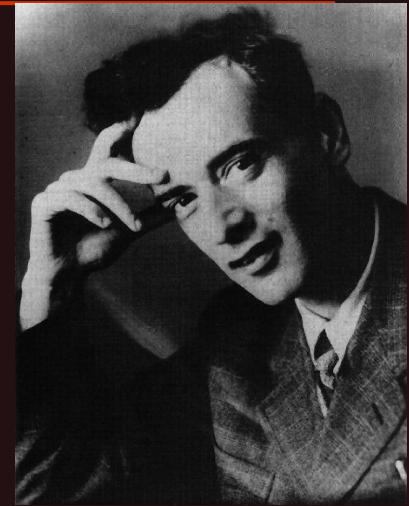

Isolated Neutron Stars. Intro.

Prediction ...

Neutron stars have been predicted in 30s:

L.D. Landau: Star-nuclei (1932) + anecdote

Baade and Zwicky:
neutron stars and supernovae (1934)



(Landau)



(Baade)



(Zwicky)

(from lectures by D. Yakovlev)

In any case, with the discovery of X-ray sources and quasars, dozens of theoreticians focused their attention on the equilibrium properties of compact stars and on star collapse. But in spite of this mounting theoretical effort, most

²Baade and Zwicky (1934): “With all reserve we advance the view that supernovae represent the transitions from ordinary stars into *neutron stars*, which in their final stages consist of extremely closely packed neutrons.”

— According to Rosenfeld (1974), on the day that word came to Copenhagen from Cambridge telling of Chadwick’s discovery of the neutron in 1932, he, Bohr, and Landau spent the evening discussing possible implications of the discovery. It was then that Landau suggested the possibility of cold, dense stars composed principally of neutrons. Landau’s only publication on the subject was concerned with neutron cores (Landau, 1938).

³Giacconi, Gursky, Paolini, and Rossi (1962).

⁴Chapter 11 is devoted to this subject.

⁵The first QSO identified by Schmidt, 3C273, had a redshift $\delta\lambda/\lambda = 0.158$, which was unprecedented for a normal “star.”

⁶Salpeter (1965); in addition to this argument there was strong evidence that quasar redshifts were cosmological in origin.

Shapiro, Teukolsky (1983)

(see detailed description in the book by Haensel, Yakovlev, Potekhin and in the e-print arXiv: 1210.0682)

Landau paper BEFORE neutron discovery

ON THE THEORY OF STARS.

By L. Landau.

(Received 7 January 1932).

From the theoretical point of view the physical nature of Stellar equilibrium is considered.

The astrophysical methods usually applied in attacking the problems of stellar structure are characterised by making physical assumptions chosen only for the sake of mathematical convenience. By this is characterised, for instance, Mr. Milne's proof of the impossibility of a star consisting throughout of classical ideal gas; this proof rests on the assertion that, for arbitrary L and M , the fundamental equations of a star consisting of classical ideal gas admit, in general, no regular solution. Mr. Milne seems to have overlooked the fact, that this assertion results only from the assumption of opacity being constant throughout the star, which assumption is made only for mathematical purposes and has nothing to do with reality. Only in the case of this assumption the radius R disappears from the relation between L , M and R necessary for regularity of the solution. Any reasonable assumptions about the opacity would lead to a relation between L , M and R , which relation would be quite exempt from the physical criticisms put forward against Eddington's mass-luminosity-relation.

It seems reasonable to try to attack the problem of stellar structure by methods of theoretical physics, i. e. to investigate the physical nature of stellar equilibrium. For that purpose we must at first investigate the statistical equilibrium of a given mass without generation of energy, the condition for which equilibrium being the minimum of free energy F (for given temperature). The part of free energy due to gravitation is negative and inversely proportional to some

**Physikalische
Zeitschrift der Sowjetunion
Vol. 1, No. 2, 285-188, 1932
Written: Feb. 1931, Zurich
Received: Jan. 7, 1932
Published: Feb. 1932**

we have no need to suppose that the radiation of stars is due to some mysterious process of mutual annihilation of protons and electrons, which was never observed and has no special reason to occur in stars. Indeed we have always protons and electrons in atomic nuclei very close together, and they do not annihilate themselves; and it would be very strange if the high temperature did help, only because it does something in chemistry (chain reactions!). Following a beautiful idea of Prof. Niels Bohr's we are able to believe that the stellar radiation is due simply to a violation of the law of energy, which law, as Bohr has first pointed out, is no longer valid in the relativistic quantum theory, when the laws of ordinary quantum mechanics break down (as it is experimentally proved by continuous-rays-spectra and also made probable by theoretical considerations).¹ We expect that this must occur when the density of matter becomes so great that atomic nuclei come in close contact, forming one gigantic nucleus.

On these general lines we can try to develop a theory of stellar structure. The central region of the star must consist of a core of highly condensed matter, surrounded by matter in ordinary state. If the transition between these two states were a continuous one, a mass $M < M_0$ would never form a star, because the normal equilibrium state (i. e. without pathological regions) would be quite stable. Because, as far as we know, it is not the fact, we must conclude that the condensed and non-condensed states are separated by some unstable states in the same manner as a liquid and its vapour are, a property which could be easily explained by some kind of nuclear attraction. This would lead to the existence of a nearly discontinuous boundary between the two states.

The theory of stellar structure founded on the above considerations is yet to be constructed, and only such a theory can show how far they are true.

February 1931, Zurich.

¹ L. Landau und R. Peierls, ZS. f. Phys. 69, 56, 1931.

This is correct!

**Disappeared in reprints,
so we have difficulties**

Baade and Zwicky – theoretical prediction

W. Baade (Mt. Wilson Observatory)
F. Zwicky (Caltech)

The meeting of American Physical
Society
(Stanford, December 15-16, 1933)
Published in Physical Review
(January 15, 1934)



38. Supernovae and Cosmic Rays. W. BAADE, *Mt. Wilson Observatory*, AND F. ZWICKY, *California Institute of Technology*.—Supernovae flare up in every stellar system (nebula) once in several centuries. The lifetime of a super-

nova is about twenty days and its absolute brightness at maximum may be as high as $M_{\text{vis}} = -14^M$. The visible radiation L_v of a supernova is about 10^8 times the radiation of our sun, that is, $L_v = 3.78 \times 10^{41}$ ergs/sec. Calculations indicate that the total radiation, visible and invisible, is of the order $L_\tau = 10^7 L_v = 3.78 \times 10^{48}$ ergs/sec. The supernova therefore emits during its life a total energy $E_\tau \geq 10^5 L_\tau = 3.78 \times 10^{53}$ ergs. If supernovae initially are quite ordinary stars of mass $M < 10^{34}$ g, E_τ/c^2 is of the same order as M itself. In the *supernova* process *mass in bulk is annihilated*. In addition the hypothesis suggests itself that *cosmic rays are produced by supernovae*. Assuming that in every nebula one supernova occurs every thousand years, the intensity of the cosmic rays to be observed on the earth should be of the order $\sigma = 2 \times 10^{-3}$ erg/cm² sec. The observational values are about $\sigma = 3 \times 10^{-3}$ erg/cm² sec. (Millikan, Regener). With all reserve we advance the view that supernovae represent the transitions from ordinary stars into *neutron stars*, which in their final stages consist of extremely closely packed neutrons.

$t_1 = 10^6$ years + 410 seconds for 10^{11} volt electrons.

$t_2 =$ " + 47.6 days " 10^9 " "

$t_3 =$ " + 44 years " 10^{11} " protons.

These time lags $t_i - t$ would tend to smear out the change of intensity caused by the flare-up of individual supernovae. Dr. R. M. Langer in one of our seminars was the first to call attention to the straggling of simultaneously ejected particles.

5. *The super-nova process*

We have tentatively suggested that the super-nova process represents the transition of an ordinary star into a neutron star. If neutrons are produced on the surface of an ordinary star they will "rain" down towards the center if we assume that the light pressure on neutrons is practically zero. This view explains the speed of the star's transformation into a neutron star. We are fully aware that our suggestion carries with it grave implications regarding the ordinary views about the constitution of stars and therefore will require further careful studies.

W. BAADE

F. ZWICKY

Mt. Wilson Observatory and
California Institute of Technology, Pasadena.
May 28, 1934.

Good old classics

For years two main types of NSs have been discussed:
radio pulsars and accreting NSs in close binary systems



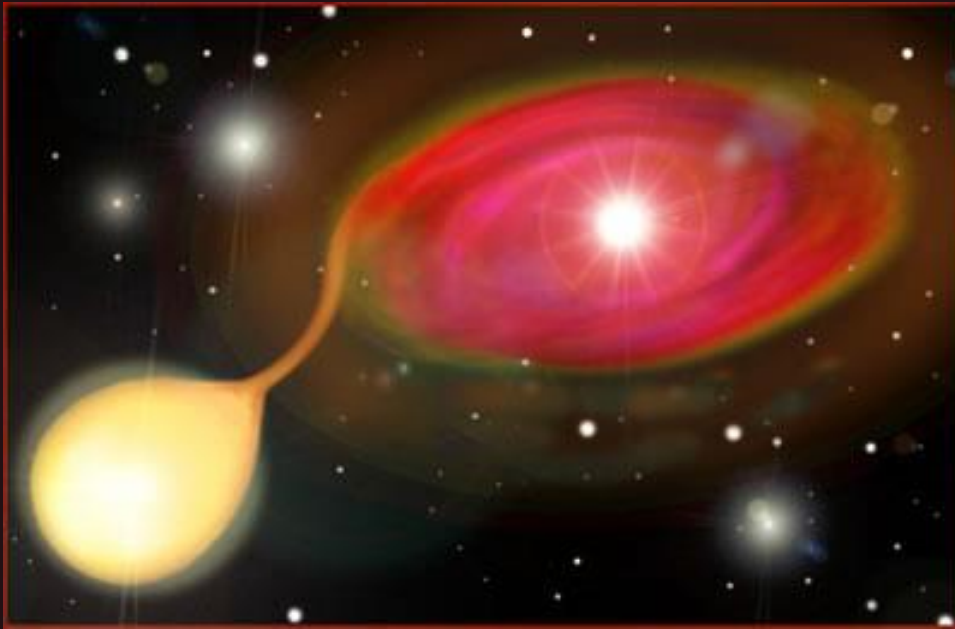
The pulsar in the Crab nebula

A binary system

The old zoo of neutron stars

In 60s the first X-ray sources have been discovered.

They were neutron stars in close binary systems, BUT ...
.... they were «not recognized»....

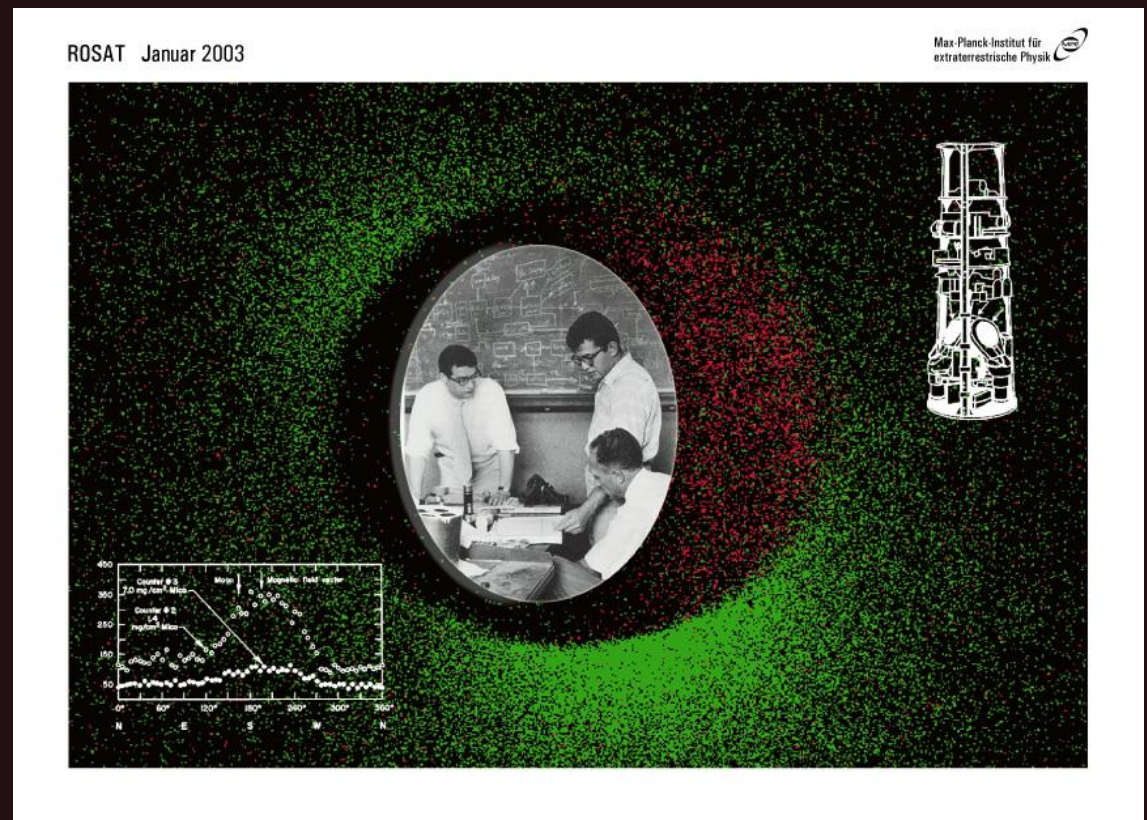


Now we know hundreds of X-ray binaries with neutron stars in the Milky Way and in other galaxies.

Rocket experiments. Sco X-1

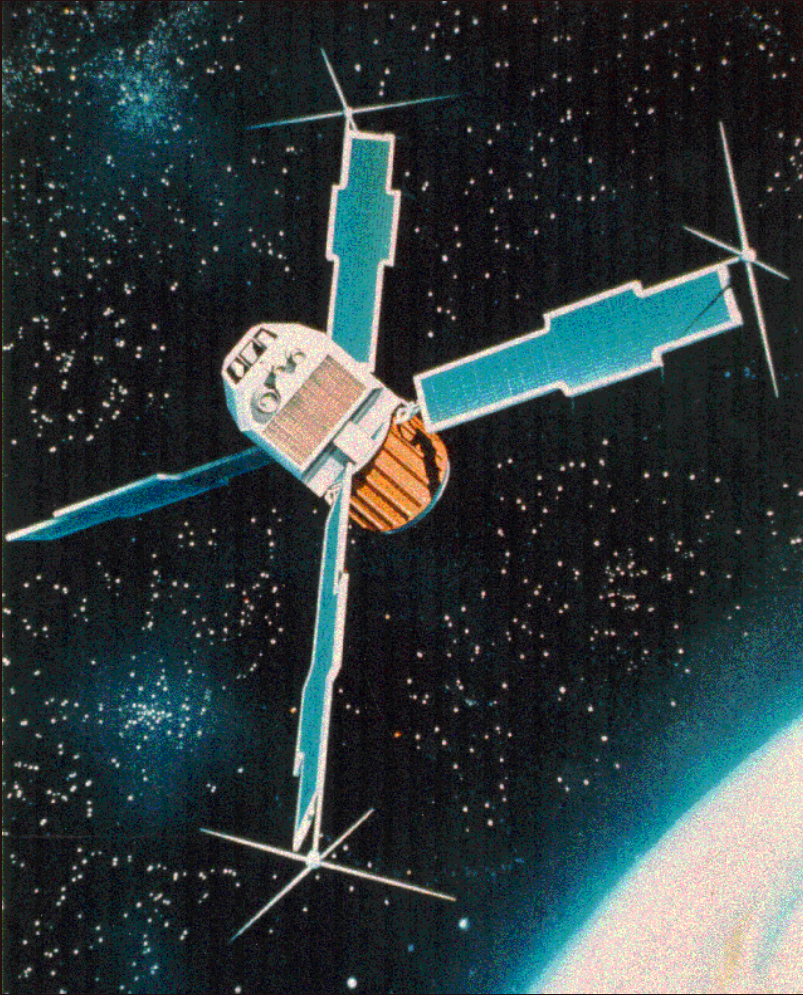
Giacconi et al. 1962

In 2002 R. Giacconi was awarded with the Nobel prize.



On the photo: Giacconi, Gursky, Hendel

UHURU



The satellite was launched on December 12, 1970.

The program was ended in March 1973.

The other name SAS-1

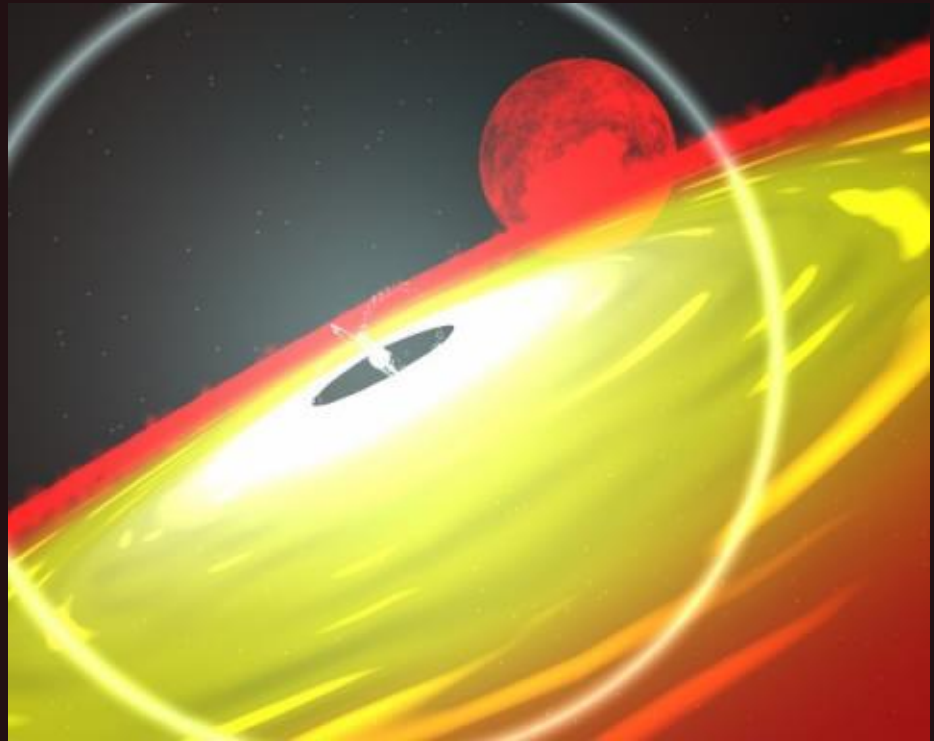
2-20 keV

The first full sky survey.
339 sources.

Accretion in close binaries

Accretion is the most powerful source of energy realized in Nature, which can give a huge energy output.

When matter fall down onto the surface of a neutron star up to 10% of mc^2 can be released.



Accretion disc



The theory of accretion discs was developed in 1972-73 by N.I. Shakura and R.A. Sunyaev.

Accretion is important not only in close binaries, but also in active galactic nuclei and many other types of astrophysical sources.

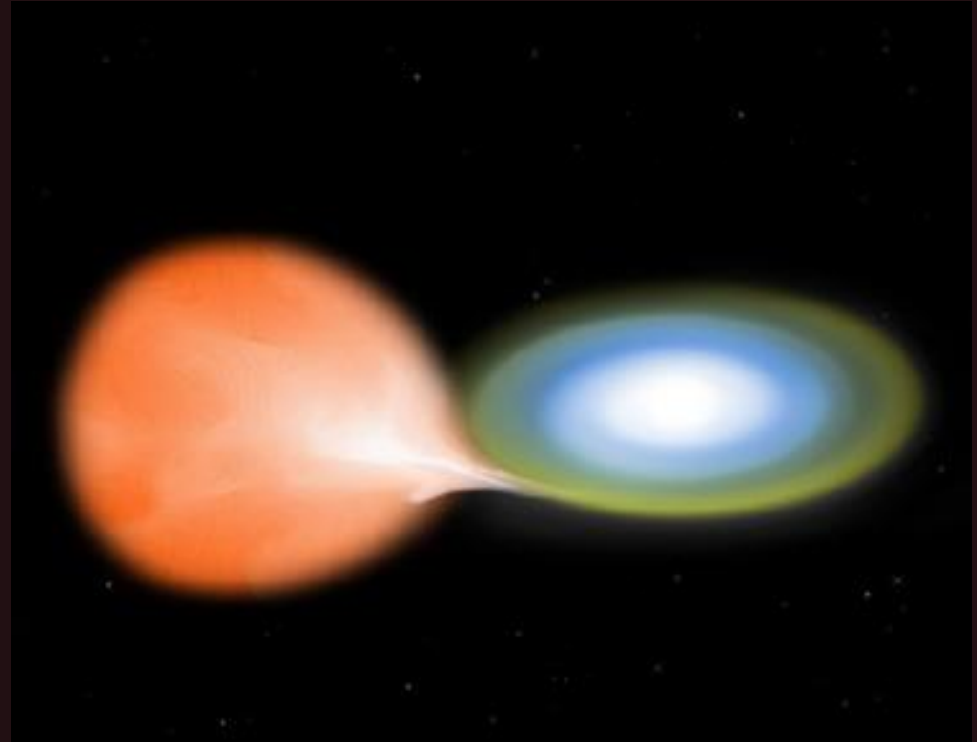
Close binary systems

About 1/2 of massive stars
Are members of close binary
systems.

Now we know many dozens
of close binary systems with
neutron stars.

$$L = \dot{M} \eta c^2$$

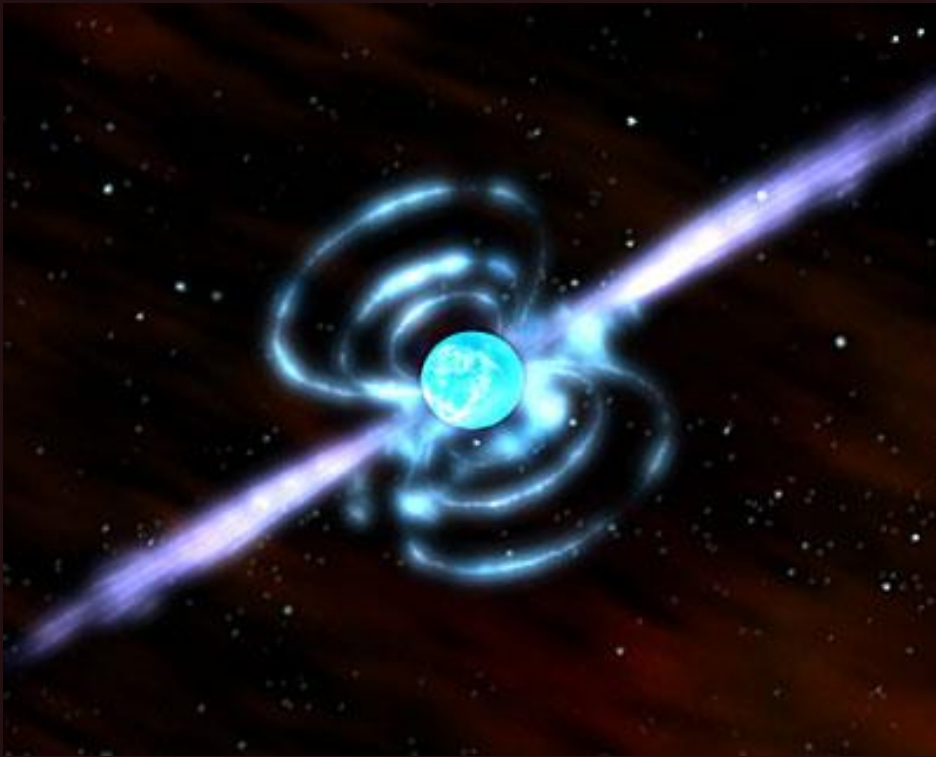
The accretion rate can be up to 10^{20} g/s;
Accretion efficiency – up to 10%;
Luminosity – thousands of hundreds of the solar.



Discovery !!!!

1967: Jocelyn Bell. Radio pulsars.

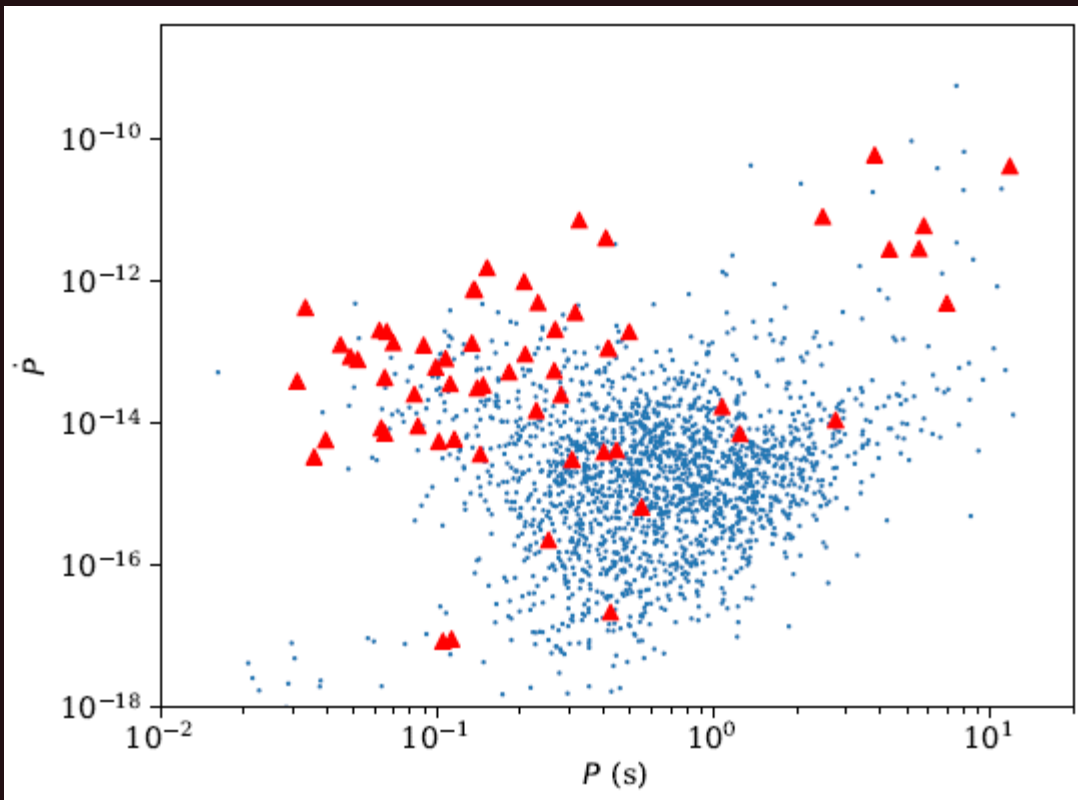
Serendipitous discovery.



