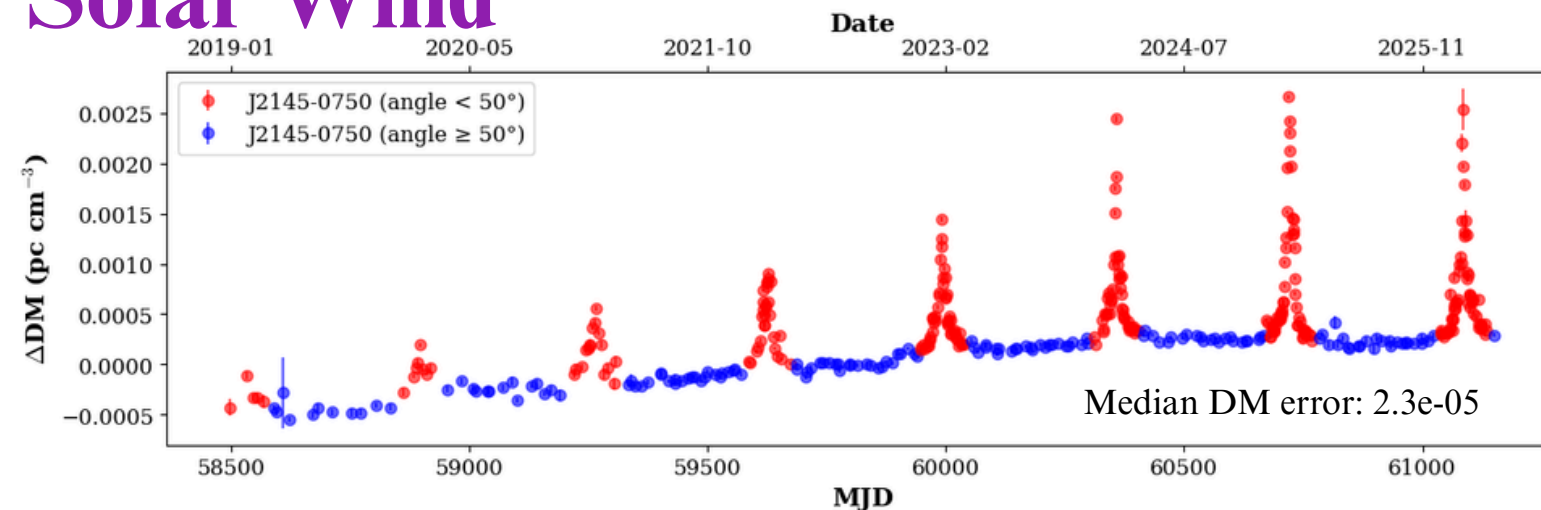


- **NenuFAR data are highly sensitive to DM variations**
- **LOFAR data provide a longer time baseline and complementary frequency coverage**

Temporal variations in Dispersion Measure

- Relative motion between pulsar, ISM and observer
- Turbulence
- Occasional Extreme Scattering Events
- Periodic or systematic contributions

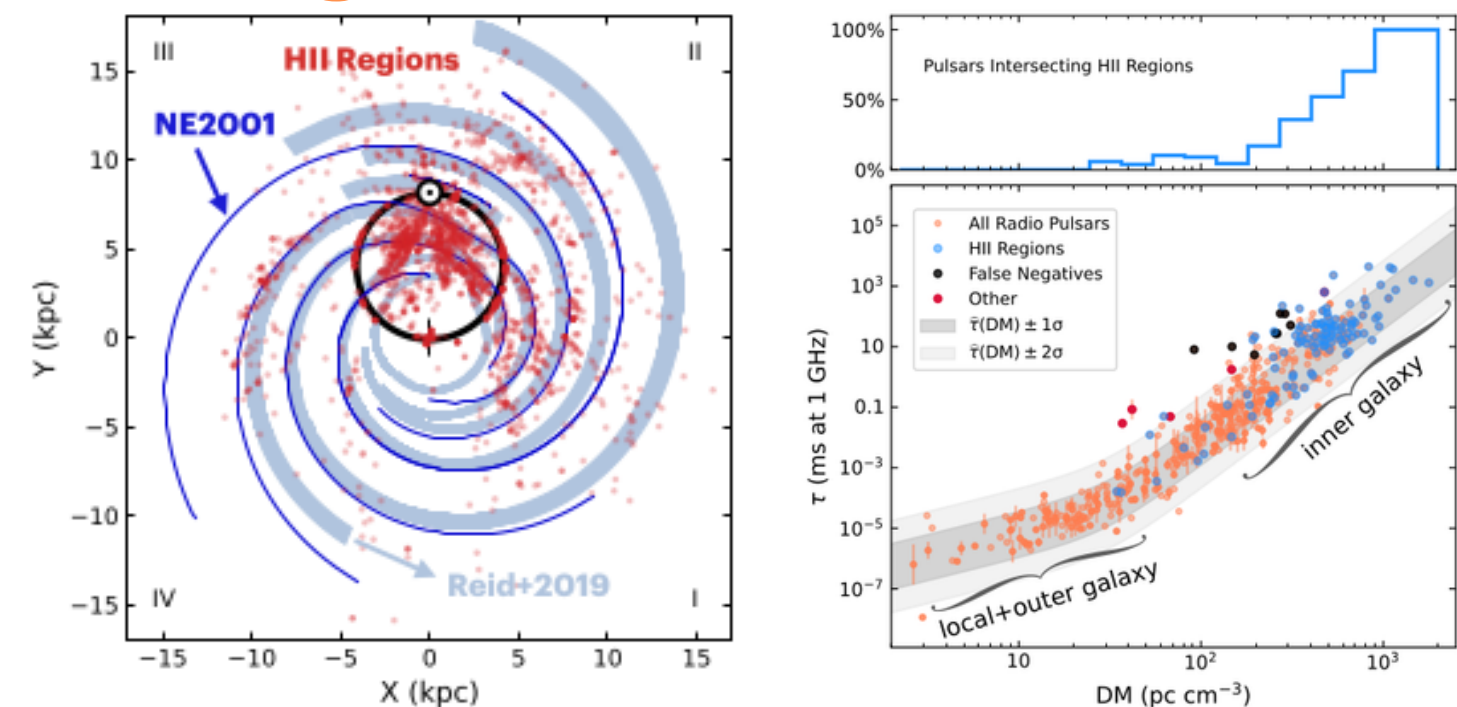
• Solar Wind



Spherically symmetric density model:

$$DM_{\text{sw}} = n_{e,\text{sw}} \frac{\sin \rho}{\rho} [1 \text{ AU}]^2$$

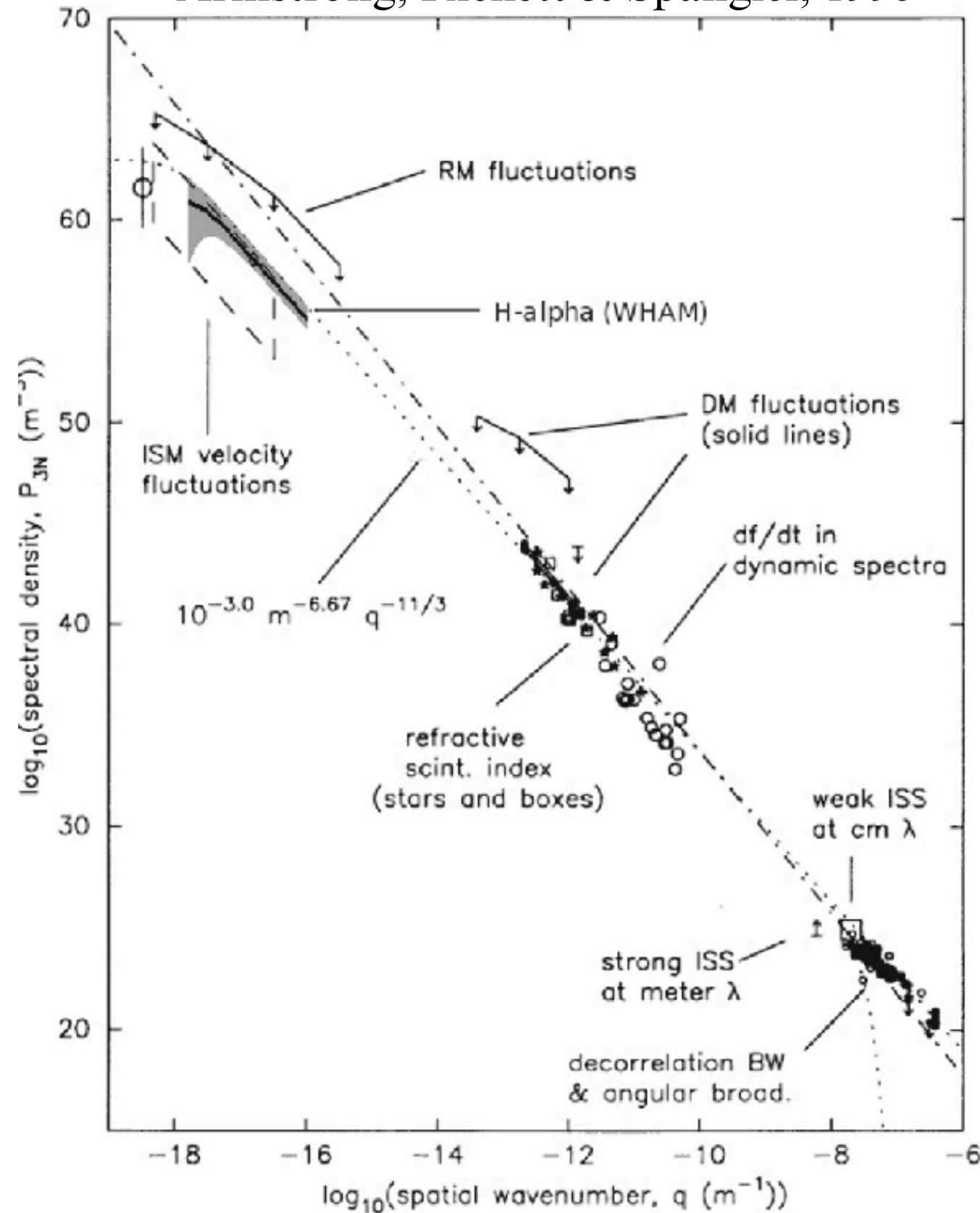
• HII regions



Ocker et al. 2024

Turbulence in the IISM

Armstrong, Rickett & Spangler, 1995



- **Electron density fluctuations** across a wide range of spatial scales

- **Power spectrum:**

$$P_{\delta n_e}(\mathbf{q}) = C_n^2 q^{-\beta}, \quad \begin{array}{c} \text{outer and inner scales} \\ \downarrow \qquad \qquad \downarrow \\ q_0 \leq q \leq q_i \end{array}$$

