The X-ray outburst of the Galactic Centre magnetar SGR J1745-2900

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The discovery of SGR J1745-2900

Large Flare from Sgr A* Detected by Swift

ATel #5006; *N. Degenaar, M. T. Reynolds, J. M. Miller (Michigan), J. A. Kennea (Penn State), R Wijnands (Amsterdam)*
on 25 Apr 2013; 00:54 UT

Swift/BAT detection of an SGR-like flare from near Sgr A*

ATel #5009; *J. A. Kennea (PSU), H. Krimm, S. Barthelmy, N. Gehrels, C. Markwardt, J. Cummings, F. Marshall (GSFC), T. Sakamoto (AGU), N. Degenaar, M. T. Reynolds, J. M. Miller (Michigan), C. Kouveliotou (MSFC)*
on 26 Apr 2013; 02:48 UT

NuSTAR discovery of a 3.76 second pulsar in the Sgr A* region

ATel #5020; *Kaya Mori, Eric V. Gotthelf (Columbia University), Nicolas M. Barriere (UC Berkeley), Charles J. Hailey (Columbia Univerity) , Fiona A. Harrison (Caltech), Victoria M. Kaspi (McGill University), John A. Tomsick (UC Berkeley), Shuo Zhang (Columbia University)*
on 27 Apr 2013; 05:40 UT

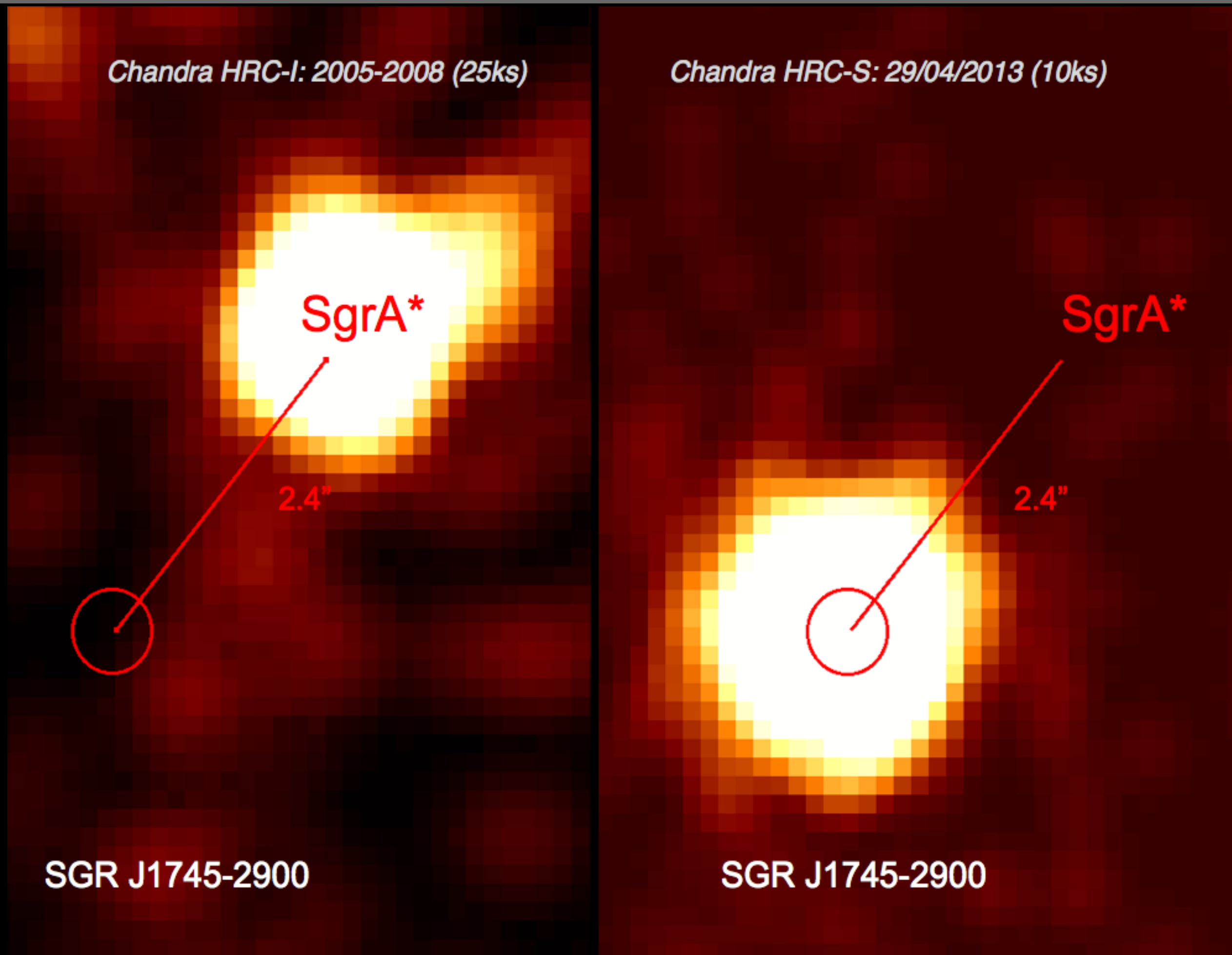
Chandra localization of the soft gamma repeater in the Galactic Center region

ATel #5032; *N. Rea (CSIC-IEEC), P. Esposito, G. L. Israel (INAF), A. Papitto (CSIC-IEEC), A. Tiengo (IUSS/INAF), F. Baganoff (MIT), D. Haggard (Northwestern/CIERA), S. Mereghetti, M. Burgay, A. Possenti (INAF), S. Zane (MSSL), on behalf of a larger collaboration*
on 30 Apr 2013; 21:53 UT

Detection of radio pulsations from the direction of the NuSTAR 3.76 second X-ray pulsar at 8.35 GHz

ATel #5040; *Ralph Eatough (Max-Planck-Institut fuer Radioastronomie: MPIfR), Ramesh Karuppusamy (MPIfR), Michael Kramer (MPIfR), Bernd Klein (MPIfR), David Champion (MPIfR), Alex Kraus (MPIfR), Evan Keane (Jodrell Bank Centre for Astrophysics: JBCA), Cees Bassa (JBCA), Andrew Lyne (JBCA), Patrick Lazarus (MPIfR), Joris Verbiest (MPIfR), Paulo Freire (MPIfR), Andreas Brunthaler (MPIfR), Heino Falcke (ASTRON, Nijmegen)*
on 2 May 2013; 21:48 UT

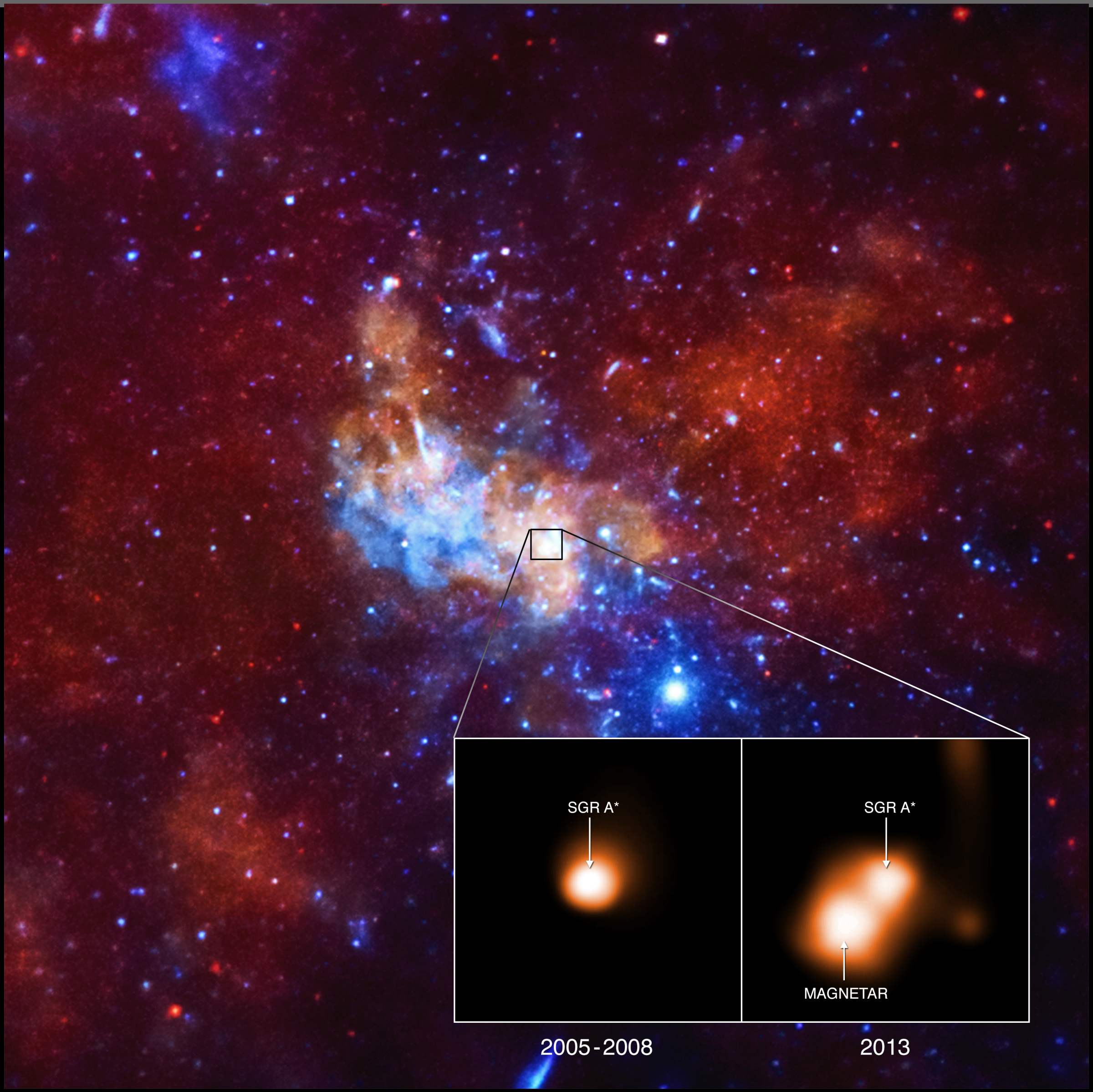
The closest pulsar to a black hole



Chandra/HRC images of the field of Sgr A* (Rea et al. 2013)

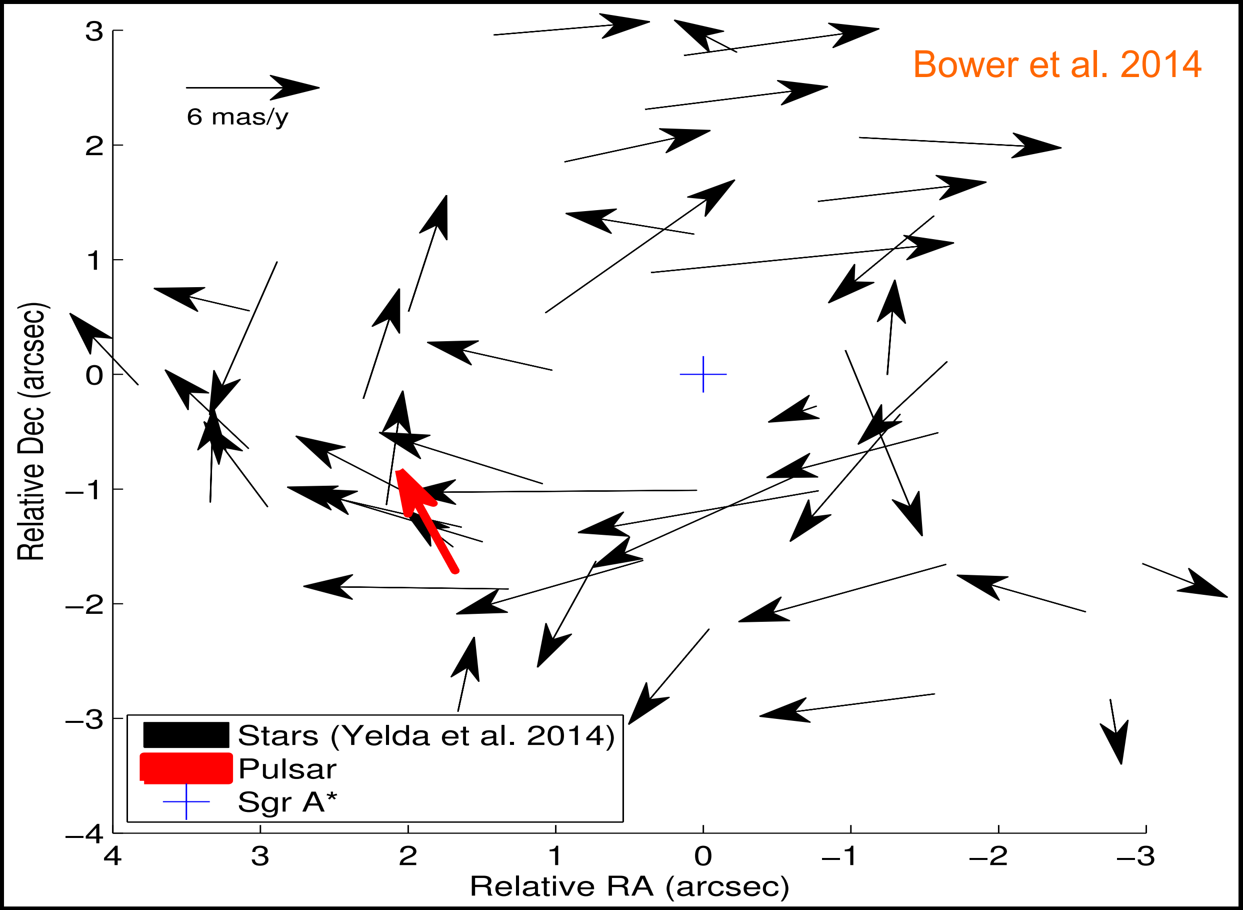
a 2.4" projected distance translates in a minimum physical separation
d = 0.09+/-0.02 pc (90% CL) for D=8.3 kpc

The closest pulsar to a black hole



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

Is it bounded to Sgr A*?

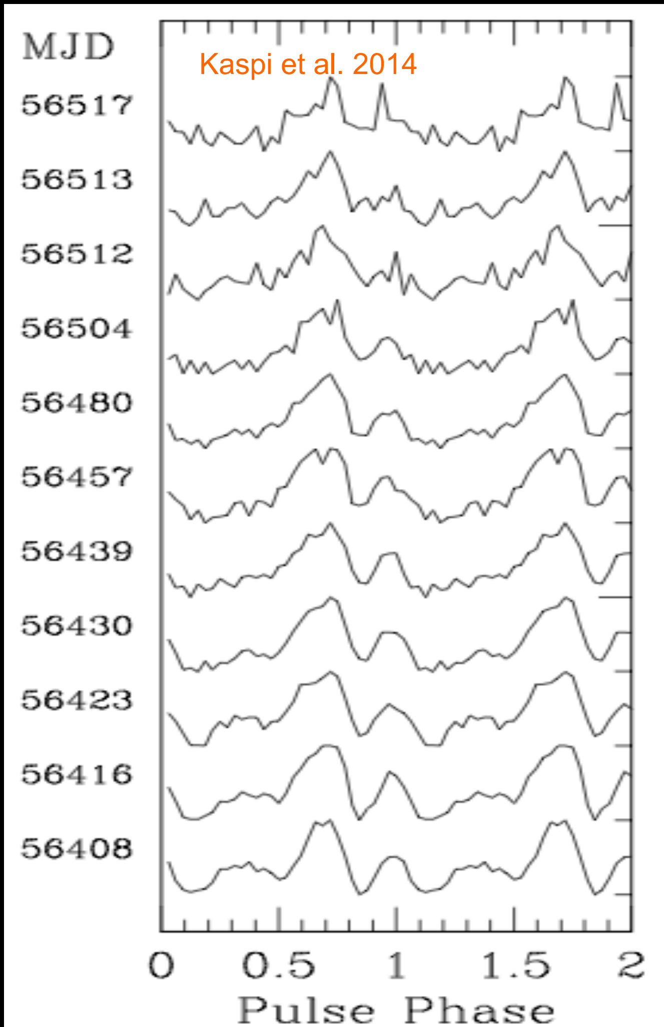


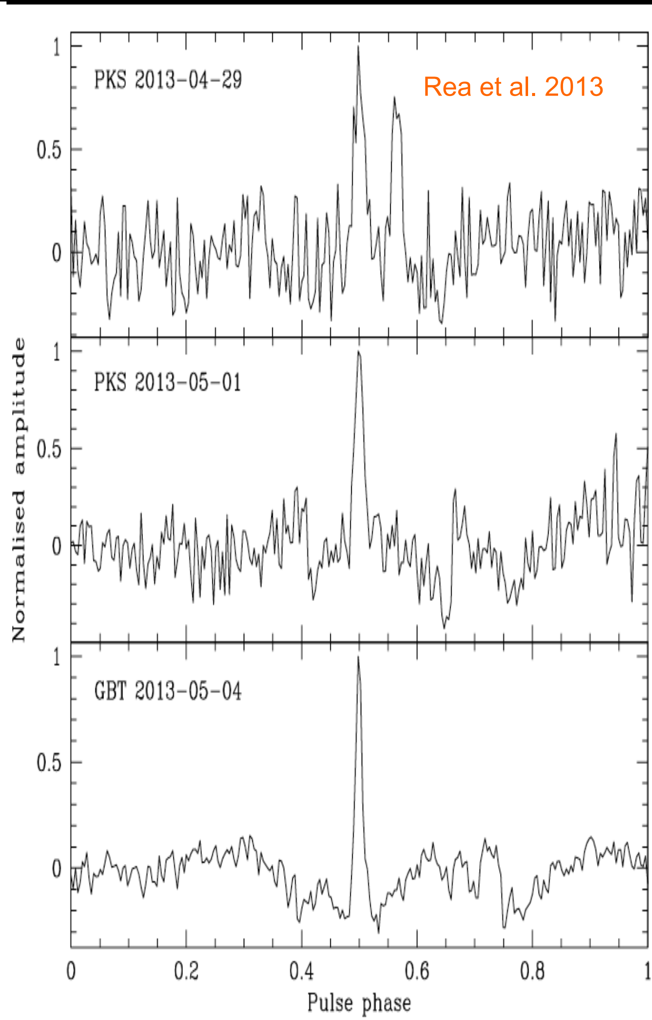
Proper motion from *VLBA* observations

Transverse velocity of 236+/-11 km/s at a position angle 22+/-2 deg East-of-North

