

Trombones, Profile Broadening, and Frequency-Dependent Activity Windows: Connecting PSR B0950+08 and FRB 20201124A

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ex-ASTRON (Netherlands)

**The Apertif Radio Transient System (ARTS):
Design, Commissioning, Data Release, and Detection of the
first 5 Fast Radio Bursts**

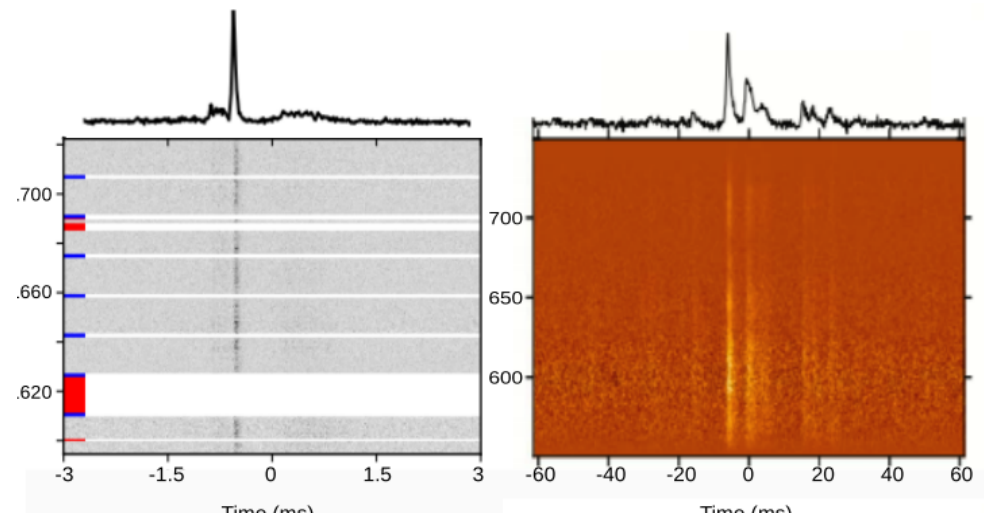
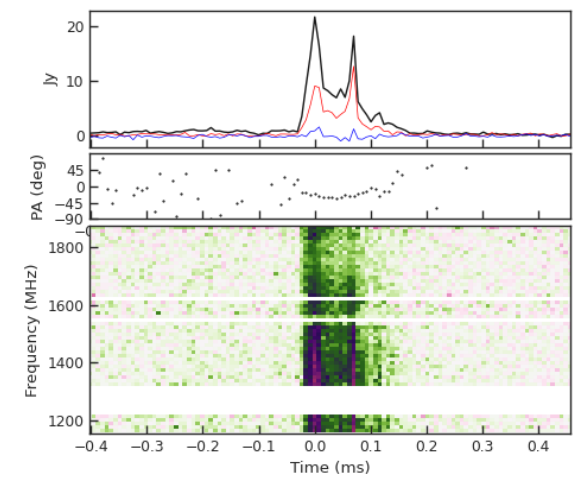
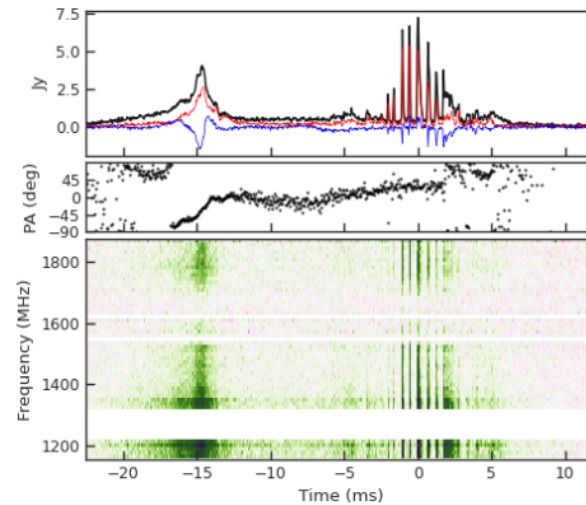
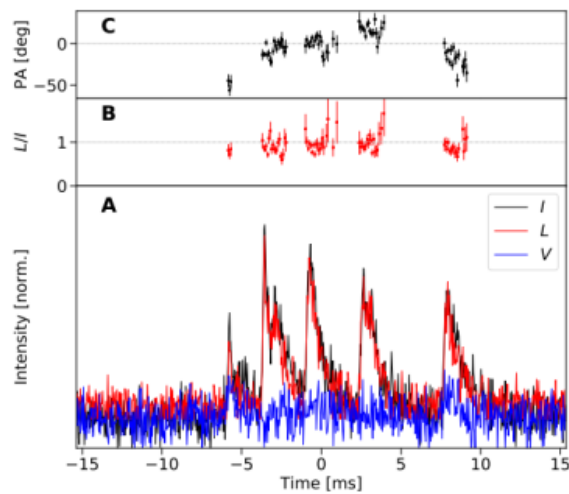
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A. W. Zanting¹, and J. Ziemke^{1,18}

PI: van Leeuwen



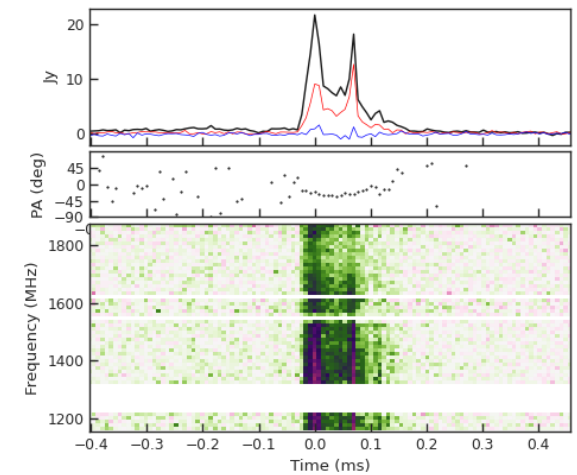
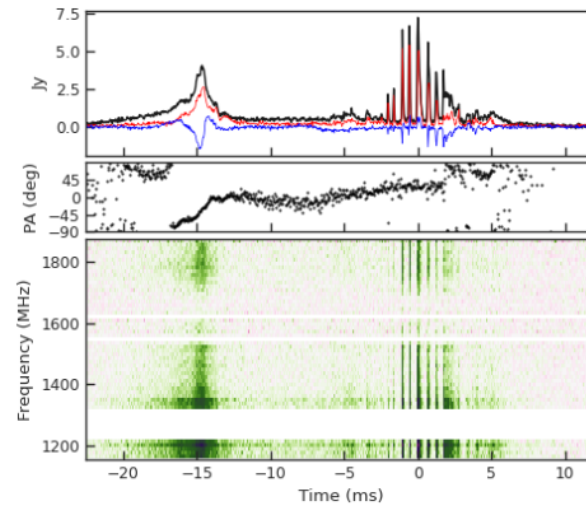
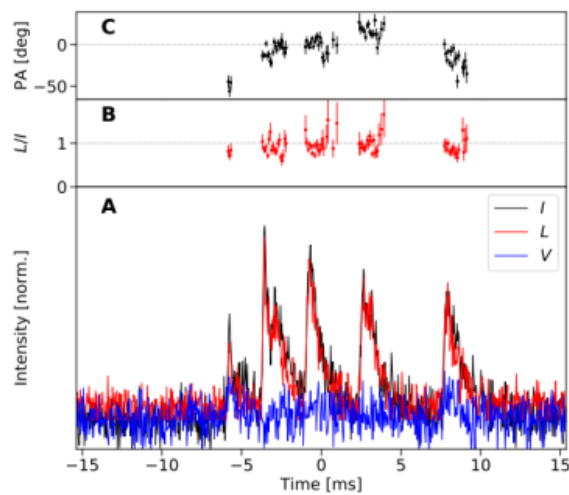
- 
- Single Pulses from rotationally powered neutron stars (pulsars)
 - Single Pulses from magnetically powered neutron stars (magnetars)
 - Fast Radio Bursts from yet unknown sources

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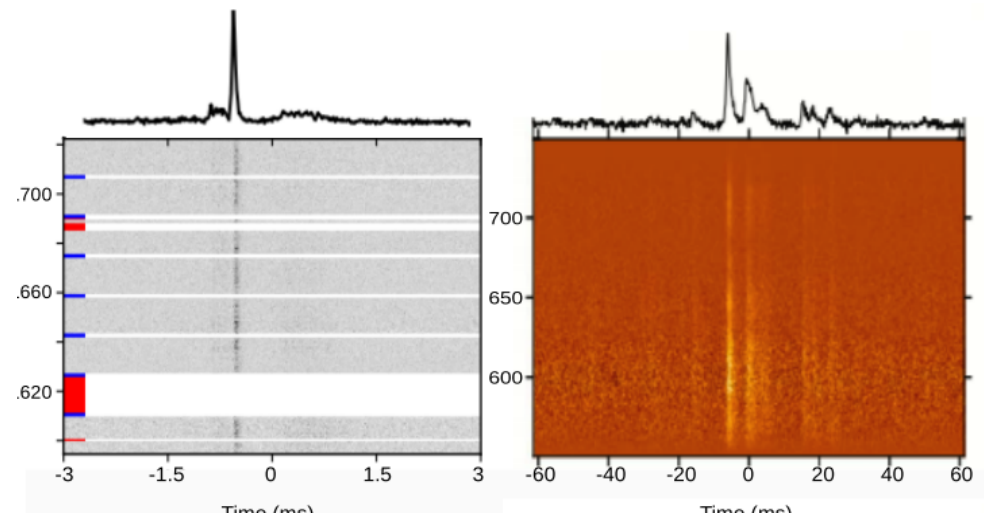


- Single Pulses from rotationally powered neutron stars (pulsars)
- Single Pulses from magnetically powered neutron stars (magnetars)
- Fast Radio Bursts from yet unknown sources

look quite similar
from observer's
point of view

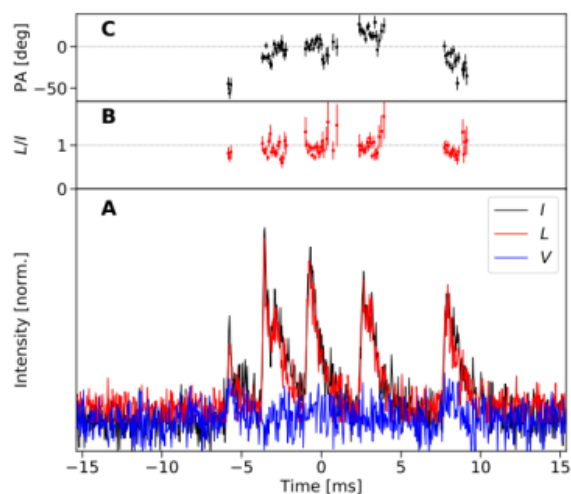


- similar intensities ($\sim$ Jy)
- ms-duration
- temporal substructure
- high fractional polarization

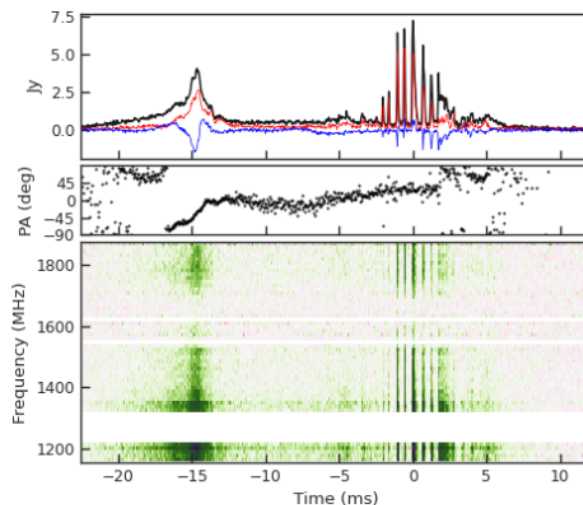


- Single Pulses from rotationally powered neutron stars (pulsars)
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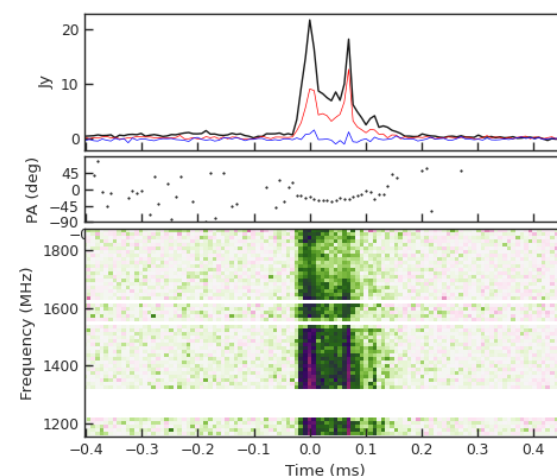
FRB 20210213A



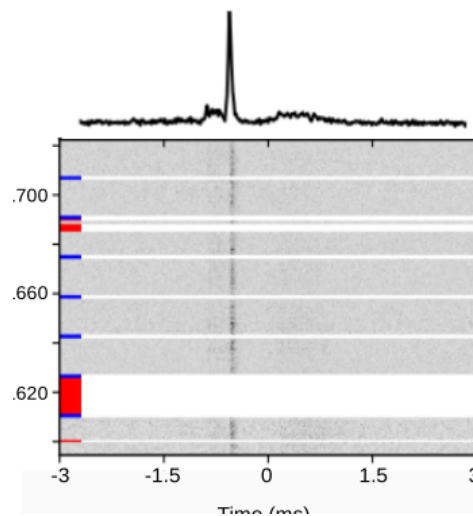
PSR B1133+16



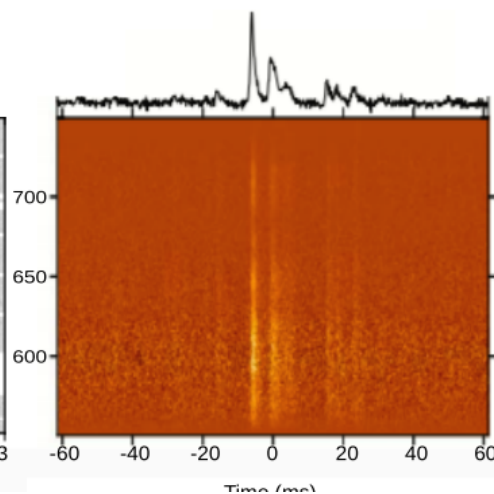
PSR B0950+08



B) FRB 180916.J0158+65



C) magnetar XTE J1810-197

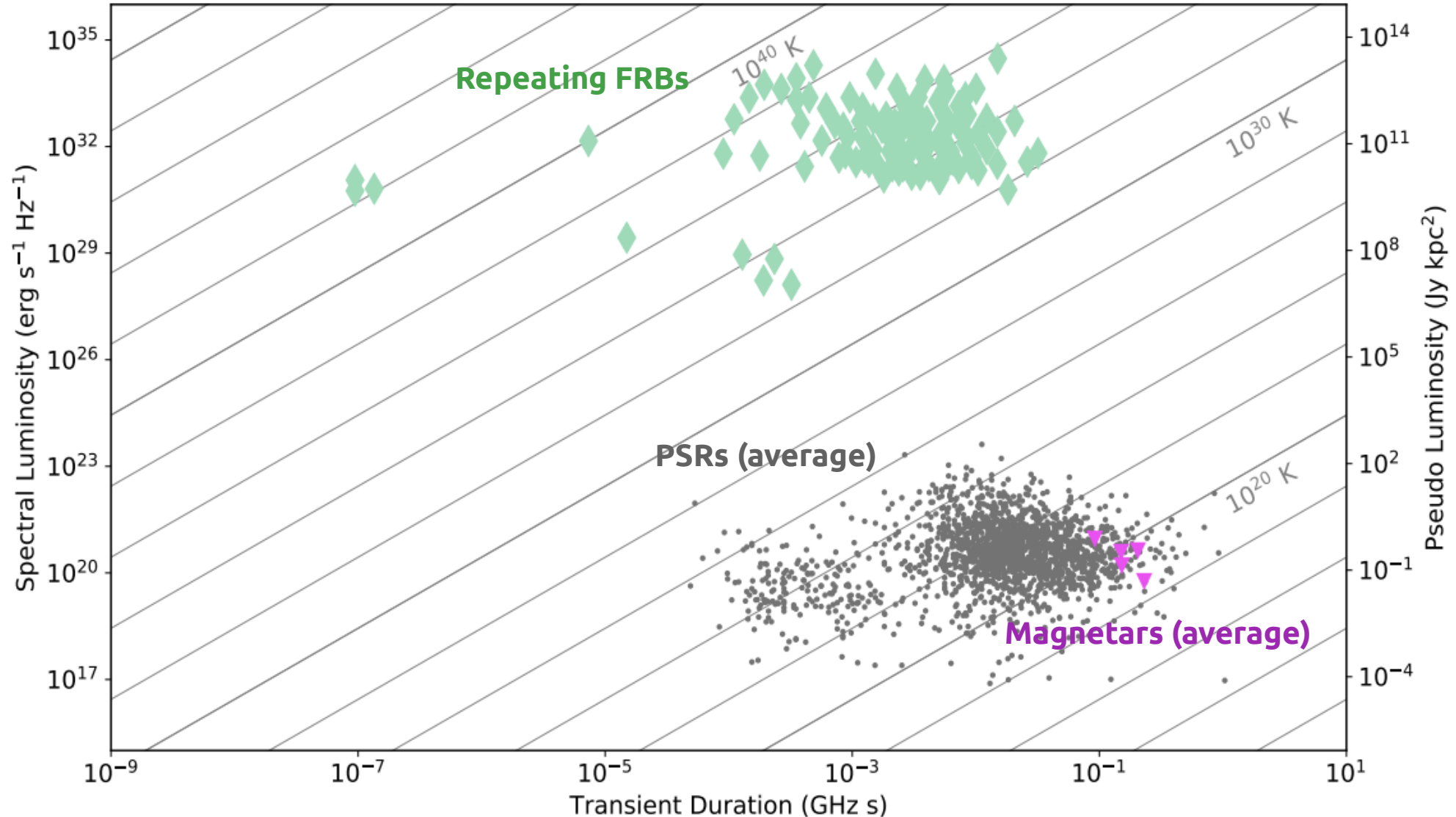


- similar intensities ($\sim$ Jy)
- ms-duration
- temporal substructure
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Key difference – distance

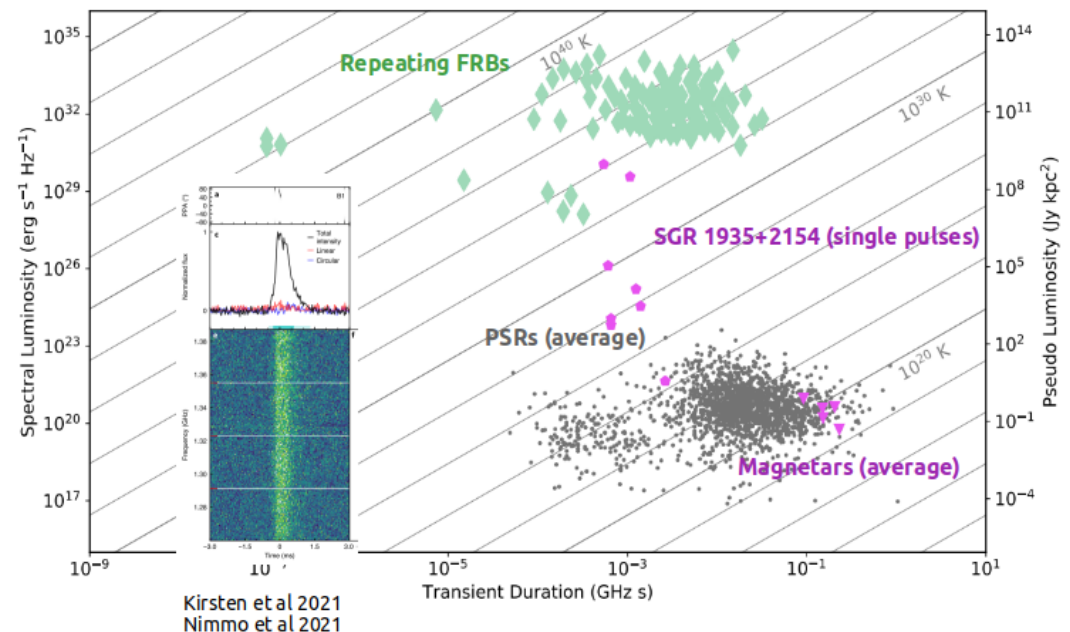
Single Radio Pulses: ~pc

Fast Radio Bursts: ~Mpc



Are some FRBs emitted in magnetospheres of NS?

