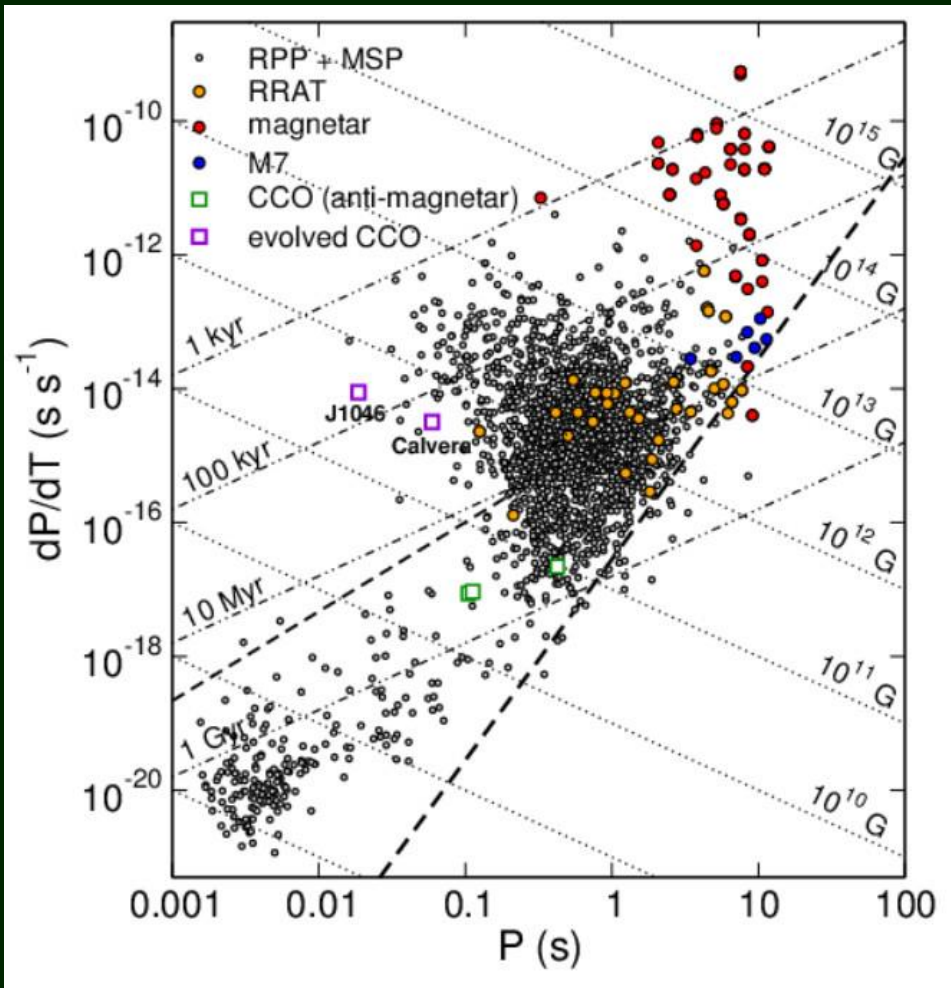# Evolution with decaying and re-emerging magnetic field

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
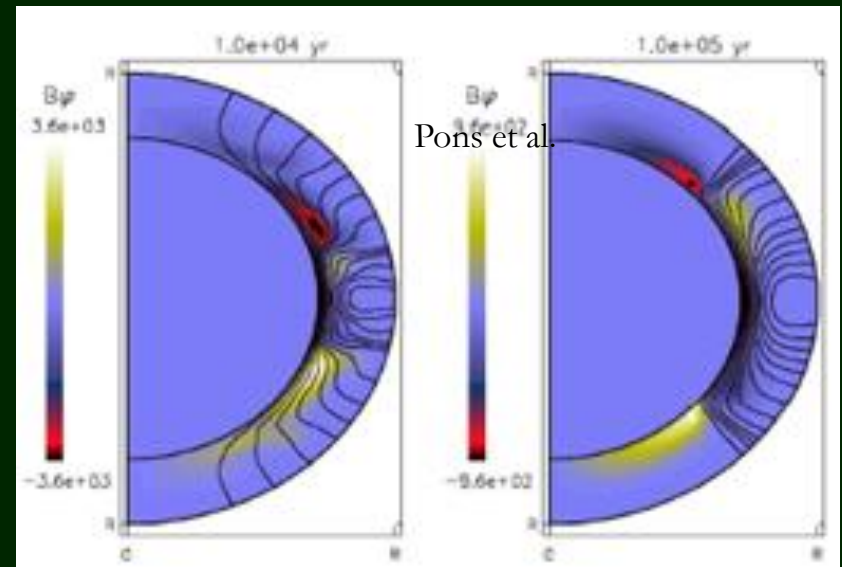o The Magnificent Seven & Co.
o Transient radio sources (RRATs)

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

PSRs, magnetars and M7 unified in the model by Popov et al. (2010).

Pires et al. 2015

Three main ingredients of a unified model

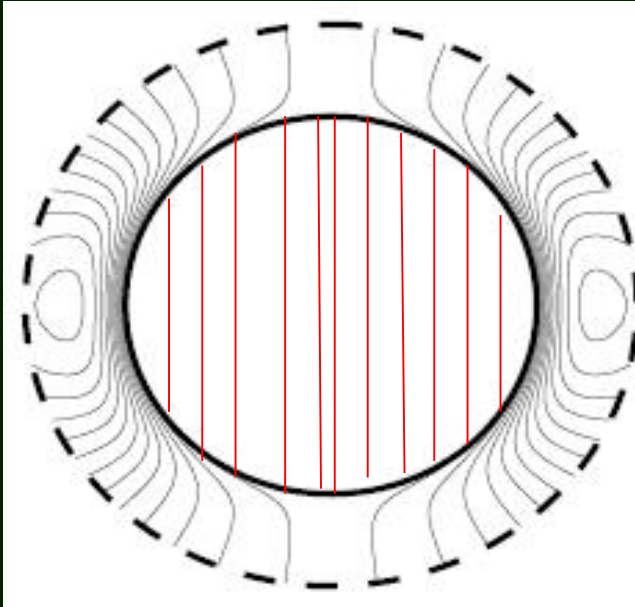Aguilera et al.

Page et al.

Pons et al.
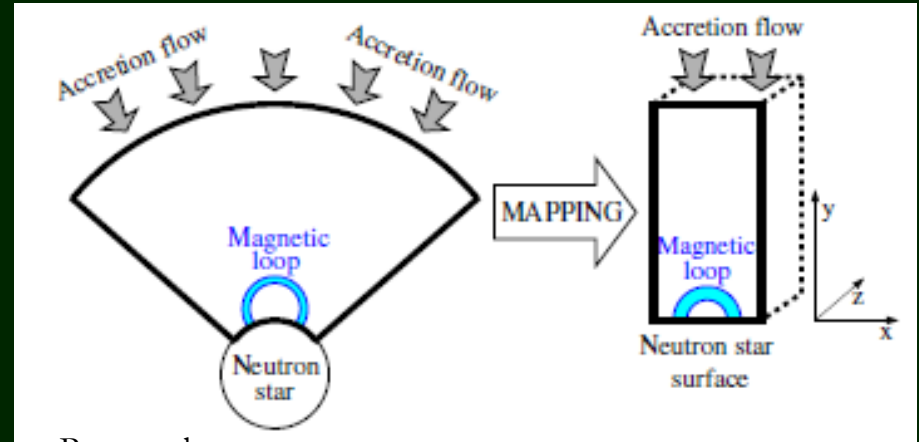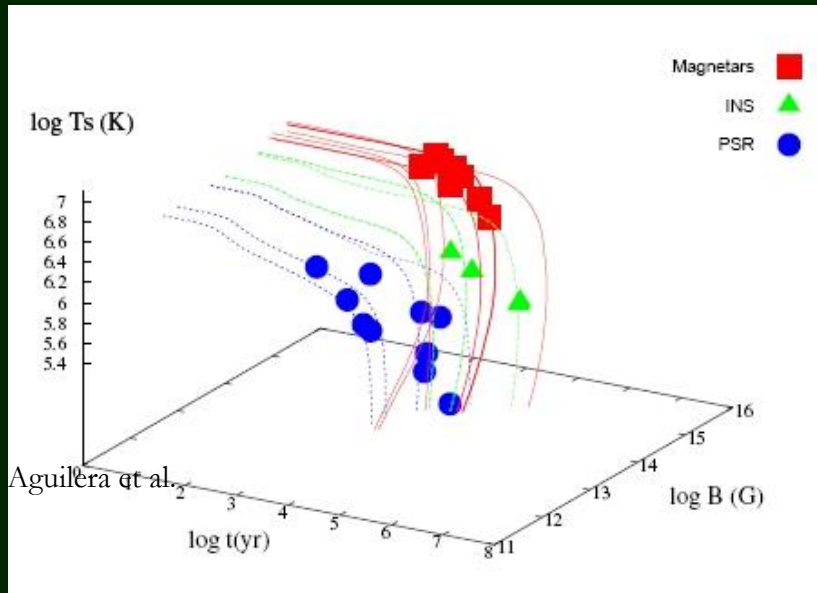
- Field decay

  - Emerging magnetic field

    - Toroidal magnetic field

Magnetic field decay

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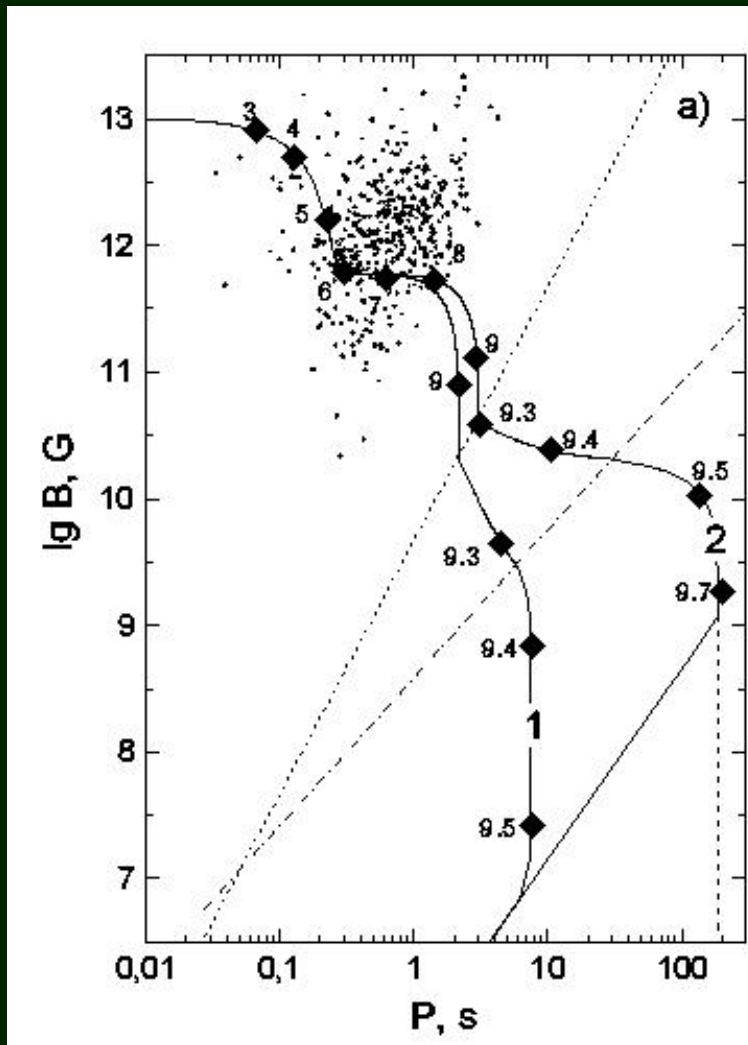due to decay of currents which support them.**

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.

Period evolution with field decay

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.
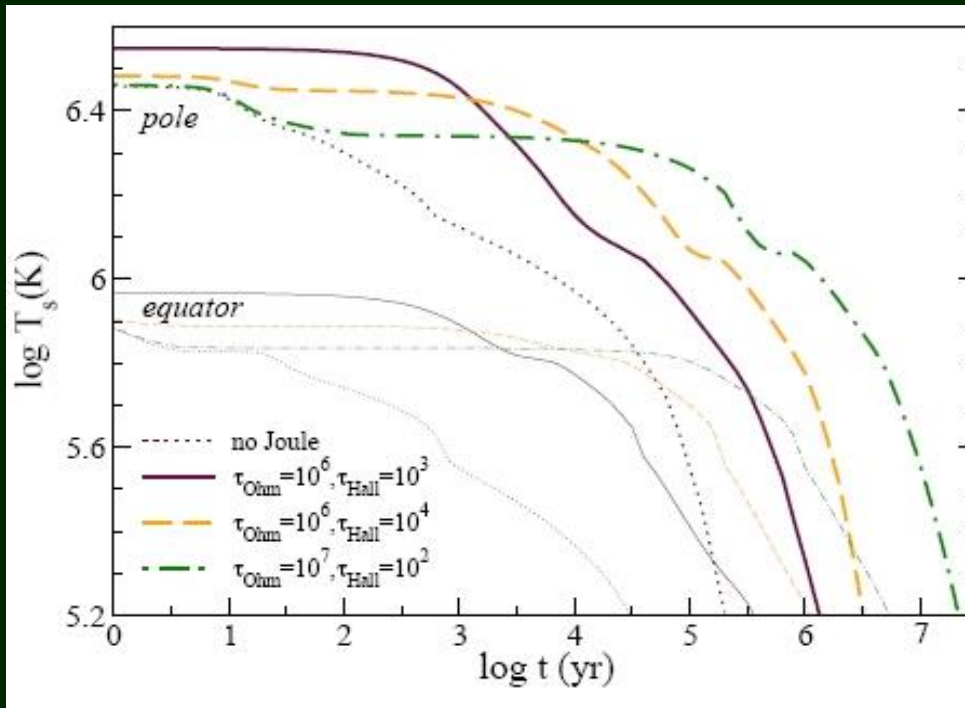
astro-ph/9707318

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.).
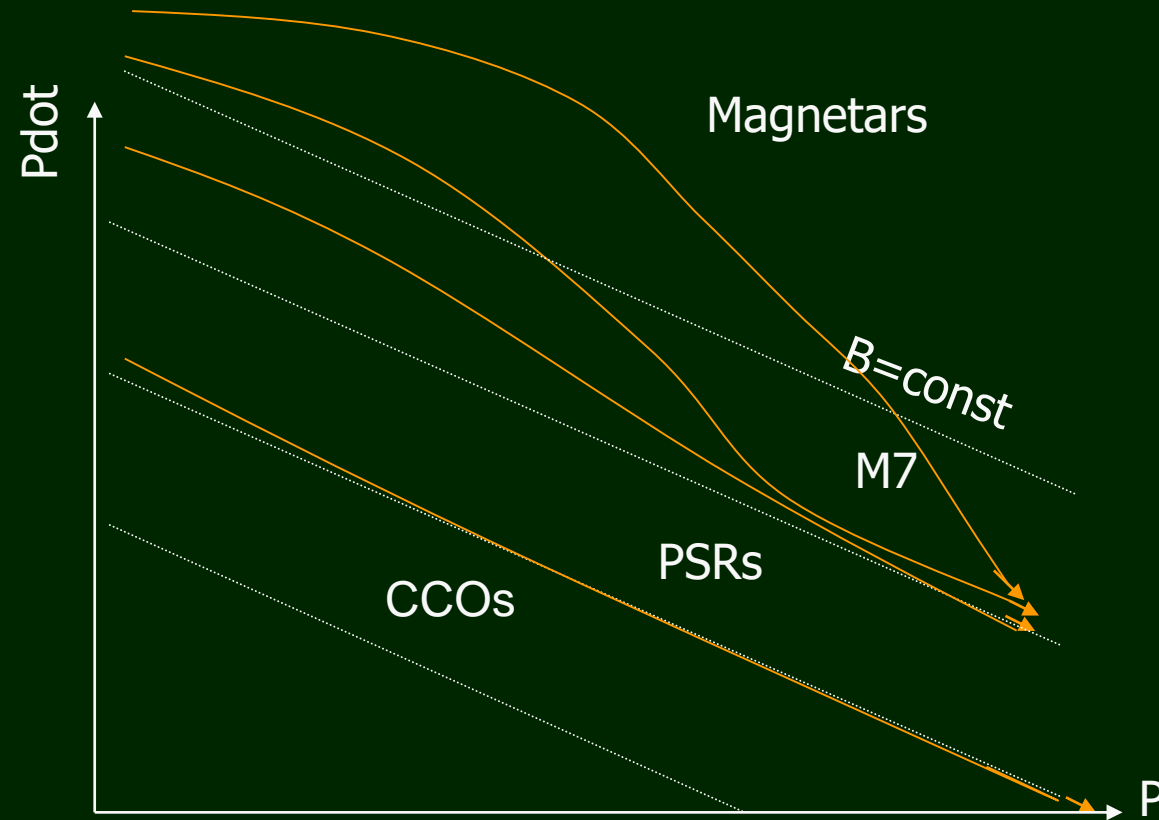
Magnetic field decay vs. thermal evolution

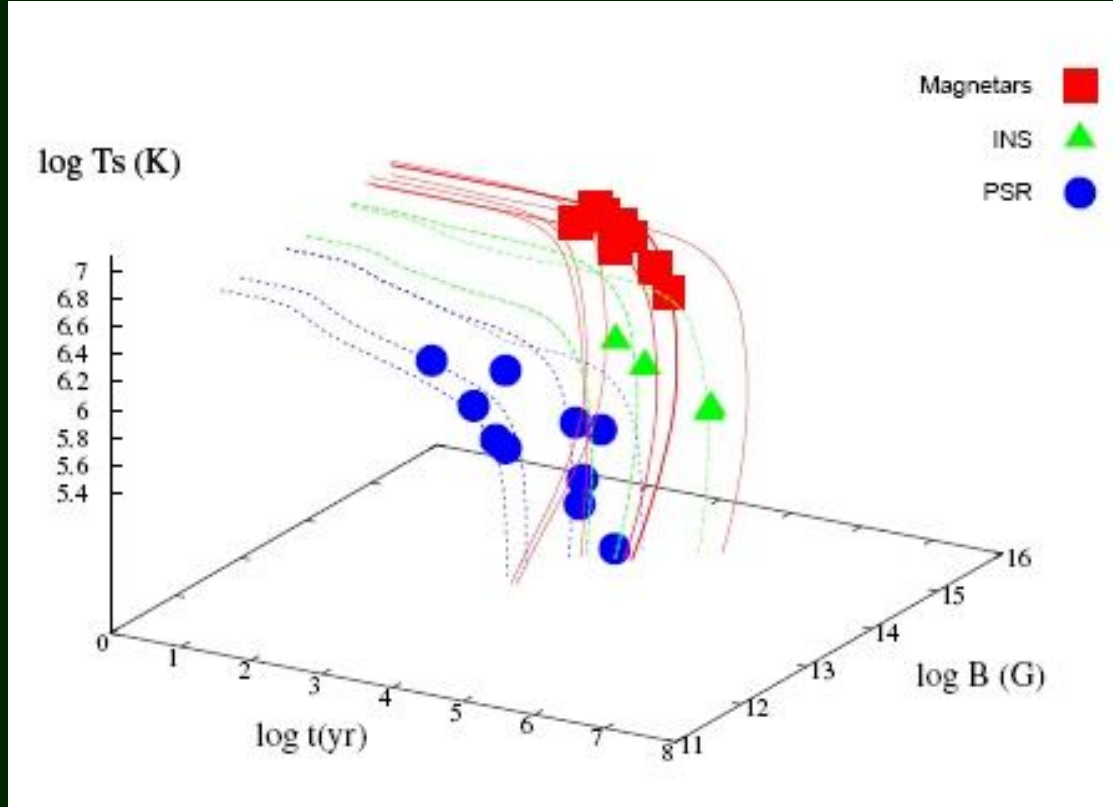**Magnetic field decay can be an important source of NS heating.**

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).

Ohm and Hall decay

arxiv:0710.0854 (Aguilera et al.)

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

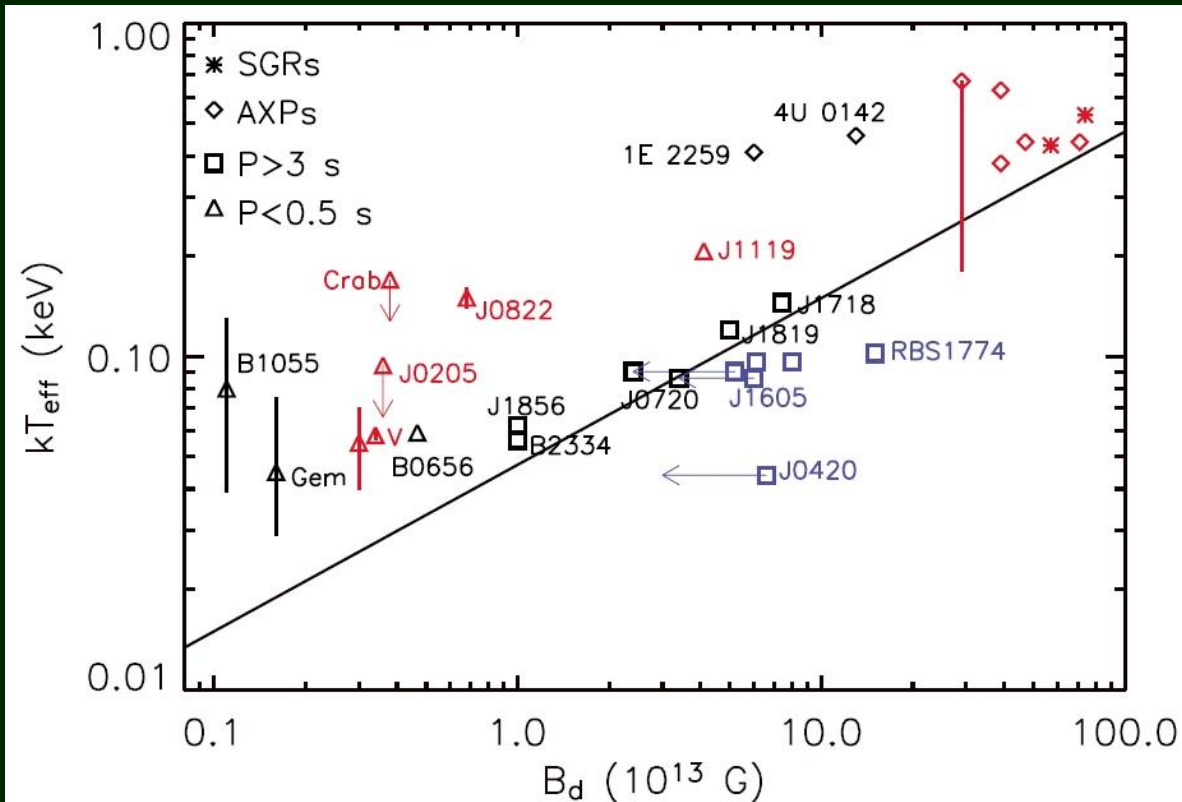# Joule heating for everybody?

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!

arXiv: 0710.4914 (Aguilera et al.)

Magnetic field vs. temperature

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:
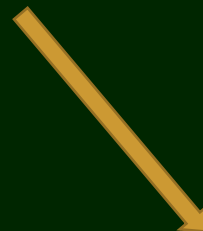
$$T_{eff} \sim B_d^{1/2}$$

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

(astro-ph/0607583)

What kind of decay do we see?
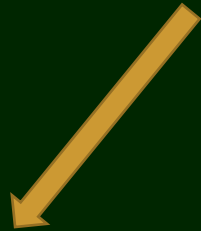
Ohmic decay due to phonons

Hall cascade

Both time scales fit, and in both cases we can switch of decay at ~10
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 field evolution

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

advection   Ohm   Hall

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

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

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

With only Hall term we have:

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

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

astro-ph/0402392
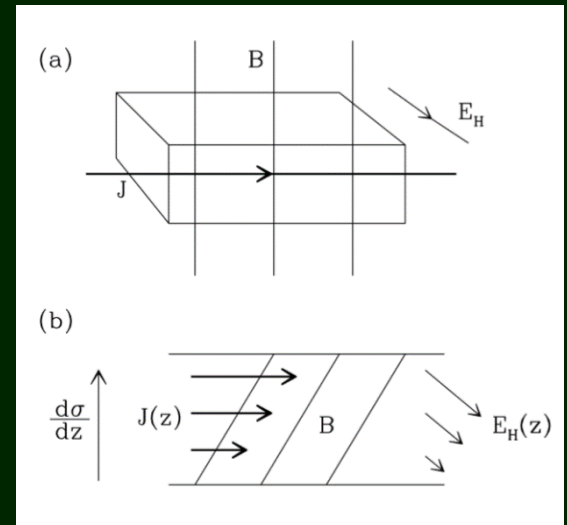
Characteristic timescales

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

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

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

Resistivity can be due to
- Phonons
- Impurities

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

Ohmic decay depends on the conductivity

$$\sigma = \frac{\sigma_Q \sigma_{\text{ph}}}{\sigma_Q + \sigma_{\text{ph}}}.$$

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

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

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

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

P-Pdot diagram and field decay
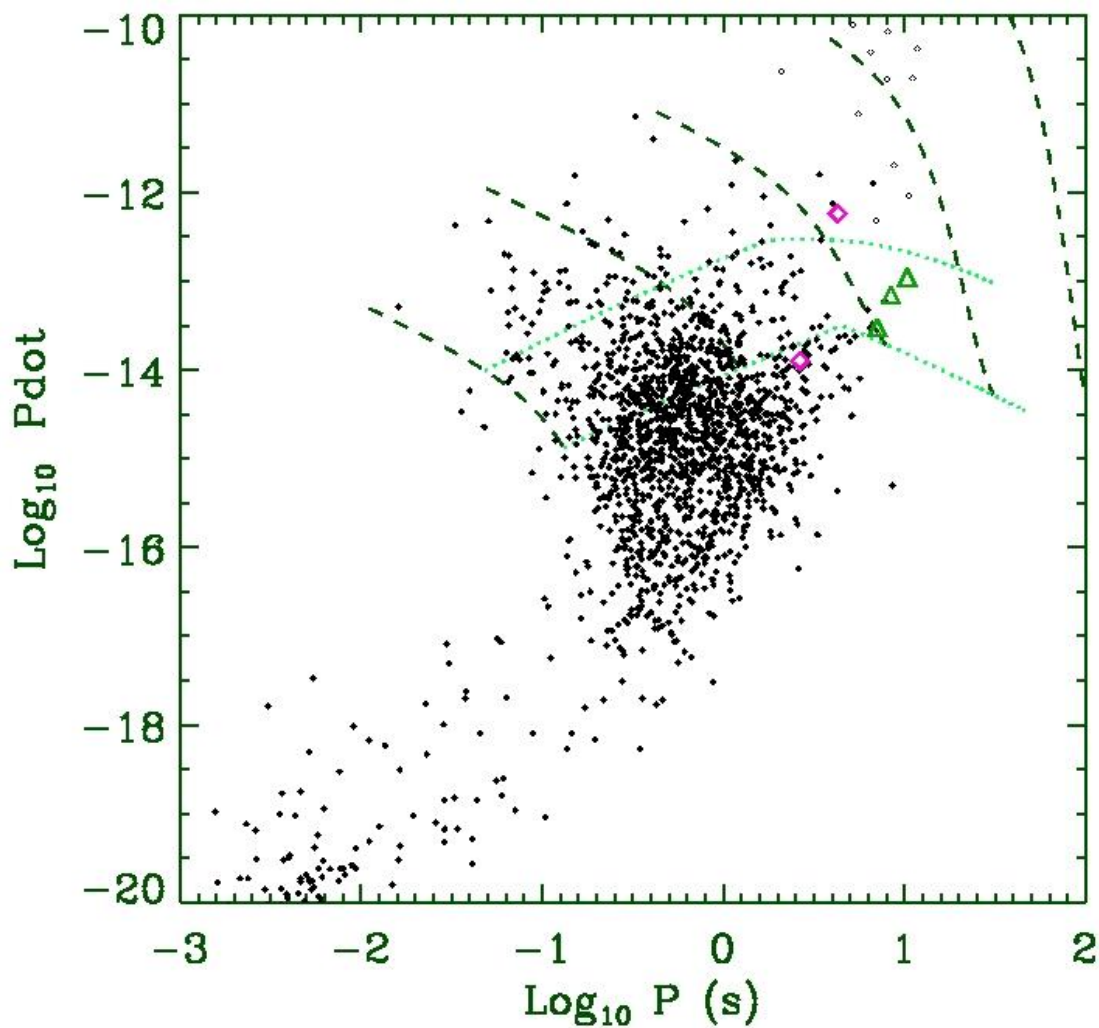
$$B = B_0 \frac{\exp\left(-t/\tau_{\text{Ohm}}\right)}{1 + \frac{\tau_{\text{Ohm}}}{\tau_{\text{Hall}}}(1 - \exp\left(-t/\tau_{\text{Ohm}}\right))}$$
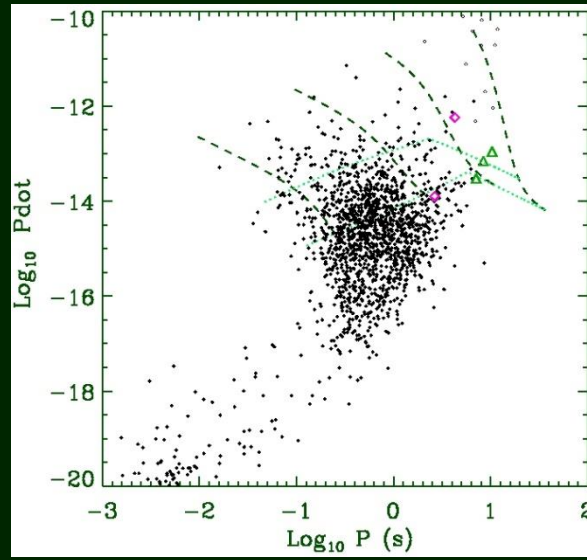
$\tau_{\text{Ohm}} = 10^6$ yrs
$\tau_{\text{Hall}} = 10^4/(B_0/10^{15}\text{ G})$ yrs
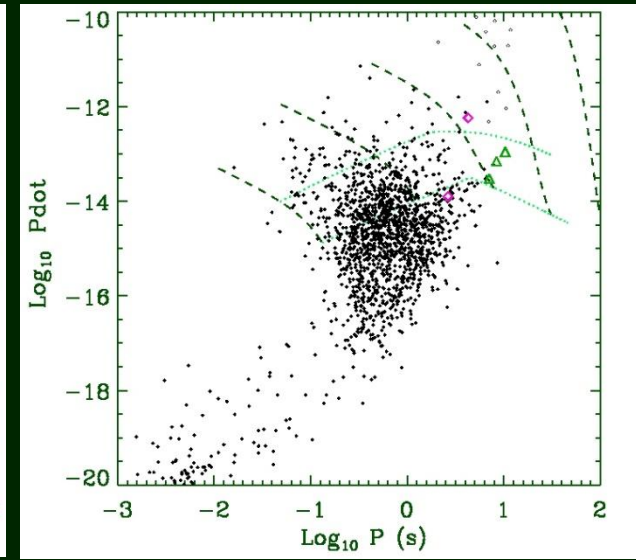
(Popov et al. MNRAS 2010. arXiv: 0910.2190)

Decay parameters and P-Pdot
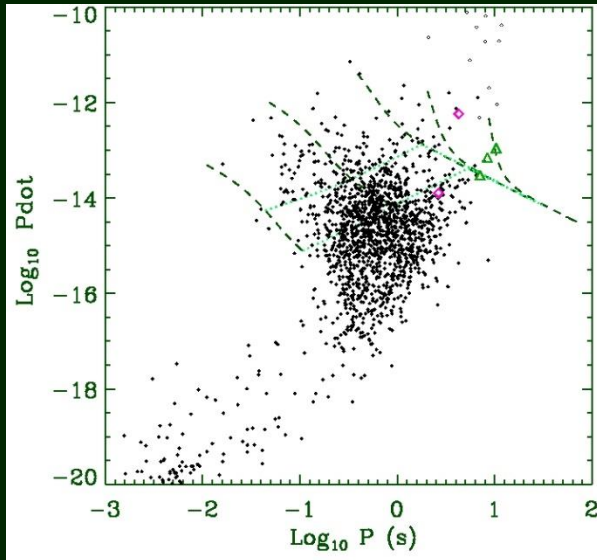
$\tau_{Ohm}=10^7$ yrs
$\tau_{Hall}=10^2/(B_0/10^{15}\,G)$

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

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

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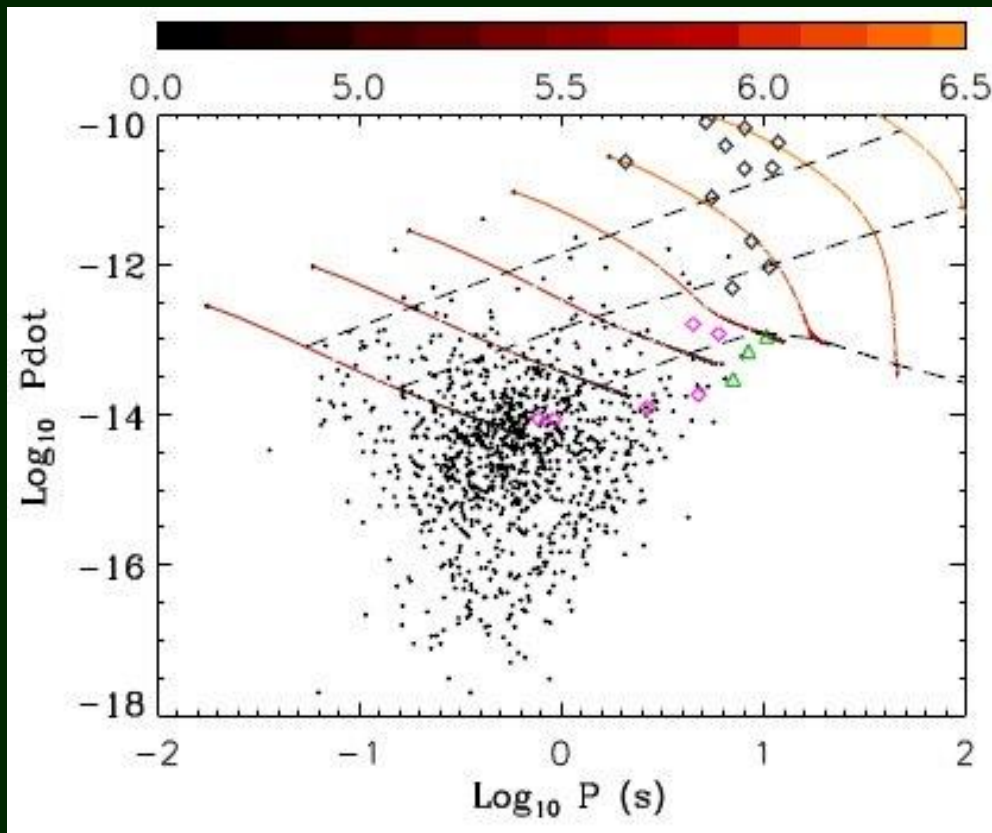
Using the model by Pons et al. (arXiv: 0812.3018) we plot realistic tracks for NS with masses 1.4 Msolar.

