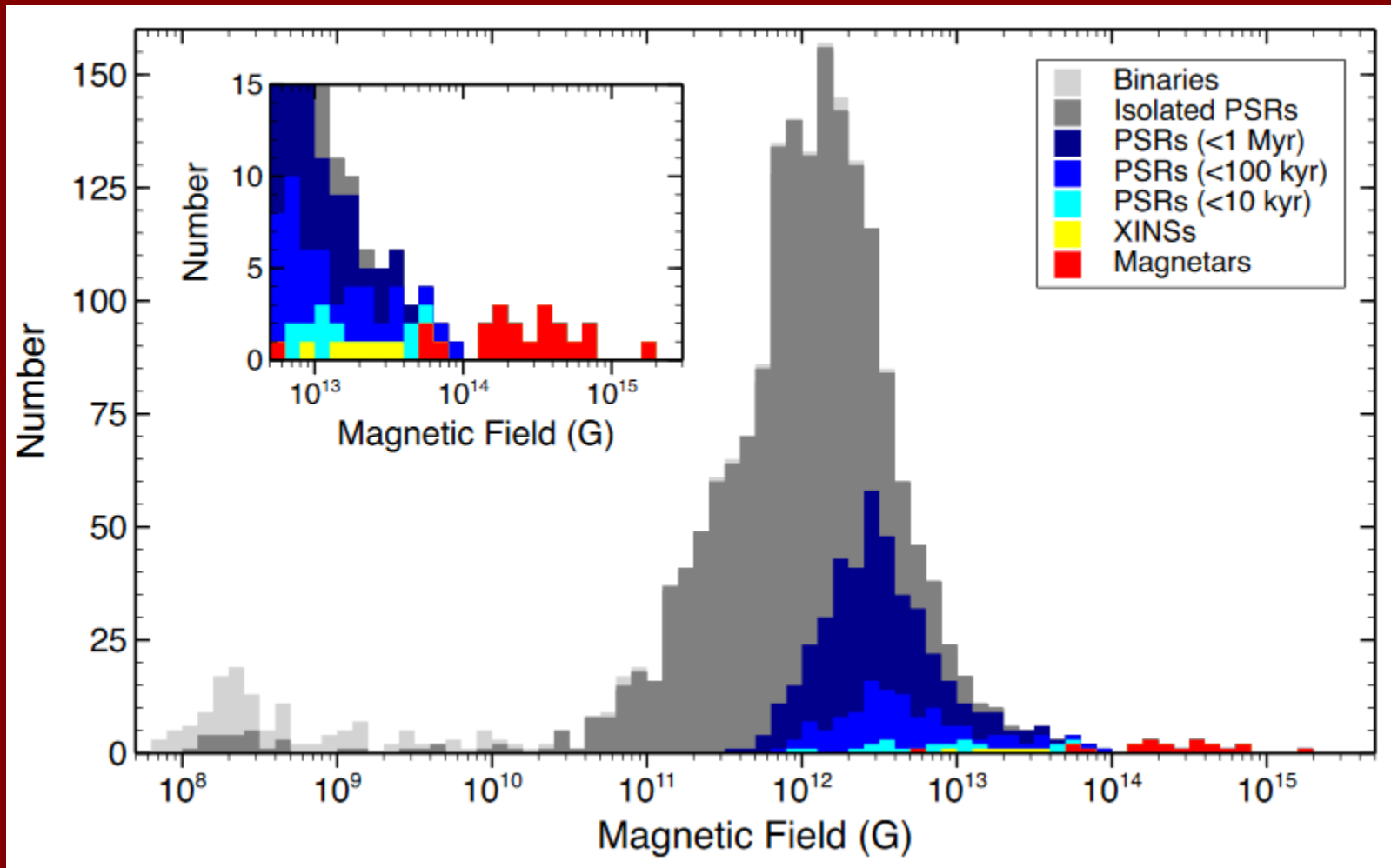


# Magnetars: SGRs and AXPs

# Magnetic field distribution



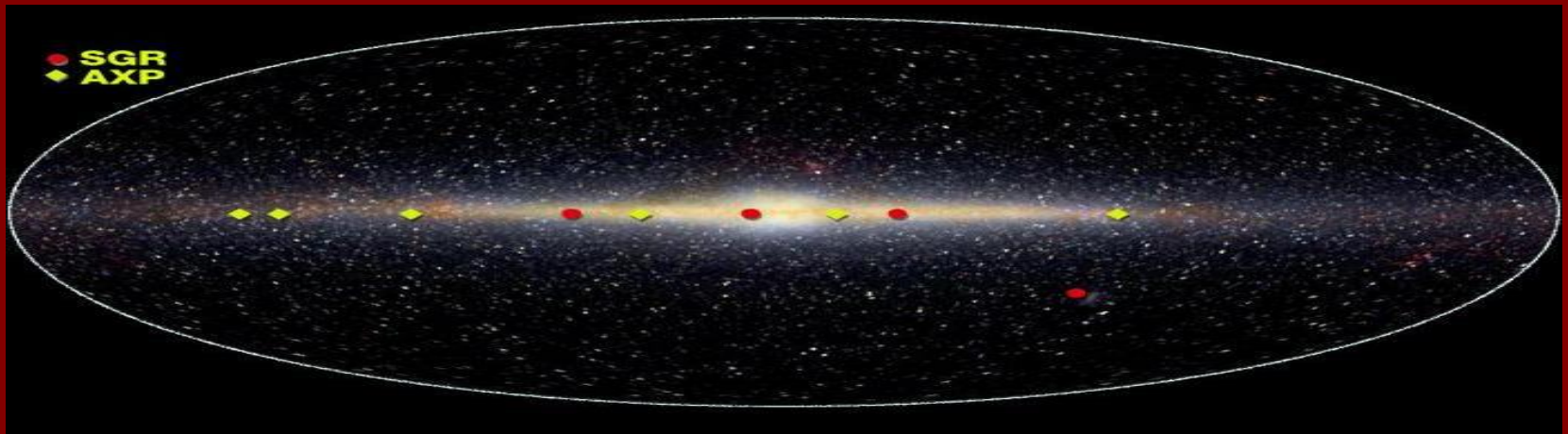
Fields from P-Pdot using magneto-dipole formula

1805.01680 (taken from Olausen, Kaspi 2014)

