Ionized interstellar medium studies using pulsar scattering observations from polish LOFAR (POLFAR) stations.

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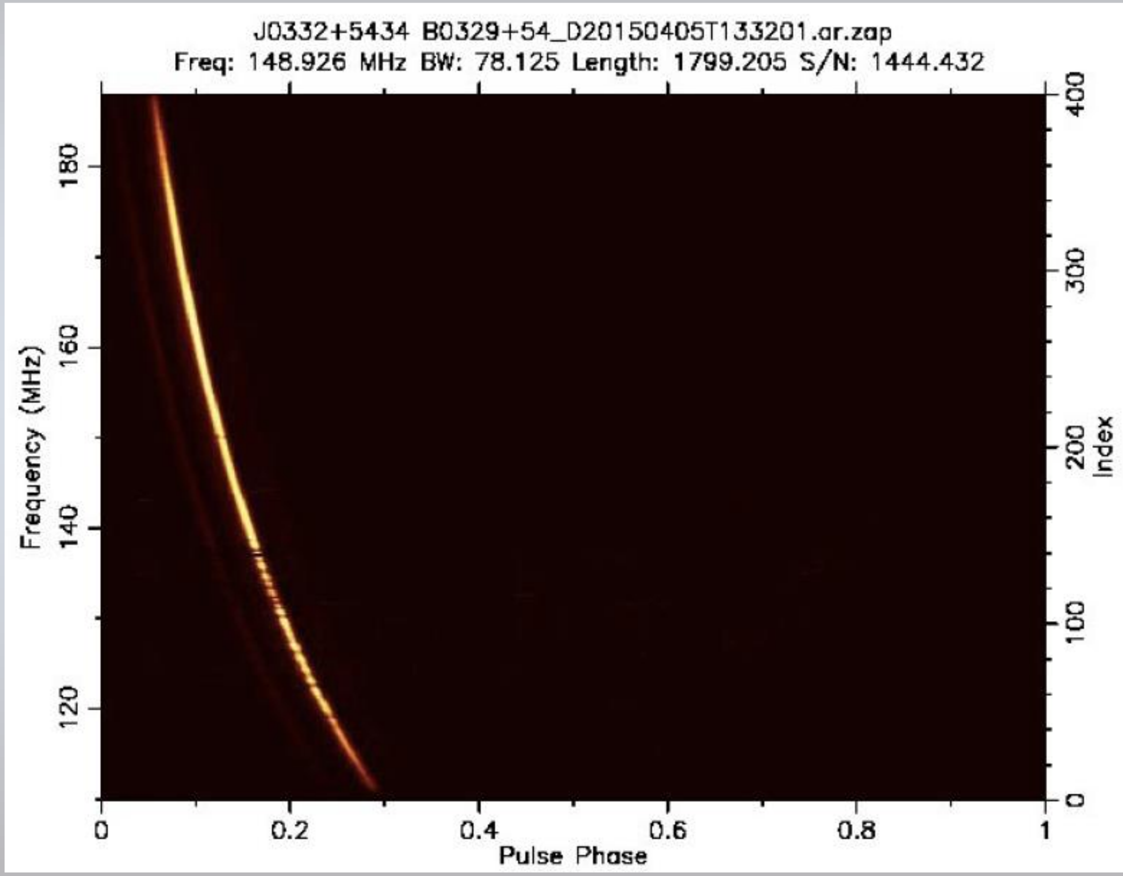
Studies of the (Ionised) Interstellar Medium (ISM):

Dispersion measure (and its variations): also important for pulsar timing

The ionized matter is a dispersive medium for radio waves. The propagation velocity will depend on frequency, because the refractive index does.

The Dispersion Measure (DM) is a column density of electrons along the LoS.

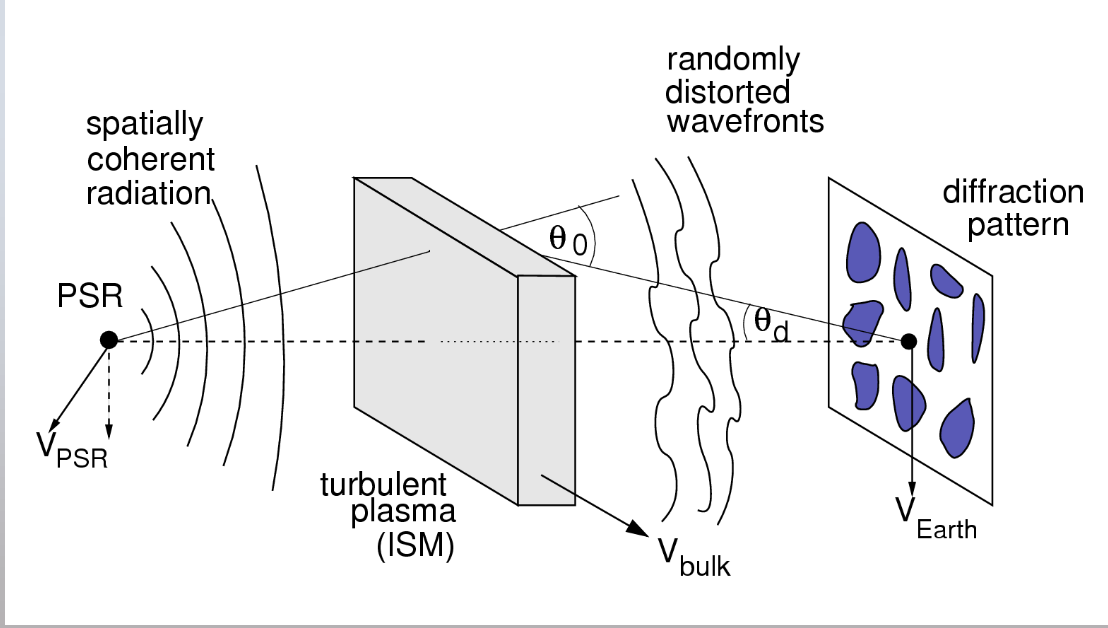
$$\mathrm{DM} = \int_0^d n_\mathrm{e}\,\mathrm{d}l$$



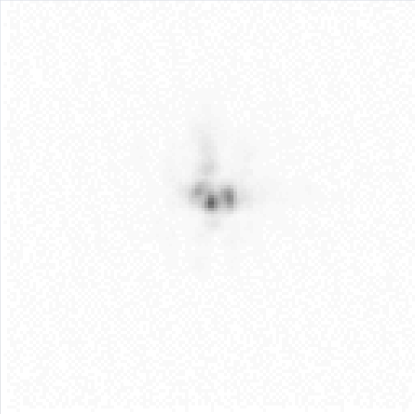
The interaction of pulsar radiation with the ionized ISM: Interstellar Scattering

The **Interstellar Medium (ISM)** is neither uniform nor isotropic.

The presence of **free electrons** cause the radio waves to **disperese**, and fluctuations in the electron density give rise to ***interstellar scattering*** and ***scintillation***.



