Fifth Workshop on Millimetre Astronomy in Italy

Bologna – 13 June 2023

Neutron stars pulsating in the mm-band: Italian perspectives

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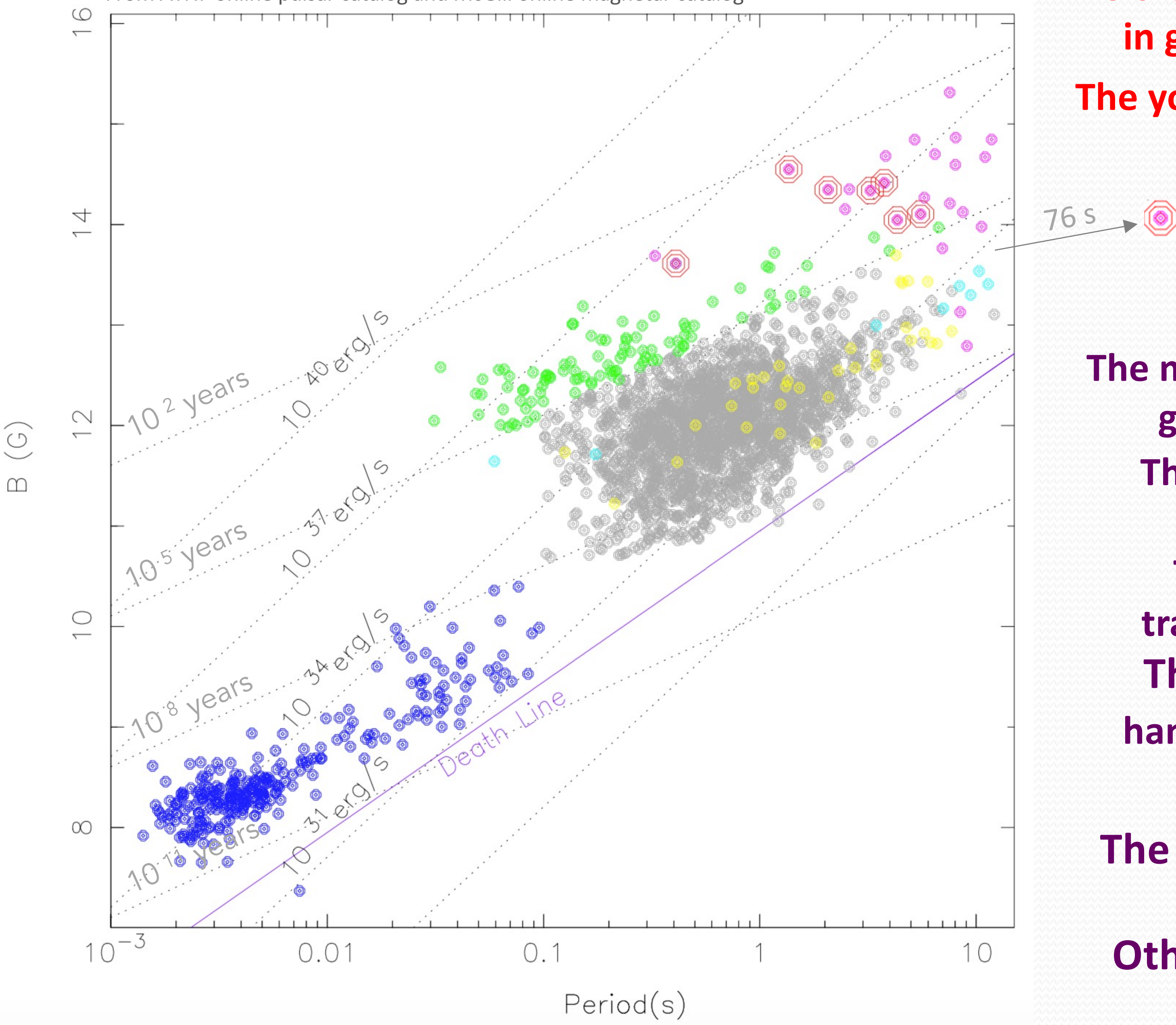
The spin period vs surface magnetic field plot

From ATNF online pulsar catalog and McGill online magnetar catalog



The ordinary galactic pulsars not in globular clusters: 1797

The young galactic pulsars: 98

The mildly and fully recycled galactic pulsars: 268

The X-ray dim galactic neutron stars: 7

The rotating radio transients (RRATs): 34

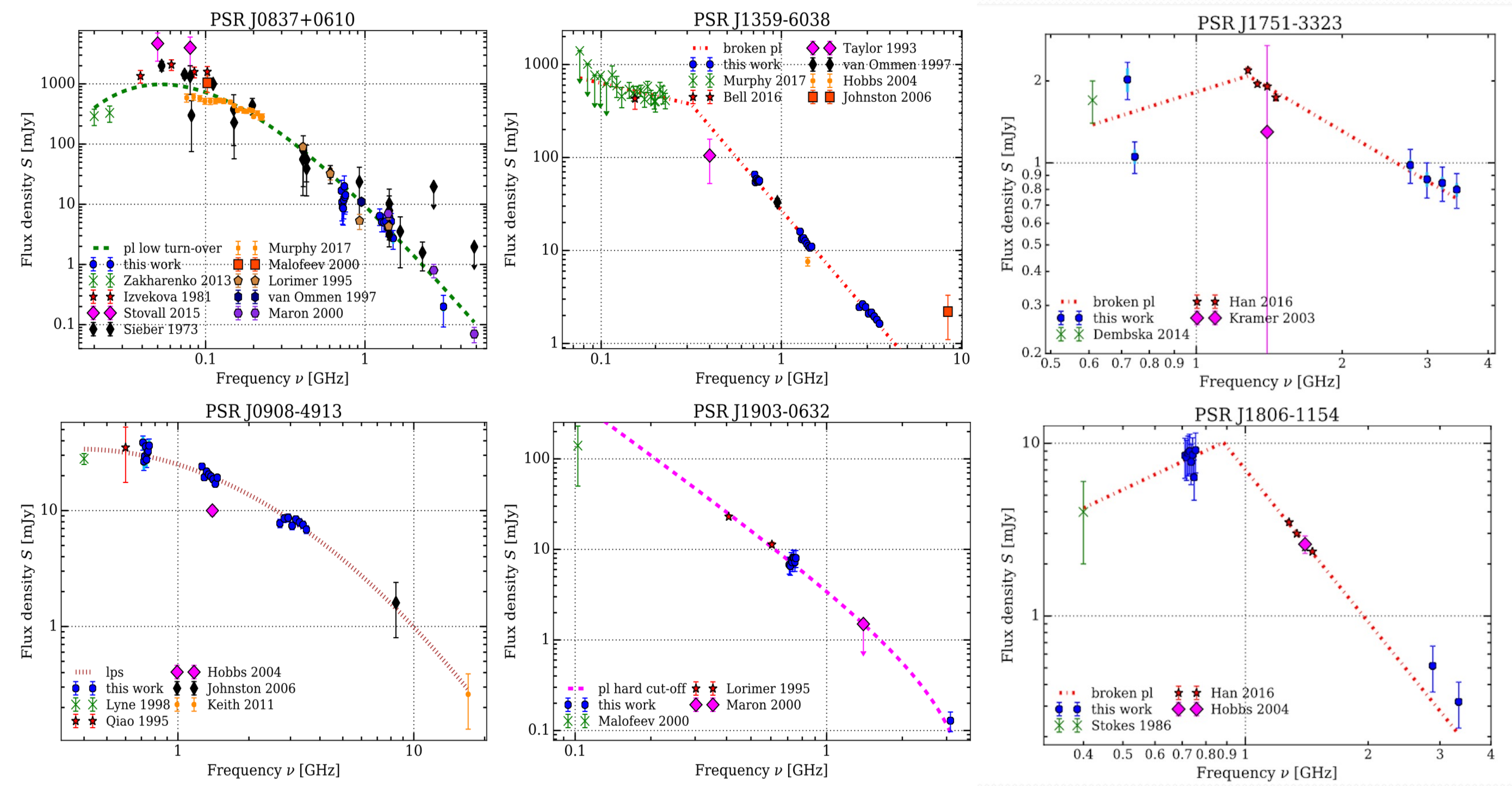
The magnetars: 24 + handful of candidates

The radio magnetars: 7

Other transitional ...: 2

The pulsar spectra

A variety of pulsar spectra…

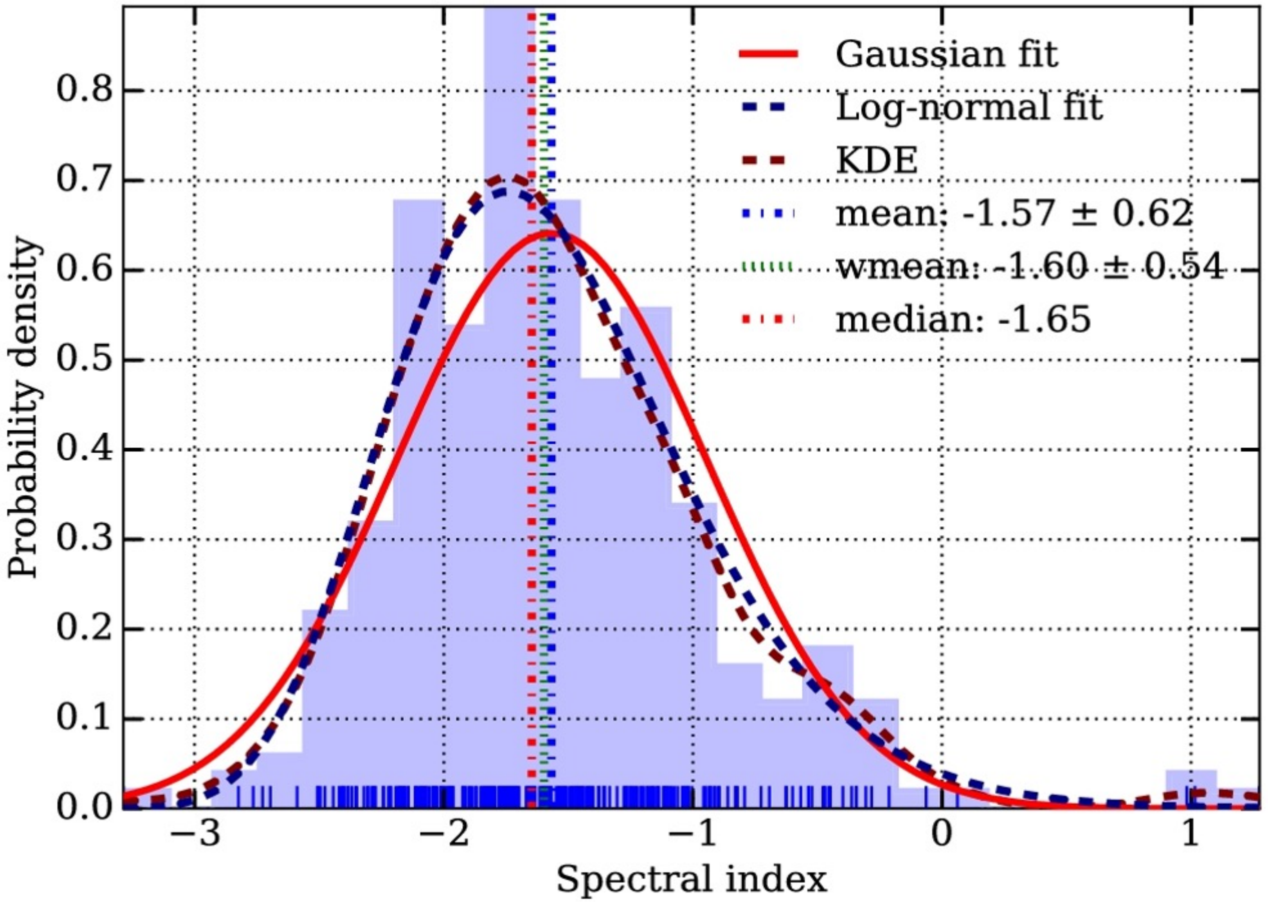


… but all of them going very steep at high freq ≳ few GHz

The pulsar spectra

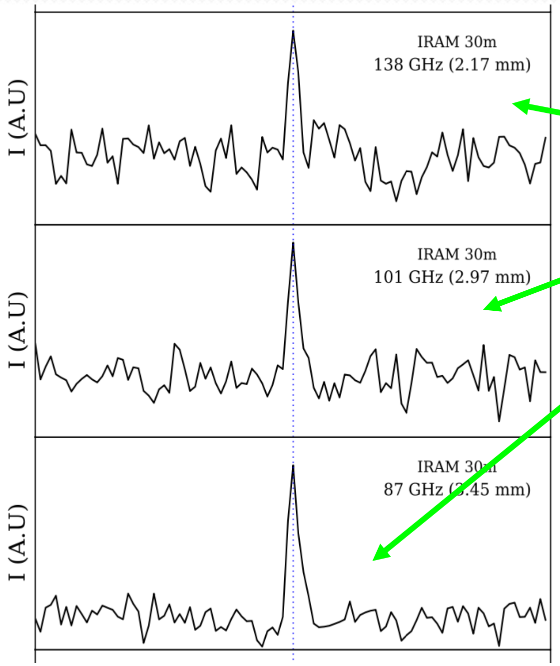
Set	#Pulsars	$\bar{\alpha}$
This work	276	-1.60 ± 0.03
Lorimer et al. (1995)	279	-1.6
Maron et al. (2000)	263	-1.8 ± 0.2
Toscano et al. (1998)	216 (169[a])	-1.72 ± 0.04
Malofeev et al. (2000)	175	-1.47 ± 0.06
Bilous et al. (2016)	48	-1.4
Han et al. (2016)	228	-2.2

