Magnetars: unique laboratories to study the physics of ultra-magnetized objects

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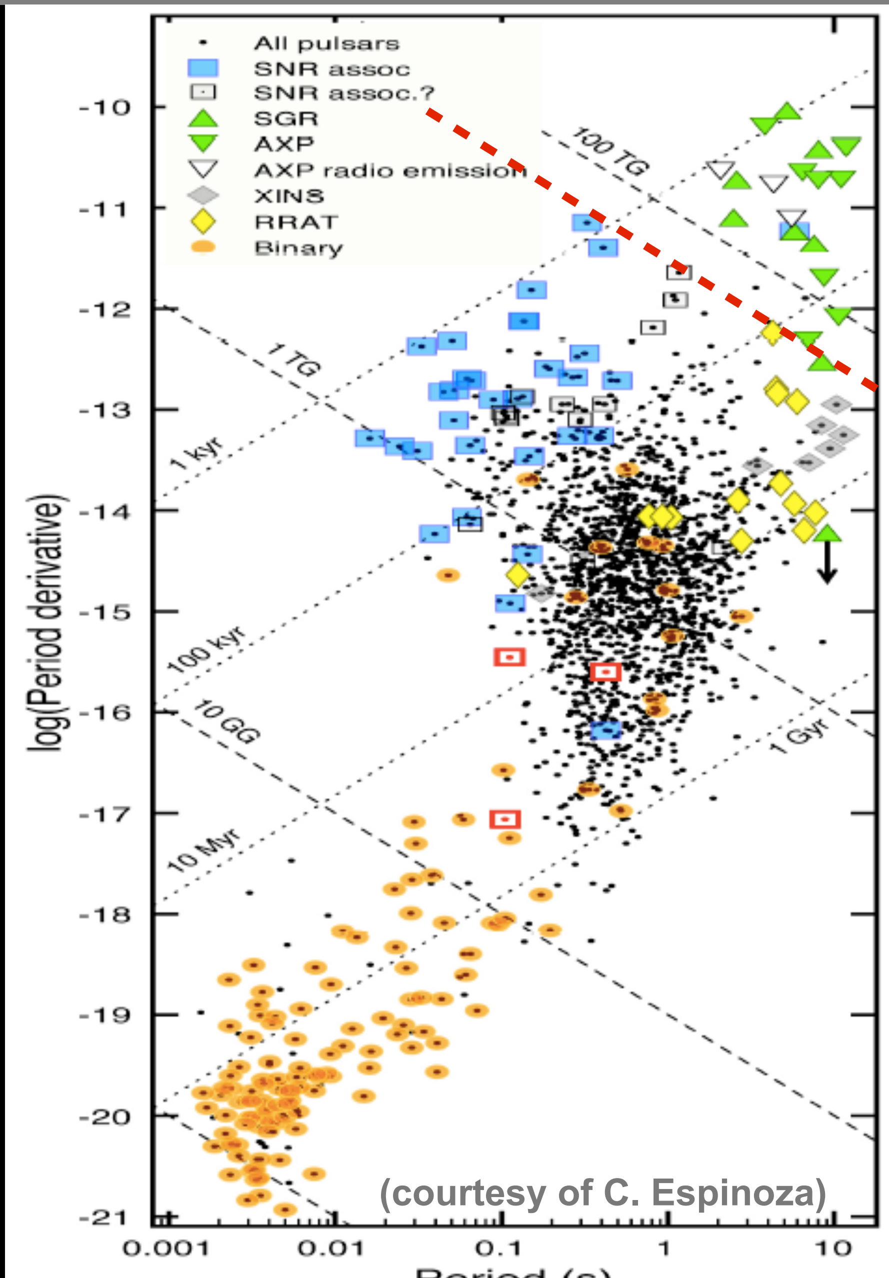
Different classes of neutron stars



$$\dot{E}_{rot} = -\frac{2}{3c^3}|\dot{m}|^2 = -\frac{2B^2R^6\Omega^4\sin^2\alpha}{3c^3}$$

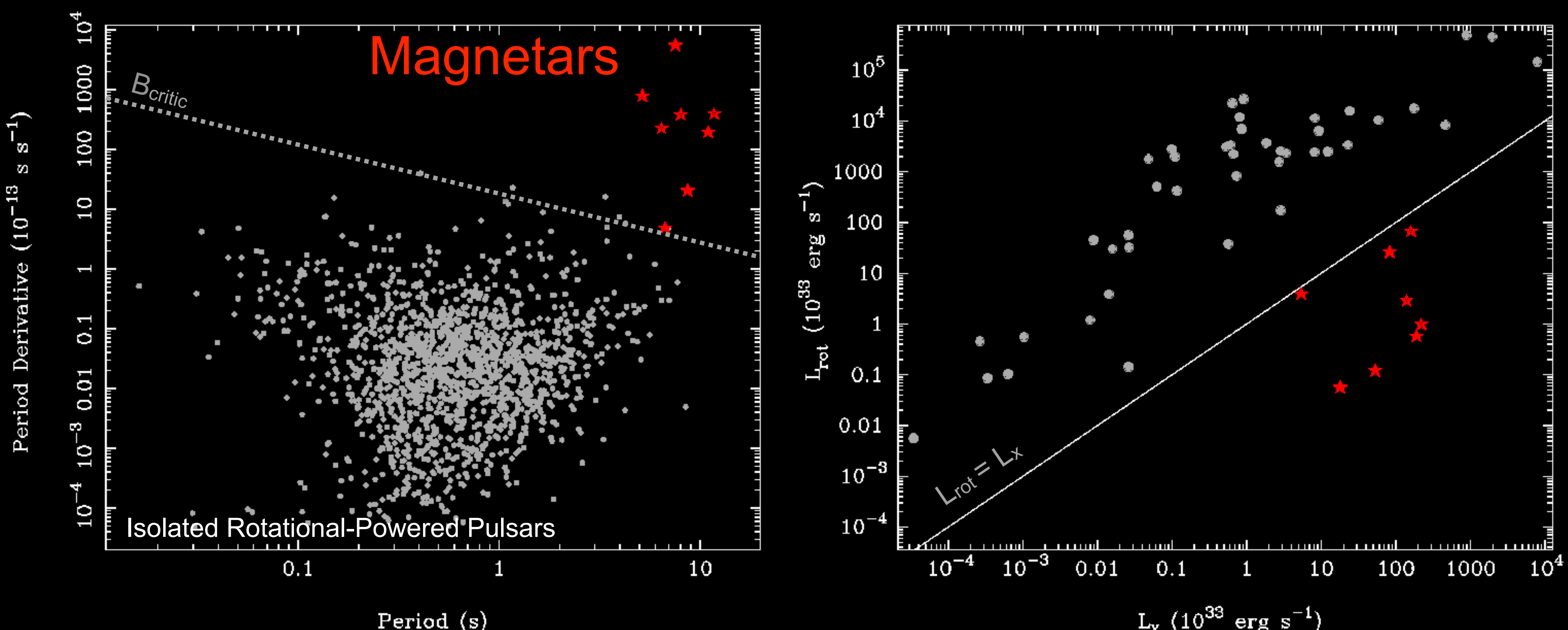
$$P\dot{P} = \left(\frac{8\pi^2 R_{ns}^6}{3c^3 I}\right) B_0^2 \sin^2\alpha$$

$$B_{critic} = \frac{m_e^2 c^3}{e\hbar} = 4.414\times10^{13}\,Gauss$$

Critical Electron Quantum B-field

Magnetars a decade ago….

- Magnetic fields > B critical ~4.4×10^{13} Gauss
- X-ray luminosities exceed rotational power
- Stable soft X-ray pulsars with P~5-10s and Lx~10^{34-35} erg/s
- Radio quiet X-ray pulsars



(Woods & Thompson 2006)

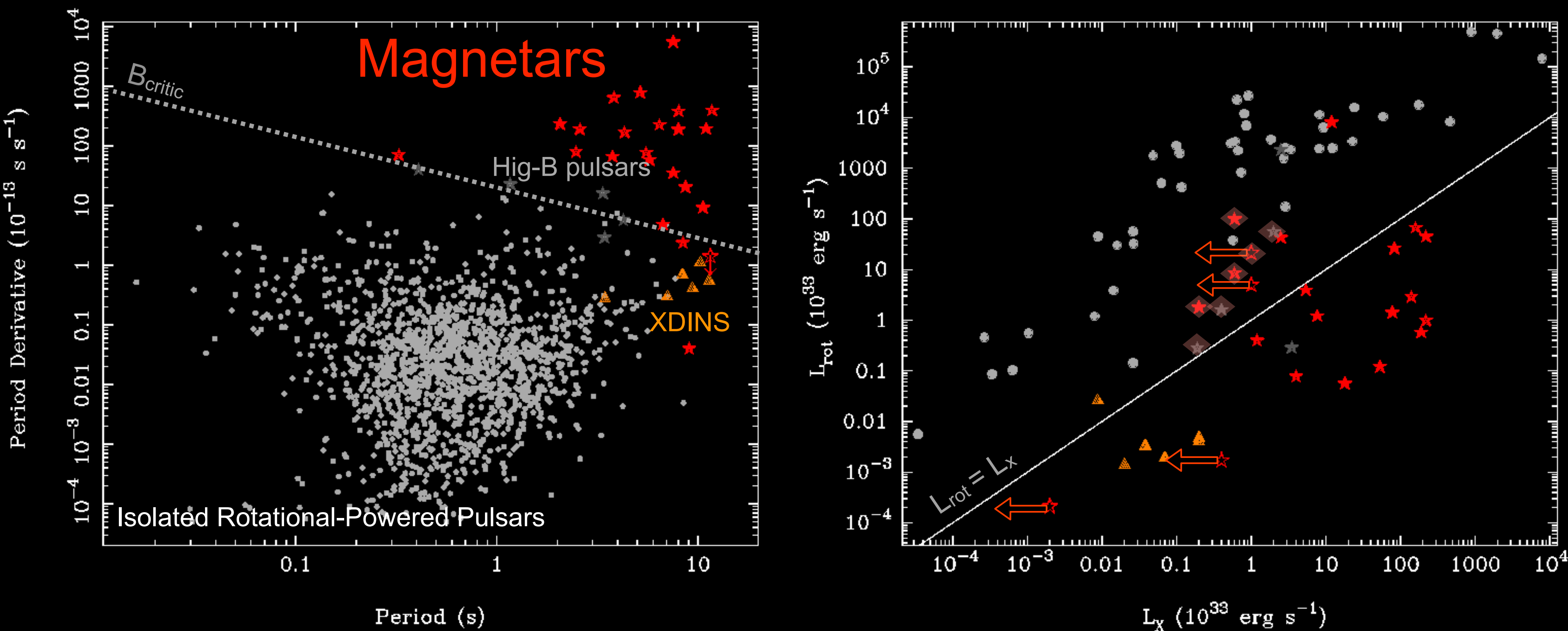
Magnetars and related neutron stars now…

