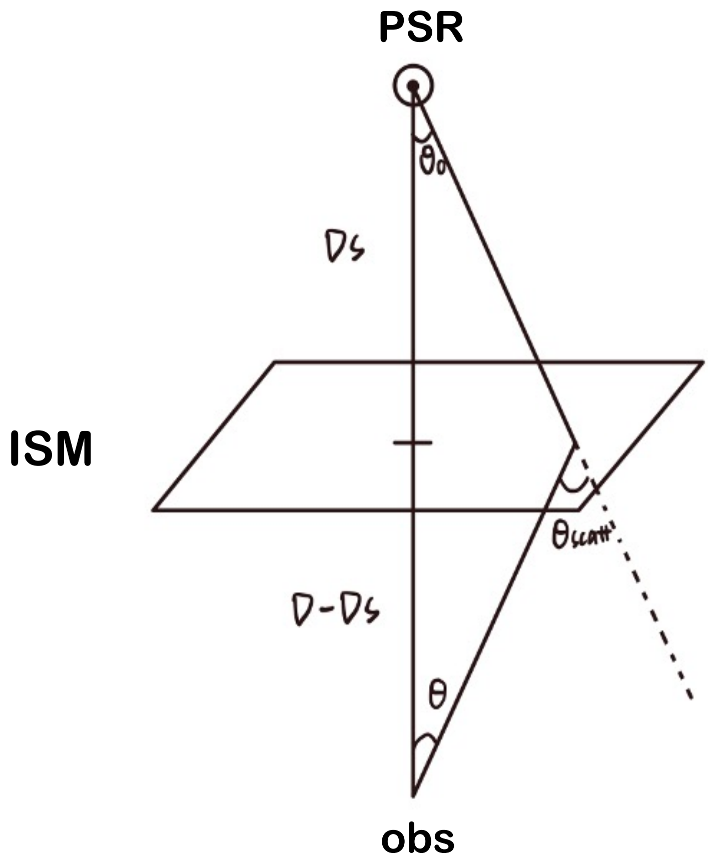
The Galactic distribution of pulsar scattering and the $\tau - \text{DM}$ relation

Speaker: Qiuyi He (YNU)
Supervisor: Prof. Xun Shi

He Q., Shi X., 2024, MNRAS, 527, 5183
He Q., Shi X., in preparation

CONTENT

1. Introduction



pulsar flux density → fluctuations (minutes to months)

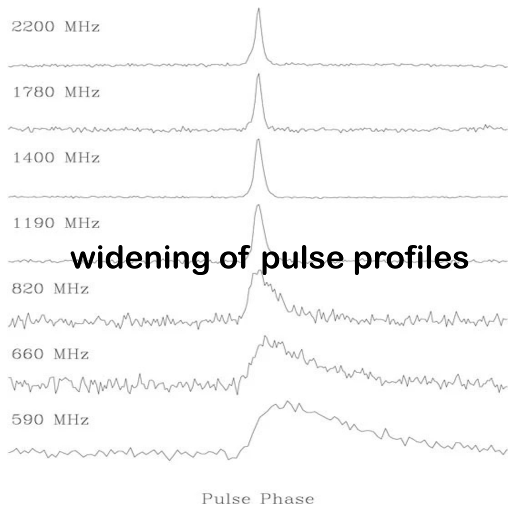
WHY?