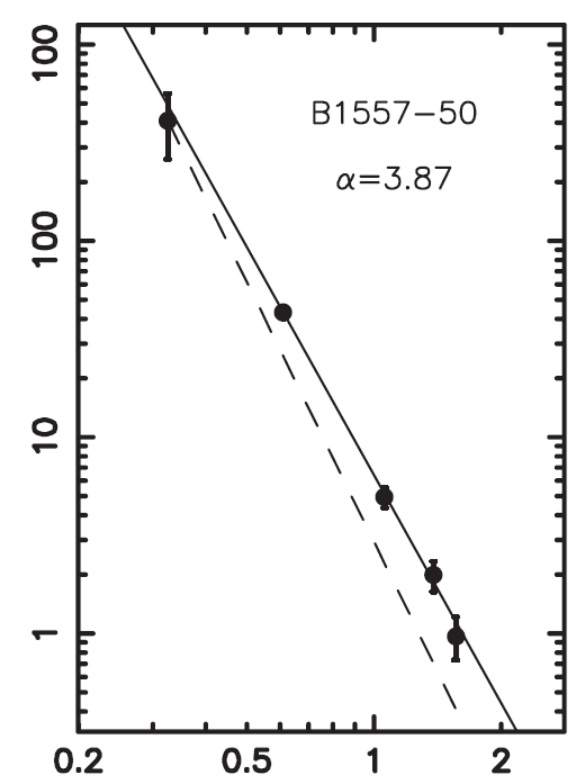
Lorimer & Kramer (2005)



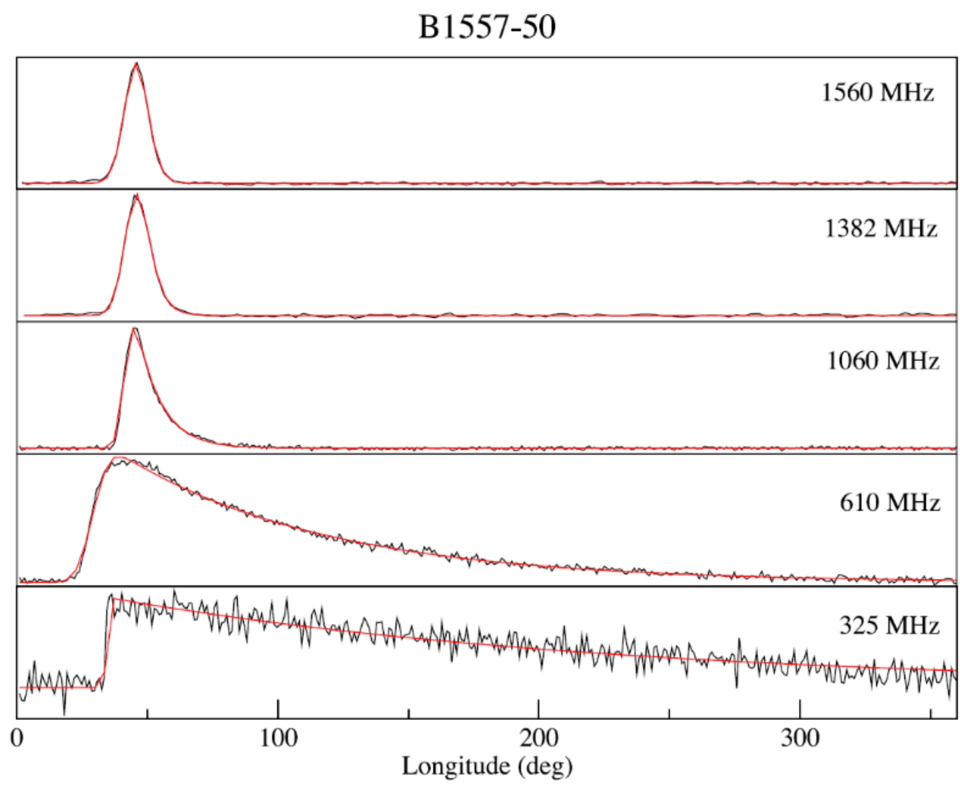
Scintillations are similar to the atmospheric seeing – only in the radio regime we do not have spatial resolution to resolve it.

Interstellar Scattering (cont.)

Scattering is frequency dependant, and is clearly more noticeable at lower frequencies. This frequency dependance gives us a way to estimate the energy spectrum of the turbulence in the ISM.



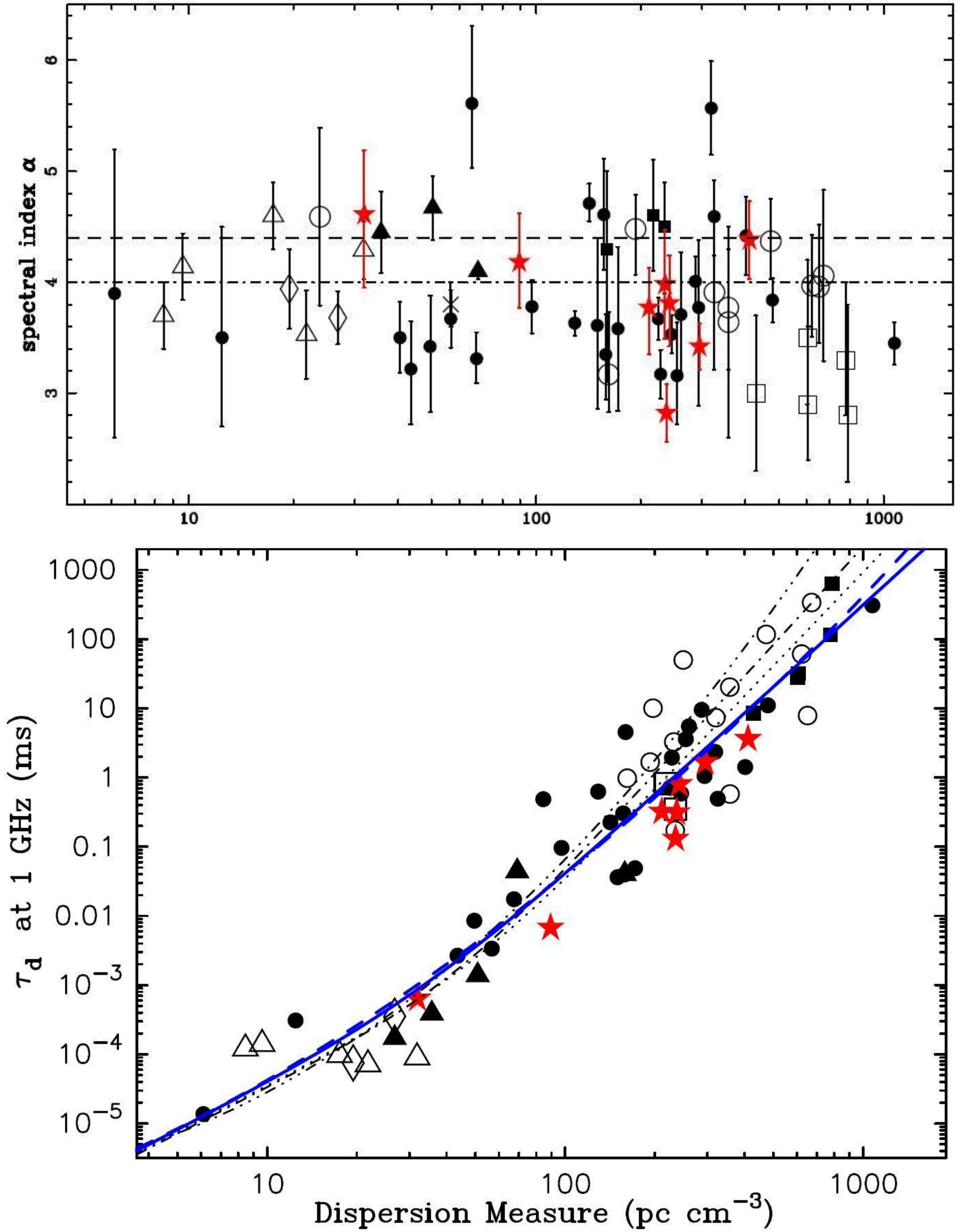
Lewandowski et al. (2013), MNRAS



$$P_{n_e}(q) = C^2_{n_e} q^{-\beta},$$

$$\beta = 2\alpha/(\alpha - 2)$$

For Kolmogorov's turbulence spectrum (**β=11/3**) the expected **α=4.4**.