- dense sequence of bursts (rate of $\sim s^{-1}$) are more naturally explained by magnetospheric emission than by catastrophic models
- scintillation properties of FRB 20221022A point to compact source of emission, compatible with magnetospheric sizes (Nimmo et al 2024)
- large and rapid changes in RM point to intense magneto-ionic environment (e.g. Xu et al 2022)
- properties similar to single radio pulsars
- FRB directly detected from a magnetar



Building bridges further

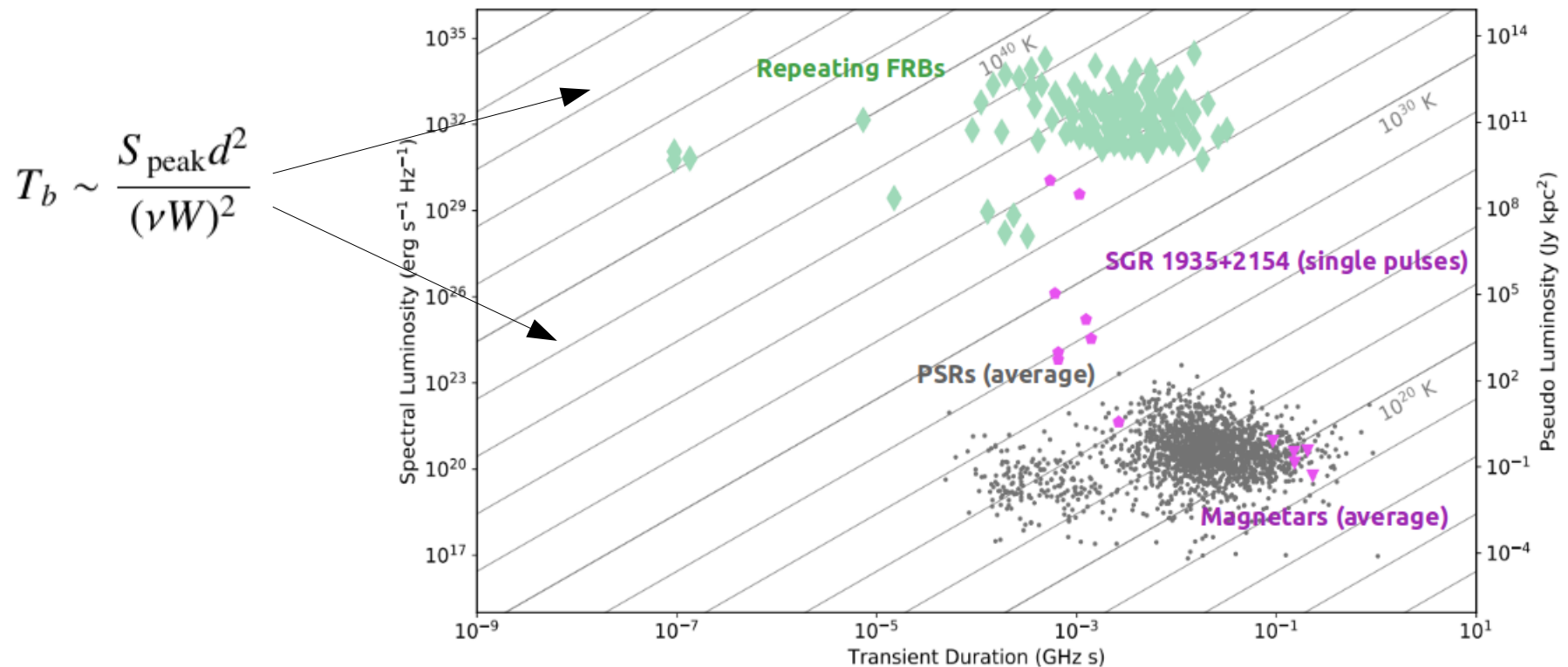
A) Brightness temperature

B) Trombones, sad or happy

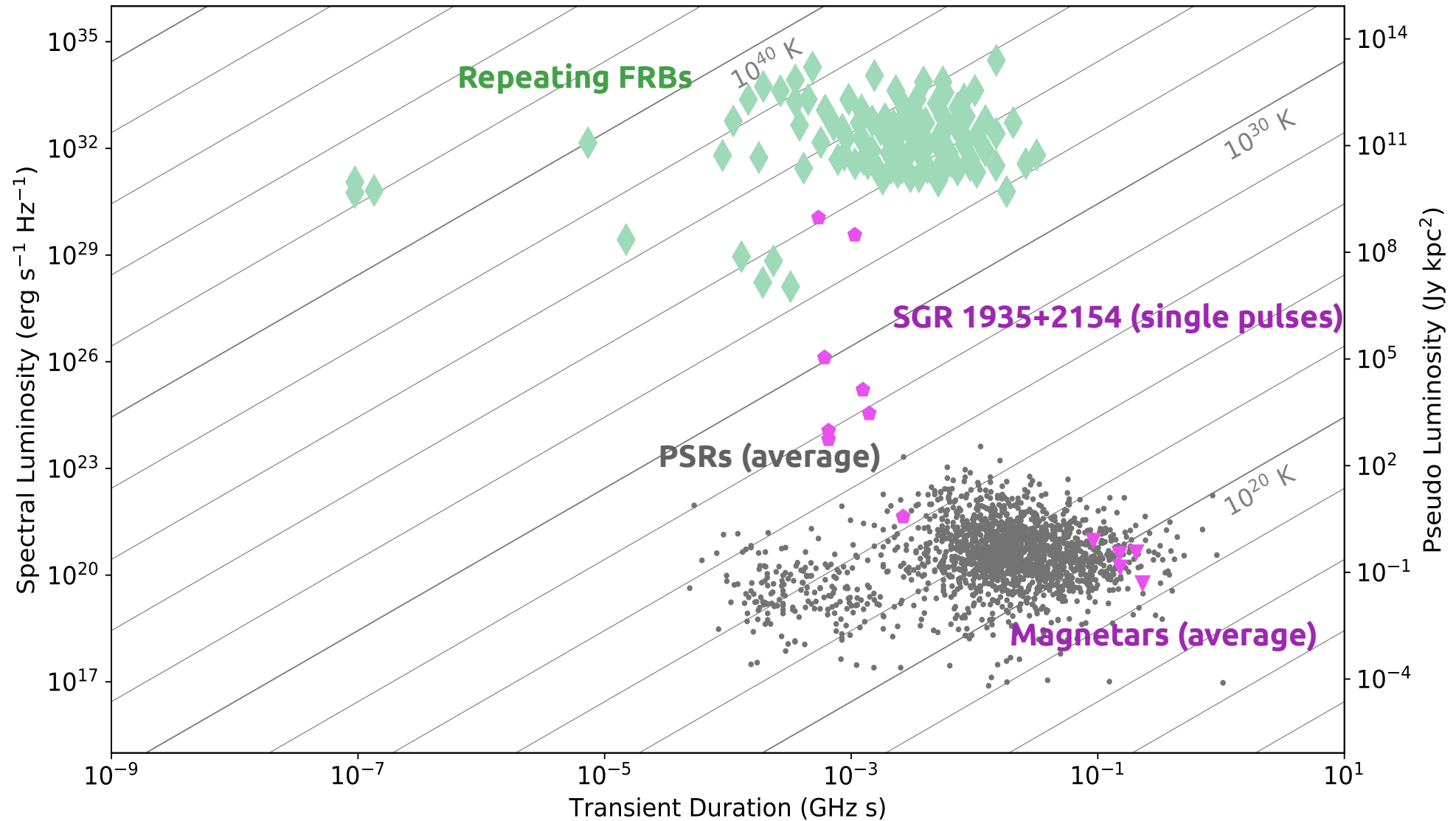
C) Profile broadening / frequency-dependent activity window

A) Brightness temperature

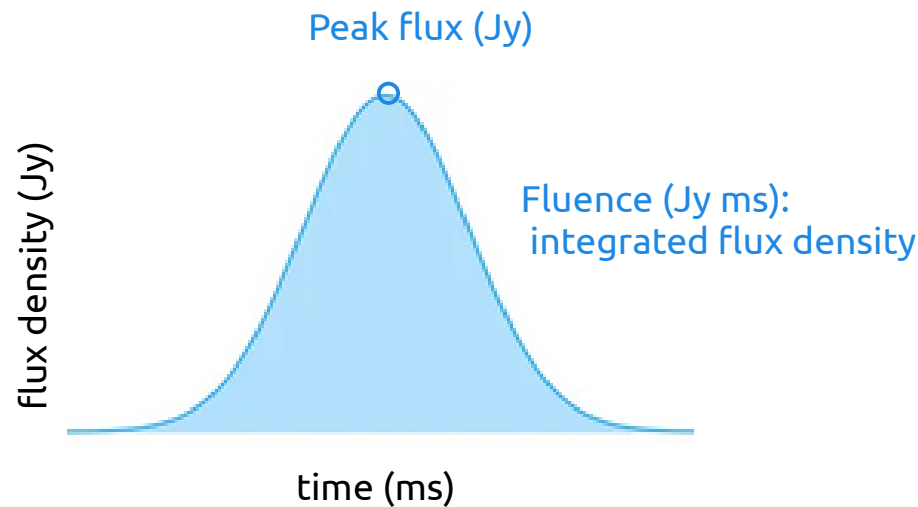
- A measure of how intense a source is, expressed as the temperature of a blackbody that would produce the same radio brightness
- FRBs exhibit T_b values as high as $10^{32} - 10^{42}$ K, far exceeding any known incoherent source
- Together with short duration of FRBs, high T_b points to coherent radiation from particle bunches or maser-like processes originating in extremely small source regions (~ 10 -300 km)



How bright single radio pulses can be?



Definitions: fluence, peak flux, survival function



$$T_b \sim \frac{S_{\text{peak}} d^2}{(\nu W)^2}$$

Instead of peak flux density, it is more common to measure fluence.

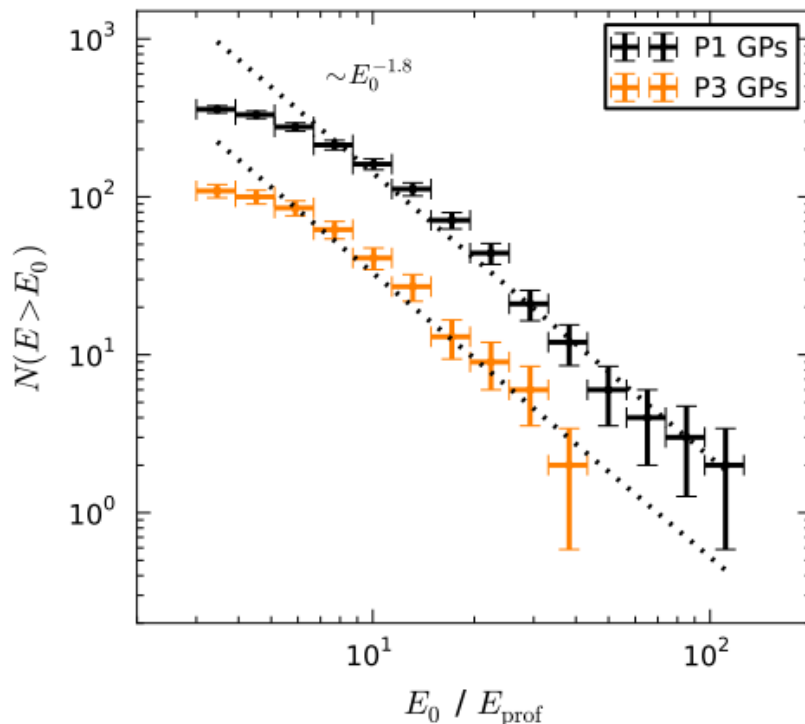
Fluence is less biased by scattering or instrumental time resolution

Fluence distributions

Survival function:

$N(F > F_0)$ as a function of threshold fluence F_0 .

Can also be normalized by observing time, or spin period.

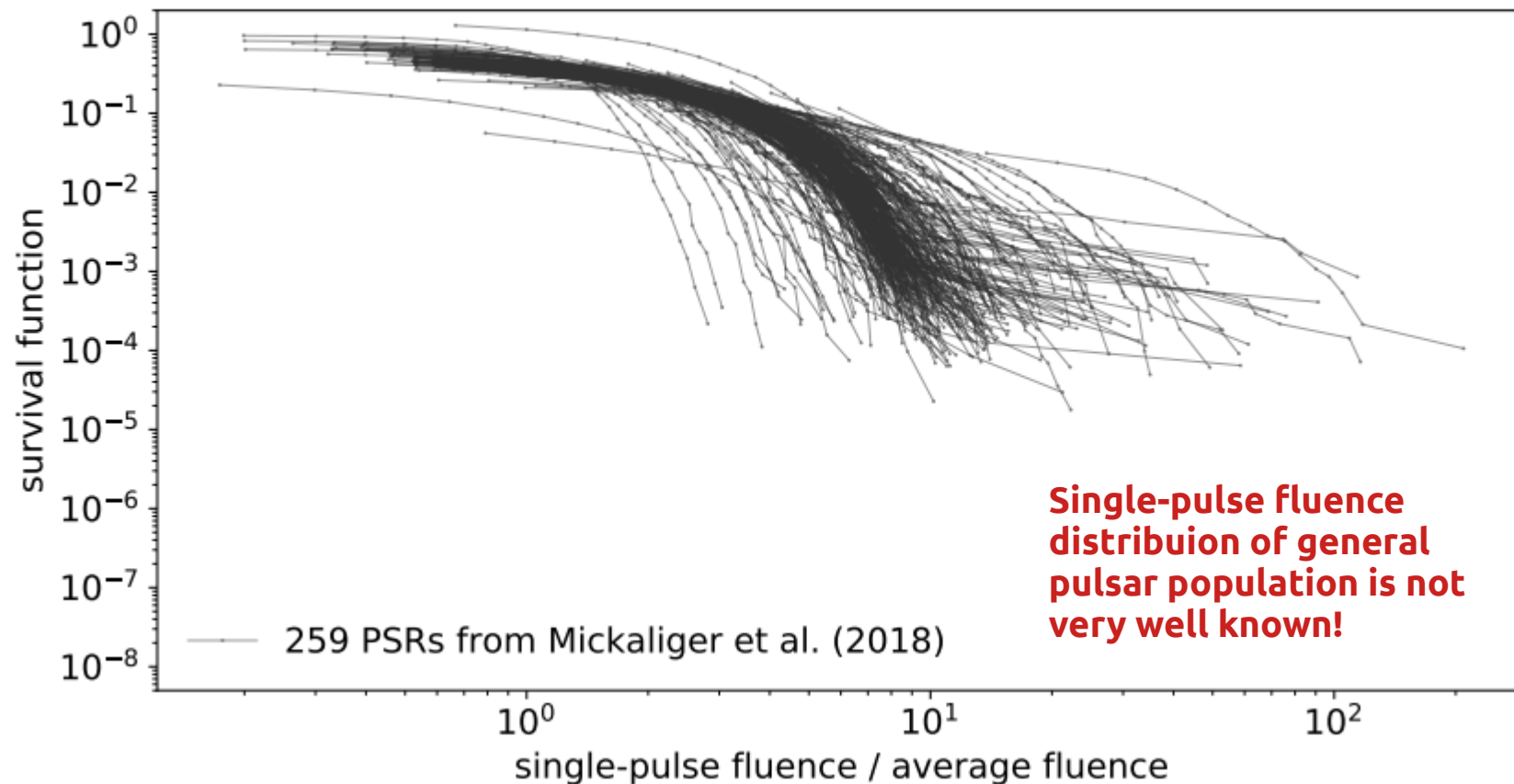


How bright SRPs can be?

Largest surveys:

Burke-Spolaor et al 2012 (315 pulsars)

Mickaliger et al 2018 (259 pulsars)

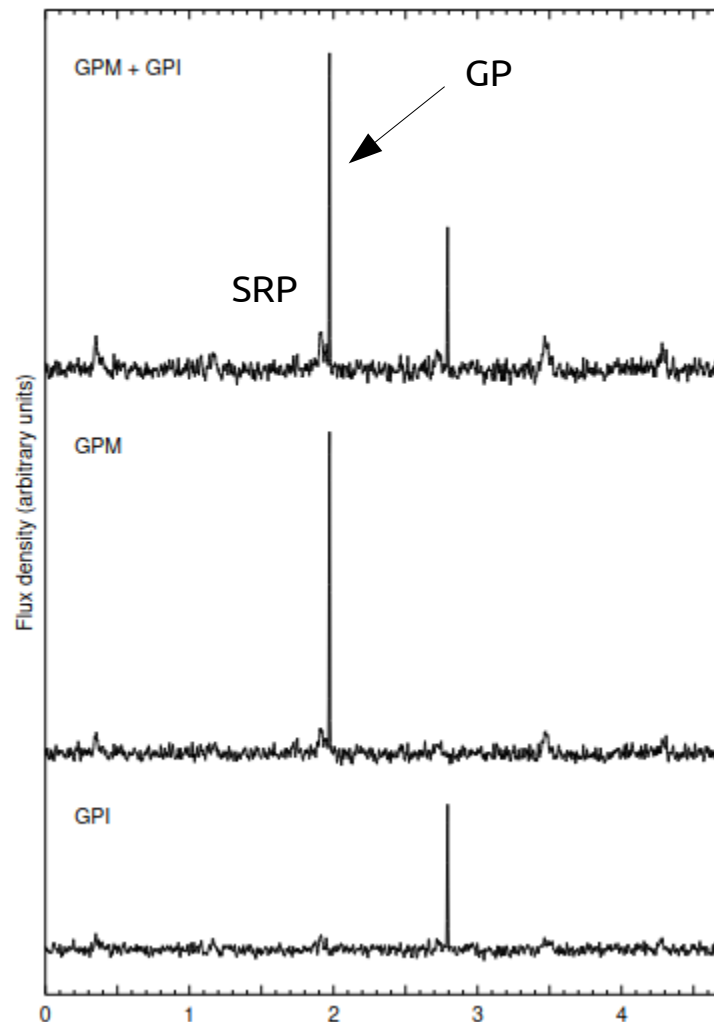


- Most massive studies cover only ~10% of all known pulsars
- Rates till $\sim 10^{-4}$ P, one in ~3 hour, limited by typical observing time

More than one type of single pulses:

- Giant Pulses
- Giant Micropulses
- Abnormally Intensive Pulses
- Spiky Emission
- Dwarf Pulses

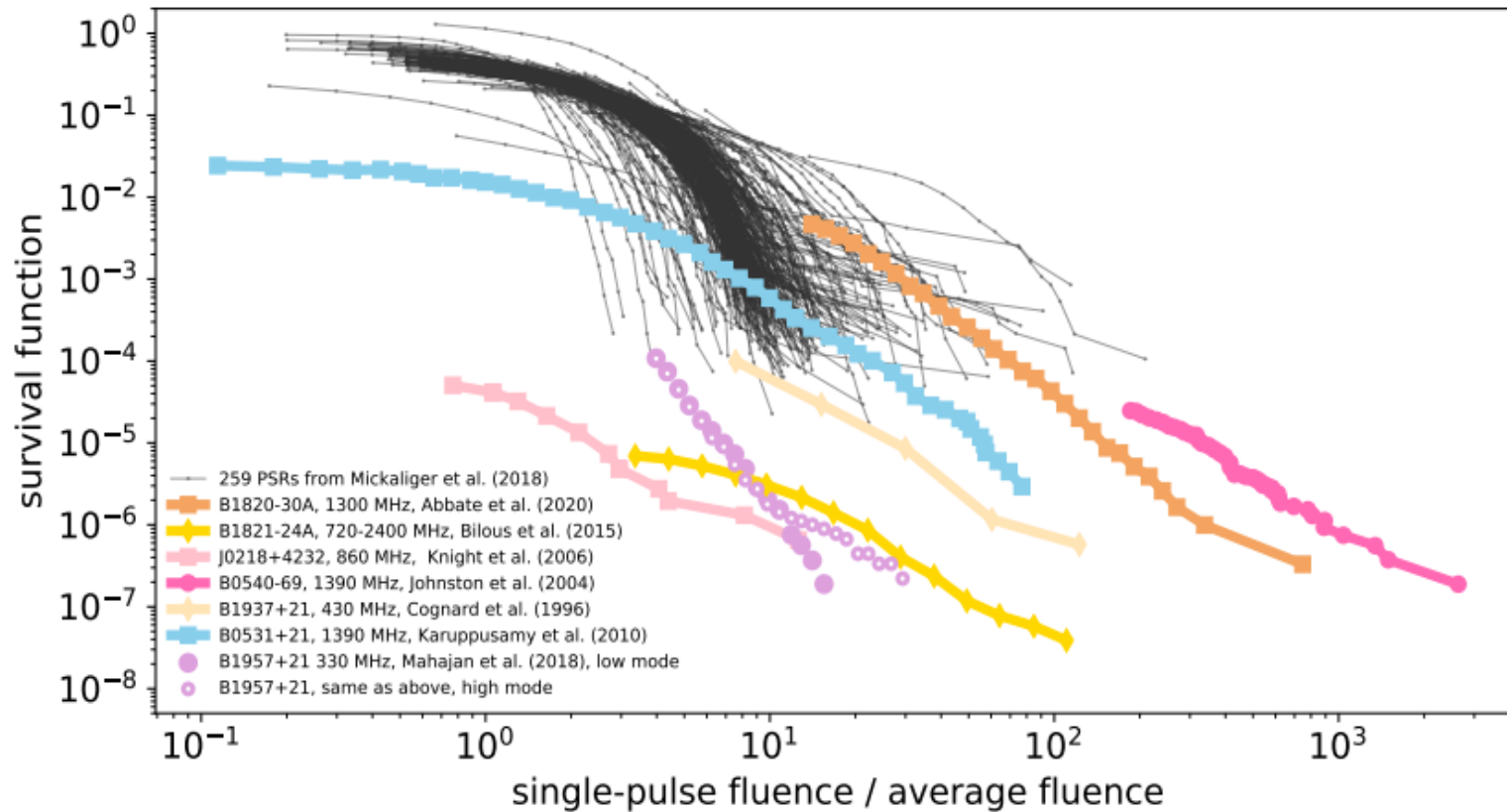
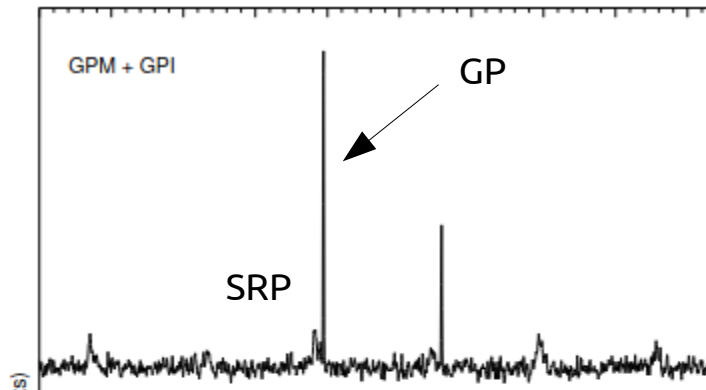
Giant Pulses: special kind of single pulses



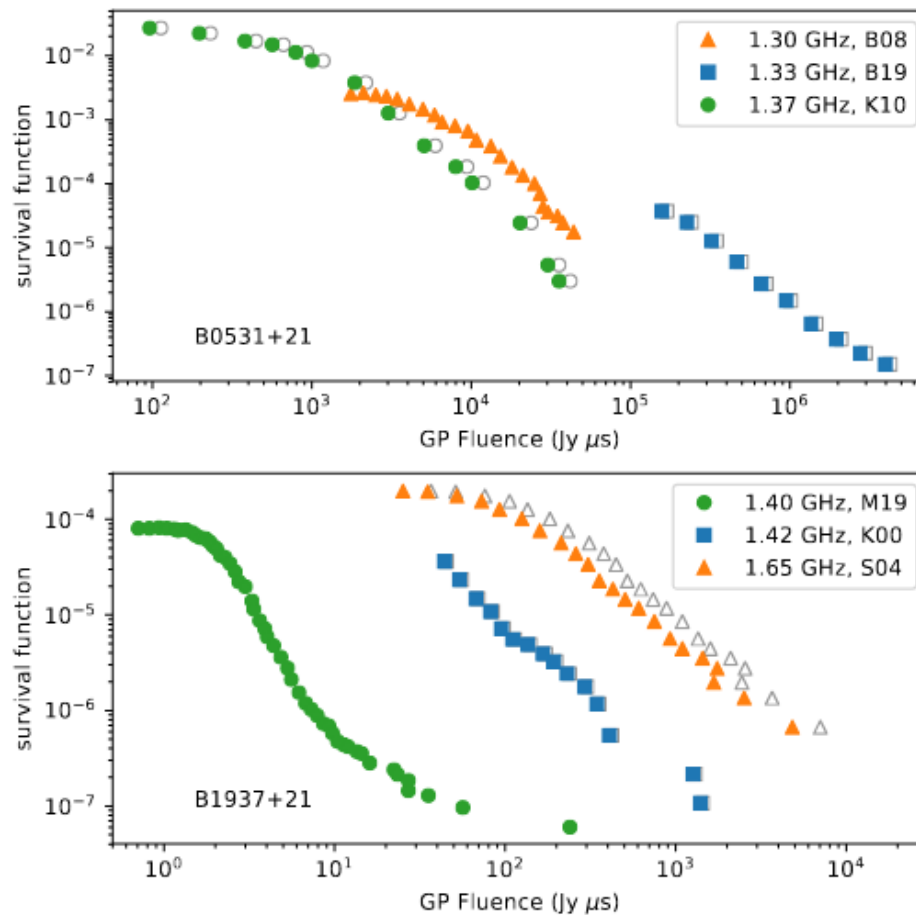
B1937+21 (Soglasnov et al 2004)

- Rare (~7 out of 2500 pulsars)
- Ultra-bright (up to MJy)
- Ultra short (from μ s to ns!)
- Power-law energy distribution
- High degree of polarization
- Longitudes aligned with high-energy emission
- Pulsars with GPs have large magnetic field at light cylinder

Giant Pulses: special kind of single pulses



No consensus on how bright GPs are



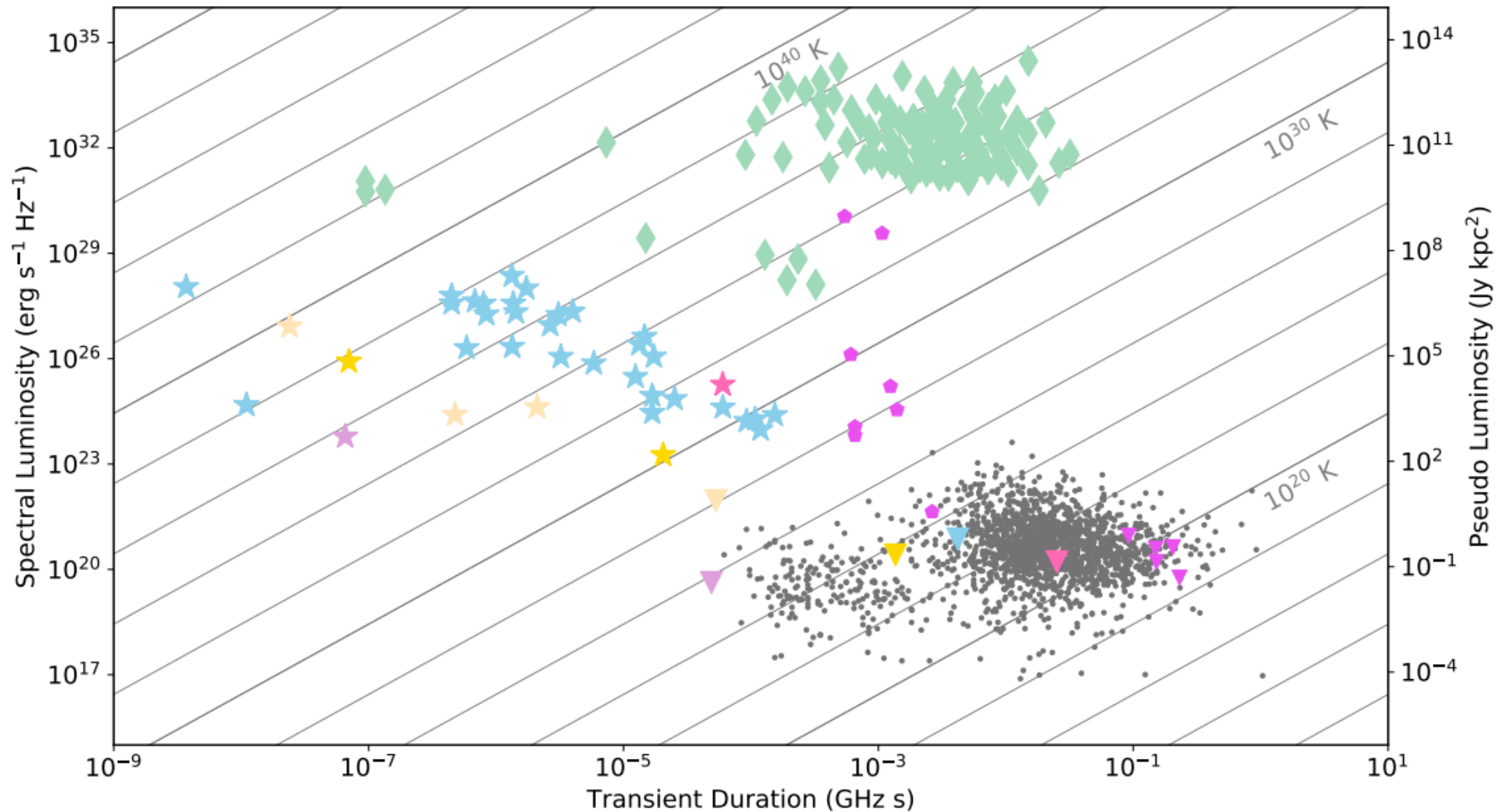
Intrinsic variability?
Scintillation?
Telescope miscalibration?

