Magnetars: neutron stars with huge magnetic storms

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Magnetic Field Tree

0.6 G – The Earth magnetic field measured at the North pole

100 G – A common hand-held magnet like those used to stick papers on a refrigerator

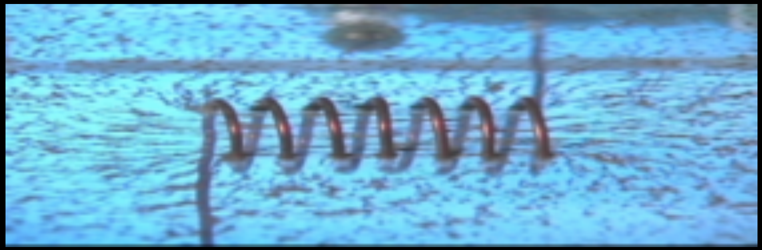
10^7 G – The strongest man-made field ever achieved, made using focussed explosive charges, lasting only 4-8 s

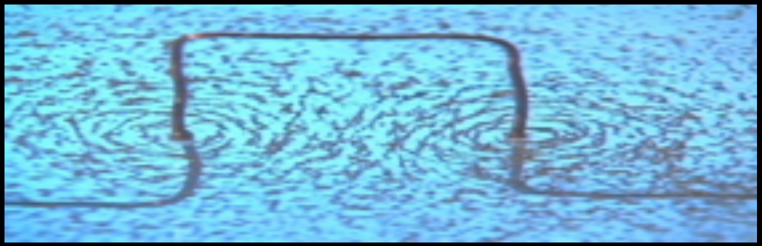
10^{12} G – Typical neutron star magnetic fields

4.4×10^{13} G – Electron critical magnetic field

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

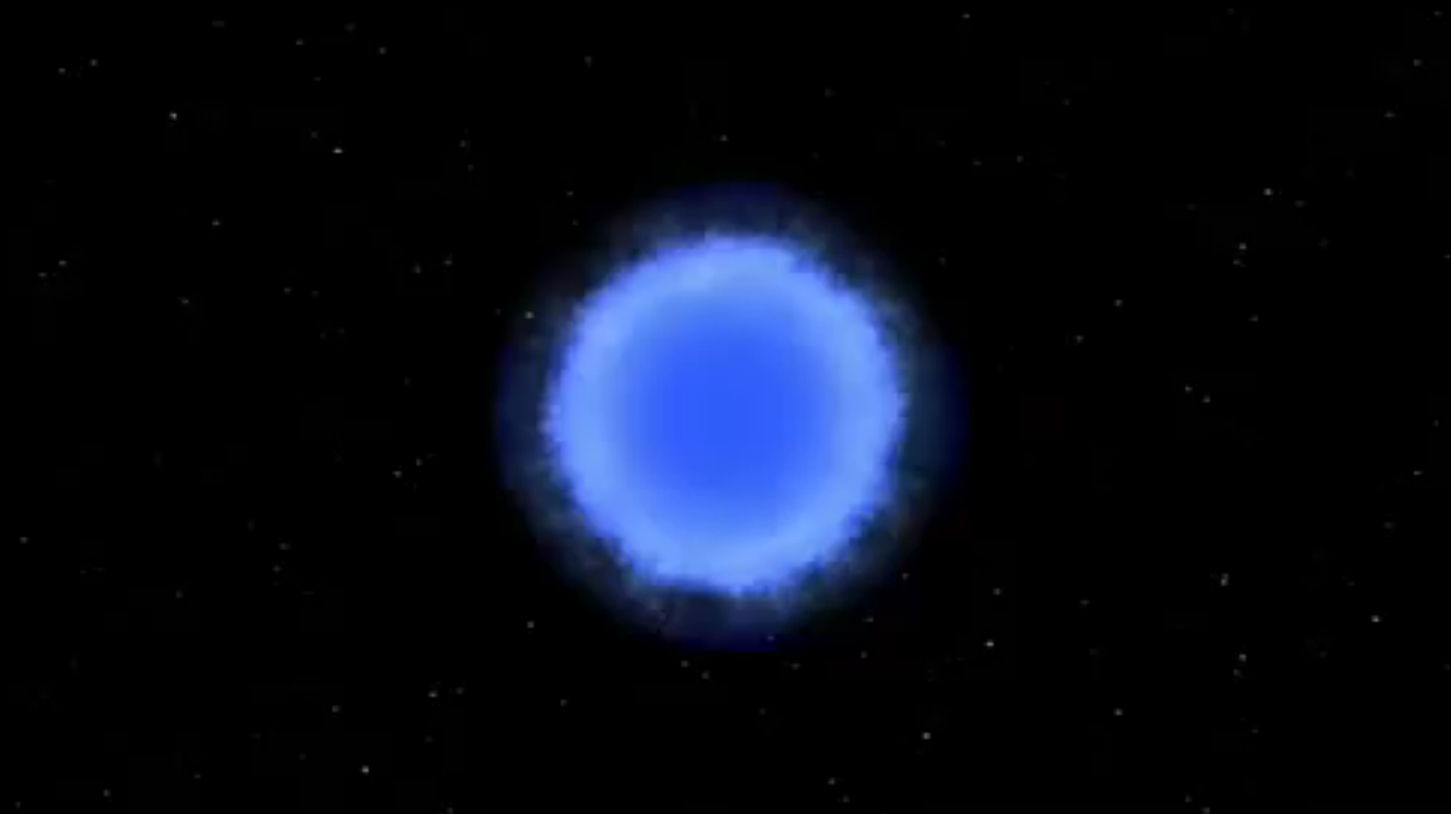
10^{14}-10^{15} G: Magnetars overtake this limit…





Unique places to study the physics of plasma embedded in very high magnetic and gravitational fields

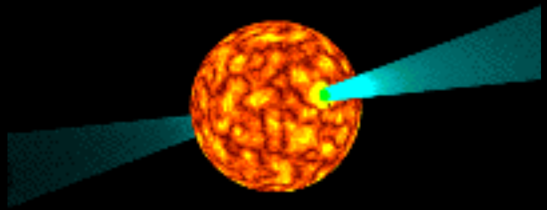
Neutron star formation & Magnetars

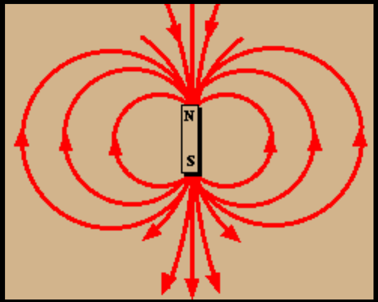


Magnetars are neutron stars with the highest magnetic fields

Those huge fields are believed to form either via alpha-dynamo soon after birth or as fossil fields from a very magnetic progenitor

How do we measure neutron stars’ magnetic fields

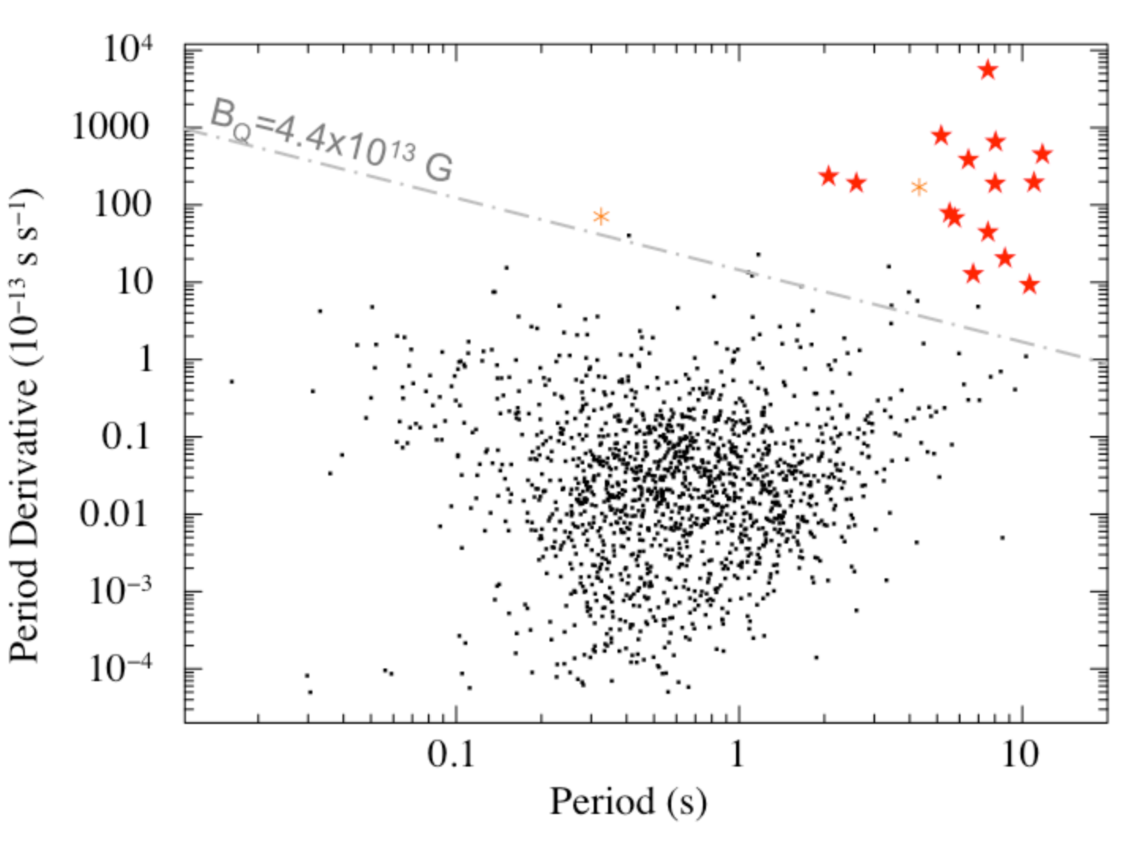




$$\dot{E}_{rot} = -\frac{2}{3c^3}|\ddot{m}|^2 = -\frac{2B^2R^6\Omega^4\sin^2\alpha}{3c^3}$$

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

Isolated Neutron Stars: P-Pdot diagram



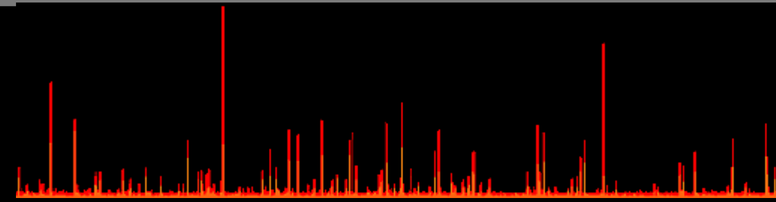
$$P\dot{P} = \left(\frac{8\pi^2 R_{ns}^{\;6}}{3c^3 I}\right) B_0^{\;2} \sin^2\alpha$$

$$B_{critic} = \frac{m_e^2 c^3}{e\hbar} = 4.414 \times 10^{13}\, Gauss$$

Critical Electron Quantum B-field

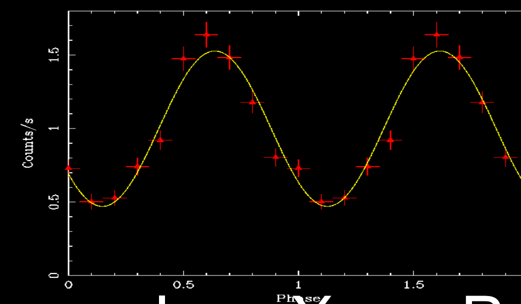
How magnetars were/are discovered

Short x/gamma-ray bursts (initially though to be GRBs)