90% probability on average of being bound to the SMBH if born within 1 parsec.
Depending on eccentricity and semi-mayor axis, it can have an orbital period from a minimum of 500 yr to several kyrs (Rea et al. 2013)

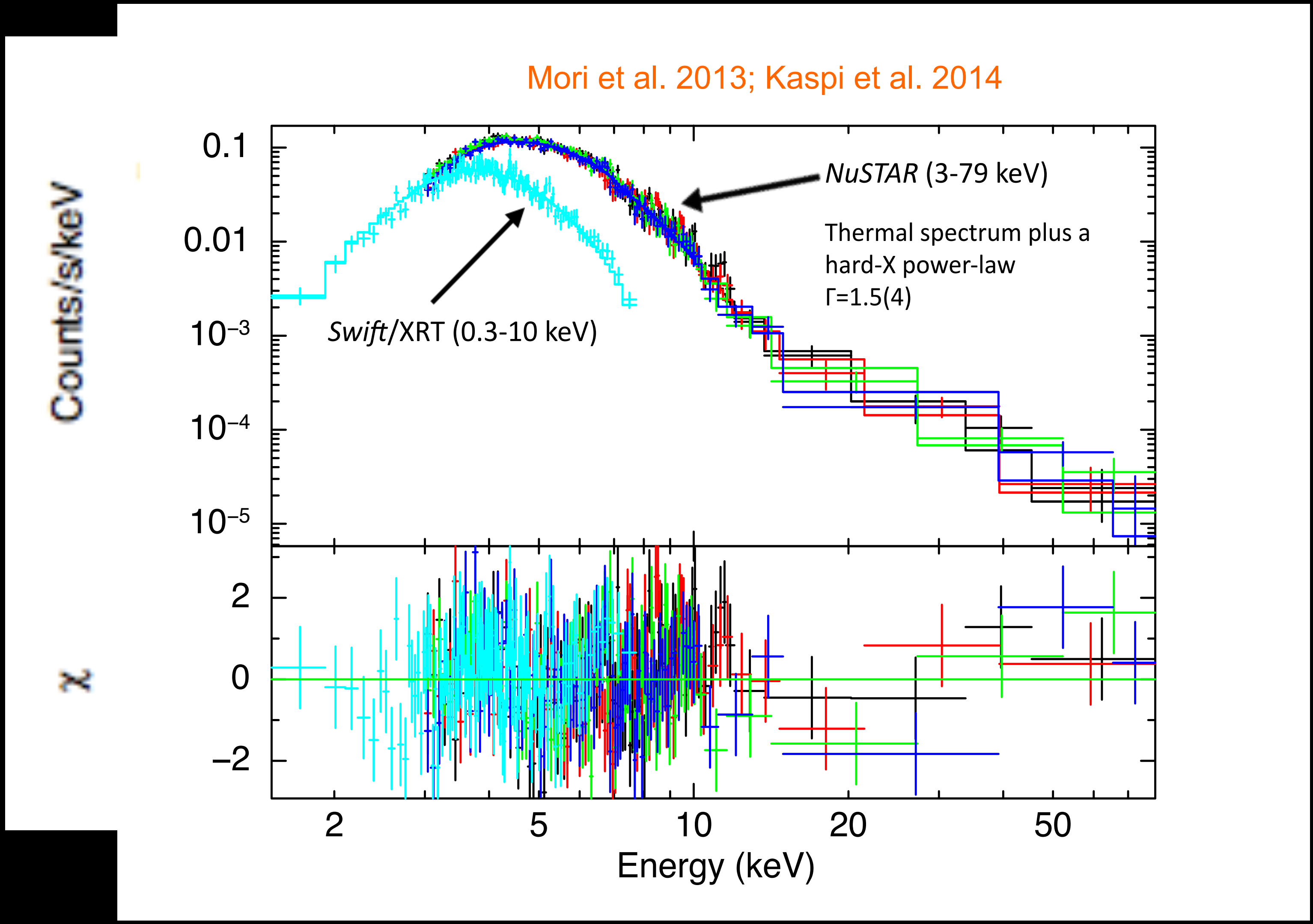
X-ray and radio pulsed emission





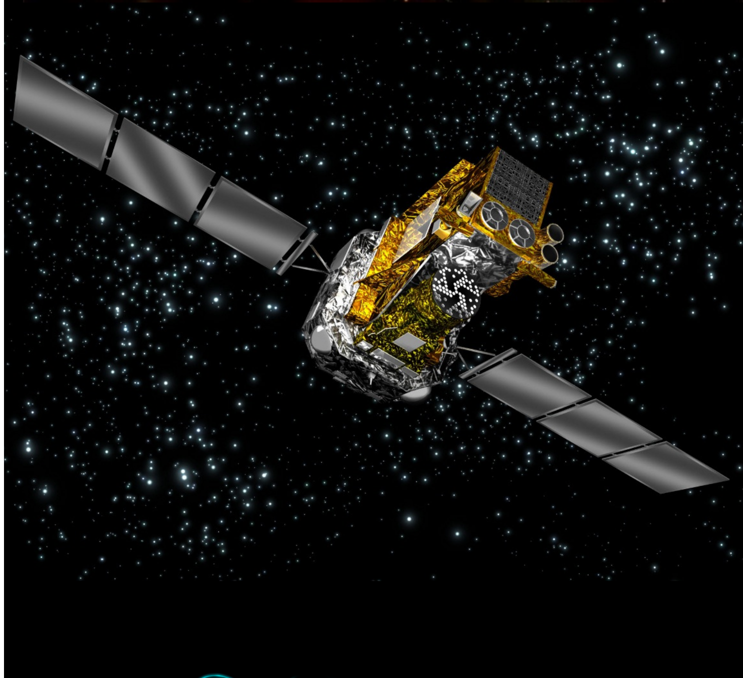
$P = 3.76$ s
Pdot ~ 0.4 - 6.6x10^{-12} s/s
B_{dip} ~ 2x10^{14} G
L_{sd} = 5x10^{33} erg/s
τ_c ~ 9 kyr

X-ray spectrum

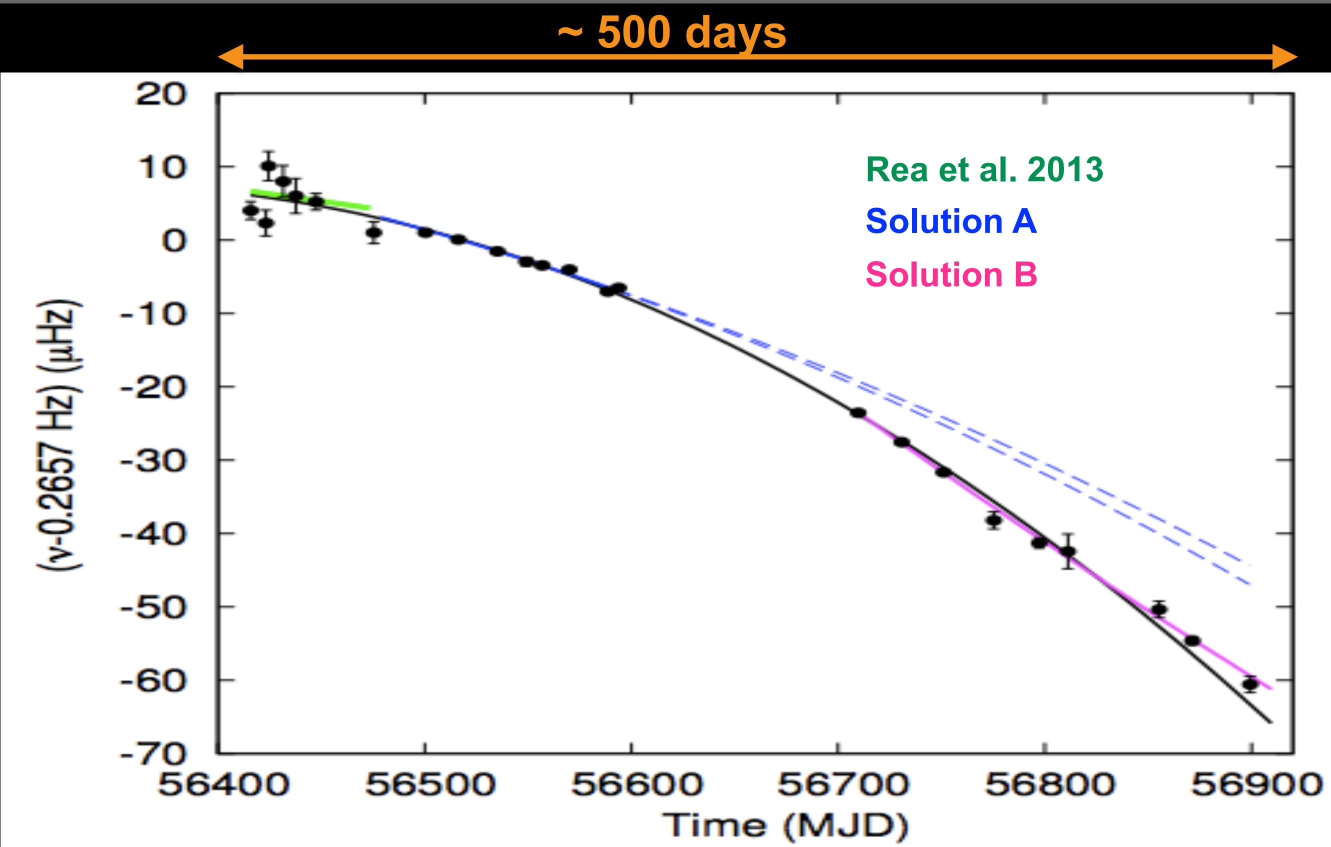


25 *Chandra* and 8 *XMM-Newton* observations: an unprecedented dataset

Obs. ID	MJD	Start time (TT) (yyyy/mm/dd hh:mm:ss)	End time (TT) (yyyy/mm/dd hh:mm:ss)	Exposure time (ks)	Source net counts ($\times 10^3$)
14702[a]	56424.55	2013/05/12 10:38:50	2013/05/12 15:35:56	13.7	7.4
15040[b]	56437.63	2013/05/25 11:38:37	2013/05/25 18:50:50	23.8	3.5
14703[a]	56447.48	2013/06/04 08:45:16	2013/06/04 14:29:15	16.8	7.6
15651[b]	56448.99	2013/06/05 21:32:38	2013/06/06 01:50:11	13.8	1.9
15654[b]	56452.25	2013/06/09 04:26:16	2013/06/09 07:38:28	9.0	1.2
14946[a]	56475.41	2013/07/02 06:57:56	2013/07/02 12:46:18	18.2	7.1
15041	56500.36	2013/07/27 01:27:17	2013/07/27 15:53:25	45.4	15.7
15042	56516.25	2013/08/11 22:57:58	2013/08/12 13:07:47	45.7	14.4
0724210201[c]	56535.19	2013/08/30 20:30:39	2013/08/31 12:28:26	55.6/57.2/57.2	39.7
14945	56535.55	2013/08/31 10:12:46	2013/08/31 16:28:32	18.2	5.3
0700980101[c]	56545.37	2013/09/10 03:18:13	2013/09/10 14:15:07	35.7/37.3/37.3	24.9
15043	56549.30	2013/09/14 00:04:52	2013/09/14 14:19:20	45.4	12.5
14944	56555.42	2013/09/20 07:02:56	2013/09/20 13:18:10	18.2	5.0
0724210501[c]	56558.15	2013/09/22 21:33:13	2013/09/23 09:26:52	41.0/42.6/42.5	26.5
15044	56570.01	2013/10/04 17:24:48	2013/10/05 07:01:03	42.7	10.9
14943	56582.78	2013/10/17 15:41:05	2013/10/17 21:43:58	18.2	4.5
14704	56588.62	2013/10/23 08:54:30	2013/10/23 20:43:44	36.3	8.7
15045	56593.91	2013/10/28 14:31:14	2013/10/29 05:01:24	45.4	10.6
16508	56709.77	2014/02/21 11:37:48	2014/02/22 01:25:55	43.4	6.8
16211	56730.71	2014/03/14 10:18:27	2014/03/14 23:45:34	41.8	6.2
0690441801[c]	56750.72	2014/04/03 05:23:24	2014/04/04 05:07:01	83.5/85.2/85.1	34.3
16212	56751.40	2014/04/04 02:26:27	2014/04/04 16:49:26	45.4	6.2
16213	56775.41	2014/04/28 02:45:05	2014/04/28 17:13:57	45.0	5.8
16214	56797.31	2014/05/20 00:19:11	2014/05/20 14:49:18	45.4	5.4
16210	56811.24	2014/06/03 02:59:23	2014/06/03 08:40:34	17.0	1.9
16597	56842.98	2014/07/04 20:48:12	2014/07/05 02:21:32	16.5	1.6
16215	56855.22	2014/07/16 22:43:52	2014/07/17 11:49:38	41.5	3.8
16216	56871.43	2014/08/02 03:31:41	2014/08/02 17:09:53	42.7	3.6
16217	56899.43	2014/08/30 04:50:12	2014/08/30 15:45:44	34.5	2.8
0743630201[c]	56900.02	2014/08/30 19:37:28	2014/08/31 05:02:43	32.0/33.6/33.6	9.2
0743630301[c]	56901.02	2014/08/31 20:40:57	2014/09/01 04:09:34	25.0/26.6/26.6	7.8
0743630401[c]	56927.94	2014/09/27 17:47:50	2014/09/28 03:05:37	25.7/32.8/32.8	7.7
0743630501[c]	56929.12	2014/09/28 21:19:11	2014/09/29 08:21:11	37.8/39.4/39.4	11.7

