Magnetars vs. High-B Field Pulsars: Is there a Real Dichotomy?

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- ✔ Introduction.
- ✔ Thermal evolution.
- ✔ Coupled magneto-thermal evolution. Feedback.
- ✔ Population synthesis.
- ✔ Crustal magnetic field evolution. Implications.
- ✔ AXP 1E2259 vs. PSR J1814+1744
- ✔ SGR 0418+1744

Reminder :
Neutron stars do have magnetic fields

- Last 10 years: increasing evidence of B field influencing (surface/magnetospheric) thermal spectra. Non trivial B fields.

- Cooling of magnetized NSs just beginning to be considered, not yet in a fully consistent way. Until recently only 1D cooling, and decoupled B-T evolution. Can we put constraints on fast/slow cooling models with 1D, non-magnetic models ?

- The magnetar problem more and more puzzling. Why do some objects display giant flares(SGRs), while others (AXPs) do not? Why at least one case of ``low-B'' Nss (SGR~0418+5729) flared, if the magnetic field is their driving force ?

Our present knowledge

- in "low field NSs" ($B<10^{12}$ G)

1D models are reasonably correct (anisotropy, if any, in the envelope)
Joule heating by crustal magnetic field decay not relevant.
Or maybe in old NSs too cool to be observable.

- in "magnetars" ($B>10^{14}$ G)

Some consensus in the fact that they are "too hot for their age" and the magnetic energy is maintaining the high temperature and it is somehow responsible for the burst/flare phenomenology.

What happens to intermediate B objects ?

(Which, by the way, are most of them ! And many of those we use to establish constraints on dense matter with cooling curves …)

Why do we need complicated simulations of the magneto-thermal evolution of NSs ?

As the SN community started more two decades ago, or the burst community started quite recently, at some point one needs to go beyond back-of-the-envelope estimates and oversimplified one zone models. Because of the magnetic field, the problem is intrinsically multi-D

If we really want to say anything about properties of high density/exotic matter, or about evolutionary links between different objects, we must go beyond current (probably over simplified) NS evolution/cooling models. Need to keep updating new advances in microphysics at ALL densities and perform realistic simulations with all the relevant physics (not always simple: superconductivity, magneto-elasticity).

Our goal: study the evolution of a NS during its first Myrs of life considering the feedback between T and B evolution in the crust.

Magneto-thermal evolution of NSs

- Neutron star model (structure, EOS)
- Thermal evolution (energy balance equation): standard cooling of NSs but need to go multi-D and consider Joule heating.
- Microphysics ingredients (thermal conductivity, electrical resistivity, neutrino emission processes …)
- Elastic properties of the crust: shear modulus, breaking strength. To understand tectonic activity.
- Magnetic field evolution in the crust: Hall induction equation
- Magnetic field evolution inthe core: superfluid/superconducting fluid dynamics, interaction between vortices/fluxoids ???
- Put everything in a numerical code. Results from simulations. Makes sense of the results.

Thermal diffusion

- Diffusion equation in axial symmetry

$$C_v e^{\Phi(r)} \frac{\partial T}{\partial t} + \vec{\nabla} \cdot (-\hat{\kappa} \cdot \vec{\nabla}(e^{\Phi(r)} T)) = e^{2\Phi(r)} Q$$

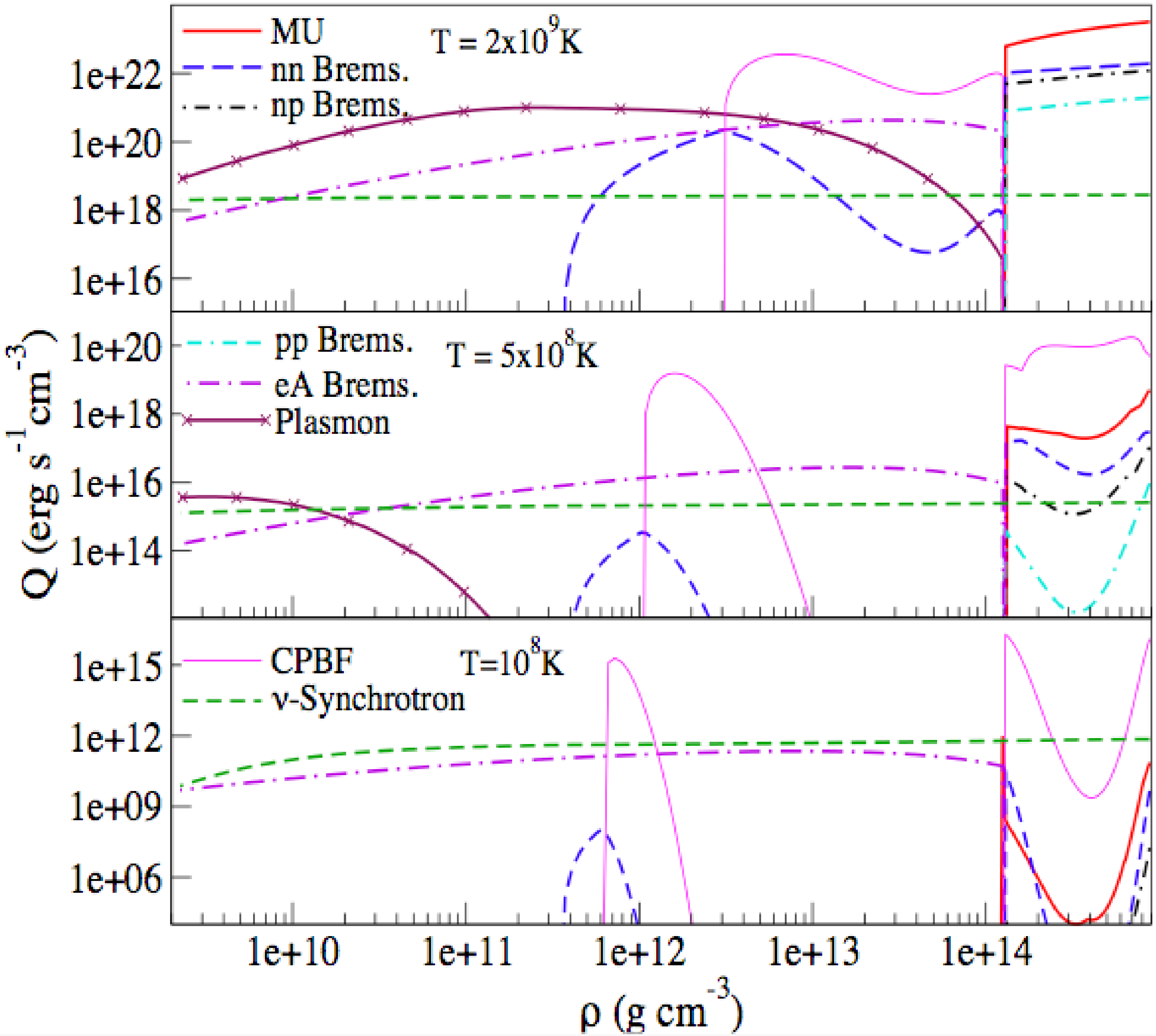
Thermal diffusion

- Diffusion equation in axial symmetry

$$C_v e^{\Phi(r)} \frac{\partial T}{\partial t} + \vec{\nabla} \cdot (-\hat{\kappa} \cdot \vec{\nabla}(e^{\Phi(r)} T)) = e^{2\Phi(r)} Q$$

energy loses/gains: ν, γ-emission/Joule

Neutrino emissivities



- Crust
  1. eA Bremsstrahlung
  2. Plasmon decay
  3. Pair $e - e^+$ formation
  4. nn Bremsstrahlung
  5. Cooper pairing of n
  6. Synchrotron
- Core
  1. Modified Urca
  2. nn Bremsstrahlung
  3. Direct Urca
  4. Cooper pairing of n, p

Thermal diffusion

- Diffusion equation in axial symmetry

$$C_v e^{\Phi(r)} \frac{\partial T}{\partial t} + \vec{\nabla} \cdot (-\hat{\kappa} \cdot \vec{\nabla}(e^{\Phi(r)} T)) = e^{2\Phi(r)} Q$$

