Magnetic field decay in radio pulsars

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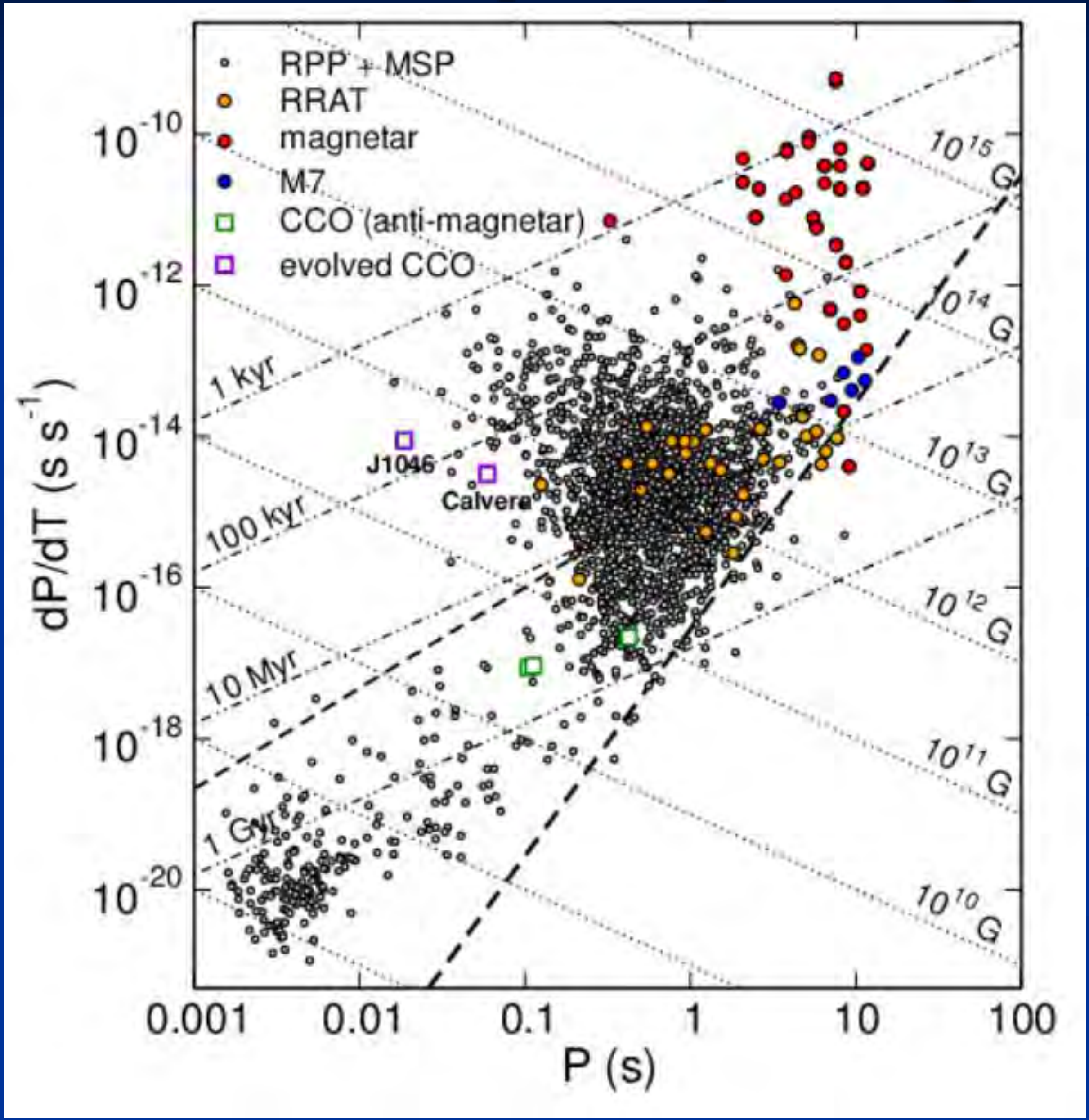
Diversity of young neutron stars

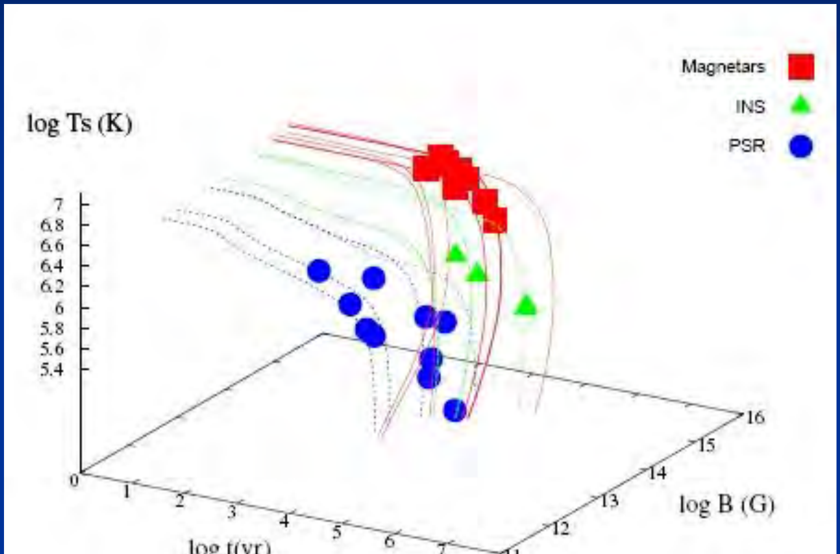


Pires et al. 2015

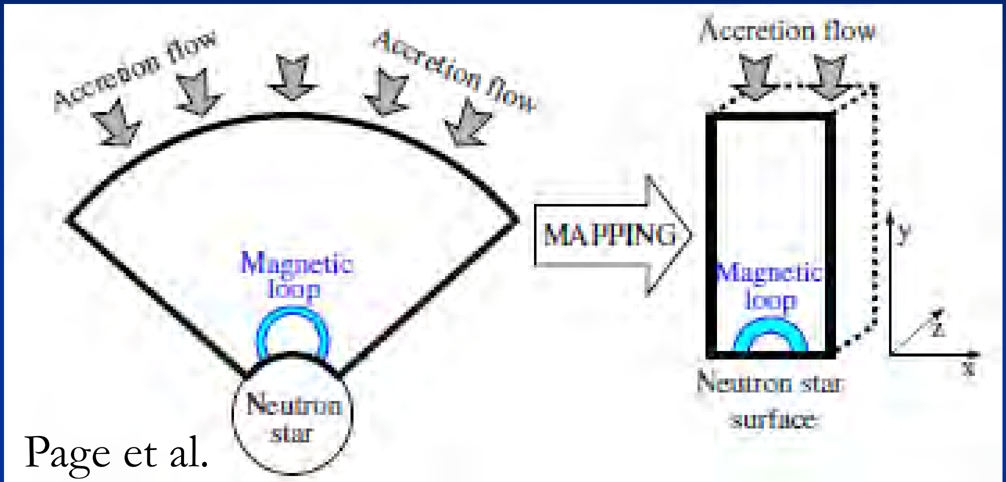
The term "GRAND UNIFICATION FOR NEUTRON STARS" was coined by Kaspi (2010)

First steps done in Popov et al. (2010).

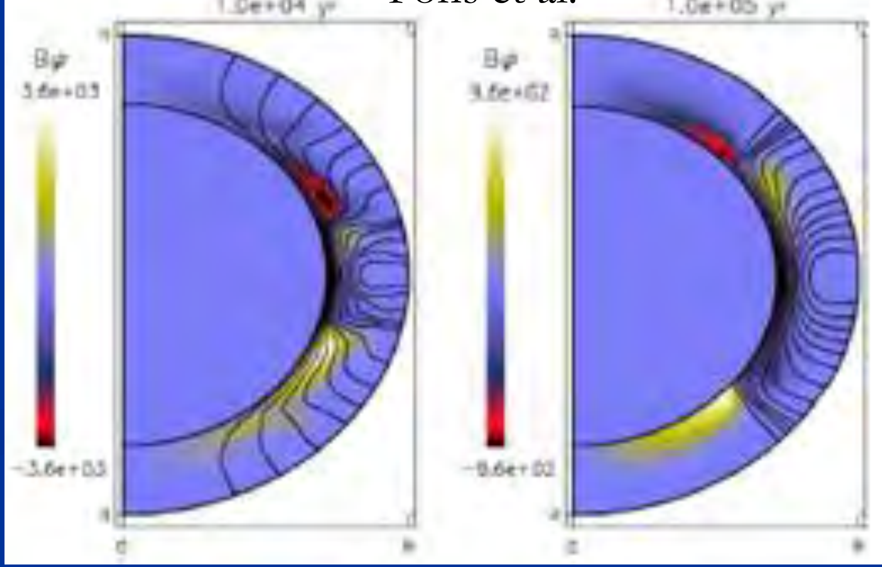
Three main ingredients of a unified model



Aguilera et al.



Page et al.

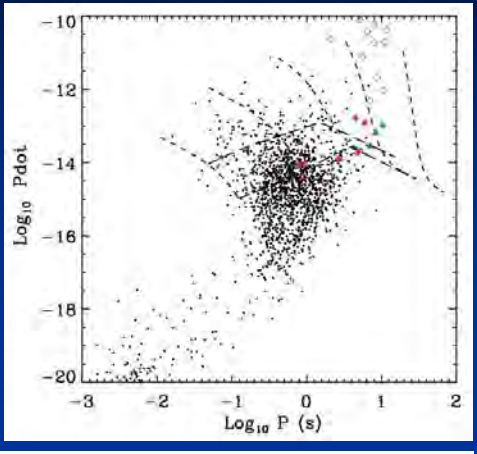

Pons et al.

