THE MANY LIVES OF MAGNETIZED NEUTRON STARS

How the magnetic field shapes the appearance and evolutionary path of Neutron Stars

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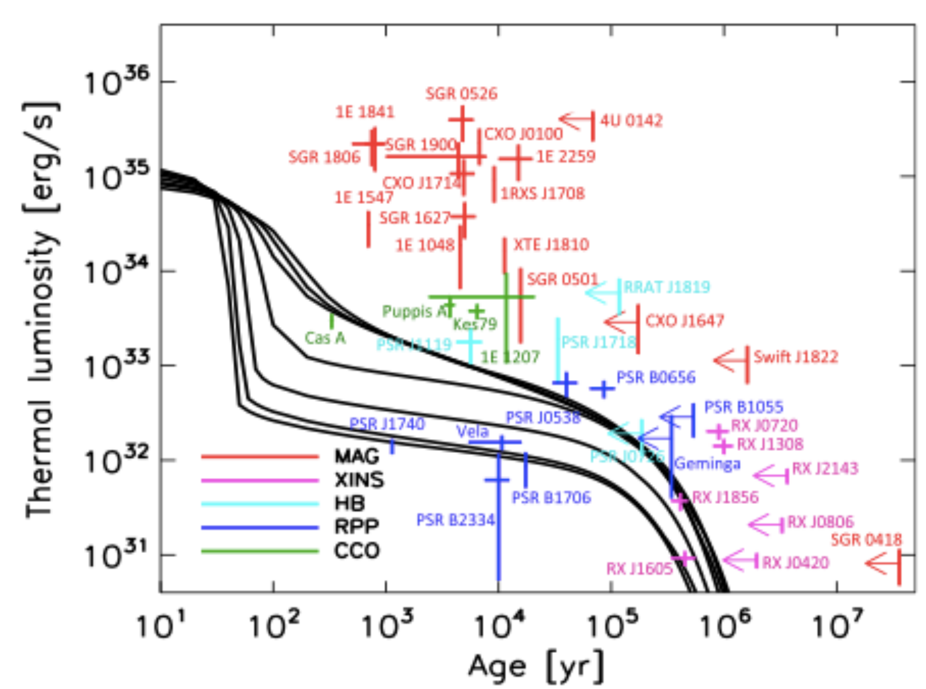
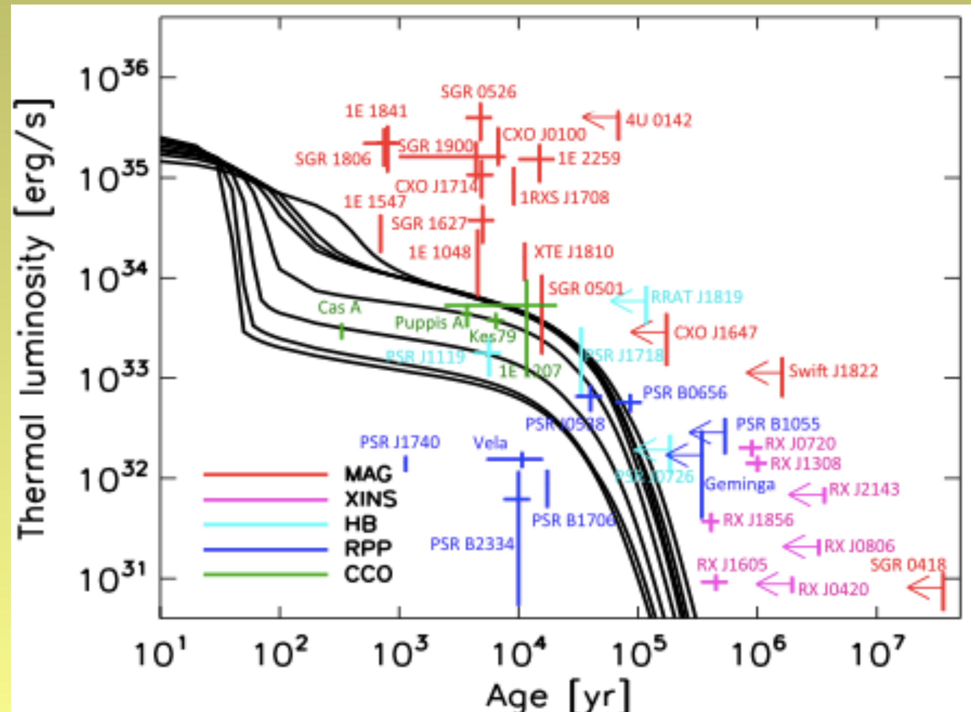
Why do we believe that the magnetic field of a Neutron Star must play a major role in its observational appearance?

I. Cooling curves at B=0 are unable to account for the X-ray luminosities of a large fraction of NSs

Iron Envelope, range of NS masses

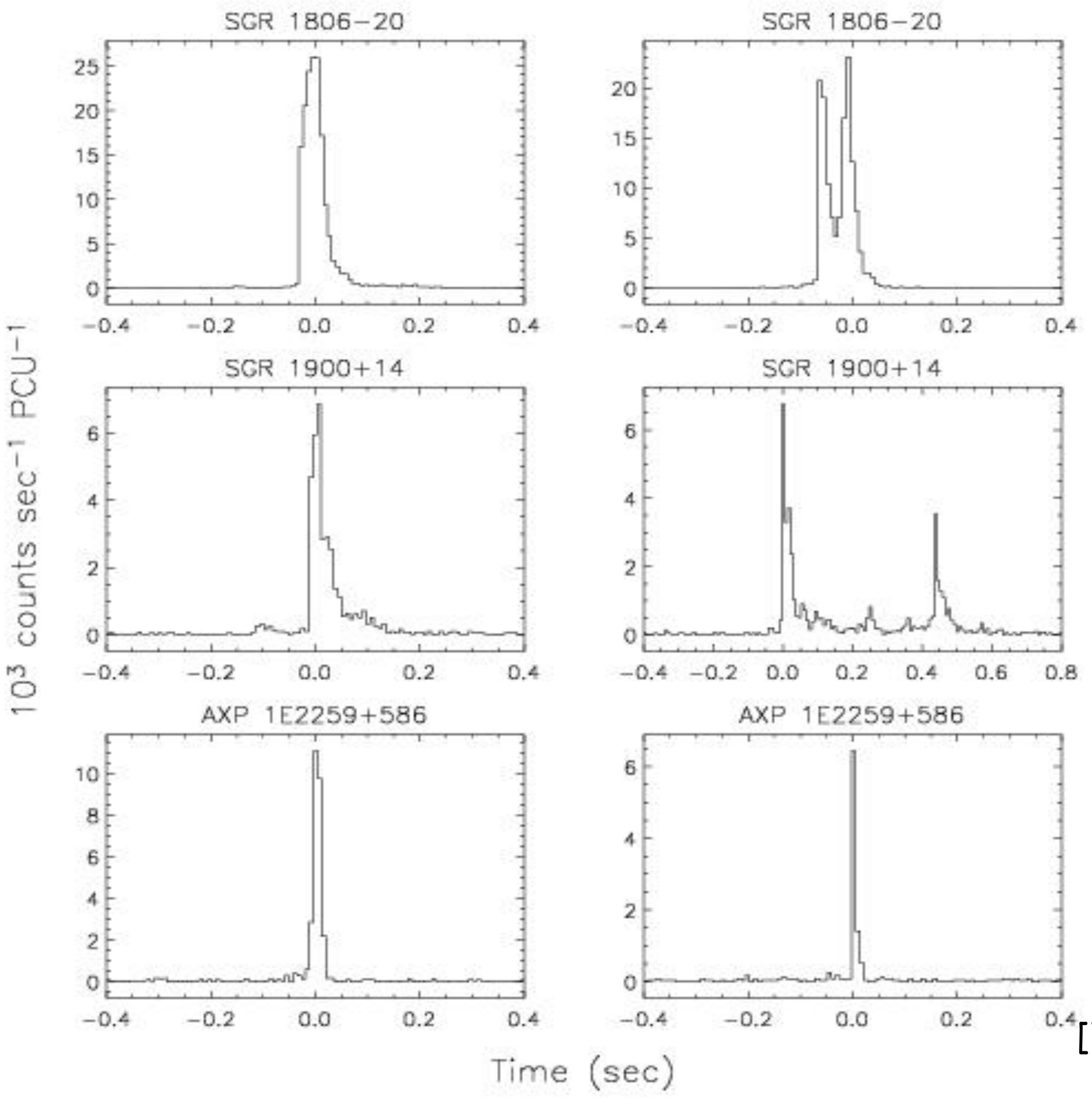


Light envelope – range of masses



[Vigano' et al. 2013]

