Neutron star periods

Sergei Popov
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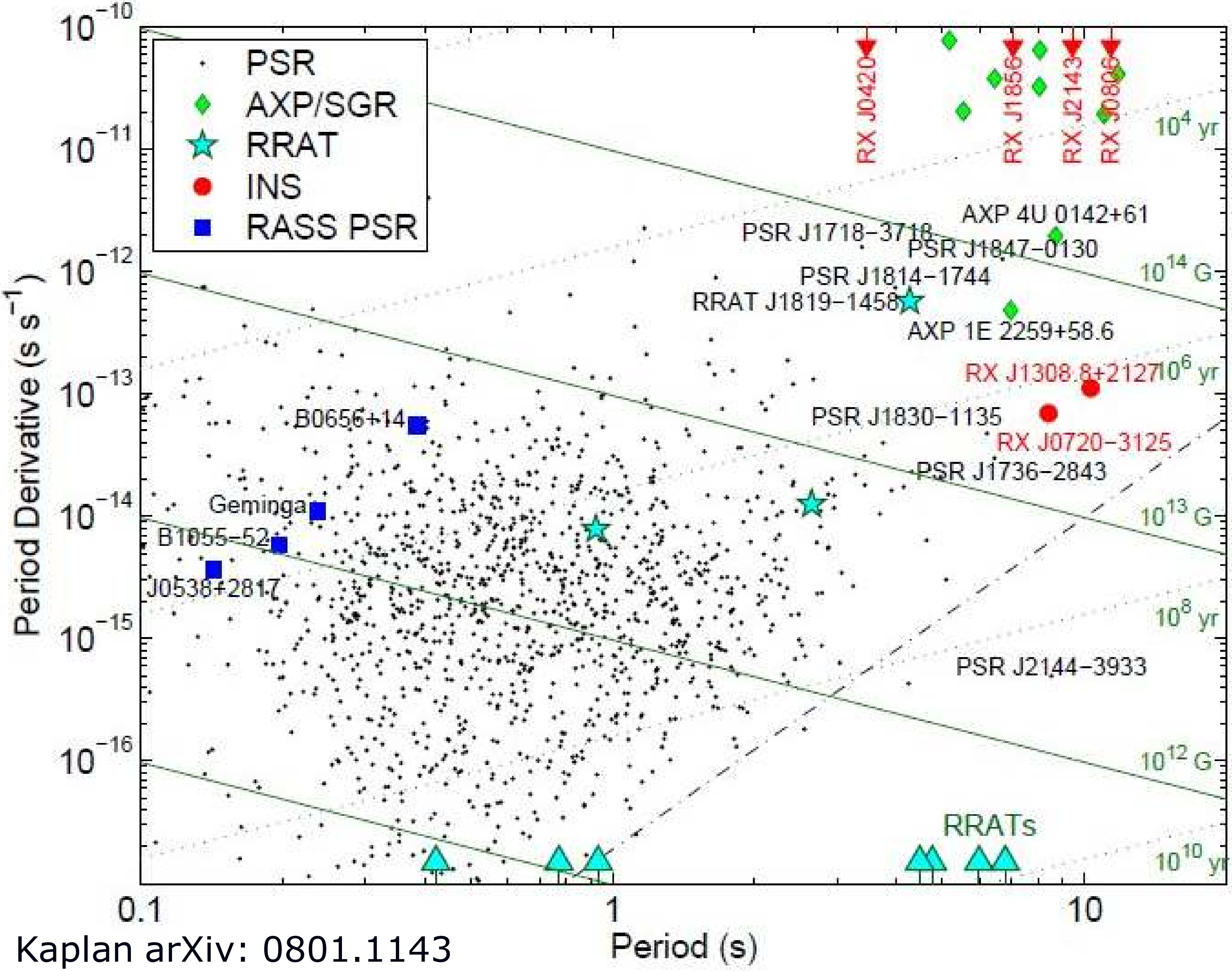

Kaplan arXiv: 0801.1143

Diversity of young neutron stars

Young isolated neutron stars
can appear in many flavors:

- o Radio pulsars
- o Compact central X-ray sources
  in supernova remnants._
- o Anomalous X-ray pulsars
- o Soft gamma repeaters
- o The Magnificent Seven & Co.
- o Transient radio sources (RRATs)
- o ……………………

"GRAND UNIFICATION" is welcomed!
(Kaspi 2010)

See a recent review in 1111.1158

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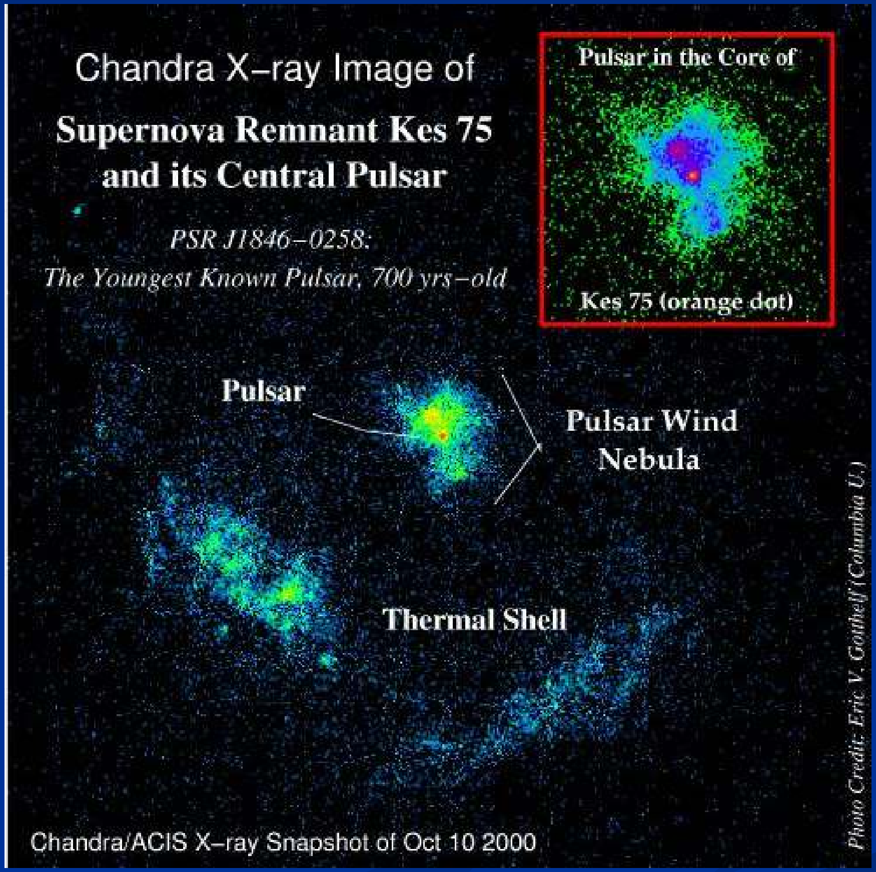
- Episode 4. Close-by cooling INSs: “One second problem”

Episode 1.
Initial spin periods of neutron stars

Sergei Popov (SAI MSU)
Roberto Turolla (Univ. Padua)

arXiv: 1204.0632, 1206.2819

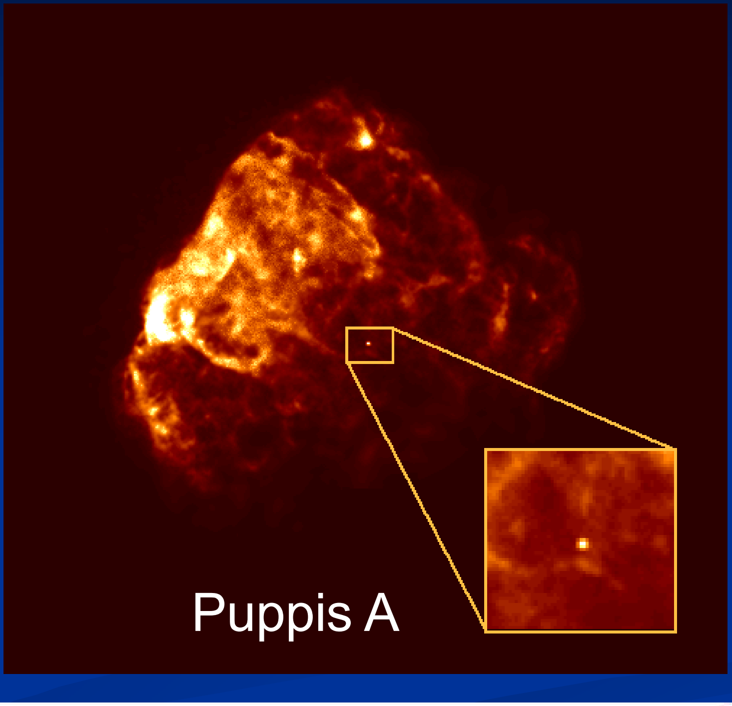
PSRs in SNRs



See a review on NSs in SNRs in 1011.3731

CCOs

For two 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 and
PSR J1852+0040 in Kesteven 79
[see Halpern et al. arxiv:0705.0978]



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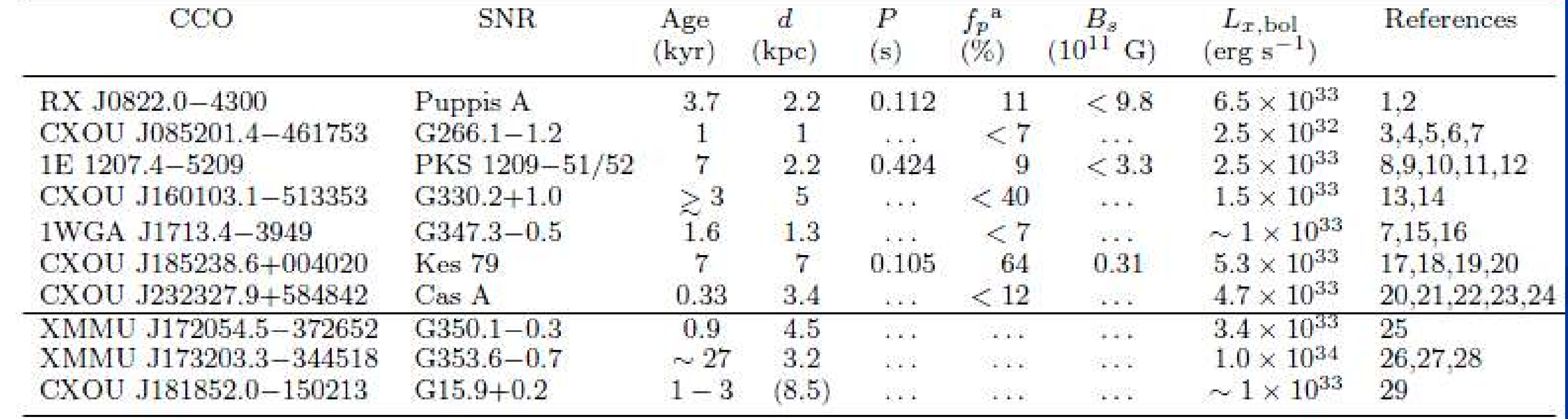


CCO	SNR	Age (kyr)	d (kpc)	P (s)	f_p[a] (%)	B_s (10^{11} G)	$L_{x,\mathrm{bol}}$ (erg s^{-1})	References
RX J0822.0−4300	Puppis A	3.7	2.2	0.112	11	< 9.8	6.5×10^{33}	1,2
CXOU J085201.4−461753	G266.1−1.2	1	1	…	< 7	…	2.5×10^{32}	3,4,5,6,7
1E 1207.4−5209	PKS 1209−51/52	7	2.2	0.424	9	< 3.3	2.5×10^{33}	8,9,10,11,12
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

Sample of PSRs+SNRs

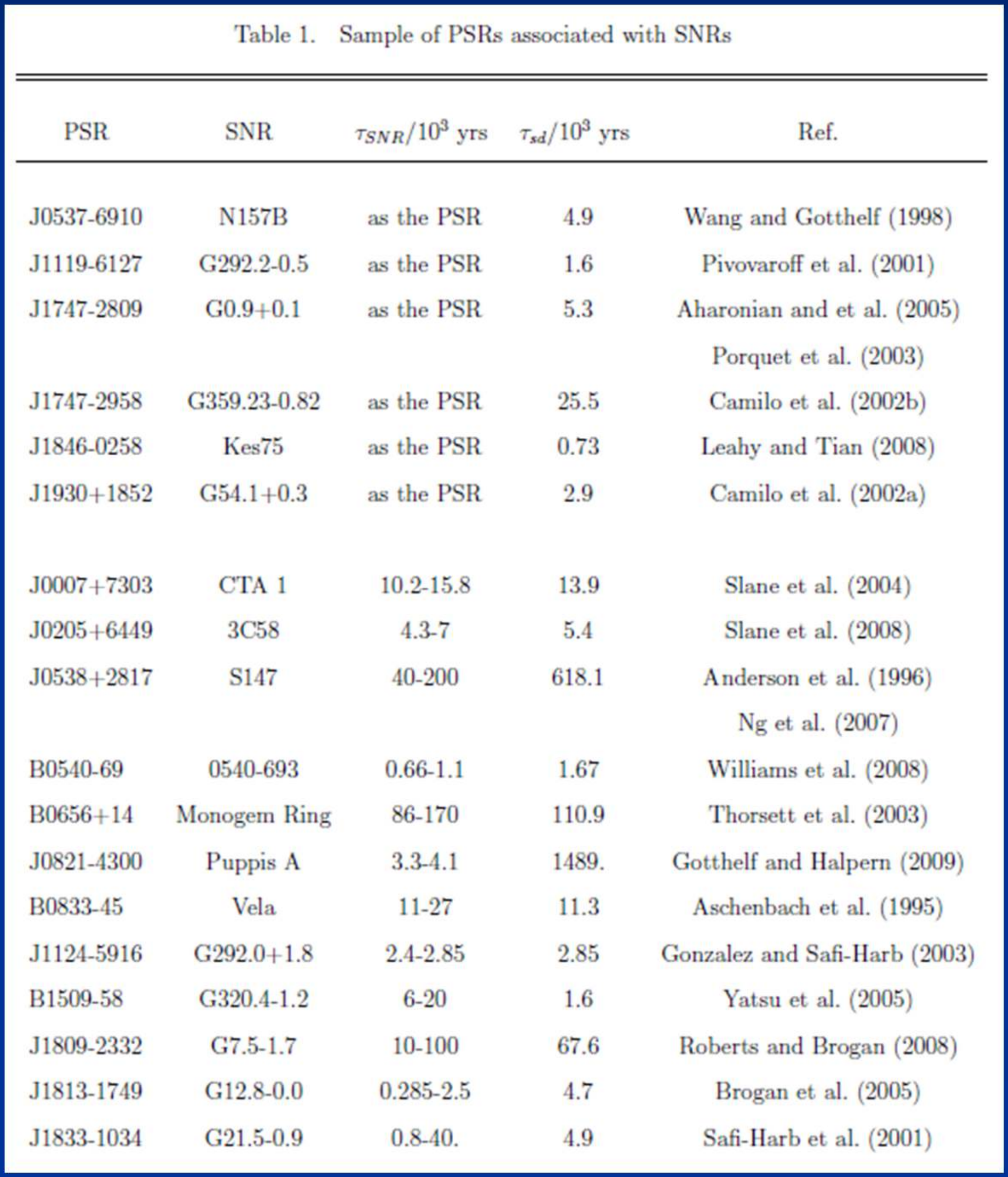


Table 1. Sample of PSRs associated with SNRs

PSR	SNR	$\tau_{SNR}/10^3$ yrs	$\tau_{sd}/10^3$ yrs	Ref.
J0537-6910	N157B	as the PSR	4.9	Wang and Gotthelf (1998)
J1119-6127	G292.2-0.5	as the PSR	1.6	Pivovaroff et al. (2001)
J1747-2809	G0.9+0.1	as the PSR	5.3	Aharonian and et al. (2005) Porquet et al. (2003)
J1747-2958	G359.23-0.82	as the PSR	25.5	Camilo et al. (2002b)
J1846-0258	Kes75	as the PSR	0.73	Leahy and Tian (2008)
J1930+1852	G54.1+0.3	as the PSR	2.9	Camilo et al. (2002a)
J0007+7303	CTA 1	10.2-15.8	13.9	Slane et al. (2004)
J0205+6449	3C58	4.3-7	5.4	Slane et al. (2008)
J0538+2817	S147	40-200	618.1	Anderson et al. (1996) Ng et al. (2007)
B0540-69	0540-693	0.66-1.1	1.67	Williams et al. (2008)
B0656+14	Monogem Ring	86-170	110.9	Thorsett et al. (2003)
J0821-4300	Puppis A	3.3-4.1	1489.	Gotthelf and Halpern (2009)
B0833-45	Vela	11-27	11.3	Aschenbach et al. (1995)
J1124-5916	G292.0+1.8	2.4-2.85	2.85	Gonzalez and Safi-Harb (2003)
B1509-58	G320.4-1.2	6-20	1.6	Yatsu et al. (2005)
J1809-2332	G7.5-1.7	10-100	67.6	Roberts and Brogan (2008)
J1813-1749	G12.8-0.0	0.285-2.5	4.7	Brogan et al. (2005)
J1833-1034	G21.5-0.9	0.8-40.	4.9	Safi-Harb et al. (2001)