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

Color on the track encodes surface temperature.

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

(Popov et al. MNRAS 2010)

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 $<\log B_0> \sim 13.25$ and $\sigma \sim 0.6$ gives a good fit. ~10% of magnetars.

Cooling curves with decay
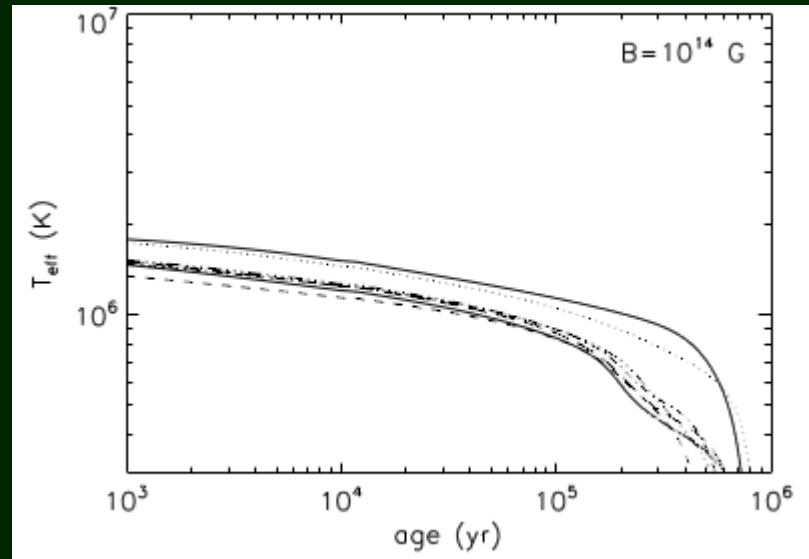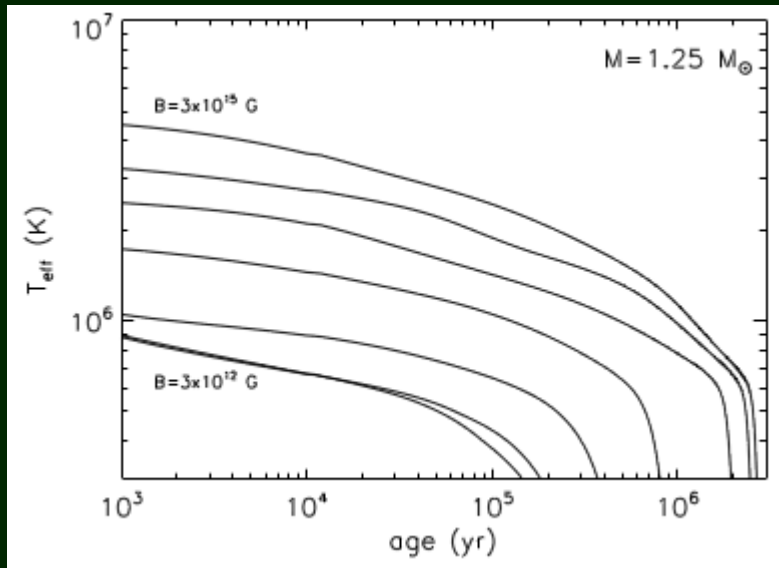
Magnetic field distribution is more important than the mass distribution.
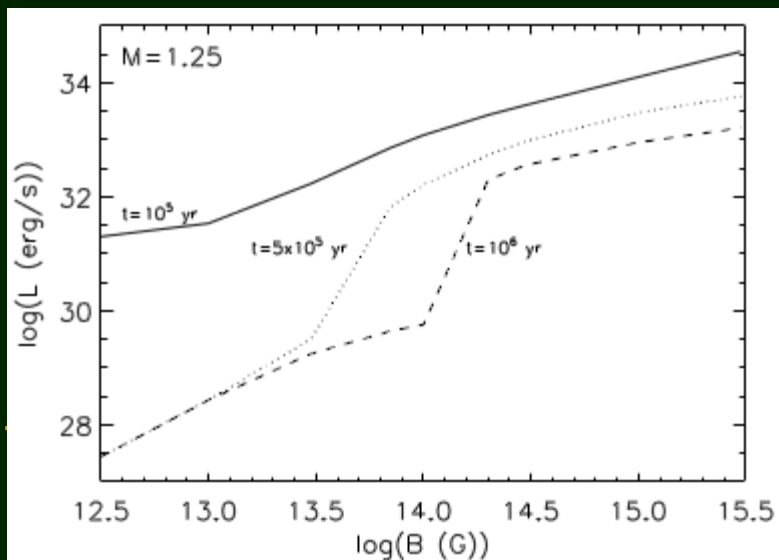
Observational evidence?
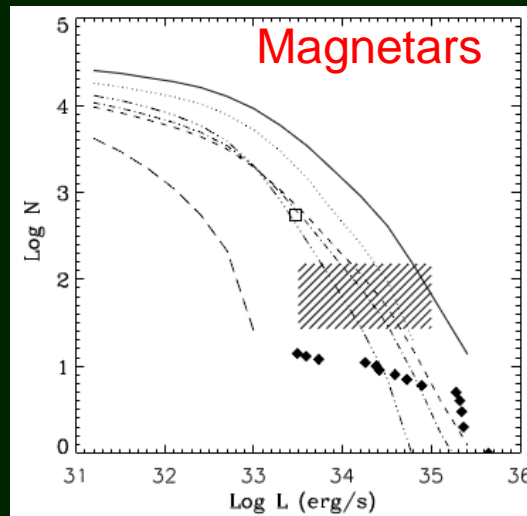

Kaplan & van Kerkwijk arXiv: 0909.5218
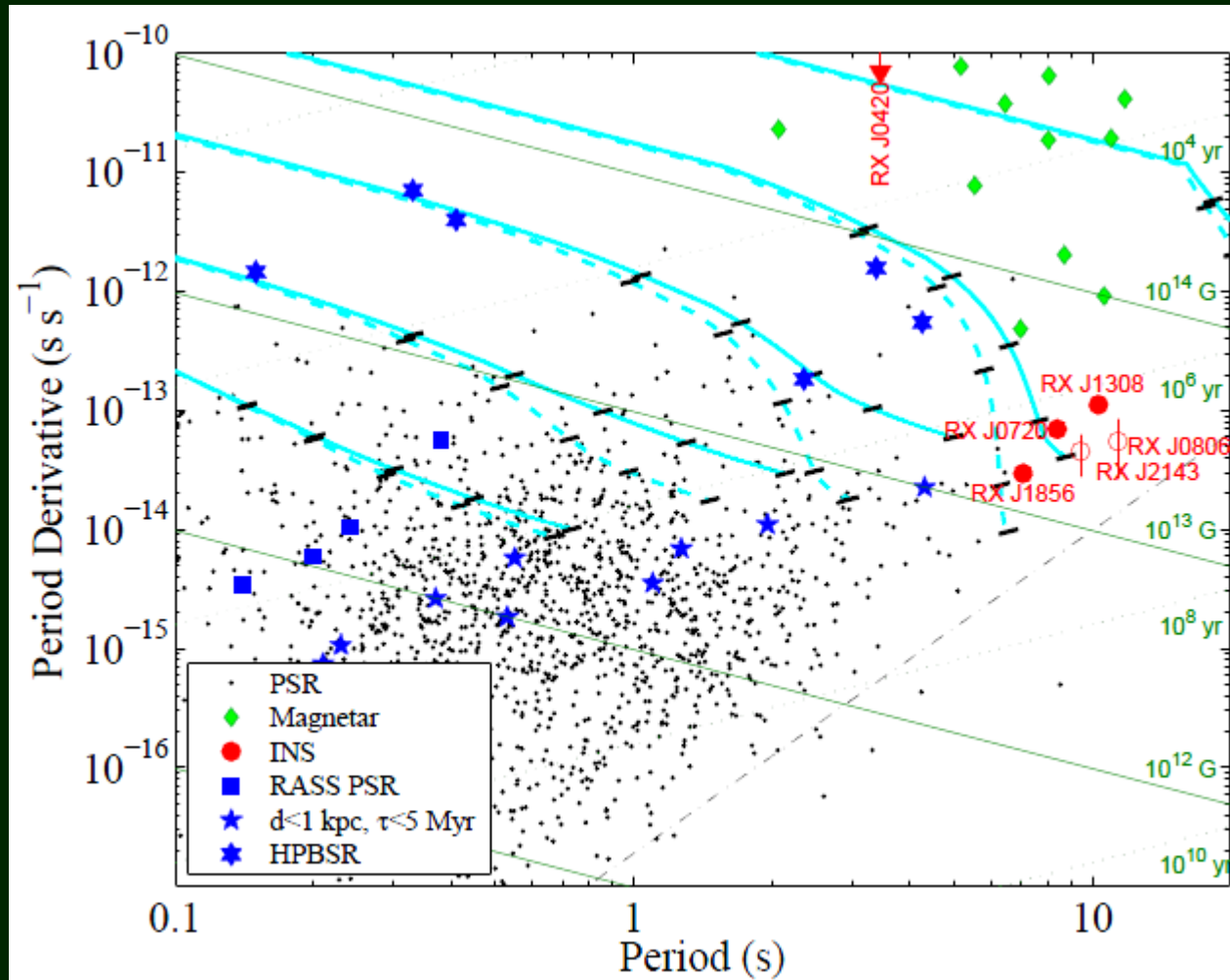
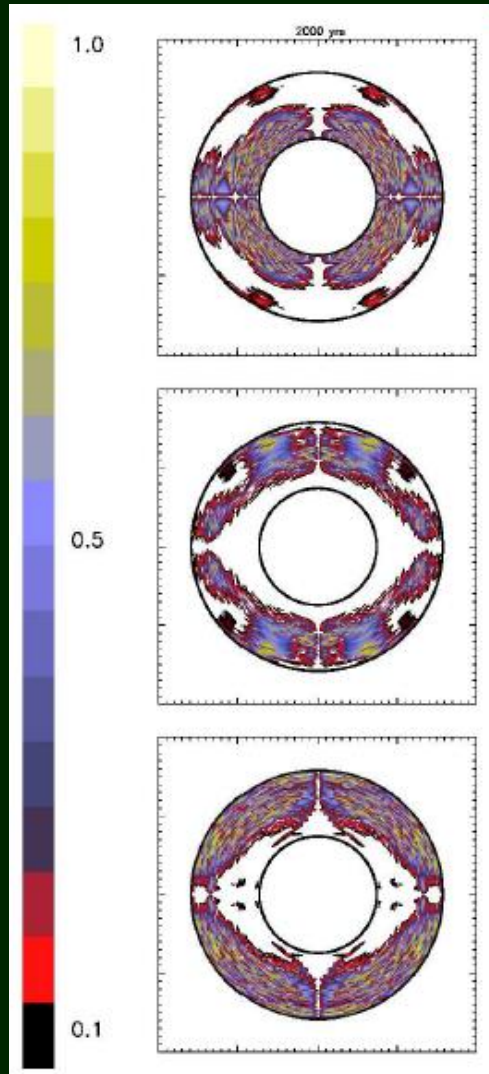# Extensive population synthesis: M7, magnetars, PSRs

M7
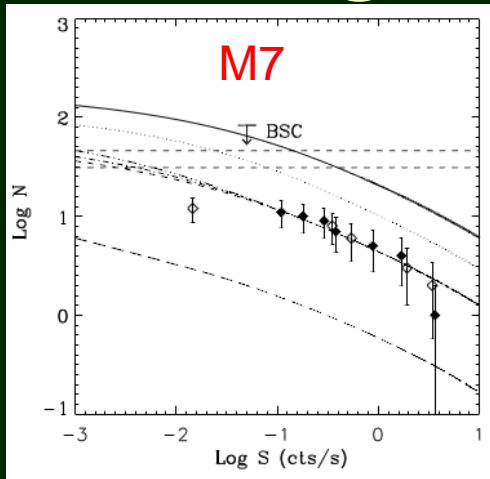
Using one population it is difficult or impossible to find unique initial distribution for the magnetic field

M7

All three populations are compatible with a unique distribution.

Of course, the result is model dependent.

Magnetars

PSRs
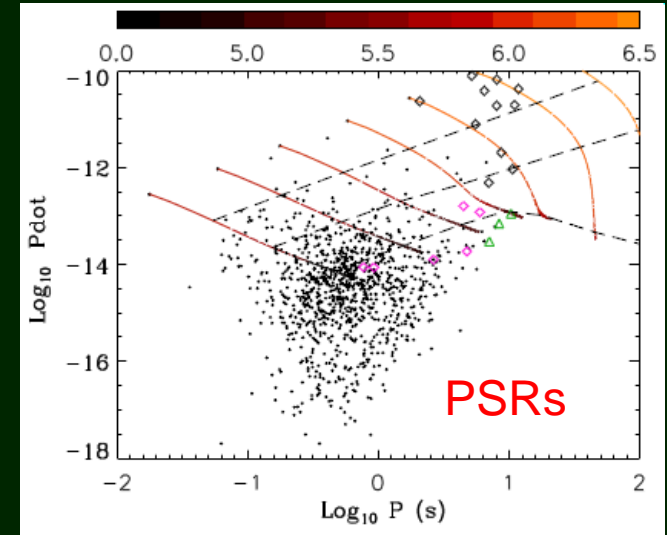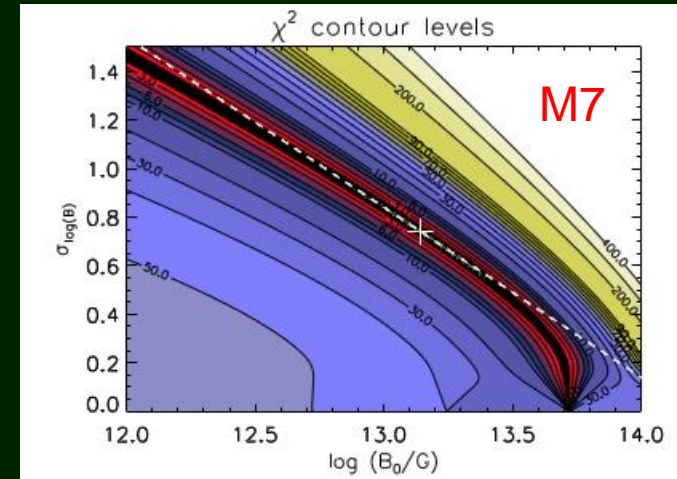
Magnetars bursting activity due to decay

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.
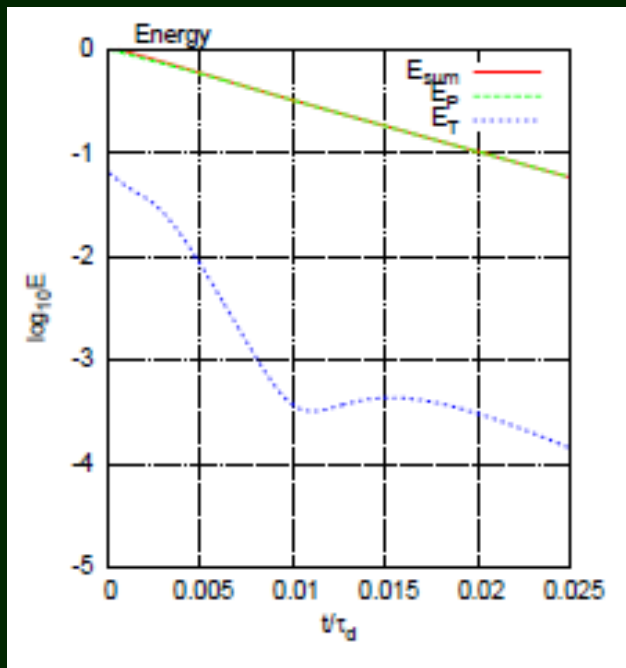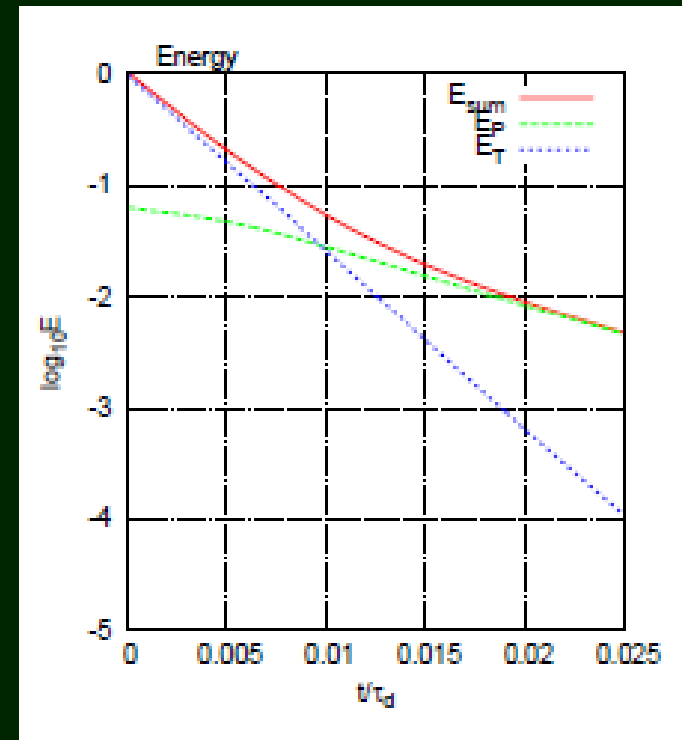

1101.1098
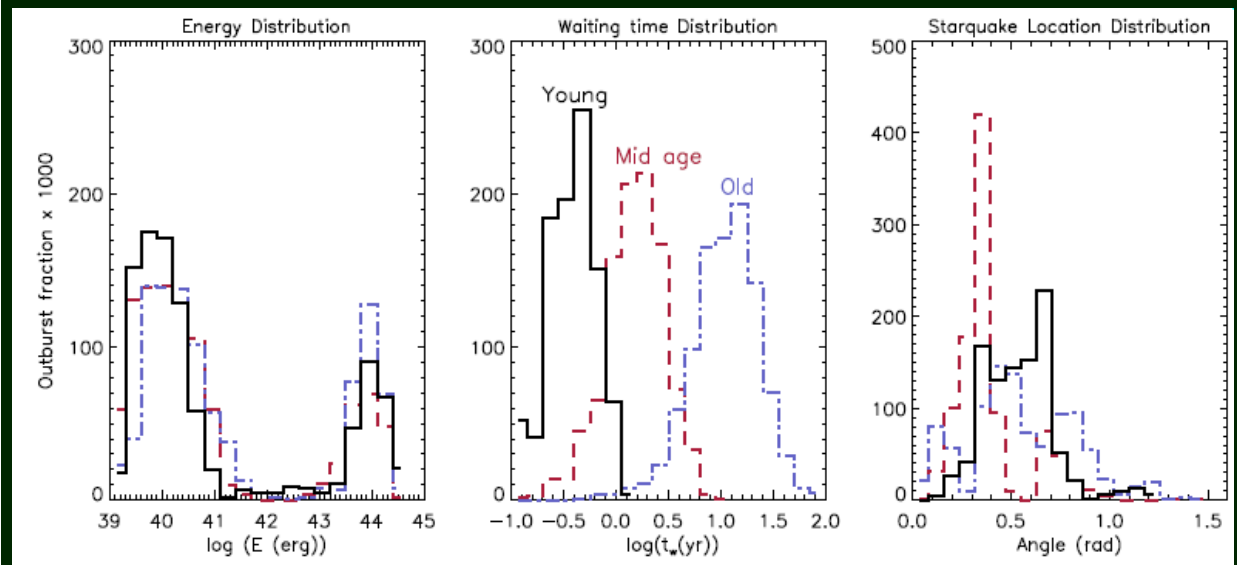
An illustrative model

Poloidal
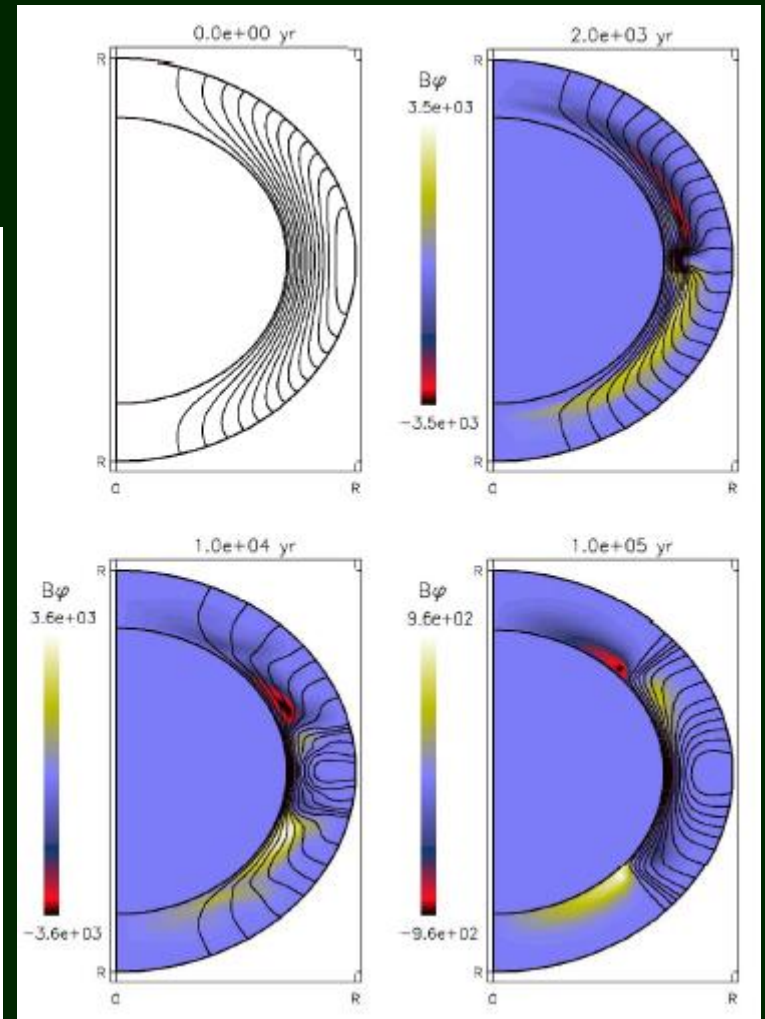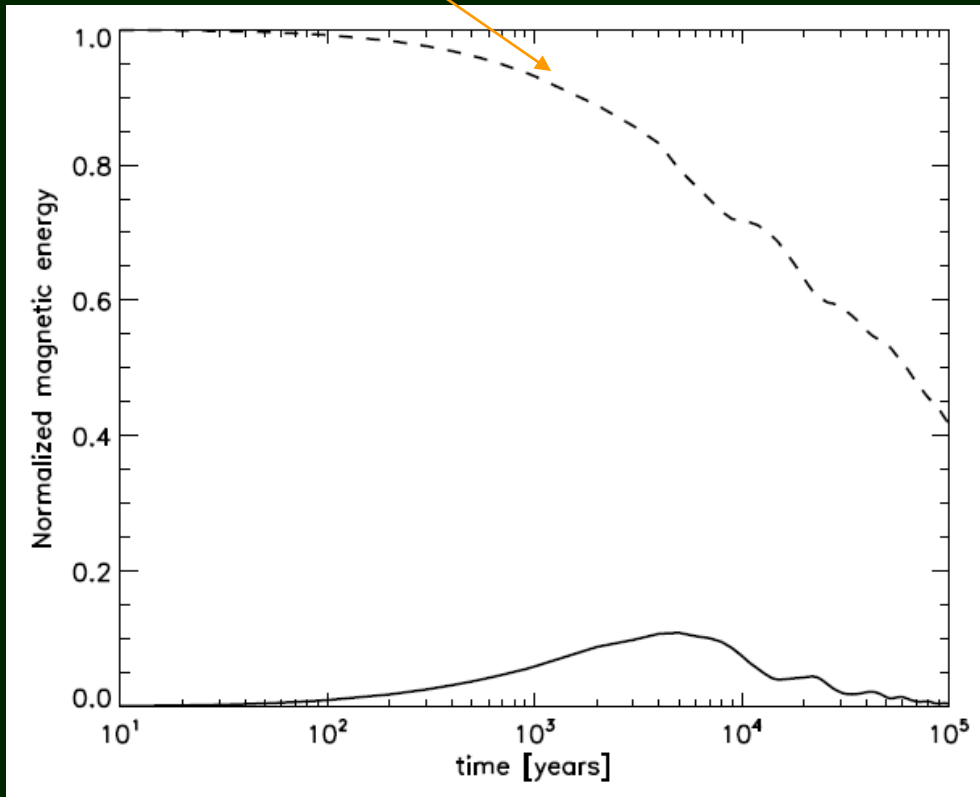
Test illustrates the evolution of initially purely poloidal field

1204.4707

Another model

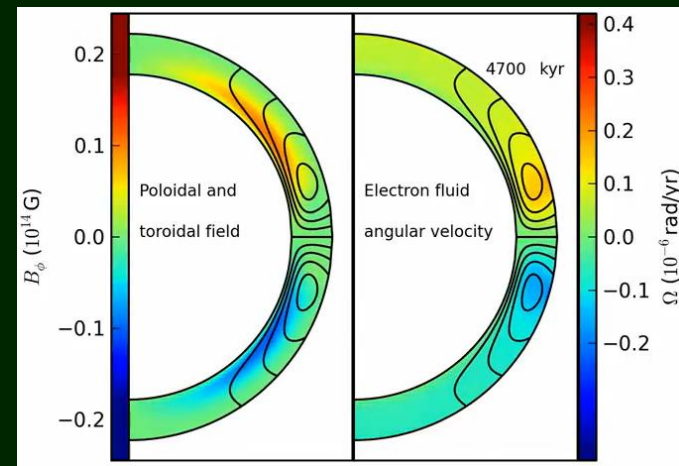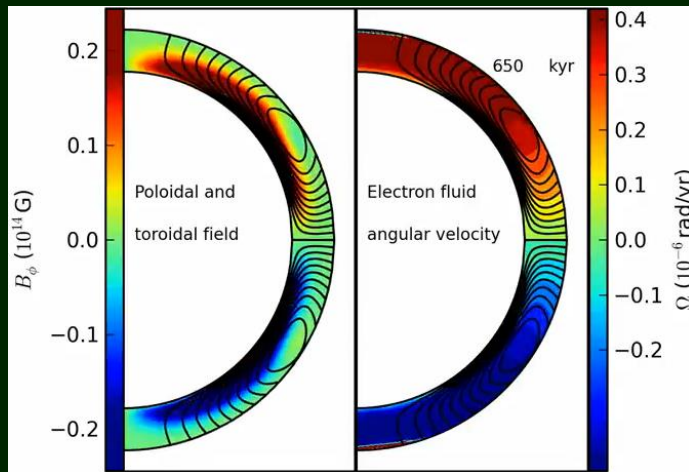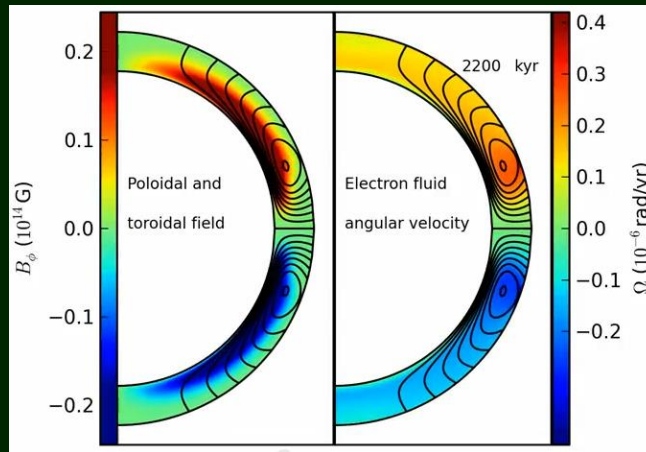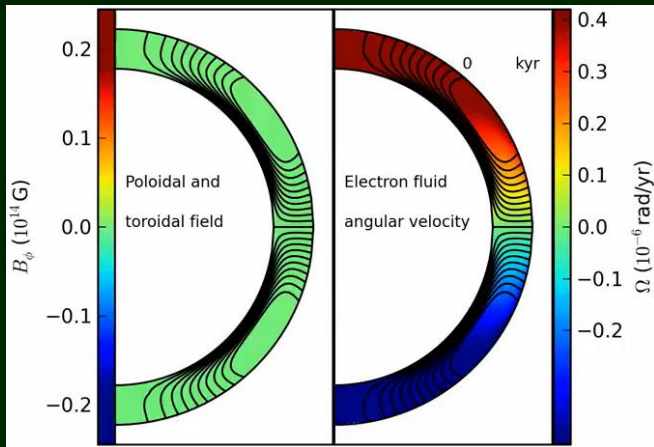Initially the poloidal field is large.

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.

