

Single-Pulse-Based Interstellar Scintillation of Compact Radio Sources

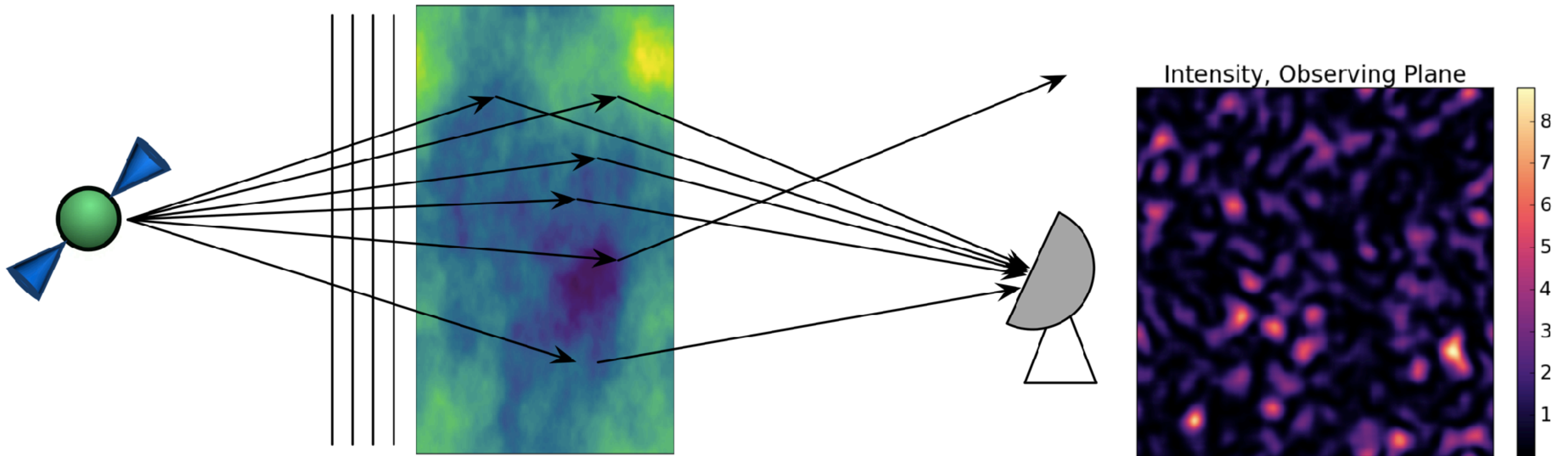
Ziwei Wu

And Weiwei Zhu, Bing Zhang, Robert A.Main, FAST FRB KSP

National Astronomical Observatories, Chinese Academy of Sciences

May/13/2025

Scintillation



Compact Radio Sources

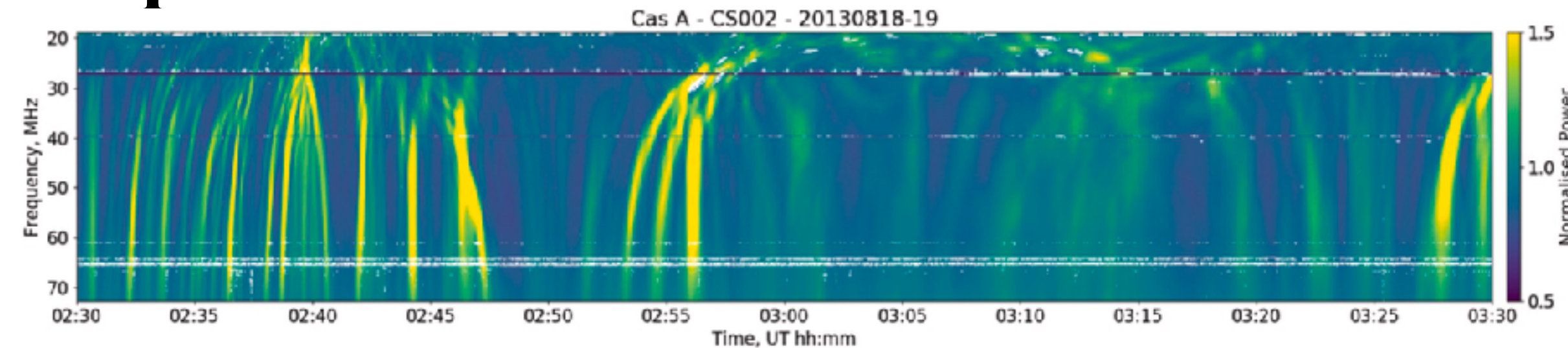
The critical source diameter that quenches the scintillation:

- Ionosphere scintillation:
arcminutes
- Interplanetary scintillation:
arcseconds

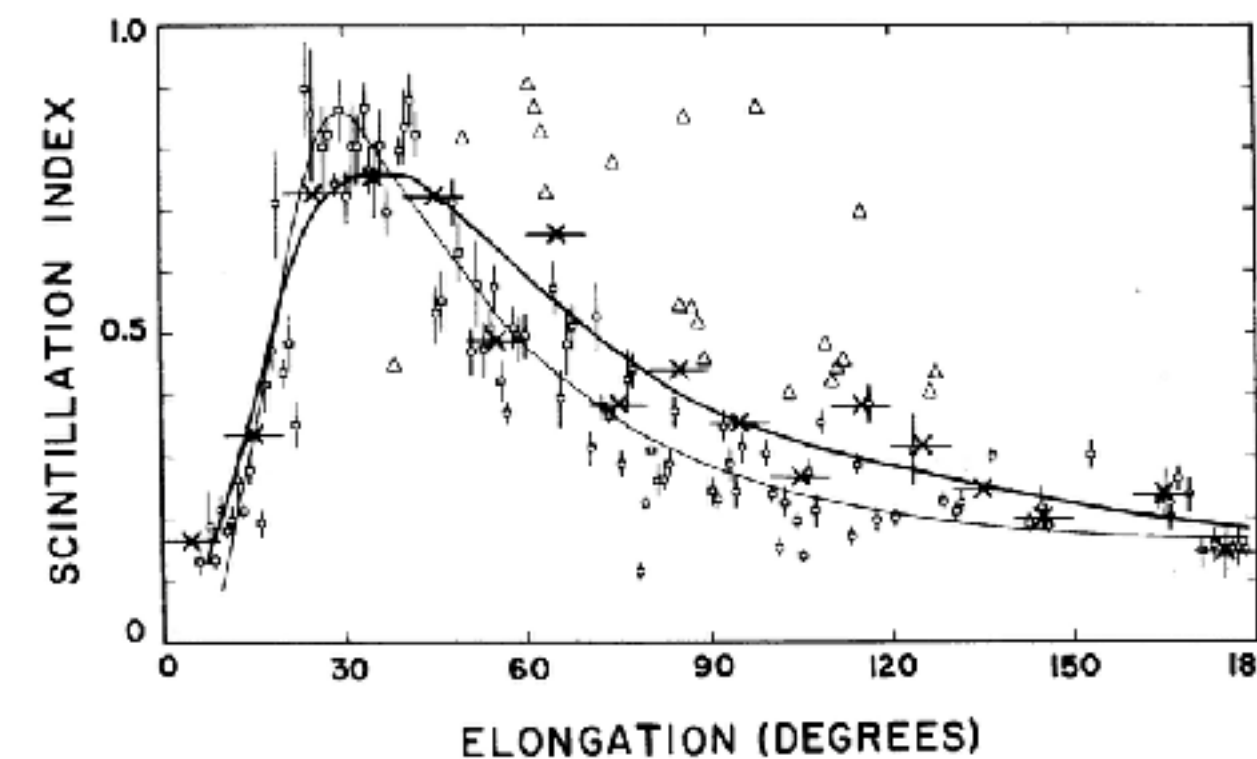
Modulation index:

$$m = \sqrt{\langle I^2 \rangle - \langle I \rangle^2} / \langle I \rangle$$

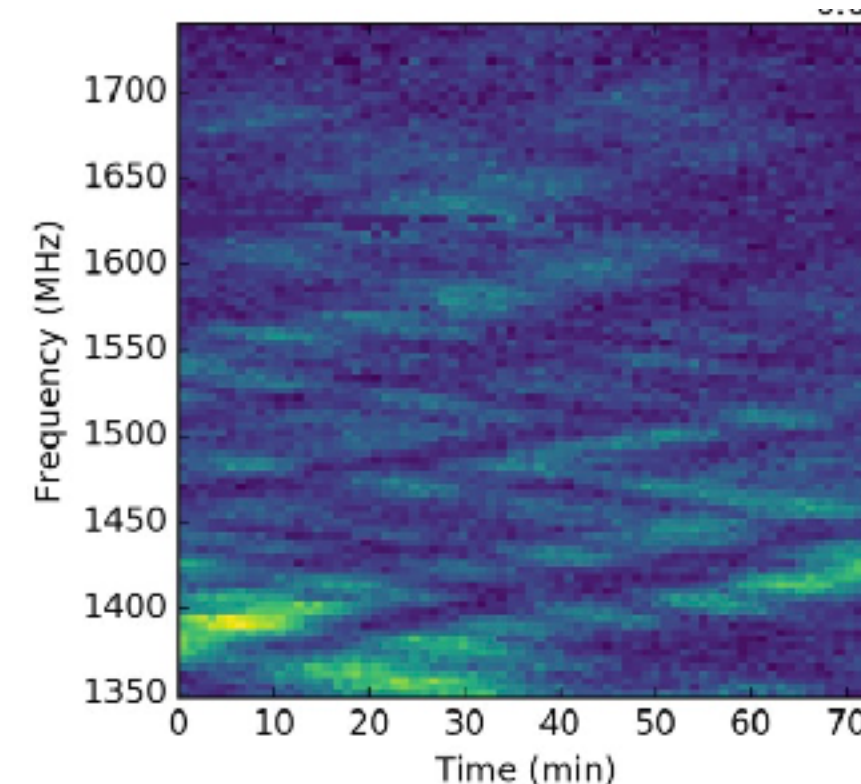
- Interstellar scintillation:
milli- to micro-arcseconds



Cassiopeia A:
(Fallows et al.2020)



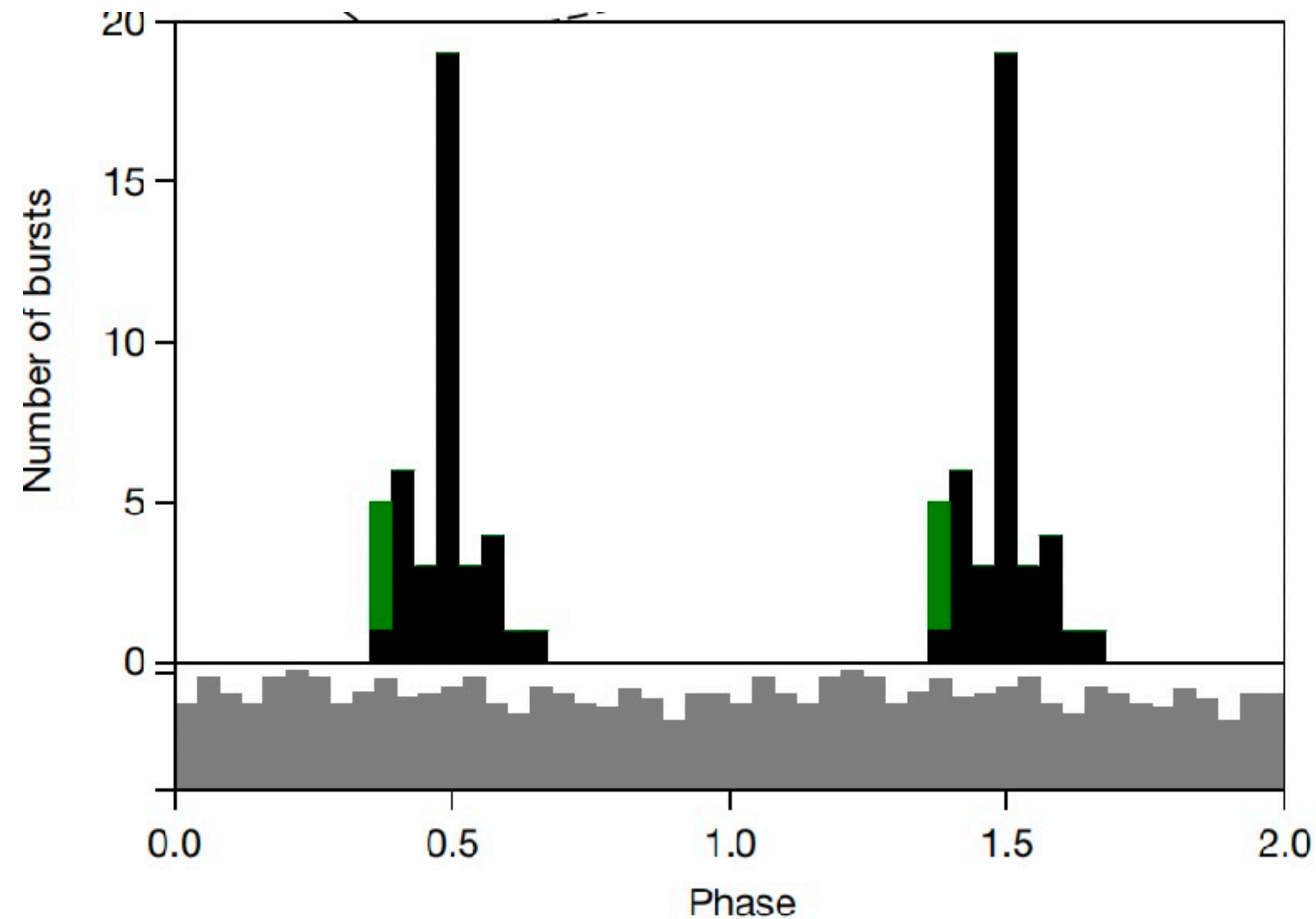
Crab (0.2 arcsec):
(Coles et al. 1977)