$\hat{\kappa}$: thermal conductivity tensor

Thermal diffusion

- Diffusion equation in axial symmetry

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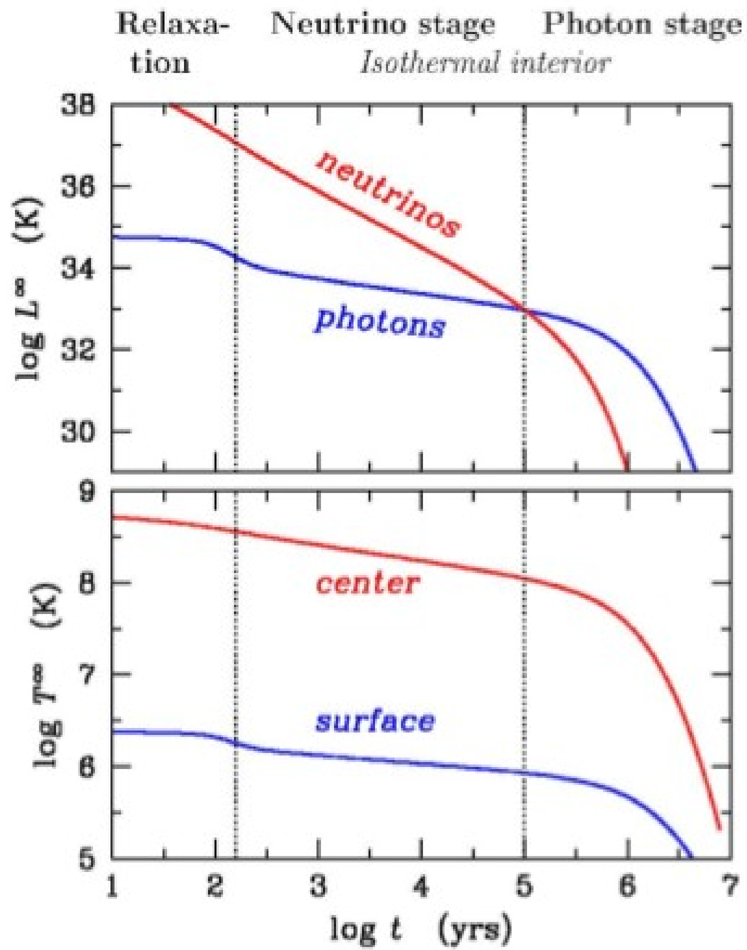
$\hat{\kappa}$: thermal conductivity tensor

- B induces anisotropic heat transport

$$\frac{\kappa_{\parallel}}{\kappa_{\perp}} = 1 + (\omega_B \tau_e)^2 >> 1 \quad \text{at low } T$$

