An observational overview on highly magnetic neutron stars

Francesco Coti Zelati

Institute of Space Sciences (ICE), CSIC-IEEC, Barcelona

MODE-SNR-PWN 2019, Orleans (France), April 10, 2019

Magnetars

- about 25 X-ray pulsars with Lx ~ 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 ~ 0.3 - 12 s

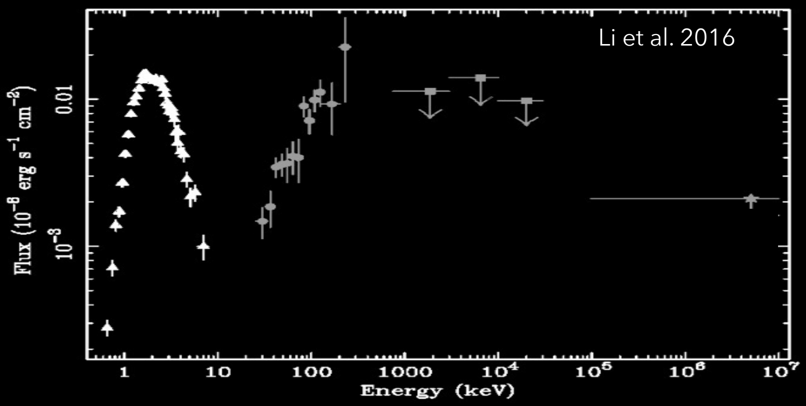
- magnetic fields of $B_p \sim 10^{13} - 10^{15}$ Gauss

- flaring activity in X-ray/gamma-ray energy range (0.01 - 10^2 s; $L_x \sim 10^{38} - 10^{46}$ erg s^{-1})

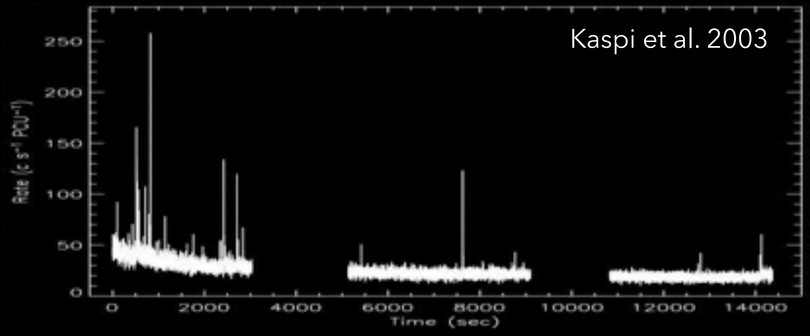
- large outbursts (months-years; $E \sim 10^{40} - 10^{43}$ erg)

- transient radio emission (in 4 cases)

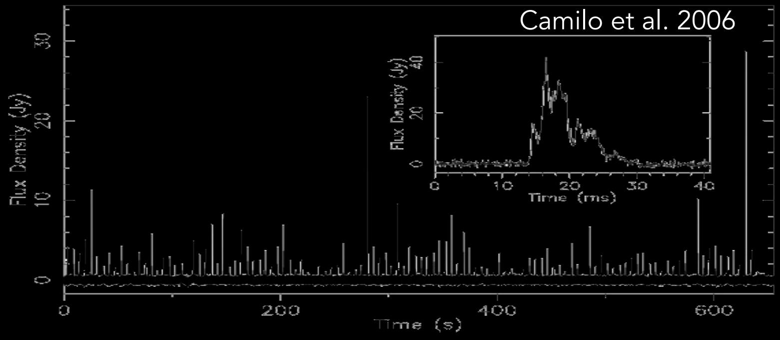
Turolla et al. 2015; Kaspi & Beloborodov 2017; Esposito et al. 2018



Li et al. 2016

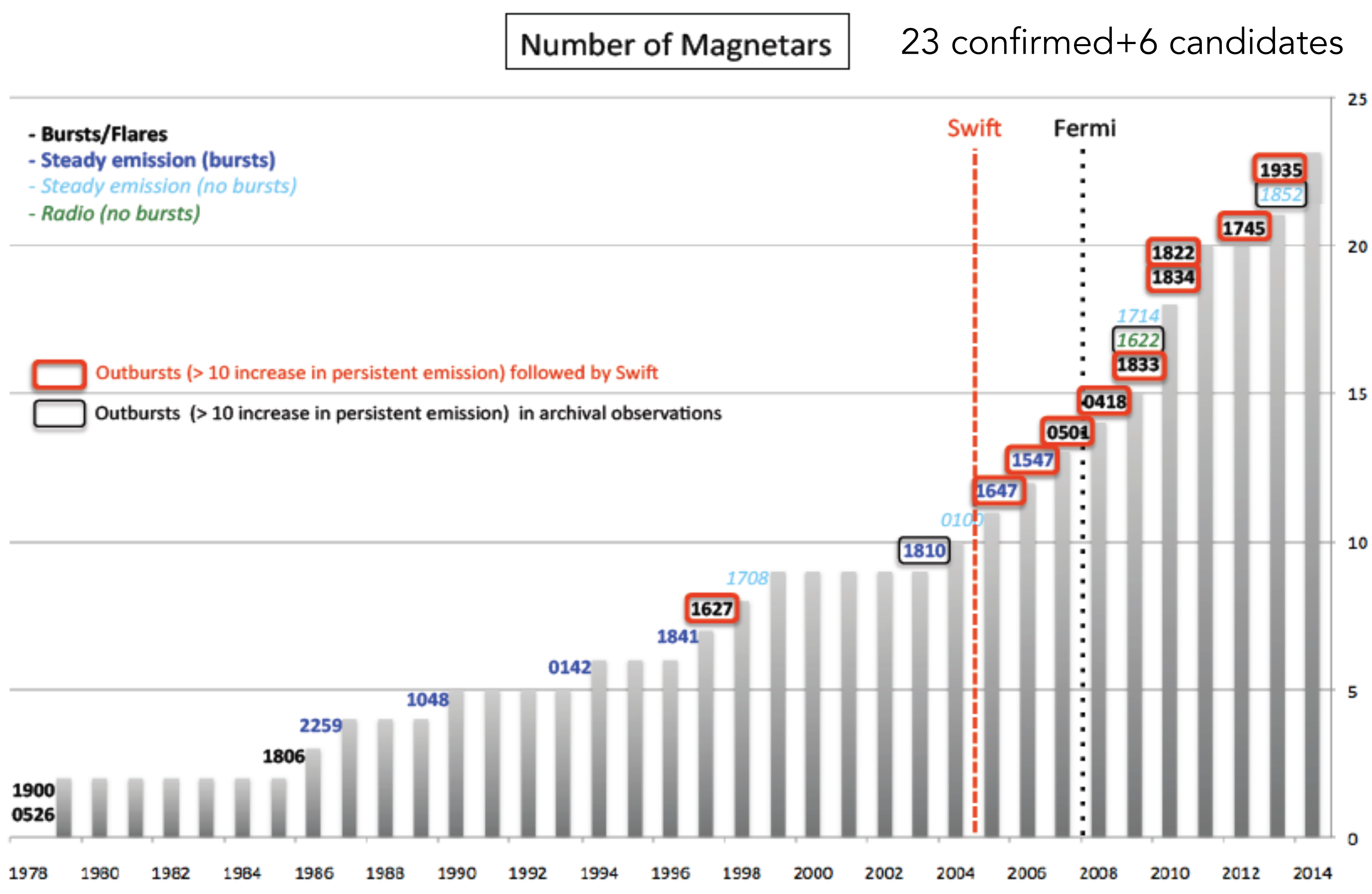


Kaspi et al. 2003



Camilo et al. 2006

Discovery rate

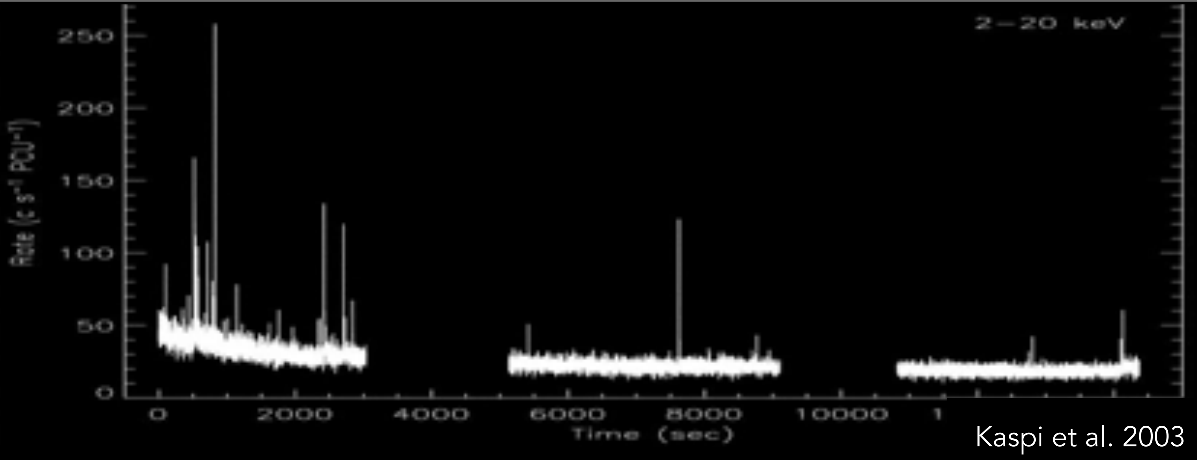


Flaring activity (timescale: sec/min)

Short bursts

- duration ~0.01-1s
- L_x ~10^{39}-10^{41} erg s^{-1}
- soft γ-rays thermal spectra

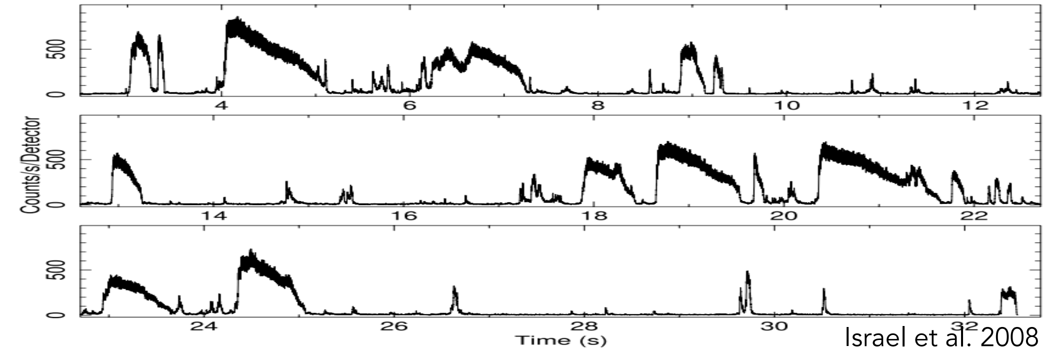
(kT ~ 10-40 keV)



Kaspi et al. 2003

Intermediate bursts

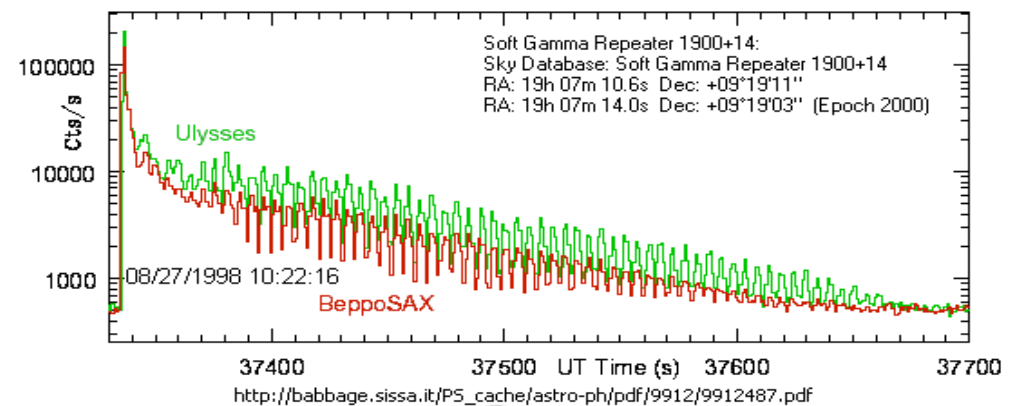
- duration 1-40 s
- peak ~10^{41}-10^{43} erg s^{-1}
- abrupt on-set
- usually soft γ-rays thermal spectra



Israel et al. 2008

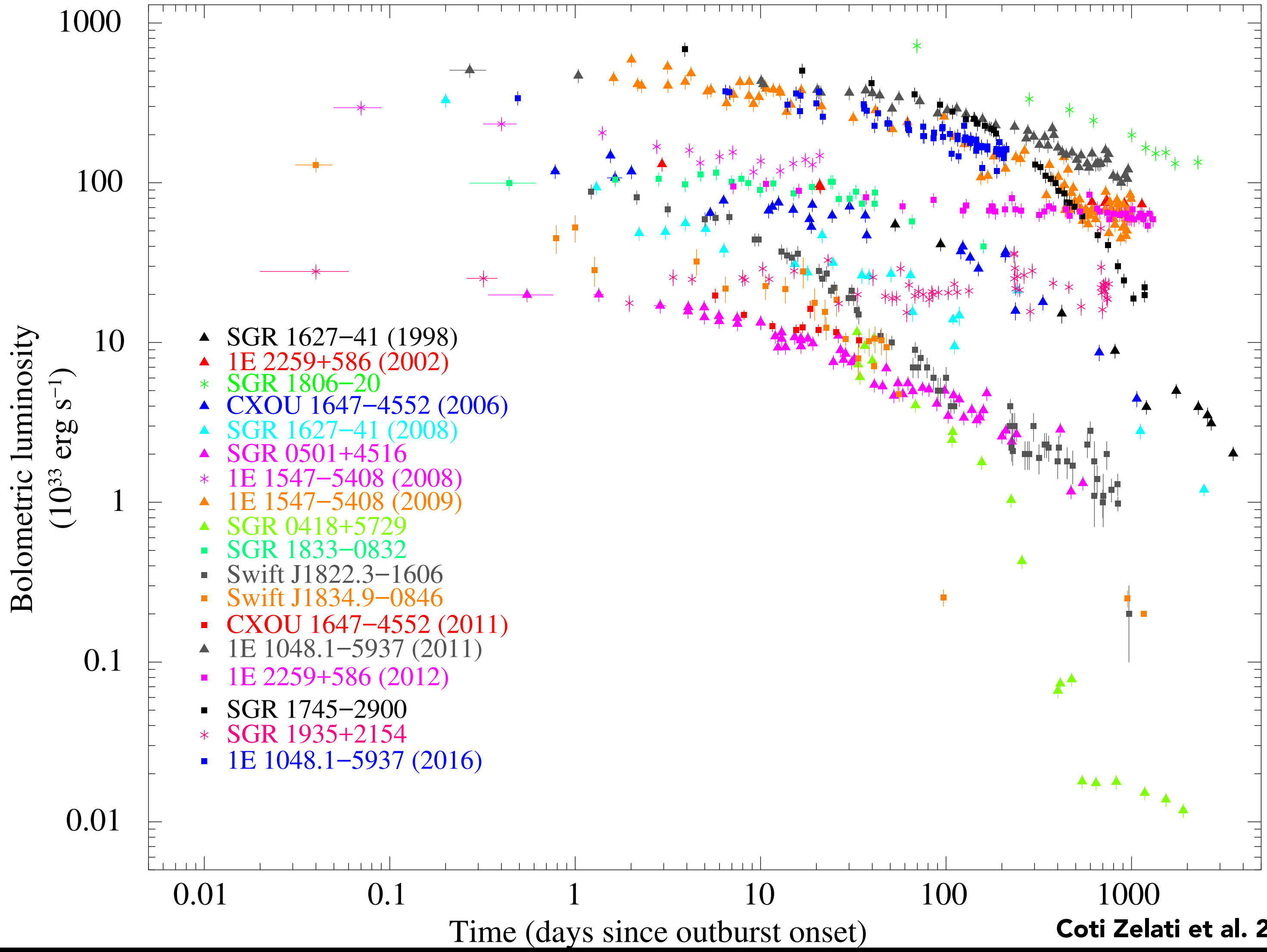
Giant Flares

- very rare events (only 3 observed)
- L_x > 3×10^{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

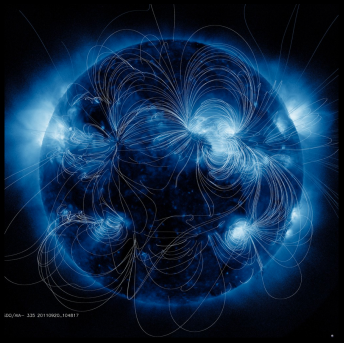
Outburst activity (timescale: months/years)



Coti Zelati et al. 2018

Outburst activity: mechanisms

Internal source of heat

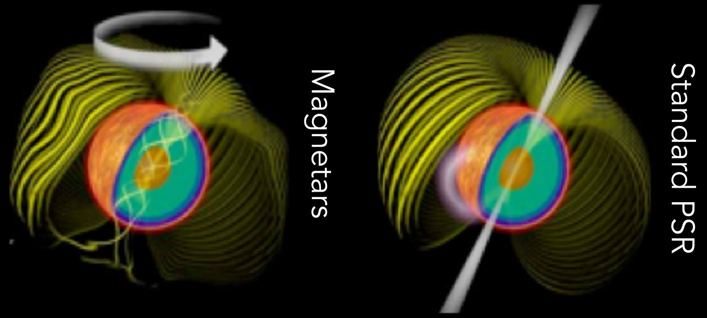


Magnetic stresses in localised parts of the crust

Plastic flows convert magnetic energy into heat

Heat conducted up and radiated

External source of heat



Crustal displacements twist up the external B-field.

