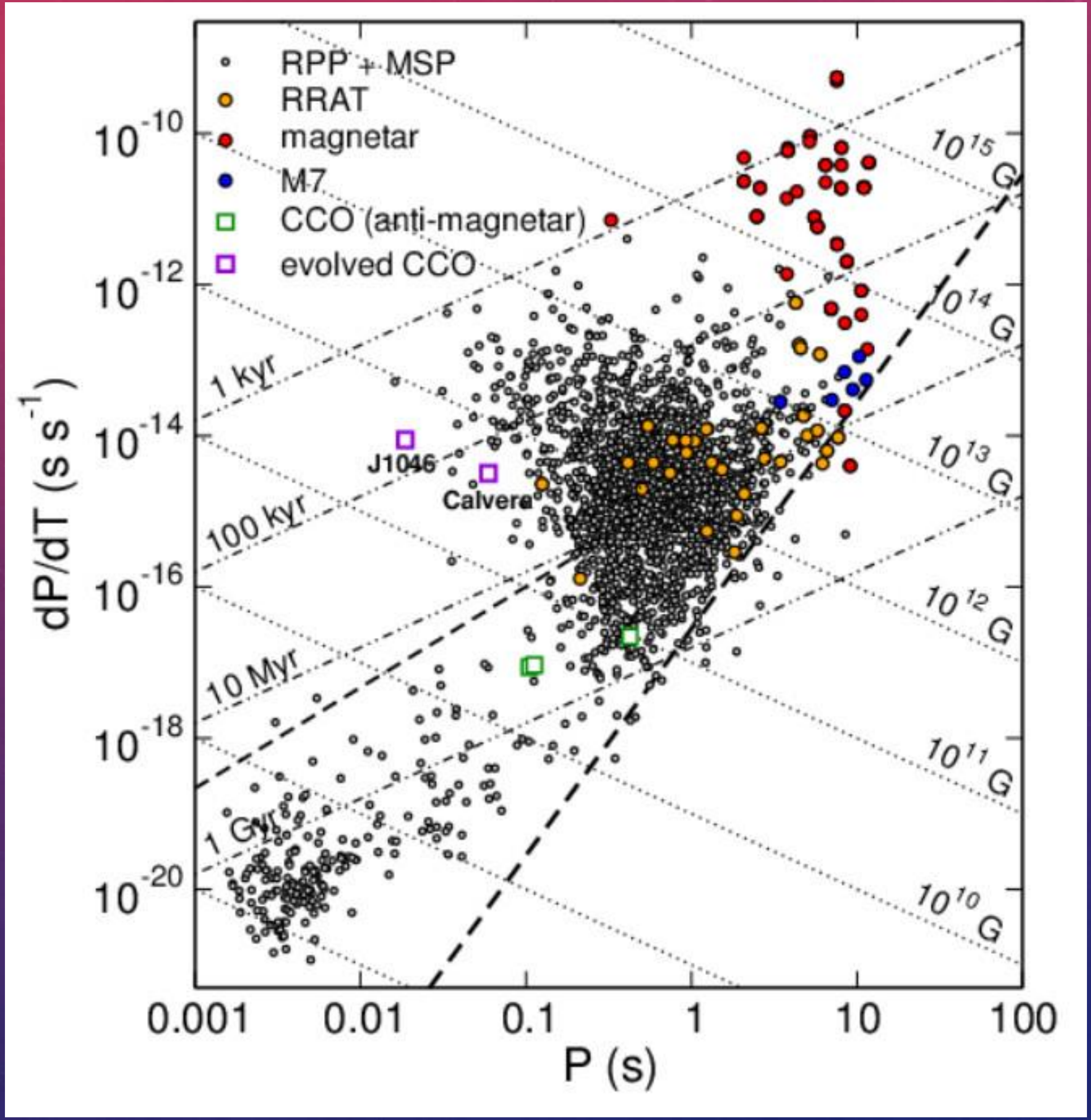
LOOKING FOR HALL ATTRACTOR IN KNOWN NEUTRON STARS

SERGEI POPOV, ANDREI IGOSHEV, ROBERTO TAVERNA, ROBERTO TUROLLA

1710.09190, 1709.10385

DIVERSITY OF NEUTRON STARS

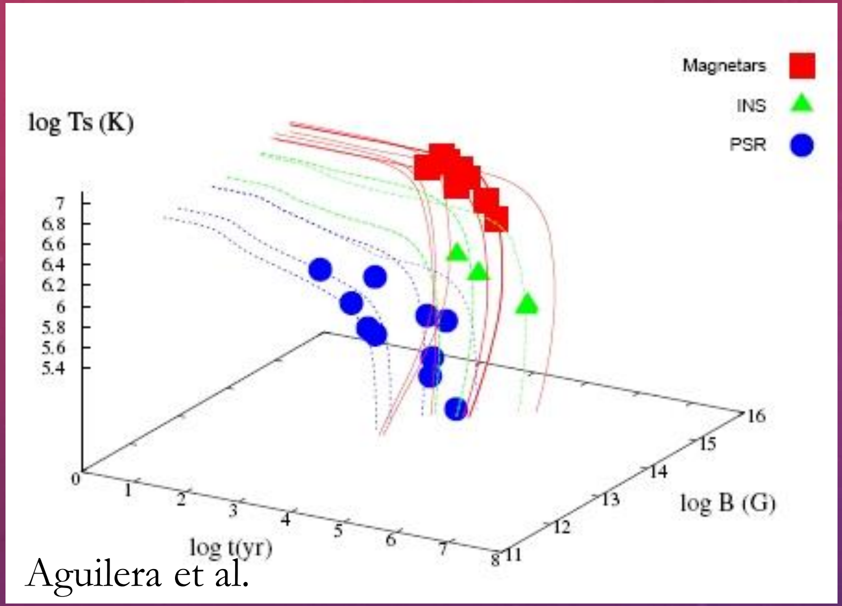


Pires et al. 2015

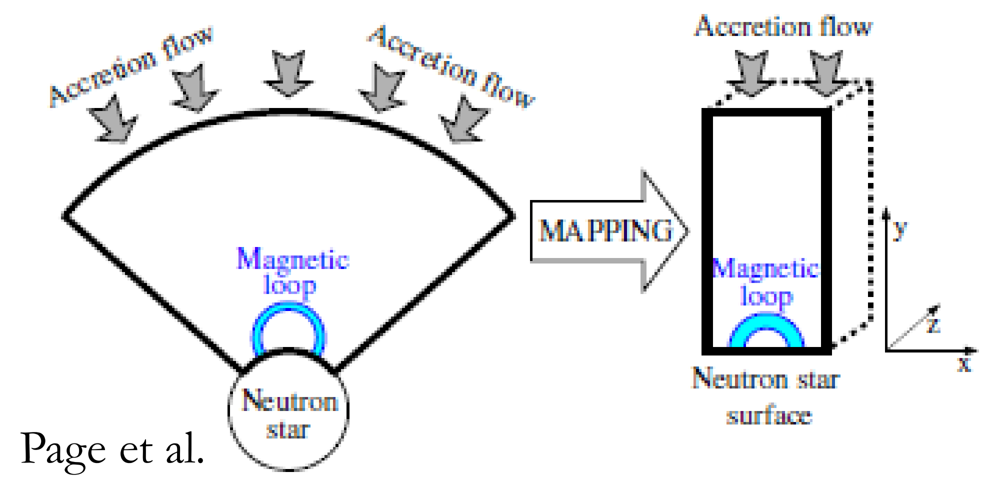
The term
“GRAND UNIFICATION
FOR NEUTRON STARS”
was coined by Kaspi (2010)

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

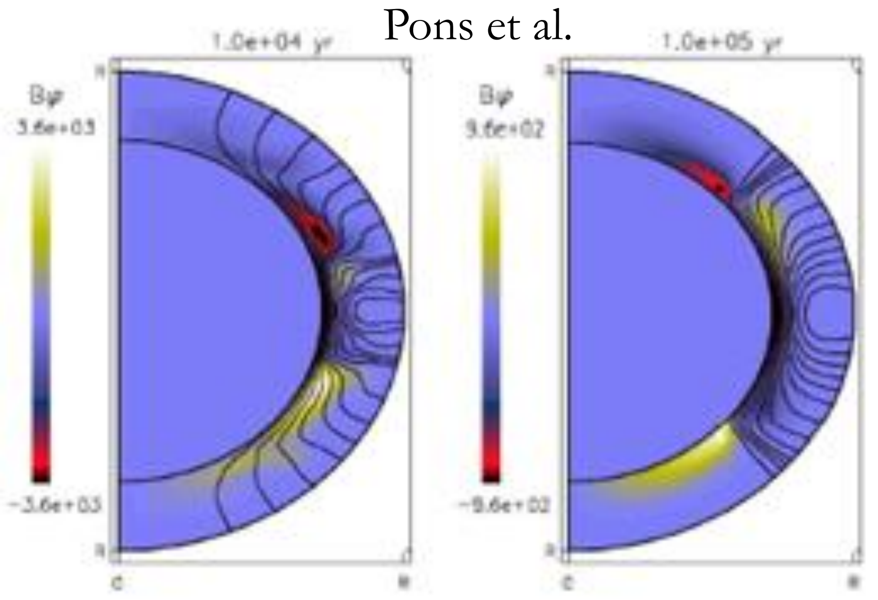
THREE MAIN INGREDIENTS OF A UNIFIED MODEL



Aguilera et al.



Page et al.

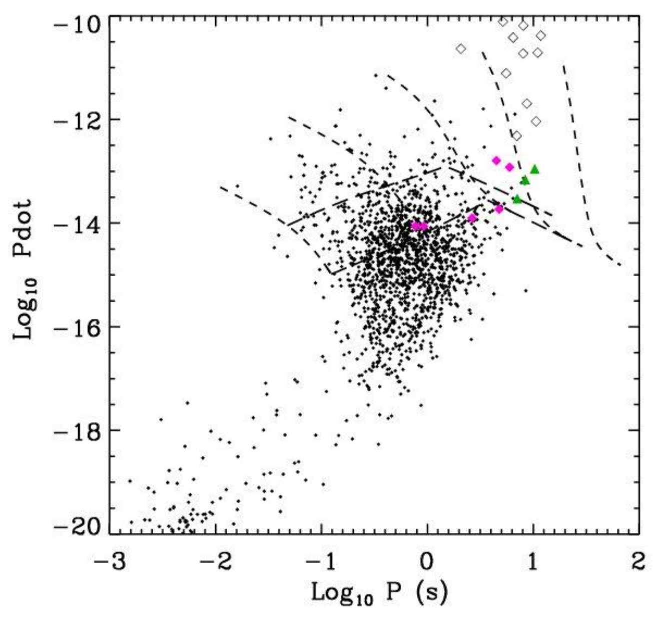


Pons et al.

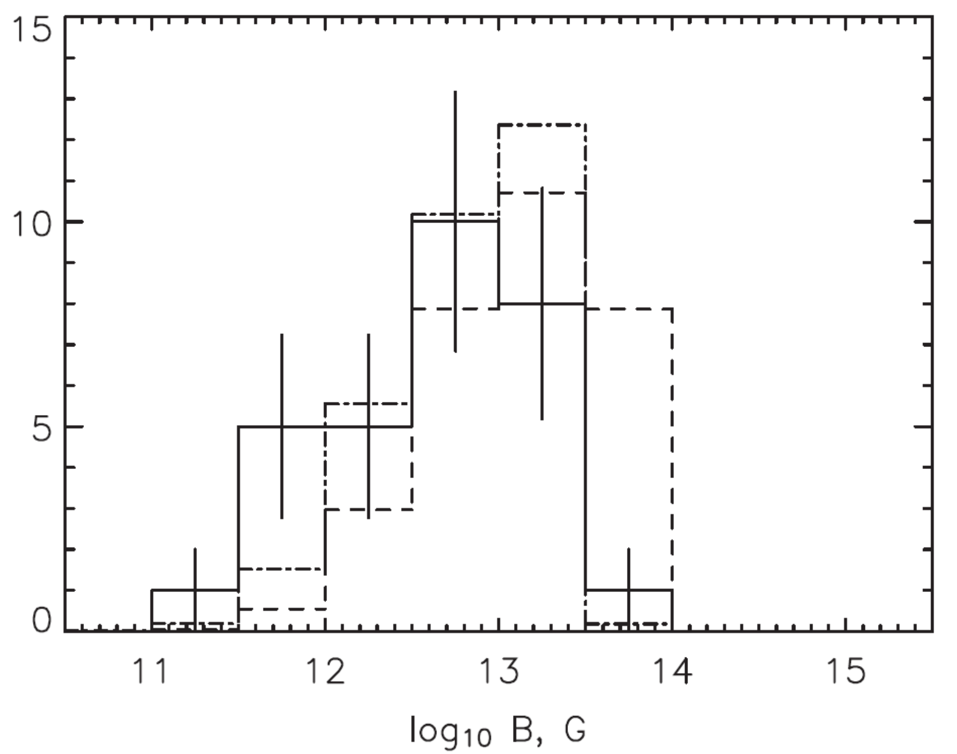
- Field decay
    - Emerging magnetic field
        - Toroidal magnetic field

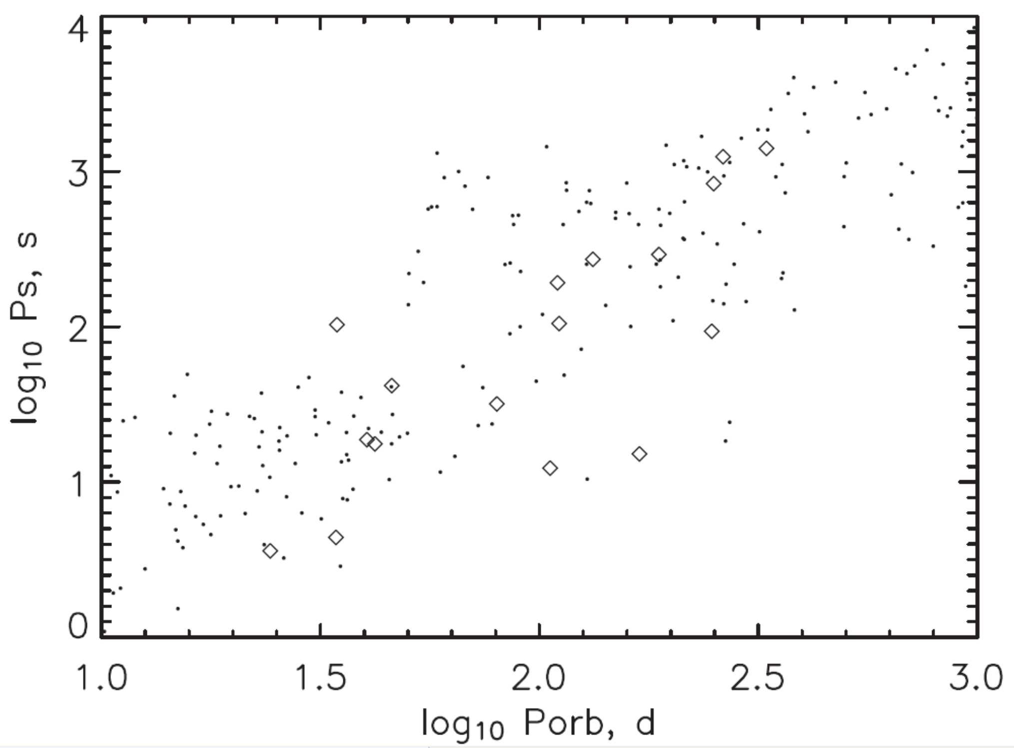
FIELD DECAY IN HMXBS

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



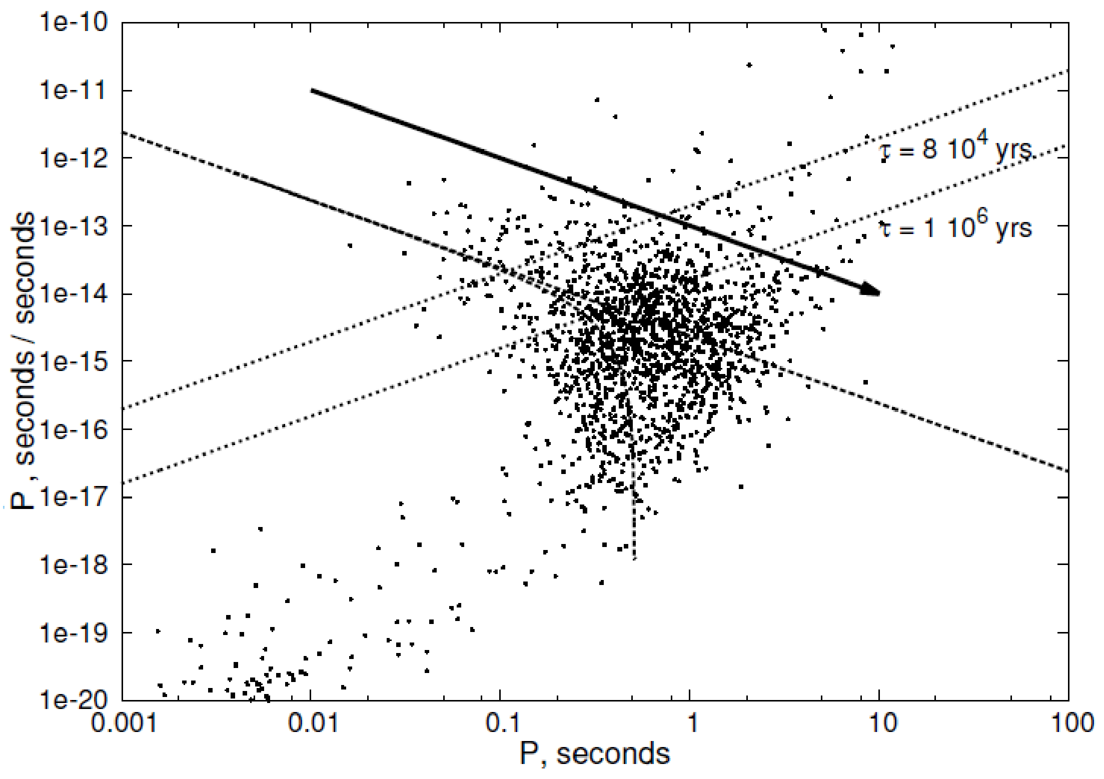
Chashkina, Popov (2012)





