Highly magnetic neutron stars: an observational update

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CSIC Consejo Superior de Investigaciones Científicas

IEEC

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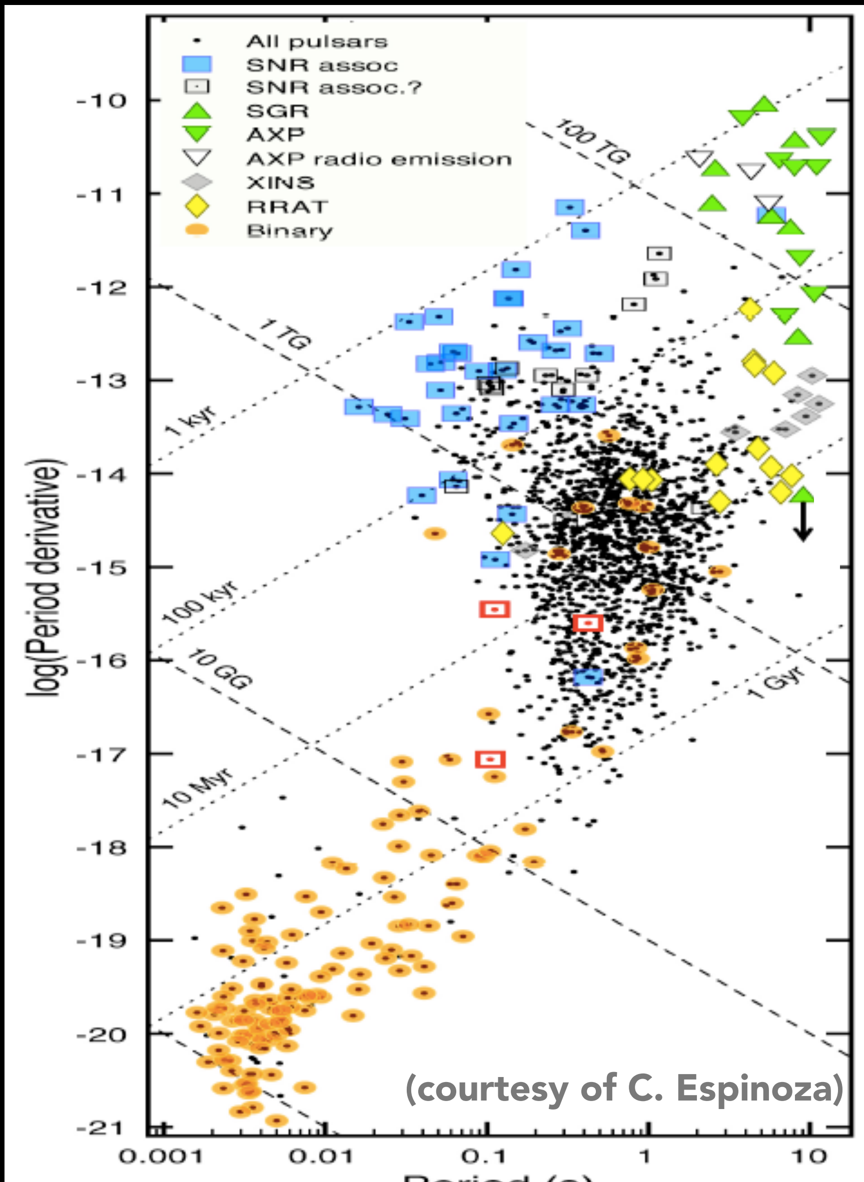
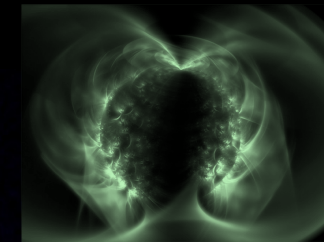
Different emission channels: the pulsar zoo

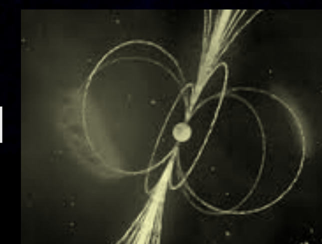


Magnetars: B-powered

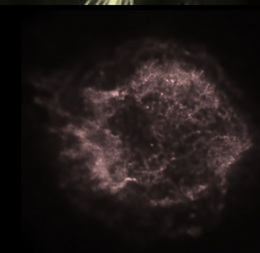


XDINS: kT-powered

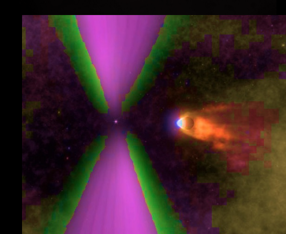
Pulsars: rotation- powered



CCOs: kT-powered



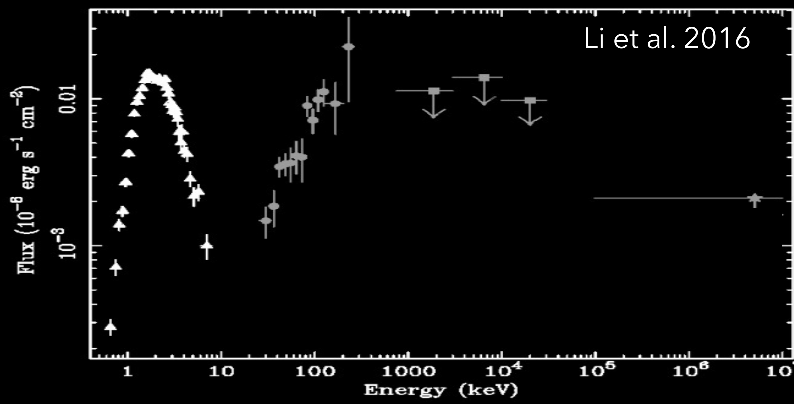
Recycled binaries: rotation-powered

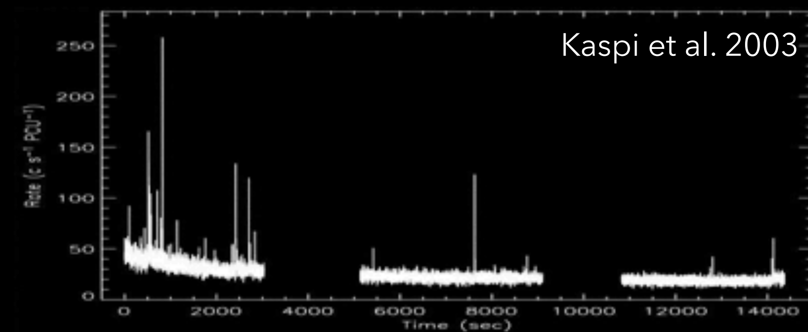


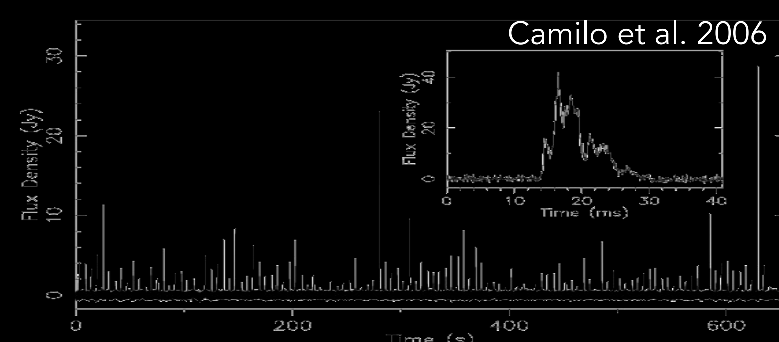
Magnetars

- about 25 X-ray pulsars with $L_X \sim 10^{31} - 10^{36}$ 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 + non-thermal spectral components
- rotating with $P \sim 0.3 - 12$ s
- magnetic fields of $B_p \sim 10^{13} - 10^{15}$ Gauss
- flaring activity in soft gamma-rays ($0.01 - 10^2$ s; $L_x \sim 10^{38} - 10^{46}$ erg s^{-1})
- large outbursts (months-years; $E \sim 10^{40} - 10^{43}$ erg)
- transient radio emission (in 4 cases)

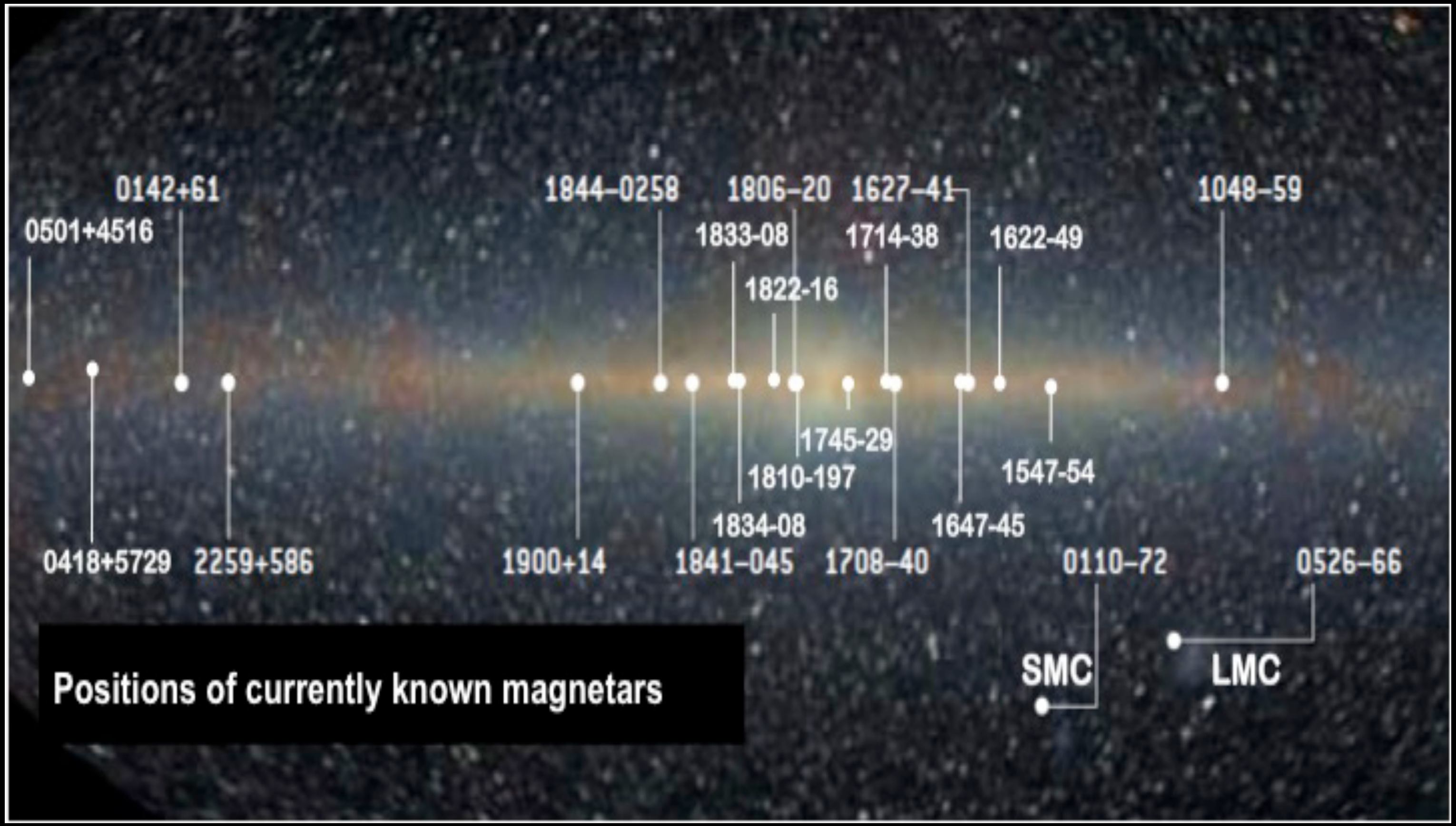
Turolla et al. 2015; Kaspi & Beloborodov 2017; Esposito et al. 2018