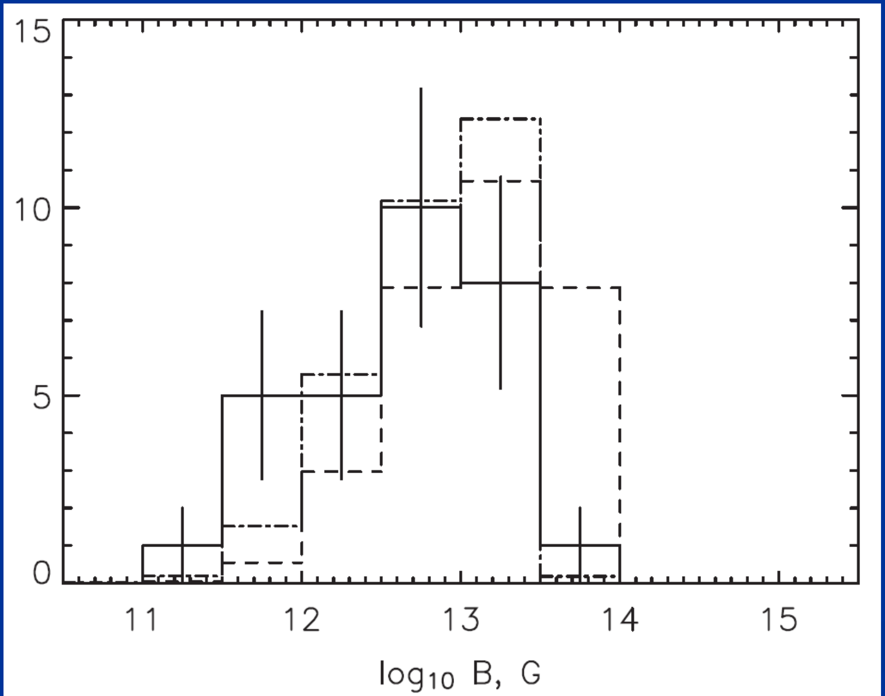
- Field decay
- Emerging magnetic field
- Toroidal magnetic field

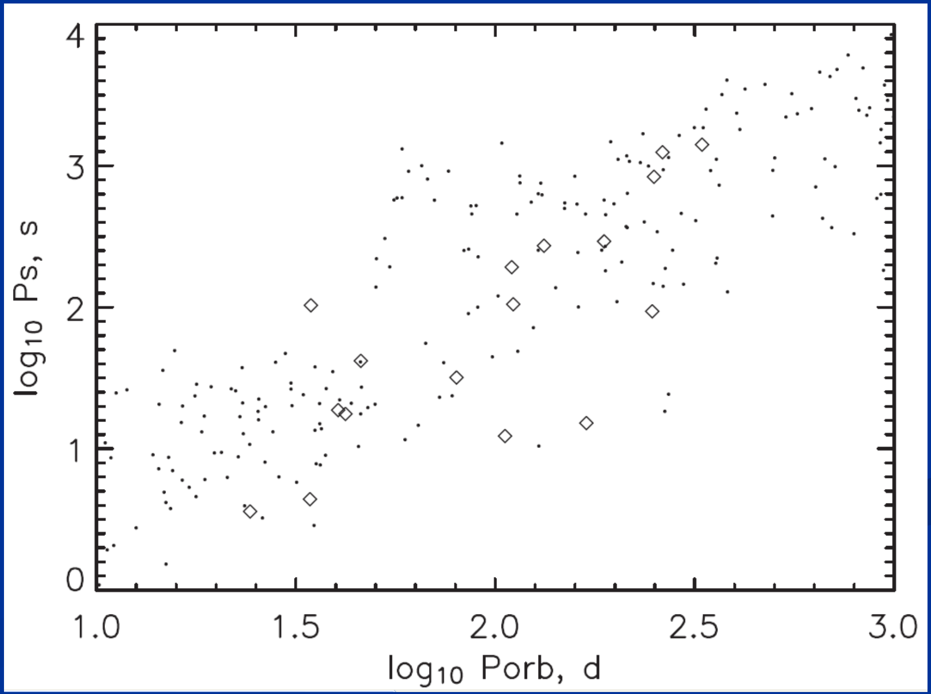
Field decay in HMXBs

It is possible to use HMXBs to test models of field decay on time scale >1 Myr (Chashkina, Popov 2012).

We use observations of Be/X-ray binaries in SMC to derive magnetic field estimates, and compare them with prediction of the Pons et al. model.



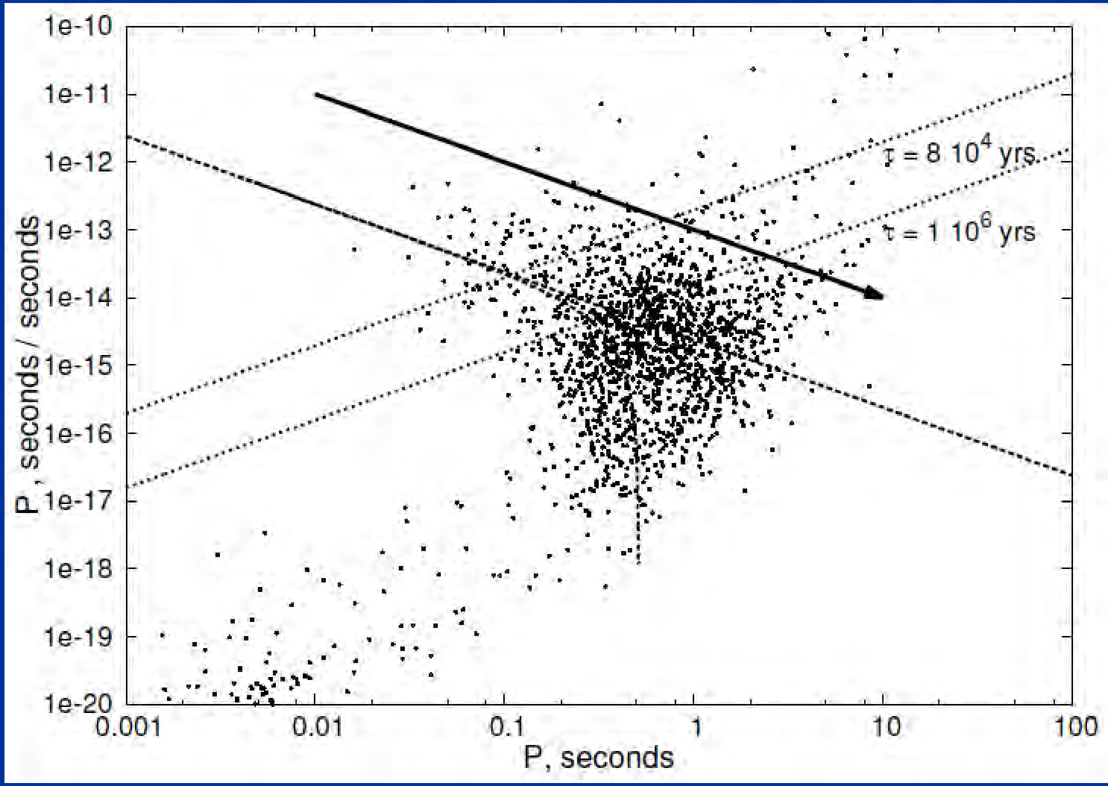




Chashkina, Popov (2012)

Modified pulsar current

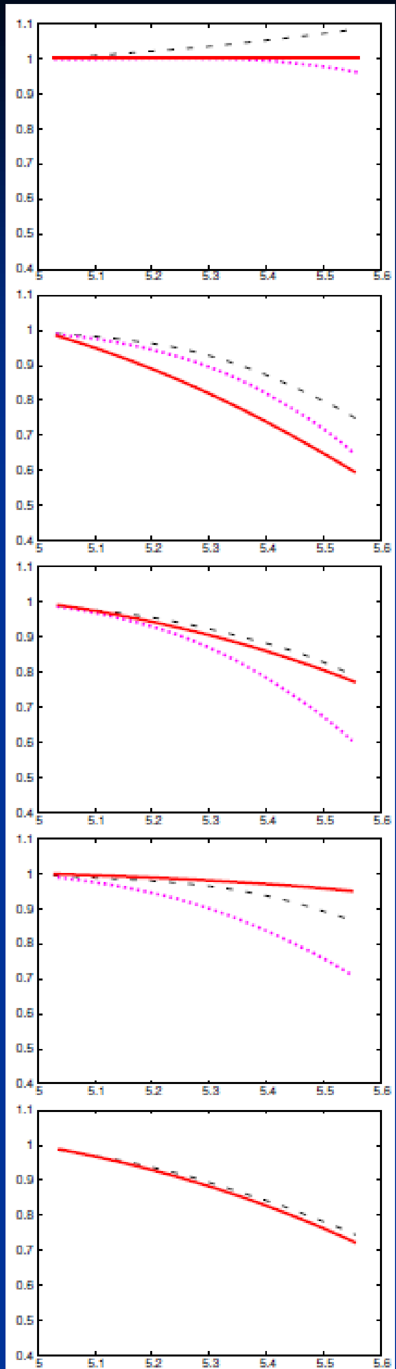
We perform a modified pulsar current analysis. In our approach we analyse the flow not along the spin period axis, as it was done in previous studies, but study the flow along the axis of growing characteristic age.



The idea is to probe magnetic field decay. Our method can be applied only in a limited range of ages.

We use distribution in characteristic ages to reconstruct the field evolution.

