# Discovery of a radio-emitting neutron star with an ultra-long spin period of 76 s

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2022.6

# Contents

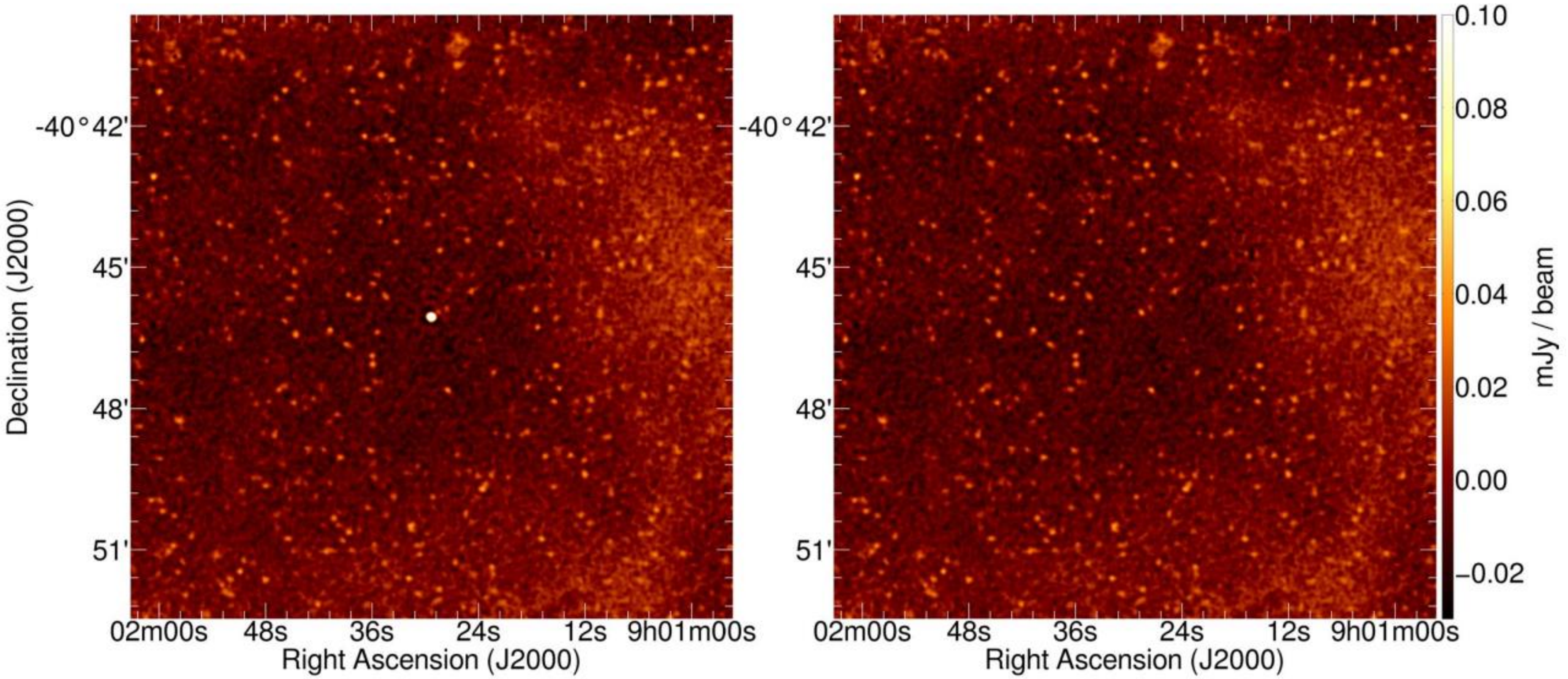
# I. Discovery and basic properties

2020/9/27 MeerKAT in South Africa

MeerTRAP and ThunderKAT projects, directed at HMXB Vela X-1

Image and time domain searches' data review (1.284MHz)

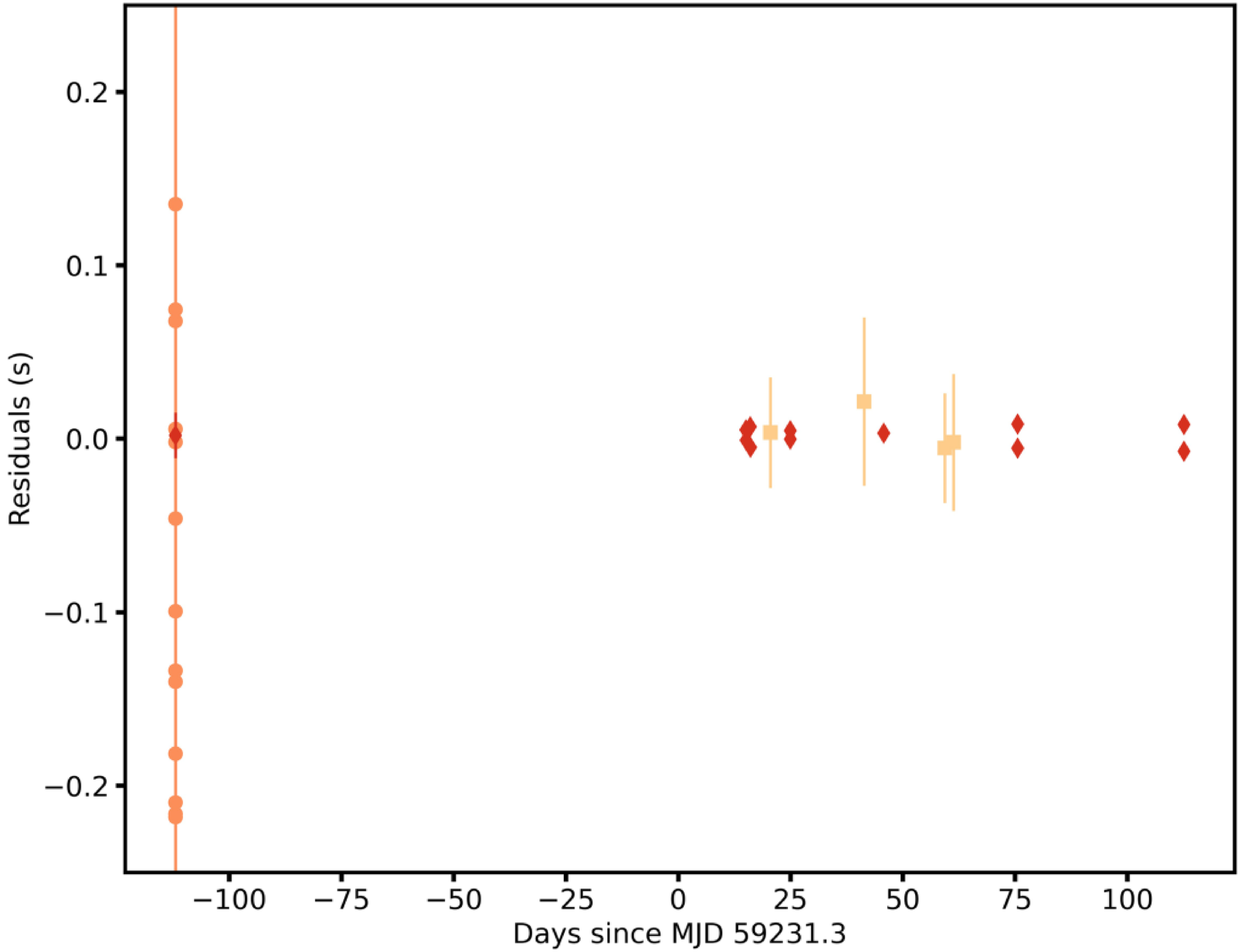
➔➔➔Find weaker pulses with period 75.89±0.01s




https://www.engineeringnews.co.za/article/meerkat-telescope-takes-part-in-start-of-new-era-of-astronomy-2017-10-16

MeerKAT image: a point source and a shell-like structure, no pulsars in 2° nearby.

**Follow up:** 6 L-band (856-1712MHz) and 1 UHF band (544-1088MHz) observations during 2020/9-2021/5. Pulsar timing is made with 29 ToAs.




Orange points: original MeerTRAP detection

Red diamonds: single pulses (MeerKAT)

Light coloured: Parkes UWL observation

**Table 2 | MeerKAT observations of the PSR J0901-4046 field**

| Date (UT, J2000) | Block ID | RA (J2000) | Dec (J2000) | Band | $N_{ant}$ | $T_{obs}$ (h) | $T_{int}$ (s) | Origin |
|---|---|---|---|---|---|---|---|---|
| 25 September 2020 | 1600995961 | 09 h 02 min 06.86 s | −40°33′16.9″ | L | 59 | 0.5 | 8 | TKAT |
| 27 September 2020 | 1601168939 | 09 h 02 min 06.86 s | −40°33′16.9″ | L | 61 | 0.5 | 8 | TKAT |
| 11 October 2020 | 1602387062 | 09 h 02 min 06.86 s | −40°33′16.9″ | L | 60 | 0.5 | 8 | TKAT |
| 1 February 2021 | 1612141271 | 09 h 01 min 29.35 s | −40°46′03.6″ | L | 64 | 1 | 2 | DDT |
| 2 February 2021 | 1612227667 | 09 h 01 min 29.35 s | −40°46′03.6″ | L | 61 | 1 | 2 | DDT |
| 10 February 2021 | 1612994791 | 09 h 01 min 29.35 s | −40°46′03.6″ | L | 62 | 1 | 2 | DDT |
| 3 March 2021 | 1614794470 | 09 h 01 min 29.35 s | −40°46′03.6″ | L | 63 | 1 | 2 | DDT |
| 2 April 2021 | 1617367872 | 09 h 01 min 29.35 s | −40°46′03.6″ | L | 63 | 1 | 2 | DDT |
| 2 April 2021 | 1617376889 | 09 h 01 min 29.35 s | −40°46′03.6″ | UHF | 62 | 1 | 2 | DDT |
| 6 May 2021 | 1620567645 | 09 h 01 min 29.35 s | −40°46′03.6″ | L | 62 | 1 | 2 | DDT |

The first three rows labelled TKAT are discovery observations targeting the Vela X-1 field, while the rest labelled DDT are follow-up observations. $N_{ant}$, $T_{obs}$ and $T_{int}$ represent the number of antennas, the total time spent on target, and the correlator integration time per visibility point.

