Radio Pulsar Emission and Crustal Field Evolution

Ulrich R.M.E. Geppert
DLR Bremen
University of Zielona Gora

Collaboration:

J. Gil & G. Melikidze

radio pulsar physics

J. Pons & D. Viganò

EMHD, **numerics**

Partially Screened Gap Model for Radio Pulsars

(see talk of A. Szary, NS2014)

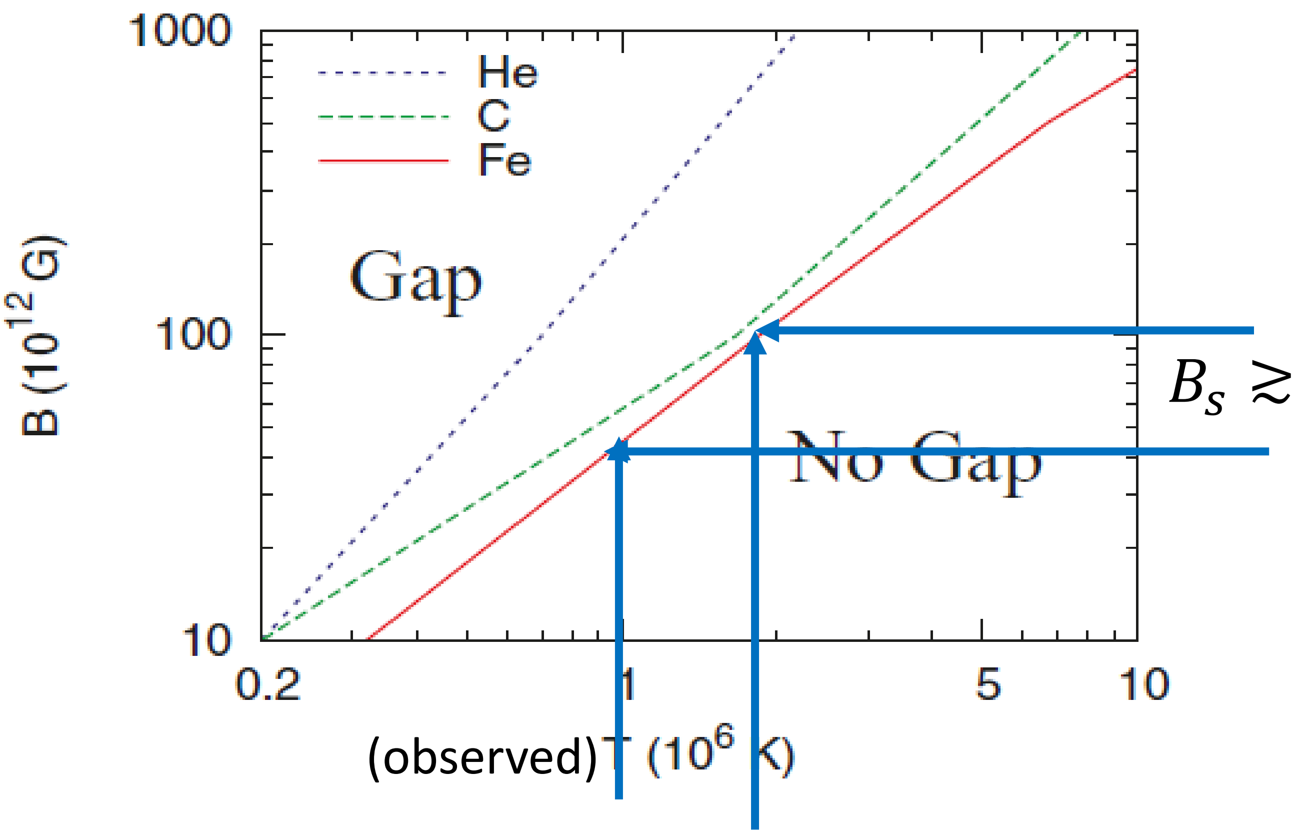
Conditions for sufficient electron positron pair creation:

1. surface field $\vec{B}_s > 5 \cdot 10^{13}$G

2. curvature radius of $\vec{B}_s \lesssim 10$km

1. surface field $\vec{B}_s > 5 \cdot 10^{13}$G

Medin & Lai 2007: $E_{cohesive}(B) > k_B T$ for gap creation



$B_s \gtrsim 5 \cdot 10^{13} \dots 10^{14}$ G

2. curvature radius of $\vec{B}_s \lesssim 10\text{km}$

part of particle energy transferred to radiation

$$\epsilon \sim 2 \cdot 10^{-13} \frac{\gamma^3}{R_{cur}^2} l$$

gap height $l \sim 10^4\text{cm}$, $\gamma \sim 5 \cdot 10^6$

dipolar field $R_{cur} \sim 10^8\text{cm} \quad \rightarrow \epsilon \sim 10^{-5}$

⇨ $R_{cur} \lesssim 10^6\text{cm}$ for $\epsilon \sim \ldots\%$

Can crustal field evolution provide such structures?

