POST FALL-BACK EVOLUTION OF NEUTRON STARS

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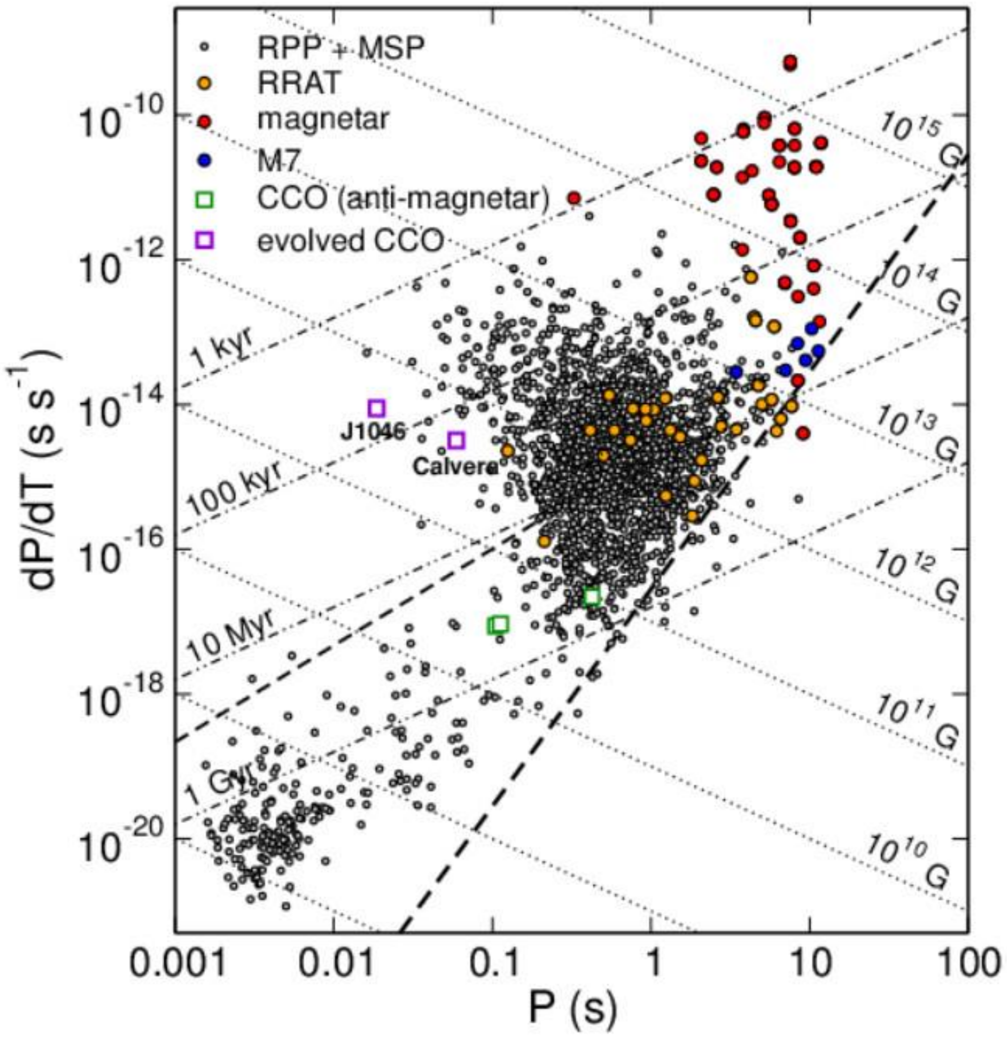
Justin Elfritz,
Sergei Popov

IN THE BEGINNING WAS THE ….

PUZZLE

VARIETY OF YOUNG NS



Pires et al. 2015

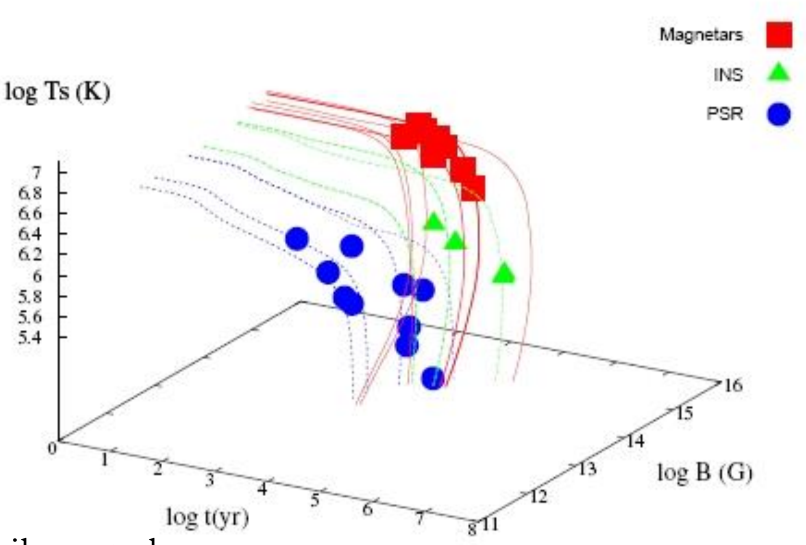
Pulsars, Magnetars, Magnificent seven, CCOs …

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

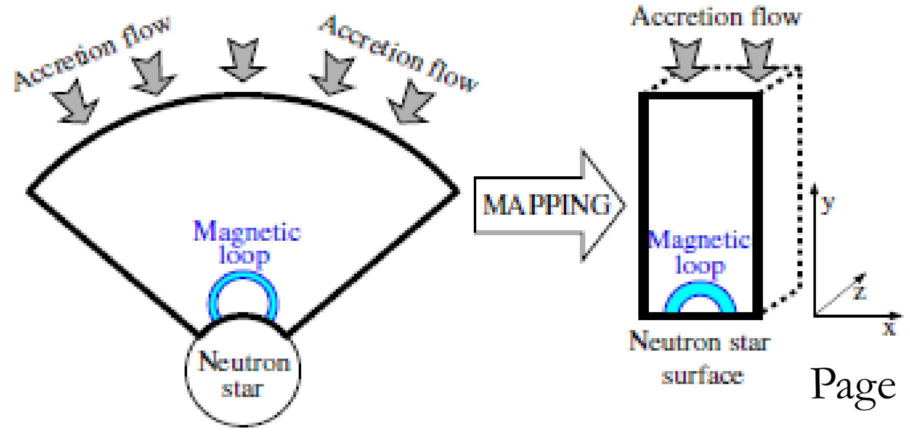
First steps have been done by Popov et al. (2010).
Later it was developed by Vigano et al.
and Gullon et al.

Unified models which include all types of NSs
still cannot explain all important features
of these sources.

THREE IMPORTANT INGREDIENTS OF A UNIFIED MODEL

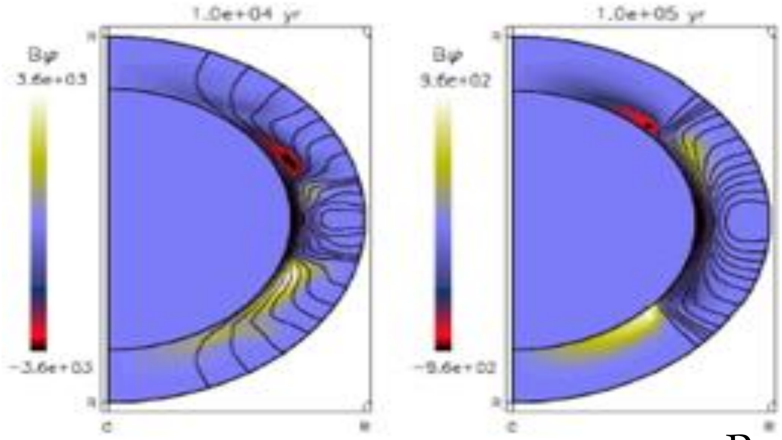


Aguilera et al.



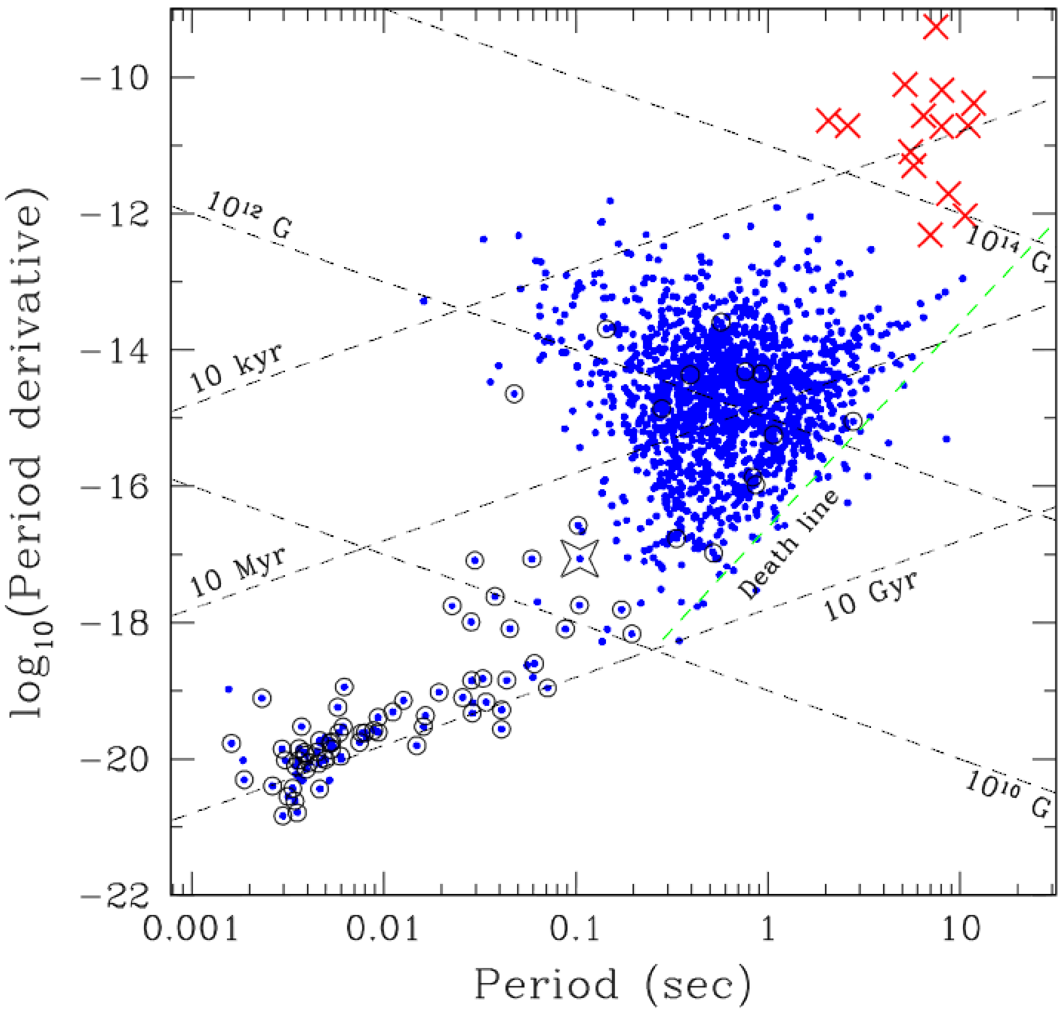
Page et al.

- Field decay
  - Emerging magnetic field
  - Toroidal magnetic field



Pons et al.