II. Some NSs exhibit a bursting behaviour: Small and more common bursts (AXPs, SGRs)

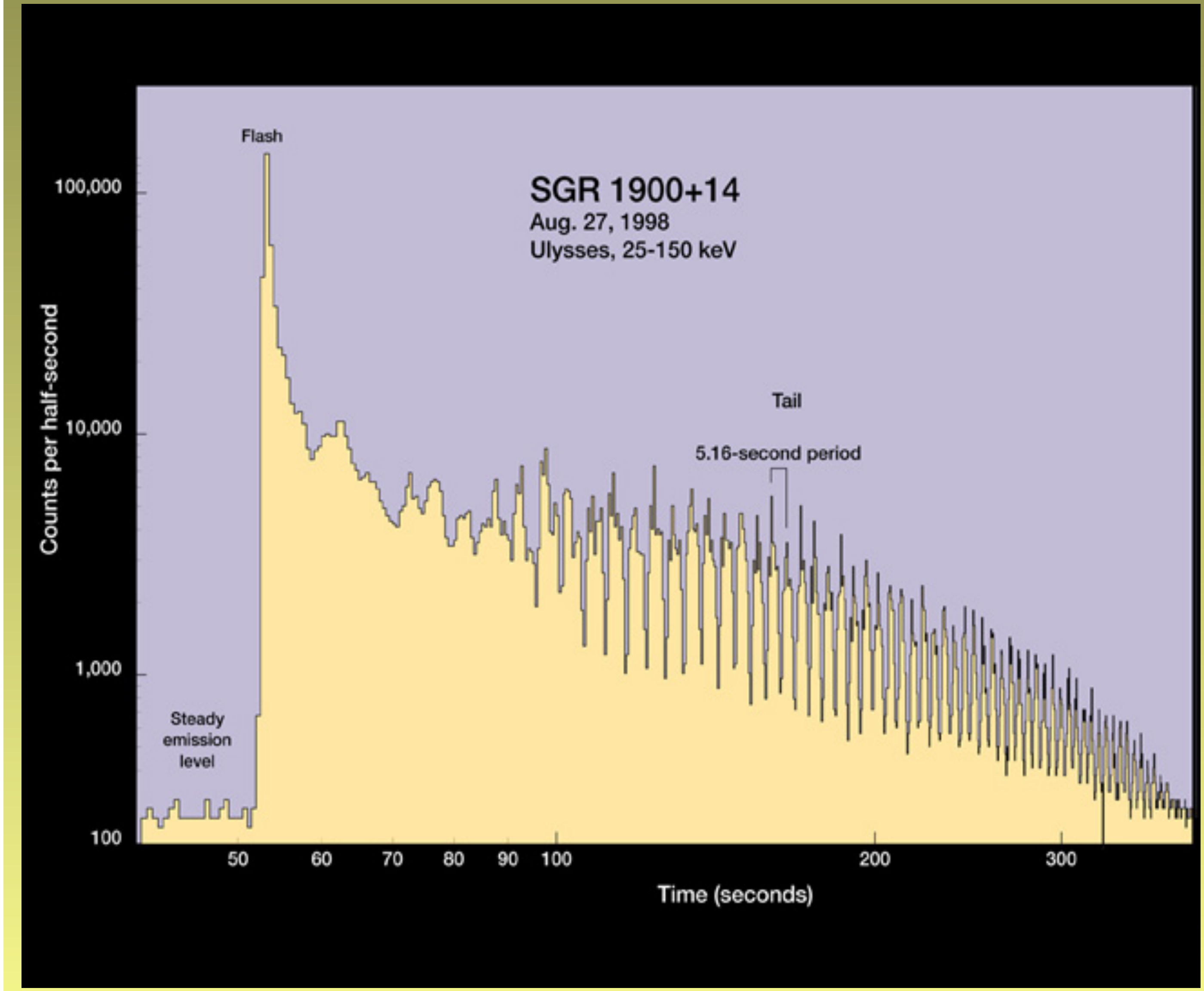


Main characteristics:
Short durations (~0.1 sec);
Thermal spectra;
Peak luminosities up to 10^{41} erg/s;
Frequency: weeks to years

Observations with RXTE; luminosity in the 2-20 keV band with 7.8 ms time resolution.

[Woods et al. 2004]

GIANT FLARES FROM SGRs



[Courtesy: K. Hurley]

Main characteristics:

Frequency: tens of years;
Peak luminosities: ~ 10^{44-45} erg/s;
Spectrally harder (kT ~ 250-500 keV) than small bursts;
Duration: several hundreds of seconds.

Other properties of these 'peculiar' NSs:
ANOMALOUS X-RAY PULSARS (AXPs) and
SOFT GAMMA-RAY REPEATERS (SGRs)

- P ~ 6-12 sec
- (rather) steady spin down
- Lx ~ 10^{34} - 10^{36} erg/s (high quiescent X-ray luminosities)
- Ages ~ 10^{3} - 10^{5} yr
- High surface temperatures ~ 0.2-0.4 keV

WHAT IS PROVIDING THE ENERGY SOURCE?

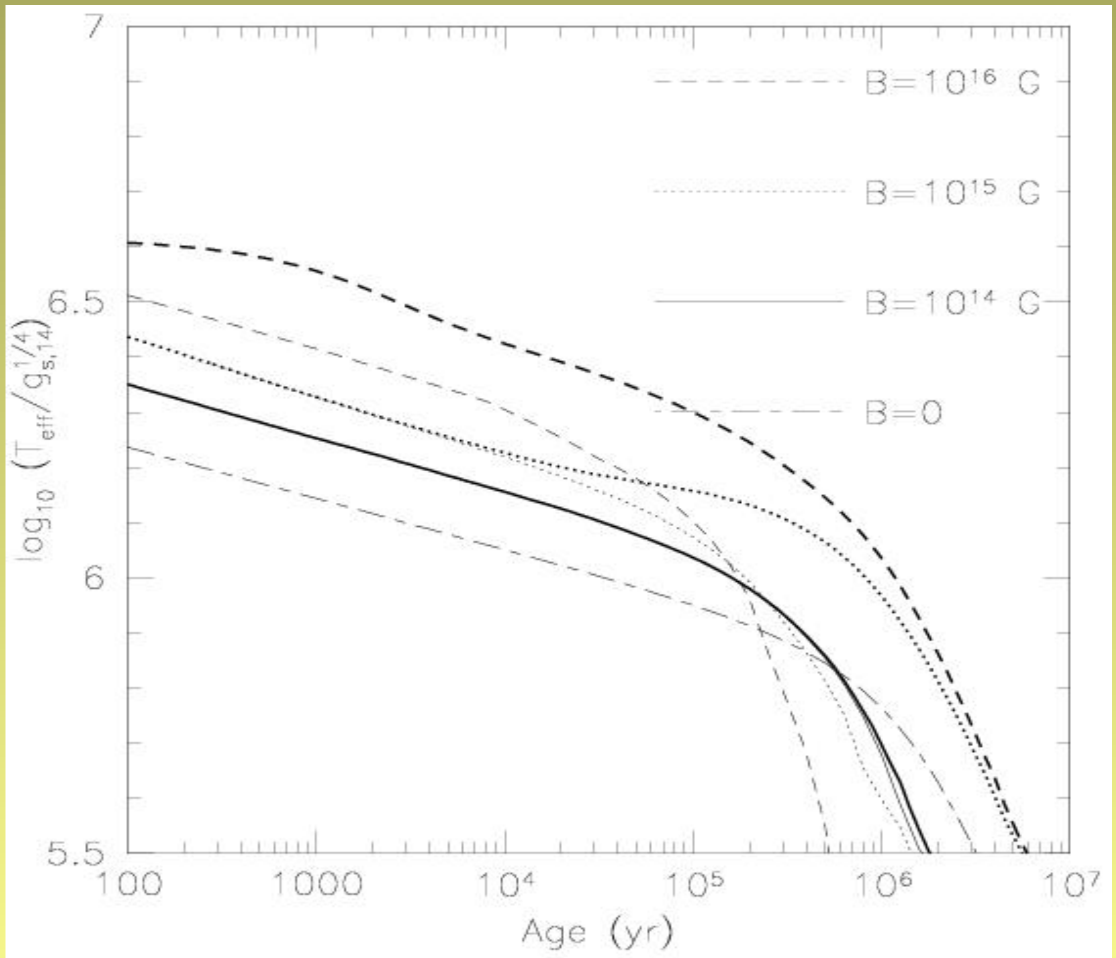
Natural candidates:

- *Rotational Energy* $\dot{E}_{rot} << L_X$ at least for some objects
- *Accretion from companion* No evidence for companion
- *Accretion from fallback disk* Could explain quiescent L_X - no satisfactory model for outbursts

Magnetic energy believed to be the 'culprit'

Magnetic energy: enhanced temperature

Magnetic field dissipation in interior of magnetar results in higher surface temperatures ⟶ higher L_x



10^{35} erg/s
in ~ 3×10^5 yr
needs ~ 10^{48} ergs

Enough energy to maintain enhanced X-ray emission for tens of thousands of years

[Heyl & Kulkarni 1998]

Magnetic energy: outbursts

$$E_B \sim B^2/(8\pi)\ V \sim 2\times10^{48}\ [B/(3\times10^{15}G)]^2\ \mathrm{erg}$$

Enough energy to power outbursts

Outbursts produced when magnetic stresses within the crust exceed breaking stress of crust
[Thompson & Duncan 1994, 1995]

