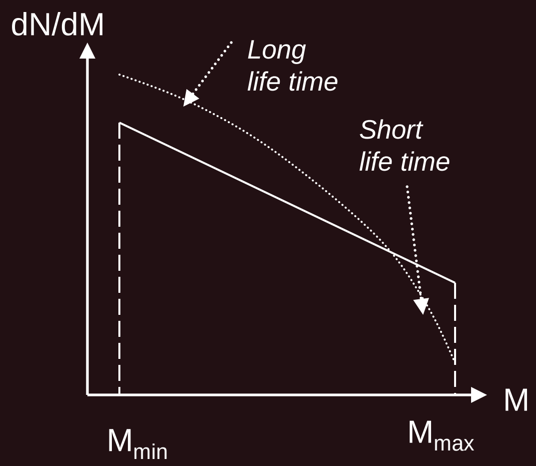
# Isolated Neutron Stars. Intro.

# Stars in the Galaxy

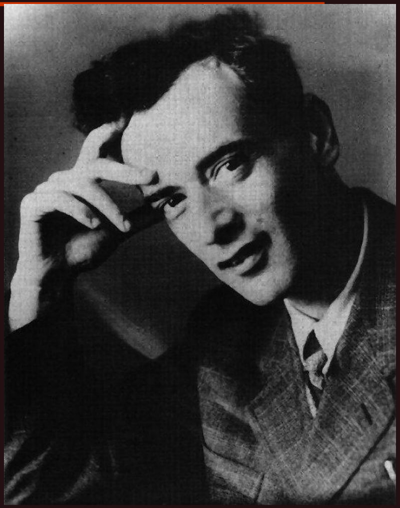



Salpeter (1955) mass function:
$dN/dM \sim M^{-2.35}$

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.

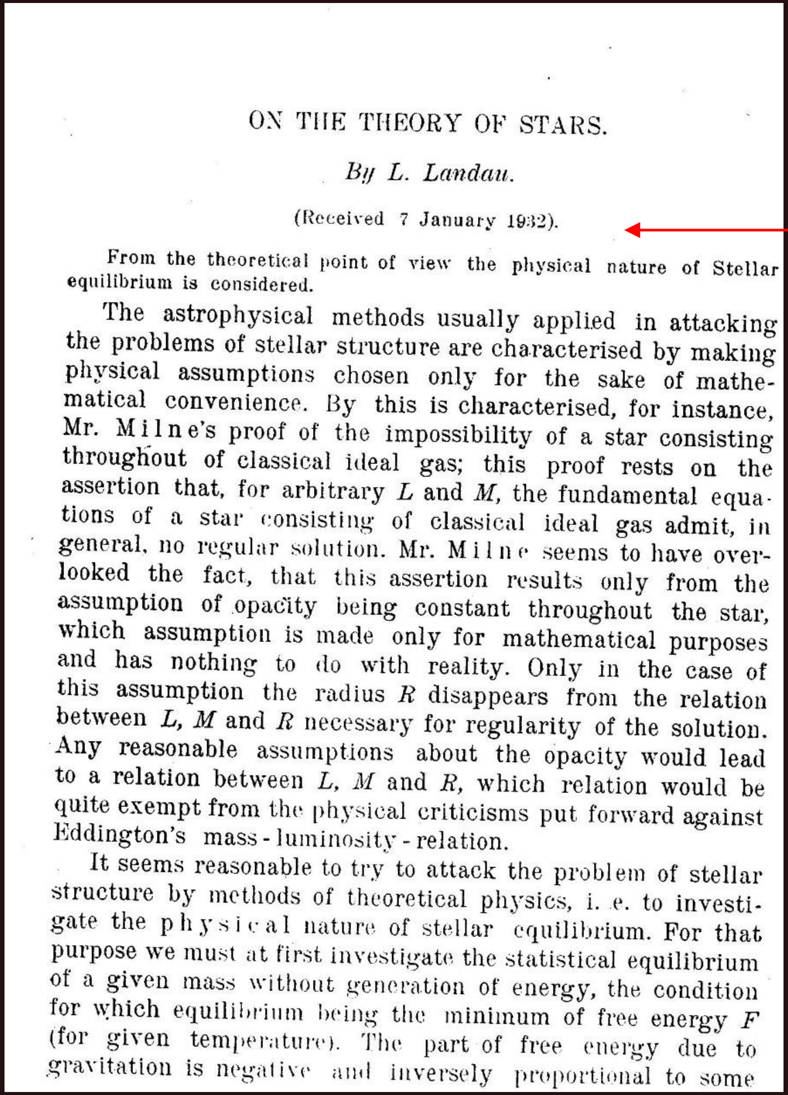
[5]The first QSO identified by Schmidt, 3C273, had a redshift $\delta\lambda/\lambda = 0.158$, which was unprecedented for a normal "star."

[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

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.

This is correct!

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.

Disappered in reprints,
so we have difficulties

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

# 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 a[t] maximum may be as high as $M_{\text{vis}} = -14^M$. The visibl[e] radiation $L_\nu$ of a supernova is about $10^8$ times the radiatio[n] of our sun, that is, $L_\nu = 3.78 \times 10^{41}$ ergs/sec. Calculation[s] indicate that the total radiation, visible and invisible, i[s] of the order $L_\tau = 10^7 L_\nu = 3.78 \times 10^{48}$ ergs/sec. The super-nova therefore emits during its life a total energy $E_\tau \gtrsim 10^5 L_\tau = 3.78 \times 10^{53}$ ergs. If supernovae initially are quite ordinary stars of mass $M < 10^{34}$ g, $E_\tau / c^2$ 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.

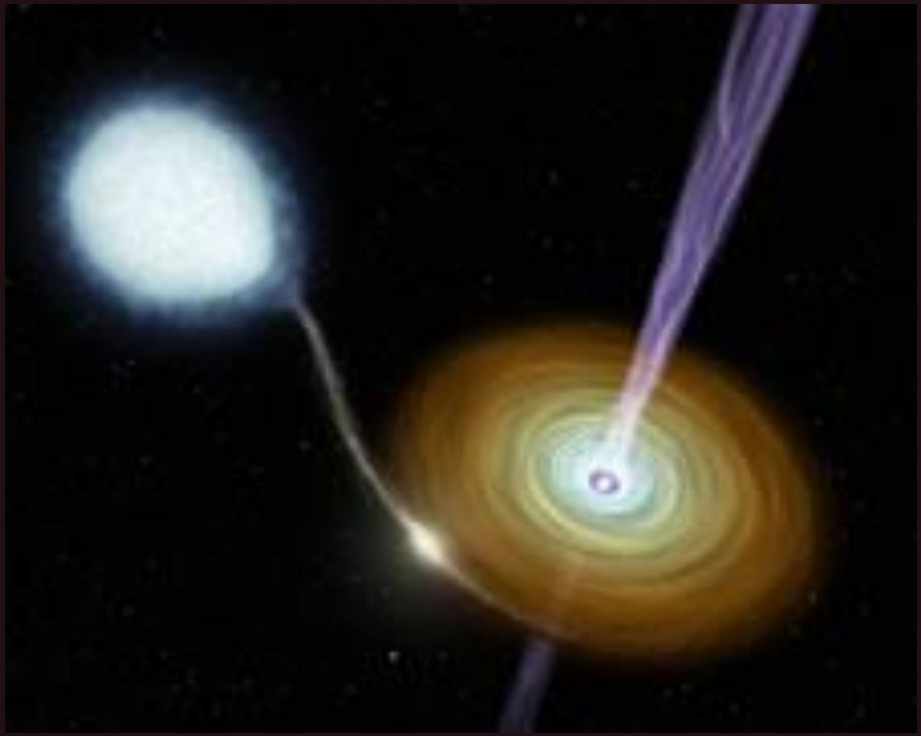
W. Baade
F. Zwicky

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

Phys. Rev. 46, 76, 1934 July 1

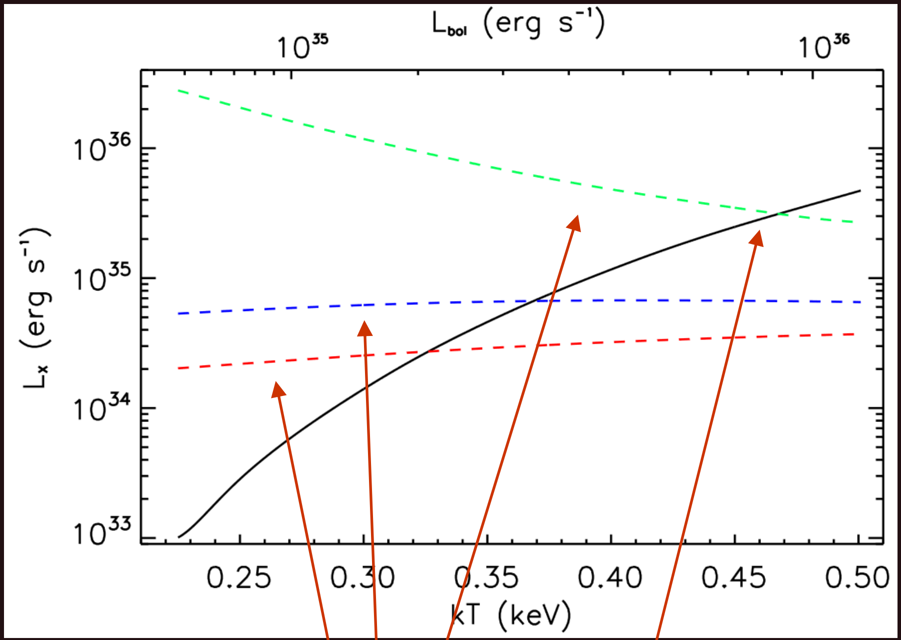
# Good old classics

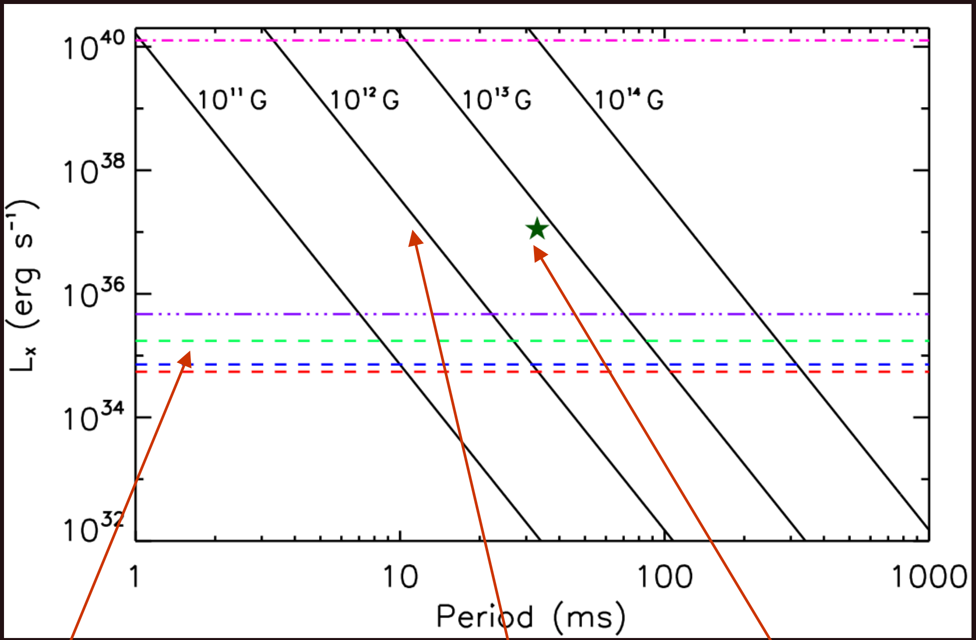
*For years two main types of NSs have been discussed: radio pulsars and accreting NSs in close binary systems*



*The pulsar in the Crab nebula* *A binary system*

# What formed in SN 1987A?




Limits for different $N_H$.

2-8 keV luminosity
for different temperatures

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

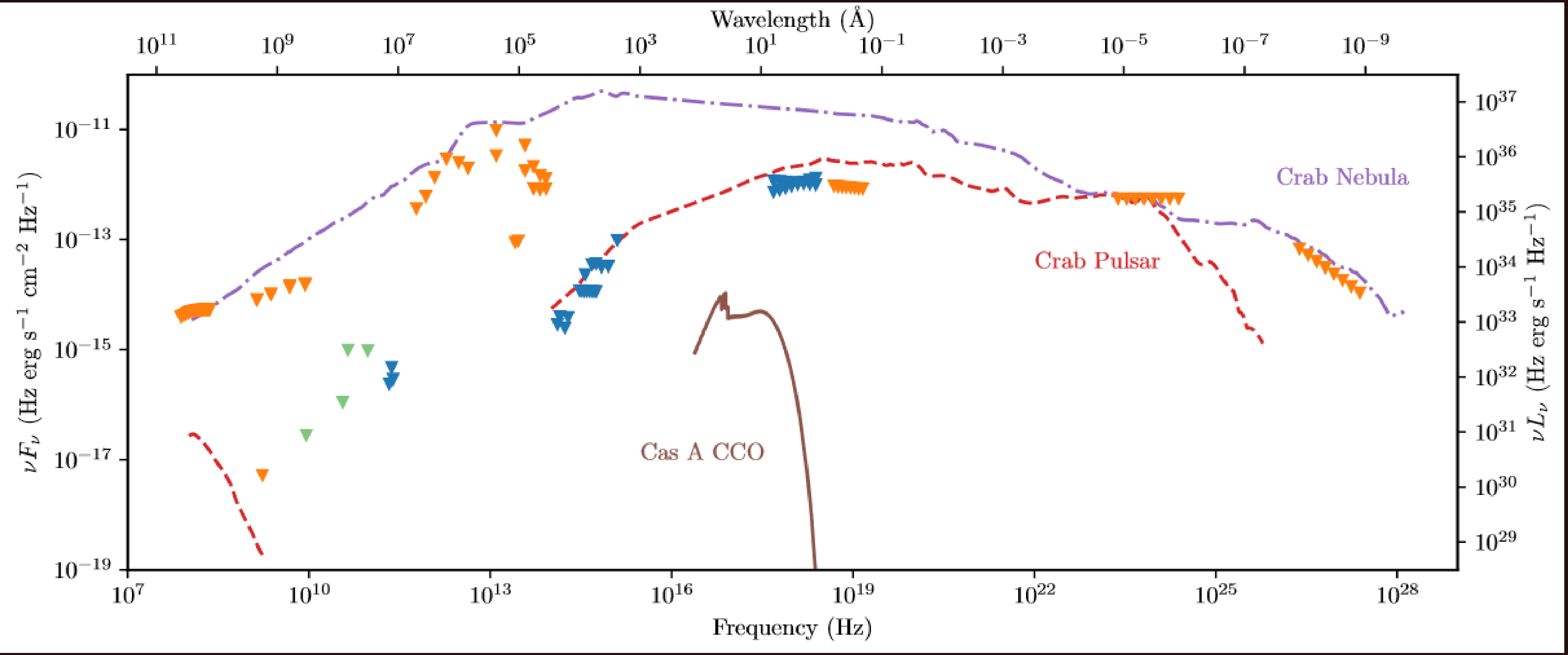
Crab

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

1803.04692

See also 1805.04526

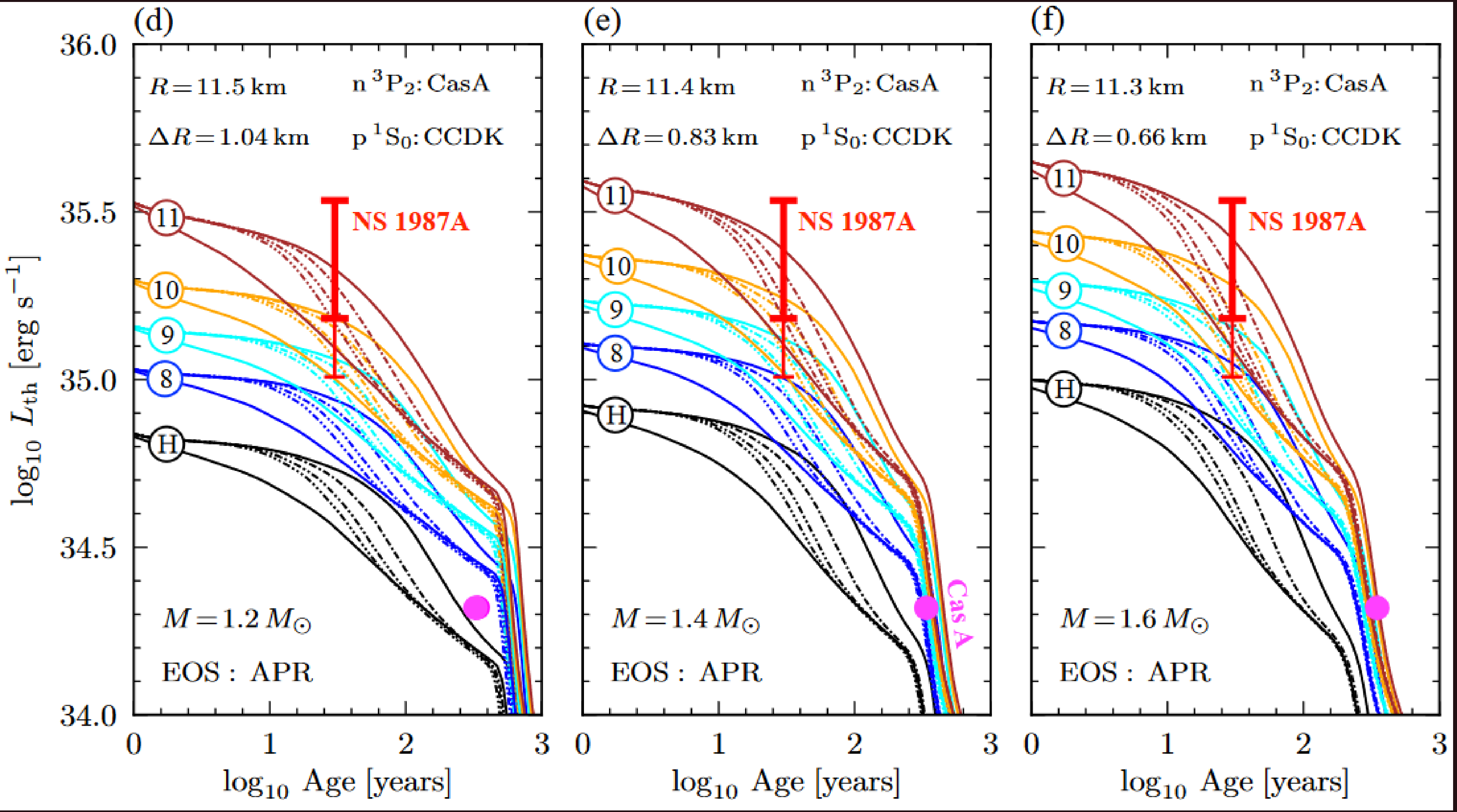
# More limits on SN1987A




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

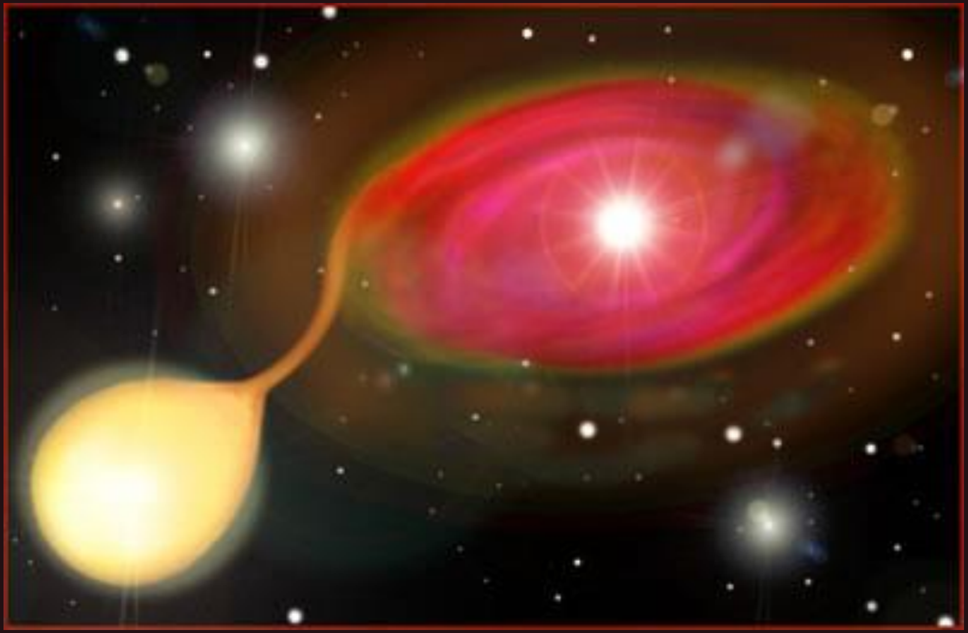



2004.06078

# 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»....

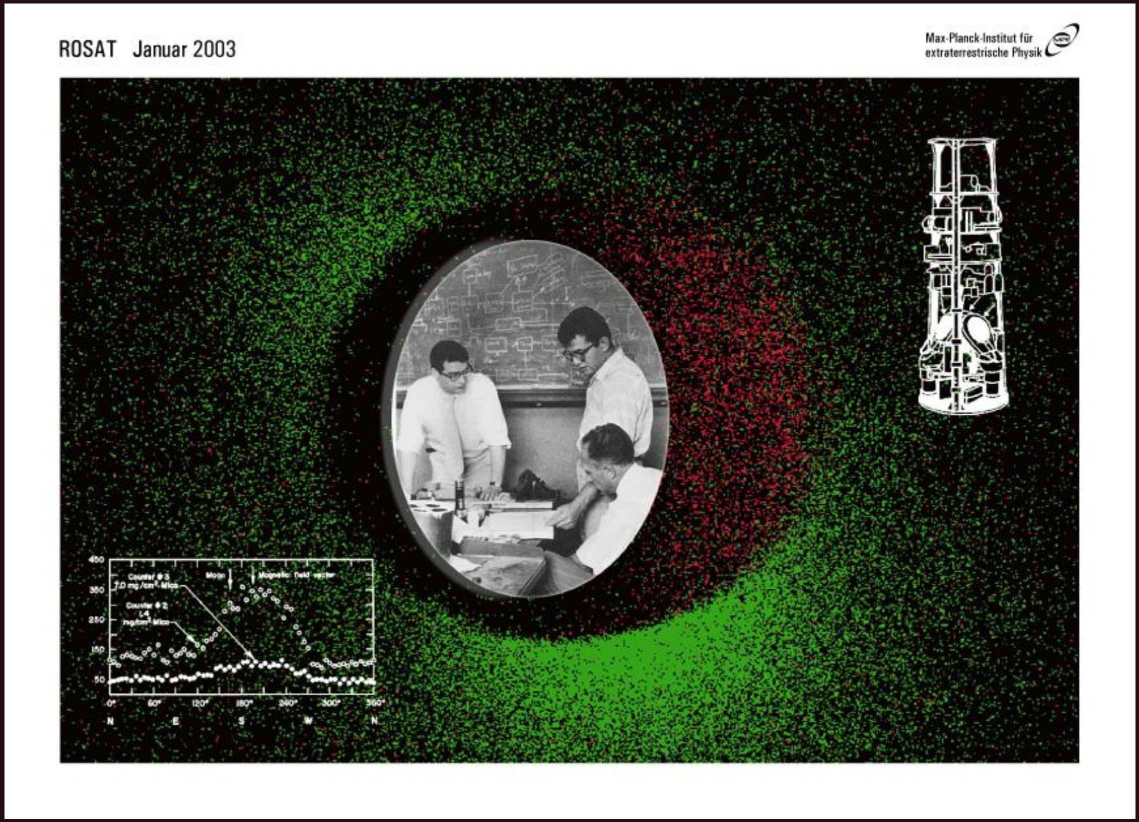


Now we know hundreds of X-ray binaries with neutron stars in the Milky Way and in other galaxies.