ANTIMAGNETARS



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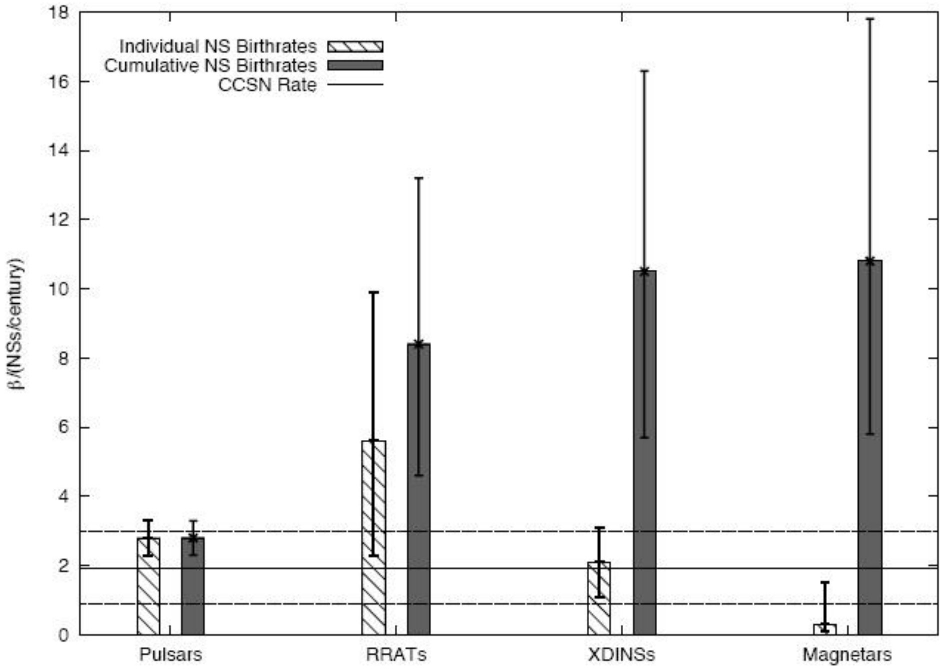

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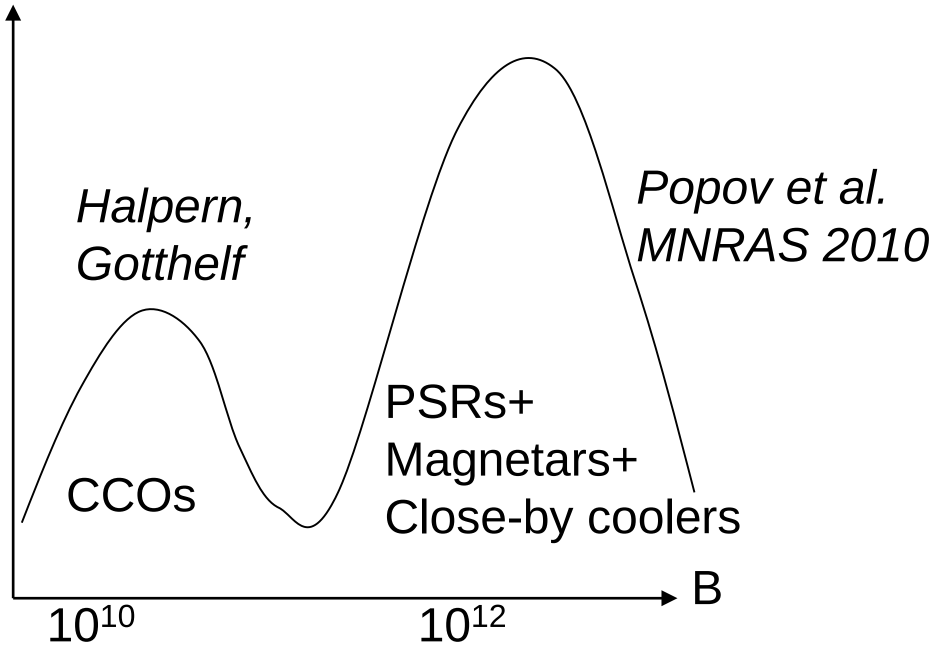
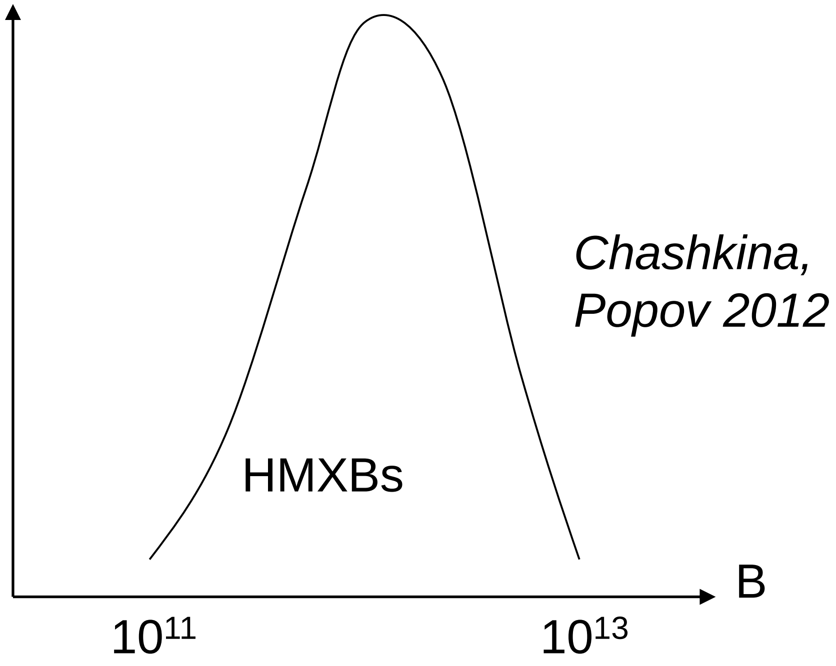
Note, that there is no room for antimagnetars
from the point of view of birthrate
in many studies of different NS populations.

FURTHER EVOLUTION OF CCO

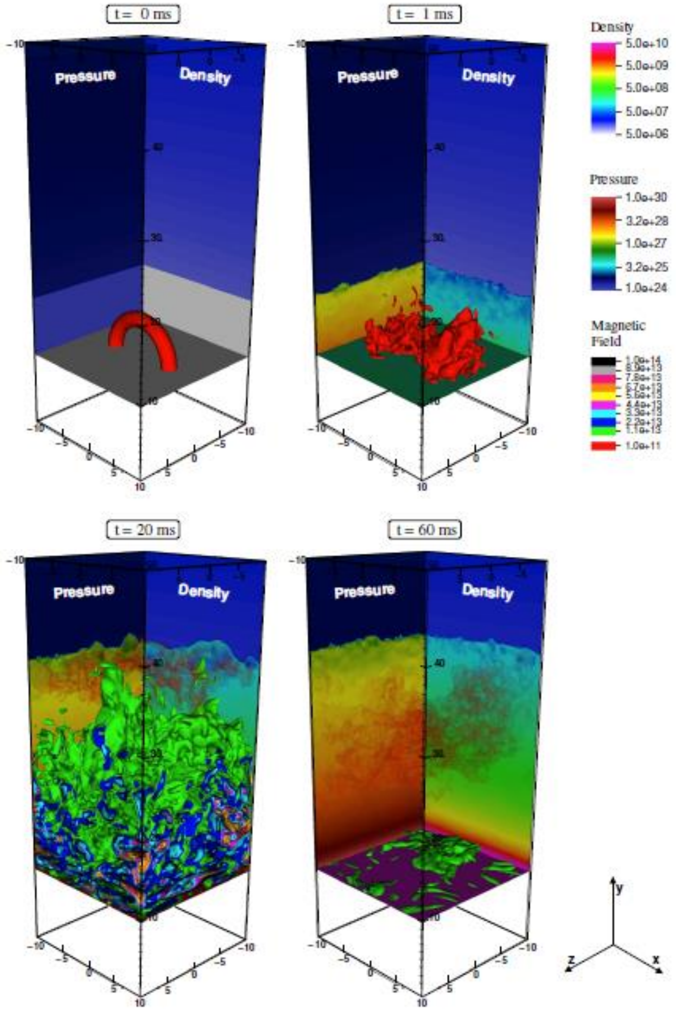




Among young isolated NSs about 1/3 can be related to CCOs. If they are anti-magnetars, then we can expect that 1/3 of NSs in HMXBs are also low-magnetized objects. They are expected to have short spin periods <1 sec. Still, there are no many sources with such properties.

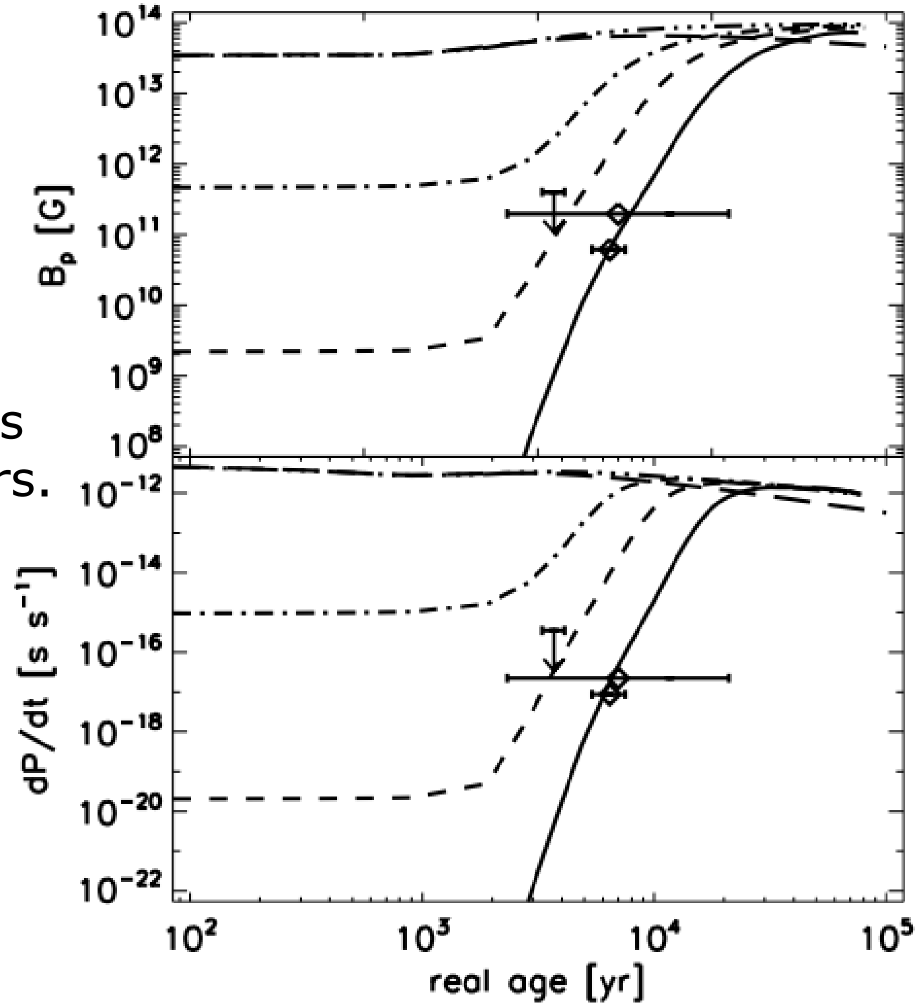
Possible solution: emergence of magnetic field (see Ho 2011).

FINAL ELEMENT FOR THE GUNS?

