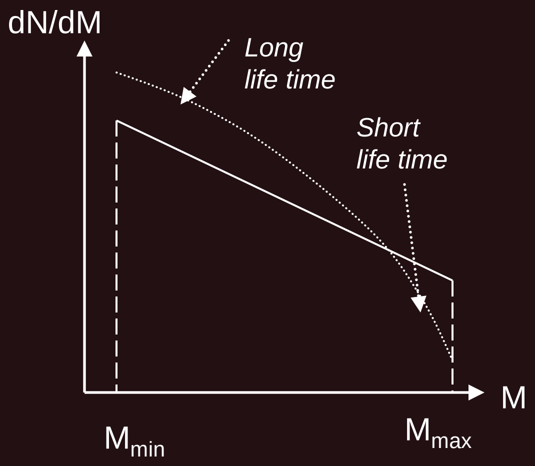
Isolated Neutron Stars. Intro.

Stars in the Galaxy

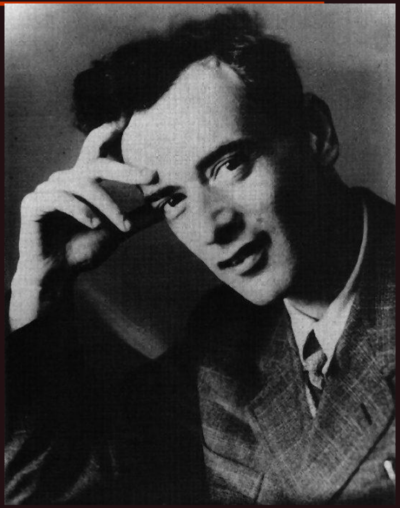


Salpeter (1955) mass function:
dN/dM ~ $M^{-2.35}$

There are many modification (Miller-Scalo, Kroupa etc.).
At high masses the slope is usually steeper.
Note: it is *initial* mass function, not the present day!

It is possible to estimate the number of NS and BH progenitors.
Then using there average lifetime we can estimate the birth rate
and total numbers (with a given age of the Galaxy and assuming constant rate)
taking into account SFR~(3-5) solar mass per year.
[see also Ch.1 in Shapiro, Teukolsky]

Prediction ...



(Landau)

Neutron stars have been predicted in 30s:

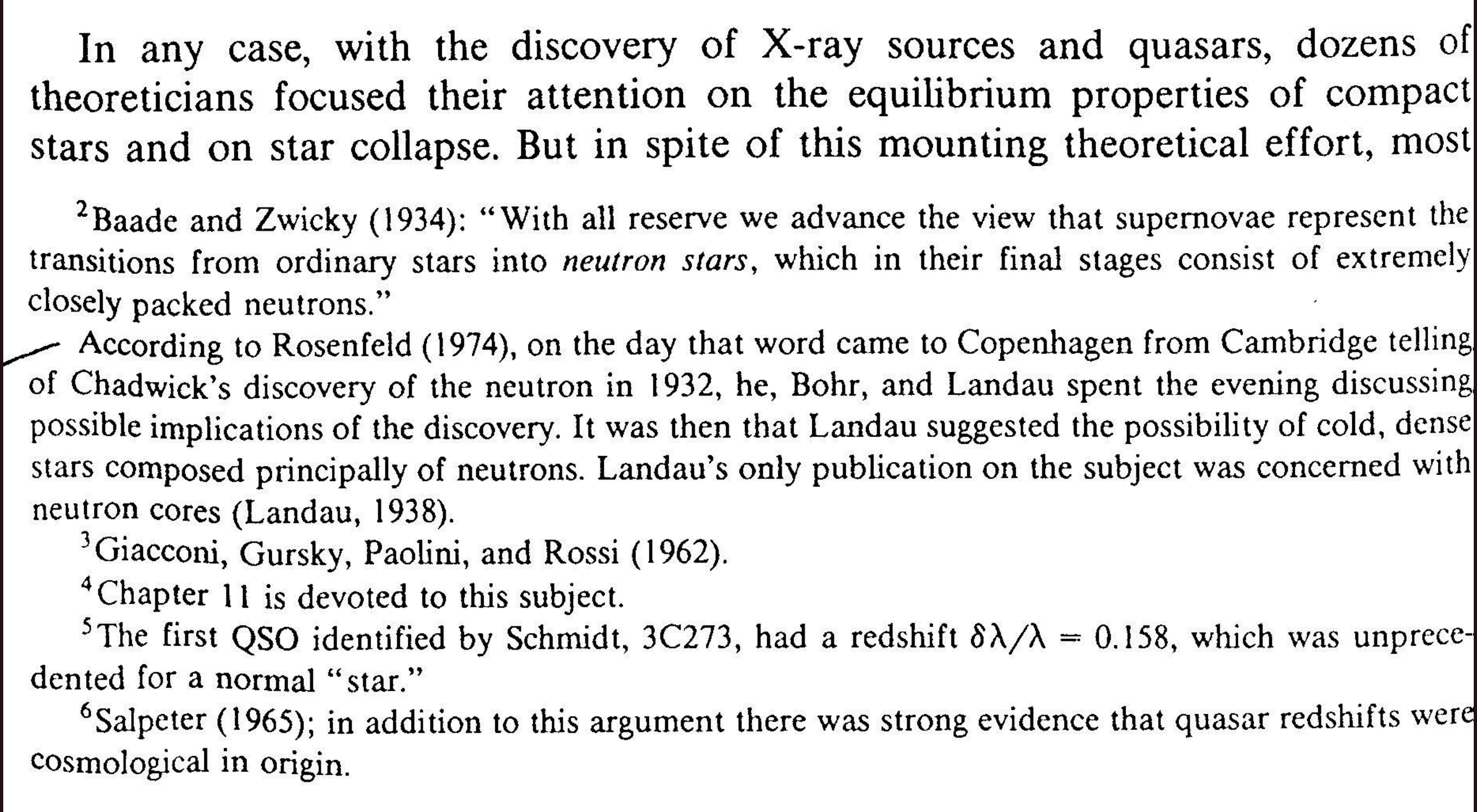
L.D. Landau: Star-nuclei (1932) + anecdote

Baade and Zwicky:
neutron stars and supernovae (1934)

(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

[2] Baade 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).

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

[4] Chapter 11 is devoted to this subject.

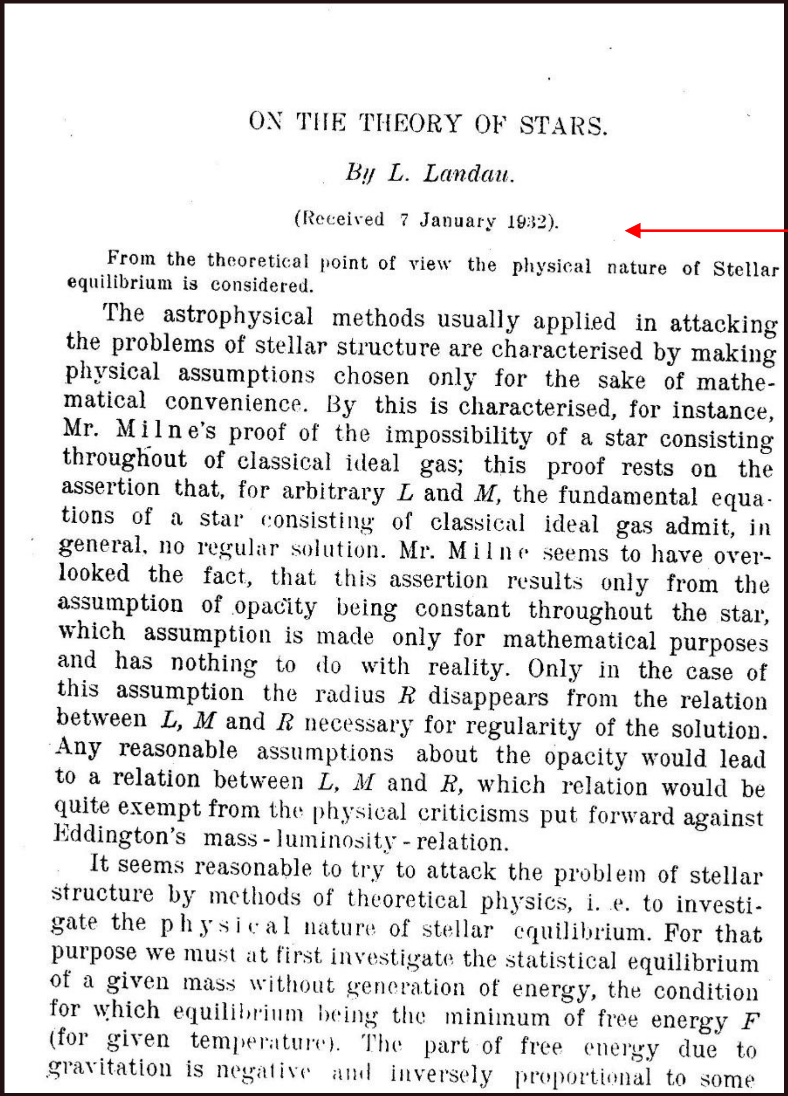
[5] The first QSO identified by Schmidt, 3C273, had a redshift $\delta\lambda/\lambda = 0.158$, which was unprecedented for a normal "star."

[6] Salpeter (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

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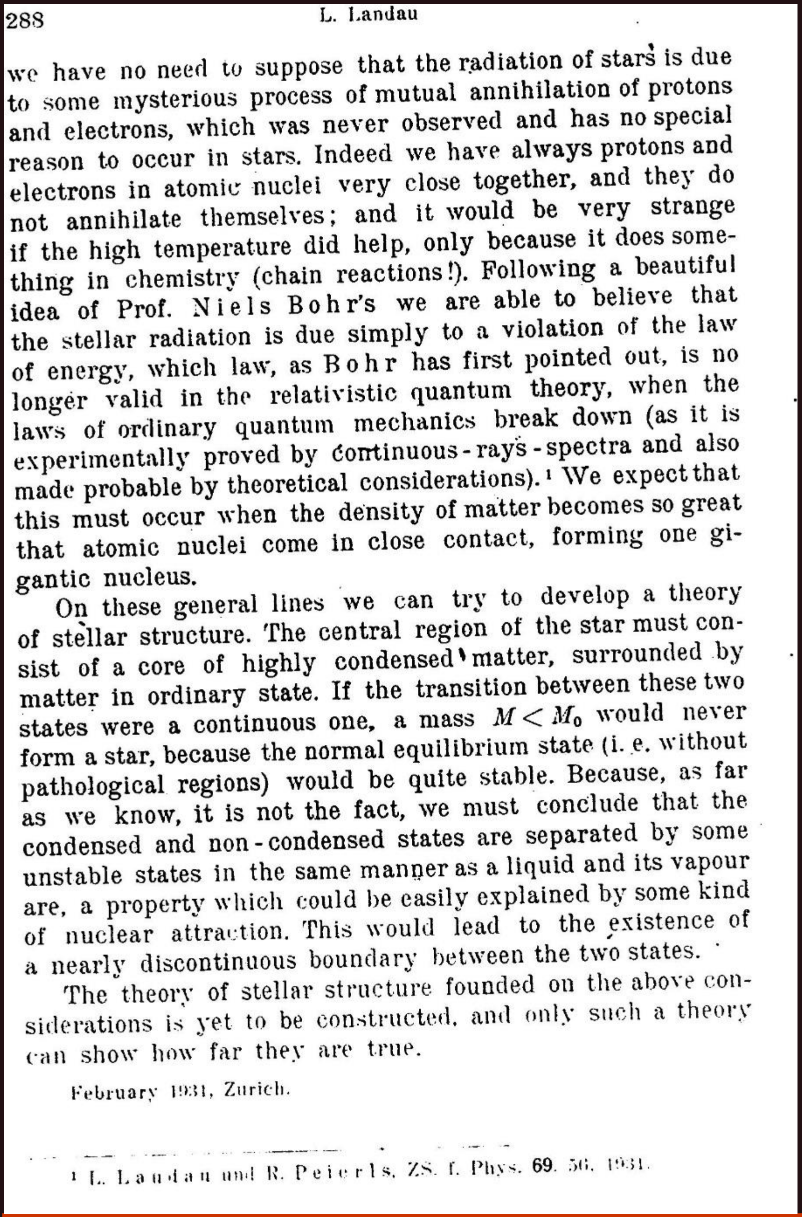
Vol. 1, No. 2, 285-188, 1932
Written: Feb. 1931, Zurich
Received: Jan. 7, 1932
Published: Feb. 1932



288 L. Landau

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.

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

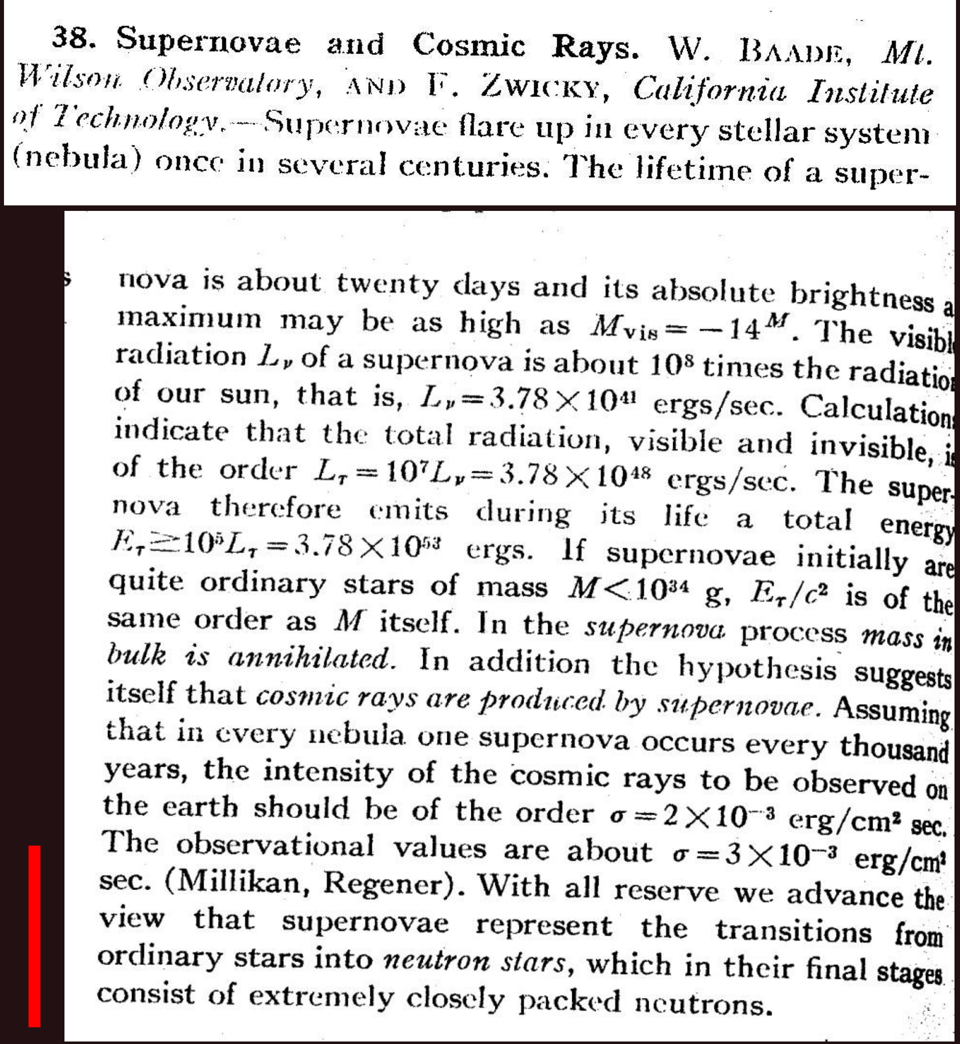
This is correct!

Disappered in reprints,
so we have difficulties

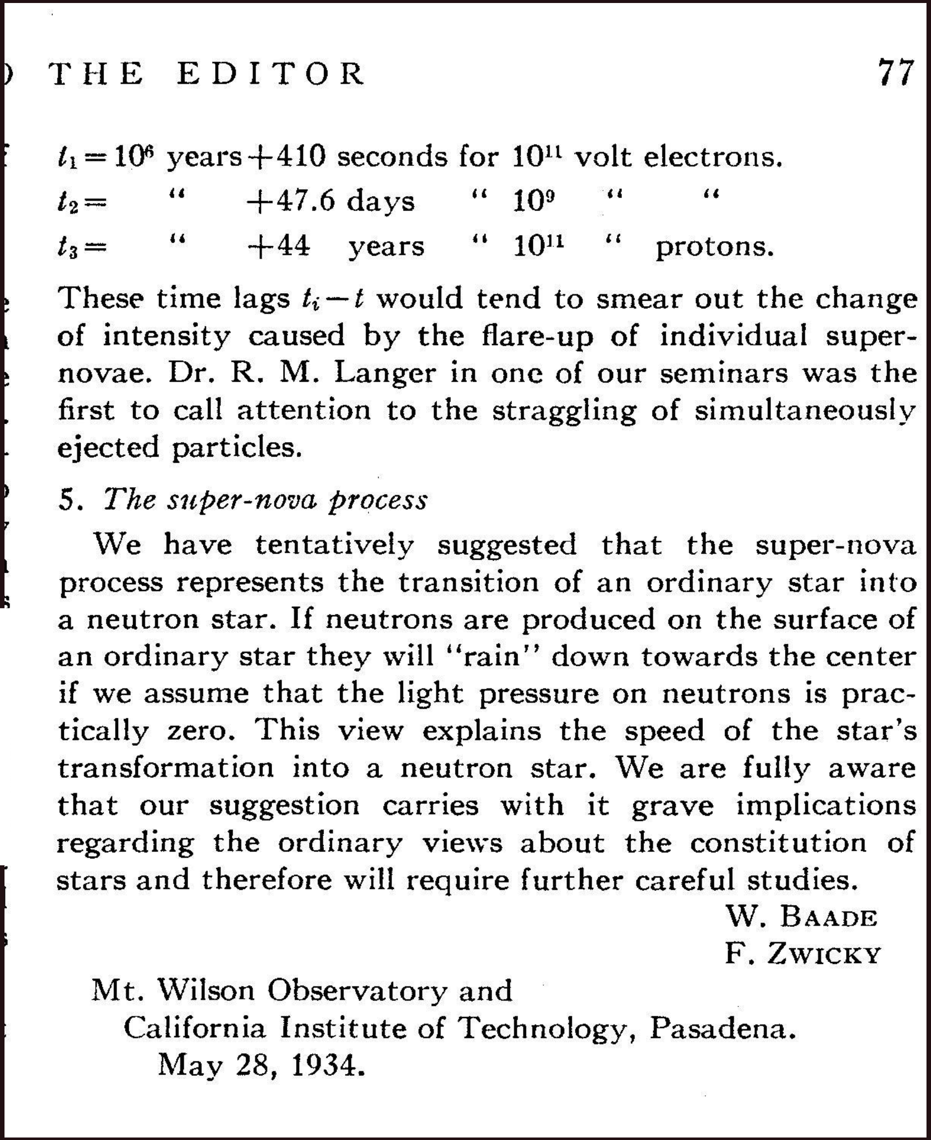
Baade and Zwicky – theoretical prediction

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 supernova is about twenty days and its absolute brightness a maximum may be as high as $M_{\text{vis}} = -14^{M}$. The visibl radiation L_ν of a supernova is about 10^8 times the radiatio of our sun, that is, $L_\nu = 3.78 \times 10^{41}$ ergs/sec. Calculation indicate that the total radiation, visible and invisible, i of the order $L_\tau = 10^7 L_\nu = 3.78 \times 10^{48}$ ergs/sec. The supernova therefore emits during its life a total energy $E_\tau \geqq 10^5 L_\tau = 3.78 \times 10^{53}$ 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 super-novae. 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

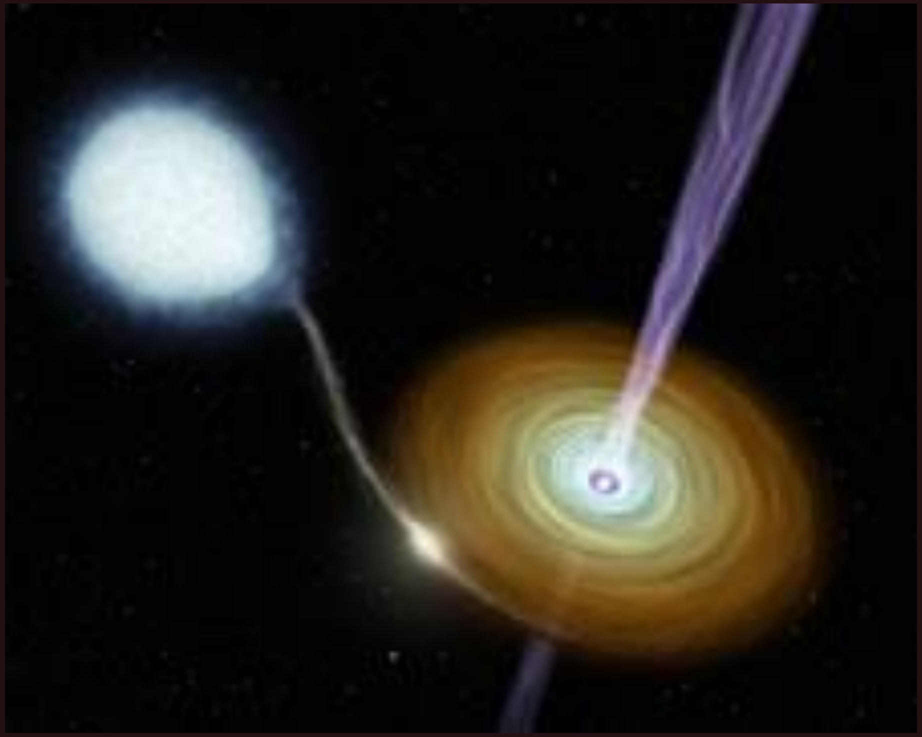
Mt. Wilson Observatory and
California Institute of Technology, Pasadena.
May 28, 1934.

Phys. Rev. 46, 76, 1934 July 1

Good old classics

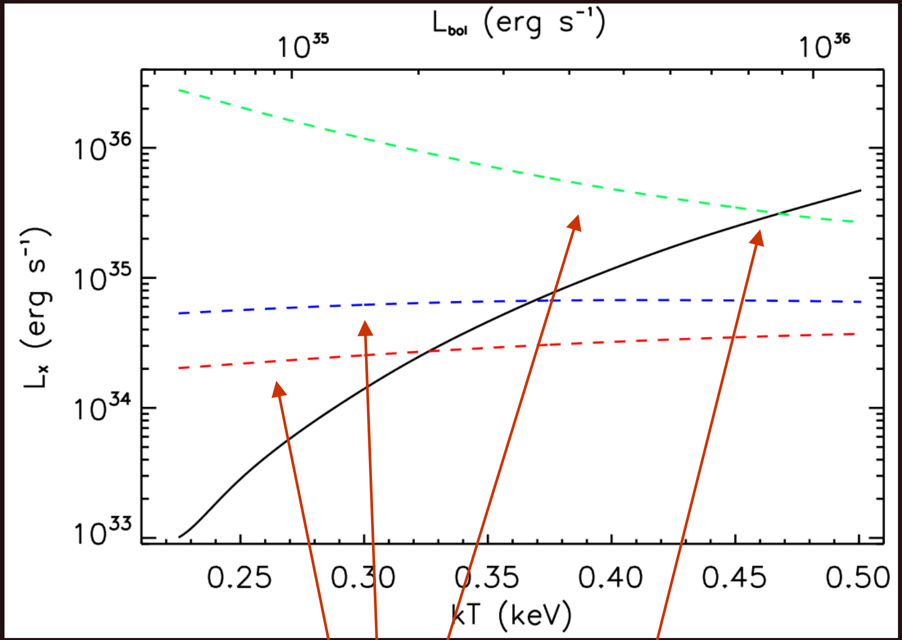
For years two main types of NSs have been discussed: radio pulsars and accreting NSs in close binary systems

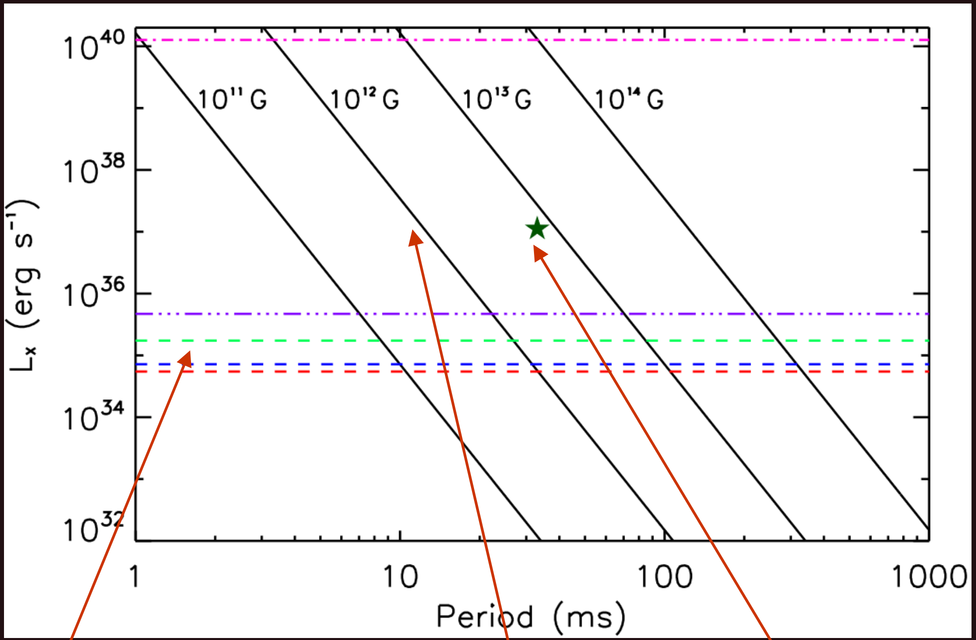
The pulsar in the Crab nebula



A binary system

What formed in SN 1987A?





Crab

Dashed and
dot-dashed –
different limits
(as on the left)

Limits for different N_H.

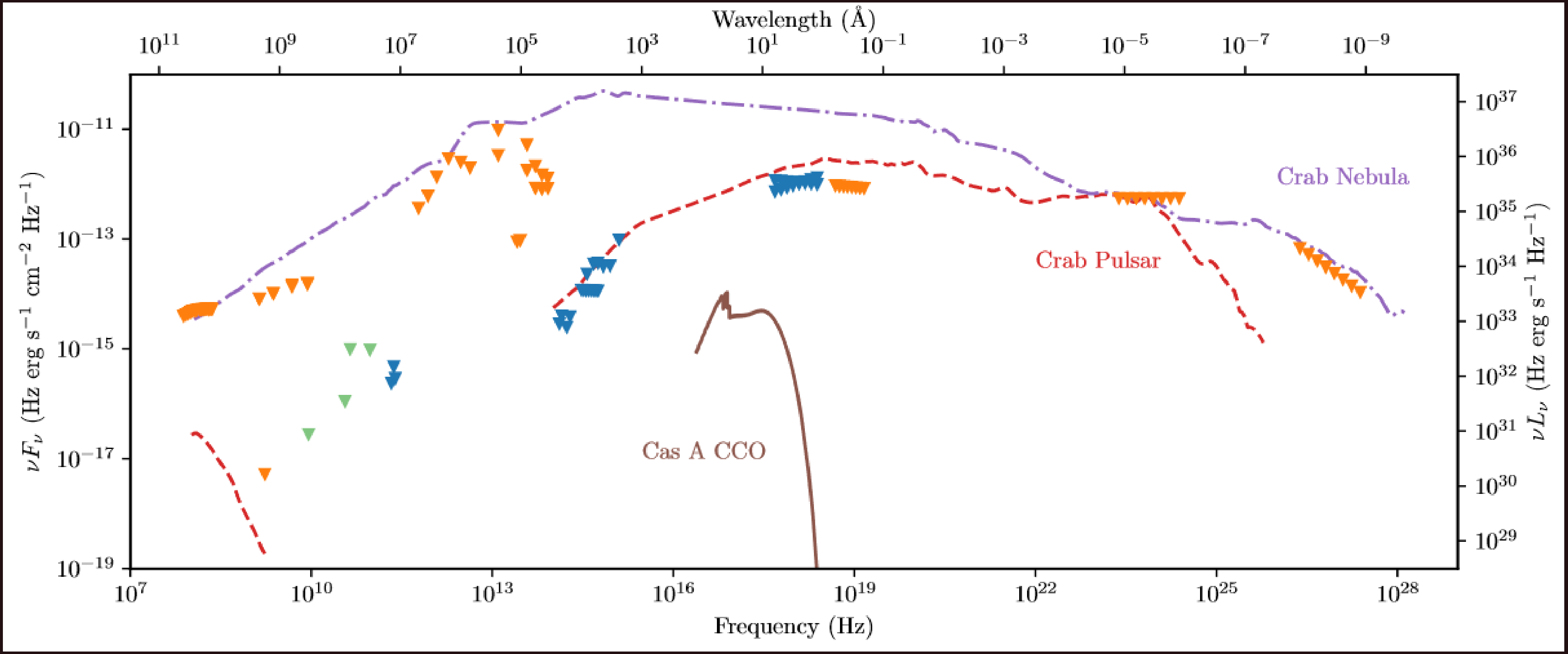
Black solid:
2-8 keV luminosity
for different fields.

2-8 keV luminosity
for different temperatures

1803.04692

See also 1805.04526

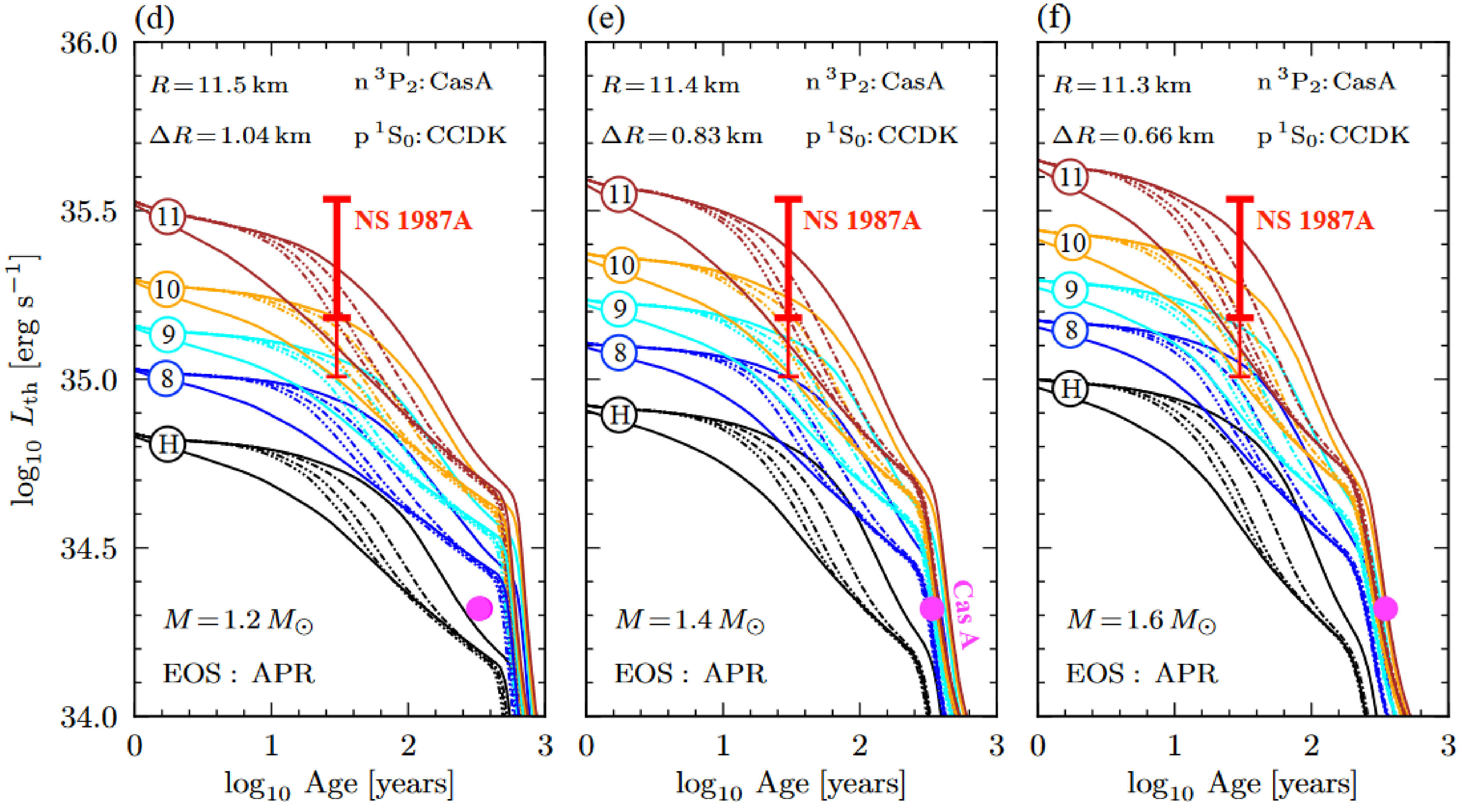
More limits on SN1987A



Still, it is possible that a NS is formed in SN 1987A.
But very energetic pulsars or/and magnetars are mostly excluded despite strong uncertainties in absorption.
About absorption see 1805.04528.

