EVOLUTION OF NEUTRON STARS: LOOKING FOR HALL ATTRACTOR IN KNOWN NEUTRON STARS

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1710.09190

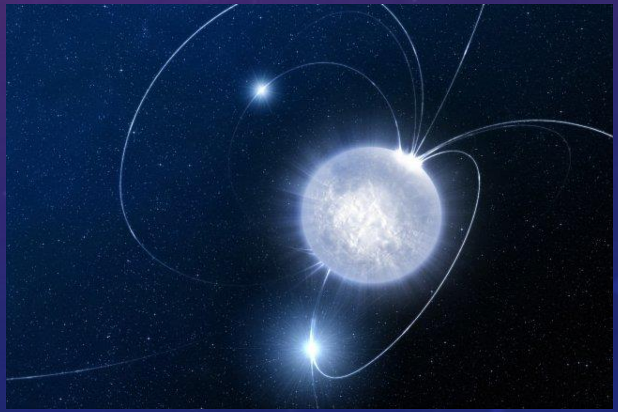
EVOLUTION OF NEUTRON STARS

Thermal

Magneto-rotational

Observational appearence of a NS can depend on:

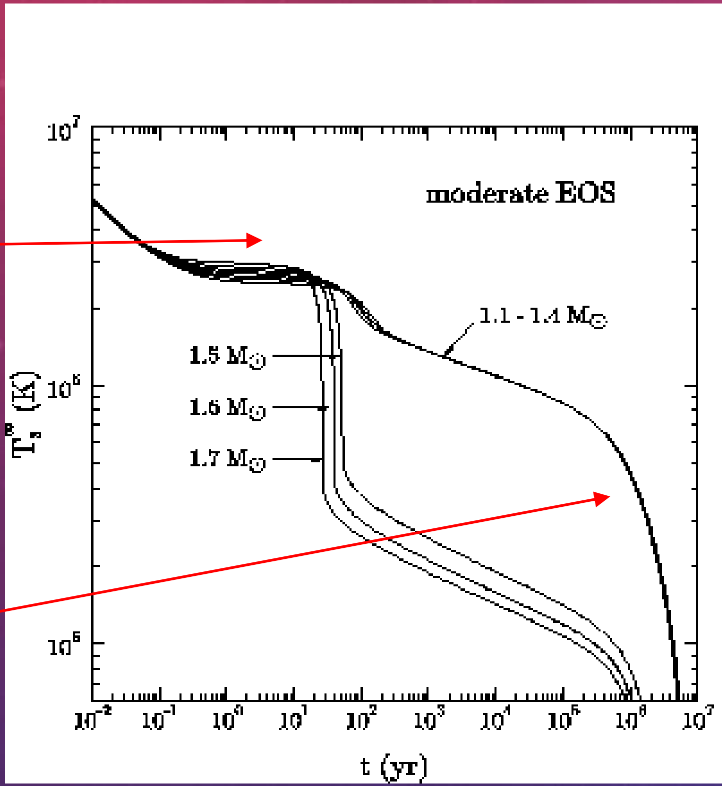
- Temperature
- Period
- Magnetic field
- Velocity

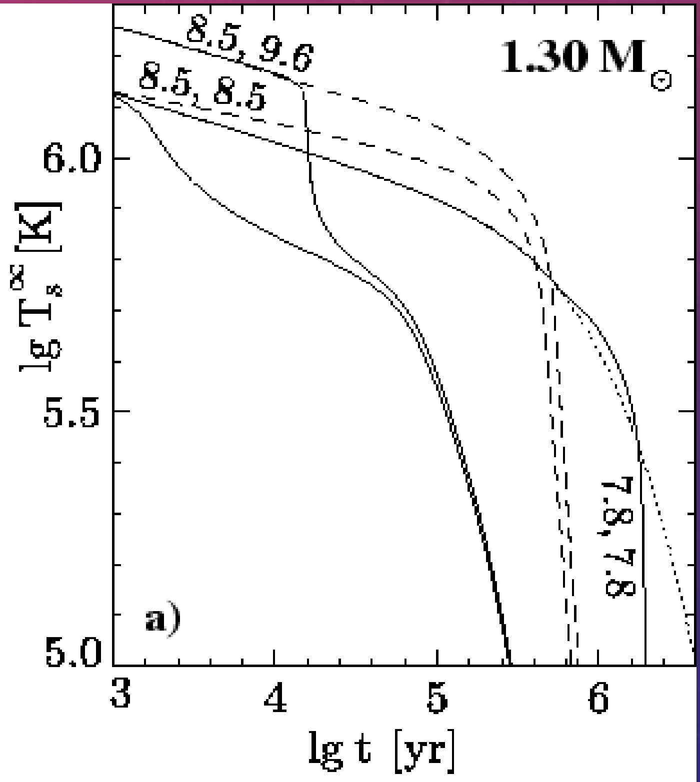


EVOLUTION OF NSS: TEMPERATURE

Neutrino cooling stage

Photon cooling stage



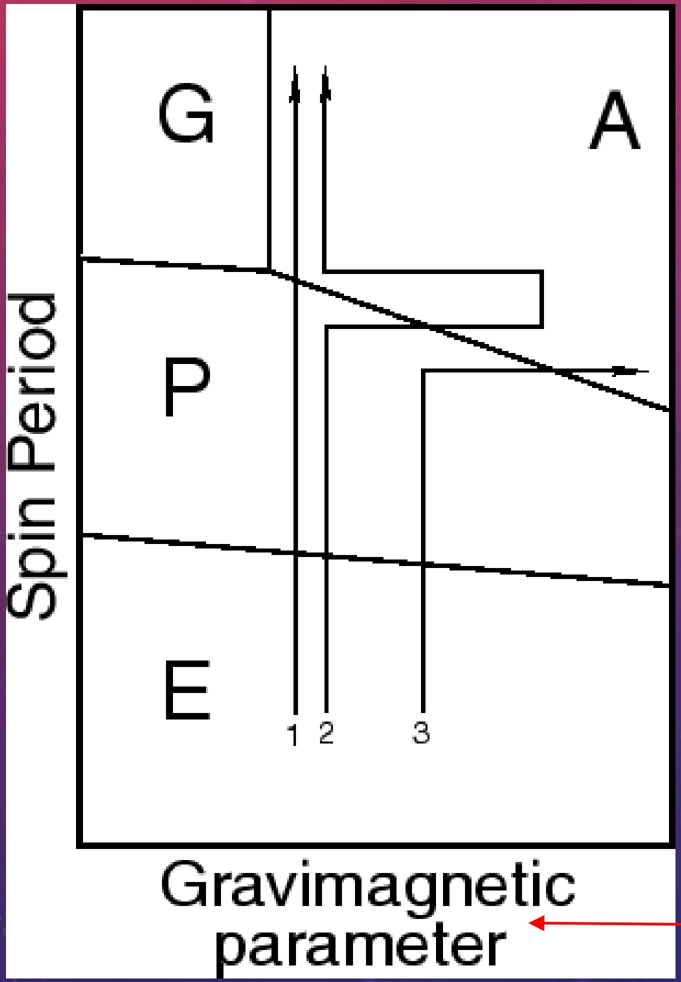


First papers on the thermal evolution appeared already in early 60s, i.e. before the discovery of radio pulsars.

[Yakovlev et al. (1999) Physics Uspekhi]

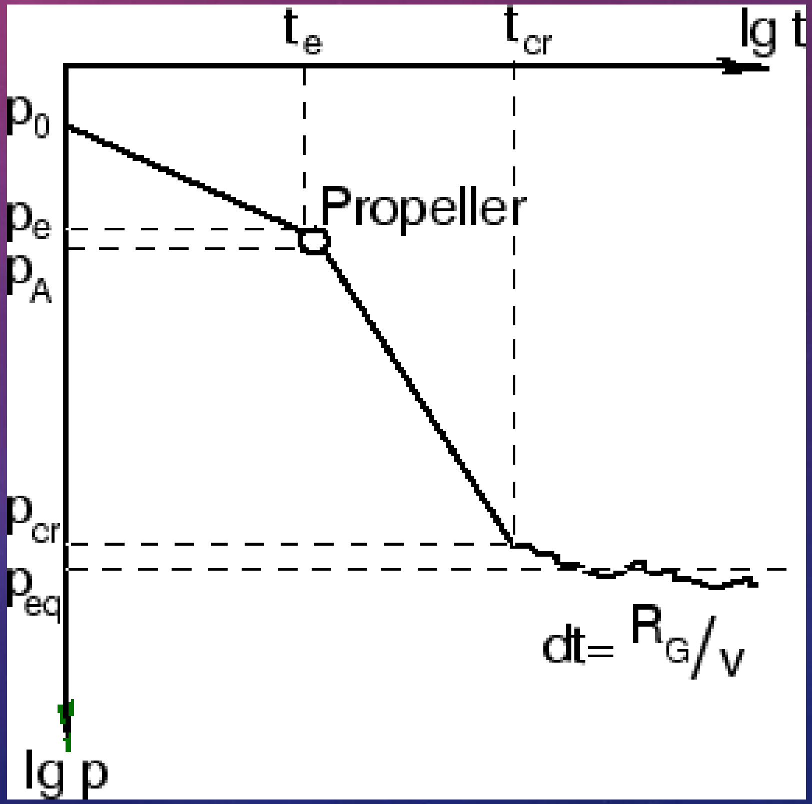
EVOLUTION OF NEUTRON STARS: ROTATION + MAGNETIC FIELD

Ejector → Propeller → Accretor → Georotator



$\dot{M}/\mu^2$

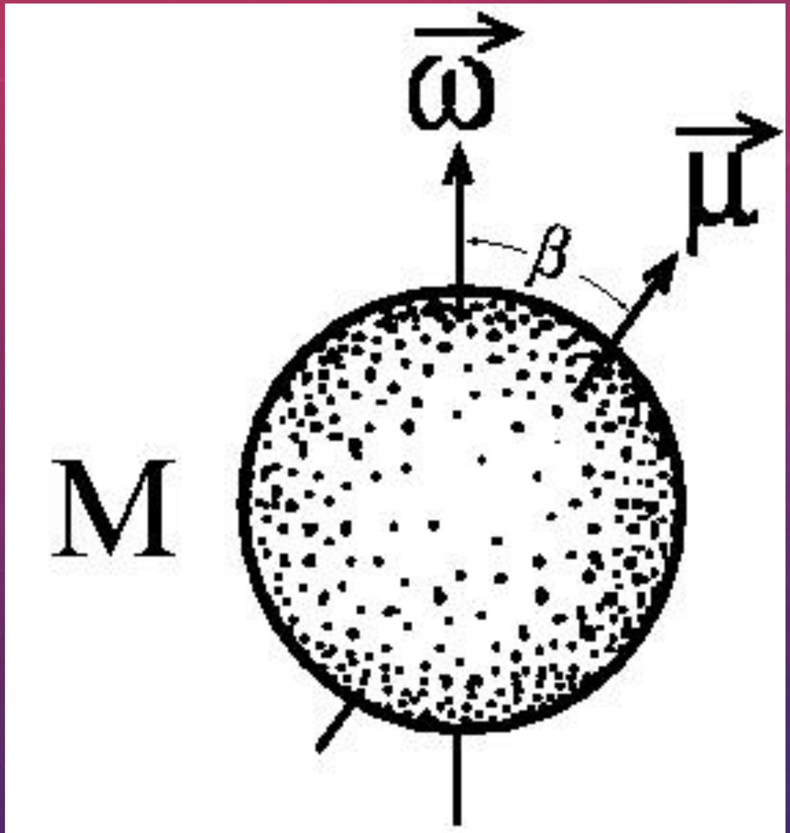
1 – spin down
2 – passage through a molecular cloud
3 – magnetic field decay



astro-ph/0101031

See the book by Lipunov (1987, 1992)

MAGNETIC ROTATOR

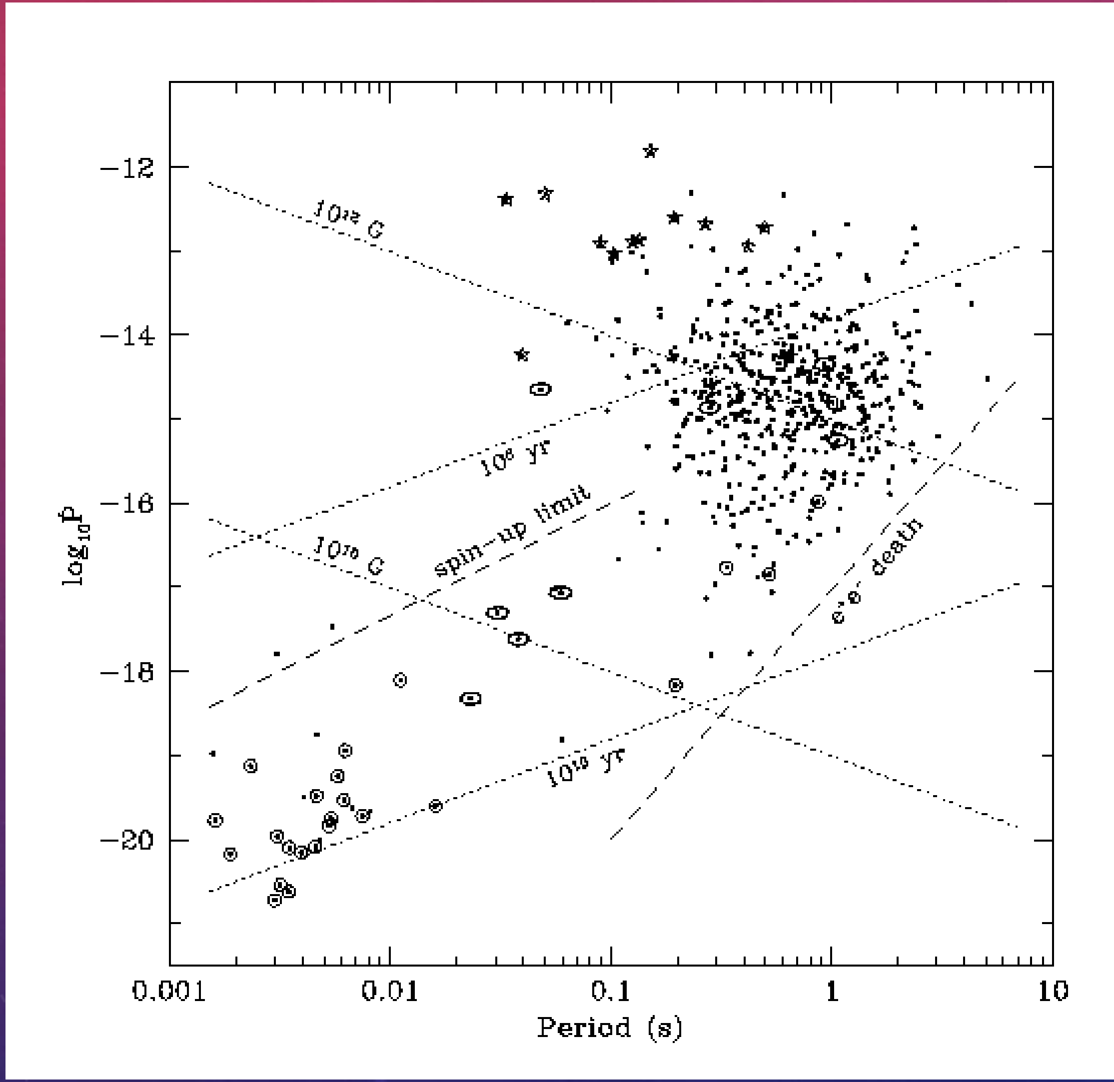


Observational appearances of NSs
(if we are not speaking about cooling)
are mainly determined by P, Pdot, V, B,
(and, probably, by the inclination angle χ),
and properties of the surrounding medium.
B is not evolving significantly in most cases,
so it is important to discuss spin evolution.

Together with changes in B (and χ)
one can speak about
magneto-rotational evolution

We are going to discuss the main stages
of this evolution, namely:
Ejector, Propeller, Accretor, and *Georotator*
following the classification by Lipunov

MAGNETO-ROTATIONAL EVOLUTION OF RADIO PULSARS



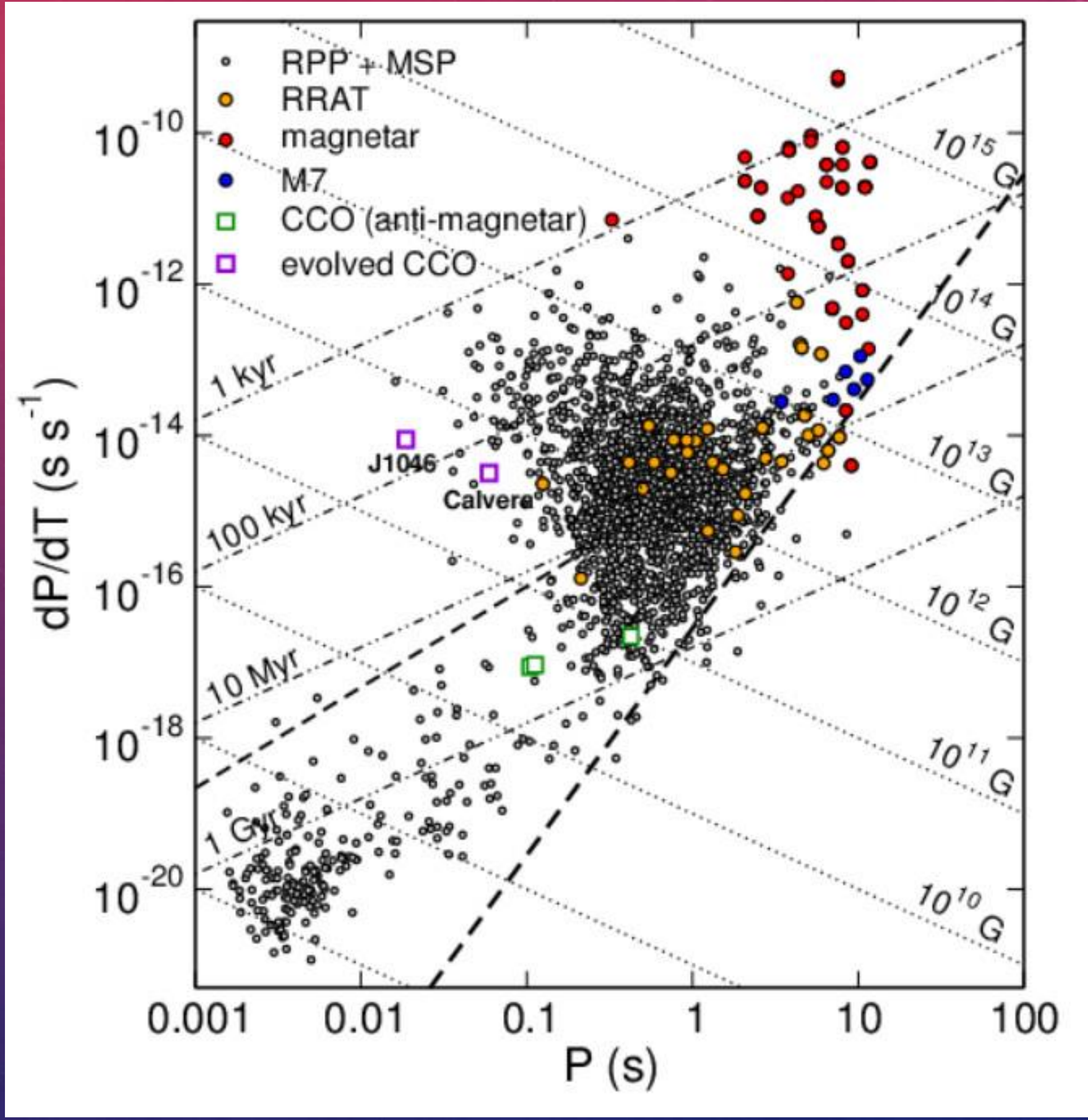
For radio pulsar magneto-rotational evolution is usually illustrated in the P-Pdot diagram.
However, we are interested also in the evolution after this stage.

$$L_m = \frac{2}{3}\frac{\mu^2\omega^4}{c^3}\sin^2\beta = \kappa_t\frac{\mu^2}{R_l^3}\omega\,,$$

$$B \sim 3.2 \times 10^{19}\,(PdP/dt)^{1/2}\ \mathrm{G}.$$

Spin-down.
Rotational energy is released.
The exact mechanism is still unknown.