The pulsar in the Crab nebula



SNRs and PSRs



There are:

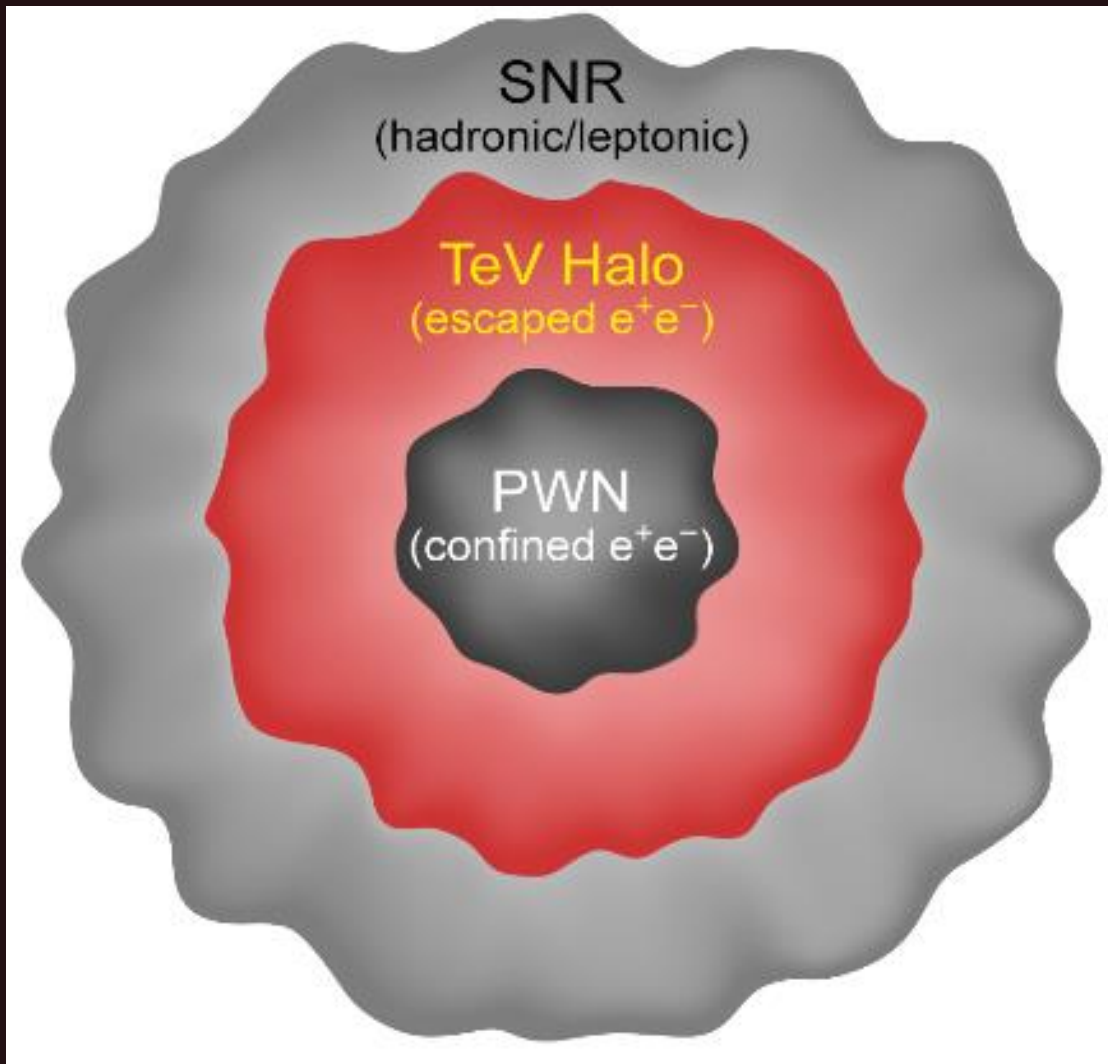
- Young PSRs within SNRs (see 2110.00179);
- Young PSRs without SNRs (see 1204.0632);
- SNRs without PSRs (see 2101.12486)

No PSRs – due to low sensitivity;

No remnants due to the ISM.

Joint studies of NSs and their SNRs are very useful to improve our understanding of initial parameters and early evolution of compact objects (see e.g., 2104.10052).

TeV halos

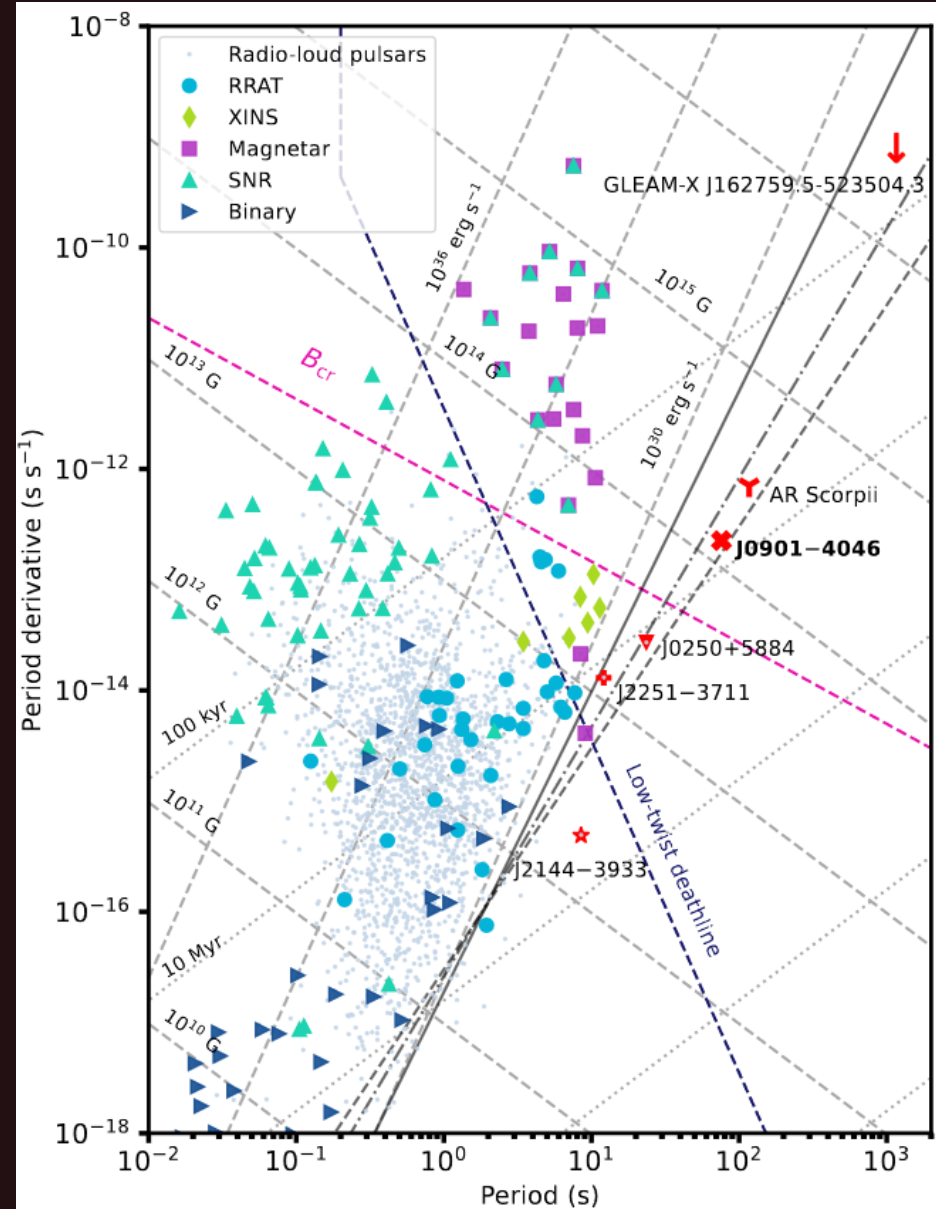


Milagro and HAWC

TeV halos are powered by electrons and positrons from PWNe, but their farther diffusion outside a PWN is suppressed.

New record: 76 seconds

PSR J0901-4046
MeerKAT observations



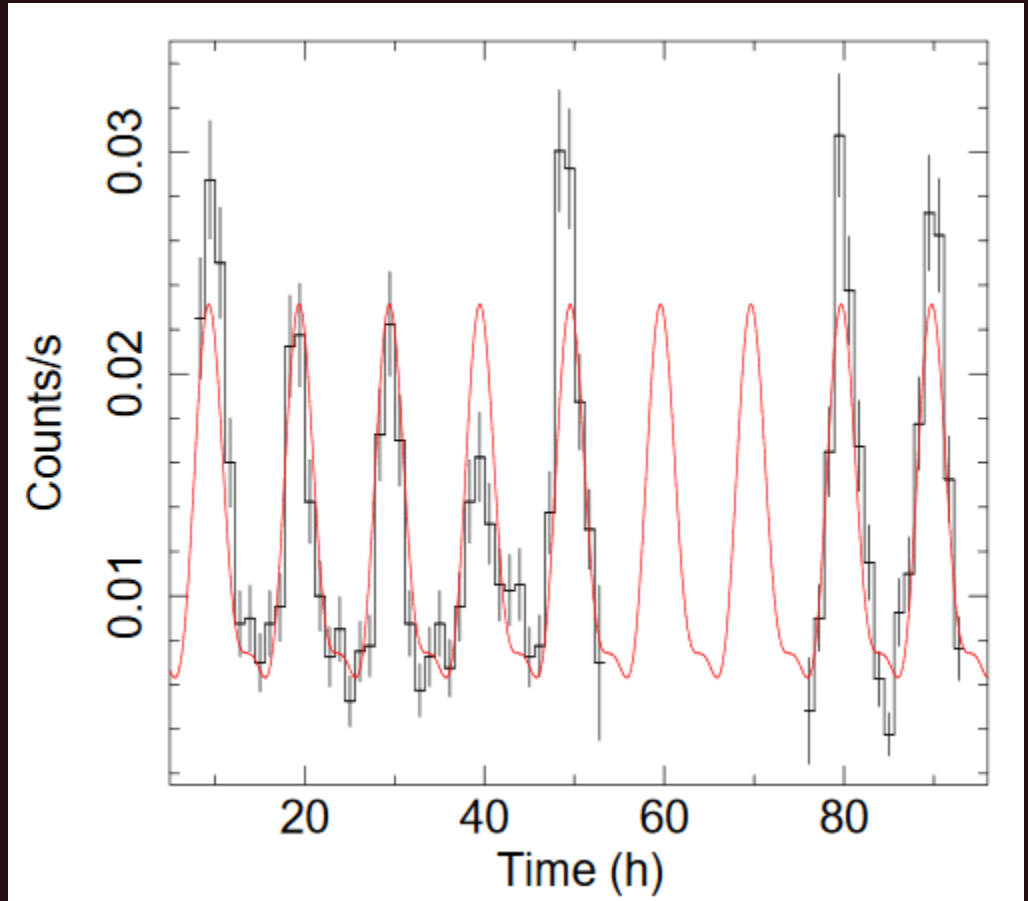
2206.01346

$$L_m = \frac{2 \mu^2 \omega^4}{3 c^3} \sin^2 \beta = \kappa_t \frac{\mu^2}{R_t^3} \omega,$$

Slowly rotating NSs – in binaries

AX J1910.7+0917

$P > 10$ hours! (36200 \pm 100 sec)



18-minutes PSR period?

Murchison Widefield Array

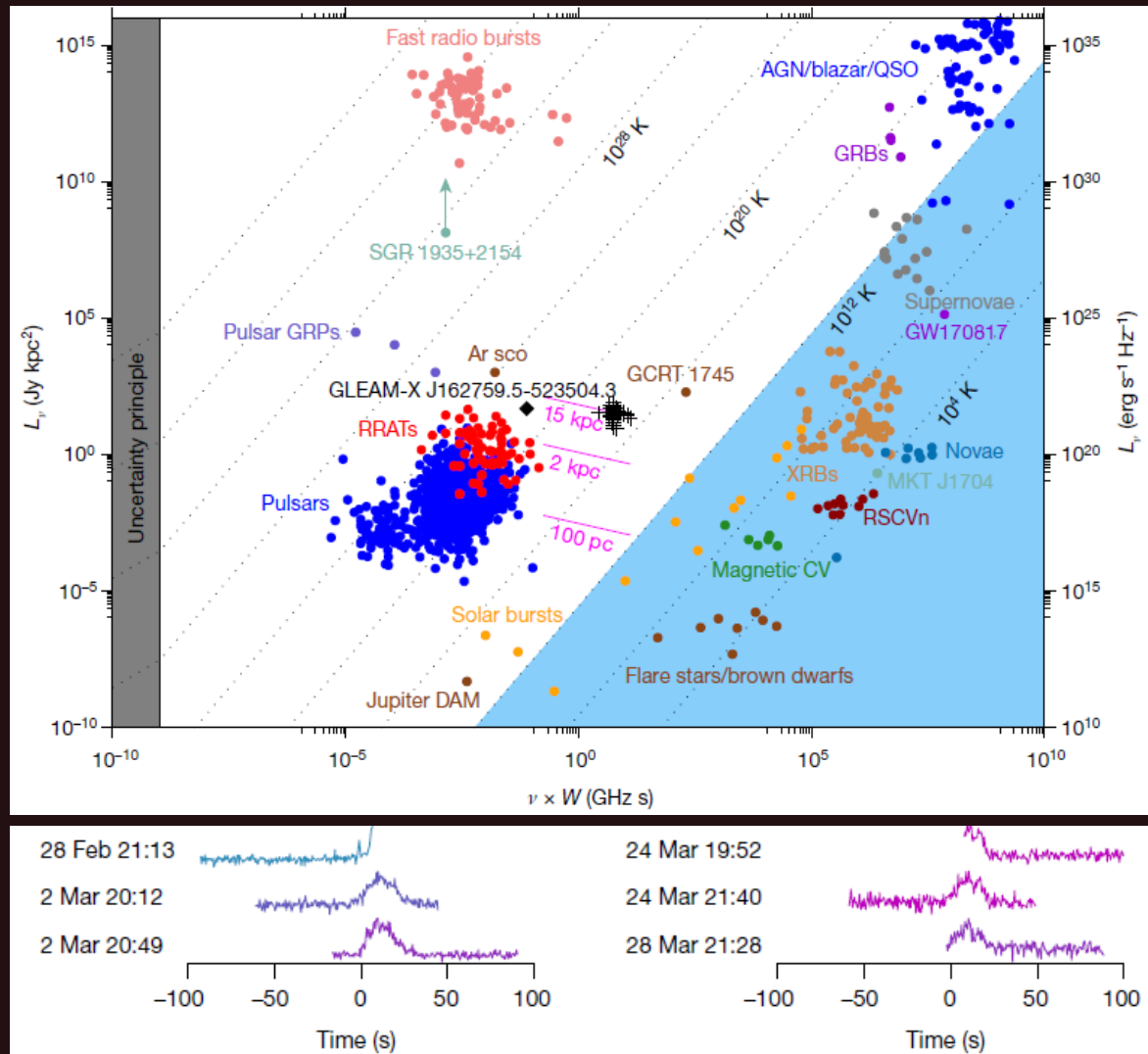
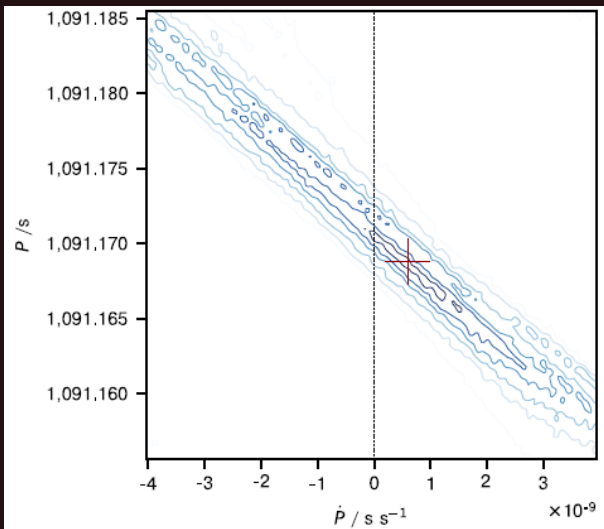
GLEAM-X J162759.5-523504.3

72–231 MHz

DM=57 ± 1 pc cm⁻³

d=1.3 ± 0.5 kpc

RM=-61 ± 1 rad m⁻²



28 Feb 21:13

2 Mar 20:12

2 Mar 20:49

24 Mar 19:52

24 Mar 21:40

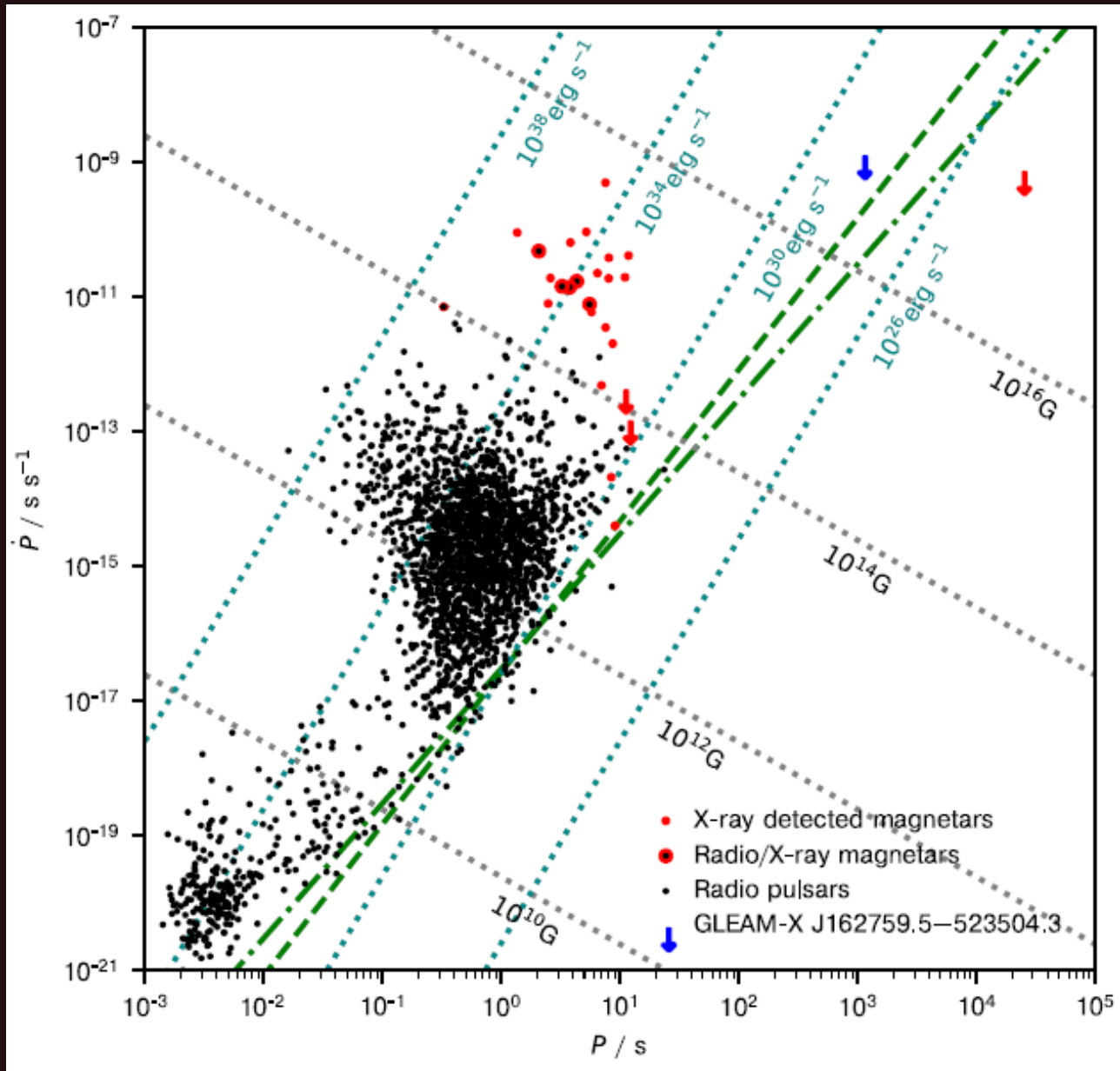
28 Mar 21:28

-100 -50 0 50 100

Time (s)

-100 -50 0 50 100

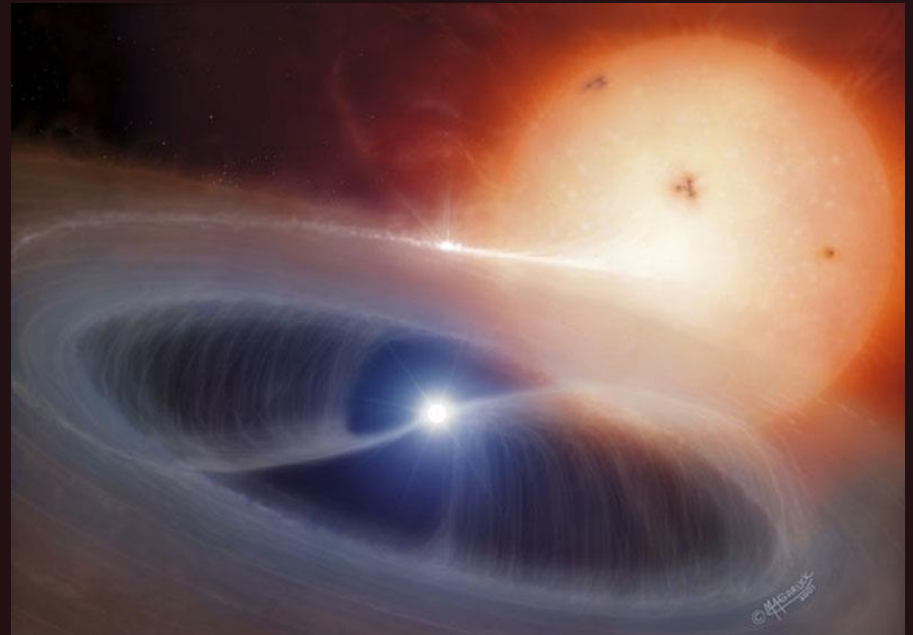
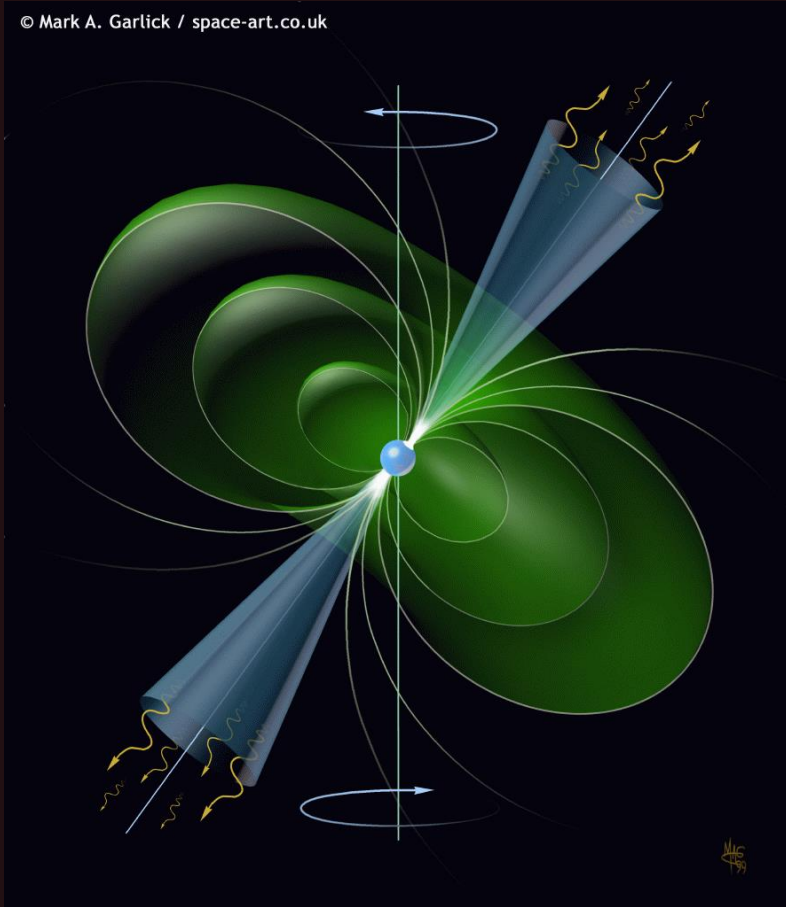
Time (s)



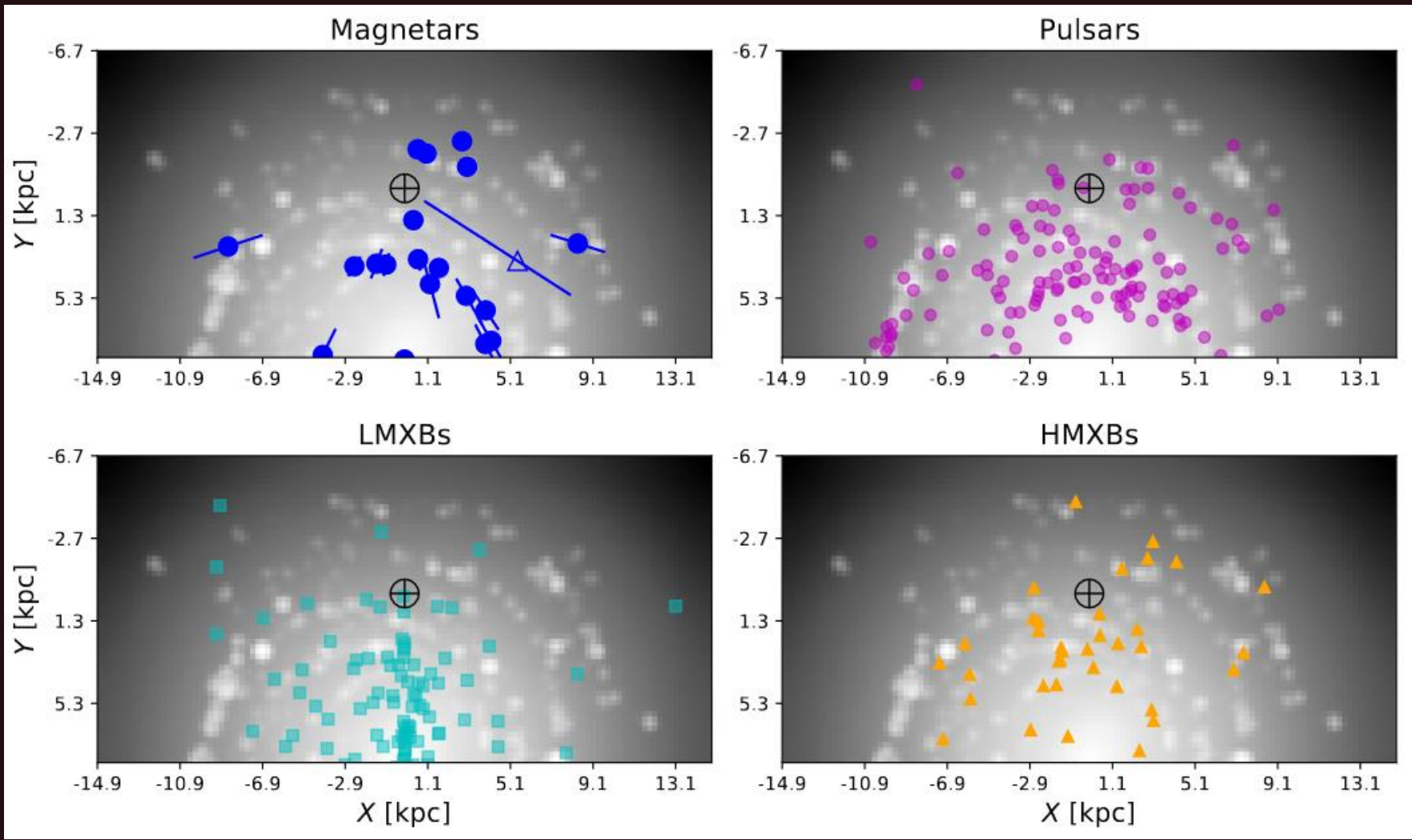
Hurley-Walker et al. 2022

The old Zoo: young pulsars & old accretors

© Mark A. Garlick / space-art.co.uk



NSs in the Milky Way



The new zoo of young neutron stars

During last ~ 25 years it became clear that neutron stars can be born very different. In particular, absolutely non-similar to the Crab pulsar.