Fig. 14. Survival function of the fluence distributions for two most studied GP pulsars, the Crab pulsar PSR B0531+21 and PSR B1937+21 from the works of [Bhat et al. \(2008, B08\)](#), [Bera & Chengalur \(2019, B19\)](#), [Karuppusamy et al. \(2010, K10\)](#), [McKee et al. \(2019, M19\)](#), [Kinkhabwala & Thorsett \(2000, K00\)](#), and [Soglasnov et al. \(2004, S04\)](#). The gray unfilled markers show fluences rescaled to a common frequency (1.3 GHz for the Crab and 1.4 GHz for PSR B1937+21) using broadband spectral fits from [Bilous et al. \(2016\)](#) and [Kondratiev et al. \(2018\)](#).

There may be a widespread lurking inconsistency of flux density values reported by different telescopes. Be careful when comparing small datasets!

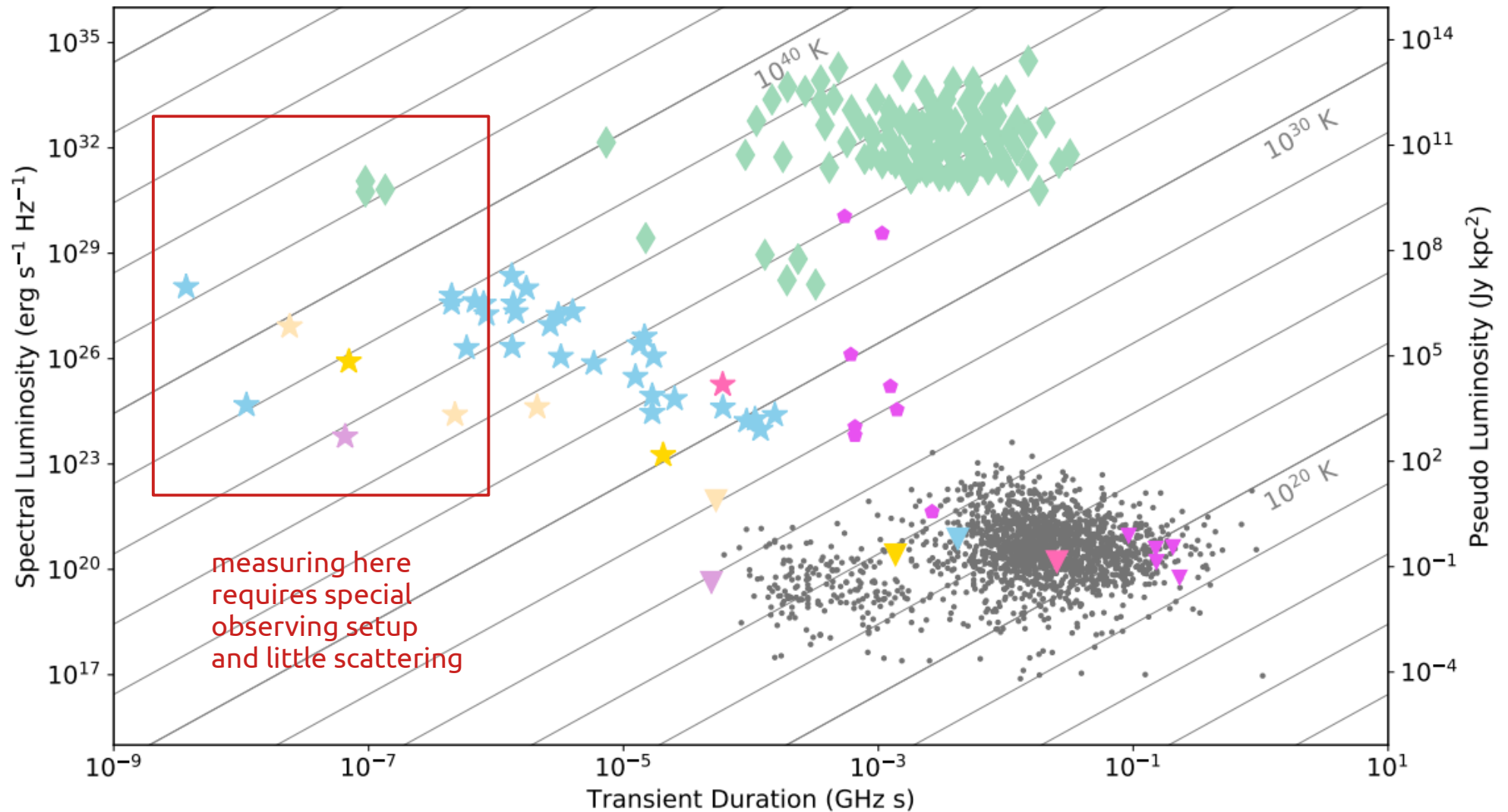
GPs have typical T_b of FRBs

- PSRs, average pulse
- ◆ Repeating FRBs
- ▼ Magnetars, average pulse
- ◆ SGR 1935+2154, single pulses
- ★ B0531+21, GPs
- ★ B0531+21, average pulse
- ★ B0540-69, GPs
- ★ B0540-69, average pulse
- ★ B1821-24A, GPs
- ★ B1821-24A, average pulse
- ★ B1937+21, GPs
- ▼ B1937+21, average pulse
- ★ B1957+20, GPs
- ▼ B1957+20, average pulse

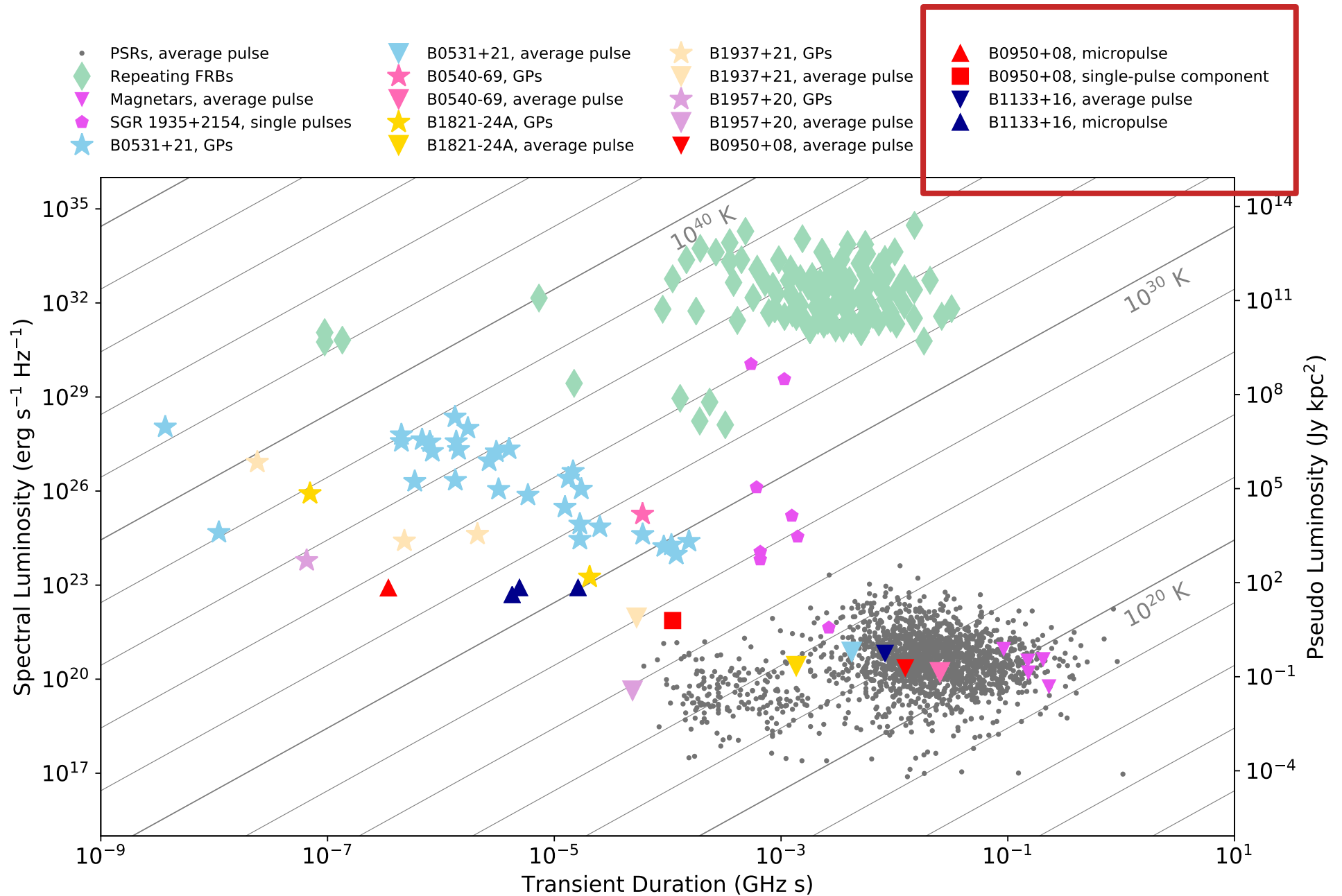


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- ★ B1937+21, GPs
- ▼ B1937+21, average pulse
- ★ B1957+20, GPs
- ▼ B1957+20, average pulse



Bright components of normal SRPs?



Very bright microstructure in PSR B0950+08

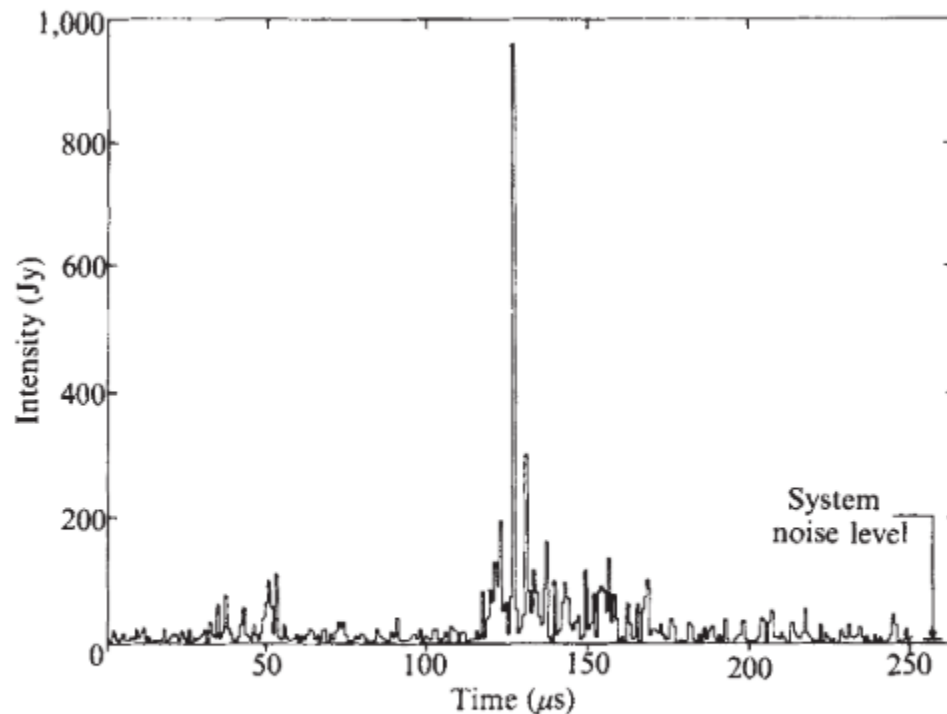


Fig. 2 An unresolved micropulse is plotted with the full $0.8 \mu\text{s}$ resolution. The horizontal base line is the detector zero-output level. Note that the system noise level is negligible.

Strong unresolved sub-mus subpulse
with peak flux f 1 kJy at 430 MHz

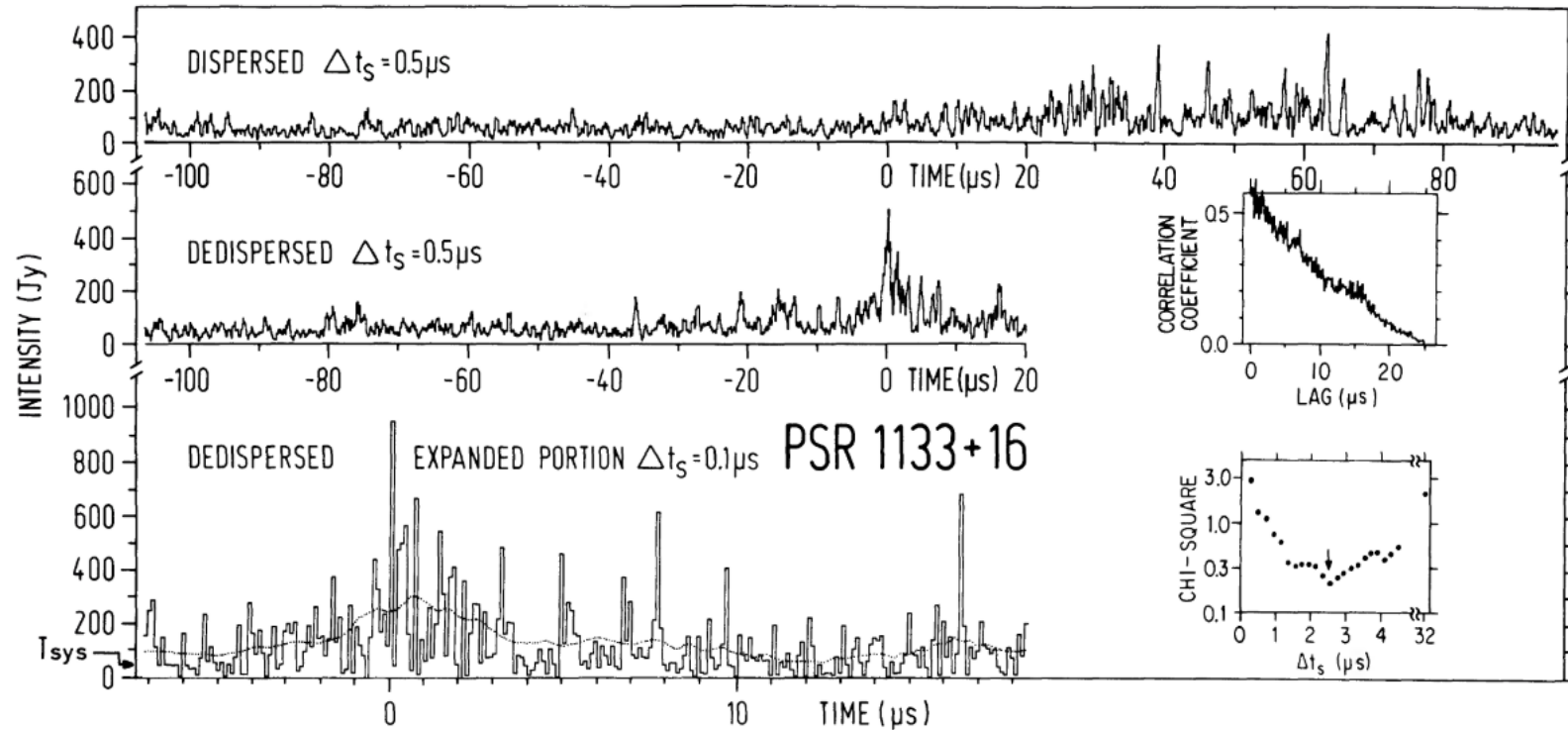
$$T_b > 3 \times 10^{31} \text{ K}$$

(T_b from average emission $\sim 10^{22} \text{ K}$)

Hankins & Boriakoff 1978

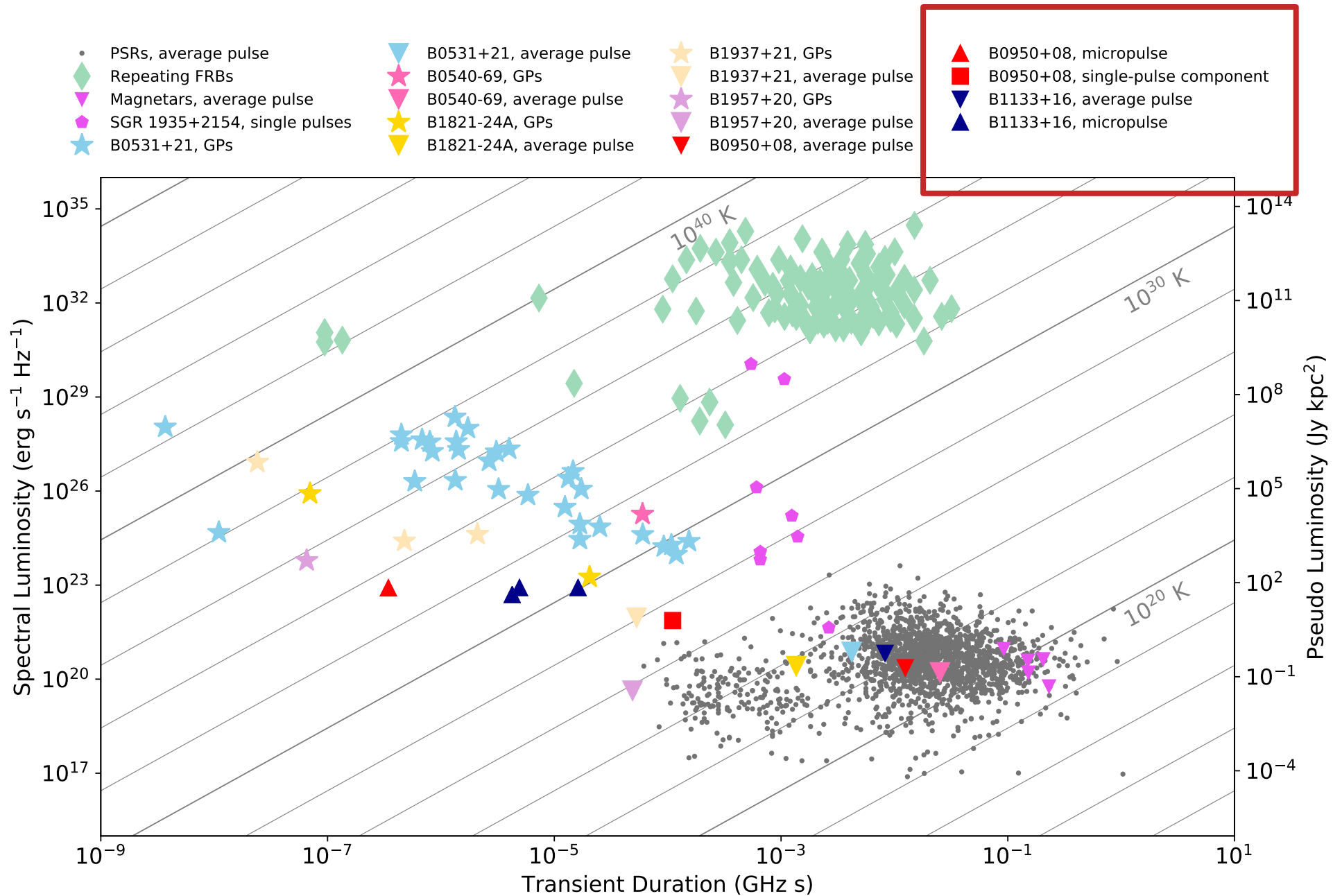
And in PSR B1133+16

$$T_b \sim 10^{30} \text{ K}$$



Bartel & Hankins 1981

Bright components of normal SRPs?