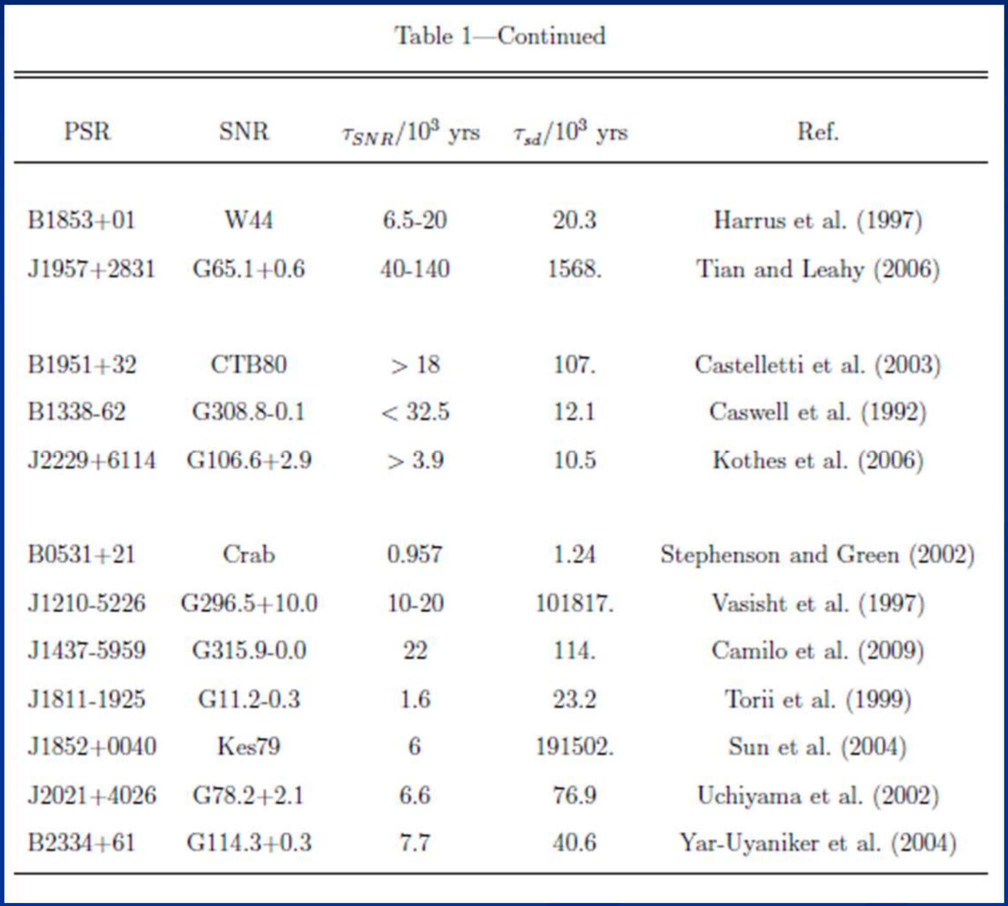


Table 1—Continued

PSR	SNR	$\tau_{SNR}/10^3$ yrs	$\tau_{sd}/10^3$ yrs	Ref.
B1853+01	W44	6.5-20	20.3	Harrus et al. (1997)
J1957+2831	G65.1+0.6	40-140	1568.	Tian and Leahy (2006)
B1951+32	CTB80	> 18	107.	Castelletti et al. (2003)
B1338-62	G308.8-0.1	< 32.5	12.1	Caswell et al. (1992)
J2229+6114	G106.6+2.9	> 3.9	10.5	Kothes et al. (2006)
B0531+21	Crab	0.957	1.24	Stephenson and Green (2002)
J1210-5226	G296.5+10.0	10-20	101817.	Vasisht et al. (1997)
J1437-5959	G315.9-0.0	22	114.	Camilo et al. (2009)
J1811-1925	G11.2-0.3	1.6	23.2	Torii et al. (1999)
J1852+0040	Kes79	6	191502.	Sun et al. (2004)
J2021+4026	G78.2+2.1	6.6	76.9	Uchiyama et al. (2002)
B2334+61	G114.3+0.3	7.7	40.6	Yar-Uyaniker et al. (2004)

30 pairs: PSR+SNR

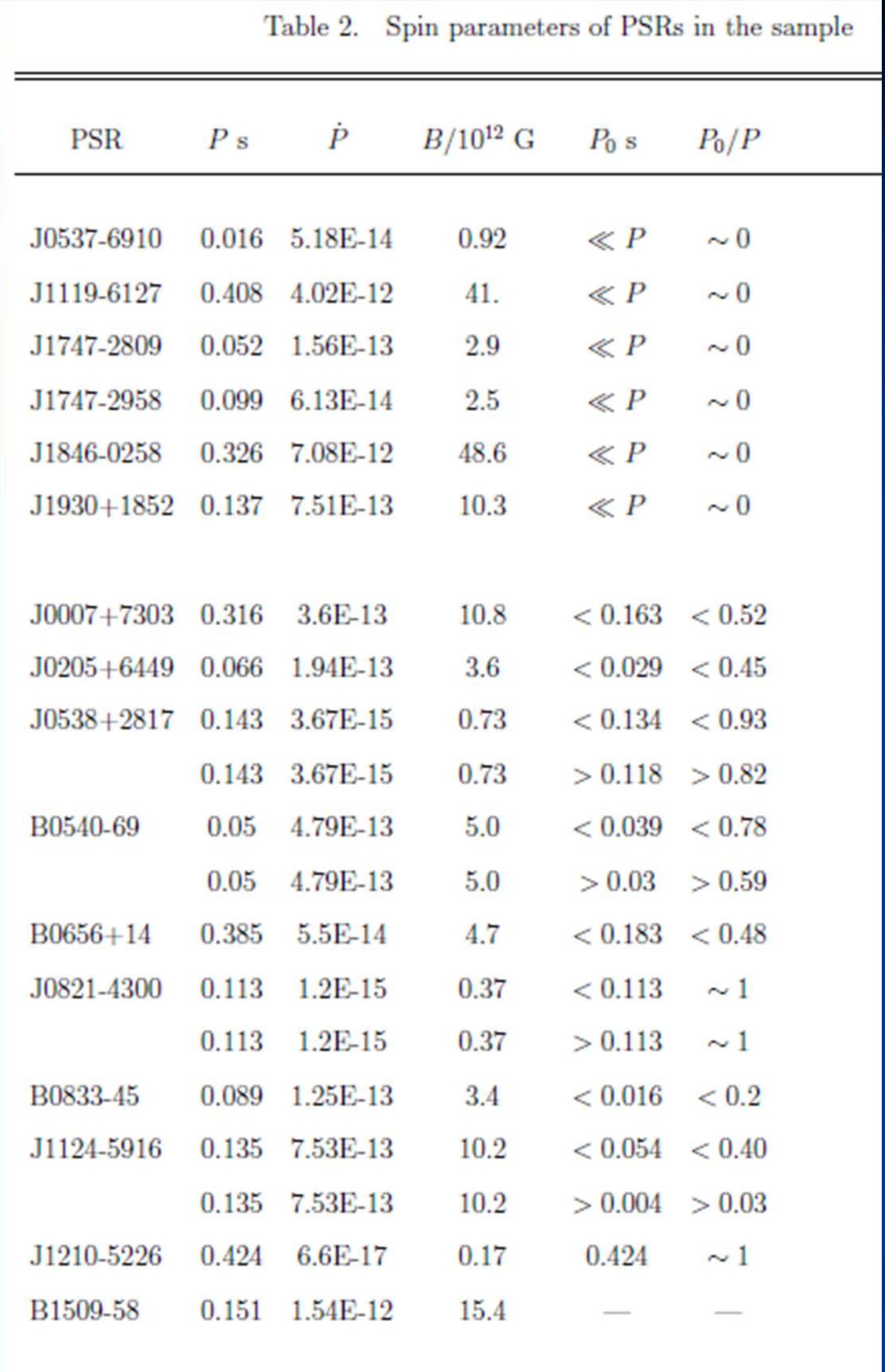


Table 2. Spin parameters of PSRs in the sample

PSR	P s	$\dot{P}$	$B/10^{12}$ G	P_0 s	P_0/P
J0537-6910	0.016	5.18E-14	0.92	$\ll P$	~ 0
J1119-6127	0.408	4.02E-12	41.	$\ll P$	~ 0
J1747-2809	0.052	1.56E-13	2.9	$\ll P$	~ 0
J1747-2958	0.099	6.13E-14	2.5	$\ll P$	~ 0
J1846-0258	0.326	7.08E-12	48.6	$\ll P$	~ 0
J1930+1852	0.137	7.51E-13	10.3	$\ll P$	~ 0
J0007+7303	0.316	3.6E-13	10.8	< 0.163	< 0.52
J0205+6449	0.066	1.94E-13	3.6	< 0.029	< 0.45
J0538+2817	0.143	3.67E-15	0.73	< 0.134	< 0.93
	0.143	3.67E-15	0.73	> 0.118	> 0.82
B0540-69	0.05	4.79E-13	5.0	< 0.039	< 0.78
	0.05	4.79E-13	5.0	> 0.03	> 0.59
B0656+14	0.385	5.5E-14	4.7	< 0.183	< 0.48
J0821-4300	0.113	1.2E-15	0.37	< 0.113	~ 1
	0.113	1.2E-15	0.37	> 0.113	~ 1
B0833-45	0.089	1.25E-13	3.4	< 0.016	< 0.2
J1124-5916	0.135	7.53E-13	10.2	< 0.054	< 0.40
	0.135	7.53E-13	10.2	> 0.004	> 0.03
J1210-5226	0.424	6.6E-17	0.17	0.424	~ 1
B1509-58	0.151	1.54E-12	15.4	—	—

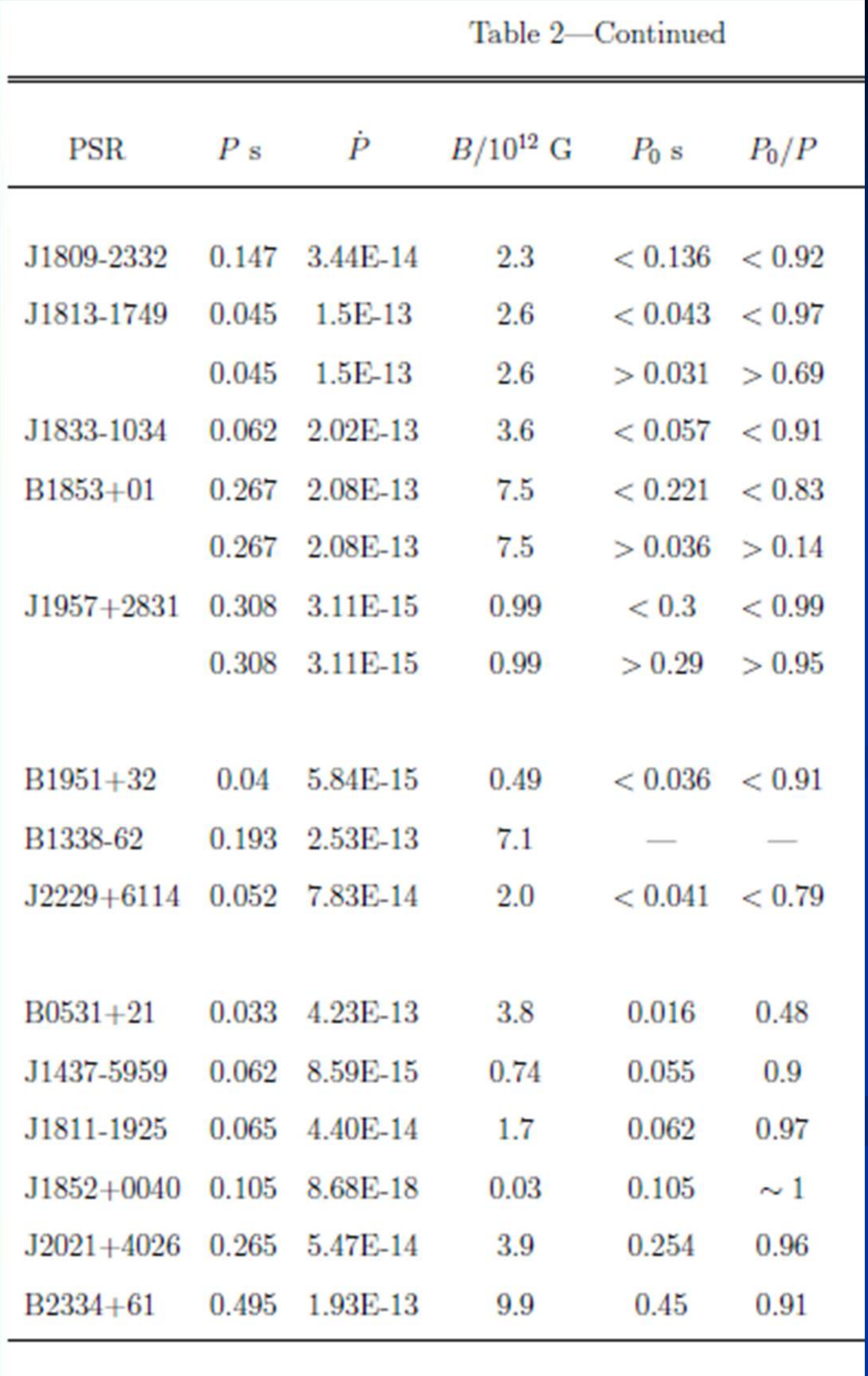
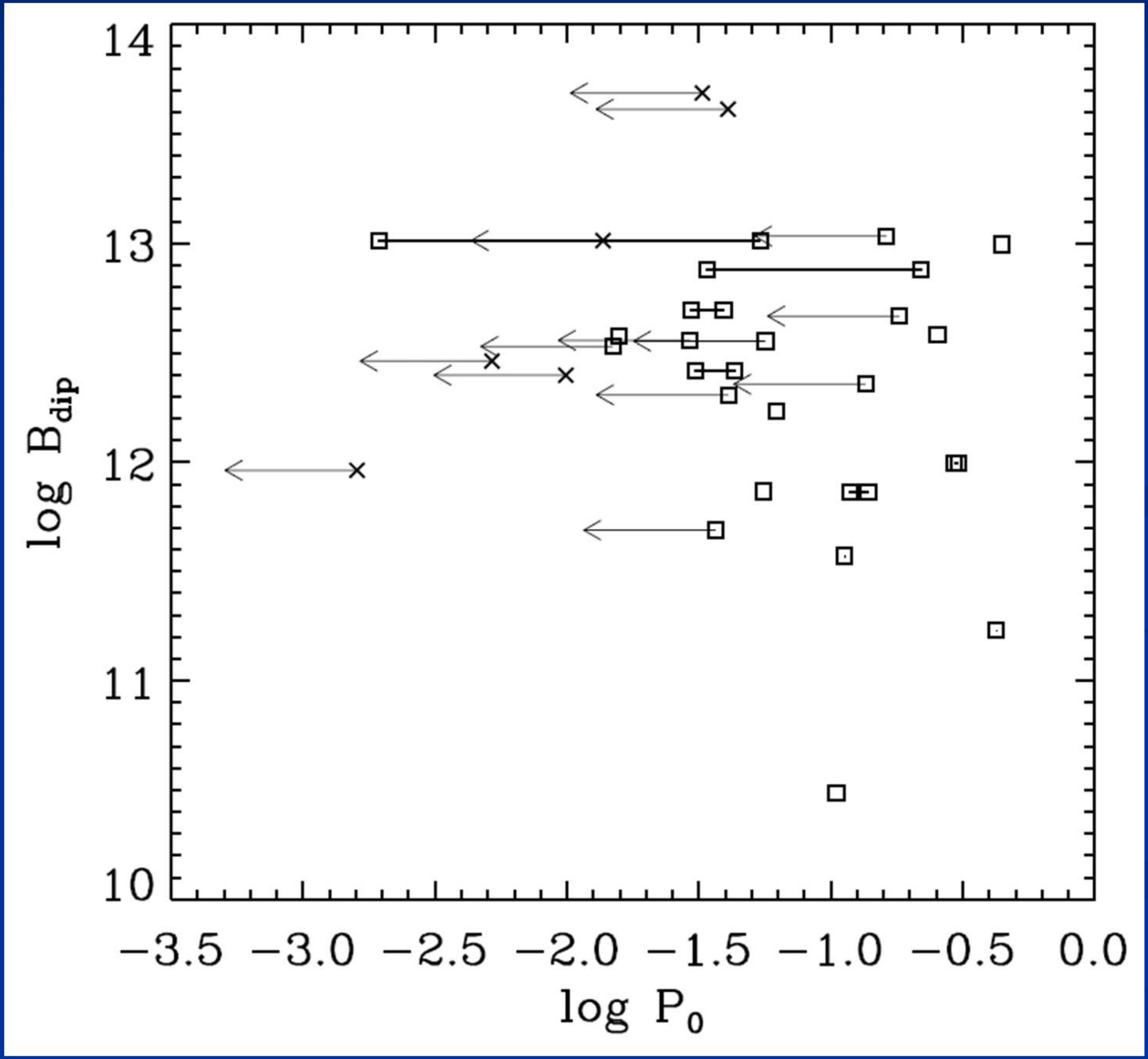