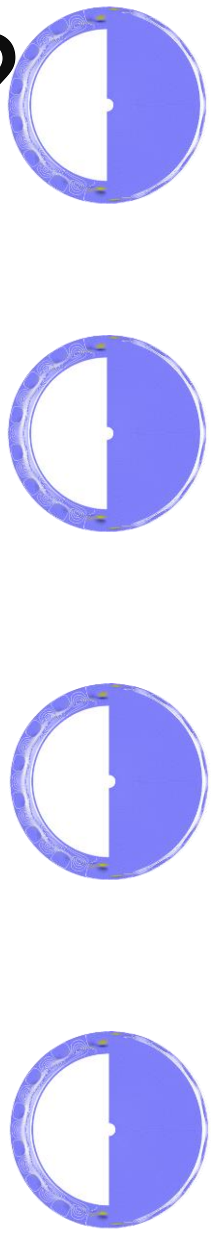


Bernal, Page, Lee 2013

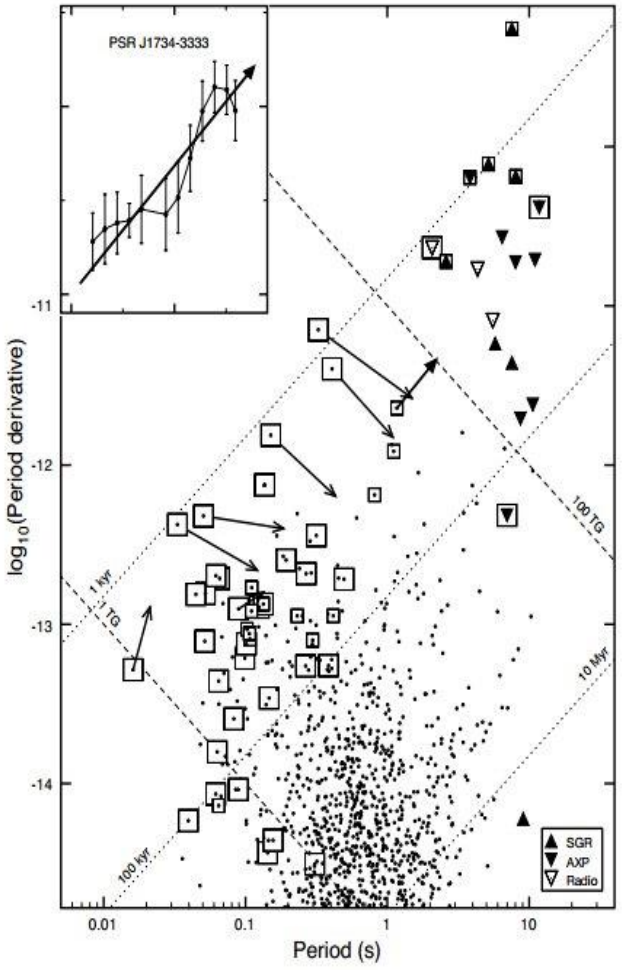
The field is buried
by fall-back,
and then re-emerges
on the scale ~10^4 yrs.



Vigano, Pons 2012



EMERGED PULSARS IN THE P-PDOT DIAGRAM



Espinoza et al. arXiv: 1109.2740

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).

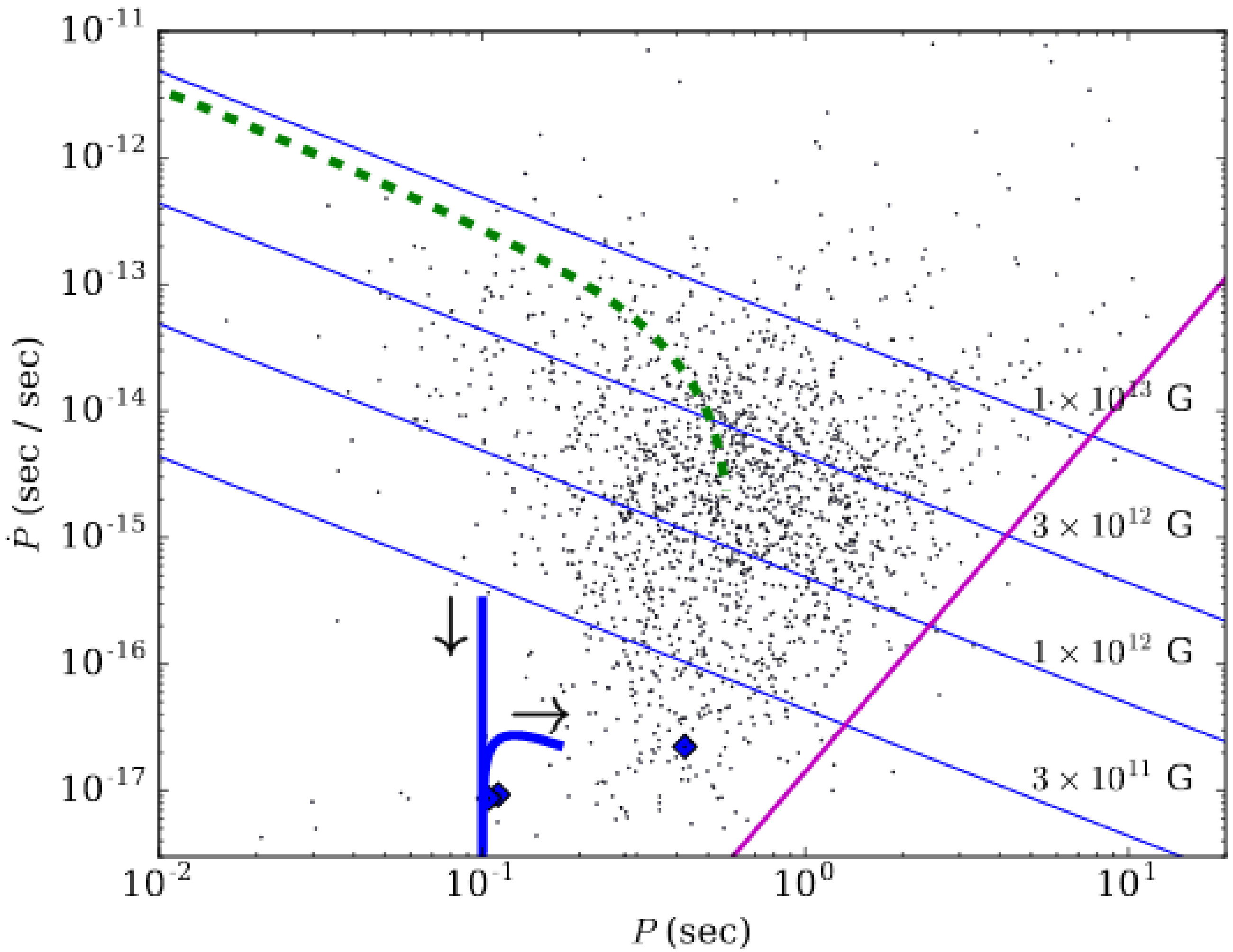
Part of PSRs supposed to be born with
long (0.1-0.5 s) spin periods can be
matured CCOs.

THE PUZZLE

We do not see young NSs

at the post-CCO stage!

P-PDOT, CCO AND ROUTS

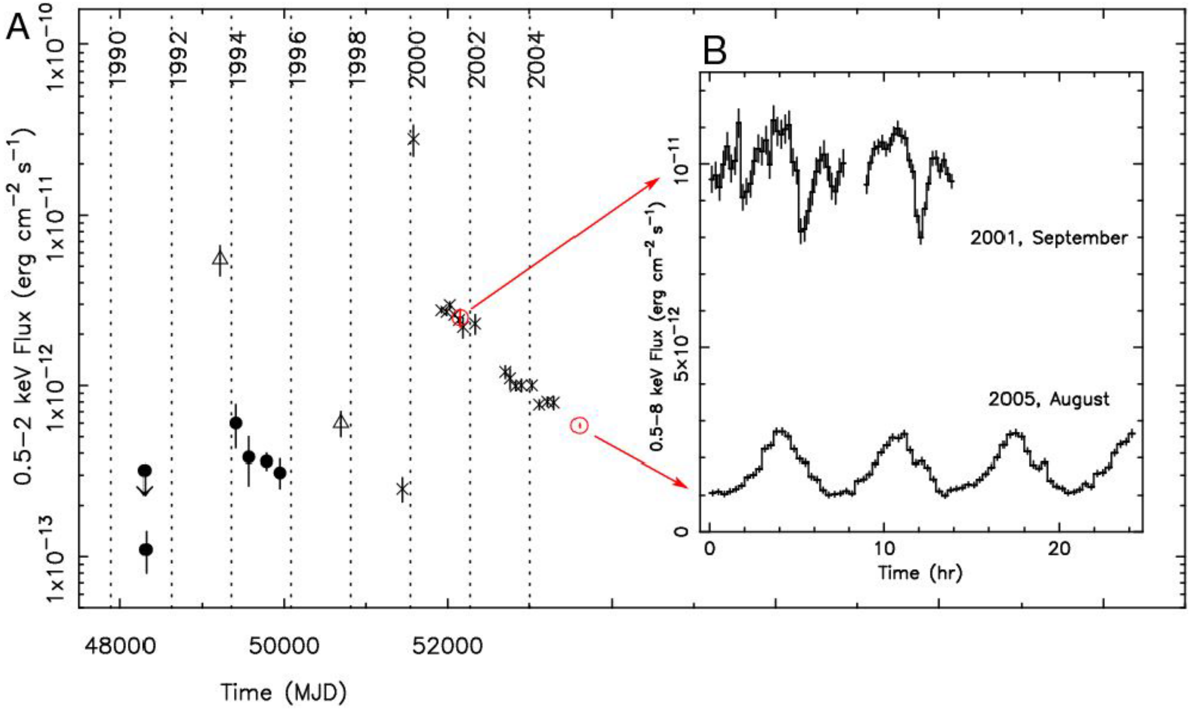


CCOs are supposed to be young NS which experienced strong fall–back. Now their magnetic field is slowly re–emerging.

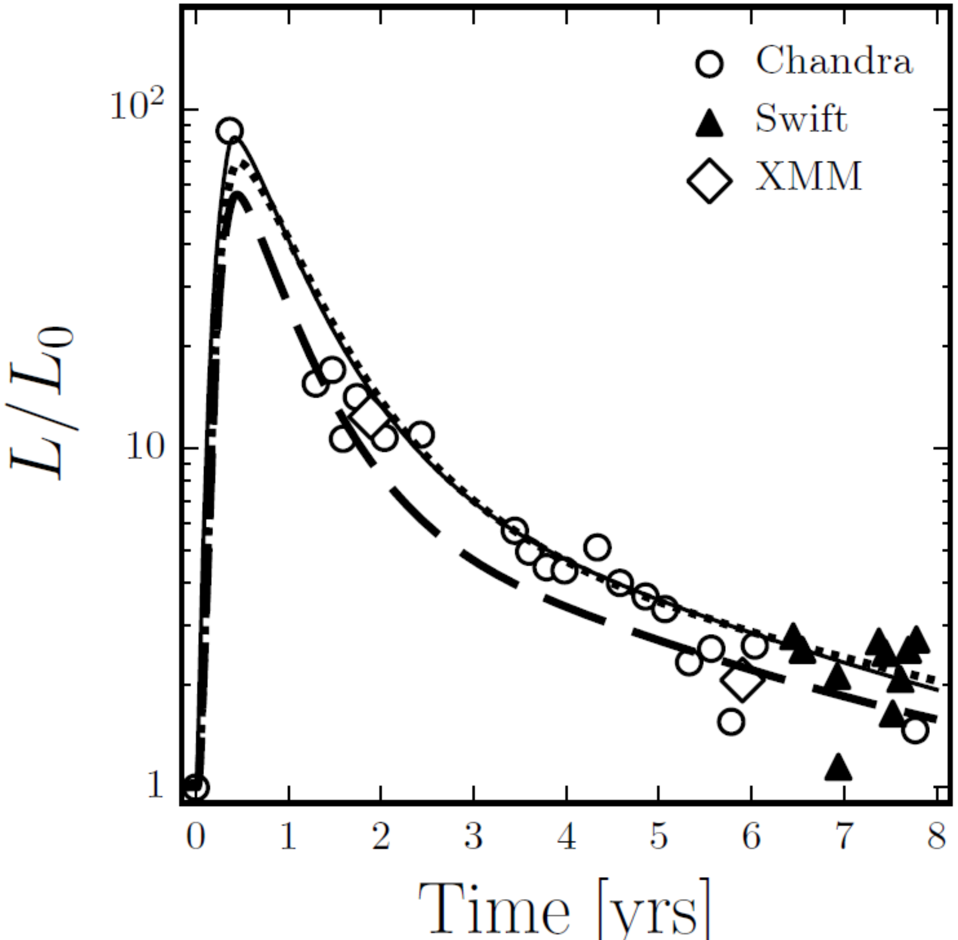
CCOs are situated above the death–line, however they are not seen as PSRs.