1201.1346

Hall cascade and attractor

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

http://www.physics.mcgill.ca/~kostasg/research.html
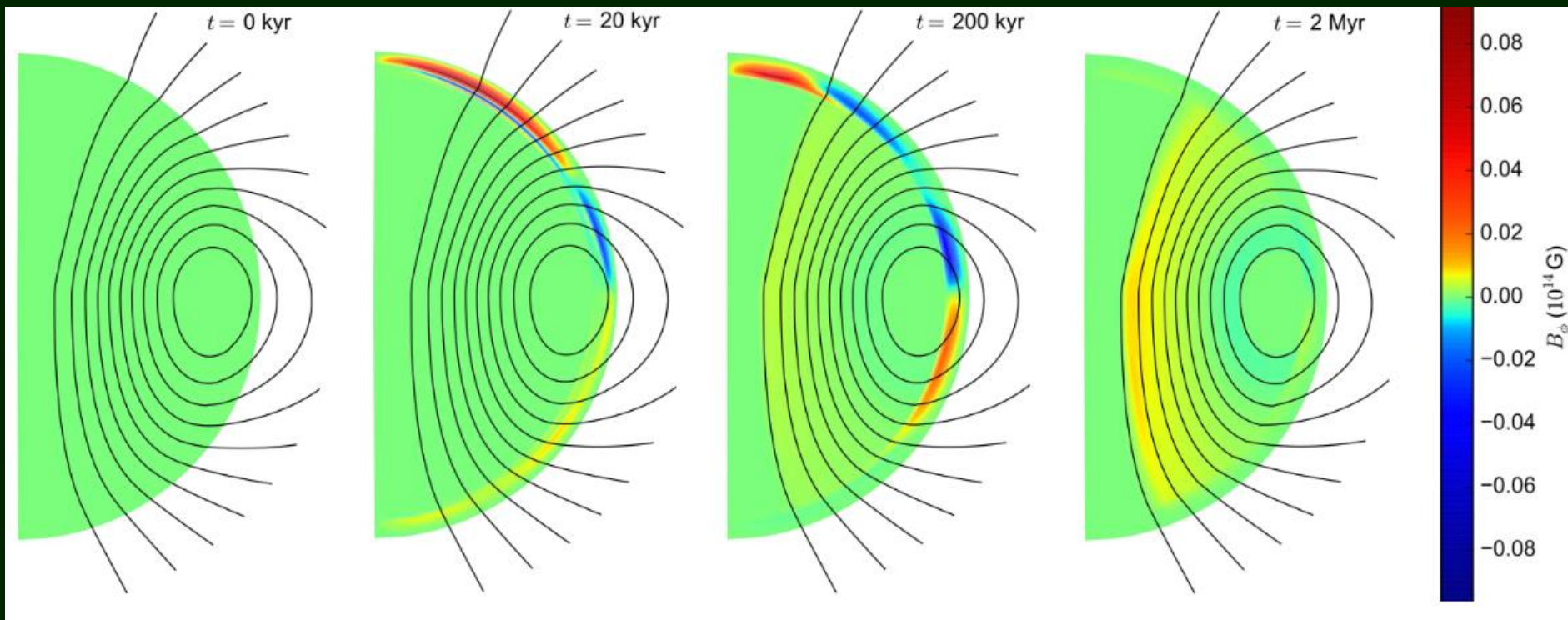
Evolution of different components
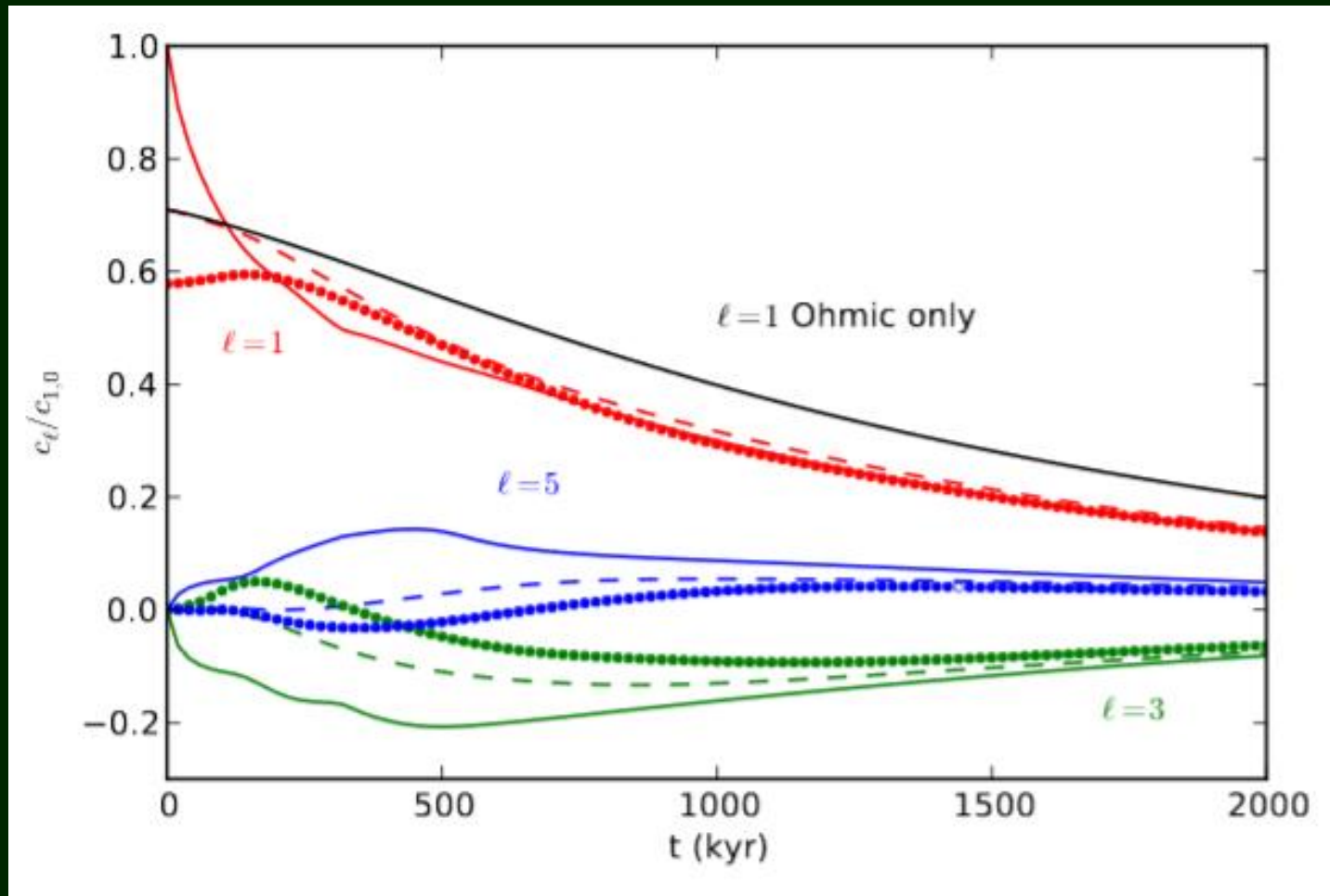
Hall attractor mainly consists of dipole and octupole (+l5)
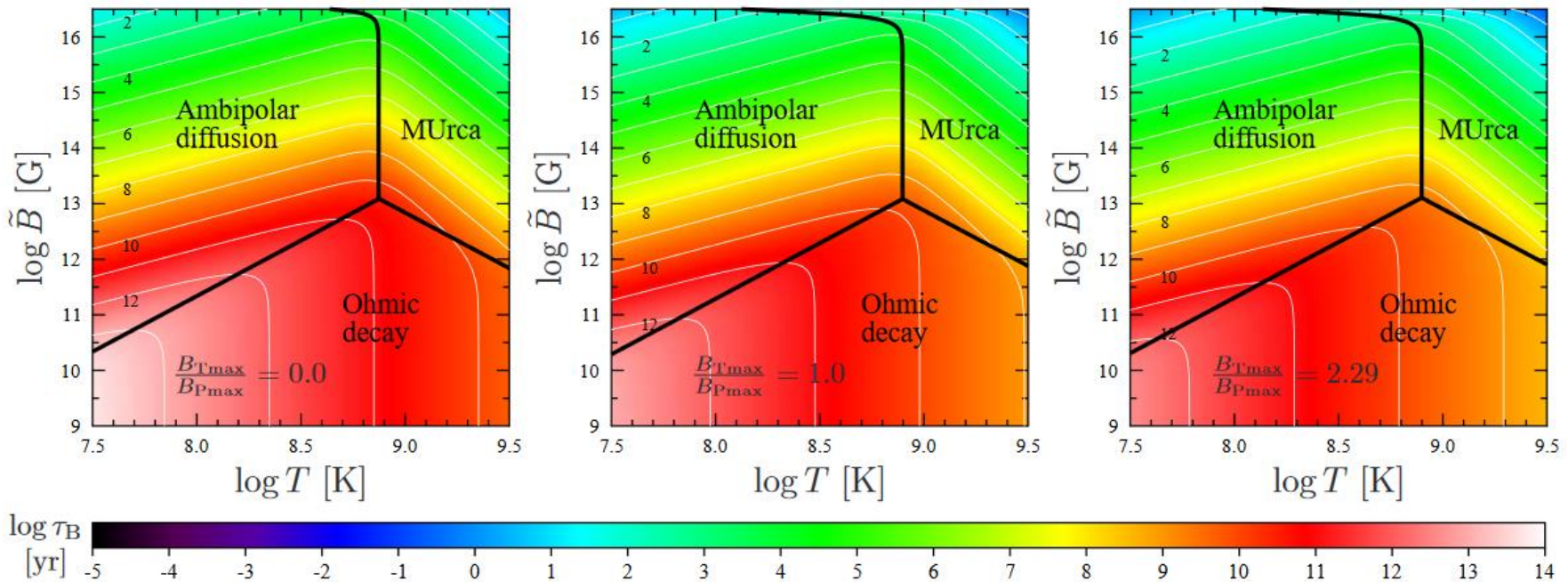
New studies of the hall cascade

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

1501.05149
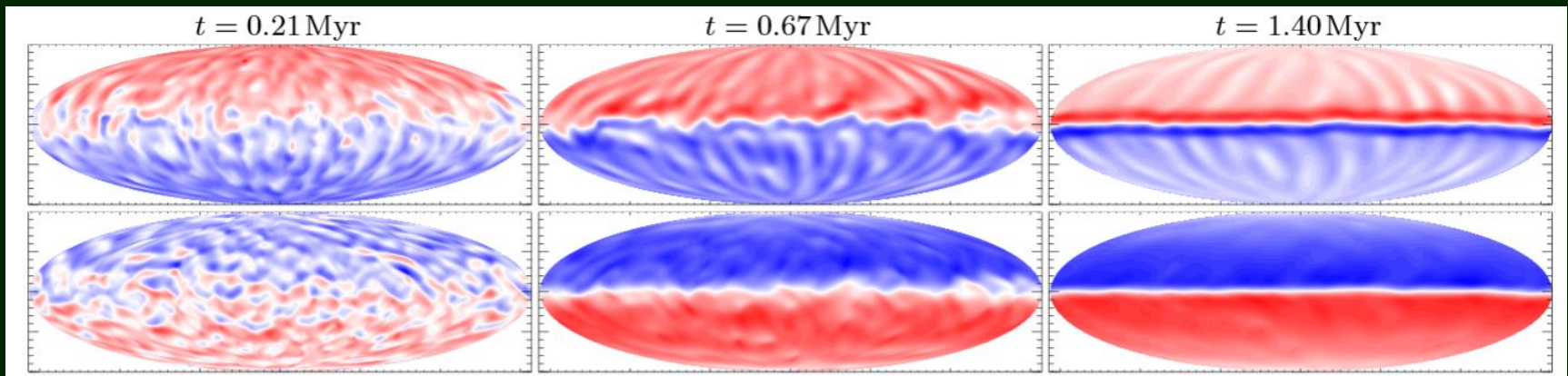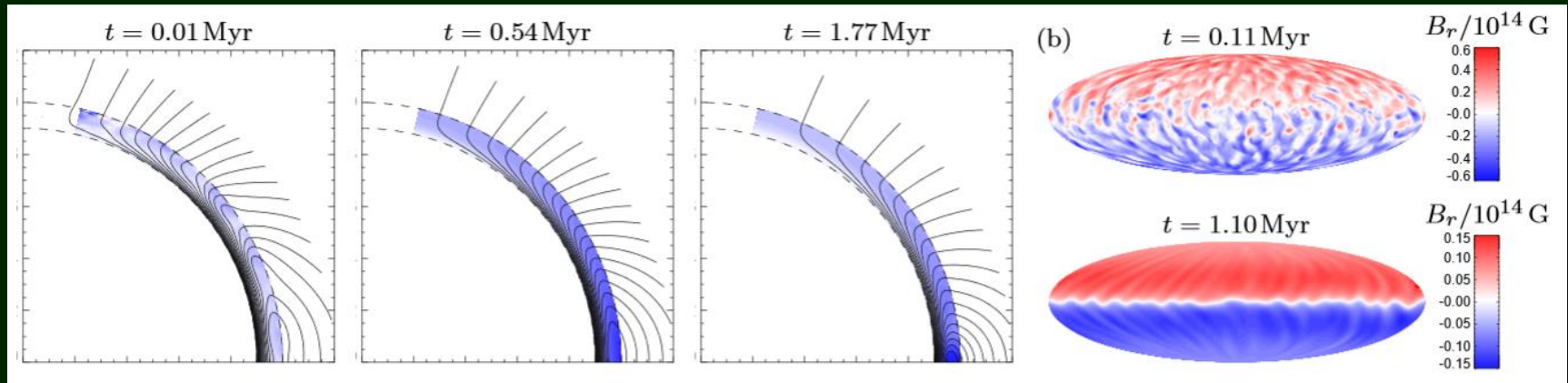
# Core and crust field evolution

Hall attractor is confirmed.

1709.09167

Core field evolution

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

1705.00508, 1805.03956

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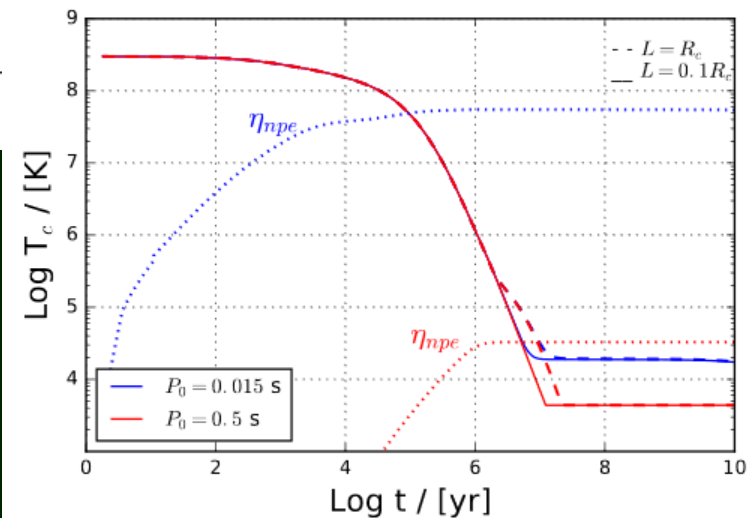
$$t_{Ohm} \ll t_{AD},$$

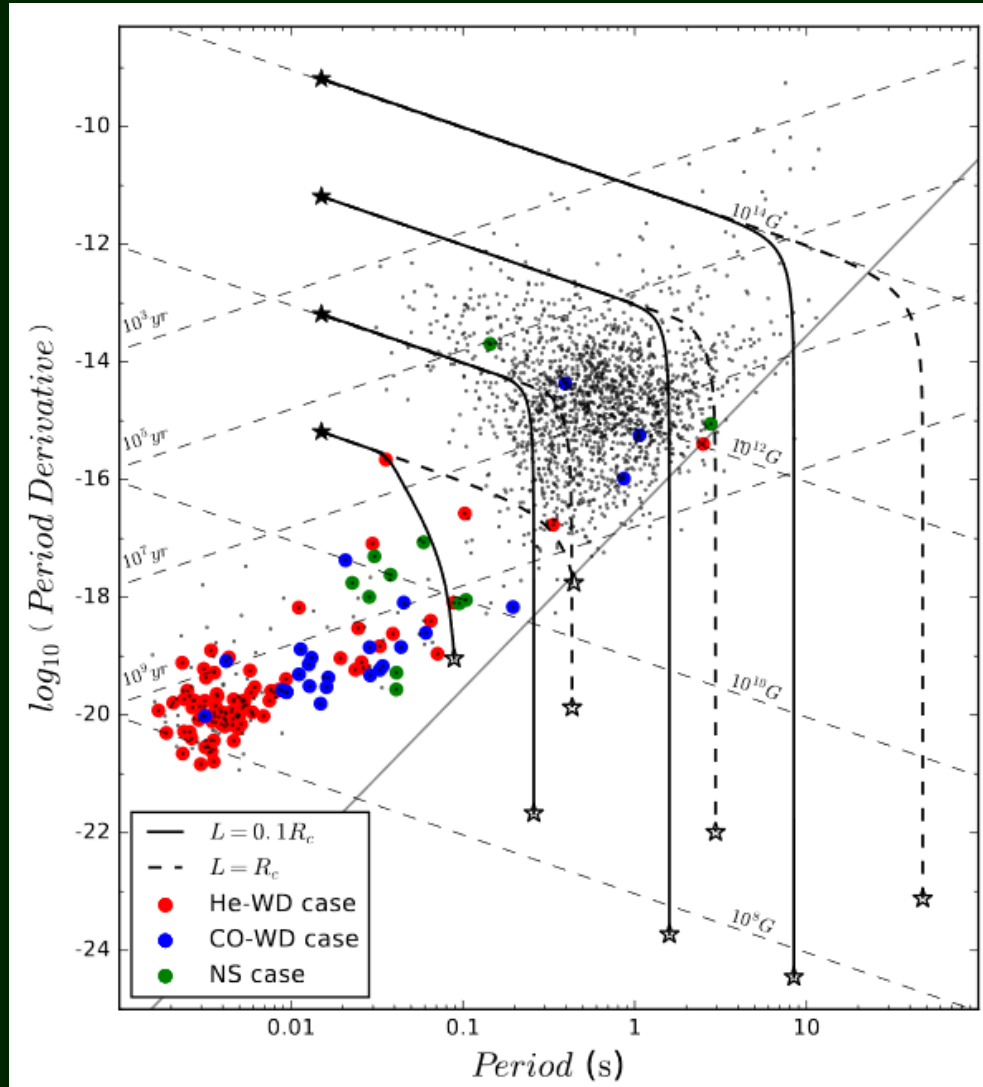$$\dot{B} \approx -\frac{B}{t_{AD}},$$
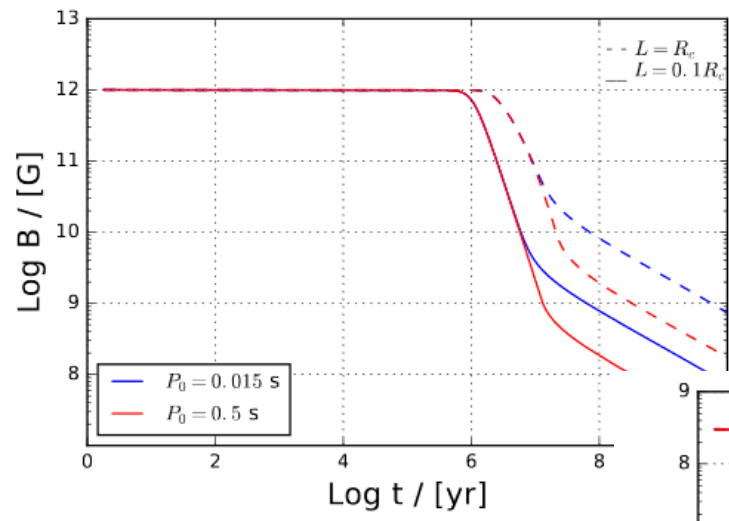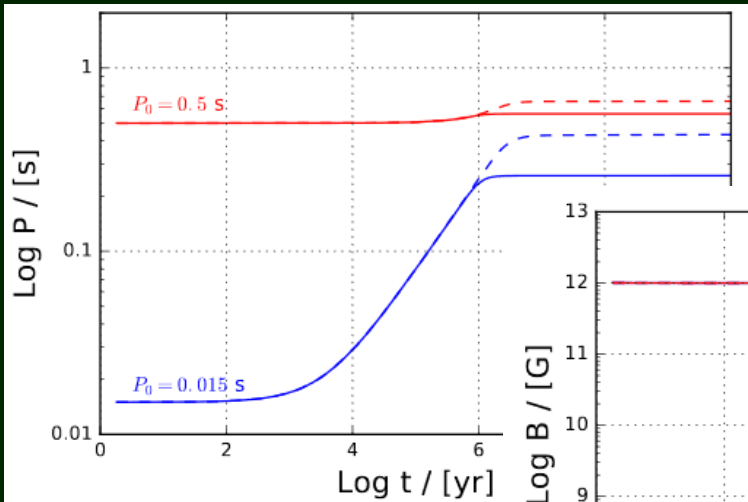
the magnetic field is transported by the charged particles at the ambipolar diffusion velocity

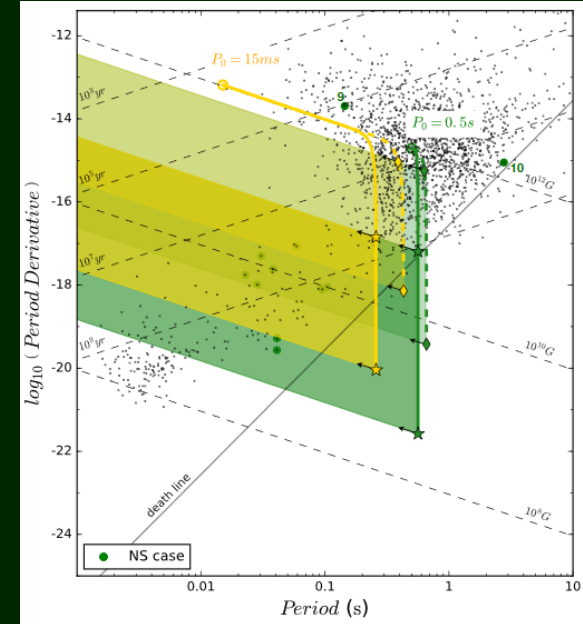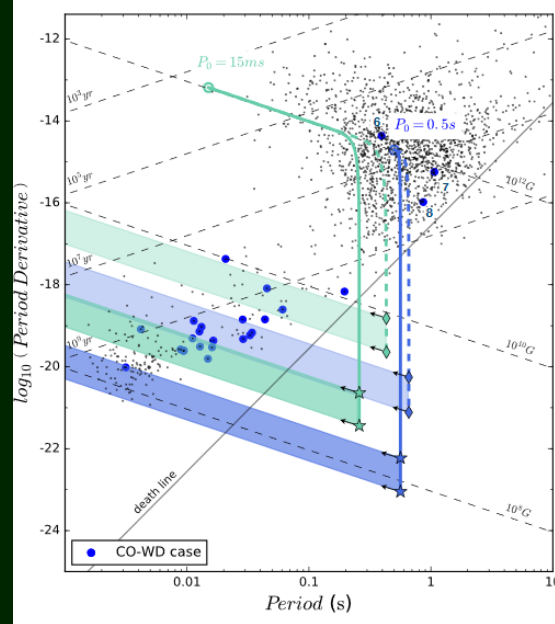$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{v}_{AD} \times \vec{B} \right)$$
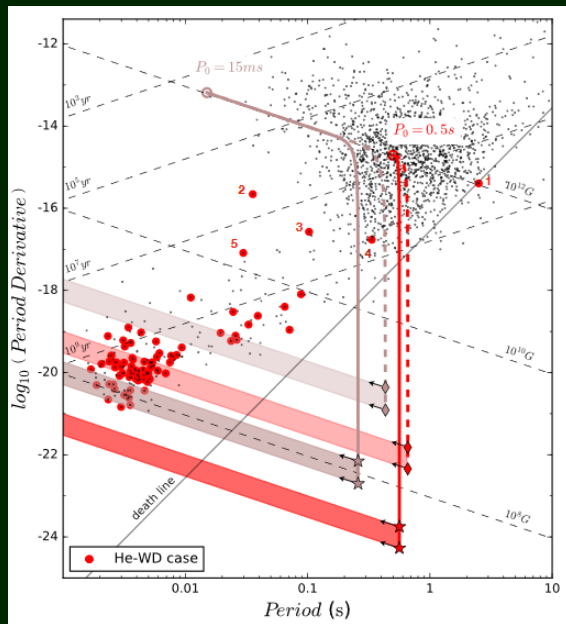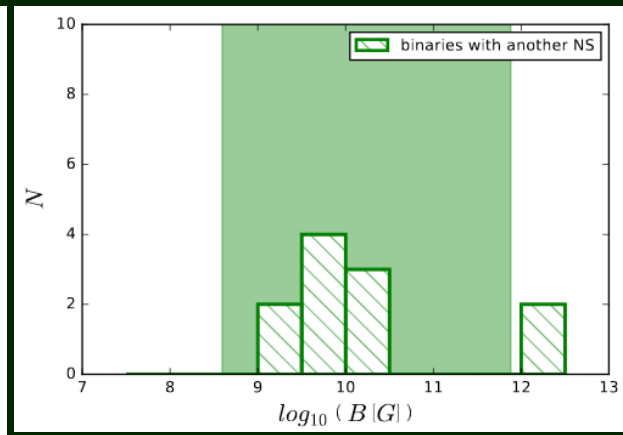
$$t_{AD} = 3 \times 10^9 \frac{T_4^2 L_5^2}{B_8^2} \text{ yr},$$

1906.06076

Evolution on the P-Pdot diagram

1906.06076

Different types of companions

1906.06076
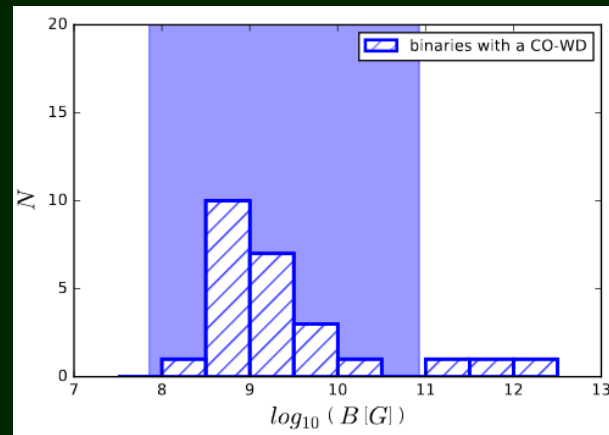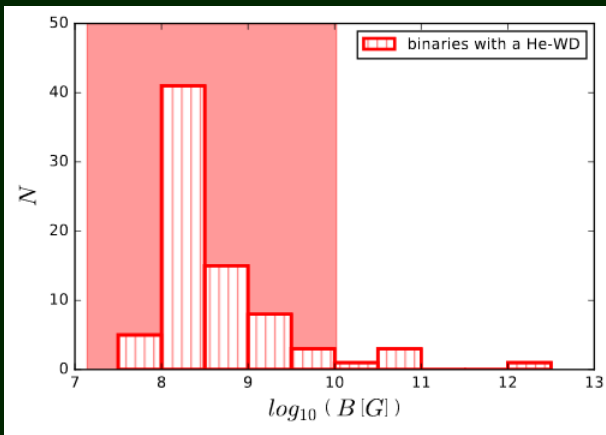
Wide initial spin period distribution
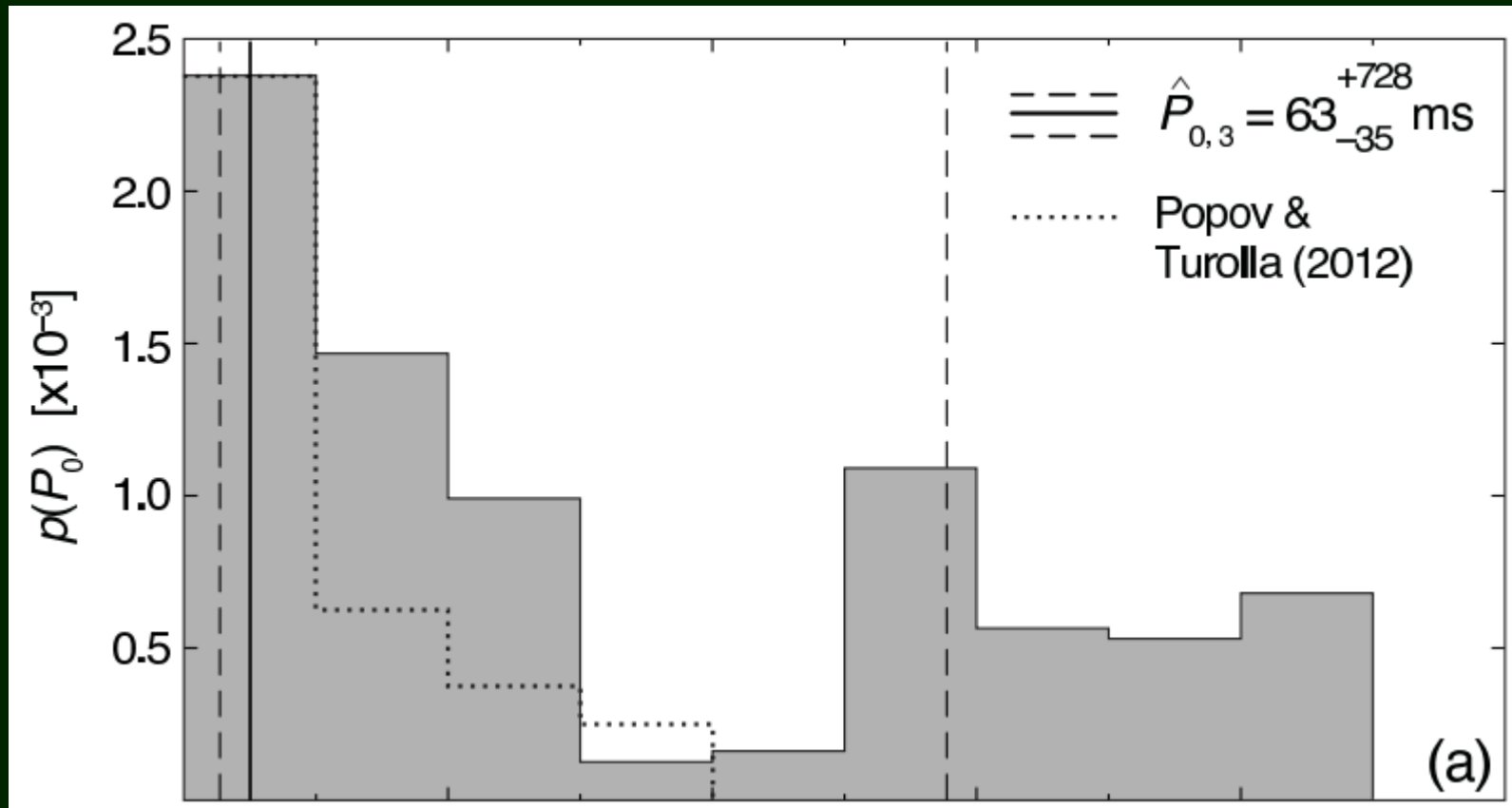
Based on kinematic ages. Mean age – few million years.
Note, that in Popov & Turolla (2012) only NSs in SNRs
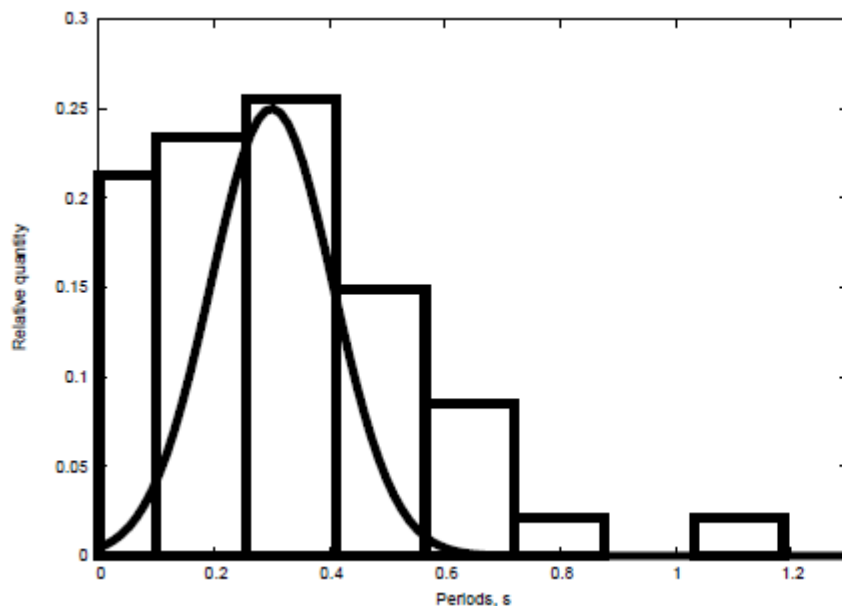were used, i.e. the sample is much younger!
Can it explain the difference?

1301.1265

Magnetic field decay and P_0

One can suspect that magnetic field decay can influence the reconstruction of the initial spin period distribution.
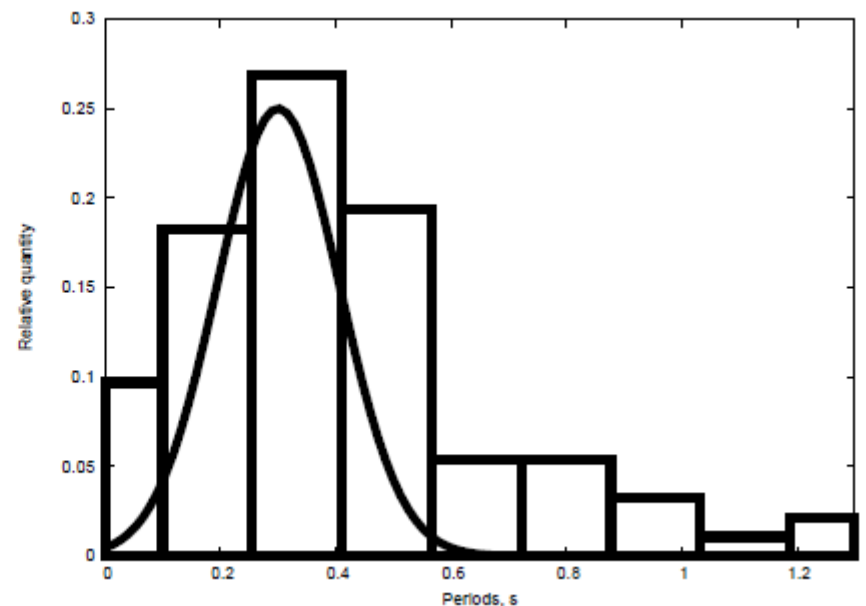
Exponential field decay with τ=5 Myrs.
$<P_0>$=0.3 s, σ_P=0.15 s; $<\log B_0/[G]>$=12.65, σ_B=0.55

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

τ<10^7 yrs, 10^5<t 10^5<t<10^7 yrs

Igoshev, Popov 2013

Real vs. reconstructed P_0
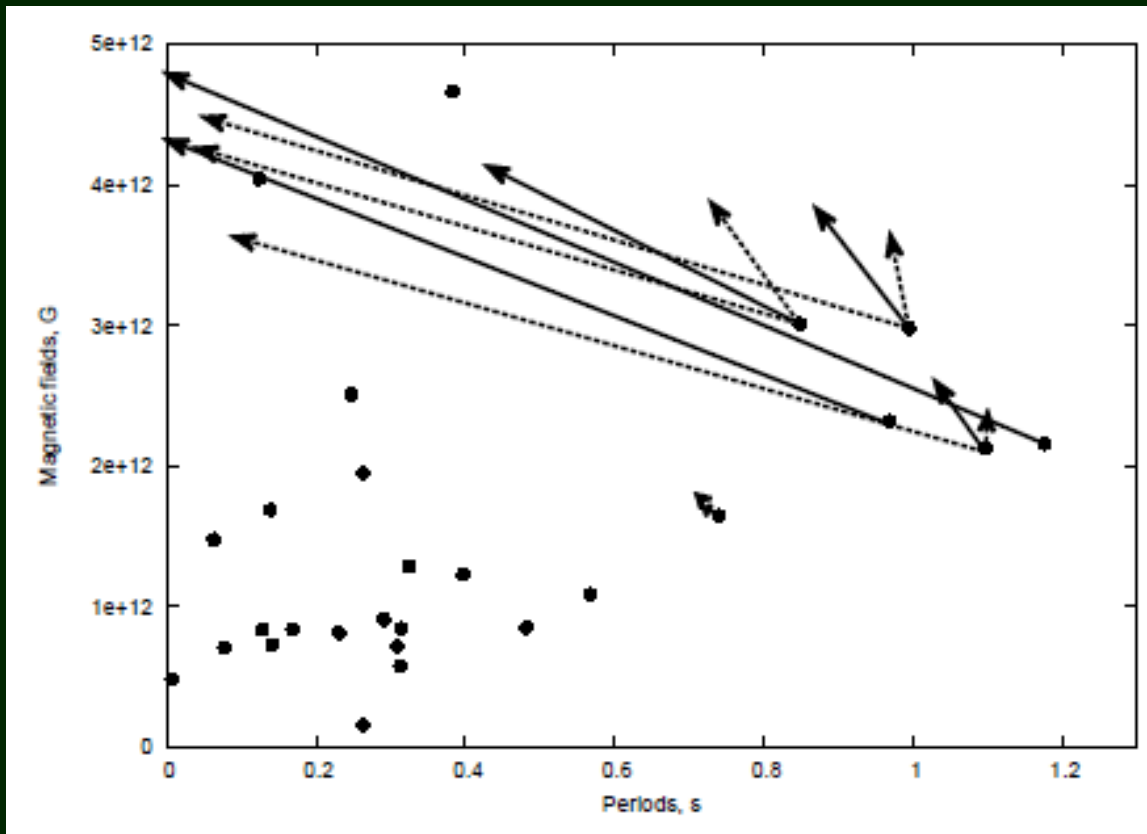

Arrows point to initial parameters of pulsars if the exponential magnetic field decay was operating.