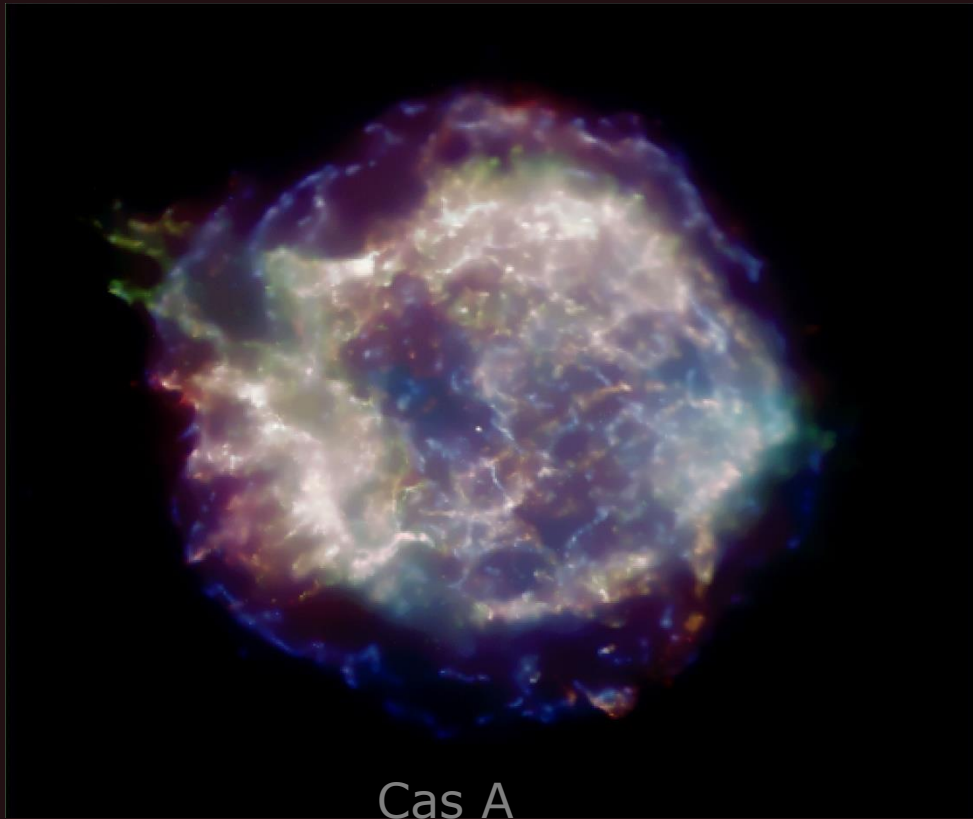
- o High-B PSRs
- o Compact central X-ray sources in supernova remnants.
- o Anomalous X-ray pulsars
- o Soft gamma repeaters
- o The Magnificent Seven
- o Transient radio sources (RRATs)



Old and new zoos: Harding [arXiv:1302.0869](https://arxiv.org/abs/1302.0869)

See a more recent review in [1712.06040](https://arxiv.org/abs/1712.06040)

Compact central X-ray sources in supernova remnants



Rapid cooling
(Heinke et al. 1007.4719)

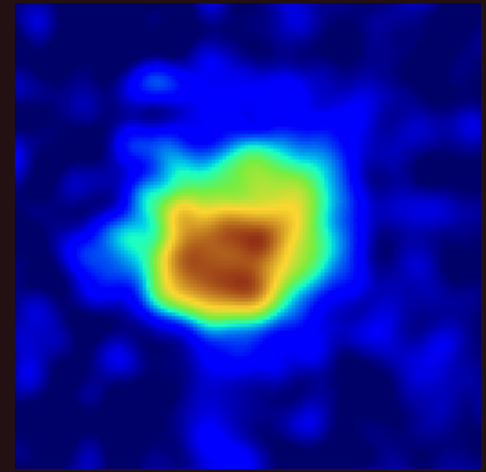


6.7 hour period
(de Luca et al. 2006)

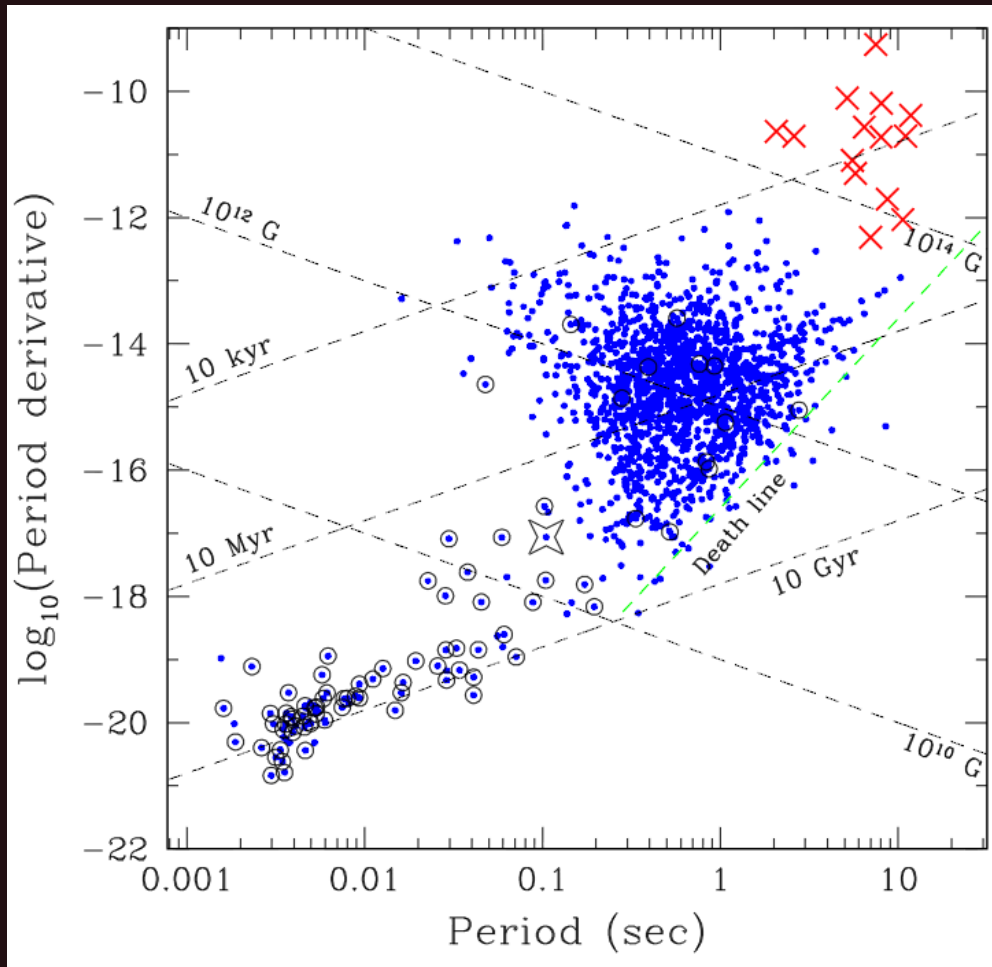
Catalogue of CCOs

CCO	SNR	SNR Age (kyr)	d (kpc)	P (s)	PF (%)	B_s (10^{10} G)	L_x bol (erg s $^{-1}$)
RX J0822.0-4300	Puppis A	4.5	2.2	0.112	11	2.9	5.6×10^{33}
CXOU J085201.4-461753	G266.1-1.2	1	1	-	< 7	-	2.5×10^{32}
1E 1207.4-5209	PKS 1209-51/52	7	2.2	0.424	9	9.8	2.5×10^{33}
CXOU J160103.1-513353	G330.2+1.0	> 3	5	-	< 40	-	1.5×10^{33}
1WGA J1713.4-3949	G347.3-0.5	1.6	1.3	-	< 7	-	$\sim 1 \times 10^{33}$
XMMU J172054.5-372652	G350.1-0.3	0.9	4.5	-	-	-	3.9×10^{33}
XMMU J173203.3-344518	G353.6-0.7	~ 27	3.2	-	< 8	-	1.3×10^{34}
CXOU J181852.0-150213	G15.9+0.2	1-3	(8.5)	-	-	-	$\sim 1 \times 10^{33}$
CXOU J185238.6+004020	Kes 79	7	7	0.105	64	3.1	5.3×10^{33}
CXOU J232327.9+584842	Cas A	0.33	3.4	-	< 12	-	4.7×10^{33}

+ candidates + RCW103



Anti-magnetars



Star marks the CCO from
0911.0093

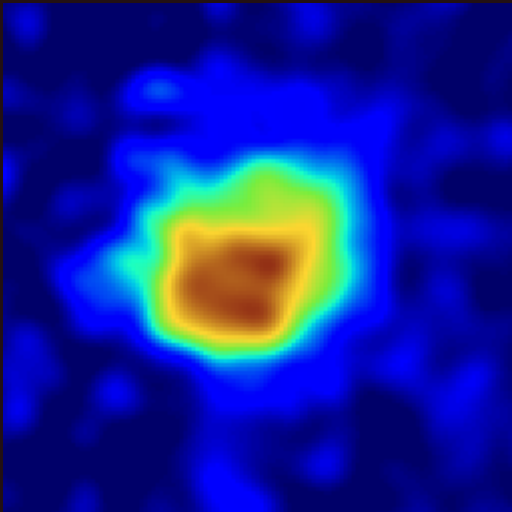
1301.2717:
Spins and derivative are
measured for
PSR J0821-4300 and
PSR J1210-5226

0911.0093

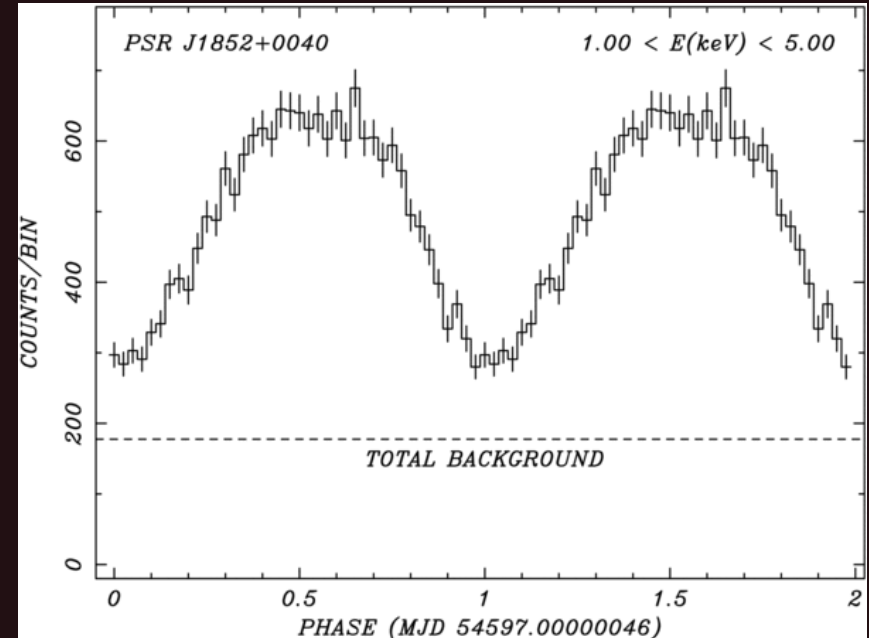
“Hidden” magnetars

Kes 79. PSR J1852+0040. $P \sim 0.1$ s

Shabaltas & Lai (2012) show that large pulse fraction of the NS in Kes 79 can be explained if its magnetic field in the crust is very strong: $\text{few} \times 10^{14}$ G.



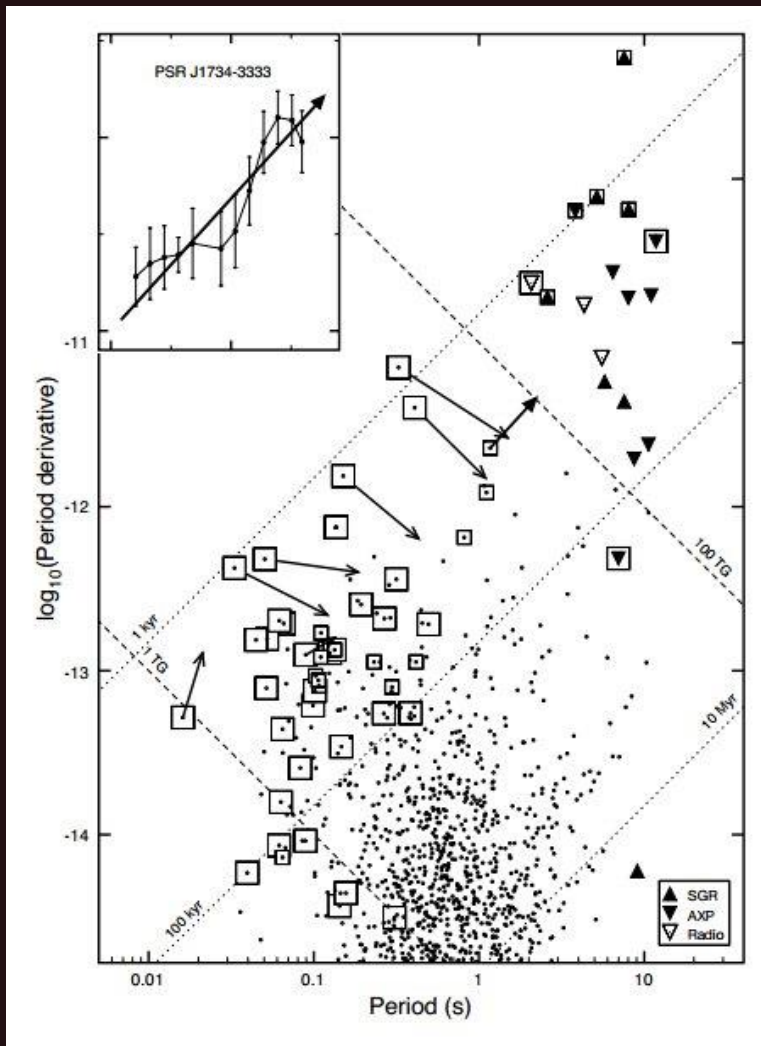
Kes 79



Halpern, Gotthelf 2010

- If submergence of the field happens rapidly, so the present day period represents the initial one
- Then, the field of PSR 1852 was not enhanced via a dynamo mechanism
- Detection of millisecond “hidden” magnetars will be a strong argument in favour of dynamo.

A pulsar with growing field?



PSR J1734-3333

$n=0.9\pm 0.2$

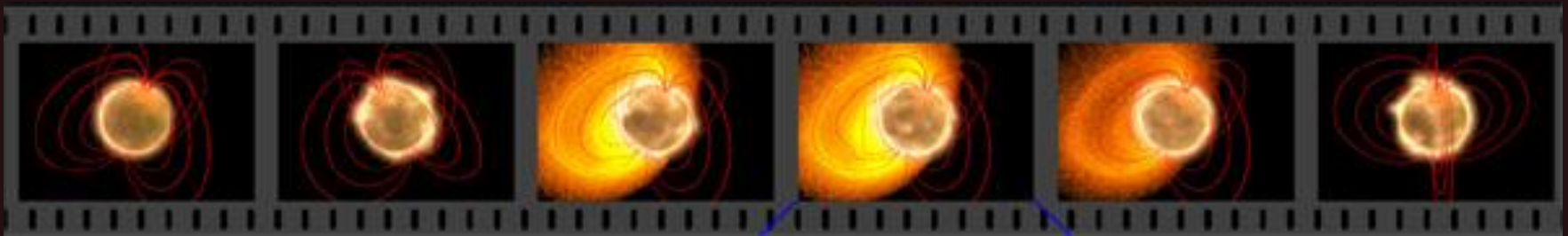
Will it become a magnetar?

Magnetars

- $dE/dt > dE_{\text{rot}}/dt$
- By definition: The energy of the magnetic field is released

Magnetic fields 10^{14} – 10^{15} G

~30 sources known

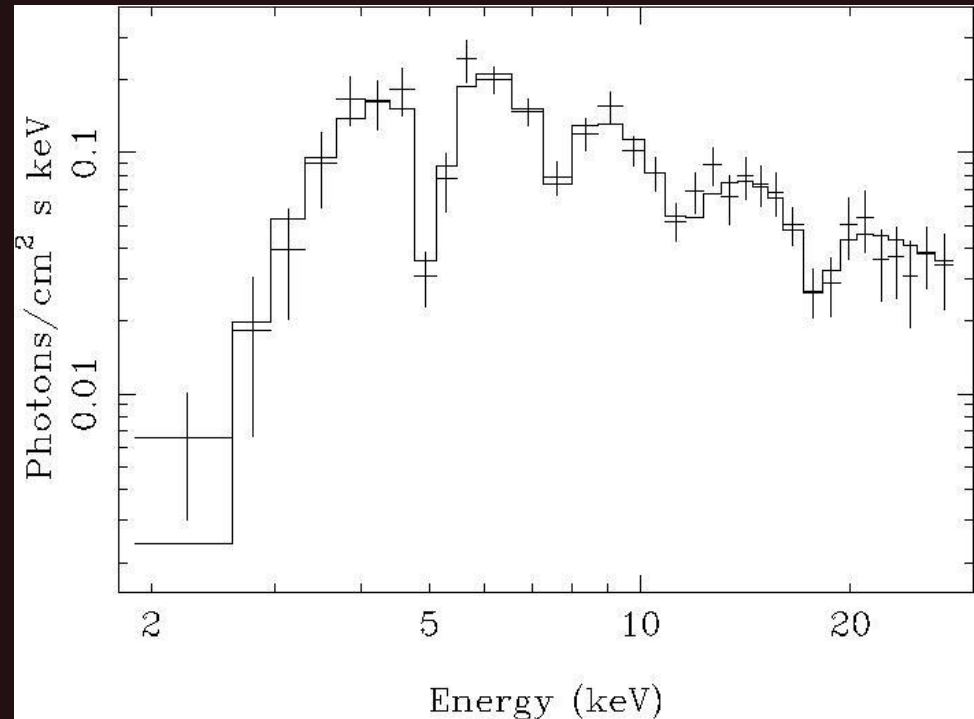


Magnetic field estimates

- Spin down
- Long spin periods

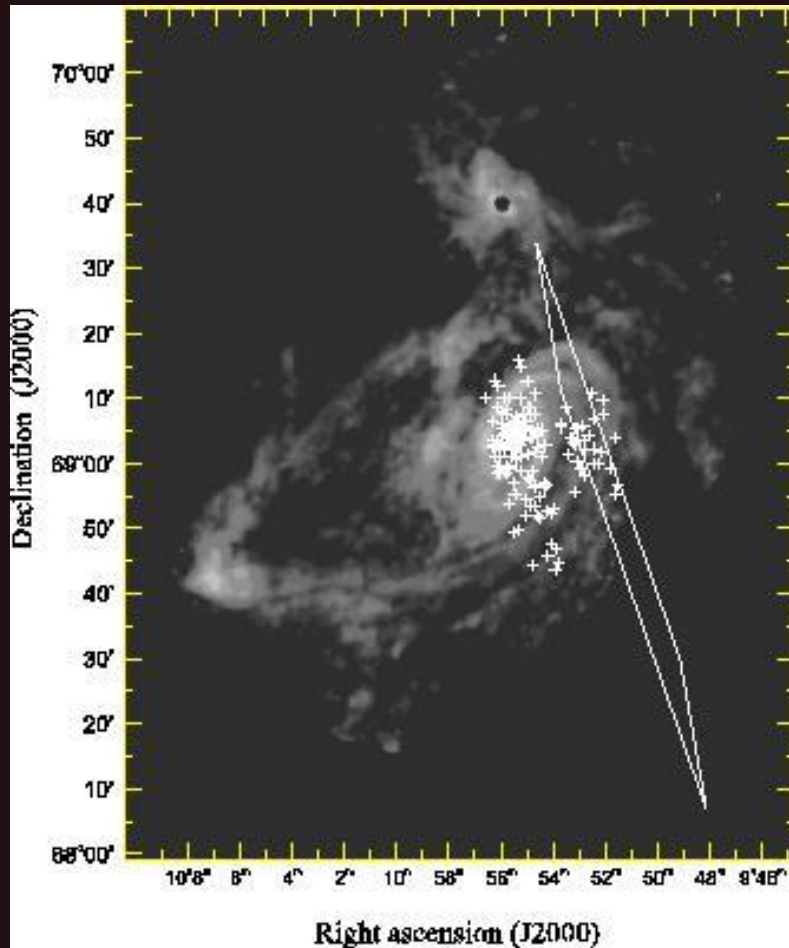
- Energy to support bursts
- Field to confine a fireball (tails)
- Duration of spikes (alfven waves)

- Direct measurements of magnetic field (cyclotron lines)



Ibrahim et al. 2002

Extragalactic SGRs



It was suggested long ago (Mazets et al. 1982) that present-day detectors could already detect giant flares from extragalactic magnetars.

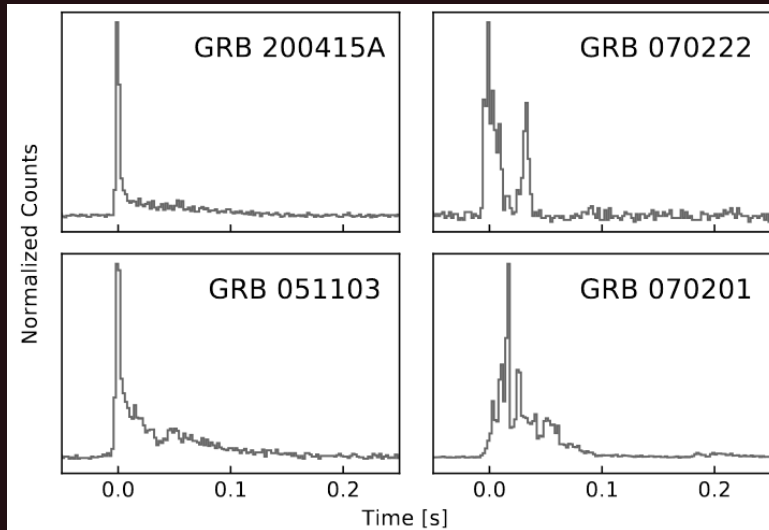
However, all searches in, for example, BATSE database did not provide good candidates (Lazzati et al. 2006, Popov & Stern 2006, etc.).

Finally, recently several good candidates have been proposed by different groups (Mazets et al., Frederiks et al., Golenetskii et al., Ofek et al, Crider, see [arxiv:0712.1502](https://arxiv.org/abs/0712.1502) and references therein, for example).

▼
Burst from M31

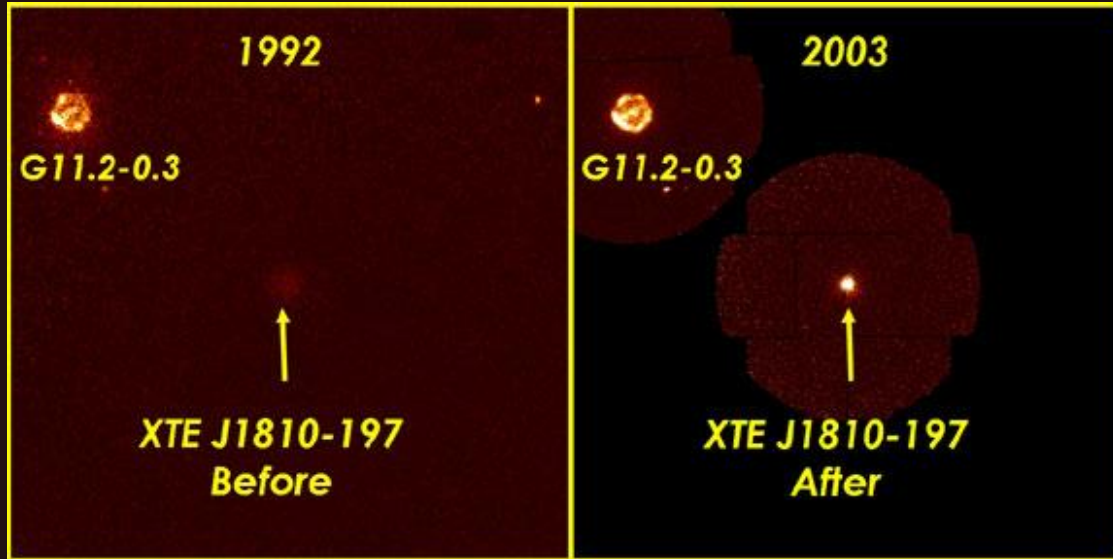
Recent summary can be found in Burns et al. ApJ (2021) 2101.05144

Extragalactic hyperflares



	Known			Extragalactic			
MGF Event	790305B	980827	041227	200415A	070222	051103	070201
Origin							
False Alarm Rate	0	0	0	4.9×10^{-6}	7.8×10^{-6}	1.5×10^{-5}	1.2×10^{-4}
BNS Excl. [Mpc]					6.7	5.2	3.5
Galaxy Properties							
Catalog Name	LMC	MW	MW	NGC253	M83	M82	M31
Distance [Mpc]	0.054	0.0125	0.0087	3.5	4.5	3.7	0.78
SFR [M_{\odot}/yr]	0.56	1.65	1.65	4.9	4.2	7.1	0.4
GRB Properties							
Duration [s]	<0.25	<1.0	<0.2	0.100	0.038	0.138	0.010
Rise Time [ms]	~2	~4	~1	2	4	2	24
L_{iso}^{Max} [10^{46} erg/s]	0.65	2.3	35	140	40	180	12
E_{iso} [10^{45} erg]	0.7	0.43	23	13	6.2	53	1.6
Index			-0.7	0.0	-1.0	-0.2	-0.6
E_{peak} [keV]	500	1200	850	1080	1290	2150	280

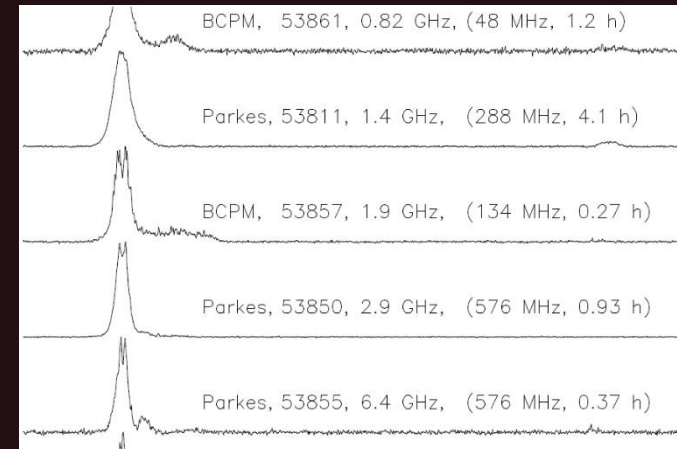
Transient radio emission from AXP



← ROSAT and XMM images
an X-ray outburst
happened in 2003.