SOME OF CCOS CAN BE MAGNETARS

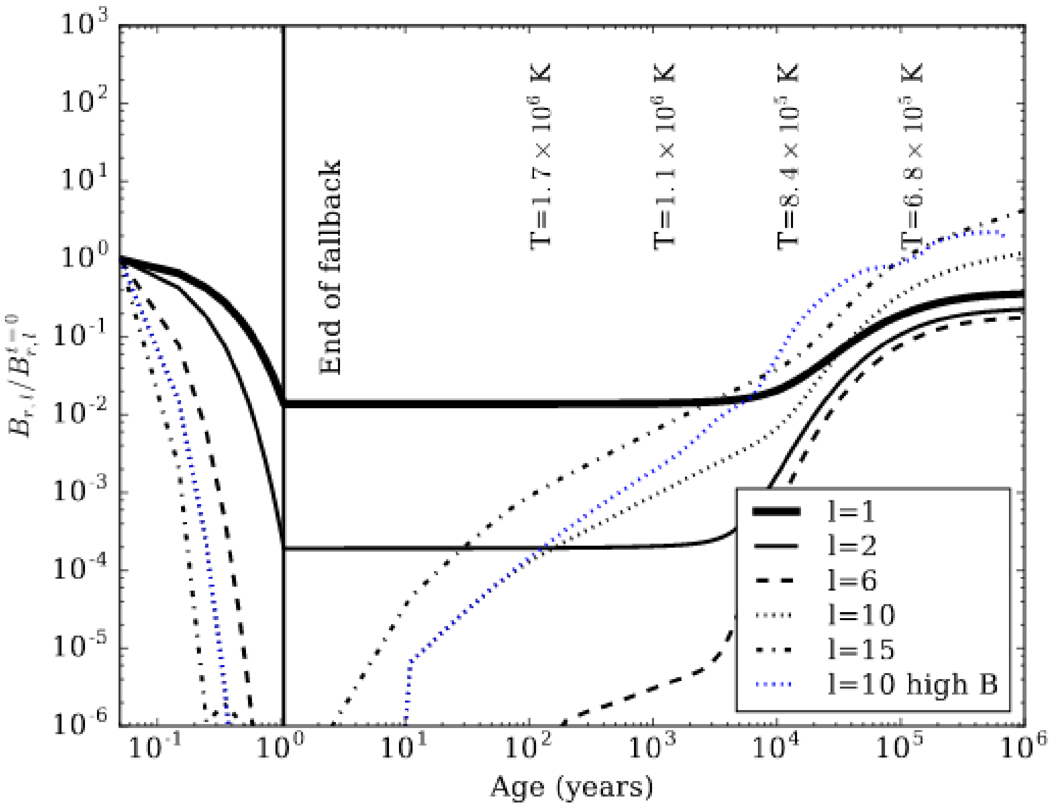
De Luca et al. (2006)

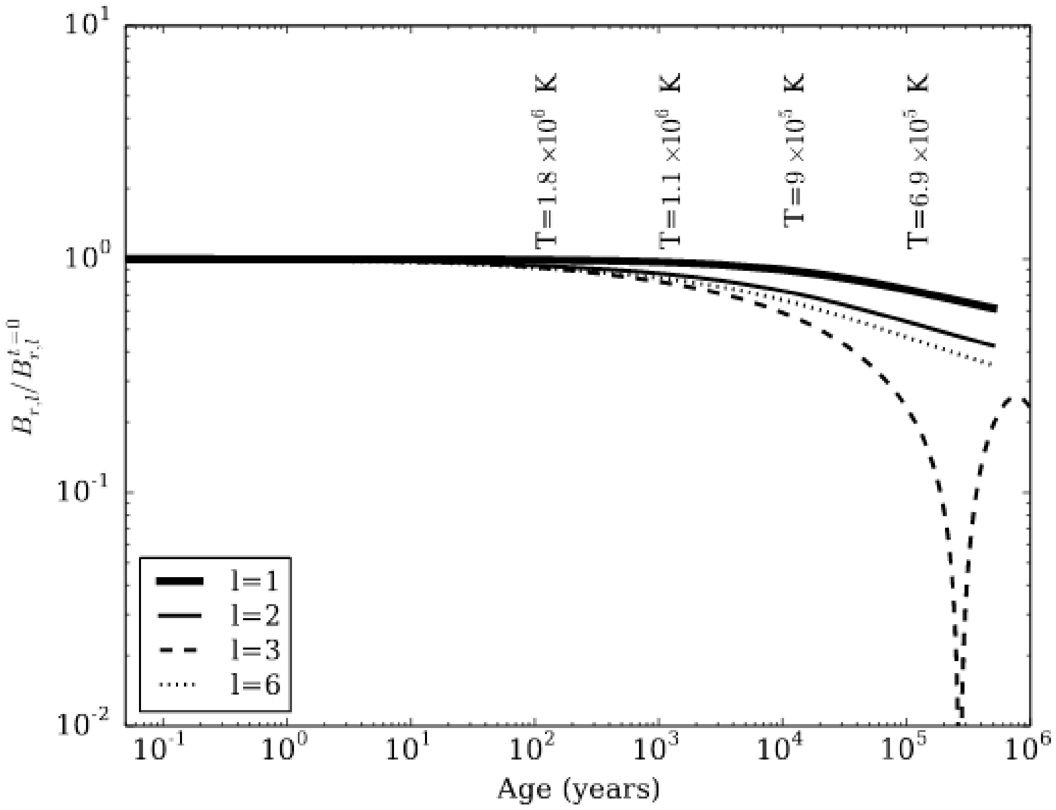


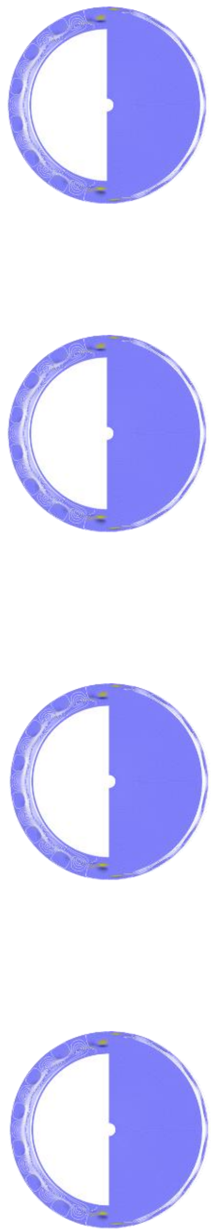
Behaviour of RCW103 have been interpreted by Popov et al. (2016) due to magnetic energy release in the crust of the NS.
Later on magnetar flares were discovered (Rea et al. 2016; D’Ai et al. 2016).



FIELD EVOLUTION AND FALL-BACK







Field is submerged due to accretion of 0.001 solar mass in a year.
Then the field slowly re-emerges.

MAIN EQUATIONS

$$\frac{\partial \vec{B}}{\partial t} = -\vec{\nabla} \times [\eta \vec{\nabla} \times \vec{B} + f_h(\vec{\nabla} \times \vec{B}) \times \vec{B} + \vec{v}_{\rm accr} \times \vec{B}].$$

Ohmic term

Hall term

Accretion,
switched-off in a year

$\eta = c^2/4\pi\sigma$ – magnetic diffusivity $\qquad f_h = c/4\pi e n_e$

Thermal evolution: $c_v \frac{\partial T}{\partial t} - \vec{\nabla} \cdot [\hat{\kappa} \cdot \vec{\nabla} T] = \sum_i Q_i$

The code was developed by Pons et al.
New addition is related to multipoles
in initial conditions

$$\partial_t B_\phi = -\vec{\nabla} \times \left[f_h(\vec{\nabla} \times \vec{B}_{\rm pol}) \times \vec{B}_{\rm pol} \right]$$

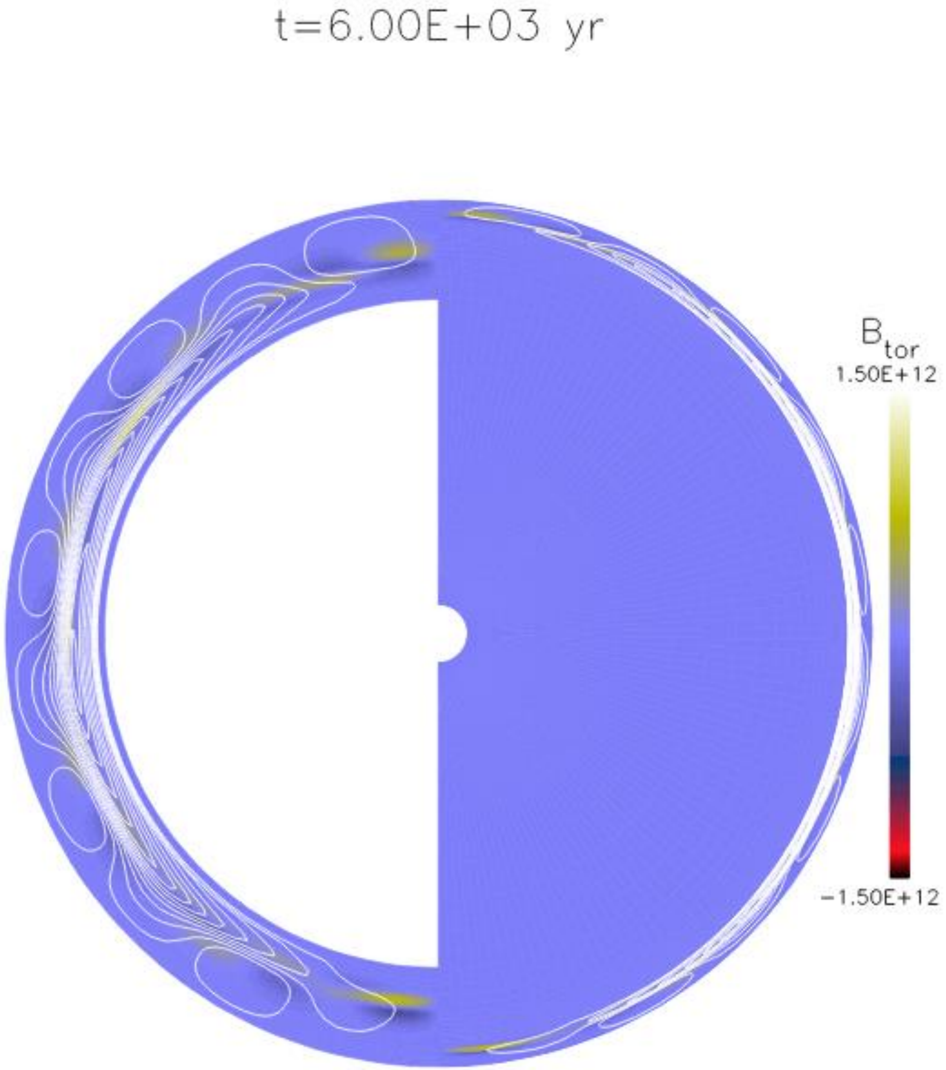
$$\partial_t \vec{B}_{\rm pol} = -\vec{\nabla} \times \left[f_H \left(\vec{\nabla} \times \vec{B}_{\rm tor} \right) \times \vec{B}_{\rm pol} \right]$$

