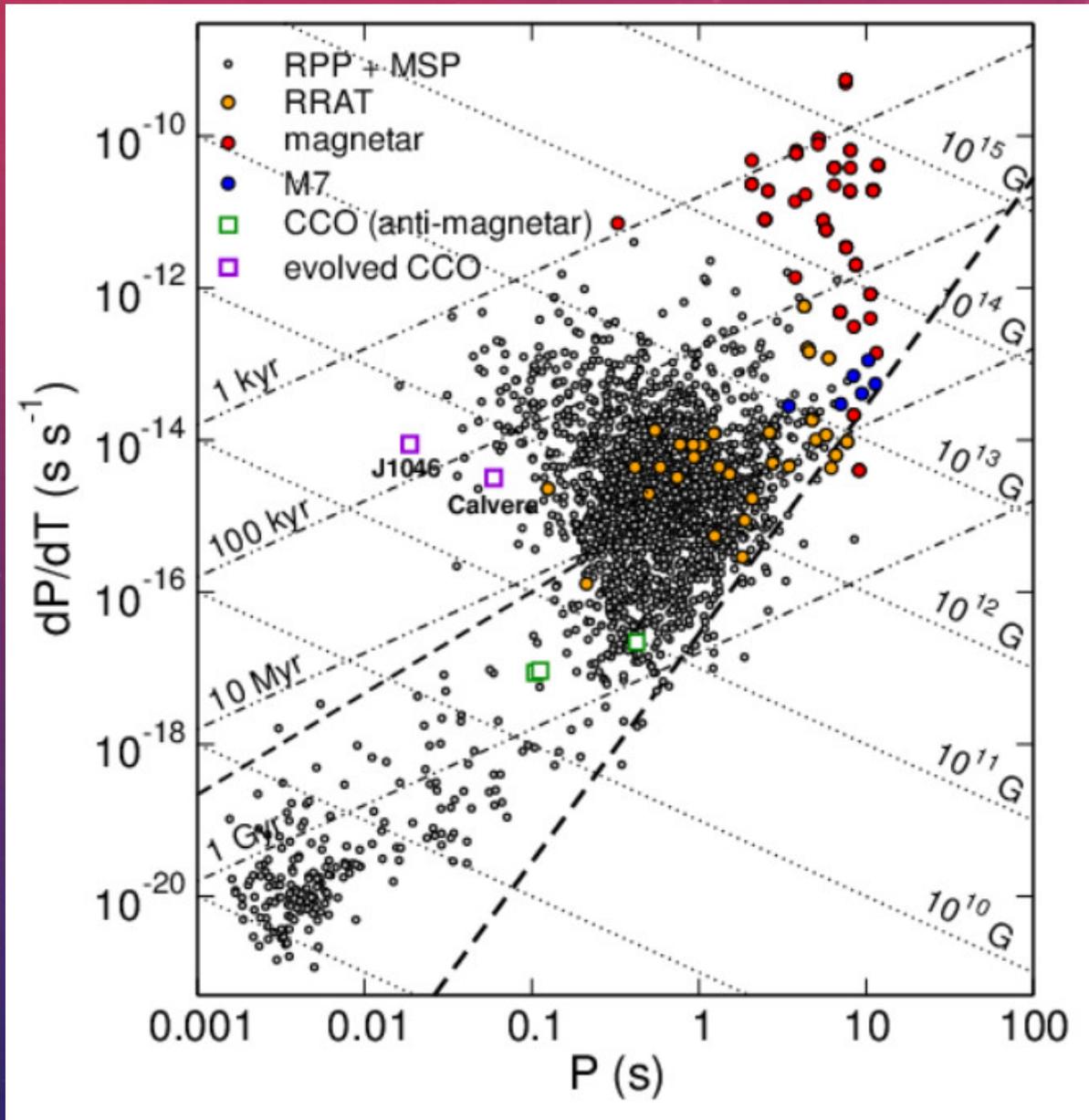
The background features a gradient from red at the top to blue at the bottom, overlaid with faint, semi-transparent circular patterns and a scale. The scale is a large arc on the left side, with numerical labels from 140 to 260 in increments of 10. Several concentric circles and dashed lines with arrows are scattered across the background, suggesting a technical or scientific theme.

SURFACE MAGNETIC FIELD STRUCTURE AND HALL EVOLUTION IN THE CRUST

SERGEI POPOV,

ANDREI IGOSHEV, ROBERTO TAVERNA, ROBERTO TUROLLA

DIVERSITY OF YOUNG NEUTRON STARS

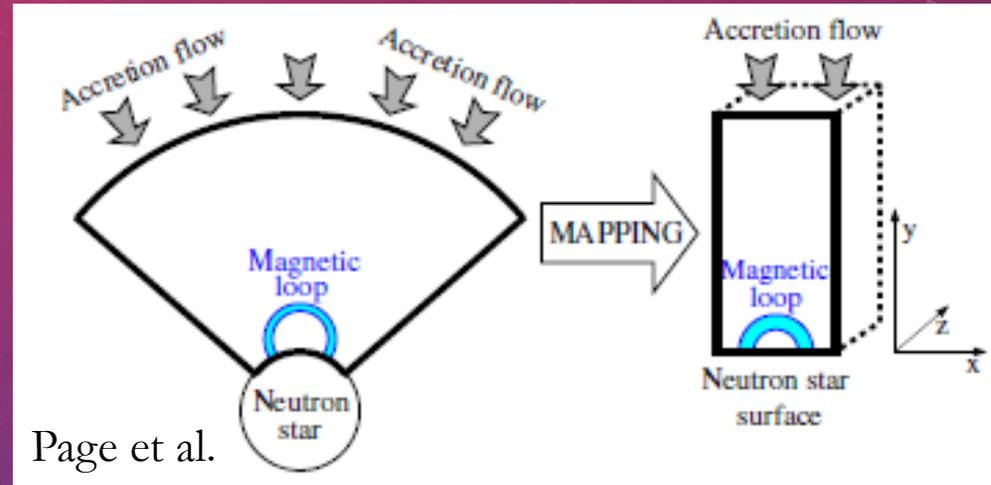
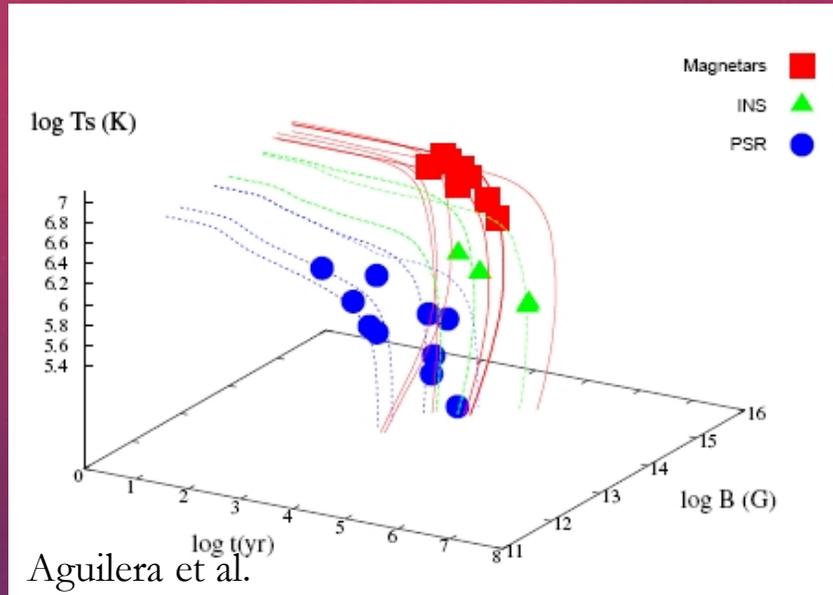


Pires et al. 2015

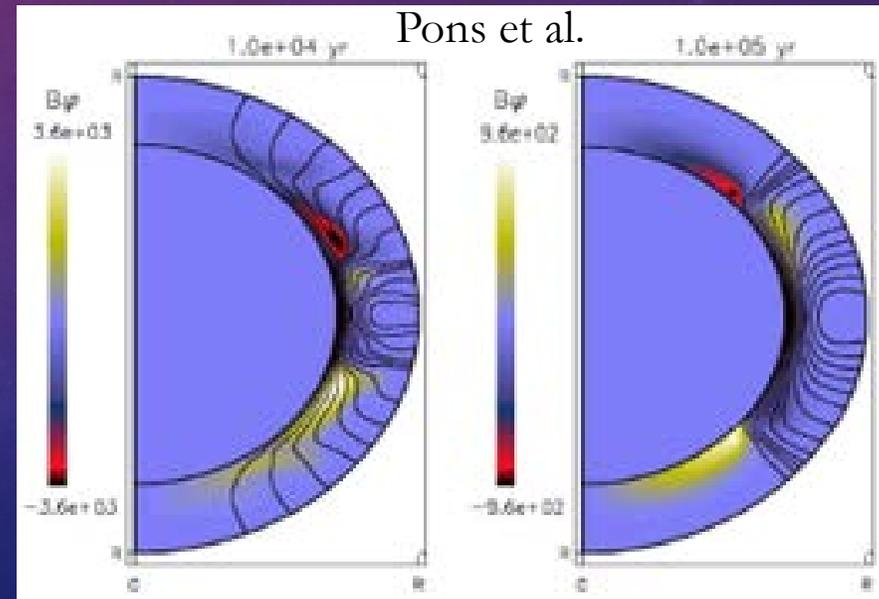
The term
"GRAND UNIFICATION
FOR NEUTRON STARS"
was coined by Kaspi (2010)

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

THREE MAIN INGREDIENTS OF A UNIFIED MODEL

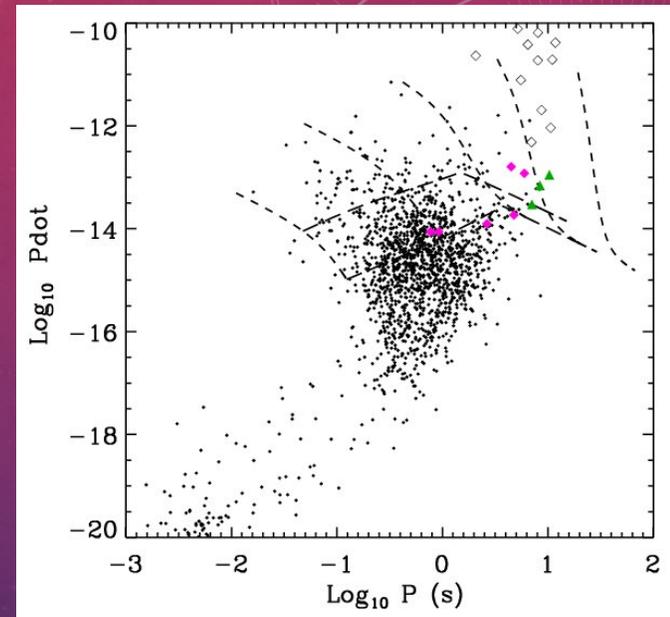


- Field decay
- Emerging magnetic field
- Toroidal magnetic field

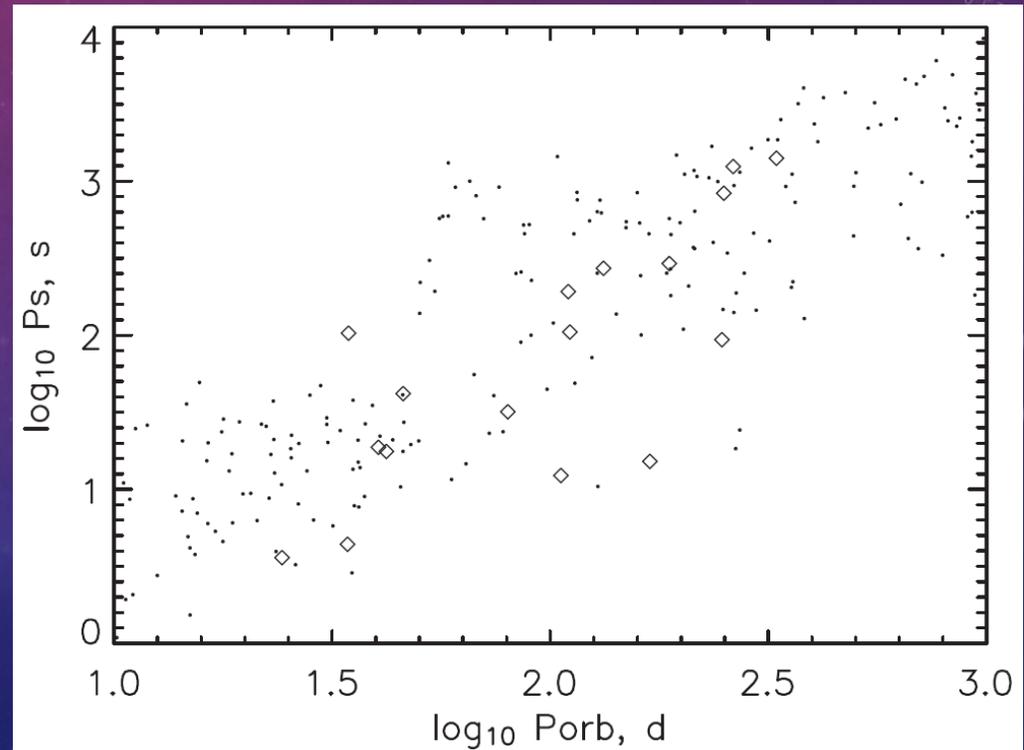
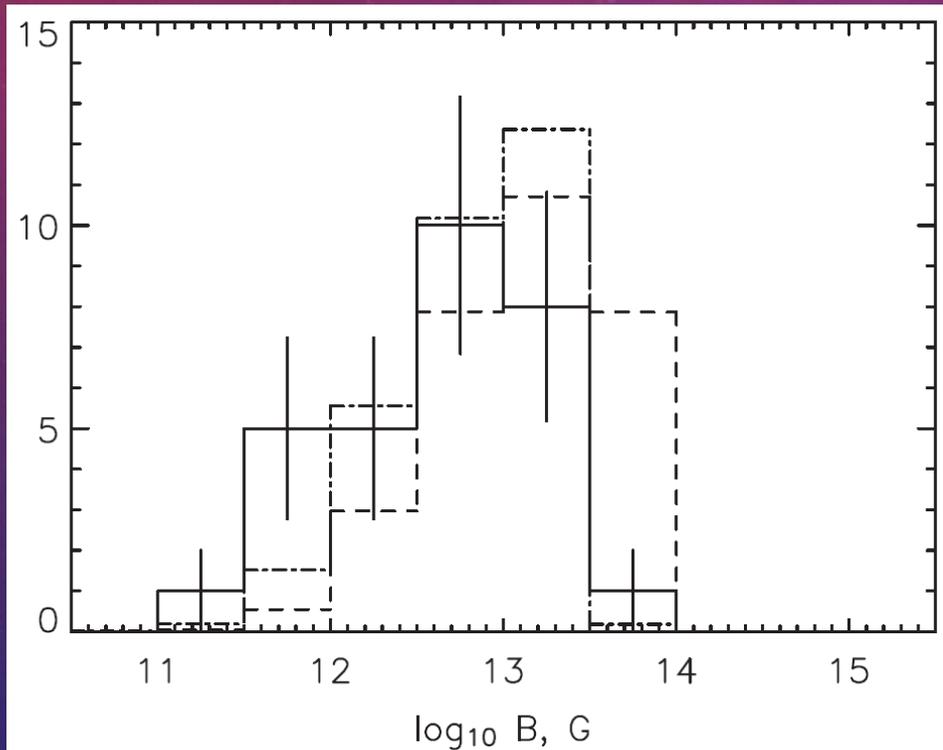


FIELD DECAY IN HMXBS

It is possible to use HMXBs to test models of field decay on time scale >1 Myr (Chashkina, Popov 2012). We use observations of Be/X-ray binaries in SMC to derive magnetic field estimates, and compare them with prediction of the Pons et al. model.