- Following a **power-law spectrum** consistent with **Kolmogorov turbulence:**

$$P_{\delta n_e} \propto q^{-\beta}, \quad \beta \simeq \frac{11}{3}$$

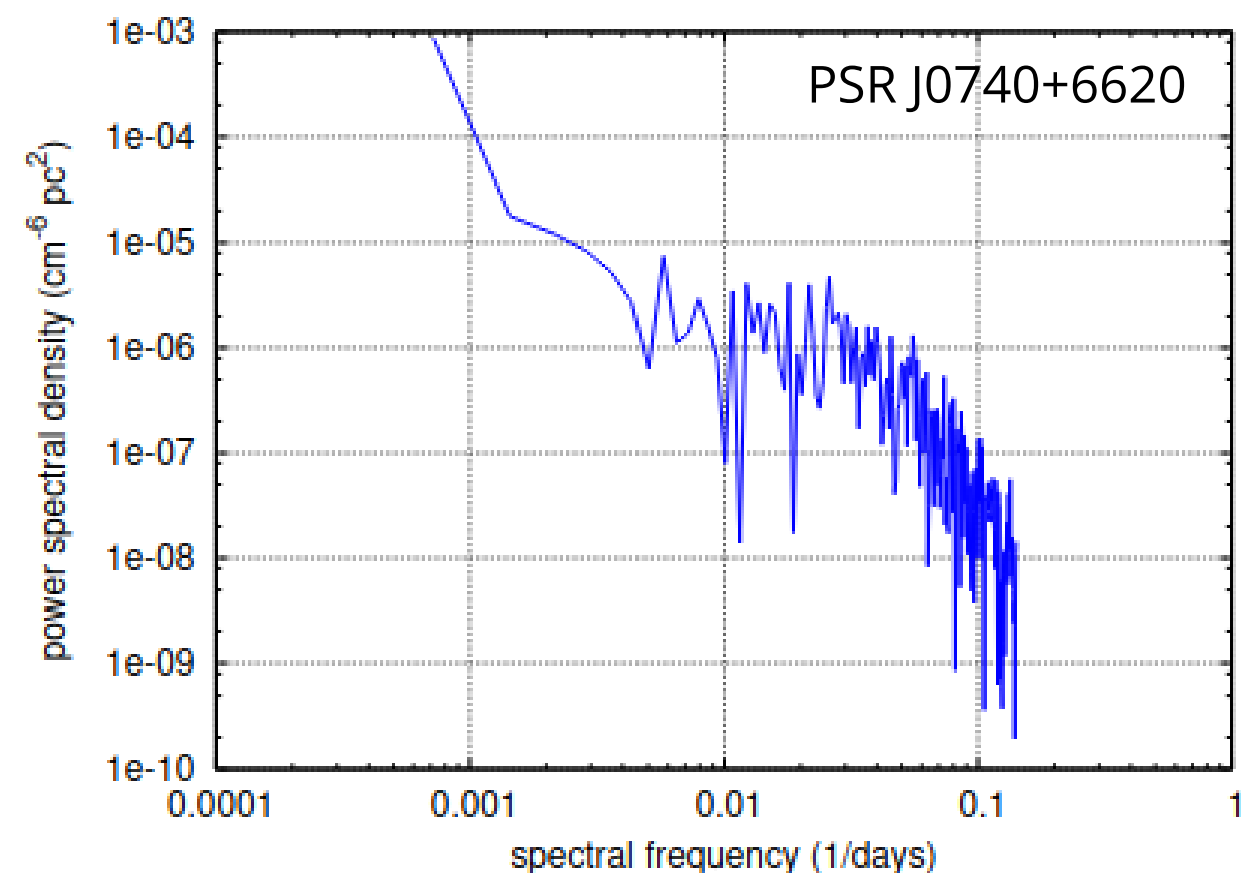
- ionized ISM behaves like a **turbulent cascade**
- Energy injected at large scales $\rightarrow$ transferred down to small scales

Characterising IISM turbulence

- **Power Spectra**

$$P_{\delta n_e}(\mathbf{q}) = C_n^2 q^{-\beta}, \quad \begin{matrix} \text{outer and inner scales} \\ \downarrow \qquad \qquad \downarrow \\ q_0 \leq q \leq q_i \end{matrix}$$

LOFAR data



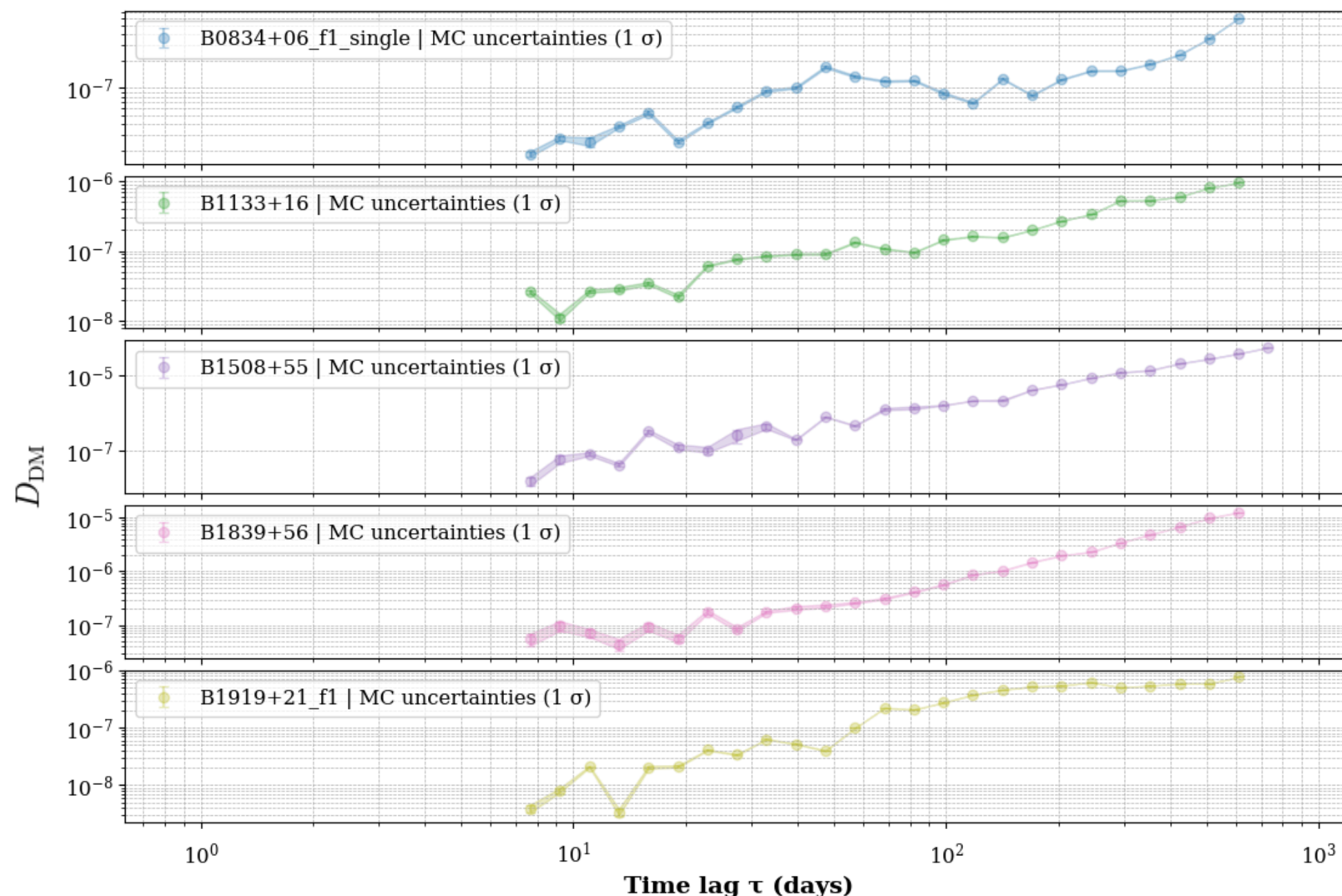
from Donner, 2022 (PhD Thesis)

→ **Inferring the amplitude and spectral properties of n_e fluctuations**

- **Structure function:**

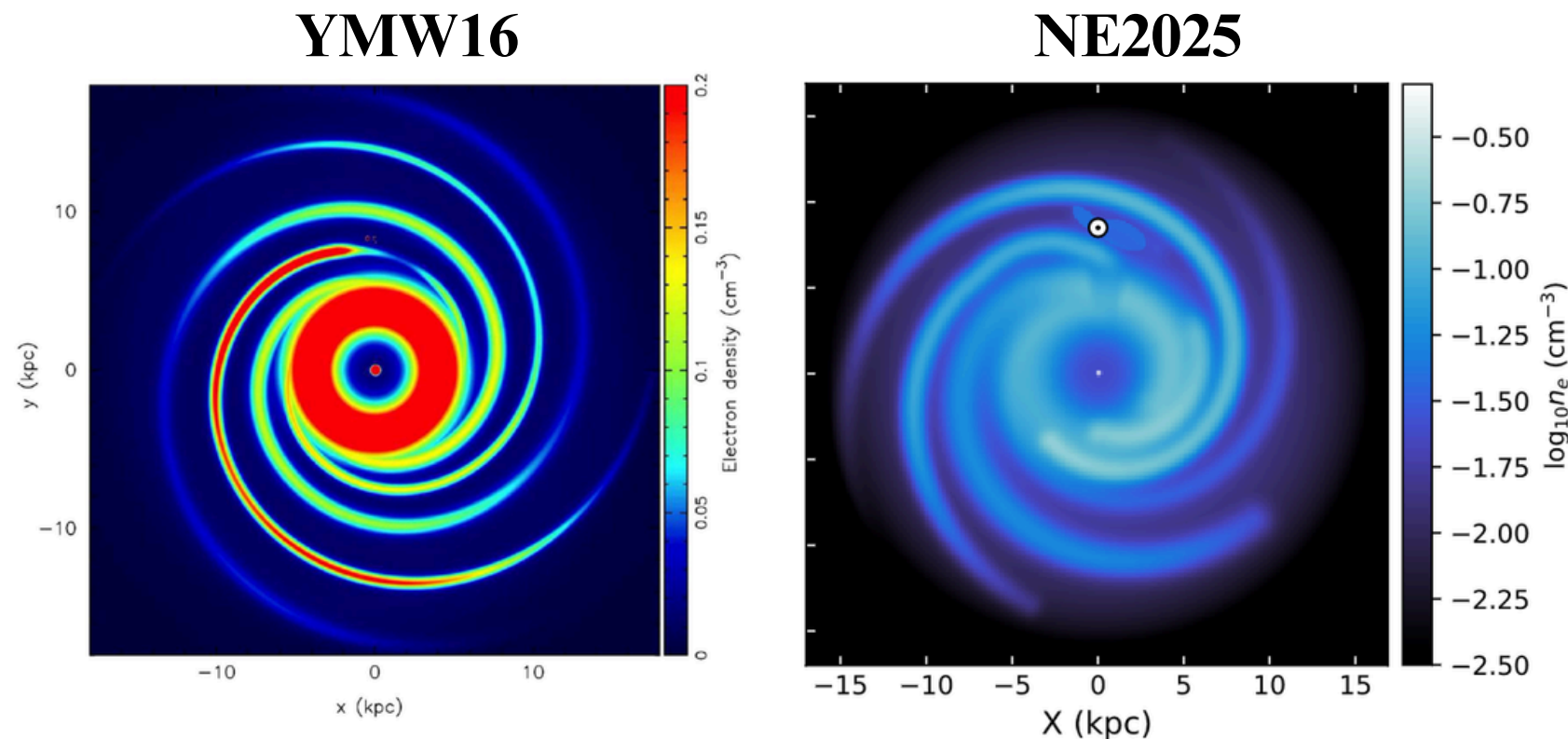
$$D_{\text{DM}}(\tau) = \langle [\text{DM}(t + \tau) - \text{DM}(t)]^2 \rangle$$

for a **Kolmogorov spectrum**: $D_{\text{DM}}(\tau) \propto \tau^{5/3}$

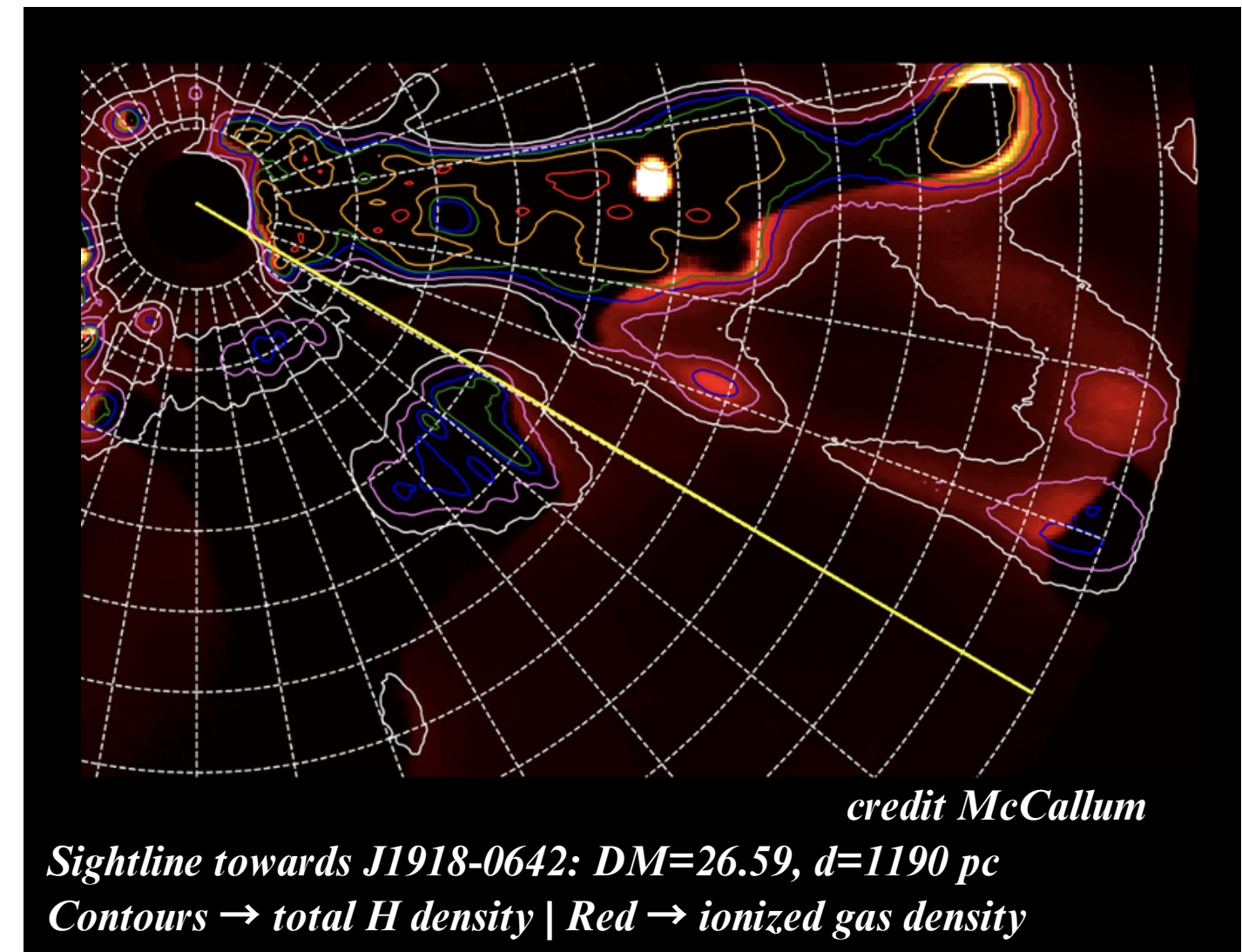


Constraining Galactic electron density models

- New approaches based on **stellar parallax, 3D dust map and radiative-transfer simulations** of ionizing Lyman-continuum photons