1805.04526

Limits on thermal emission



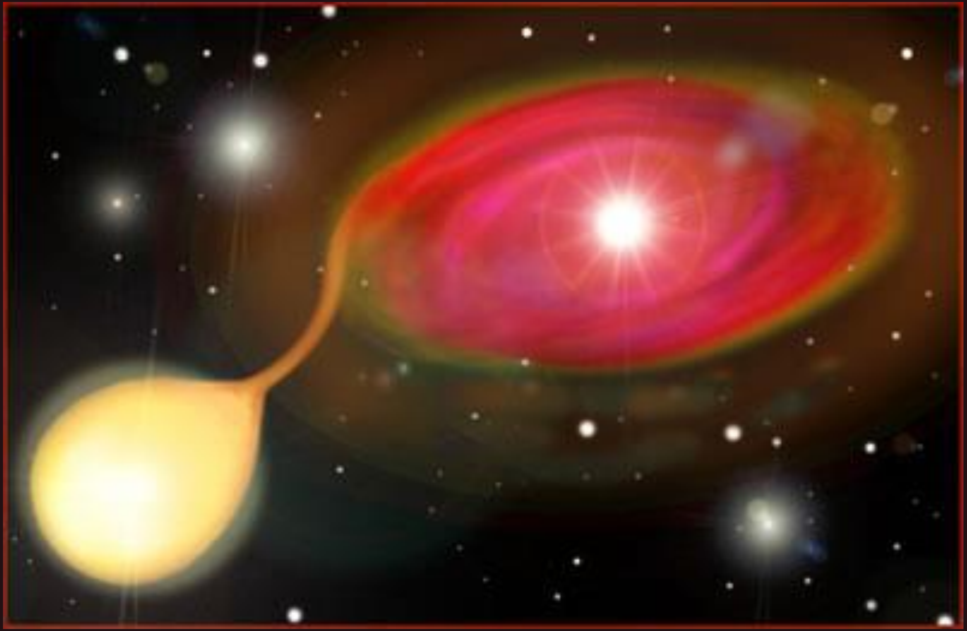
2004.06078

Most recent limits: 2103.02612. No compact object, yet.

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»....

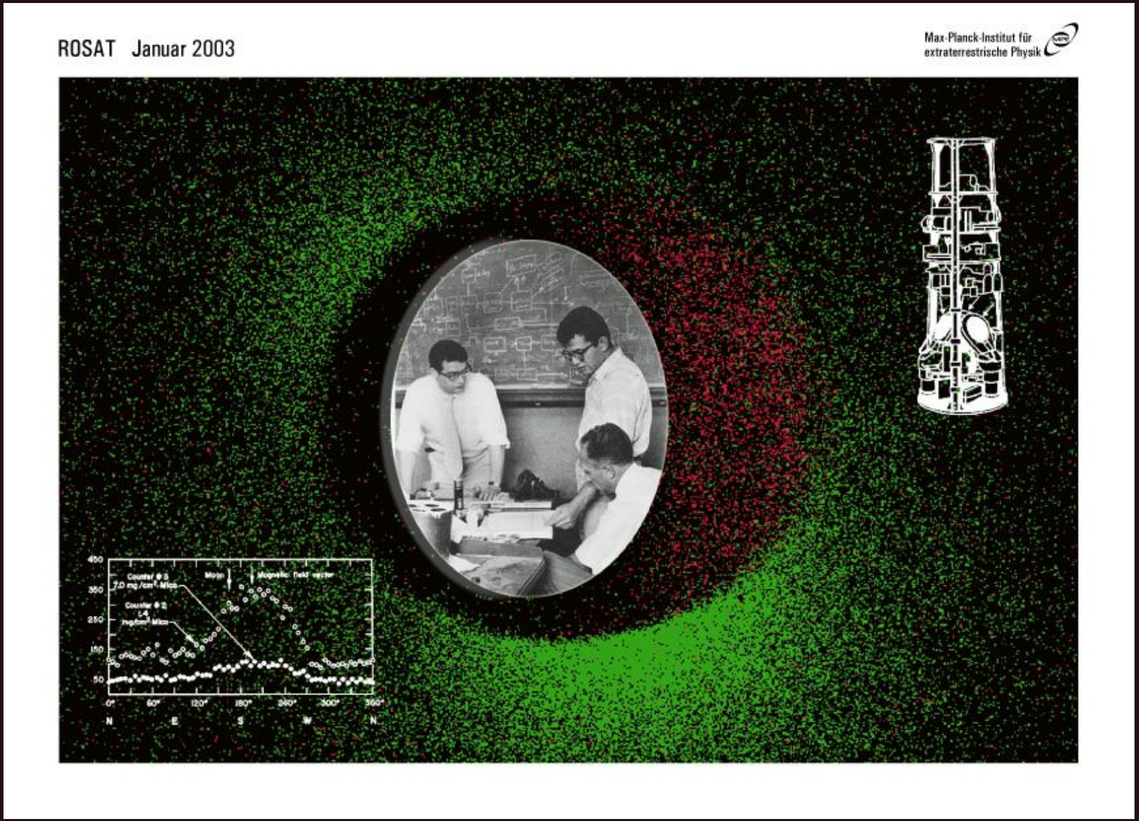


Now we know hundreds of X-ray binaries with neutron stars in the Milky Way and in other galaxies.

Rocket experiments. Sco X-1

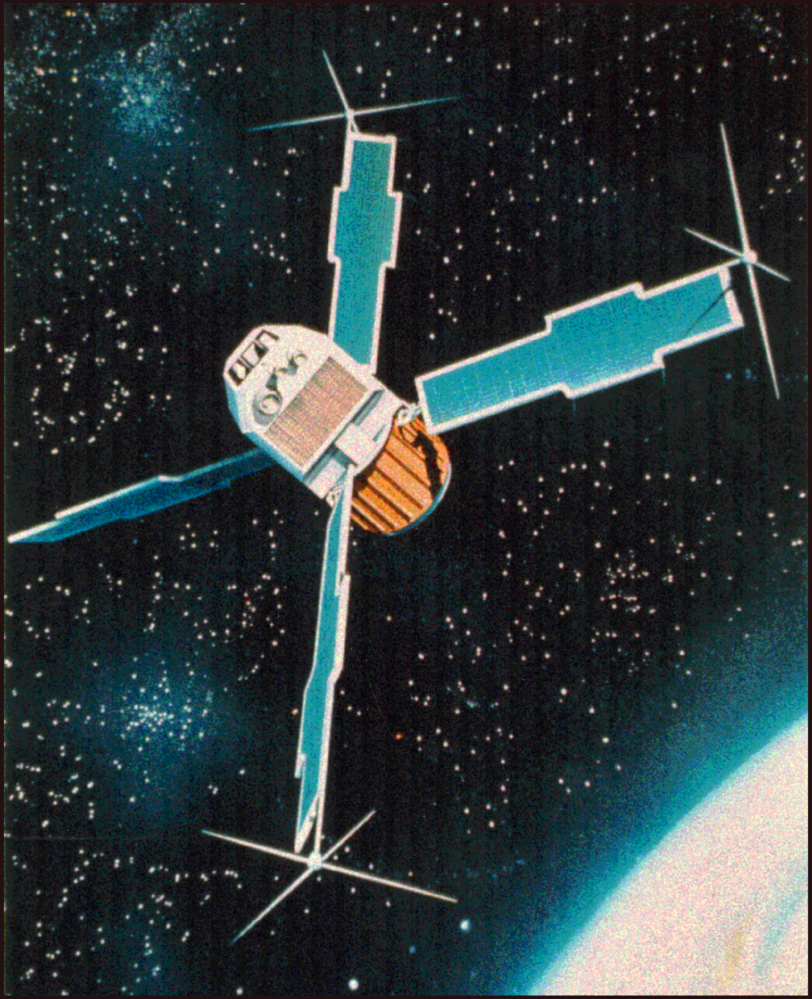
Giacconi et al. 1962

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

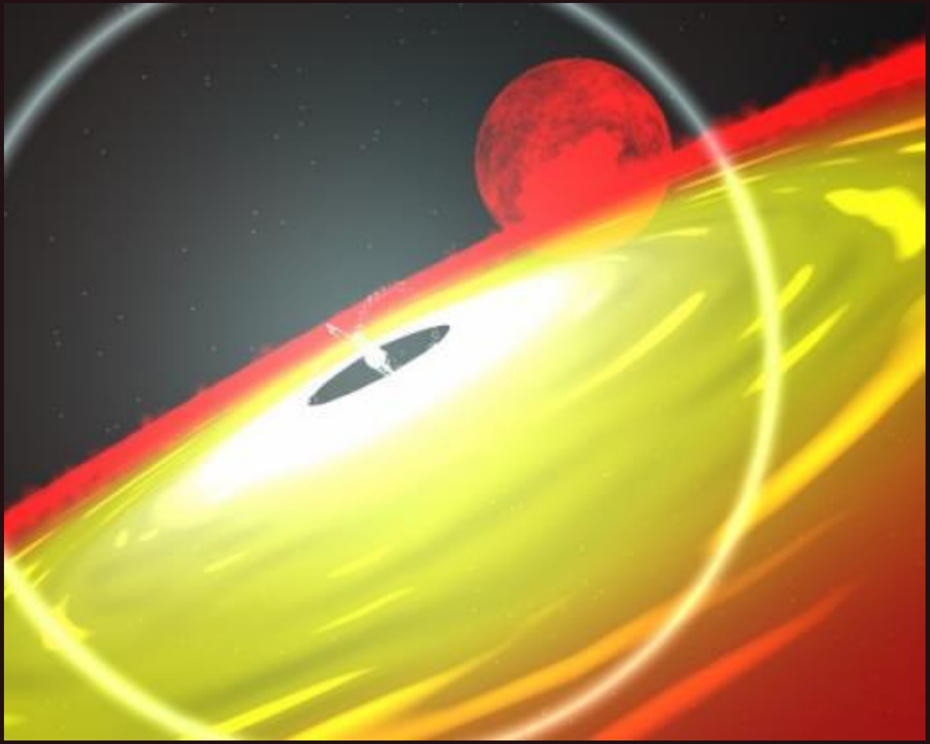
2-20 keV

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.

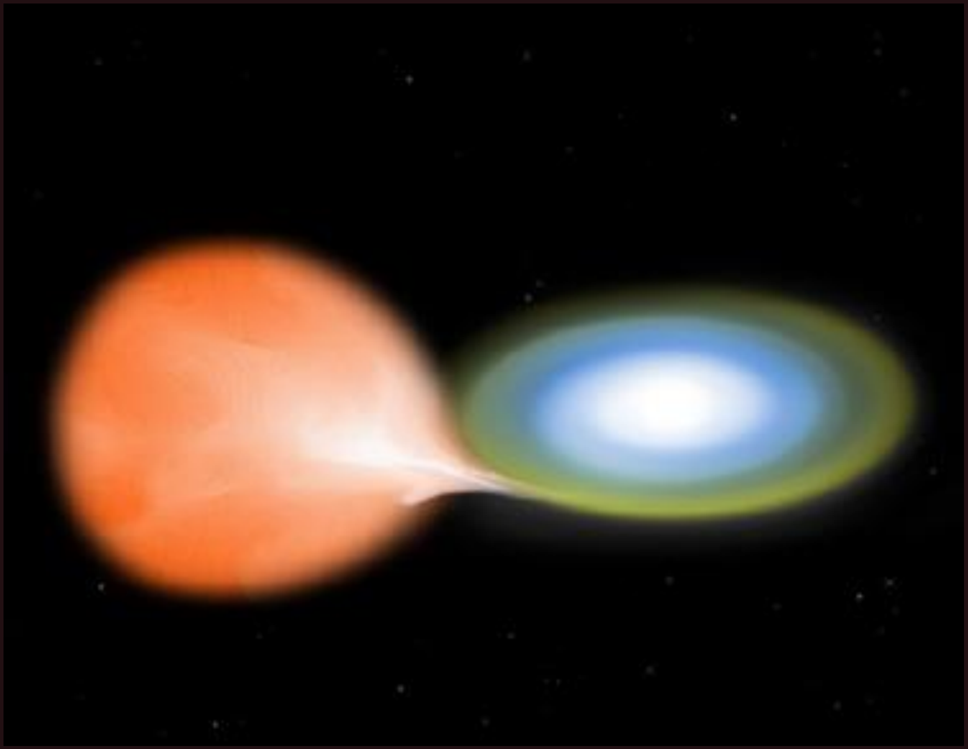
Accretion is important not only in close binaries, but also in active galactic nuclei and many other types of astrophysical sources.

Close binary systems

About ½ of massive stars
Are members of close binary systems.

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

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

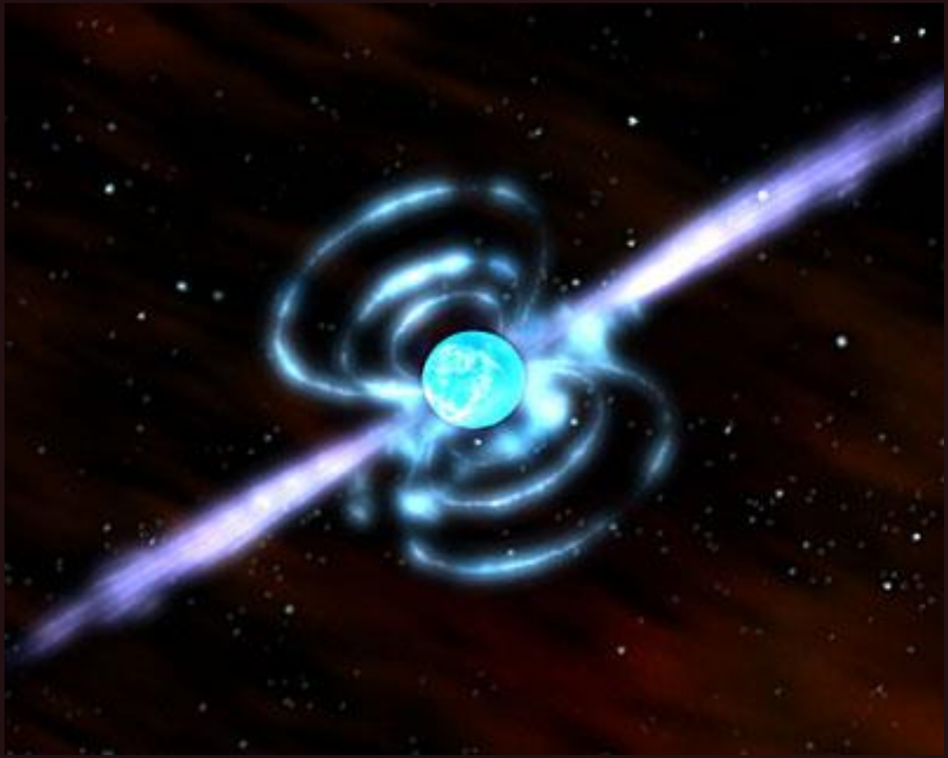


The accretion rate can be up to 10^{20} g/s;
Accretion efficiency – up to 10%;
Luminosity –thousands of hundreds of the solar.

Discovery !!!!

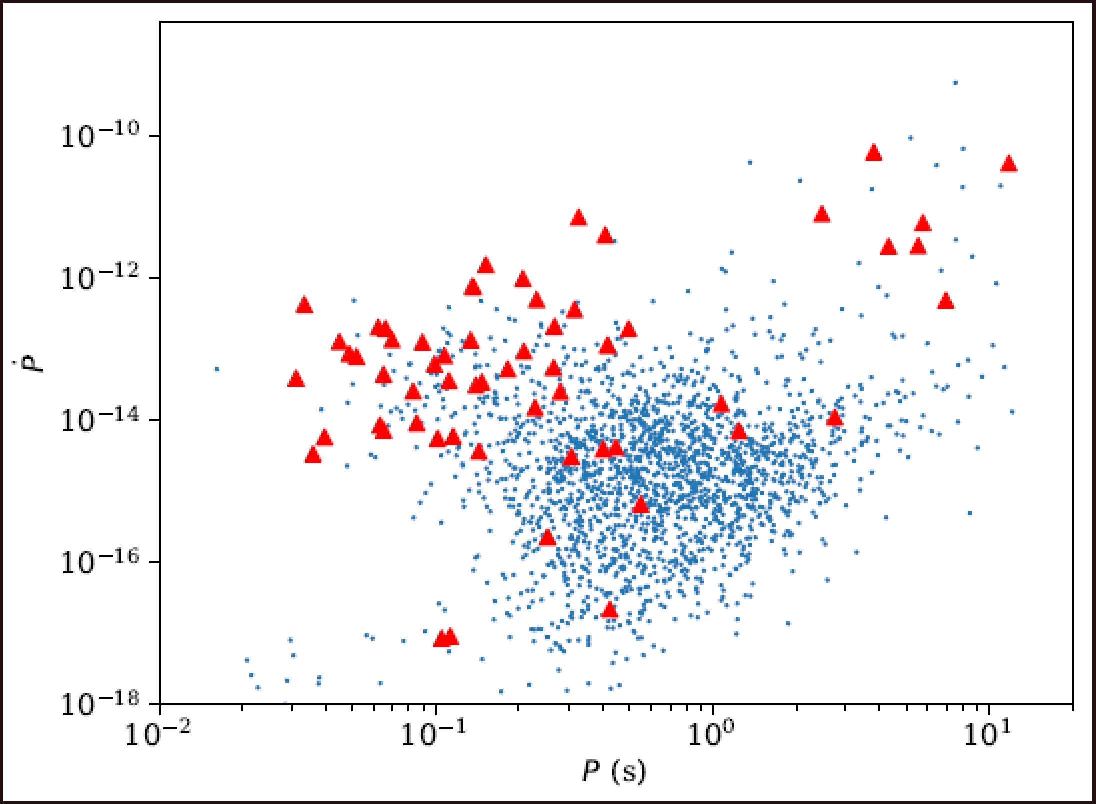
1967: Jocelyn Bell. Radio pulsars.

Seredipitous discovery.



The pulsar in the Crab nebula

SNRs and PSRs



Igoshev et al. 2022

There are:

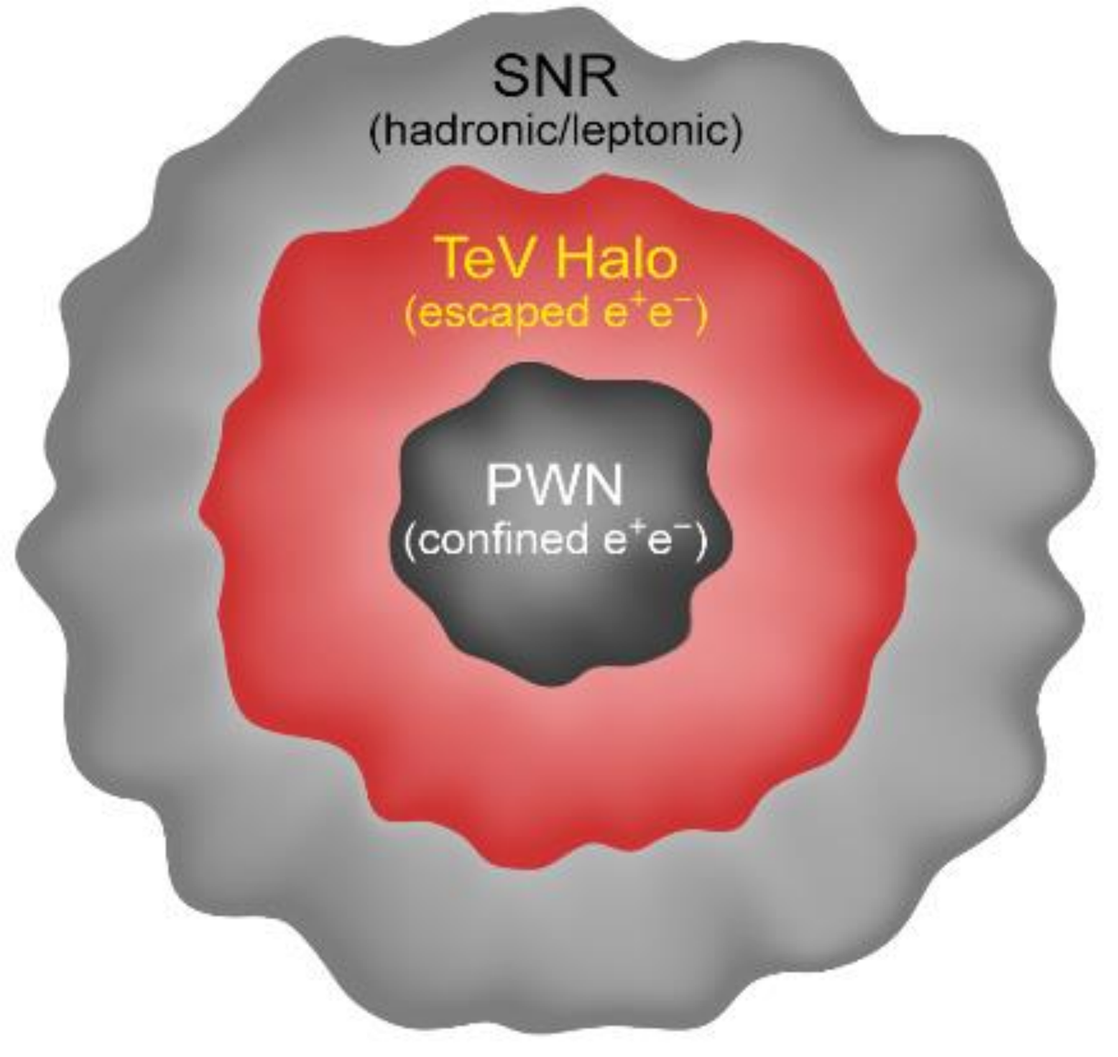
- Young PSRs within SNRs (see 2110.00179);
- Young PSRs without SNRs (see 1204.0632);
- SNRs without PSRs (see 2101.12486)

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

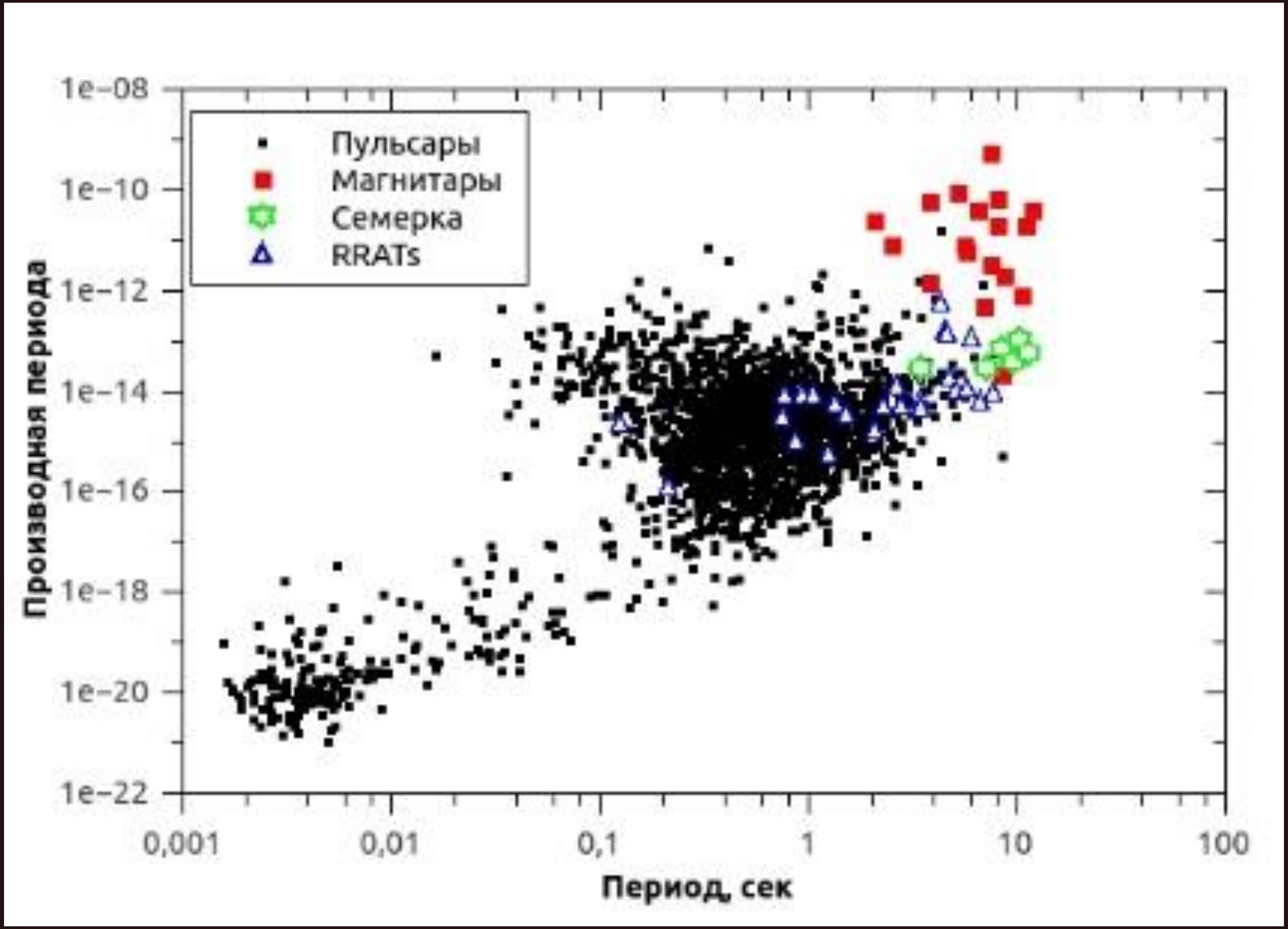


Milagro and HAWC

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

1902.08203

Pulsar spin-down: P-Pdot diagram



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

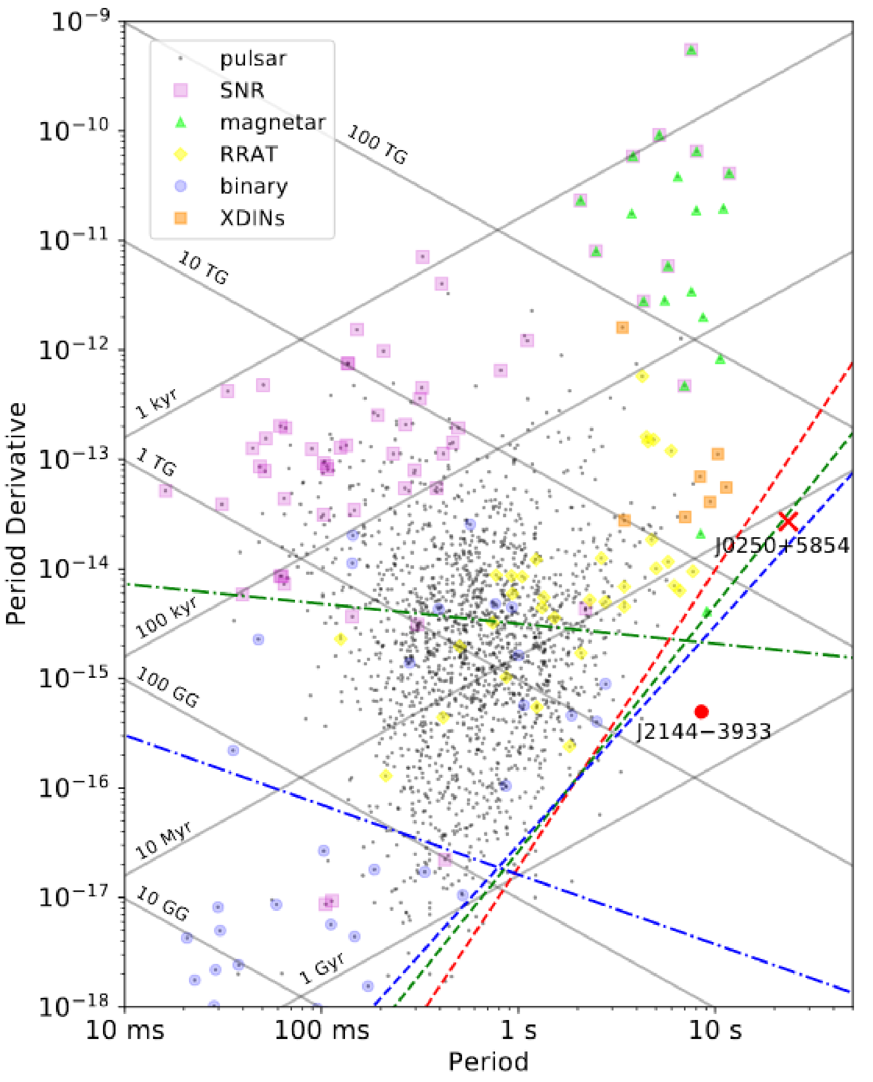
Record slow radio pulsar

PSR J0250+5854
spin period of 23.5 s

LOFAR detection

May be field decay
was important for
this radio pulsar.

In 2021 a new record was announced:
76 seconds
(MTP0013; Caleb et al. 2021, in press).

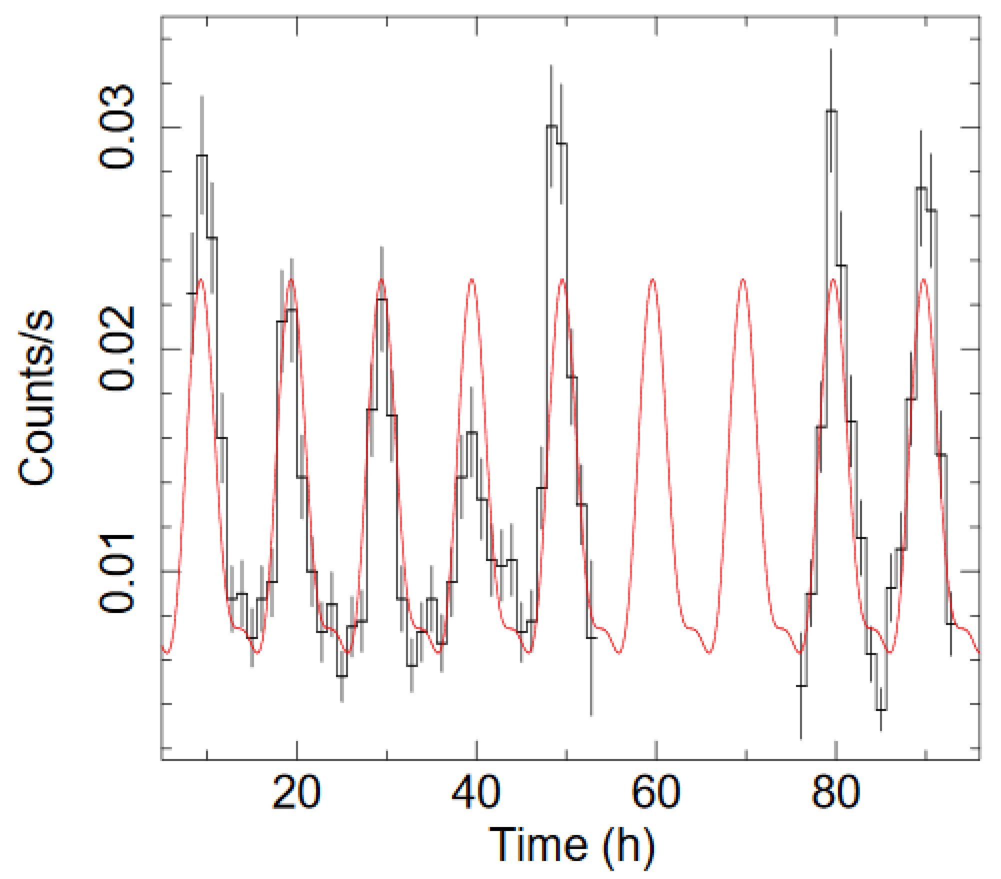


1809.00965

Slowly rotating NSs – in binaries

AX J1910.7+0917

P>10 hours! (36200+/-100 sec)



1705.01791

18-minutes PSR period?