Igoshev, Popov (2014). arXiv:1407.6269



Tests

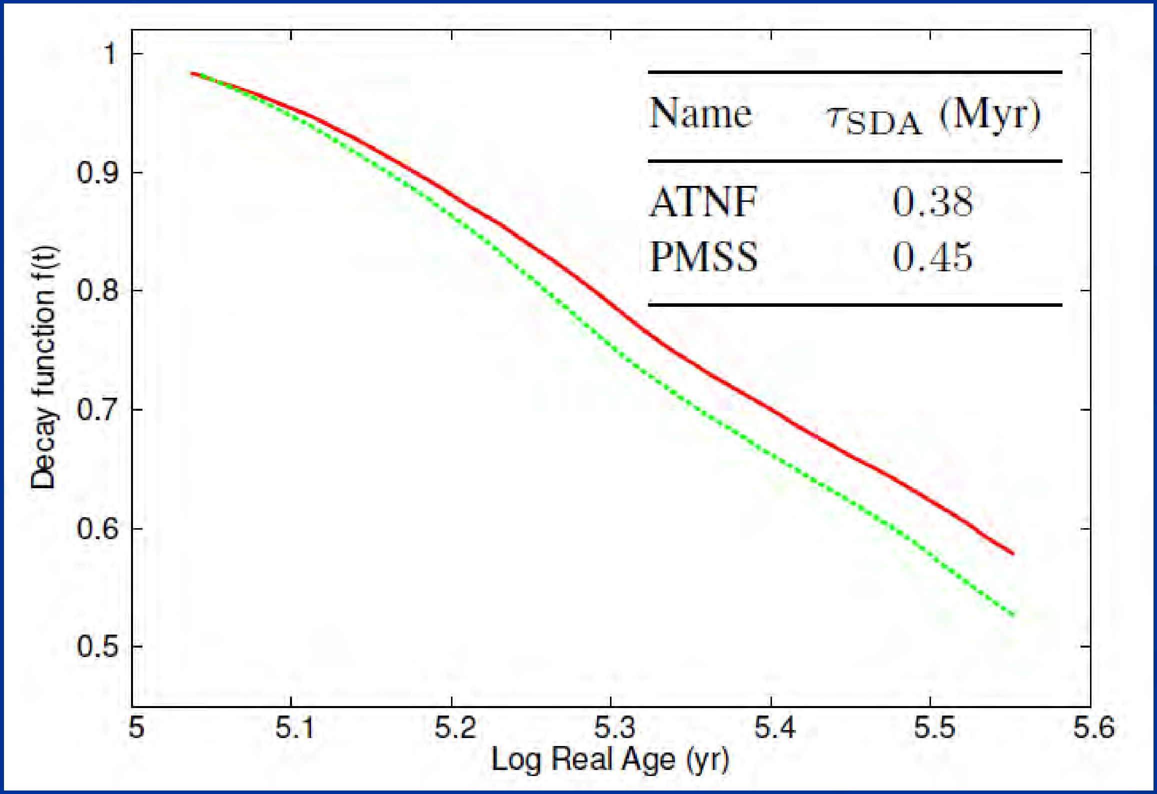
We make extensive tests of the method and obtain that in most of the cases it is able to uncover non-negligible magnetic field decay (more than a few tens of per cent during the studied range of ages) in normal radio pulsars for realistic initial properties of neutron stars.

Name	$\log \mu_{B_0}$ [G]	$\log \sigma_{B_0}$ [G]	μ_{P_0} [s]	σ_{P_0} [s]	α	$\tau_{\rm D}$ [Myr]	$\tau_{\rm SDA}$ [Myr]
A1	12.60	0.47	0.33	0.23	0.50	∞	∞
A2	12.95	0.55	0.30	0.15	0.50	∞	10
B1	12.60	0.47	0.33	0.23	0.50	0.5	1.00
B2	12.95	0.55	0.30	0.15	0.50	0.5	0.690
C1	12.60	0.47	0.33	0.23	0.50	1	1.15
C2	12.95	0.55	0.30	0.15	0.50	1	0.560
D1	12.60	0.47	0.33	0.23	0.50	5	2.00
D2	12.95	0.55	0.30	0.15	0.50	5	0.80
E	13.04	0.55	0.22	0.32	0.44	~ 0.8	0.880

(Synthetic samples are calculated by Gullon, Pons, Miralles)

Application to real data

We apply our methods to large observed samples of radio pulsars to study field decay in these objects. As we need to have as large statistics as possible, and also we need uniform samples, in the first place we study sources from the ATNF catalogue (Manchester et al. 2005).
Then we apply our methods to the largest uniform subsample of the ATNF — to the PMSS (stands for the Parkes Multibeam and Swinburne surveys) (Manchester et al. 2001).



We reconstruct the magnetic field decay in the range of true (statistical) ages:
$8\ 10^4 < t < 3.5\ 10^5$ yrs
which corresponds to characteristic ages
$8\ 10^4 < \tau < 10^6$ yrs.
In this range, the field decays roughly by a factor of two.
With an exponential fit this corresponds to the decay time scale ~4 10^5 yrs.
Note, this decay is limited in time.

Igoshev, Popov (2014)

What kind of decay do we see?

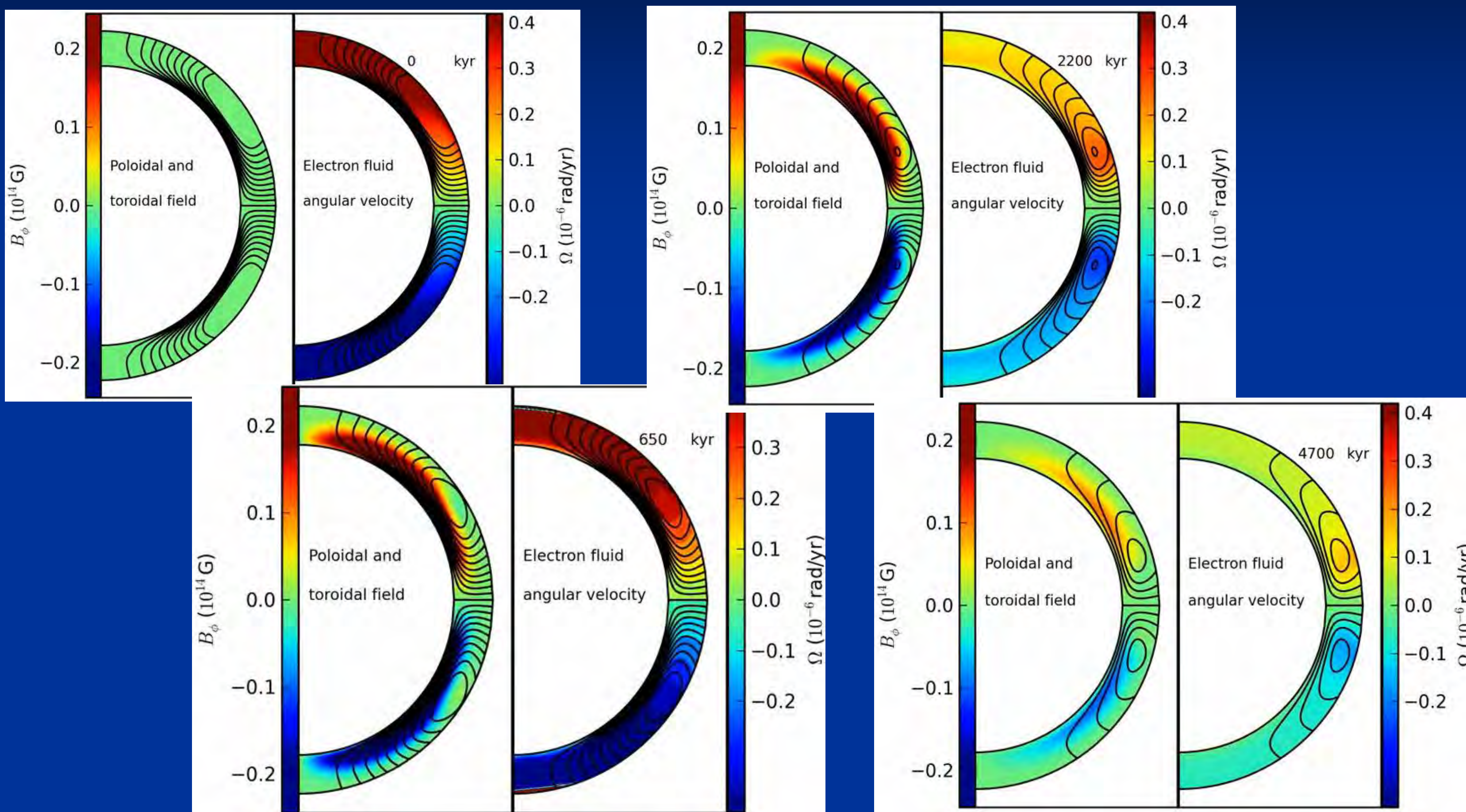
Ohmic decay due to phonons

Hall cascade

Both time scales fit, and in both cases we can switch of decay at ~10^6 yrs either due to cooling, or due to the Hall attractor.

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

Hall cascade and attractor

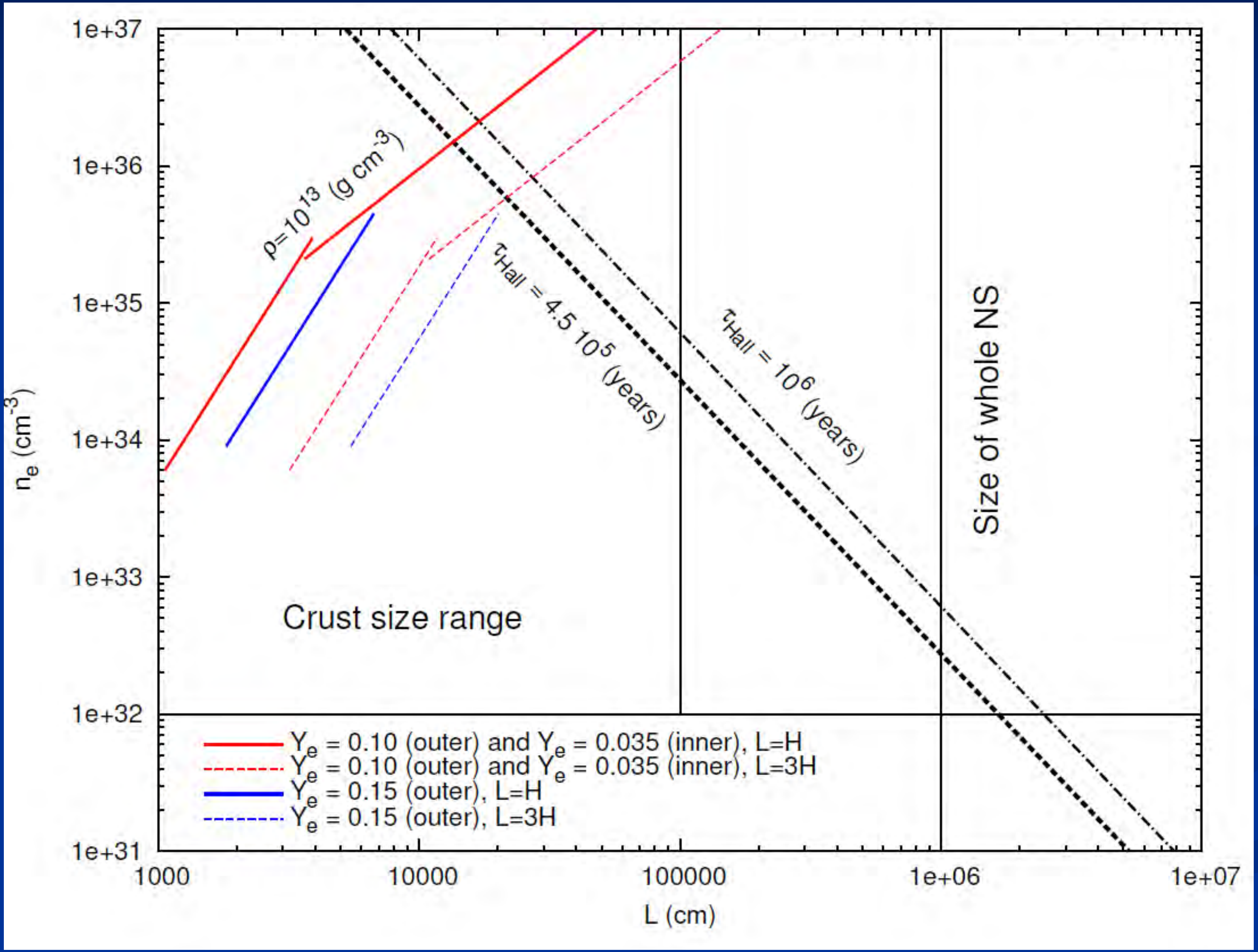


Gourgouliatos and Cumming 2013

http://www.physics.mcgill.ca/~kostasg/research.html

Hall cascade can reach the stage of so-called Hall attractor, where the field decay stalls for some time (Gourgouliatos, Cumming).