MODIFIED PULSAR CURRENT

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



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

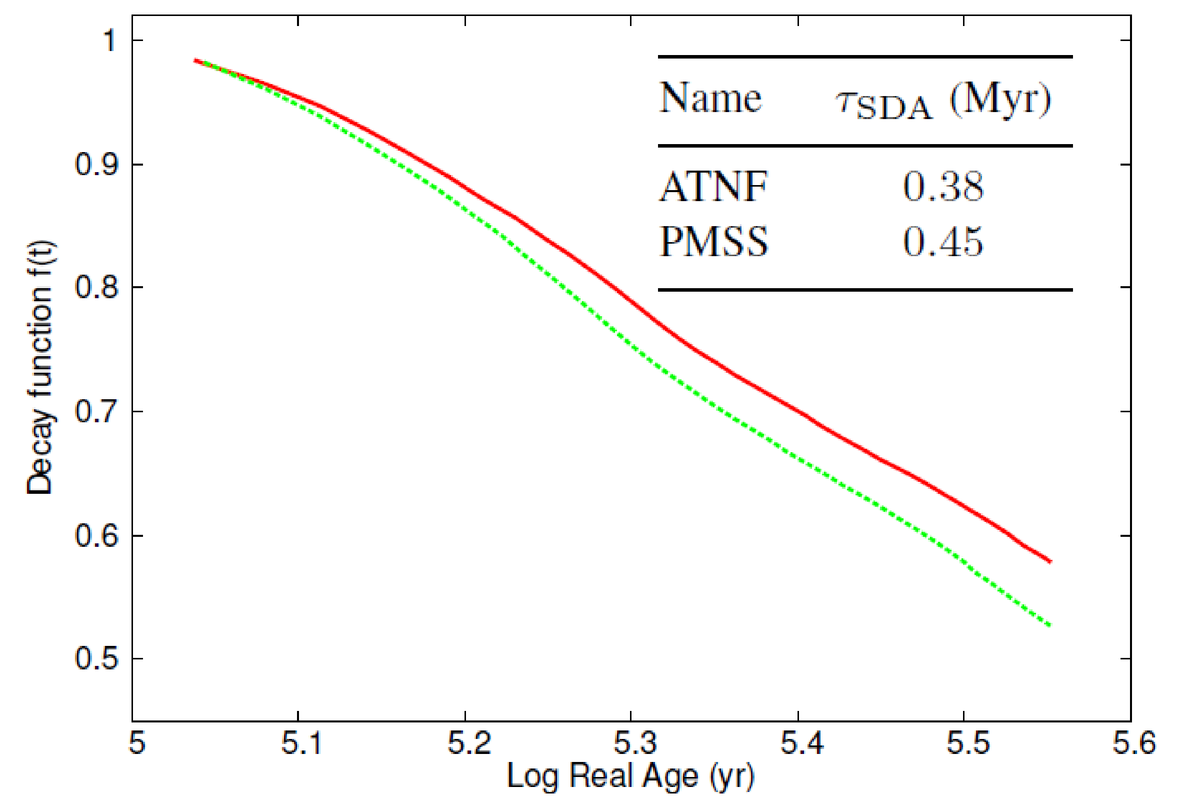
We use distribution in characteristic ages
to reconstruct the field evolution.

Igoshev, Popov (2014). arXiv:1407.6269

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).



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

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 ~$4\ 10^5$ yrs.
Note, this decay is limited in time.

WHAT KIND OF DECAY DO WE SEE?

Ohmic decay due to phonons

Hall cascade

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

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

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

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

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

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

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

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

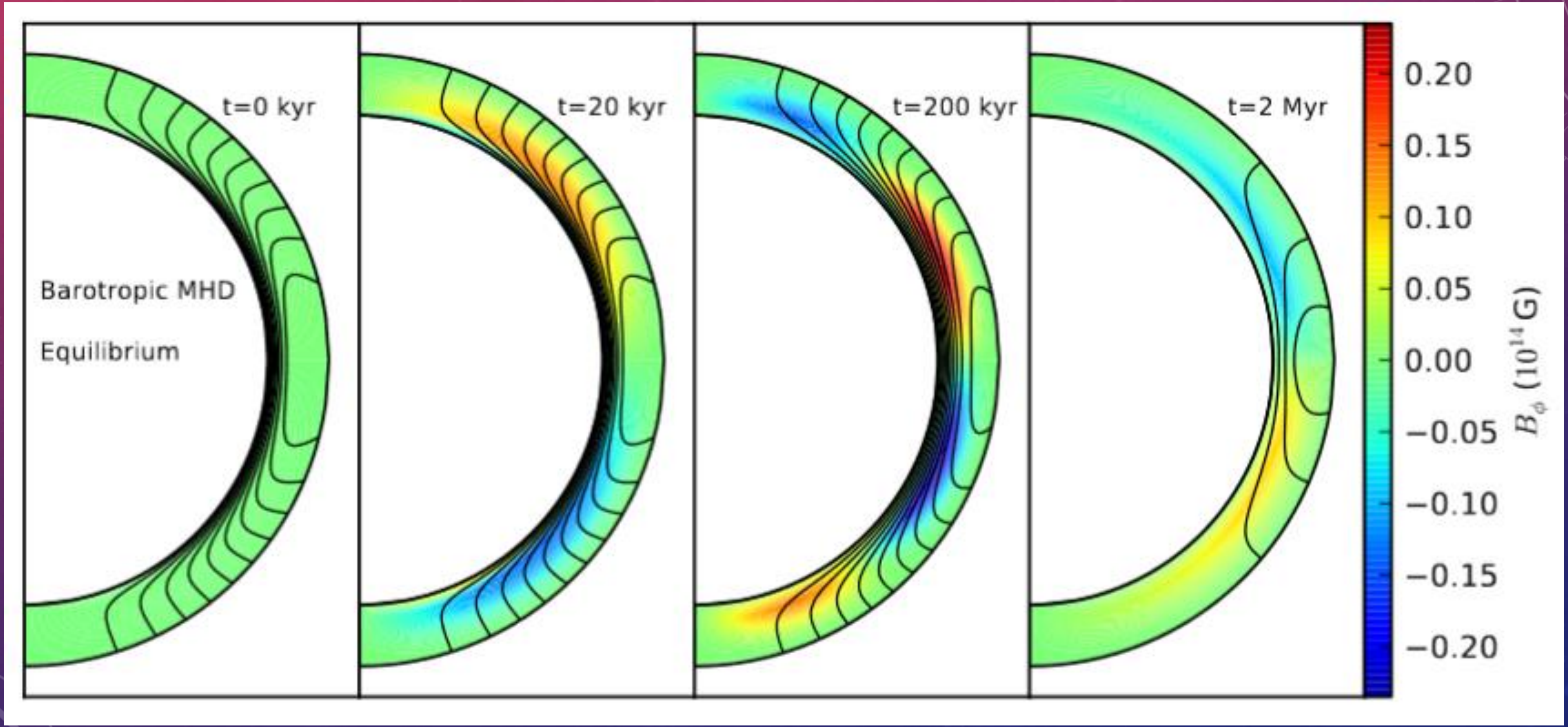
Resistivity can be due to

- Phonons
- Impurities

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

HALL CASCADE AND ATTRACTOR

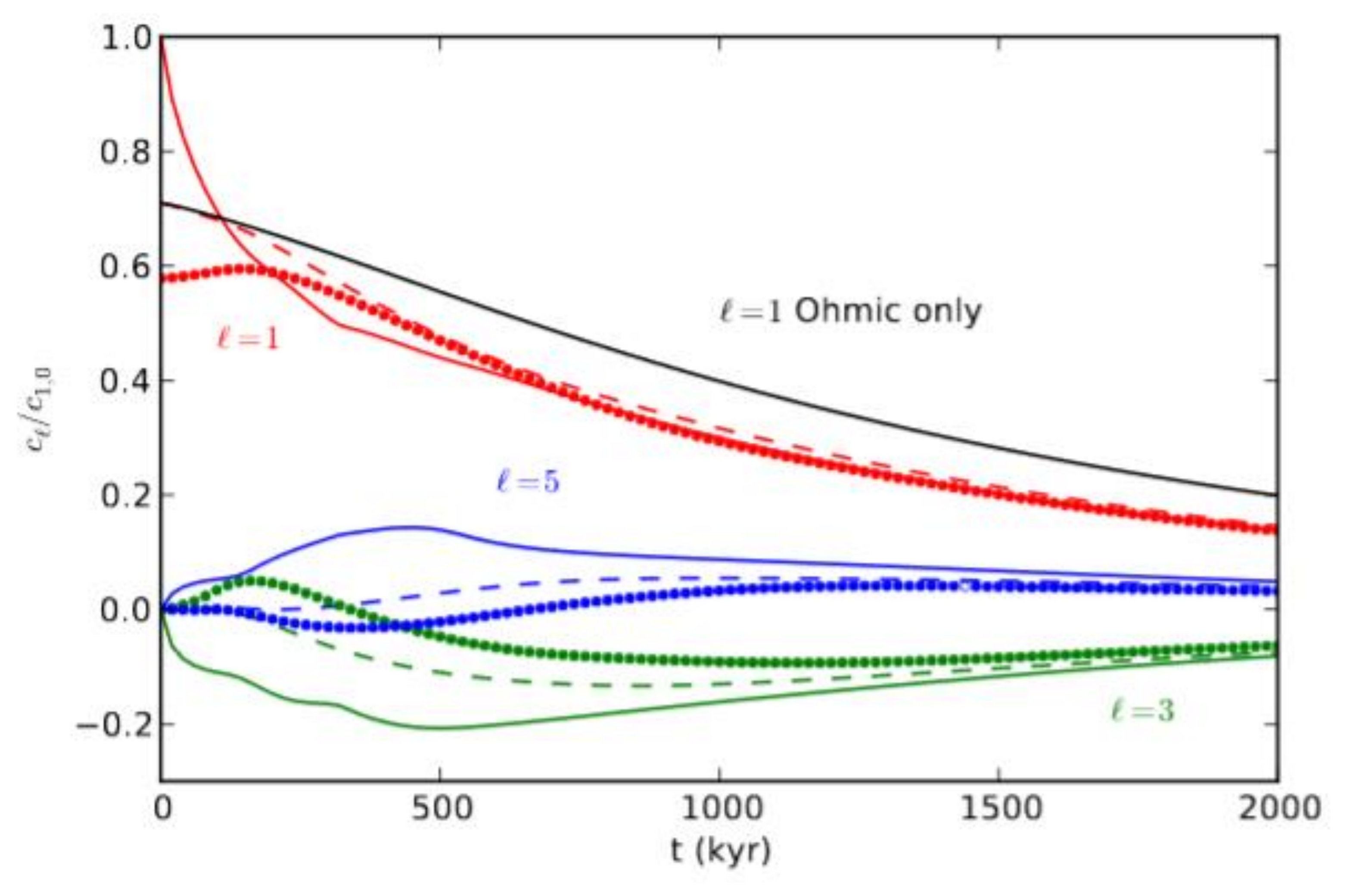
The system is trying to relax towards a state of isorotation, with the electron fluid having the same angular velocity on a poloidal field line.