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

Igoshev, Popov 2013

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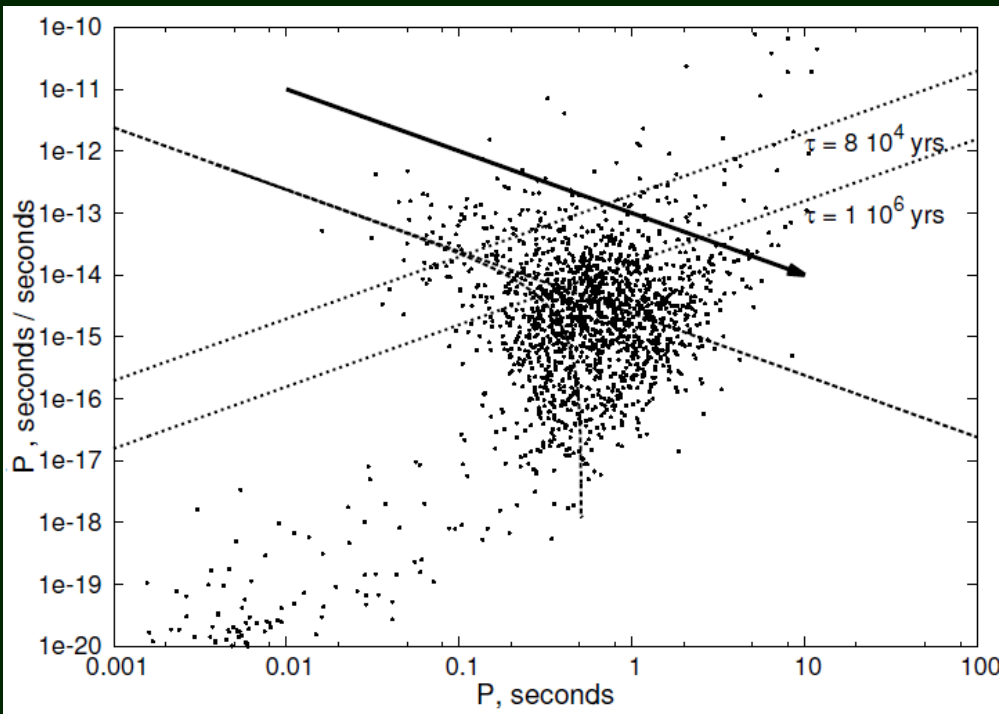
The idea is to probe magnetic field decay.
Our method can be applied only
in a limited range of ages.

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

Igoshev, Popov (2014). MNRAS

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).
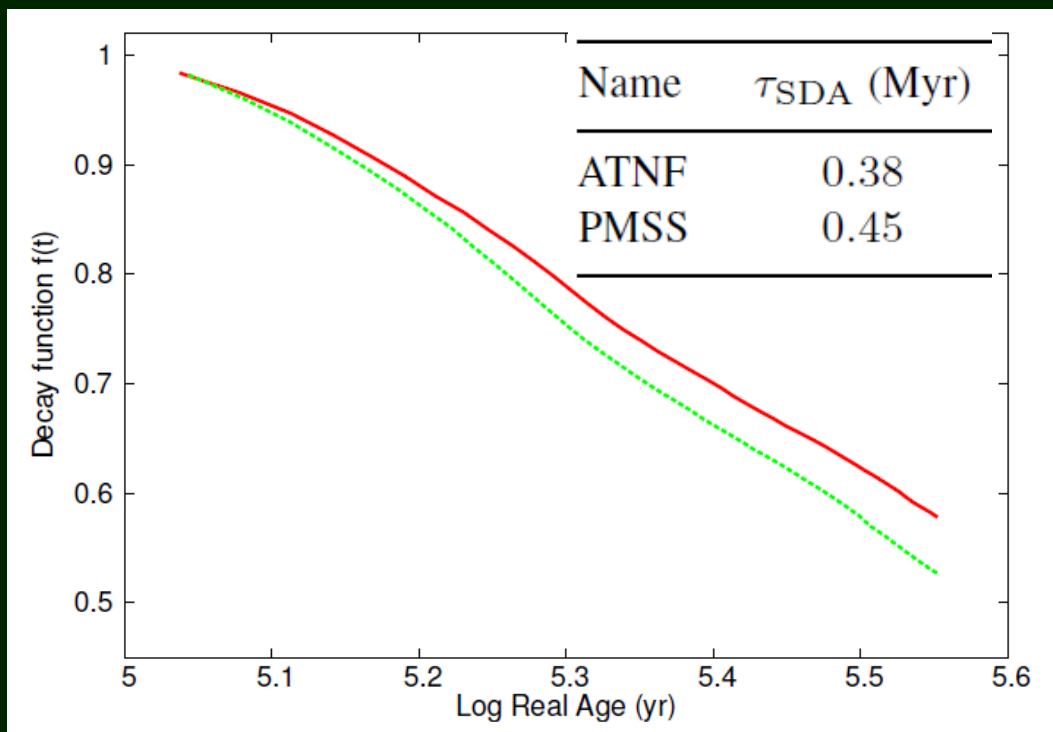
We reconstruct the magnetic field decay in the range of true (statistical) ages:
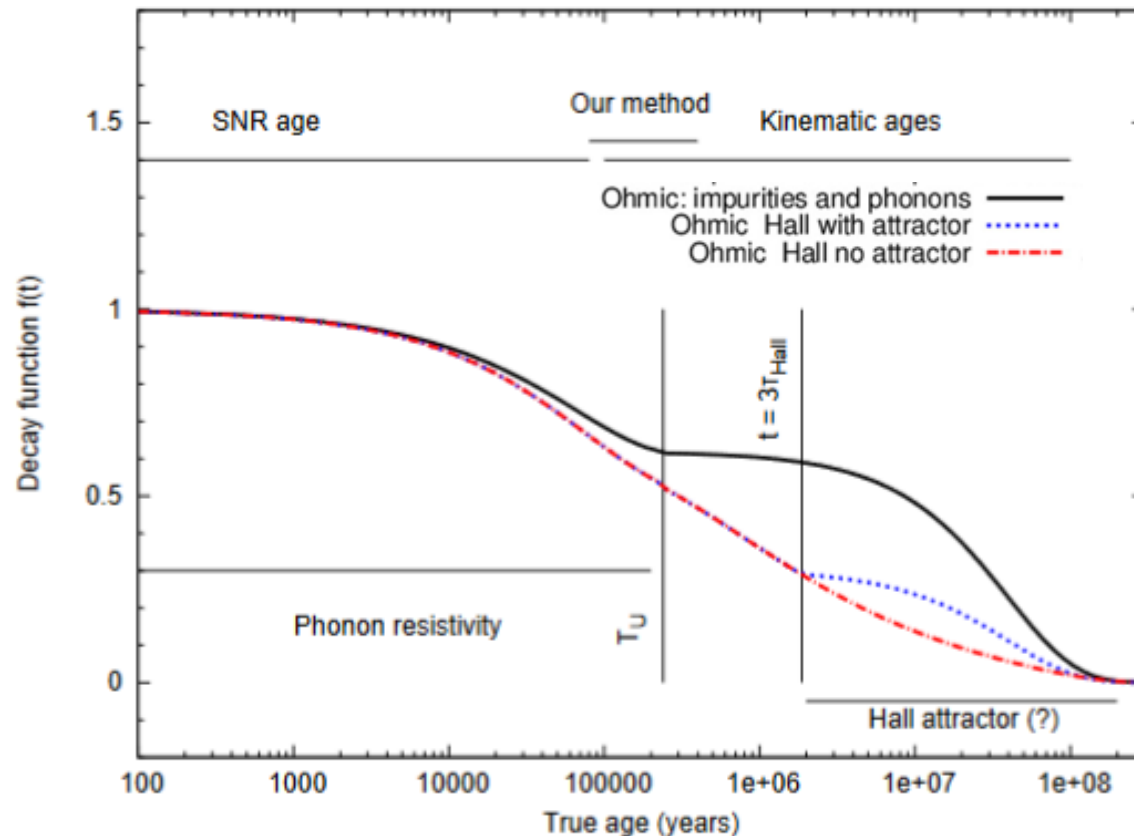$8\ 10^4 < t < 3.5\ 10^5$ yrs
which corresponds to characteristic ages
$8\ 10^4 < \tau < 10^6$ yrs.

In this range, the field decays roughly by a factor of two.
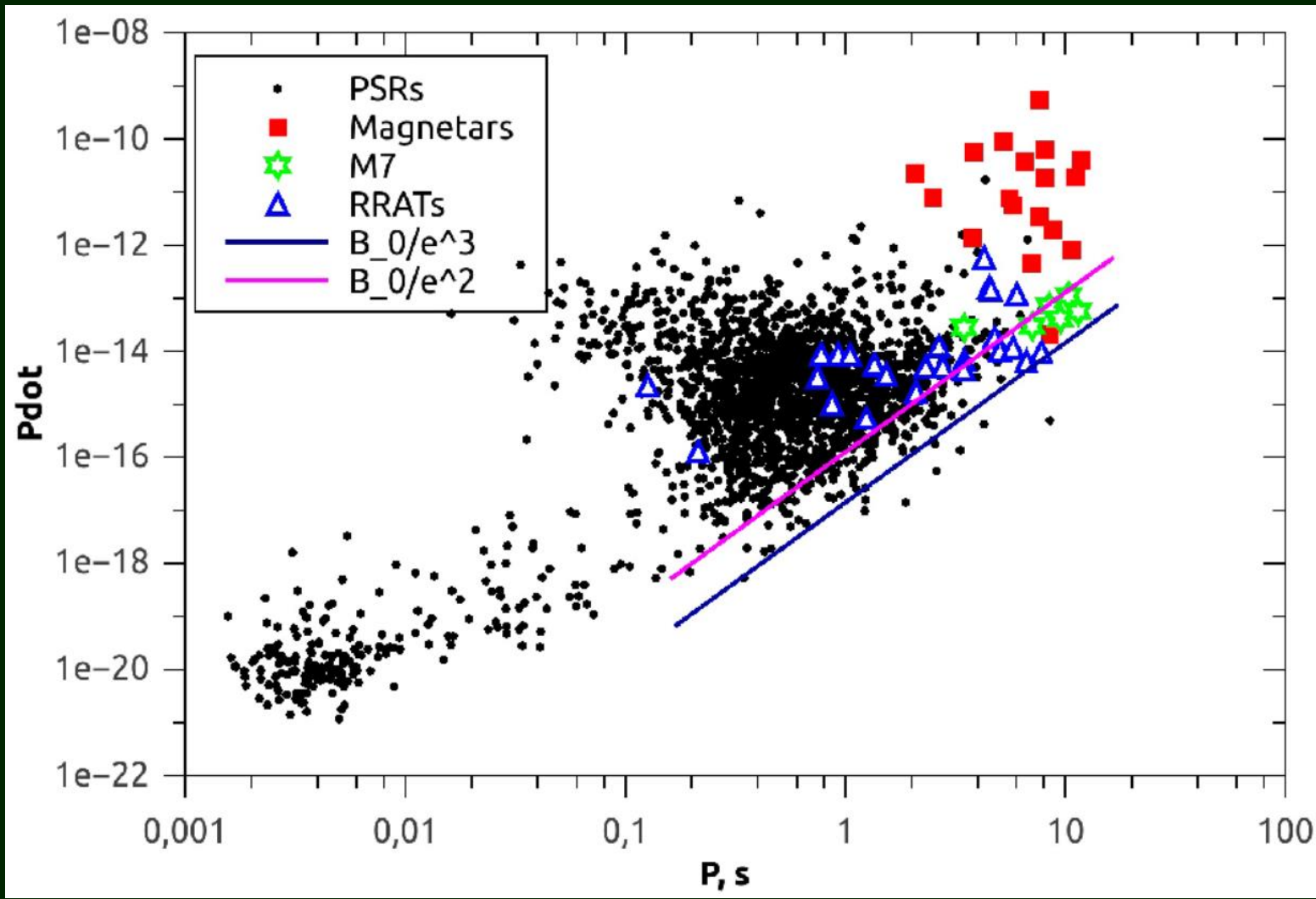With an exponential fit this corresponds to the decay time scale $\sim 4\ 10^5$ yrs.
Note, this decay is limited in time.

Igoshev, Popov (2014)
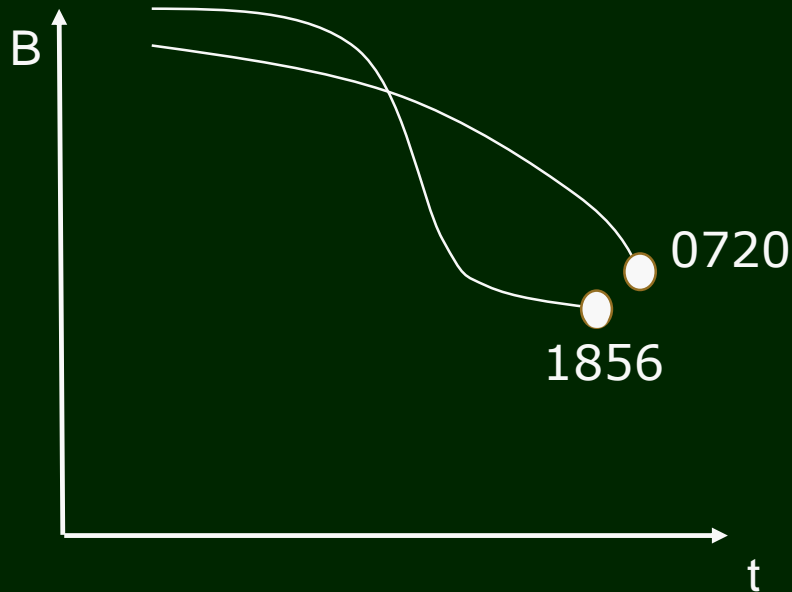
Comparison of different options

We think that at the ages $\sim 10^5$ yrs and below for normal pulsars we see mostly Ohmic decay, which then disappears as NSs cool down below the critical T.

Igoshev, Popov (2015)

Getting close to the attractor

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.
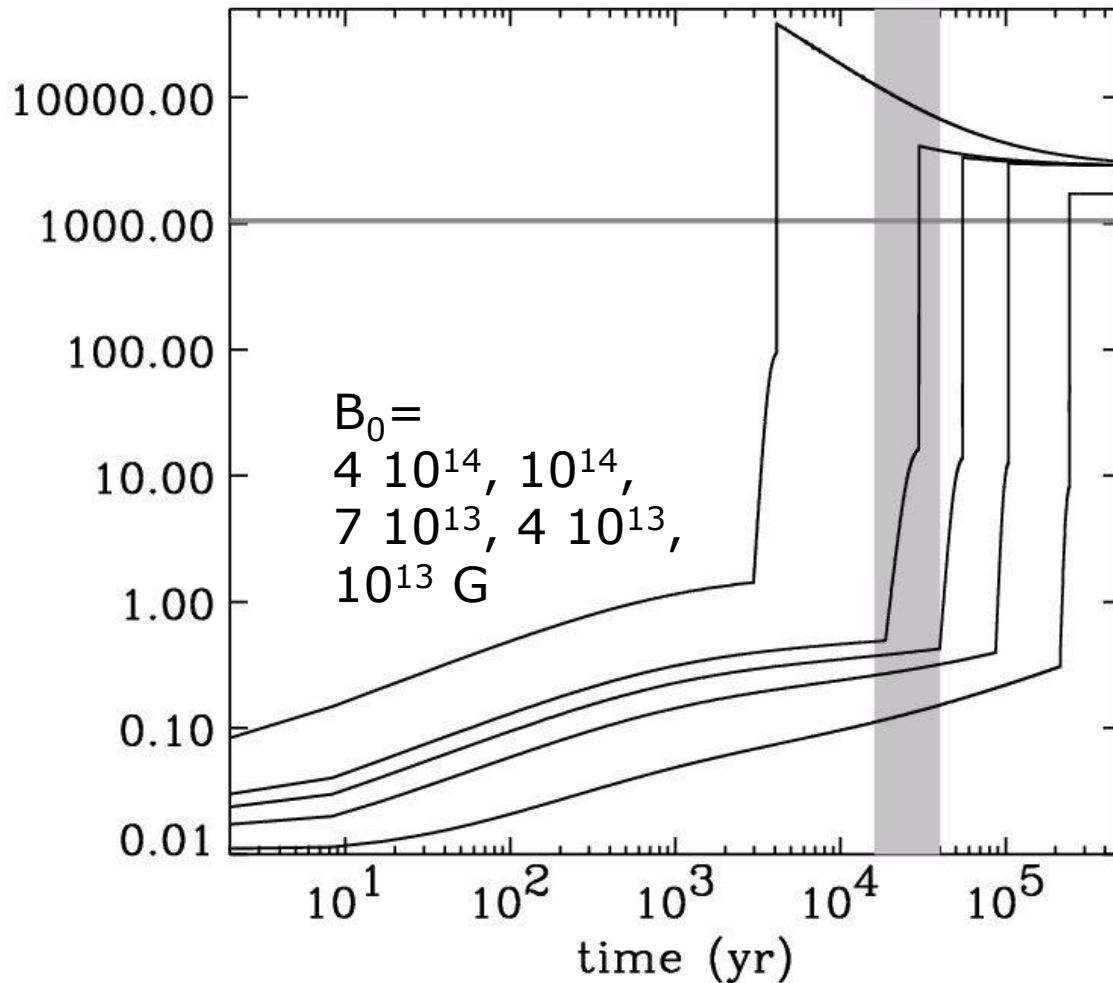
Non-monotonic evolution?

SXP 1062

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

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

Evolution of SXP 1062

$B_0=$
$4 \cdot 10^{14}, 10^{14},$
$7 \cdot 10^{13}, 4 \cdot 10^{13},$
10^{13} G
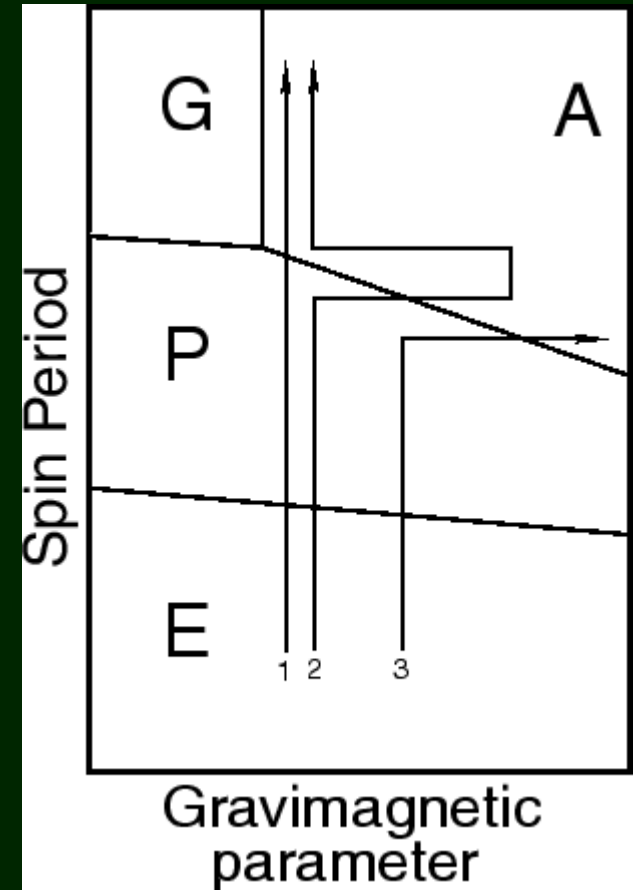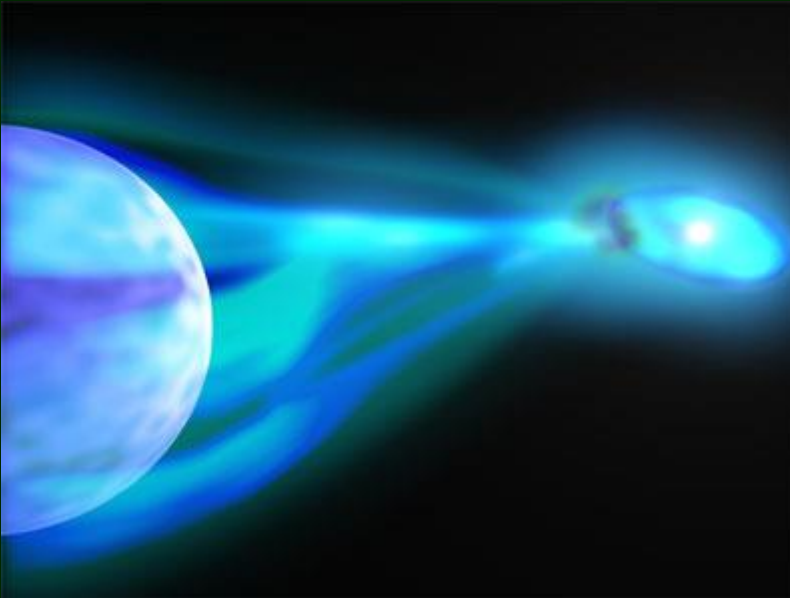
A model of a NS with initial field $\sim 10^{14}$ G which decayed down to $\sim 10^{13}$ G can explain the data on SXP 1062.
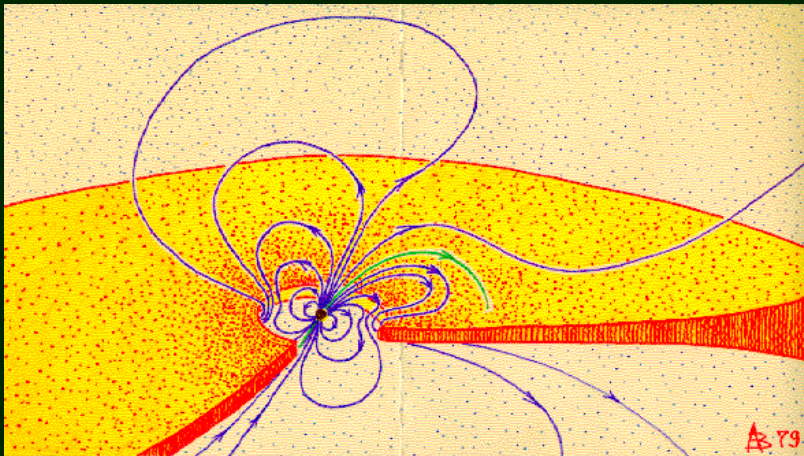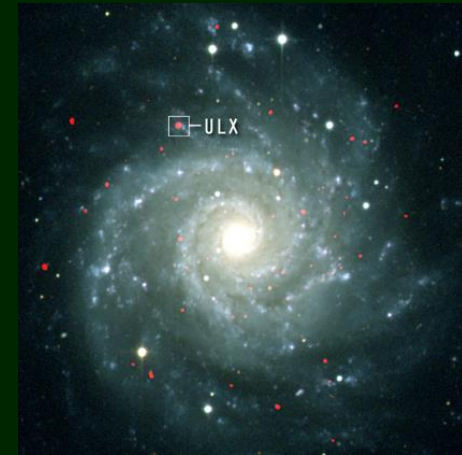
1112.2507

Some new data in
1304.6022

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.
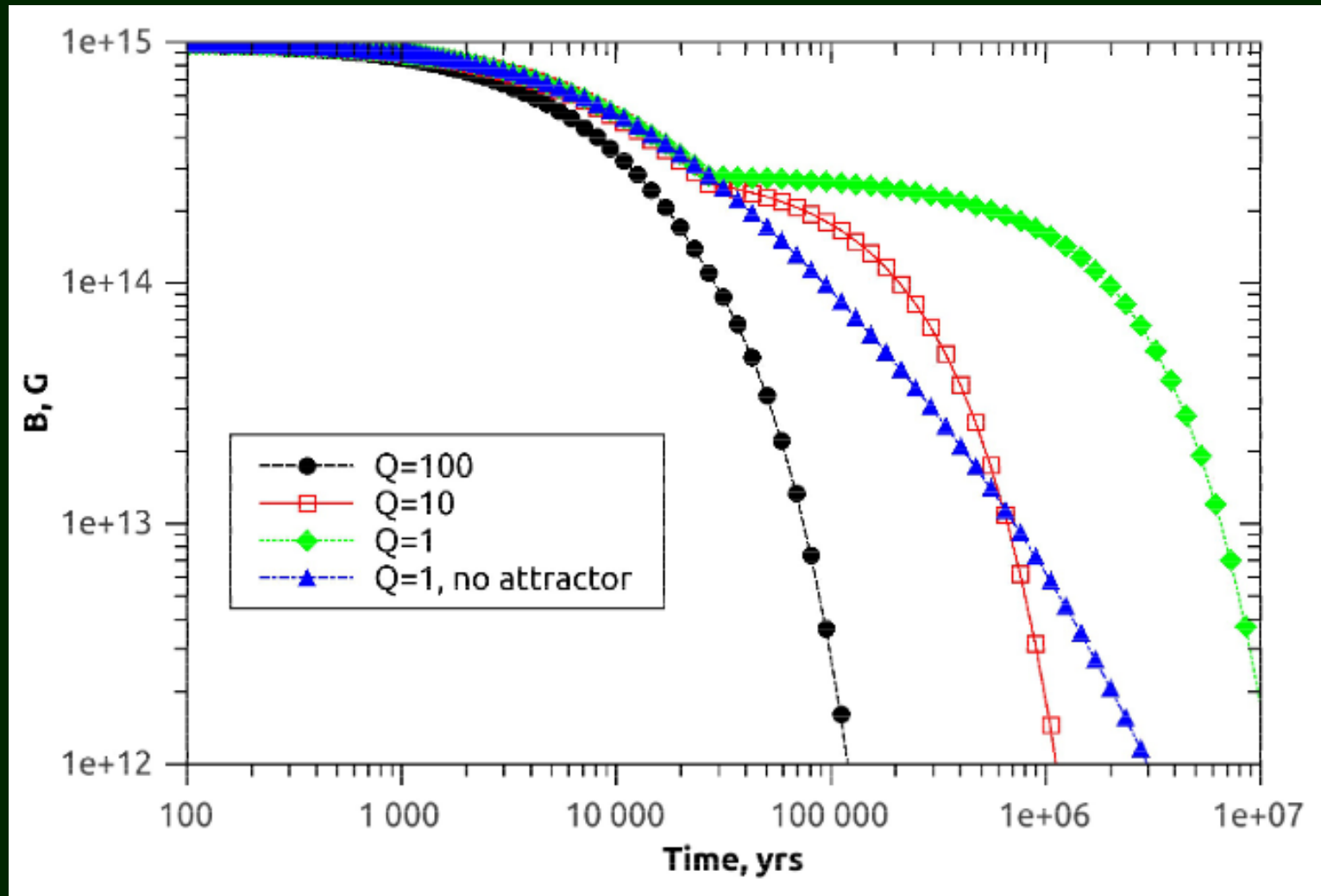

- Spin-up
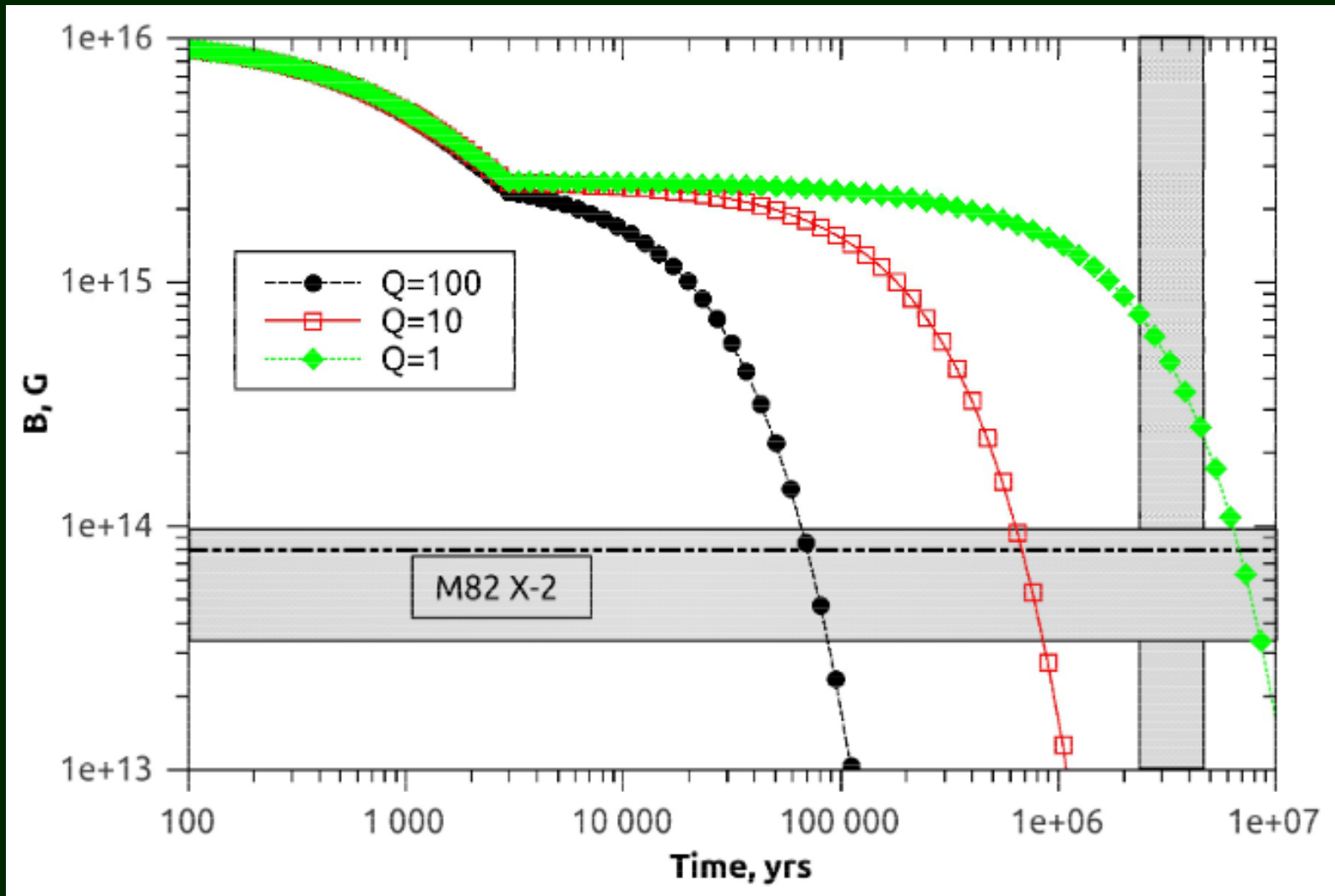- Spin-down
- Equilibrium period
- Accretion model
- ....

- 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)
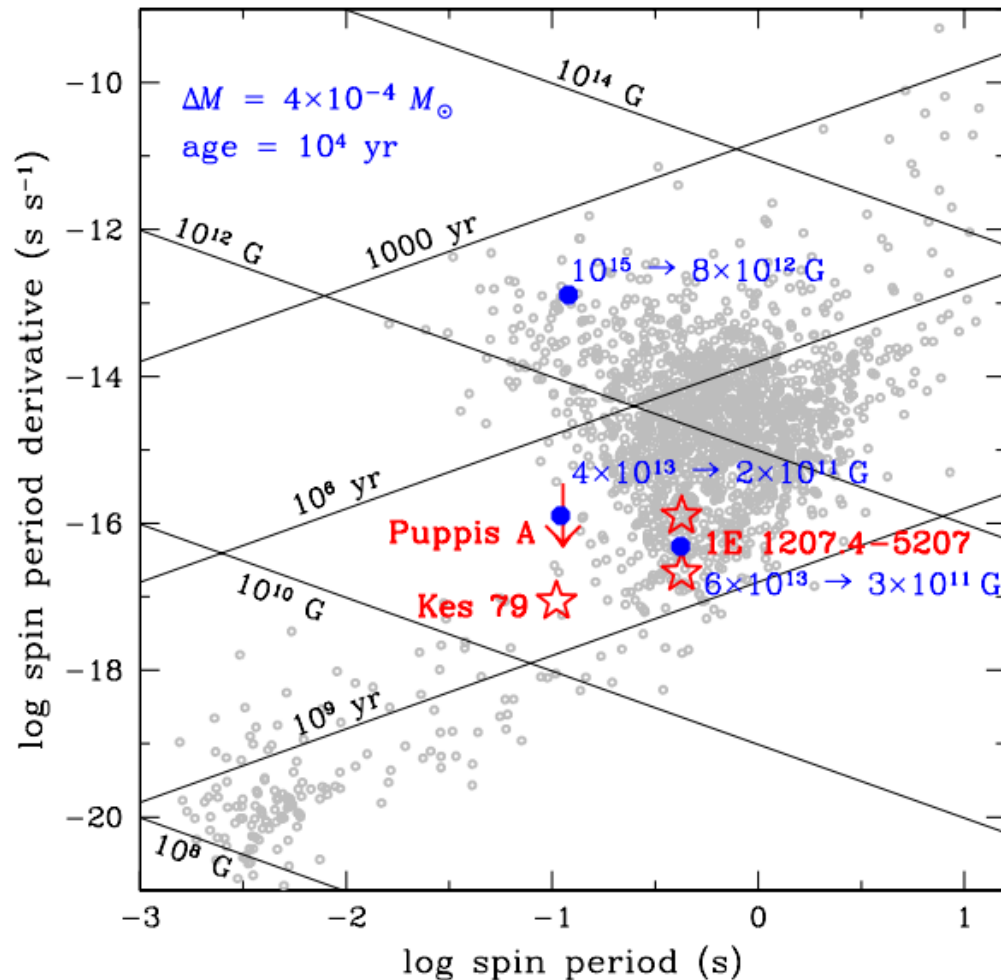- Swift J045106.8-694803. Klus et al. (2013).