↓

scattering effect

scattering within the ISM ↓

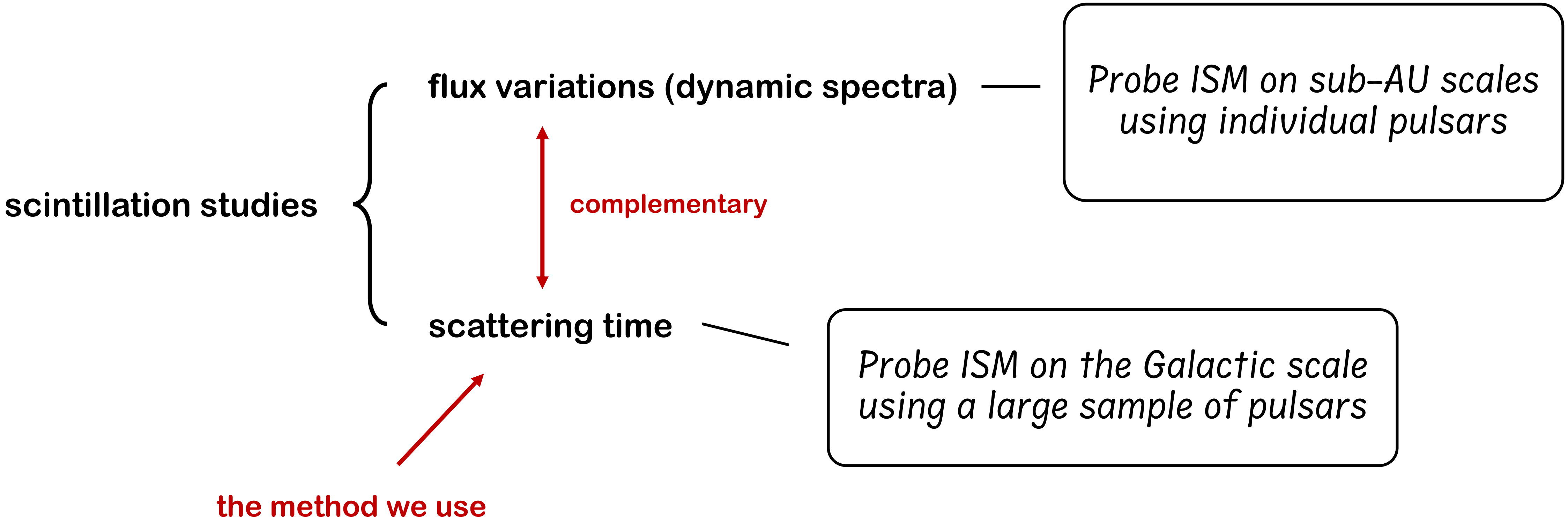
broadening effect



pulse profile $\mathbf{PBF}(t) \sim \mathbf{exp}(-t/\tau)$

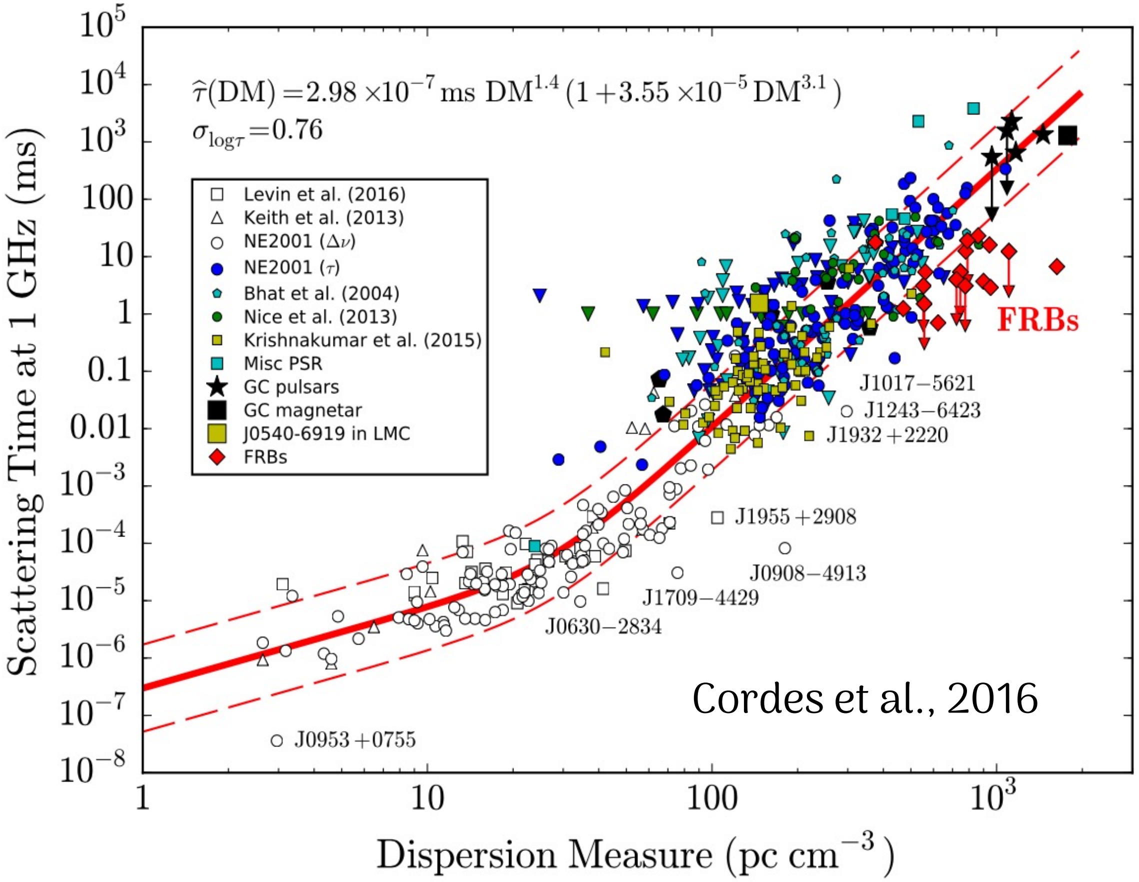
pulse spreading time

1. Introduction

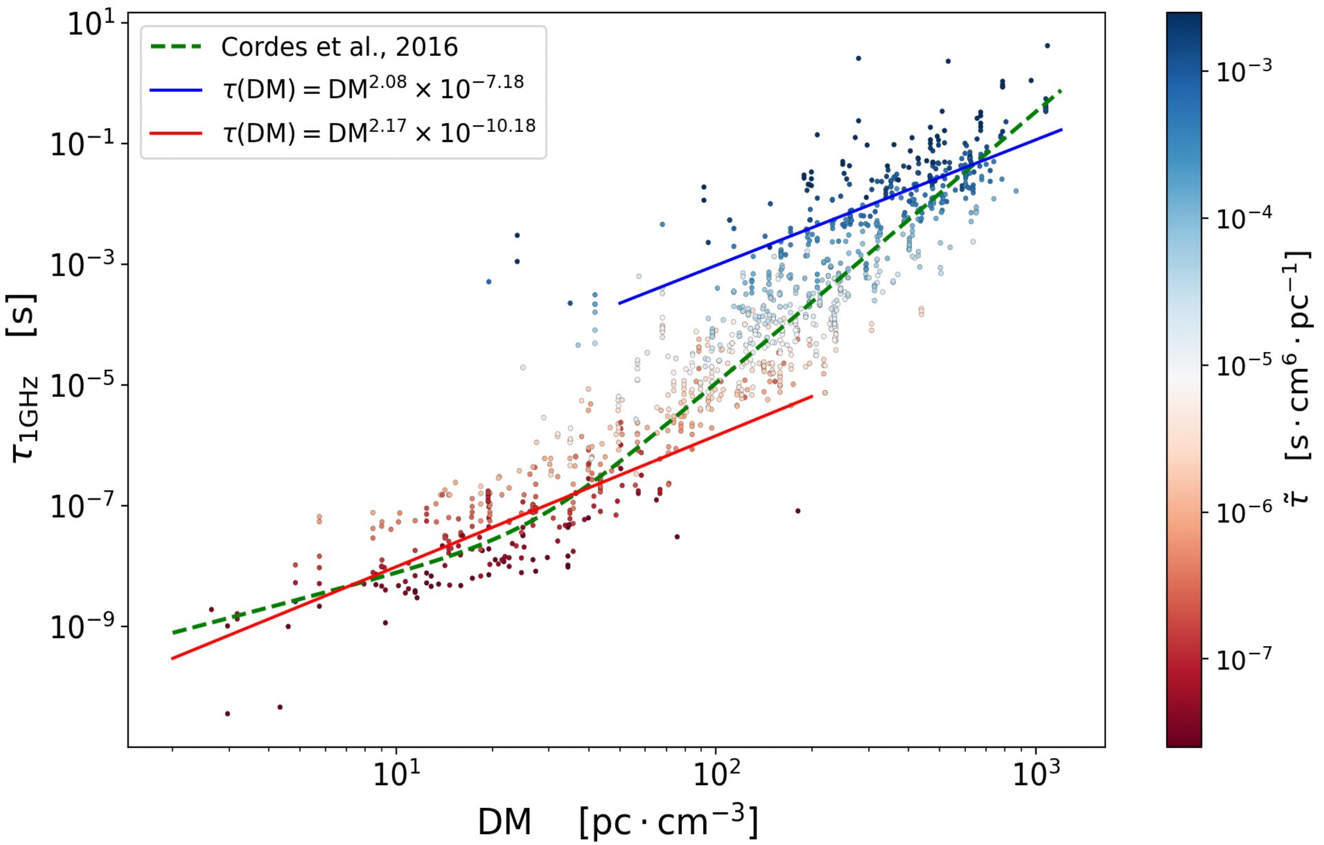


1. Introduction

Unified τ-DM relation → **2-population picture**



Sutton 1971; Ramachandran et al. 1997; Bhat et al. 2004; Krishnakumar et al. 2015; Cordes et al. 2016 …



Our results

2. Data collection

Our data is published on the CDS website.
https://cdsarc.cds.unistra.fr/viz-bin/cat/J/MNRAS/527/5183