Exploring bright micropulses from nearby pulsars

Pulsar sample

<u>PSR</u>	Period (s)	DM (pc cm ⁻³)	Observing time (hrs)
B0329+54	0.715	26.8	1.7
B0823+26	0.531	19.5	2
B0950+08	0.253	3.0	2
B133+16	1.188	4.9	4.3
B1929+10	0.227	3.2	2
B2016+28	0.558	14.2	2
B2020+28	0.343	24.6	2.3



- GBT / VEGAS / @1.1 – 1.9 GHz
- Aug 2022 – Apr 2023
- BW = 800 MHz, 128 chan, $\Delta t = 2.56 \mu s$
- Coh. dedisp. search mode
- Full polarisation
- Flux calib / noise-cal & pcal scans

- ☐ DSPSR (-s -K)
- ☐ Flux / pol calibration (pcal)
- ☐ RFI removal (psrzap, paz)
- ☐ Faraday rotation corrected (pam -R)
- ☐ → full Stokes (pam -S)
- ☐ psrchive.py

Goals:

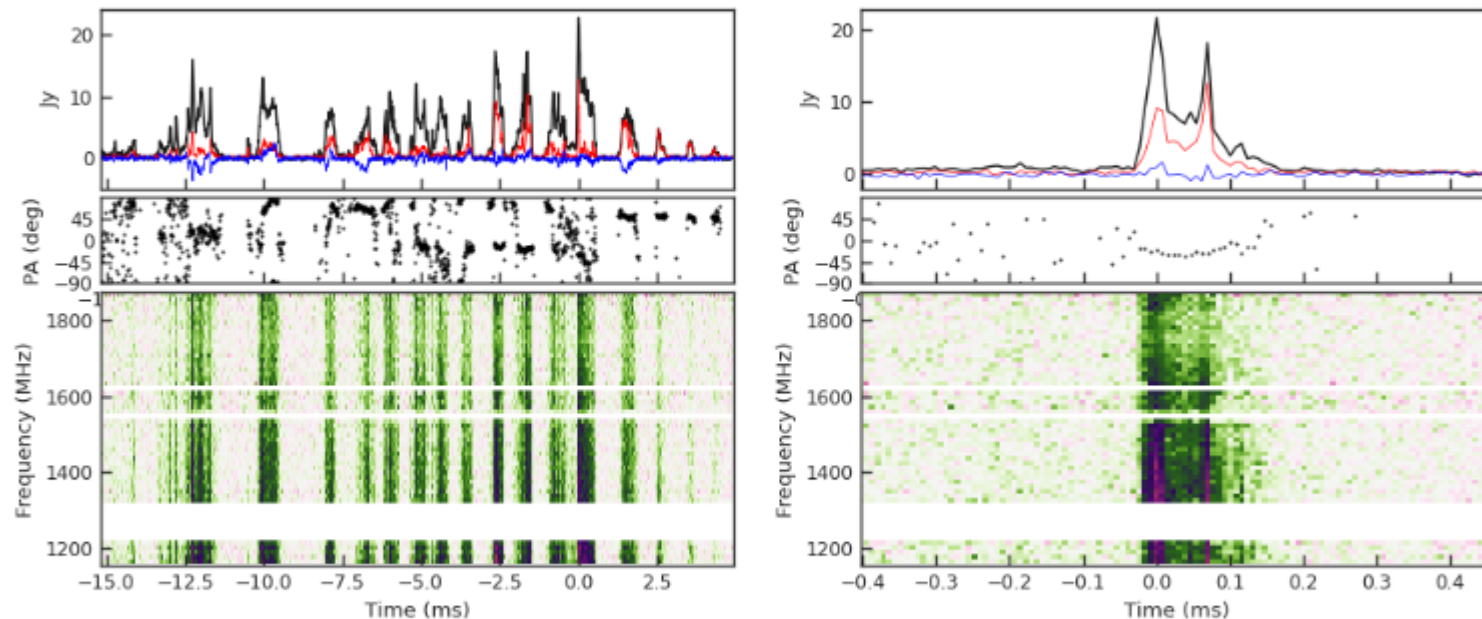
- peak flux density distribution
- width distribution
- polarization measurements
- quasi-periodicity

Kondratiev et al (in prep)

Exploring bright micropulses from nearby pulsars

B0950+08: individual pulses (2)

PRELIMINARY



“Boxy” sequences of pulses consisting of supposedly half-merged spikes

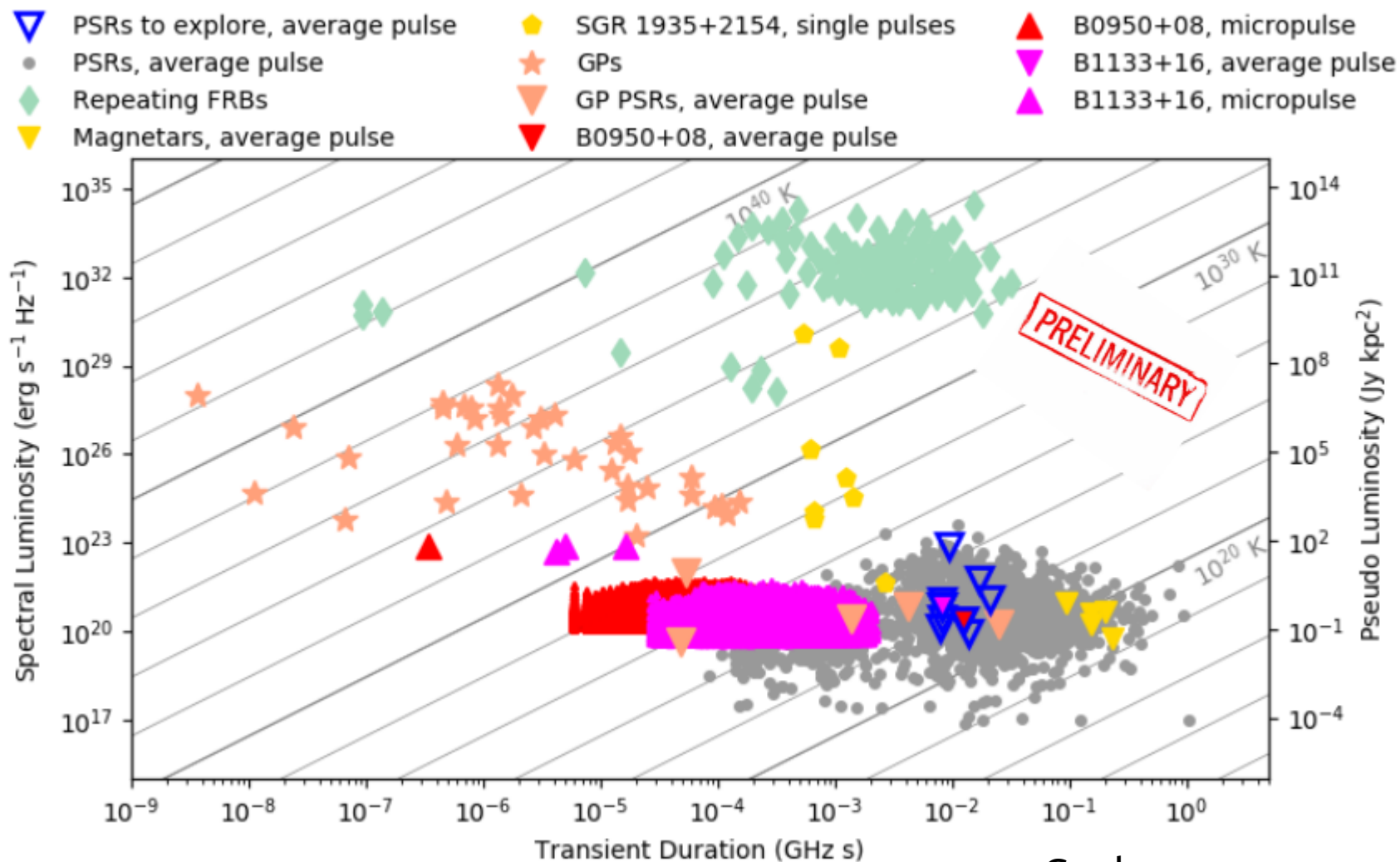
$\Delta t \sim 7.7 \mu s$

Goals:

- peak flux density distribution
- width distribution
- polarization measurements
- quasi-periodicity

Kondratiev et al (in prep)

Exploring bright micropulses from nearby pulsars



Goals:

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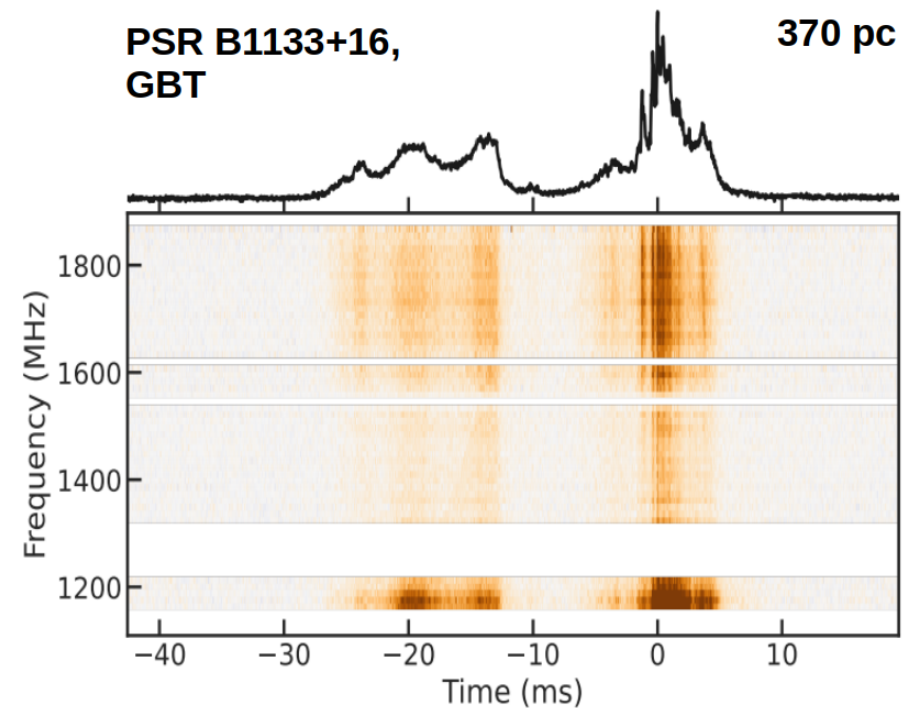
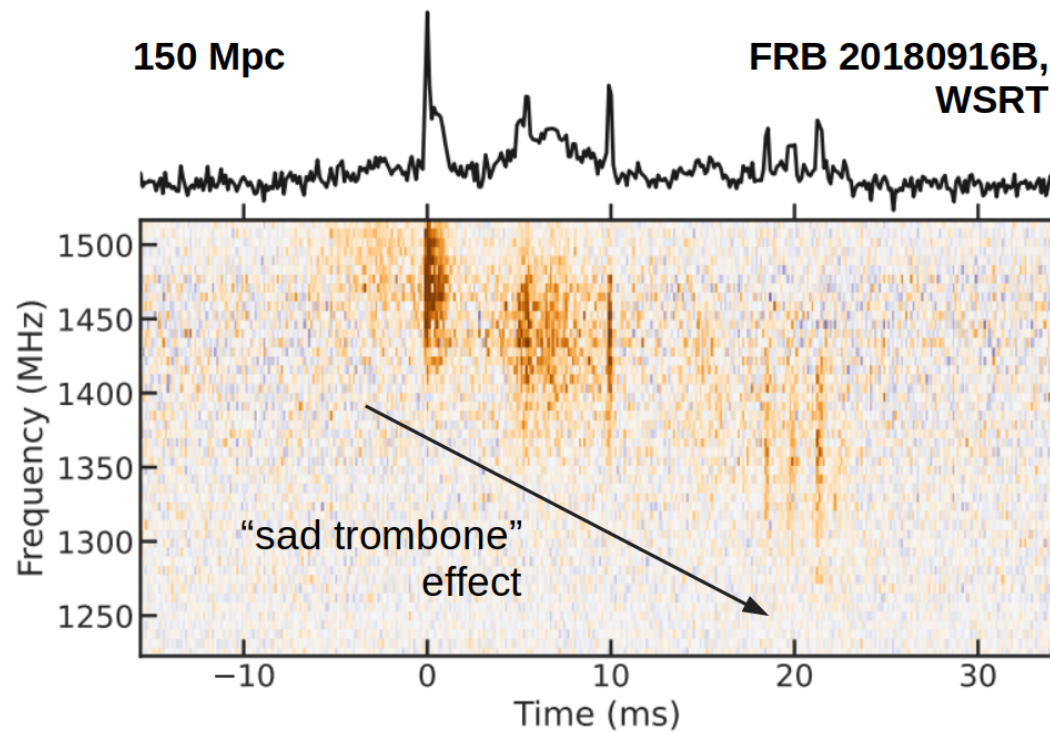
Kondratiev et al (in prep)

Have not yet achieved the best time resolution due to processing difficulties

Conclusions

- Brightness distribution of single-pulse subcomponents from pulsars may be even less well known than that of FRBs!
- There is a dire need of a large-scale uniform survey, preferably with good time resolution
- Potential plethora of data for FRB emission mechanisms

B) Spectral features: trombone effect



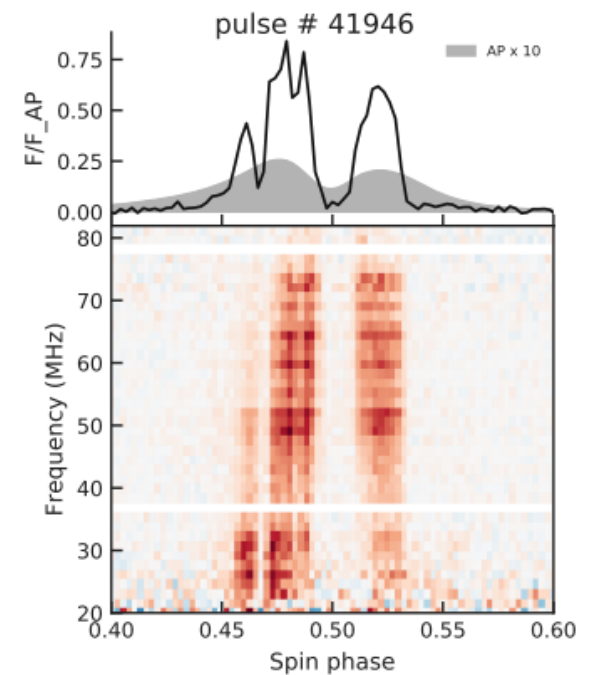
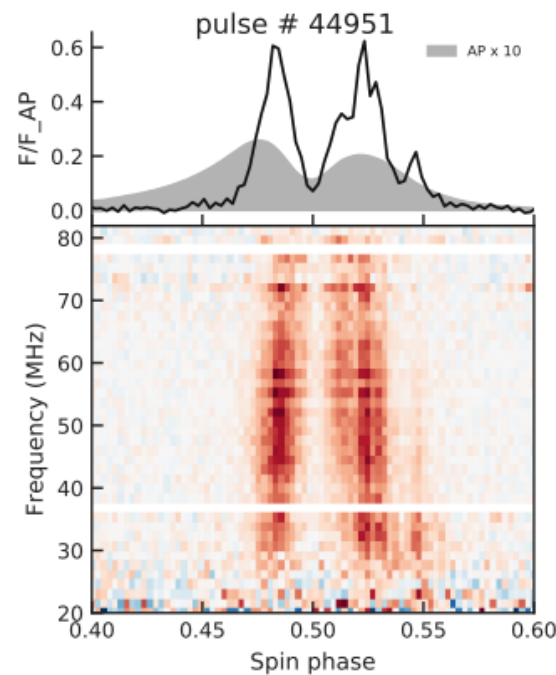
Unexpected discovery at low frequencies



NenuFAR – very low-frequency phased array optimised for the frequency range from 10 MHz to 85 MHz (30 m to 4 m).

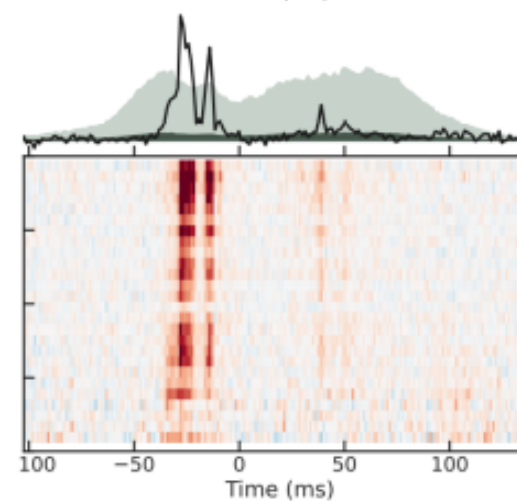
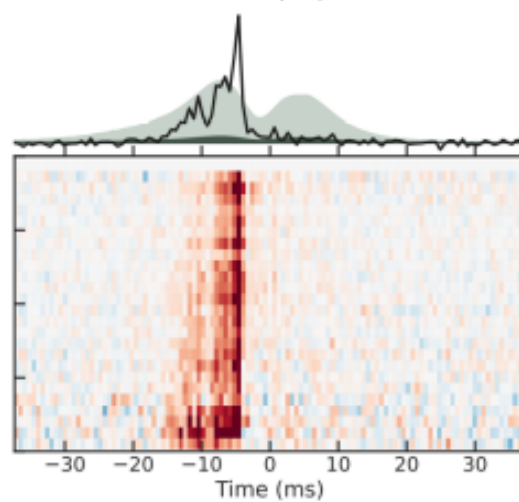
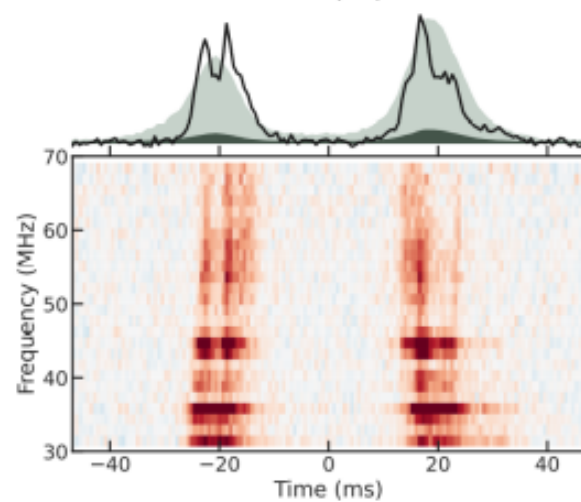
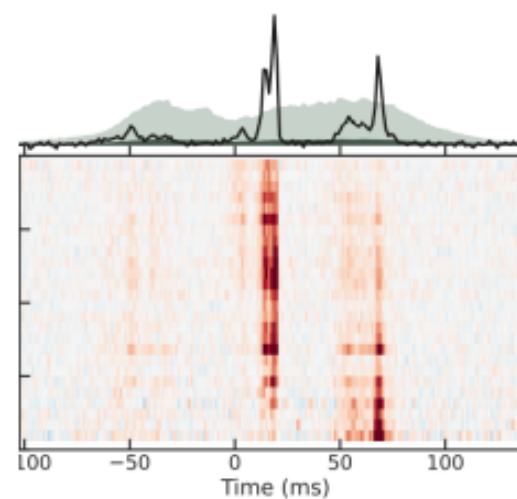
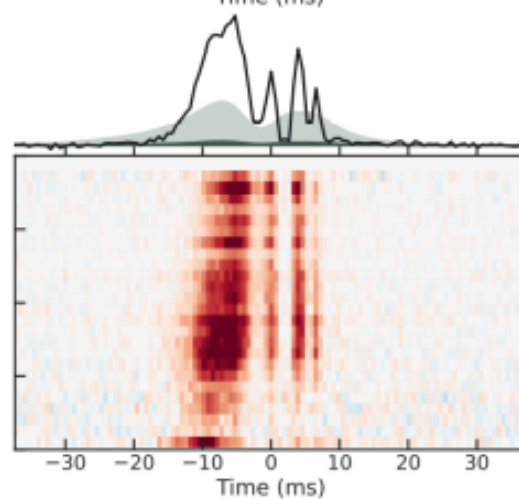
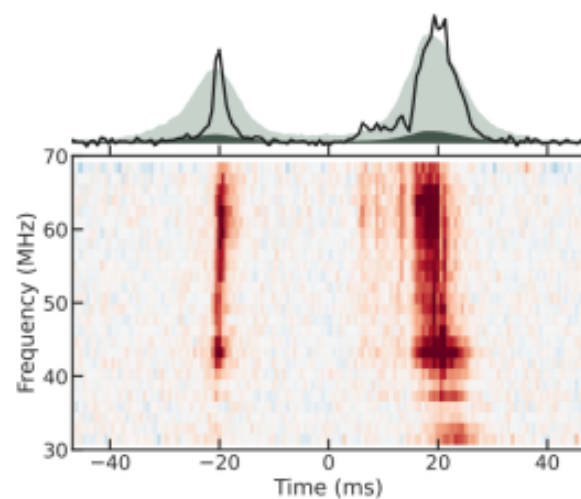
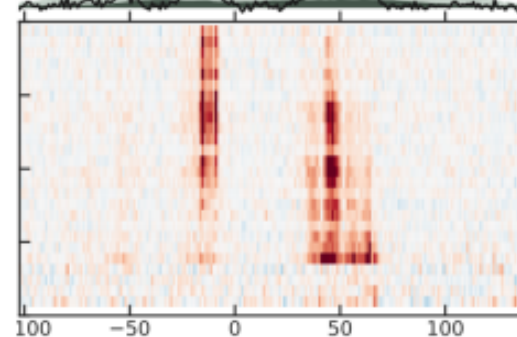
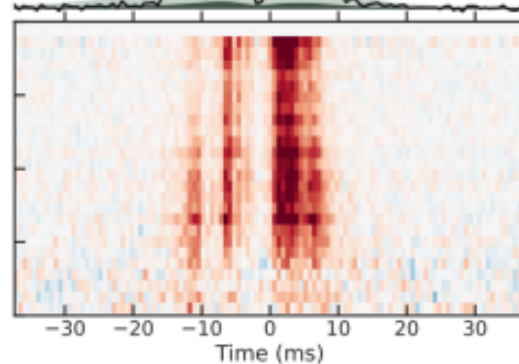
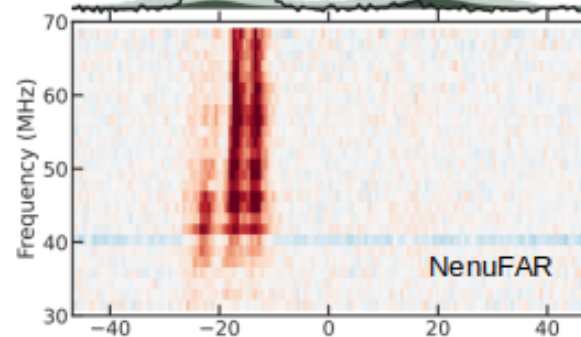


PSR B0950+08 exhibits trombone-like frequency drift!