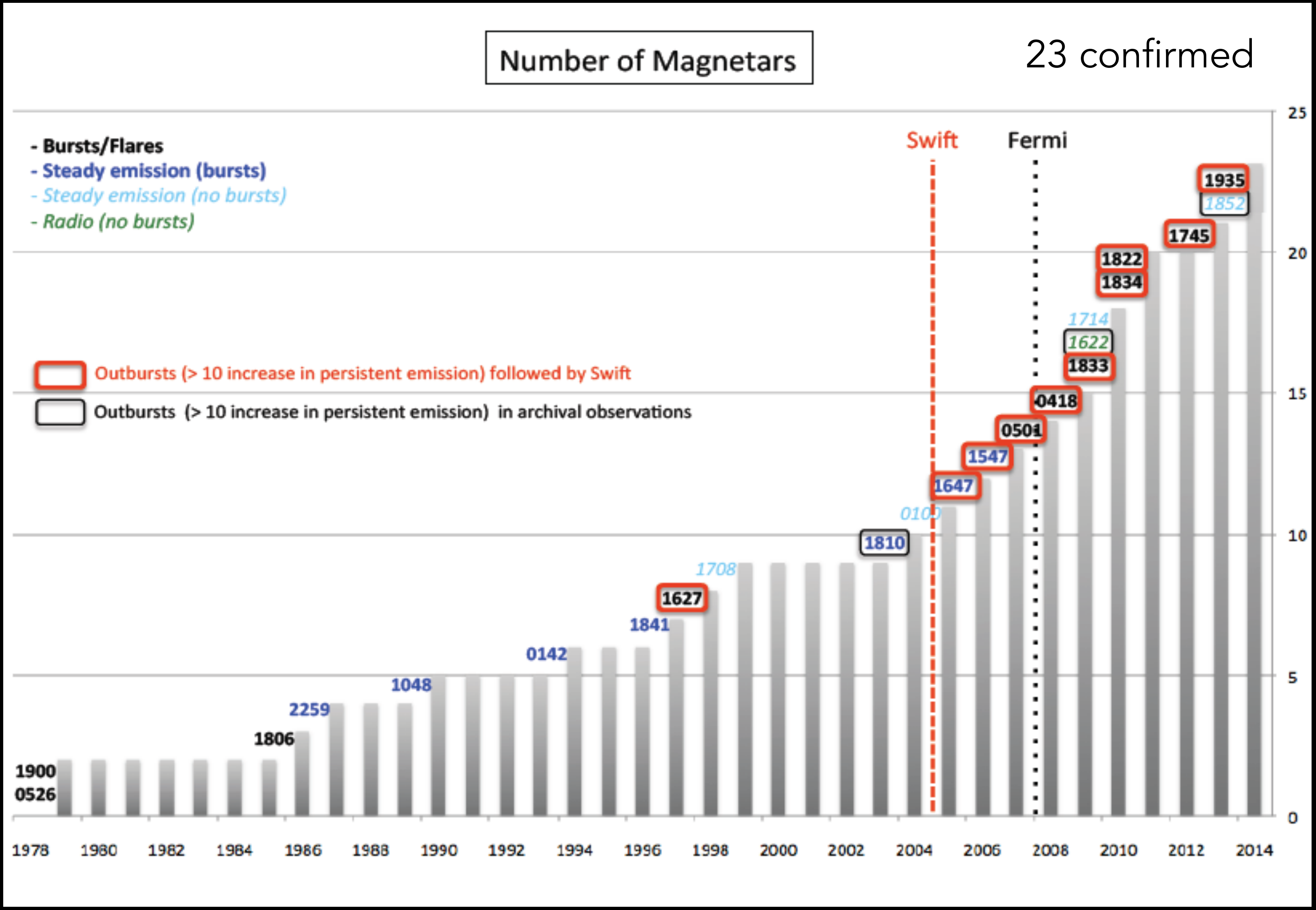


Distribution in the Galaxy



McGill Online Magnetar Catalogue; Olausen & Kaspi 2014

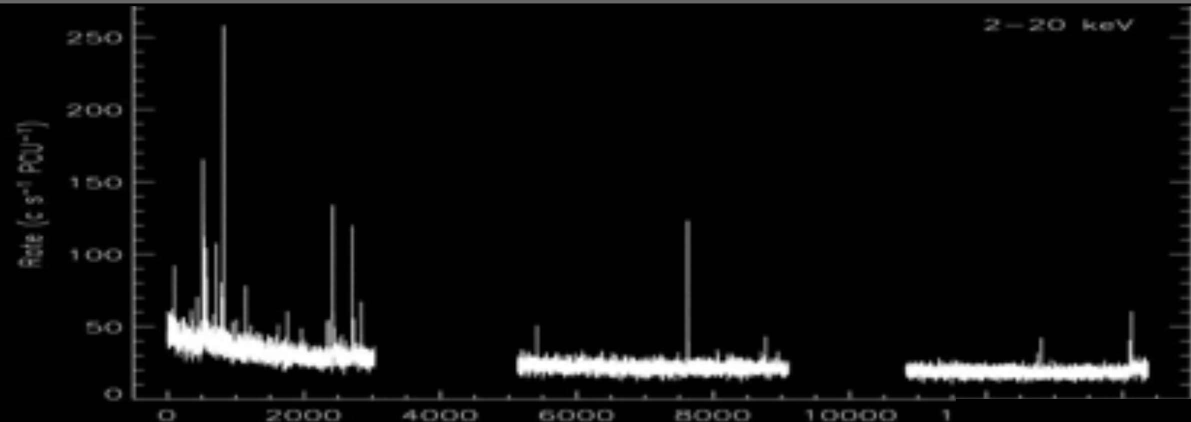
Discovery rate



Flaring activity (timescale: sec/min)

Short bursts

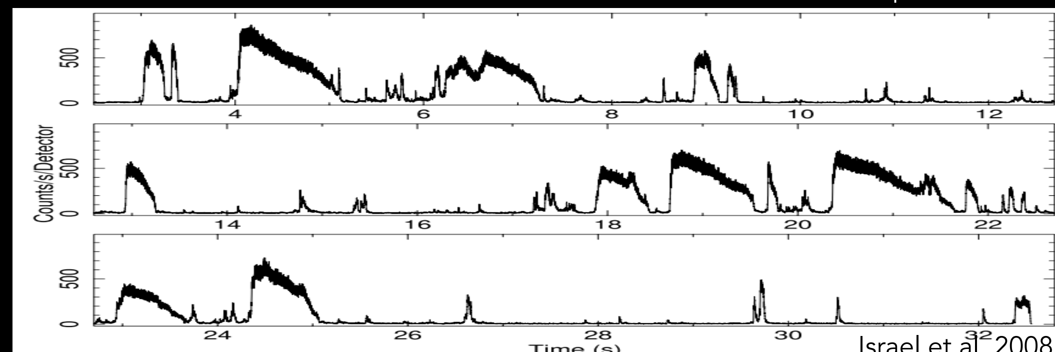
- duration ~0.01-1s
- L_x ~10^{39}-10^{41} erg s^{-1}
- soft γ-rays thermal spectra (kT ~ 30-40 keV)



Kaspi et al. 2003

Intermediate bursts

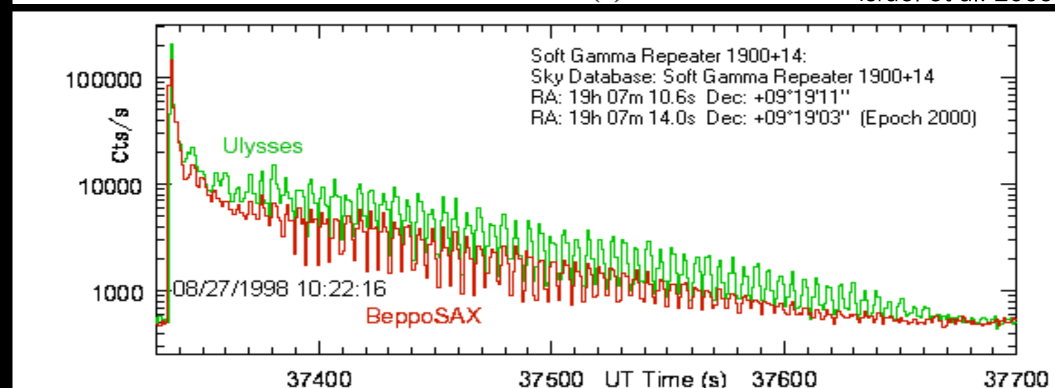
- duration 1-40 s
- peak ~10^{41}-10^{43} erg s^{-1}
- abrupt on-set
- usually soft γ-rays thermal spectra



Israel et al. 2008

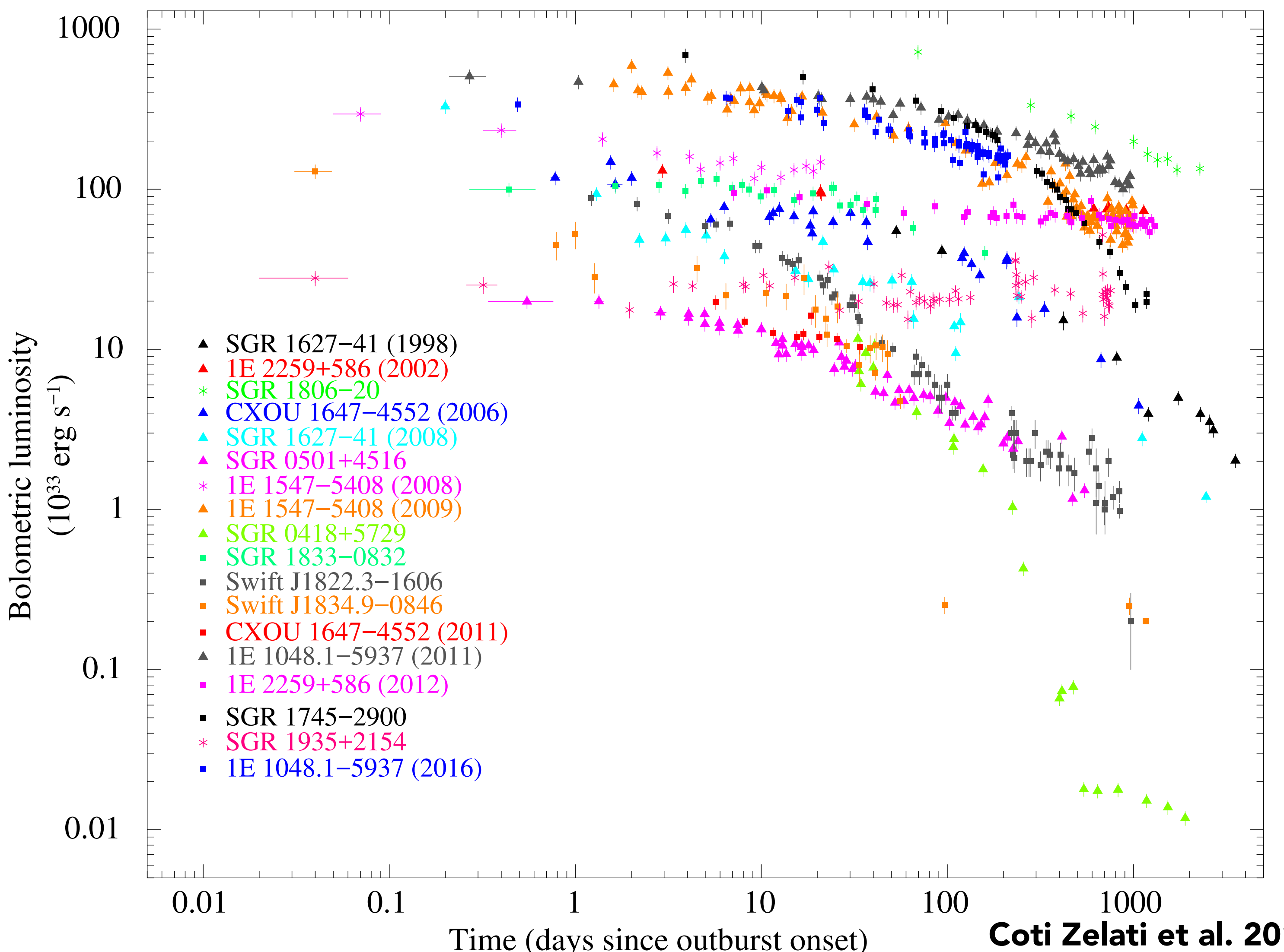
Giant Flares

- very rare events (only 3 observed)
- L_x > 3x10^{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



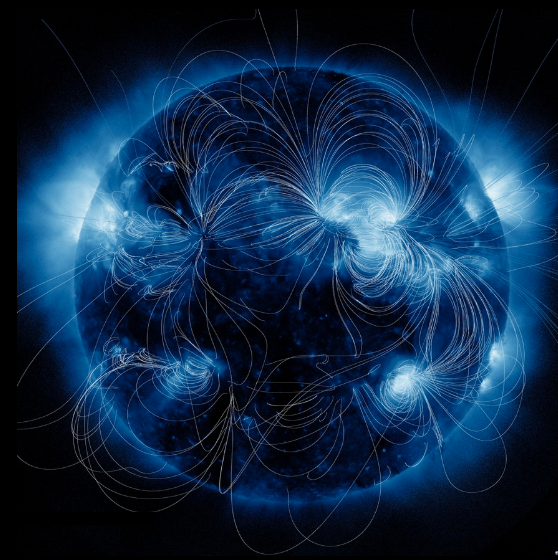
http://babbage.sissa.it/PS_cache/astro-ph/pdf/9912/9912487.pdf

Outburst activity (timescale: months/years)



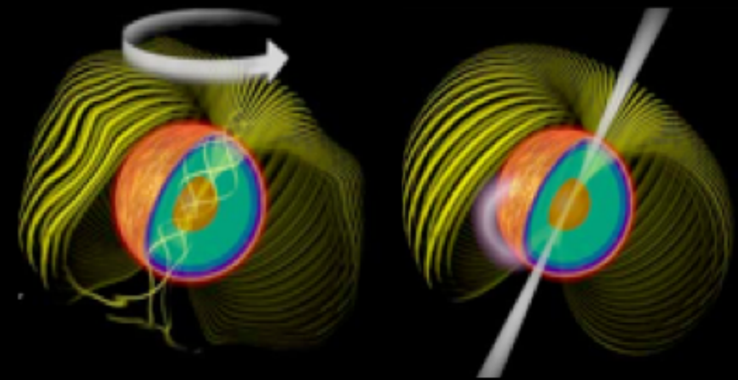
Coti Zelati et al. 2018

Outburst activity: 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)