Scatter time scalling for frequency and DM

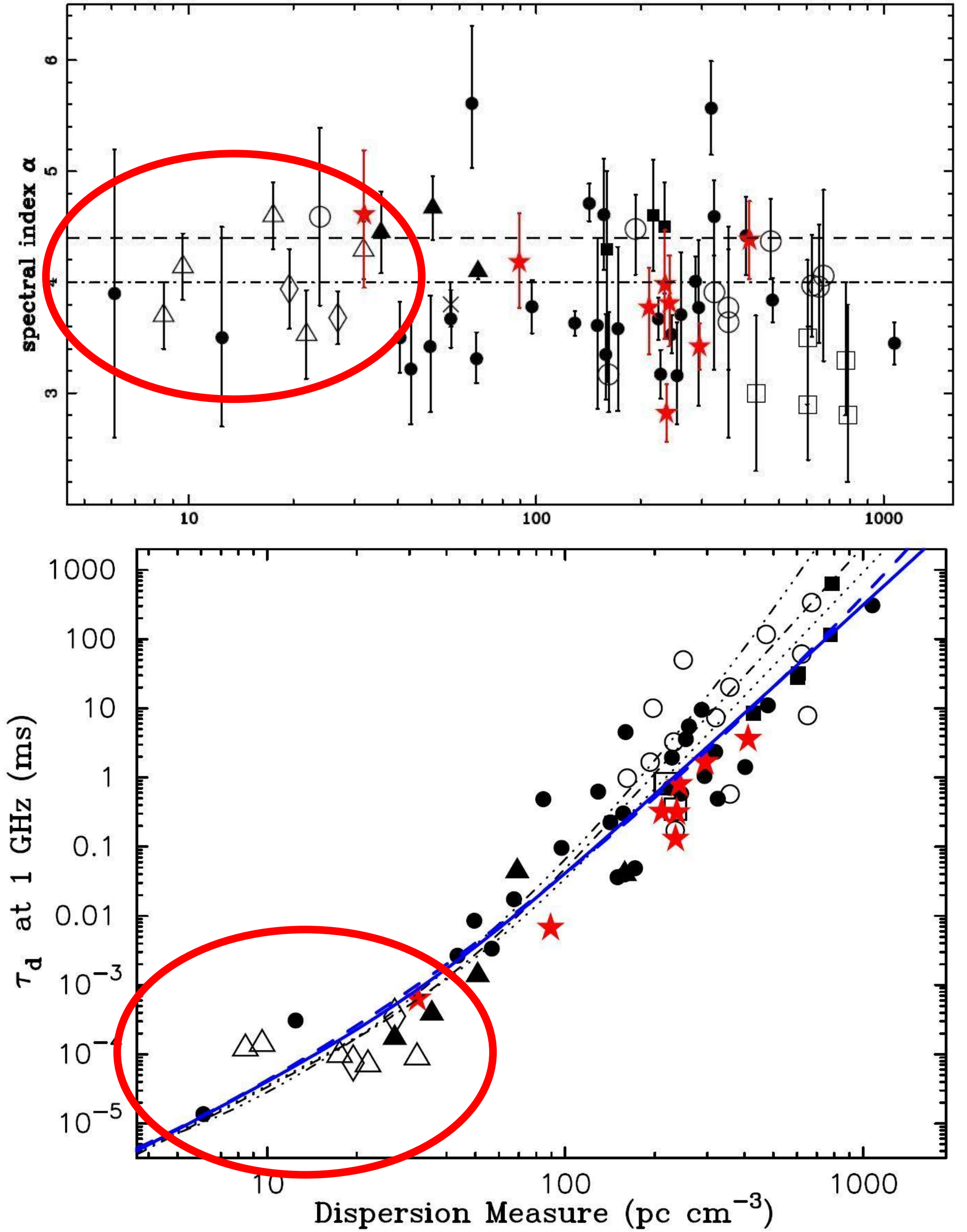
Theory predicts the values of α between **4.0** (the critical spectrum) and **4.4** (Kolmogorov's spectrum).

Most of the pulsars lie beyond this range, and lower values of α dominate!

Departures from the theoretical predictions can bee seen regardless of DM (and distance)

Non-Kolmogorov ISM turbulence?
Multiple screens?
Anisotropy?
Inner turbulence scale effects?

Lewandowski et al. 2013, 2015a,b



The scattering parameters for some of the pulsars on these plots are not from actual scattering parameters!

Low-DM pulsars only show measurable scattering at the lowest frequencies.

The values included in these plots are actually derived from scintillation observations:

$$2\pi \tau_d \Delta\nu_d = C_1,$$

And this is where LOFAR observations come in!

Lewandowski et al. 2013, 2015a,b

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PL612, Bałdy near Olsztyn (Google Maps)

Since 2018 we are observing pulsars regulary using PL611 station in Łazy (Jagiellonian University) and PL612 in Bałdy (UWM),

Utilizing most of the stand alone time (especially in PL611), 30+ hours a week, 4-5 observing sessions every month.

Data from PL612 is handled locally in Olsztyn, data from the PL611 station is transmited to Zielona Góra and the acquisition is performed by the University of Zielona Góra Computer Centre.

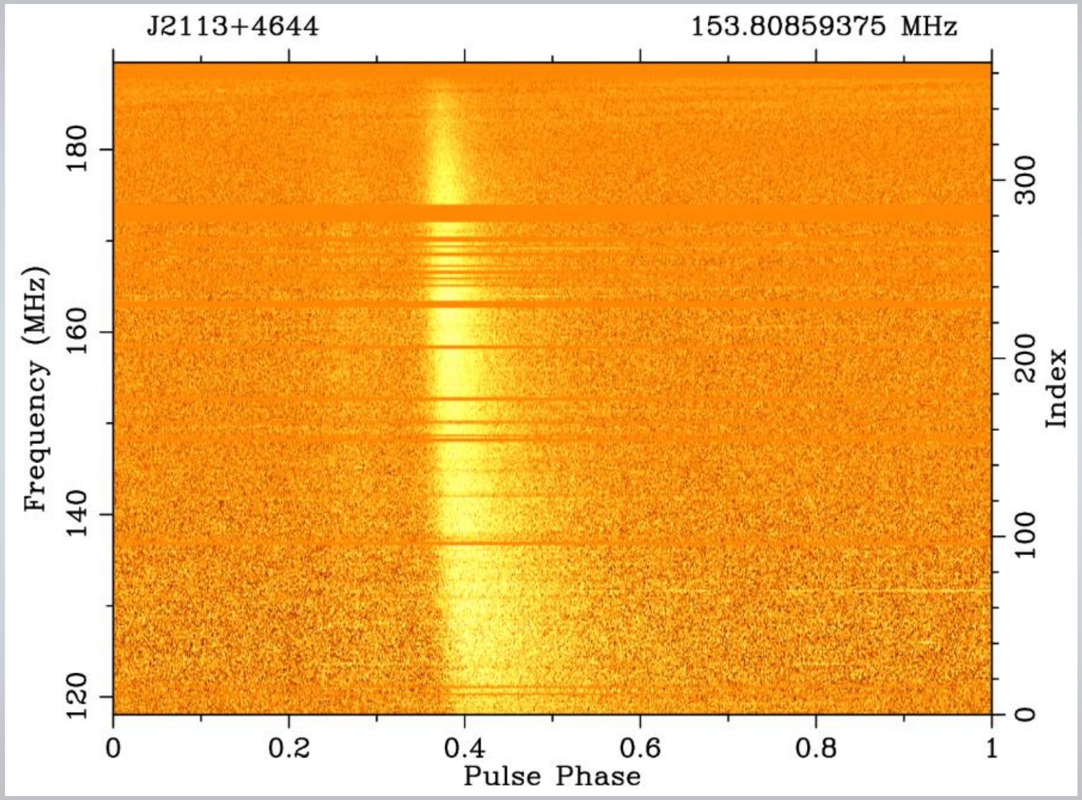
PL611, Łazy near Kraków (photo by M. Soida)