- Describing the **global distribution of ionized gas** in the Galaxy
- Relying on **pulsar distances, dispersion measures and scattering**

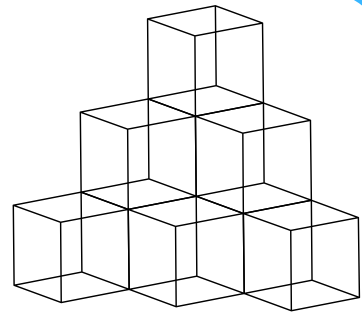


Calibrating Galactic Electron Density Models

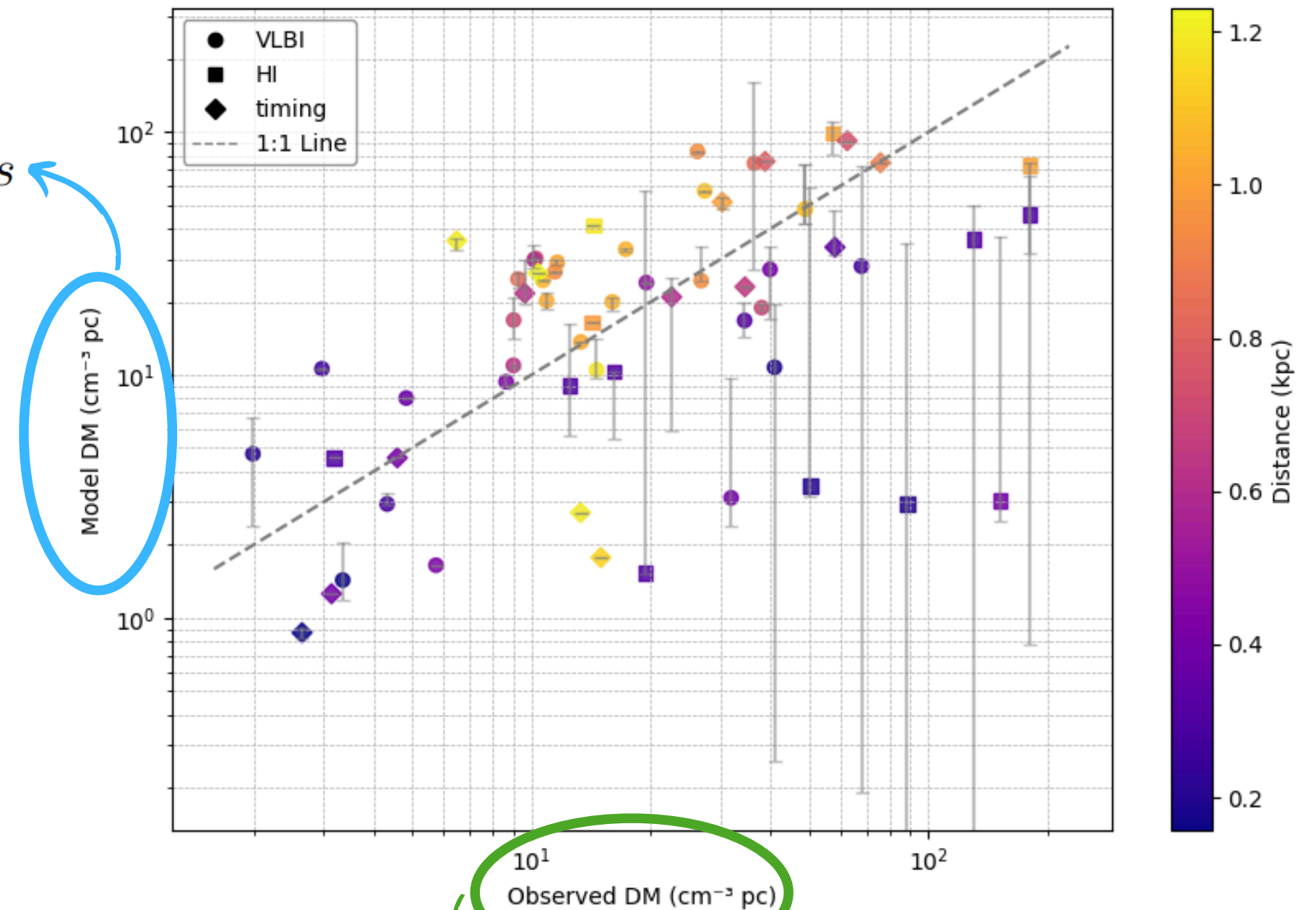
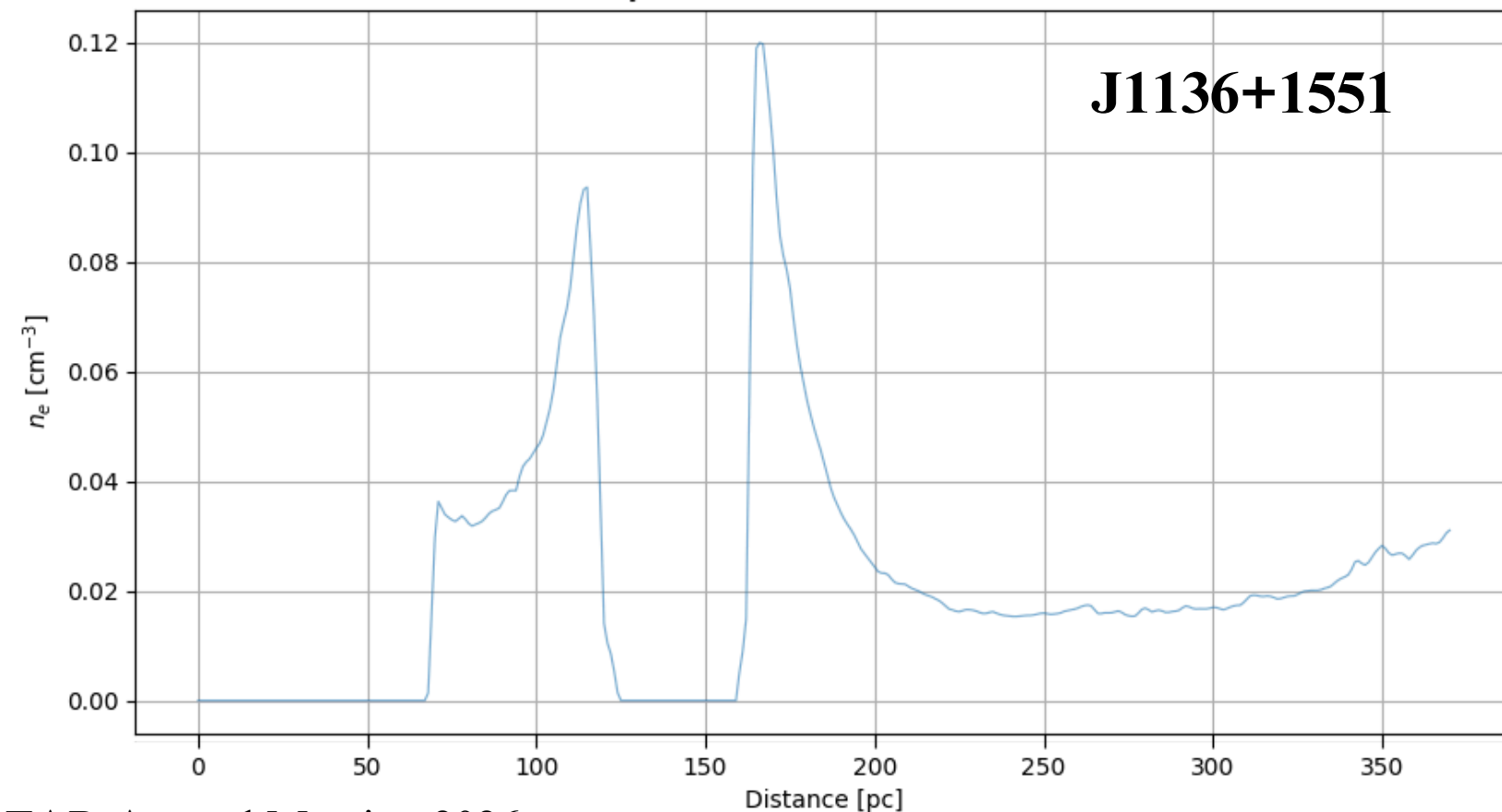
- DM predicted from *McCallum et al. 2025*:

Simulation Box

- Shape: Cube
- Size: **2.5 kpc per side**
- Sun Position: at the center (0, 0, 0)
- Grid Resolution: **1024³ voxels**
- Voxel Size: **2.44 pc per voxel**