# L-band timing results are as follows

| Variable | Value |
|---|---|
| Data and model fit quality | |
| Modified Julian date (MJD) range | 59119.0 to 59343.6 (7.4 months) |
| Number of TOAs | 29 |
| Weighted r.m.s. timing residual | 5.7 ms |
| Measured quantities | |
| Right ascension (J2000) | 09 h 01 min 29.249 s ± 1.0″ |
| Declination, $\delta$ (J2000) | −40° 46′ 02.984″ ± 1.0″ |
| Pulse frequency, $\nu$ | $0.013177739873 \pm 9.9 \times 10^{-12}\ s^{-1}$ |
| First derivative of pulse frequency, $\dot{\nu}$ | $-3.9 \pm 0.2\ s^{-2}$ |
| Pulse period, $P$ | $75.88554711 \pm (6 \times 10^{-8})$ s |
| Period derivative, $\dot{P}$ | $(2.25 \pm 0.1) \times 10^{-13}\ s\ s^{-1}$ |
| Dispersion measure, DM | $52 \pm 1\ pc\ cm^{-3}$ |
| Full-width at half-maximum, $W_{50}$ (L band) | 299 ± 1 ms |
| Full-width at half-maximum, $W_{50}$ (UHF band) | 296 ± 4 ms |
| Spectral index, $\alpha$ | −1.7 ± 0.9 |
| Rotation measure, RM | $-64 \pm 2\ rad\ m^{-2}$ |
| Fractional linear polarization | 12.2 ± 0.2% |
| Fractional circular polarization | 21.0 ± 1.9% |
| Inferred quantities | |
| Distance (YMW16), $d_1$ | 328 pc |
| Distance (NE2001), $d_2$ | 467 pc |
| Characteristic age, $_c$ | 5.3 Myr |
| Surface dipole magnetic field strength, $B$ | $1.3 \times 10^{14}$ G |
| Spin-down luminosity, $\dot{E}$ | $2.0 \times 10^{28}\ erg\ s^{-1}$ |
| Period-averaged radio luminosity, $L_{1,400}$ at $d_2$ | $89\ \mu Jy\ kpc^2$ |
| X-ray Luminosity, $L_X$ (0.5–10 keV) at $d_2$ | $\lesssim 3.2 \times 10^{30}\ erg\ s^{-1}$ |

Uncertainties in parentheses as 1$\sigma$ errors on the last significant quoted digit

# Some comments in the article:

| | |
|---|---|
| Full-width at half-maximum, $W_{50}$ (L band) | $299 \pm 1$ ms |
| Full-width at half-maximum, $W_{50}$ (UHF band) | $296 \pm 4$ ms |

(i) No evidence for radius-to-frequency mapping

| | |
|---|---|
| Pulse period, $P$ | $75.88554711 \pm (6 \times 10^{-8})$ s |

(ii) Long period —— large light cylinder, compact polar cap. $R_{LC} = cP/2\pi = 3.62 \times 10^6\,\mathrm{km}$

Consistent with pulsars' W-P relation. $R_p = \sqrt{2\pi R^3/cP} = 16.62\,\mathrm{m}$

| | |
|---|---|
| Period derivative, $\dot{P}$ | $(2.25 \pm 0.1) \times 10^{-13}\,\mathrm{s\,s^{-1}}$ |

| | |
|---|---|
| Characteristic age, $_c$ | 5.3 Myr |
| Surface dipole magnetic field strength, $B$ | $1.3 \times 10^{14}$ G |
| Spin-down luminosity, $\dot{E}$ | $2.0 \times 10^{28}\,\mathrm{erg\,s^{-1}}$ |

| | |
|---|---|
| Period-averaged radio luminosity, $L_{1,400}$ at $d_2$ | 89 μJy kpc$^2$ |

(iii) Pulse-averaged peak flux densities:

L band: $89.3 \pm 2.7\,\mathrm{mJy\,beam^{-1}}$

UHF band: $169.3 \pm 14\,\mathrm{mJy\,beam^{-1}}$

period-averaged flux density an L band: $408 \pm 5\,\mu\mathrm{Jy\,beam^{-1}}$

| | |
|---|---|
| Dispersion measure, DM | $52 \pm 1$ pc cm$^{-3}$ |

| | |
|---|---|
| Distance (YMW16), $d_1$ | 328 pc |
| Distance (NE2001), $d_2$ | 467 pc |

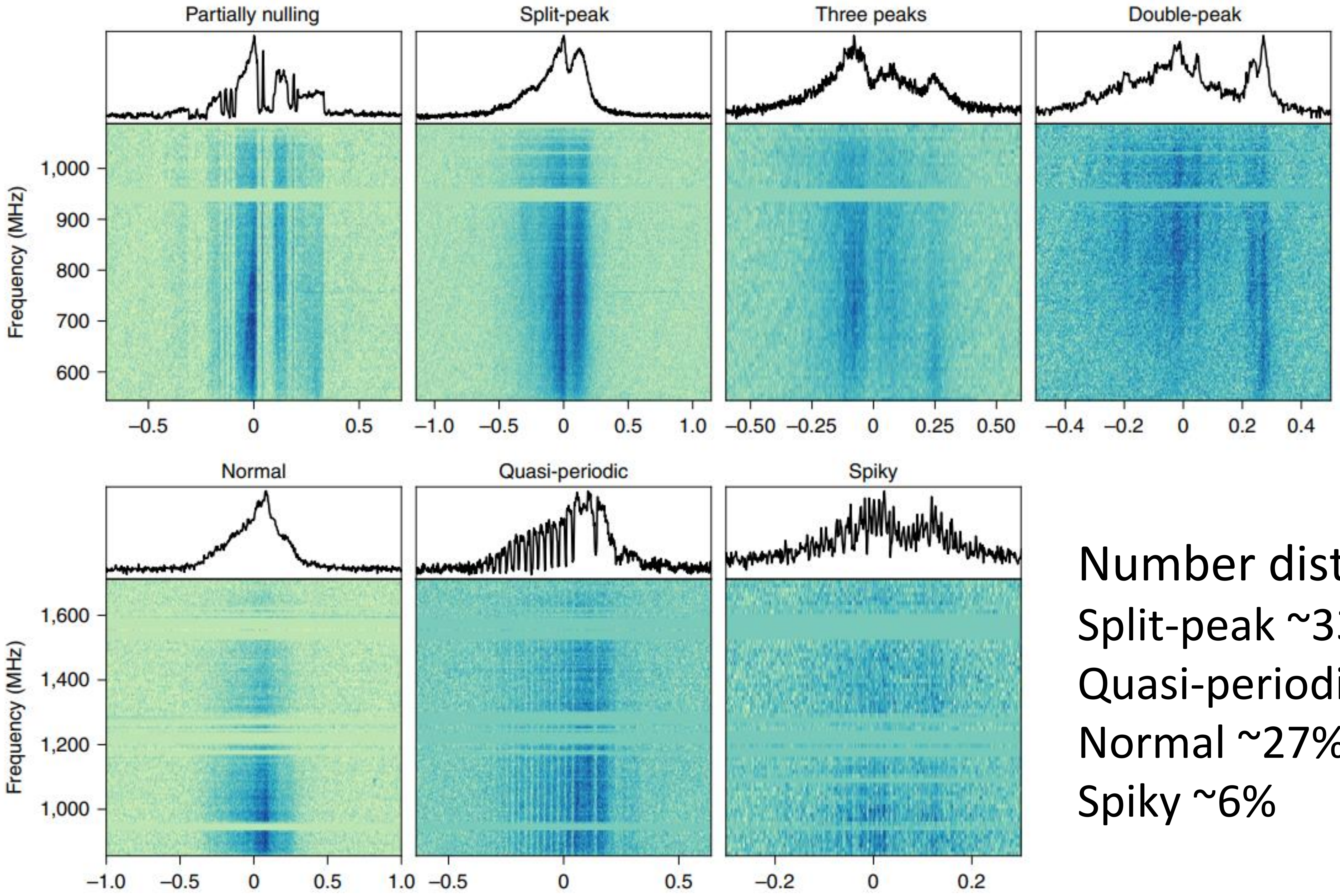
(iv) Distances calculated under different galactic electron density models.

# More discussions in the following slides

# II. Series of discussions

## (1) Single pulses' morphology

Variable both inter-epoch and intra-epoch.
Grouped into 7 different types:



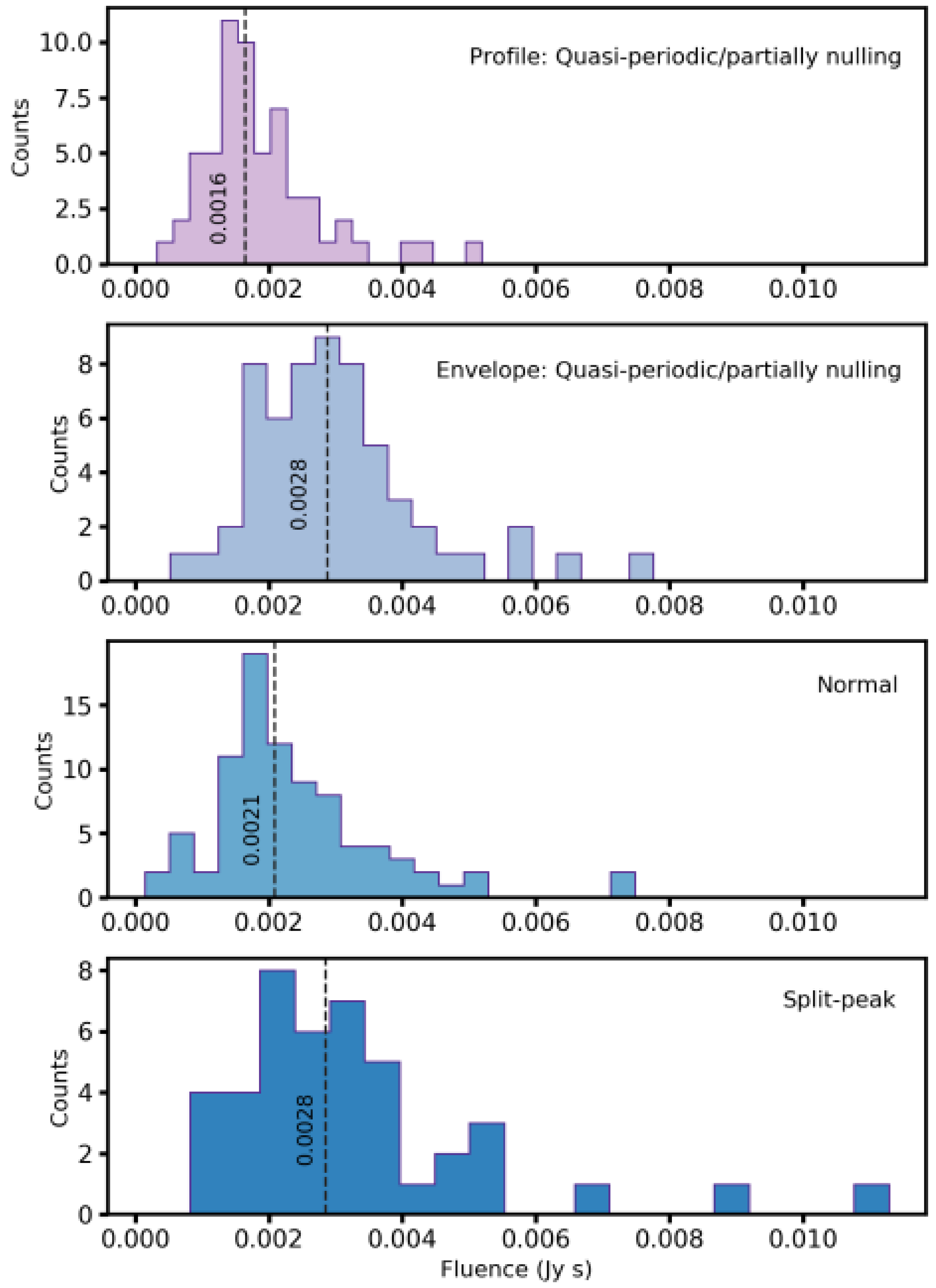

Number distribution:
Split-peak ~33%
Quasi-periodic and partially nulling ~34%
Normal ~27%
Spiky ~6%

# Energy distribution:

For quasi-periodic and partially nulling, 40% energy is lost in the dropouts/dips.

After modelling the pulse envelope, the energy distributions for different types look similar.

No overall increase in particle flow.