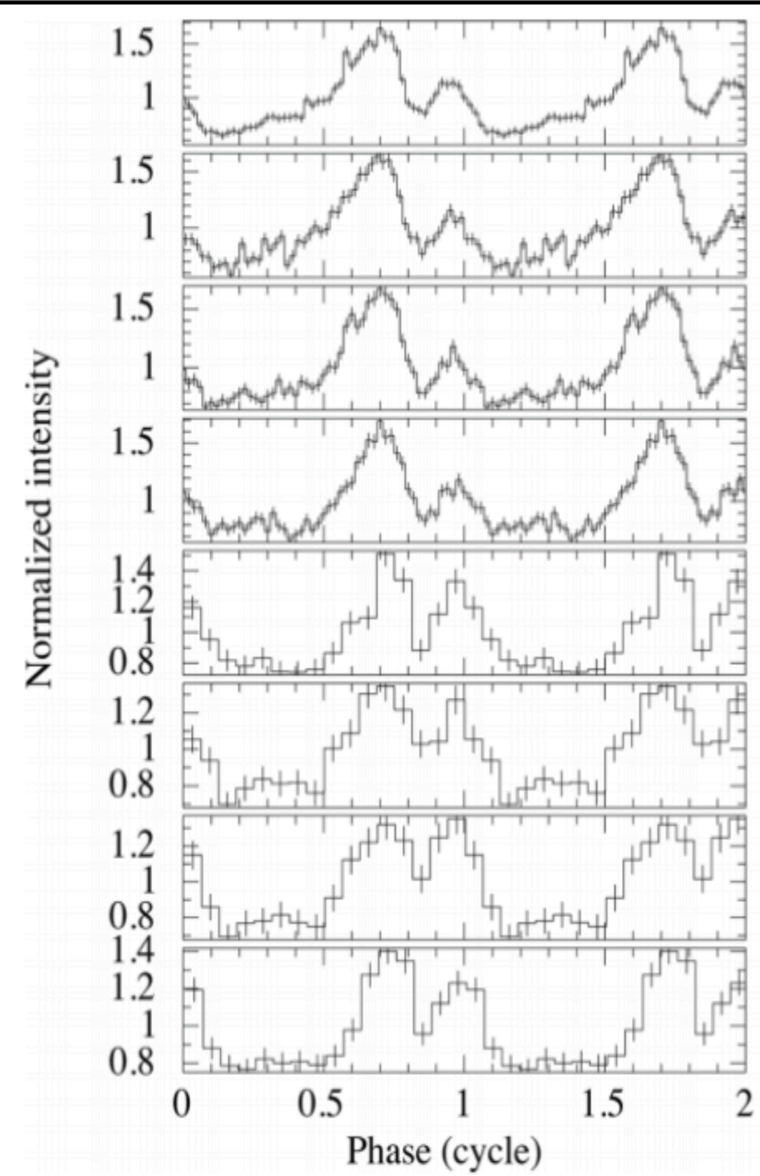


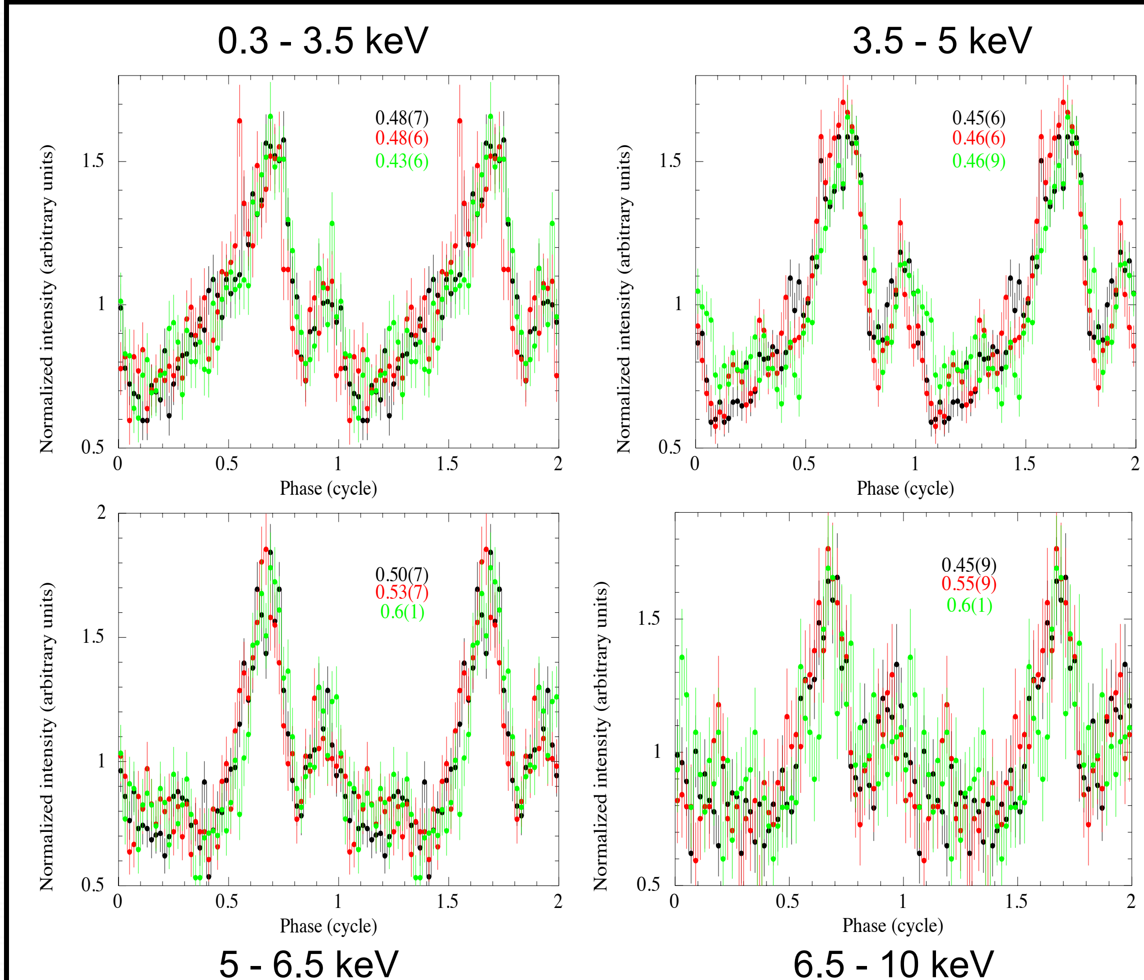
Timing properties



Solution	Rea et al. (2013b)	Kaspi et al. (2014)	This work (solution A)	This work (solution B)
Epoch T_0 (MJD)	56424.5509871	56513.0	56513.0	56710.0
Validity range (MJD)	56411.6–56475.3	56457–56519	56500.1–56594.1	56709.5–56929
$P(T_0)$ (s)	3.7635537(2)	3.76363824(13)	3.76363799(7)	3.7639772(12)
$\dot{P}(T_0)$	$6.61(4) \times 10^{-12}$	$1.385(15) \times 10^{-11}$	$1.360(6) \times 10^{-11}$	$3.27(7) \times 10^{-11}$
$\ddot{P}$ (s^{-1})	$4(3) \times 10^{-19}$	$3.9(6) \times 10^{-19}$	$3.7(2) \times 10^{-19}$	$(-1.8 \pm 0.8) \times 10^{-19}$
$\nu(T_0)$ (Hz)	0.265706368(14)	0.265700350(9)	0.26570037(5)	0.26567642(9)
$\dot{\nu}(T_0)$ (Hz s^{-1})	$-4.67(3) \times 10^{-13}$	$-9.77(10) \times 10^{-13}$	$-9.60(4) \times 10^{-13}$	$-2.31(5) \times 10^{-12}$
$\ddot{\nu}$ (Hz s^{-2})	$-3(2) \times 10^{-20}$	$-2.7(4) \times 10^{-20}$	$-2.6(1) \times 10^{-20}$	$(1.3 \pm 0.6) \times 10^{-20}$
rms residual	0.15 s	51 ms	0.396 s	1.0 μHz
χ^2_ν (d.o.f.)	0.85 (5)	1.27 (41)	6.14 (44)	0.66 (10)

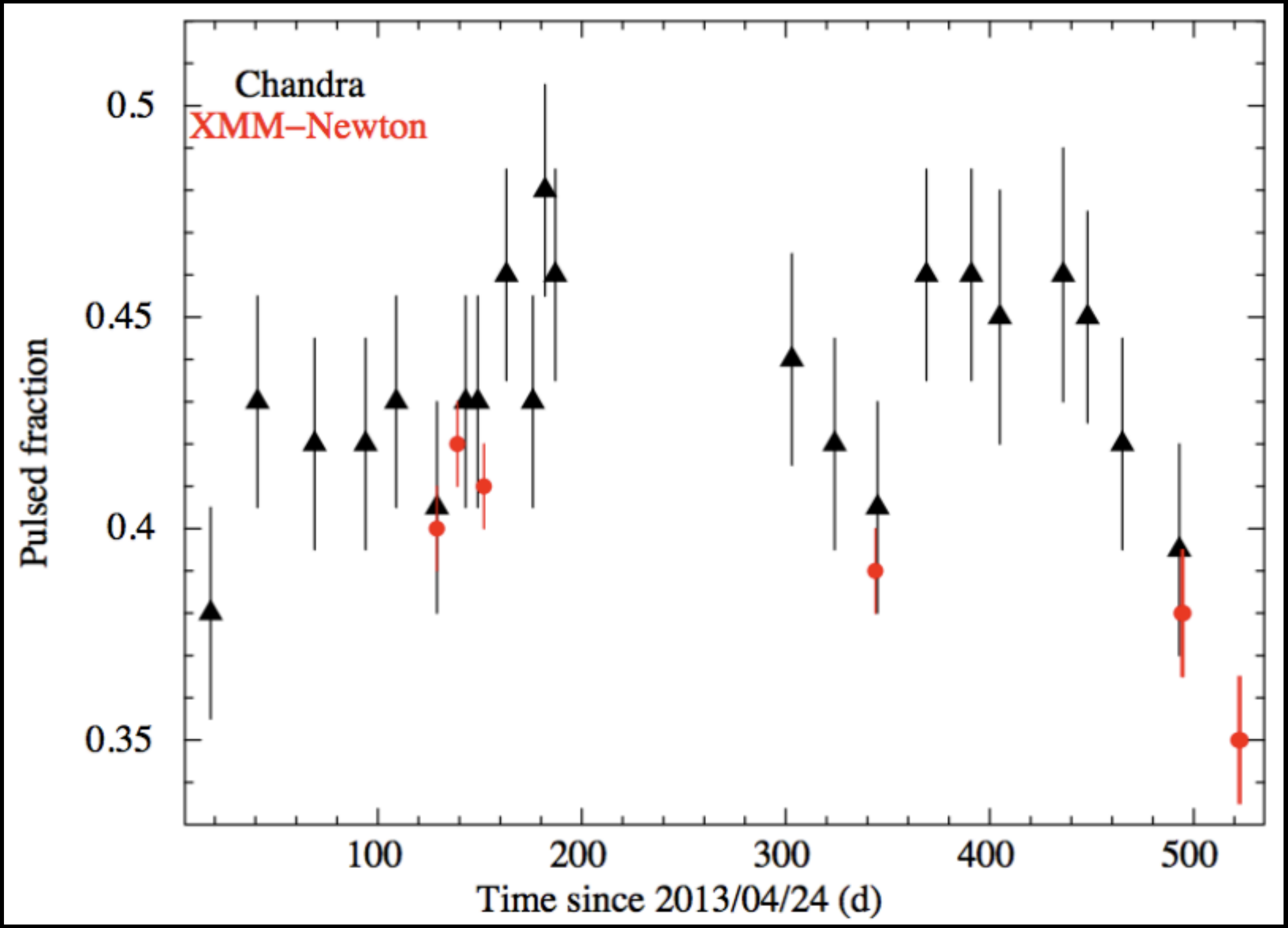
Pulse profiles



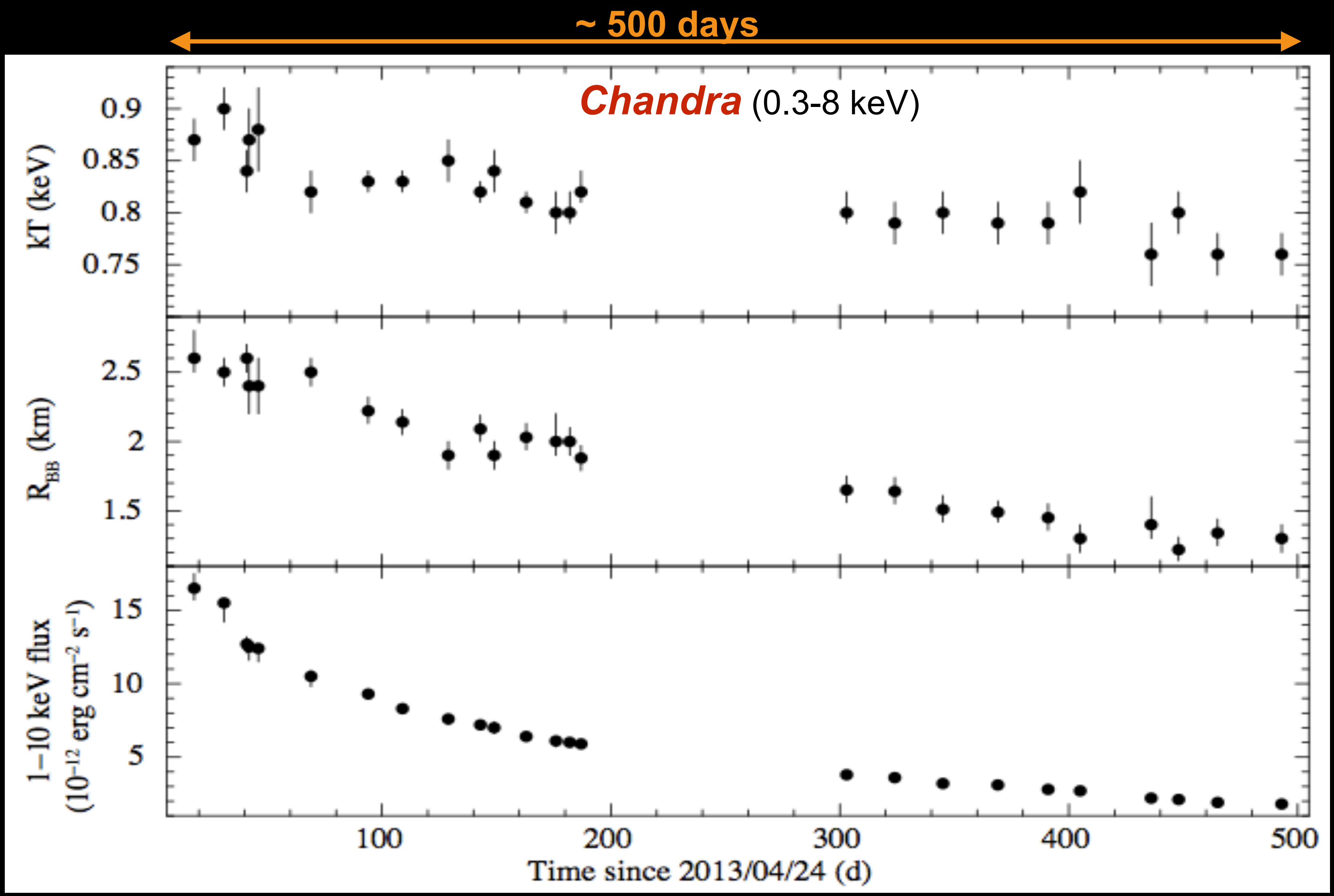


XMM-Newton observations (0.3-10 keV)

Pulsed fraction evolution

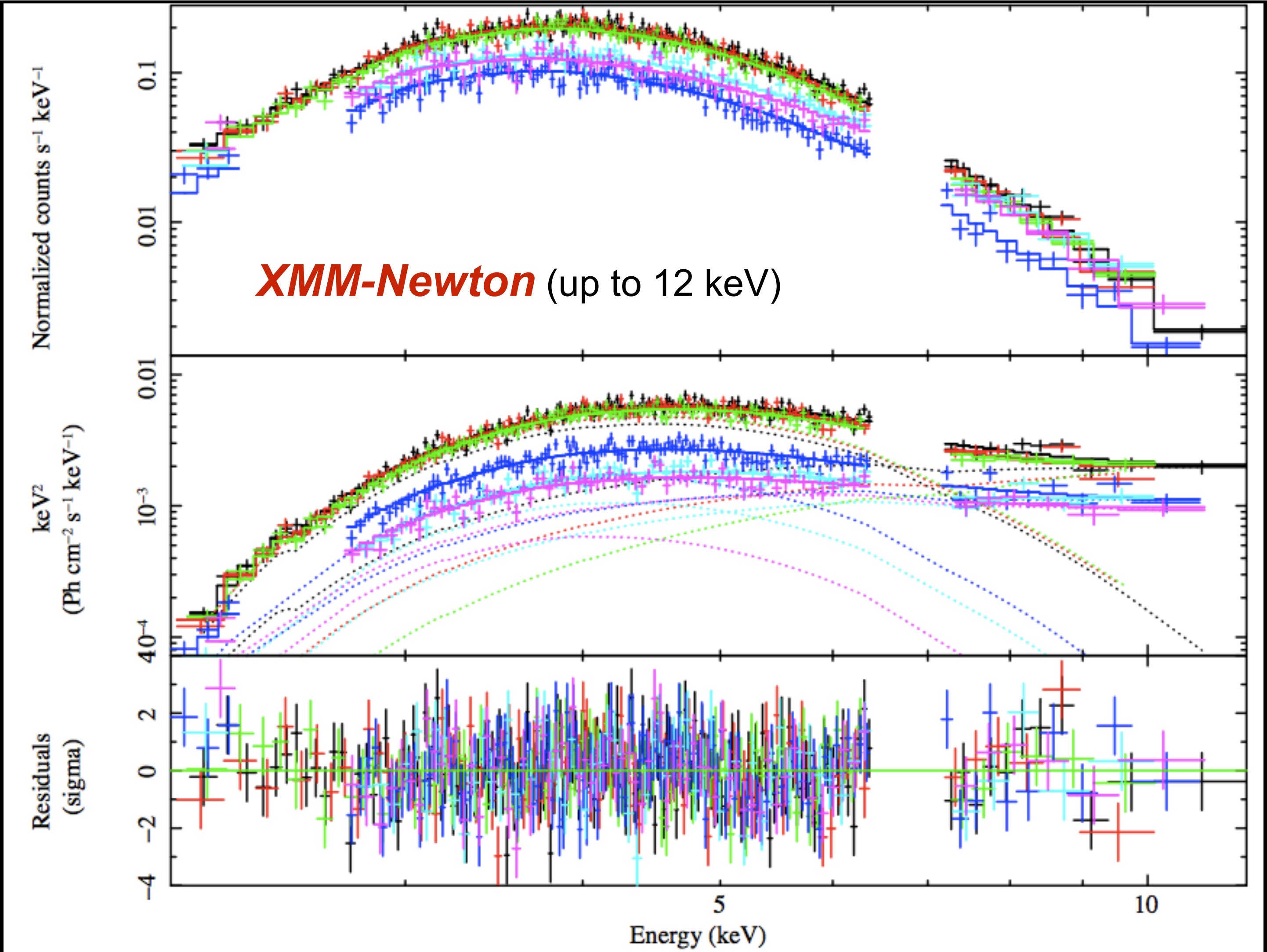


A very slow spectral decay



thermal spectrum, very high absorption: N_H = 1.90+/-0.02 x 10^{23} cm^{-2},
very slow spectral decay