Soft Gamma Repeaters

Bright X-ray pulsars with 0.5-10keV spectra modelled by a thermal plus a non-thermal component



Anomalous X-ray Pulsars

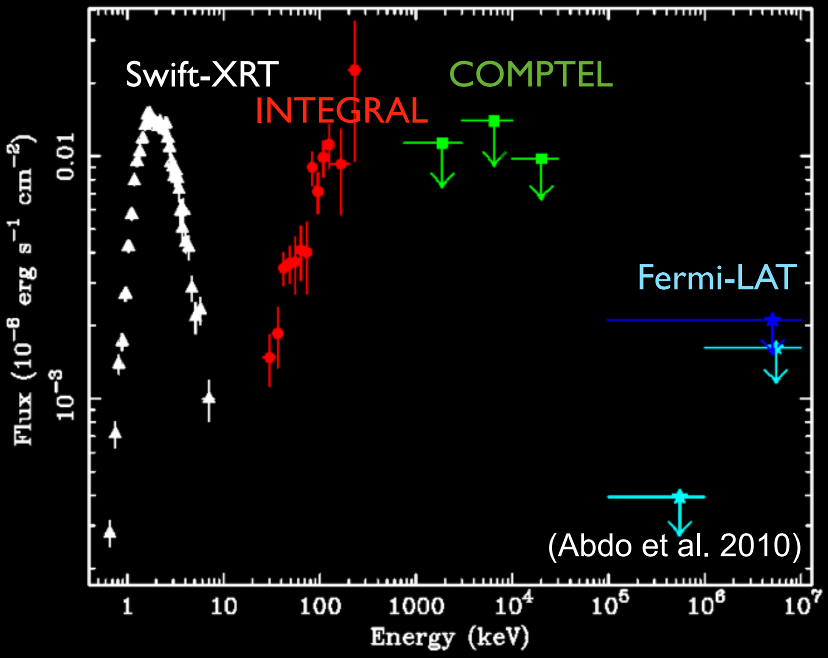
Bright X-ray transients!

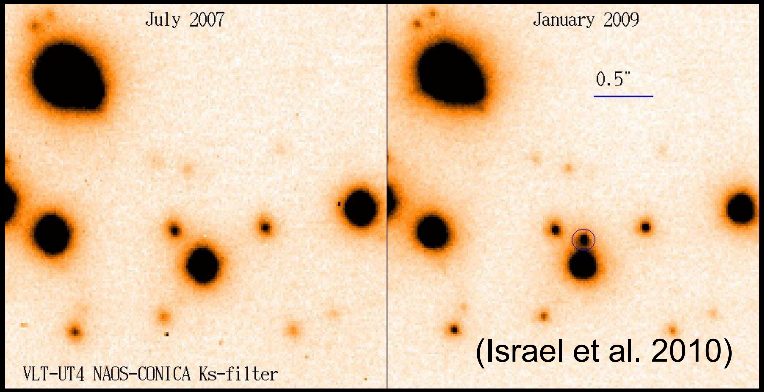
Transients

No more distinction between Anomalous X-ray Pulsars, Soft Gamma Repeaters, and transient magnetars: all showing all kind of magnetars-like activity.

Magnetars general properties

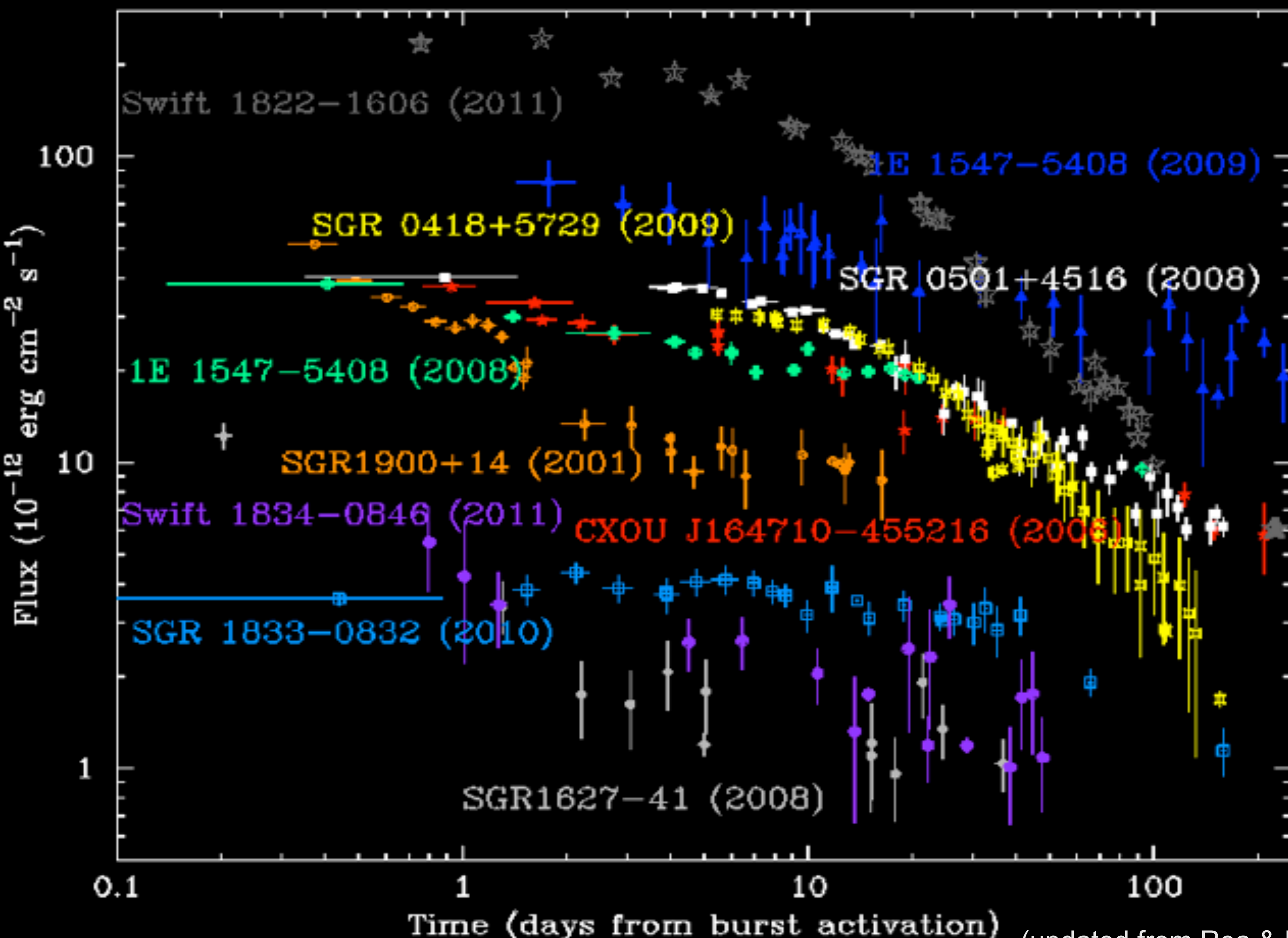
- bright X-ray pulsars Lx ~ 10^{33}-10^{36} erg/s
- strong soft and hard X-ray emission
- short (<1s) x/gamma-ray bursts
- pulsed fractions ranging from ~2-80 %
- rotating with periods of ~2-12s
- period derivatives of ~10^{-13}-10^{-11} s/s
- magnetic fields of ~10^{14}-10^{15} Gauss
- glitches and timing noise
- faint infrared/optical emission (K~20; sometimes pulsed and transient)





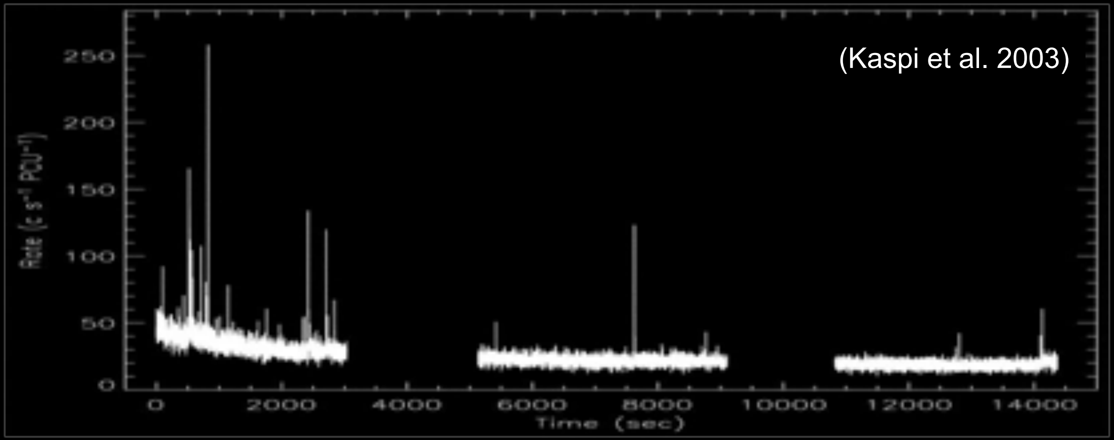
(see Woods & Thompson 2006, Mereghetti 2008, Rea & Esposito 2011 for a review)

Magnetar outbursts



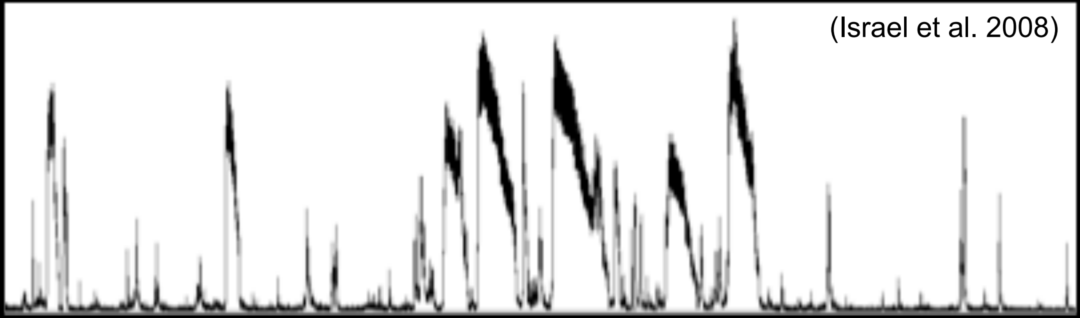
(updated from Rea & Esposito 2011)