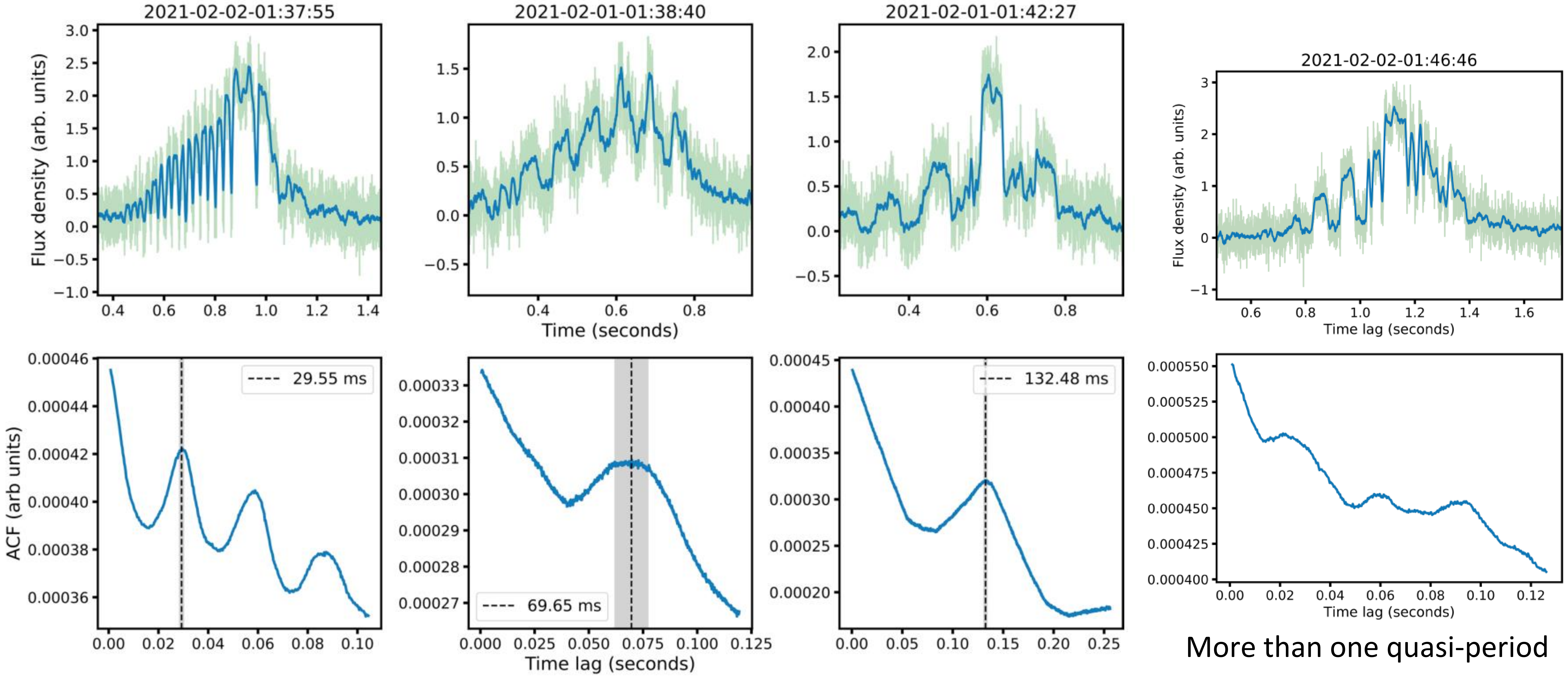



Supplementary Fig. 8

# (2) Quasi-periodicity in sub-pulses

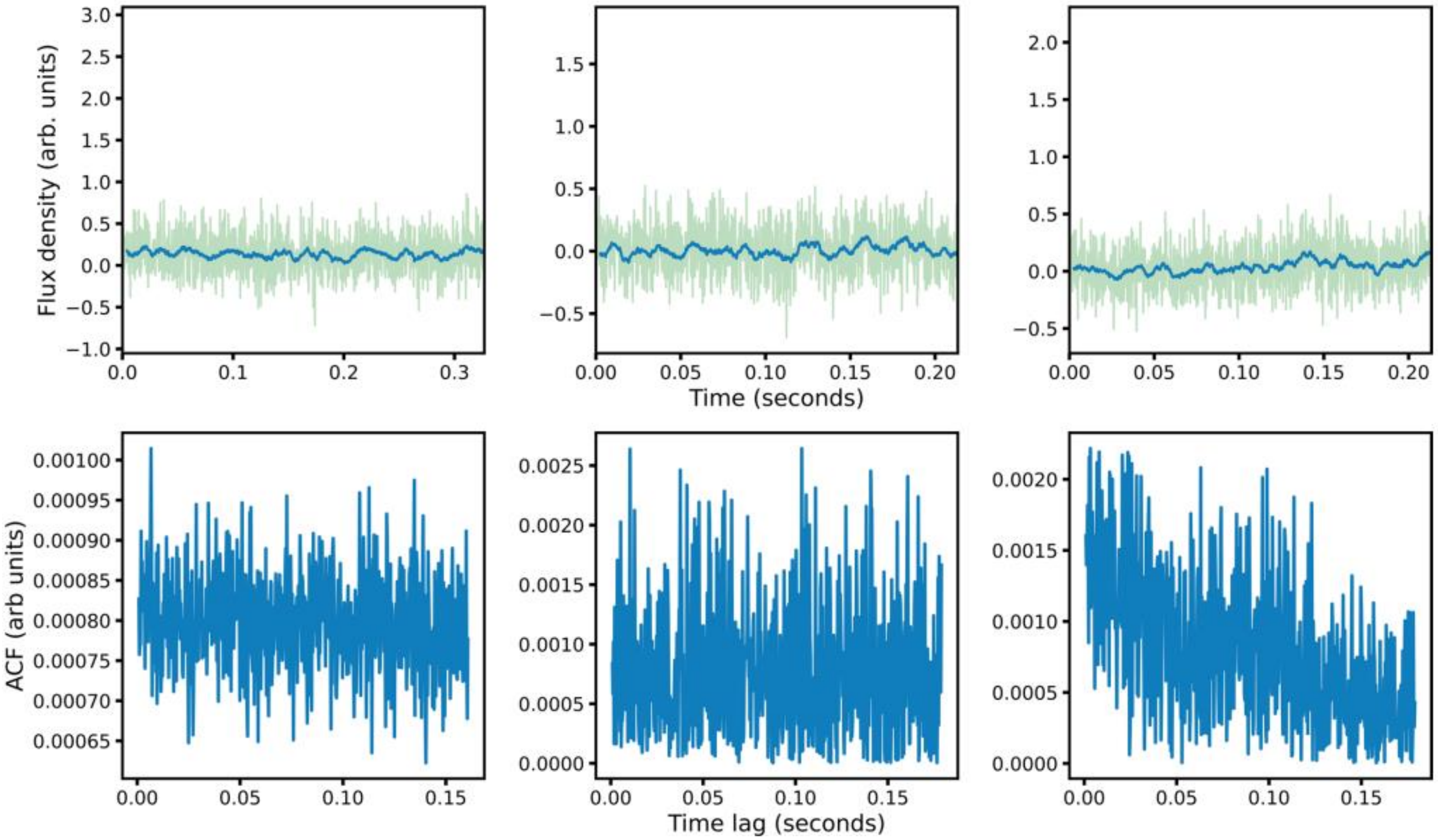
$$\mathrm{ACF}(\tau) = \int_0^t f(t) f(t-\tau)\, \mathrm{d}t$$