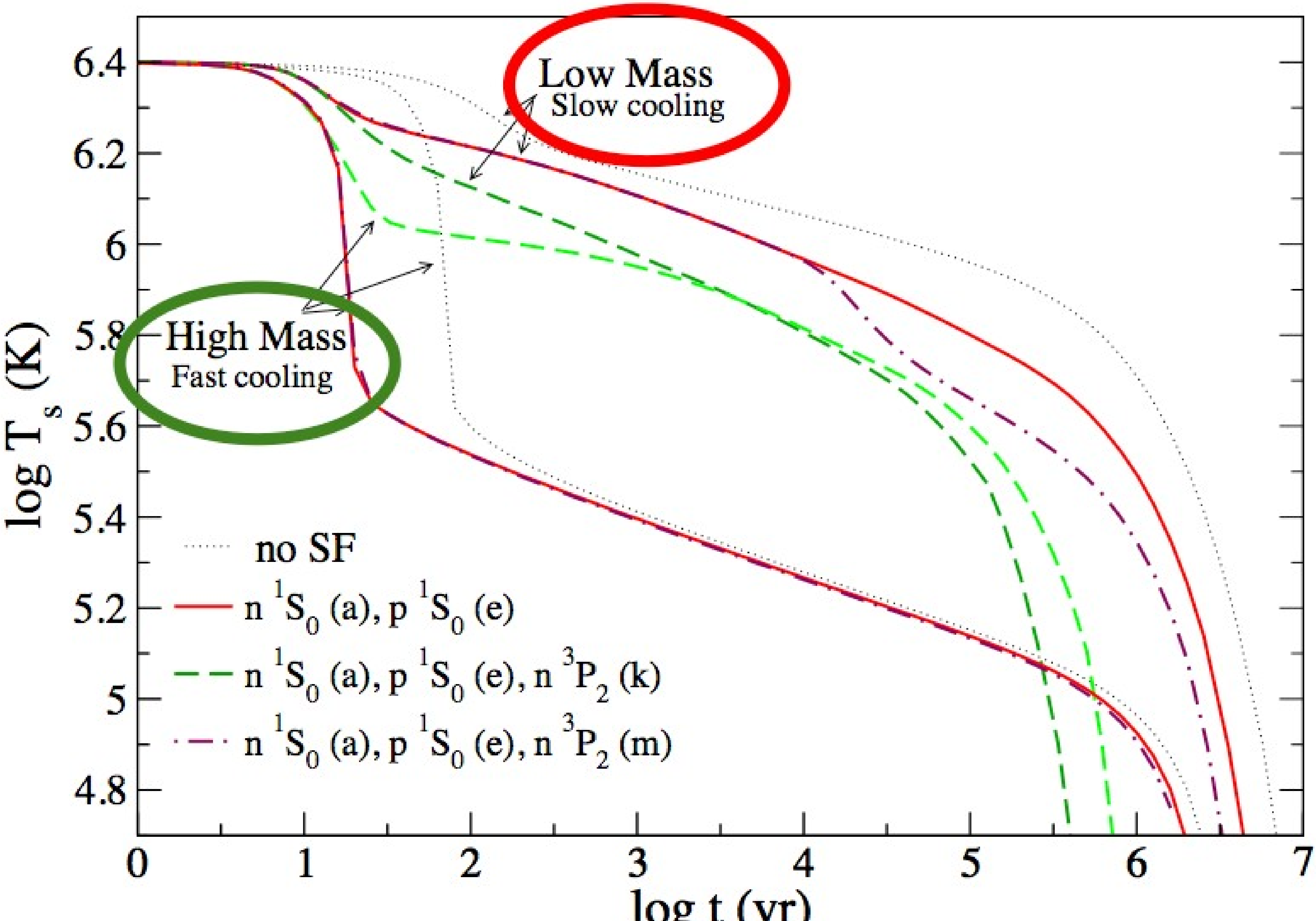
- 2D treatment is necessary

THREE COOLING STAGES

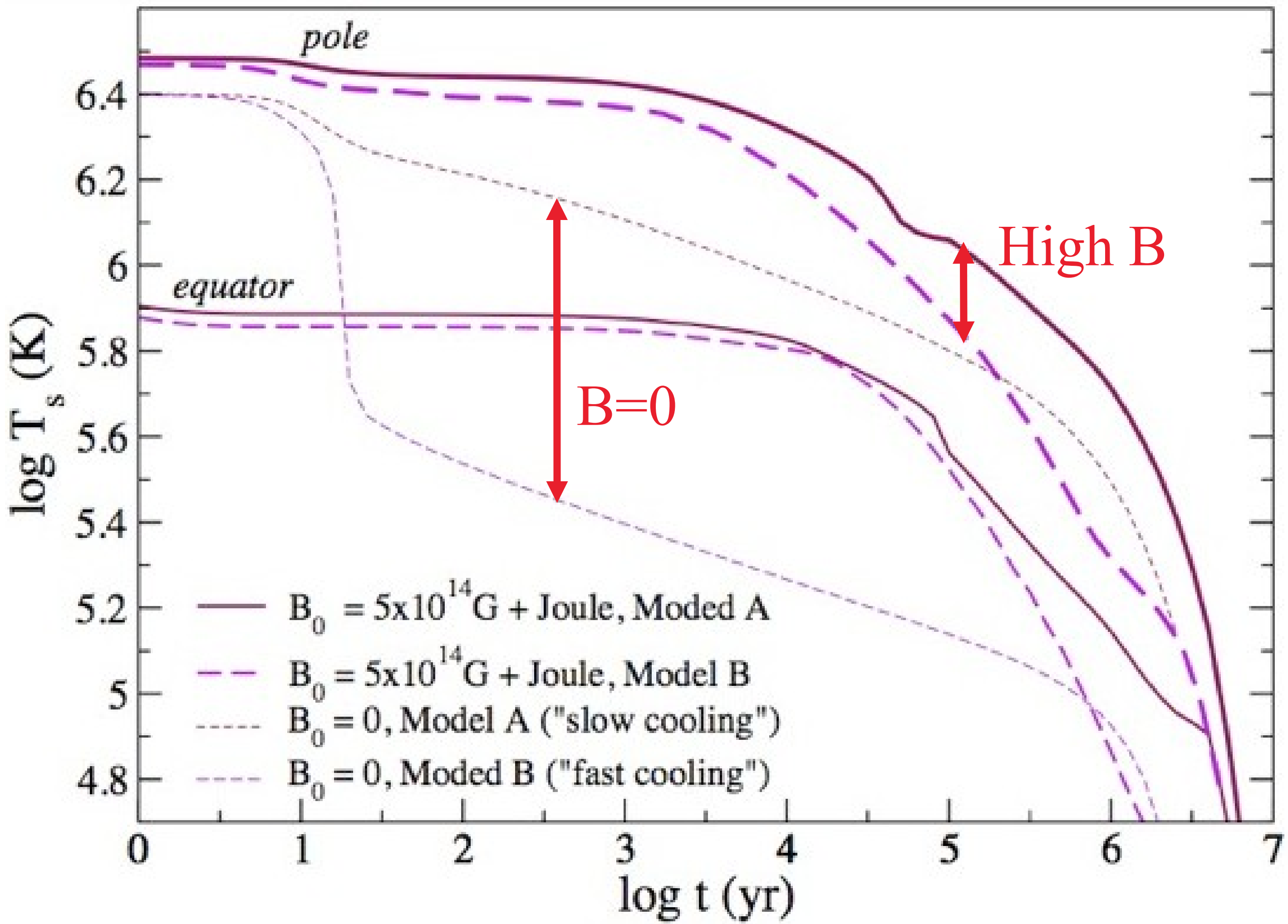


Stage	Duration	Physics
Relaxation	10—100 yr	Crust
Neutrino	10-100 kyr	Core, surface
Photon	infinite	Surface, core, reheating

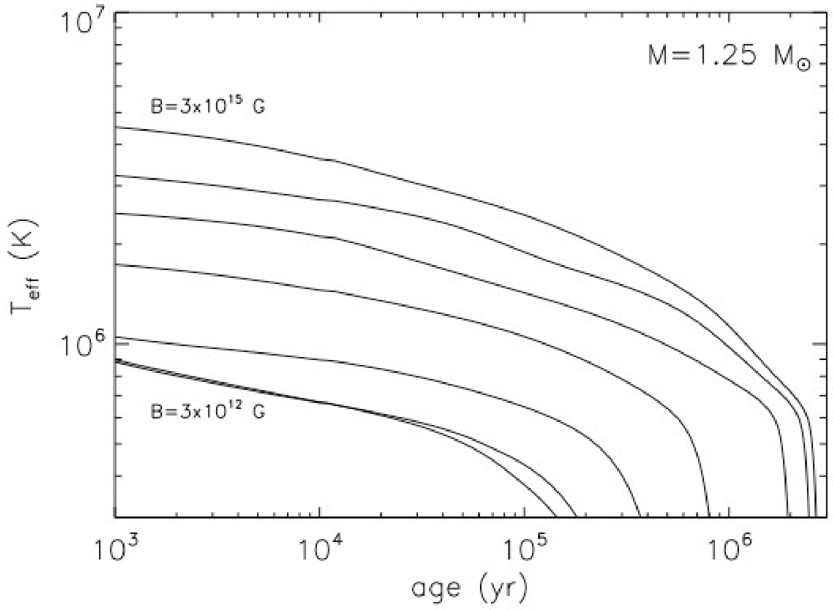
Weakly magnetized NSs (<10^{12}G)

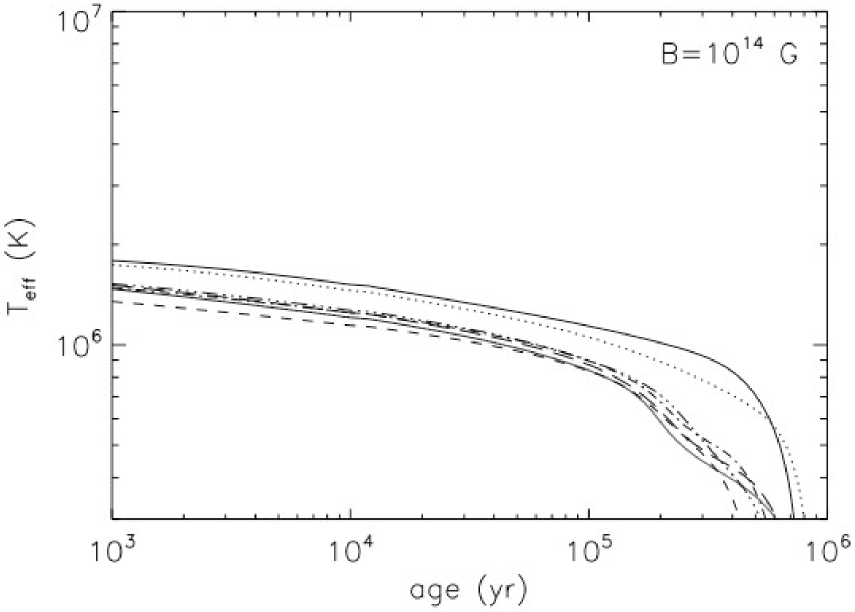


High B masquerades fast cooling ?



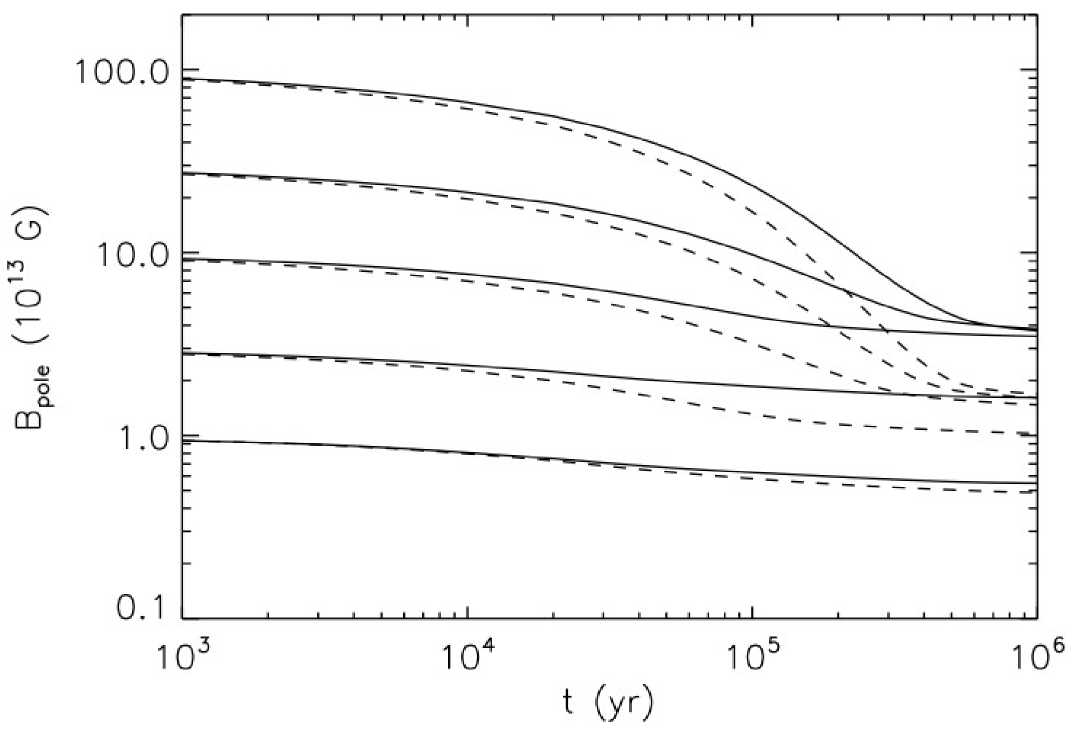
Joule heating masquerades fast cooling ?





Mass dependence vs. B field dependence:
B field rules the thermal evolution.
All NSs with fast cooling not ruled out !