Table 2—Continued

PSR	P s	$\dot{P}$	$B/10^{12}$ G	P_0 s	P_0/P
J1809-2332	0.147	3.44E-14	2.3	< 0.136	< 0.92
J1813-1749	0.045	1.5E-13	2.6	< 0.043	< 0.97
	0.045	1.5E-13	2.6	> 0.031	> 0.69
J1833-1034	0.062	2.02E-13	3.6	< 0.057	< 0.91
B1853+01	0.267	2.08E-13	7.5	< 0.221	< 0.83
	0.267	2.08E-13	7.5	> 0.036	> 0.14
J1957+2831	0.308	3.11E-15	0.99	< 0.3	< 0.99
	0.308	3.11E-15	0.99	> 0.29	> 0.95
B1951+32	0.04	5.84E-15	0.49	< 0.036	< 0.91
B1338-62	0.193	2.53E-13	7.1	—	—
J2229+6114	0.052	7.83E-14	2.0	< 0.041	< 0.79
B0531+21	0.033	4.23E-13	3.8	0.016	0.48
J1437-5959	0.062	8.59E-15	0.74	0.055	0.9
J1811-1925	0.065	4.40E-14	1.7	0.062	0.97
J1852+0040	0.105	8.68E-18	0.03	0.105	~ 1
J2021+4026	0.265	5.47E-14	3.9	0.254	0.96
B2334+61	0.495	1.93E-13	9.9	0.45	0.91

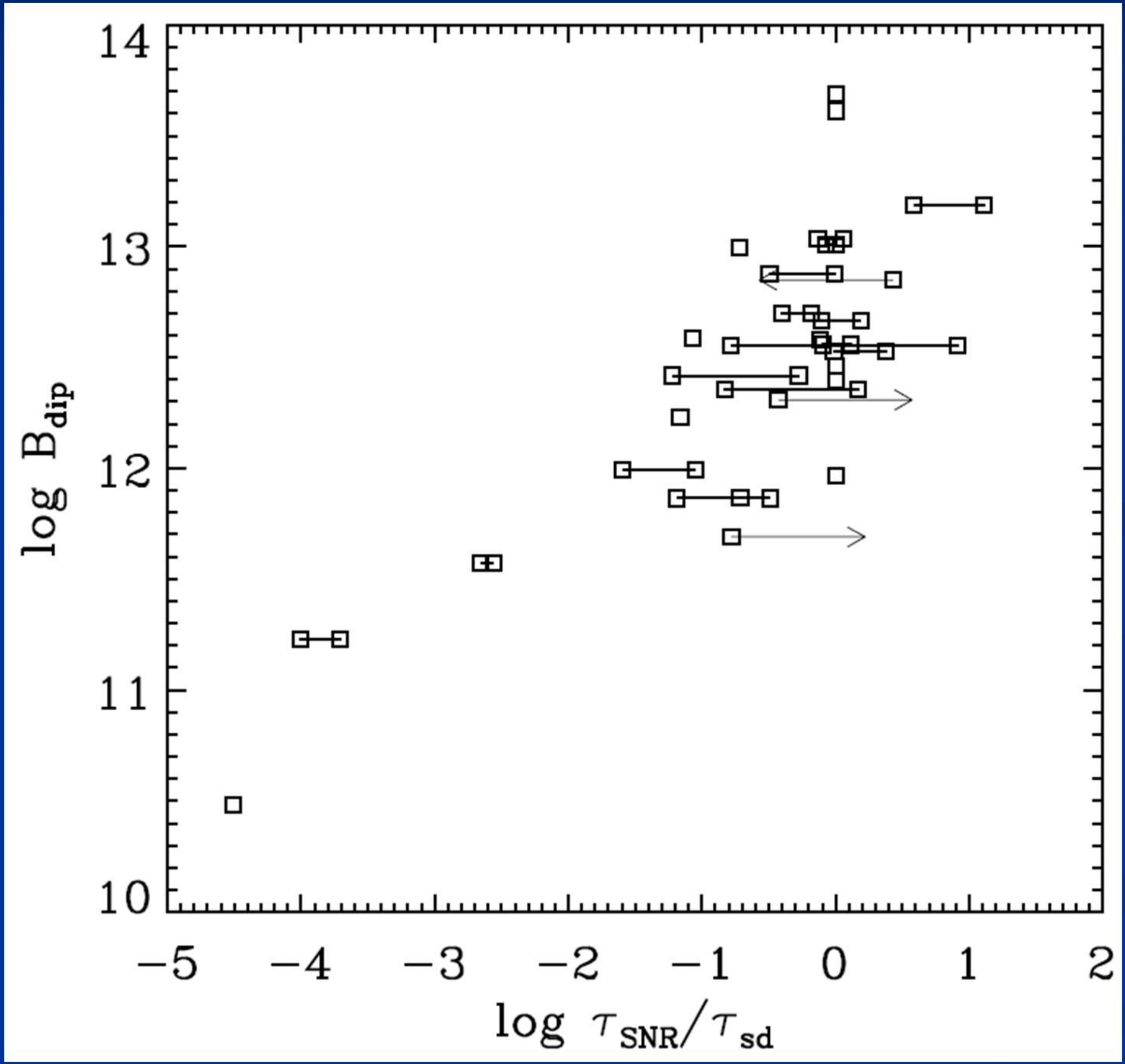
B vs. P_0



All presented estimates are made for standard assumptions:
n=const=3.
So, field is assumed to be constant, as well as the angle between spin and magnetic axis.

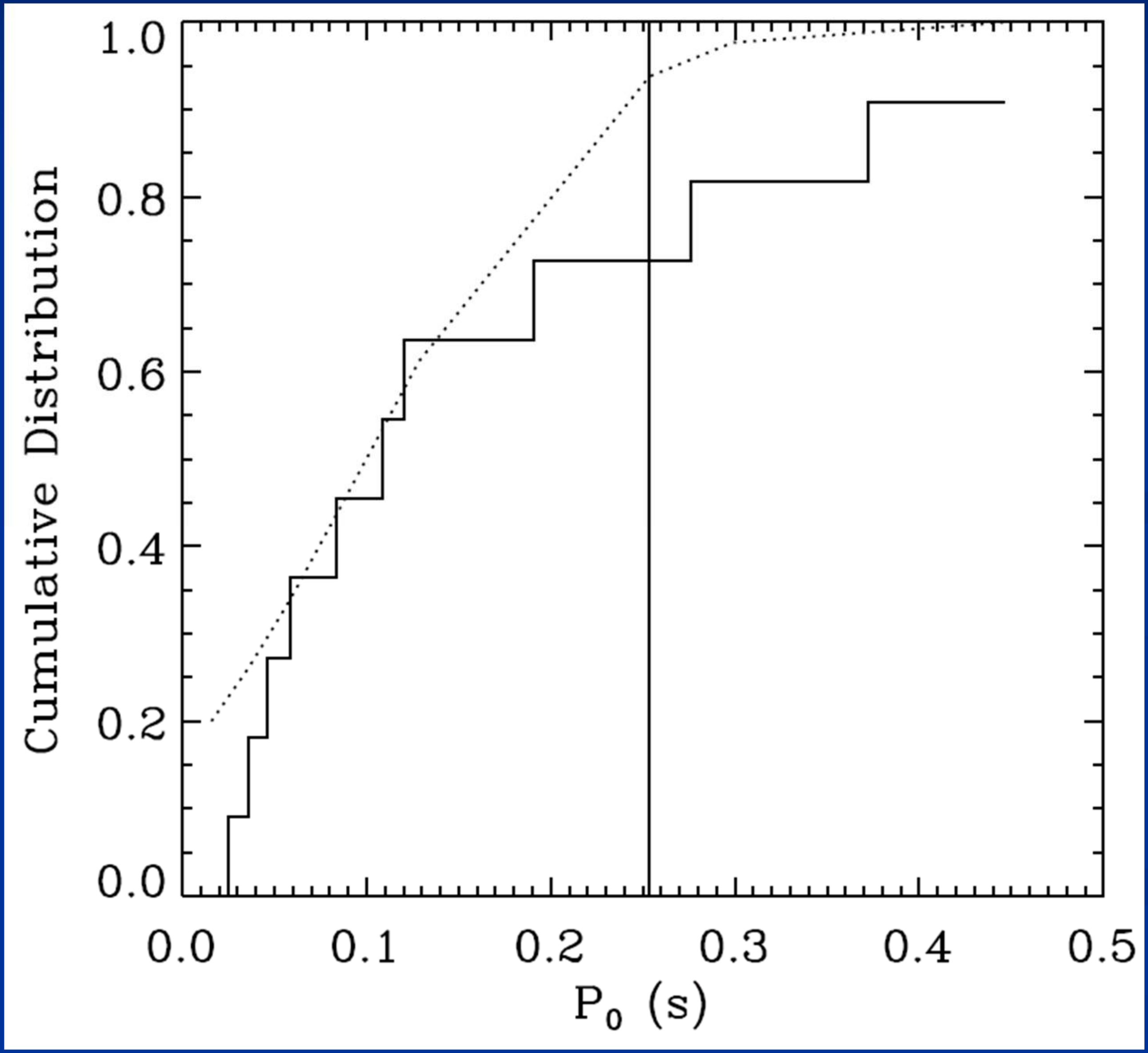
Crosses – PSRs in SNRs (or PWN) with ages just consistent with spin-down ages. We assume that $P_0<0.1P$

B vs. τ_{SNR}/τ_{SD}



Recently, Zhang and Xie (2011) proposed that such a plot can be explained by field decay. We believe that a much more natural explanation is to assume significant P_0.

Checking gaussian



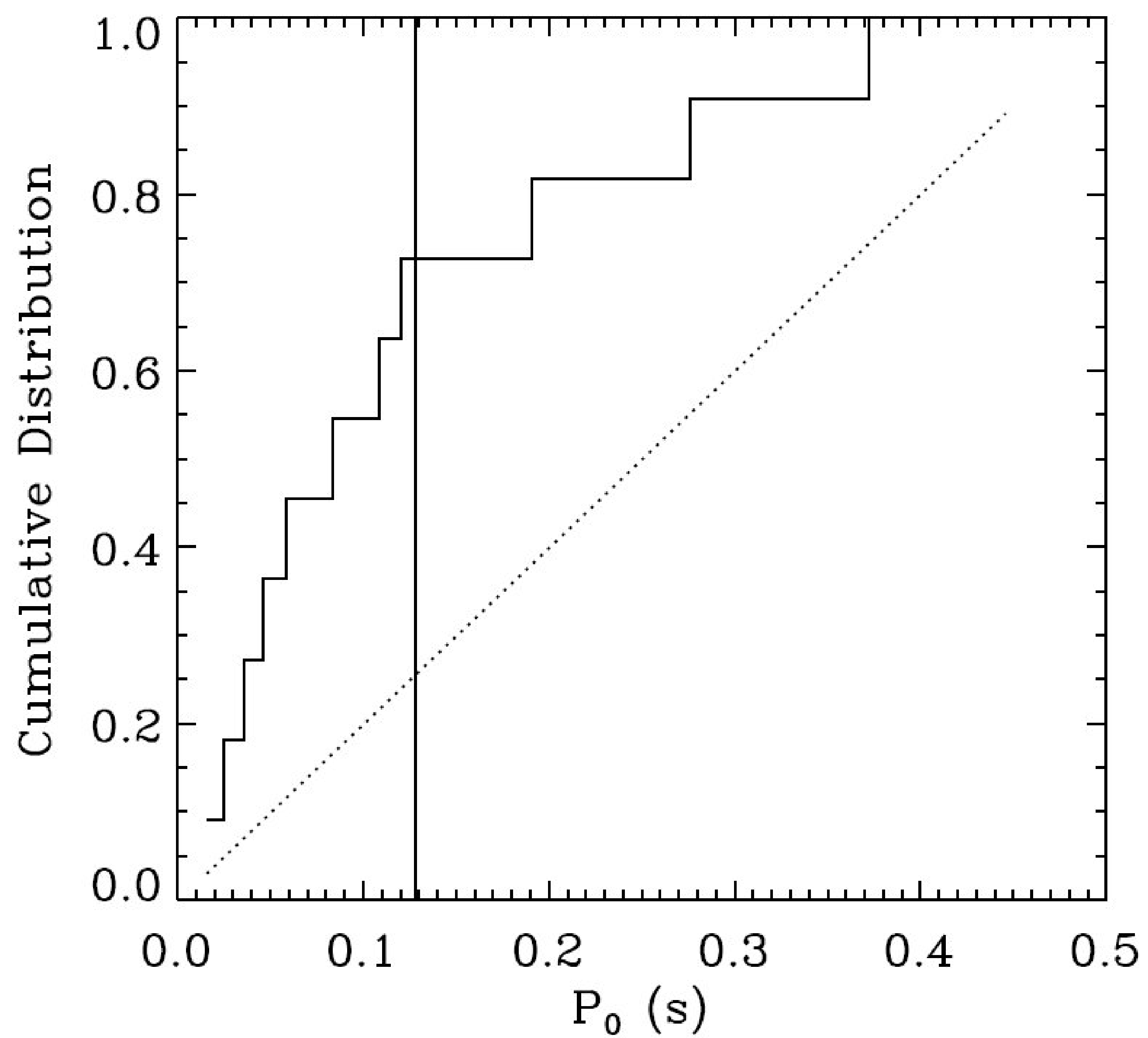
The data we have is not enough to derive the shape of the P_0 distribution.
However, we can exclude very wide and very narrow distributions, and also we can check if some specific distributions are compatible with our results.

Here we present a test for a gaussian distribution, which fits the data.

Still, we believe that the fine tuning is premature with such data.

P_0=0.1 s; σ=0.1 s

Checking flat distrbution



Flat between 0.001 and 0.5 s.

Very wide distributions
in general do not fit
the data we have.