Murchison Widefield Array

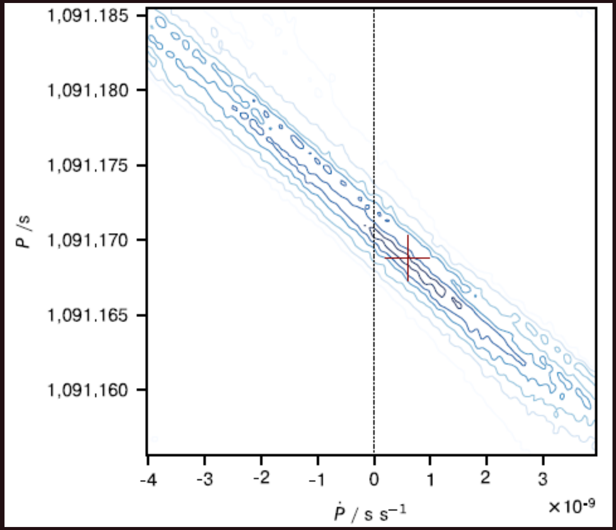
GLEAM-X J162759.5-523504.3

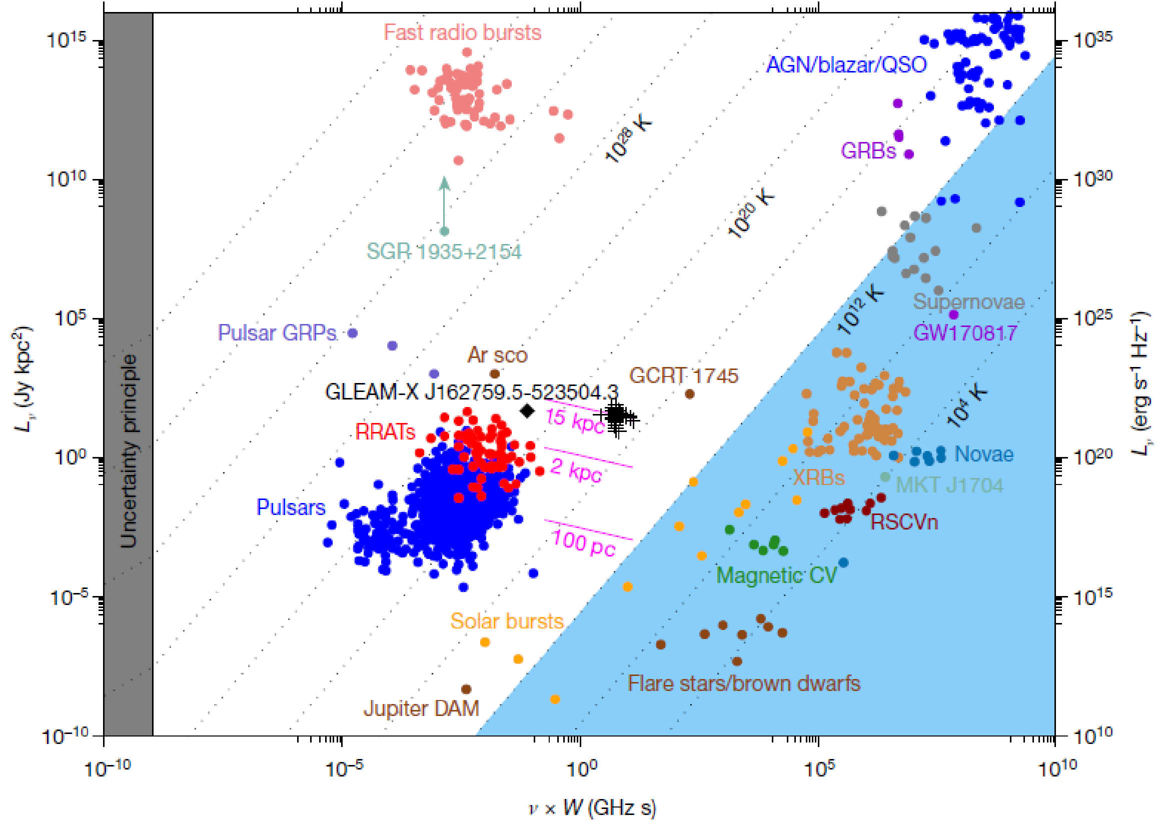
72–231 MHz

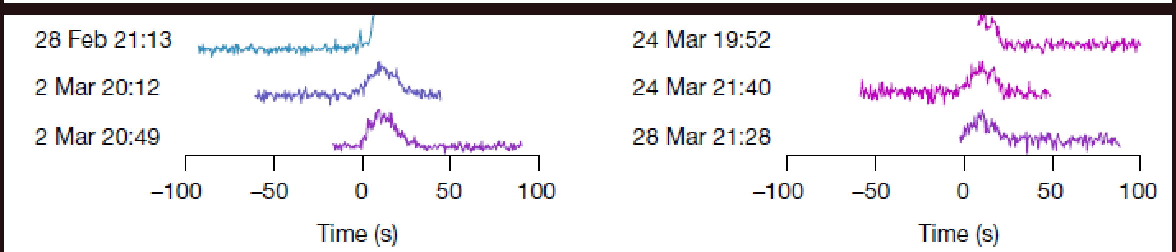
DM=57 ± 1 pc cm^{-3}

d=1.3 ± 0.5 kpc

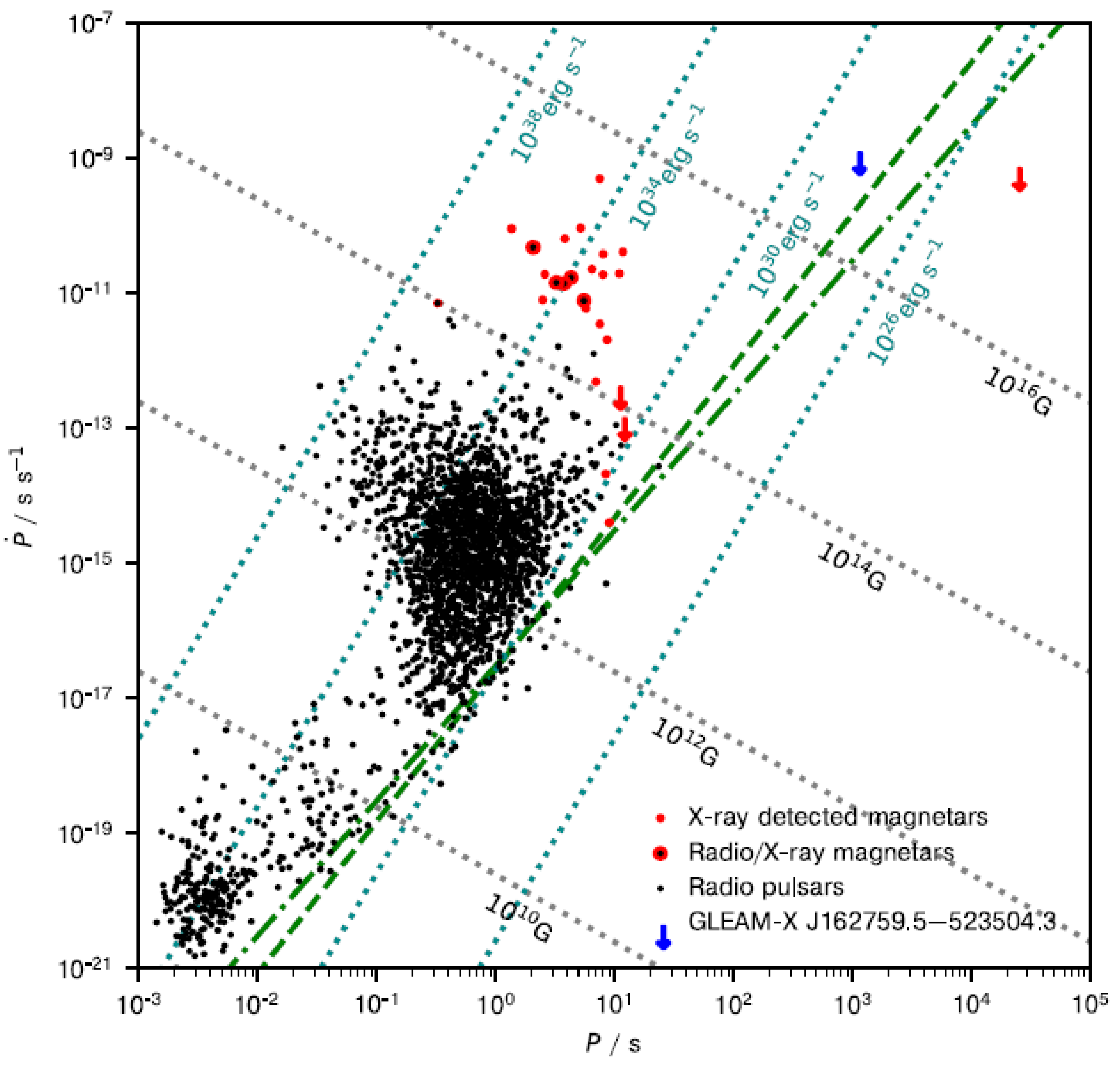
RM=−61 ± 1 rad m^{-2}





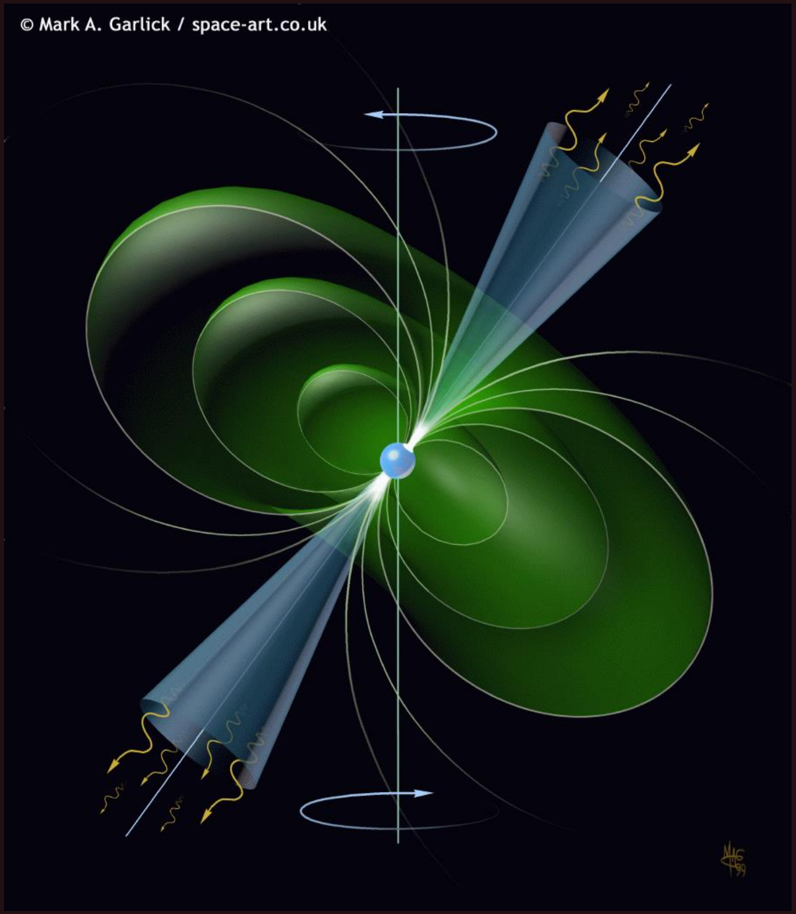


Hurley-Walker et al. 2022

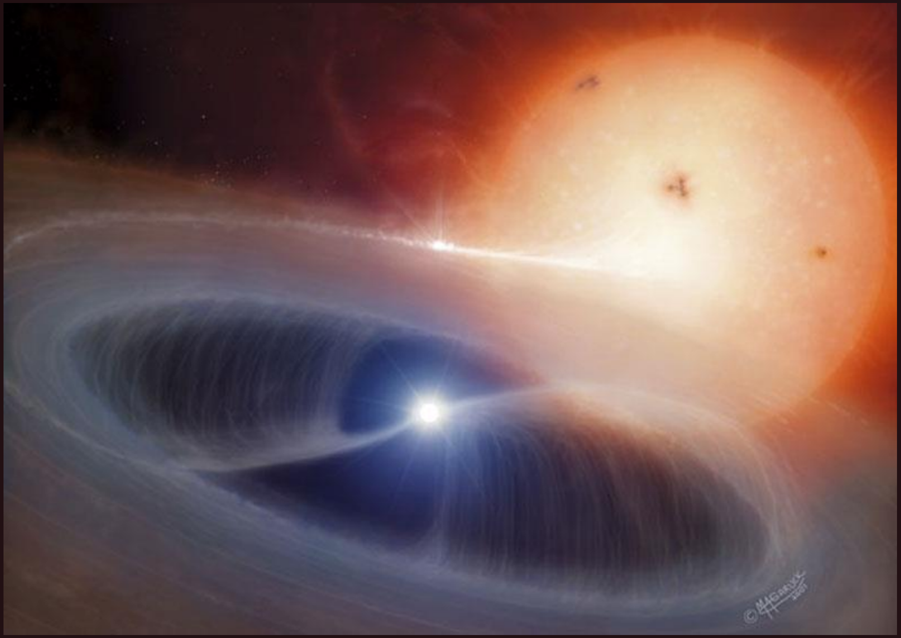


Hurley-Walker et al. 2022

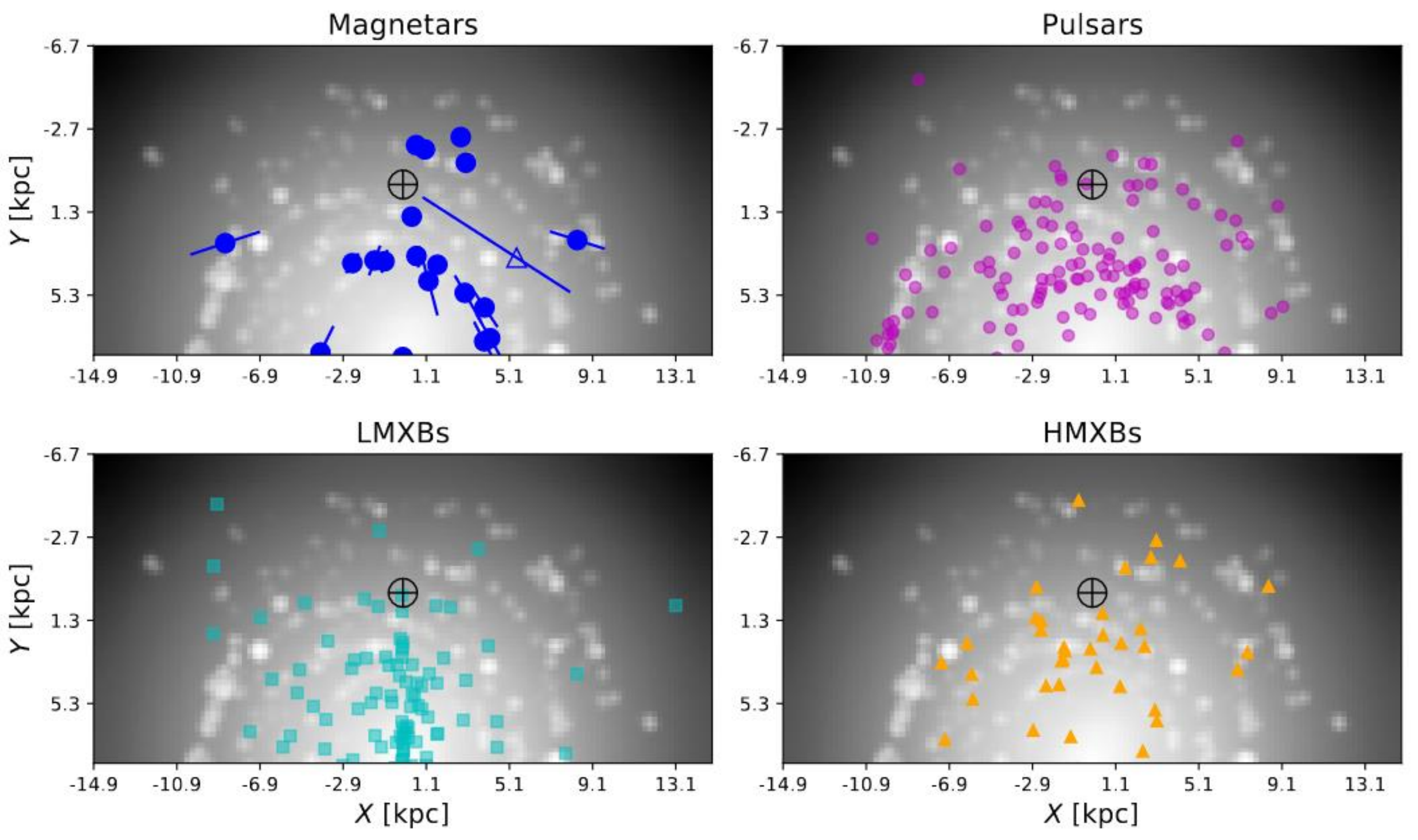
The old Zoo: young pulsars & old accretors



© Mark A. Garlick / space-art.co.uk



NSs in the Milky Way



2105.04549

The new zoo of young neutron stars

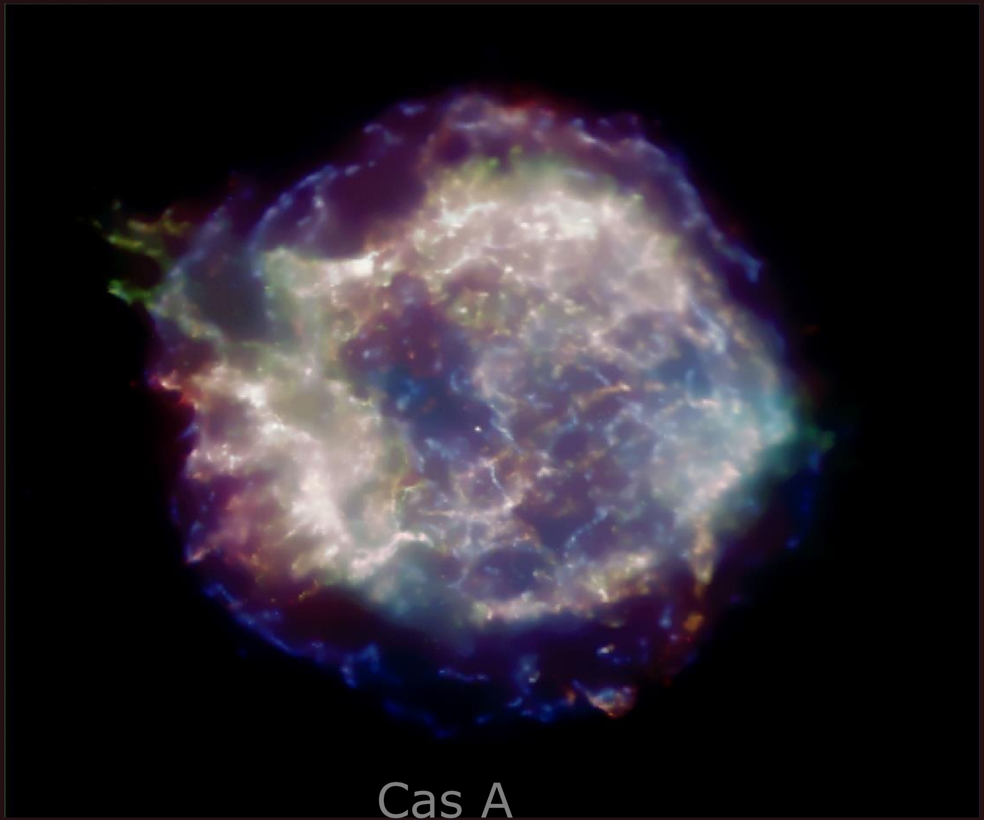
During last ~25 years
it became clear that neutron stars
can be born very different.
In particular, absolutely
non-similar to the Crab pulsar.

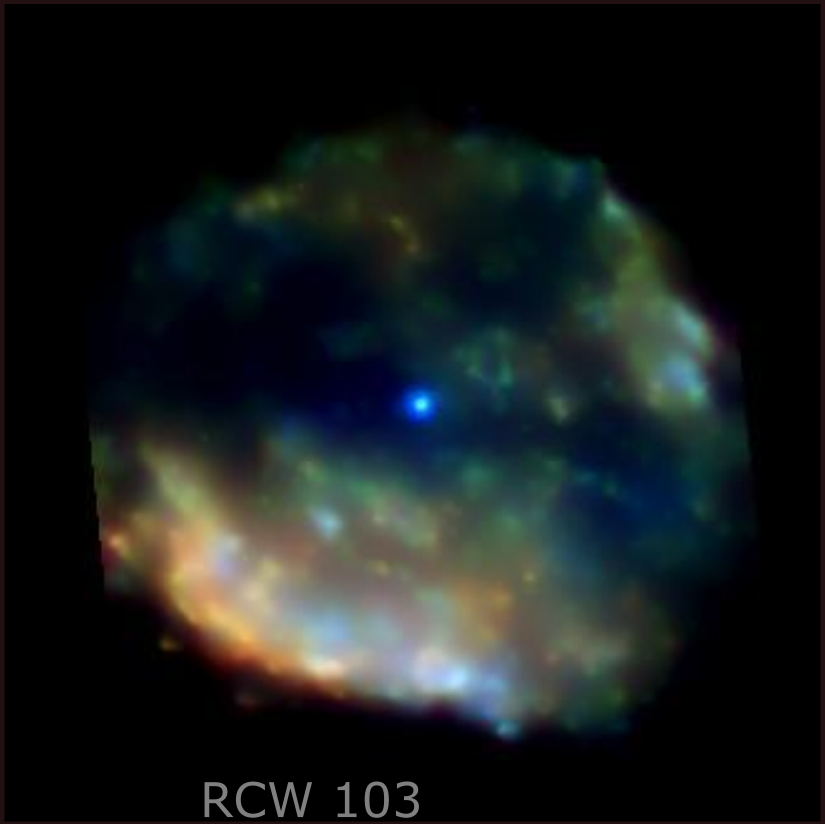
o High-B PSRs
o Compact central X-ray sources
   in supernova remnants.
o Anomalous X-ray pulsars
o Soft gamma repeaters
o The Magnificent Seven
o Transient radio sources (RRATs)

Old and new zoos: Harding arXiv:1302.0869

See a more recent review in 1712.06040

Compact central X-ray sources in supernova remnants



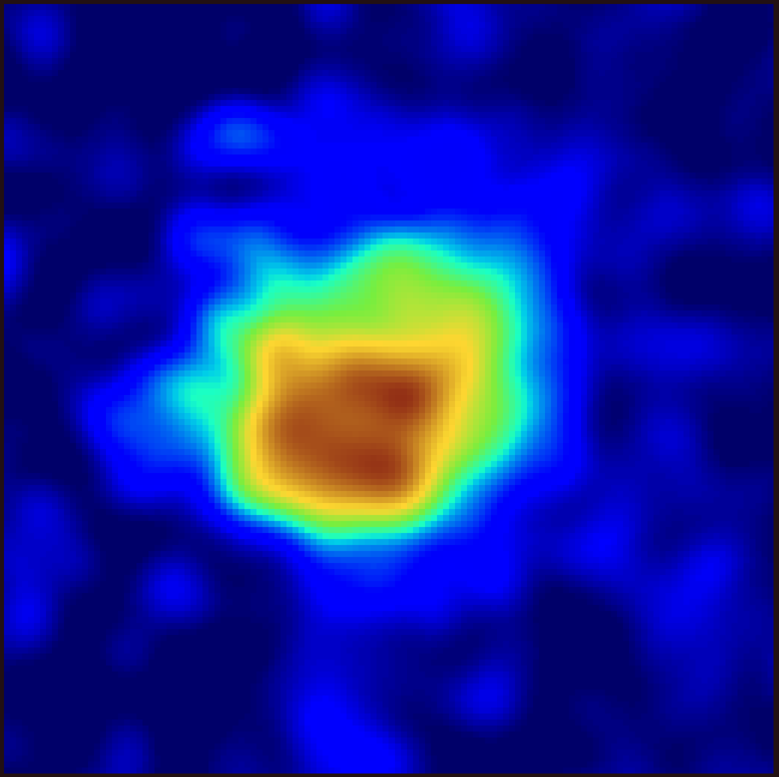


Rapid cooling
(Heinke et al. 1007.4719)

6.7 hour period
(de Luca et al. 2006)

CCOs in SNRs

		Age	Distance
J232327.9+584843	Cas A	0.32	3.3–3.7
J085201.4−461753	G266.1−1.2	1–3	1–2
J082157.5−430017	Pup A	1–3	1.6–3.3
J121000.8−522628	G296.5+10.0	3–20	1.3–3.9
J185238.6+004020	Kes 79	~9	~10
J171328.4−394955	G347.3−0.5	~10	~6

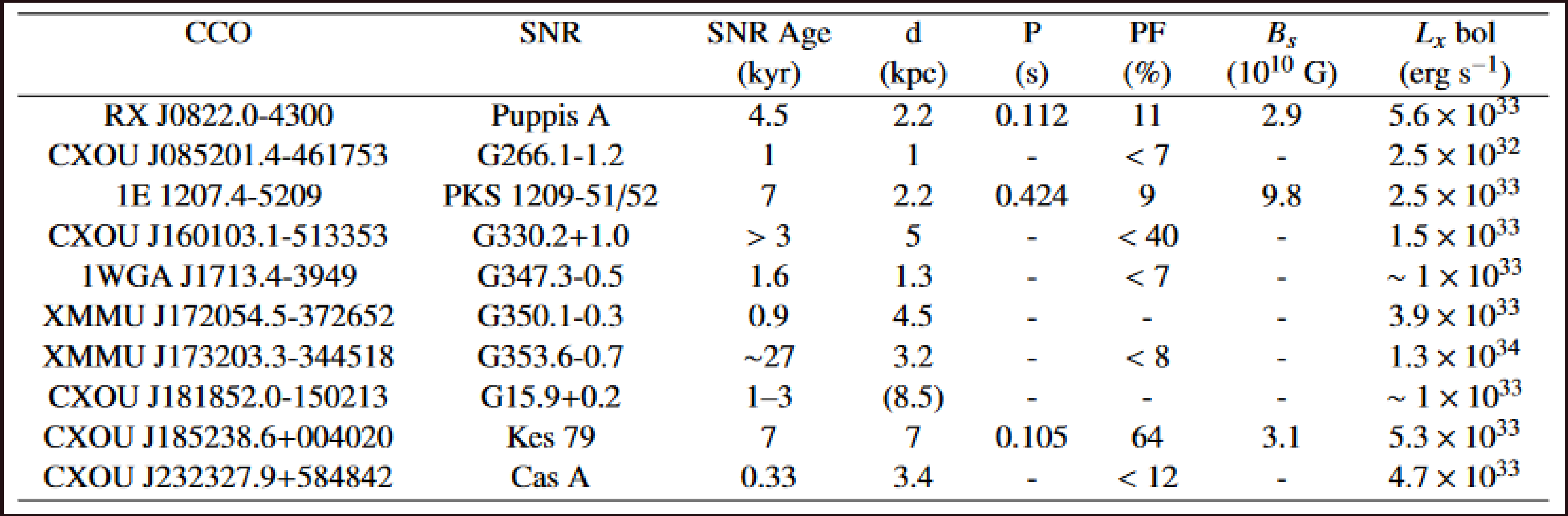


[Pavlov, Sanwal, Teter: astro-ph/0311526,
de Luca: arxiv:0712.2209]

For three sources there are strong indications for large (>~100 msec) initial spin periods and low magnetic fields:

1E 1207.4-5209 in PKS 1209-51/52
PSR J1852+0040 in Kesteven 79
PSR J0821-4300 in Puppis A
[see Halpern et al. arxiv:0705.0978 and 1301.2717]

Catalogue of CCOs



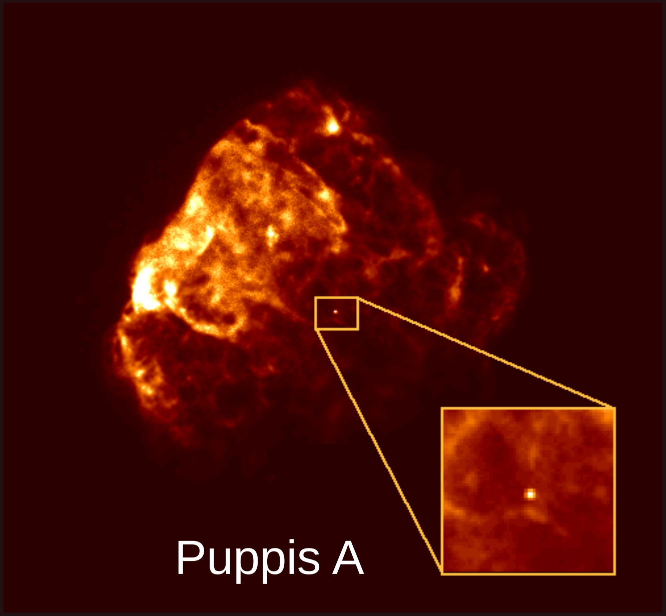
CCO	SNR	SNR Age (kyr)	d (kpc)	P (s)	PF (%)	B_s (10^{10} G)	L_x bol (erg s^{-1})
RX J0822.0-4300	Puppis A	4.5	2.2	0.112	11	2.9	5.6×10^{33}
CXOU J085201.4-461753	G266.1-1.2	1	1	-	< 7	-	2.5×10^{32}
1E 1207.4-5209	PKS 1209-51/52	7	2.2	0.424	9	9.8	2.5×10^{33}
CXOU J160103.1-513353	G330.2+1.0	> 3	5	-	< 40	-	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}

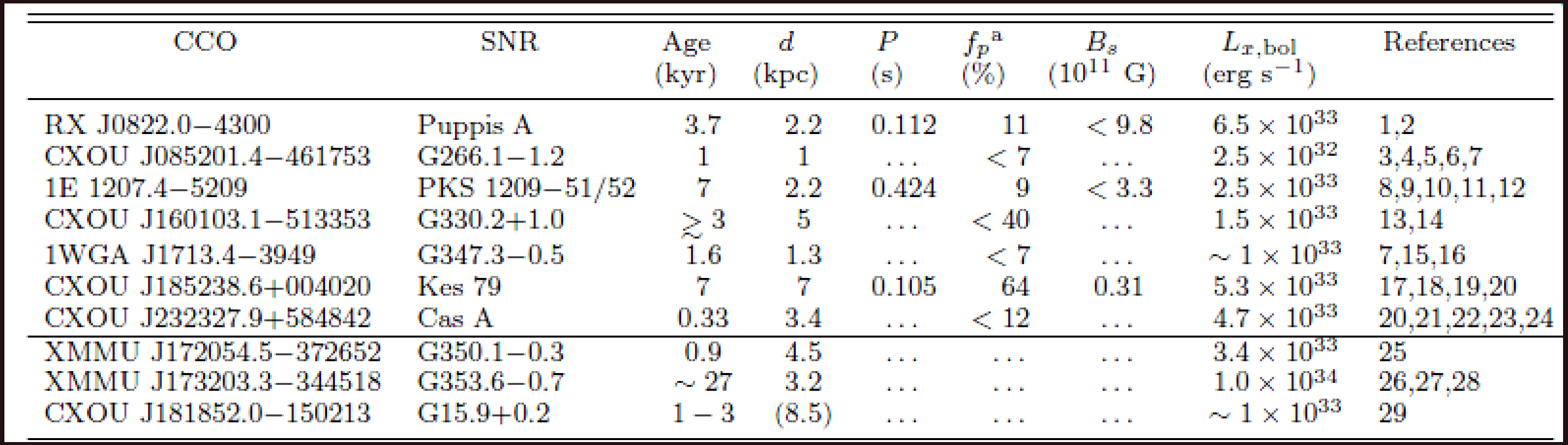
http://www.iasf-milano.inaf.it/~deluca/cco/main.htm