# Rocket experiments. Sco X-1

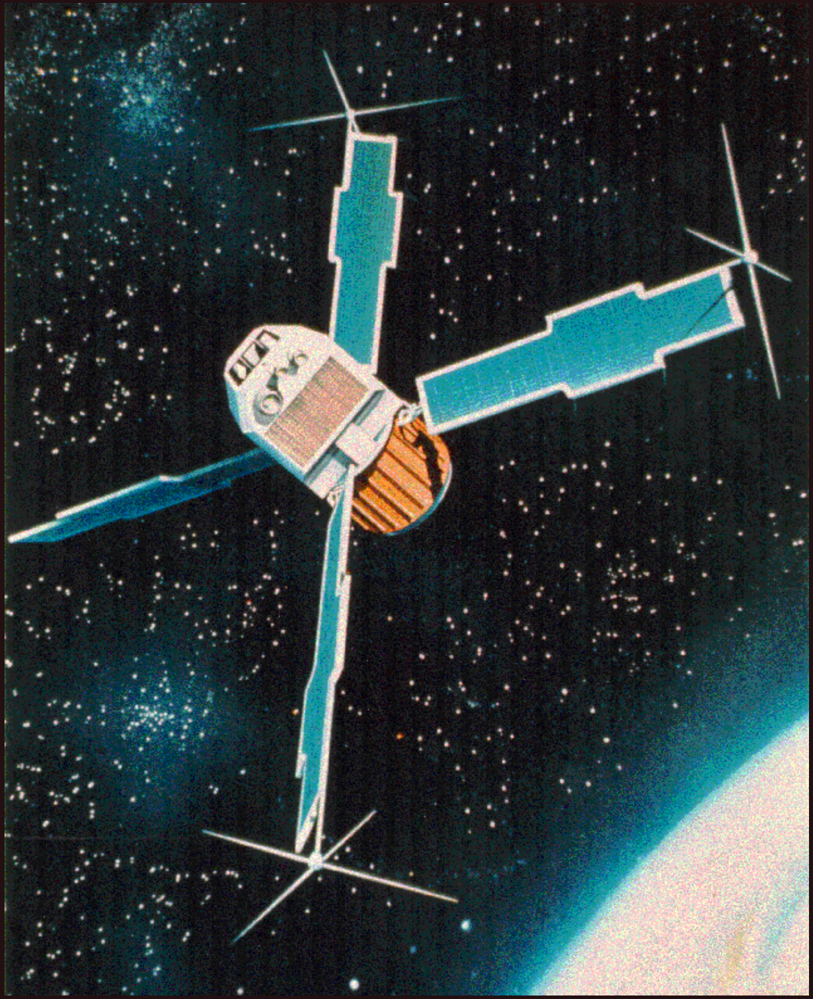
Giacconi et al. 1962

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

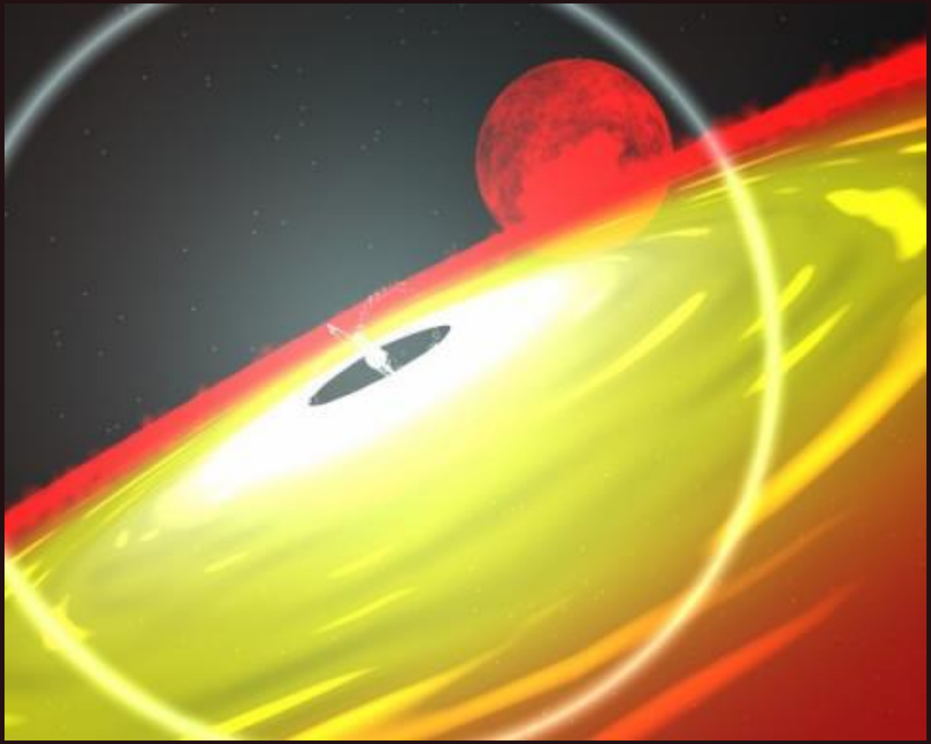
2-20 keV

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

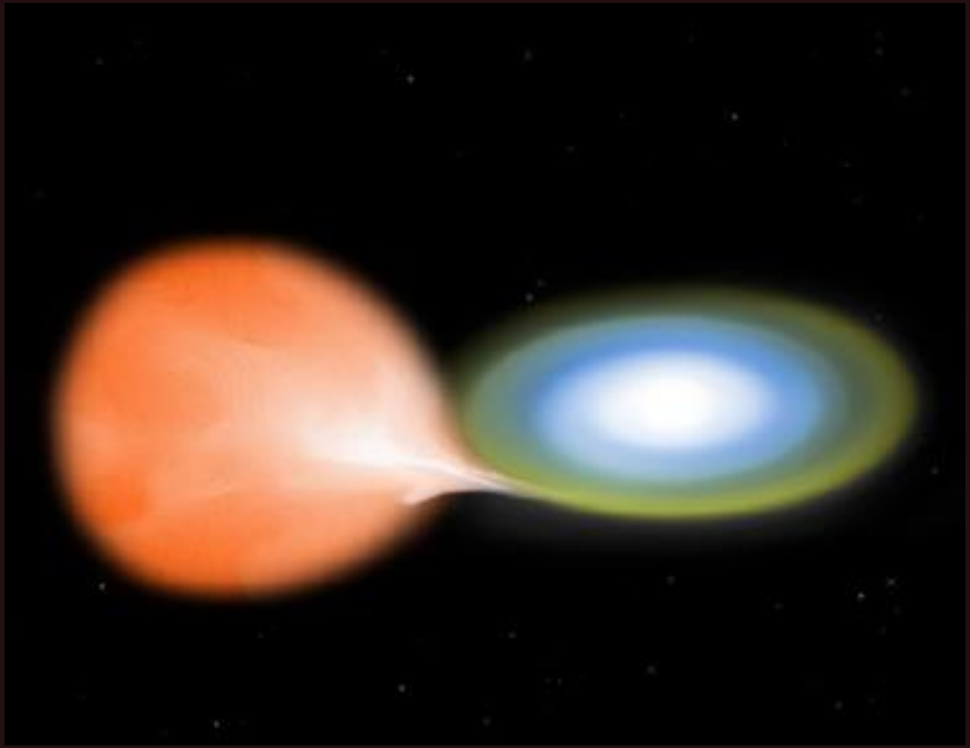
The theory of accretion discs was developed in 1972-73 by N.I. Shakura and R.A. Sunyaev.

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.



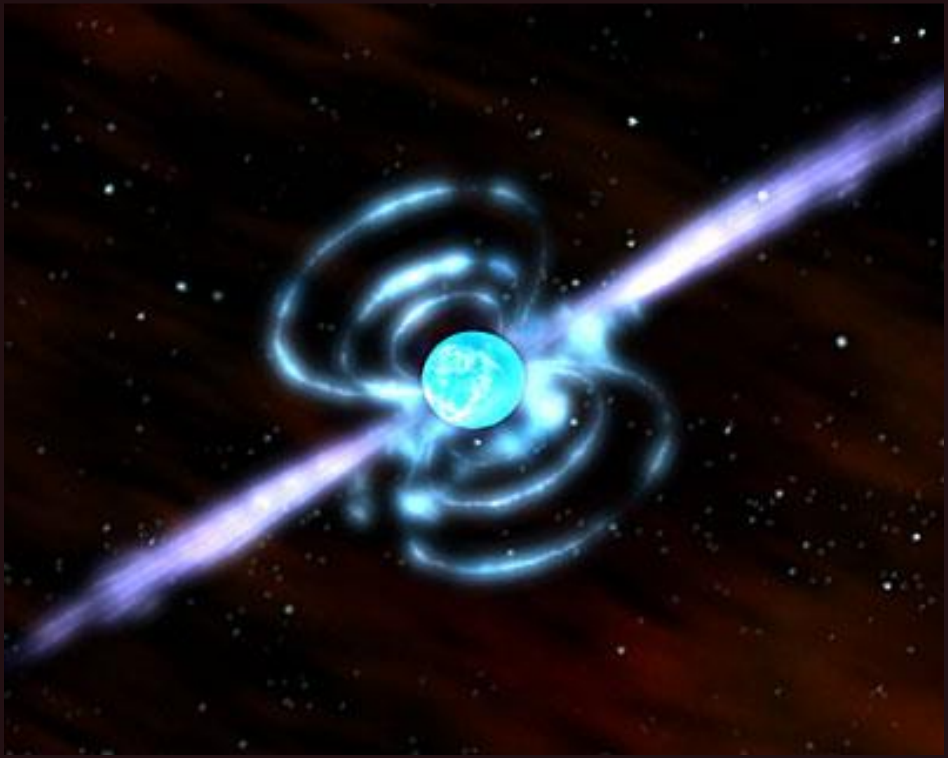
$$L = \dot{M} \eta c^2$$

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

# Discovery !!!!

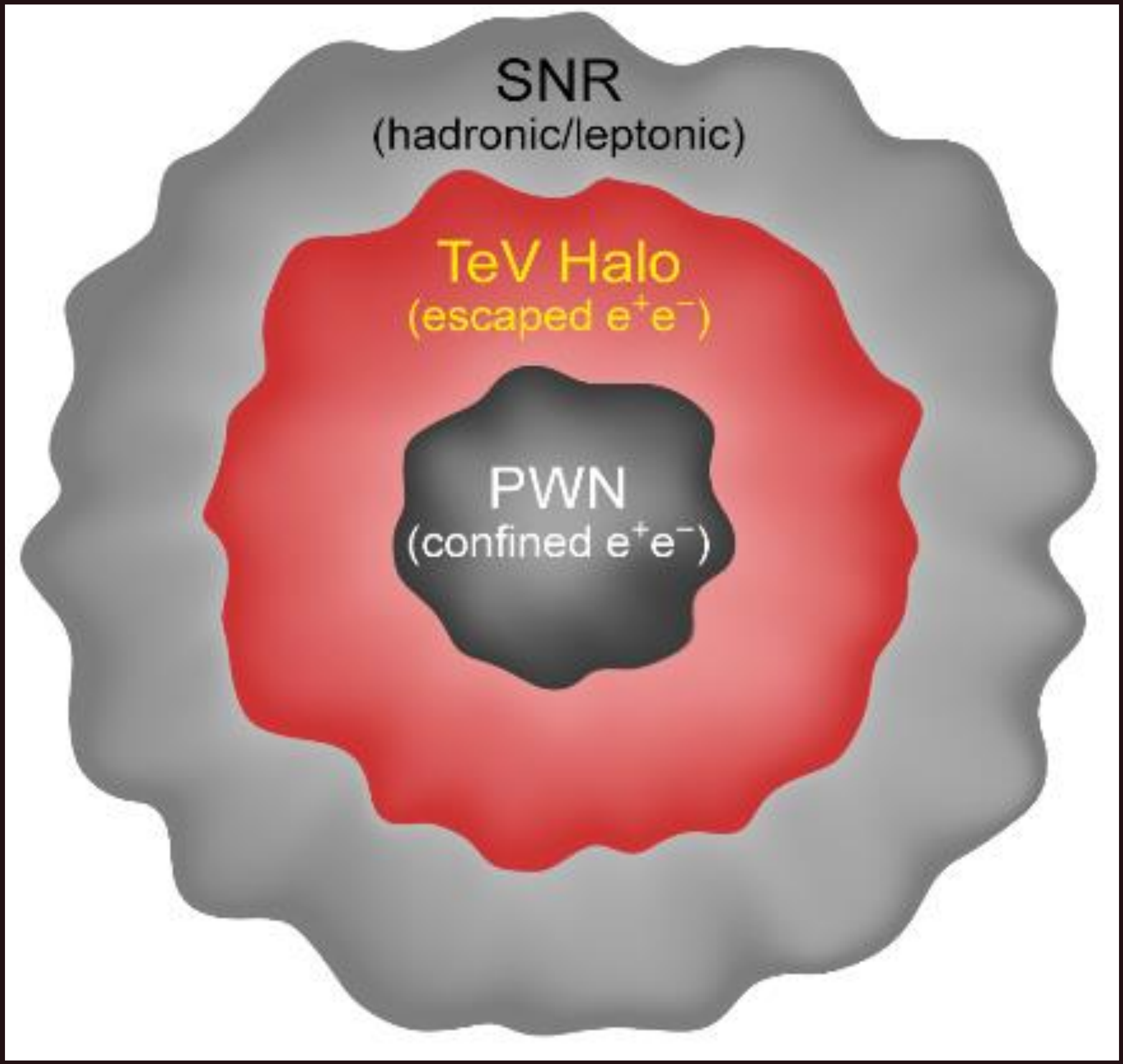
1967: Jocelyn Bell. Radio pulsars.

Seredipitous discovery.



# The pulsar in the Crab nebula

# TeV halos

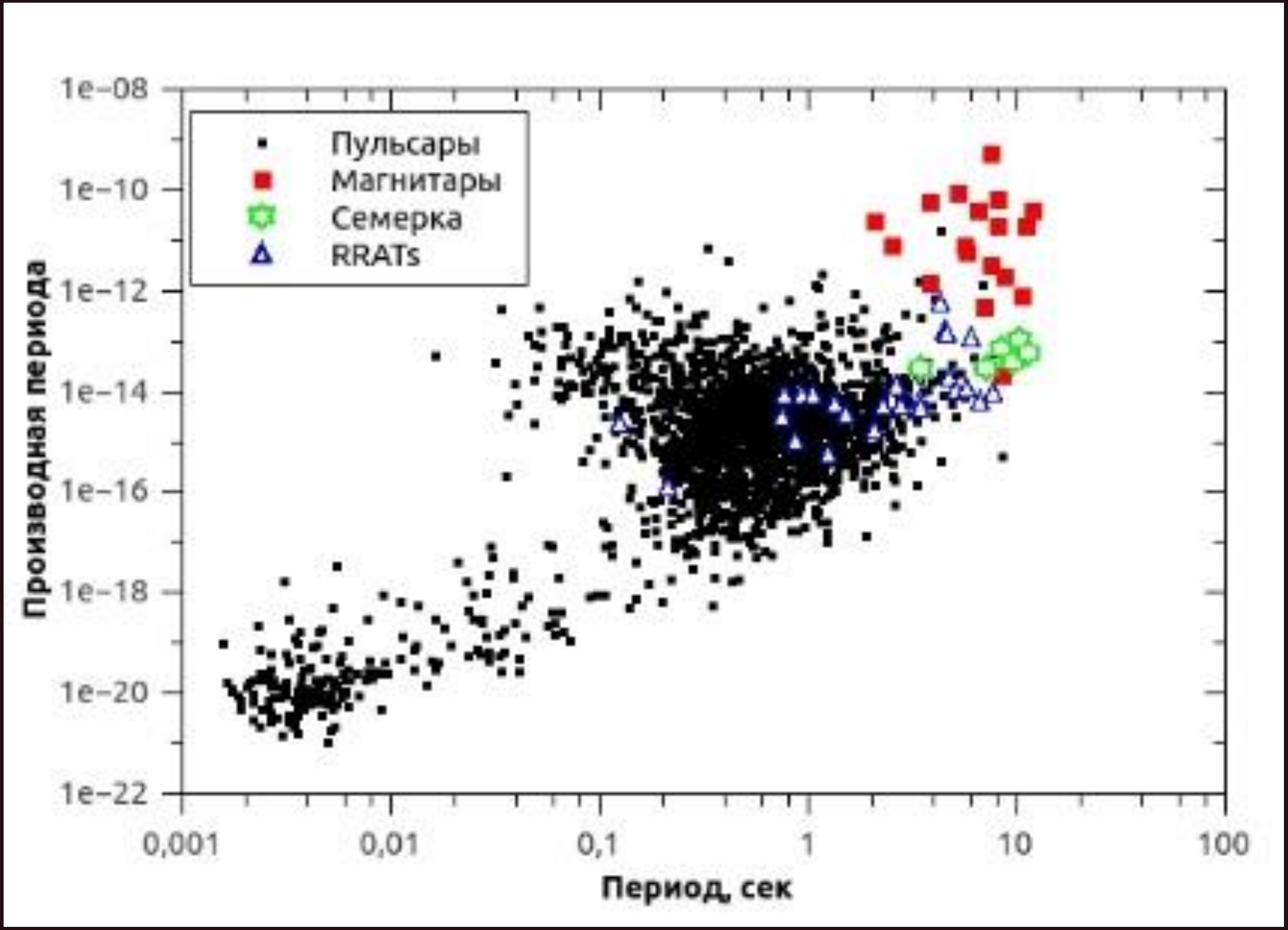



Milagro and HAWC

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



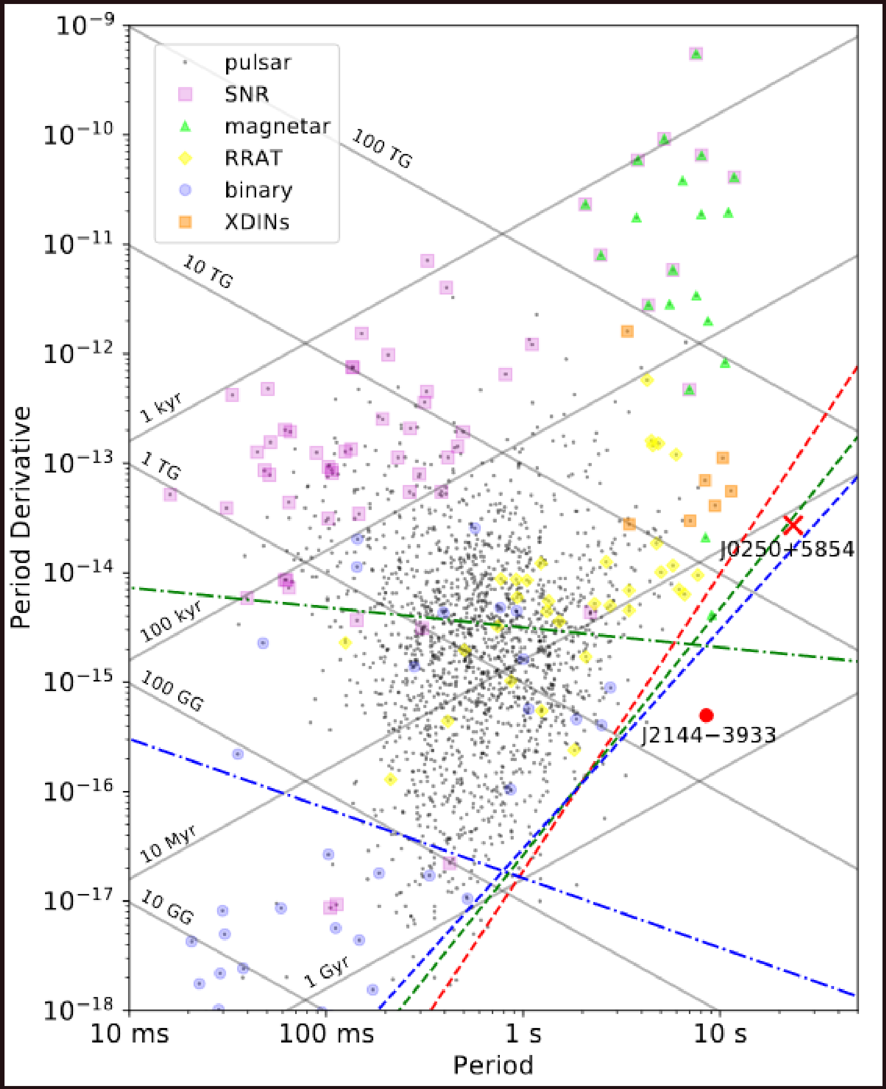

$$L_m = \frac{2}{3}\frac{\mu^2\omega^4}{c^3}\sin^2\beta = \kappa_t \frac{\mu^2}{R_l^3}\omega\,,$$

# Record slow radio pulsar

PSR J0250+5854
spin period of 23.5 s

LOFAR detection

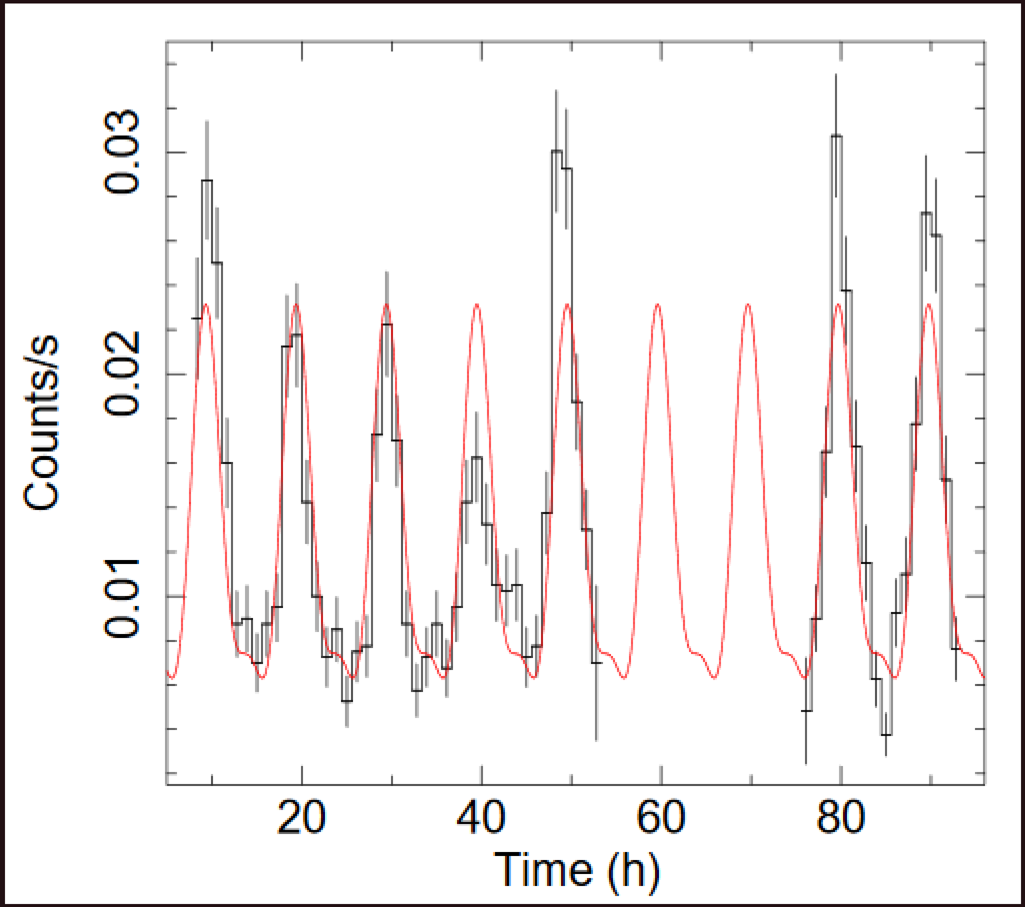
May be field decay
was important for
this radio pulsar.