Coupled B–T evolution



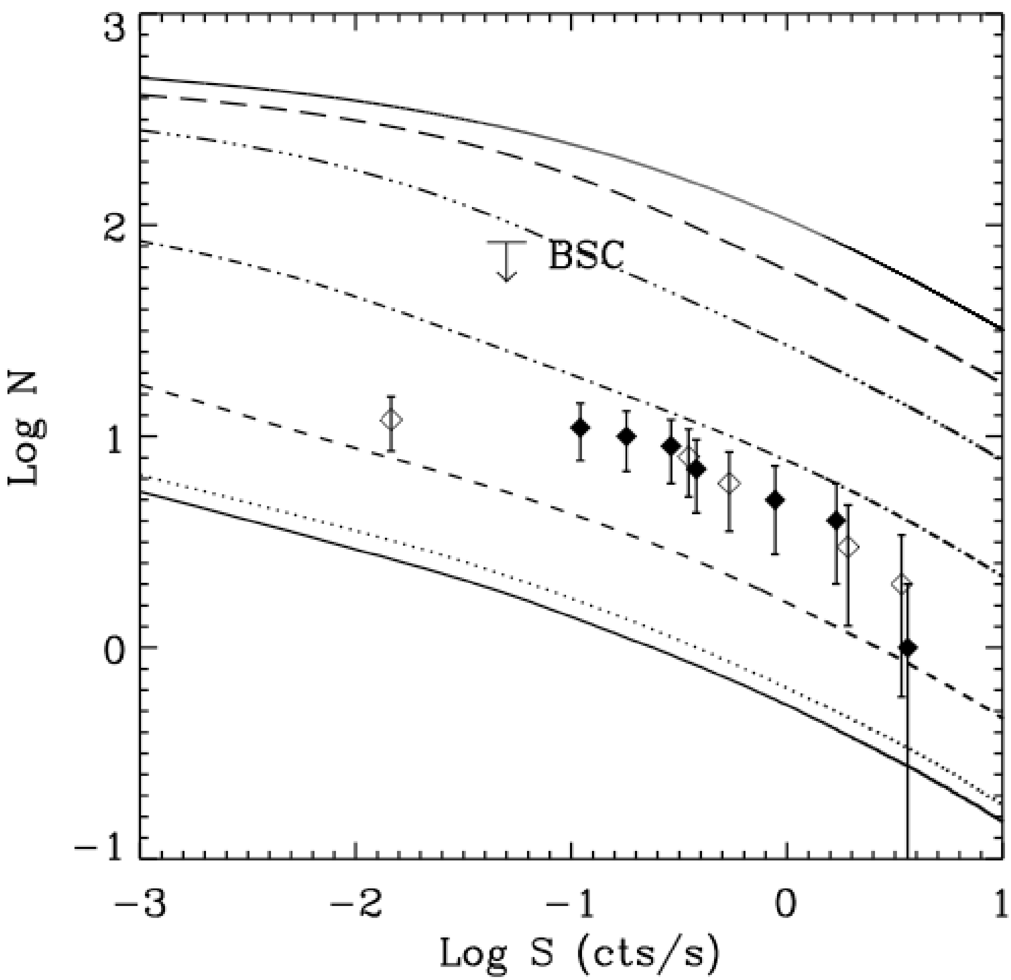
- maximum B field for old NSs !!

- higher fields = more heating = higher resistivity = faster decay

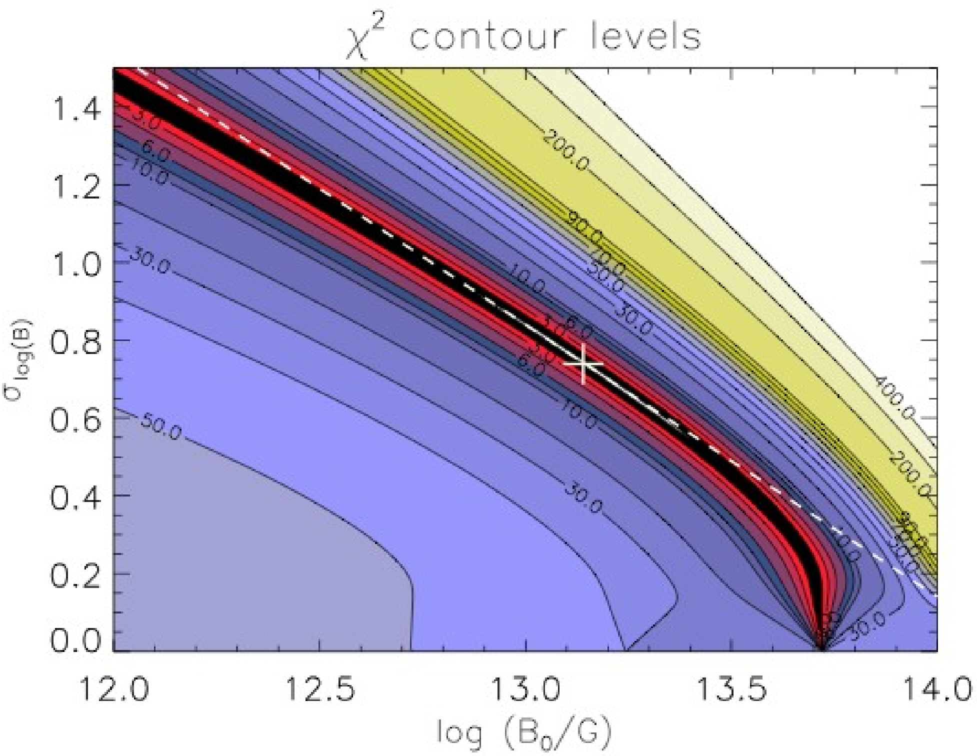
Pons, Miralles, Geppert A&A 2009

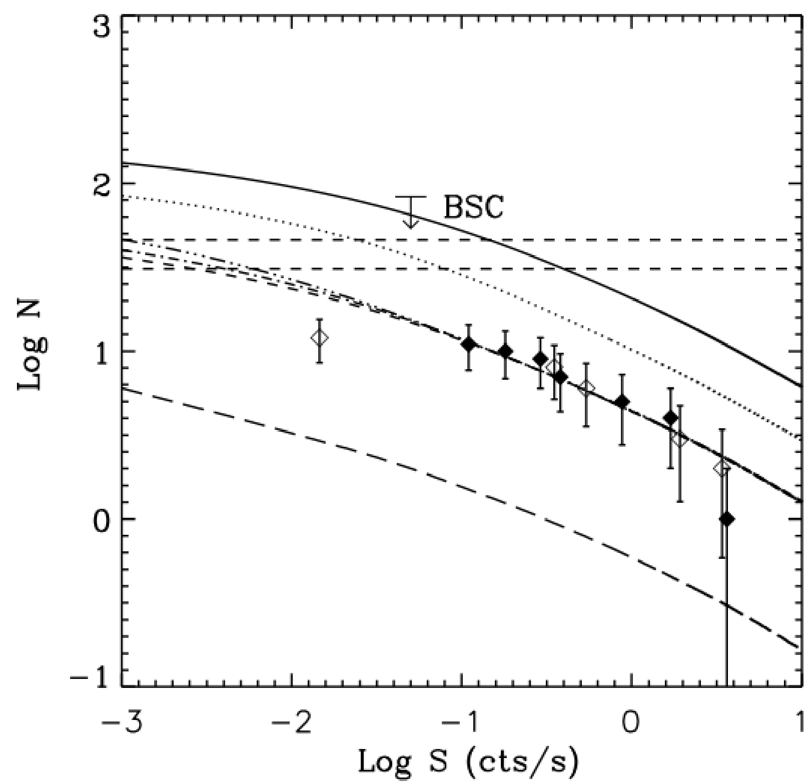
Population synthesis I: nearby thermally emitting NS

- LogN–LogS study of known NSs at d<3 kpc
- Same underlying physical model, same magnetic field geometry, only varying strength.
- Only ROSAT all sky survey with flux > 0.1 counts per second is "complete".