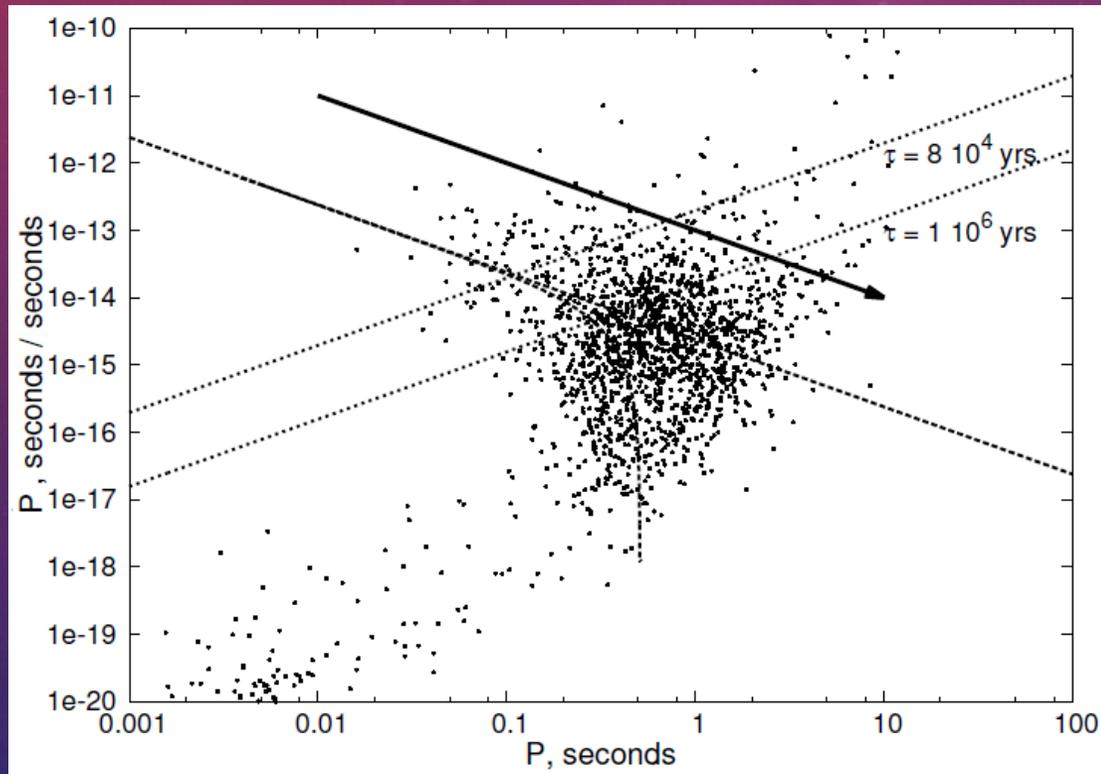


Chashkina, Popov (2012)



MODIFIED PULSAR CURRENT

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



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

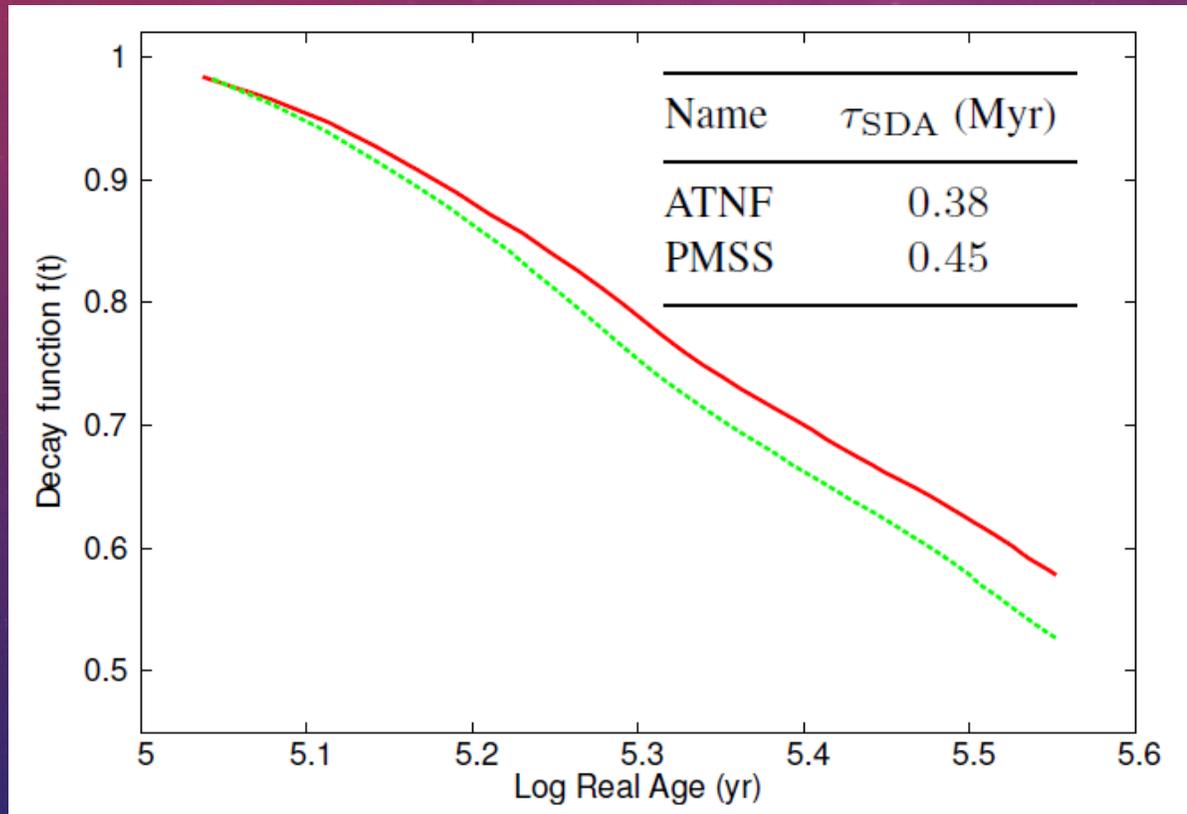
We use distribution in characteristic ages to reconstruct the field evolution.

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).

Igoshev, Popov (2014)



We reconstruct the magnetic field decay in the range of true (statistical) ages:

$8 \cdot 10^4 < t < 3.5 \cdot 10^5$ yrs

which corresponds to characteristic ages $8 \cdot 10^4 < \tau < 10^6$ yrs.

In this range, the field decays roughly by a factor of two.

With an exponential fit this corresponds to the decay time scale $\sim 4 \cdot 10^5$ yrs.

Note, this decay is limited in time.

WHAT KIND OF DECAY DO WE SEE?

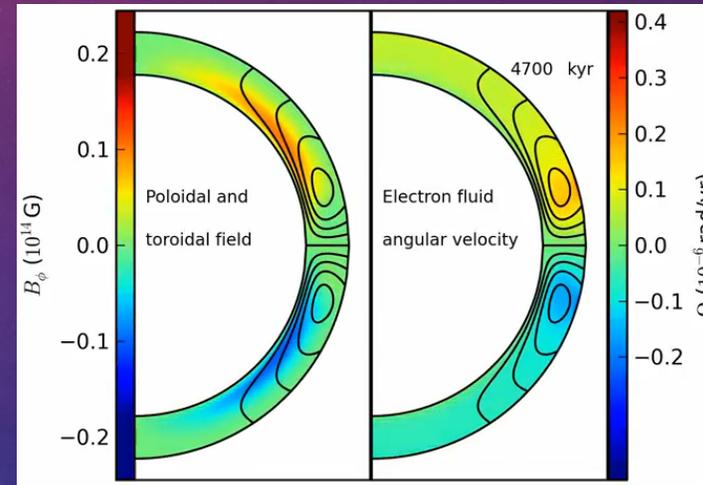
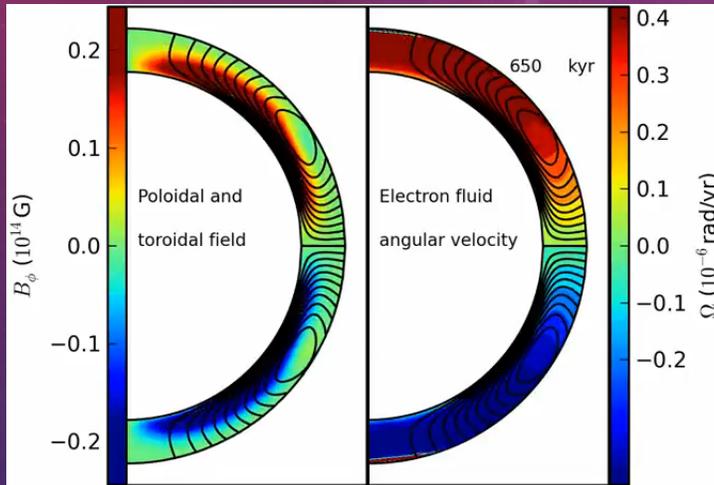
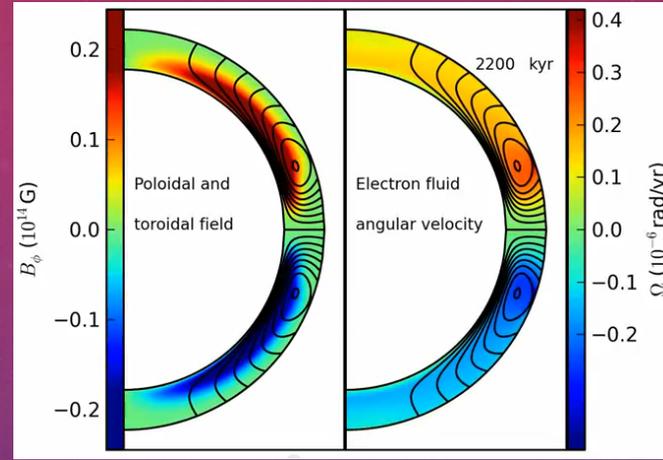
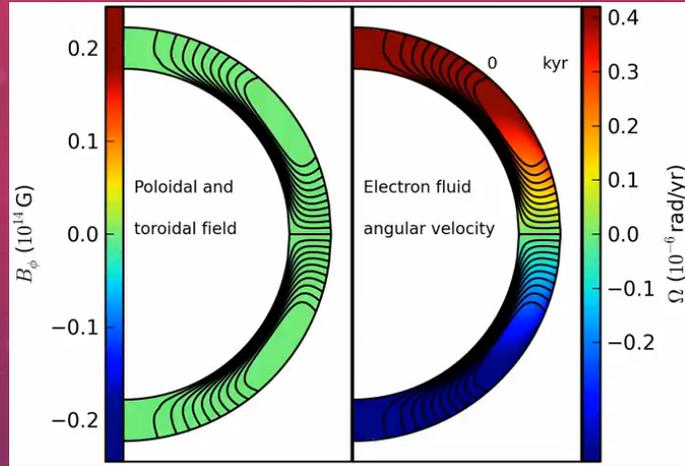
Ohmic decay due to phonons

Hall cascade

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

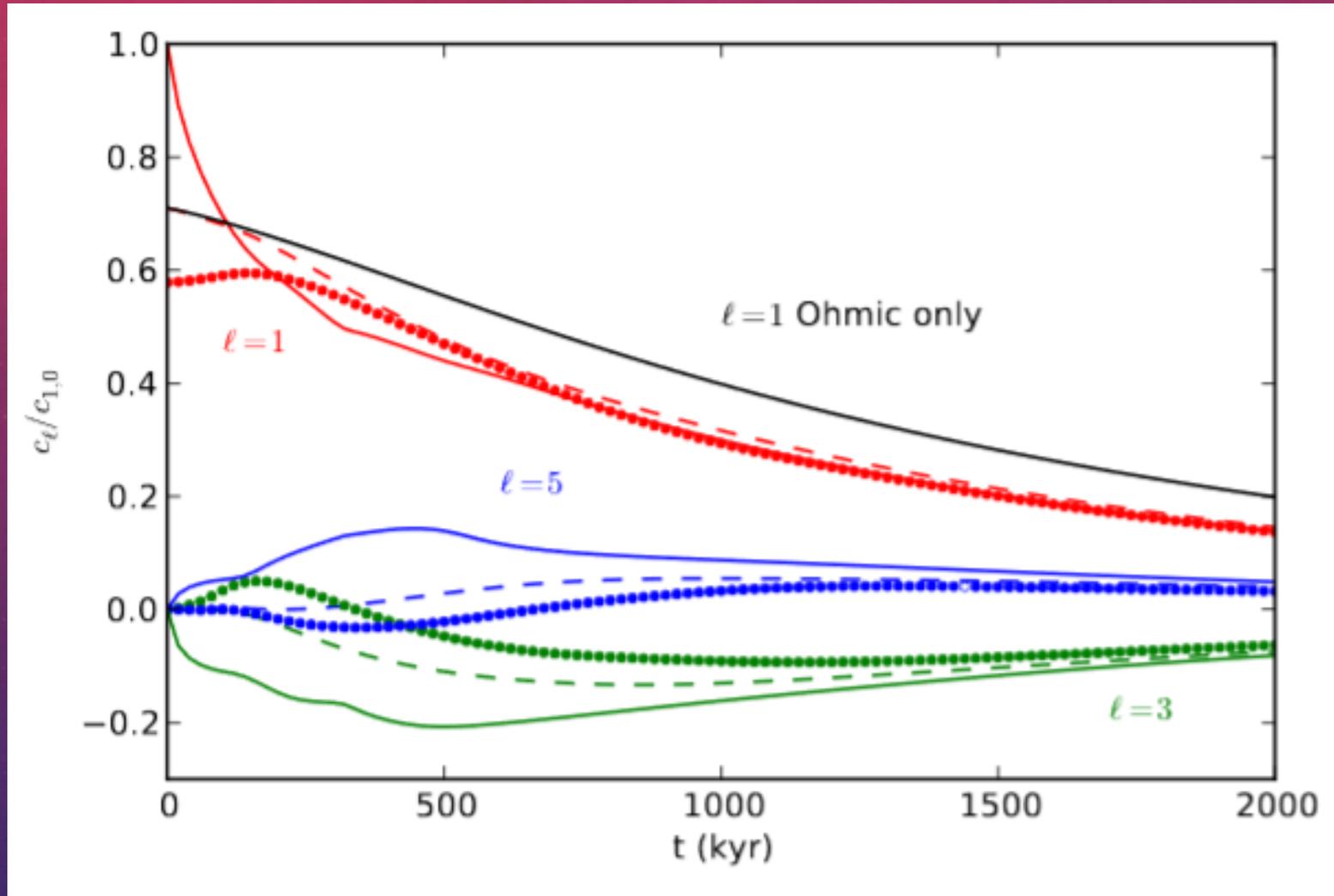
Both time scales fit, and in both cases we can switch off decay at $\sim 10^6$ yrs either due to cooling, or due to the Hall attractor.

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).