Data analysis: we are using a system similar to the one used for pulsar observations by the members of the german GLOW consortium: the setup of the system was assisted by the *University of Bielefeld* pulsar group (S. Oslowski).

Coherent dedispersion is performed with **DSPSR** package (van Straten & Bailes, 2011).

Further preliminary analysis using **PSRCHIVE** (Hotan et al., 2004).

Scattering measurements performed using the method (and modified codes) from **Geyer and Karastergiou (2016),** also used for LOFAR Core scattering analysis (Geyer et al. 2017)



Exam[ple observation of a highly scattered pulsar with the PL611 station from 2022. Note the width of the profile change across the band!

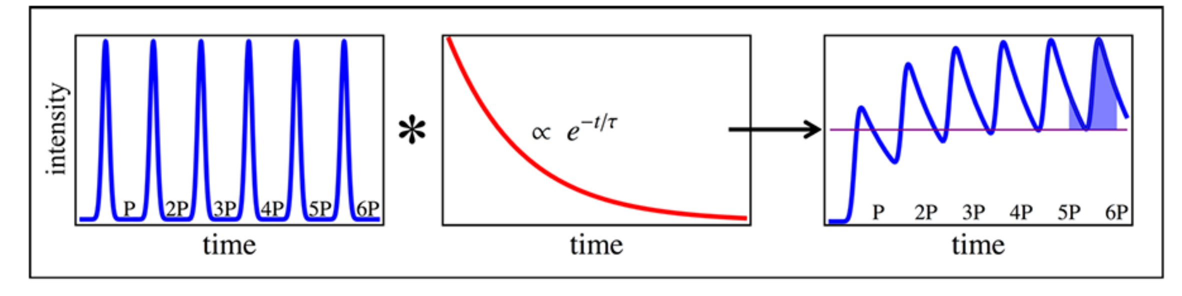
The scatter time estimation:

The observed pulse shape is a convolution of the intrinsic pulse profile, the ISM response function (Pulse Broadening Function, PBF), the dispersion smearing (if present, relevant if not using coherent dedispersion) and the instrumental effects.

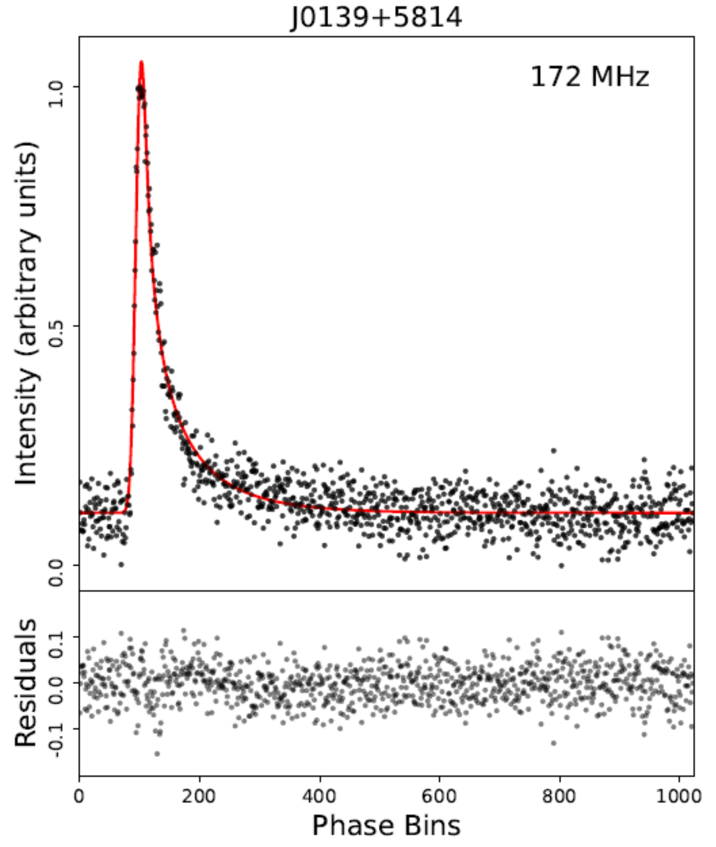
$$P^{\mathrm{O}}(t) = P^{\mathrm{I}}(t) * s(t) * d(t) * i(t),$$

The intrinsic profile shape is usually assumed to be gaussian-like, or a sum of gaussians.