AXP has spin period 5.54 s

Radio emission was detected from XTE J1810-197 during its active state.
Clear pulsations have been detected.
Large radio luminosity.
Strong polarization.
Precise \dot{P} measurement.
Important to constrain models, for better distance and coordinates determinations, etc.



(Camilo et al. astro-ph/0605429)

Recent radio data on this source: 1903.02660

Another AXP detected in radio

1E 1547.0-5408

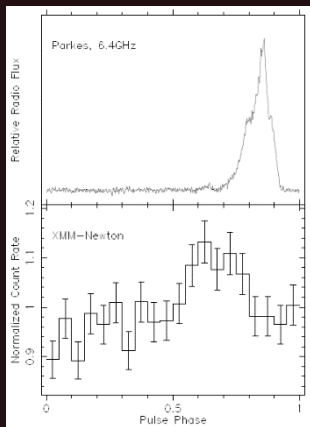
P= 2 sec

SNR G327.24-0.13

Pdot changed significantly on the scale of just
~few months

Rotation and magnetic axis seem to be aligned

Also this AXP demonstrated weak
SGR-like bursts (Rea et al. 2008, GCN 8313)

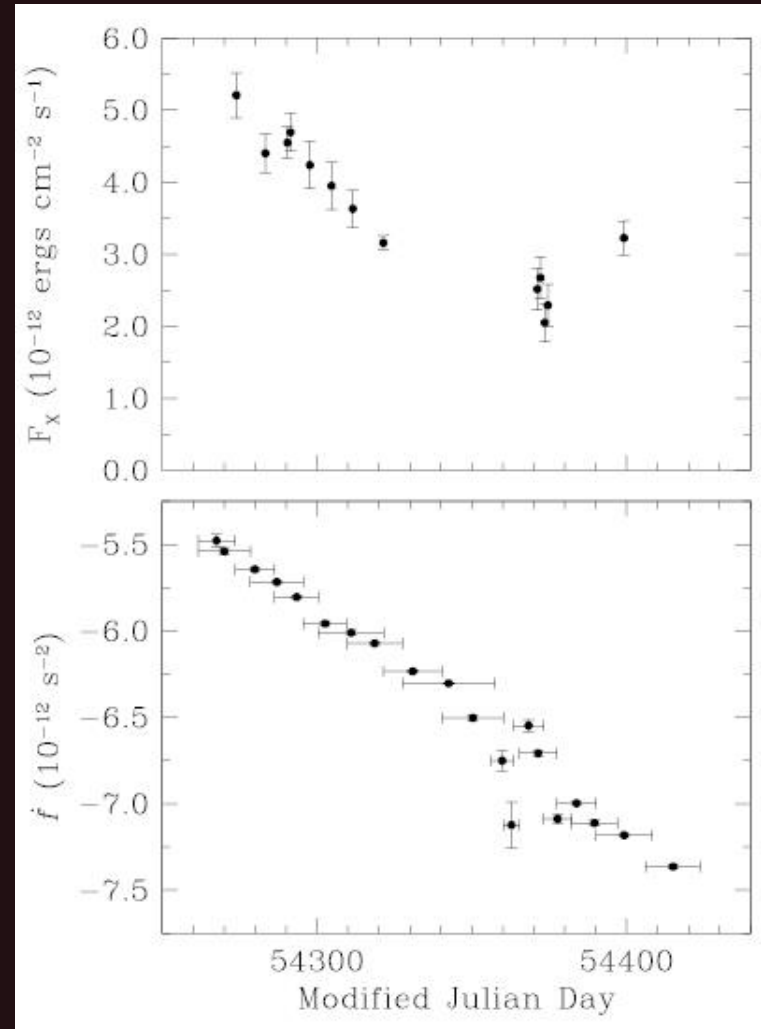


Radio

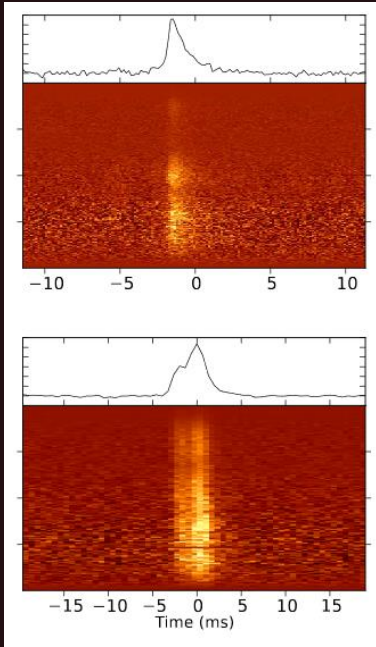
[simultaneous]



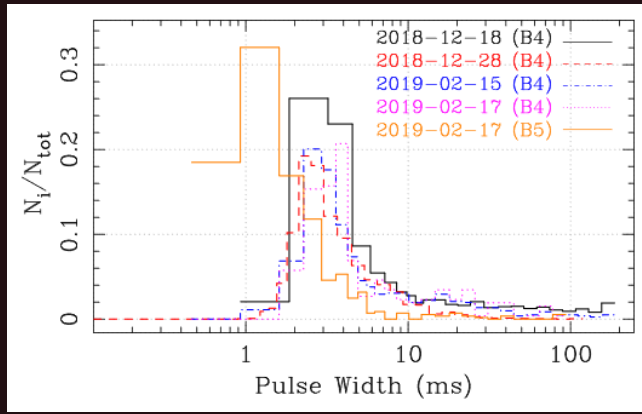
X-rays



Short radio pulses from magnetars

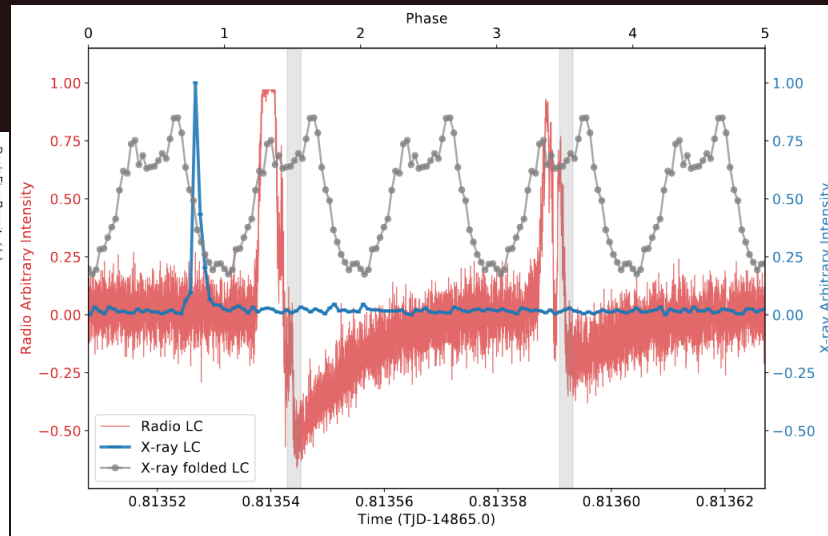
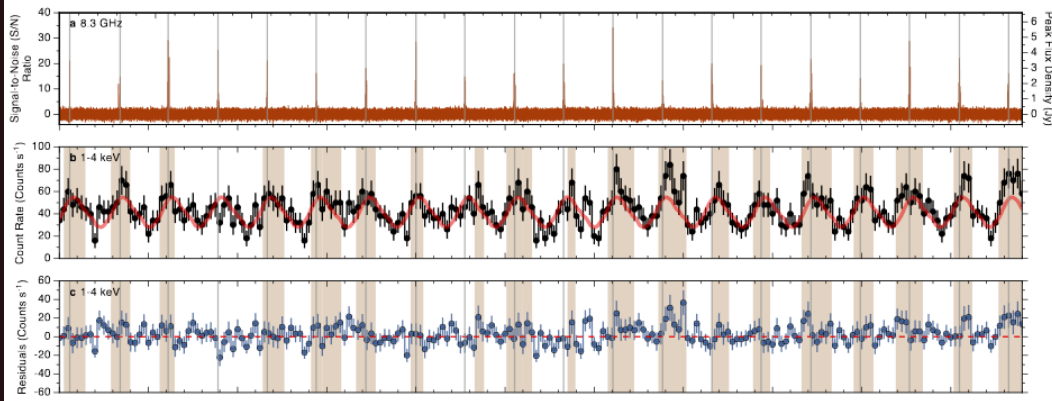


XTE 1810



1908.04304

1E 1547.0-5408



2005.08410

2011.06607

Transient radiopulsar

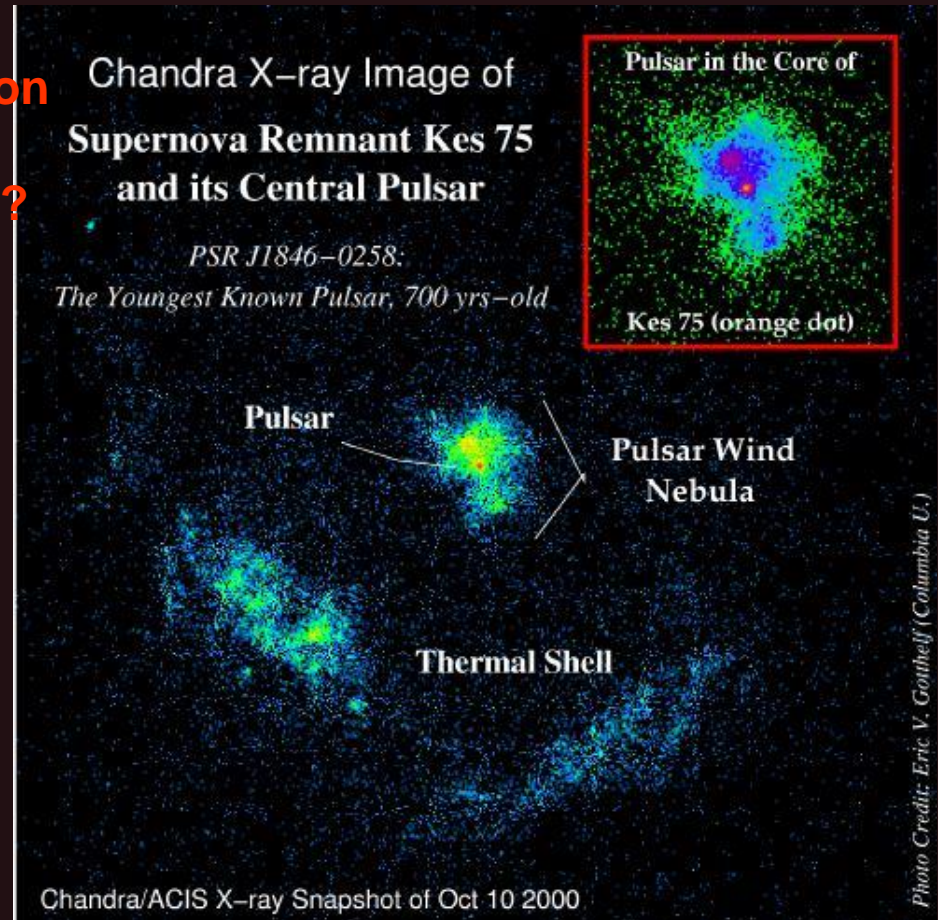
PSR J1846-0258 **However,**
P=0.326 sec **no radio emission**
B=5 10^{13} G **detected.**
Due to beaming?

Among all rotation powered
PSRs it has the largest \dot{E} .
Smallest spindown age (884 yrs).

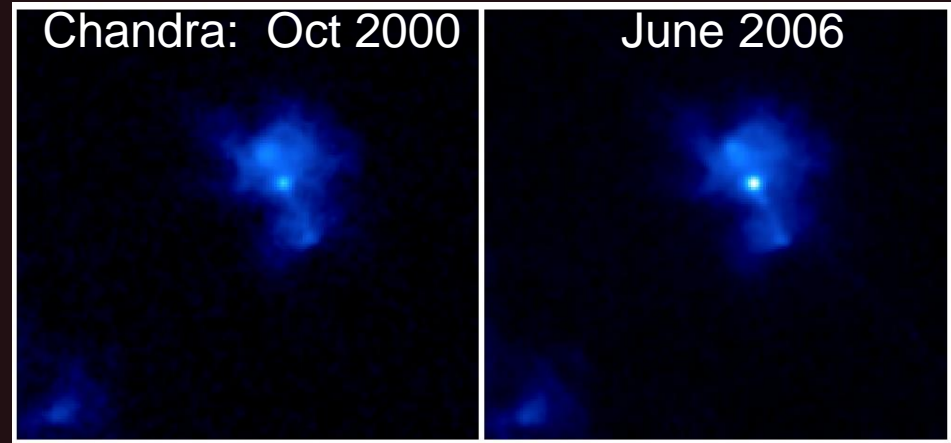
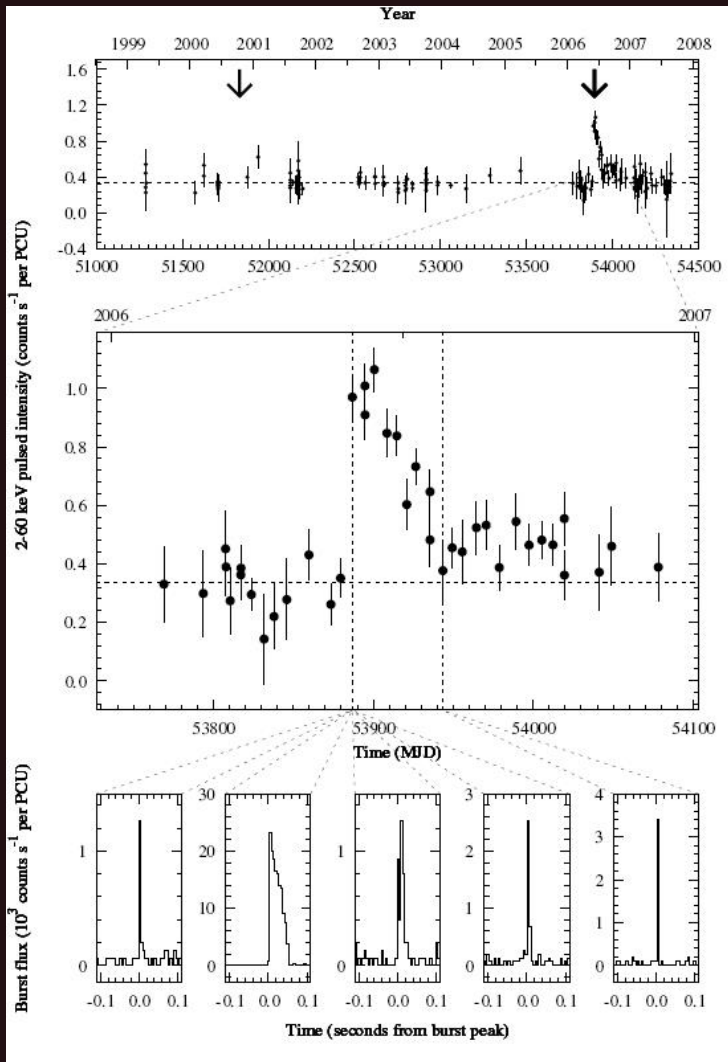
The pulsar increased
its luminosity in X-rays.
Increase of pulsed X-ray flux.
Magnetar-like X-ray bursts (RXTE).
Timing noise.

See additional info about this pulsar
at the web-site

http://hera.ph1.uni-koeln.de/~heintzma/SNR/SNR1_IV.htm

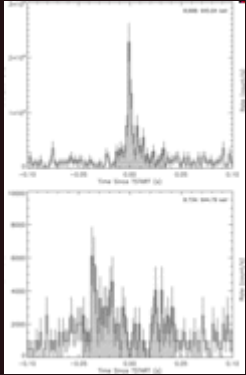


Bursts from the transient PSR



	Burst 1	Burst 2	Burst 3	Burst 4	Burst 5
Temporal properties					
Burst day (MJD)	53886	53886	53886	53886	53943
Burst start time (fraction of day)	0.92113966(5)	0.93247134(1)	0.93908845(2)	0.94248467(5)	0.45543551(1)
Rise time, t_r (ms)	$4.2^{+3.5}_{-2.0}$	$1.1^{+0.9}_{-0.5}$	$1.90^{+1.7}_{-0.9}$	$4.1^{+3.1}_{-1.9}$	$0.9^{+2.2}_{-0.7}$
T_{90} (ms)	$71.8^{+38.0}_{-5.5}$	$42.9^{+0.3}_{-0.2}$	$137.0^{+11.4}_{-36.2}$	$33.4^{+29.1}_{-23.1}$	$65.3^{+0.7}_{-0.5}$
Phase (cycles)	-0.49(1)	-0.04(1)	-0.20(1)	-0.05(1)	-0.08(1)
Fluences and fluxes					
T_{90} Fluence (counts/PCU)	8.9 ± 0.7	712.8 ± 2.5	18.3 ± 0.7	18.4 ± 0.7	18.4 ± 1.1
T_{90} Fluence (10^{-10} erg/cm ²)	4.1 ± 2.4	289.9 ± 13.1	6.6 ± 2.5	5.8 ± 1.7	5.3 ± 2.0
Flux for 64 ms (10^{-10} erg/s/cm ²)	57 ± 36	4533 ± 227	99 ± 41	97 ± 31	79 ± 32
Flux for t_r (10^{-10} erg/s/cm ²)	678 ± 427	5783 ± 885	810 ± 385	828 ± 284	2698 ± 1193
Spectral properties					
Power-law index	0.89 ± 0.58	1.05 ± 0.04	1.14 ± 0.34	1.36 ± 0.25	1.41 ± 0.31
χ^2/DoF (DoF)	0.42 (1)	1.16 (55)	0.97 (3)	0.35 (2)	1.18 (2)

Weak dipole field magnetar

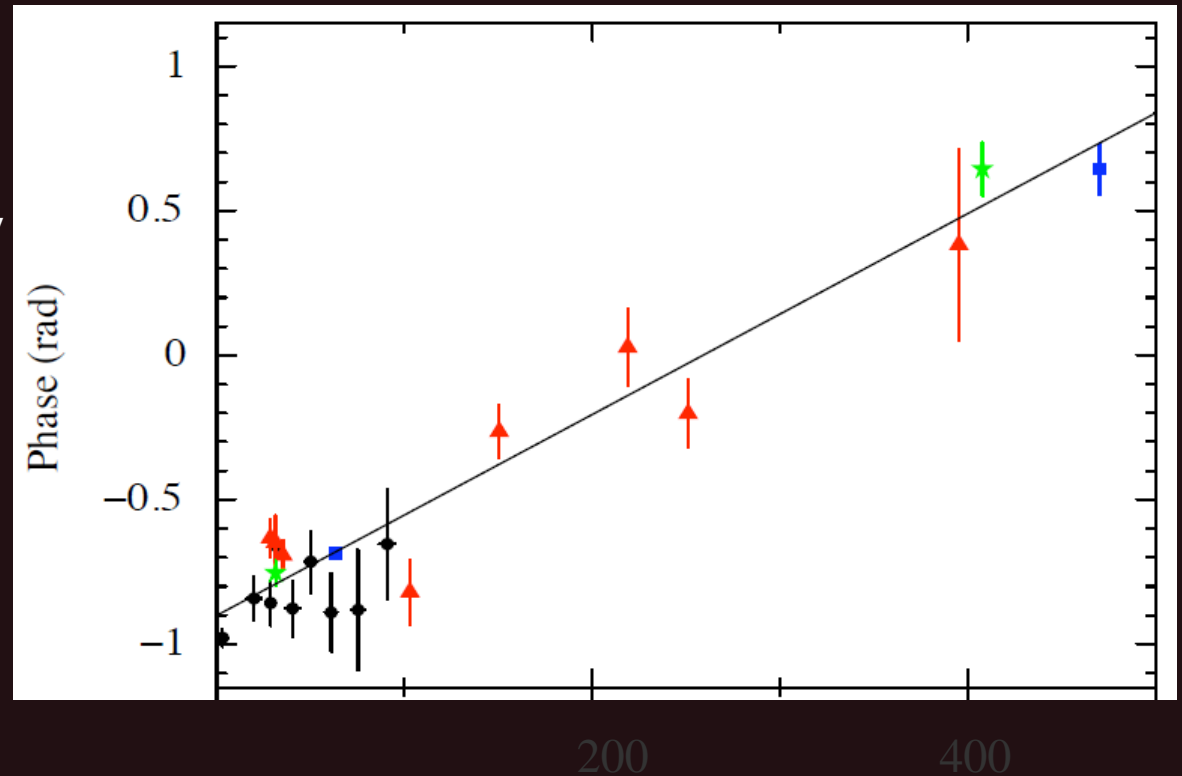


Spin period of a neutron star grows.
The rate of deceleration is related to the dipole magnetic field.
Measuring the spin-down rate we measure the field.

The source is a soft gamma-ray
repeater: SGR 0418+5729
 $P=9.1$ s

The straight line in the plot
corresponds to a constant
spin periods: i.e. no spin-down
 $B < 7.5 \cdot 10^{12}$ G (arXiv:1010.2781)

Old magnetar ? (1107.5488)



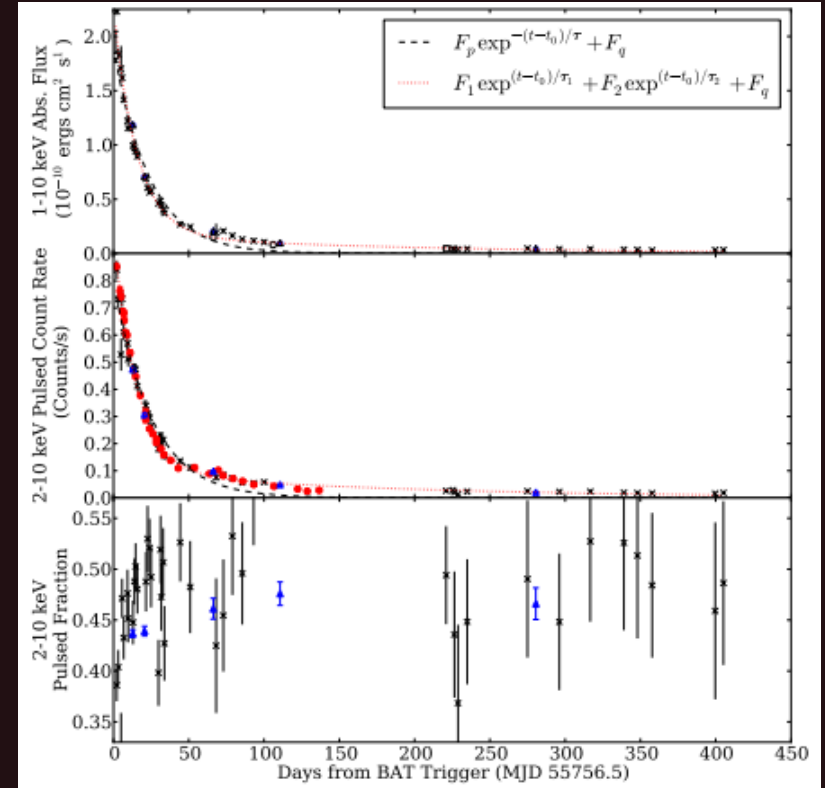
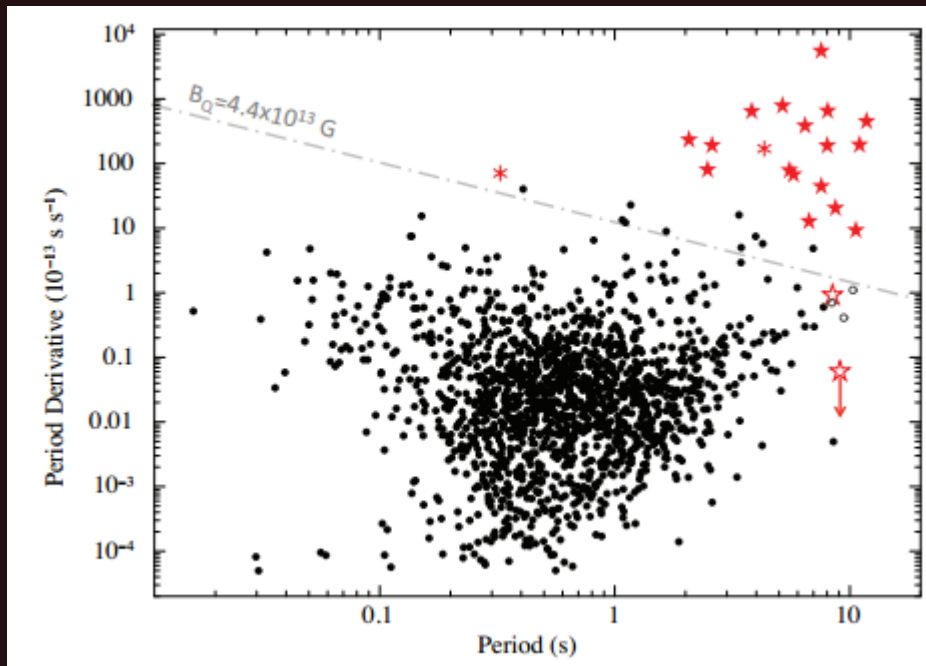
Spectral data suggests high field on the surface: 1103.3024

Another low field magnetar

Swift J1822.3-1606 (SGR 1822-1606)