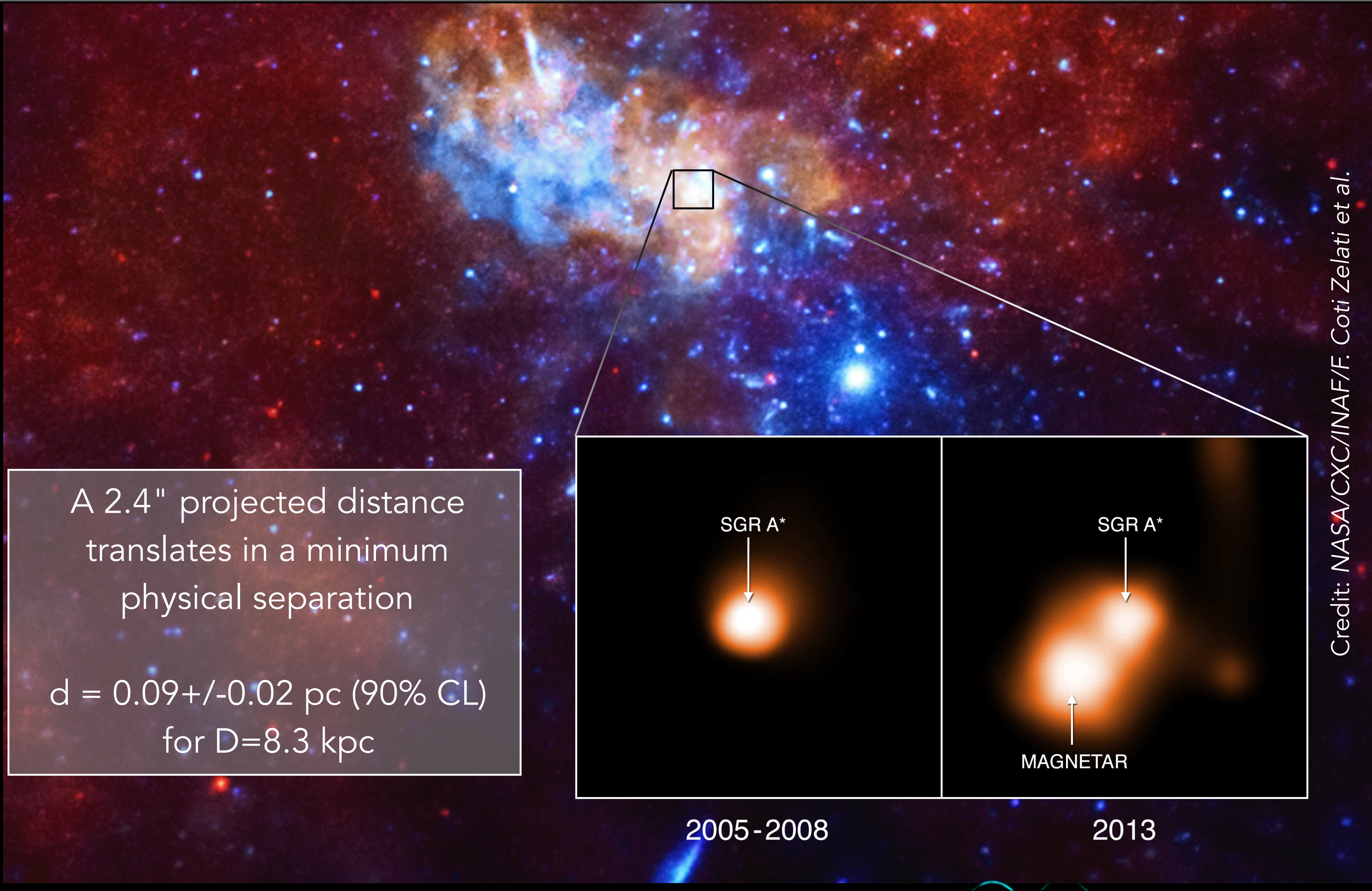
Returning currents hit the surface

The bundle dissipates as the energy supply from the star interior decreases

Both processes are likely at work.

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

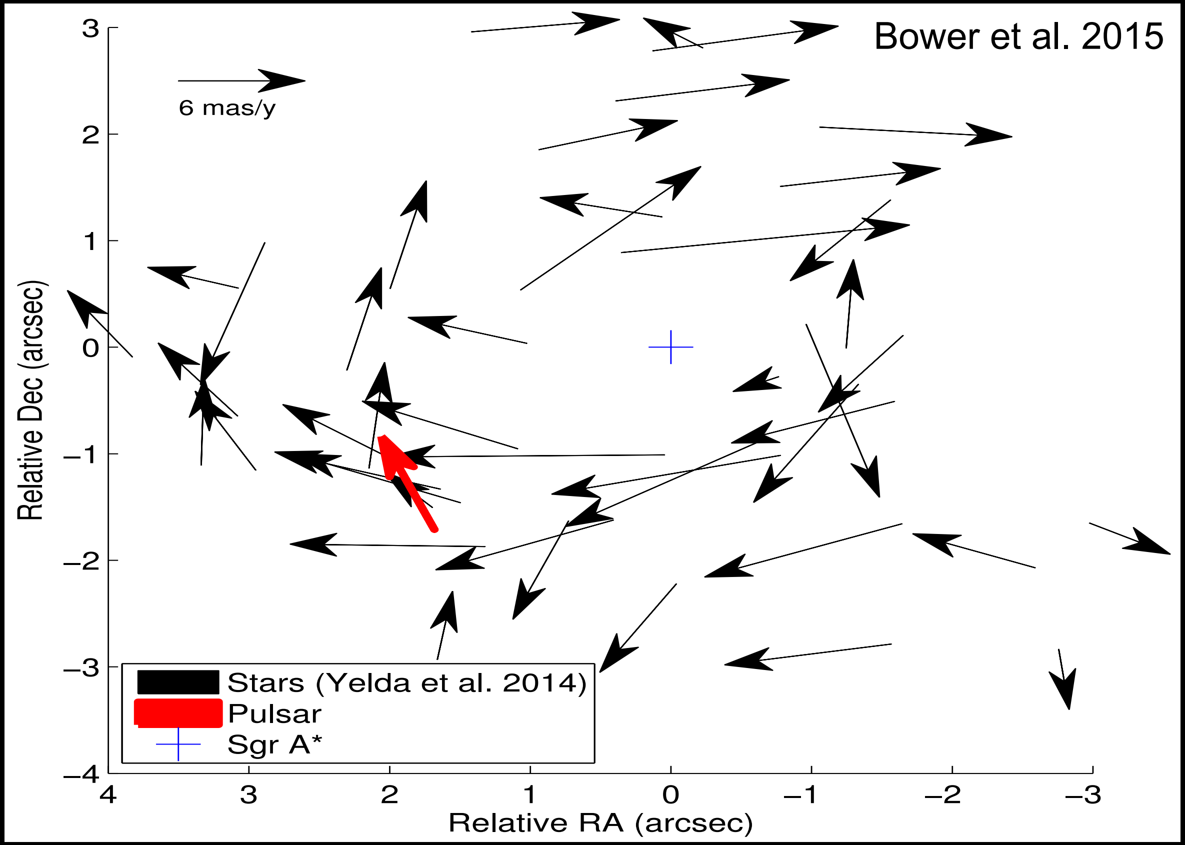


A 2.4" projected distance translates in a minimum physical separation

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

Credit: NASA/CXC/INAF/F. Coti Zelati et al.

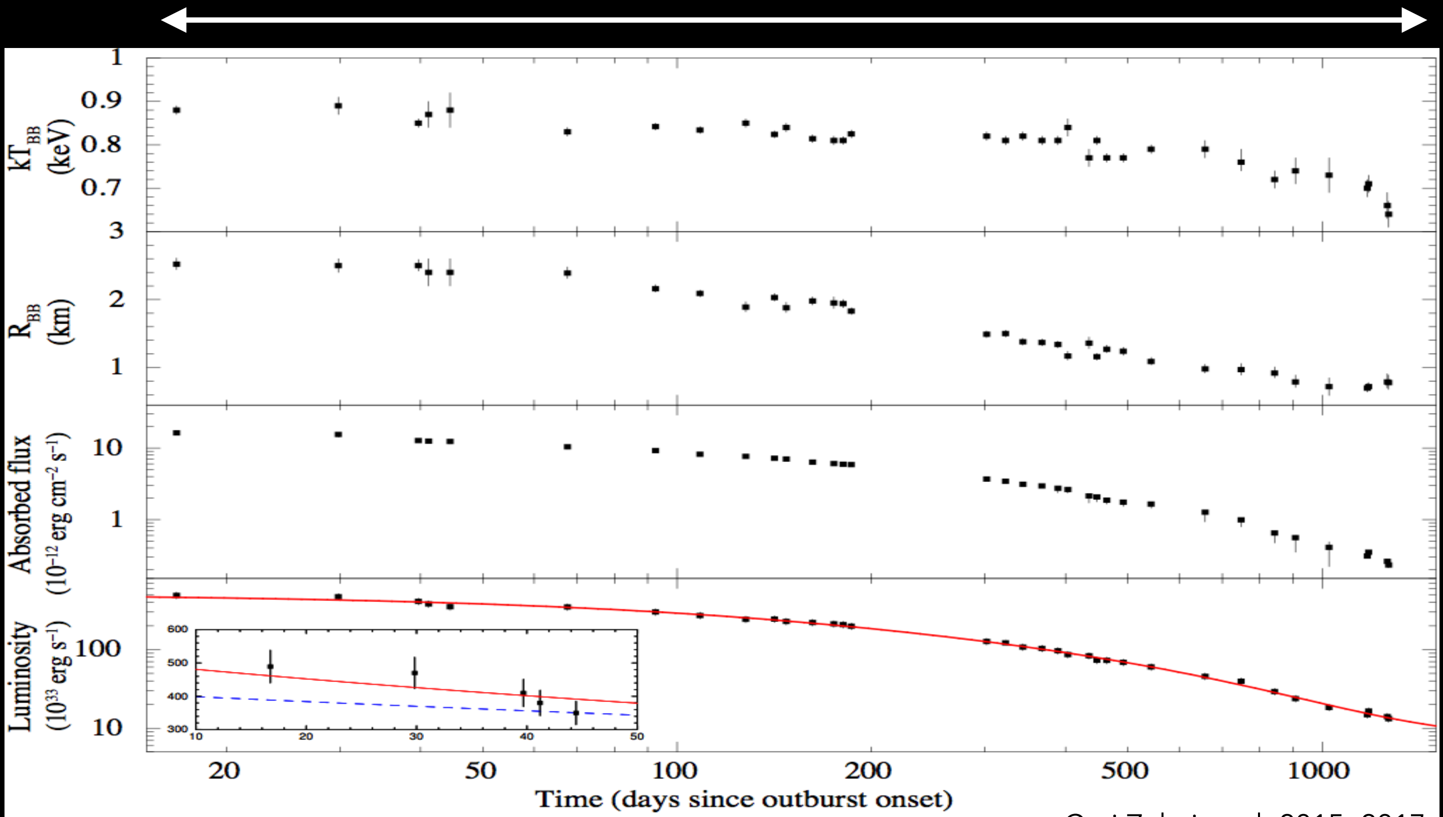
The magnetar in the Galactic Centre: SGR 1745-2900


Bower et al. 2015

Proper motion from *VLBA* observations

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

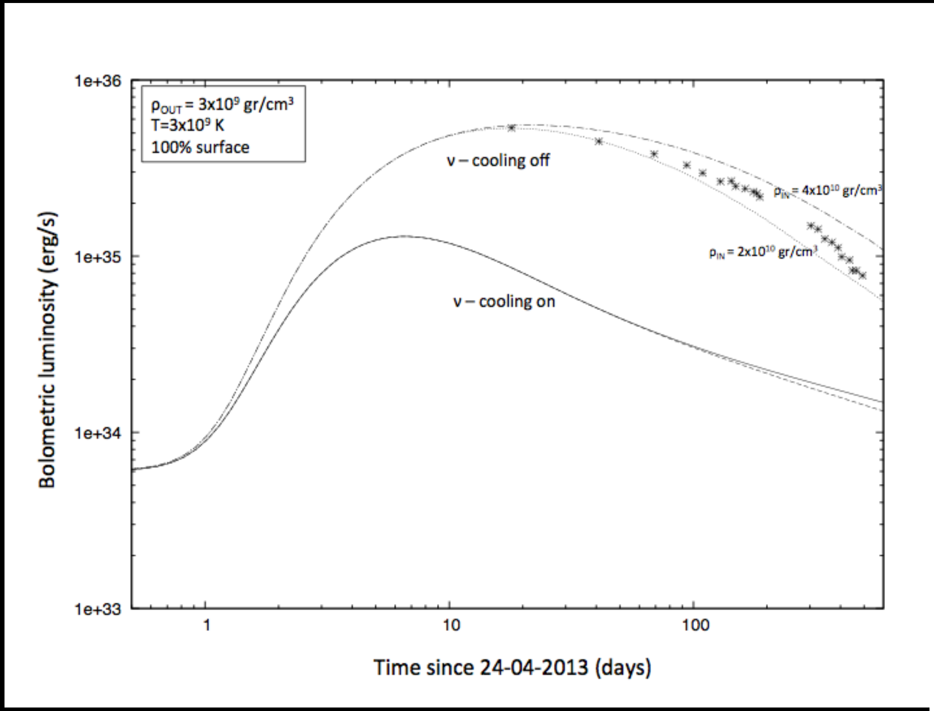
The magnetar in the Galactic Centre: SGR J1745-2900



~ 3.5 years

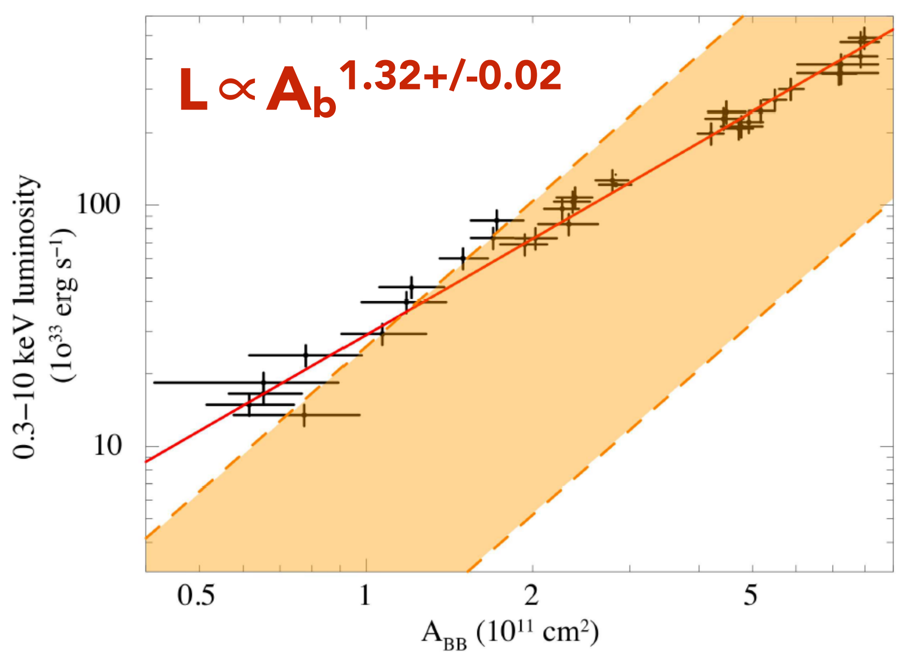
Coti Zelati et al. 2015, 2017

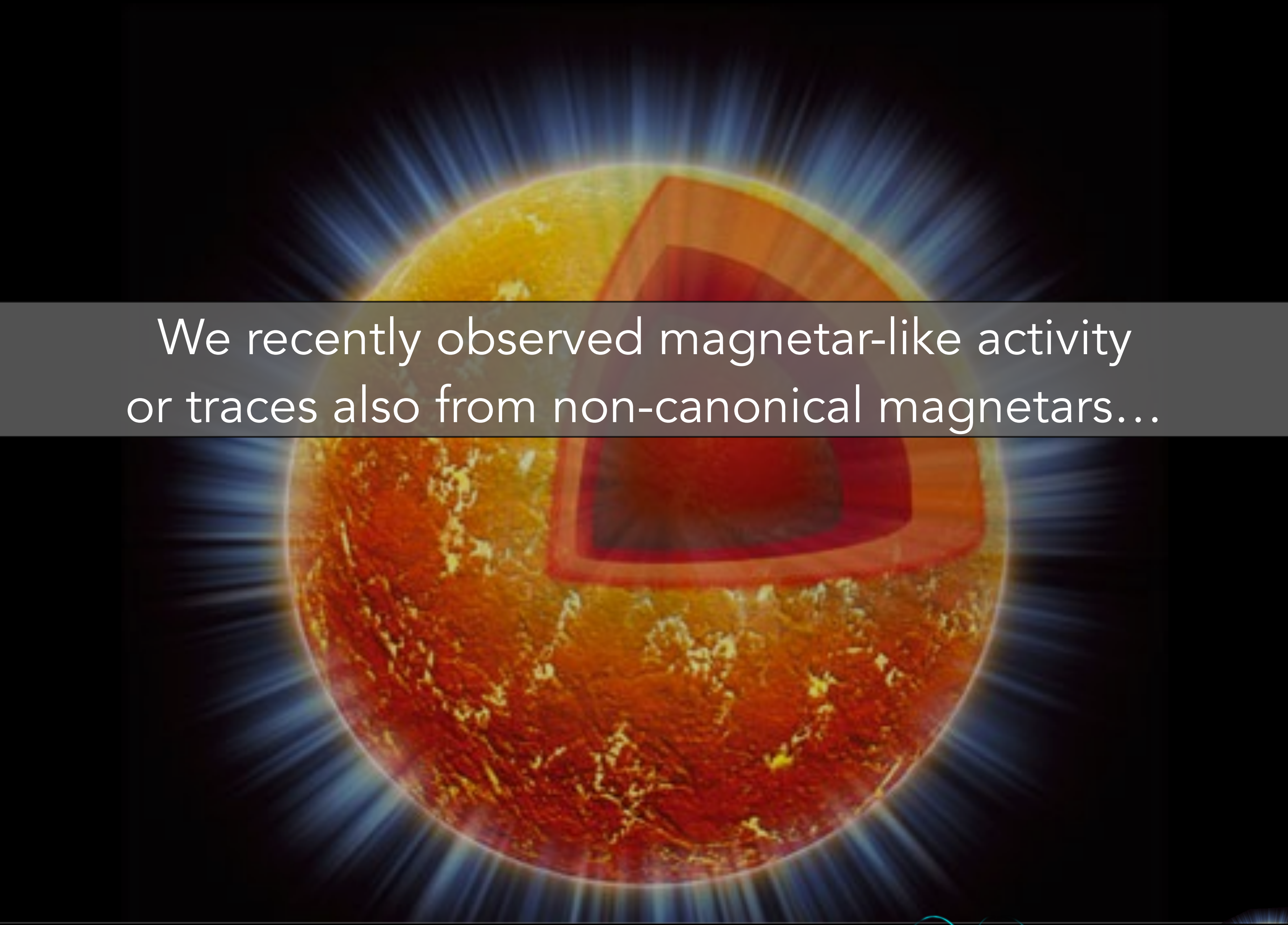
The magnetar in the Galactic Centre: SGR J1745-2900



Cannot be only crustal cooling from a single injection.

Qualitative agreement with bundle untwisting. Bombardment of magnetospheric currents?