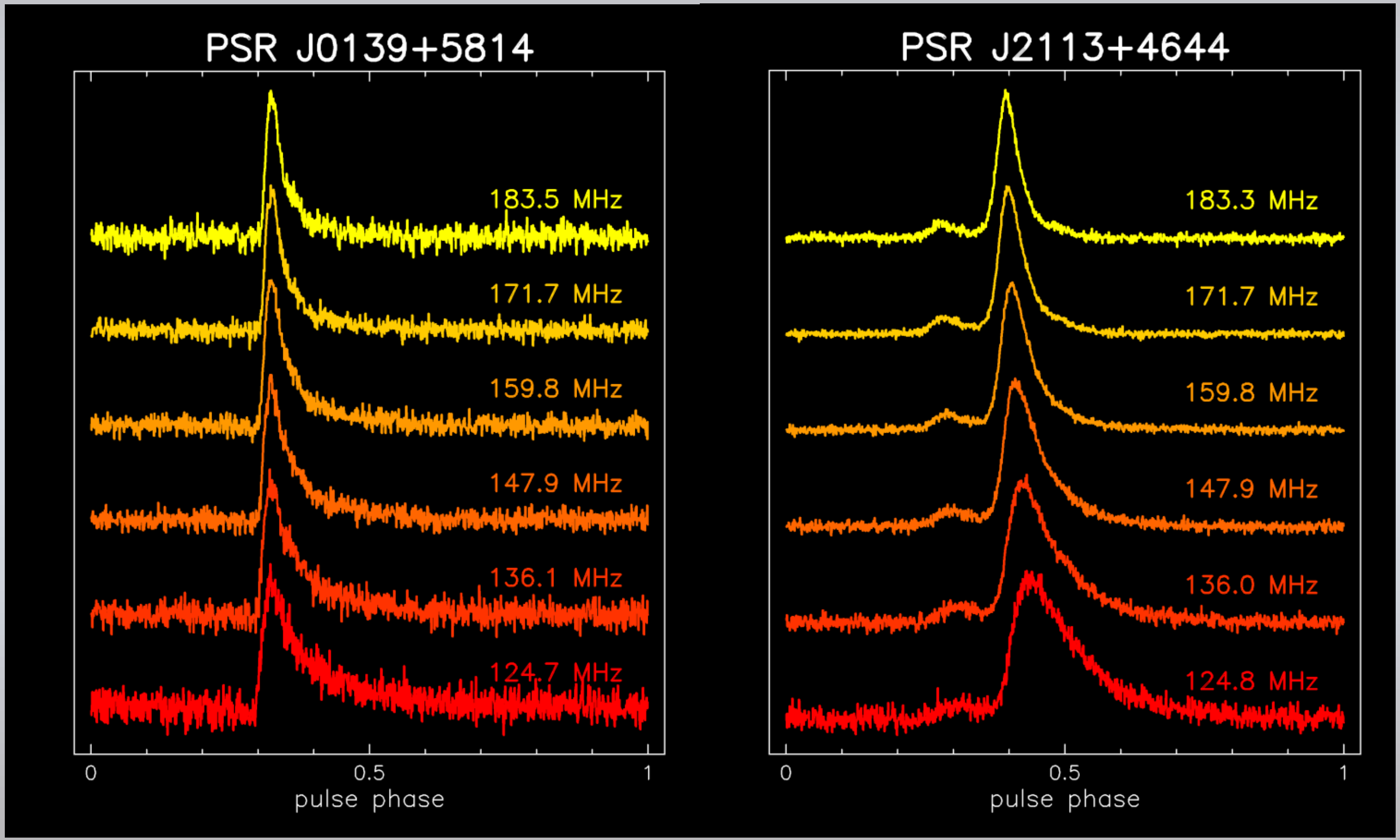
The PBF function depends on the scattering model used (thin screen, thick streen, extended screen, anisotropy)



The pulse train method (Geyer and Karastergiou (2016),



Main advantage of using LOFAR: for a large number of low- to mid-DM pulsars one can see significant change in scattering across the LOFAR bandwidth.
This allows for a direct measurement of the scatter time frequency slope α (linked to the turbulence characteristics of ISM) from a single observation.



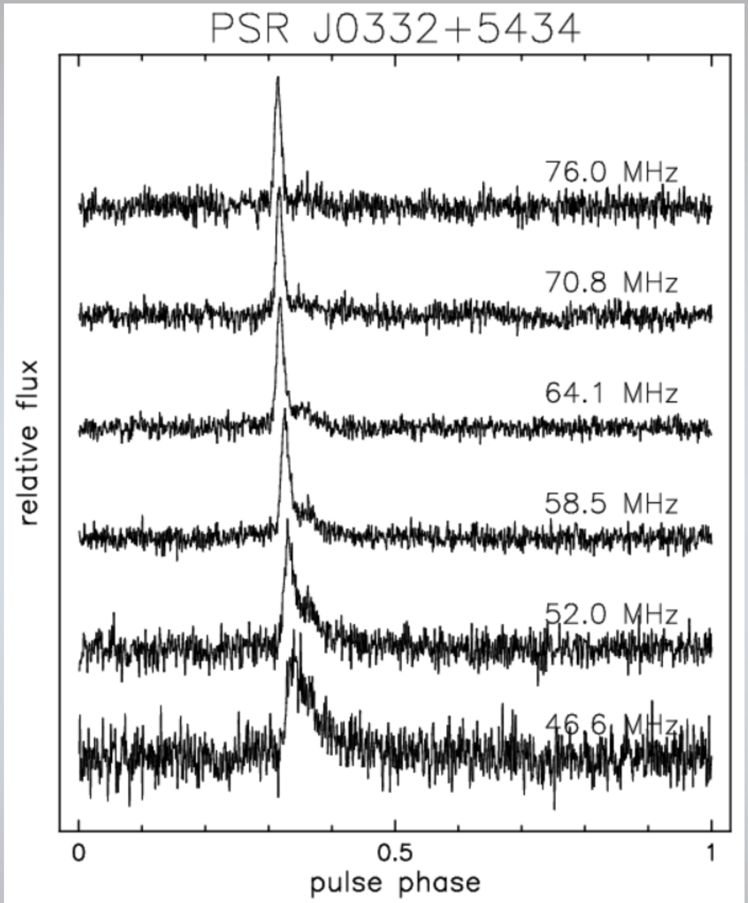
Scattered pulse profiles from the PL-612 station in Bałdy near Olsztyn, (120 minutes)
In collaboration with L. Błaszkiewicz, T. Sidorowicz, A. Krankowski (UWM)

HBA observations, 3-4 Times per month, every pulsar observed at least once a month:

- 30+ pulsars on the list, 3-hour long integrations
- Utilizimg 3 (out of 4) data lanes
- Central frequency of 154 MHz
- 8 bit sampling: **72 MHz bandwidth (118-190 MHz)**

LBA observations, one LBA session per month:

- 10 pulsars, 3h integrations
- 3 data lanes,
- 16bit sampling,
- **36 MHz bandwidth (44-80 MHz)**
- Data analysis (and especially coherent dedispersion) is extremely time consuming



LBA pulsar observation from the PL611 station

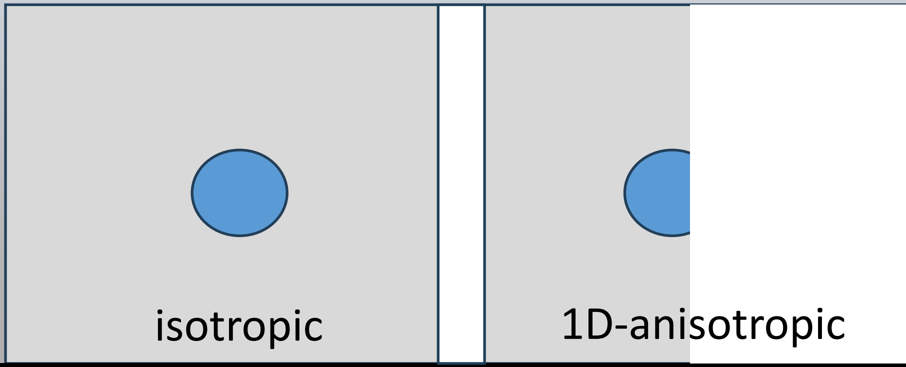
The results: average τ_{150} and α values

pulsar	DM ($pc\ cm^{-3}$)	P(ms)	isotropic		anisotropic	
			α	$\tau_{150}(ms)$	α	$\tau_{150}(ms)$
J0139+5814	73.81	272.45	4.88 ± 0.99	115.94 ± 23.69	2.97 ± 0.44	46.19 ± 6.87
J0358+5413	57.14	156.38	1.70 ± 0.28	35.84 ± 0.76	1.35 ± 0.16	19.62 ± 0.73
J0525+1115	79.42	354.44	4.45 ± 0.75	124.45 ± 43.03	2.92 ± 0.82	58.45 ± 10.39
J0614+2229	96.91	334.96	3.87 ± 0.70	133.84 ± 23.82	1.92 ± 0.58	37.62 ± 3.73
J1543+0929	34.98	748.45	1.98 ± 0.31	8.93 ± 0.44	1.26 ± 0.37	13.06 ± 1.63
J1645-0317	35.76	387.69	1.10 ± 0.12	1.29 ± 0.09	1.25 ± 0.19	1.88 ± 0.22
J1913-0440	89.39	825.94	4.26 ± 0.41	19.38 ± 1.32	3.50 ± 0.31	10.70 ± 0.53
J1917+1353	94.54	194.63	4.18 ± 0.81	97.05 ± 16.11	3.88 ± 1.04	50.89 ± 6.48
J2113+4644	141.26	1014.68	3.69 ± 0.16	50.77 ± 0.96	4.38 ± 0.23	103.01 ± 5.05
J2139+2242	44.16	1083.51	2.55 ± 0.64	29.11 ± 3.71	1.72 ± 0.34	22.26 ± 1.53

