Systematic study of magnetar outbursts

Francesco Coti Zelati

Institute for Space Sciences, CSIC-IEEC, Barcelona

In collaboration with

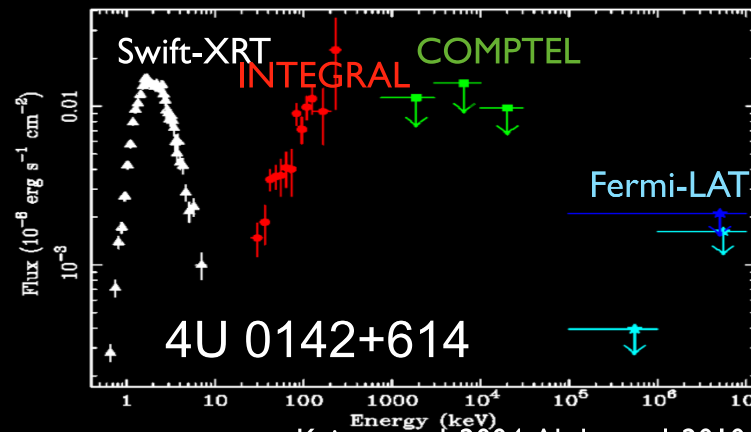
N. Rea (CSIC-IEEC, U. Amsterdam), **_J. A. Pons_** (U. Alicante),
S. Campana (INAF-OAB), **_P. Esposito_** (U. Amsterdam)

Coti Zelati et al., submitted

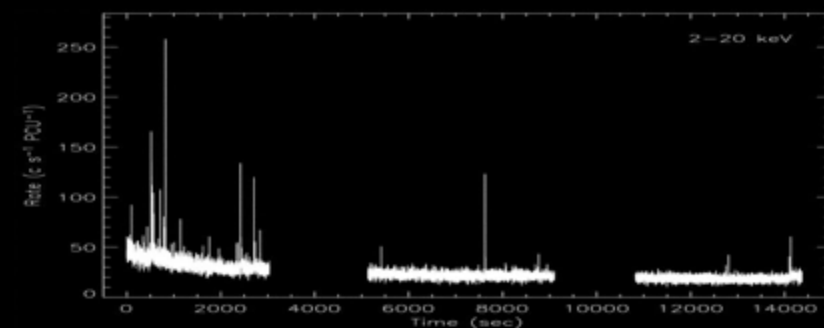
Physics of Neutron Stars – 2017, Ioffe Institute, Saint Petersburg, July 10, 2017

Observational properties

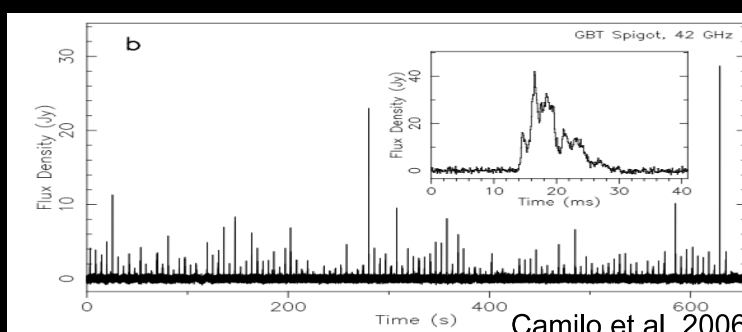
- About 25 X-ray pulsars with $L_x \sim 10^{33} - 10^{36}$ erg s^{-1}
- X-ray luminosity generally larger than the rotational energy loss rate
- soft and hard X-ray emission (0.5-200 keV); thermal + PL spectrum
- rotating with $P \sim 2 - 12$ s
- magnetic fields of $\sim 10^{13} - 10^{15}$ Gauss
- flaring activity in soft gamma-rays ($0.01 - 10^2$ s; $L_x \sim 10^{39} - 10^{47}$ erg s^{-1})
- faint infrared/optical emission
- transient pulsed radio emission (in 4 cases)



Kuiper et al. 2004; Abdo et al. 2010



Kaspi et al. 2003



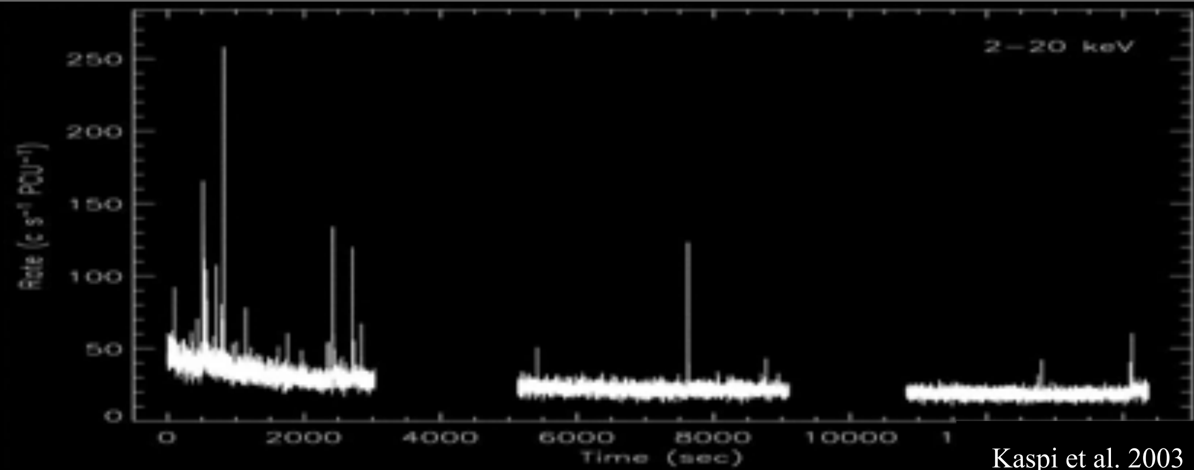
Camilo et al. 2006

see Rea & Esposito (2011); Turolla et al. (2015); Kaspi & Beloborodov (2017) for reviews

Magnetar flaring activity (timescale: seconds/minutes)

Short bursts

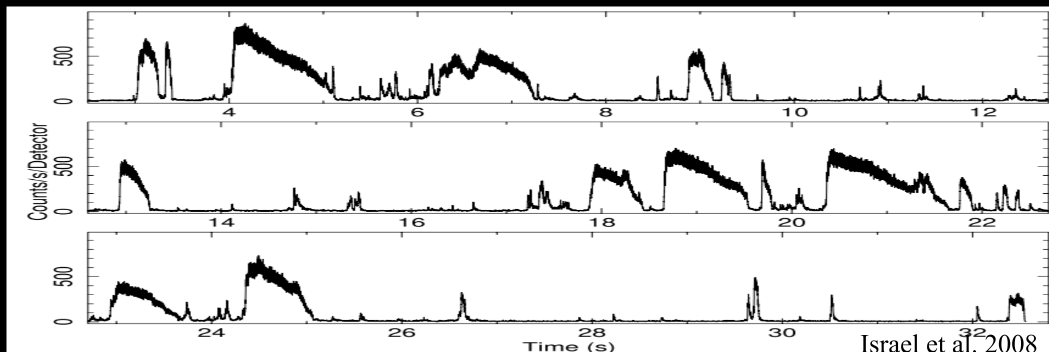
- duration ~0.01-1s
- $L_X \sim 10^{39}$-10^{41} erg s^{-1}
- soft γ-rays thermal spectra (kT ~ 30-40 keV)