Where the currents are located?

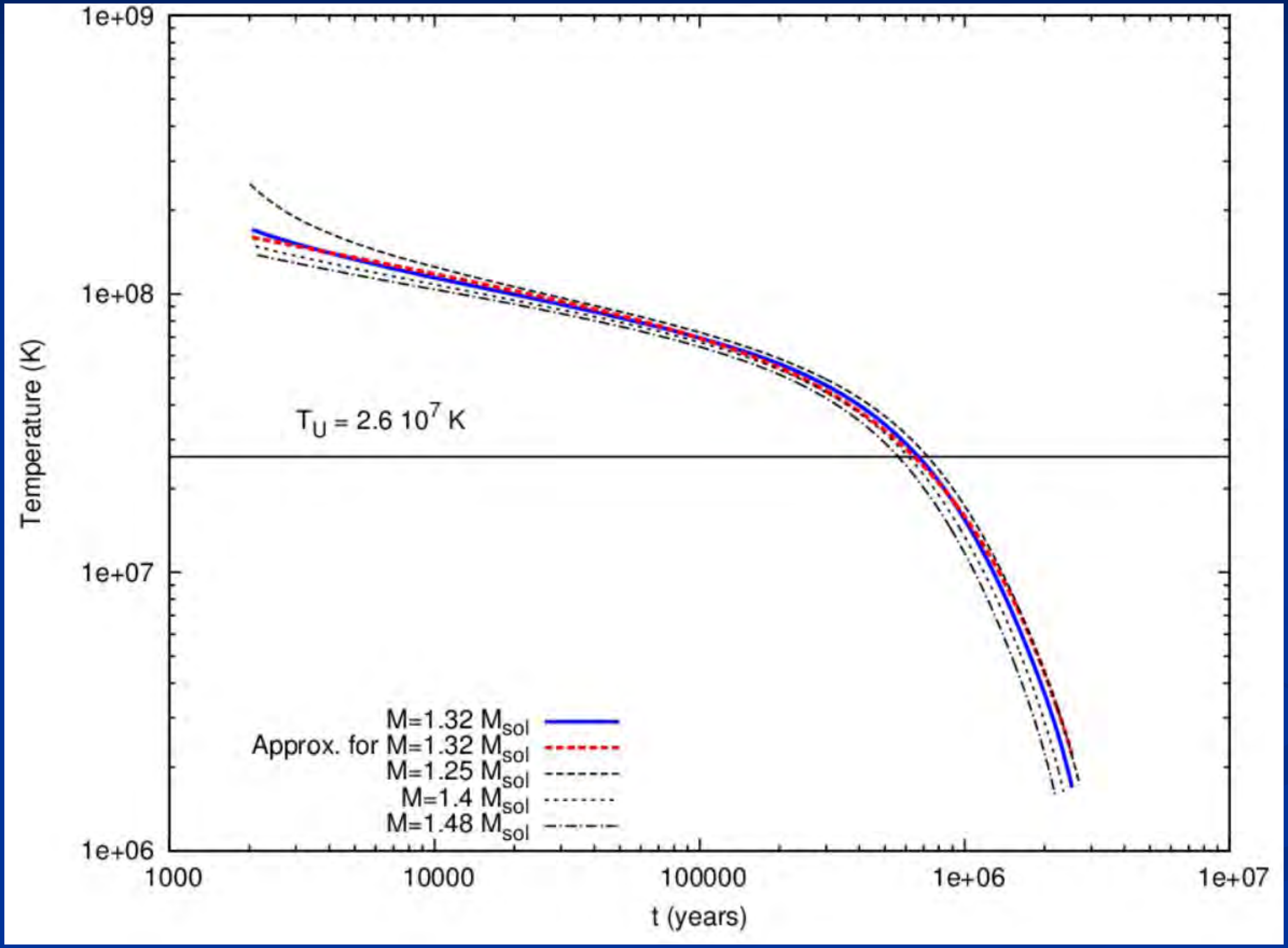


$$\tau_{\rm Hall} \approx \frac{4\pi e L^2 n_e}{cB}$$

$$L \approx H = P(\rho)/(\rho g)$$

Igoshev, Popov (in progress)

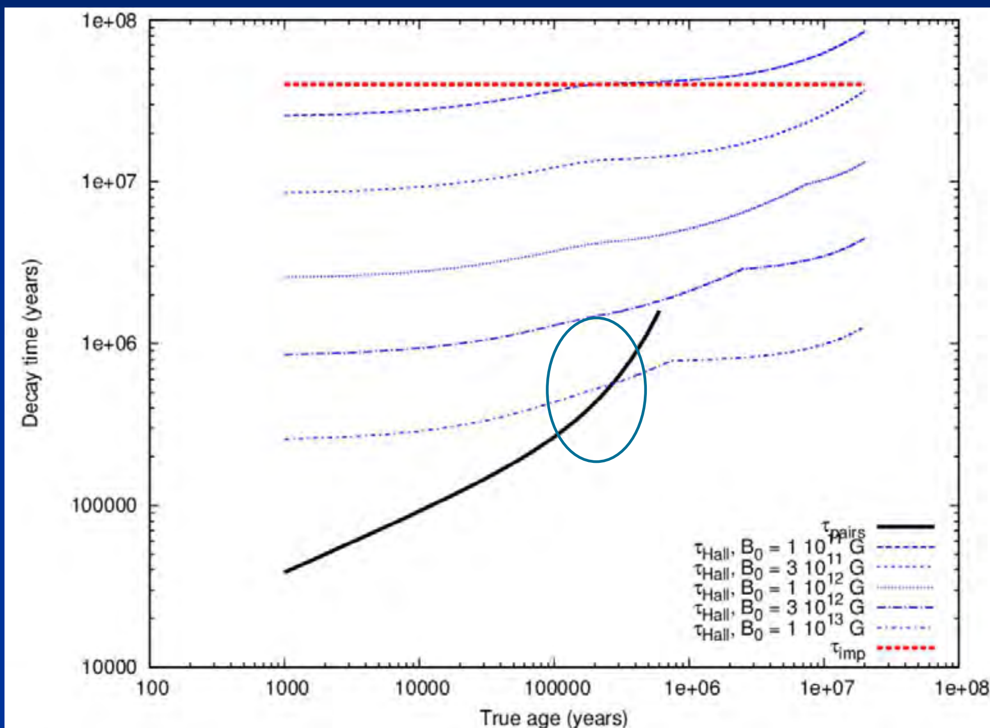
Thermal evolution



Calculations are made by Shternin et al.

We fit the numerical results to perform a population synthesis of radio pulsars with decaying field.

Different decay time scales



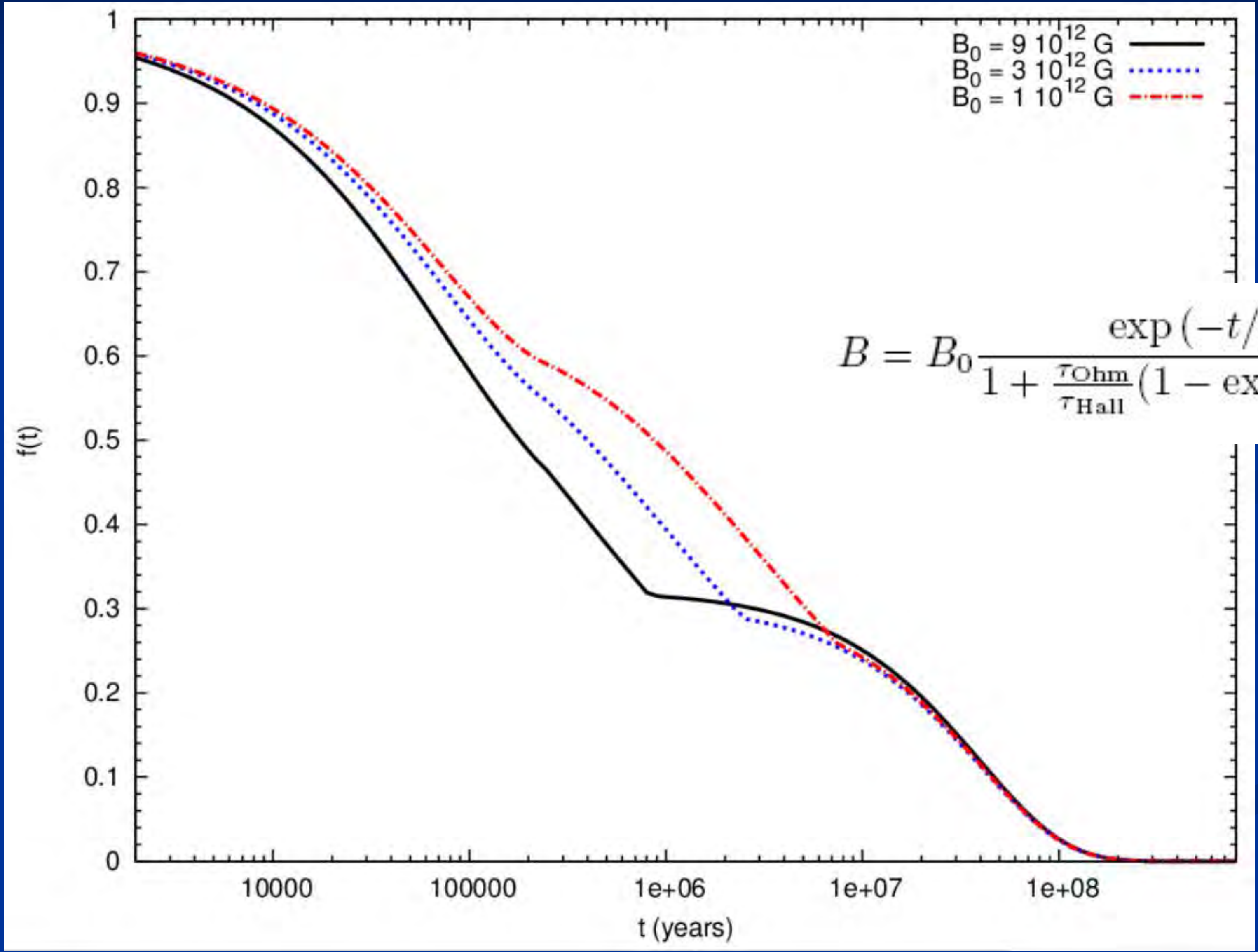
In the range of ages interesting for us the Hall rate is about the same value as the rate of Ohmic dissipation due to phonons.