# Slowly rotating NSs – in binaries

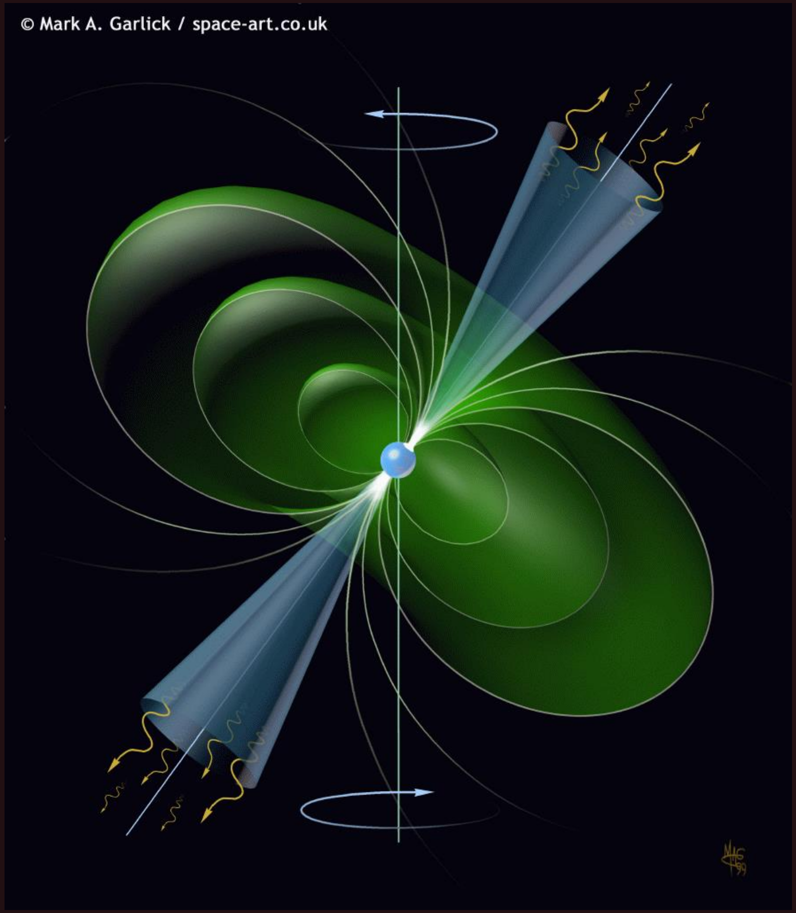
AX J1910.7+0917

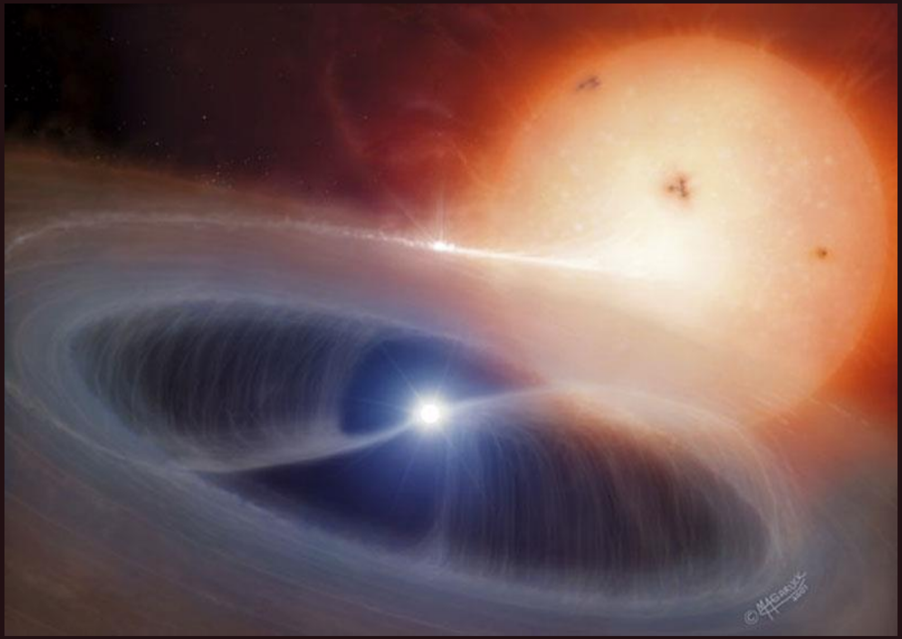
P>10 hours! (36200+/-100 sec)




1705.01791

# The old Zoo: young pulsars & old accretors



# The new zoo of young neutron stars

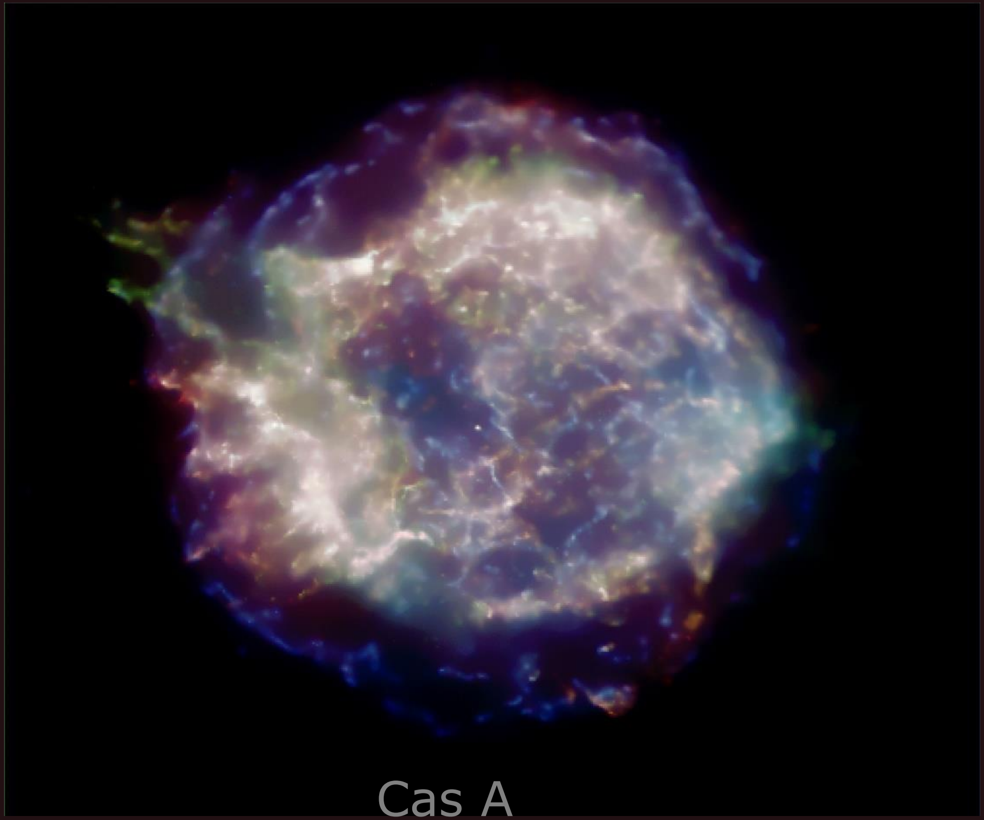
During last ~25 years
it became clear that neutron stars
can be born very different.
In particular, absolutely
non-similar to the Crab pulsar.

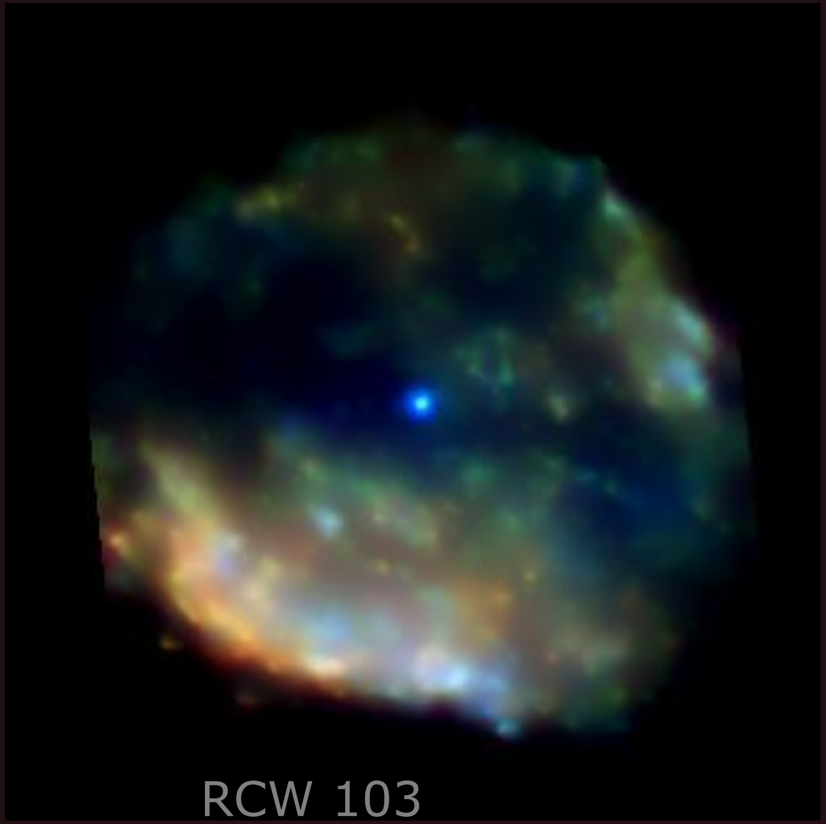
- o High-B PSRs
- o Compact central X-ray sources
  in supernova remnants.
- o Anomalous X-ray pulsars
- o Soft gamma repeaters
- o The Magnificent Seven
- o Transient radio sources (RRATs)

Old and new zoos: Harding arXiv:1302.0869

See a more recent review in 1712.06040

# Compact central X-ray sources in supernova remnants



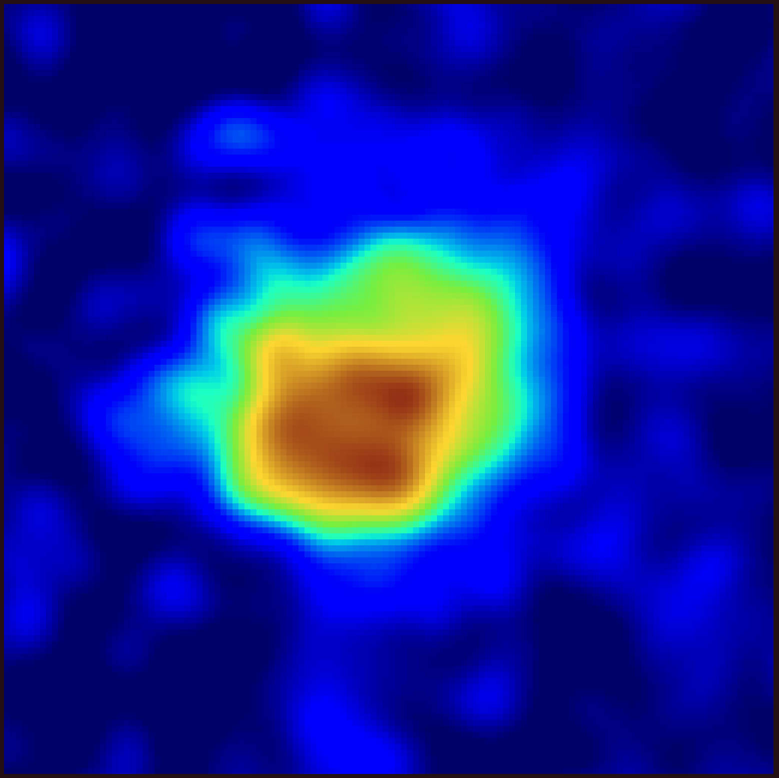




Rapid cooling
(Heinke et al. 1007.4719)

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]

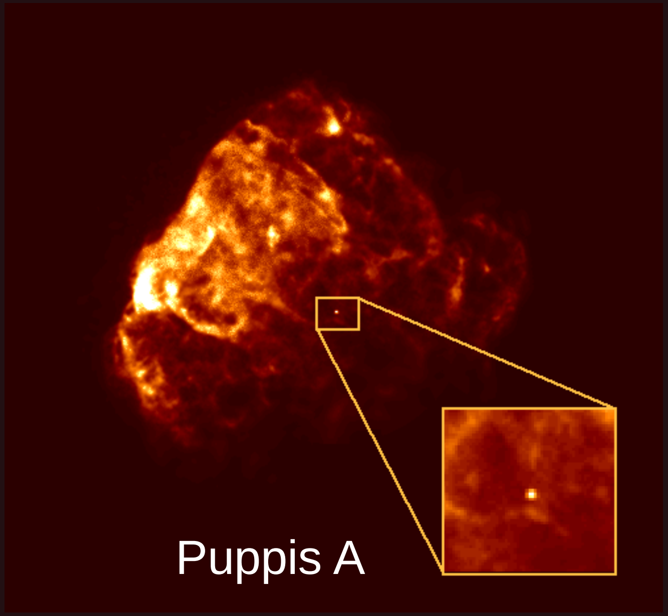
For three sources there are strong indications for large (>~100 msec) initial spin periods and low magnetic fields:

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]

# CCOs

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

2005.09457

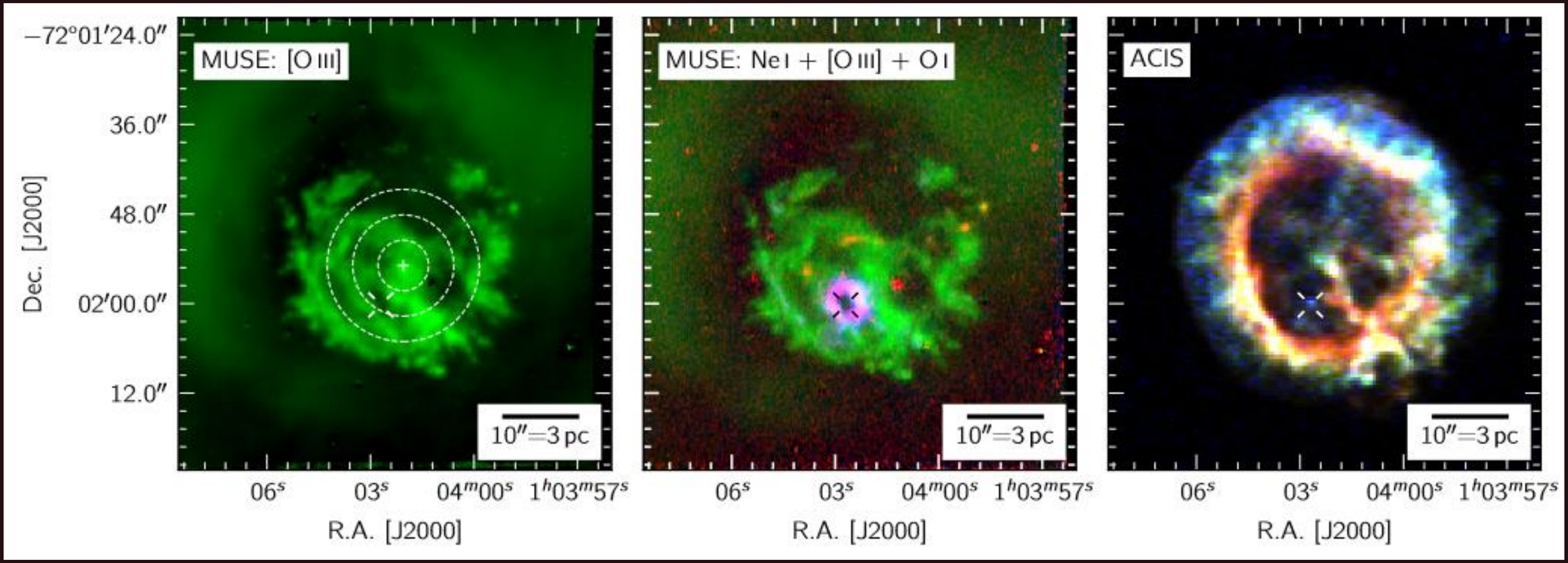



| CCO | SNR | Age (kyr) | $d$ (kpc) | $P$ (s) | $f_p$ [a] (%) | $B_s$ ($10^{11}$ G) | $L_{x,\mathrm{bol}}$ (erg $s^{-1}$) | References |
|---|---|---|---|---|---|---|---|---|
| RX J0822.0−4300 | Puppis A | 3.7 | 2.2 | 0.112 | 11 | $< 9.8$ | $6.5 \times 10^{33}$ | 1,2 |
| CXOU J085201.4−461753 | G266.1−1.2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

0911.0093

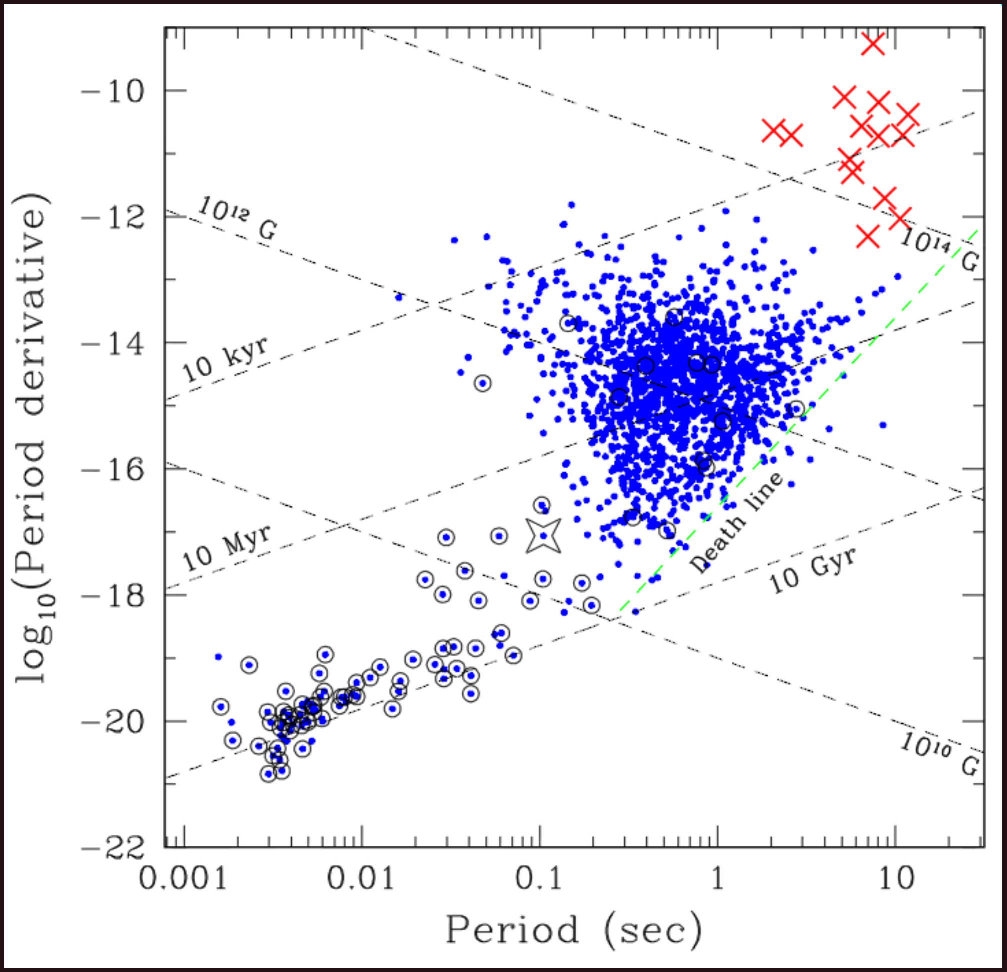
# The first CCO in SMC 1E 0102.2-7219

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




1803.01006

# Anti-magnetars




Star marks the CCO from 0911.0093

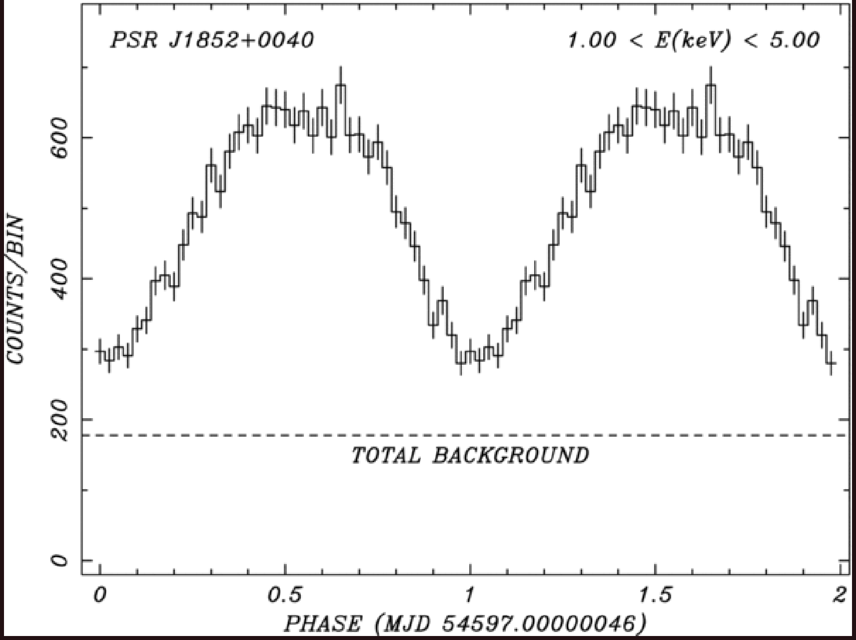
New results 1301.2717
Spins and derivative are measured for
PSR J0821-4300 and
PSR J1210-5226

0911.0093

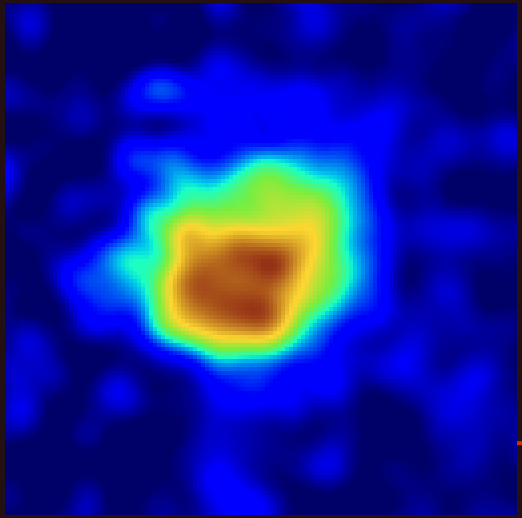
# "Hidden" magnetars

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 $\times 10^{14}$ G.




Halpern, Gotthelf 2010



Kes 79

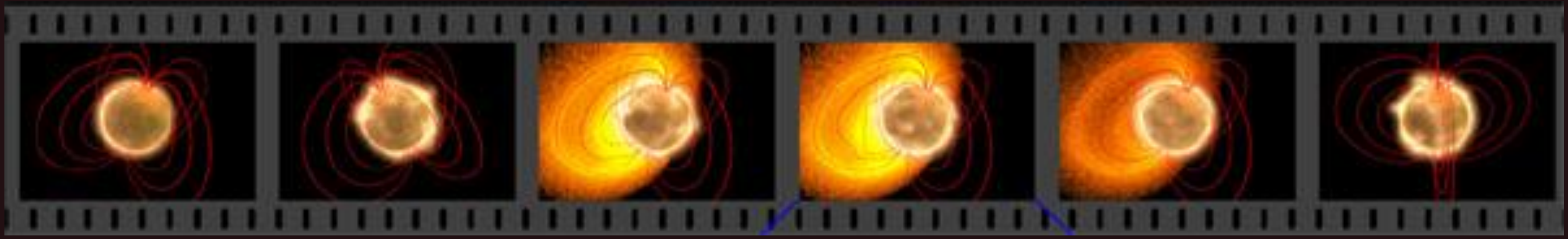
- If submergence of the field happens rapidly, so the present day period represents the initial one
- Then, the field of PSR 1852 was not enhanced via a dynamo mechanism
- Detection of millisecond "hidden" magnetars will be a strong argument in favour of dynamo.

arXiv: 1307.3127

# Magnetars

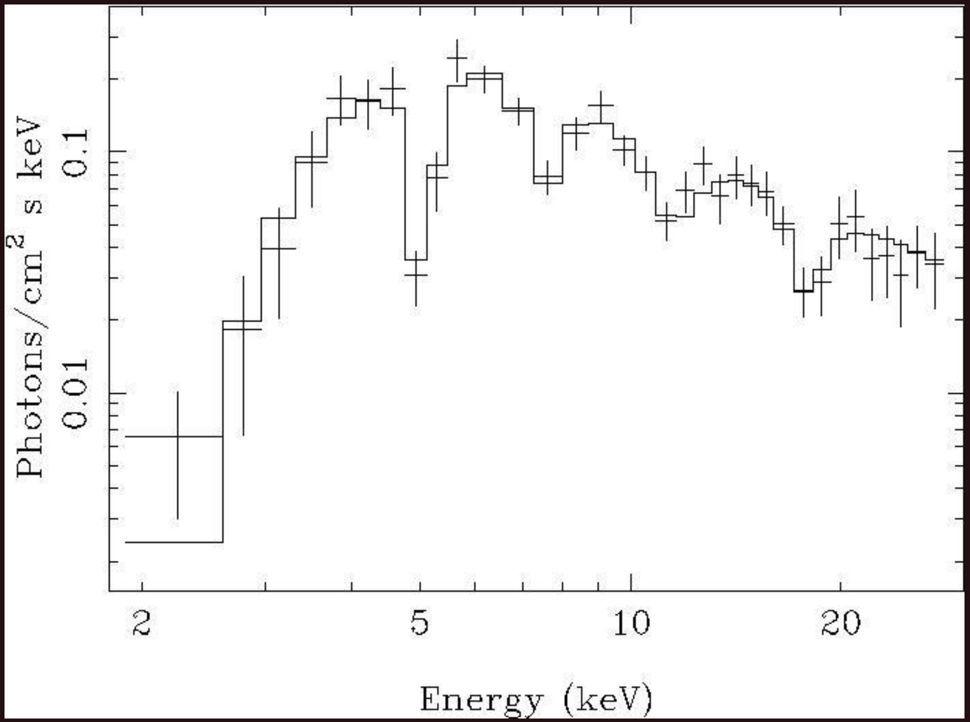
- $dE/dt > dE_{rot}/dt$
- By definition: The energy of the magnetic field is released

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)