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

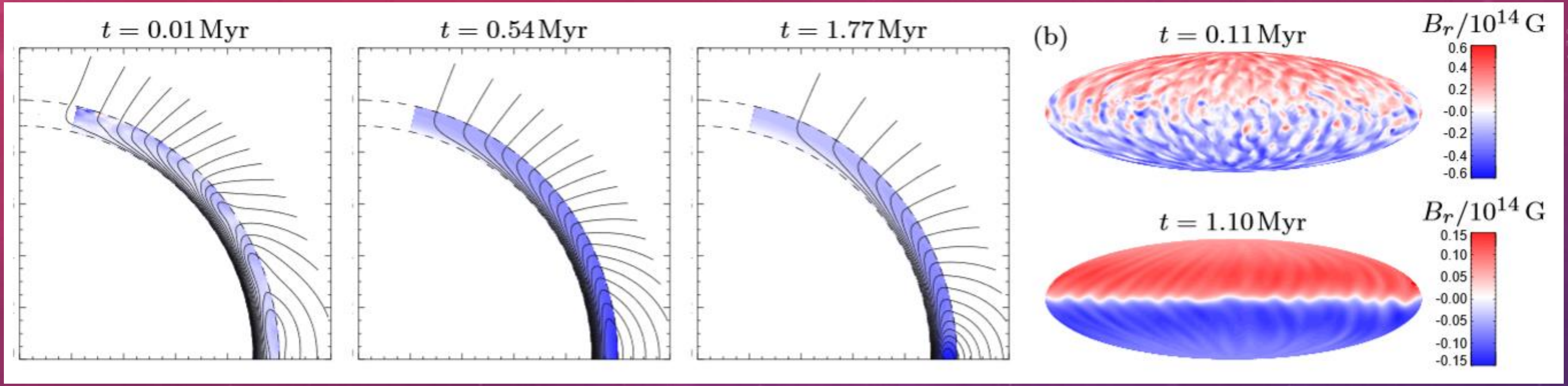
EVOLUTION OF DIFFERENT COMPONENTS

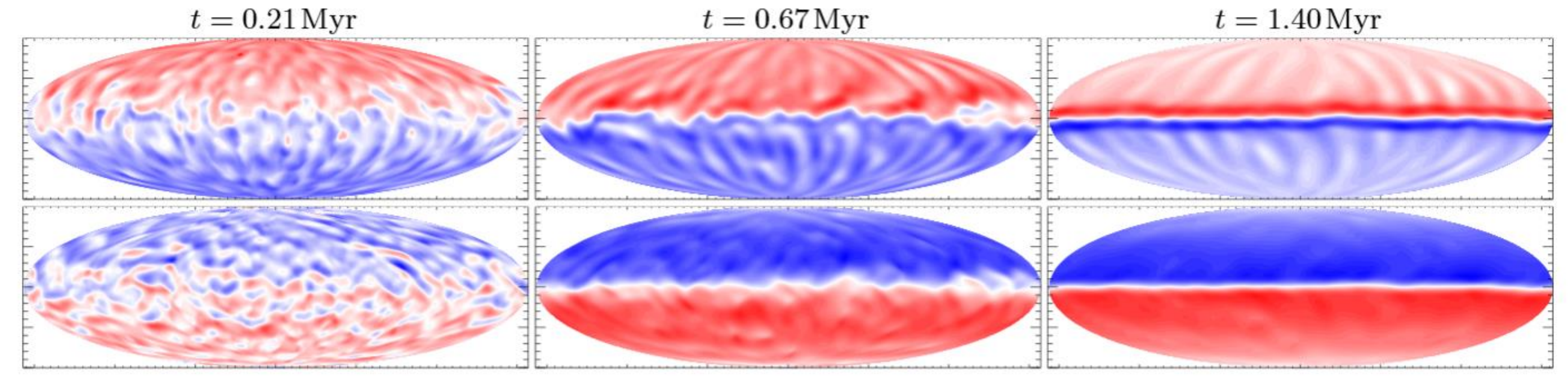
1311.7004



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

NEW STUDIES OF THE HALL CASCADE



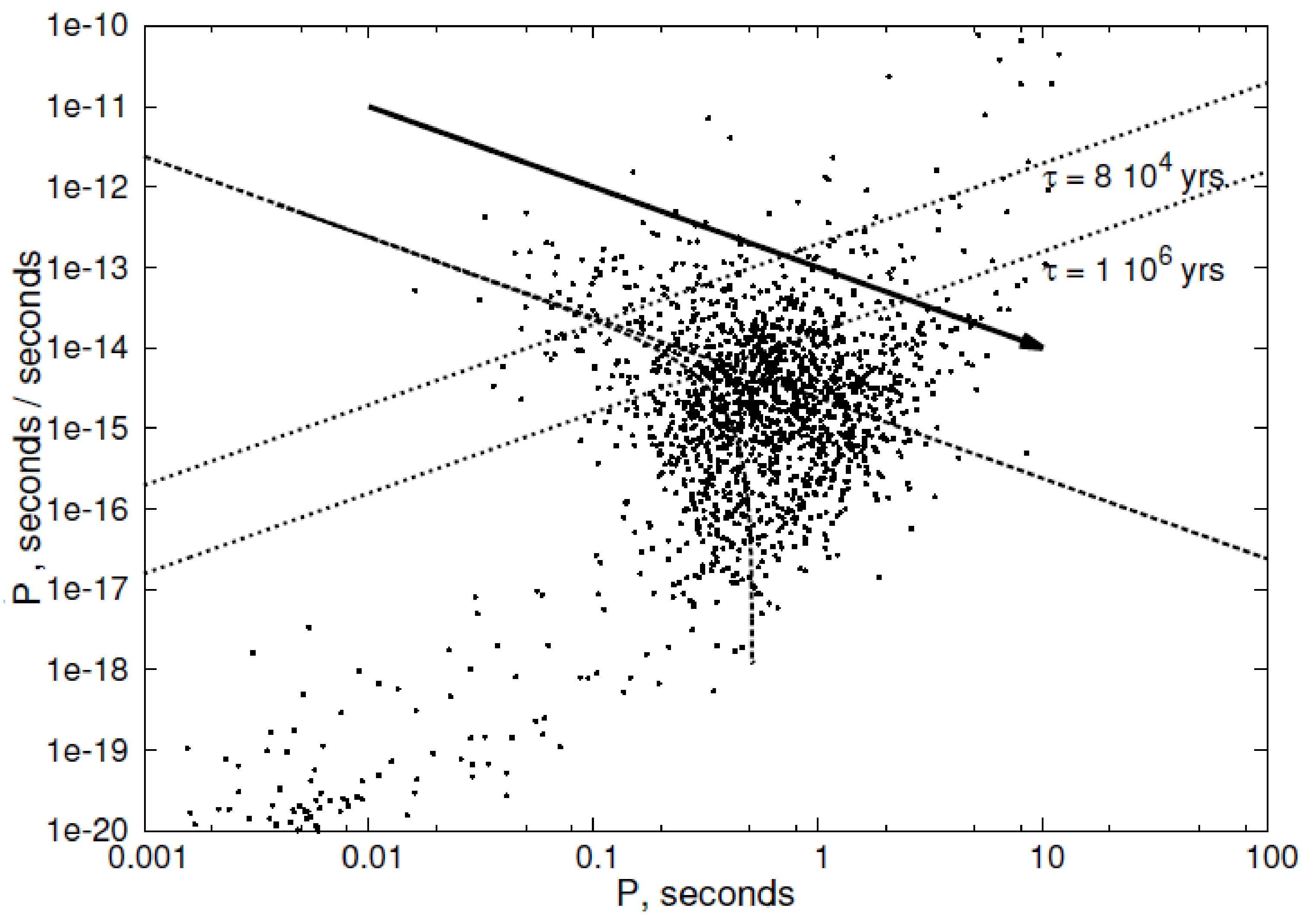


1501.05149

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

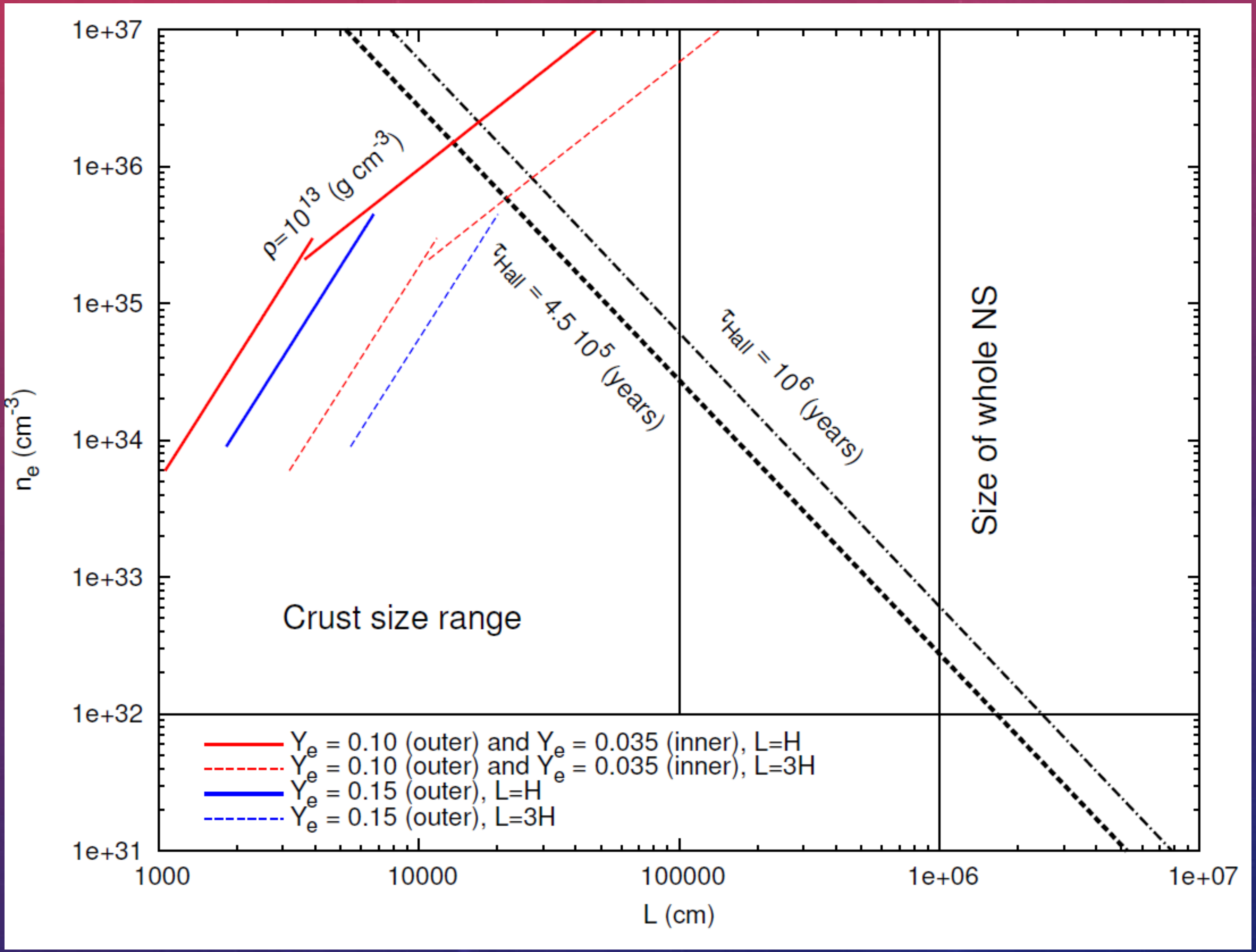
See also 1604.01399

CAN WE SEE THE HALL ATTRACTOR ???



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

WHERE THE CURRENTS ARE LOCATED?



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

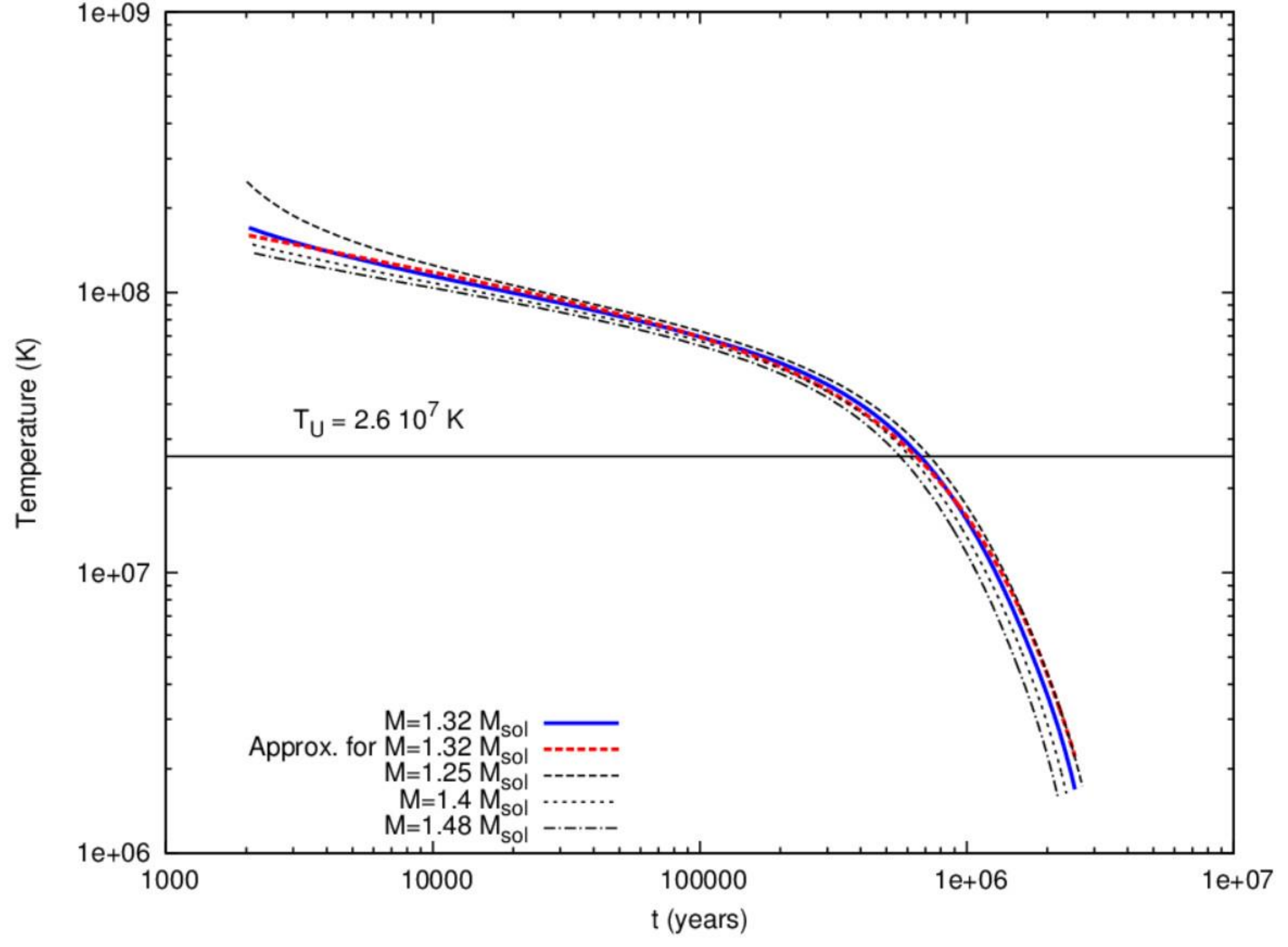
$$L \approx H = P(\rho)/(\rho g)$$

Igoshev, Popov (2015). arXiv: 1507.07962

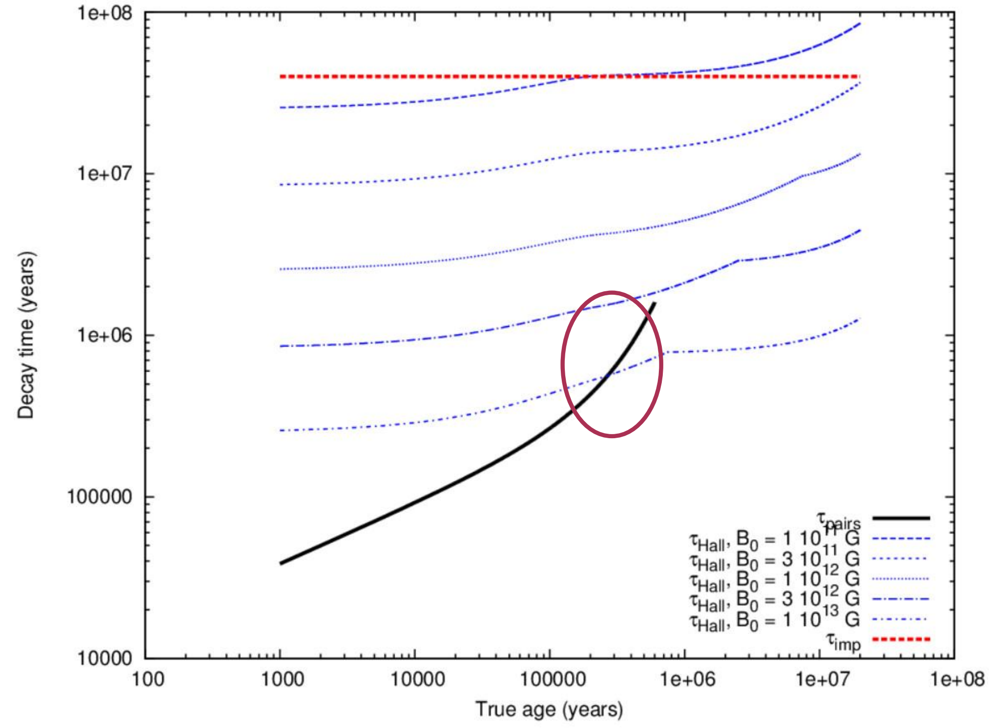
THERMAL EVOLUTION

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.

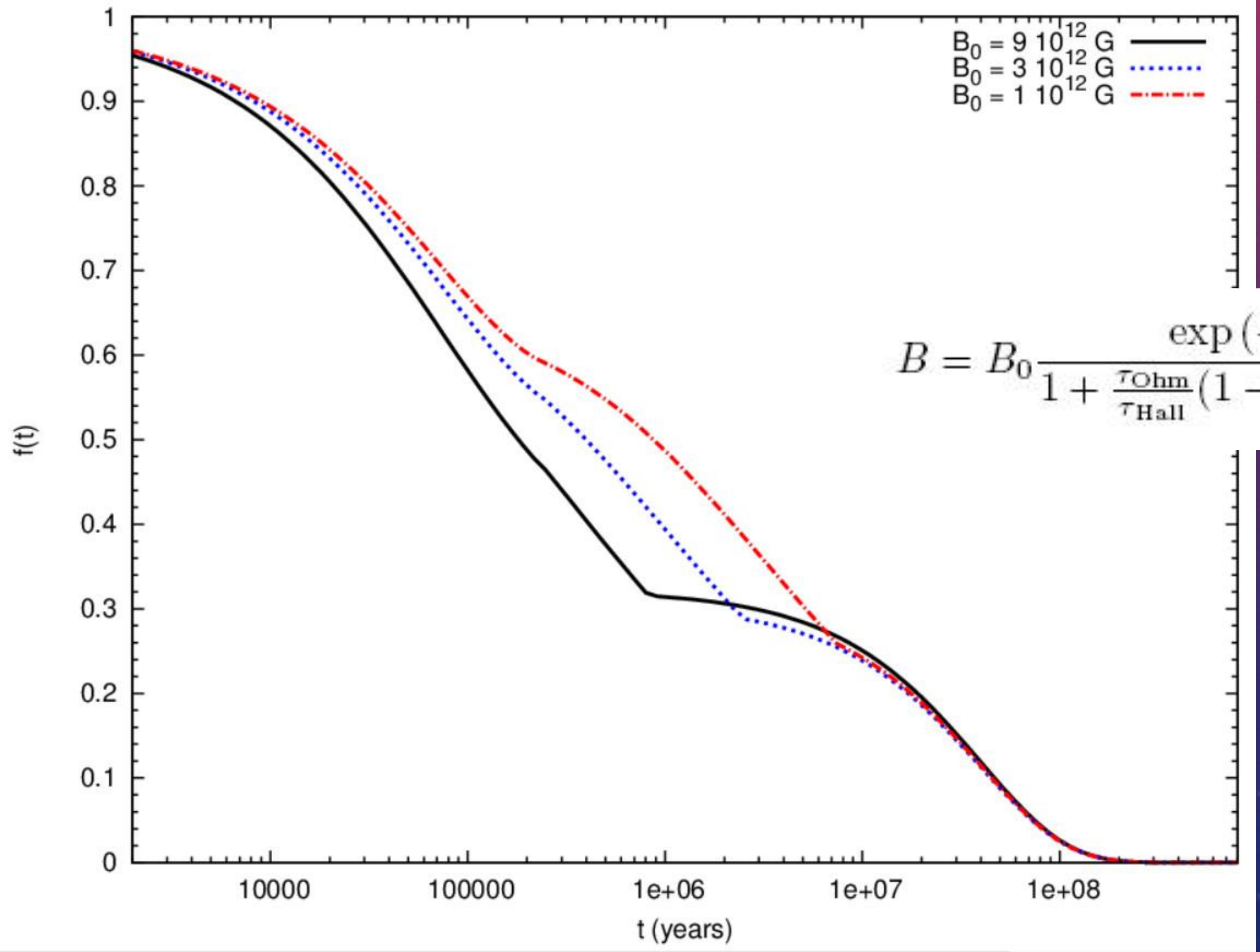
$$B = B_0 \frac{\exp\left(-t/\tau_{\rm Ohm}\right)}{1 + \frac{\tau_{\rm Ohm}}{\tau_{\rm Hall}}\left(1 - \exp\left(-t/\tau_{\rm Ohm}\right)\right)}$$