complex magneto-thermal processes

code that can model them: Viganò, Pons, Miralles 2012

successfully applied by Viganò etal. 2013
(see talk of J. Pons)

Field evolution in the crust:

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \left[\frac{c^2}{4\pi\sigma} \nabla \times \left(e^{\nu} \vec{B} \right) + \frac{c}{4\pi e n_e} \left[\nabla \times \left(e^{\nu} \vec{B} \right) \right] \times \vec{B} \right]$$

microphysics, EoS and on thermal history

$$c_V e^{\nu} \frac{\partial T}{\partial t} - \nabla \cdot \left[e^{\nu} \hat{\kappa} \cdot \nabla \left(e^{\nu} T \right) \right] = e^{2\nu} \left(-Q_{\nu} + Q_h \right)$$

main problem: „initial“ conditions

strength and structure of $\vec{B}_{pol}$ and $\vec{B}_{tor}$ at the „beginning“

field structure at the beginning:

- MHD equilibrium?
- Hall equilibrium?

} immediately after PNS phase?

- onset of crystallization? few hours, days later

Ohmic diffusion/dissipation

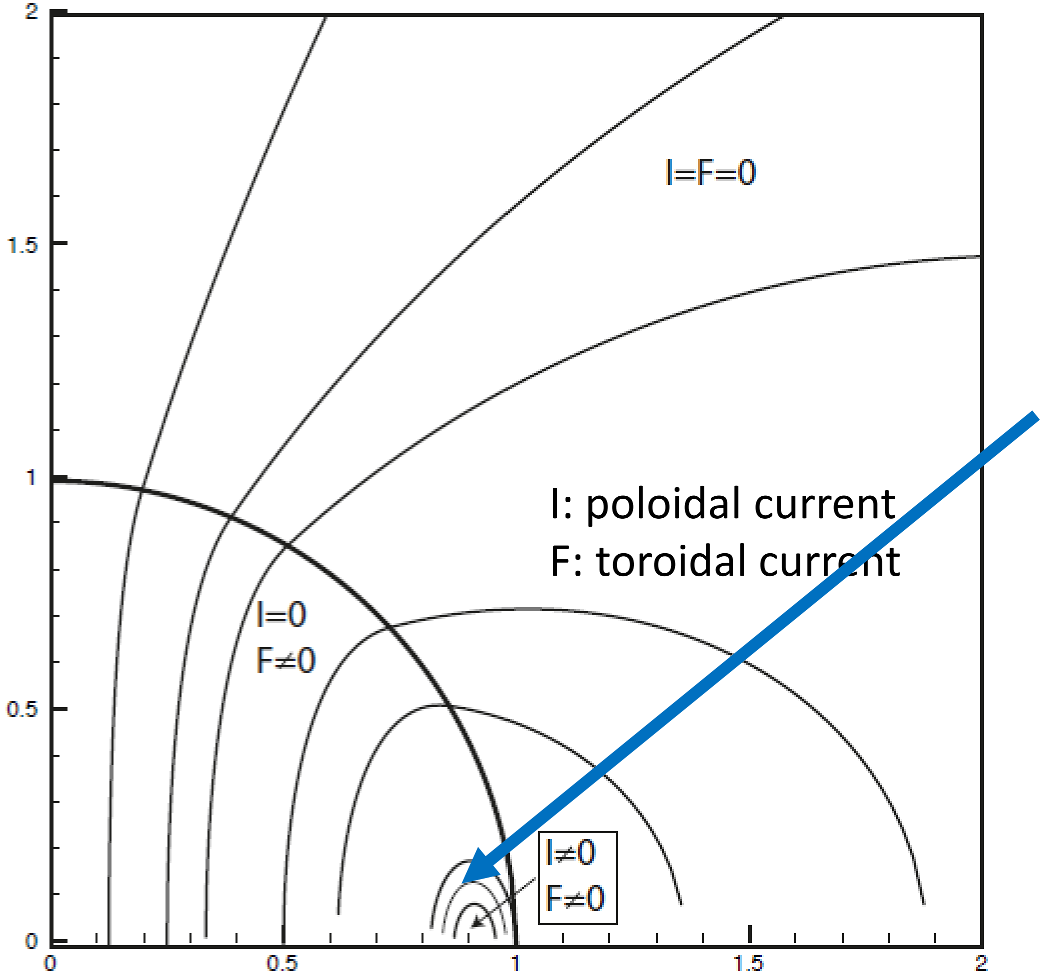
MHD equilibrium: $$\frac{1}{c\rho}\vec{j}\times\vec{B}=\frac{1}{\rho}\nabla P+\nabla\Phi$$

⇒ $$\nabla\times\left(\frac{\nabla\times\vec{B}}{\rho}\times\vec{B}\right)=0$$

⇒ toroidal component of $\vec{F}_{Lorentz}$ has to vanish

⇒ $\vec{B}_{tor}\neq 0$ only within closed (within the star) field lines of $\vec{B}_{pol}$

Lyutikov, 2010



MHD equilibrium in normal matter, const. density

B_{tor} confined to a small equatorial belt of closed poloidal field lines

qualitatively similar form for barotropic and non-barotropicEoS

(Fujisawa, Yoshida,Eriguchi, 2012),

for stratified and SCII

(Lander, Andersson, Glampedakis, 2012)

MHD equilibrium stable?