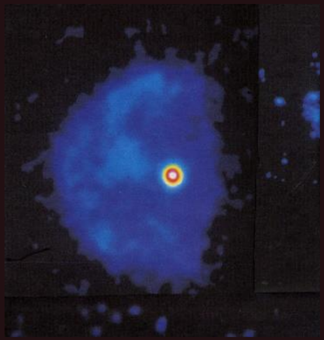



Ibrahim et al. 2002

# 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 (?)



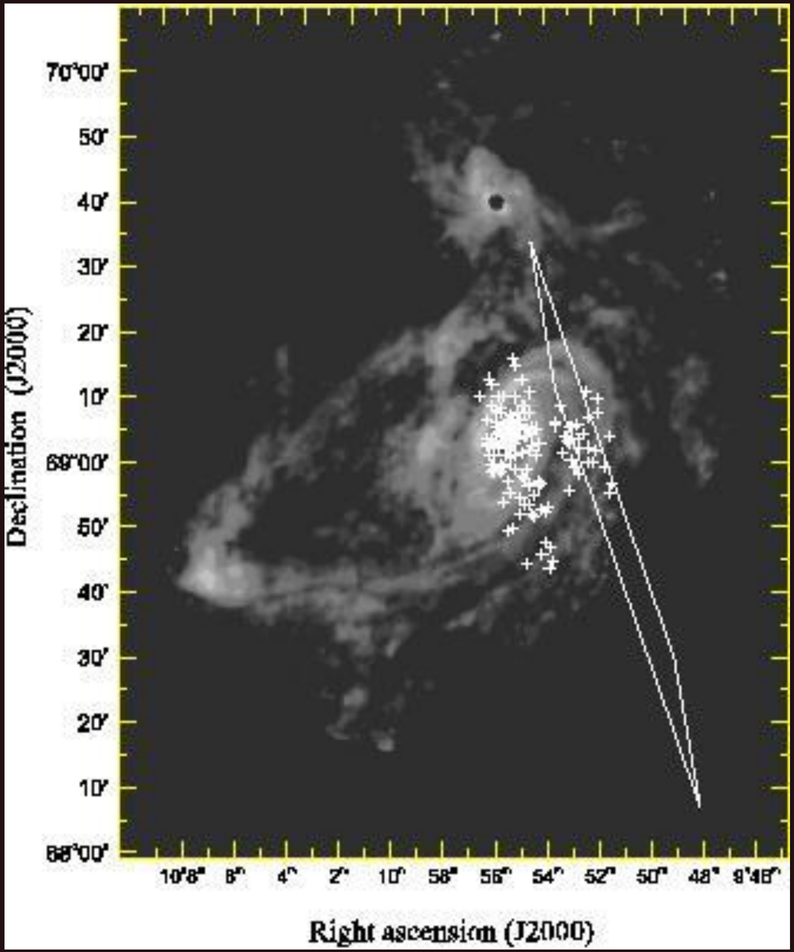
(CTB 109)

## 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.

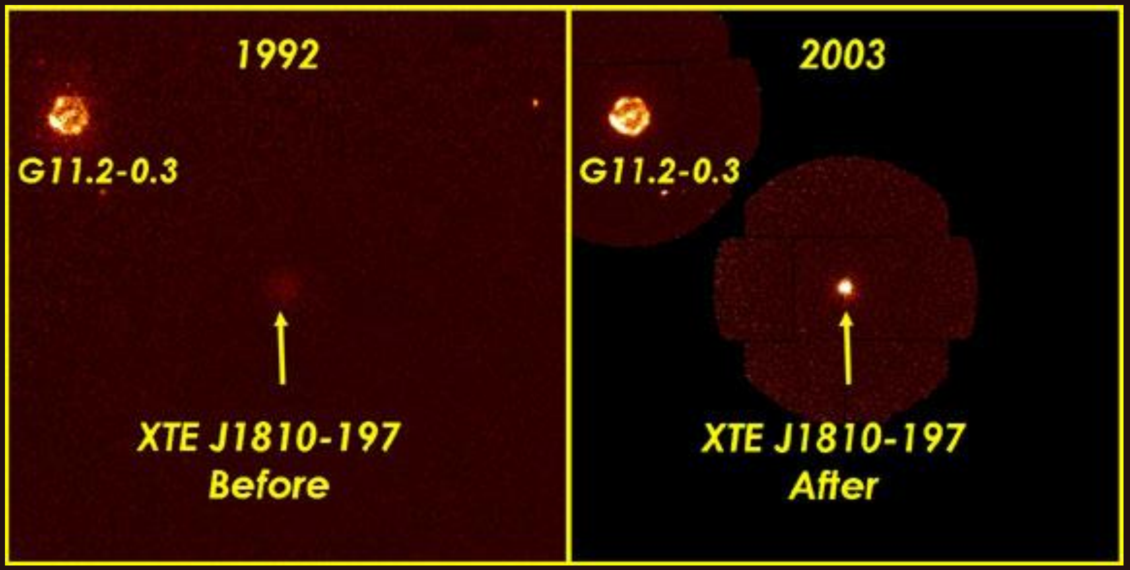
However, all searches in, for example, BATSE database did not provide god candidates (Lazzati et al. 2006, Popov & Stern 2006, etc.).

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

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

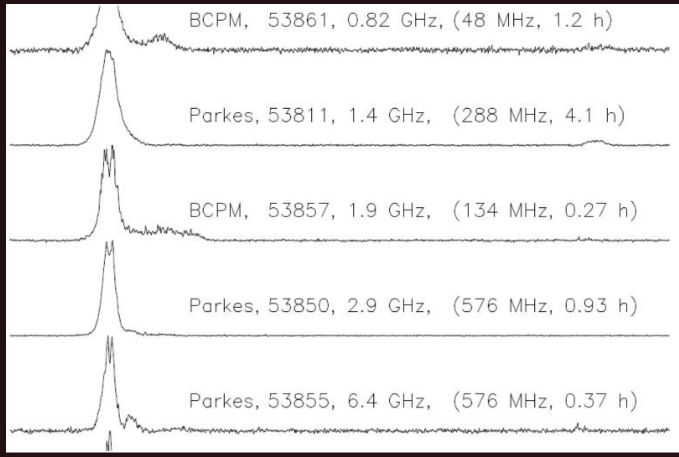
# Transient radio emission from AXP




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.



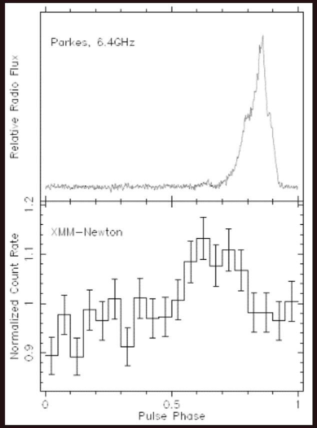

(Camilo et al. astro-ph/0605429) Recent radio data on this source: 1903.02660

# 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

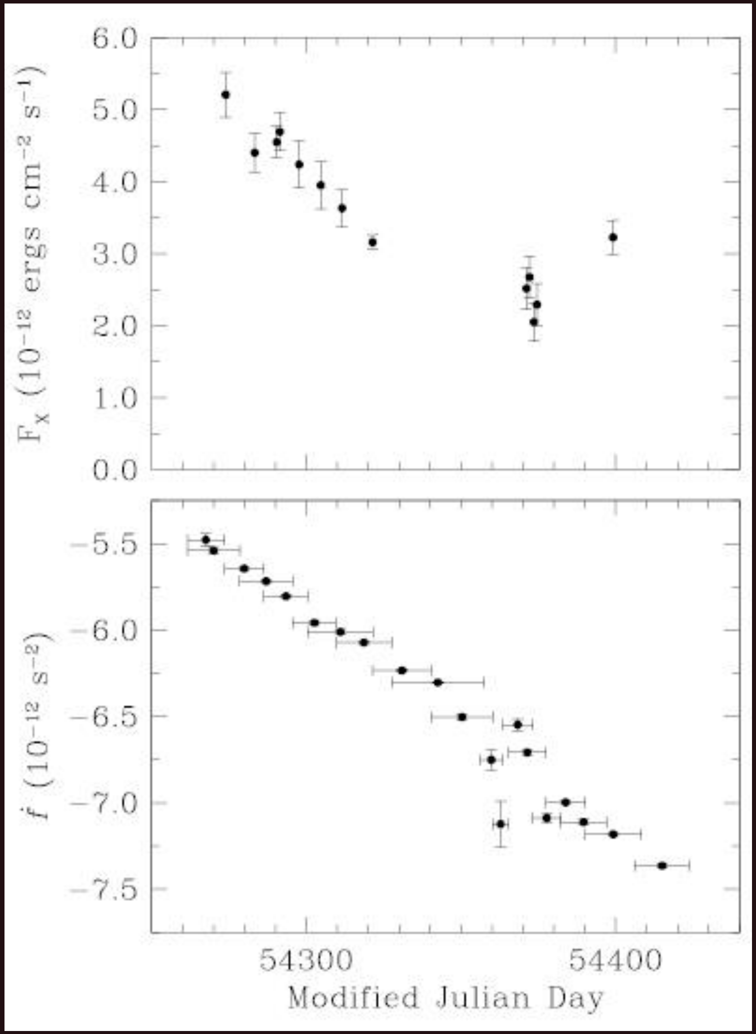
Also this AXP demonstrated weak
SGR-like bursts (Rea et al. 2008, GCN 8313)




Radio

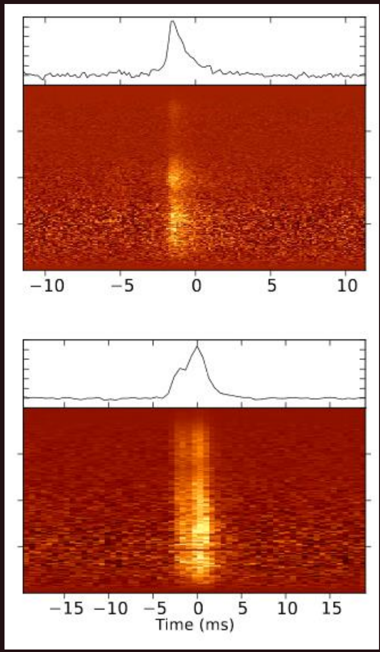
[simultaneous]

X-rays

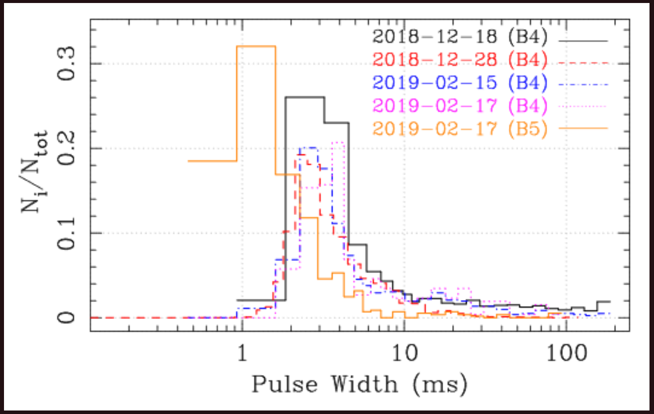



0802.0494 (see also arxiv:0711.3780 )

# Short radio pulses from magnetars

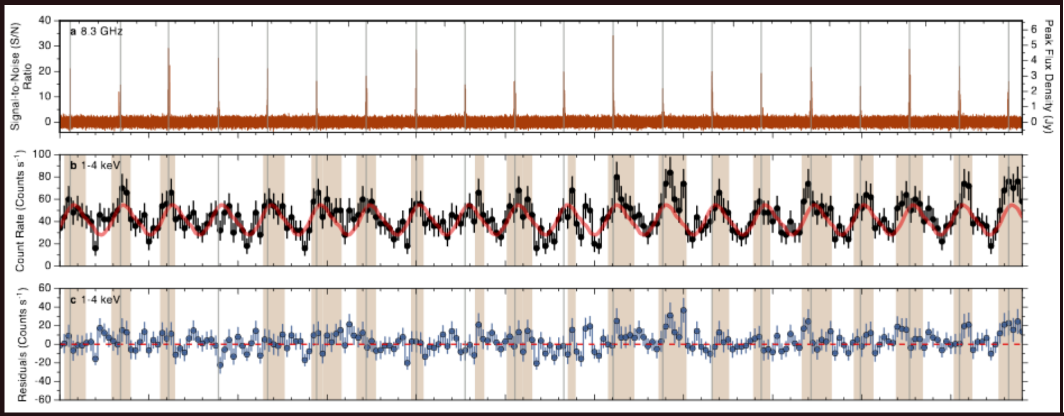


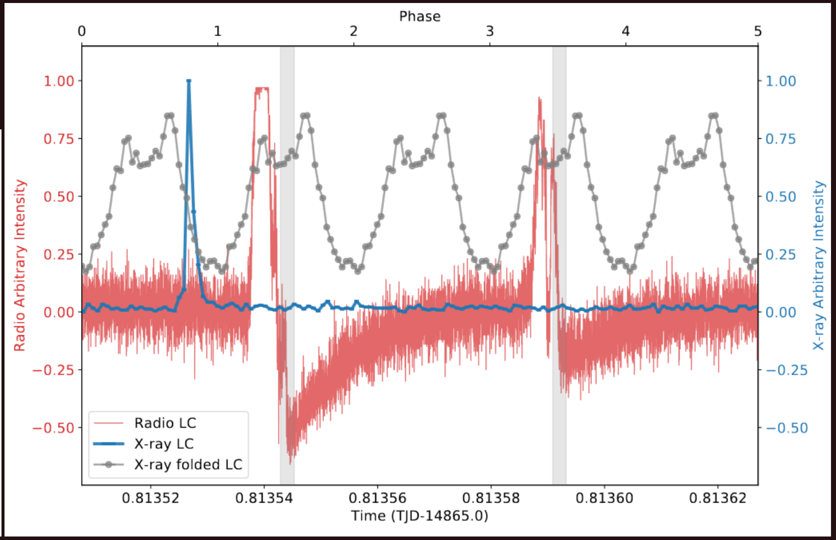

XTE 1810




1908.04304

1E 1547.0–5408




2005.08410

2011.06607

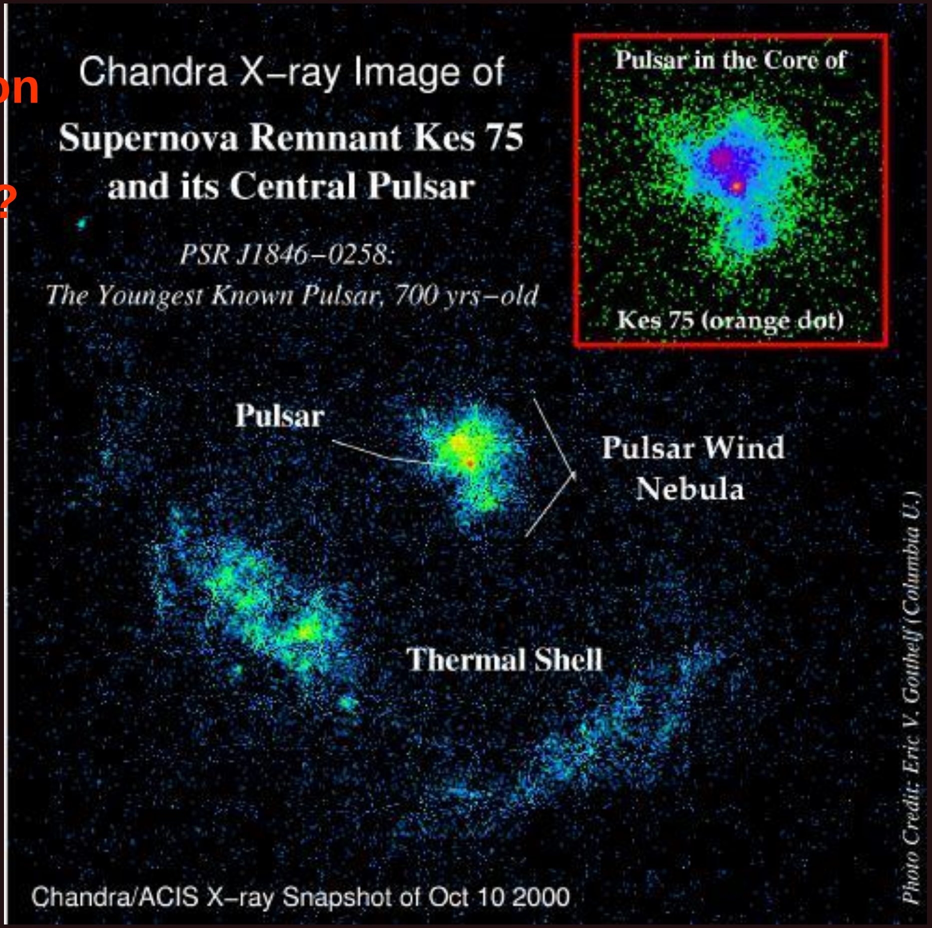
# Transient radiopulsar

**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).**

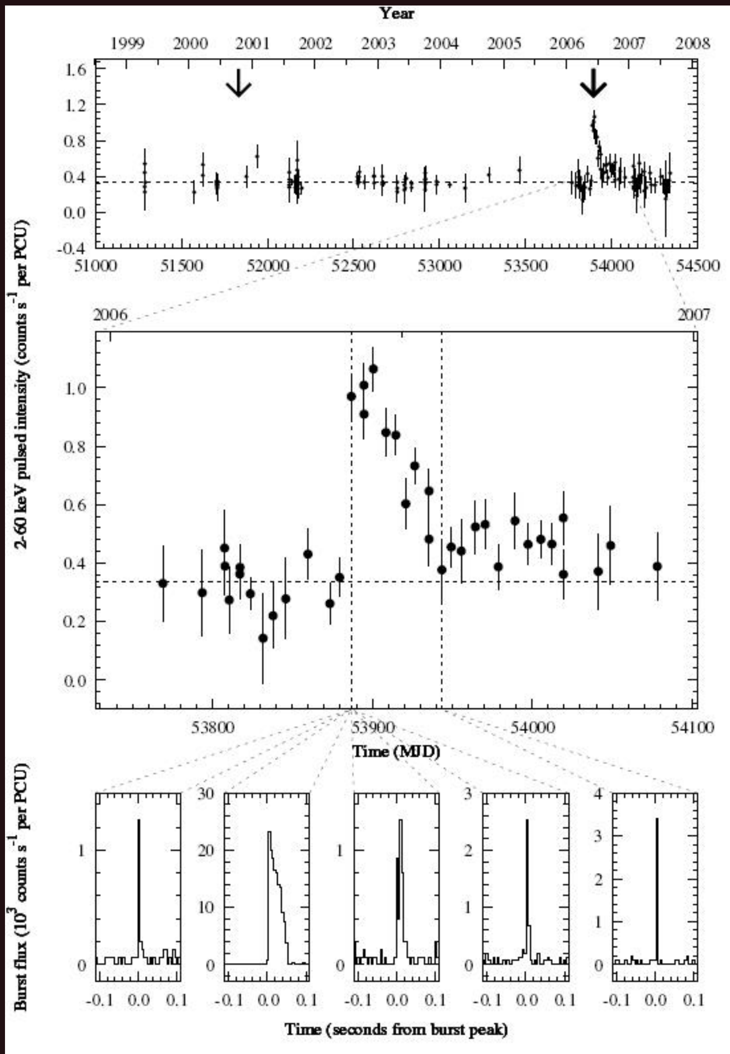
The pulsar increased
its luminosity in X-rays.
Increase of pulsed X-ray flux.
Magnetar-like X-ray bursts (RXTE).
Timing noise.




*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



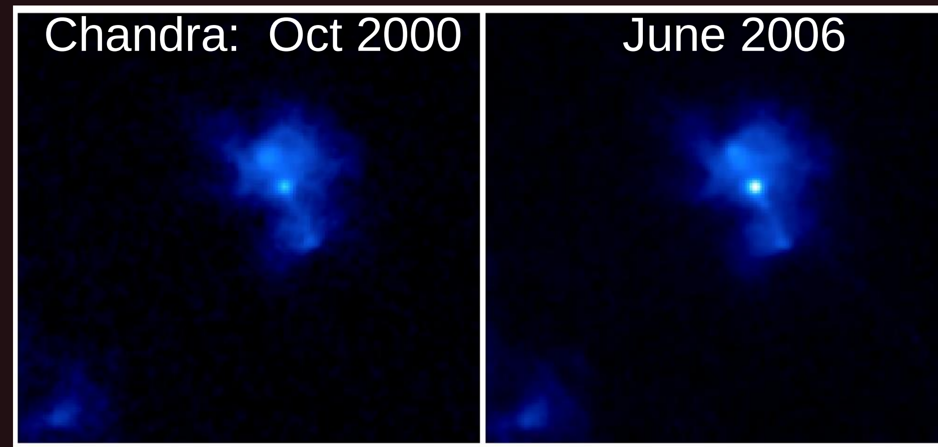
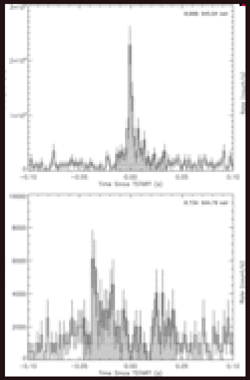




Table 1 PSR J1846−0258 Burst Temporal and Spectral Properties

| | 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 |
| $\chi^2$/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



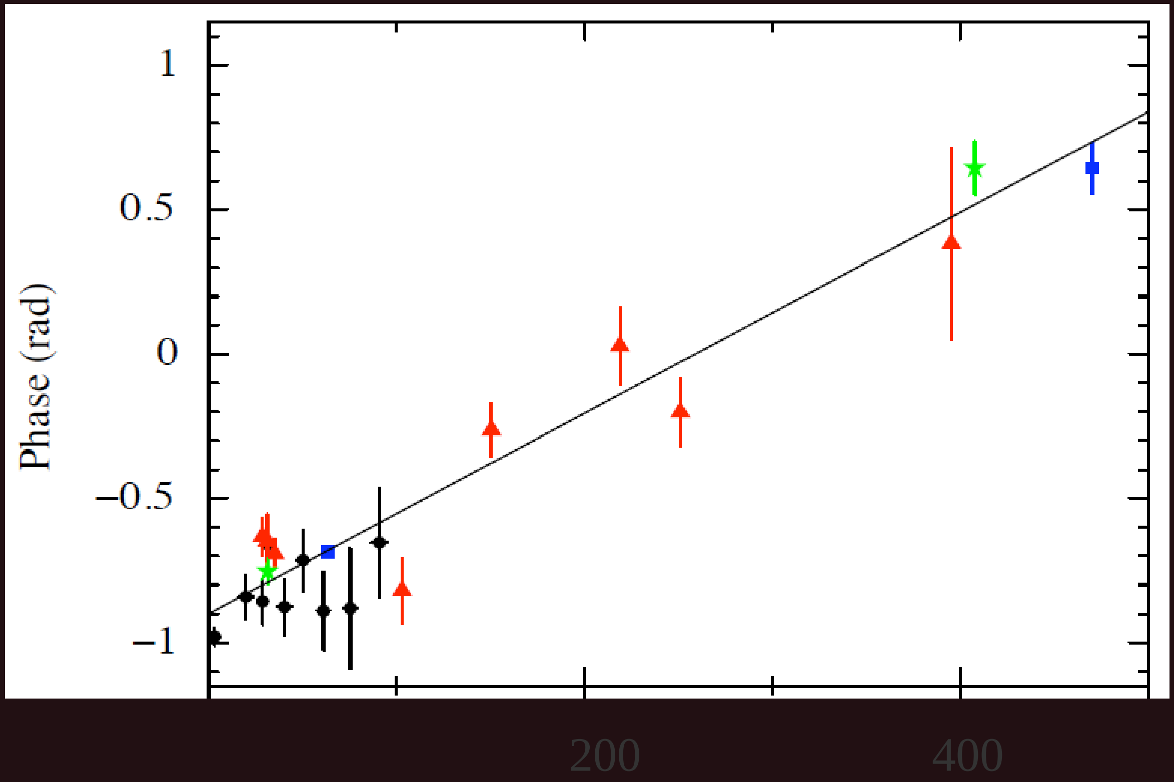
Spin period of a neutron star grows.
The rate of deceleration is related to the dipole magnetic field.
Measuring the spin-down rate we measure the field.