# Magnetars in the Galaxy

- ~25 SGRs and AXPs, plus 6 candidates, plus radio pulsars with high magnetic fields (about them see arXiv: 1010.4592)...
- Young objects (about  $10^{3-5}$  year).

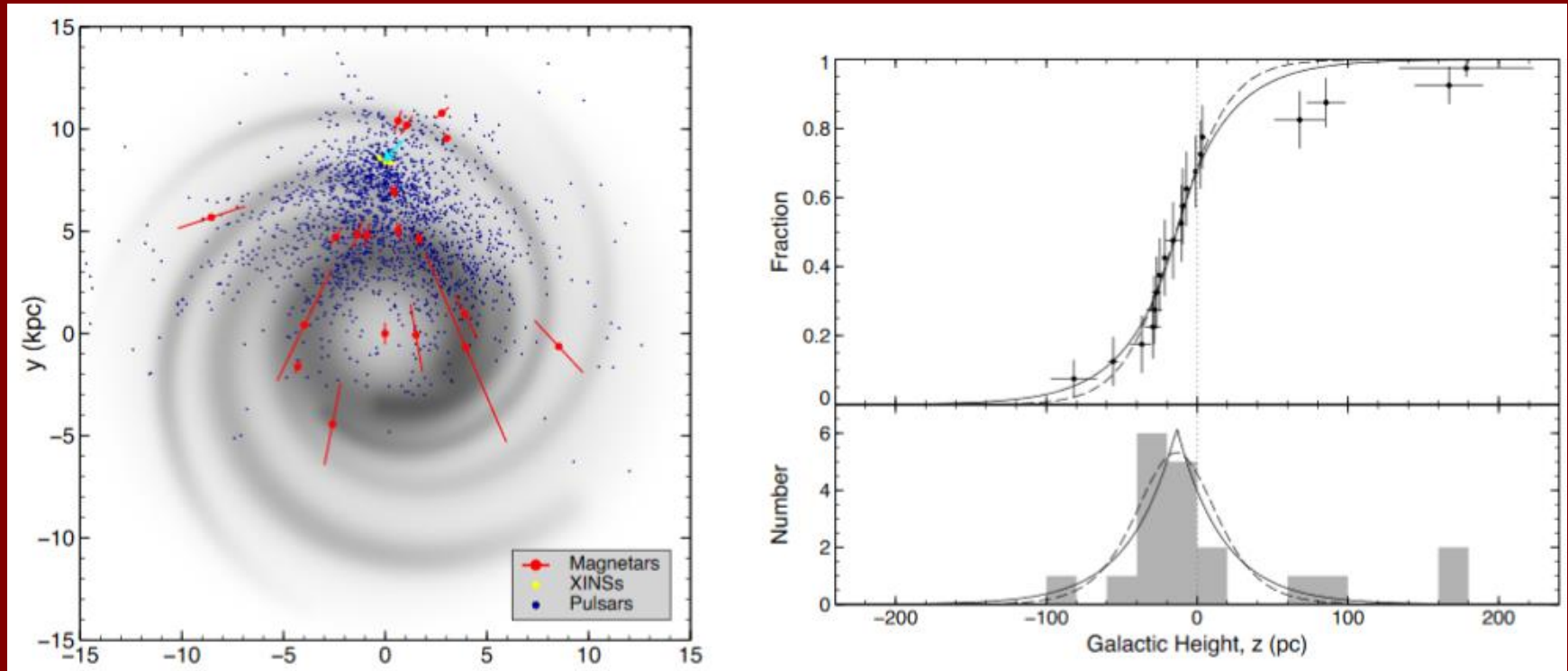
Catalogue: <http://www.physics.mcgill.ca/~pulsar/magnetar/main.html>