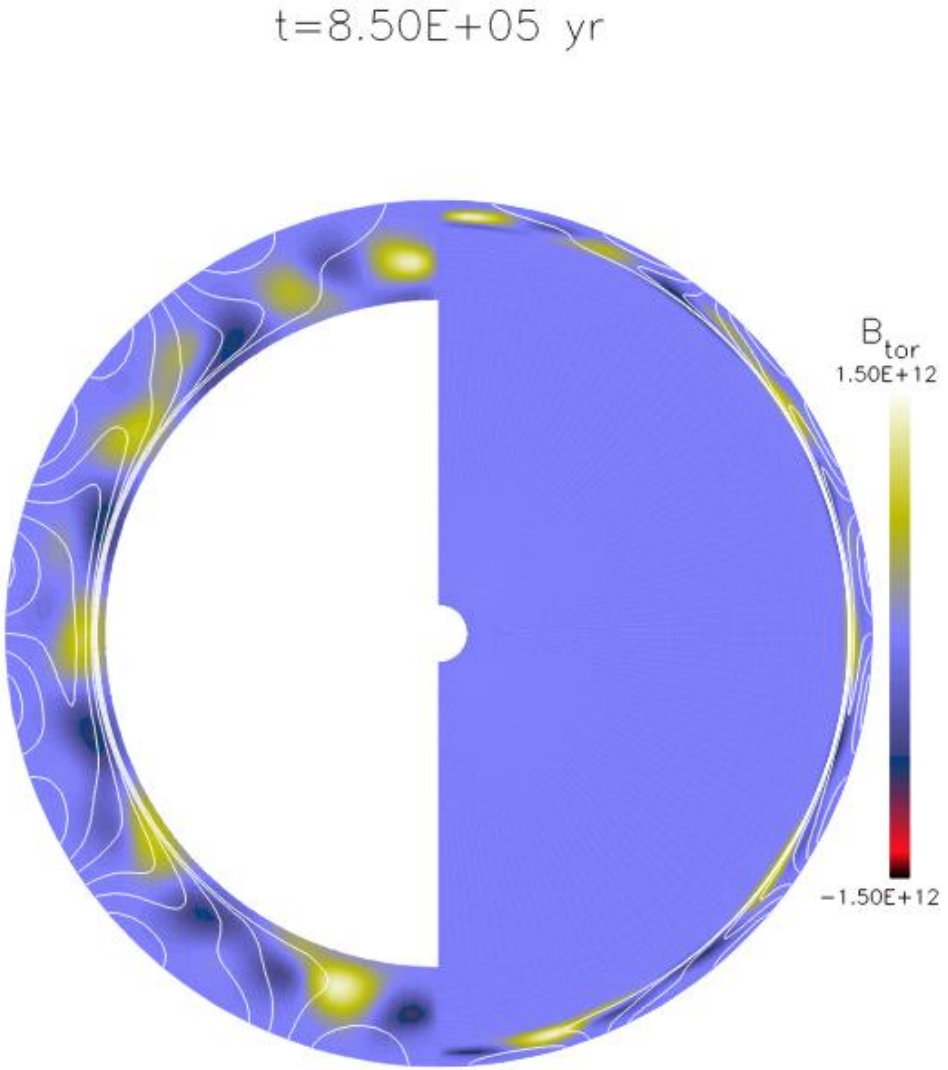
Poloidal and toroidal fields influence each other

Time of re-emergence: $\Delta t_{\rm re-em} \approx \frac{\Delta r_{\rm burial}}{v_0 \cdot l \cdot B_\phi}$

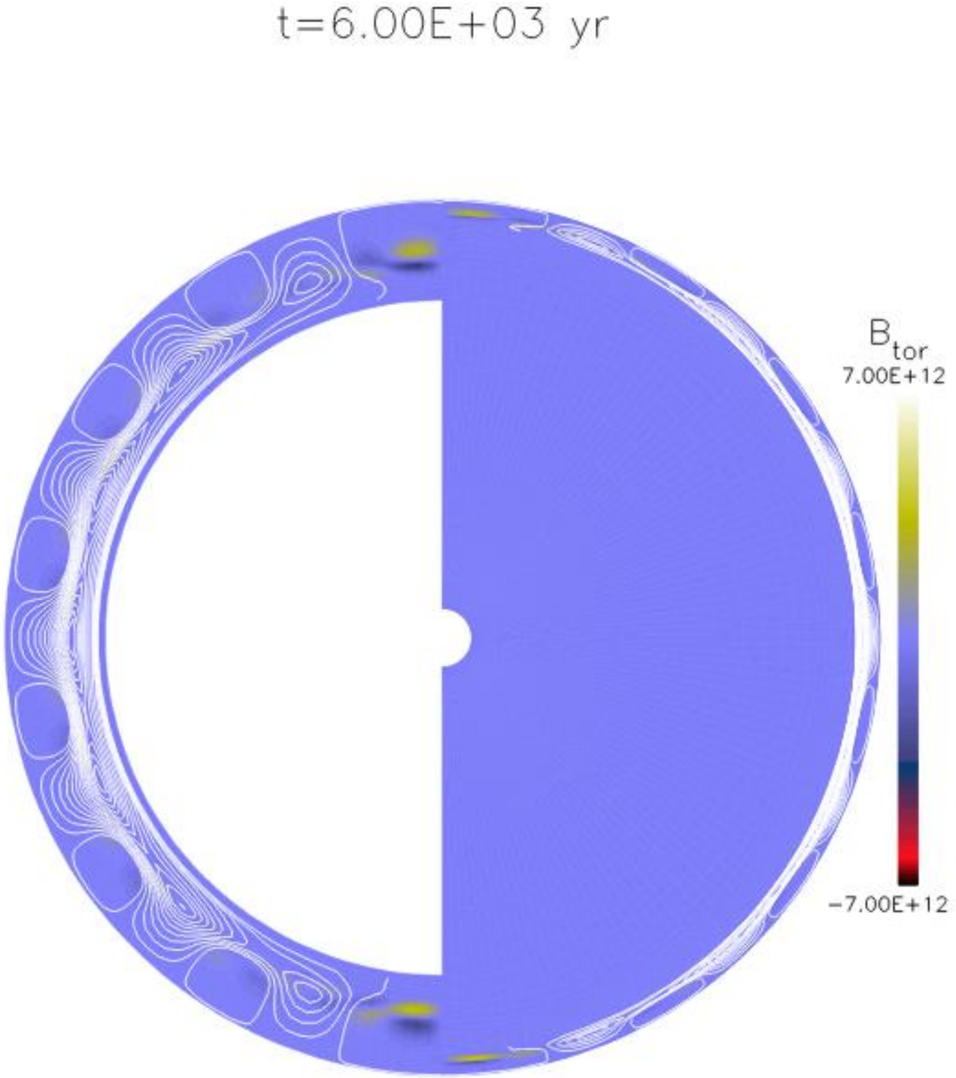
For B_0=1.5 10^{12} G and Δr=0.35 km we have: $\Delta t_{\rm re-em} \approx \frac{670}{l}$ kyrs.