$P=8.44$ s

$B=3-5 \times 10^{13}$ G



1204.1034

1203.6449

New data: 1211.7347

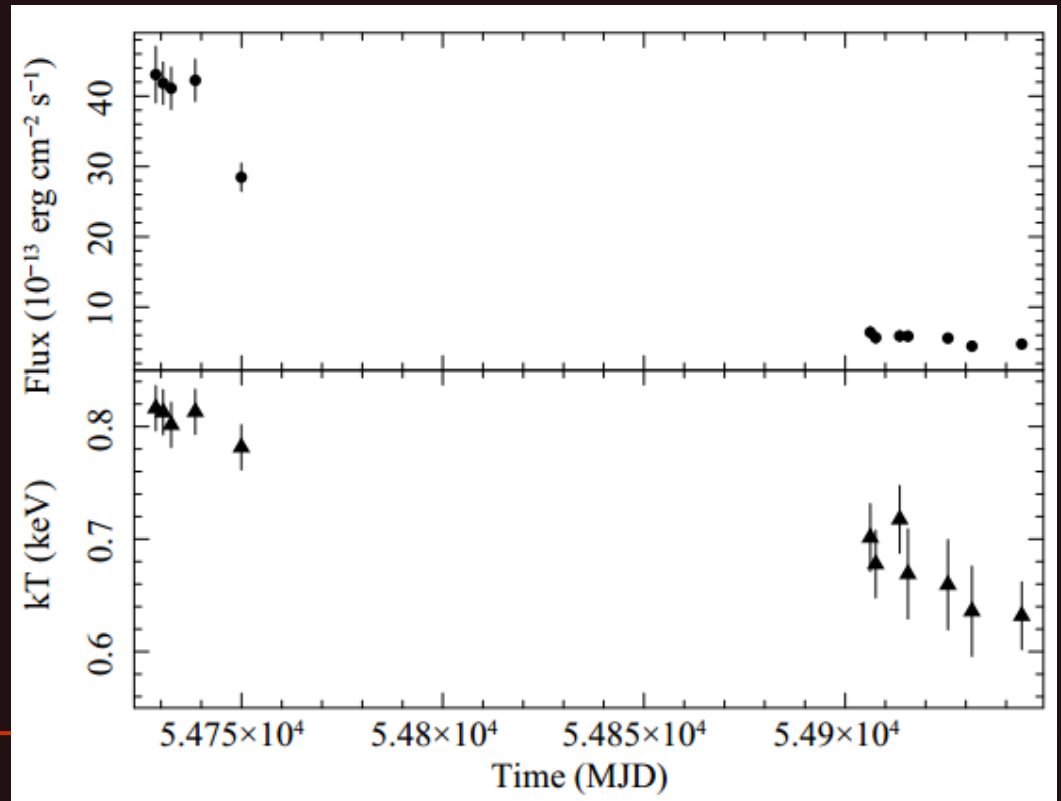
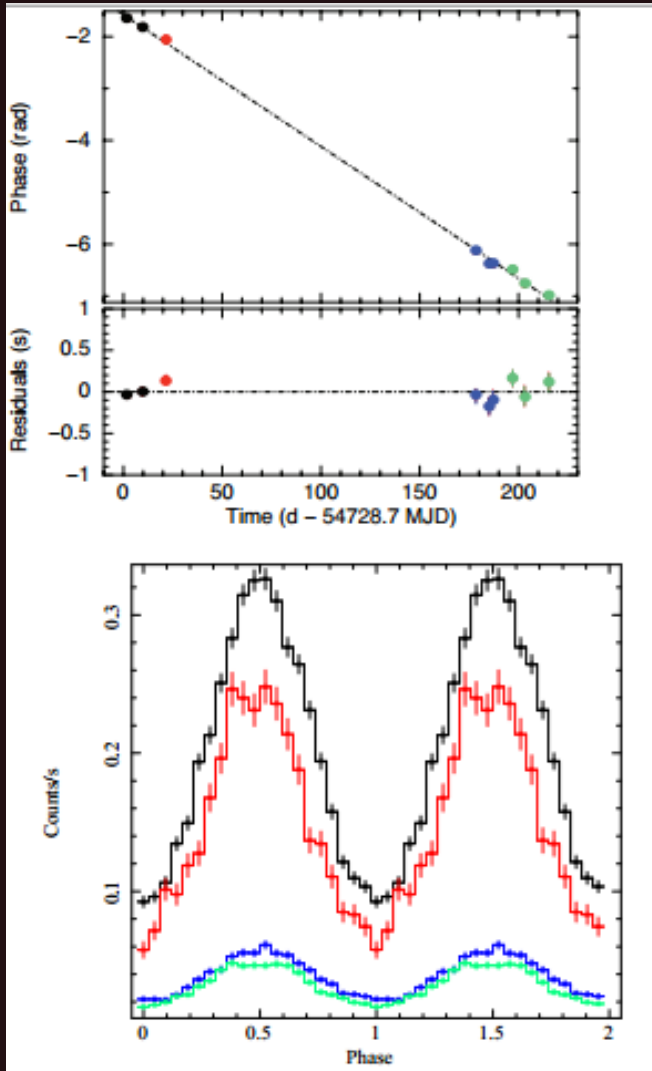
One more low-field magnetar

3XMM J185246.6+003317

$P=11.5$ s No spin-down detected after 7 months

$B < 4 \times 10^{13}$ G

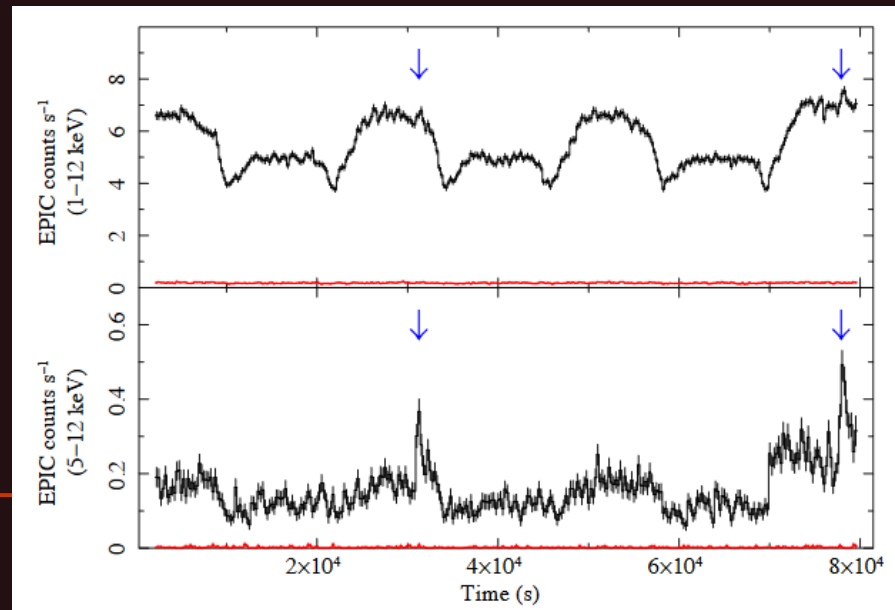
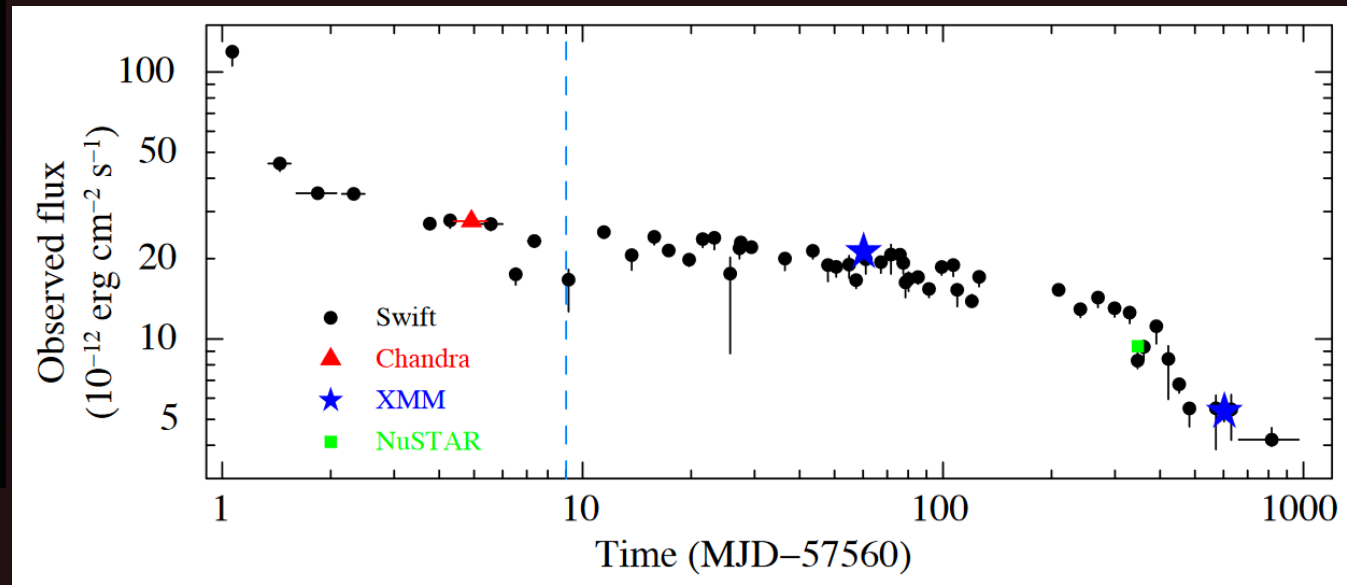
Transient magnetar



RCW103 – a special kind of magnetar



Looked like a CCO
6.7 hours spin period!
SGR-like bursts.



1904.05424

Quiescent magnetar J1622–4950

Normally, magnetars are detected via their strong activity: gamma-ray bursts or enhanced X-ray luminosity.

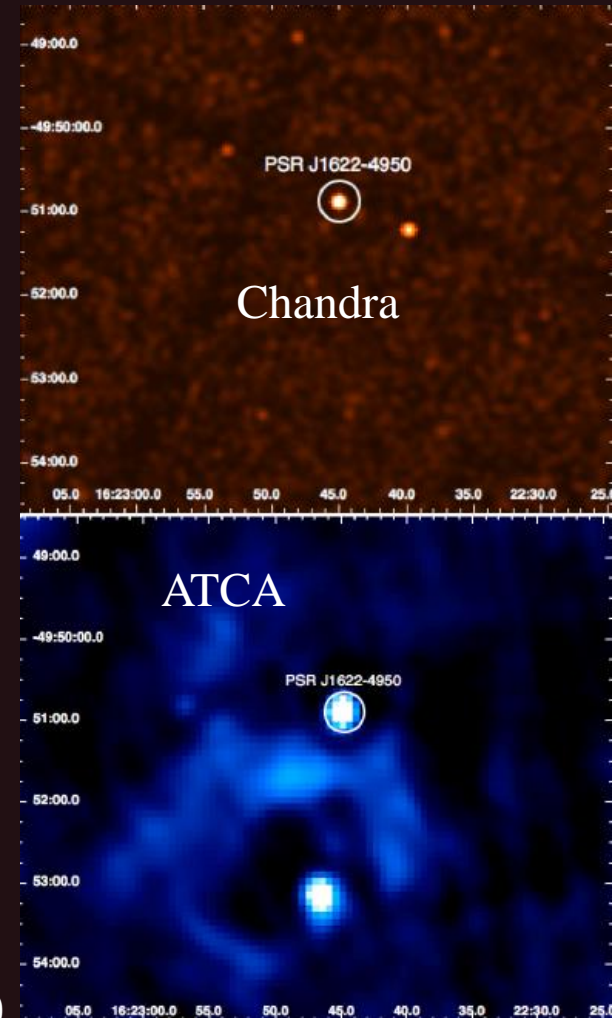
This one was detected in radio observations
The field is estimated to be $B \sim 3 \times 10^{14}$ G

It seems to be the first magnetar to be
Detected in a quiescent state.

PSR J1622–4950 was detected in a radio survey
As a pulsar with $P=4.3$ s.

Noisy behavior in radio

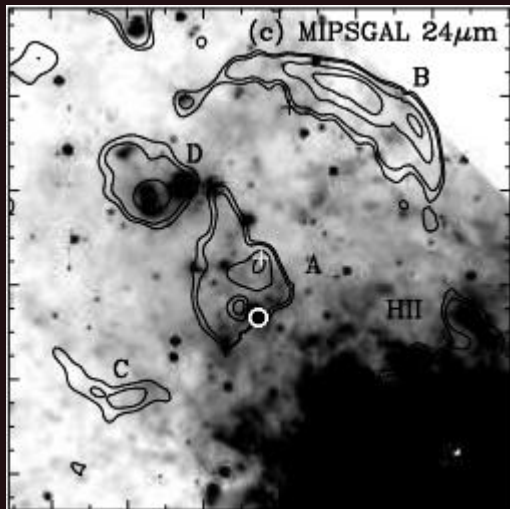
See reviews on high-B PSRs in 1010.4592, 1805.01680



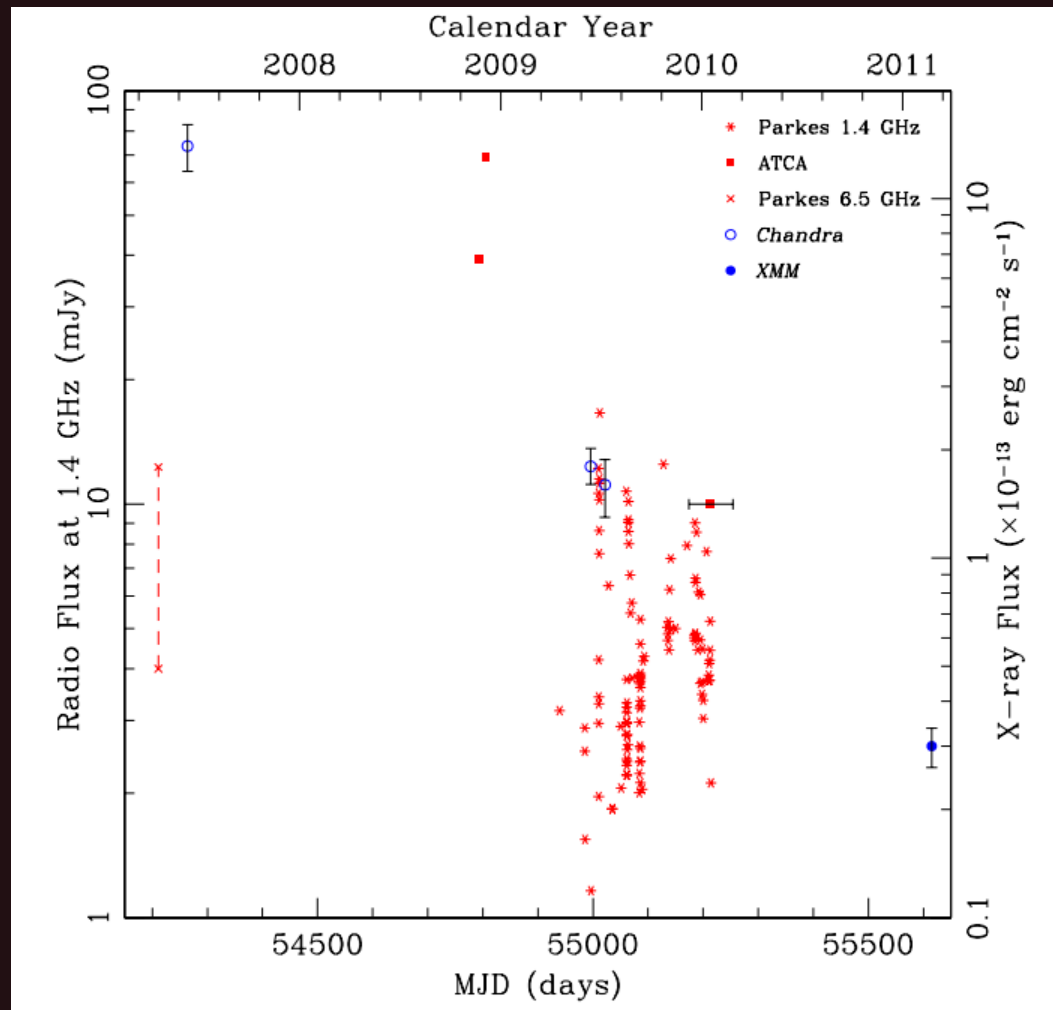
Is J1622–4950 a transient magnetar?

PSR J1622–4950

X-ray flux is decaying
for several years.
Probably, the source
was active years before.



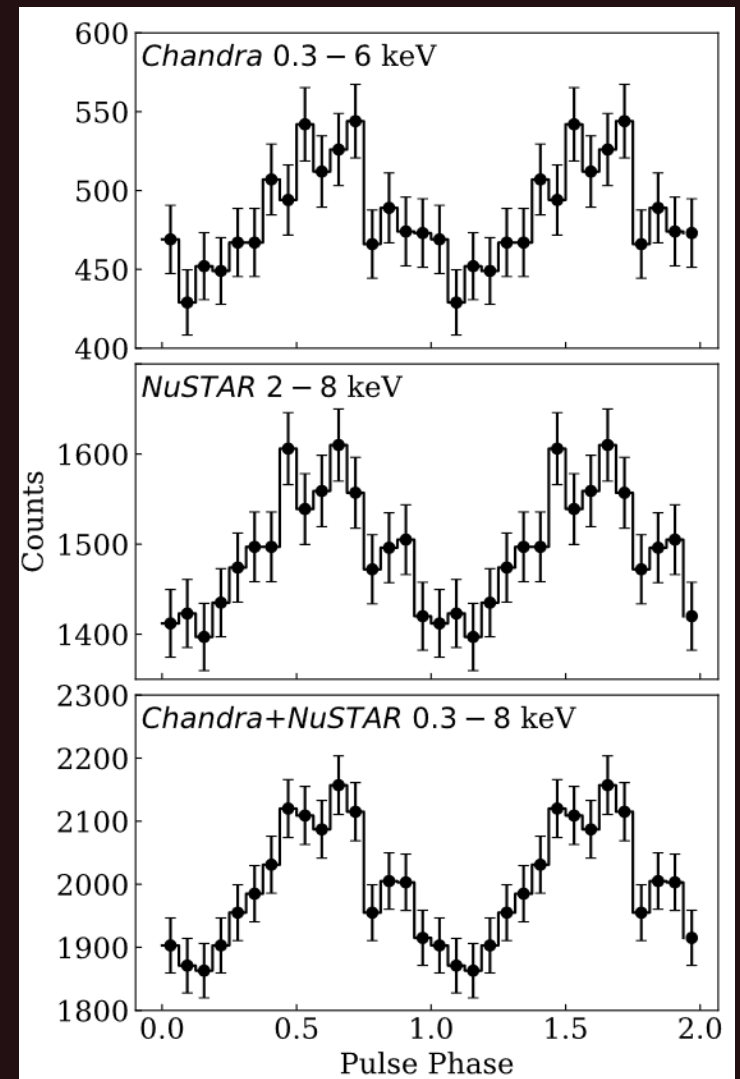
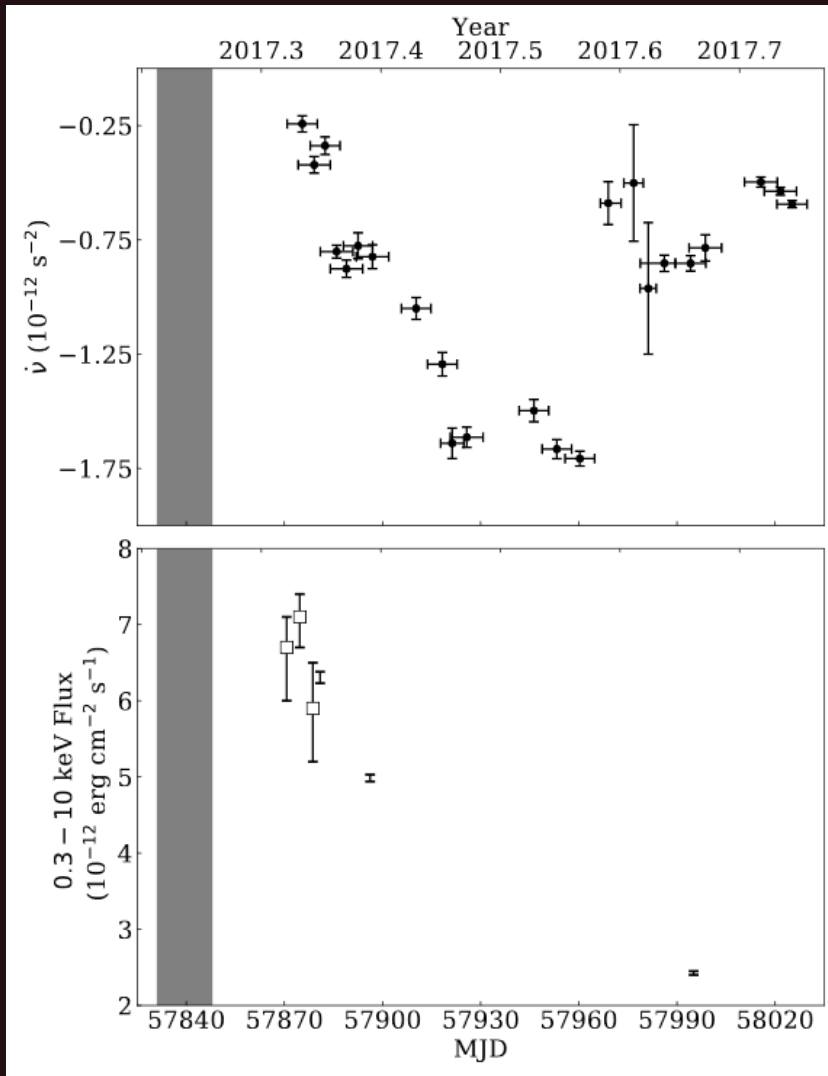
G333.9+0.0 SNR ?



1203.2719

See also 1204.2045

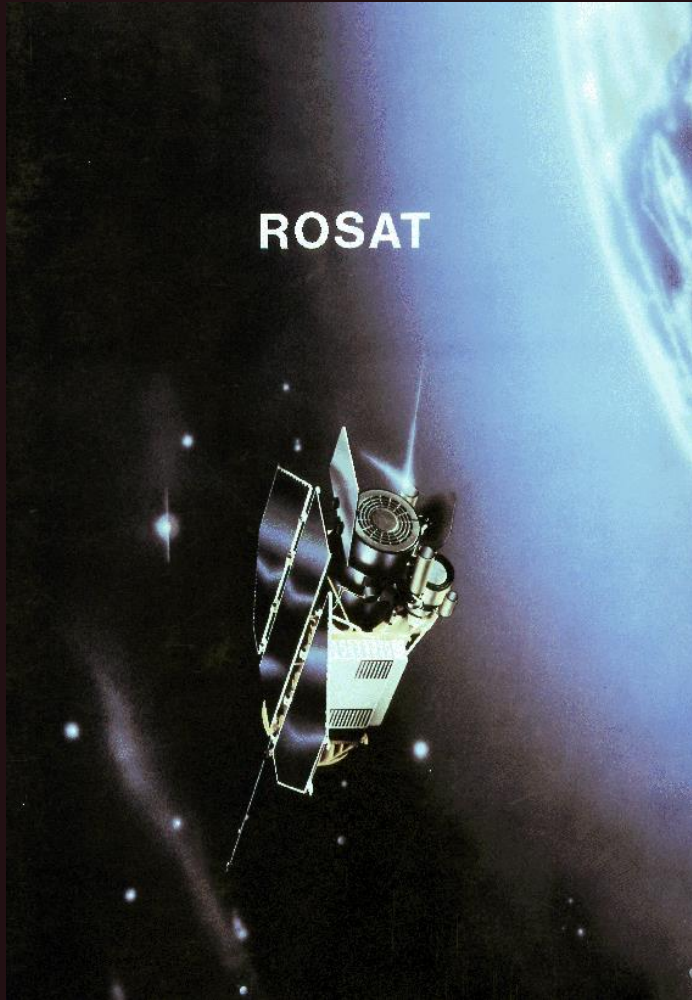
Yes! Revival of J1622–4950



1804.01933

Among few (~5) magnetars with detected radio emission.

ROSAT

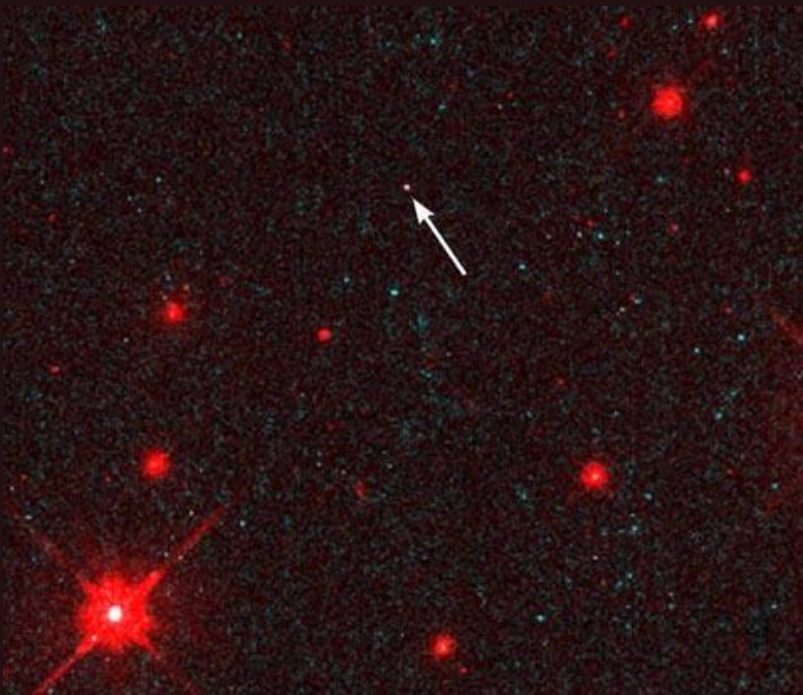


ROentgen SATellite

German satellite
(with participation of US and UK).

Launched 01 June 1990.
The program was successfully ended
on 12 Feb 1999.