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

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

MAGNETIC FIELD EVOLUTION

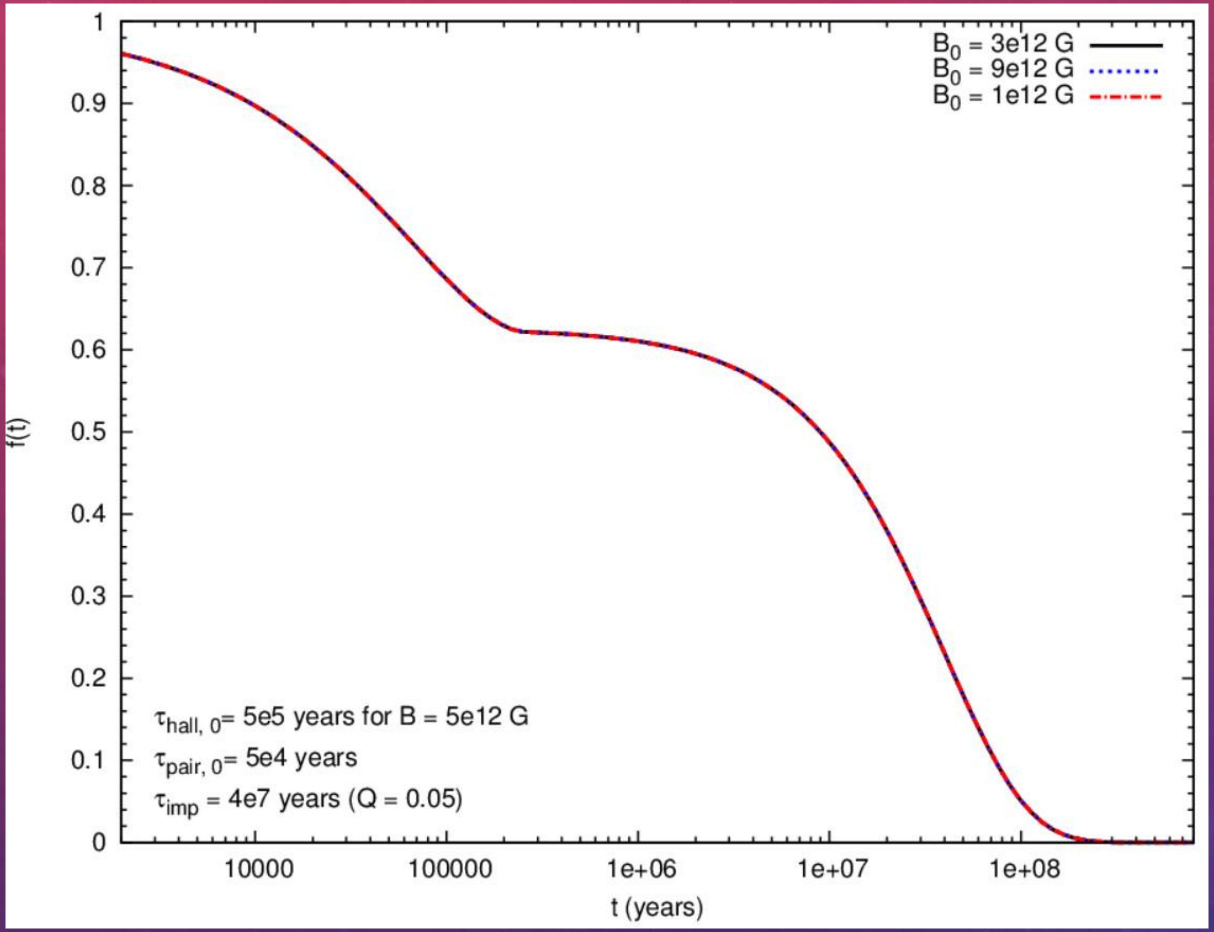
Igoshev, Popov (2015) arXiv: 1507.07962



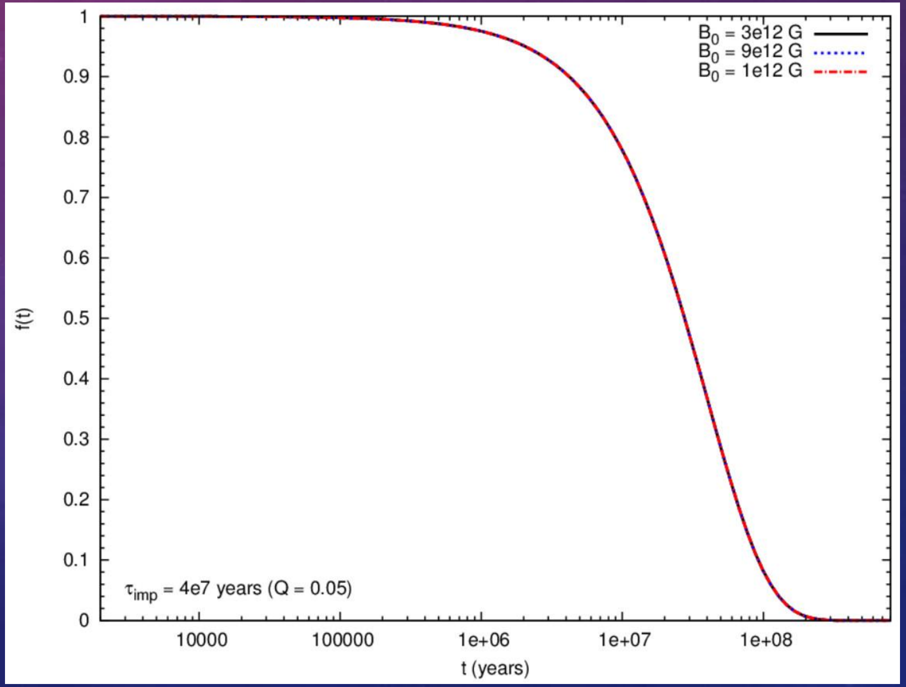
$$B = B_0 \frac{\exp\left(-t/\tau_{\mathrm{Ohm}}\right)}{1 + \frac{\tau_{\mathrm{Ohm}}}{\tau_{\mathrm{Hall}}}\left(1 - \exp\left(-t/\tau_{\mathrm{Ohm}}\right)\right)}$$

All inclusive:
- Hall
- Phonons
- Impurities

ONLY OHMIC DECAY



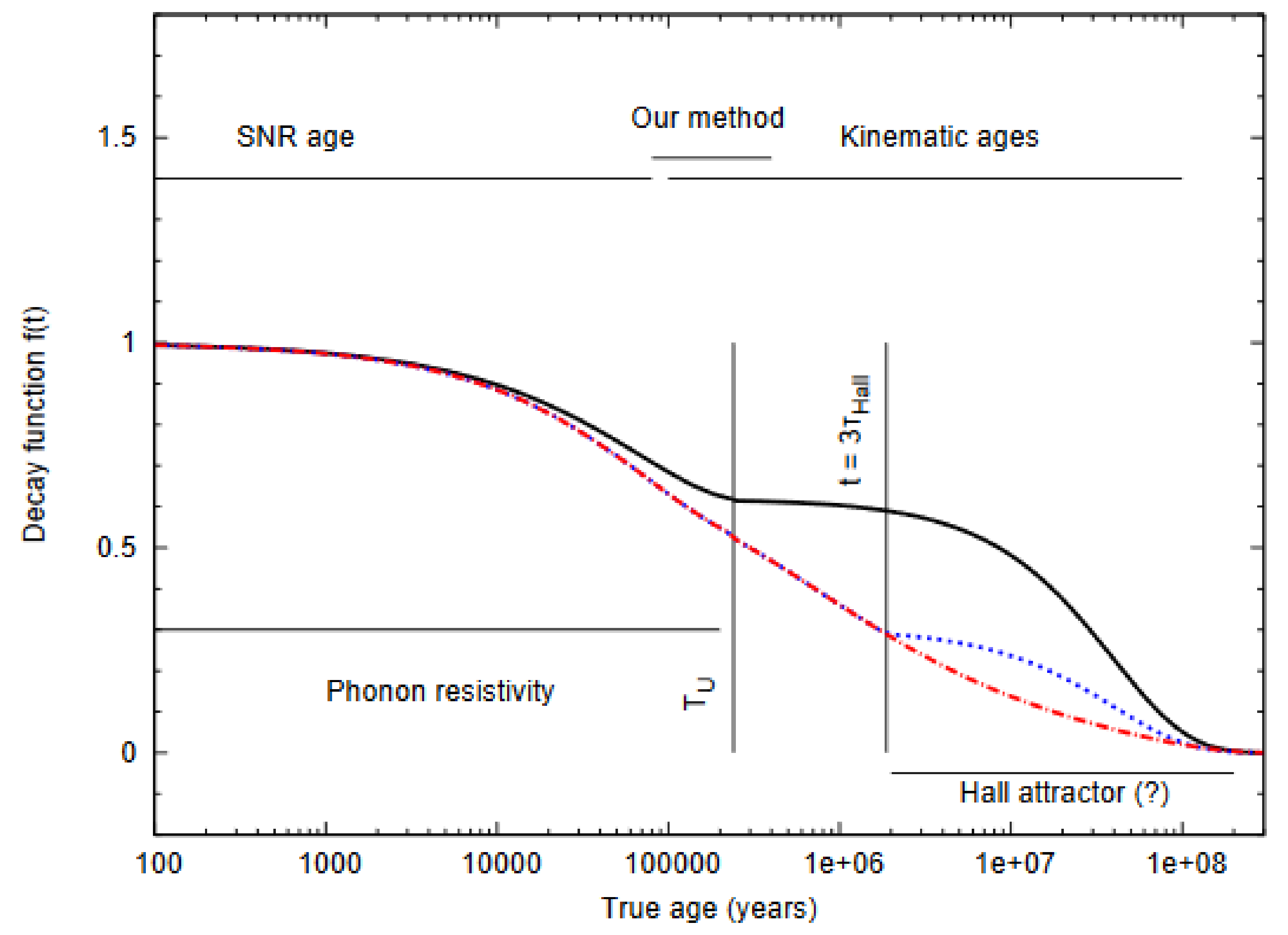
Here the Hall cascade is switched off



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

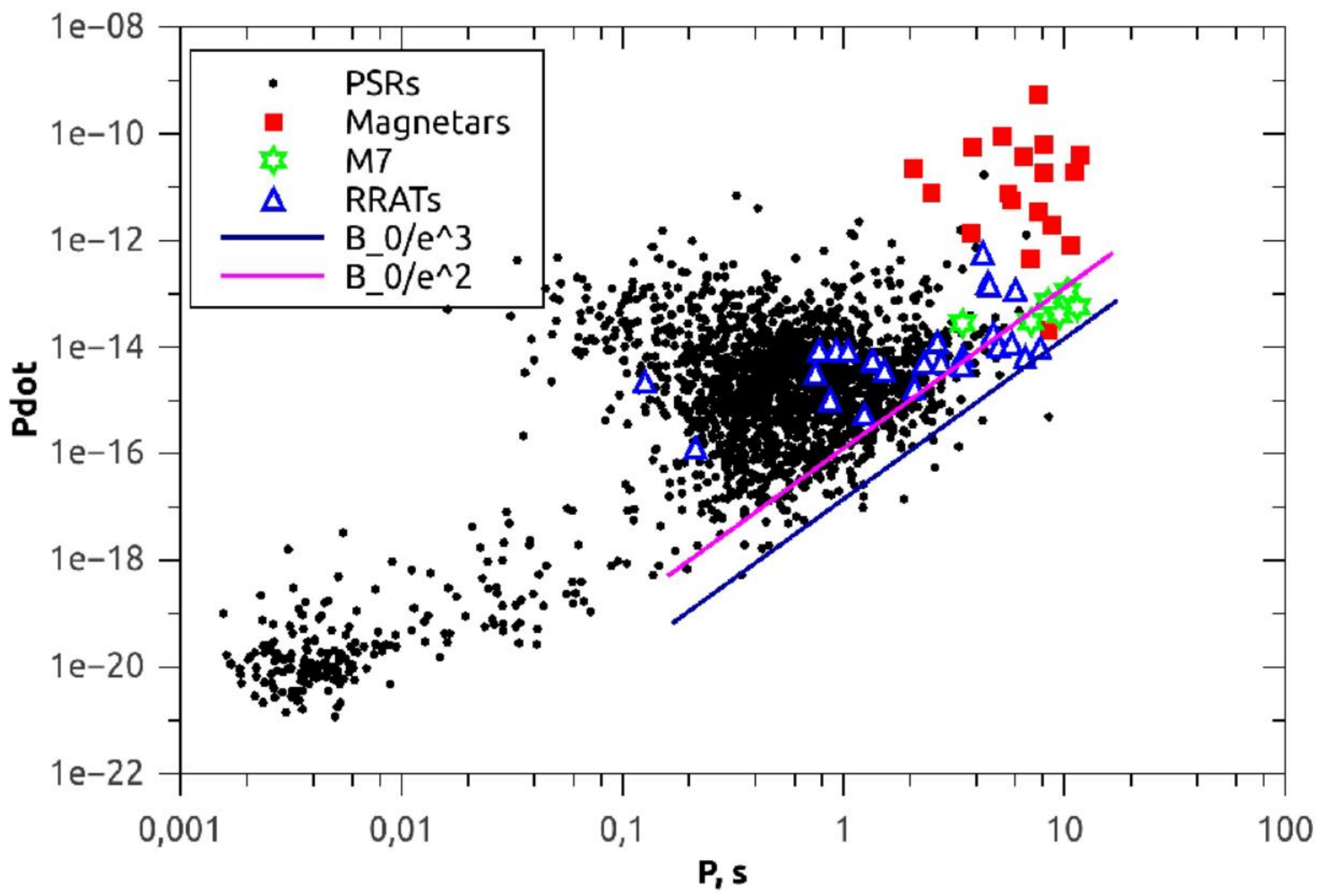
COMPARISON OF DIFFERENT OPTIONS

Igoshev, Popov (2015) arXiv: 1507.07962

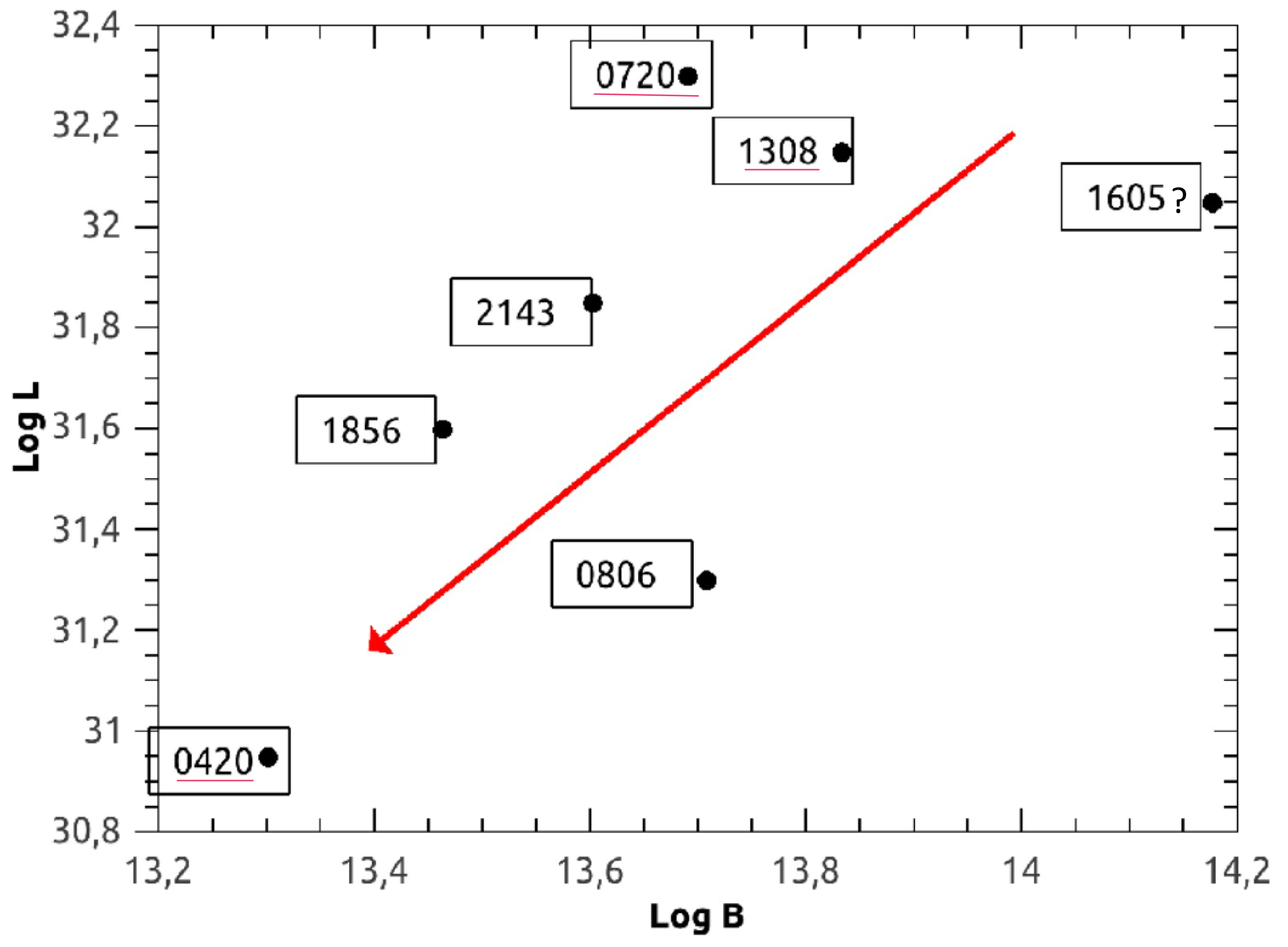


We think that in the range ~10^5 – 10^6 yrs we see mostly Ohmic decay, which then disappears as NSs cool down below the critical T.