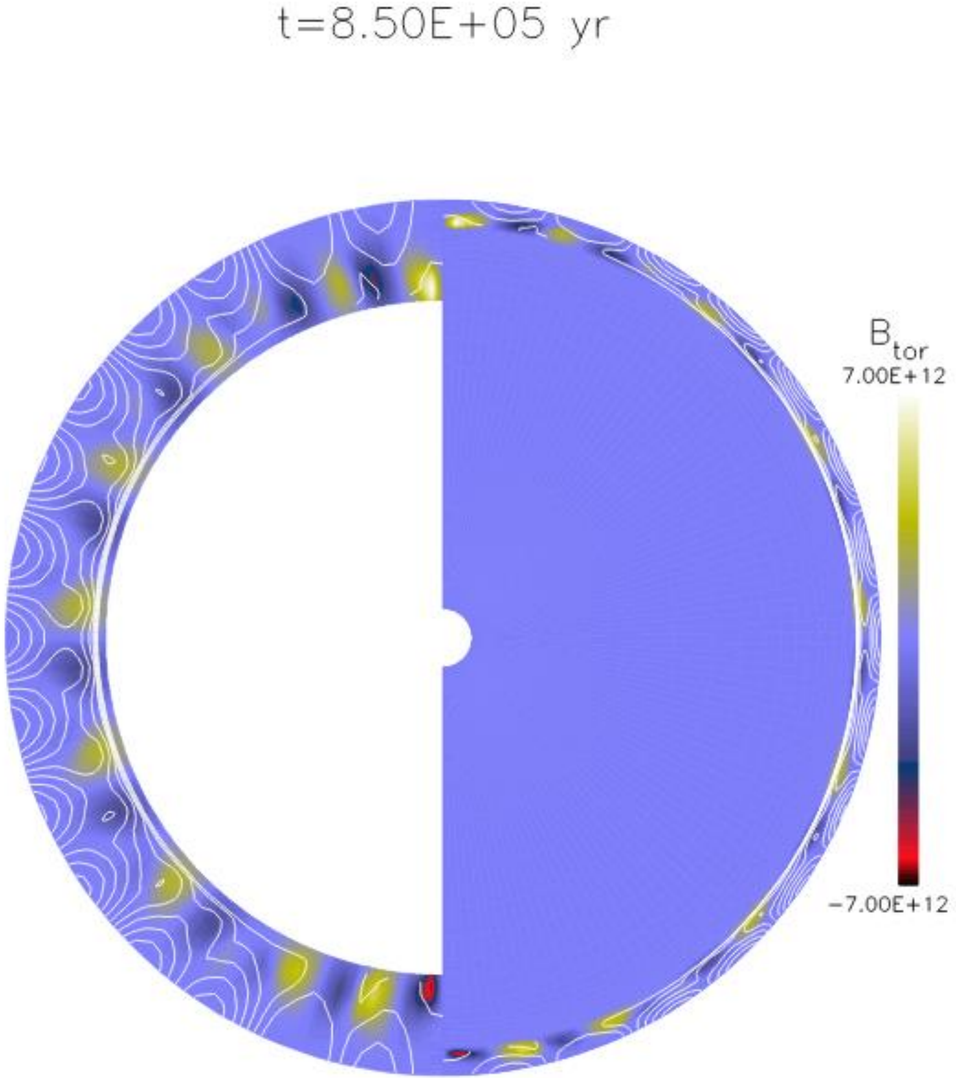
DIPOLE AND L=10

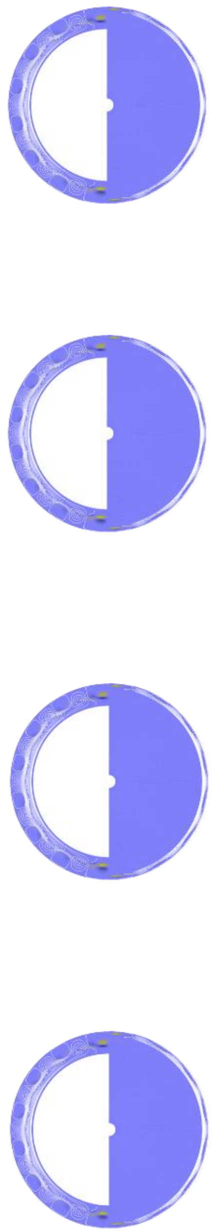




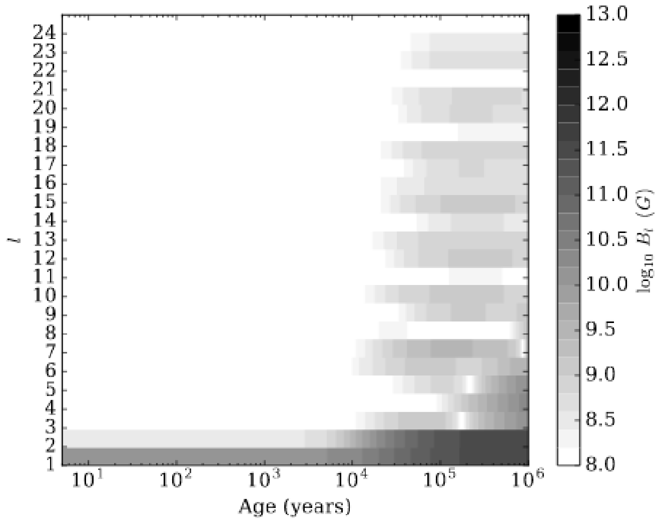
DIPOLE AND L=15

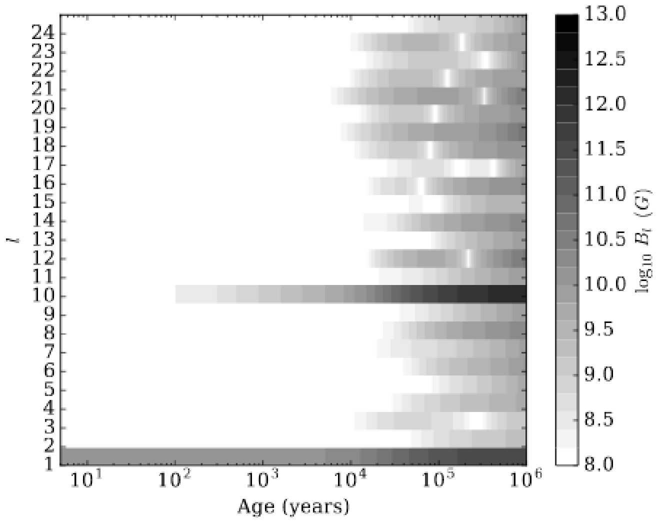


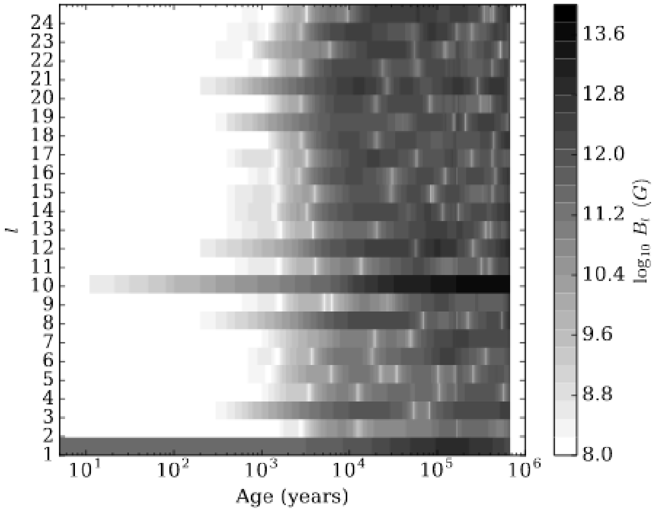




SURFACE POLOIDAL FIELD DECOMPOSITION





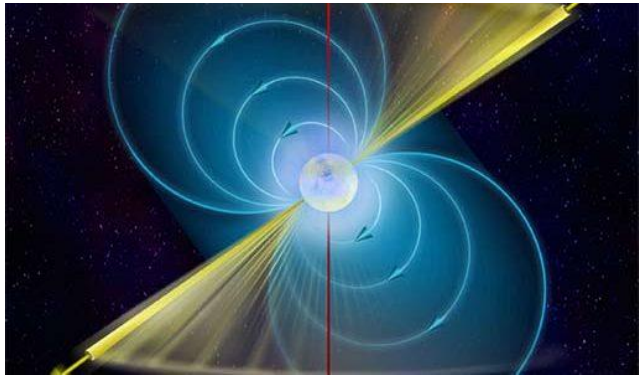


Field evolution results in appearance of different components.

REQUIRED CURVATURE RADIUS

$$E_{\rm CR} = \frac{3}{2}\gamma^3 \frac{\hbar c}{\rho},$$

Dipole is not enough!



$$B_\perp \sim \frac{hB}{\rho} \quad h \approx 0.01 R_{\rm NS} - 0.1 R_{\rm NS}$$

$$l_{\rm CR} = 2\frac{\hbar^2}{m_e e^2} B_q \frac{\rho}{hB}\frac{1}{T(\chi)},$$

$$B_q = 4.414 \times 10^{13}\ {\rm G}$$

$$\chi = \frac{1}{2}\frac{E_{\rm CR}}{m_e c^2}\frac{B_\perp}{B_q} = \frac{3}{4}\frac{\hbar}{m_e c B_q}\frac{\gamma^3 h B}{\rho^2}$$

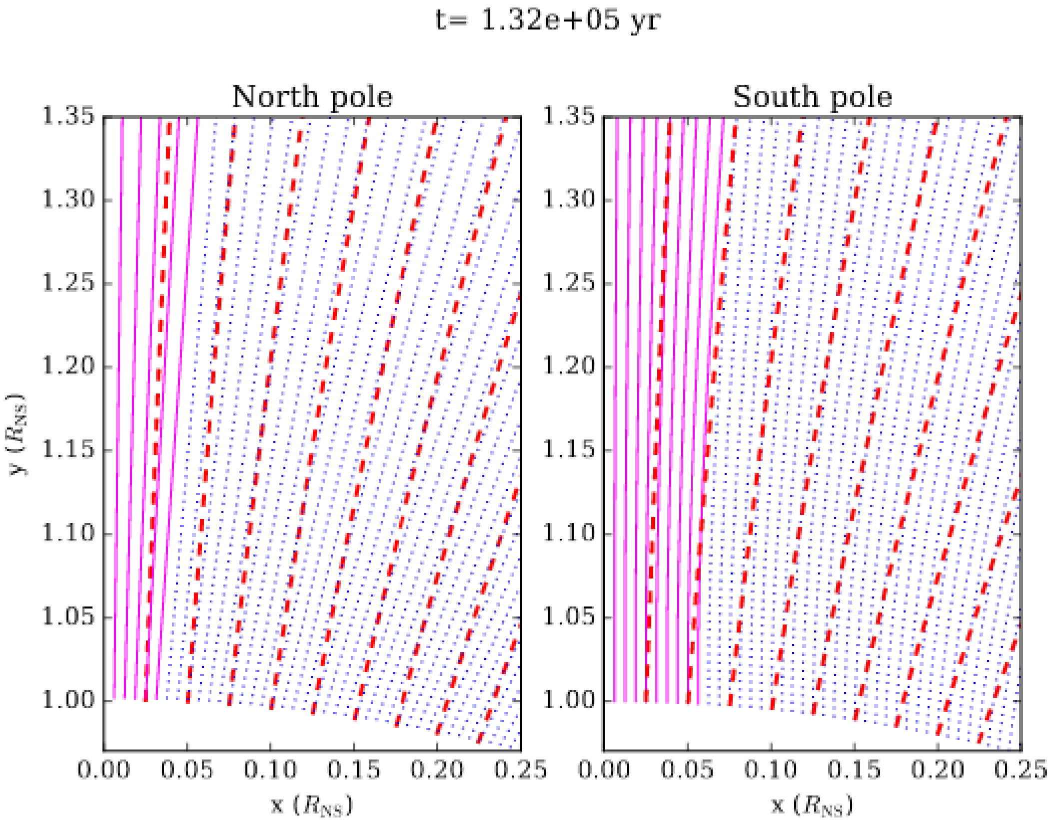
$$l_{\rm CR} = 2.8 \times 10^6 \frac{\rho}{hB}\chi \frac{1}{K_{1/3}^2(2/3\chi)}$$

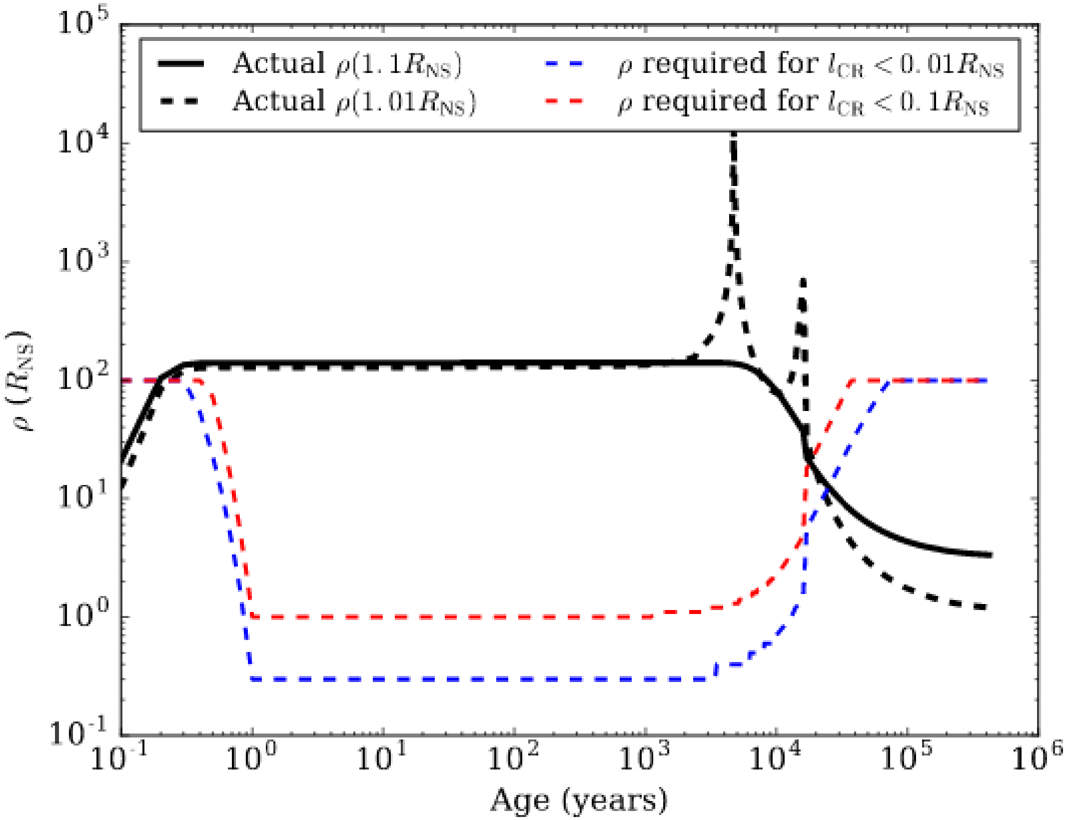
$$T(\chi) \approx 0.16 \chi^{-1} K_{1/3}^2(2/3\chi)$$