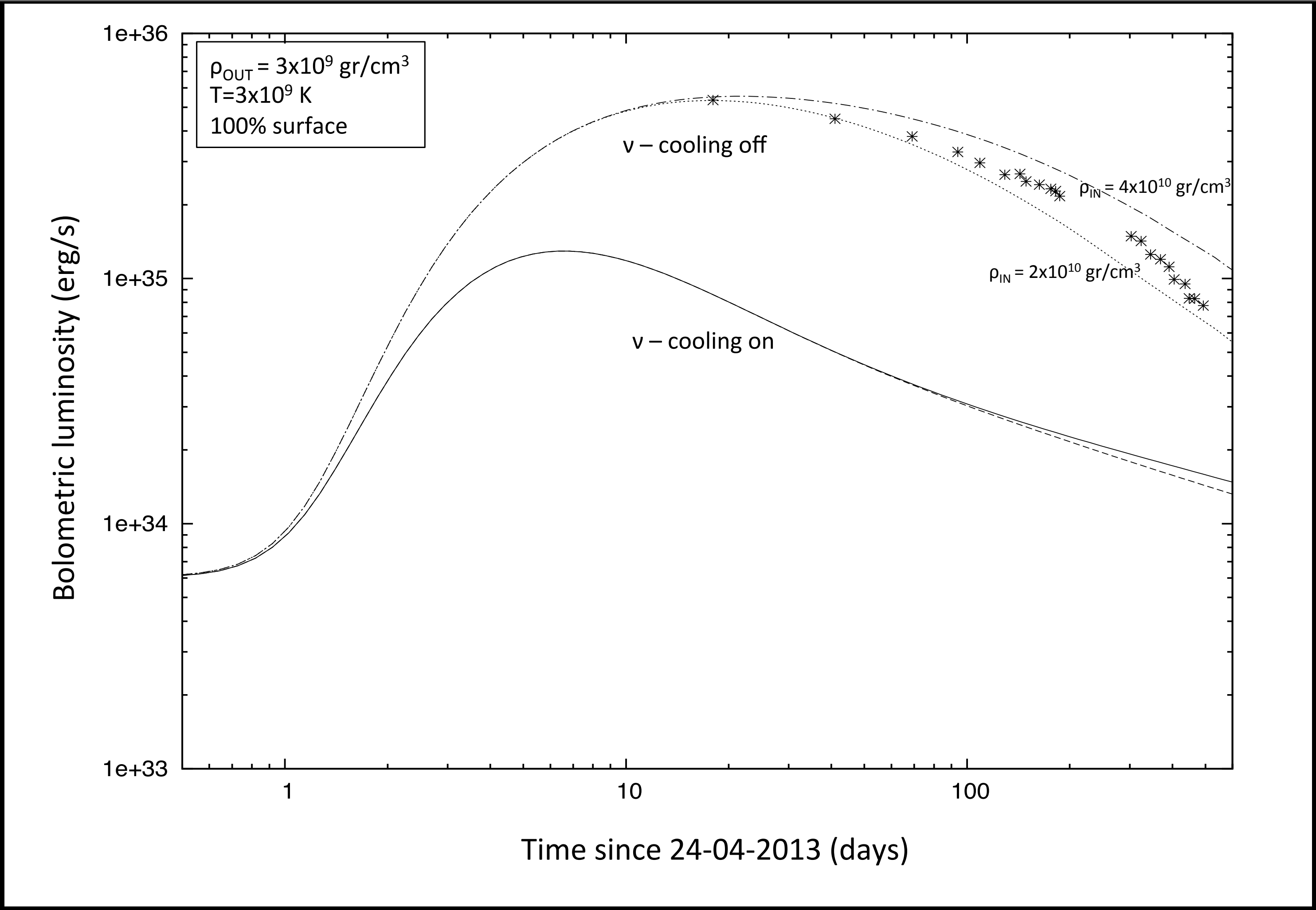
A prolonged, faint non-thermal component



- power law component at E ≥ 8 keV

- Γ ~ 1.7–2.6: consistence with *NuSTAR* (Mori et al. 2013; Kaspi et al. 2014)

Outburst modeling

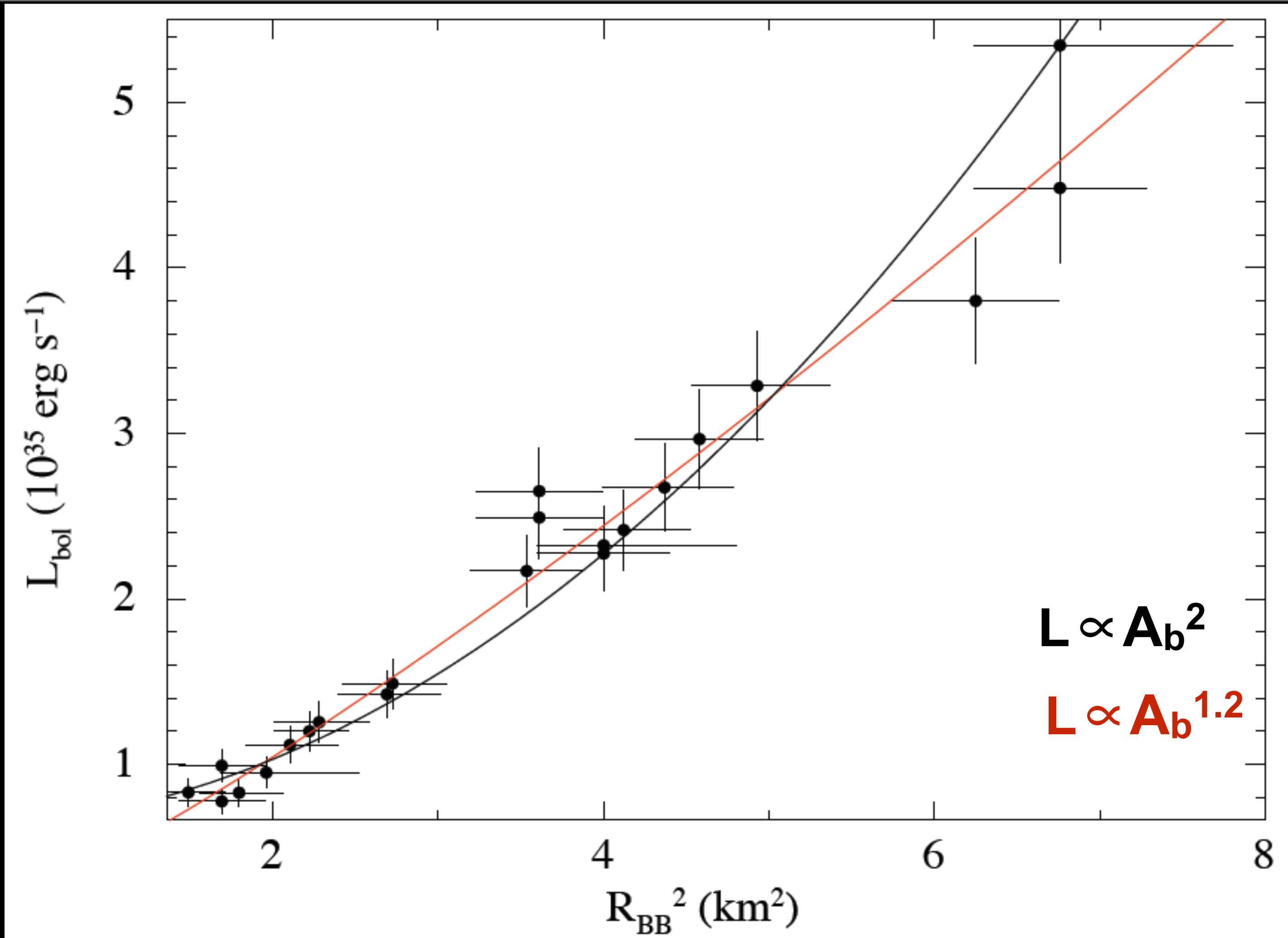


Bad modeling when injecting an energy of 10^{45} erg in the inner crust ($\rho_{IN}<\rho<\rho_{OUT}$)

Better modeling if neutrino emissions are switched off…BUT they should be at work!

Pons & Rea 2012

Bombardment of magnetospheric currents



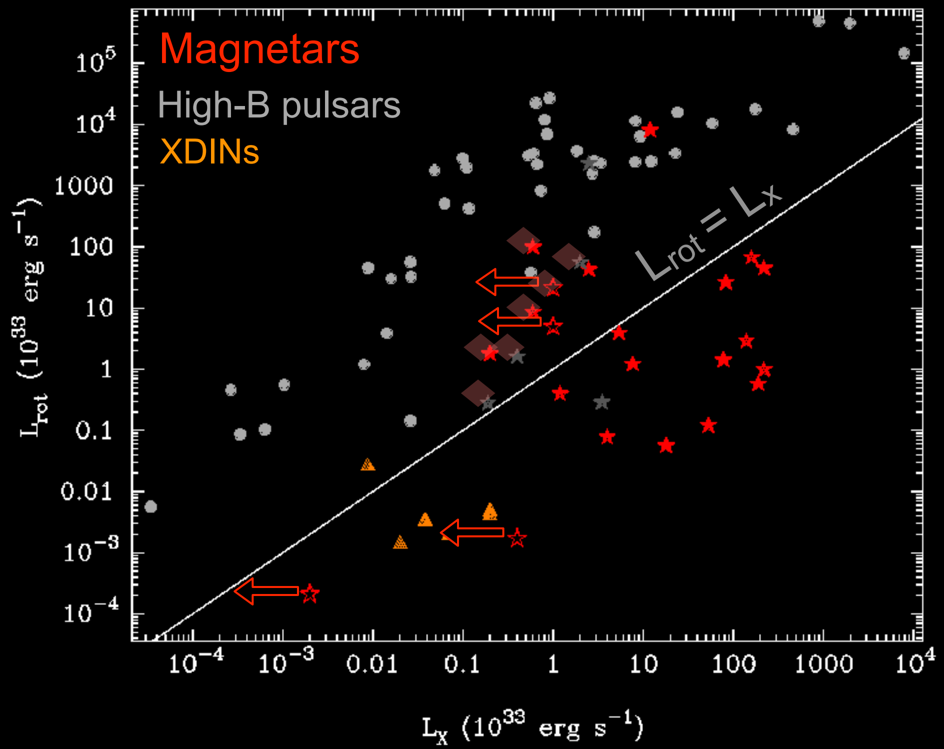
Currents in a bundle of twisted field lines keep slamming on to the NS surface and form a hot spot

As the bundle untwists, the hot spot cools and shrinks. L should decrease as $L \propto A_b^2$

Beloborodov 2009

A radio magnetar that is no exception

- quiescent X-ray luminosity:
  $L_{x,q} \lesssim 10^{33}$ erg/s (0.5-10 keV)
- spin-down power:
  $L_{sd} = 5\text{x}10^{33}$ erg/s



1) quiescent radio magnetars might be rotation-powered, as normal radio pulsars

2) possible magnetar radio activity can be predicted if P, Pdot, and L_X are known

"The fundamental plane for radio magnetars" (readapted from Rea et al. 2012)

Conclusions

- SGR J1745-2900 is the closest pulsar to a BH detected so far (≥0.07 pc from Sgr A*)

- It is probably bound to Sgr A*.

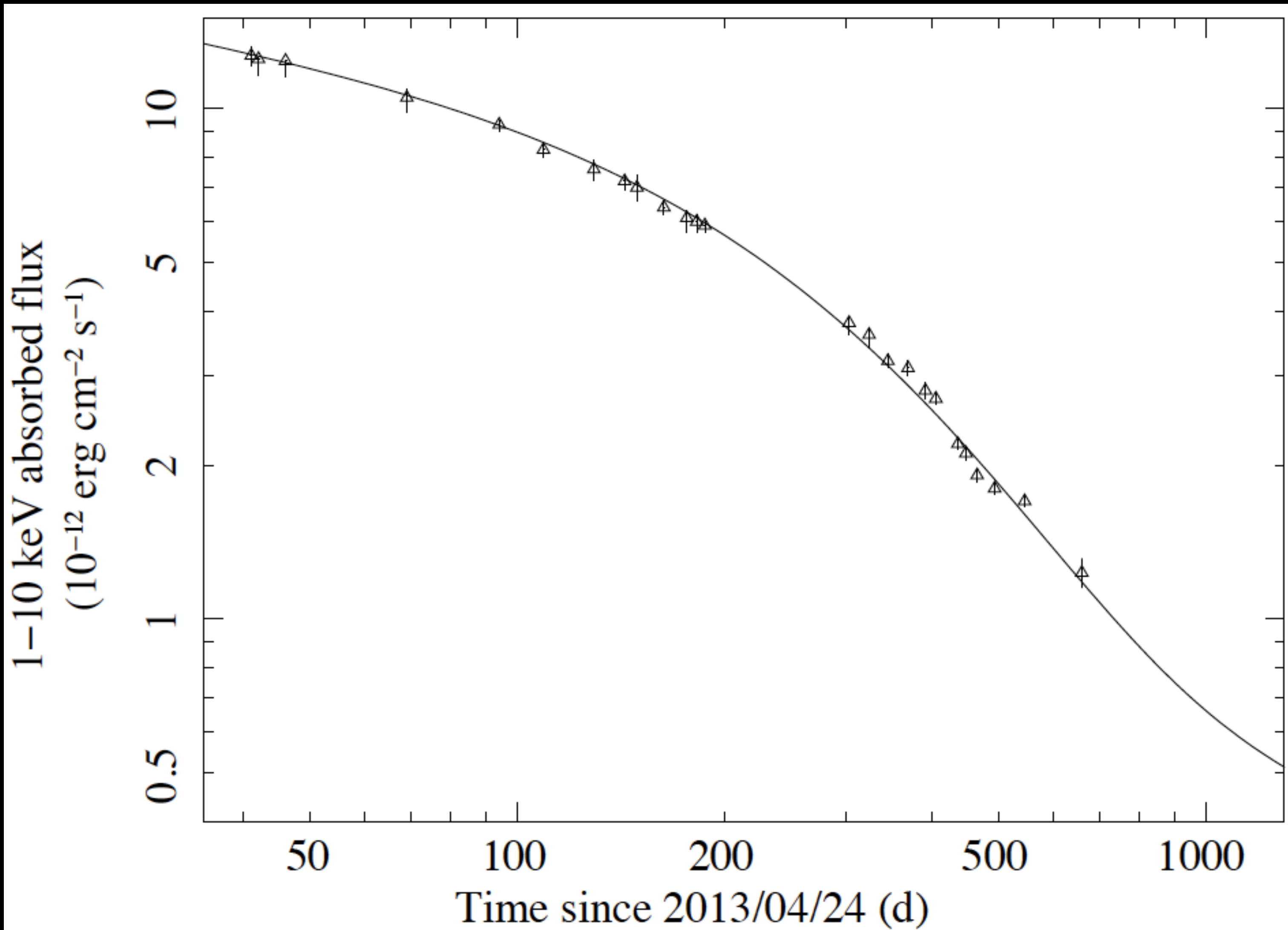
- An unprecedented dataset of X-ray observations
  Study of the outburst properties on a long temporal baseline (500 days)

- A very slow spectral decay. A power law is observed above ~8 keV

- The cooling is challenging most of the crustal models.
  Large contribution from bombardment of magnetospheric currents (twisted j-bundle)