Jankowski+ 2017



Ordinary pulsars observed at high freq

Torne 2016



PSR	P (ms)	α	
B0355+54	156.382	−1.2	✓
B2021+51	529.196	−1.5	X
B1929+10	226.517	−1.6	X
B0329+54	714.519	−2.2	X
B0531+21	33.392	−3.1	X
J1022+1001	16.452	−1.4	X

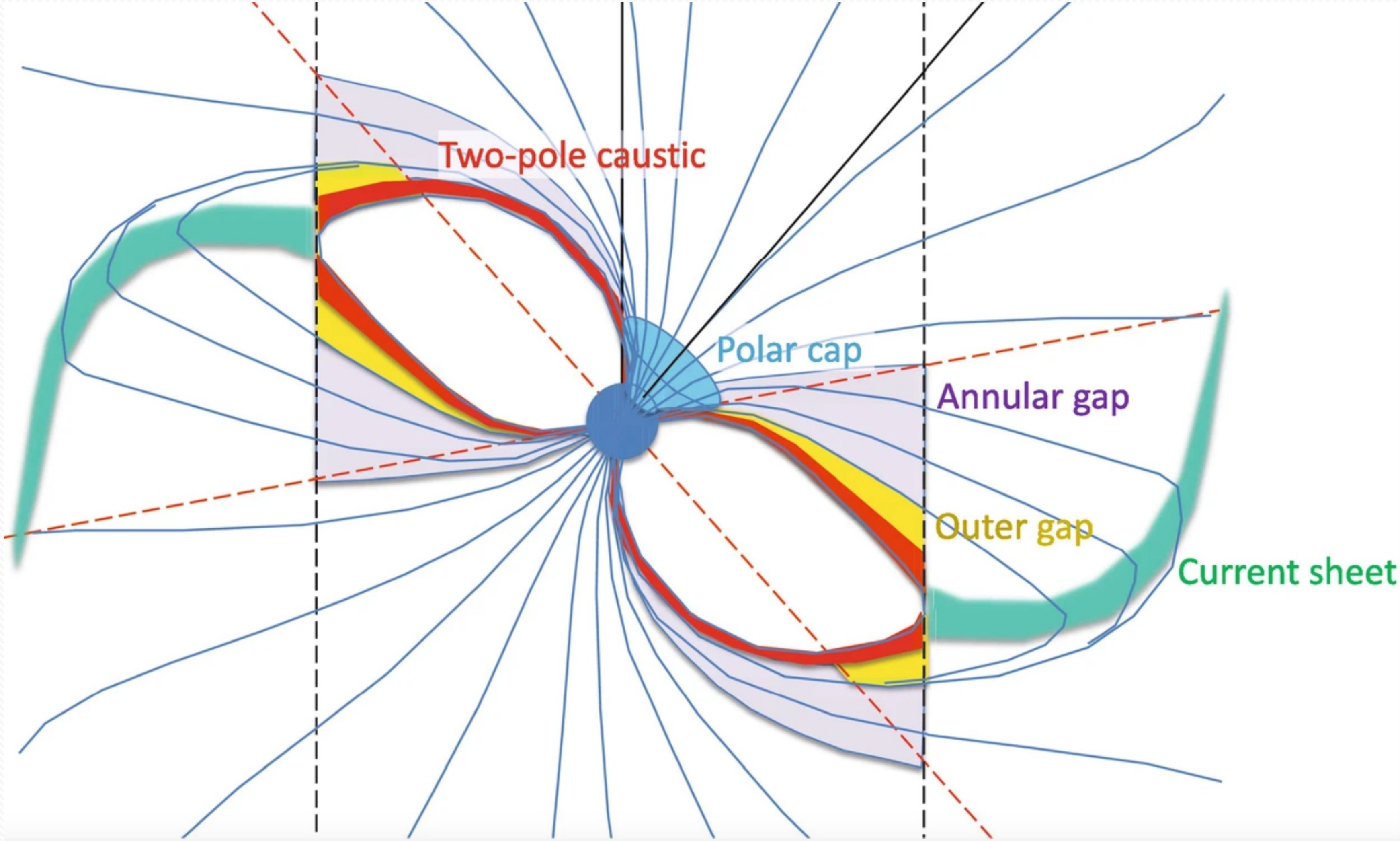
Pulses detected above 87 GHz for only one ordinary pulsar so far

Millisecond pulsars very hard to be seen above 10 GHz

The pulsar emission models

No self-coherent and predictive model available so far !

Harding 2021



Seeing pulses at high frequency would be a very useful tool

Coherency of pulsed mm/submm emission

First detection ever of a pulsar at sub-mm band

THE ASTROPHYSICAL JOURNAL LETTERS, 851:L10 (6pp), 2017 December 10 https://doi.org/10.3847/2041-8213/aa9c3e

CrossMark

The First Detection of a Pulsar with ALMA

R. P. Mignani[1,2], R. Paladino[3], B. Rudak[4], A. Zajczyk[5], A. Corongiu[6], A. de Luca[1], W. Hummel[7], A. Possenti[6], U. Geppert[2], M. Burgay[6], and G. Marconi[8]
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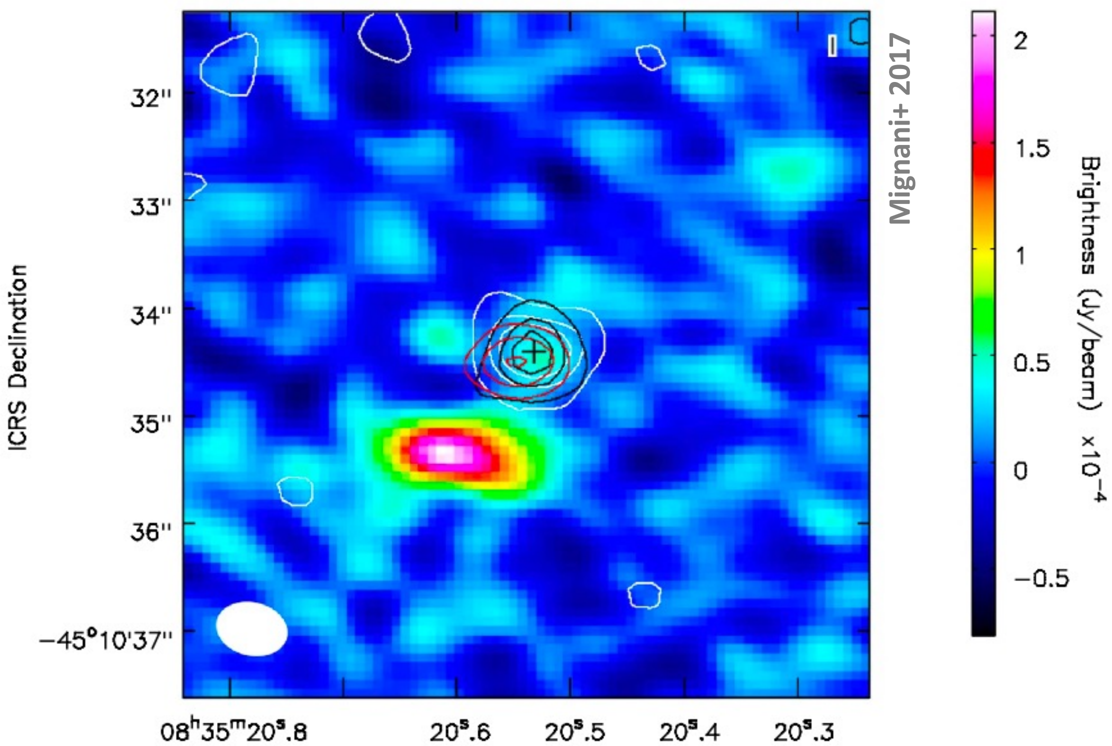
Received 2017 October 11; revised 2017 November 17; accepted 2017 November 20; published 2017 December 6



Mignani+ 2017

An Italian driven result

Transition from coherent to uncoherent ?

Mignani+ 2017

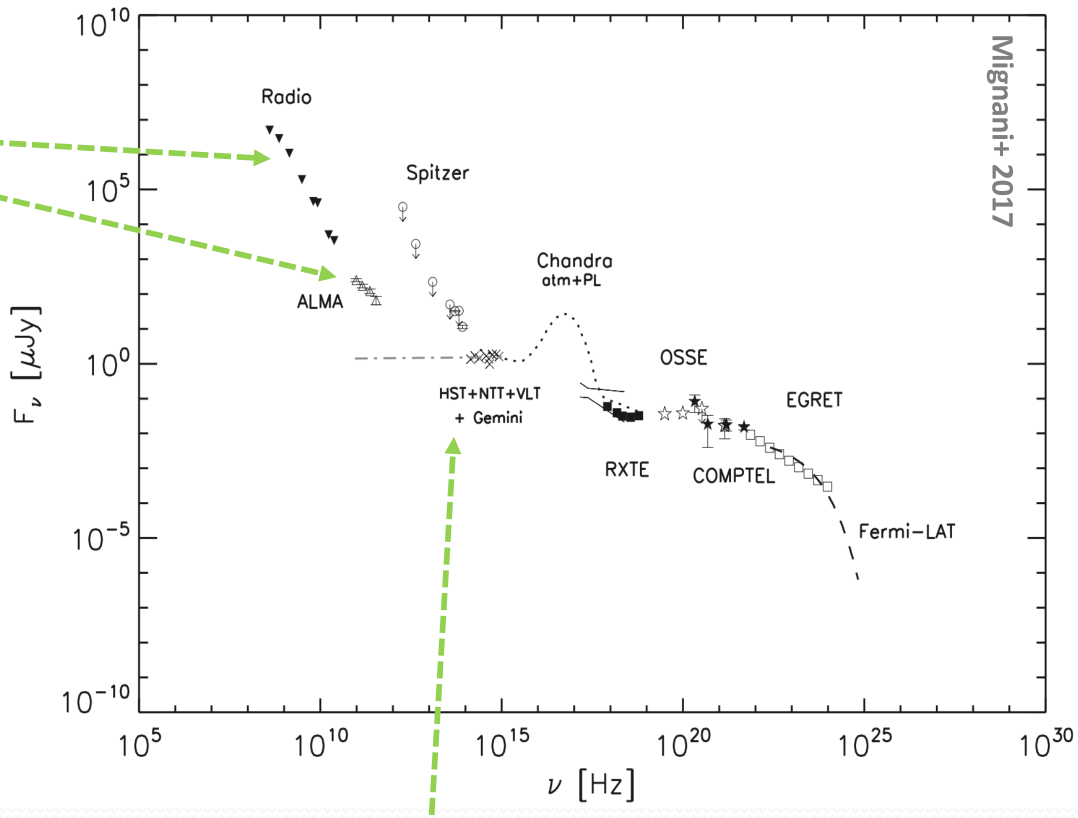
Summary of the ALMA Observations of the Vela Pulsar