DIVERSITY OF NEUTRON STARS

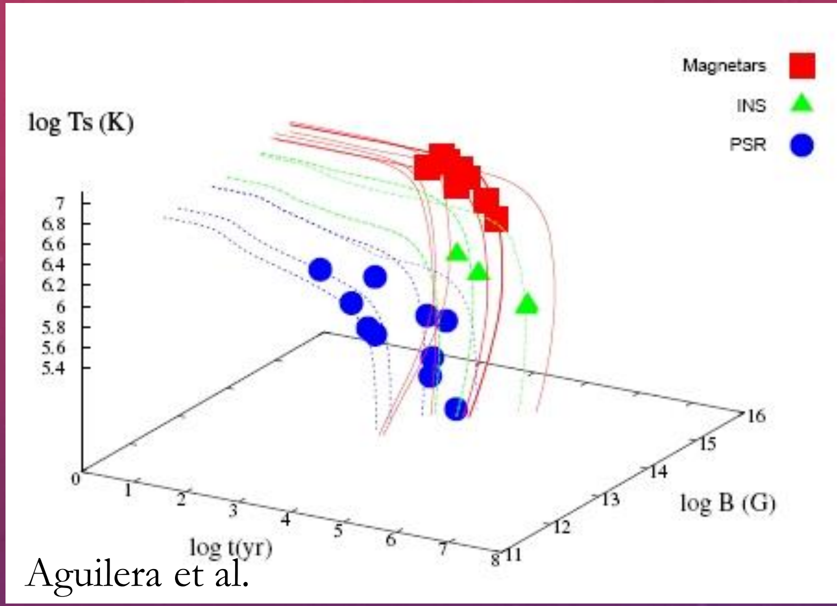


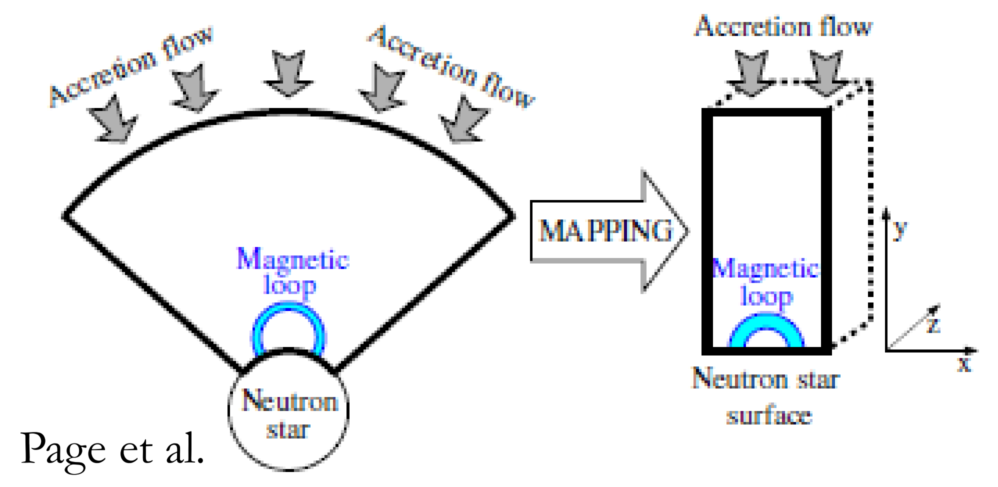
Pires et al. 2015

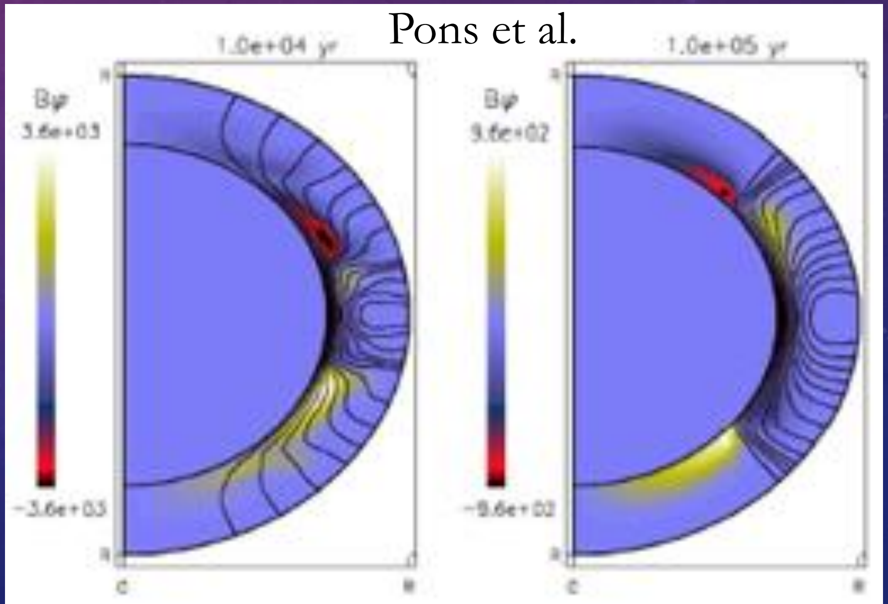
The term "GRAND UNIFICATION FOR NEUTRON STARS" was coined by Kaspi (2010)

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

THREE MAIN INGREDIENTS OF A UNIFIED MODEL

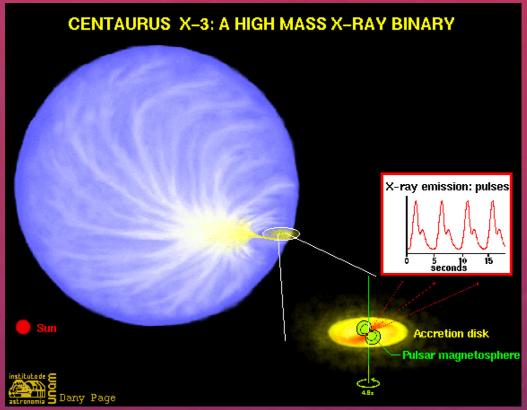




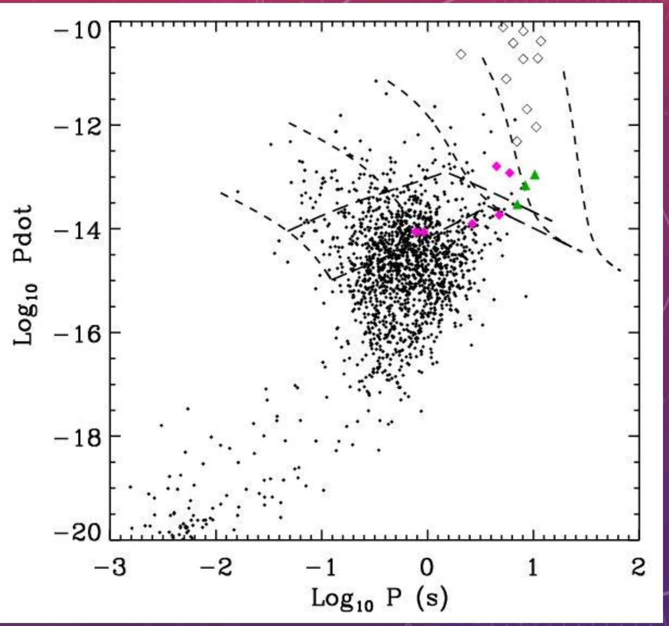


- Field decay
  - Emerging magnetic field
    - Toroidal magnetic field

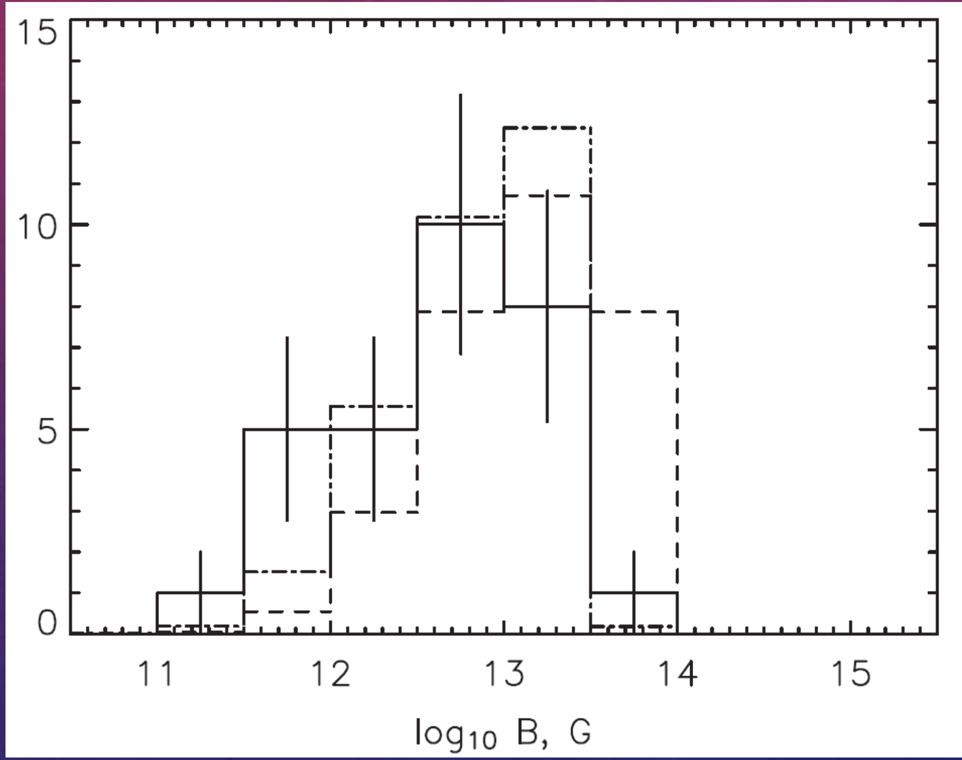
FIELD DECAY IN HMXBS

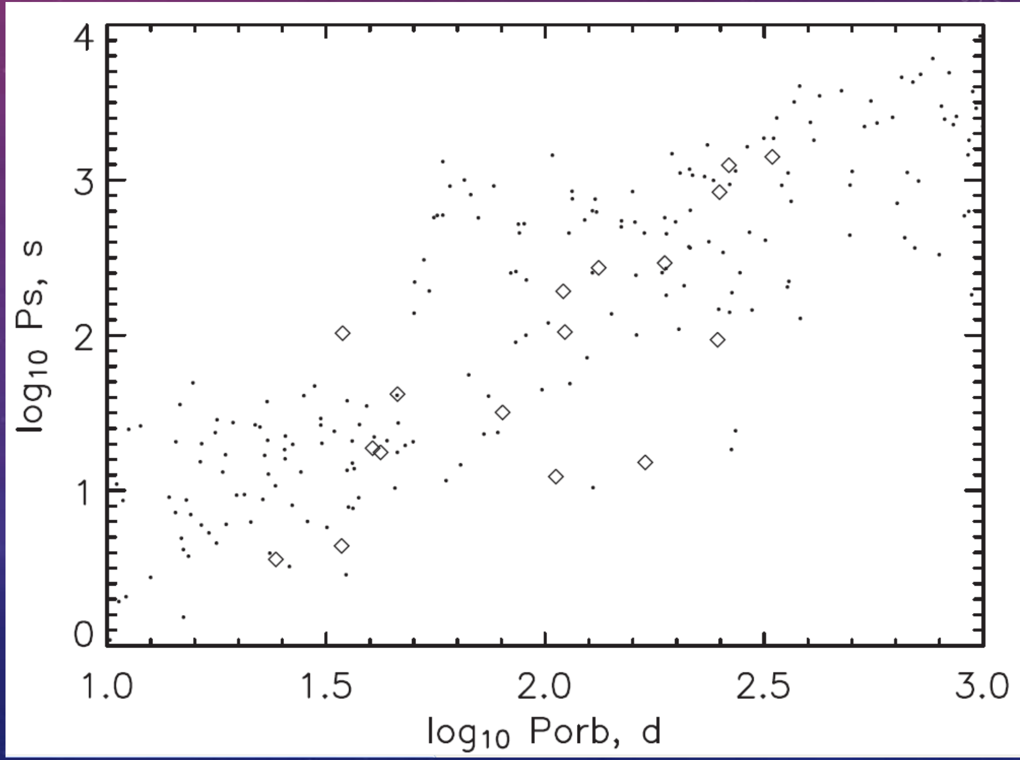


It is possible to use HMXBs to test models of field decay on time scale >1 Myr (Chashkina, Popov 2012).
We use observations of Be/X-ray binaries in SMC to derive magnetic field estimates, and compare them
with prediction of the Pons et al. model.



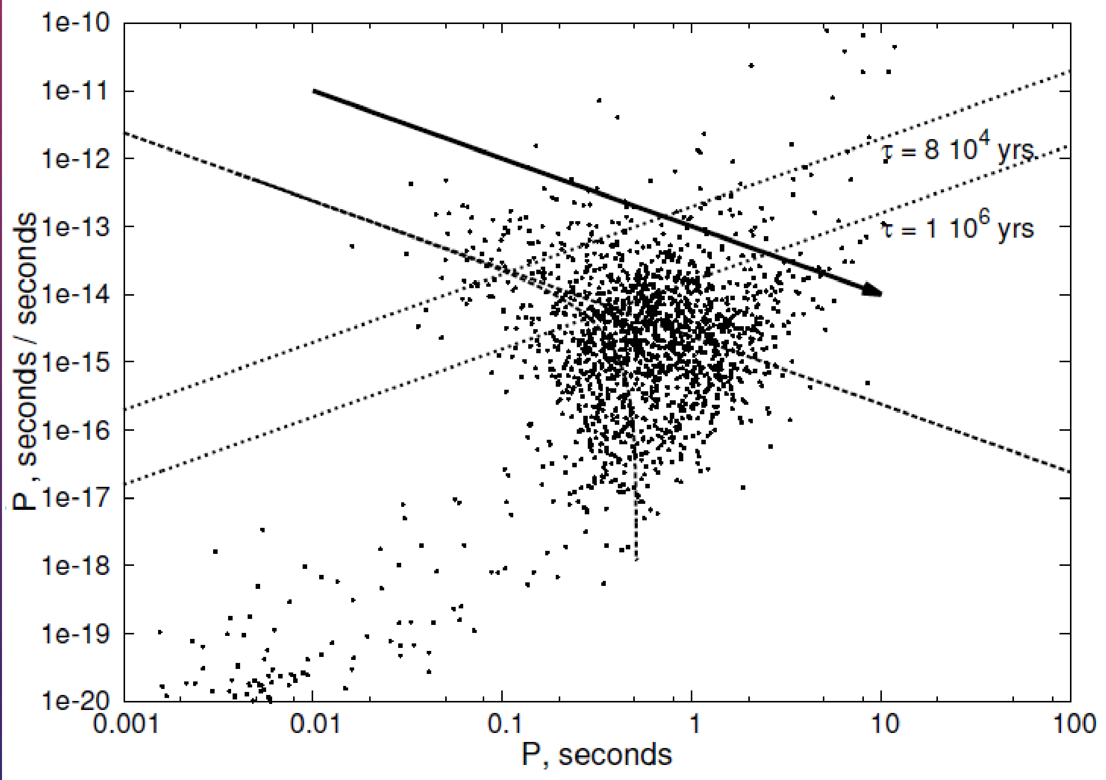
Chashkina, Popov (2012)





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.

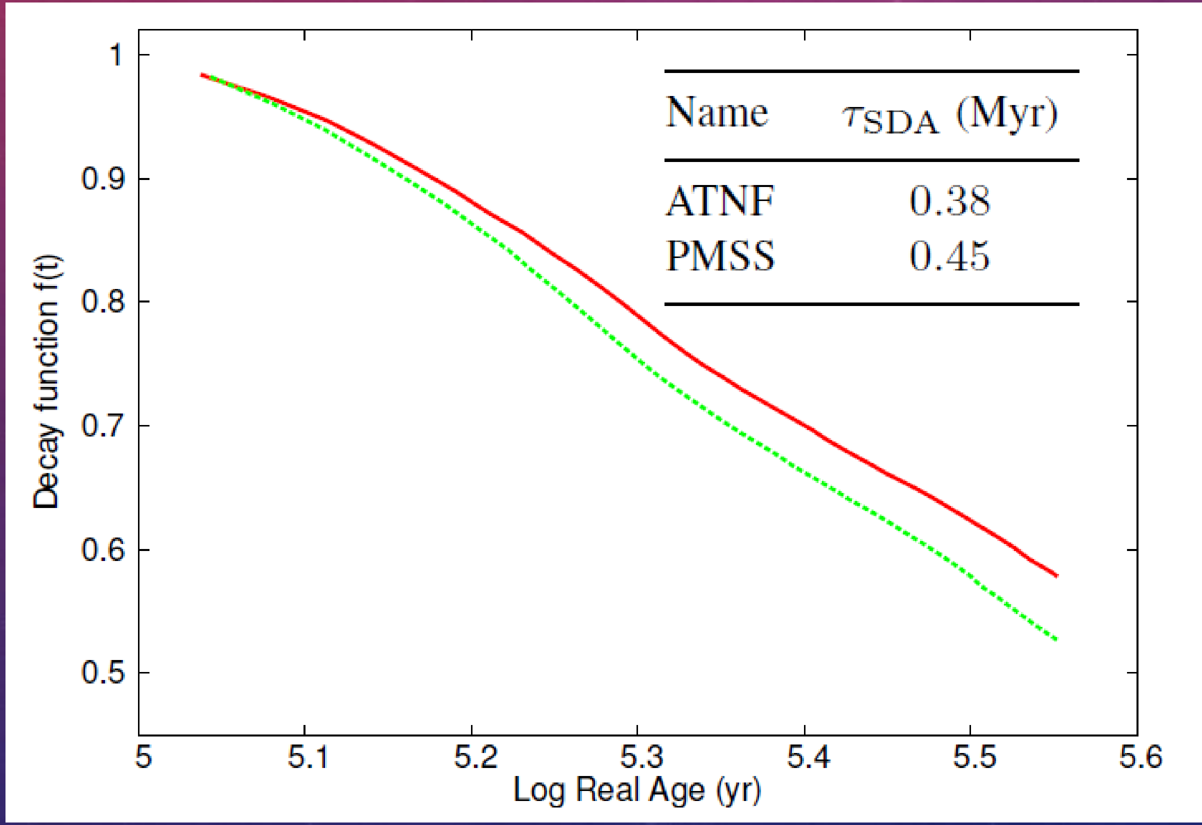
We use distribution in characteristic ages to reconstruct the field evolution.