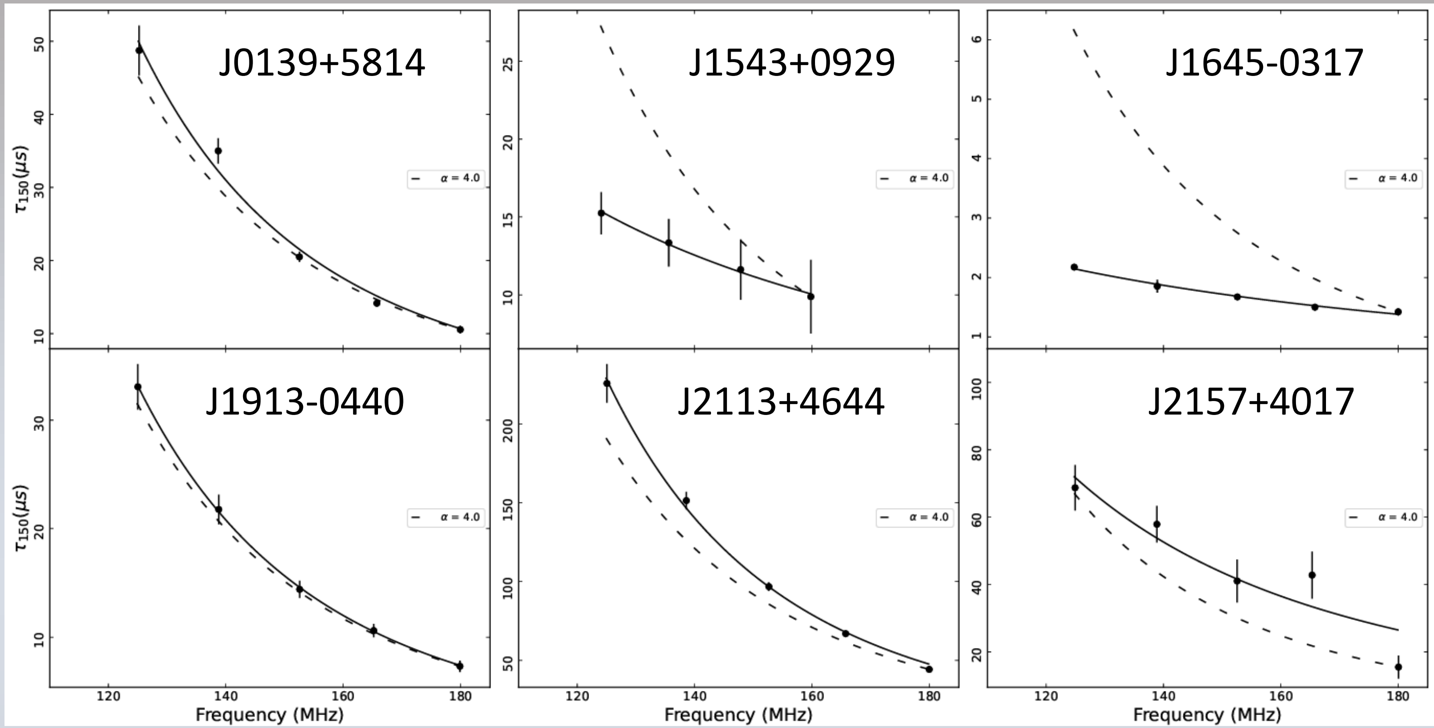
The isotropic model is the typical thin screen PBF with exponentially decaying tail.

The anisotropic model is the 1D truncated screen model.

Pulsar angular broadening such causes such anisotropy to affect the PBF and the observed pulse shape.



Scatter time vs frequency plots for 6 pulsars from our sample: individual observations with the frequency scaling index α closest to the average value