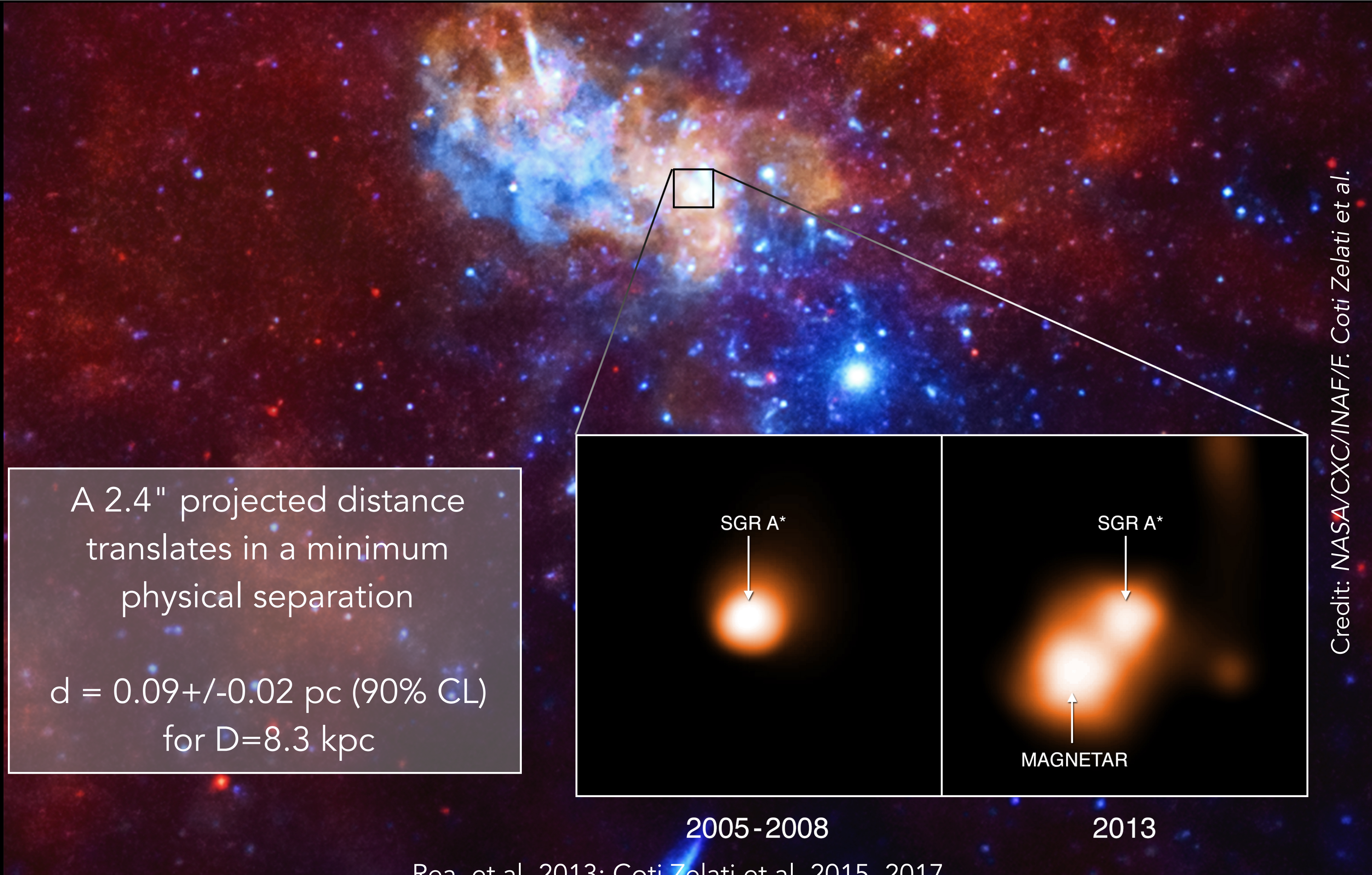
2. **External source of heat:** Crustal displacements twist up the external B-field. Returning currents hit and heat the NS surface. The bundle dissipates as the energy supply from the star interior decreases.



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

Nobili, Turolla & Zane 2008a,b; Beloborodov 2009; Pons & Rea 2012; Parfrey et al. 2013; Beloborodov & Levin 2014 Beloborodov & Li 2016; Li et al. 2016; Li et al. 2018

The magnetar in the Galactic Centre: SGR J1745-2900

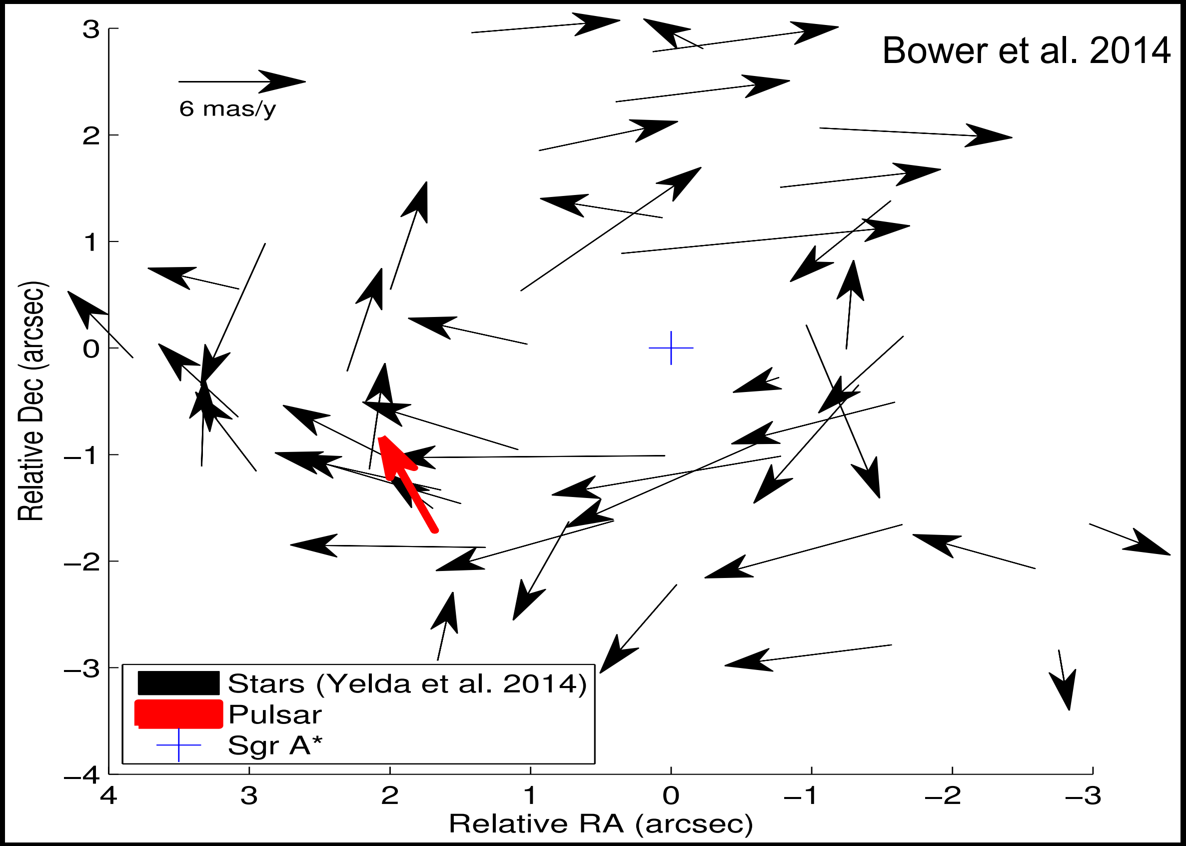


A 2.4" projected distance translates in a minimum physical separation

d = 0.09+/-0.02 pc (90% CL) for D=8.3 kpc

Rea et al. 2013; Coti Zelati et al. 2015, 2017

The magnetar in the Galactic Centre: SGR 1745-2900



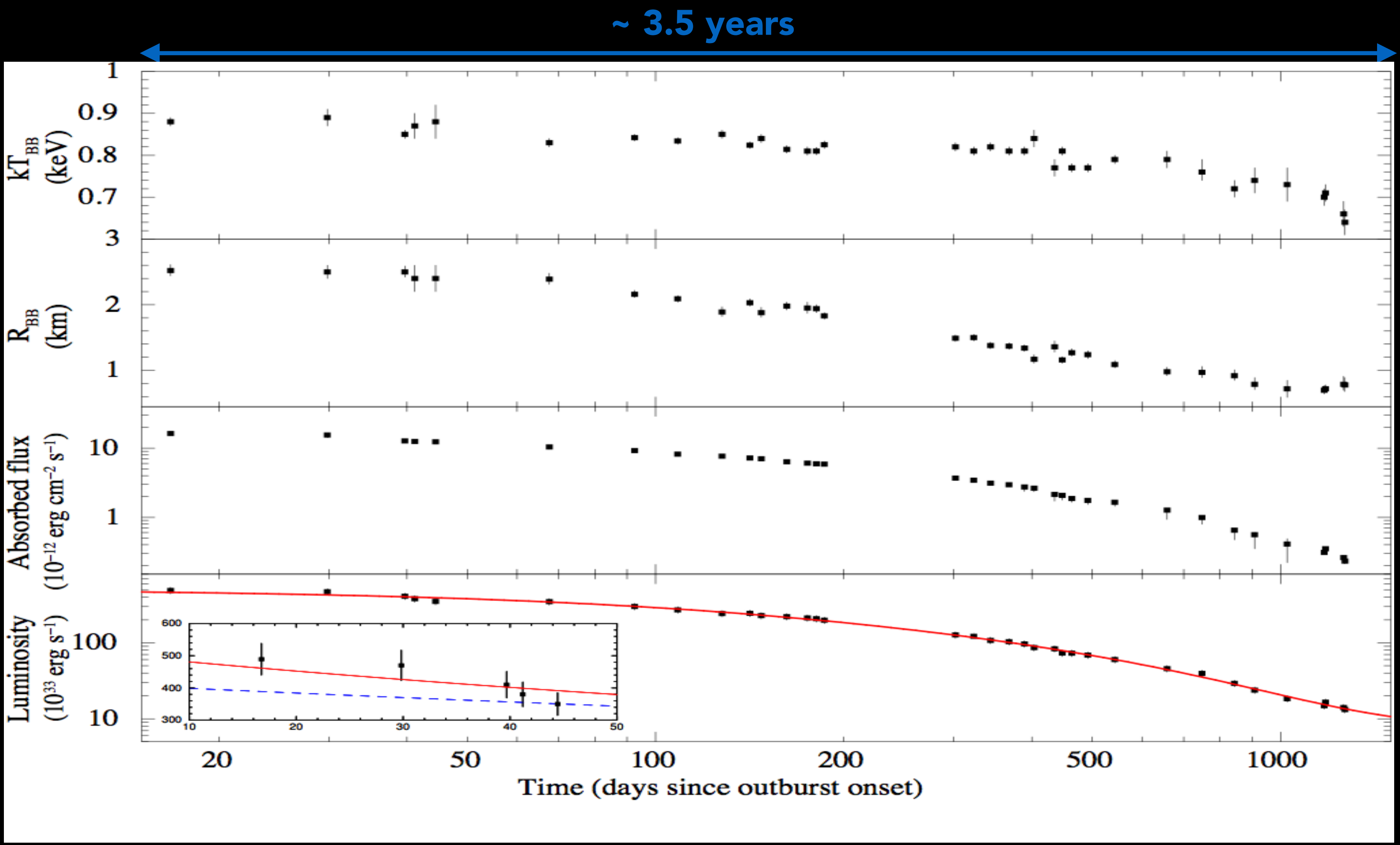
Proper motion from *VLBA* observations

Transverse velocity of 236+/-11 km/s at PA = 22+/-2 deg East-of-North

90% probability on average of being bound to the SMBH if born within 1 pc.

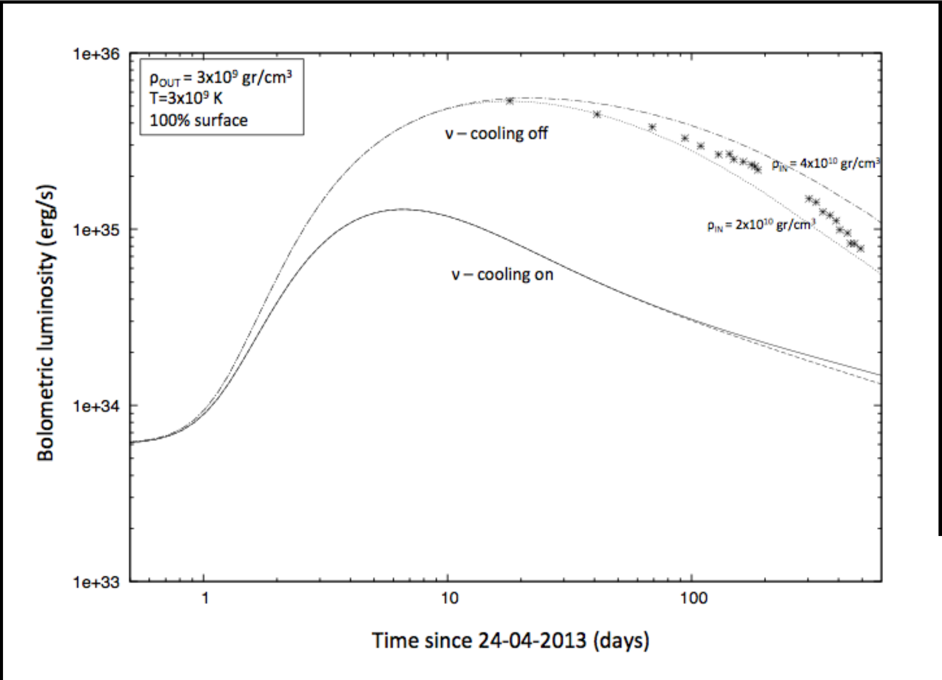
P_{orb} ~ 500 yr - several kyrs (Rea et al. 2013)