1709.10385
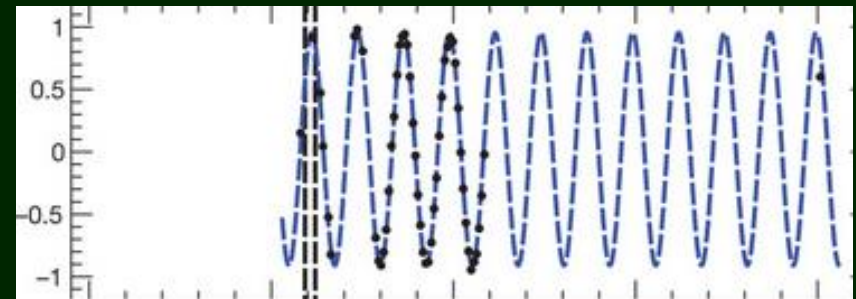
Field evolution in a magnetar
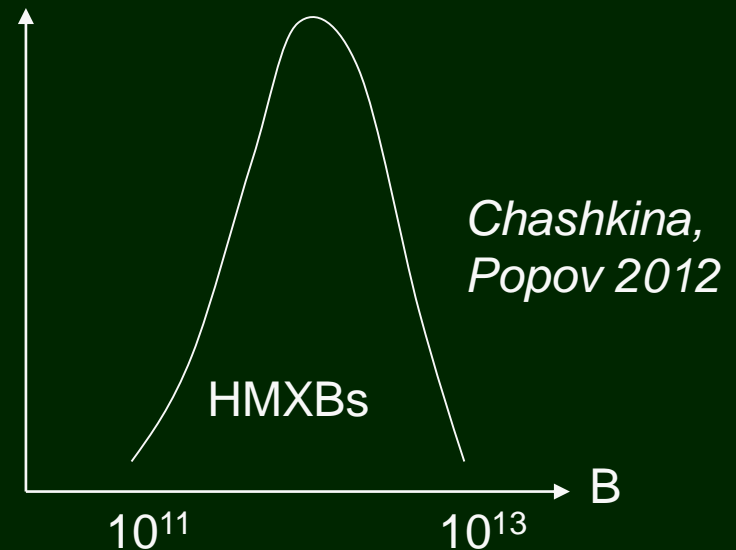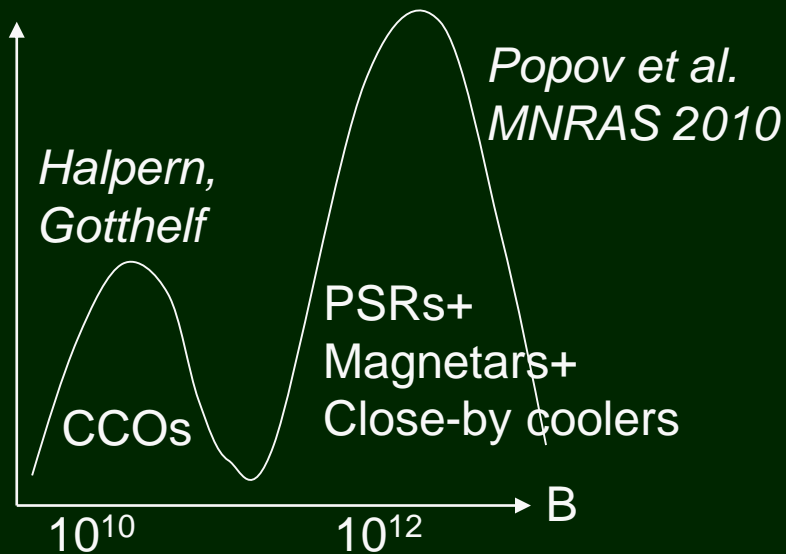
Parameters of ULX M82 X-2

Anti-magnetars

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

Ho 1210.7112

Evolution of CCOs

Halpern, Gotthelf

CCOs

PSRs+
Magnetars+
Close-by coolers

Popov et al. MNRAS 2010

10^{10} 10^{12} B

HMXBs

Chashkina, Popov 2012

10^{11} 10^{13} B

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.
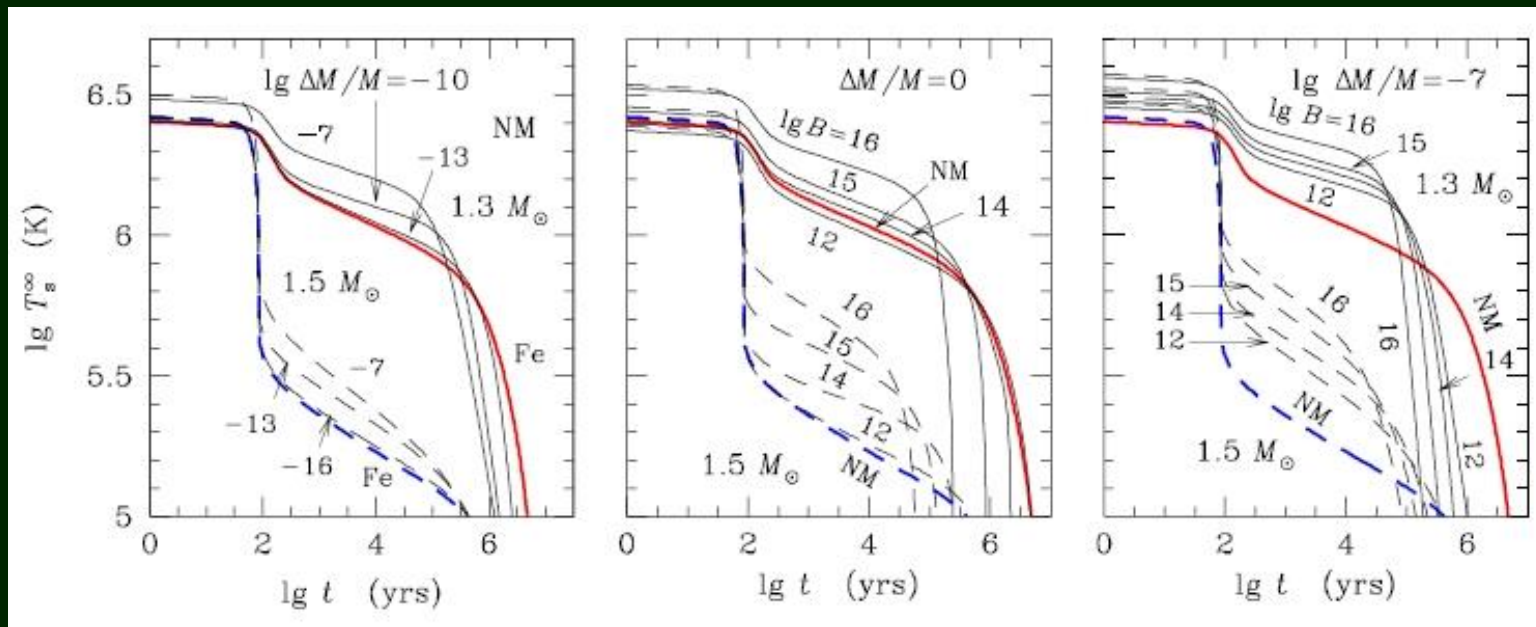The only good example - SAX J0635+0533. An old CCO?

Possible solution: emergence of magnetic field
(see 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)
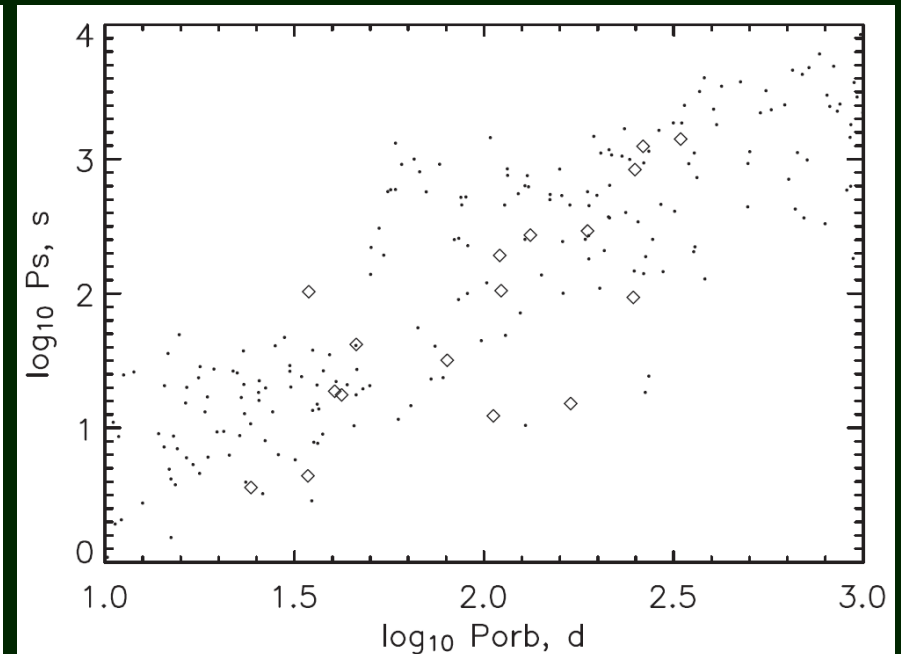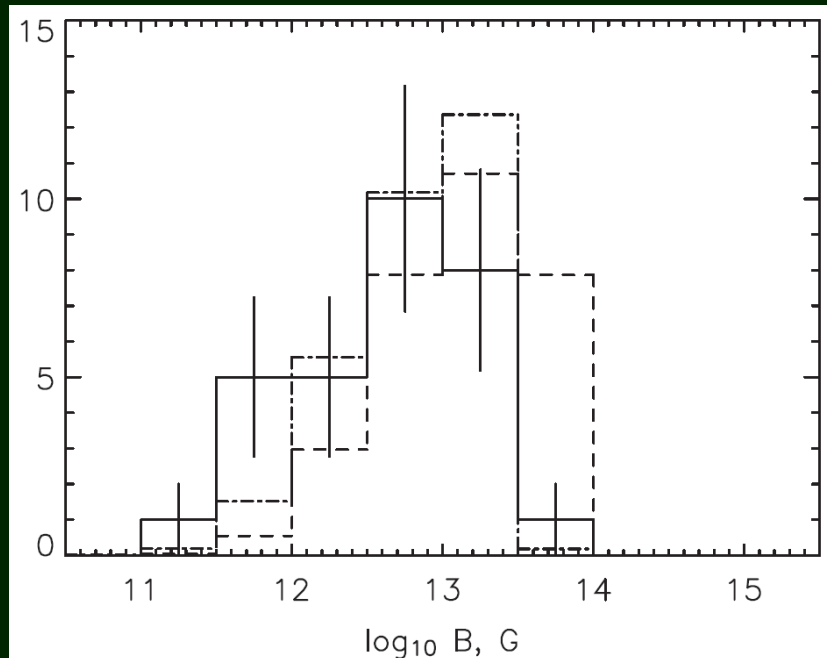
Where are old CCOs?

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
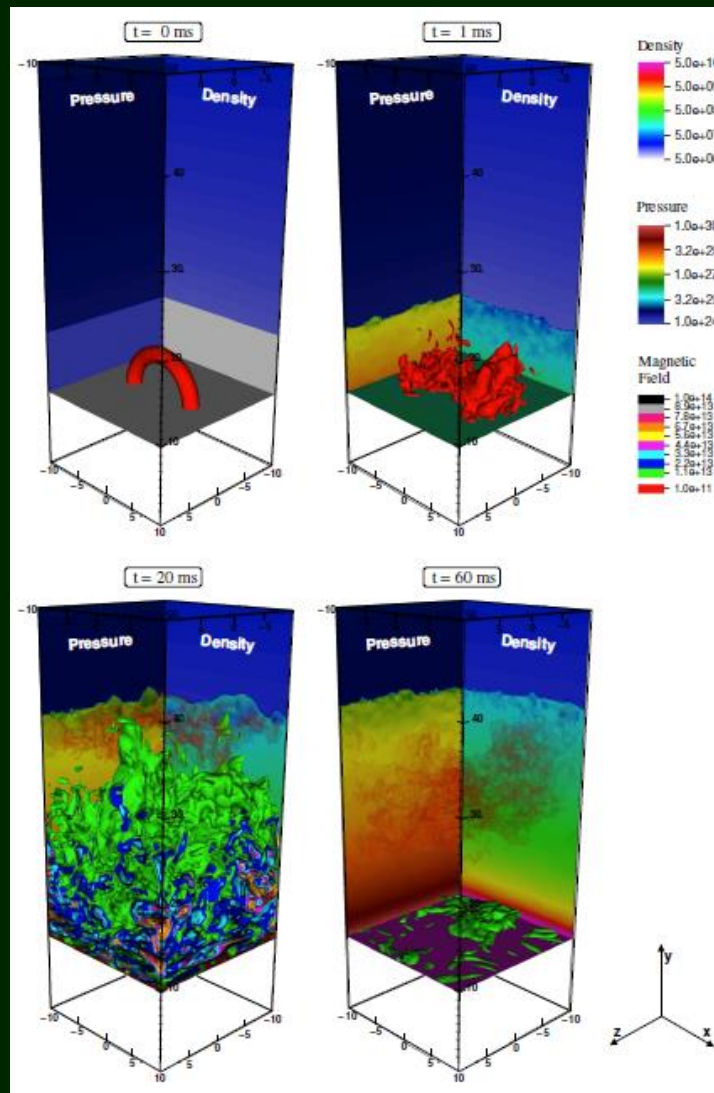cooling NS is known (Calvera is also a possible candidate).

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 thermal emission for which additional heating was proposed
can be descendants of CCOs with emerged field.
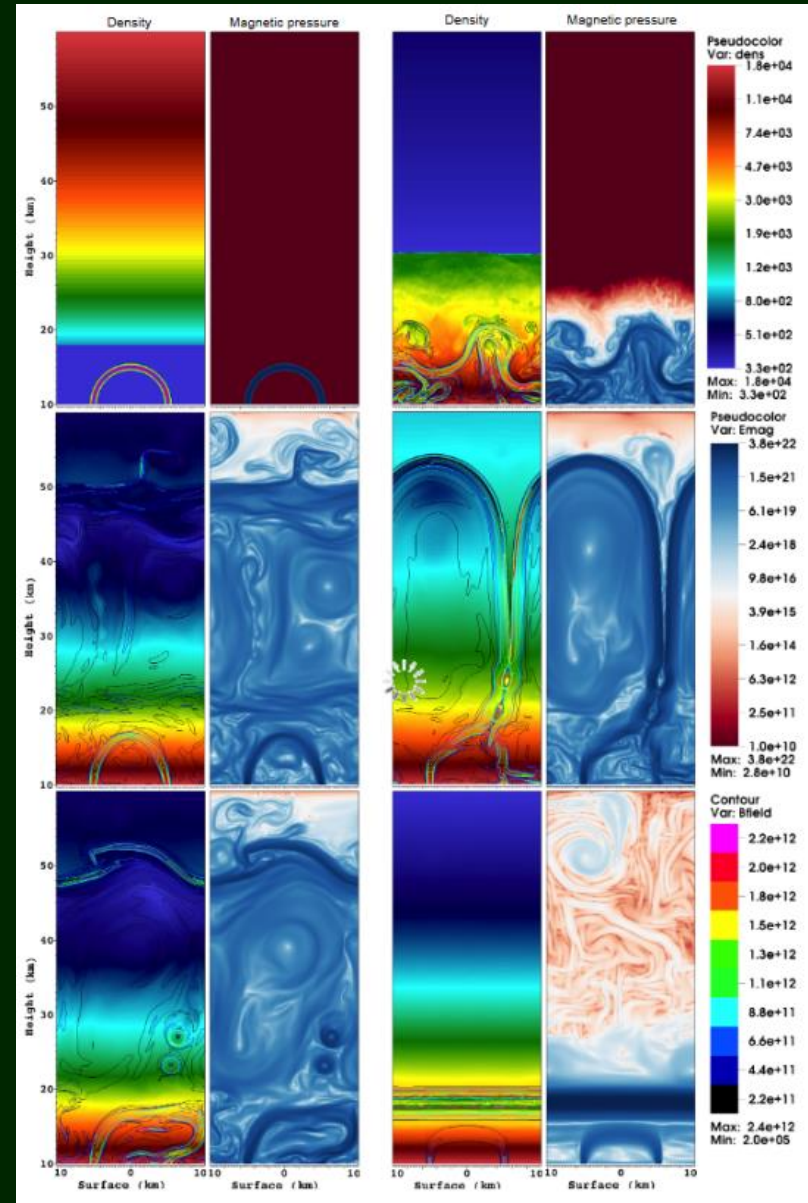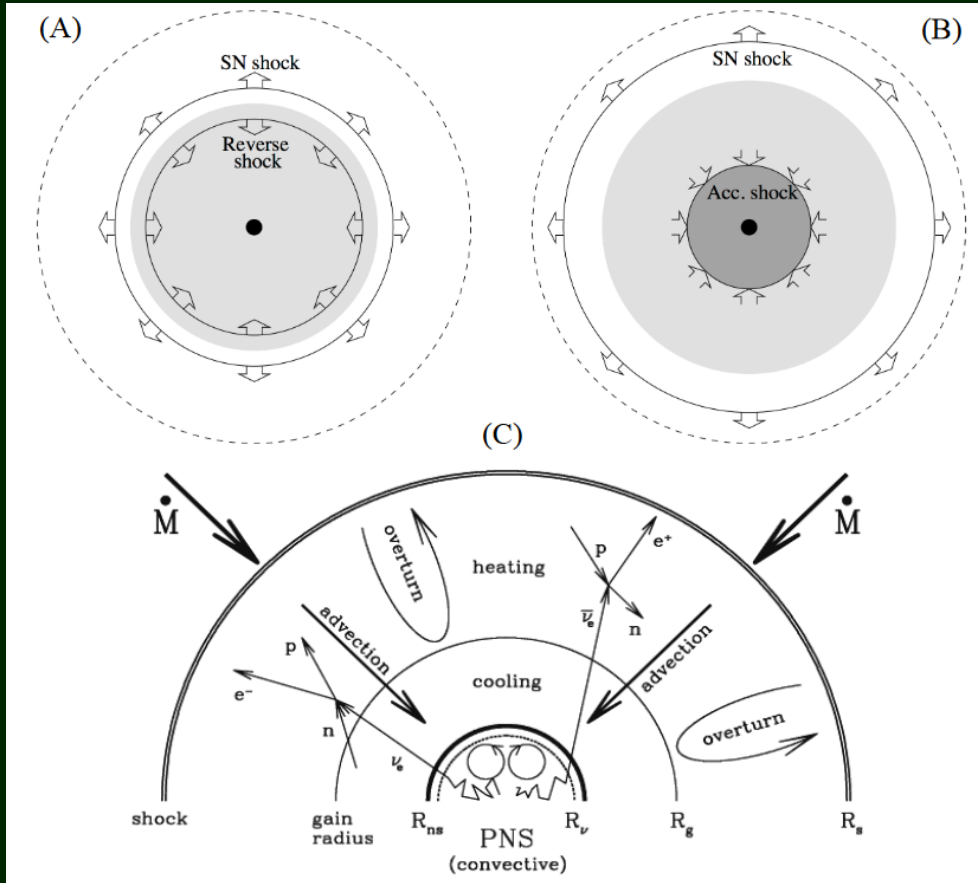
How the field is buried
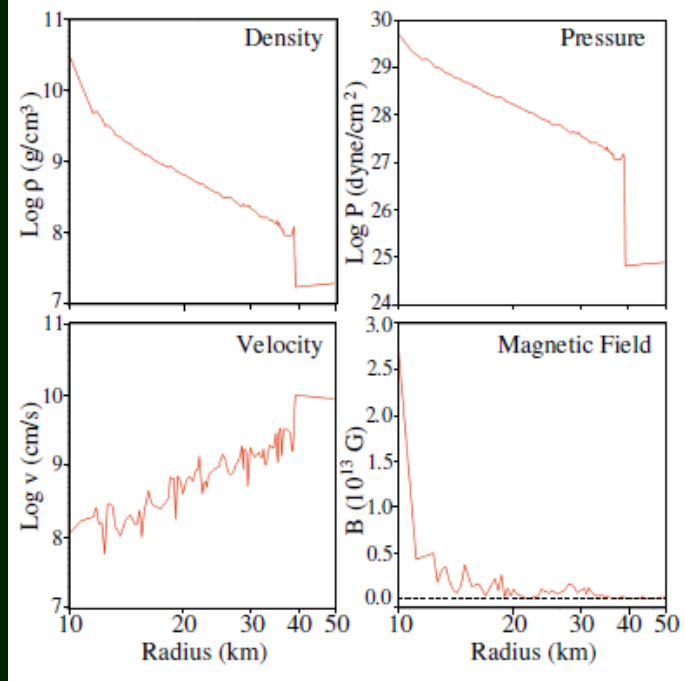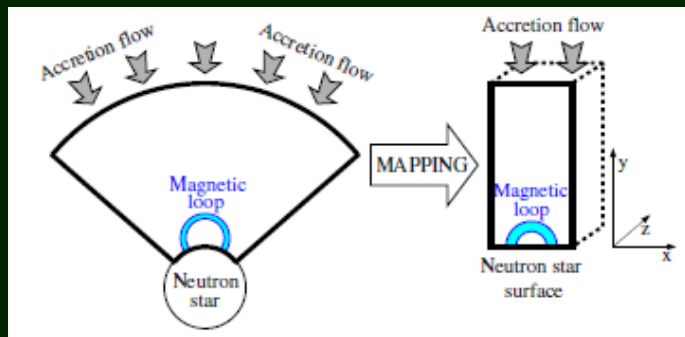
For t=60 msec

1212.0464

See 1210.7112 for a review of CCOs magnetic fields
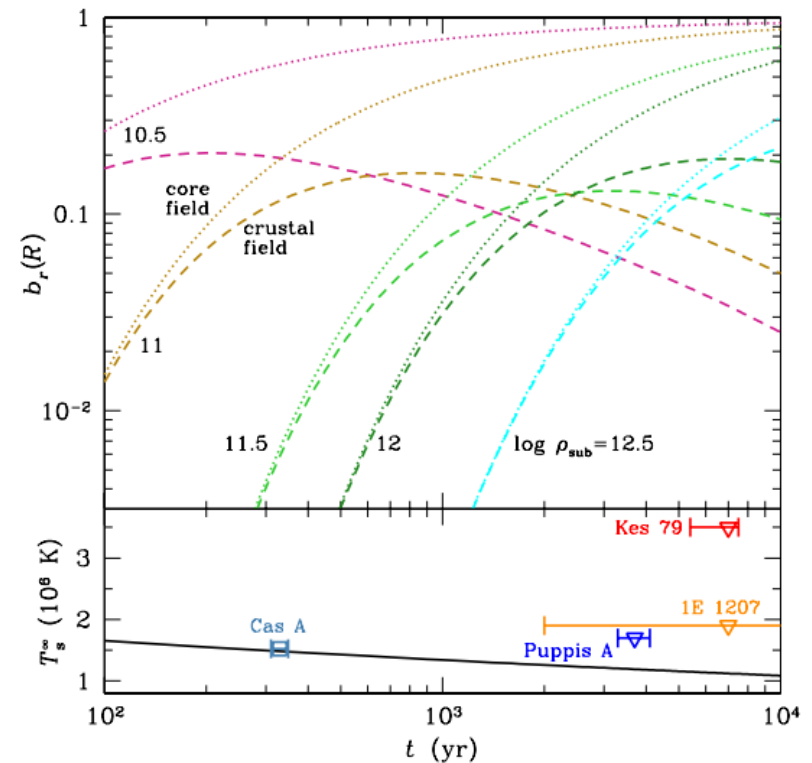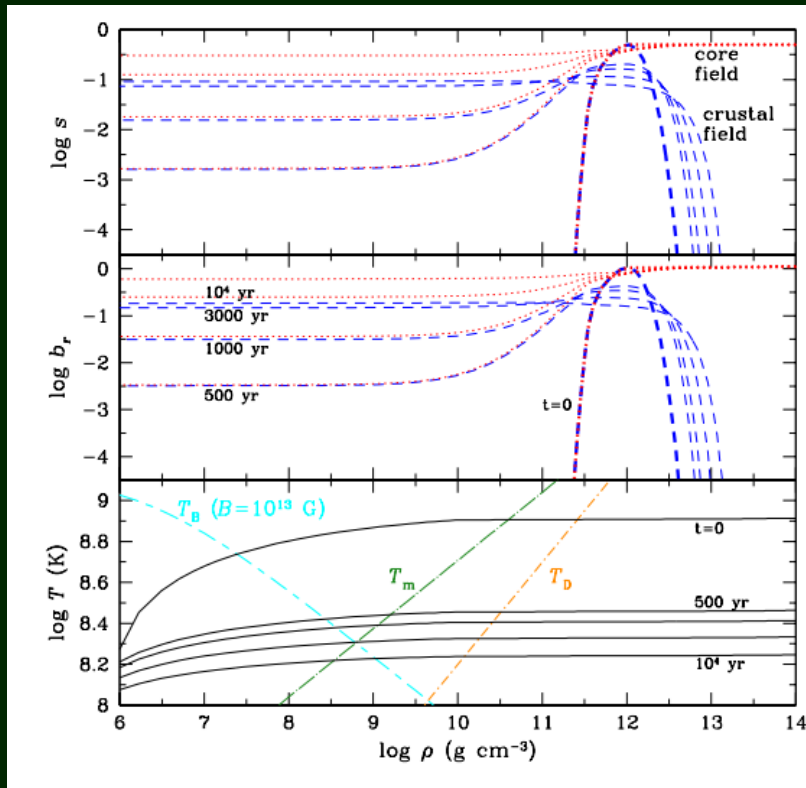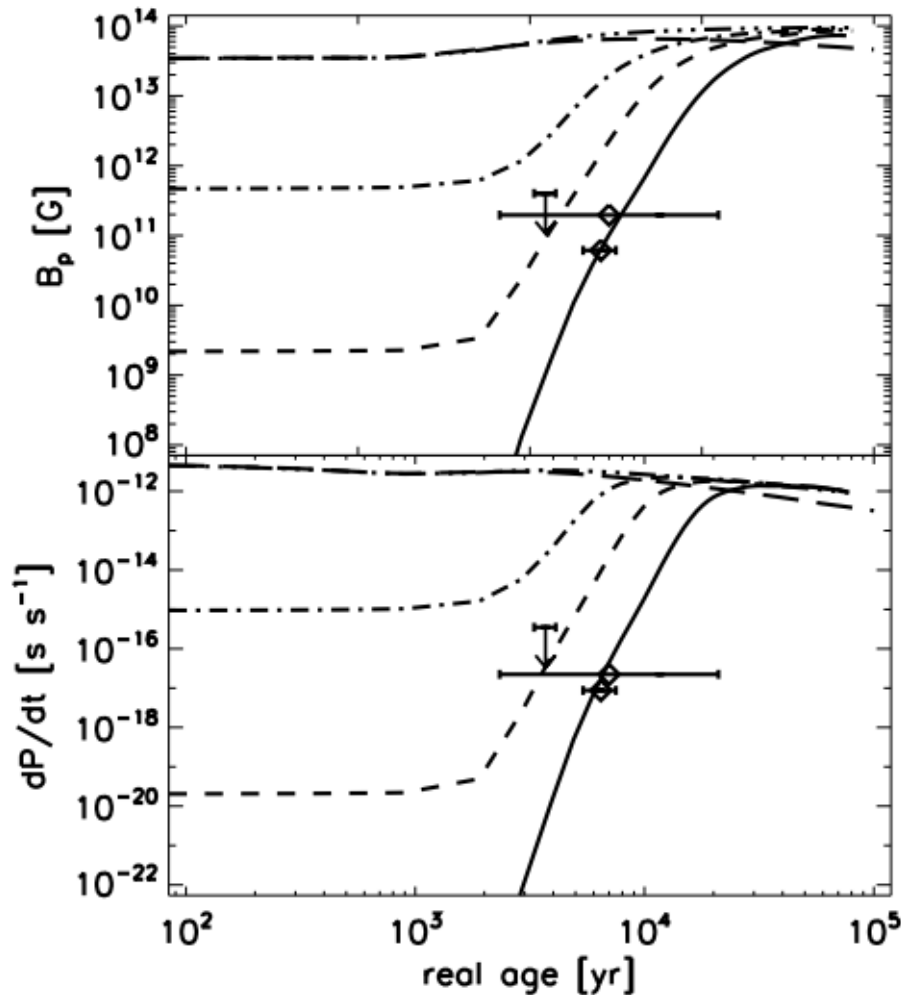
Recent model

Emerging field: modeling

1D model of field emergence

Dashed – crustal, dotted – core field
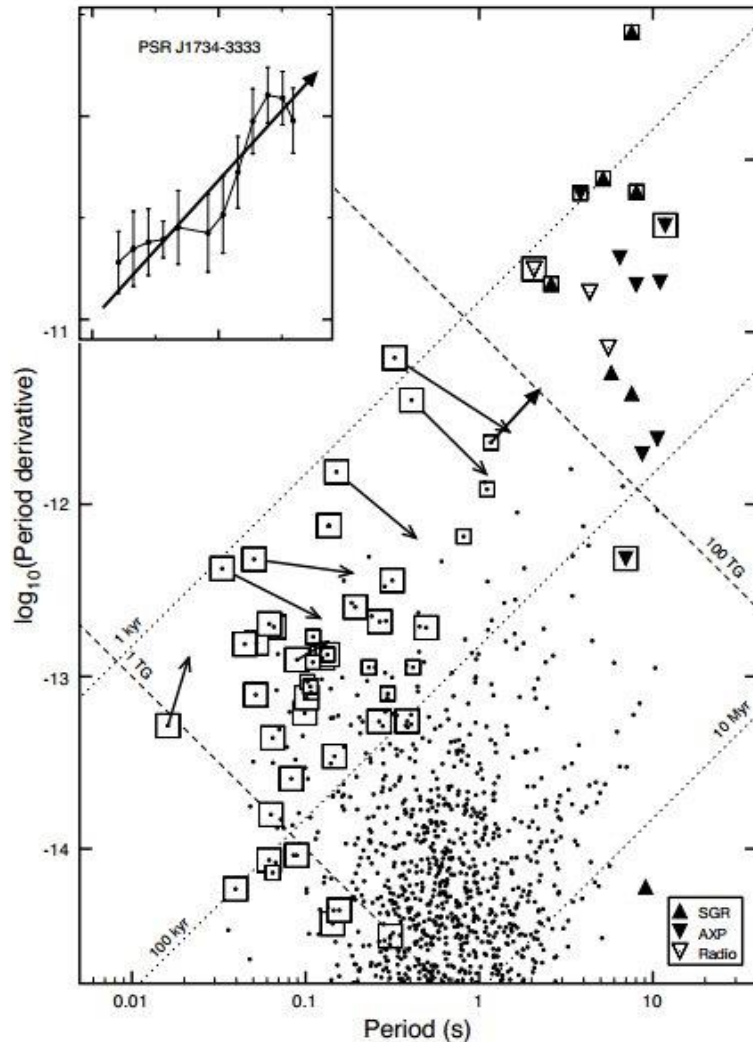

Ho 2011

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 2012 1206.2014

Emerged pulsars in the P-Pdot diagram

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
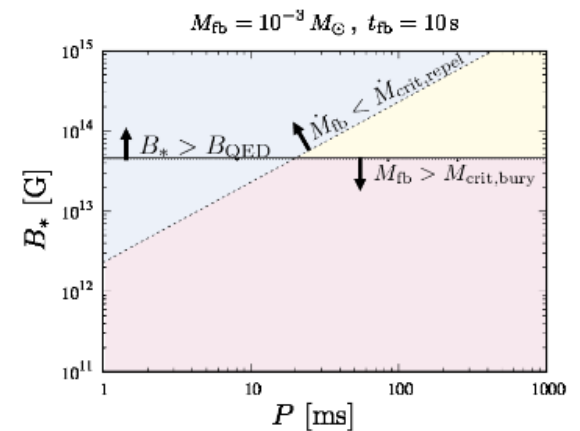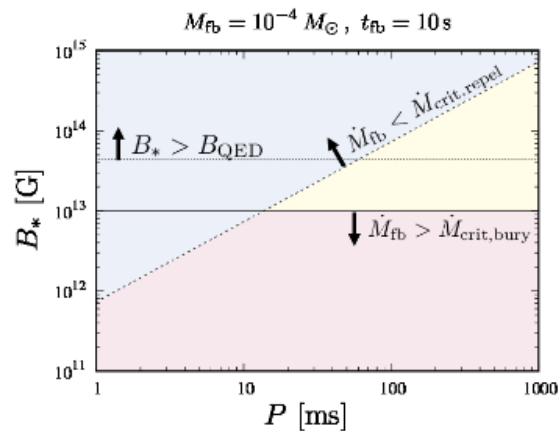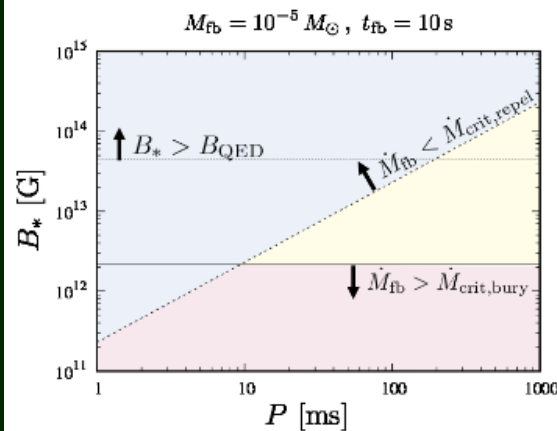do not contradict recent pulsar current studies
(Vranesevic, Melrose 2011).