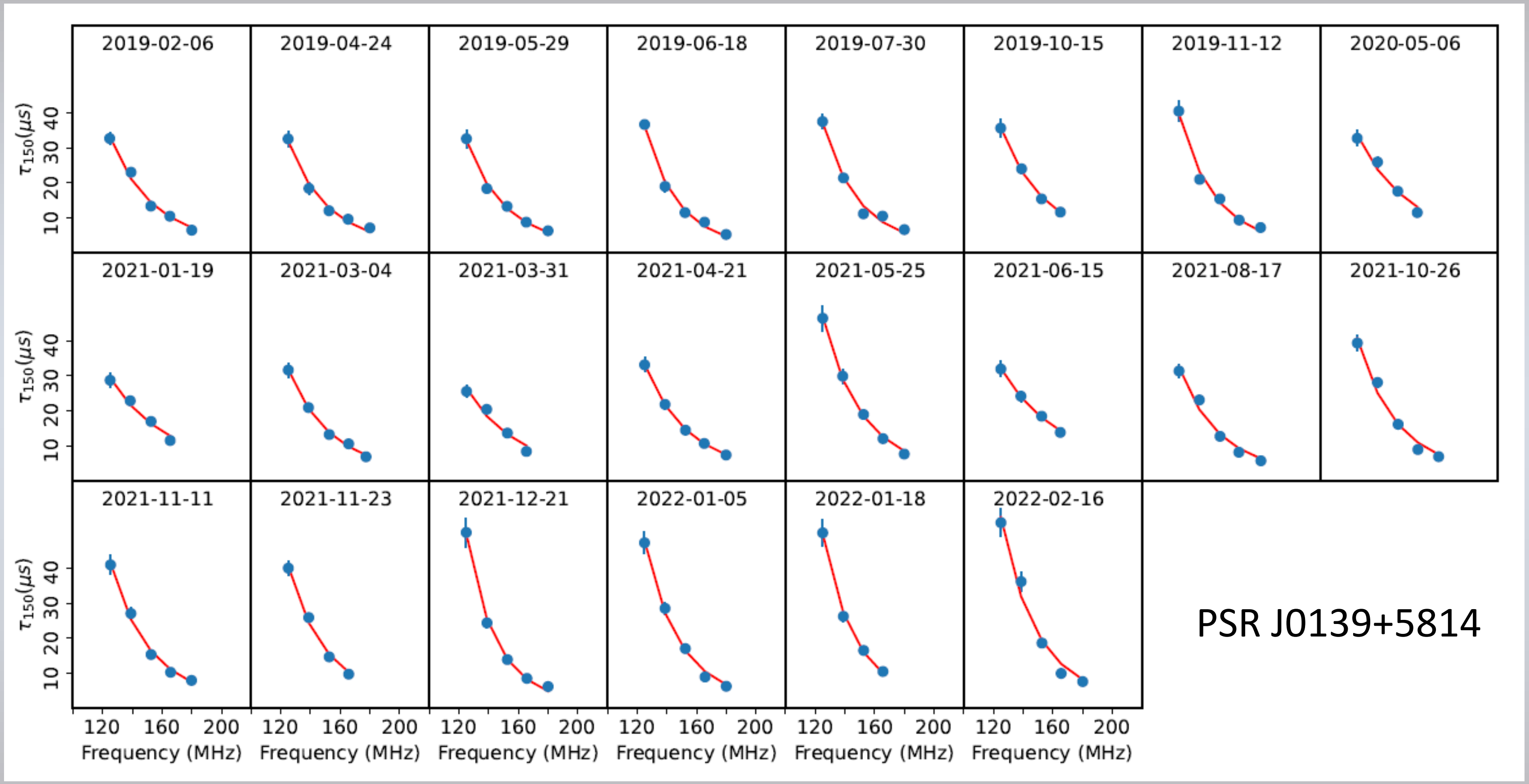


The dashed line represents the trend expected by the thin screen model with Kolmogorov turbulence (α= 4.4).

Note some missing data points: 6 subbands were usually used, with some lost due to RFI lowering the S/N in the affected subbands.

The $\boldsymbol{\tau_{150}}$ value is interpolated from the fitted model.

Each of our pulsars was observed roughly once every month since early 2019 – we have collected up to 40+ epochs for most of them.



This allows ust to study time variation of the scattering parameters (τ_{150} and α) , as well as the Dispersion Measure over the period of 4 years.

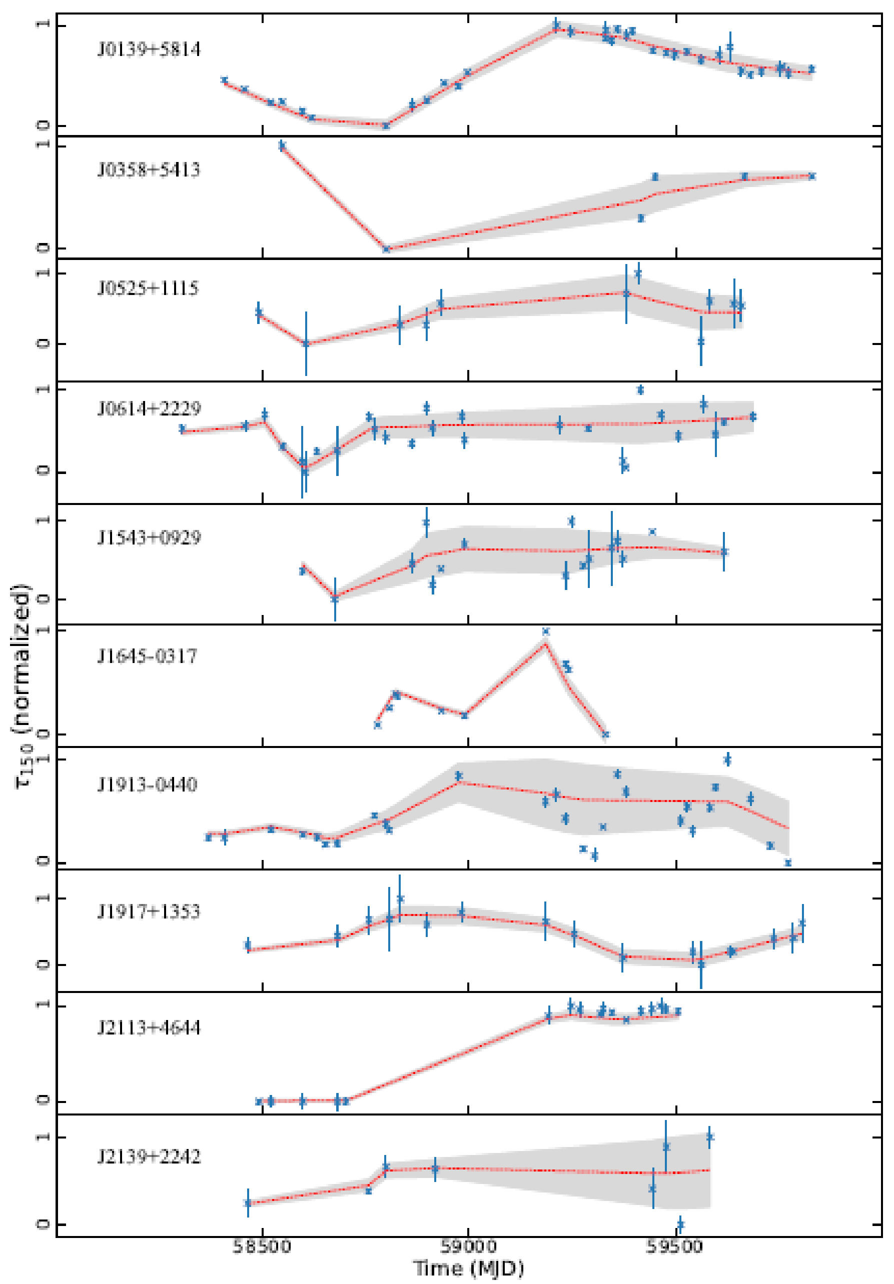
Variations of the scatter time for selected pulsars from our observing sample

In most of the cases the variations are statisticaly significant.

The grey envelopes show the confidence levels of the models fitted

Several deep learning methods to estimate the model confidence were used, with the Gaussian Processes (GP) and Random Forrest (RF) methods usually overfitting the model.

The Neural Networks method seems to work the best with our datasets.