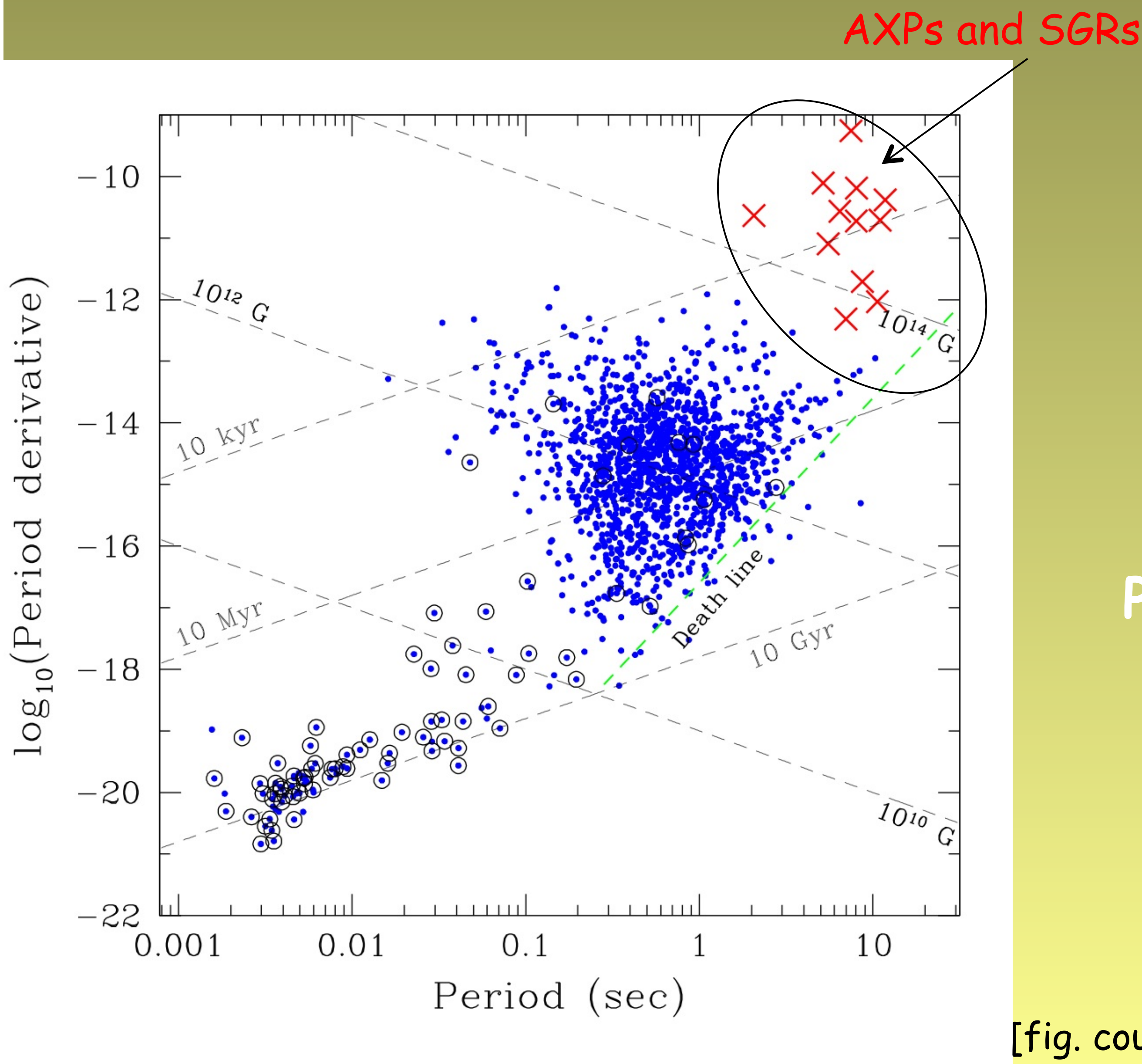
Note on 'starquakes' in a NS

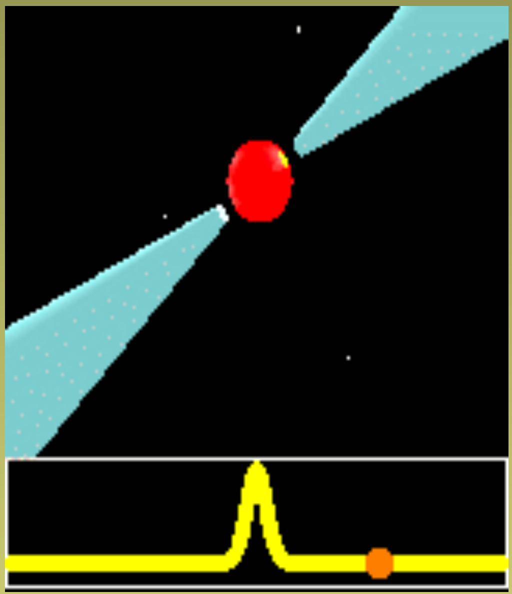
- Molecular-dynamical simulations (Horowitz & Kadau 2009; Chugonov & Horowitz 2010) indeed find that the NS crust breaks down suddenly when it is shear-stressed above some critical level.

- However, it is possible that for some B-field configurations, the magnetic force rather causes a plastic deformation of the crust (Levin & Lyutikov 2012).

→ More comprehensive investigations of cracks in highly magnetized NSs are needed to settle this issue

Consistent with ‘location’ of AXPs and SGRs in $P\dot{P}$ diagram





Pure dipole losses:

$$B \propto \sqrt{P\dot{P}}$$

$$\tau \propto P / \dot{P}$$

[fig. courtesy of F. Camilo]

Recent theoretical developments:

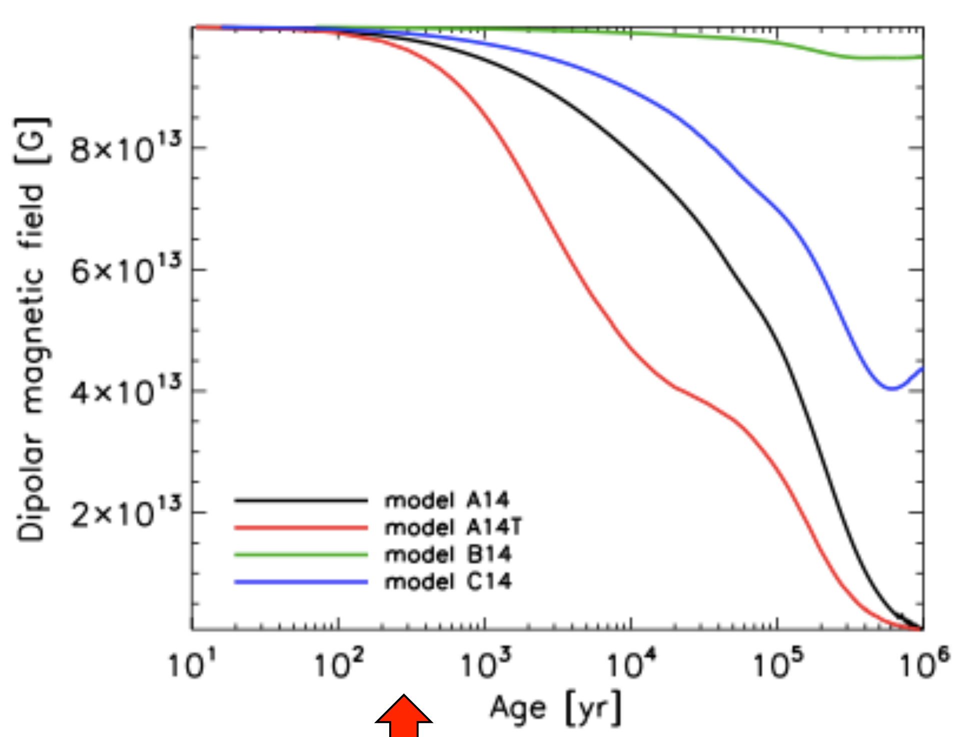
First 2D simulations to fully couple
THERMAL + MAGNETIC ='MAGNETOTHERMAL'
Evolution of Isolated Neutron Stars
[Vigano, Rea, Pons, Perna, Miralles, Aguillera 2013]

Coupling due to:

a) Magnetic fields generate currents which produce Joule heating → B evolution influences thermal evolution

b) Temperature affects value of conductivity present in Induction eq. → T evolution influences magnetic evolution

Sample Results [Vigano' et al. 2013]

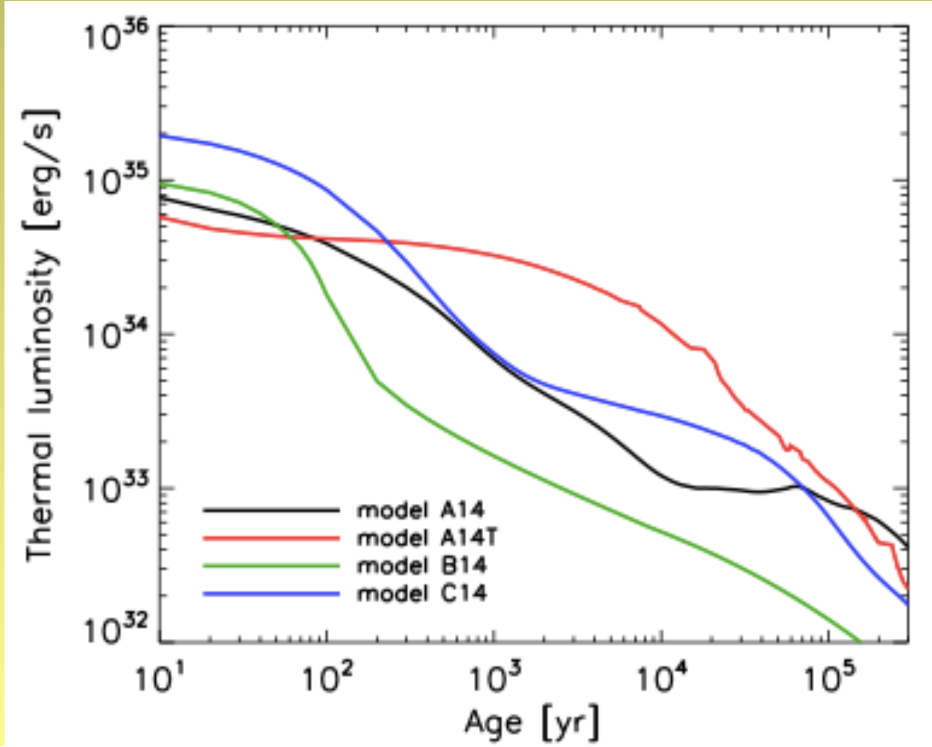


Model	current location	B_p^0 [G]	B_t^0 [G]
A14	crust	10^{14}	0
A15	crust	10^{15}	0
A14T	crust	10^{14}	5×10^{15}
B14	core	10^{14}	0
C14	crust+core	10^{14}	0

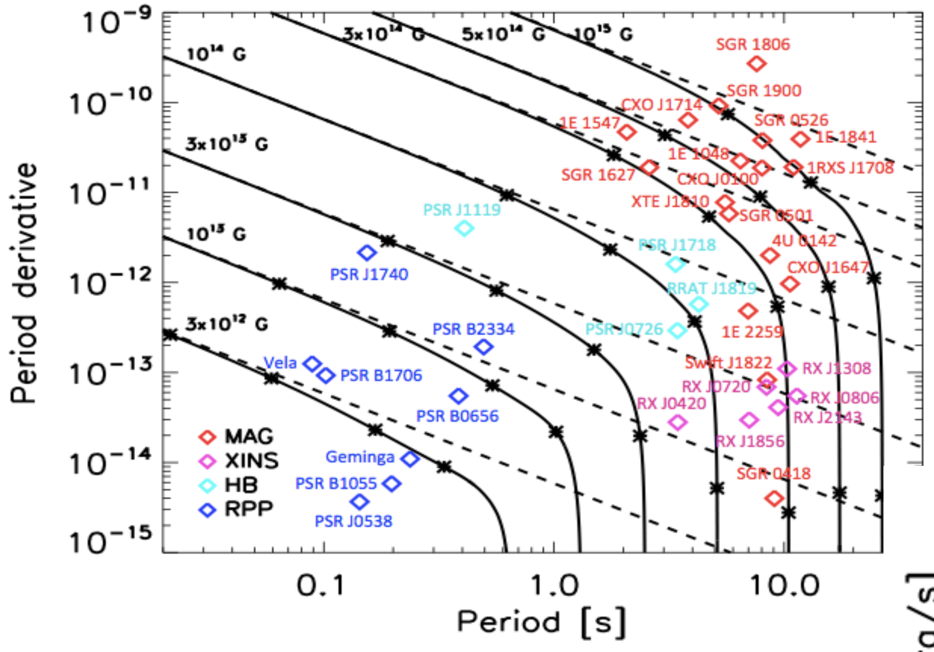
Magnetic

Thermal

Evolution

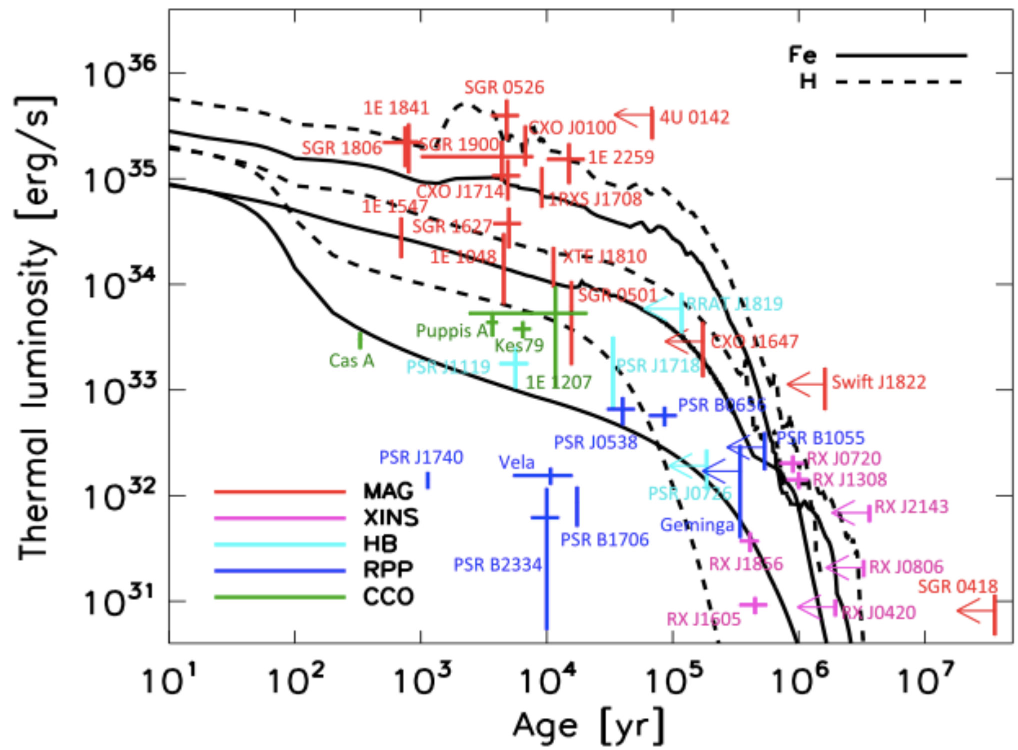


Magnetothermal evolution: confronting Theory with Observations [Vigano' et al. 2013]



← Period Evolution

Thermal Evolution →



Overall 'magnetar' picture not as simple…

(especially so for the outburst properties)

- Why some objects appear *'SGR-like'* while others *'AXP-like'* if they have similar B fields?