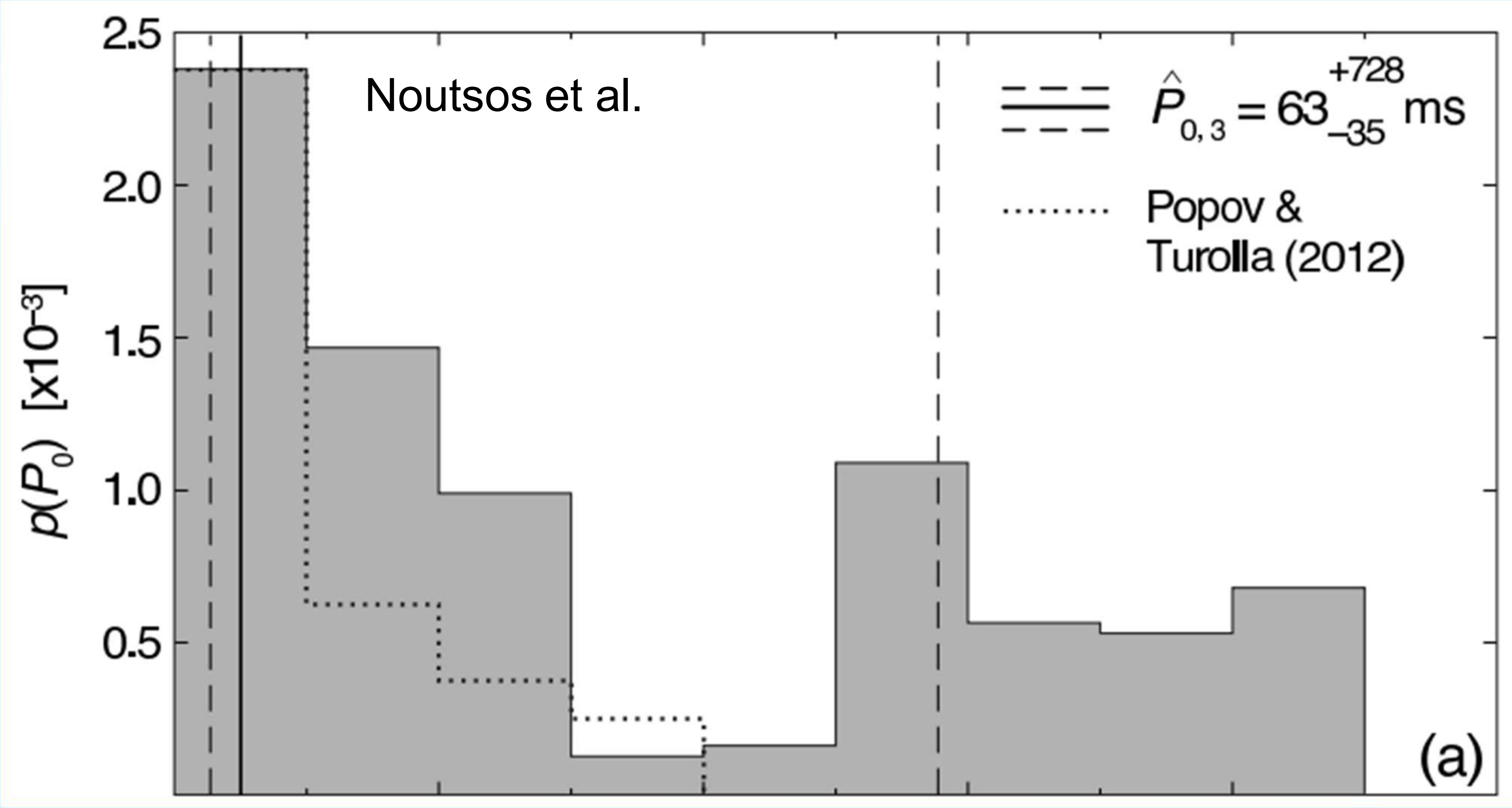
Episode 2.

Initial periods and field decay

Sergei Popov (SAI MSU)
Andrei Igoshev (Radbound Univ.)

arXiv: 1303.5258, 1309.4917

Wide initial spin period distribution



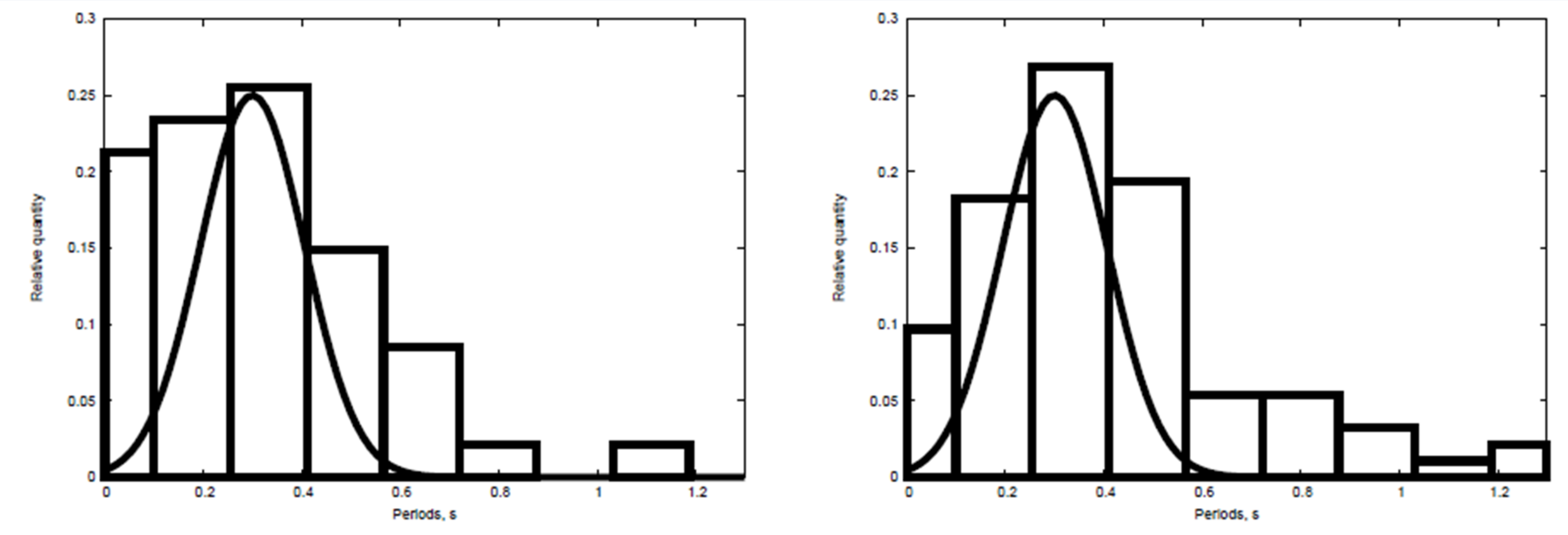
Based on kinematic ages. Mean age – few million years.
Note, that in Popov & Turolla (2012) only NSs in SNRs were used, i.e. the sample is much younger!
Can it explain the difference?

Magnetic field decay and P_0

One can suspect that magnetic field decay can influence the reconstruction of the initial spin period distribution.

Exponential field decay with τ=5 Myrs.
$\langle P_0 \rangle = 0.3$ s, $\sigma_P = 0.15$ s; $\langle \log B_0/[G] \rangle = 12.65$, $\sigma_B = 0.55$

$$P_0 = P\sqrt{1 - \frac{t}{\tau}}.$$

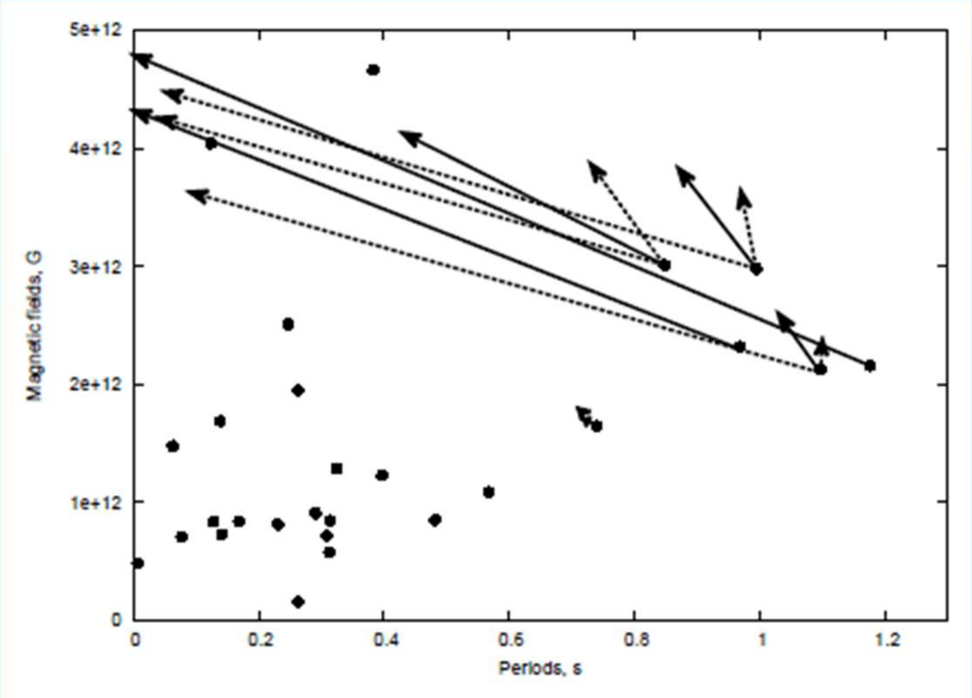


τ<10^7 yrs, 10^5<t

10^5<t<10^7 yrs

Igoshev, Popov MNRAS arXiv: 1303.5258

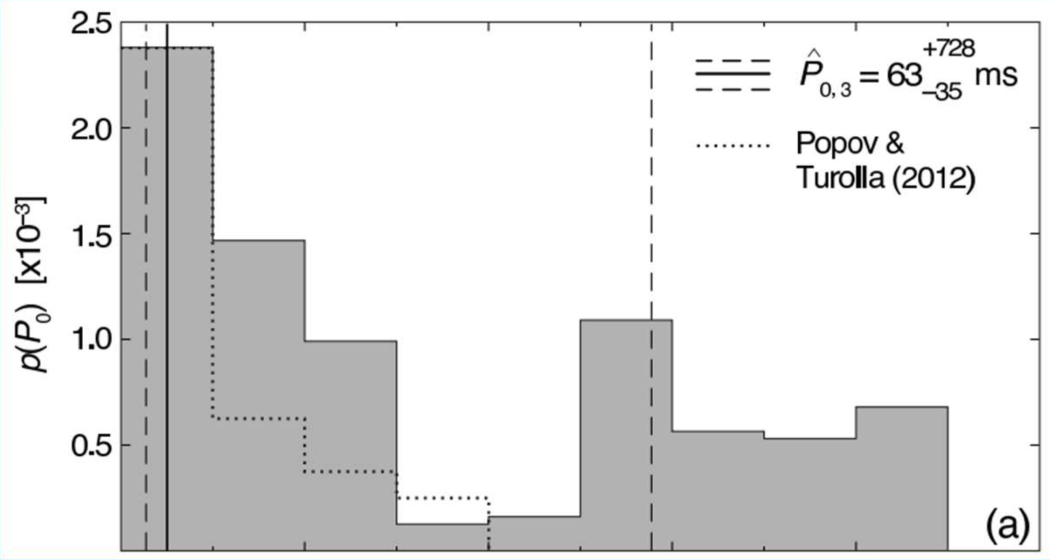
Real vs. reconstructed P_0



How long reconstructed initial periods changed due to not taking into account the exponential field decay

The amount of field decay necessary to explain this shift is in correspondence with the radio pulsar data

Another option: emerging field



The problem is just with few (6)
most long-period NSs.
Is it possible to hide them
when they are young,
and make them visible
at the age ~few million years?

Yes! Emerging magnetic field!!!

Then we probably
need correlations between
different initial parameters

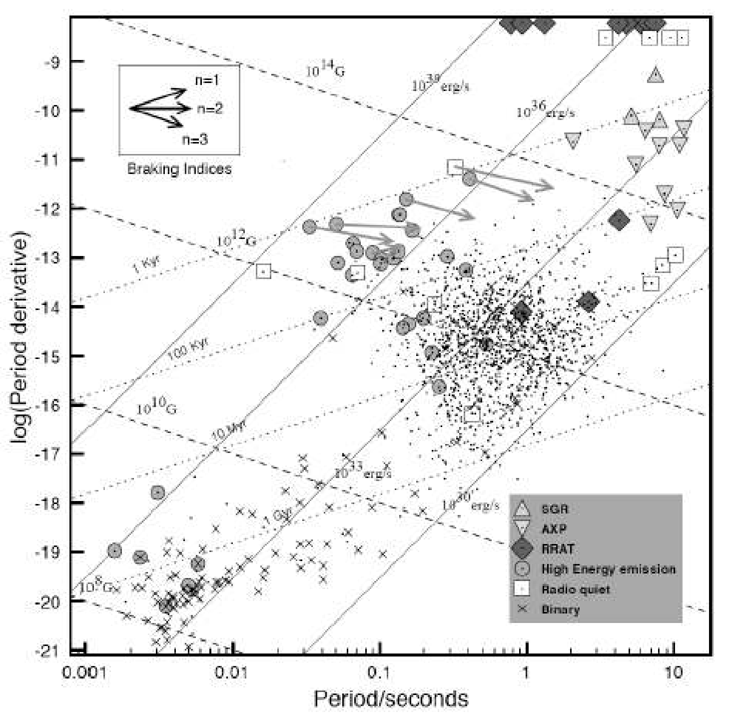
Episode 3.

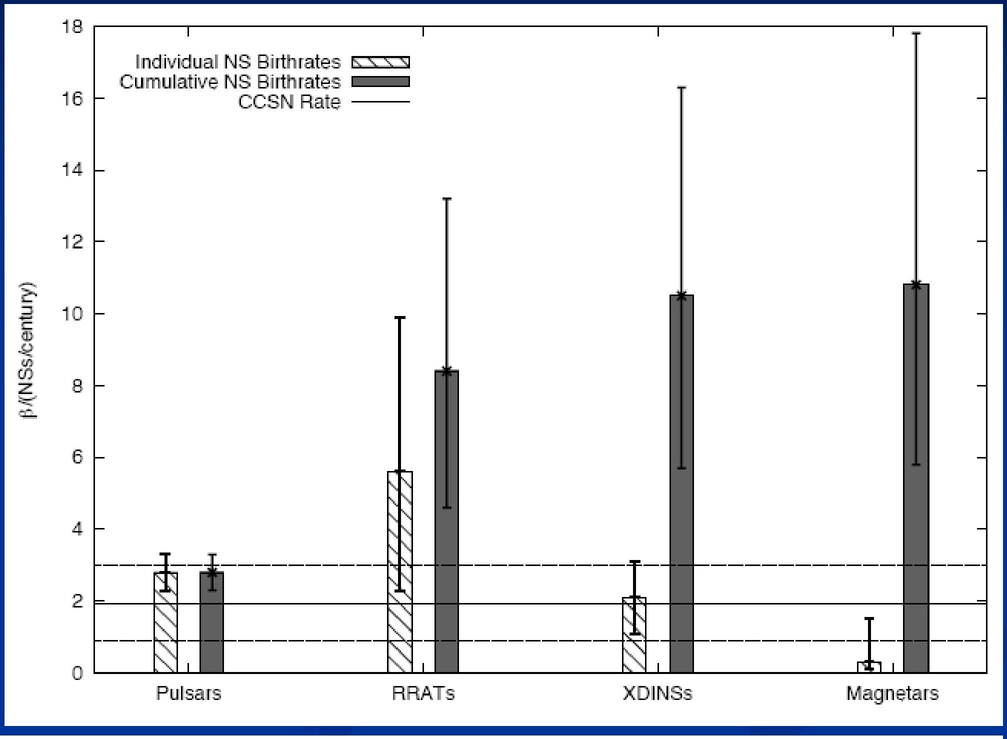
CCOs and emerging magnetic fields

Sergei Popov (SAI MSU)
Roberto Turolla (Univ. Padua)

arXiv: 1206.2819

NS birth rate

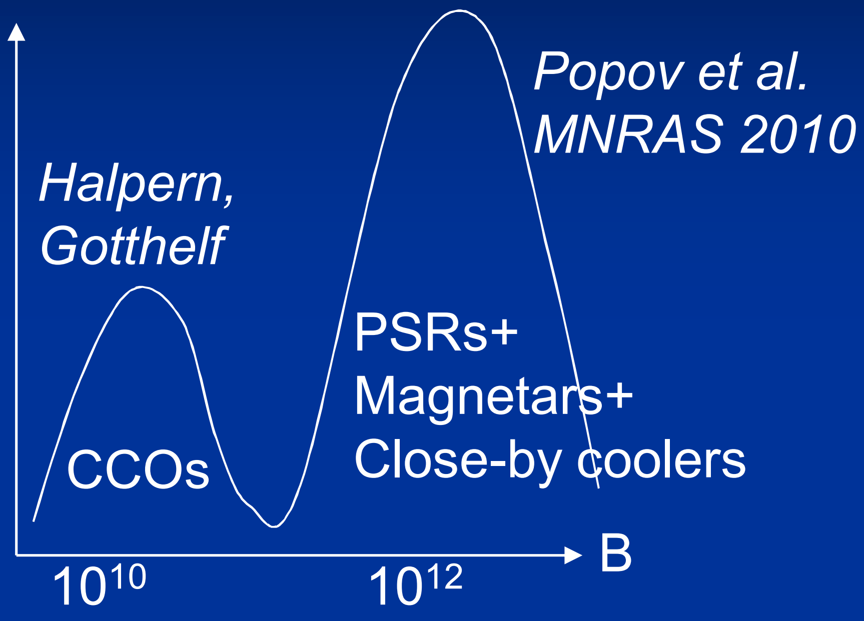


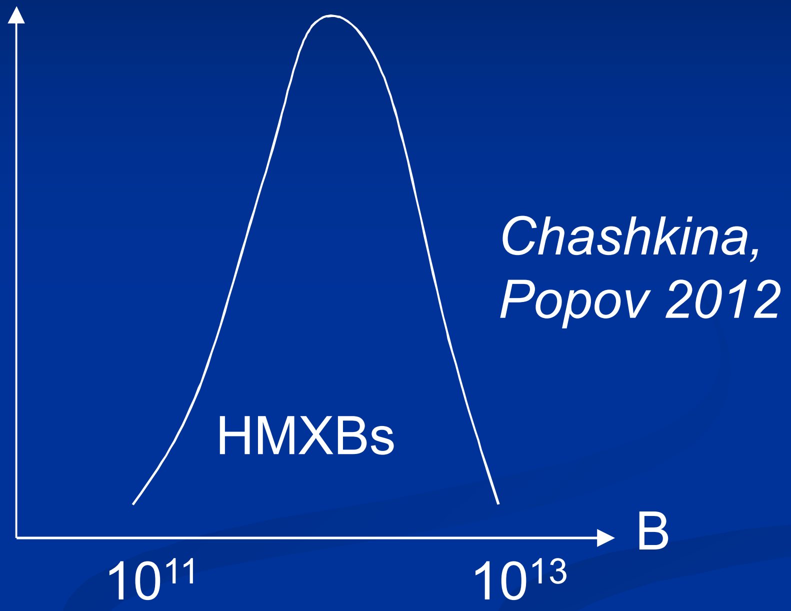


$\beta_{\rm PSR}$, $n_{\rm e}$	PSRs	RRATs	XDINSs	Magnetars	Total	CCSN rate
FK06, NE2001	2.8 ± 0.5	$5.6^{+4.3}_{-3.3}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$10.8^{+7.0}_{-5.0}$	1.9 ± 1.1
L+06, NE2001	1.4 ± 0.2	$2.8^{+1.6}_{-1.6}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$6.6^{+4.0}_{-3.0}$	1.9 ± 1.1
L+06, TC93	1.1 ± 0.2	$2.2^{+1.7}_{-1.3}$	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