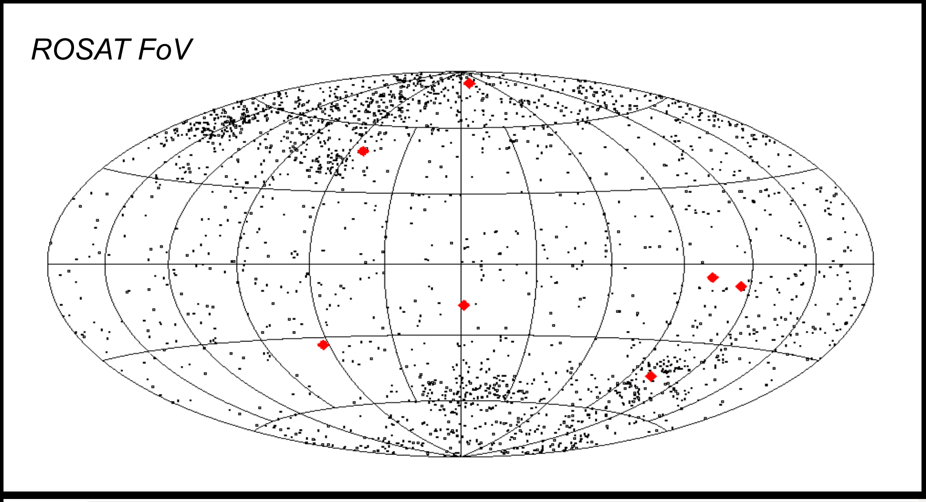


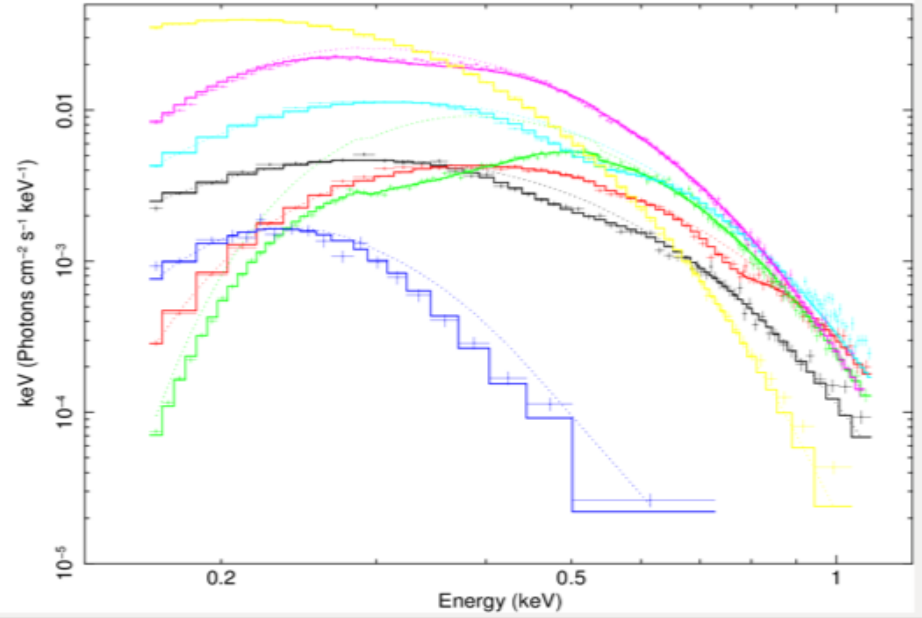


We recently observed magnetar-like activity or traces also from non-canonical magnetars…

Thermally emitting neutron stars (XDINSs)

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

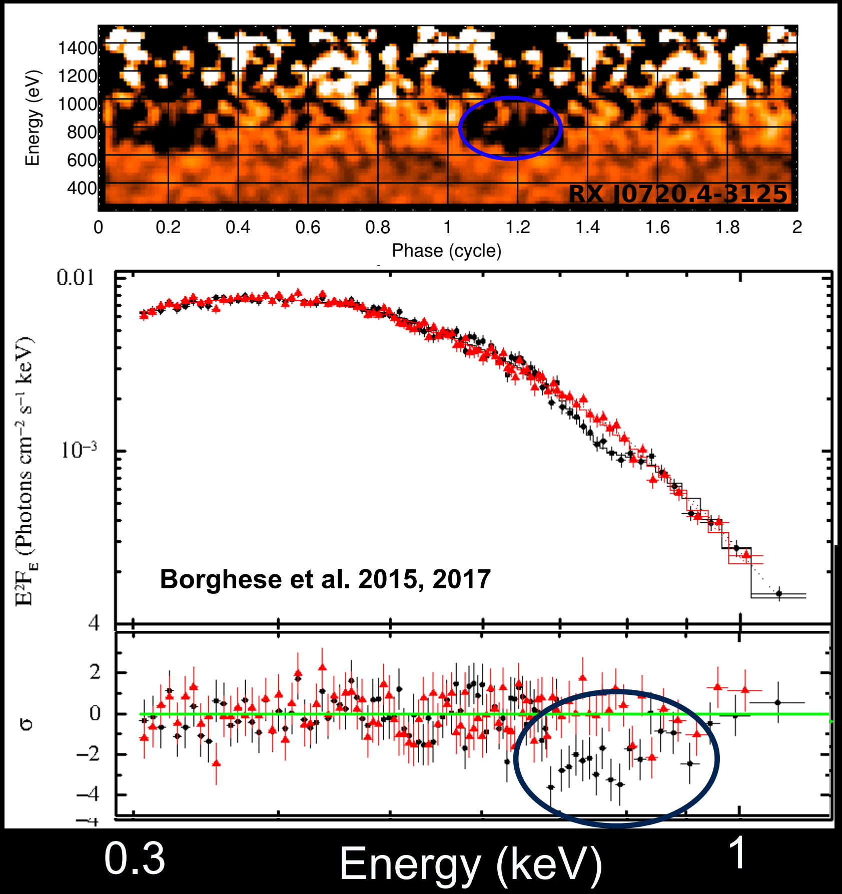


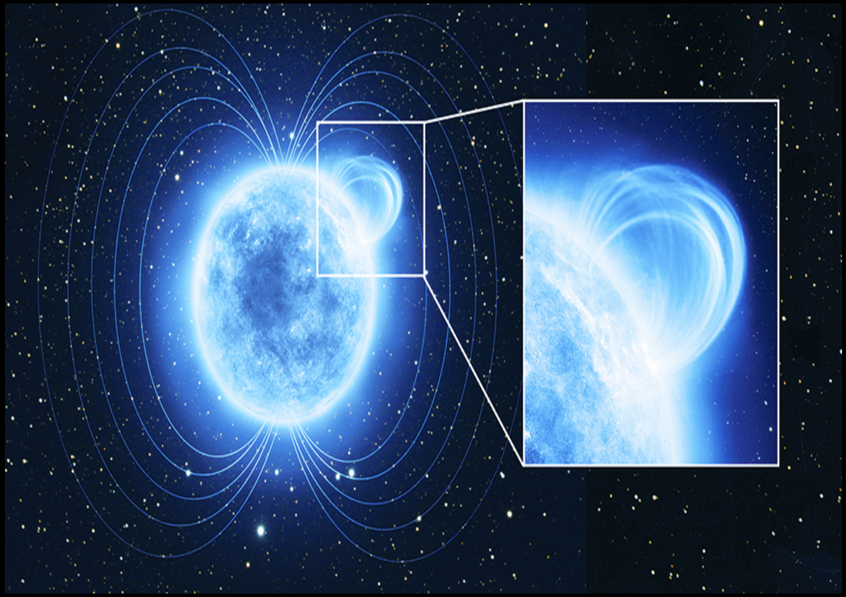


Thermal X-ray spectra
(kT_{BB} ~ 40-110 eV)

Phase-dependent absorption features

Narrow phase-dependent absorption features in the spectrum of RX J0720.4-3125 and RX J1308+2127





- Proton cyclotron resonant scattering in a small magnetic loop

$B_{loop} \approx 1.8 \times 10^{14}$ G

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

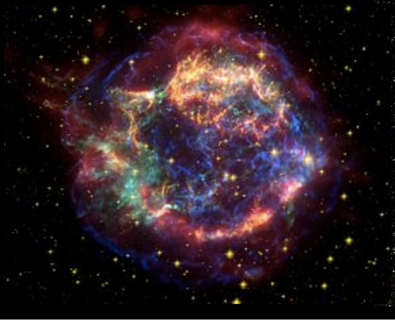
First observational evidence of a complex magnetic field in the XDINSs

Evolutionary connection between XDINSs and magnetars (see also Tiengo et al. 2013)

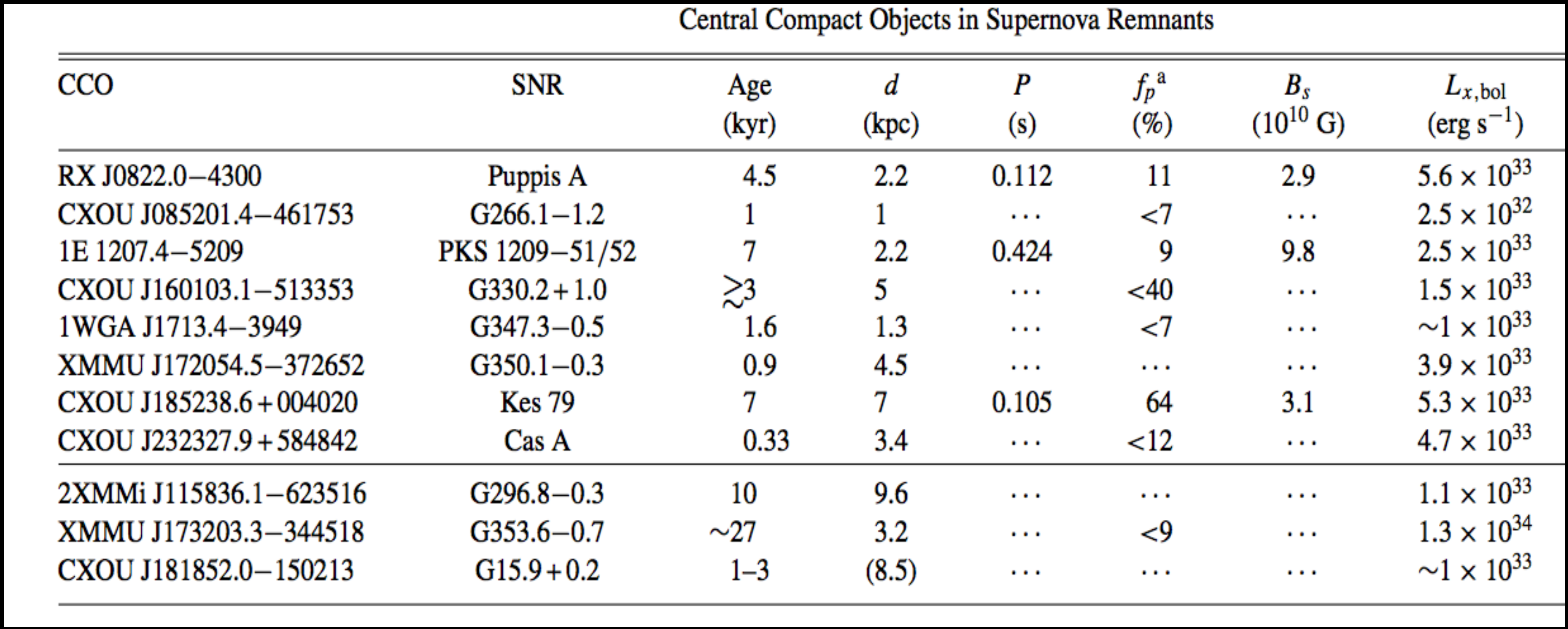
Central compact objects (CCOs)

- 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}

Cas A



RCW103

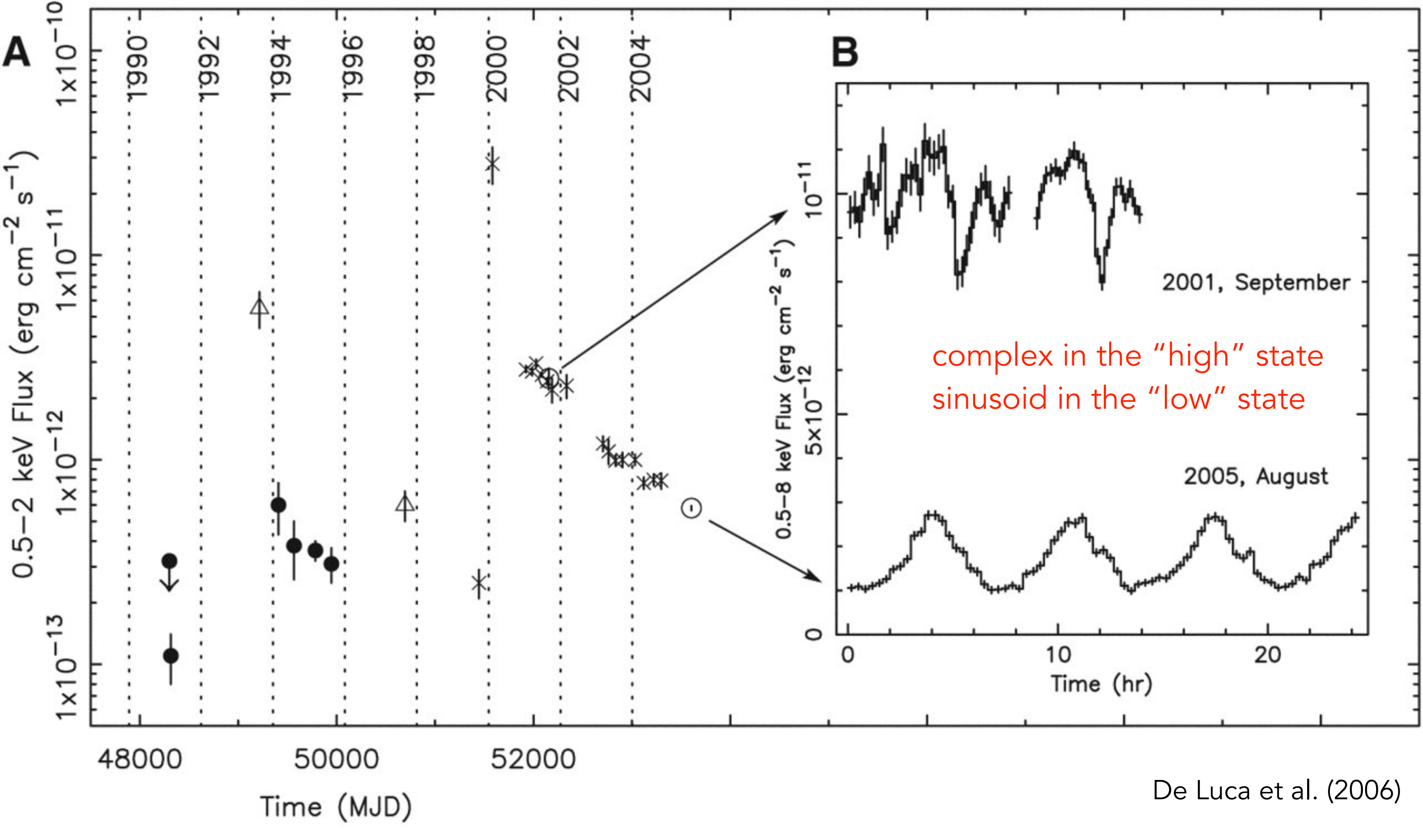


Central Compact Objects in Supernova Remnants

CCO	SNR	Age (kyr)	d (kpc)	P (s)	f_p[a] (%)	B_s (10^{10} G)	$L_{x,\rm bol}$ (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



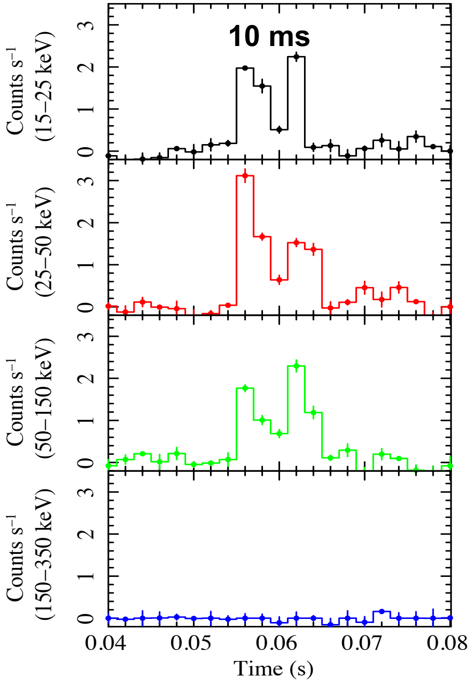
complex in the “high” state
sinusoid in the “low” state

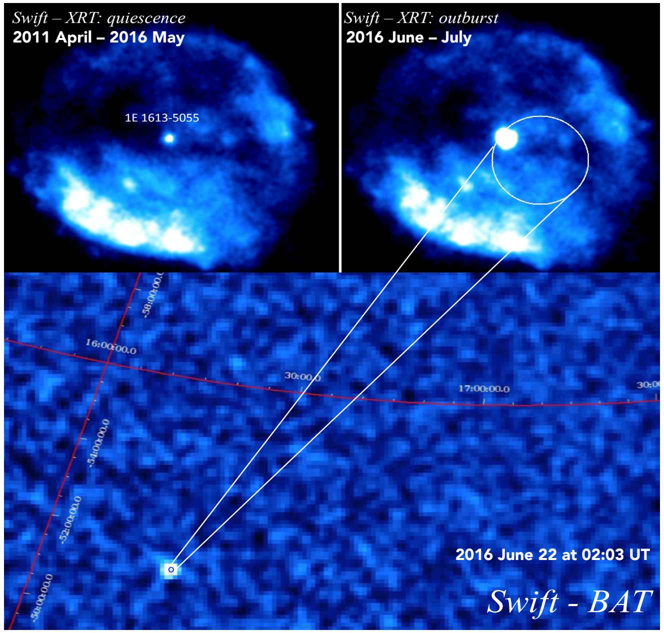
De Luca et al. (2006)

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)



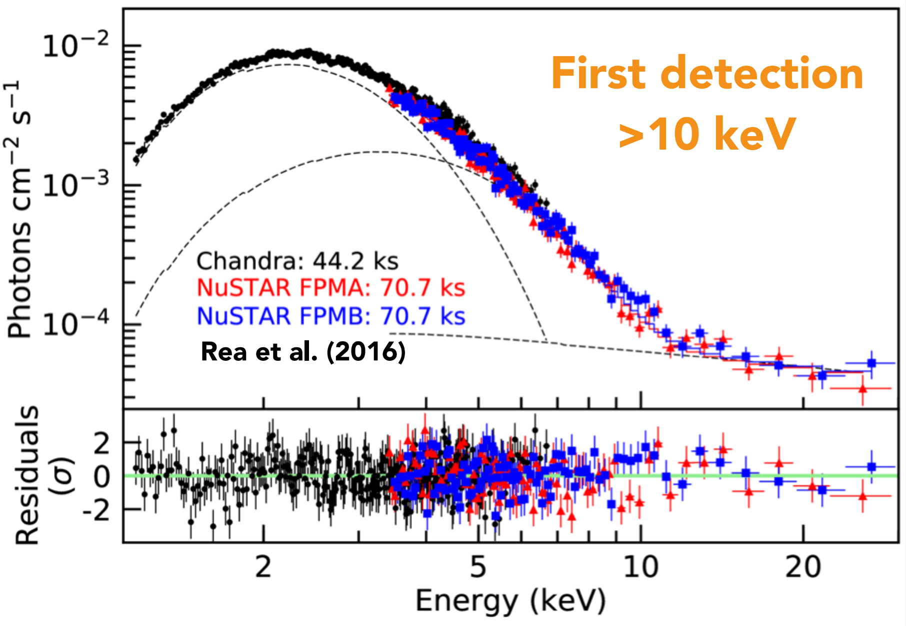


$L_{15\text{-}150\ \mathrm{keV}} = 2\mathrm{x}10^{39}$ erg s^{-1}

$F_{1\text{-}10\mathrm{keV}}$ ~1.2x10^{-10} erg cm^{-2} s^{-1} wrt
$F_{1\text{-}10\mathrm{keV(q)}}$ ~1.7x10^{-12} erg cm^{-2} s^{-1}