Magnetar flares



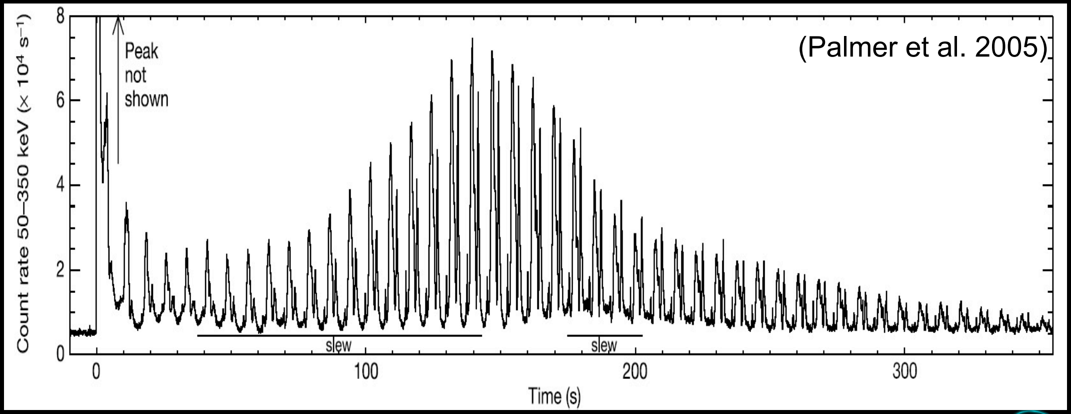
Short bursts

- the most common
- they last ~0.1s
- peak ~10^{41} ergs/s
- soft γ-rays thermal spectra



Intermediate bursts

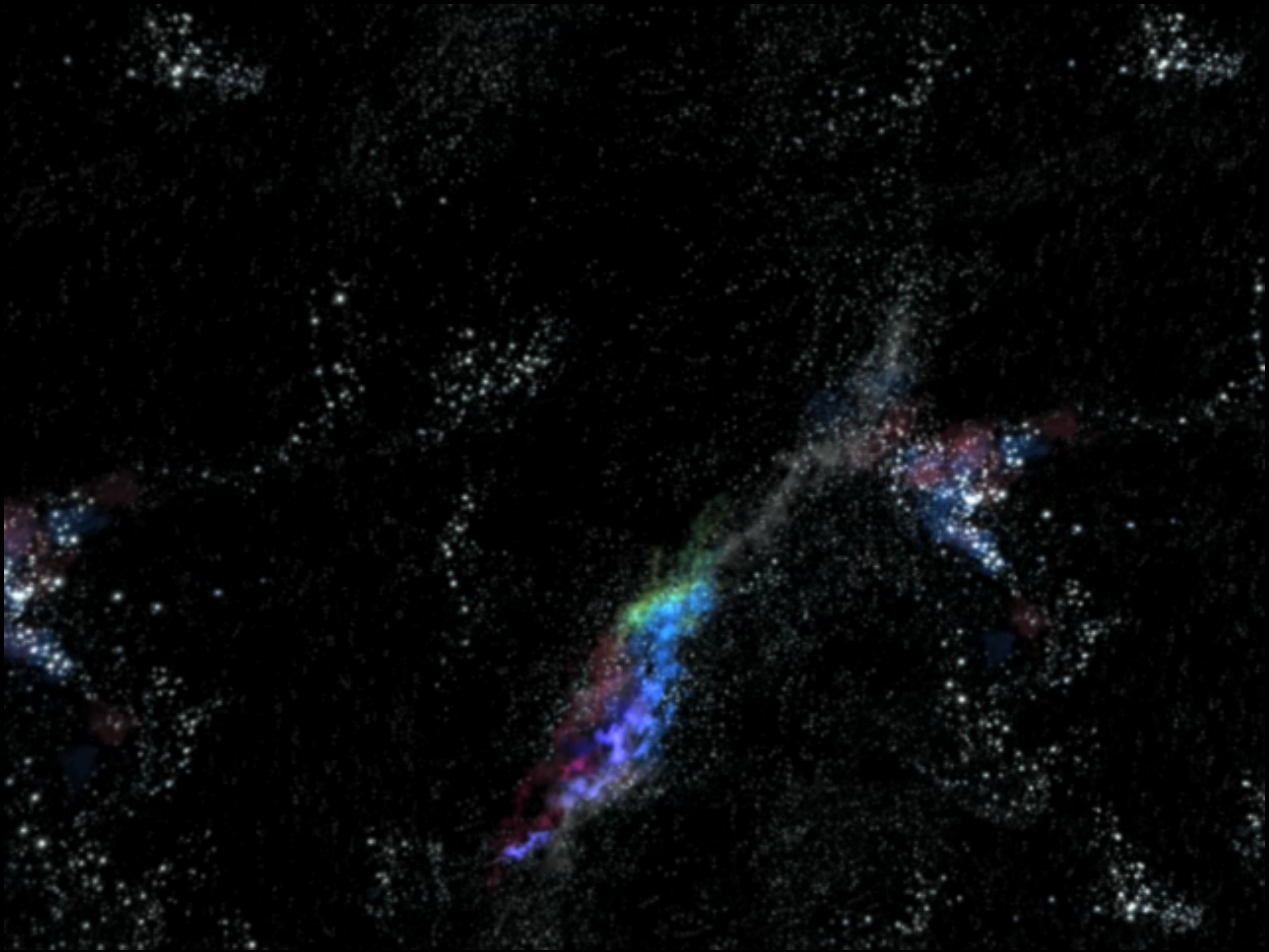
- they last 1-40 s
- peak ~10^{41}-10^{43} ergs/s
- abrupt on-set
- usually soft γ-rays thermal spectra



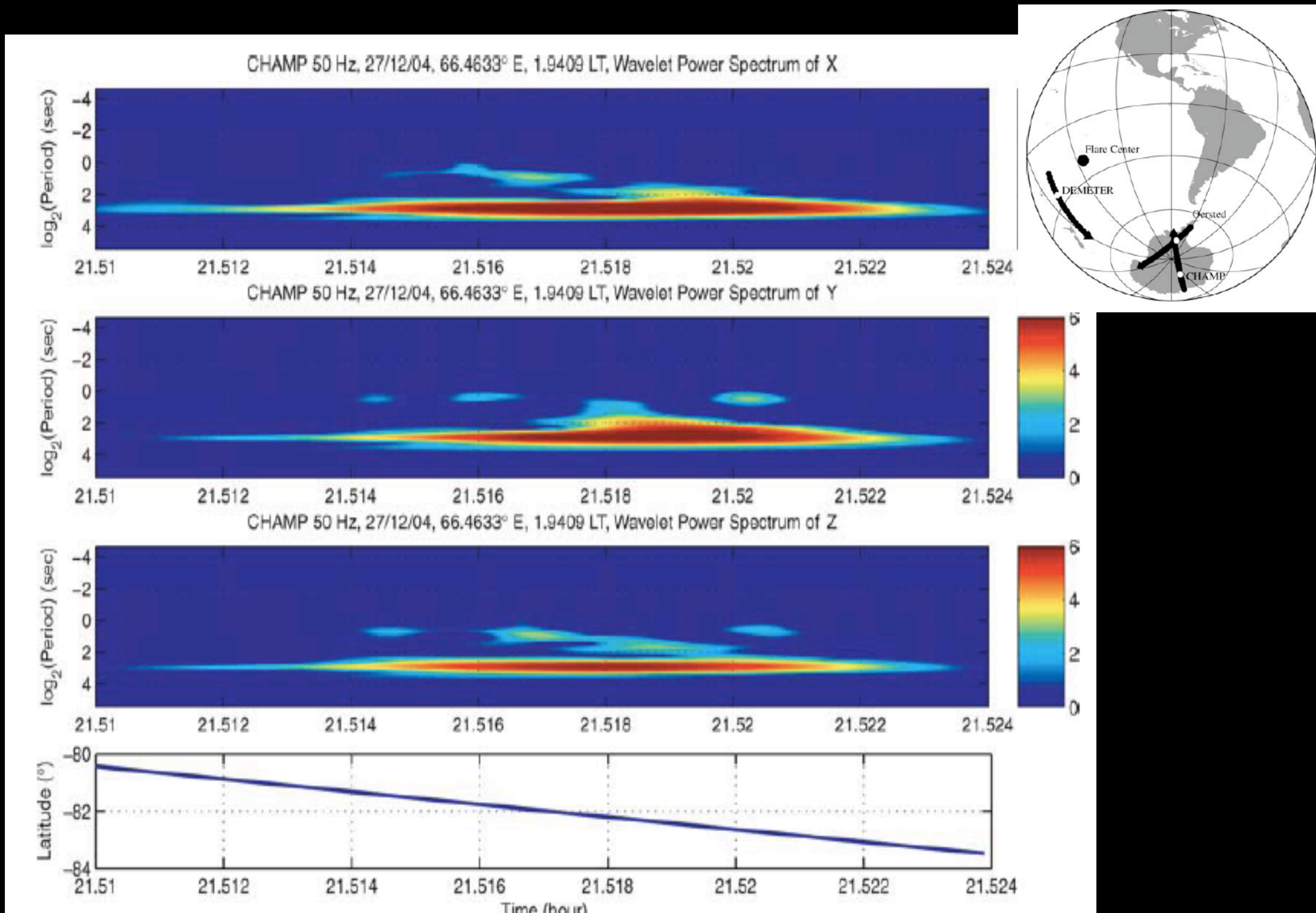
Giant Flares

- their output of high energy is exceeded only by blazars and GRBs
- peak energy > 3x10^{44} ergs/s
- <1 s initial peak with a hard spectrum which rapidly become softer in the burst tail that can last > 500s, showing the NS spin pulsations.