Igoshev, Popov (2014). arXiv:1407.6269

DATA ANALYSIS

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:
$8\ 10^4 < t < 3.5\ 10^5$ 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.

WHAT KIND OF DECAY DO WE SEE?

Ohmic decay due to phonons

Hall cascade

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

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.

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.

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

Ohmic decay depends on the conductivity

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

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

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

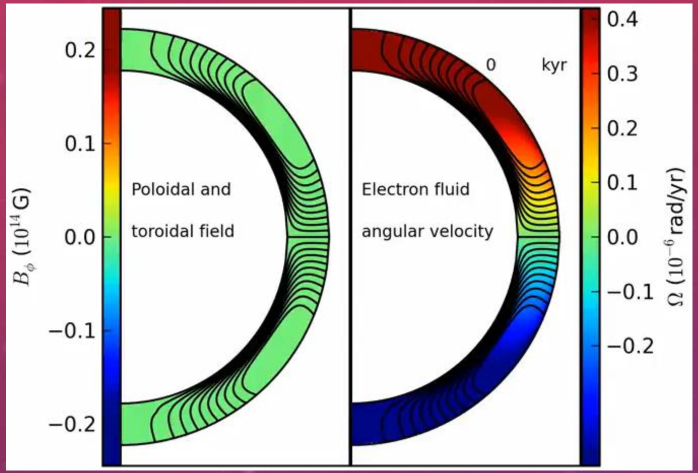
$$Q = n_{\rm ion}^{-1}\Sigma_i n_i \times (Z^2 - \langle Z\rangle^2).$$

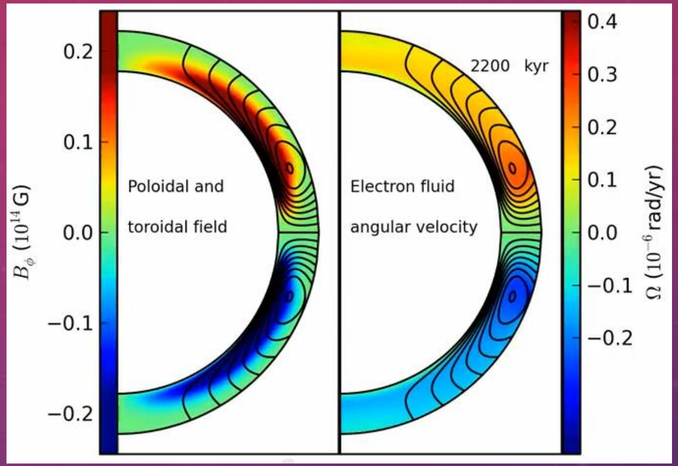
Resistivity can be due to

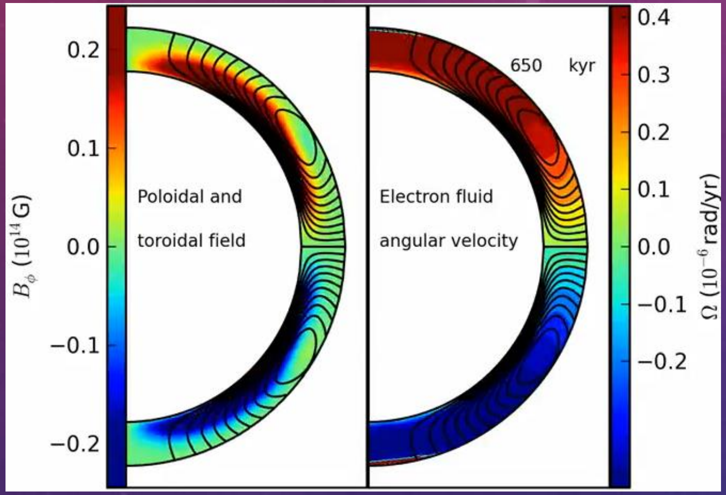
- Phonons
- Impurities

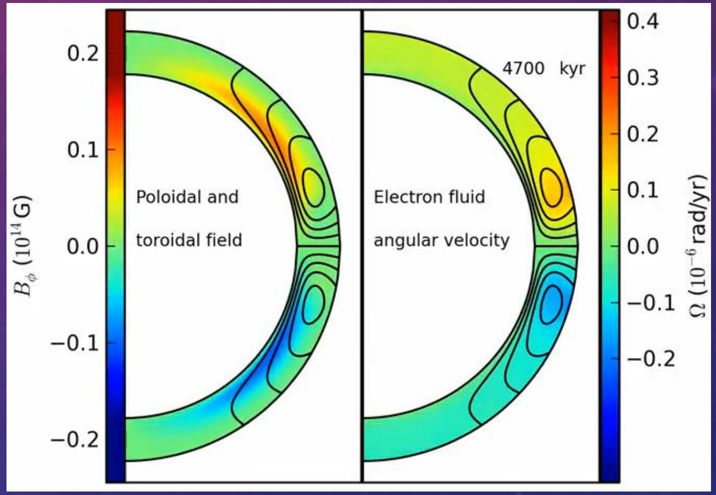
$$\sigma_{\rm ph} = 1.8\times 10^{25}{\rm s}^{-1}\left(\frac{\rho_{14}^{7/6}}{T_8^2}\right)\left(\frac{Y_e}{0.05}\right)^{5/3},$$

HALL CASCADE AND ATTRACTOR









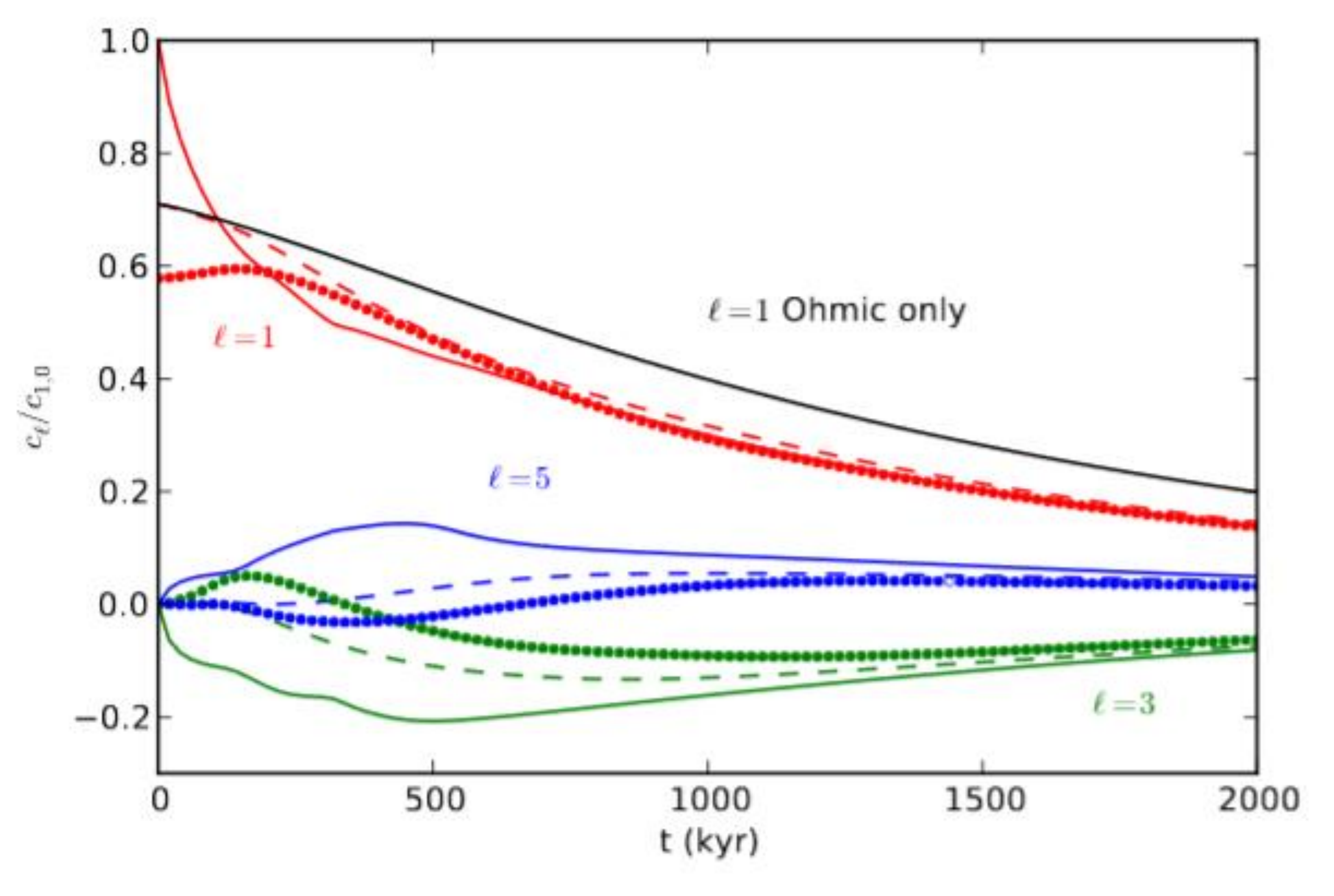
Gourgouliatos and Cumming 2013

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

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

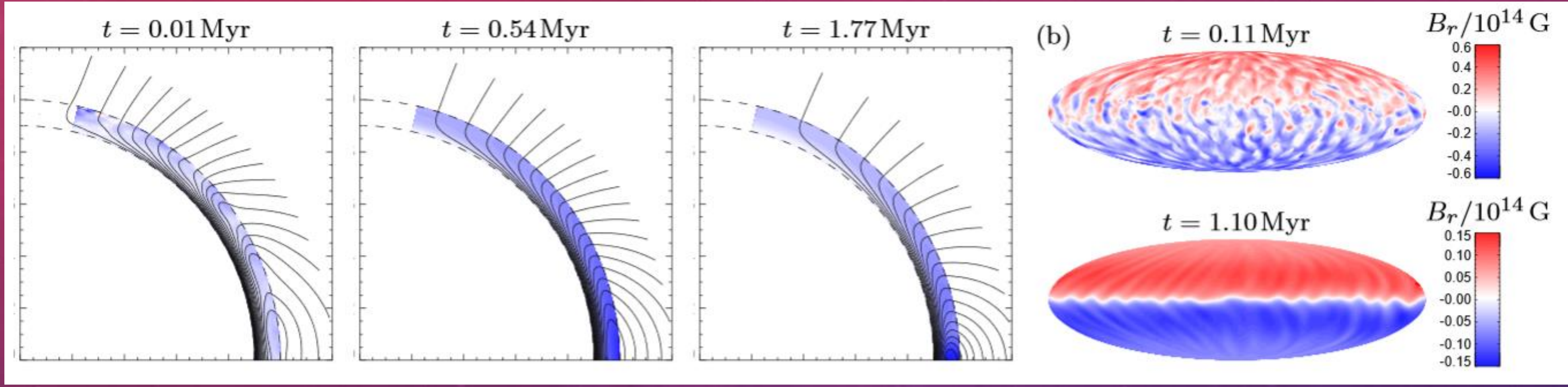
EVOLUTION OF DIFFERENT COMPONENTS

1311.7004

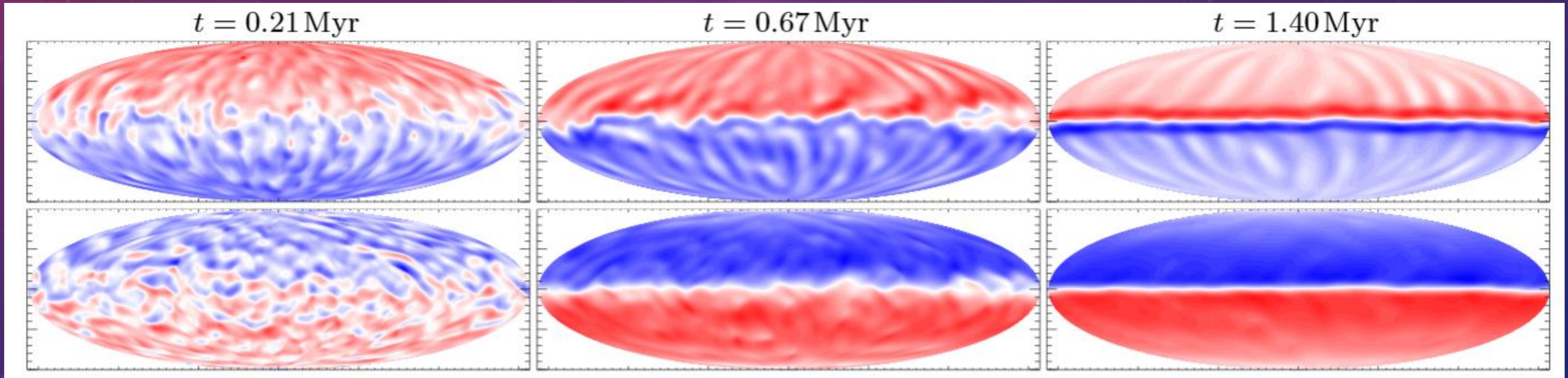


Hall attractor mainly consists of dipole and octupole (+l5)

NEW STUDIES OF THE HALL CASCADE

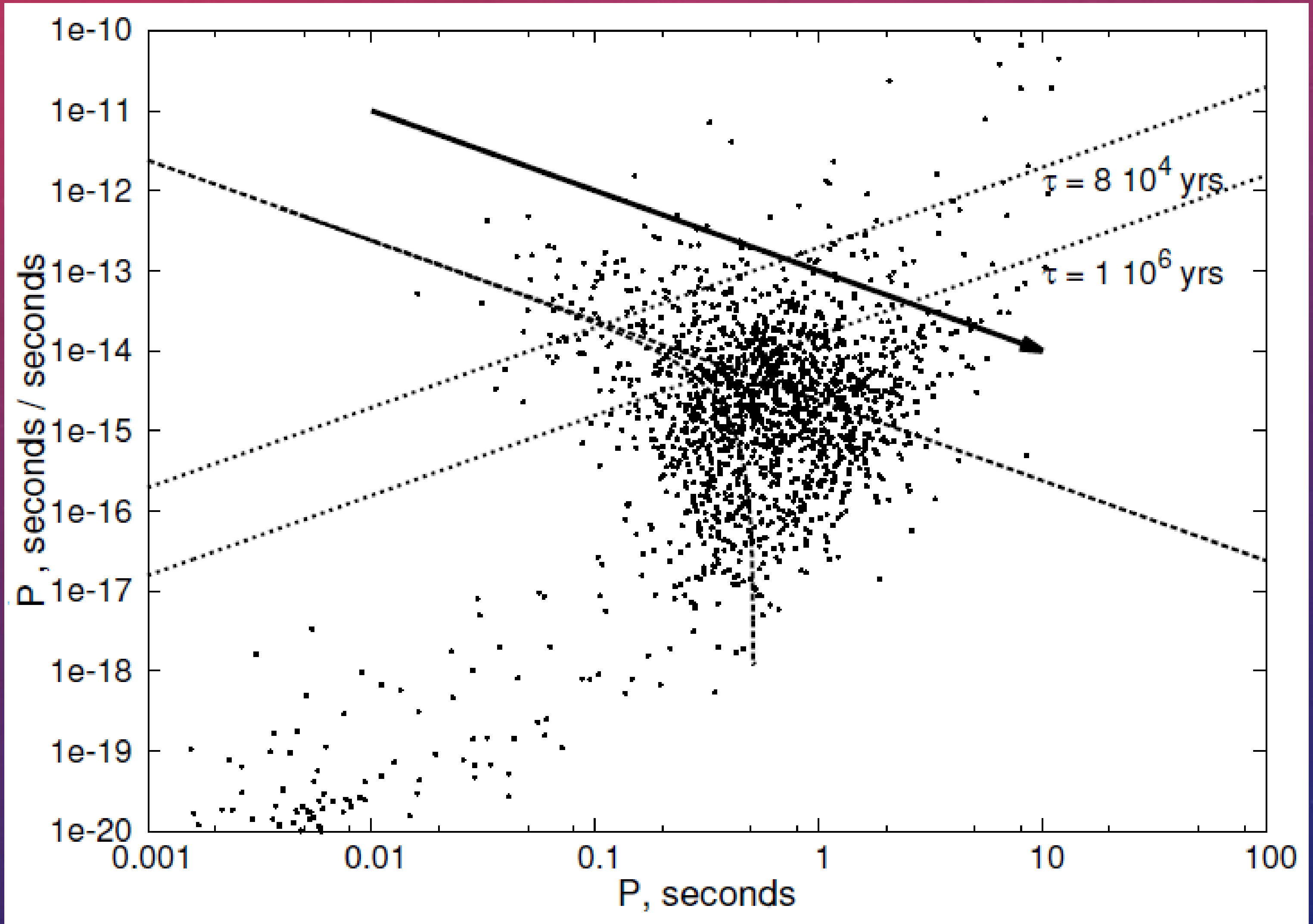


1501.05149



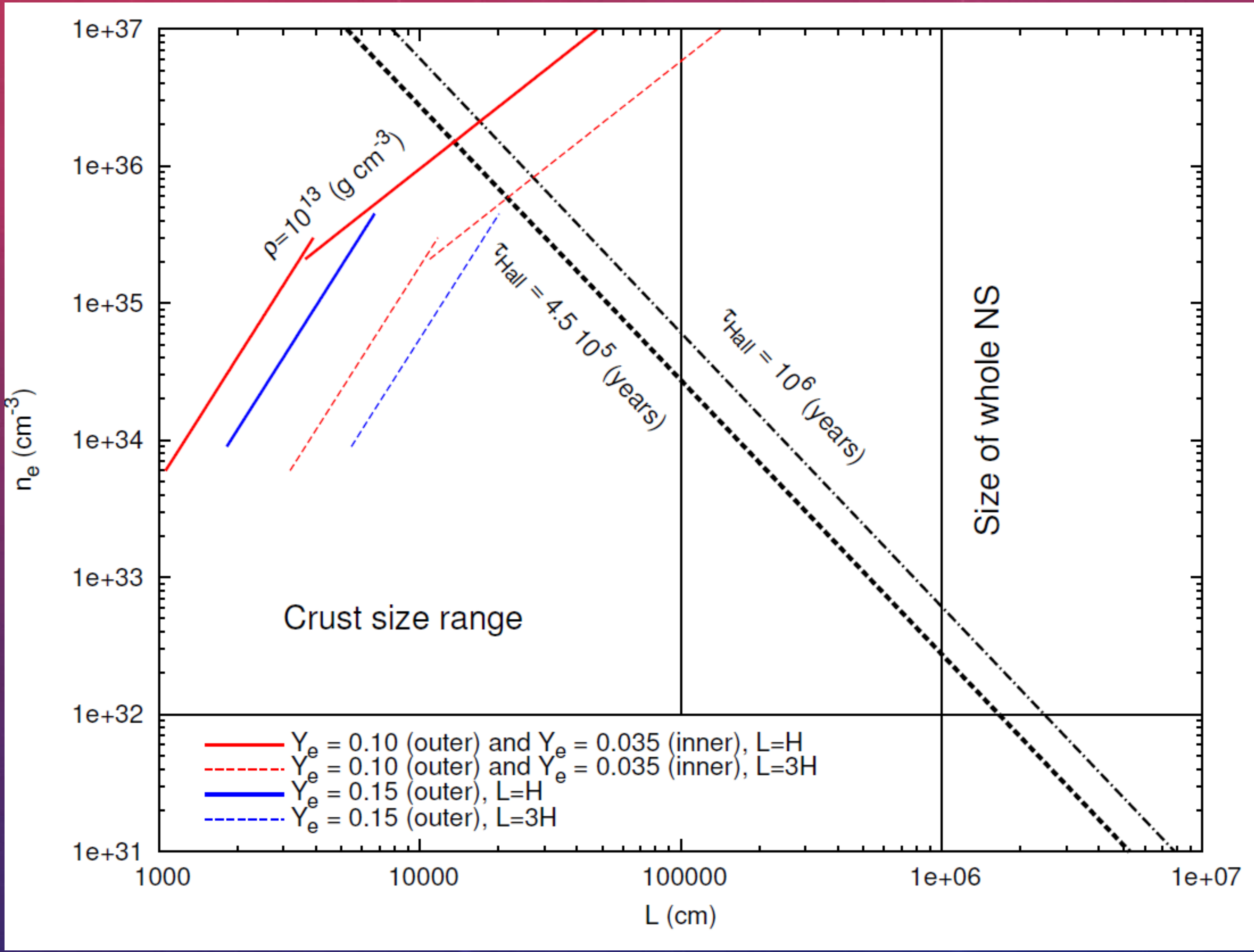
New calculations support the idea of a kind of stable configuration.