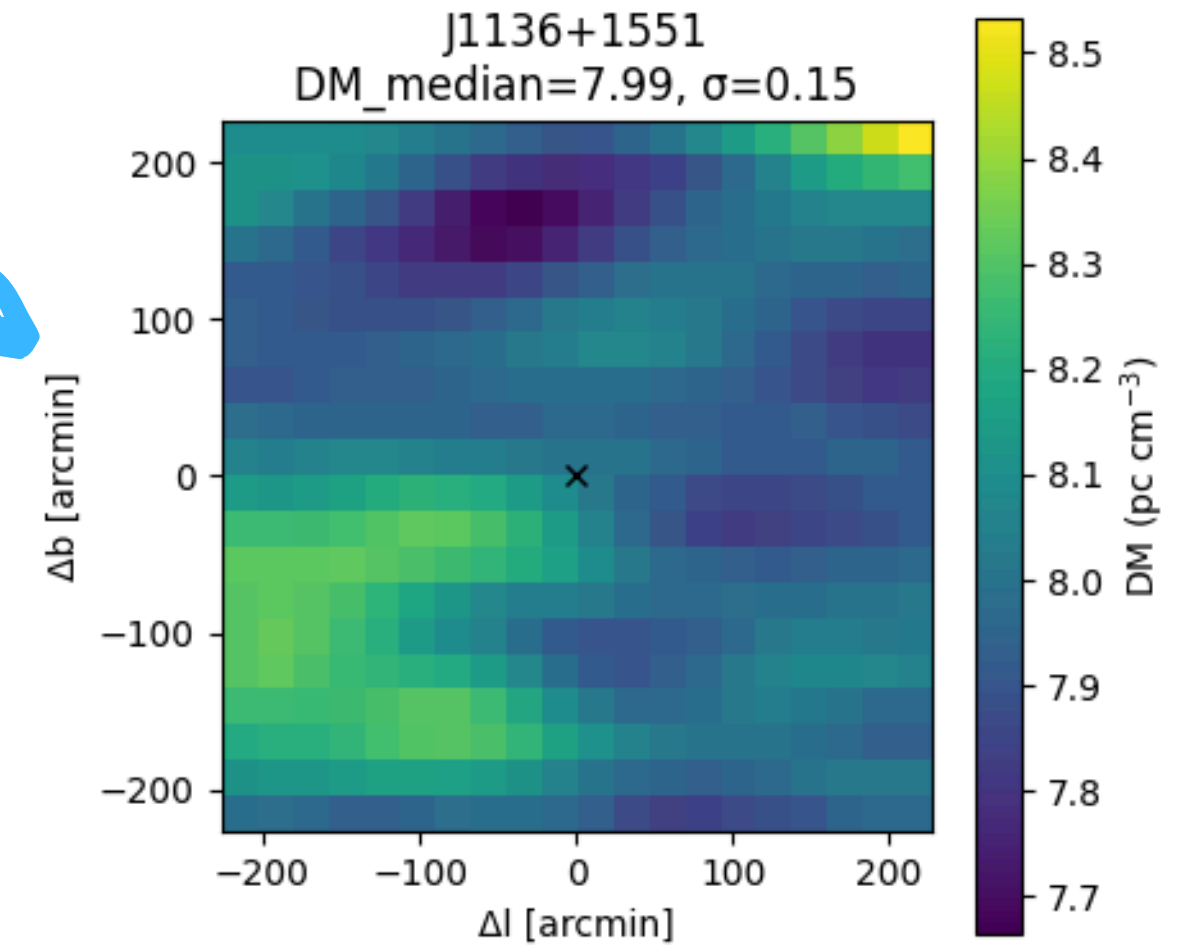
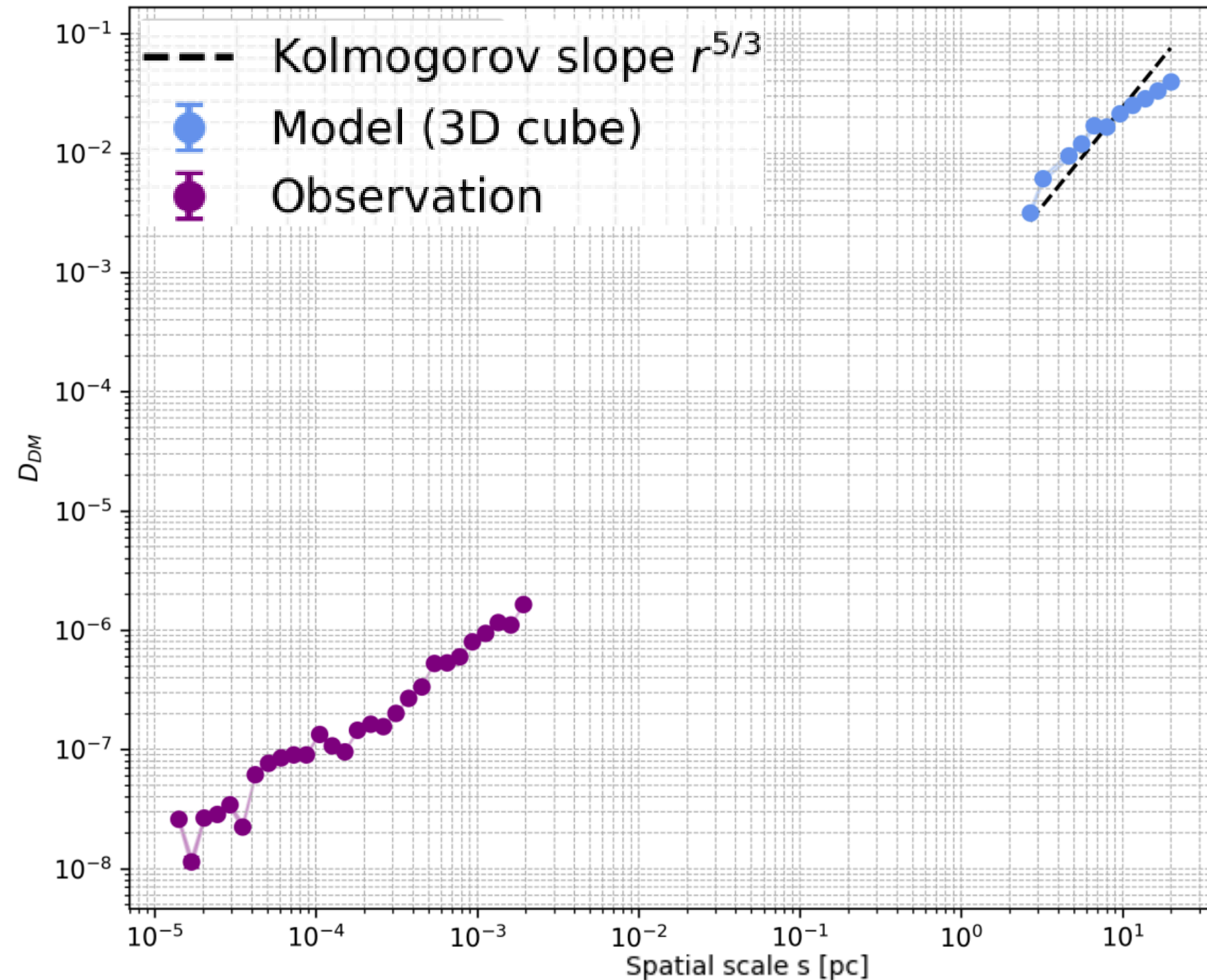
$$DM = \int_0^d n_e(s) ds$$
$$\approx \sum_i n_e(s_i) \Delta s$$



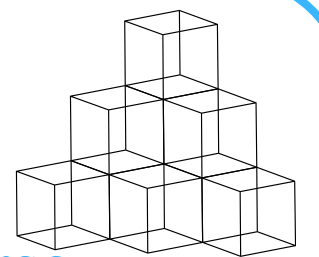
ATNF Pulsar Catalogue
(Version: 2.7.0)

Connecting small scales with to the global structure

J1136+1551



- n_e cube resolution: **2.44 pc per voxel**
- Extreme pulsar transverse velocity: **800 km s⁻¹**
- Displacement over 10 years: **≈ 0.008 pc $\approx 3 \times 10^{-3}$ voxel**



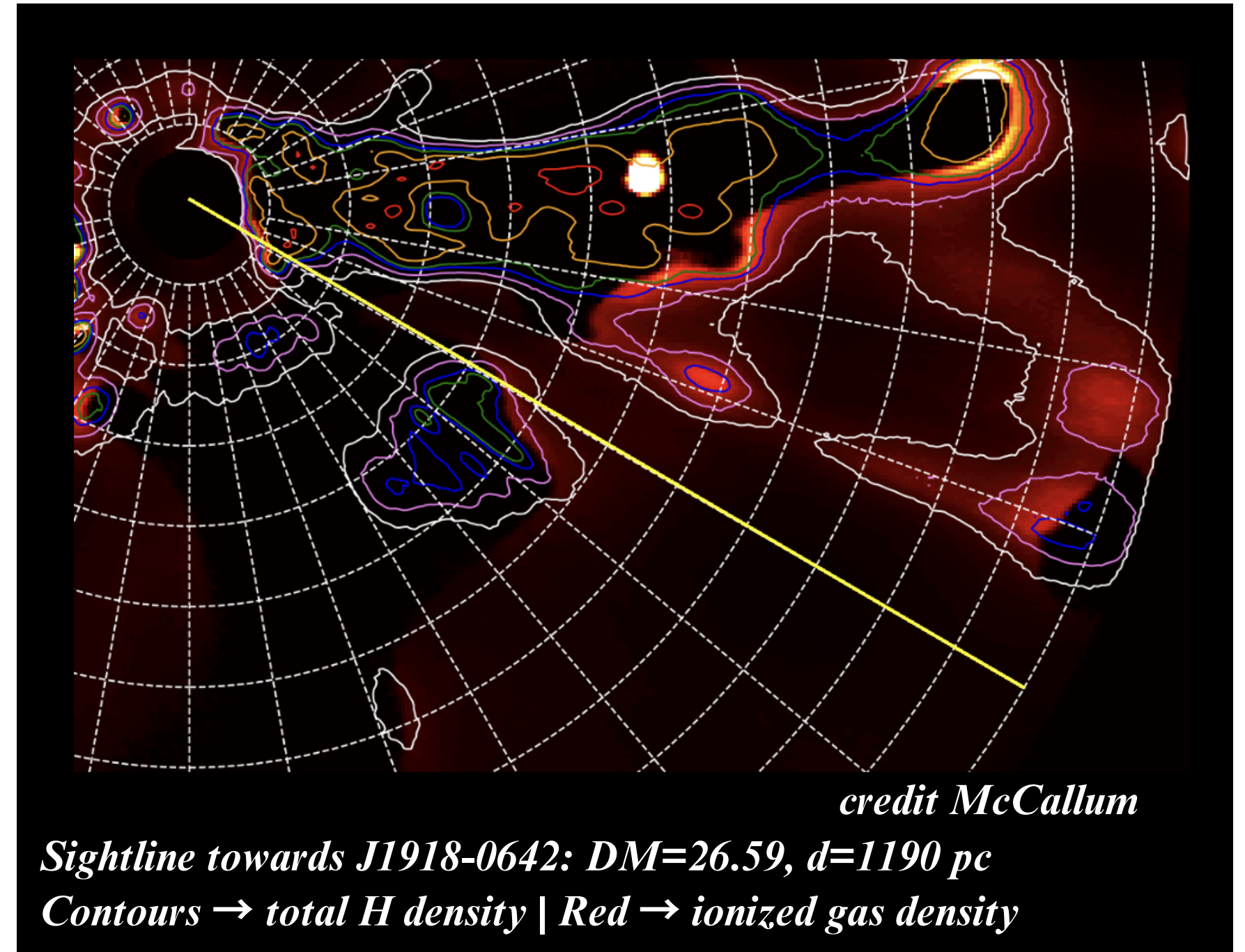
Conclusion

- **Low-frequency observations of pulsars** provide highly sensitive probes of electron-density fluctuations in the ISM
- **NenuFAR** delivers **DM precision of a few $\times 10^{-5}$**
- Combining datasets: **long-baseline HBAs and LBAs** + highly sensitive NenuFAR
- **Structure functions** consistent with turbulent ISM fluctuations
- **Constraining Galactic electron density models**
- **Connecting small scales with to the global structure**

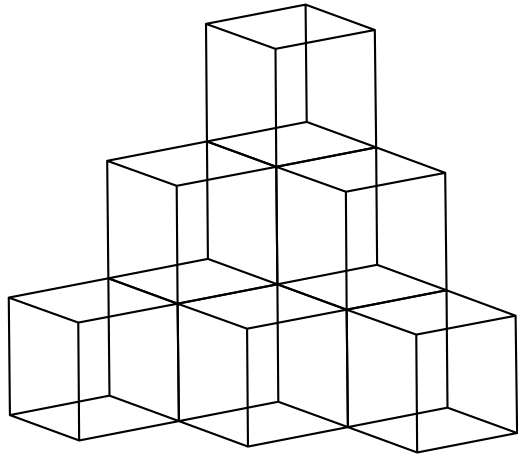
Backup

McCallum+25a,b → **spatial distribution of ionized gas** within **~1.25 kpc of the Sun**.

- Using the known **3D distribution of O stars** as ionizing sources (parallax distances *from GAIA*),
- **3D map of the spatial distribution of dust** as absorbers of ionizing photons (*from Edenhofer et al. 2024*),
- Assuming a **constant gas-to-dust ratio** throughout the volume,
- Performing full **3D radiative transfer of Lyman continuum photons**