New catalog of τ

BNAME	JNAME	l	b	d	Z	X	Y	DM	f	tau	Reference	parallax
B0011+47	J0014+4746	116.497	-14.631	1.776	-0.449	1.538	9.267	30.405	111.0	0.004	1	no
J0023+0923	J0023+0923	111.383	-52.849	1.111	-0.886	0.625	8.745	14.3	1500.0	6.2e-09	2	no
J0026+6320	J0026+6320	120.176	0.593	6.619	0.069	5.722	11.827	245.06	325.0	0.0476	3	no
J0026+6320	J0026+6320	120.176	0.593	6.619	0.069	5.722	11.827	245.06	610.0	0.0075	3	no
J0030+0451	J0030+0451	113.141	-57.611	0.303	-0.25	0.149	8.364	4.332772	440.0	1.236e-09	4	yes
J0034-0534	J0034-0534	111.492	-68.069	1.348	-1.25	0.468	8.684	13.765	111.0	0.001	1	no
B0031-07	J0034-0721	110.42	-69.815	1.075	-1.003	0.348	8.429	10.922	44.0	0.003	1	yes
B0031-07	J0034-0721	110.42	-69.815	1.075	-1.003	0.348	8.429	10.922	1000.0	4.229e-09	5	yes
B0037+56	J0040+5716	121.452	-5.567	9.804	-0.945	8.324	13.391	92.5146	150.0	0.04	47	yes