CAN WE SEE THE HALL ATTRACTOR ???



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

WHERE THE CURRENTS ARE LOCATED?



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

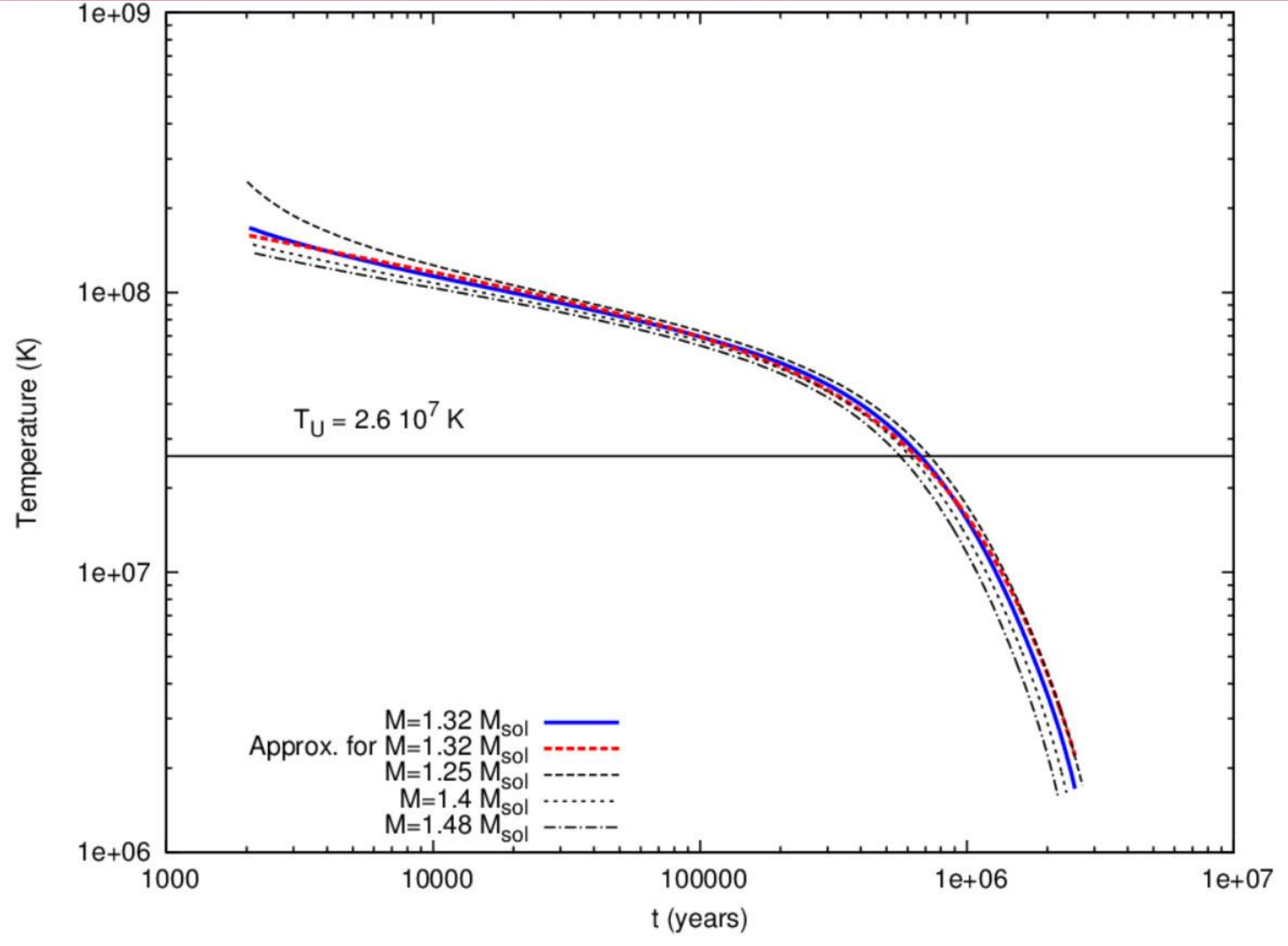
$$L \approx H = P(\rho)/(\rho g)$$

Igoshev, Popov (2015). [arXiv: 1507.07962]

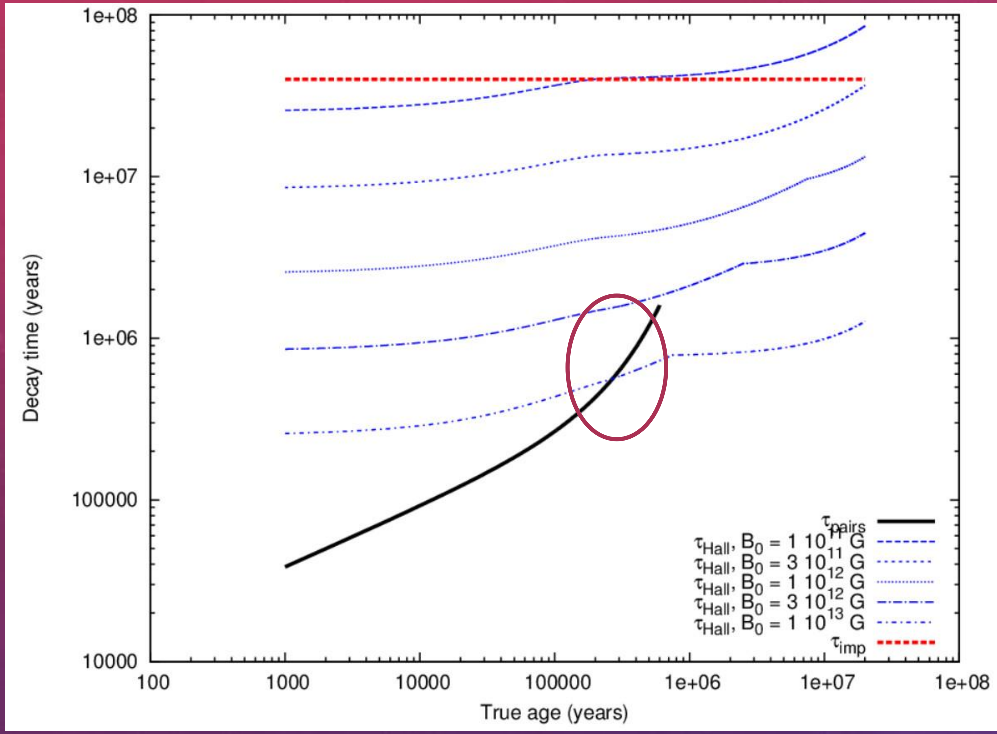
THERMAL EVOLUTION

Calculations are made by Shternin et al.

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



DIFFERENT DECAY TIME SCALES



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

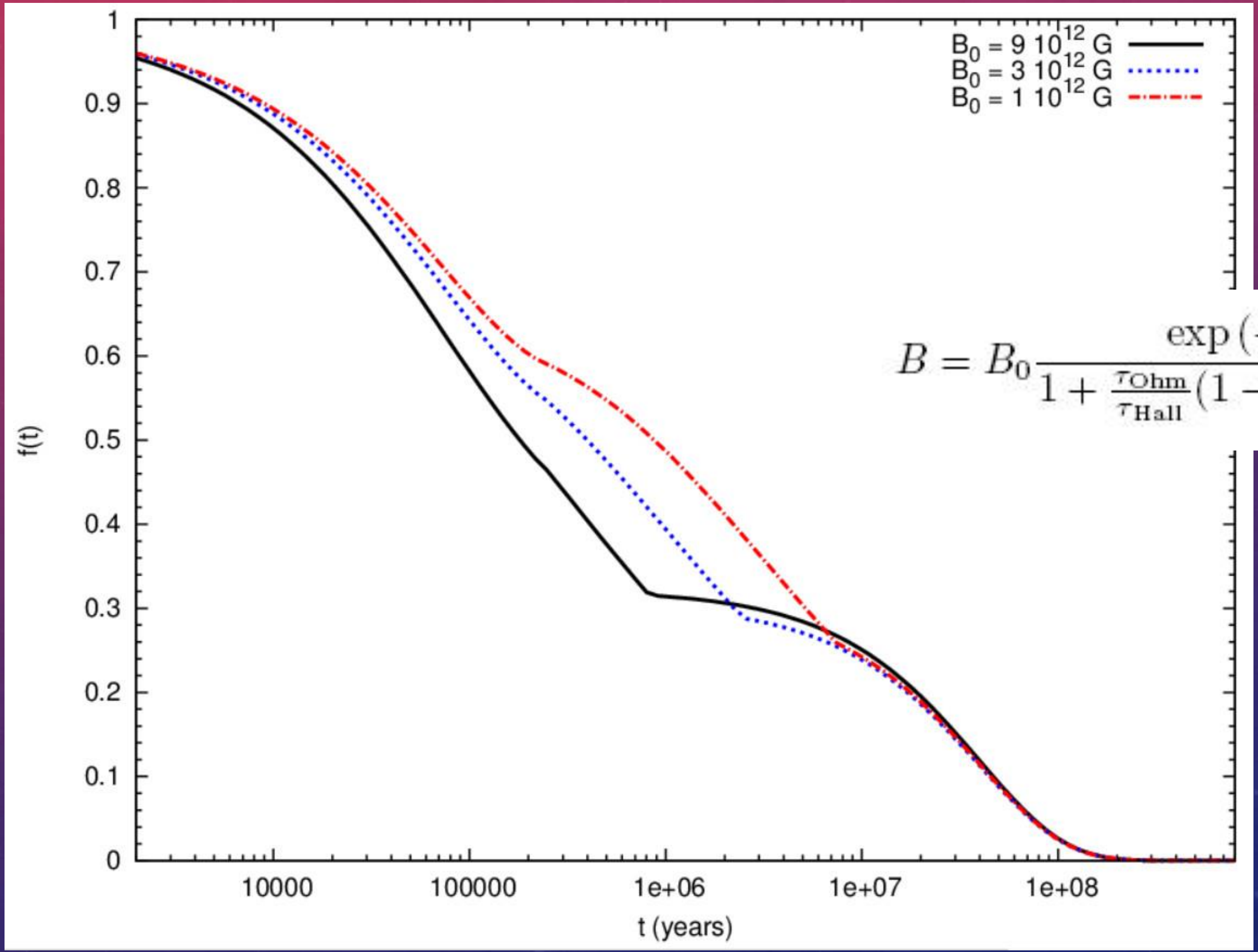
$$B = B_0 \frac{\exp\left(-t/\tau_{\rm Ohm}\right)}{1 + \frac{\tau_{\rm Ohm}}{\tau_{\rm Hall}}\left(1 - \exp\left(-t/\tau_{\rm Ohm}\right)\right)}$$

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

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

MAGNETIC FIELD EVOLUTION

Igoshev, Popov (2015) arXiv: 1507.07962

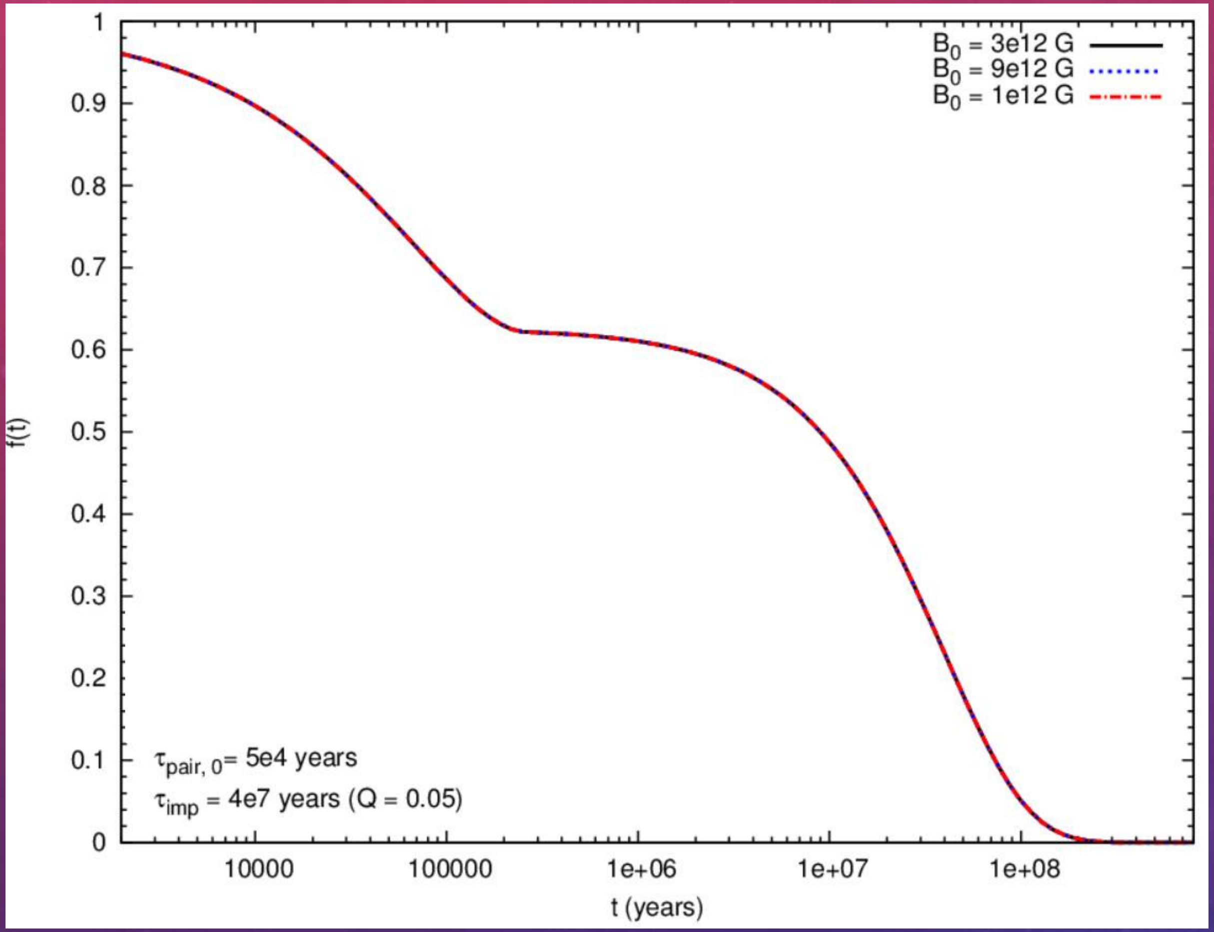


$$B = B_0 \frac{\exp\left(-t/\tau_{\mathrm{Ohm}}\right)}{1 + \frac{\tau_{\mathrm{Ohm}}}{\tau_{\mathrm{Hall}}}\left(1 - \exp\left(-t/\tau_{\mathrm{Ohm}}\right)\right)}$$

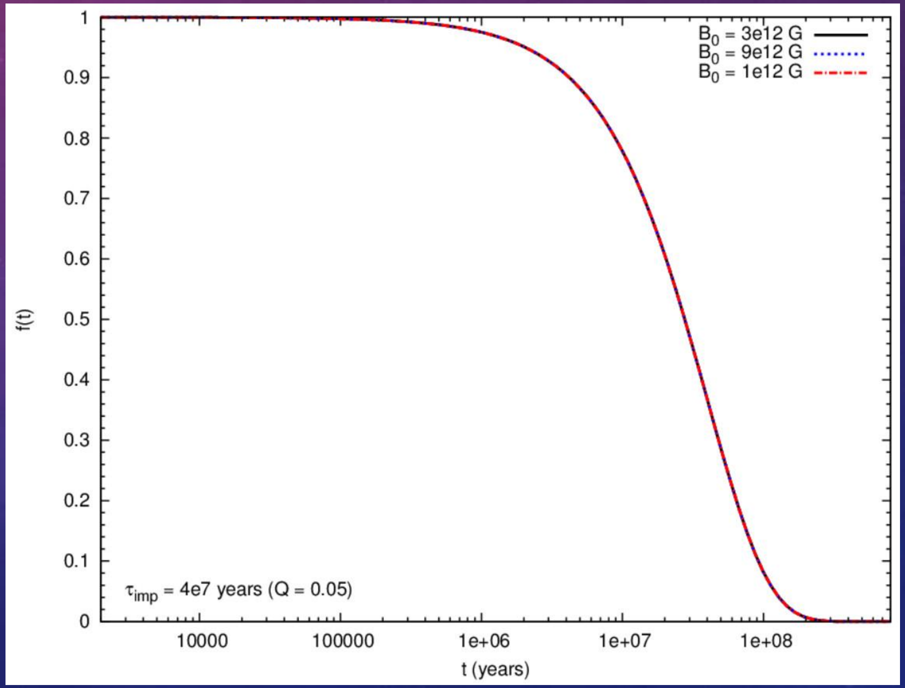
All inclusive:

- Hall
- Phonons
- Impurities

ONLY OHMIC DECAY



Here the Hall cascade is switched off

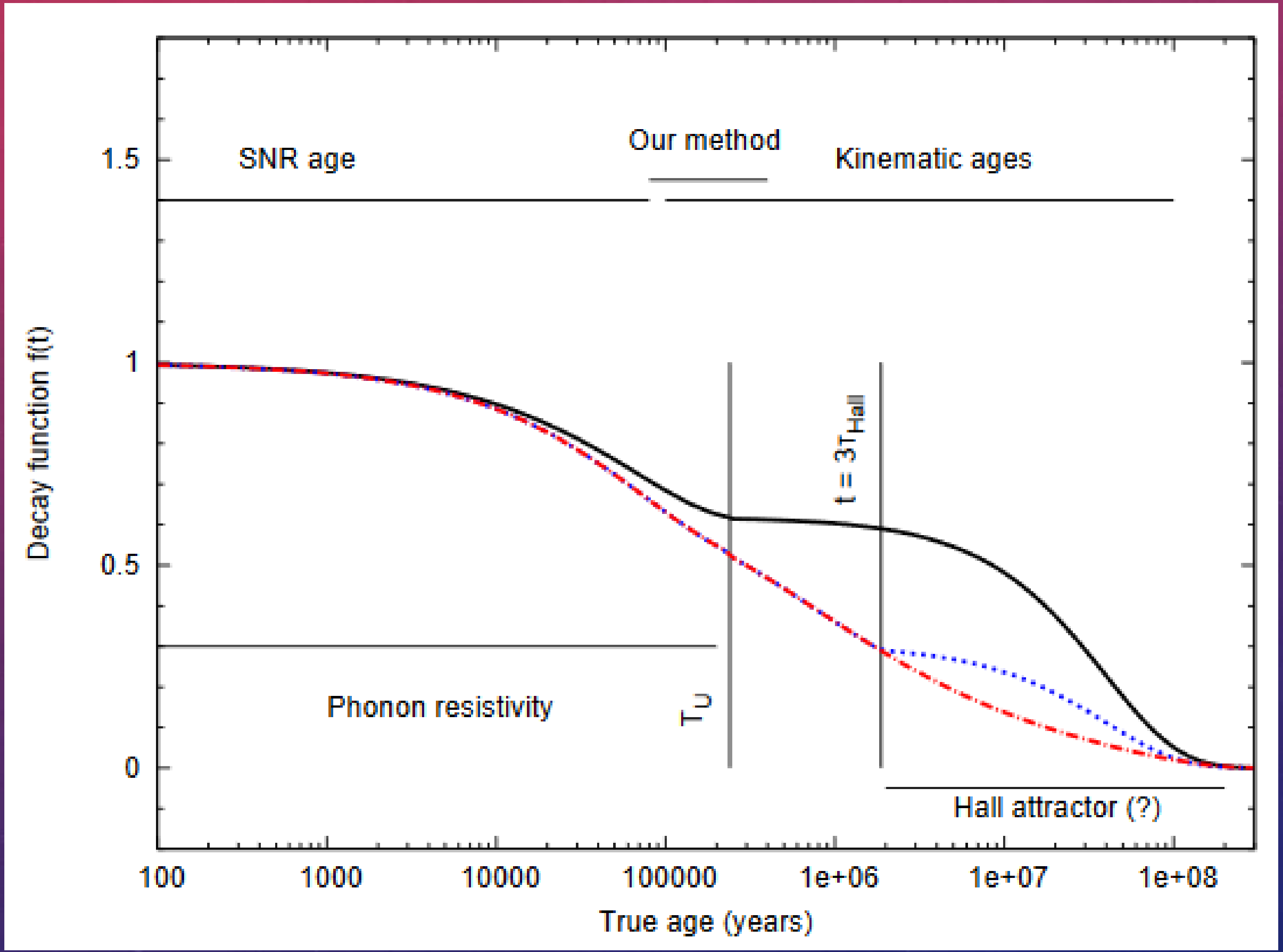


In one figure we have Ohmic decay only due to impurities, on another one – phonons are added.