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

1E 161348–505: magnetar-like activity

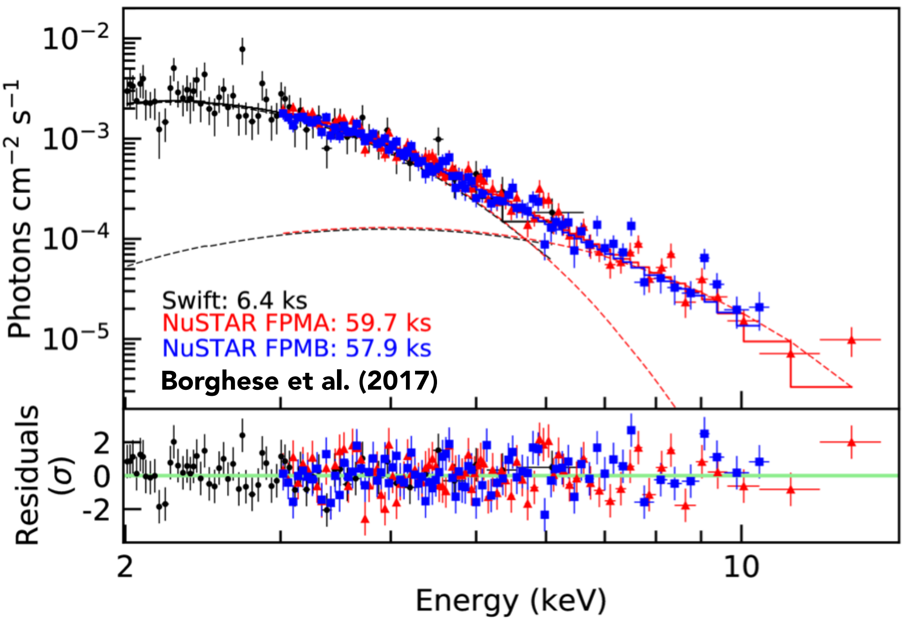


First detection >10 keV

Rea et al. (2016)

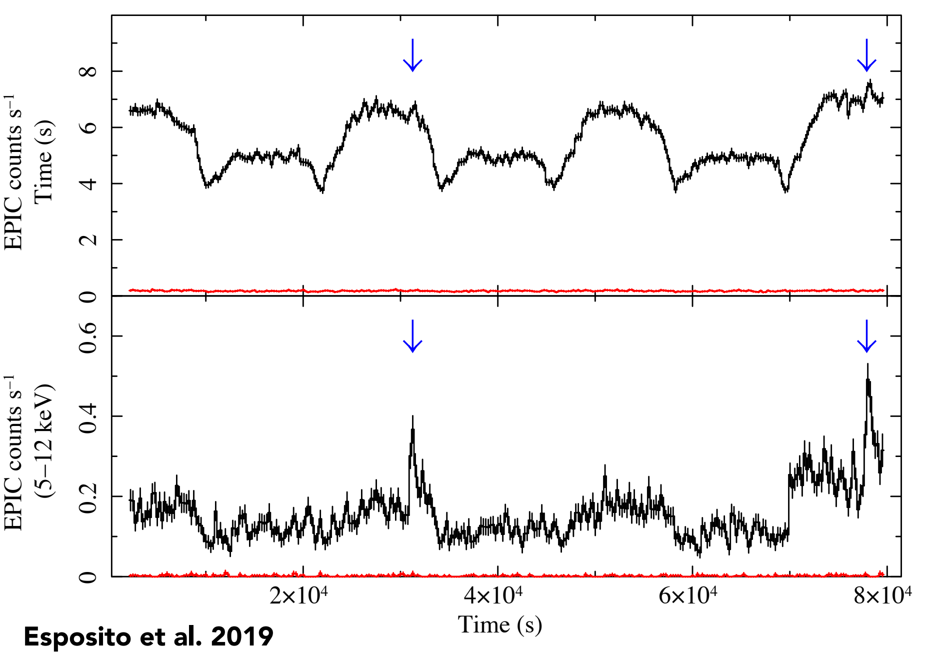
A magnetar-like spectrum at the outburst peak

Softening along the decay (about 1 year later)



Borghese et al. (2017)

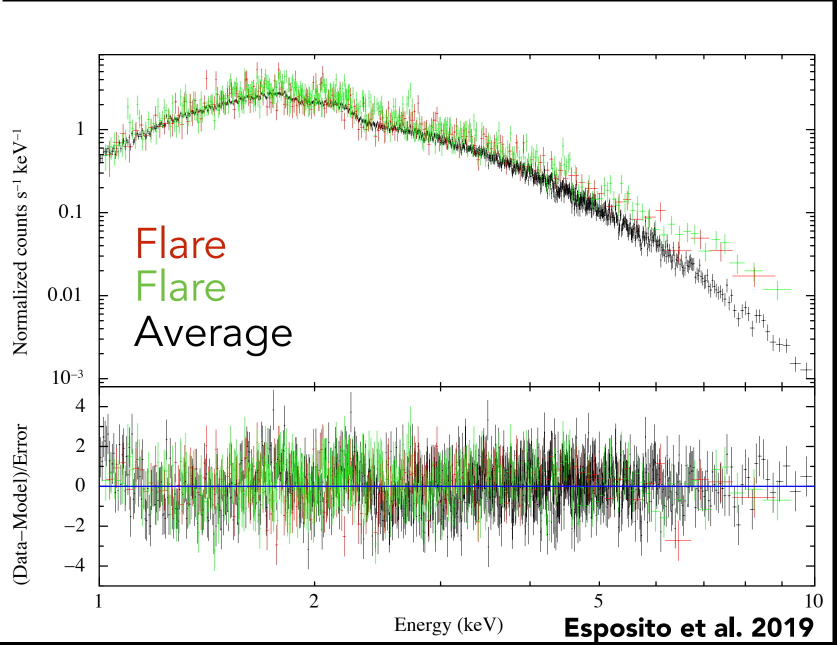
1E 161348–505: unusual long flares



Esposito et al. 2019

Long (~1 ks)

Faint (Lx ~ 10^{34} erg s^{-1})



Esposito et al. 2019

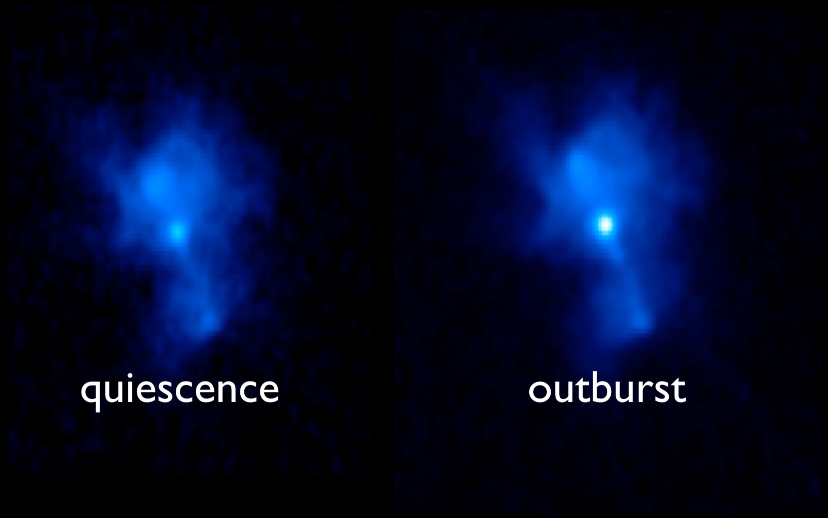
Comparatively soft spectra

A spot on the surface heated by back-flowing currents?

Magnetar-like activities from two young RPPs

PSR 1846-0258

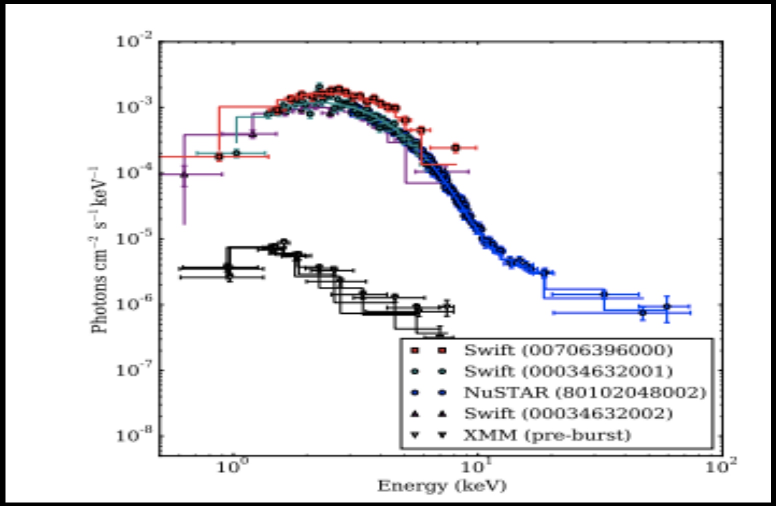
- rotational power of Edot ~ 8×10^{36} erg s^{-1}
- rotating with *P* ~ 0.3 s
- magnetic fields *B* ~ 5×10^{13} Gauss
- X-ray rotation-powered pulsar
- magnetar-like bursts and outburst in 2008


quiescence

outburst

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
- 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

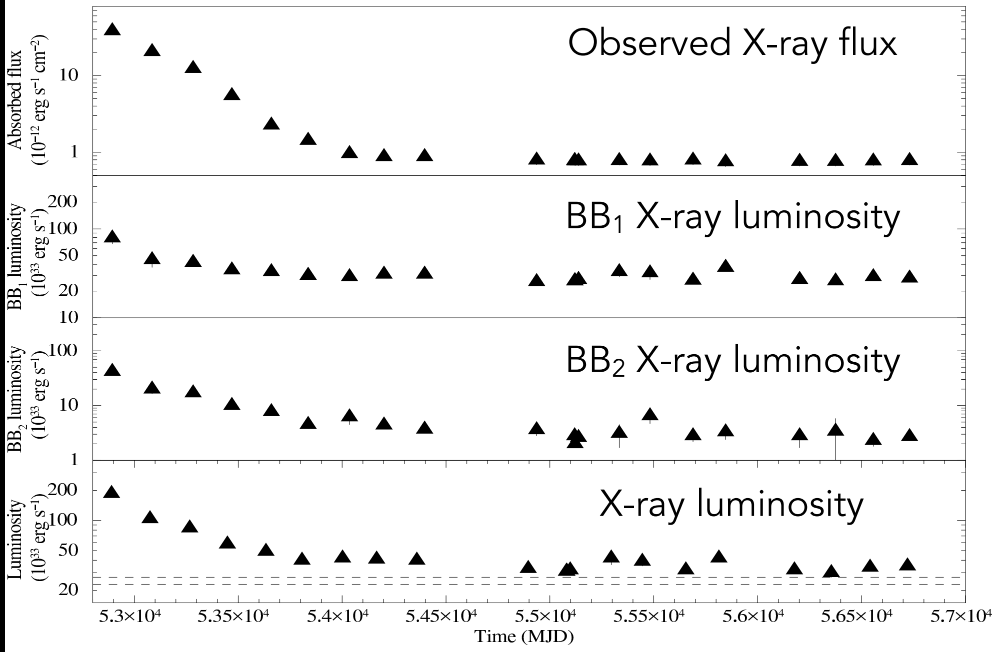
Magnetar Outburst Online Catalog

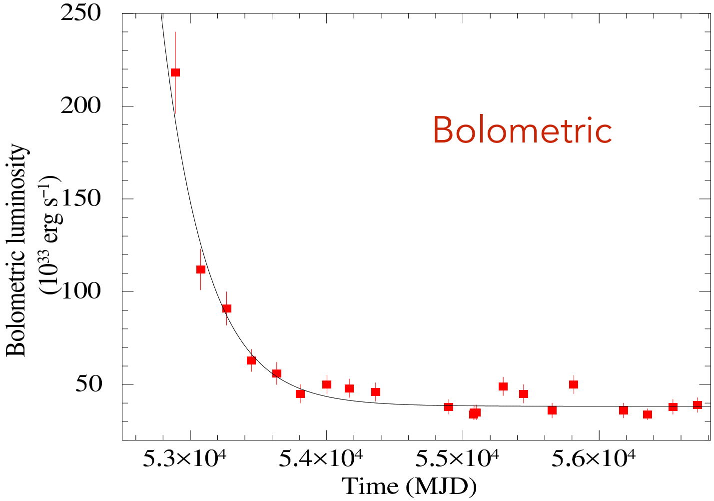
http://magnetars.ice.csic.es/

- about 1100 X-ray observations (12 Ms) between from 1998 to 2017
- spectral fitting with empirical and more physically-motivated models
- light curve modelling and estimate of energetics and decay time scale

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

Cooling curves, empirical modelling



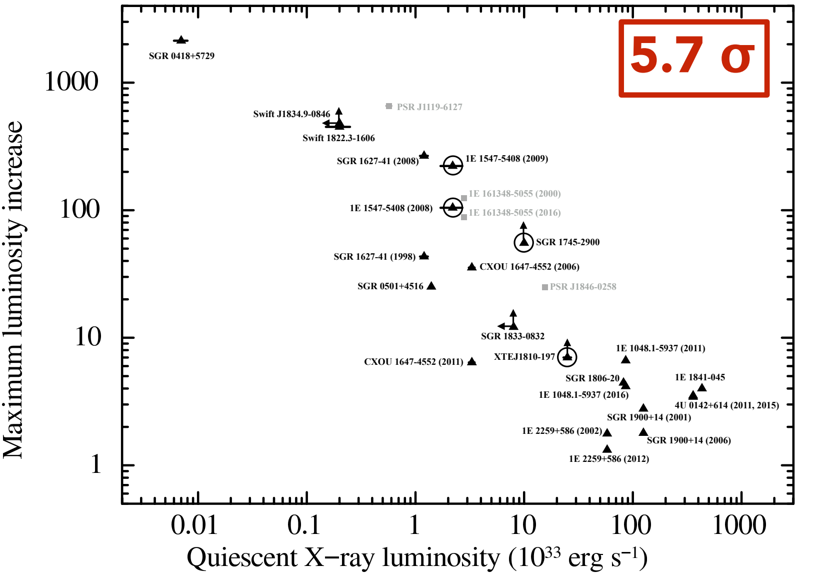


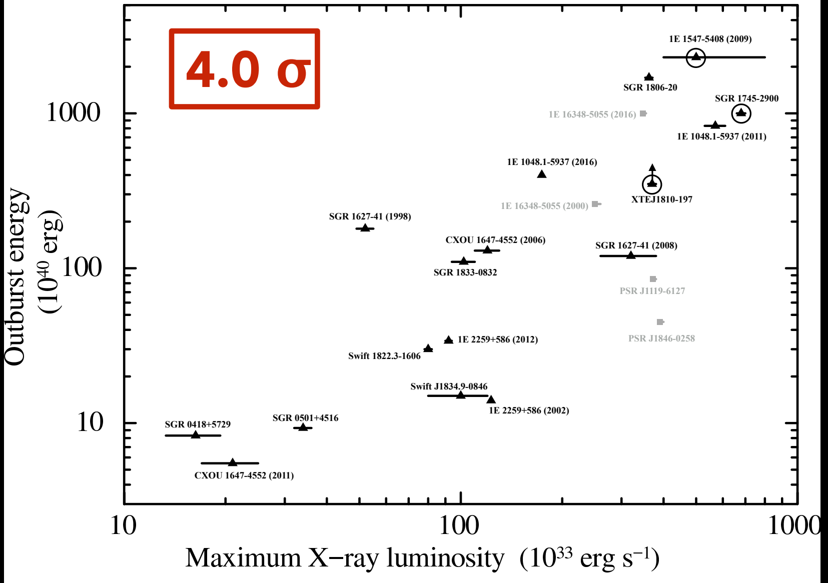
Estimate of the outburst decay-timescale and energetics

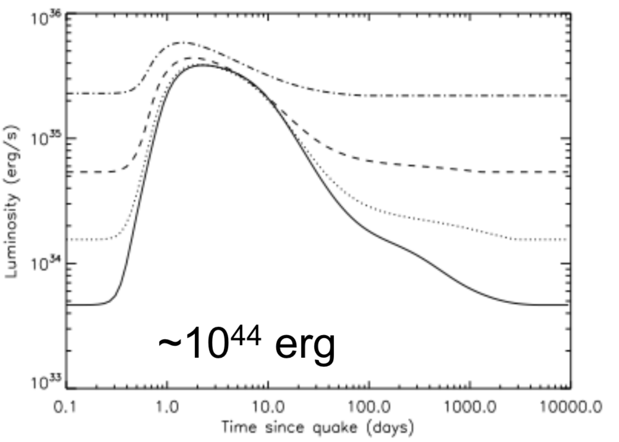
$$L(t) = L_q + \sum_{i=1}^{j} A_i \times \exp(-\mathrm{t}/\tau_\mathrm{i})$$

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

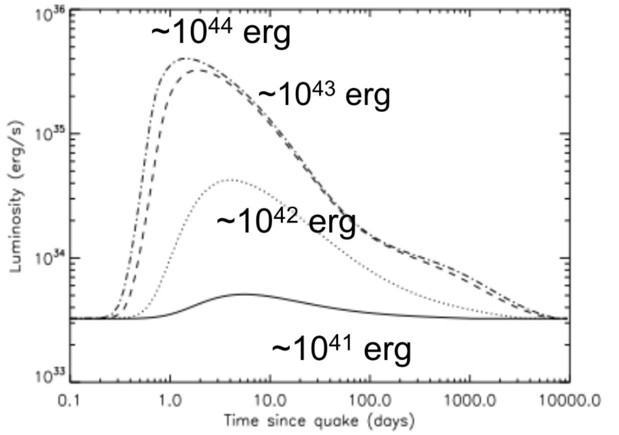
Correlations and anticorrelations (I)





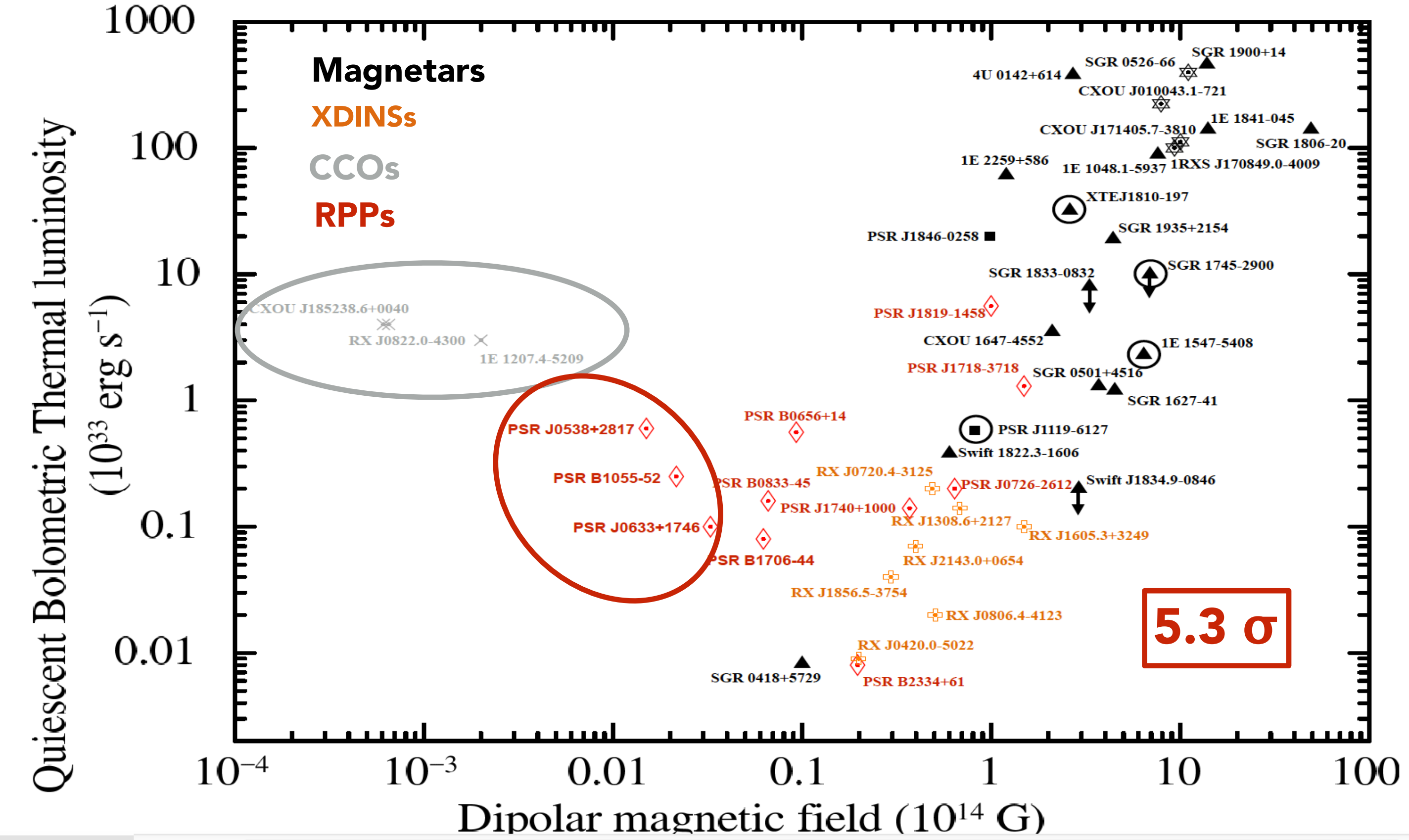


Large flux enhancements observable only in faint quiescent magnetars.