GETTING CLOSE TO THE ATTRACTOR

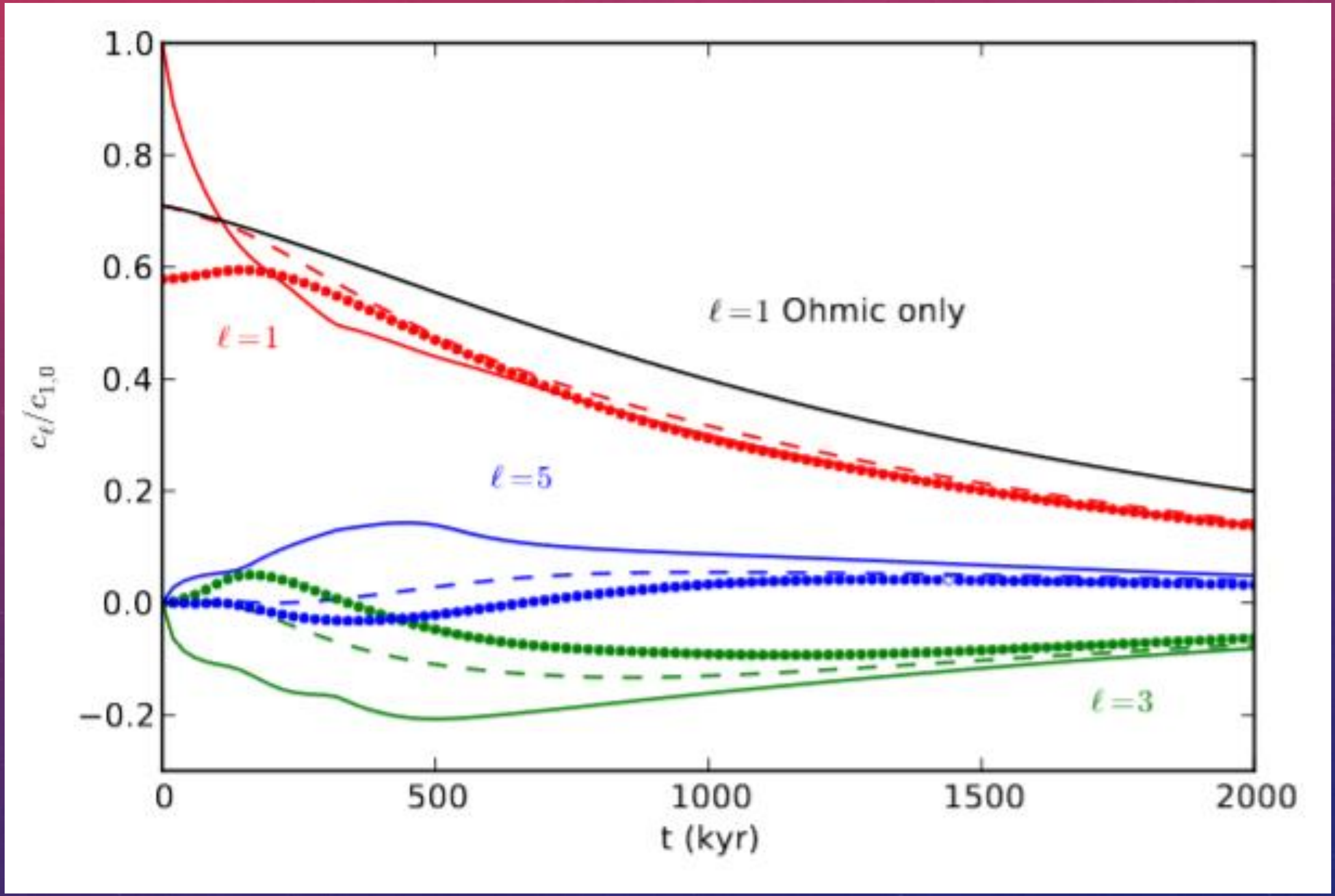


WHO IS CLOSER TO THE ATTRACTOR STAGE?



EVOLUTION OF DIFFERENT COMPONENTS

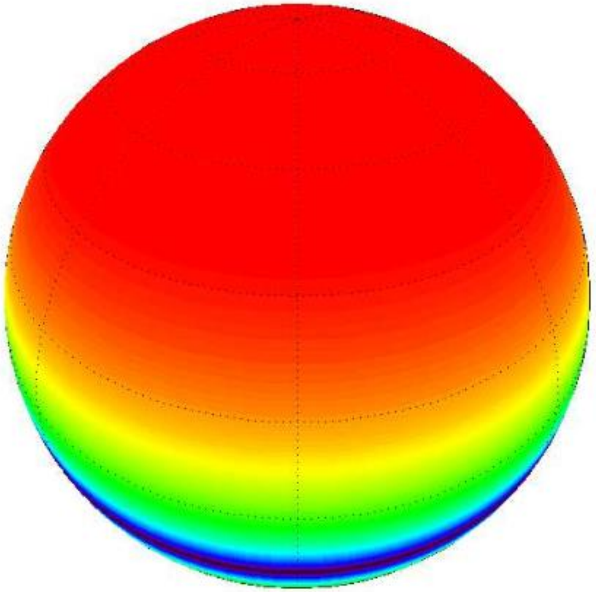
1311.7004

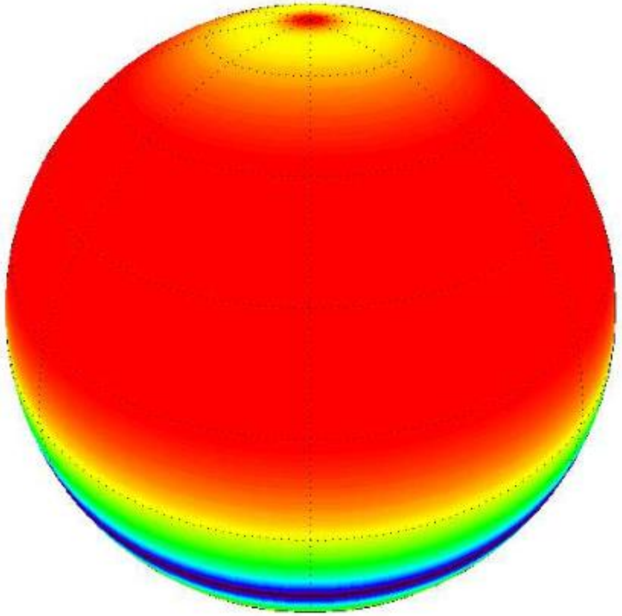


Hall attractor mainly consists of dipole and octupole

TEMPERATURE MAPS

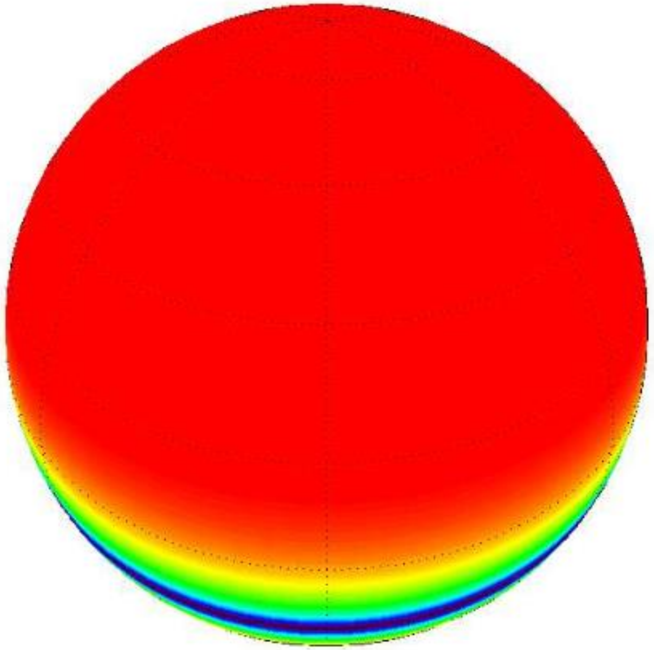
Pure dipole

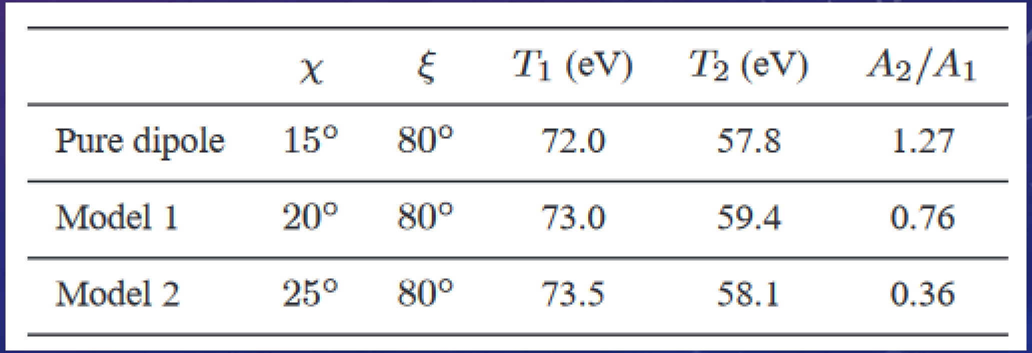




Dipole + octupole
(Model 1)