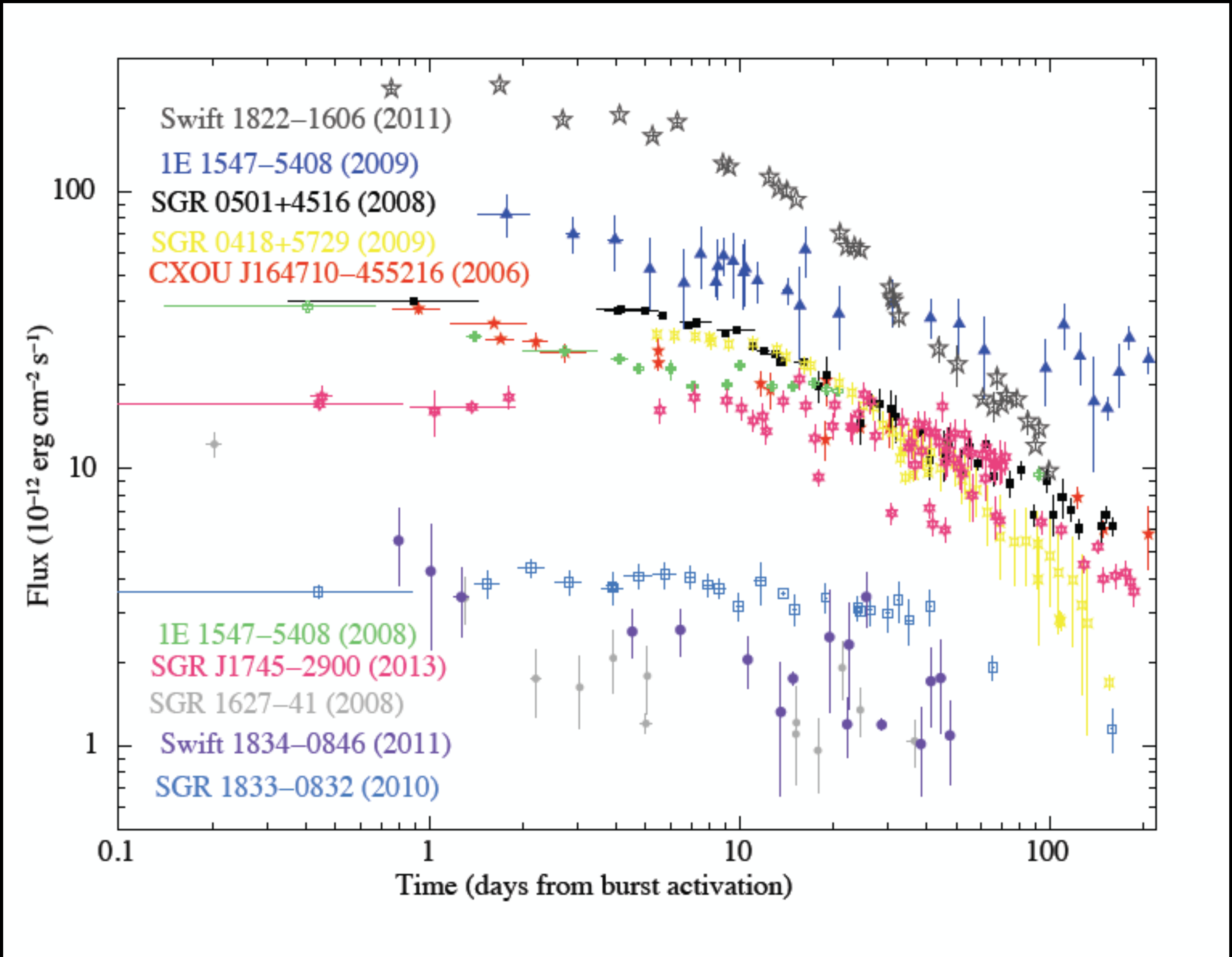
- SGR J1745-2900 and radio magnetars might behave as radio pulsars in quiescence

Really inexhaustible….



the X-ray monitoring campaign of the GC is ongoing.
still 750 days after the outburst onset, the magnetar is incredibly hot (~ 0.8 keV) and bright

Transient magnetars



Coti Zelati et al. 2015

Monte Carlo numerical simulations

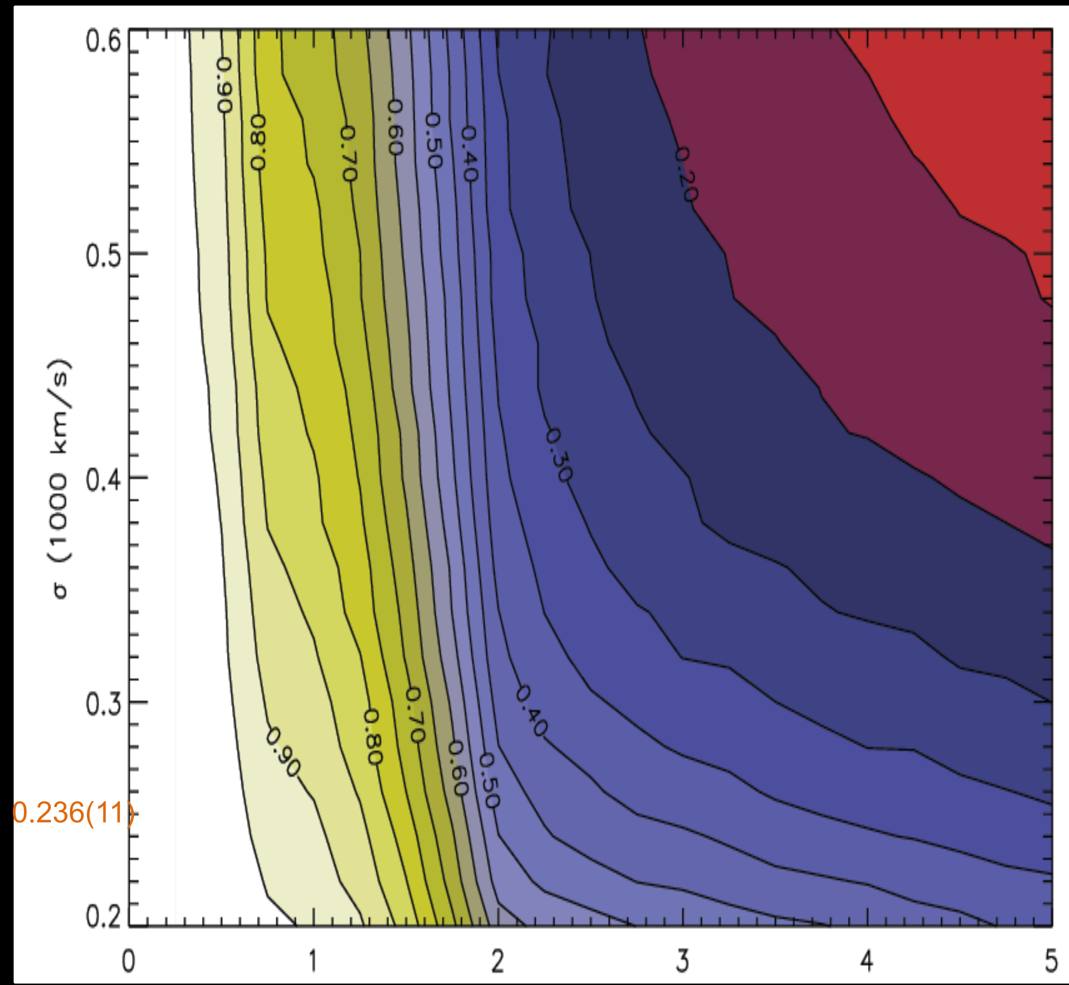
- numerical simulation is performed for 10^6 stars by integrating the equations of motion in the gravitational potential of the BH (Newtonian gravity is assumed)

- for each orbit, the initial radial distance *d* is fixed (0.05 pc ≲ *d* ≲ 5 pc) and the NS kick velocity at birth is drawn from a Gaussian distribution with 200 km/s < σ < 600 km/s

- orbits are calculated for 0 ≲ t ≲ 9 kyr. The total energy *E* of the star is measured at t=9 kyr

- the fraction of bound orbits is

N(E<0)/N$_{tot}$



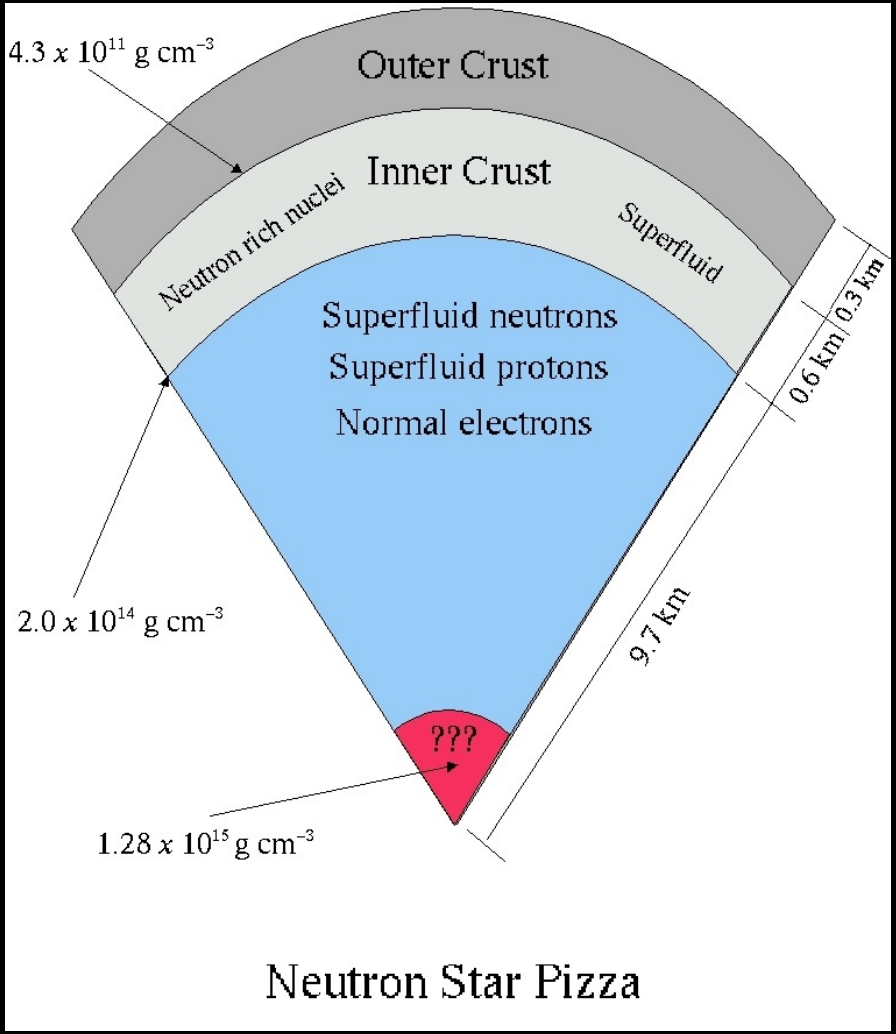
Crustal cooling models

Recipe:

- inject a fixed amount of energy in a fraction of the crust volume (on a very short timescale) and at different depths

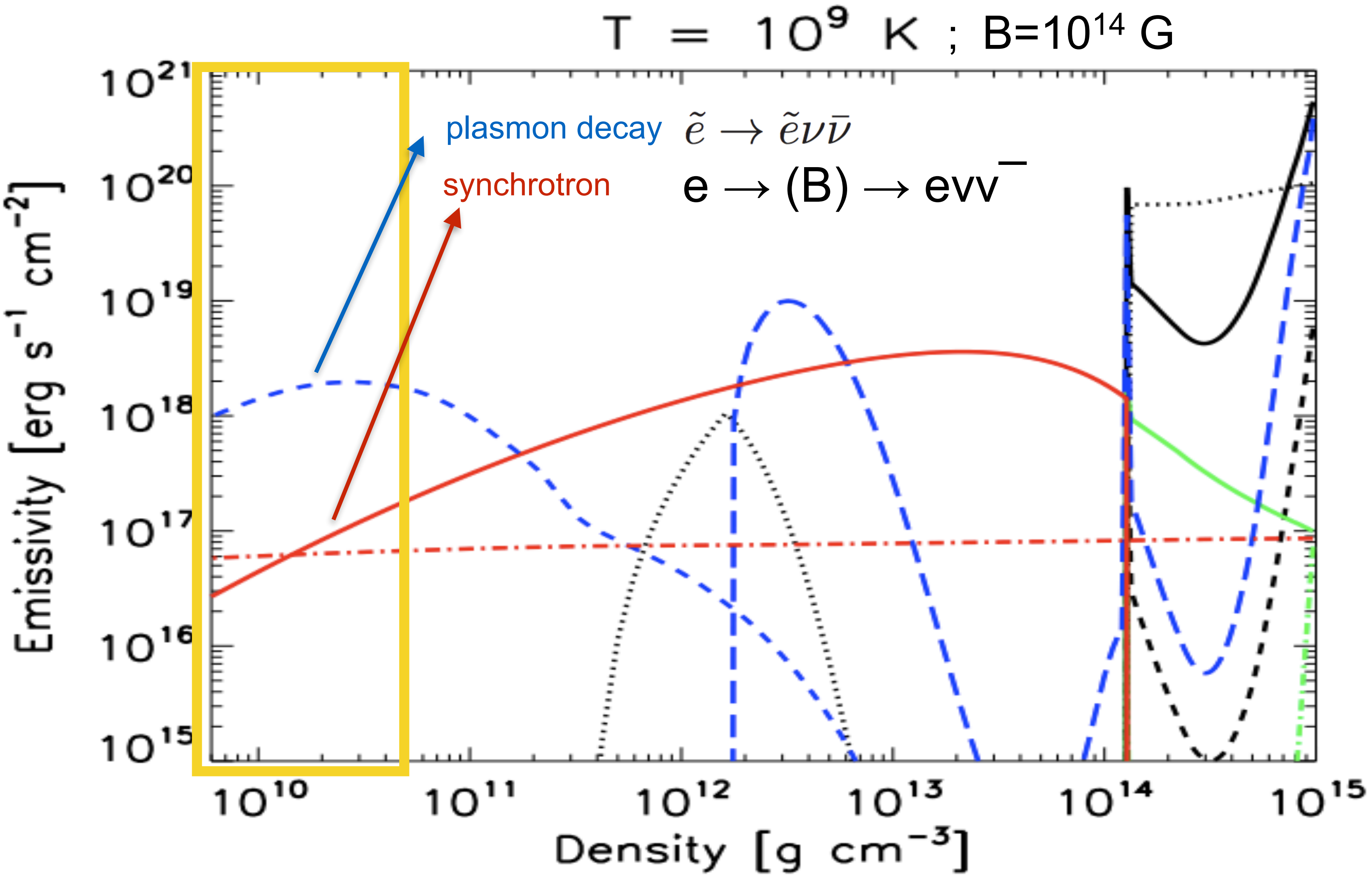
- follow the evolution of the thermal structure until it returns to the original state.