Close-by radioquiet NSs



RX J1856.5-3754

- Discovery: Walter et al. (1996)
- Proper motion and distance: Kaplan et al.
- No pulsations
- Thermal spectrum
- Later on: six brothers

Magnificent Seven

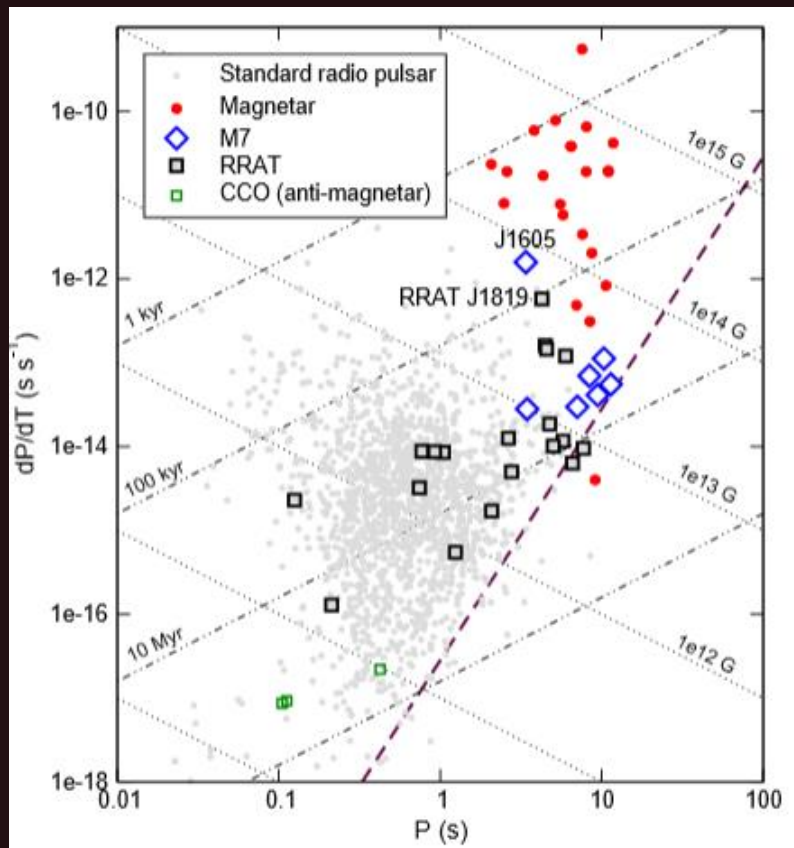
Name	Period, s
RX 1856	7.05
RX 0720	8.39
RBS 1223	10.31
RBS 1556	-----
RX 0806	11.37
RX 0420	3.45
RBS 1774	9.44



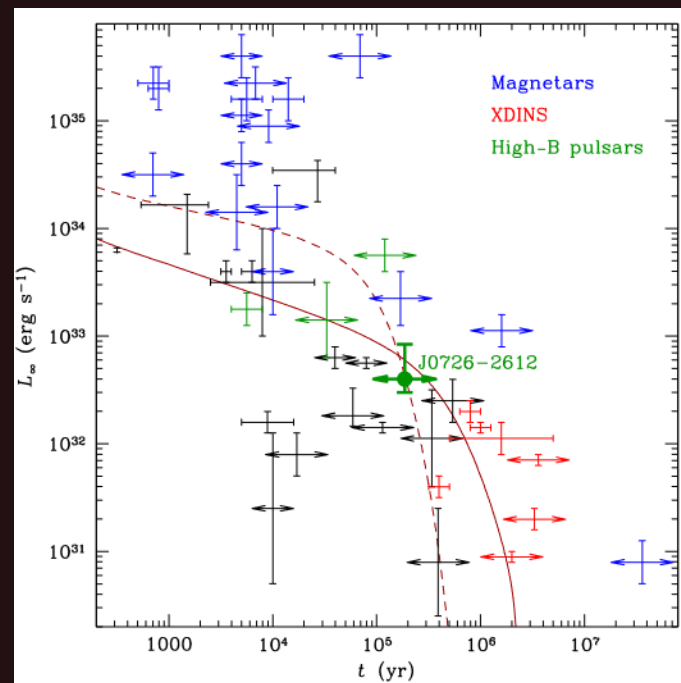
Radioquiet
Close-by
Thermal emission
Absorption features
Long periods

For RBS 1556 (RX J1605) the period is uncertain: 1901.08533, 1906.02806

Object	kT_∞ (eV)	P (s)	p_f (%)	$\log(P)$ (s s ⁻¹)	$\log(\dot{E})$ (erg s ⁻¹)	$\log(\tau_{\text{ch}})$ (yr)	$\log(t_{\text{kin}})$ (yr)	$\log(B_{\text{dip}})$ (10 ¹³ G)	$\log(B_{\text{cyc}})$ (10 ¹³ G)	Reference
RX J1856.5-3754	61	7.06	1	-13.527	30.580	6.58	5.62	13.17	-	[1]
RX J0720.4-3125	84 - 93	8.39	11	-13.156	30.726	6.28	5.93	13.39	13.75	[2]
RX J1605.3+3249	100	3.39	4	-11.796	33.267	4.53	5.65	13.87	13.92	[3]
RX J1308.6+2127	100	10.31	18	-12.951	30.663	6.16	5.95	13.54	13.60	[4]
RX J2143.0+0654	104	9.43	4	-13.398	30.332	6.57	-	13.29	14.15	[5]
RX J0806.4-4123	95	11.37	6	-13.260	30.227	6.51	-	13.40	13.96	[6]
RX J0420.0-5022	48	3.45	17	-13.553	31.487	6.29	-	13.00	-	[7]



Several radio pulsars can be similar to M7.
E.g. PSR J0726-2612 (see 1906.01372).



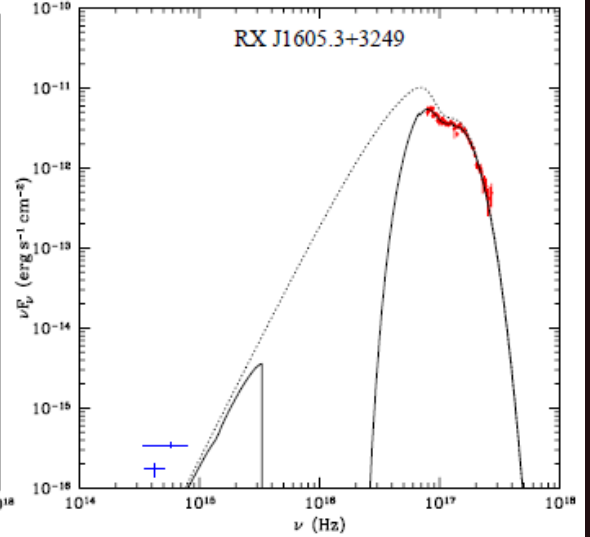
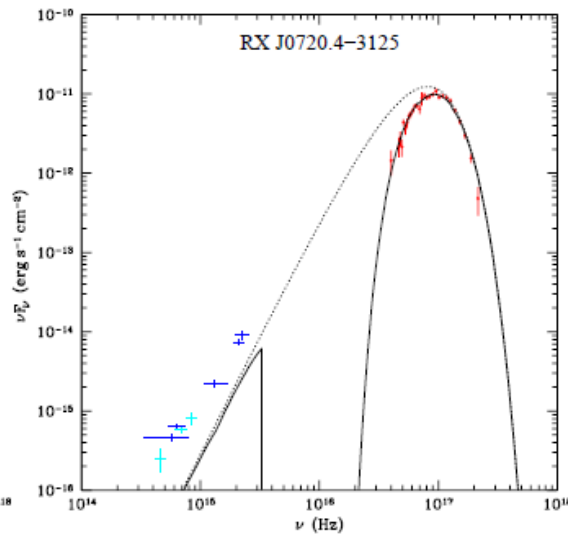
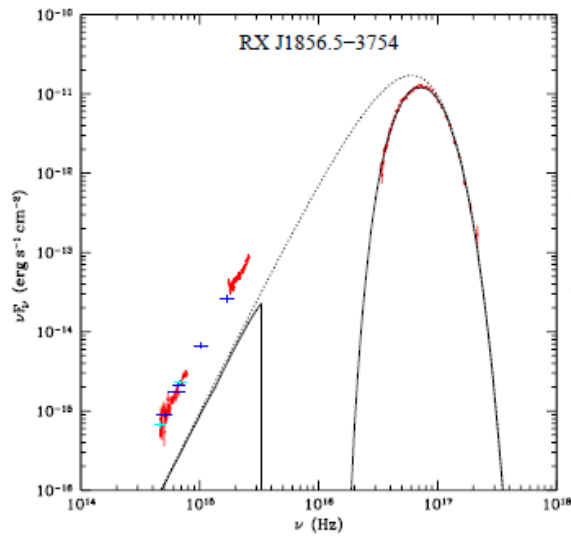
Radio observations

Up to now the M7 are not detected for sure at radio wavelengths, however, there was a paper by Malofeev et al., in which the authors claim that they had detect two of the M7 at very low wavelength ($< \sim 100$ MHz).

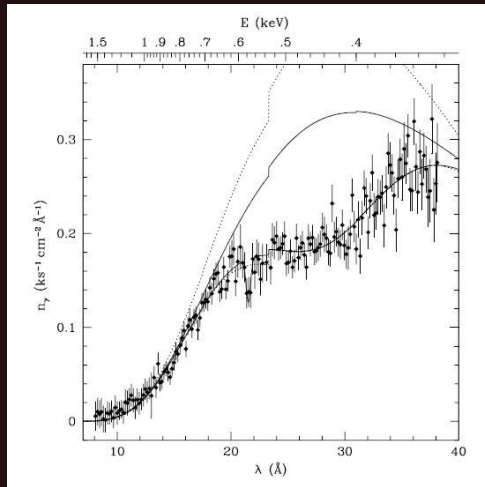
At the moment the most strict limits are given by Kondratiev et al. Non-detection is still consistent with narrow beams.

XDINS	Pulsed emission			Bursty emission		
	S_{lim} (μJy)	$L_{1400}^{\text{p,max}}$ (mJy kpc^2)	$L_{820}^{\text{p,max}}$ (mJy kpc^2)	rate upper limit (hr^{-1})	$S_{\text{lim}}^{\text{sp}}$ (mJy)	$L_{1400}^{\text{b,max}}$ (mJy kpc^2)
RX J0720.4–3125	8	4×10^{-4}	10^{-3}	0.25	21	1
RX J0806.4–4123	10	4×10^{-3}	10^{-2}	0.32	18	6.9
RX J1308.6+2127	10	4×10^{-3}	10^{-2}	0.24	17	6.5
RX J1605.3+3249	8	3×10^{-3}	8×10^{-3}	0.25	22	8.4
RX J1856.5–3754	14	1.4×10^{-4}	3.6×10^{-4}	0.32	24	0.2
RX J2143.0+0654	13	5×10^{-3}	1.3×10^{-2}	0.36	20	7.6

Spectral properties



Kaplan arXiv: 0801.1143



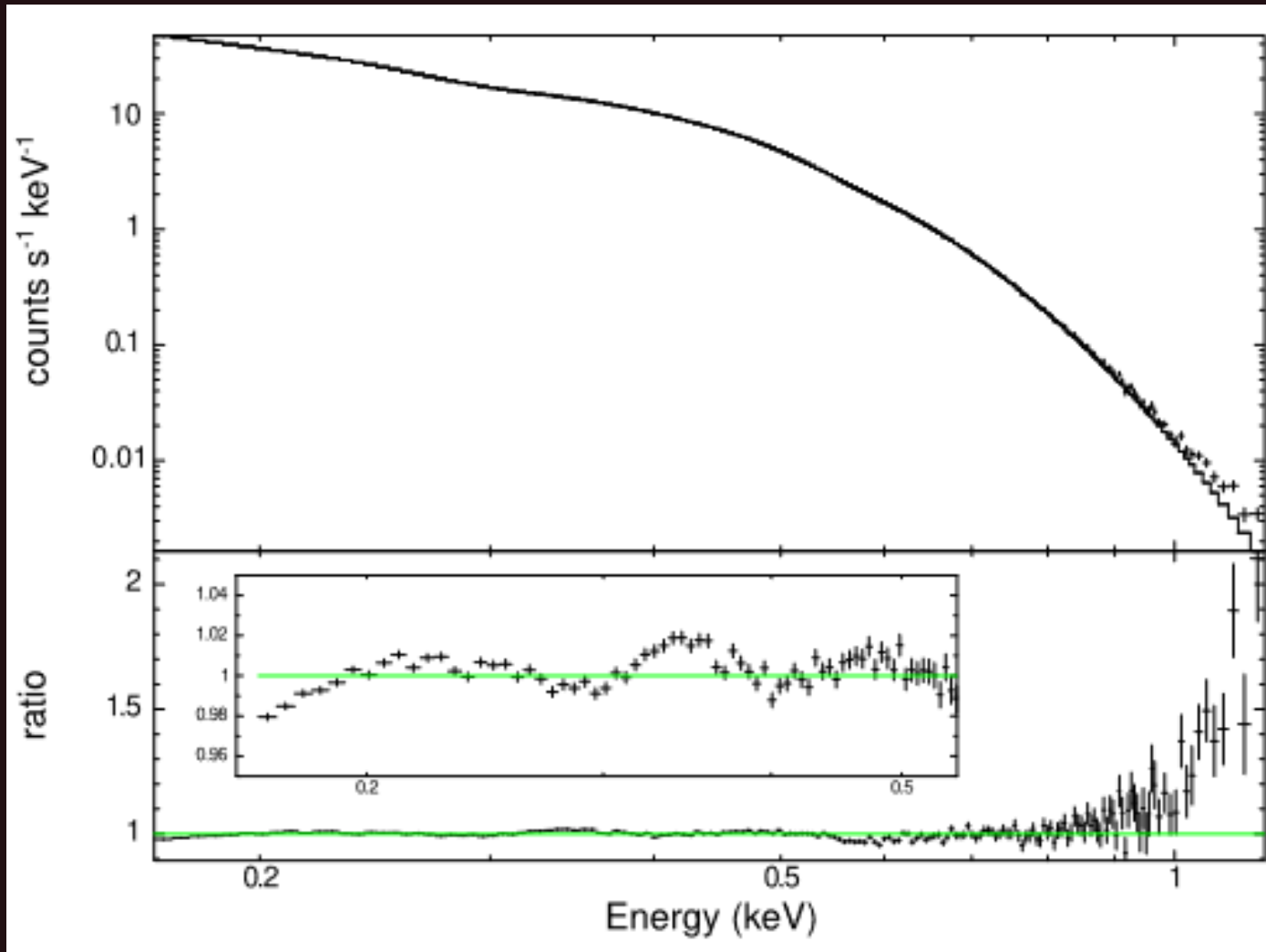
Spectra are blackbody plus one or several wide absorption features.

The origin of features is not understood, yet.

New data: Kaplan et al. 1105.4178

Possible hard X-ray excesses are reported for two out of the M7: 1910.02956.

Hard X-ray excess in RX J1856

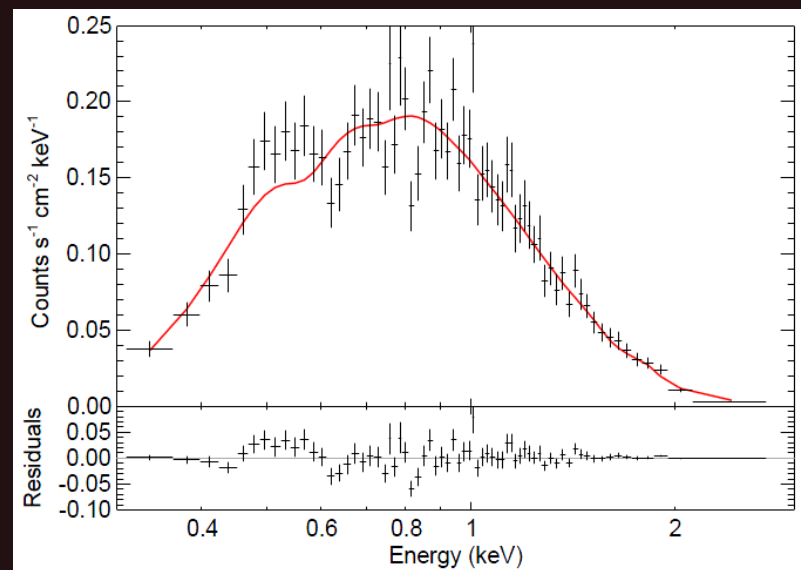


Calvera et al.



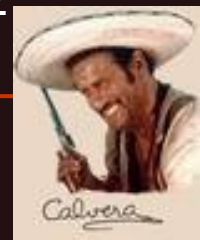
In 2008 Rutledge et al. reported the discovery of an enigmatic NS candidate dubbed *Calvera*. It is high above the galactic plane.

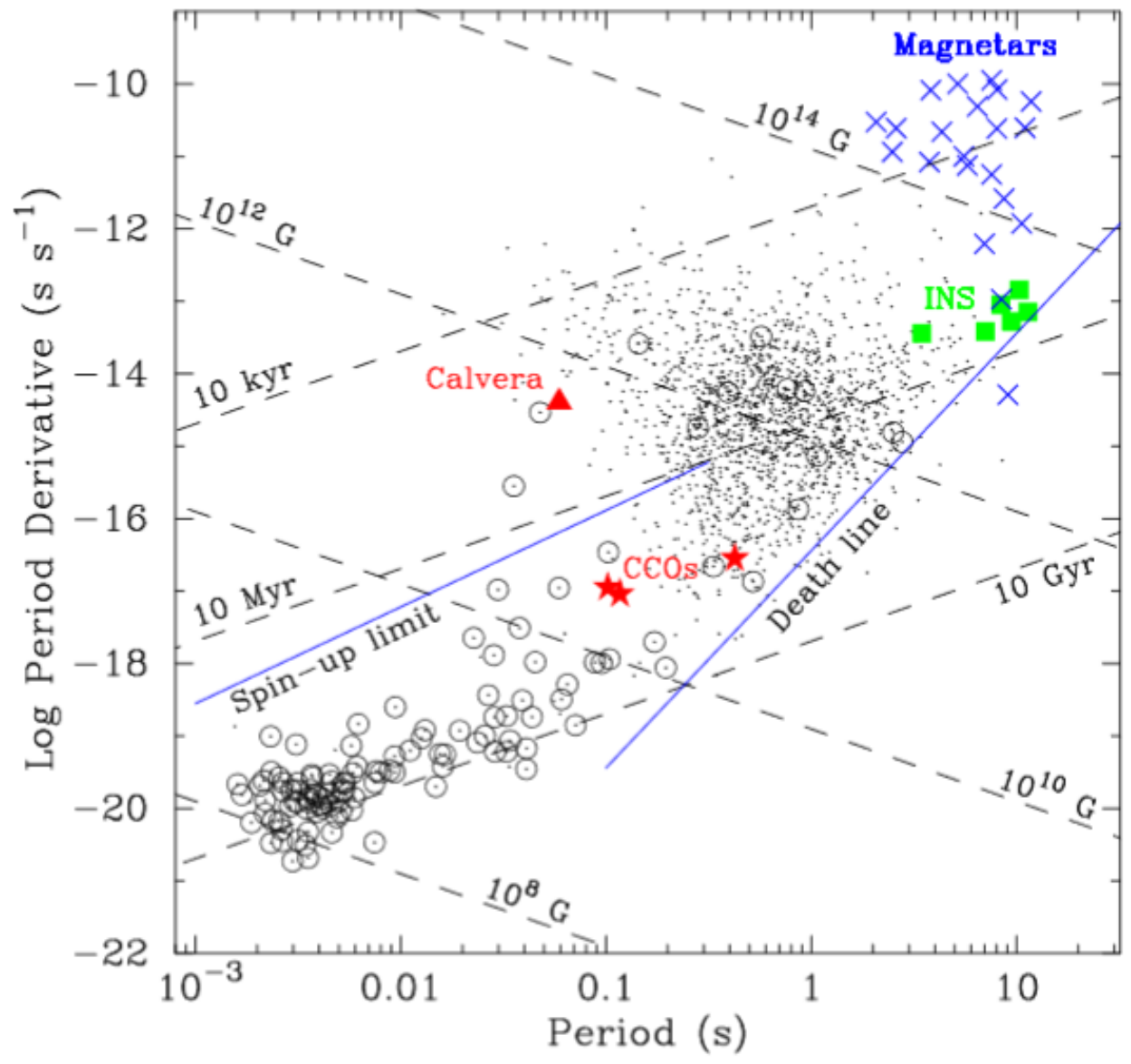
Characteristic	Value
Right Ascension (J2000)	14 ^h 12 ^m 55 ^s .759
Declination (J2000)	+79° 22' 03".41
Uncertainty Ellipse	0.31" (R.A.) × 0.25" (Dec.)
Absorbed Blackbody ^a	
N_{H}	0 (limit)
kT_{eff}	229 eV
$(R_{\text{km}}/D_{10 \text{ kpc}})^2$	26.6
Observed X-ray Flux (0.3–9.5 keV)	$7.1 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$
χ^2_{ν} (ν)	2.04 (67 dof)
NS Hydrogen Atmosphere (NSA) ^b	
N_{H}	$3.1^{+0.9}_{-0.9} \times 10^{20} \text{ cm}^{-2}$
kT_{eff}	109^{+1}_{-1} eV
D_{kpc}^{-2}	$7.71^{+0.41}_{-0.38} \times 10^{-2}$
Observed X-ray Flux (0.3–9.5 keV)	$7.62 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$
χ^2_{ν} (ν)	1.31 (67 dof)



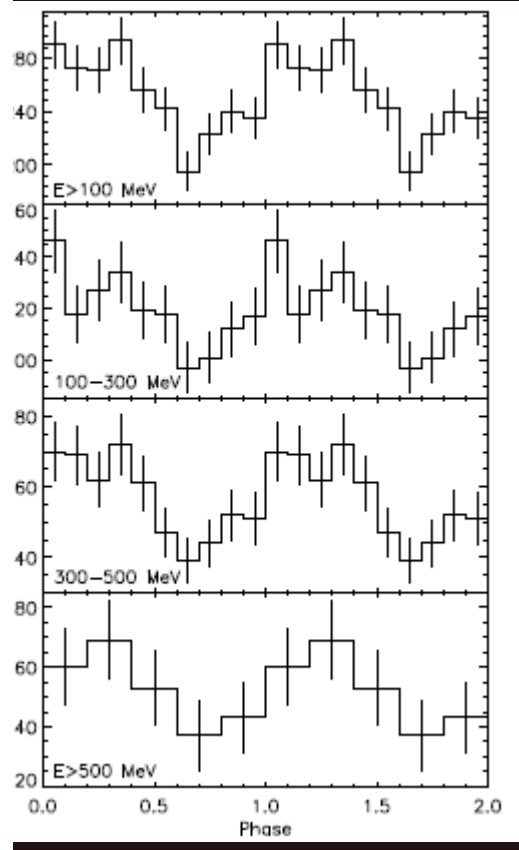
Shevchuk et al. arXiv: 0907.4352

Possible discovery of Calvera's supernova remnant 2207.14141





50 eV and ~80/250 eV)



New data 1510.00683, 1902.00144, 2110.14930

The isolated neutron star candidate 2XMM J104608.7-594306

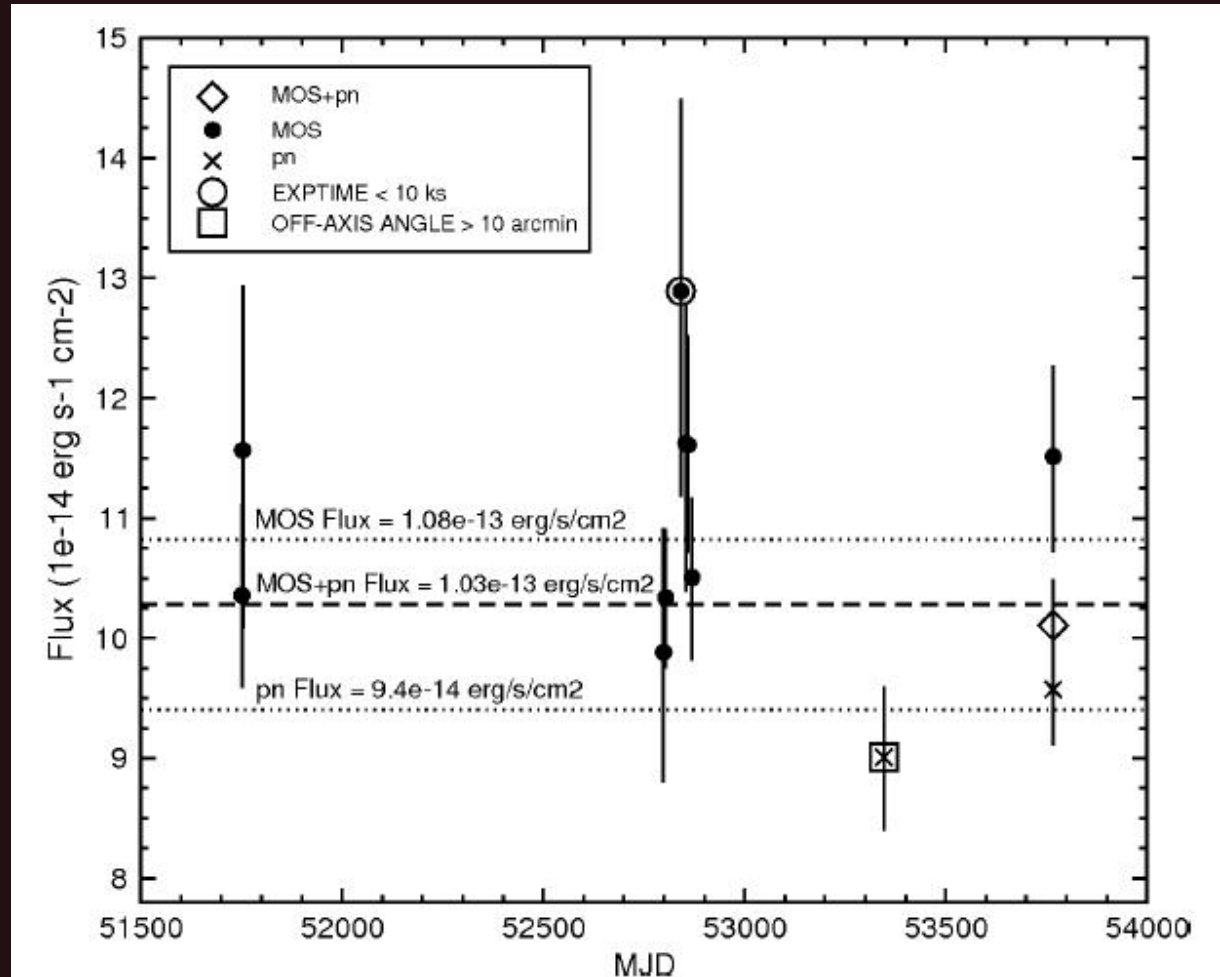
A new INS candidate.

$B > 26$, $V > 25.5$, $R > 25$
(at 2.5σ confidence level)

$\log(F_X/F_V) > 3.1$
 $kT = 118 \pm 15$ eV

unabsorbed X-ray flux:
 $F_X \sim 1.3 \cdot 10^{-12}$ erg s $^{-1}$ cm $^{-2}$
in the 0.1–12 keV band.