- Magnetic fields NOT always > B critical ~4.4×10^{13} Gauss

- X-ray luminosities does NOT always exceed rotational power

- NOT stable soft and hard X-ray pulsars (P~0.3-10s and Lx~10^{30-35} erg/s)

- NOT radio quiet, but radio on during transient events



(Merghetti 2008; Rea & Esposito 2011; Israel & Rea 2014 submitted)

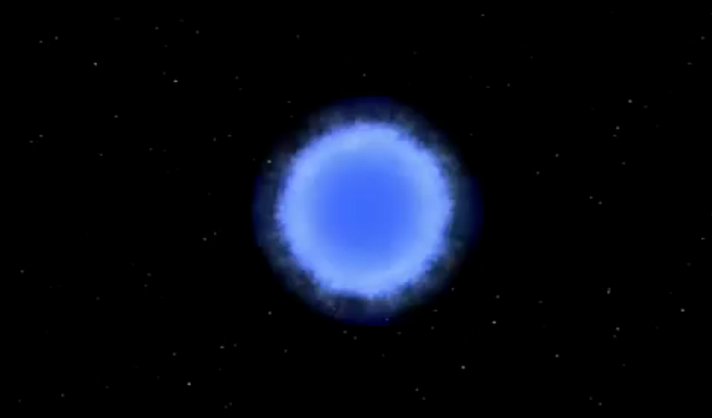
Formation: magnetars vs pulsars

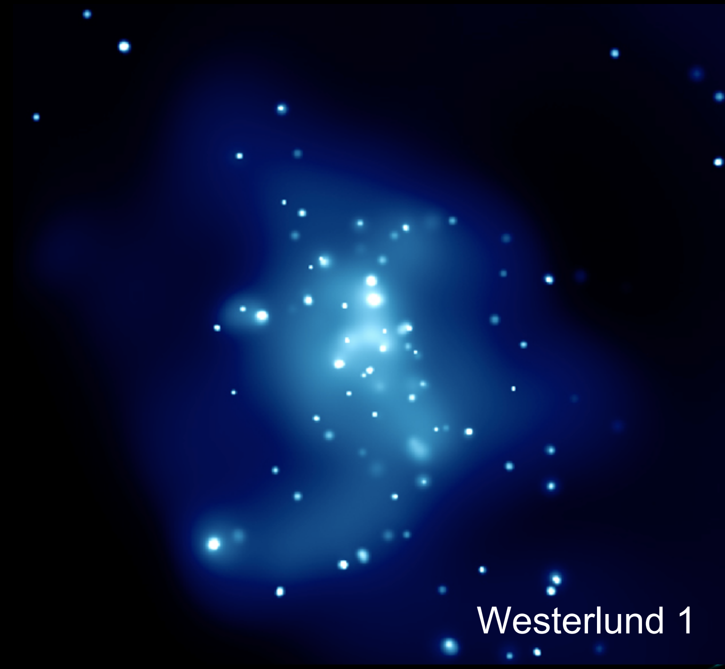
There are big uncertainties on how these huge fields are formed. Hand waiving ideas are that they are created:

- - via alpha-dynamo soon after birth

- - as fossil fields from a very magnetic progenitor

- - from massive star binary progenitors

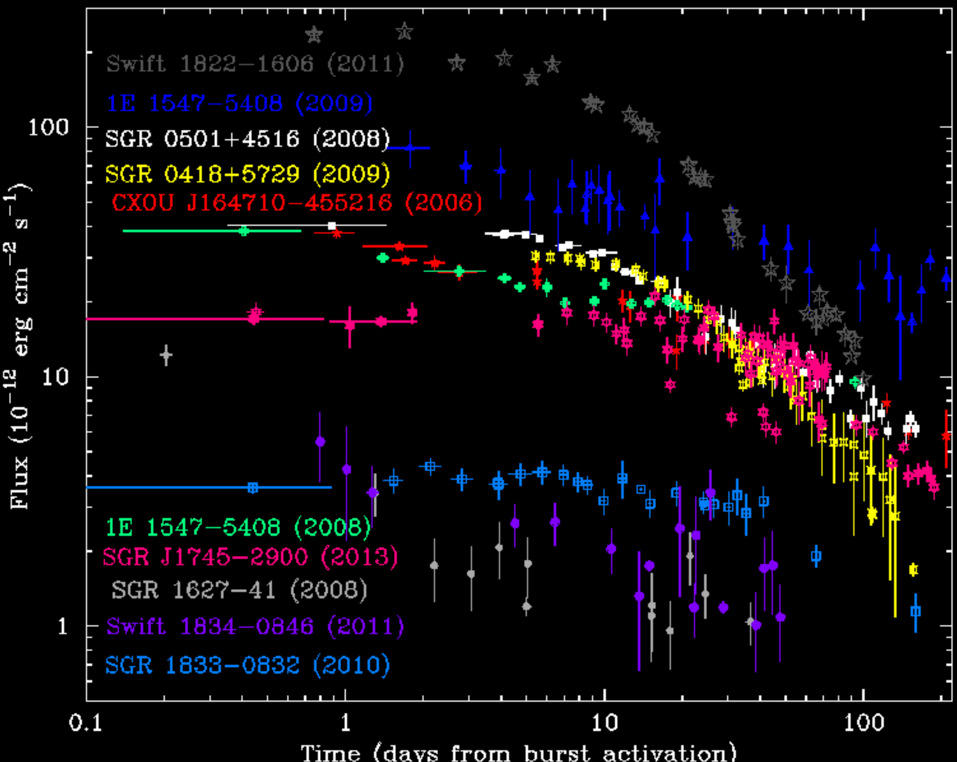




(Thompson & Duncan 1993; Ferrario & Winkramasinge 2006; Vink & Kuiper 2006; Martin et al. 2014 submitted; Clark et al. 2014)

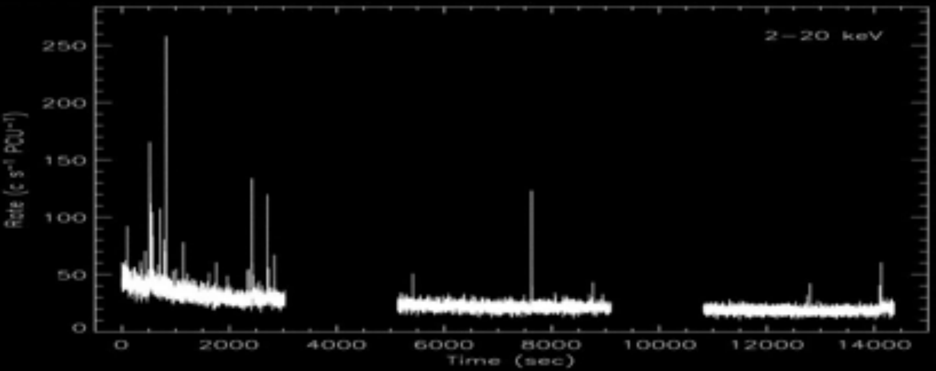
Magnetar flares and outbursts

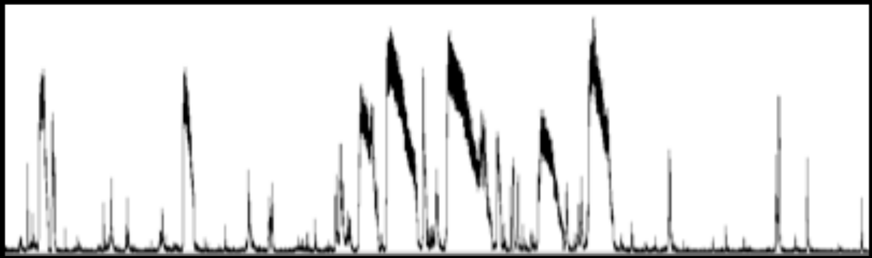
Outbursts

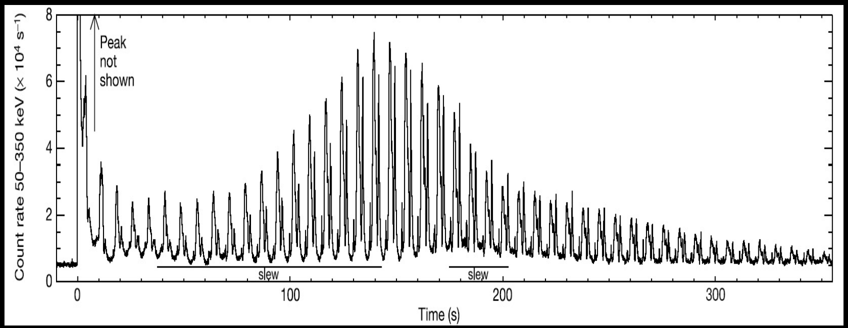


(Rea & Esposito 2011; Israel & Rea 2014 submitted)