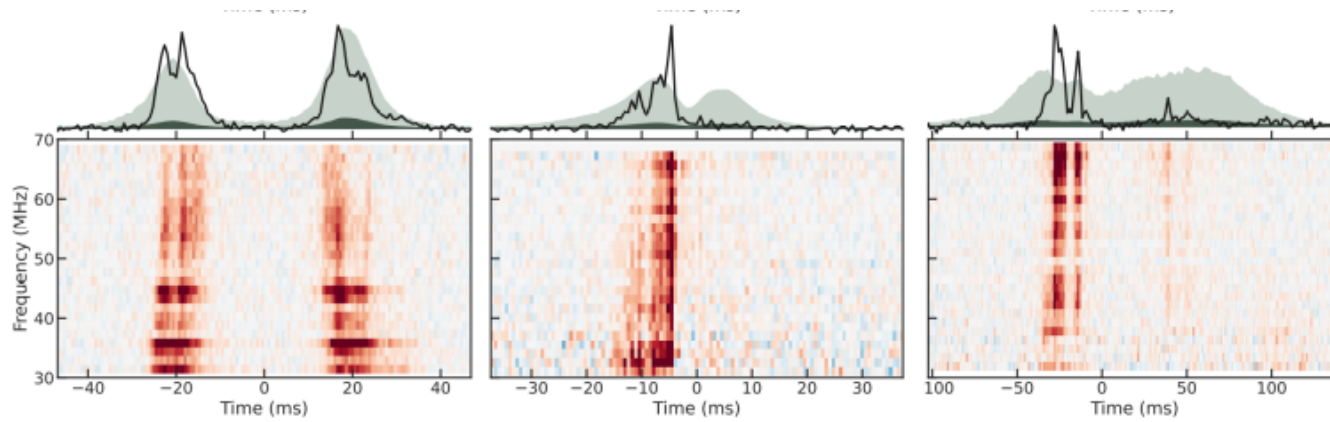


B1133+16**B0950+08****B0809+74**

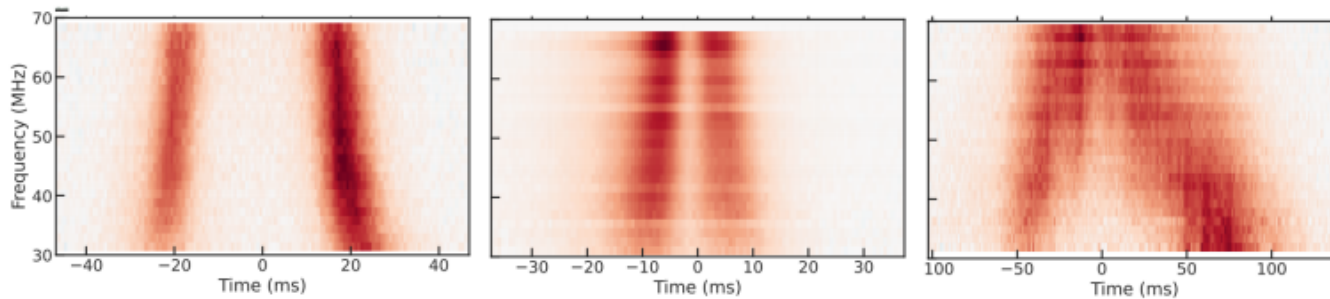
x10 average pulse



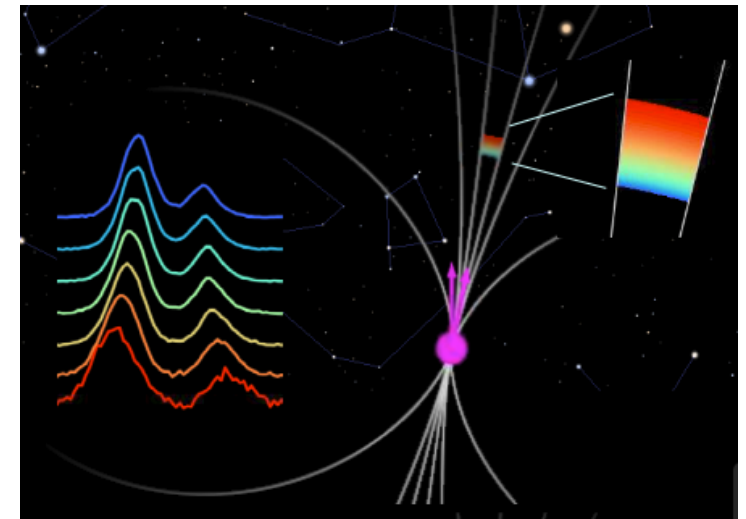
Averaged to typical profile broadening



Average spectra (thousands of pulses):

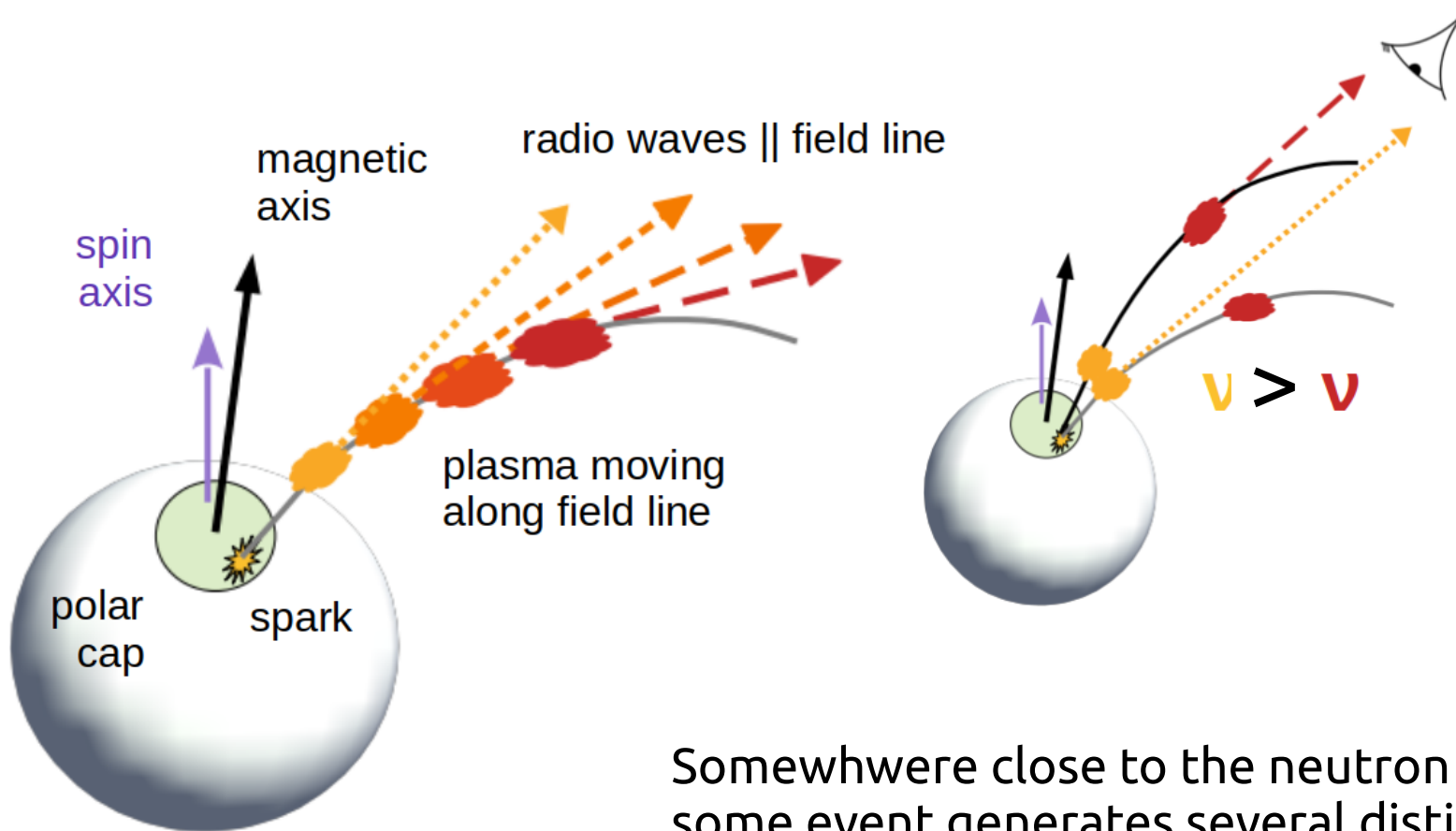


Radius-to-frequency mapping (RFM):
component profiles diverging
towards lower frequencies
can be mapped to diverging
dipole field lines.



RFM-like model of pulsar trombone drift

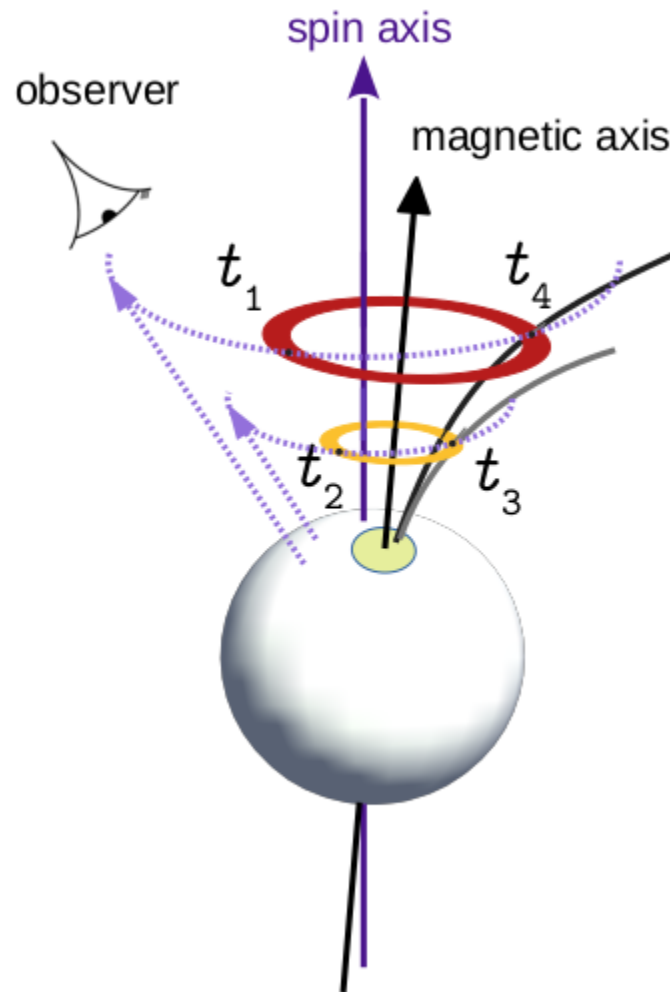
based on Wang et al (2019, 2021) for FRBs



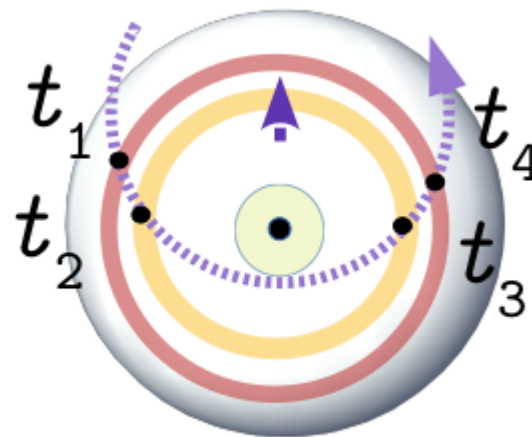
Somewhere close to the neutron star surface some event generates several distinct clumps of plasma. These clumps are moving along the field lines emitting collimated radio waves at altitude-dependent radio frequency.

RFM-like model of pulsar trombone drift

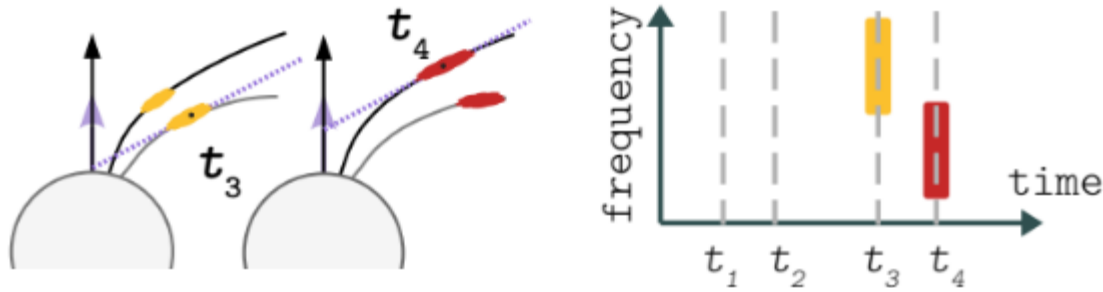
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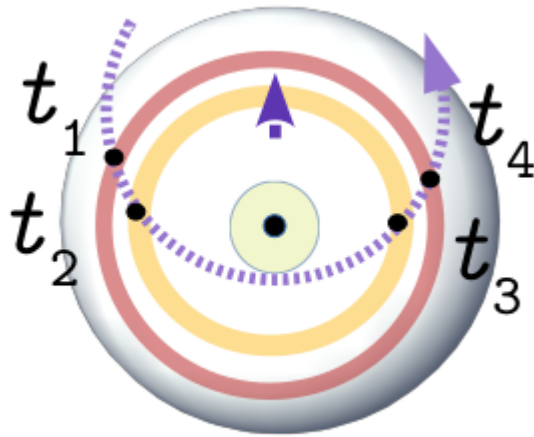
As the star rotates, observer's line of sight (LOS) samples different field lines / emission altitudes. Since clumps move forward only, the direction of LOS movement becomes crucial.



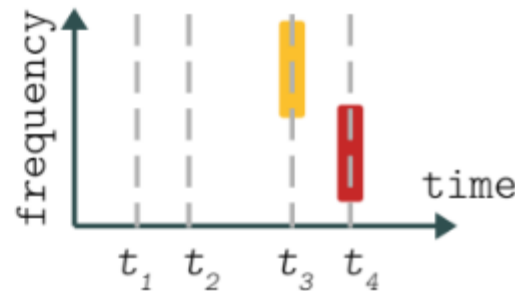
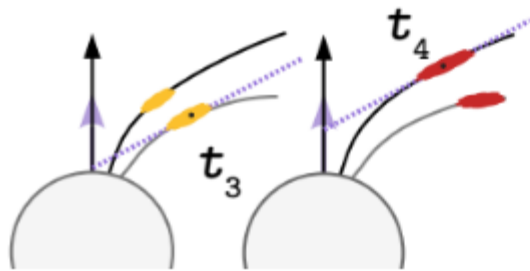
A) Sad trombone (downward drift)



LOS fortuitously aligns with radio emission from one clump at higher radio frequency, and, shortly afterwards, with another clump at lower frequency.

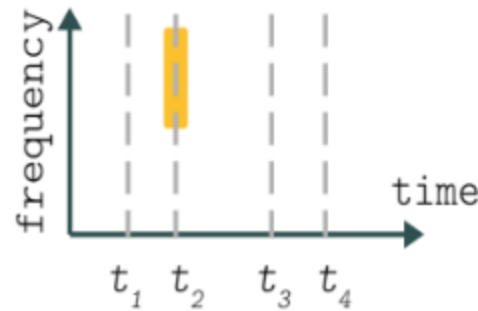
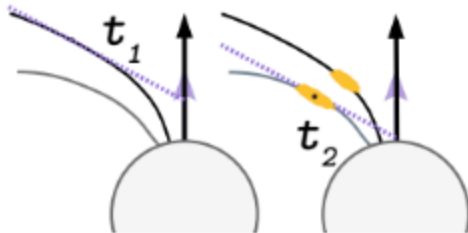


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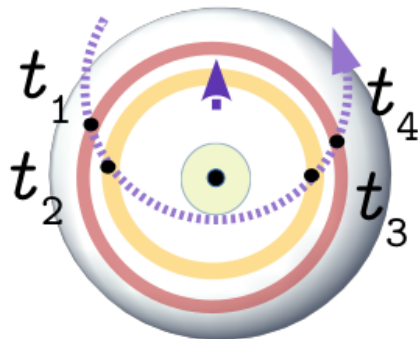


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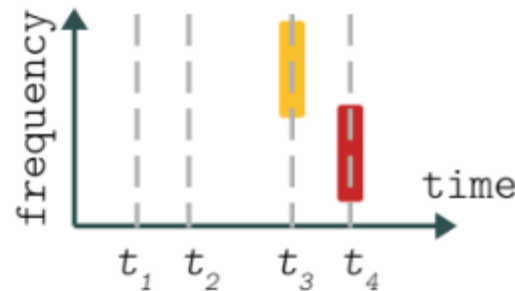
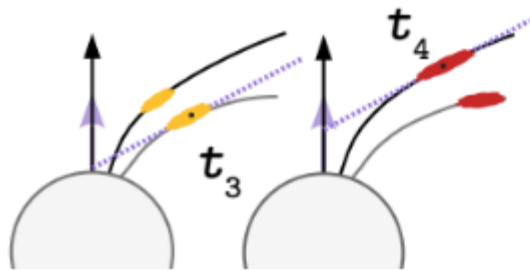
B) No trombone



LOS passes higher-altitude (lower-frequency) emission region first, but no clump has arrived there yet. Only higher radio frequencies are detected.

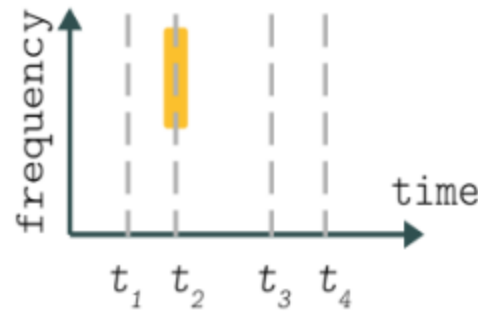
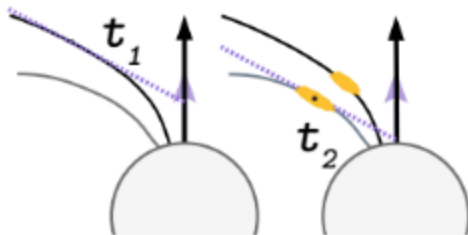


A) Sad trombone (downward drift)



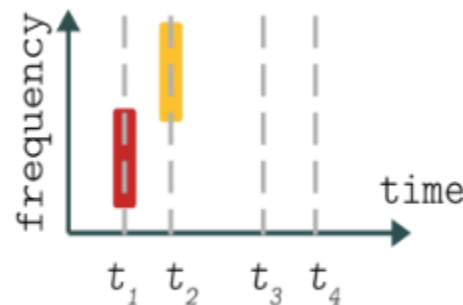
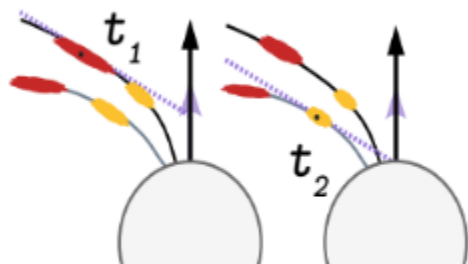
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B) No trombone



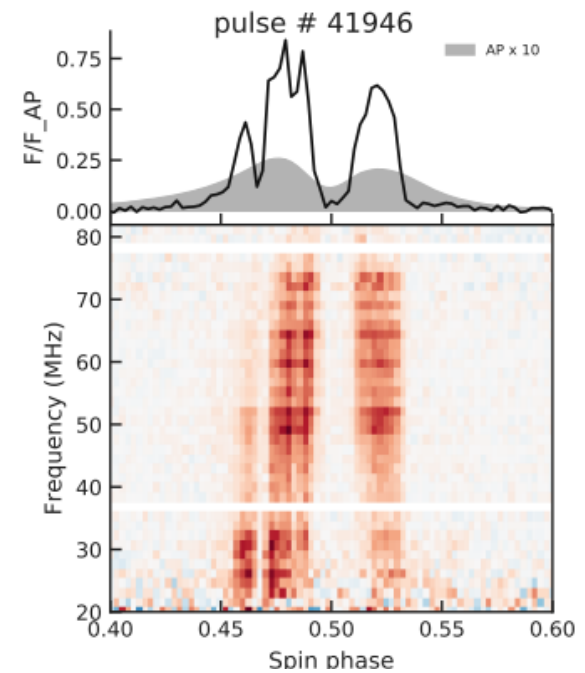
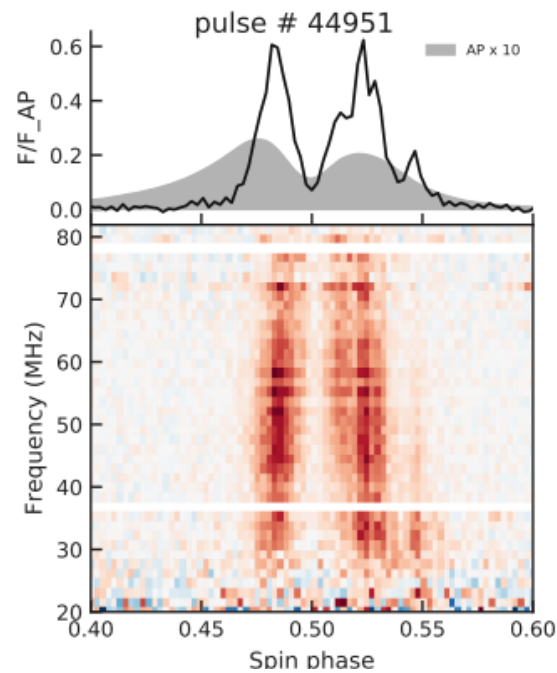
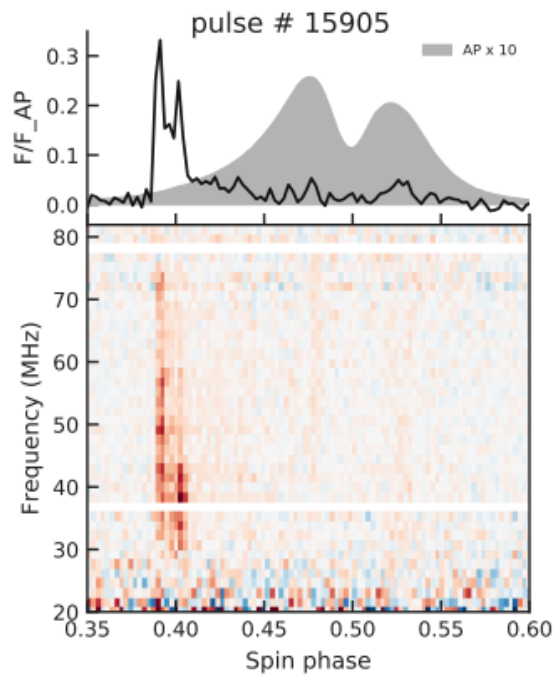
LOS passes higher-altitude (lower-frequency) emission region first, but no clump has arrived there yet. Only higher radio frequencies are detected.

C) Happy trombone (upward drift)



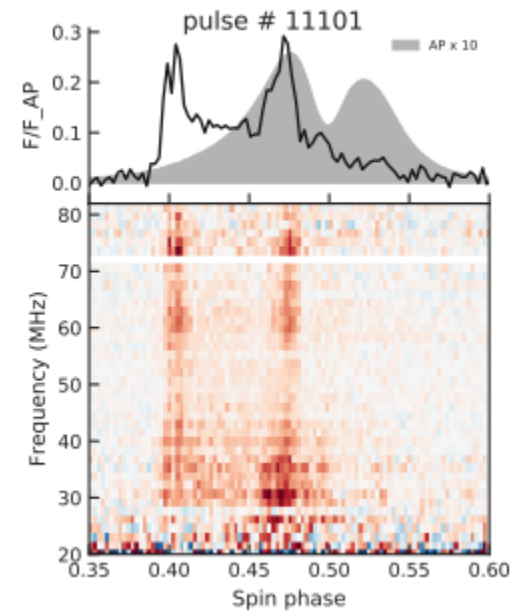
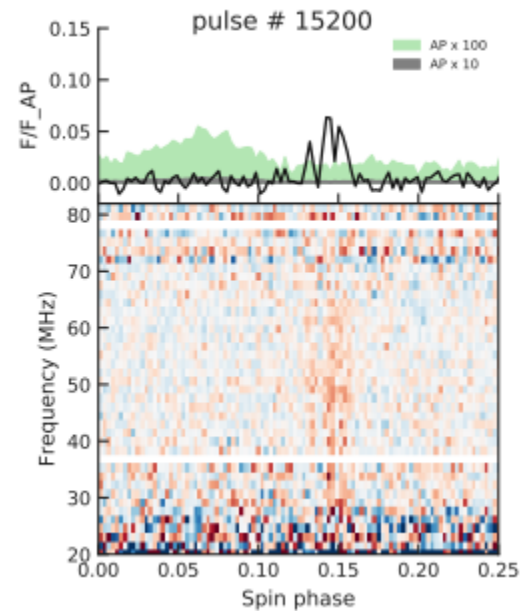
If clumps are generated frequently (but yet they are distinct), LOS can pick emission from two different batches of clumps, generating upward frequency drift.