The magnetar in the Galactic Centre: SGR J1745-2900

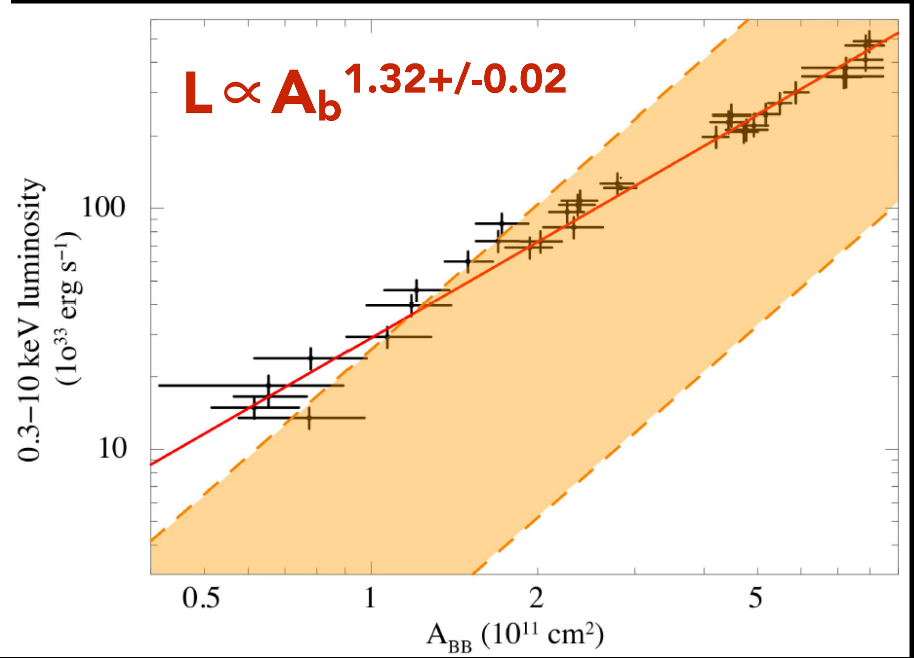


Coti Zelati et al. 2015, 2017; Coti Zelati et al. in prep

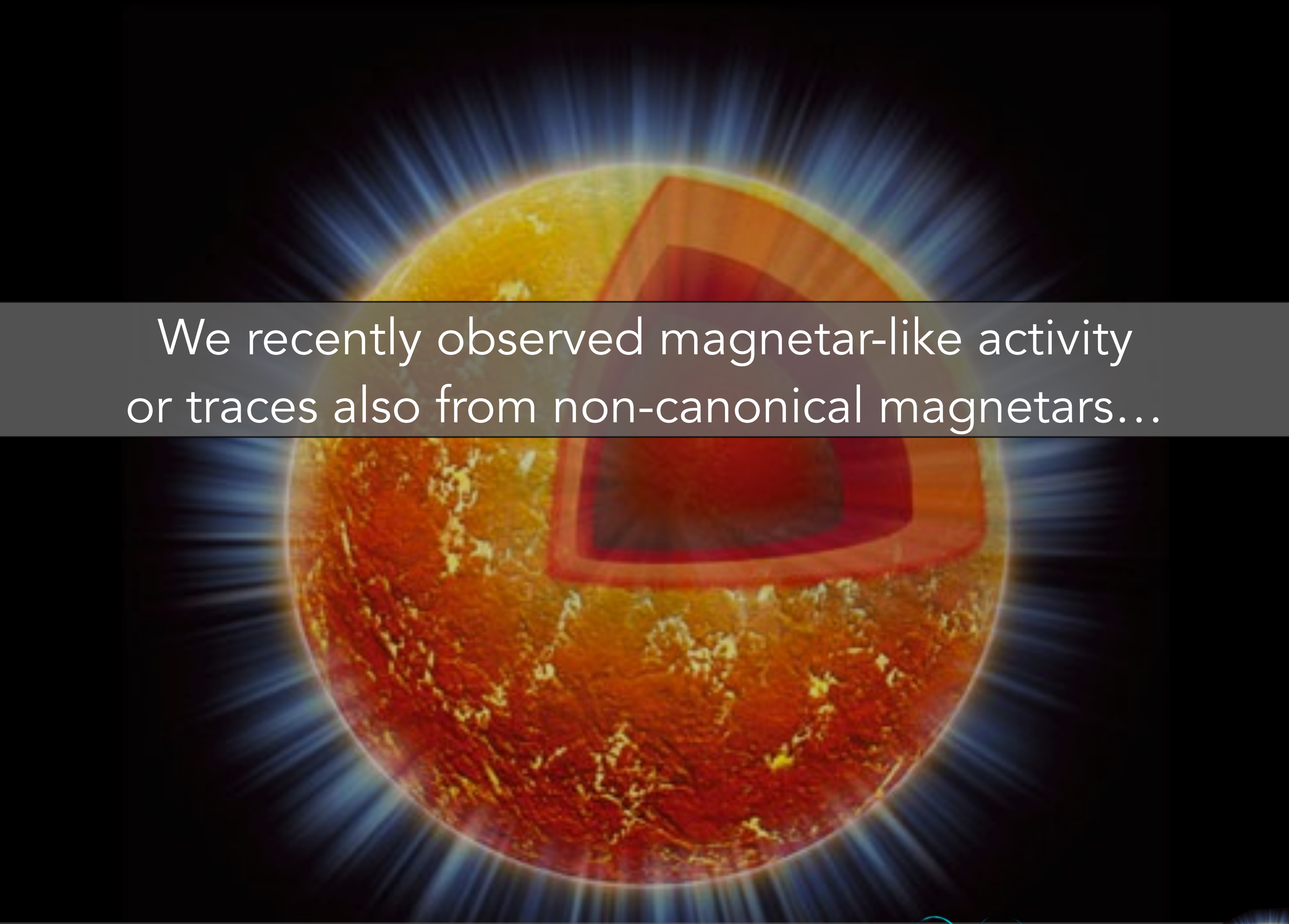
The magnetar in the Galactic Centre: SGR J1745-2900



Cannot be only crustal cooling from a single injection.



Qualitative agreement with bundle untwisting. Bombardment of magnetospheric currents?

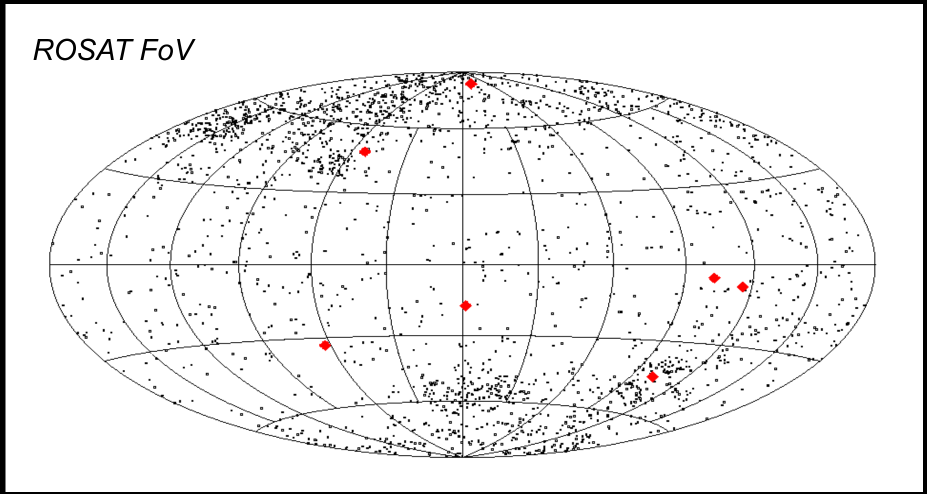


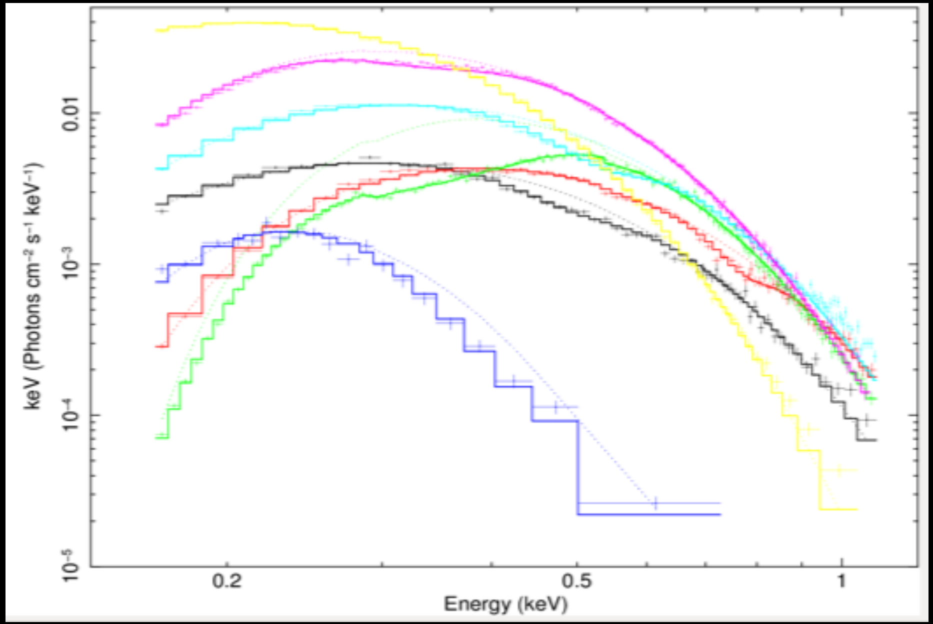
We recently observed magnetar-like activity
or traces also from non-canonical magnetars…

Thermally emitting neutron stars (XDINSs)

- Distances : *D*<500 pc
- Spin periods: *P*~3-11 s
- Magnetic dip-fields: $B \sim 10^{13}$ G
- Age: *t*~0.1-1 Myr
- Luminosities: $L_X \sim 10^{30}$-10^{33} erg s^{-1}
- L_X >> Rotational energy loss rate
- No radio emission
- $F_x/F_{opt} \sim 10^4$ - 10^5

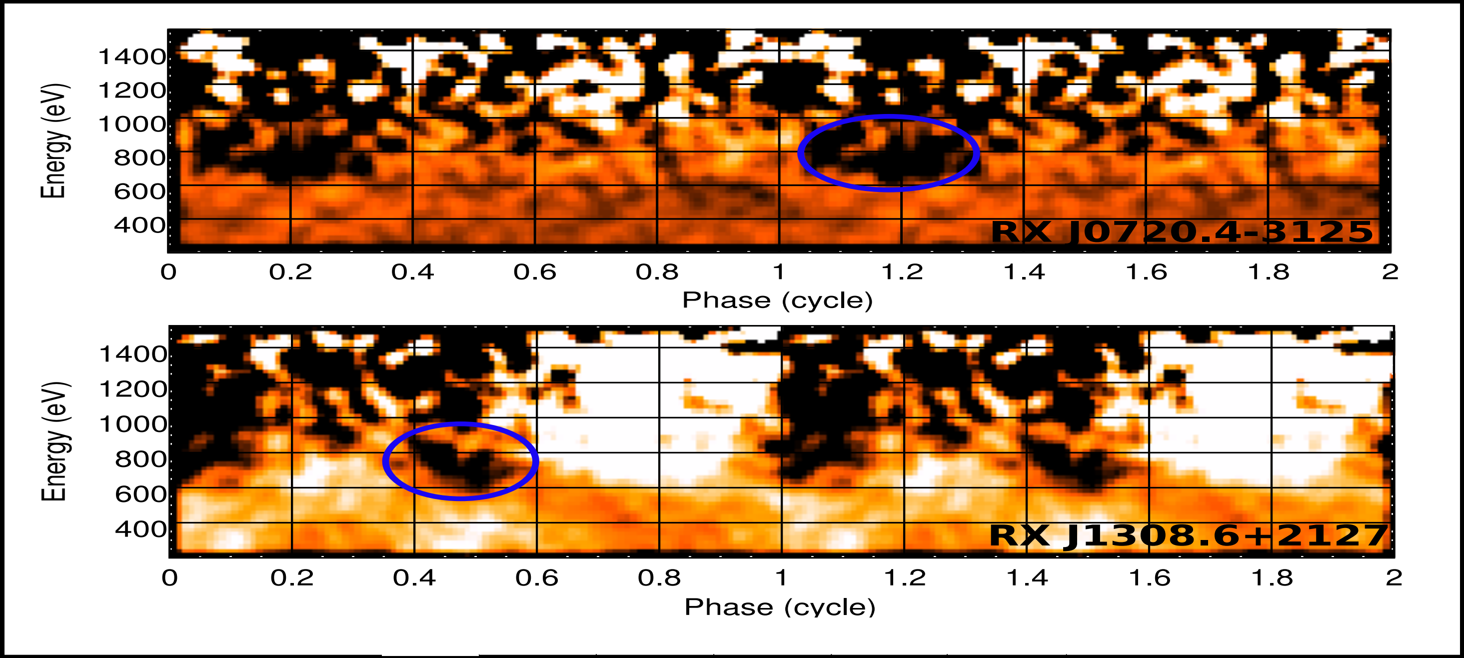
Thermal X-ray spectra
(kT_{BB} ~ 40-110 eV)



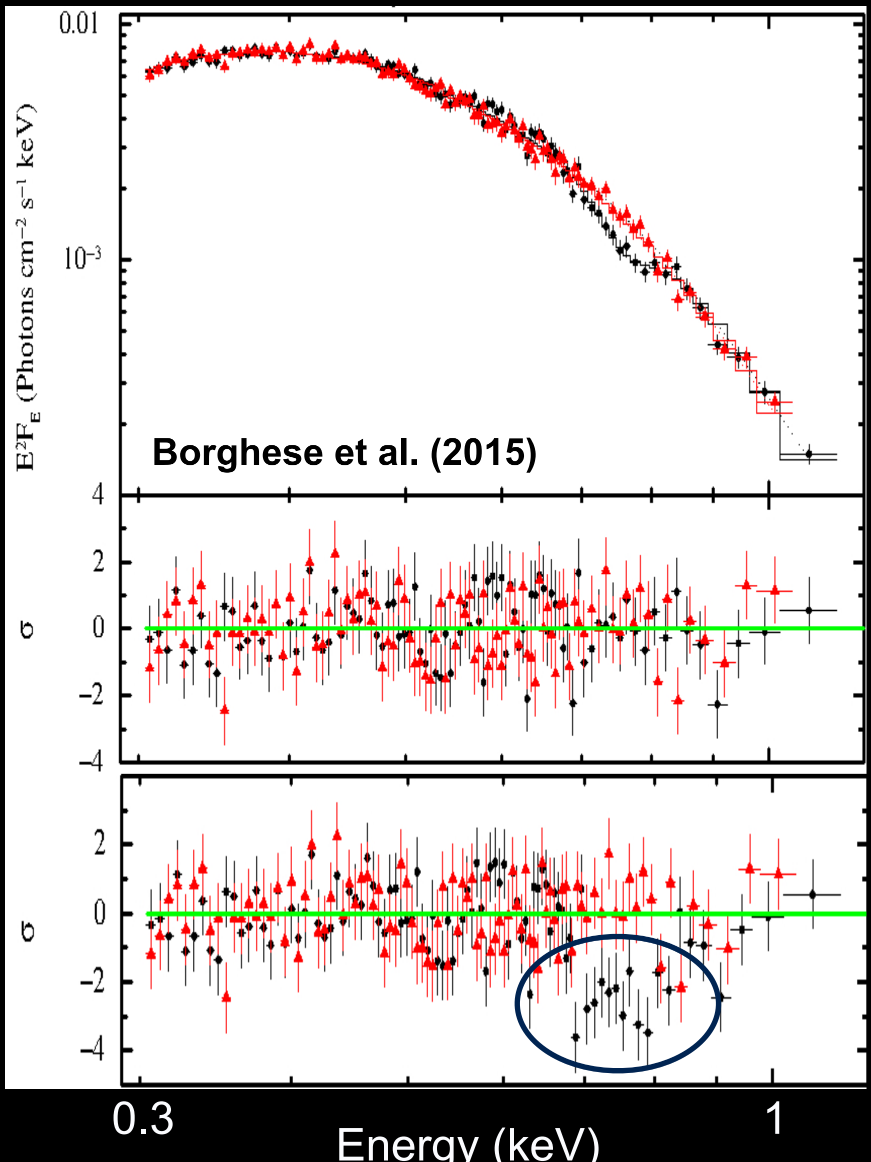


Phase-dependent absorption features

Systematic search for narrow phase-dependent absorption features in all XDINSs.
Narrow feature found in the spectrum of RX J0720.4-3125 and RX J1308+2127