Kaspi et al. 2003

Intermediate bursts

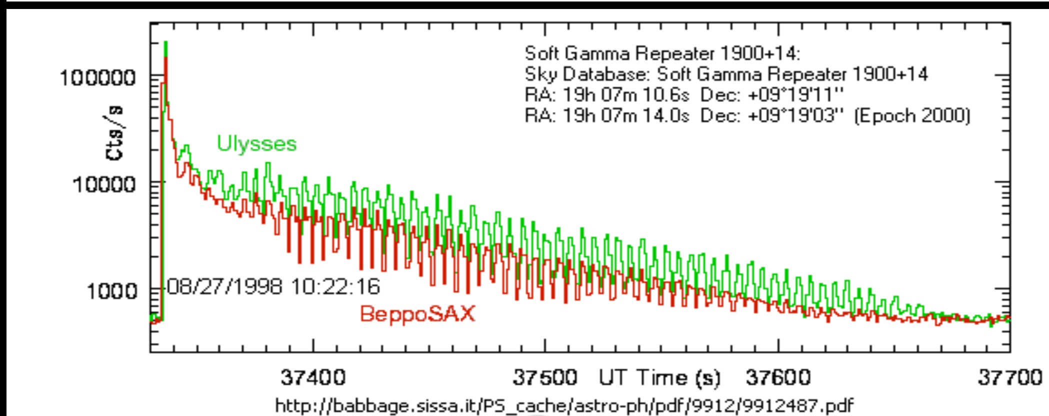
- duration 1-40 s
- peak ~10^{41}-10^{43} erg s^{-1}
- abrupt on-set
- usually soft γ-rays thermal spectra



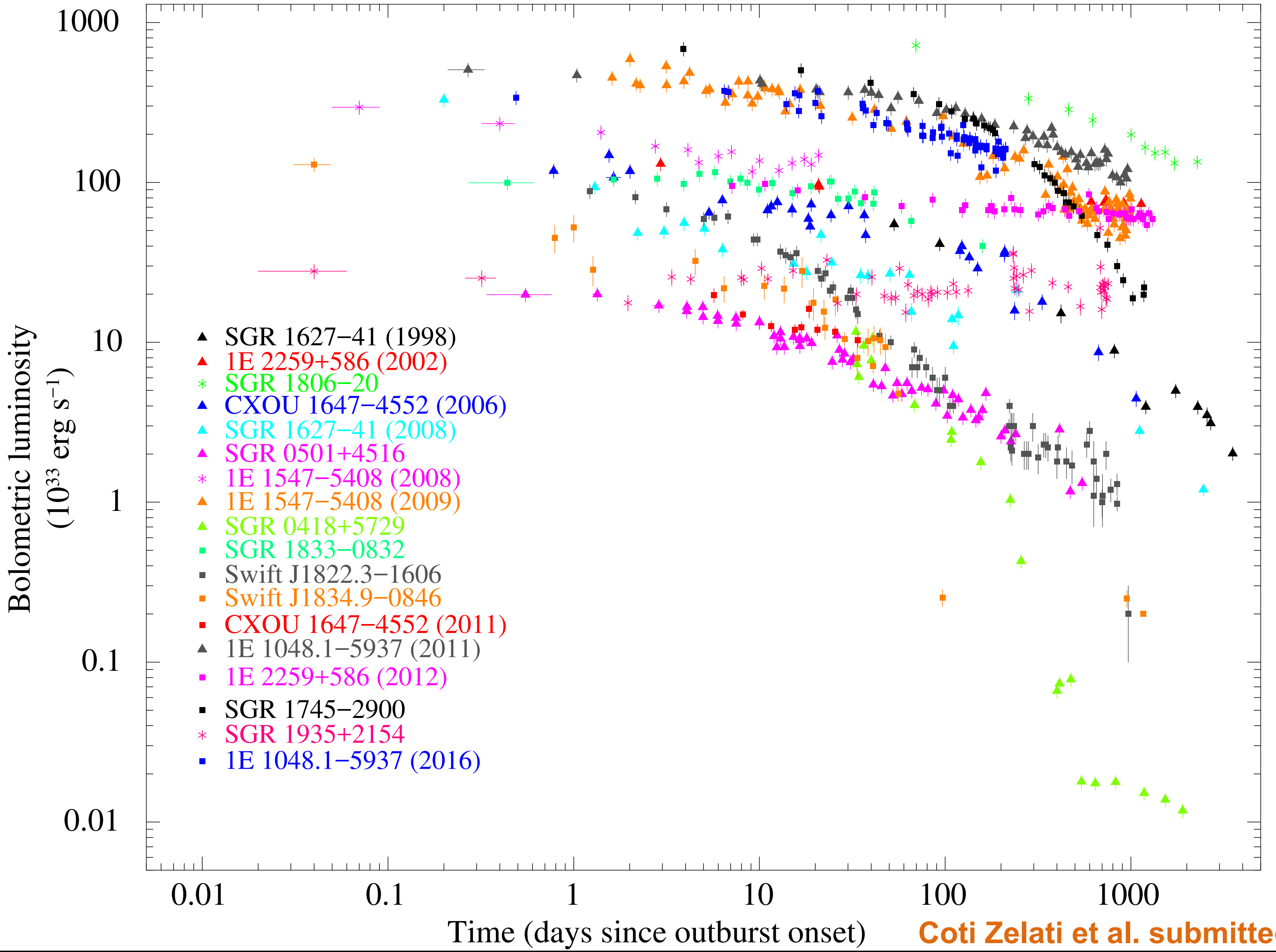
Israel et al. 2008

Giant Flares

- very rare events (only 3 observed)
- $L_X > 3\times10^{44}$ erg s^{-1}
- initial peak lasting <1 s with a hard spectrum
- ringing tail that can last > 500s, with softer spectrum and showing the NS spin pulsations



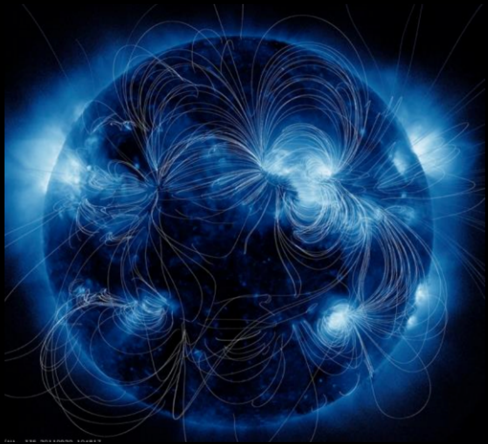
Magnetar outburst activity (timescale: months/years)



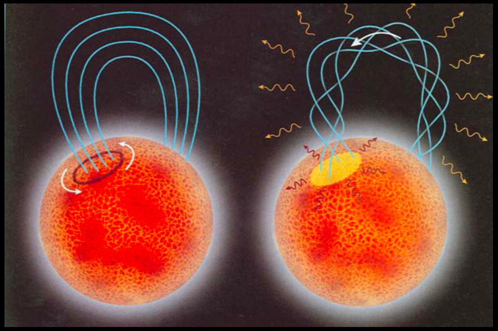
Coti Zelati et al. submitted

Outburst mechanisms

1. **Internal source of heat:** Local magnetic stresses deform part of the stellar crust. Plastic flows convert the magnetic energy into heat. Partly is conducted up to the surface and radiated (thermal afterglow)



2. **External source of heat:** Crustal displacements twist up the external B-field. Returning currents hit and heat the NS surface. The bundle dissipates as the energy supply from the star interior decreases.



Both processes are likely at work.
Emission can be sustained up to a few years.