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)

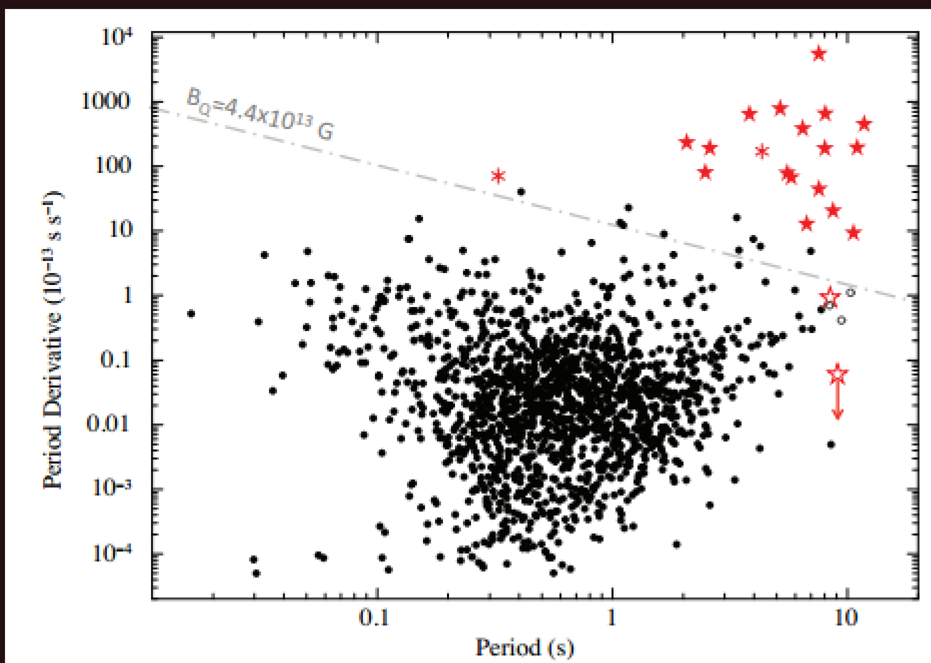


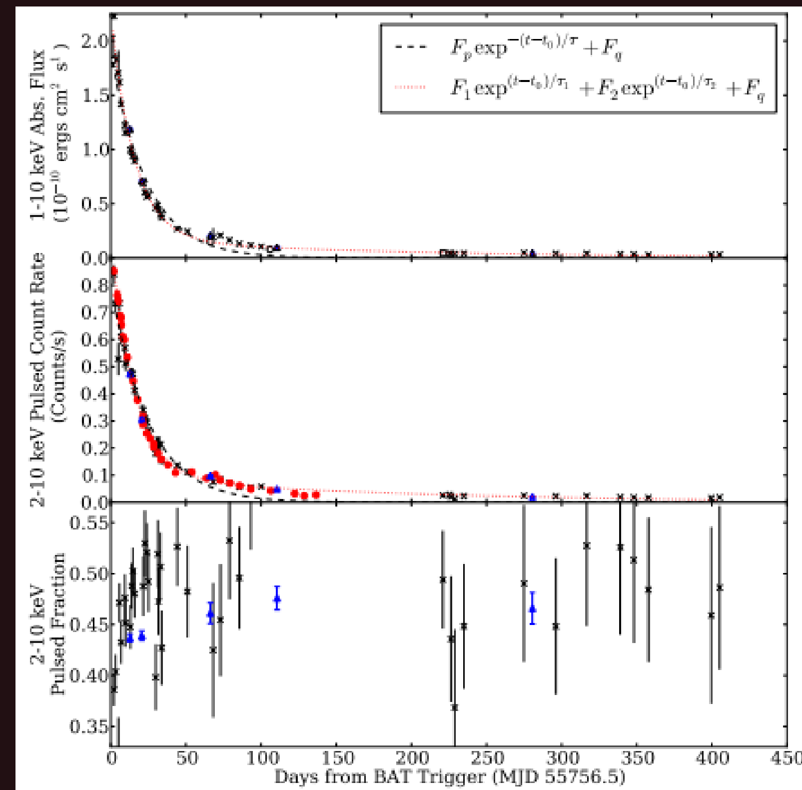

Spectral data suggests high field on the surface: 1103.3024

# Another low field magnetar

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

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



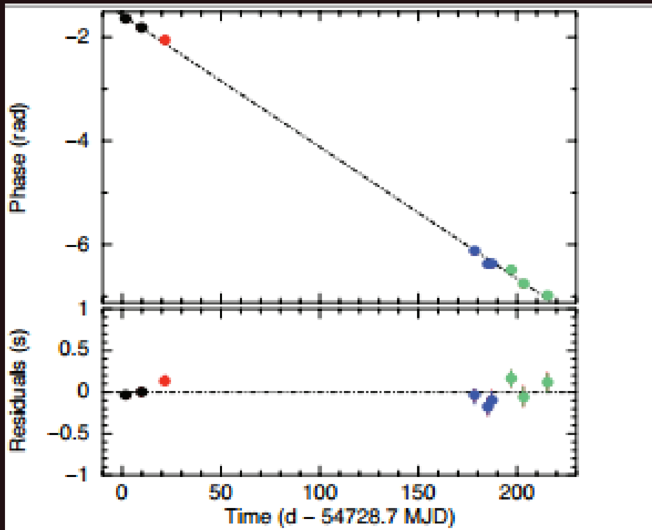



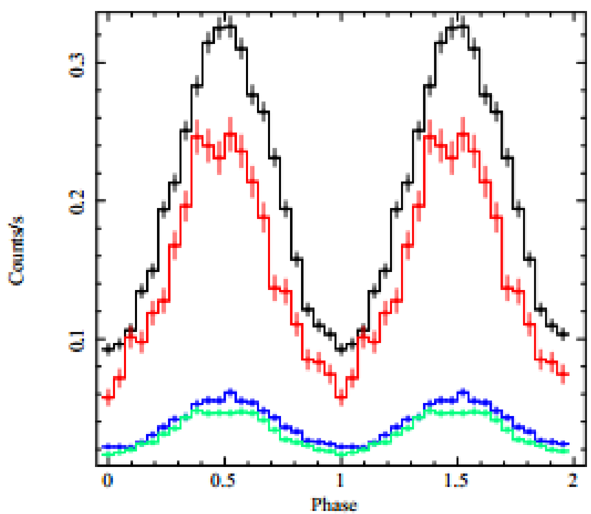

1204.1034

1203.6449

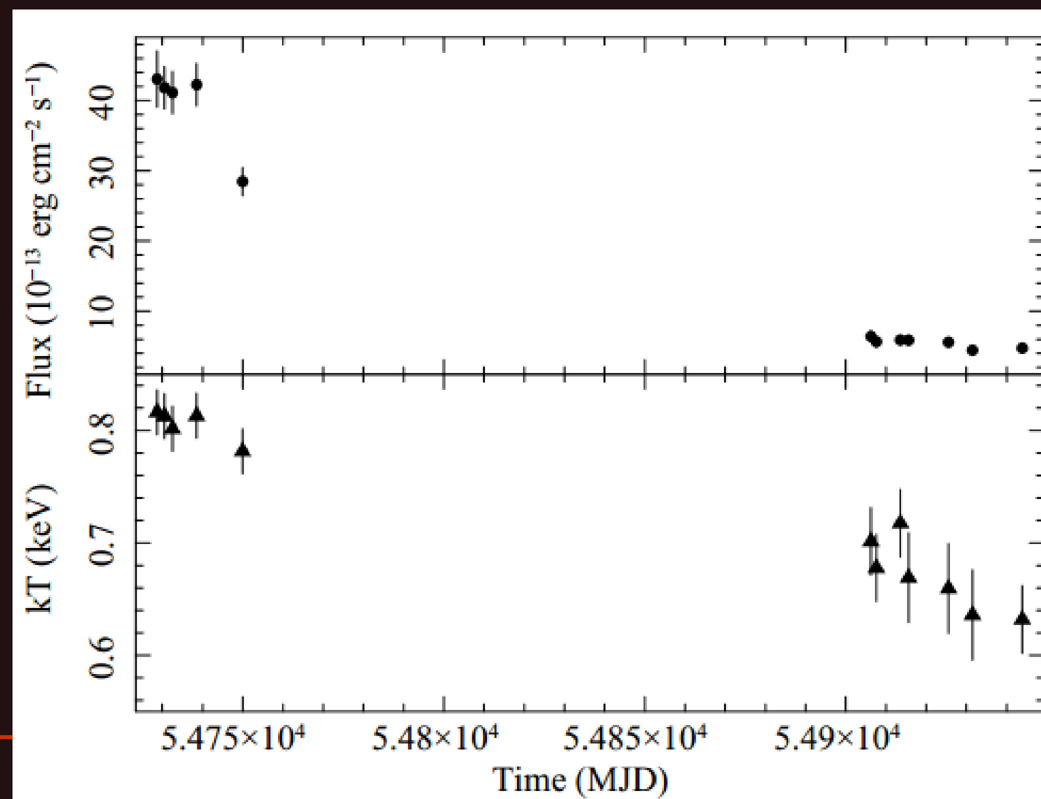
New data: 1211.7347

# 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

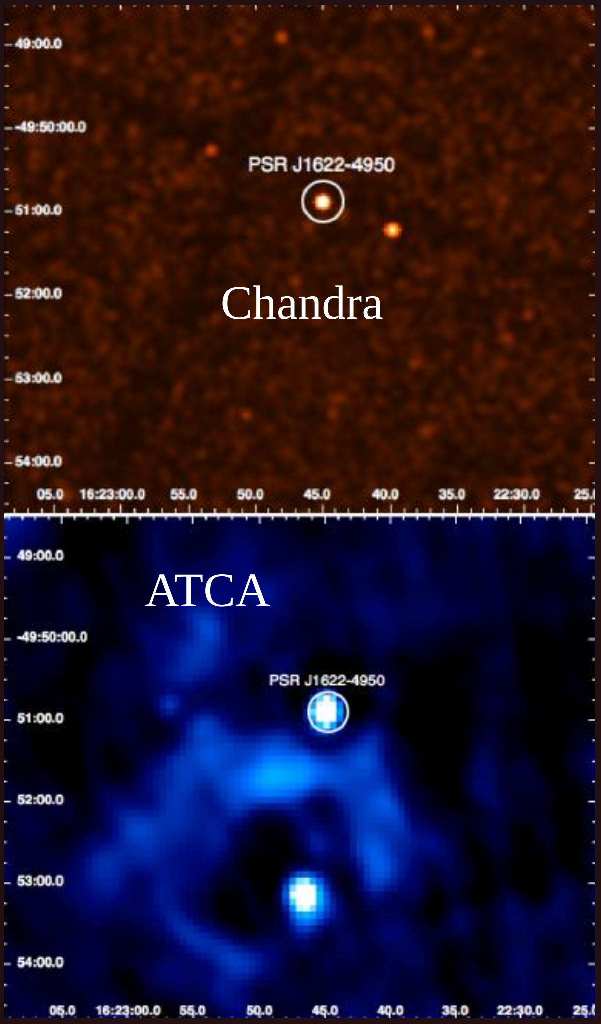
Normally, magnetars are detected via their strong activity: gamma-ray bursts or enhanced X-ray luminosity.

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



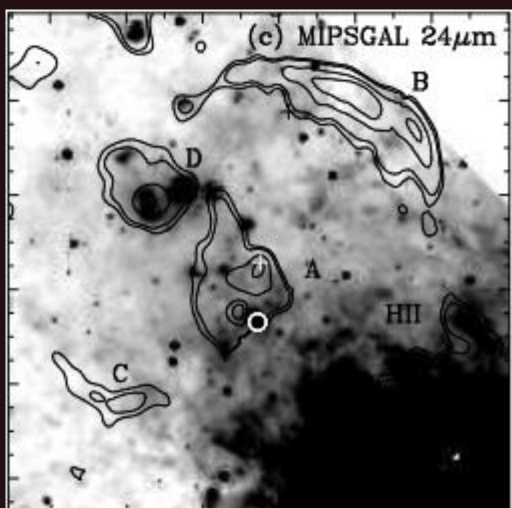

See reviews on high-B PSRs in 1010.4592, 1805.01680

arXiv: 1007.1052

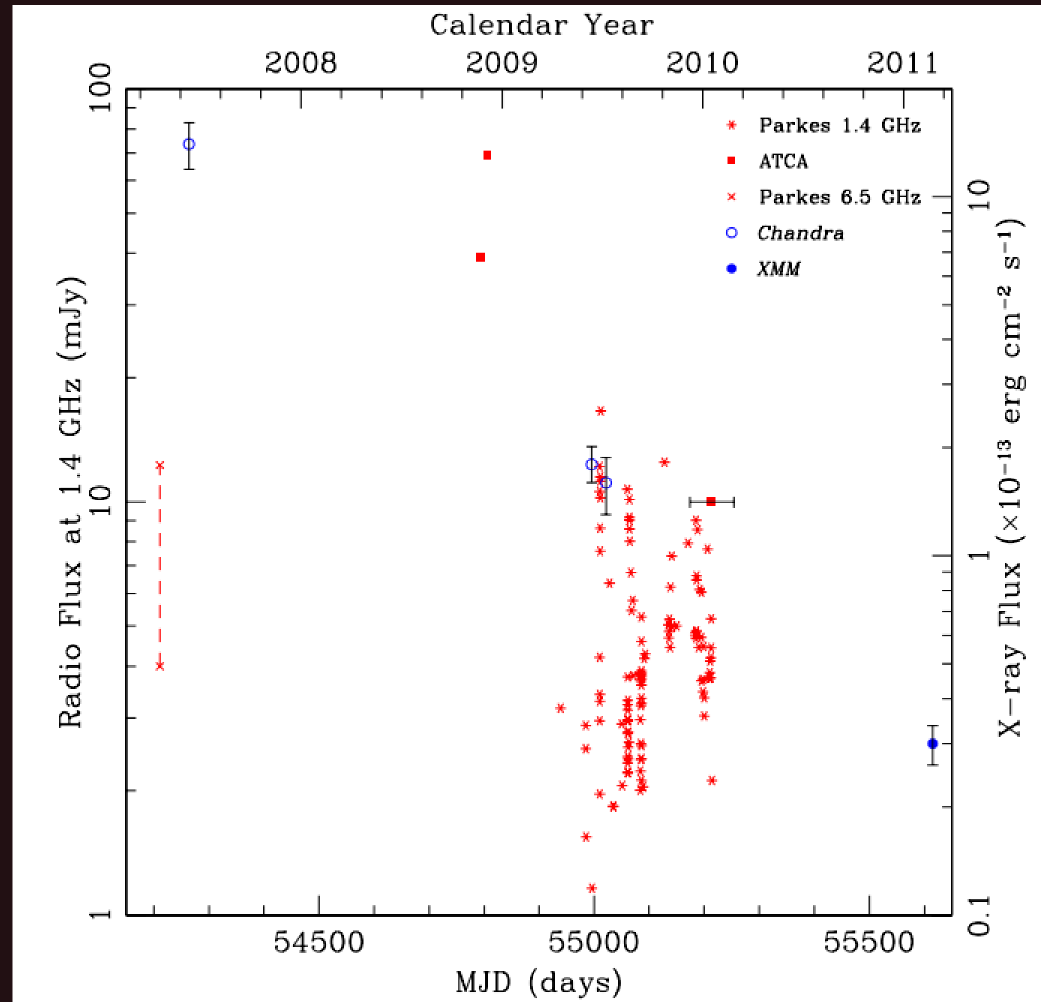
# Is J1622–4950 a transient magnetar?

PSR J1622–4950

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



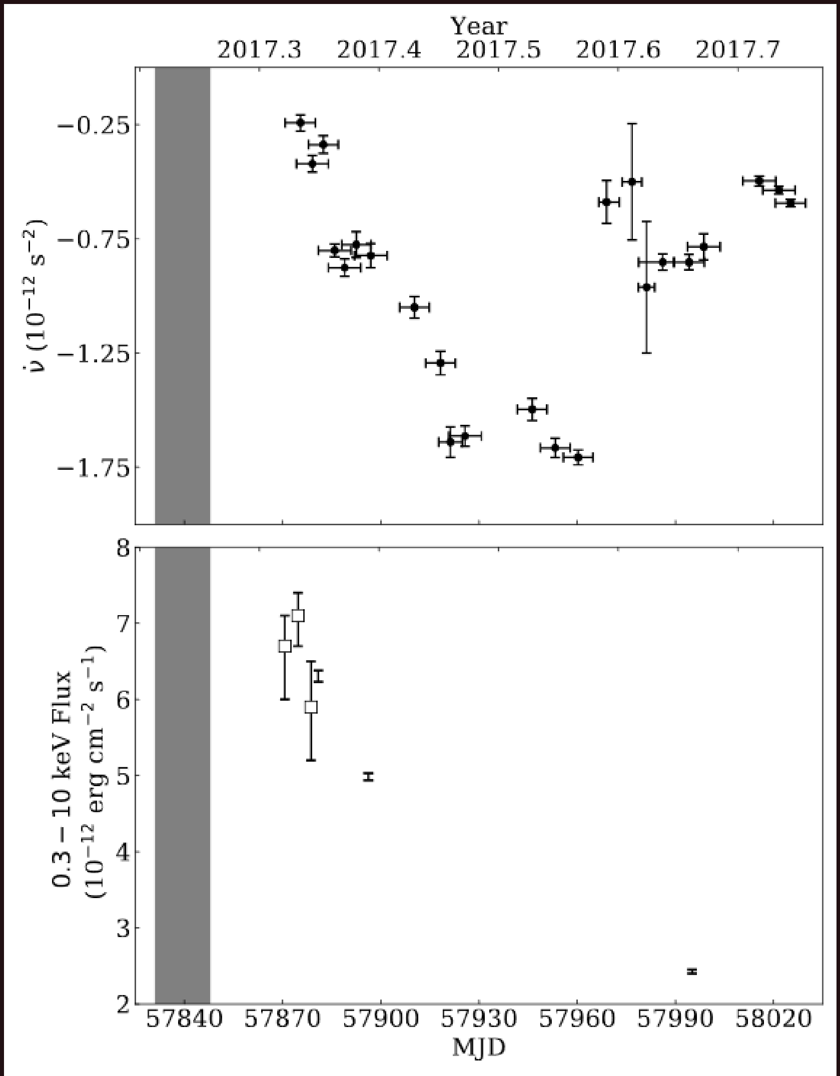

G333.9+0.0 SNR ?

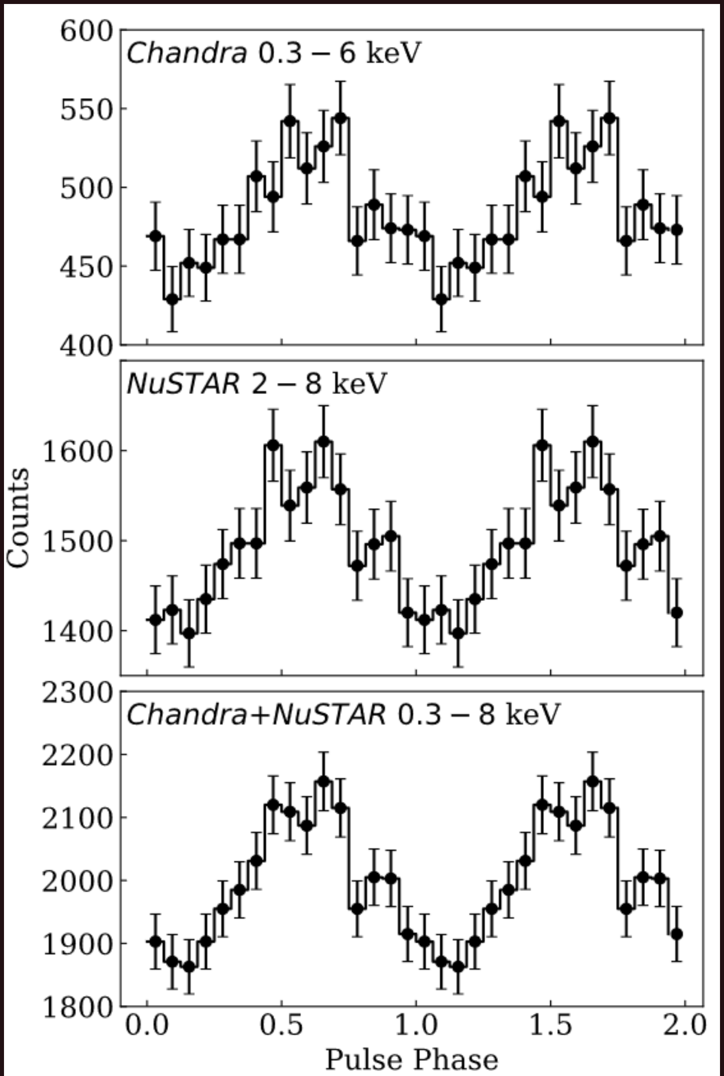



1203.2719

See also 1204.2045

# Yes! Revival of J1622–4950

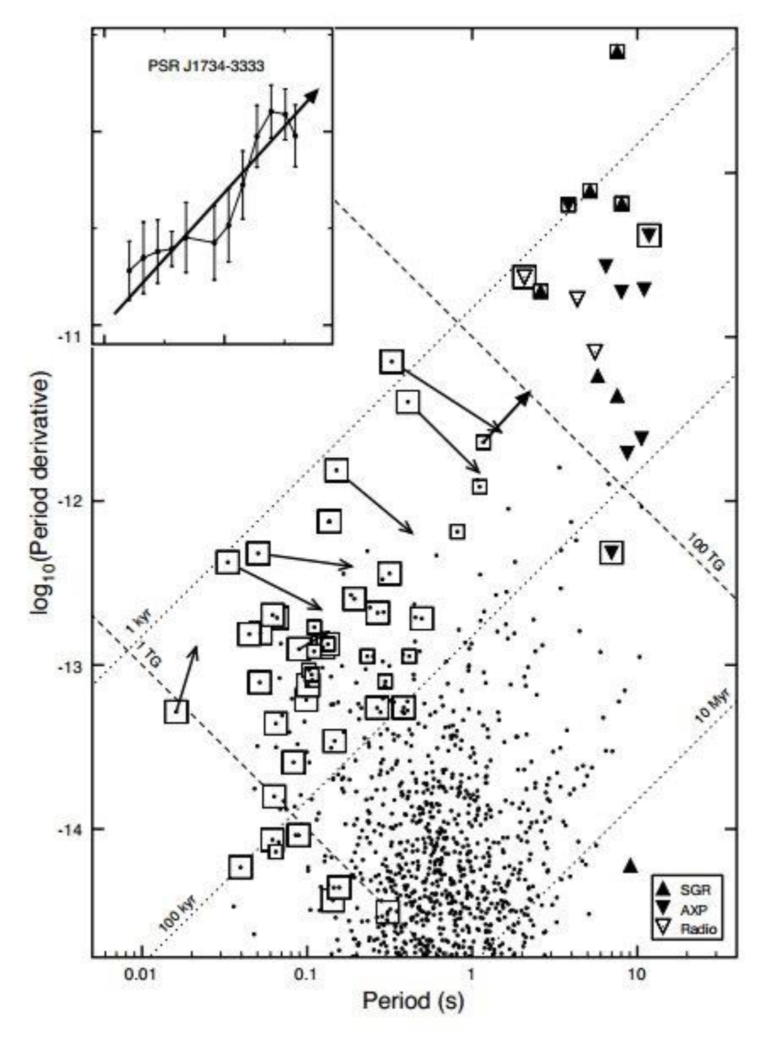



1804.01933

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

# A pulsar with growing field?

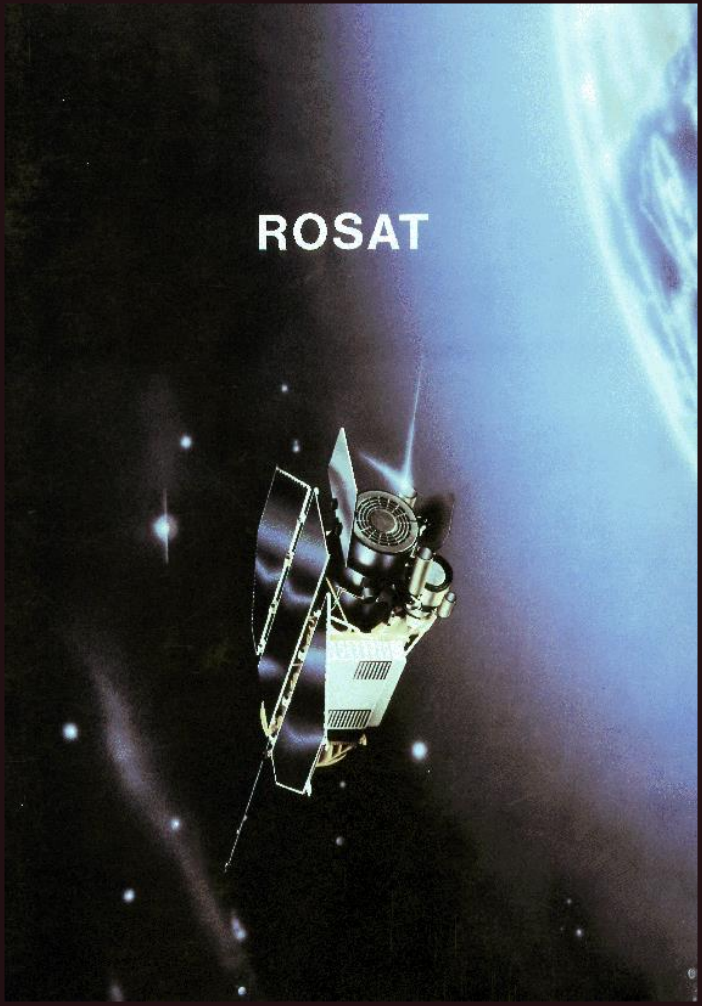



PSR J1734−3333
n=0.9+/-0.2

Will it become a magnetar?