Pons & Rea (2012)

Correlations and anticorrelations (II)

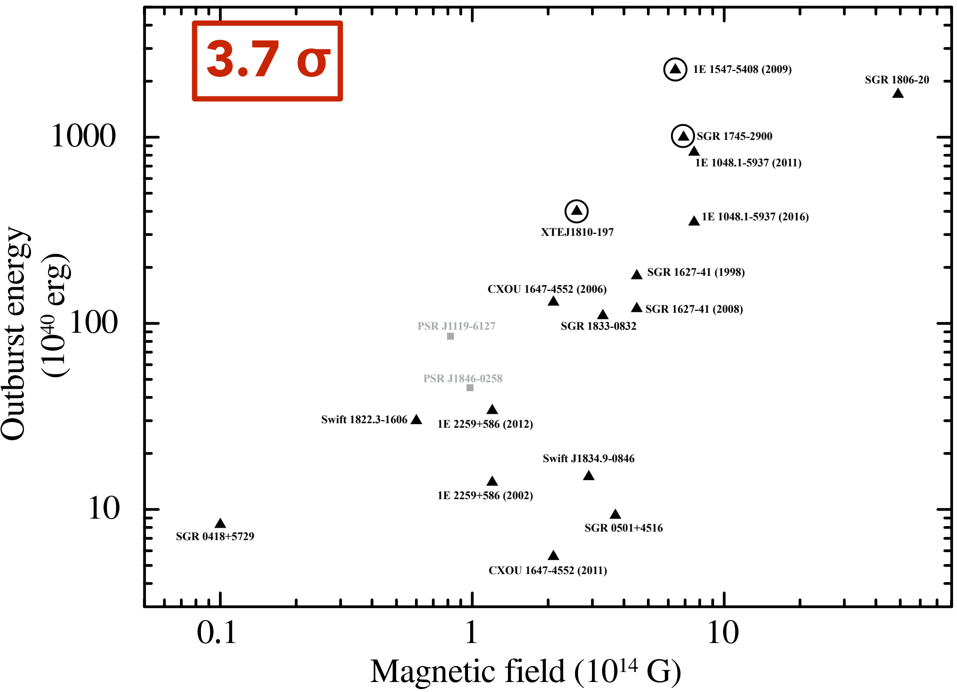


CCOs depart significantly from the trend: expected in the '*hidden magnetic field*' scenario

The external *B* field is lower than the internal 'hidden' *B* field: not a good tracer for the bolometric luminosity

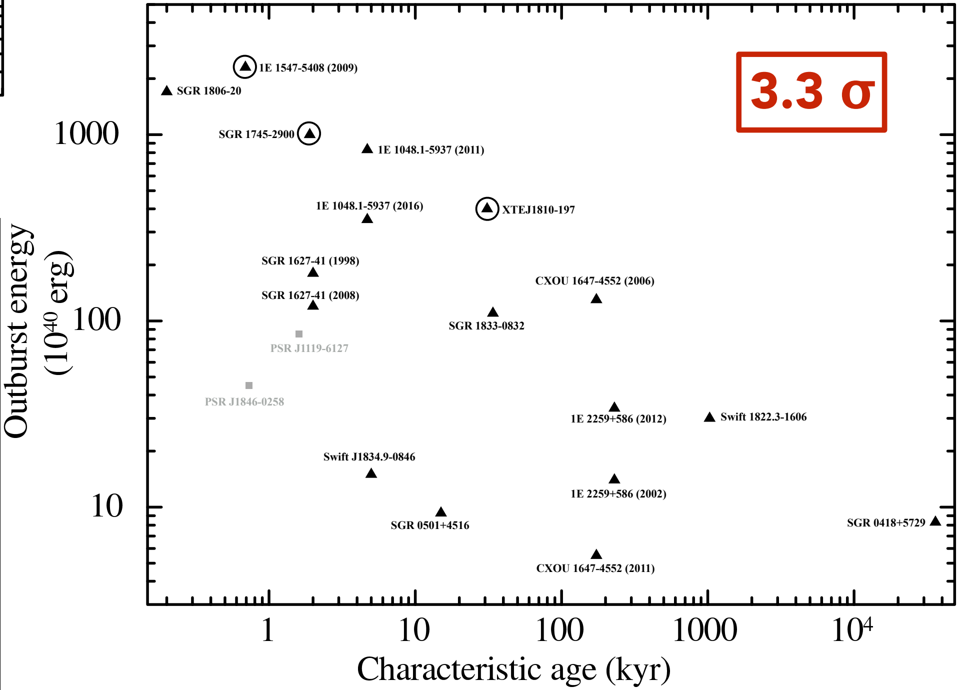
Large luminosity of RPPs likely due to slamming particles heating the NS surface

Correlations and anticorrelations (III)

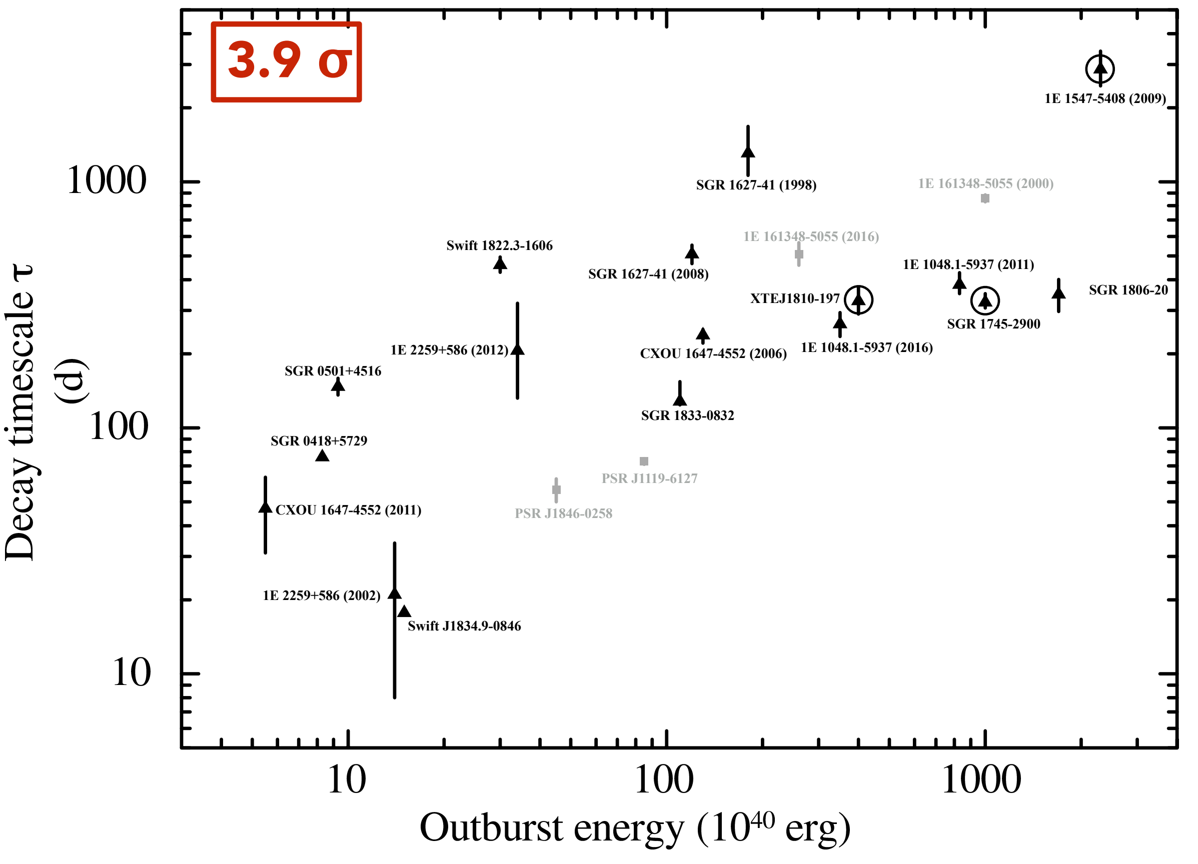


Magnetar outbursts
are ultimately powered by
the dissipation of the B-field

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 magnetar outburst online catalogue

X axis: Beq ☑ Log

Y axis: luminosity_bol_qui ☑ Log

Fit your favourite function to different parameters

Source: SGR1745-2900

Click on any observation to download the spectra file

Download all data and analyse them

Summary and conclusions

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

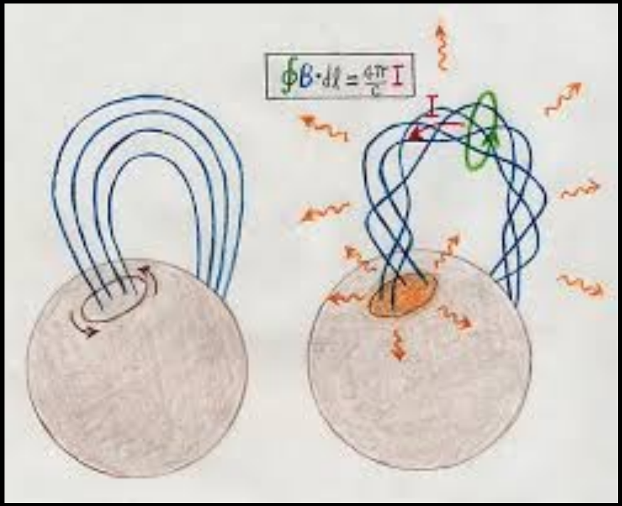
- The intensive follow-up of magnetar outbursts is giving new key discoveries and results (e.g. the Galactic Centre magnetar, multi-outburst activity from the same source, the CCO in RCW 103)

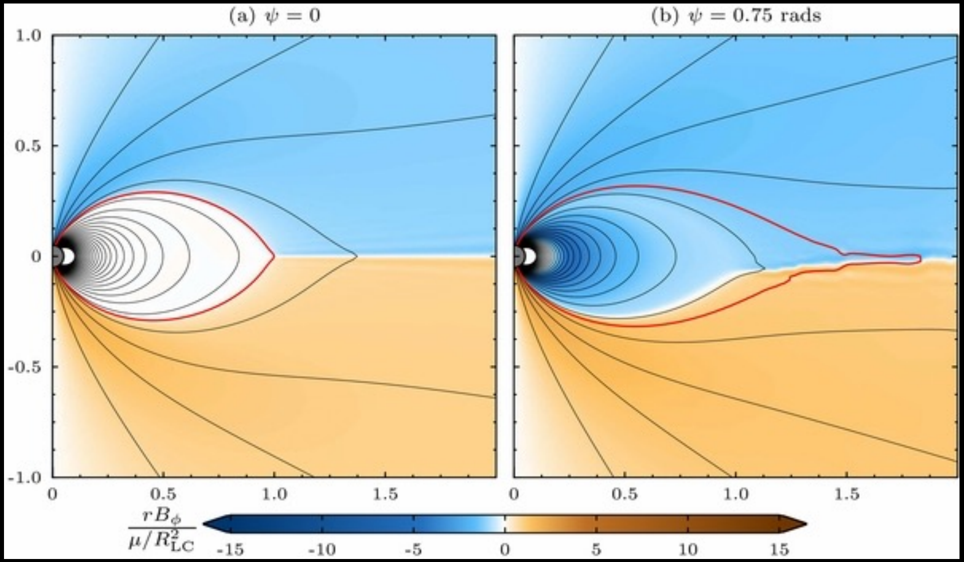
- Magnetar activity likely has a larger spread within the neutron star population

- ***General Utility***. The Magnetar Outbursts Online Catalogue

The magnetar in the Galactic Centre: SGR 1745-2900

The twist initially grows, the spin-down torque increases





Parfrey et al. (2013)

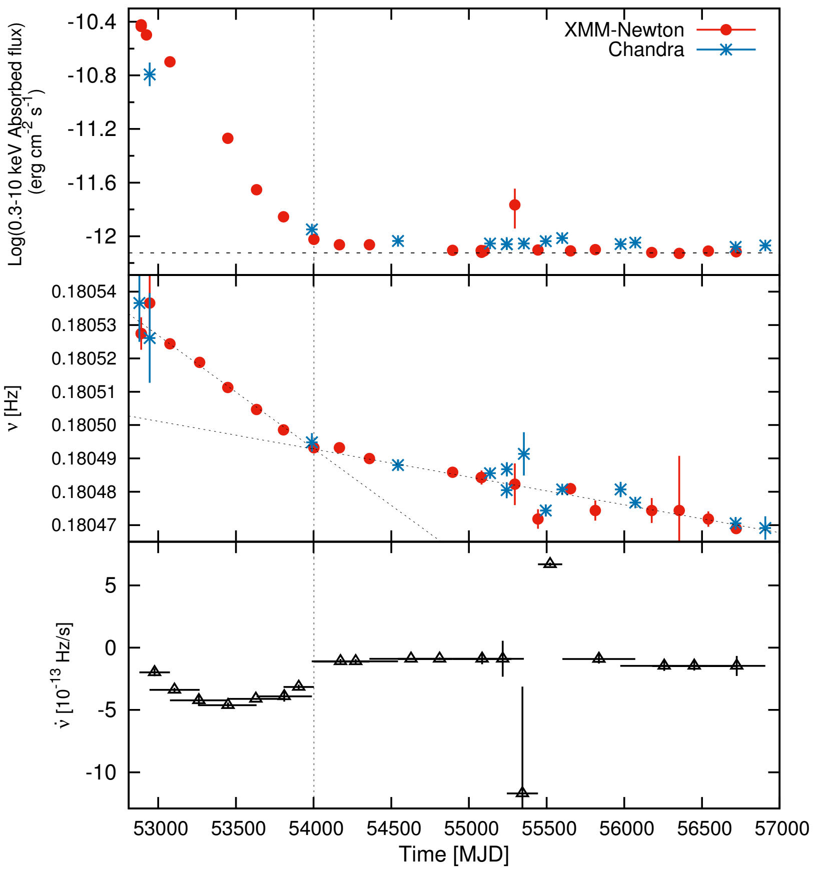
The twist decays in the long-term, the spin-down torque decreases

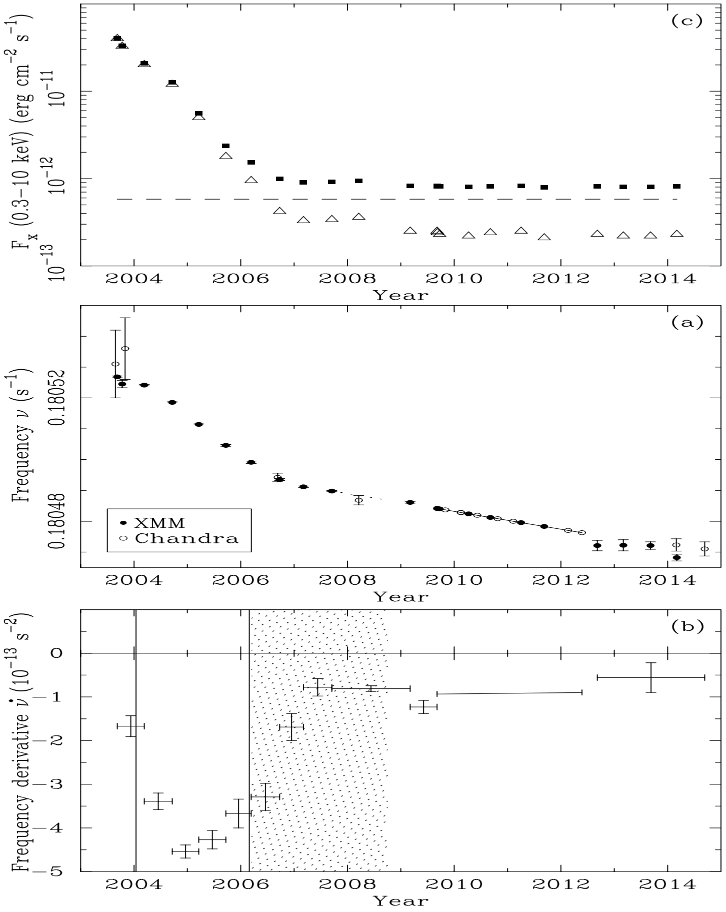
A result of prolonged, delayed effects of a strong initial twist?