From short bursts to Giant Flares



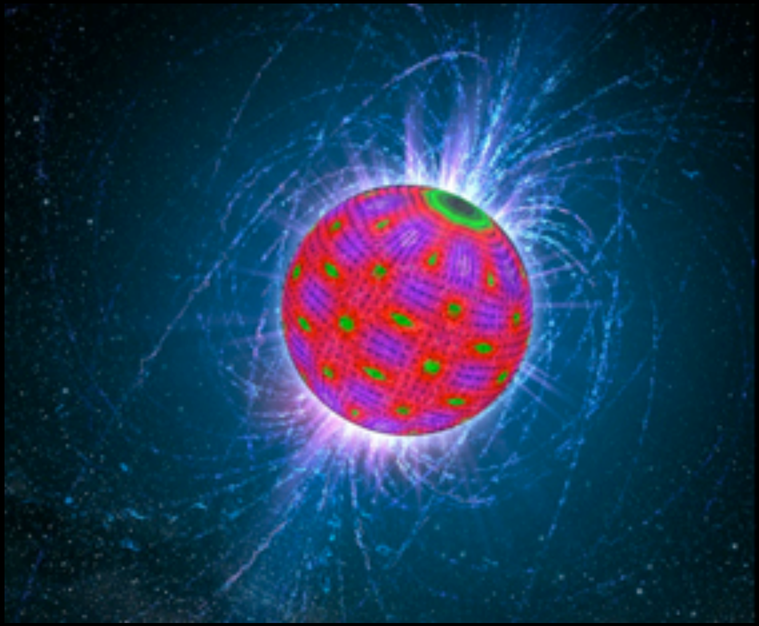




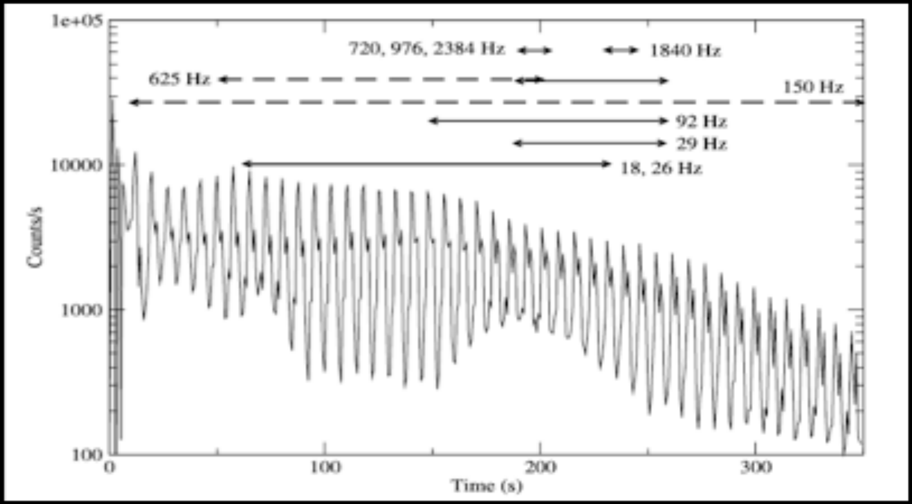
(Kaspi et al. 2003; Palmer et al. 2005; Israel et al. 2008)

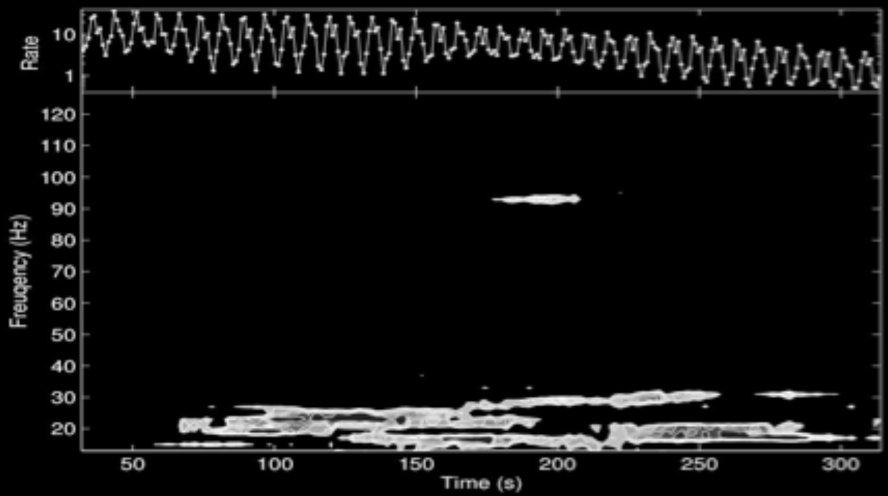
Magnetar flaring activity: quasi-periodic oscillations

- star-quakes on a neutron star!

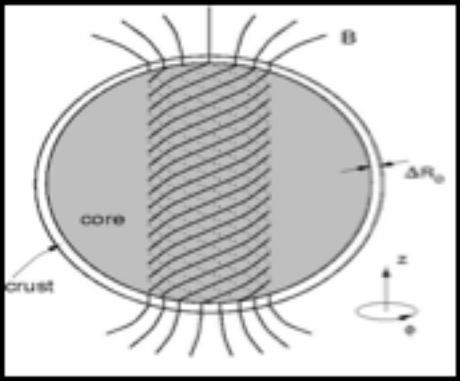


(Israel et al. 2005; Stromayer & Watts 2006)



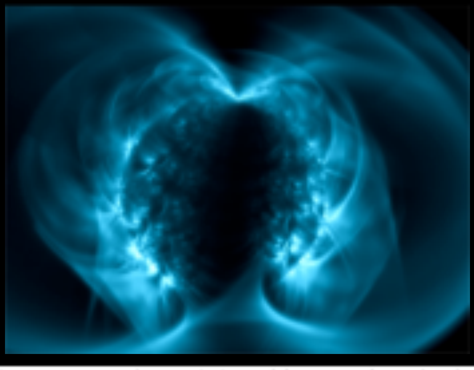


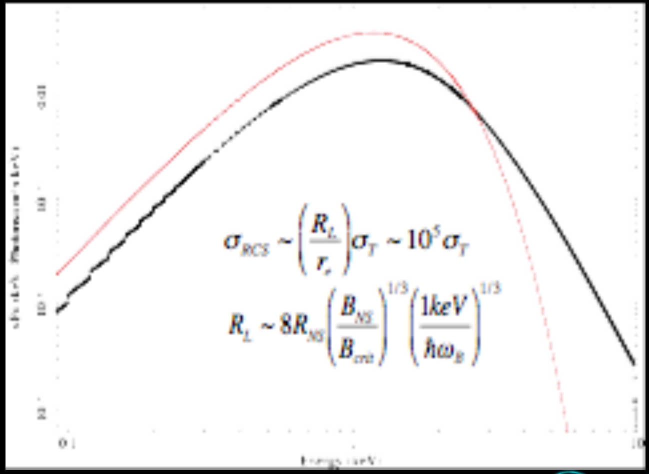
Magnetar theory in a nutshell: persistent thermal+non-thermal



Magnetars have magnetic fields twisted up, inside and outside the star. The surface of a young magnetar is so hot that it glows brightly in X-rays.

Magnetar magnetospheres are filled by charged particles trapped in the twisted field lines, interacting with the surface thermal emission through resonant cyclotron scattering.

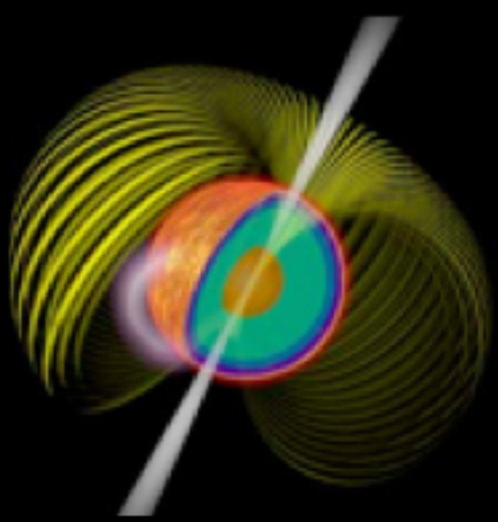




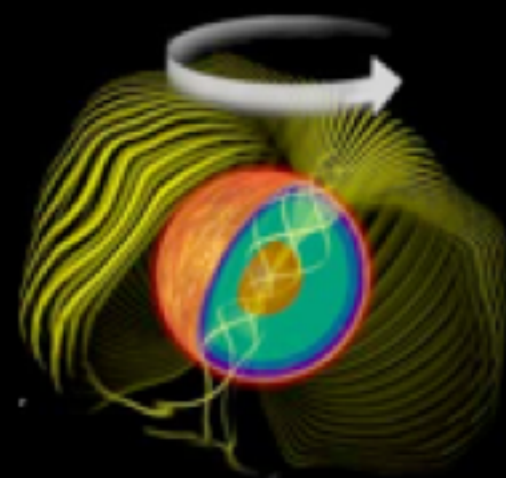
(Thompson, Lyutikov & Kulkarni 2002; Fernandez & Thompson 2008; Nobili, Turolla & Zane 2008a,b; Rea et al. 2008, Zane et al. 2009)

Magnetar theory in a nutshell: outburst mechanisms

- Their internal magnetic field is twisted up to 10 times the external dipole. At intervals, stresses build up in the crust which might cause causing glitches, flares...



High-B PSR



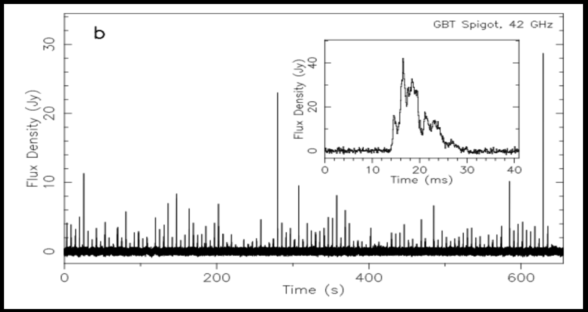
SGR/AXP

(Thompson & Duncan 1992; 1993; Thompson, Lyutikov & Kulkarni 2002; Beloborodov 2007)

New insights unifying the different neutron star classes

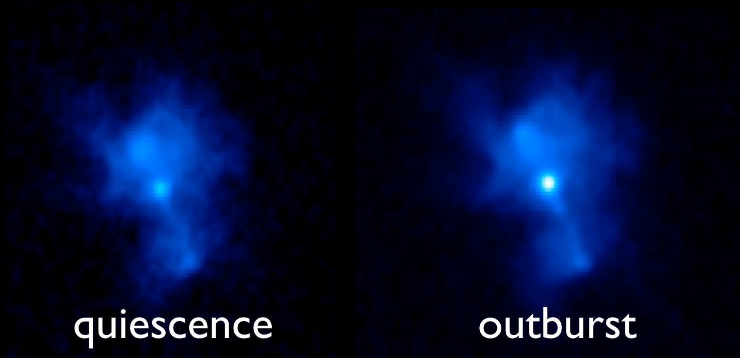
1. Magnetars can be radio pulsar during outbursts.