COMPARISON OF DIFFERENT OPTIONS

arXiv: 1507.07962

Igoshev, Popov (2015)

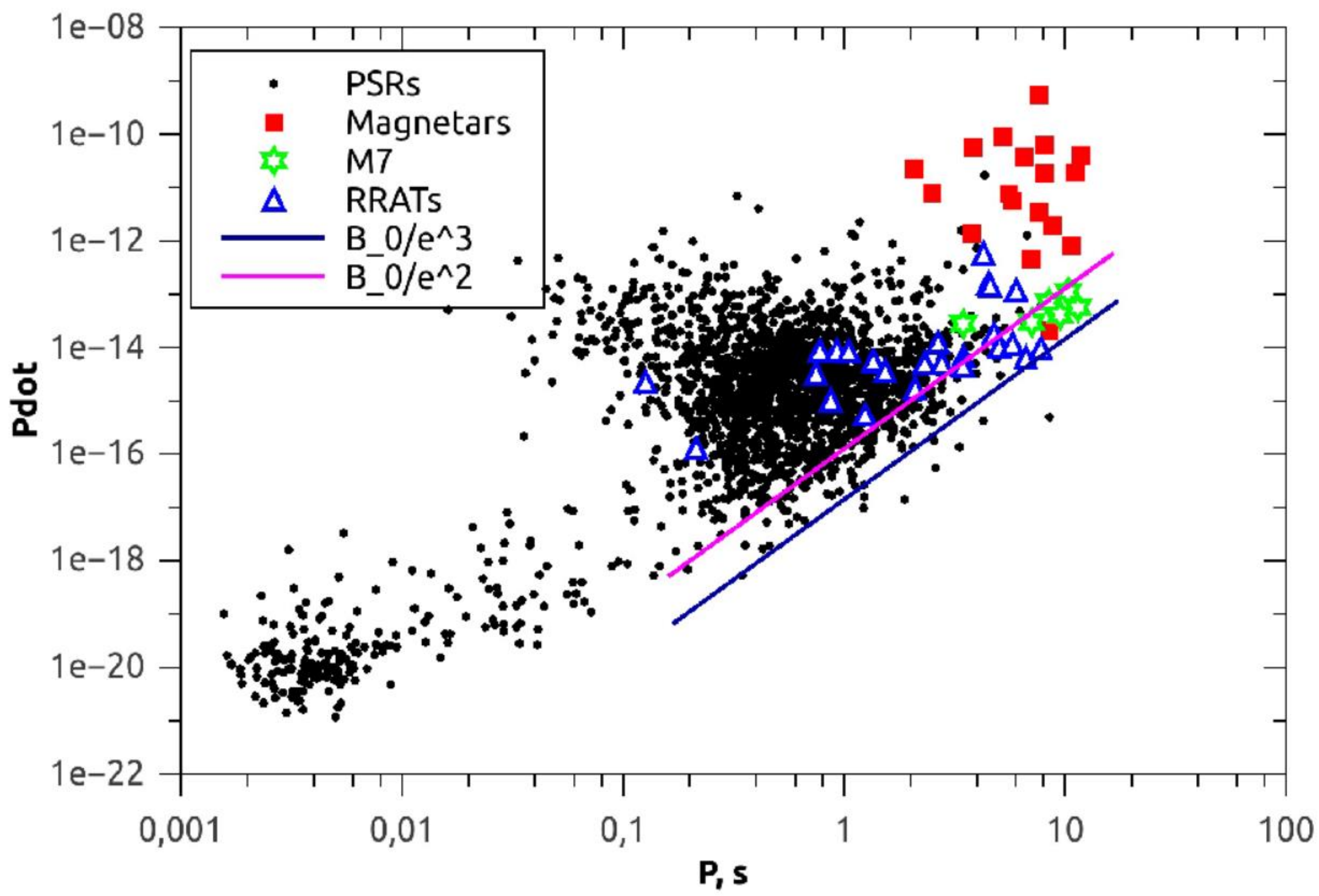


no Hall cascade (solid), Hall cascade with the Hall attractor (dotted), Hall cascade without attractor (dot-dashed).

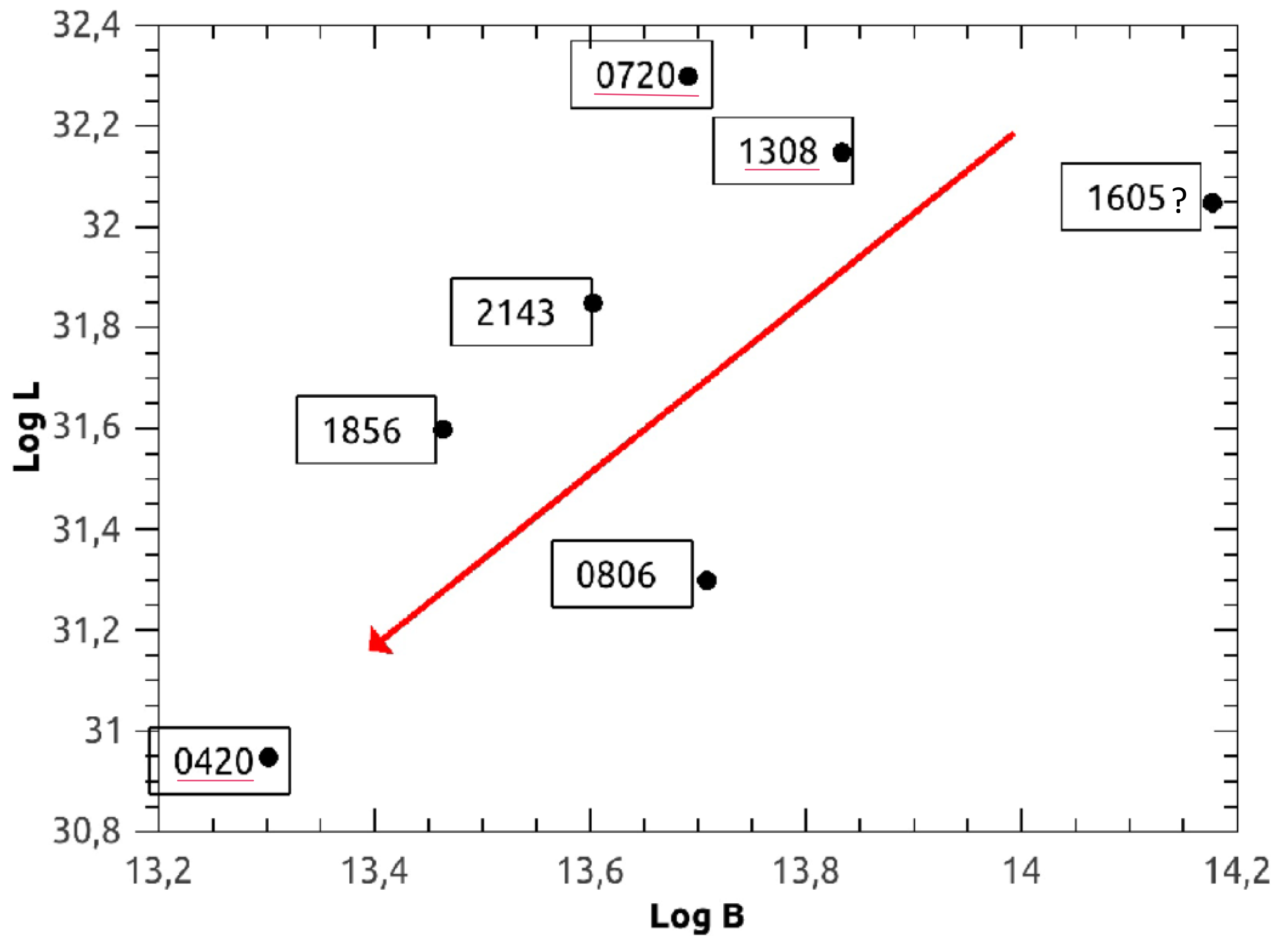
We think that in the range ~10^5 – 10^6 yrs we see mostly Ohmic decay, which then disappears as NSs cool down below the critical T.

Initial field was 5 1012 G.

GETTING CLOSE TO THE ATTRACTOR

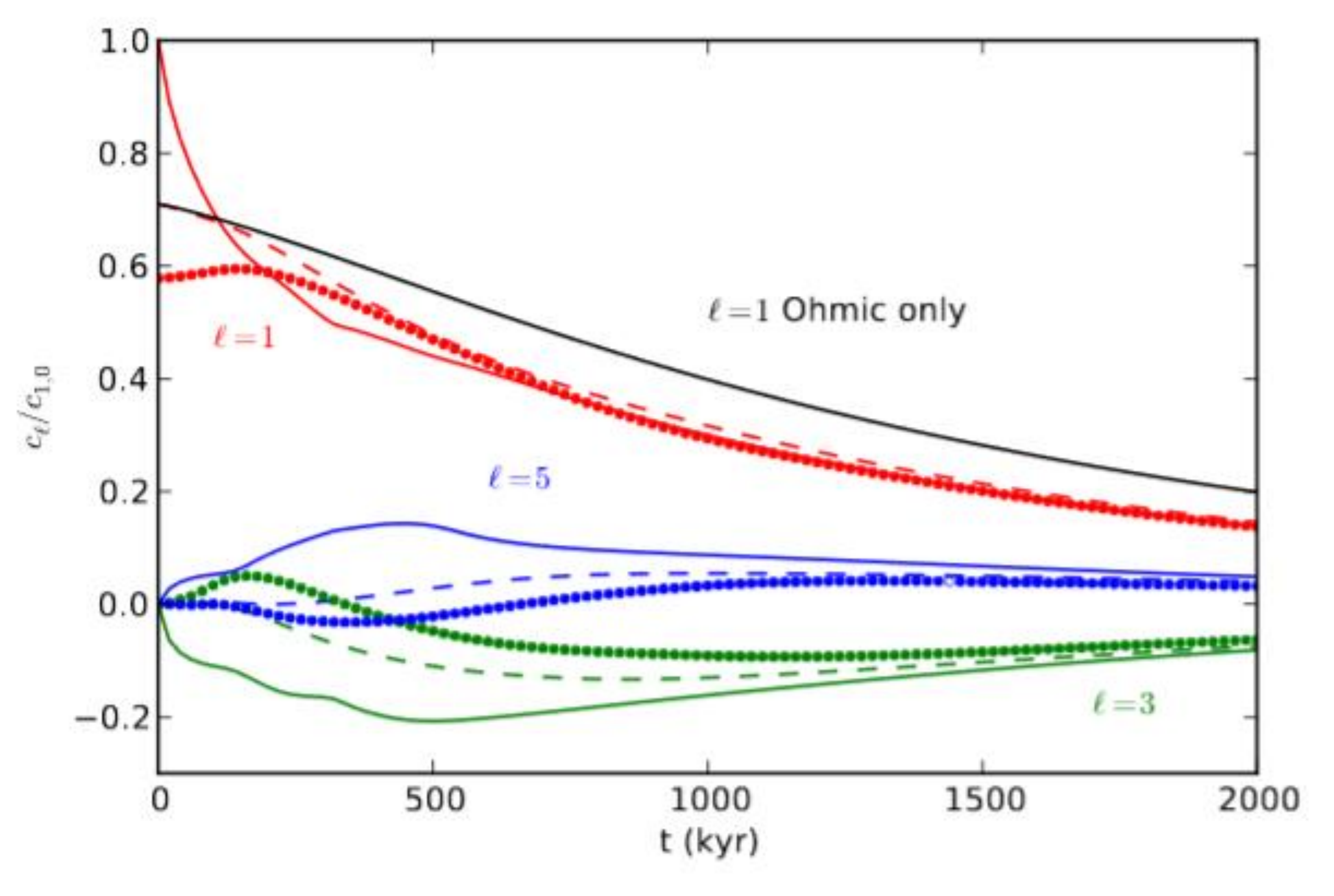


WHO IS CLOSER TO THE ATTRACTOR STAGE?



EVOLUTION OF DIFFERENT COMPONENTS

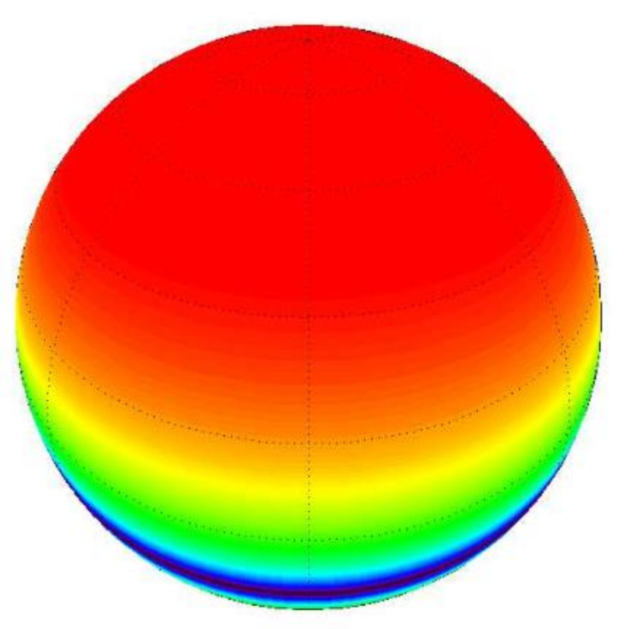
1311.7004

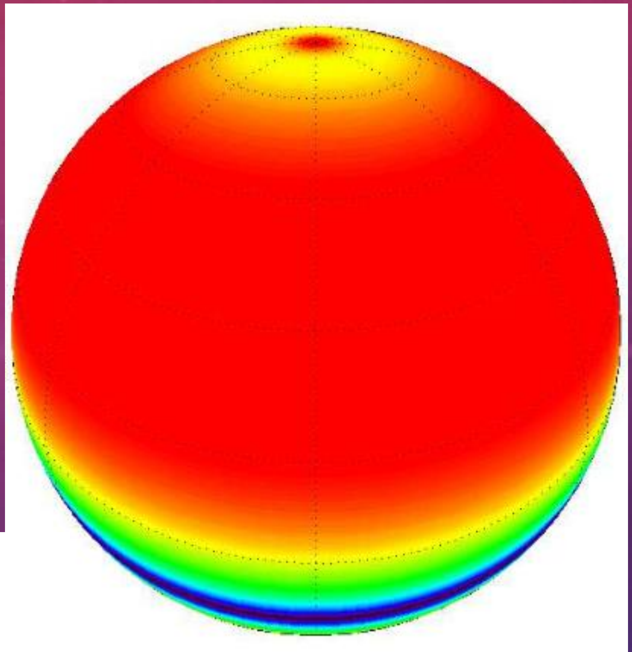


Hall attractor mainly consists of dipole and octupole

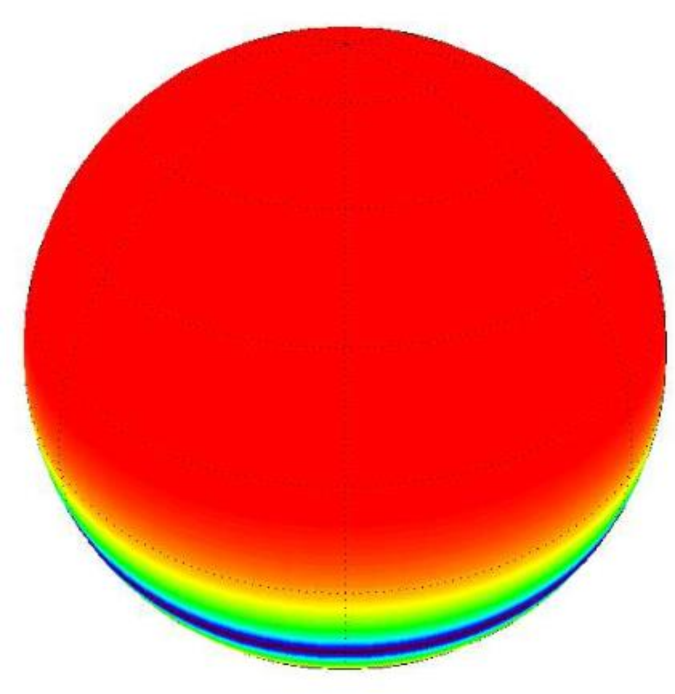
TEMPERATURE MAPS

Pure dipole

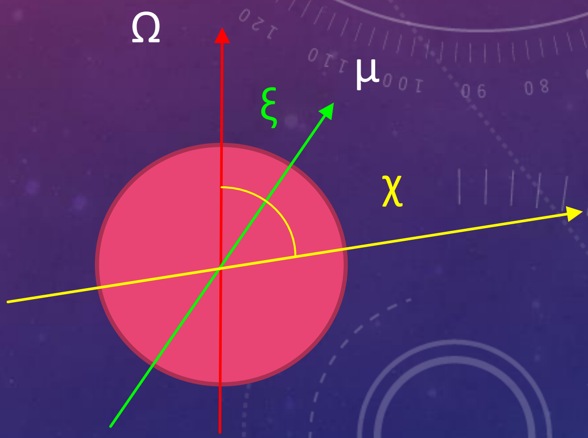




Dipole + octupole
(Model 1)