[Keane, Kramer 2008, arXiv: 0810.1512]

Evolution of CCOs

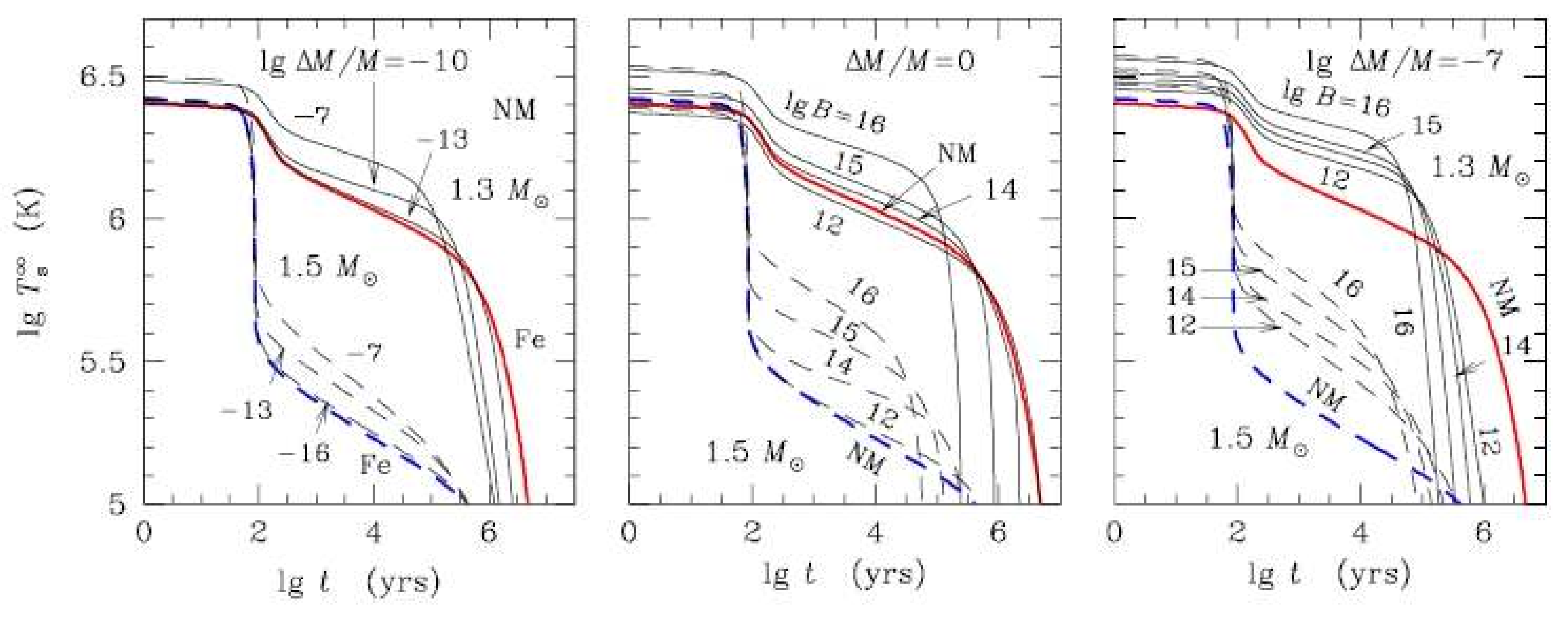




Among young isolated NSs about 1/3 can be related to CCOs.
If they are anti-magnetars, then we can expect that 1/3 of NSs in HMXBs are also low-magnetized objects.
They are expected to have short spin periods <1 sec.
However, there are no many sources with such properties.
The only good example - SAX J0635+0533. An old CCO?

Possible solution: emergence of magnetic field (see Ho 2011).

Where are old CCOs?



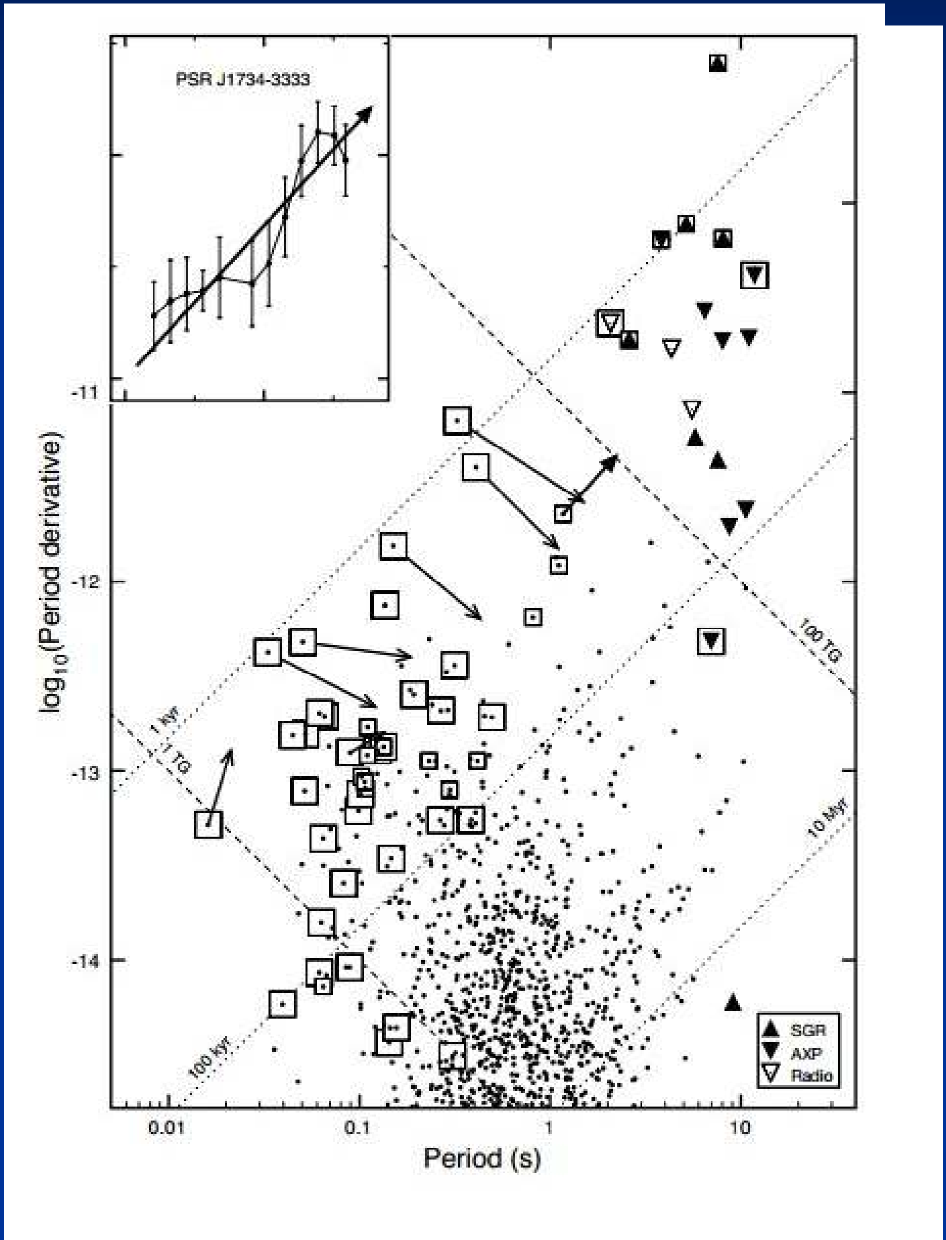
Yakovlev, Pethick 2004

According to cooling studies they have to be bright till at least 10^5 years.
But only one candidate (2XMM J104608.7-594306 Pires et al.) to be a low-B cooling NS is known (Calvera is also a possible candidate).

We propose that a large set of data on HMXBs and cooling NSs is in favour of field emergence on the time scale $10^4 \le \tau \le 10^5$ years.

Some PSRs with thermal emission for which additional heating was proposed can be descendants of CCOs with emerged field.

Emerged pulsars in the P-Pdot diagram



Espinoza et al. arXiv: 1109.2740

Emerged pulsars are expected to have
P~0.1-0.5 sec
B~10^{11}-10^{12} G
Negative braking indices or at least n<2.
About 20-40 of such objects are known.

Parameters of emerged PSRs:
similar to “injected” PSRs
(Vivekanand, Narayan, Ostriker).

The existence of significant fraction
of “injected” pulsars formally
do not contradict recent pulsar current studies
(Vranesevic, Melrose 2011).

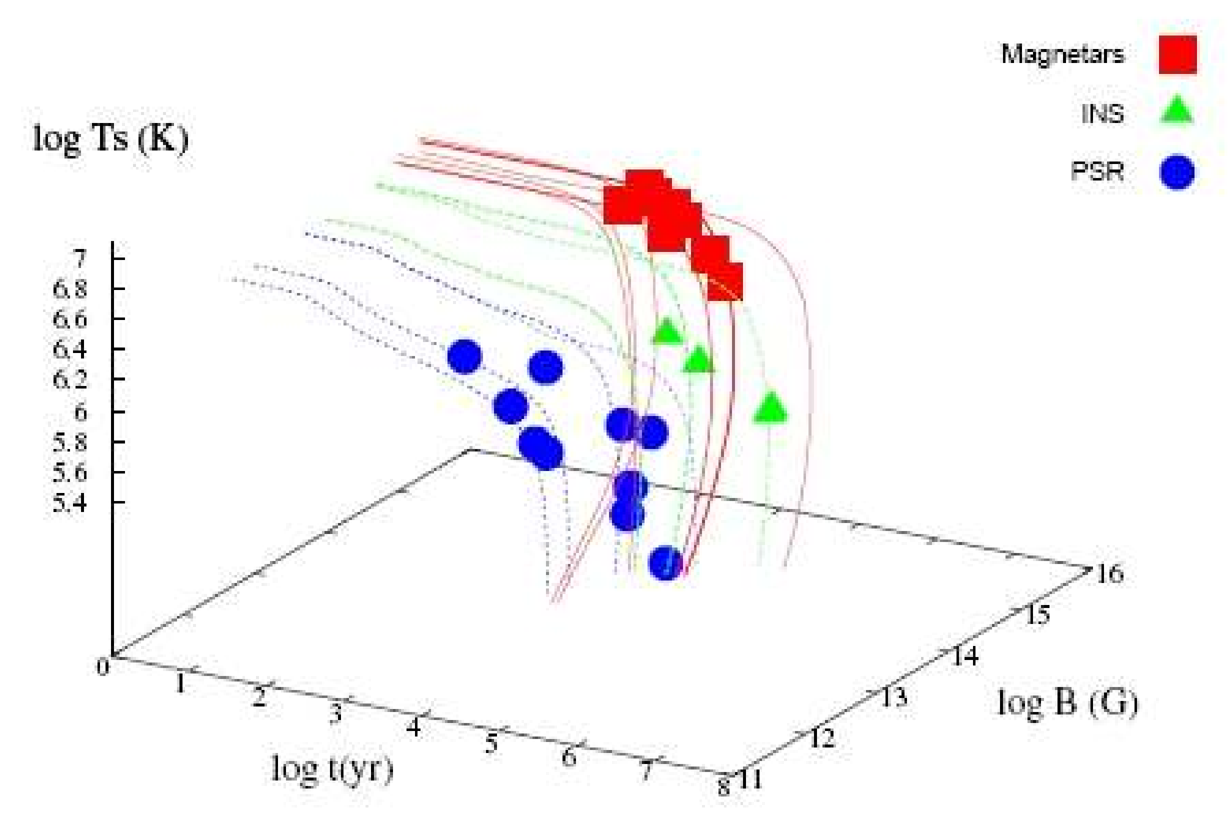
Part of PSRs supposed to be born with
long (0.1-0.5 s) spin periods can be
matured CCOs.

Episode 4.
Close-by cooling NSs
and “One second problem”

Sergei Popov (SAI MSU)
Co-authors: Jose Pons et al.
arXiv: 1309.4917

Magnetic field decay

A model based on the initial field-dependent decay
can provide an evolutionary link between different populations (Pons et al.).



$$B = B_0 \frac{\exp\left(-t/\tau_{\mathrm{Ohm}}\right)}{1 + \frac{\tau_{\mathrm{Ohm}}}{\tau_{\mathrm{Hall}}}\left(1 - \exp\left(-t/\tau_{\mathrm{Ohm}}\right)\right)}$$

arXiv: 0710.4914 (Aguilera et al.)

Extensive population synthesis

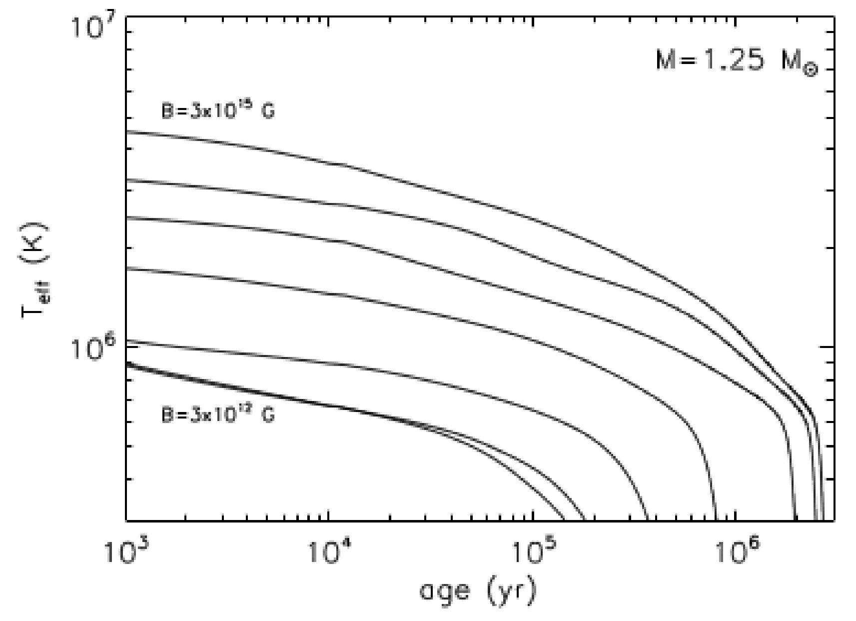
We want to make extensive population synthesis studies using as many approaches as we can to confront theoretical models with different observational data

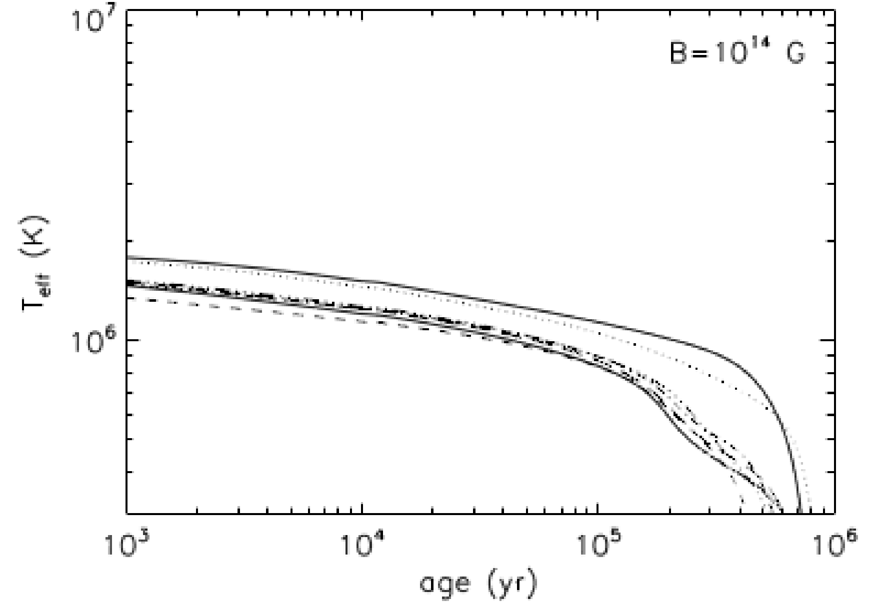
- Log N – Log S for close-by young cooling isolated neutron stars
- Log N – Log L distribution for galactic magnetars
- P-Pdot distribution etc. for normal radio pulsars