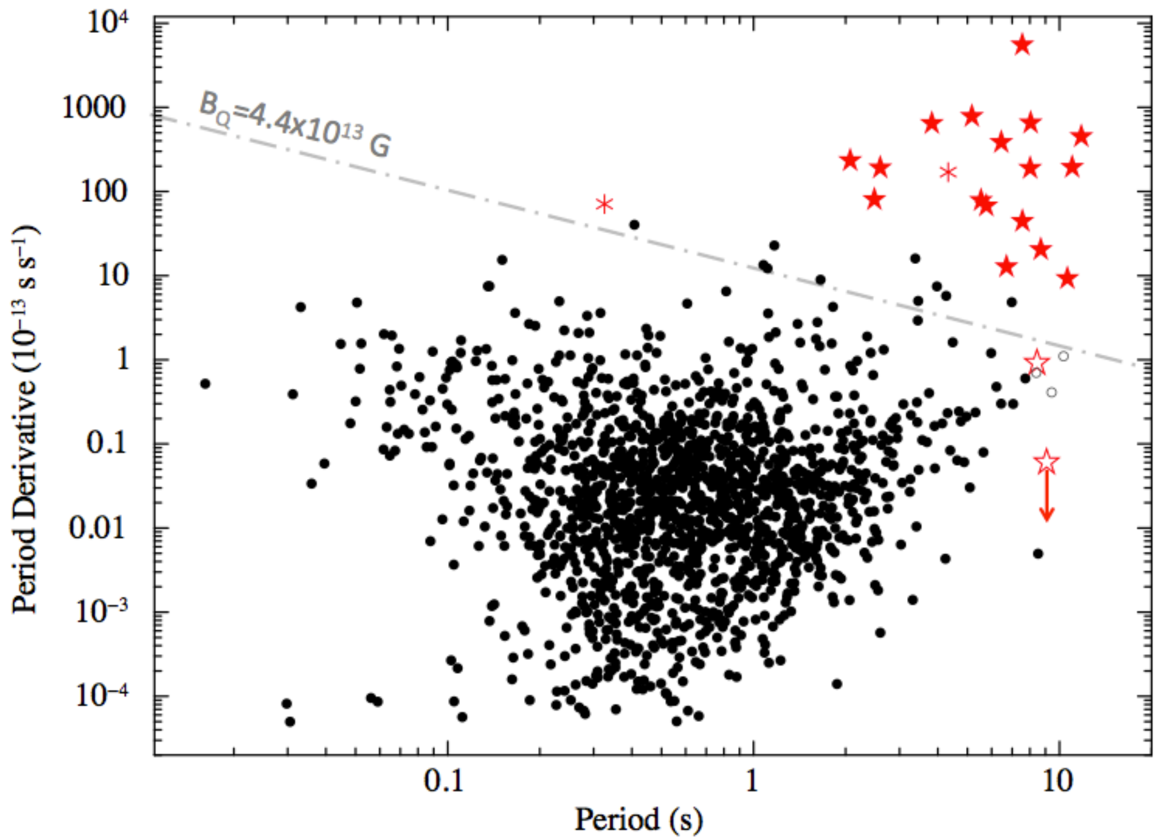
'SGR-like' objects :

•Generally more active,
•Can display large flares,
•Outbursts tend to be uncorrelated with phase (pulsation max.) → occur all over the surface of the star

'AXP-like' objects :

•More moderate activity,
•Do not display large flares,
•Outbursts tend to be correlated with phase (pulsation max.) → occur closer to region of max emission

Even more puzzling…



★ 'standard' magnetars

☆ 'low-B' magnetars

✱ 'high-B' radio pulsars

[Rea et al. 2012]

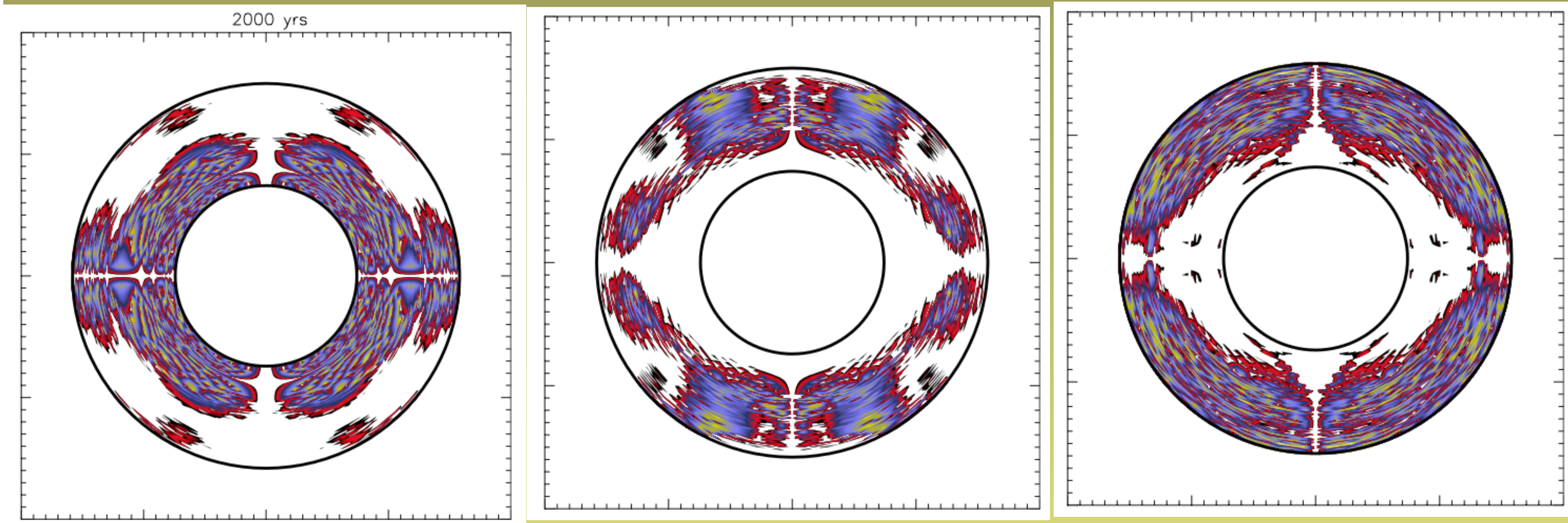
- Some objects have similar inferred B fields, but very different behaviour, e.g. PSRJ1814-1744 with B_d=5.7x10^{13}G is a 'normal radio pulsar' with L_x~ 10^{33} erg/s and no bursting behavior, while 1E 2259+589 with B_d=5.9x10^{13}G is an 'AXP' with with L_x~ 10^{35} erg/s and frequent bursts.
- An 'SGR'-like object has B<6x10^{12}G.... [Rea et al. 2010]

In search of a *"grand unification"* which can describe not only Periods and X-ray Luminosities, *but also Outburst Statistics*

First simulations to couple magneto-thermal evolution in the NS crust with computation of breaking stress in NS crust [Perna & Pons 2011, Pons & Perna 2011]

⇨ Theoretical predictions for frequency and energetics of 'starquakes' as a function of B field strength, topology (B_{dip}, B_{tor}), NS age.

Deviation of components of magnetic stress from equilibrium, normalized to breaking stress of crust – yellow corresponds to breaking of crust



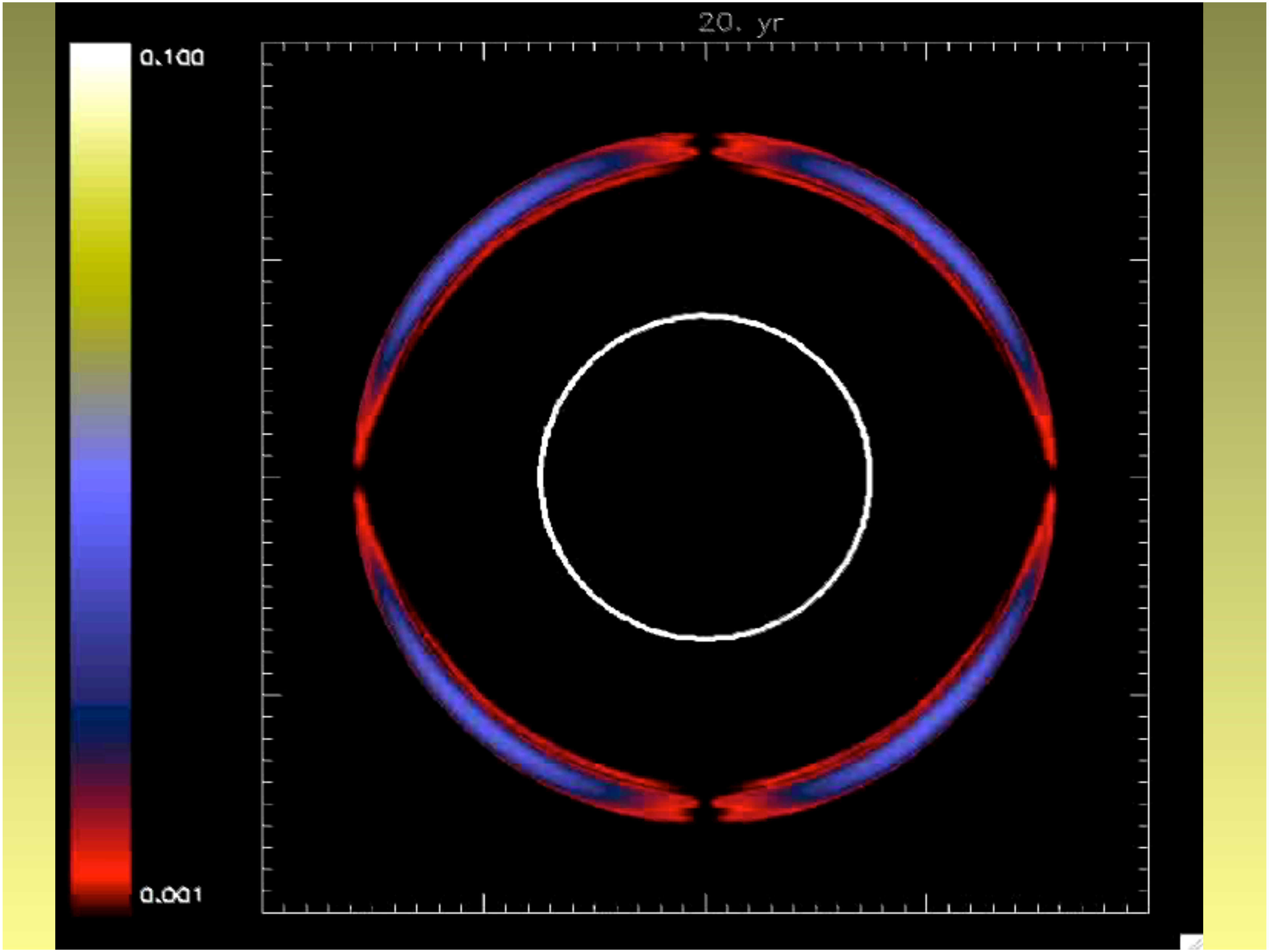
[Perna & Pons 2011]