(Camilo et al. 2006, Nature; Camilo et al. 2007, ApJ)



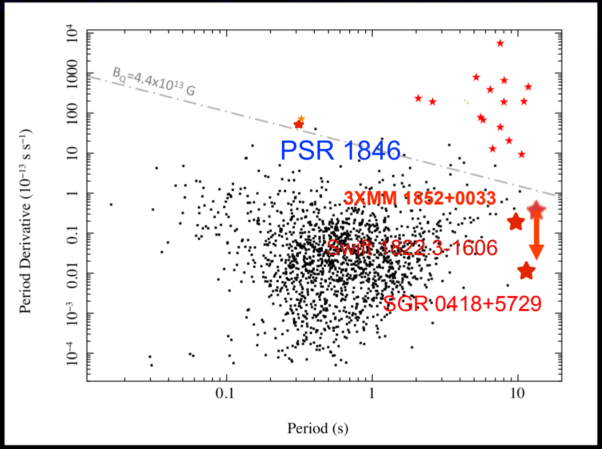
2. A "normal" X-ray pulsar showed magnetar activity.

(Gavriil et al. 2008, Science; Kumar & Safi-Harb, 2008, ApJ)



3. Magnetars were discovered having also low B-field.

(Rea et al. 2010, Science; Rea et al. 2012, 2013, 2014 ApJ)

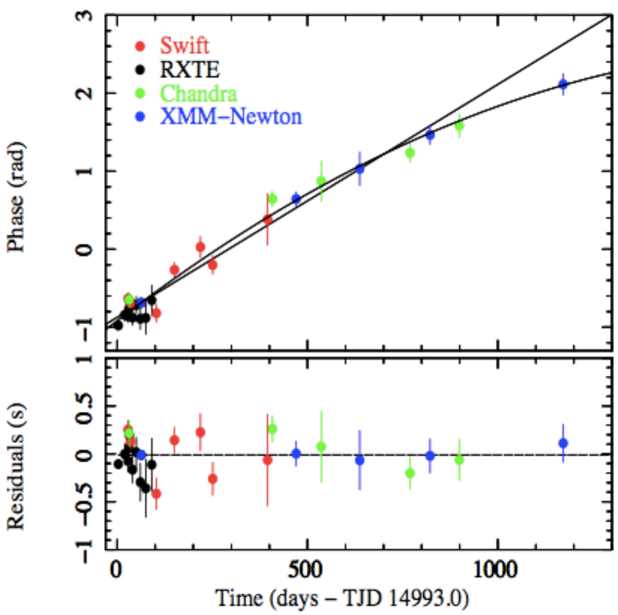


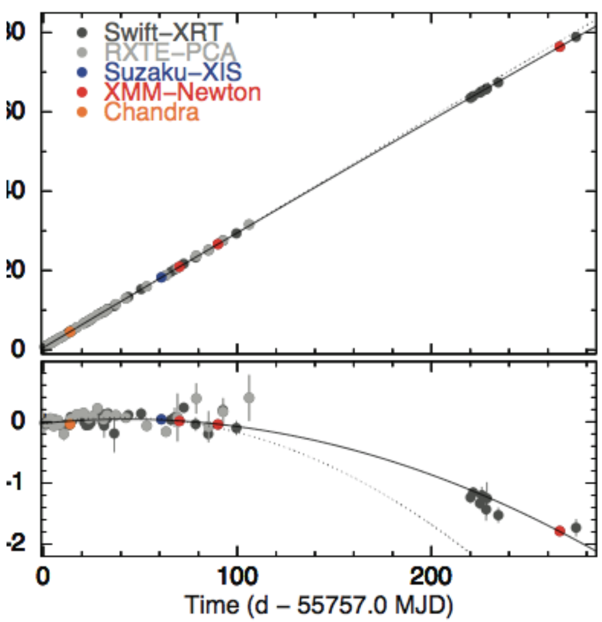
Low magnetic field magnetars: we have three now!

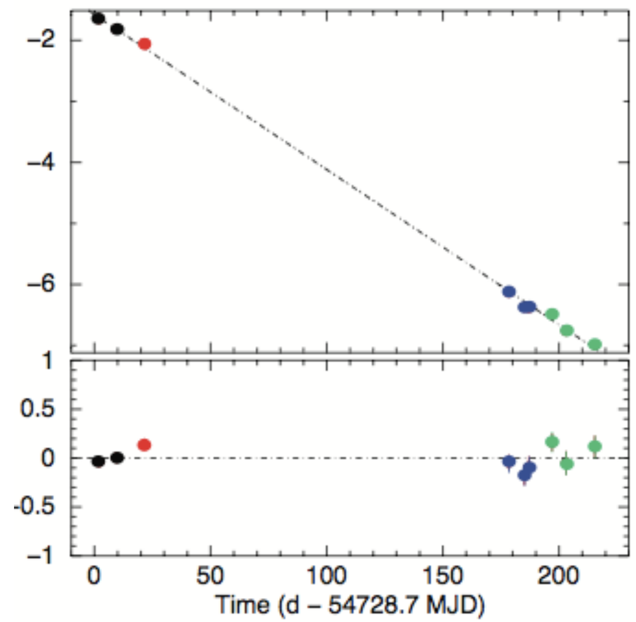
$B = 6.2 \times 10^{12}$ G

$B = 2.3 \times 10^{13}$ G

$B < 4 \times 10^{13}$ G







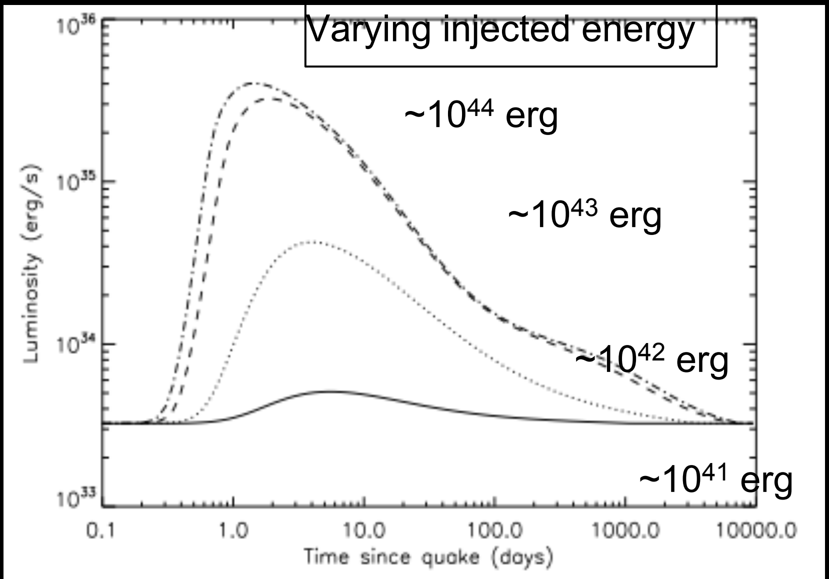
SGR 0418+5729

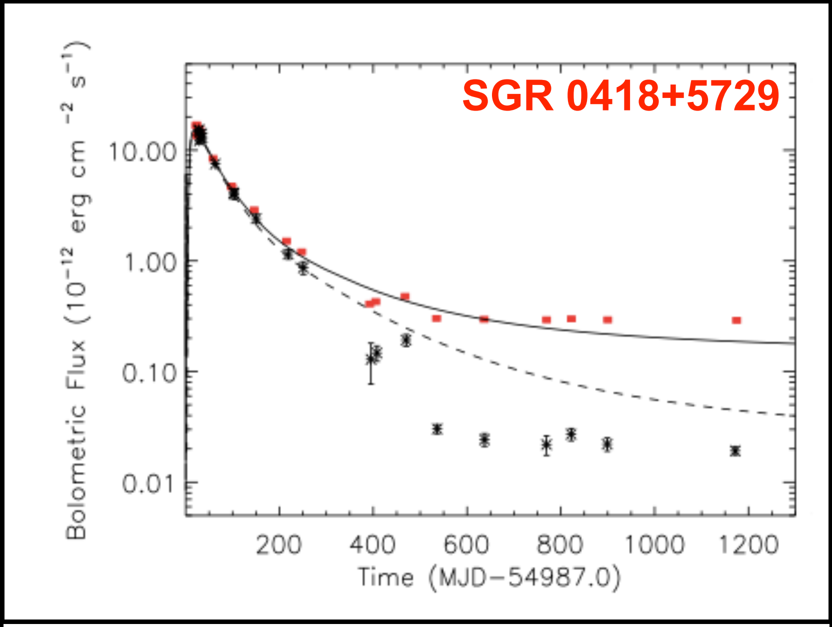
Swift 1822-1606

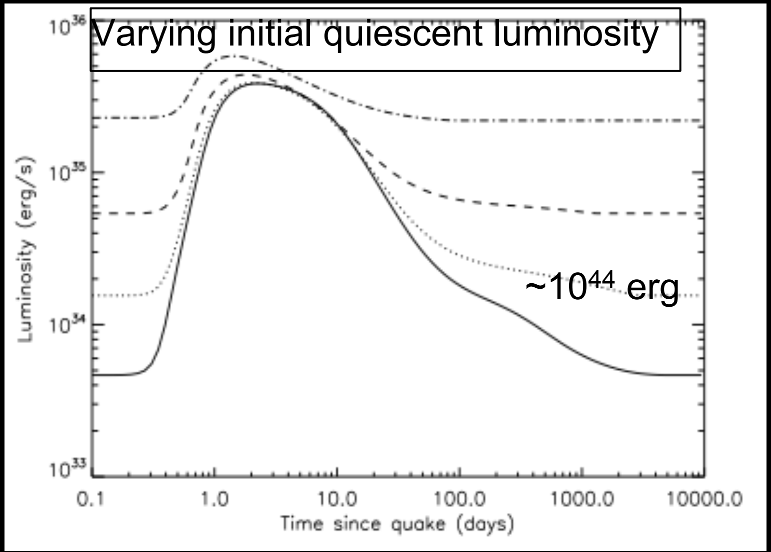
3XMM 1852+0033

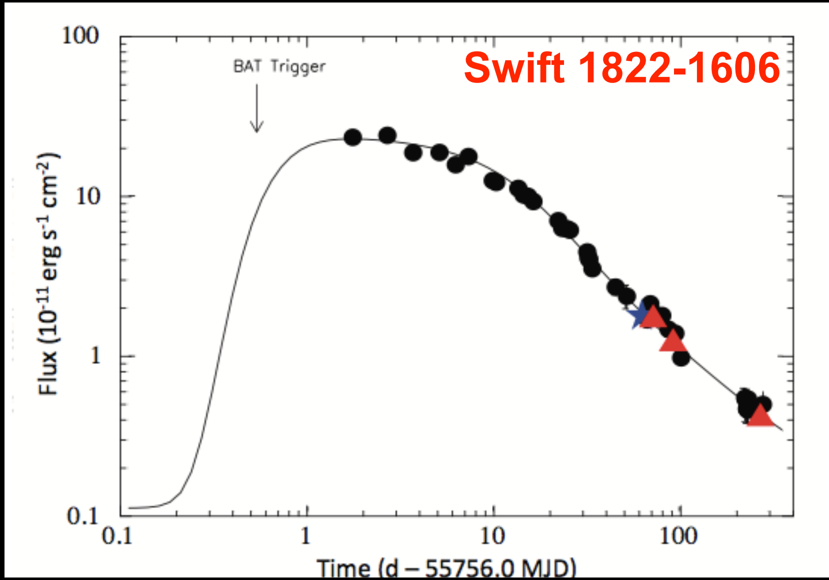
(Rea et al. 2010, Rea et al. 2012; Scholtz et al. 2012; Rea et al. 2013; Zou et al. 2014; Rea et al. 2014)