Band	ν (GHz)	Date (2016)	Time (minutes)	Beam (arcsec × arcsec)	rms (μJy/beam)	Flux Density (μJy)
3	97.5	Jul 23	22	0.75 × 0.68	25	252 ± 35
4	145	Jul 14	22	0.77 × 0.74	20	170 ± 26
6	233	Apr 17	46	0.88 × 0.73	18	122 ± 22
7	343.5	Mar 10, 26, 28	120	0.66 × 0.49	18	67 ± 19

The mm/submm emission is a coherent process ($T_b \approx 10^{15} - 10^{17}$ K)

Somewhere a turn-up in the spectrum

Blandford & Scharlemann 1976; Michel 1982



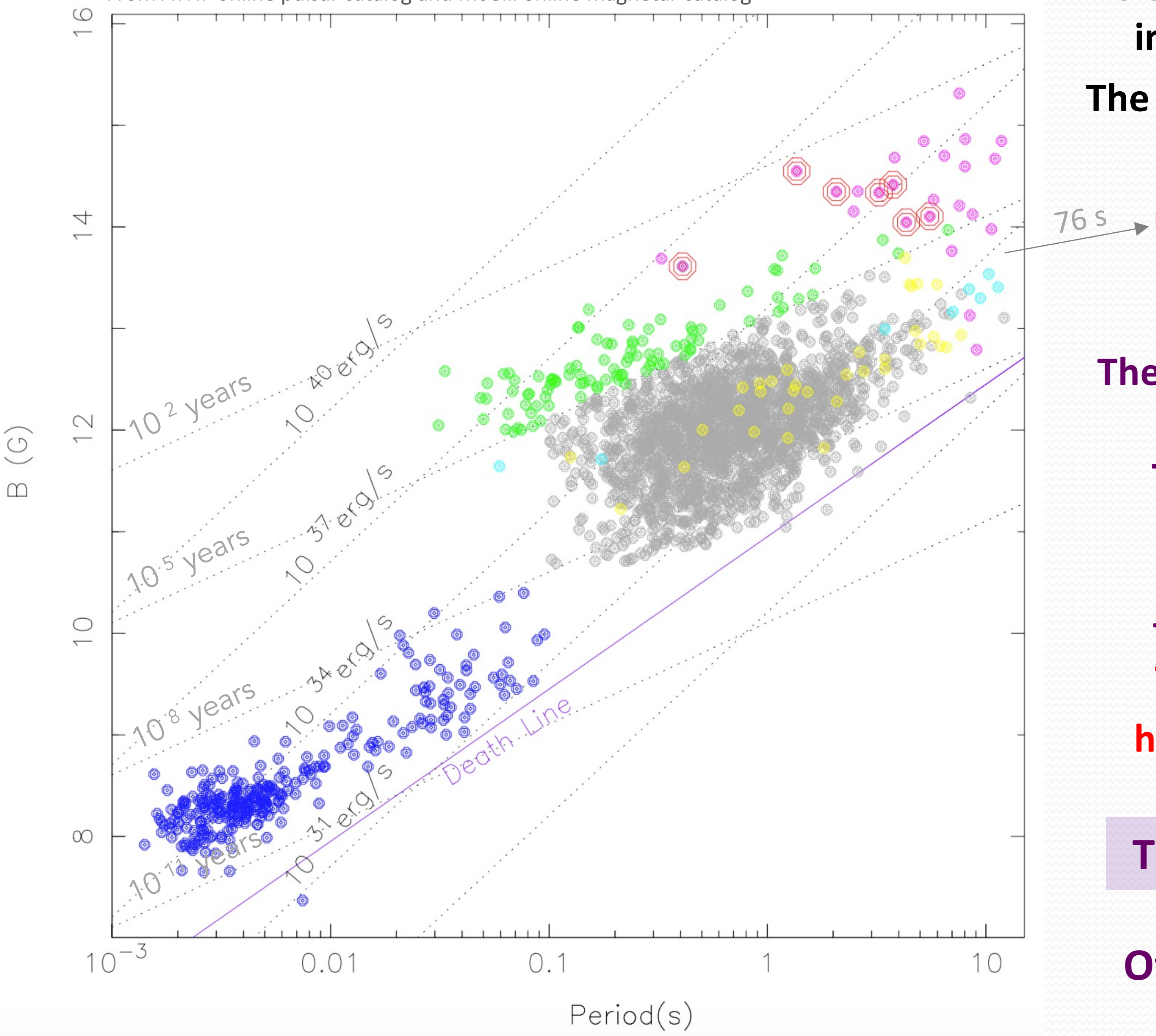
Different population of relativistic particles
Different location of the emission regions in the magnetosphere?
Different emission mechanisms?

IR/optical emission appears to be an uncoherent process

Zyuzin+ 2013

A favorable case of study

From ATNF online pulsar catalog and McGill online magnetar catalog



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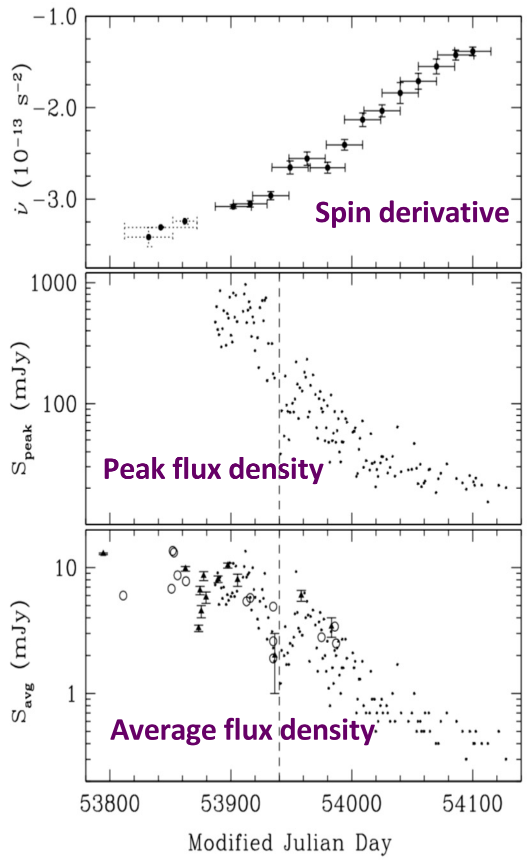
Basic parameters of radio magnetars

Name	Period (s)	Pdot (s/s)	B (Gauss)	Edot (erg/s)	Age (year)	DM (pc/cm^3)	RM (rad/m^2)	Dist (kpc)	Association
PSR J0901-4046 (tbc)	75.88	2.25E-13	1.3E+14	2.0E+28	5.3E+6	52	-64	0.4	
PSR J1119-6127	0.4079	4.02E-12	4.10E+13	2.34E+36	1.61E+3	704.80	853.0	8.4	SNR G292.2-0.5
1E 1547.0-5408	2.0721	4.77E-11	3.18E+14	2.11E+35	6.89E+2	830	-1860	4.5	SNR G327.24-0.13
PSR J1622-4950	4.3261	1.7E-11	2.74E+14	8.29E+33	4.03E+3	820.00	-14840	9	SNR G333.9+0.0
SGR J1745-2900	3.7636	1.385E-11	2.31E+14	1.03E+34	4.31E+3	1778.0	-66080	8.3	Galactic Center
XTE J1810-197	5.5403	7.77E-12	2.10E+14	1.80E+33	1.13E+4	178.0	77.0	3.5	
Swift J1818.0-1607	1.3634	9E-11	3.54E+14	1.40E+36	2.40E+2	706	1442	4.8	
SGR 1935+2154	3.2450	1.43E-11	2.18E+14	1.65E+34	3.60E+3	333	107	6.0	SNR G57.2+0.8

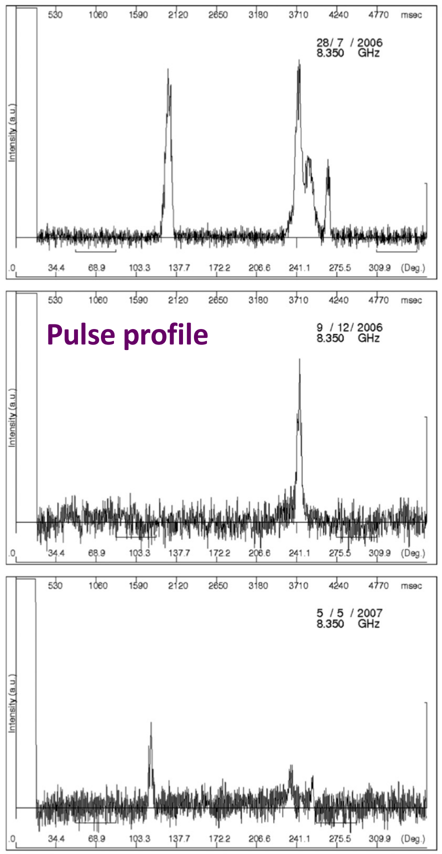
XTE J1810-197: an uncommon pulsar

Several emission properties are often very distinct from radio pulsars

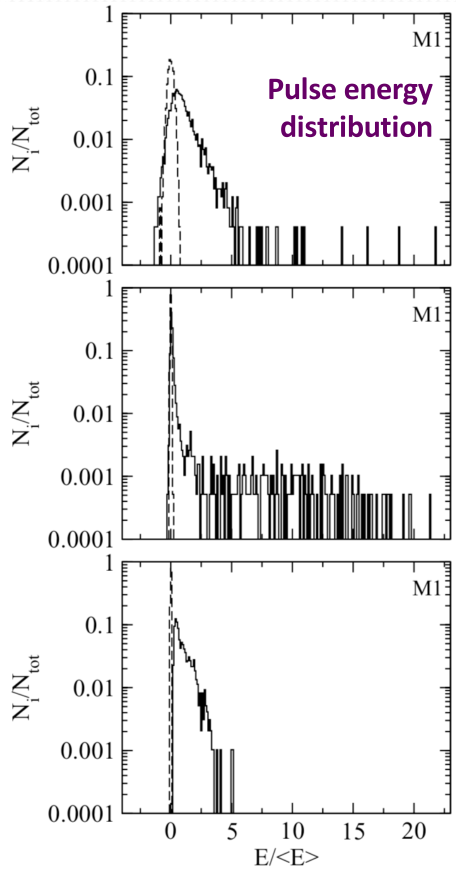
Camilo+ 2007 July



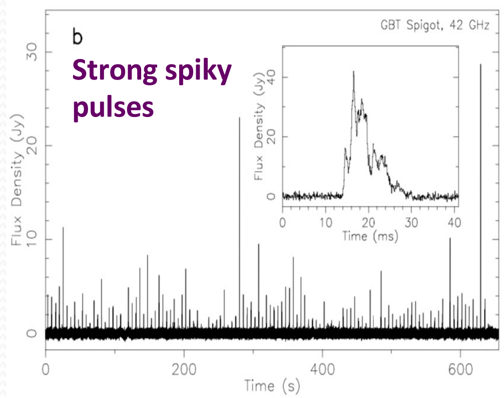
Lazaridis+ 2008



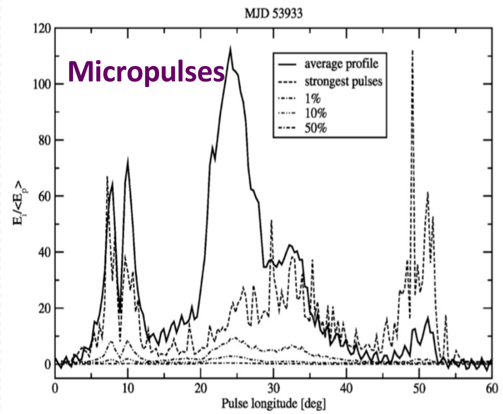
Serylak+ 2009



Camilo+ 2006



Serylak+ 2009

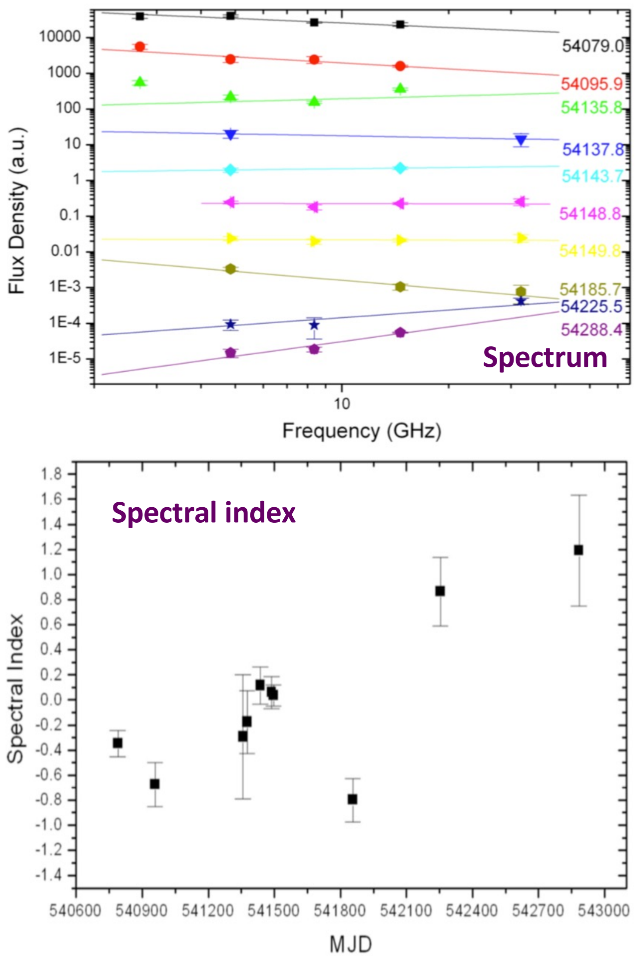


Significant, irregular, and often rapid time variations in torque, fluxes, pulse profile, pulse energy distribution. Strong spiky pulses and micropulses not following the statistics seen in most radio pulsars