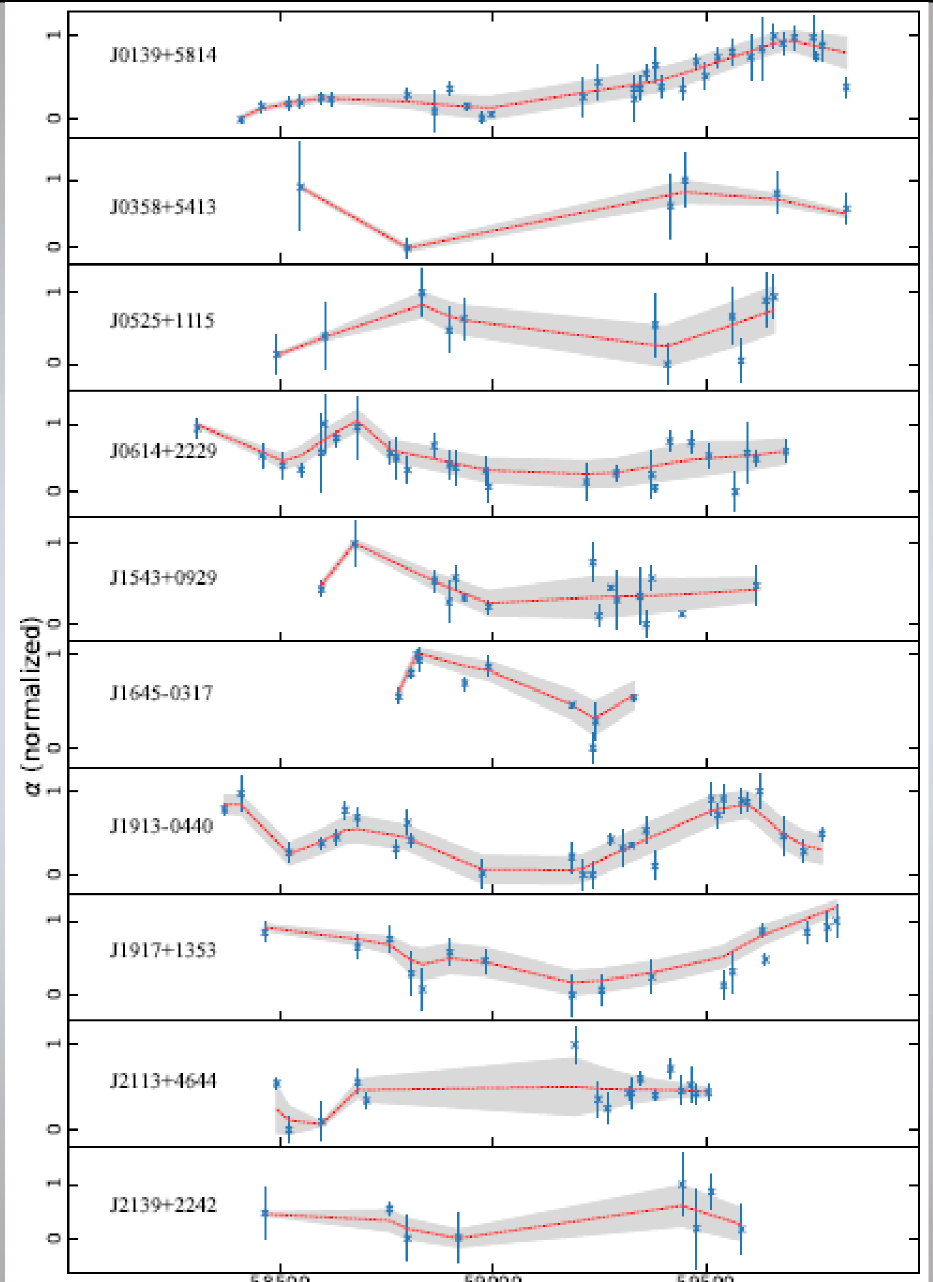


Similar plots for the frequency scaling index α.

The data is less conclusive due to relatively larger errorbars for α estimates.

Both the variations in the scatter time an the changes in the frequency slope of scattering give us an insight into the **anisotropy and inhomogeneity properties of ISM.**

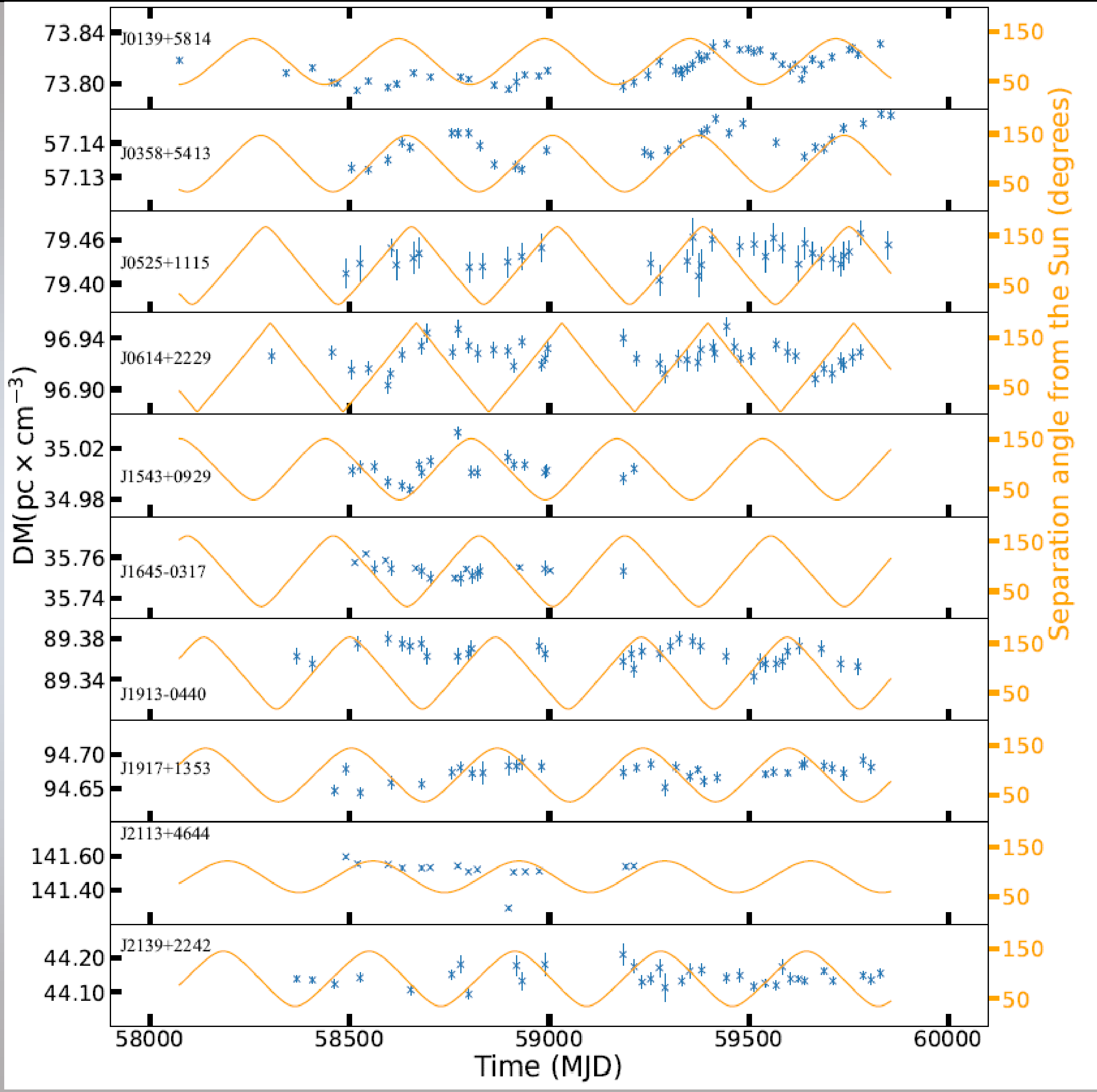
Characteristic timescales of the variations can be (through the pulsar proper motion) translated into spatial scales of the inhomogeneity of turbulence in the ISM.



Using our observations we can also estimate the **variations in the pulsar dispersion measures (DM)**

Plots show a few examples of DM variations over the period of a few years.

These do not seem to be caused by the inter-planetary medium or solar wind: none of these pulsars come closer than 25 degrees from the Sun.



Summary

- Individual LOFAR stations can be very useful tools for the ISM studies. Our results are amongst the first of its kind.
- The unique advantage of such projects is the ability for long-term monitoring (4 years and beyond).
- The observed variability of the scattering parameters is significant and can be used to estimate the anisotropy and inhomogeneity of the turbulence in the ISM.
- Long term DM variation studies can help with that regard as well.
- We intend to continue the monitoring of approx. 20 sources

Thanks for your attention!