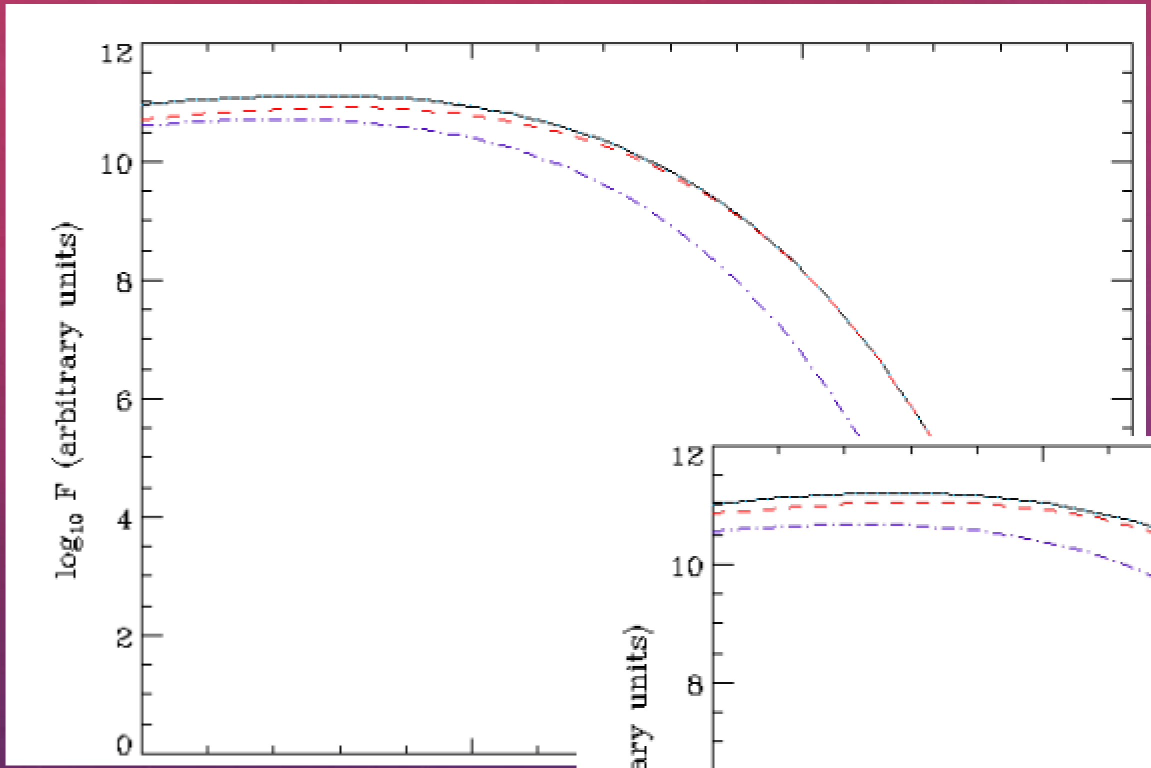


Dipole+octupole+l5

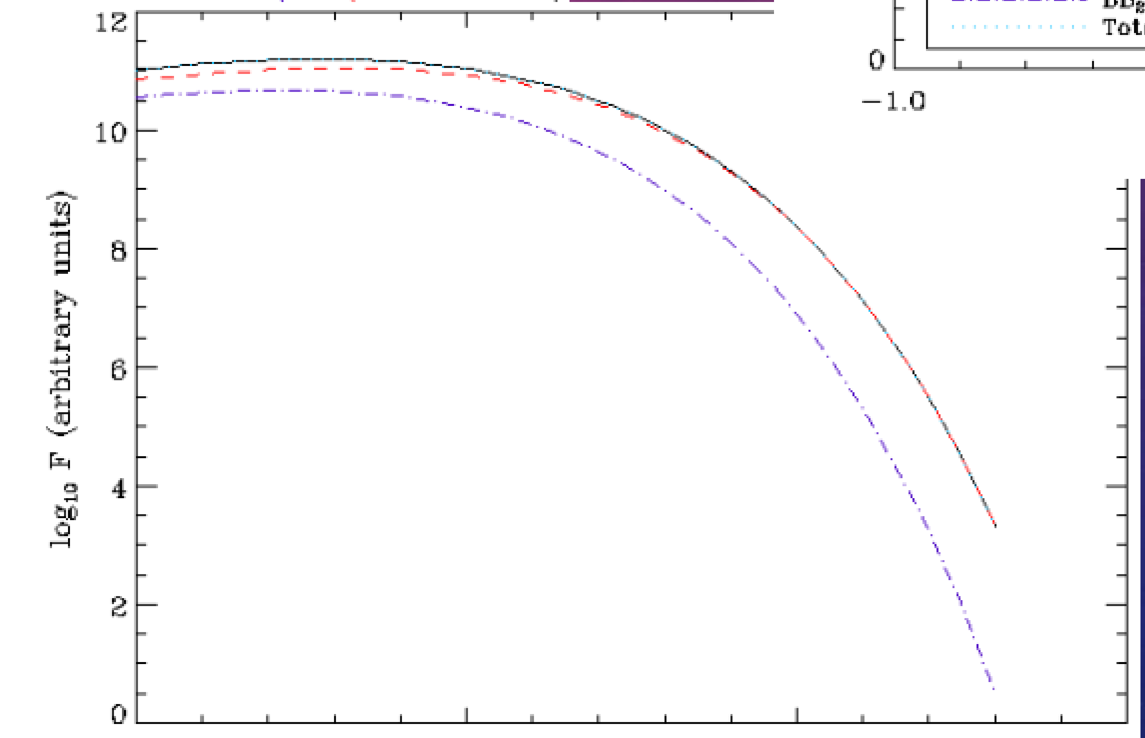


	χ	ξ	T_1 (eV)	T_2 (eV)	A_2/A_1
Pure dipole	15°	80°	72.0	57.8	1.27
Model 1	20°	80°	73.0	59.4	0.76
Model 2	25°	80°	73.5	58.1	0.36