The Earth responding to magnetar flares

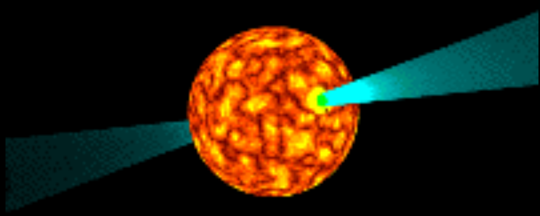


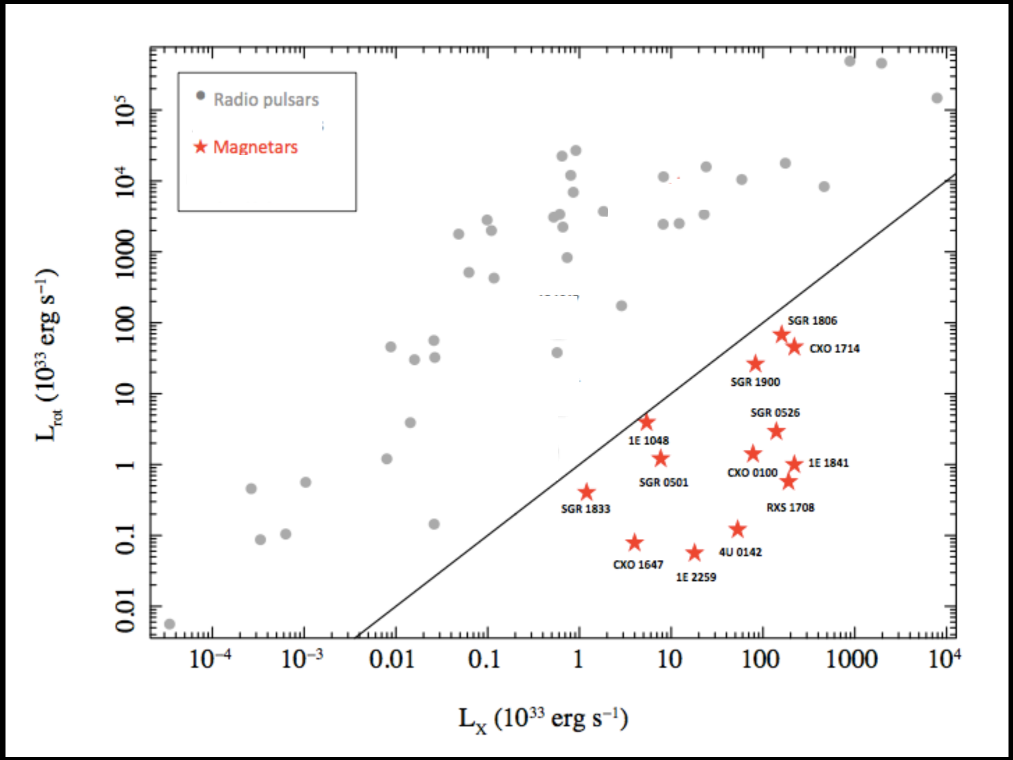
The Earth responding to magnetar flares



(Mandea & Balasis 2006, Geophysical Journal)

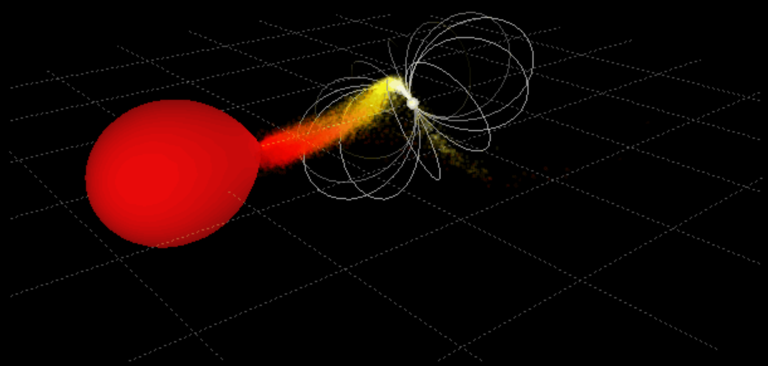
Can they be rotational powered as normal pulsars?

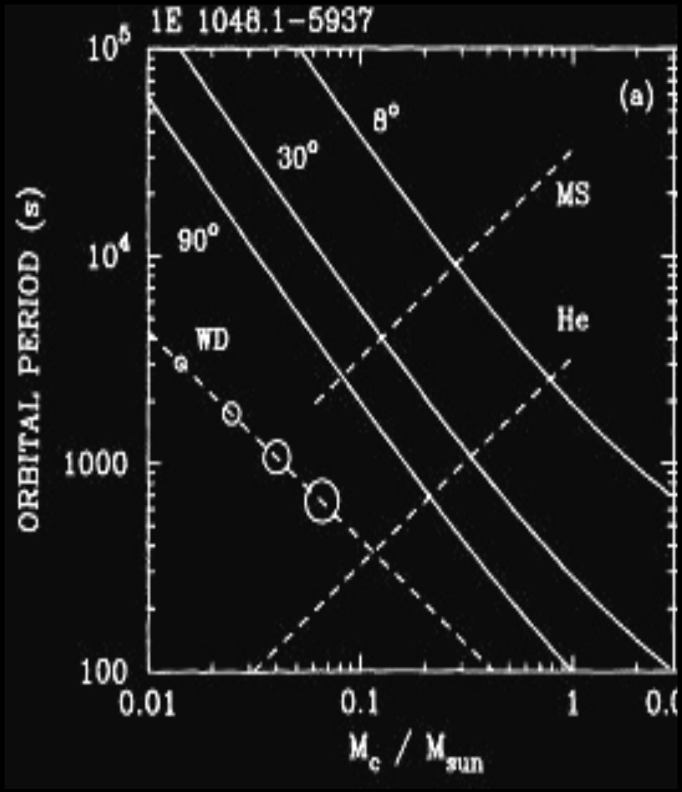




NO. X-ray emission overtaking their rotational budget.

Can they be accretion powered by a low-mass companion star?

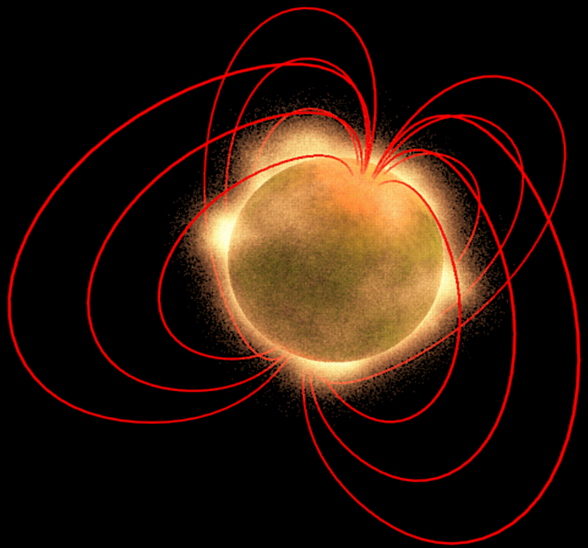




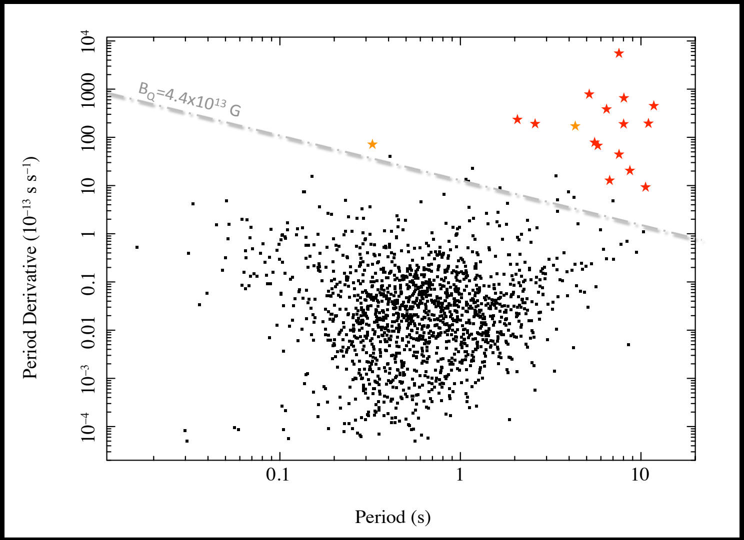
(Mereghetti, Israel & Stella 1998)

NO. Very stringent limits on possible companions.

Why magnetars?

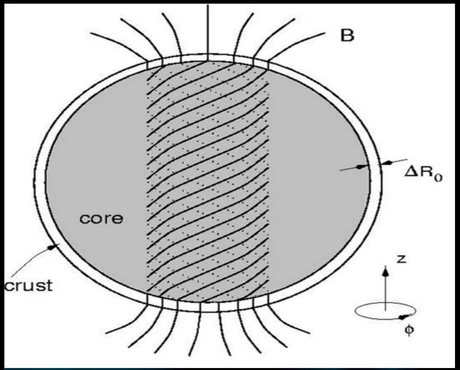


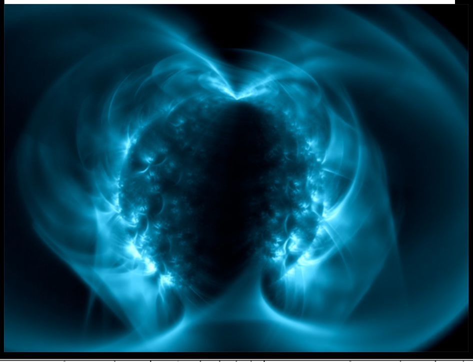
Another energy resevoir
was needed



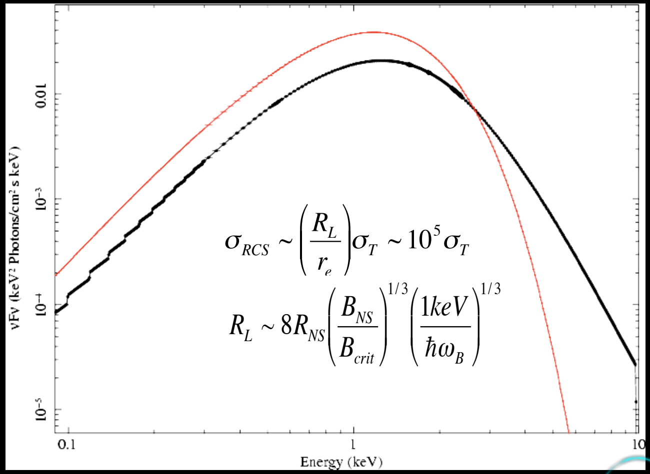
How magnetar persistent emission is believed to work?

(Thompson & Duncan 1992; 1993; 1995;1996)





- Magnetars differ from radio pulsars since their internal magnetic field is twisted up to 10 times the external dipole one.
- 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.