$$\chi = 1.3 \times 10^{-25}\frac{hB}{\rho^2}(\theta_{\rm max}^2 B_d^s)^3$$

$$l_{\rm CR} < h,$$

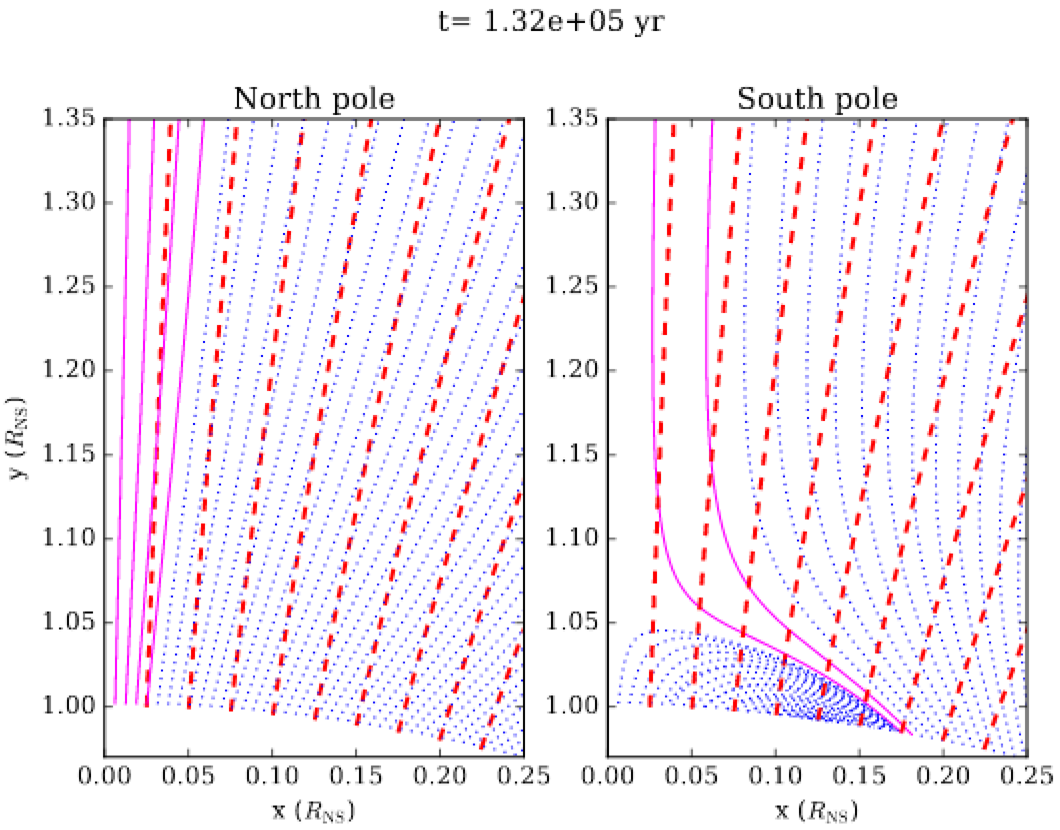
DIPOLE AND L=6

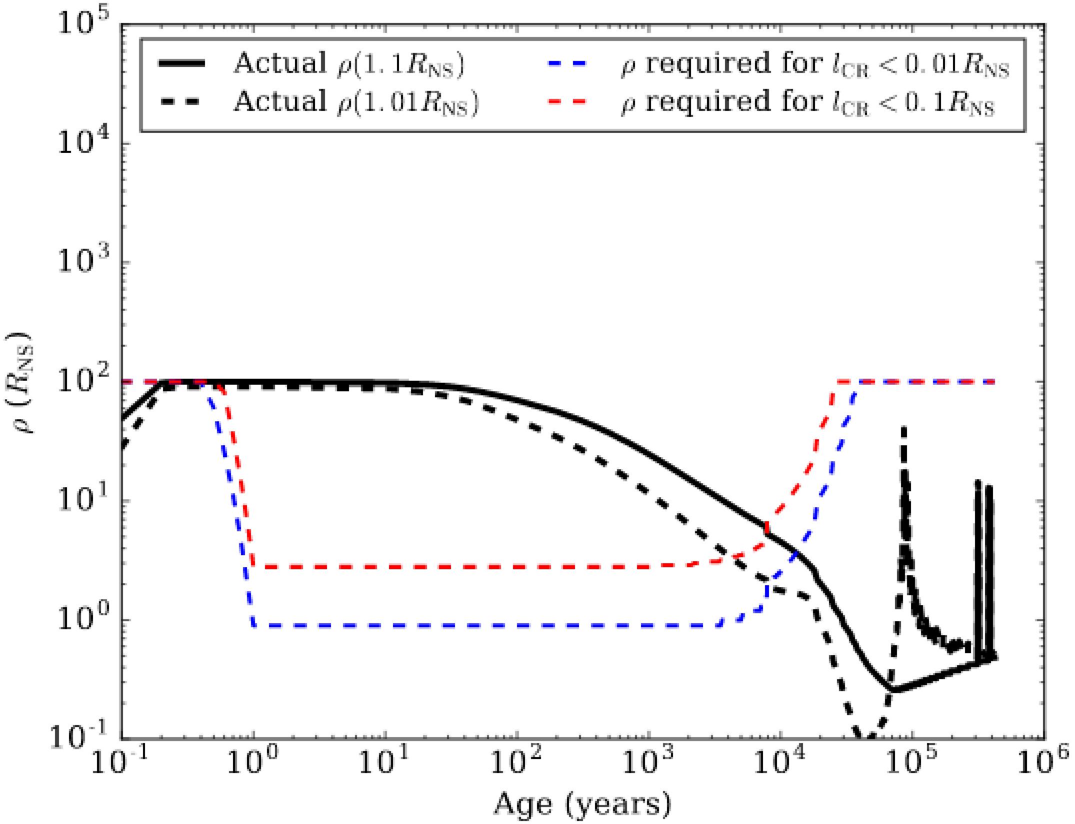




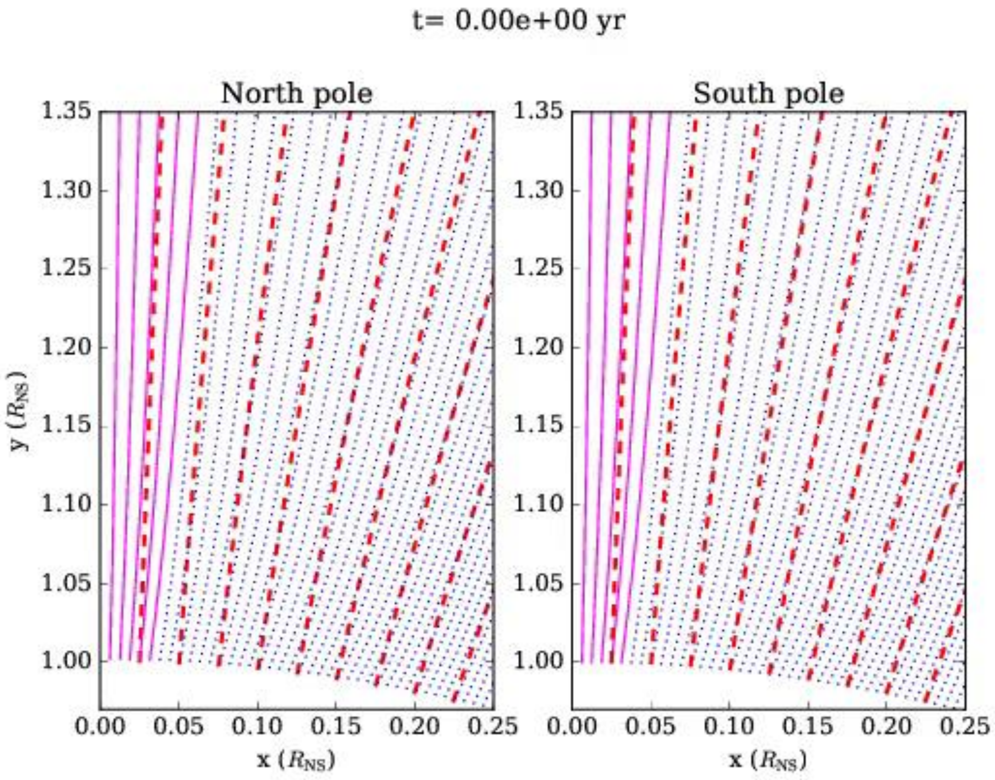
It takes more than 10 000 years for higher multipoles to re-appear,
such that the curvature radius becomes small enough to allow curvature radiation.
At the moment the pulsar is switched on.