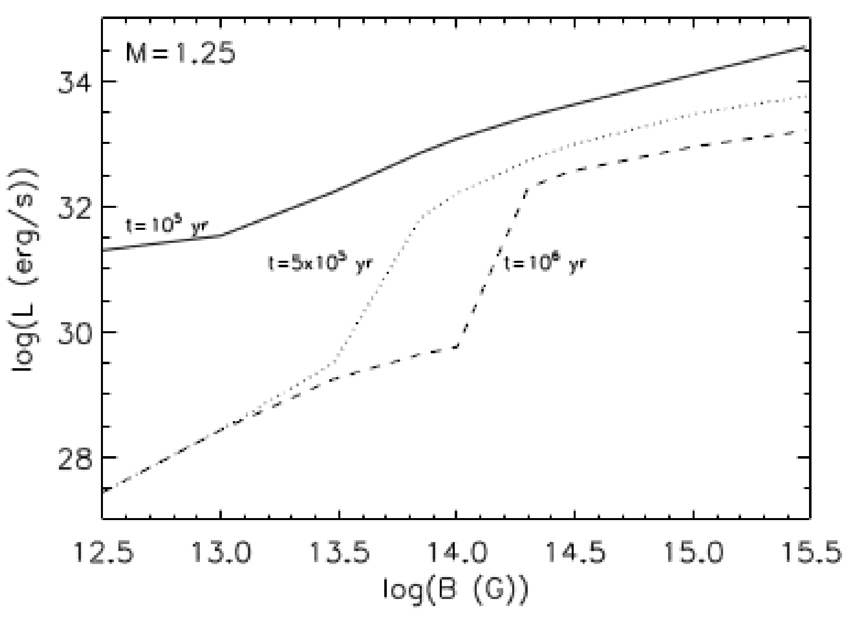
MNRAS 401, 2675 (2010)
arXiv: 0910.2190

See a review of the population synthesis technique in
Popov, Prokhorov *Physics Uspekhi* vol. 50, 1123 (2007)
[ask me for the PDF file, if necessary - it is not in the arXiv]

Cooling curves with decay

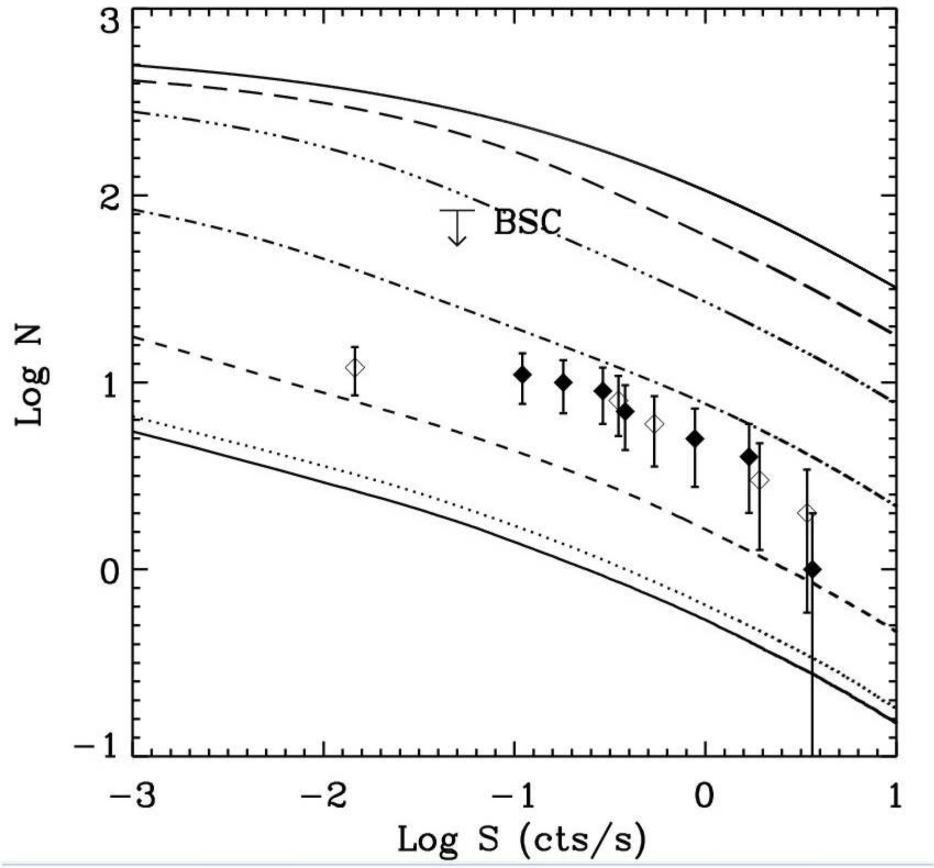




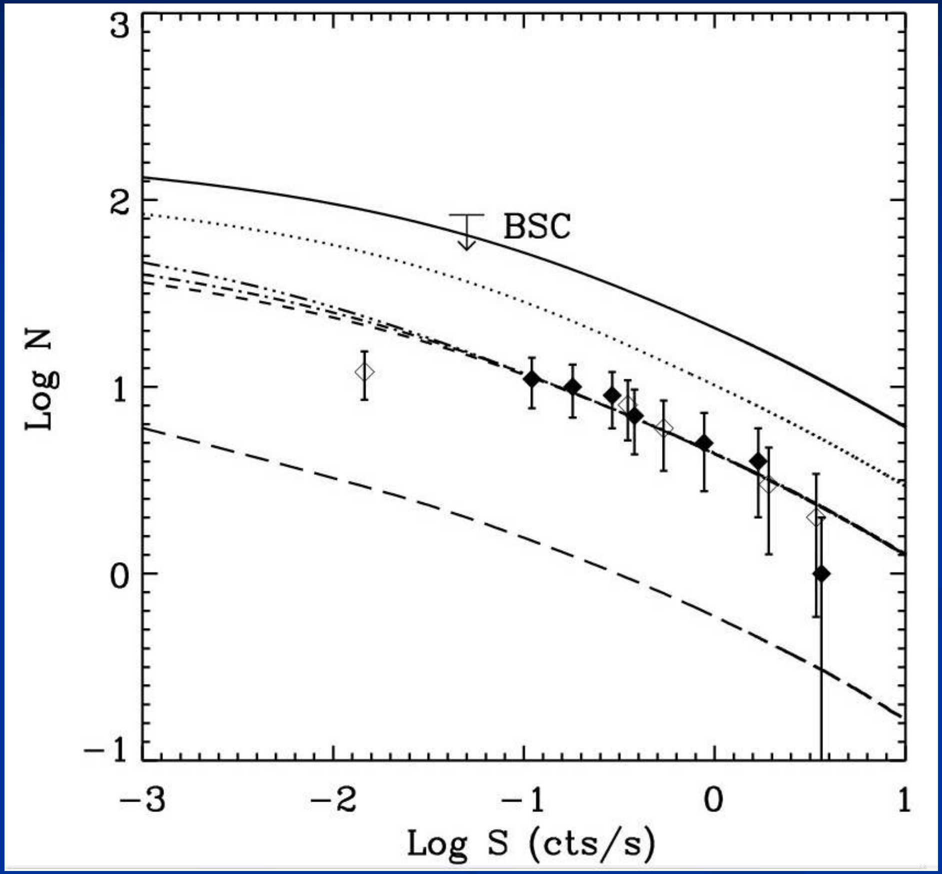


Magnetic field distribution is more important than the mass distribution.

Log N – Log S with heating



Log N – Log S for 7 different magnetic fields.

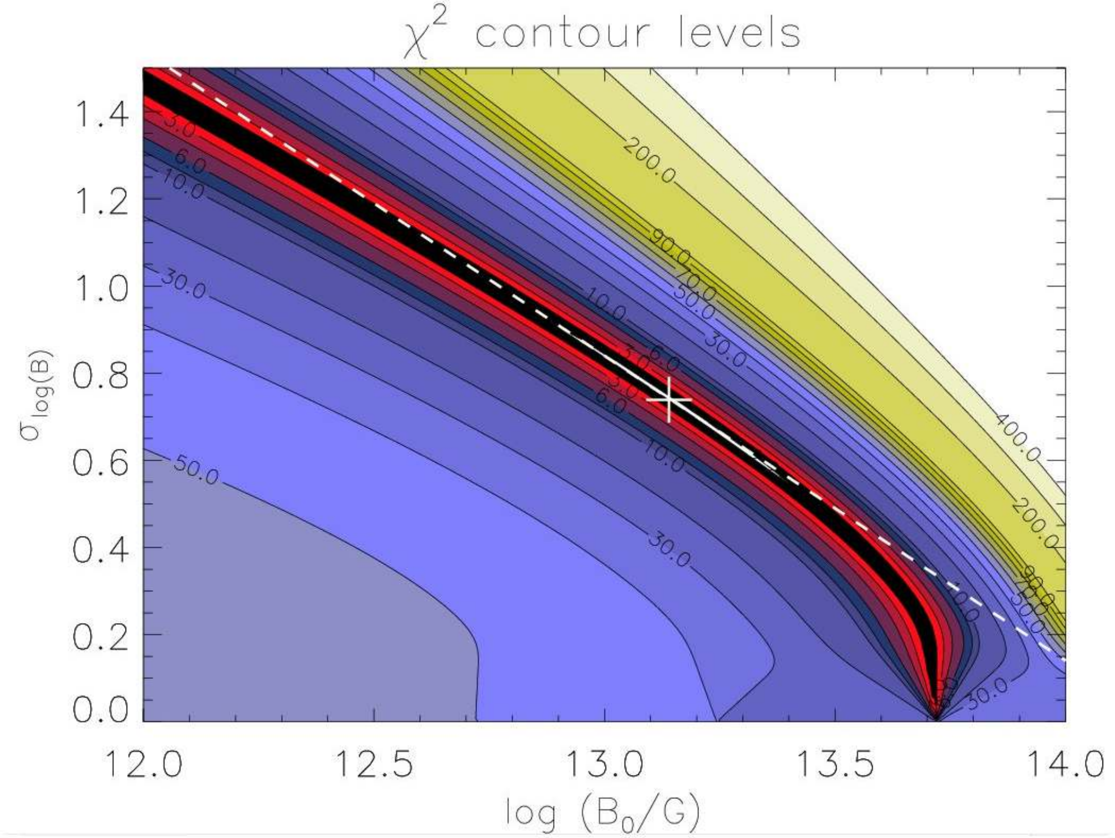


Different magnetic field distributions.

1. $3\ 10^{12}$ G 2. 10^{13} G
3. $3\ 10^{13}$ G 4. 10^{14} G 5. $3\ 10^{14}$ G
6. 10^{15} G 7. $3\ 10^{15}$ G

[The code used in Posselt et al. A&A (2008) with modifications]

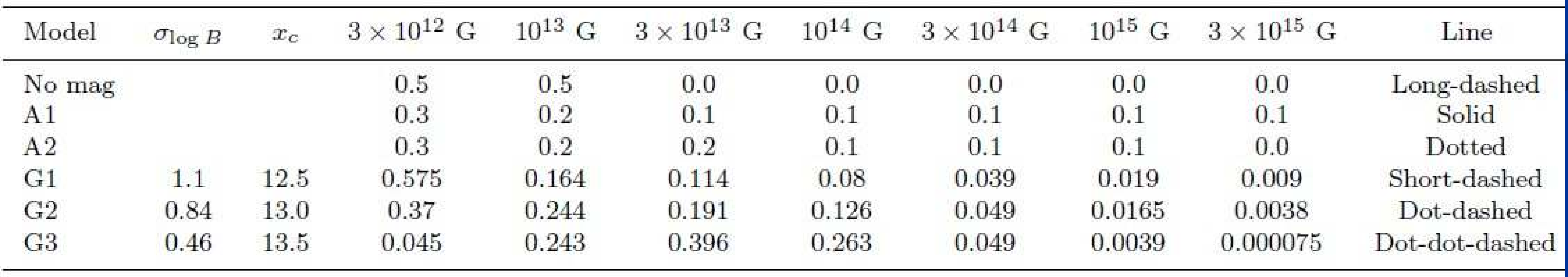
Fitting Log N – Log S



We try to fit the Log N – Log S with log-normal magnetic field distributions, as it is often done for PSRs.

We cannot select the best one using only Log N – Log S for close-by cooling NSs.

We can select a combination of parameters.



Model	$\sigma_{\log B}$	x_c	3×10^{12} G	10^{13} G	3×10^{13} G	10^{14} G	3×10^{14} G	10^{15} G	3×10^{15} G	Line
No mag			0.5	0.5	0.0	0.0	0.0	0.0	0.0	Long-dashed
A1			0.3	0.2	0.1	0.1	0.1	0.1	0.1	Solid
A2			0.3	0.2	0.2	0.1	0.1	0.1	0.0	Dotted
G1	1.1	12.5	0.575	0.164	0.114	0.08	0.039	0.019	0.009	Short-dashed
G2	0.84	13.0	0.37	0.244	0.191	0.126	0.049	0.0165	0.0038	Dot-dashed
G3	0.46	13.5	0.045	0.243	0.396	0.263	0.049	0.0039	0.000075	Dot-dot-dashed

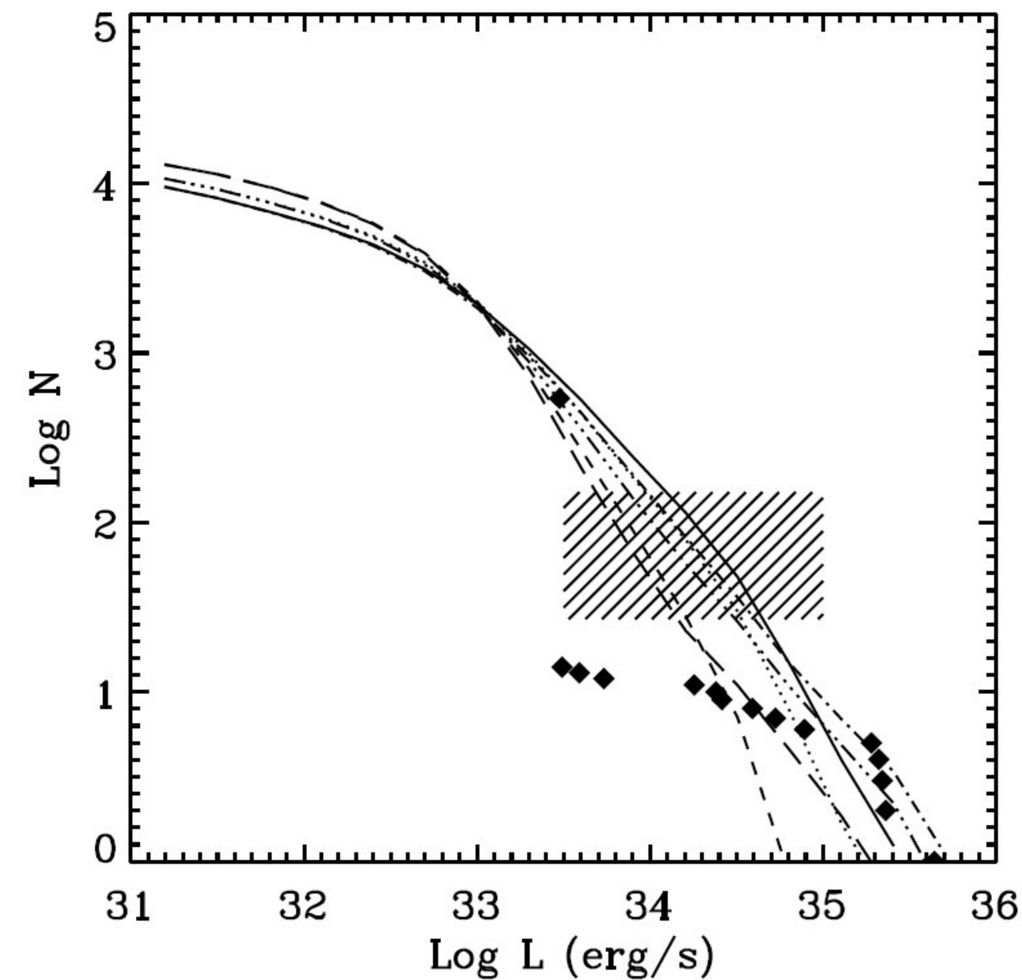
Log N – Log L for magnetars

We used the same initial magnetic field distributions.