Auto-correlation function



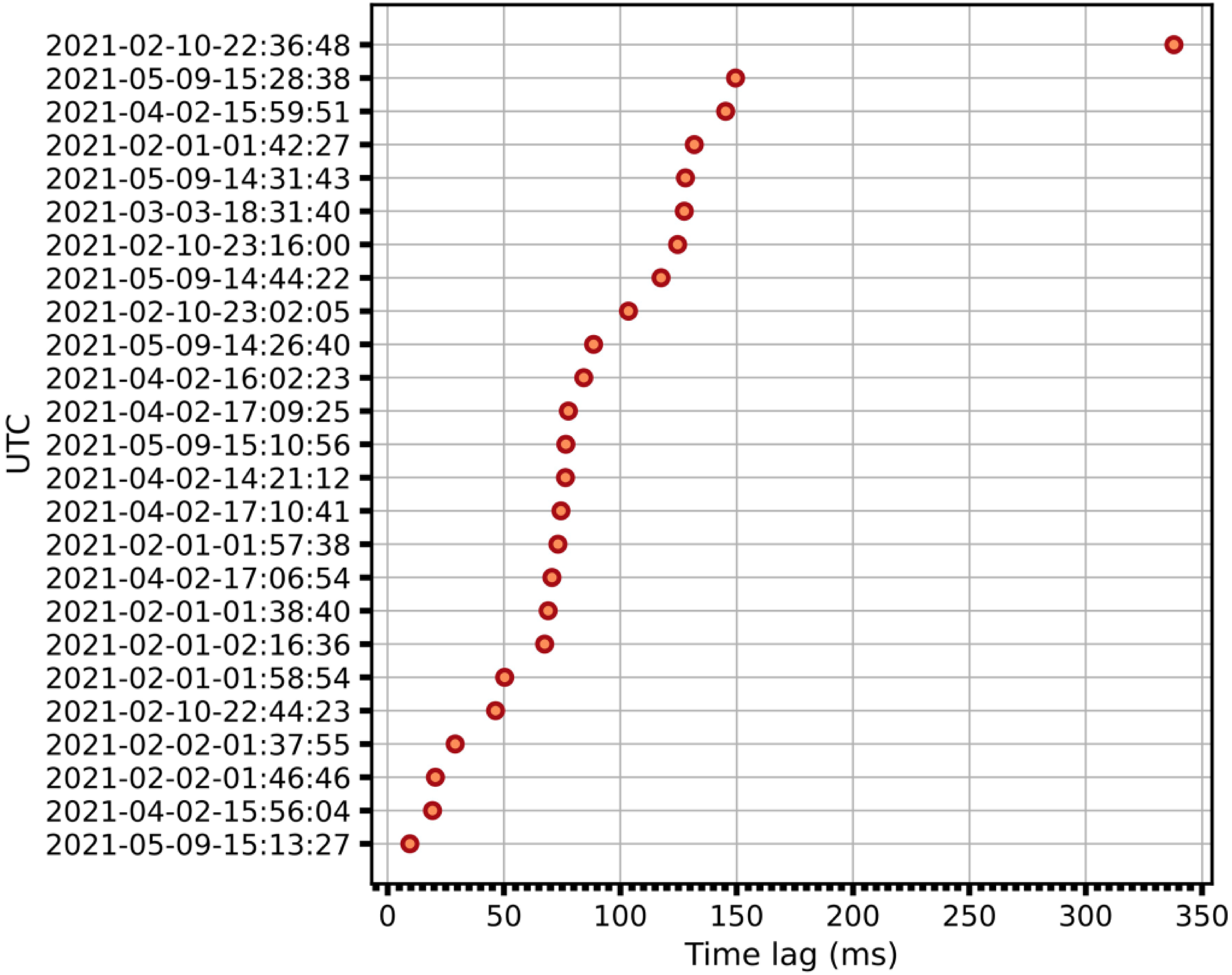

More than one quasi-period

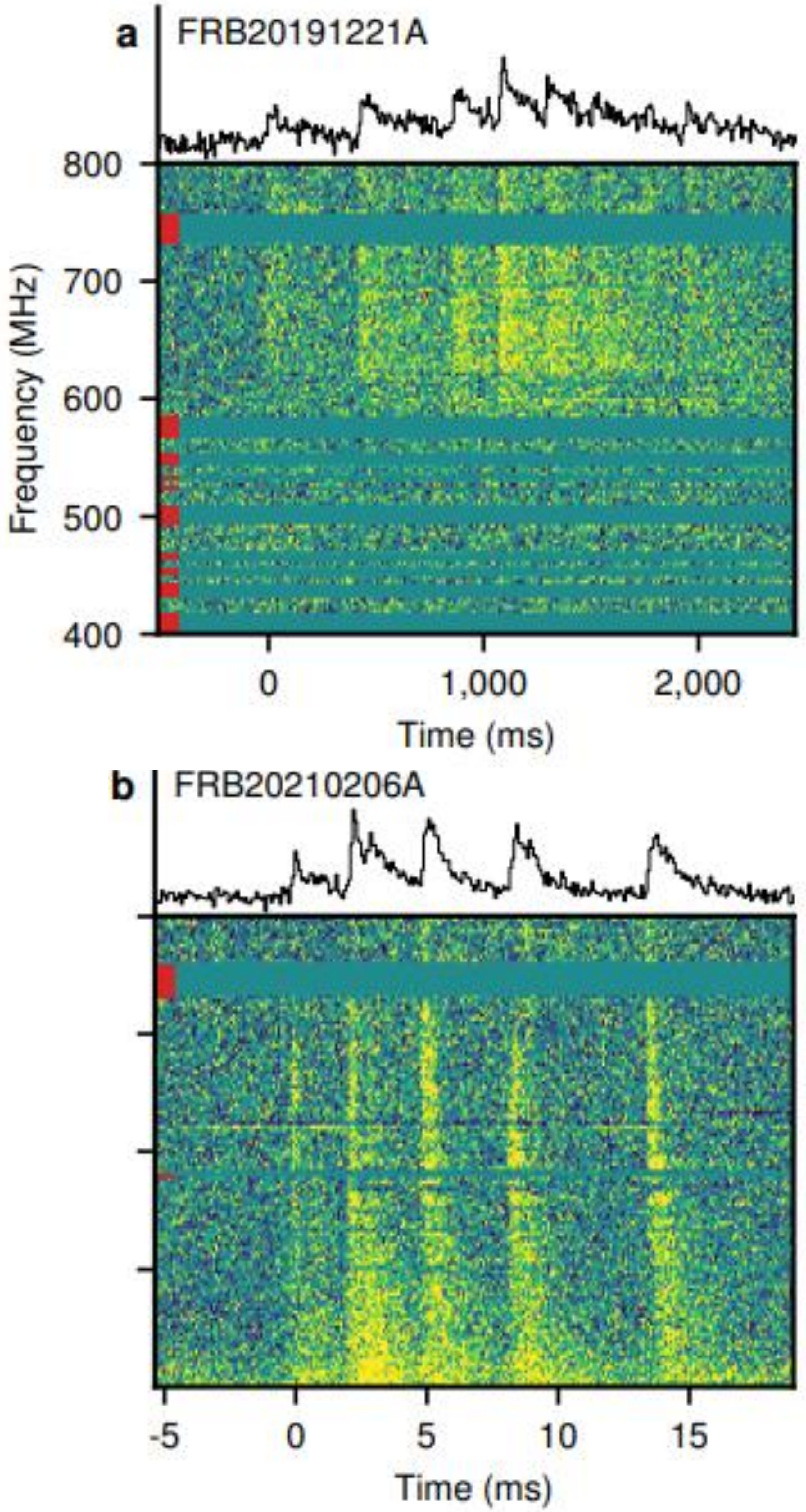
# Off-pulse region:



Quasi-periods distribution:

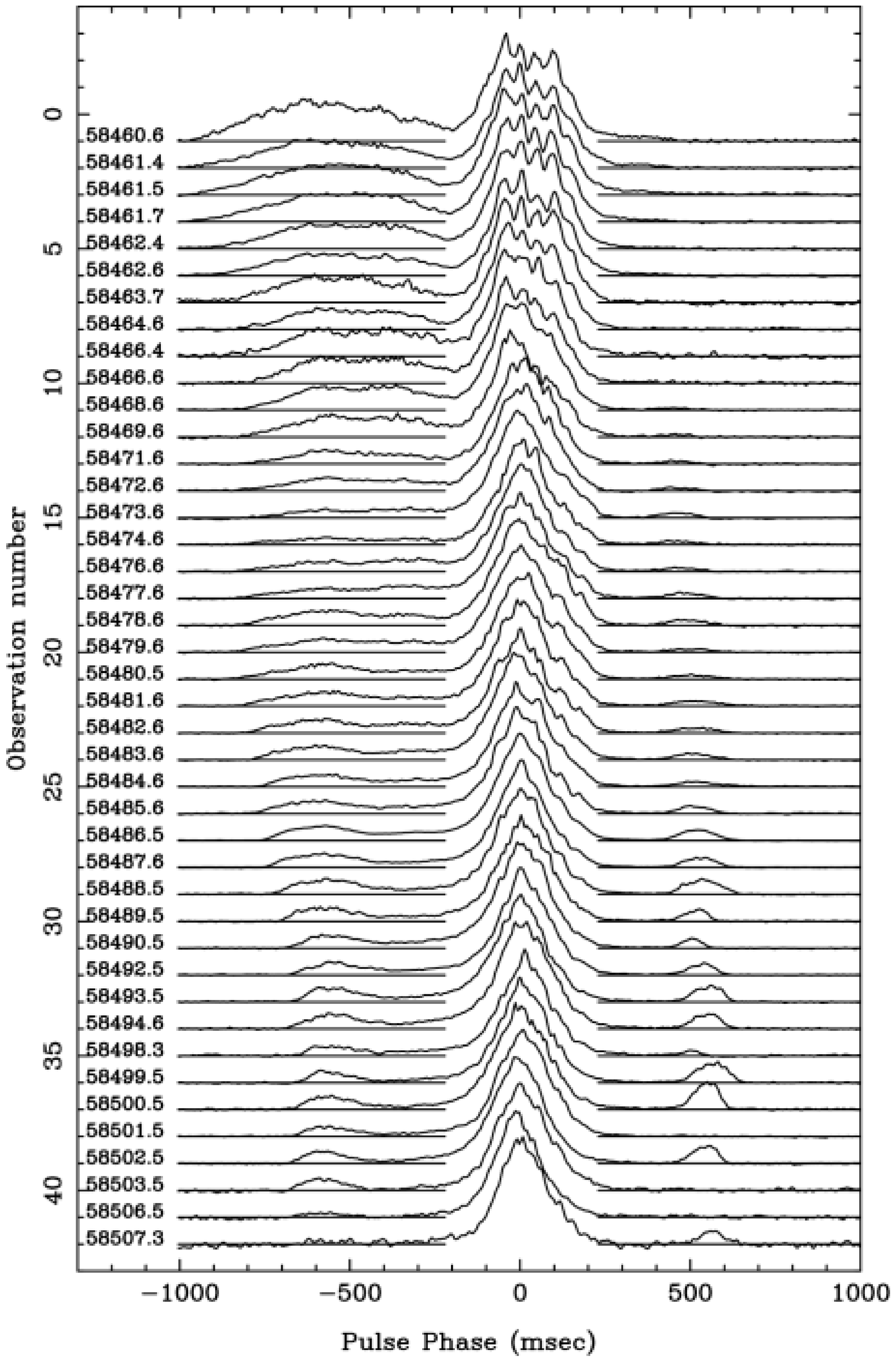
Most common: ~76ms (P/1000)