RESOLUTION AND PULSAR TRANSVERSE MOTION

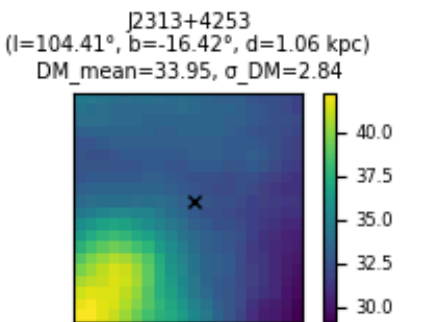
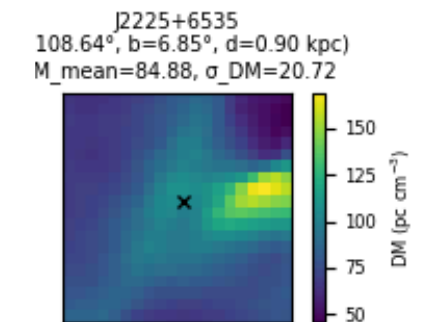
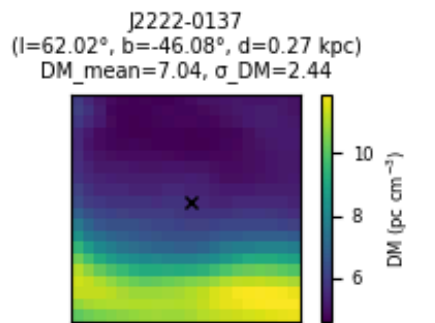
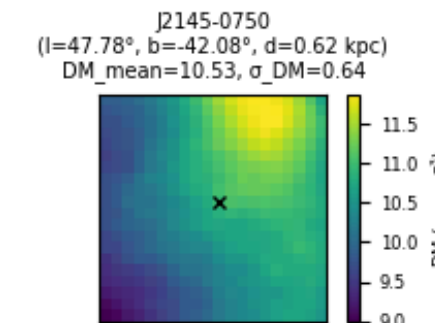
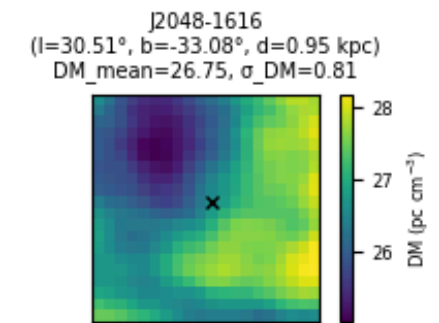
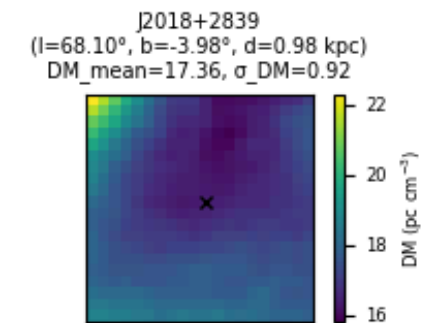
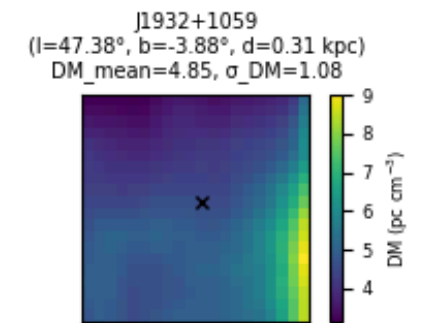
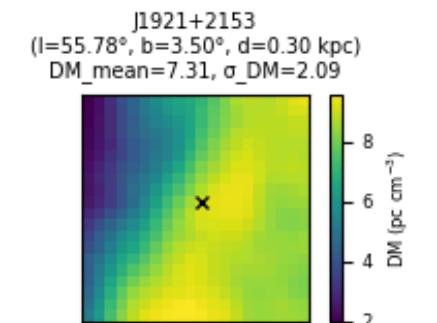
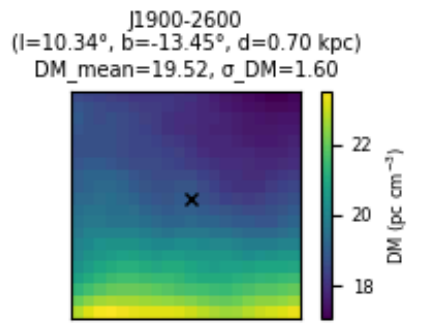
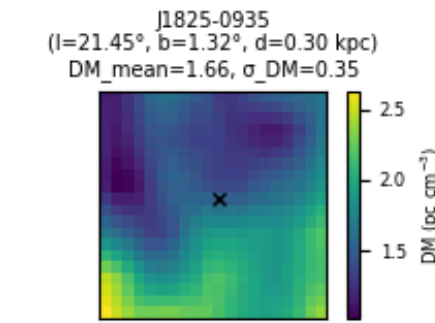
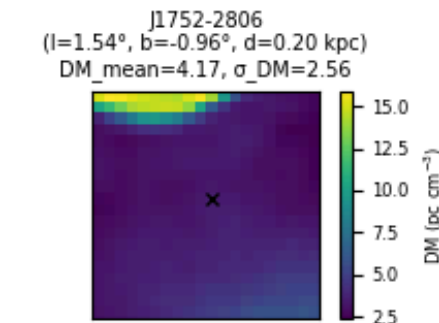
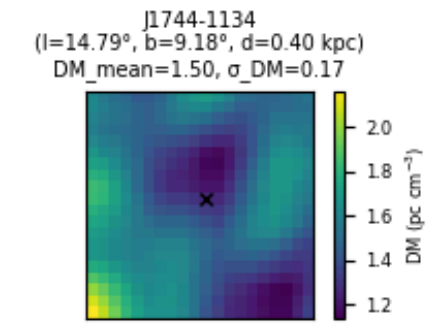
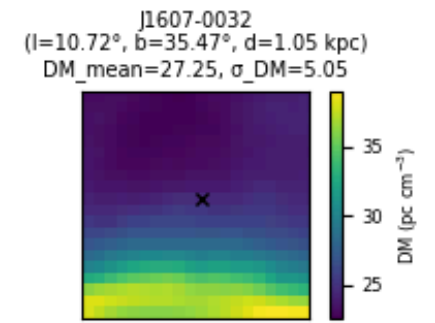
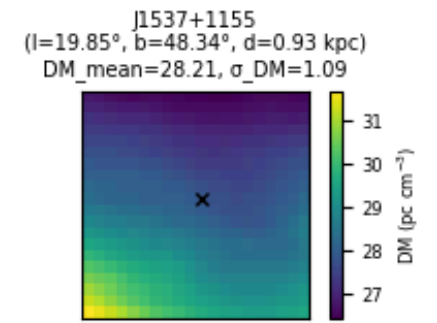
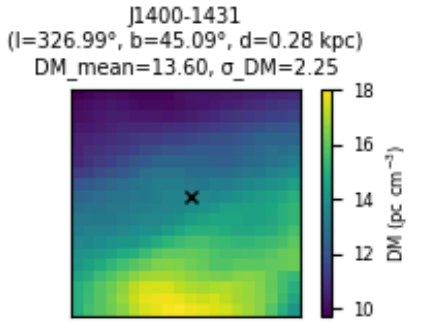
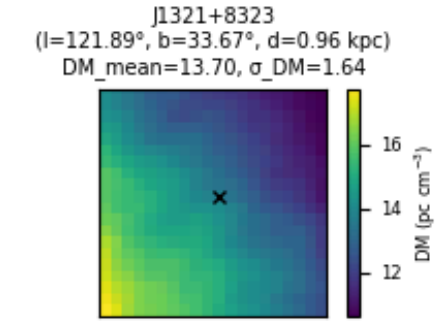
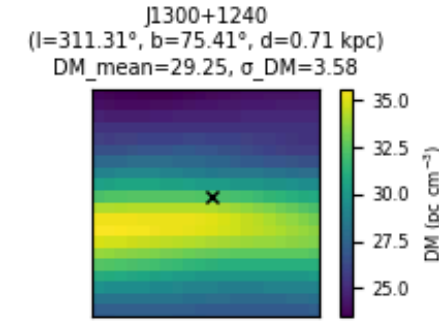
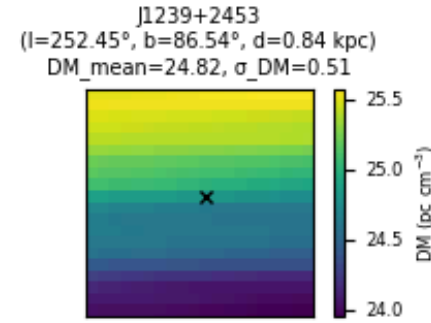
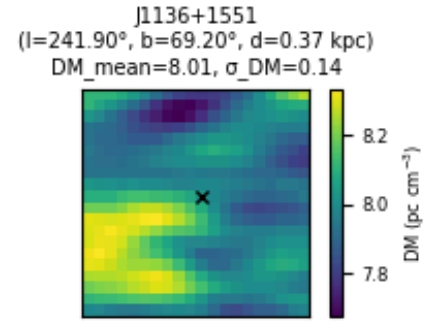
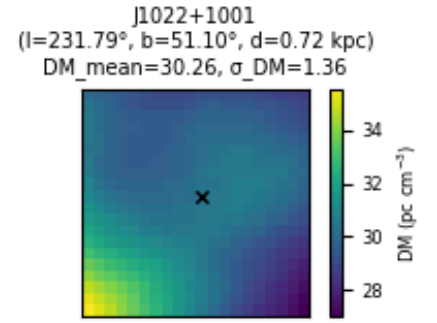
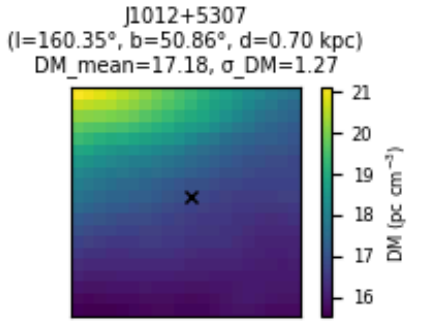
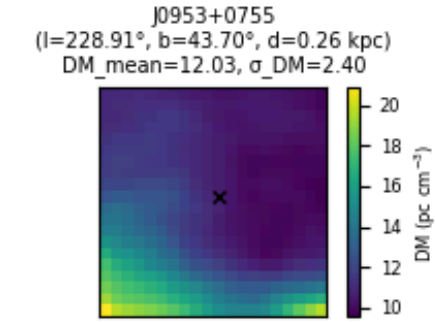
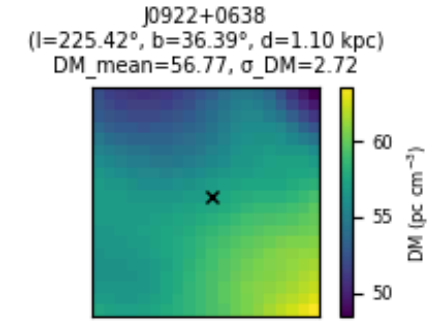
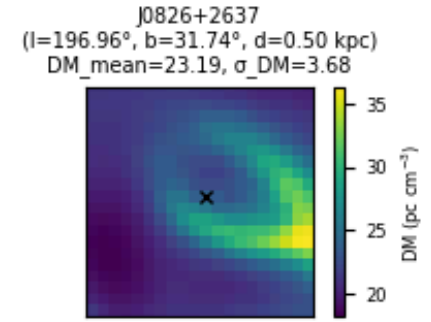
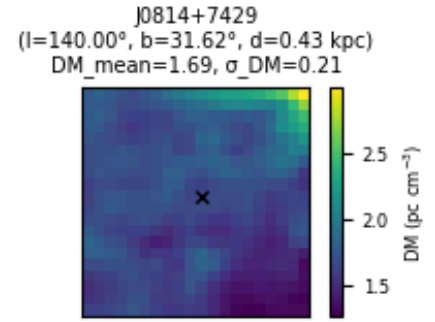
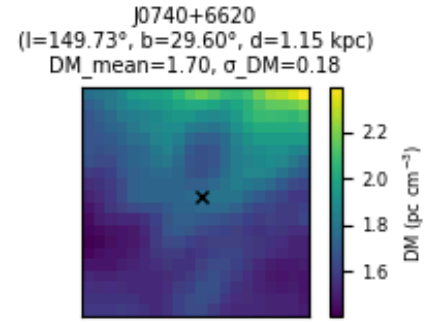
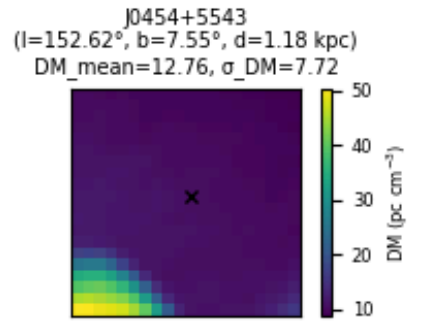
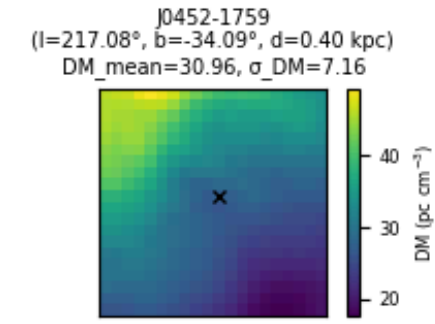
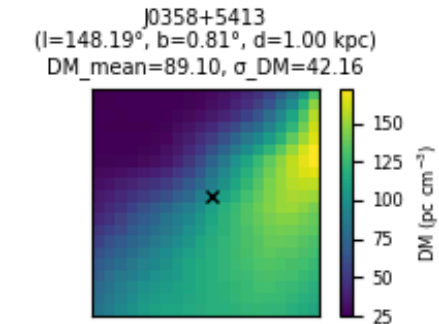
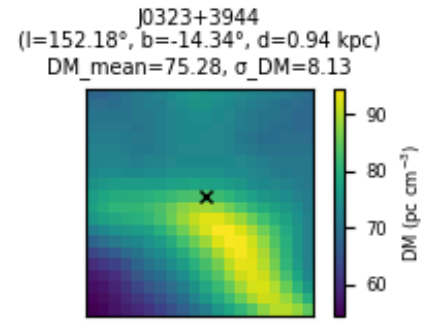
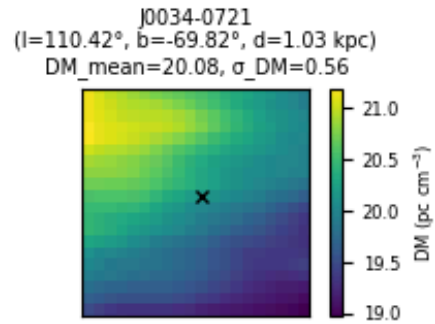
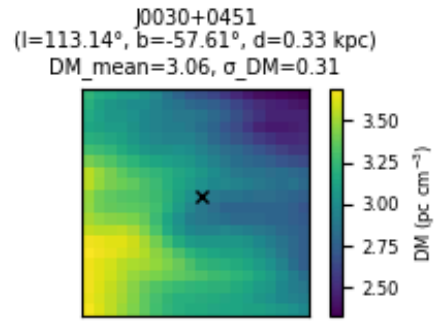