Espinoza et al. arXiv: 1109.2740

# ROSAT

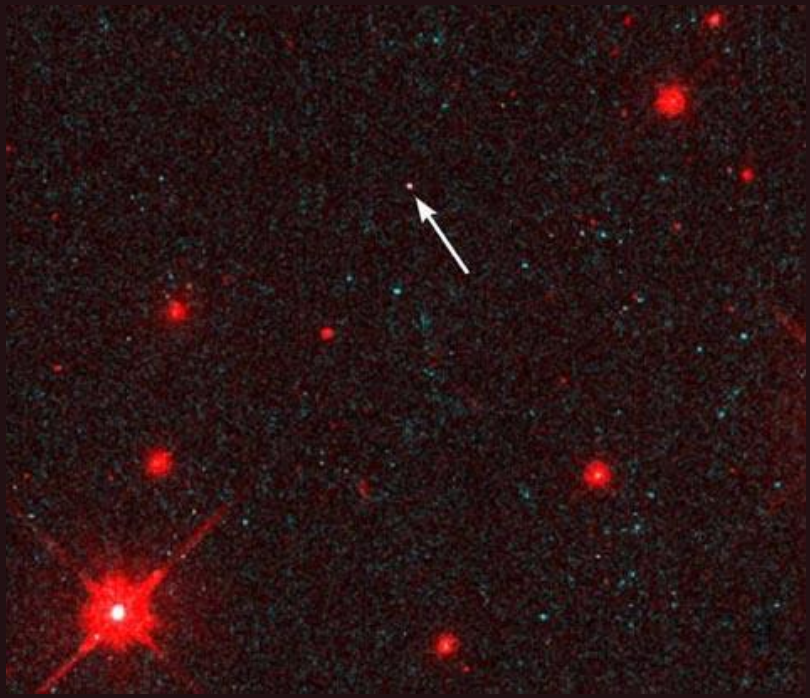



ROentgen SATellite

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

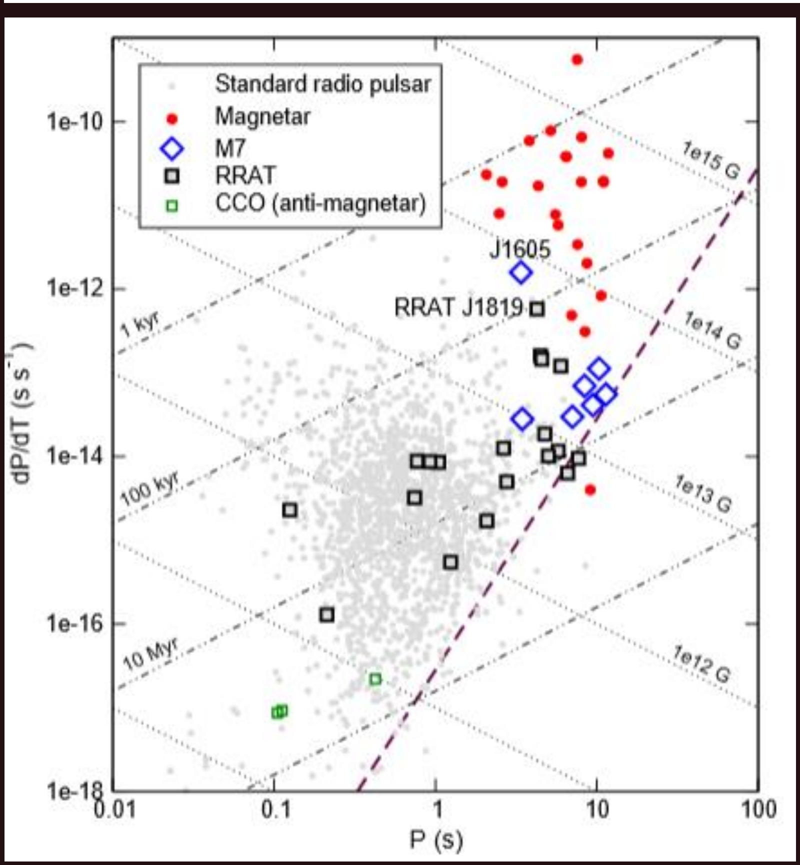
| RX J | Spin[*] | | | Spectrum[†] | | | | | Astrometry[**] | | References |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | P (s) | $\dot{P}$ ($10^{-14}$) | PF (%) | $N_{H,20}$ ($cm^{-2}$) | kT (eV) | PN ($s^{-1}$) | $E_{abs}$ (keV) | $m_B$ (mag) | $\mu$ (mas $yr^{-1}$) | d (pc) | |
| 1856.5−3754 | 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

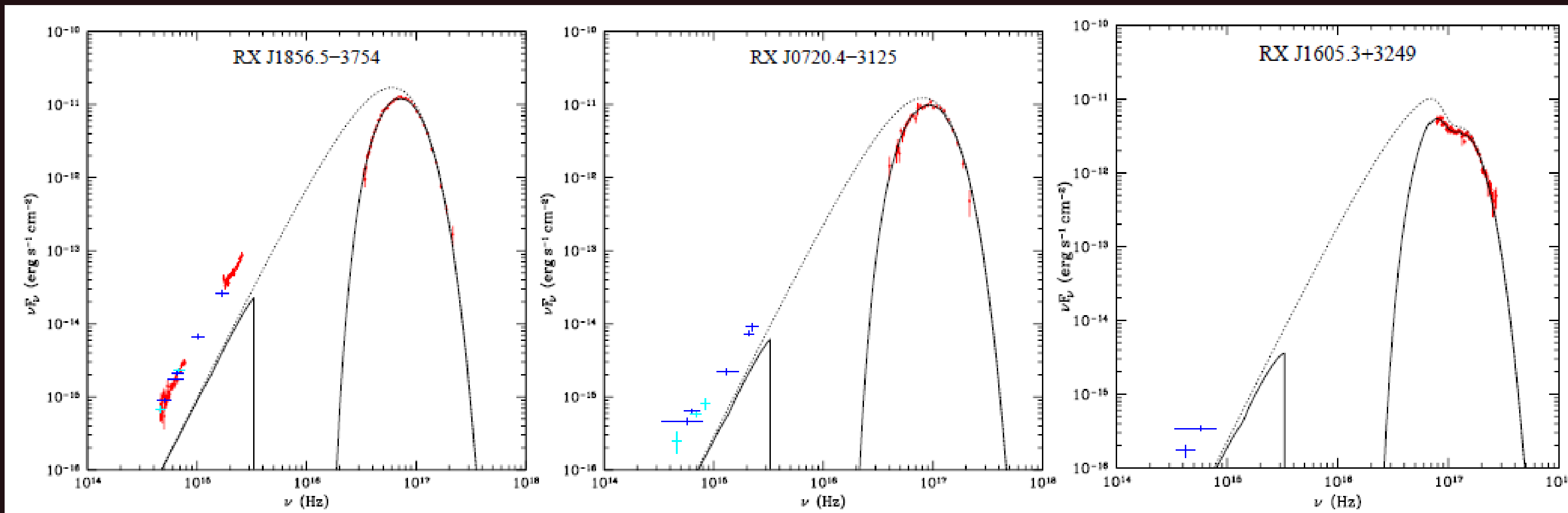
| Object | $kT_\infty$ (eV) | $P$ (s) | $p_f$ (%) | $\log(\dot{P})$ ($s\,s^{-1}$) | $\log(\dot{E})$ ($erg\,s^{-1}$) | $\log(\tau_{ch})$ (yr) | $\log(t_{kin})$ (yr) | $\log(B_{dip})$ ($10^{13}$ G) | $\log(B_{cyc})$ ($10^{13}$ G) | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| RX J1856.5-3754 | 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] |



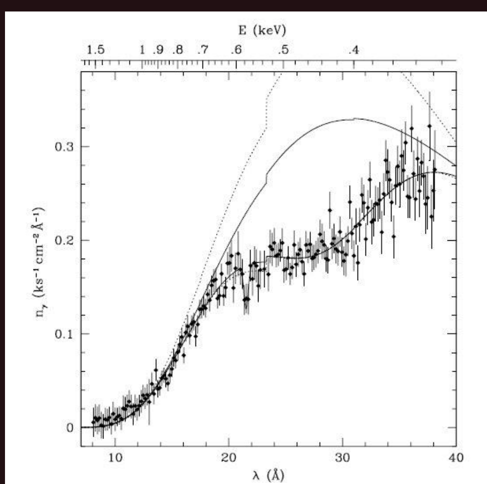

Several radio pulsars can be similar to M7.
E.g. PSR J0726−2612 (see 1906.01372).

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.

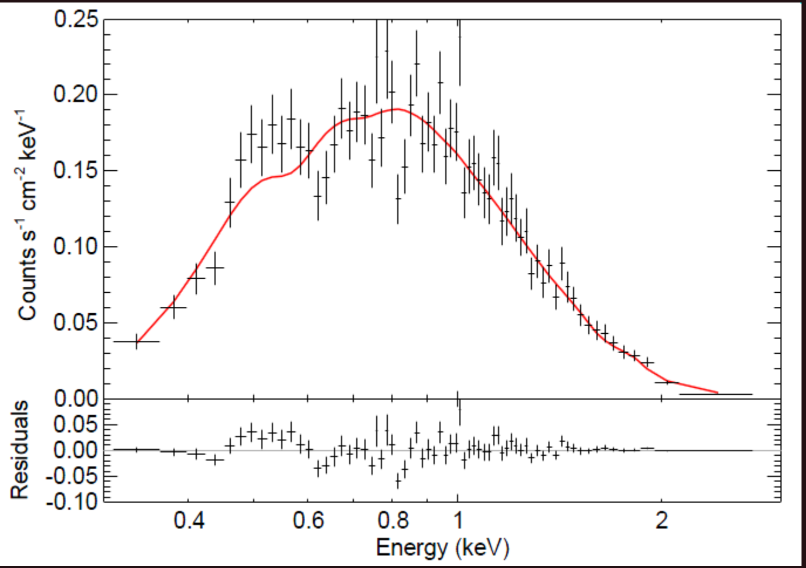
| XDINS | Pulsed emission | | | Bursty emission | | |
|---|---|---|---|---|---|---|
| | $S_{\rm lim}$ ($\mu$Jy) | $L_{1400}^{\rm p,max}$ (mJy kpc$^2$) | $L_{820}^{\rm p,max}$ (mJy kpc$^2$) | rate upper limit (hr$^{-1}$) | $S_{\rm lim}^{\rm sp}$ (mJy) | $L_{1400}^{\rm b,max}$ (mJy kpc$^2$) |
| RX J0720.4−3125 | 8 | $4\times10^{-4}$ | $10^{-3}$ | 0.25 | 21 | 1 |
| RX J0806.4−4123 | 10 | $4\times10^{-3}$ | $10^{-2}$ | 0.32 | 18 | 6.9 |
| RX J1308.6+2127 | 10 | $4\times10^{-3}$ | $10^{-2}$ | 0.24 | 17 | 6.5 |
| RX J1605.3+3249 | 8 | $3\times10^{-3}$ | $8\times10^{-3}$ | 0.25 | 22 | 8.4 |
| RX J1856.5−3754 | 14 | $1.4\times10^{-4}$ | $3.6\times10^{-4}$ | 0.32 | 24 | 0.2 |
| RX J2143.0+0654 | 13 | $5\times10^{-3}$ | $1.3\times10^{-2}$ | 0.36 | 20 | 7.6 |

Kondratiev et al. arXiv: 0907.0054

# Calvera et al.

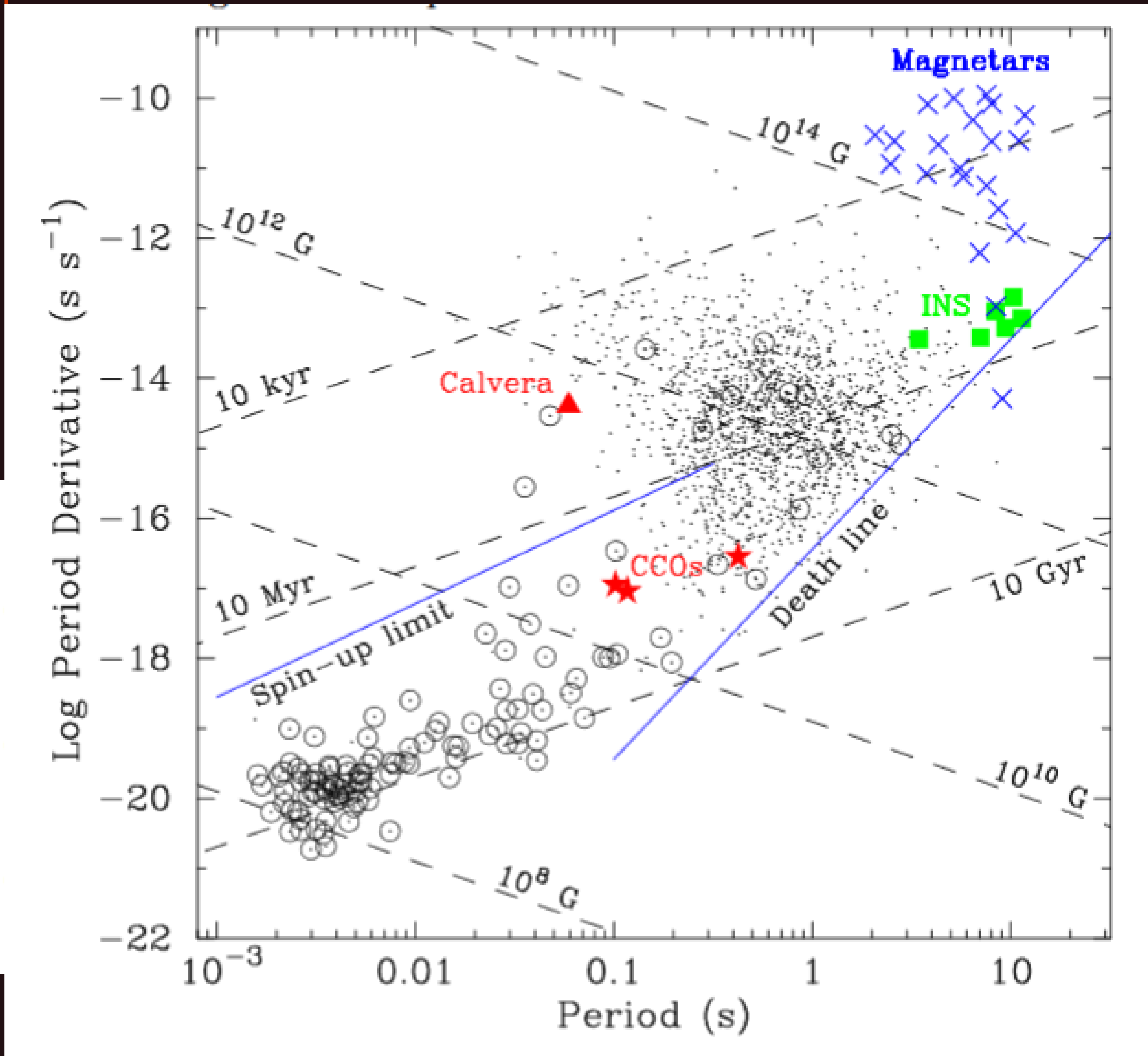
In 2008 Rutledge et al. reported the discovery of an enigmatic NS candidated dubbed *Calvera*. It is high above the galactic plane.

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



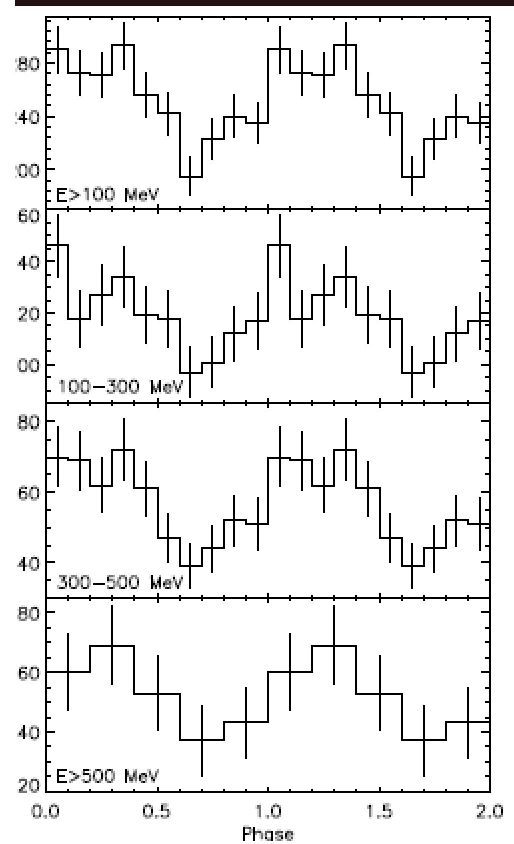

Shevchuk et al. arXiv: 0907.4352

1310.6789




0 eV and ~80/250 eV)

Norm. Intensity




New data 1510.00683, 1902.00144

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

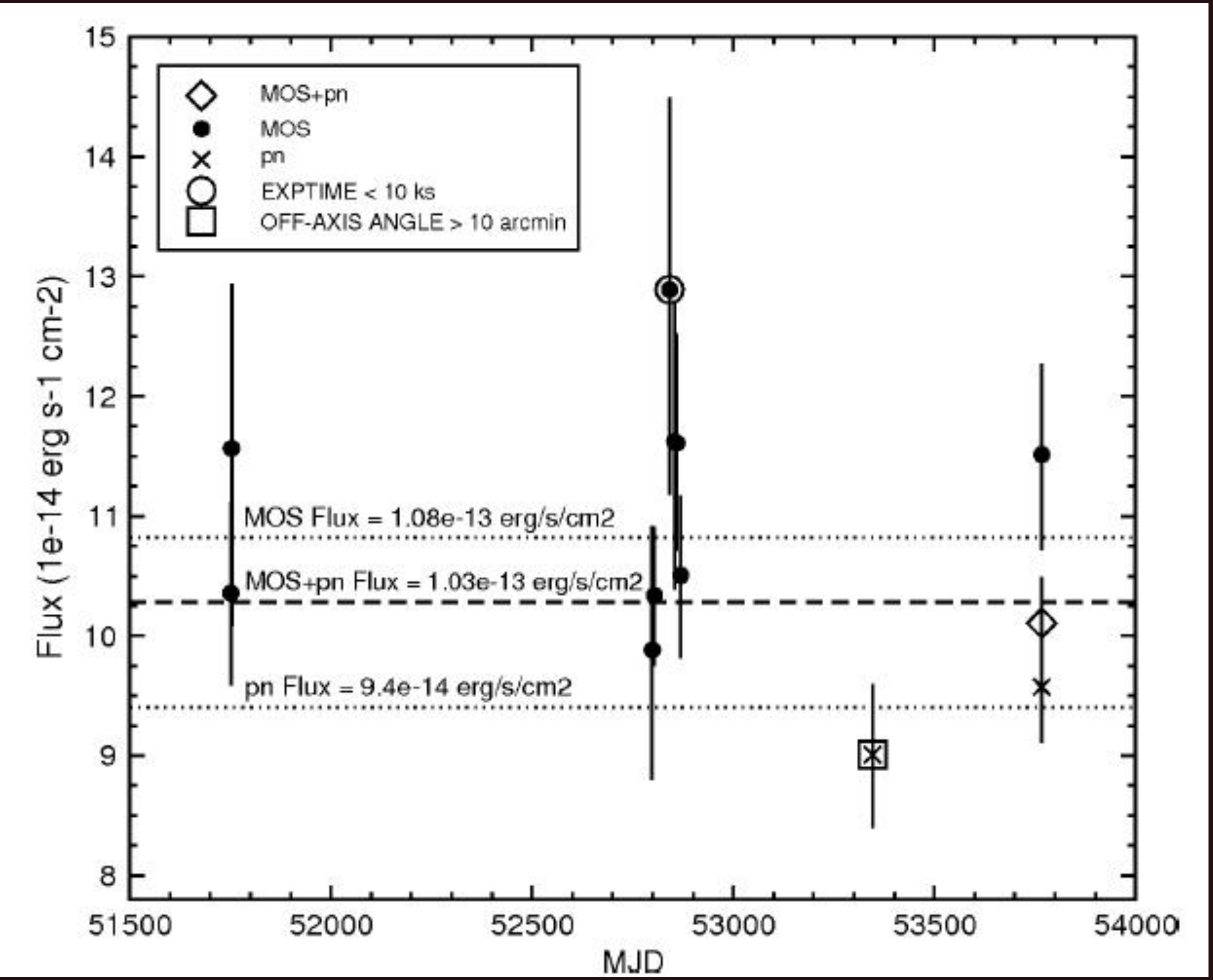
A new INS candidate.

*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.

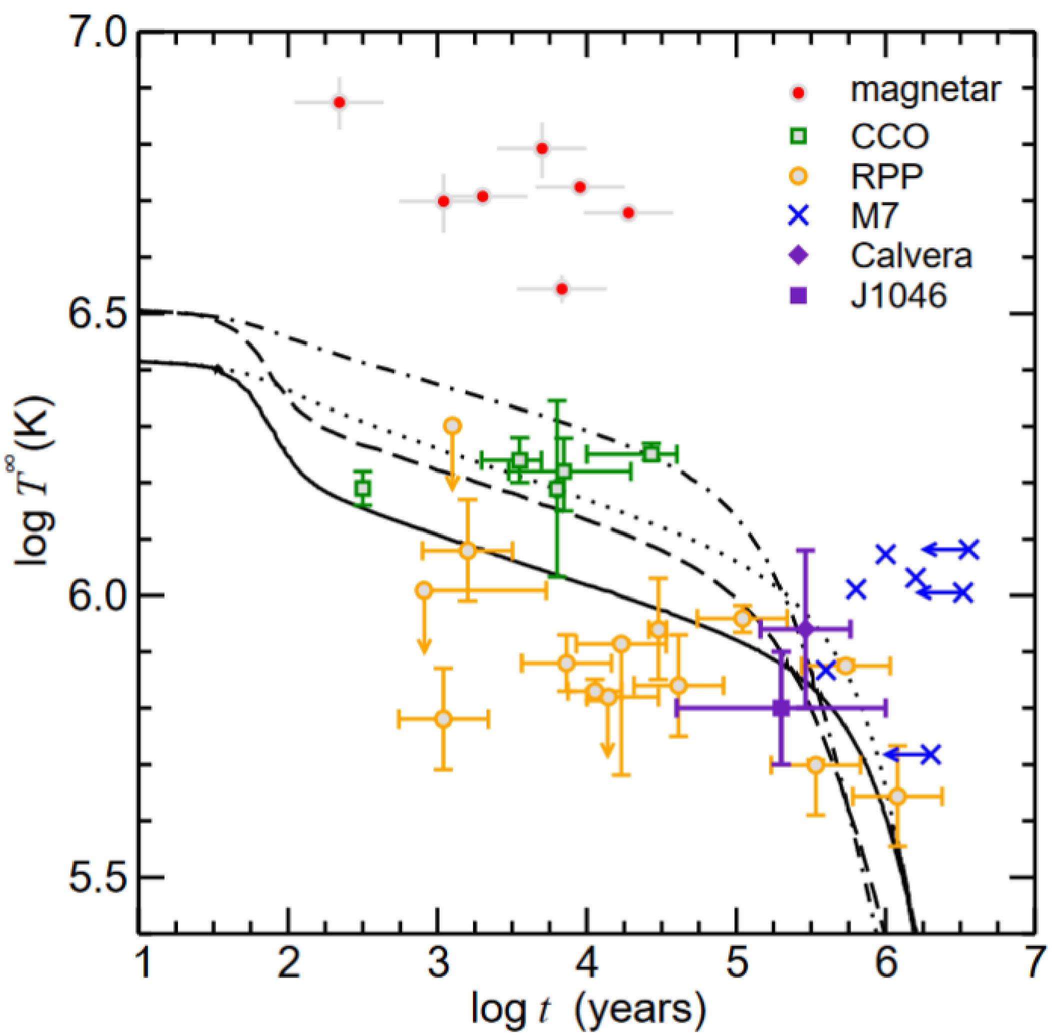
At 2.3 kpc (Eta Carina)
the luminosity is
$L_X \sim 8.2\ 10^{32}$ erg s$^{-1}$
$R_\infty \sim 5.7$ km