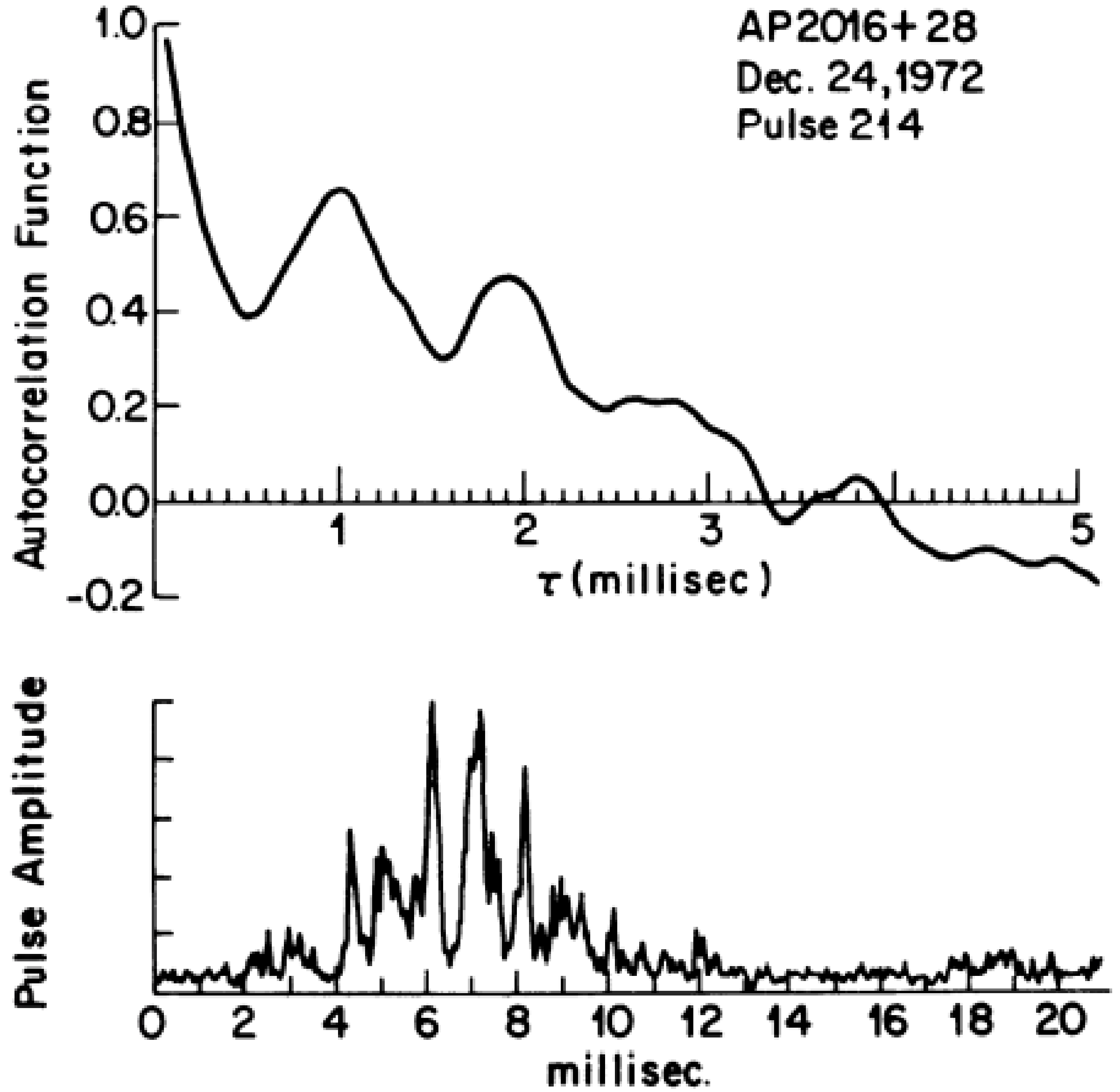



The CHIME/FRB Collaboration et al. 2021

Magnetar XTE J1810-197




Levin et al. 2019




Boriakoff 1976

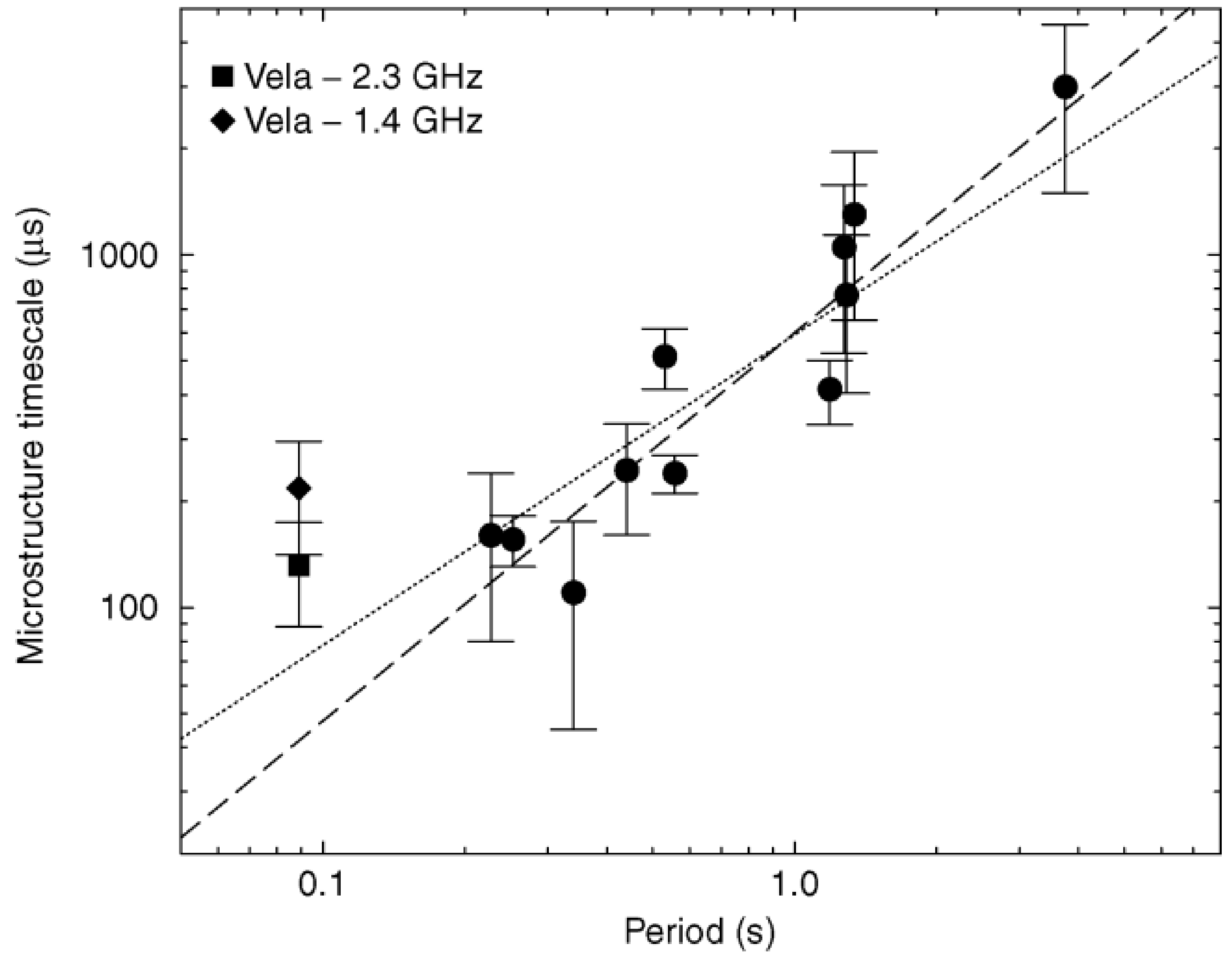
Quasi-periodic features (micro structures) in FRBs, magnetar and pulsar.

# Origin of quasi-periodicity?

——Temporal/angular mechanism of beamlets?

(quasi-period scaling with period, beamlets making up sub-pulses)

——Sub-pulses' drifting?

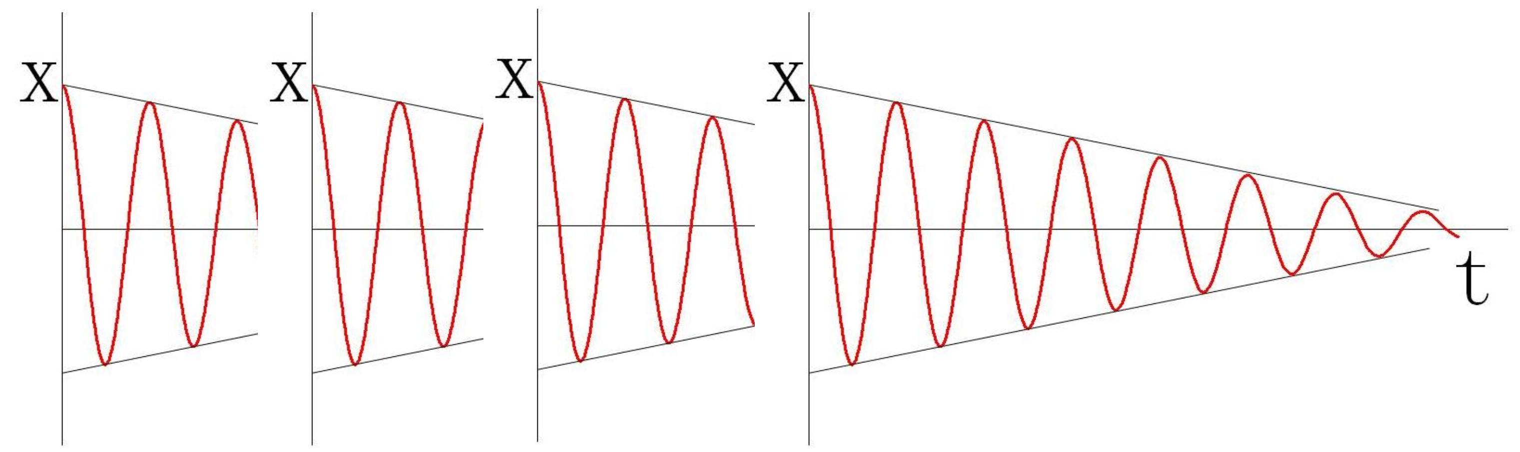



Kramer et al. 2002

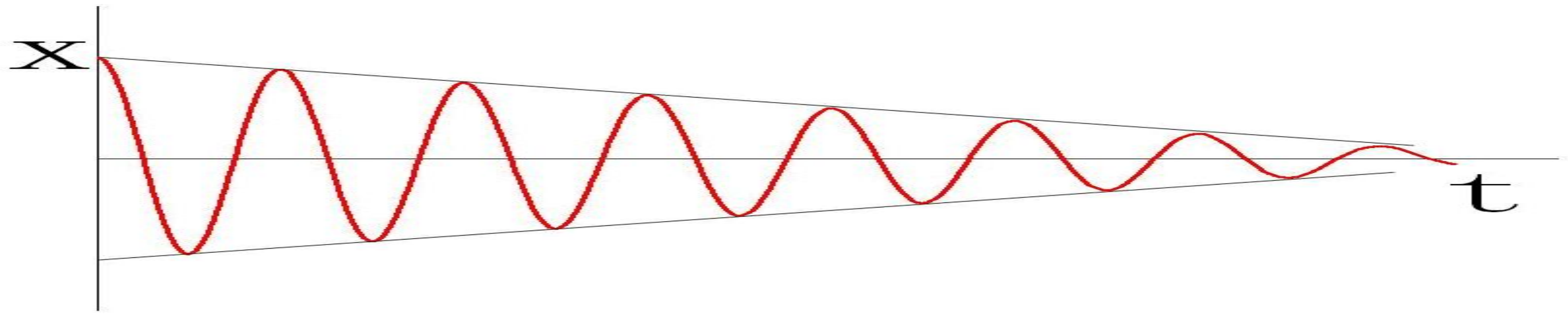
——Neutron star's magneto-elastic oscillation?

(produce Alfvén wave to the magnetosphere resulting in radio emission, an explanation for FRB)

(but for this case (pulsar-like), repeated trigger and/or very long damping times are needed)

