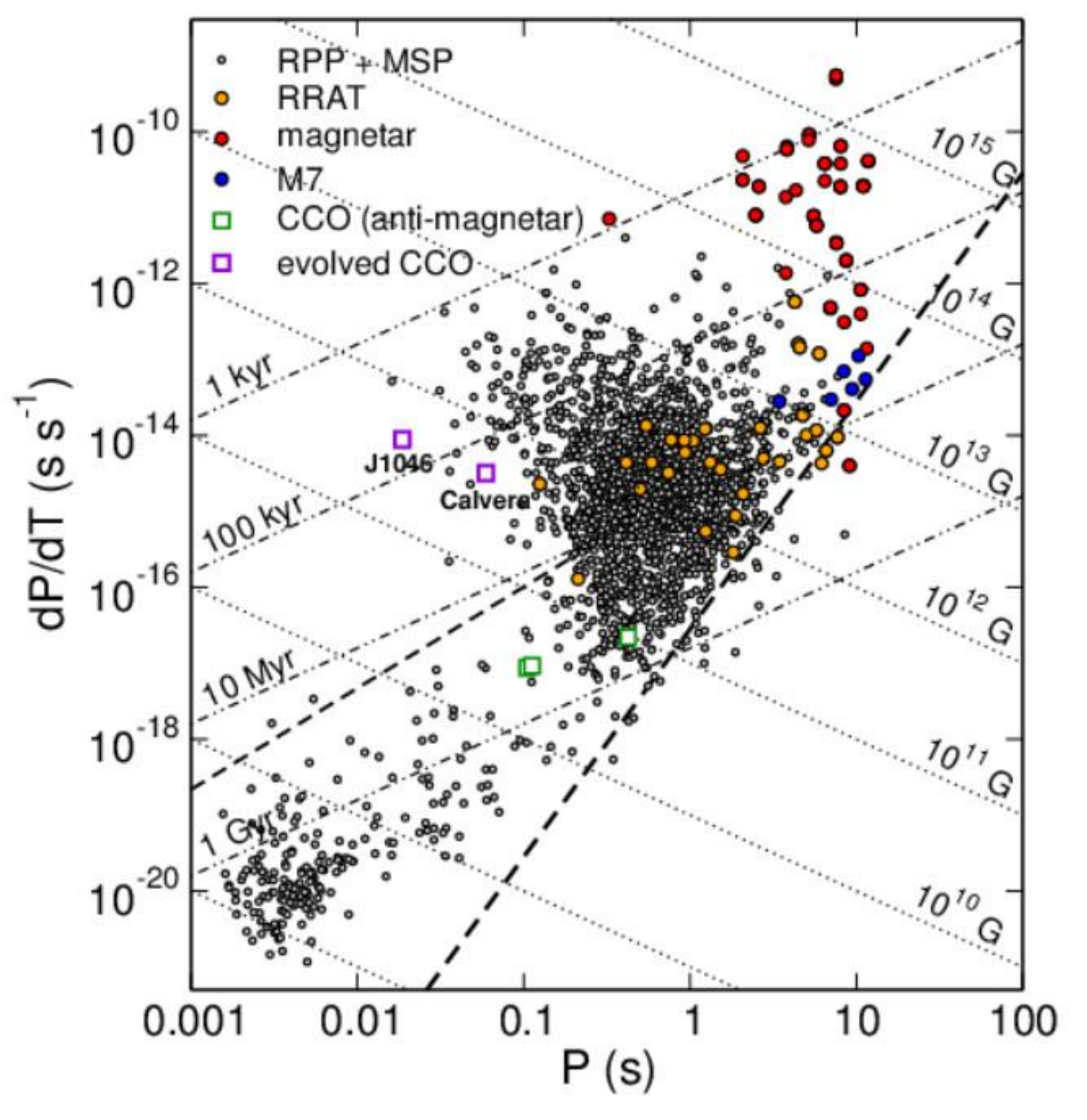
LIFE OF NEUTRON STARS WITH EVOLVING MAGNETIC FIELD

Sergei Popov

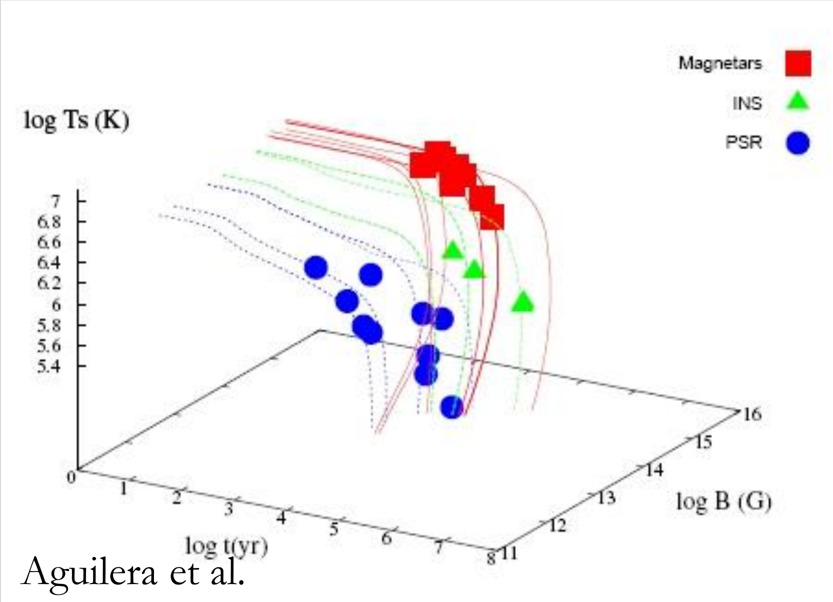
Diversity of neutron stars

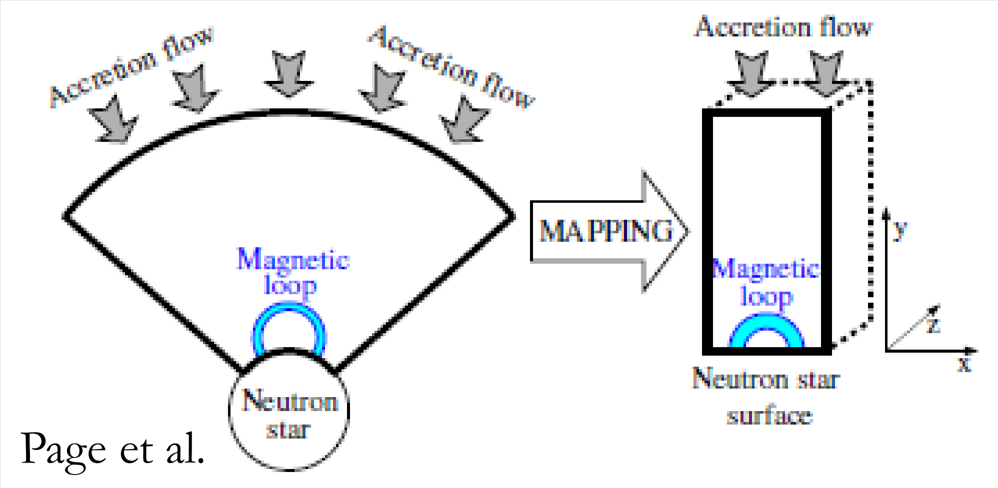


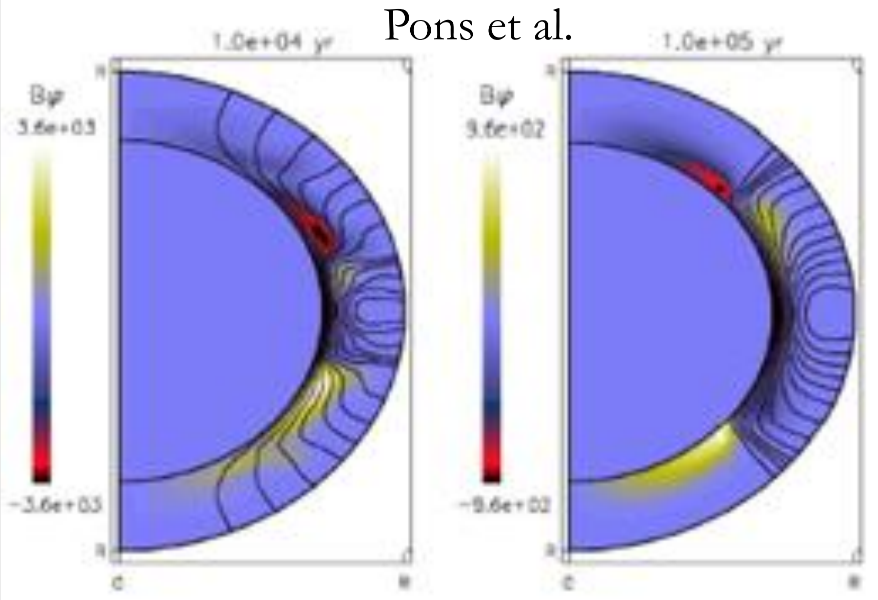
Pires et al. 2015

During last ~10 years
many attempts
have been made
to build a model of
“GRAND UNIFICATION
FOR NEUTRON STARS”.

Main ingredients of a unified model: magnetic field evolution



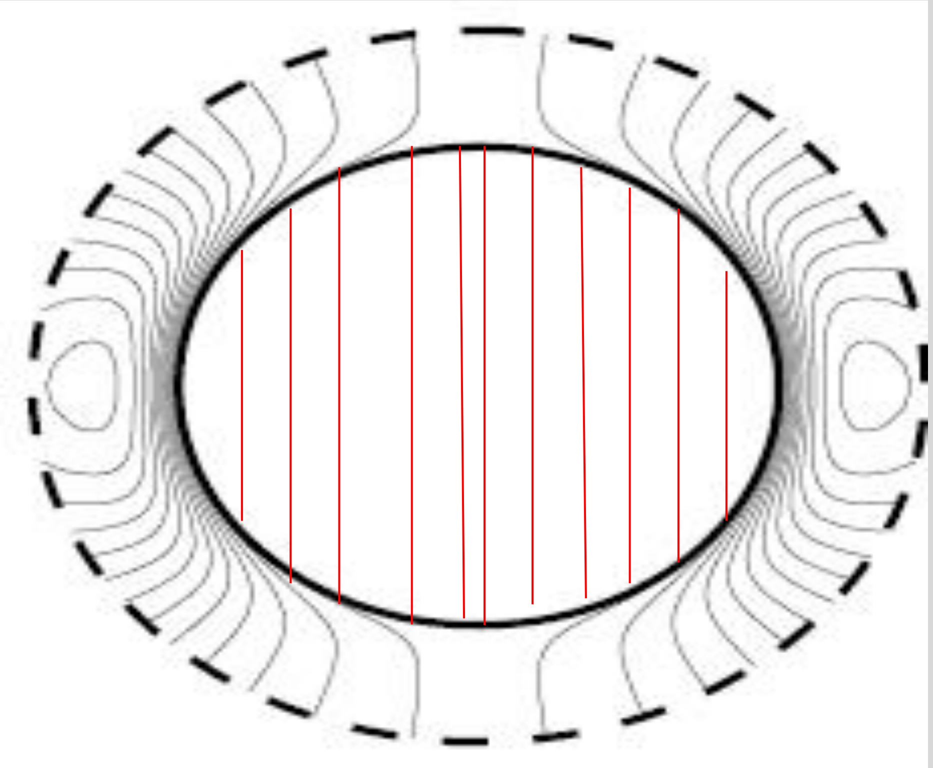




- Field decay
  - Emerging magnetic field
    - Magnetic field topology

Magnetic field decay

Magnetic fields of NSs are expected to decay due to decay of currents which support them.



Crustal field of core field?

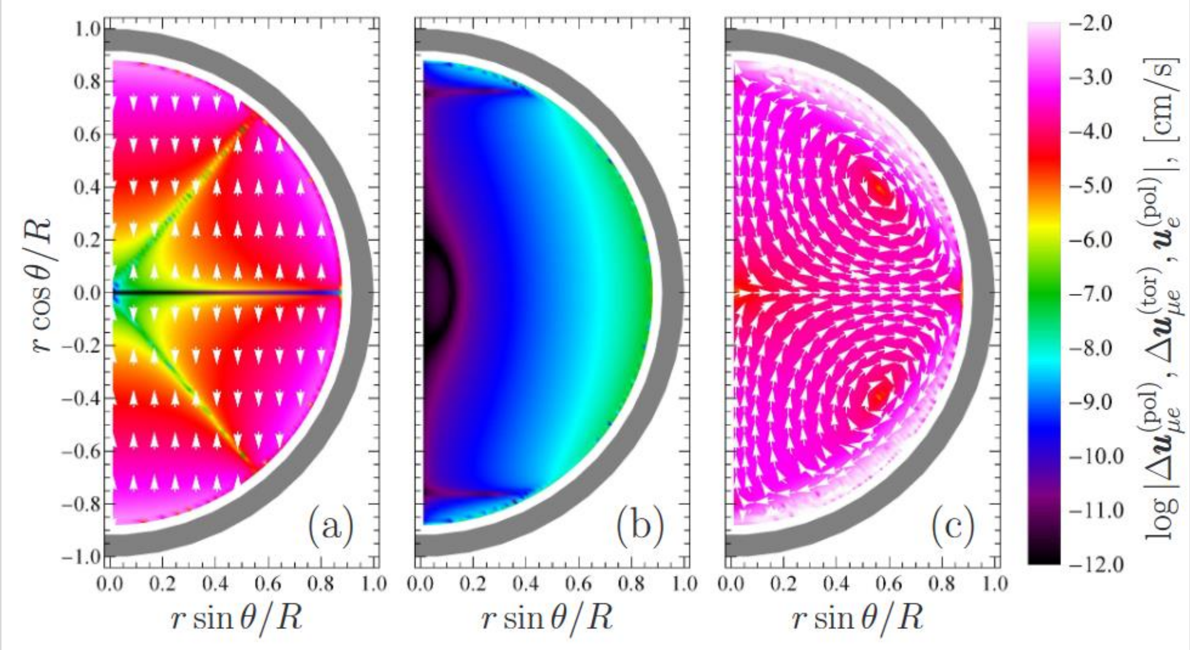
It is easy to decay in the crust.

In the core the filed is in the form
of superconducting vortices.
They can decay only when they are
moved into the crust (during spin-down).

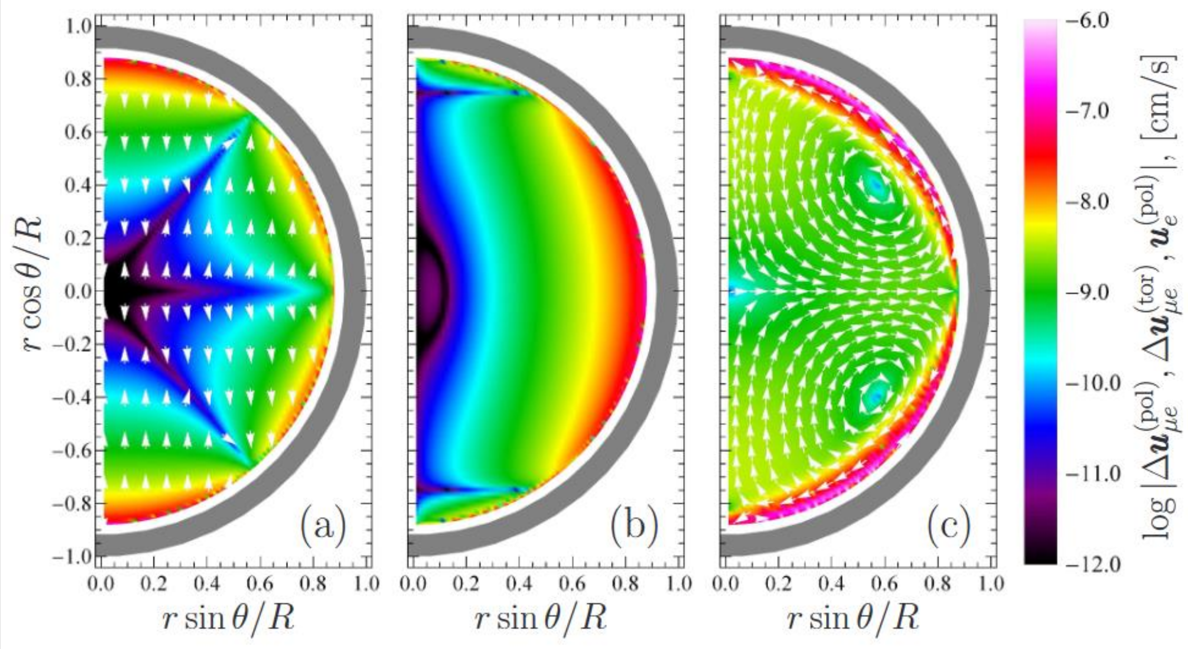
Still, in most of models strong fields decay.

Field evolution in the core

2010.07673



Panels (a) and (b) present, respectively, poloidal and toroidal components of the relative velocity of muons and electrons.
Panel (c) presents poloidal component of the velocity of electrons.
The homogeneous magnetic field is directed upwards.



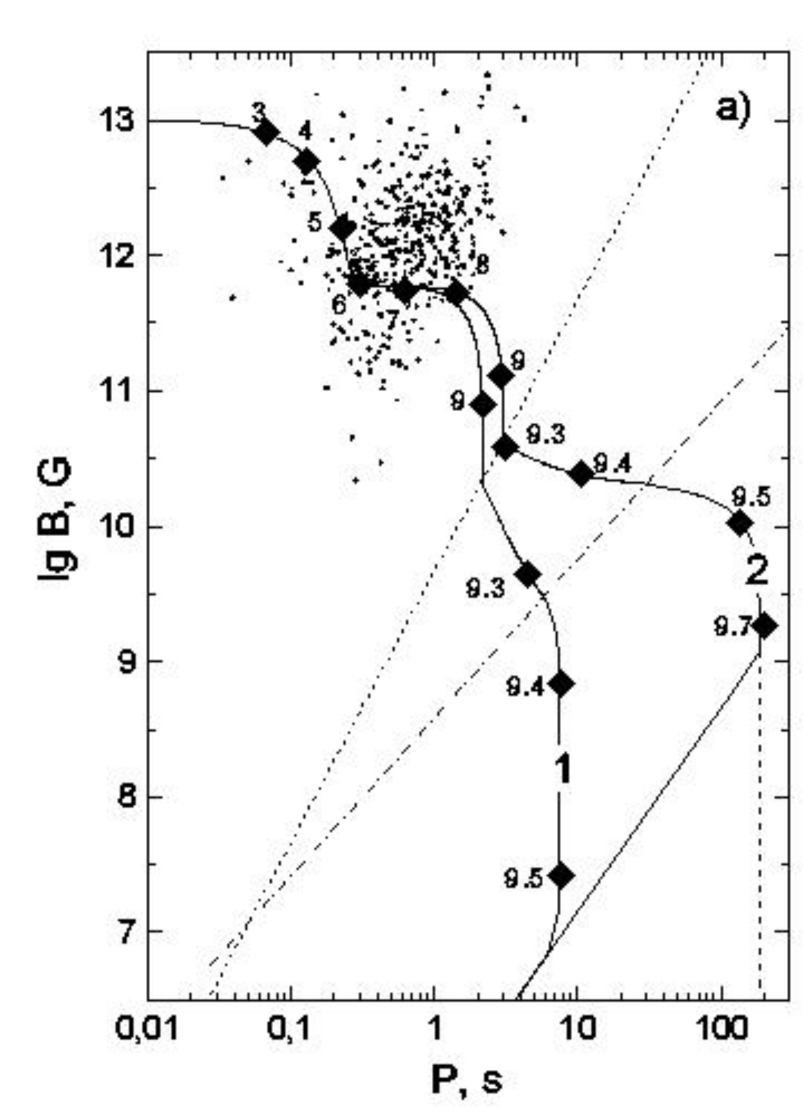
Left figure – before the field is re-arranged.
Right – after. Then the field evolves slower.

$$\tau_1 \sim \frac{L}{V_L} \sim \frac{\tau}{C} \sim \frac{3\times10^8}{C}\frac{L_6^2}{H_{c1,15}}\ \text{yr.}$$

$$C \sim 10,$$

Period evolution with field decay

astro-ph/9707318



An evolutionary track of a NS is very different in the case of decaying magnetic field.

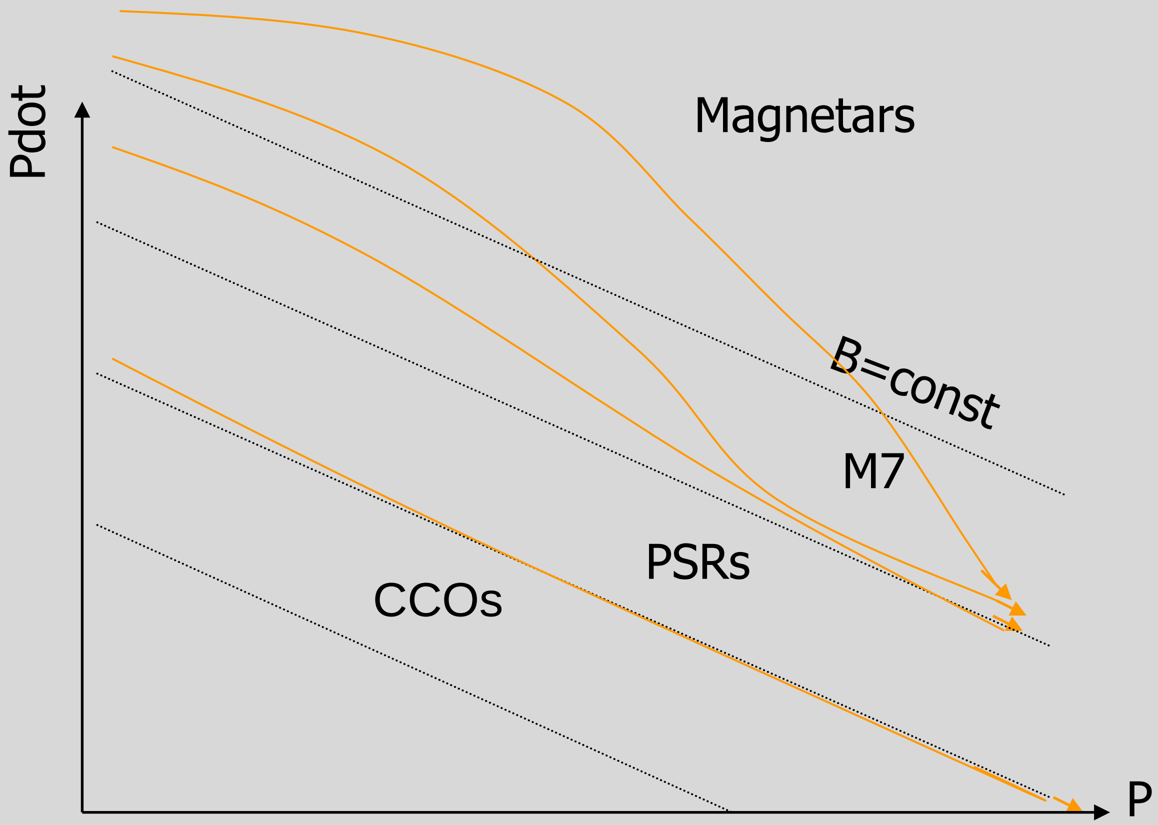
The most important feature is slow-down of spin-down.
Finally, a NS can nearly freeze at some value of spin period.

Several episodes of relatively rapid field decay can happen.

Number of isolated accretors can be both decreased or increased in different models of field decay.
But in any case their average periods become shorter and temperatures lower.

Magnetars, field decay, heating

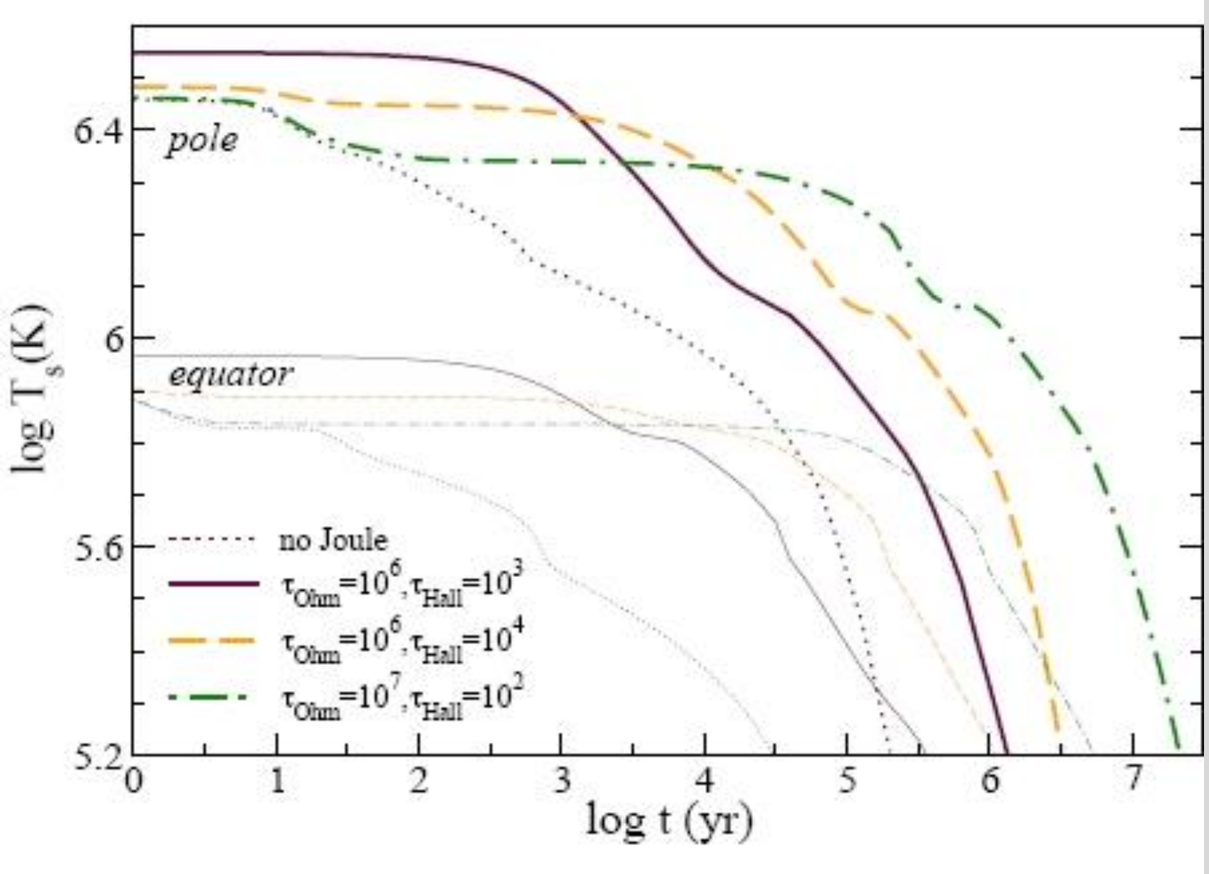
A model based on field-dependent decay of the magnetic moment of NSs can provide an evolutionary link between different populations (Pons et al.).



Magnetic field decay vs. thermal evolution

Magnetic field decay can be an important source of NS heating.

arxiv:0710.0854 (Aguilera et al.)



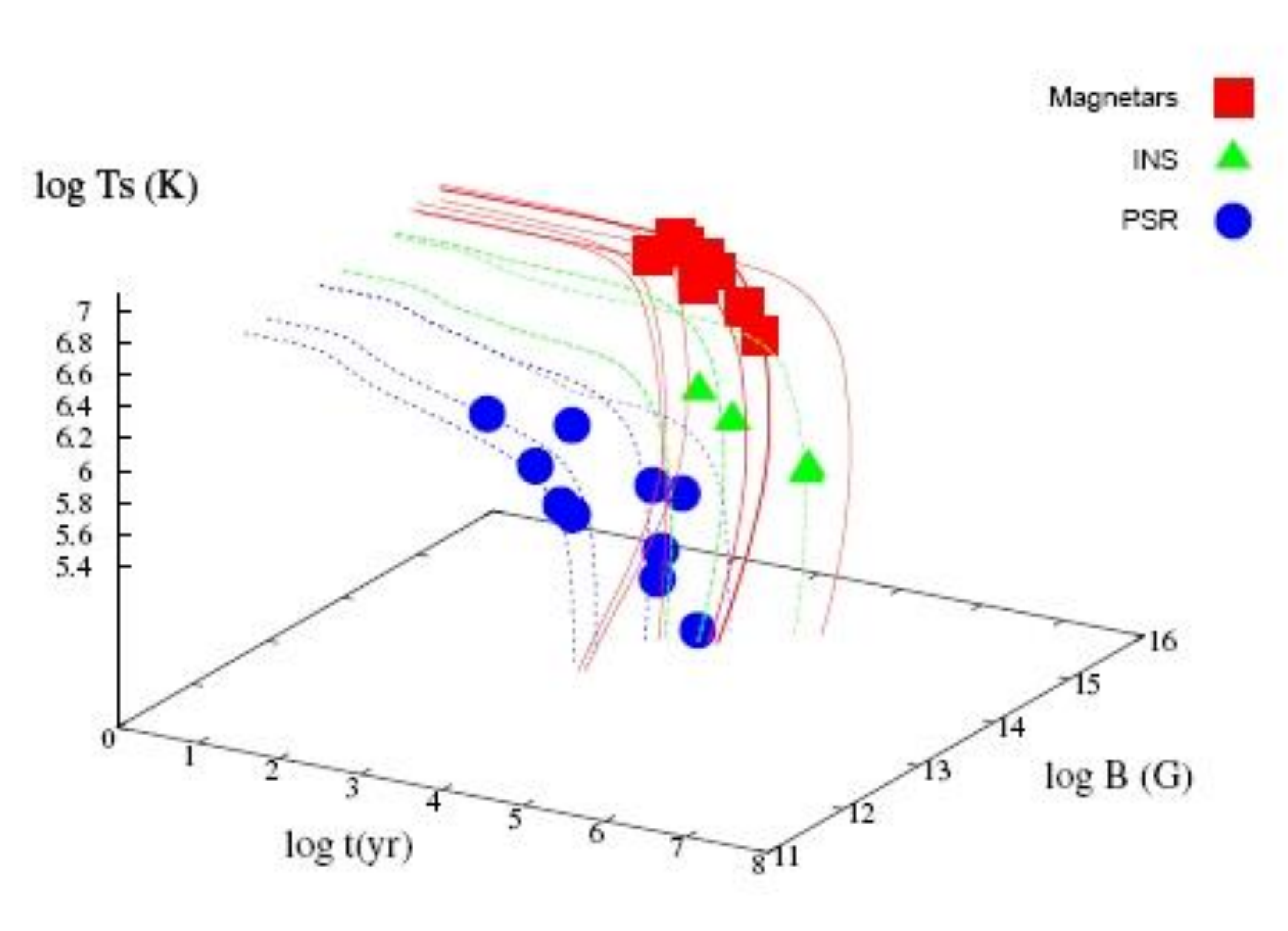
Ohm and Hall decay

Heat is carried by electrons.
It is easier to transport heat along field lines. So, poles are hotter.
(for light elements envelope the situation can be different).

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

Joule heating for everybody?

arXiv: 0710.4914 (Aguilera et al.)



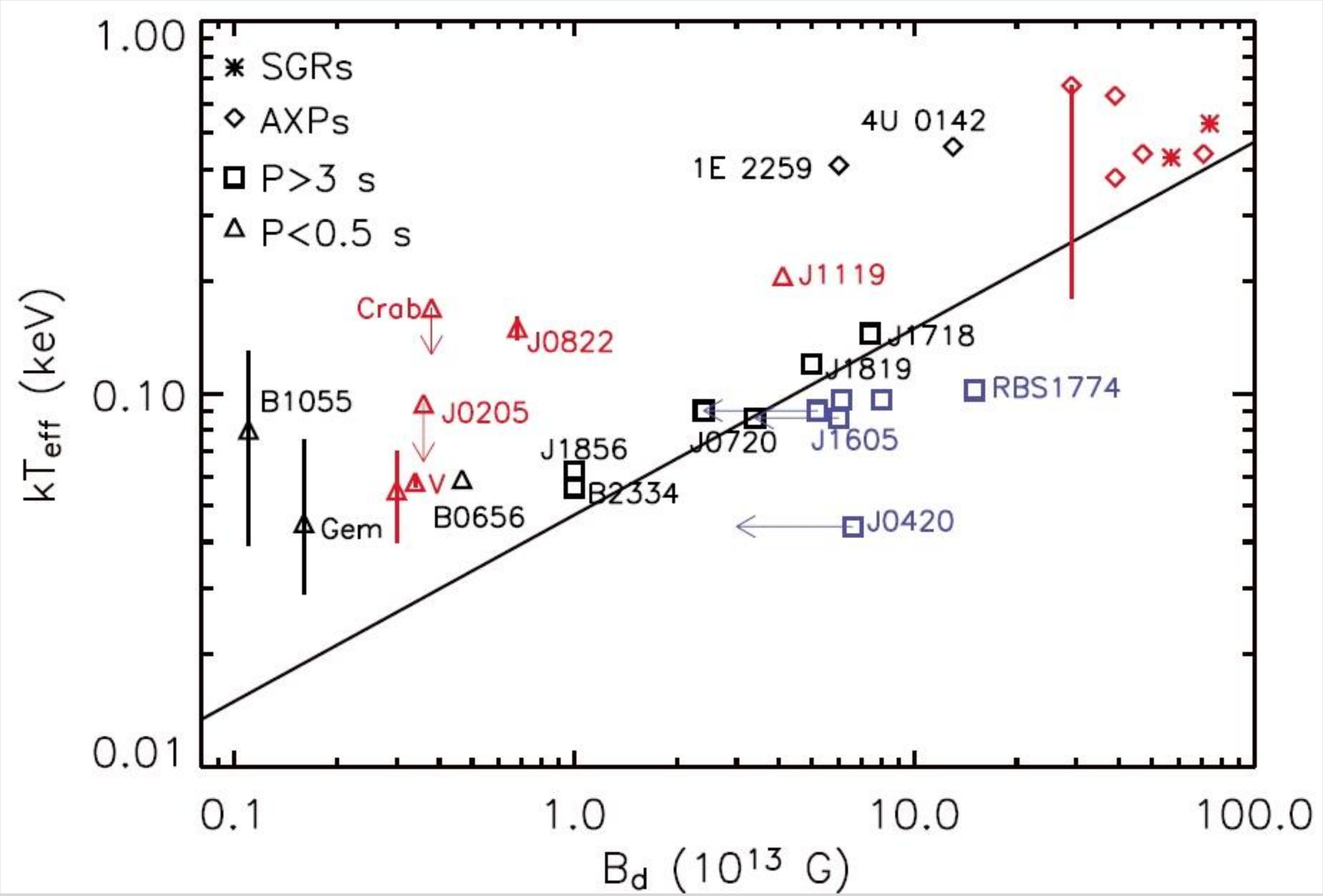
It is important to understand the role of heating by the field decay for different types of INS.

In the model by Pons et al. the effect is more important for NSs with larger initial B.

Note, that the characteristic age estimates (P/2 Pdot) are different in the case of decaying field!

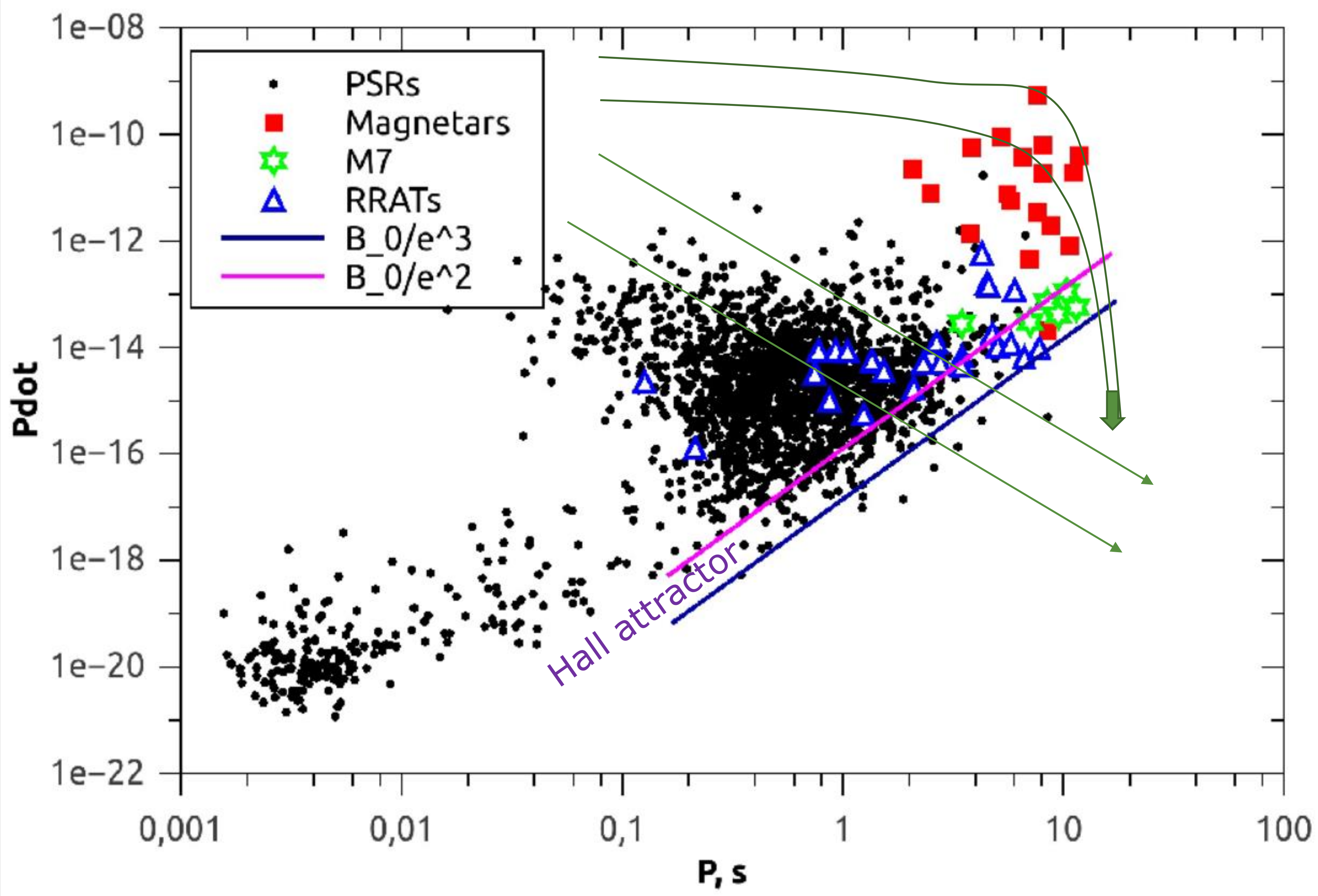
Magnetic field vs. temperature

astro-ph/0607583



The line marks balance between heating due to the field decay and cooling. It is expected that a NS evolves downwards till it reaches the line, then the evolution proceeds along the line: $T_{eff} \sim B_d^{1/2}$

Selection effects are not well studied here.
A kind of population synthesis modeling is welcomed.