Yes, twisted torus field (Braithwaite&Nordlund, 2004)

after hours … days: crystallization starts at crust-core interface

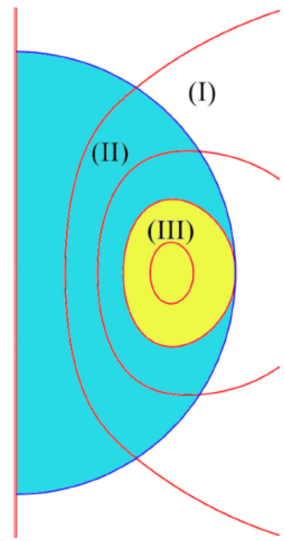
there: electron MHD

Hall equilibrium? $$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\frac{\nabla \times \vec{B}}{4\pi e n_e} \times \vec{B} \right) = 0$$

Hall equilibrium: $$\nabla \times \left(\frac{\nabla \times \vec{B}}{n_e} \times \vec{B} \right) = 0$$

quite similar to MHD equilibrium

Gourgouliatos etal. 2013:



Can it be established at all? Continuous Ohmic decay!

Drives difference between MHD and eMHD evolution?

Gourgouliatos etal. 2013:

even if MHD equilibrium at $t = 0$:

$$\left(\nabla \times \vec{B}\right) \times \vec{B} = \rho \nabla S_{MHD}, \qquad S_{MHD} = g(r) sin^2\vartheta$$

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\frac{\nabla \times \vec{B}}{4\pi e n_e} \times \vec{B}\right)$$

electron fraction $Y_e = \frac{n_e}{\rho}$

$$\delta \vec{B} = \frac{c}{2\pi e} \frac{g(r)}{r Y_e^2} \frac{dY_e}{dr} sin\vartheta cos\vartheta \delta t \vec{e}_\varphi$$

Y_e increases towards the surface

⇒ quadrupolar toroidal component

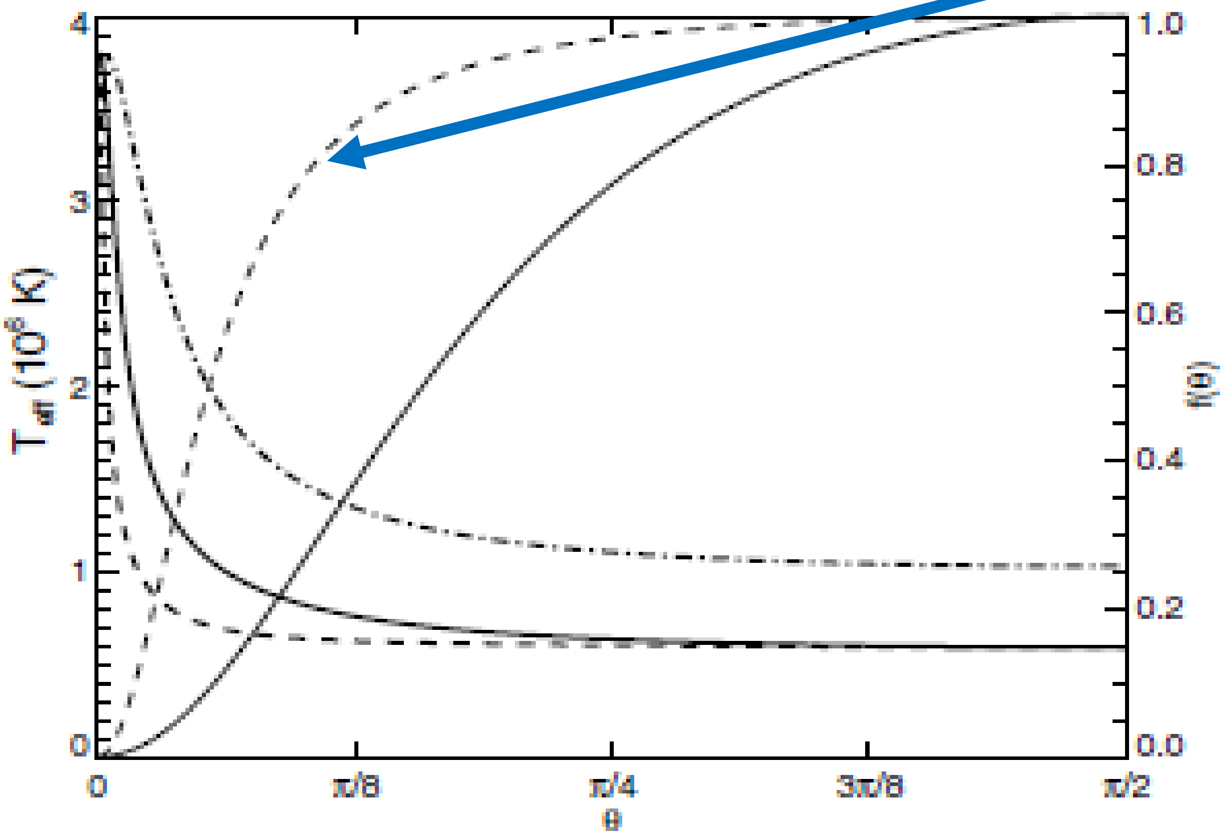
⇒ higher order poloidal and toroidal multipoles