Potential tool for constraining emission regions



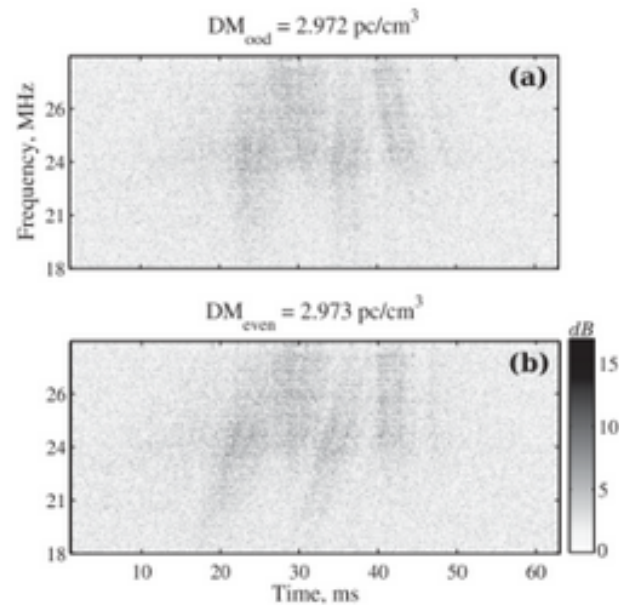
But not so simple:

for example, B0950+08 has two additional components, precursor and bridge.



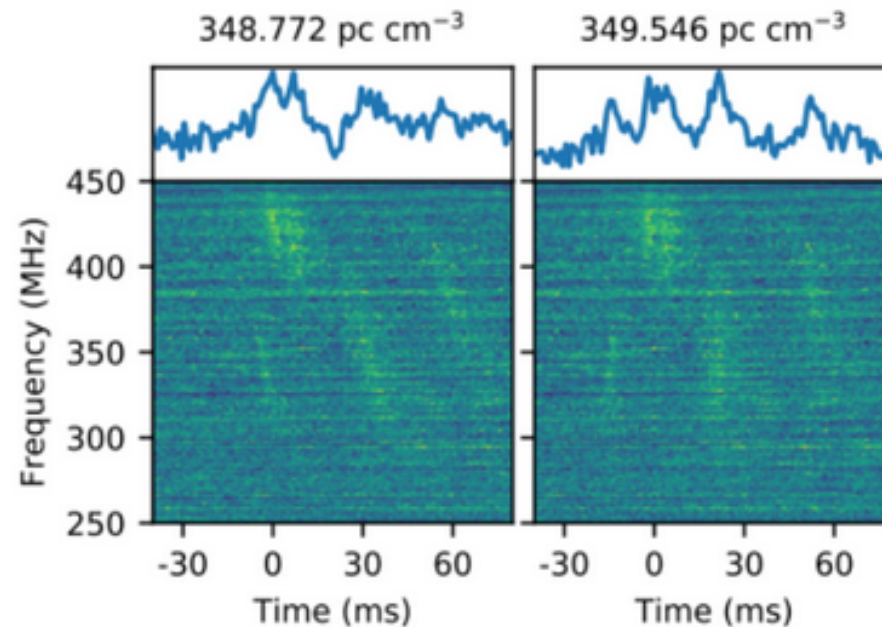
Even more complex at the very low frequencies

B0950+08 Ulyanov et al. (2016)

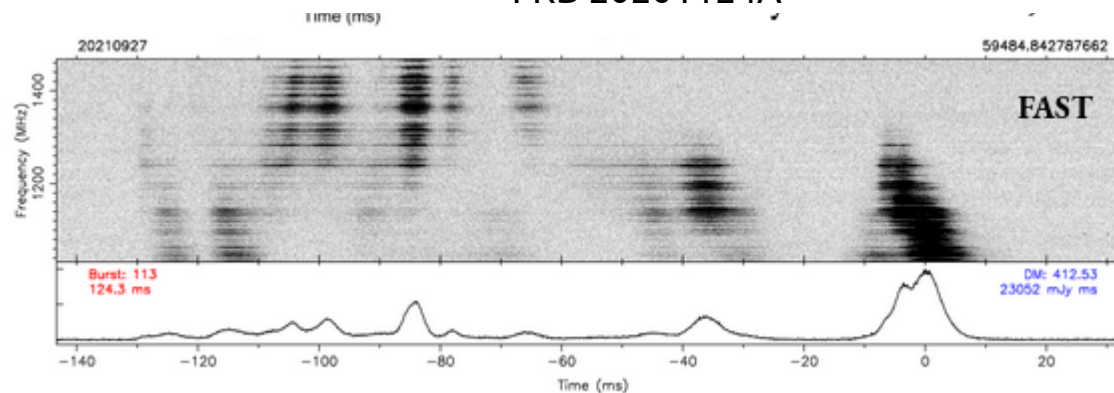


FRB 20180916B

Pleunis et al. (2021)



FRB 20201124A



Zhou et al. (2022)

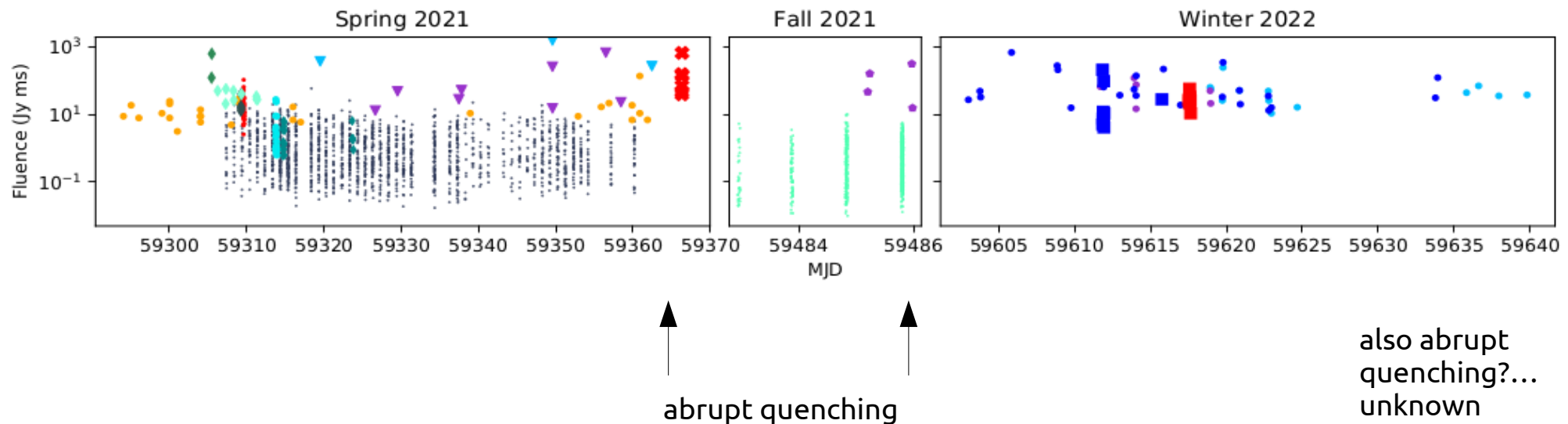
Potential for further work:

- Trombone drift in pulsars can potentially be used to constrain emission regions and magnetospheric geometry, complementing existing approaches
- Same approach can be then applied to FRBs
- Assuming same emission mechanism, is there a combination of magnetic field strength, field curvature radii, particle Lorentz factors, and plasma density that can explain trombone-like drift for both pulsar single pulses and FRBs, and can account for 10^{12} difference in luminosity?

C) Frequency-dependent activity window

FRB20201124A

- One of the most prolific FRB repeaters
- 1.2 billion light years away!
- Highly irregular aperiodic activity
- Activity cycles end abruptly



ALERT

- Survey for FRBs with good localization
- State-of-the-art convolutional neural network candidate sifting algorithm
- Real-time triggers
- Polarization
- Detected many one-off FRBs



Second-to-last day of ~4-year observing program:

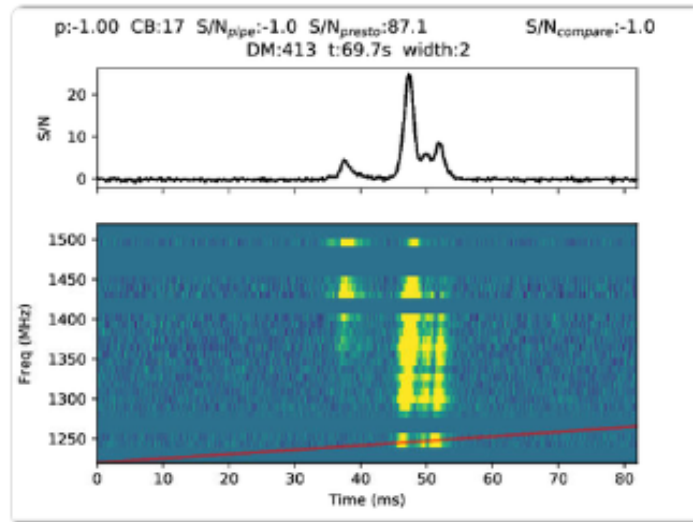


Anya Bilous Feb 2nd, 2022 at 11:13 AM

Ladies and gentlemen (@channel), may I present you the rich and powerful burst from FRB 20201124:

Spotted by @Pikky Atri yesterday at midnight when the primary OSA was celebrating GBT proposal deadline. There's a second one in the same session, it'll come in a minute. (edited)

image.png ▼



4 replies



Oliver Boersma Feb 2nd, 2022 at 11:21 AM

Periodic last three bursts 🤔?



Inés Pastor-Marazuela Feb 2nd, 2022 at 11:26 AM

It's beautiful!!!



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Wonderful! This guy is indeed active.



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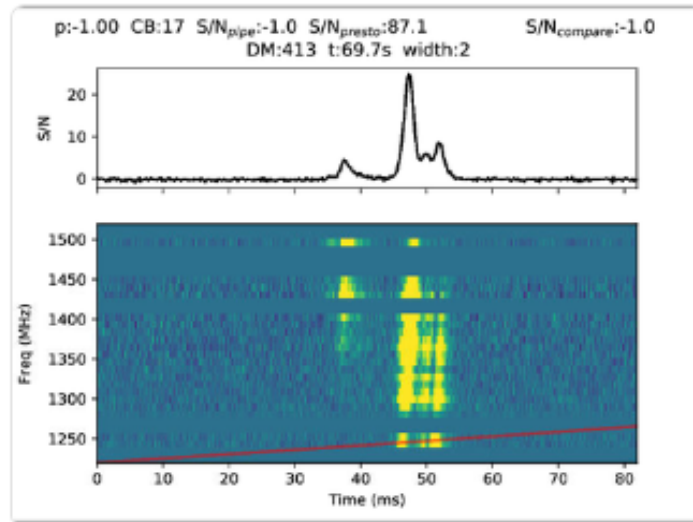


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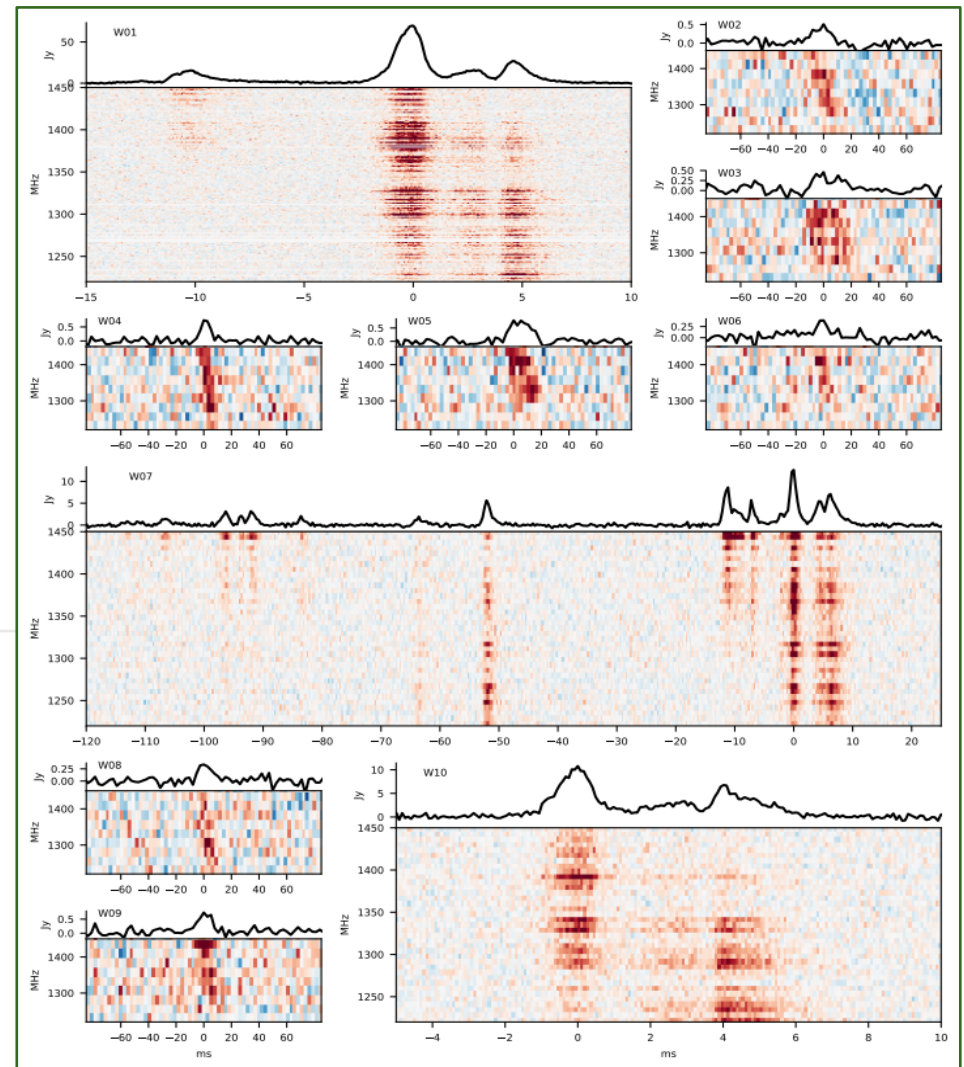


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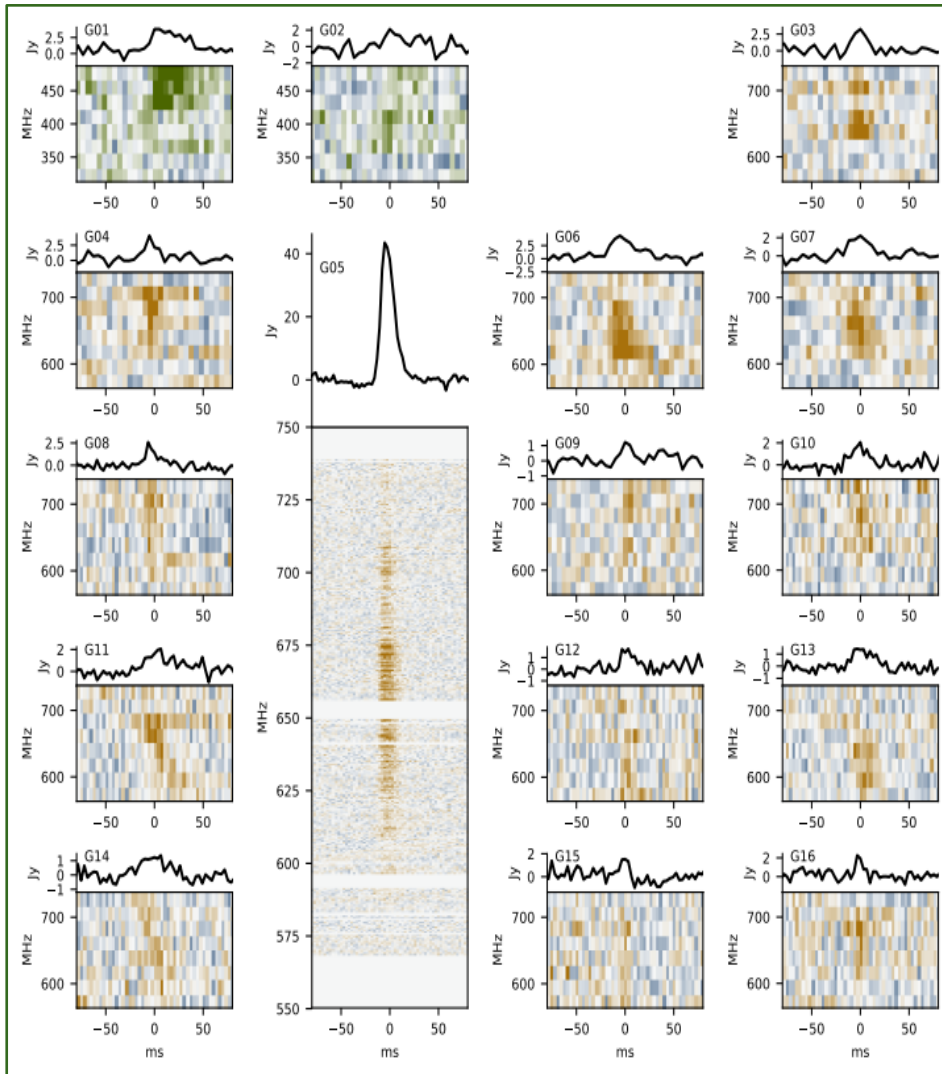
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Feb 2022, L-band

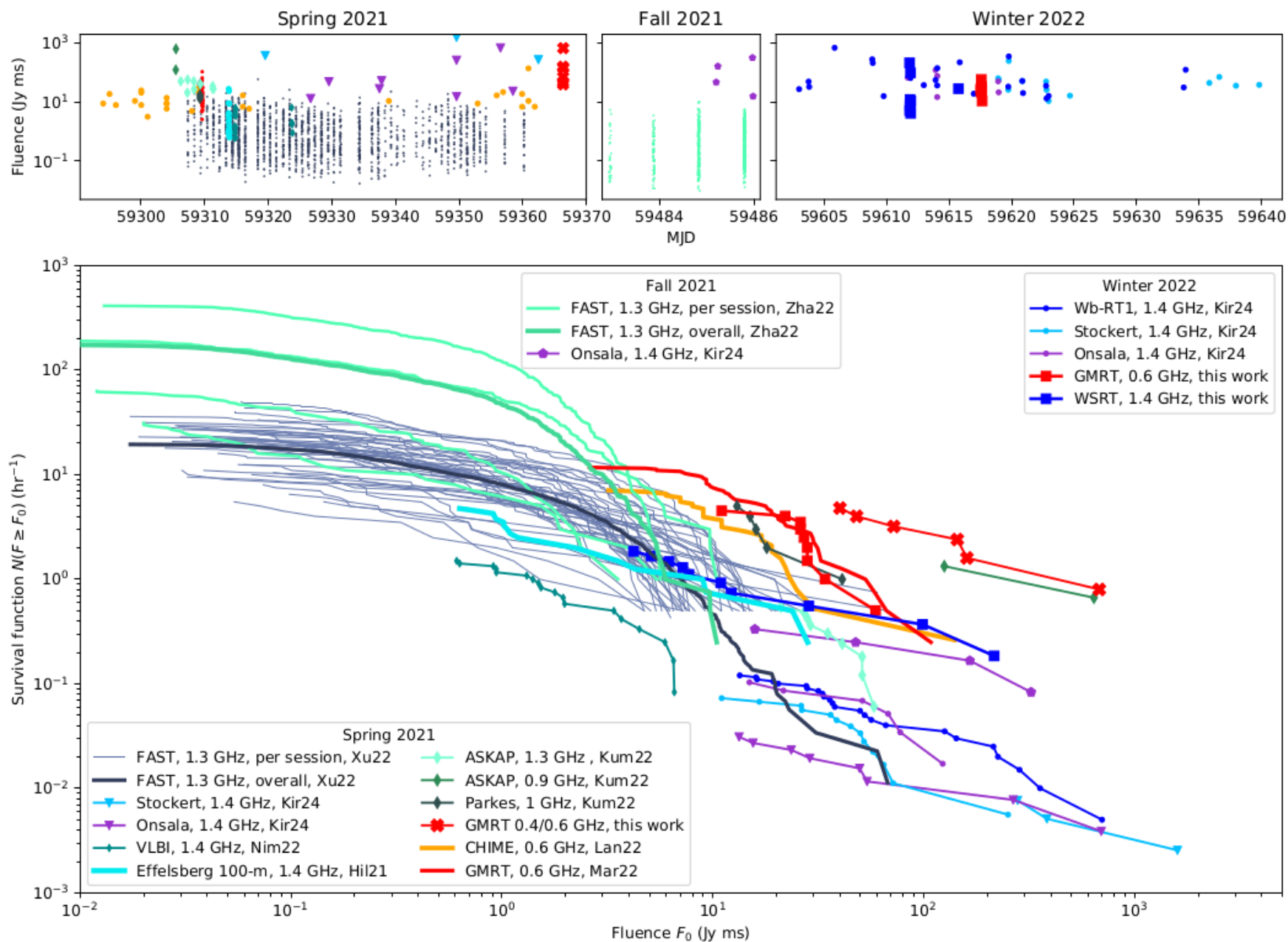


Added: GMRT observations in the end of Spring 2021 activity window



Lower frequencies: 400 MHz or 650 MHz

Fluence distributions

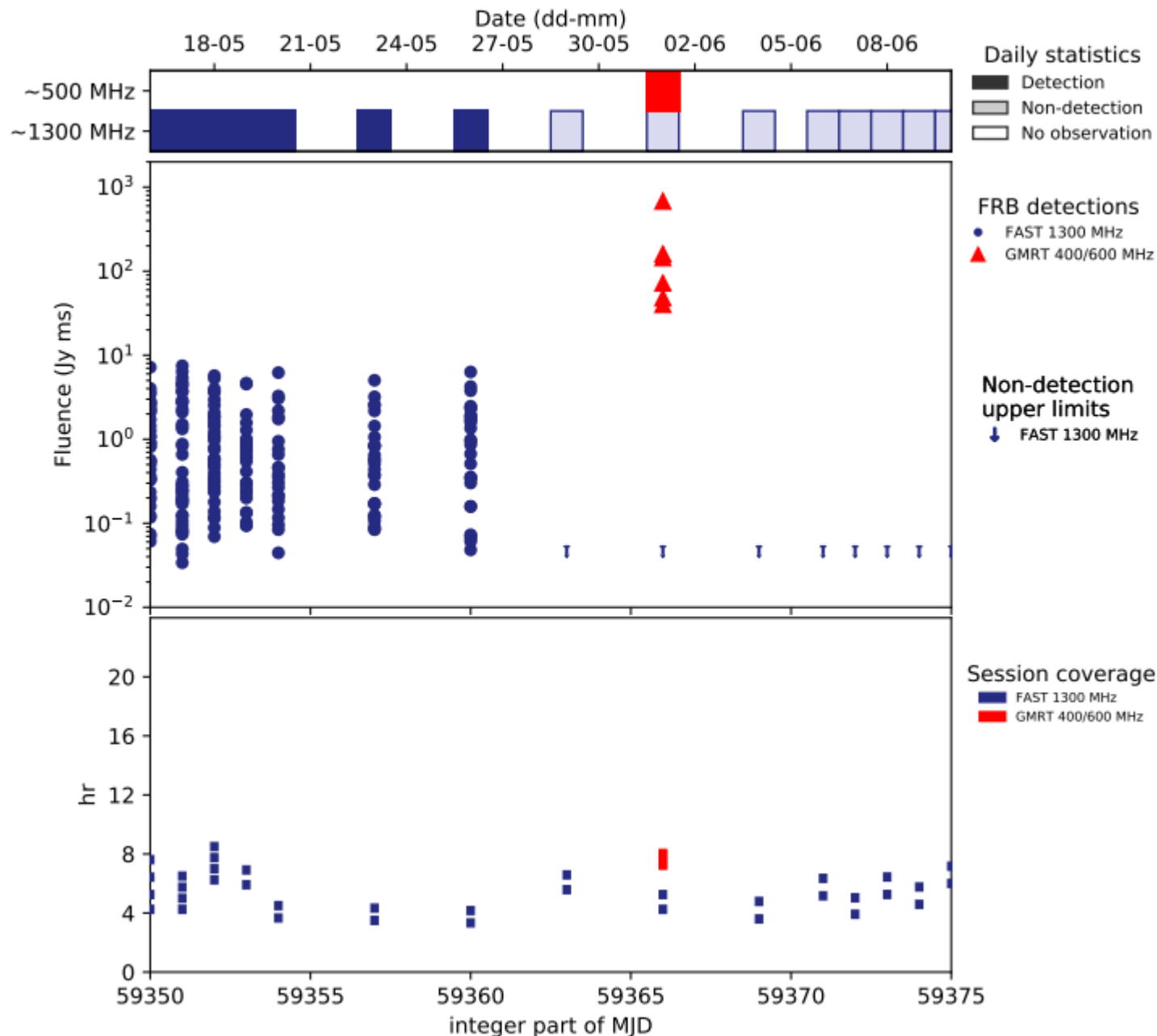


Running results of the analysis

Bilous et al 2025

- Winter 2022: observations in activity cycle that was not covered by FAST
- Ruling out large (few $\text{pc}/\text{cm}^3/\text{month}$) DM gradients between activity windows
- Unresolved trombone drift can bias phase-maximized DMs up to $10 \text{ pc}/\text{cm}^3$, even for relatively bright bursts
- Scintillation does not change between activity windows
- WSRT: bursts with seemingly periodic components, but without significant quasi-periodicity
- WSRT: flat fluence distribution, but hardly significant given small sample of bursts
- GMRT: different fluence distributions from two activity windows mostly due to small sample size