B0037+56	J0040+5716	121.452	-5.567	9.804	-0.945	8.324	13.391	92.5146	200.0	0.017	54	yes
B0045+33	J0048+3412	122.255	-28.666	4.5	-2.159	3.339	10.607	39.922	111.0	0.003	1	no
B0052+51	J0055+5117	123.621	-11.576	2.857	-0.567	2.331	9.85	44.013	111.0	0.007	1	yes
...	...	...	...	...	...	...	...	...	...	...	...	...

- ATNF ++
- Frequency information

54 papers

473 pulsars

1110 τ values

single frequency: 224 pulsars

multi-frequency: 229 pulsars

2. Data and method

$$\mathbf{DM} \propto \int_0^D n_e \, dl = \langle n_e \rangle D$$

$$\tau \propto \int_0^D (n_e^2 - \overline{n_e}^2) \, dl = \langle \Delta n_e^2 \rangle D$$

↓

$$\tilde{\tau} = \frac{\tau \cdot D}{\mathbf{DM}^2} \sim \frac{\langle \Delta n_e^2 \rangle}{\langle n_e \rangle^2}$$

reduced scattering strength

No apparent dependence on D or $\langle n_e \rangle$

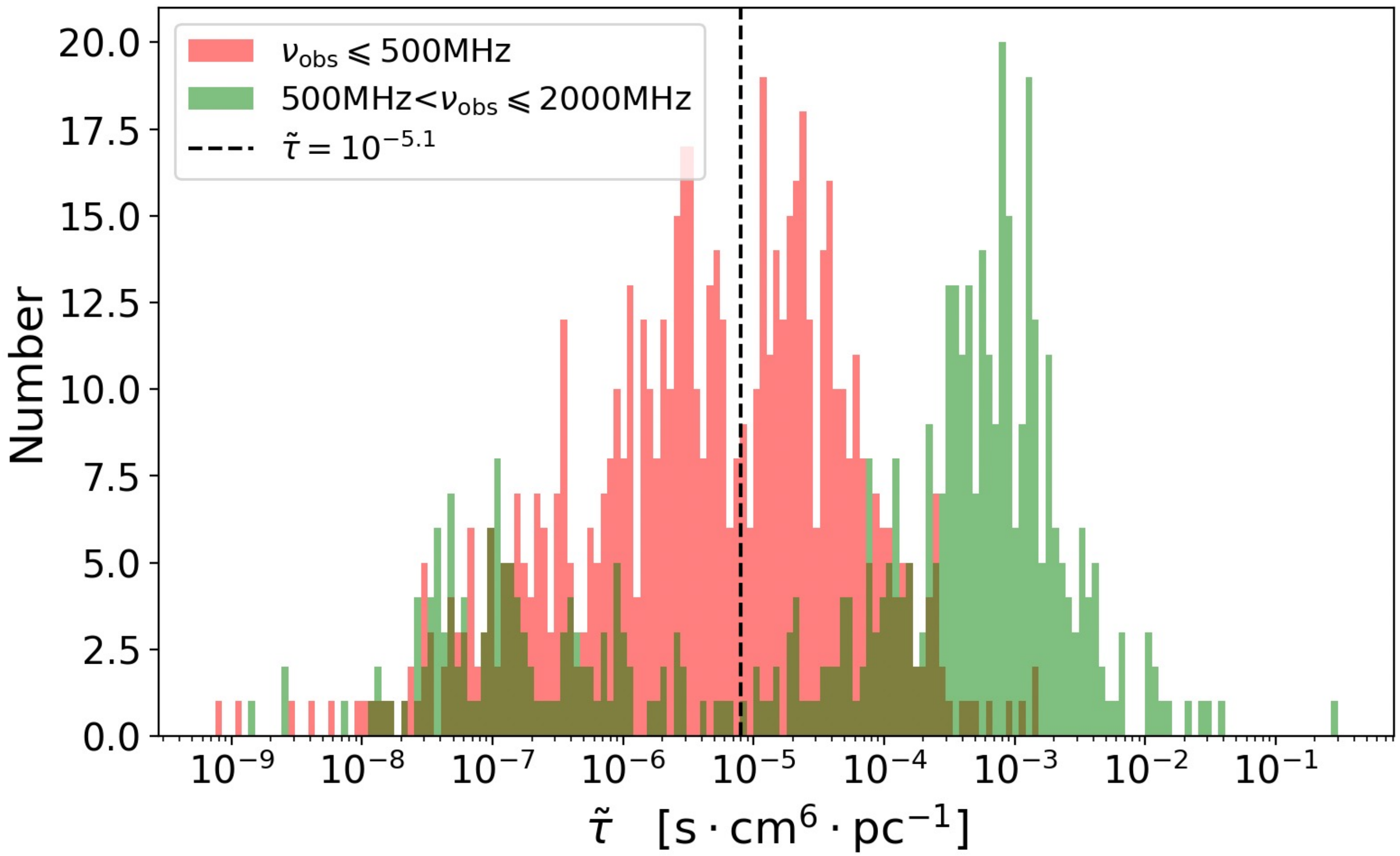
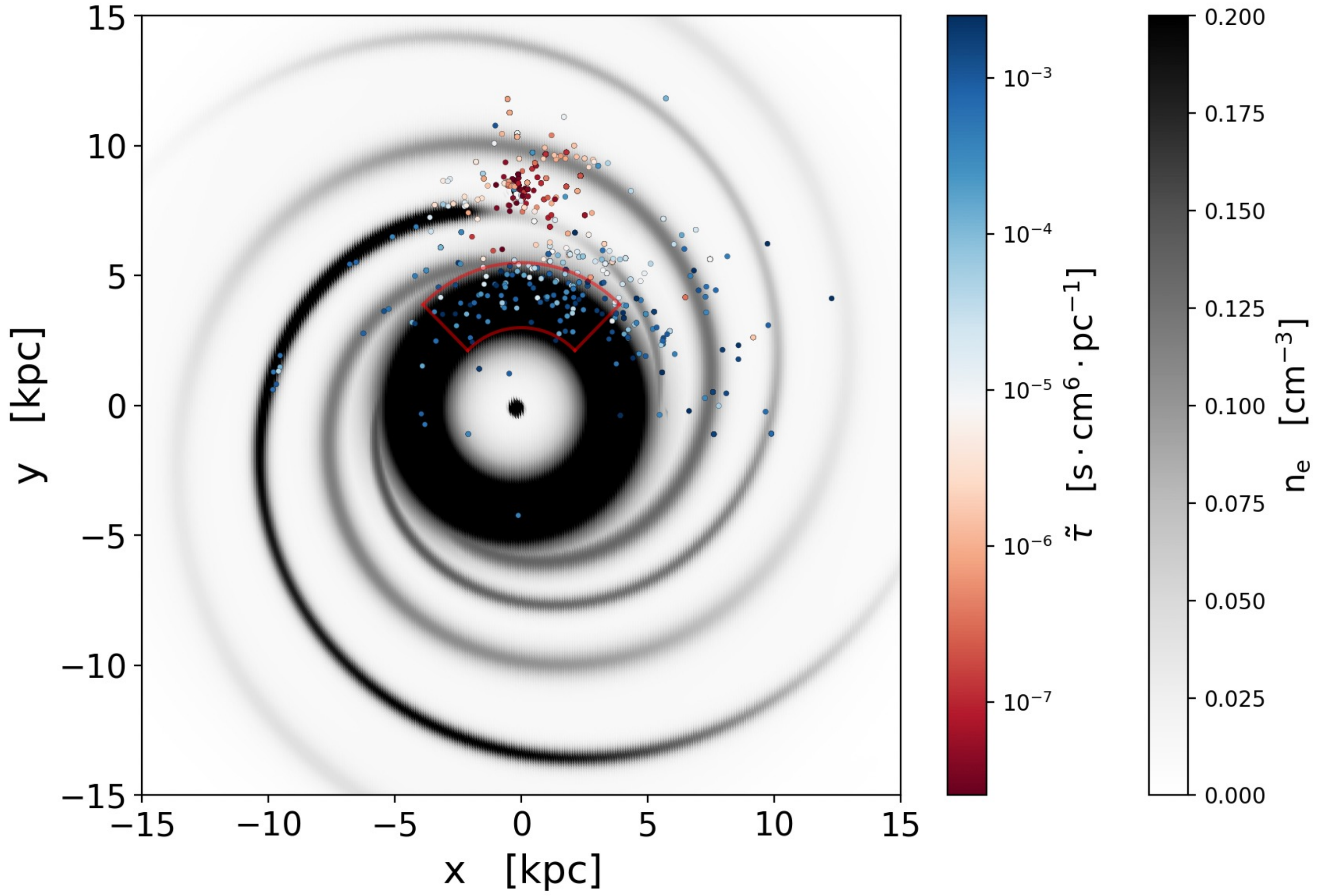