- n_e cube resolution: **2.44 pc per voxel**
- Extreme pulsar transverse velocity: **800 km s⁻¹**
- Displacement over 10 years: **$\approx 0.008 \text{ pc} \approx 3 \times 10^{-3} \text{ voxel}$**

→ Pulsars are stationary with respect to the 3D ISM model

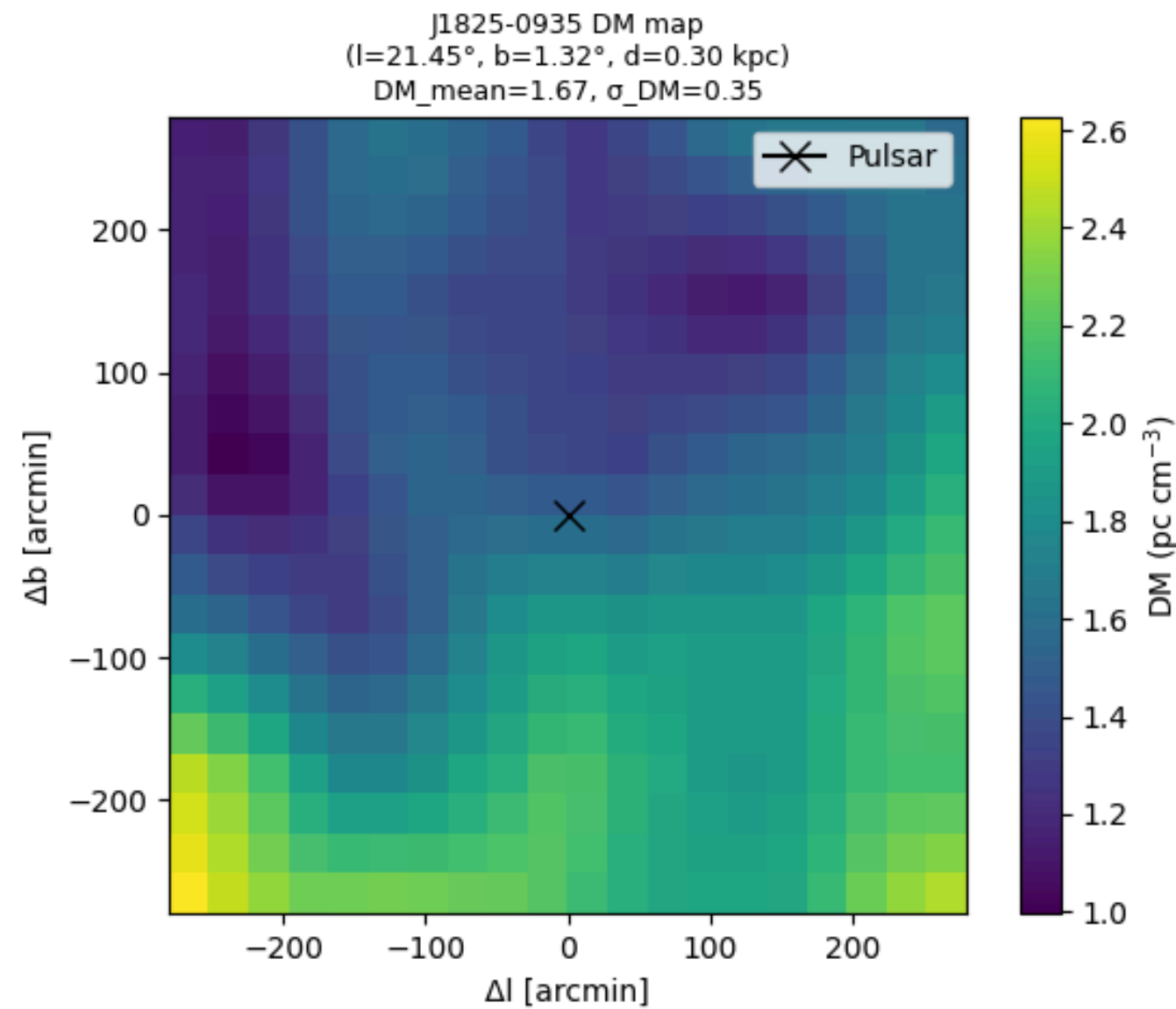
→ Transverse motion cannot probe pc-scale structure

2D DM MAPS AROUND PULSARS



DM MAPS AROUND PULSARS

- 20 pixels per side
- Pulsar Position: at the center (0, 0)
- Pixel Size: 2.44 pc /Dist

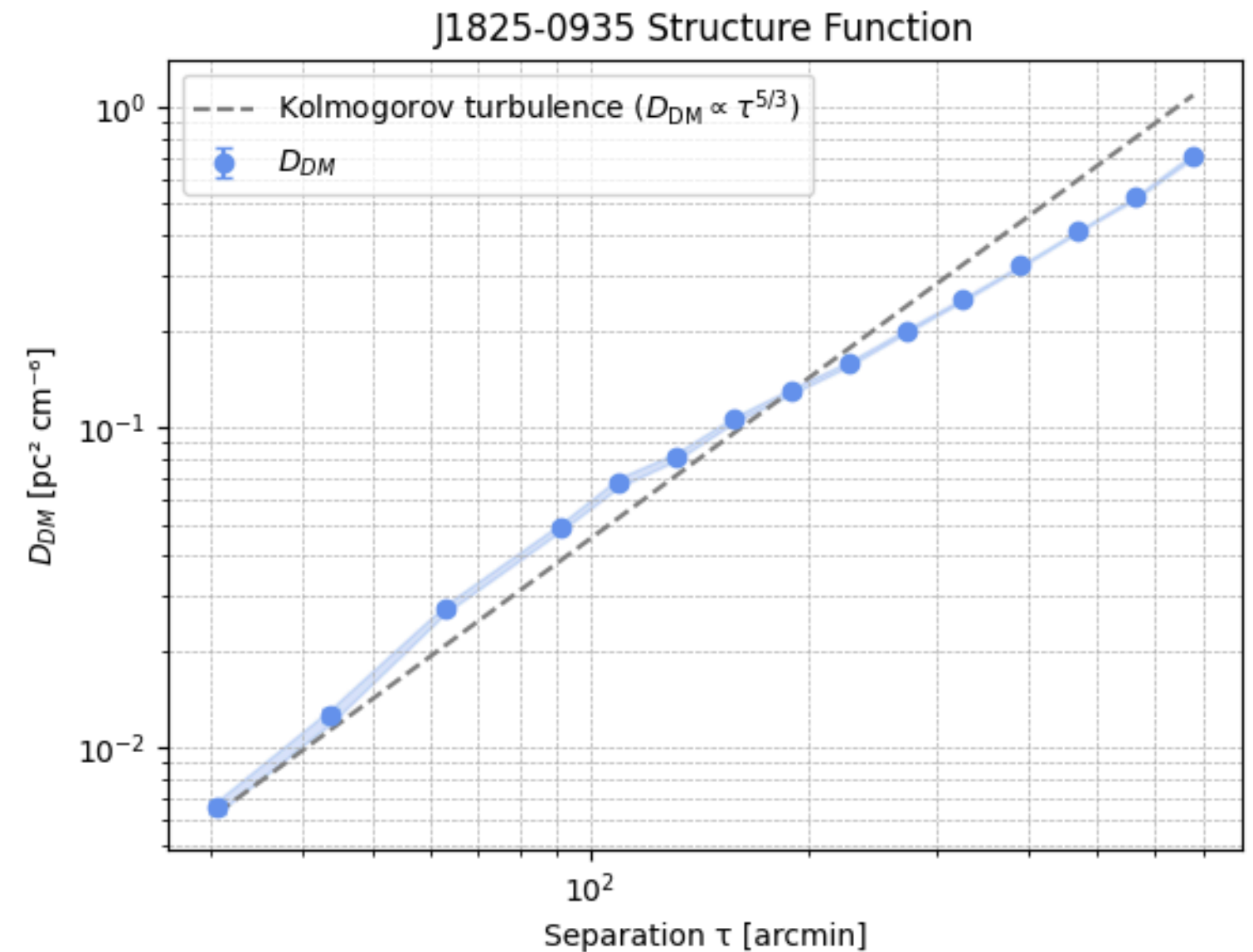


- **Structure function:**

$$D_{DM}(\tau) = \langle [DM(x + \tau) - DM(x)]^2 \rangle$$

for a Kolmogorov spectrum:

$$D_{DM}(\tau) \propto \tau^{5/3}$$

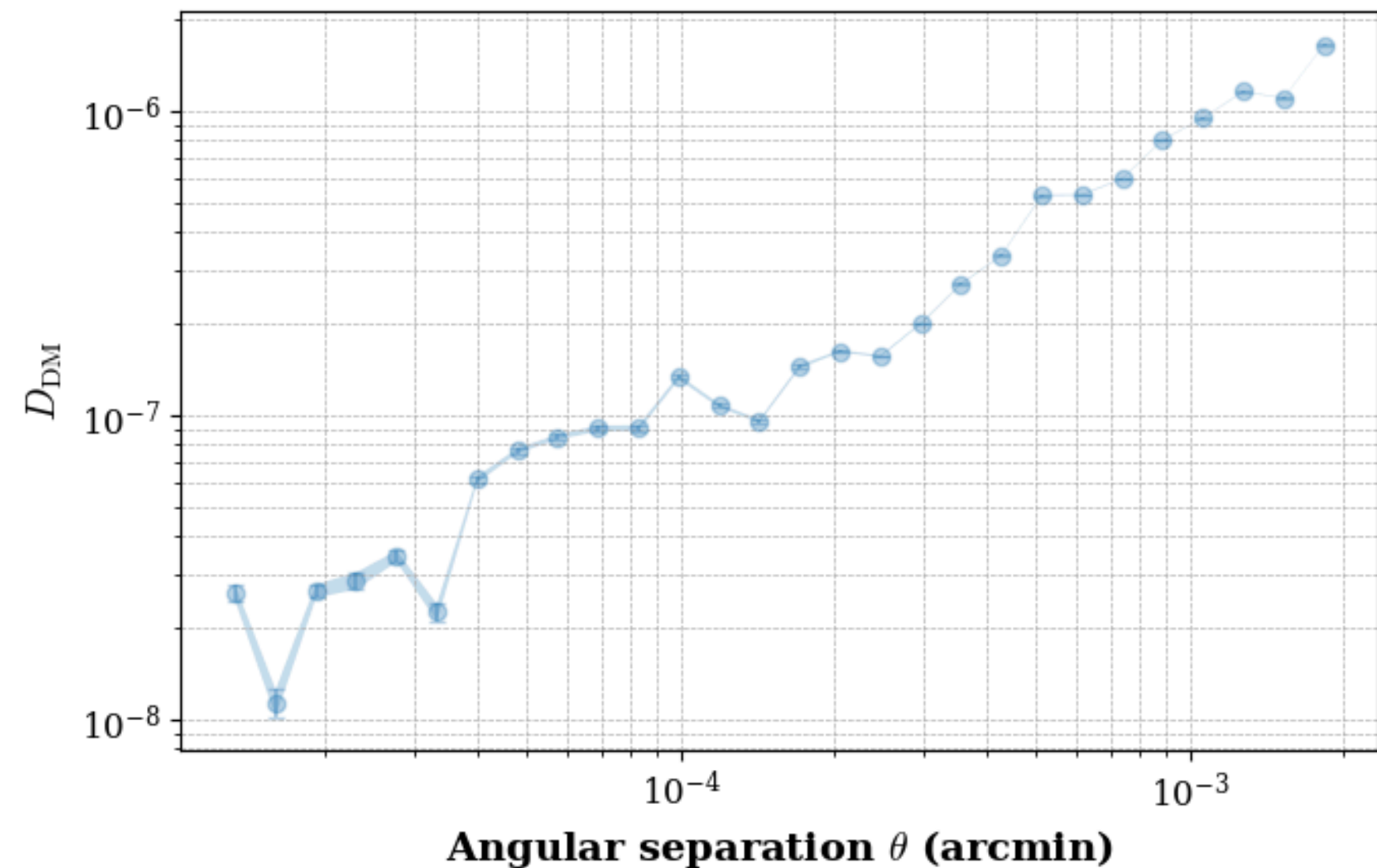
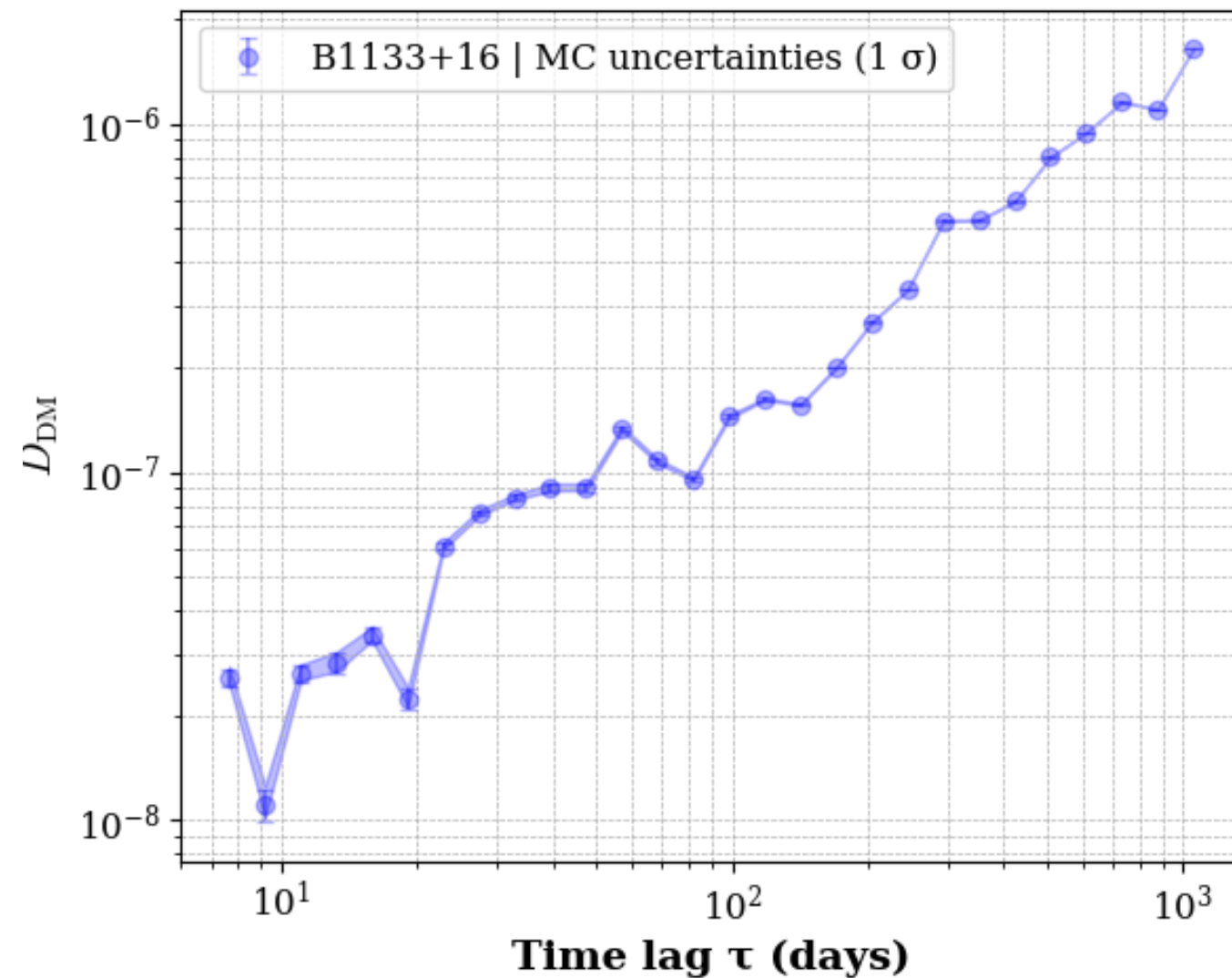
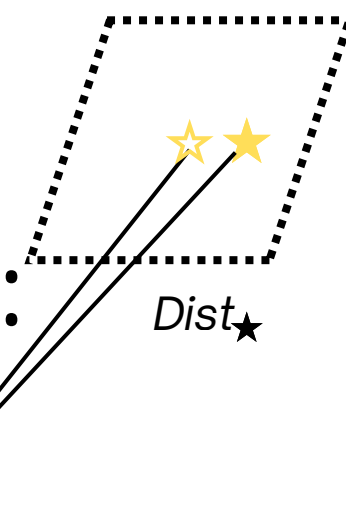