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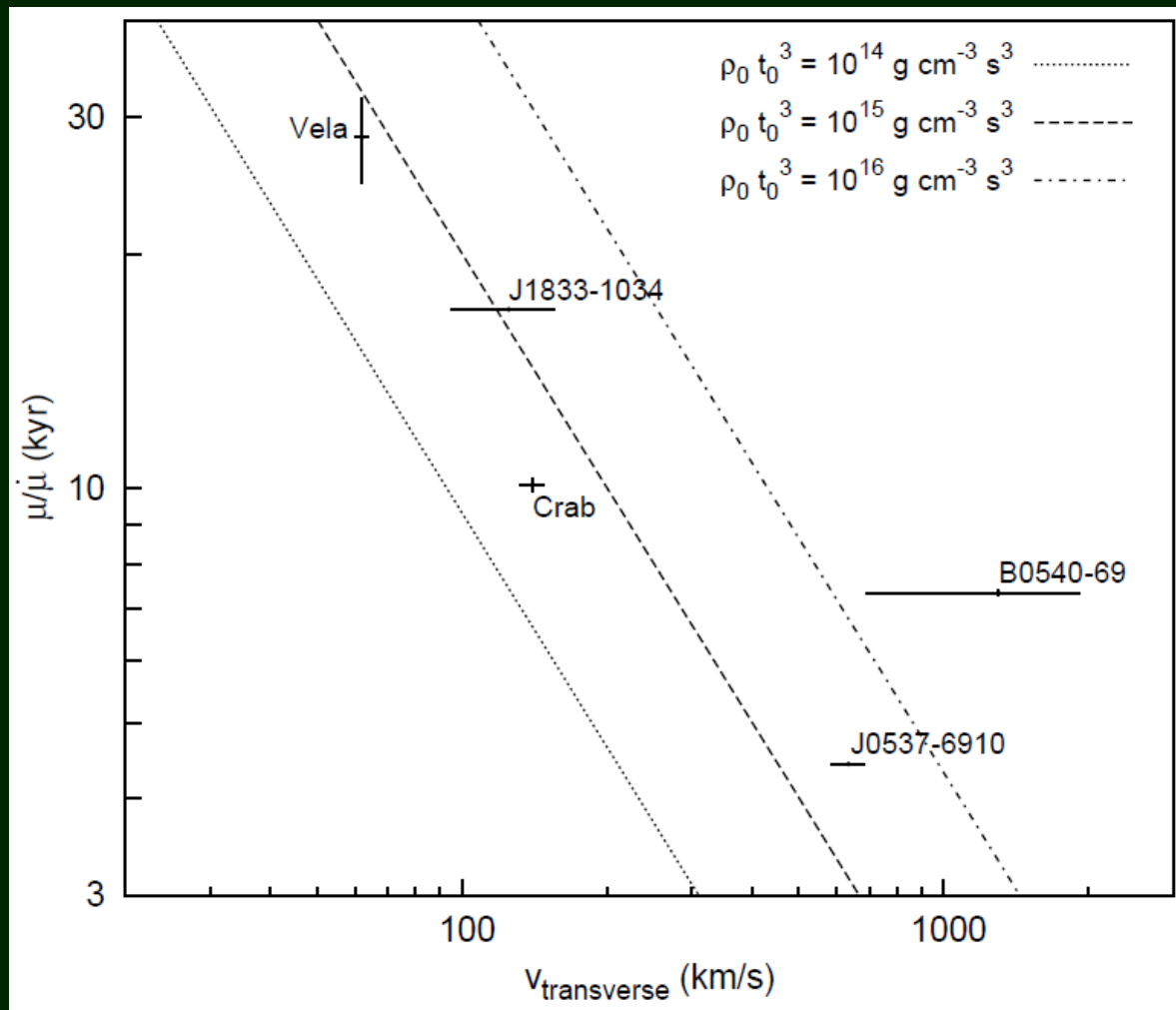long (0.1-0.5 s) spin periods can be
matured CCOs.

Espinoza et al. arXiv: 1109.2740, 1211.5276

Field, rotation, fallback

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

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

$$\dot{M}_{\mathrm{crit,bury}} \sim 3 \times 10^{-6}\, M_\odot\, \mathrm{s}^{-1} \left(\frac{B_*}{10^{13}\,\mathrm{G}}\right)^2$$
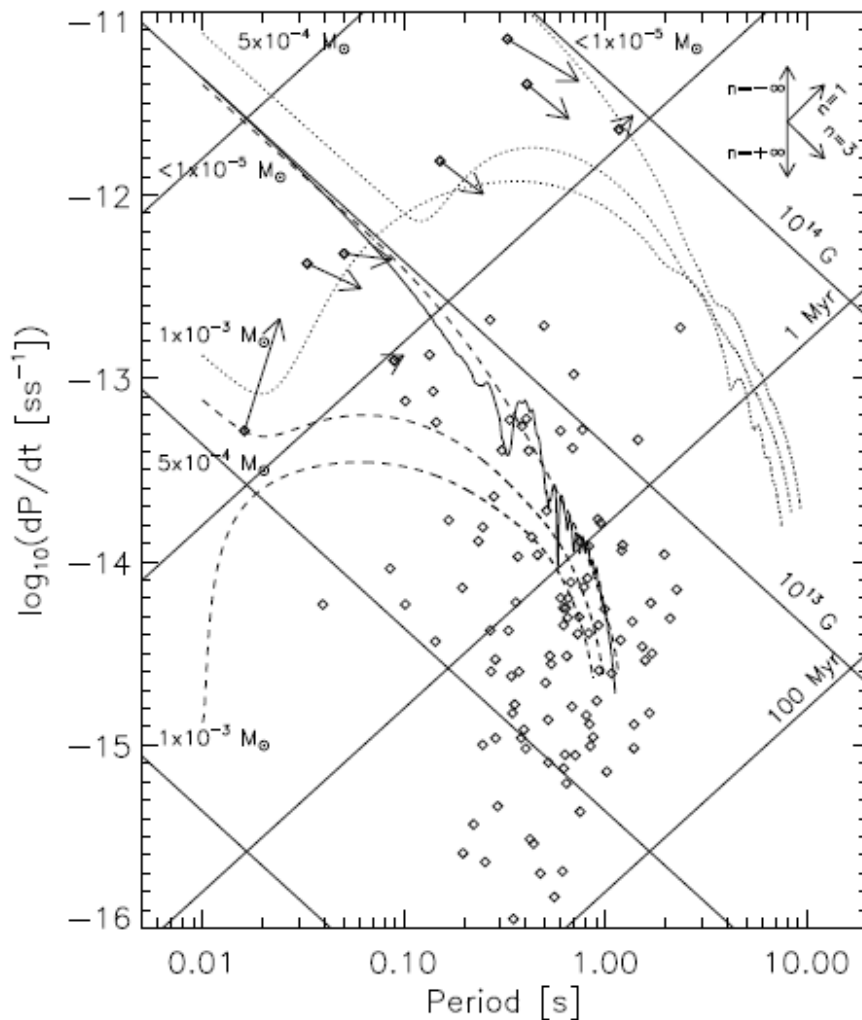
Growing field and kick velocities?

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.

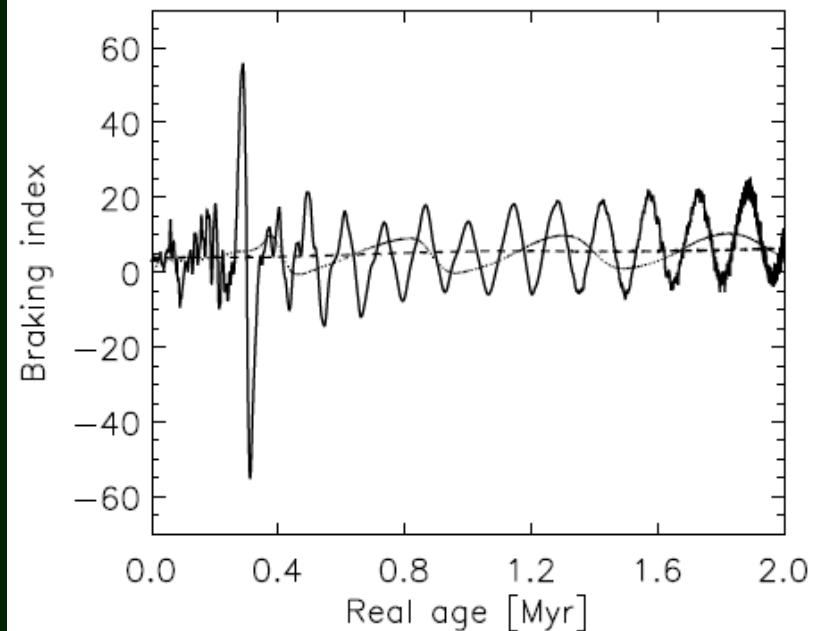Larger kick –
- smaller fallback –
   - faster field growing

1207.1219

Evolution of PSRs with evolving field

Three stages:
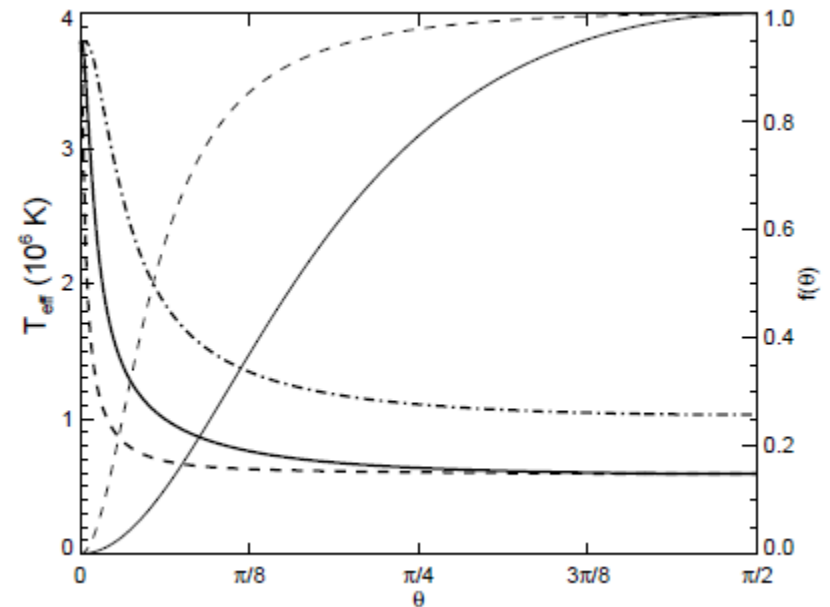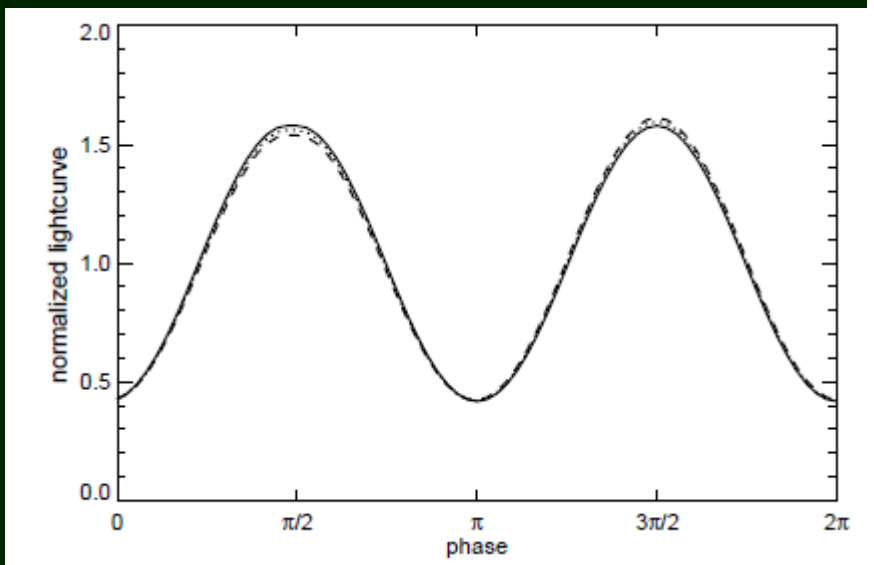1. n<=3 Standard + emerging field
2. n>3 Orhmic field decay
3. oscillating and large n – Hall drift

$$n = 3 - 4\frac{\dot{B_0}}{B_0}\tau_c \equiv 3 - 4\frac{\tau_c}{\tau_B},$$


1209.2273

Buried field in Kes79?

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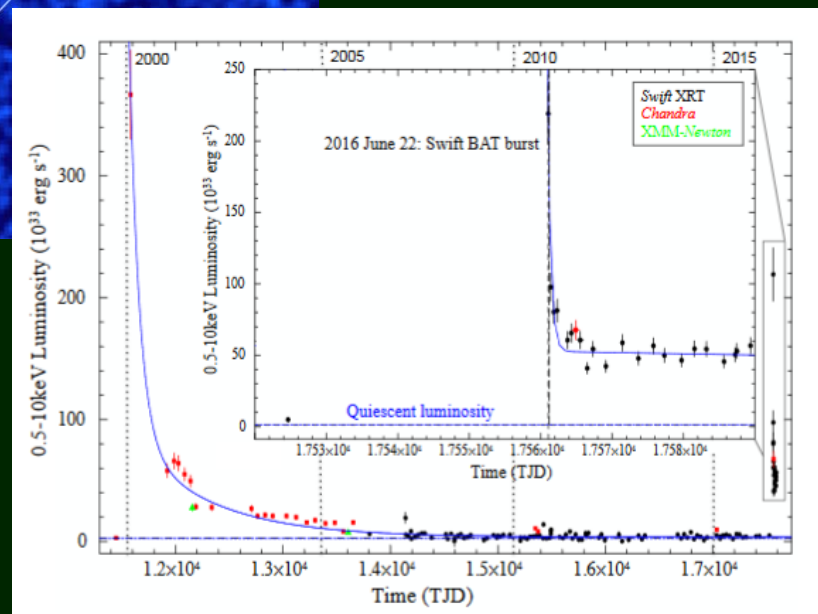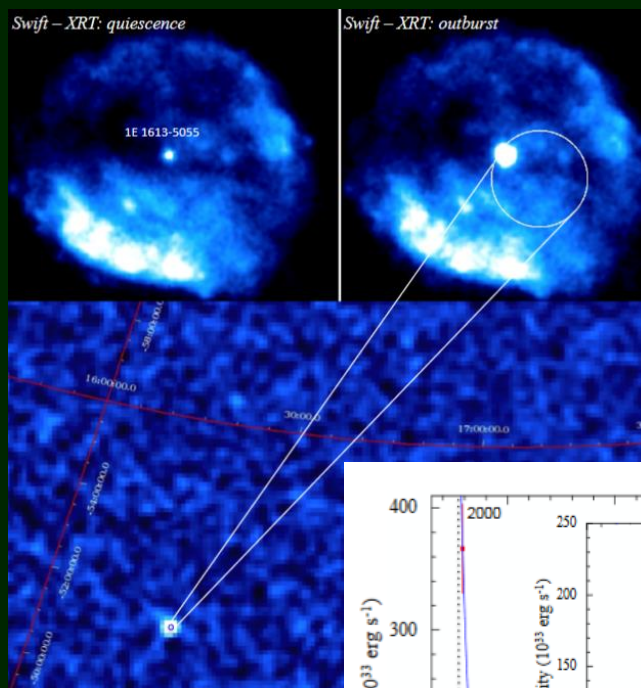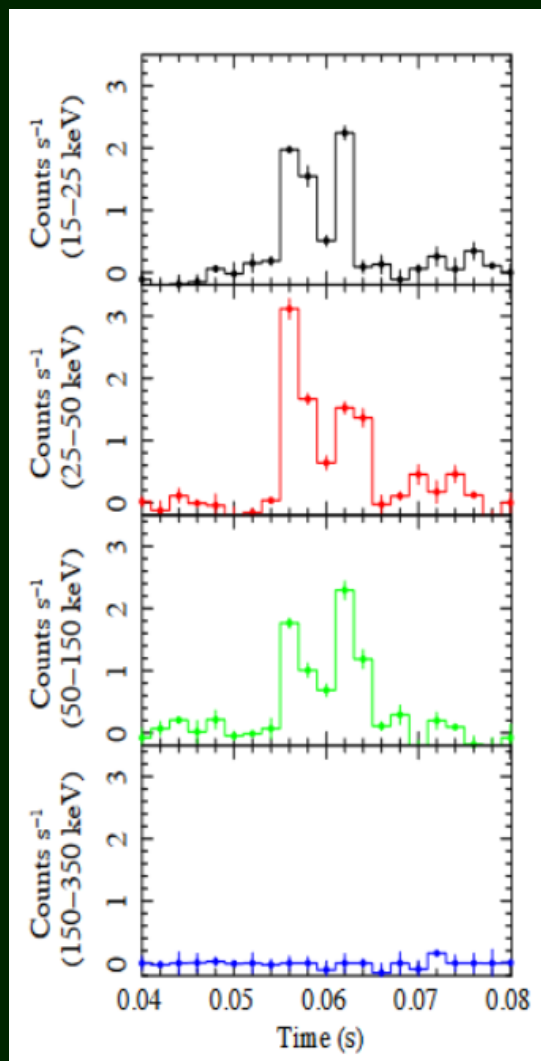field configuration can produce it.

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.

1110.3129

Hidden magnetar in RCW103
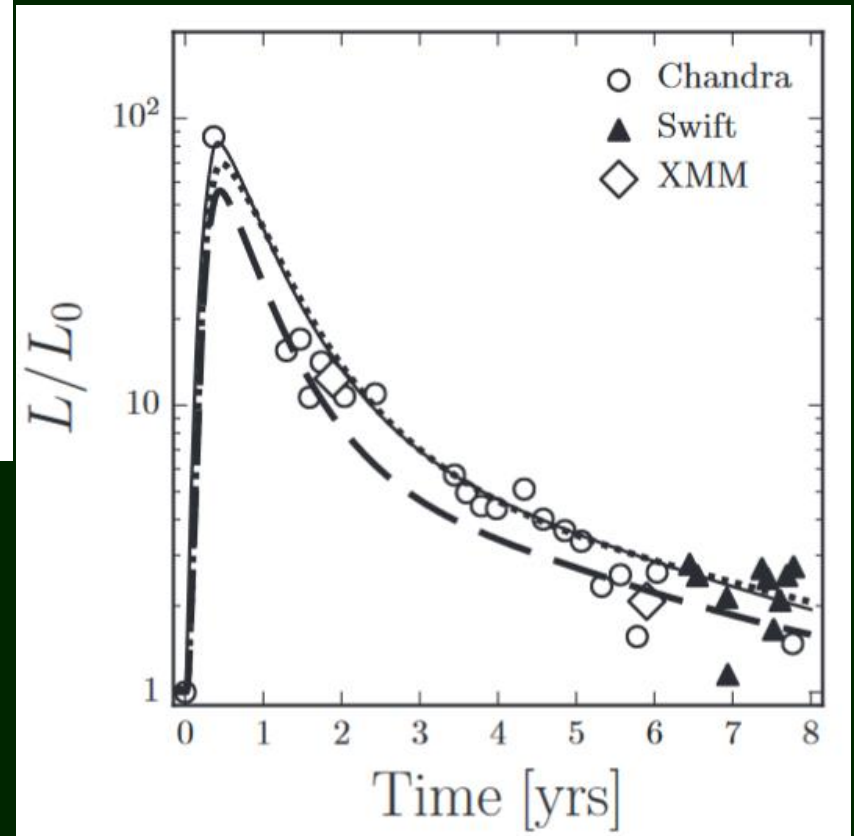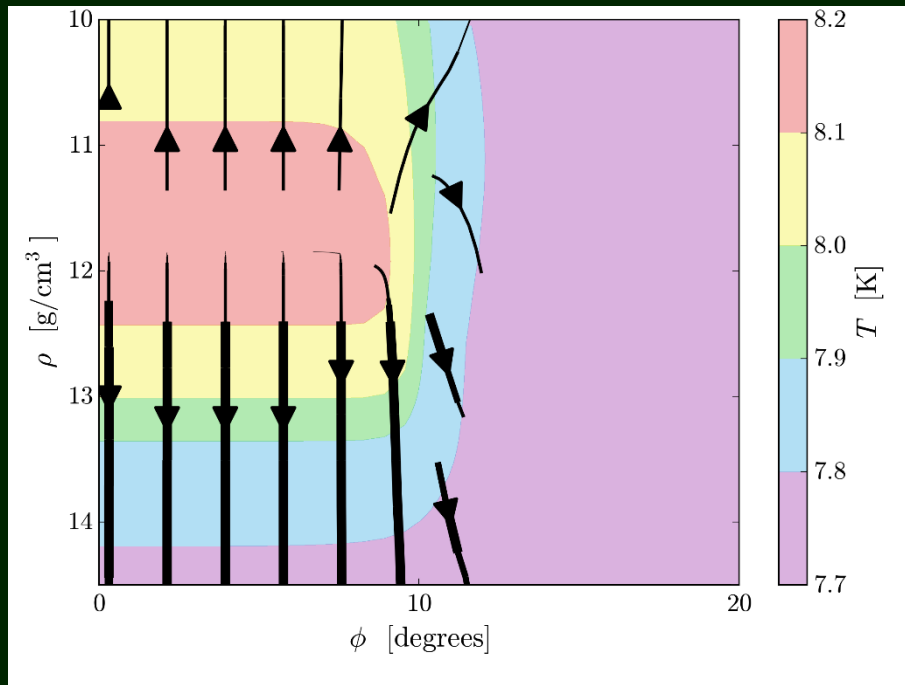
Not so hidden!

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

$$L_{tot} = \frac{1}{f_B}\left(\eta_{prop}L_{prop} + \eta_{dip}L_{dip}\right)$$
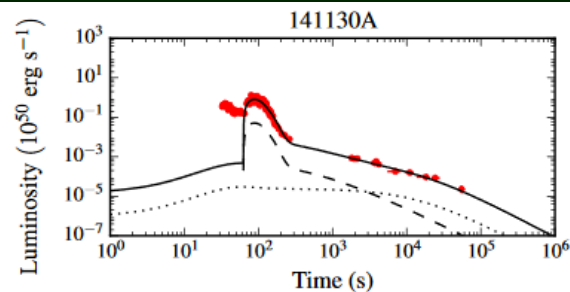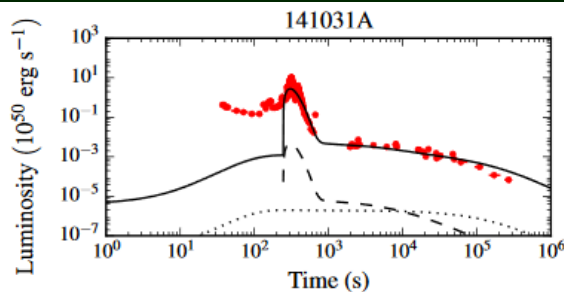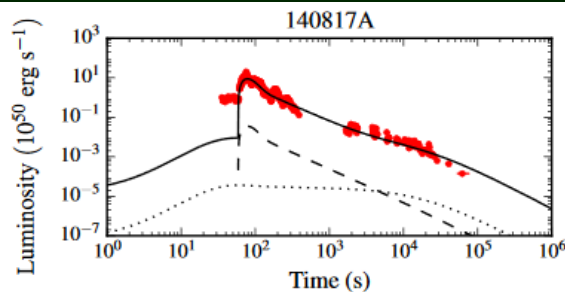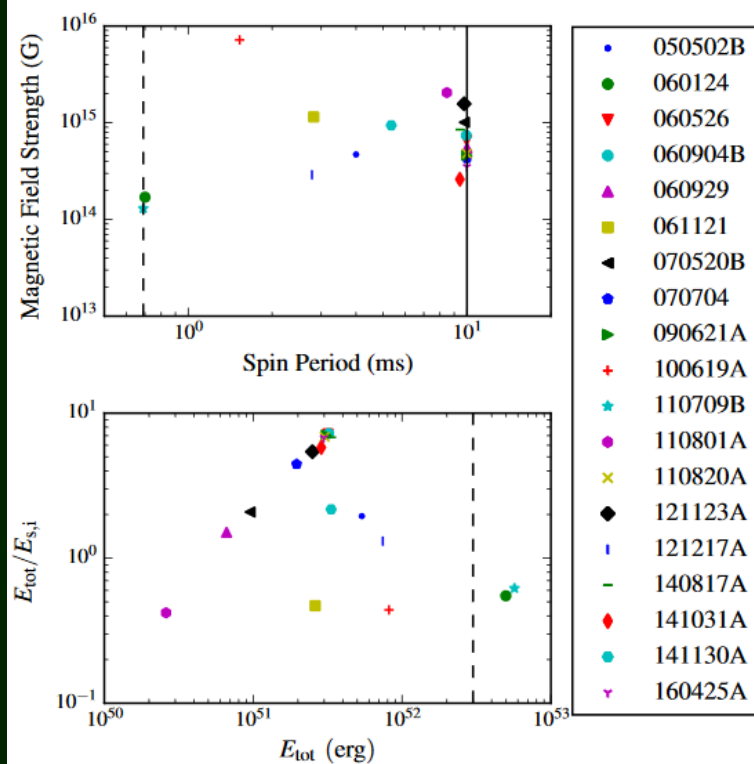
Fallback to power SN
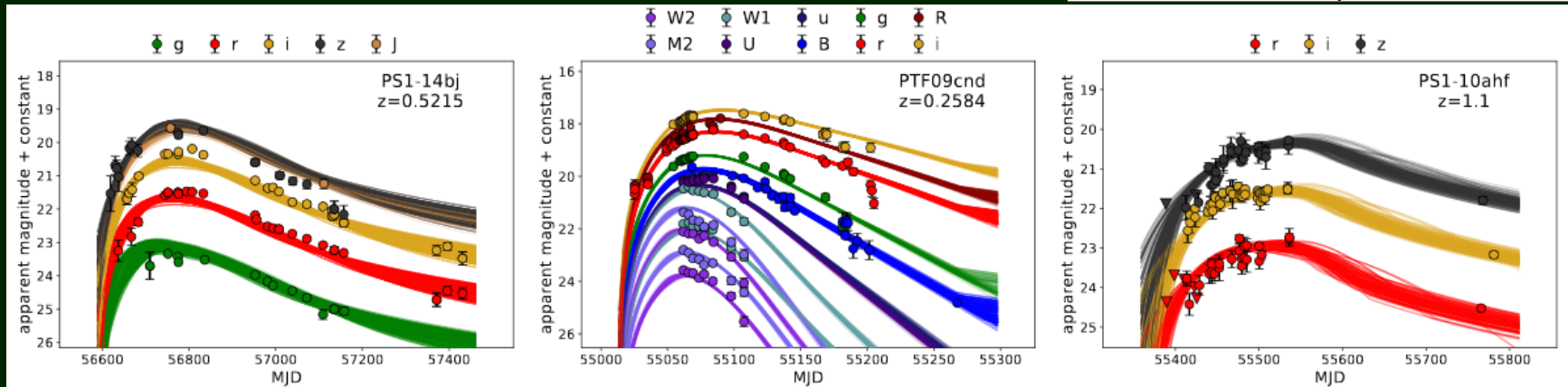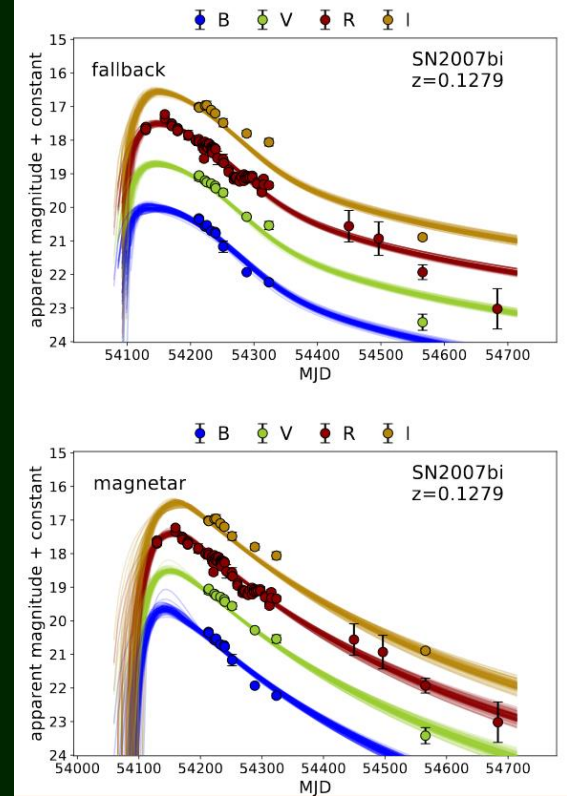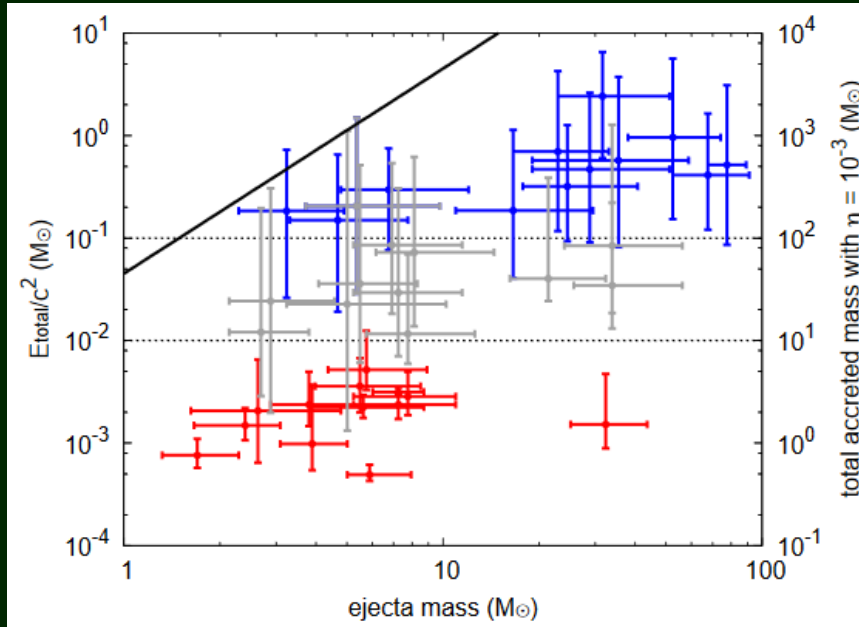
$$L_{\text{fallback}}(t) = \begin{cases} L_1 \left(\frac{t_{\text{tr}}}{1 \text{ sec}}\right)^{-\frac{5}{3}} \equiv L_{\text{flat}} & (t < t_{\text{tr}}) \\ L_1 \left(\frac{t}{1 \text{ sec}}\right)^{-\frac{5}{3}} & (t \geq t_{\text{tr}}) \end{cases}$$

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
- 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.
- Recent studies indicate that in the life of normal radio pulsars there is a period when their magnetic field decay
- 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 NSs are at the attractor stage, as its properties are predicted by GC2013
- Probably, the attractor stage is reached later, or its properties are different form the predicted ones.

Papers to read

- Pons, Geppert "Magnetic field dissipation in neutron star crusts: from magnetars to isolated neutron stars " astro-ph/0703267
- Popov et al. "Population synthesis studies of isolated neutron stars with magnetic field decay" MNRAS (2009) arXiv: 0910.2190
- Ho ``Evolution of a buried magnetic field in the central compact object neutron stars '' arXiv:1102.4870
- Pons et al. "Pulsar timing irregularities and the imprint of magnetic field Evolution" arXiv: 1209.2273
- Cumming et al. "MAGNETIC FIELD EVOLUTION IN NEUTRON STAR CRUSTS DUE TO THE HALL EFFECT AND OHMIC DECAY" astro-ph/0402392

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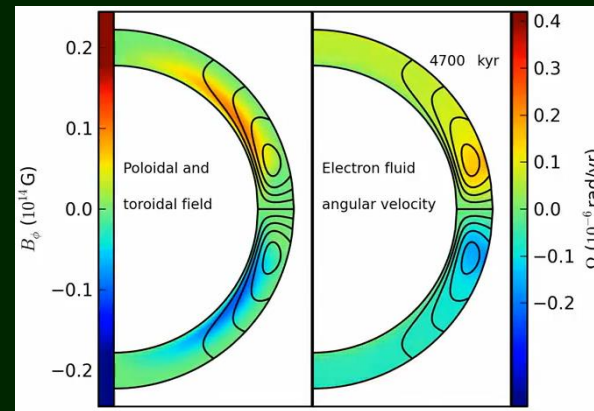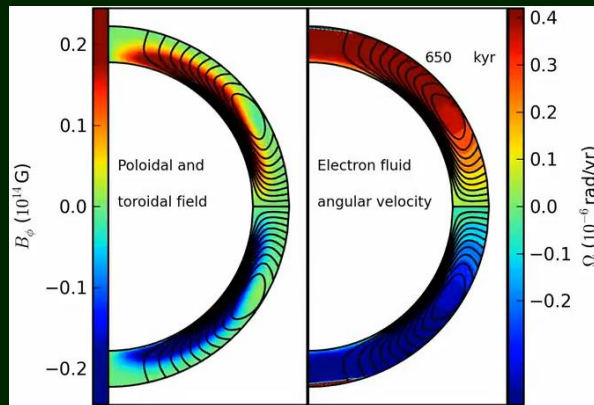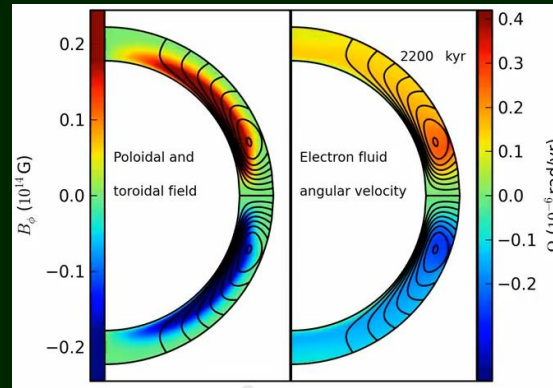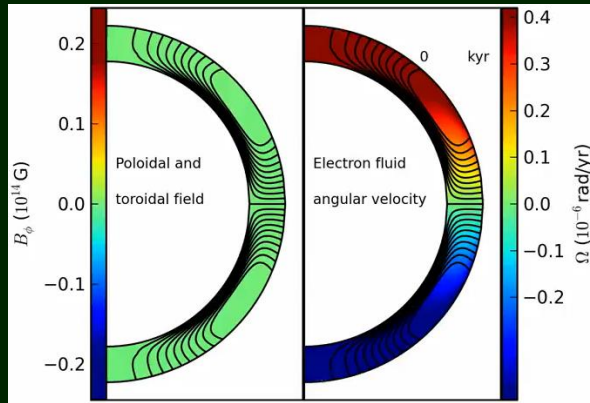
Hall cascade can reach the stage of so-called Hall attractor,
where the field decay stalls for some time (Gourgouliatos, Cumming).