PSRs
Magnetars
M7
RRATs
B_0/e^3
B_0/e^2
Hall attractor
Pdot
P, s
1e−08
1e−10
1e−12
1e−14
1e−16
1e−18
1e−20
1e−22
0,001
0,01
0,1
1
10
100

Hall cascade and field evolution

$$\frac{\partial B}{\partial t} = -c\nabla \times E,$$

advection Ohm Hall

$$E = -\frac{1}{c}v \times B + \frac{J}{\sigma} + \frac{J \times B}{n_e ec},$$

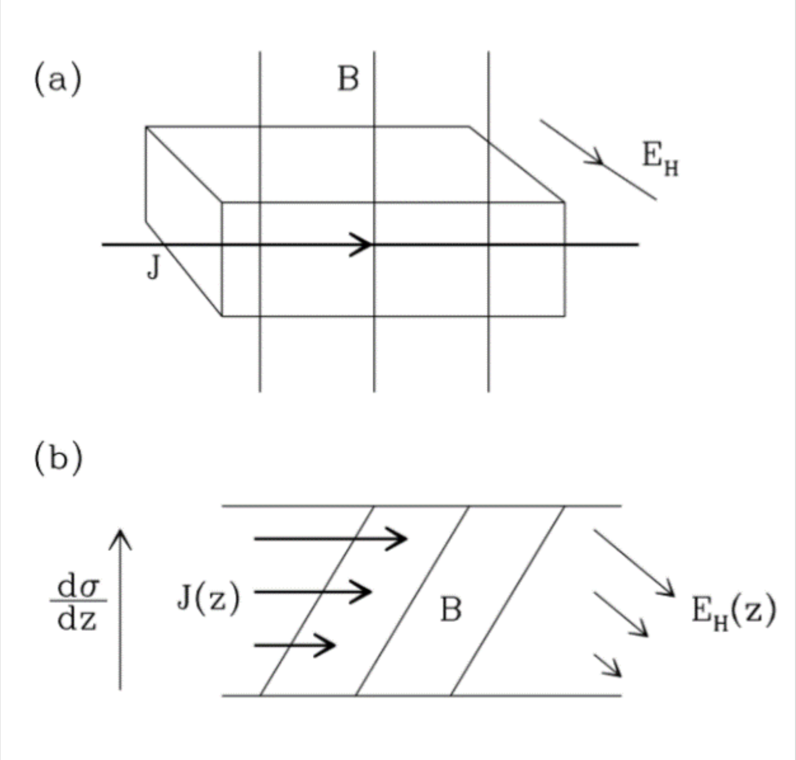
$$\tau_{\mathrm{Ohm}} = \frac{4\pi\sigma L^2}{c^2}.$$

$$J = (c/4\pi)(\nabla \times B)$$

With only Hall term we have:

$$\frac{\partial B}{\partial t} = -\nabla \times \left(\frac{J \times B}{n_e e}\right),$$

$$t_{\mathrm{Hall}} = \frac{n_e eL}{J} = \frac{4\pi n_e eL^2}{cB},$$



astro-ph/0402392

Characteristic timescales

$$\frac{dB_{\rm p}}{dt} = -\frac{B_{\rm p}}{\tau_{\rm Ohm}(T_{\rm crust})} - \frac{1}{B_0}\frac{B_{\rm p}^2}{\tau_{\rm Hall_0}}.$$

Aguilera et al. 2008

$$\tau_{\rm Hall} = \frac{4\pi e n_e L^2}{cB(t)},$$

$$\tau_{\rm Hall} = \tau_{\rm Hall,0}\frac{B_0}{B(t)}.$$

Hall time scale strongly depends on the current value of the field.

$$\tau_{\rm Ohm} = \frac{4\pi\sigma L^2}{c^2},$$

Ohmic decay depends on the conductivity

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\frac{c}{4\pi e}\nabla\times\left(\frac{\nabla\times\boldsymbol{B}}{n_e}\times\boldsymbol{B}\right) - \frac{c^2}{4\pi}\nabla\times\left(\frac{\nabla\times\boldsymbol{B}}{\sigma}\right).$$

$$\sigma = \frac{\sigma_{\rm Q}\sigma_{\rm ph}}{\sigma_{\rm Q}+\sigma_{\rm ph}}.$$

$$\tau_{\rm Ohm}^{-1} = \tau_{\rm Ohm,ph}^{-1} + \tau_{\rm Ohm,Q}^{-1}.$$

Resistivity can be due to

- Phonons
- Impurities

$$\sigma_Q = 4.4\times10^{25}{\rm s}^{-1}\left(\frac{\rho_{14}^{1/3}}{Q}\right)\left(\frac{Y_e}{0.05}\right)^{1/3}\left(\frac{Z}{30}\right),$$

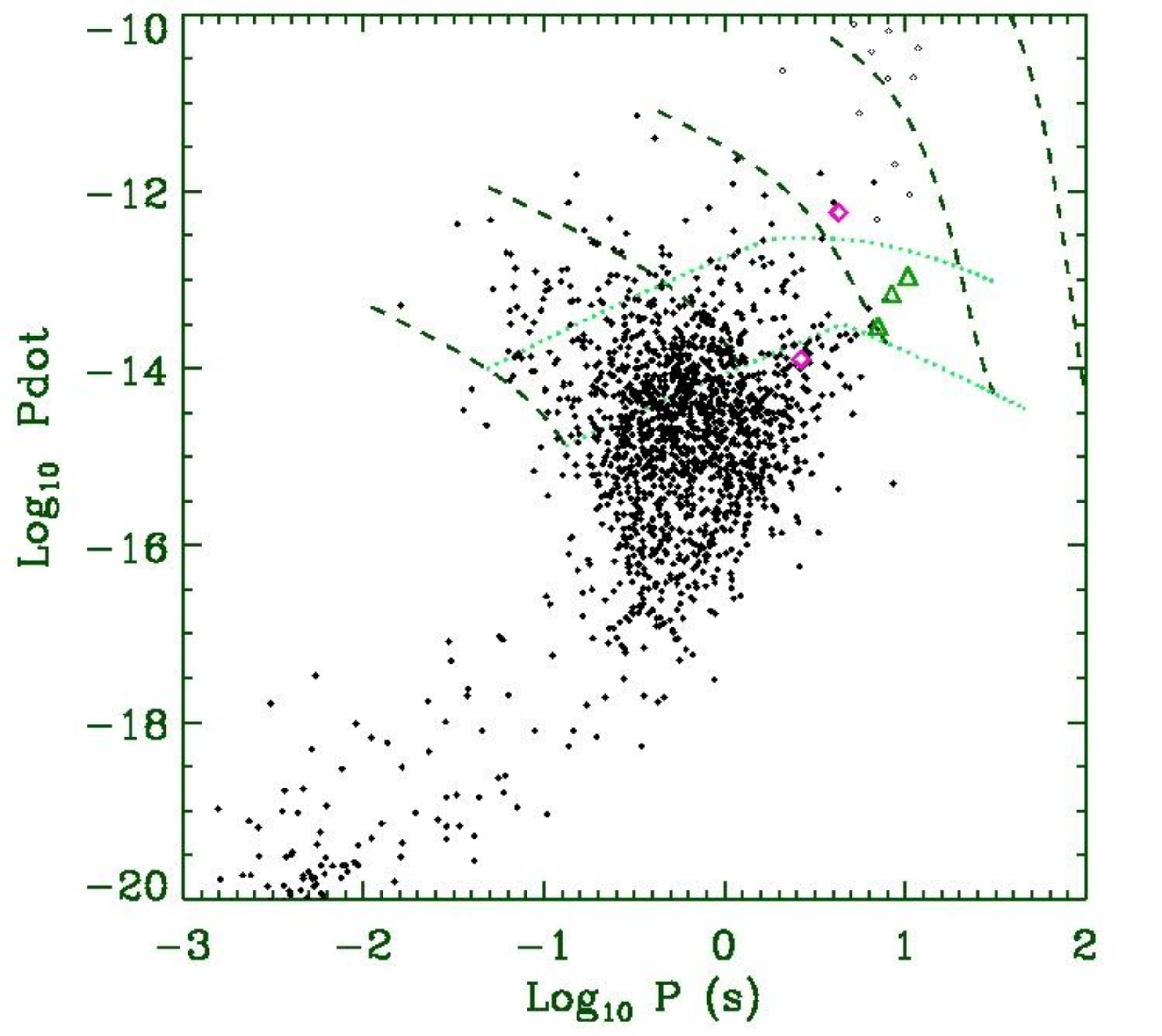
$$Q = n_{\rm ion}^{-1}\Sigma_i n_i\times(Z^2-\langle Z\rangle^2).$$

$$\sigma_{\rm ph} = 1.8\times10^{25}{\rm s}^{-1}\left(\frac{\rho_{14}^{7/6}}{T_8^2}\right)\left(\frac{Y_e}{0.05}\right)^{5/3},$$

See Cumming et al. 2004

P-Pdot diagram and field decay

Chashkina, Popov 2012. arXiv: 1112.1123



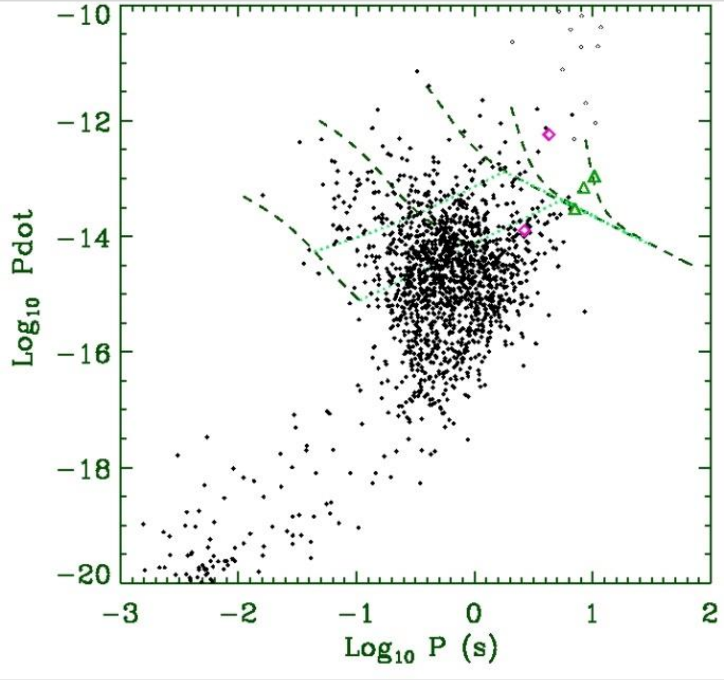
$$B = B_0 \frac{\exp\left(-t/\tau_{\rm Ohm}\right)}{1 + \frac{\tau_{\rm Ohm}}{\tau_{\rm Hall}}\left(1 - \exp\left(-t/\tau_{\rm Ohm}\right)\right)}$$

$\tau_{\rm Ohm}=10^6$ yrs

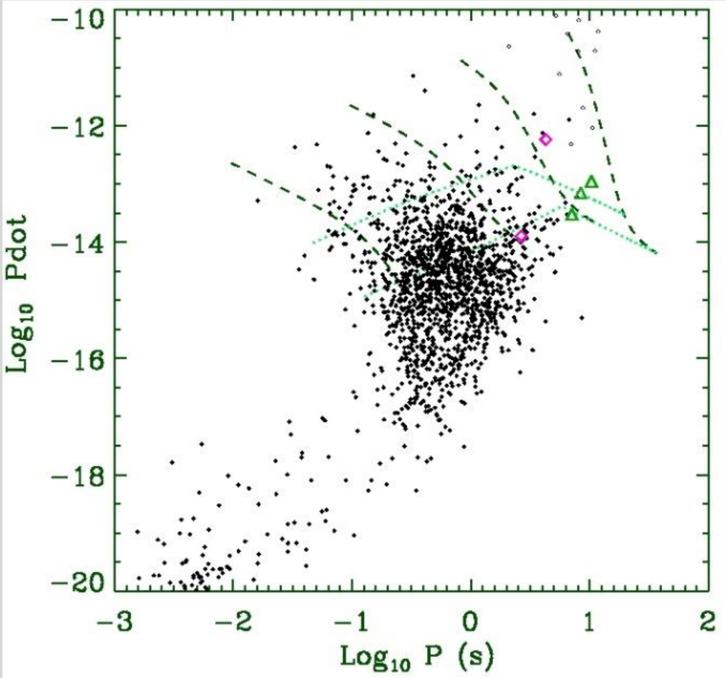
$\tau_{\rm Hall}=10^4/(B_0/10^{15}$ G) yrs

Decay parameters and P-Pdot

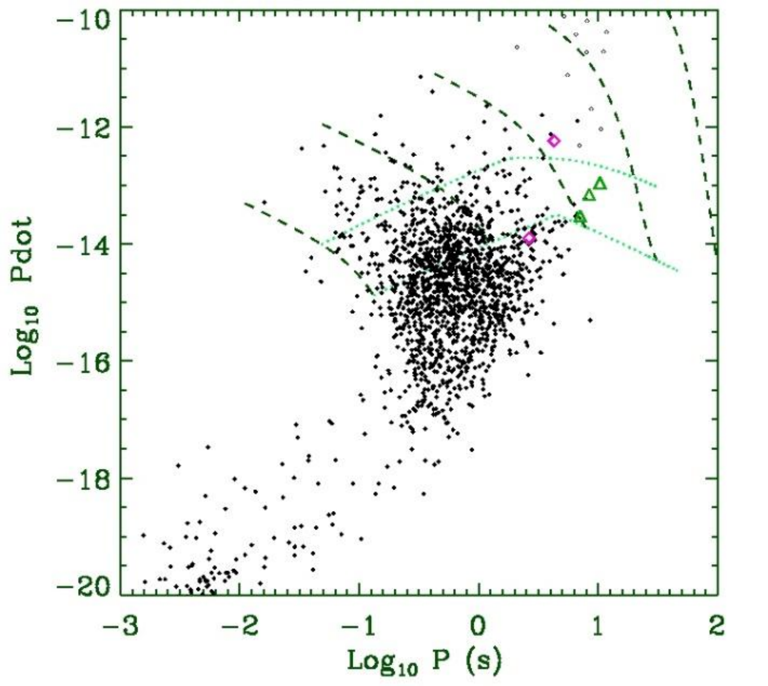
Chashkina, Popov 2012. arXiv: 1112.1123



τ_{Ohm}=10^7 yrs
τ_{Hall} =$10^2/(B_0/10^{15}$ G)



τ_{Ohm}=10^6 yrs
τ_{Hall} =$10^3/(B_0/10^{15}$ G)



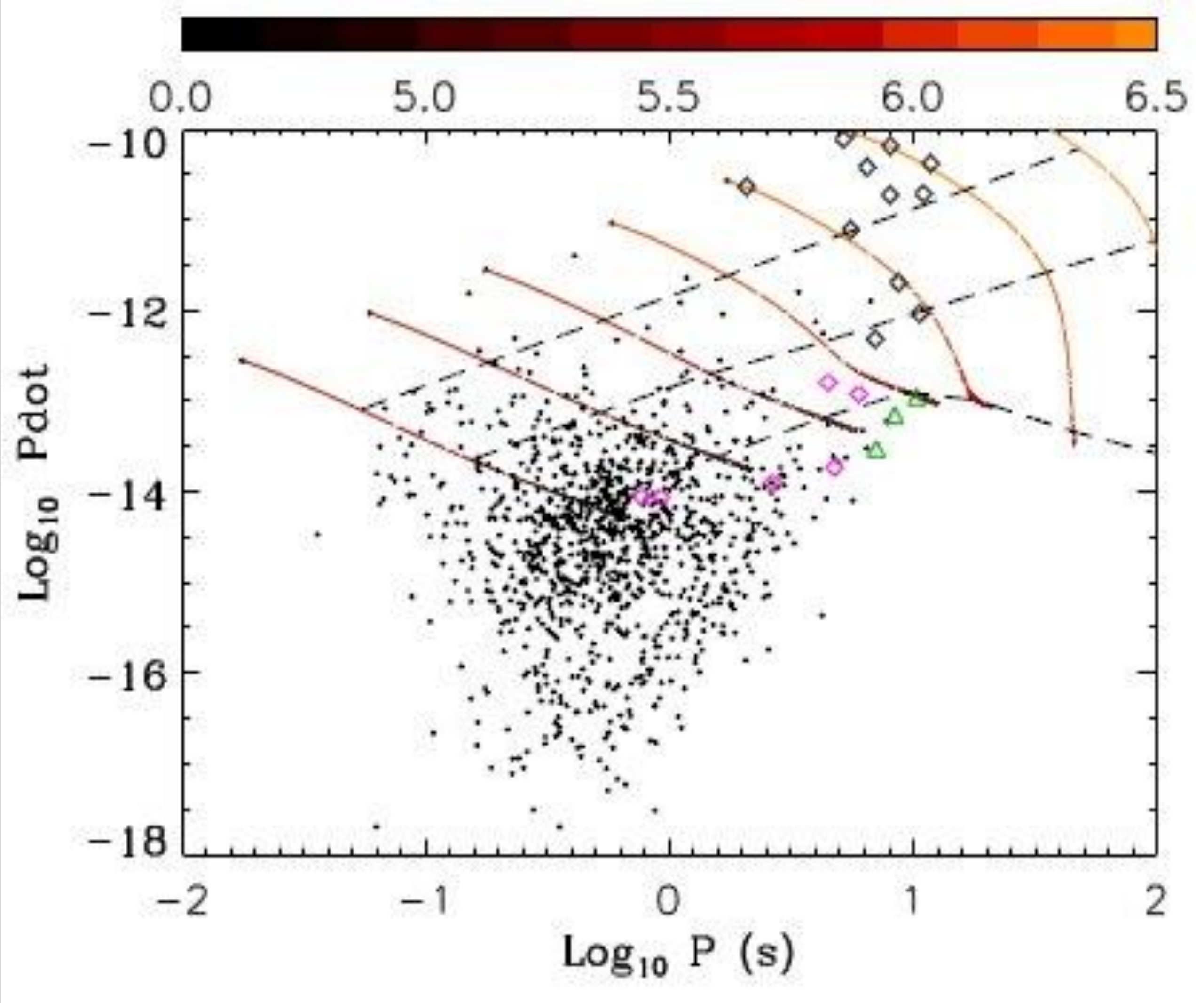
τ_{Ohm}=10^6 yrs
τ_{Hall} =$10^4/(B_0/10^{15}$ G)

Longer time scale for the Hall field decay is favoured.

It is interesting to look at HMXBs to see if it is possible to derive the effect of field decay and convergence.

Realistic tracks

Popov et al. MNRAS 2010



Using the model by Pons et al. (arXiv: 0812.3018) we plot realistic tracks for NS with masses 1.4 Msolar.

Initial fields are:
$3\ 10^{12}$, 10^{13}, $3\ 10^{13}$, 10^{14},
$3\ 10^{14}$, 10^{15}

Color on the track encodes surface temperature.

Tracks start at 10^{3} years, and end at $2\ 10^{6}$ years.

See newer calculations in Gullon et al.

Joint description of NS evolution with decaying magnetic field

The idea to describe all types of NSs with a unique model using one initial distribution (fields, periods, velocities) and to compare with observational data, i.e. to confront vs. all available observed distributions:

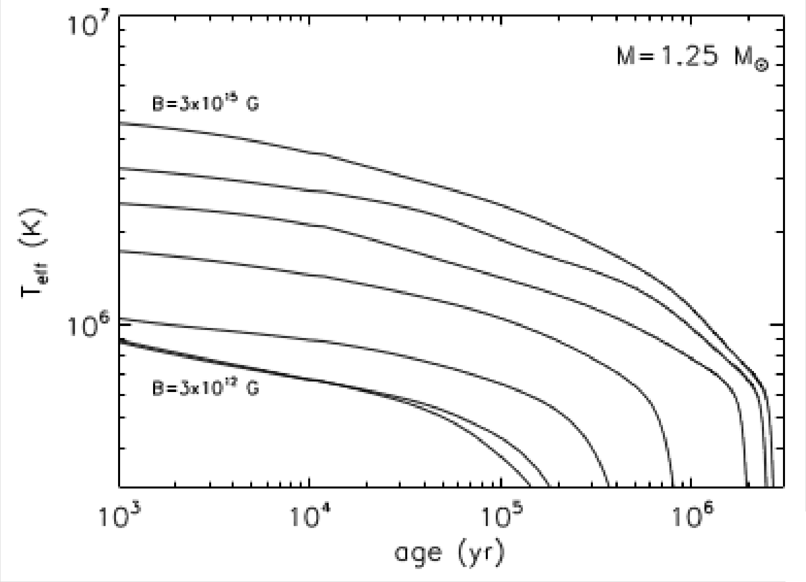
- P-Pdot for PSRs and other isolated NSs
- Log N – Log S for cooling close-by NSs
- Luminosity distribution of magnetars (AXPs, SGRs)
- ……………..

The first step is done in Popov et al. (2010)

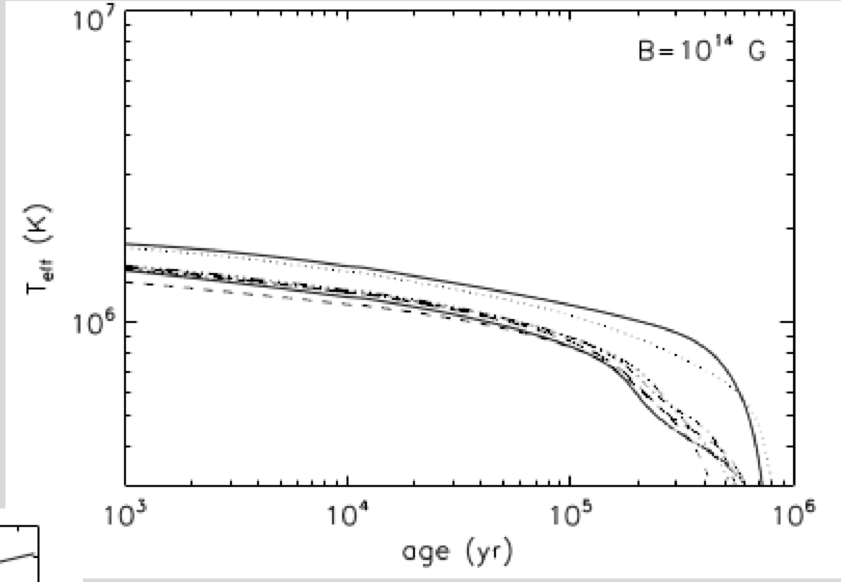
The initial magnetic field distribution with $\langle \log B_0 \rangle \sim 13.25$ and $\sigma \sim 0.6$ gives a good fit.
~10% of magnetars.

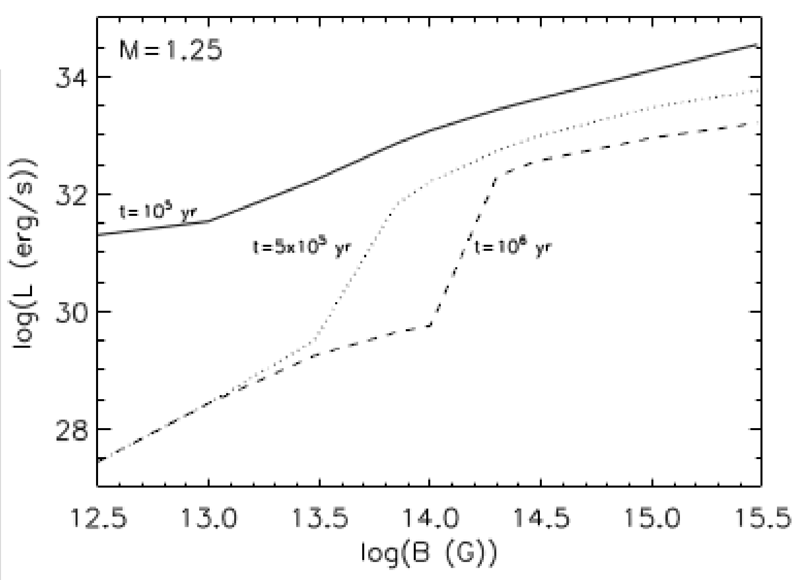
GRAND UNIFICATION FOR NEUTRON STARS

Cooling curves with decay



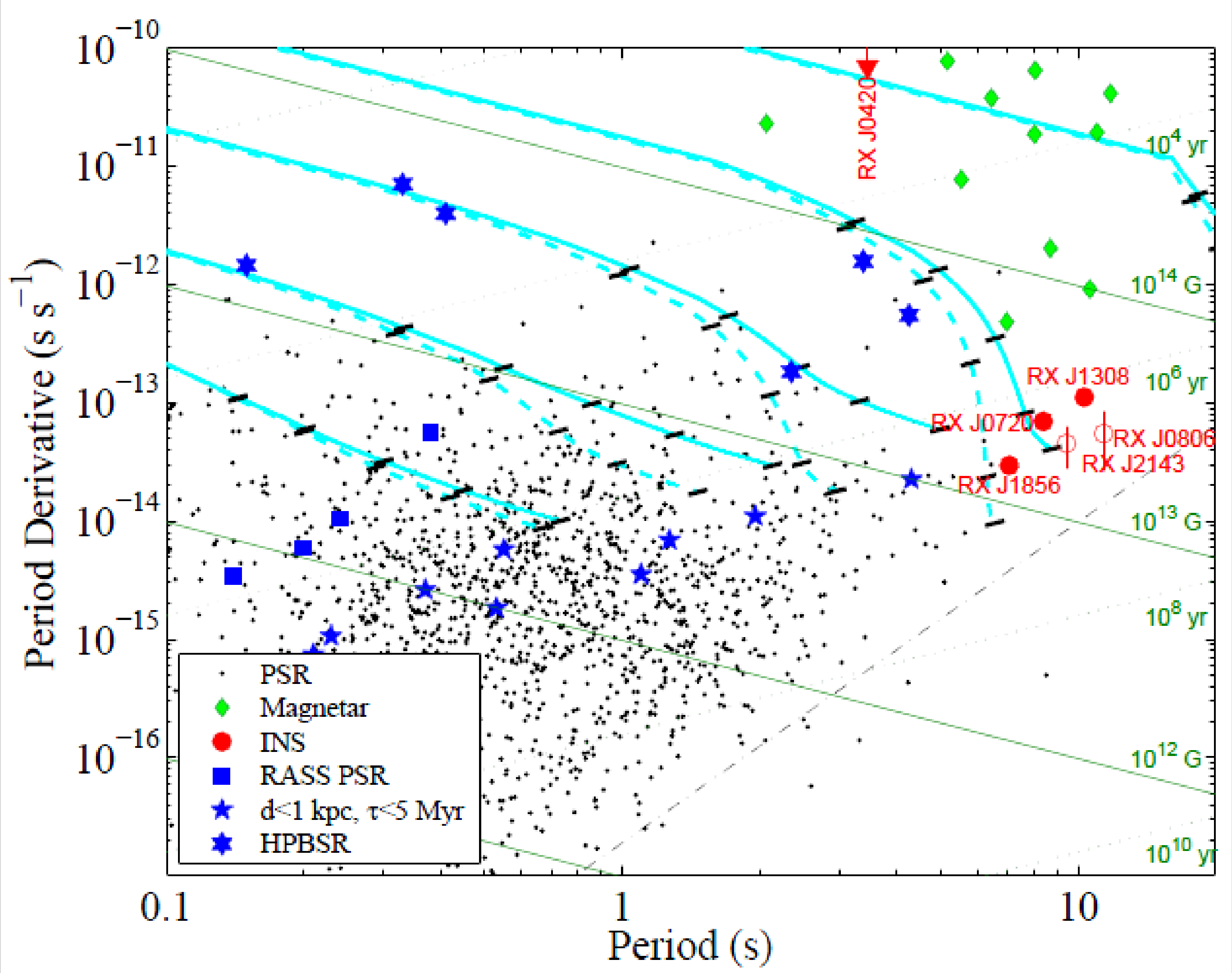
Magnetic field distribution
is more important
than the mass distribution.



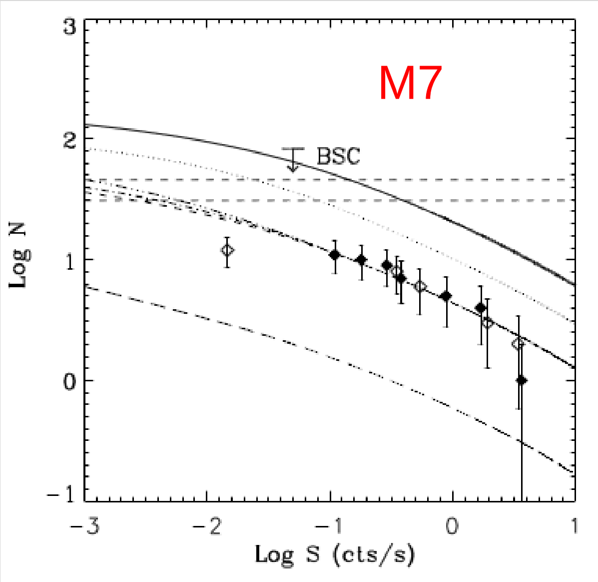


Observational evidence?

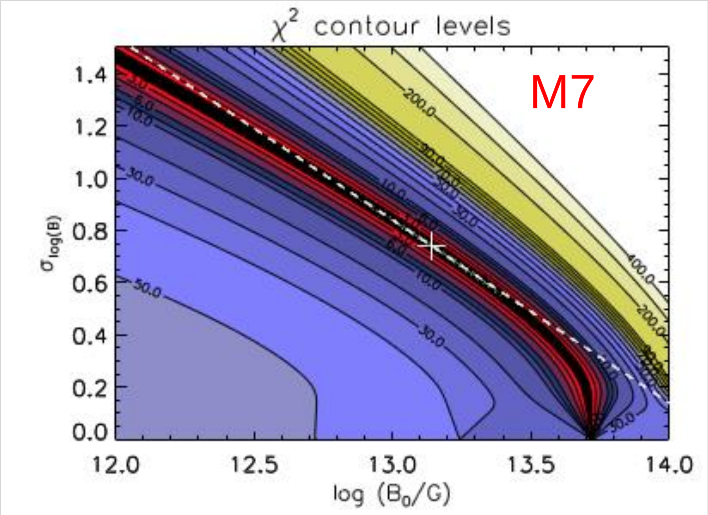
Kaplan & van Kerkwijk arXiv: 0909.5218



Extensive population synthesis: M7, magnetars, PSRs

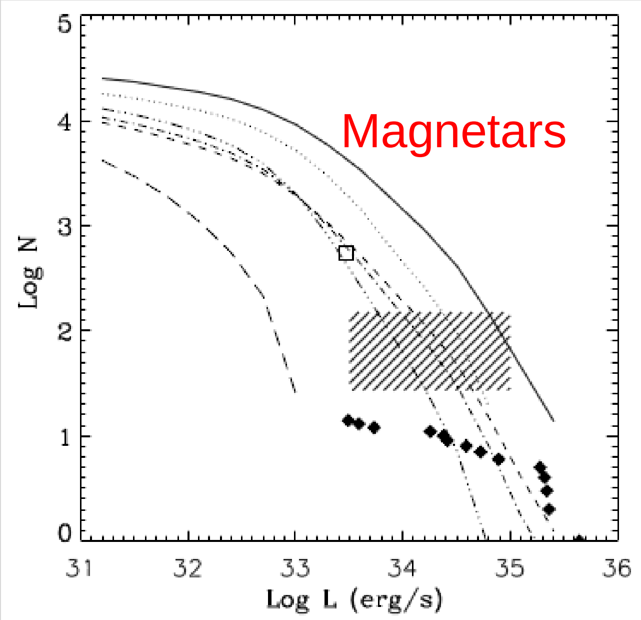


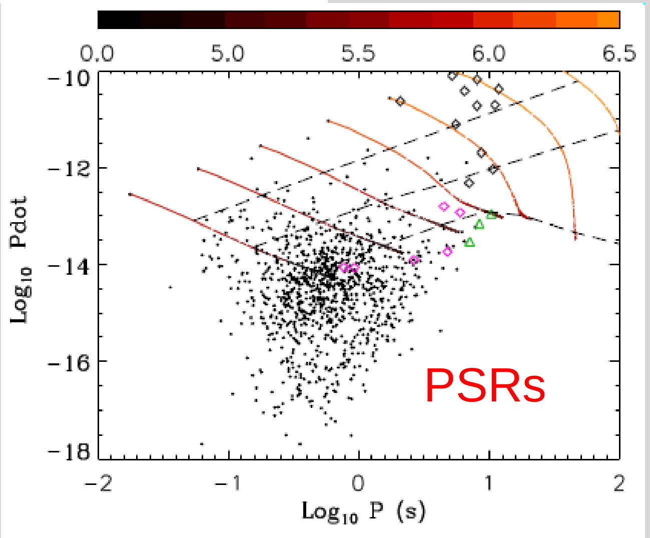
Using one population
it is difficult or impossible
to find unique initial
distribution for the
magnetic field



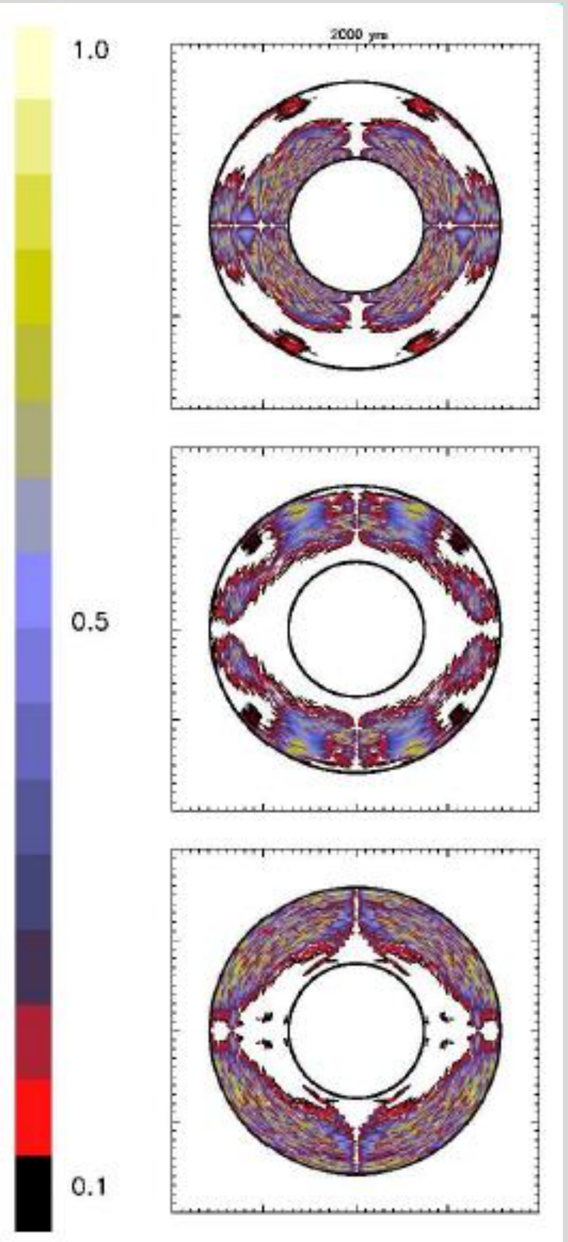
All three populations are
compatible with a
unique distribution.

Of course, the result
is model dependent.