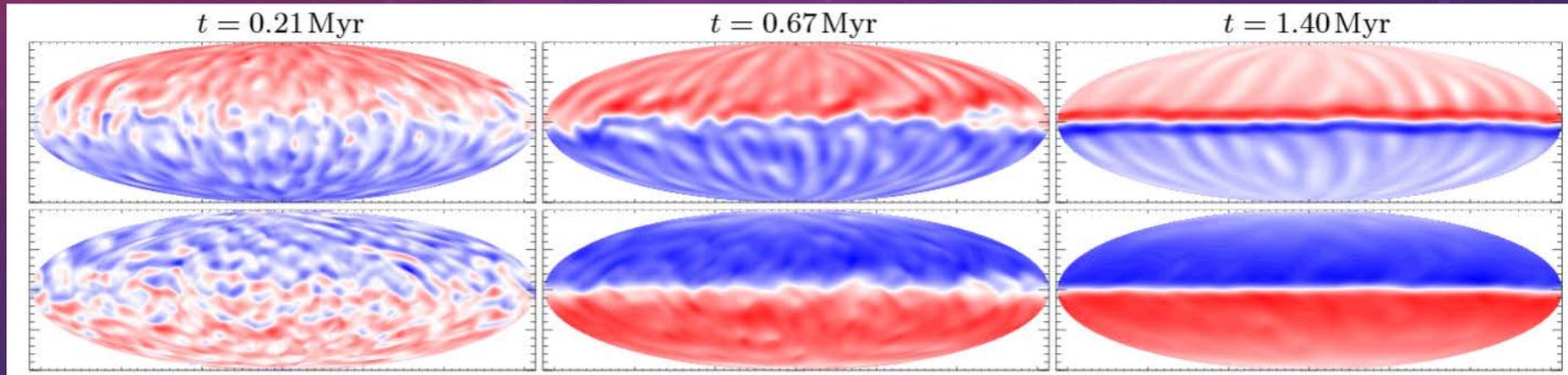
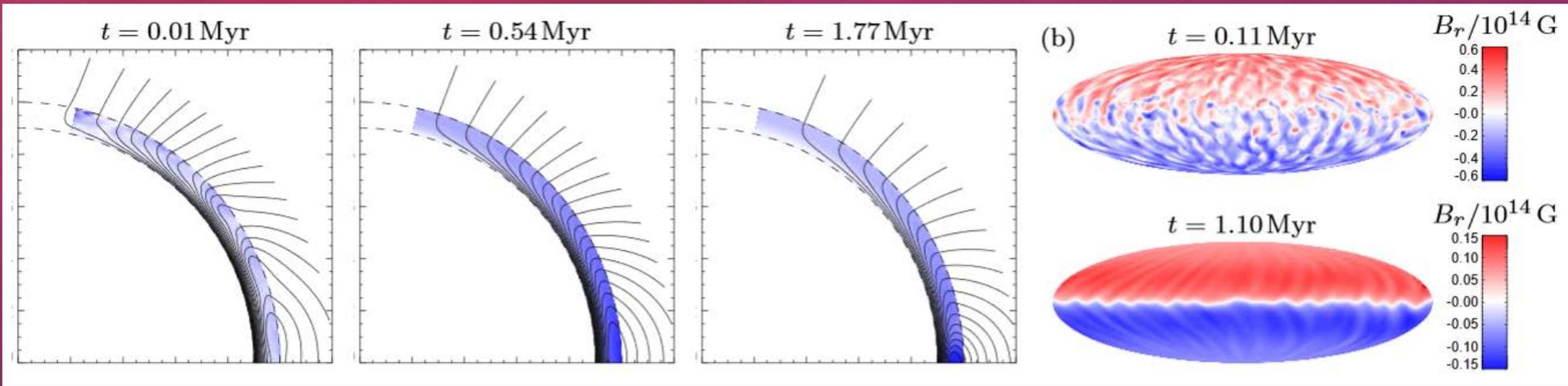
EVOLUTION OF DIFFERENT COMPONENTS



1311.7004

Hall attractor mainly consists of dipole and octupole (+15)

NEW STUDIES OF THE HALL CASCADE

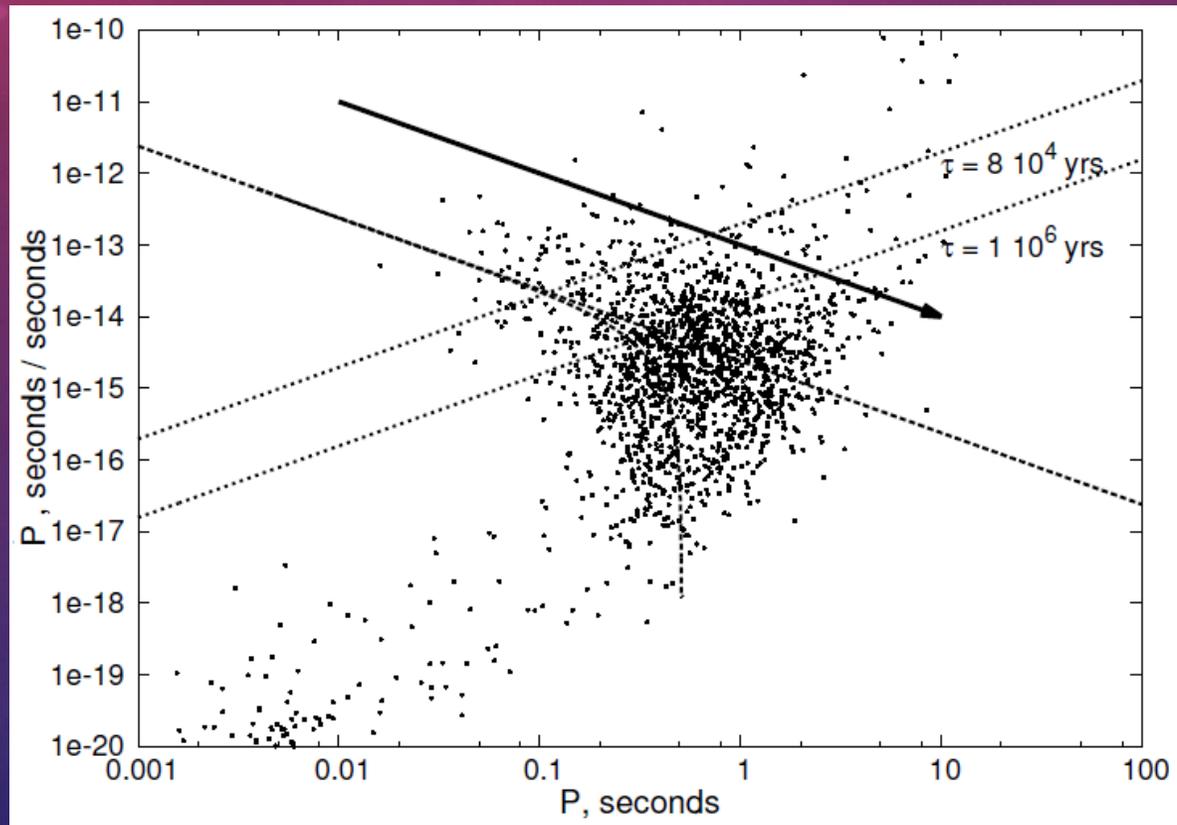


1501.05149

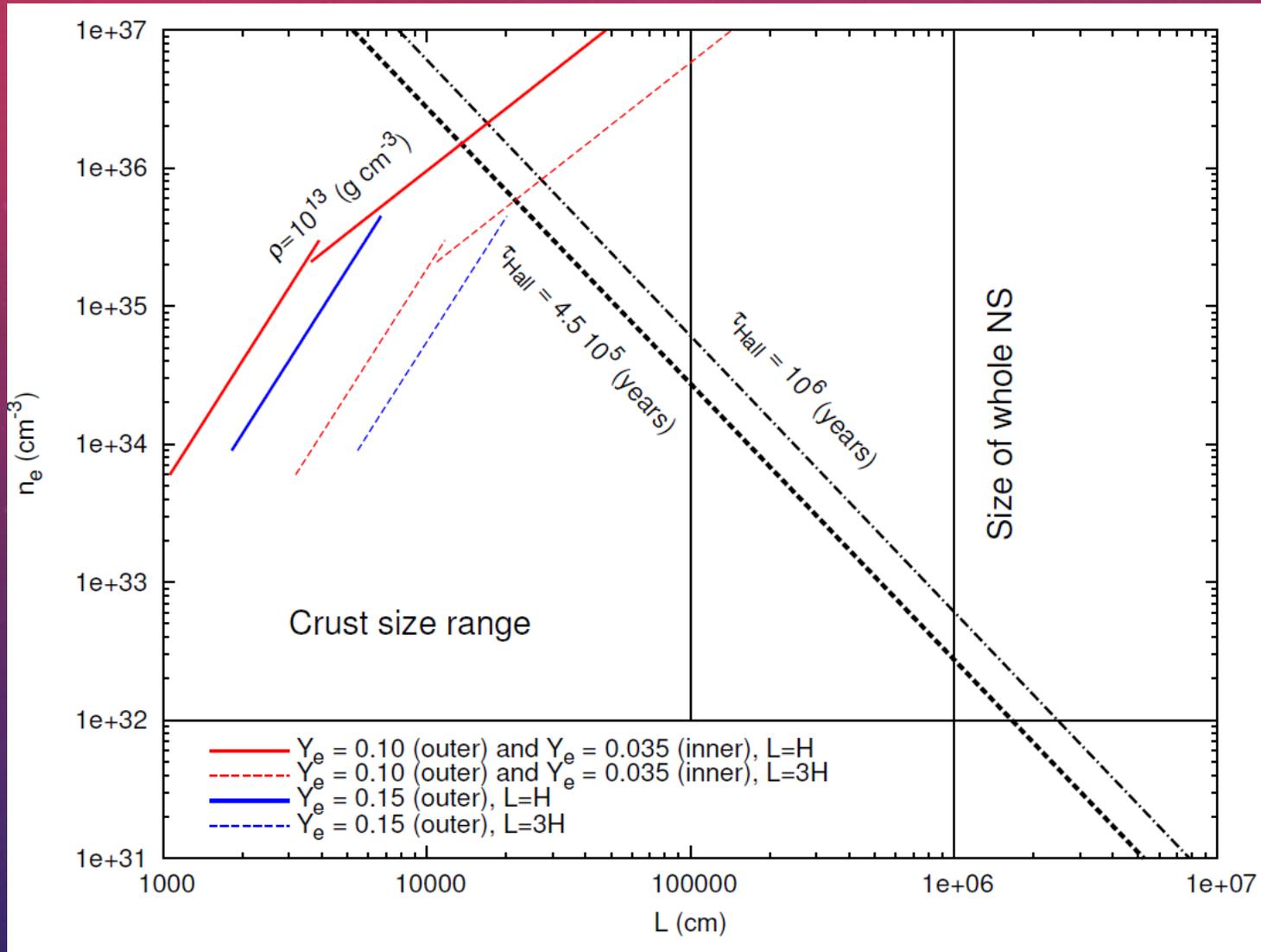
New calculations support the idea of a kind of stable configuration.

CAN WE SEE THE HALL ATTRACTOR?????

May be in normal pulsars, as we need to stop field decay?



WHERE THE CURRENTS ARE LOCATED?



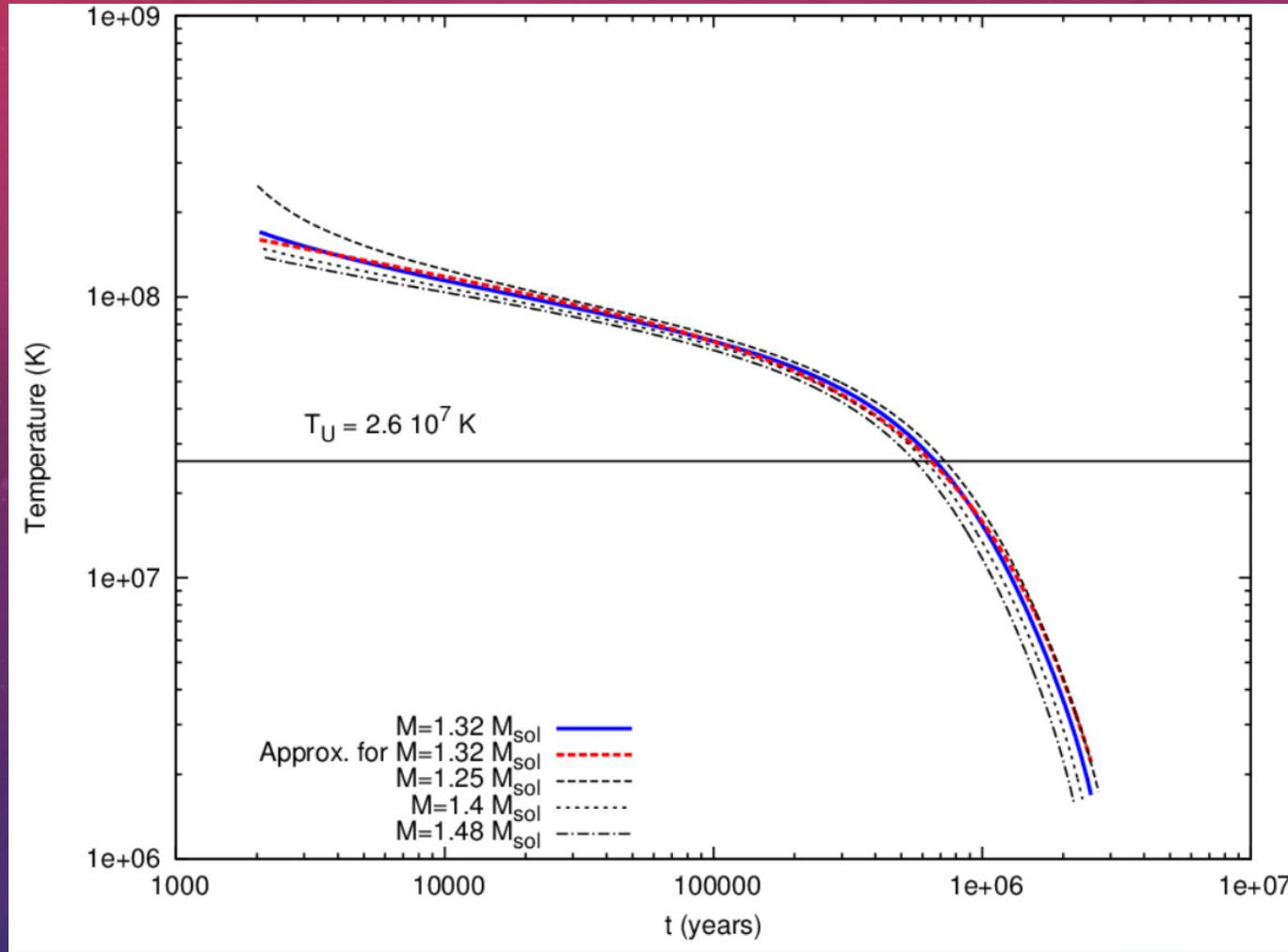
$$\tau_{\text{Hall}} \approx \frac{4\pi e L^2 n_e}{cB}$$

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

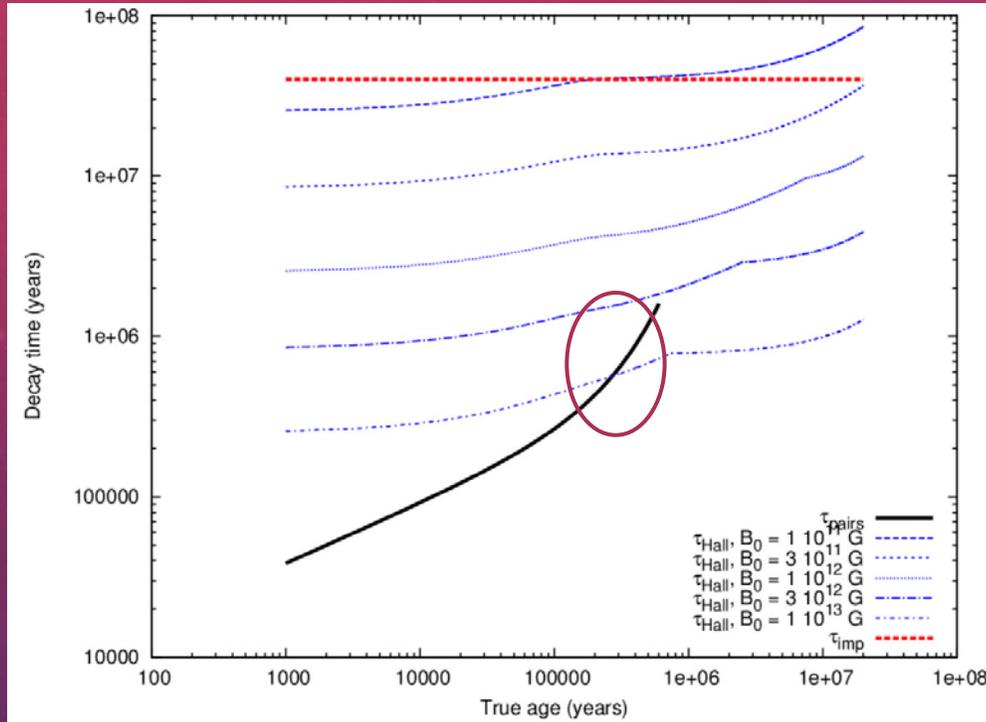
THERMAL EVOLUTION

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.