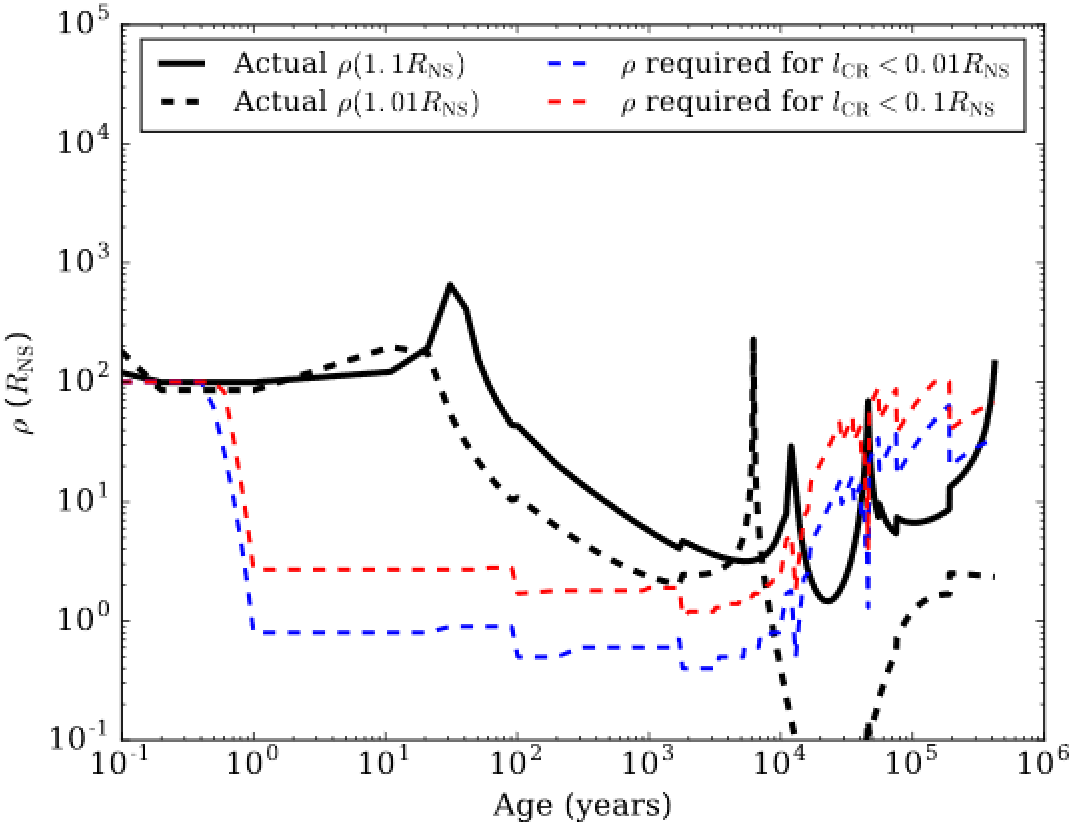
DIPOLE AND L=10



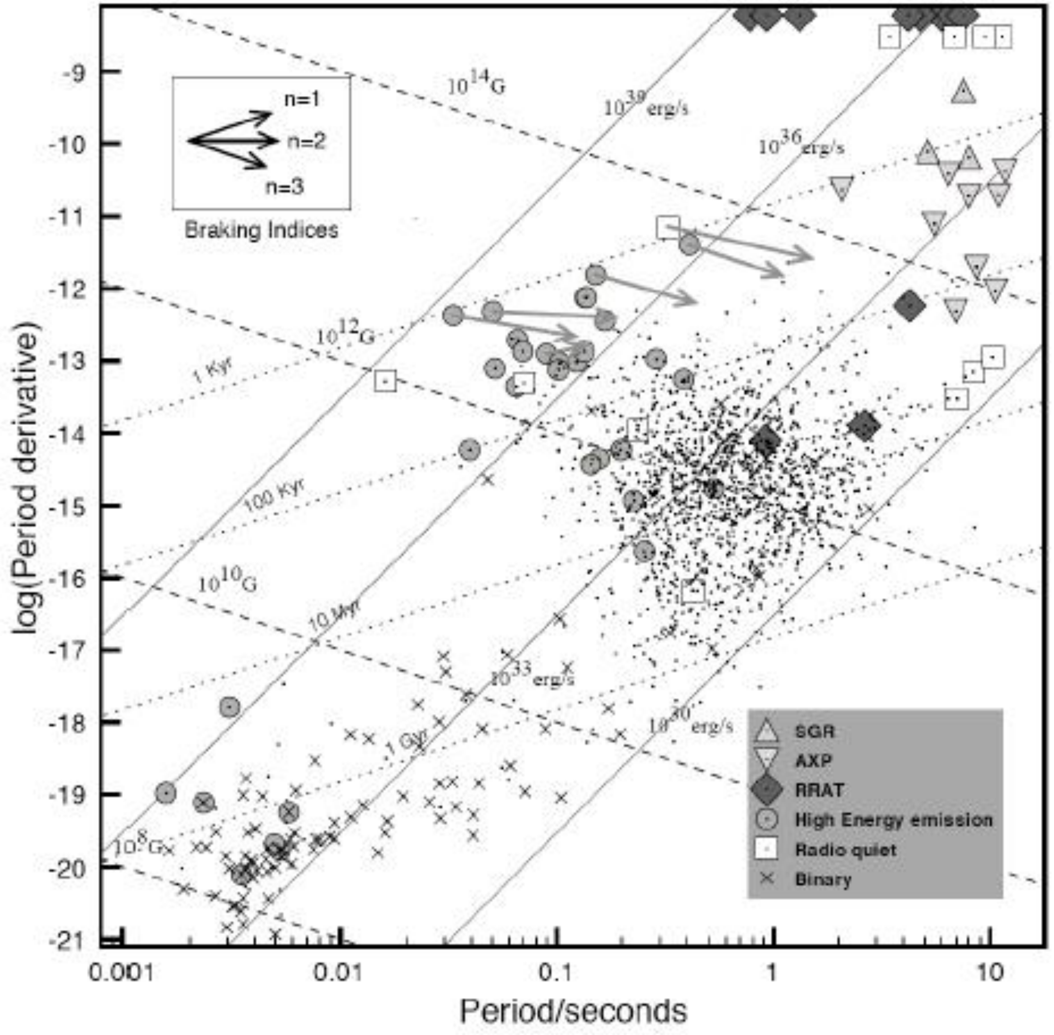


DIPOLE AND L=15





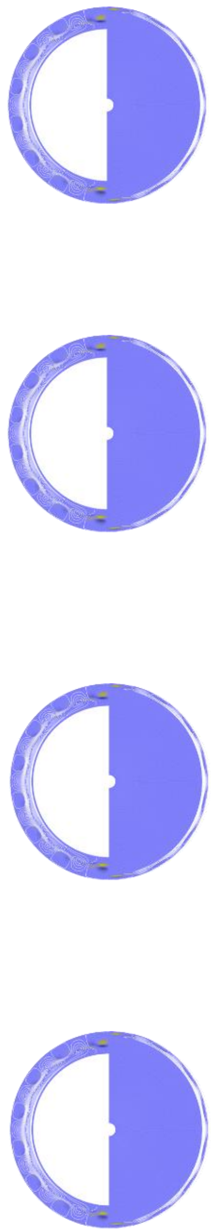
WE EXPLAIN CCOS!!!



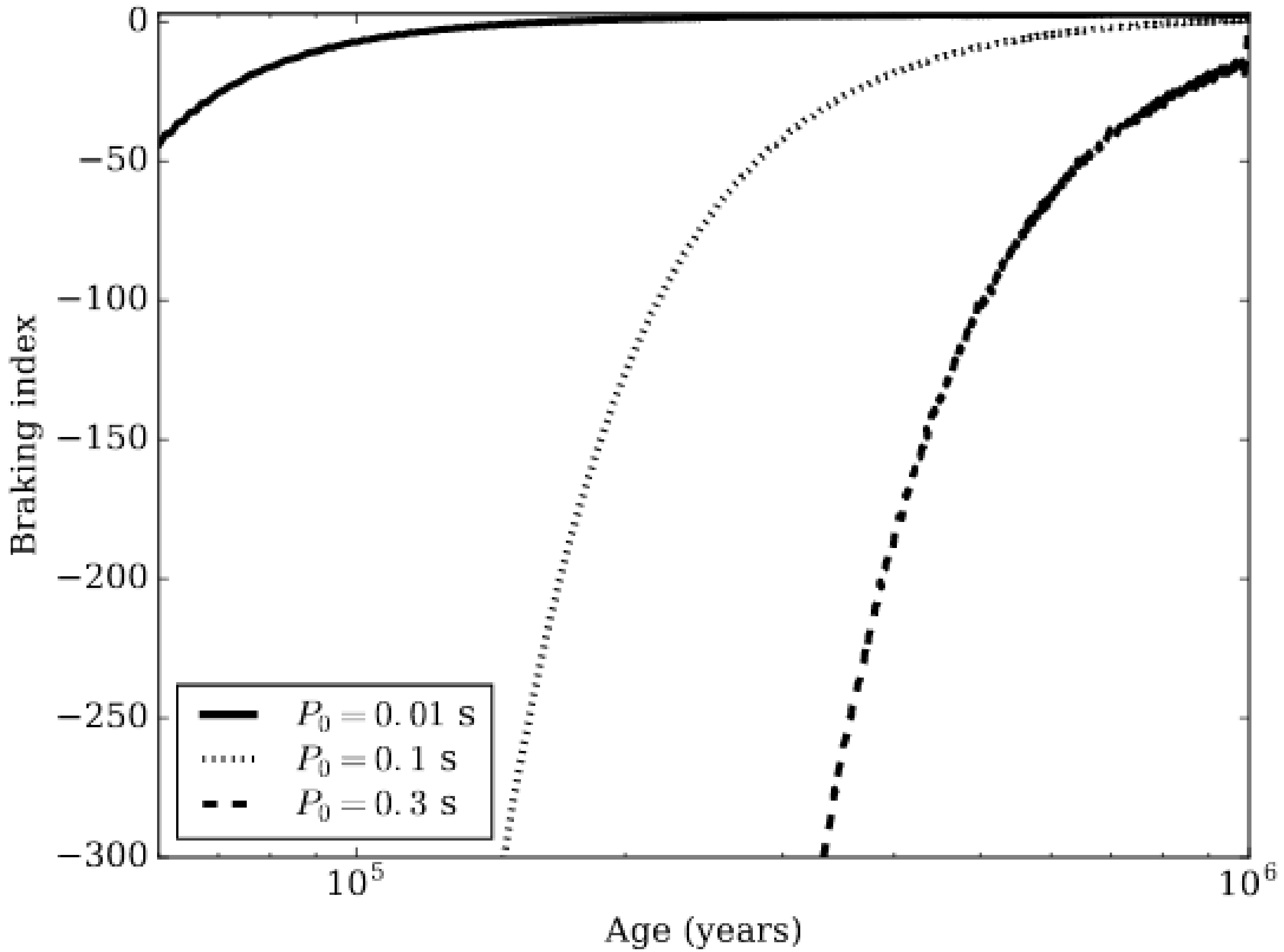
What is the crucial parameter?

Our results demonstrate that the most important parameter it is not the dipolar field which formally determines position of a NS in the P-Pdot diagram, but higher multipoles which determine curvature of magnetic field lines close to a NS surface.

Evolution of smaller scale field components is responsible for switch-on of a PSR.



EVOLUTION OF BRAKING INDEX



$$n = 3 - 2\frac{\dot{B}}{B}\frac{P}{\dot{P}} = 3 - \frac{4}{\gamma_{\rm br}}\frac{\dot{B}}{B^3}P^2.$$

$$\gamma_{\rm br} \approx 4\pi^2 R_{\rm NS}^6/(3c^3 I),$$

$$\gamma_{\rm br} \approx 10^{-39}\,{\rm G}^{-2}\,{\rm s},$$

A PSR with emerging field can be identified by its anomalous braking index.

SEARCHING FOR POST-CCO RE-EMERGED RADIO PULSARS

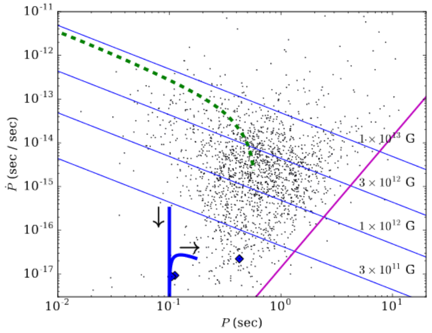
Bogdanov et al. (2014) looked for thermal surface emission from 8 PSRs in SNRs at d< 6 kpc. Nothing was found, and the authors concluded that these sources do not look like evolved CCOs.

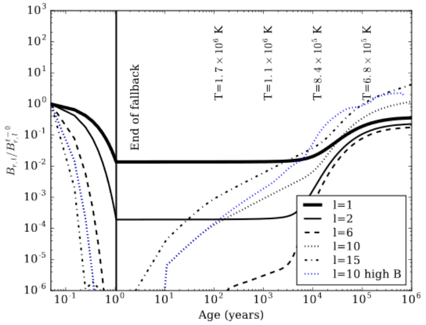
Luo et al. (2015) used a different approach.
They selected 12 non-millisecond (P>0.05 s) PSRs
with relatively low fields (<10^{11} G) at |z|<100 pc.
None of these sources demonstrated any traces of a SNR or thermal surface emission.
Limits for the temperature are <~50–100 eV.

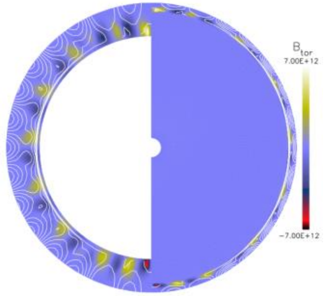
According to our results, typical post-CCO PSRs might be slightly older than it was assumed earlier. Thus, they might be colder.
We proposed a list of sources for deep XMM observations:

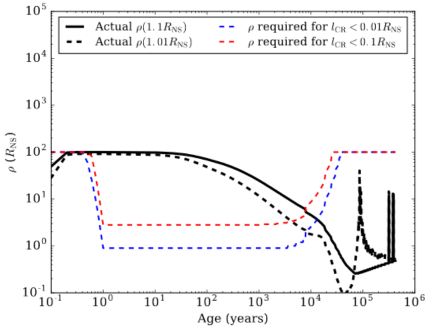
Name	gl	gb	P_0 s	D kpc	Possible association
J1107-5907	289.94	1.11	0.252773323418	1.81	CAR OB1, COLL 228, CAR OB2, NGC3766
J1154-6250	296.47	-0.68	0.28201171065	2.06	CRU OB1
J1739-3951	350.04	-4.69	0.341772476799	1.13	SCO OB4, TR 27

CONCLUSIONS









- We study the magnetic field evolution after fall-back
- We follow re-emergence and appearance of different field components
- We propose that switch-on of a PSR happens when a specific condition for curvature radiation is fulfilled
- Re-emergence of higher multipole components which is responsible for small curvature radius is the crucial ingredient for radio pulsar switch-on
- Under this hypothesis we explain why up to now no post-CCO PSRs have been detected and propose a short list of candidates for future studies.

MNRAS 462, 3689 (2016)
arXiv: 1608.08806

THANK YOU!