Outburst modelling





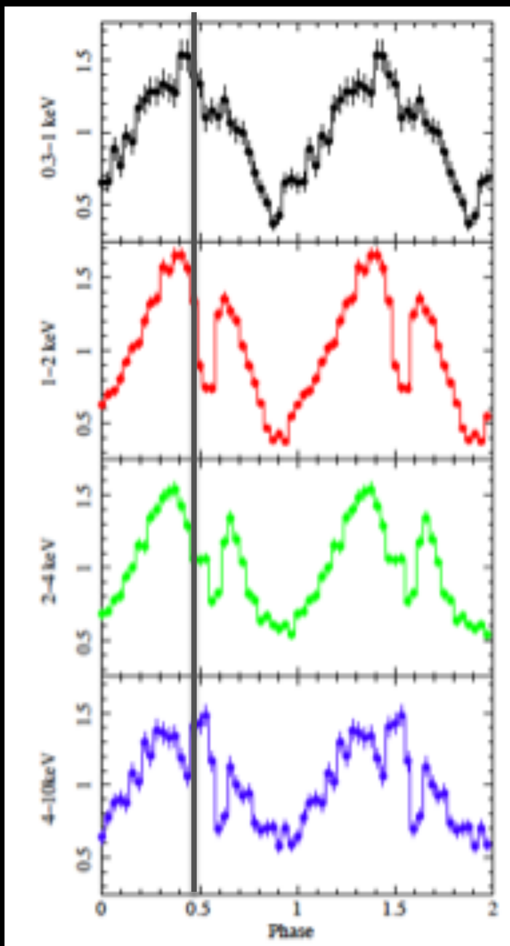




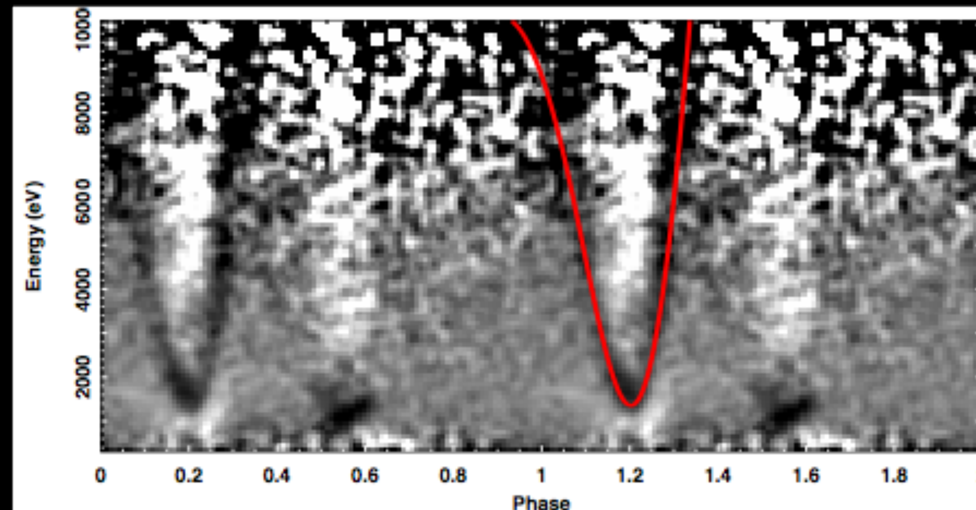
(Pons & Rea 2012; Rea et al. 2012, 2013)

The lowest magnetic magnetars (B_{dip}~6x10^{12} G): SGR 0418+5729

During the outburst peak it showed a phase variable absorption feature



(Rea et al. 2013)

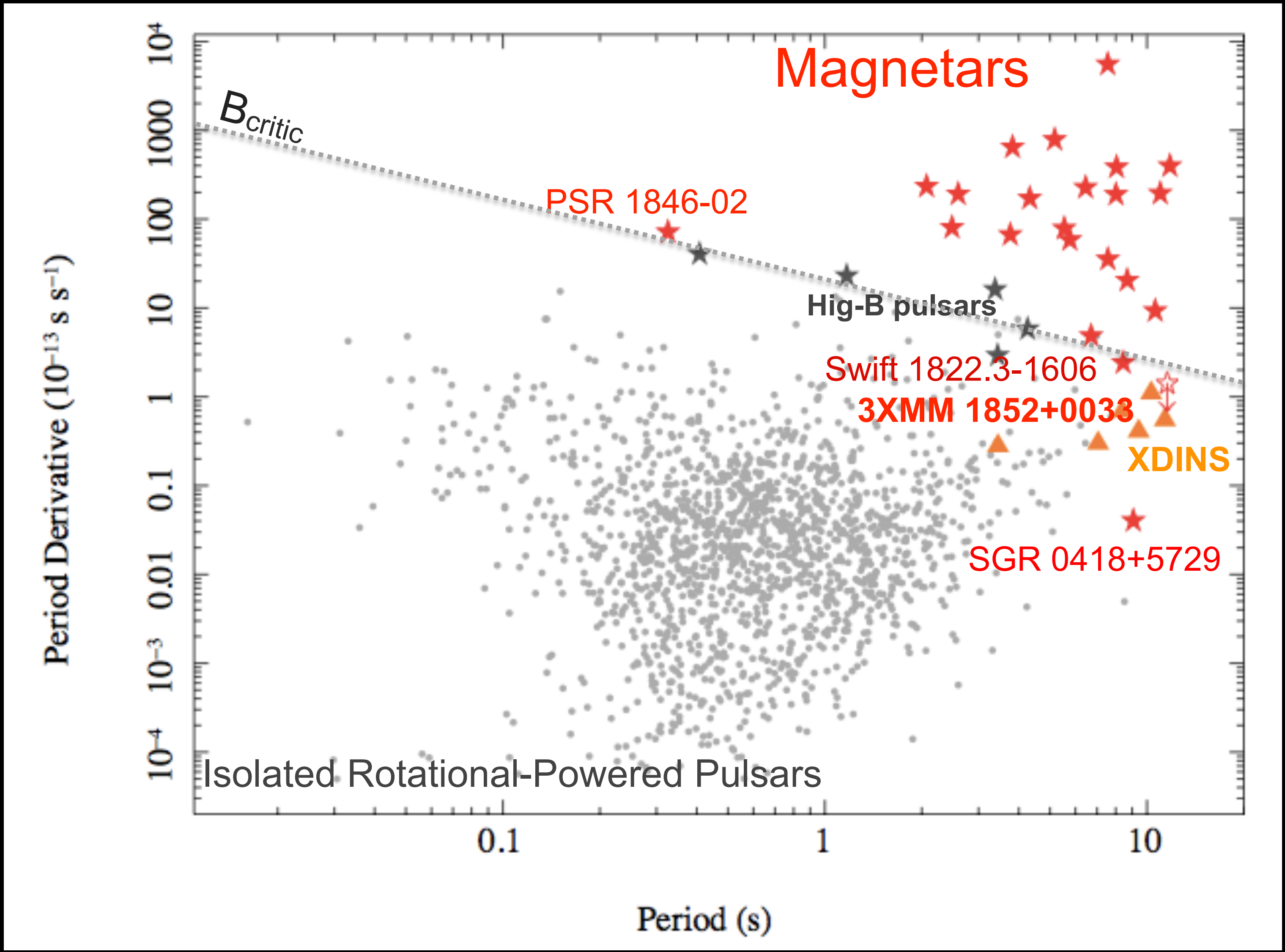


Different geometries can be envisaged, but our toy-model shows that the hypothesis of proton cyclotron resonant scattering in a magnetar loop is a viable scenario.