Phase-resolved spectral analysis



Phase-dependent line:

$E_{line} = 745_{-27}^{+17}$ eV

$\sigma_{line} = 42_{-33}^{+51}$ eV

$Eqw = 28_{-11}^{+9}$ eV

Complex structure of the external magnetic field

Possible origin: proton cyclotron resonant scattering in a small magnetic loop close to the surface

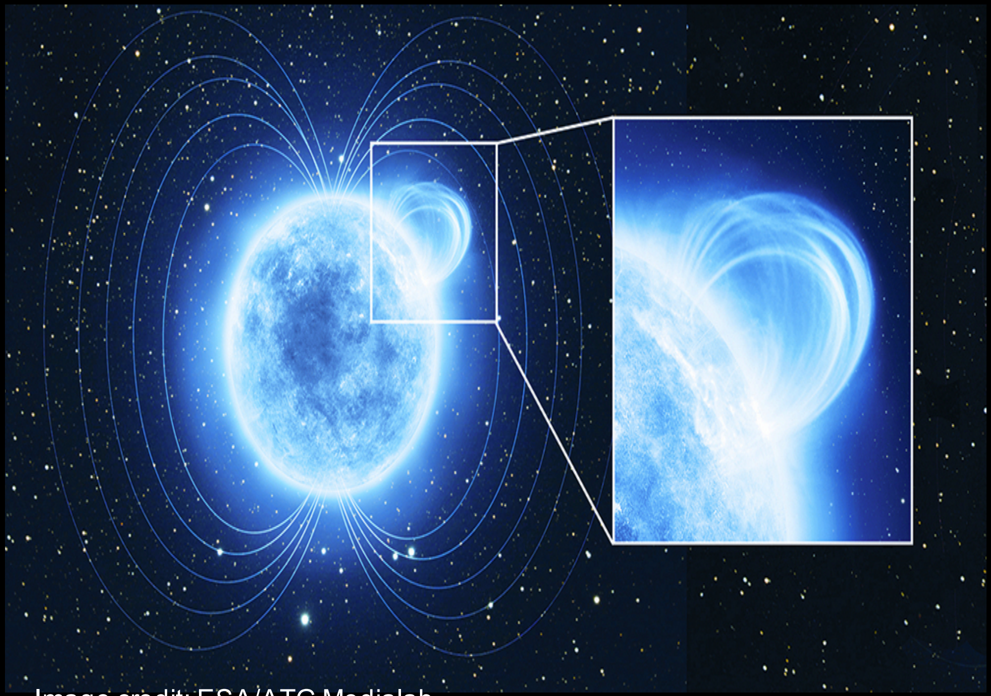


Image credit: ESA/ATG Medialab

$$E_{line} = 0.63\ (B_{loop}/10^{14}\ G)\ (1+z)^{-1}\ keV$$

↓

$$B_{loop} \approx 1.8 \times 10^{14}\ G$$
$$(B_{dipole} \approx 2.5 \times 10^{13}\ G)$$

First observational evidence of a complex magnetic field in the XDINSs

Evolutionary connection between XDINSs and magnetars.

Central compact objects (CCOs)

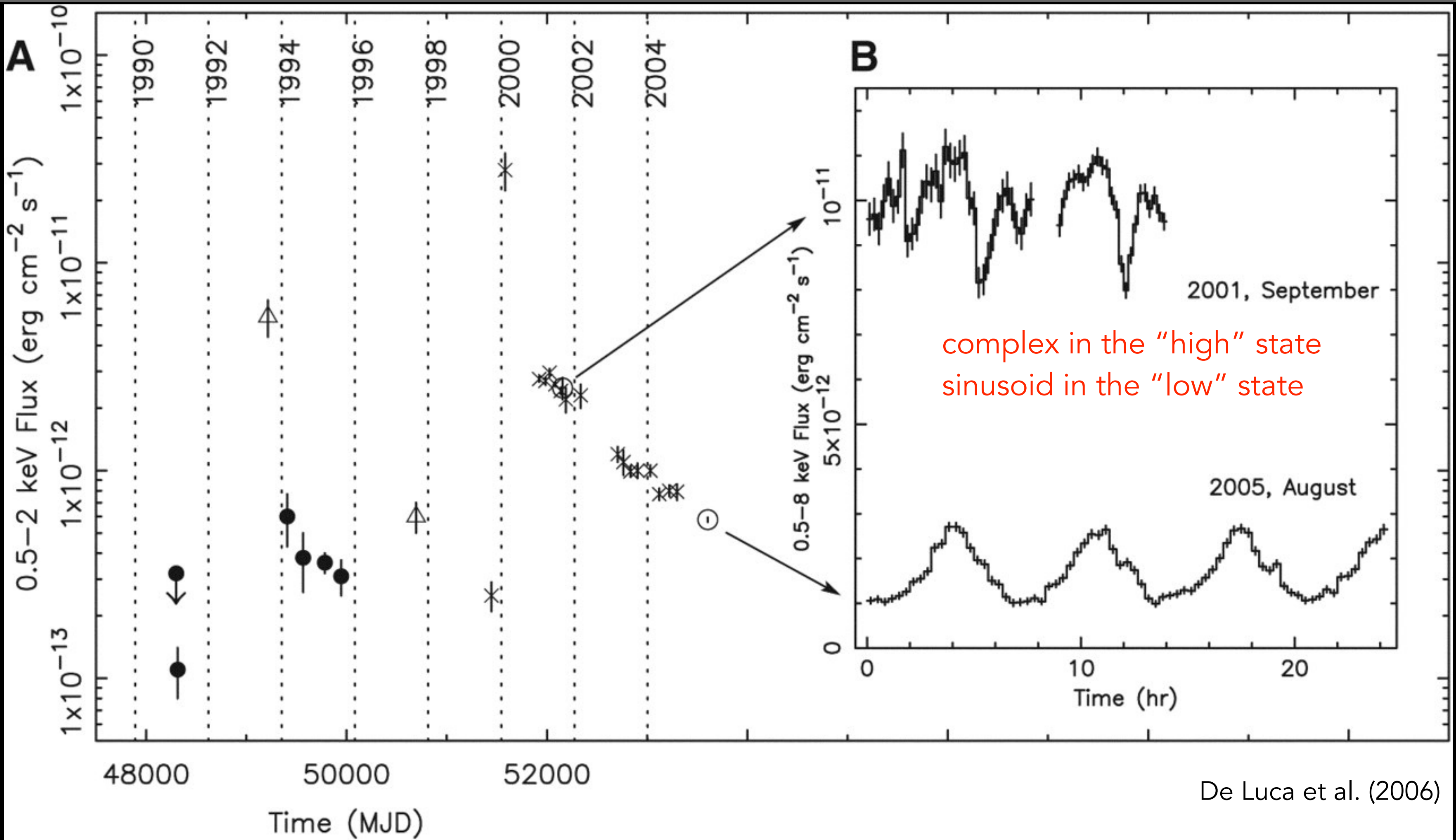
- Point-like X-ray sources close to centre of SNRs
- No counterparts at other wavelengths.
- Thermal-like emission
- $L_X \sim$ few 10^{33} erg s^{-1}

Central Compact Objects in Supernova Remnants

CCO	SNR	Age (kyr)	d (kpc)	P (s)	f_p [a] (%)	B_s (10^{10} G)	$L_{x,\mathrm{bol}}$ (erg s^{-1})
RX J0822.0−4300	Puppis A	4.5	2.2	0.112	11	2.9	5.6×10^{33}
CXOU J085201.4−461753	G266.1−1.2	1	1	...	<7	...	2.5×10^{32}
1E 1207.4−5209	PKS 1209−51/52	7	2.2	0.424	9	9.8	2.5×10^{33}
CXOU J160103.1−513353	G330.2+1.0	$\gtrsim 3$	5	...	<40	...	1.5×10^{33}
1WGA J1713.4−3949	G347.3−0.5	1.6	1.3	...	<7	...	$\sim 1 \times 10^{33}$
XMMU J172054.5−372652	G350.1−0.3	0.9	4.5	...	...	...	3.9×10^{33}
CXOU J185238.6+004020	Kes 79	7	7	0.105	64	3.1	5.3×10^{33}
CXOU J232327.9+584842	Cas A	0.33	3.4	...	<12	...	4.7×10^{33}
2XMMi J115836.1−623516	G296.8−0.3	10	9.6	...	...	...	1.1×10^{33}
XMMU J173203.3−344518	G353.6−0.7	~27	3.2	...	<9	...	1.3×10^{34}
CXOU J181852.0−150213	G15.9+0.2	1–3	(8.5)	...	...	...	$\sim 1 \times 10^{33}$

Gotthelf et al. 2013, De Luca 2017

1E 161348–505: a unique phenomenology



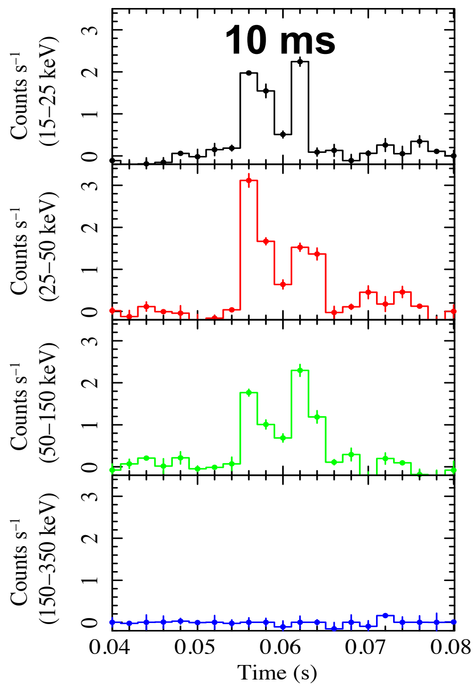
De Luca et al. (2006)

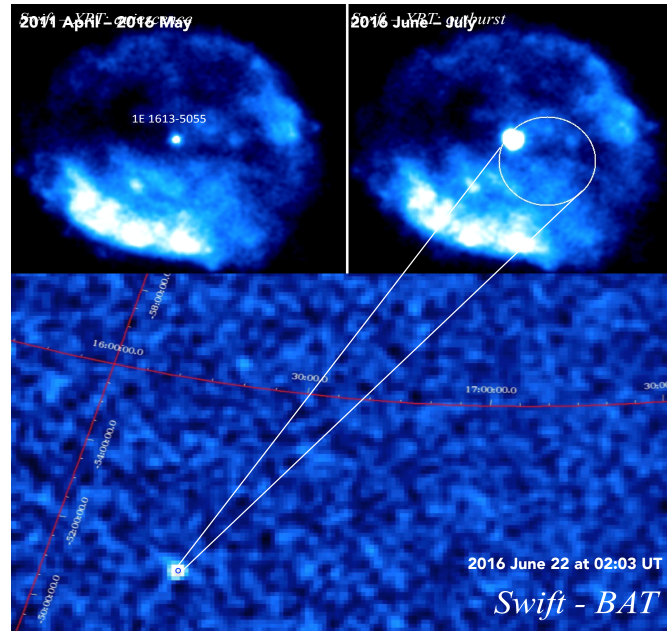
Factor ~100 flux variability on months/yrs

P = 6.67 hr, variable profile, age of 2kyr

1E 161348–505: magnetar-like activity

A magnetar-like burst (*Swift* BAT, 2016/06/22)





Double-peak profile

$L_{15\text{-}150\ keV} = 2\times10^{39}$ erg s^{-1}

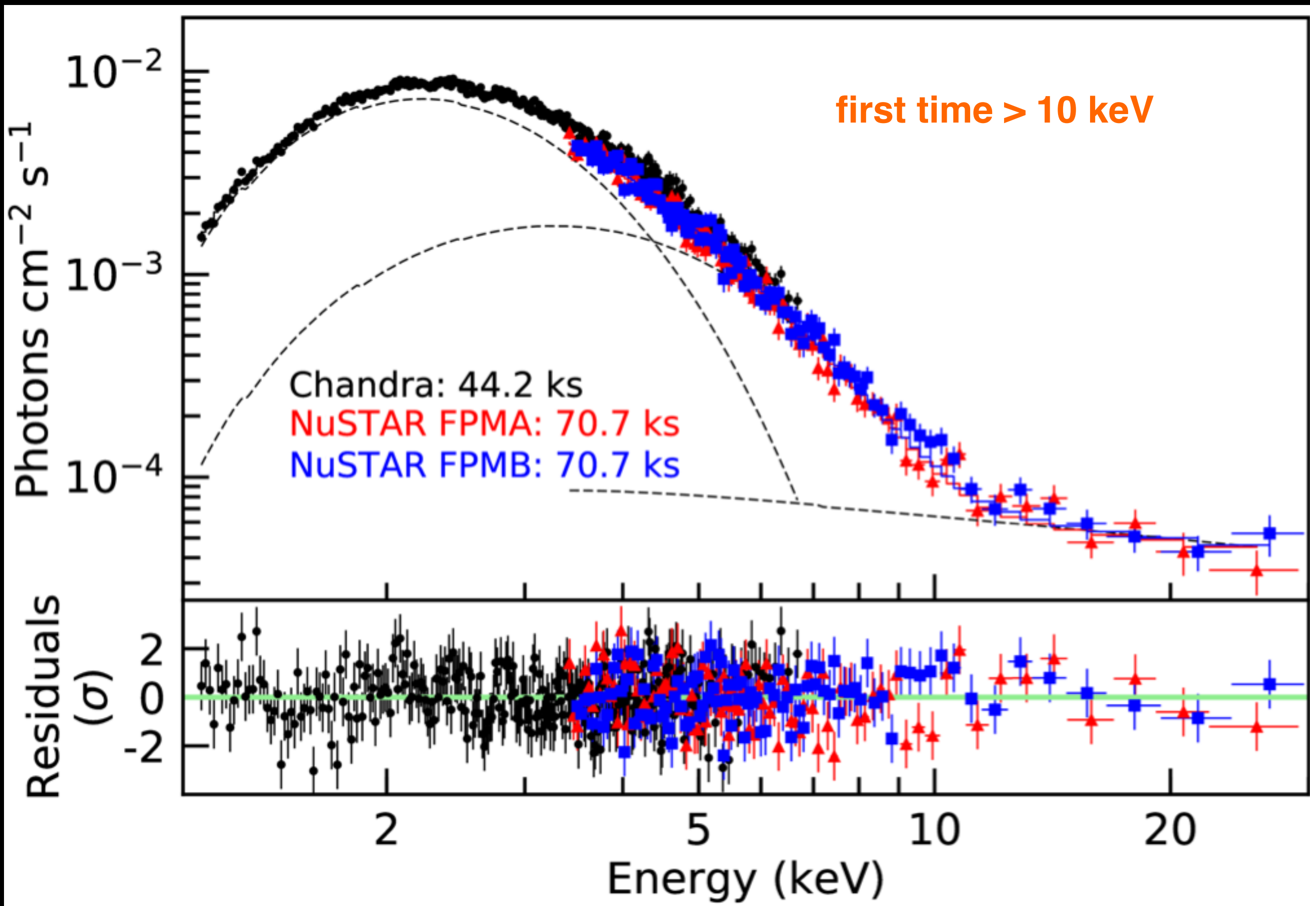
$F_{1\text{-}10keV}$ ~1.2×10^{-10} erg cm^{-2} s^{-1} wrt