Curves are shown for three log-normal distributions with and without a "transient" behaviour.

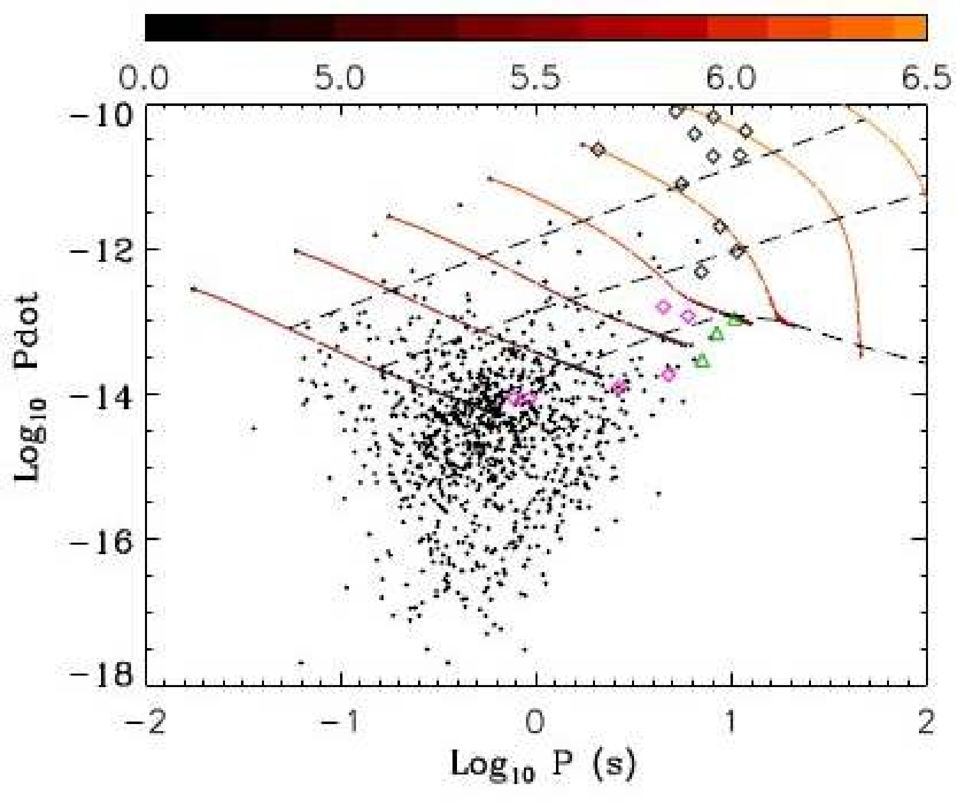
It is assumed that the total luminosity can be well approximated by the energy release due to field decay.

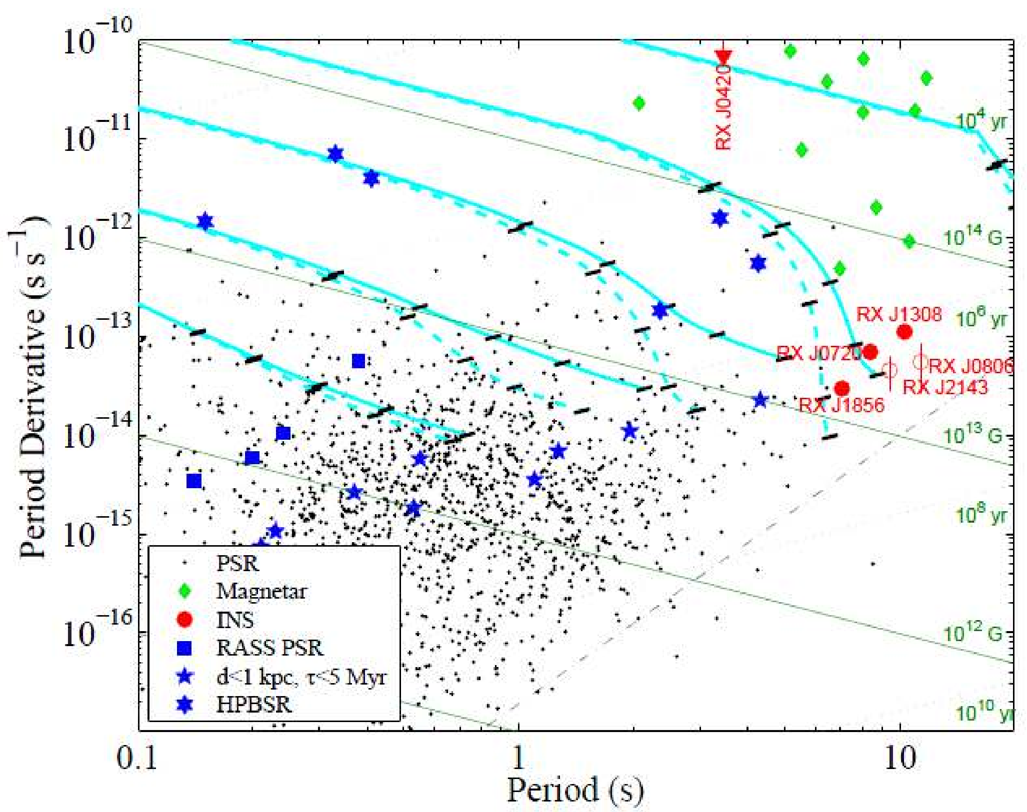
It is seen that the same log-normal distributions can reasonably well describe the data for magnetars.



Data points from the McGill catalogue.
Limits - from Muno et al. (2008)

P-Pdot tracks



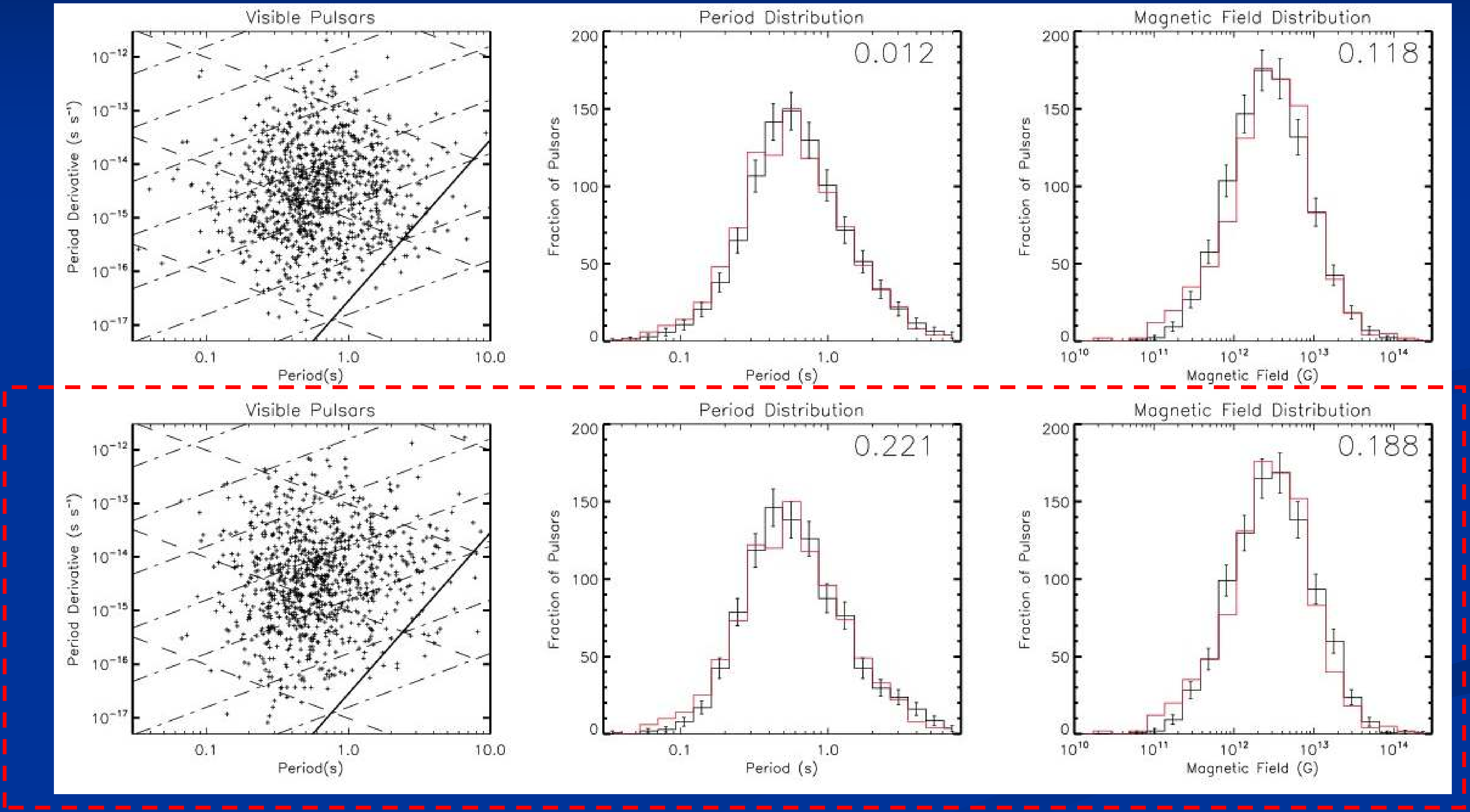


Kaplan & van Kerkwijk arXiv: 0909.5218

Color on the track encodes surface temperature.

Tracks start at 10^3 years, and end at ~3 10^6 years.

Population synthesis of PSRs

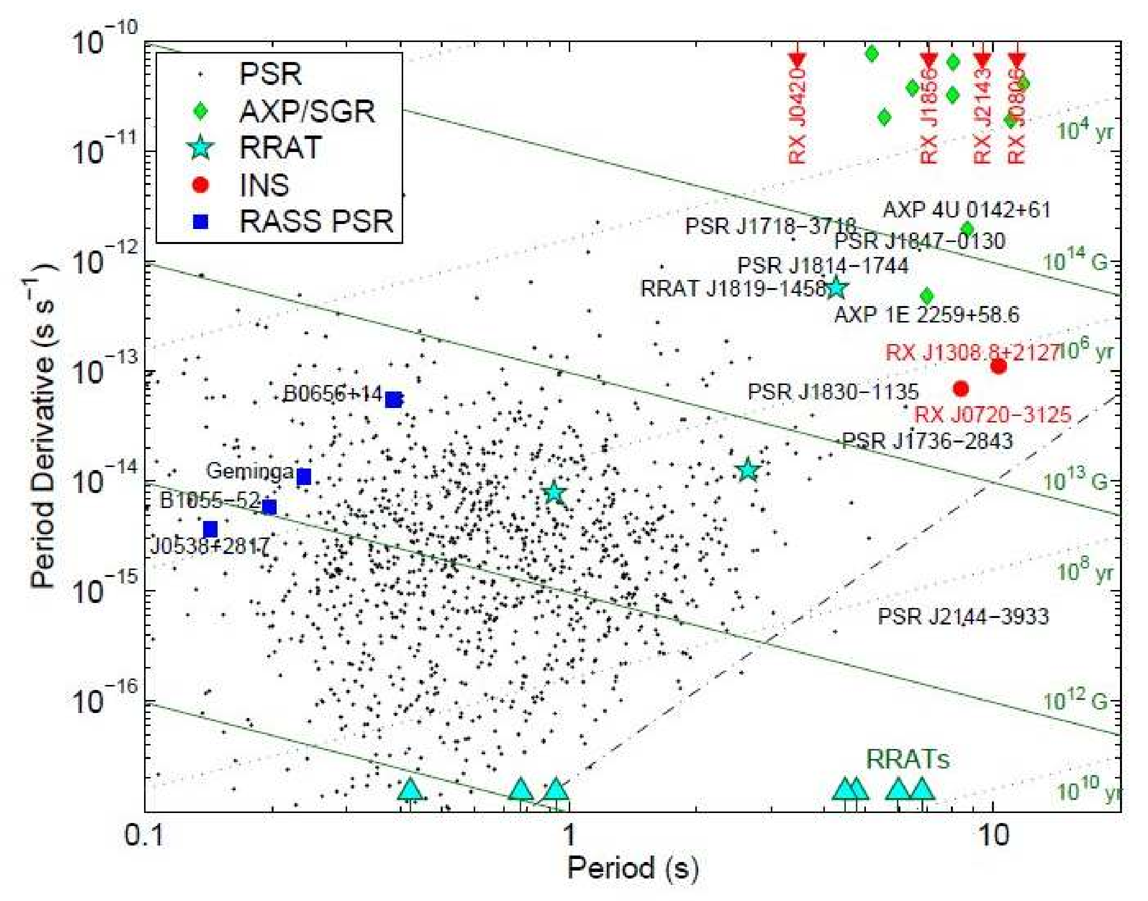


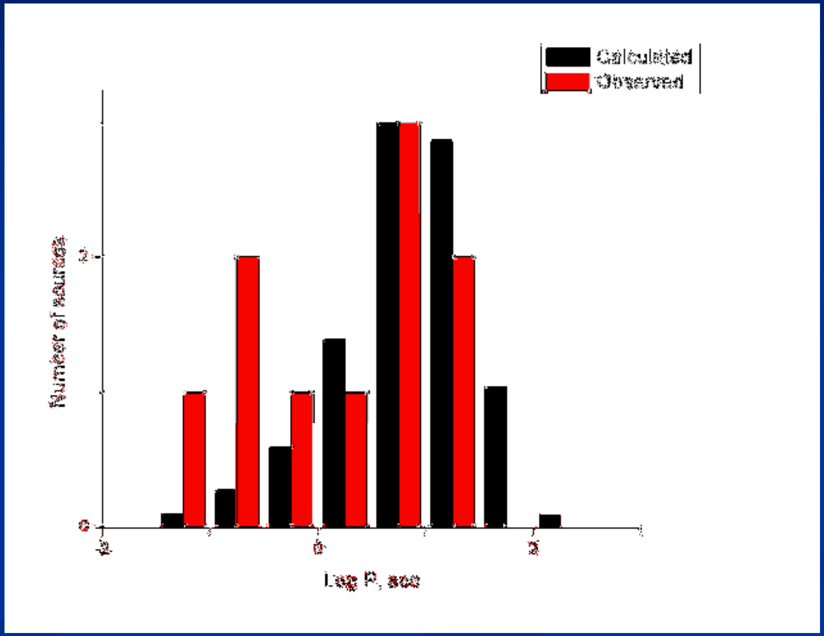
Best model: $\langle\log(B_0/[G])\rangle = 13.25$, $\sigma_{\log B0}=0.6$, $\langle P_0\rangle = 0.25$ s, $\sigma_{P0} = 0.1$ s

The “one second” problem

Two types of sources are observed:

- Radiopulsars (P<1 sec)
- Magnificent Seven (P>1 sec)





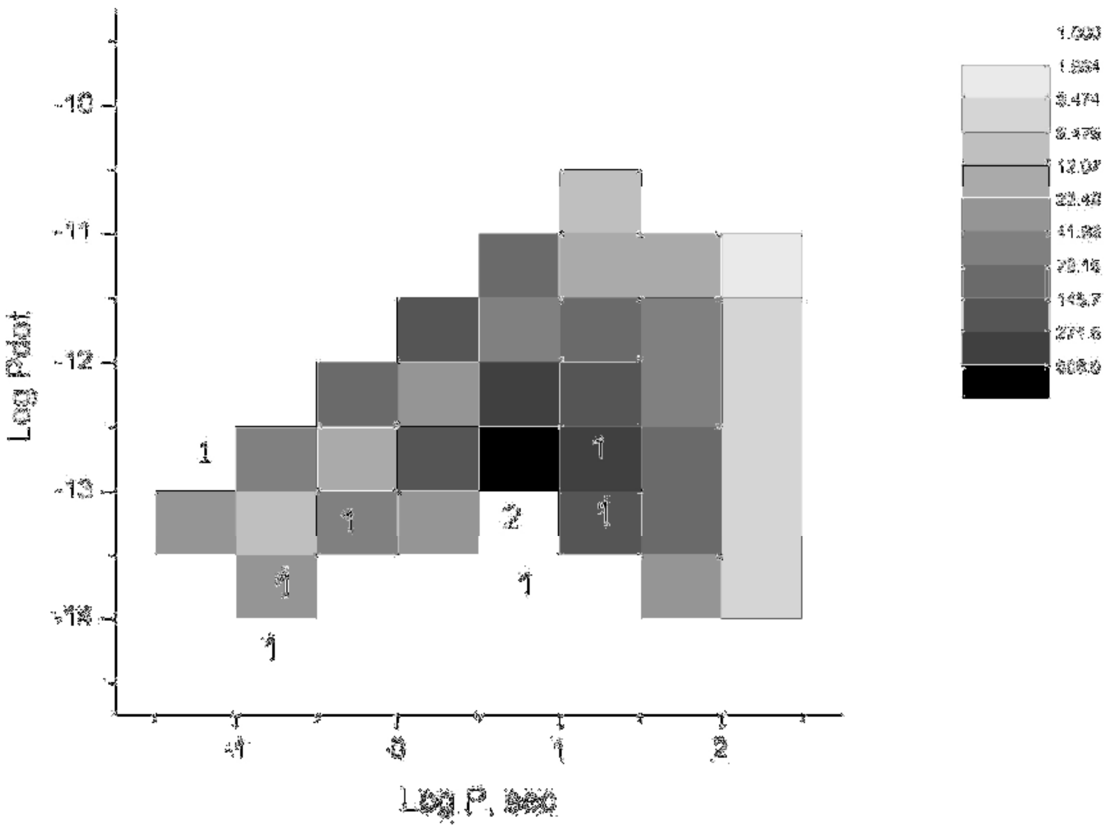
No close-by cooling NSs in the range ~-0.5 <log P< ~0.5