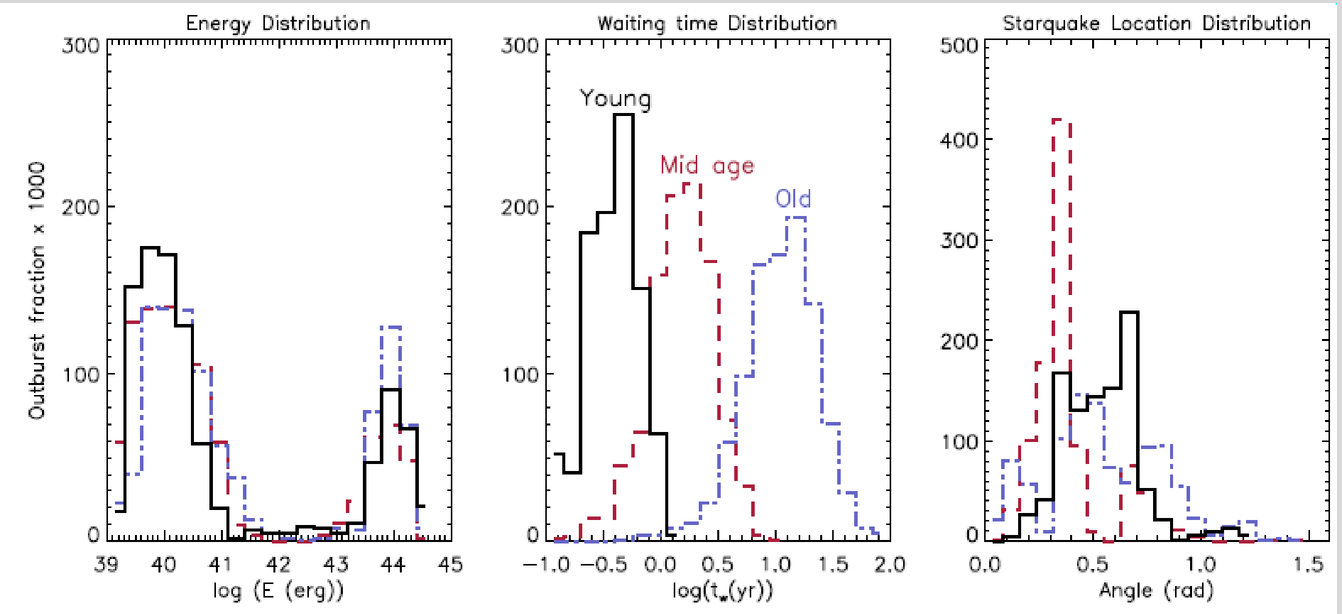


Magnetars bursting activity due to field decay



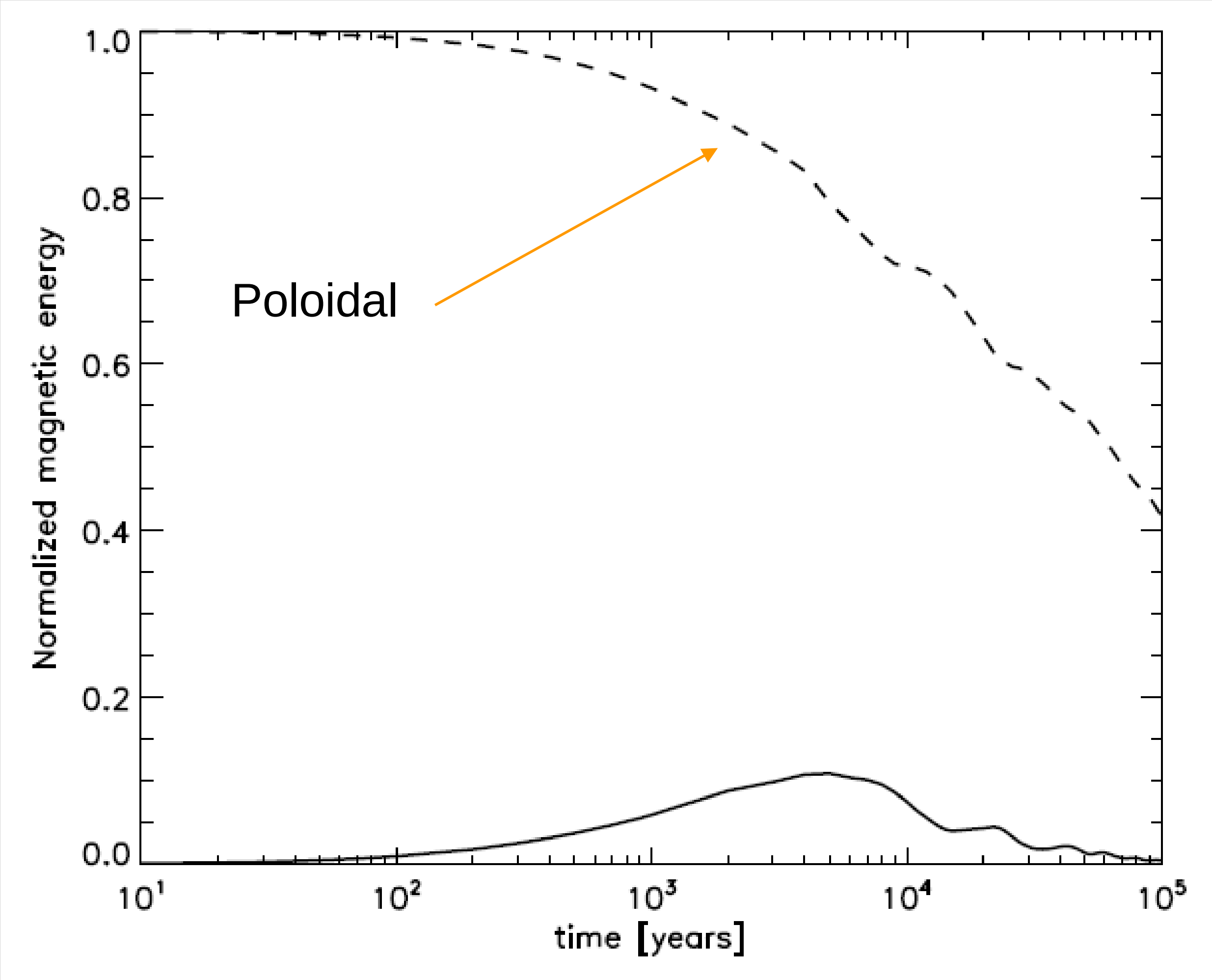
In the field decay model it is possible to study burst activity. Bursts occur due to crust cracking. The decaying field produce stresses in the crust that are not compensated by plastic deformations. When the stress level reaches a critical value the crust cracks, and energy can be released.

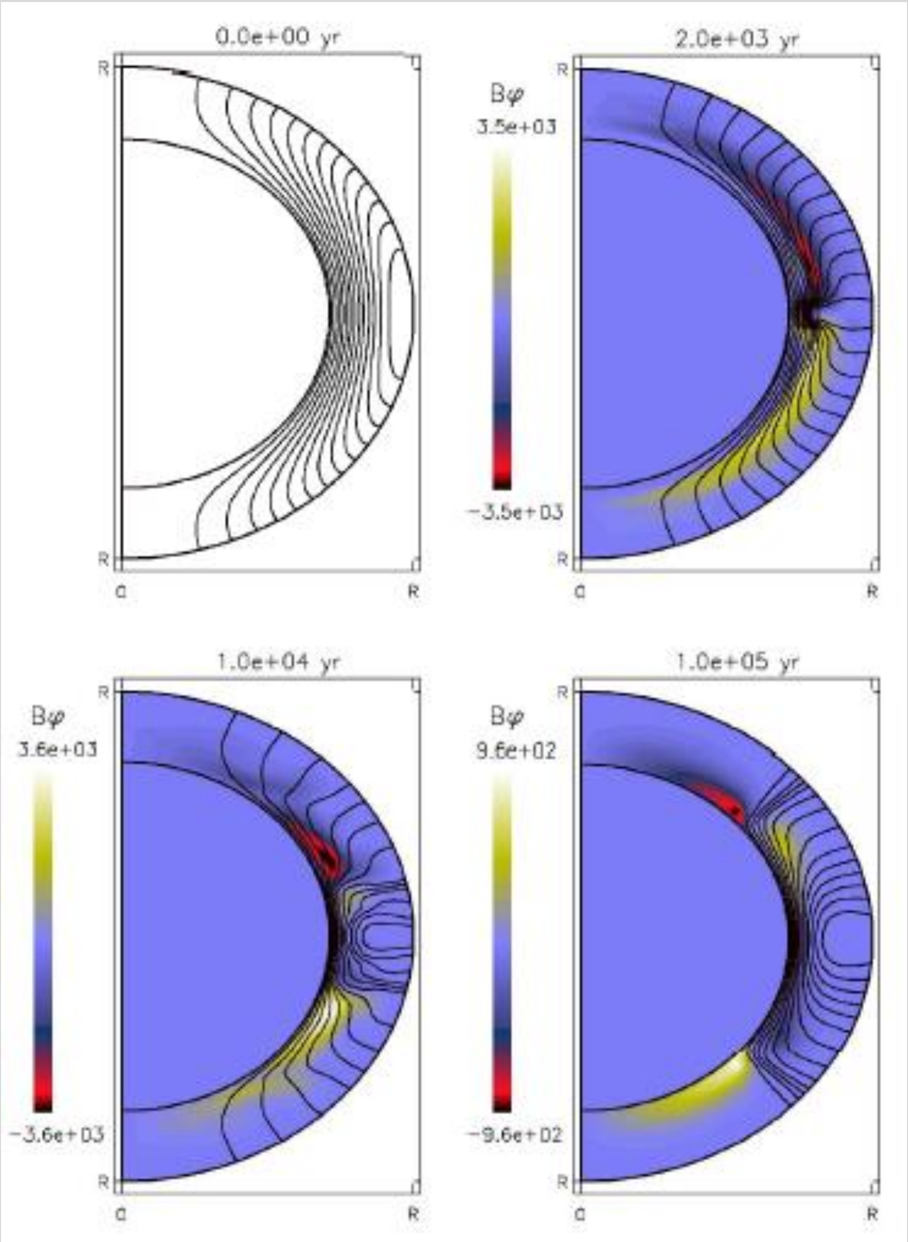
At the moment the model is very simple, but this just the first step.



1101.1098

An illustrative model





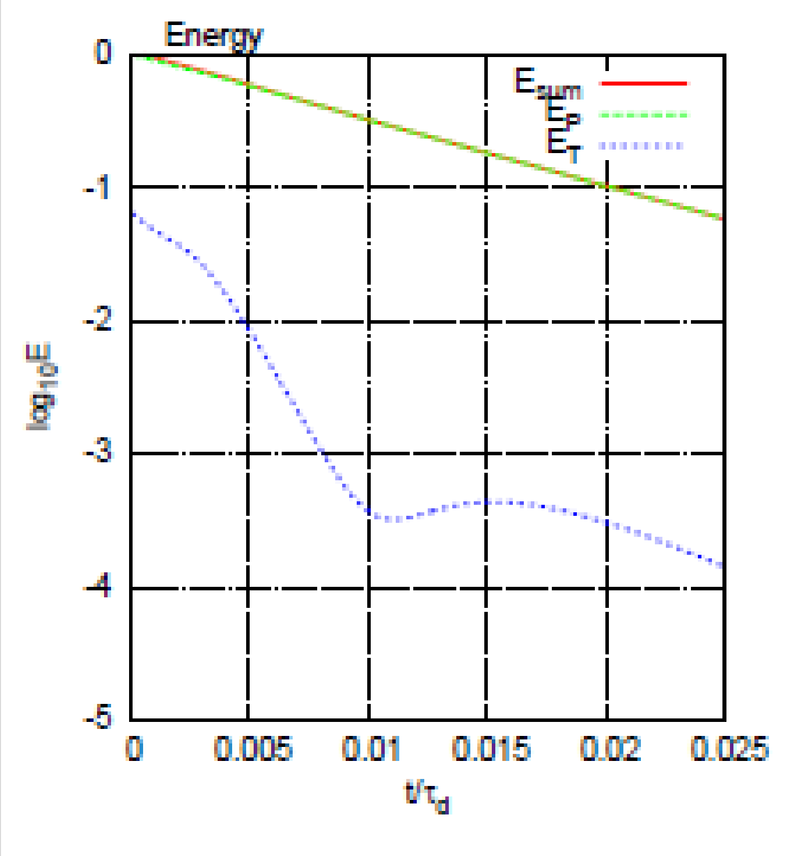
1204.4707

Test illustrates the evolution of initially purely poloidal field

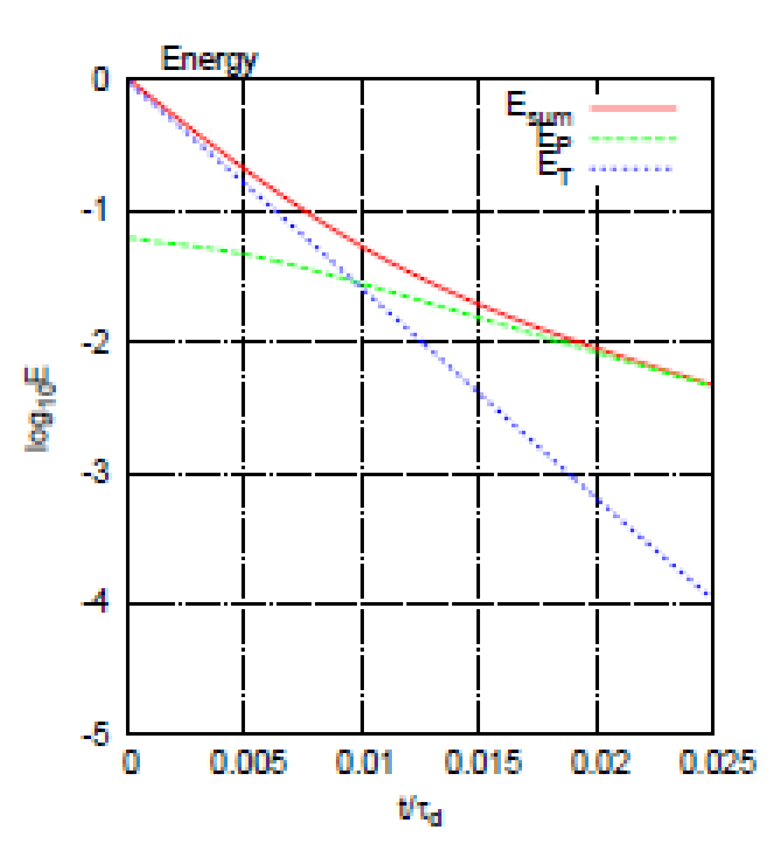
Another model

1201.1346

Initially the poloidal field is large.



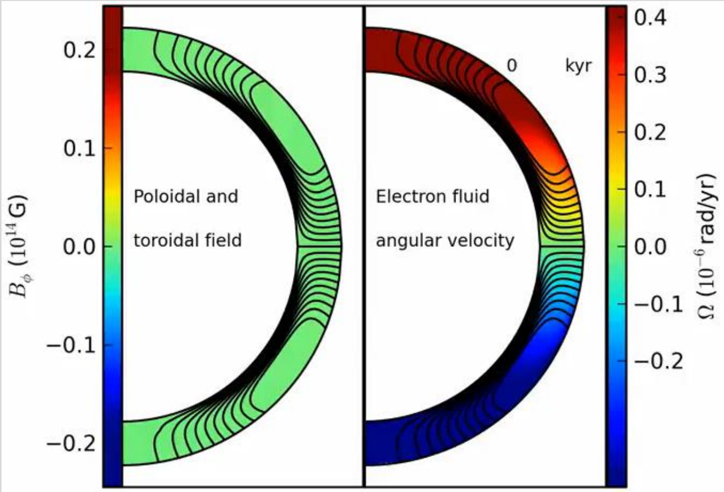
Initially the toroidal field is large.

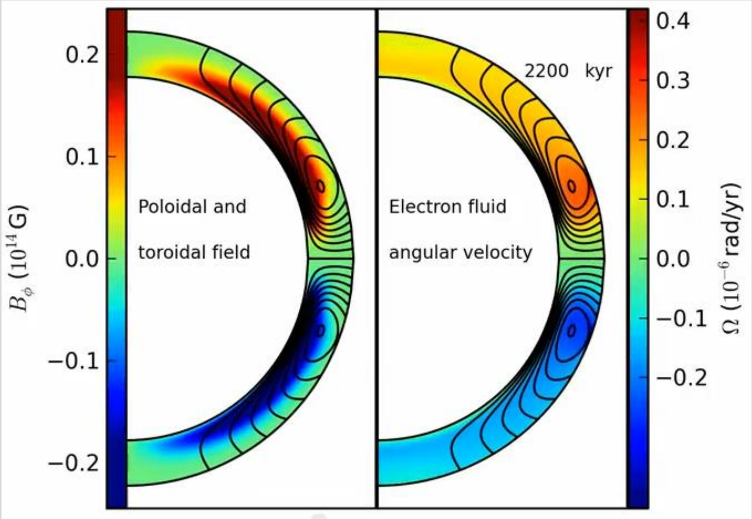


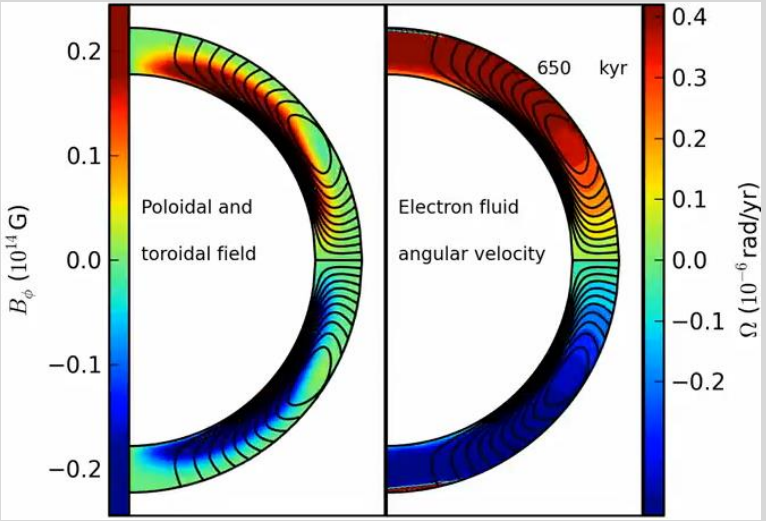
If the toroidal field dominates initially then significant energy is transferred to the poloidal component during evolution.
In the opposite case, when the poloidal component initially dominates, energy is not transferred.
The toroidal component decouples.

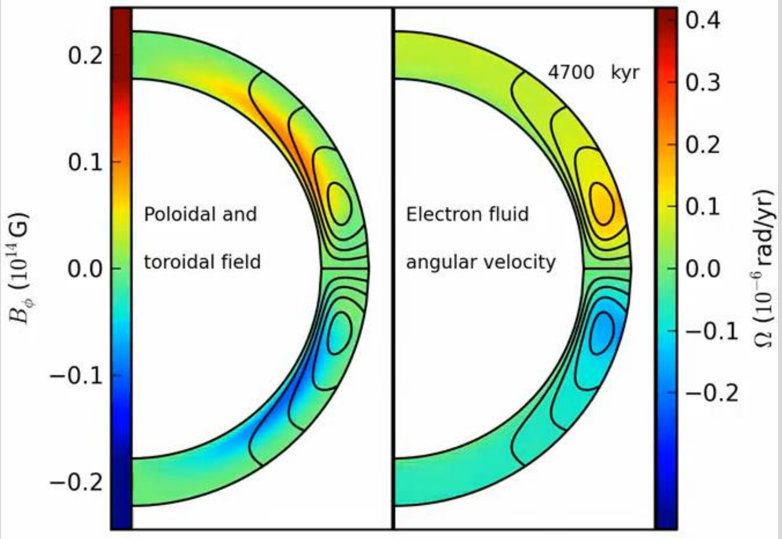
Hall cascade and attractor

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







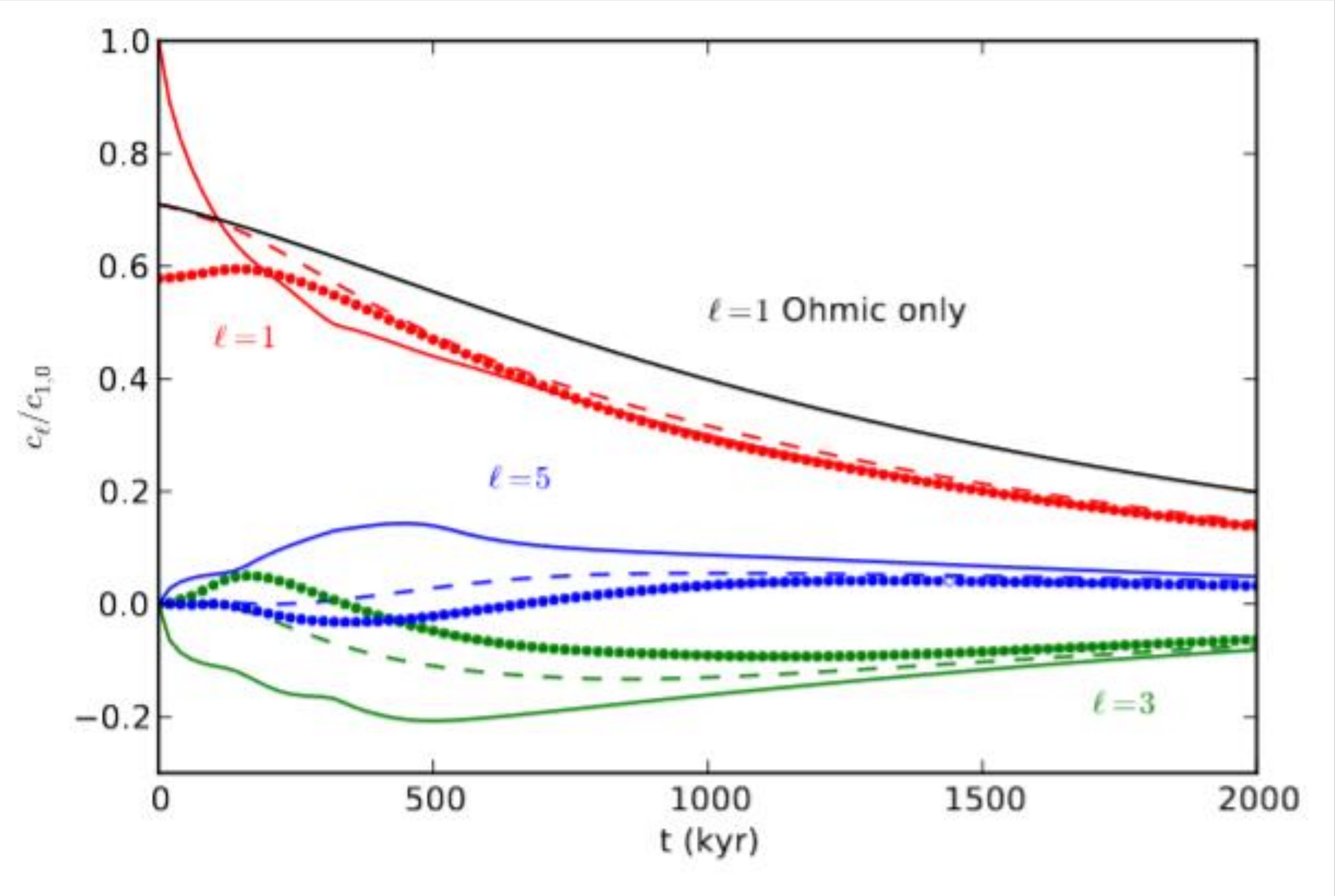


Gourgouliatos and Cumming 2013

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

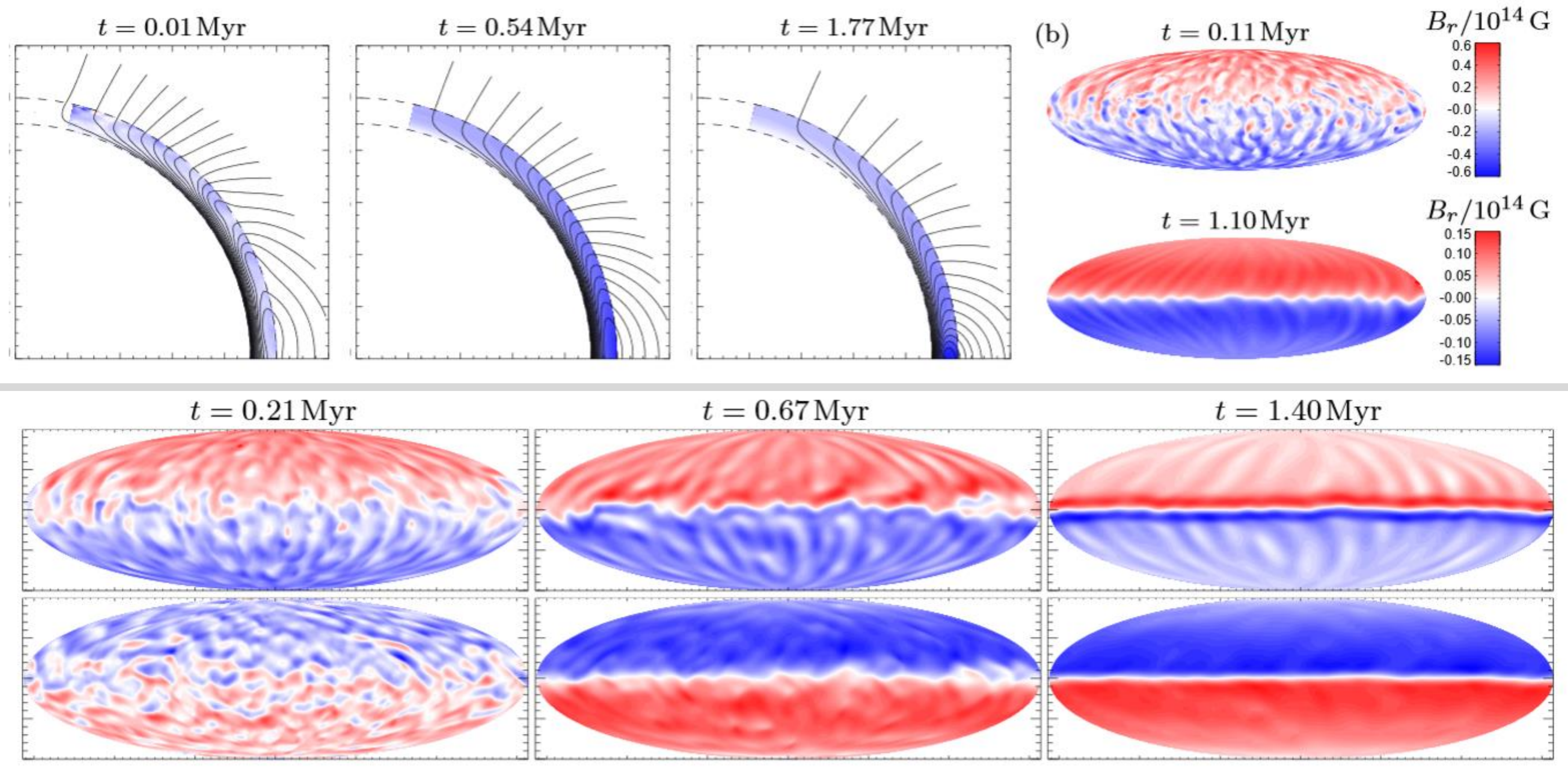
Evolution of different components

1311.7004



Hall attractor mainly consists of dipole and octupole (+l5)

New studies of the hall cascade

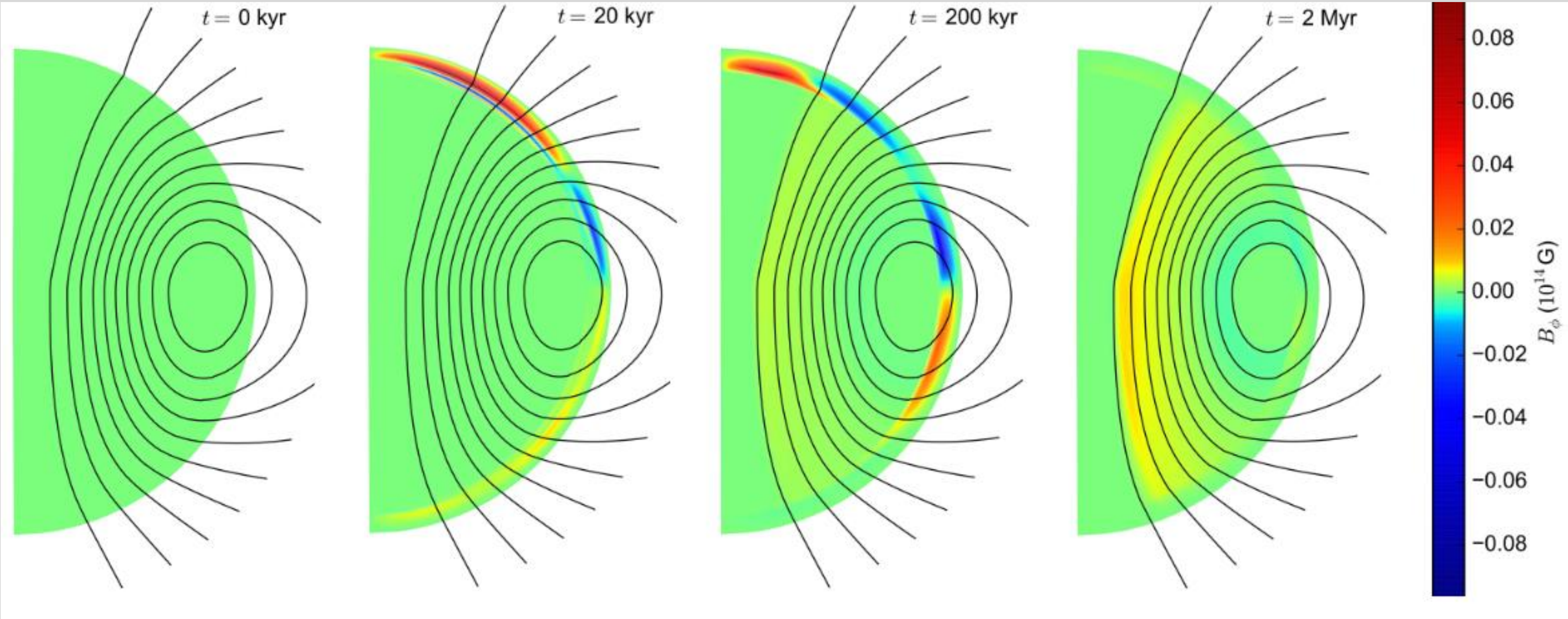


New calculations support the idea of a kind of stable configuration.

1501.05149

Core and crust field evolution

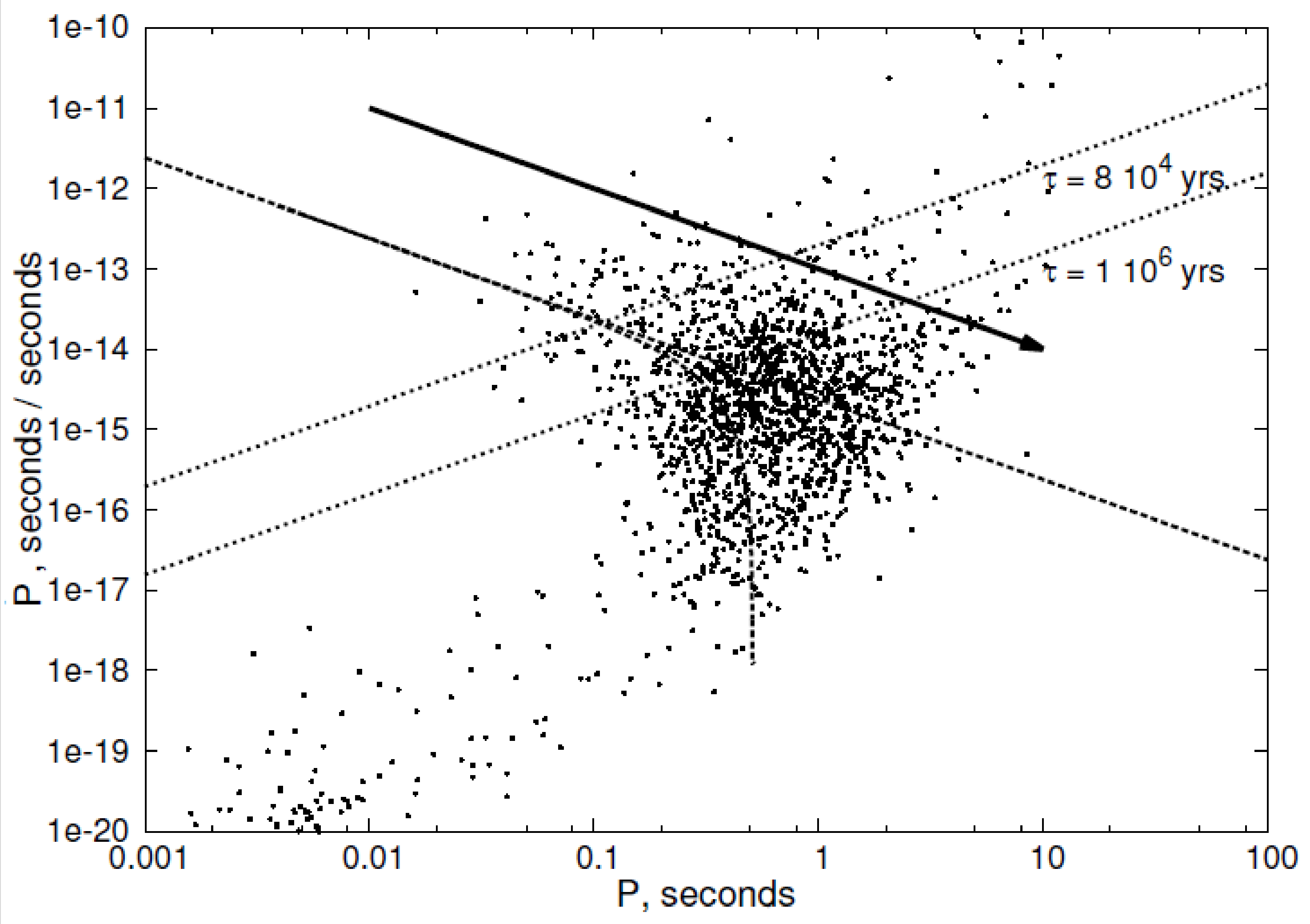
1709.09167



Hall attractor is confirmed.

Magnetic field decay on P-Pdot diagram

Igoshev, Popov (2014). arXiv:1407.6269



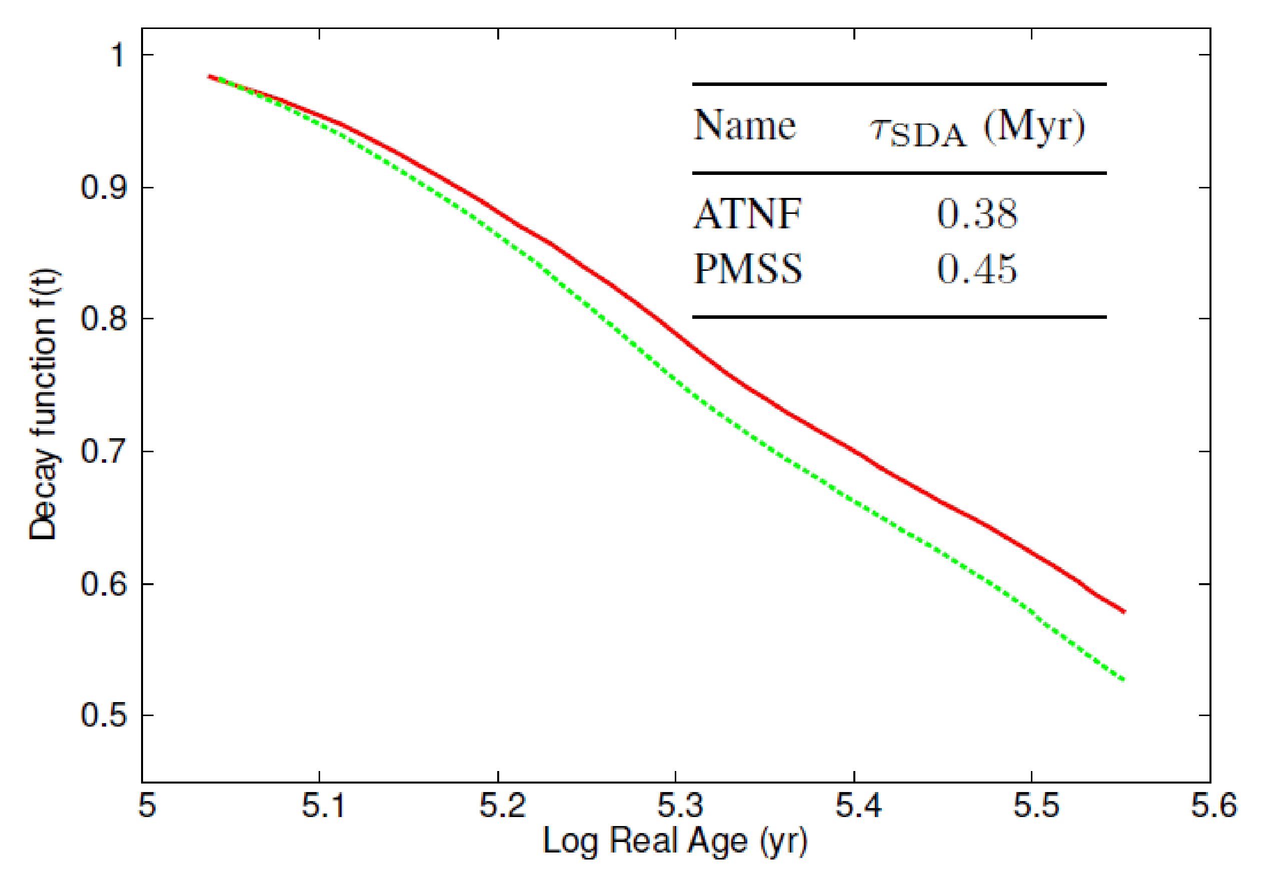
It is not clear
if magnetic field
significantly decays
during at least some
episodes of lifetime of
normal radio pulsars.