A reversal in the behaviour should be observed in the future

The X-ray monitoring of this source is ongoing

Analogy with the case of XTE J1810-197

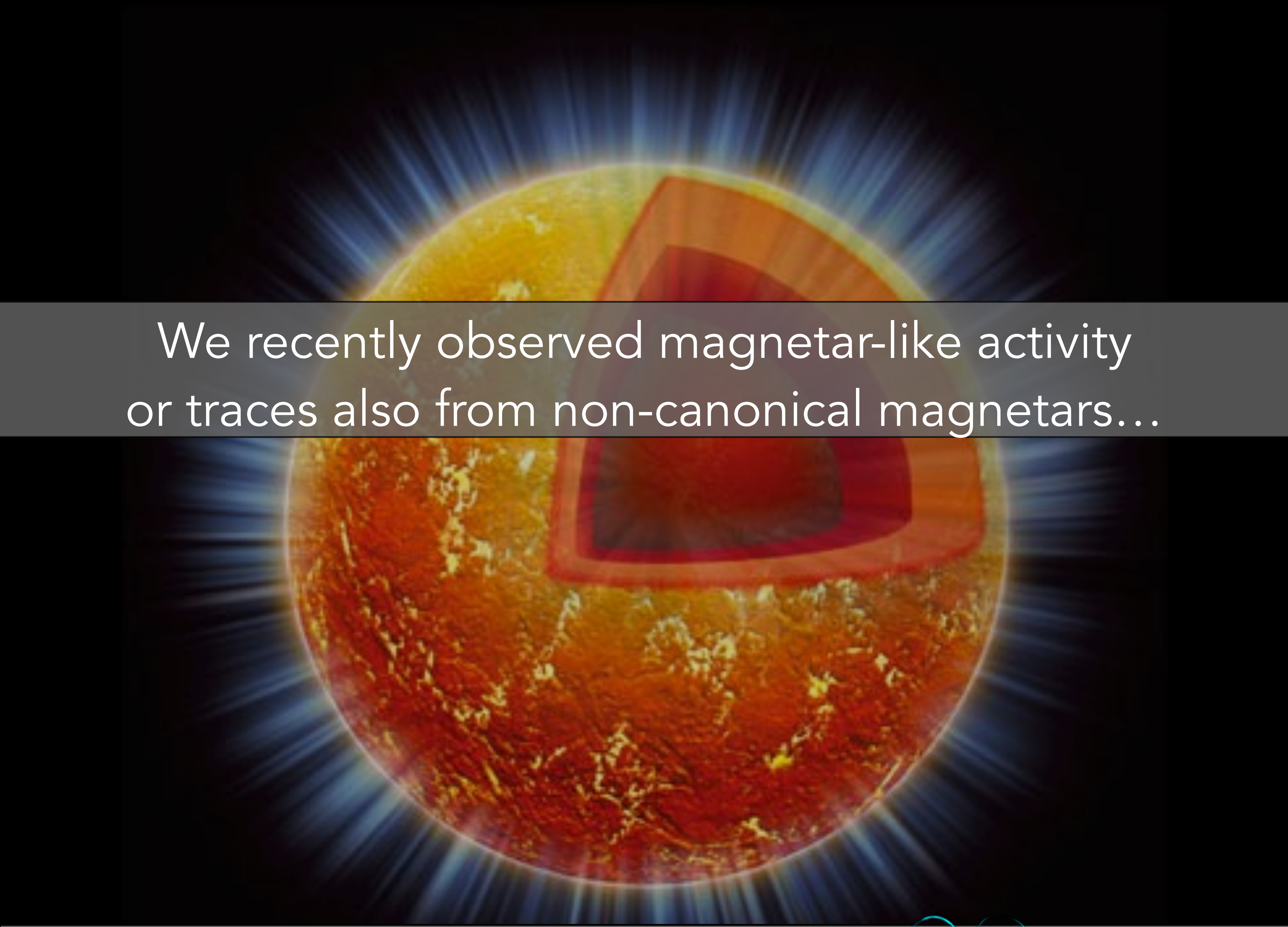




Pintore et al. 2016

Camilo et al. 2016

Strong initial twists might regulate the rotational properties of several magnetars along their outbursts

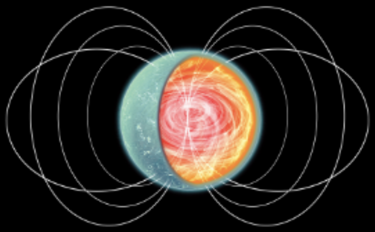


We recently observed magnetar-like activity
or traces also from non-canonical magnetars…

Current picture of the “non-magnetar” magnetars

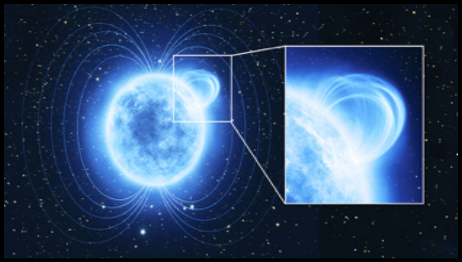
1. Magnetars were discovered having also low dipolar B-fields and strong magnetic structures.

   Rea et al. 2010, 2012, 2014, Tiengo et al. 2013



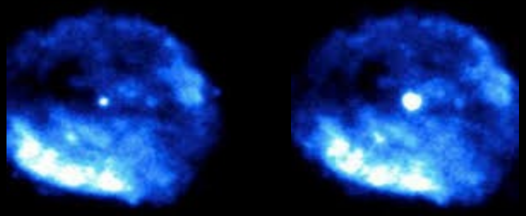
2. Two X-ray Dim Isolated NSs show evidence of strong magnetic structures

   Borghese et al. 2015, 2017



3. A central compact objects (CCO) with a 6.7 hr period showed magnetar-like activity.

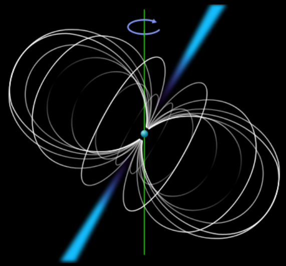
   D’Ai et al. 2016 ; Rea et al. 2016; Borghese et al. 2017



quiescence outburst

4. Two young rotation-powered RPPs showed magnetar activity.

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



Neutrino processes in the crust

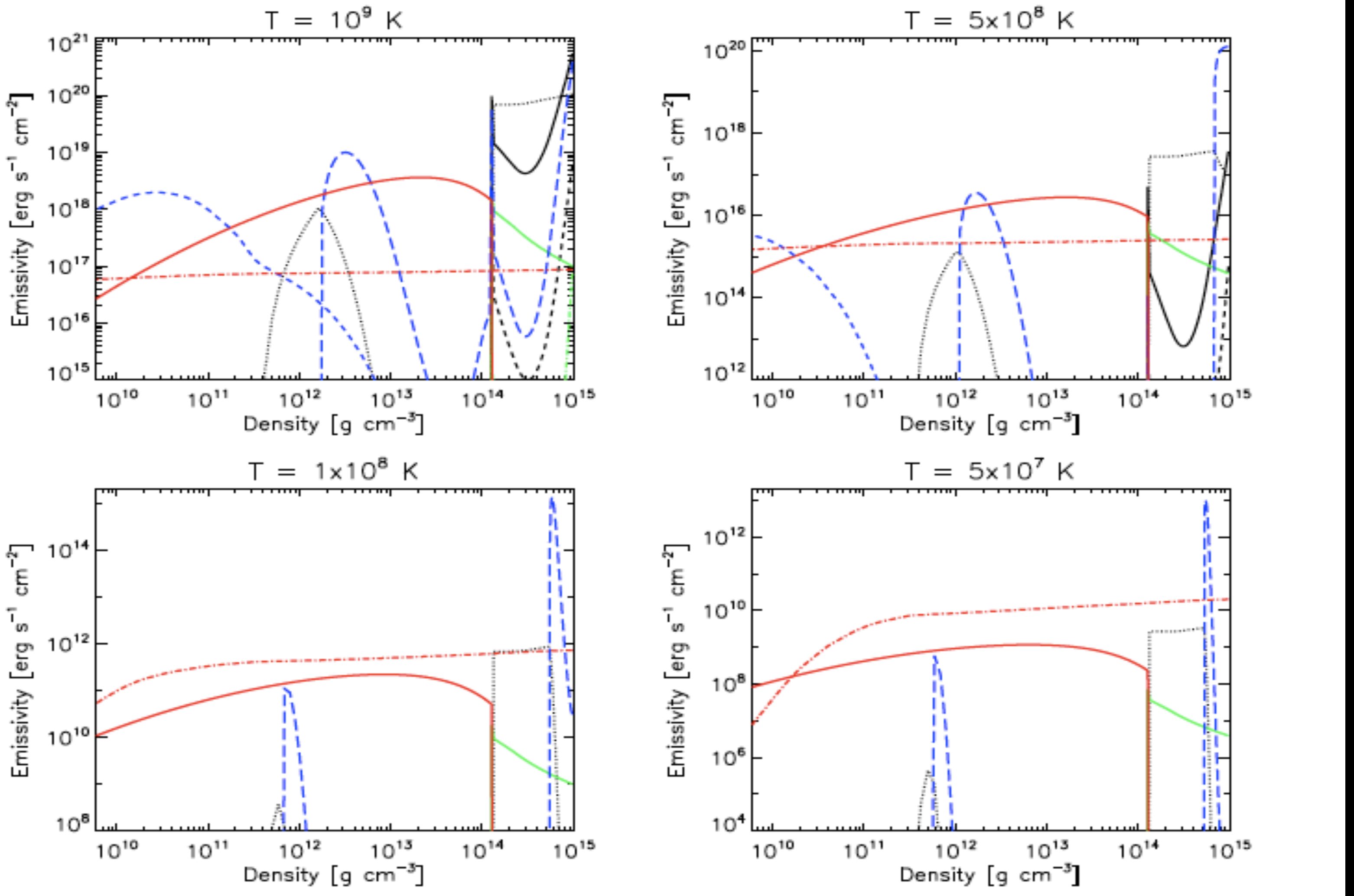
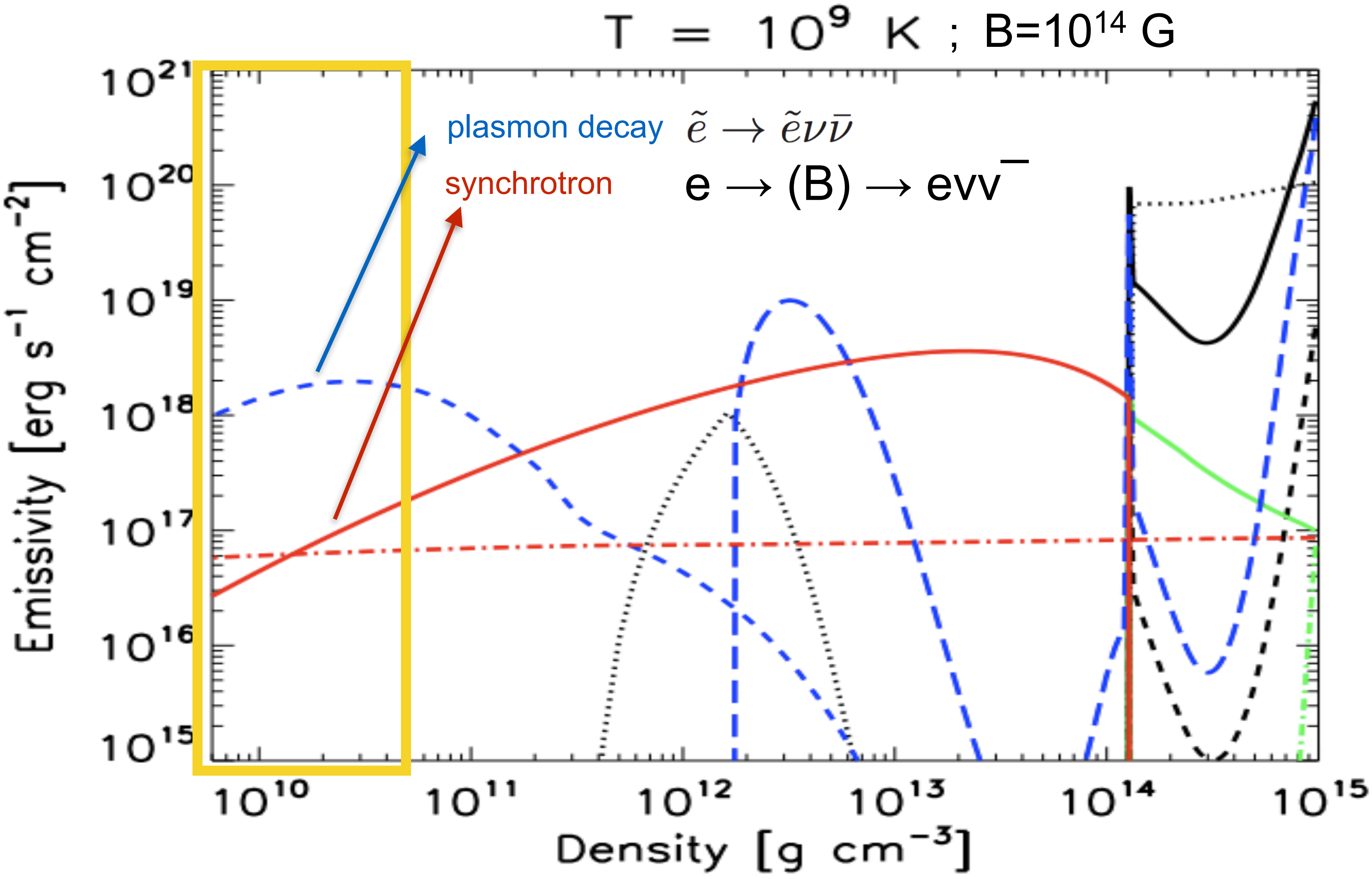


Figure 4.7: Neutrino emissivities in the crust and in the core at the four indicated temperatures, with the chosen equation of state and superfluid gaps (see text), and mass $M = 1.4\ M_\odot$ (no direct URCA). Lines denote: modified URCA (black solid line), n-n Bremsstrahlung (black dots), n-p Bremsstrahlung (black dashes), e-p Bremsstrahlung (green solid), e-A Bremsstrahlung (red solid),