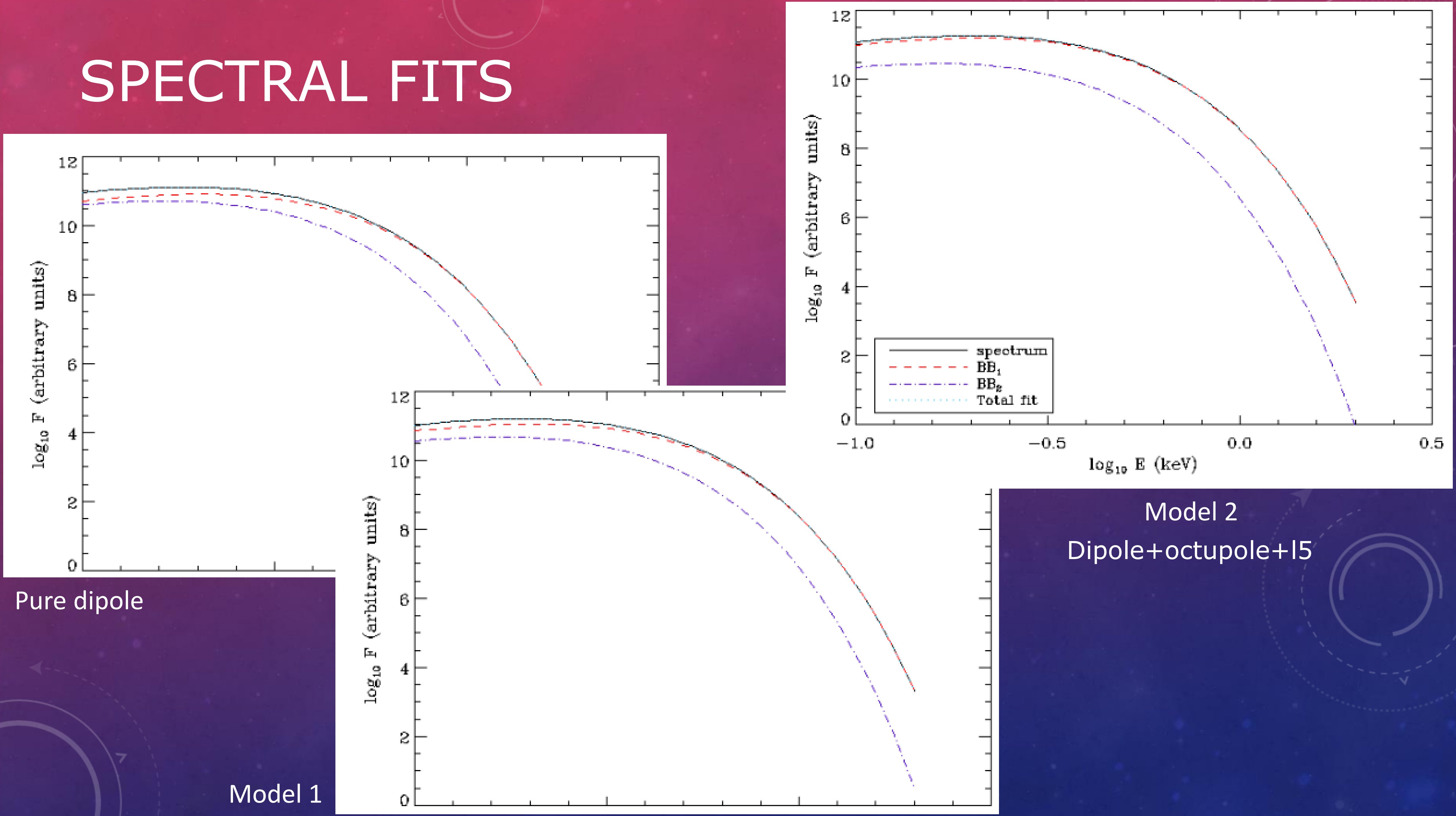
Dipole+octupole+l5





	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



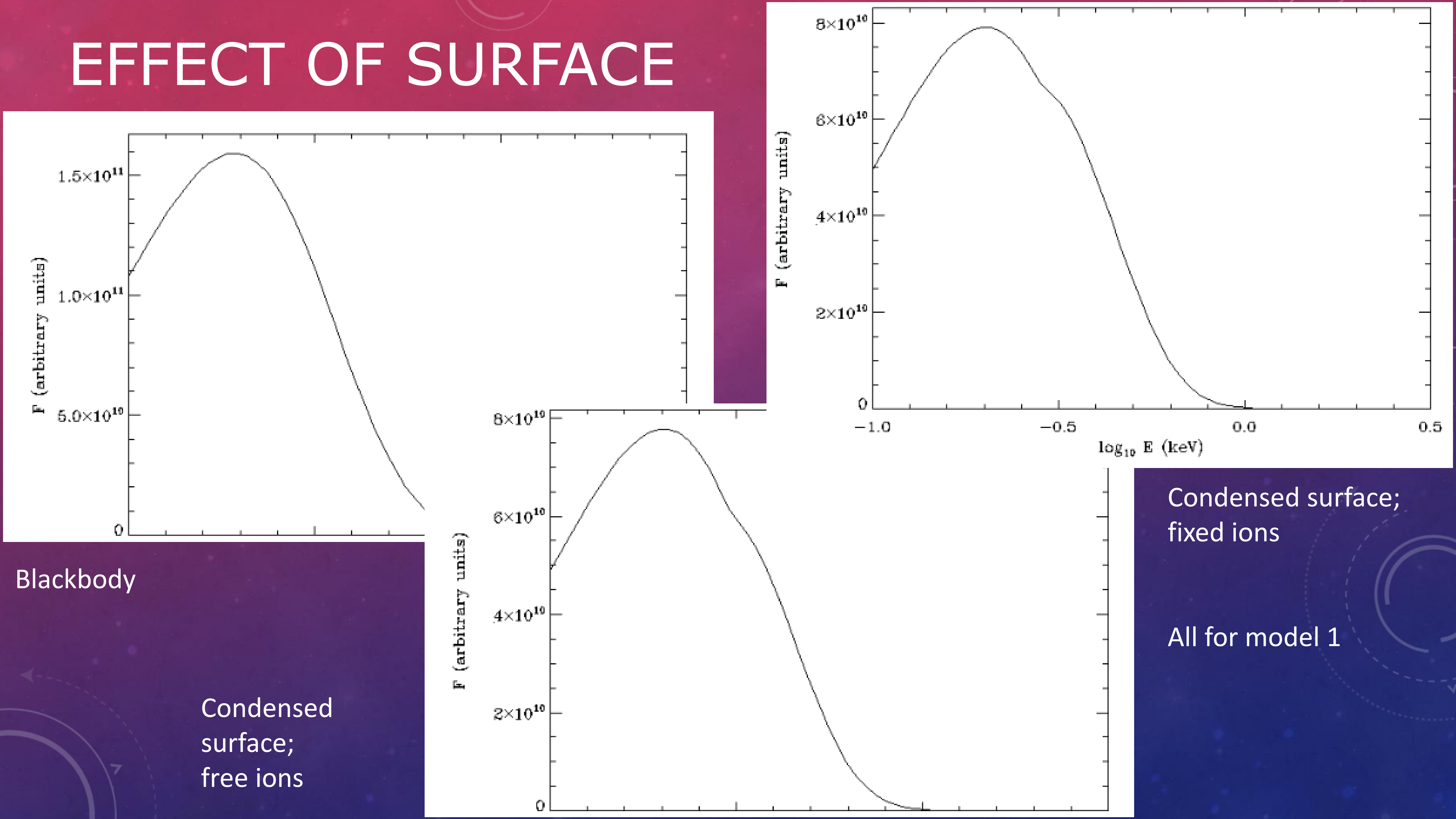
Pure dipole

Model 1

Model 2

Dipole+octupole+l5

EFFECT OF SURFACE



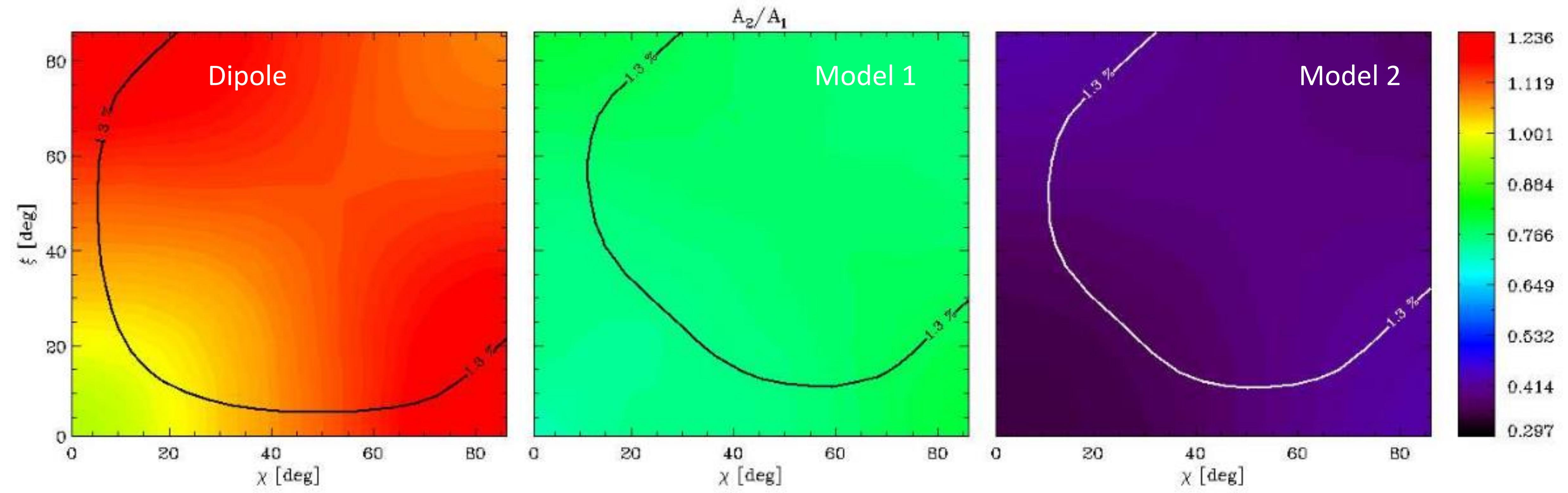
Blackbody

Condensed surface;
free ions

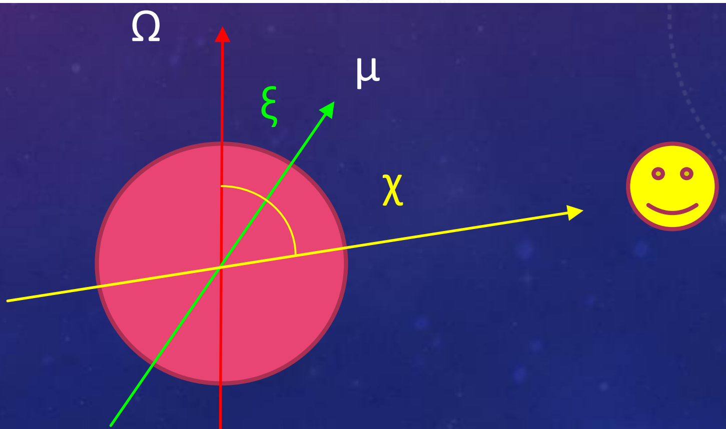
Condensed surface;
fixed ions

All for model 1

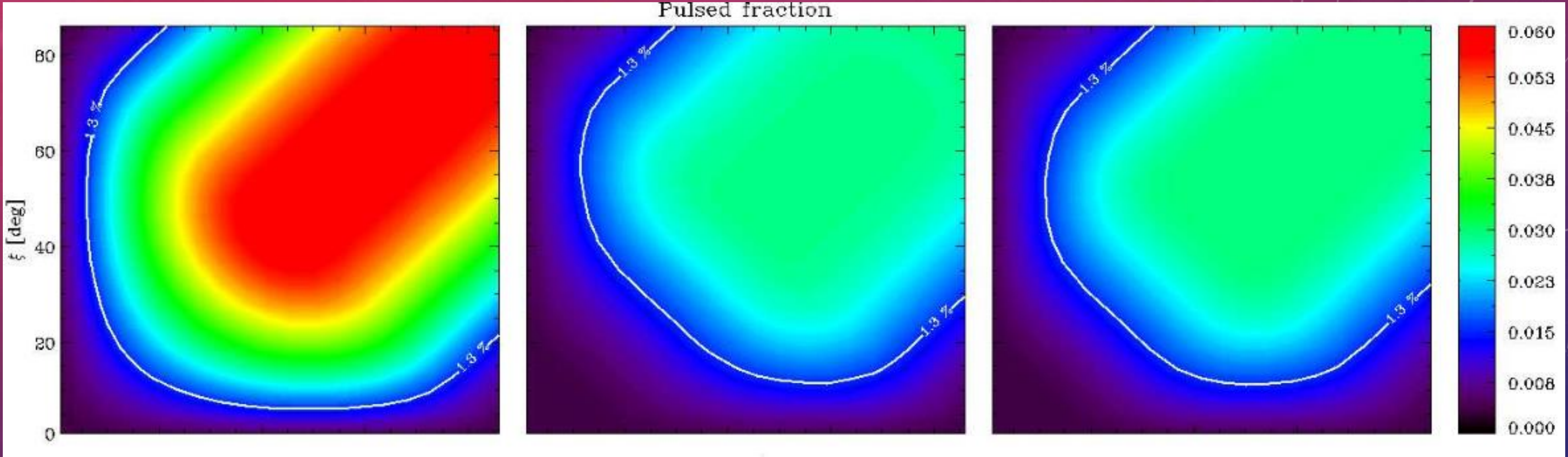
EMITTING AREAS

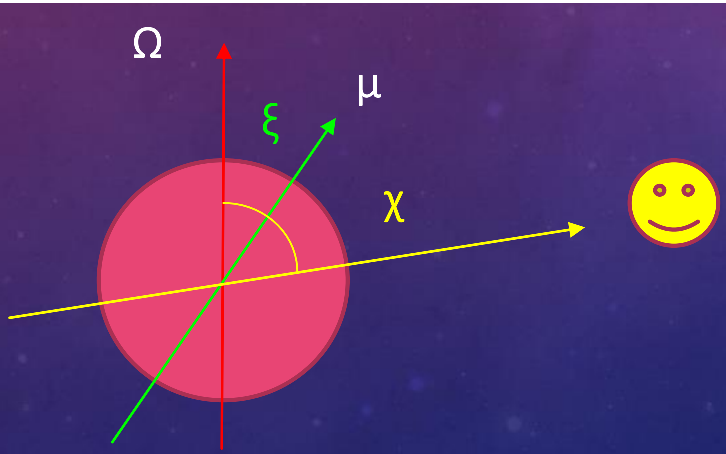


Only for dipole the emitting area corresponding to cooler region is larger.

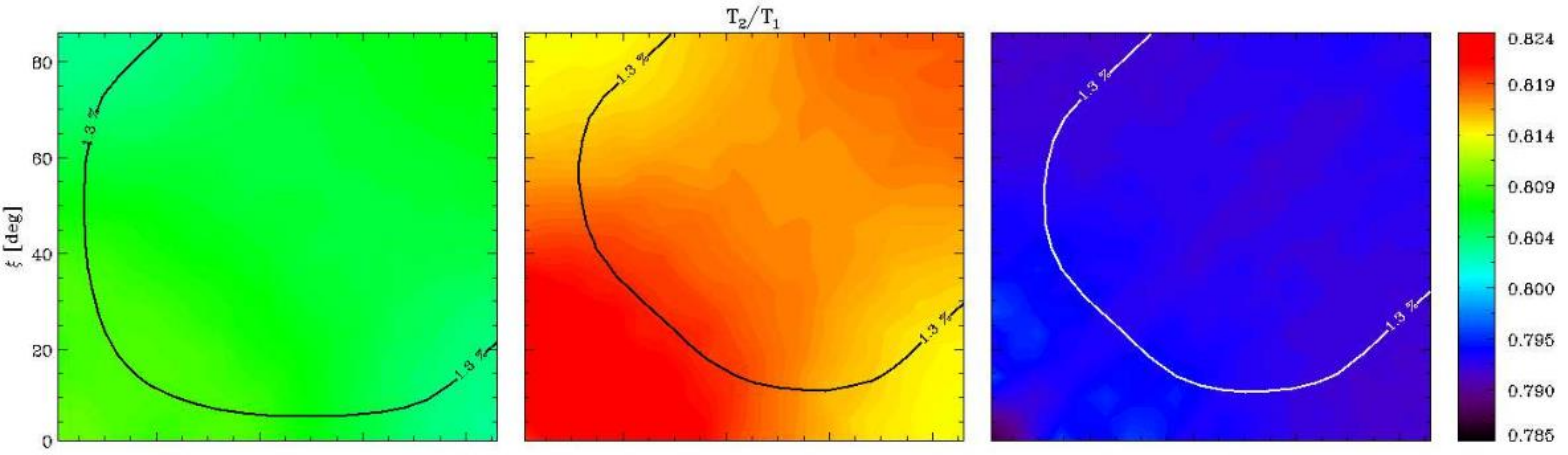


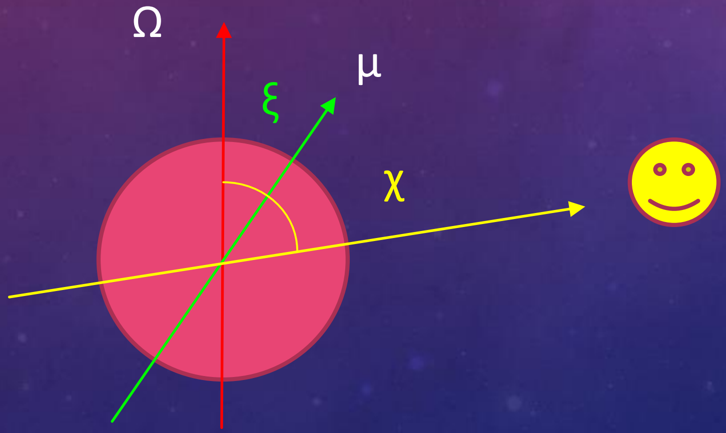
PULSED FRACTION





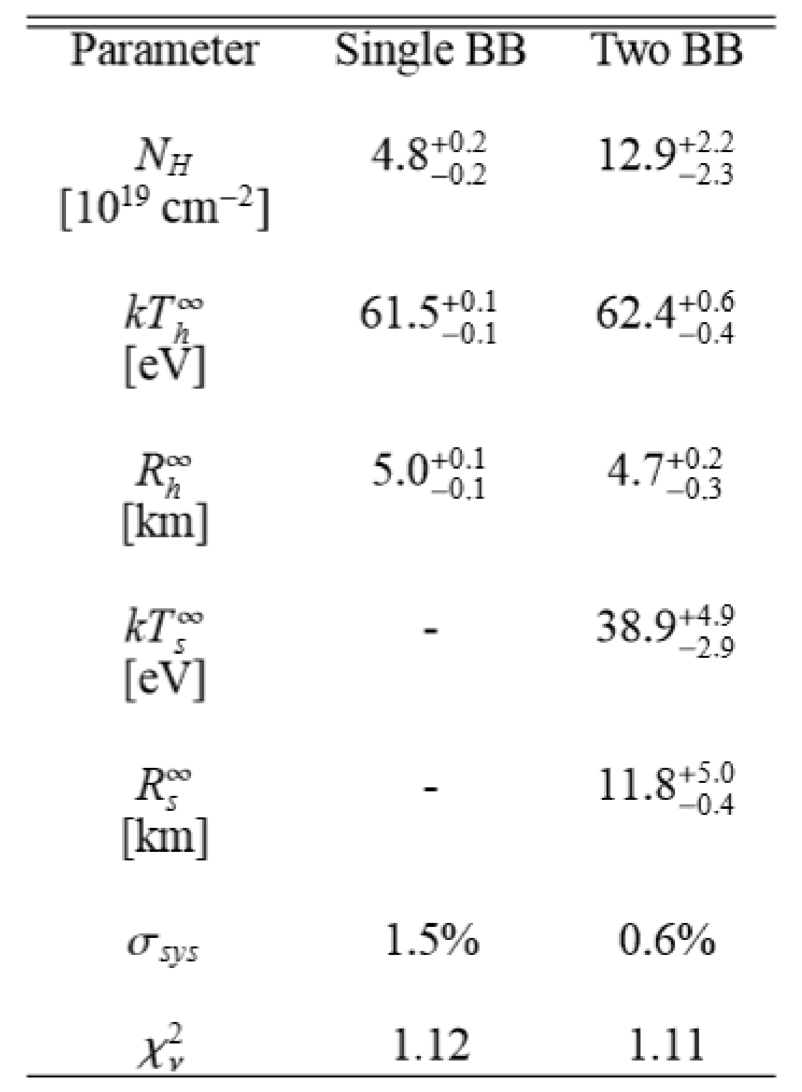
TEMPERATURE RATIO





OBSERVATIONAL DATA

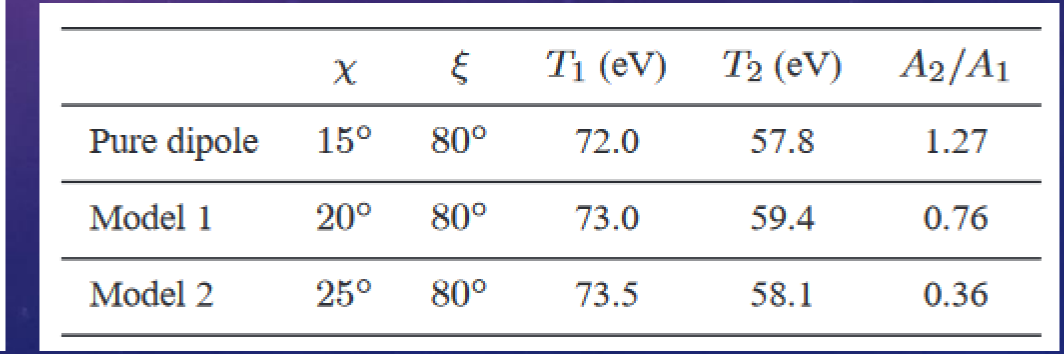
1202.2121



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



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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

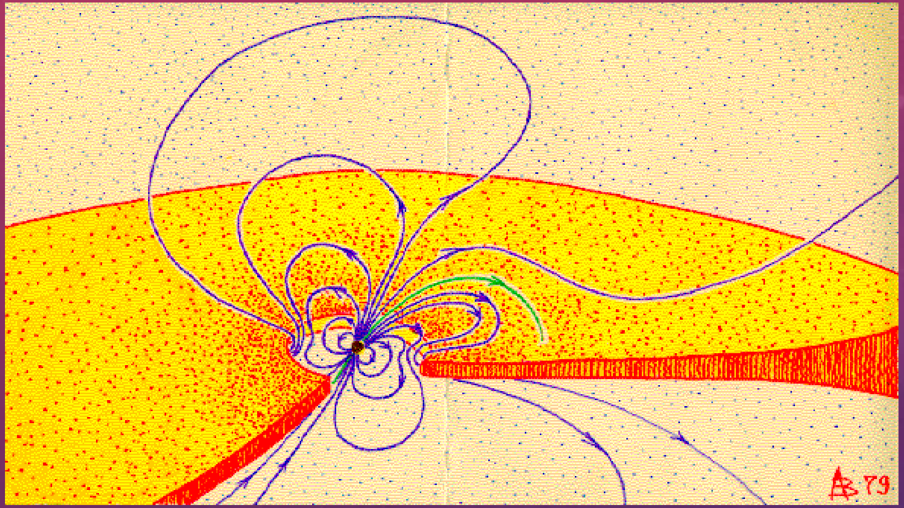
Kinematic age is larger for 0720,
but characteristic age – for 1856.

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

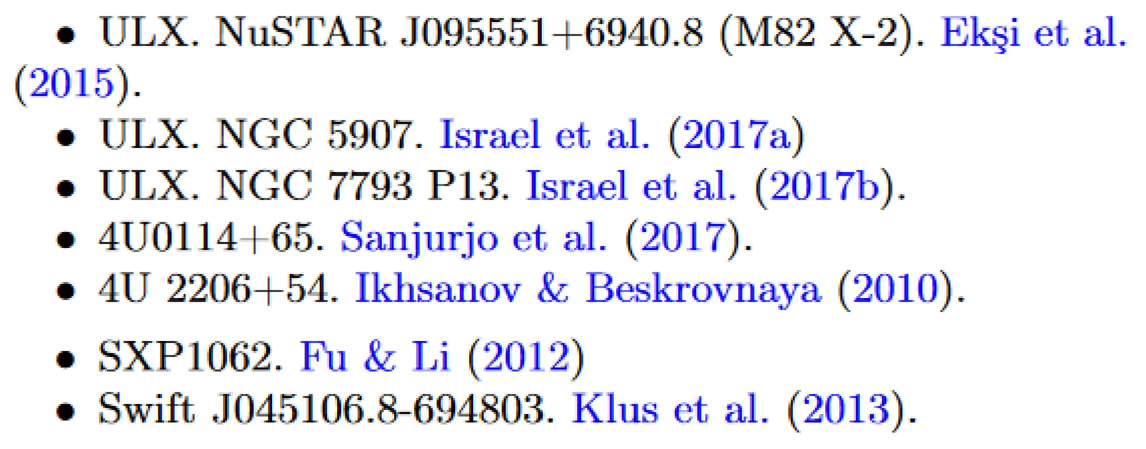
RX J0720 shows several types
of activity, but RX J1856 is
a very quiet source.