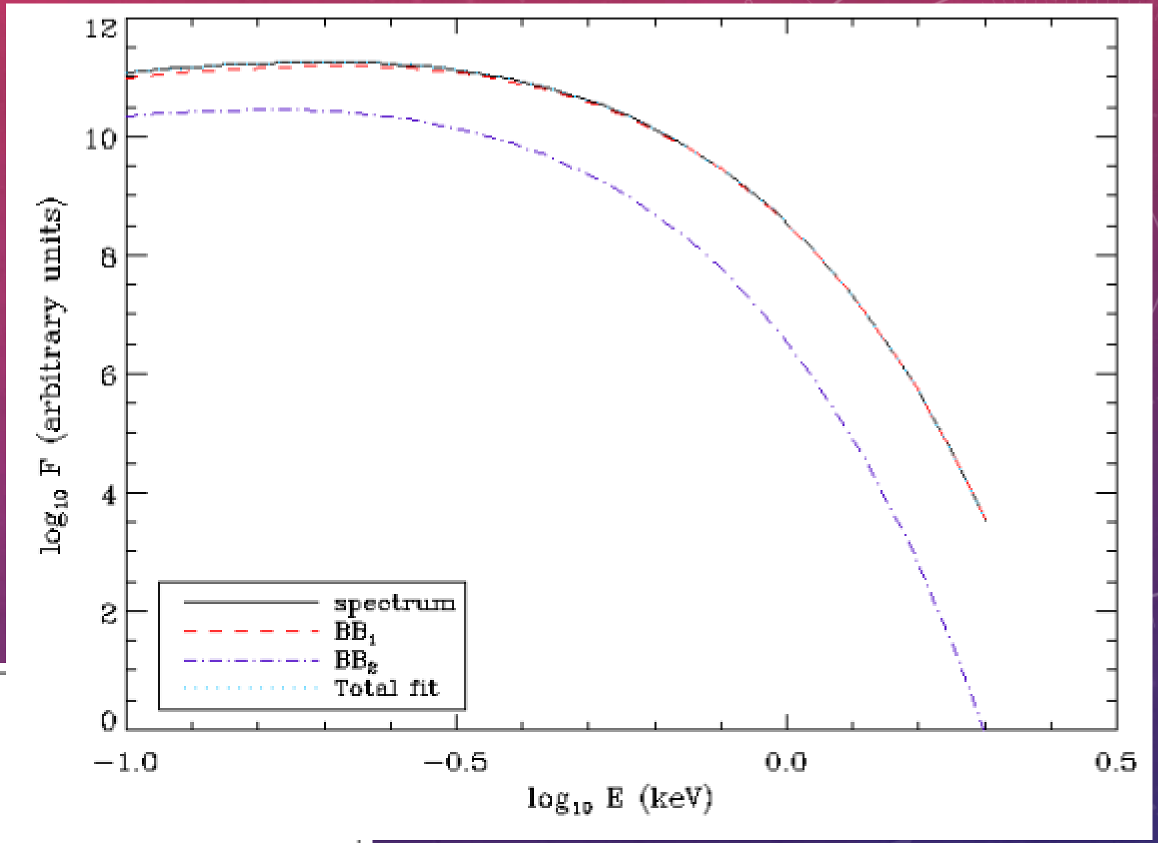
SPECTRAL FITS



Pure dipole



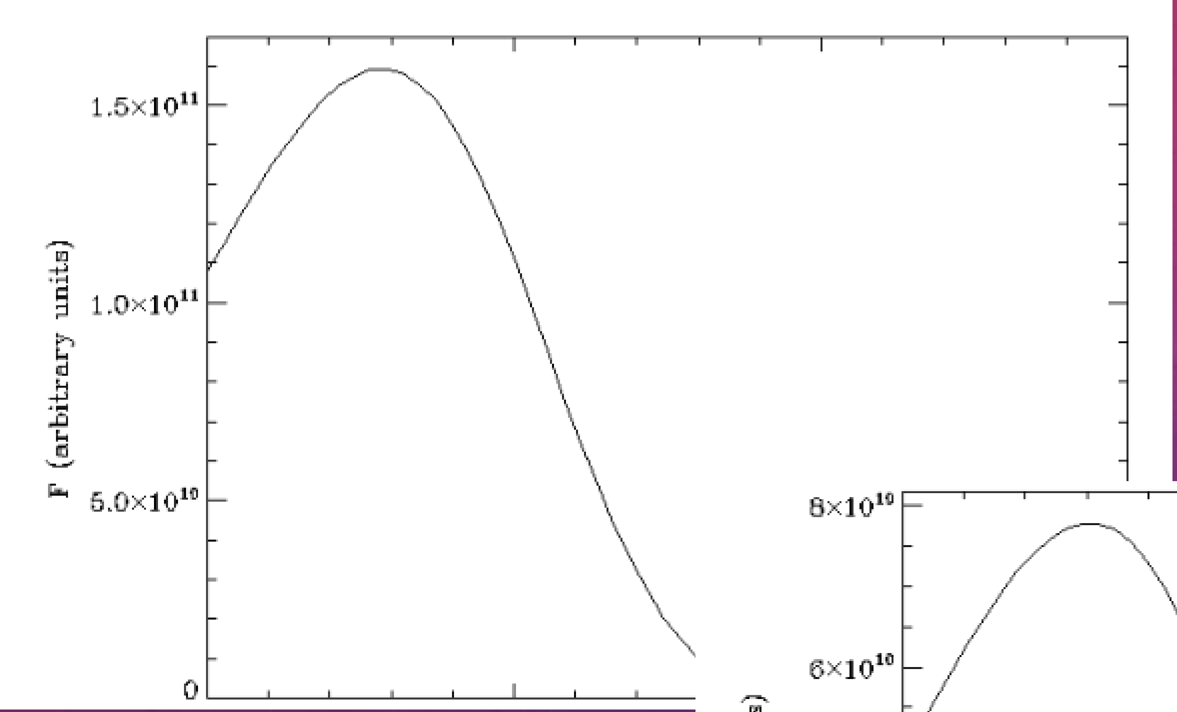
Model 1



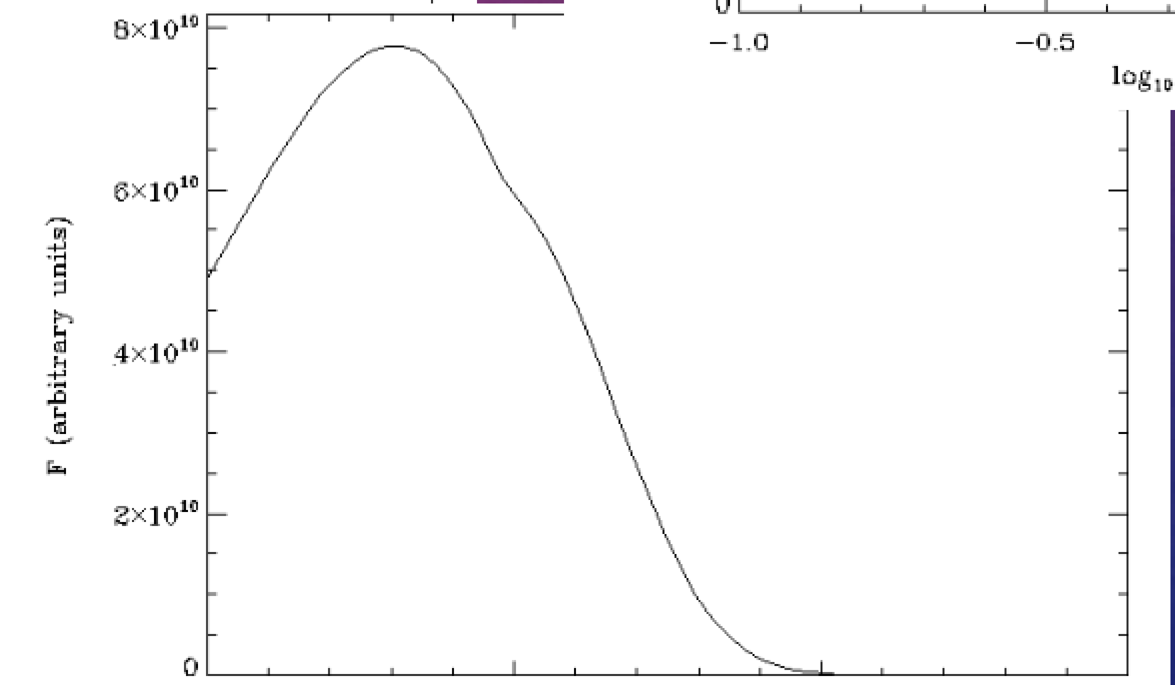
Model 2

Dipole+octupole+l5

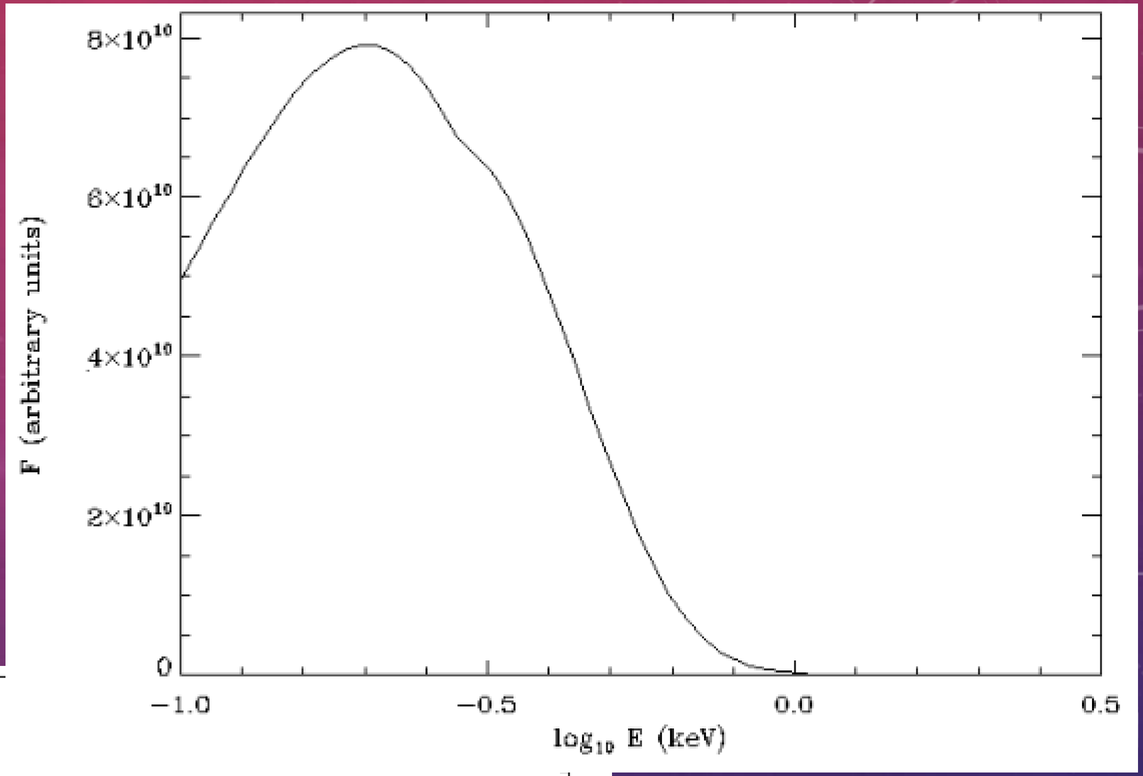
EFFECT OF SURFACE



Blackbody

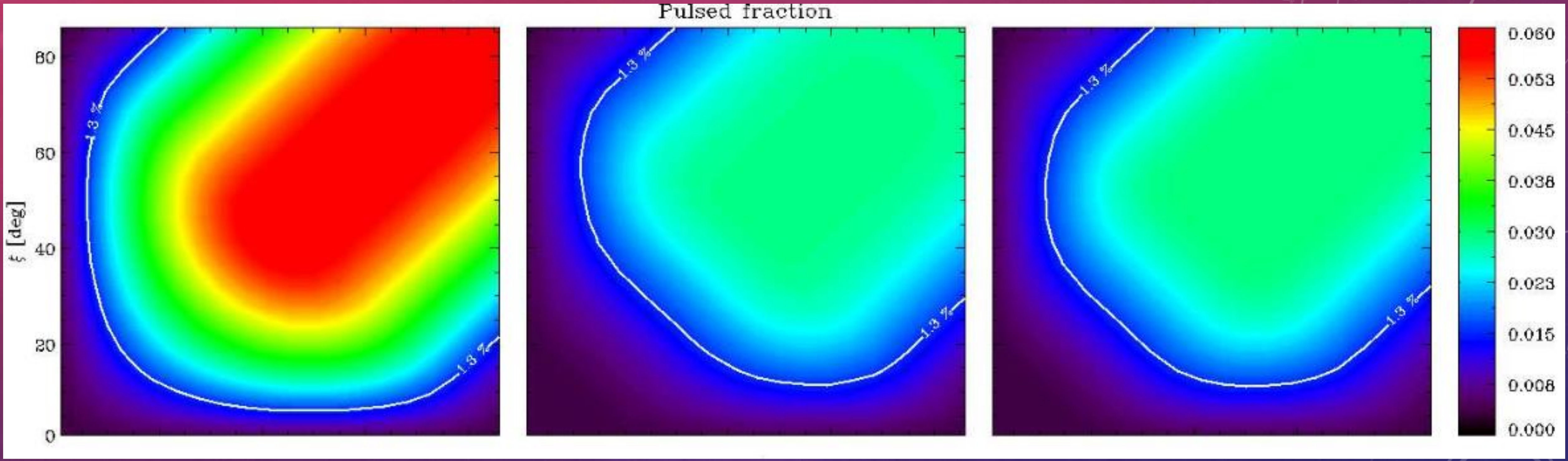


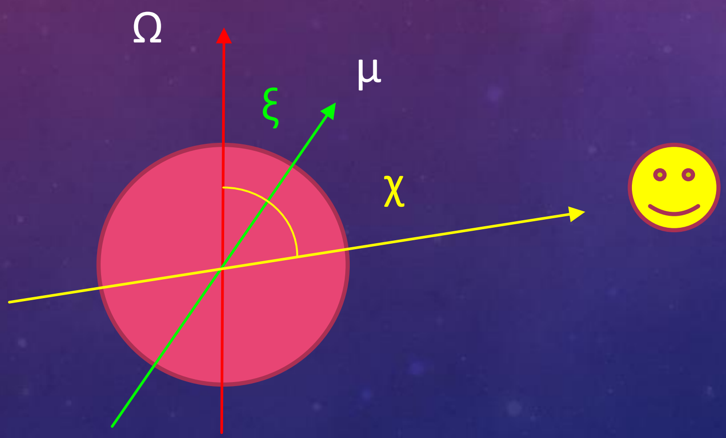
Condensed surface; free ions



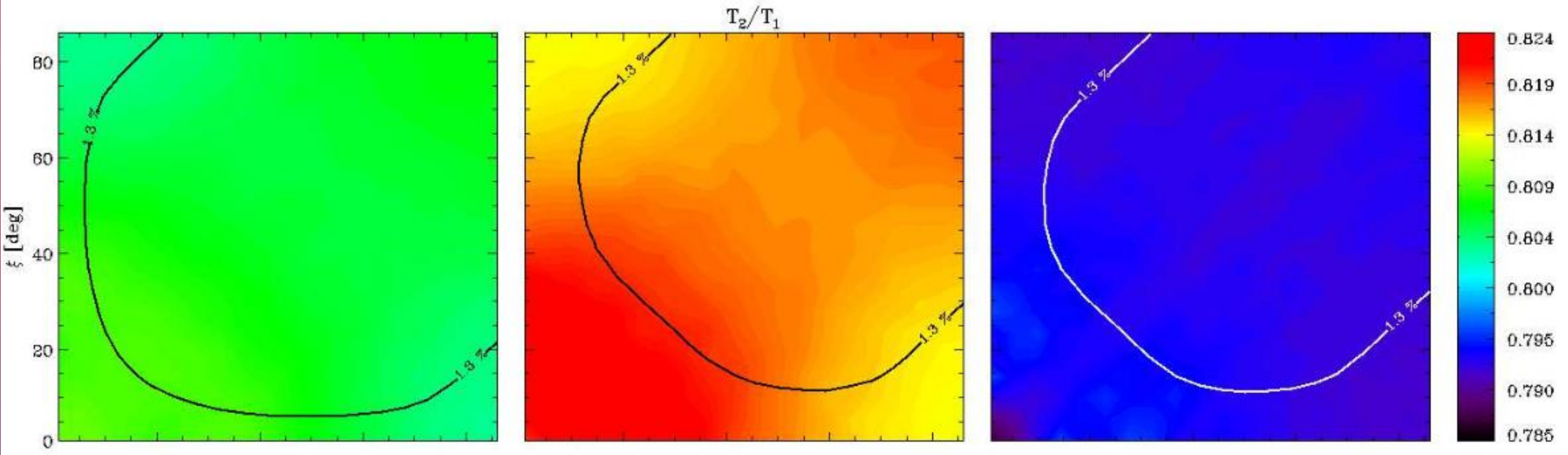
Condensed surface; fixed ions

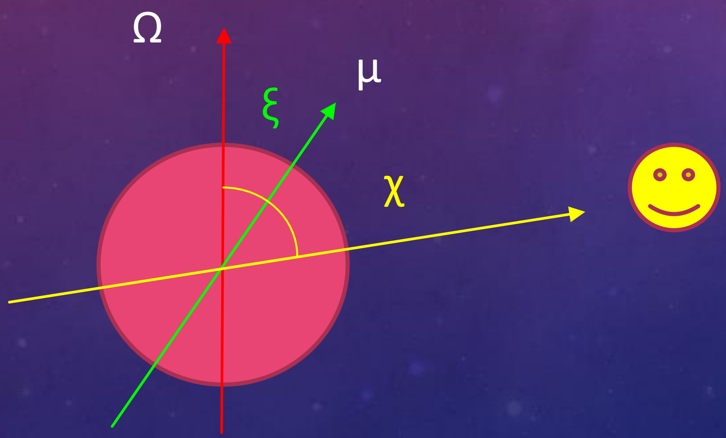
PULSED FRACTION



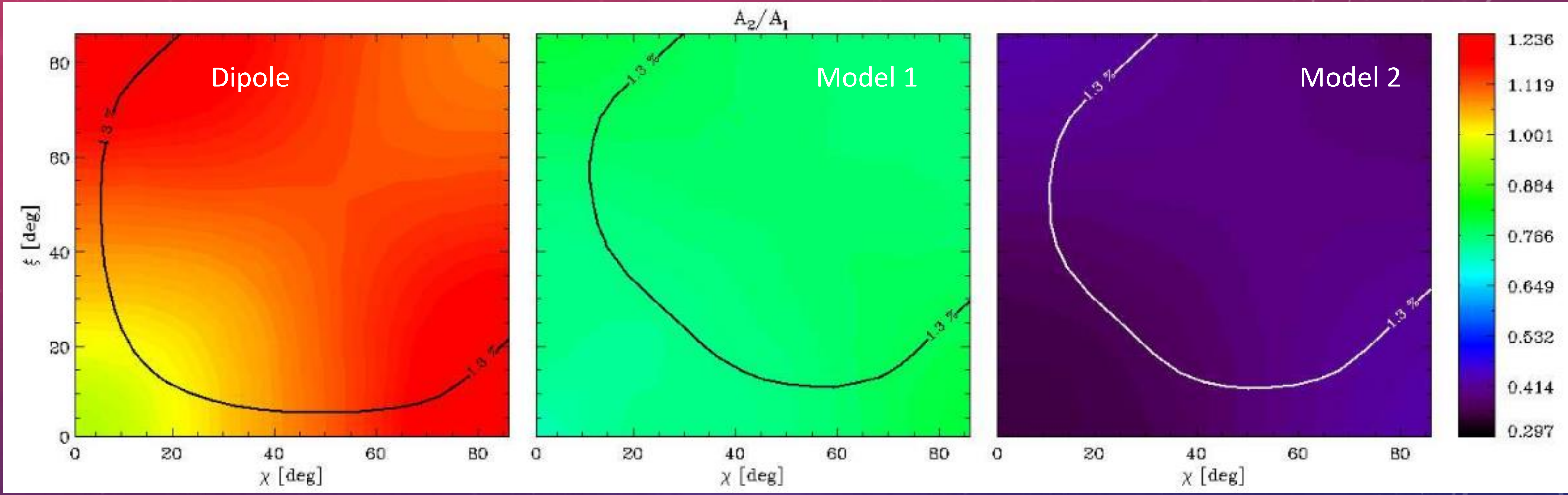


TEMPERATURE RATIO

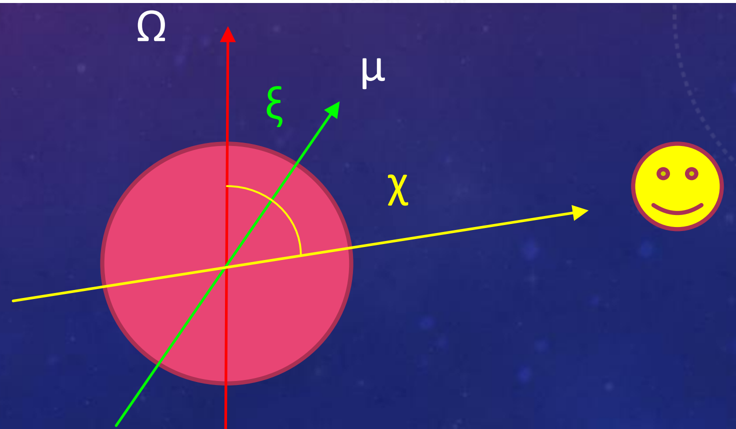




EMITTING AREAS



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



OBSERVATIONAL DATA

1202.2121

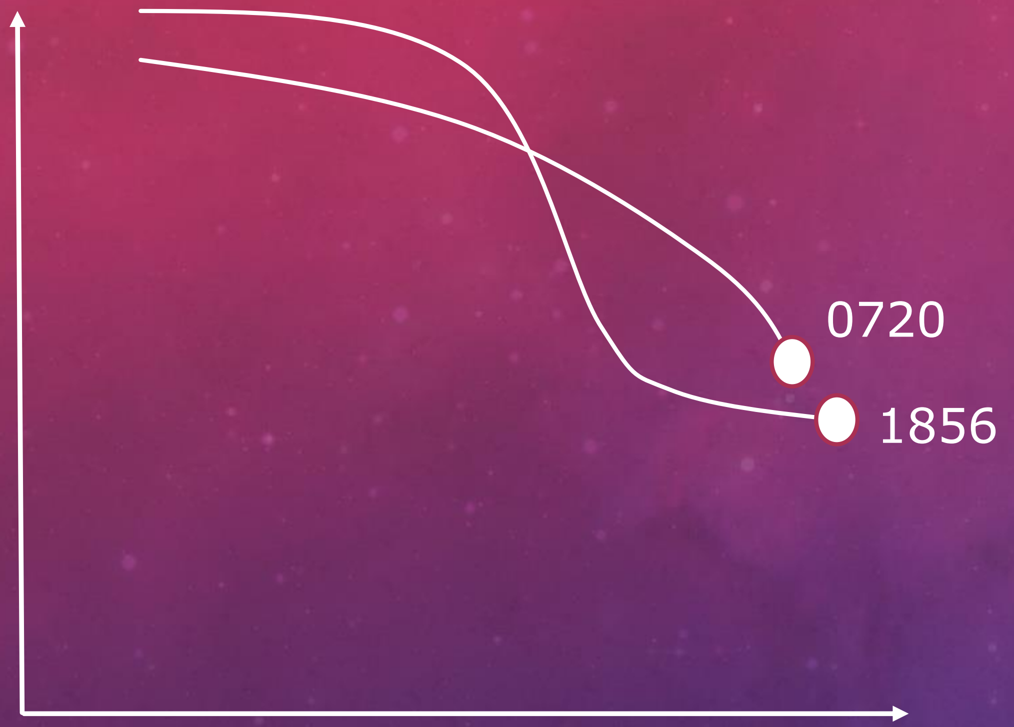
Parameter	Single BB	Two BB
N_H [10^{19} cm^{-2}]	$4.8^{+0.2}_{-0.2}$	$12.9^{+2.2}_{-2.3}$
kT_h^∞ [eV]	$61.5^{+0.1}_{-0.1}$	$62.4^{+0.6}_{-0.4}$
R_h^∞ [km]	$5.0^{+0.1}_{-0.1}$	$4.7^{+0.2}_{-0.3}$
kT_s^∞ [eV]	-	$38.9^{+4.9}_{-2.9}$
R_s^∞ [km]	-	$11.8^{+5.0}_{-0.4}$
σ_{sys}	1.5%	0.6%
χ^2_ν	1.12	1.11

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



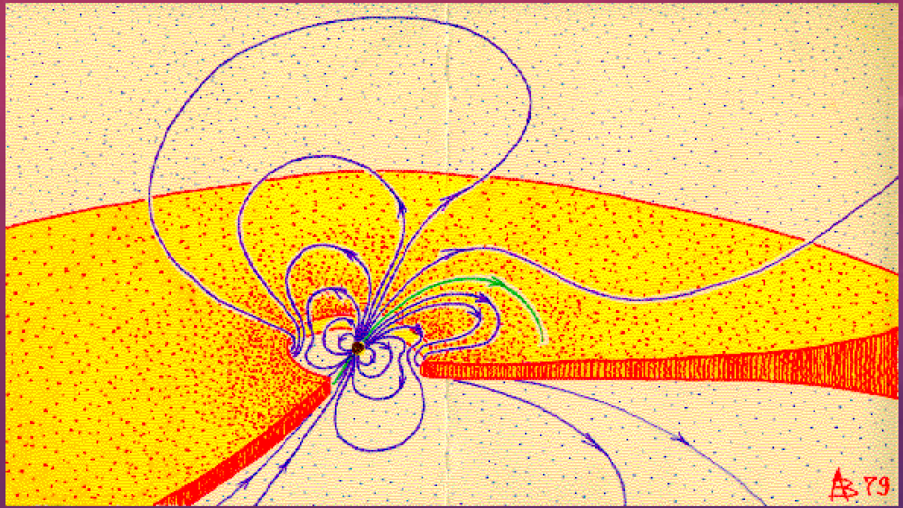
Kinematic age is larger for 0720, but characteristic age – for 1856.

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

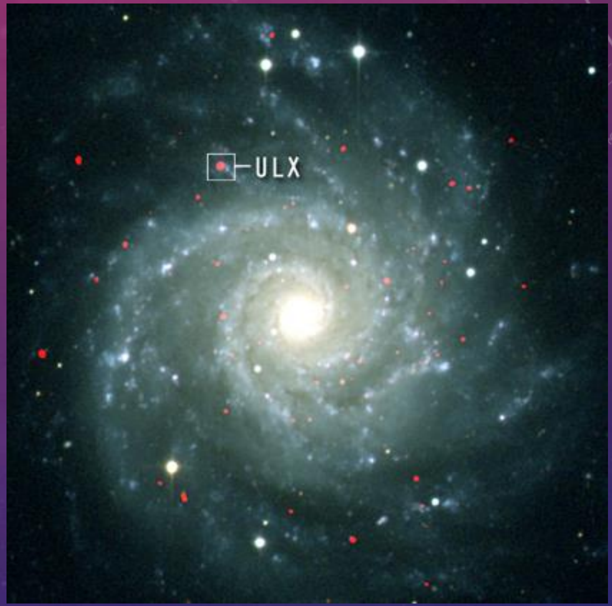
RX J0720 shows several types of activity, but RX J1856 is a very quiet source.

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).

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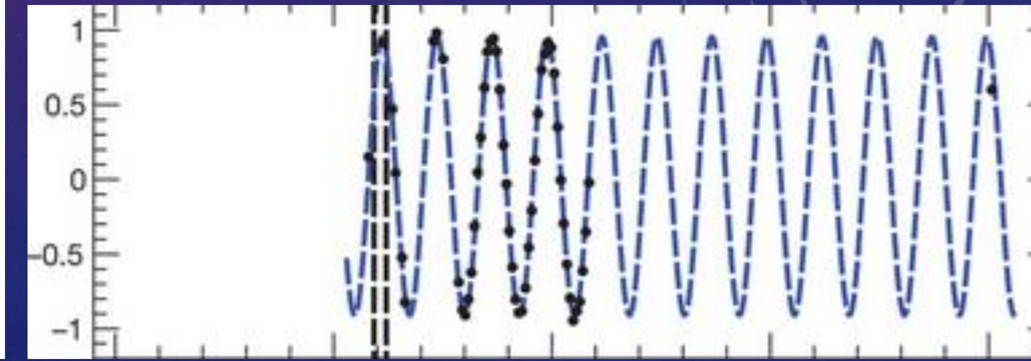

FIELD EVOLUTION IN A MAGNETAR

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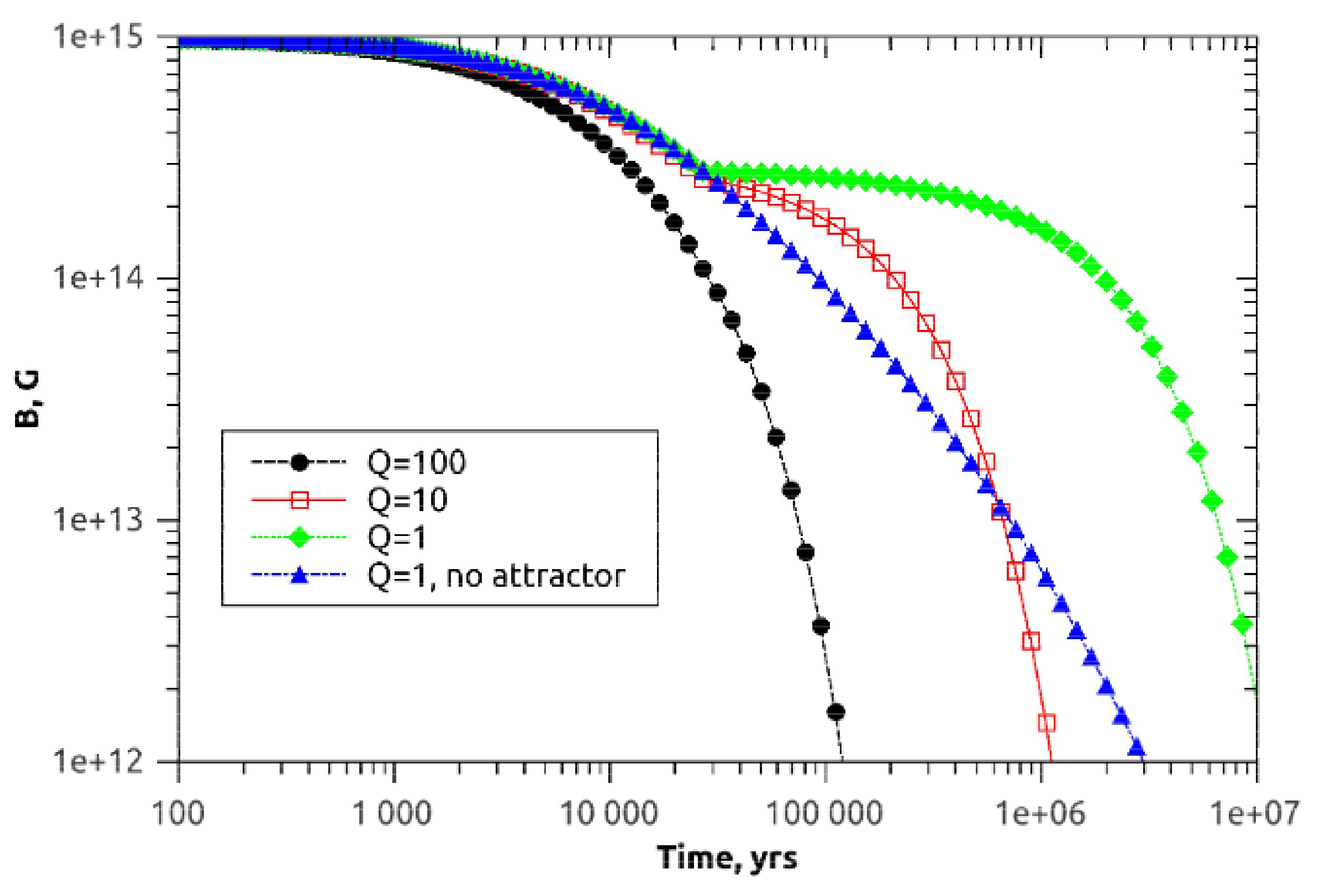
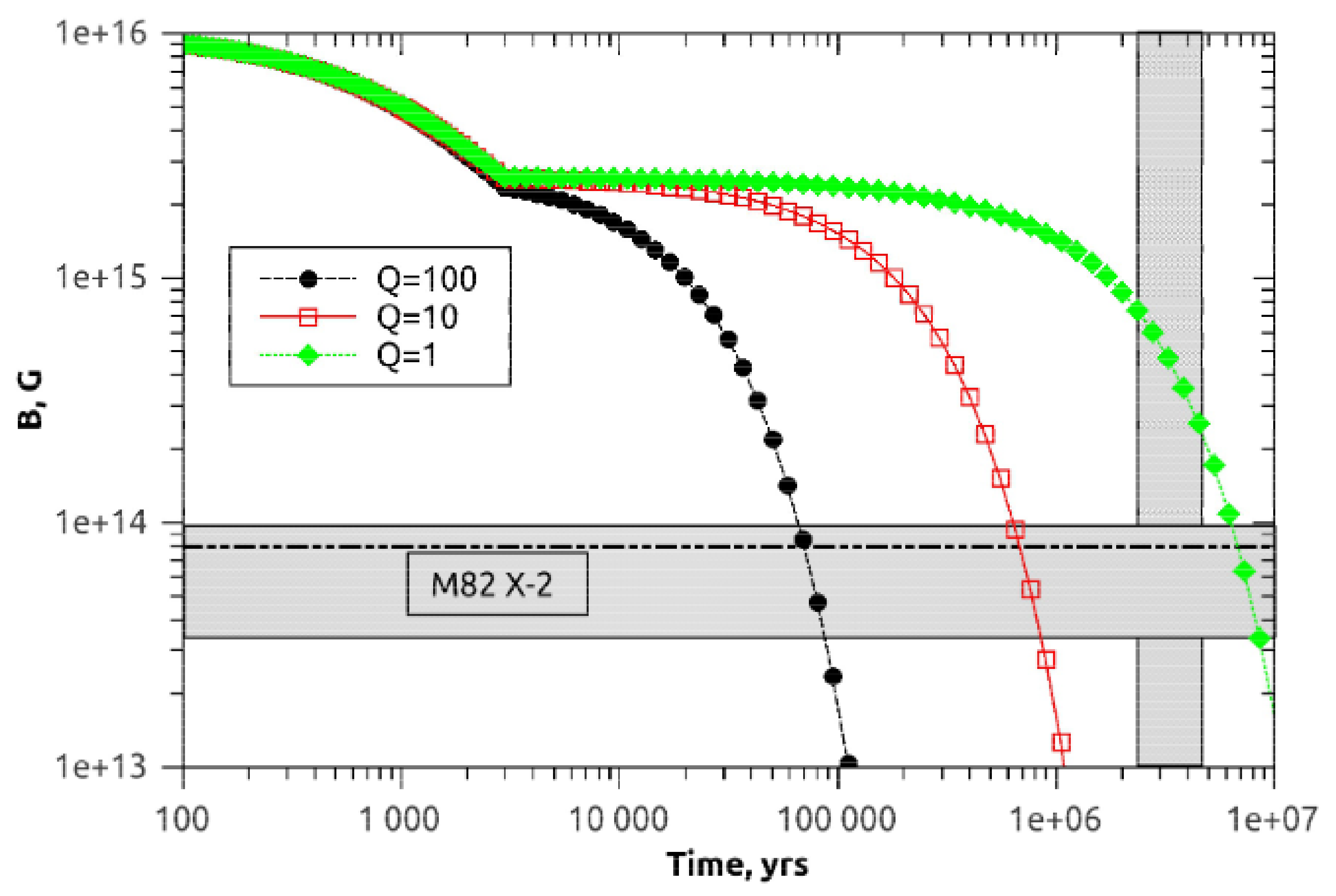