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

$$\tau_{\rm imp} = 5.7 \frac{\rho_{14}^{5/3}}{Q} \left(\frac{Z}{30}\right) \left(\frac{Y_e}{0.05}\right)^{1/3} \left(\frac{Y_n}{0.8}\right)^{10/3} \times$$
$$\times \left(\frac{f}{0.5}\right)^2 \left(\frac{g_{14}}{2.45}\right) \text{ Myrs,}$$

$$\tau_{\rm phonon} = 2.2 \frac{\rho_{14}^{15/6}}{T_8^2} \left(\frac{Y_e}{0.05}\right)^{5/3} \left(\frac{Y_n}{0.8}\right)^{10/3} \times$$
$$\times \left(\frac{f}{0.5}\right)^2 \left(\frac{g_{14}}{2.45}\right)^{-2} \text{ Myrs,}$$

Magnetic field evolution

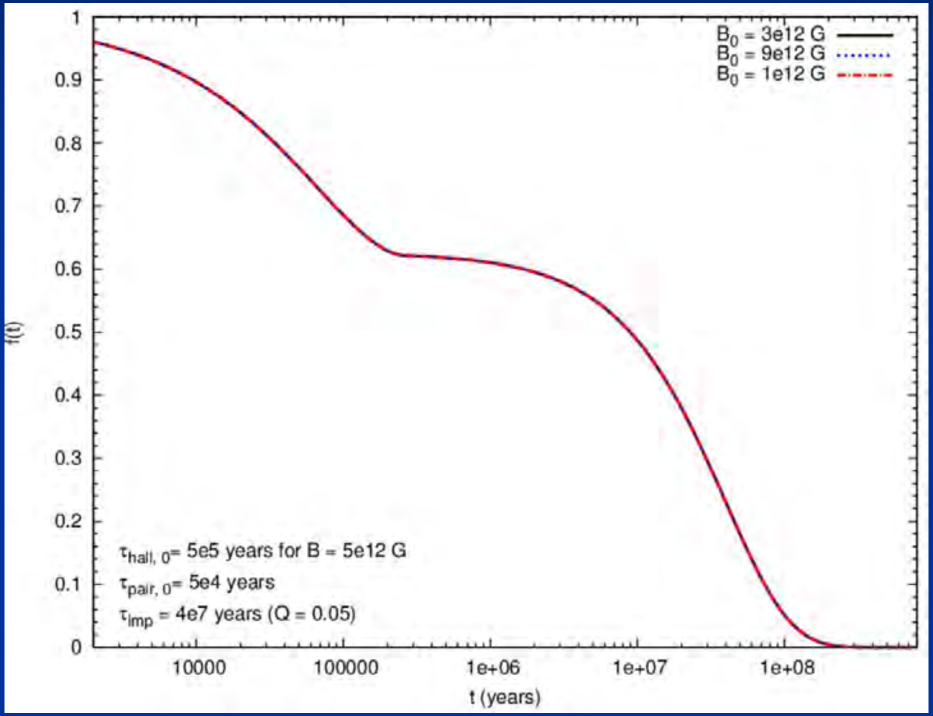


All inclusive:
- Hall
- Phonons
- Impurities

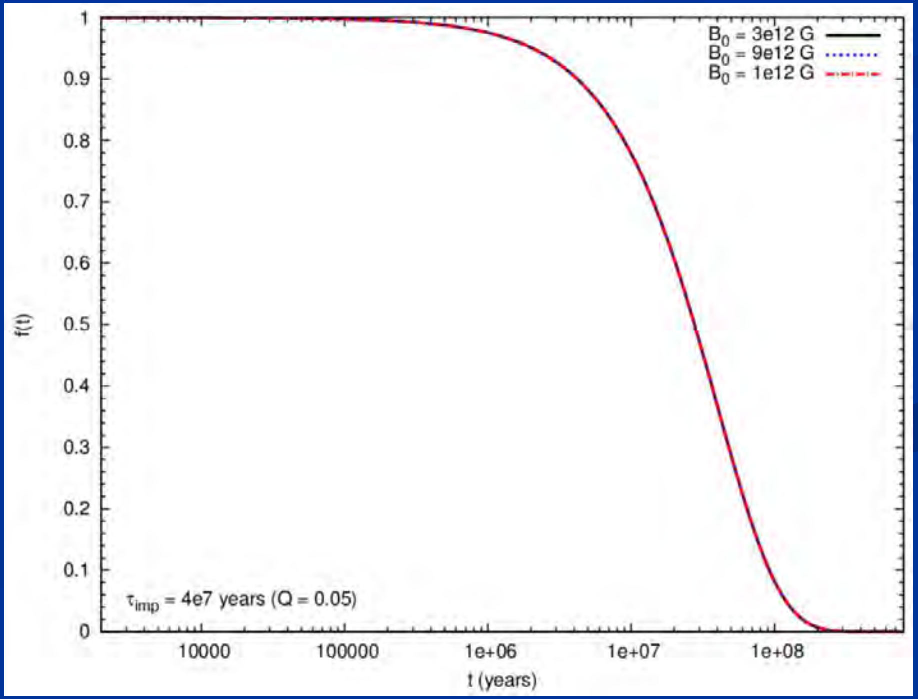
$$B = B_0 \frac{\exp\left(-t/\tau_{\rm Ohm}\right)}{1 + \frac{\tau_{\rm Ohm}}{\tau_{\rm Hall}}\left(1 - \exp\left(-t/\tau_{\rm Ohm}\right)\right)}$$

Igoshev, Popov (in progress)

Only Ohmic decay

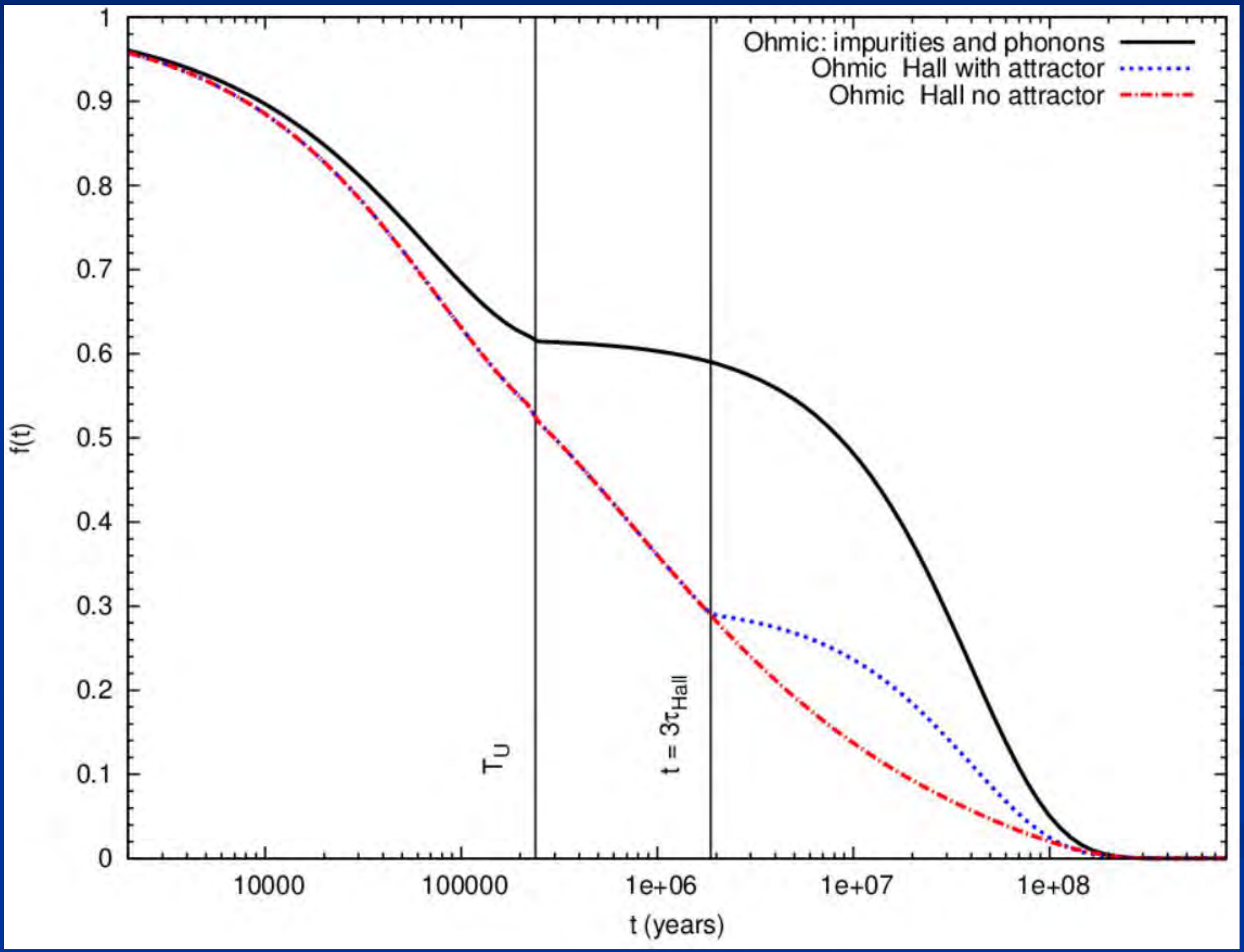


Here the Hall cascade is switched off



In one figure we have Ohmic decay only due to impurities, on another one – phonons are added.