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

$$\tau_{\text{imp}} = 5.7 \frac{\rho_{14}^{5/3}}{Q} \left(\frac{Z}{30}\right) \left(\frac{Y_e}{0.05}\right)^{1/3} \left(\frac{Y_n}{0.8}\right)^{10/3} \times$$

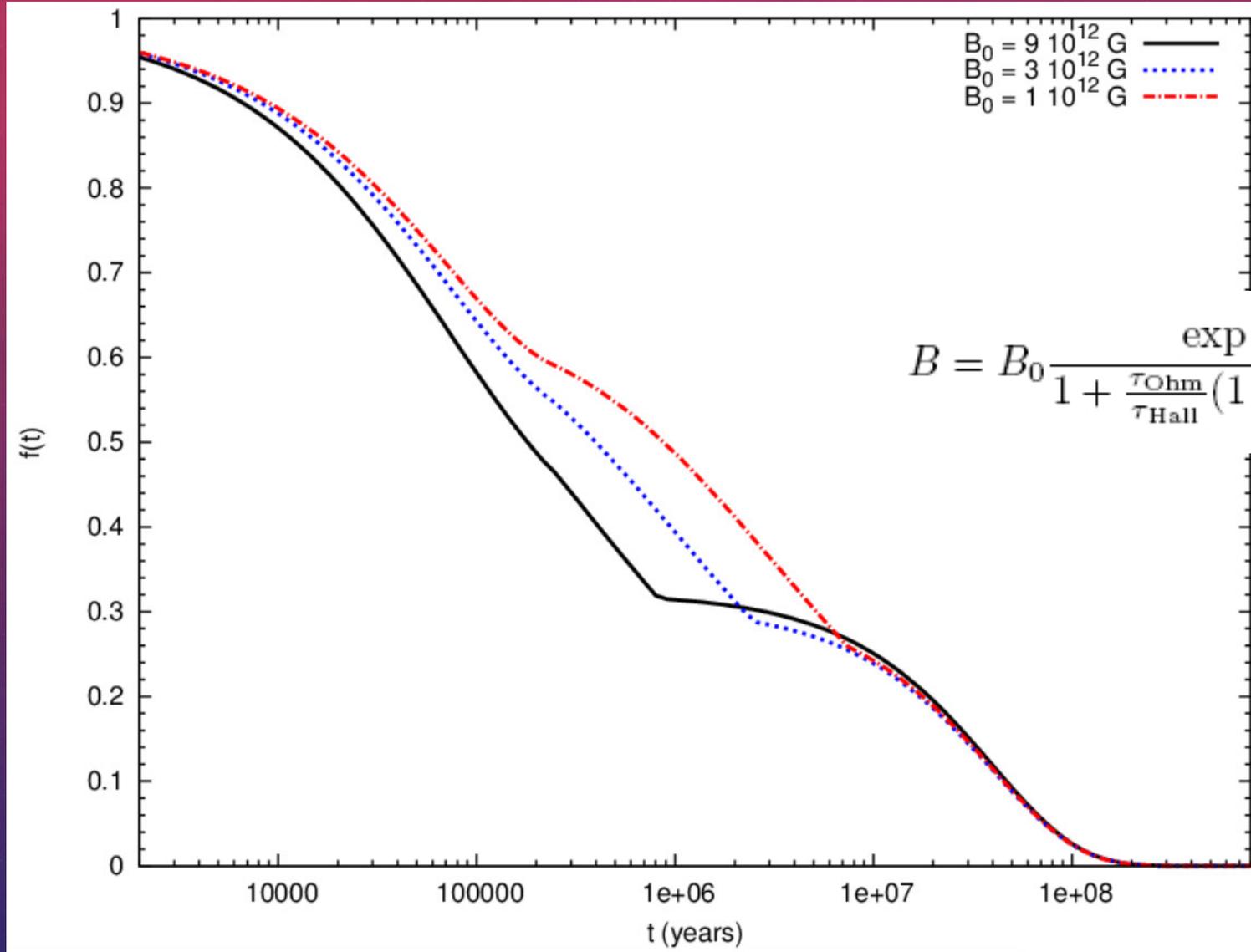
$$\times \left(\frac{f}{0.5}\right)^2 \left(\frac{g_{14}}{2.45}\right) \text{ Myrs,}$$

$$\tau_{\text{phonon}} = 2.2 \frac{\rho_{14}^{15/6}}{T_8^2} \left(\frac{Y_e}{0.05}\right)^{5/3} \left(\frac{Y_n}{0.8}\right)^{10/3} \times$$

$$\times \left(\frac{f}{0.5}\right)^2 \left(\frac{g_{14}}{2.45}\right)^{-2} \text{ Myrs,}$$

MAGNETIC FIELD EVOLUTION

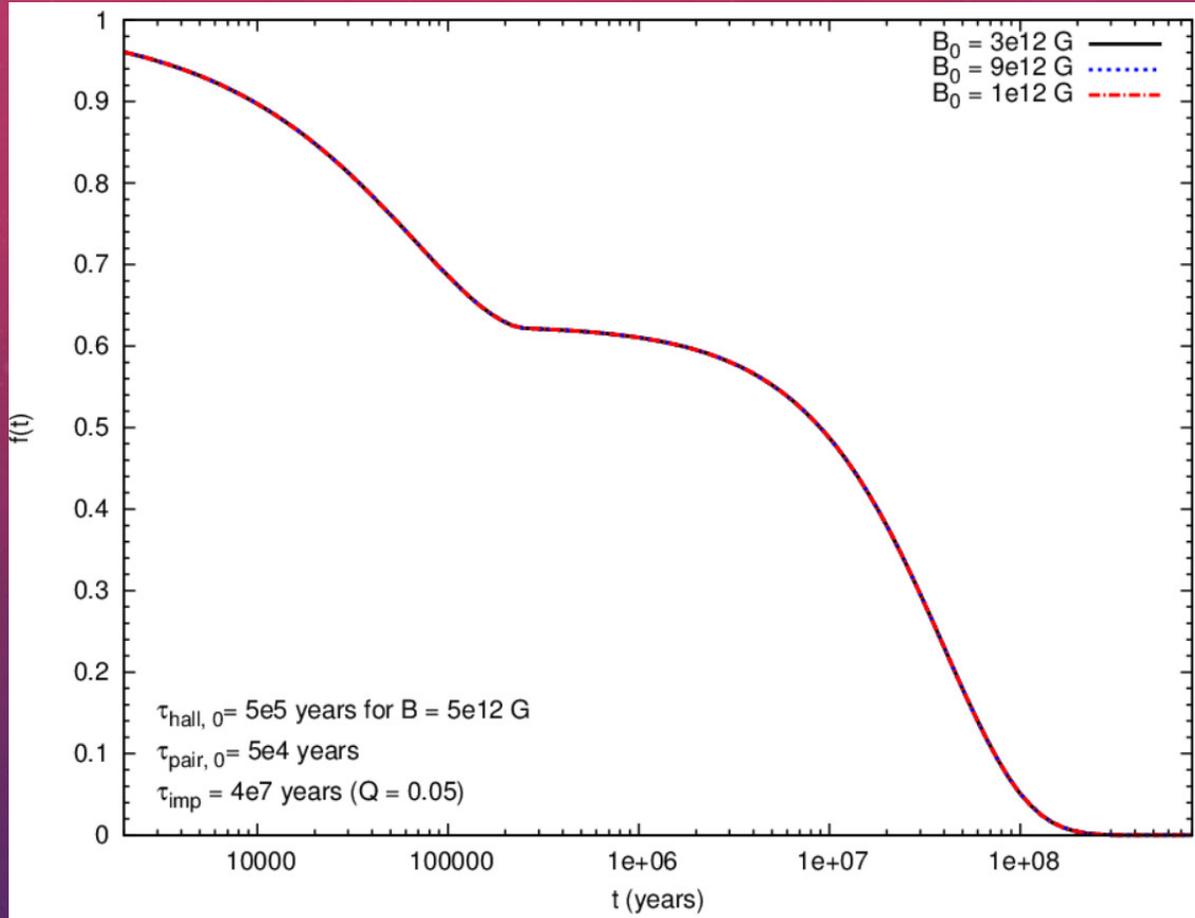
Igoshev, Popov (2015) [arXiv: 1507.07962](https://arxiv.org/abs/1507.07962)



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

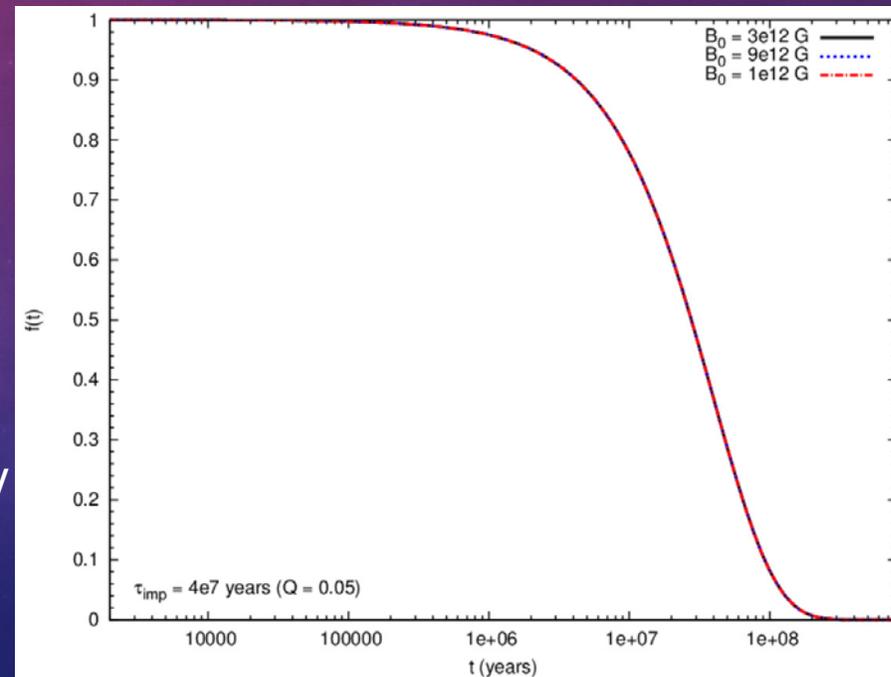
- All inclusive:
- Hall
 - Phonons
 - Impurities

ONLY OHMIC DECAY



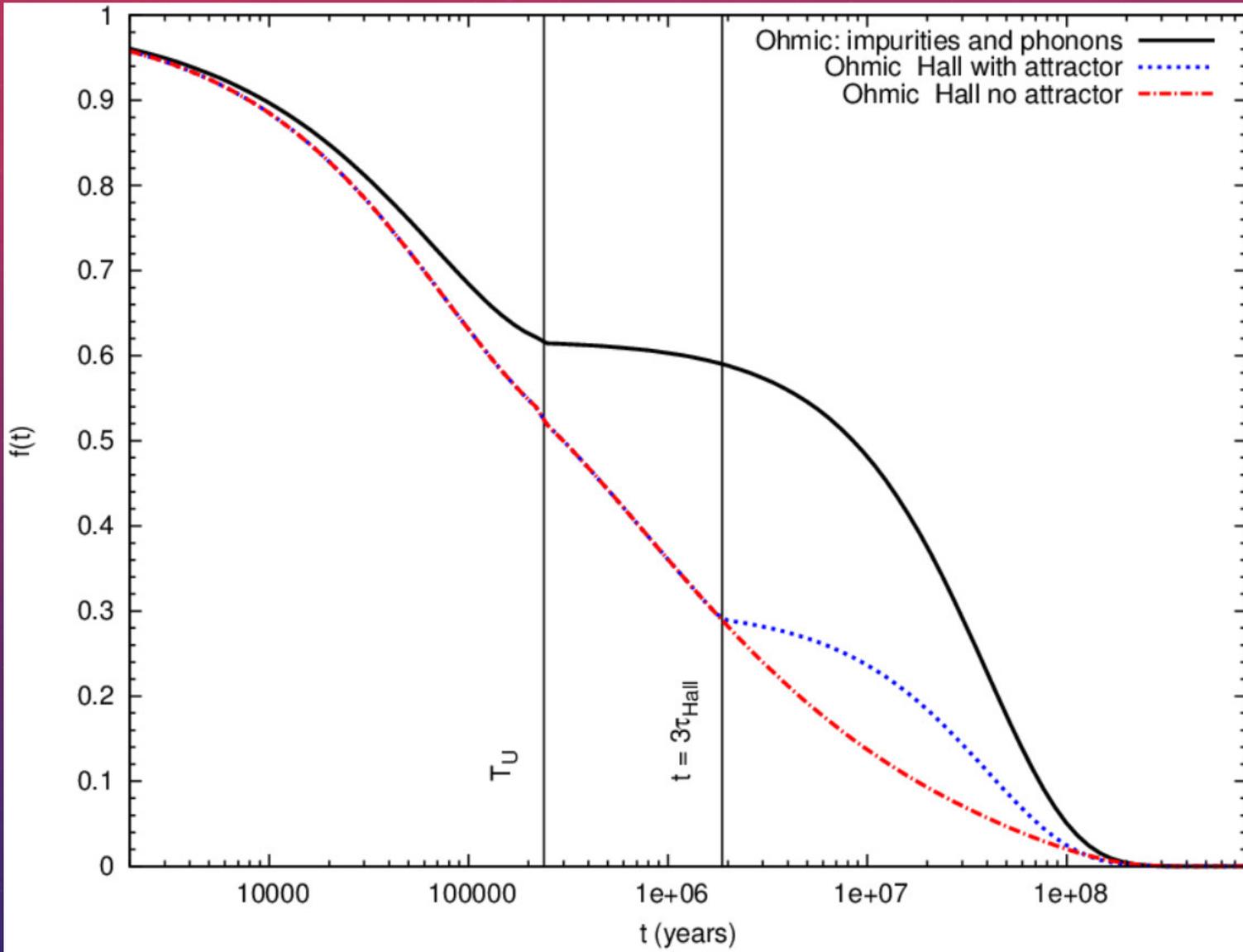
In one figure we have Ohmic decay only due to impurities, on another one – phonons are added.