$F_{1\text{-}10keV(q)}$ ~1.7×10^{-12} erg cm^{-2} s^{-1}

D'Ai' et al. 2016; Rea et al. 2016

Spectral analysis: outburst peak

Simultaneous observations with *Chandra* and *NuSTAR* on 2016 June 25



Rea et al. 2016

Model

2 blackbodies

$N_H = 2.05(5) \times 10^{22}$ cm^{-2}

$kT_1 = 0.52 \pm 0.01$ keV

$R_1 = 2.7 \pm 0.7$ km

$kT_2 = 0.93 \pm 0.05$ keV

$R_2 = 0.4 \pm 0.2$ km

power law

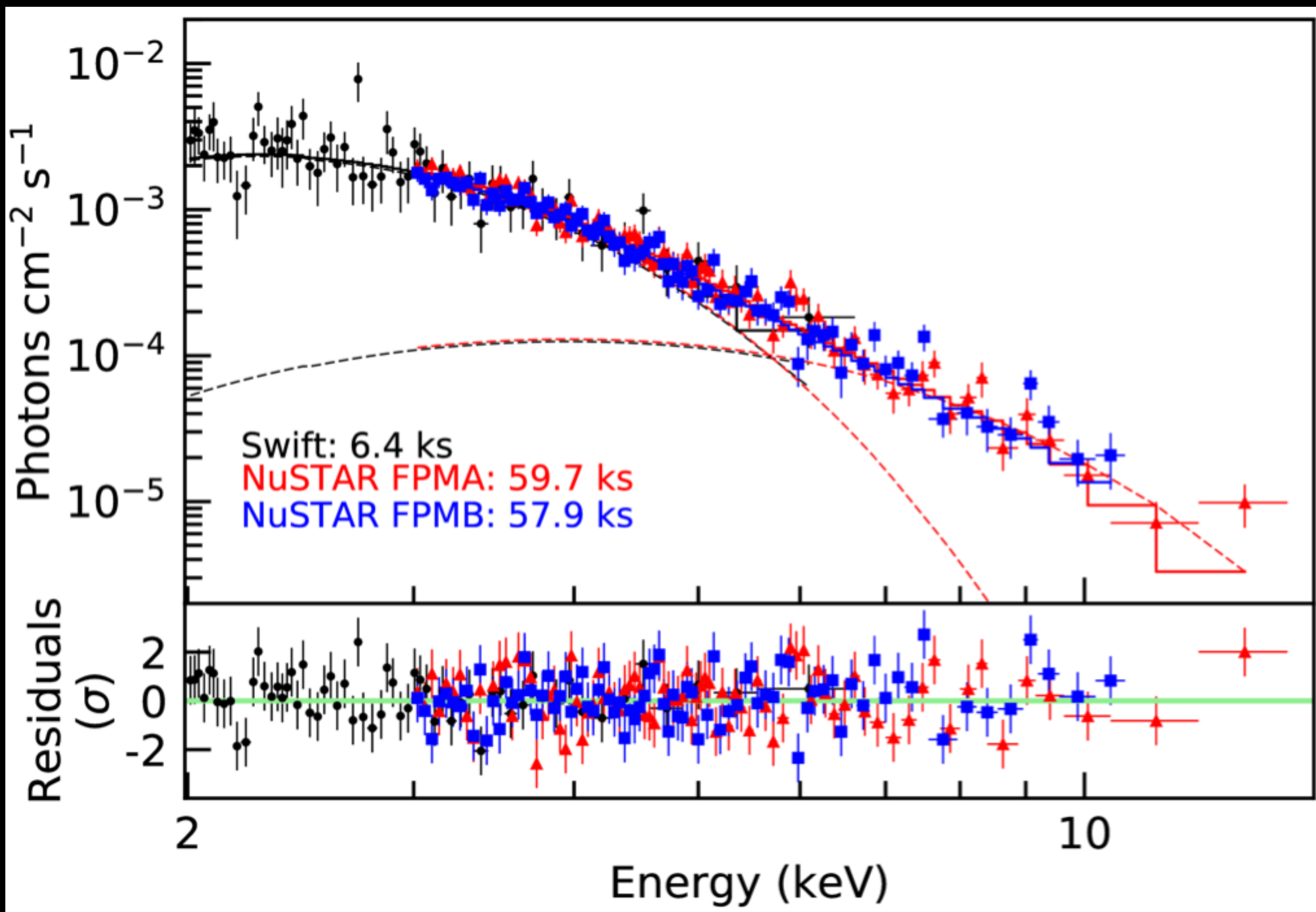
$\Gamma = 1.20 \pm 0.25$

$F_{obs,\ 0.5\text{-}30\ keV}$

3.7×10^{-11} erg cm^{-2} s^{-1}

Spectral analysis: outburst decay

345 days after the outburst onset



Borghese et al. 2017

Model
2 blackbodies

$KT_1 = 0.53 \pm 0.01$ keV

$R_1 = 1.48 \pm 0.10$ km

$KT_2 = 1.26 \pm 0.09$ keV

$R_2 = 0.07 \pm 0.02$ km

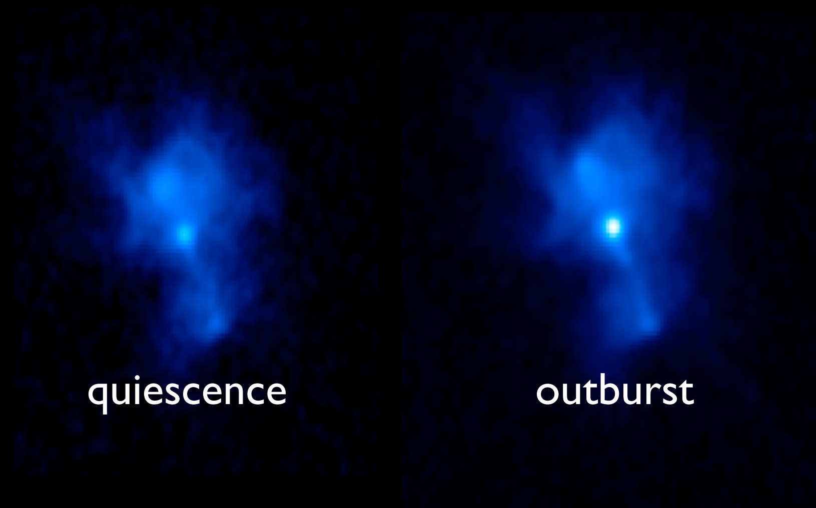
$F_{obs,\ 0.5\text{-}30\ keV}$

9.2×10^{-12} erg cm^{-2} s^{-1}

Magnetar-like activities from two young RPPs

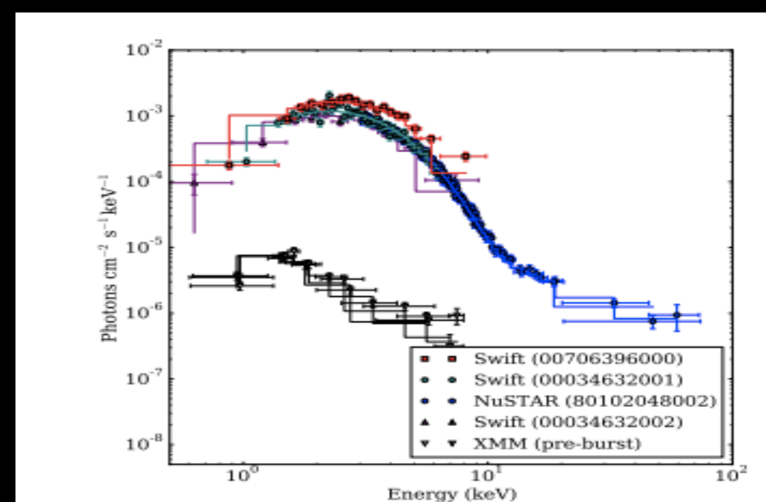
PSR 1846-0258

- rotational power of Edot ~ 8×10^{36} erg s^{-1}
- rotating with P ~ 0.3 s
- magnetic fields B ~ 5×10^{13} Gauss
- Kes 75 and with a PWN
- X-ray rotation-powered pulsar
- magnetar-like bursts and outburst in 2008



PSR 1119-6127

- rotational power of Edot ~ 2.3×10^{36} erg s^{-1}
- rotating with P ~ 0.4 s
- magnetic fields B ~ 4×10^{13} Gauss
- with a PWN
- Radio/X-ray rotation-powered pulsar
- magnetar-like bursts and outburst in 2016



Gavriil et al. 2008, Kumar & Safi-Harb 2008, Archibald et al. 2016, Gogus et al. 2016

Systematic study of magnetar outbursts

MOOC
Magnetar Outburst Online Catalog

Coti Zelati et al. 2018
Magnetar Outburst Online Catalog
http://magnetars.ice.csic.es/

- 23 outbursts from 14 magnetars + 2 high-*B* RPPs + CCO in RCW 103
- about 1100 X-ray observations (12 Ms) between from 1998 to 2017
- extraction of spectra for all observations
- spectral fitting with empirical and more physically-motivated models
- light curve extraction, modelling and estimate of energetics and decay time scale

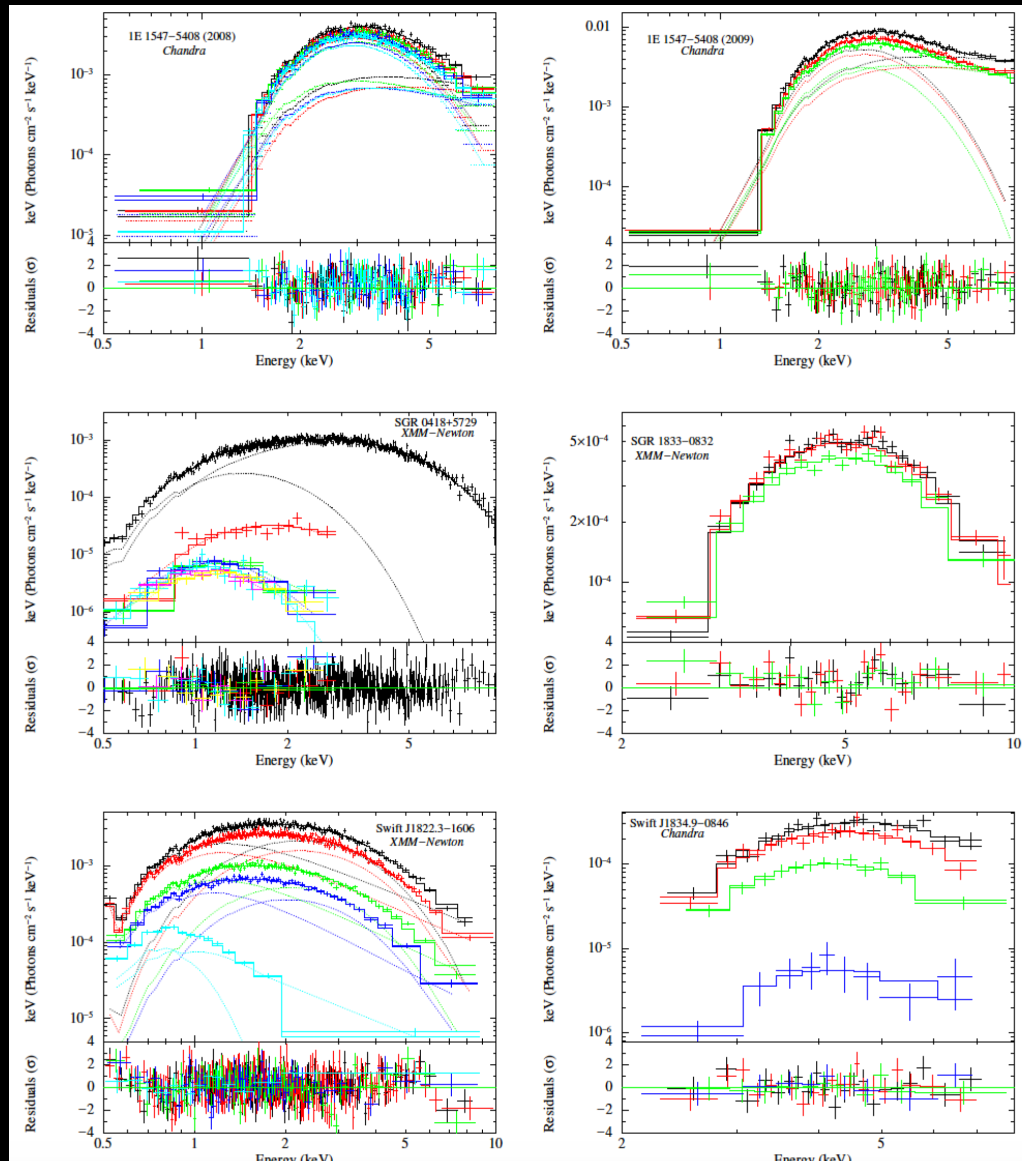
All performed in a homogeneous and consistent way for the first time!