PARAMETERS OF ULX M82 X-2



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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 form the predicted ones.
- If accreting magnetars do exist, the attractor might be necessary to explain their properties.

A.P. Igoshev, S.B. Popov
``Magnetic field decay in normal radio pulsars''
AN, vol. 336 pp. 831-834 (2015)
arXiv: 1507.07962

A.P. Igoshev, S.B. Popov
``How to make a mature accreting magnetar''
MNRAS vol. 473 pp. 3204-3210 (2018)
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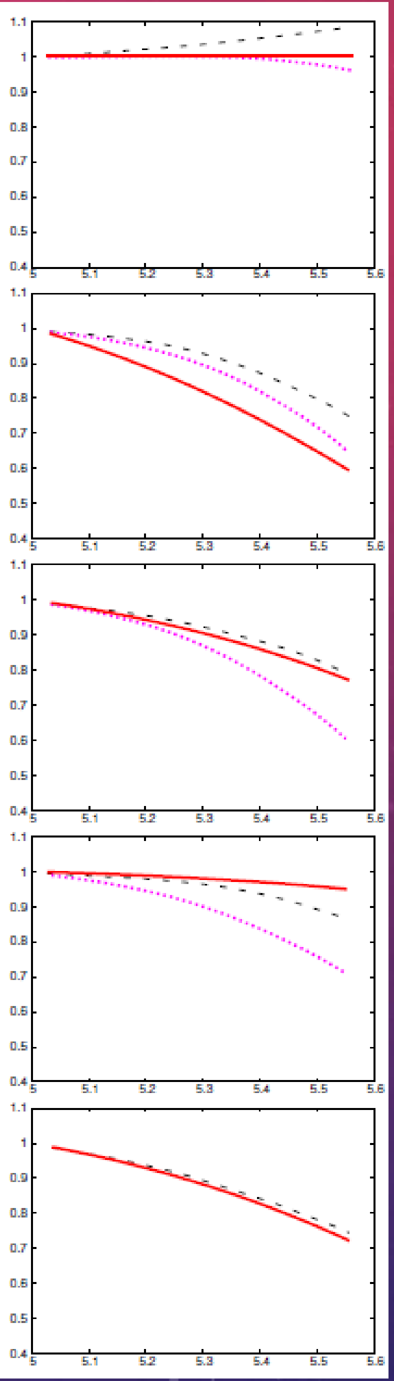
S.B. Popov, R. Taverna, R.Turolla
``Probing the surface magnetic field structure in RX J1856.5-3754''
MNRAS vol. 464, 4390 (2017)
arXiv: 1610.05050

S.B. Popov, A.P. Igoshev, R. Taverna, R. Turolla
``Looking for Hall attractor in astrophysical sources''
JoP: Conference Series vol. 932, p. 012048 (2017)
1710.09190



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.

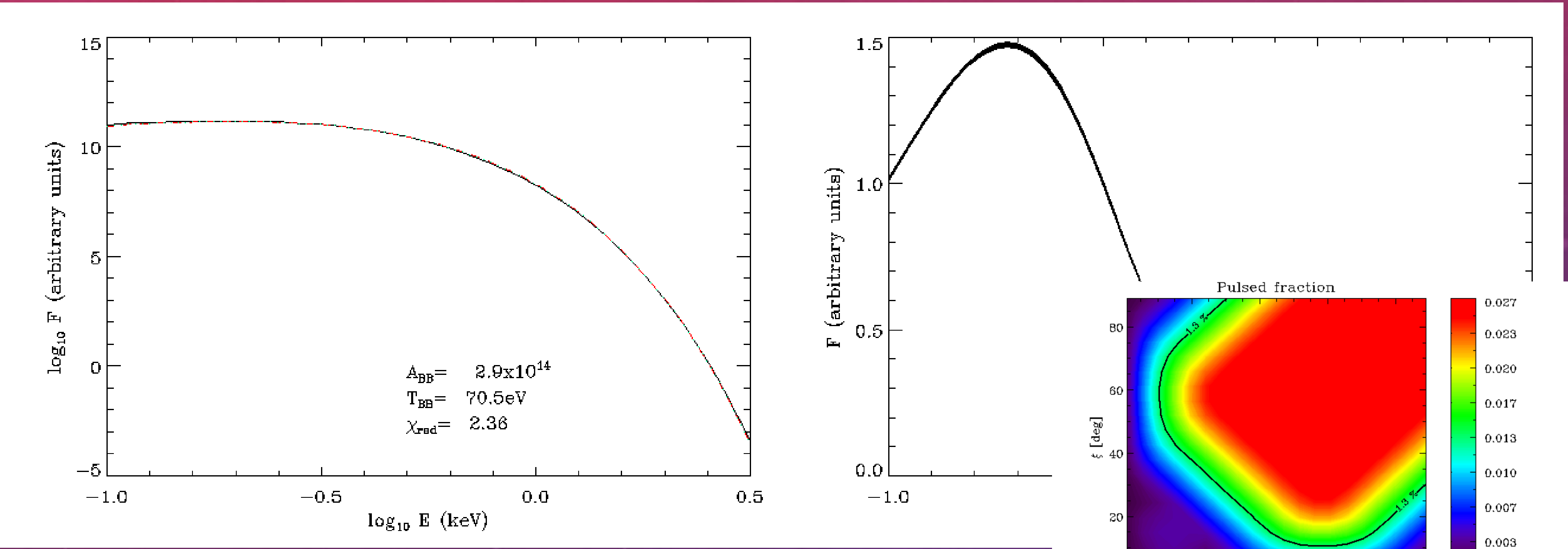
Name	$\log \mu_{B_0}$ [G]	$\log \sigma_{B_0}$ [G]	μ_{P_0} [s]	σ_{P_0} [s]	α	τ_D [Myr]	τ_{SDA} [Myr]
A1	12.60	0.47	0.33	0.23	0.50	∞	∞
A2	12.95	0.55	0.30	0.15	0.50	∞	10
B1	12.60	0.47	0.33	0.23	0.50	0.5	1.00
B2	12.95	0.55	0.30	0.15	0.50	0.5	0.690
C1	12.60	0.47	0.33	0.23	0.50	1	1.15
C2	12.95	0.55	0.30	0.15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

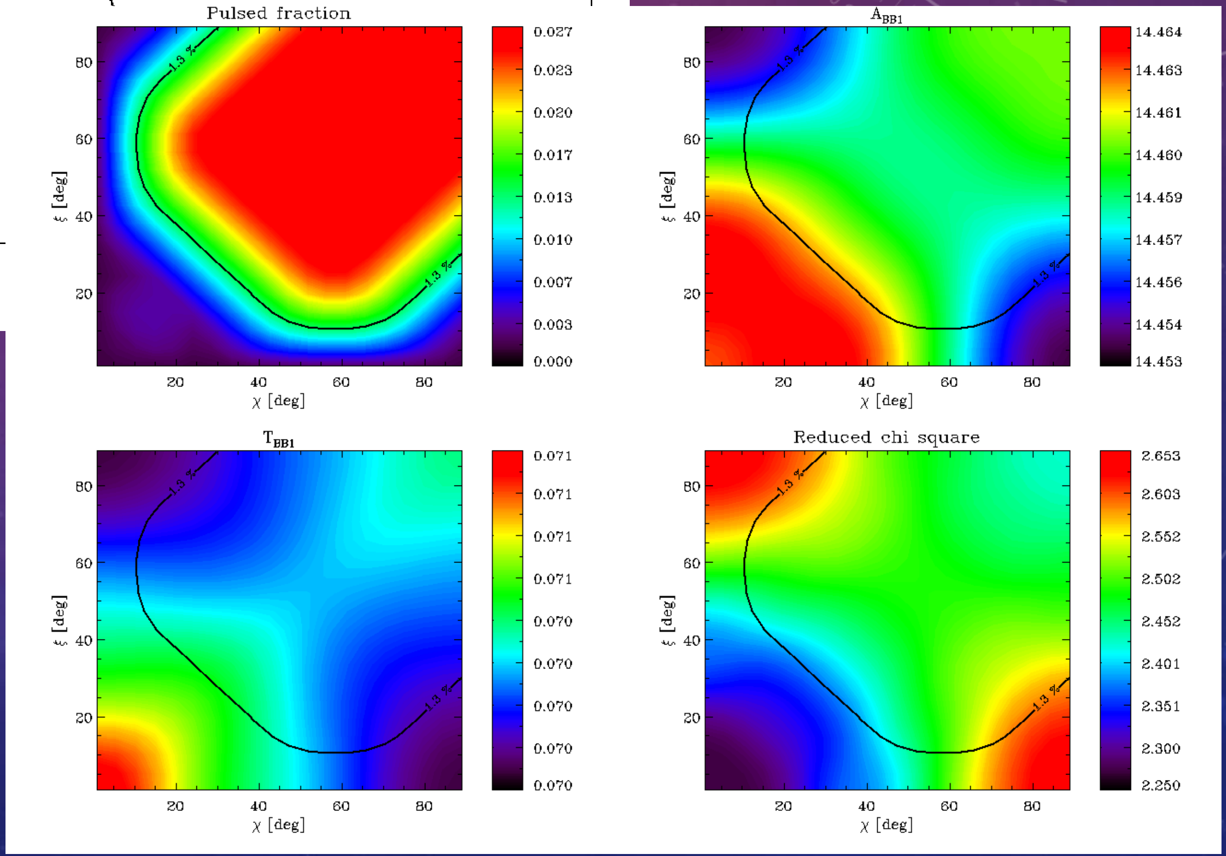
(Synthetic samples are calculated by Gullon, Pons, Miralles)

FURTHER REFERENCES

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

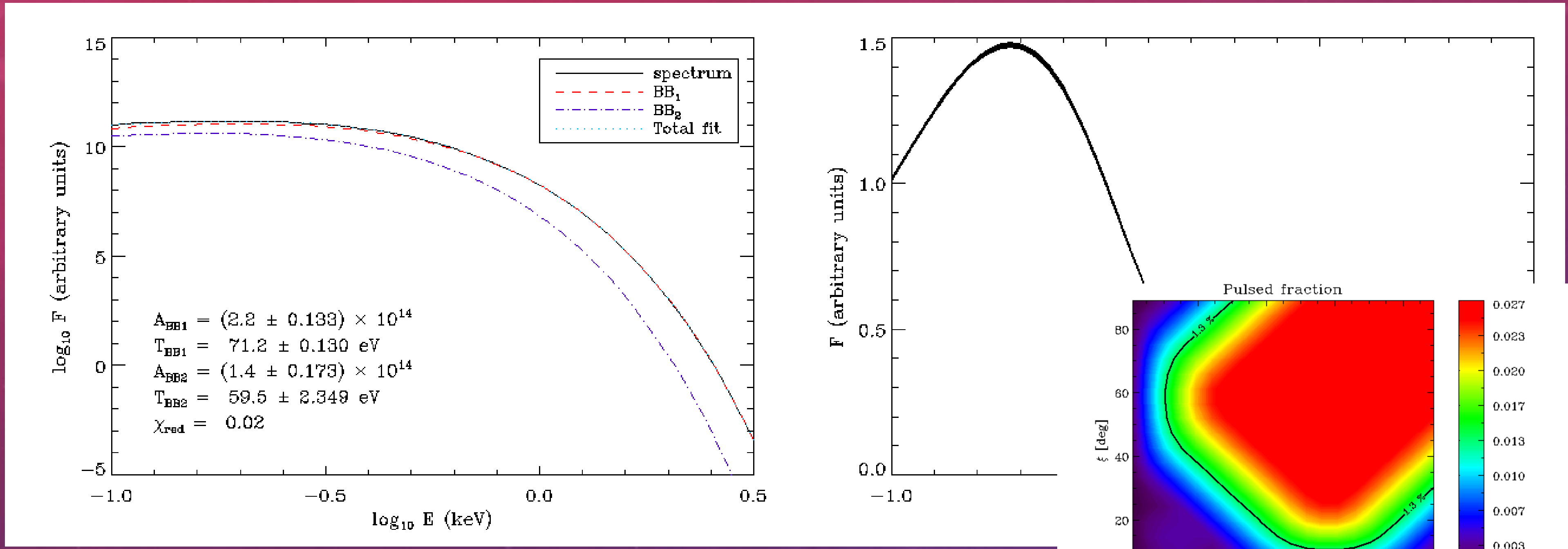
SPECTRAL FITS: SINGLE BLACKBODY

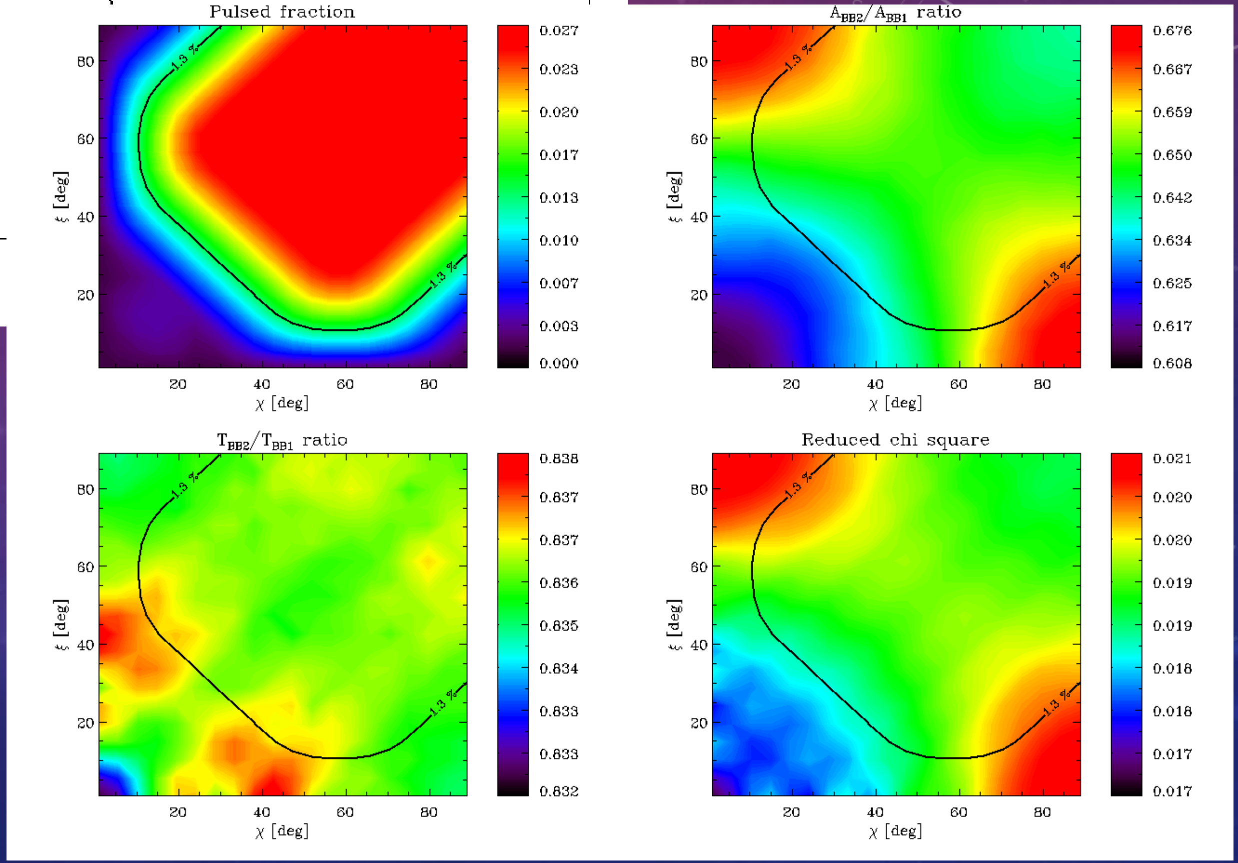




Single black body does not provide a good fit, even using, in addition, a line, or condensed surface.

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 ….

EVOLUTION WITH FIELD DECAY