Here the Hall cascade is switched off



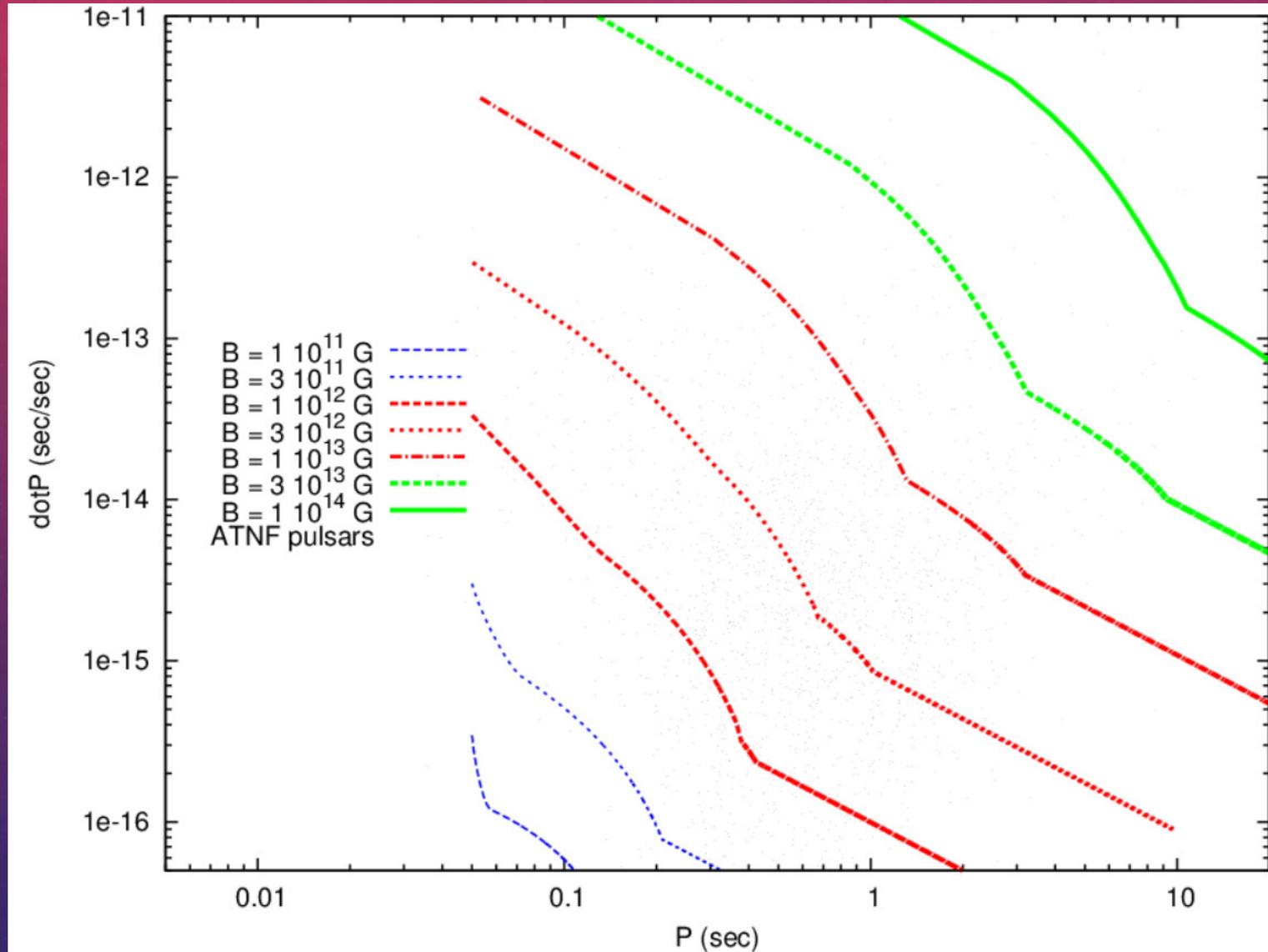
COMPARISON OF DIFFERENT OPTIONS

Igoshev, Popov (2015) [arXiv: 1507.07962](https://arxiv.org/abs/1507.07962)

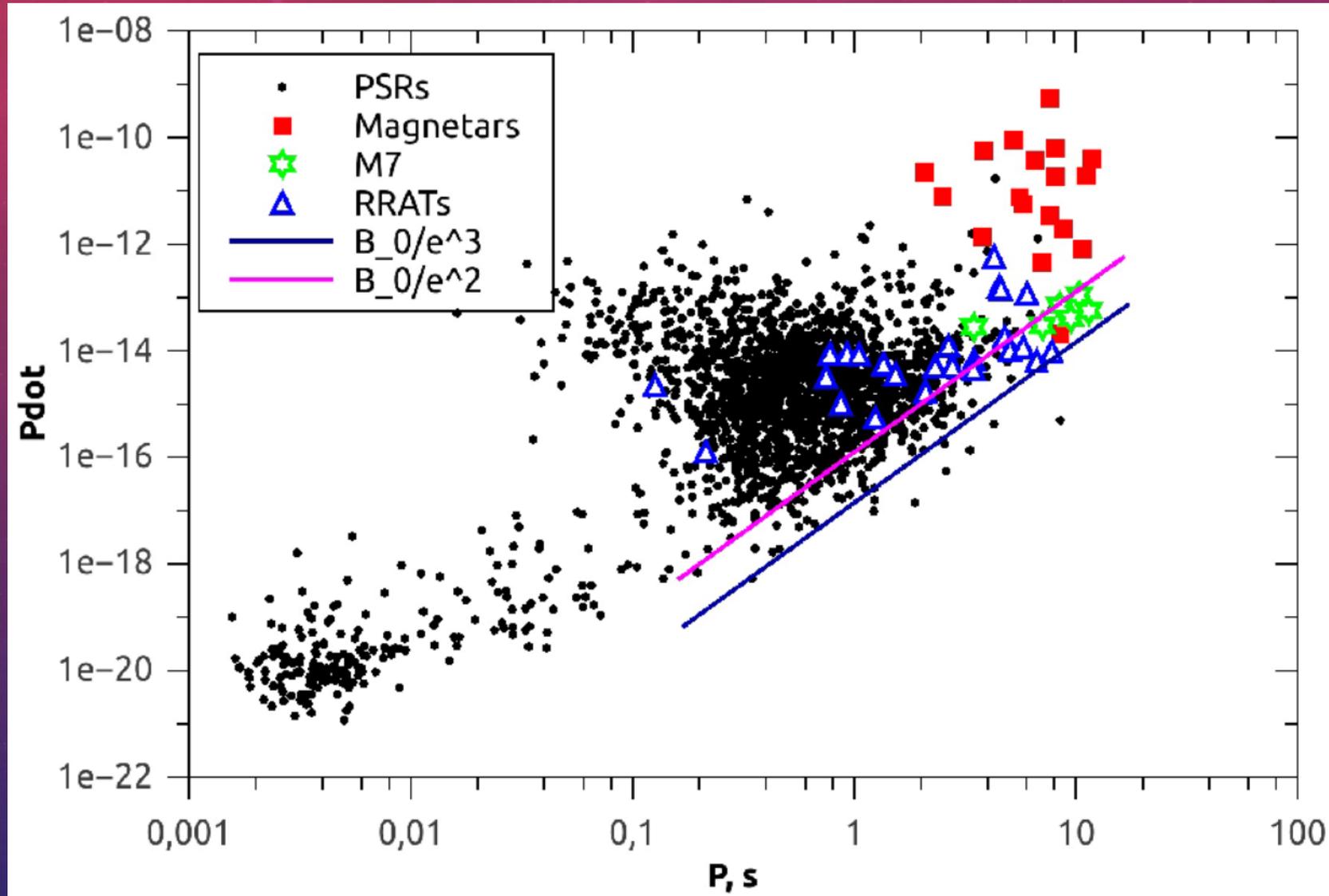


We think that in the range $\sim 10^5 - 10^6$ yrs we see mostly Ohmic decay, which then disappears as NSs cool down below the critical T.

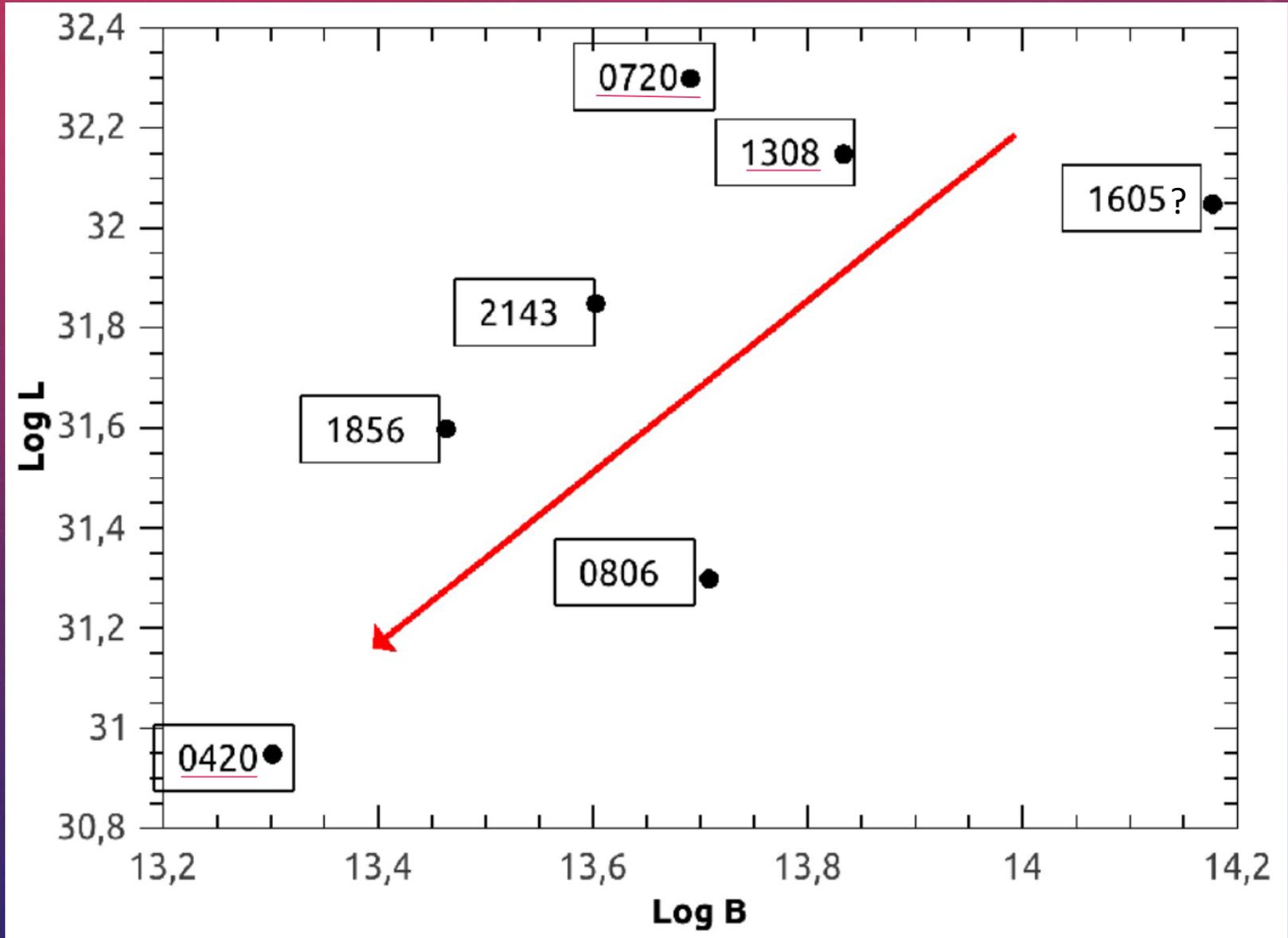
EVOLUTION WITH FIELD DECAY



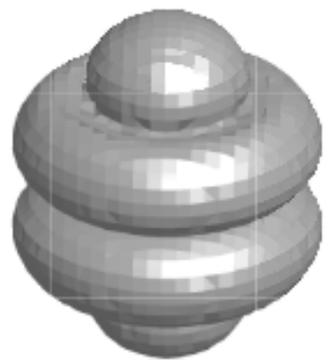
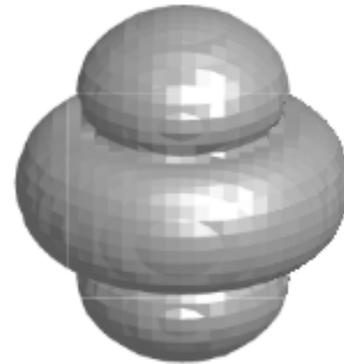
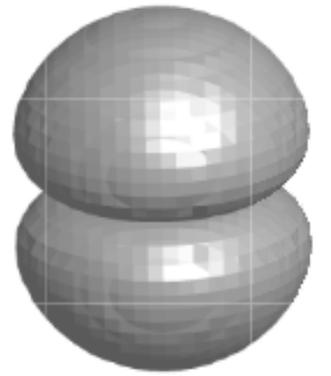
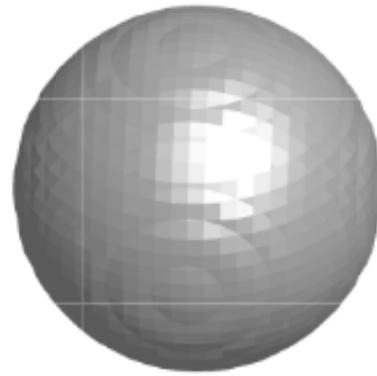
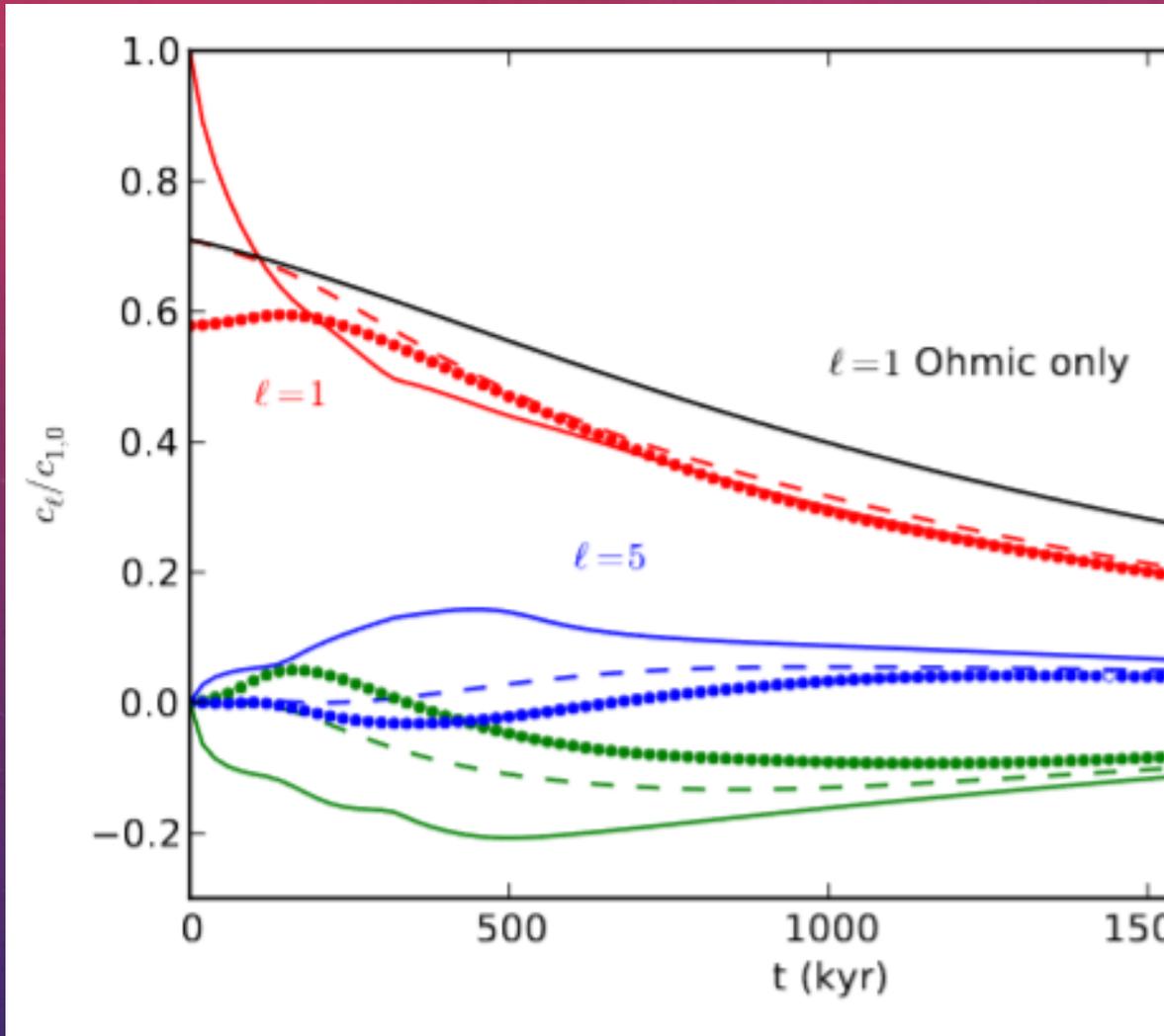
GETTING CLOSE TO THE ATTRACTOR



WHO IS CLOSER TO THE ATTRACTOR STAGE?