CCOs

High proper motion of CCO in Pup A.
Velocity 763+/- 73 km/s

2005.09457


Puppis A

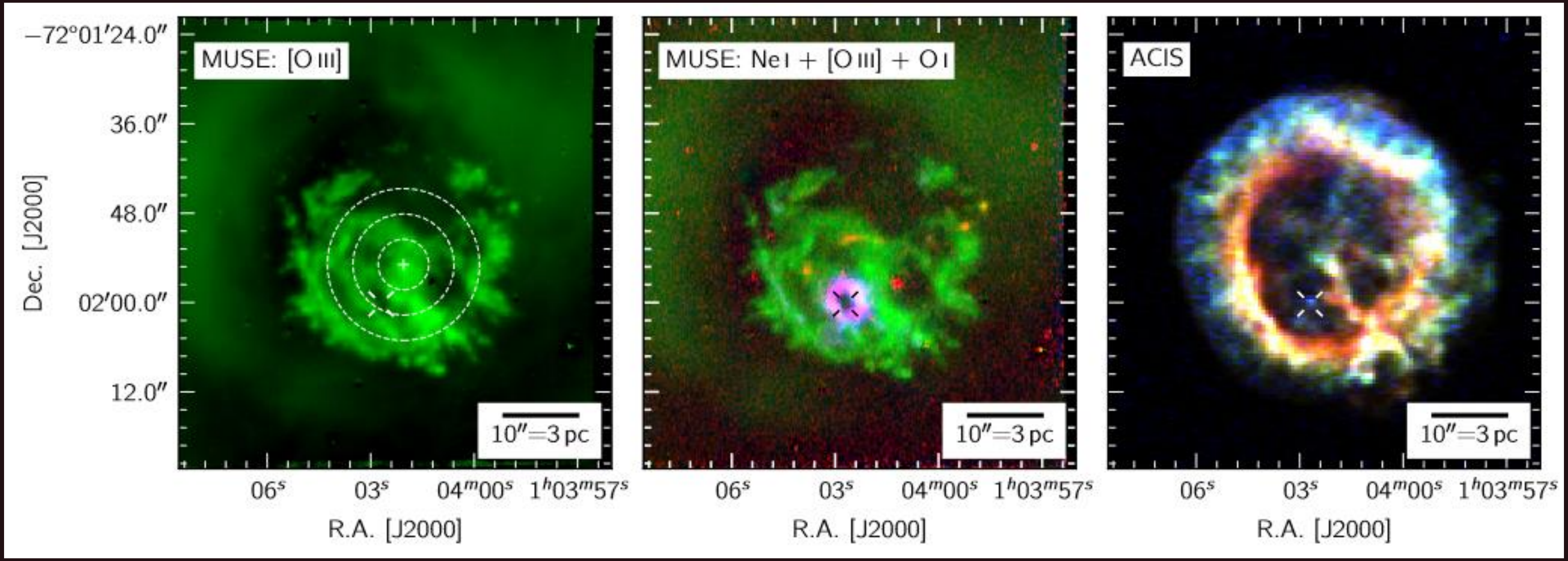


CCO	SNR	Age (kyr)	d (kpc)	P (s)	f_p[a] (%)	B_s (10^{11} G)	$L_{x,\mathrm{bol}}$ (erg s^{-1})	References
RX J0822.0−4300	Puppis A	3.7	2.2	0.112	11	< 9.8	6.5×10^{33}	1,2
CXOU J085201.4−461753	G266.1−1.2	1	1	…	< 7	…	2.5×10^{32}	3,4,5,6,7
1E 1207.4−5209	PKS 1209−51/52	7	2.2	0.424	9	< 3.3	2.5×10^{33}	8,9,10,11,12
CXOU J160103.1−513353	G330.2+1.0	$\gtrsim 3$	5	…	< 40	…	1.5×10^{33}	13,14
1WGA J1713.4−3949	G347.3−0.5	1.6	1.3	…	< 7	…	$\sim 1 \times 10^{33}$	7,15,16
CXOU J185238.6+004020	Kes 79	7	7	0.105	64	0.31	5.3×10^{33}	17,18,19,20
CXOU J232327.9+584842	Cas A	0.33	3.4	…	< 12	…	4.7×10^{33}	20,21,22,23,24
XMMU J172054.5−372652	G350.1−0.3	0.9	4.5	…	…	…	3.4×10^{33}	25
XMMU J173203.3−344518	G353.6−0.7	~ 27	3.2	…	…	…	1.0×10^{34}	26,27,28
CXOU J181852.0−150213	G15.9+0.2	$1 - 3$	(8.5)	…	…	…	$\sim 1 \times 10^{33}$	29

0911.0093

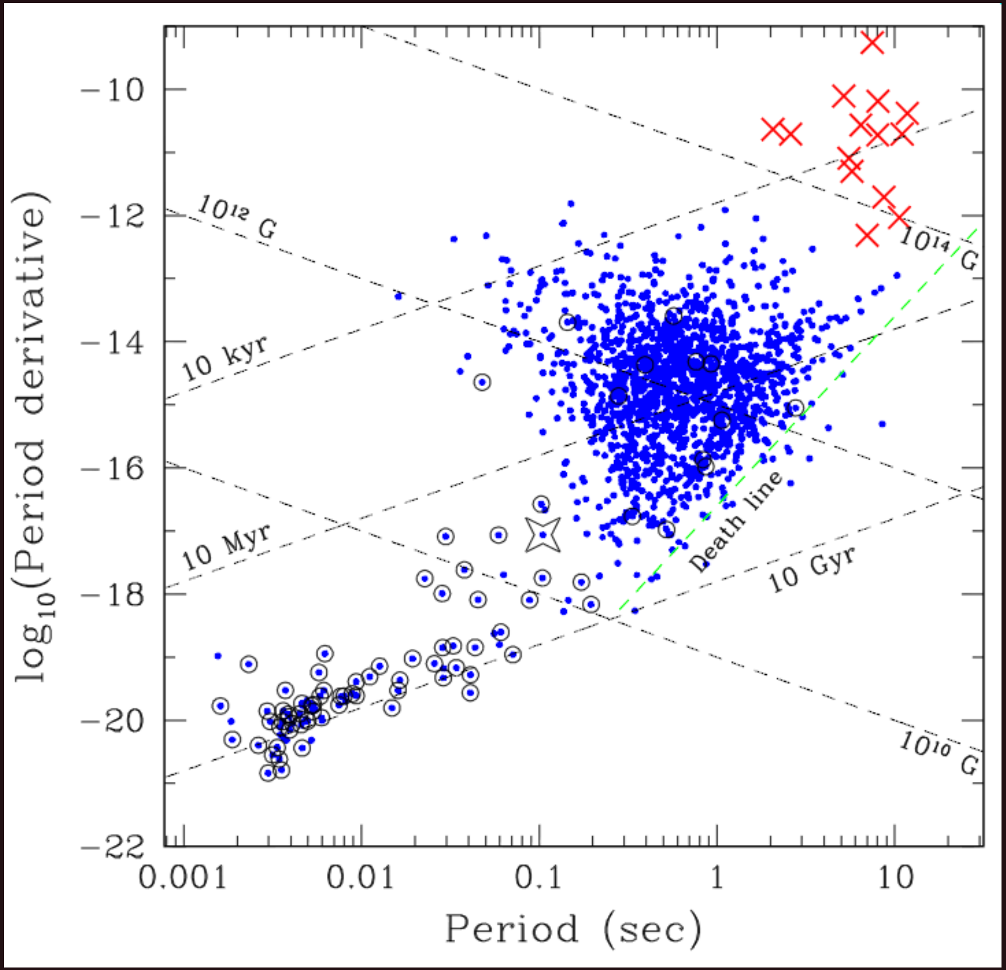
The first CCO in SMC 1E 0102.2-7219

The first CCO identified outside the Galaxy.
L~10^{33} erg/s.



1803.01006

Anti-magnetars



Star marks the CCO from 0911.0093

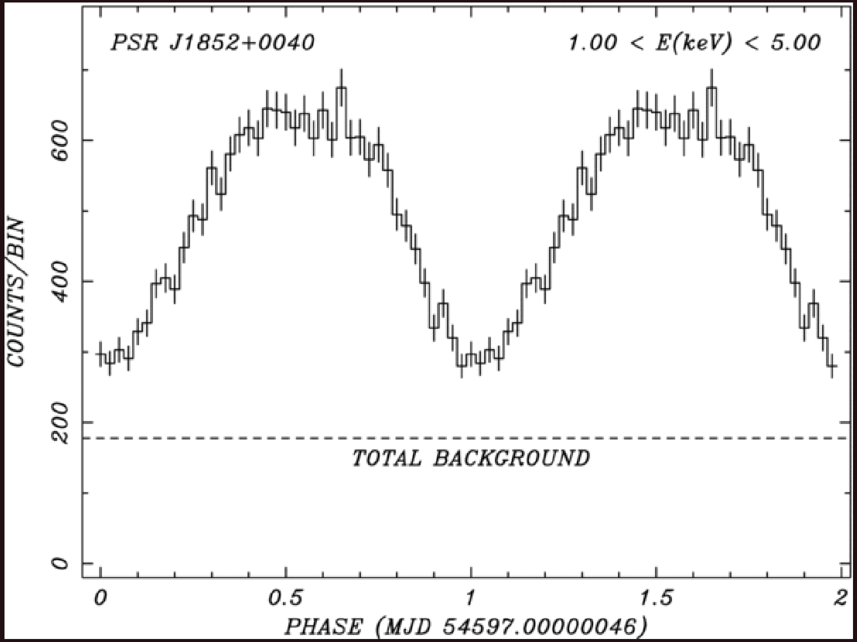
1301.2717:
Spins and derivative are measured for
PSR J0821-4300 and
PSR J1210-5226

0911.0093

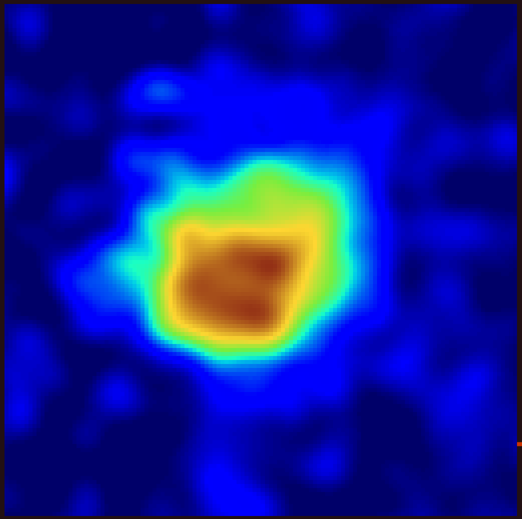
“Hidden” magnetars

Kes 79. PSR J1852+0040. P~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: few ×10^{14} G.



Halpern, Gotthelf 2010



Kes 79

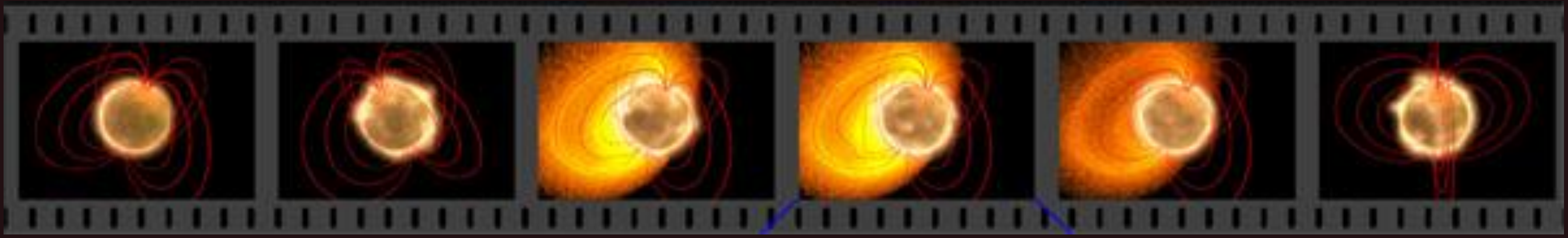
- If submergence of the field happens rapidly, so the present day period represents the initial one
- Then, the field of PSR 1852 was not enhanced via a dynamo mechanism
- Detection of millisecond “hidden” magnetars will be a strong argument in favour of dynamo.

arXiv: 1307.3127

Magnetars

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

Magnetic fields 10^{14}–10^{15} G

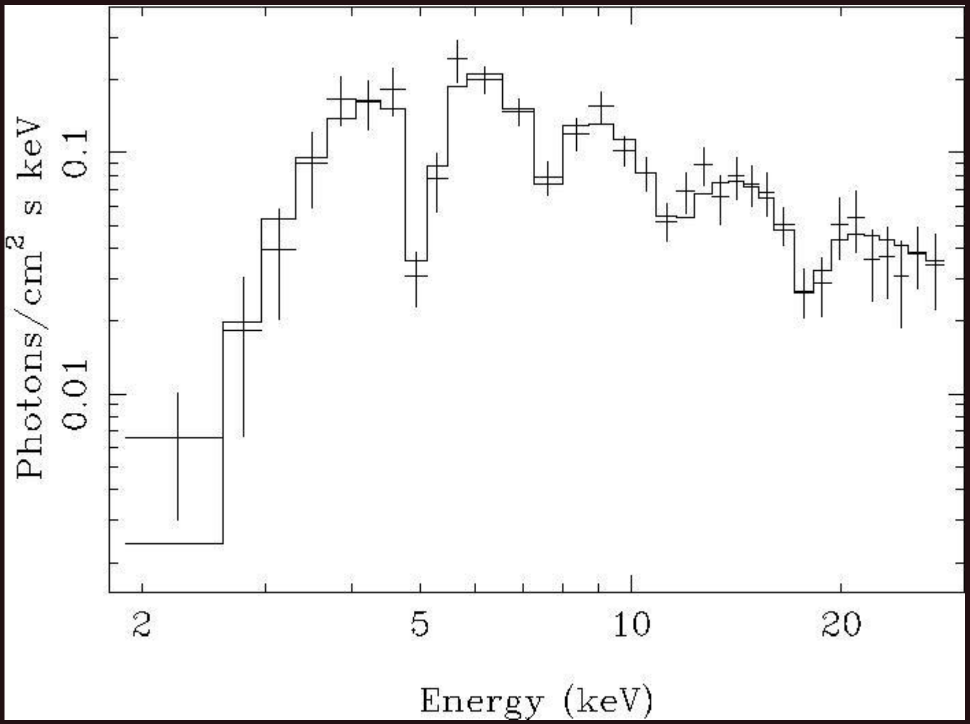


Magnetic field estimates

- 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)

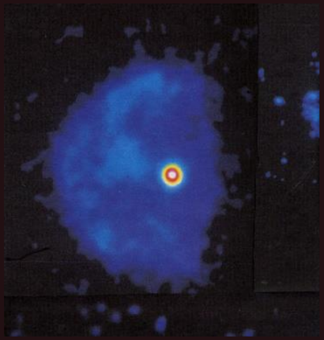


Ibrahim et al. 2002

Some of known magnetars

SGRs

- 0526-66
- 1627-41
- 1806-20
- 1900+14
- 0501+4516
- 0418+5729
- 1833-0832
- 1822-1606
- 1834-0846
- 1801-23 (?)
- 2013+34 (?)



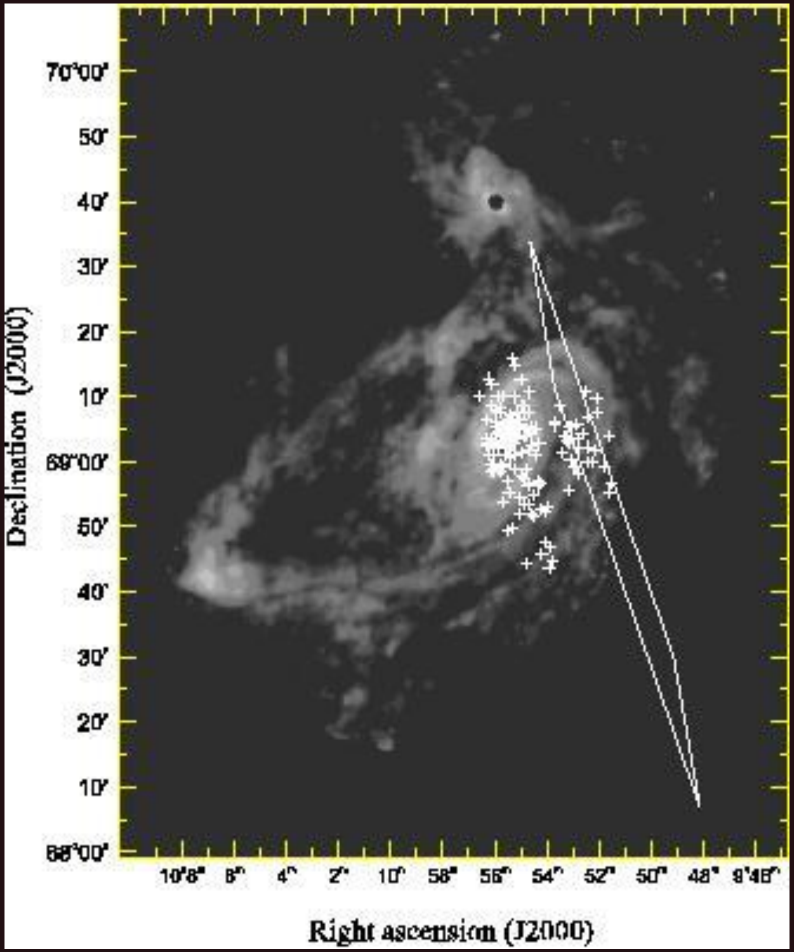
(CTB 109)

AXPs

- CXO 010043.1-72
- 4U 0142+61
- 1E 1048.1-5937
- CXO J1647-45
- 1 RXS J170849-40
- XTE J1810-197
- 1E 1841-045
- AX J1845-0258
- 1E 2259+586
- 1E 1547.0-5408
- PSR J1622-4950
- CXO J171405-381031

Catalogue: http://www.physics.mcgill.ca/~pulsar/magnetar/main.html, 1309.4167

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 god candidates (Lazzati et al. 2006, Popov & Stern 2006, etc.).

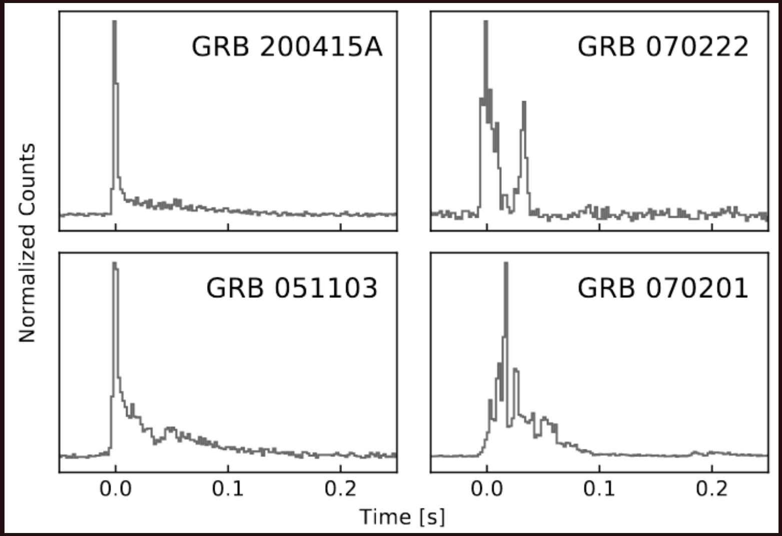
Finally, recently several good candidates have been proposed by different groups (Mazets et al., Frederiks et al., Golenetskii et al., Ofek et al, Crider ...., see arxiv:0712.1502 and references therein, for example).

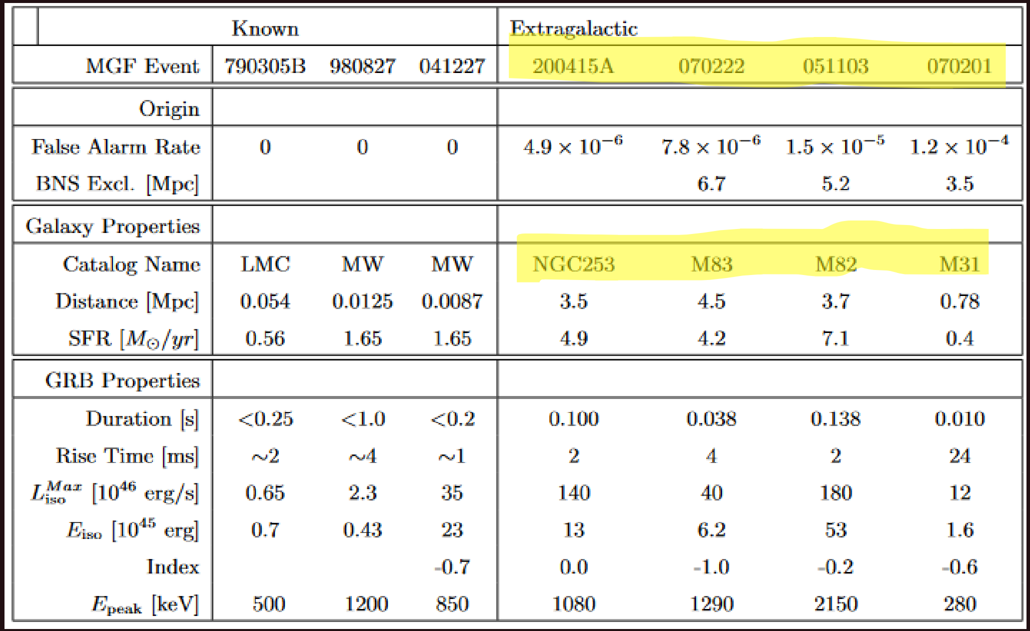
Burst from M31

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

[D. Frederiks et al. astro-ph/0609544]

Extragalactic hyperflares

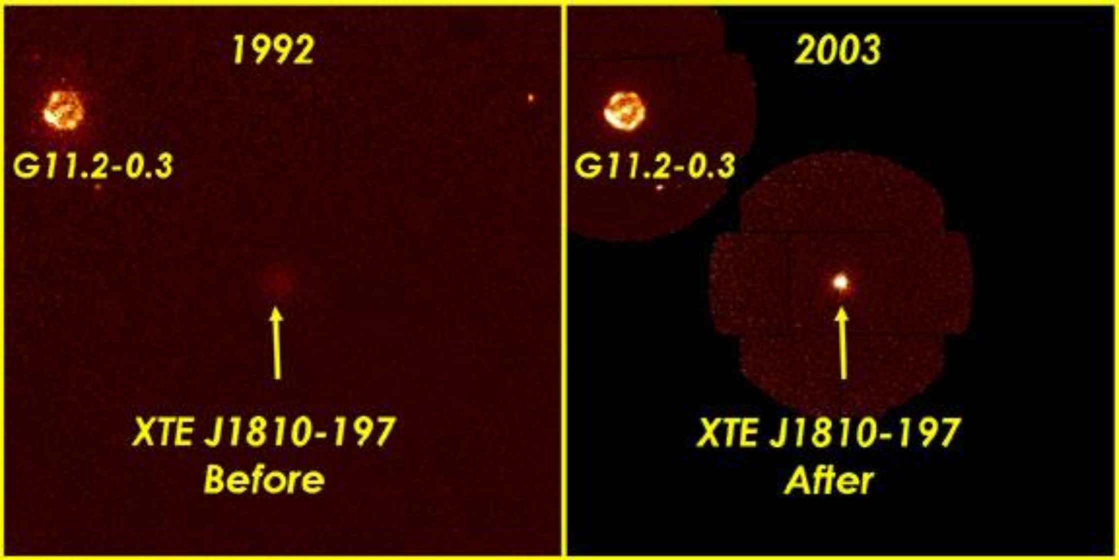




	Known			Extragalactic			
MGF Event	790305B	980827	041227	200415A	070222	051103	070201
Origin							
False Alarm Rate	0	0	0	4.9×10^{-6}	7.8×10^{-6}	1.5×10^{-5}	1.2×10^{-4}
BNS Excl. [Mpc]					6.7	5.2	3.5
Galaxy Properties							
Catalog Name	LMC	MW	MW	NGC253	M83	M82	M31
Distance [Mpc]	0.054	0.0125	0.0087	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
$L_{\rm iso}^{Max}$ [10^{46} erg/s]	0.65	2.3	35	140	40	180	12
$E_{\rm iso}$ [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
$E_{\rm peak}$ [keV]	500	1200	850	1080	1290	2150	280

2101.05144

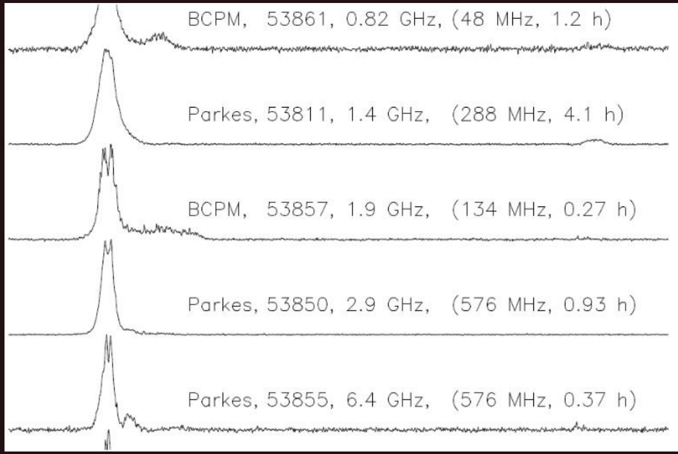
Transient radio emission from AXP



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 Pdot measurement.
Important to constrain models, for better distance and coordinates determinations, etc.



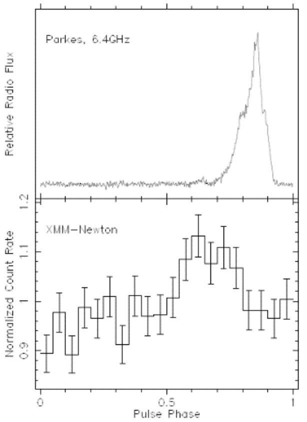
(Camilo et al. astro-ph/0605429) Recent radio data on this source: 1903.02660

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

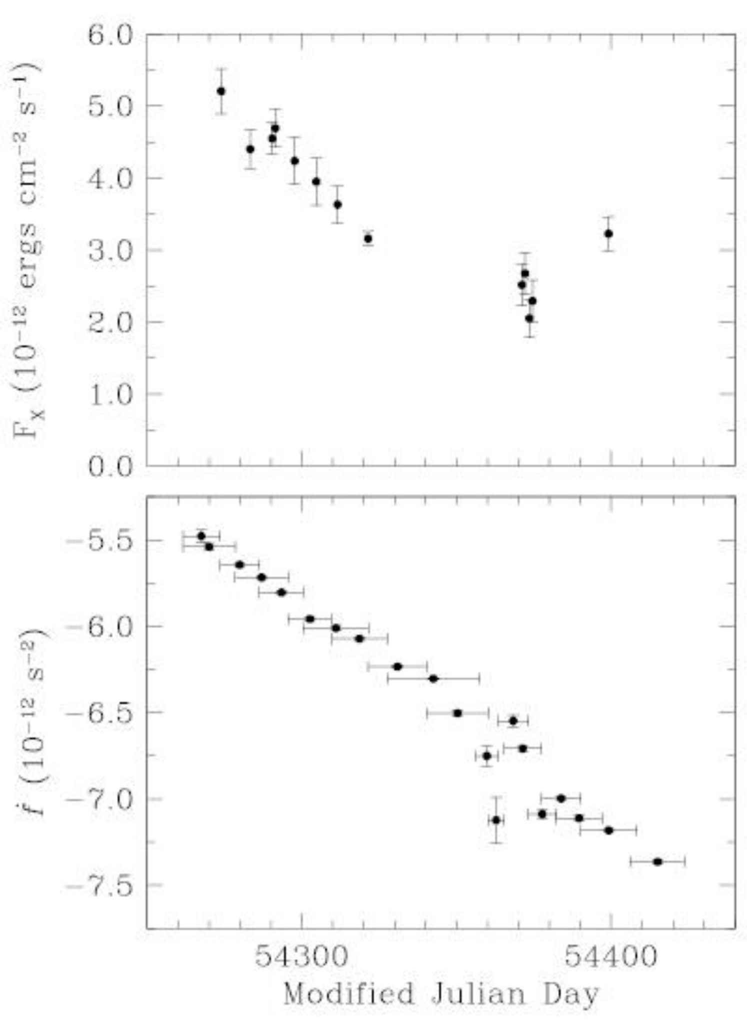
Also this AXP demonstrated weak
SGR-like bursts (Rea et al. 2008, GCN 8313)



Radio

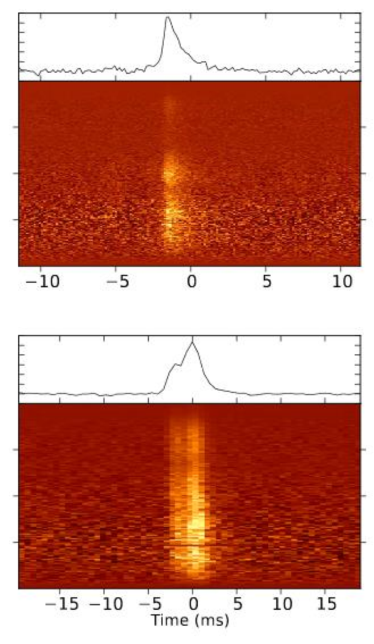
[simultaneous]

X-rays

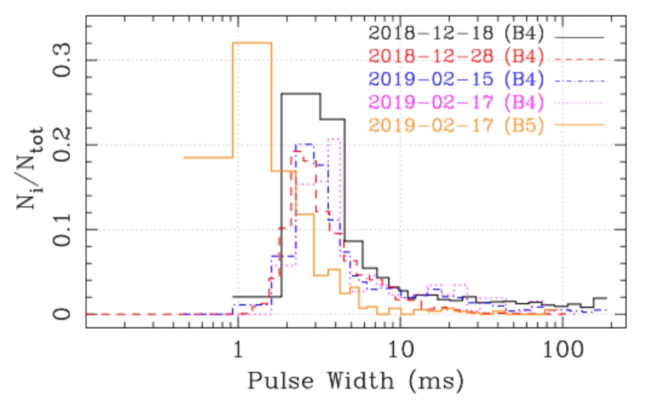


0802.0494 (see also arxiv:0711.3780)

Short radio pulses from magnetars

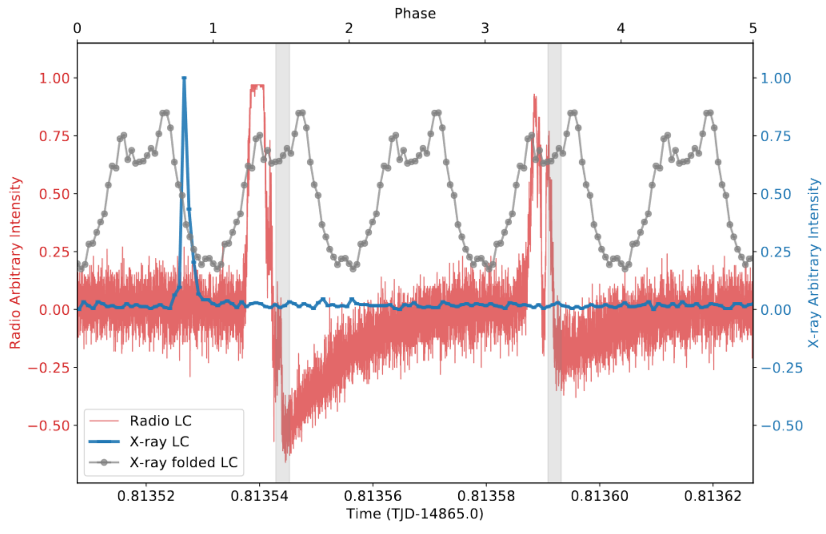


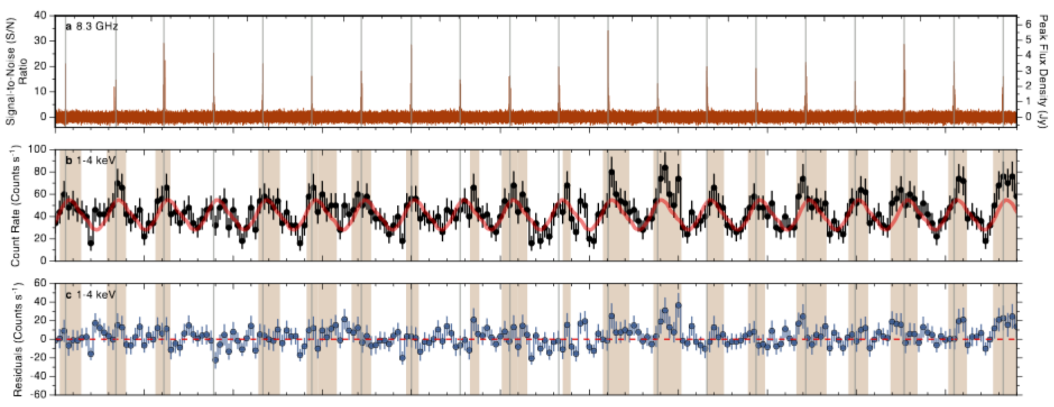
XTE 1810



1908.04304

1E 1547.0–5408





2005.08410

2011.06607

Transient radiopulsar

PSR J1846-0258
P=0.326 sec
$B=5\ 10^{13}$ G

However,
no radio emission
detected.
Due to beaming?