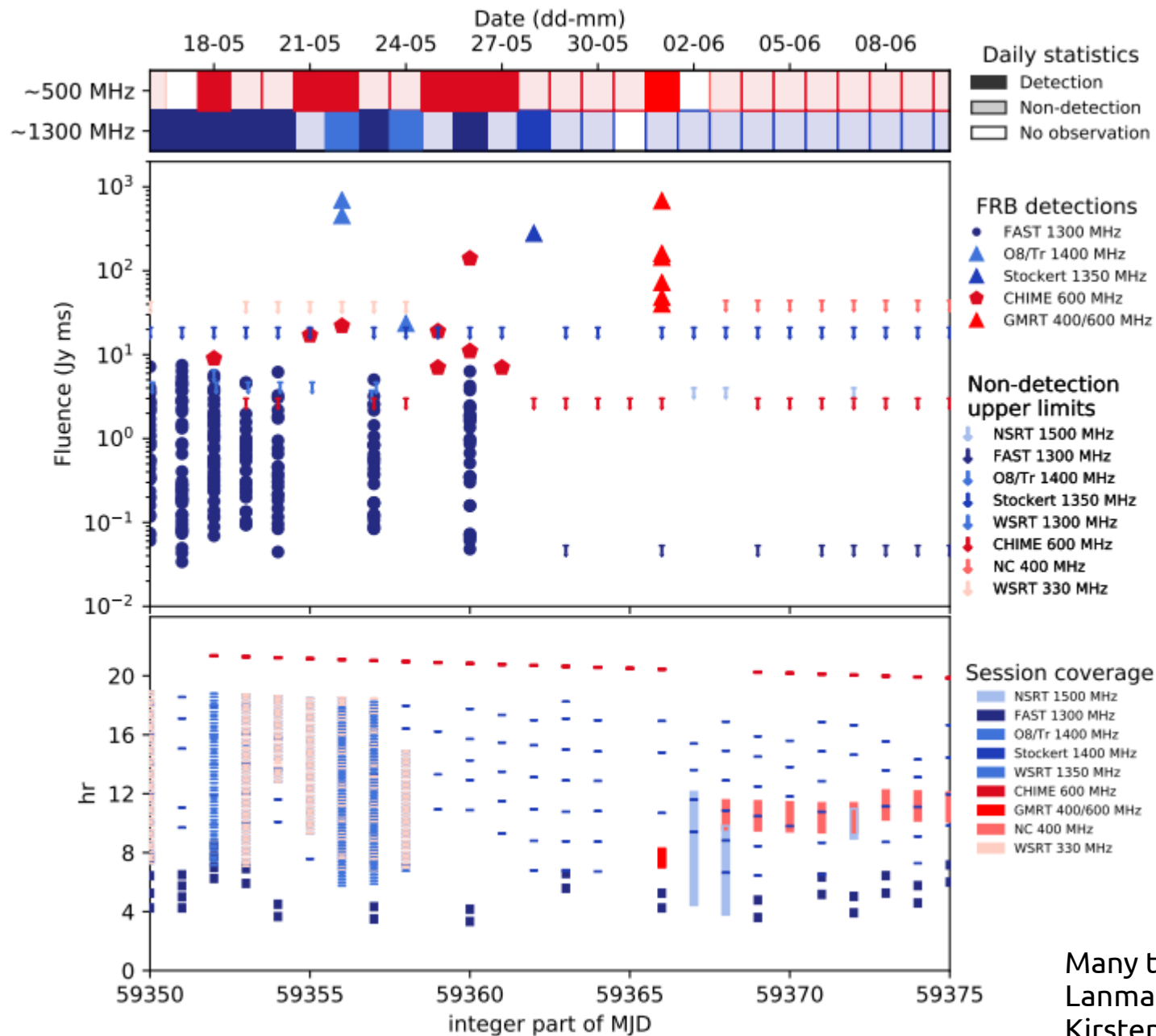
Frequency-dependent activity window edge



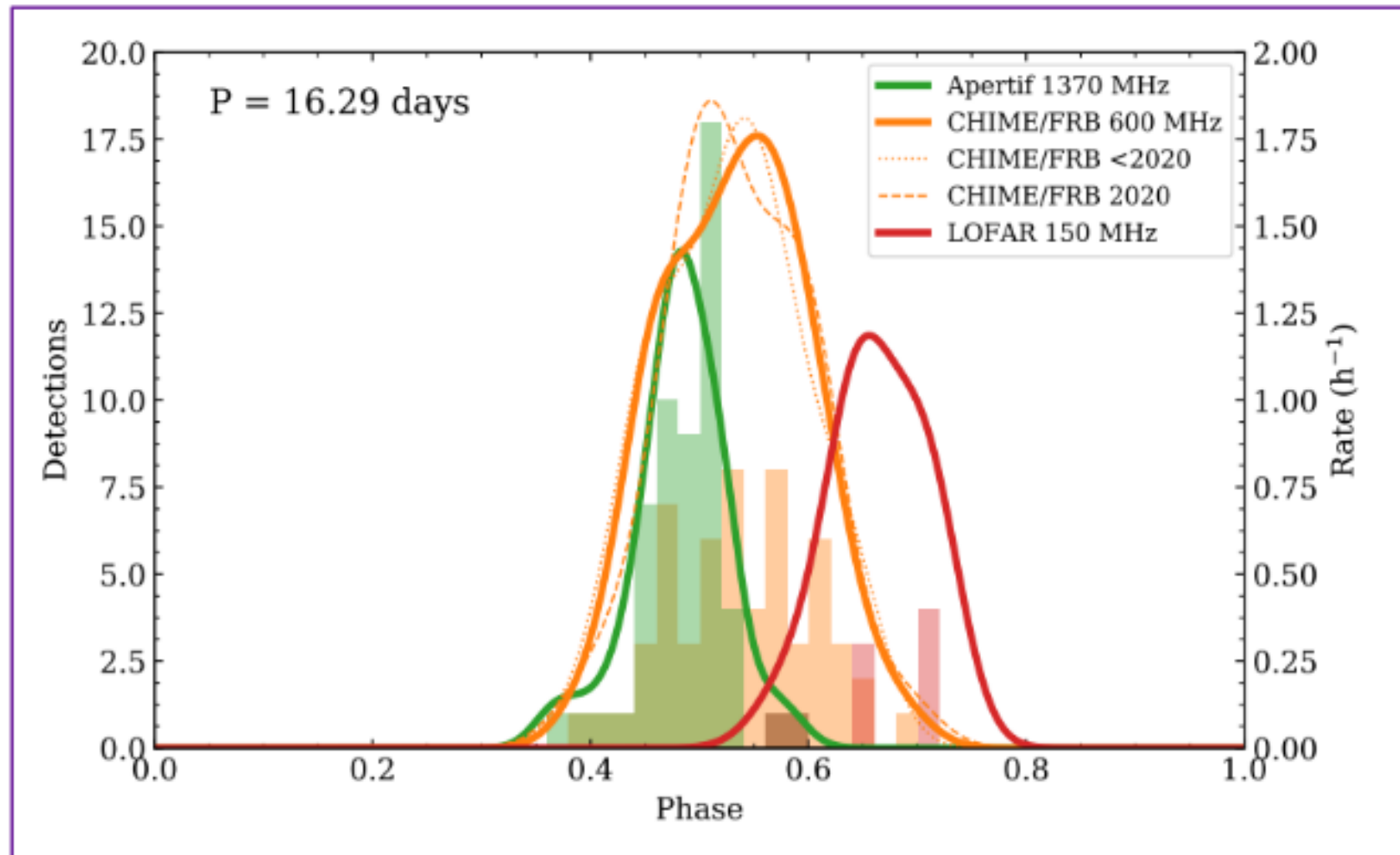
Strong bursts were detected at GMRT at 300-600 MHz just few hours after FAST placed >1000 times more stringent upper limits on emission at 1350 MHz.

Low-frequency emission was present for 3-6 days after high-frequency quenching.

Including all other telescopes

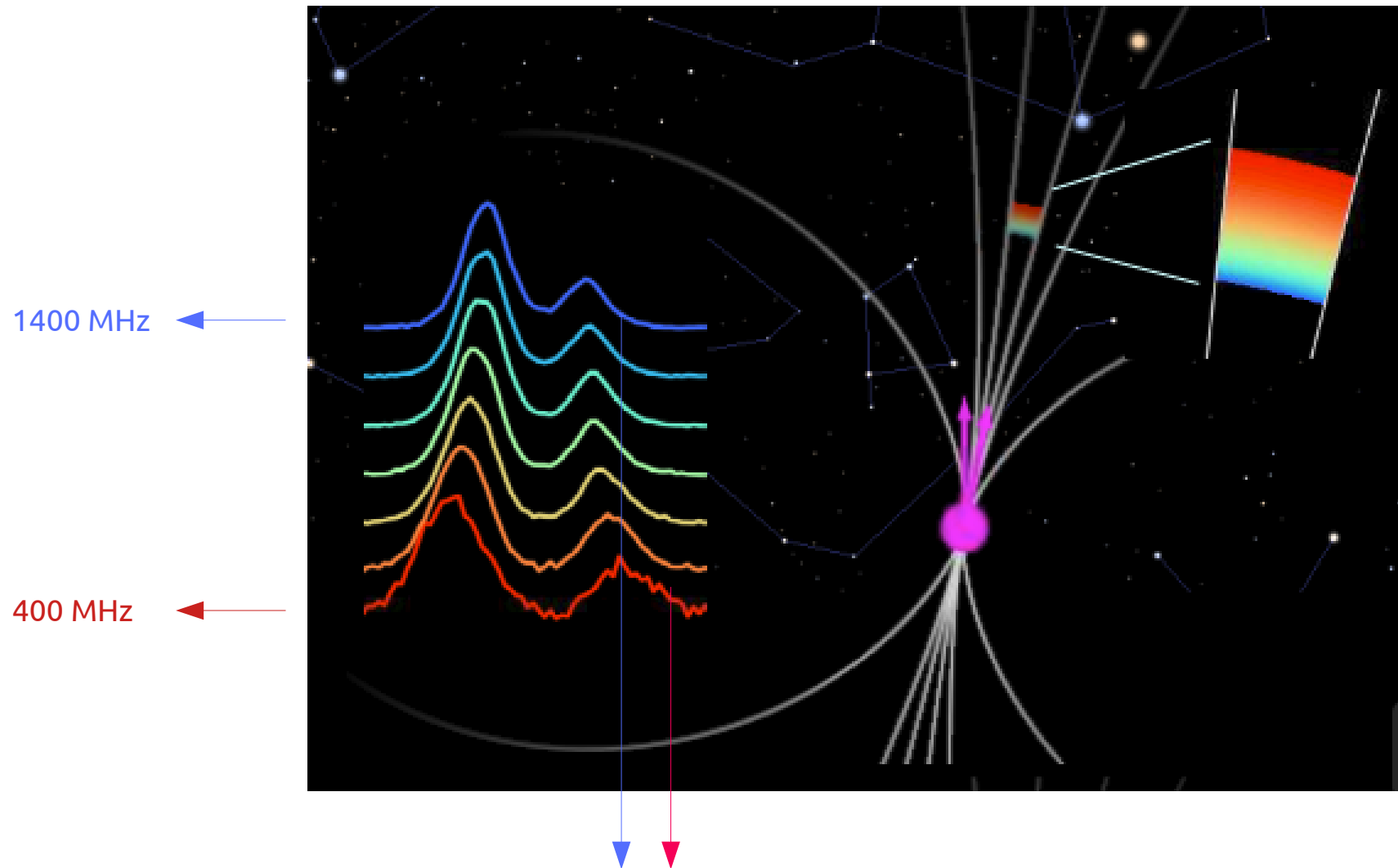


Many thanks to Matteo Trudu, Adam Lanman, Jian-Ping Yuan, and Franz Kirsten for providing extra information about observing times



The other detection of chromatic activity: FRB 20180916B. The source shows a 16.3-day activity periodicity. Several emission cycles combined, reveal a 150-MHz activity edge lagging a few days behind the 1350-MHz one (Pastor-Marazuela et al 2022).

Can this be a sign of “profile broadening”?



FRB20201124A – ultra-long period magnetar?

- spin period of months or more
- possible in theory (Beniamini et al 2023)
- would explain the absence of periodicity in the bursts, on timescales of few ms - 10 days (Niu et al 2022)

FRB emission model (Wadiasingh & Timokhin 2019):

- Magnetars with low-twist magnetosphere (charge-starved)
- Local crustal cracks dislocate footpoints of the field lines generating strong transient electric fields
- Avalanche pair production
- Pulsar-like emission mechanism (so standard pulsar phenomenological models can in principle be applied)
- Radio emission is not confined to open field line regions
- Cracks can happen anywhere – location of emitting field lines is highly irregular

FRB20201124A – ultra-long period magnetar?

Assuming:

- Very long period – unknown
- Highly irregular emission window – unknown

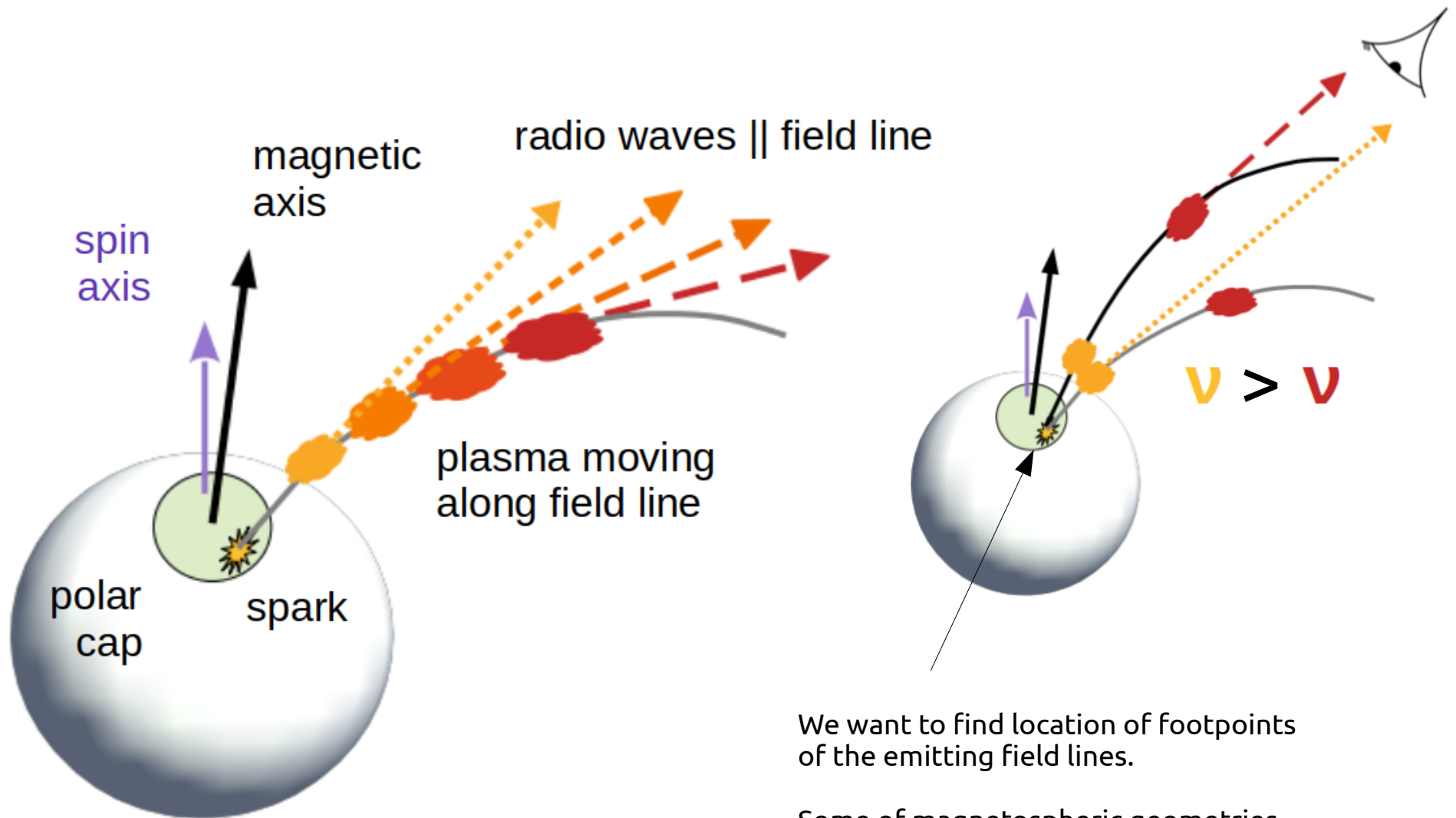
Input data:

- Frequency-dependent edge – 3-6 days delay between 400 MHz and 1400 MHz

What constraints can we put on magnetospheric geometry and location of emission regions?

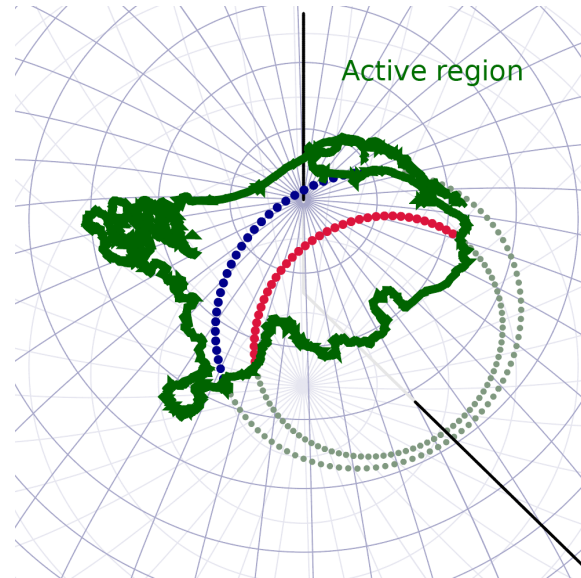
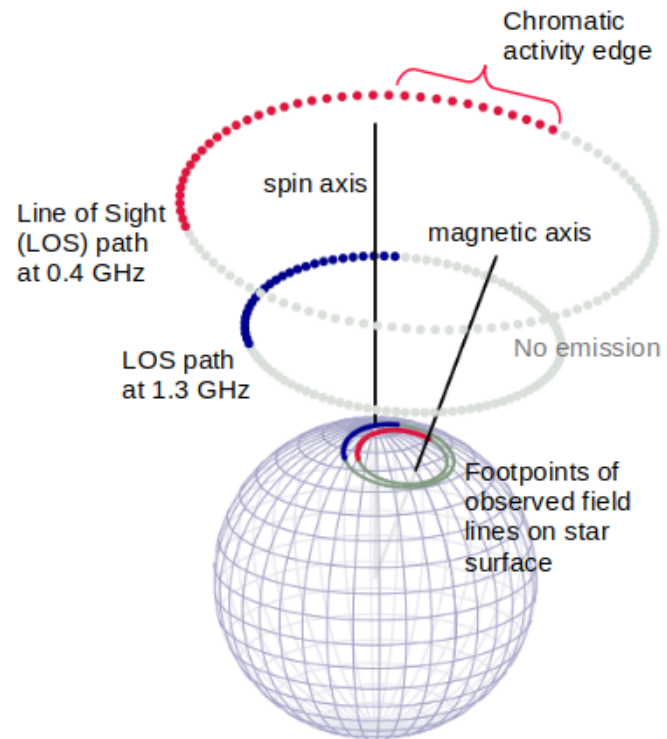
The low-twist magnetar hypothesis of FRB generation makes specific predictions for the times of arrival (TOAs) of individual bursts, and for the quasi-periodicity of sub-bursts, existing evidence does not prove or disprove the predictions (Bilous et al 2025).

Must include plausible emission heights for radio waves being able to escape magnetosphere.

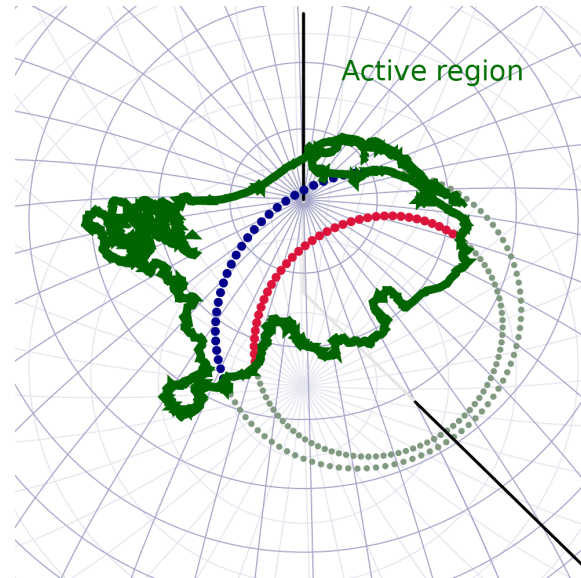
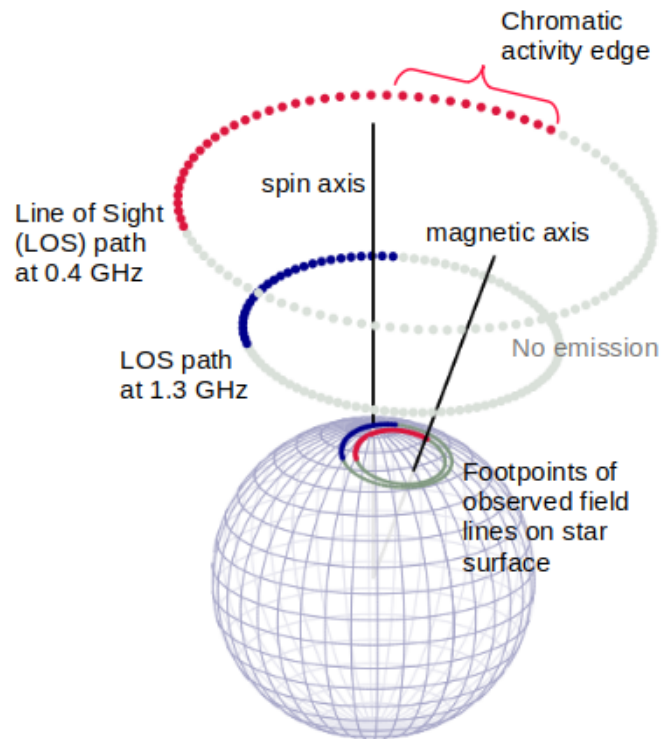


We want to find location of footpoints of the emitting field lines.