B can be assumed constant on this timescale



Pons & Rea 2012, ApJ Letters, 750, L6

Neutrino processes in the crust (and the core)



Yakovlev et al. 2001; Viganò 2013

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

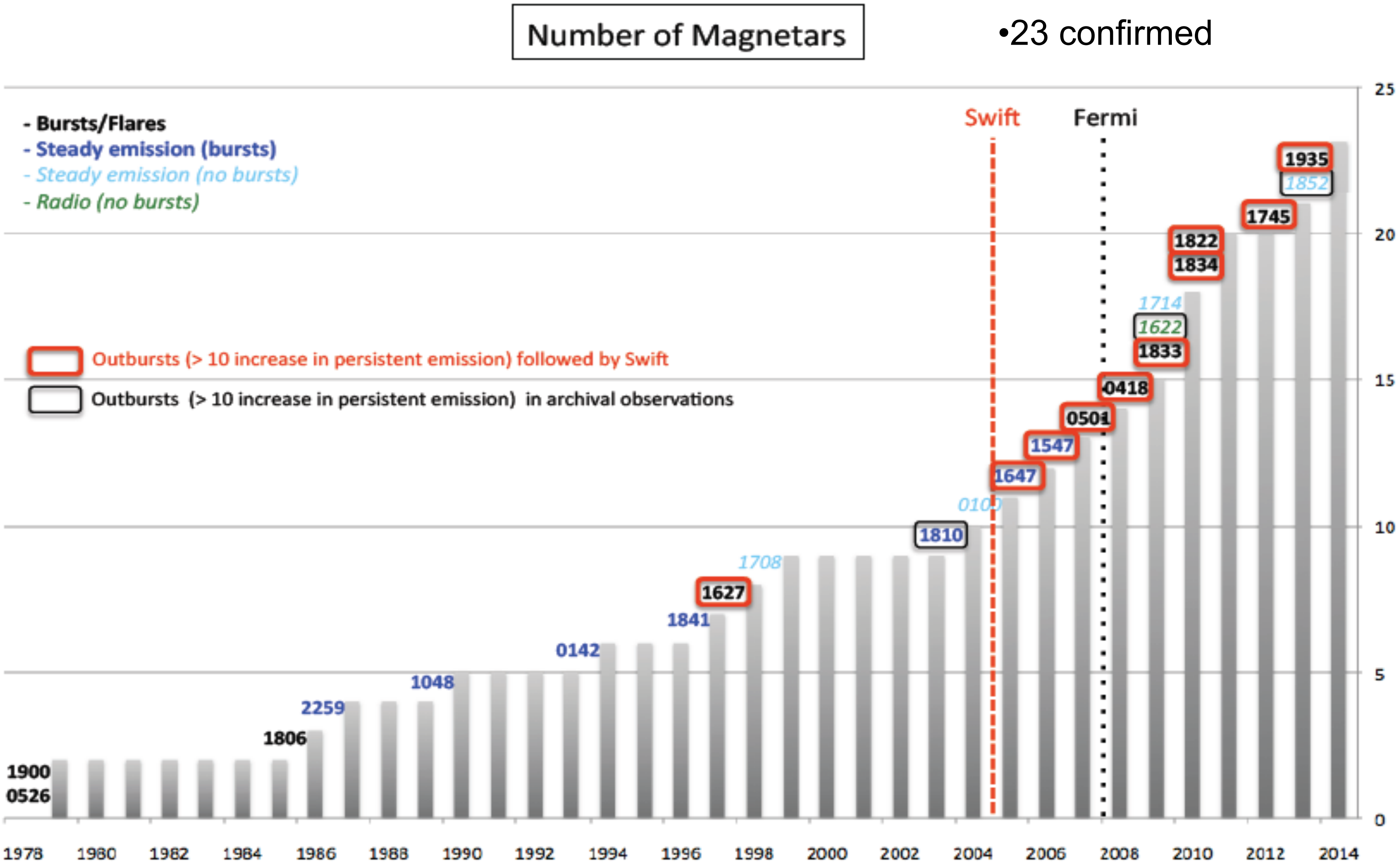
A non-thermal spectral component and a small heated region suggest the presence of twisted magnetic field lines confined in a narrow bundle

Credit: *NASA/Wiessinger*

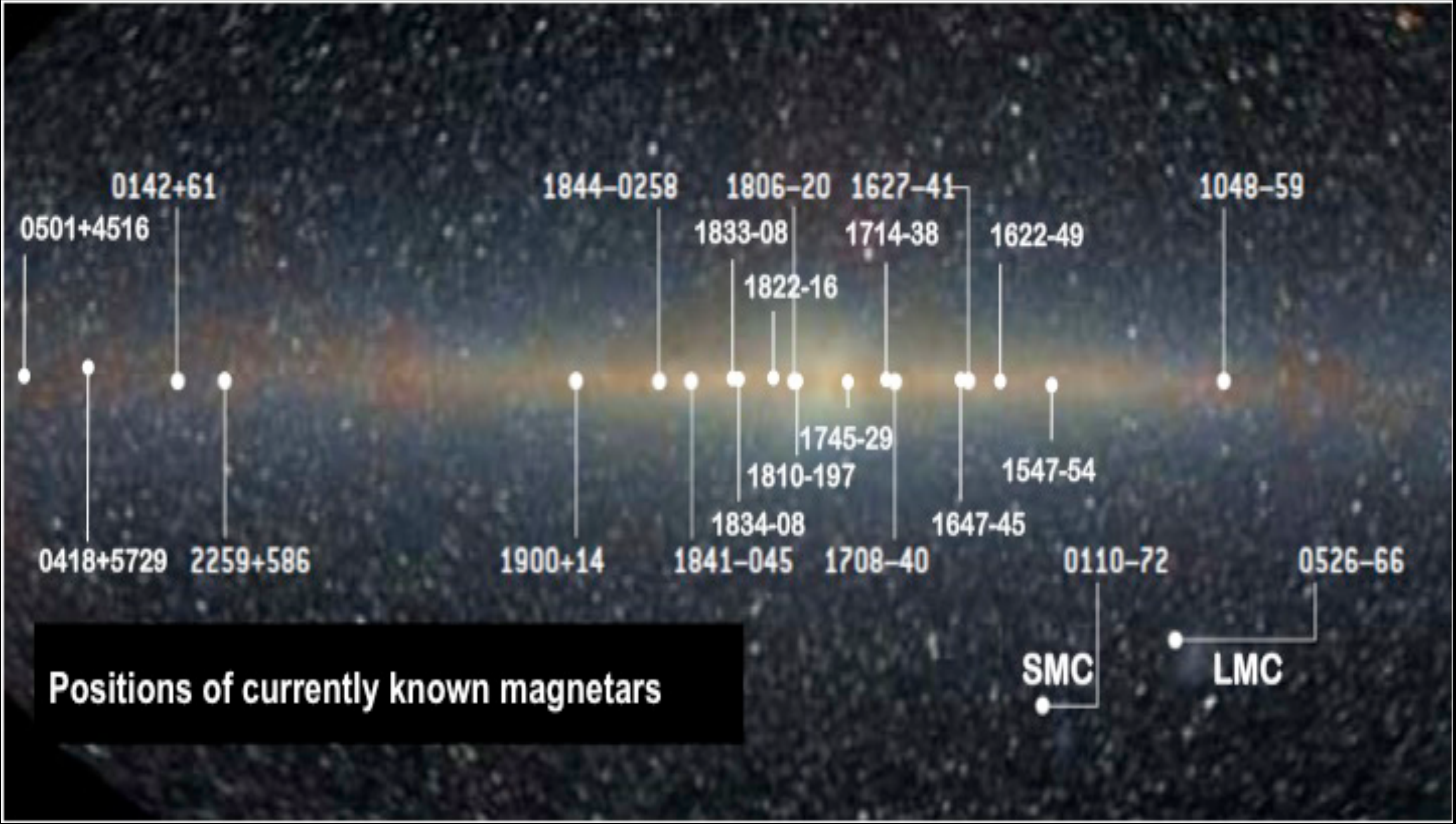
Beloborodov 2009, ApJ, 703, 1044

Currently known magnetars

•23 confirmed

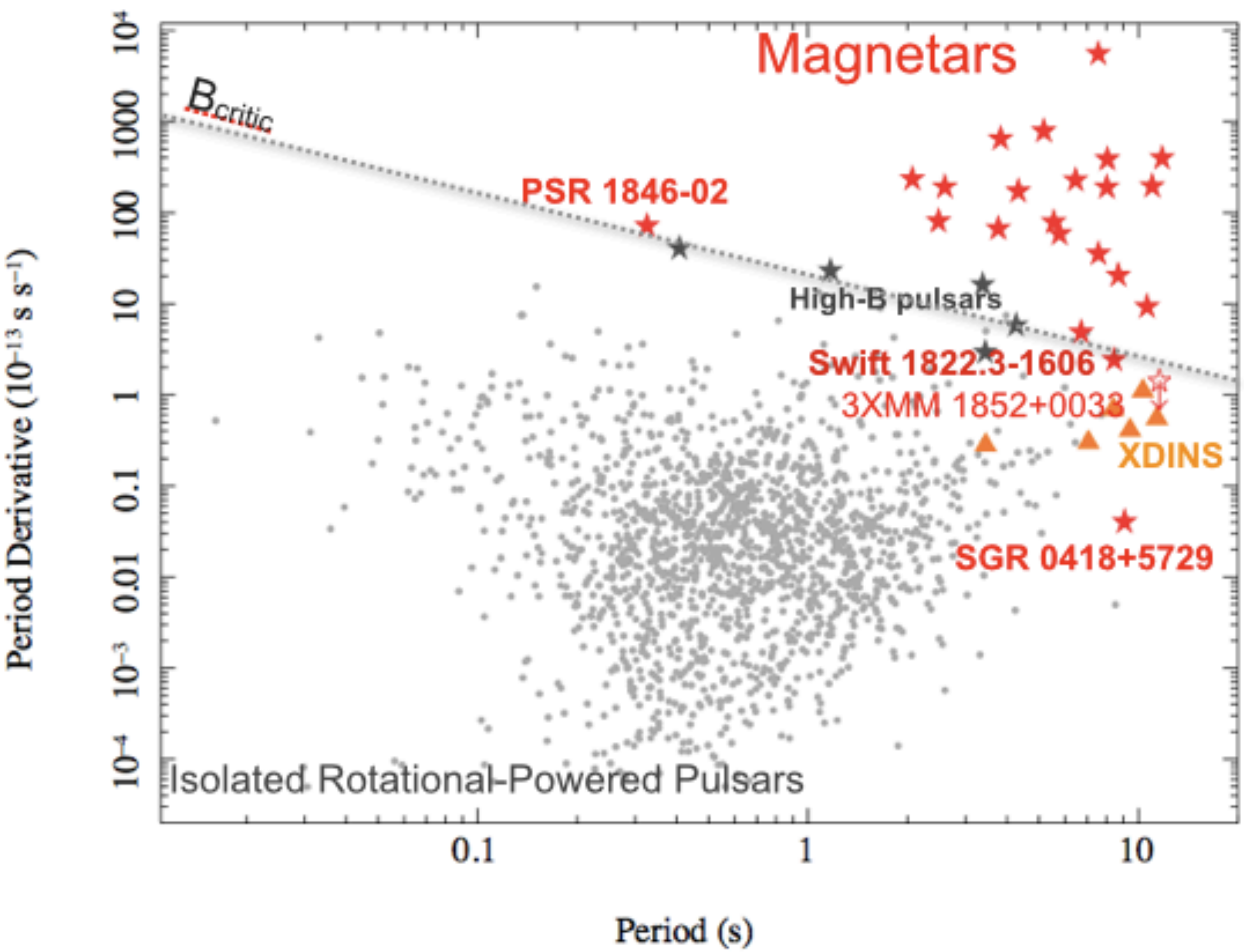


Distribution in the Galaxy



McGill Online Magnetar Catalogue; Olausen & Kaspi 2014

P-P_{dot} diagram



From the pulsed X-ray emission we can calculate:

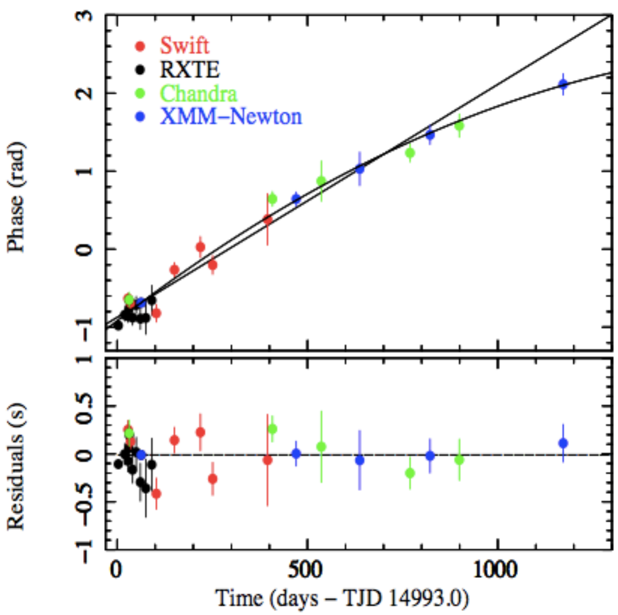
$$\tau = \frac{P}{2\dot{P}}$$

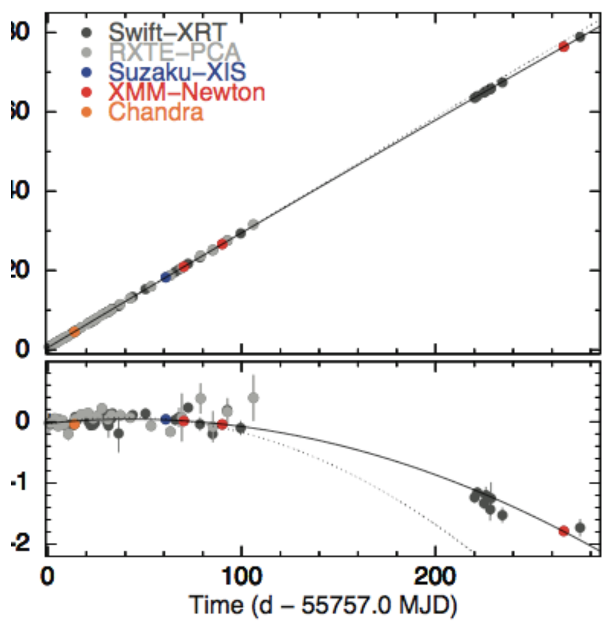
$$\frac{dE_{rot}}{dt} = 4\pi^2 I\dot{P}/P^3$$

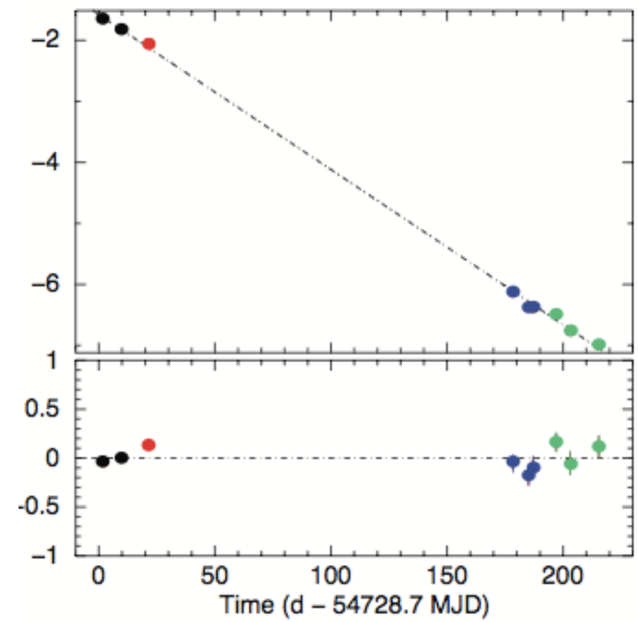
$$B = 3.2 \cdot 10^{19}\sqrt{P\dot{P}} \text{ Gauss.}$$

rotating magnetic dipole model

$B = 6.2 \times 10^{12}$ G	$B = 2.3 \times 10^{13}$ G	$B < 4 \times 10^{13}$ G







SGR 0418+5729

Esposito et al. 2010, MNRAS
Rea et al. 2010, Science
Rea et al. 2013, ApJ

Swift 1822-1606

Rea et al. 2012, ApJ
Scholtz et al. 2012, ApJ

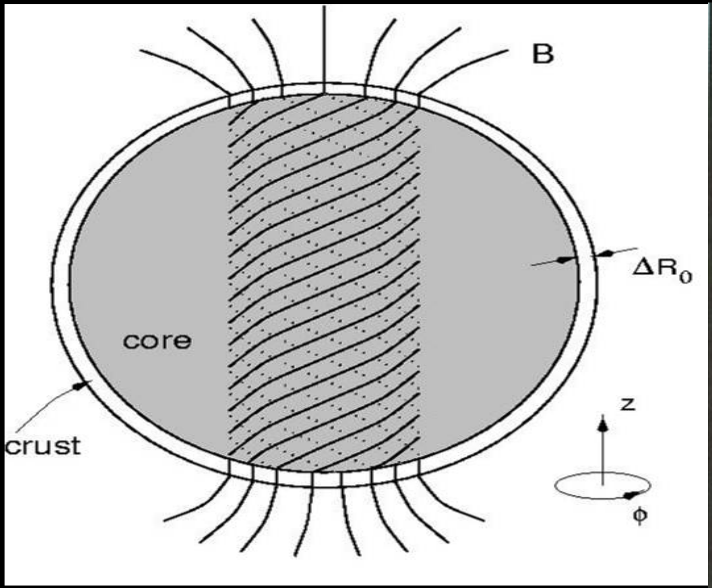
3XMM 1852+0033

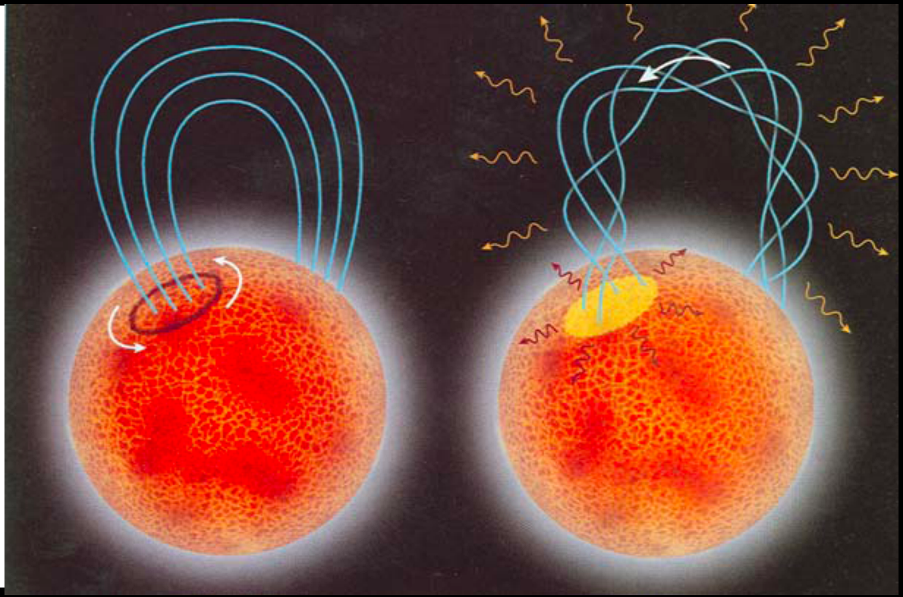
Rea et al. 2014, ApJL
Zou et al. 2014, ApJL

Magnetar theory in a nutshell: persistent emission

- huge internal field evolves diffusively over timescales of ~10 kyr, heating the core and deep crust —-> the magnetar surface is so hot that it glows brightly in X-rays.