$E_{cycl,p}$= 0.6 B_{14} keV
⇒ B ~ (2-20) x 10^{14} G

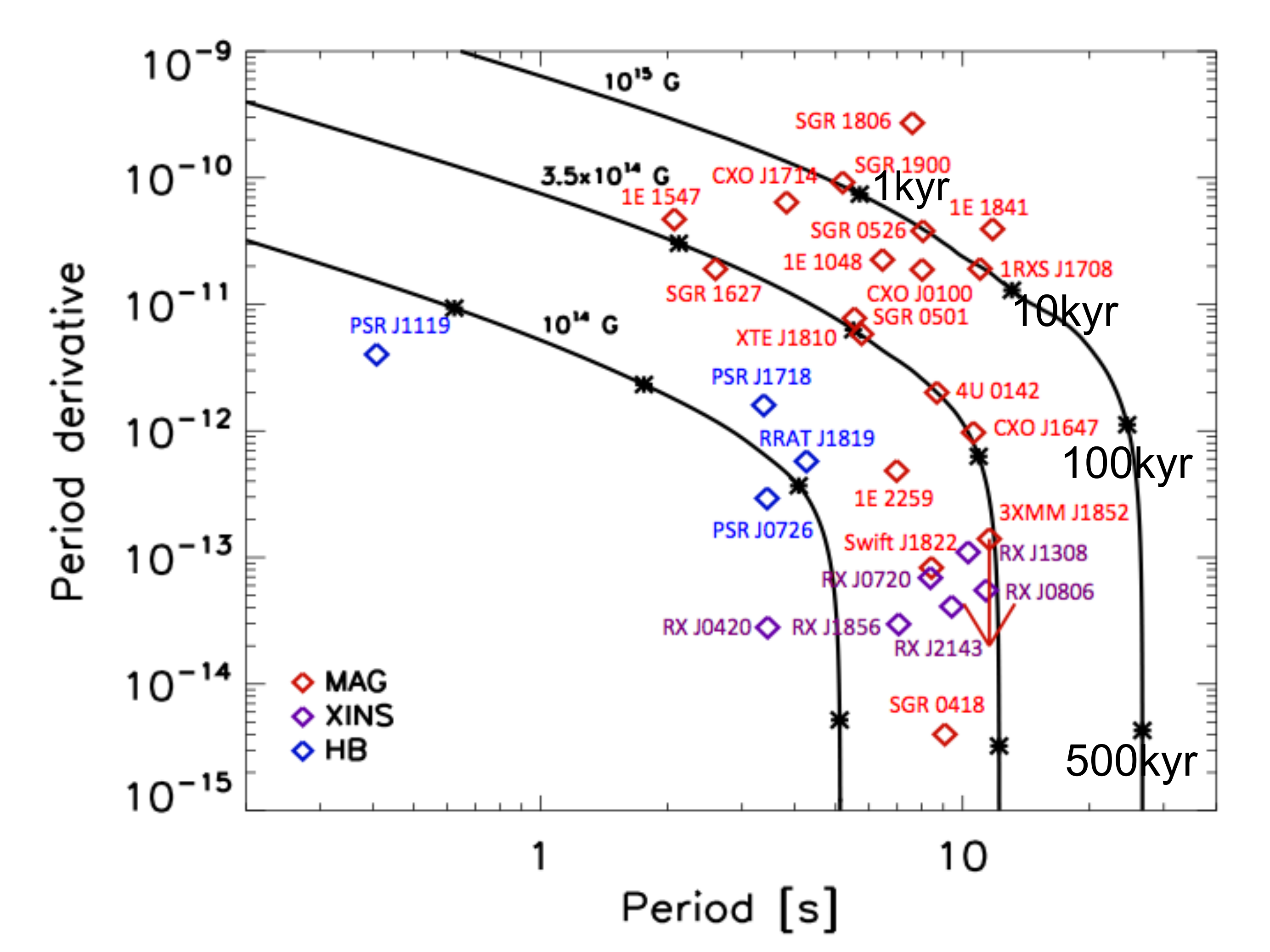
(Tiengo et al. 2013, Nature)

Filling the gap around the critical magnetic field…



Are all those objects in line with the magnetar/pulsar model?

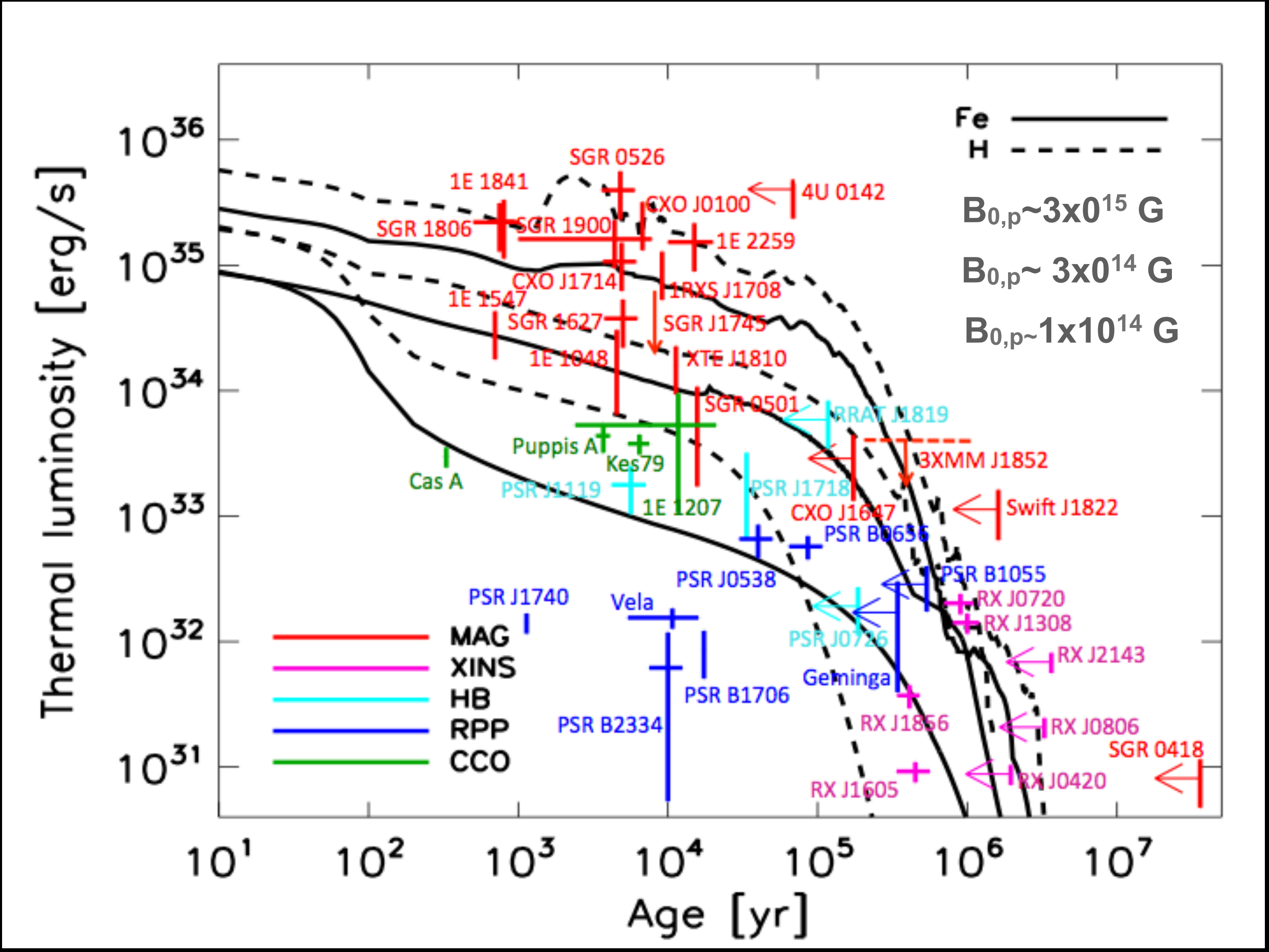
Magnetic evolution of neutron stars: toward a unification



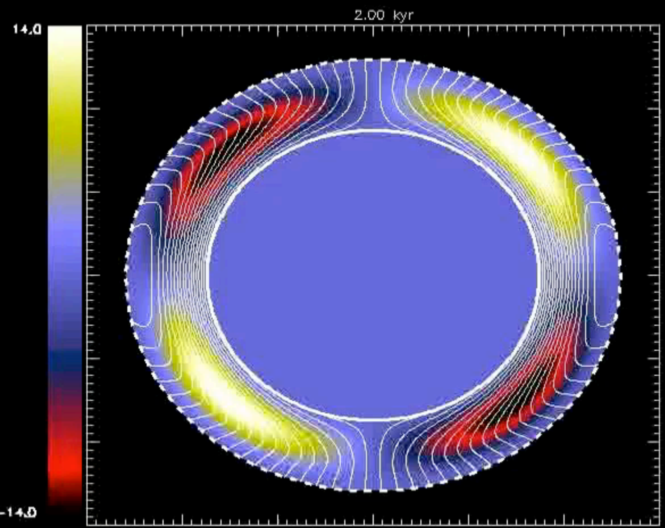
(Vigano', Rea, Pons, Perna, Aguilera & Miralles 2013; Rea, Vigano', Israel, Pons & Torres 2014)

Magnetic evolution of neutron stars: toward a unification

http://neutronstarcooling.info/



Magnetic evolution of neutron stars: toward a unification

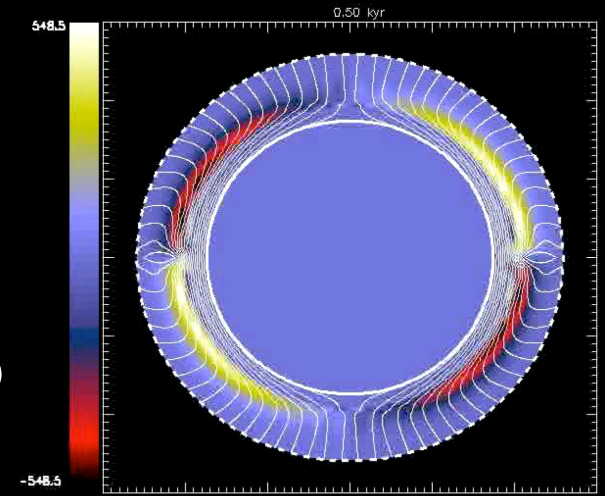


Normal Pulsar

Intial conditions:

B_{dip}~10^{13} G (white lines)

B_{int}~ 10^{14} G (colors)



Young Active Magnetar

Intial conditions:

B_{dip}~10^{15} G (white lines)

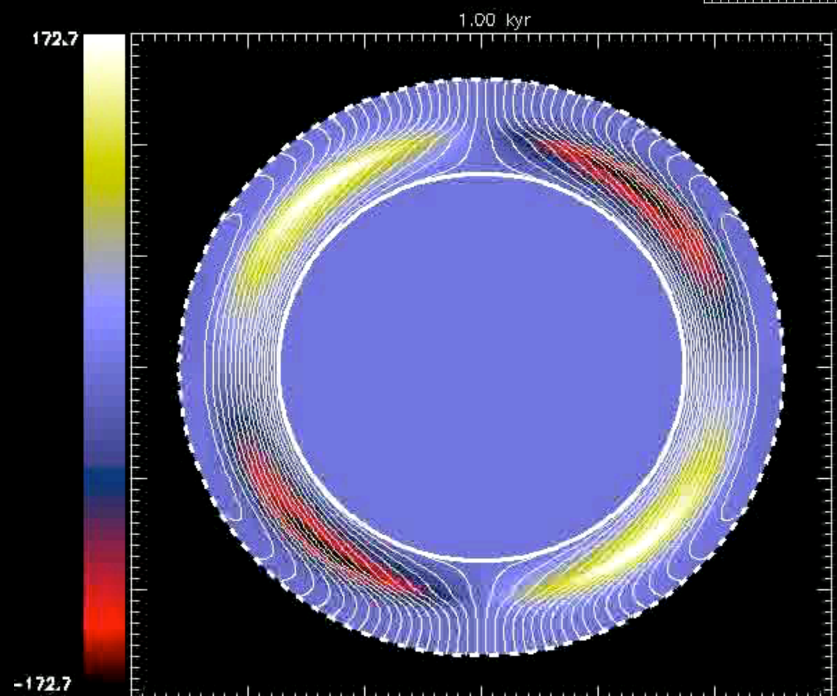
B_{int}~ 10^{16} G (colors)