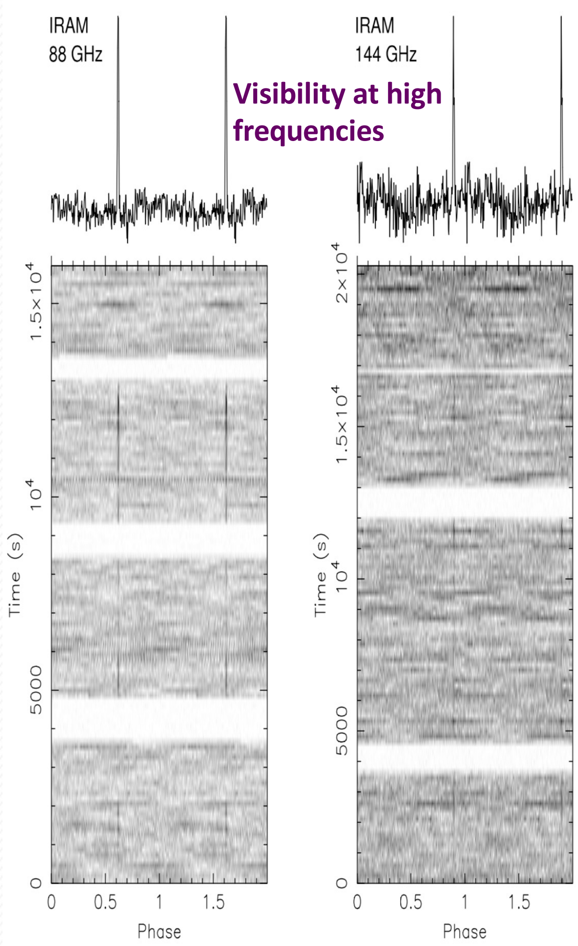
XTE J1810-197: an uncommon pulsar

the case for high frequency radio emission

Lazaridis+ 2008



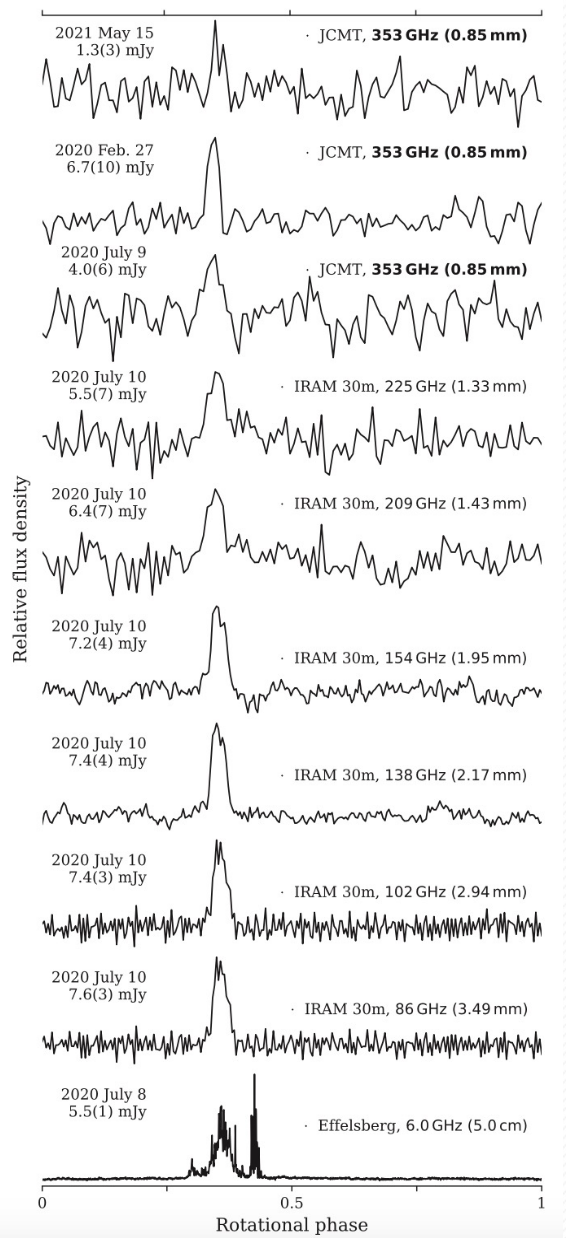
Camilo+ 2007 Nov



Unprecedented visibility at high frequencies

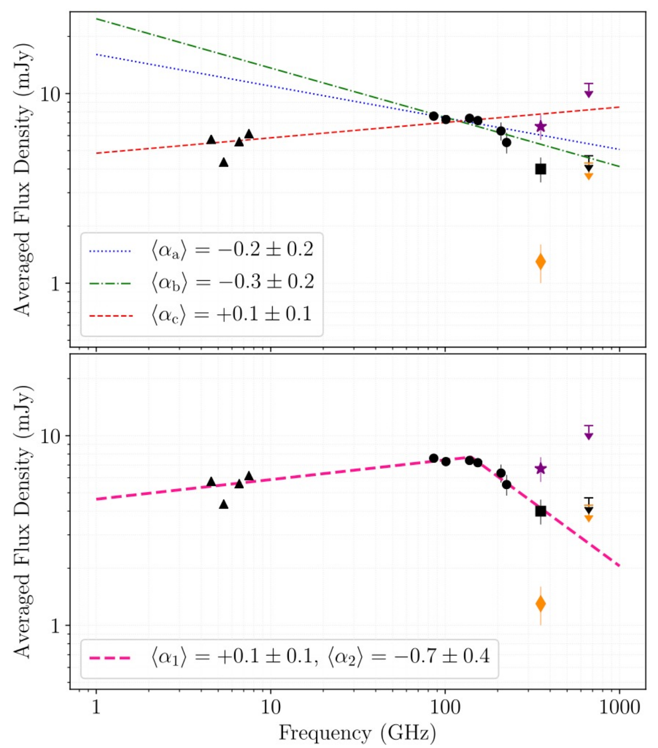
Significant, irregular, and often rapid time variations in spectral index

XTE J1810-197: spectral shape and peaks



Torne+ 2022

- new record of pulsar detection at 353 GHz with JCMT
- Not seen at 666 GHz with JCMT
- spectral index -1.1±0.3 in the mm-band