Thompson et al. 2002; Beloborodov 2009; Pons & Rea 2012;
Parfrey et al. 2013; Beloborodov & Levin 2014 Beloborodov & Li 2016; Li et al. 2016

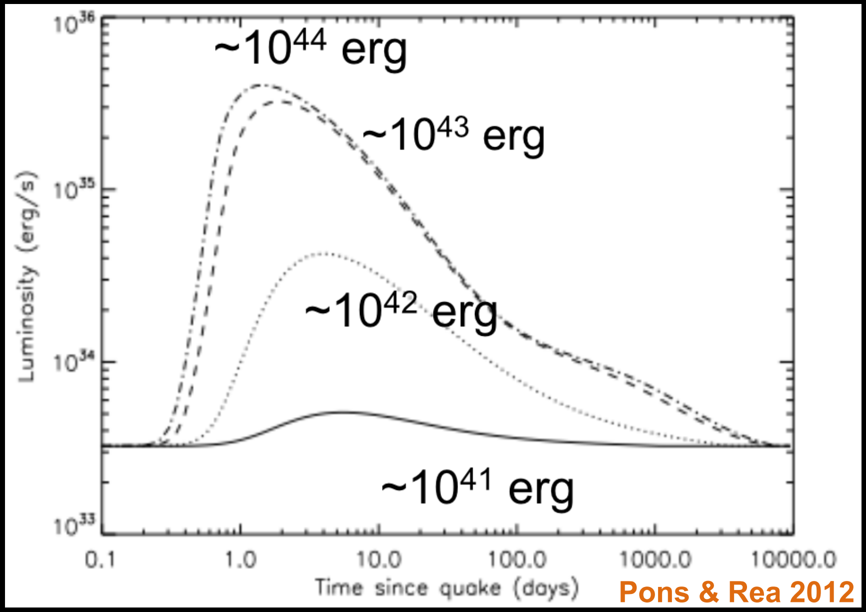
Motivation for the study

A systematic and homogeneous analysis of the spectral properties of magnetars in outbursts is needed to:

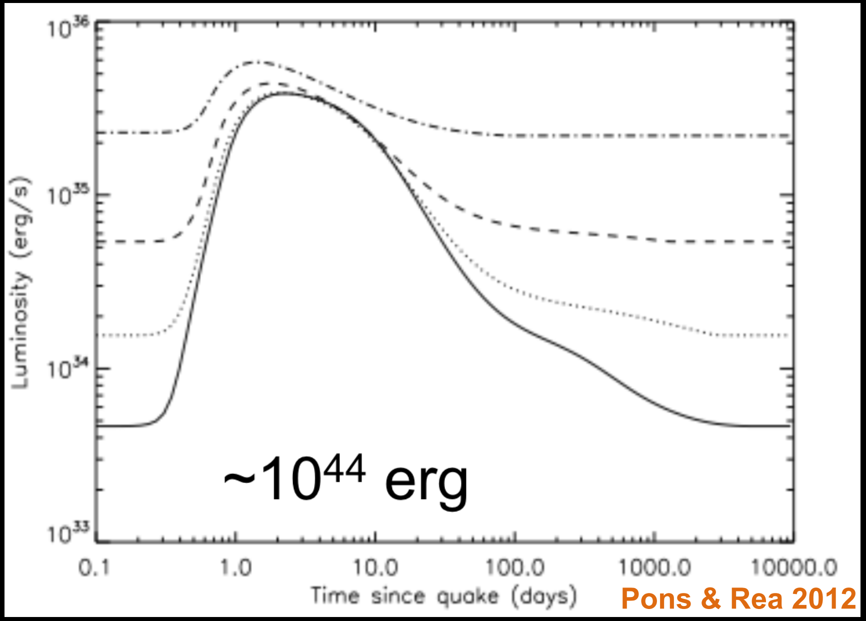
(i) model all outbursts cooling curves in a consistent way;

(ii) unveil possible correlations among different parameters

Deeper insight into the emission processes via modelling with internal crustal cooling codes.