Among all rotation powered PSRs it has the largest Edot.
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.

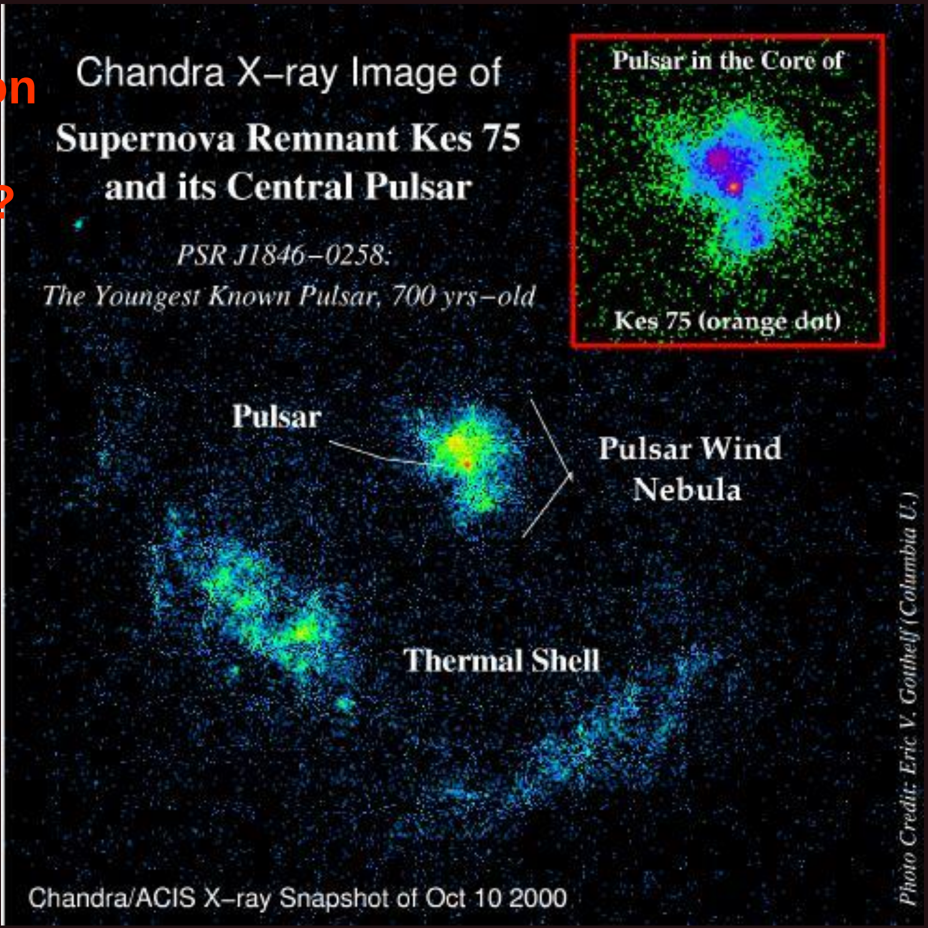
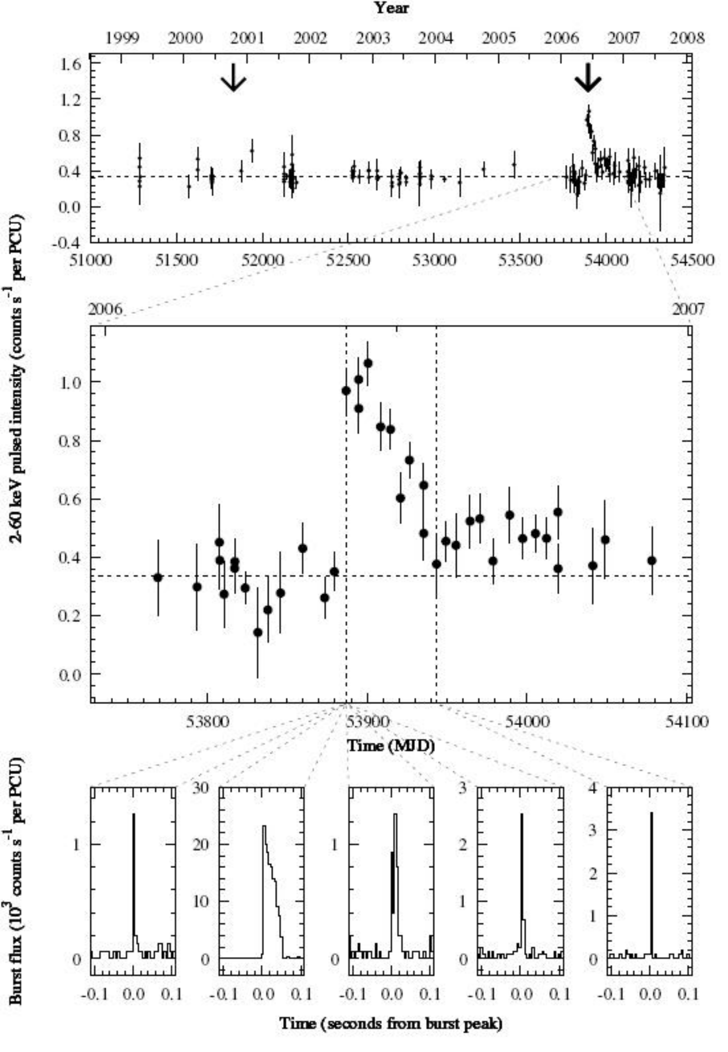


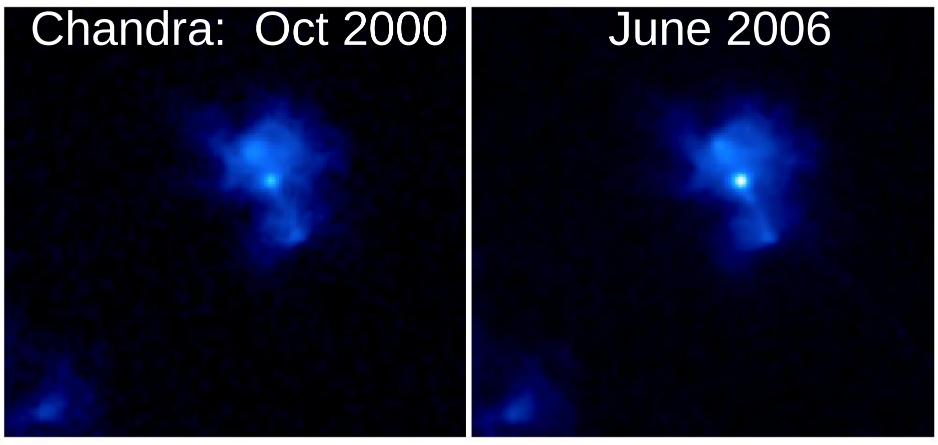
Photo Credit: Eric V. Gotthelf (Columbia U.)

See additional info about this pulsar at the web-site http://hera.ph1.uni-koeln.de/~heintzma/SNR/SNR1_IV.htm

0802.1242, 0802.1704

Bursts from the transient PSR





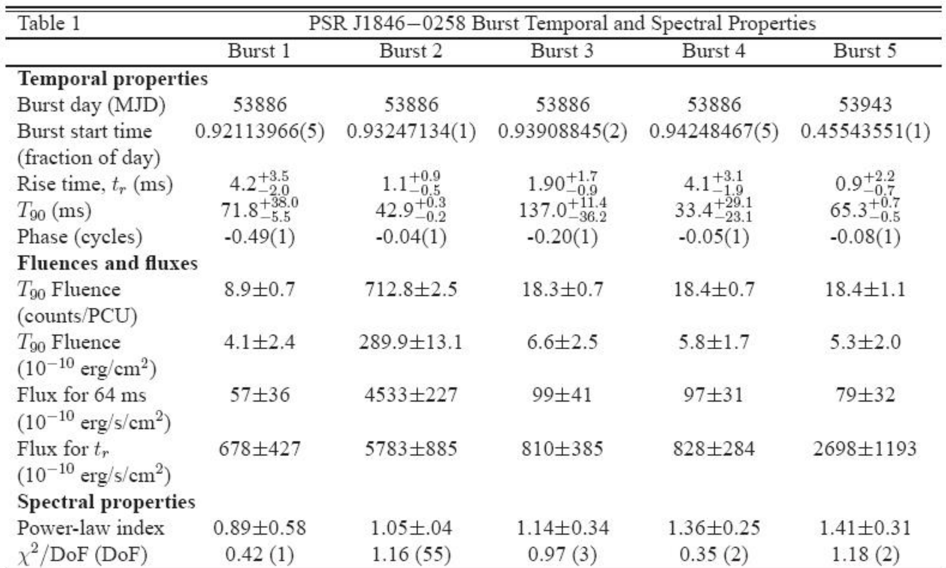
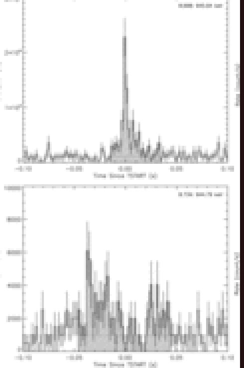


Table 1 PSR J1846−0258 Burst Temporal and Spectral Properties

	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±.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)

Gavriil et al. 0802.1704

Weak dipole field magnetar



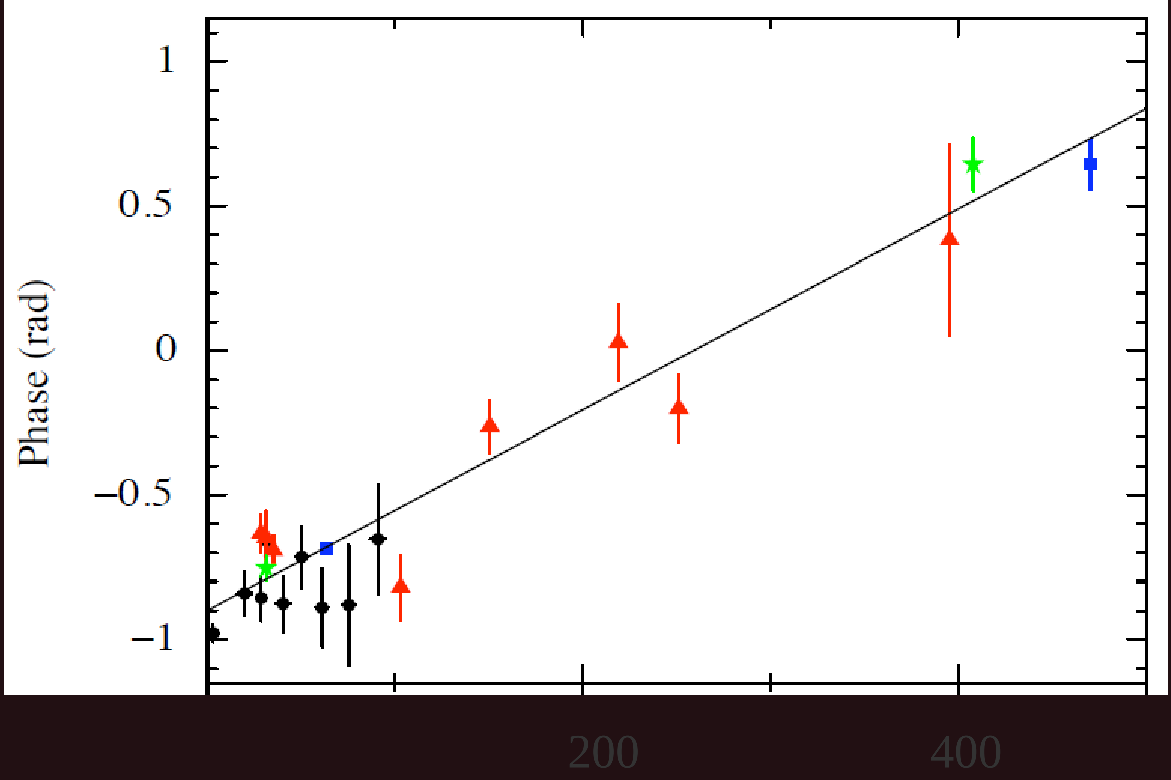
Spin period of a neutron star grows.
The rate of deceleration is related to the dipole magnetic field.
Measuring the spin-down rate we measure the field.

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 10^{12} G (arXiv:1010.2781)

Old magnetar ? (1107.5488)

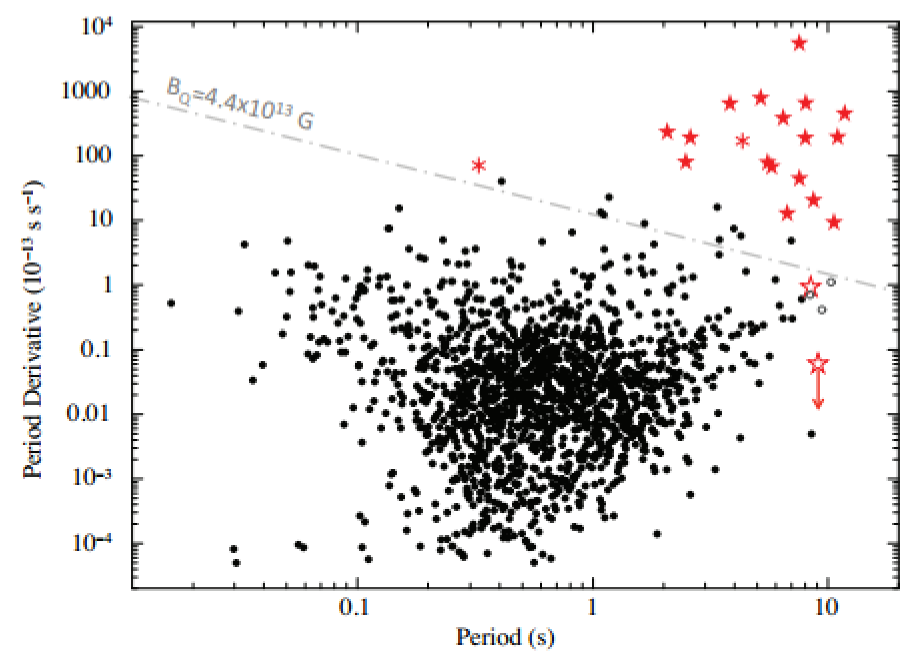


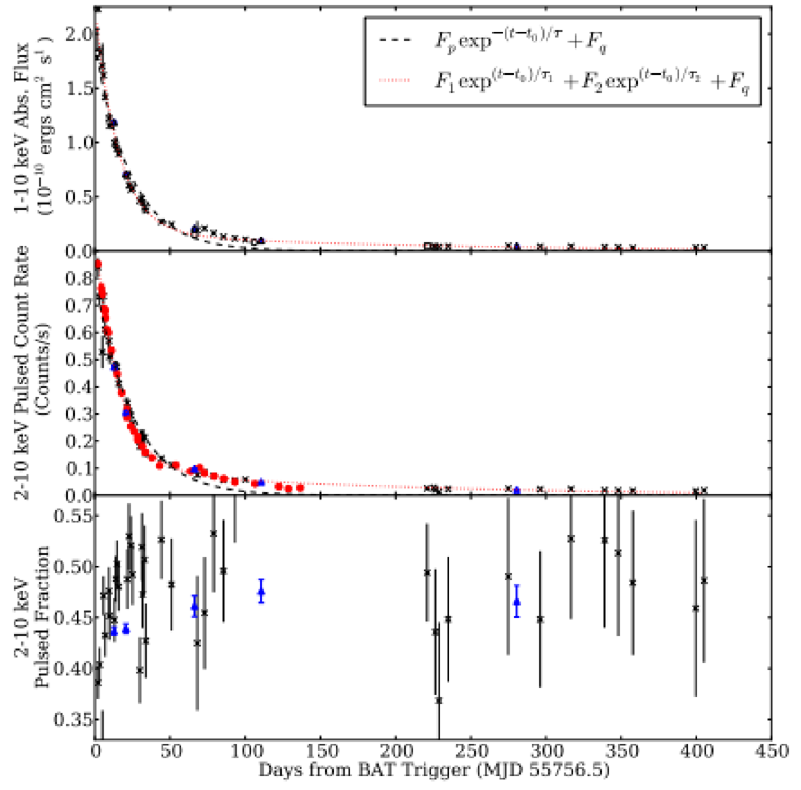
Spectral data suggests high field on the surface: 1103.3024

Another low field magnetar

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

P=8.44 s
B=3-5 10^{13} G



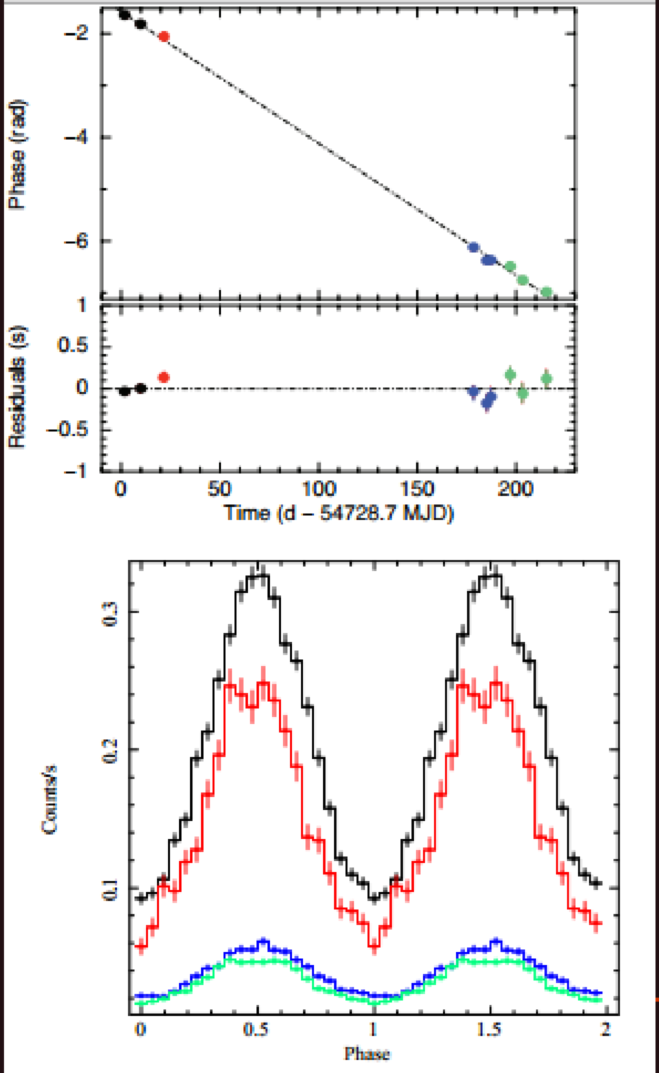


1204.1034

1203.6449

New data: 1211.7347

One more low-field magnetar

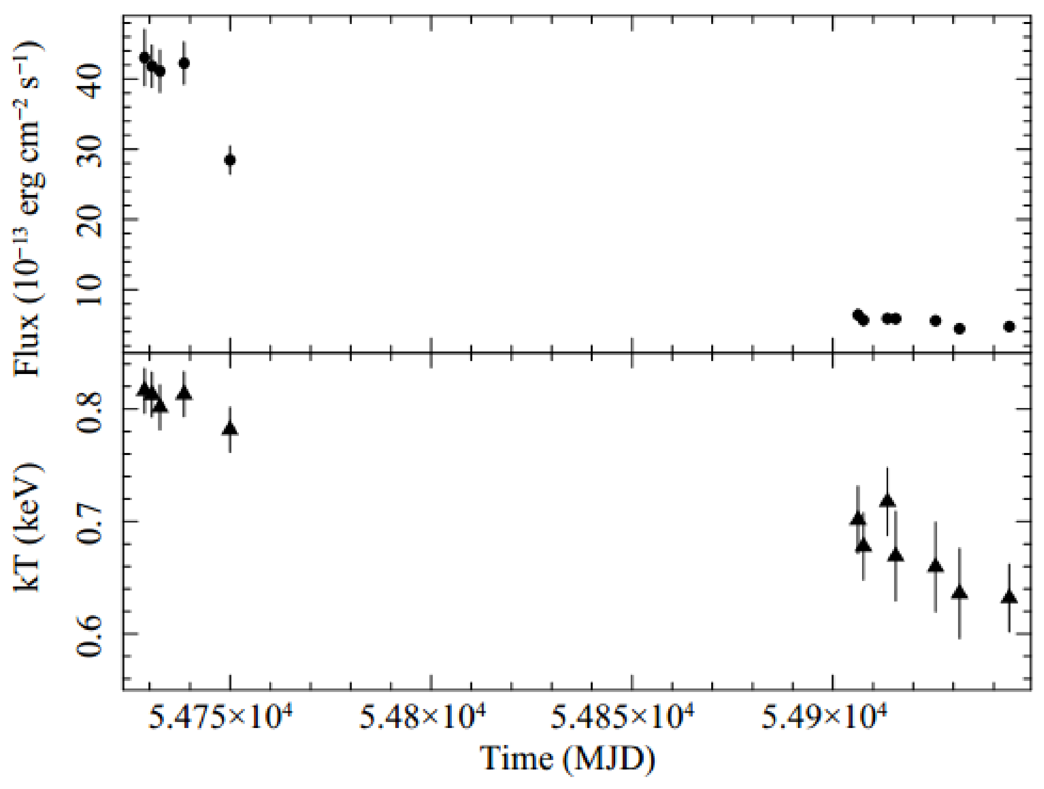


3XMM J185246.6+003317

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

B<4 10^{13} G

Transient magnetar



1311.3091

Quiescent magnetar J1622–4950

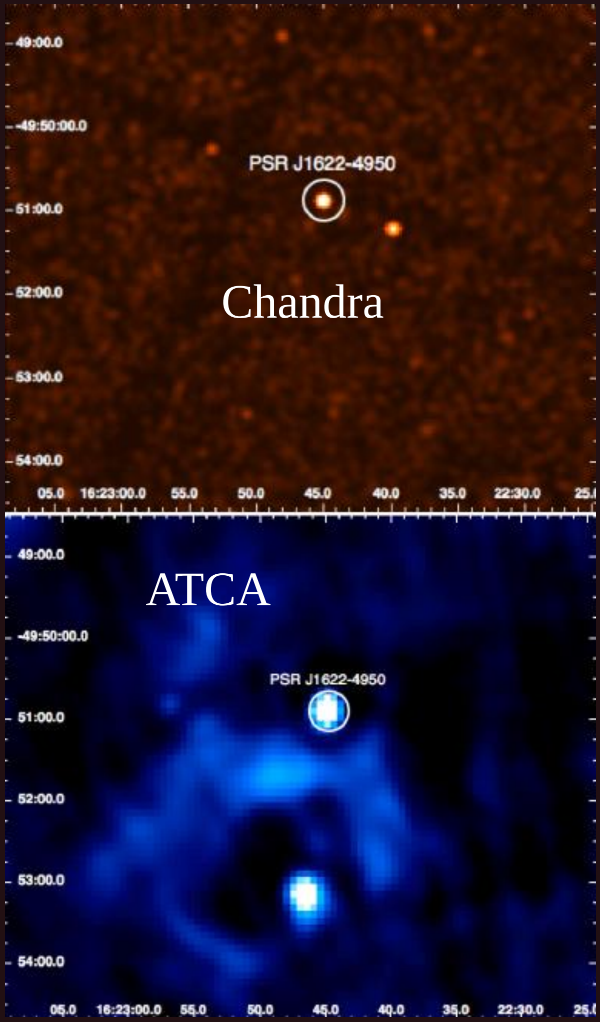
Normally, magnetars are detected via their strong activity: gamma-ray bursts or enhanced X-ray luminosity.

This one was detected in radio observations
The field is estimated to be $B\sim3\ 10^{14}$ 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



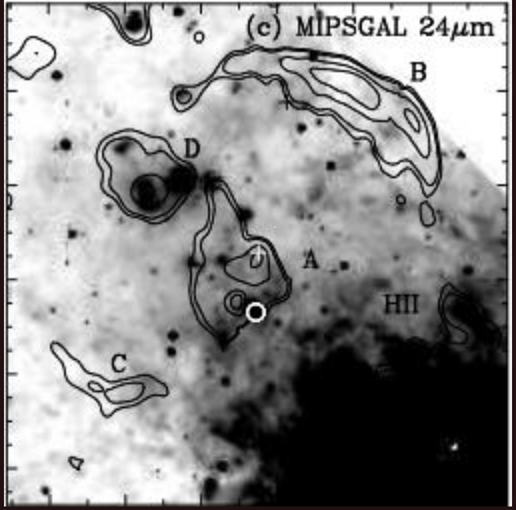
See reviews on high-B PSRs in 1010.4592, 1805.01680

arXiv: 1007.1052

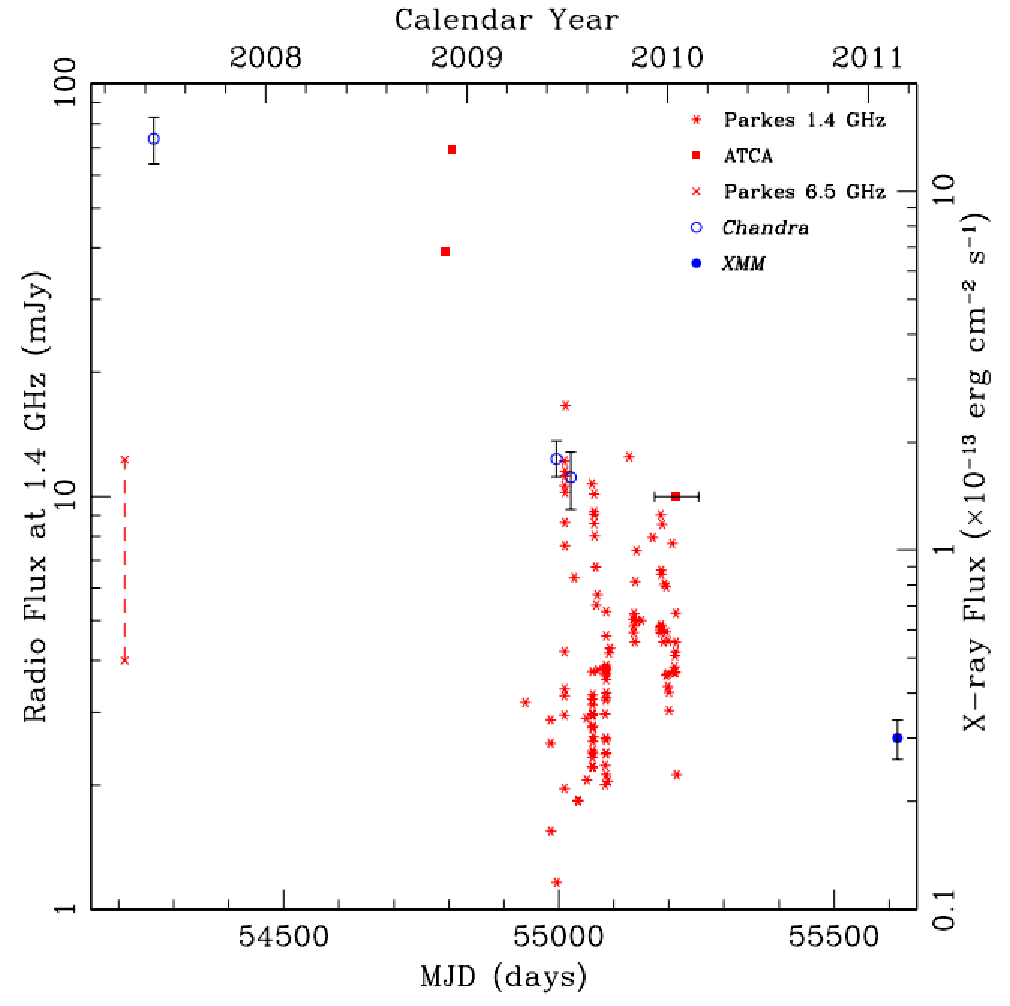
Is J1622–4950 a transient magnetar?

PSR J1622–4950

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



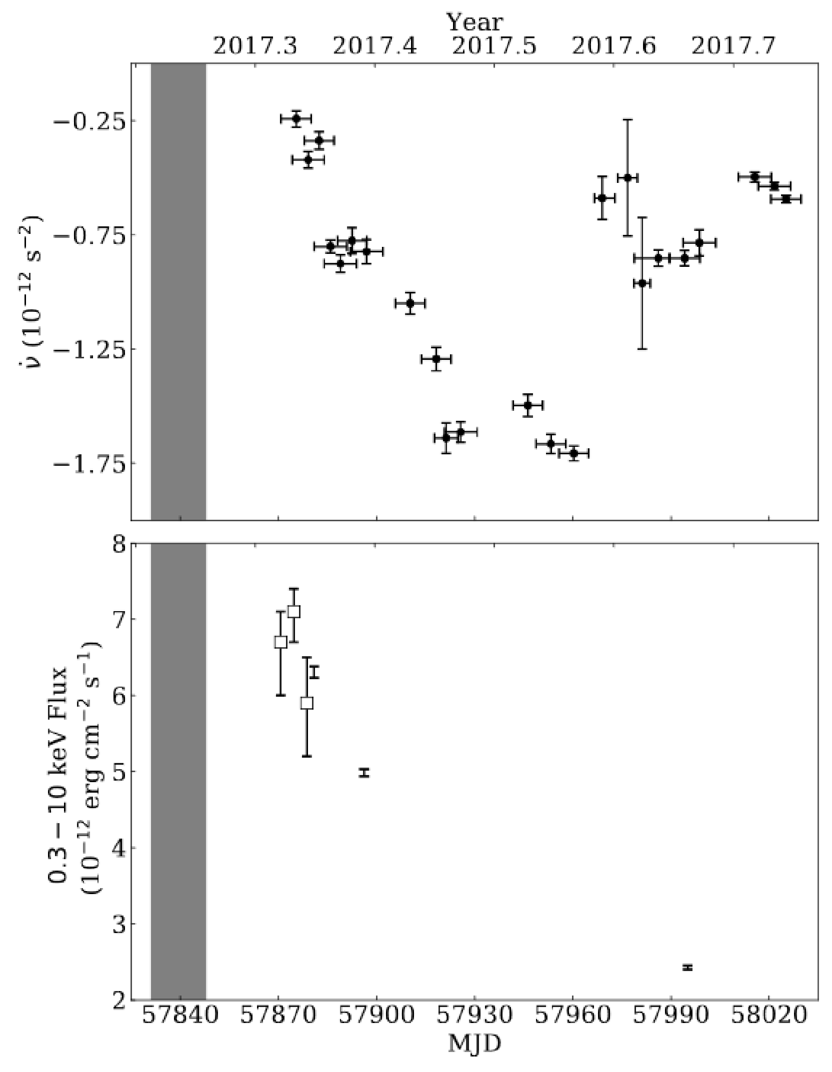
G333.9+0.0 SNR ?