EVOLUTION OF DIFFERENT COMPONENTS



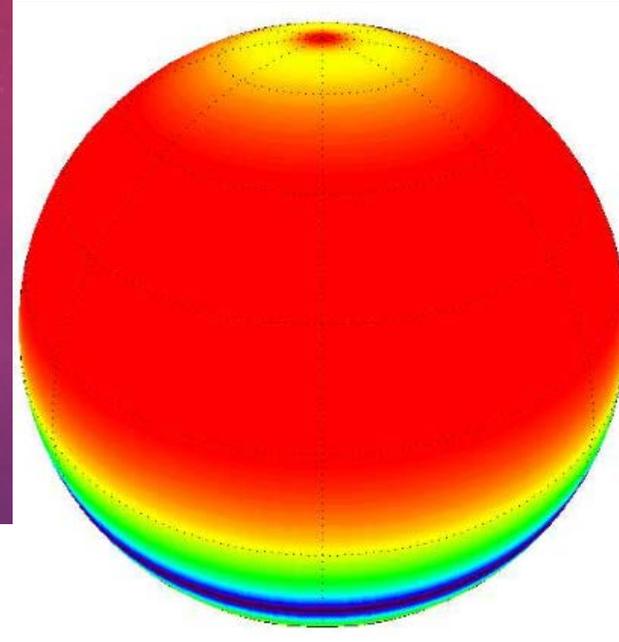
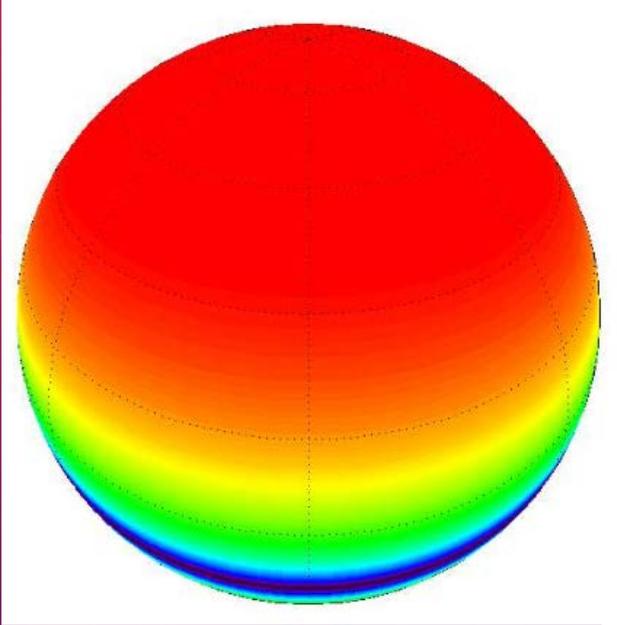
1311.7004

Hall attractor mainly consists of dipole and octupole

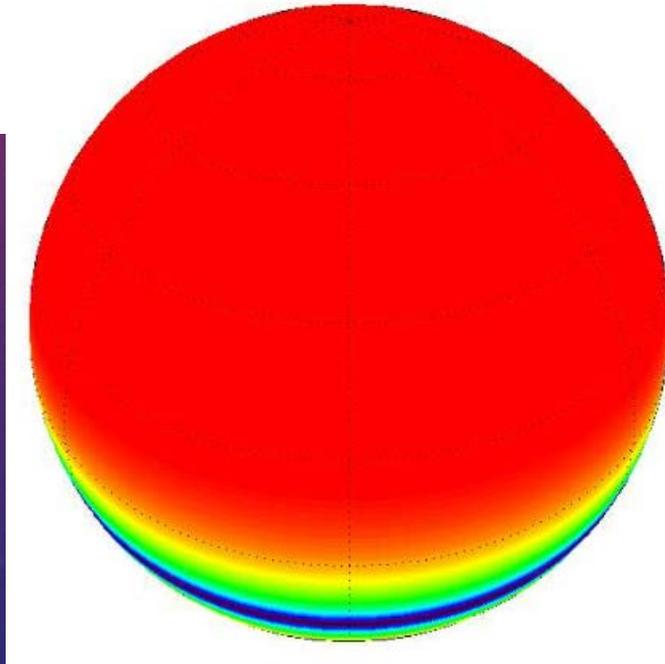
0902.0720

TEMPERATURE MAPS

Pure dipole



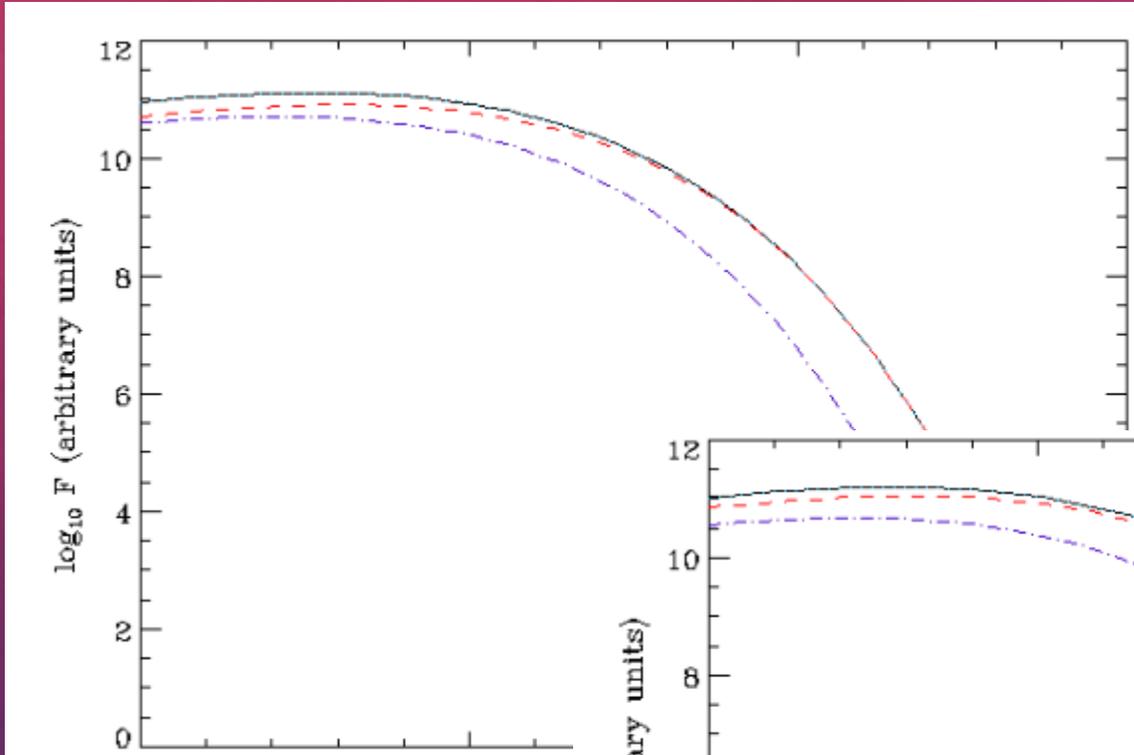
Dipole + octupole + I5



Dipole + octupole
(Model 1)

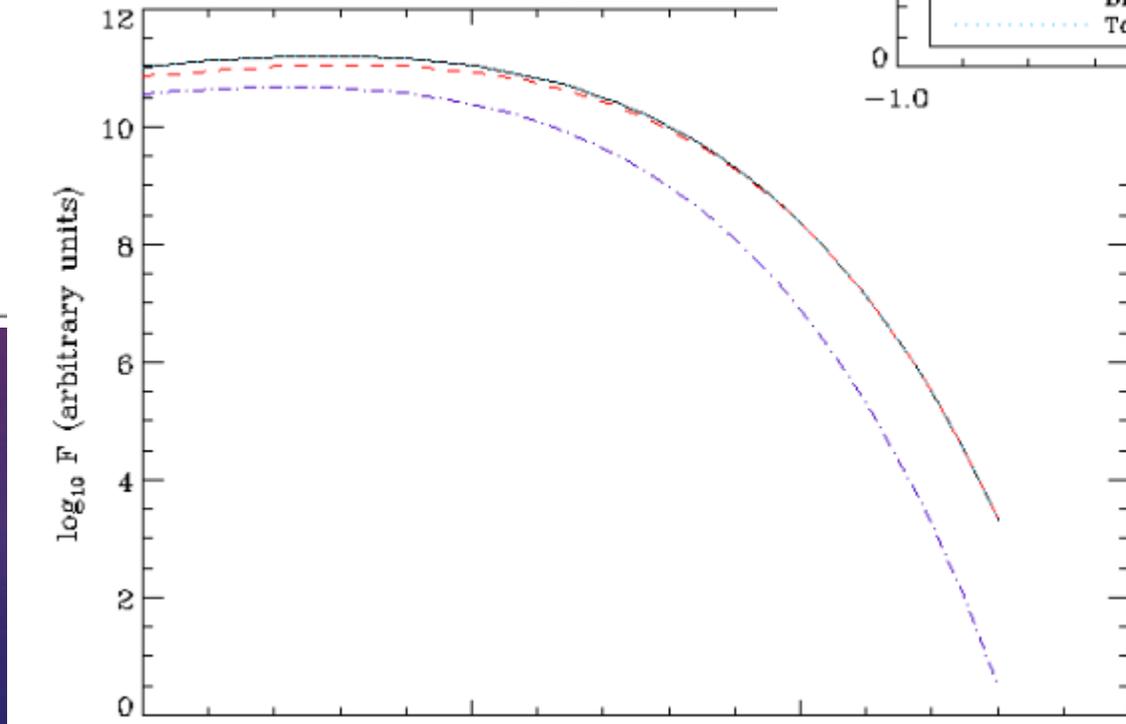
	χ	ξ	T_1 (eV)	T_2 (eV)	A_2/A_1
Pure dipole	15°	80°	72.0	57.8	1.27
Model 1	20°	80°	73.0	59.4	0.76
Model 2	25°	80°	73.5	58.1	0.36