Figure 1. Distribution of the sample over the reduced scattering intensity $\tilde{\tau}$. For both low and high-frequency observations, the number of measurements around $\tilde{\tau} = 10^{-5.1}$ s cm^6 pc^{-1} is relatively small, leading to a bimodal distribution of $\tilde{\tau}$.

3. Results

3.1 τ-DM relation



reduced scattering strength

$$\tilde{\tau} = \frac{\tau \cdot D}{\mathrm{DM}^2} \sim \frac{\langle \Delta n_e^2 \rangle}{\langle n_e \rangle^2}$$

Inner (blue pulsar) — larger $\tilde{\tau}$

Local (red pulsar) — smaller $\tilde{\tau}$

Figure 2. The Galactic distribution of low galactic latitude pulsars (the vertical distance to the plane of the galaxy is less than 0.4 kpc) color-coded by their reduced scattering strength $\tilde{\tau}$ superimposed on the mid-plane Galactic electron density distribution given by the YMW16 model. The two peaks in the value of $\tilde{\tau}$ (Fig. 1) are clearly dominated by two pulsar populations.

3. Results

3.1 τ-DM relation

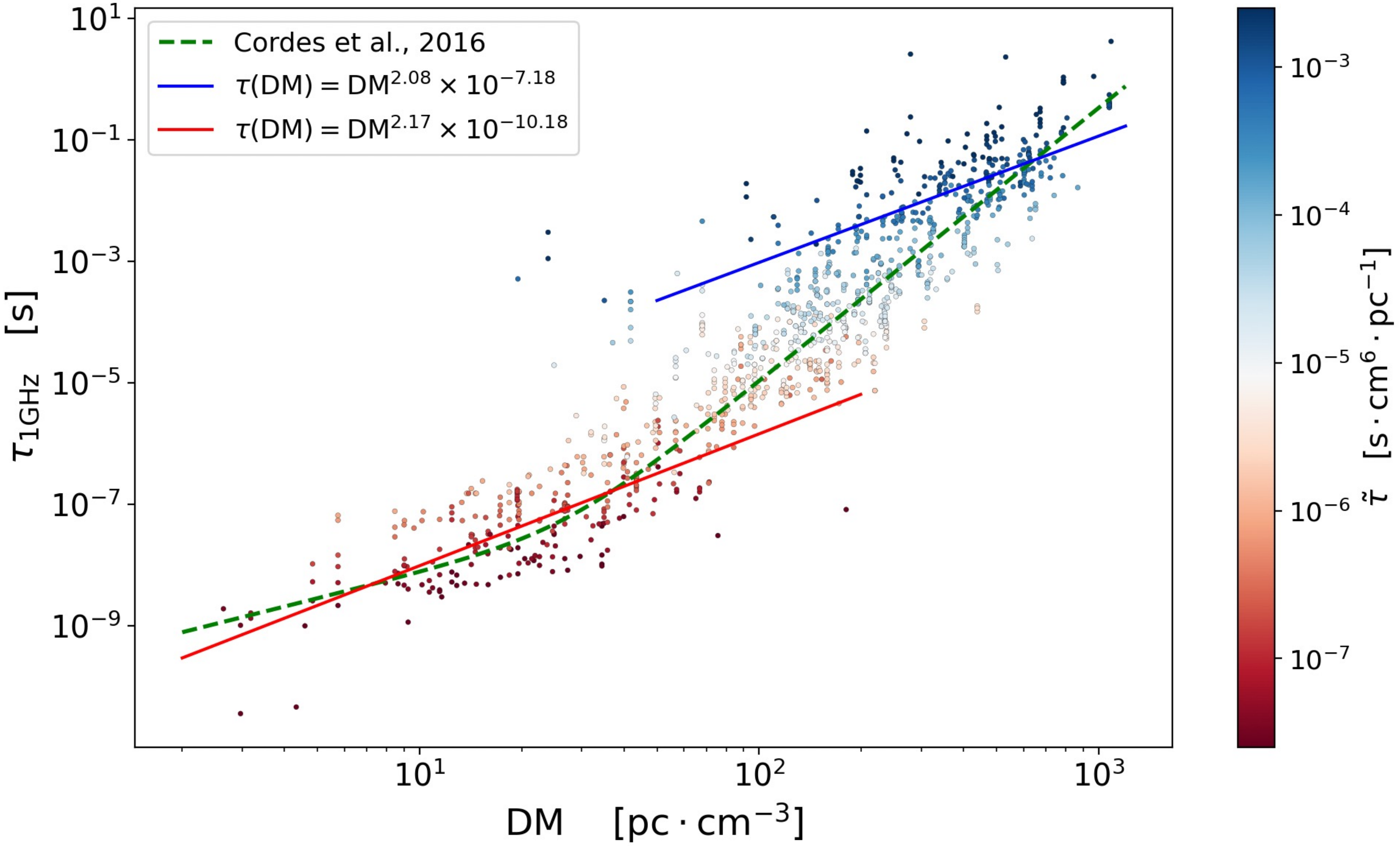
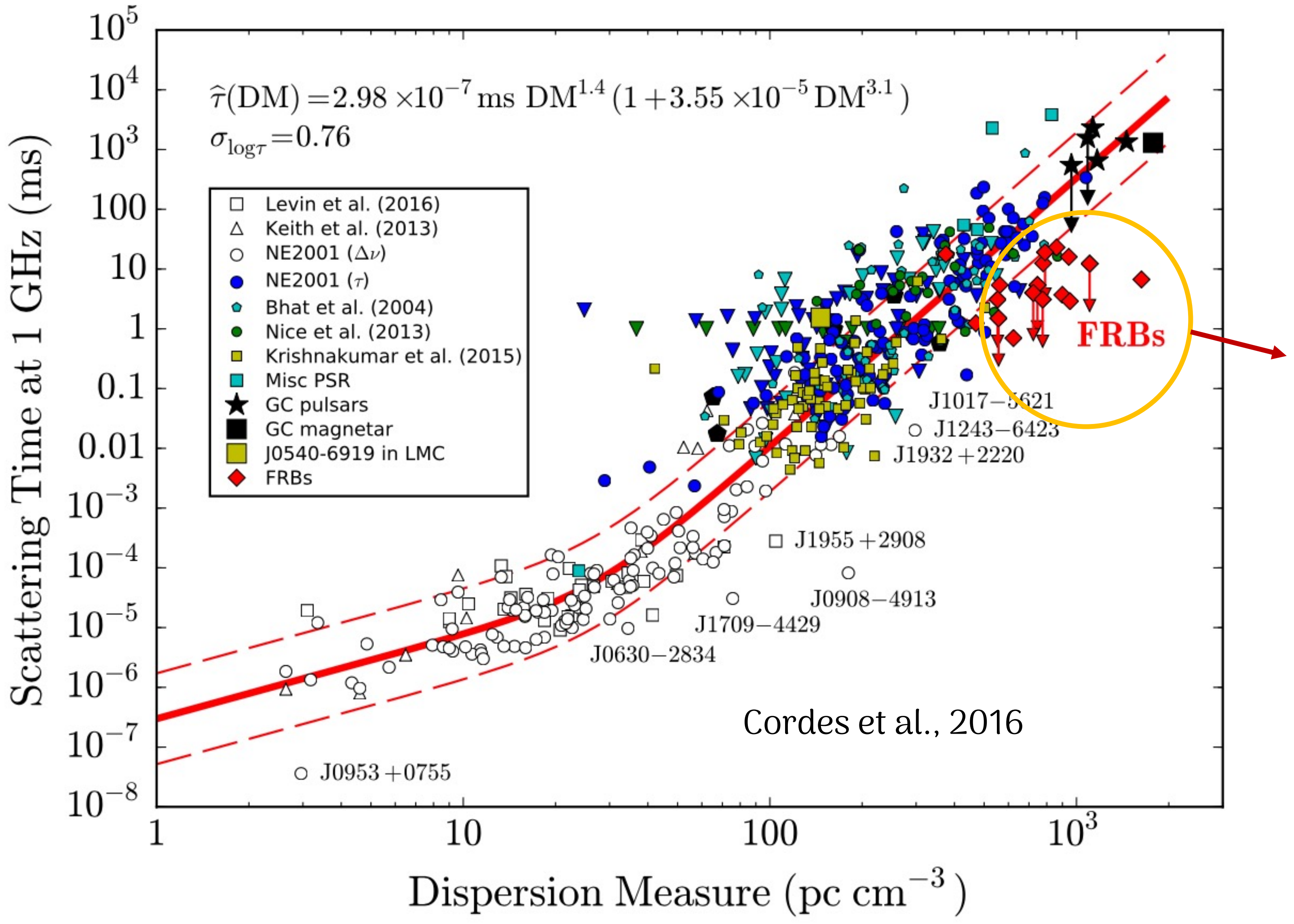


Figure 3. Scatter plot of the scattering time delay τ versus dispersion measure DM using our sample. The fitting curve of Cordes et al., 2016 (green dashed line) is consistent with the enlarged sample. Nevertheless, we suggest fitting $\tau - \mathrm{DM}$ relation for individual pulsar samples. The two pulsar populations with $\tilde{\tau} < 10^{-6.1}$ s cm^6 pc^{-1} and $\tilde{\tau} > 10^{-4.1}$ s cm^6 pc^{-1} have power-law $\tau - \mathrm{DM}$ relations with very different amplitudes (red and blue line, respectively).

3. Results

3.1 τ-DM relation



FRBs are under average τ-DM relation

3. Results

3.2 Correlation with other data

- **Gum Nebular**

Blue circles —— 'NE2001'

Red circle —— 'YMW16'