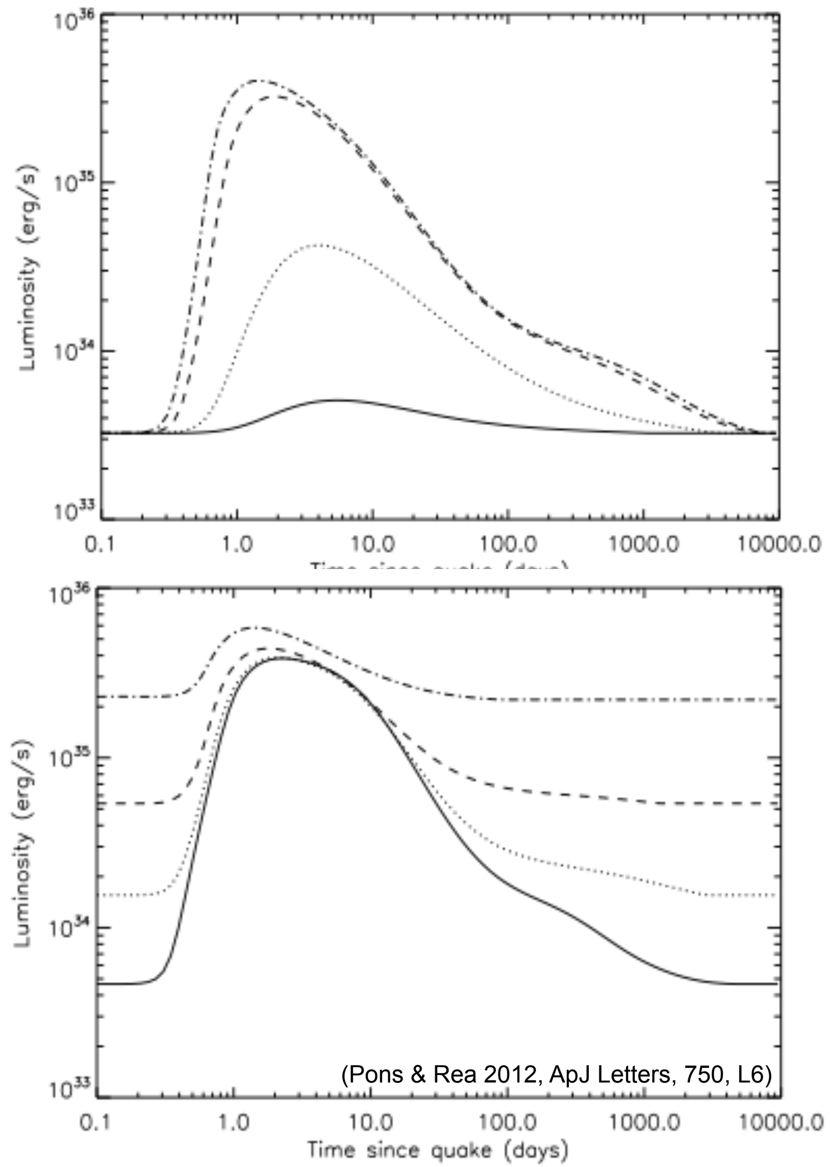


(Thompson, Lyutikov & Kulkarni 2002; Fernandez & Thompson 2008; Nobili, Turolla & Zane 2008a,b; Rea et al. 2008, Zane et al. 2009)

How magnetar outbursts and flares are believed to work?

- The twisted magnetic geometry of a magnetar, at intervals, it can twist up, and stresses build up in the neutron star crust causing glitches, flares, and all sort of instabilities.

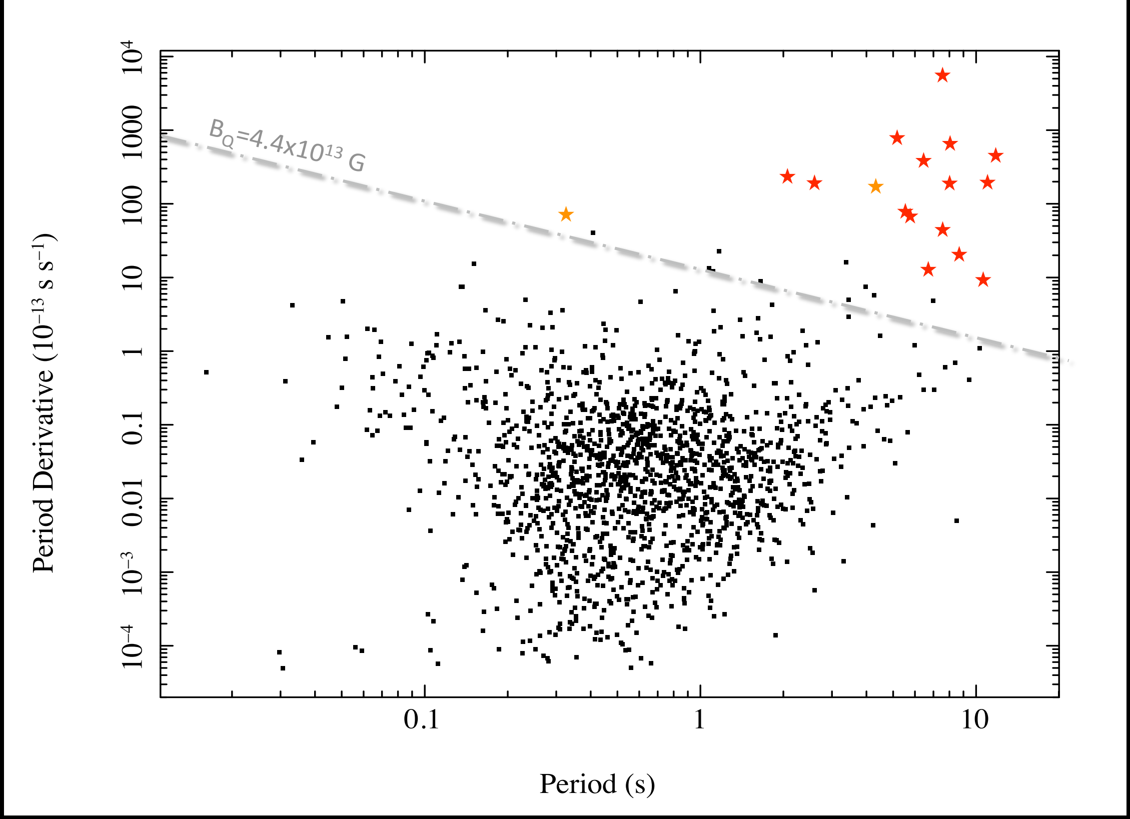
(Thompson, Lyutikov & Kulkarni 2002, ApJ 574, 332)



What we believed until recently...

1. A magnetar has necessarily a high dipole field !

2. Normal pulsars and magnetars are two distinct classes of neutron stars



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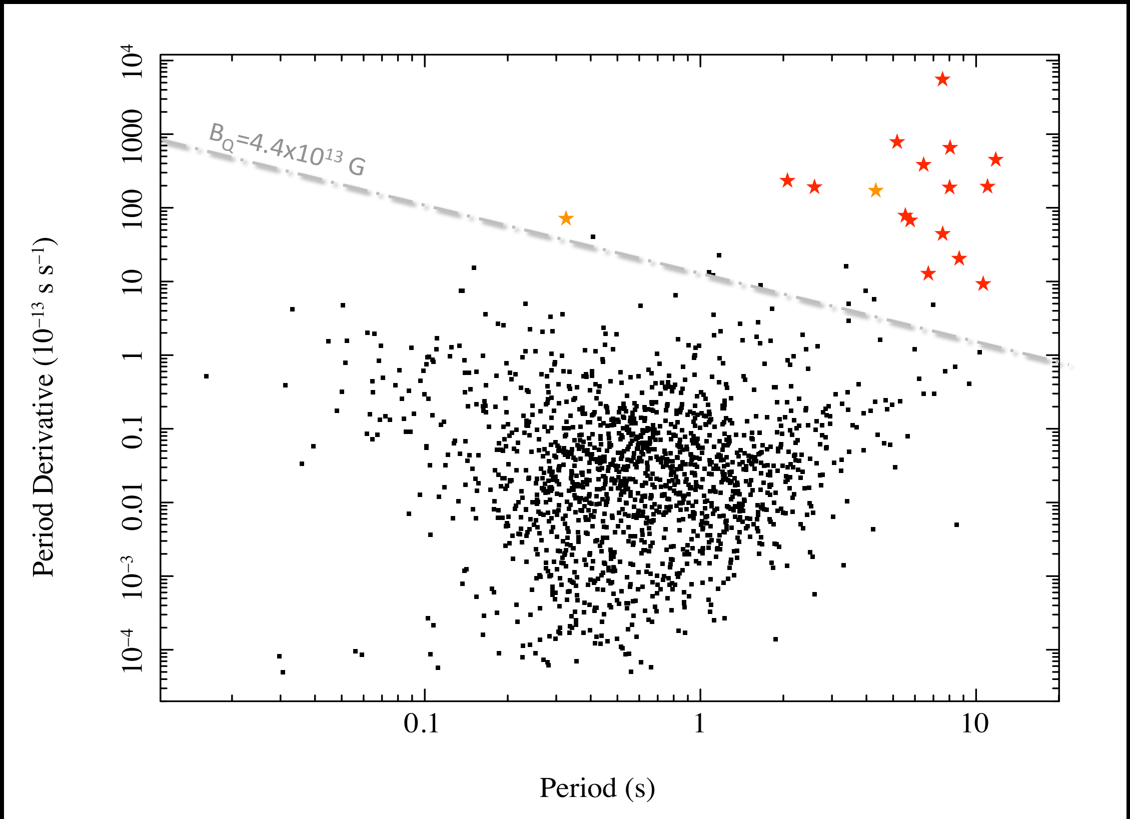
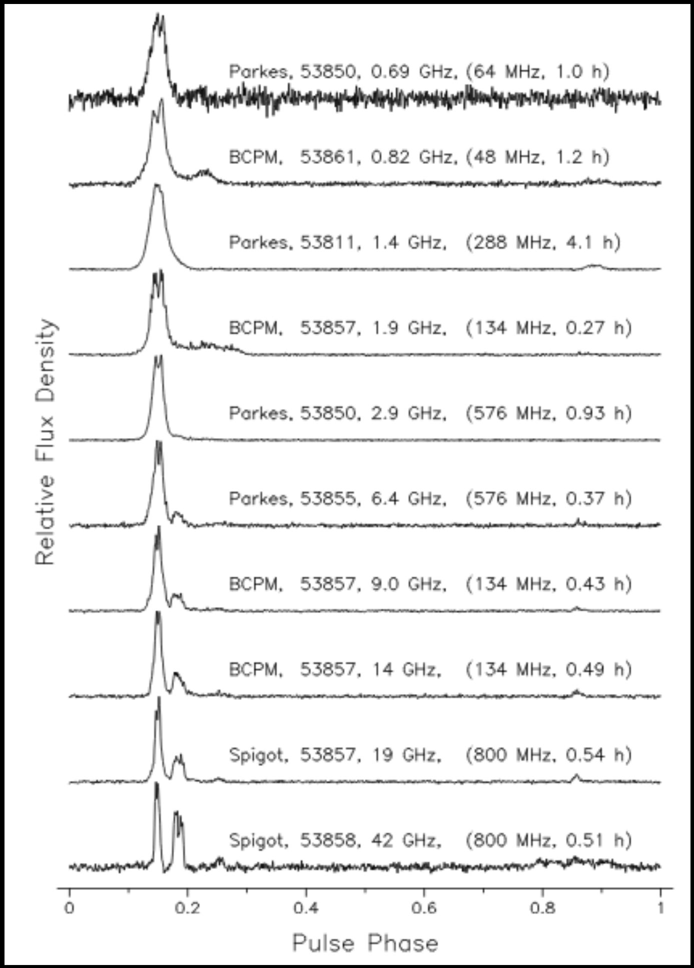
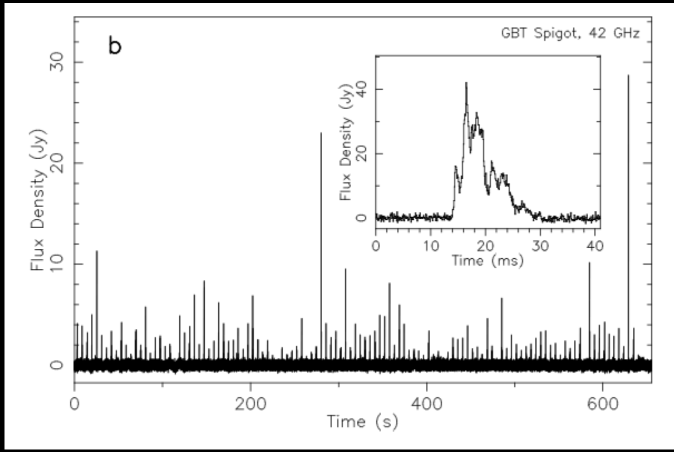