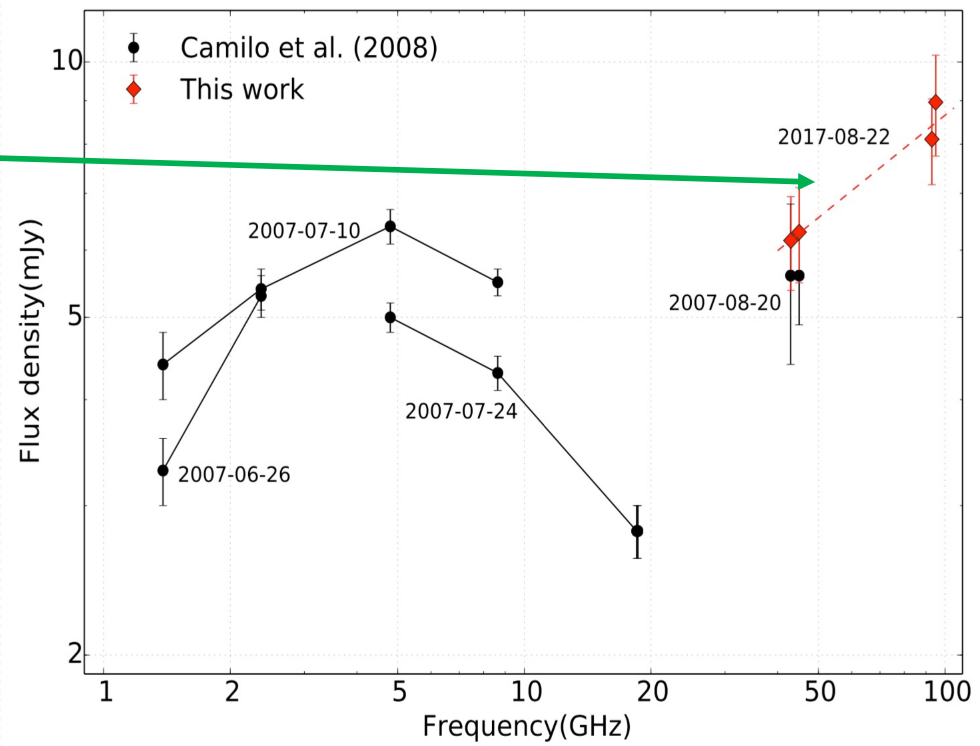


Torne+ 2022

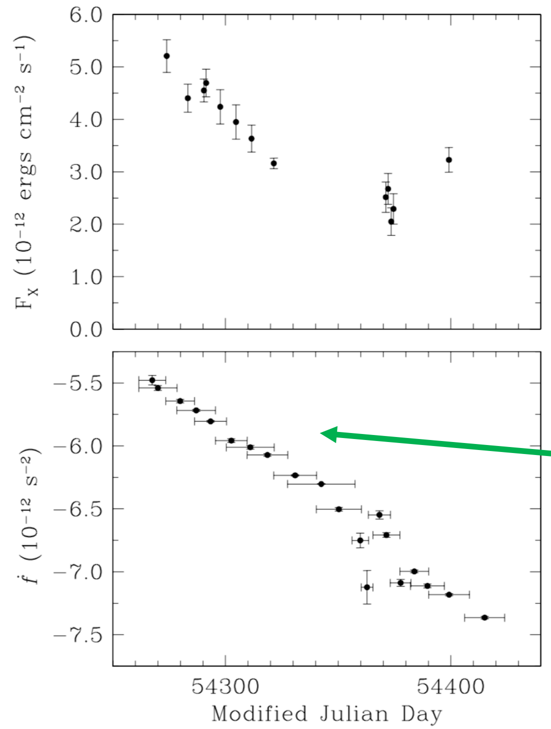
1E J1547-5408: reinforcing the paradigm

High frequency emission and spectral variations

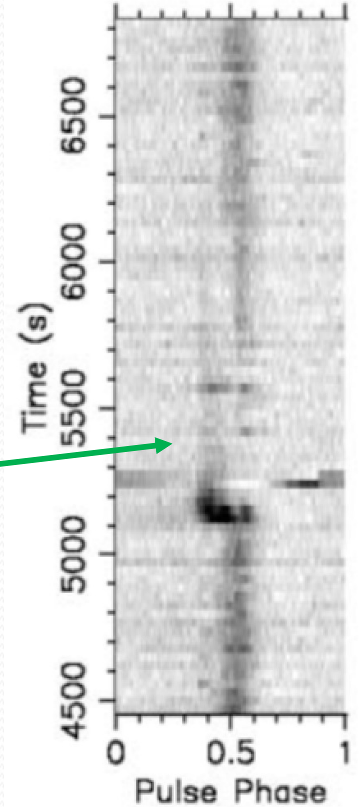
Chu+ 2021 Sept



Camilo+ 2008



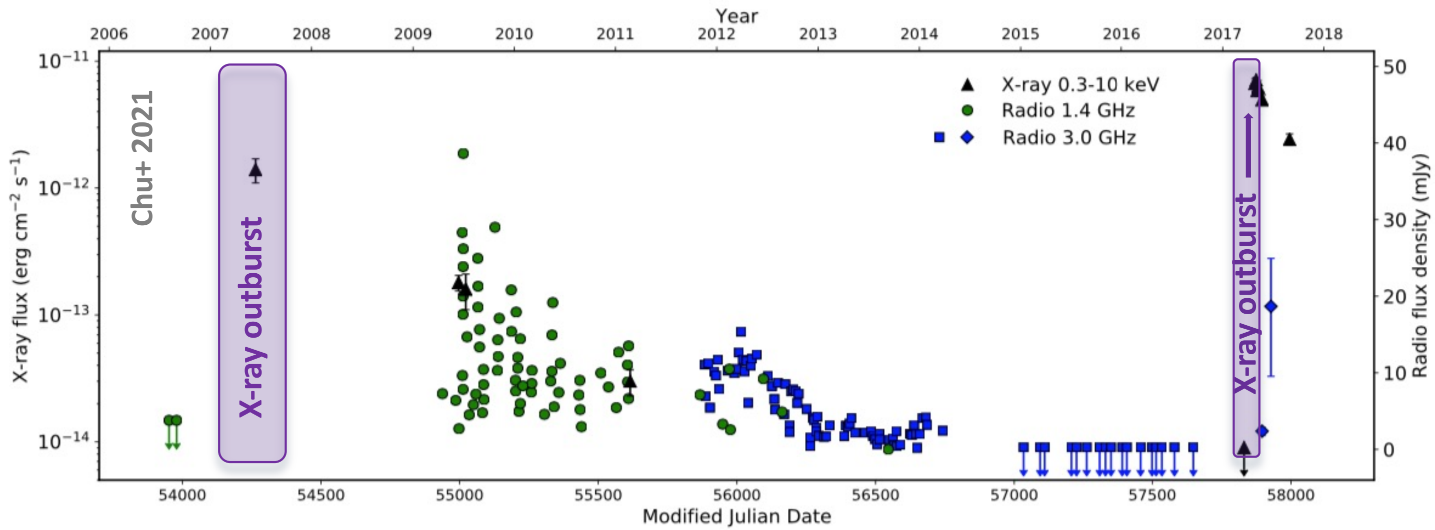
Camilo+ 2007 Sept



Significant, irregular time variations in torque, fluxes, pulse profile, polarization

Many properties reminiscent of the case of XTE J1810-197

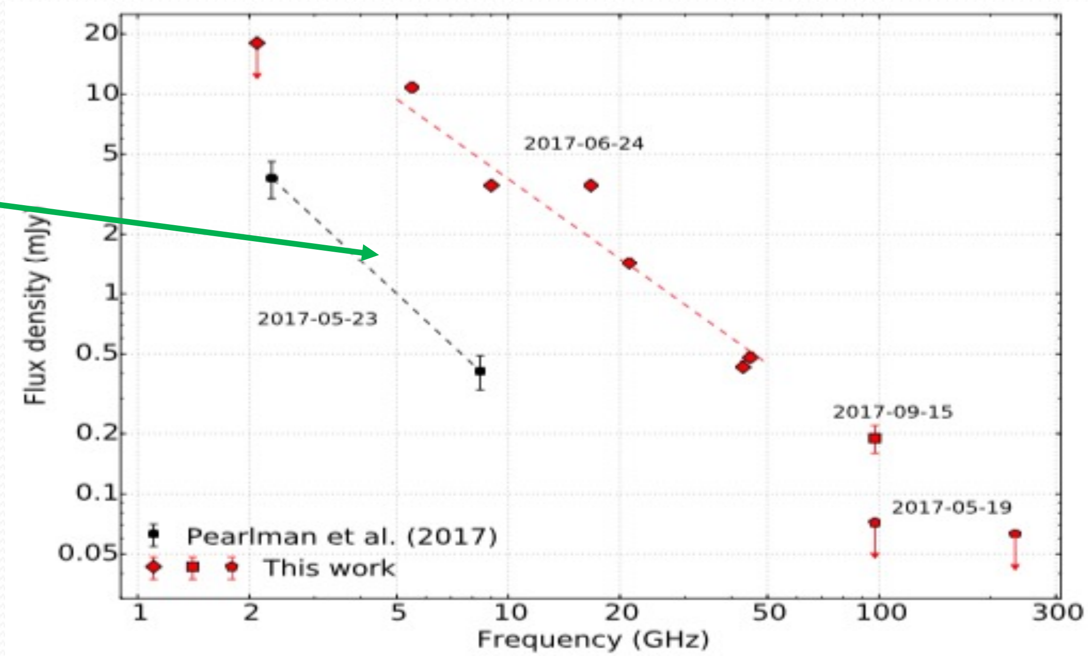
PSR J1622-4950: the 1st discovered in radio



A new X-ray outburst (≈800x) in March 2017 and subsequent re-activation in radio (≈100x)

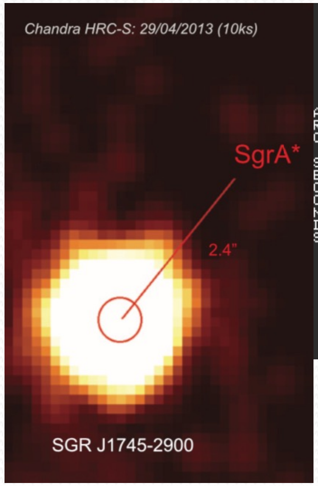
Chu+ 2021

Some properties changed wrt the previous radio life: e.g. steeper spectrum

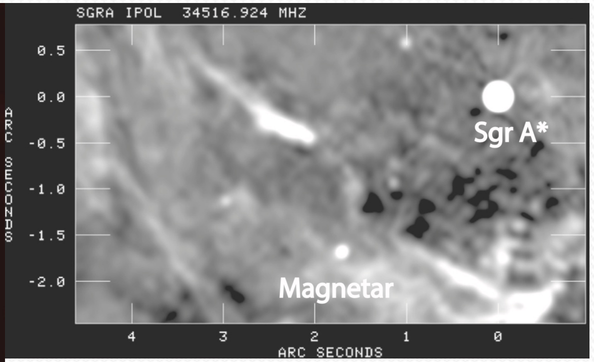


SGR 1745-2900: a magnetar close to Sgr A*

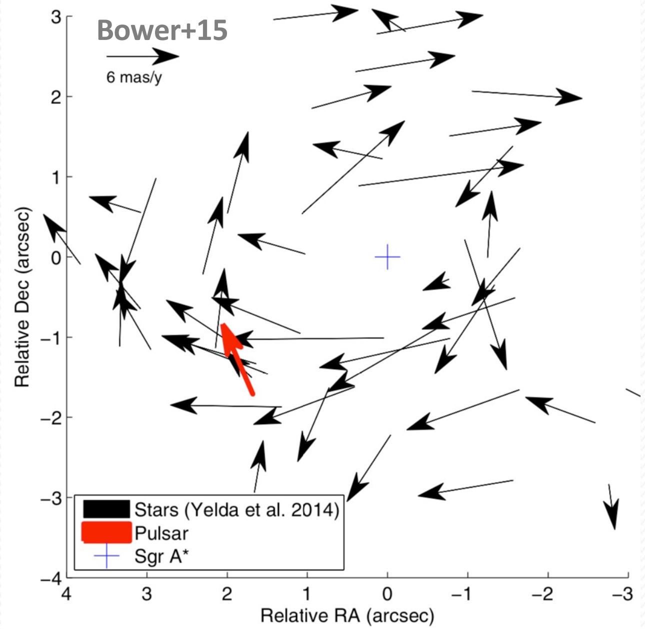
Rea+ 2013



Yusef-Zadeh+15

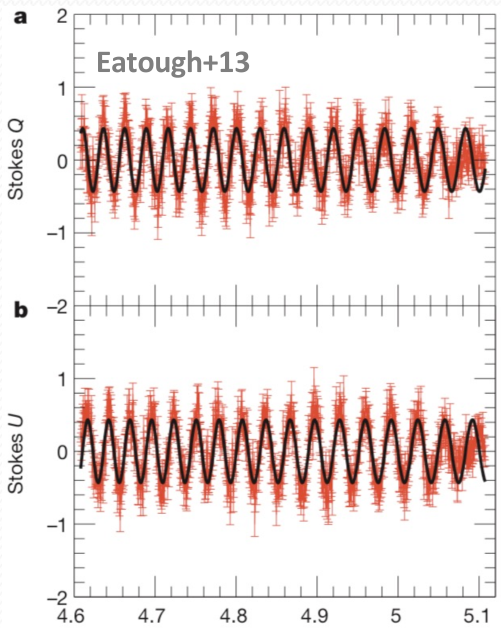


Outburst on April 2013: a displacement of 2,4”

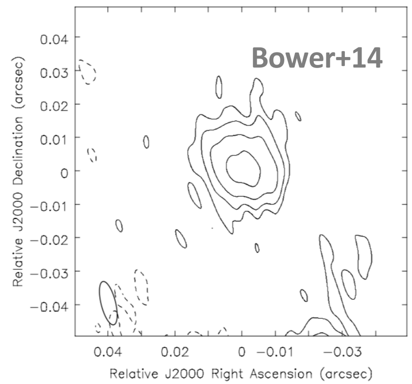


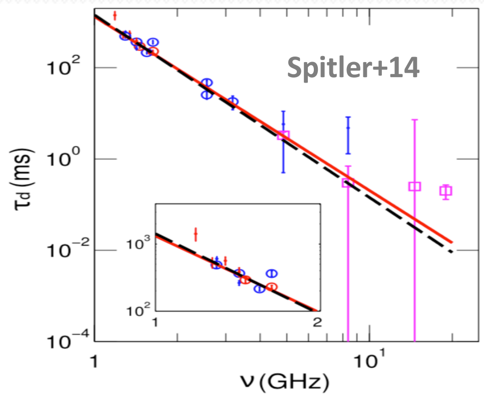
magnetar origin is within the clockwise disk of massive stars orbiting Sgr A* ?

Also supported by RM and DM variations



Rotation Measure RM≈67000 rad m^{-2} : presence of a dynamically important magnetic field near the black hole

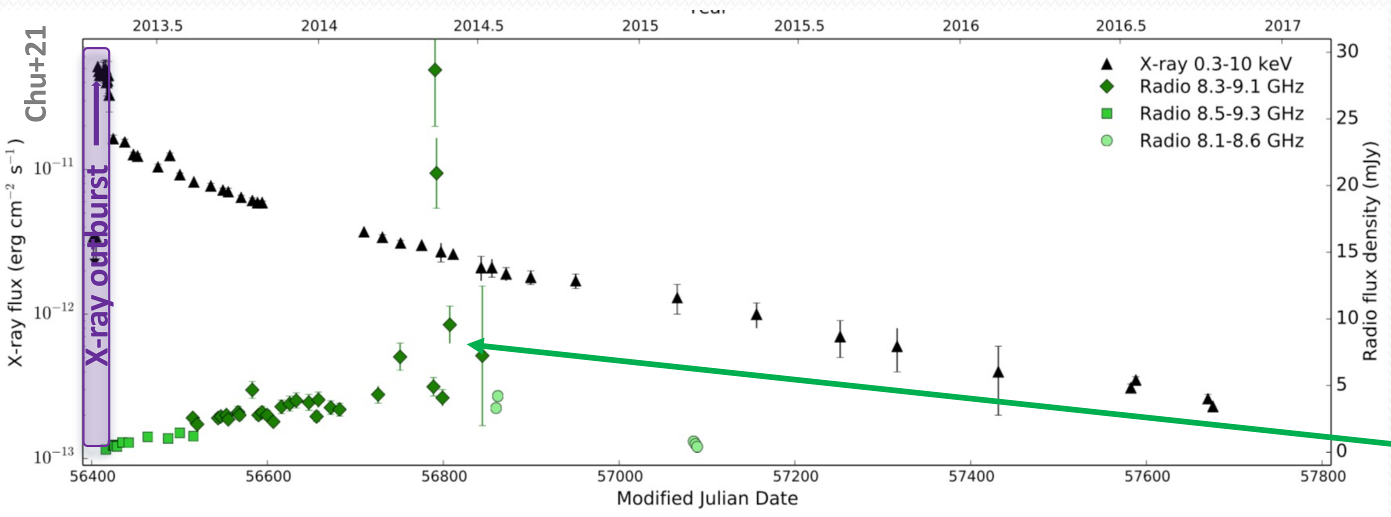




Thin scattering screen at ≈ 5.8 kpc from Sgr A*.