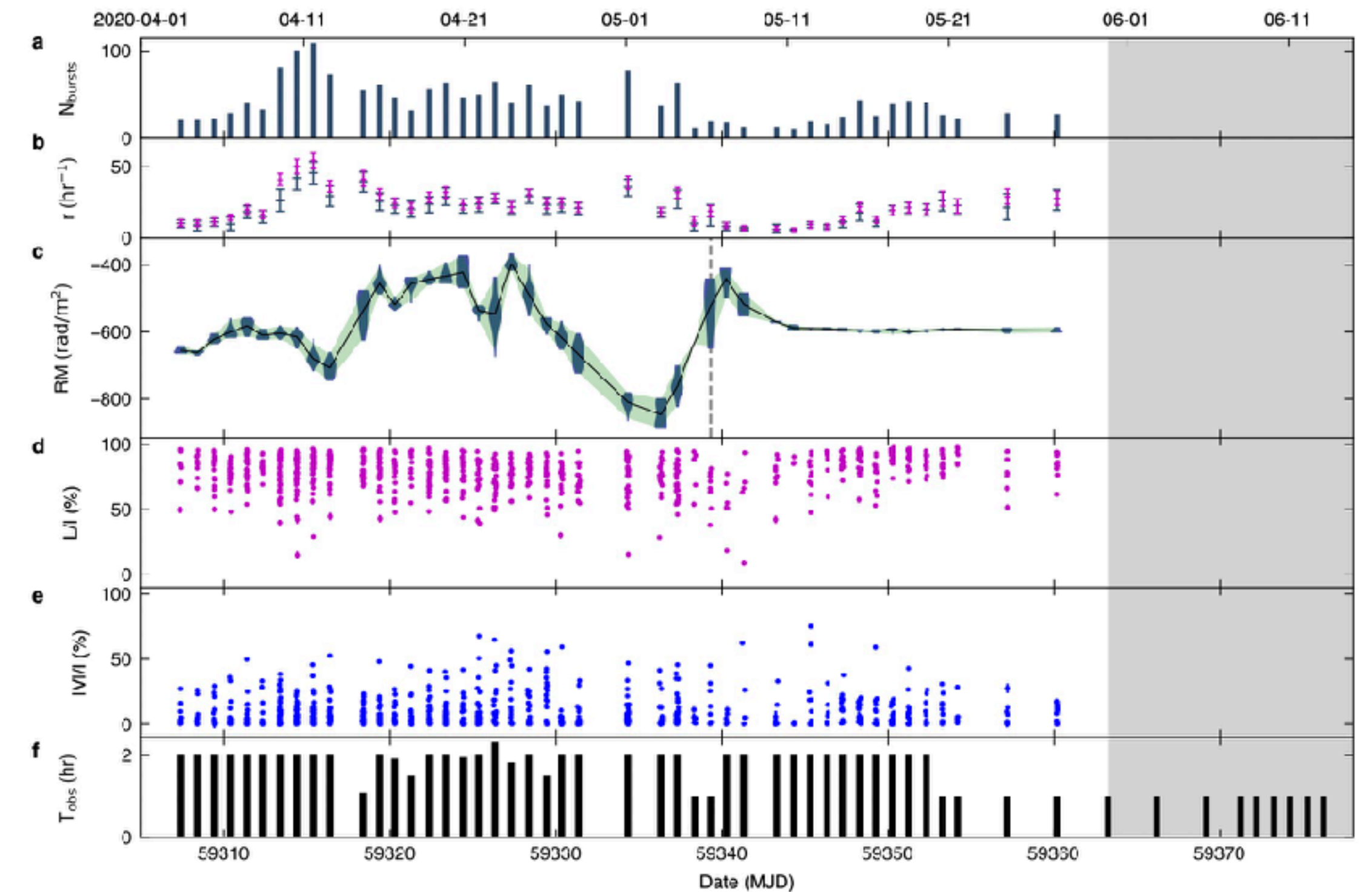
J0636+5128
(Liu et al.2022)

Fast Radio Bursts

- Aim: to study the orbital motion and nearby IISM
- Evidences:



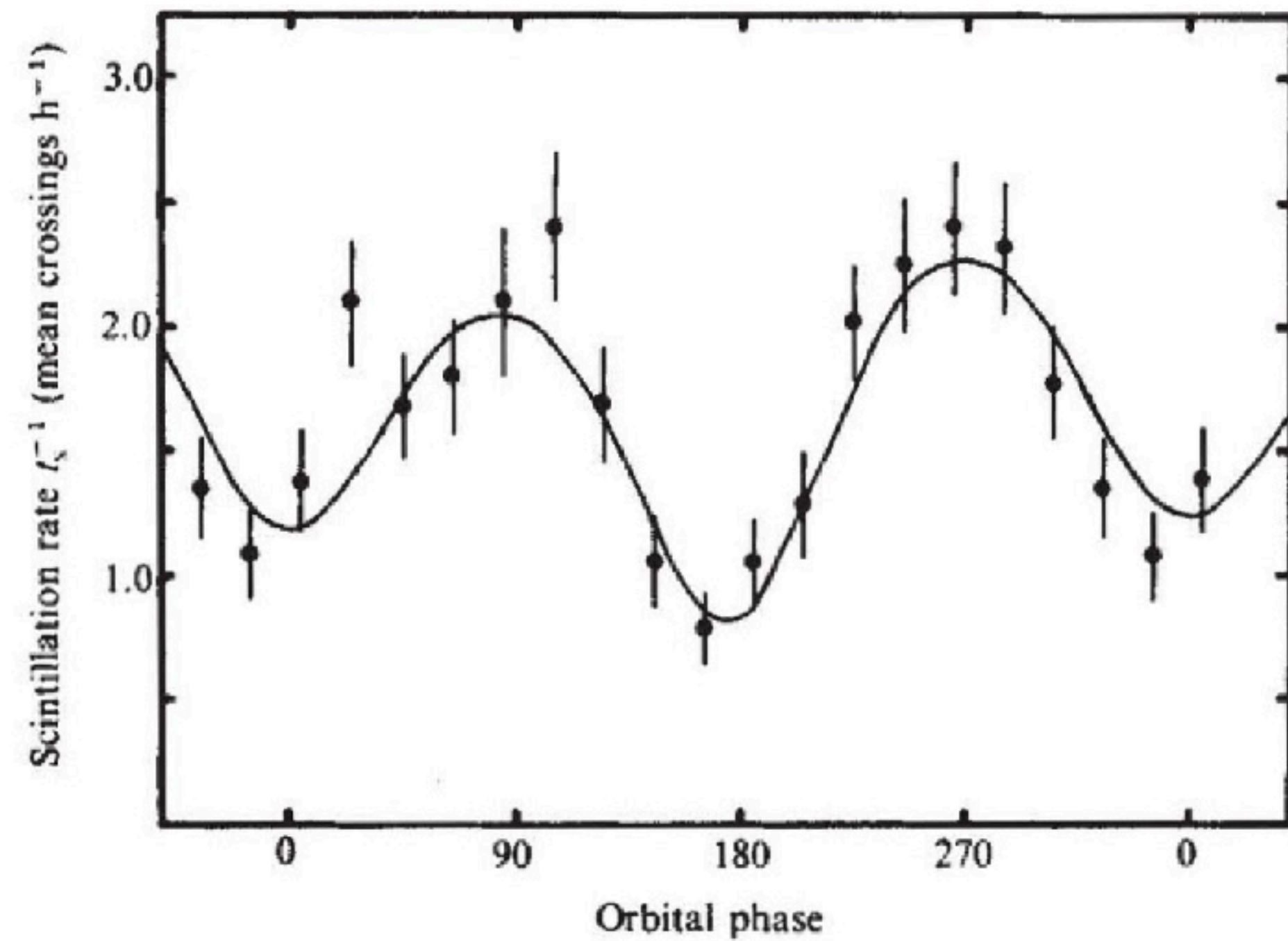
CHIME, Nature, 2020



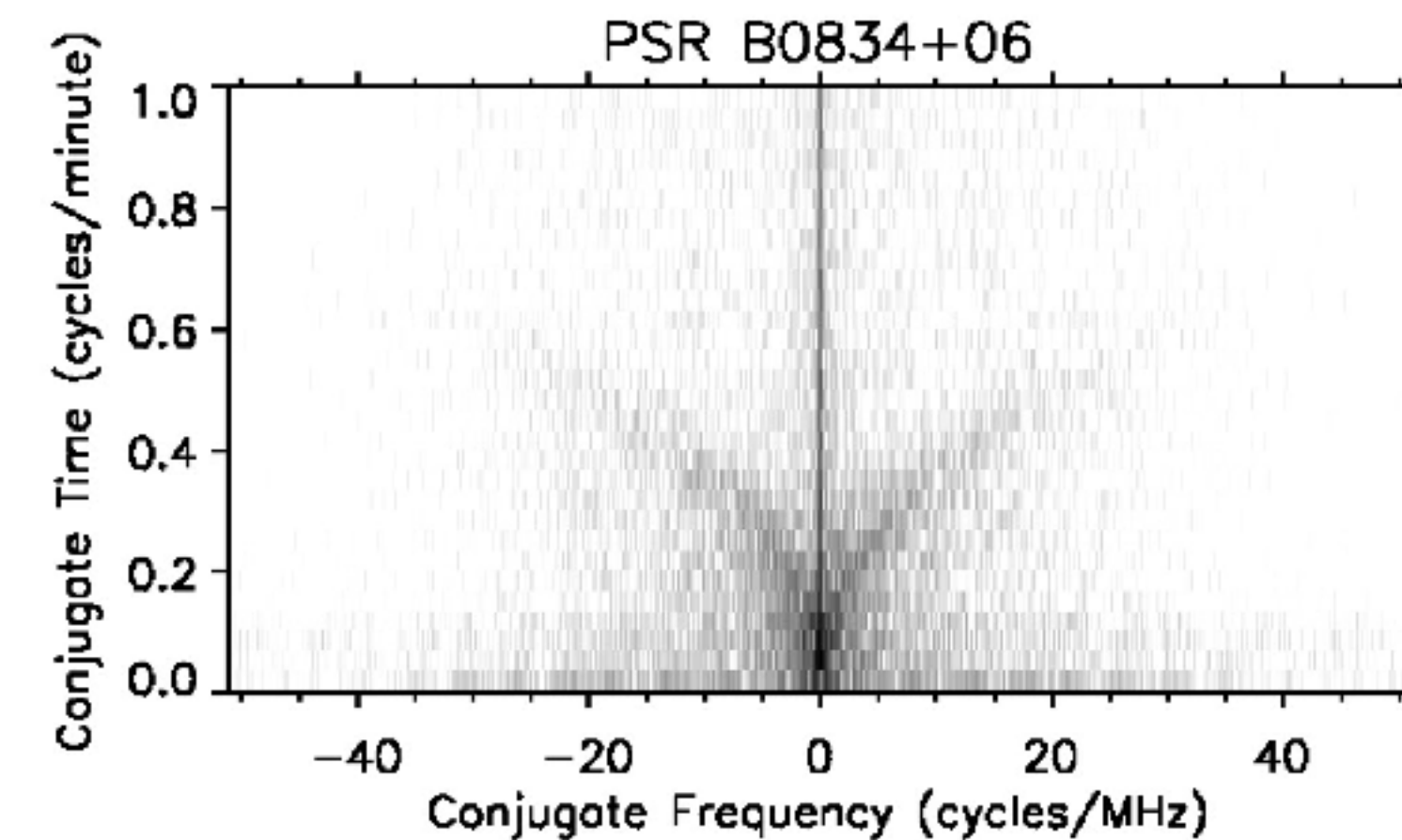
Xu et al. Nature, 2022

The history of pulsar ISS

- Orbital modulated scintillation
- localization the dominated IISM



Lyne, nature, 1984

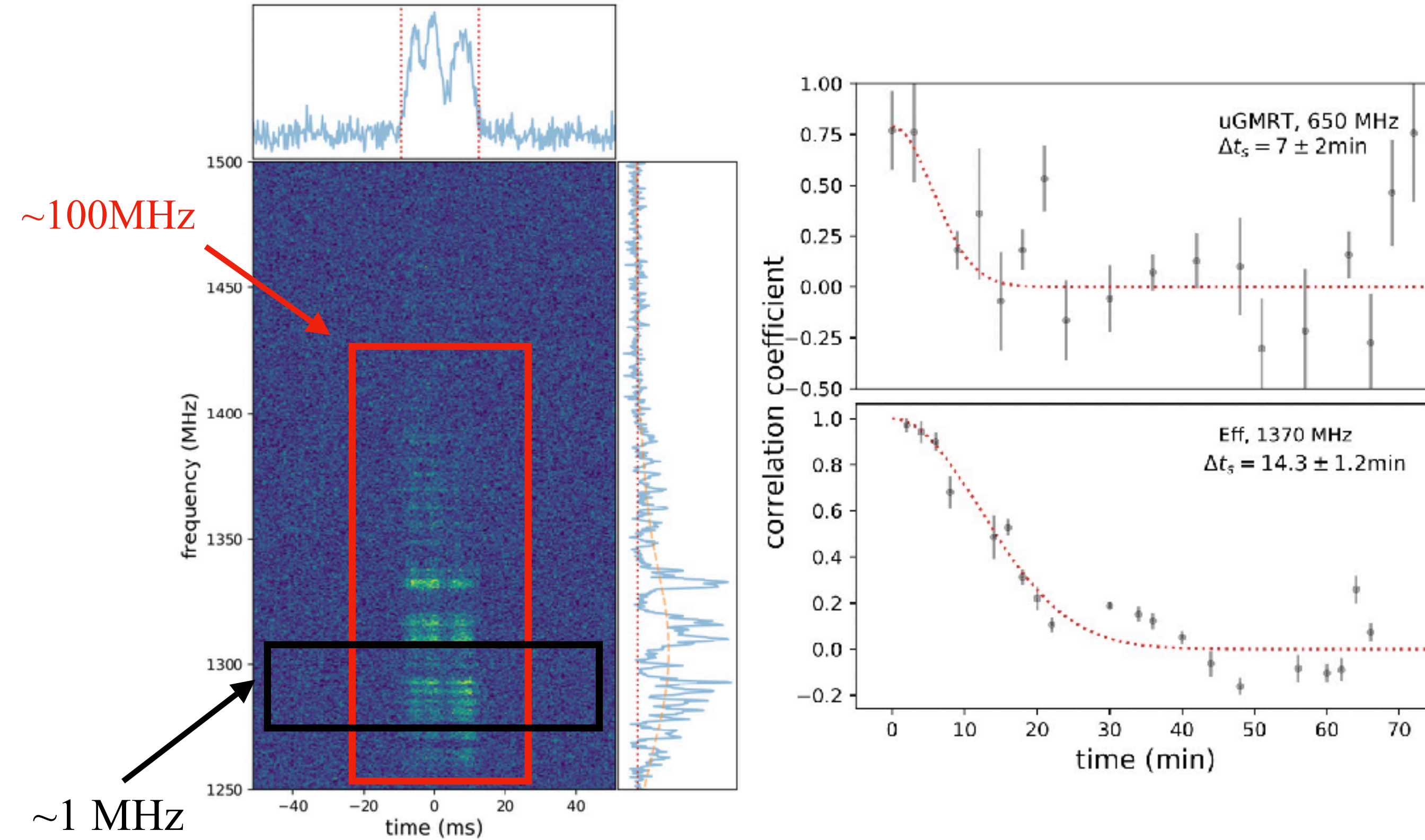


Stinebring et al. ApJ, 2001

Difficulties of single-pulse-based ISS

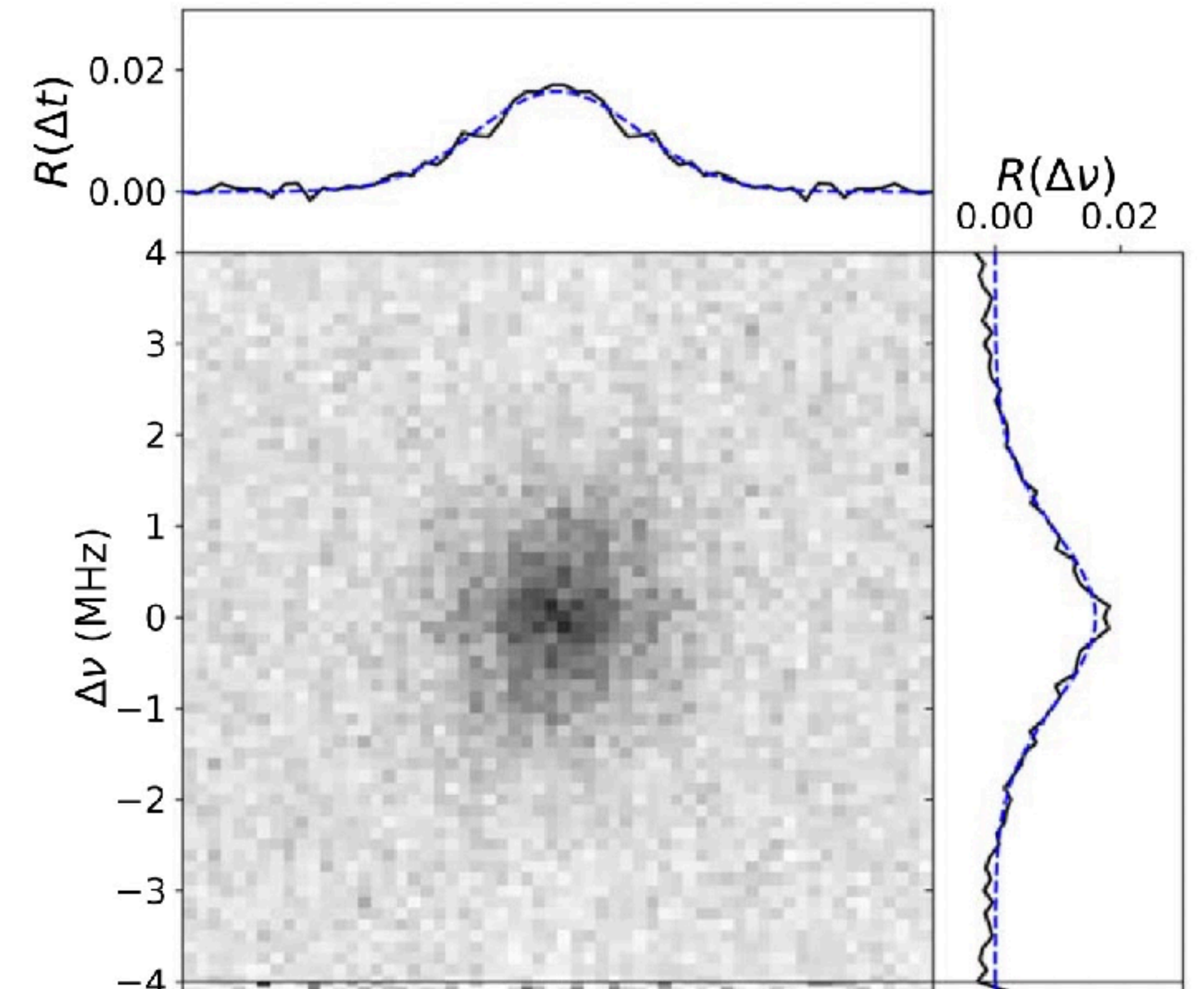
Difficulties: Background, Signal-to-noise ratio, **Intrinsic Variability** (intensity and pulse profile)

FRB 20201124A:



Main et al. MNRAS, 2022

Crab giant pulses

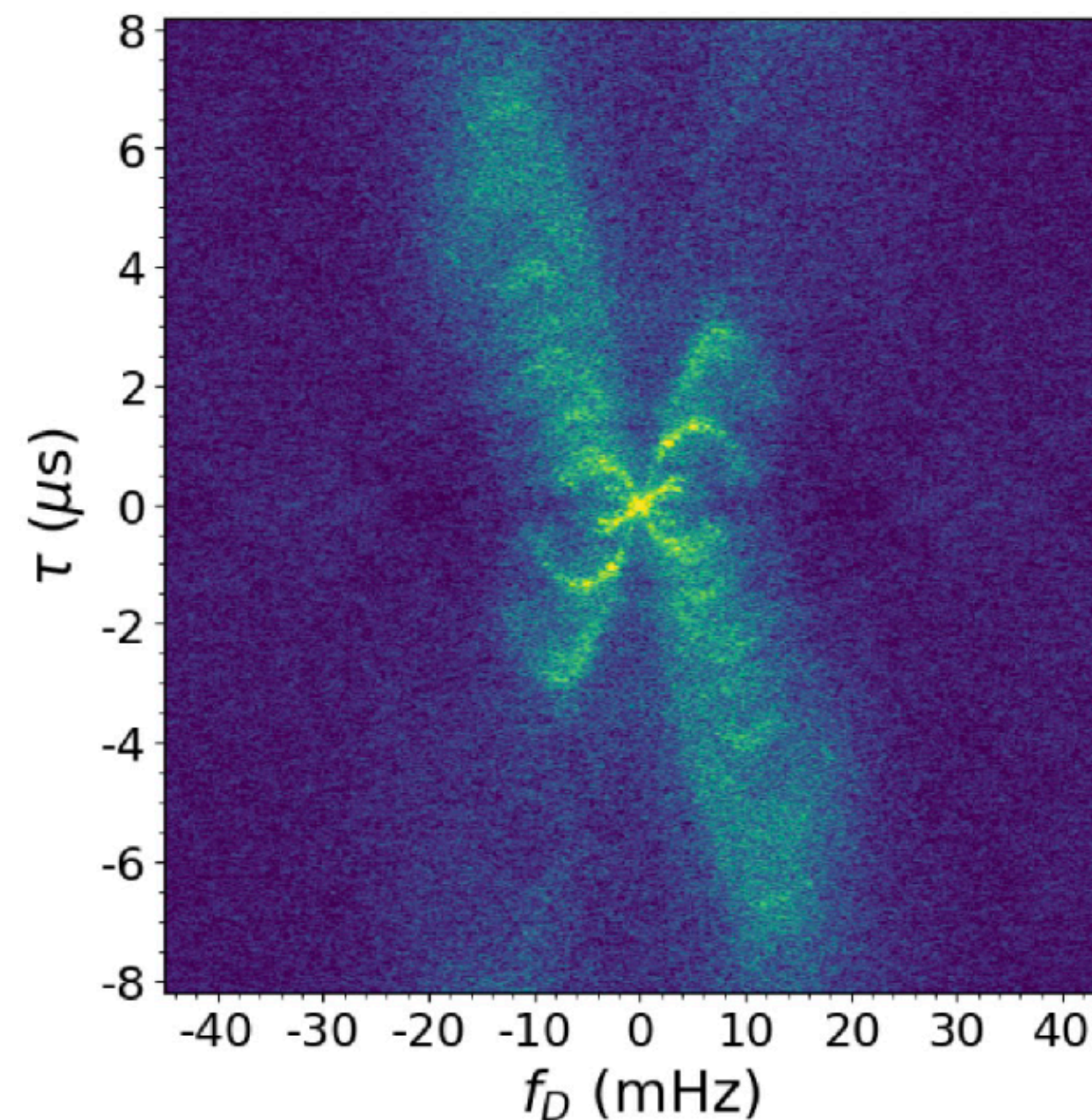
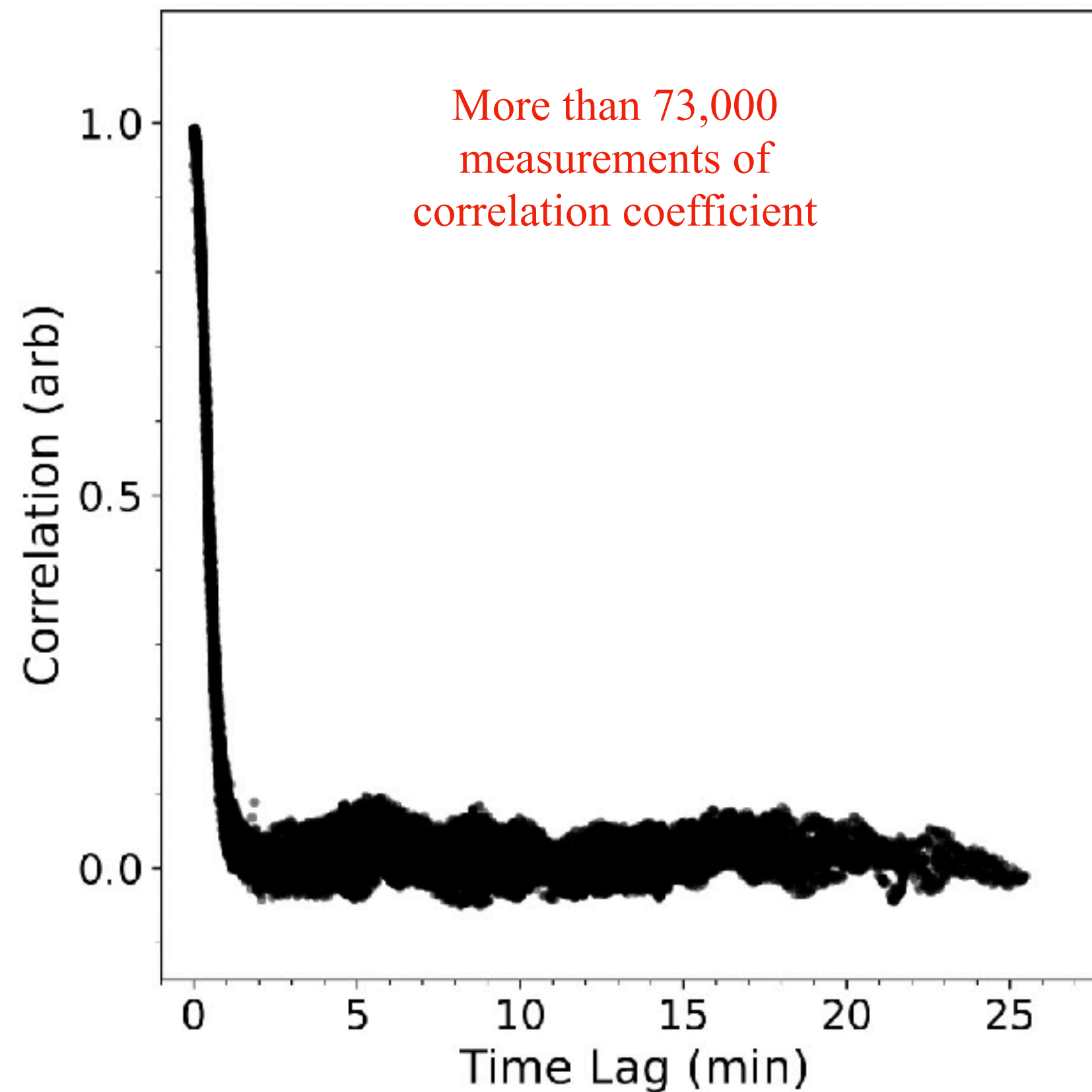


Main et al. MNRAS, 2021

Single pulse based ISS on pulsars (Wu et al. ApJL, 2025)

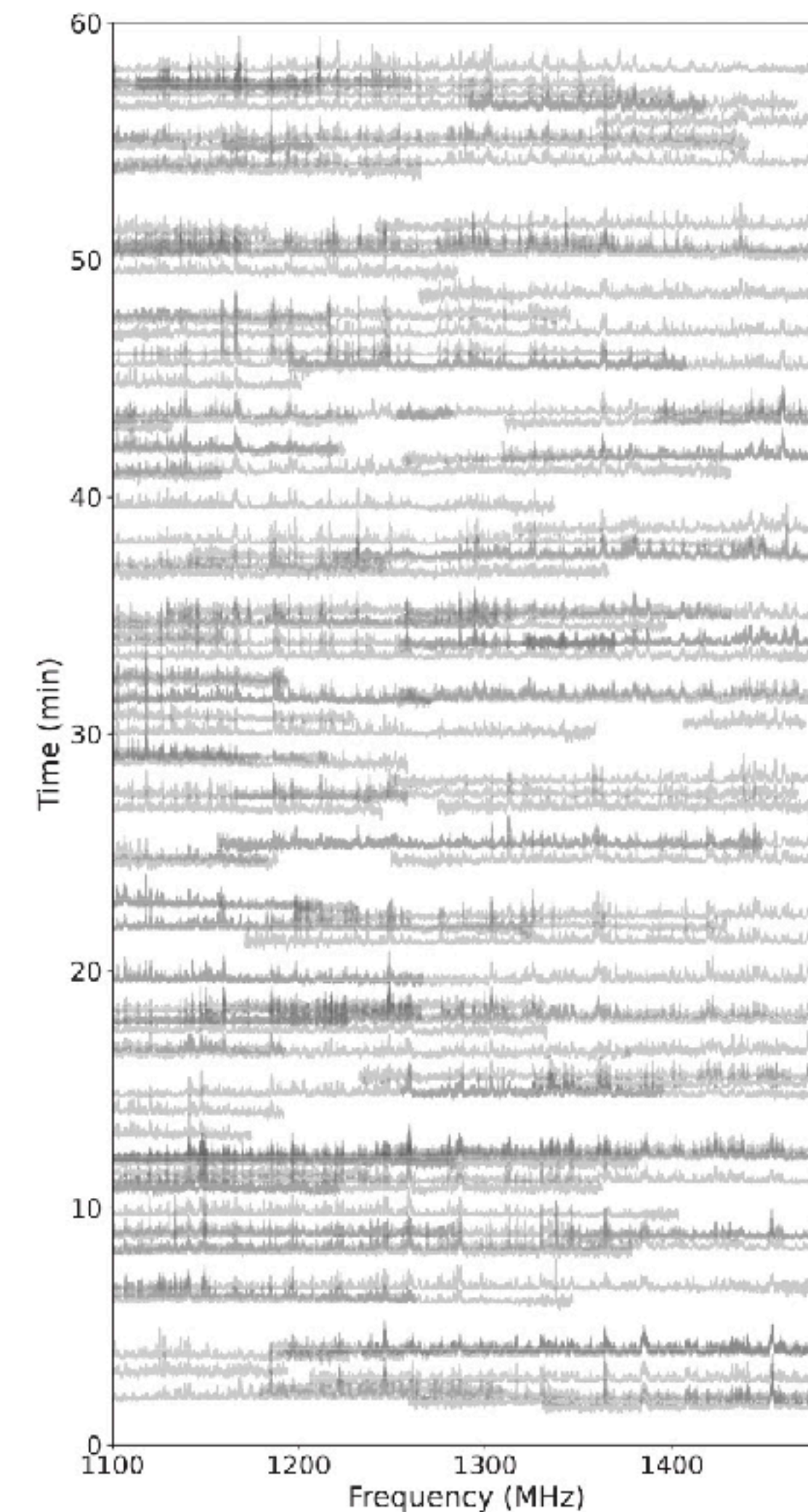
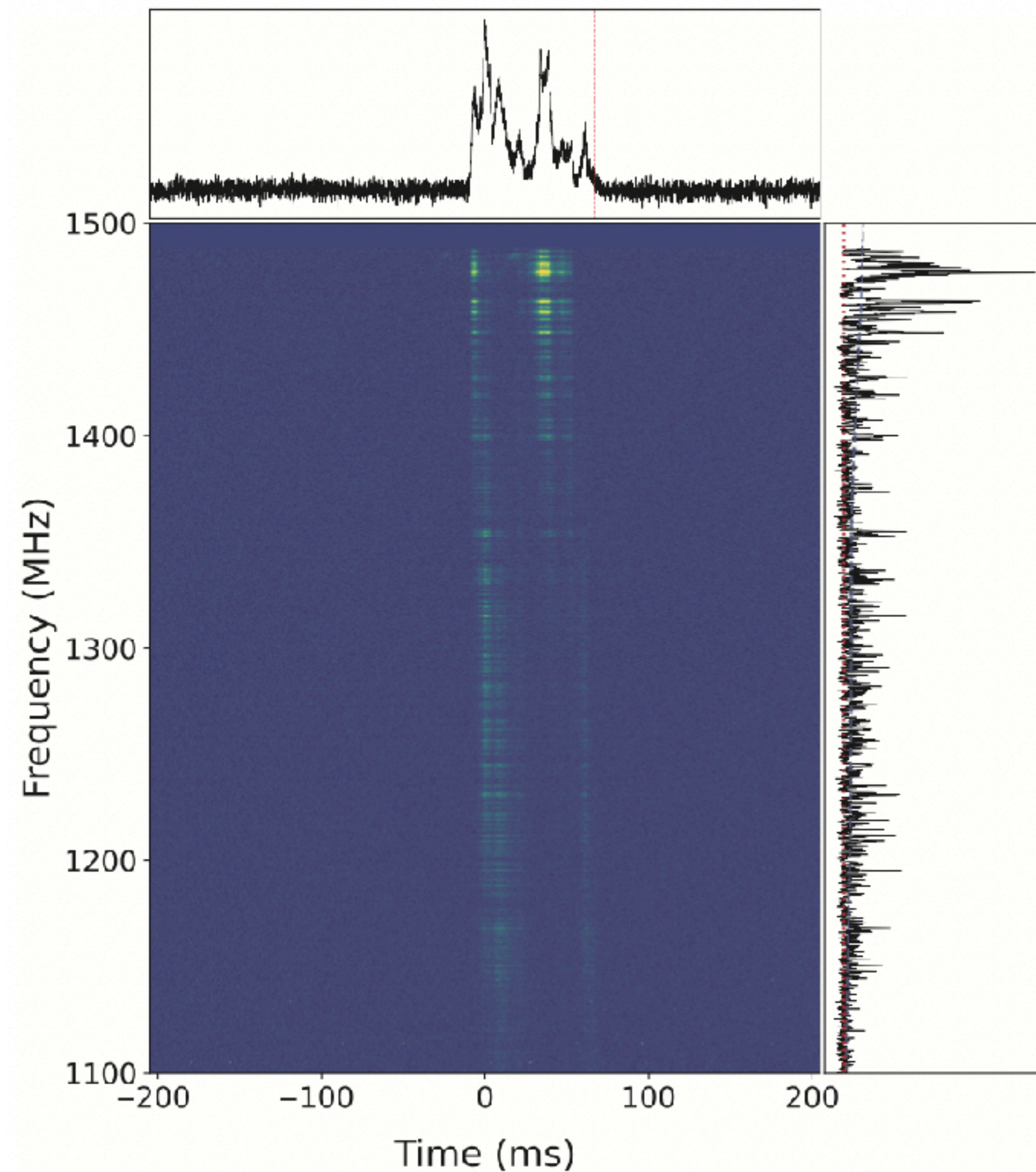
PSR J1509+5531:

271 selected single pulses with FAST



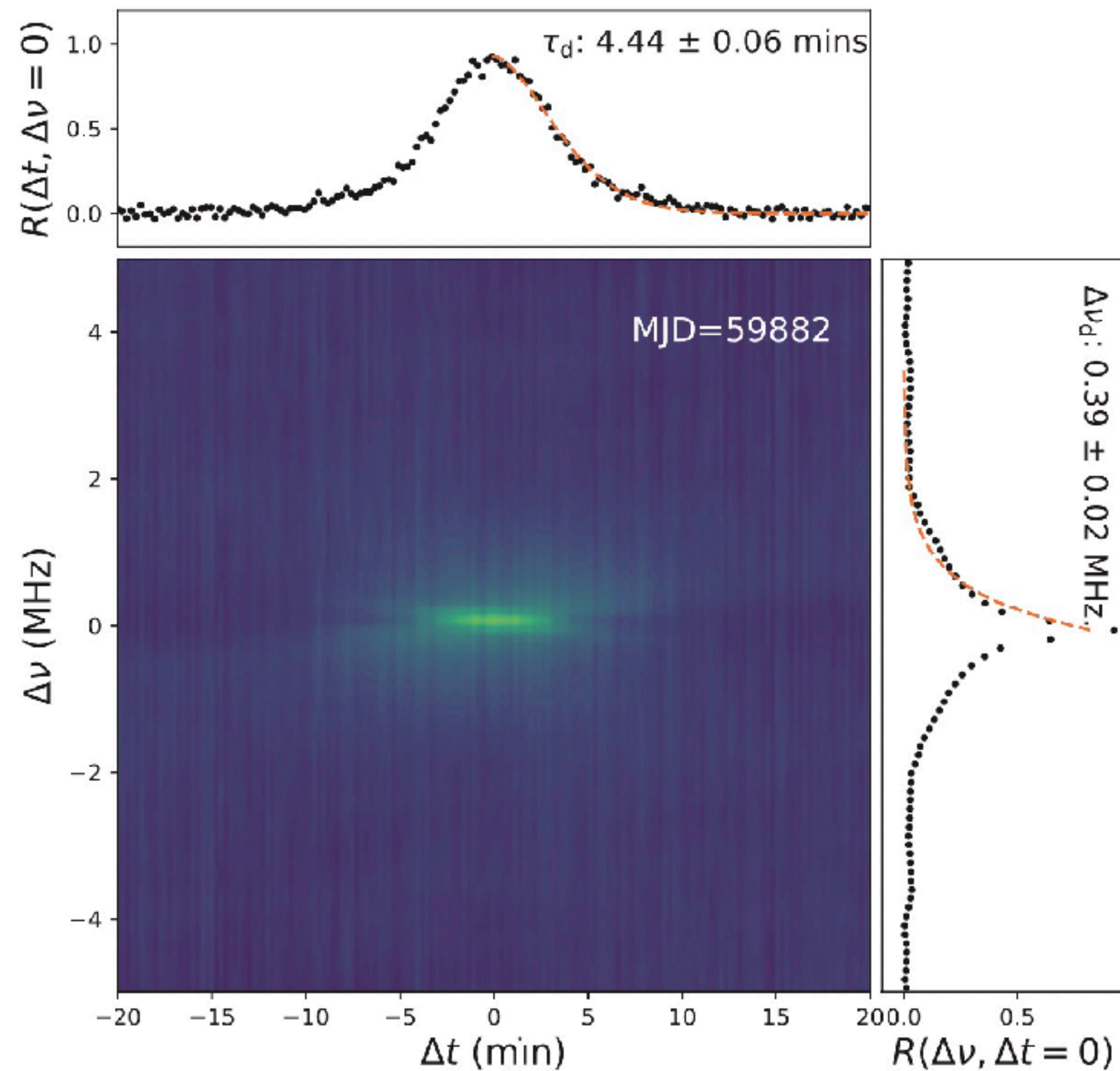
FRB 20220912A (Wu et al. SCMPA, 2024a)

- To get frequency spectrum for each burst
- To get dynamic spectrum of an observation

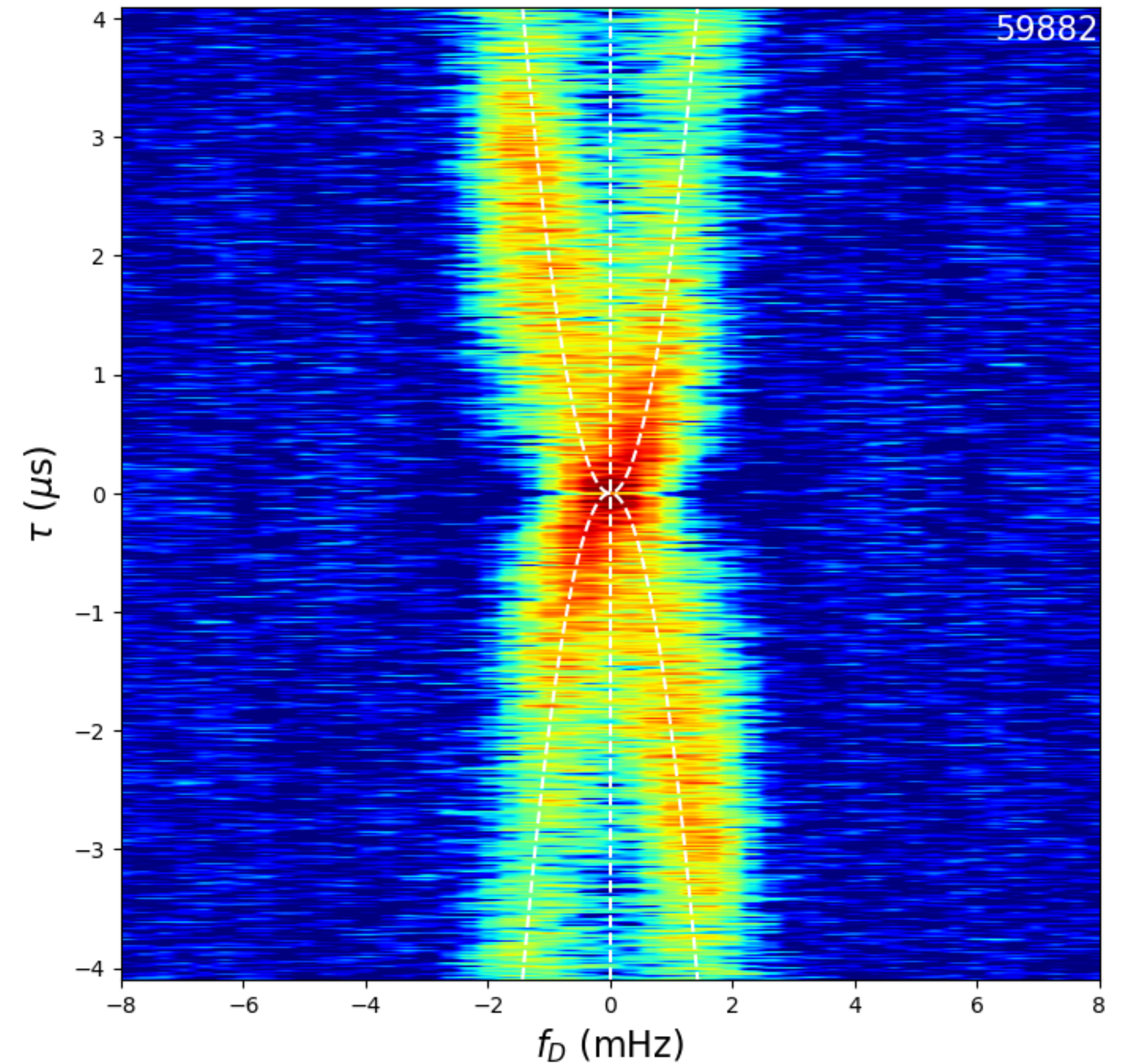


FRB 20220912A (Wu et al. SCMPA, 2024a)

- The 2D ACF

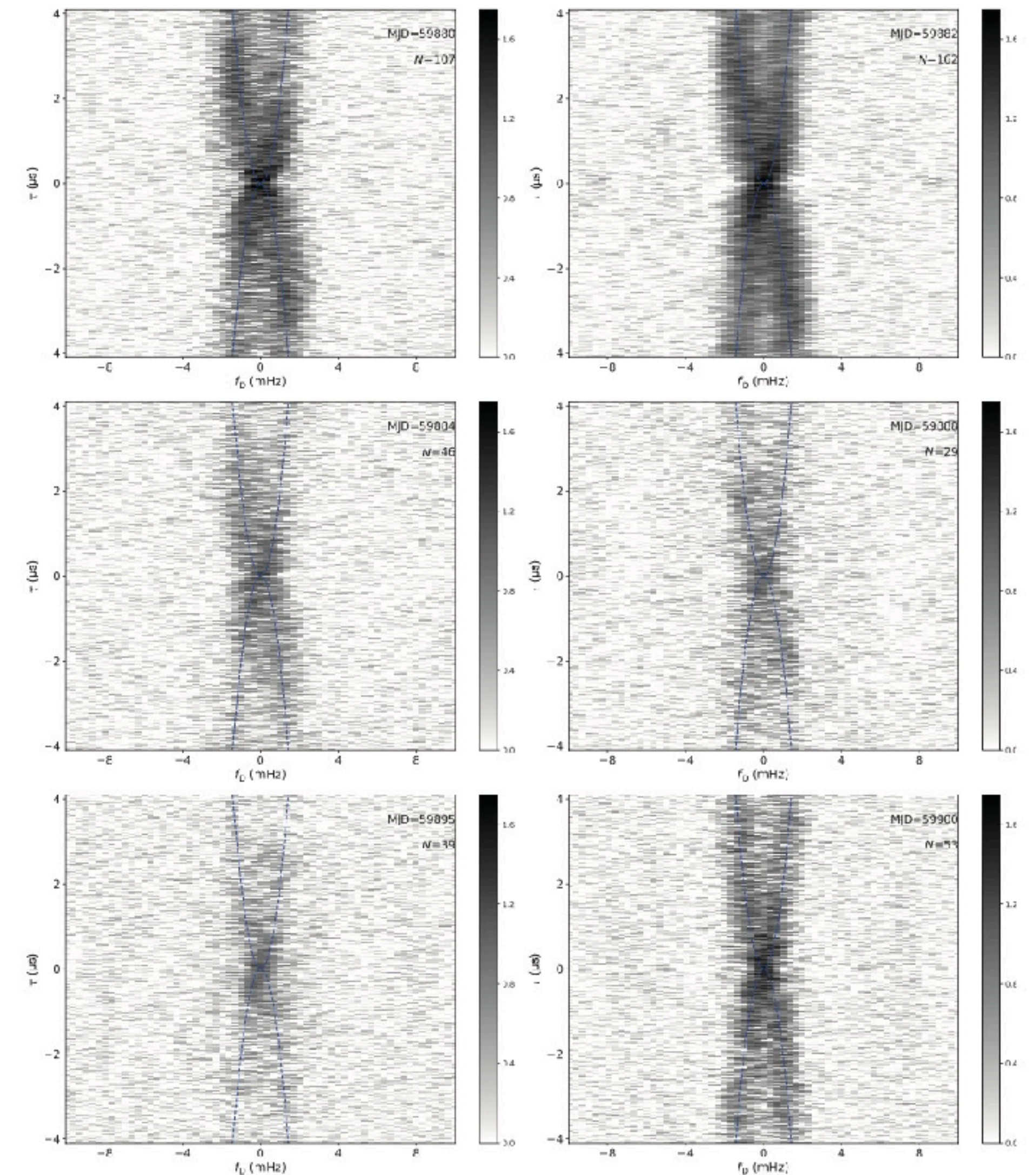
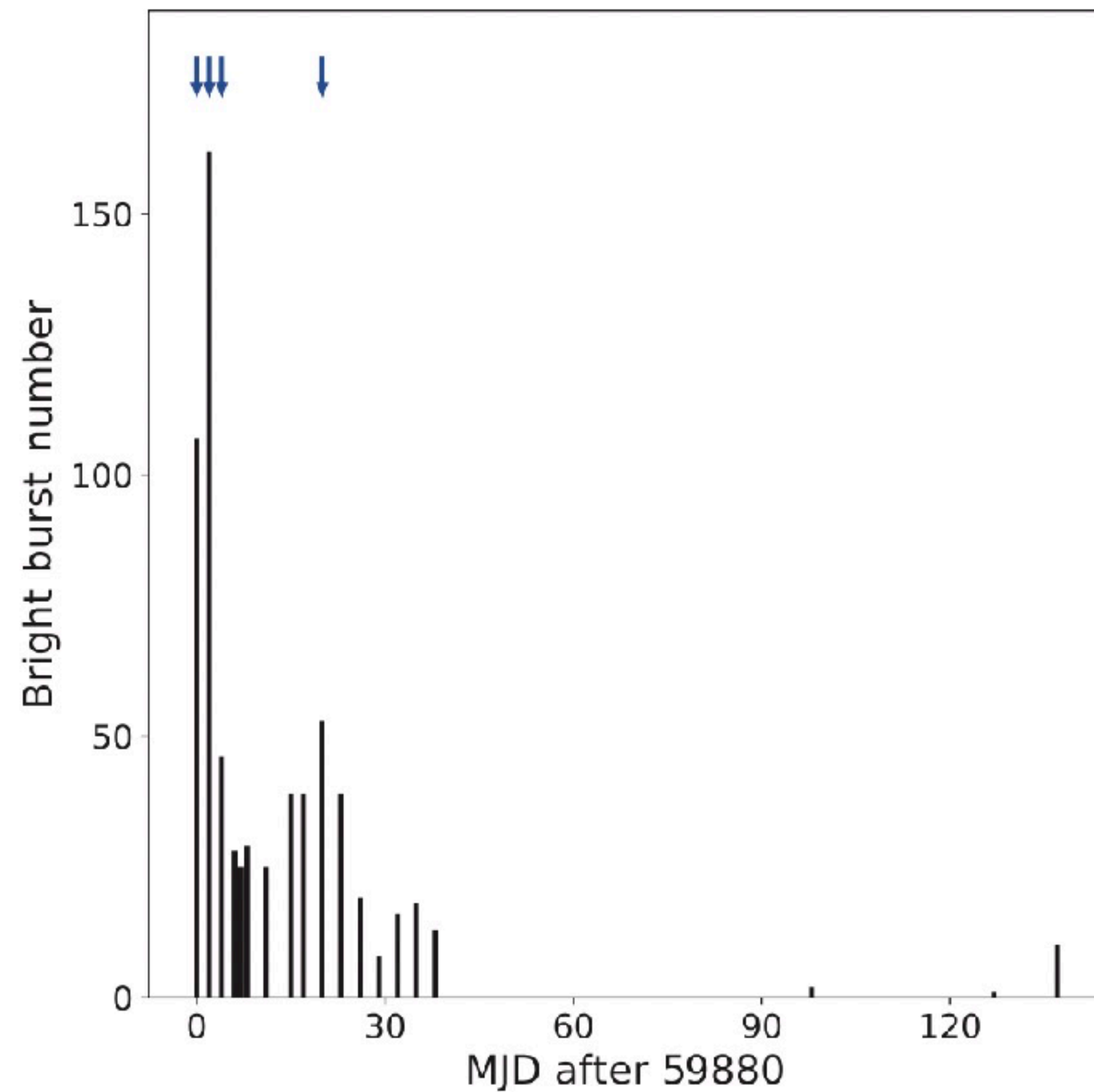