Our result

235° < *l* < 285°

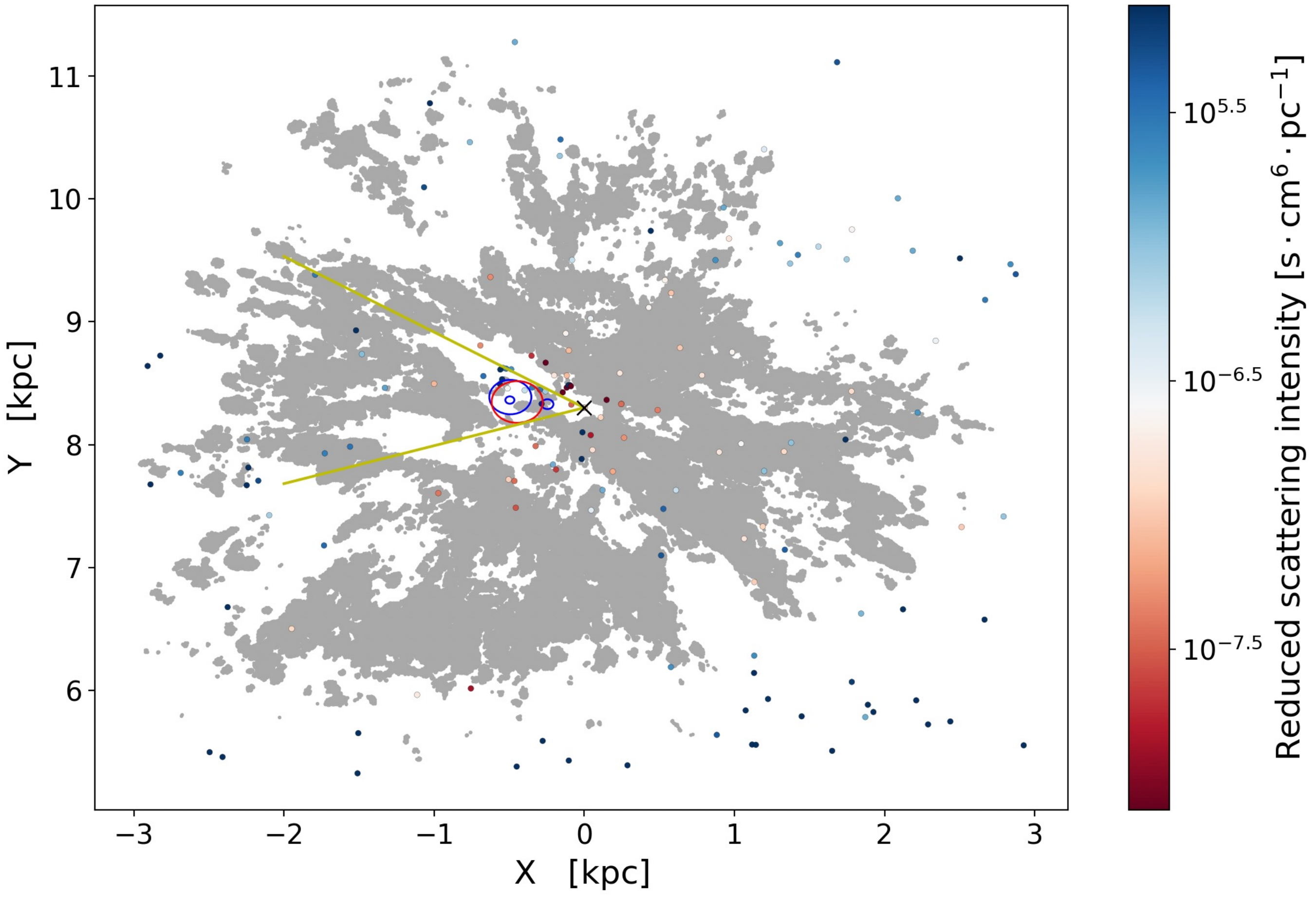


Figure 5. We correlated our pulsar samples with the dust map, which has been converted to Galactic coordinates, using the dust map as a background. The blue circles indicate the position of the Gum Nebula as given by the NE2001 model, the red circle represents its location according to the YMW16 model, and the yellow lines demarcate the area influenced by the Gum structure on pulsar scattering as derived from our pulsar data.

3. Results

3.2 Correlation with other data

- **Super bubble**

D = 2.32 ± 0.32 kpc
Scale 0.054 kpc

similar to **local bubble**

JNAME	l	b	d	DM	$\log \tilde{\tau}$
J1853+0505	37.65	1.956	9.127	279.0	-1.040
J1853+0545	38.354	2.064	6.546	198.7	-2.367
J1855+0422	37.314	1.052	10.948	455.6	-2.566
J1856+0404	37.128	0.745	6.213	341.3	-2.917
J1857+0526	38.438	1.187	12.257	466.4	-2.819

H II regions

$37^\circ < l < 38.5^\circ$
$0.5^\circ < b < 2^\circ$

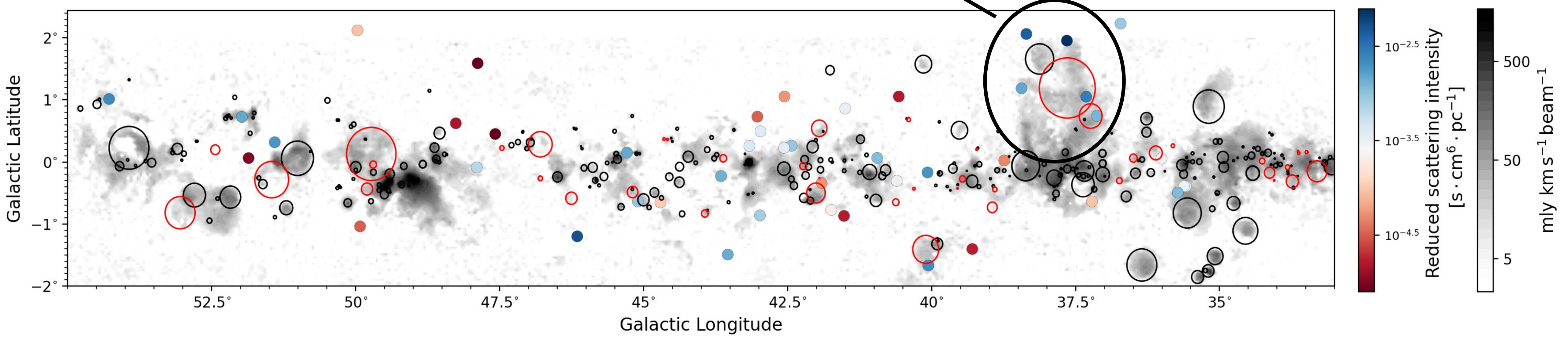


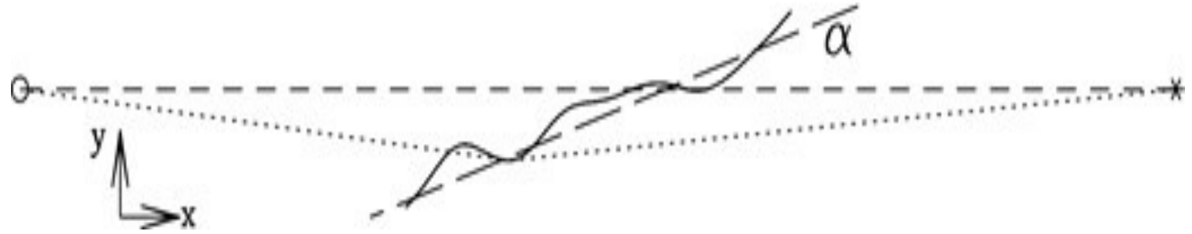
Figure 6. We conducted a correlation analysis using the RRL data from Hou et al. (2022) as the background (covering $33^\circ < l < 55^\circ$ and $-2^\circ < b < 2^\circ$) with our sample. The newly certified H ii regions by them are marked with red circles, while previously recognized H ii regions are indicated by black circles.