But other options are possible: scattering variations on a pulse period timescale Pearlman+18

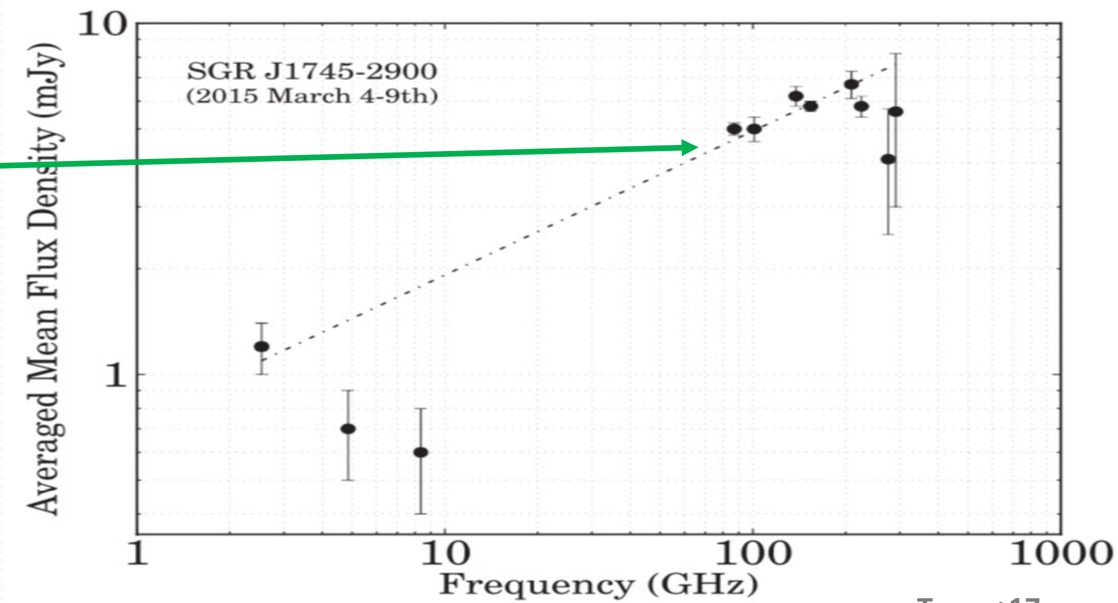
SGR 1745-2900: typical features



Significant variations in fluxes, pulse profile, RM, polarization, and torque

Peak of radio emission ≈1 year later of the onset of the X-ray outburst

spectrum (GPS?) also extends to very high frequencies



Torne+17

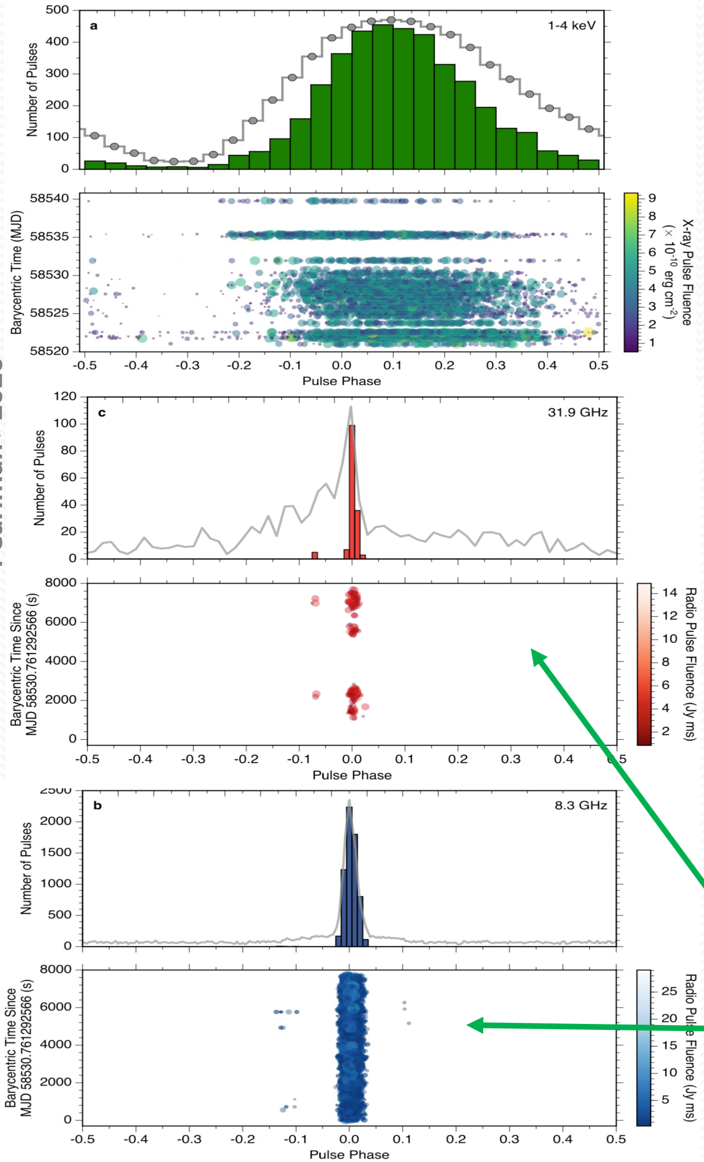
Recap: non so many commonalities

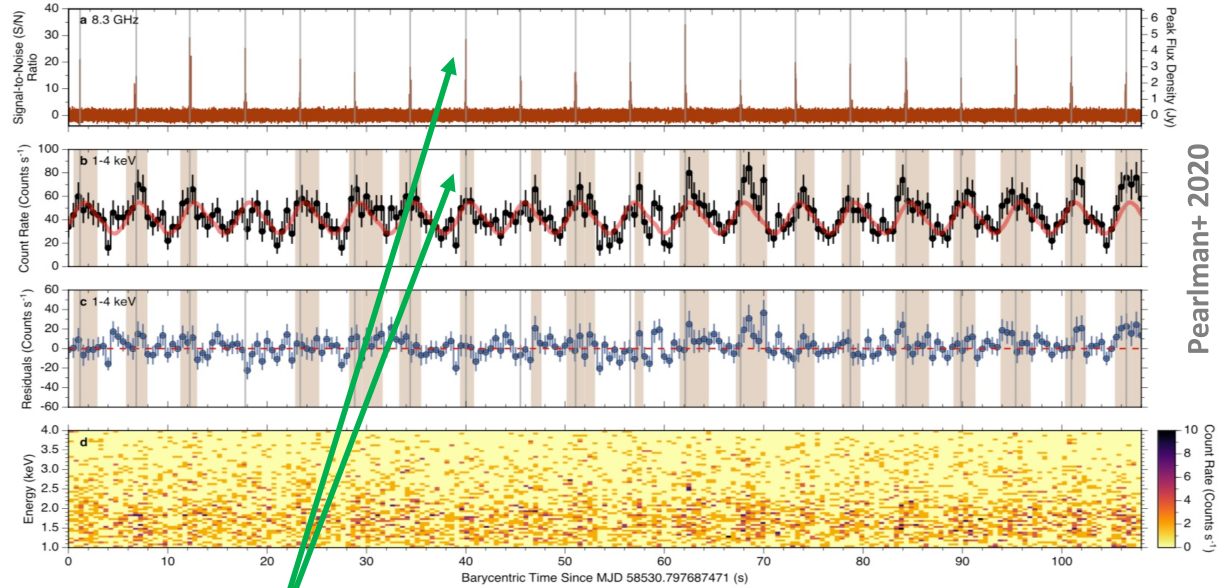
Radio Magnetars	Pulsars
Broad-band spectrum	Broad-band spectrum
Often flat spectrum	Typical steep spectrum
Variable spectral index	Stable spectral index
Variable pulse profile	Stable pulse profile
In some case mode switching	In some case mode switching
Variable flux density	Stable flux density
High % of linear polarization	High % of linear polarization
Some variability in PA sweep	Stability in PA sweep
Irregular variations of torque	Usually stable torque

Radio Emission connected to X-ray outbursts

XTE J1810-197: single pulses in radio and X-ray

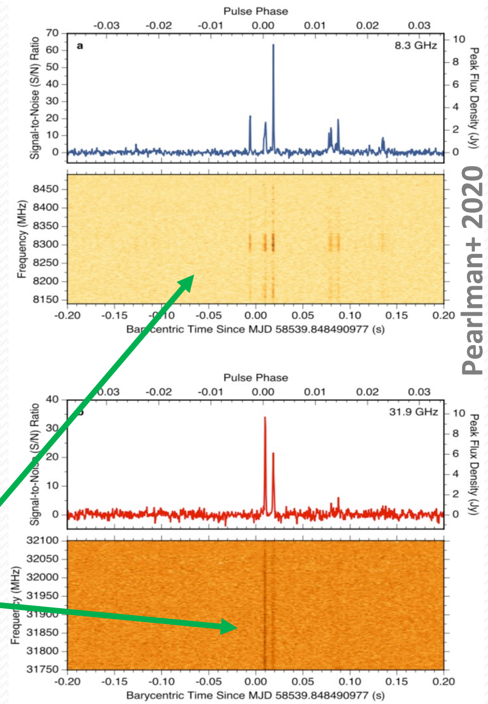
Pearlman+ 2020





Pearlman+ 2020

65% of X-ray bright pulses (visible also outside a flaring state and due to thermal emission from hot spots) within 0.5 sec from bright radio pulses



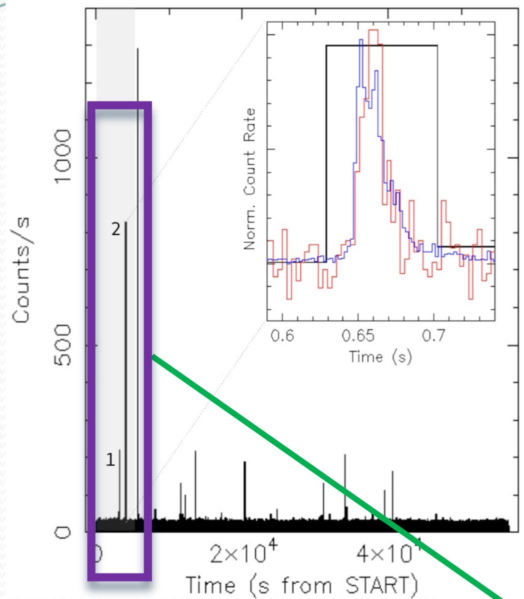
Pearlman+ 2020

Only a fraction of bright radio pulses visible at both 31.9 GHz and 8.3 GHz

Frequency structure at 8.3 GHz

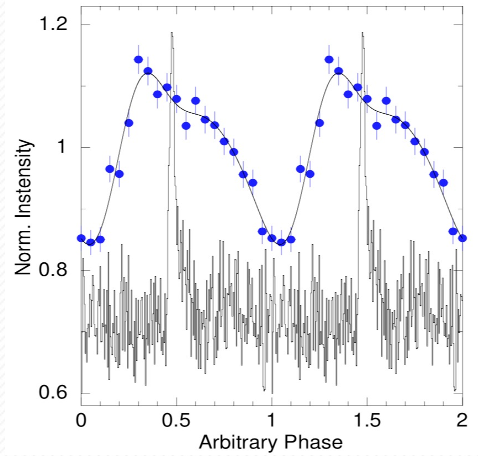
1E J1547-5408: strong radio and X-ray pulses/bursts