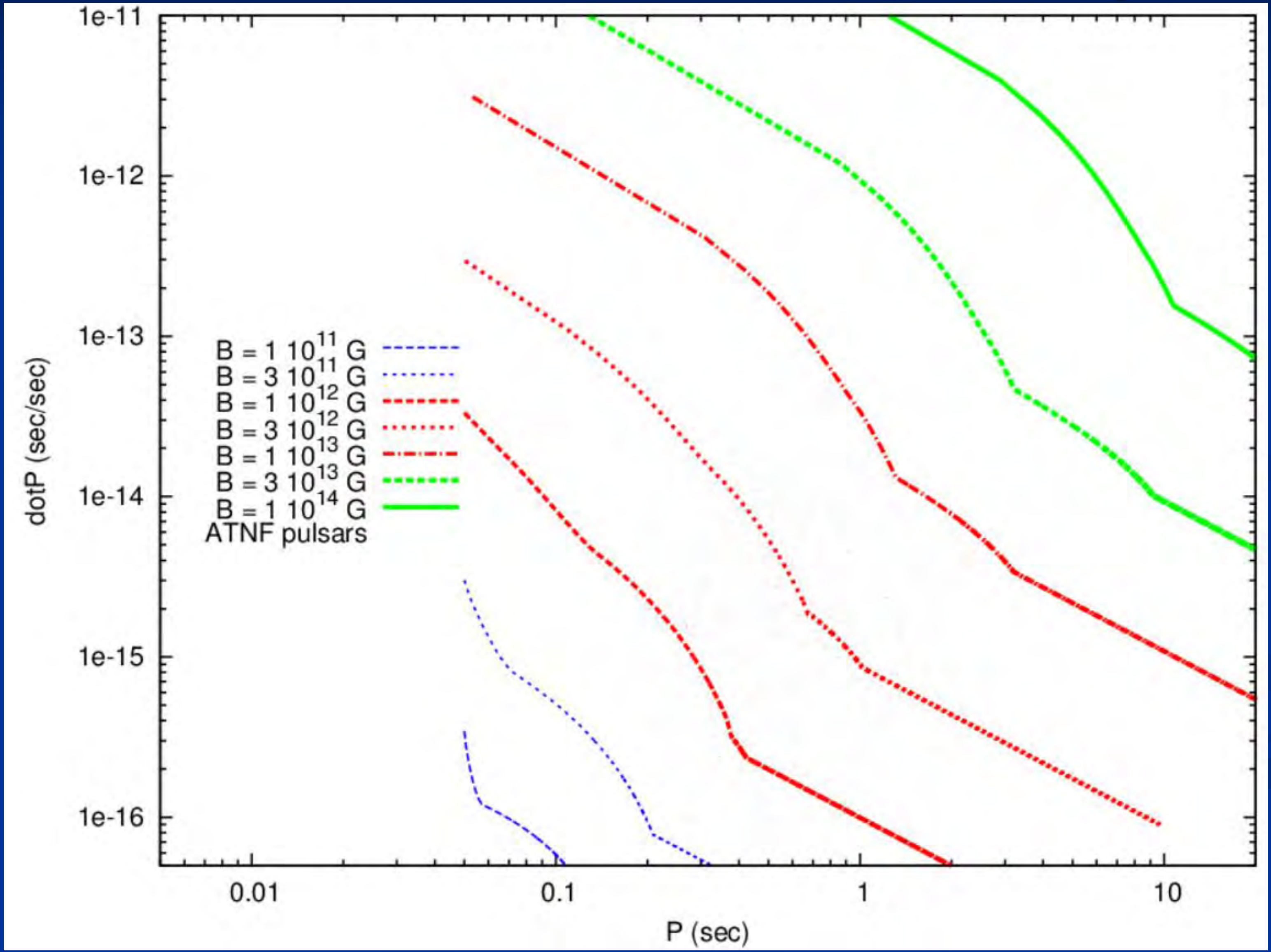
Comparison of different options



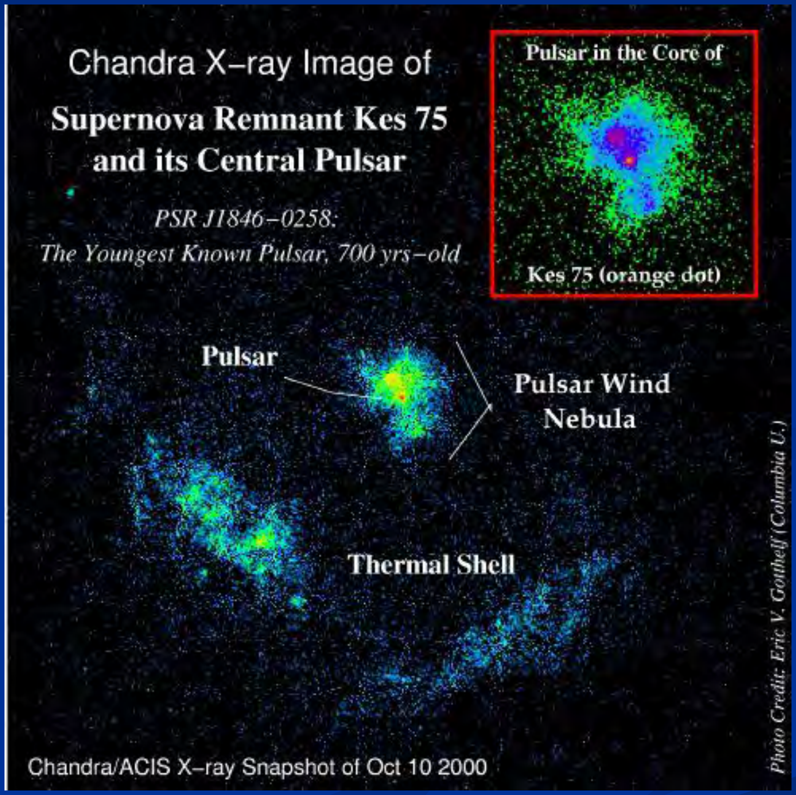
We think that in the range ~$10^5 - 10^6$ yrs we see mostly Ohmic decay, which then disappears as NSs cool down below the critical T.

Igoshev, Popov (in progress)

Evolution with field decay



PSRs in SNRs



See a review on NSs in SNRs in 1011.3731

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

Popov, Tutolla arXiv: 1204.0632, 1206.2819

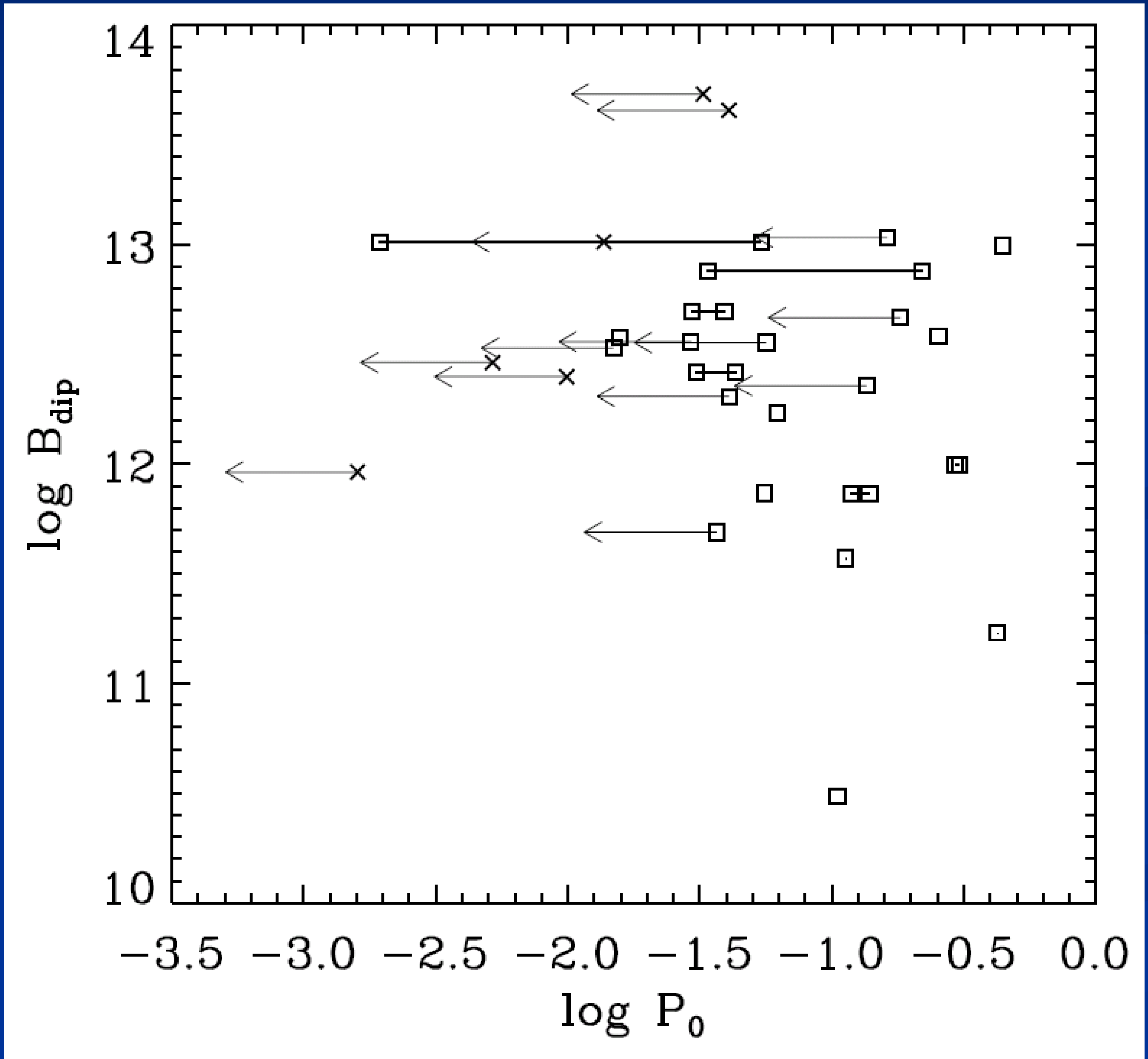
Table 2. Spin parameters of PSRs in the sample