Modified pulsar current

We applied our methods to large observed samples of radio pulsars to study field decay in these objects:

- ATNF catalogue (Manchester et al. 2005).
- PMSS (Parkes Multibeam and Swinburne surveys) (Manchester et al. 2001).

Igoshev, Popov (2014)



Name	τ_{SDA} (Myr)
ATNF	0.38
PMSS	0.45

We reconstructed the magnetic field decay in the range of true (statistical) ages:
$8\ 10^4 < t < 3.5\ 10^5$ 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.

Thermal evolution. Low fields

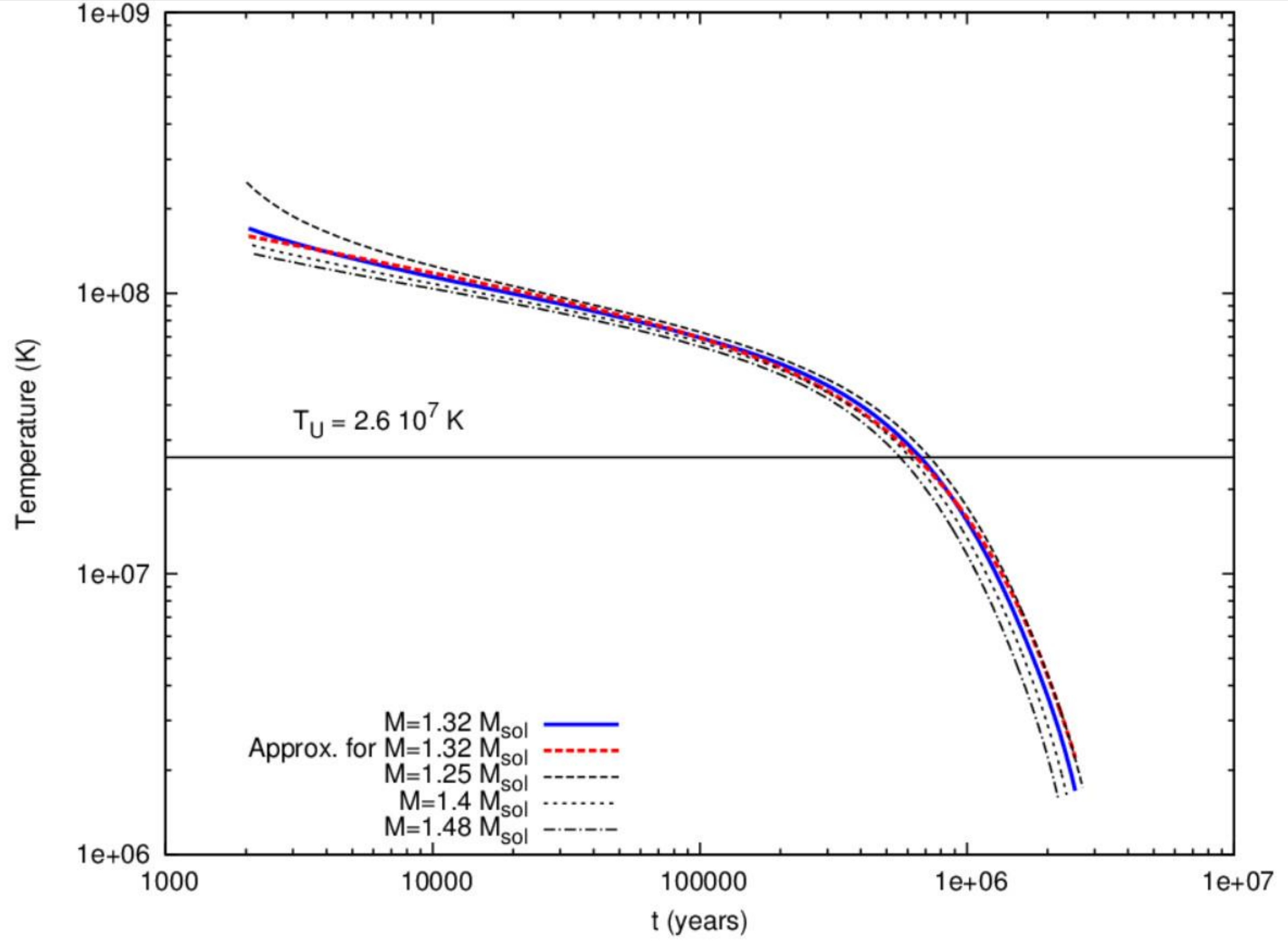
All types of heating
are neglected.

Calculations are made
by Shternin et al. (2011).

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

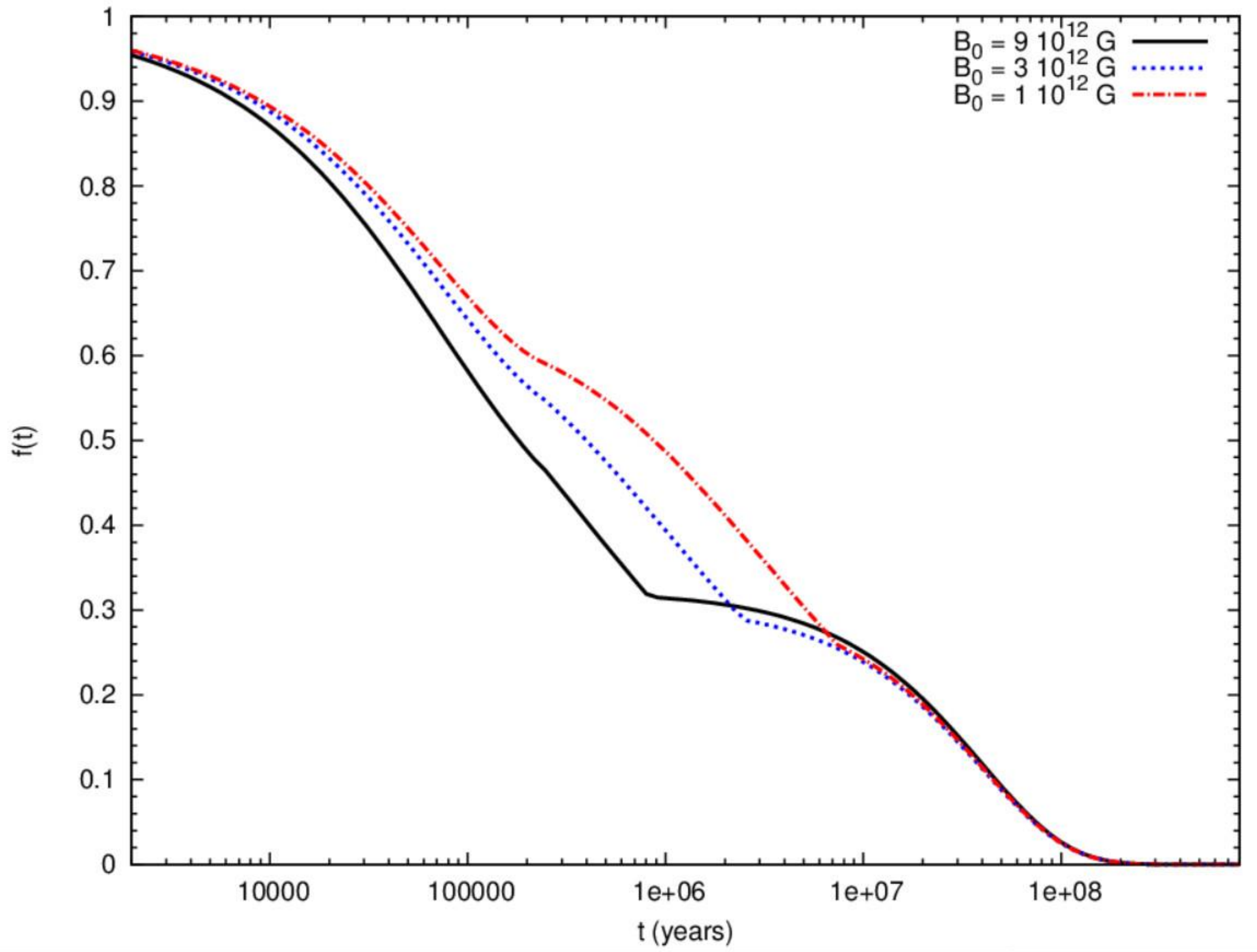
$$T = b \left(\frac{t}{1\mathrm{yr}} \right)^{a} \exp(-t/\tau_{\mathrm{c}}).$$

Also valid when
the Hall cascade is off.



Magnetic field evolution

Igoshev, Popov (2015) arXiv: 1507.07962



$$\frac{dB_{\rm p}}{dt} = -\frac{B_{\rm p}}{\tau_{\rm Ohm}(T_{\rm crust})} - \frac{1}{B_0}\frac{B_{\rm p}^2}{\tau_{\rm Hall_0}}.$$

All inclusive:
- Hall
- Phonons
- Impurities

What kind of decay do we see?

Ohmic decay due to phonons

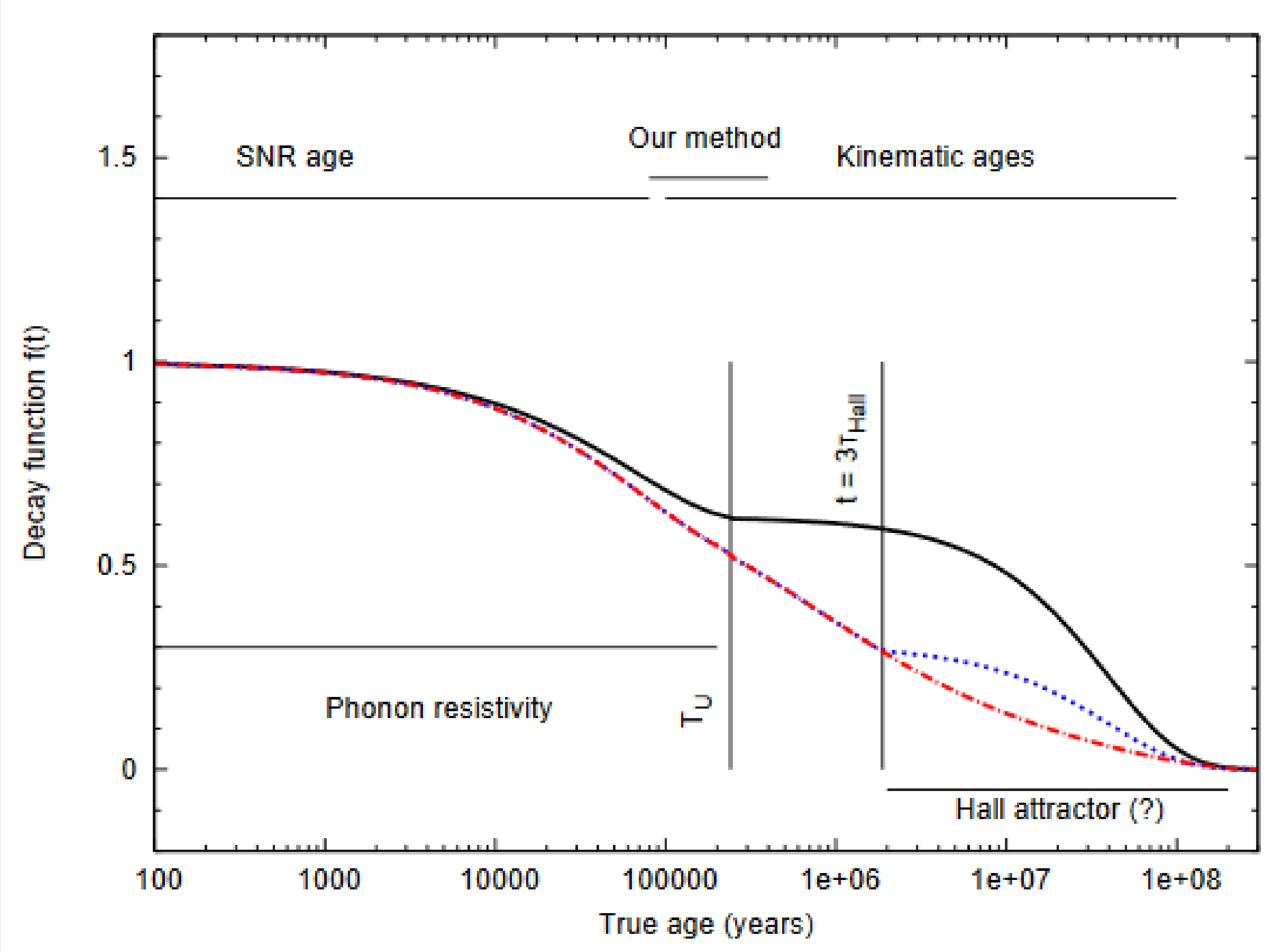
Hall cascade

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

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

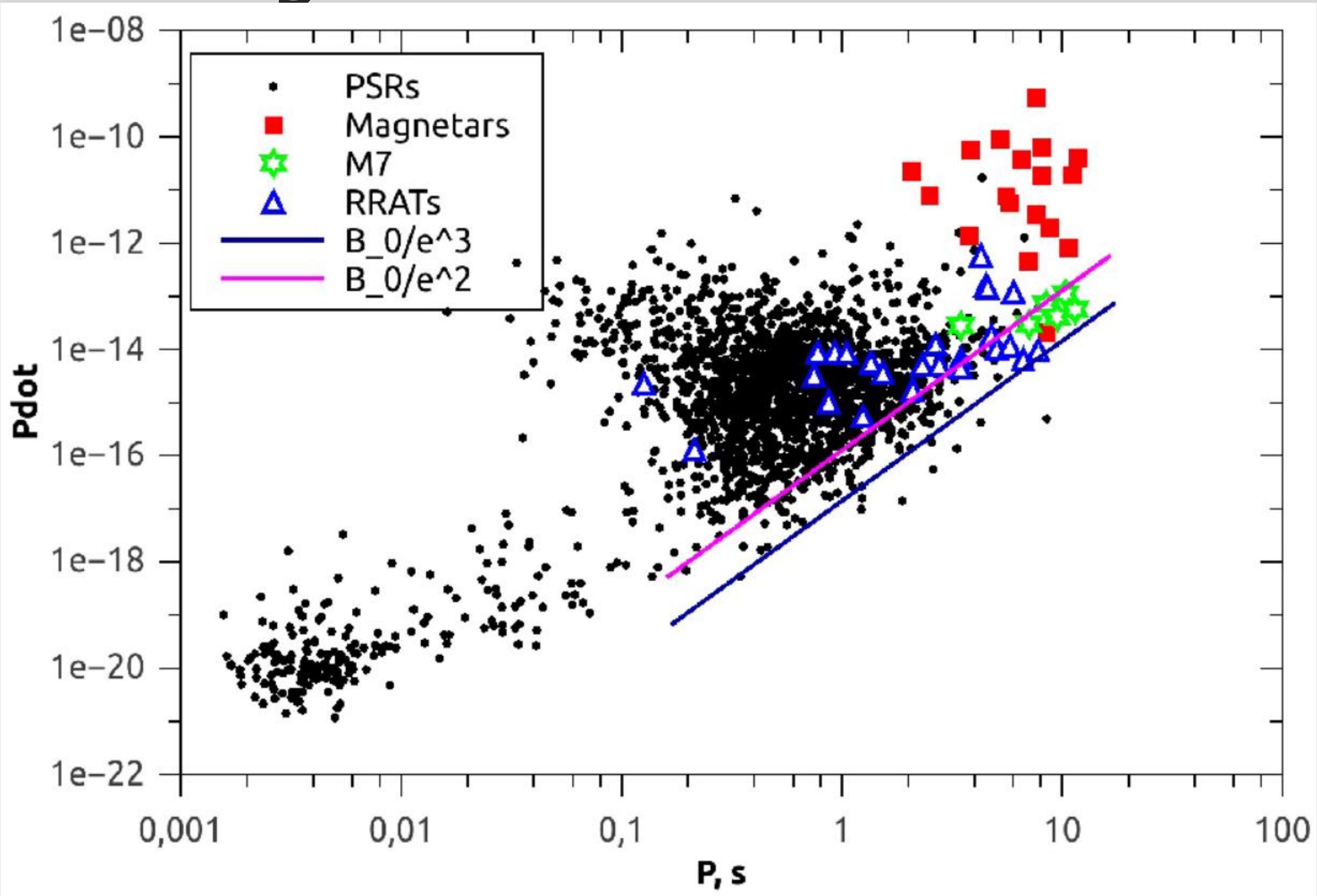
Comparison of different options

Igoshev, Popov (2015) arXiv: 1507.07962



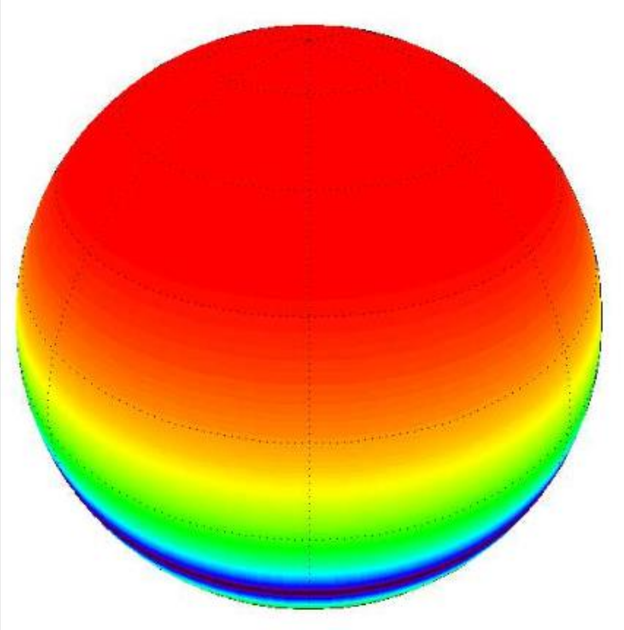
We think that in the range ~10^5 – 10^6 yrs in the case of normal pulsars we see mostly Ohmic decay, which then disappears as NSs cool down.

Getting close to the attractor



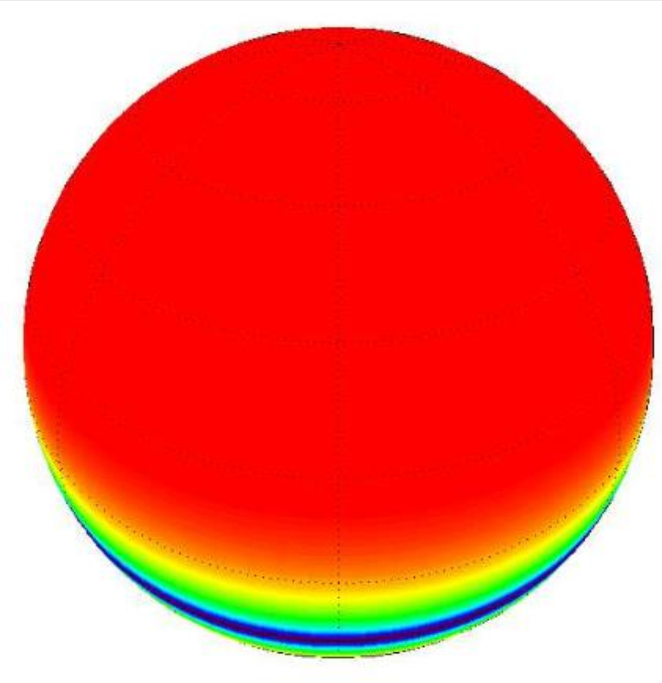
Temperature maps

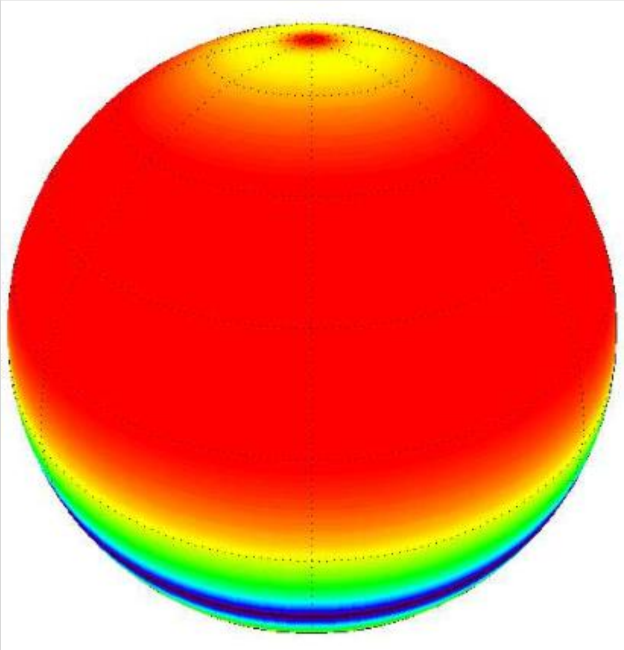
arXiv: 1610.05050



Pure dipole

Dipole+octupole+l5





Dipole + octupole
(Model 1)

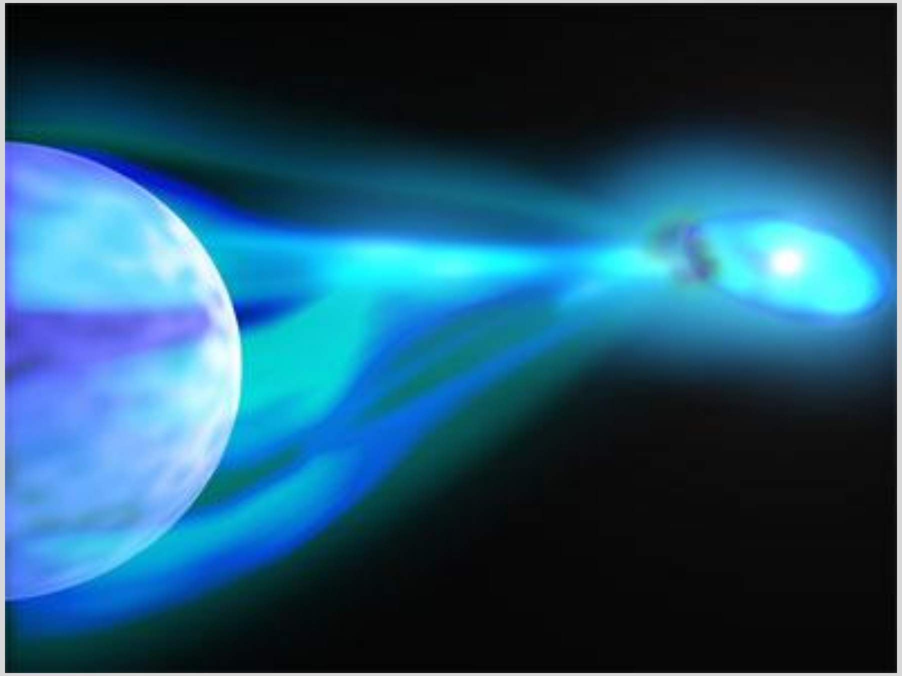
	χ	ξ	T_1 (eV)	T_2 (eV)	A_2/A_1
Pure dipole	15°	80°	72.0	57.8	1.27
Model 1	20°	80°	73.0	59.4	0.76
Model 2	25°	80°	73.5	58.1	0.36

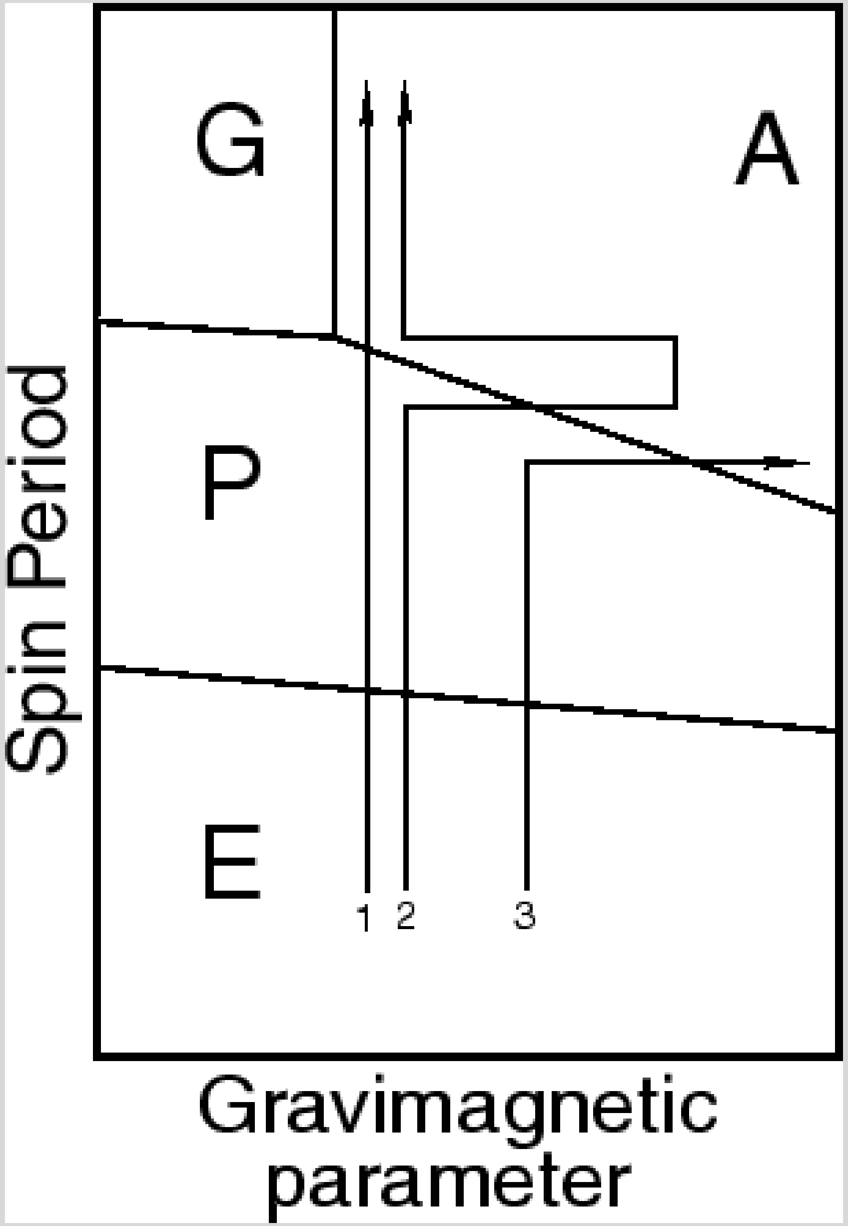
New results in 2009.04331

SXP 1062

A peculiar source was discovered in SMC.
Be/Xray binary, P=1062 sec.
A SNR is found. Age ~10^4 yrs.
(1110.6404; 1112.0491)

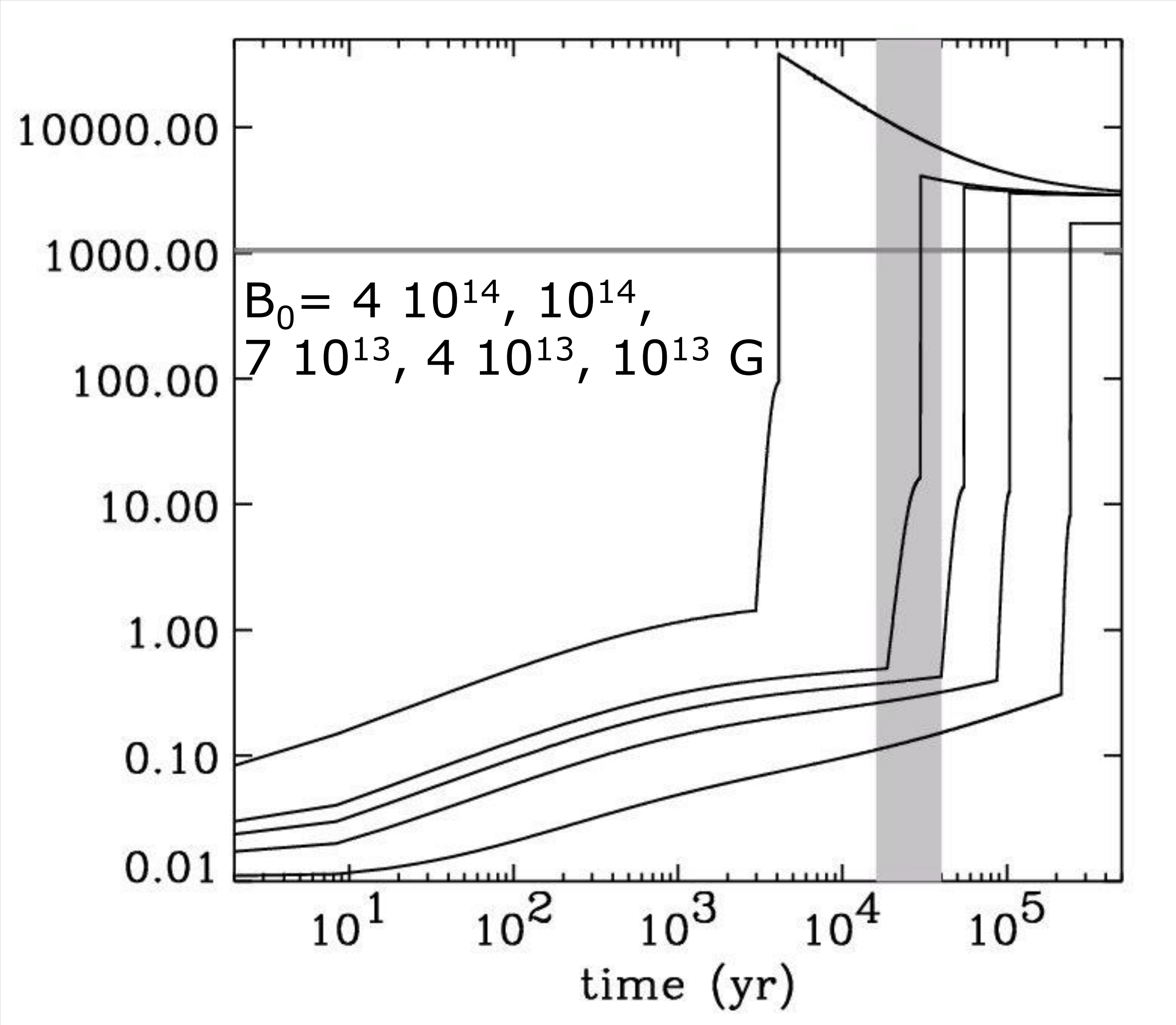
Typically, it can take ~1 Myr for a NS with B~10^{12} G to start accretion.





Evolution of SXP 1062

1112.2507



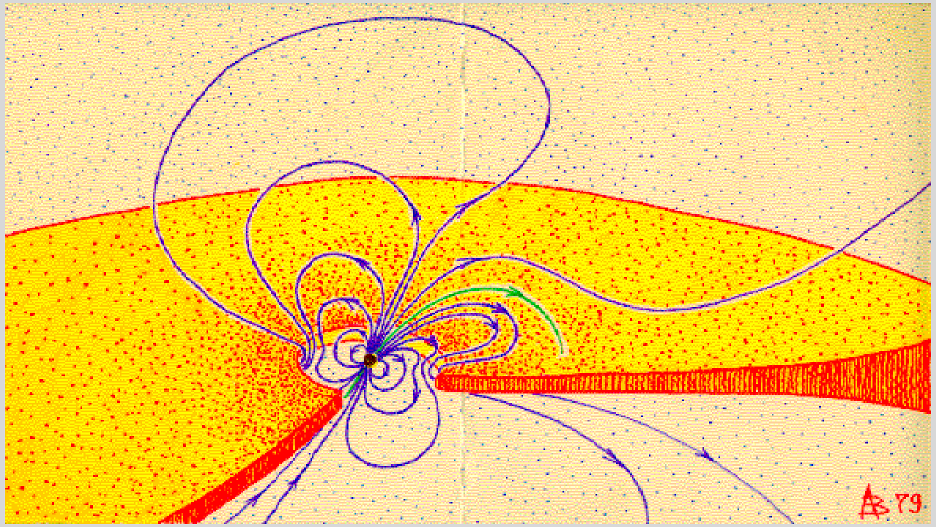
A model of a NS with initial field ~10^{14} G which decayed down to ~10^{13} G can explain the data on SXP 1062.

Some new data in arXiv: 1706.05002

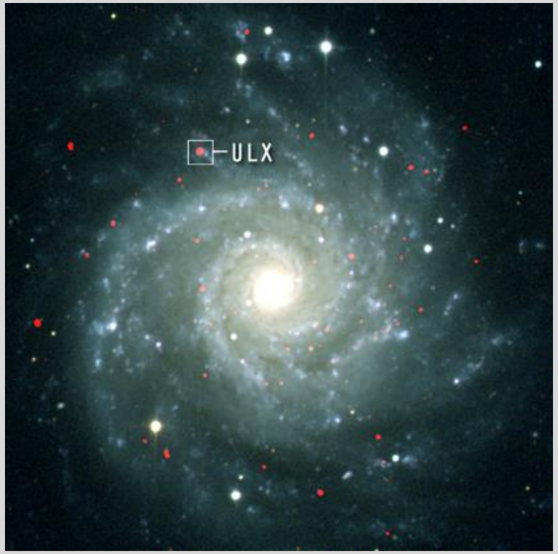
Many other scenarios have been proposed. We need new observational data.

Accreting magnetars

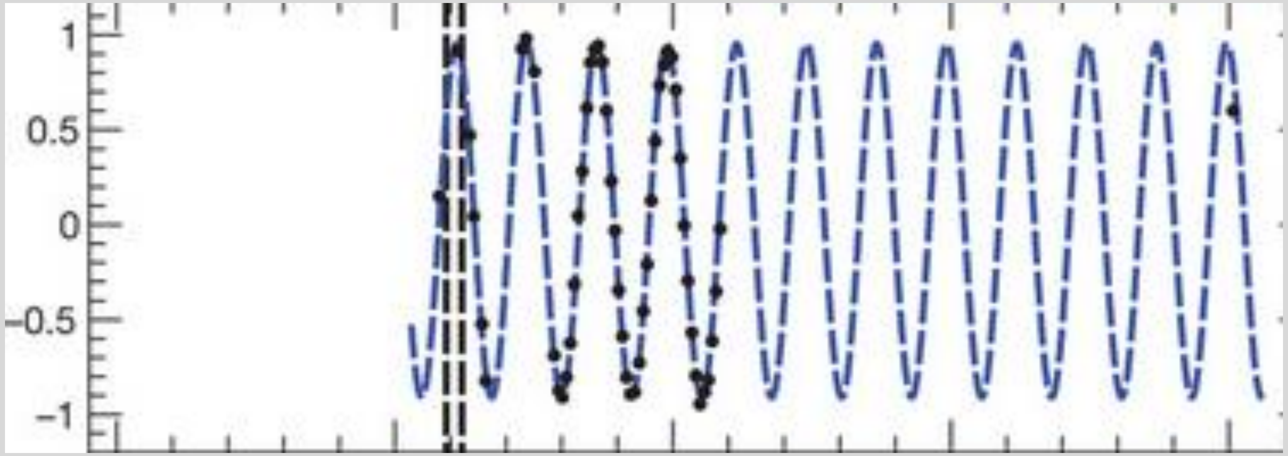
Typically magnetic fields of neutron stars in accreting X-ray binaries are estimated with indirect methods.



- Spin-up
- Spin-down
- Equilibrium period
- Accretion model
- …….

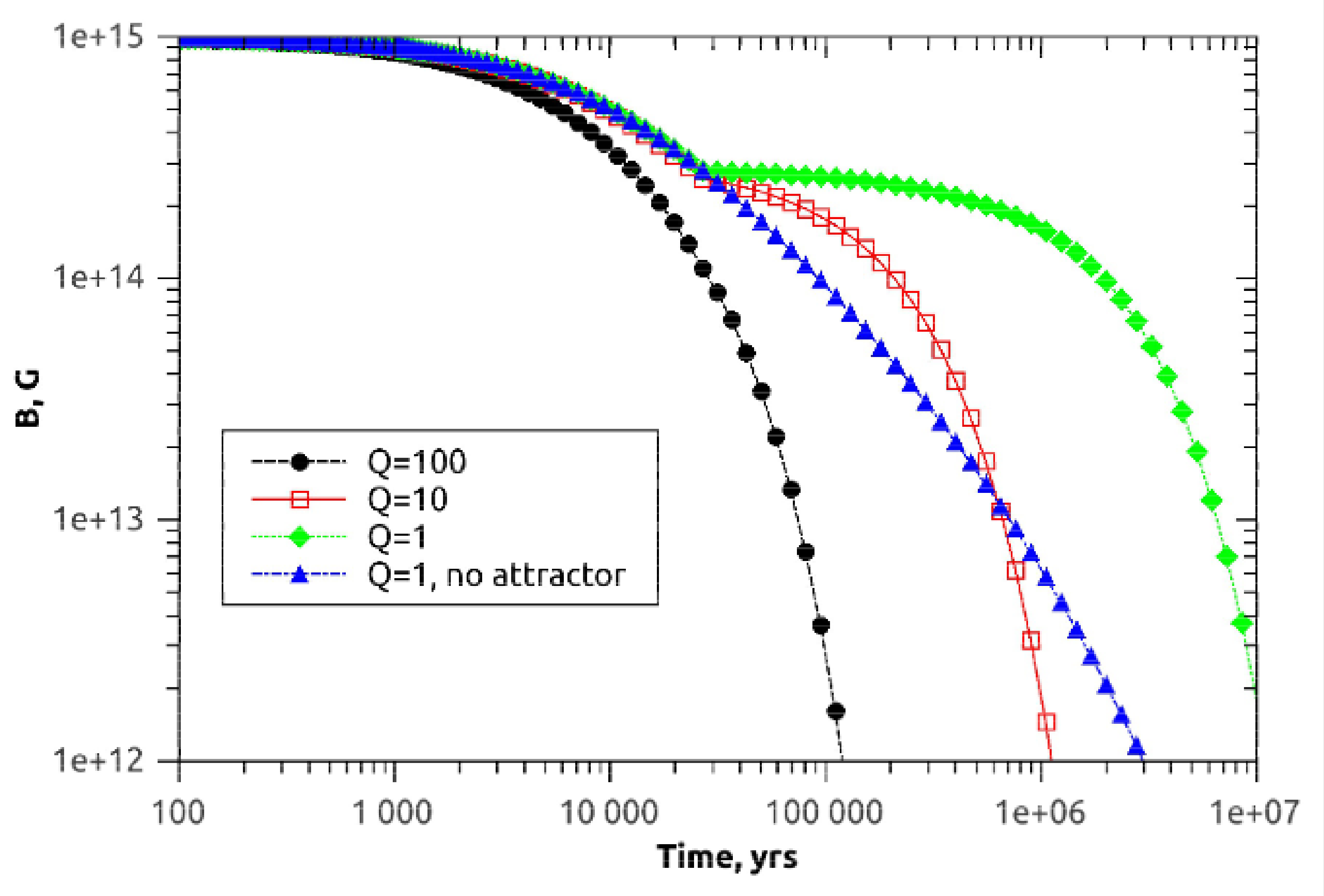


- ULX. NuSTAR J095551+6940.8 (M82 X-2). Ekşi et al. (2015).
- ULX. NGC 5907. Israel et al. (2017a)
- ULX. NGC 7793 P13. Israel et al. (2017b).
- 4U0114+65. Sanjurjo et al. (2017).
- 4U 2206+54. Ikhsanov & Beskrovnaya (2010).
- SXP1062. Fu & Li (2012)
- Swift J045106.8-694803. Klus et al. (2013).