$(\theta\phi)$ — More frequent, lower energy events

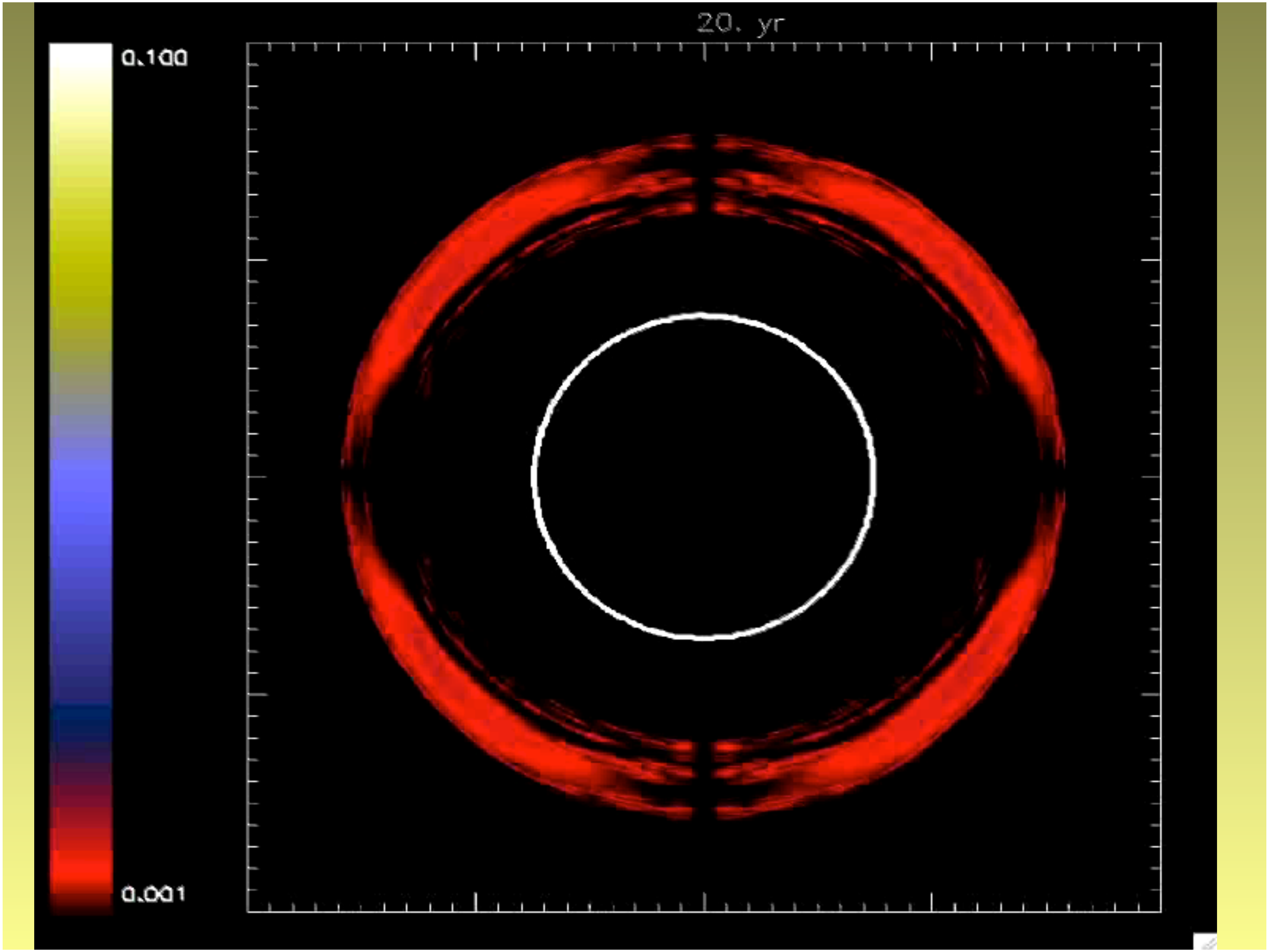
$(r\phi)$ — Less frequent, more energetic events

$(r\theta)$ — Spans all energy ranges, less frequent in old NSs

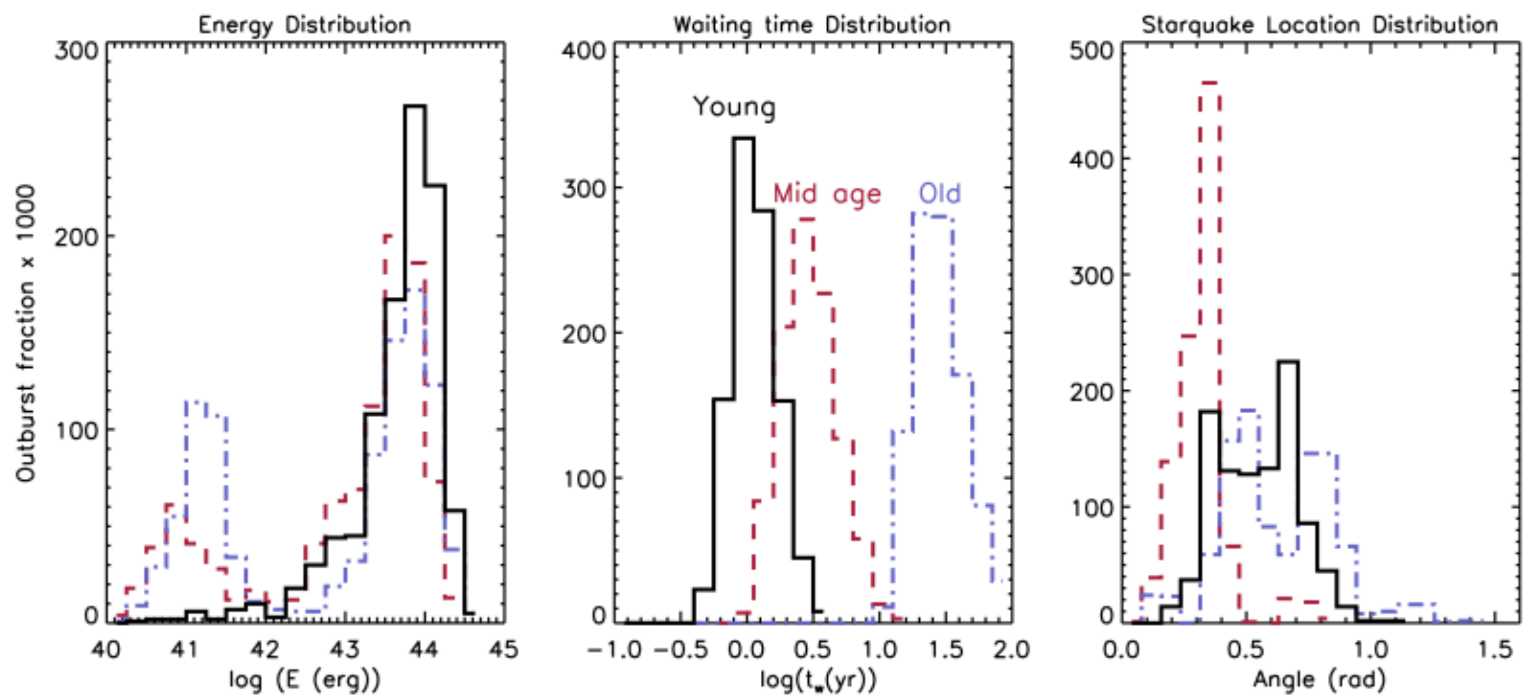
Snapshot of magnetic stresses at t=2000 yr for an NS born with $B_{dip}=8\times10^{14}G$ and $B_{tor}=2\times10^{15}G$



20. yr
0.100
0.001



20. yr
0.100
0.001

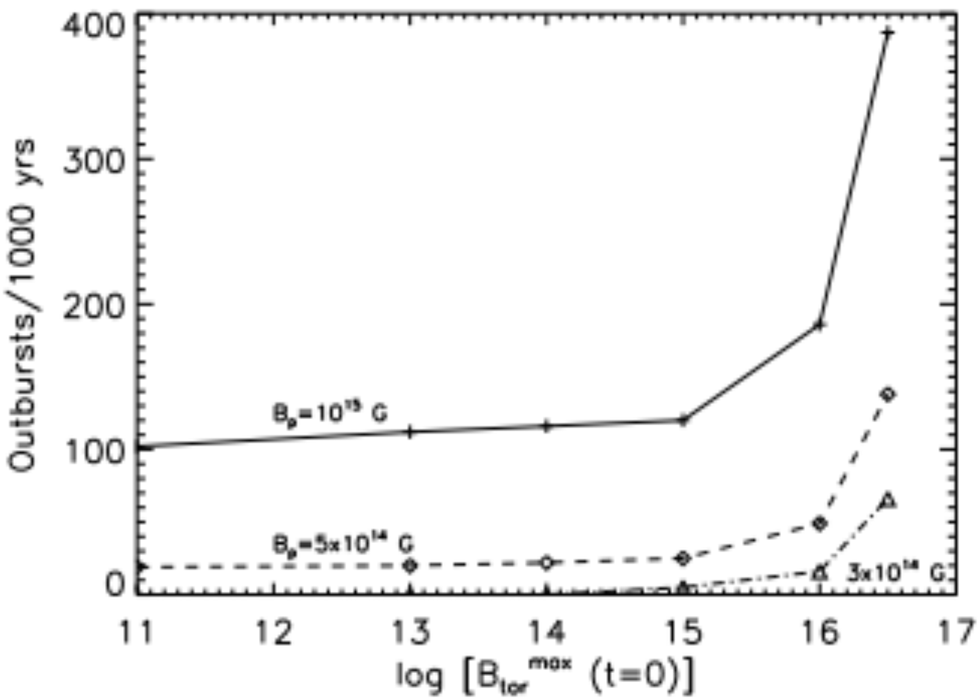


Initial cond.:
B_{dip}=8x10^{14}G
B_{tor}=2x10^{15}G

Young: 0.4-1.6kyr; Mid Age:7-10kyr; Old: 60-100kyr

[Perna & Pons 2011]