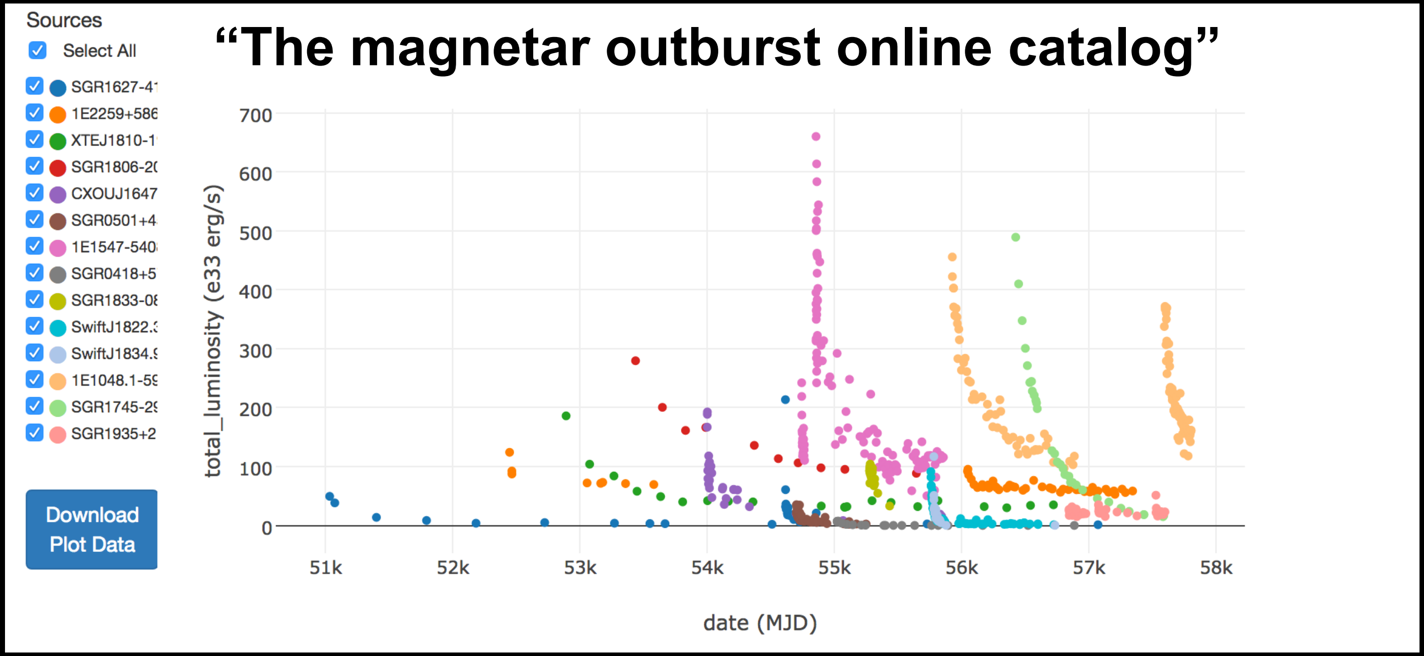


Varying the injected energy



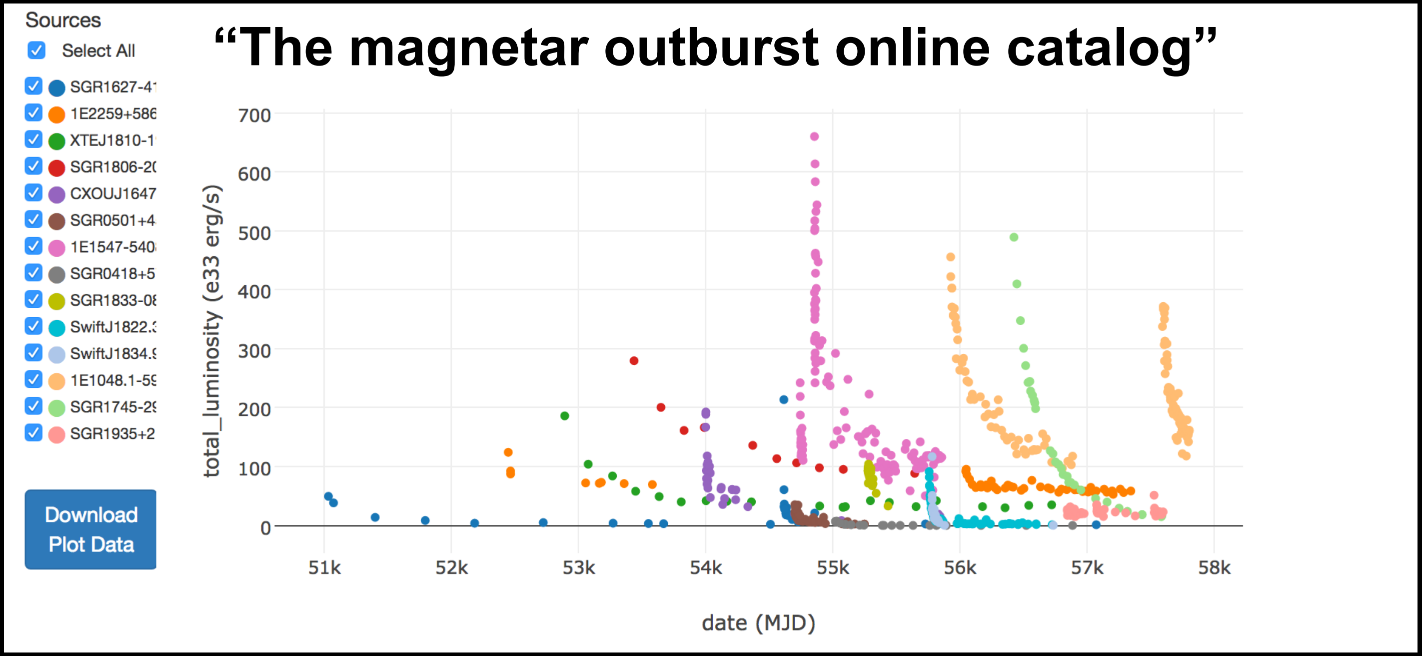
Varying the quiescent luminosity

Systematic study magnetar outbursts: some numbers



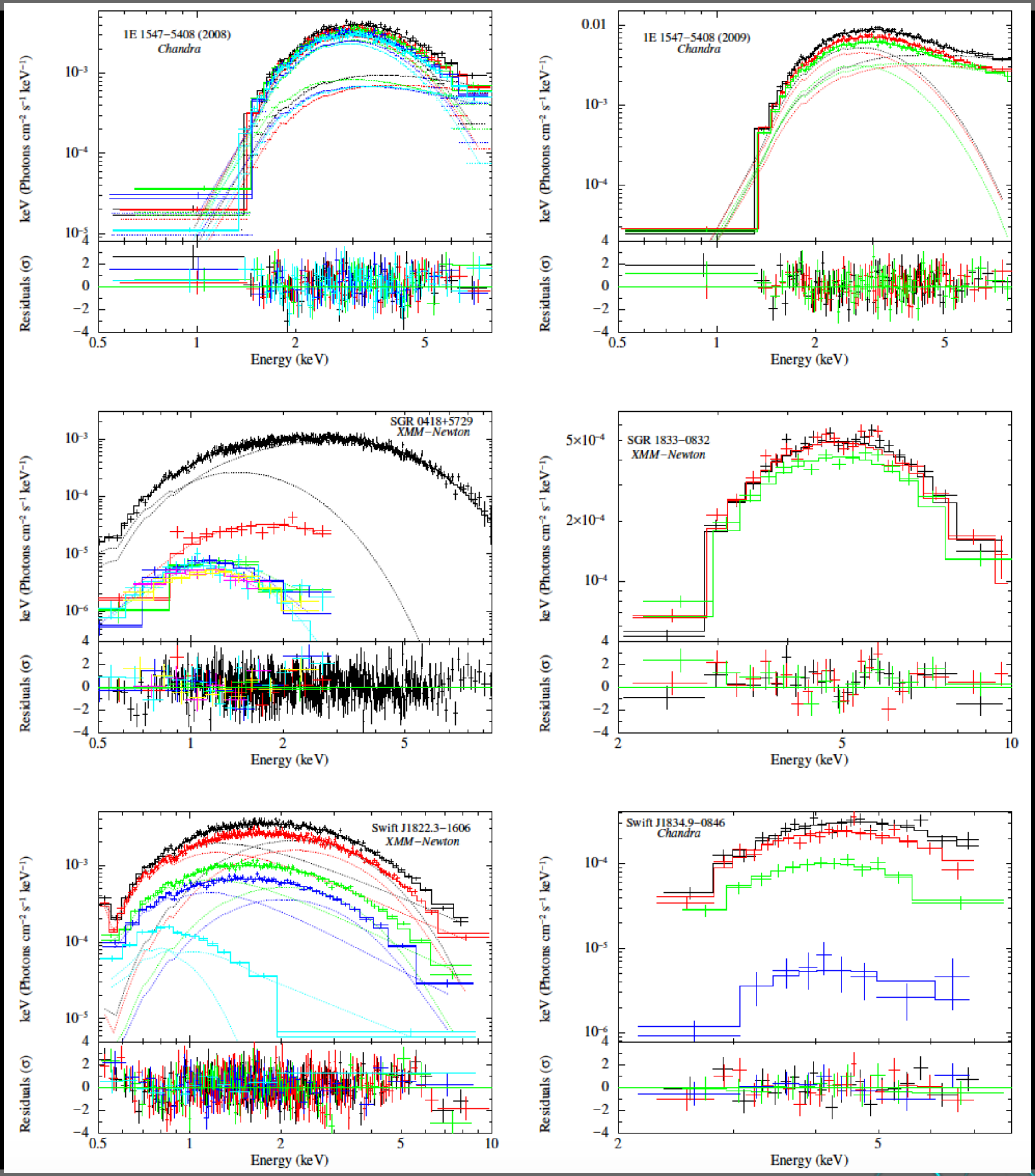
- 23 outbursts
- 14 magnetars + 2 high-B RPPs + CCO in RCW 103
- about 1100 X-ray observations (12 Ms) between 1998 and mid May 2017

Systematic study magnetar outbursts: data analysis



- reduction of raw data sets, extraction of spectra for all observations
- spectral fitting with BB, 2BB, BB+PL and more physically-motivated models
- extraction of fluxes and luminosities in each observation
- extraction of the light curves
- empirical modelling of the bolometric cooling curves
- estimate of the outburst energetics and decay-timescale