⇒ Hall equilibrium will be reached only when $\vec{B}_{tor}$ has been dissipated much observational clues on internal field structure:

Shabaltas & Lai 2012: lightcurve of young NS in Kes79

relatively weak dipole field
strong crustal toroidal field

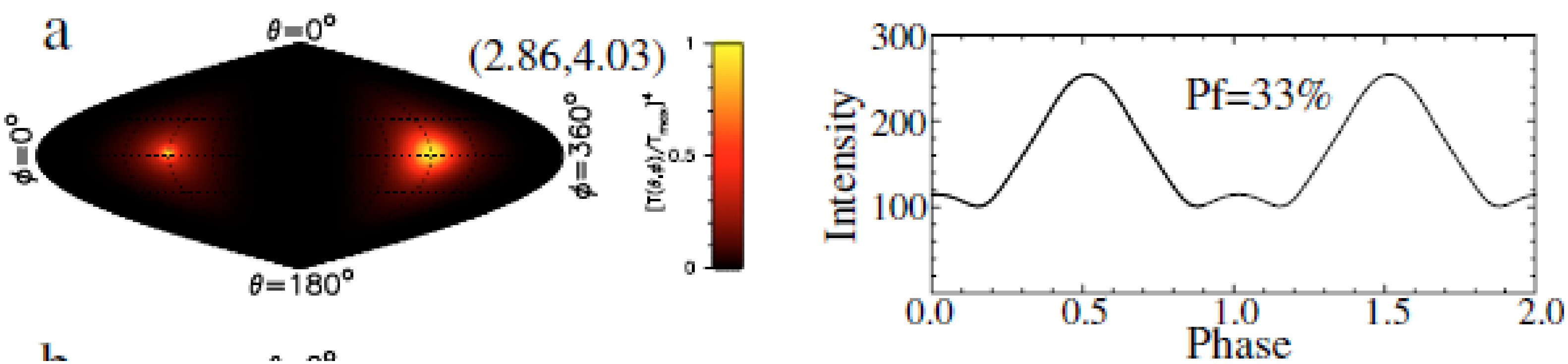
best fit: $B_{tor} = B_0 f(\theta)$



Rea etal. 2010: SGR 0418+5729

„…,a large fraction of the radio pulsar population may have magnetar like internal fields not reflected in their normal dipolar component.“

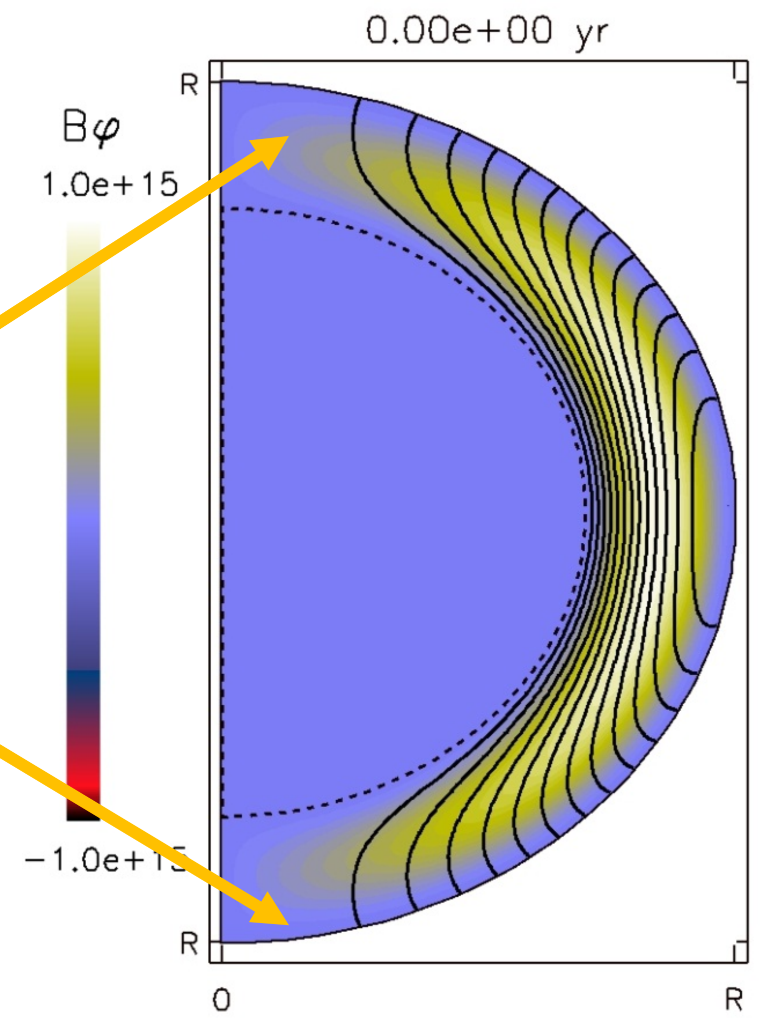
Geppert etal. 2006: pulsed thermal X-ray emission