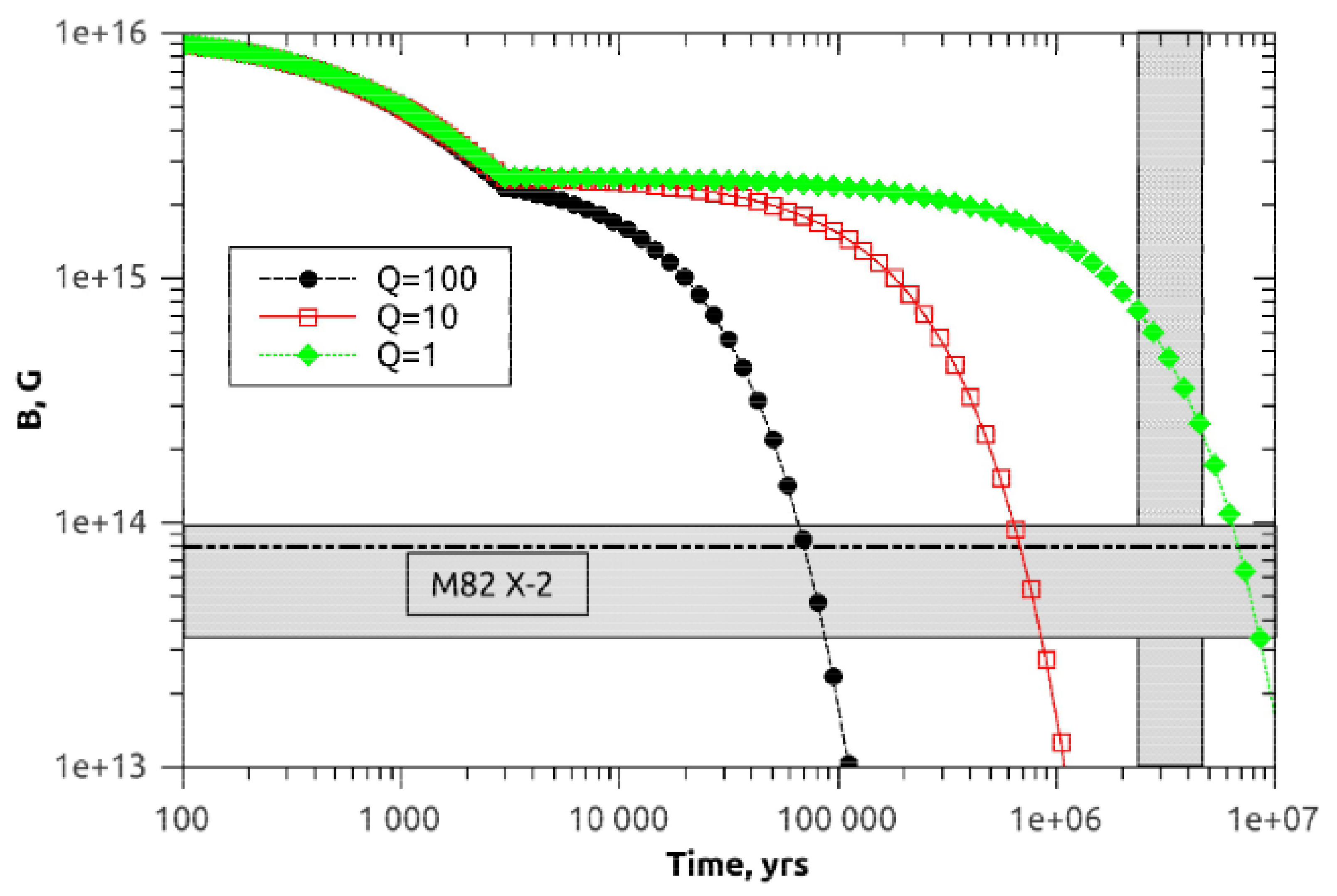
1709.10385

Field evolution in a magnetar



1709.10385

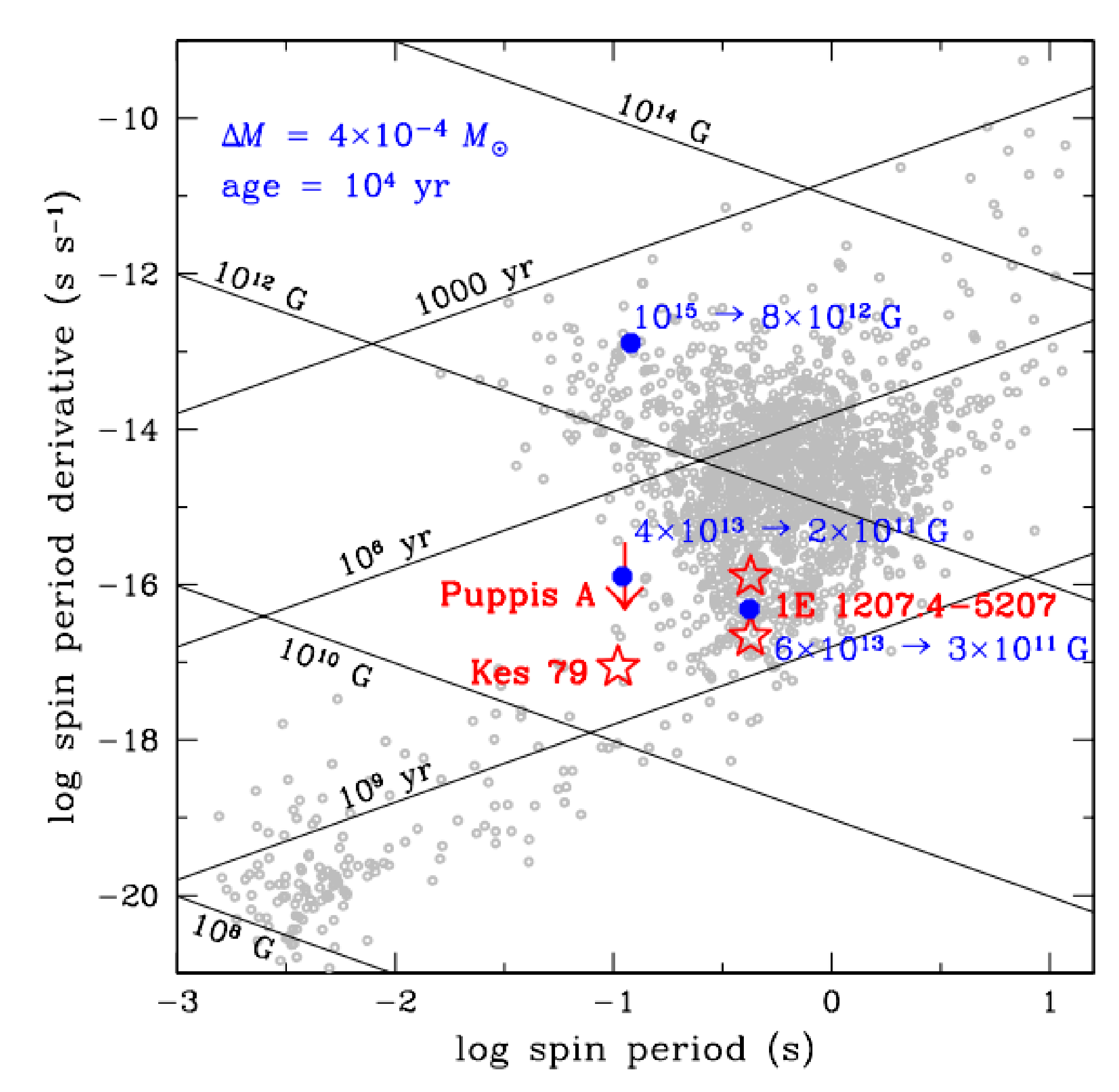
Parameters of ULX M82 X-2



1709.10385

Anti-magnetars

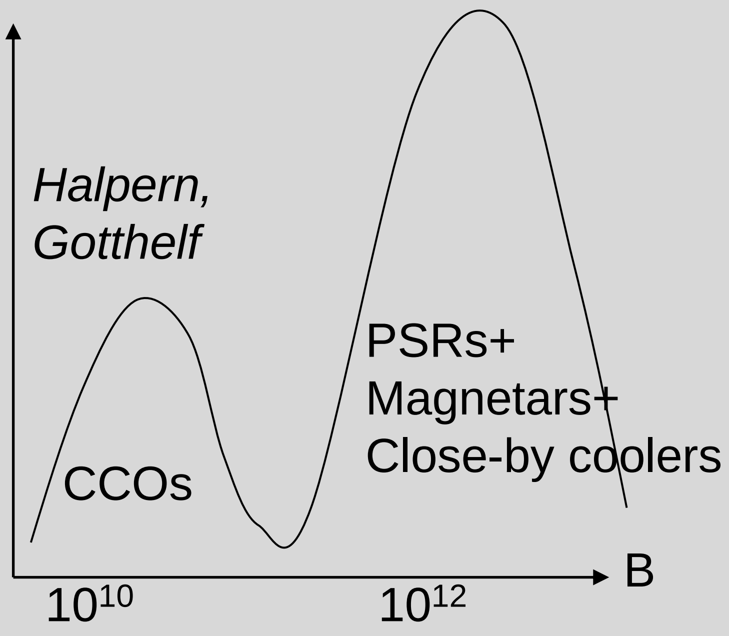
Ho 1210.7112



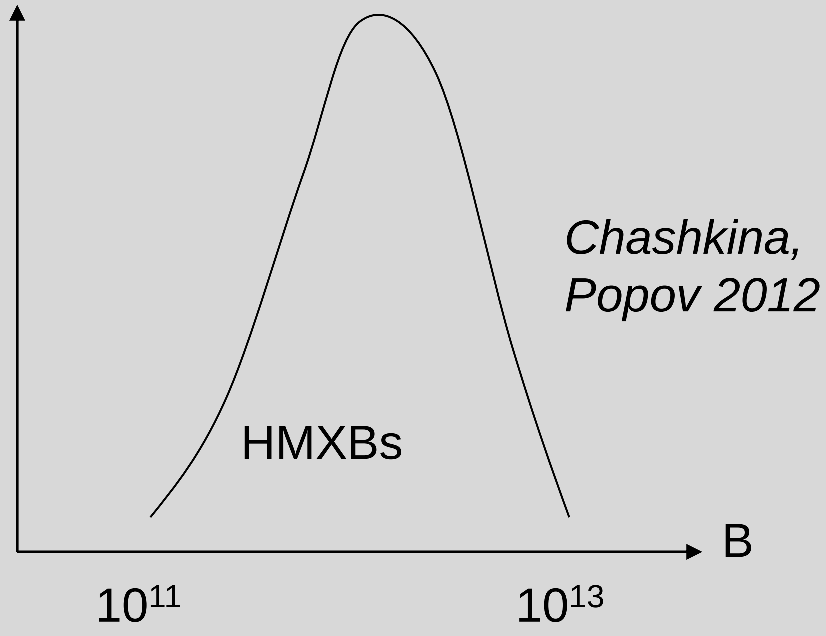
Note, that there is no room for antimagnetars from the point of view of birthrate in many studies of different NS populations.

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

Evolution of CCOs



Popov et al.
MNRAS 2010



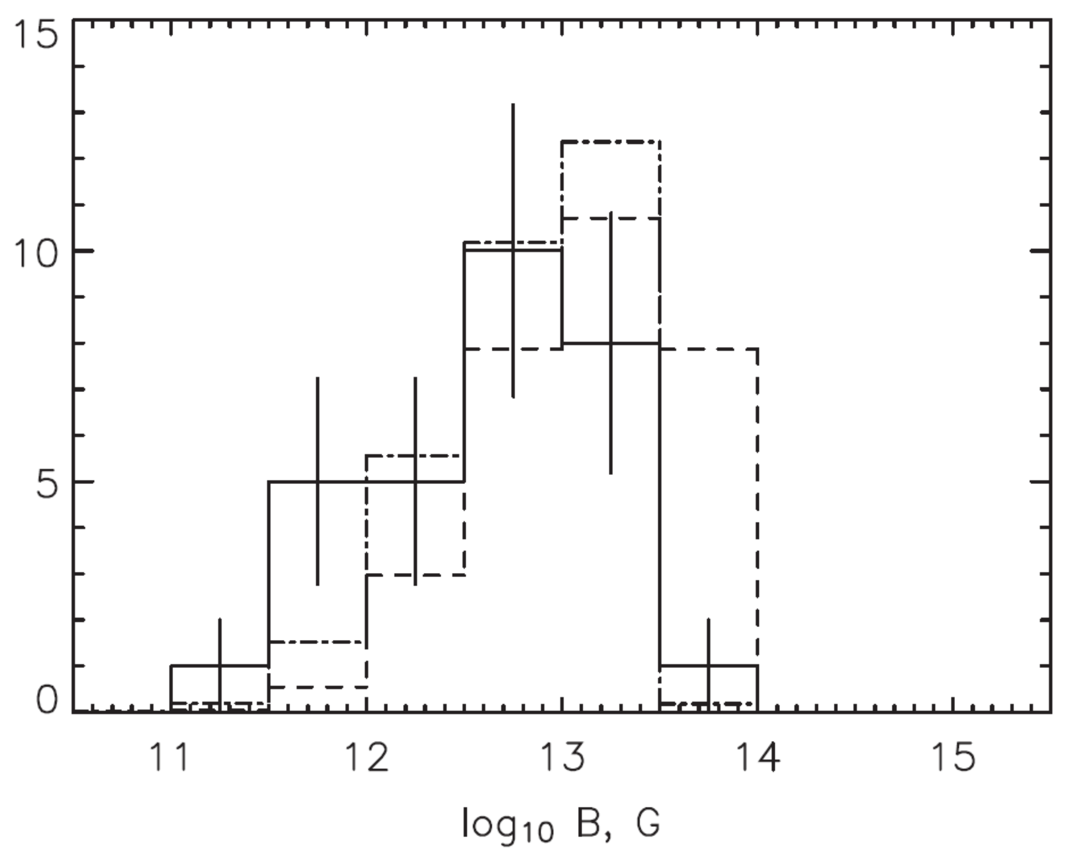
Among young isolated NSs about 1/3 can be related to CCOs.
If they are anti-magnetars, then we can expect that 1/3 of NSs in HMXBs are also low-magnetized objects.
They are expected to have short spin periods. However, there are no many sources with such properties.
The only good example - SAX J0635+0533.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

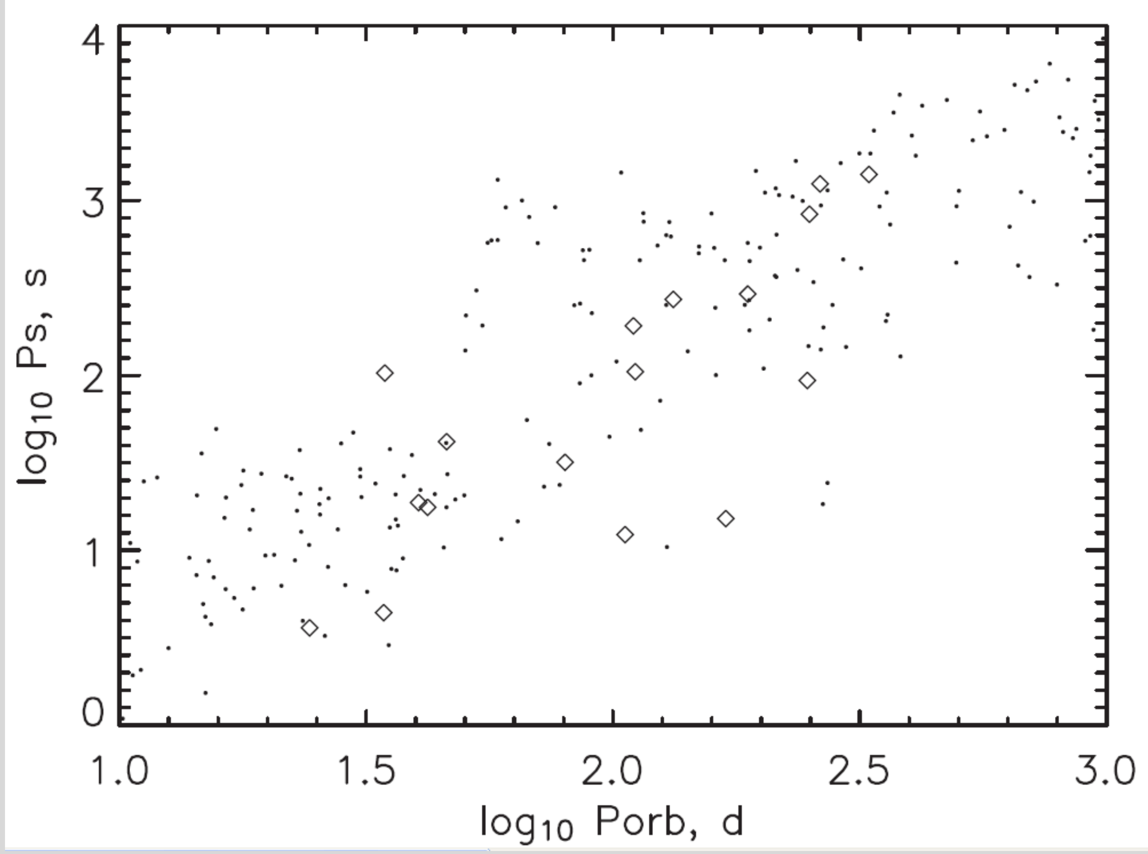
Possible solution: emergence of magnetic field (see physics in Ho 2011, Vigano, Pons 2012).

Observations vs. theory

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.

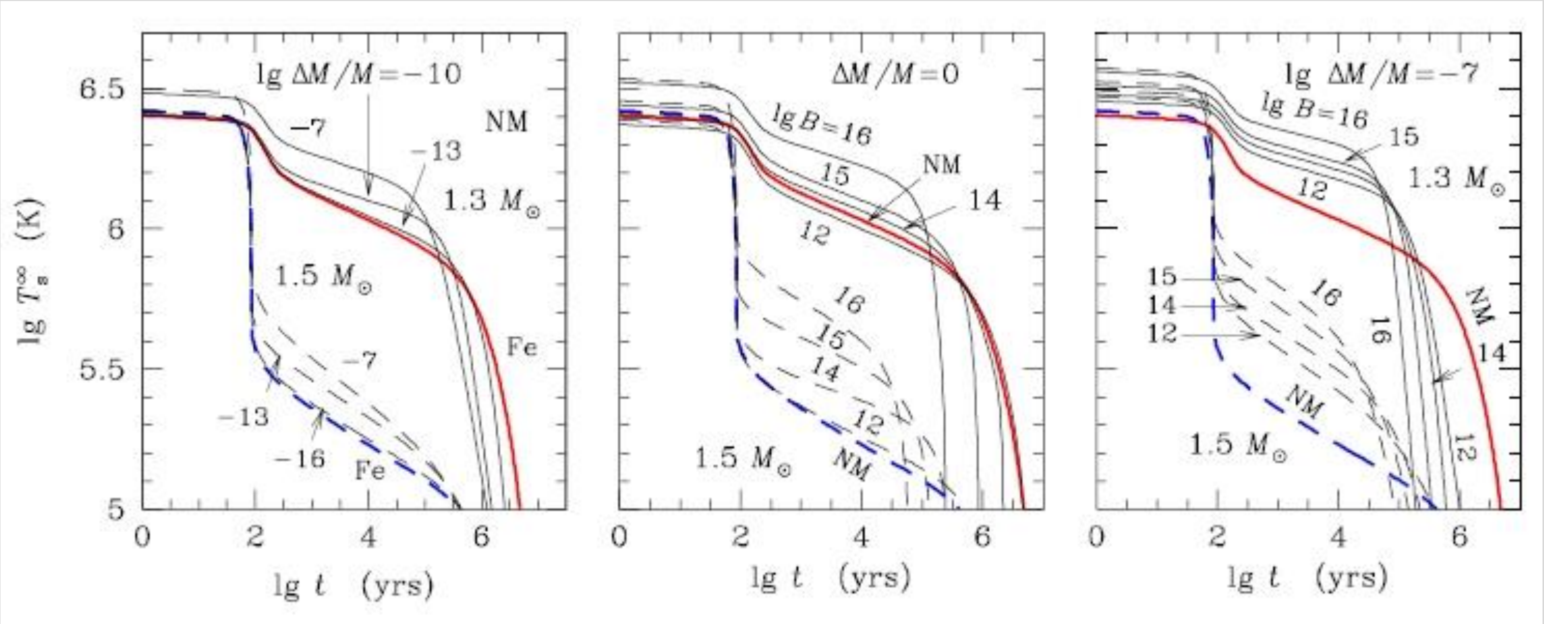
Chashkina, Popov (2012)





Where are old CCOs?

Yakovlev, Pethick 2004

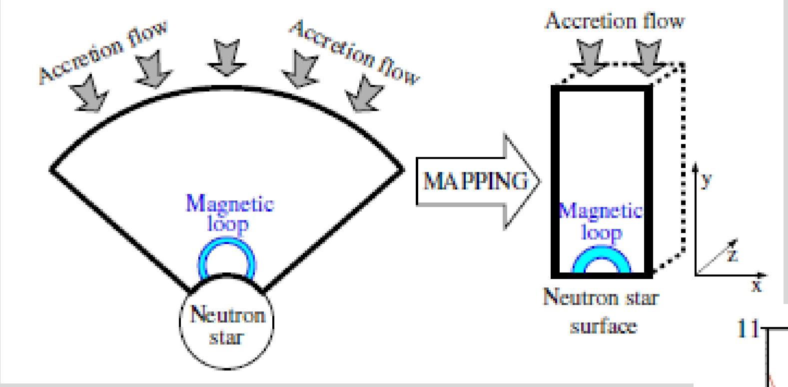


According to cooling studies they have to be bright till at least 10^5 years.
But only one candidate (2XMM J104608.7-594306 Pires et al.) to be a low-B cooling NS is known (Calvera is also a possible candidate).

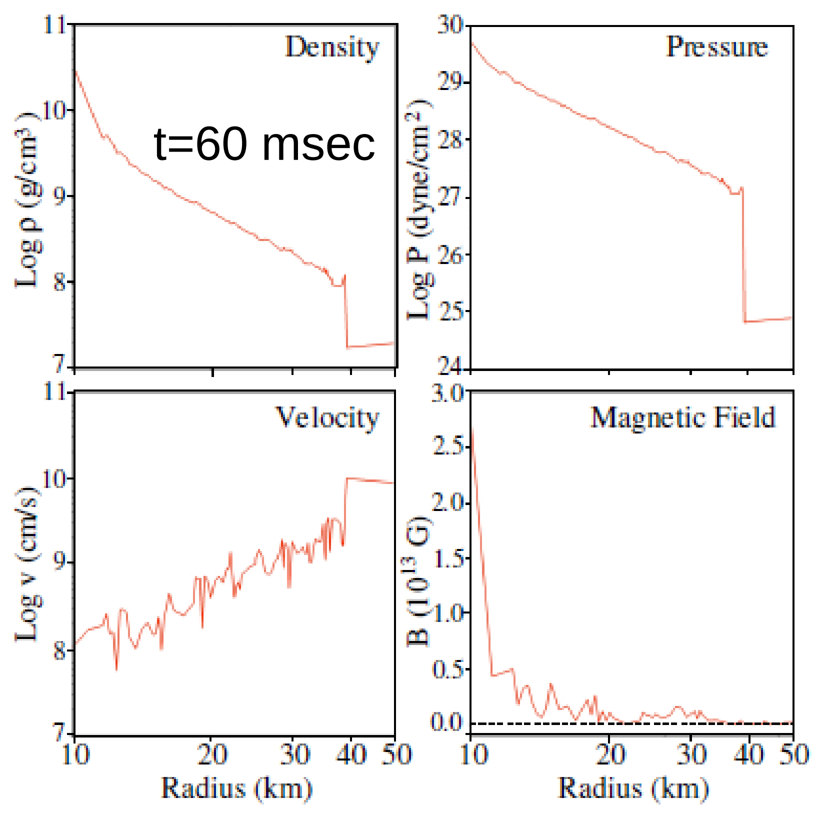
We propose that a large set of data on HMXBs and cooling NSs is in favour of field emergence on the time scale $10^4 \leq \tau \leq 10^5$ years (arXiv:1206.2819).

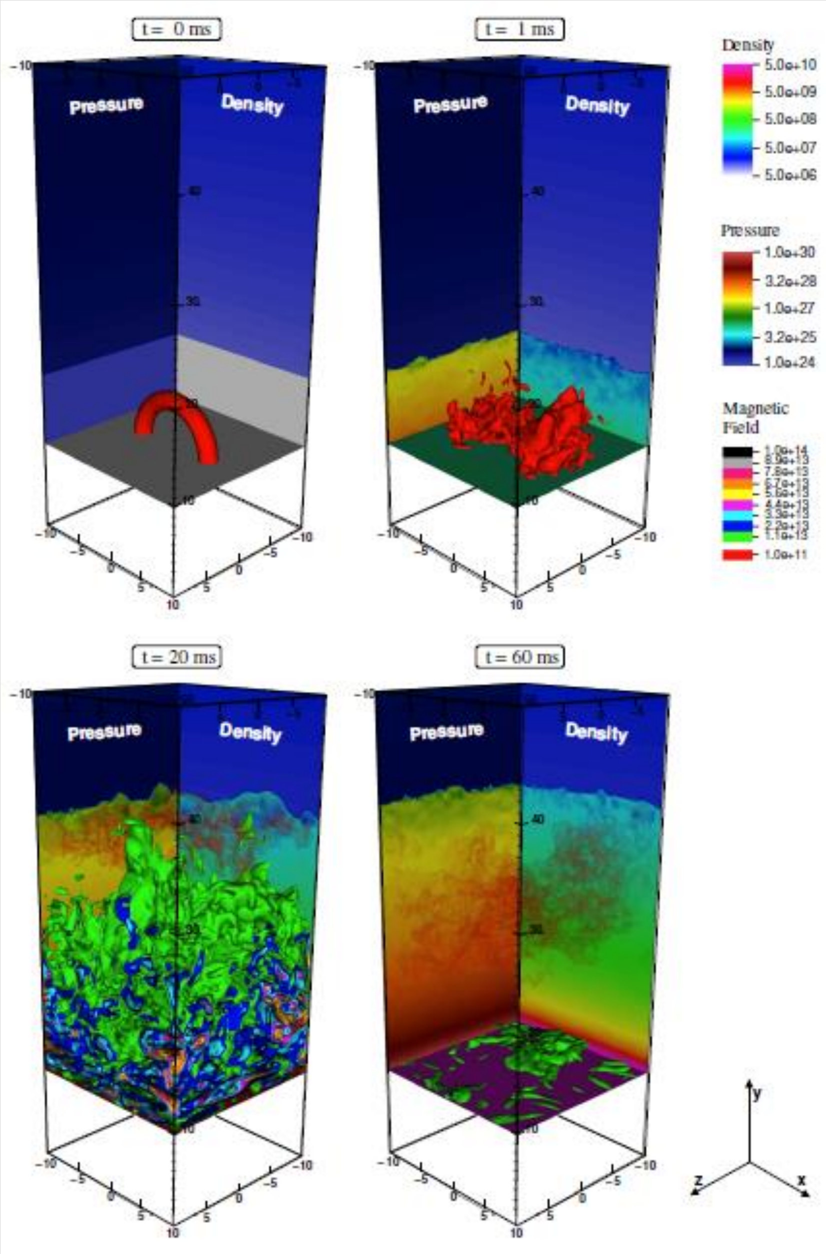
Some PSRs with "additional heating" can be descendants of CCOs with emerged field.