High quality X-ray spectra



1E 1547-5408 (2008)
Chandra

1E 1547-5408 (2009)
Chandra

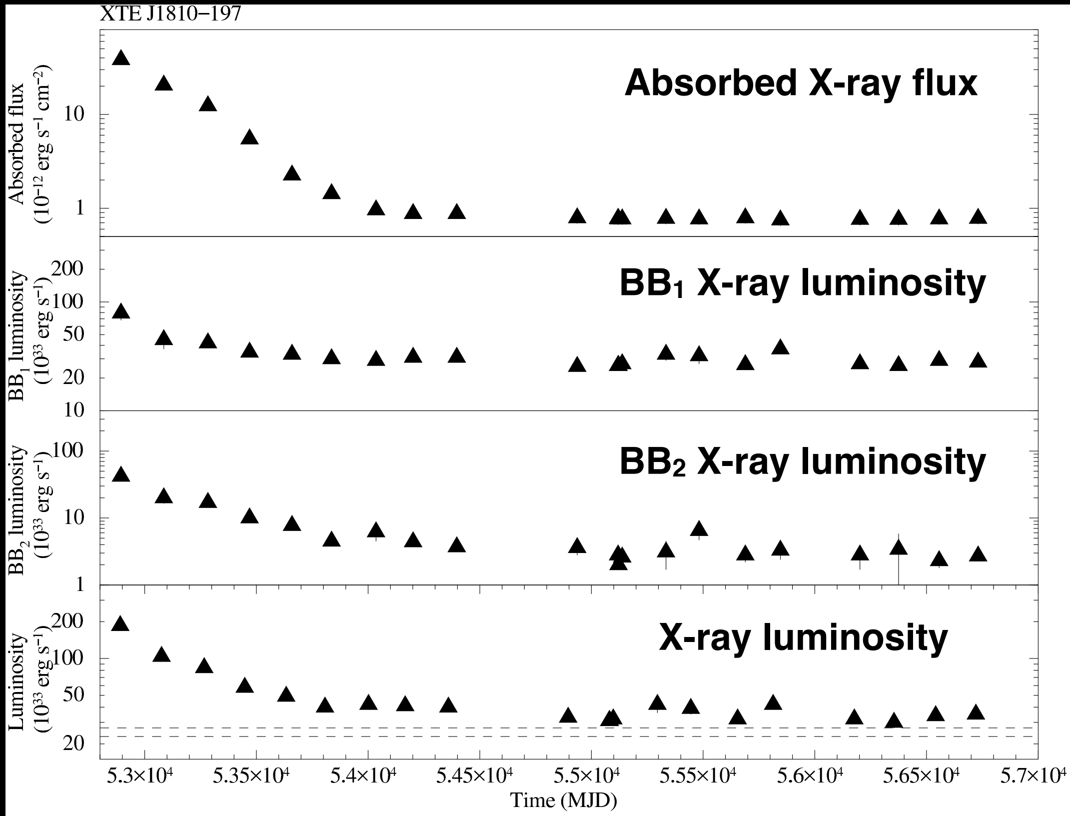
SGR 0418+5729
XMM-Newton

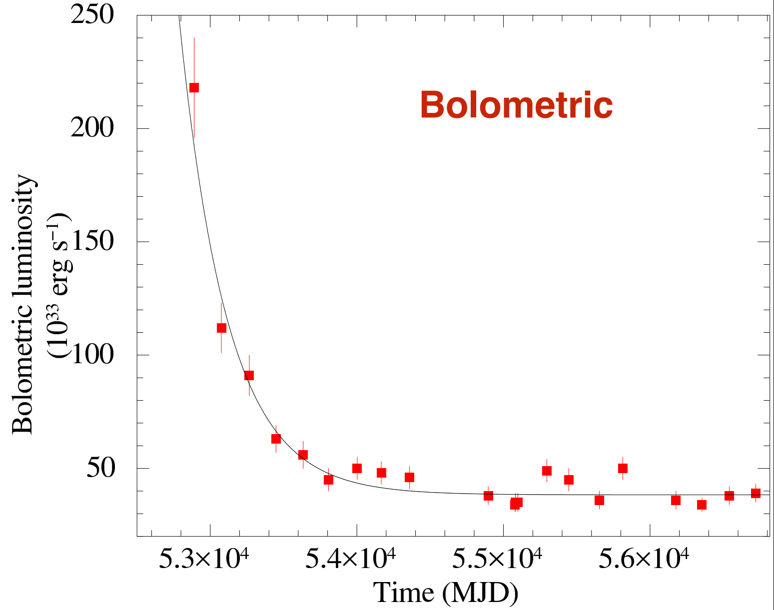
SGR 1833-0832
XMM-Newton

Swift 1822.3-1606
XMM-Newton

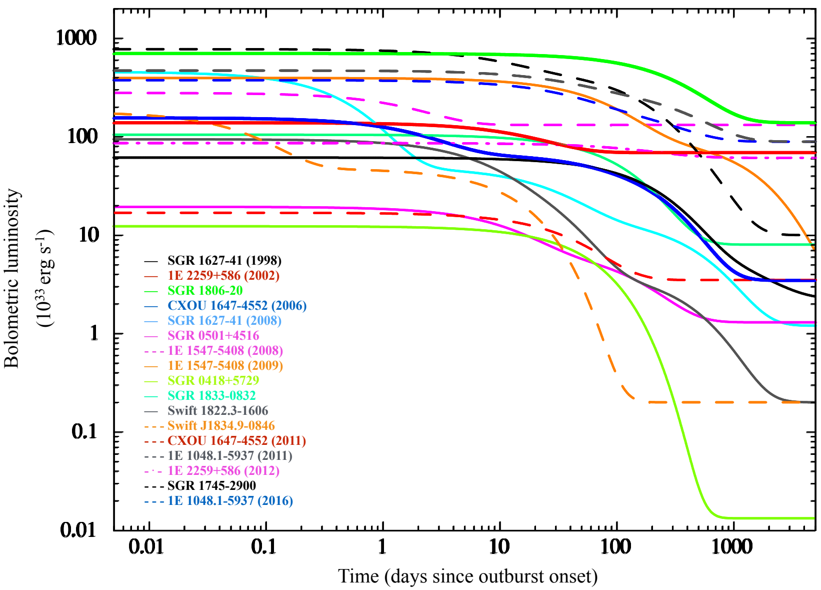
Swift 1834.9-0846
Chandra

Cooling curves: XTE J1810-197





The outburst sample, fitted models, energetics and timescales



$$L(t) = L_q + \sum_{i=1}^{j} A_i \times \exp(-t/\tau_i)$$

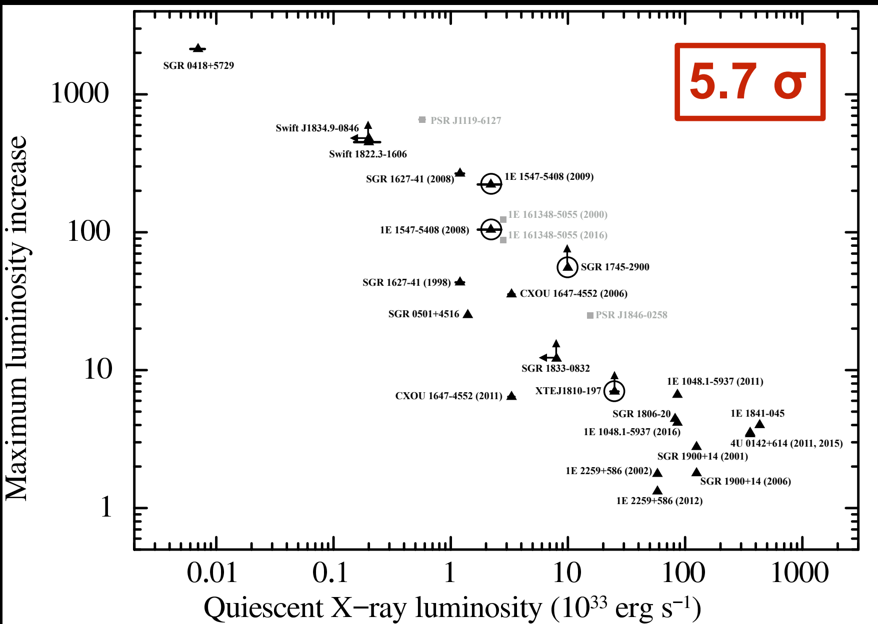
$$E = \int_0^{t_{qui}} L(t)dt$$

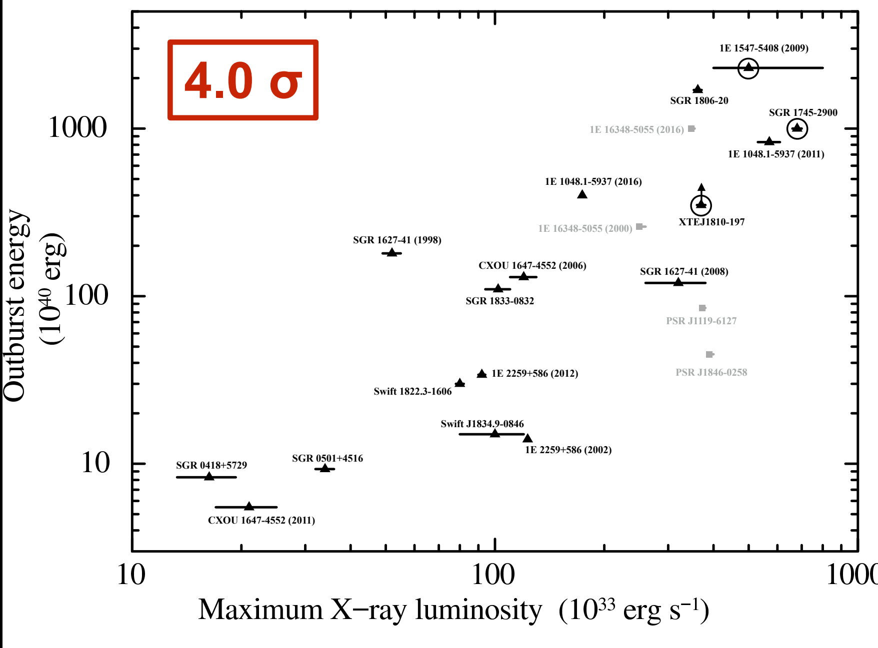
Source	Component	Best-fitting decay model	τ (d)	τ_1 / τ_2 / τ_3 (d)	E (erg)
SGR 1627−41 (1998)	BB/bol	2EXP	–	234^{+37}_{-38} / 1307^{+373}_{-245}	2×10^{42}
1E 2259+586 (2002)	BB1	EXP	1.41 ± 0.05	–	–
	BB2	EXP	47^{+40}_{-16}	–	–
	bol	EXP	21 ± 13	–	10^{41}
XTE J1810−197	BB1	EXP	376^{+72}_{-58}	–	–
	BB2	EXP	372^{+33}_{-29}	–	–
	bol	EXP	328^{+44}_{-38}	–	4×10^{42}
SGR 1806−20	bol	EXP	349 ± 52	–	2×10^{43}
CXOU J1647−4552 (2006)	BB	3EXP	–	2.9 ± 0.7 / 91^{+54}_{-27} / 225^{+32}_{-57}	–
	PL	2EXP	–	3 ± 1 / 458^{+64}_{-60}	–
	bol	3EXP	–	$2.4^{+0.8}_{-0.6}$ / 53 ± 3 / 238^{+13}_{-17}	10^{42}
SGR 1627−41 (2008)	BB/bol	3EXP	–	$0.56^{+0.07}_{-0.06}$ / 31^{+5}_{-4} / 508^{+45}_{-43}	10^{42}
SGR 0501+4516	BB	EXP	33 ± 2	–	–
	PL	2EXP	–	9^{+3}_{-2} / 345^{+68}_{-51}	–
	bol	2EXP	–	13 ± 2 / 147^{+12}_{-11}	9×10^{40}
1E 1547−5408 (2009)	BB	2EXP	–	$4.8^{+0.7}_{-0.6}$ / 1131^{+156}_{-120}	–
	PL	EXP	364 ± 15	–	–
	bol	3EXP	–	3 ± 1 / 109 ± 8 / 2870^{+528}_{-416}	2.4×10^{43}
SGR 0418+5729	BB/bol	EXP	76 ± 1	–	8×10^{40}
SGR 1833−0832	BB/bol	EXP	128^{+26}_{-4}	–	10^{42}
Swift J1822.3−1606	BB	3EXP	–	$0.78^{+0.4}_{-0.3}$ / $16.7^{+1.0}_{-0.9}$ / 207^{+12}_{-11}	–
	PL	2EXP		14.6 ± 0.8 / 817^{+54}_{-47}	–