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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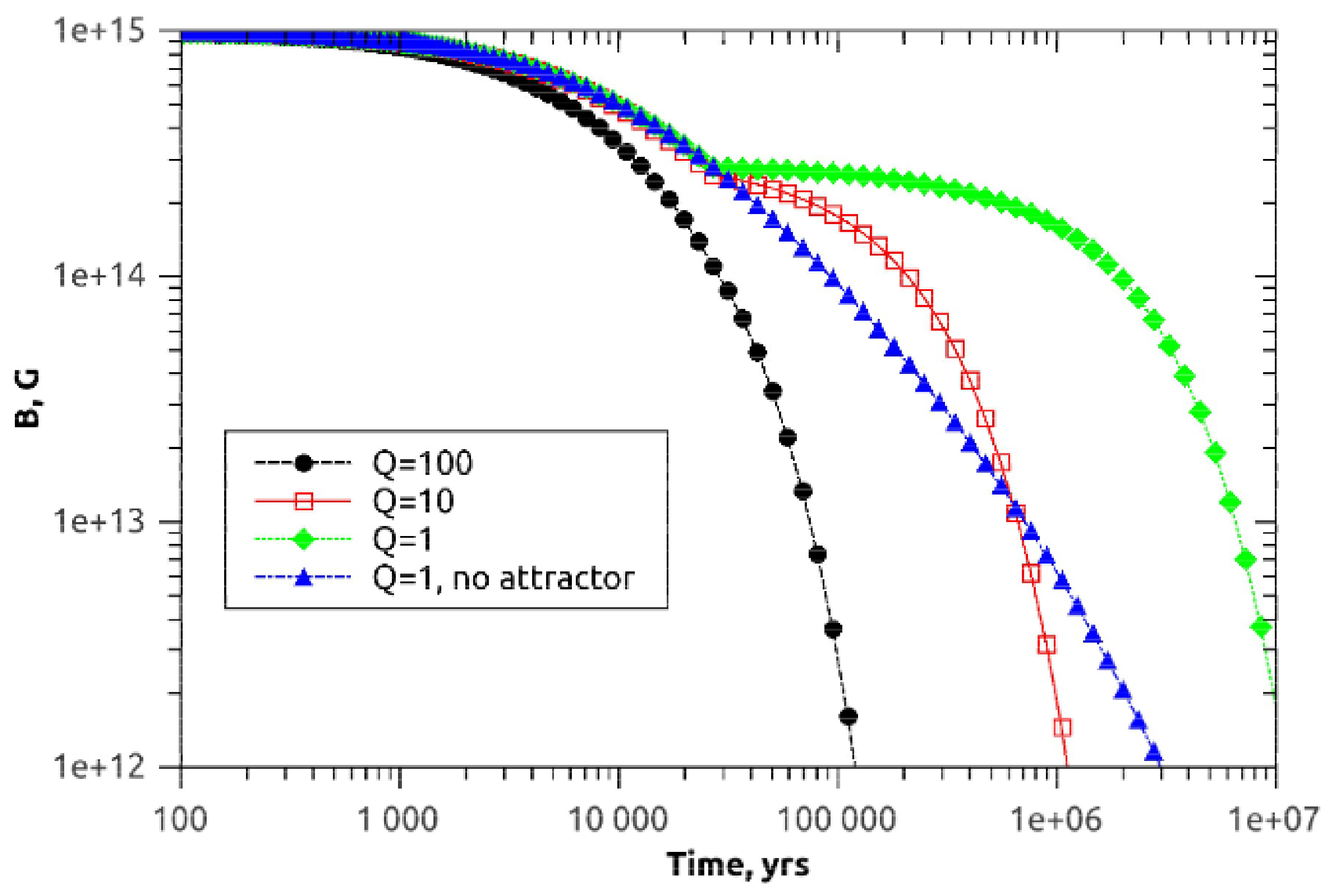
FIELD EVOLUTION IN A MAGNETAR



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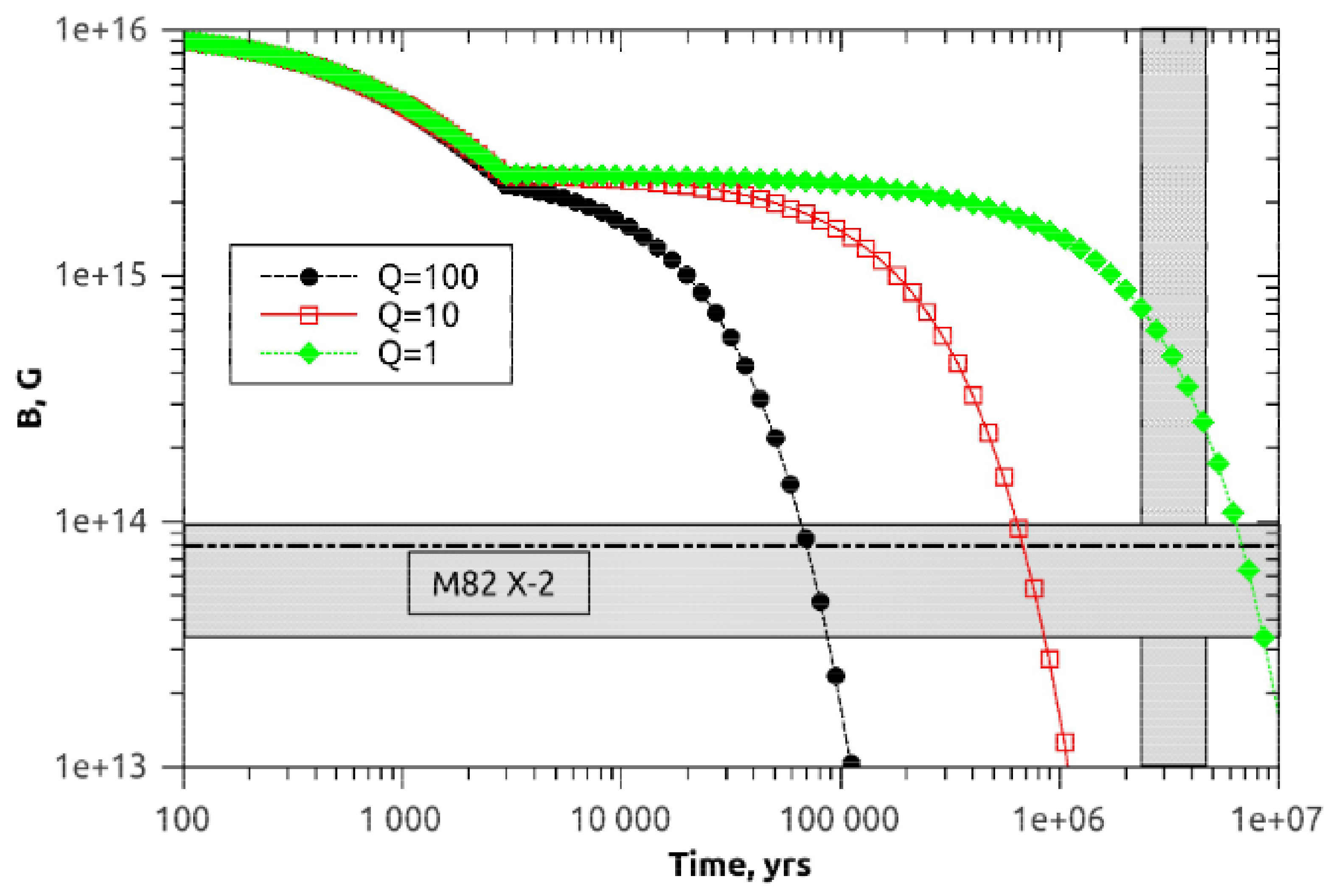
PARAMETERS OF ULX M82 X-2



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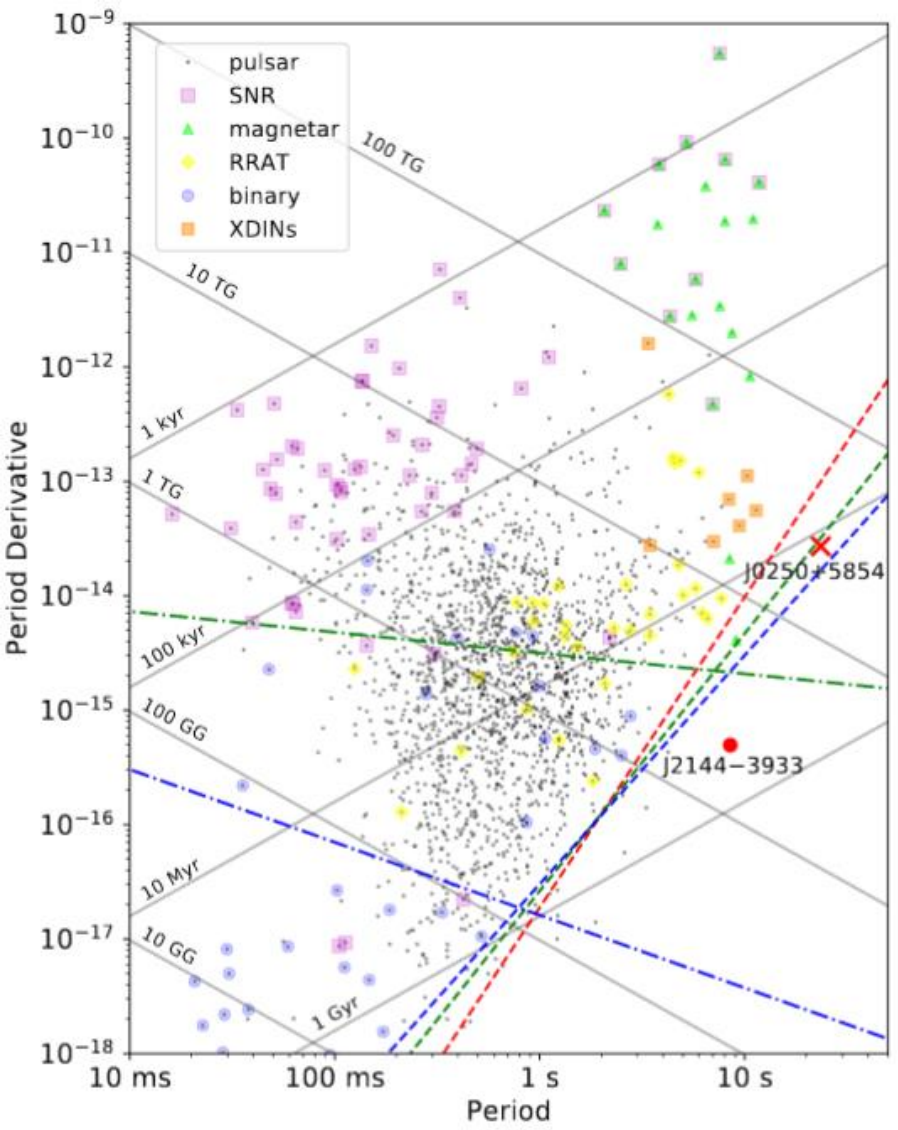
RECORD LONG SPIN PERIOD RADIO PULSAR



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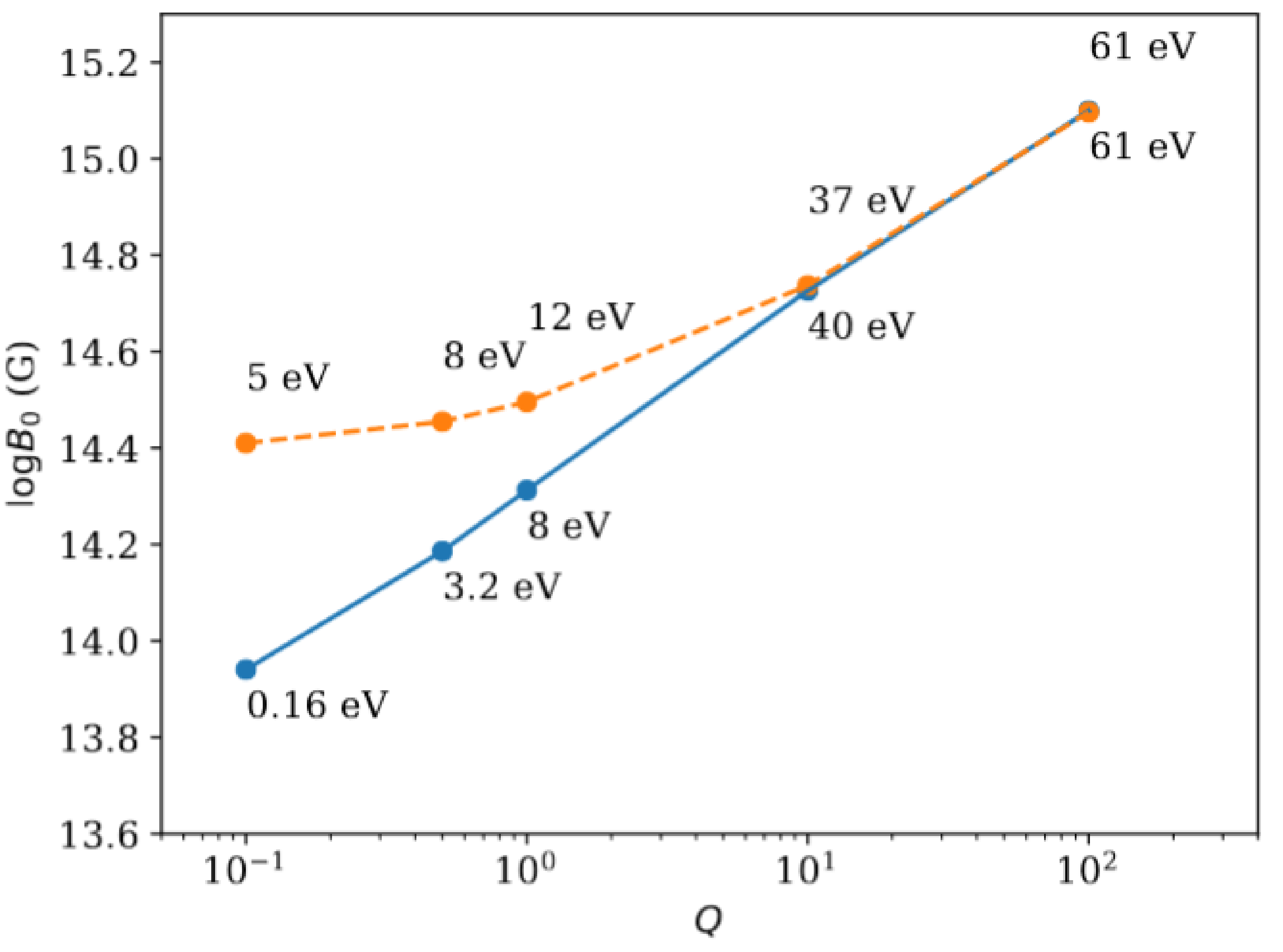

1809.07968

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.
- PSR J0250+5854 can be a magnetar descendant at the Hall attractor stage

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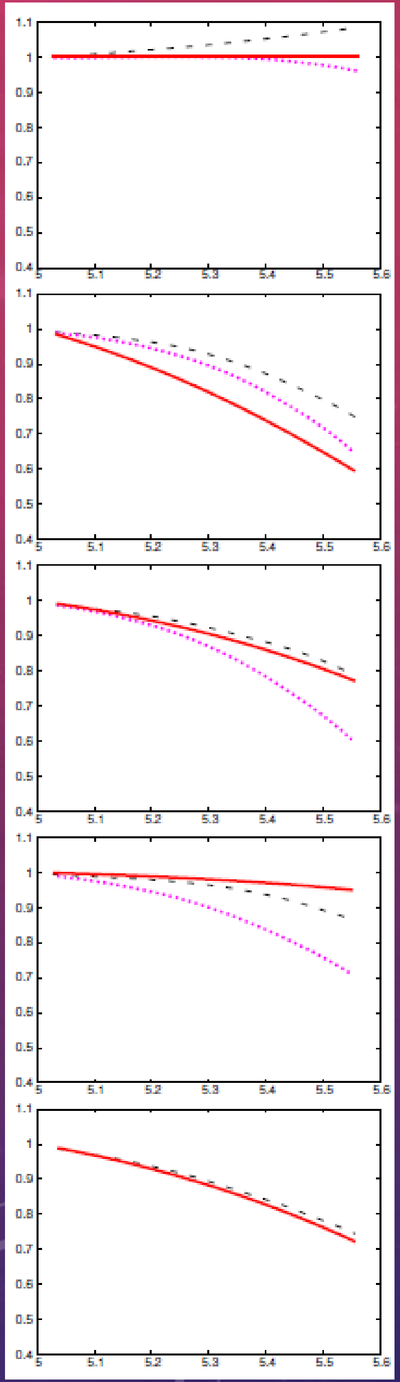
A.P. Igoshev, S.B. Popov
``Magnetic field decay in normal radio pulsars''
AN, vol. 336 pp. 831-834 (2015)
arXiv: 1507.07962

A.P. Igoshev, S.B. Popov
``How to make a mature accreting magnetar''
MNRAS vol. 473 pp. 3204-3210 (2018)
1709.10385

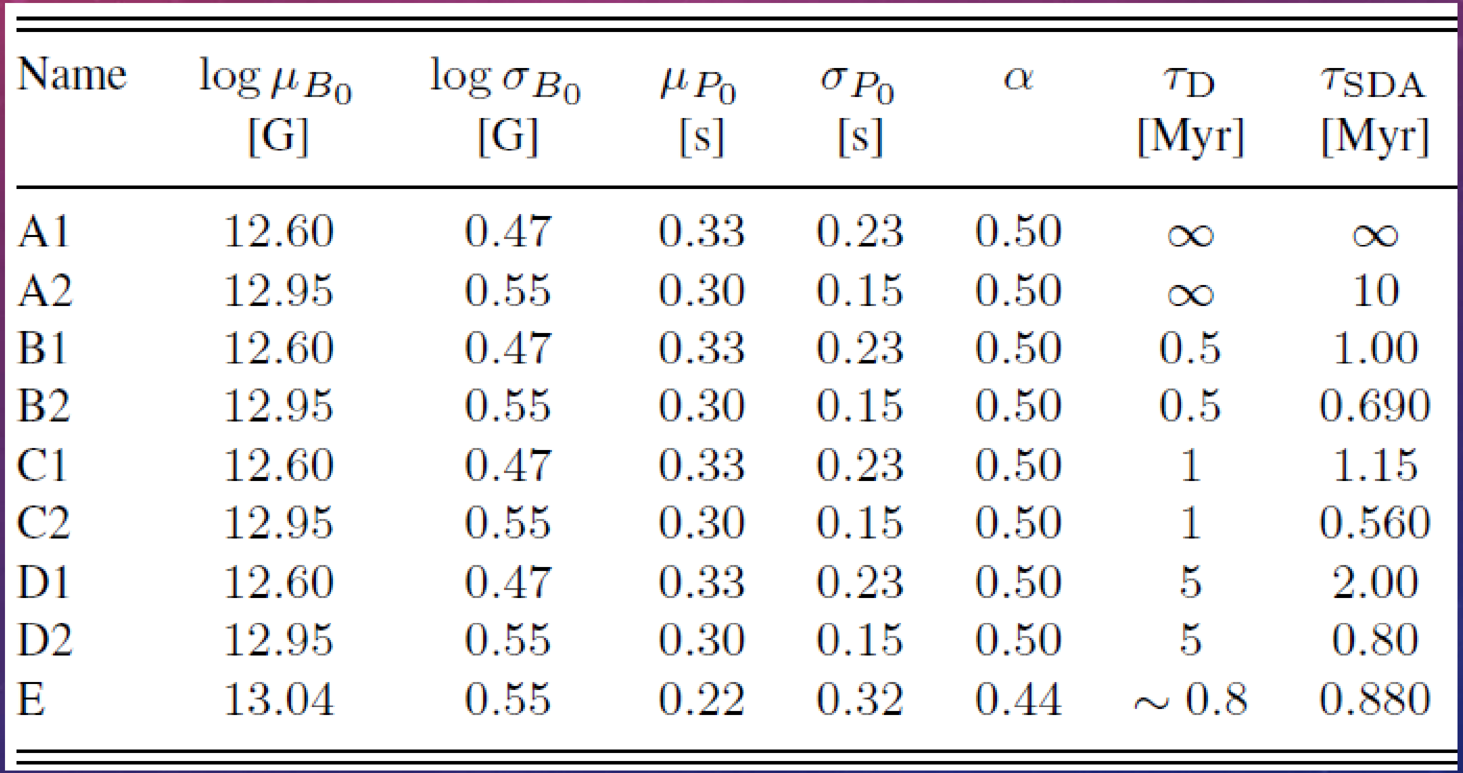
S.B. Popov, R. Taverna, R.Turolla
``Probing the surface magnetic field structure in RX J1856.5-3754''
MNRAS vol. 464, 4390 (2017)
arXiv: 1610.05050

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.