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

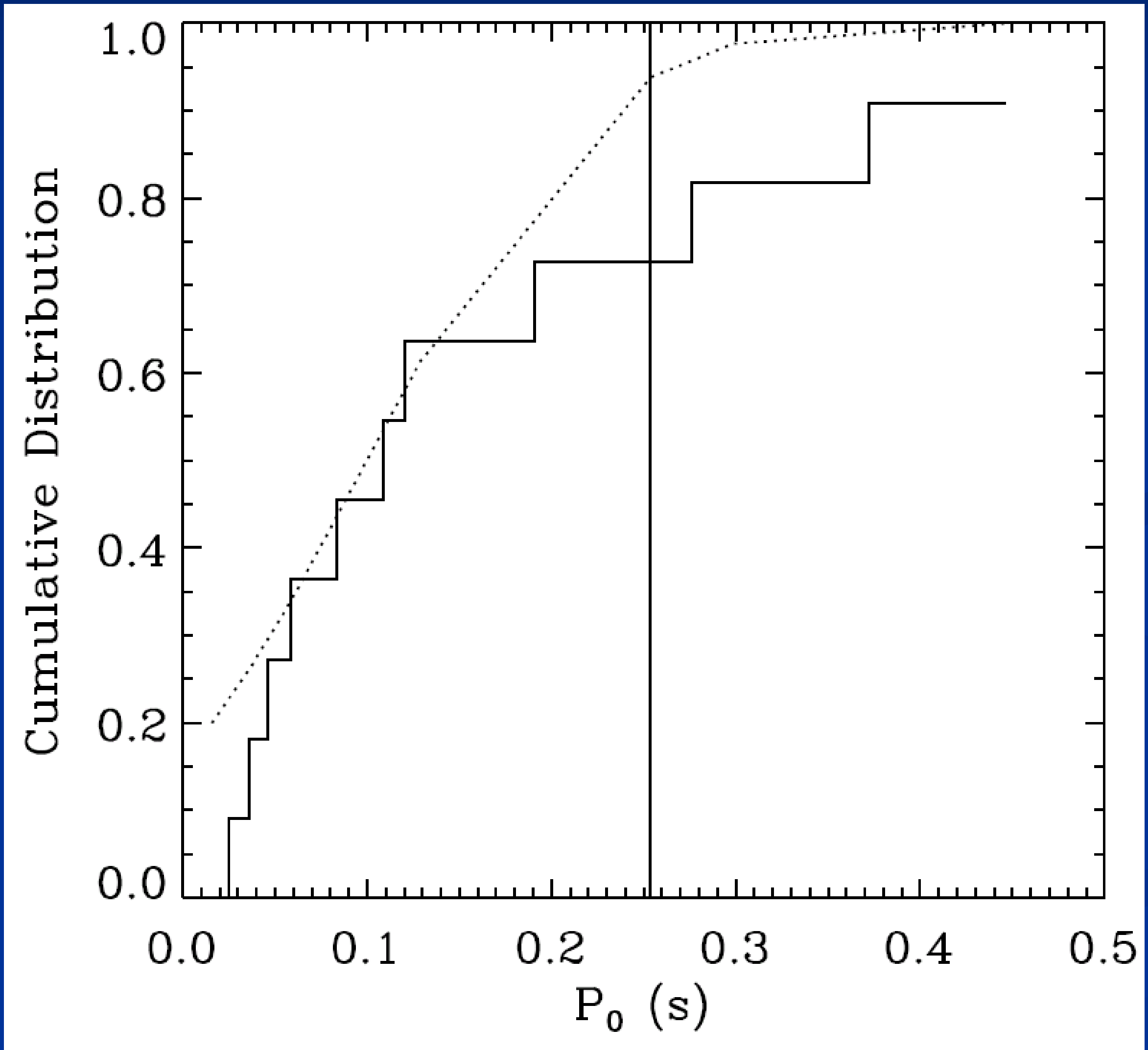


All presented estimates are made for standard assumptions:
n=const=3.
So, field is assumed to be constant, as well as the angle between spin and magnetic axis.

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

arXiv: 1204.0632, 1206.2819

Checking gaussian



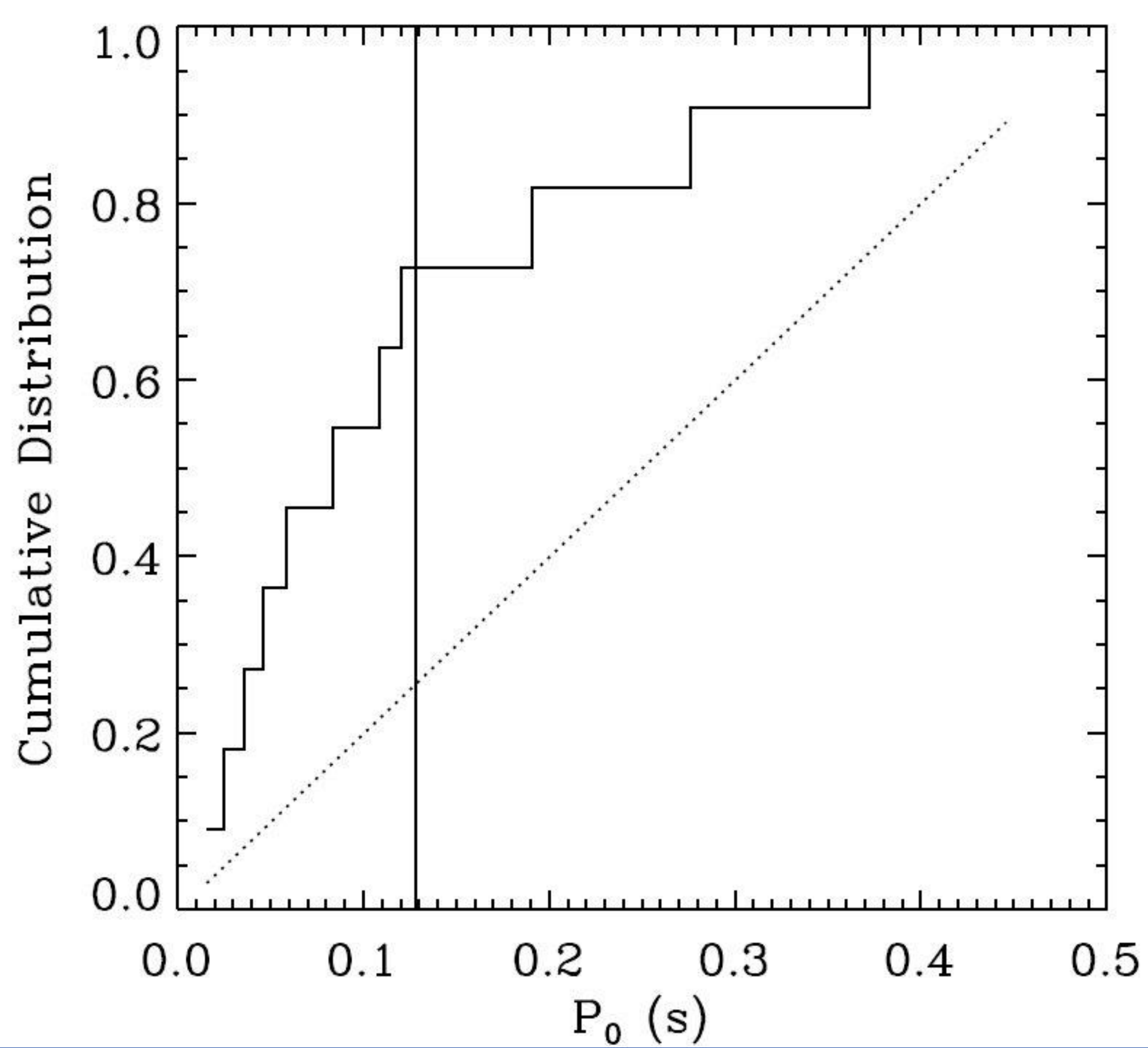
The data we have is not enough to derive the shape of the P_0 distribution.
However, we can exclude very wide and very narrow distributions, and also we can check if some specific distributions are compatible with our results.