	bol	3EXP	–	7 ± 2 / 28^{+4}_{-3} / 460^{+35}_{-31}	3×10^{41}
Swift J1834.9−0846	BB/bol	2EXP	–	0.08 ± 0.01 / 17.7 ± 0.4	2×10^{41}
CXOU J1647−4552 (2011)	BB/bol	EXP	47 ± 16	–	6×10^{40}
1E 1048.1−5937 (2011)	BB/bol	2EXP	–	39^{+26}_{-16} / 382^{+45}_{-31}	8×10^{42}
1E 2259+586 (2012)	BB1	EXP	79^{+59}_{-35}	–	–
	BB2	EXP	33.7^{+9}_{-8}	–	–
	bol	EXP	206^{+115}_{-74}	–	3×10^{41}
SGR 1745−2900	BB/bol	2EXP	–	81^{+6}_{-20} / 324^{+27}_{-17}	10^{43}
1E 1048.1−5937 (2016)	BB/bol	2EXP	–	42^{+8}_{-6} / 264^{+30}_{-29}	4×10^{42}
PSR J1119−6127	bol	3EXP	–	0.25 ± 0.06 / 18 ± 2 / 73 ± 2	8.5×10^{41}
PSR J1846−0258	bol	EXP	56 ± 6	–	4.5×10^{41}
1E 161348−5055 (2000)	bol	2EXP	–	110^{+13}_{-15} / 856^{+29}_{-27}	10^{43}
1E 161348−5055 (2016)	bol	2EXP	–	$0.5^{+0.2}_{-0.1}$ / 507^{+59}_{-49}	2.6×10^{42}

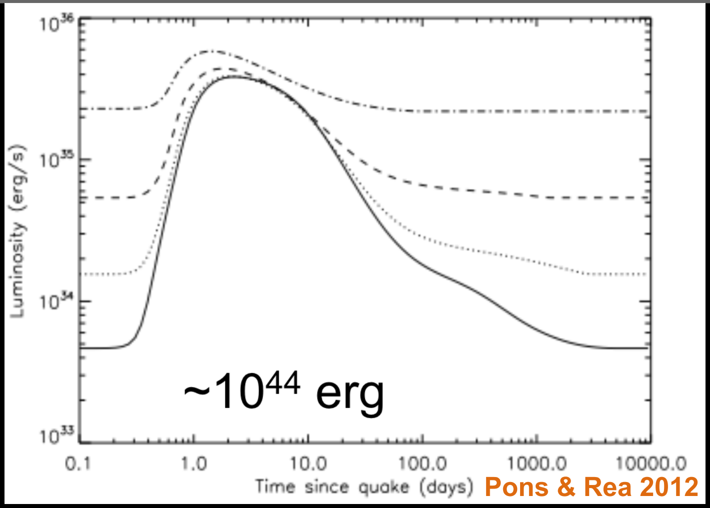
Correlations & Anticorrelations

First parameter	Second parameter	Corr/Anticorr, Significance (σ) (c) or (a), Spearman / Kendall τ	PL index
Quiescent X-ray flux	Maximum flux increase	(a) , 5.4 / 4.6	-0.7
Quiescent X-ray luminosity	Maximum luminosity increase	(a) , 5.7 / 4.9	-0.7
Spin-down luminosity	Quiescent bolometric thermal luminosity	–	–
Dipolar magnetic field	Quiescent bolometric thermal luminosity	(c) , 3.2 / 2.9	2.0
Dipolar magnetic field	Peak luminosity	(c) , 2.5 / 2.4	0.5
Dipolar magnetic field	Decay timescale	–	–
Dipolar magnetic field	Outburst energy	(c) , 3.7 / 3.3	1.0
Characteristic age	Outburst energy	(a) , 3.3 / 3.0	-0.4
Peak luminosity	Outburst energy	(c) , 4.0 / 3.7	1.4
Quiescent bolometric thermal luminosity	Outburst energy	–	–
Peak luminosity	Decay timescale	–	–
Outburst energy	Decay timescale	(c) , 3.9 / 3.6	0.5
Outburst energy	Maximum luminosity increase	–	–
Decay timescale	Maximum luminosity increase	–	–