- The secondary spectrum



FRB 20220912A (Wu et al. SCMPA, 2024a)

- Long-term evolution of scintillation arc



FRB 20220912A (Wu et al. SCMPA, 2024a)

- The effective scintillation velocity (Cordes et al. 1998):

$$V_{\text{eff}} = (1 - s)(V_{\text{FRB}} + V_o) + sV_E - V_{\text{sc}}(s)$$

- Scintillation in host galaxy:

$$\eta \approx \frac{cd_{\text{sc,HG}}}{2v^2} \frac{1}{[(V_{\text{FRB}} + V_o - V_{\text{sc}}) \cos \psi]^2}$$

- Scintillation in MW:

$$\eta \approx \frac{cd_{\text{sc,MW}}}{2v^2} \frac{1}{[(V_E - V_{\text{sc}}) \cos \psi]^2}$$

In order to interpret scintillation arc curvature:

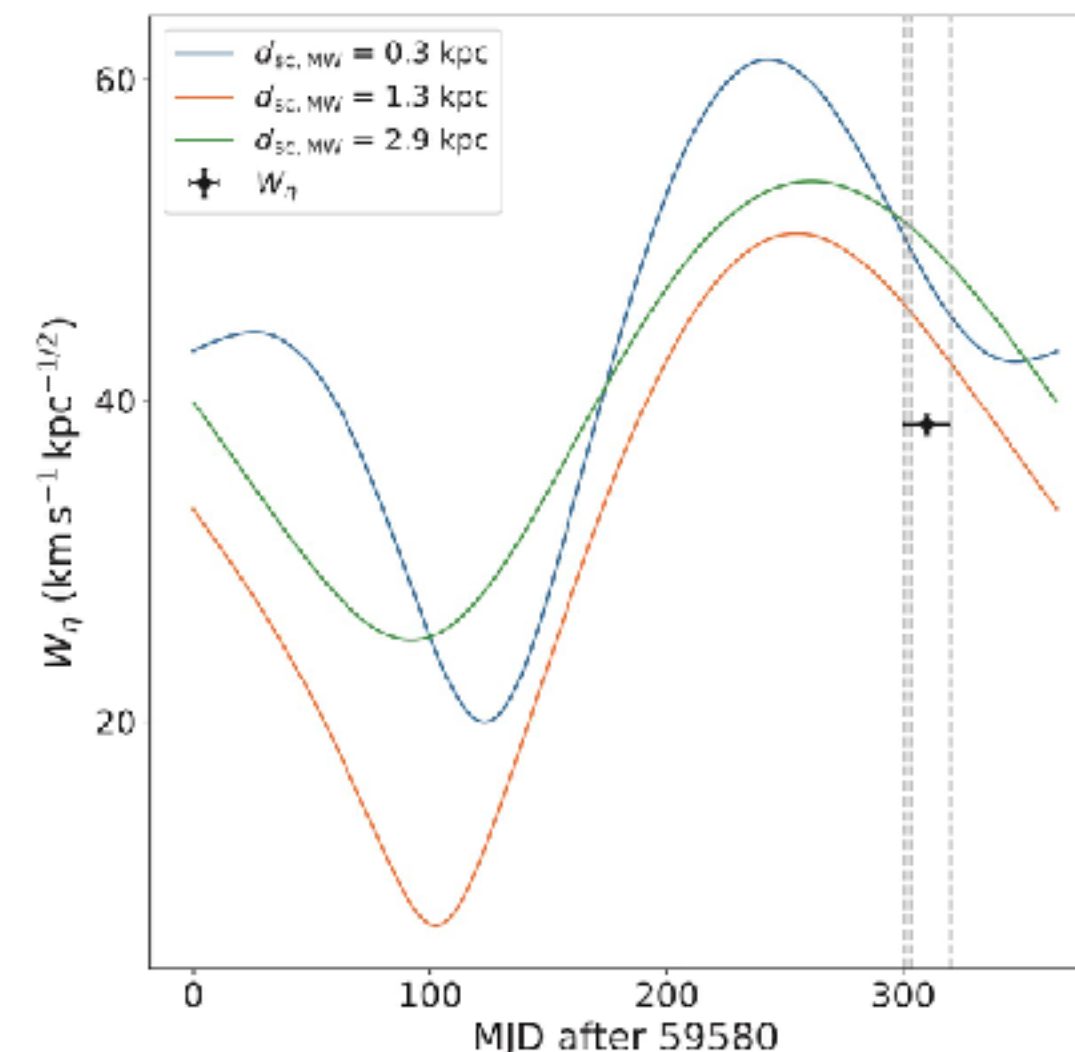
Case 1 (young pulsar origin):

high transverse velocity ~ 500 km/s , $d_{\text{sc,HG}} \sim 170$ kpc

Case 2 (supernova remnant):

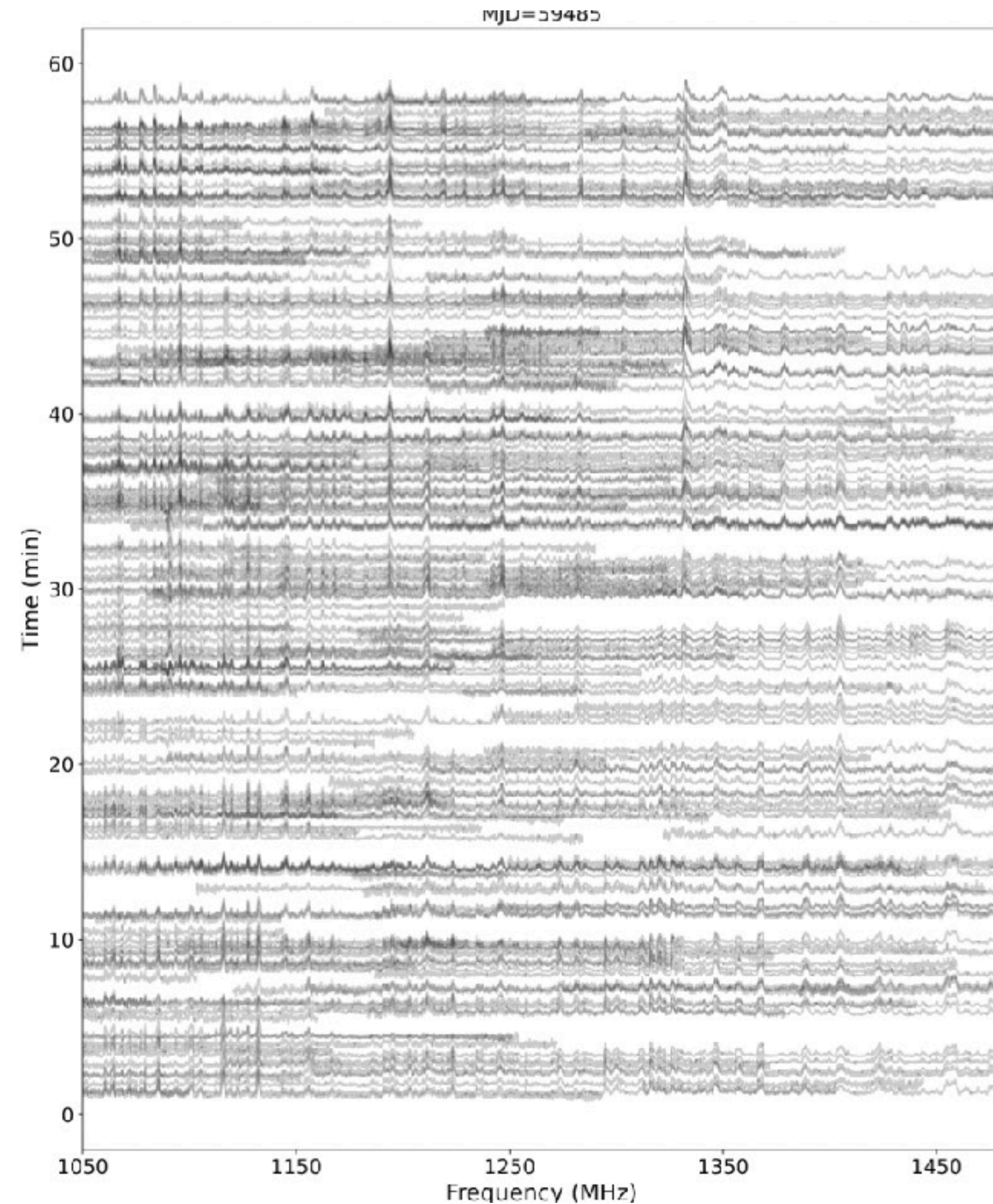
$d_{\text{sc,HG}} \sim 10$ pc, $V_{\text{FRB}} \sim 4$ km/s