Population synthesis I: nearby thermally emitting NS





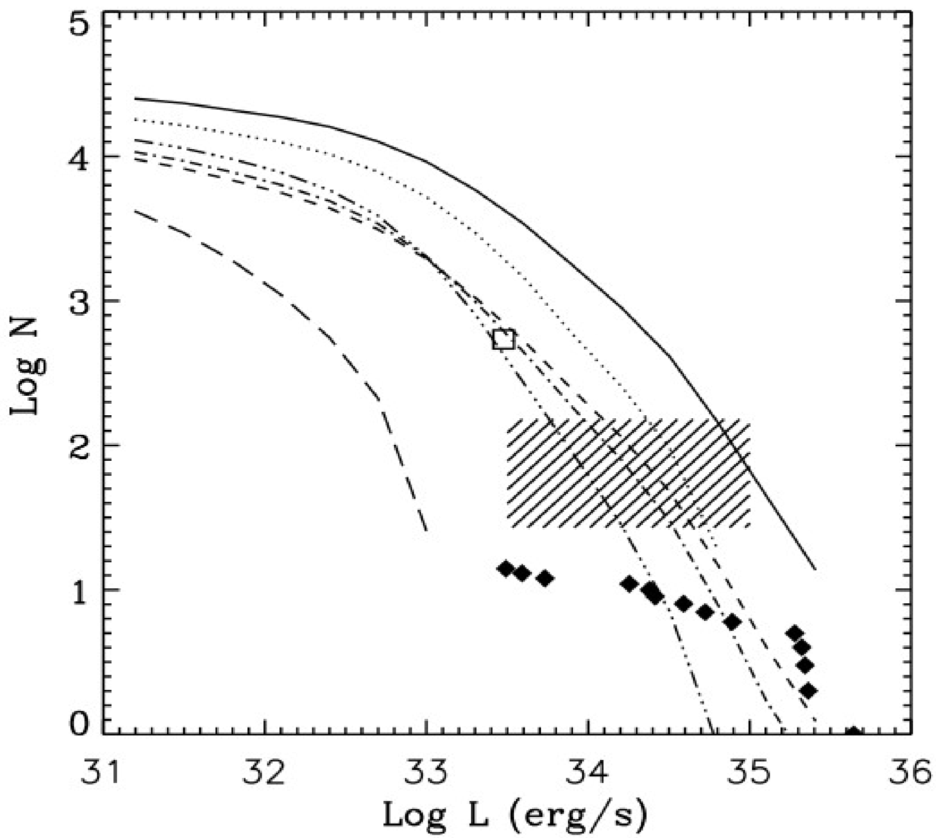
Log-normal B field distributions

Population synthesis II: galactic magnetars

Same distributions are consistent with magnetar population.

Degenaracy in parameter space not broken

Maybe some extra luminosity needed for young objects (<1 kyr)



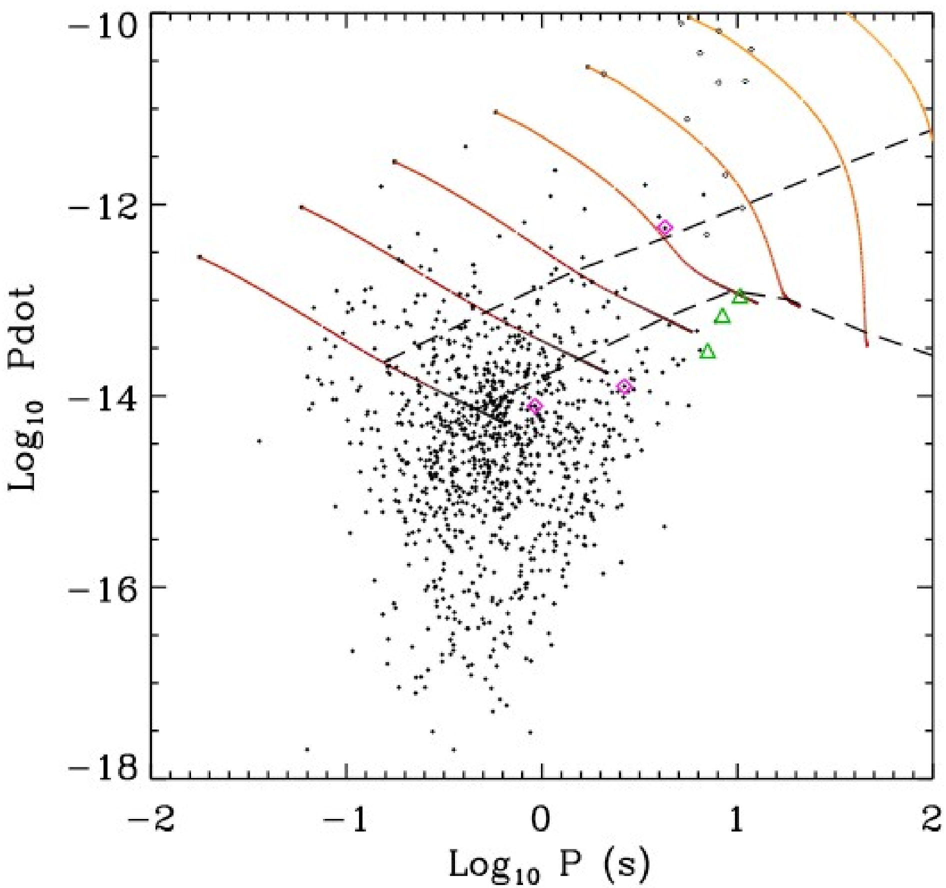
Magnetar data from McGill online catalogue (luminosities !)
Muno et al. 2008 estimates in shaded box and square.

Population synthesis III: radio-pulsars

Evolution with field decay affects mainly to highly magnetized objects and the first Myr of evolution.

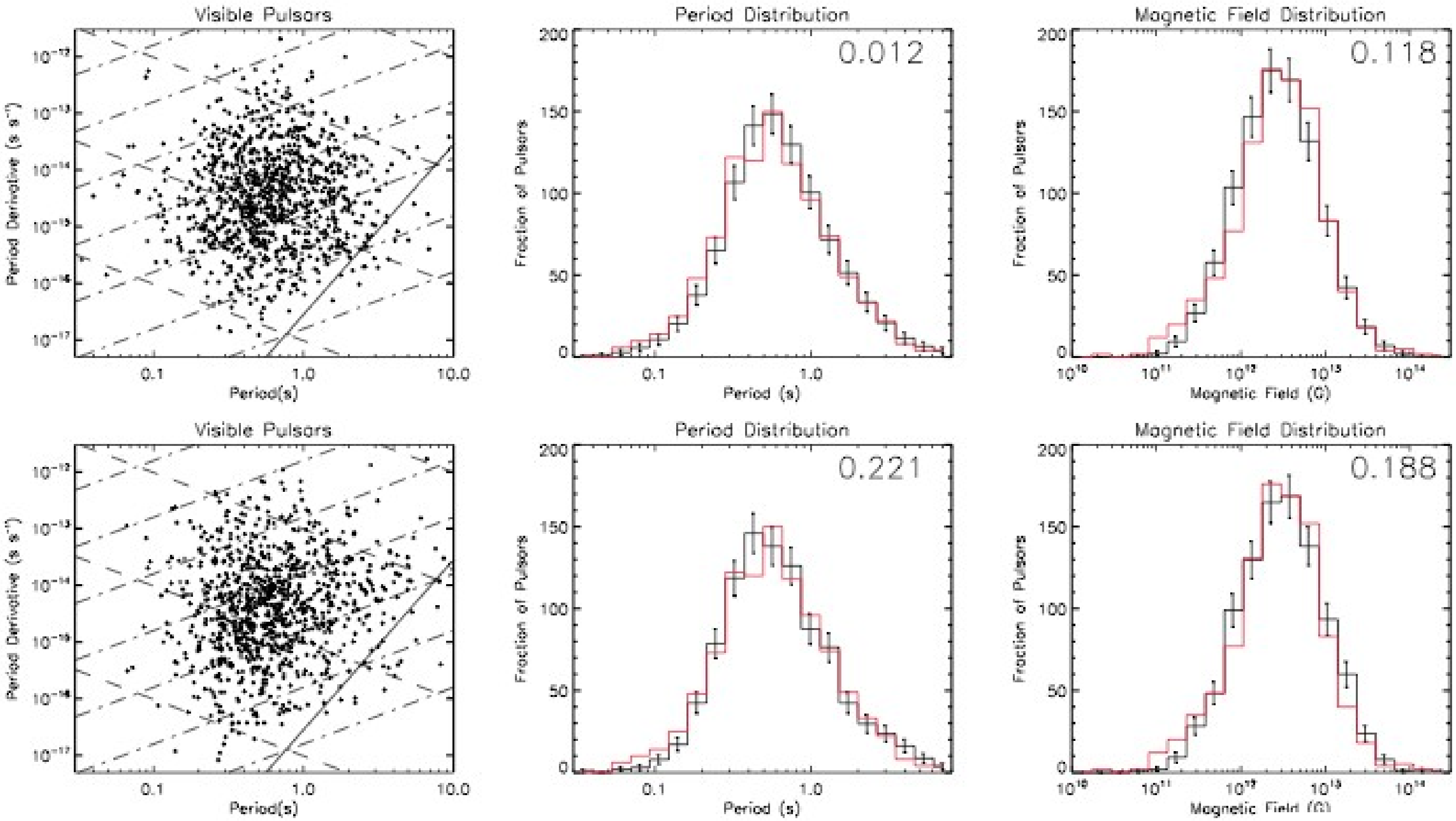
Spin-down ages overestimated

Can we find statistically acceptable results for these models ?