SPECTRAL FITS

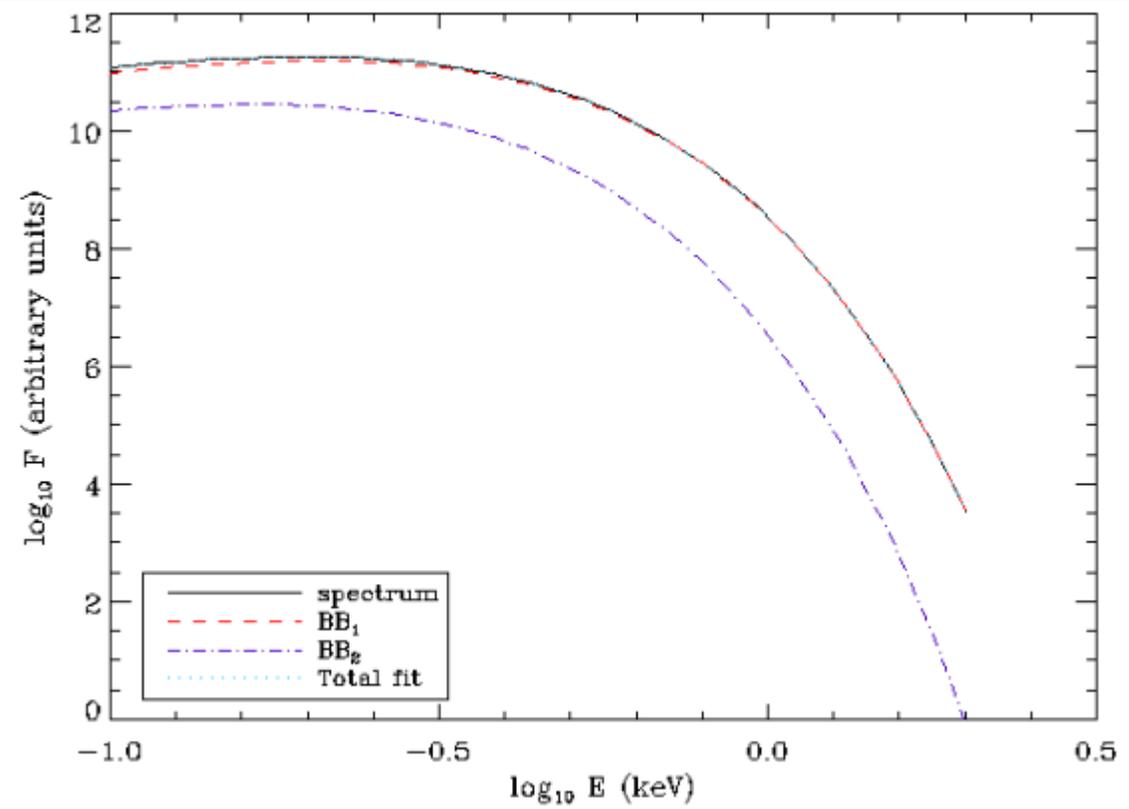


Pure dipole

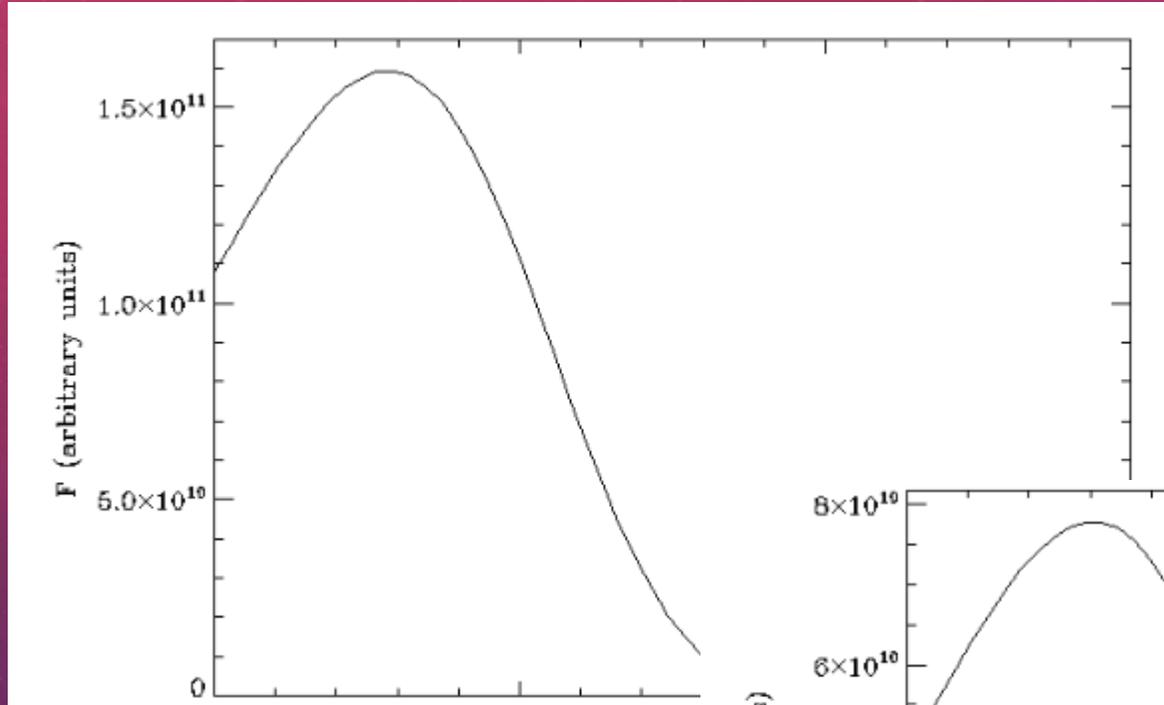
Model 1



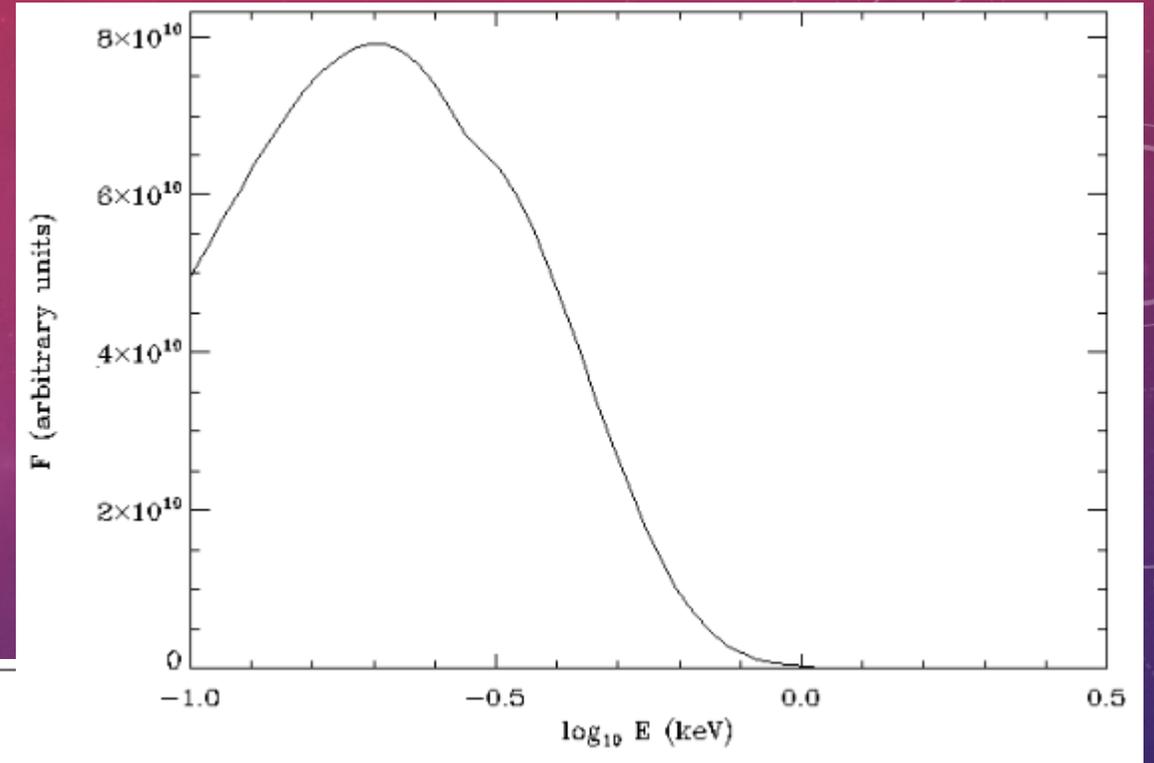
Model 2
Dipole+octupole+I5



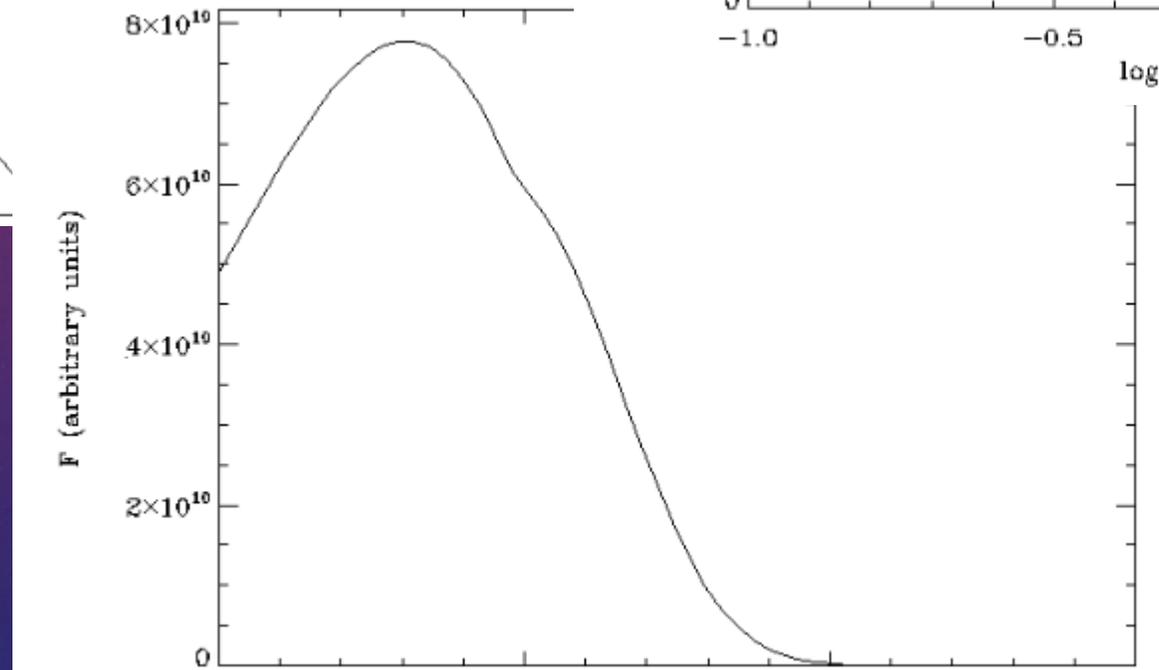
EFFECT OF SURFACE



Blackbody

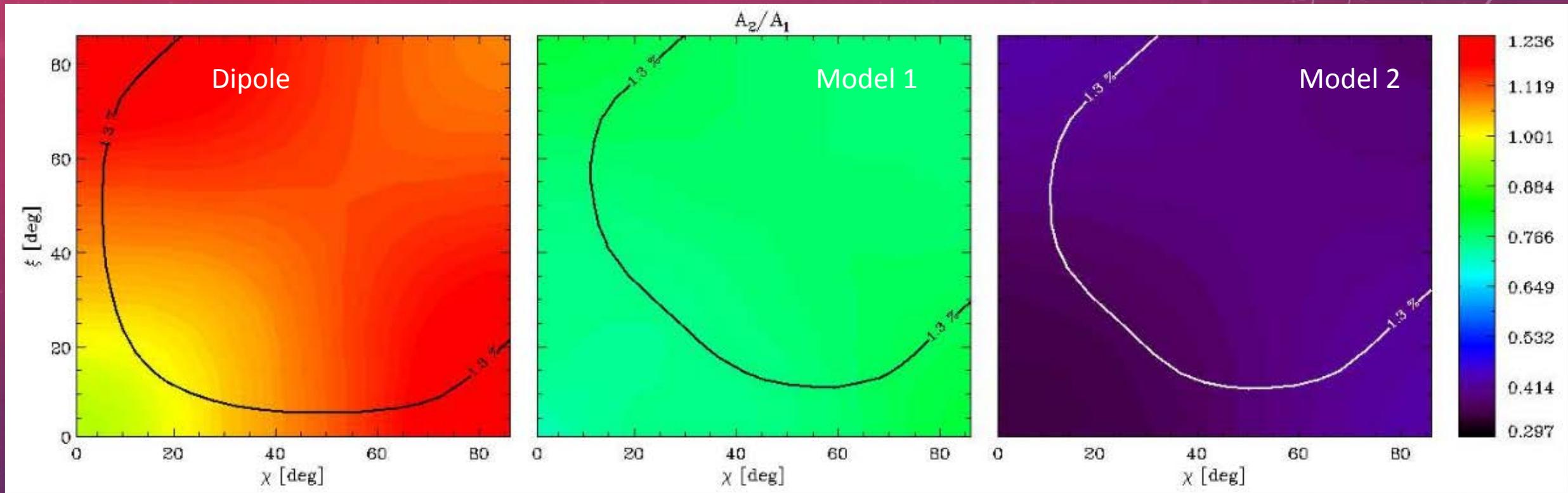


Condensed surface;
fixed ions

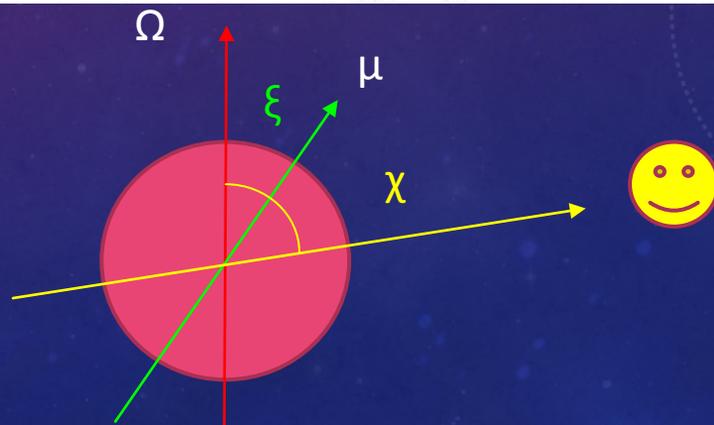


Condensed
surface;
free ions

EMITTING AREAS

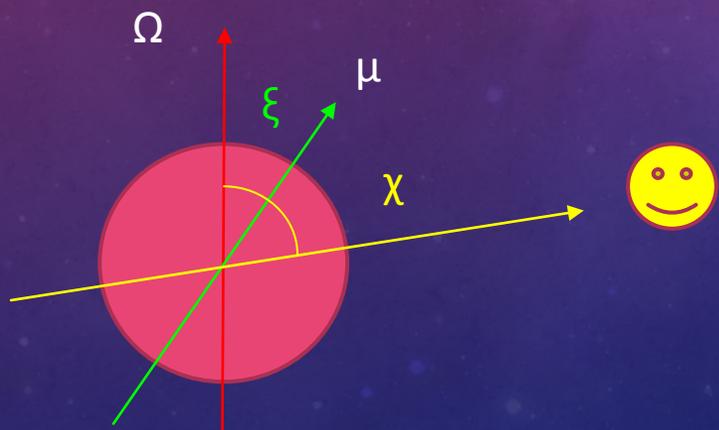
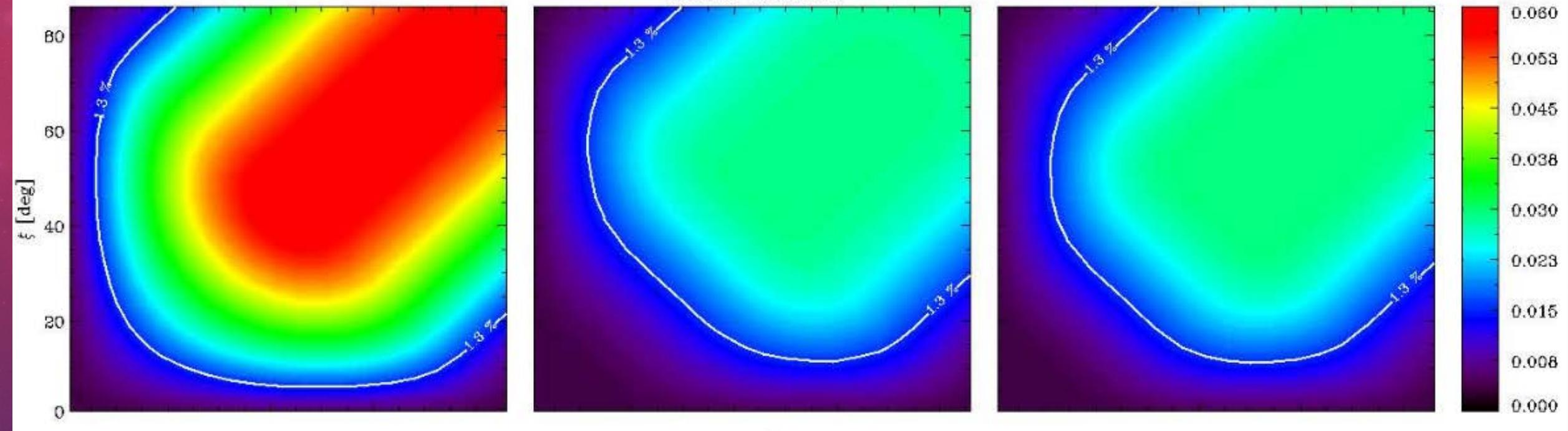


Only for dipole the emitting area corresponding to cooler region is larger.

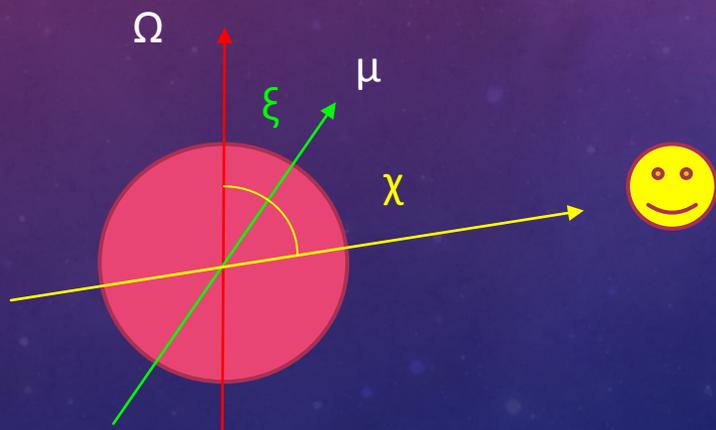
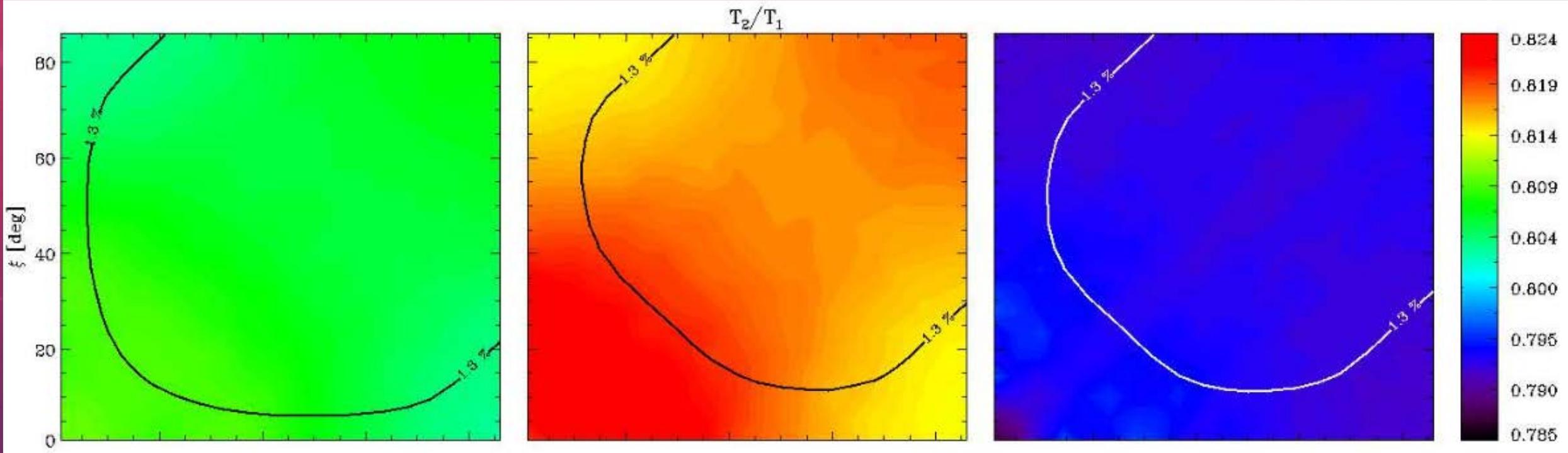


PULSED FRACTION

Pulsed fraction



TEMPERATURE RATIO



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^2_{ν}	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).