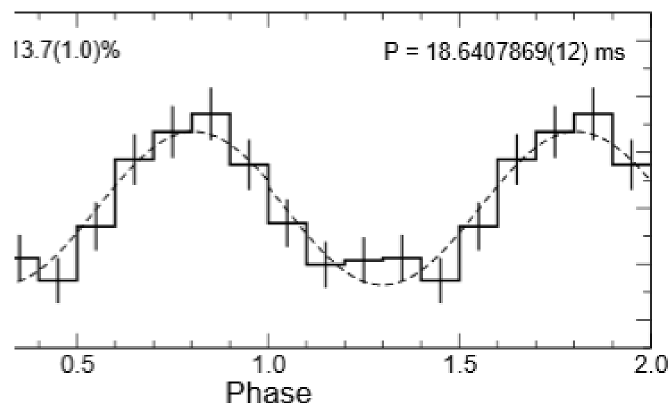

**M7-like? Yes!**
**But P=19 msec**

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

# Spin period of 2XMM J1046-5943



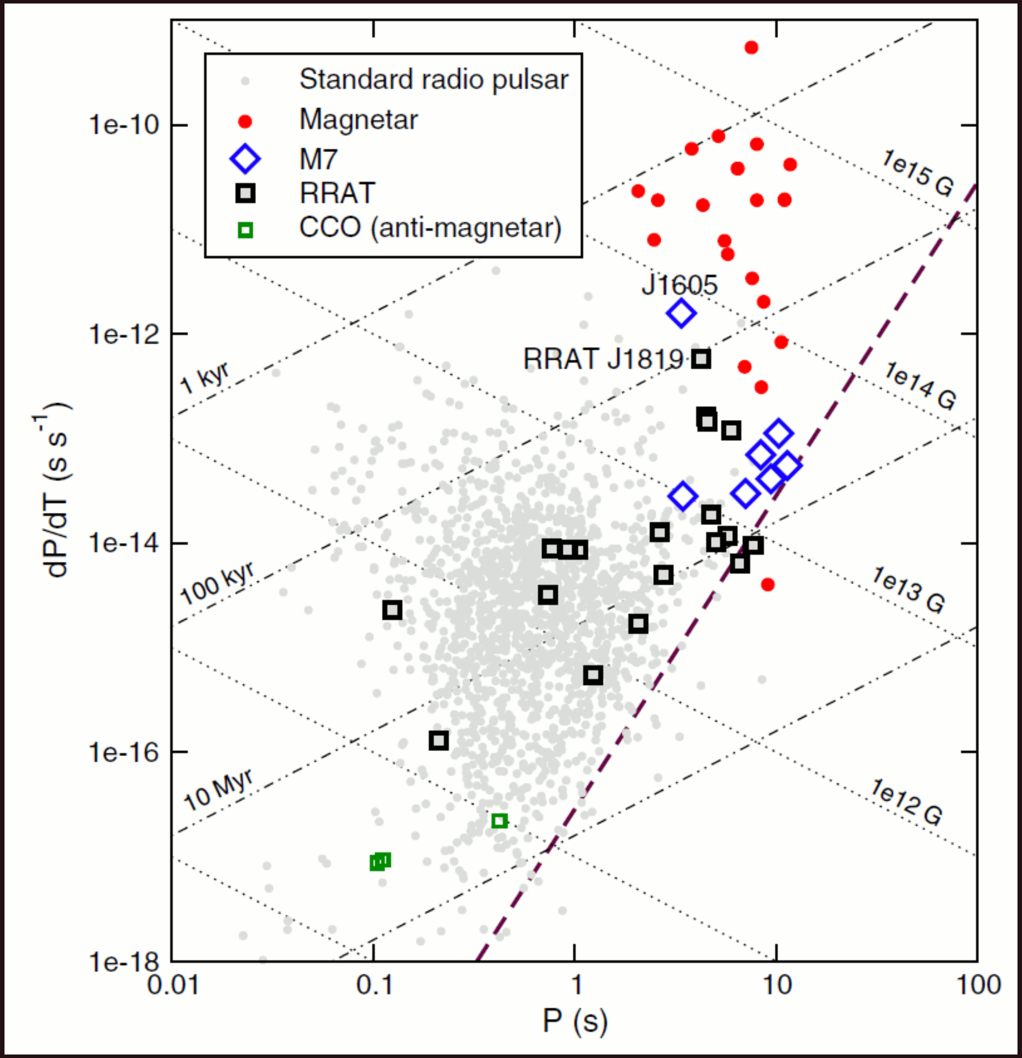

Calvera-like?




$$T_{\rm eff} = (6-10)\times10^5\ {\rm K,\ and}\ L_X = (1.1-7.4)\times10^{32}\ {\rm erg\ s^{-1}}$$

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.

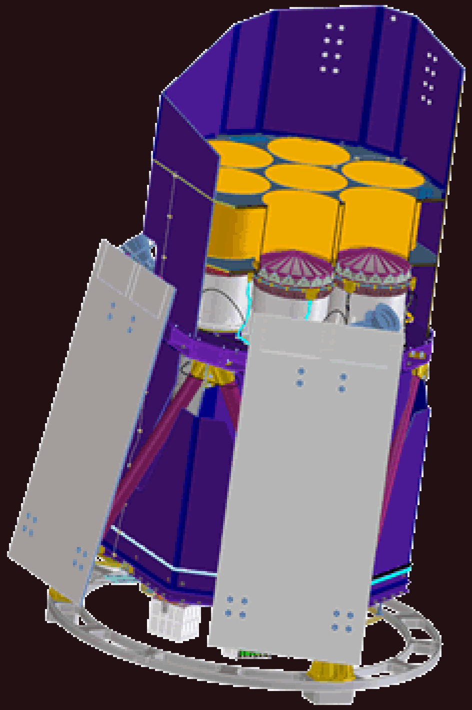
Or, can be a different population.

Pires et al. (2015), A&A

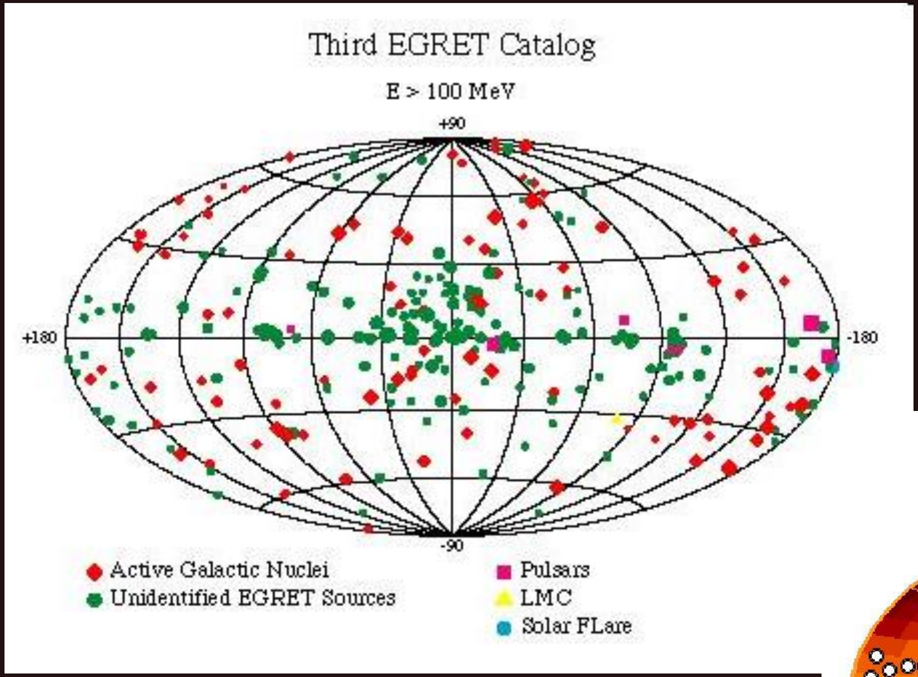
# How to find new candidates?

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.)

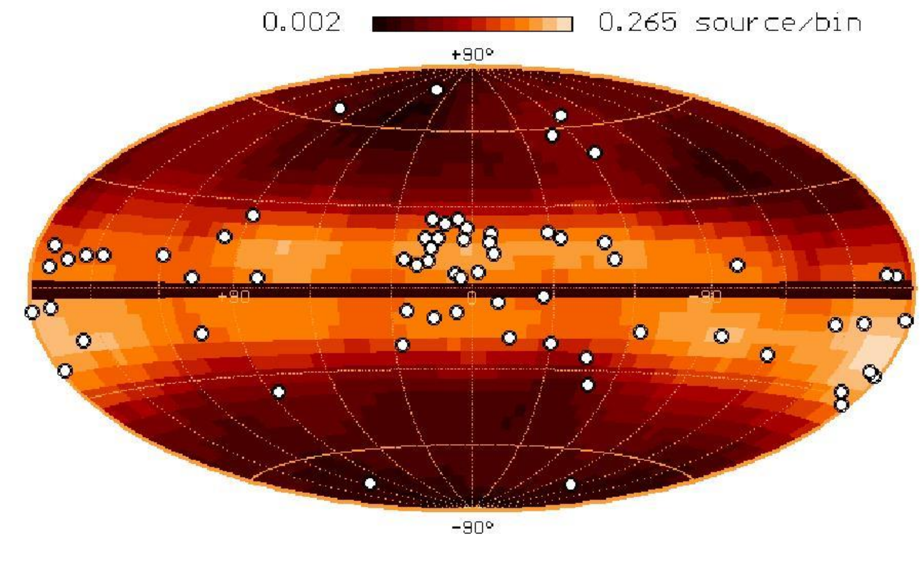


# Pulsars invisible in radio?



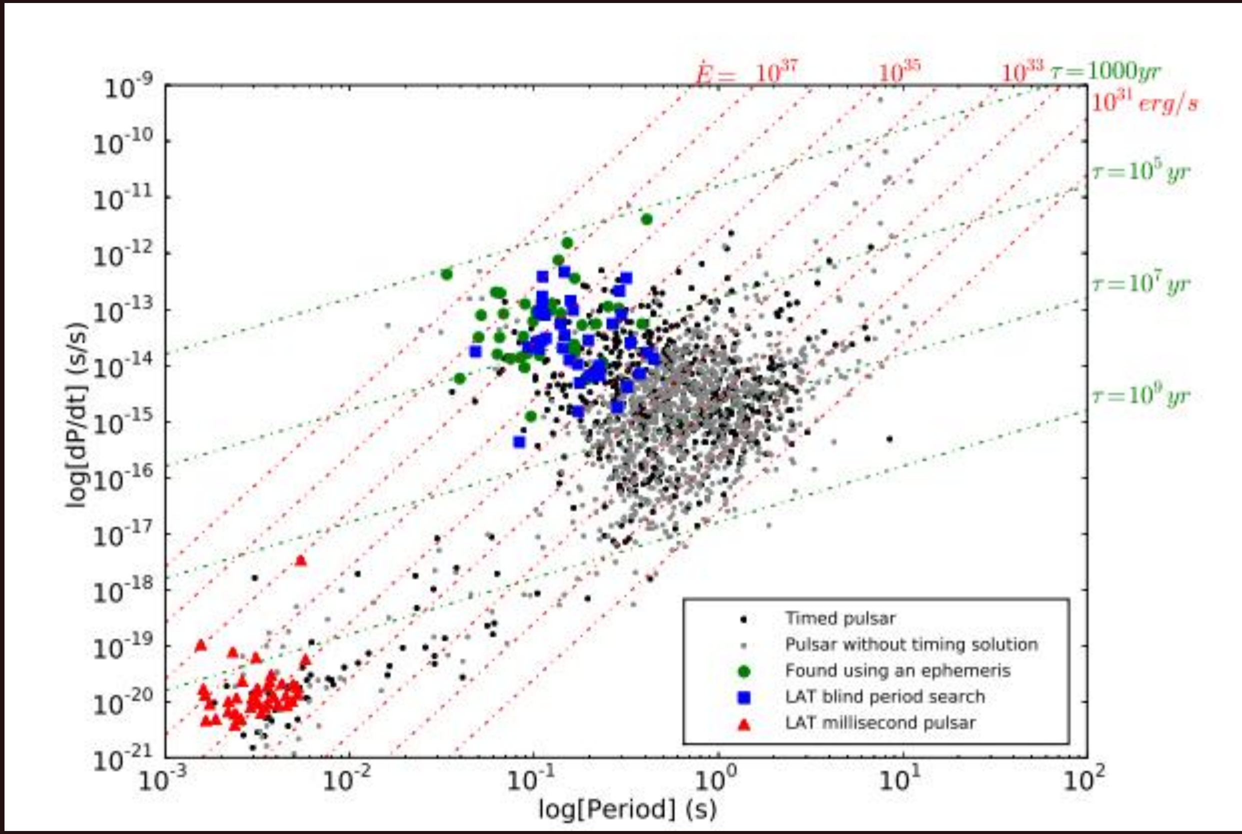

EGRET data
Many unidentified sources

(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

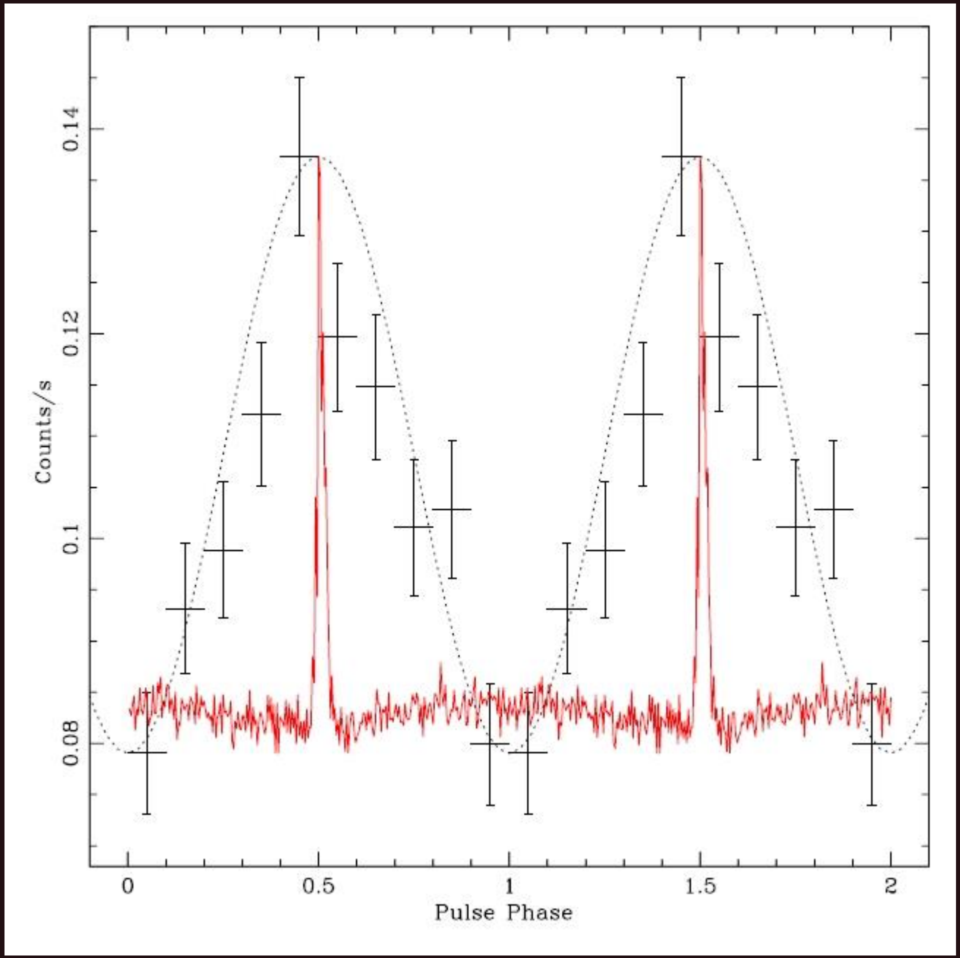
>100 sources known.

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

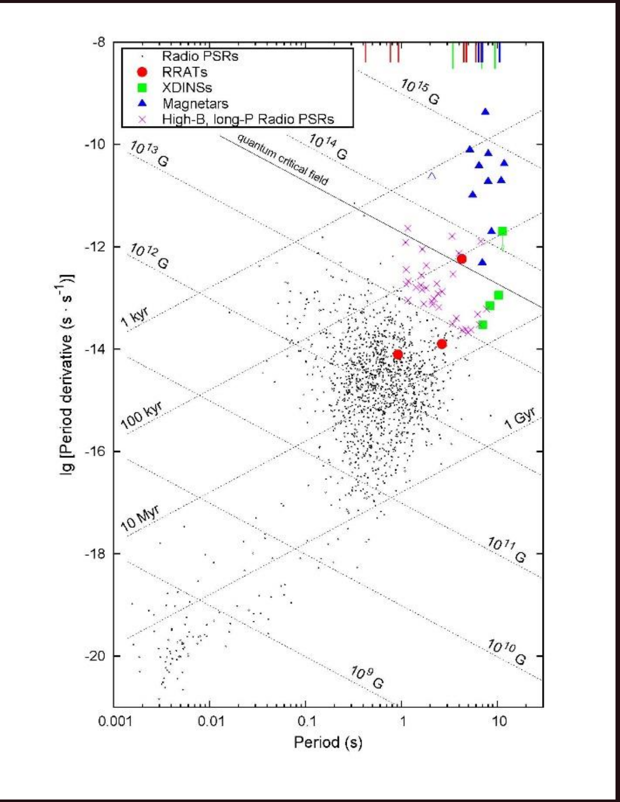
Review: 1109.6896

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

# RRATs. X-ray + radio data

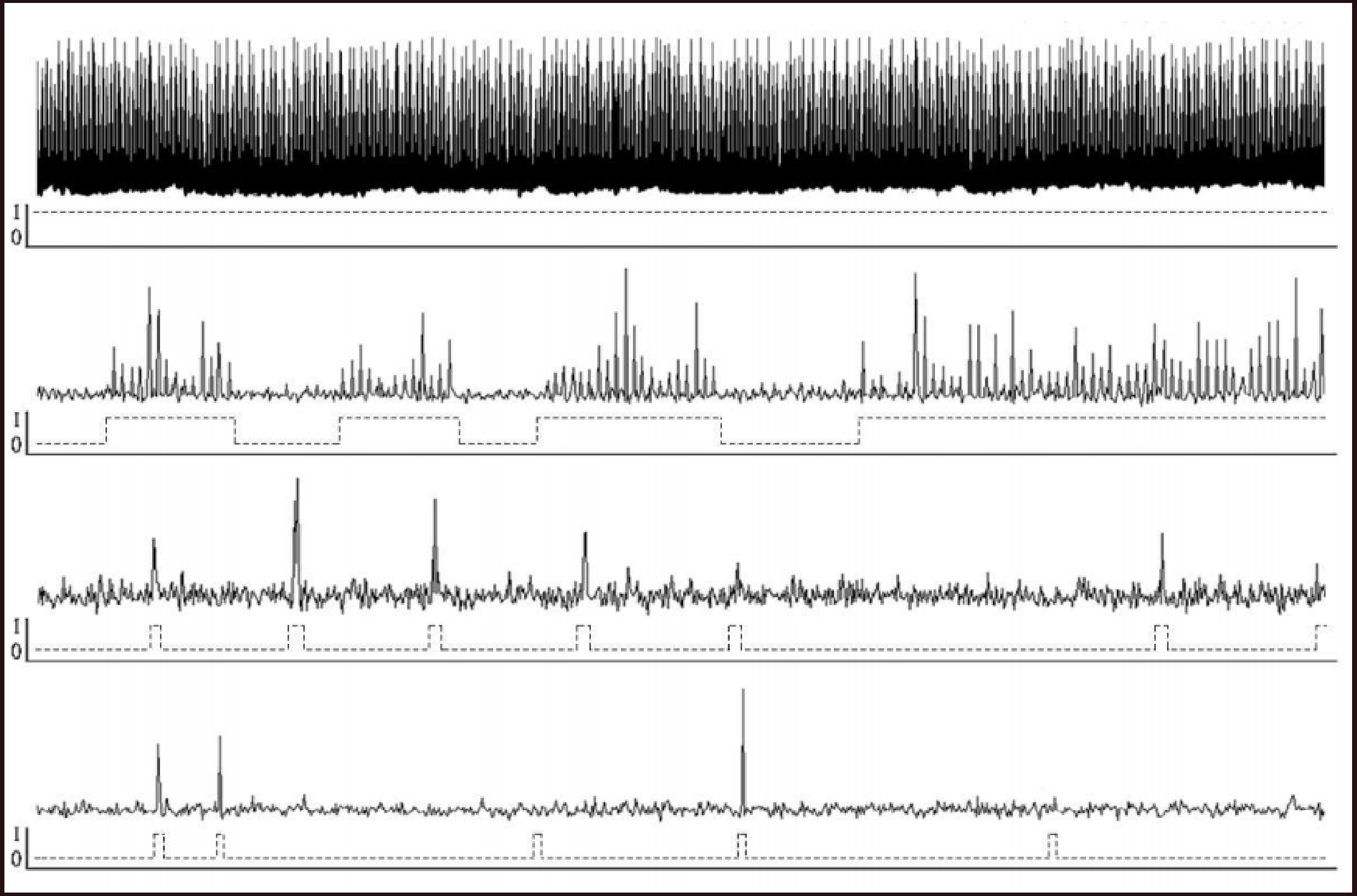



X-ray pulses overlaped on radio data of RRAT J1819-1458.




arXiv: 0710.2056

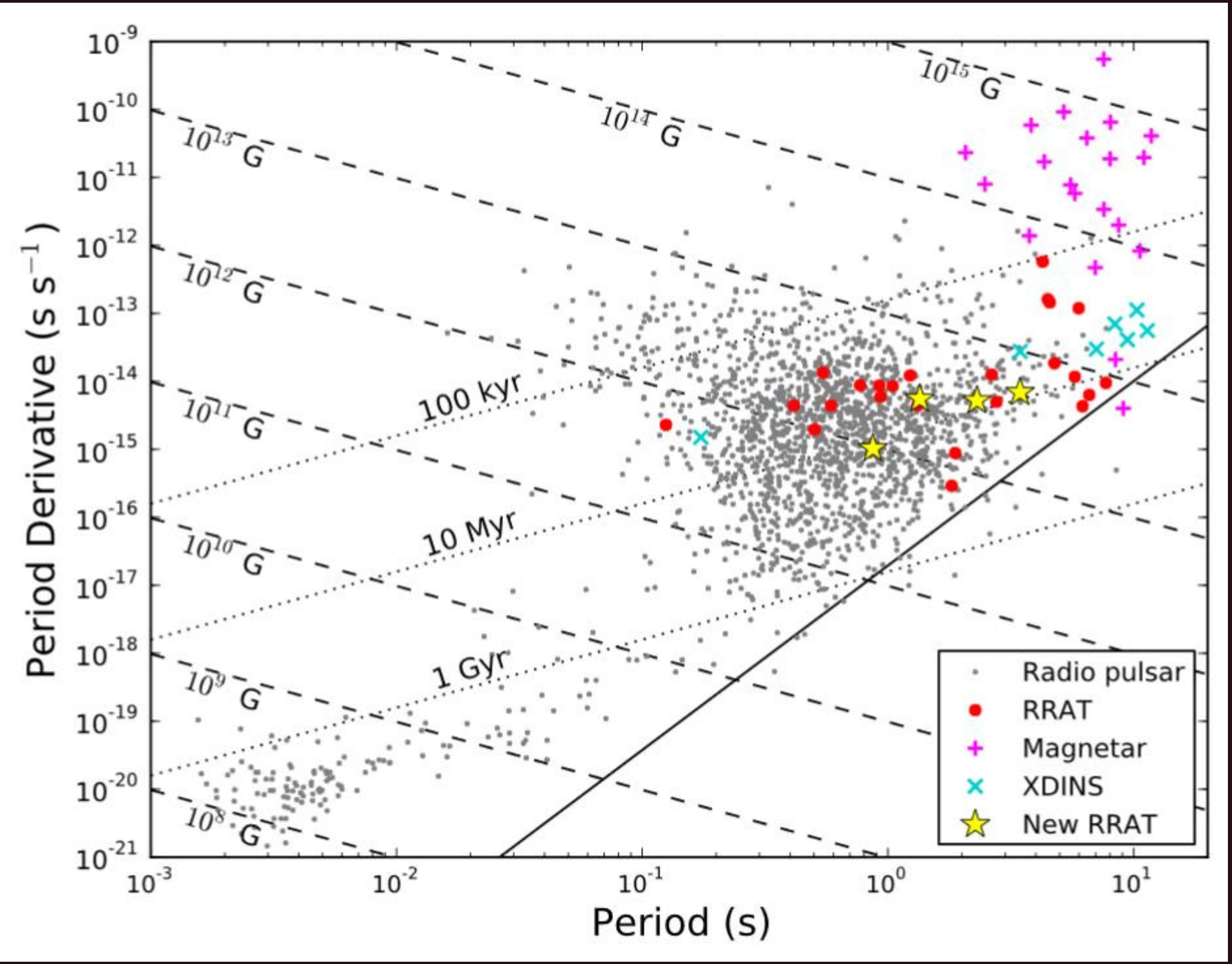
# RRAT – are pulsars?