Old Weak Magnetar

Initial conditions:

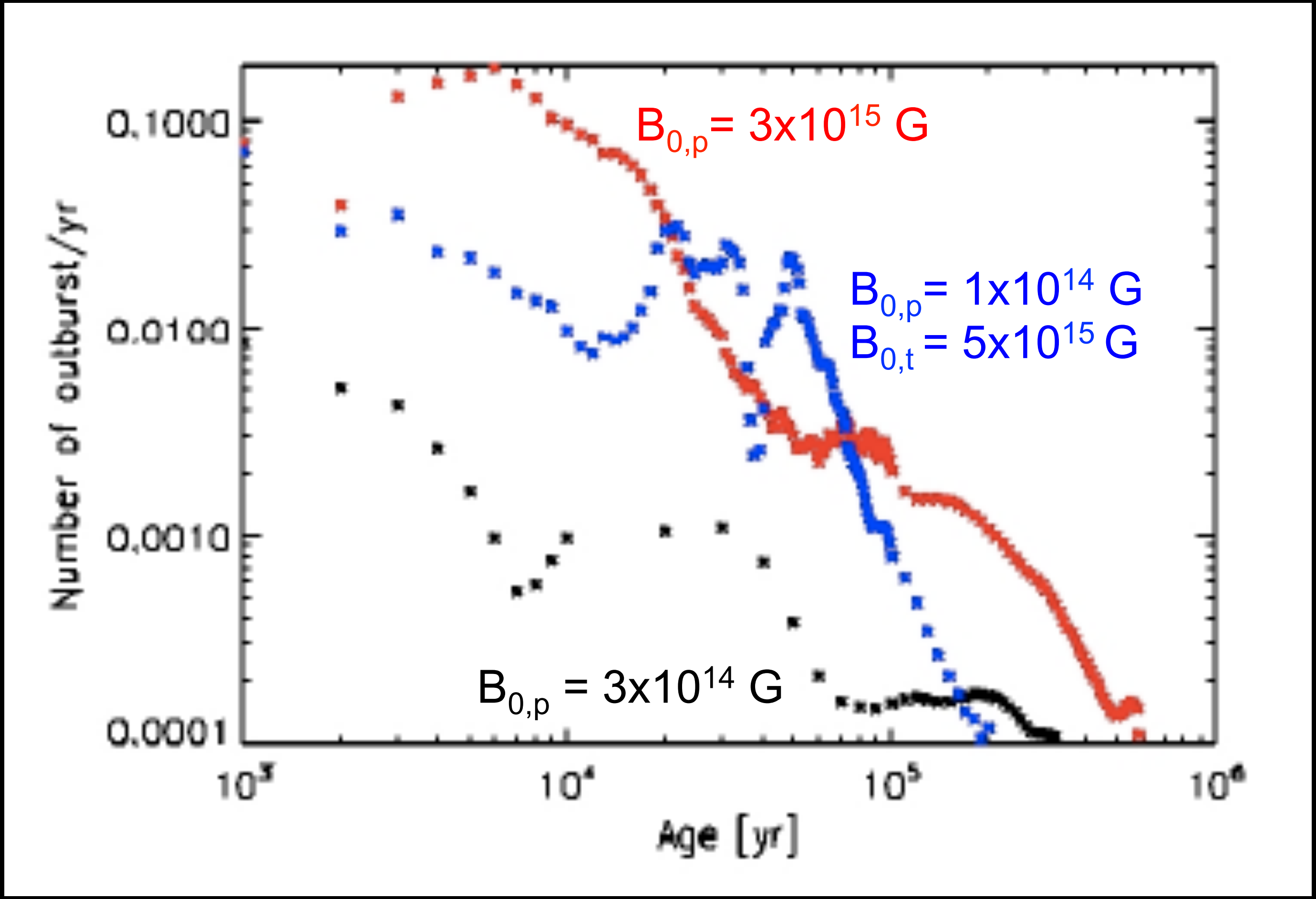
B_{dip}~10^{14} G (white lines)

B_{int}~ 10^{15} G (colors)

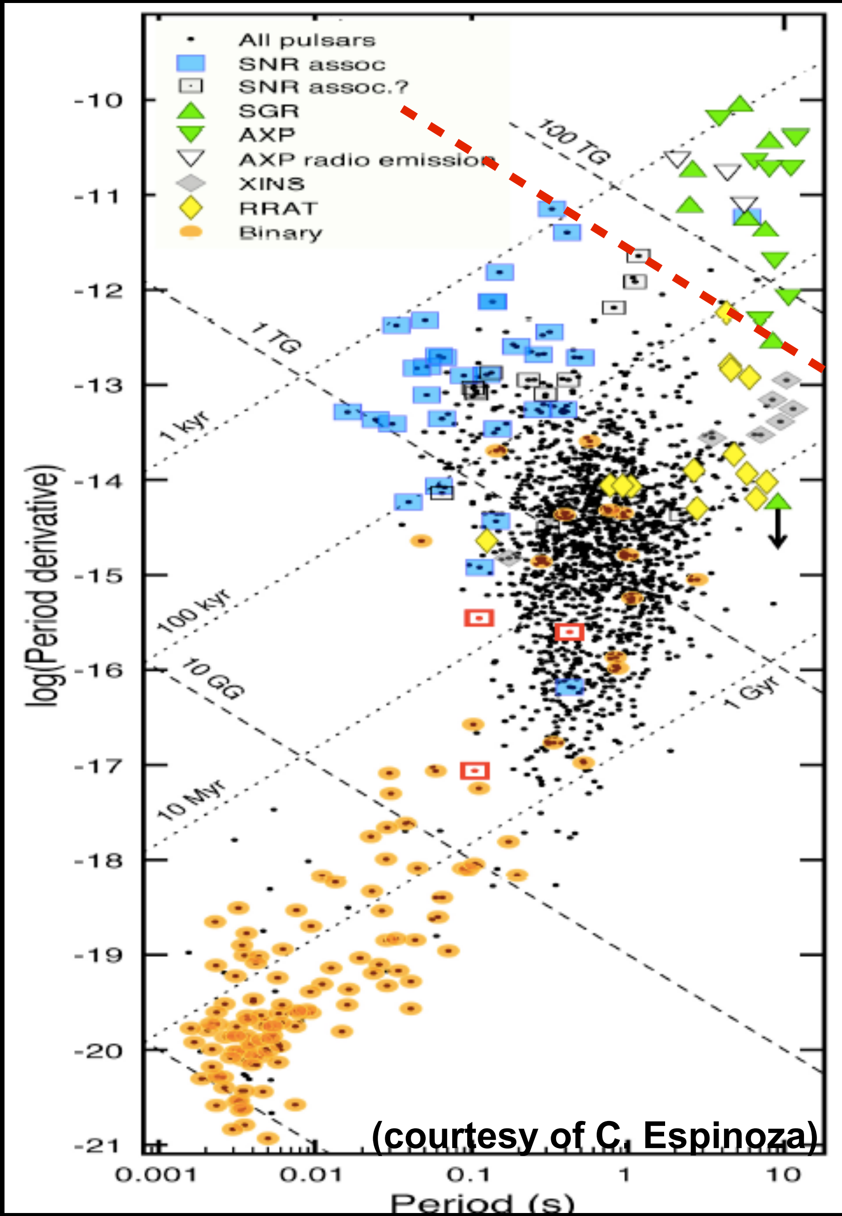


Magnetar bursting rate

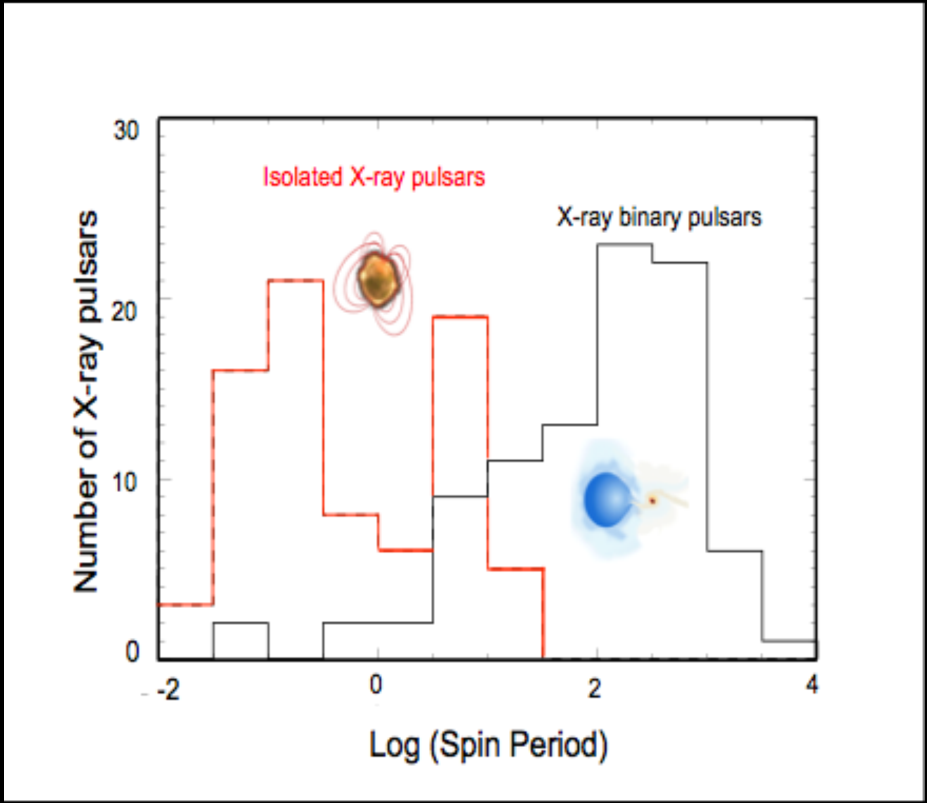
Can a neutron star with 6×10^{12} Gauss dipolar field, as SGR 0418+5729, show a magnetar-like outburst and flares?