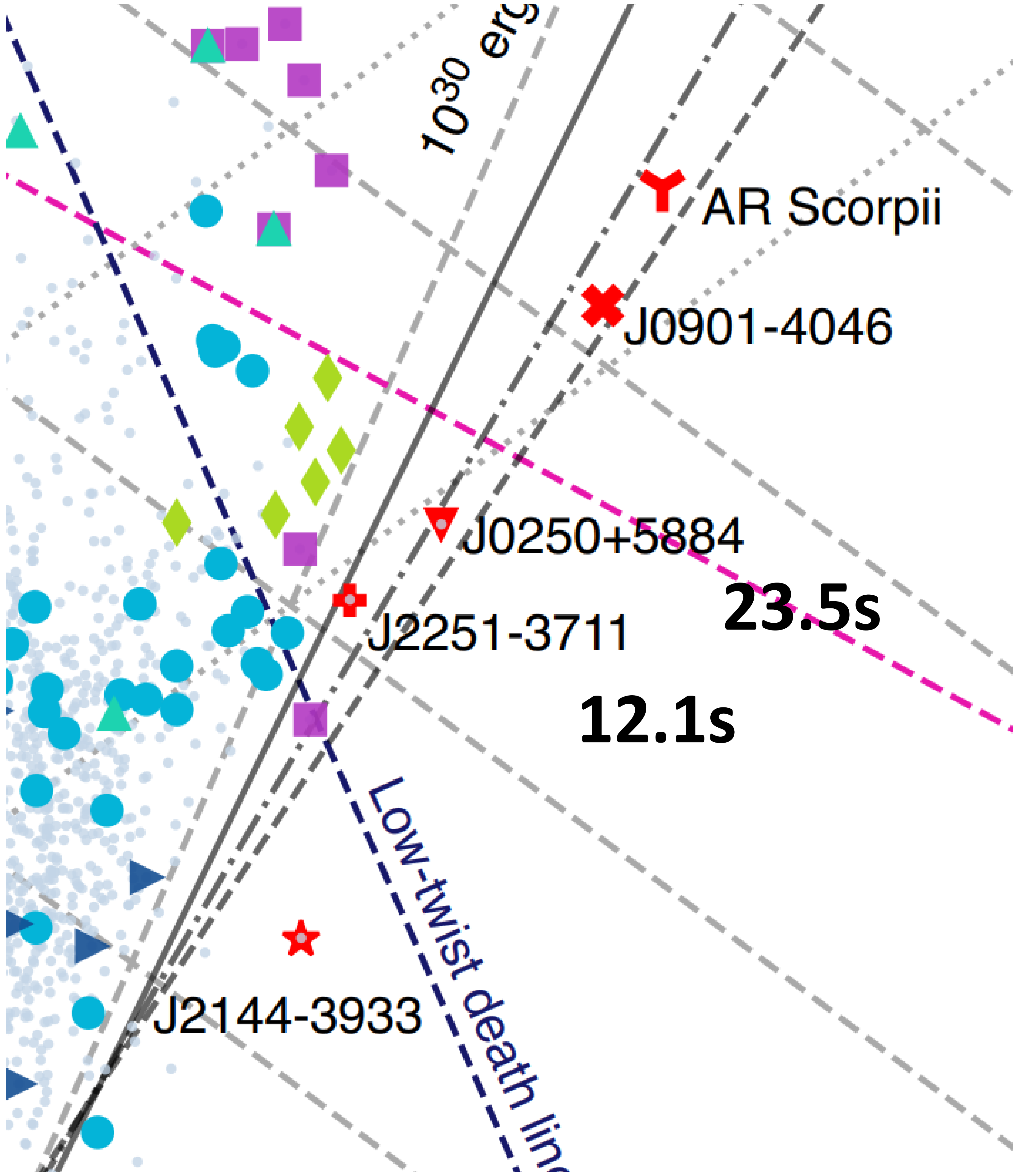



**OR**

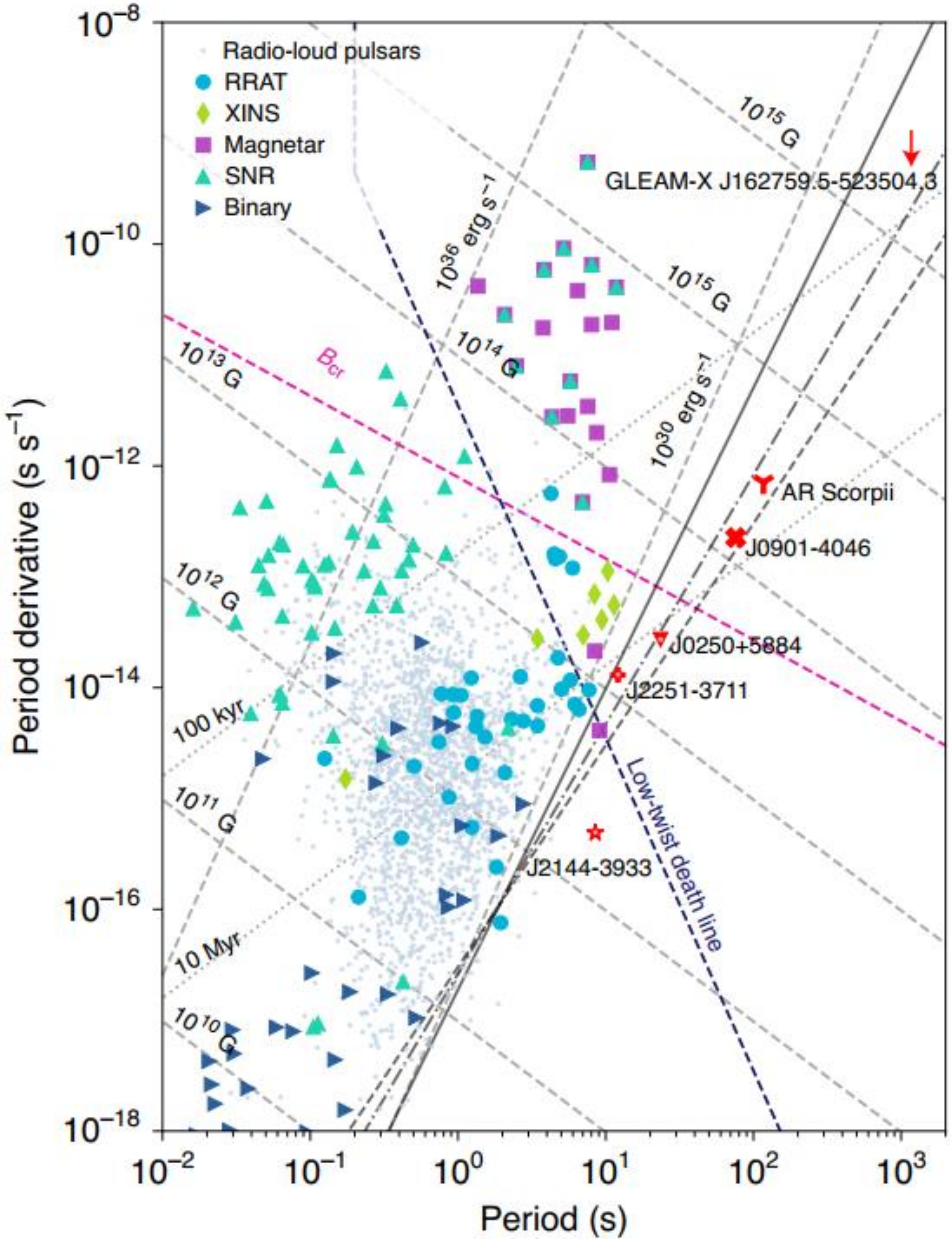



Originally from https://baike.baidu.com/item/%E5%BA%93%E4%BB%91%E9%98%BB%E5%B0%BC/10432990

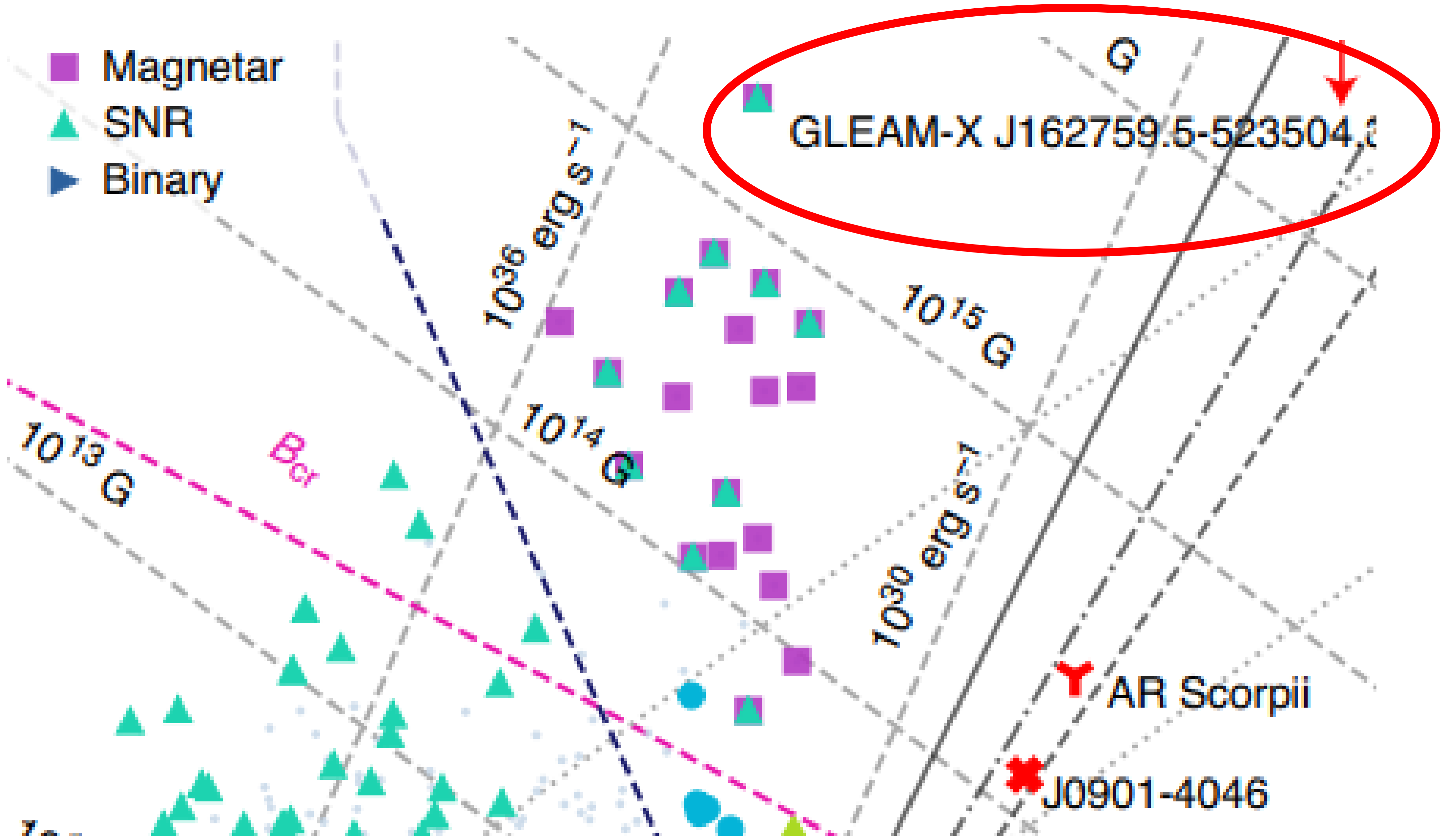
# (3) About P-Pdot diagram




J0250+5854? 84?



# J0901-4046 and magnetars?




Offset from the known magnetar population.

A **ultra-long-period magnetar**?
(ULPM, Beniamini et al. 2020)
It's above the low-twisted death line.

CLEAM-X J162759.5-523504.3
(Hurley-Walker et al. 2022)
may be a ULPM.

**An old magnetar?**
——Characteristic soft X-ray emission, but no radio emission detected so far.
(Yoneyama et al. 2019, Vigano et al. 2013)

# J0901-4046 also differs from common magnetars in:

——No radical changes in P-dot observed.

——Spectral index:

| | |
|---|---|
| Spectral index, $\alpha$ | $-1.7 \pm 0.9$ |

Magnetars' radio spectral is shallow,
J0901-4046's spectral index is like pulsars.