3. Results

3.3 Scattering scale height of the inner disk

scattering

interstellar structure



corrugated plasma reconnection sheets

- **HII regions**

  Stinebring et al. 2000 …

- **superbubble shells**

  Stinebring et al. 2022 …

- **supernova remnants**

  Ocker et al. 2020; Yao et al. 2021 …

- **ionized skins of molecular clumps**

  Walker et al. 2017 …

- **filaments ionized by hot stars**

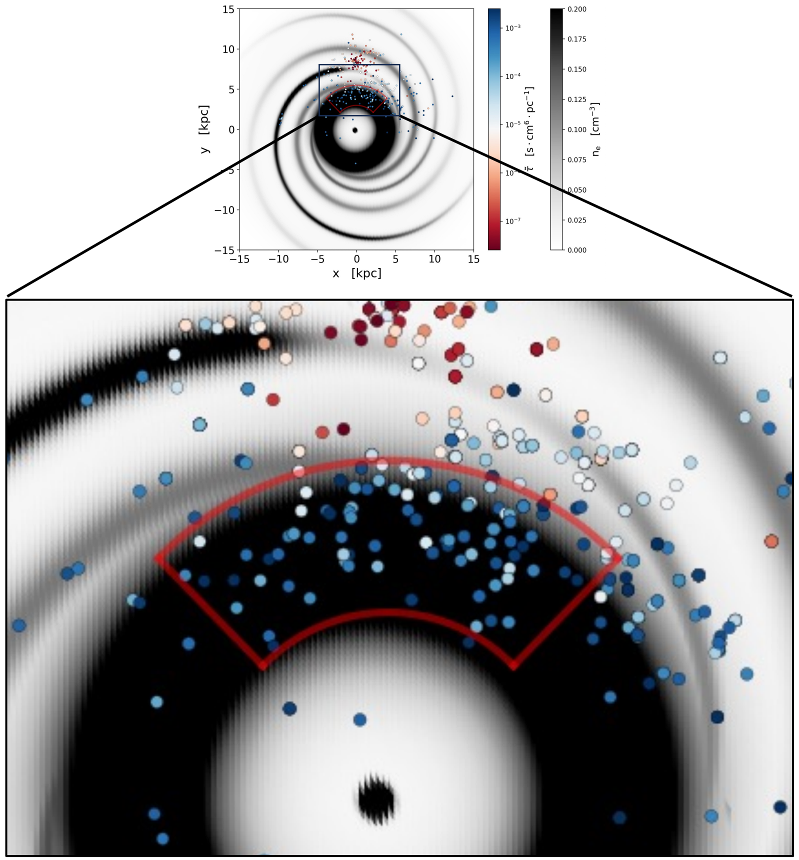
  Walker et al. 2017 …

- **corrugated plasma reconnection sheets**

  Pen & King 2012; Pen & Levin 2014; Liu et al. 2016; Simard & Pen 2018 …

3. Results

3.3 Scattering scale height of the inner disk



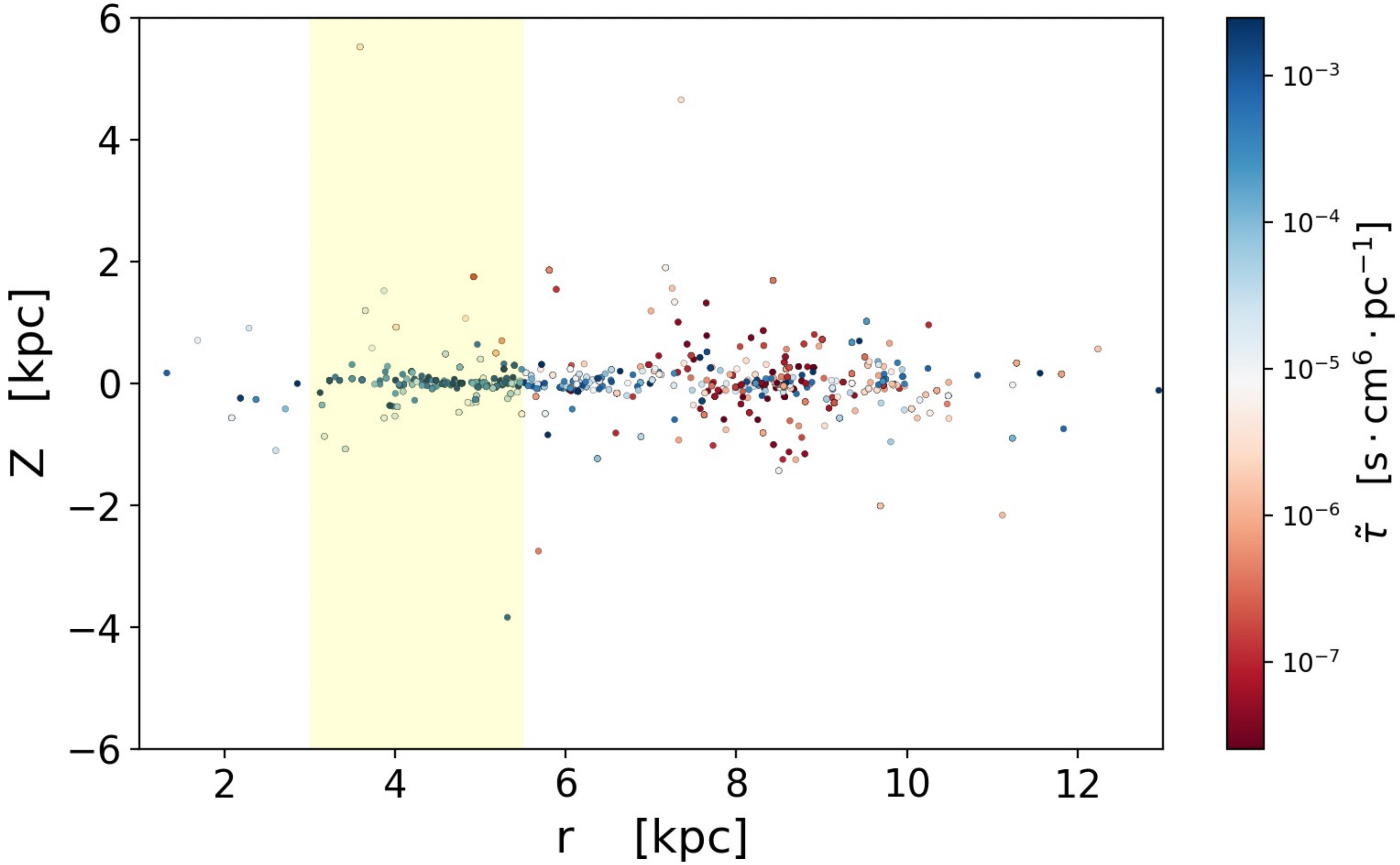


Figure 7. Galactic $r - Z$ distribution of our pulsar sample. Pulsars with distances to the Galactic Center in the range of 3 kpc $< r <$ 5.5 kpc (yellow shaded region) have reduced scattering intensities (color-coding) that show little dependence on r, allowing us to select a homogeneous `inner disk' population from this region.