High-quality X-ray spectra

1E 1547-5408 (2008)
Chandra

SGR 0418+5729
XMM-Newton

Swift 1822.3-1606
XMM-Newton

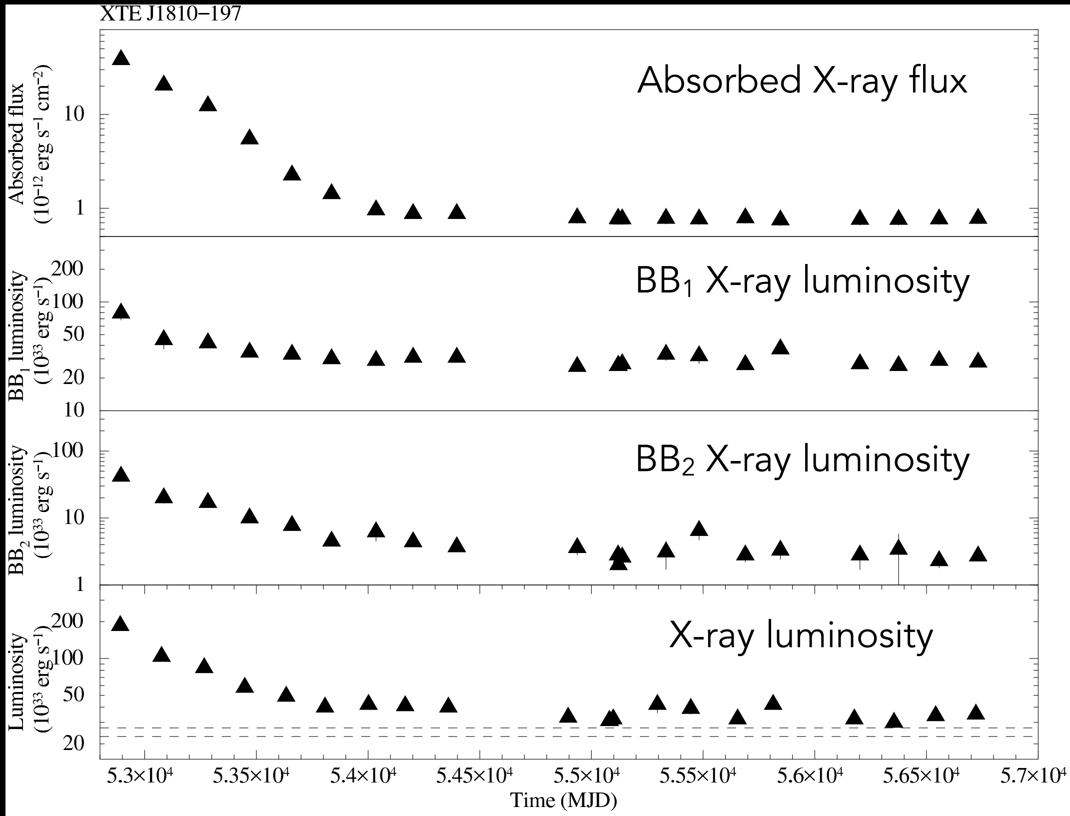


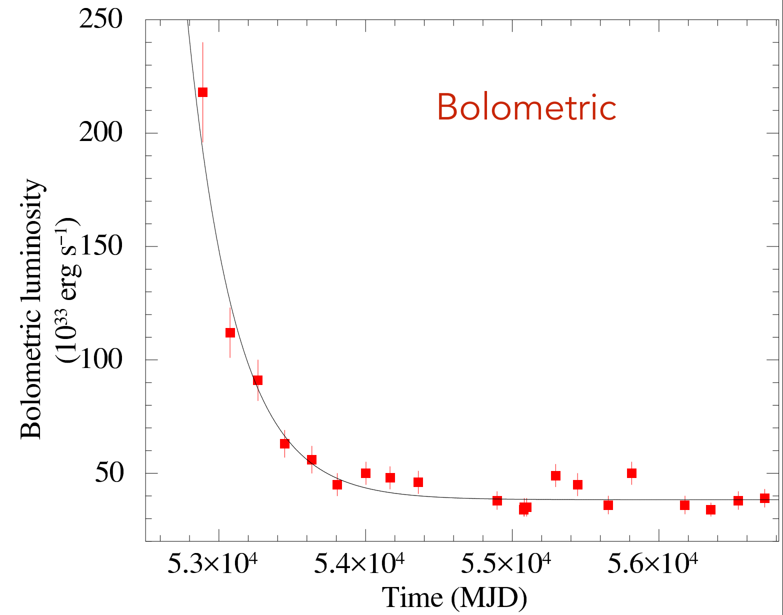
1E 1547-5408 (2009)
Chandra

SGR 1833-0832
XMM-Newton

Swift 1834.9-0846
Chandra

Cooling curves and empirical modelling





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

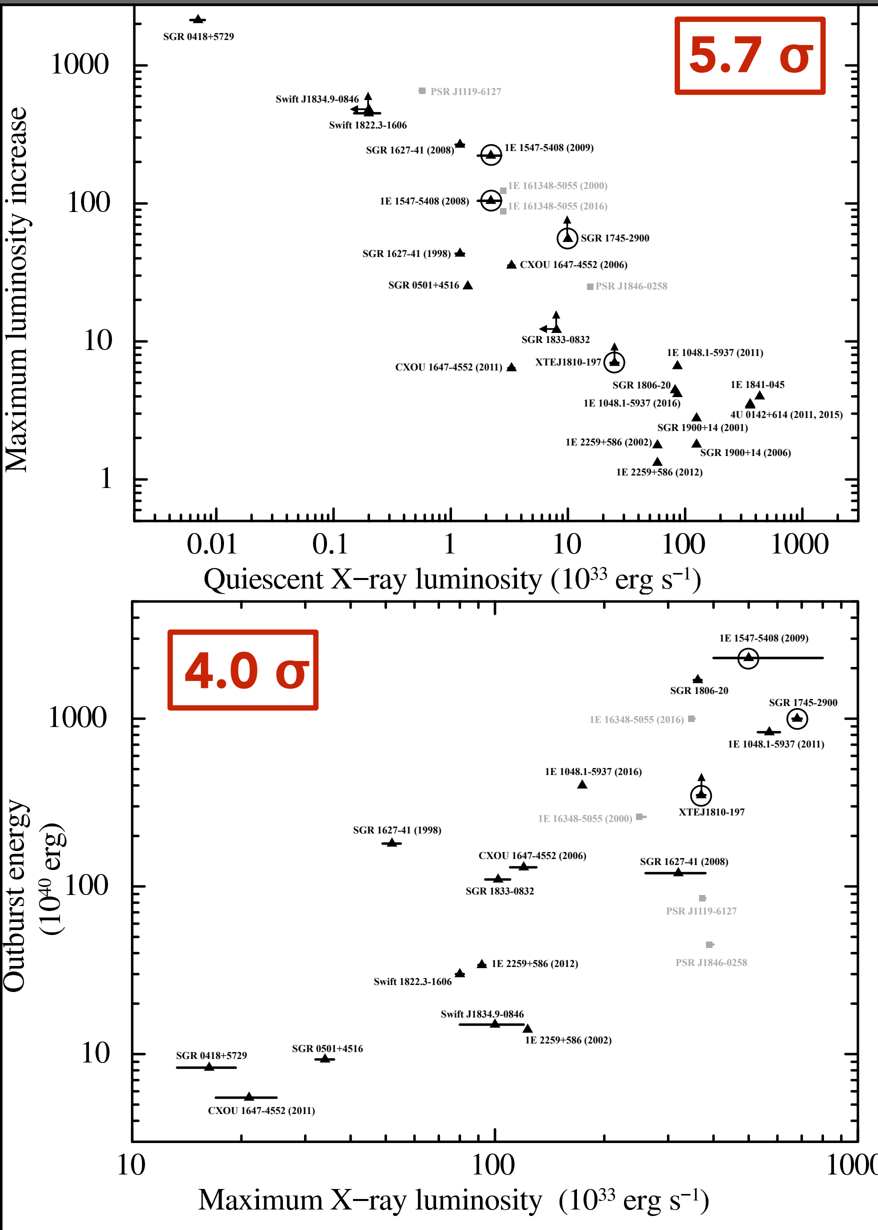
Estimate of the outburst
decay-timescale and energetics

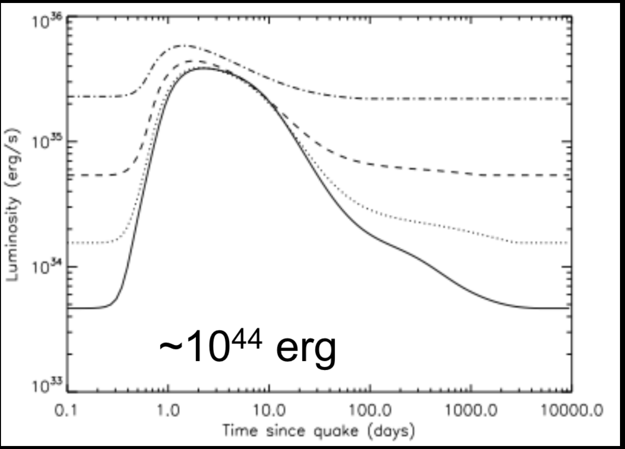
$$E = \int_0^{t_{qui}} L(t)dt$$

Correlations and anticorrelations

First parameter	Second parameter	Corr (c) or anticorr (a), Significance (σ) for Spearman / Kendall τ tests	PL index	Reference figure	Correlation expected? Internal cooling / untwisting bundle
Quiescent X-ray luminosity	Maximum luminosity increase	(a) , 5.7 / 4.9	-0.7	Fig. 3	Yes / yes
Spin-down luminosity	Quiescent bolometric luminosity	–	–	Fig. 4	No/no
Dipolar magnetic field	Quiescent bolometric luminosity	(c) , 3.2 / 2.9	2.0	Fig. 4	Does not apply
Dipolar magnetic field	Maximum luminosity	(c) , 2.5 / 2.4	0.5	Fig. 5	Yes/yes
Dipolar magnetic field	Decay time-scale	–	–	Fig. 5	Yes/yes
Dipolar magnetic field	Outburst energy	(c) , 3.7 / 3.3	1.0	Fig. 6	Yes / yes
Characteristic age	Outburst energy	(a) , 3.3 / 3.0	-0.4	Fig. 6	Yes / ?
Maximum luminosity	Outburst energy	(c) , 4.0 / 3.7	1.4	Fig. 6	Yes / yes
Quiescent bolometric luminosity	Outburst energy	–	–	Fig. 6	No / no
Maximum luminosity	Decay time-scale	–	–	Fig. 7	No / no
Outburst energy	Decay time-scale	(c) , 3.9 / 3.6	0.5	Fig. 7	Yes / yes
Outburst energy	Maximum luminosity increase	–	–	Fig. 8	No/no
Decay time-scale	Maximum luminosity increase	–	–	Fig. 8	No/no

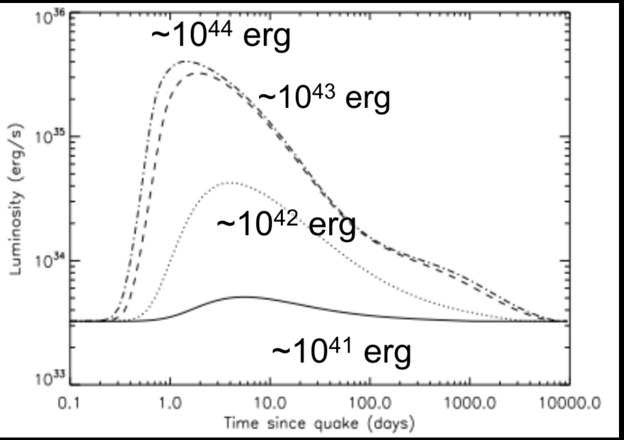
Correlations and anticorrelations (I)





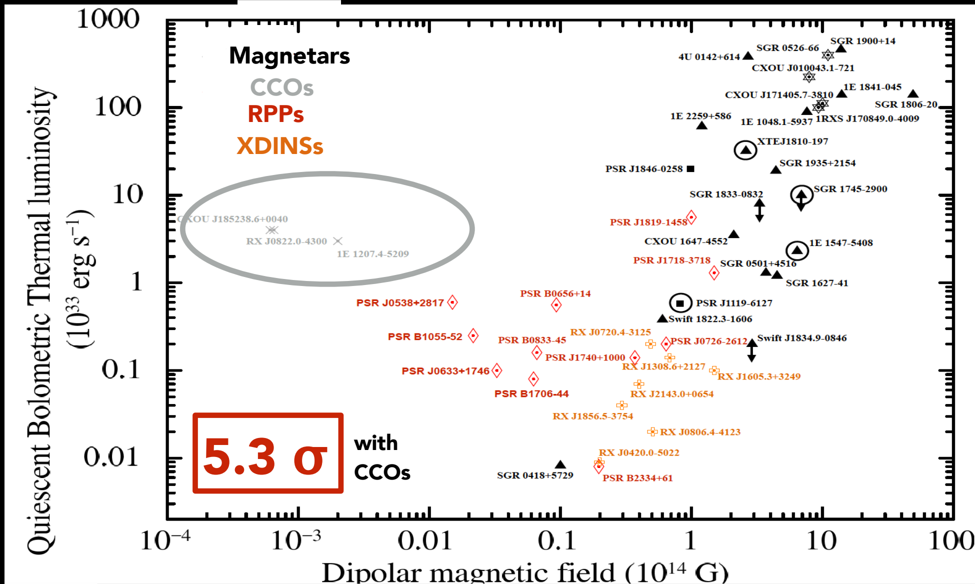
Large flux enhancements can only be observed in faint quiescent magnetars