- For same initial B field, younger objects are more active and their outbursts more energetic.
- At same age, the stronger B, the more frequent the outbursts.
- Younger objects more "SGR-like", while older objects more "AXP-like", but no real difference

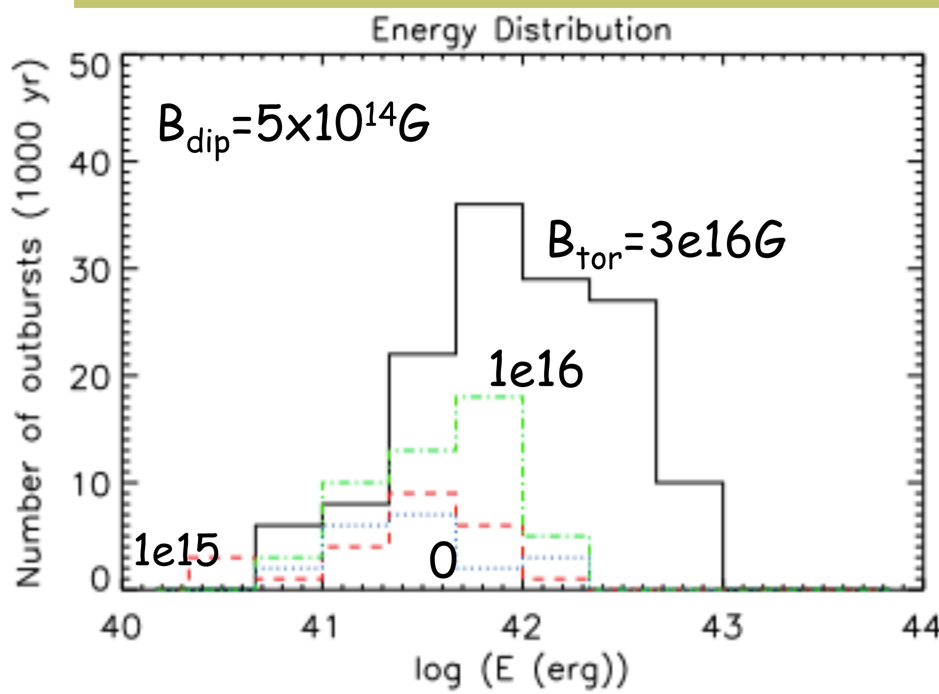


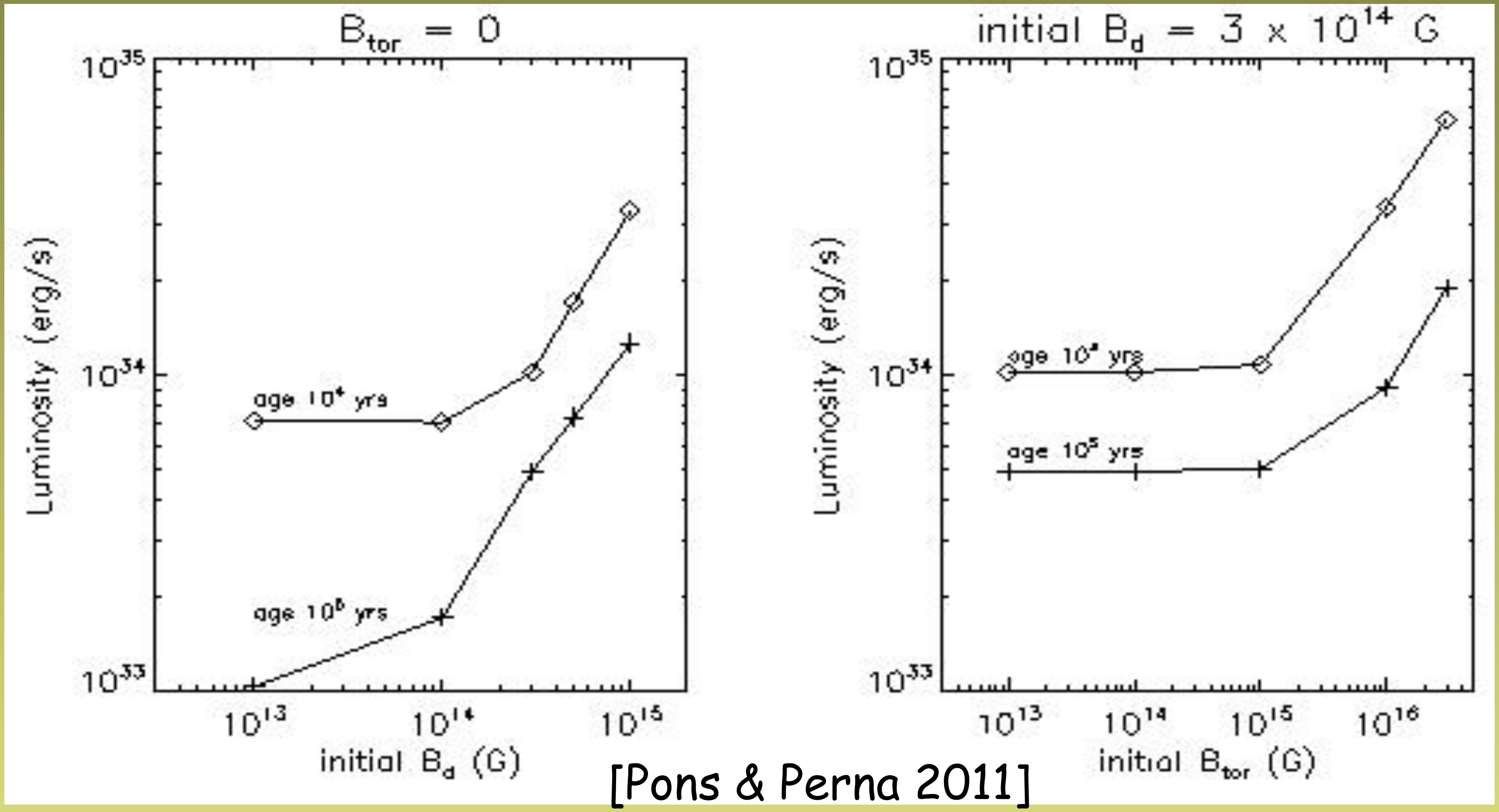
For the same B_{dip}, the outburst frequency is a strong function of B_{tor}

NS age = 10^5 yr

[Pons & Perna 2011]

For the same B_{dip}, more energetic outbursts occur for larger values of B_{tor}





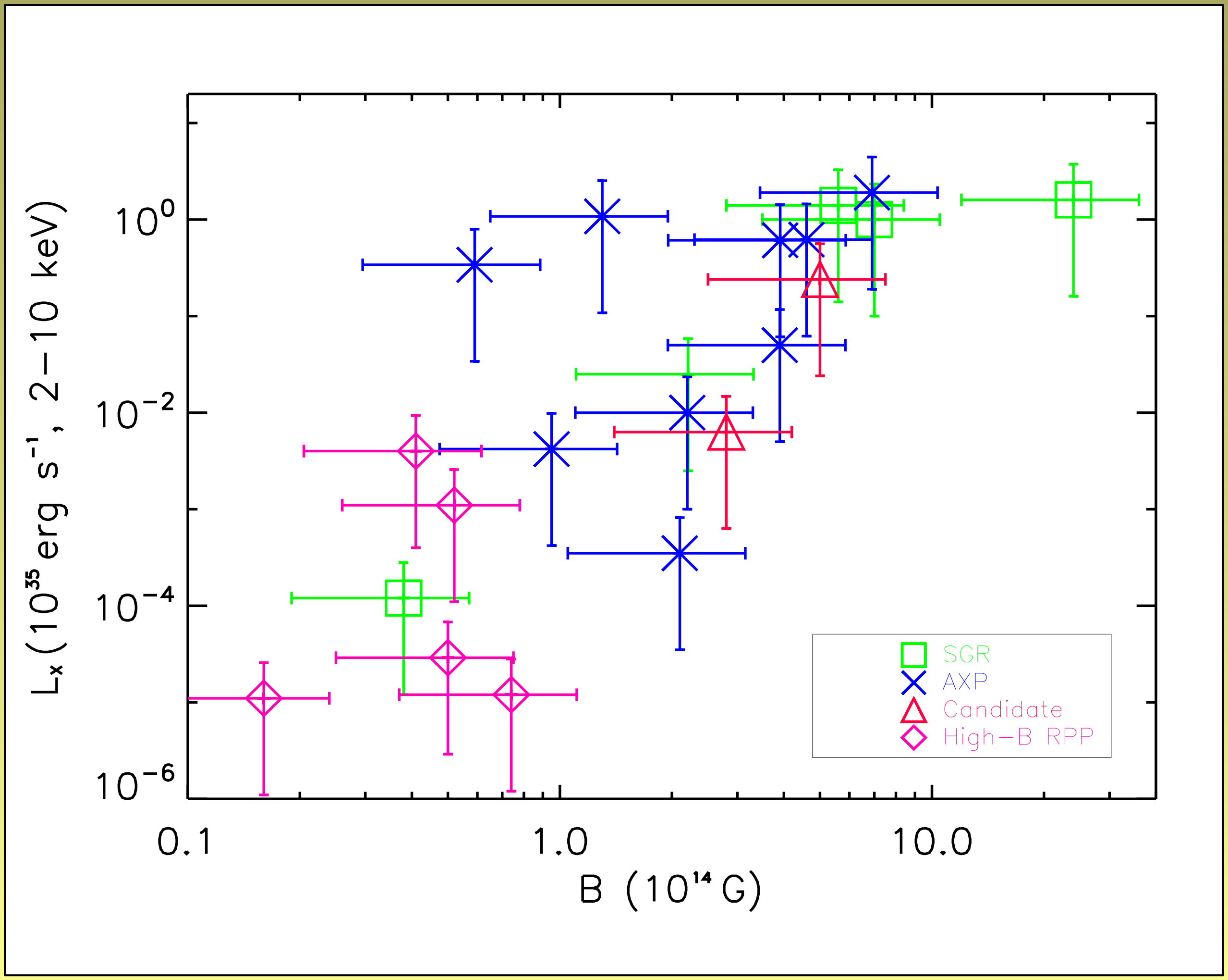
[Pons & Perna 2011]