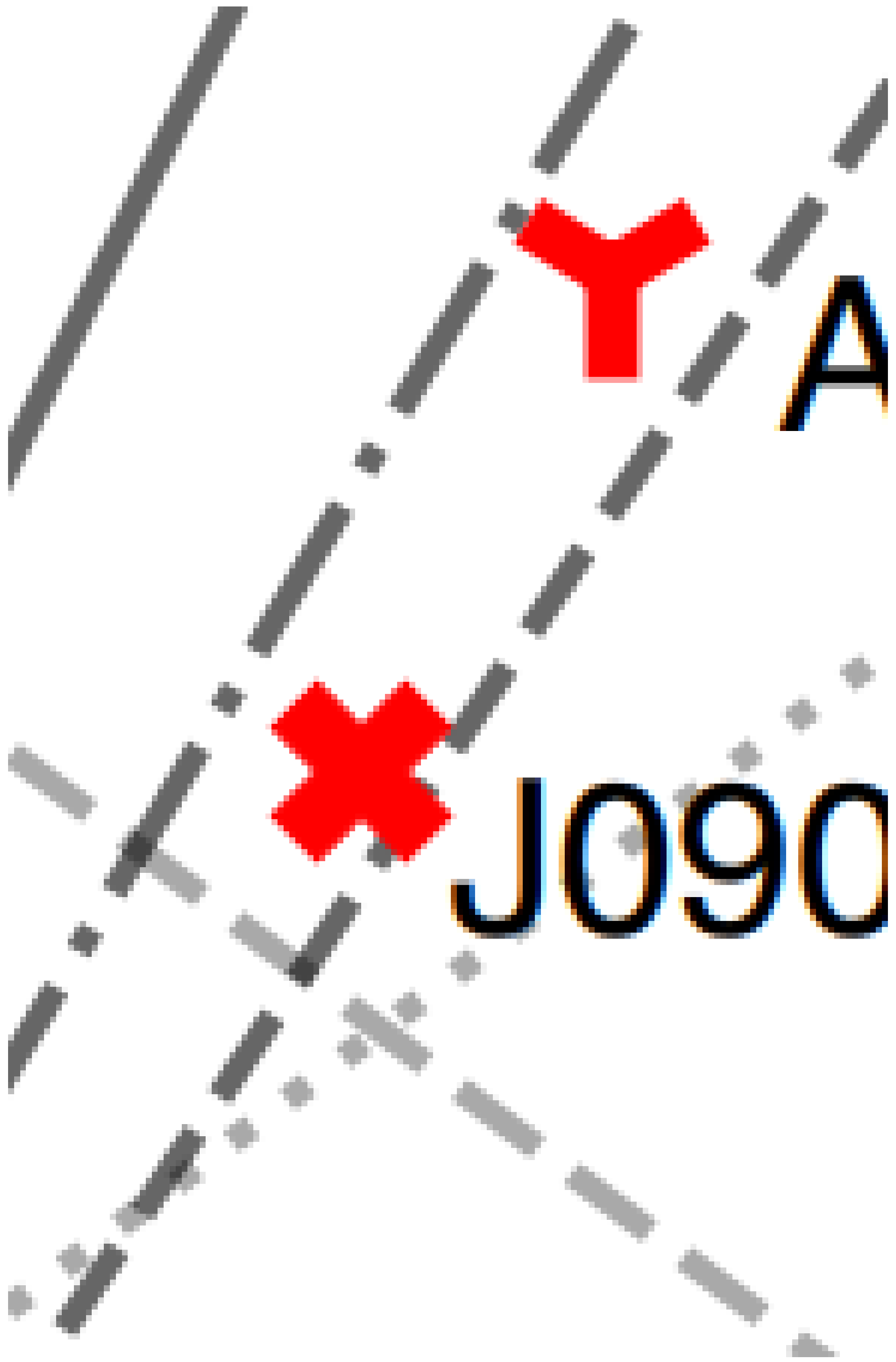
——Small duty cycle.

# J0901-4046 and death lines:

Beyond the **vacuum gap curvature radiation** death line
Above the **space-charge-limited flow** death line.

Space-charge-limited flow (Arons & Scharlemann 1979):
Free flow of charges from pulsar surface, interacting with multipole field, pair cascade happens……

——Multipolar magnetic field may play an important role on J0901-4046's surface.

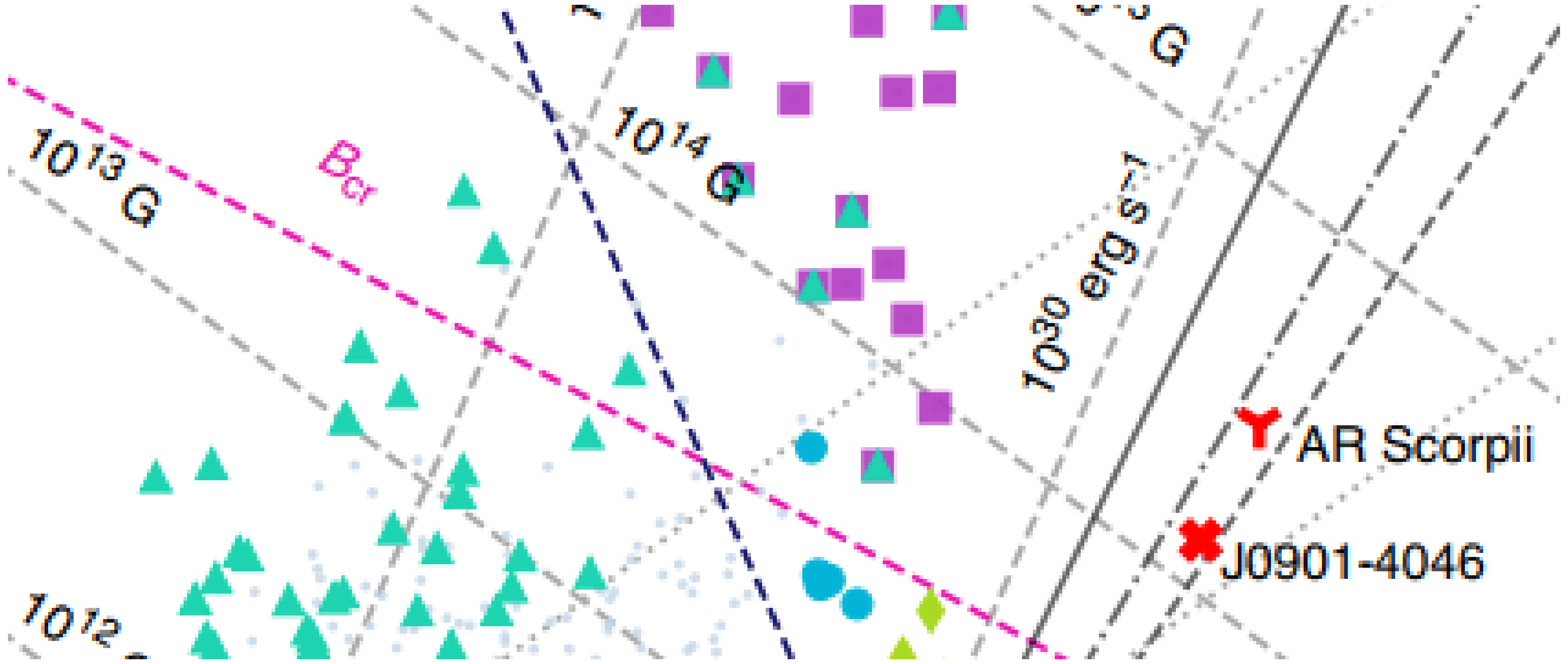


# J0901-4046 and B lines:

$$B_{cr} = 4.413 \times 10^{13}\,\mathrm{G}$$

Above $B_{cr}$: “radio quiet” pulsar

Similar to many magnetars.




| | |
|---|---|
| Surface dipole magnetic field strength, $B$ | $1.3\times10^{14}$ G |

# (4) X-ray observation and brightness variation

Magnetars with radio emission are usually emitting X-ray.

With Swift/XRT, the authors monitor J0901-4046 during MeerKAT's observation on 2021/2/1 and 2021/2/2

——But no detection.

They give an upper limit.

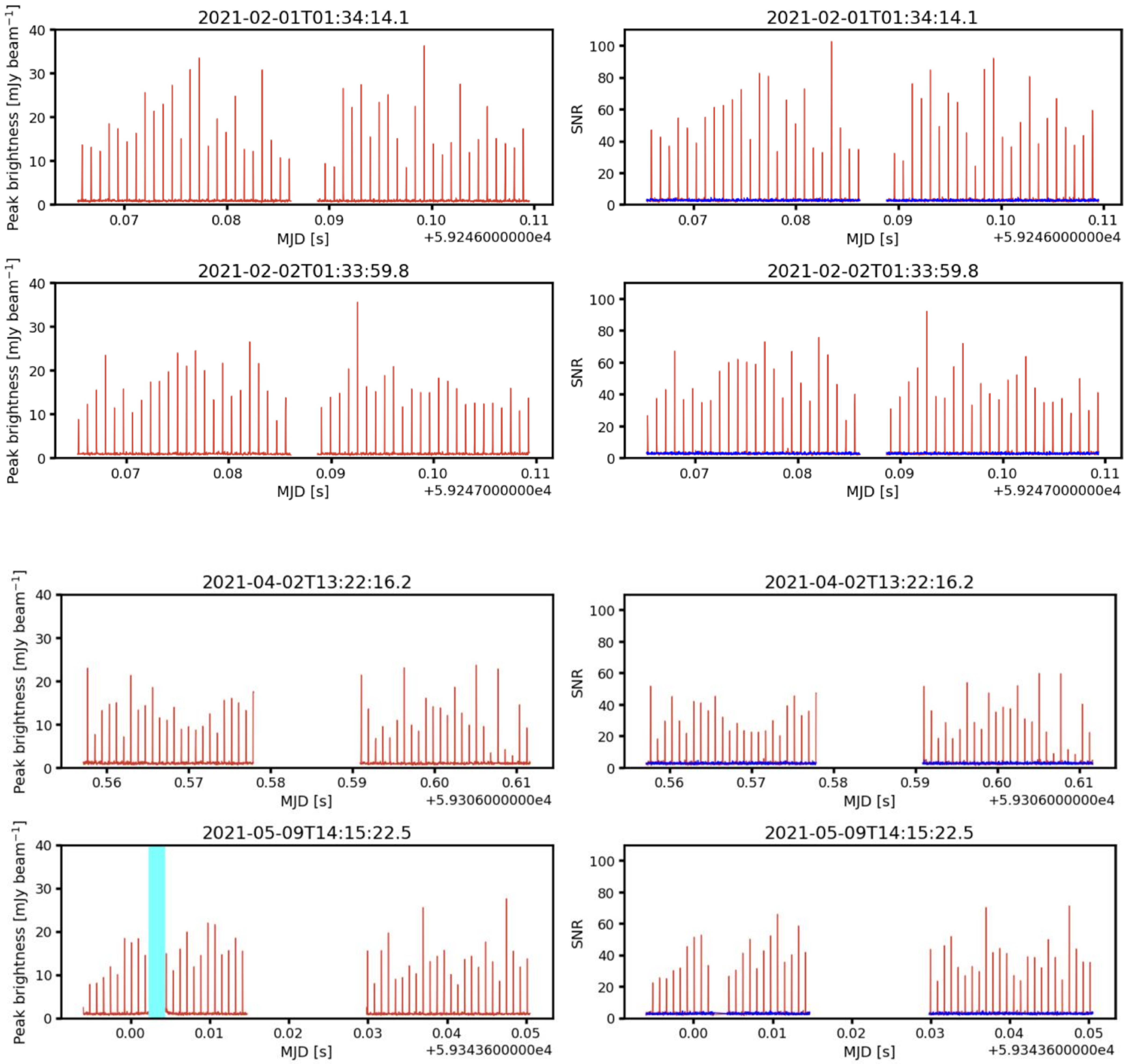
| | |
|---|---|
| X-ray Luminosity, $L_X$ (0.5–10 keV) at $d_2$ | $\lesssim 3.2\times10^{30}$ erg s$^{-1}$ |

| | |
|---|---|
| Spin-down luminosity, $\dot{E}$ | $2.0\times10^{28}$ erg s$^{-1}$ |