Population synthesis III: radio-pulsars

Faucher-Guiguere and Kaspi (2006), no field decay



Popov et al. (2009) $< \log(B_0/[G]) >\sim 13.25$ $\sigma_{\log B_0} \sim 0.6$

Crustal B field evolution

- In a real NS the crust is not a fluid, so the MHD approximation is not valid. It is more appropriate to describe it as a Hall plasma, where ions have very restricted mobility and only electrons can move freely through the lattice.
- The proper equations are Hall MHD. If ions are strictly fixed in the lattice, the limit is known as EMHD (electron MHD)
- There are two basic wave modes: in the homogeneous limit (constant electron density), whistler or helicon waves, and also Hall drift waves in the inhomogeneous case.

Hall induction equation

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

Electrical resistivity depends strongly on T

Understanding the burst/flare Phenomenology : the quake model

In Equilibrium

$$M_{ij}^{\rm eq}(r,\theta) = \frac{B_i(r,\theta,t^{\rm eq})B_j(r,\theta,t^{\rm eq})}{4\pi} \sim \sigma_b(r,\theta,t^{\rm eq})$$

Magnetic field evolves in the crust (helicon waves, Hall waves) and dissipates. This changes the stress balance.

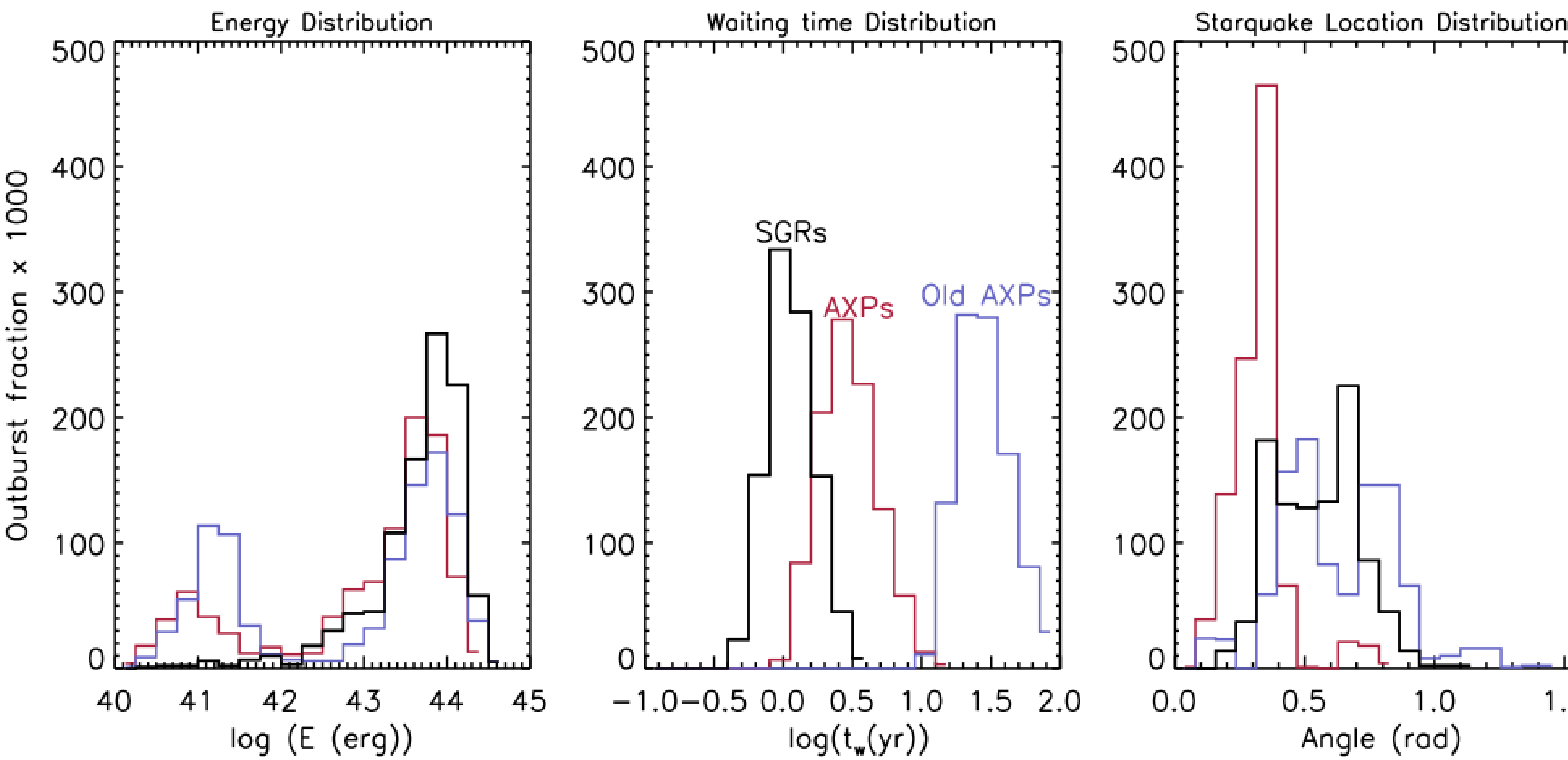
$$\sigma_b^{\rm max} = \left(0.0195 - \frac{1.27}{\Gamma - 71}\right) n_i \frac{Z^2 e^2}{a}$$

Chugunov & Horowitz (2010)

When the stress imbalance exceeds the shear breaking strength of the crust, the crust breaks, and elastic/magnetic energy is released and converted into electromagnetic energy.

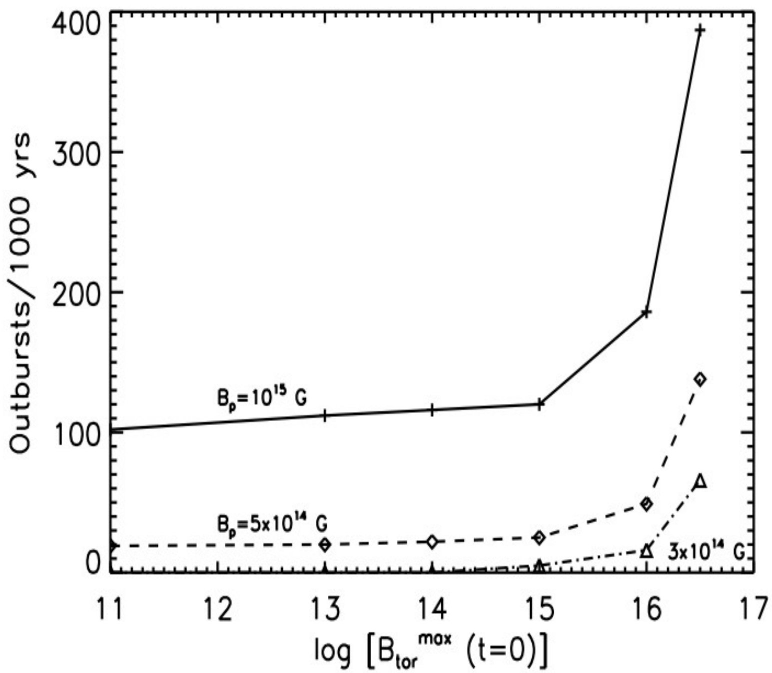
See also the thermo-resistive instability (Price, Link, Epstein, Hui, 2011)