How the field is buried



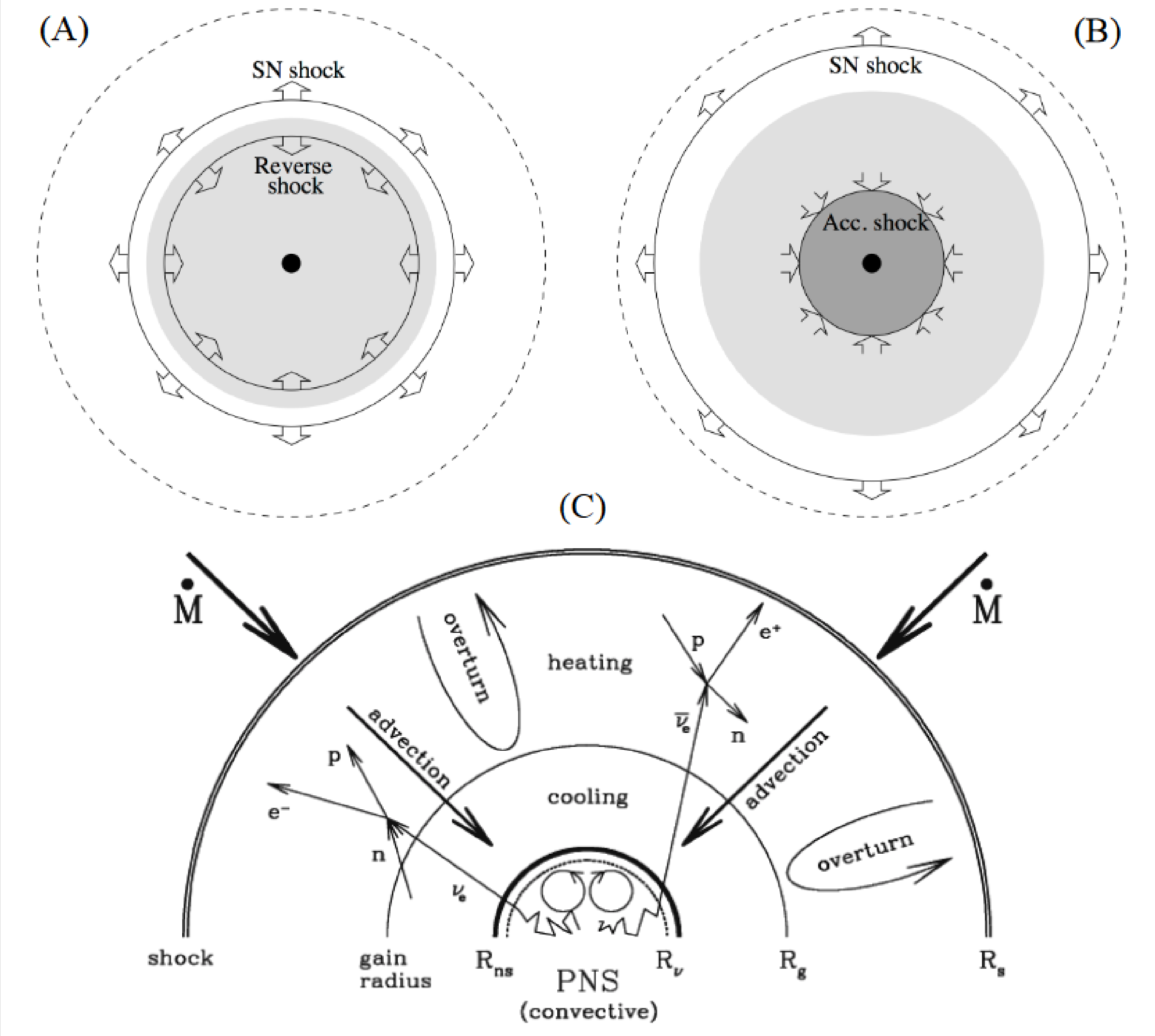
1212.0464

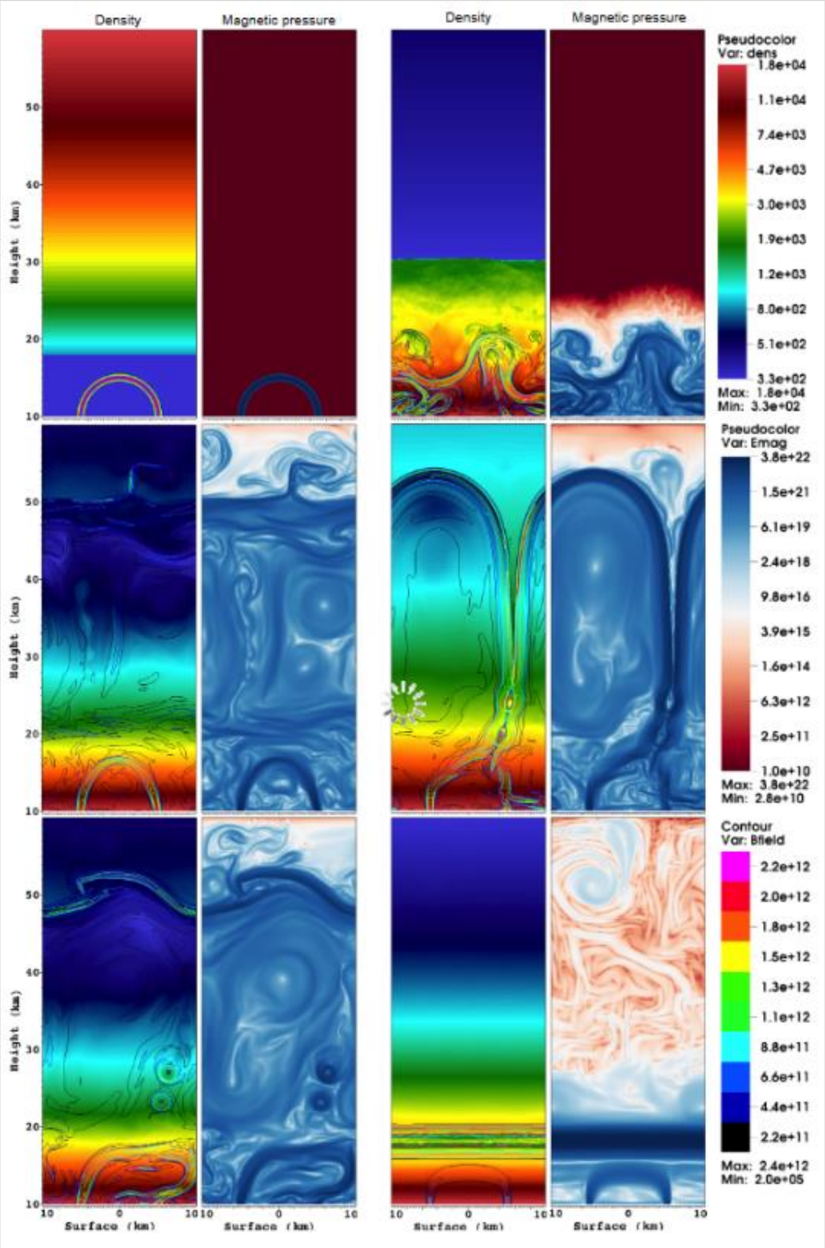




Recent model

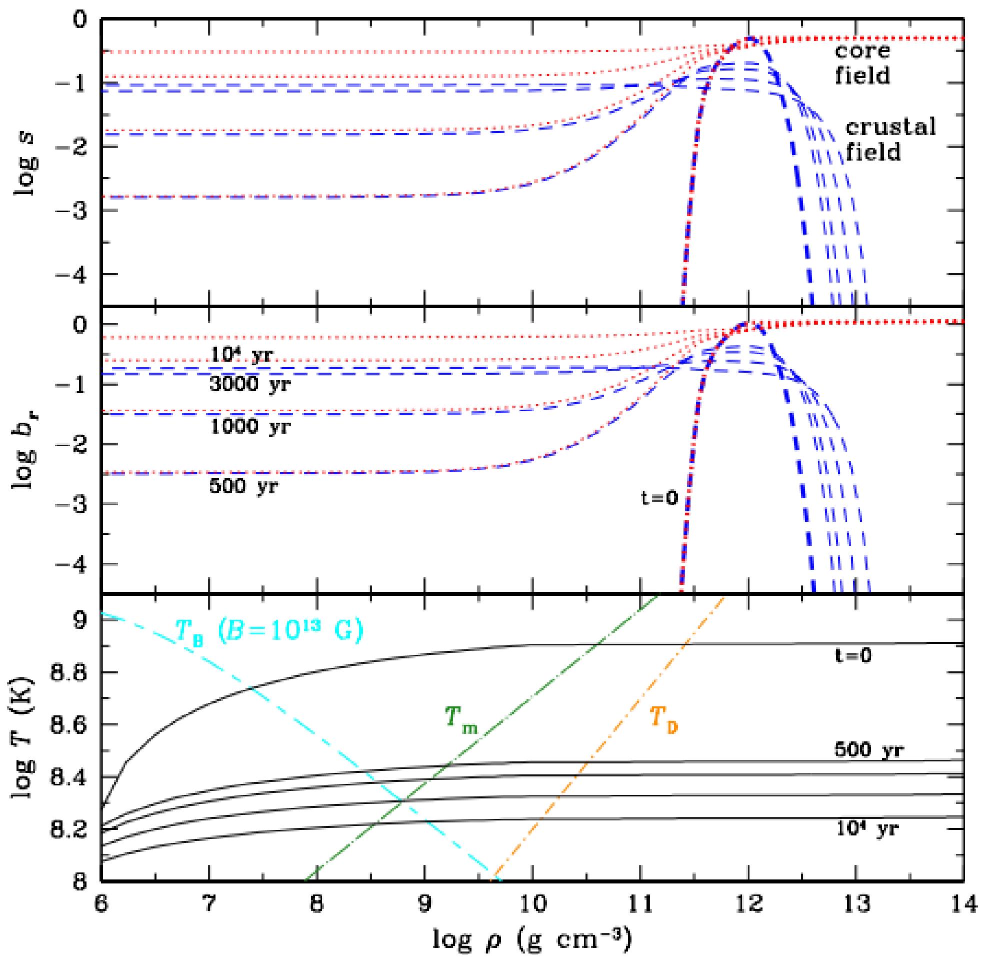
1809.07057



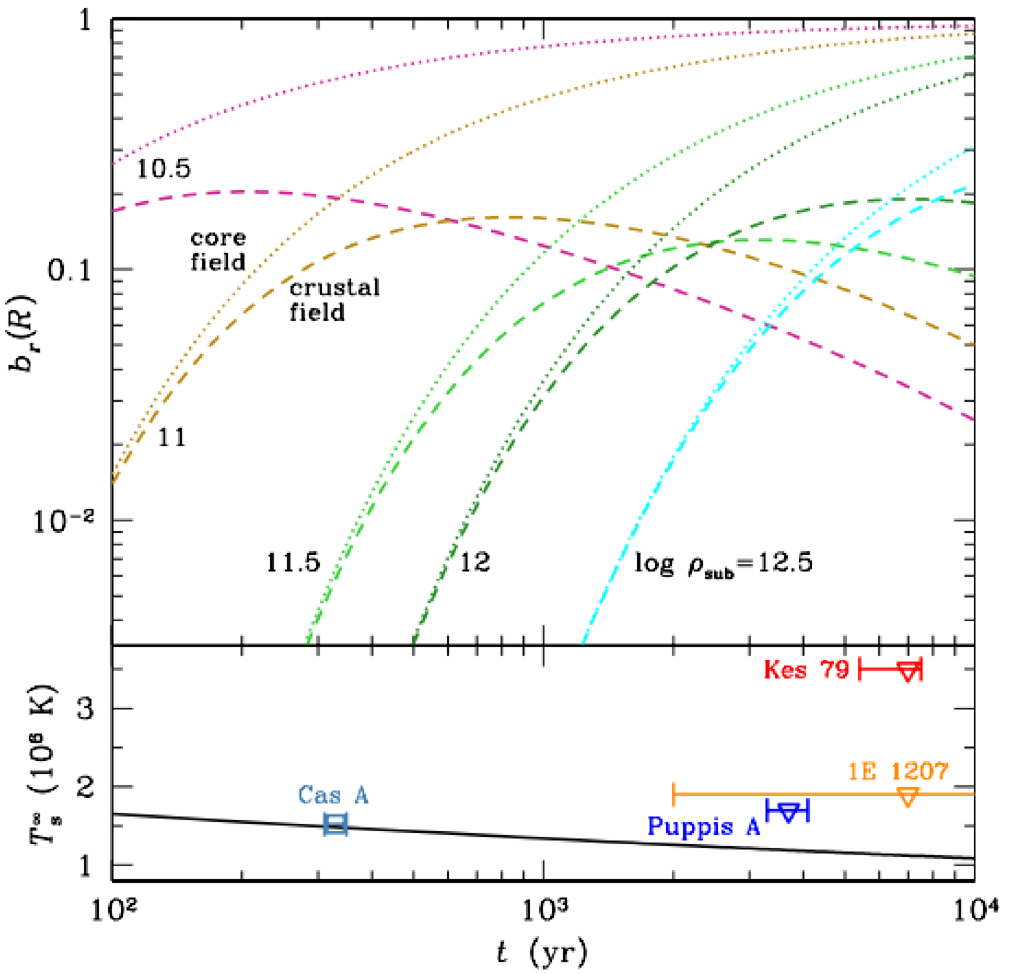


Emerging field: modeling

1D model of field emergence



Dashed – crustal, dotted – core field



Ho 2011

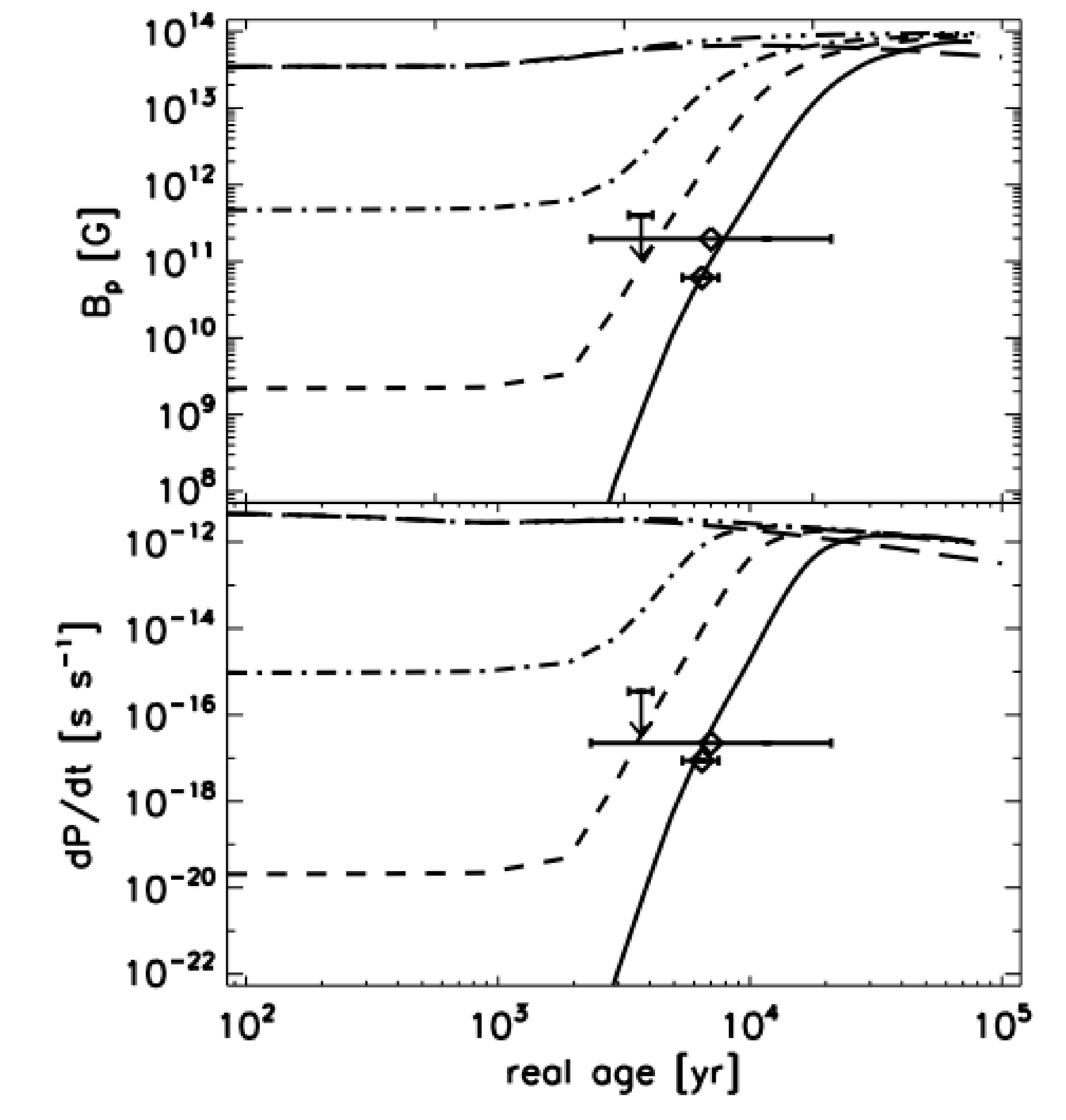
Another model

2D model with field decay

Ohmic diffusion dominates in field emergence, but Hall term also can be important.

Calculations confirm that emergence on the time scale 10^3-10^5 years is possible.

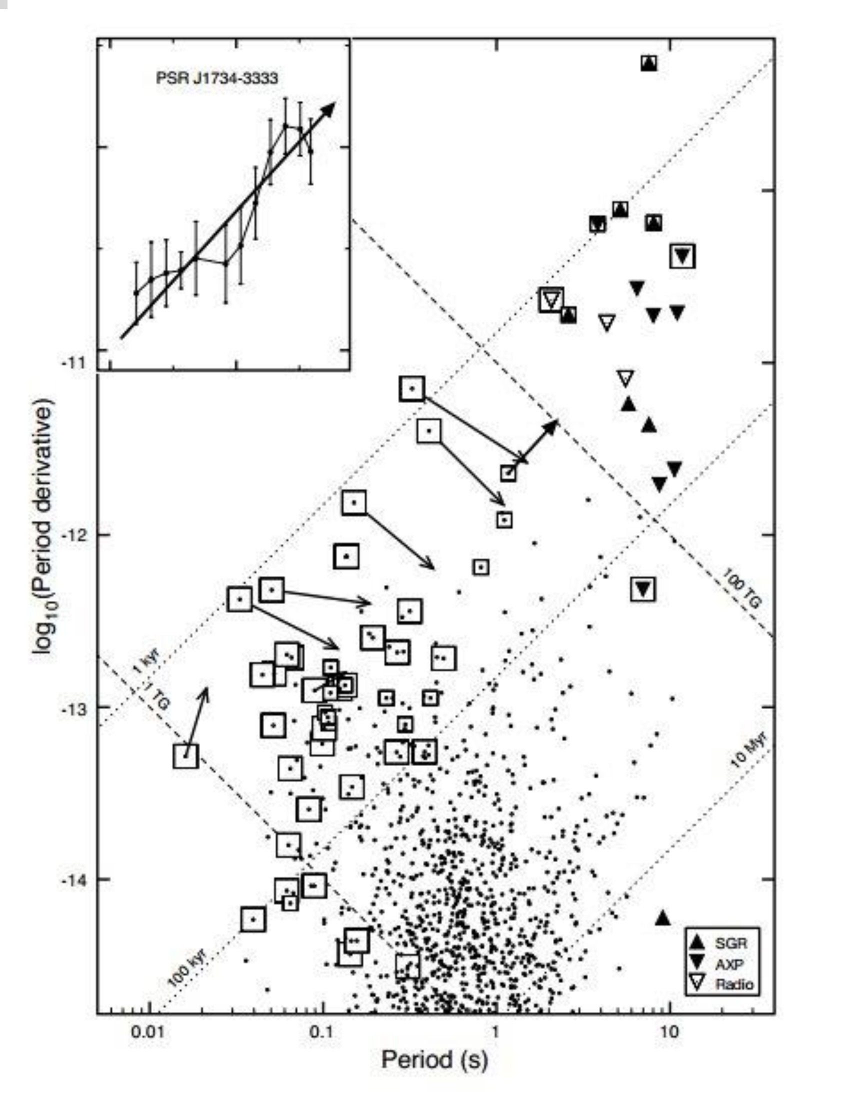
$B_{0p}=10^{14}$ G



Vigano, Pons 1206.2014

Emerged pulsars in the P-Pdot diagram

Espinoza et al. arXiv: 1109.2740, 1211.5276



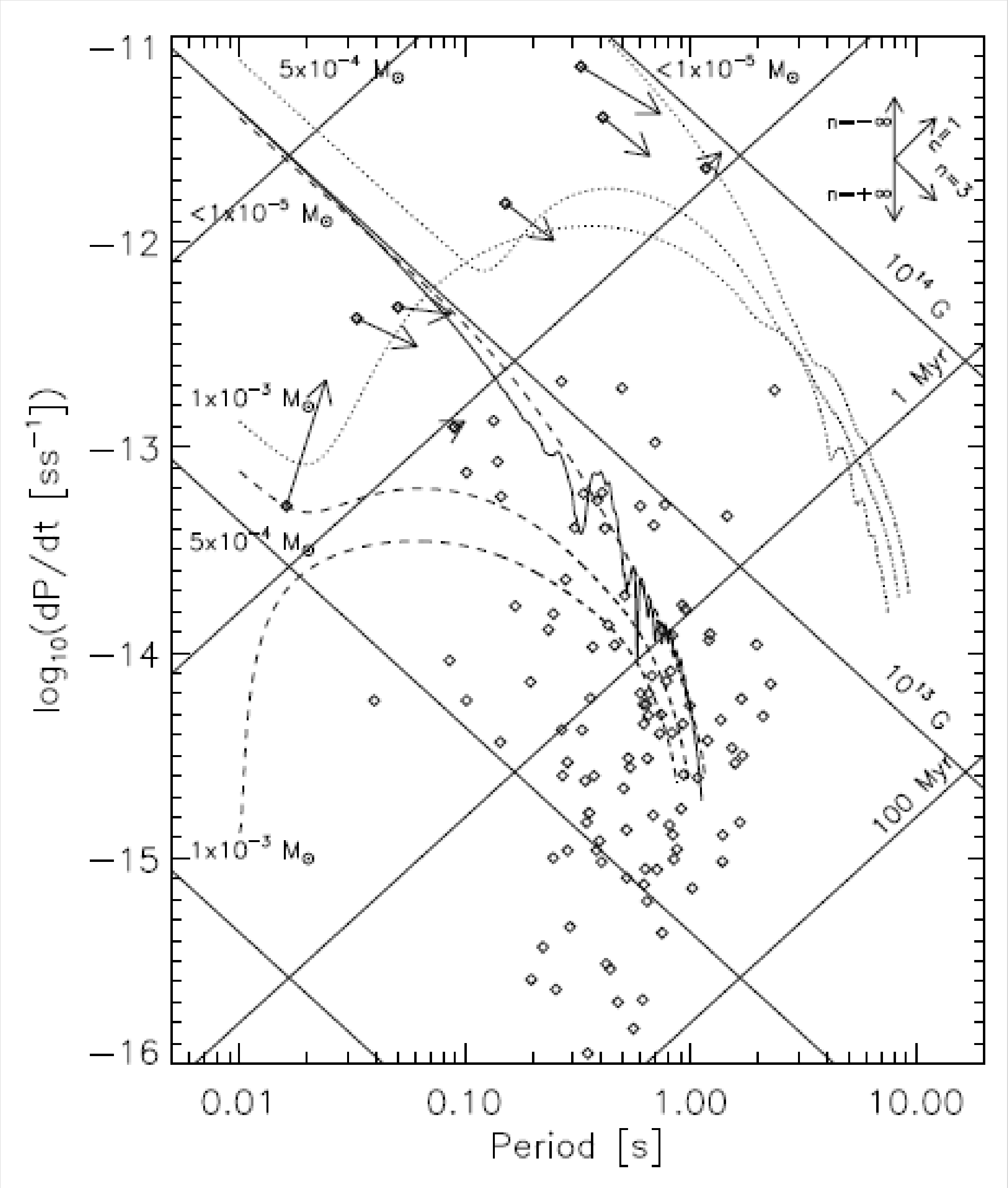
Emerged pulsars are expected to have
P~0.1-0.5 sec
B~10^{11}-10^{12} G
Negative braking indices or at least n<2.
About 20-40 of such objects are known.

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).

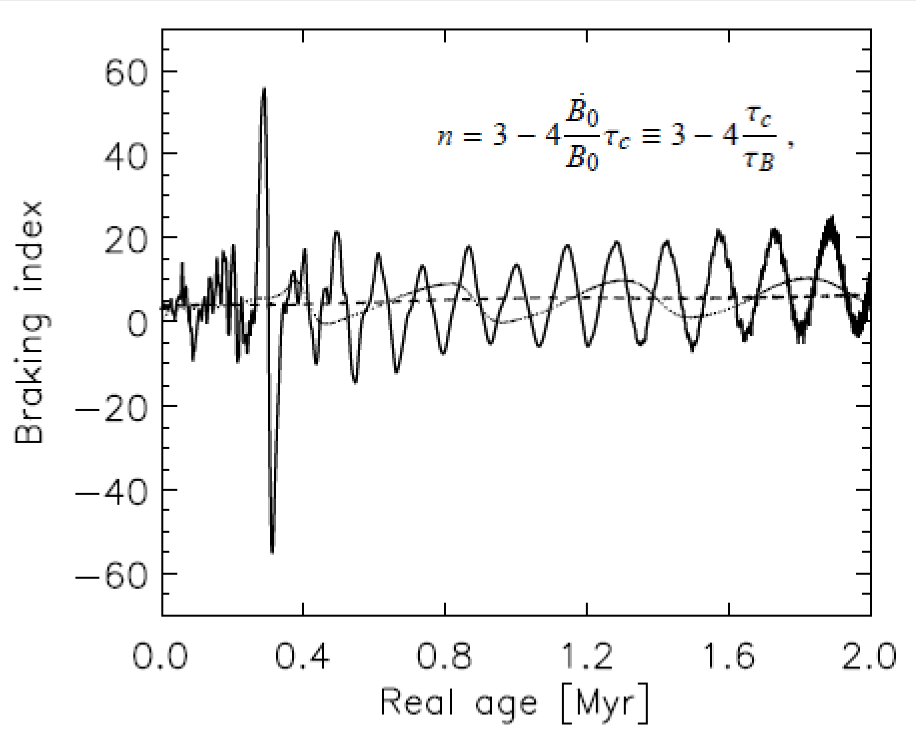
Part of PSRs supposed to be born with
long (0.1-0.5 s) spin periods can be
matured CCOs.

Evolution of PSRs with evolving field



Three stages:

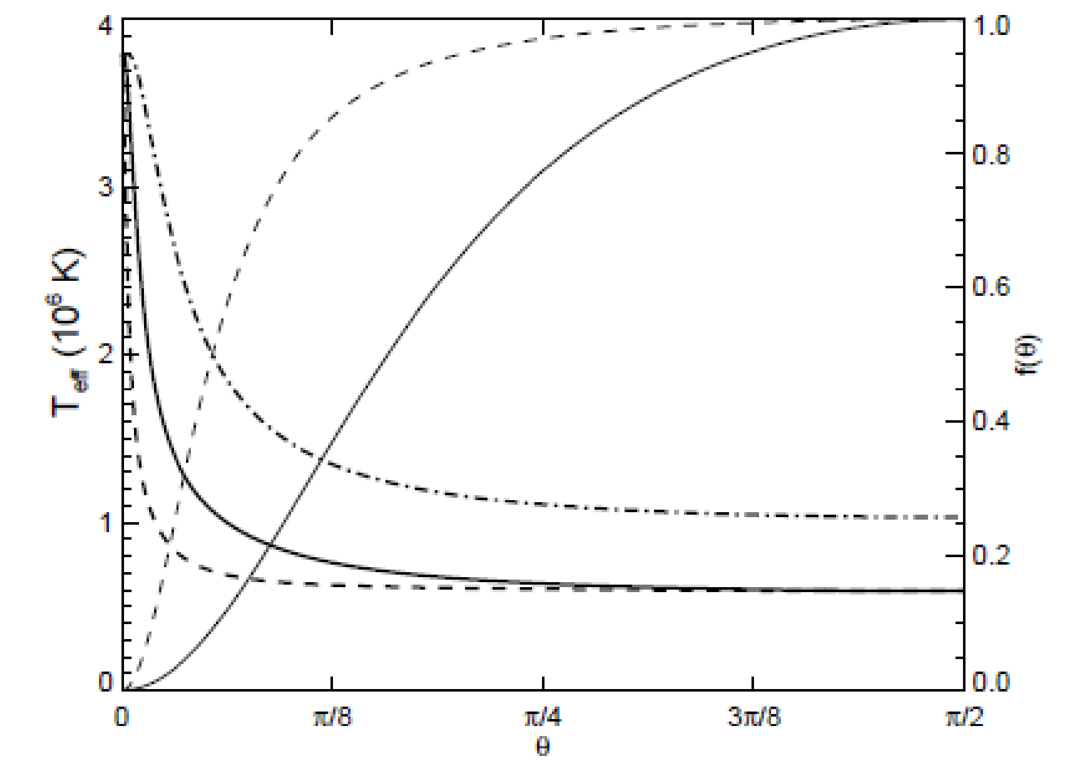
1. n<=3 Standard + emerging field
2. n>3 Ohmic field decay
3. oscillating and large n – Hall drift

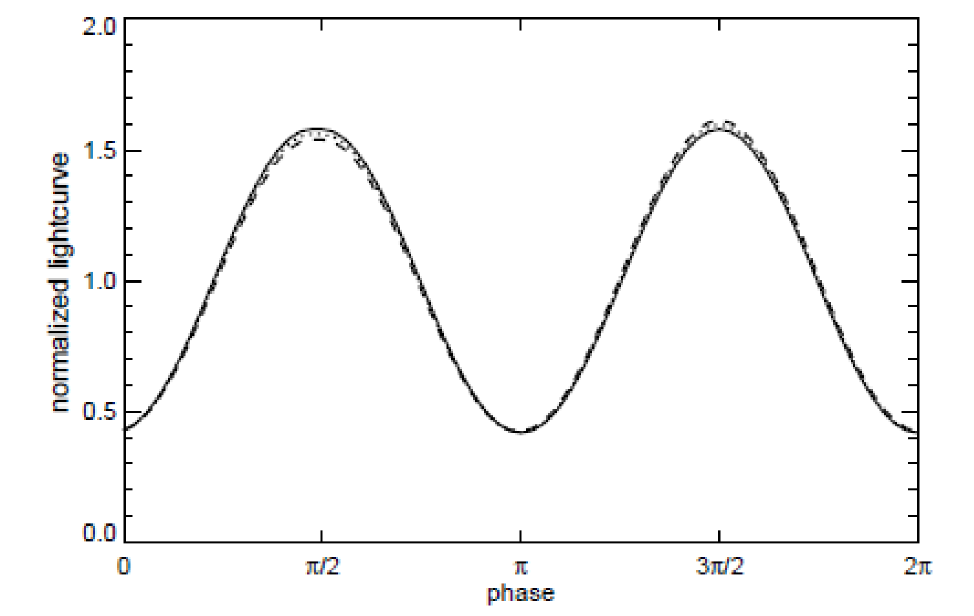


1209.2273

Buried field in Kes79?

The idea is to reconstruct surface temperature distribution, and then calculate which field configuration can produce it.

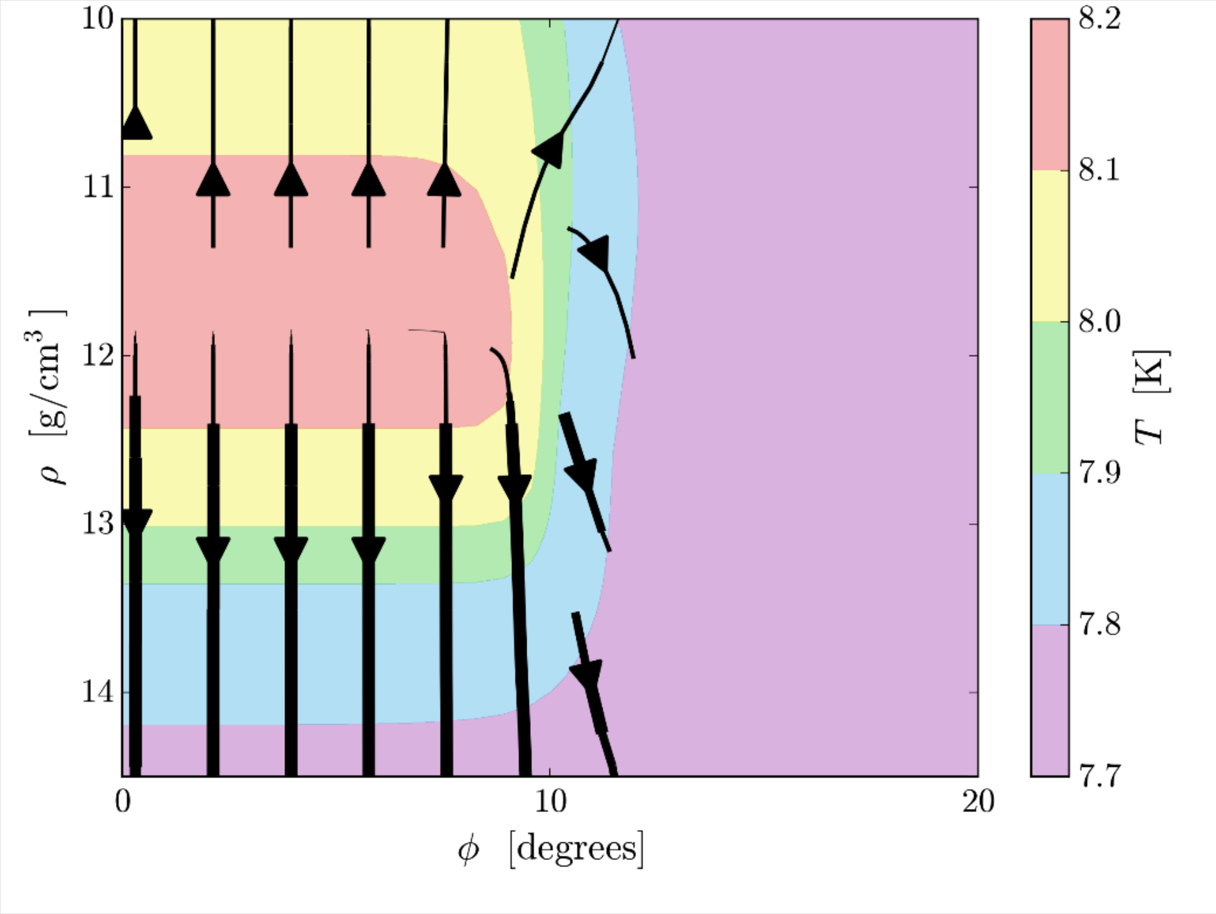


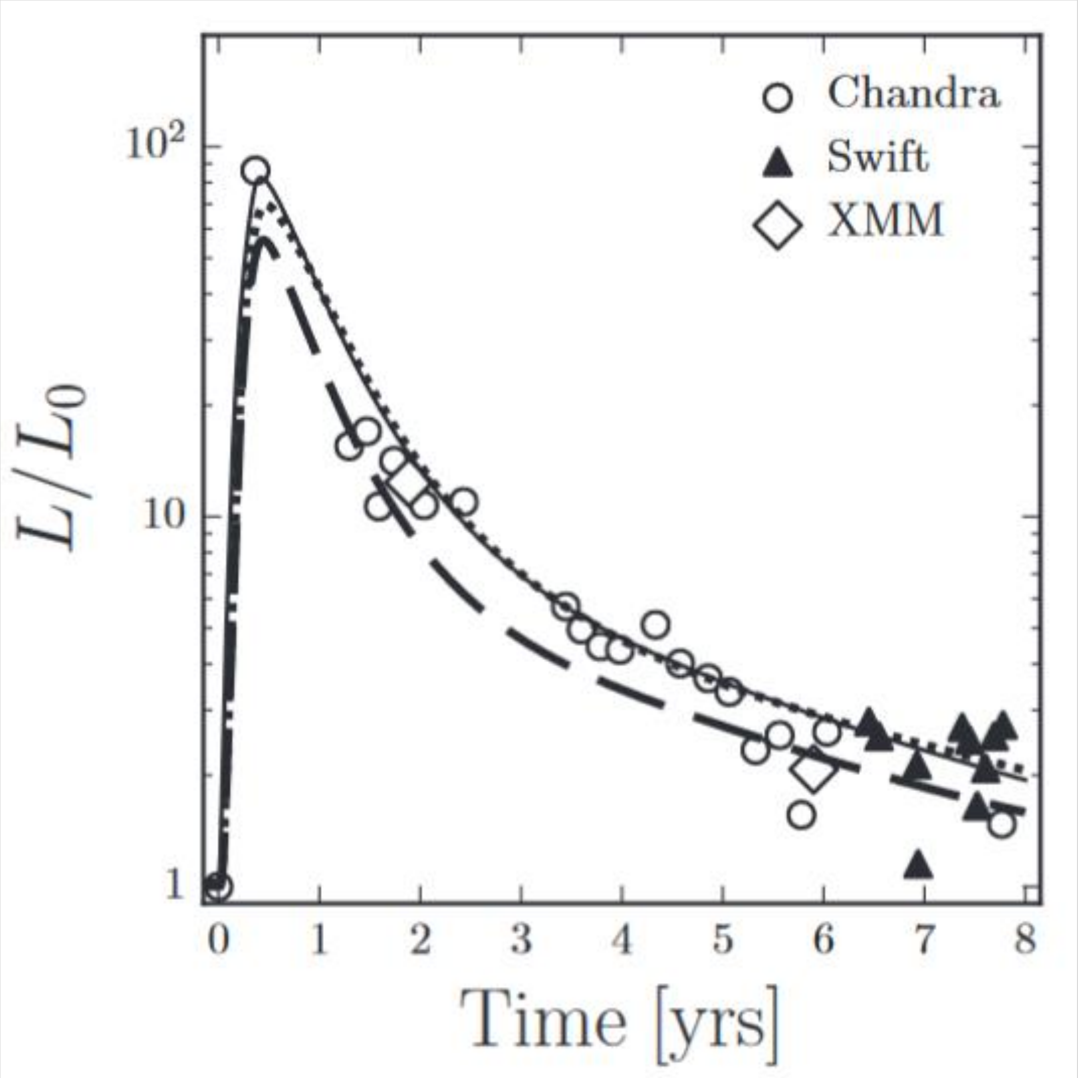


1110.3129

Very large pulse fraction (64%) in the anti-magnetar Kes 79.
Large sub-surface magnetic field can explain
the existence of compact hot spots.
Then the field must have been buried in a fall-back episode.

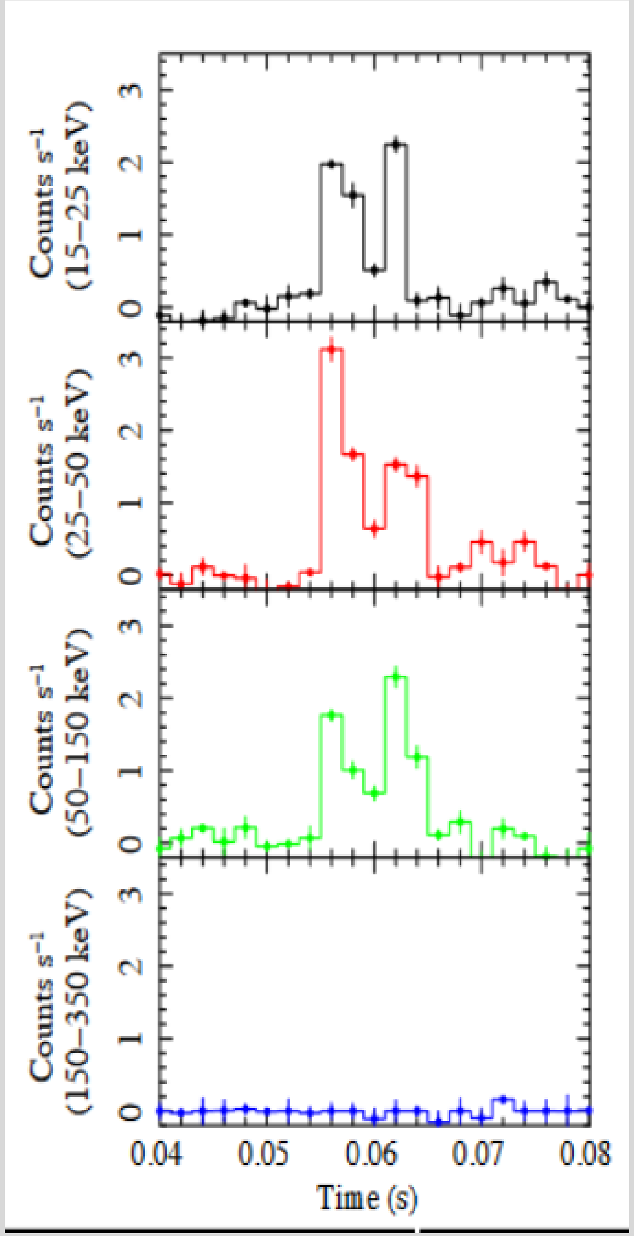
Hidden magnetar in RCW103



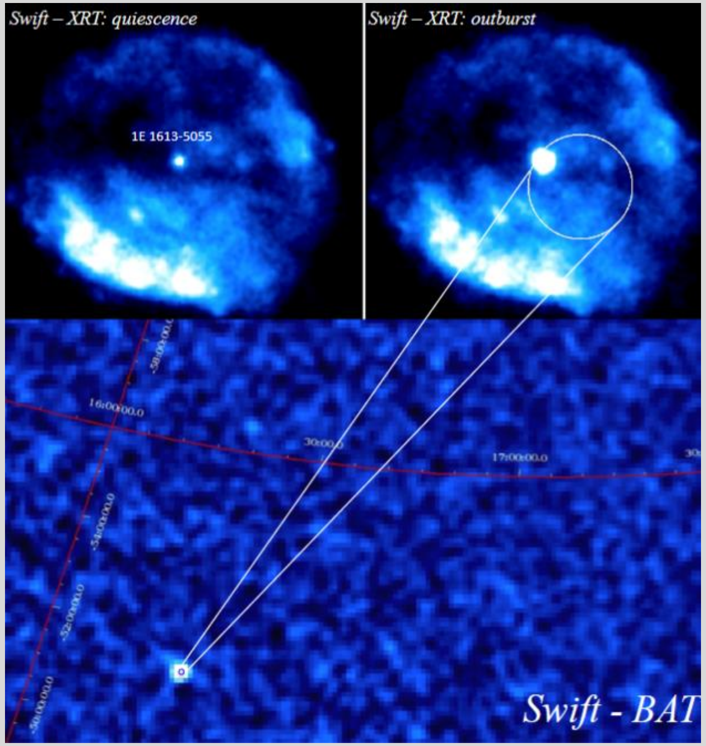


1504.03279

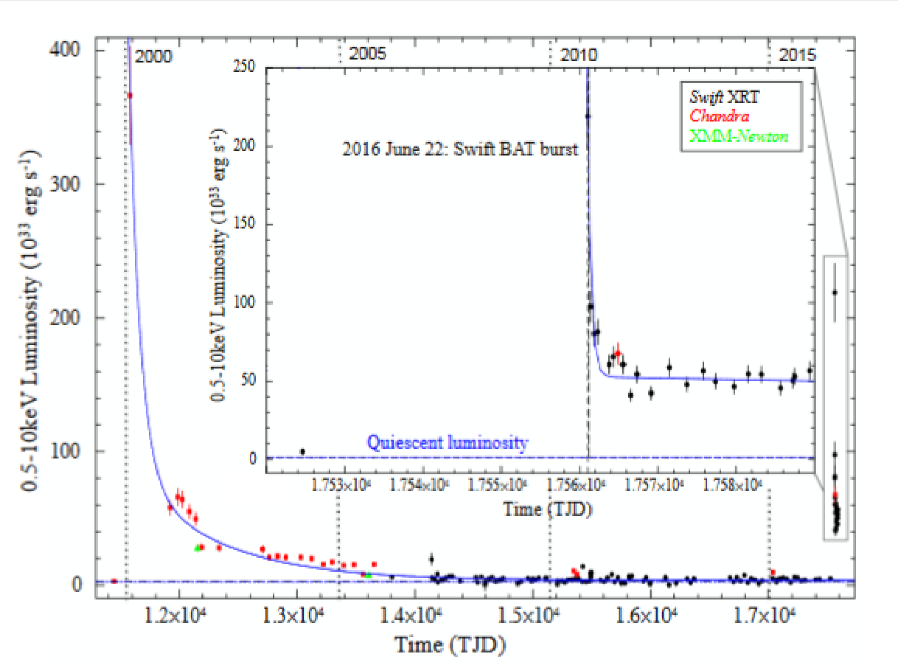
Not so hidden!



1607.04107



Typical SGR activity was reported.