The definition of "transient" and "persistent" magnetars is deceptive: it only reflects their different quiescent luminosities



Pons & Rea (2012)

Correlations and anticorrelations (II)



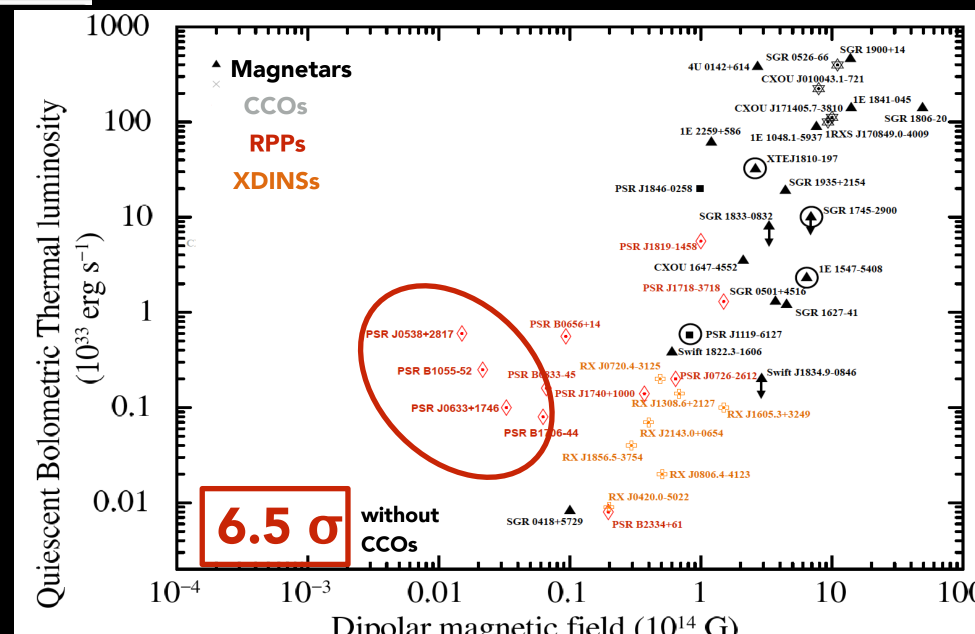
CCOs depart significantly from the trend.

Expected in the '***hidden magnetic field***' scenario (Viganò & Pons 2012; Torres-Forné et al. 2016)

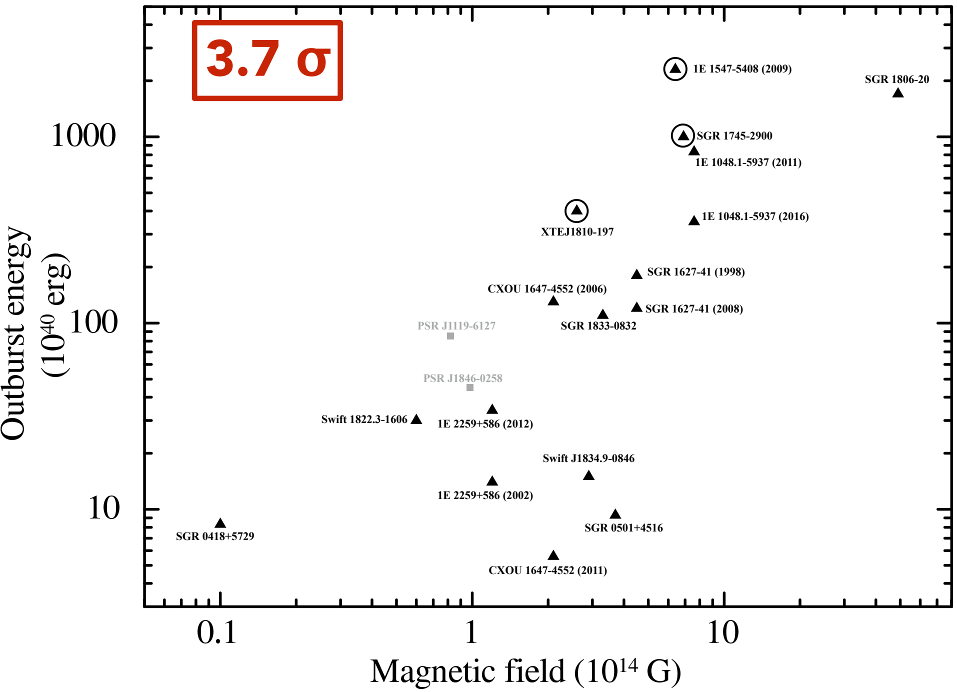
The external *B* field is lower than the internal 'hidden' *B* field, hence does not trace the bolometric luminosity

RPPs depart a bit from the trend

The larger luminosity wrt the prediction likely due to **slamming particles** heating the NS surface

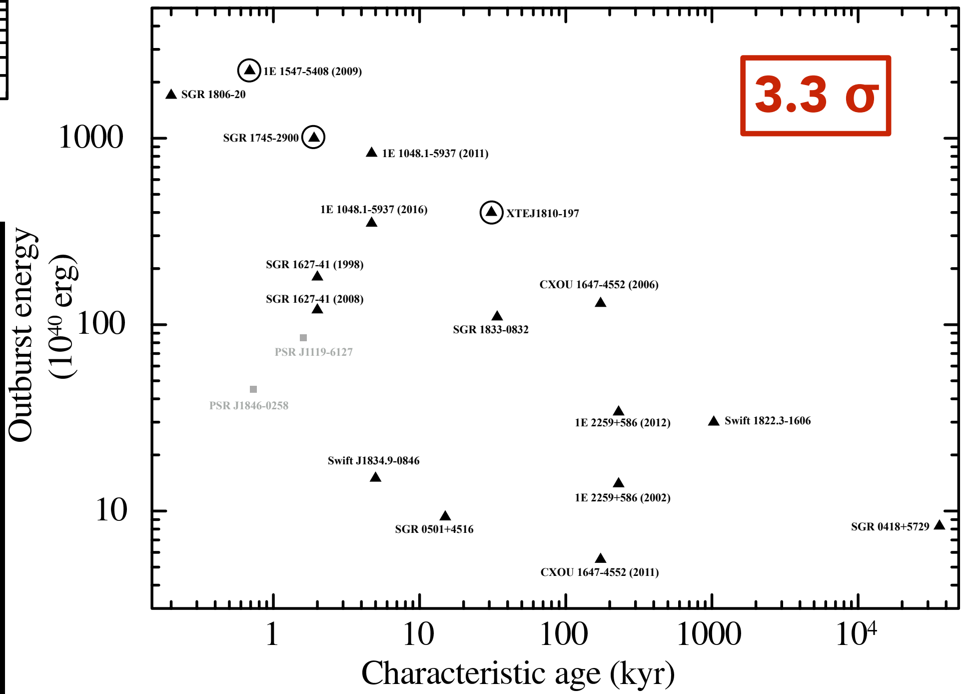


Correlations and anticorrelations (III)

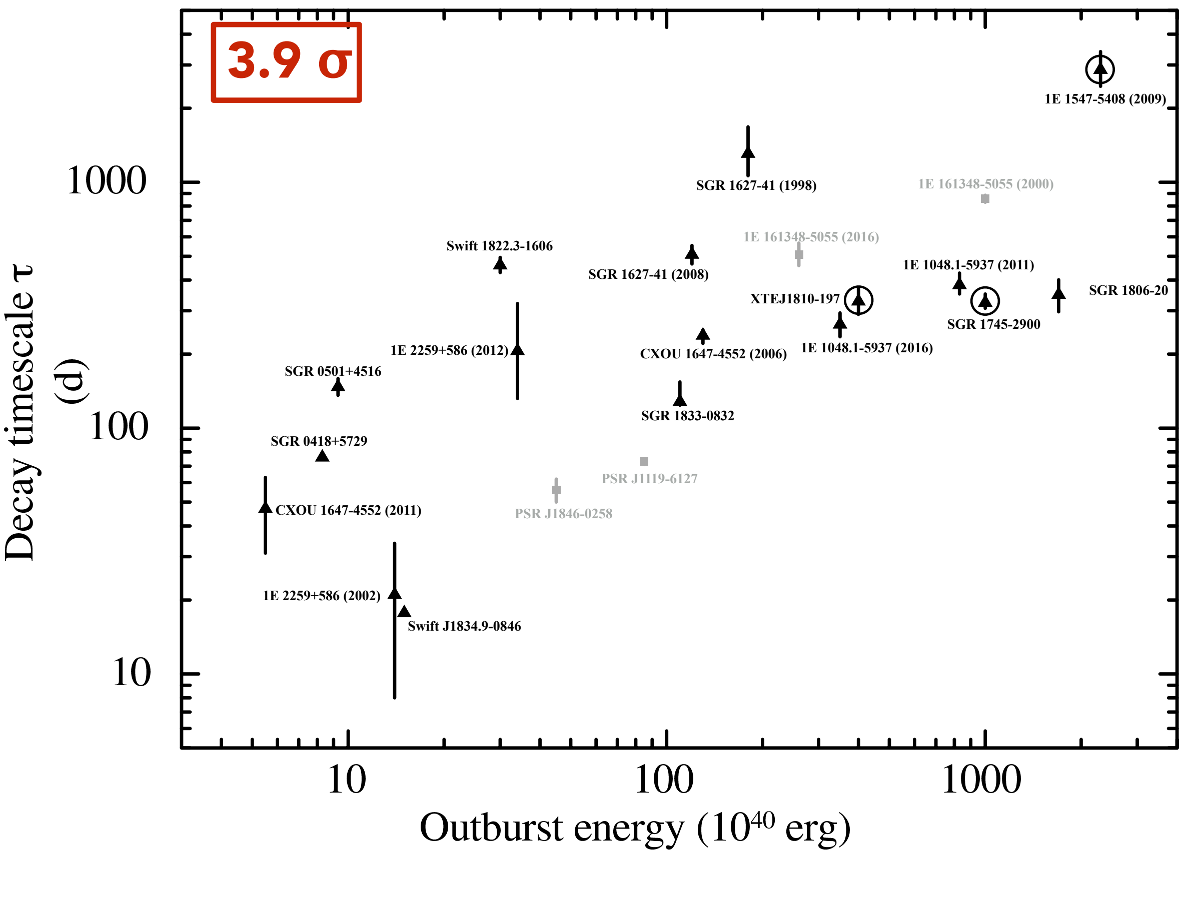


Magnetar outbursts are ultimately powered by the dissipation of the B-field

Younger magnetars undergo more energetic outbursts



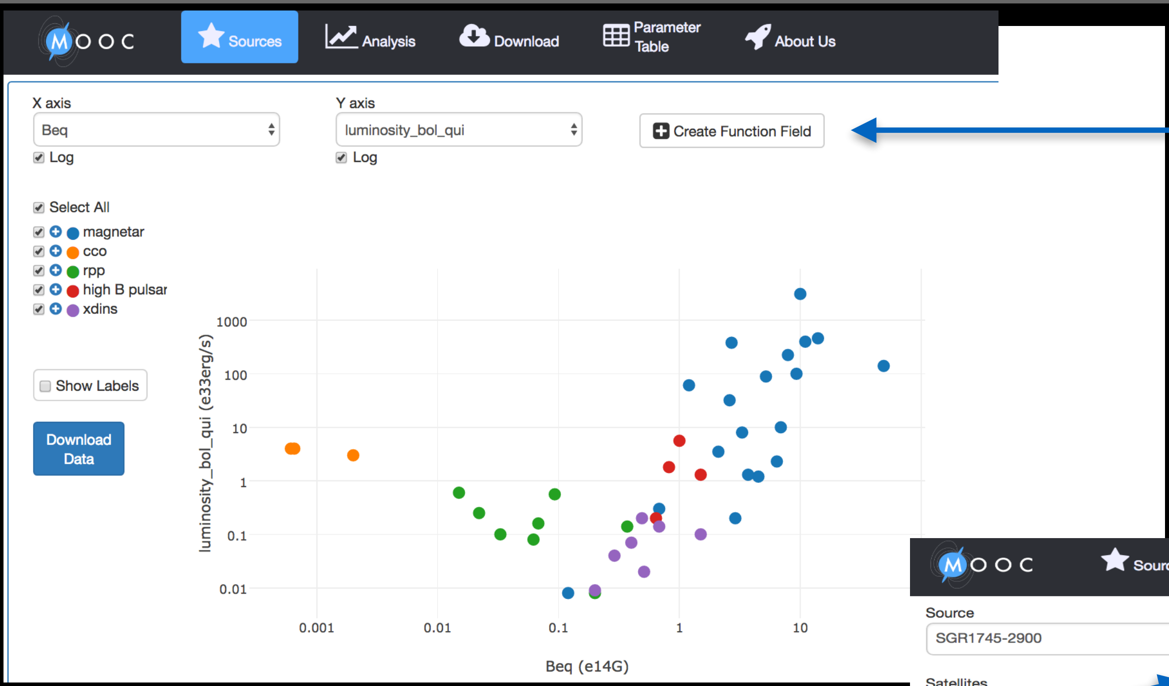
Correlations and anticorrelations (IV)



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)

The magnetar outburst online catalogue



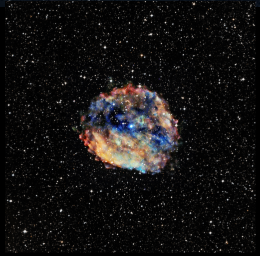
Fit your favourite function to different parameters!

Download all data and analyse them!

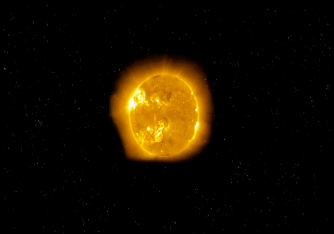
Francesco Coti Zelati (CSIC-IEEC)

Summary and conclusions

- Magnetars are unique laboratories to study the effects on matter embedded in extreme magnetic fields.



- The intensive follow-up of magnetar outbursts is giving new key discoveries and results (e.g. the Galactic Centre magnetar and the CCO in RCW 103)



- Magnetar activity likely has a larger spread within the neutron star population

- General Utility. The Magnetar Outbursts Online Catalogue