strong crustal toroidal fields

initial field configuration:

axial symmetry: vanishing B_{tor} in the polar region

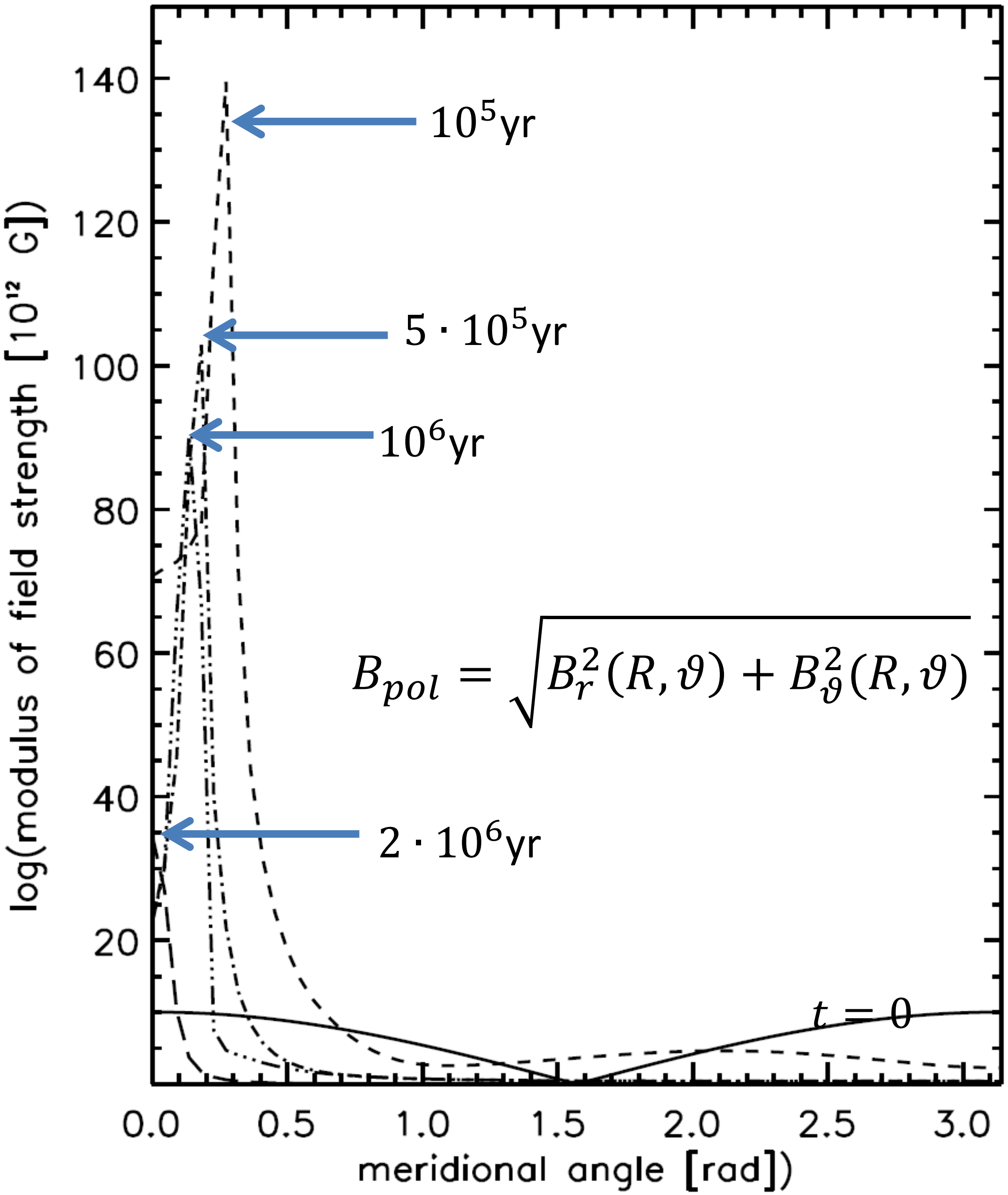


promising model:

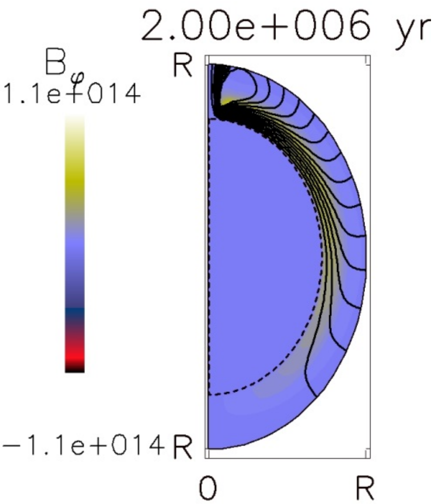
$M = 1.4 M_{\odot}$, i.e. standard cooling

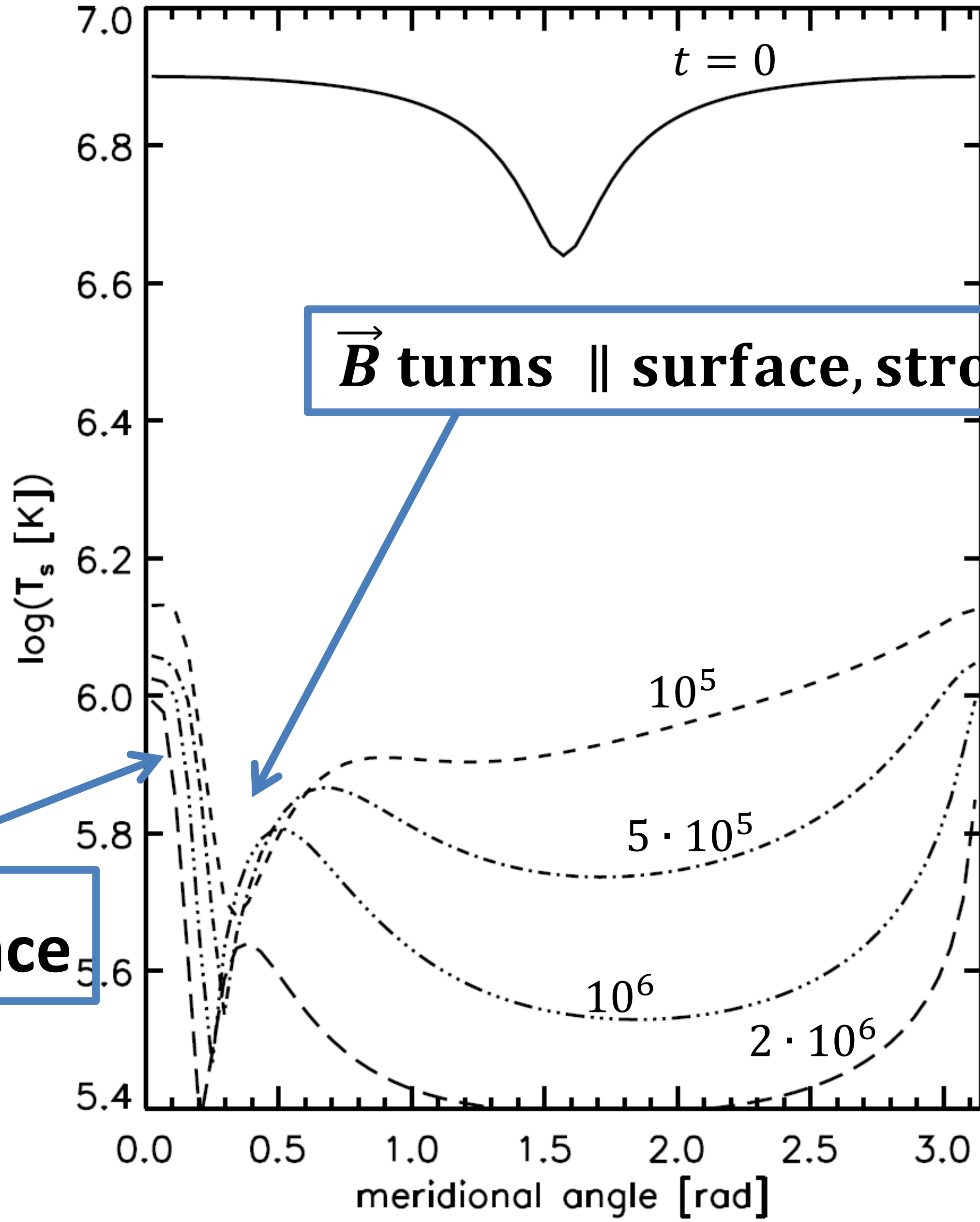
at $t = 0$:
$\vec{B}_{pol}(r = R, \vartheta = 0) = 10^{13}$G, $\vec{B}_{tor}^{max} = 1.5 \cdot 10^{15}$G

impurity parameter:
$Q_{pasta}(\rho > 6 \cdot 10^{13} \mathrm{g\ cm}^{-1}) = 100$
$Q_{imp}(\rho \leq 6 \cdot 10^{13} \mathrm{g}\ cm^{-1}) = 0.1$