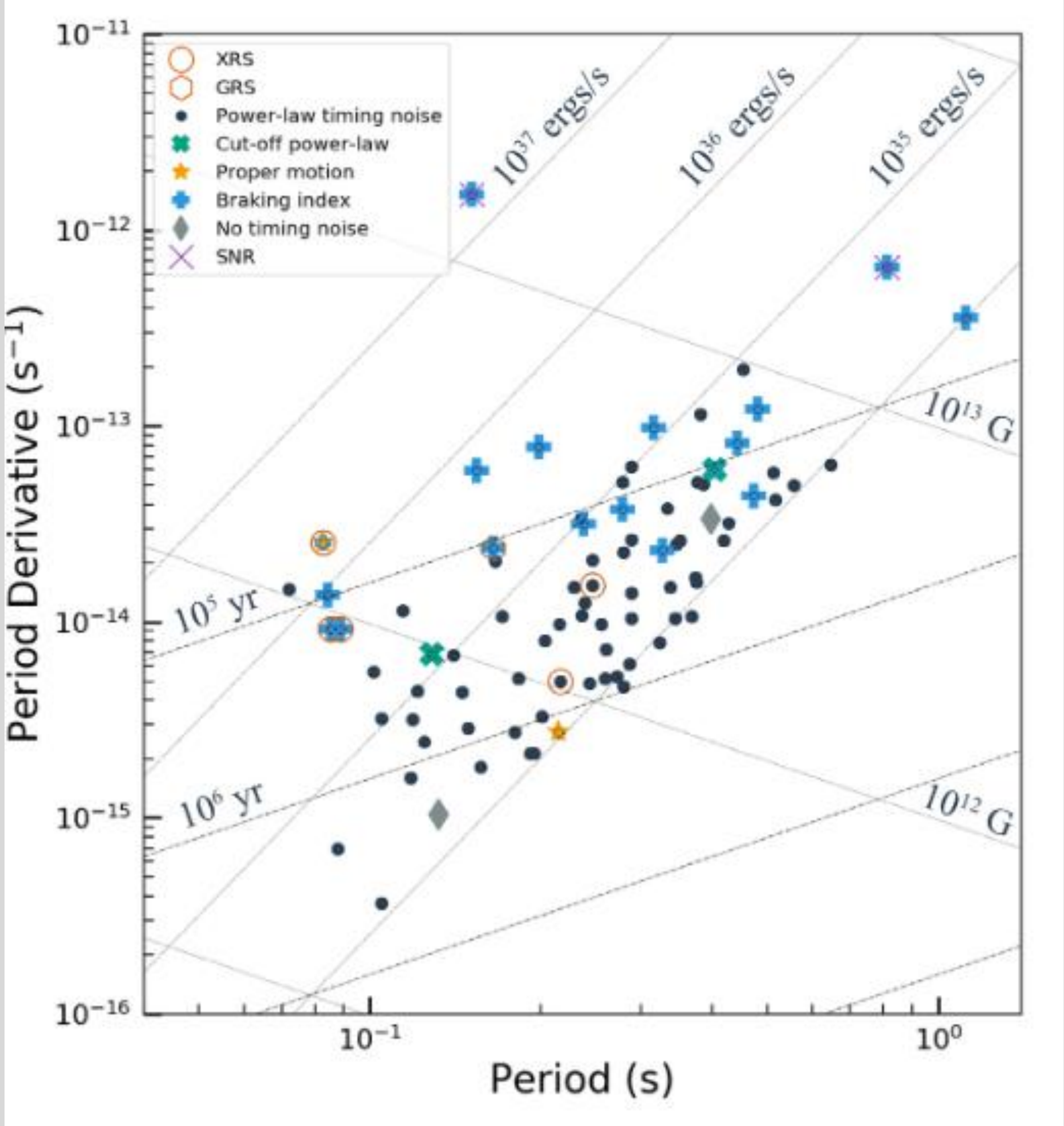
1607.04264

Pulsar timing

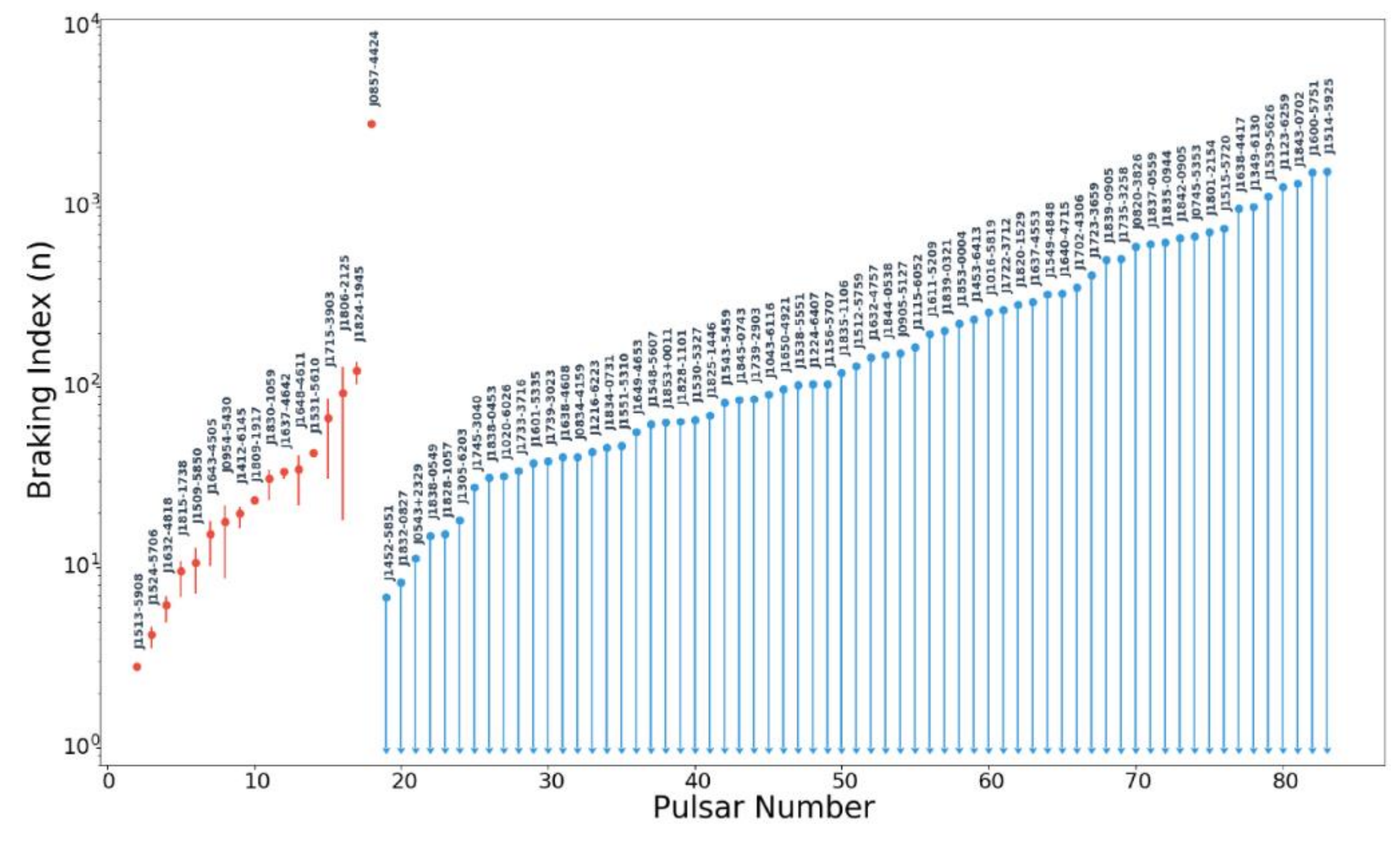
Recently, Parthasarathy et al. (2019) presented detailed timing of 85 pulsars.

For many of them braking indices were measured.

We analyze different approaches to explain these results, and conclude that the best explanation is related to an episode of field decay in young, still relatively hot, NSs.



Braking index measurements



$$n = \frac{\Omega\ddot{\Omega}}{\dot{\Omega}^2} = 2 - \frac{P\ddot{P}}{\dot{P}^2}.$$

$$P\dot{P} = \frac{2}{3}\beta B_p^2$$

where β is:

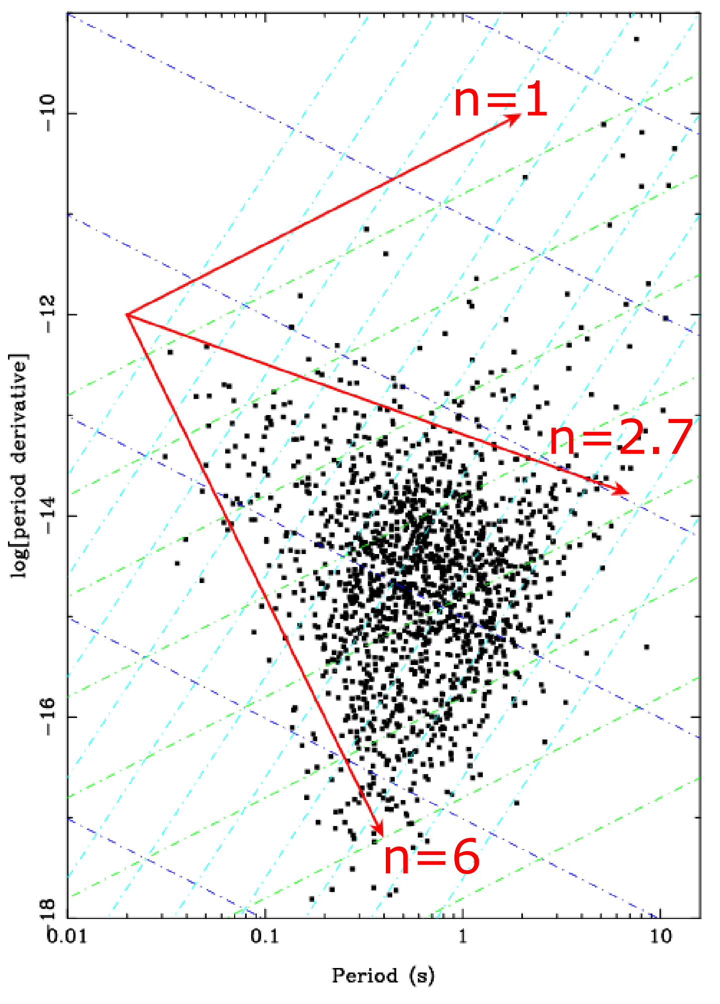
$$\beta = \frac{\pi^2 R_{\rm NS}^6}{Ic^3},$$

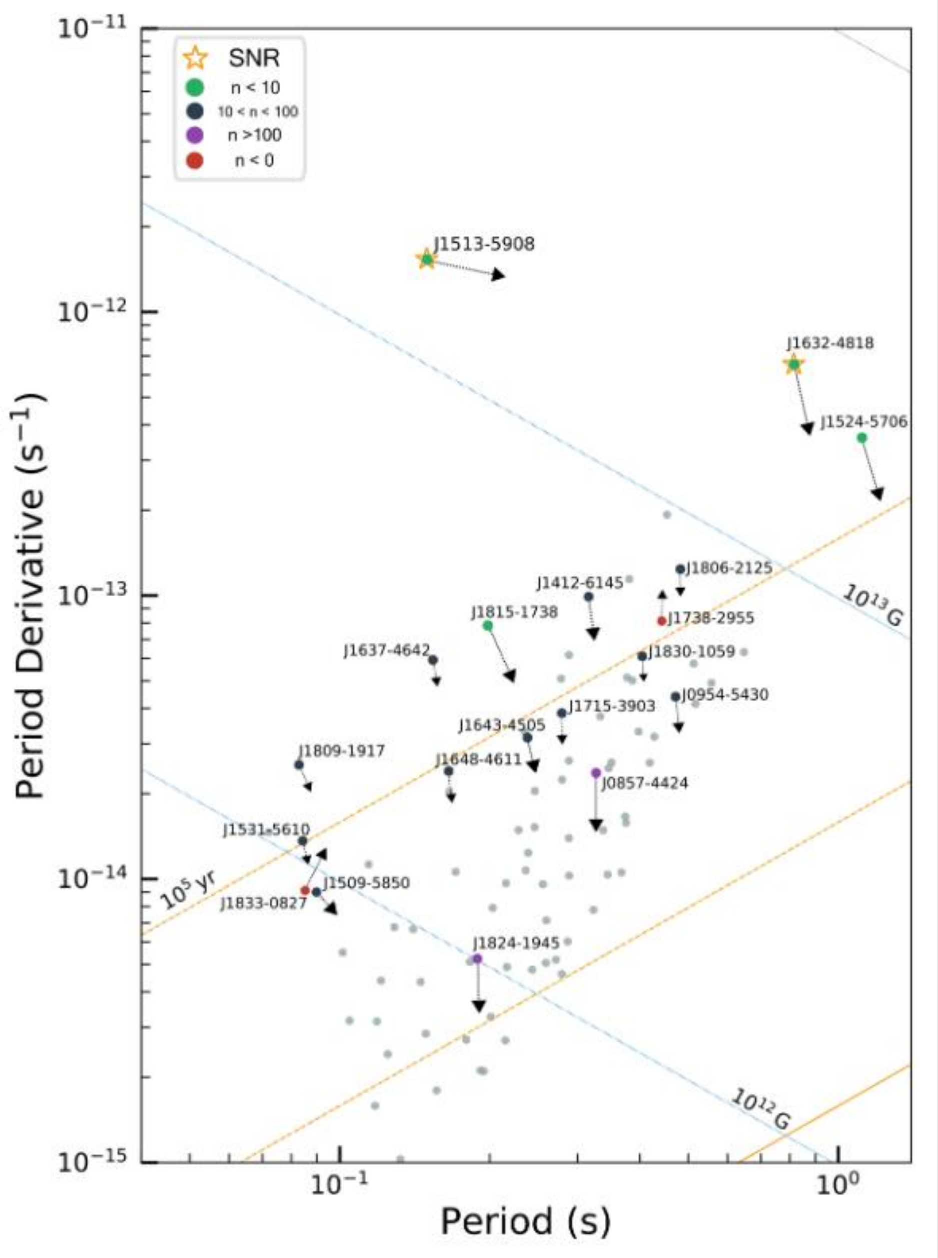
Parthasarathy et al. (2020) MNRAS 494, 2012

Braking and P-Pdot

For constant field n=3.
n>3 can be an indication of decaying fields.

1702.03616





Parthasarathy et al. (2020) MNRAS 494, 2012

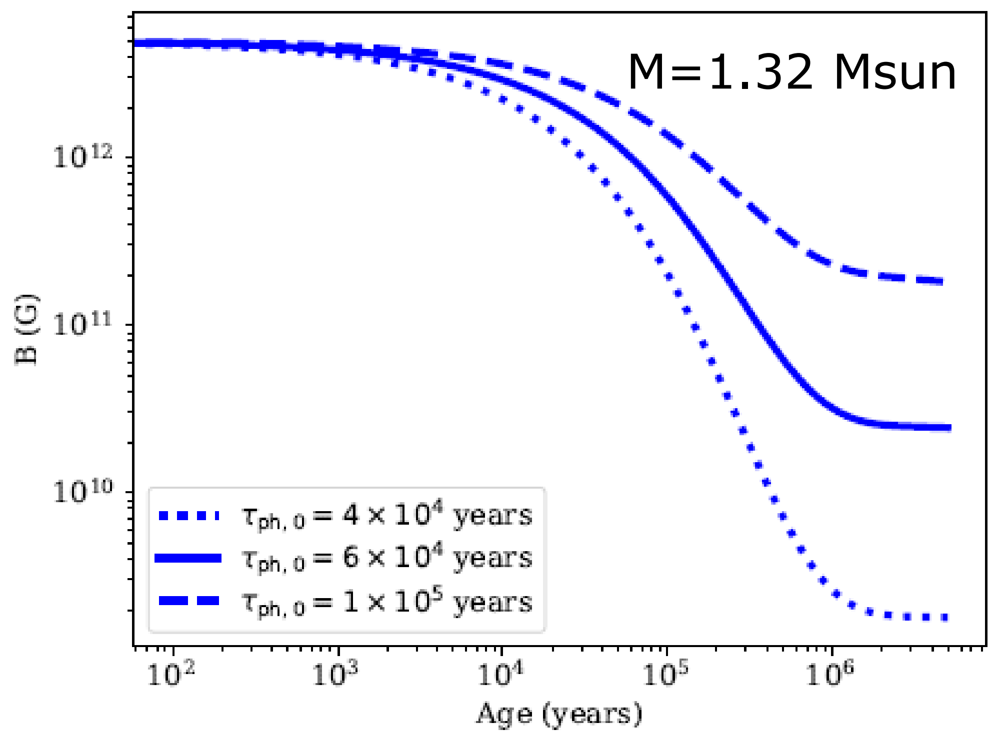
Large braking indices due to field decay

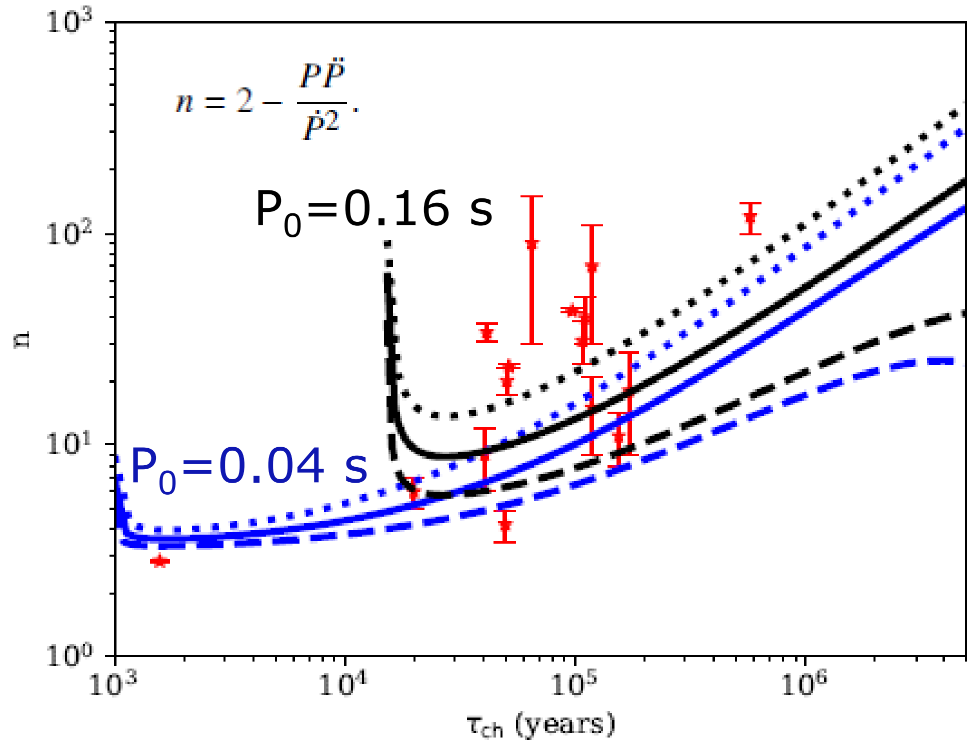
$$\tau_{\rm ph} = 2.2\,{\rm Myr}\,\frac{\rho_{14}^{15/6}}{T_8^2}\left(\frac{Y_{\rm e}}{0.05}\right)^{5/3}\left(\frac{Y_{\rm n}}{0.8}\right)^{10/3}\left(\frac{f}{0.5}\right)^{2}\left(\frac{g_{14}}{2.45}\right)^{-2} = \frac{\tau_{\rm ph,0}}{T_8^2} \qquad (13)$$

$$n = 3 - 2\frac{P}{\dot P}\frac{\dot B_p}{B_p}.$$

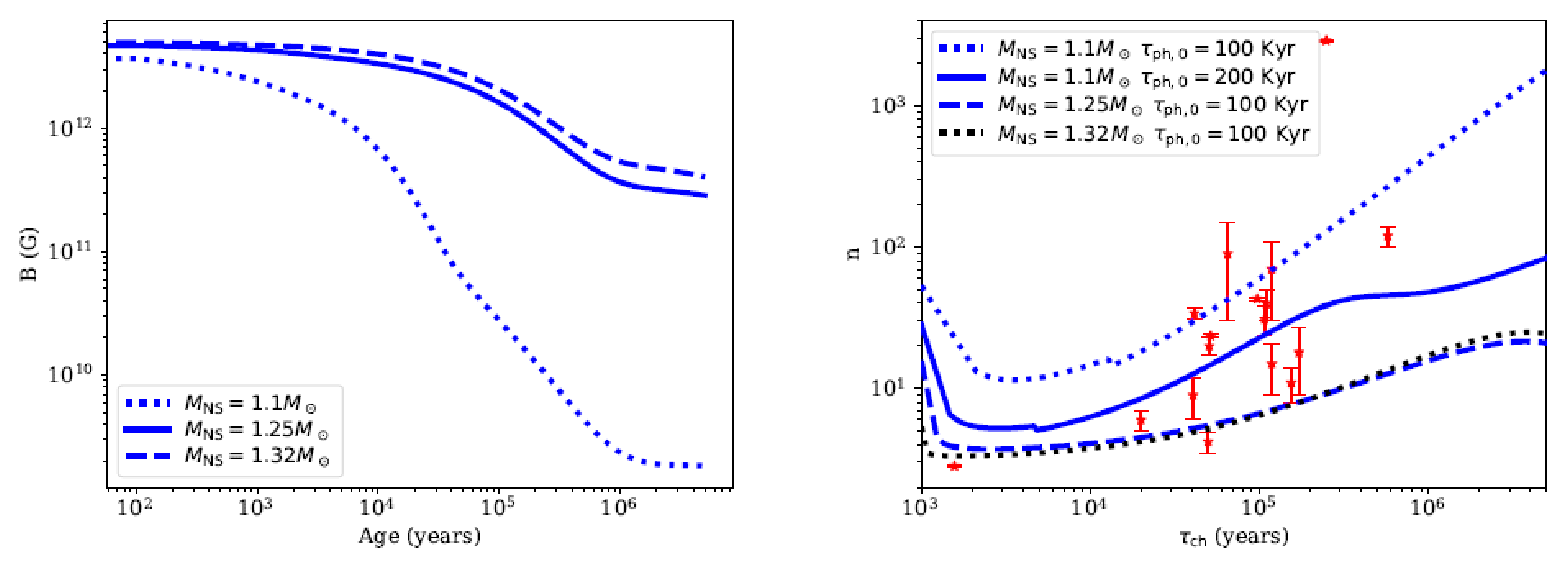
$$n = 3 + 2\frac{P}{\dot P}\frac{1}{\tau_{\rm Ohm}}.$$

$$n = 3 + 4\frac{\tau_{\rm ch}}{\tau_{\rm Ohm}}.$$



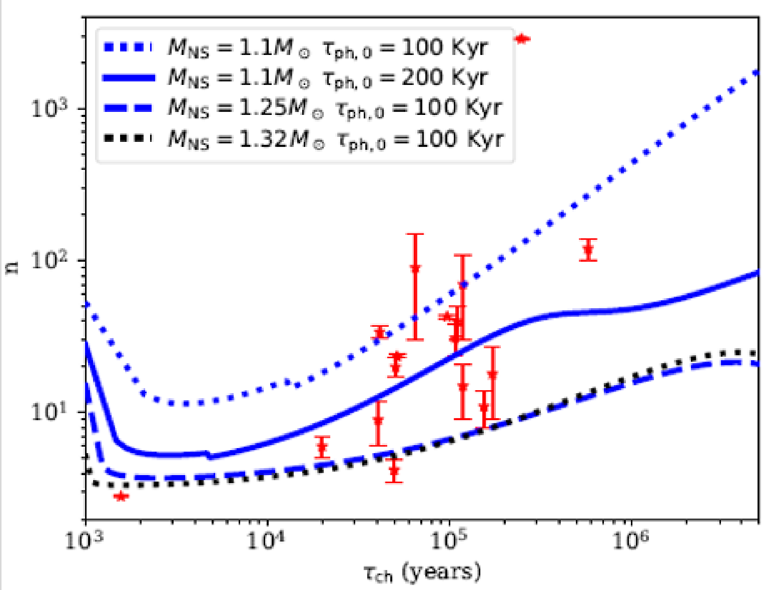


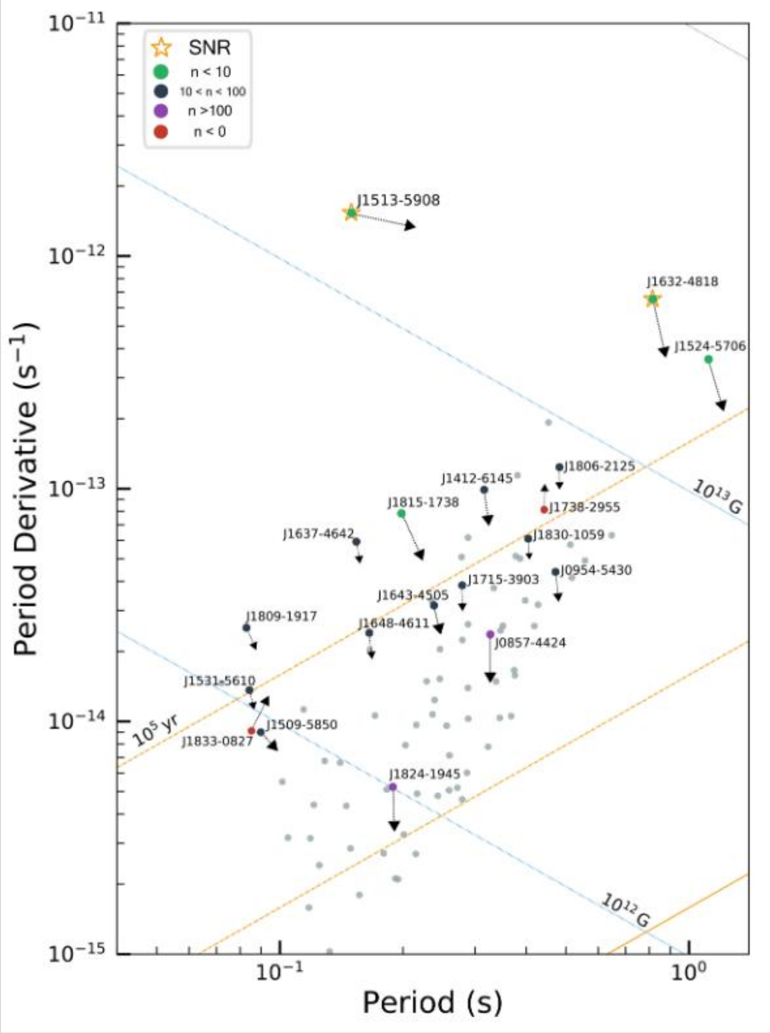
Field decay is due to phonons



Lighter NSs (M~1-1.2 Msun) have higher temperatures, and so – more rapid field decay due to phonons at ages ~few kyrs.
This can explain large braking indices of radio pulsars.

What we have





We analyzed different models to explain large braking indices recently measured for a sample of normal radio pulsars.

We conclude that these results can be better explained in the model of magnetic field decay in low-mass NSs due to scatter of electrons off crystal phonons.

These findings are in correspondence with our previous results on magnetic field decay in young normal radio pulsars.

Conclusions

• Decaying magnetic field results in additional heating of a NS and decreasing its spin-down rate.

• Field decay can be more important for large initial fields, for "standard" fields (~10^{12} G) it is not important,
but can be detectable. Recent studies indicate
that in the life of normal radio pulsars there is a period when their magnetic field decay.

• It is possible to describe different types of young NSs (PSRs, magnetars, M7 etc.)
in the model with decaying magnetic field.

• Re-merging magnetic field can be an important ingredient.

• With re-emerging field we can add to the general picture also CCOs.

•Hall cascade (and attractor) can be an important ingredient of the field evolution:

- At the moment we cannot state that we see the Hall attractor in the population of normal radio pulsars;
- Also, we do not see that any of the M7 are at the Hall attractor stage with properties predicted by GC2013;
- Probably, the attractor stage is reached later, or its properties are different form the predicted ones.

Papers to read

- Cumming et al.
  “Magnetic field evolution in neutron star crust due to Hall effect and Ohmic decay”
  astro-ph/0402392

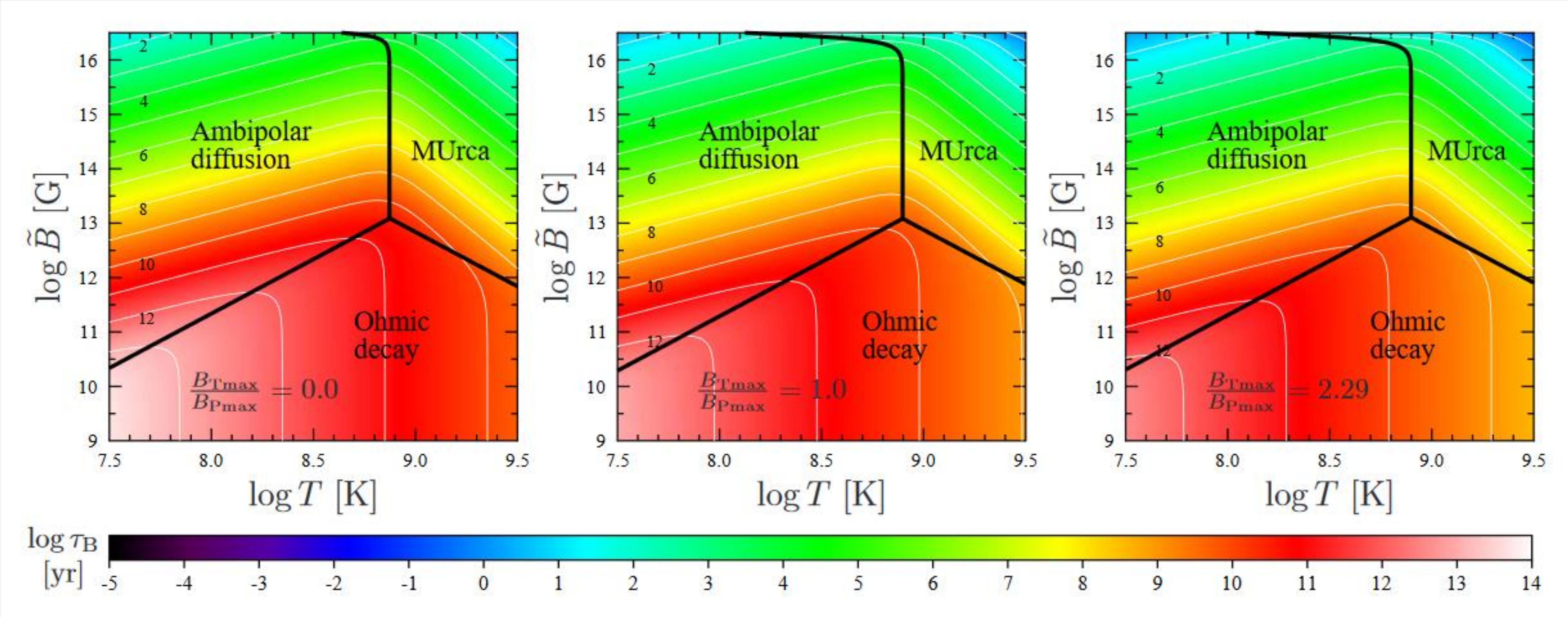
- Pons, Vigano
  “Magnetic, thermal and rotational evolution of isolated neutron stars”
  arXiv: 1911.03095

- Gusakov et al.
  “Magnetic field evolution timescales in superconducting neutron stars”
  arXiv: 2010.07673

- Igoshev, Popov
  “Braking indices of young radio pulsars: theoretical perspective”
  arXiv: 2008.11737

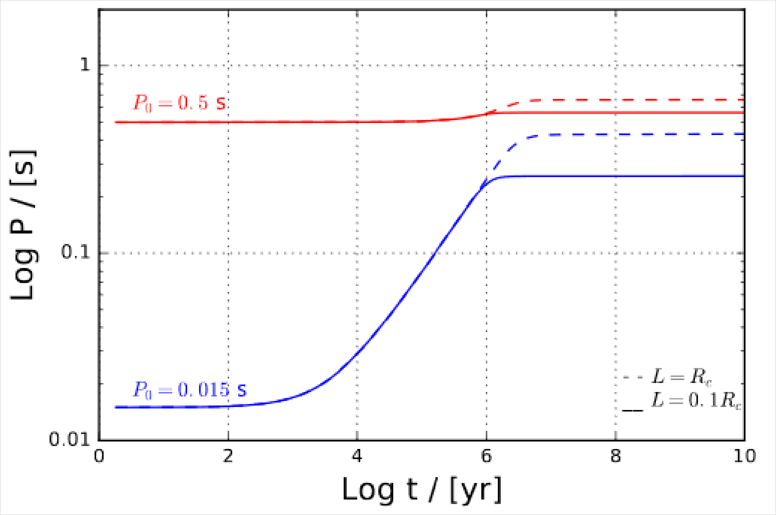
Core field evolution

1705.00508, 1805.03956

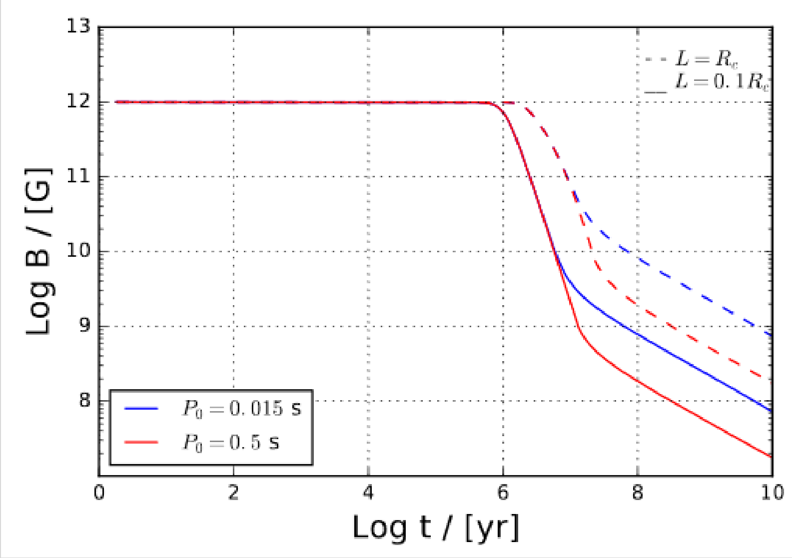


Typical timescales for the magnetic field dissipation as functions of temperature and the magnetic field strength.

Field evolution due to ambipolar diffusion



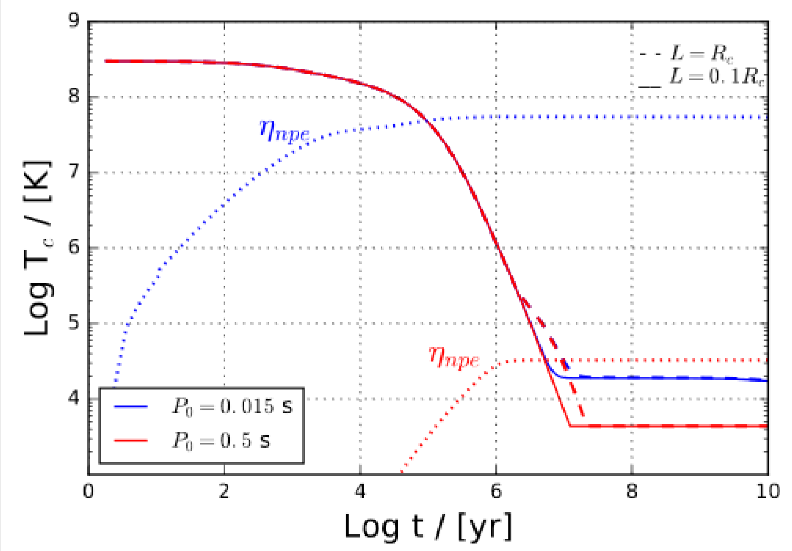
Hypothesis: field decay in MSPs is caused by ambipolar diffusion in the NS core in the non-superfluid/superconductor regime.