3. Results

3.3 Scattering scale height of the inner disk

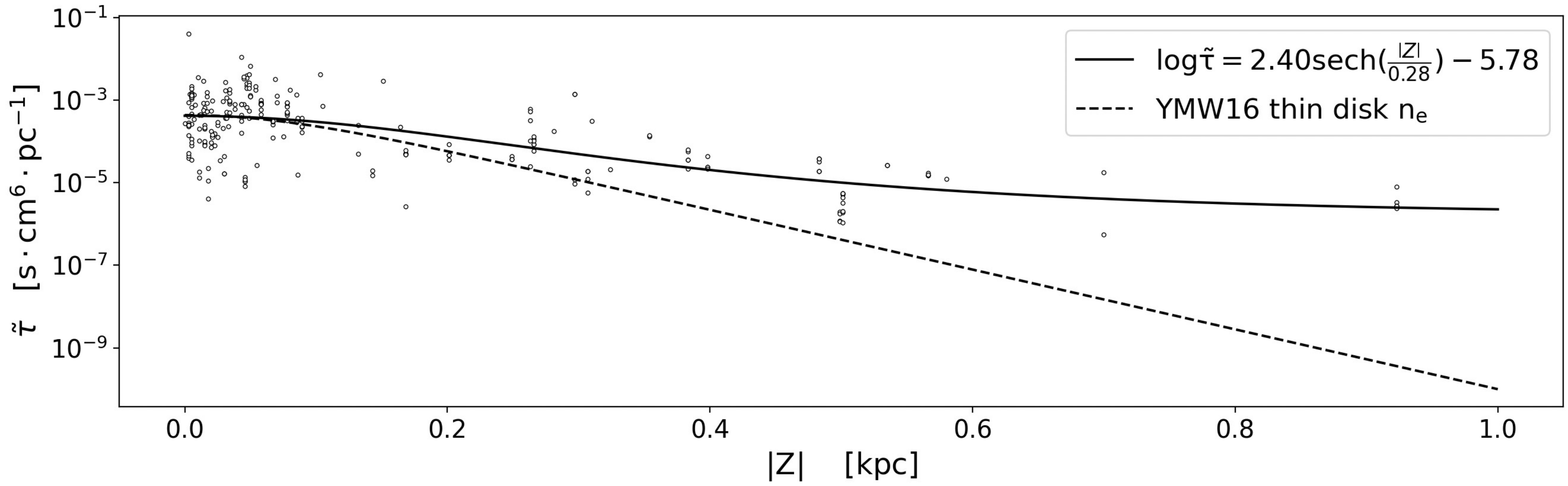


Figure 8. Pulse reduced scattering strength distribution over distance to the Galactic plane for pulsars in the selected inner disk region (the red fan-shaped region) where scattering is predominantly dependent on Z. Our fits are given by the solid lines. As a comparison, the dashed lines show the Z-dependence of the thin-disk electron number density in the YMW16 model (scaled to share the same value with the solid lines at $Z = 0$ kpc.)

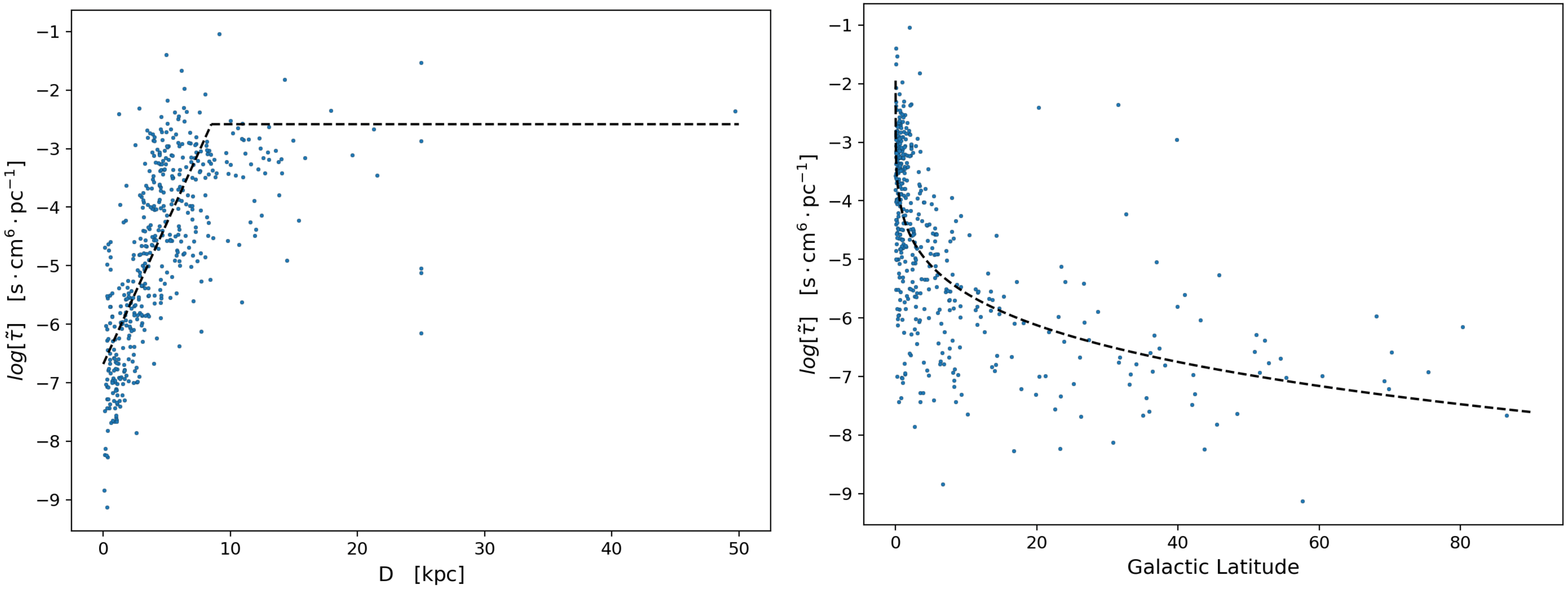
Our result

Scattering 0.28kpc

HI disk	**0.1 kpc**
molecular gas	**0.05kpc**
OB stars	**0.05kpc**
“thin” stellar disk	**0.3kpc**

3. Results

3.4 Scattering Contributions from the Galaxy



$$\log \tilde{\tau}_{\rm Galaxy} = -2.017 \times |b|^{0.155} + 0.315 \times d \times H(8.5 - d) + 2.6775 \times H(d - 8.5) - 3.740$$

→ **Same applies to Galactic scattering of FRBs**

4. Summary

- 2-population on τ-DM relation
  - $\tilde{\tau} < 10^{-5.1}$ **Local** $\tau(\mathrm{DM}) = \mathrm{DM}^{2.17} \times 10^{-10.18}$
  - $\tilde{\tau} > 10^{-5.1}$ **Inner** $\tau(\mathrm{DM}) = \mathrm{DM}^{2.08} \times 10^{-7.18}$
- reduced scattering strength $\tilde{\tau}$
- new (Super bubble) and known (Gum Nebular) structures
- scale height of the inner Galactic disk $\tilde{\tau}$: 0.28kpc
- Scattering Contributions from the Galaxy

$$\log \tilde{\tau}_{\mathrm{Galaxy}} = -2.017 \times |b|^{0.155} + 0.315 \times d \times H(8.5 - d) + 2.6775 \times H(d - 8.5) - 3.740$$

- new catalog of τ

Thanks!

He Q., Shi X., 2024, MNRAS, 527, 5183
He Q., Shi X., in preparation