Correlations & Anticorrelations

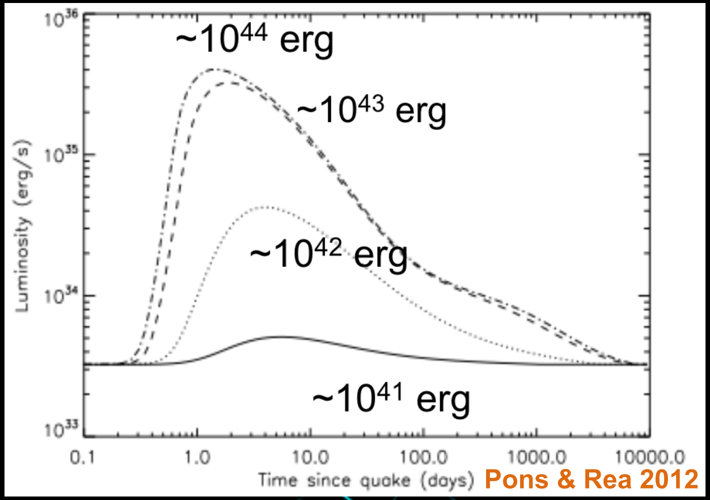




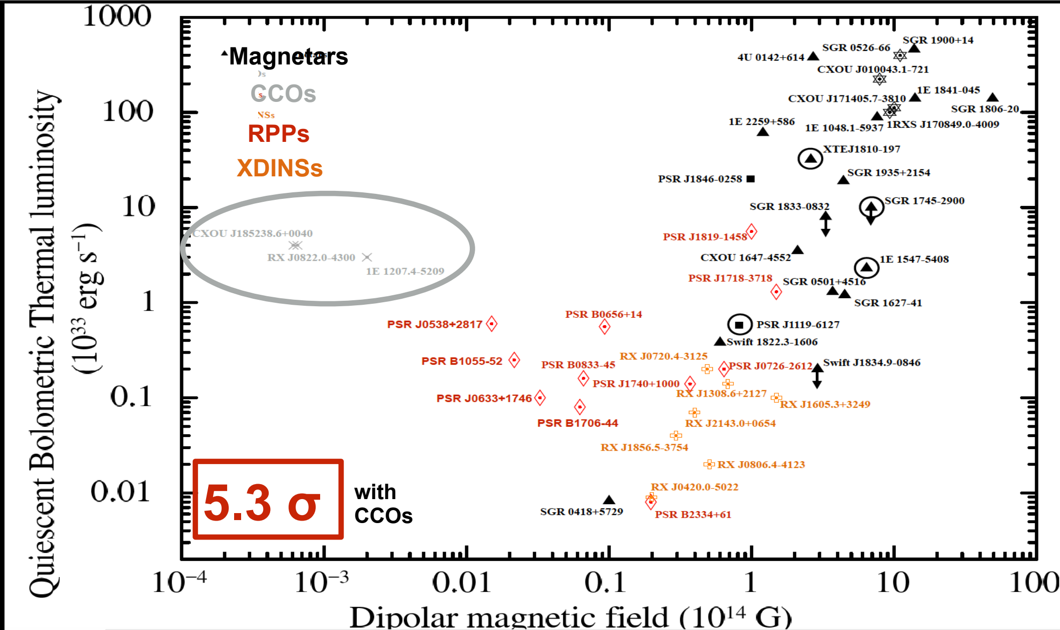


The definition of "transient" magnetars as opposed to the "persistent" magnetars is deceptive: it only reflects their different quiescent luminosities

Large flux enhancements can only be observed in faint quiescent magnetars



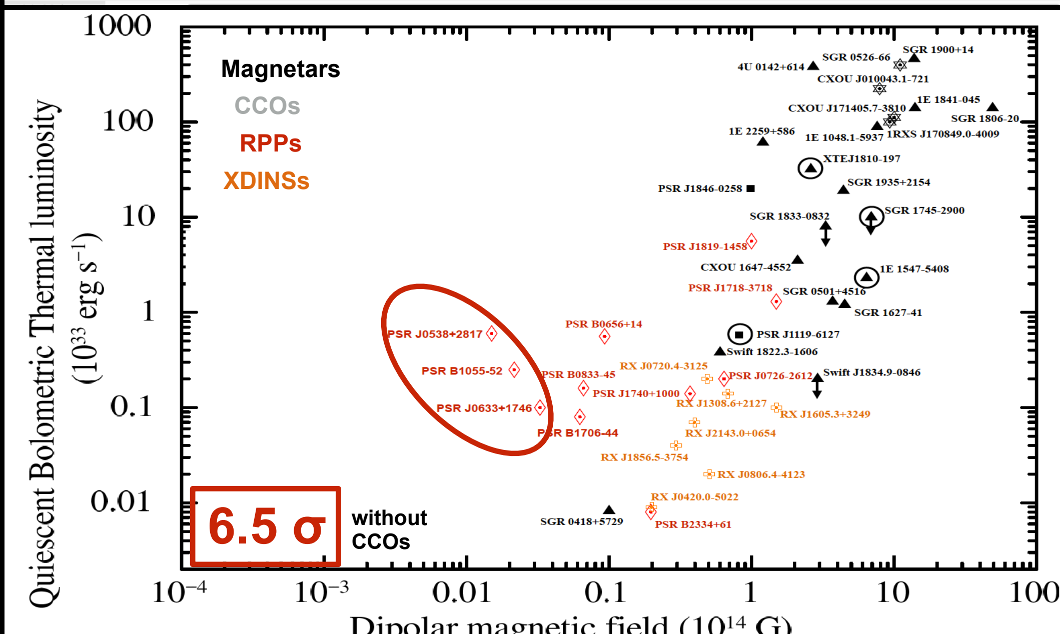
Correlations & Anticorrelations



CCOs depart significantly from the trend.

Expected in the '***hidden magnetic field***' scenario: fallback accretion onto the NS (10^{-3} - 10^{-2} M_{Sun} in hrs-days) can bury a B field of a few 10^{12} G into the inner crust (Viganò & Pons 2012; Torres-Forné et al. 2016).