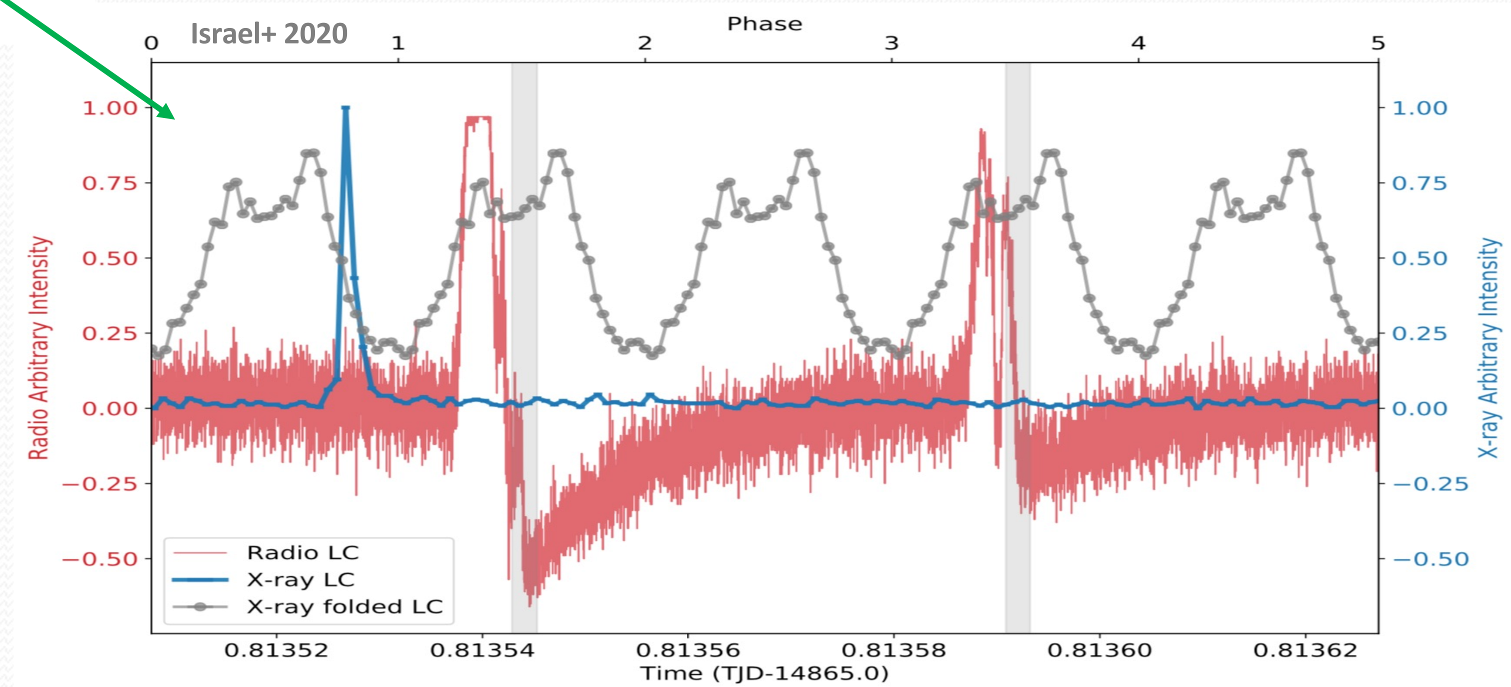
Israel+ 2020



Two strong radio bursts with a luminosity about 600 times smaller than that of the most powerful radio bursts seen in SGR J1935+2154

X-ray vs radio folded profile: ≈20% phase shift btw peaks

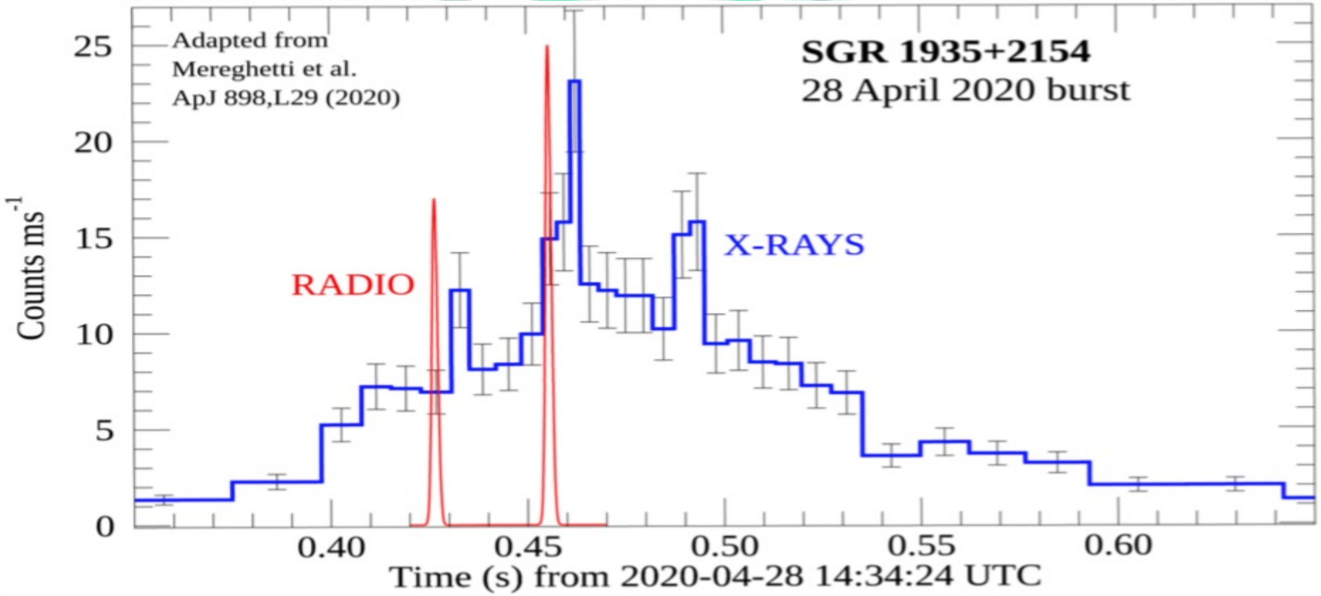


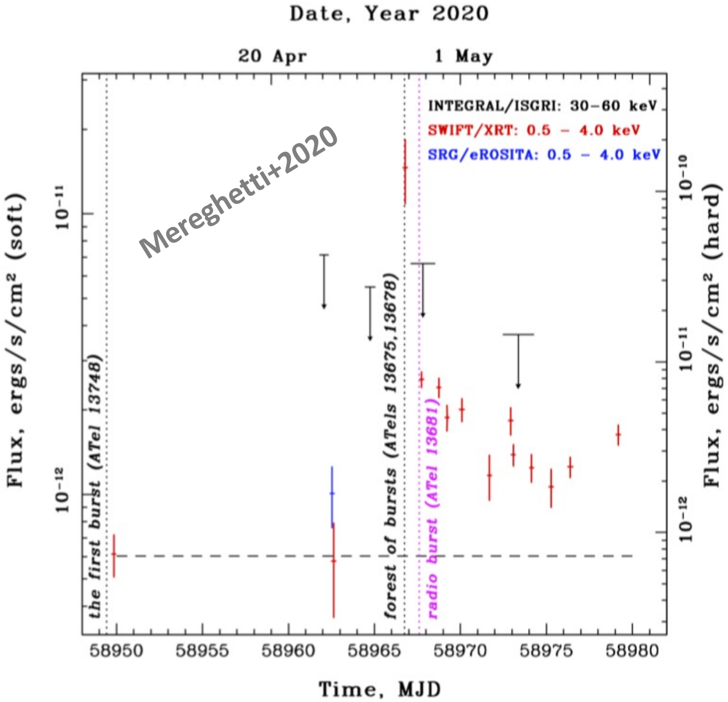


The strongest of the two following of ≈ 1 sec a bright X-ray burst

SGR 1935+2154: FRB-like bursts

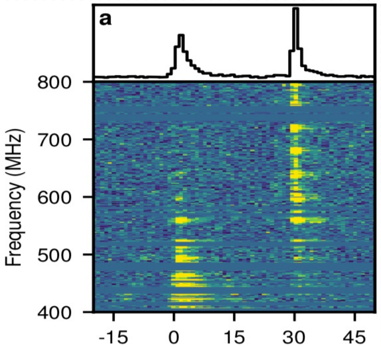
Simultaneous X-ray and radio bursts: first light on the nature of Fast Radio Bursts (FRBs)?





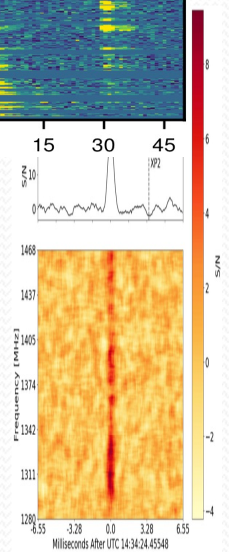
X-ray intense activity towards the end of Apr 2020

CHIME/FRB+2020



CHIME detections in far side lobes with a combined fluence of ≈0.7 MJy ms at 400-800 MHz band

Bochenek+2020

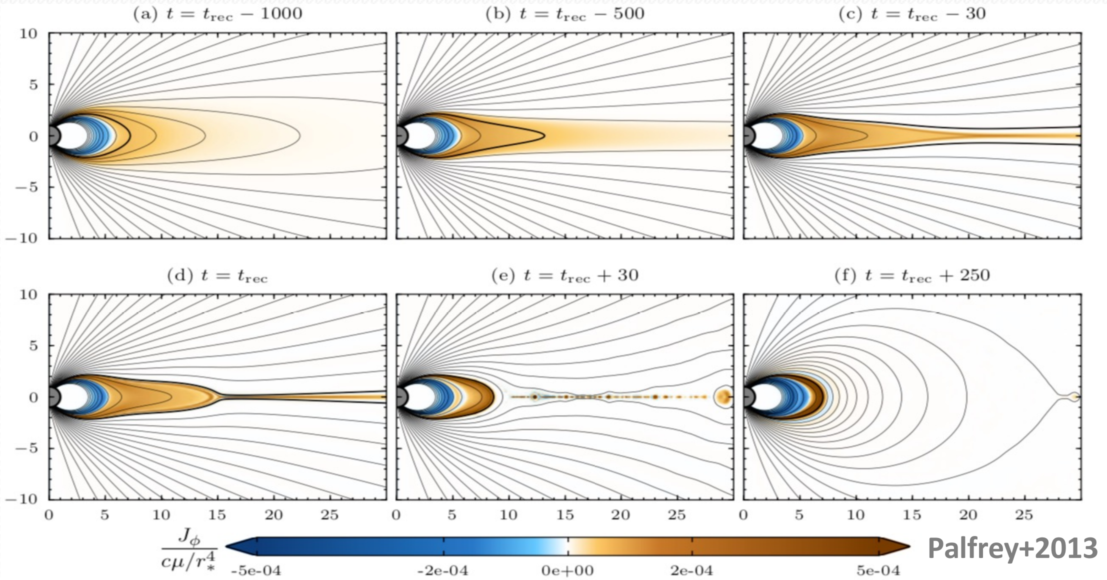


STARE2 detections with a fluence of ≈1.5 MJy ms at 1281-1468 MHz

Semi-heuristic considerations for the onset of pulsed radio emission

Despite very encouraging recent progresses, especially via 3D numerical MHD simulations, a satisfactorily and agreed explanation for the coherent radio emission from an ordinary pulsar is still missing…

… however, the association with X-ray outbursts (supposedly due to topological variations in B-field and then an increased twisting of the magnetosphere) and the rapid variation in the observed radio phenomenology could point to a magnetospheric origin e.g. Kaspi & Beloborodov 2017 and ref therein