- strong toroidal internal magnetic field causes twist of external poloidal field (footpoint motion)——-> a magnetar has a magnetic field twisted up.





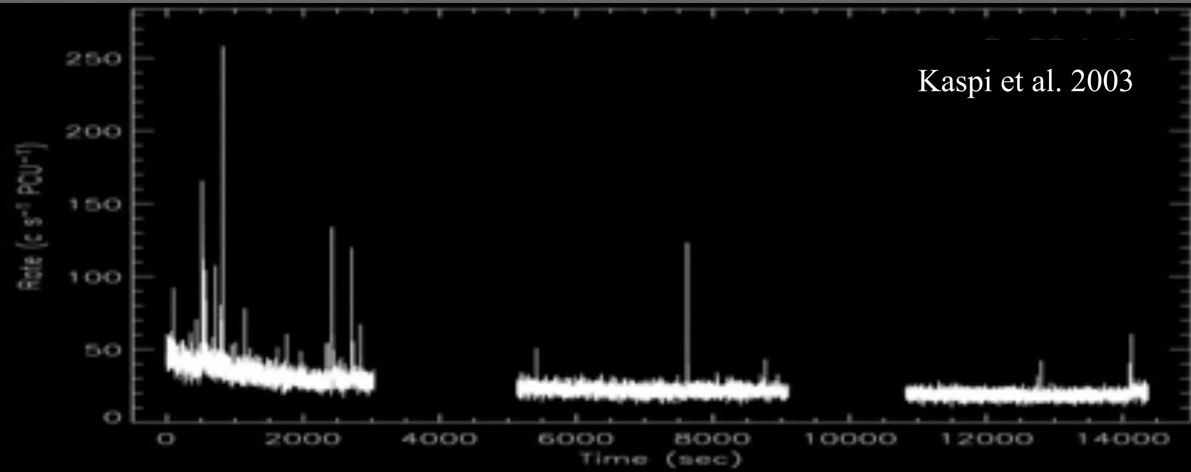
- The magnetosphere is filled by charged particles trapped in the twisted field lines, interacting with the surface thermal emission through resonant cyclotron scattering.

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

Magnetar flaring activity

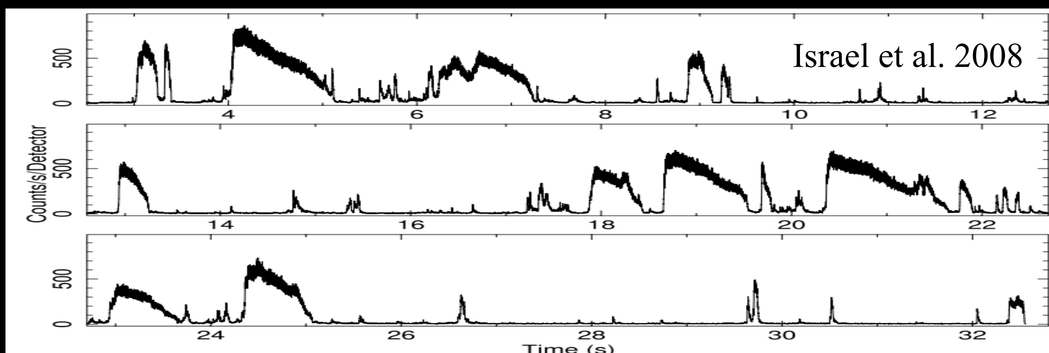
Short bursts

- duration ~0.1-1s
- L_X ~10^{39}-10^{41} ergs/s
- soft γ-rays thermal spectra (kT ~ 30-40 keV)



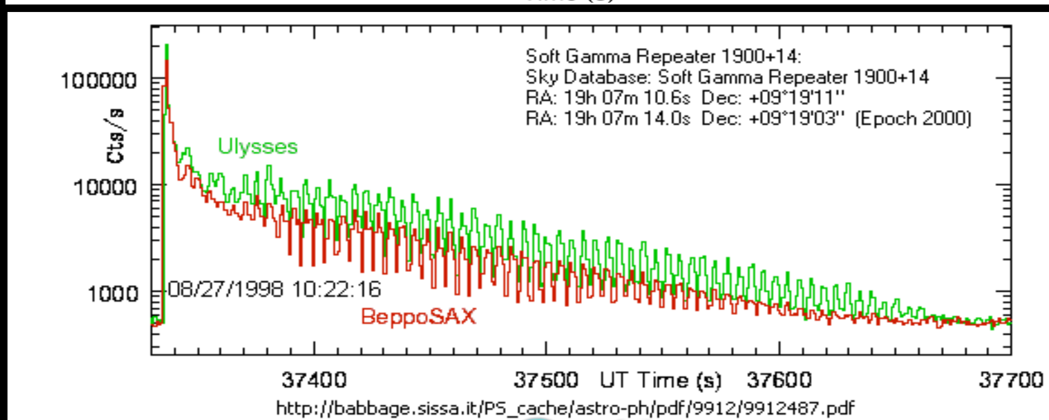
Intermediate bursts

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



Giant Flares

- very rare events (only 3 observed)
- L_X > 3x10^{44} erg s^{-1}
- initial peak that lasts <1 s with a hard spectrum
- ringing tail that can last > 500s, with softer spectrum and showing the NS spin pulsations



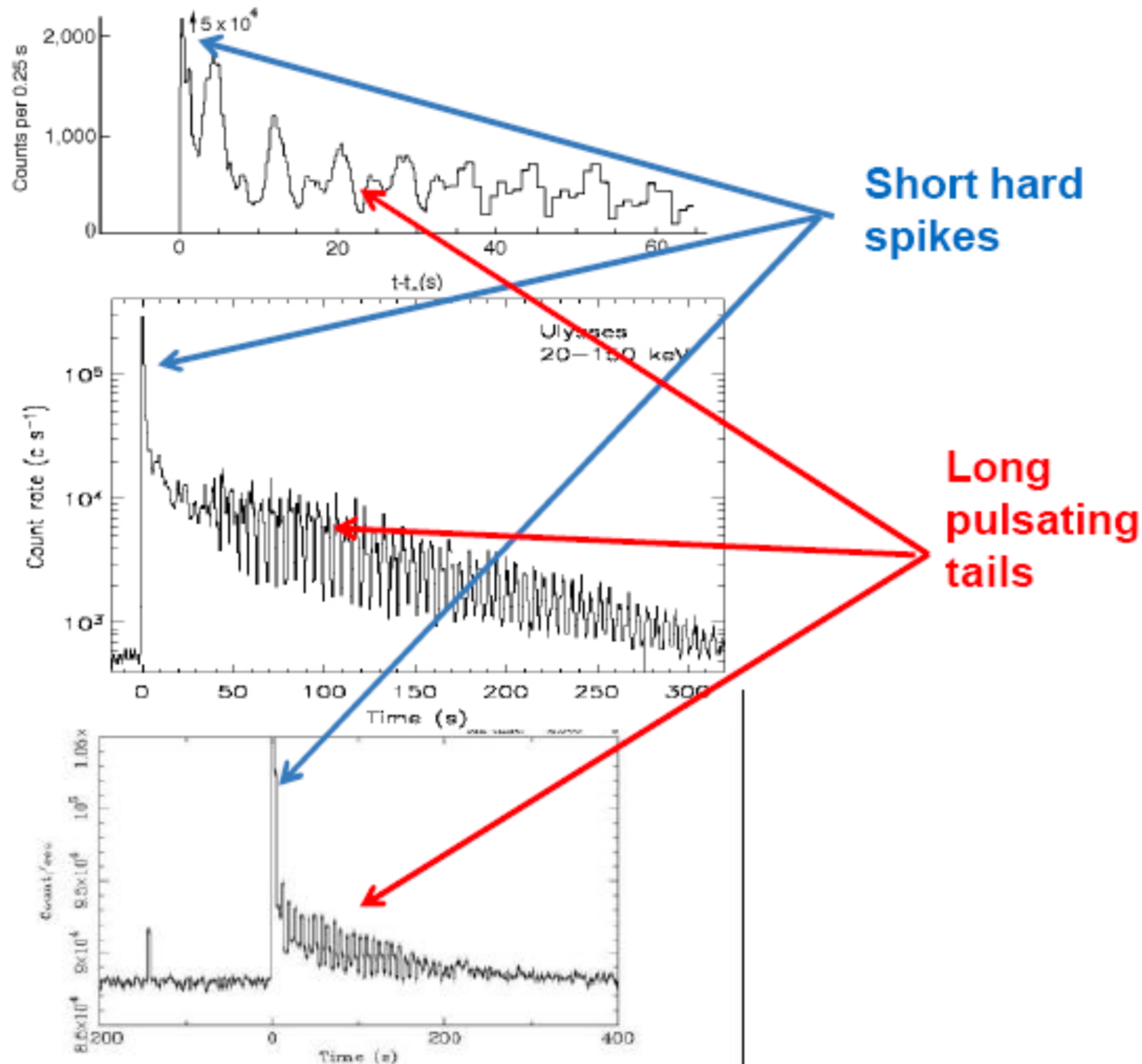
Magnetar flaring activity

The three famous Giant Flares from SGRs:

1979 March 5
SGR 0526-66
L_{peak} ~ 4 10^{44} erg/s
E_{TOT} ~ 5 10^{44} erg
(Mazets et al. 1979)

1998 August 27
SGR 1900+14
L_{peak} > 8 10^{44} erg/s
E_{TOT} > 3 10^{44} erg
(Hurley et al. 1999)

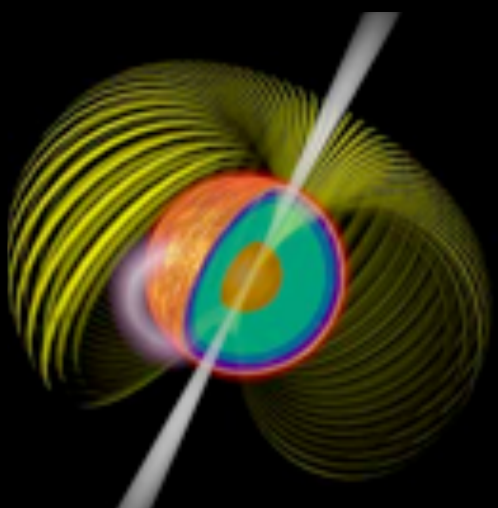
2004 December 27
SGR 1806-20
L_{peak} ~ 2-5 10^{47} erg/s
E_{TOT} ~ 2-5 10^{46} erg
(Palmer et al. 2005)



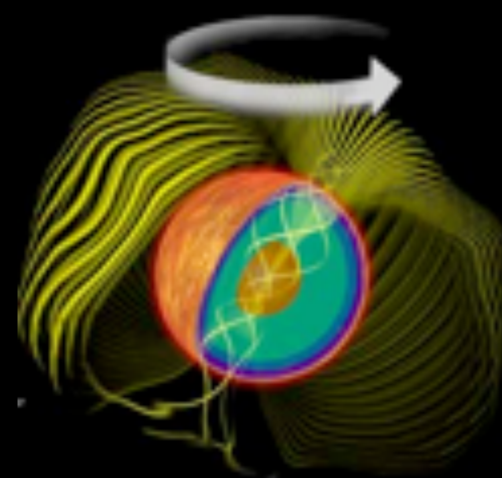
Magnetar theory in a nutshell: outburst mechanisms

- the internal magnetic field is twisted up to 10 times the external dipole. At intervals, elastic stresses build up in the crust

- the crust responds in an irreversible manner: fractures ——> magnetically driven star quakes, outbursts



High-B PSR

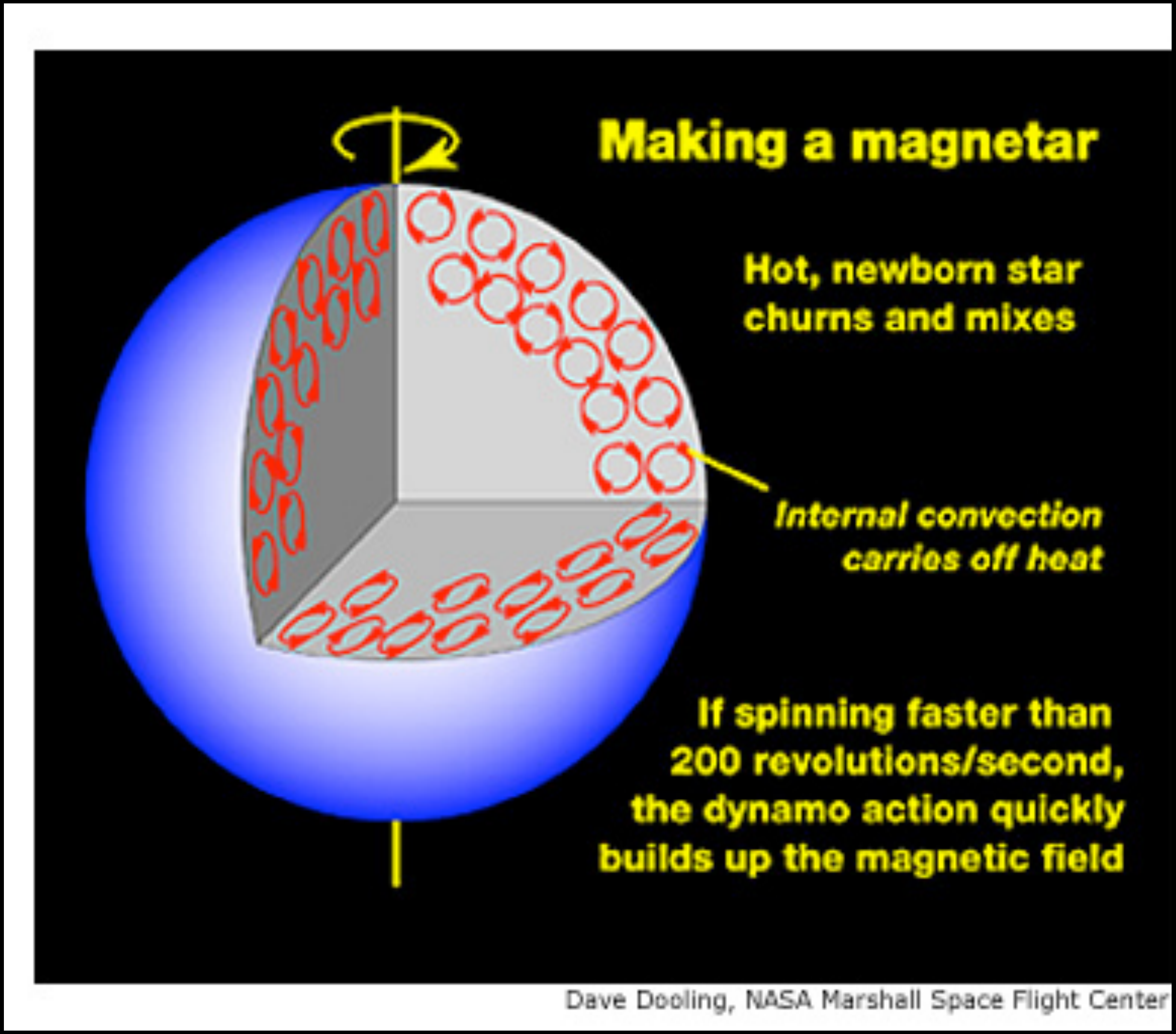


SGR/AXP

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

Magnetar theory in a nutshell: formation

If a newborn neutron star spins fast enough (P ~few ms) violent convection can amplify the magnetic field efficiently (dynamo action) up to 10^{16-17} G during the first 10-30 s.