Gourgouliatos and Cumming 2013

Hall attractor

Hall Attractor starting from a dipole field

Hall Attractor starting from an octupole field
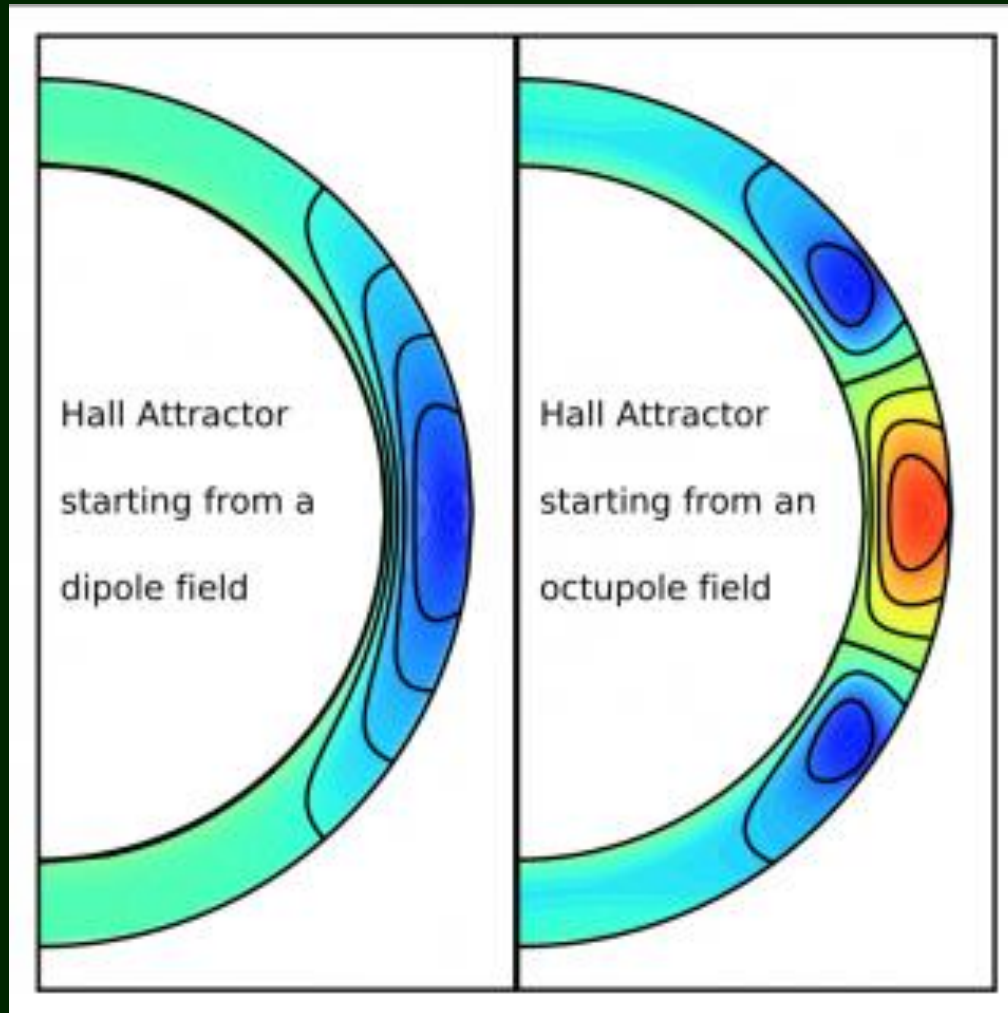
After some time the Hall cascade decays as the field finds a new| stable configuration.
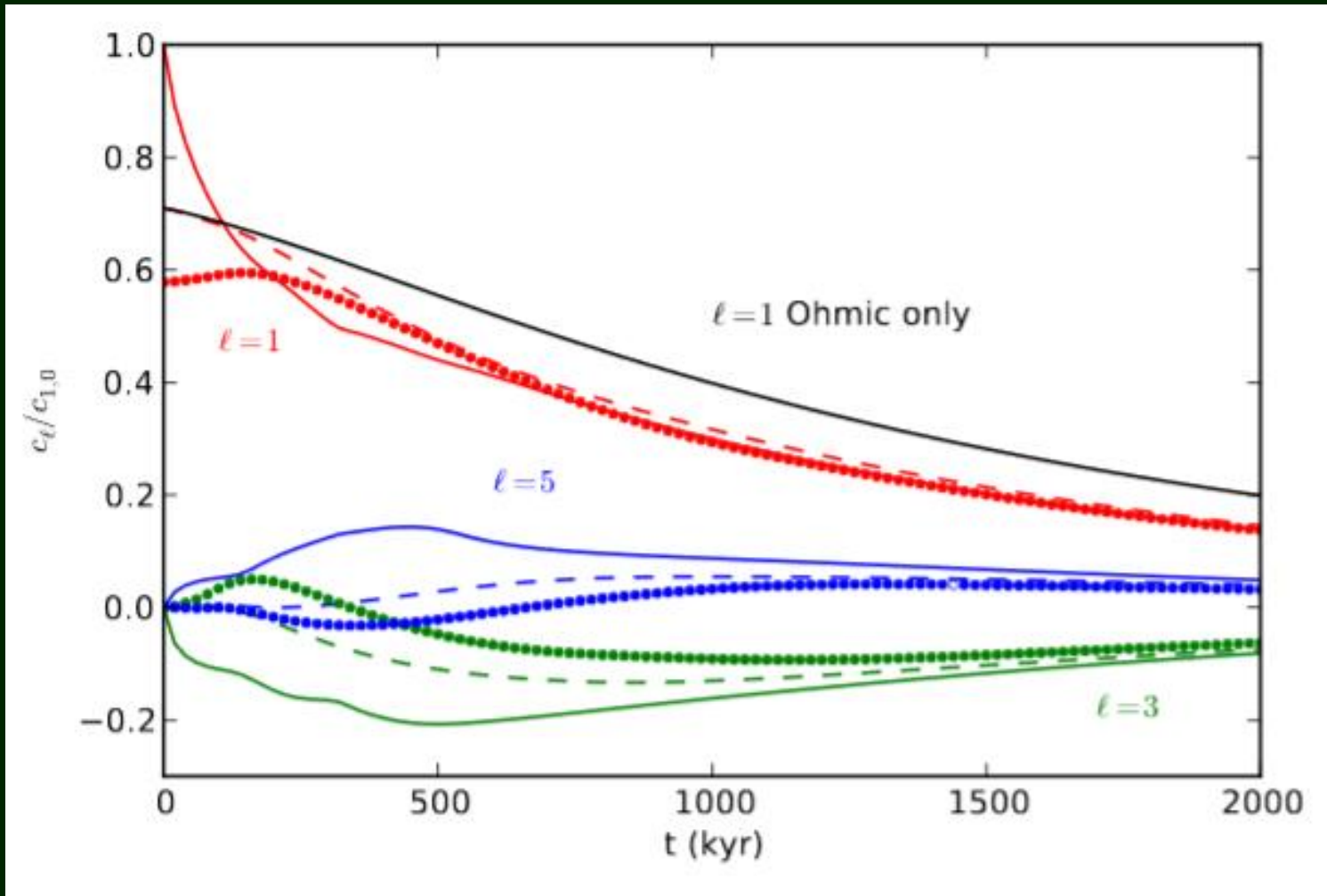
1311.7345

Evolution of different components

Hall attractor mainly consists of dipole and octupole

1311.7004

New studies of the hall cascade
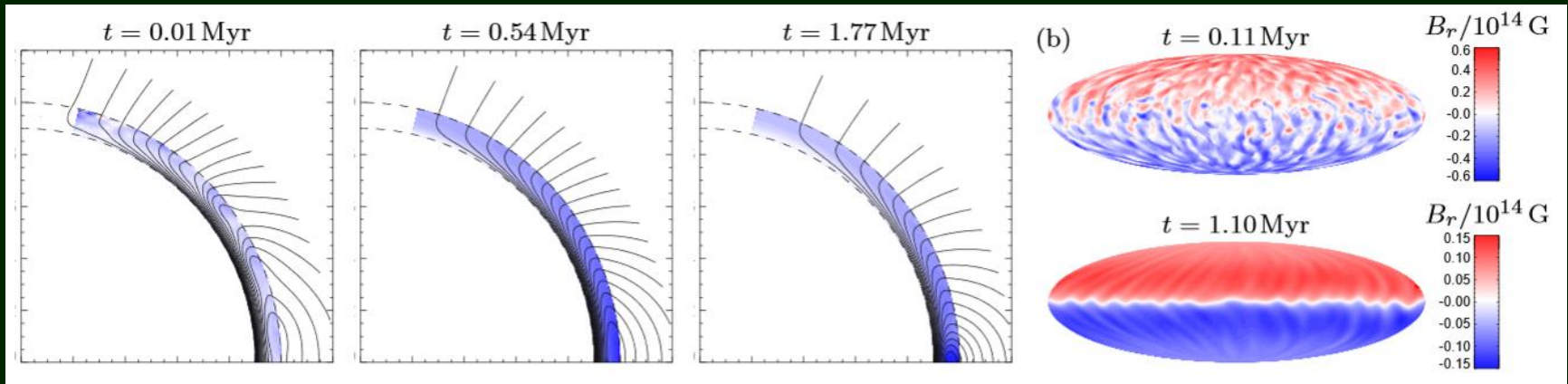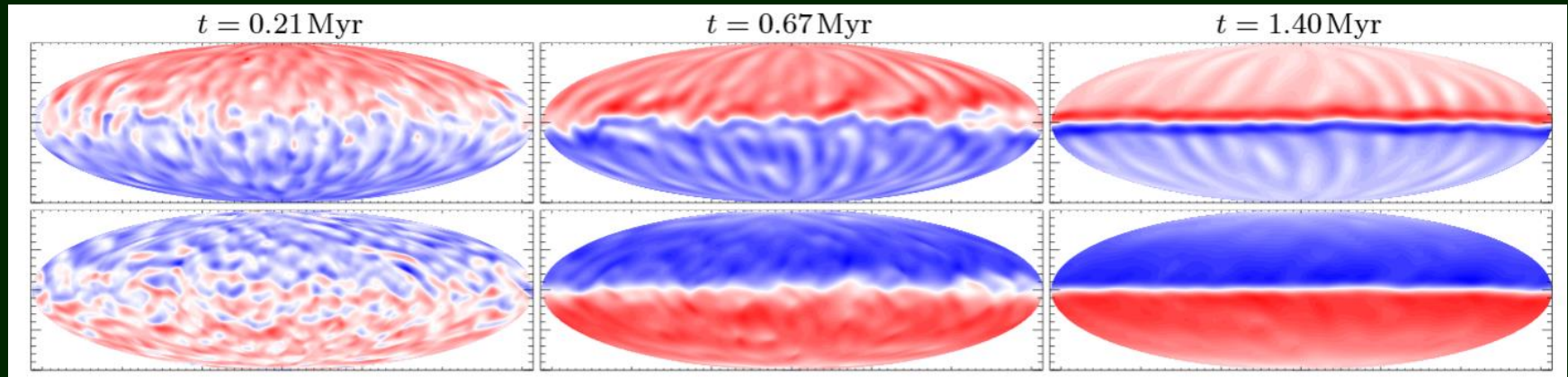

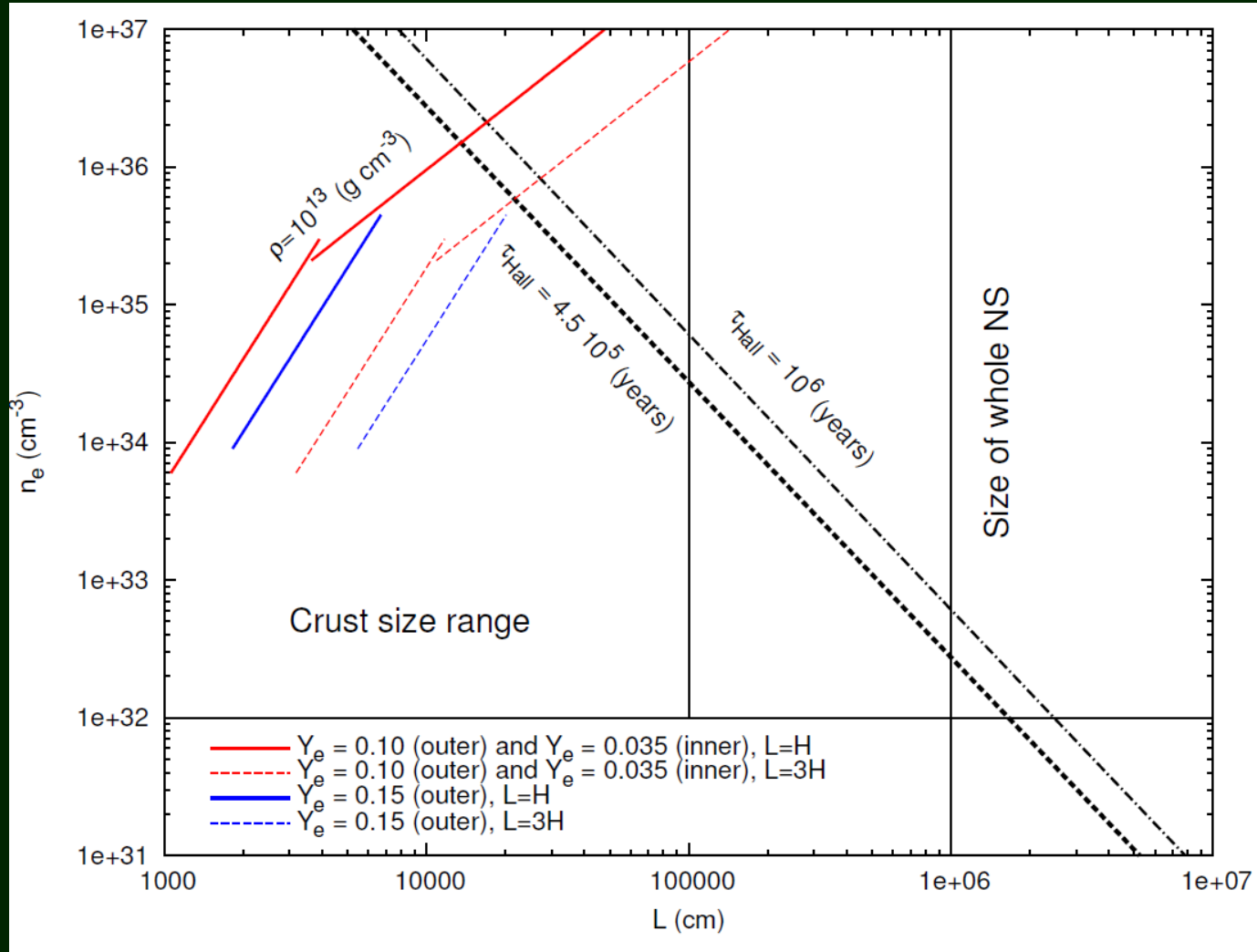New calculations support the idea of a kind of stable configuration.

1501.05149

Where the currents are located?

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

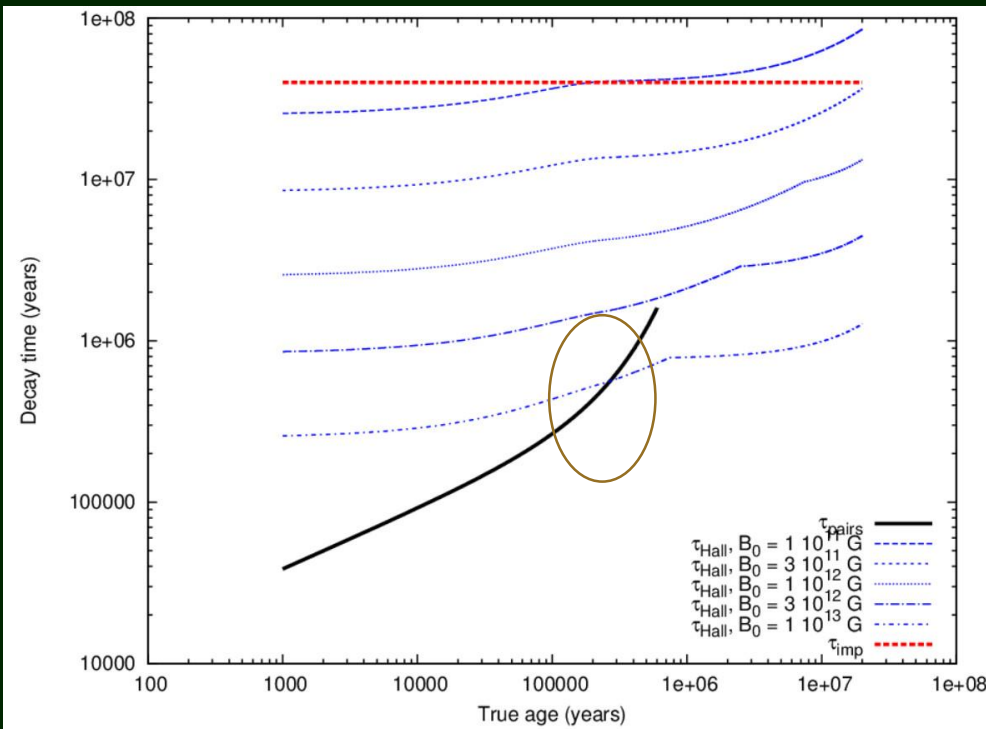$$L \approx H = P(\rho)/(\rho g)$$

Igoshev, Popov (2015)

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.
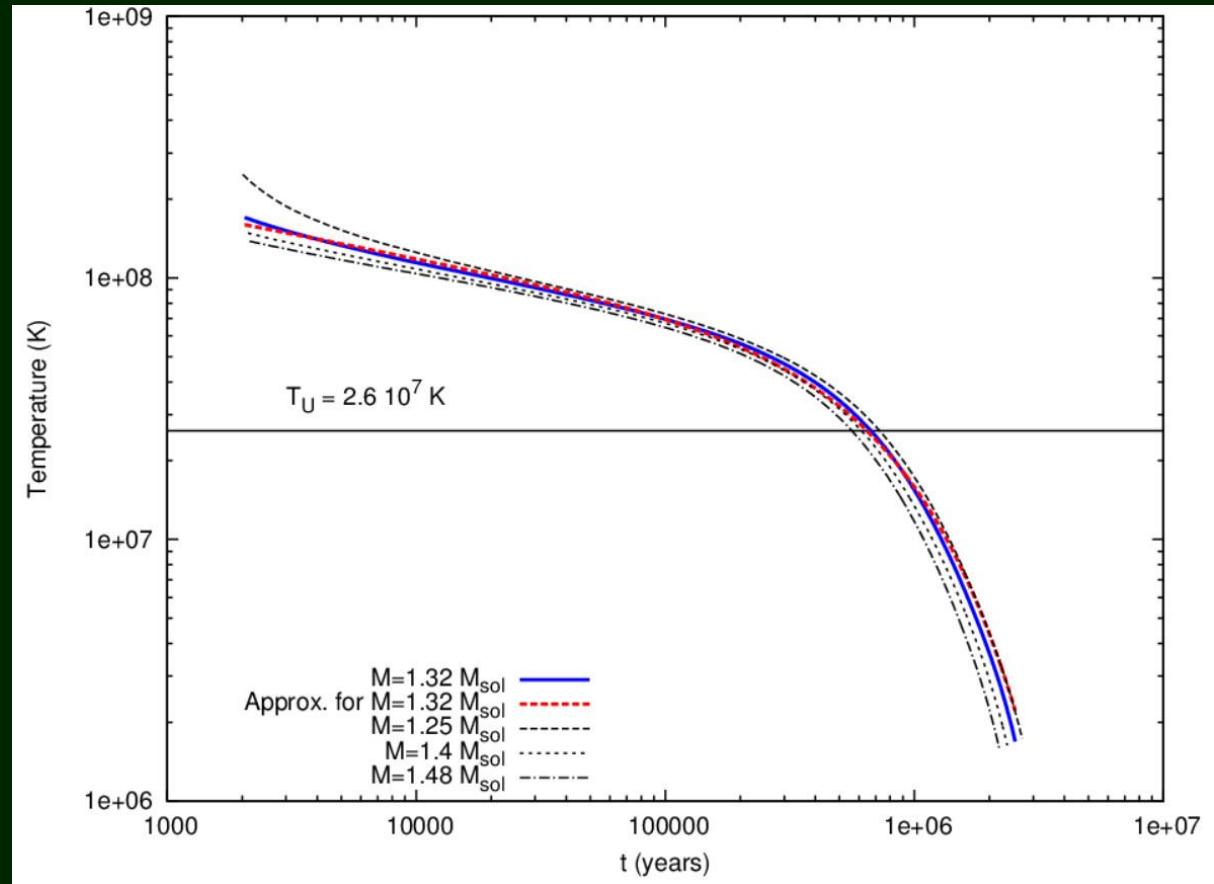
Different decay time scales

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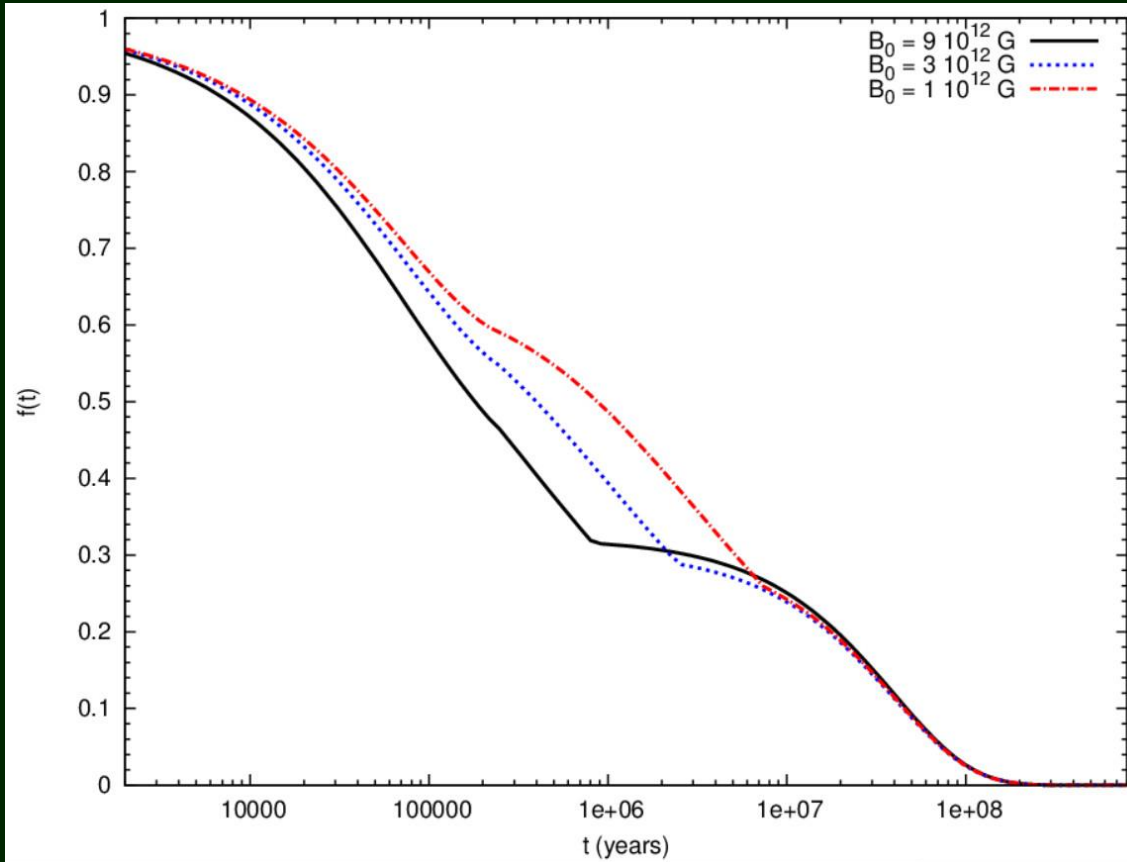the rate of Ohmic dissipation
due to phonons.

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

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

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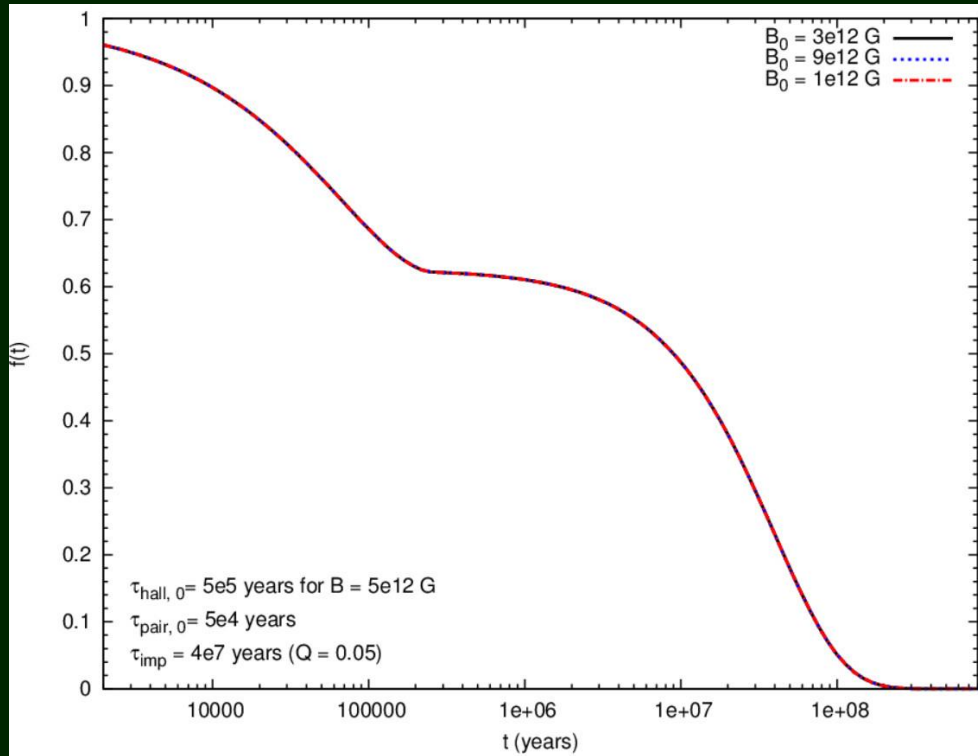
Magnetic field evolution

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

All inclusive:
- Hall
- Phonons
- Impurities

Igoshev, Popov (2015)

Only Ohmic decay

$\tau_{hall, 0}$ = 5e5 years for B = 5e12 G
$\tau_{pair, 0}$ = 5e4 years
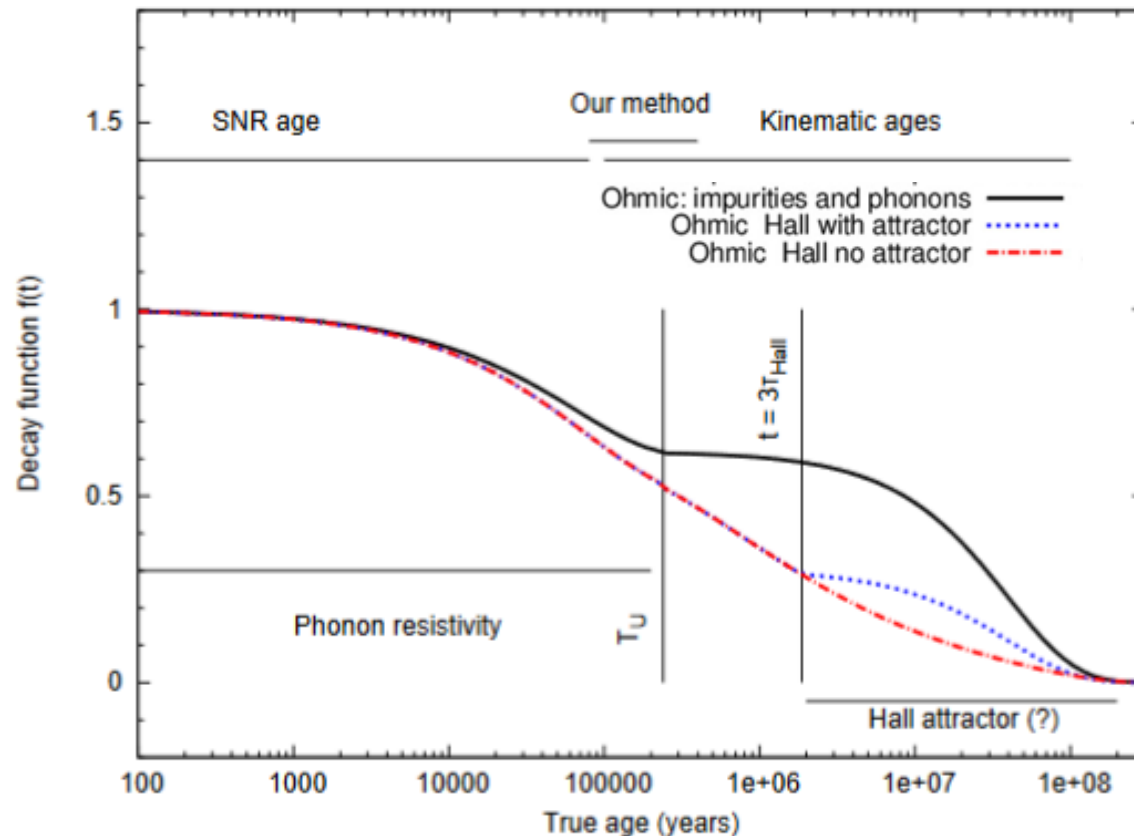τ_{imp} = 4e7 years (Q = 0.05)

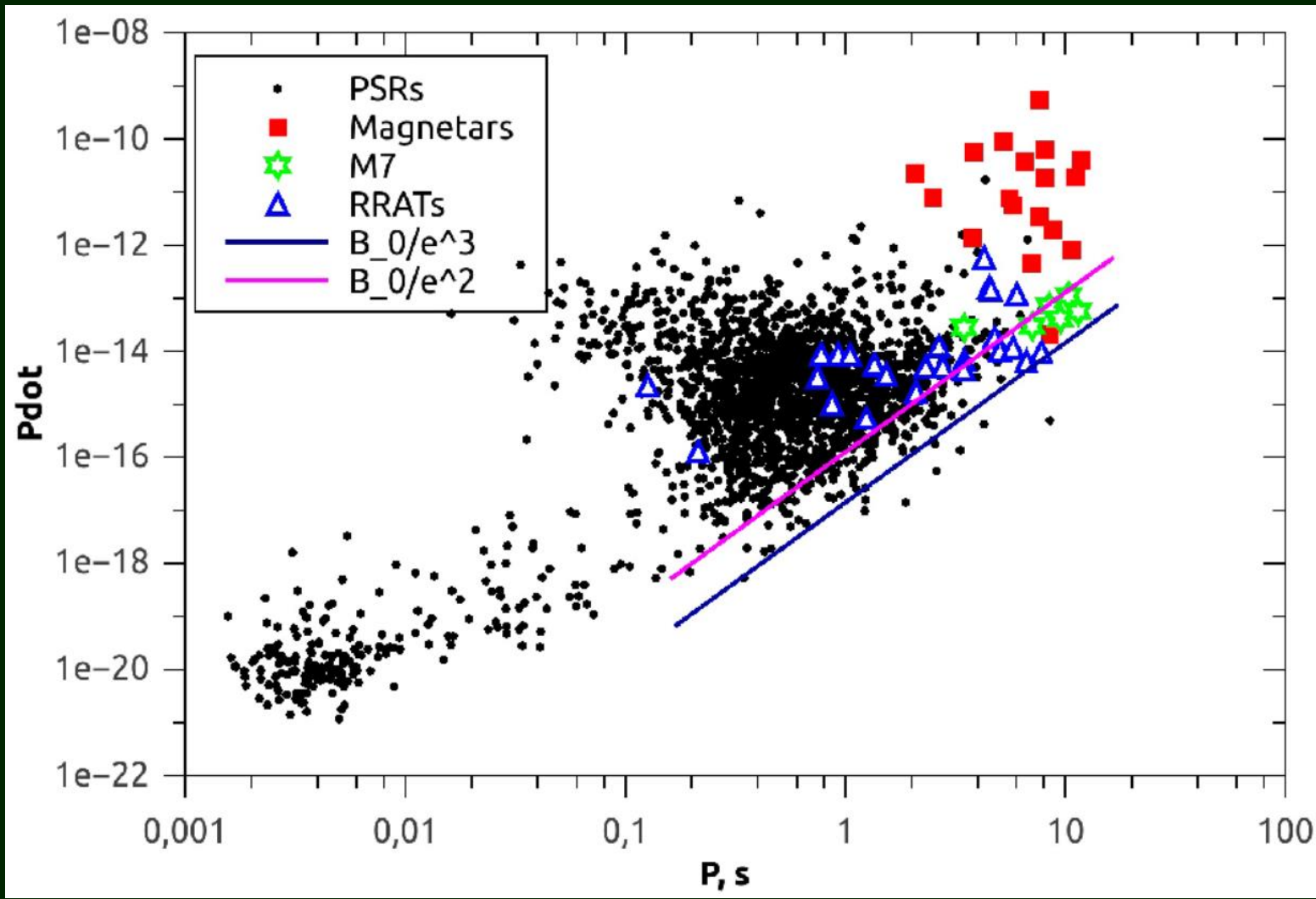Here the Hall cascade is switched off
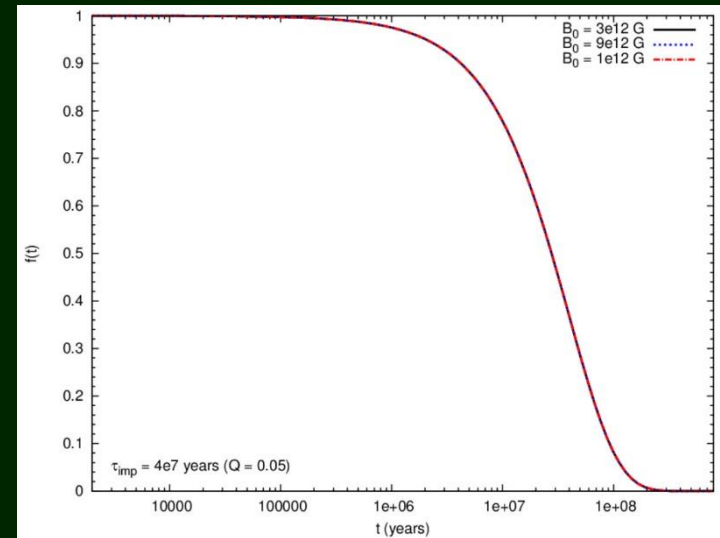
In one figure we have Ohmic decay only due to impurities, on another one – phonons are added.