Rate of internal (B-field) dissipation dependent on both B_{dip} and B_{tor}

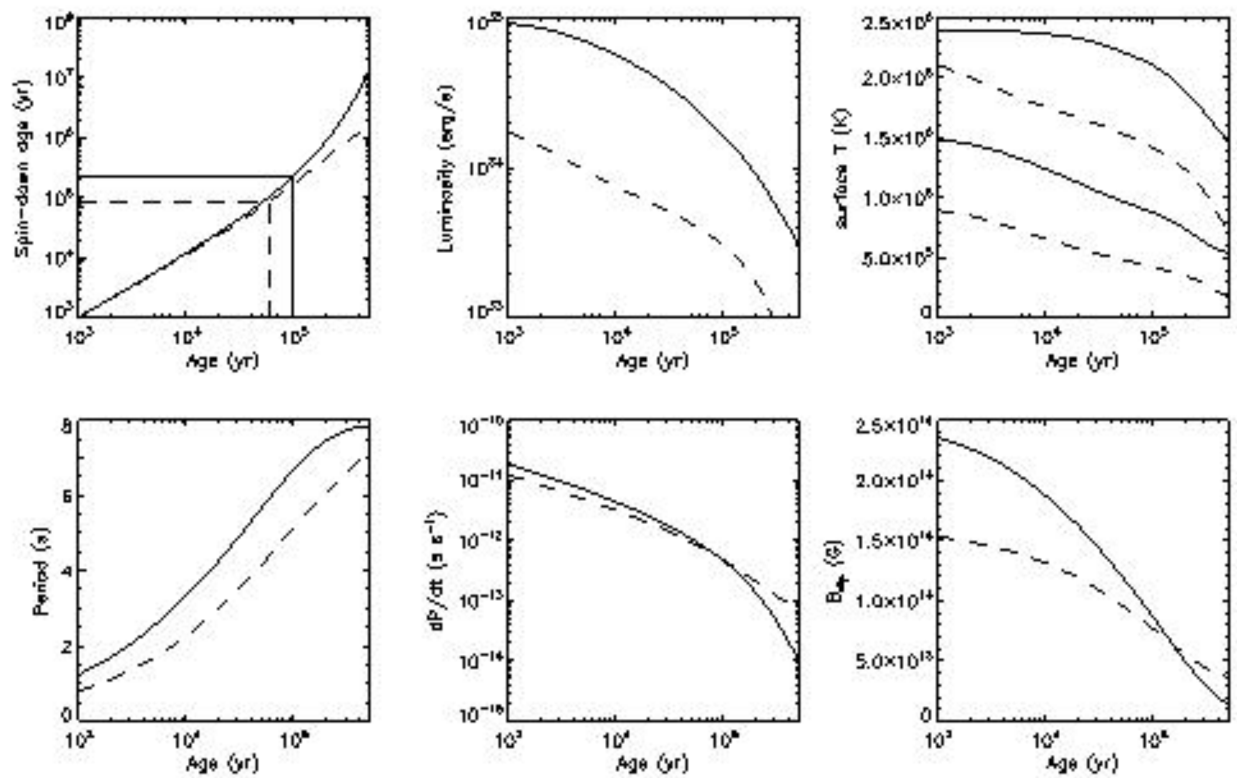
NSs of same B_{dip} and age can display very different X-ray luminosities

General prediction: Lx should increase with B_p but with a large scatter (due to the different B_{tor})

Observations show……



[An et al. 2012]



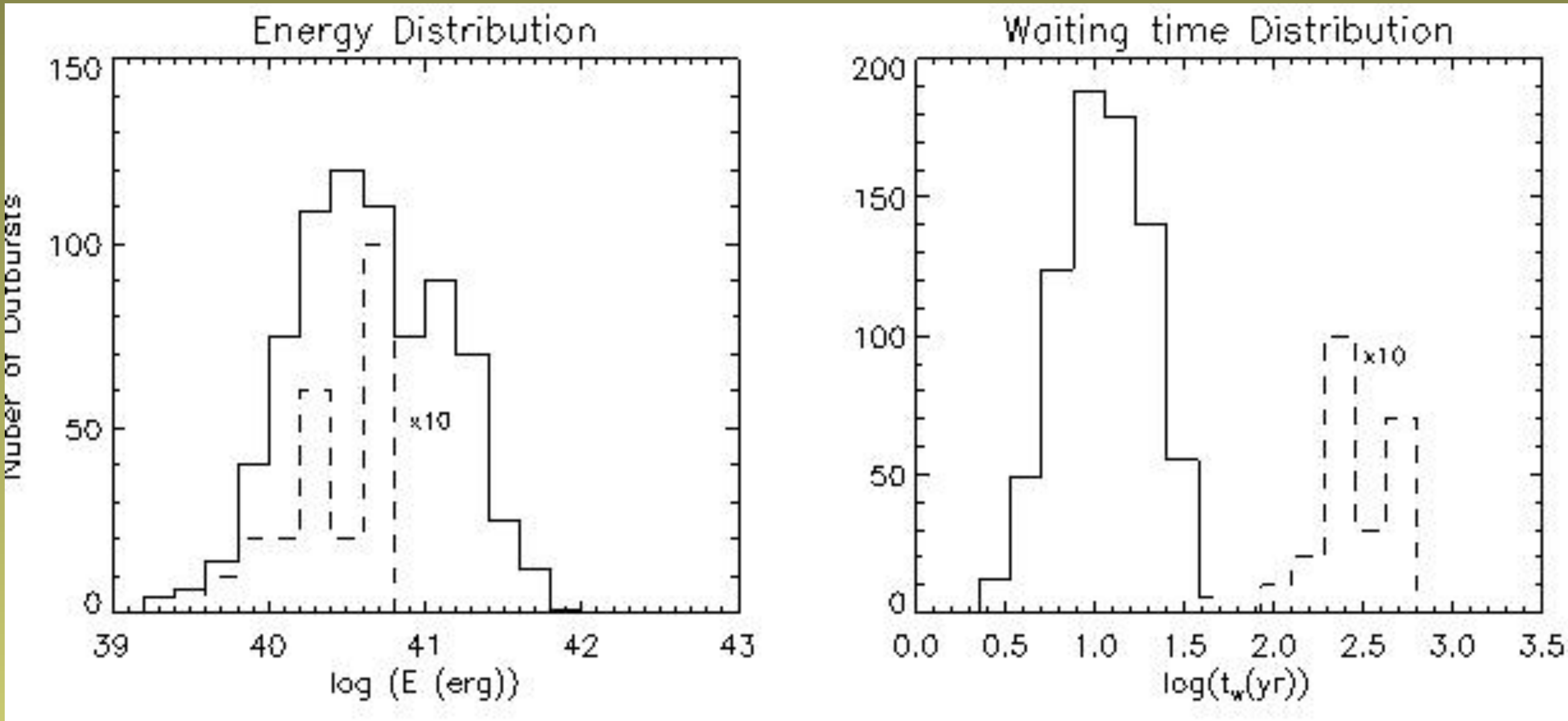
Interpreting the PSR/AXP dichotomy for same B_{dip}

[Pons & Perna 2011]

PSR J1814-1744: $B_{dip}(t=0)=1.6\times10^{14}$ G; $B_{tor}(t=0)=8\times10^{14}$ G
(evolution by dashed lines in figure)

1E 2259+586: $B_{dip}(t=0)=2.5\times10^{14}$ G; $B_{tor}(t=0)=2.6\times10^{16}$ G
(evolution by solid lines in figure)

Clue to different behavior is much stronger toroidal field of 'AXP-like' object than 'PSR-like'



[Pons & Perna 2011]

PSR J1814-1744: dashed line

1E 2259+586: solid line

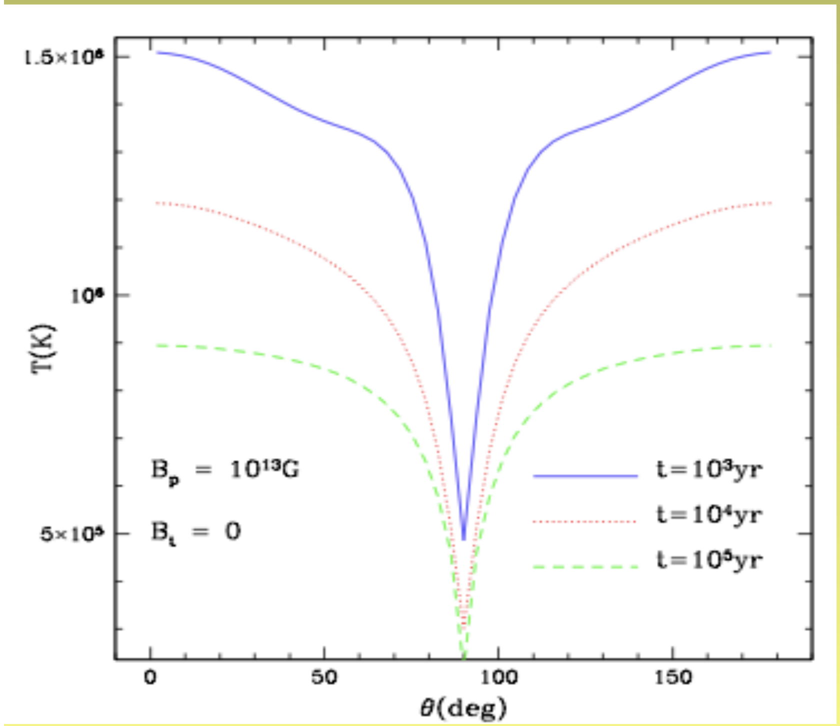
The B field configurations which reproduce the timing properties of the two objects, also *predict* that 1E 2259 would outburst every few years, while PSR J1814 every few centuries. The outbursts of 1E 2259 are predicted to be more energetic than those of PSR J1814.