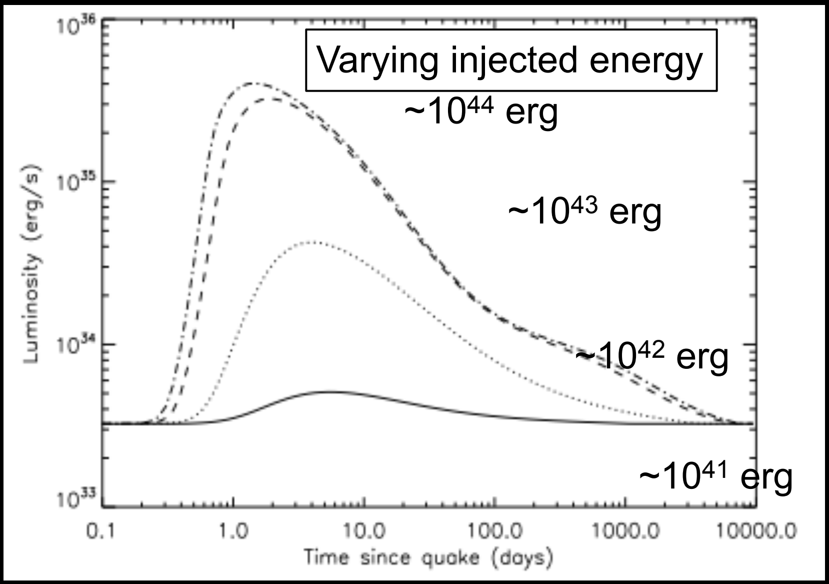
Neutrino processes in the crust

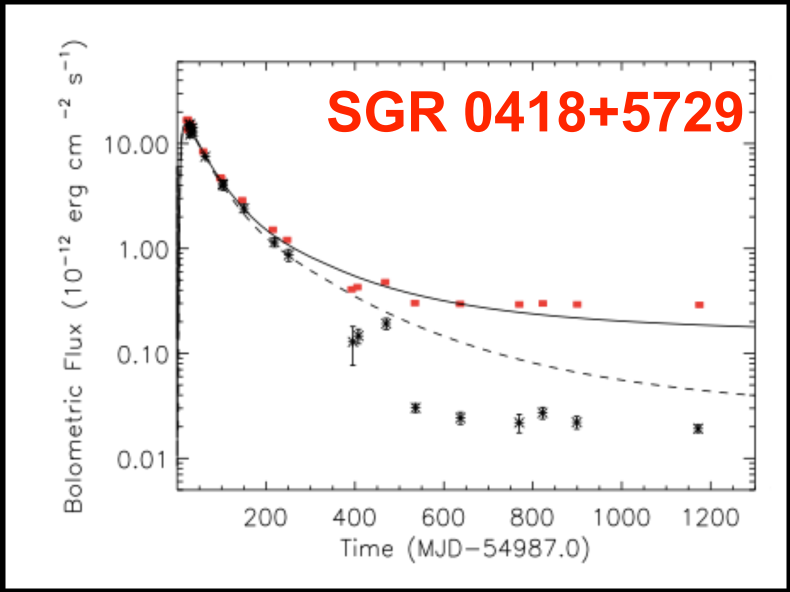
Process	Q_ν [erg cm^{-3}s^{-1}]	Onset	Ref
Core			
Modified URCA (n-branch)			
$nn \to pne\bar{\nu}_e$, $pne \to nn\nu_e$	$8 \times 10^{21}\, \mathcal{R}_n^{MU}\, n_p^{1/3}\, T_9^8$		1
Modified URCA (p-branch)			
$np \to ppe\bar{\nu}_e$, $ppe \to np\nu_e$	$8 \times 10^{21}\, \mathcal{R}_p^{MU}\, n_p^{1/3}\, T_9^8$	$Y_p^c = 0.01$	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

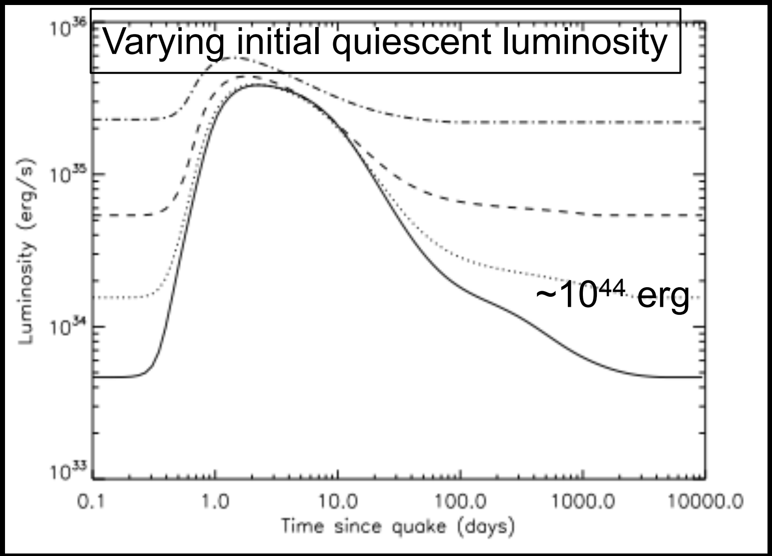
Refs.: (1) Yakovlev & Levenfish (1995); (2) Maxwell (1979); (3) Lattimer et al. (1991); (4) Kaminker & Yakovlev (1994); (5) Yakovlev et al. (2001); (6) Haensel et al. (1996); Kaminker et al. (1999); (7) Yakovlev et al. (1999); (8) Bezchastnov et al. (1997)

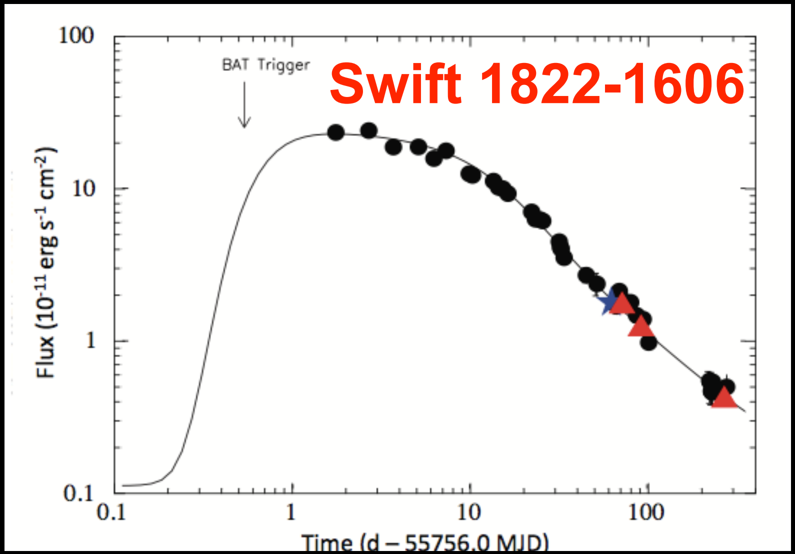
Table 4.3: *Neutrino processes and their emissivities Q_ν in the core and in the crust, taken from Aguilera et al. 2008. The third column shows the onset for some processes to operate (critical proton fraction Y_p^c). We indicate the normalized temperature $T_9 = T/10^9$ K; detailed functions and precise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

Outburst modeling



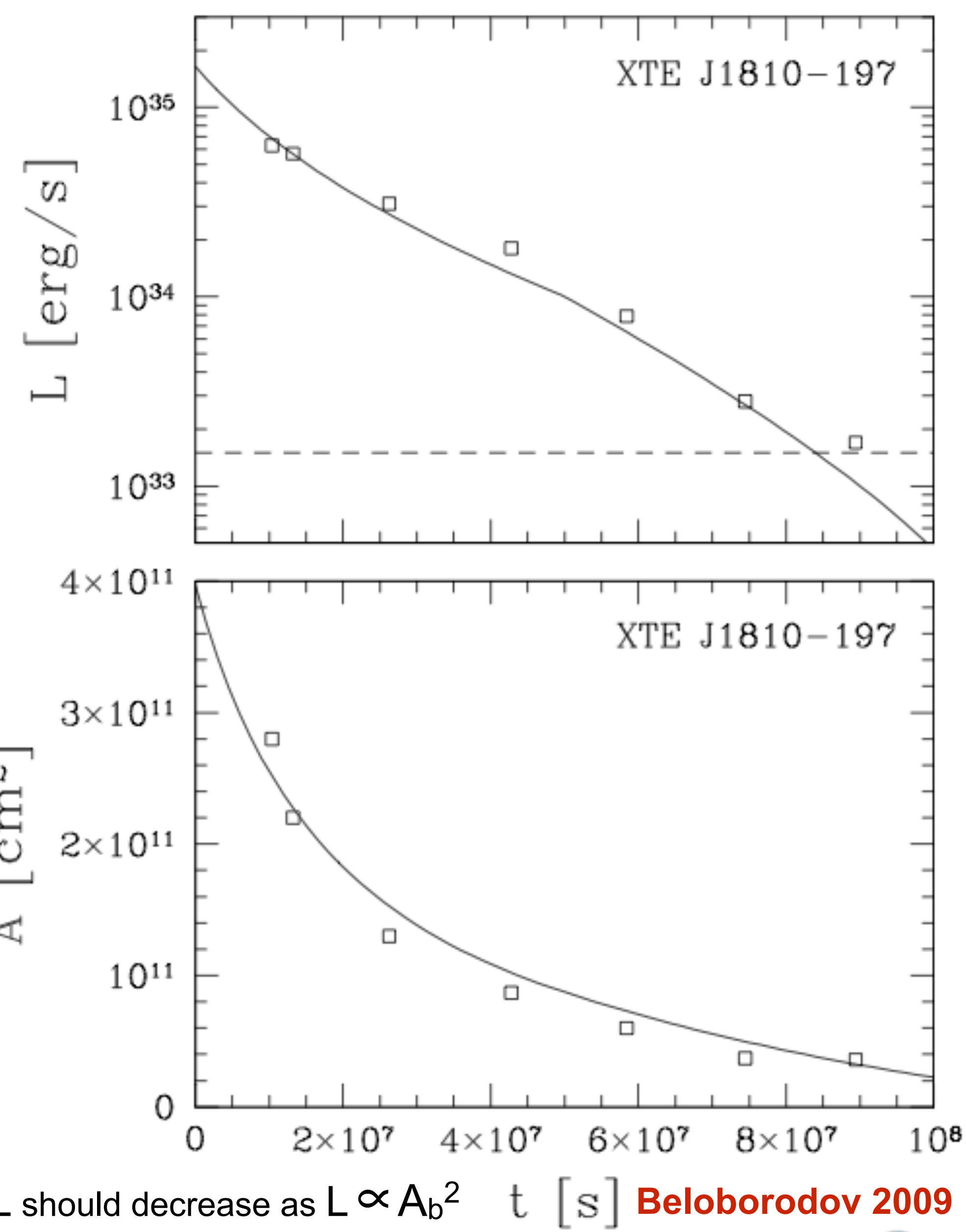






Pons & Rea 2012; Rea et al. 2012, 2013, 2014

Fitting the cooling curves

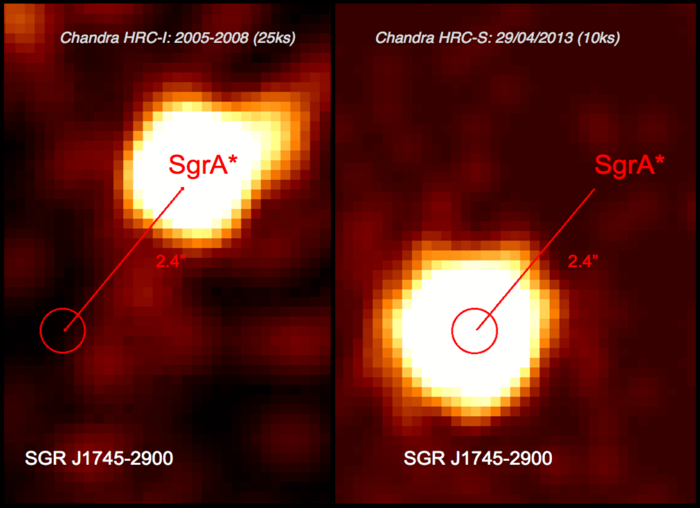


L should decrease as $L \propto A_b^2$ **Beloborodov 2009**

A magnetar within grasp of our SMBH

- with an age < 10 kyr, the probability of SGR J1745–2900 being a neutron star wandering across the line of sight is $<3\times10^{-6}$. No foreground/background object.

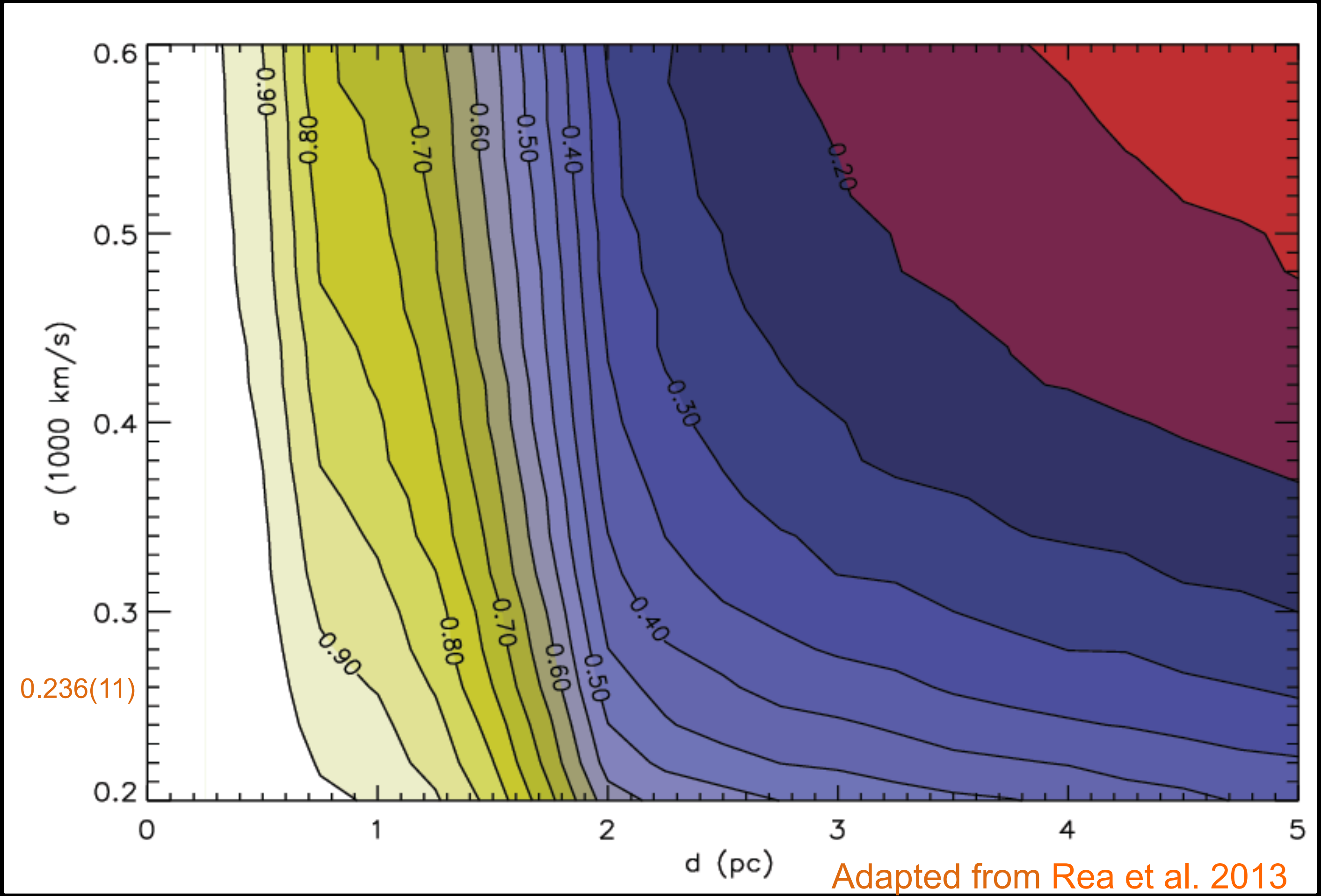
- it has been estimated that in the 1pc around the Galactic center there are ~80 pulsar with an average age of 10^7 yr, and a single or a few pulsars with < 10kyr. (see e.g. Freitag et al. 2006; Wharton et al. 2012)



0.07 pc < distance SGR-SgrA* < 2 pc (at 90% confidence level)

This is the closest neutron star to a supermassive black hole ever detected (next ones are at 200-400 pc; Deneva et al. 2009), and expected to be one of the few young neutron star so close to SgrA*.

A magnetar bounded to Sgr A*? Probably yes!



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

Depending on eccentricity and semi-mayor axis, it can have an orbital period from a minimum of 500 yr to several kyrs