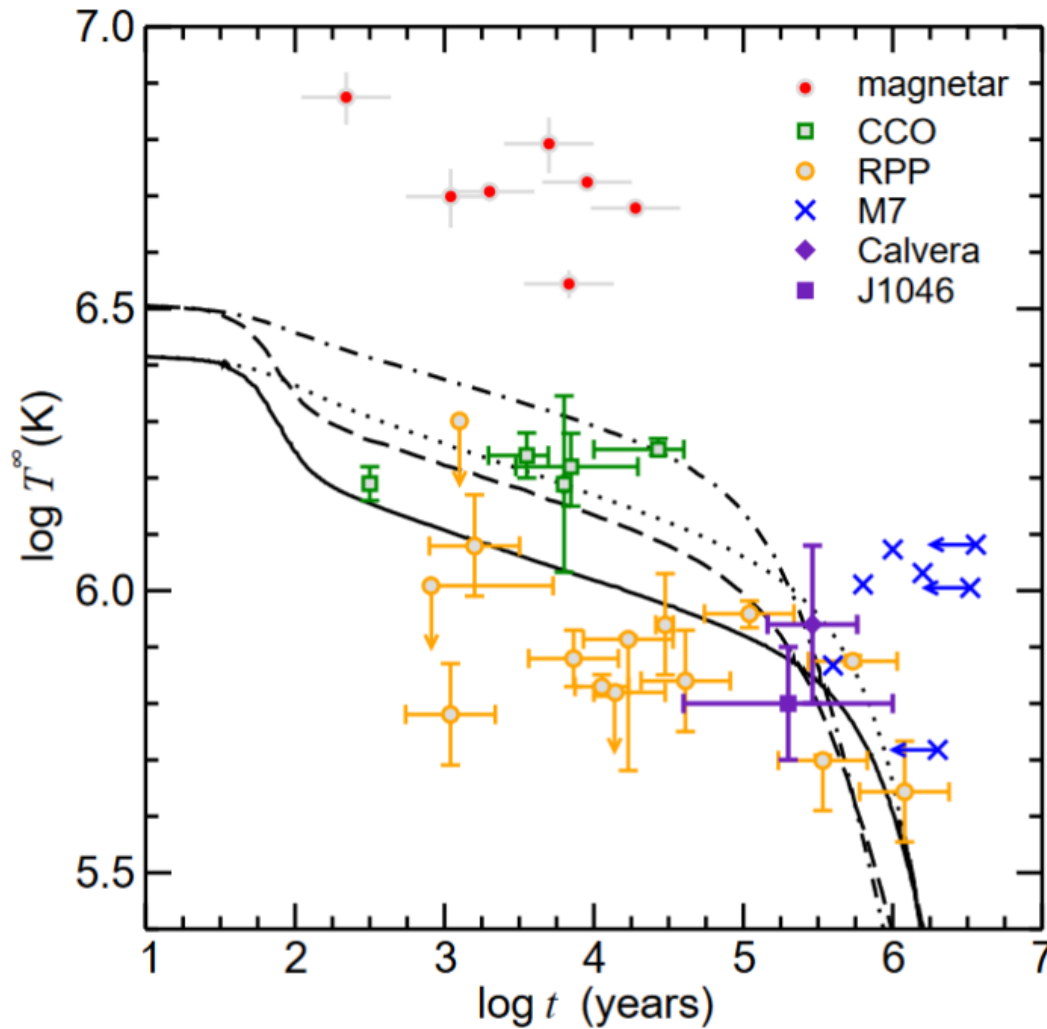
At 2.3 kpc (Eta Carina)
the luminosity is
 $L_X \sim 8.2 \cdot 10^{32}$ erg s $^{-1}$
 $R_\infty \sim 5.7$ km



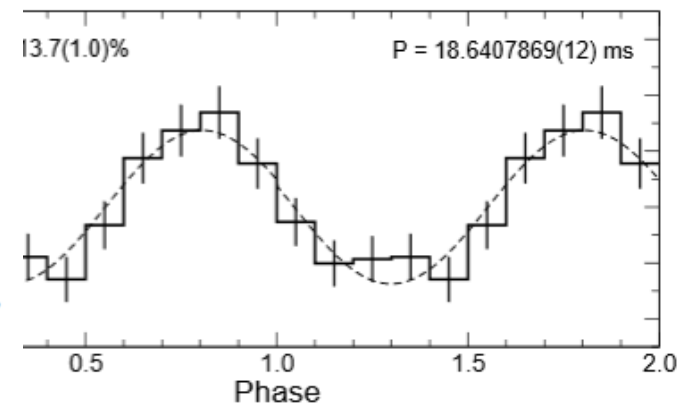
M7-like? Yes! Pires & Motch arXiv: [0710.5192](https://arxiv.org/abs/0710.5192) and Pires et al. arXiv: 0812.4151

But P=19 msec

Spin period of 2XMM J1046-5943



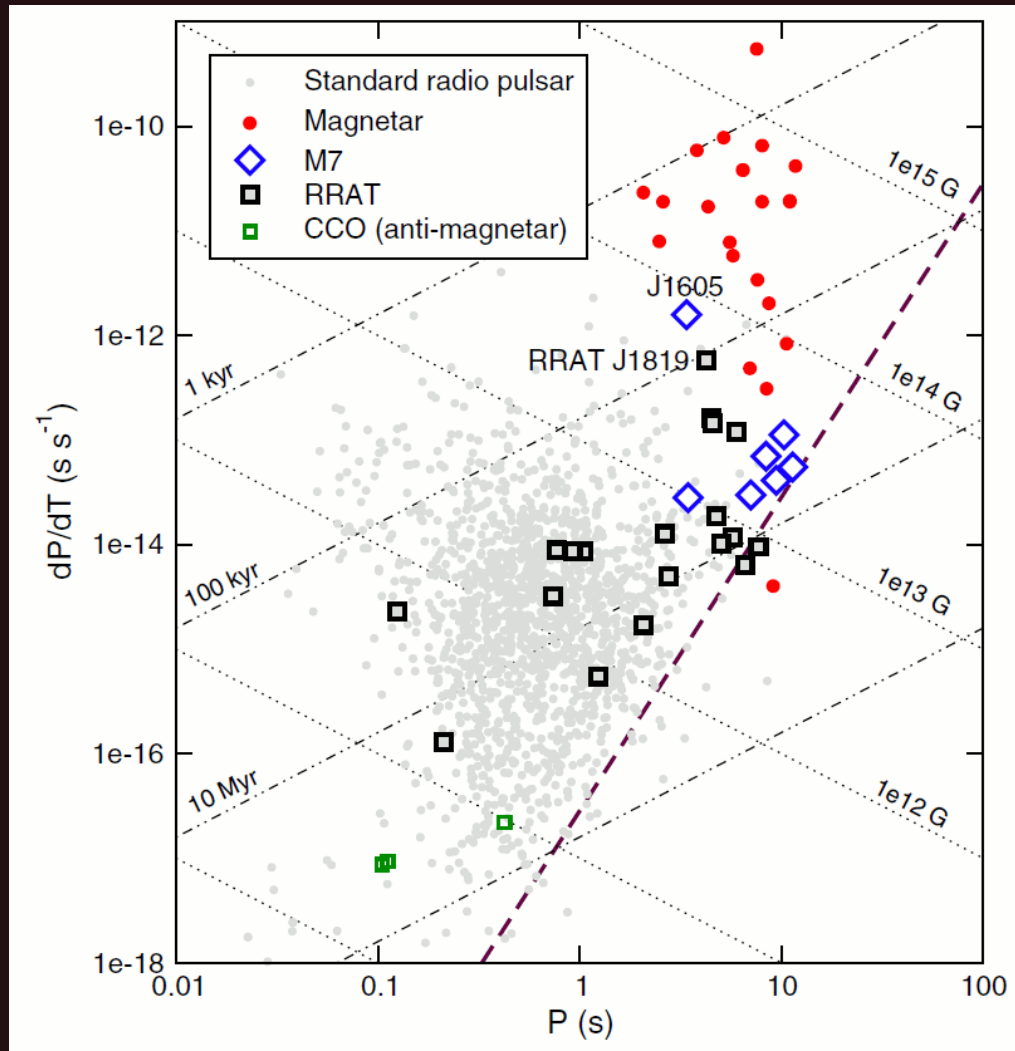
Calvera-like?



$$T_{\text{eff}} = (6 - 10) \times 10^5 \text{ K, and } L_X = (1.1 - 7.4) \times 10^{32} \text{ erg s}^{-1}$$

1508.05246

M7 among other NSs



Evolutionary links of M7 with other NSs are not clear, yet.

M7-like NSs can be numerous.

They can be descendants of magnetars.

Can be related to RRATs.

Or, can be a different population.

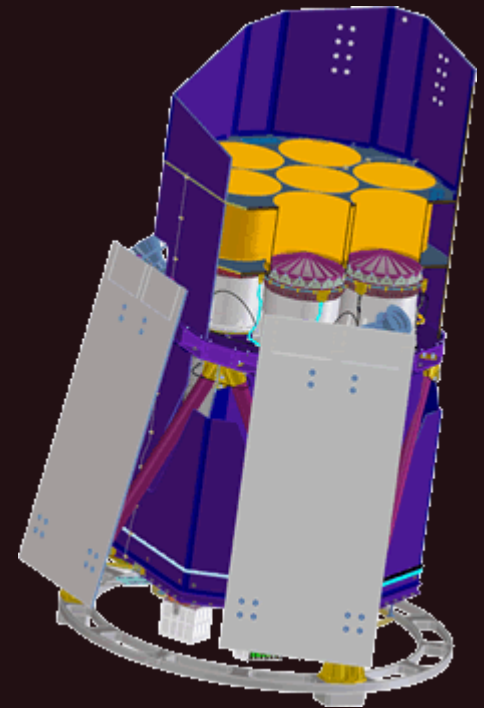
How to find new candidates?

1. Digging the data

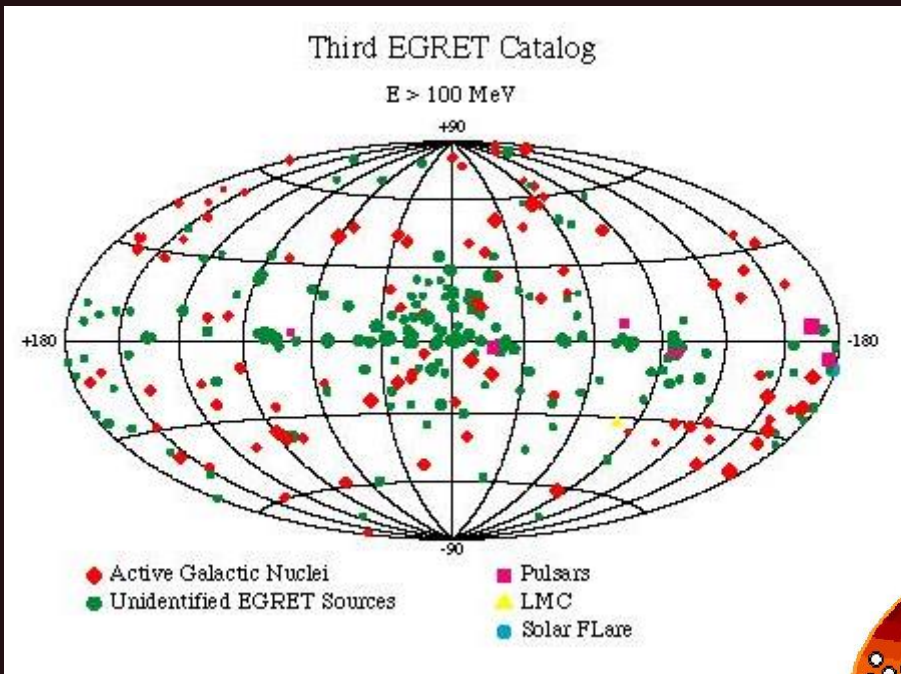
Many attempts failed. One of the latest used SDSS optical data together with ROSAT X-ray. Candidates have been observed by Chandra. Nothing was found (Agueros et al. arXiv: 1103.2132).

2. eROSITA is in orbit!

In 2019 spectrum-RG with eROSITA was launched. It is expected that with this telescope tens of new M7-like NSs can be found (Boldin et al., Pires et al.)

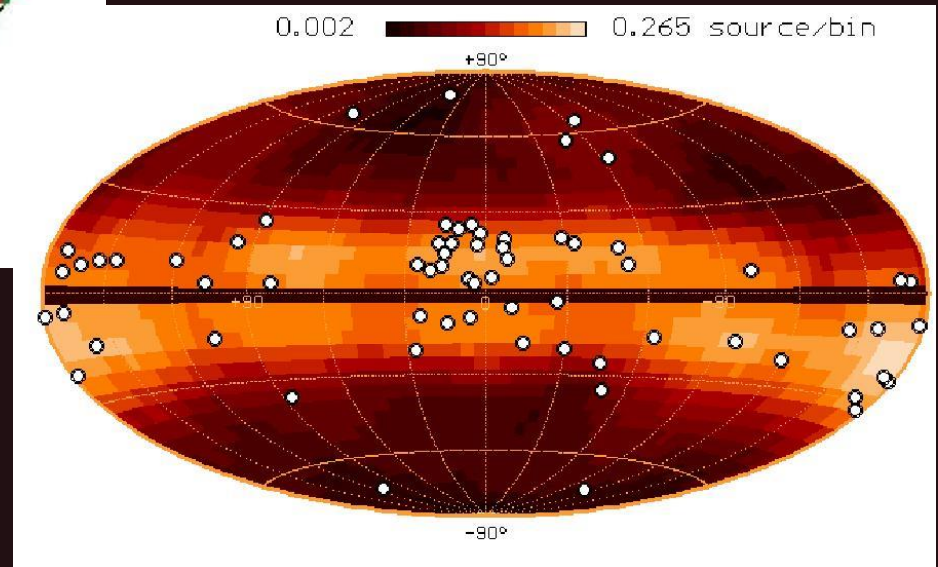


Pulsars invisible in radio?



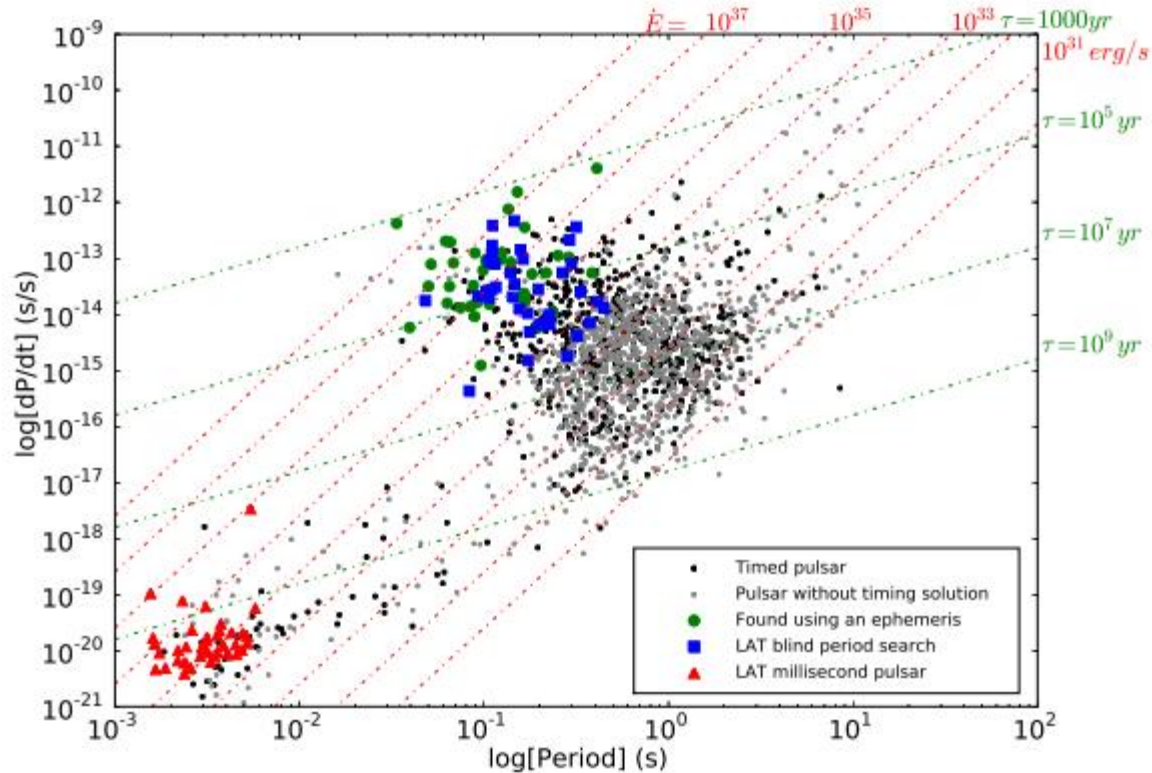
(Nolan et al. astro-ph/9607079)

EGRET data
Many unidentified sources



(Grenier astro-ph/0011298)

Fermi pulsars



In the 2nd catalogue there are 117 pulsars.

1/3 mPSR

The rest are young:

1/3 radio-loud

1/3 radio-quiet

1211.3726

Full 2nd catalogue is presented in 1305.4385

In the 3rd catalogue there are 167 pulsars

https://fermi.gsfc.nasa.gov/ssc/data/access/lat/4yr_catalog/3FGL-table/

Discovery of radio transients



McLaughlin et al. (2006) discovered a new type of sources– RRATs (Rotating Radio Transients).

For most of the sources periods about few seconds were discovered. The result was obtained during the Parkes survey of the Galactic plane.

Burst duration 2-30 ms, interval 4 min-3 hr
Periods in the range 0.4-7 s

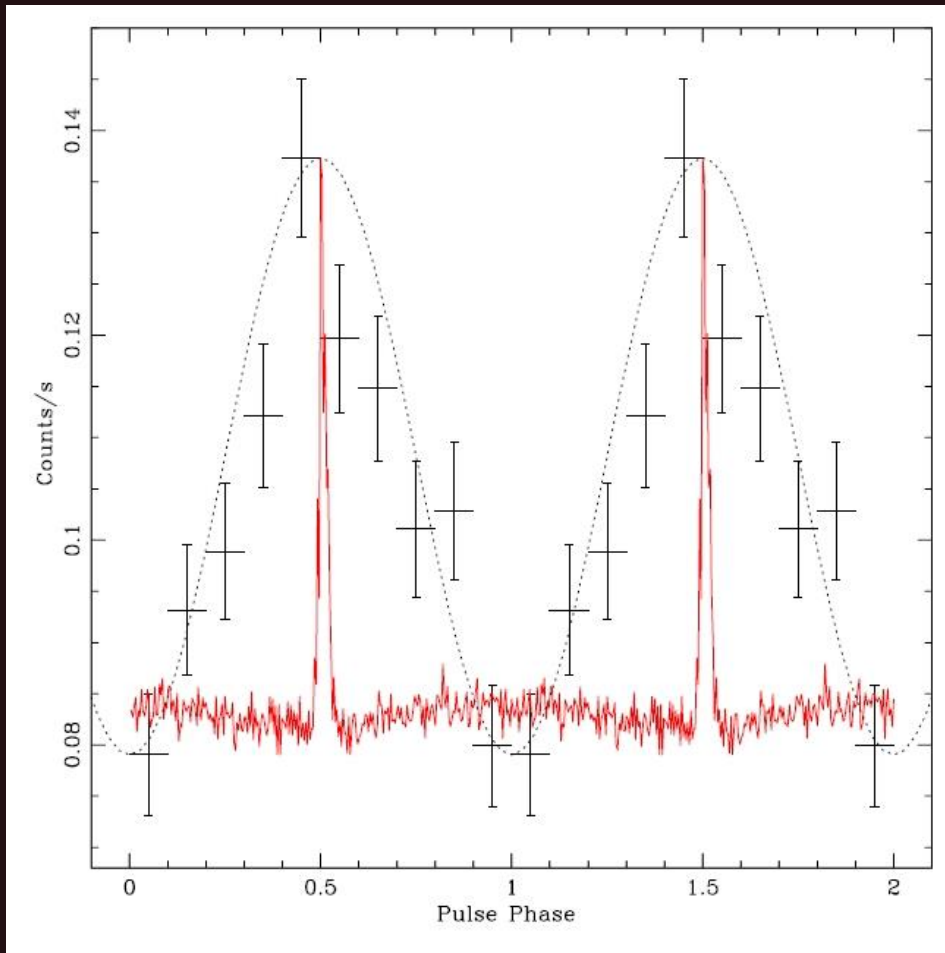
>100 sources known.

Thermal X-rays were observed from one of the RRATs (Reynolds et al. 2006). This one seems to me the youngest.

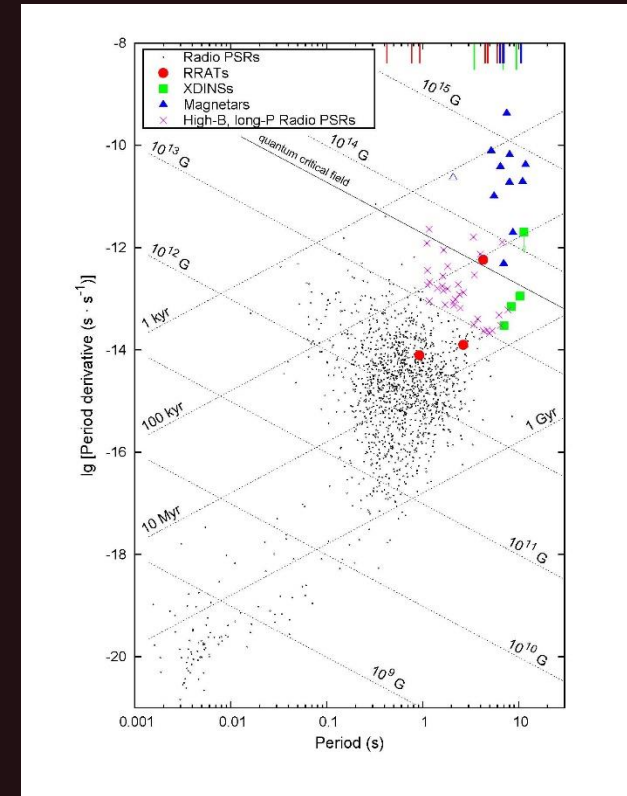
Review: 1109.6896

Catalogue: <http://www.as.wvu.edu/~pulsar/rratalog/>

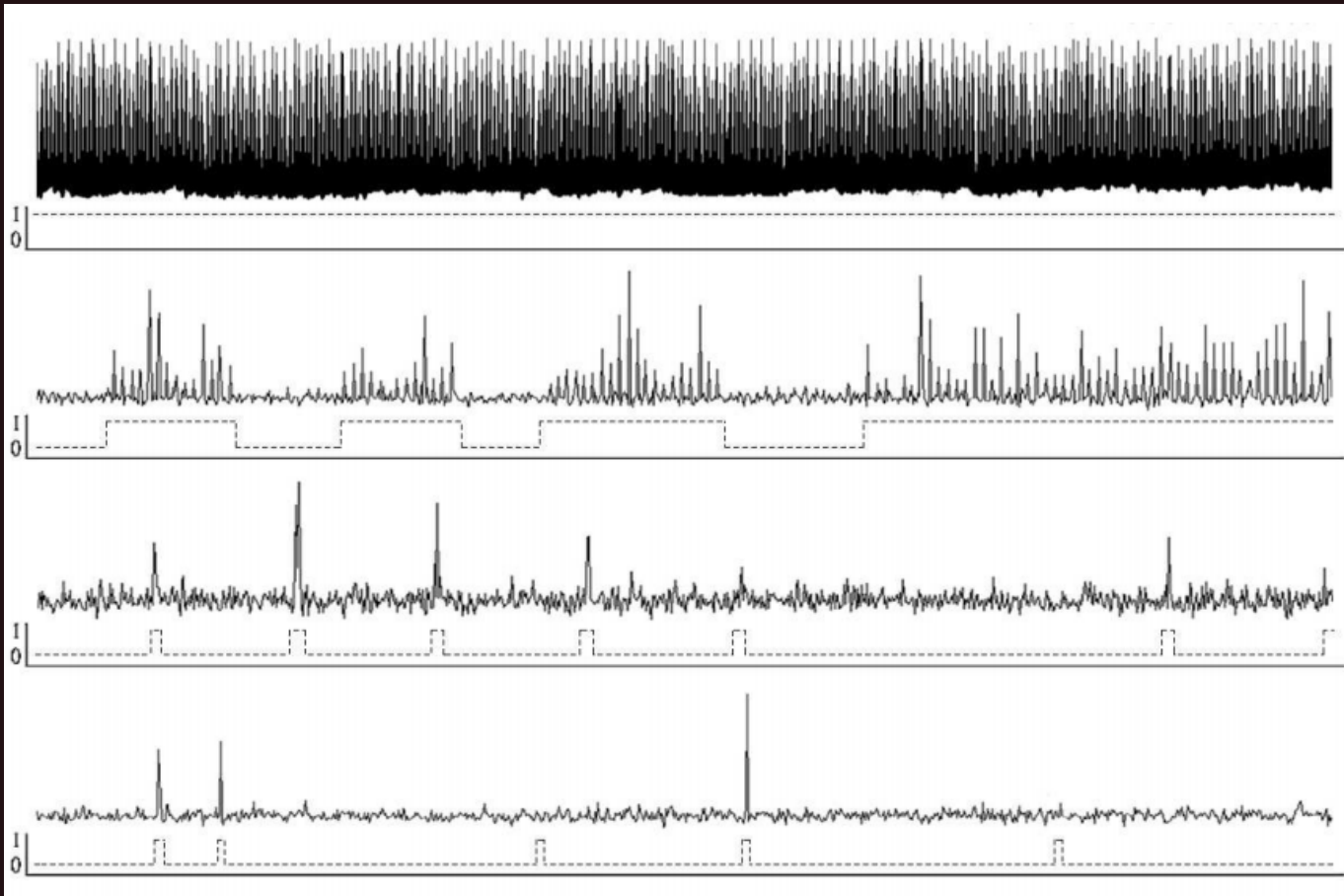
RRATs. X-ray + radio data



X-ray pulses overlaped on radio data of RRAT J1819-1458.



RRAT – are pulsars?



Vela

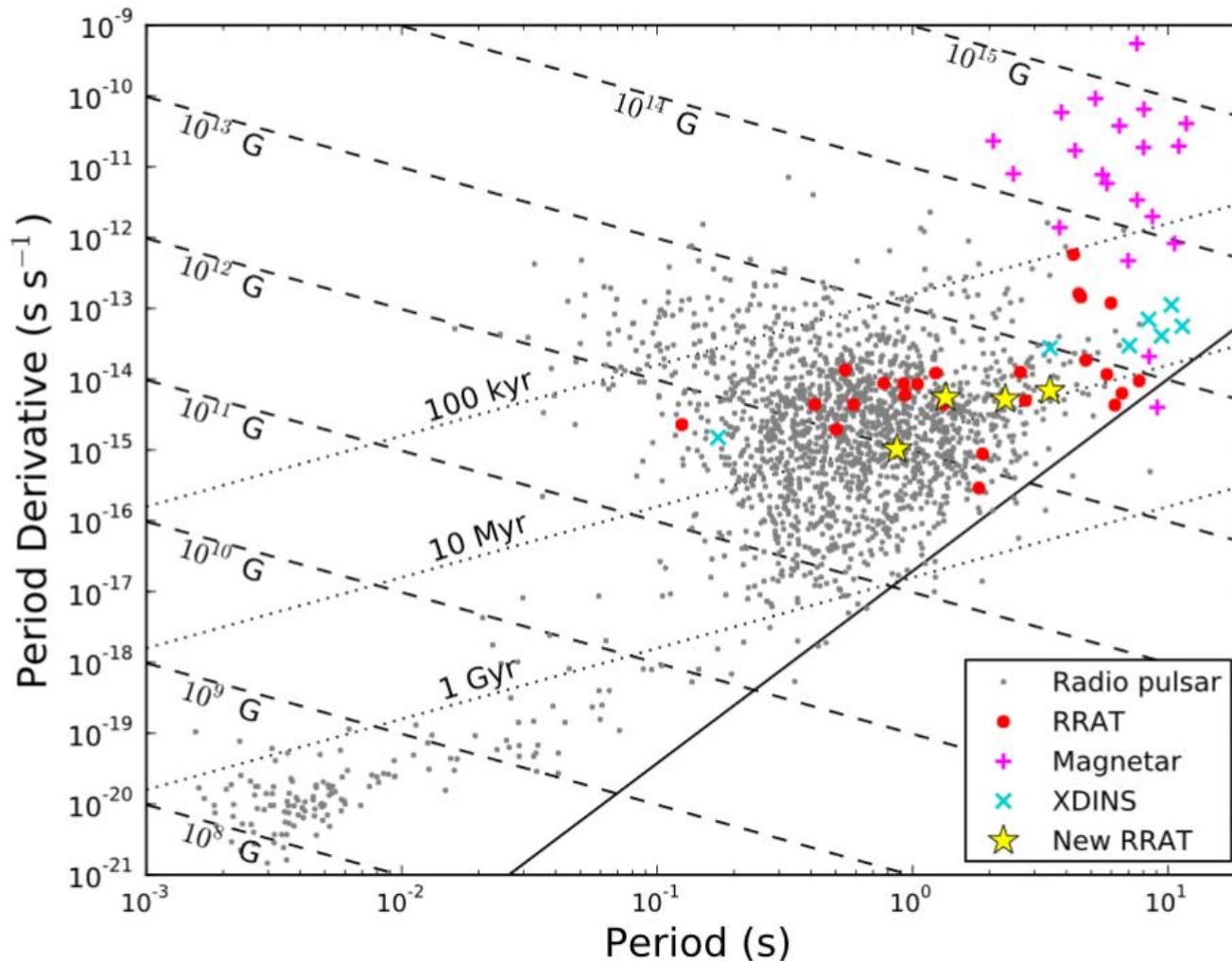
PSR
J1646-6831

J1647-36

J1226-32

It looks like RRATs bursts are just some kind of magnetospheric activity.
Some PSRs have similar bursts.
It is not easy to plot a boarder line between RRATs and PSRs.