Observational probes of the hidden toroidal field

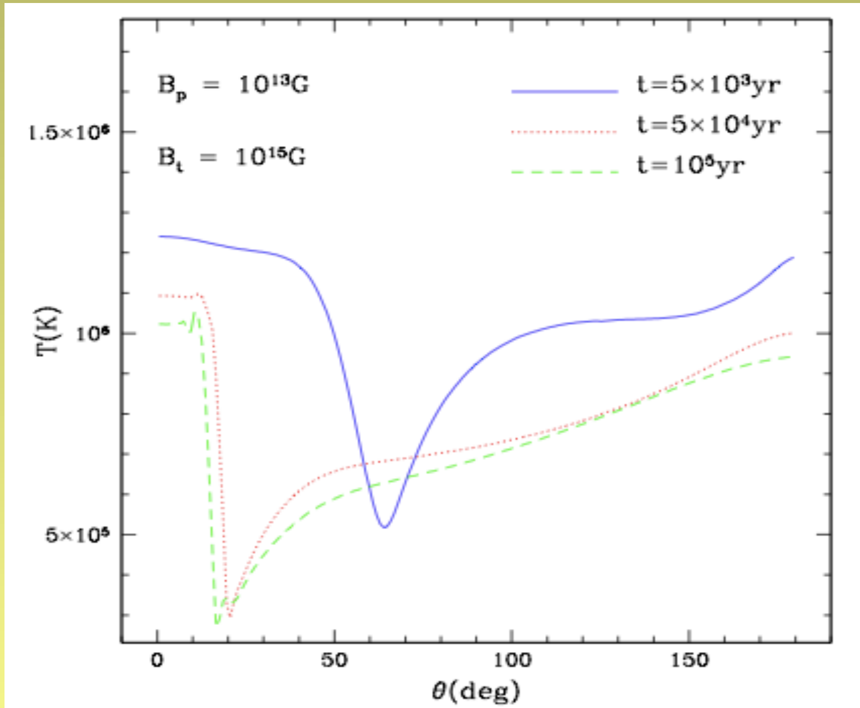
Magnetic evolution coupled with thermal evolution

→ a certain B-field configuration is associated with a specific surface temperature distribution

Poloidal field only



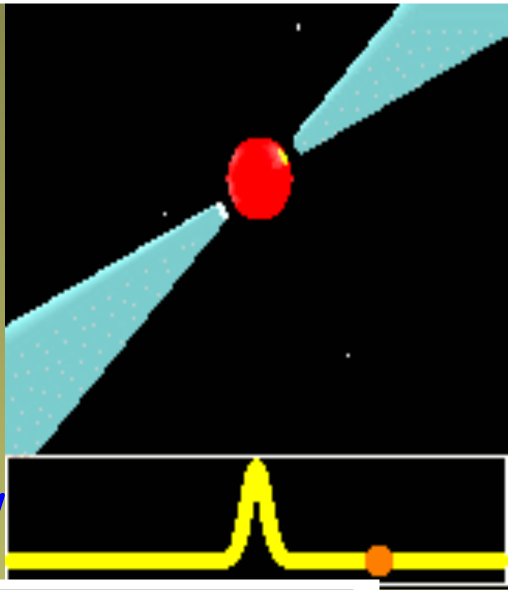
Poloidal + Toroidal field



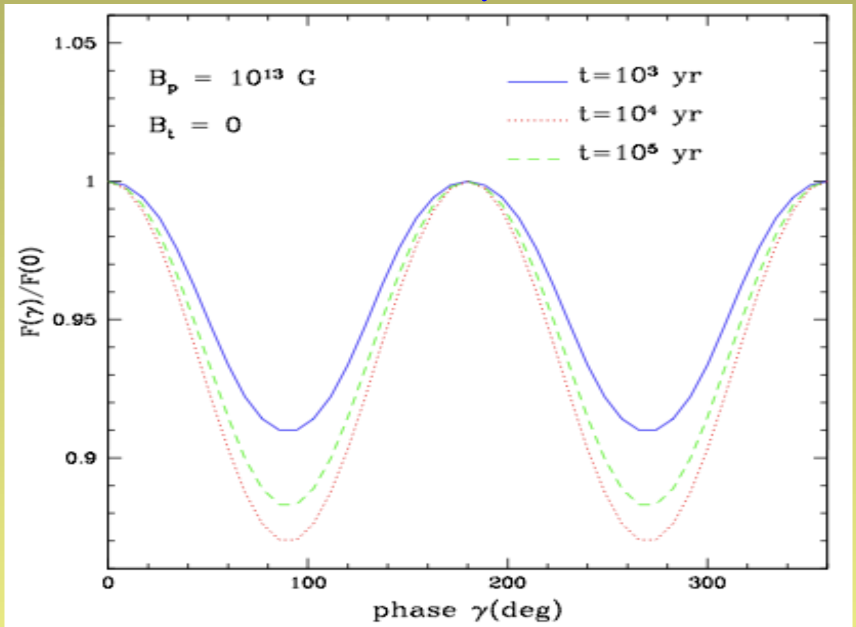
[Perna, Vigano', Pons & Rea 2013]

Observational Signatures: *Pulse profiles*

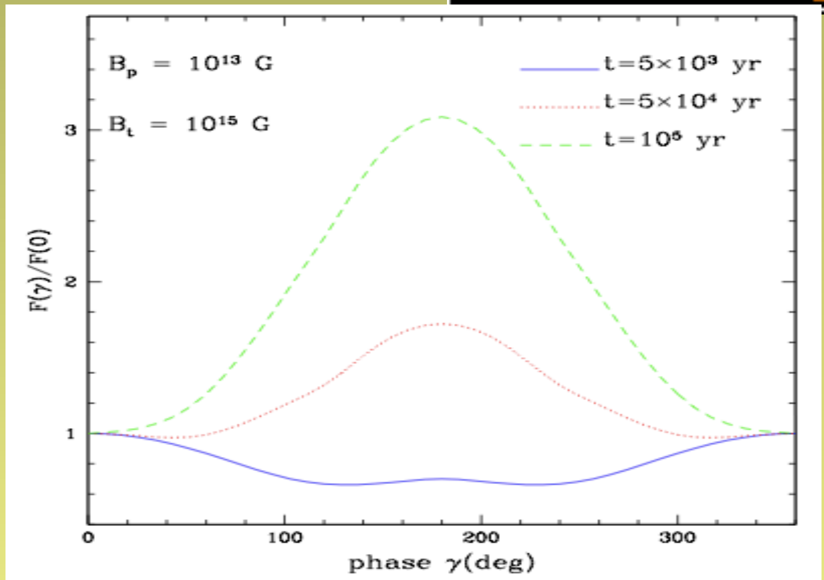
[Perna, Vigano', Pons & Rea 2013, subm.]



Poloidal field only



Poloidal + Toroidal field

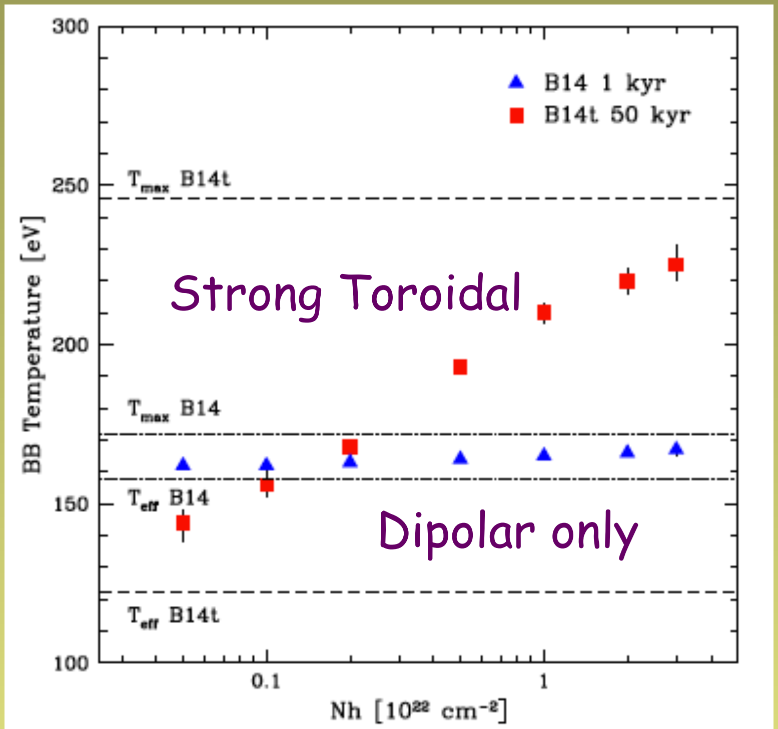


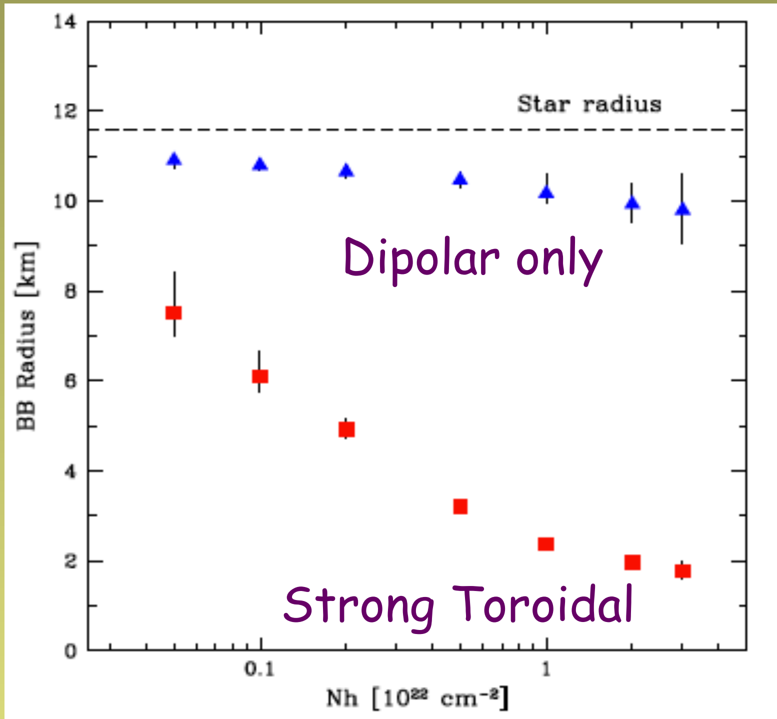
NOTE: Most magnetars are single peaked → Independent evidence for strong toroidal field!

Observational Signatures: *Spectra*

[Perna et al. 2013]

Neutron Star spectra generally fit with single blackbody





The actual NS radius is R=11.6km

NSs with a strong toroidal field (here 5e15G) seen through high absorption can have BB radii as small as ~1-2km

Typical of Magnetars!

SUMMARY

We are beginning to unravel the puzzle of what creates the bewildering variety of behaviors of highly magnetized NSs

Magnetic fields play a MAJOR role in the life of a neutron star

Theoretical work has shown that there is no 'critical B field' separating different classes of NSs, but rather a continuous of properties, modulated by the relative strengths of B_p, B_{tor} and age.