140
120
100
80
60
40
20
0.0
0.5
1.0
1.5
2.0
2.5
3.0
log(modulus of field strength [10¹² G])
meridional angle [rad])
10^5yr
$5 \cdot 10^5$yr
10^6yr
$2 \cdot 10^6$yr
$B_{pol} = \sqrt{B_r^2(R,\vartheta) + B_\vartheta^2(R,\vartheta)}$
$t = 0$





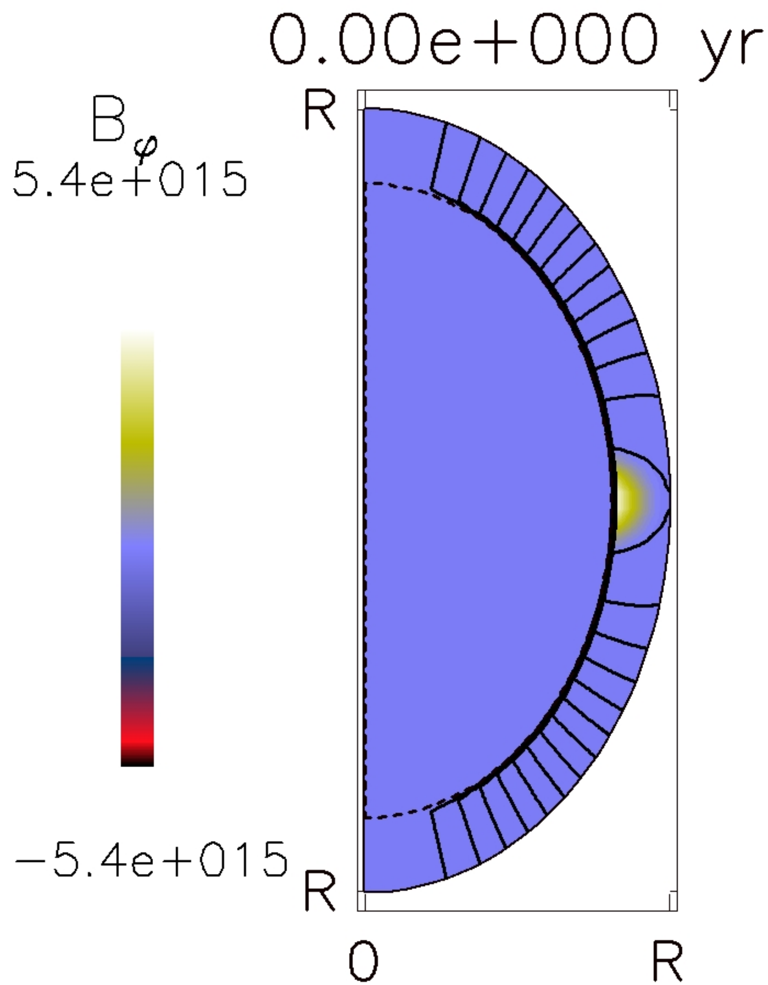
$\overrightarrow{B}$ **turns $\parallel$ surface, strongest**