RRATs properties



RRATs with P-Pdot seem to be similar to PSRs

About low-frequency detection see 1807.07565.

LIGO search for GW from PSRs

$$h(t) = H_0(H^+(\eta, \psi)A_+(t) + H^\times(\eta, \psi)A_\times(t))e^{2\pi i f_{\text{gw}}(t)t + i\phi_0}$$

$$H_0 = h_0 \sqrt{\frac{1 + 6 \cos^2 \iota + \cos^4 \iota}{4}}$$

$$h_0 = \frac{1}{d} \frac{4\pi^2 G}{c^4} I_{zz} f_{\text{gw}}^2 \epsilon.$$

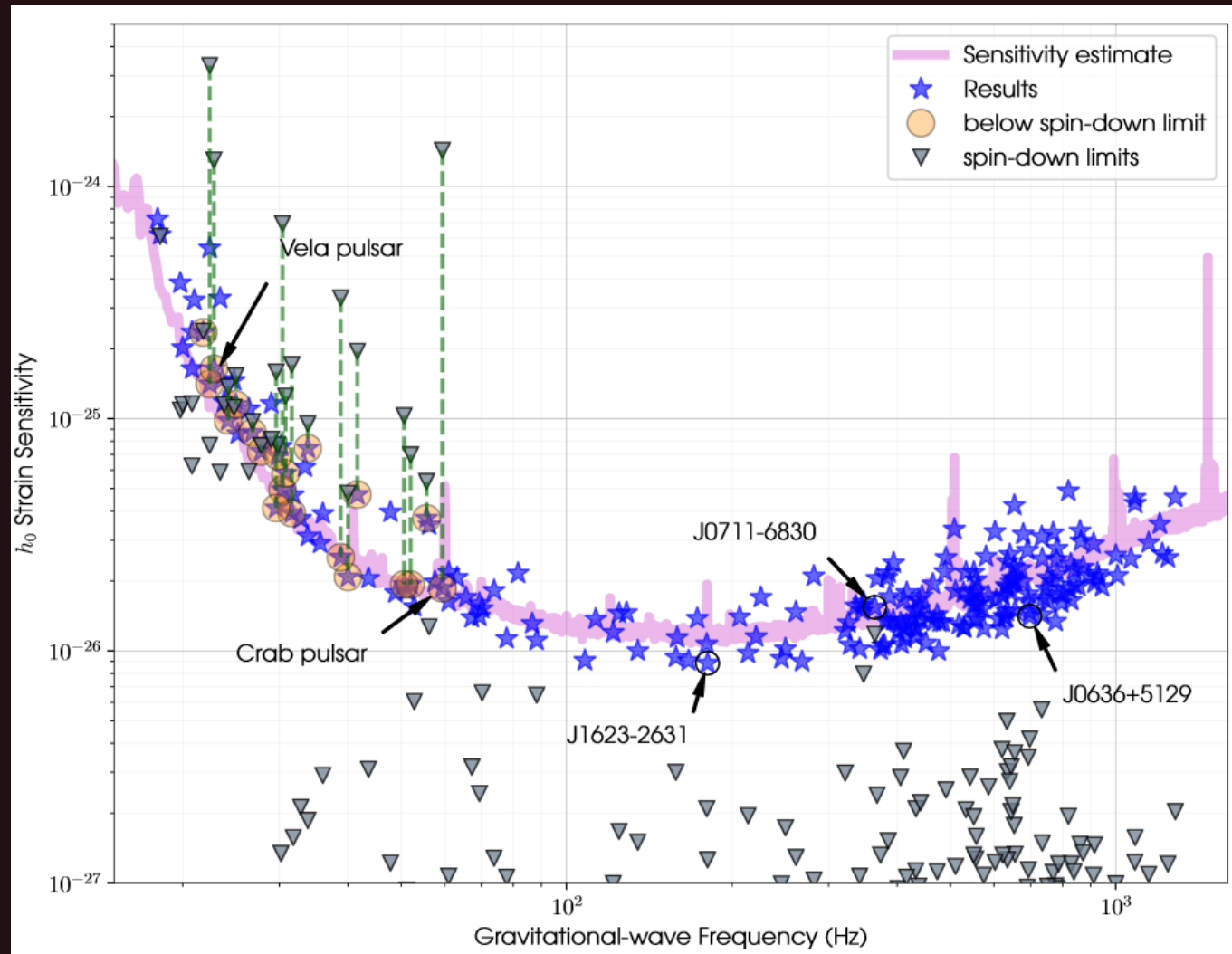
The ellipticity measures the degree of asymmetry of the star with respect to its rotation axis.

$$h_{\text{sd}} = 8.06 \times 10^{-19} I_{38}^{1/2} \left[\frac{1 \text{ kpc}}{d} \right] \left[\frac{\dot{f}_{\text{rot}}}{\text{Hz/s}} \right]^{1/2} \left[\frac{\text{Hz}}{f_{\text{rot}}} \right]^{1/2}$$

$$\epsilon_{\text{sd}} = 1.91 \times 10^5 I_{38}^{-1/2} \left[\frac{\dot{f}_{\text{rot}}}{\text{Hz/s}} \right]^{1/2} \left[\frac{\text{Hz}}{f_{\text{rot}}} \right]^{5/2}$$

LIGO search for GW from PSRs

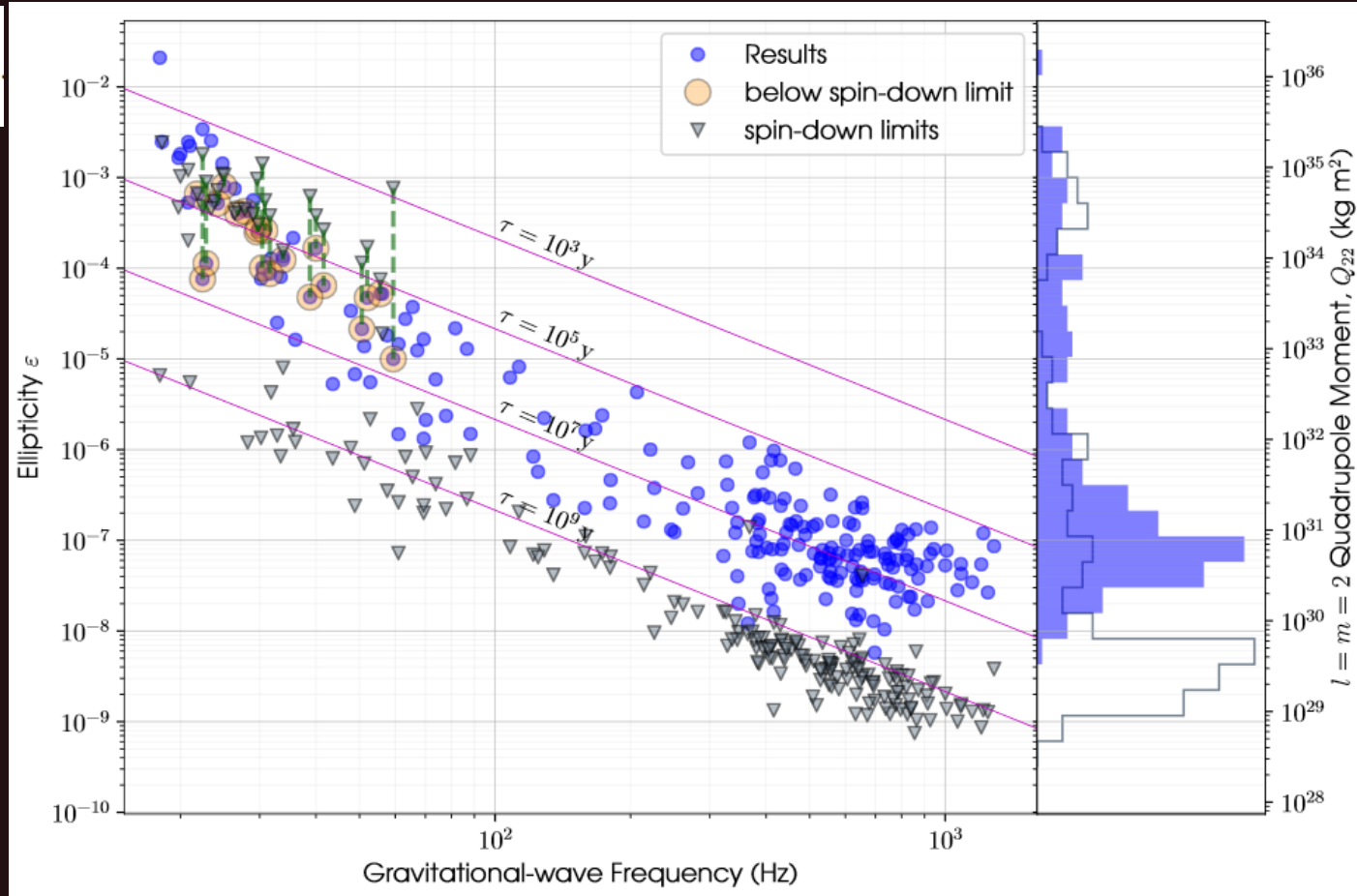
221 PSRs
data from 2015-2017



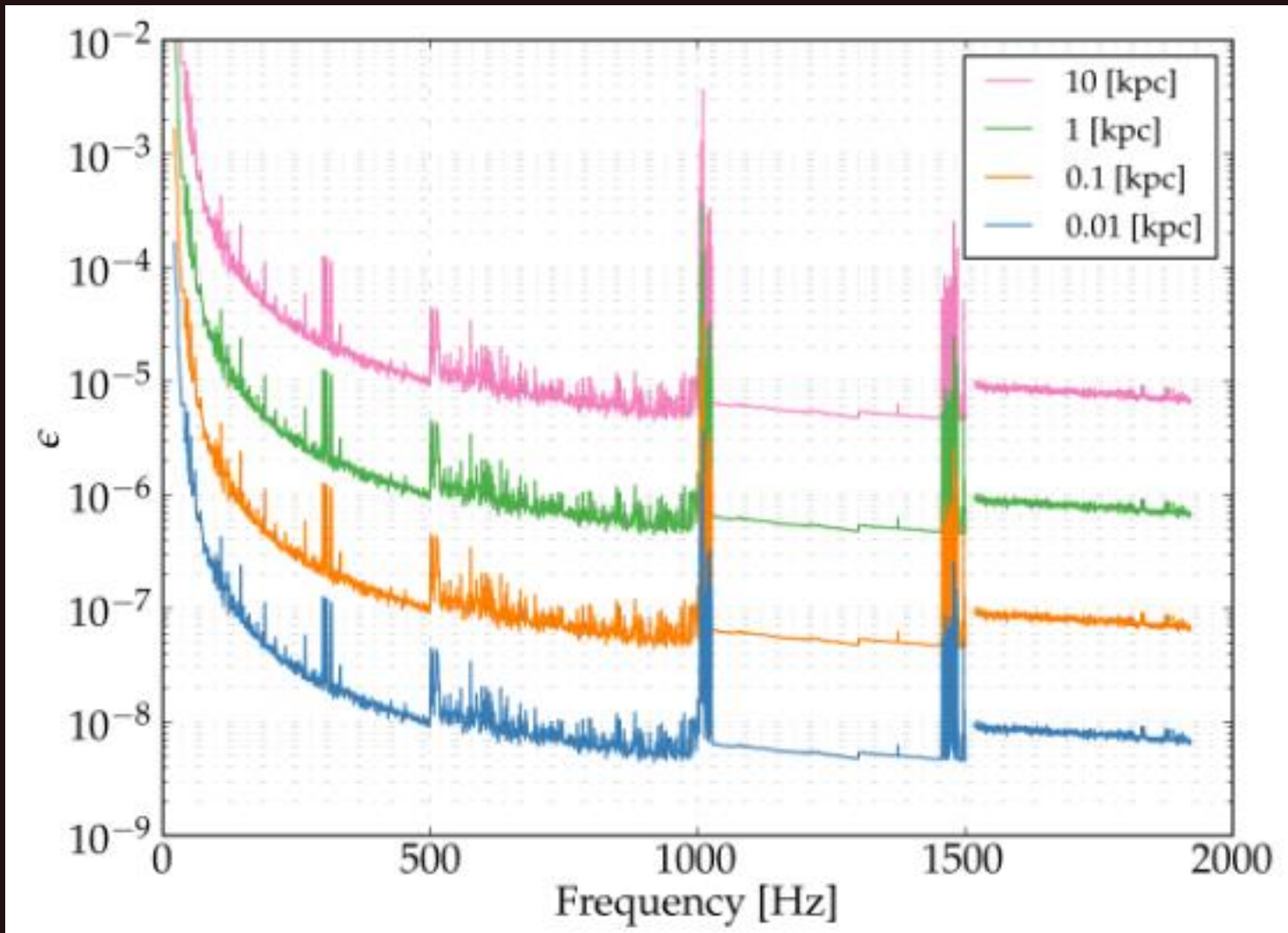
Limits on ellipticity

$$\varepsilon = \frac{Q_{22}}{I_{zz}} \sqrt{\frac{8\pi}{15}}$$

$$Q_{22} = h_0 \left(\frac{c^4 d}{16\pi^2 G f_{\text{rot}}^2} \right) \sqrt{\frac{15}{8\pi}}$$

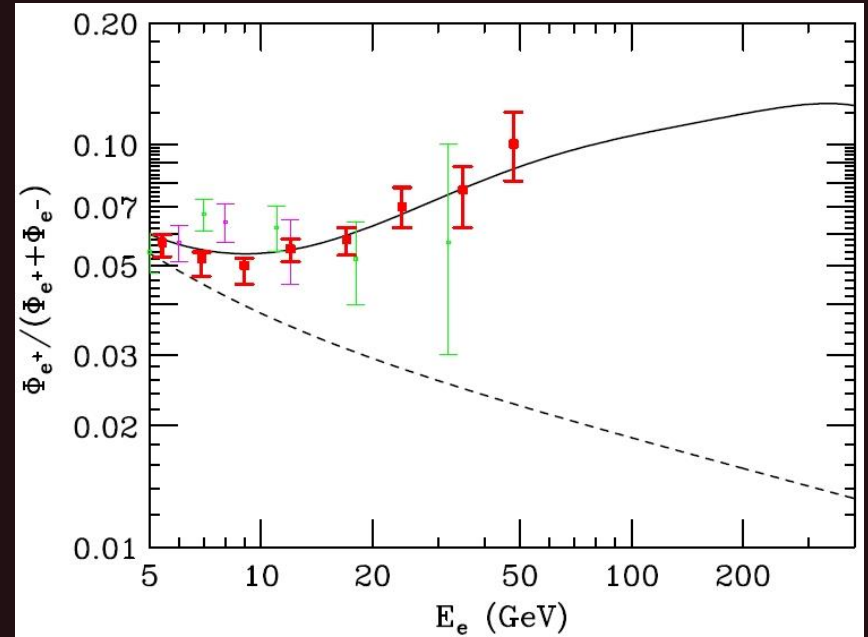
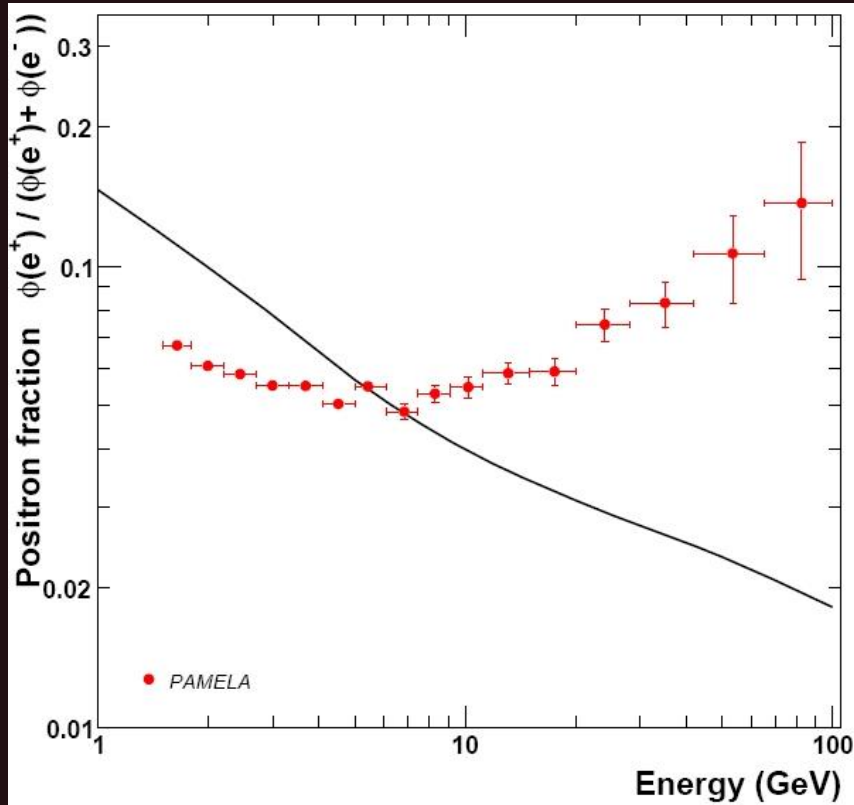


Blind search for GWs from NSs



1903.01901, new results in 2107.00600 and [2201.00697](#)

Pulsars, positrons, PAMELA

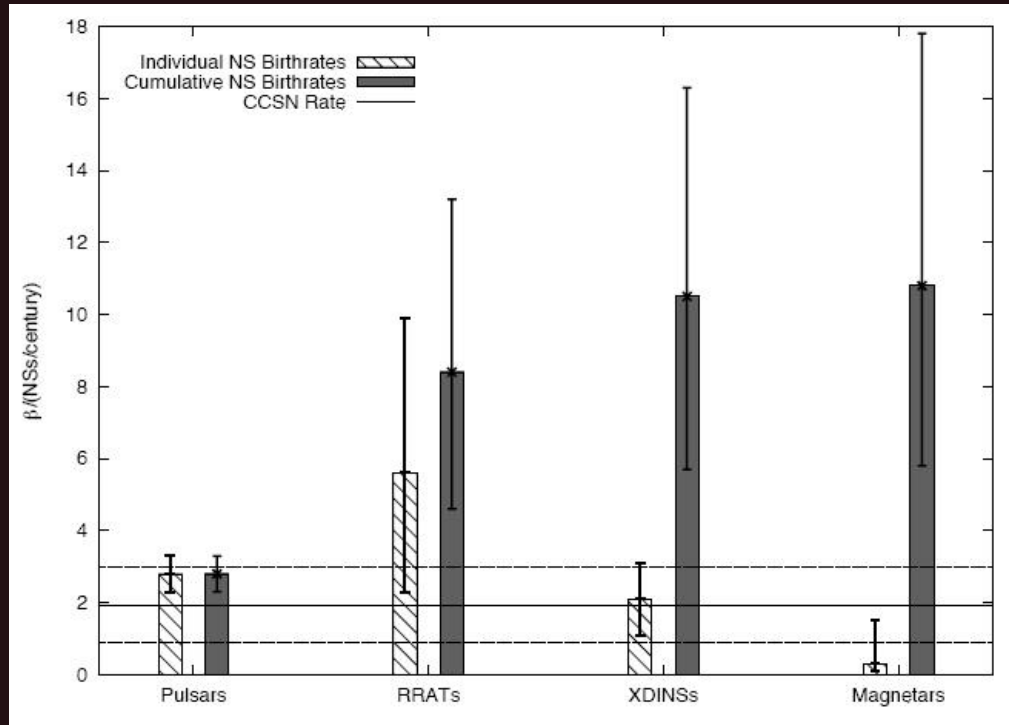
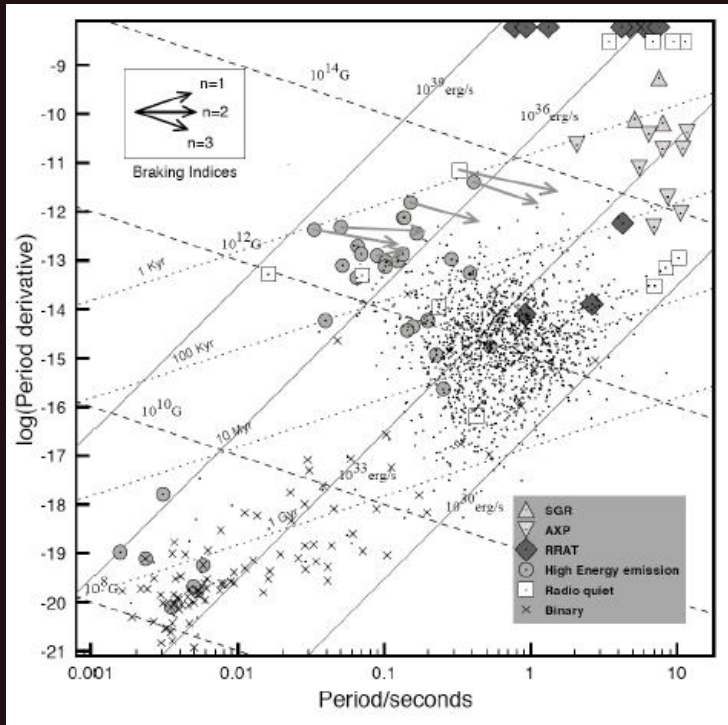


Geminga, PSR B0656+14, and all PSRs

[O. Adriani et al.] [arXiv:0810.4995](https://arxiv.org/abs/0810.4995)

[Dan Hooper et al. 2008
[arXiv: 0810.1527](https://arxiv.org/abs/0810.1527)]

NS birth rate



Too many NSs???

β_{PSR}, n_e	PSRs	RRATs	XDINSs	Magnetars	Total	CCSN rate
FK06, NE2001	2.8 ± 0.5	$5.6^{+4.3}_{-3.3}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$10.8^{+7.0}_{-5.0}$	1.9 ± 1.1
L+06, NE2001	1.4 ± 0.2	$2.8^{+1.6}_{-1.6}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$6.6^{+4.0}_{-3.0}$	1.9 ± 1.1
L+06, TC93	1.1 ± 0.2	$2.2^{+1.7}_{-1.3}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$5.7^{+4.1}_{-2.7}$	1.9 ± 1.1
V+04, NE2001	1.6 ± 0.3	$3.2^{+2.5}_{-1.9}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$7.2^{+5.0}_{-3.4}$	1.9 ± 1.1
V+04, TC93	1.1 ± 0.2	$2.2^{+1.7}_{-1.3}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$5.7^{+4.1}_{-2.7}$	1.9 ± 1.1

It seems, that the total birth rate is larger than the rate of CCSN.
 e^- - capture SN cannot save the situation, as they are $< \sim 20\%$.

Note, that the authors do not include CCOs.

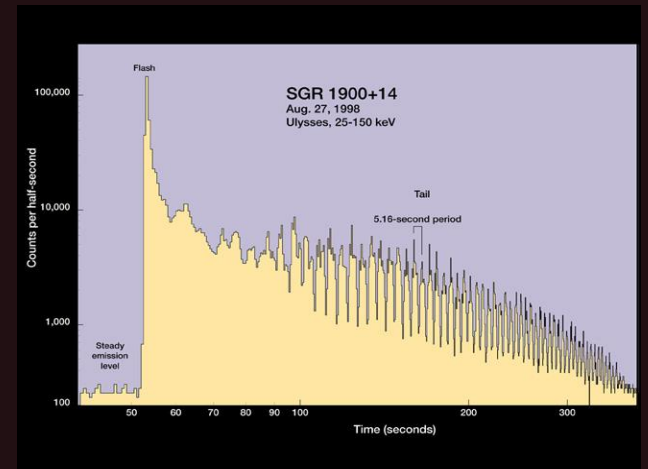
So, some estimates are wrong, or some sources evolve into others.

See also [astro-ph/0603258](https://arxiv.org/abs/astro-ph/0603258).

GRAND UNIFICATION: 1005.0876

Conclusion

- There are several types of sources: CCOs, M7, SGRs, AXPs, RRATs ...
- Magnetars
- Significant fraction of all newborn NSs are not similar to the Crab pulsar
- Unsolved problems:
 1. Are there links?
 2. Reasons for diversity



Some reviews on isolated neutron stars

- NS basics: [physics/0503245](#)
[astro-ph/0405262](#)
[1507.06186](#)
- Thermal emission [1507.02924](#)
- Magnetars: [arXiv: 1101.4472](#)
- Magnetar bursts: [astro-ph/0311526](#)
[arxiv:0712.2209](#)
- CCOs: [arxiv:0809.4228](#)
- Quark stars: [astro-ph/0609066](#)
[arxiv:0801.1143](#)
- The Magnificent Seven: [arXiv:1008.3693](#)
- RRATs: [astro-ph/0402143](#)
- Cooling of NSs: [arXiv:0705.2708](#)
- NS structure [arXiv: 1001.3294](#)
[1512.07820](#)
- EoS [1403.0074](#)
- NS atmospheres [arxiv:0711.3650](#)
- NS magnetic fields [arXiv:1005.0876](#)
[arXiv:1302.0869](#)
- Different types [arXiv: 1712.06040](#)
[1602.07738](#)
- Radio pulsars
- Internal structure and astrophysics [1603.02698](#)
- SN and compact remnants [1806.07267](#)

Lectures can be found
at my homepage:

[http://xray.sai.msu.ru/~polar/
html/presentations.html](http://xray.sai.msu.ru/~polar/html/presentations.html)

Read the OVERVIEW in the book by Haensel, Yakovlev, Potekhin