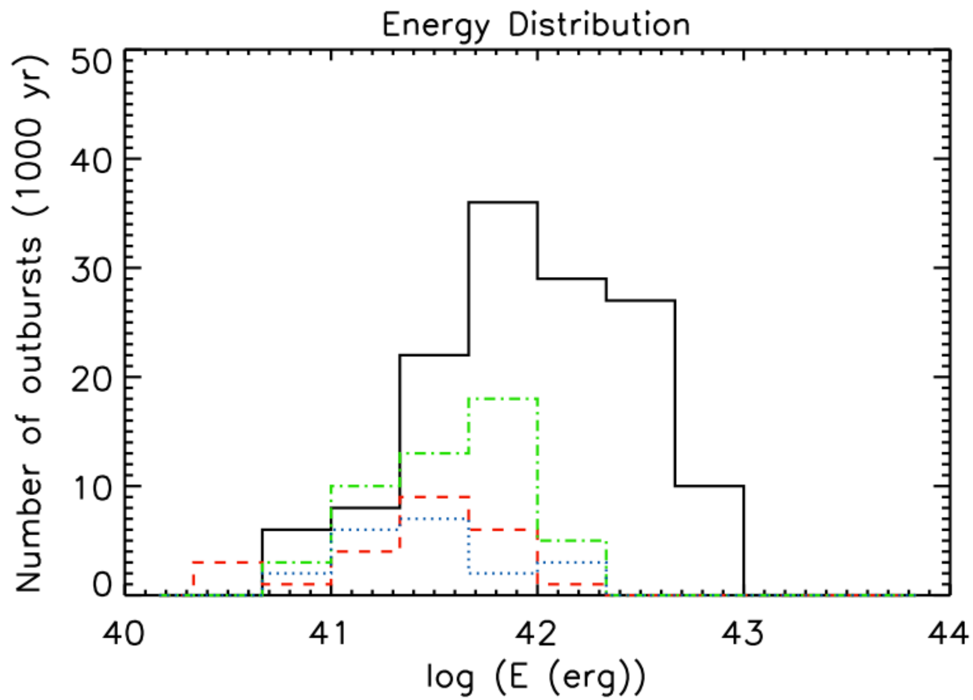
Understanding the burst/flare phenomenology: Different classes or simply aging effects ?



Perna & Pons 2011

Understanding the burst/flare phenomenology: Effect of field strength and geometry.

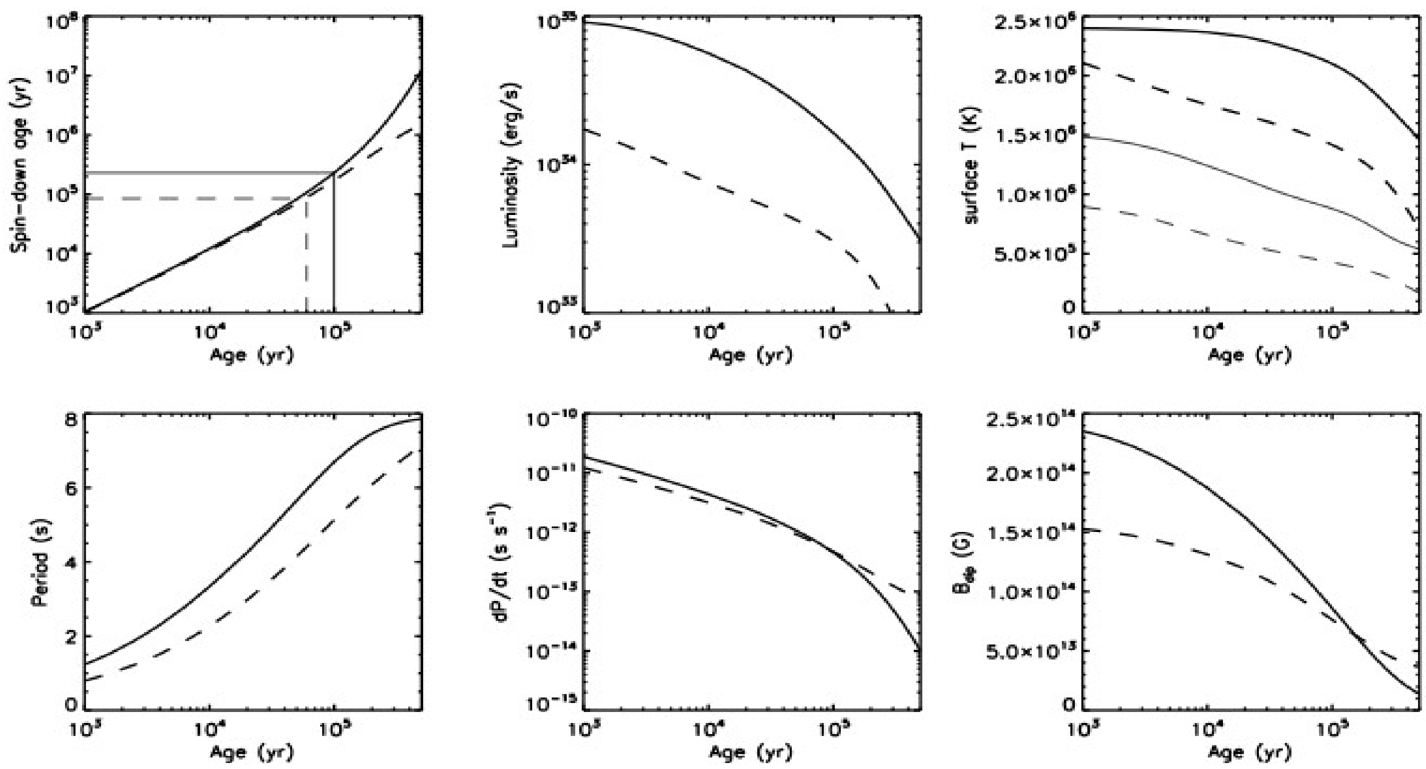




Same Bp=5e14 G,varying Btor.
Both, event rate and energy increase.

Pons & Perna 2011

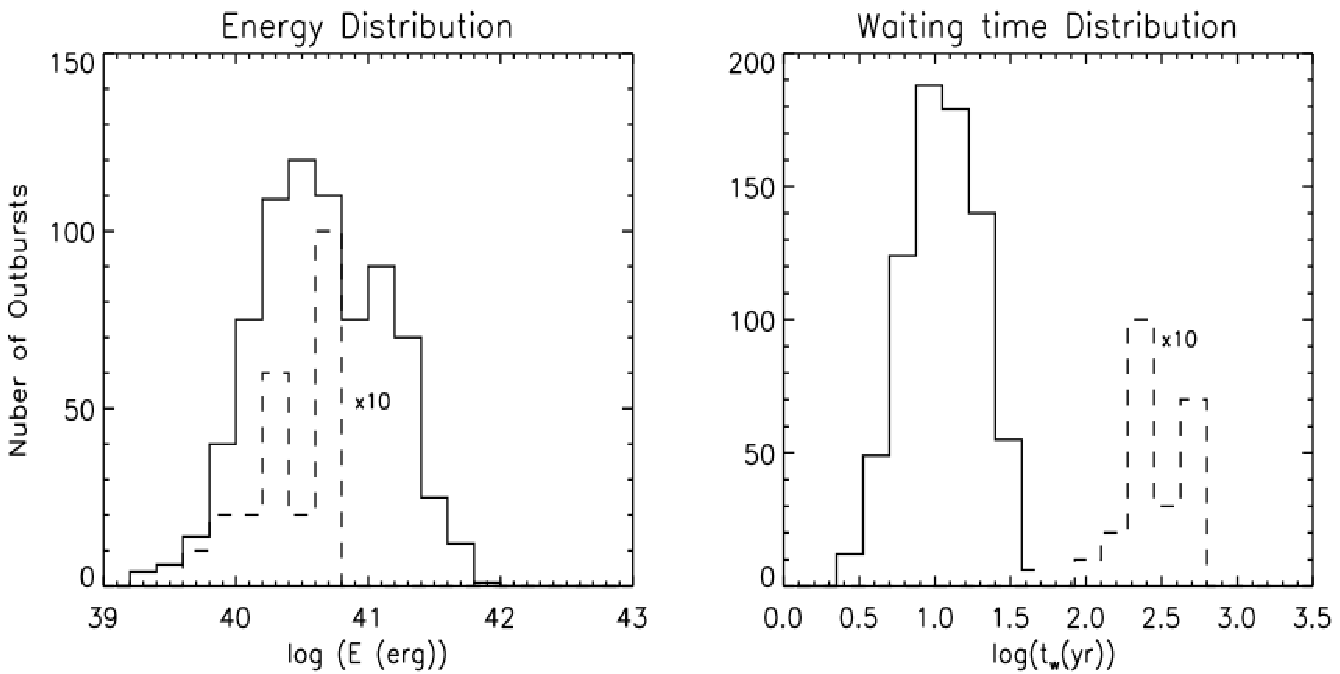
The case of 1E2259+586 vs. PSR J1814-1744



Pons & Perna 2011

A different internal toroidal field modifies Luminosities ...