Kaplan arXiv: 0801.1143

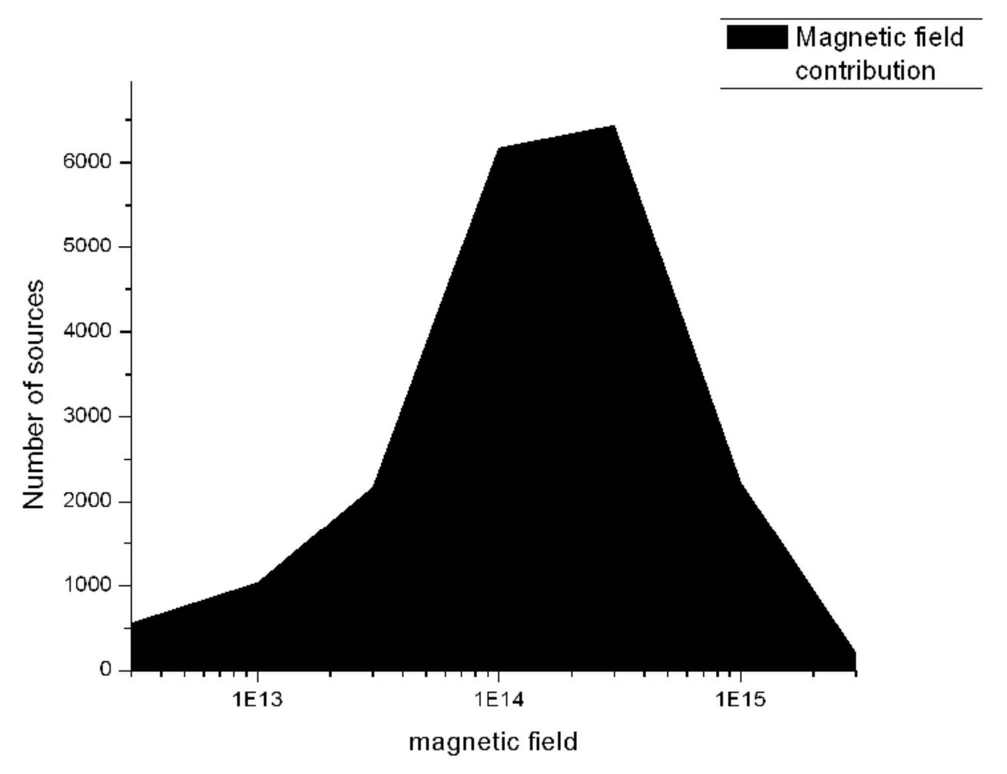
P-Pdot diagram for coolers

This is a P-Pdot diagram for close-by cooling NSs according to our model.

Numbers correspond to the observed sources.



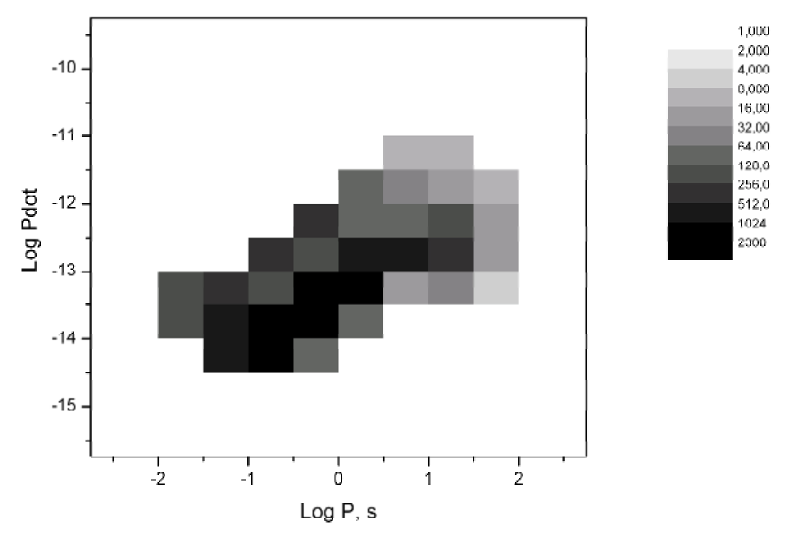
Initial magnetic fields of the modeled coolers



The plot shows the distribution of the initial magnetic fields of NSs which contribute to the Log N – Log S diagram
in the range ~0.1-10 cts/s

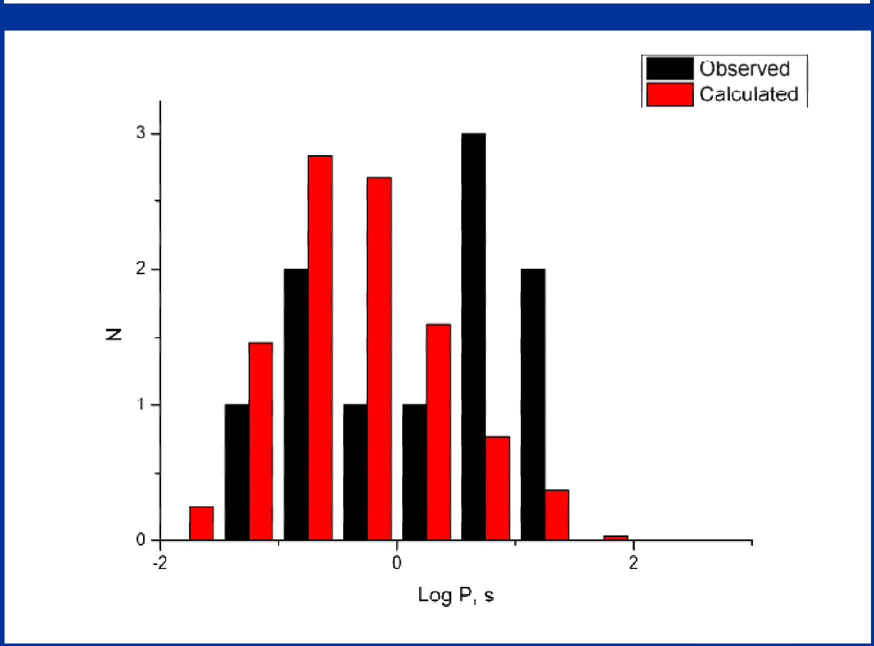
Obviously, there is the same problem as with the period distribution.

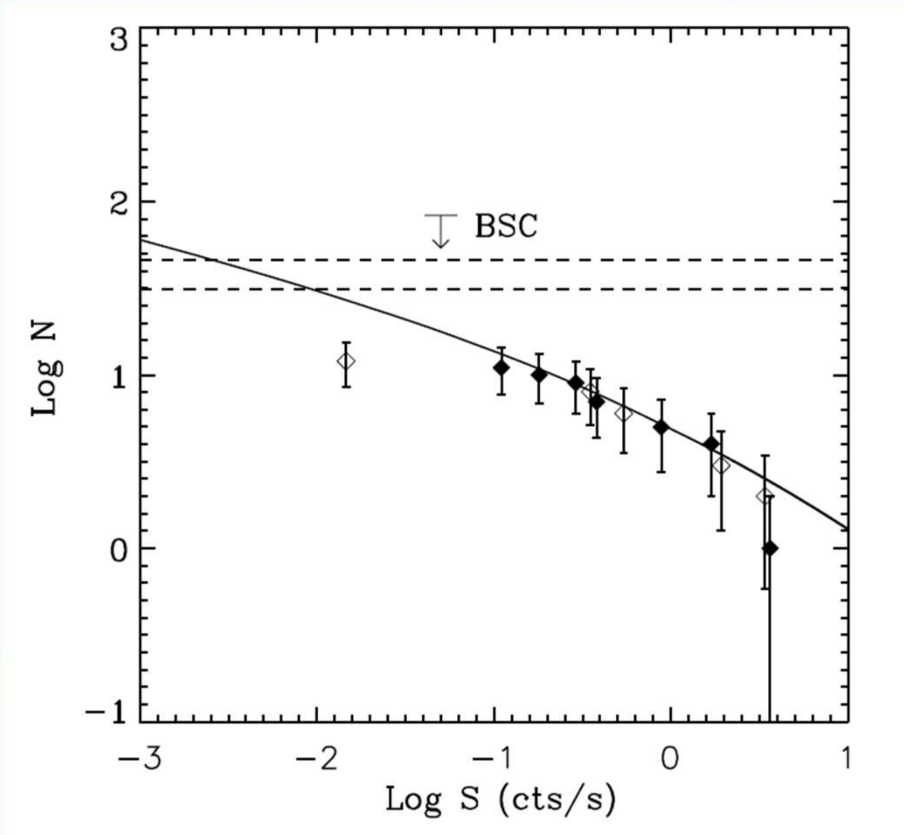
New calculations



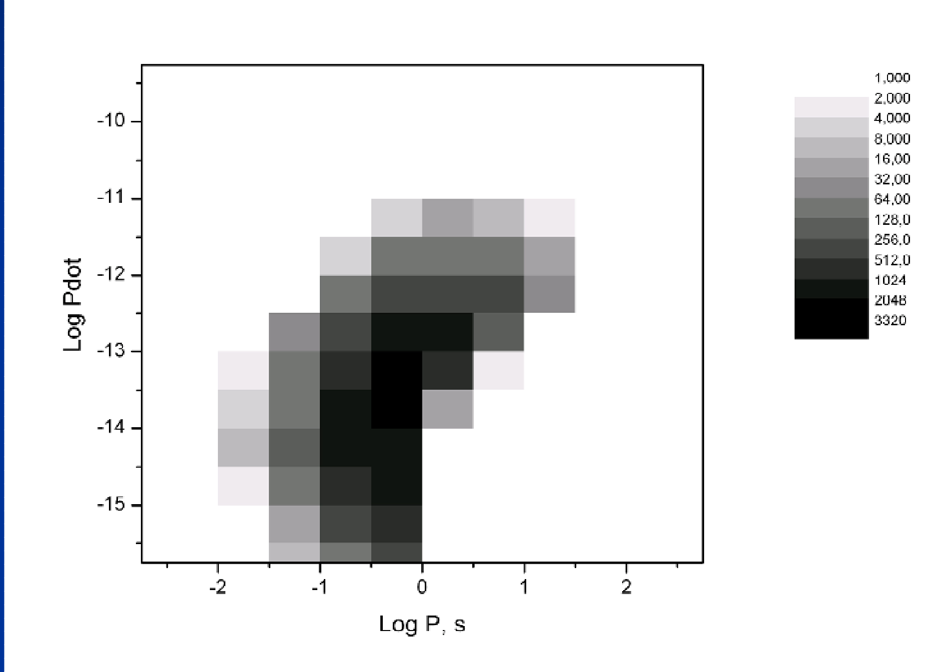
New cooling models (Pons, Vigano).
Now low-B NSs are hotter than before, and high-B NSs are colder.

Still, it is not possible to explain the P-Pdot data.
Fine tuning is necessary.

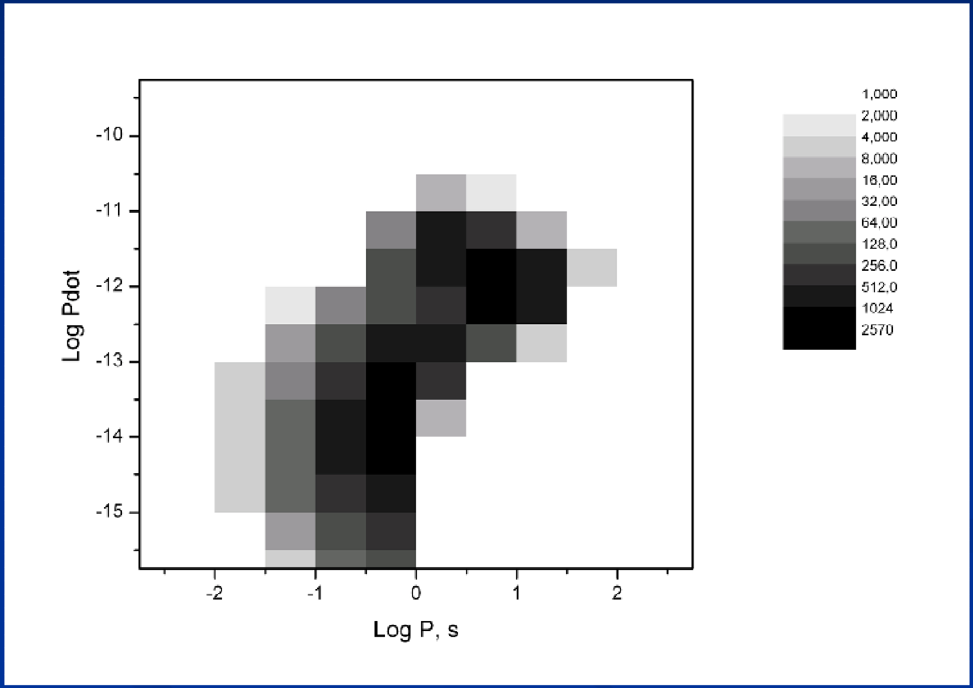




Evolution without heating



Kaspi-like population

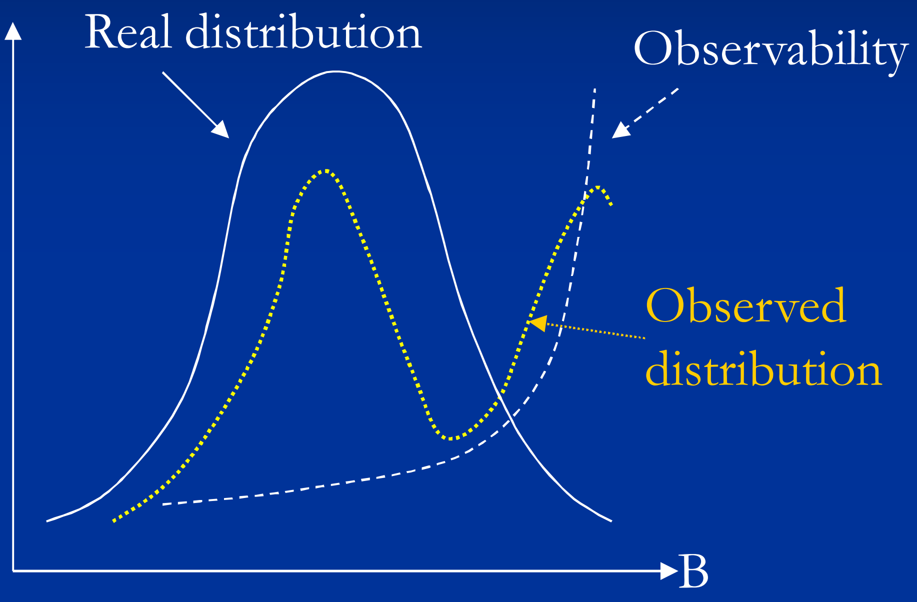


Kaspi-like population with additional peak at B=10^{14} G and small dispersion

Calculations with new cooling curves from the St.Petersburg group (Sternin, Yakovlev et al.) can easily explain the Log N – Log S, but cannot the P-Pdot without finetuning for the B-distribution (curves are not sensitive to B, so it is important only for spin evolution).

Solutions for the "one second" problem

①



② Fine-tune the thermal properties of NSs and hope that the gap is due to low statistics

③ Probably, the unique initial magnetic field distribution is a bad assumption

④ Or the whole scenario is wrong