Comparison of different options

We think that at the ages $\sim 10^5$ yrs and below for normal pulsars we see mostly Ohmic decay, which then disappears as NSs cool down below the critical T.

Igoshev, Popov (2015)

Getting close to the attractor

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	τ_D [Myr]	τ_{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)

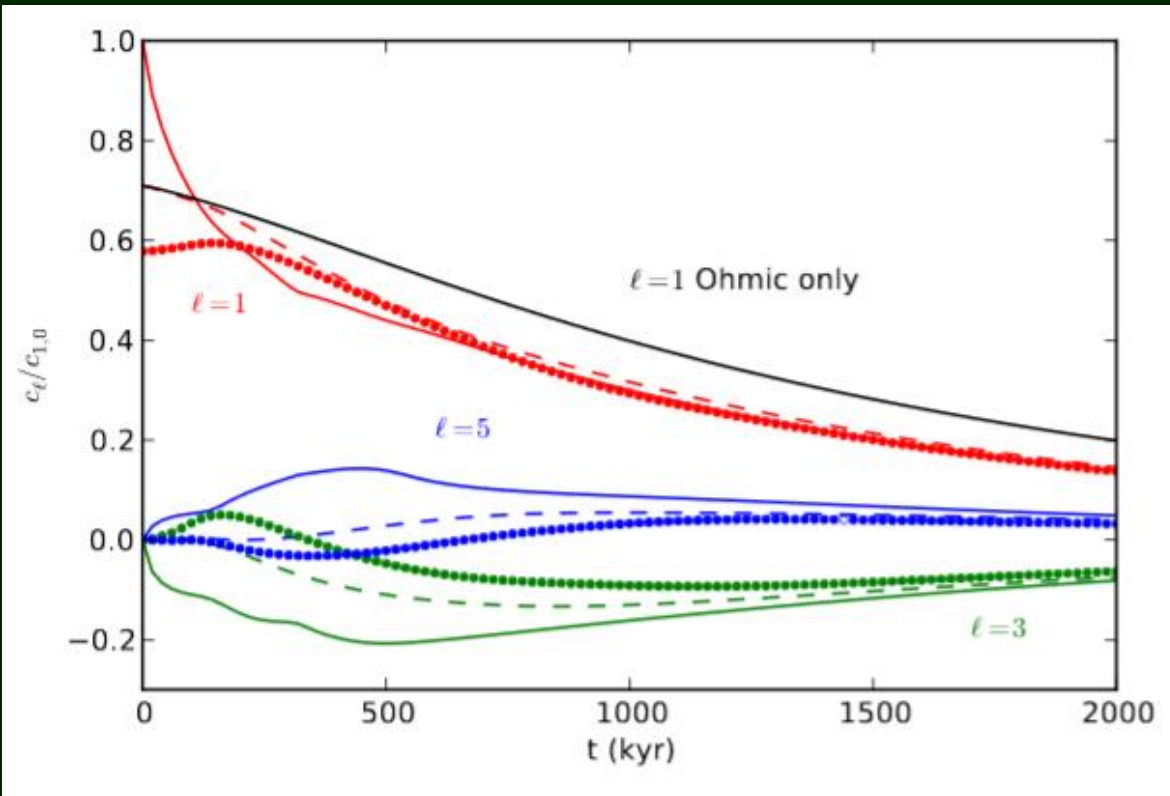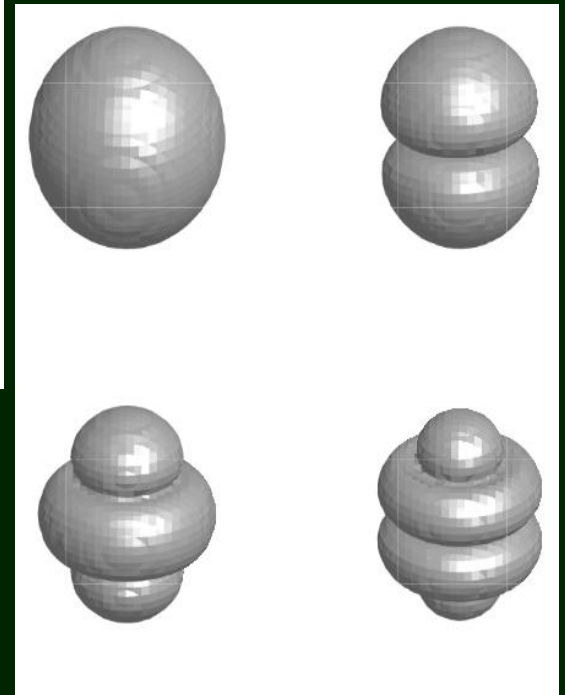# Evolution with field decay
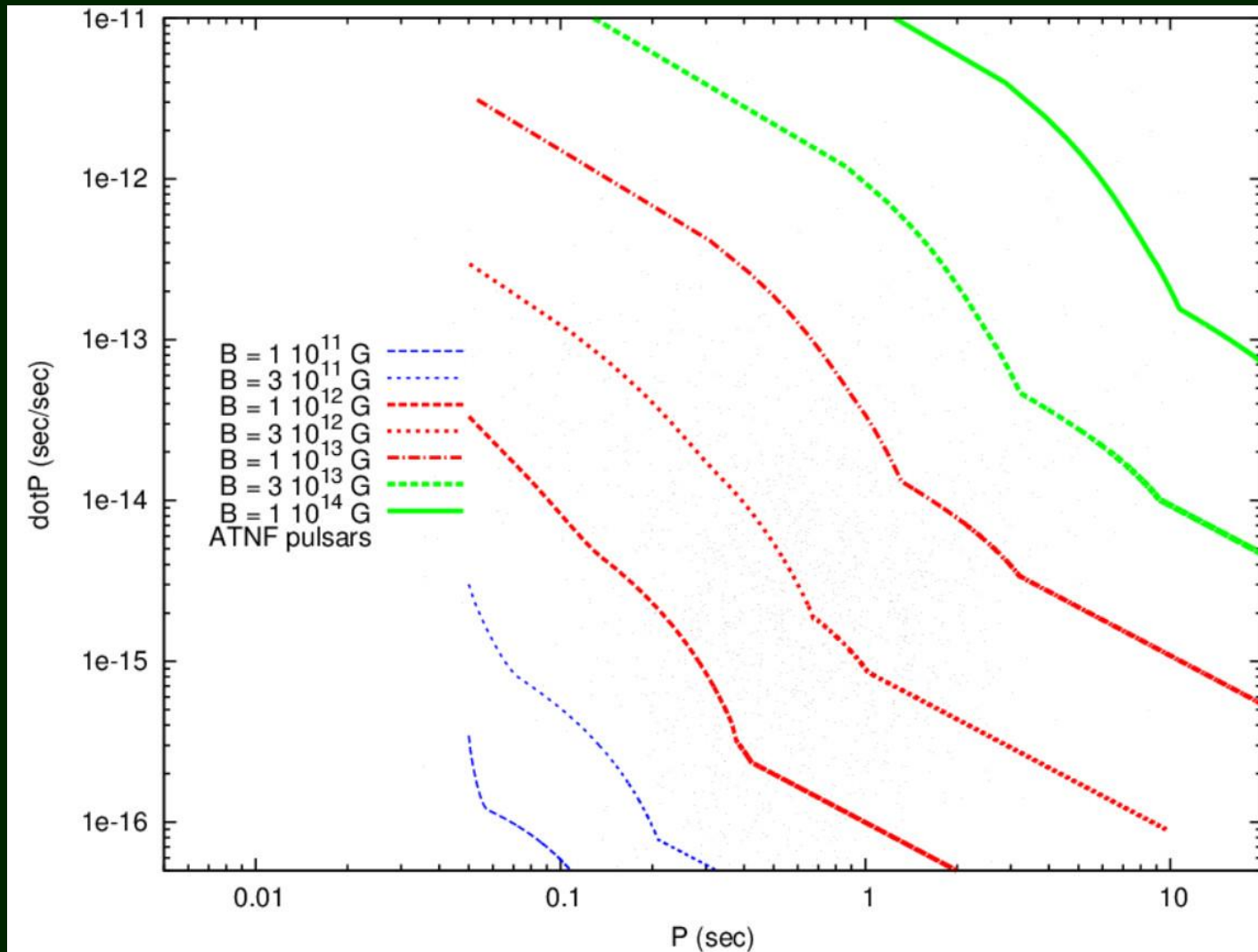
Who is closer to the attractor stage?
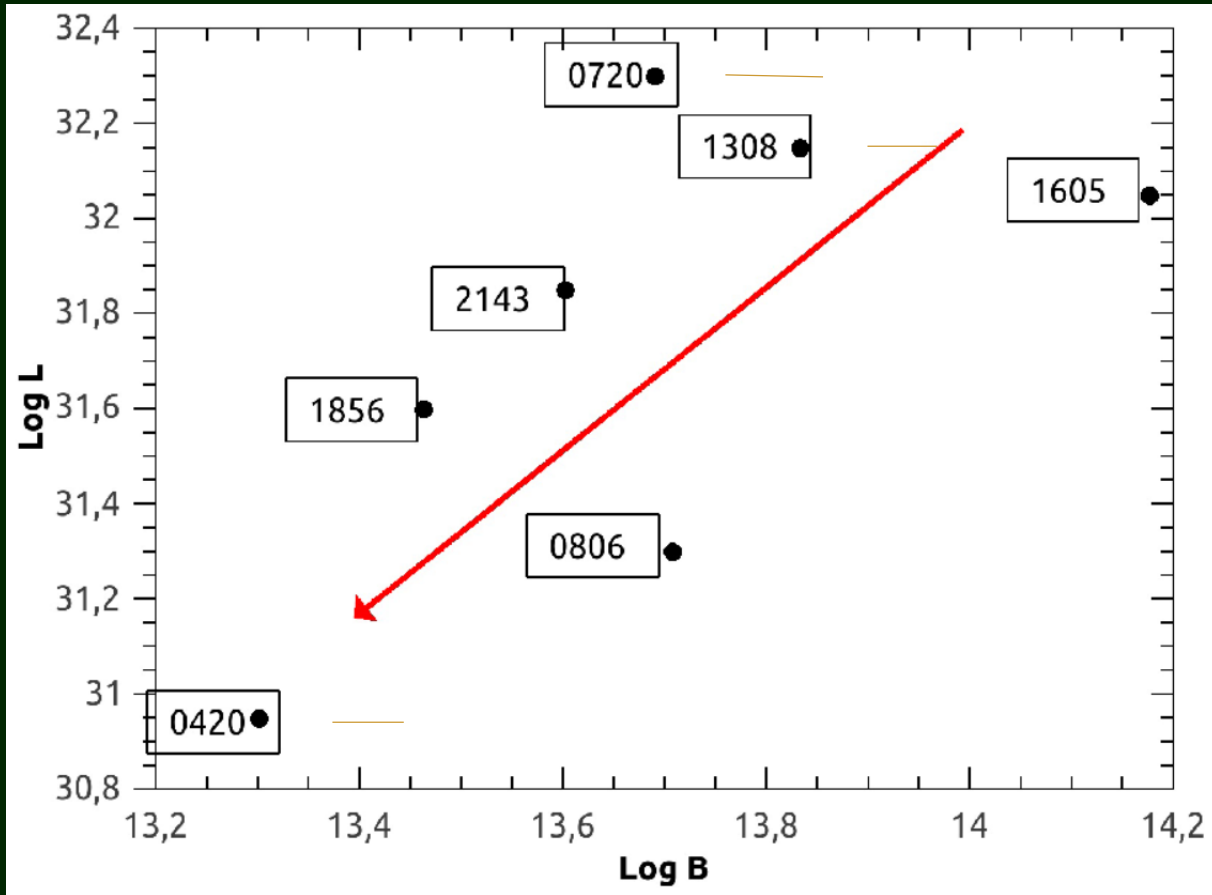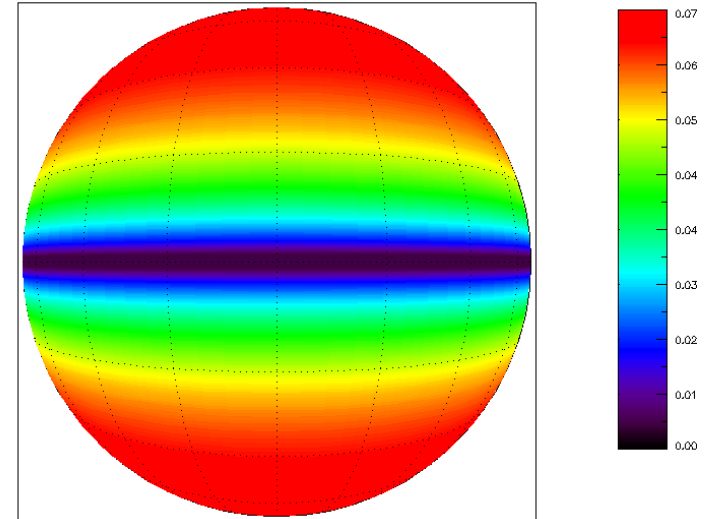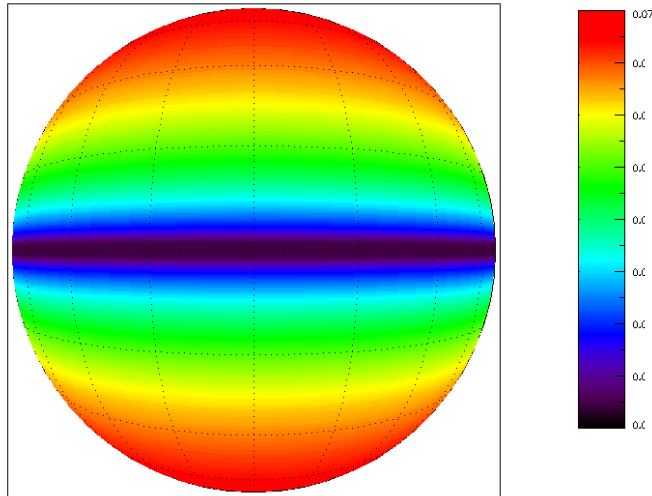
Evolution of different components

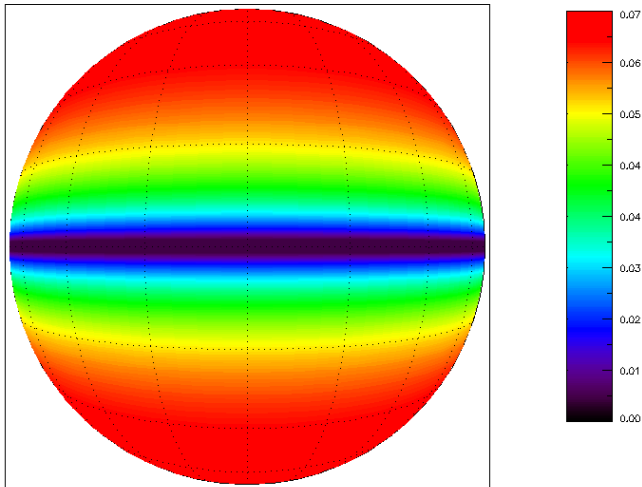Hall attractor mainly consists
of dipole and octupole
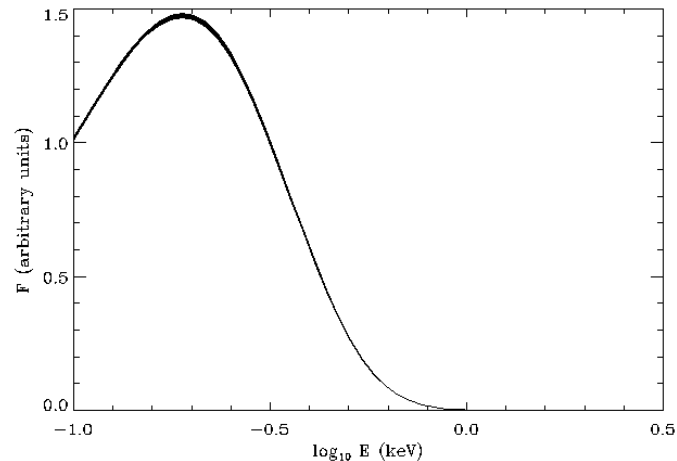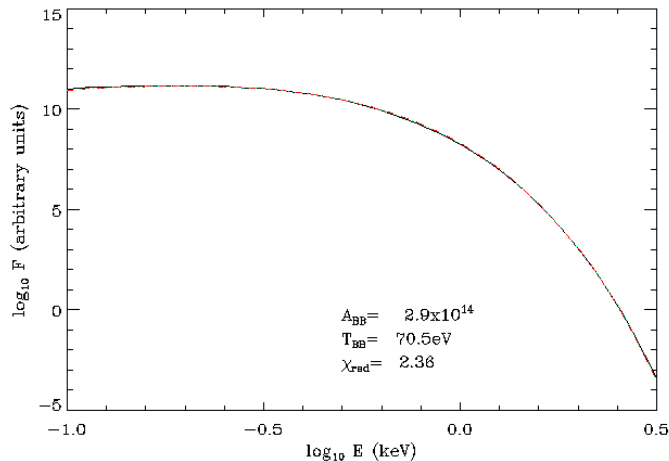
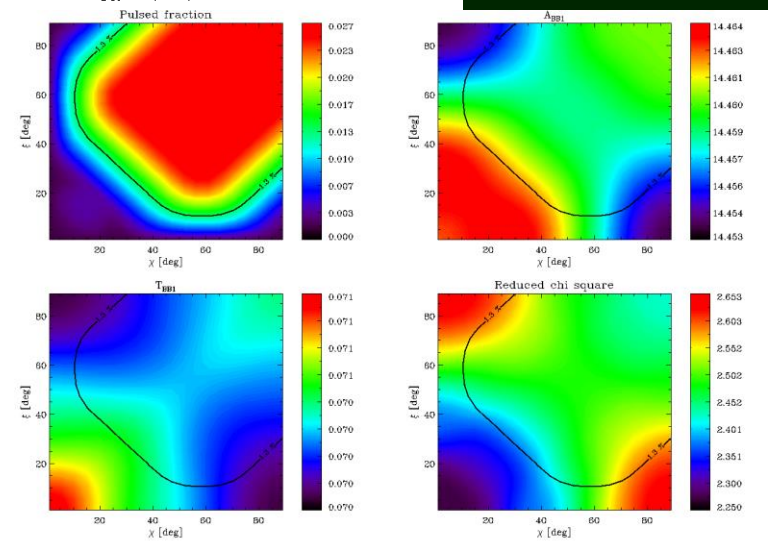# Temperature maps

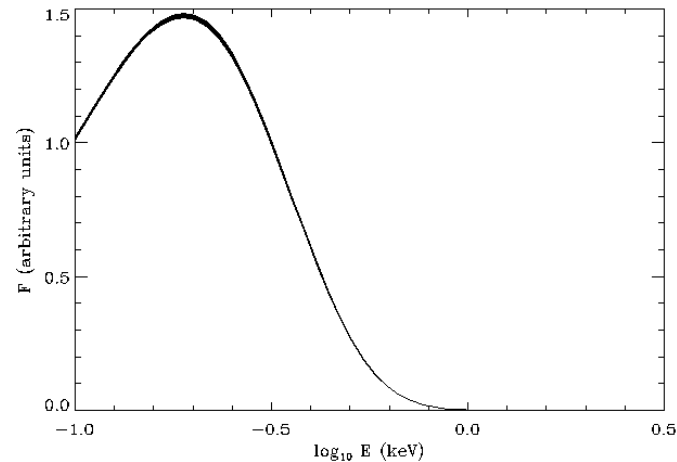Pure dipole
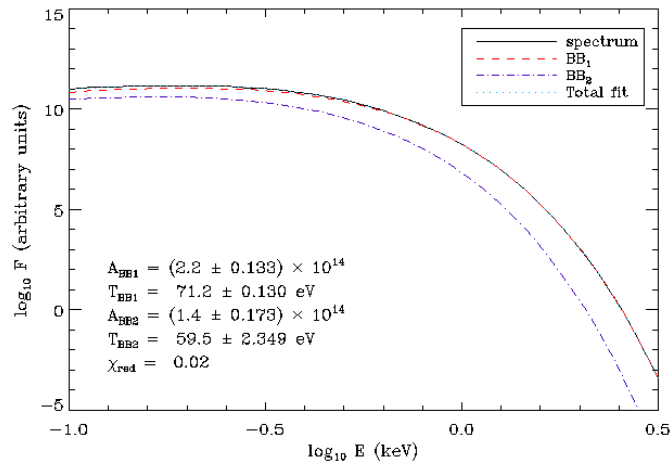
Dipole + octupole

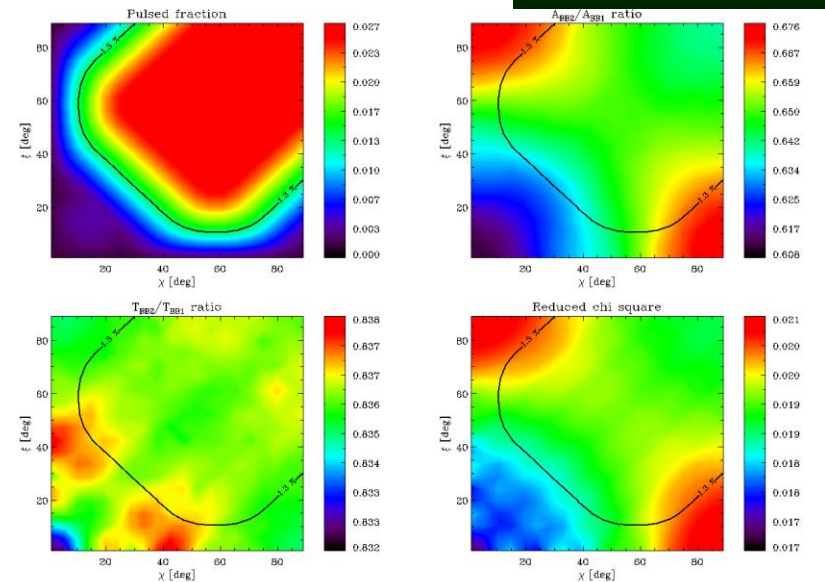Dipole+octupole+l5

Spectral fits: single blackbody

Single black body
does not provide
a good fit, even using,
in addition, a line,
or condensed surface.

Spectral fits: two black bodies

Formally, two black bodies
is the best fit for 1856.
And for dipole+octupole
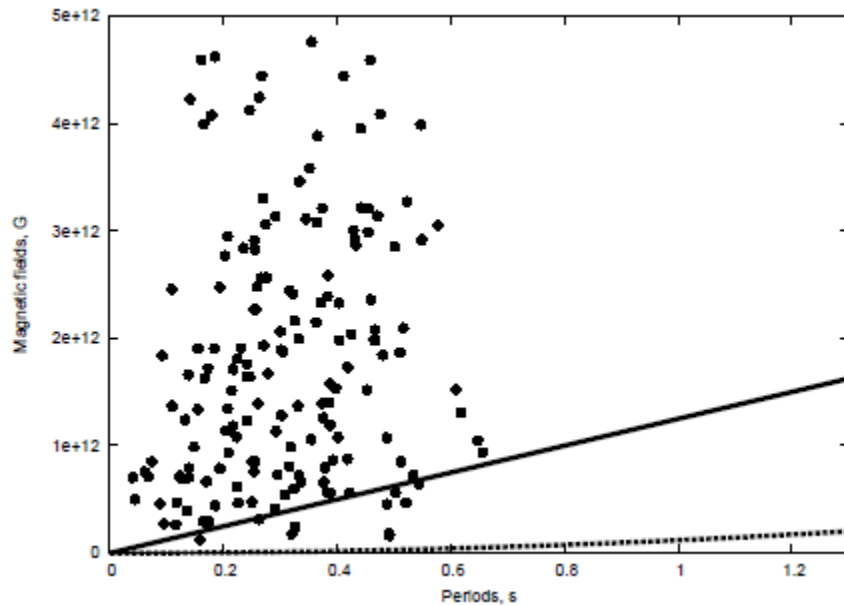we can obtain a very good fit.
But ….

Observational data

| Parameter	Single BB	Two BB
N_H $[10^{19}\ cm^{-2}]$	$4.8^{+0.2}_{-0.2}$	$12.9^{+2.2}_{-2.3}$
kT_h^{∞} [eV]	$61.5^{+0.1}_{-0.1}$	$62.4^{+0.6}_{-0.4}$
R_h^{∞} [km]	$5.0^{+0.1}_{-0.1}$	$4.7^{+0.2}_{-0.3}$
kT_s^{∞} [eV]	-	$38.9^{+4.9}_{-2.9}$
R_s^{∞} [km]	-	$11.8^{+5.0}_{-0.4}$
σ_{sys}	1.5%	0.6%
χ_ν^2	1.12	1.11

Two black bodies is the best fit.
The colder component corresponds to larger surface area.
This is in contrast with our results for the Hall attractor
proposed by GC2013
(dipole + octupole).
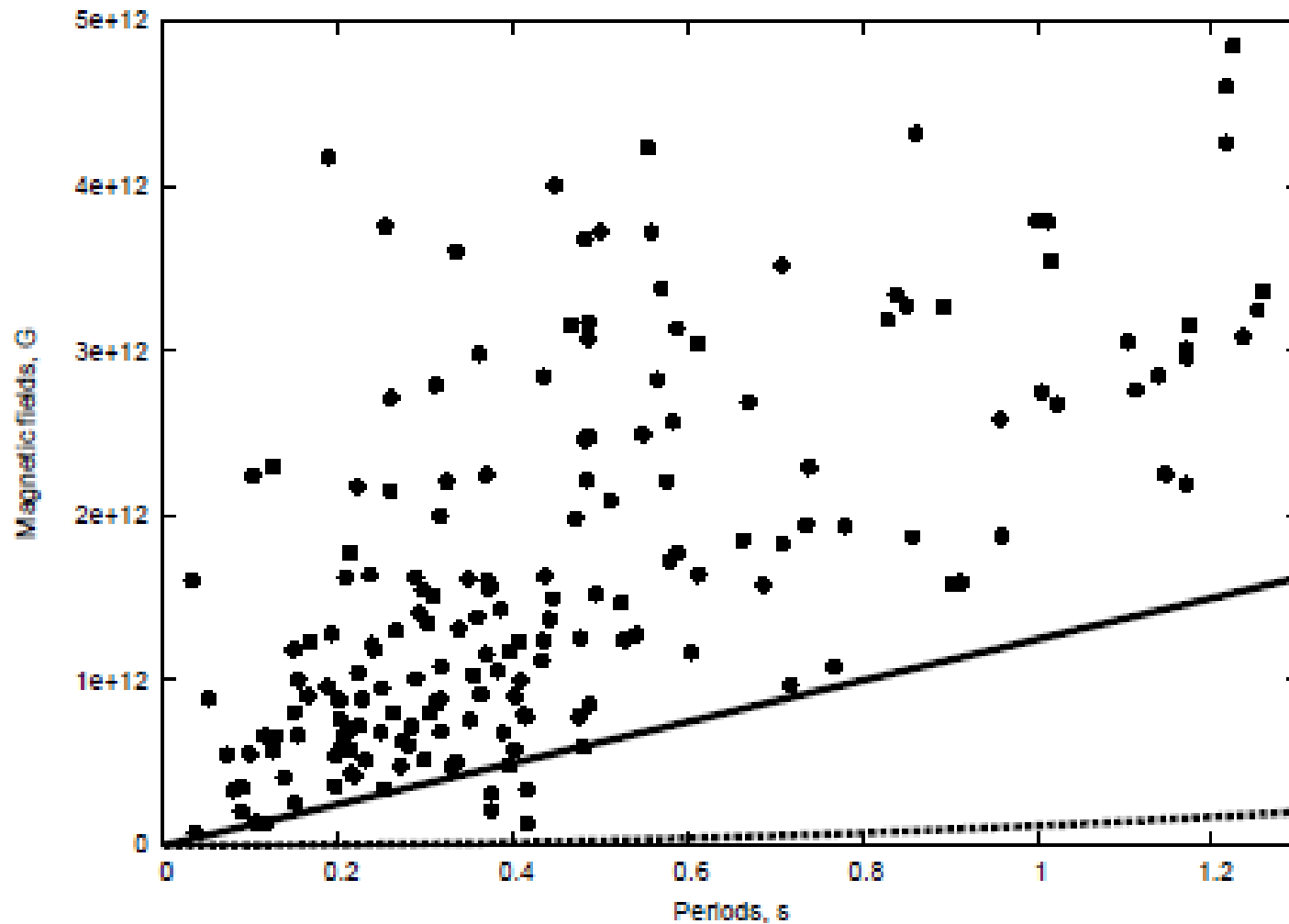
1202.2121

Synthetic populations

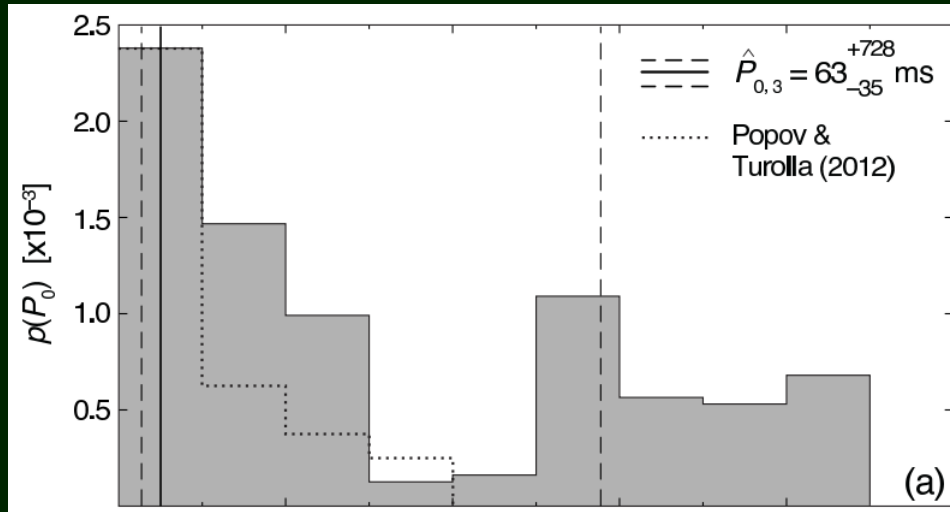Constant field   Exponential decay

$$P_0 = P \sqrt{1 - \frac{t_{\text{true}}}{\tau}}.$$

Igoshev, Popov 2013
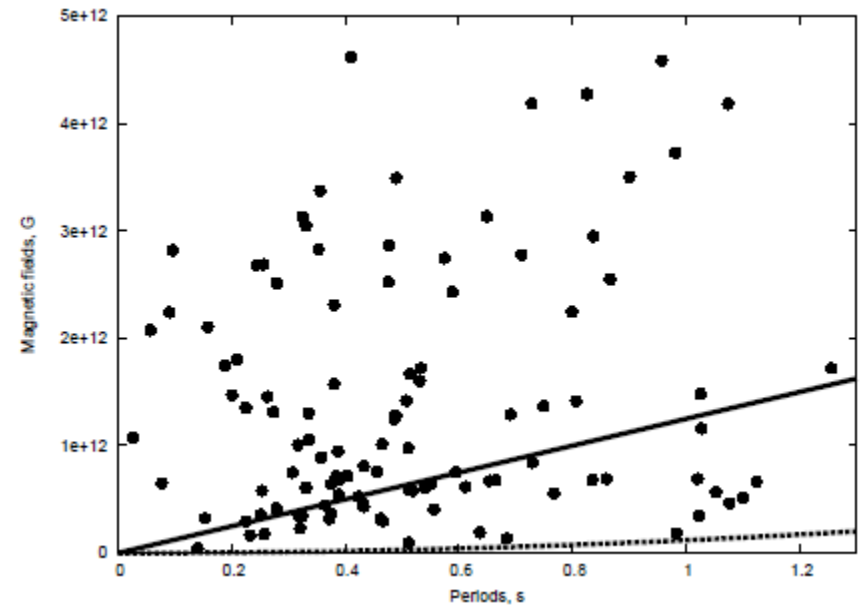
Fitting the field decay

Igoshev, Popov 2013

Another option: emerging field

(a) $\hat{P}_{0,3} = 63^{+728}_{-35}$ ms
— Popov & Turolla (2012)

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 need correlations between different parameters.

Igoshev, Popov 2013