$\overrightarrow{B} \sim \perp$ **surface**

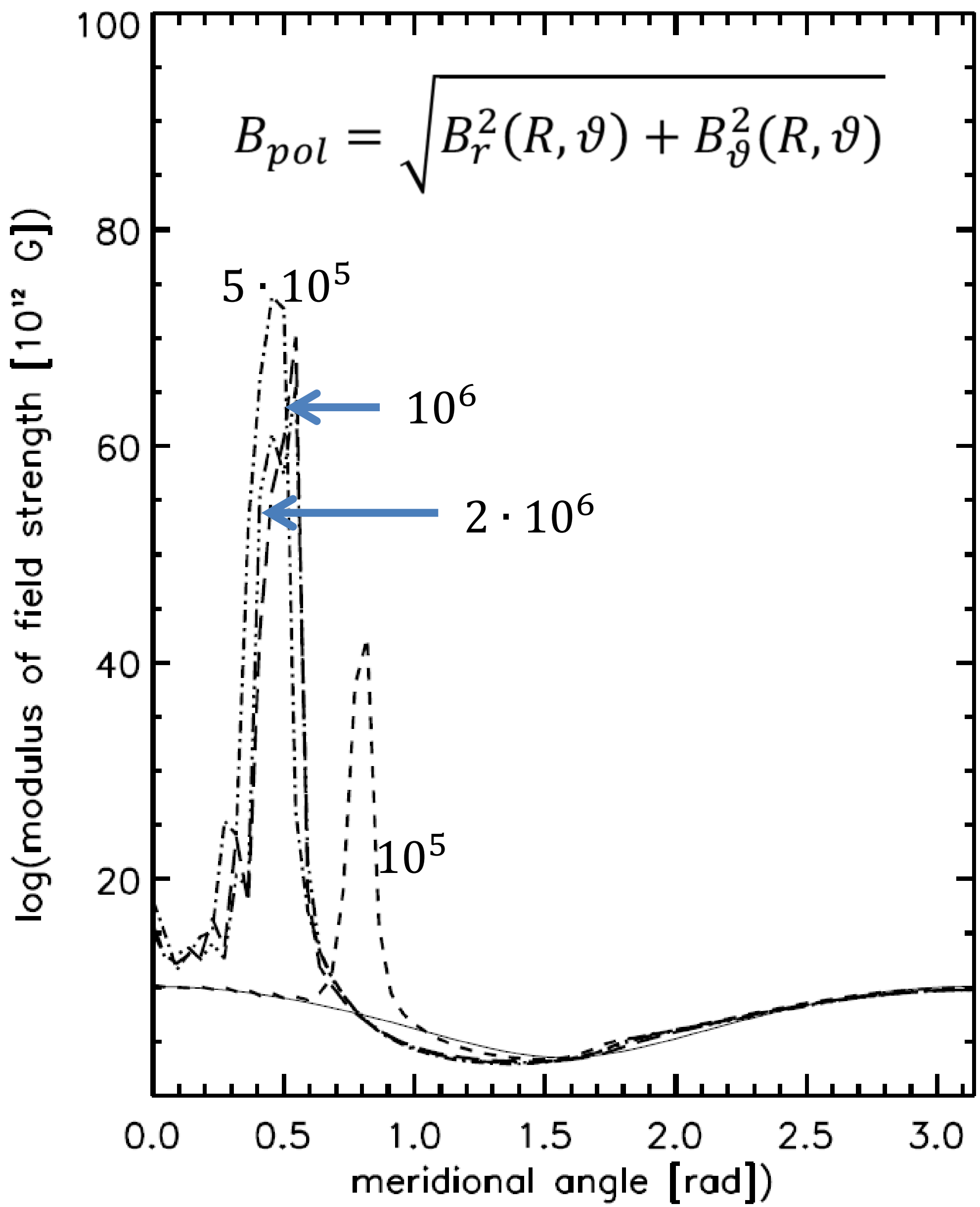
$\overrightarrow{B}$ **decays in the South**

However:

$\vec{B}_{tor}(\mathrm{t}=0)$ confinded in closed $\vec{B}_{pol}$ lines $\Longrightarrow$ similar structures



- maximum B_φ in core
- B_φ at crust core interface strong but no problem



$B_{pol} = \sqrt{B_r^2(R,\vartheta) + B_\vartheta^2(R,\vartheta)}$
$5 \cdot 10^5$
10^6
$2 \cdot 10^6$
10^5
log(modulus of field strength [10¹² G])
meridional angle [rad])
100
80
60
40
20
0.0
0.5
1.0
1.5
2.0
2.5
3.0

Conclusions:

- magnetic spot is created in $10^4 \dots 10^5$ yr

- meridional spot scale $\sim 2^o \dots 3^o$, very close to North pole if crustal confined field, at $\sim 20^\circ$ if field penetrates core

- spot is maintained over few 10^6yr

- $T_s(\vartheta)$ reflects the the influence of the field on the heat flow electric conductivity in deep crustal layer ($\rho > 6 \cdot 10^{13}\mathrm{gcm}^{-3}$) has to be not too large

$$\sigma^{-1} = \sigma_{ph}^{-1}(\rho, T, A, Z) + \sigma_{imp}^{-1}(\rho, Z, Q_{imp})$$

⇒ large impurity coefficient

⇒ important: $Q_{pasta} \sim 100$ is necessary,
while for smaller ρ: $Q_{imp} \sim 0.1 \dots 0.01$

proof: same model but $Q_{pasta} = Q_{imp} = 0.1$

Not in contradiction to Pons, Viganò, Rea 2013:

⇒

large Q_{pasta} necessary to explain slow spin of X-ray pulsars!!

→ field strength at the beginning:

if $|\vec{B}_{tor}| \lesssim 10^{14}$G : not sufficent for creation of a magnetic spot with $|\vec{B}_{pol}| \gtrsim 5 \cdot 10^{13}$G

if $|\vec{B}_{tor}| \gtrsim 5 \cdot 10^{15}$ G: too strong local Joule heating, too rapid field decay

$$10^{14}\mathrm{G} \leq \vec{B}_{tor}^{max}(t=0) \leq 5 \cdot 10^{15}\mathrm{G}$$

$$5 \cdot 10^{12}\mathrm{G} \leq \vec{B}_{pol}(t=0) \leq 5 \cdot 10^{13}\ \mathrm{G}$$

→ field structure at the beginning:

both $\vec{B}_{pol}$ and $\vec{B}_{tor} \sim$ dipolar

$\vec{B}$ can be either confined to the crust or thread the core with $\vec{B}_{tor}$ confinded within closed poloidal field lines

Required magnetic „hot spots“ are created on the right timescale and with sufficient strengths, quite independently on the initial field structure for initial field strength that are typical for young neutron stars!

Next (and urgent) task:

3D non-axialsymmetric fields!!!