Then: $L_X \lesssim 10^2 \dot{E}$

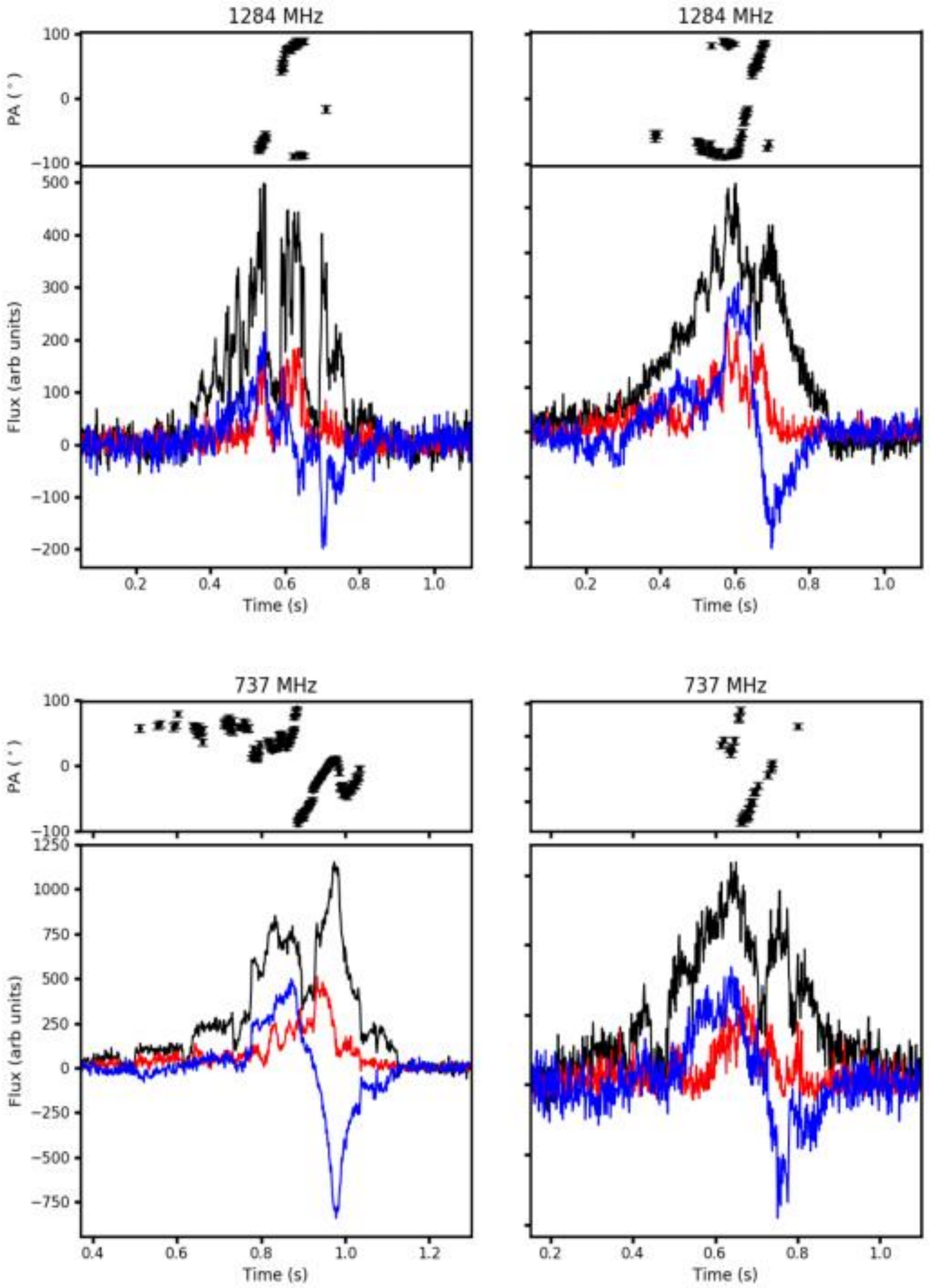
For rotation-powered pulsars: $L_X \approx 10^{-3}\dot{E}$ For magnetars: $L_X \gtrsim \dot{E}$

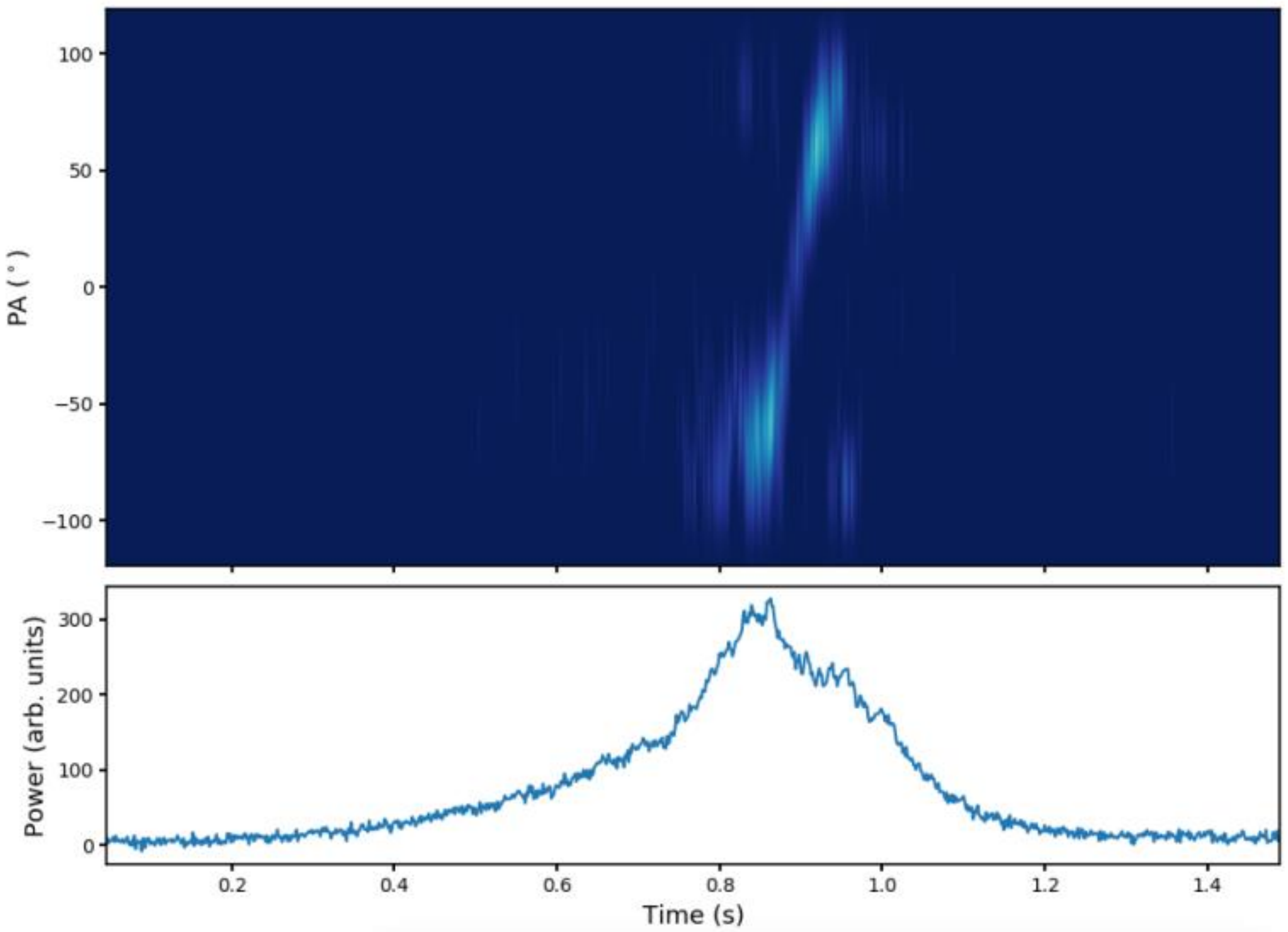
# Single pulses’ brightness Changing with time:




A radio-loud magnetar transitioning into quiescence?

# (5) Polarization




Supplementary Fig. 3

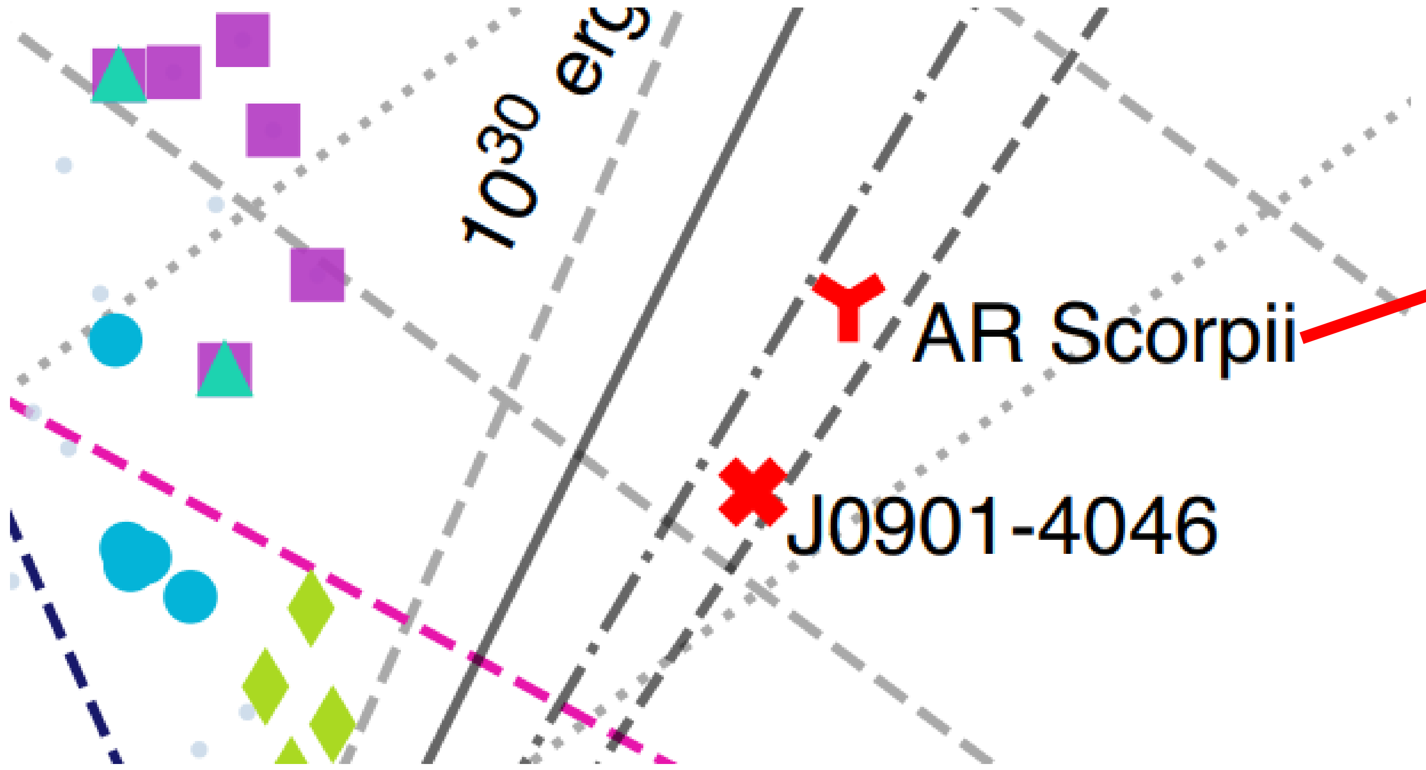
V > L: Rare for radio loud pulsars/magnetars.
S-shape PA curve: a rotating magnetic dipole?

| | |
|---|---|
| Rotation measure, RM | $-64 \pm 2\,\mathrm{rad\,m^{-2}}$ |

RM: consistent with
——Smoothed galactic foreground
——nearby pulsars’ RM

Maybe no substantial intrinsic RM.

# (6) Counterparts searching




Maybe a WD, would J0901-4046 be a WD too?

The authors did photometry and spectroscopic observation on a nearby (1” in RA, 3” in Dec) 17mag Gaia source, found it’s an single A type star——ruled out optical counterpart.

Probably more multi-wavelength observations are needed……

# Thank you for your attention