Results of modeling

	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

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.

CONCLUSIONS

- 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 from the predicted ones.

A.P. Igoshev, S.B. Popov

``Magnetic field decay in normal radio pulsars''

AN, vol. 336 pp. 831-834 (2015)

[arXiv: 1507.07962](https://arxiv.org/abs/1507.07962)

S.B. Popov, R. Taverna, R. Turolla

``Probing the surface magnetic

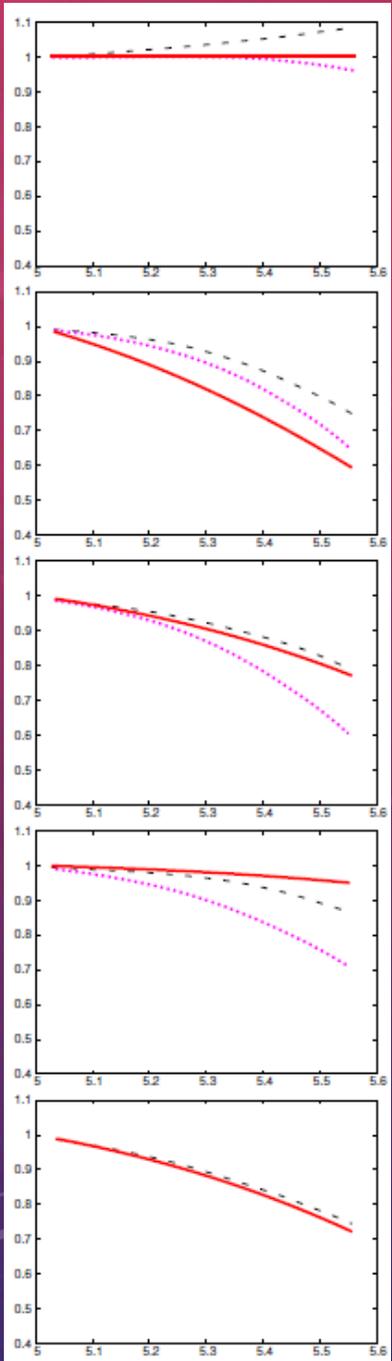
field structure in RX J1856.5-3754''

MNRAS vol. 464, 4390 (2017)

[arXiv: 1610.05050](https://arxiv.org/abs/1610.05050)

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.



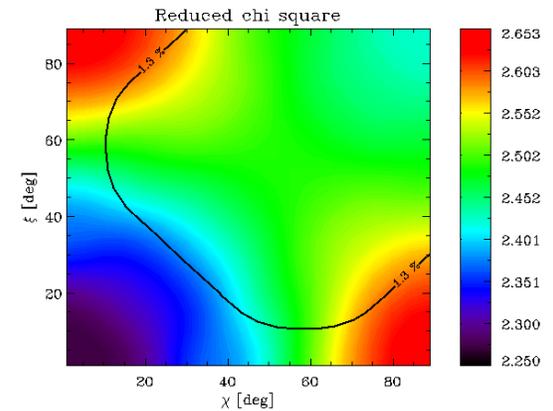
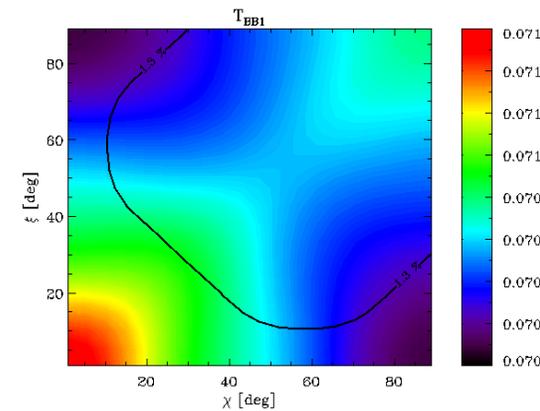
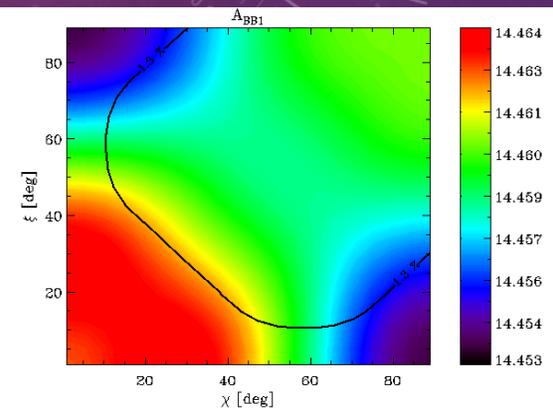
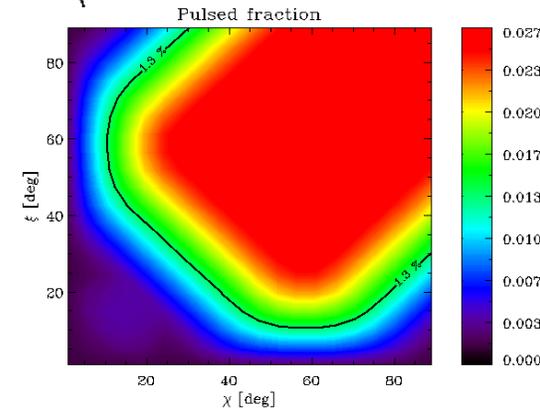
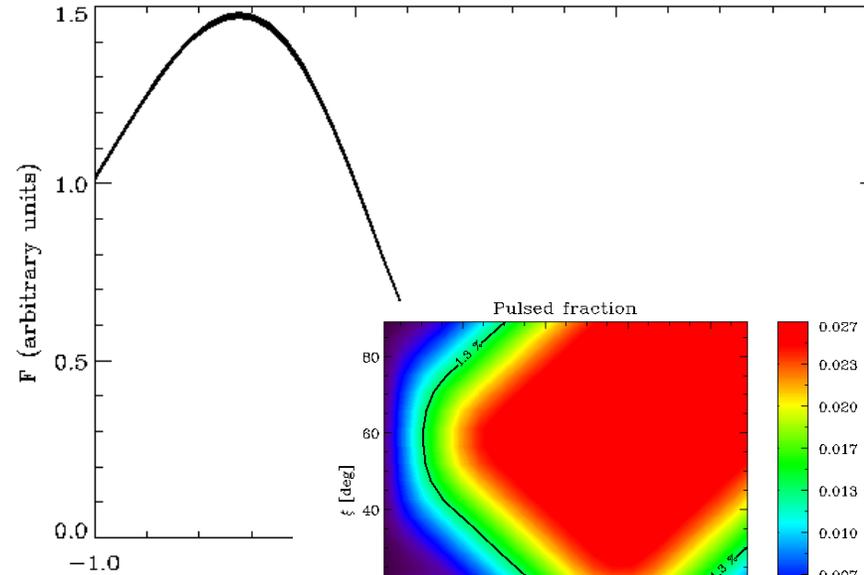
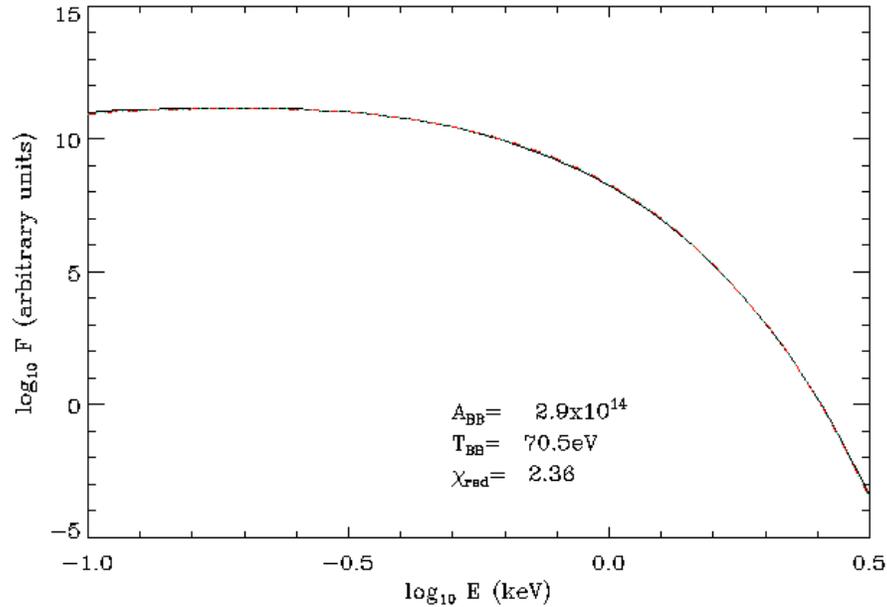
Name	$\log \mu_{B_0}$ [G]	$\log \sigma_{B_0}$ [G]	μ_{P_0} [s]	σ_{P_0} [s]	α	τ_D [Myr]	τ_{SDA} [Myr]
A1	12.60	0.47	0.33	0.23	0.50	∞	∞
A2	12.95	0.55	0.30	0.15	0.50	∞	10
B1	12.60	0.47	0.33	0.23	0.50	0.5	1.00
B2	12.95	0.55	0.30	0.15	0.50	0.5	0.690
C1	12.60	0.47	0.33	0.23	0.50	1	1.15
C2	12.95	0.55	0.30	0.15	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)

FURTHER REFERENCES

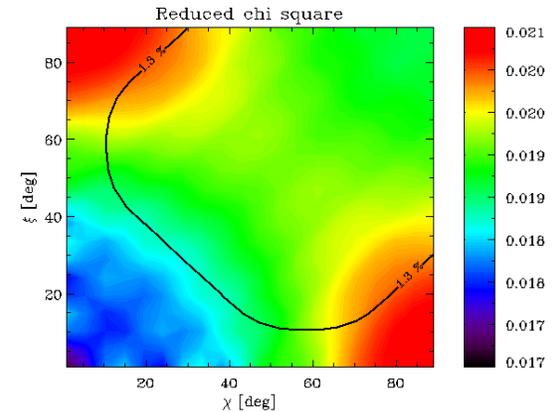
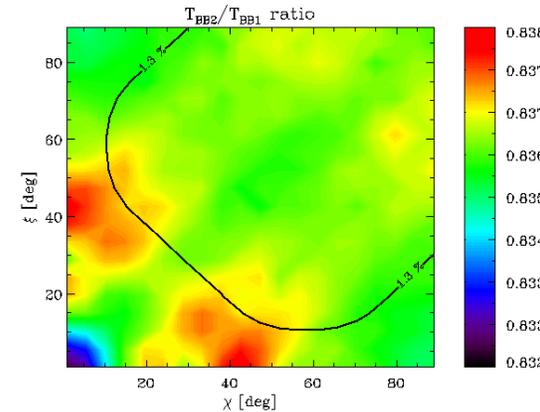
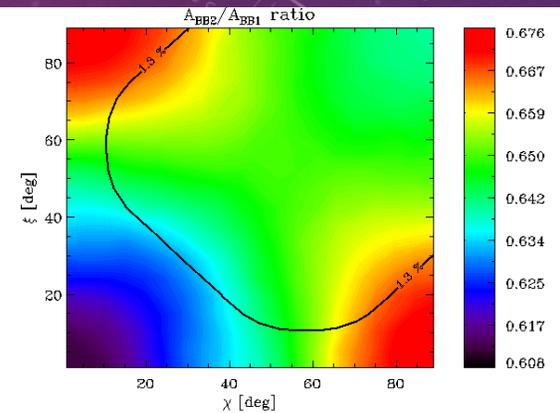
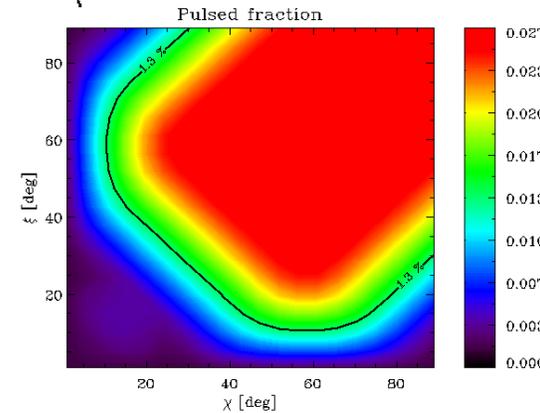
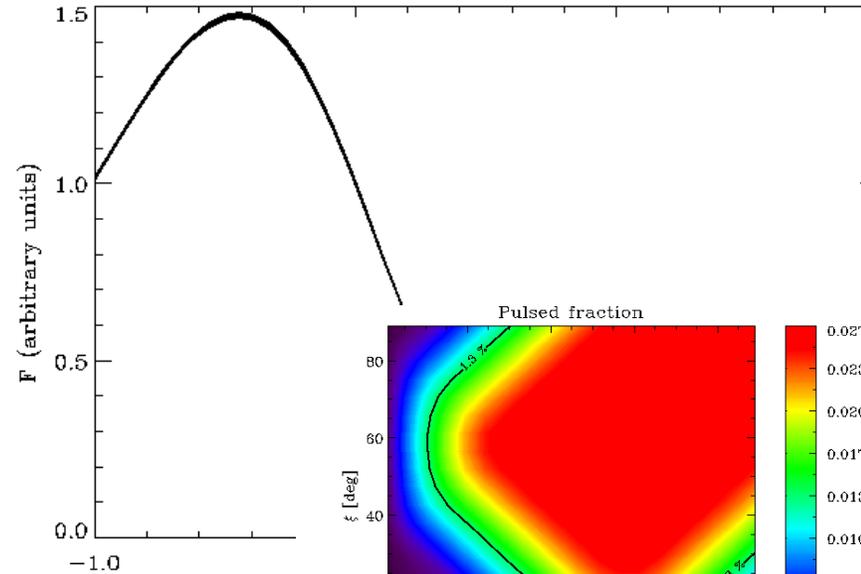
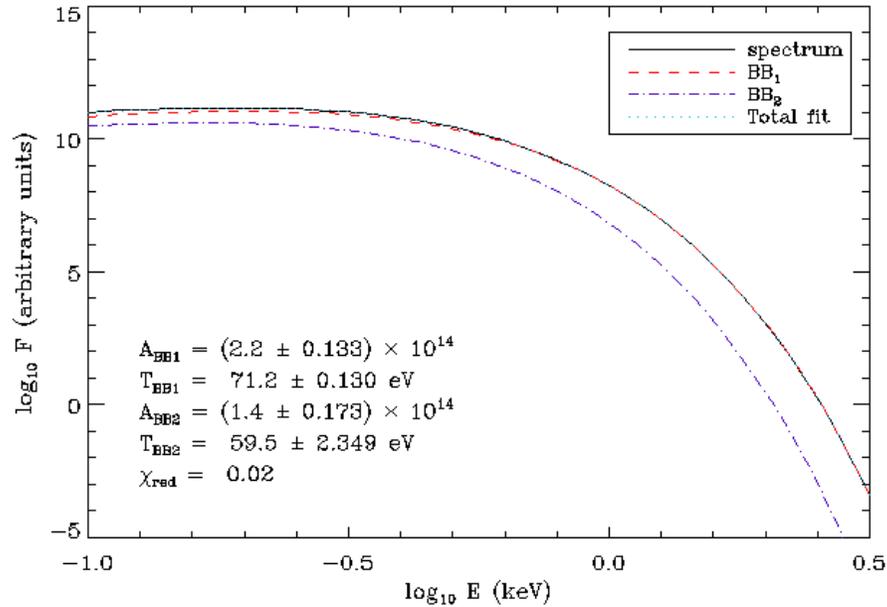
- 1105.4178 Kaplan et al. Optical and UV properties of the M7
- 1509.05023 Taverna et al. Calculation of surface emission (with polarization)
-

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