Neutrino processes in the crust



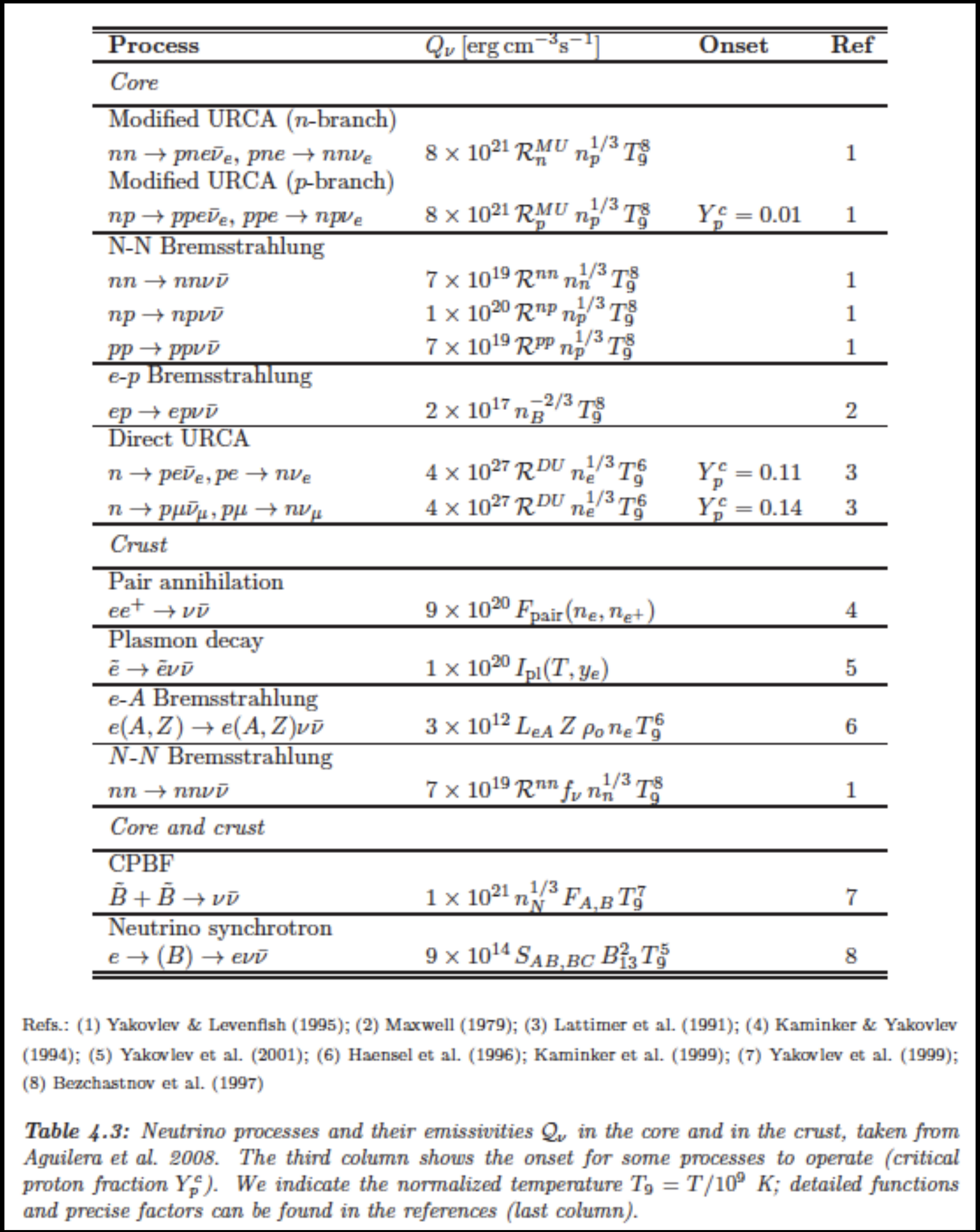
T = 10^9 K ; B=10^{14} G

plasmon decay $\tilde{e} \rightarrow \tilde{e}\nu\bar{\nu}$

synchrotron $e \rightarrow (B) \rightarrow e\nu\bar{\nu}$

Yakovlev et al. 2001; Viganò 2013

Neutrino processes in the crust

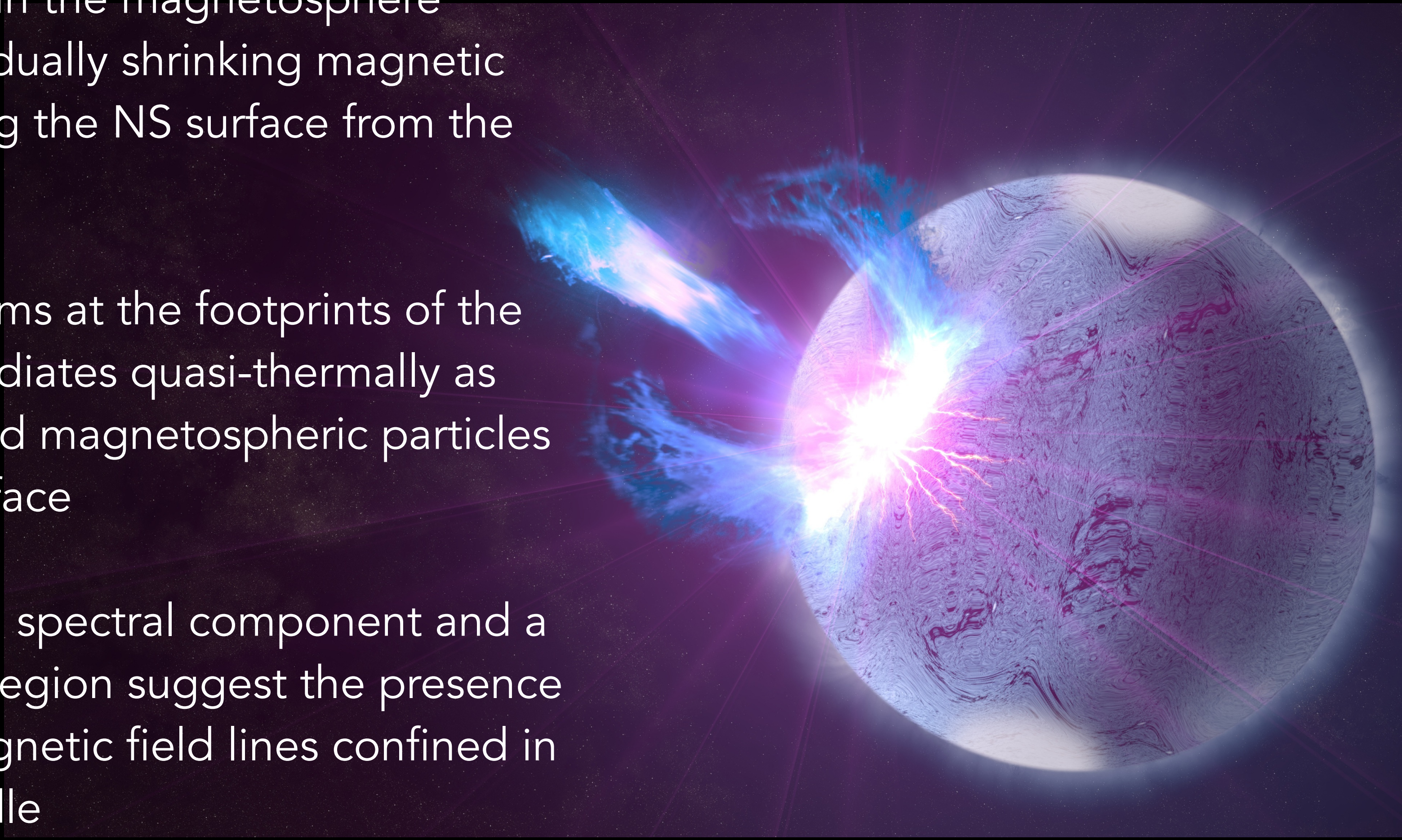


Process	Q_ν [erg cm^{-3}s^{-1}]	Onset	Ref
Core			
Modified URCA (n-branch)			
$nn \to pne\bar{\nu}_e,\ pne \to nn\nu_e$	$8 \times 10^{21}\,\mathcal{R}_n^{MU}\,n_p^{1/3}\,T_9^8$		1
Modified URCA (p-branch)			
$np \to ppe\bar{\nu}_e,\ ppe \to np\nu_e$	$8 \times 10^{21}\,\mathcal{R}_p^{MU}\,n_p^{1/3}\,T_9^8$	$Y_p^c = 0.01$	1
N-N Bremsstrahlung			
$nn \to nn\nu\bar{\nu}$	$7 \times 10^{19}\,\mathcal{R}^{nn}\,n_n^{1/3}\,T_9^8$		1
$np \to np\nu\bar{\nu}$	$1 \times 10^{20}\,\mathcal{R}^{np}\,n_p^{1/3}\,T_9^8$		1
$pp \to pp\nu\bar{\nu}$	$7 \times 10^{19}\,\mathcal{R}^{pp}\,n_p^{1/3}\,T_9^8$		1
e-p Bremsstrahlung			
$ep \to ep\nu\bar{\nu}$	$2 \times 10^{17}\,n_B^{-2/3}\,T_9^8$		2
Direct URCA			
$n \to pe\bar{\nu}_e, pe \to n\nu_e$	$4 \times 10^{27}\,\mathcal{R}^{DU}\,n_e^{1/3}\,T_9^6$	$Y_p^c = 0.11$	3
$n \to p\mu\bar{\nu}_\mu, p\mu \to n\nu_\mu$	$4 \times 10^{27}\,\mathcal{R}^{DU}\,n_e^{1/3}\,T_9^6$	$Y_p^c = 0.14$	3
Crust			
Pair annihilation			
$ee^+ \to \nu\bar{\nu}$	$9 \times 10^{20}\,F_{\rm pair}(n_e, n_{e+})$		4
Plasmon decay			
$\tilde{e} \to \tilde{e}\nu\bar{\nu}$	$1 \times 10^{20}\,I_{\rm pl}(T, y_e)$		5
e-A Bremsstrahlung			
$e(A,Z) \to e(A,Z)\nu\bar{\nu}$	$3 \times 10^{12}\,L_{eA}\,Z\,\rho_o\,n_e\,T_9^6$		6
N-N Bremsstrahlung			
$nn \to nn\nu\bar{\nu}$	$7 \times 10^{19}\,\mathcal{R}^{nn}\,f_\nu\,n_n^{1/3}\,T_9^8$		1
Core and crust			
CPBF			
$\tilde{B} + \tilde{B} \to \nu\bar{\nu}$	$1 \times 10^{21}\,n_N^{1/3}\,F_{A,B}\,T_9^7$		7
Neutrino synchrotron			
$e \to (B) \to e\nu\bar{\nu}$	$9 \times 10^{14}\,S_{AB,BC}\,B_{13}^2\,T_9^5$		8

Refs.: (1) Yakovlev & Levenfish (1995); (2) Maxwell (1979); (3) Lattimer et al. (1991); (4) Kaminker & Yakovlev (1994); (5) Yakovlev et al. (2001); (6) Haensel et al. (1996); Kaminker et al. (1999); (7) Yakovlev et al. (1999); (8) Bezchastnov et al. (1997)

Table 4.3: *Neutrino processes and their emissivities Q_ν in the core and in the crust, taken from Aguilera et al. 2008. The third column shows the onset for some processes to operate (critical proton fraction Y_p^c). We indicate the normalized temperature $T_9 = T/10^9$ K; detailed functions and precise factors can be found in the references (last column).*

Untwisting magnetosphere: an alternative scenario



Currents flow in the magnetosphere through a gradually shrinking magnetic bundle heating the NS surface from the top.

A hot spot forms at the footprints of the bundle and radiates quasi-thermally as the accelerated magnetospheric particles hit the NS surface

A non-thermal spectral component and a small heated region suggest the presence of twisted magnetic field lines confined in a narrow bundle

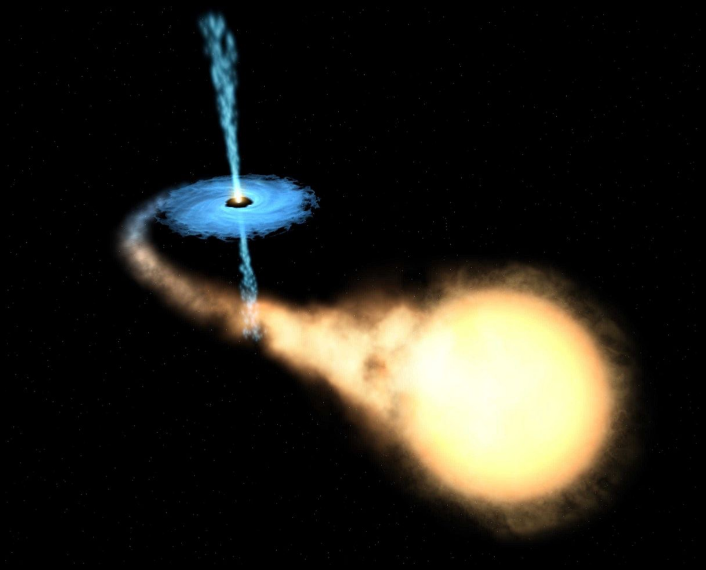
Credit: *NASA/Wiessinger*

Beloborodov 2009, ApJ, 703, 1044

An intriguing source: a LMXB or an isolated NS?

X-ray binary

Orbital period of 6.67 hours



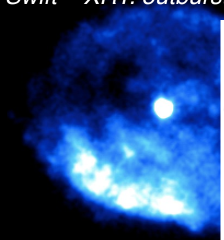
Isolated neutron star

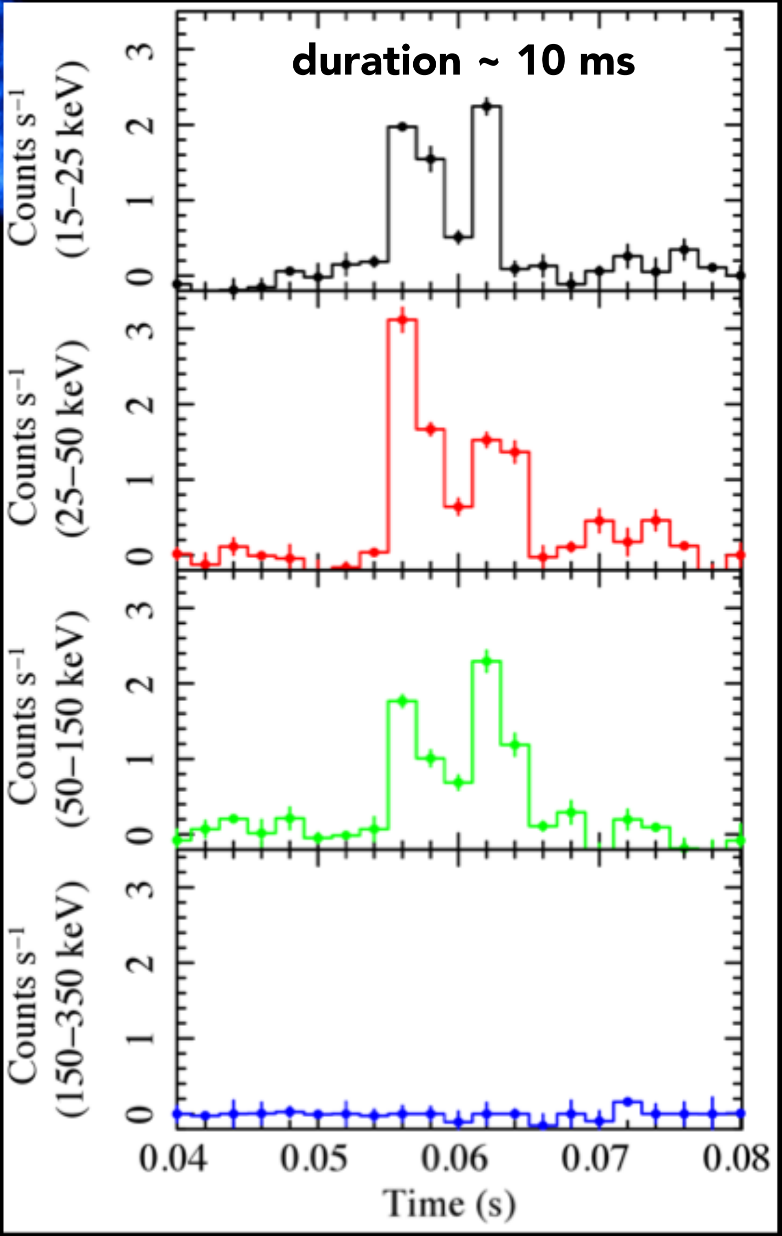
Spin period of 6.67 hours

Credit: A. Manzoni

Burst properties

Swift – XRT: outburst





duration ~ 10 ms

Double-peak profile

Thermal spectrum

$kT_1 = 9.2 \pm 0.9$ keV

$kT_2 = 6.0 \pm 0.6$ keV

$F_{\mathrm{obs,\ 15\text{-}150\ keV}}$

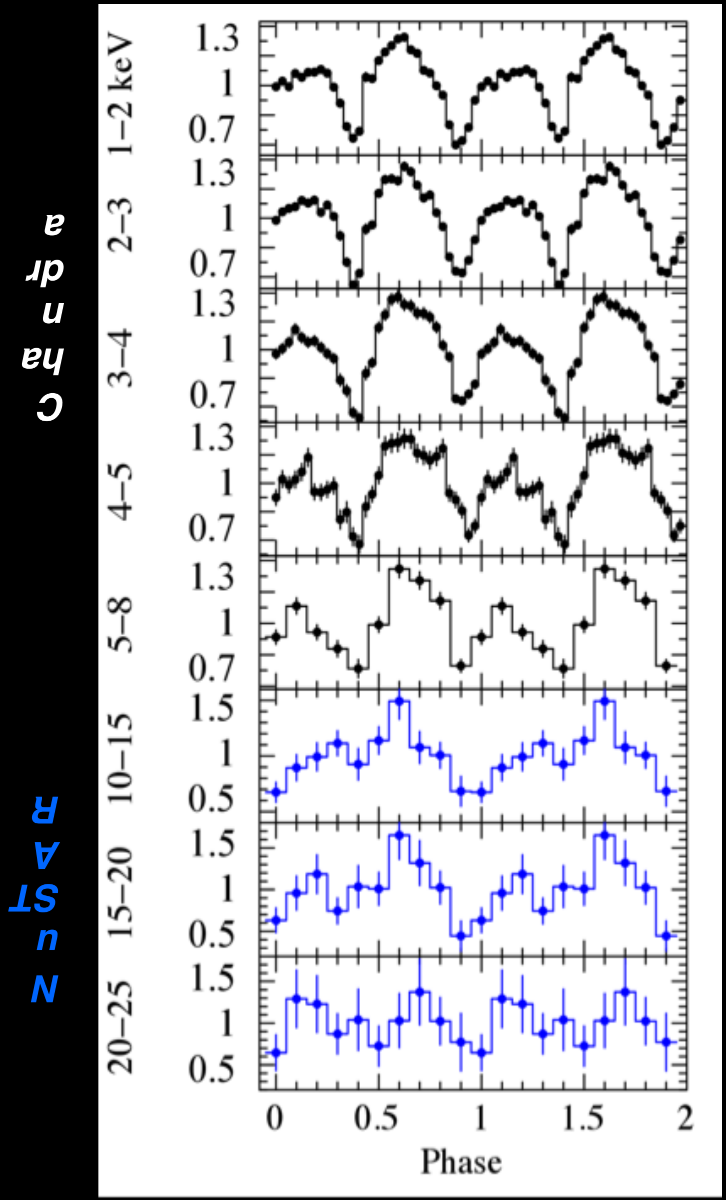
1.6×10^{-6} erg cm^{-2} s^{-1}

$L_{\mathrm{15\text{-}150\ keV}}$

2×10^{39} erg s^{-1}

Rea, Borghese et al., 2016

Timing analysis



Pulsed emission up to ~ 20 keV
Smoothing to a single peak at high energy

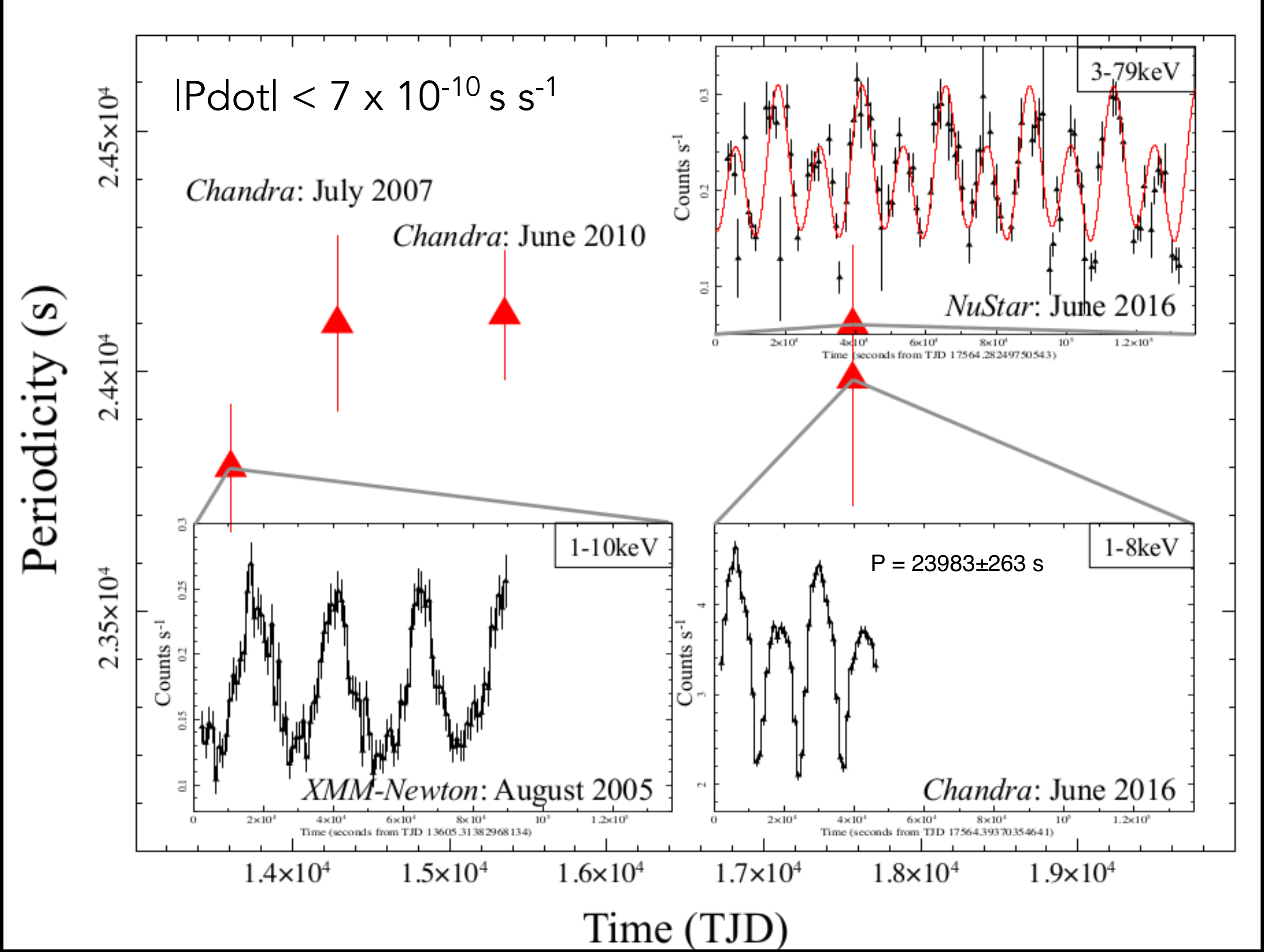
$|\dot{P}| < 7 \times 10^{-10}$ s s^{-1}

Pulsed fraction ~ 40 %

Rea, Borghese et al., 2016

Timing analysis

Profile of the 6.67-hr modulation



Is 1E1613 a magnetar?