Crab-like origin: $\eta \sim 6\text{E-}4 \text{ s}^3$



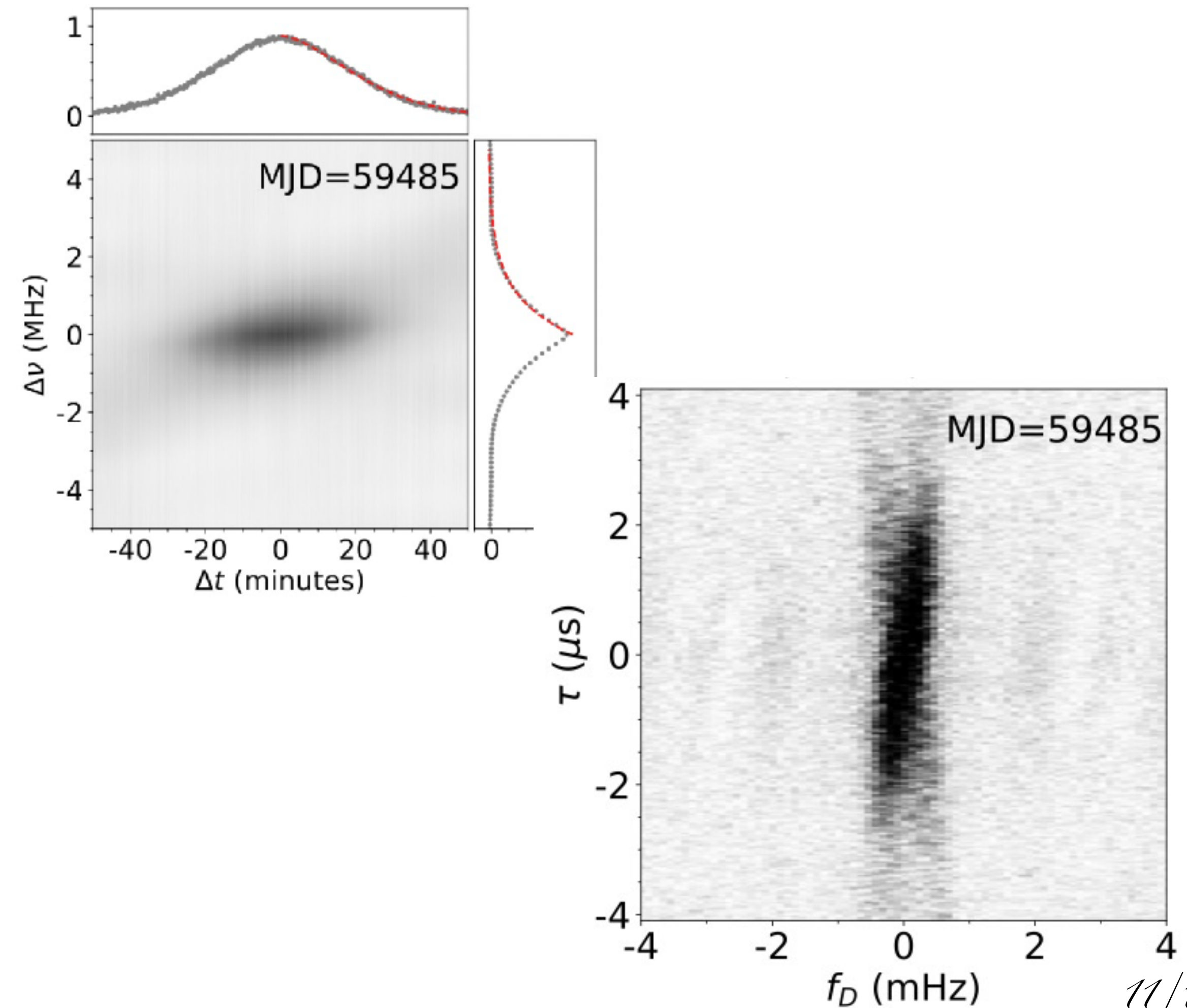
FRB 20201124A (Wu et al. ApJL, 2024b)

- Dynamic spectrum



283 bright bursts
per hour

- ACF and secondary spectrum



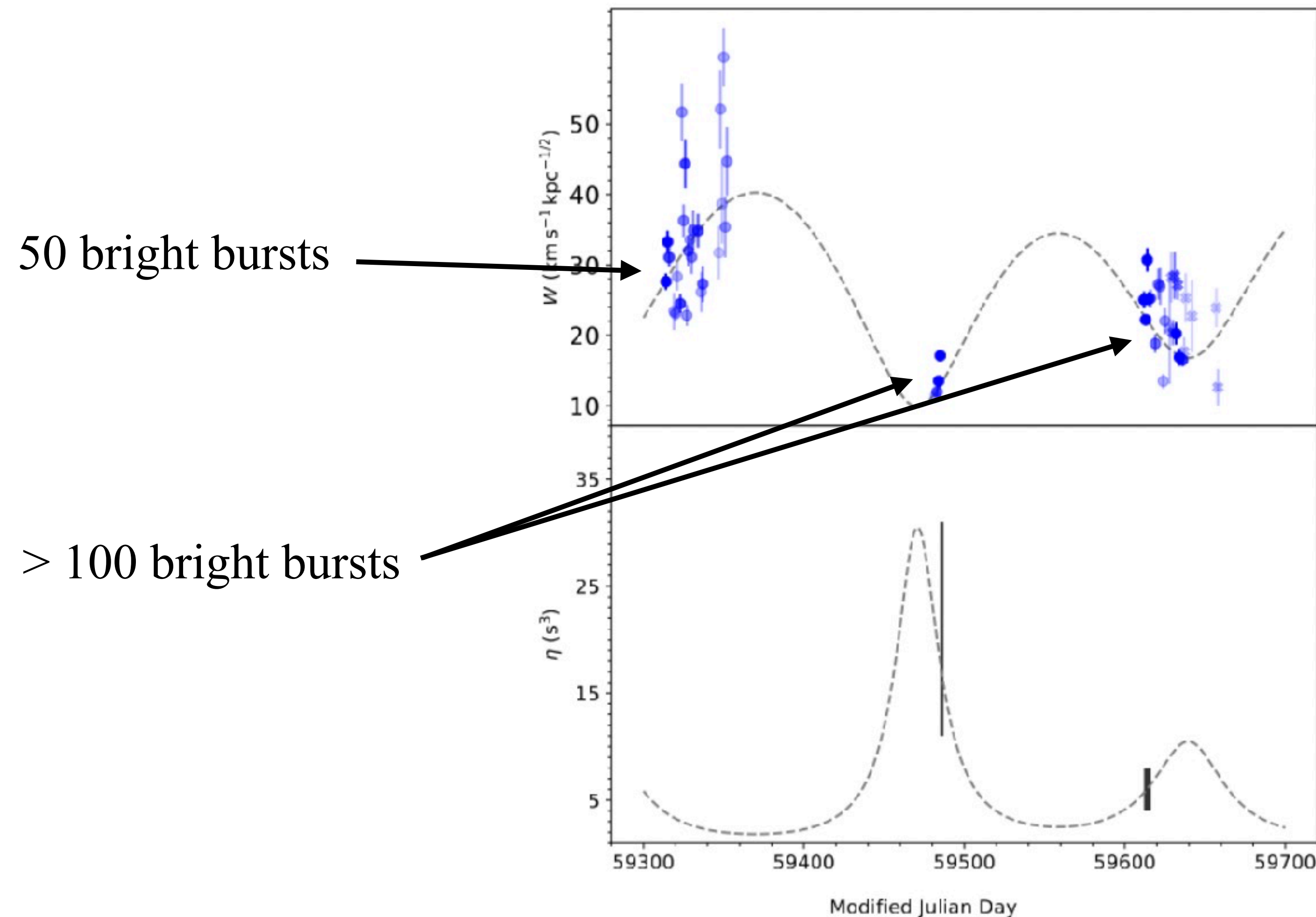
FRB 20201124A (Wu et al. ApJL, 2024b)

- Annual variation in scintillation velocity

51 observations spanning ~a year

The brightness of scintillation velocity depends on the number of blocks of data of each observation.

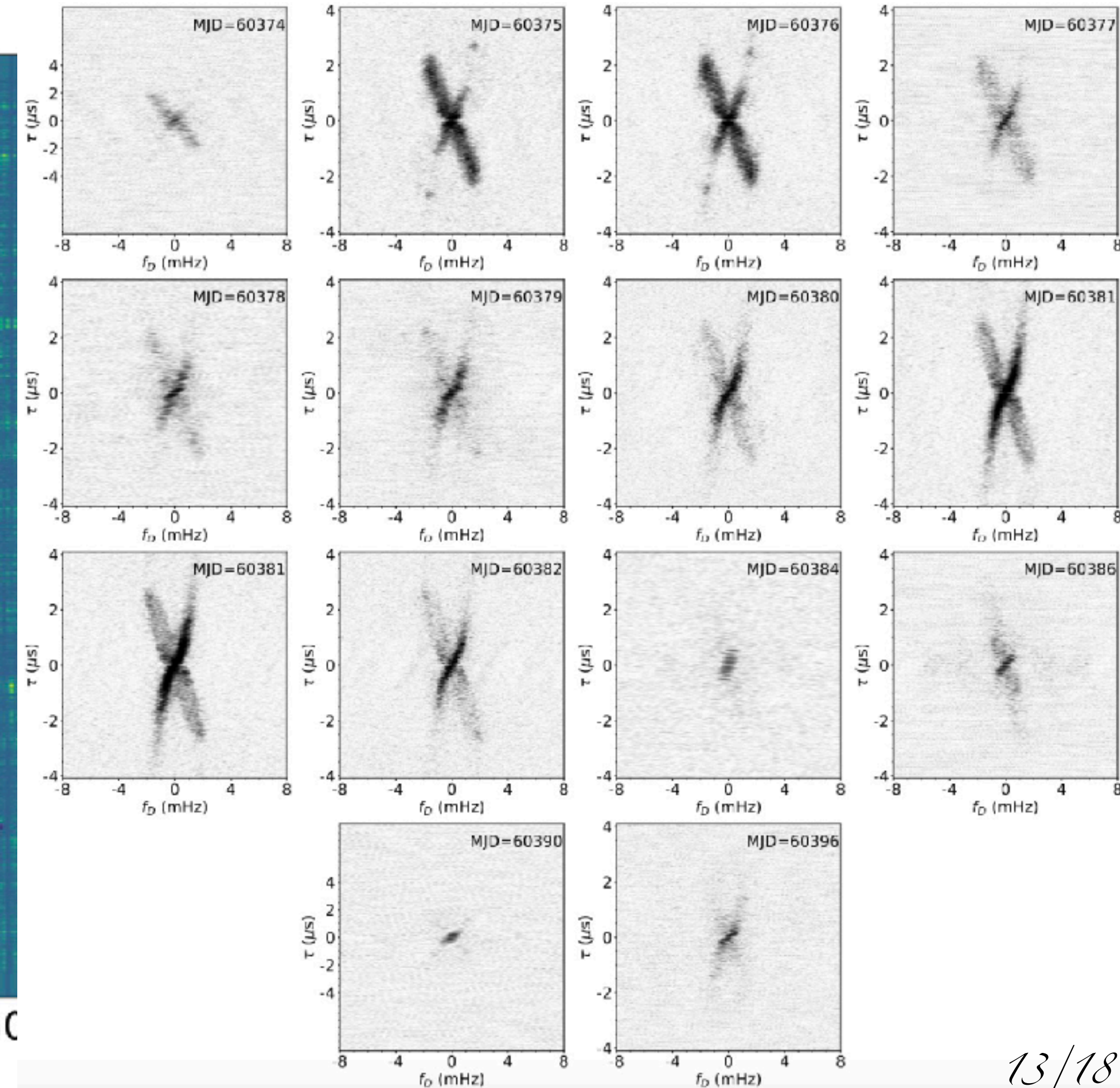
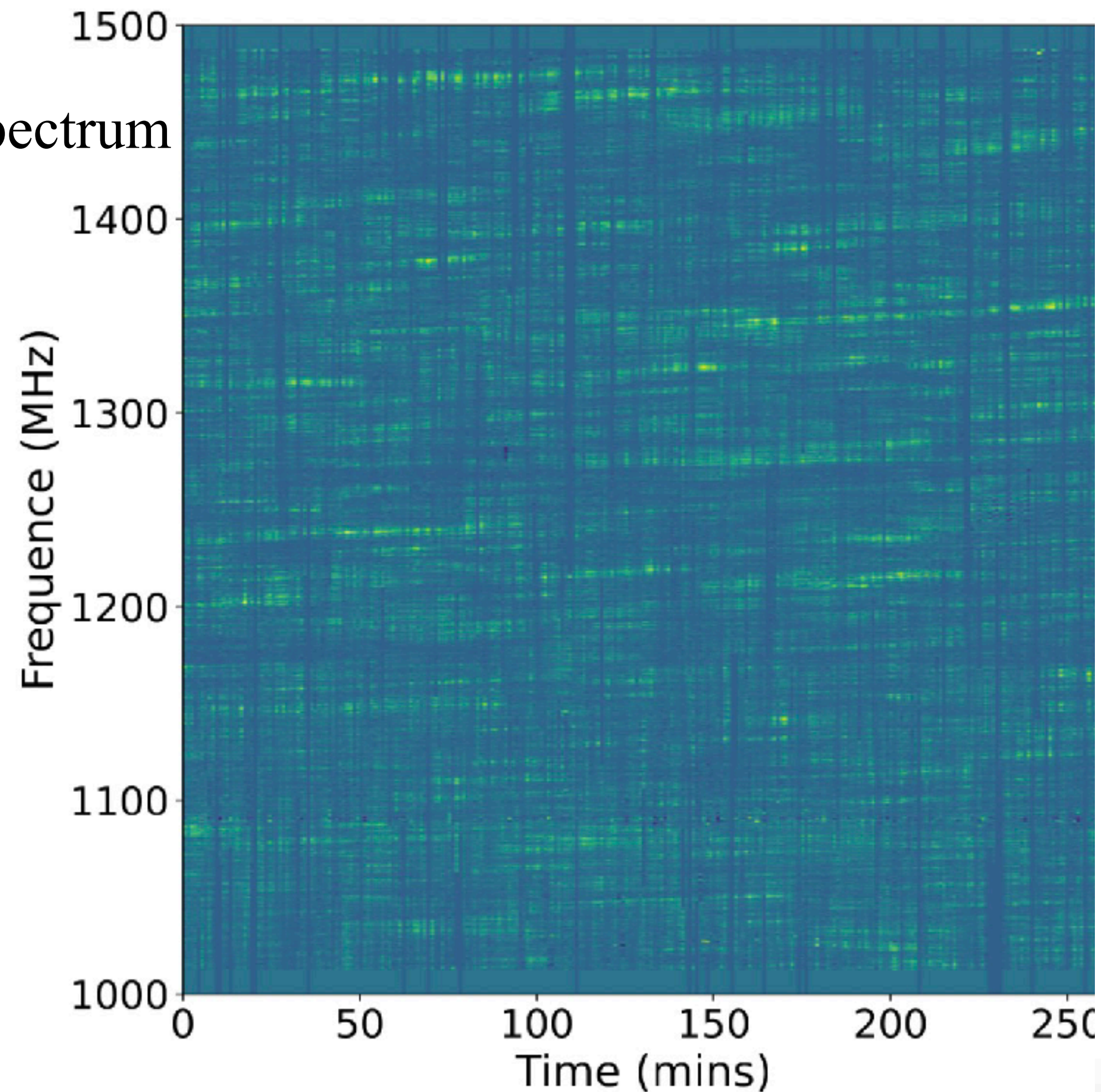
$d_{\text{sc}} = 0.4 \pm 0.1$ kpc from earth