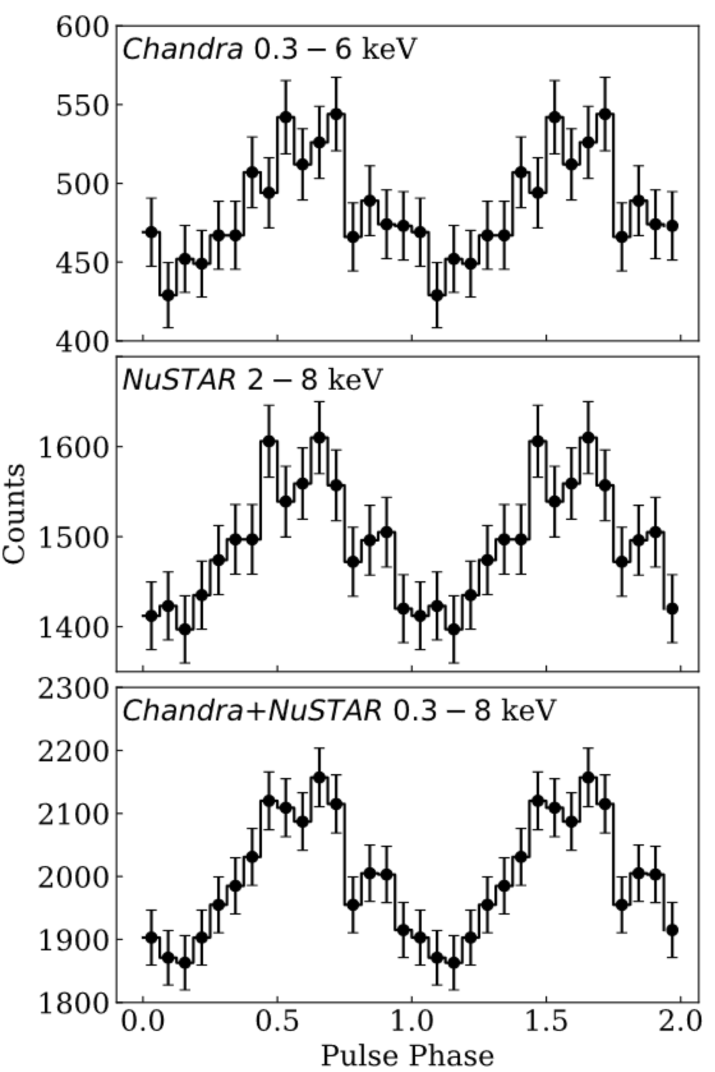


1203.2719

See also 1204.2045

Yes! Revival of J1622–4950

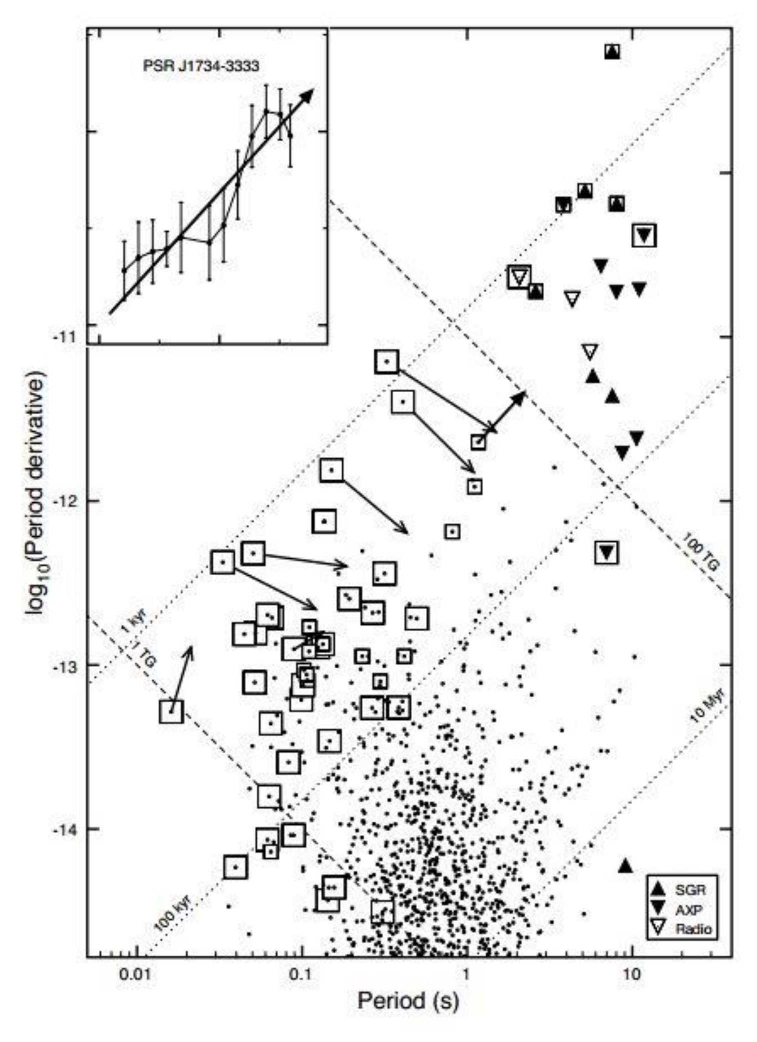




1804.01933

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

A pulsar with growing field?

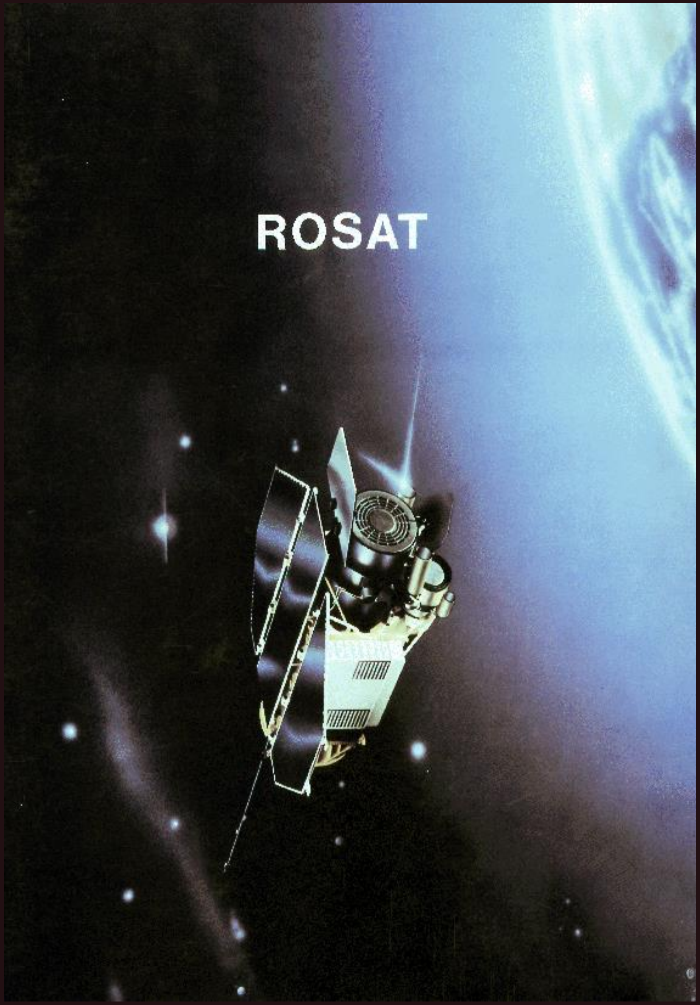


PSR J1734−3333
n=0.9+/-0.2

Will it become a magnetar?

Espinoza et al. arXiv: 1109.2740

ROSAT

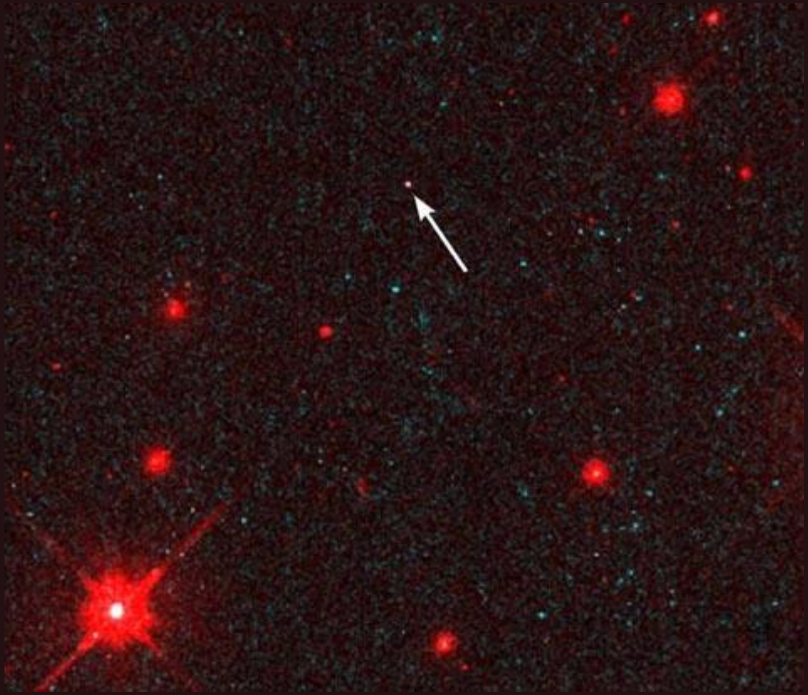


ROentgen SATellite

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

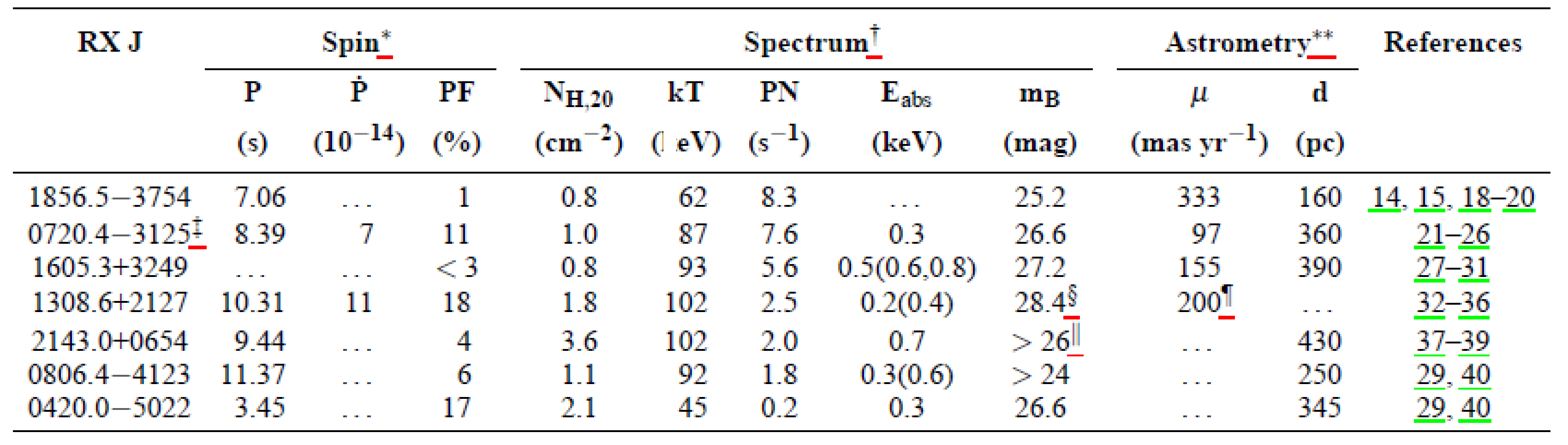
Magnificent Seven

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

Spin properties and other parameters

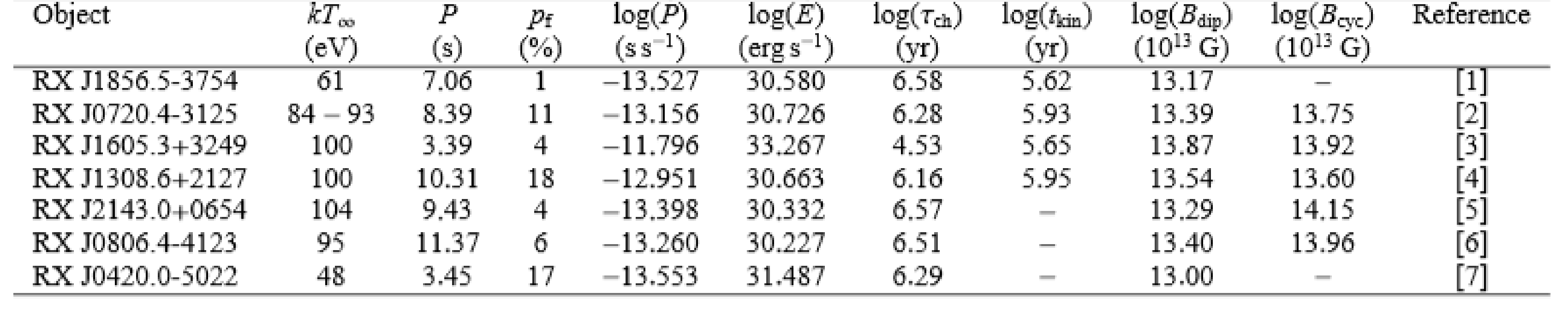


RX J	Spin[*]			Spectrum[†]					Astrometry[**]		References
	P (s)	$\dot{P}$ (10^{-14})	PF (%)	$N_{H,20}$ (cm^{-2})	kT (eV)	PN (s^{-1})	E_{abs} (keV)	m_B (mag)	μ (mas yr^{-1})	d (pc)	
1856.5−3754	7.06	…	1	0.8	62	8.3	…	25.2	333	160	14, 15, 18–20
0720.4−3125[‡]	8.39	7	11	1.0	87	7.6	0.3	26.6	97	360	21–26
1605.3+3249	…	…	< 3	0.8	93	5.6	0.5(0.6,0.8)	27.2	155	390	27–31
1308.6+2127	10.31	11	18	1.8	102	2.5	0.2(0.4)	28.4[§]	200[¶]	…	32–36
2143.0+0654	9.44	…	4	3.6	102	2.0	0.7	> 26[‖]	…	430	37–39
0806.4−4123	11.37	…	6	1.1	92	1.8	0.3(0.6)	> 24	…	250	29, 40
0420.0−5022	3.45	…	17	2.1	45	0.2	0.3	26.6	…	345	29, 40

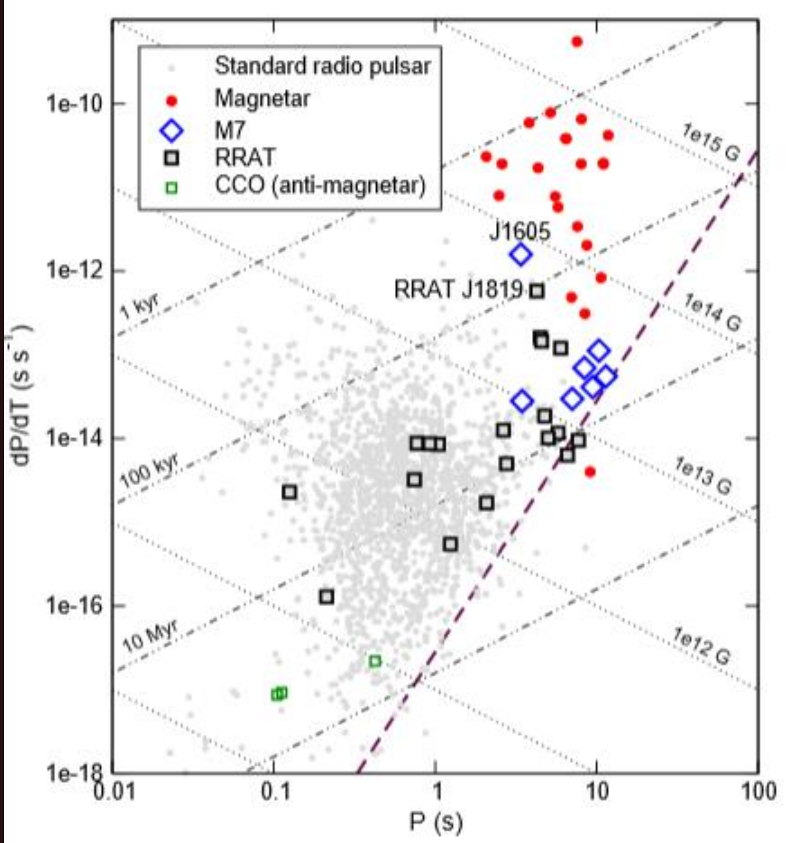
Kaplan arXiv: 0801.1143

Updates:

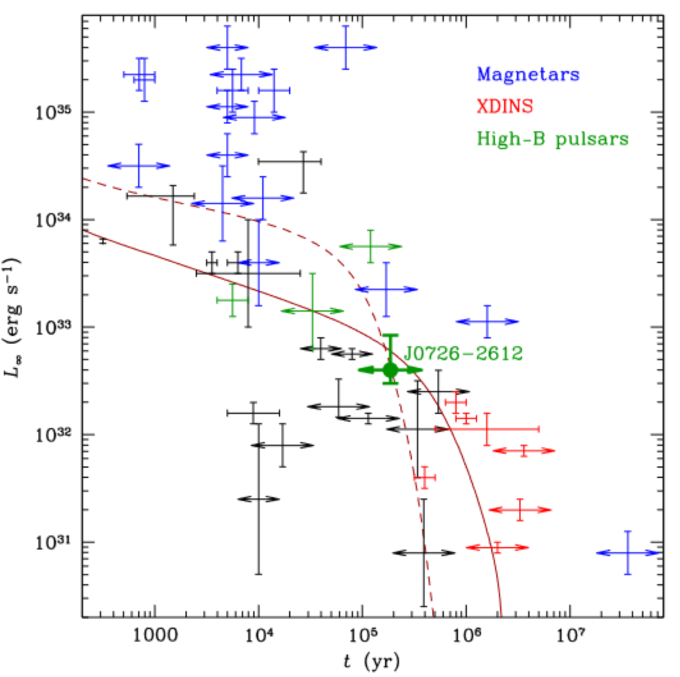
- 1856. vdot=-6 10^{-16} (| vdot|<1.3 10^{-14}) van Kerkwijk & Kaplan arXiv: 0712.3212
- 2143. vdot=-4.6 10^{-16} Kaplan & van Kerkwijk arXiv: 0901.4133
- 0806. |vdot|<4.3 10^{-16} Kaplan and van Kerkwijk arXiv: 0909.5218



Object	kT_∞ (eV)	P (s)	p_f (%)	$\log(\dot{P})$ (s s^{-1})	$\log(\dot{E})$ (erg s^{-1})	$\log(\tau_\mathrm{ch})$ (yr)	$\log(t_\mathrm{kin})$ (yr)	$\log(B_\mathrm{dip})$ (10^{13} G)	$\log(B_\mathrm{cyc})$ (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]

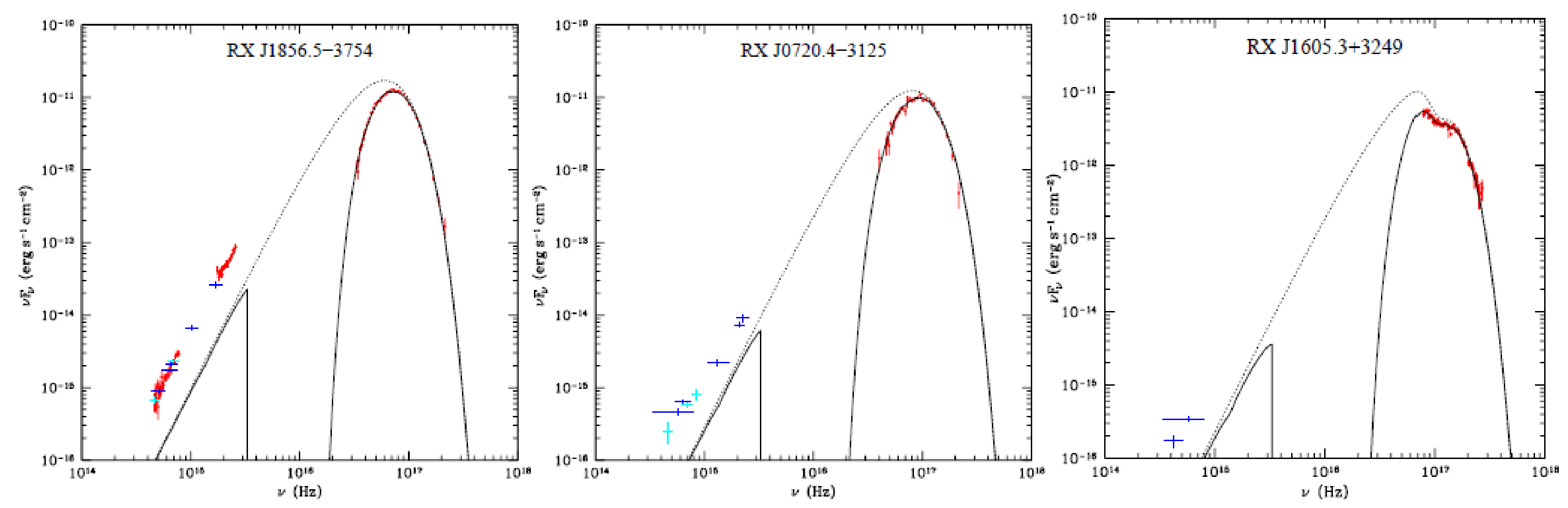


Several radio pulsars can be similar to M7. E.g. PSR J0726−2612 (see 1906.01372).

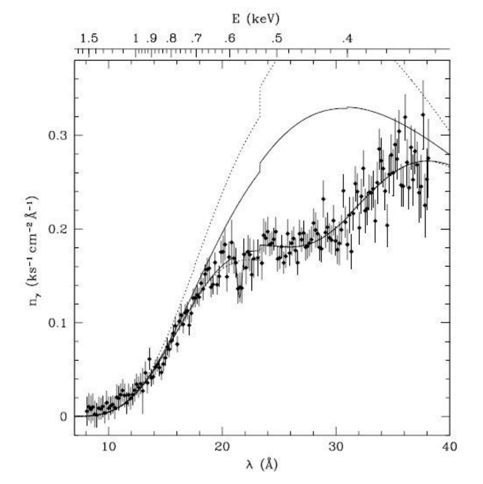


1401.7147

Spectral properties



Kaplan arXiv: 0801.1143



Van Kerkwijk et al. (2004)

Spectra are blackbody plus one or several wide absorption features.
The origin of features is not understood, yet.

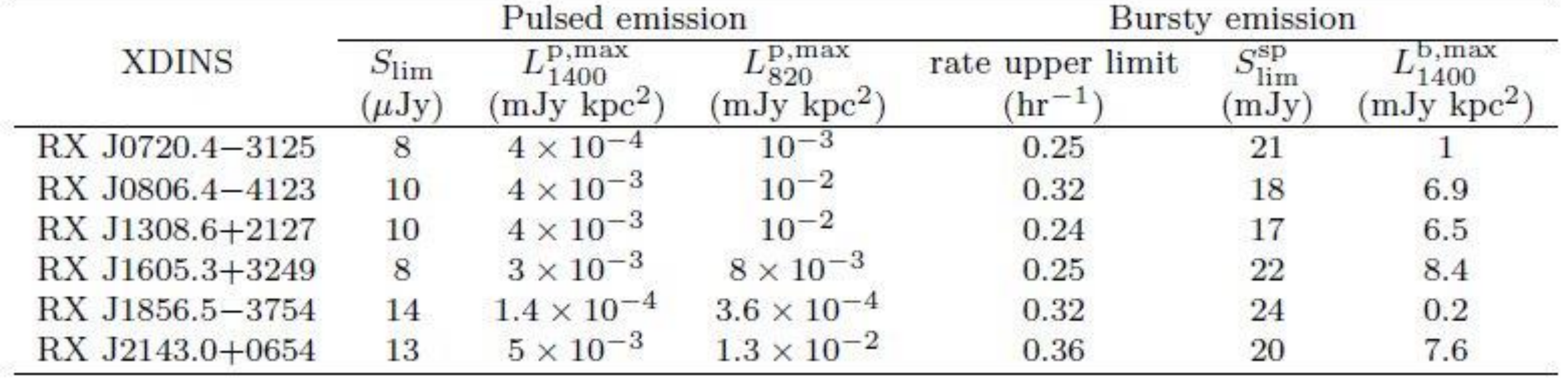
New data: Kaplan et al. 1105.4178

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

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 (<~100 MHz).

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

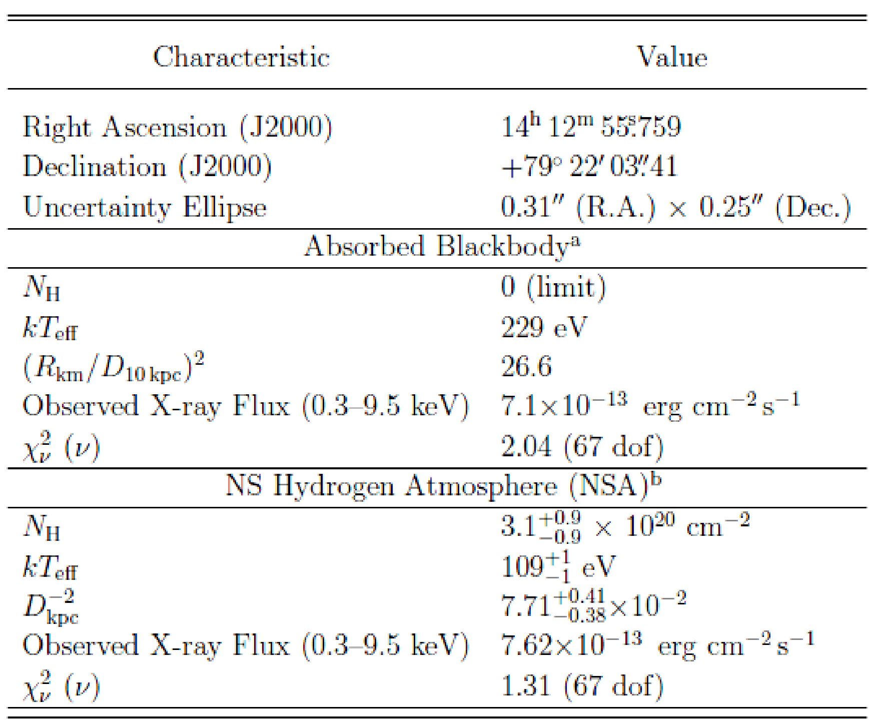


XDINS	Pulsed emission			Bursty emission		
	$S_{\rm lim}$ (μJy)	$L_{1400}^{\rm p,max}$ (mJy kpc^2)	$L_{820}^{\rm p,max}$ (mJy kpc^2)	rate upper limit (hr^{-1})	$S_{\rm lim}^{\rm sp}$ (mJy)	$L_{1400}^{\rm b,max}$ (mJy kpc^2)
RX J0720.4−3125	8	4×10^{-4}	10^{-3}	0.25	21	1
RX J0806.4−4123	10	4×10^{-3}	10^{-2}	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

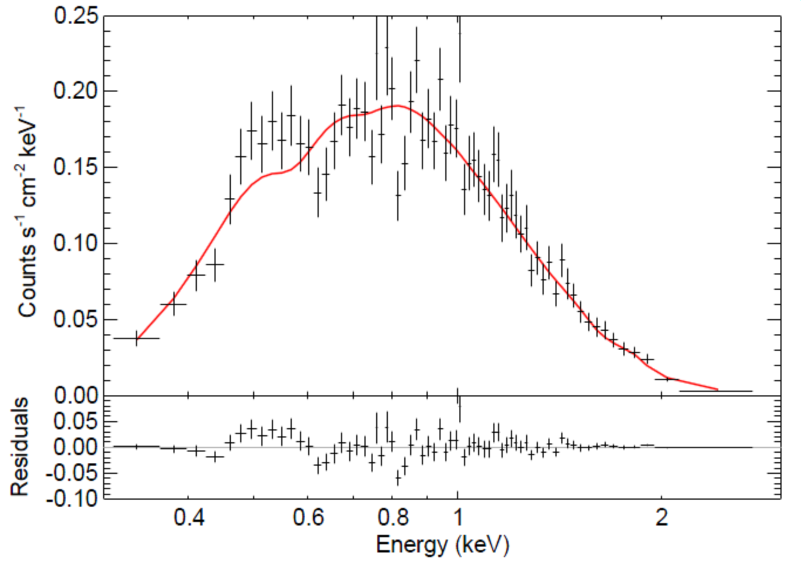
Kondratiev et al. arXiv: 0907.0054

Calvera et al.