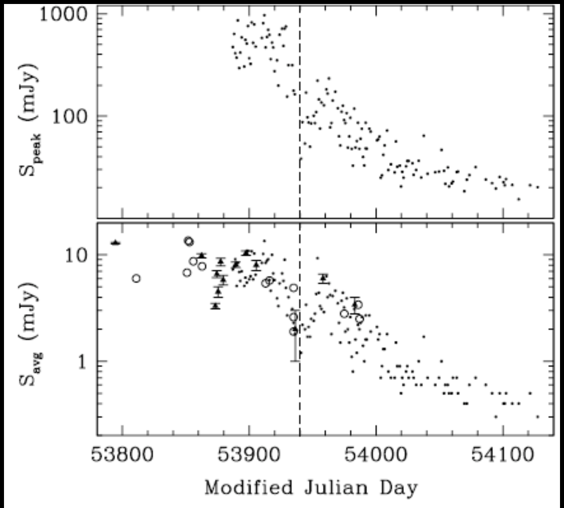
These turned out not to be totally true….

1. Magnetars can be radio pulsar during outbursts

XTE 1810-197:showed radio pulsed emission during its outburst... the discovery of two other “radio-pulsar” magnetars followed soon...

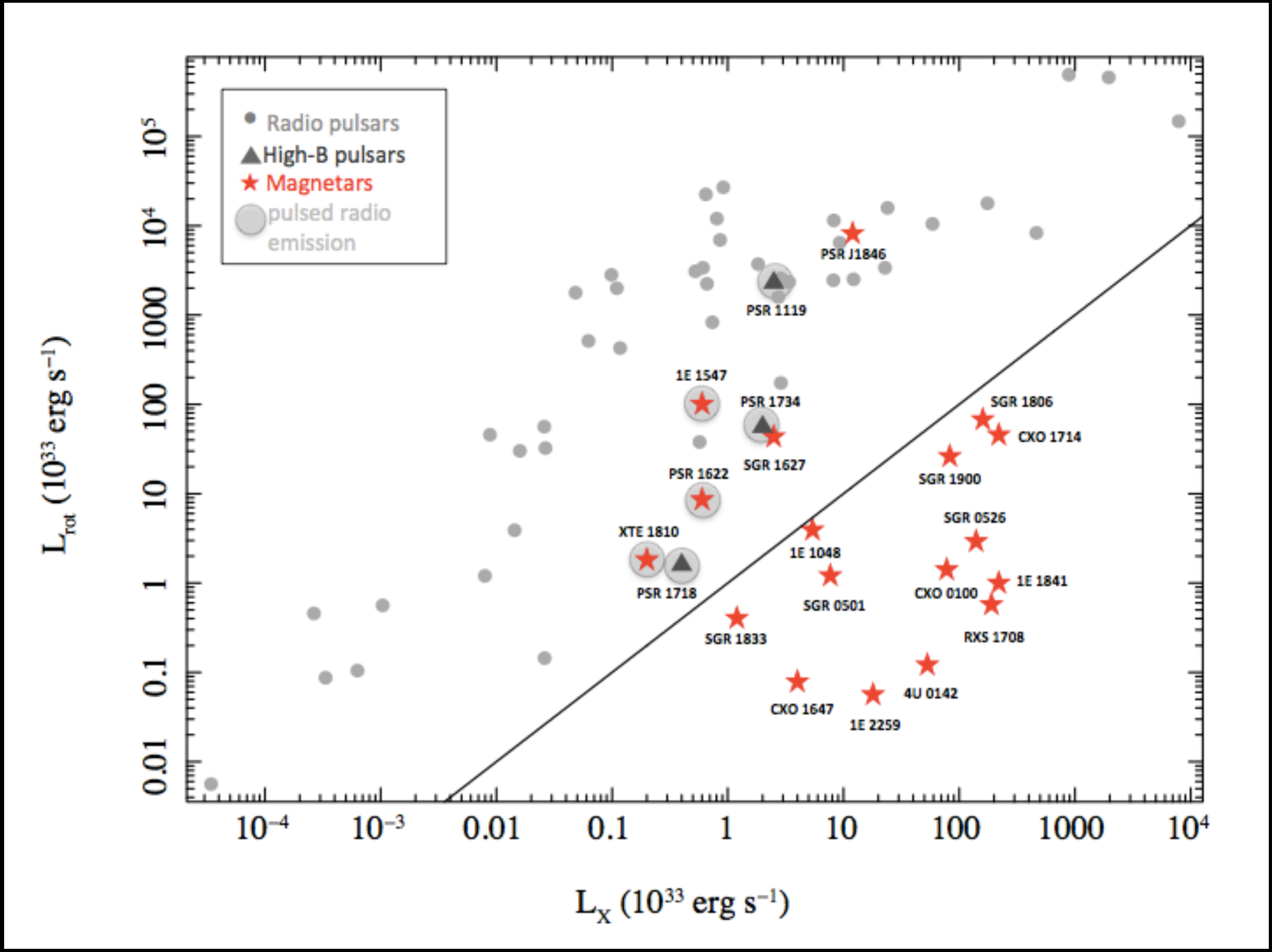






(Camilo et al. 2006, Nature 442, 892; Camilo et al. 2007, ApJ 666, L93; Levin et al. 2010, ApJ 721, L33)

2. A continuum between rotational and magnetic power...

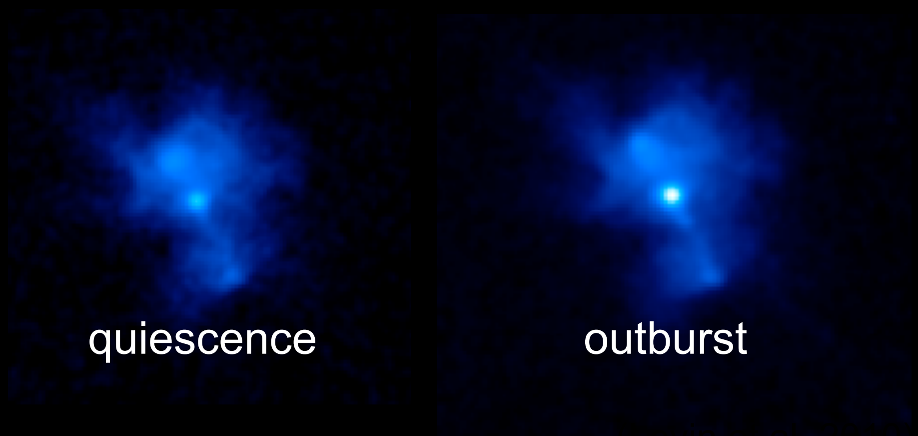


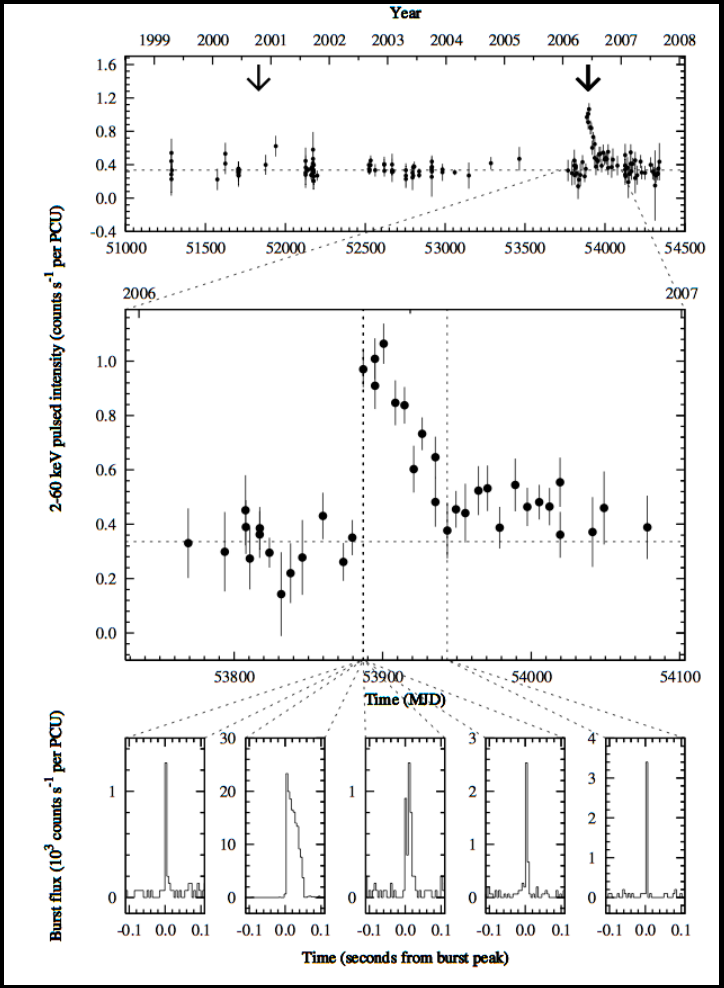
(Rea et al. 2012, ApJ Letters, 748, L12, and highlighted in *Science* as Editors' choice)

3. A “normal” X-ray pulsar showed magnetar activity...

PSR1846-0258: an energetic allegedly rotation-powered pulsar (with a high-B though...) showed SGR-like bursts

- P = 0.3 s
- B = 5×10^{13} Gauss
- $L_{spin\text{-}down}$ = $200L_X \sim 8\times10^{36}$ erg/s