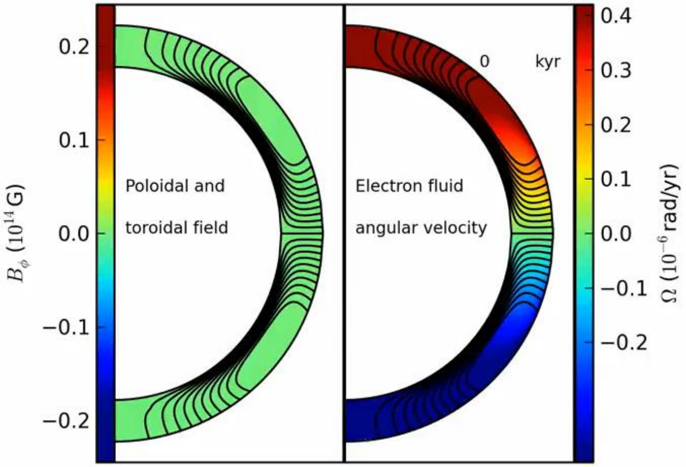
Name	$\log \mu_{B_0}$ [G]	$\log \sigma_{B_0}$ [G]	μ_{P_0} [s]	σ_{P_0} [s]	α	τ_{D} [Myr]	τ_{SDA} [Myr]
A1	12.60	0.47	0.33	0.23	0.50	∞	∞
A2	12.95	0.55	0.30	0.15	0.50	∞	10
B1	12.60	0.47	0.33	0.23	0.50	0.5	1.00
B2	12.95	0.55	0.30	0.15	0.50	0.5	0.690
C1	12.60	0.47	0.33	0.23	0.50	1	1.15
C2	12.95	0.55	0.30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

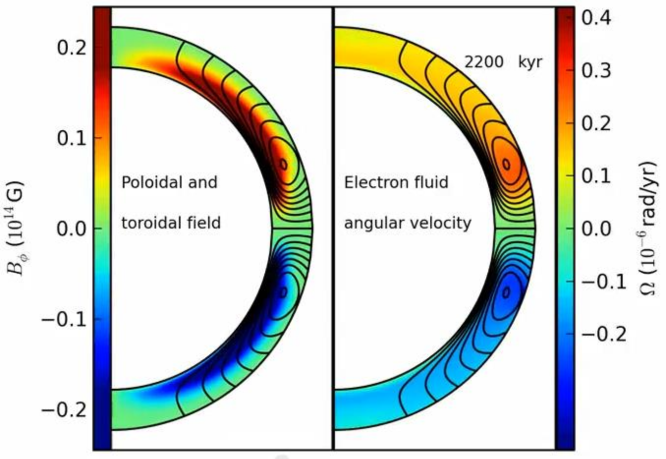
(Synthetic samples are calculated by Gullon, Pons, Miralles)

FURTHER REFERENCES

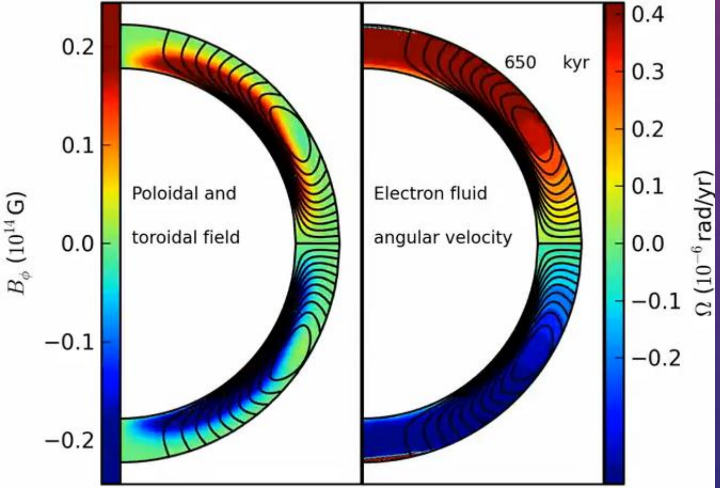
- 1105.4178 Kaplan et al. Optical and UV properties of the M7
- 1509.05023 Taverna et al. Calculation of surface emission (with polarization)
-

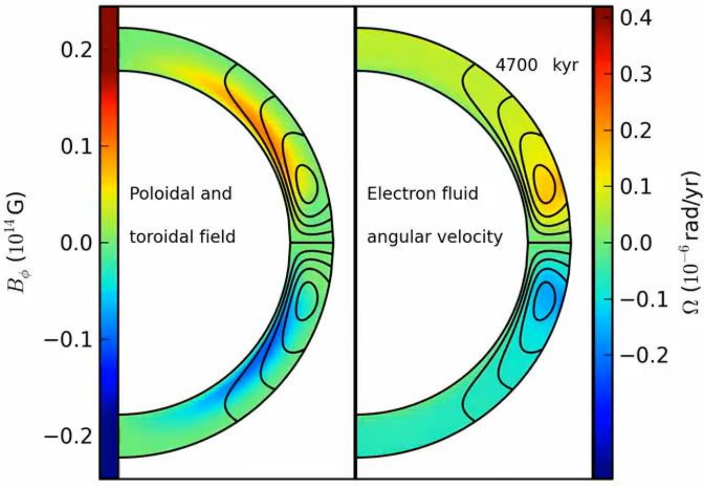
HALL CASCADE AND ATTRACTOR





The system is trying to relax towards a state of isorotation, with the electron fluid having the same angular velocity on a poloidal field line.



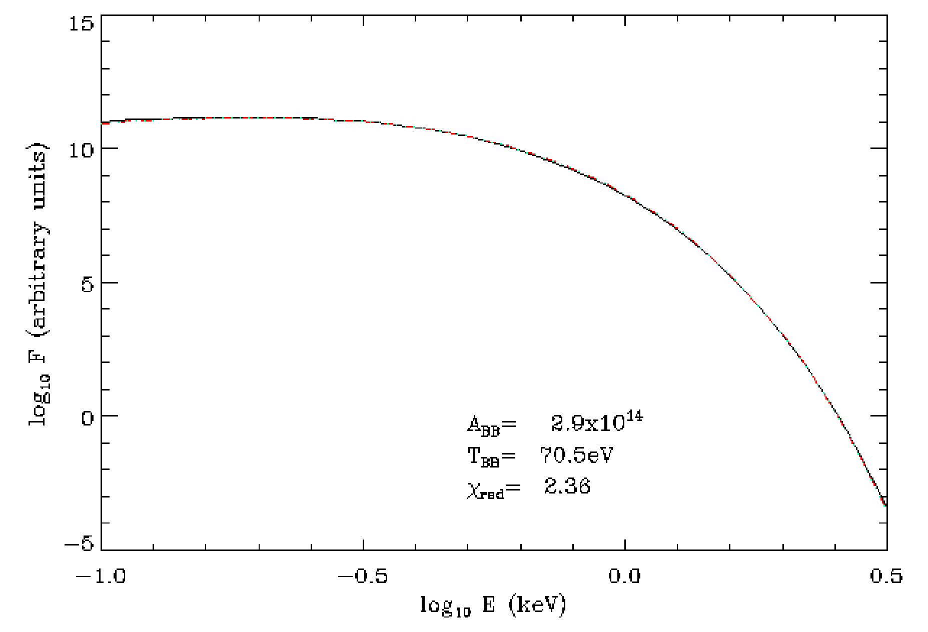


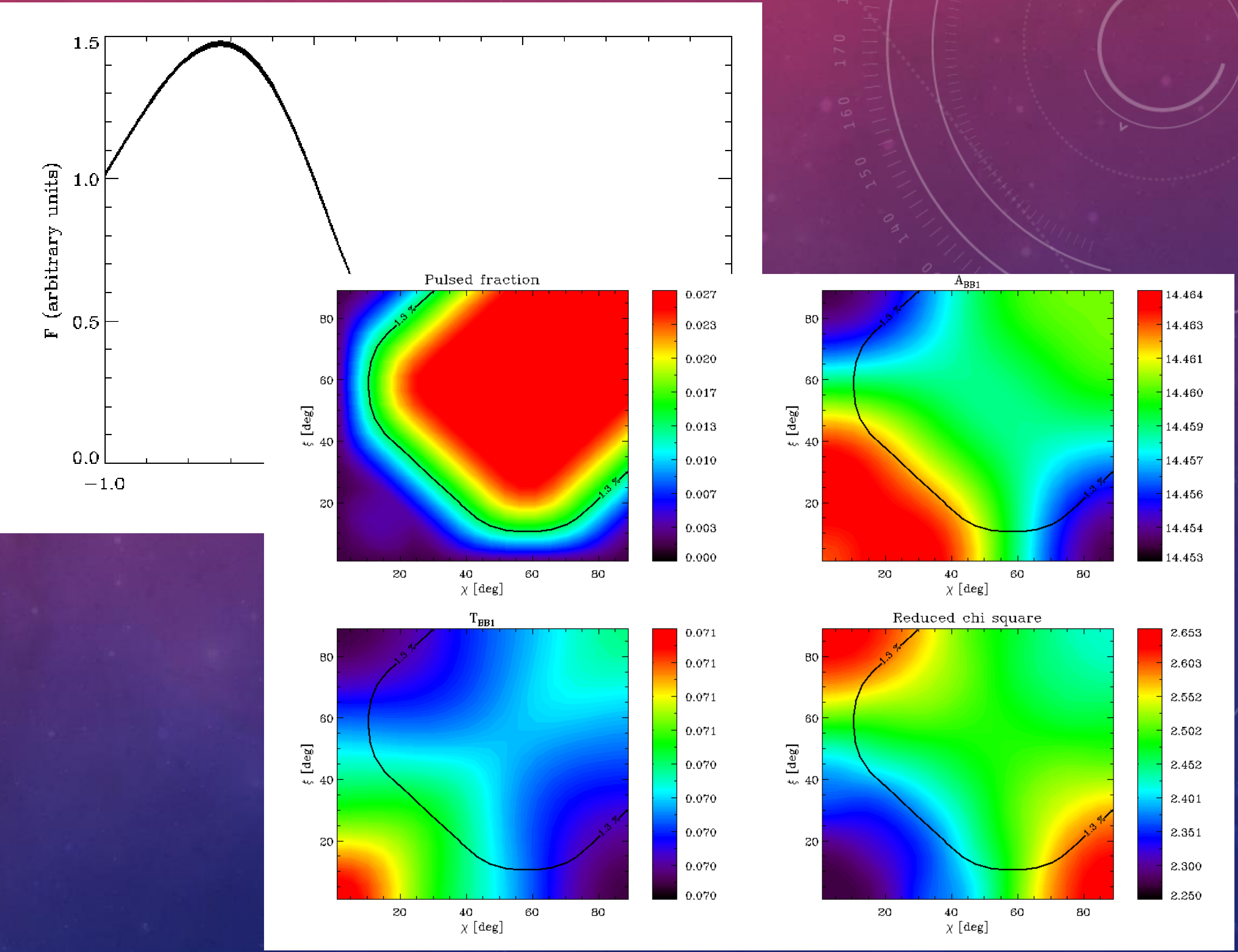
Hall cascade can reach the stage of so-called Hall attractor, where the field decay stalls for some time (Gourgouliatos, Cumming).

Gourgouliatos and Cumming 2013

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

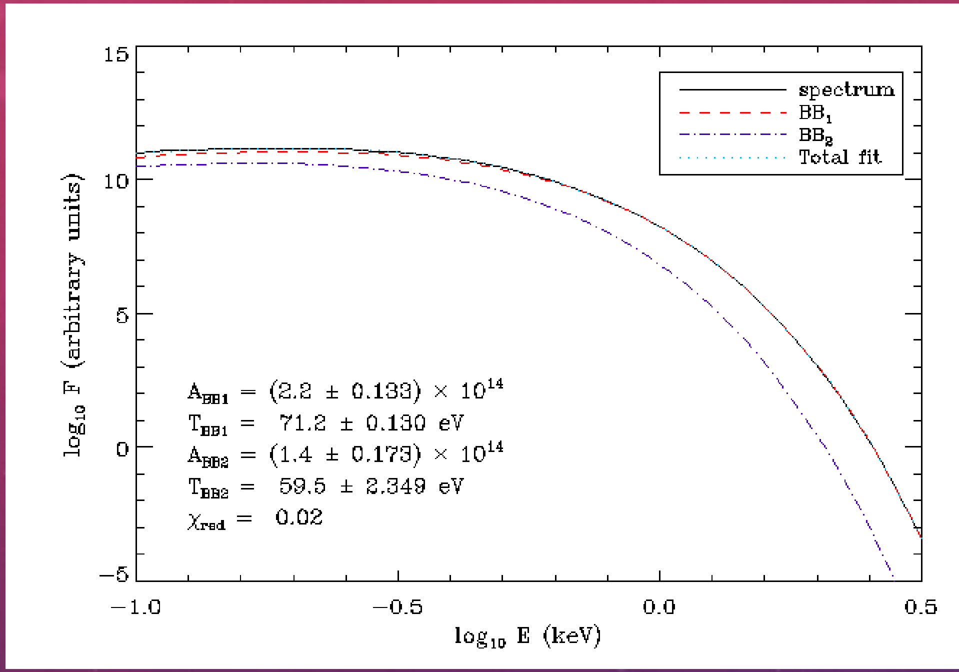
SPECTRAL FITS: SINGLE BLACKBODY

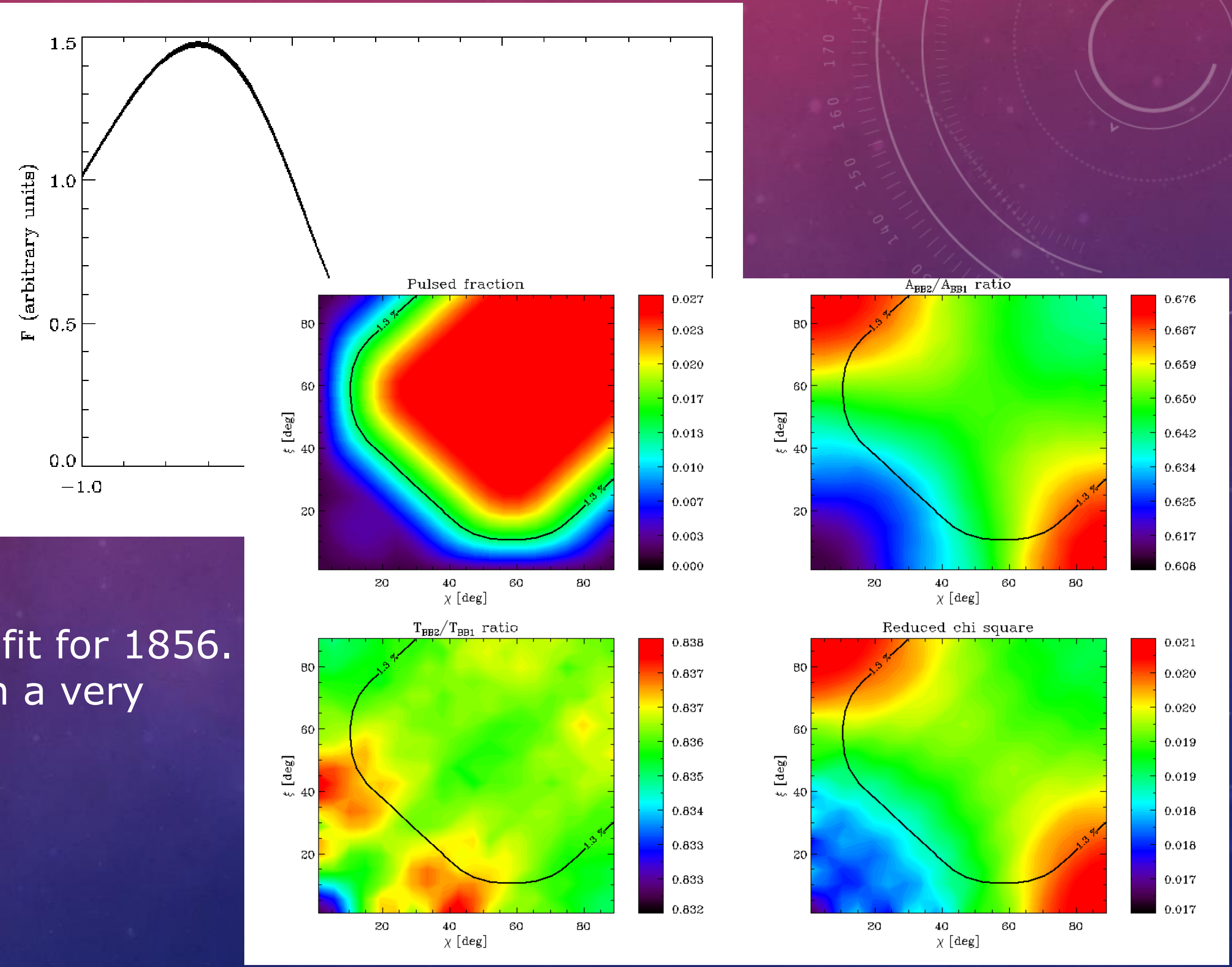




Single black body does not provide a good fit, even using, in addition, a line, or condensed surface.

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