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

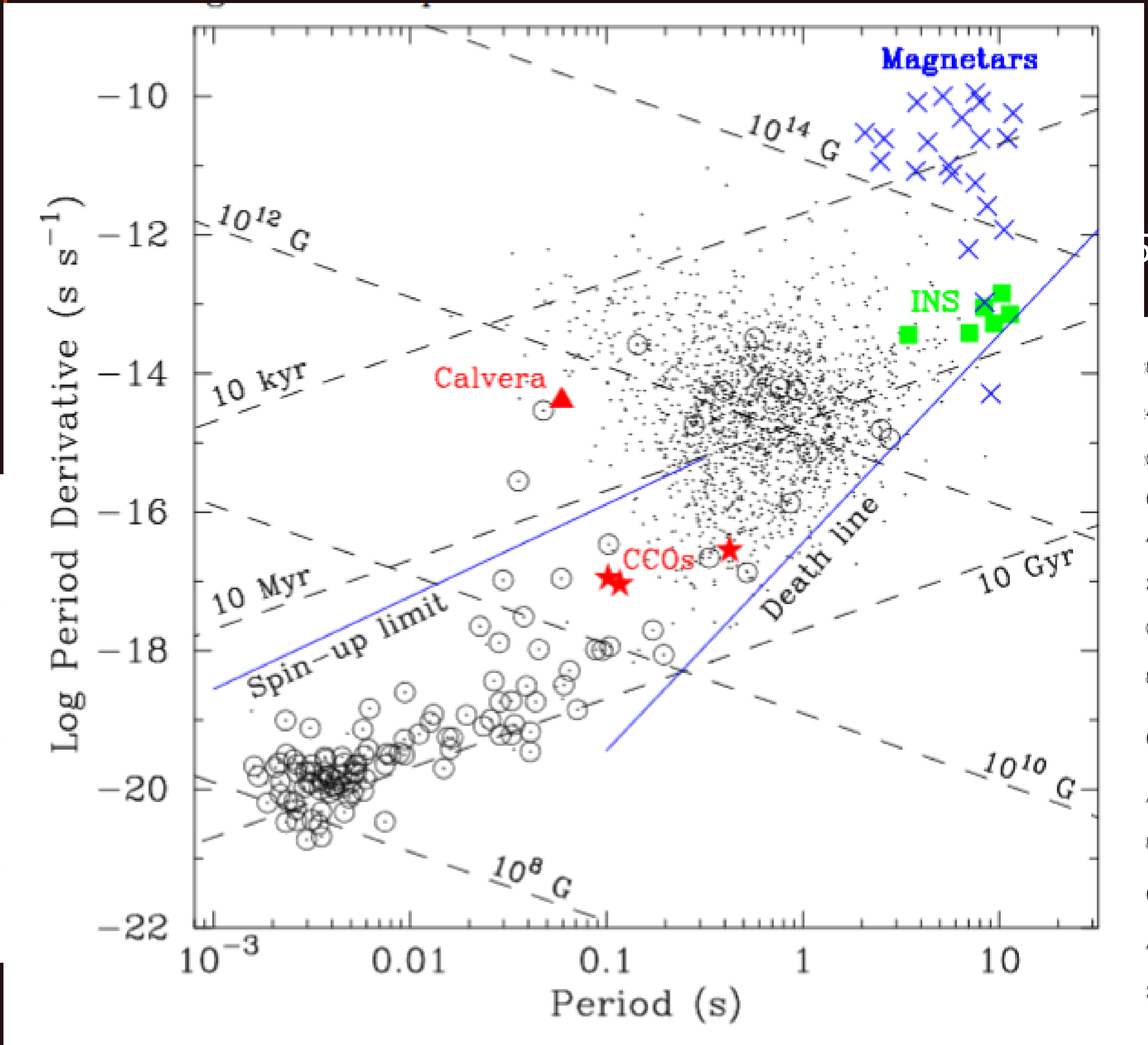


Characteristic	Value
Right Ascension (J2000)	$14^{\mathrm{h}}\,12^{\mathrm{m}}\,55\overset{\mathrm{s}}{.}759$
Declination (J2000)	$+79^{\circ}\,22'\,03\overset{''}{.}41$
Uncertainty Ellipse	$0.31''$ (R.A.) × $0.25''$ (Dec.)
Absorbed Blackbody[a]	
N_{H}	0 (limit)
kT_{eff}	229 eV
$(R_{\mathrm{km}}/D_{10\,\mathrm{kpc}})^2$	26.6
Observed X-ray Flux (0.3–9.5 keV)	7.1×10^{-13} erg cm^{-2} s^{-1}
χ^2_ν (ν)	2.04 (67 dof)
NS Hydrogen Atmosphere (NSA)[b]	
N_{H}	$3.1^{+0.9}_{-0.9}\times10^{20}$ cm^{-2}
kT_{eff}	109^{+1}_{-1} eV
D^{-2}_{kpc}	$7.71^{+0.41}_{-0.38}\times10^{-2}$
Observed X-ray Flux (0.3–9.5 keV)	7.62×10^{-13} erg cm^{-2} s^{-1}
χ^2_ν (ν)	1.31 (67 dof)

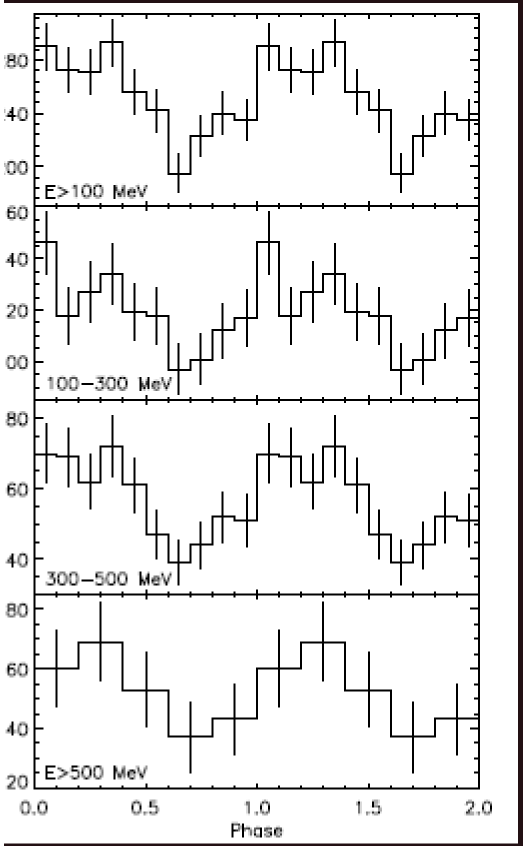


Shevchuk et al. arXiv: 0907.4352

1310.6789



0 eV and ~80/250 eV)



New data 1510.00683, 1902.00144, 2110.14930

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

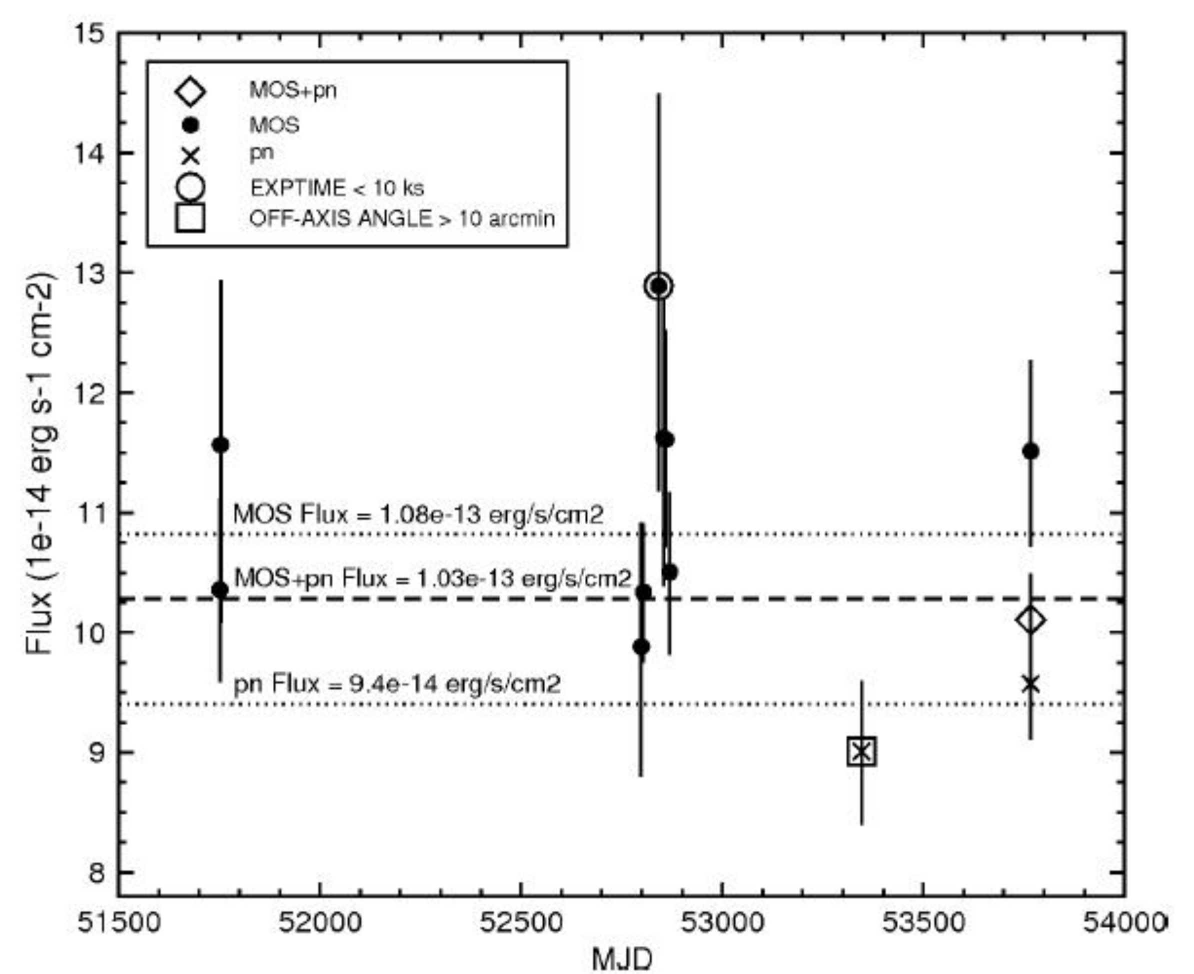
A new INS candidate.

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:
$F_x \sim 1.3\ 10^{-12}$ erg s^{-1} cm^{-2}
in the 0.1–12 keV band.

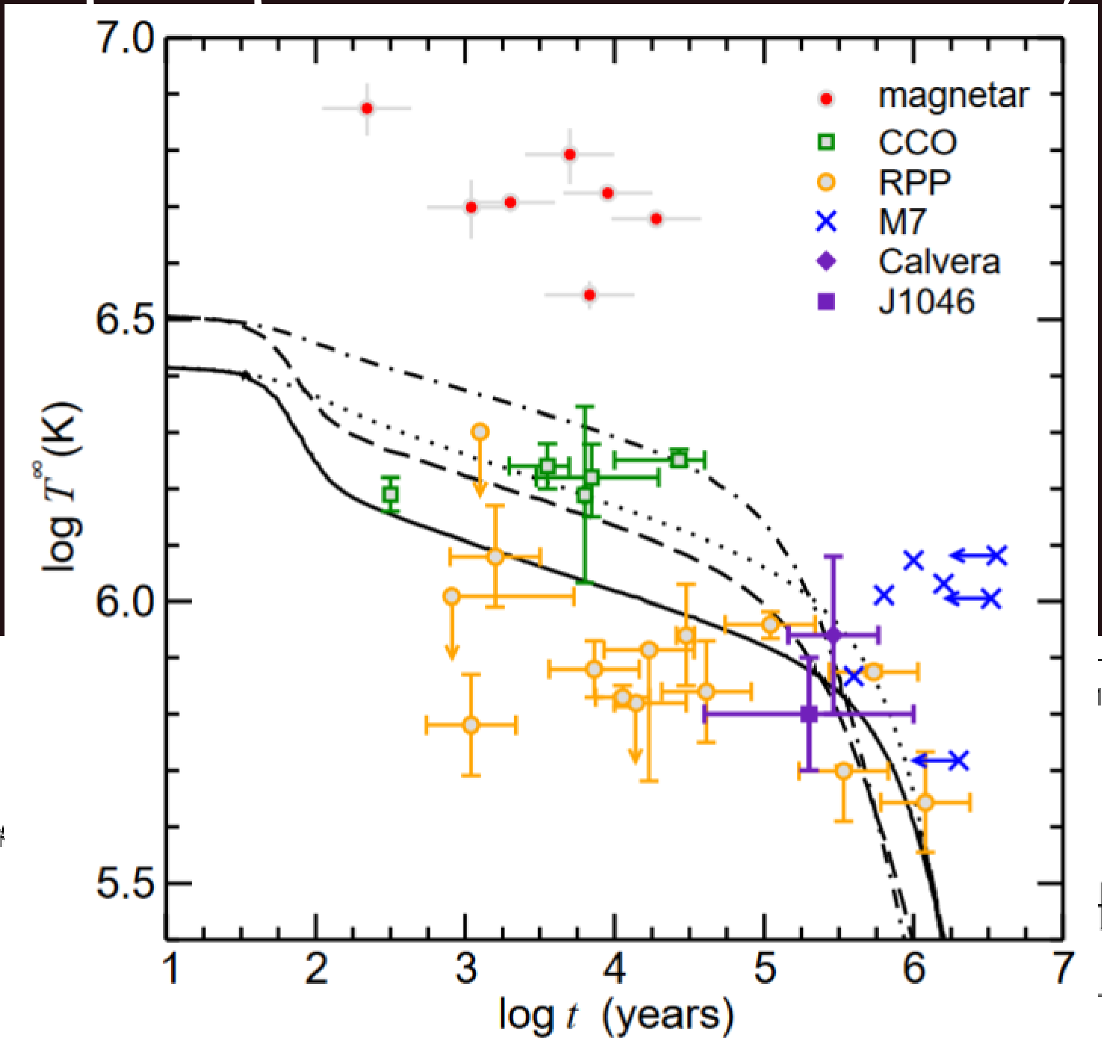
At 2.3 kpc (Eta Carina)
the luminosity is
$L_X \sim 8.2\ 10^{32}$ erg s^{-1}
$R_\infty \sim 5.7$ km



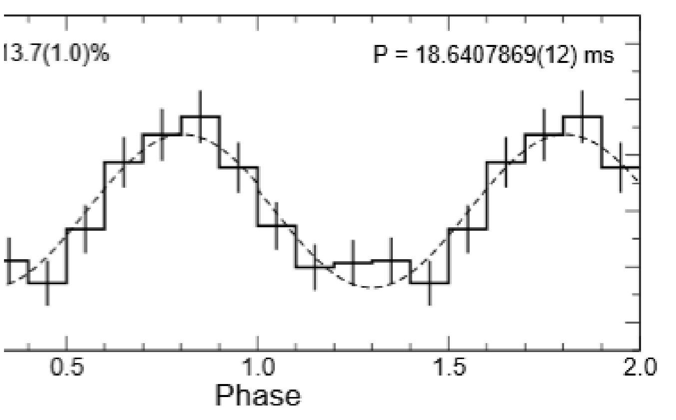
M7-like? Yes!
But P=19 msec

Pires & Motch arXiv: 0710.5192 and Pires et al. arXiv: 0812.4151

Spin period of 2XMM J1046-5943



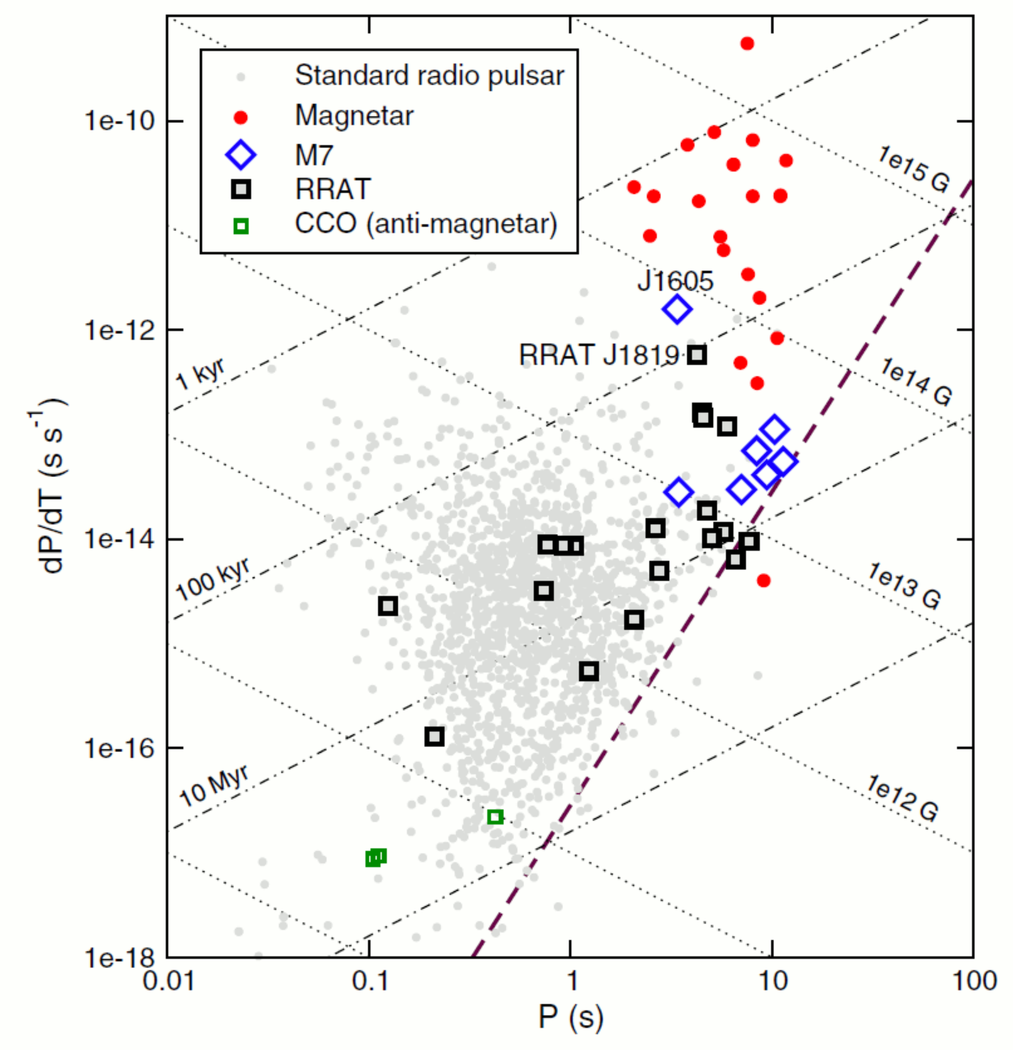
Calvera-like?



$T_{\rm eff} = (6 - 10) \times 10^5$ K, and $L_X = (1.1 - 7.4) \times 10^{32}$ 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.

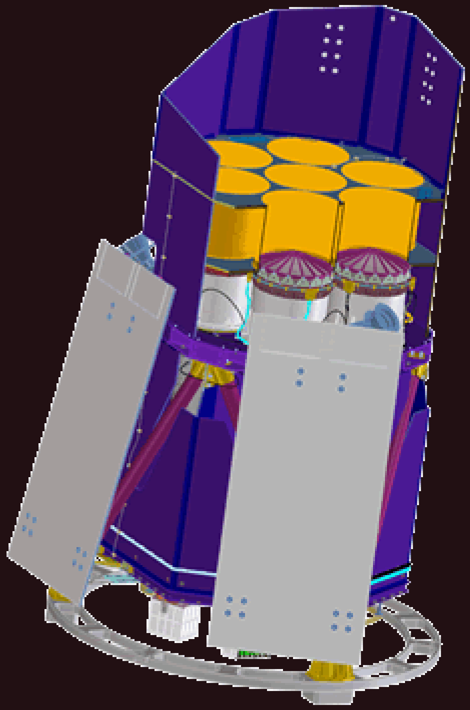
Or, can be a different population.

Pires et al. (2015), A&A

How to find new candidates?

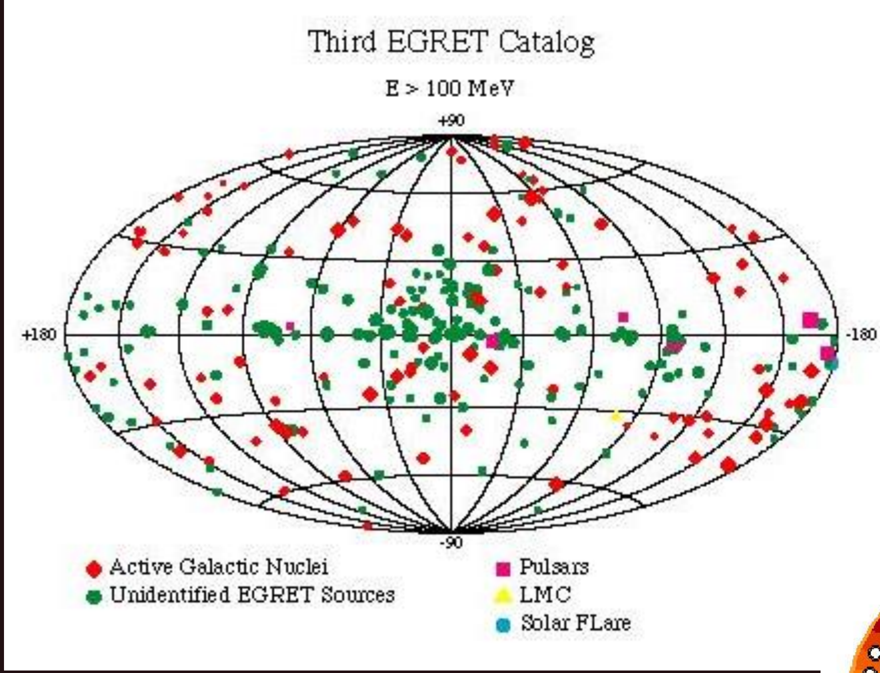
1. Digging the data
   Many attempts failed. One of the latest used SDSS optical data together with ROSAT X-ray. Candidates have been observed by Chandra. Nothing was found (Agueros et al. arXiv: 1103.2132).

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.)

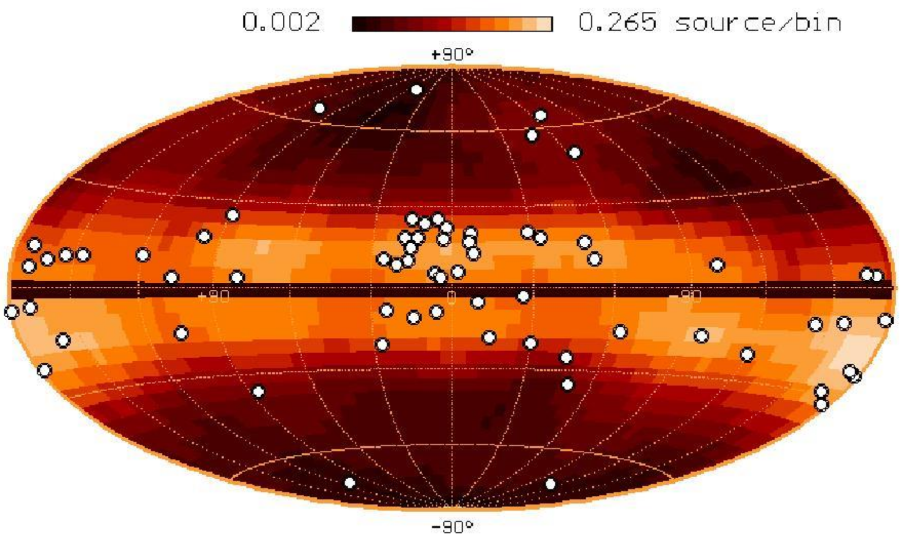


Pulsars invisible in radio?

EGRET data
Many unidentified sources

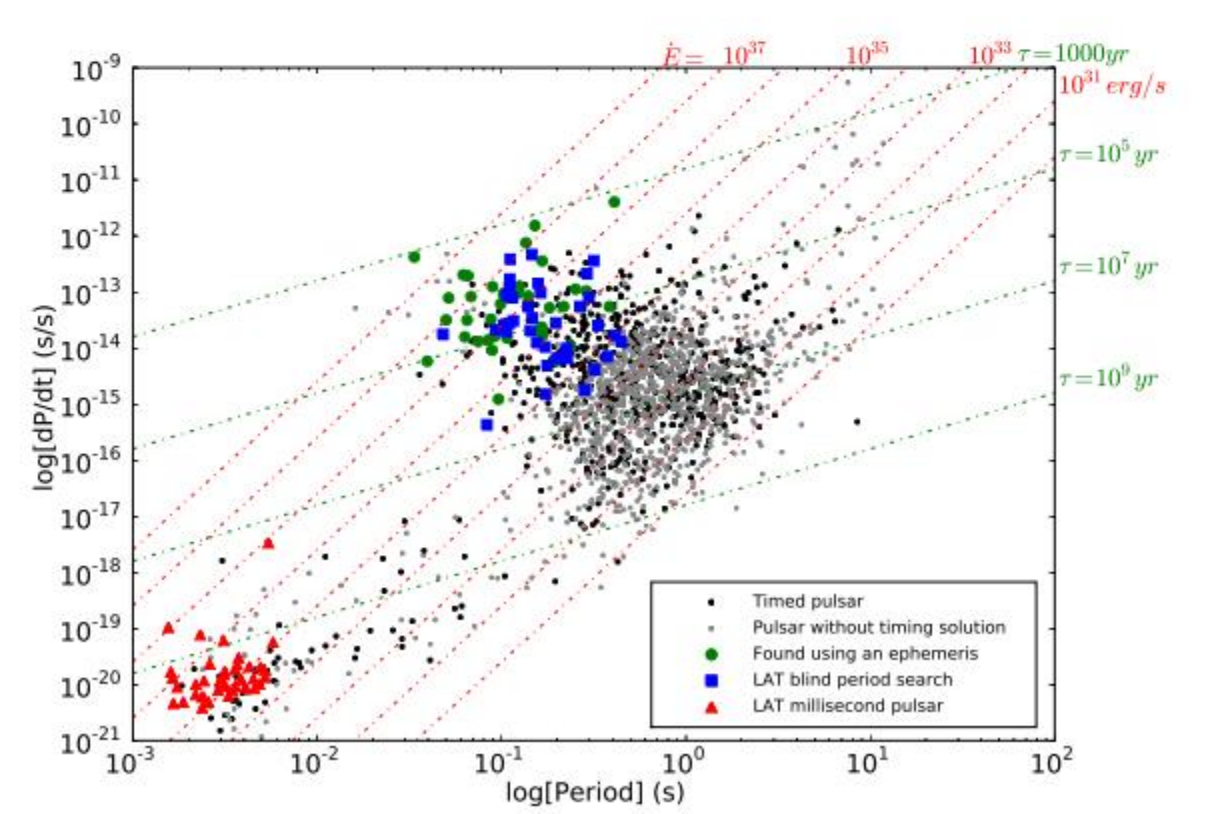


(Nolan et al. astro-ph/9607079)



(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

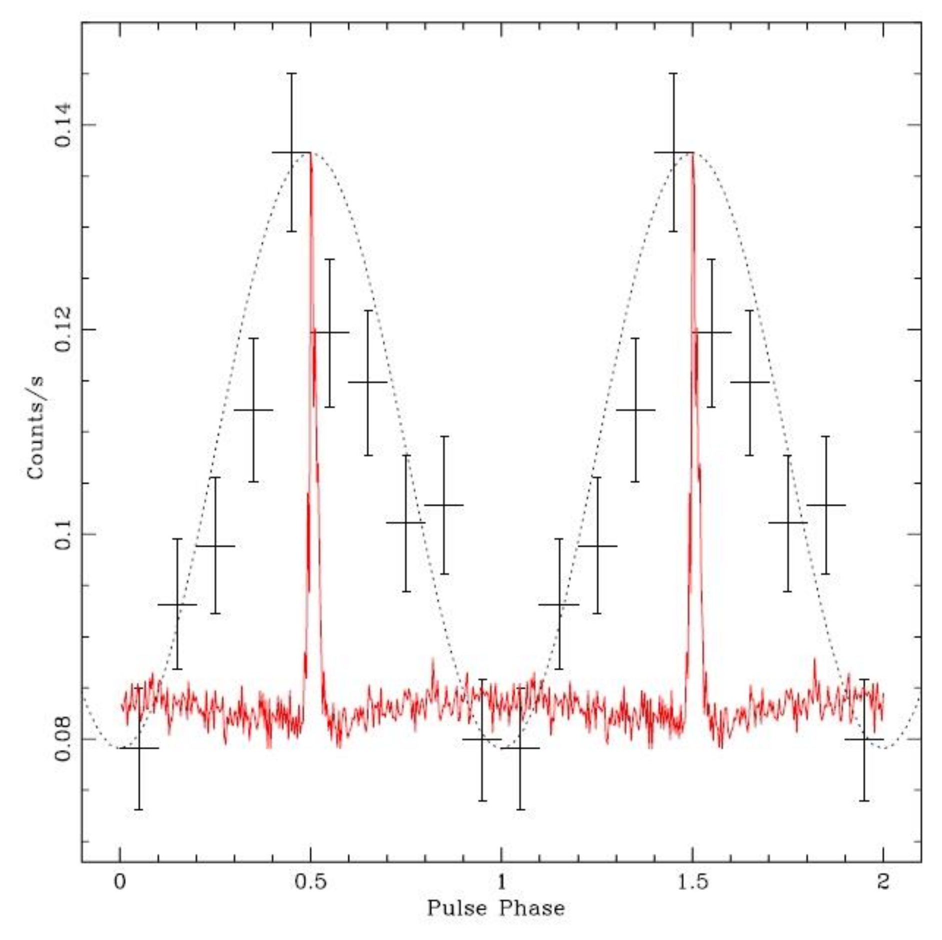
>100 sources known.

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

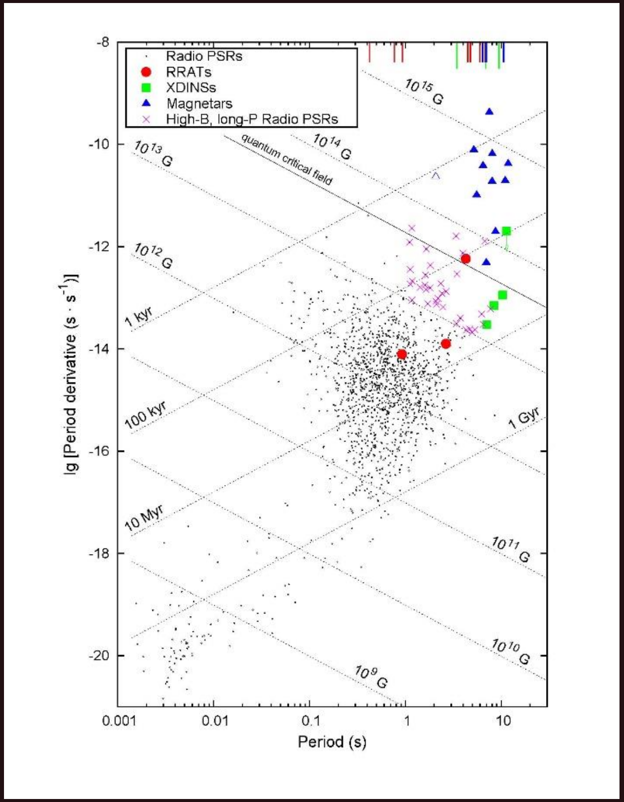
Review: 1109.6896

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

RRATs. X-ray + radio data

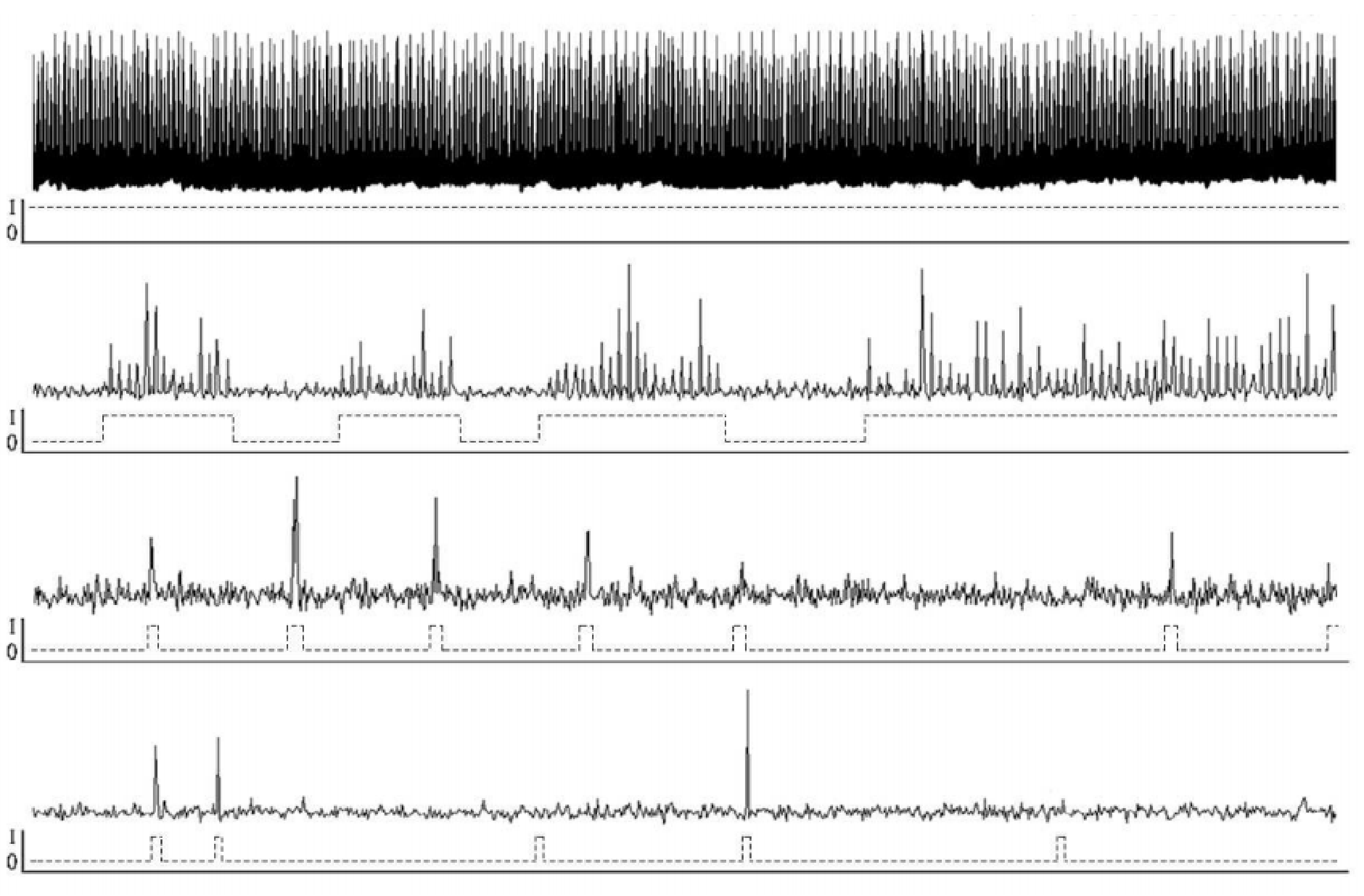


X-ray pulses overlaped on radio data of RRAT J1819-1458.



arXiv: 0710.2056

RRAT – are pulsars?