The case of 1E2259+586 vs. PSR J1814-1744



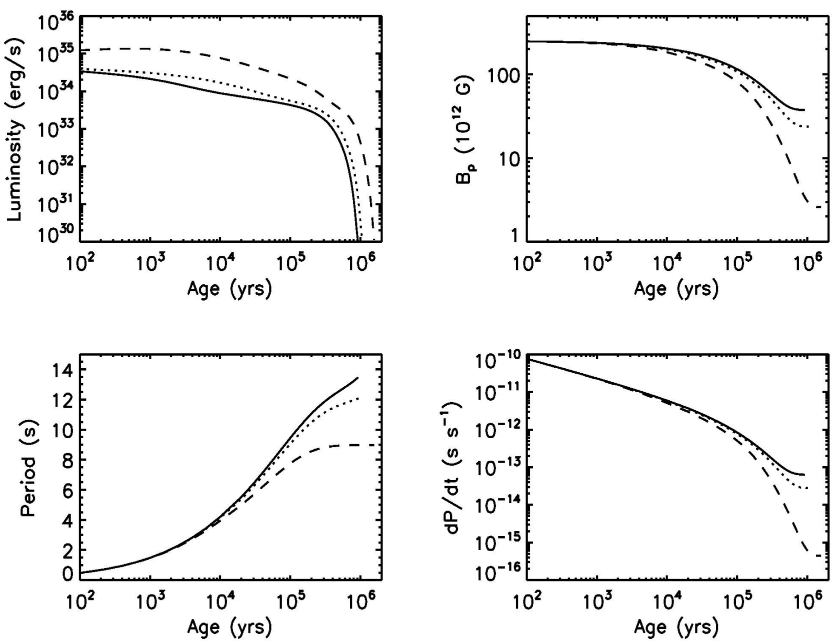
… and "activity level"

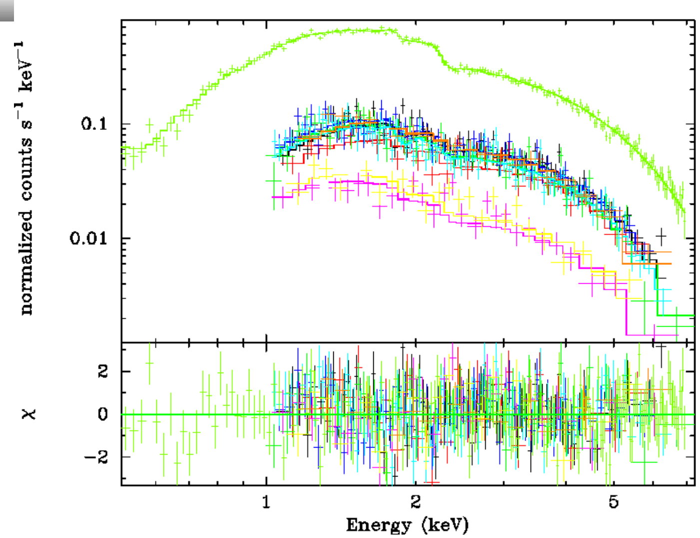
Pons & Perna 2011

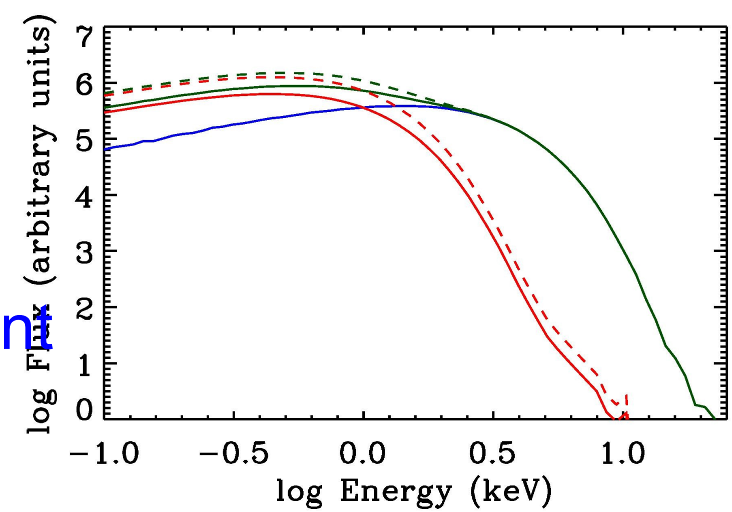
The case of SGR 0418+5729: an Old Magnetar ?

- Clues (Rea et al. 2010)
  - Large characteristic age (> 24 Myr)
  - Weak bursting activity (only 2 faint bursts)
  - Low dipole field ($B < 7.5 \times 10^{12}$ G)
- Main issues (Turolla et al. 2011)
  - P, $\dot{P}$ and B from magneto-rotational evolution
  - capacity of producing bursts
  - spectrum of the persistent emission

The case of SGR 0418+5729: an Old Magnetar ?







Both magneto-rotational history and spectral properties are consistent with the magnetar picture.

(Turolla et al. 2011)

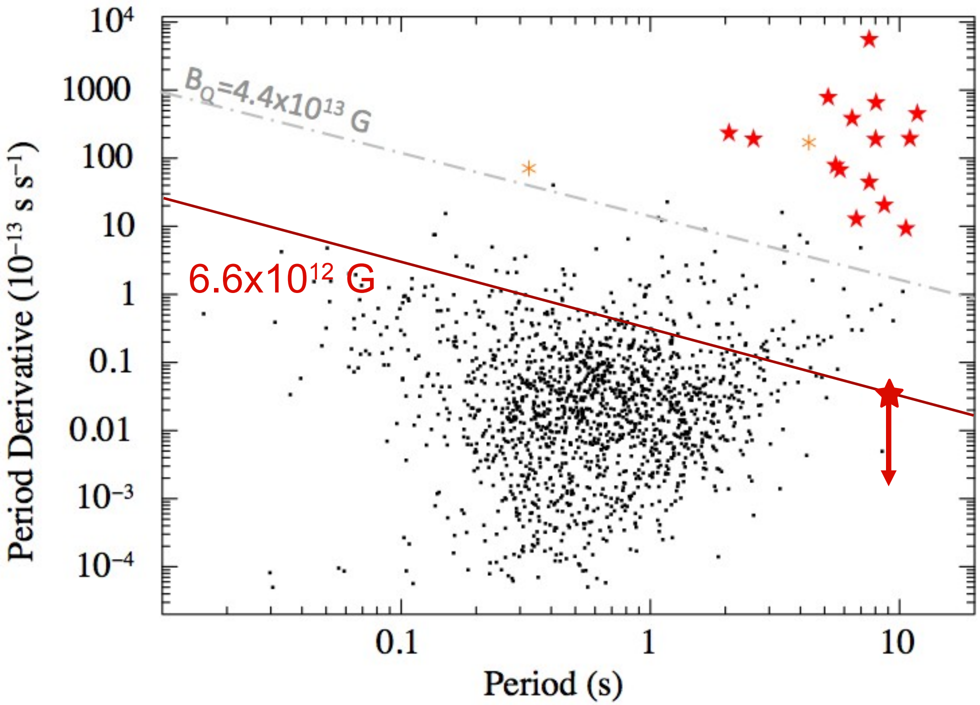
The case of SGR 0418+5729: an Old Magnetar ?

More than 20% of known radio PSRs have B_p higher than SGR 0418+5729

A continuum of magnetar-like activity across the P-$\dot{P}$ diagram

No need for a super-critical external B Field arguments

SGR 0418+5729 properties compatible with an aged magnetar ≈ 1Myr old whose internal field is still large



Summary

- The “observers” classification (AXPs, SGRs, high B field PSRs,RRATs) may not correspond to any physical motivation. All are simply “neutron stars with magnetic fields”, thay may behave differently at different ages or have different birth properties (mass, B field strength).
- Rather than separated classes, there is a continuum. Age matters, but it is only one of the issues. Few recent cases of old, low field “magnetars” or young, “inactive” high B field pulsars.
- A “human” selection effect (recurrence time of years means “active” but on timescale of centuries mean “quiet”) should not bias our understanding about the physical origin of phenomena.