$t_{Ohm} \ll t_{AD}$.

$$\dot{B} \approx -\frac{B}{t_{AD}},$$

1906.06076



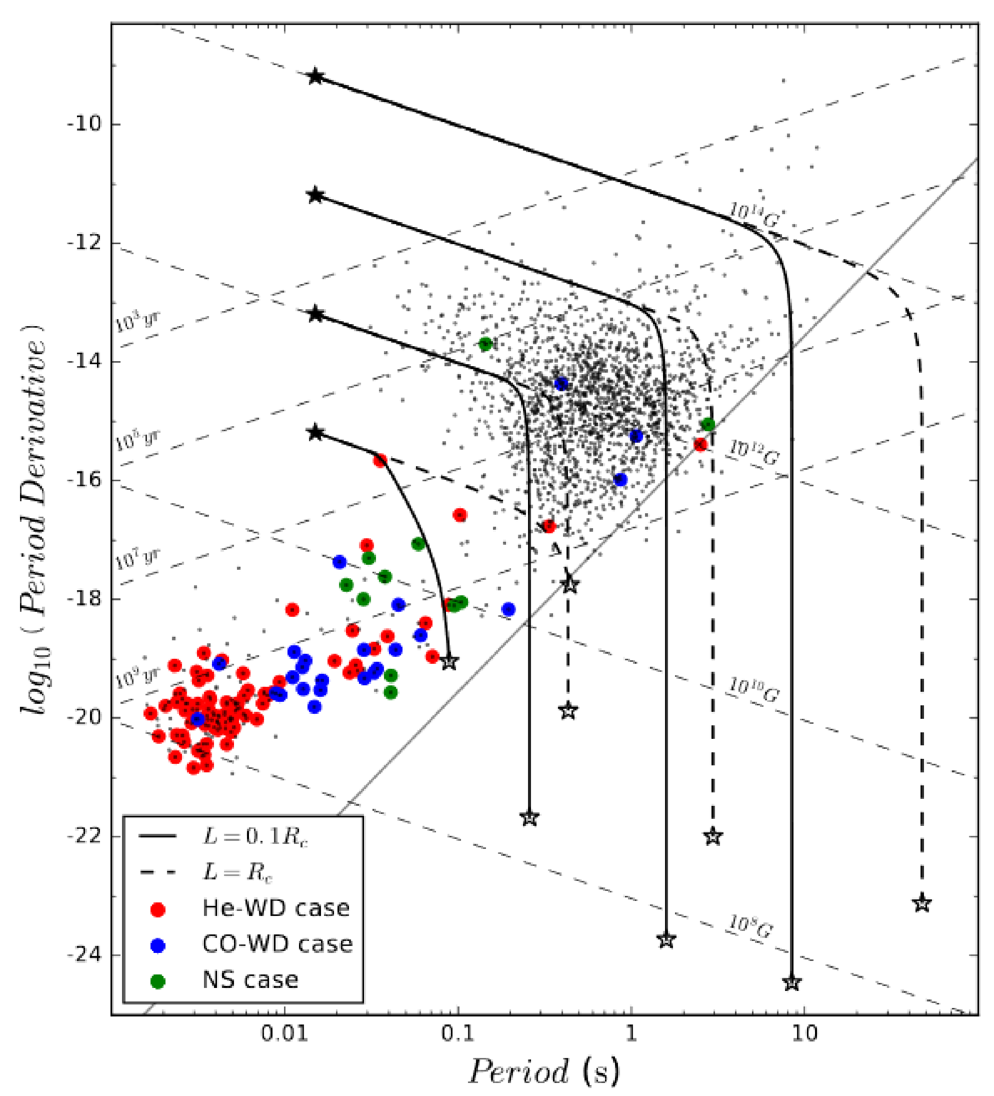
The magnetic field is transported by the charged particles at the ambipolar diffusion velocity

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{v}_{AD} \times \vec{B}\right)$$

$$t_{AD} = 3 \times 10^9 \frac{T_4^2 L_5^2}{B_8^2} \text{ yr},$$

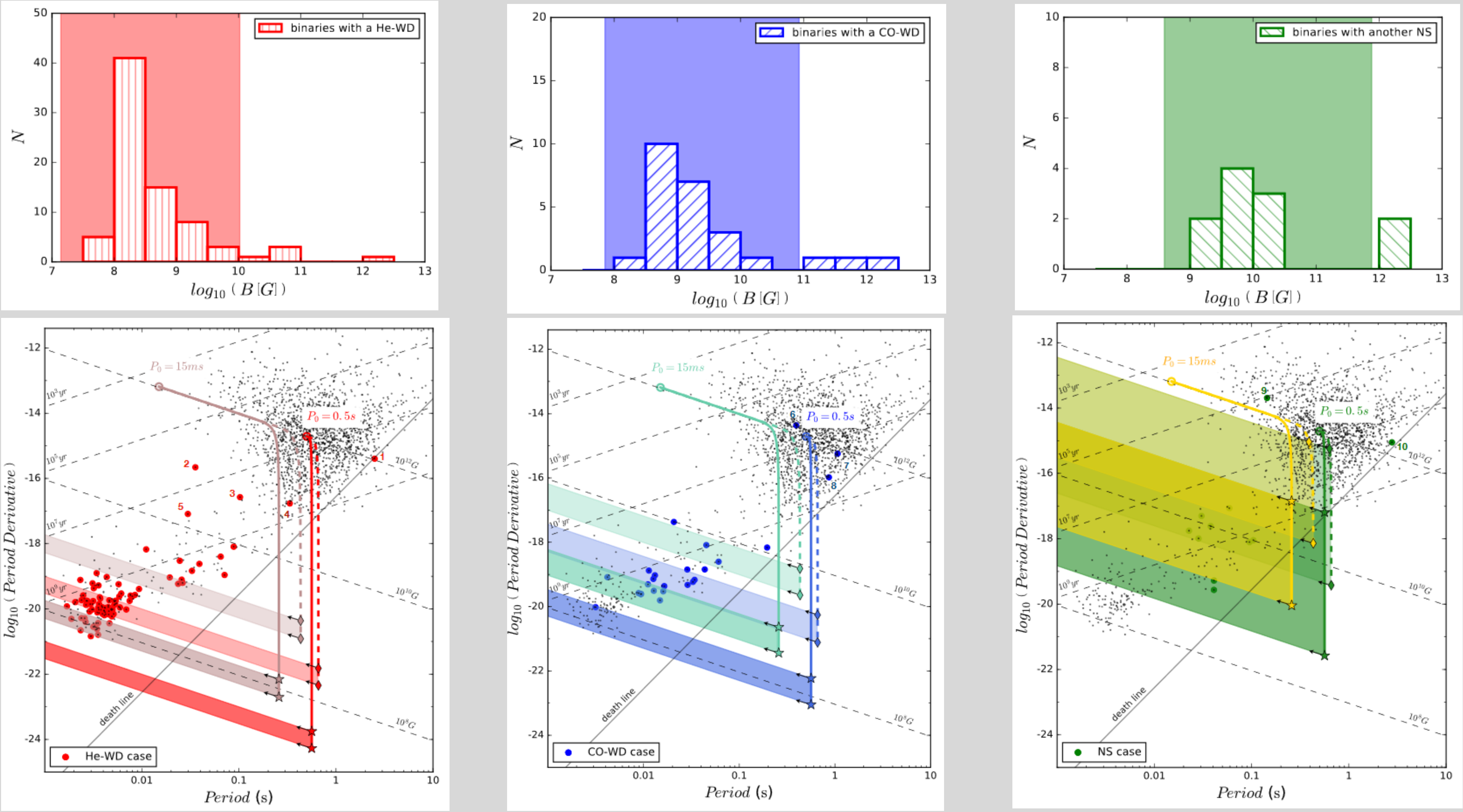
Evolution on the P-Pdot diagram

1906.06076



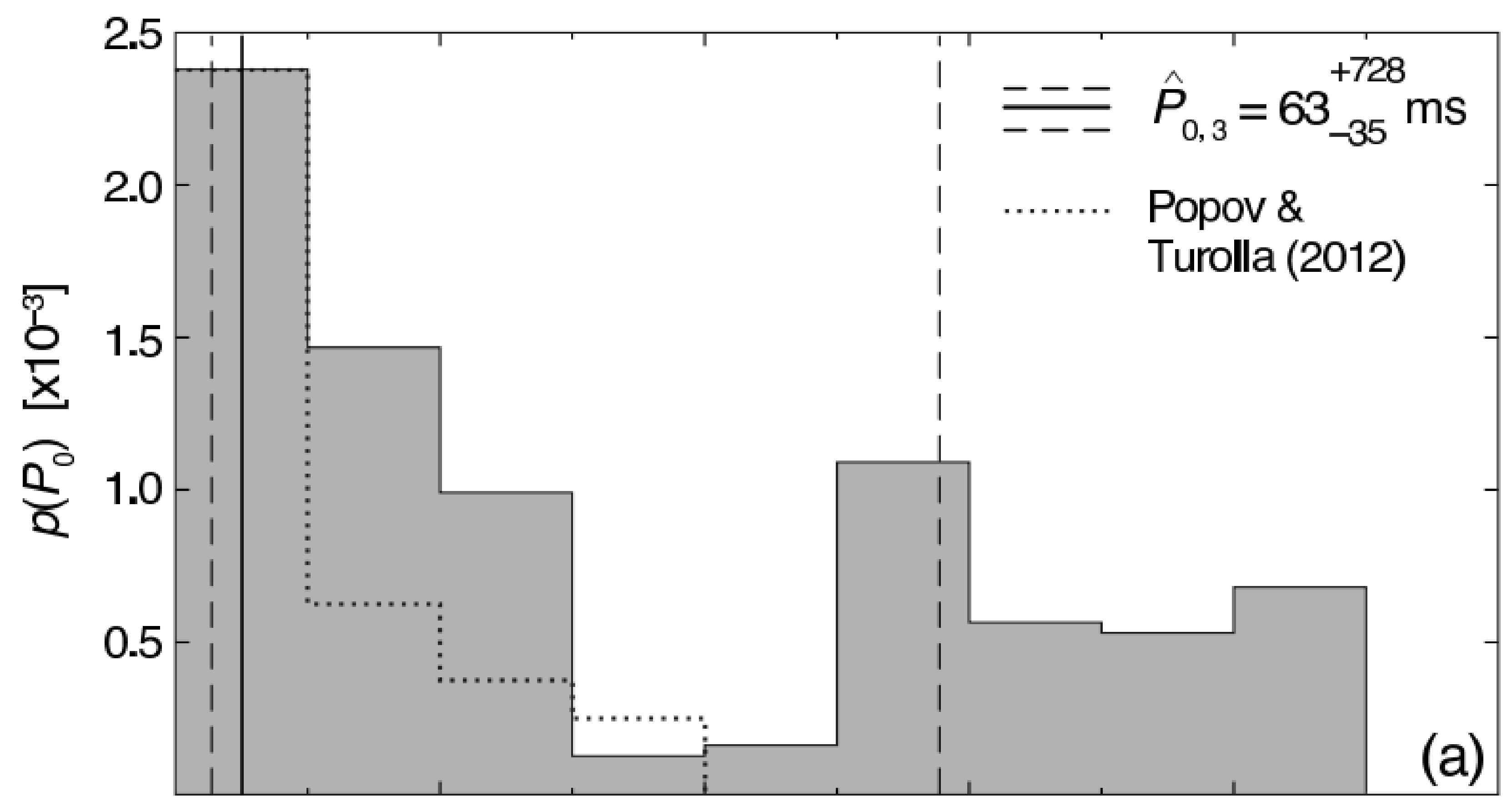
Different types of companions

1906.06076



Wide initial spin period distribution

1301.1265



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?

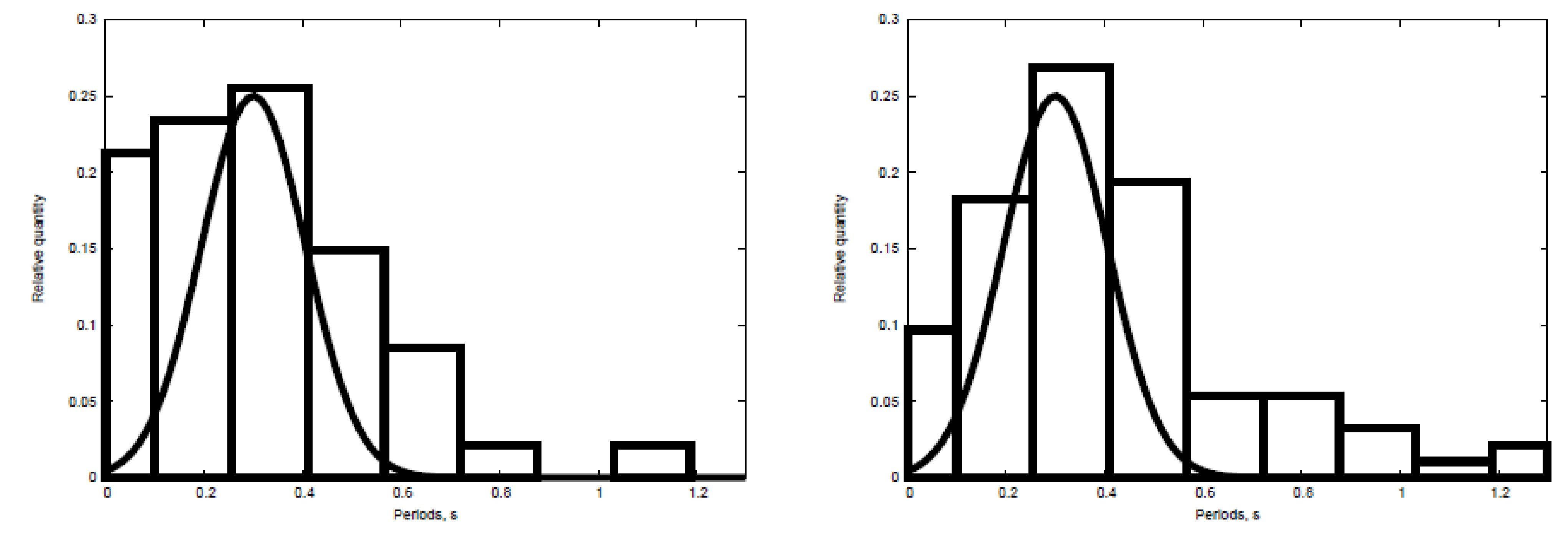
Magnetic field decay and P_0

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, σ_P=0.15 s; <log B_0/[G]>=12.65, σ_B=0.55

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

Igoshev, Popov 2013

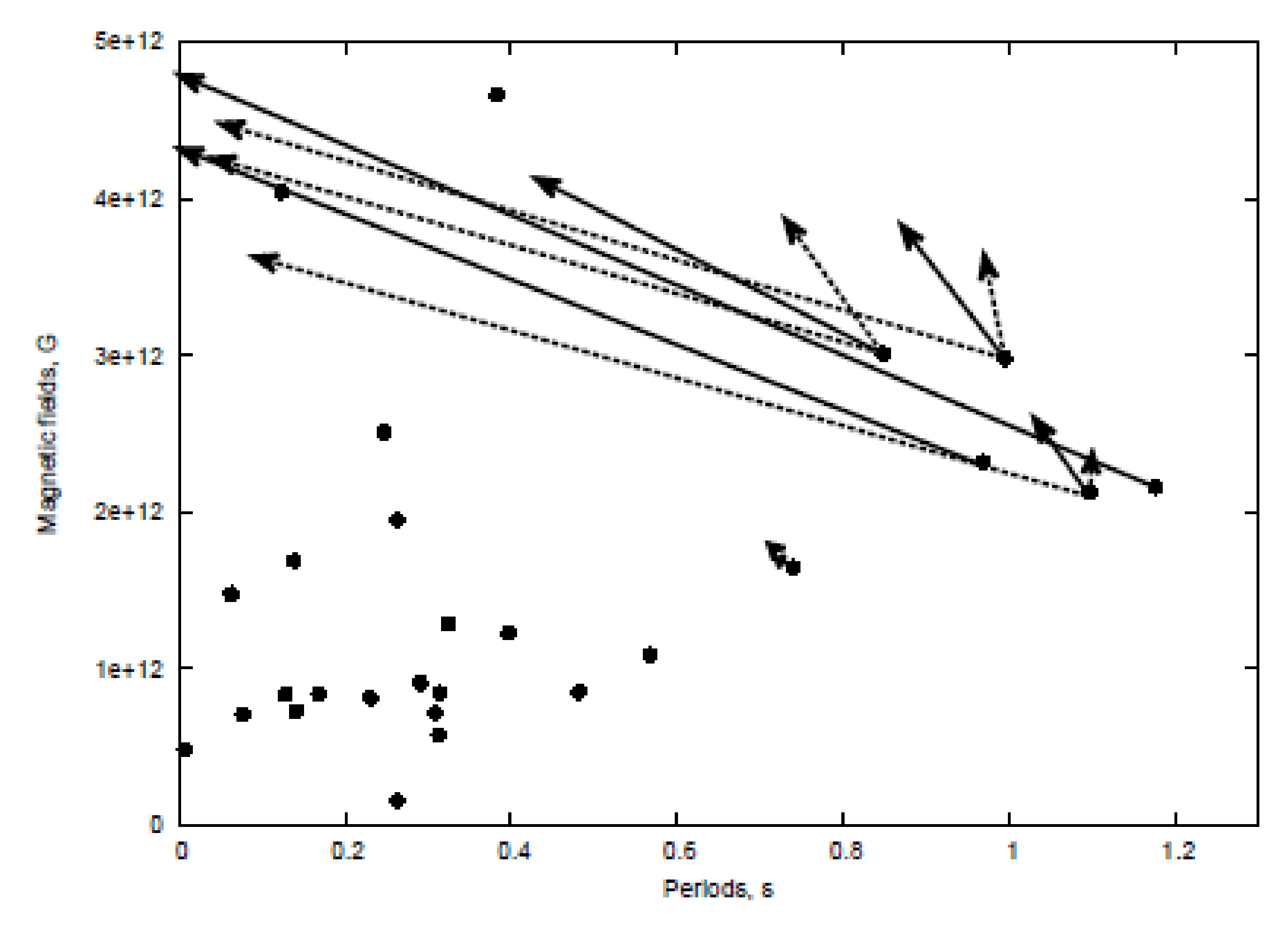


$\tau<10^7$ yrs, $10^5<t$

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

Real vs. reconstructed P_0

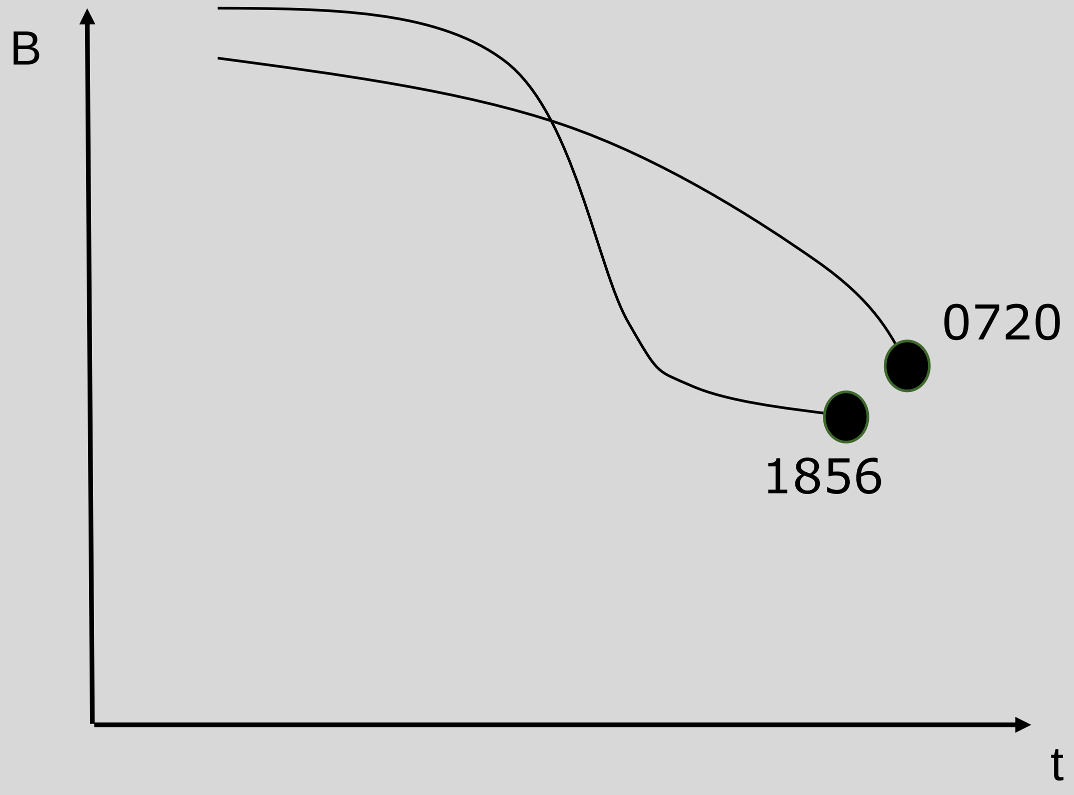
Igoshev, Popov 2013



Arrows point to initial parameters of pulsars if the exponential magnetic field decay was operating.

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

Tracks on the P-pdot diagram



Kinematic age is larger for 0720, but characteristic age – for 1856.

It seems that 1856 is now on a more relaxed stage of the magneto-rotational evolution.

RX J0720 shows several types of activity, but RX J1856 is a very quiet source.

Non-monotonic evolution?

Field, rotation, fallback

$$\dot{M}_{\rm crit,repul} \sim 3\times10^{-5}\,M_\odot\,{\rm s}^{-1}\,\frac{\xi_{\rm s,crit}}{0.2}\,\frac{(4\pi D_{\rm fb}\sqrt{\xi_{\rm s}})_{\rm crit}}{5.3}\left(\frac{B_*}{10^{13}\,{\rm G}}\right)^2\left(\frac{P}{10\,{\rm ms}}\right)^{-2}\left(\frac{t_{\rm fb}}{20\,{\rm s}}\right)^{2/3}$$

$$\frac{{B_*}^2}{8\pi} \lesssim \rho v^2 \sim \frac{\dot{M}}{4\pi R_*^2}\sqrt{\frac{GM_{\rm c}}{R_*}}$$

$$\dot{M}_{\rm crit,bury} \sim 3\times10^{-6}\,M_\odot\,{\rm s}^{-1}\left(\frac{B_*}{10^{13}\,{\rm G}}\right)^2$$

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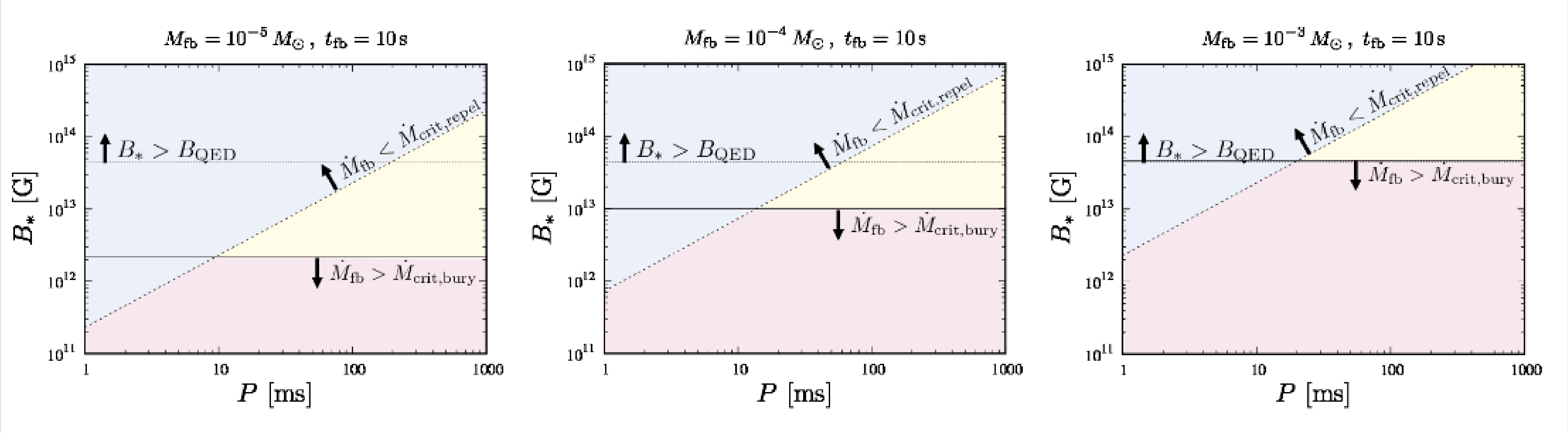
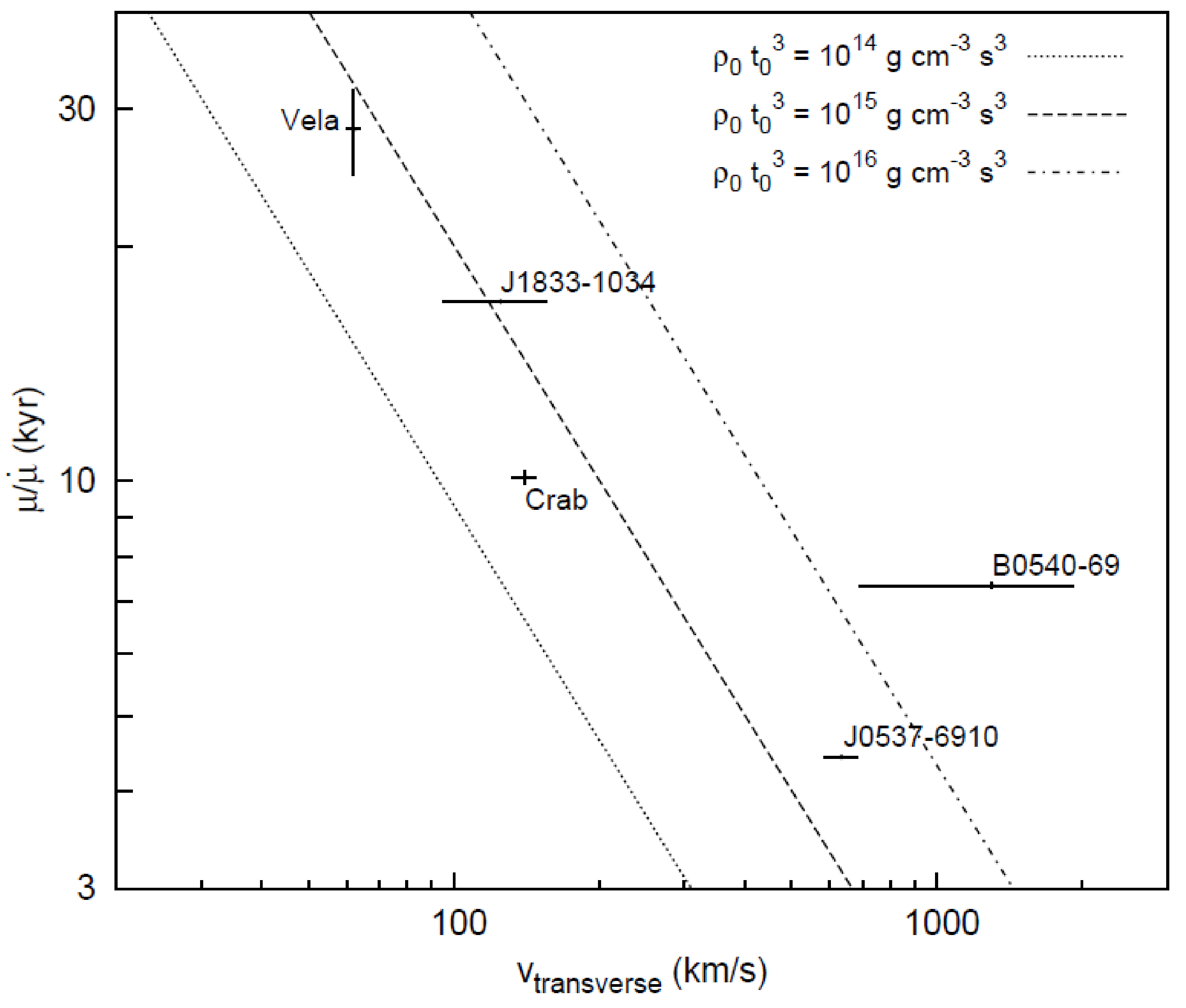


Growing field and kick velocities?



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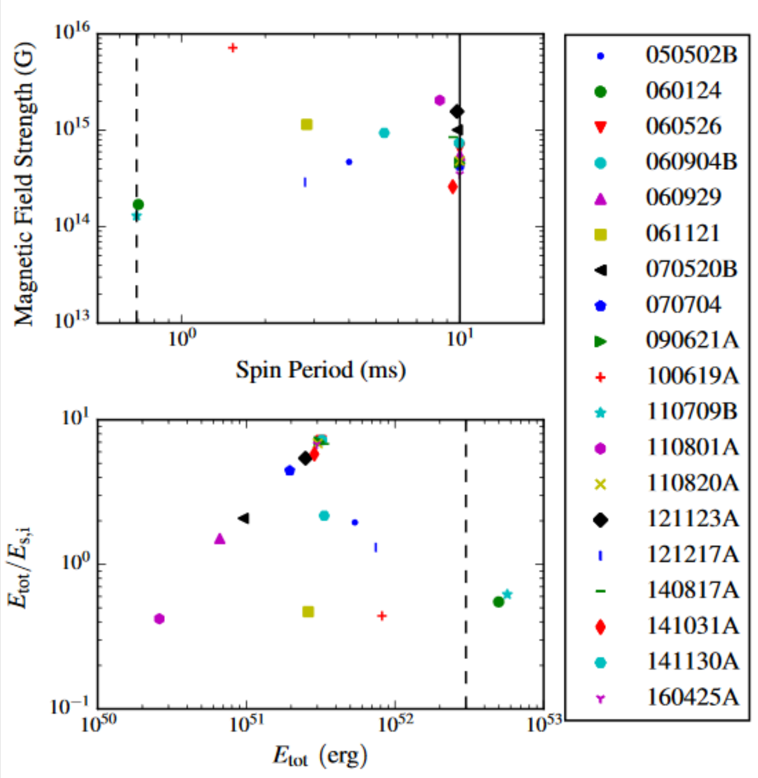
The idea is that
n<3 are explained
as due to growing field.
Then it is possible
to estimate the timescale
for growing and
plot it vs. velocity.

Larger kick –
- smaller fallback –
  - faster field growing

GRBs and fallback onto magnetars



Giant X-ray flares in GRB happen after ~30-10^5 s.
Rotational energy ~2 10^{52} erg P_{ms}^{-2}

$$\dot{M}_D(t) = \dot{M}_{fb} - \dot{M}_{acc} - \dot{M}_{prop},$$

$$\dot{M}_{fb}(t) = \frac{M_{fb}}{t_{fb}} \left(\frac{t + t_{fb}}{t_{fb}} \right)^{-\frac{5}{3}}$$

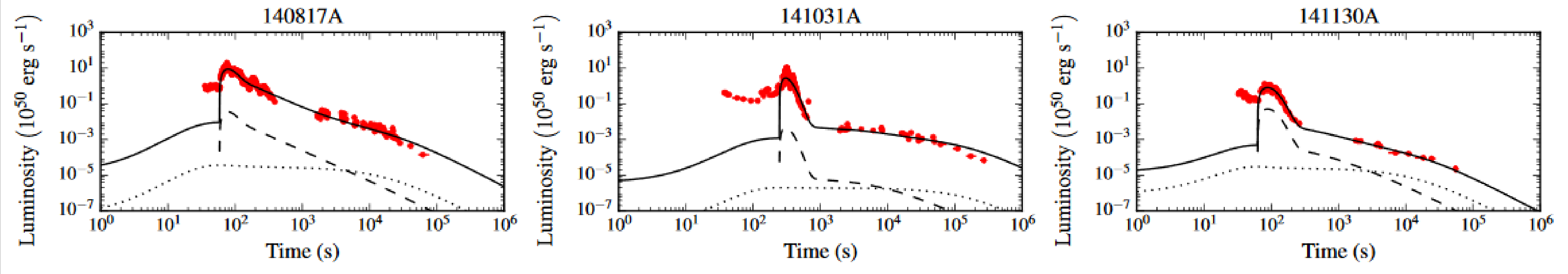
$$L_{dip} = -\tau_{dip}\omega$$

$$L_{prop} = -\tau_{acc}\omega$$

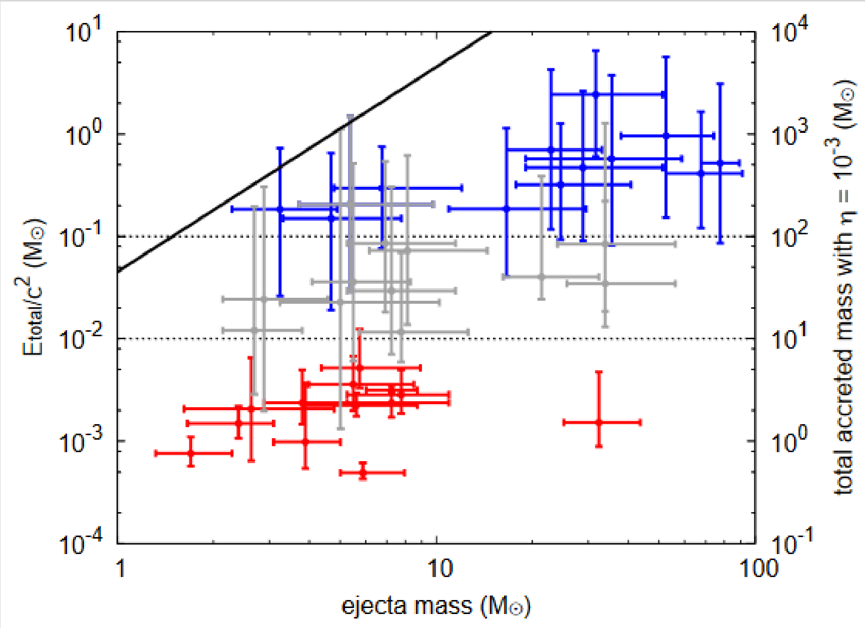
τ_{acc} and τ_{dip} are the accretion and dipole torques

$$L_{tot} = \frac{1}{f_B}\left(\eta_{prop}L_{prop} + \eta_{dip}L_{dip}\right)$$

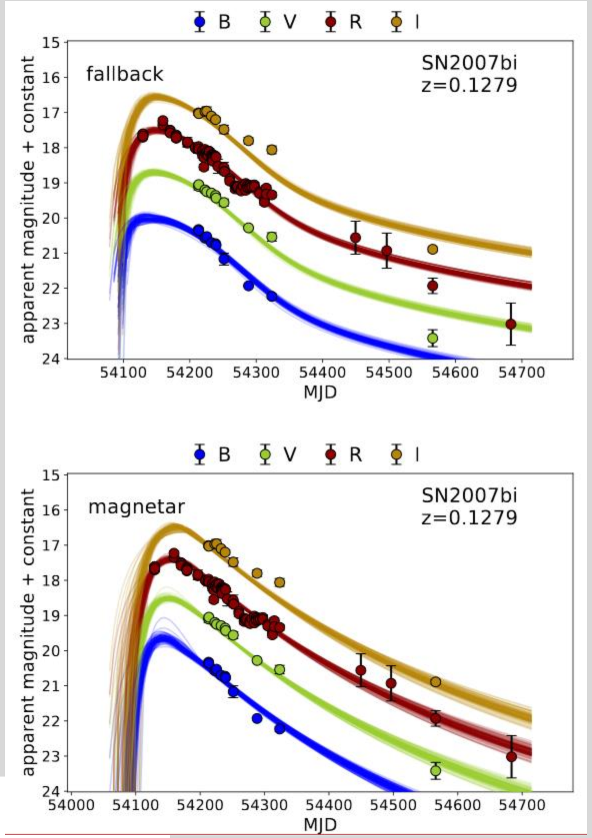
1805.09022

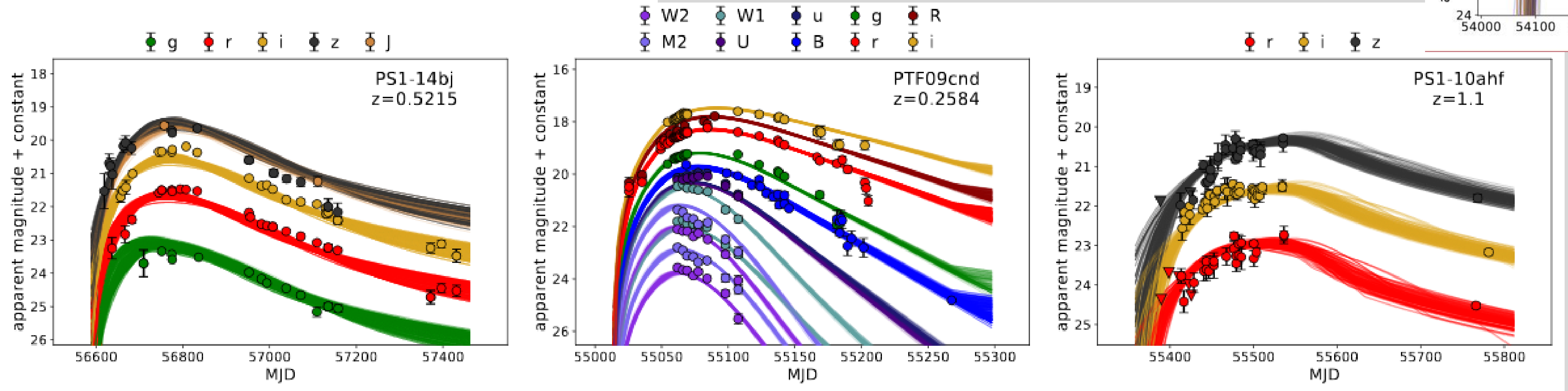


Fallback to power SN



$$L_{\rm fallback}(t) = \begin{cases} L_1 \left(\frac{t_{\rm tr}}{1\ {\rm sec}}\right)^{-\frac{5}{3}} \equiv L_{\rm flat} & (t < t_{\rm tr}) \\ L_1 \left(\frac{t}{1\ {\rm sec}}\right)^{-\frac{5}{3}} & (t \geq t_{\rm tr}) \end{cases}$$





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Characteristic timescales

$$\tau_{\rm Hall} = \frac{4\pi e n_e L^2}{cB(t)},$$

$$\tau_{\rm Hall} = \tau_{\rm Hall,0}\frac{B_0}{B(t)}.$$

Hall time scale strongly depends on the current value of the field.

$$\tau_{\rm Ohm} = \frac{4\pi\sigma L^2}{c^2},$$

$$\sigma = \frac{\sigma_{\rm Q}\sigma_{\rm ph}}{\sigma_{\rm Q}+\sigma_{\rm ph}}.$$

Ohmic decay depends on the conductivity

$$\tau_{\rm Ohm}^{-1} = \tau_{\rm Ohm,ph}^{-1} + \tau_{\rm Ohm,Q}^{-1}.$$

Resistivity can be due to

- Phonons
- Impurities

$$\sigma_Q = 4.4\times 10^{25}{\rm s}^{-1}\left(\frac{\rho_{14}^{1/3}}{Q}\right)\left(\frac{Y_e}{0.05}\right)^{1/3}\left(\frac{Z}{30}\right),$$

$$\sigma_{\rm ph} = 1.8\times 10^{25}{\rm s}^{-1}\left(\frac{\rho_{14}^{7/6}}{T_8^2}\right)\left(\frac{Y_e}{0.05}\right)^{5/3},$$

$$Q = n_{\rm ion}^{-1}\Sigma_i\, n_i\times(Z^2-\langle Z\rangle^2).$$