- Properties:
  outburst duration, spectral shape, energetics
  non-thermal hard power law tail
  pulse profile variability in time and energy
  faint NIR counterpart (Tendulkar et al., 2017)

} MAGNETAR SCENARIO

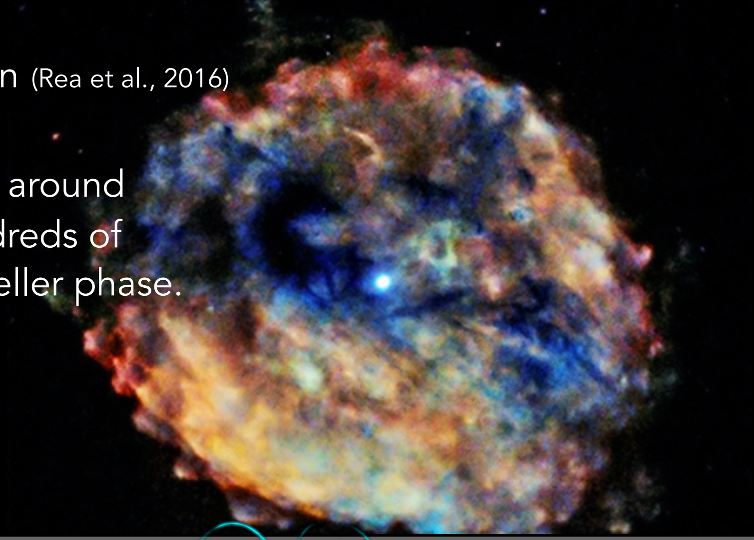
- … but a very **slow** magnetar with a spin period of **6.67 hr**

How to slow down a NS to *P* = 6.67 hr in ~ 3 kyr?

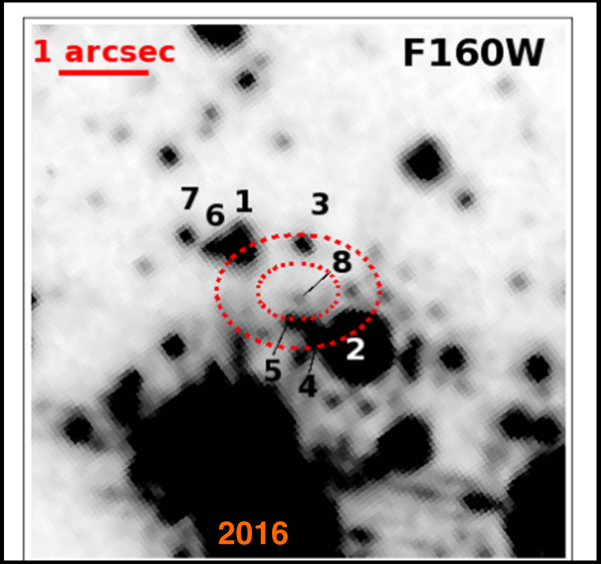
- An external torque is required – propeller interaction with fall-back disk

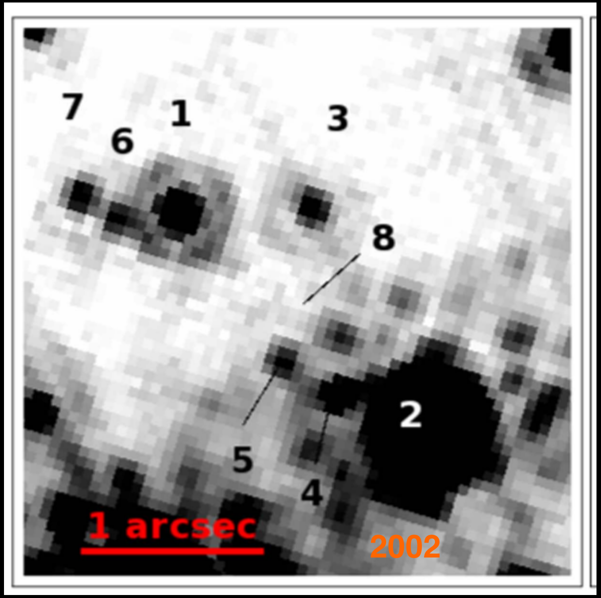
- propeller interaction in an early phase of the fall-back accretion (Rea et al., 2016)

  - Ho & Andersson (2017) predict a remnant disk (~10^{-9} Msun) around a ms NS. Initially the NS is in an ejector phase, but after hundreds of years its rotation is slow enough to allow the onset of a propeller phase.



Near infrared counterpart





Faint source (#8, m_H ~ 24) detected with Hubble Space Telescope (WFC3/IR), not seen in previous observations

Observation performed 12 and 50 days after the outburst

$L_X/L_{IR} \approx 10^5$ consistent with those of magnetars

Ruled out the possibility of a binary scenario:
compact H atmosphere white dwarf with M ~ 1.3 Msun and R<5000km

Emission form the magnetosphere or from a fall-back disk?

Tendulkar et al. 2017

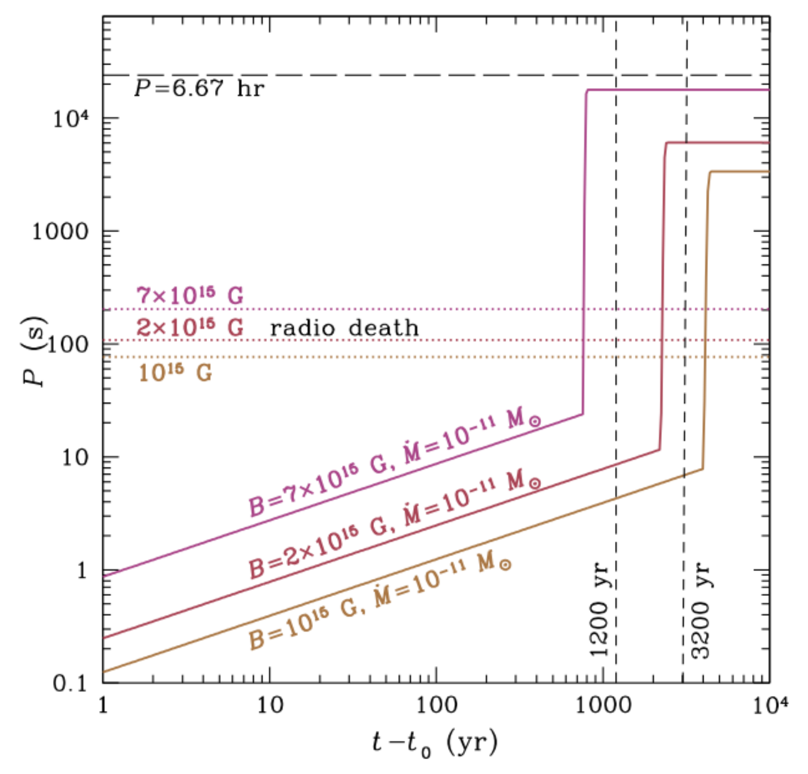
LMXB scenario

In the binary system hypothesis the periodicity of **6.67 hr** is the **orbital period**.

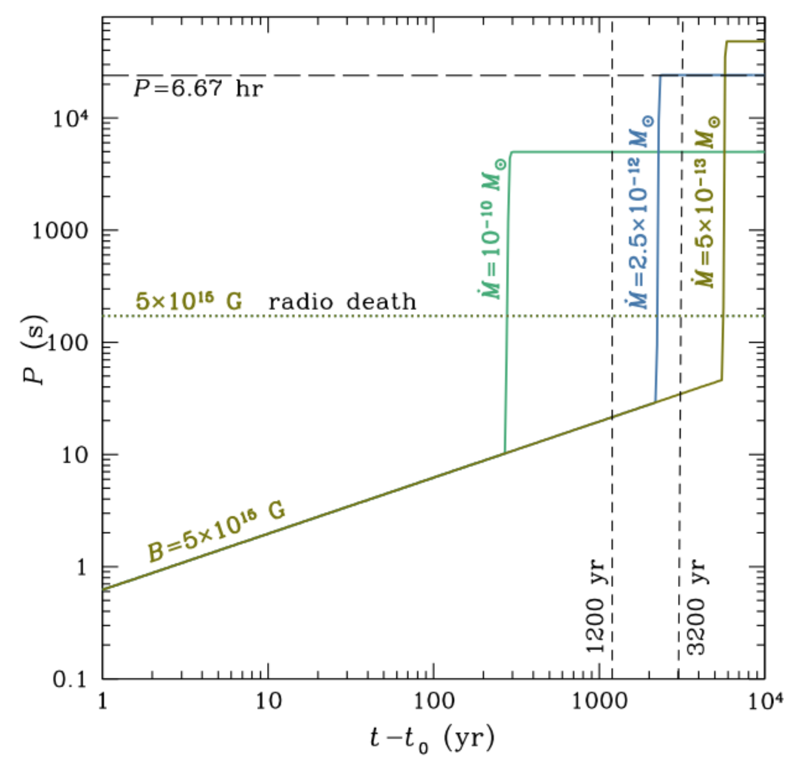
- A 0.2–0.4 Msun companion of spectral type M is compatible with the VLT/HST upper limits (De Luca et al. 2008)
- 1E 1613 is 2–3 orders of magnitude dimmer than any known transient ($L_p = 10^{38}$ erg s^{-1}) or persistent ($L = 10^{36\text{-}37}$ erg s^{-1}) LMXB
- Bursts, light curve and spectral variability and outburst energetics difficult to reconcile with a LMXB
- The complex light curve in high state has no like in the LMXB class
- 1E 1613 is much younger than any known LMXB

Slow down a pulsar

Spin period as a function of time, starting from ejector phase onset at t_0 with initial period P=1ms



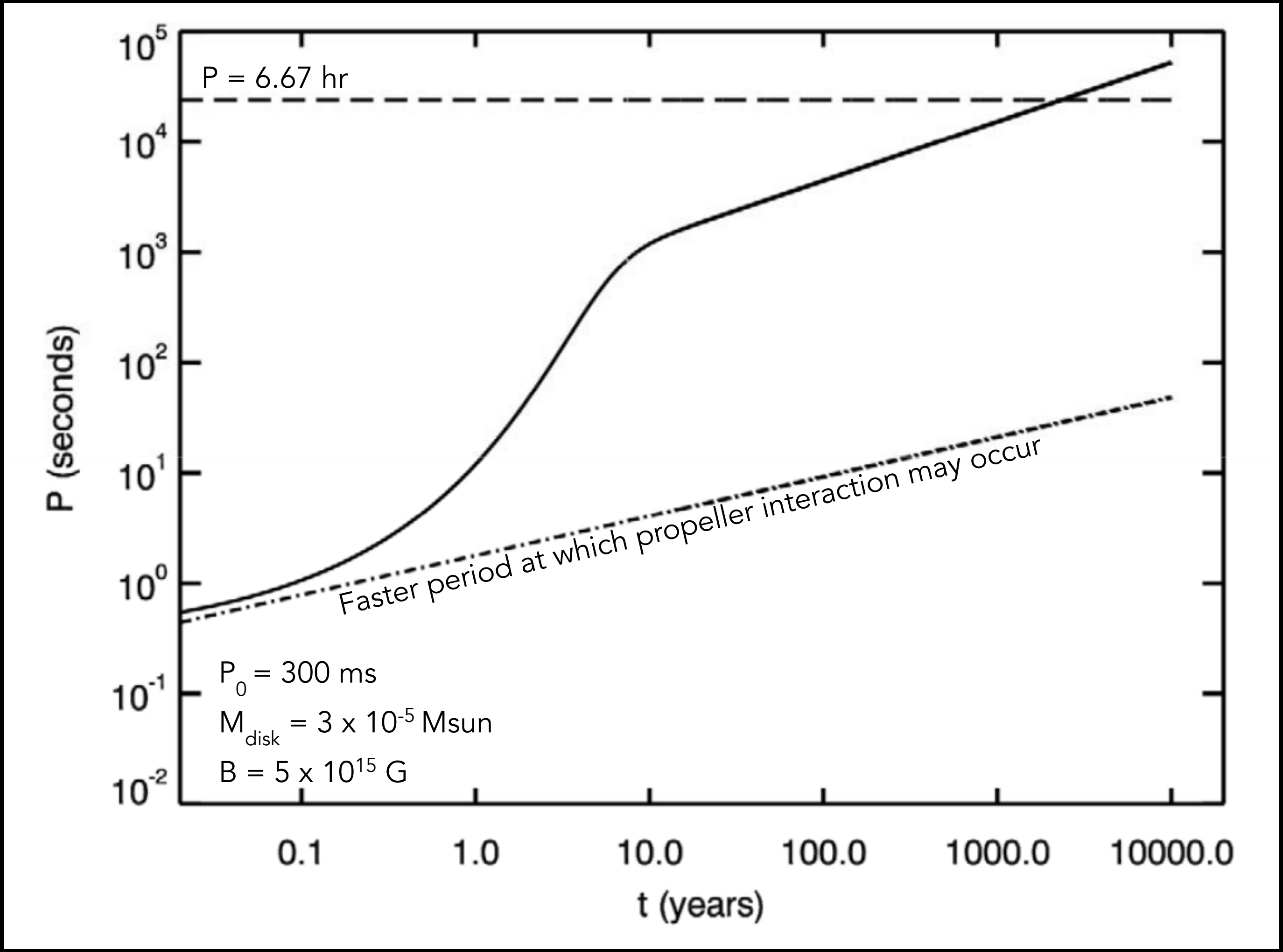
For a given Mdot, more strongly magnetized NSs reach longer periods



For a given B-field, lower Mdot produce longer spin period NSs

Ho & Andersson 2017

Slow down a pulsar



De Luca et al. 2006

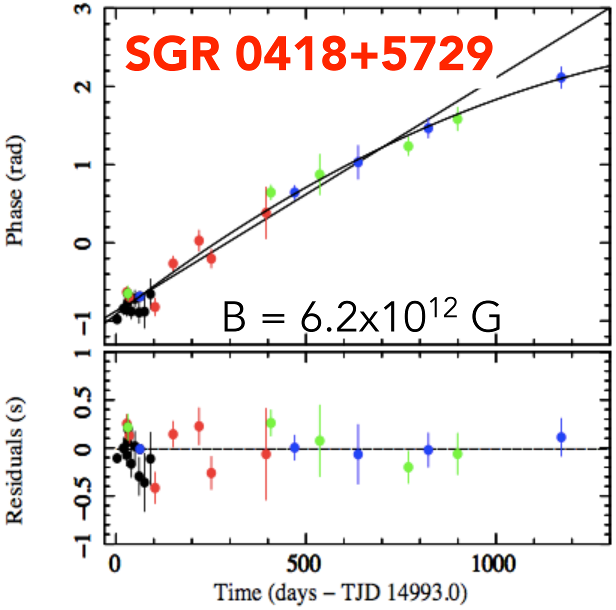
Propeller regime

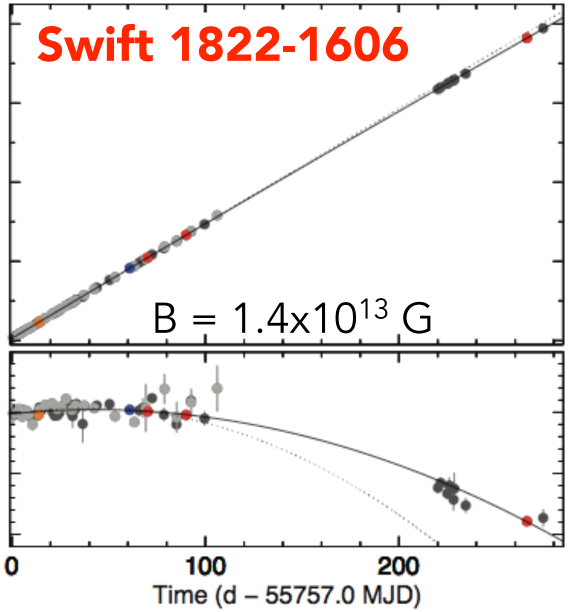
$\Omega_{NS} > \Omega_K(R_A)$

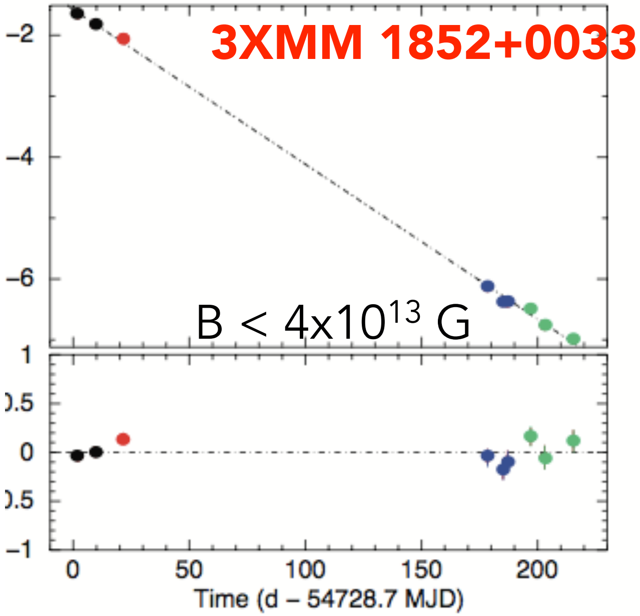
Rotational energy loss due to angular momentum transfer from the NS to the fall-back disk

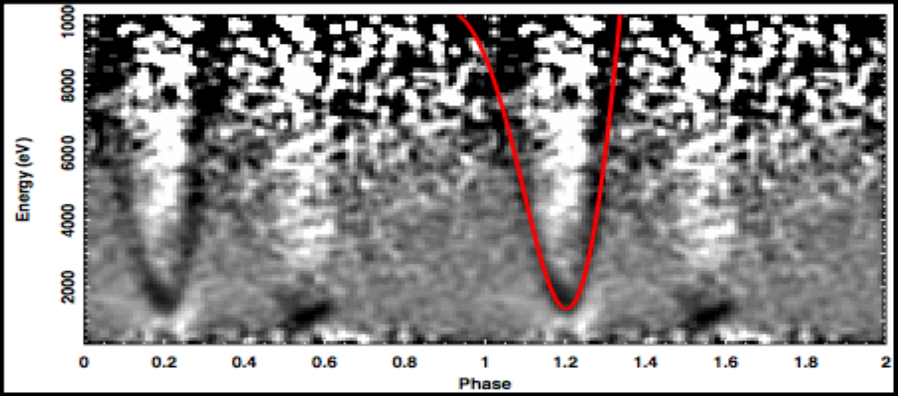
For shorter P_0, the radiation pressure of the rotating dipole would pushed away any disk (ejector phase). No efficient propeller takes place.

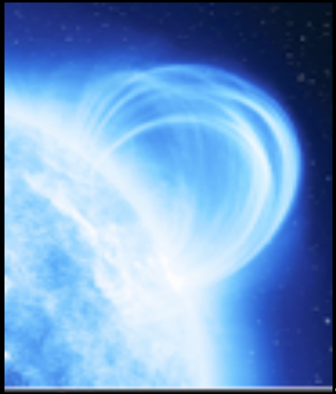
Magnetars with low "external" magnetic fields











Low-field magnetars have normal external dipolar magnetic fields while keeping strong field component close or inside the crust.

(Esposito et al. 2010; Rea et al. 2010, 2013, 2014, Tiengo et al. 2013)