Isolated neutron stars' maximum spin period

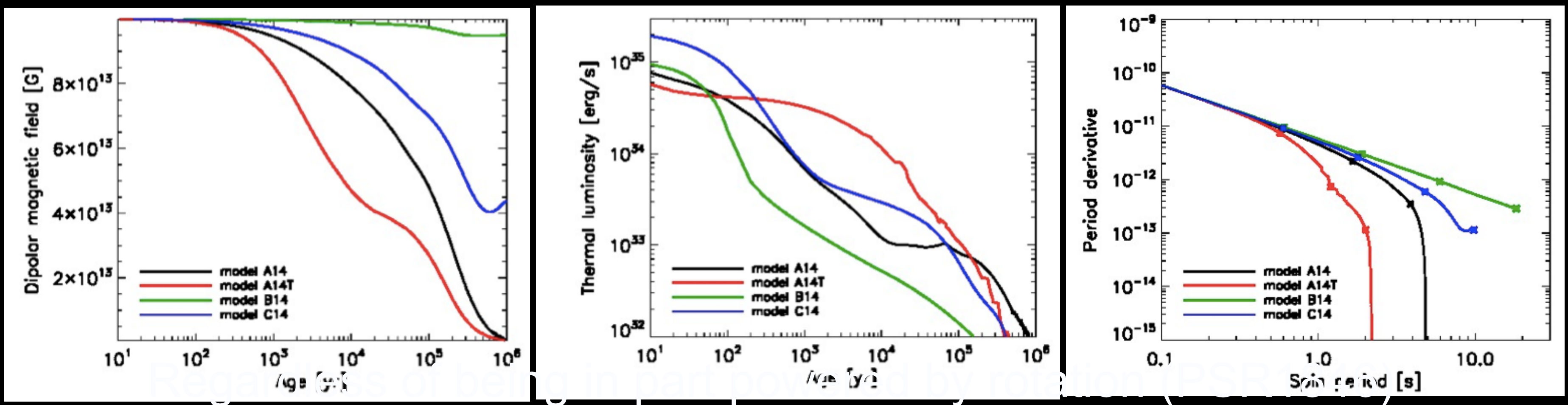


Why we do not see isolated pulsars spinning slower than 12s?

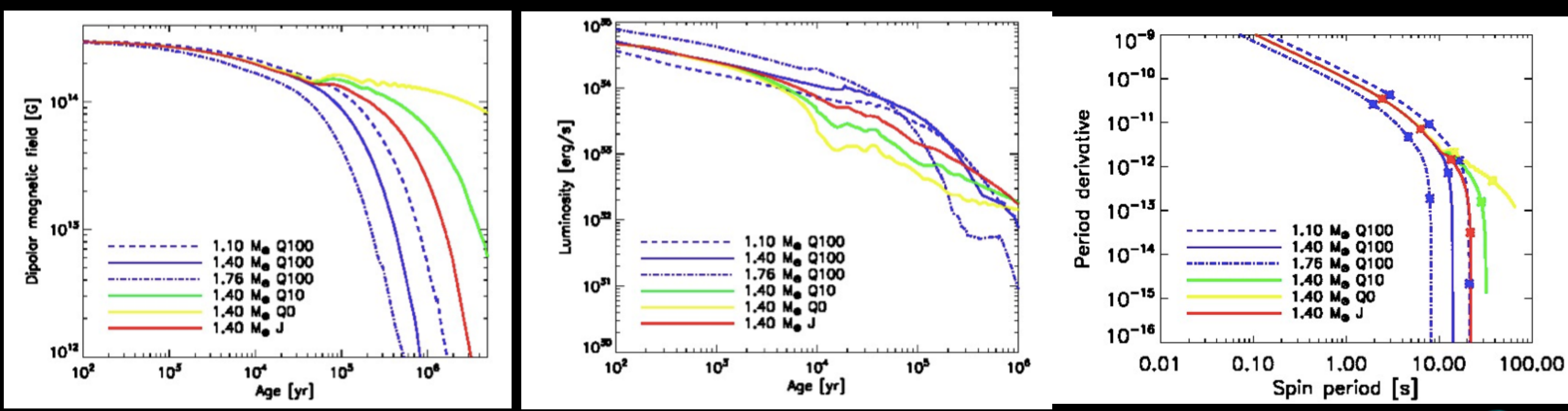


Effects of magnetic decay on pulsars period distributions

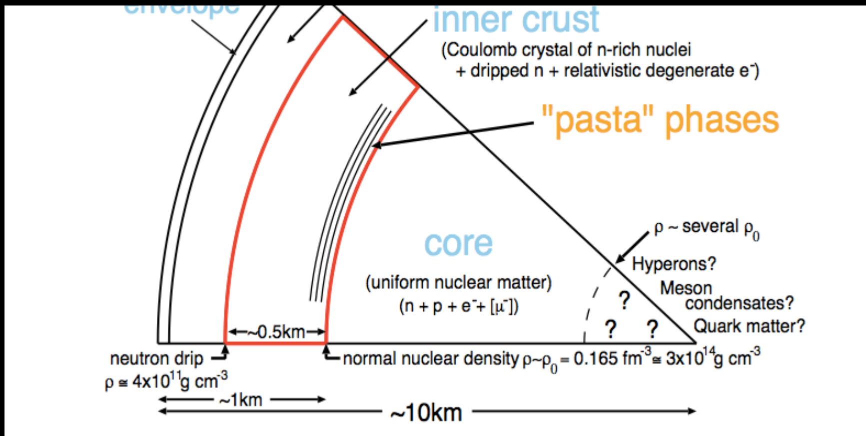
- Changing the B-field configuration: large differences between pure crustal and core fields

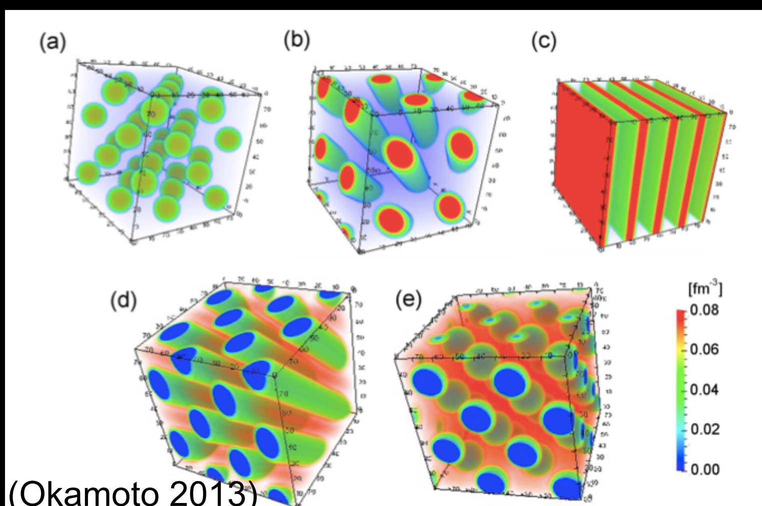


- Changing mass and impurity: the impurity parameters largely affects the evolution

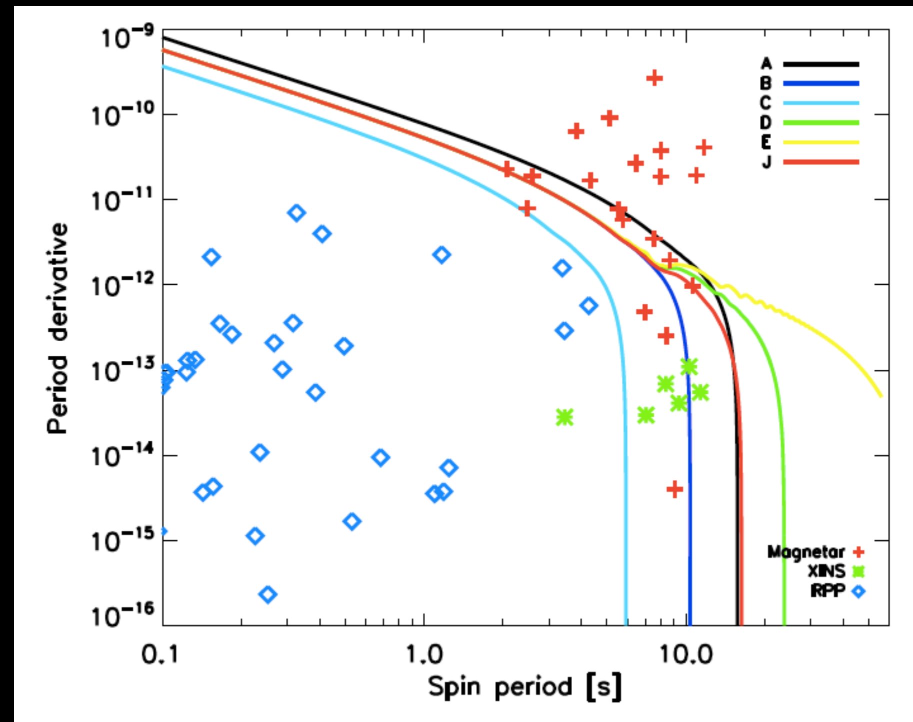


Constraining crust impurity with slow pulsars





(Okamoto 2013)



Model	$M[M_\odot]$	I_{45}	ΔR_{crust} [km]	ΔR_{pasta} [km]	Q_{max}
A	1.10	0.962	0.94	0.14	100
B	1.40	1.327	0.70	0.10	100
C	1.76	1.755	0.43	0.07	100
D	1.40	1.327	0.70	0.10	10
E	1.40	1.327	0.70	0.10	0.1
J	1.40	1.327	0.70	0.0	23

(Pons, Vigano' & Rea 2013 *Nature Physics* 9, 431)

Conclusion

** A magnetar is a neutron star which showed magnetic-powered emission!
- Regardelss of the measured surface dipolar field (SGR0418)
- Regardless of being in part powered by rotation (PSR1846)

** The huge advances in the past few years came from aggressive multi-band observing campaign, going hand in hand with advances in the theoretical simulations
- Its crucial to work on both aspects.

** The isolated neutron star emission zoo can be easily explained by age, field strength and field geometry when considering the Hall field decay
- These three parameters are driving the different emission we are seeing.

** We are now starting to probe strong-B-field physics with magnetars!
- Next step is a full 3D MHD magnetic-thermal evolution code… on his way!