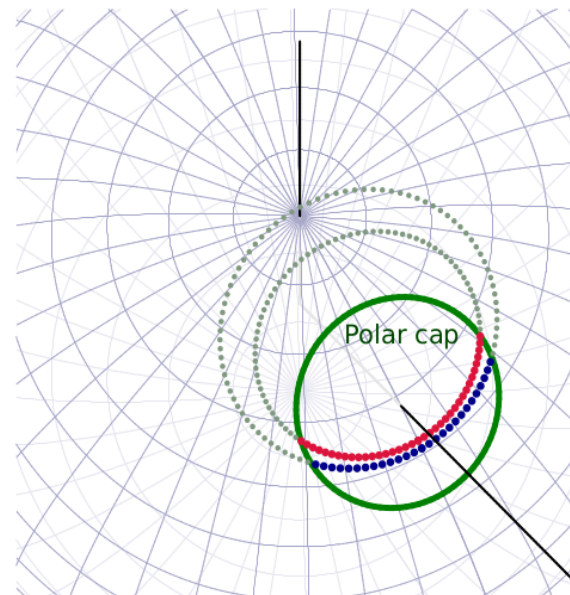
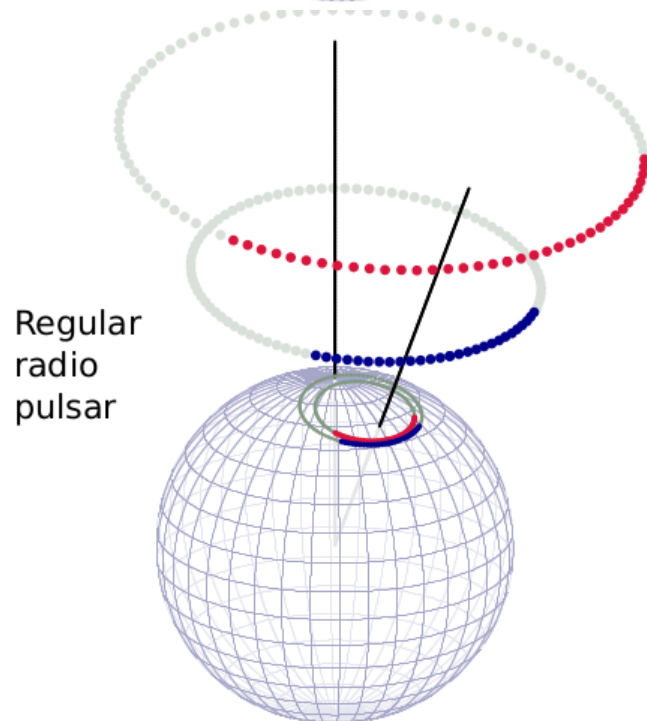
Some of magnetospheric geometries may be ruled out this way.



FRB20201124A:
active patch on
the surface has
arbitrary
irregular shape



FRB20201124A:
active patch on
the surface has
arbitrary
irregular shape



Regular pulsars:
active patch is
polar cap

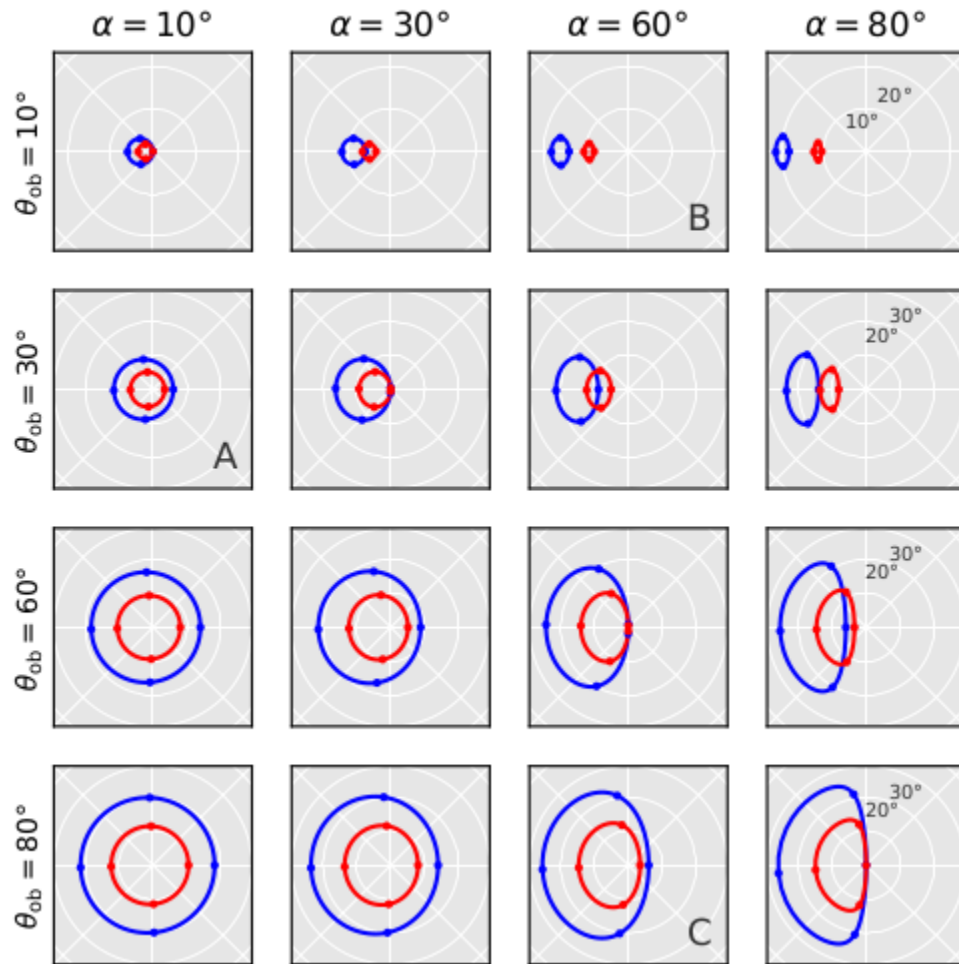
Model:

- Magnetic field of inclined dipole
- Grid of inclination and impact angles
- A range of trial periods
- Curvature radiation
- Emission not constrained to open magnetic field lines
- Least possible escape altitude for higher-frequency emission (not necessary) – $5 R_{NS}$ (Beniamini 2020)
- Chromatic delay of 3-6 days between 400 MHz and 1400 MHz

Reality check:

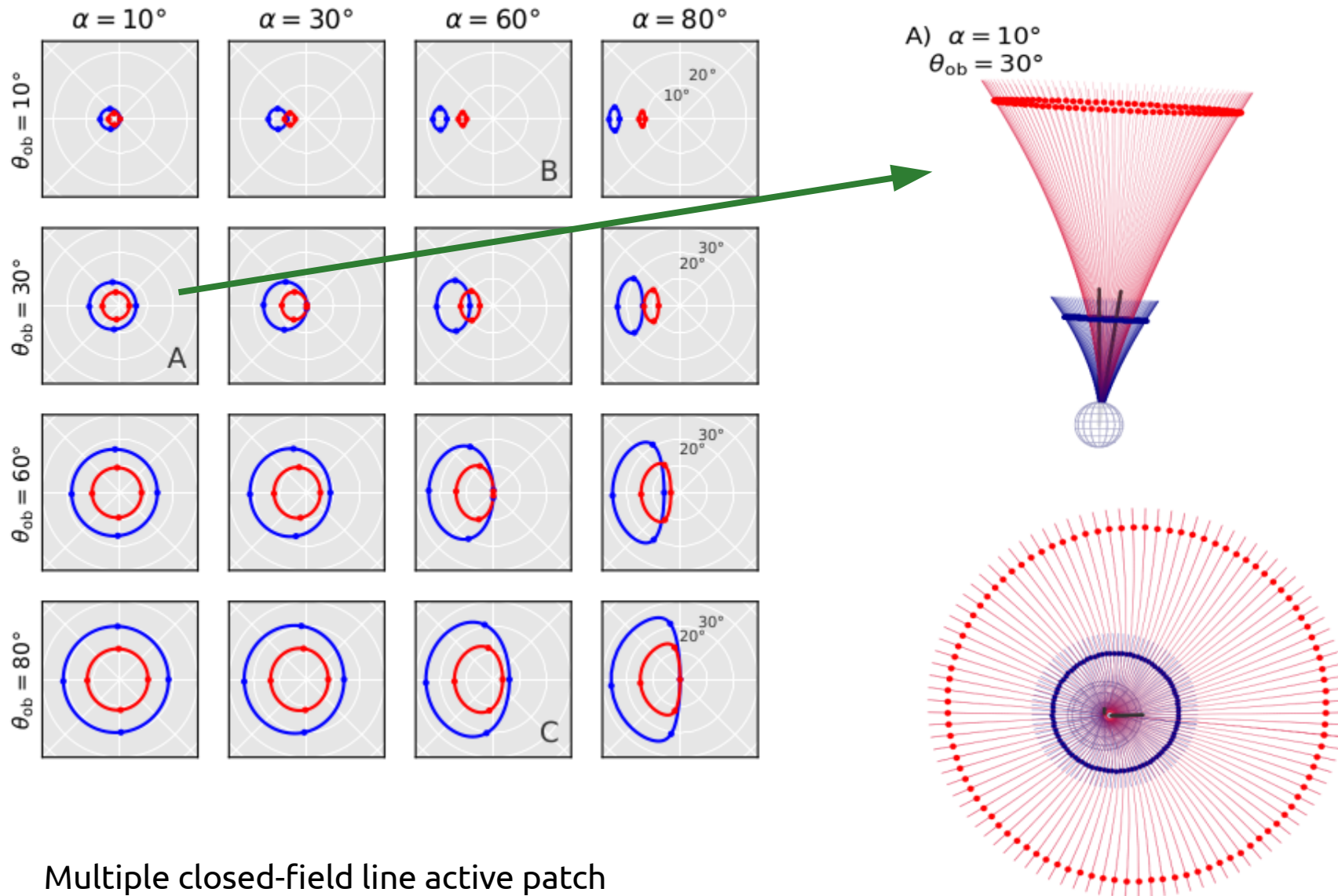
- Emission altitude for lower frequencies > minimum escape altitude for these frequencies
- Lorentz-factor of emitting plasma 50 – 200, similar to 300 adopted by Wang et al 2019.

Current data leaves geometry unconstrained



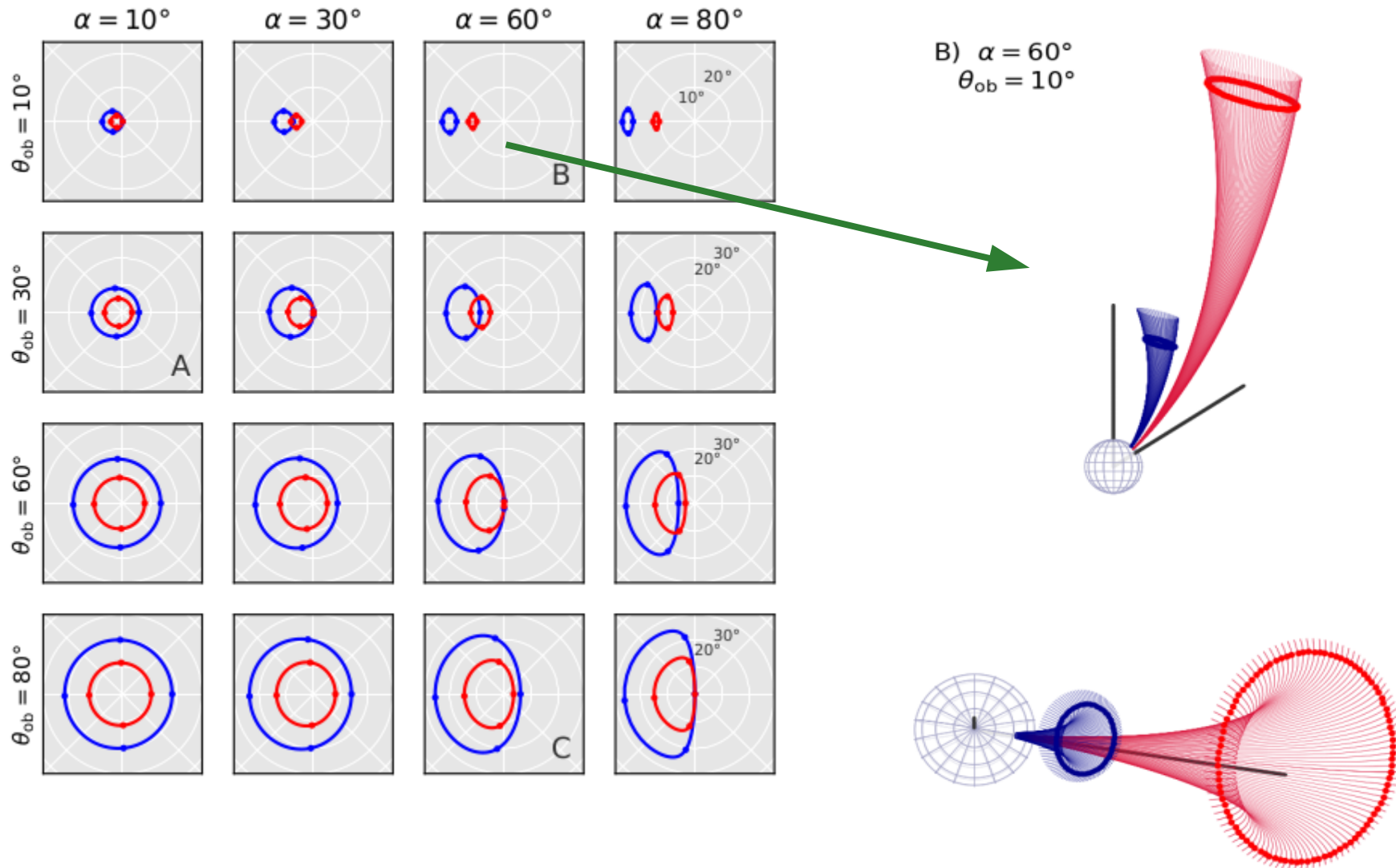
Multiple closed-field line active patch configurations are possible for any given chromatic lag and any combination of geometry angles and spin periods of > 10 days.

Current data leaves geometry unconstrained



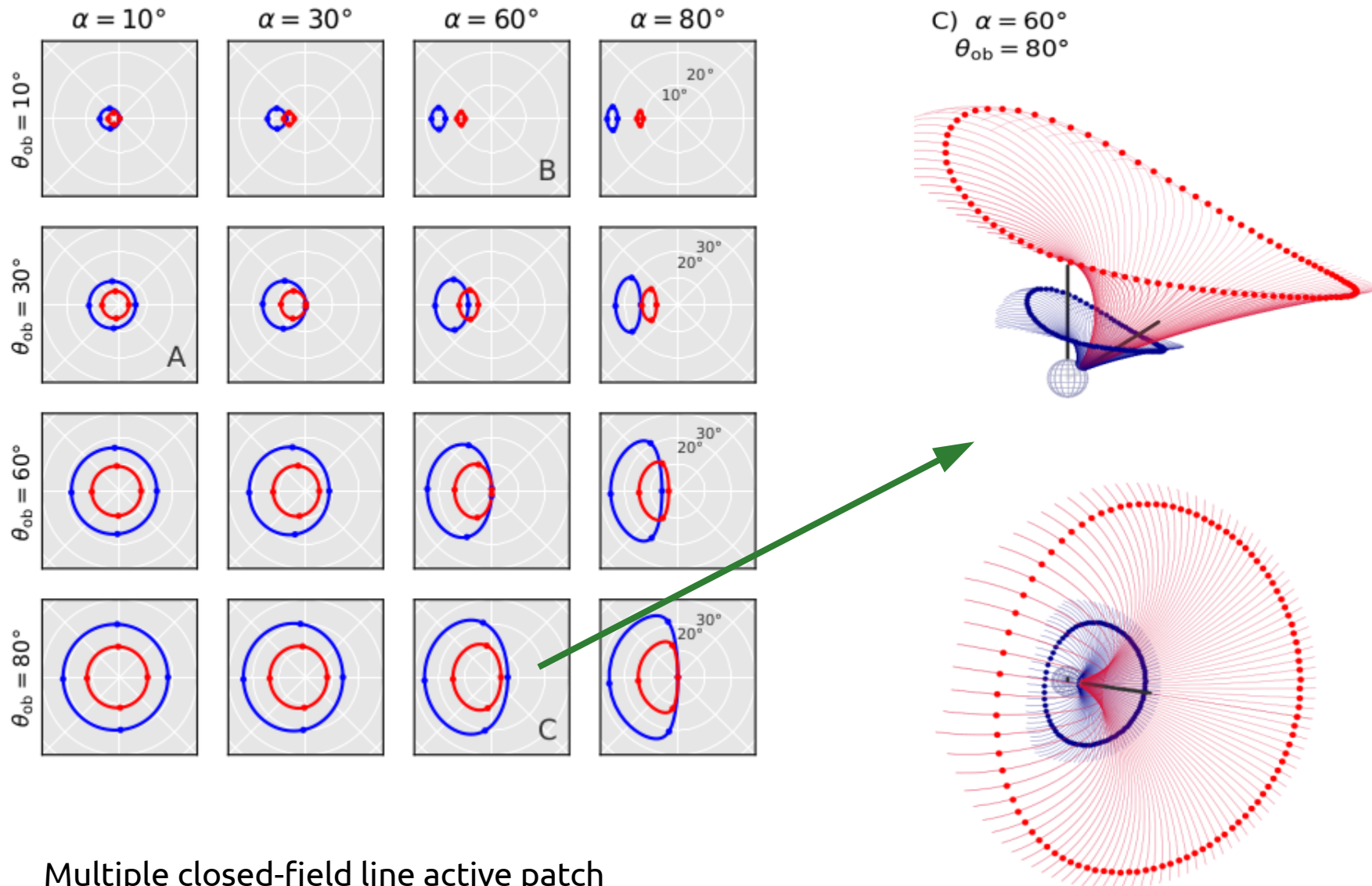
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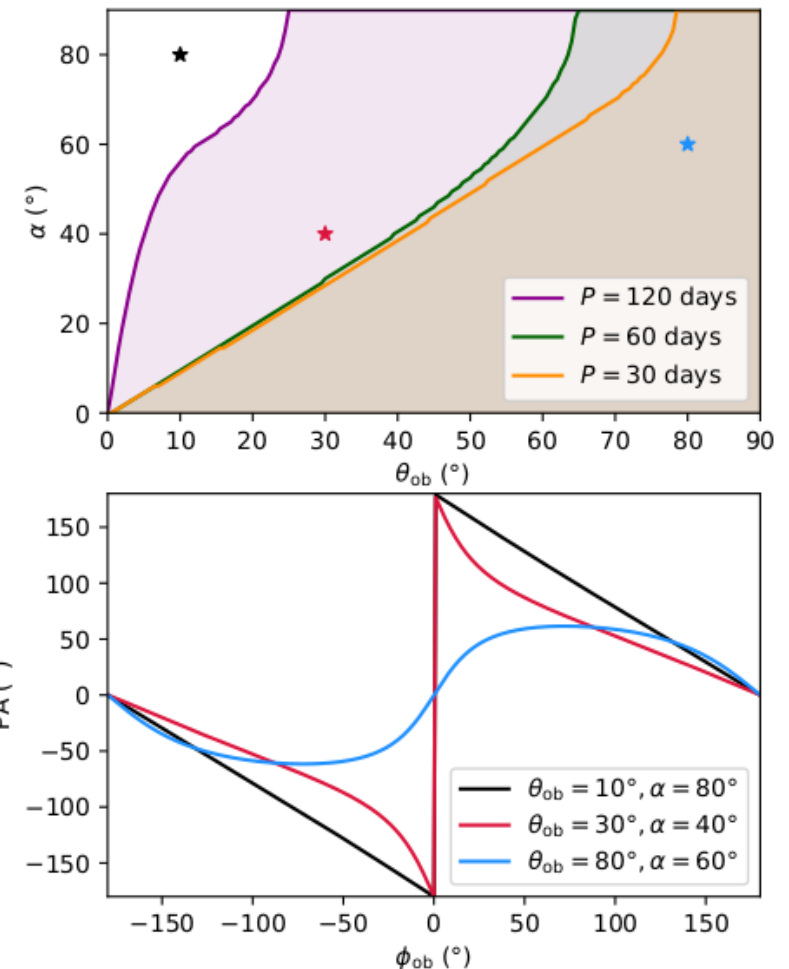
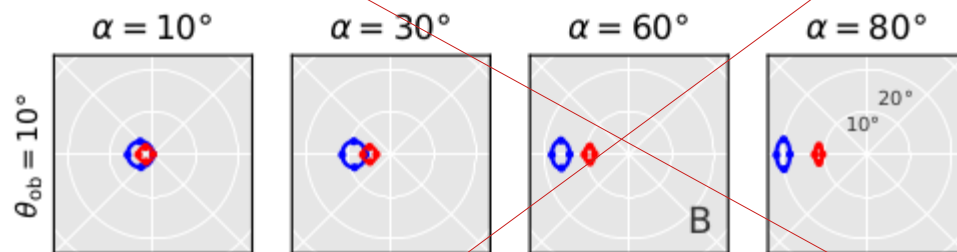
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Further constraints with RVM

Same as for SRPs, PAs of individual bursts are different, but luckily FRB20201124A has so many bursts that they can be studied statistically.

Four-day stretch at the end of the Fall 2021 activity cycle (Jiang et al. 2022): average value of the mean PA within the burst remained constant approximately within 10deg.

Limits on PA gradient!



Large inclination and small impact angles are ruled out unless period is large (several months).

Conclusions

- As of now, ultra-long period magnetar model is neither confirmed, nor disproved
- Need more data from more activity windows!!
- If the model is correct, the amount of chromaticity can be different in different activity windows (also the reverse – low-frequency emission can disappear before higher frequencies)
- Within the model, statistical polarization information is crucial for constraining magnetospheric geometry and location of emission regions

Conclusions & future work

- Brightness distribution of single-pulse subcomponents from pulsars may be even less well known than that of FRBs!
- There is a dire need of a large-scale uniform survey, preferably with good time resolution
- Potential plethora of data for FRB emission mechanisms
- Trombone drift in pulsars can potentially be used to constrain emission regions and magnetospheric geometry, complementing existing approaches
- Same approach can be then applied to FRBs
- Assuming same emission mechanism, is there a combination of magnetic field strength, field curvature radii, particle Lorentz factors, and plasma density that can explain trombone-like drift for both pulsar single pulses and FRBs, and can account for 10^{12} difference in luminosity?
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