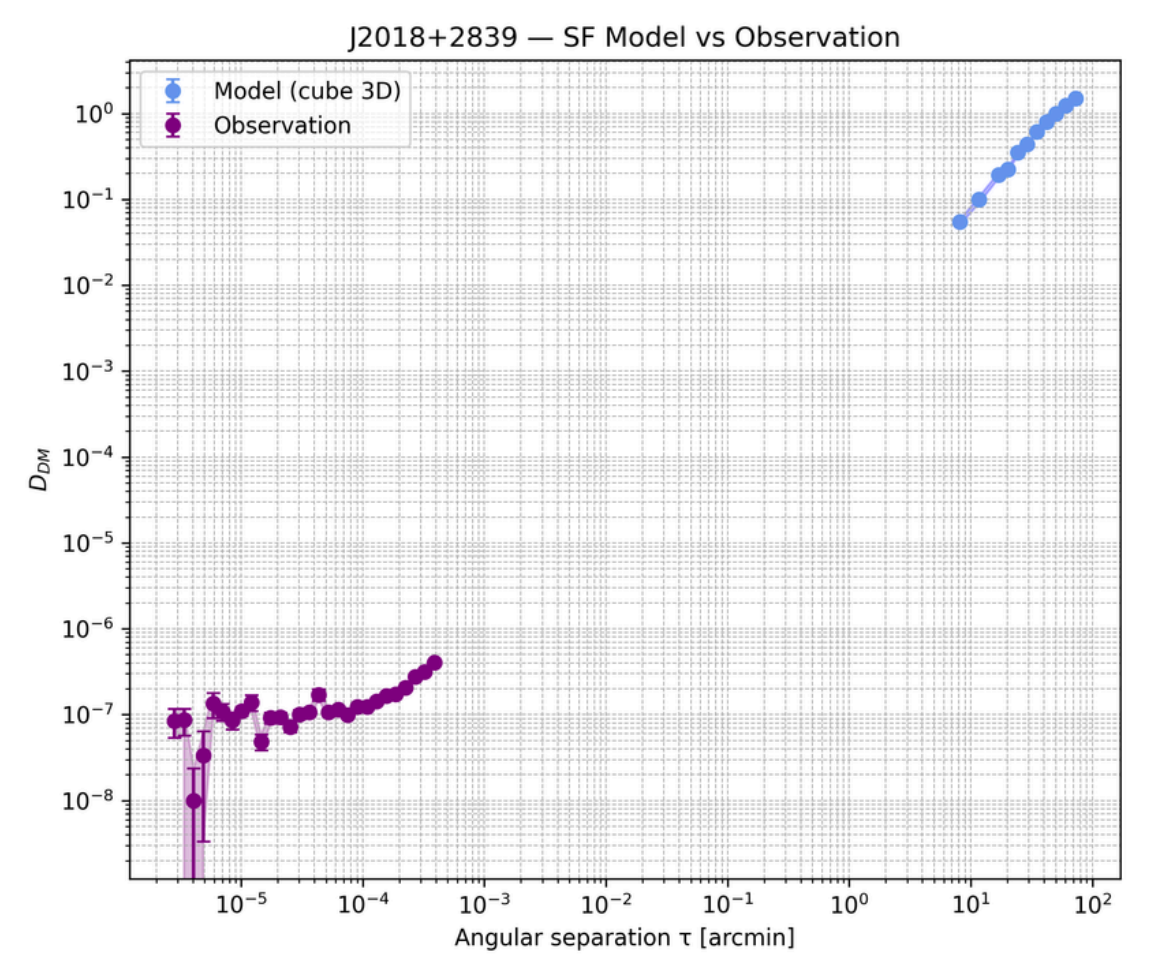
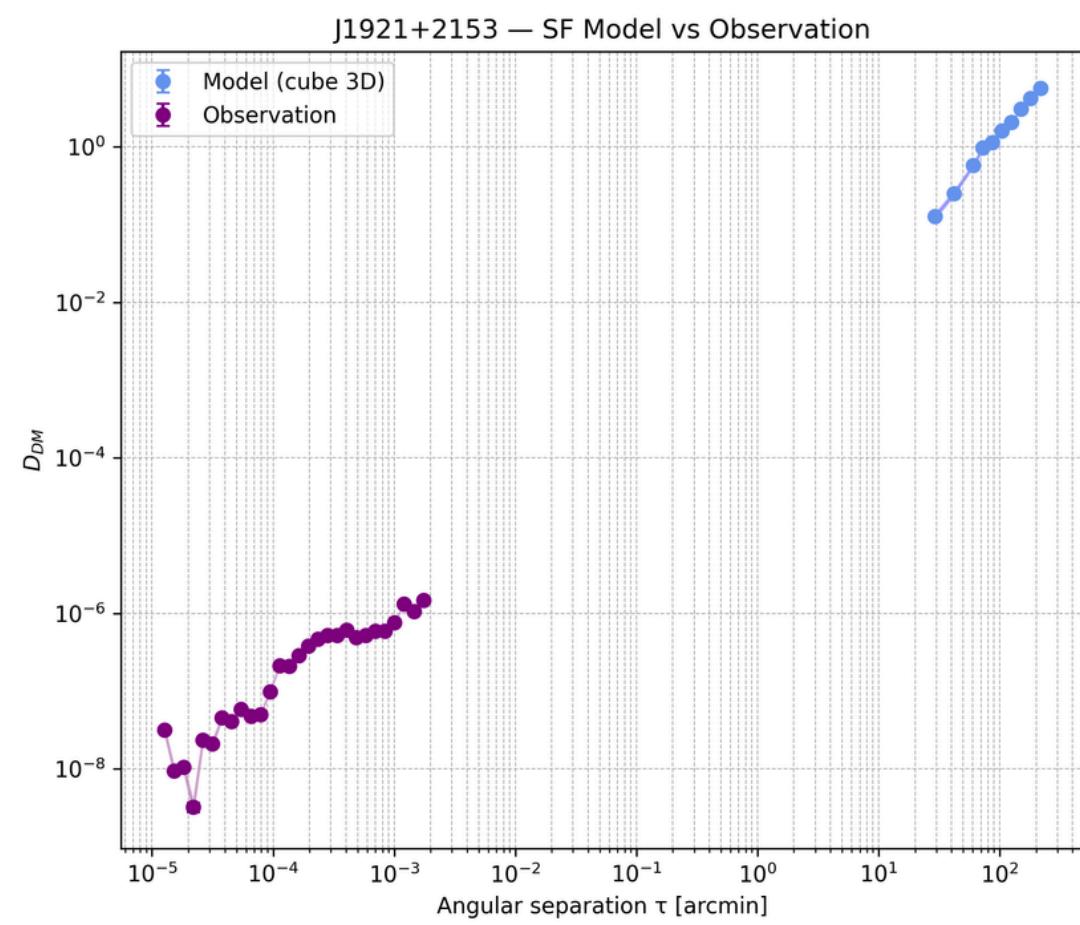
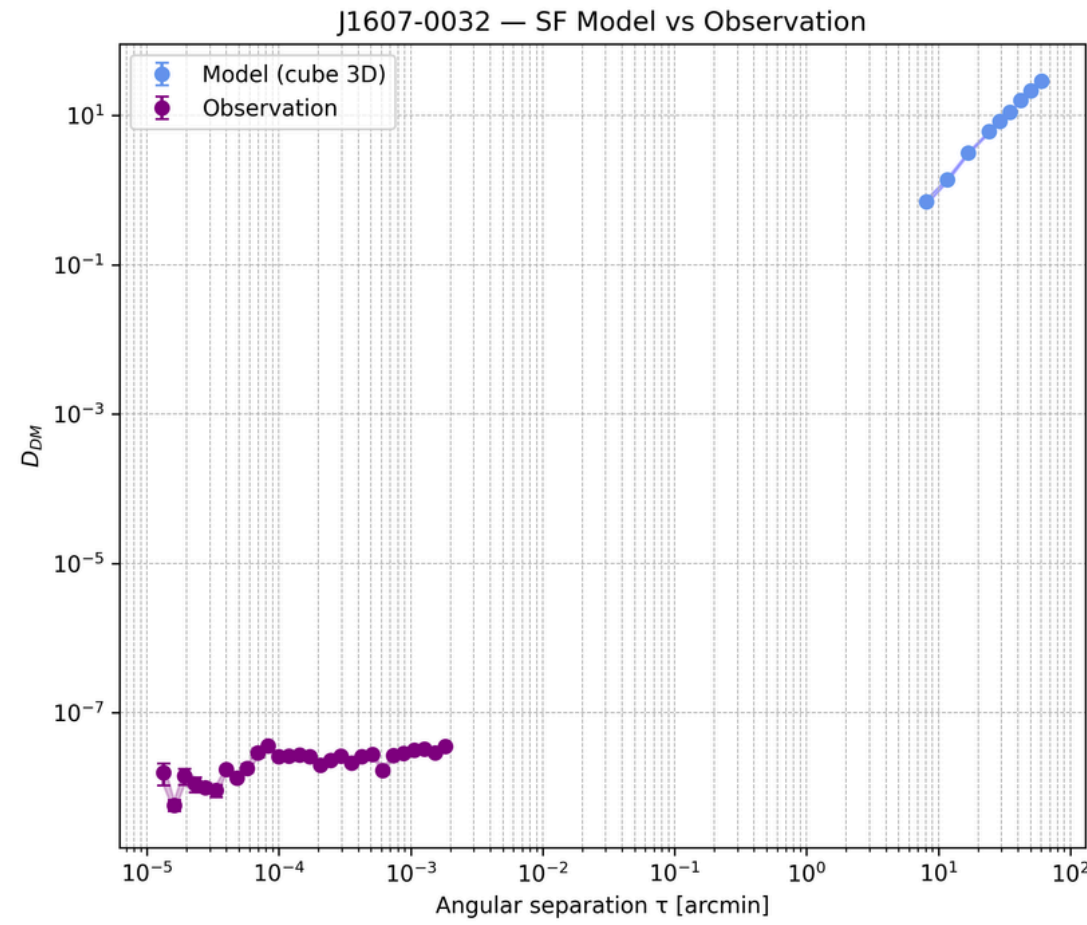
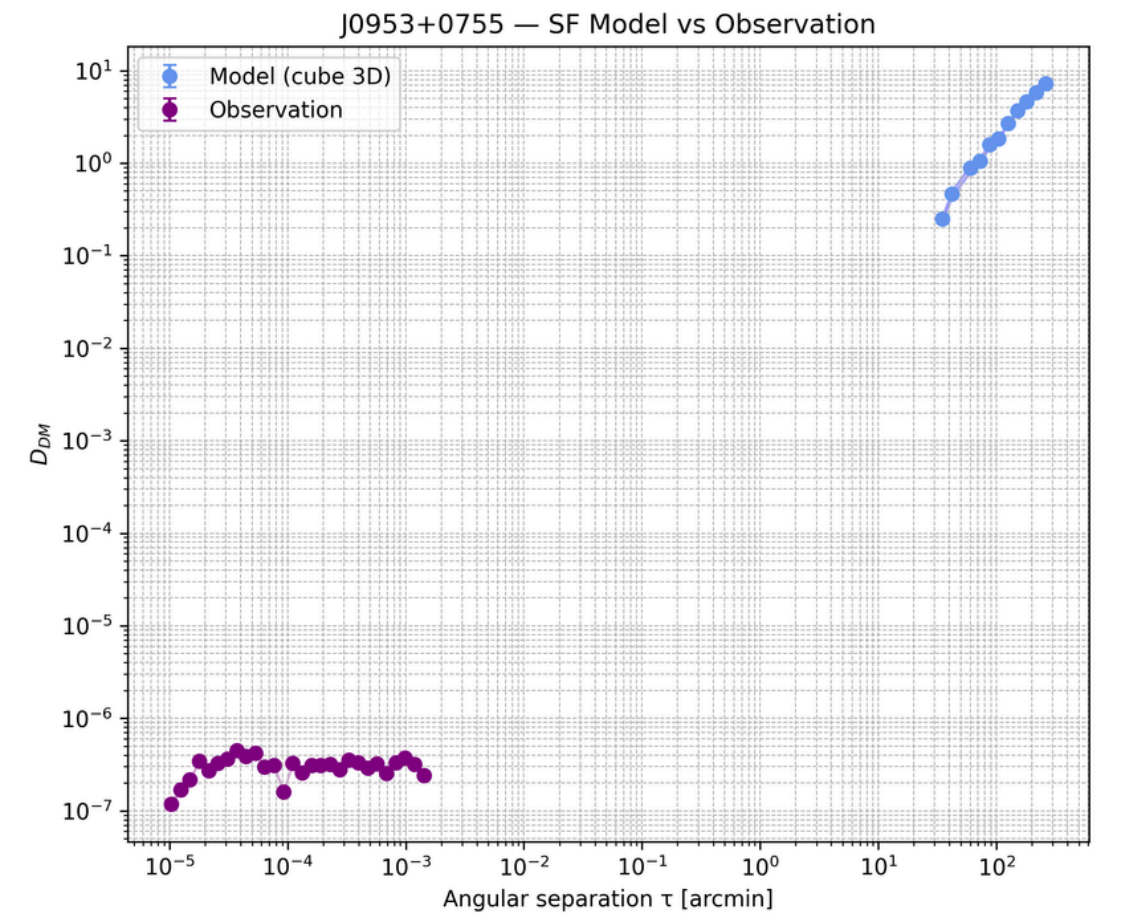
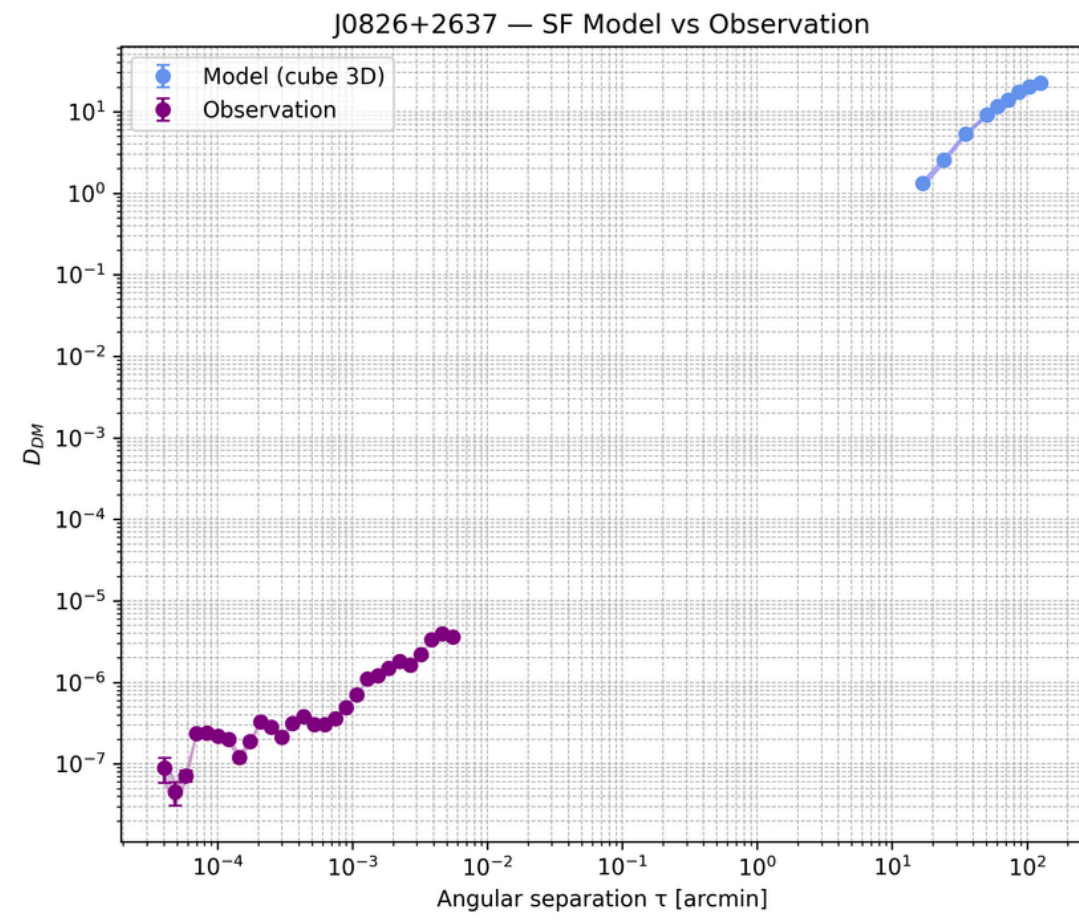
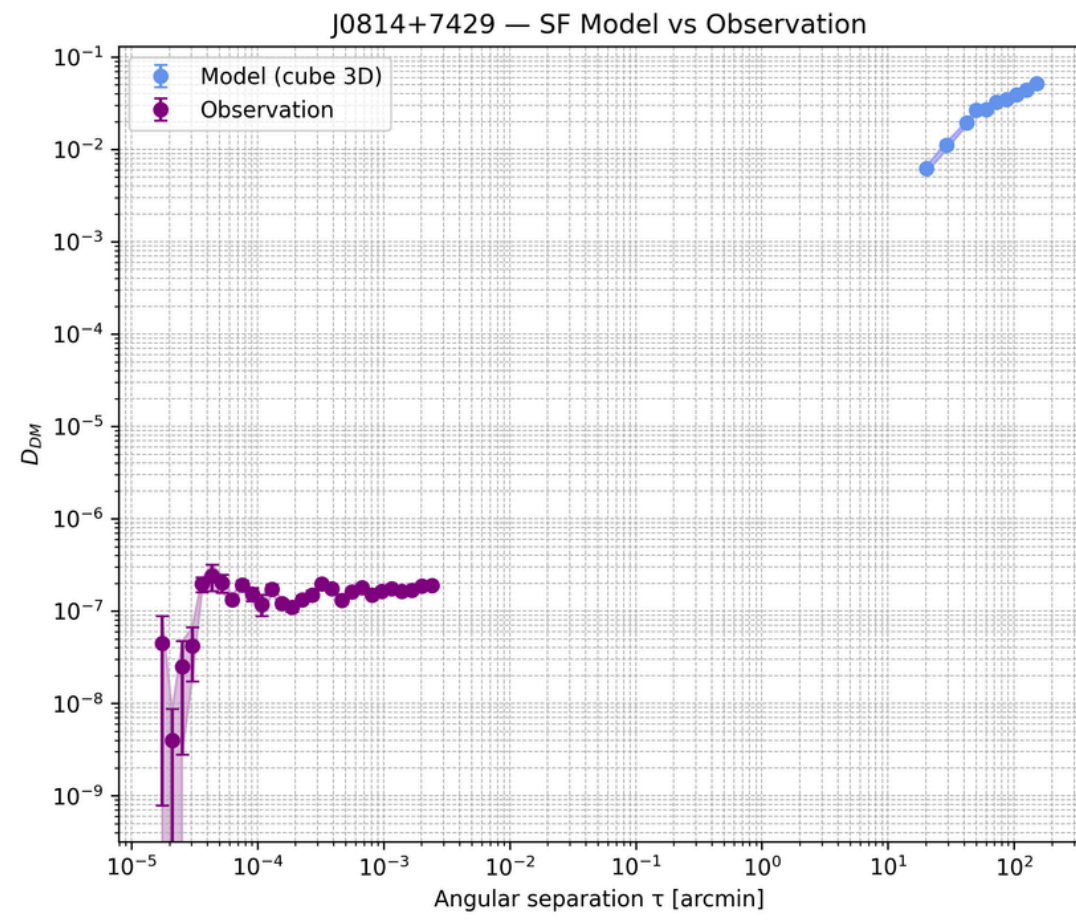
STRUCTURE FUNCTION FROM DATA

- **During** a time lag τ , the **LOS** moves transversely through the ISM
- sampling different electron density regions

→ A temporal lag τ corresponds to a **transverse spatial displacement**:

$$\theta = \frac{\ell_{\perp}}{d} = \frac{V_{\perp} \tau}{d} \Rightarrow \theta = \mu \tau$$





STRUCTURE FUNCTIONS

Preliminary Results - DM structure function of J1840+5640 (combined data)