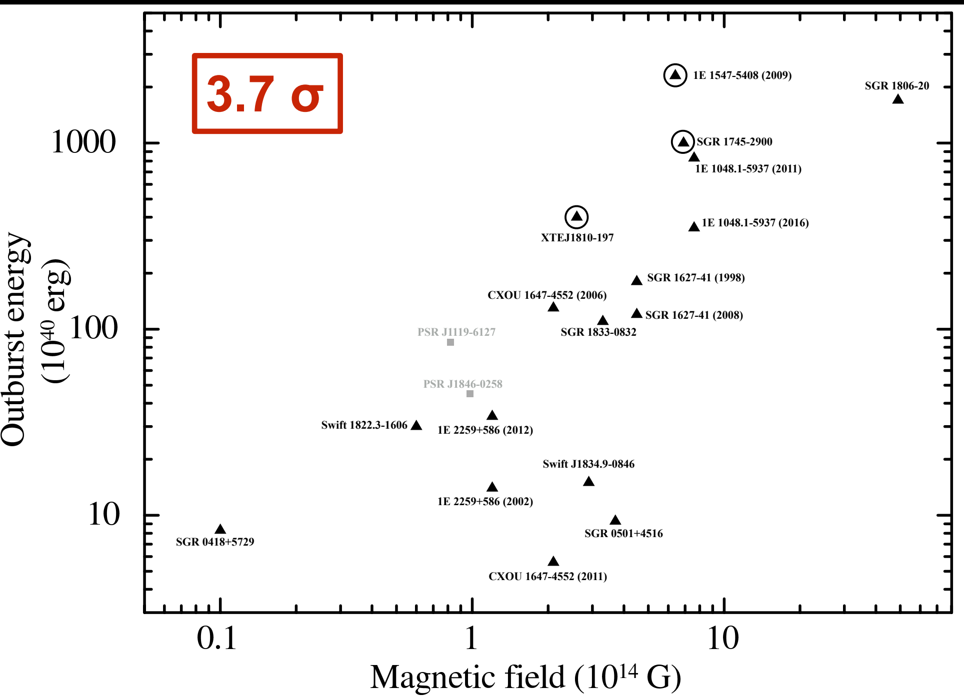
The external B field is lower than the internal 'hidden' B field, hence does not trace the bolometric luminosity



RPPs depart a bit from the trend.

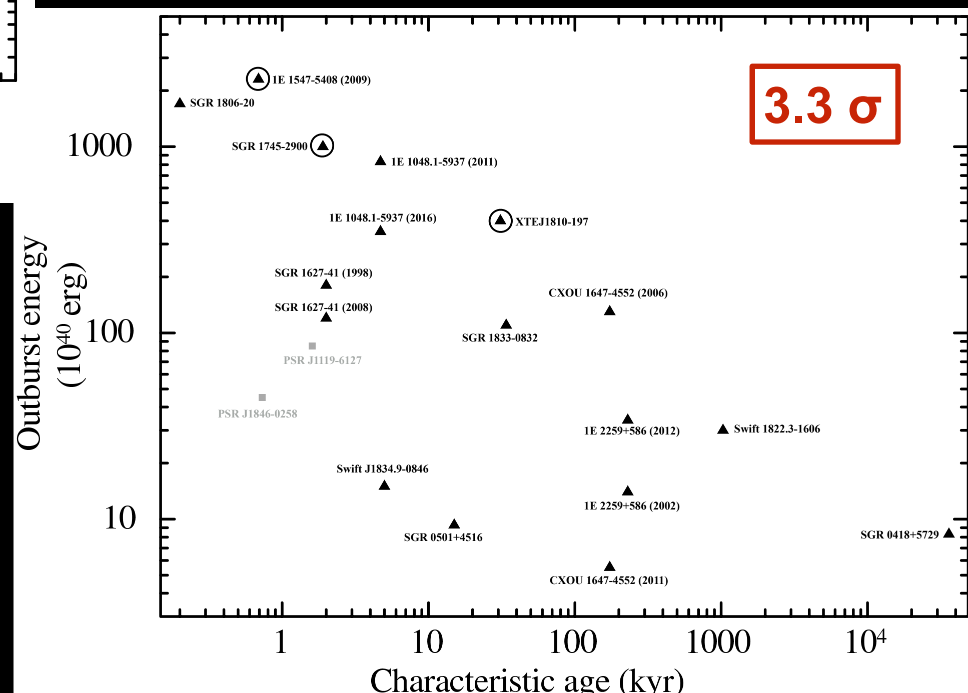
The larger luminosity wrt the prediction is likely due to **slamming particles** heating the NS surface, providing an additional source of heat

Correlations & Anticorrelations

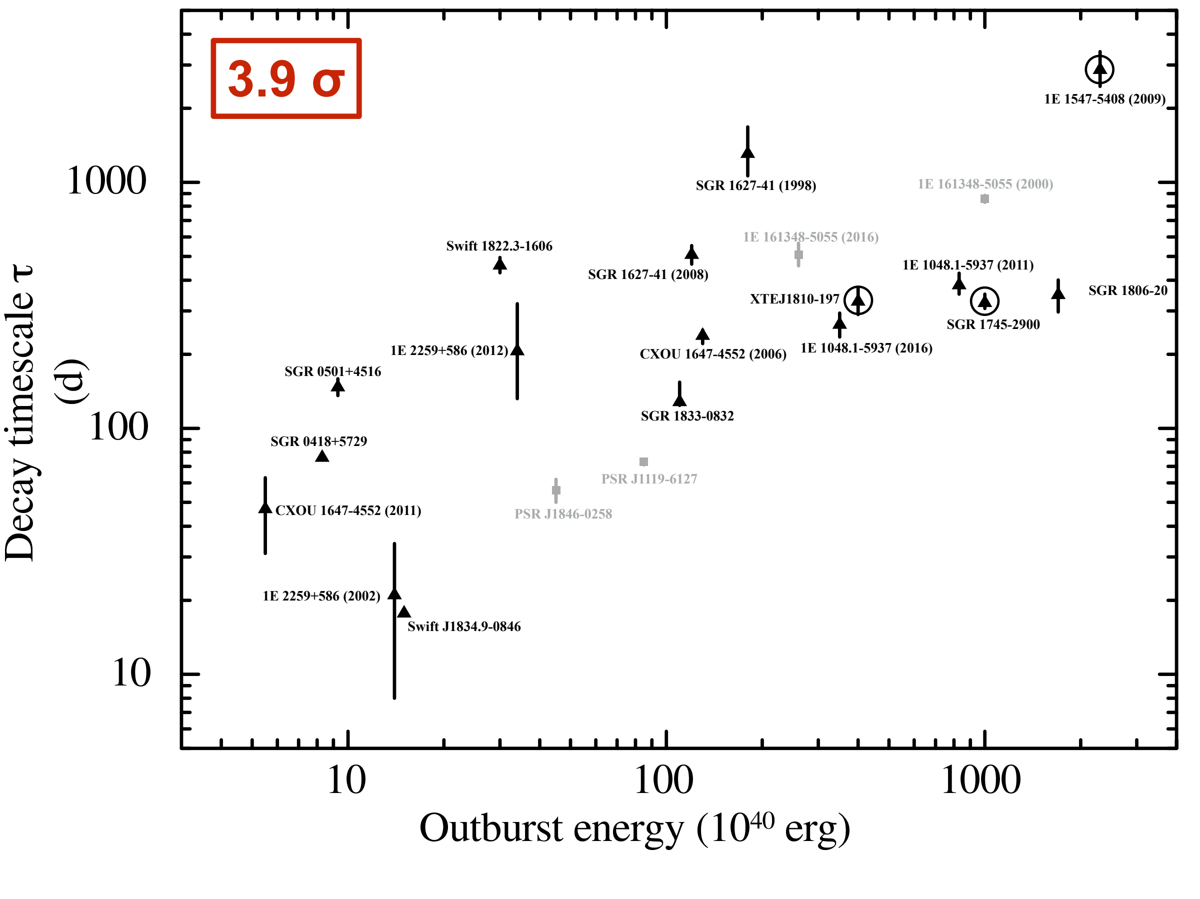


Broad agreement with the idea that magnetar outbursts are ultimately powered by the dissipation of the B-field

Young magnetars undergo more energetic outbursts



Correlations & Anticorrelations



Similar decay pattern for all magnetar outbursts

Expected in the interior crustal cooling model
(the deeper the location of the energy release, the more energetic the outburst, the longer the time for heat diffusion)

Expected in the untwisting bundle model (T ∝ E^0.5)

The magnetar outburst online catalog

magnetars.ice.csic.es

The magnetar outburst online catalog

magnetars.ice.csic.es

The magnetar outburst online catalog

magnetars.ice.csic.es