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 distribution

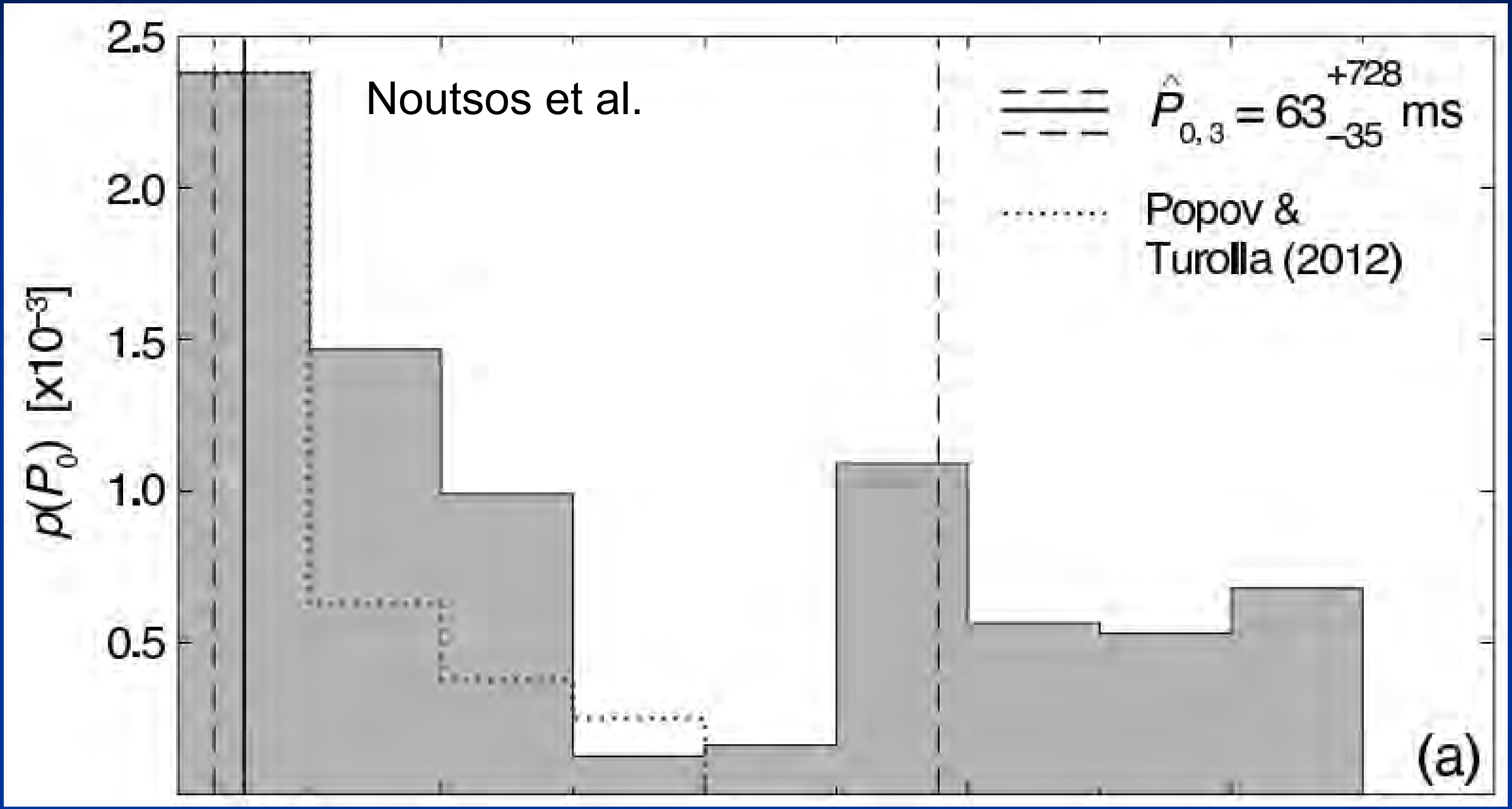


Flat between 0.001 and 0.5 s.

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

arXiv: 1204.0632, 1206.2819

Wide initial spin period distribution



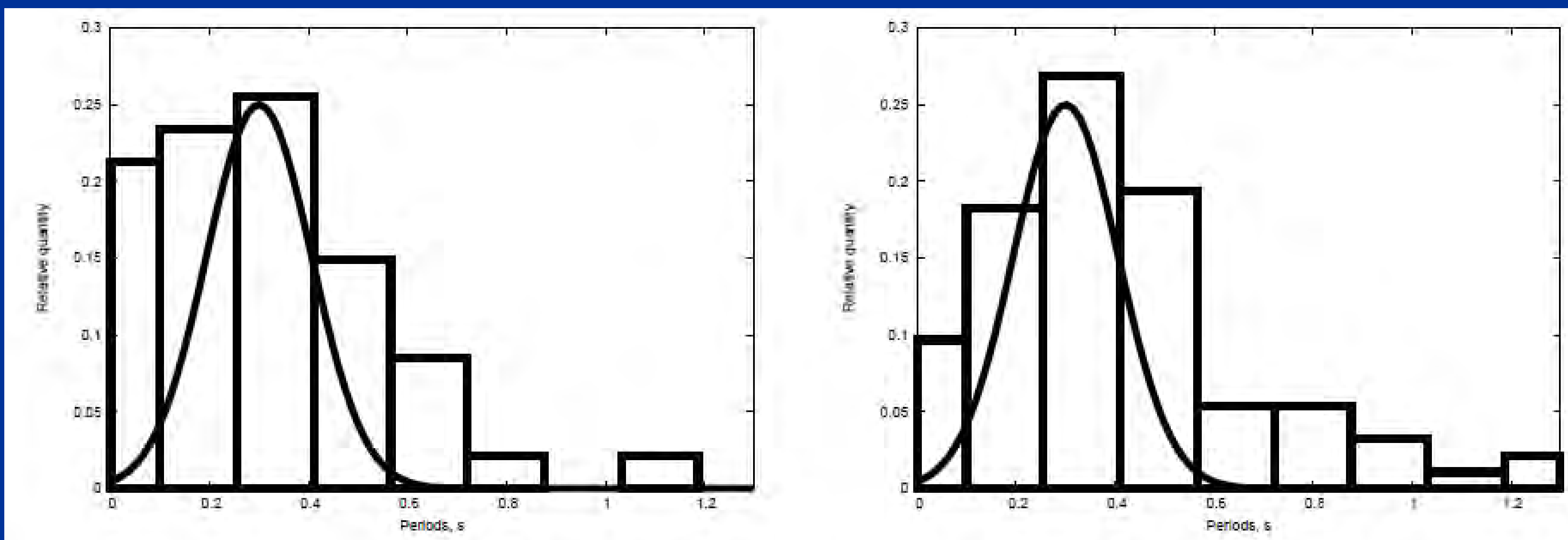
Based on kinematic ages. Mean age – few million years.
Note, that in Popov & Turolla (2012) only NSs in SNRs were used, i.e. the sample is much younger!
Can it explain the difference?

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_{decay}=5 Myrs.
$\langle P_0\rangle$=0.3 s, σ_P=0.15 s; $\langle \log B_0/[G]\rangle$=12.65, σ_B=0.55

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

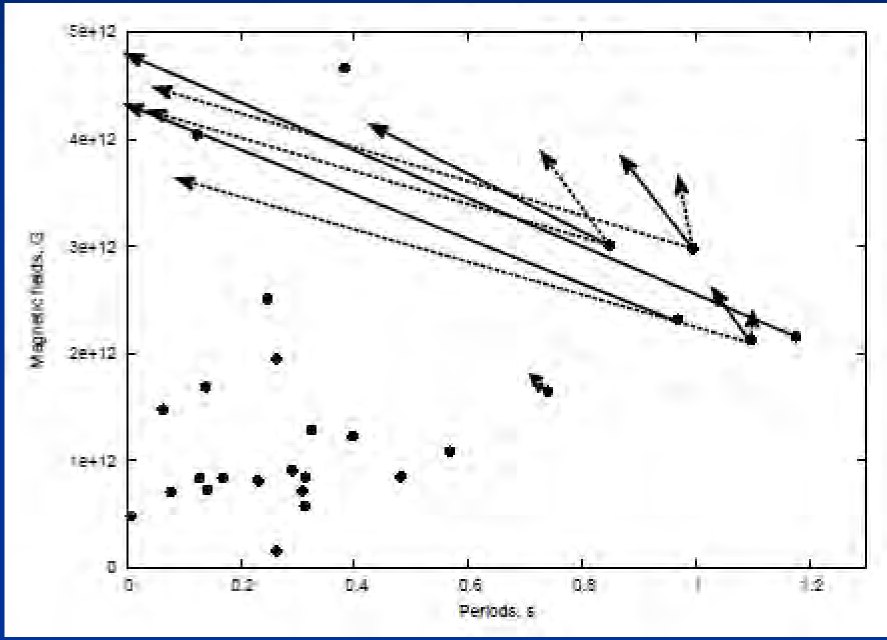


$\tau<10^7$ yrs, $10^5<t$

$10^5<t<10^7$ yrs

Igoshev, Popov MNRAS arXiv: 1303.5258

Real vs. reconstructed P_0

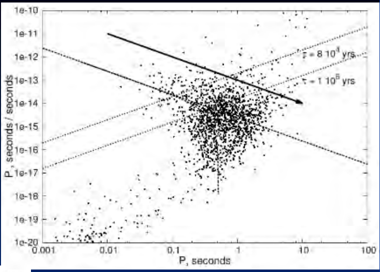


How much are
the reconstructed initial periods
changed due to not taking into account
the exponential field decay?

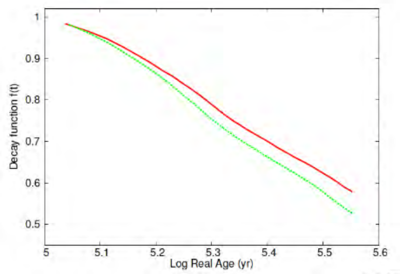
The rate of the field decay necessary
to explain this shift is in correspondence
with the radio pulsar data

Igoshev, Popov MNRAS arXiv: 1303.5258

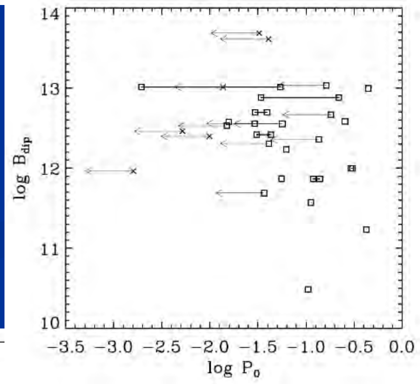
Conclusions



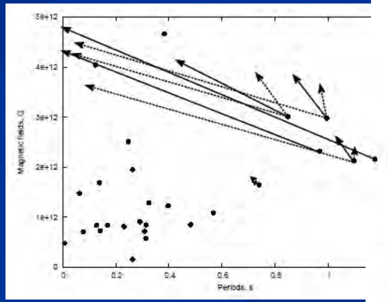
- We performed a modified pulsar current analysis to probe magnetic field decay in radio pulsars



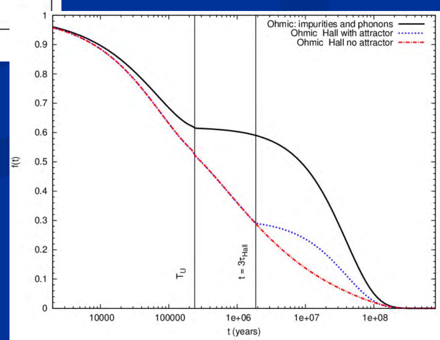
- We found that in the age range $8\ 10^4 < t < 3.5\ 10^5$ yrs the field decays by a factor ~2



- We collected the largest set of PSR+SNR pairs and derived initial spin periods for these NSs. Initial spin period distribution is in good correspondence with gaussian distributions with σ~0.1-0.2 sec and $<p_0>$~0.1-0.2 sec



- We demonstrate that claims of additional component in the p_0-distribution by Noutsos et al. can be explained by moderate field decay



- We test if the uncovered decay is mainly due to the Hall cascade and is stopped by the Hall attractor, or it is due to the Ohmic dissipation on phonons, and is stopped due to cooling of NSs.