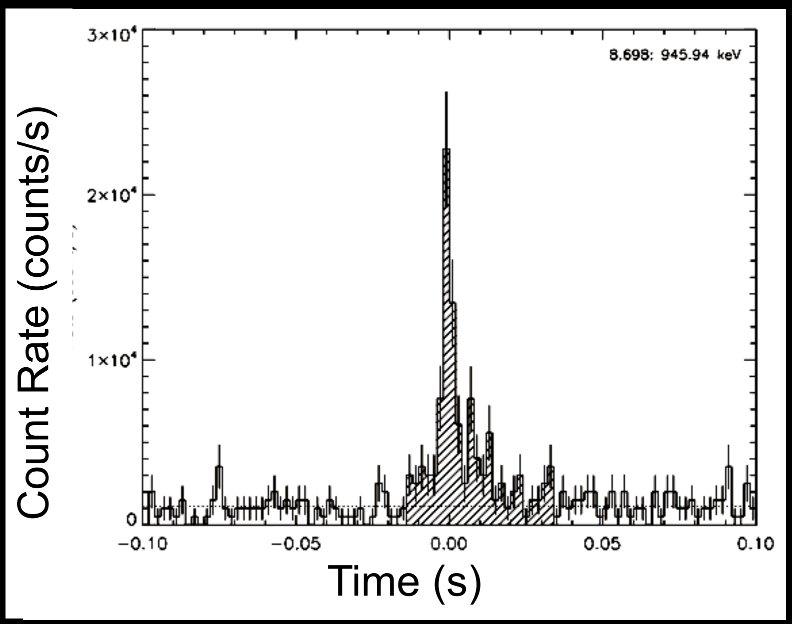




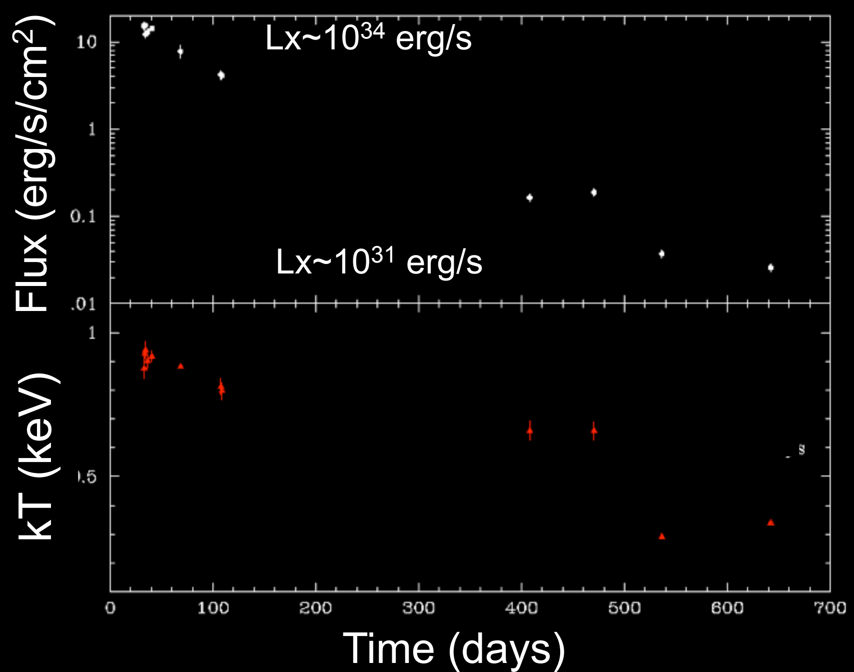
(Gavriil et al. 2008, Science, 319, 1802; Kumar & Safi-Harb, ApJ 678, L43)

4. A magnetar was discovered having a low B-field...

SGR 0418+5729: discovered as a typical transient magnetar...



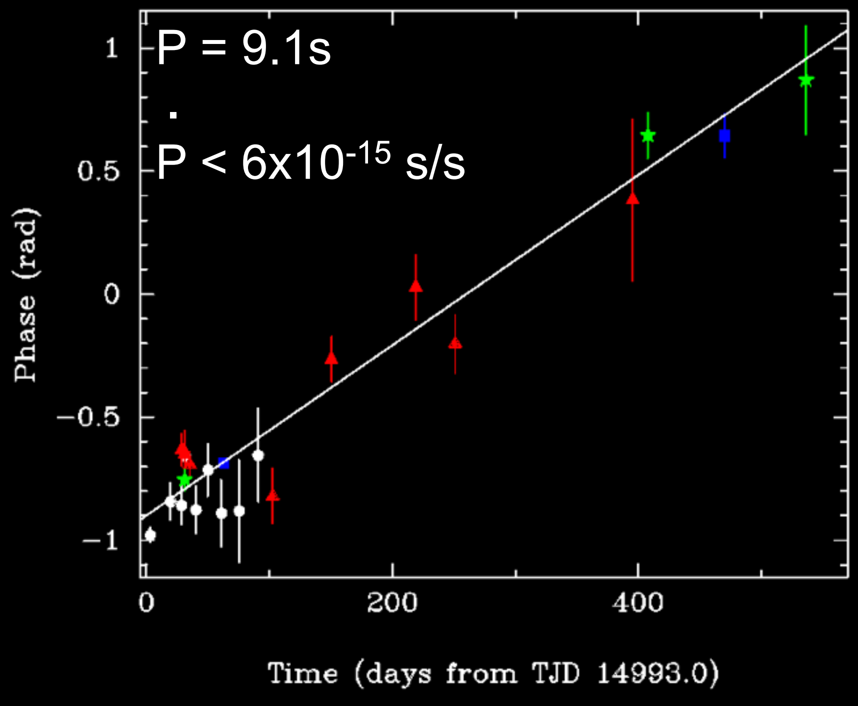
(van der Horst et al. 2010, ApJ 711, L1)



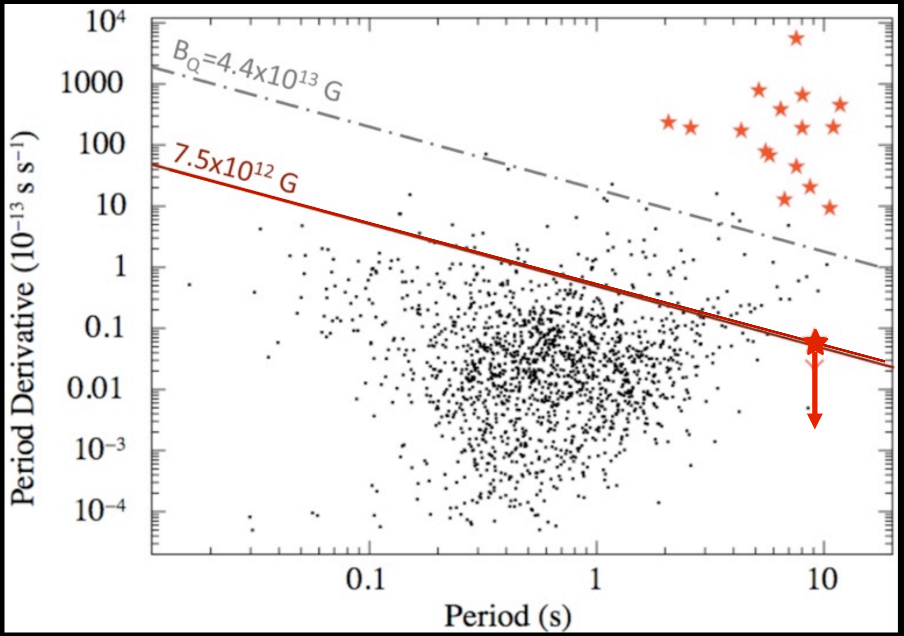
(Esposito et al. 2010, MNRAS 405, 1787;
Rea et al. 2010, Science, 330, 944)

4. A magnetar was discovered having a low B-field...

SGR 0418+5729: but having a low magnetic field!

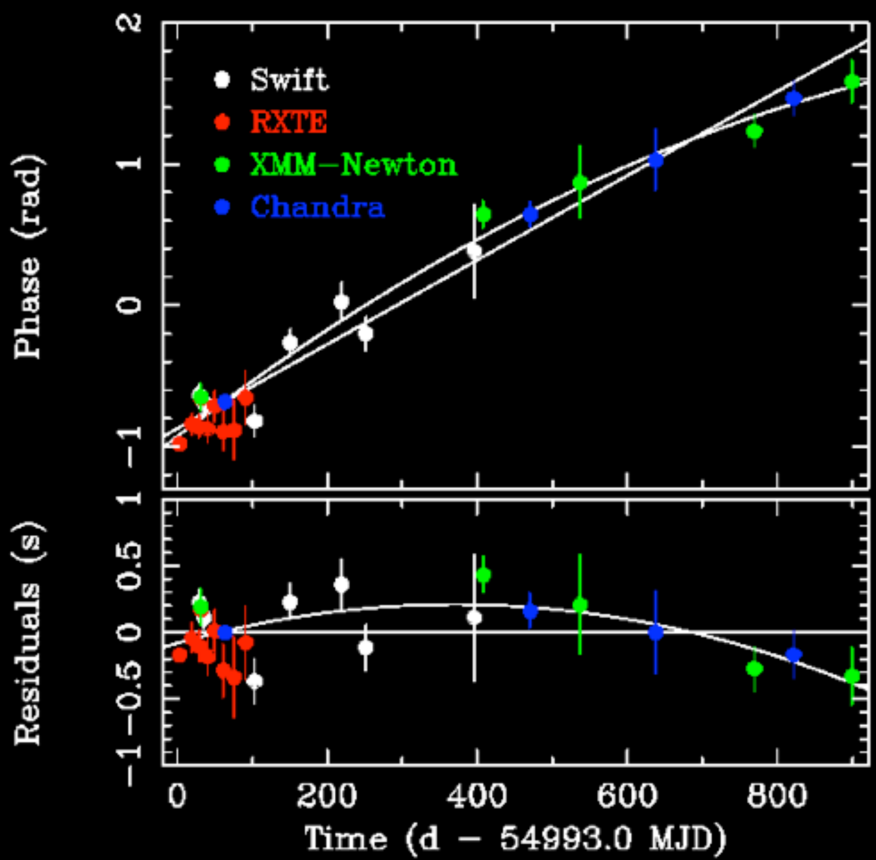


Magnetic field was:
$B < 7.5x10^{12}$ G

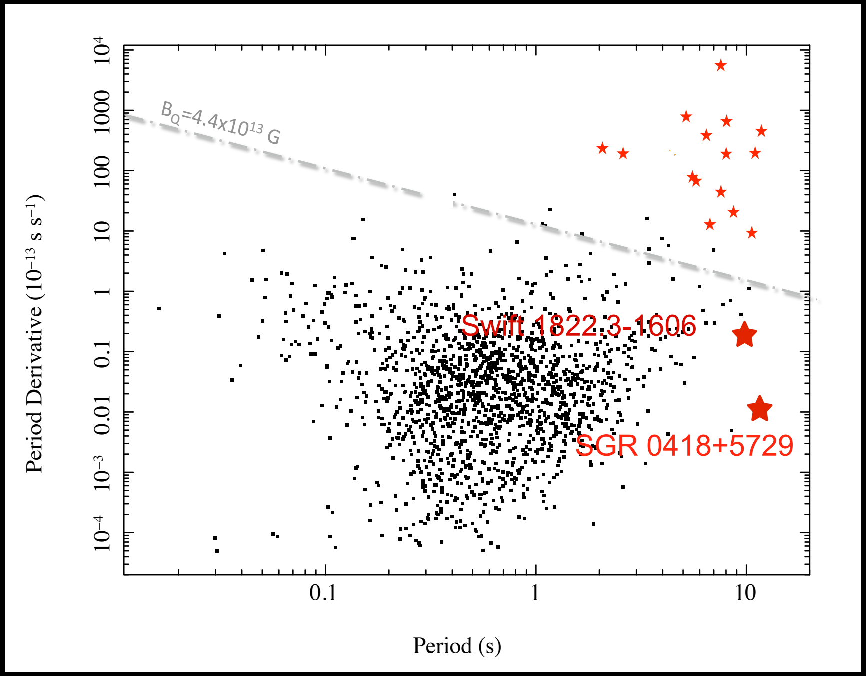


(Rea et al. 2010, Science, 330, 944)