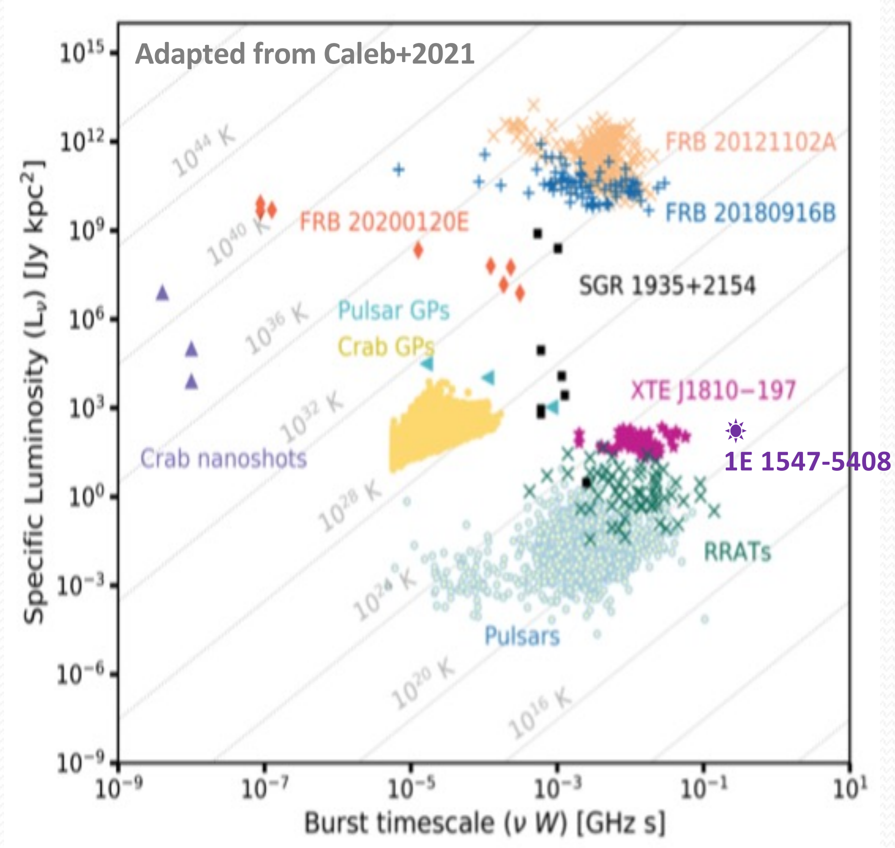


Palfrey+2013

Indeed, untwisting of the magnetic field line in the outburst aftermath should favour magnetospheric pulsed radio emission production with largest (than typical) charge density in the magnetosphere and hence a different radio phenomenology wrt ordinary pulsars Thompson 2008; Beloborodov 2009

As the outburst decays toward quiescence the magnetosphere progressively untwists, the charge density decreases, and the radio flux tend to disappear

Radio bursts: Pulsar - magnetar - rFRB connection



Energy reservoirs:

- **magnetic energy**
- **rotational energy**

The basic plane for "coherent radio emitters" is progressively filling up with no evident separated "island"

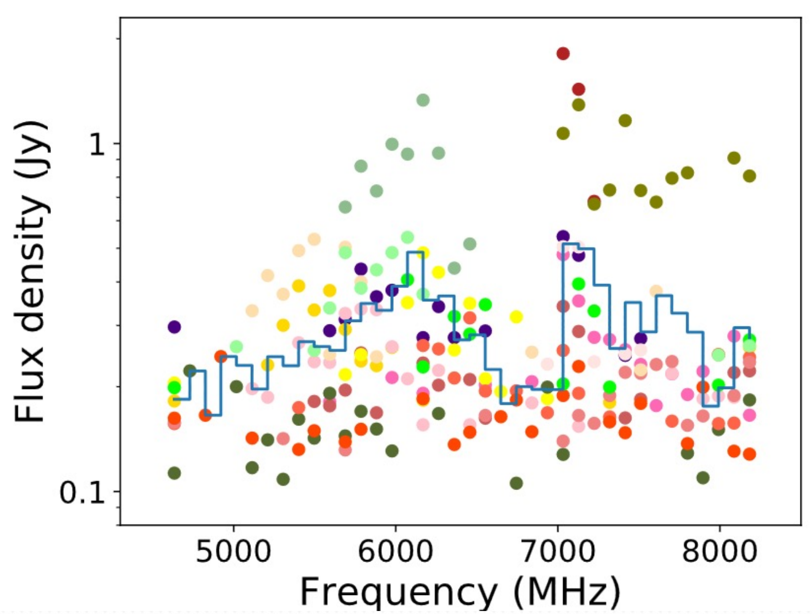
Recap: some commonalities/comparisons

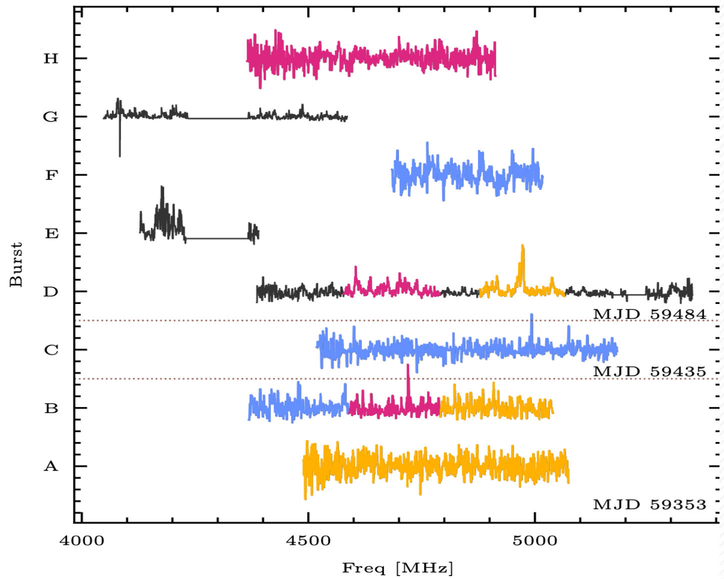
Radio Magnetars single pulses	Repeating FRBs
Often band-limited spectrum	Always band-limited spectrum
Visible at high frequency ($\lesssim$ 350 GHz)	Not seen at high frequency ($\gtrsim$10 GHz)
Variable spectral index	Variable spectral index
Variable pulse profile	Variable pulse profile
Spiky pulse substructure	Spiky pulse substructure
Variable flux density	Variable flux density
No downward drifts in frequency	Sad-trombone structure
High % of linear polarization	High % of linear polarization
Often flat PA swing	Often flat PA swing
Some correlation with X-ray	Some correlation with X-ray

The phenomenology is rich in exceptions …

FRBs at high frequencies ?

Despite the link (well established at least in one case) with the radio bursting magnetars (whose single pulses are sometimes visible up to 100s of GHz), the FRB emission has been so far only confined to low-to-intermediate frequencies





To date, the highest frequency at which an FRB has been detected is 8 GHz

However, useful observations at $\gtrsim$ 5 GHz, basically limited only to repeating FRBs, have been very sparse

SRT did one campaign at K band (about 20 GHz) on the original repeater

A new asset for the Italian community

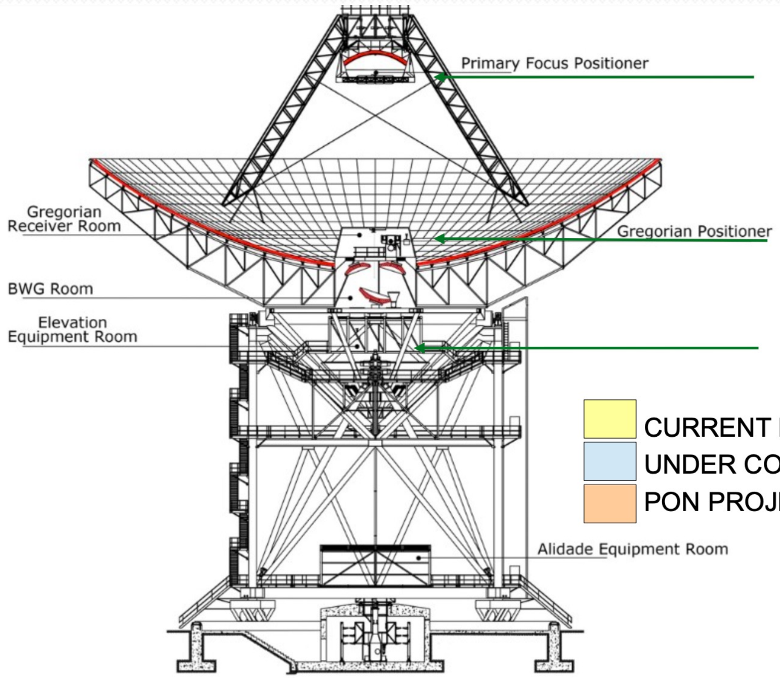
PON RICERCA E INNOVAZIONE 2014 - 2020

UNIONE EUROPEA

MINISTERO DELL'ISTRUZIONE DELL'UNIVERSITÀ E DELLA RICERCA

Ministero dell'Istruzione dell'Università e della Ricerca
Dipartimento per la Formazione Superiore e per la Ricerca
Direzione Generale per il coordinamento, la promozione e la valorizzazione della ricerca
PON Ricerca e Innovazione 2014-2020
(CCI: 2014IT16M2OP005)

stolen from Govoni's presentation 2023



P-band
L-band

K-band

C-band

GREGORIAN RECEIVERS ROOM

CURRENT RECEIVERS
UNDER CONSTRUCTION
PON PROJECT

Tri-band K/Q/W
VLBI (SRT, Medicina, Noto)
18-26, 35-50, 86-116 GHz

Millimeter Camera
80-116 GHz

Frequency

P-band 305-425 MHz

L-band 1.3-1.8 GHz

C-band 5.7-7.7 GHz

K-band multibeam 18-26.5 GHz

S-band 3.0-4.5 GHz

Clow-band 4.2-5.6 GHz

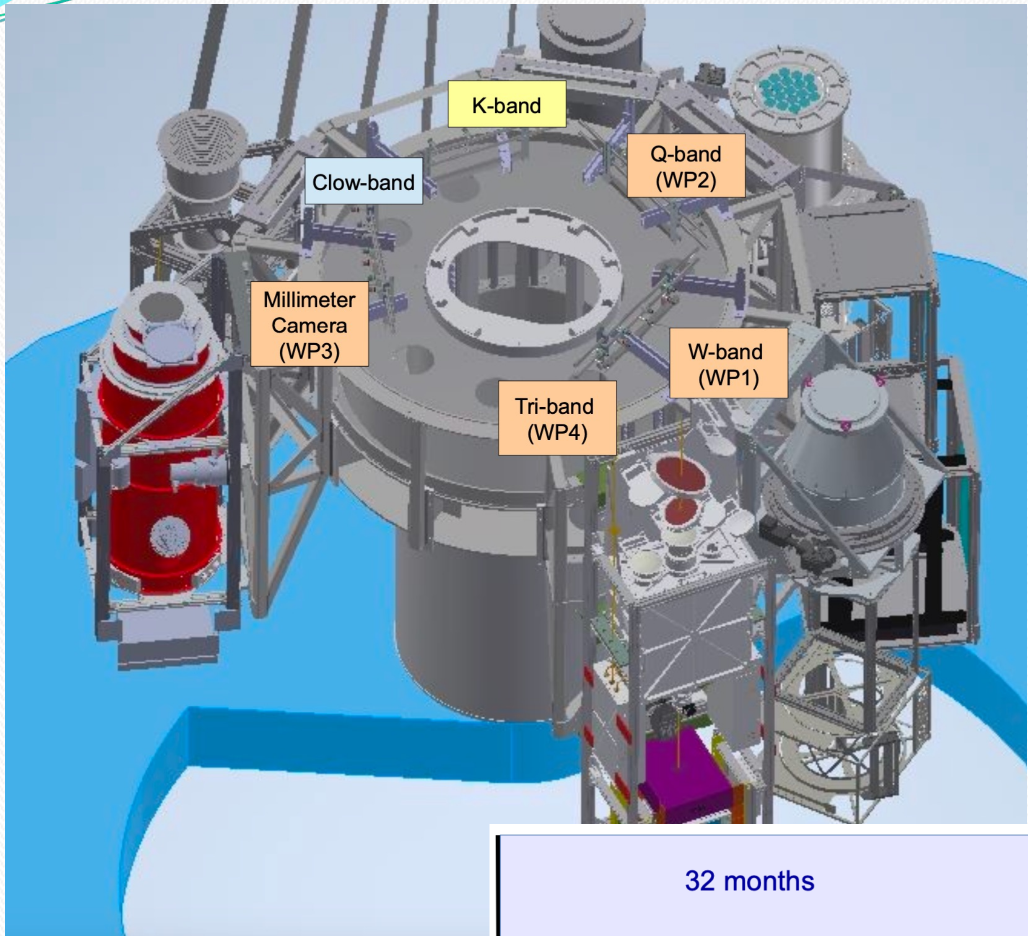
Q-band multibeam 33-50 GHz

W-band multibeam 75-116 GHz

Skype

A new asset for the Italian community

stolen from
Govoni's
presentation 2023



32 months	Extension Covid 6 months	Extension Covid 6 months	Extension 4 months	Technical/ Scientific Commissioning

25 June 2019
START OF THE PROJECT

25 February2022
END OF THE PROJECT

25 August 2022

25 February 2023

25 June 2023

January 2024

Let's investigate soon if the new fleet of receivers will finally lead to tighten the link between «magnetars» and «frbs»

Thanks for the attention !