FRB 20240114A (Wu et al, in preparation)

- A new record of FRB event rate: > 500 per hour

Restructured dynamic spectrum



FRB Long Term ISS Monitoring

Possible evolution patterns of scintillation velocity:

Case 1: Annual variation -> IISM near earth

Case 2: Non-annual periodic variation -> orbital motion of FRB

Case 3: near constant -> FRB transverse velocity

Case 4: linear variation -> expanding supernova -> age of FRB

.....

Single pulse based ISS on pulsars

Potential sources:

- To resolve scintillation timescale {
1. Fast moving pulsars
 2. Pulsars surrounded by supernova remnant
- Irregular TOA {
3. Nulling pulsars
 4. RRATs
 5. Gaint pulses

Single pulse based ISS on pulsars (Wu et al. ApJL, 2025)

- Constraining the transverse velocity of RRATs:

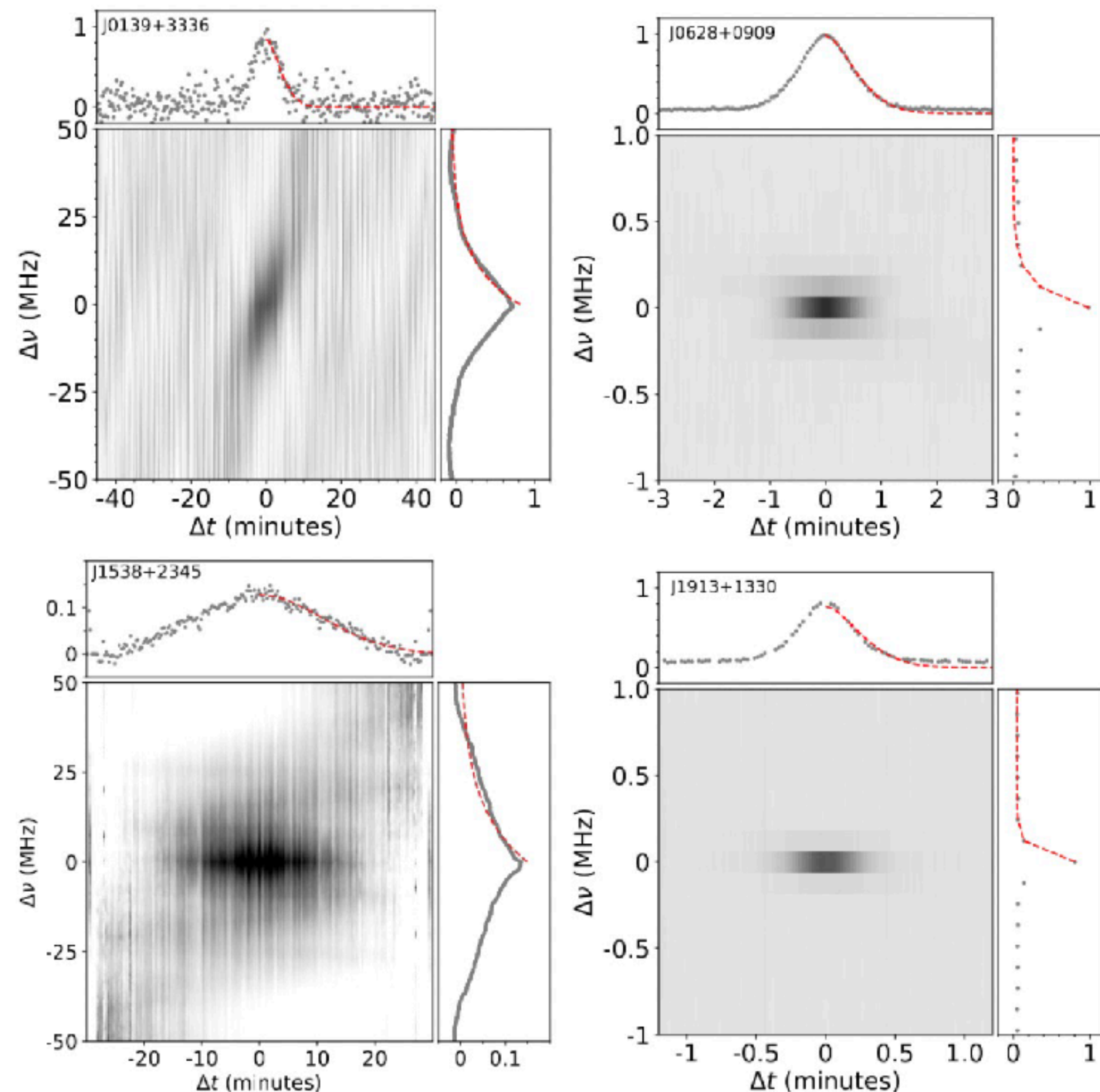
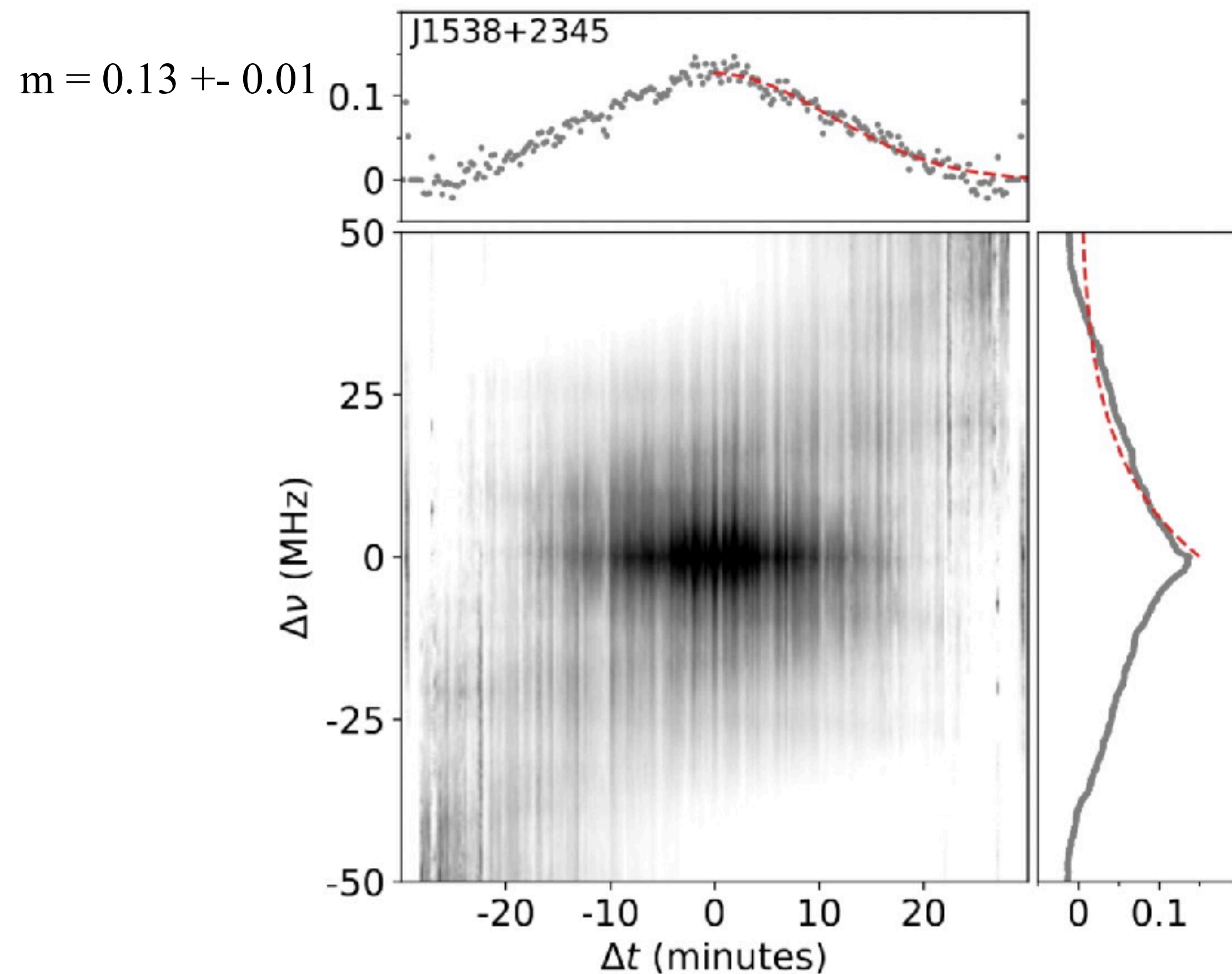


Table 1. Summary of FAST observations and scintillation properties of selected RRATs

RRATs	DM ($\text{cm}^{-3} \text{ pc}$)	P (second)	Time (MJD)	T_{obs}/P	N_p	$\Delta\nu_d$ (MHz)	τ_d (mins)	V_T (km s^{-1})	Note
J0103+54	55.6	0.4	59512	10160	0	...	...	...	No pulse
J0139+3336	21.2	1.2	58865	9616	110	4.7 ± 0.4	6.5 ± 0.2	138 ± 20	...
J0628+0909	88.3	1.2	59511	3094	162	< 0.122	0.72 ± 0.02	$< 226 \pm 30$	...
J1538+2345	14.9	3.4	58338	521	159	13.4 ± 2.2	11.1 ± 1.8	120 ± 30	...
J1854+0306	192.4	4.6	58842	829	162	...	...	...	limited Δf
J1913+1330	175.6	0.9	58833	11858	555	< 0.122	0.34 ± 0.02	$< 870 \pm 100$	...

Single pulse based ISS on pulsars (Wu et al. ApJL, 2025)

- Resolving the emission region



The modulation index:

$$m = \frac{1}{\sqrt{1 + 4\delta^2}}$$

The physical resolution of screen:

$$\Delta x = \frac{\lambda}{\sqrt{2\pi}} \sqrt{\frac{d_p - d_s}{2c\tau} \frac{d_p}{d_s}}$$

The scattering timescale:

$$\tau = \frac{\sqrt{1 + 4\delta^2}}{2\pi\Delta\nu_d}$$

Assuming a halfway location:

$R_{\{e\}} \sim \text{light-cylinder radius}$

The key point:

Properties of screen

References

1. Wu, Ziwei, Zhu, Weiwei, et al. 2025, ApJL, 982, 2, L49
2. Wu, Ziwei, Zhu, Weiwei, Zhang, B., et al. 2024, ApJL, 969, 1, L23
3. Wu, Ziwei, Main, R. A., Zhu, Weiwei, et al. 2024, Science China Physics, Mechanics, and Astronomy, 67, 1, 219512