...now we have a possible B-field measurement for SGR 0418+5729, and a new low-B magnetar (Swift 1822.3-1606)! (Rea et al. 2012, ApJ, 754, 26; see also Sholtz et al. 2012)



SGR 0418+5729 magnetic field is: B ~7x10^{12} G (still preliminary!! 3.5sigma)

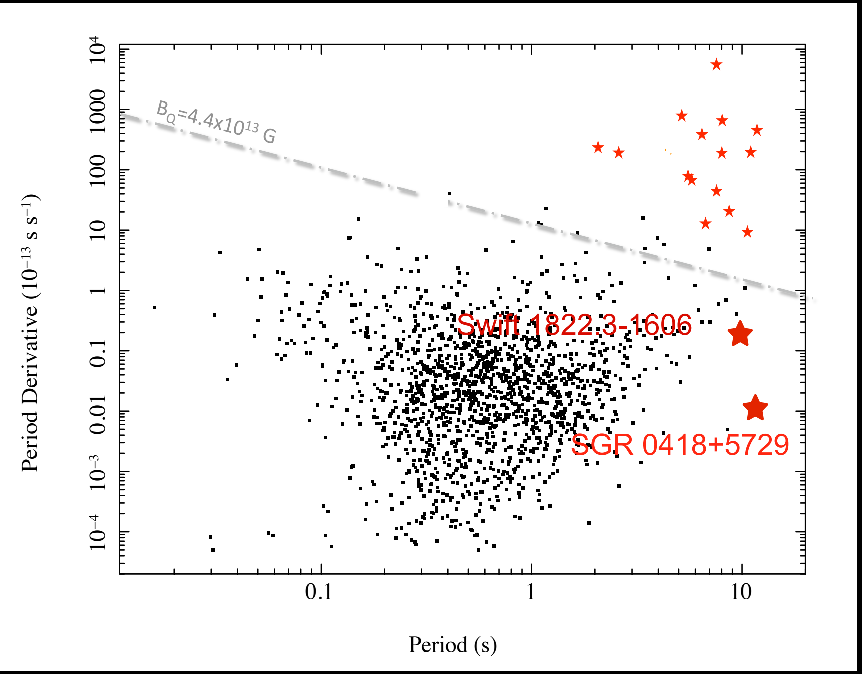


(Rea et al. 2012, in prep)

Is this still compatible with the magnetar model?

Yes!

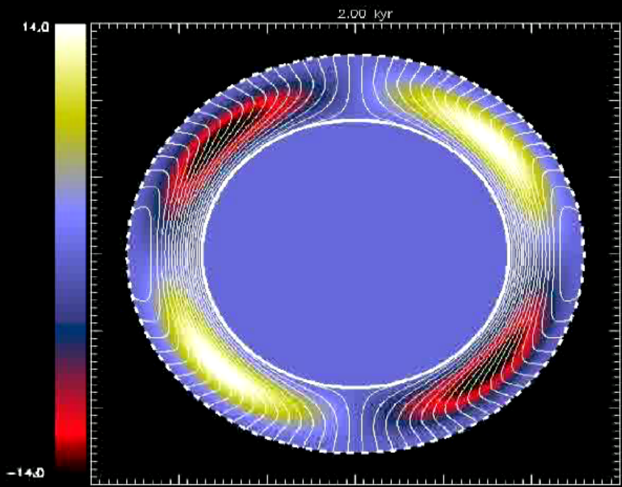
Assuming that the crustal toroidal component of the B-field can be >100 times larger than the dipolar B-field we are measuring.



Magnetars can be then hidden inside many apparently quiet pulsars!

(Turolla et al. 2012, ApJ 740, 105; Rea et al. 2012 ,in prep)

Which can be the low-B magneto-thermal evolution?

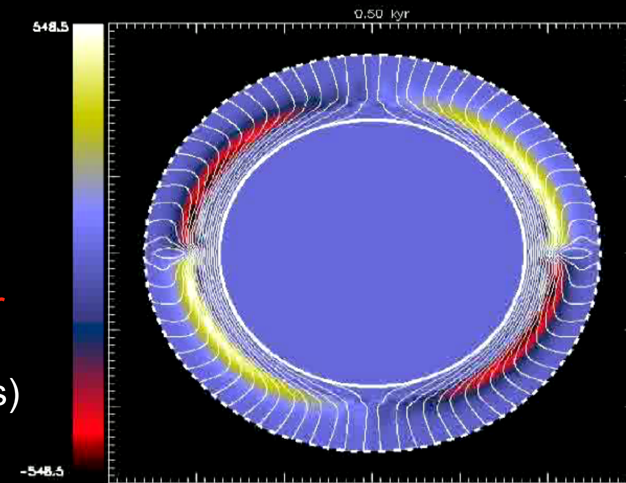


Normal Pulsar

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)

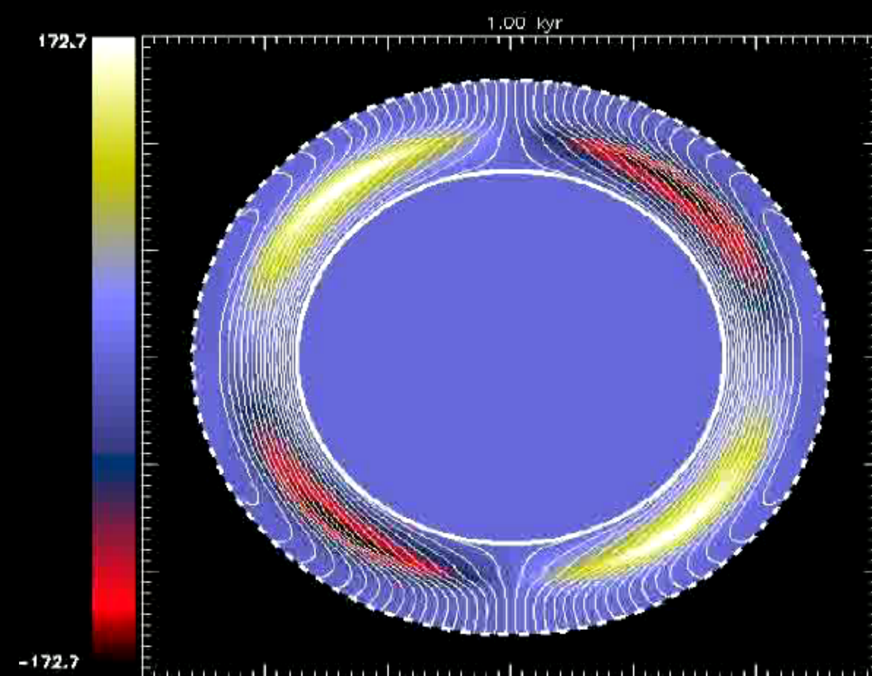
B_{int}~ 10^{16} G (colors)

Old Weak Magnetar

Initial conditions:

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

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



Simulations: Courtesy of Jose' Pons

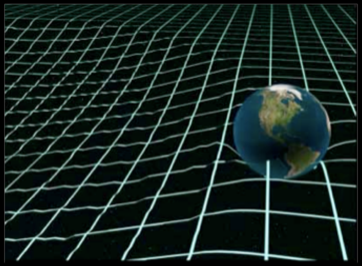
Which are the broader consequences of these discoveries?

** SN explosions

A large number of strong-B neutron stars call for a key ingredient of the NS formation model: an extreme internal B should then be a common place rather than an exception

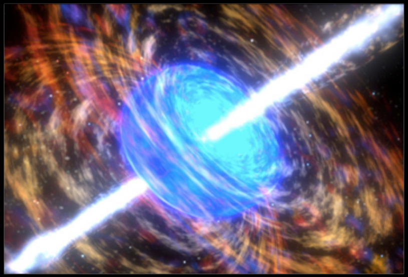
** GW radiation from newly born magnetars

The GW background radiation produced by the formation of highly magnetic neutron stars is probably underestimated given the recent results.



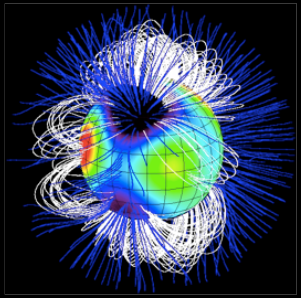
** Gamma-ray bursts

If a large fraction of the formed neutron stars have a strong B-field, hence GRBs due to the formation of such stars are way more frequent than predicted.

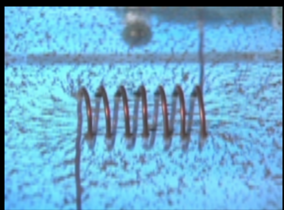


** Massive Stars

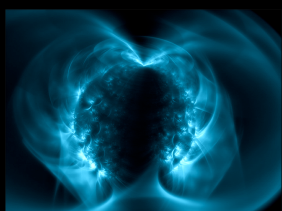
If strong-B neutron stars are formed by the explosion of highly magnetic stars, there should be many more of such stars than predicted thus far



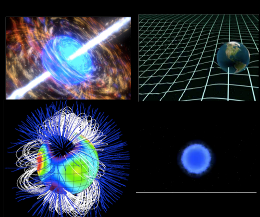
Conclusions



Magnetars are intriguing objects, and unique laboratories to test our knowledge on the physics of matter under extreme gravitational and magnetic fields.



We finally understood that behind the powerful magnetar emission there is not just a magnetic strength, but there are other important parameters: i.e. field geometry and evolution.



Many normal pulsars might be hiding a magnetar inside, hence magnetars might be the "typical" neutron stars rather than an exception, with all the due consequences.

General approach…

Count the white shirt passes...

Credit: 1999 Daniel J. Simon & Christopher Chabris

The field is rapidly evolving, and we are now in the right moment to finally catch the big picture. Stay tuned!