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.

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

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

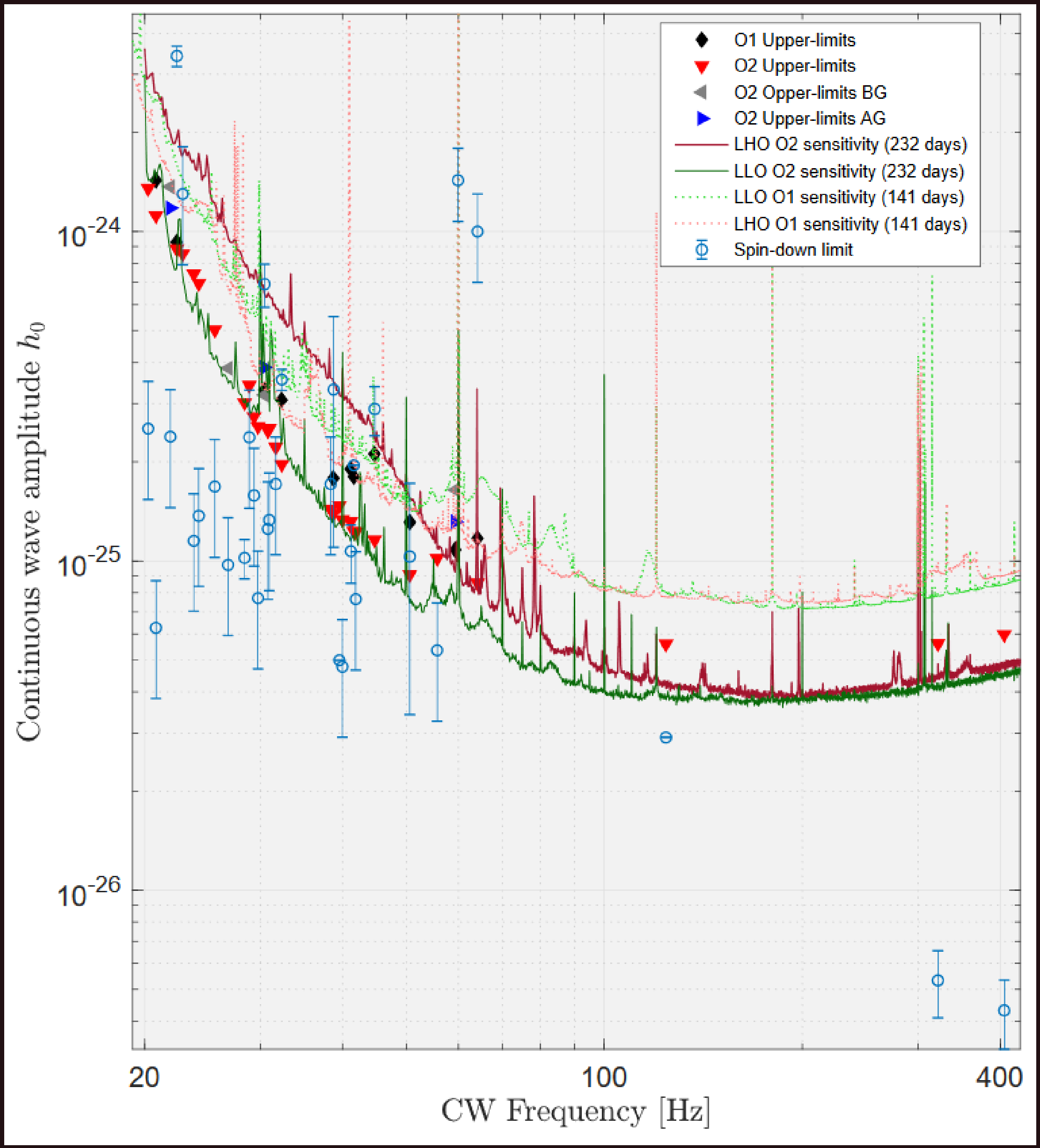
1902.08442

# LIGO results

Second run

33 PSRs studied.

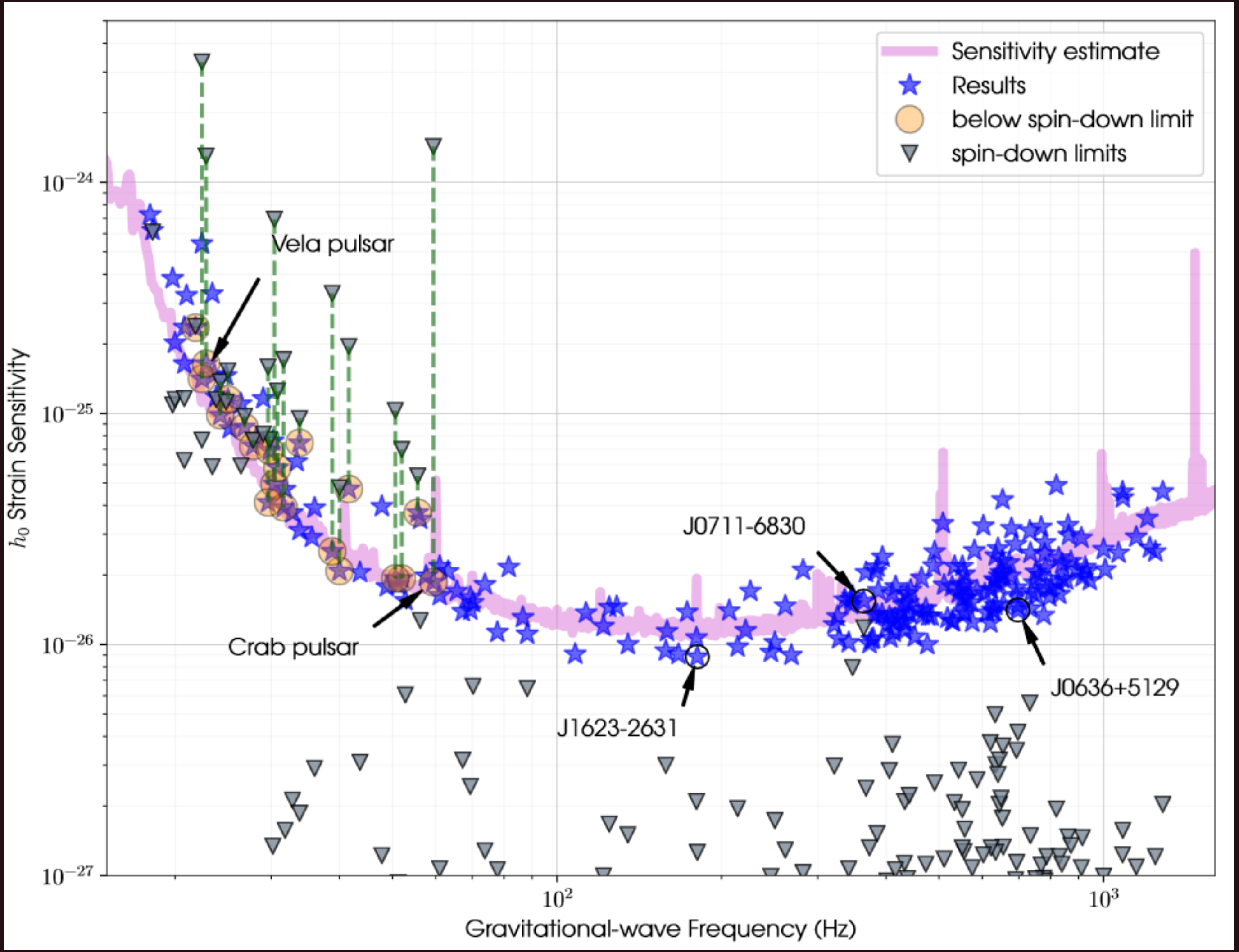
The labels “AG” and “ BG” refers to a search performed after or before the glitch of a given pulsar.




1902.08442

# LIGO search for GW from PSRs

221 PSRs
data from 2015-2017

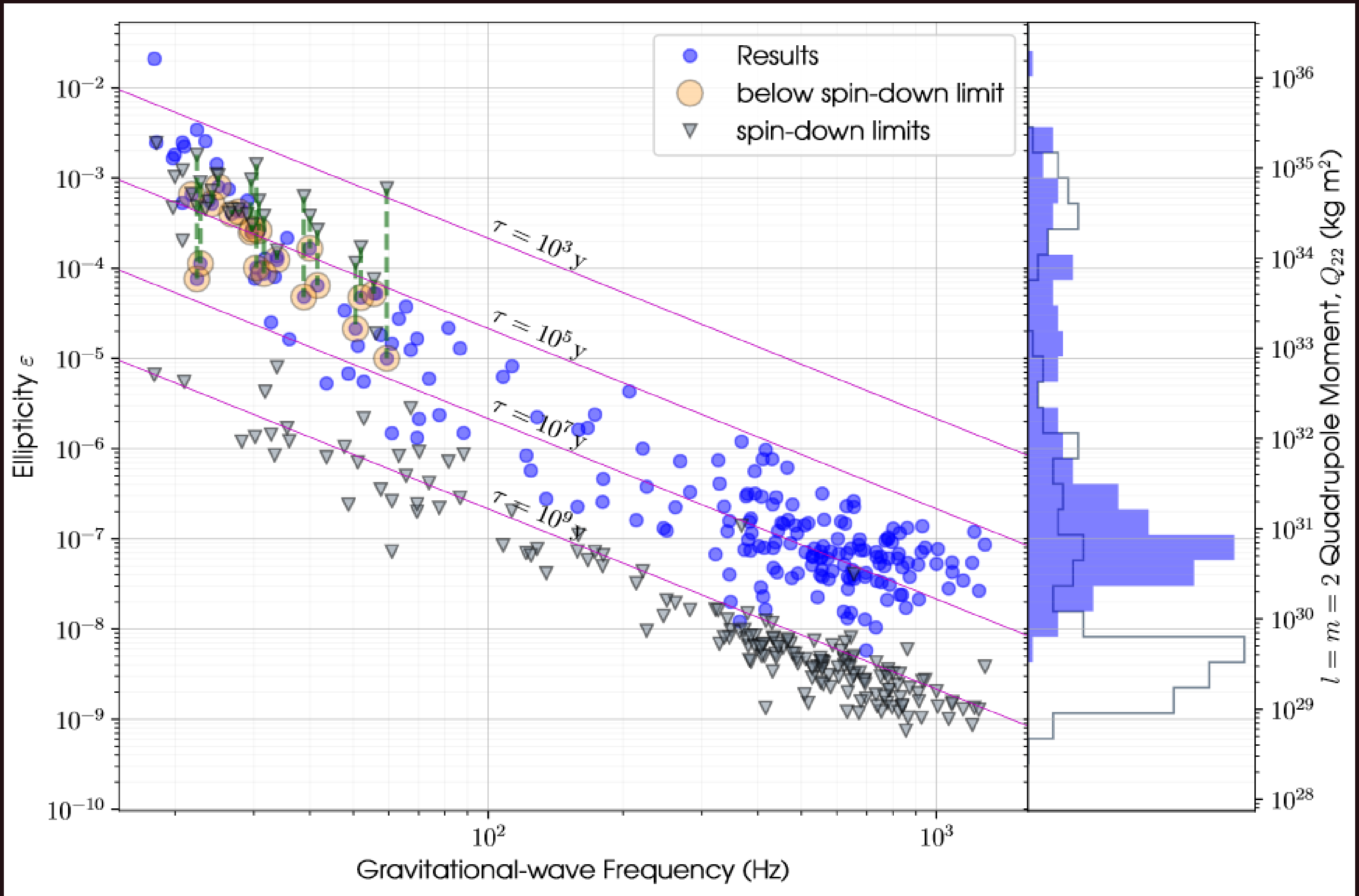



1902.08507

# Limits on ellipticity

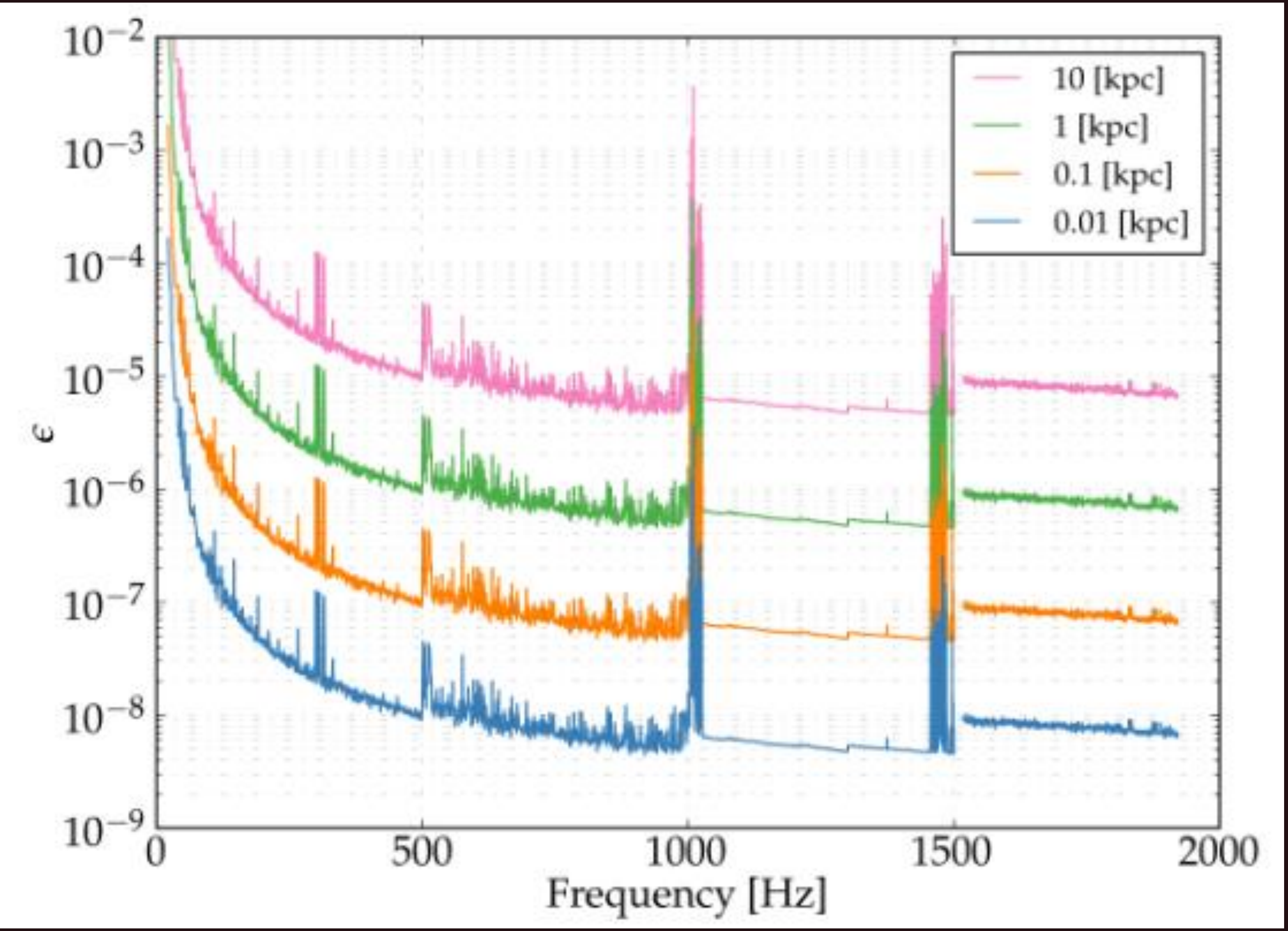
$$\varepsilon = \frac{Q_{22}}{I_{zz}}\sqrt{\frac{8\pi}{15}}$$

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



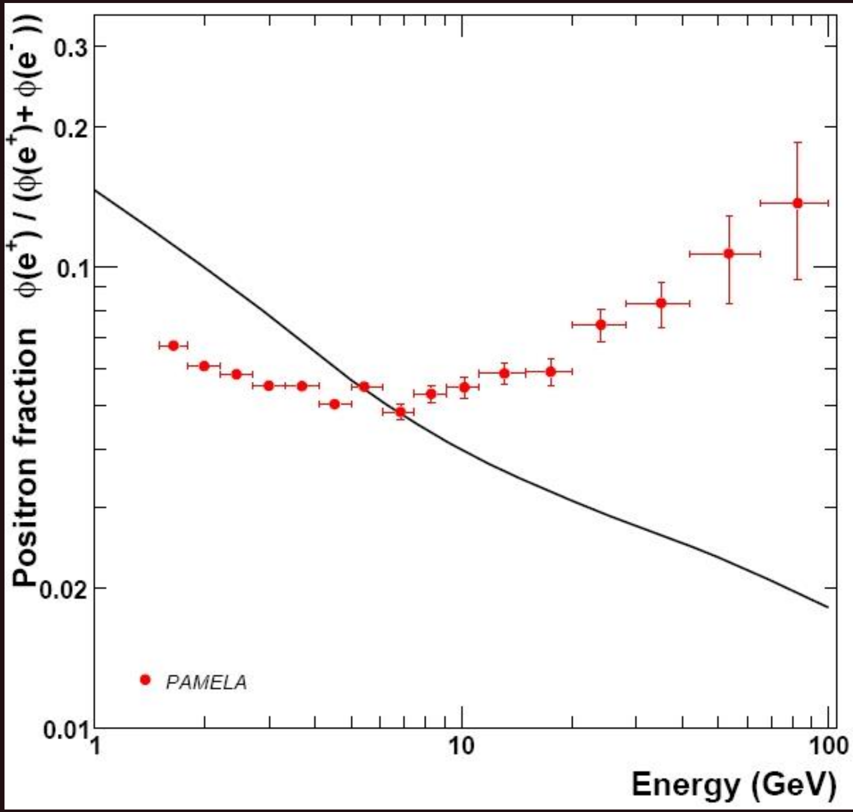

1902.08507

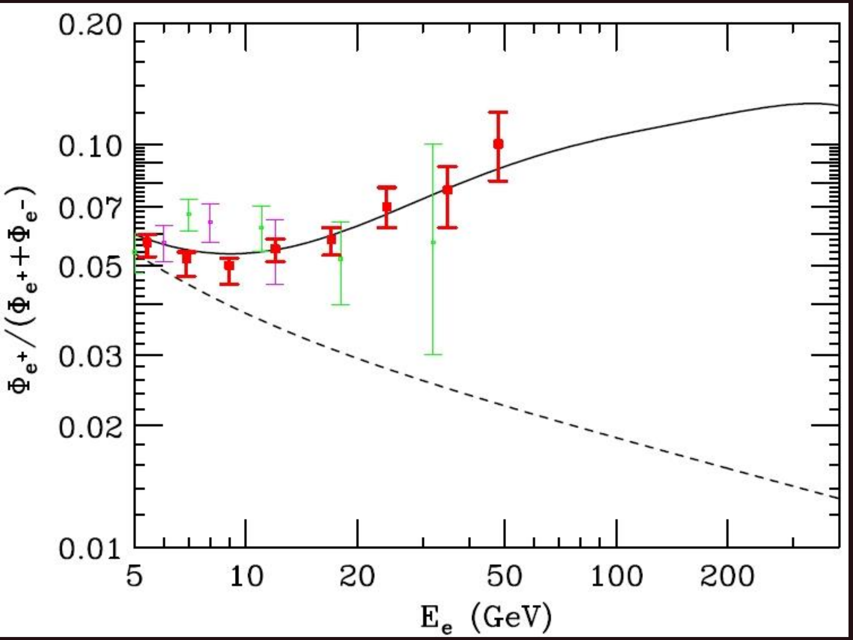
# Blind search for GWs from NSs




1903.01901

# Pulsars, positrons, PAMELA



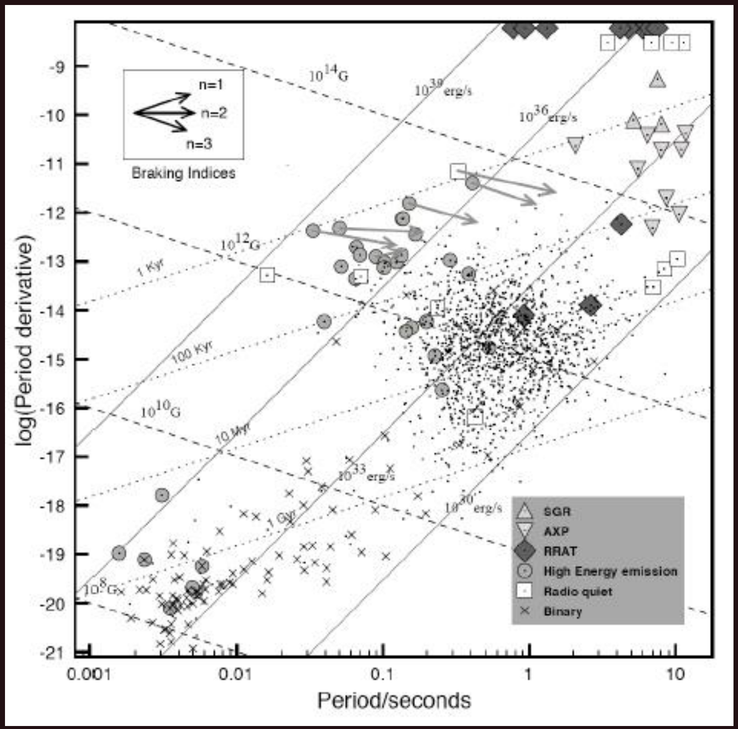



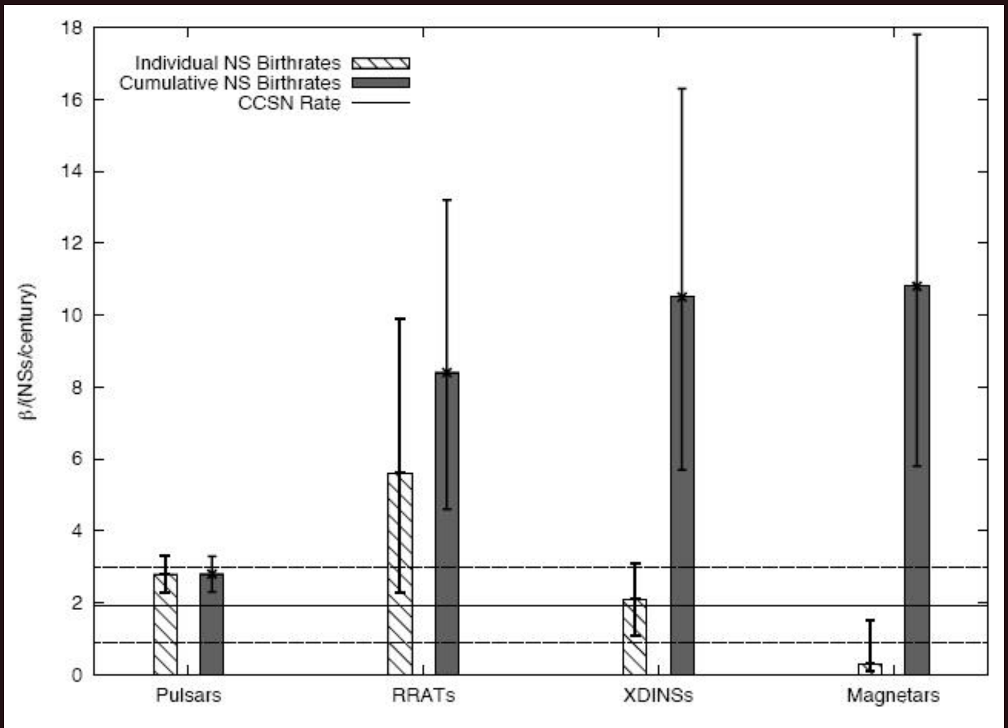

Geminga, PSR B0656+14, and all PSRs

**[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???

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

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

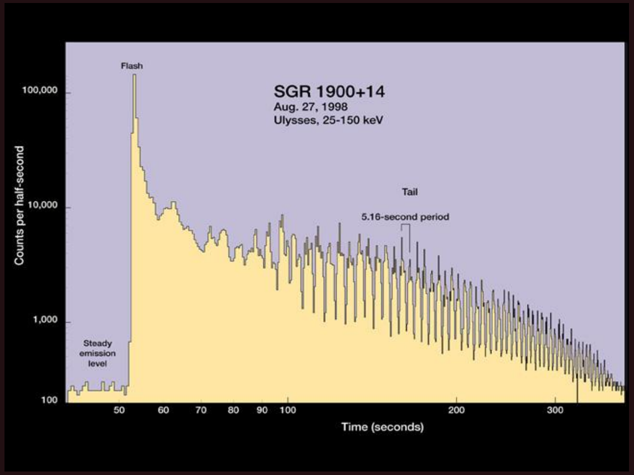
# Conclusion

- 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