Vela

PSR
J1646–6831

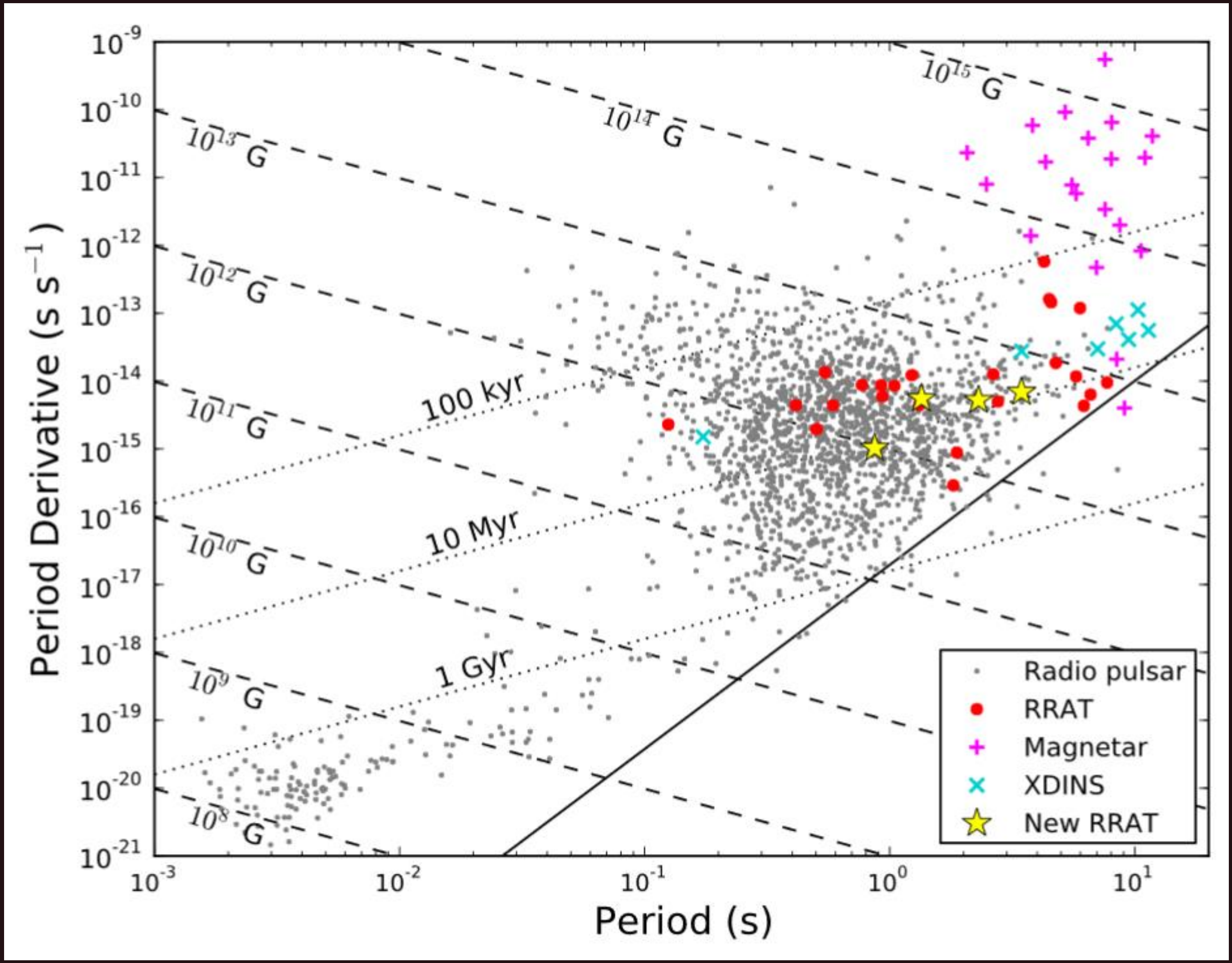
J1647–36

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.

1212.1716

RRATs properties



RRATs with P-Pdot seem to be similar to PSRs

About low-frequency detection see 1807.07565.

1503.05170

Catalogue: http://astro.phys.wvu.edu/rratalog
>100 now, see 1706.08412

LIGO search for GW from PSRs

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

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

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

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

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

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

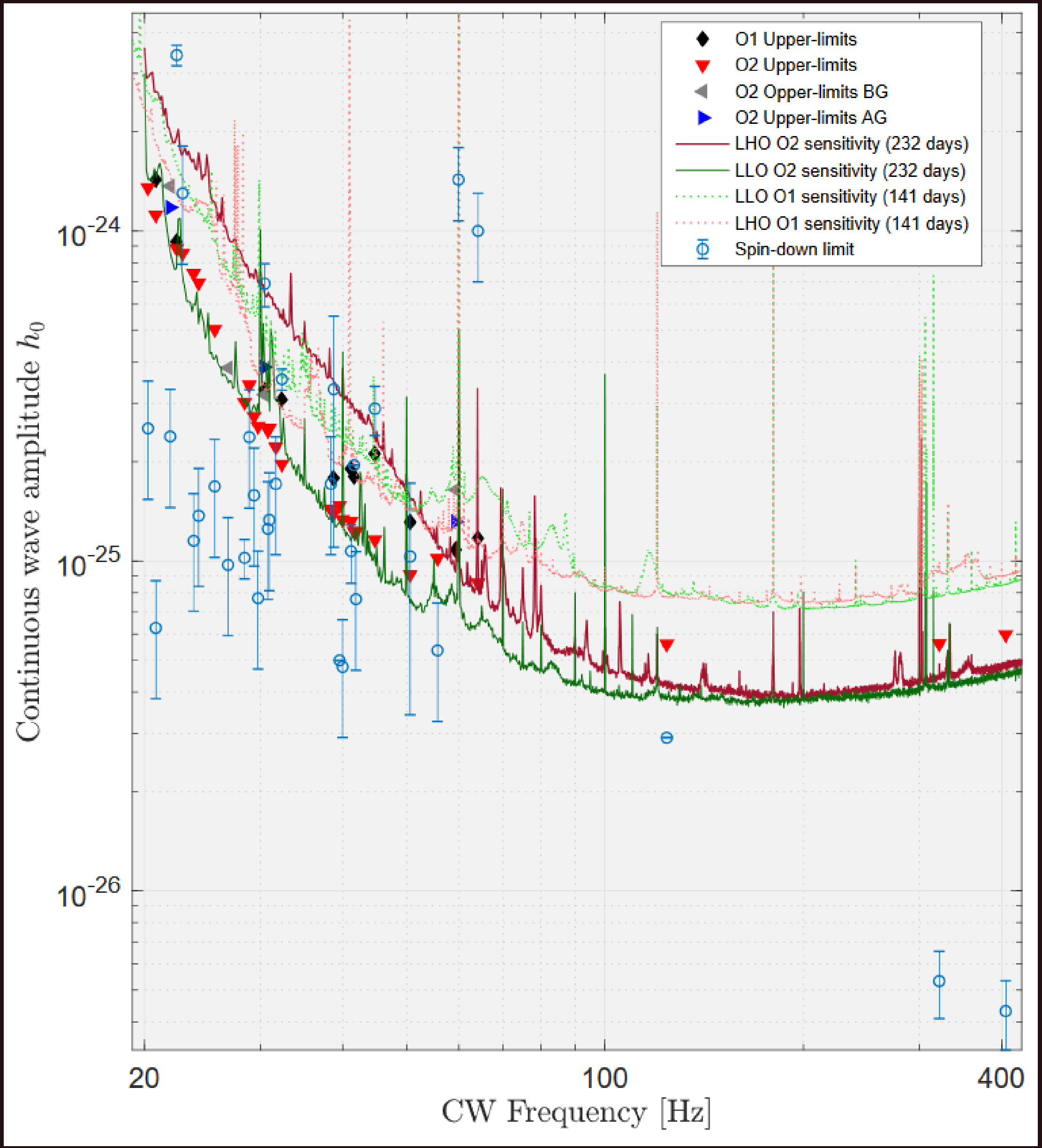
1902.08442

LIGO results

Second run

33 PSRs studied.

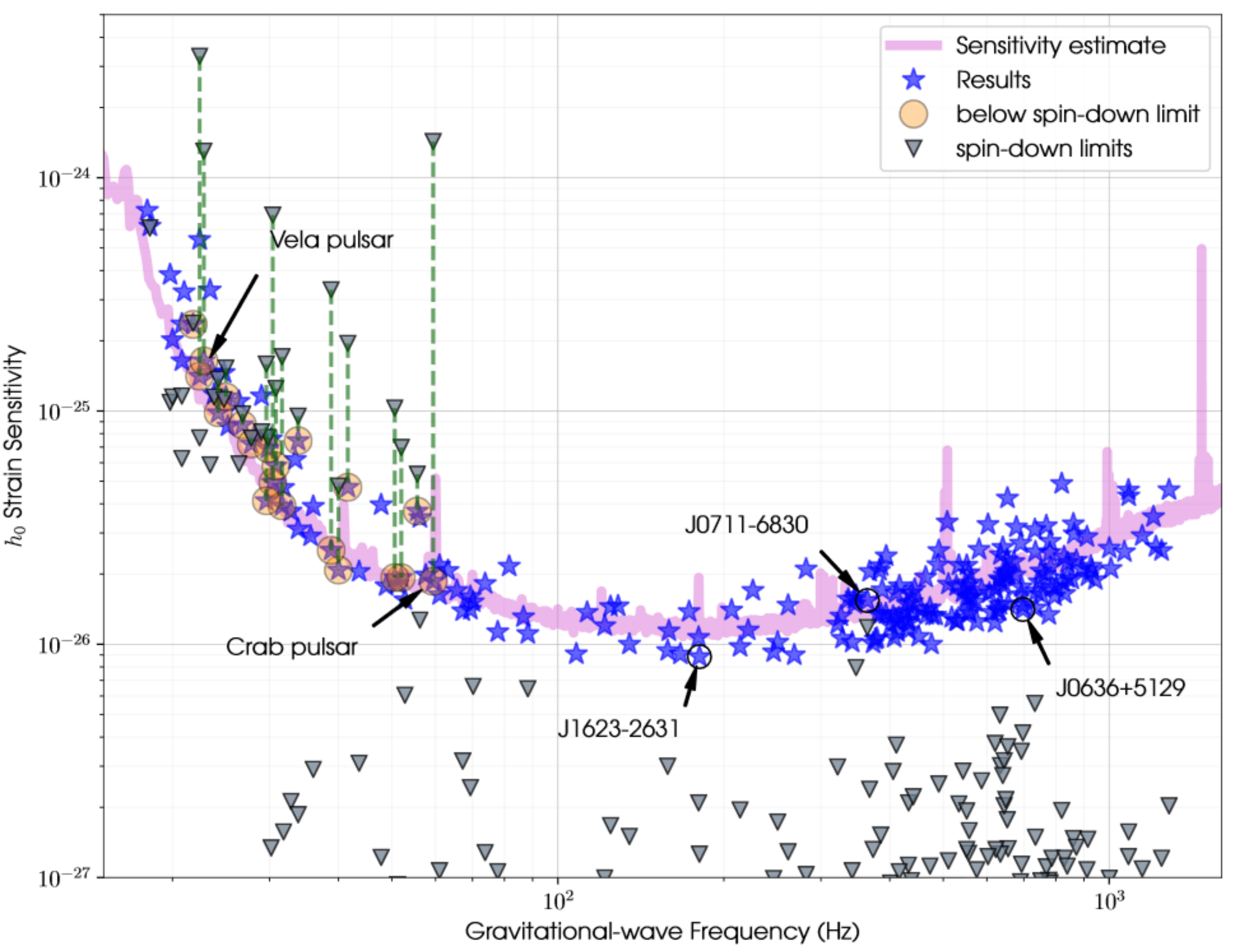
The labels “AG” and “ BG” refers to a search performed after or before the glitch of a given pulsar.



1902.08442

LIGO search for GW from PSRs

221 PSRs
data from 2015-2017

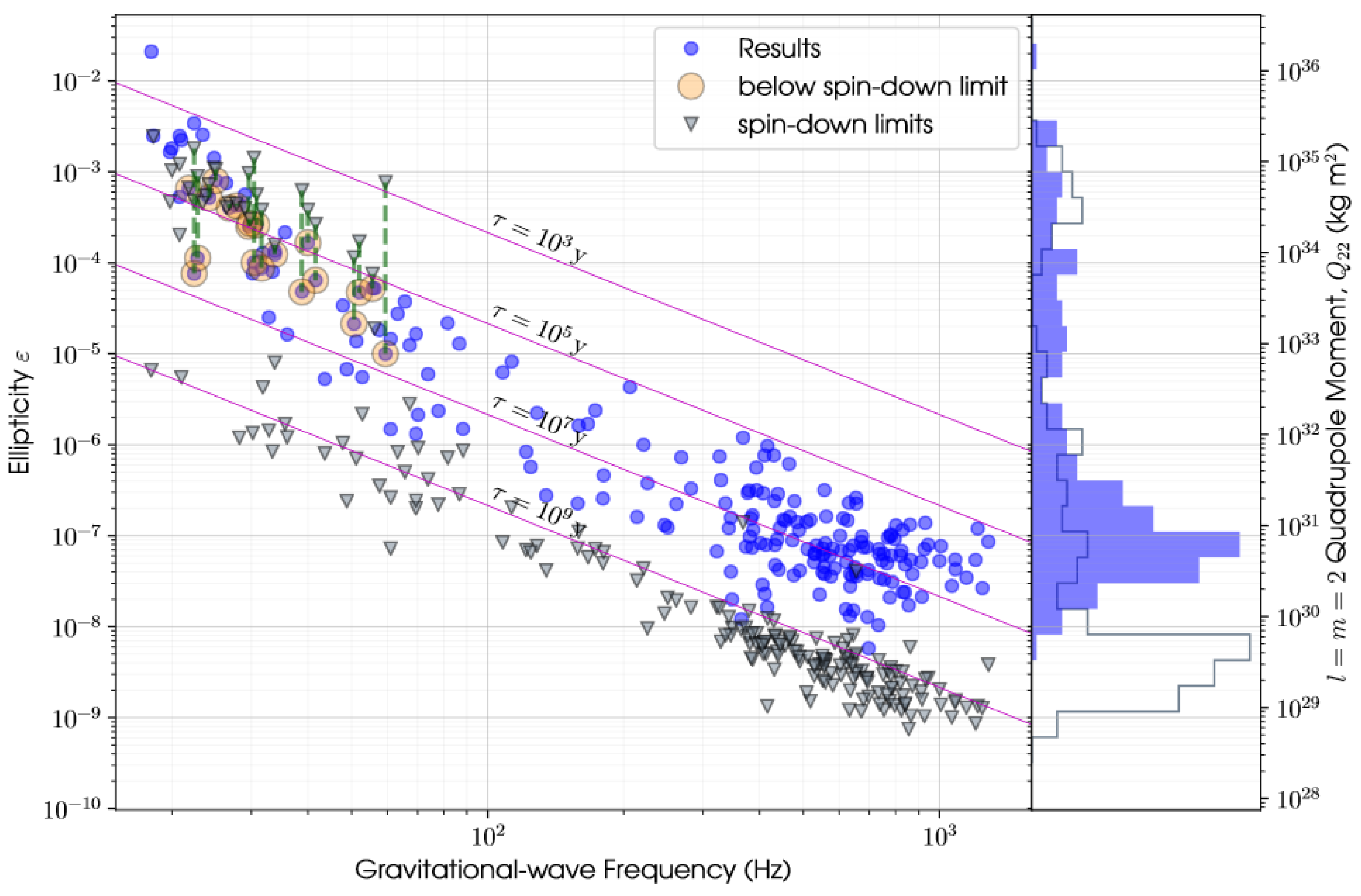


1902.08507

Limits on ellipticity

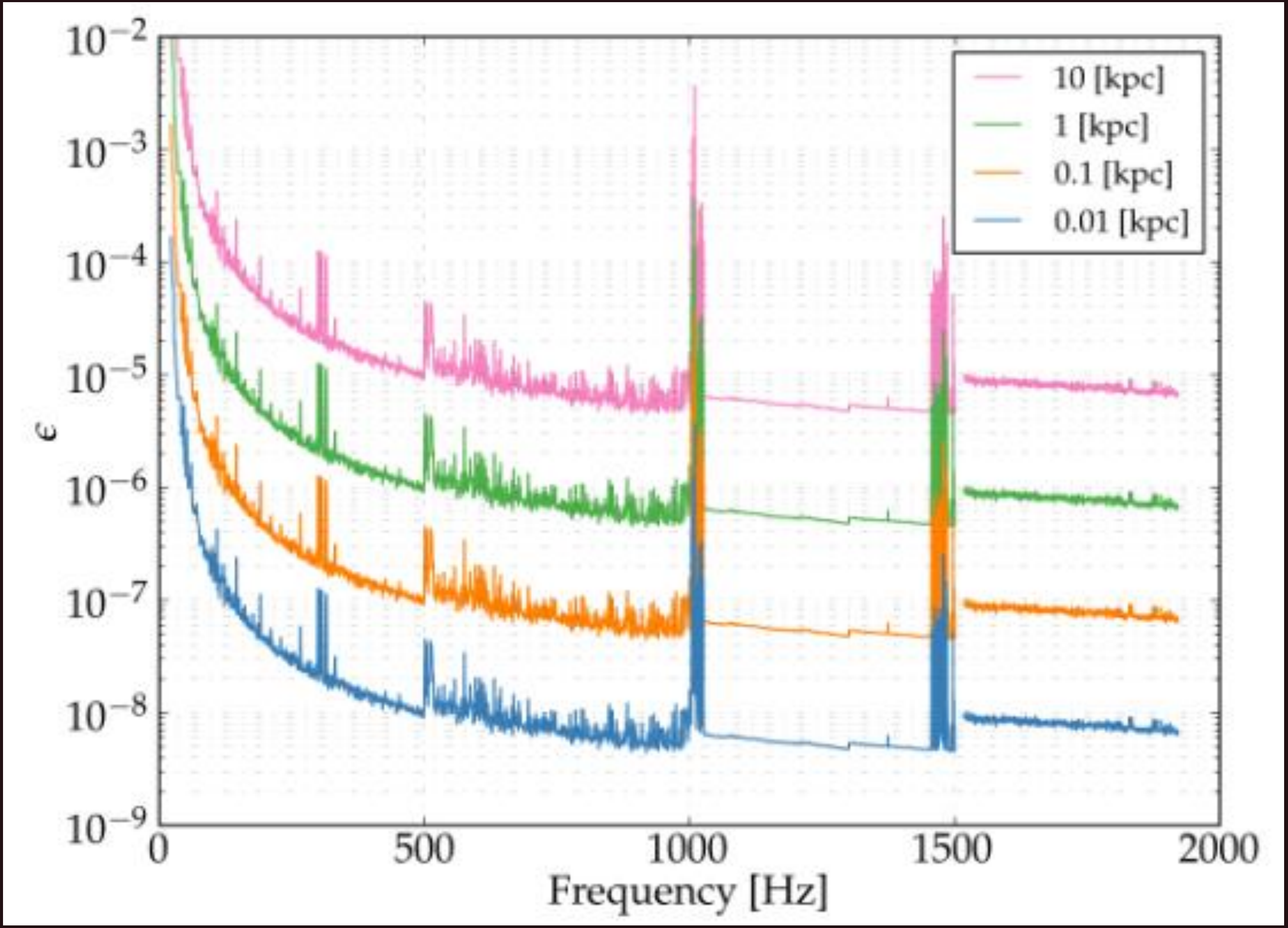
$$\varepsilon = \frac{Q_{22}}{I_{zz}}\sqrt{\frac{8\pi}{15}}$$

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



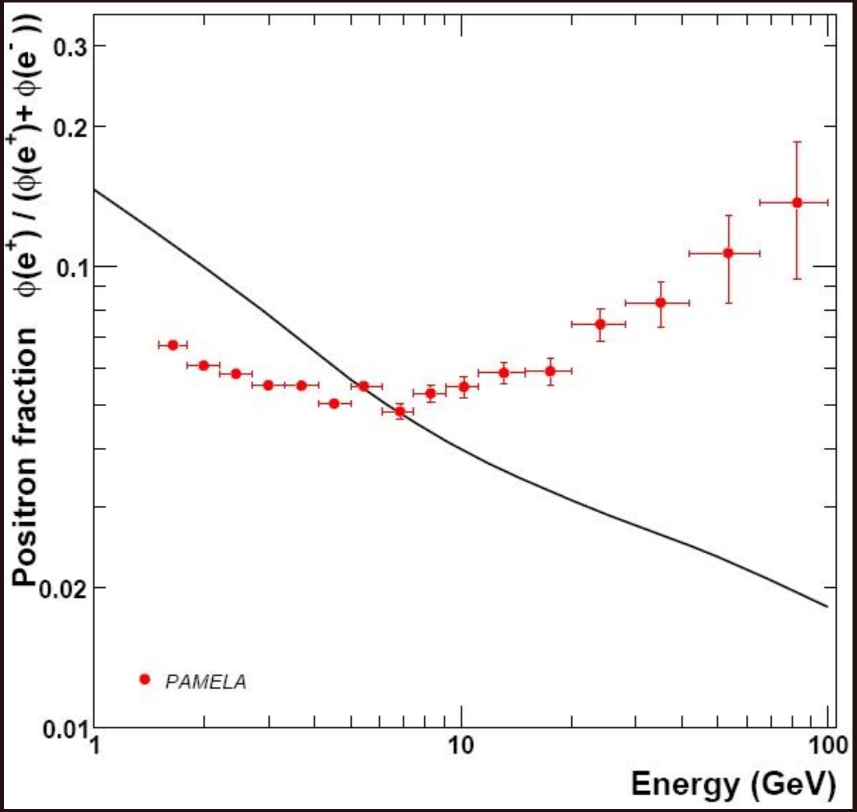
1902.08507

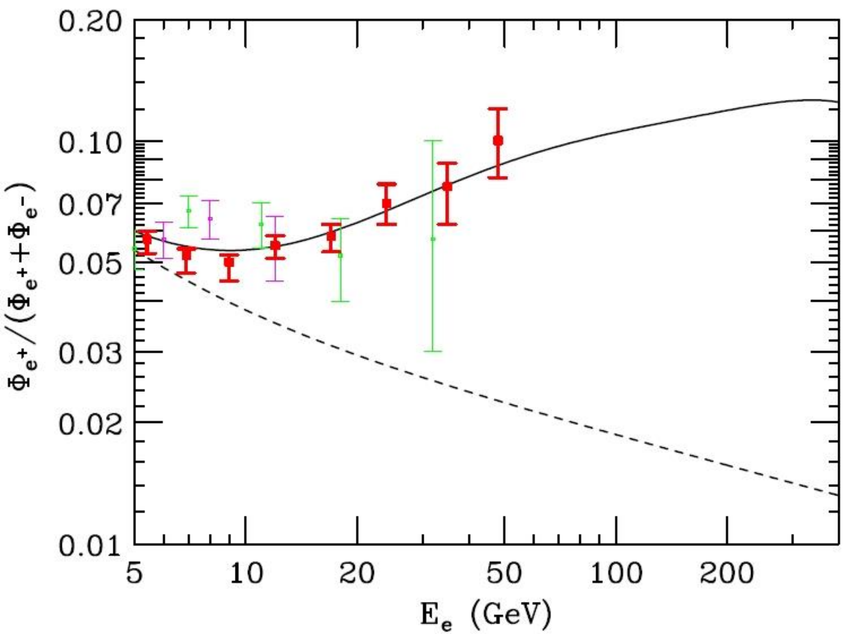
Blind search for GWs from NSs



1903.01901, new results in 2107.00600 and 2201.00697

Pulsars, positrons, PAMELA



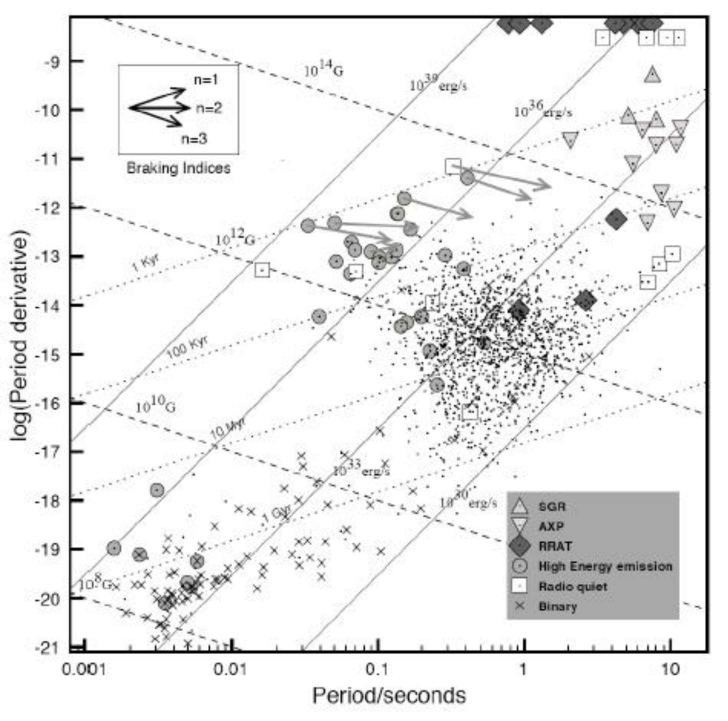


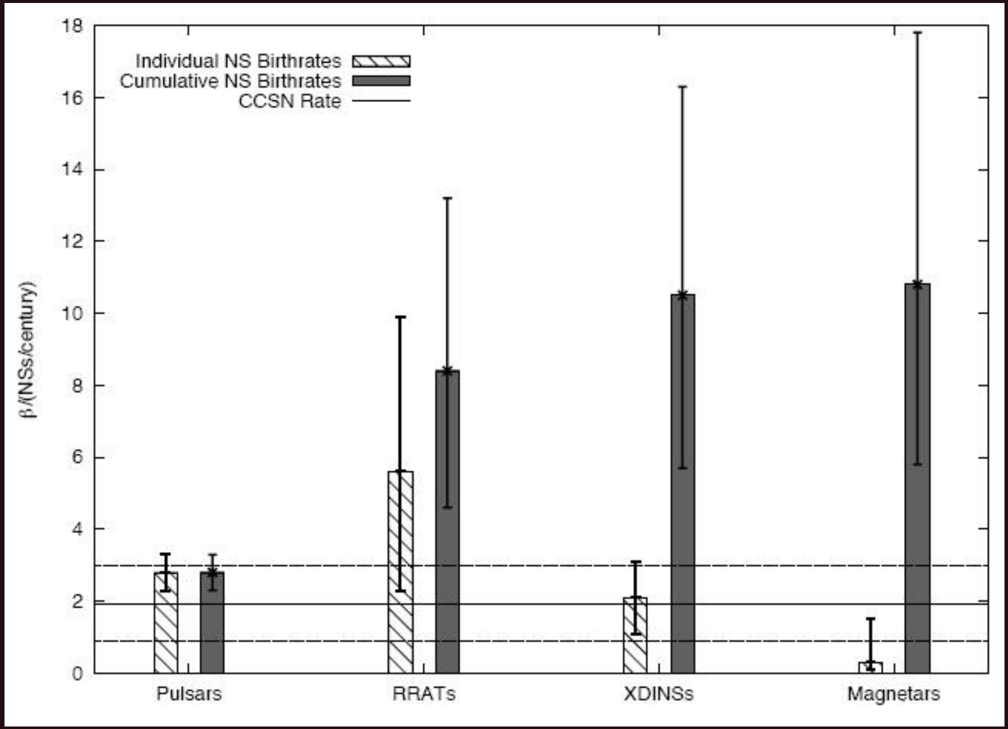
Geminga, PSR B0656+14, and all PSRs

[O. Adriani et al.] arXiv:0810.4995

[Dan Hooper et al. 2008
arXiv: 0810.1527]

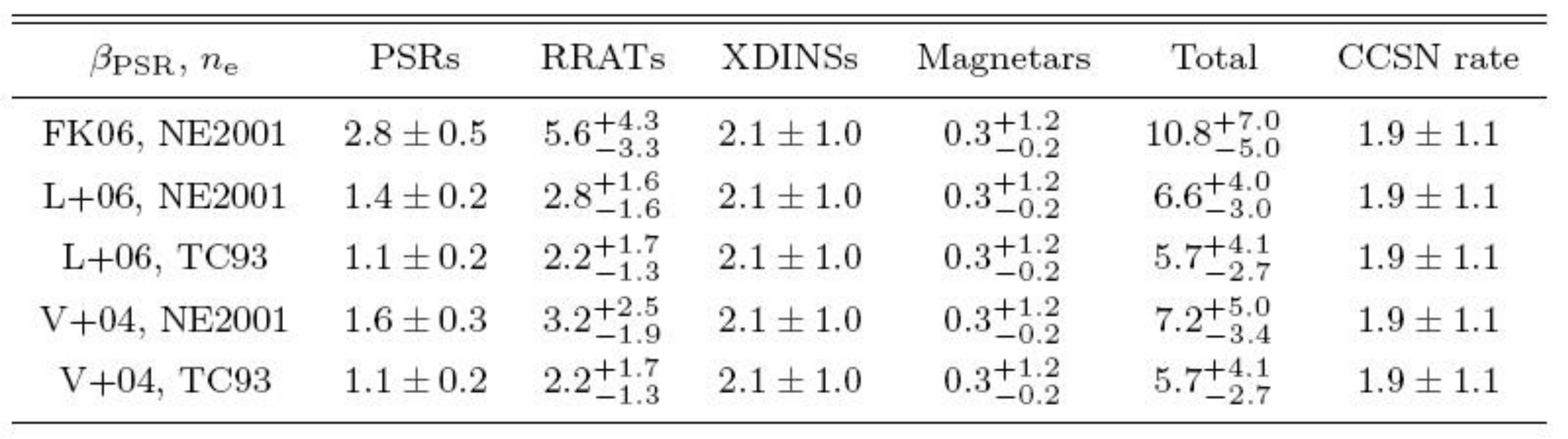
NS birth rate





Keane, Kramer 2008, arXiv: 0810.1512

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 <~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.

GRAND UNIFICATION: 1005.0876

Keane, Kramer 2008, arXiv: 0810.1512

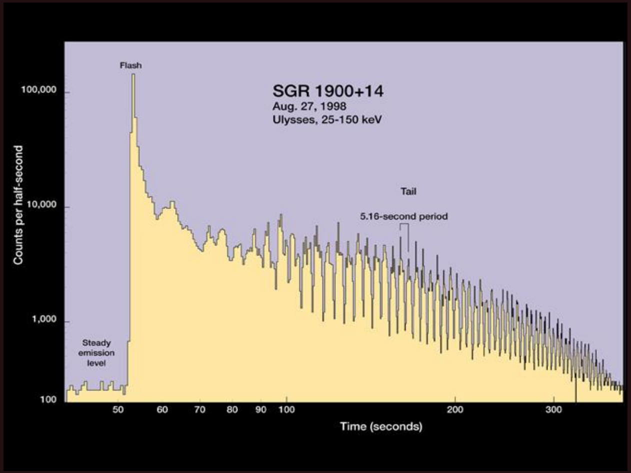
Conclusion

- 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
• Thermal emission	1507.06186
• Magnetars:	1507.02924
• Magnetar bursts:	arXiv: 1101.4472
• CCOs:	astro-ph/0311526 arxiv:0712.2209
• Quark stars:	arxiv:0809.4228
• The Magnificent Seven:	astro-ph/0609066 arxiv:0801.1143
• RRATs:	arXiv:1008.3693
• Cooling of NSs:	astro-ph/0402143
• NS structure	arXiv:0705.2708
• EoS	arXiv: 1001.3294 1512.07820
• NS atmospheres	1403.0074
• NS magnetic fields	arxiv:0711.3650
•Different types	arXiv:1005.0876 arXiv:1302.0869 arXiv: 1712.06040
•Radio pulsars	1602.07738

- 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

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