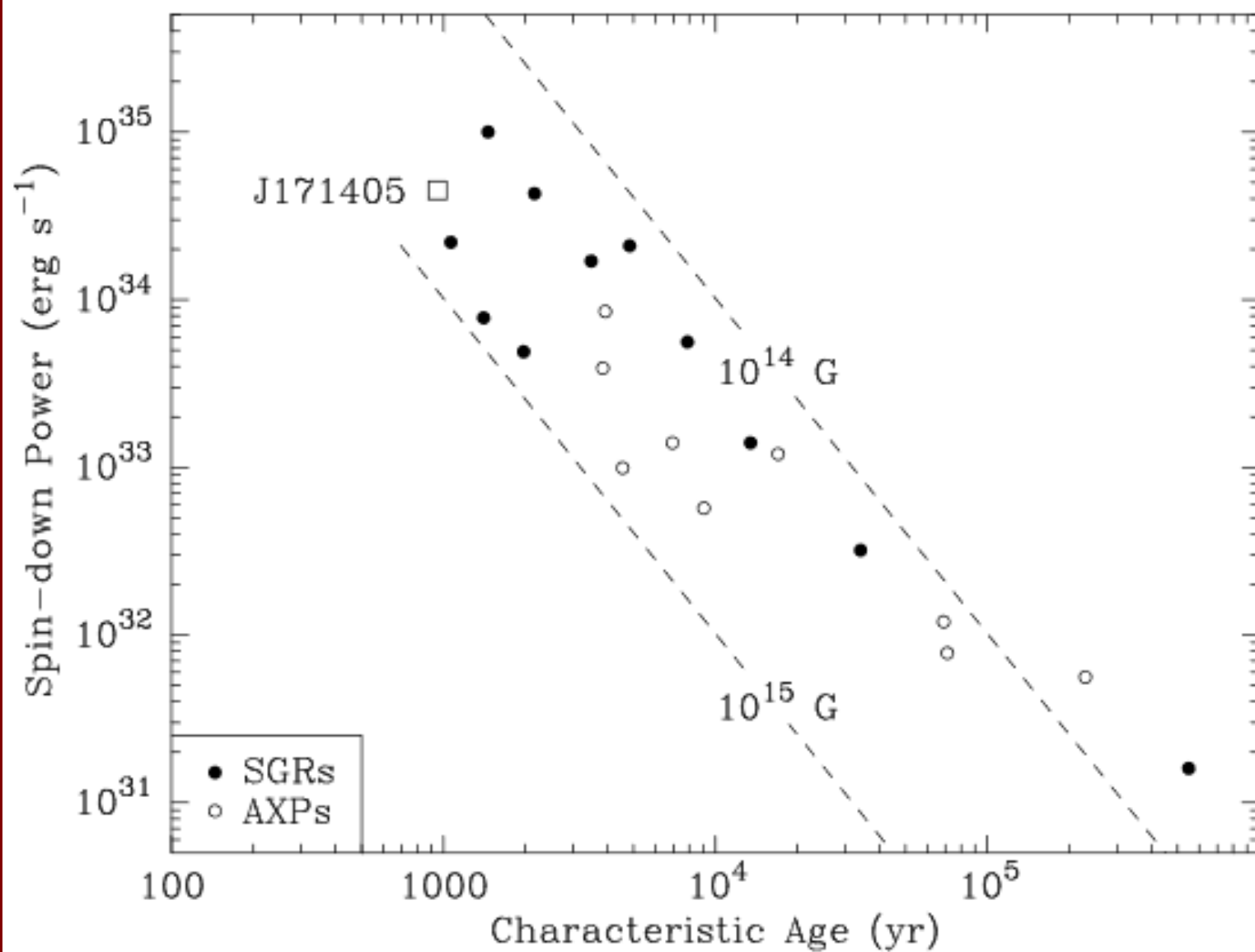
(see a recent review in arXiv:1503.06313 and the catalogue description in 1309.4167 )

# Spatial distribution

Scale height  $\sim 20$  pc



The first parallax for magnetar XTE J1810–197 was measured recently due to radio observations, 2008.06438.



# Birth rate of magnetars

Fraction of magnetars among NSs is uncertain.

Typically, the value  $\sim 10\%$  is quoted (e.g. 0910.2190).

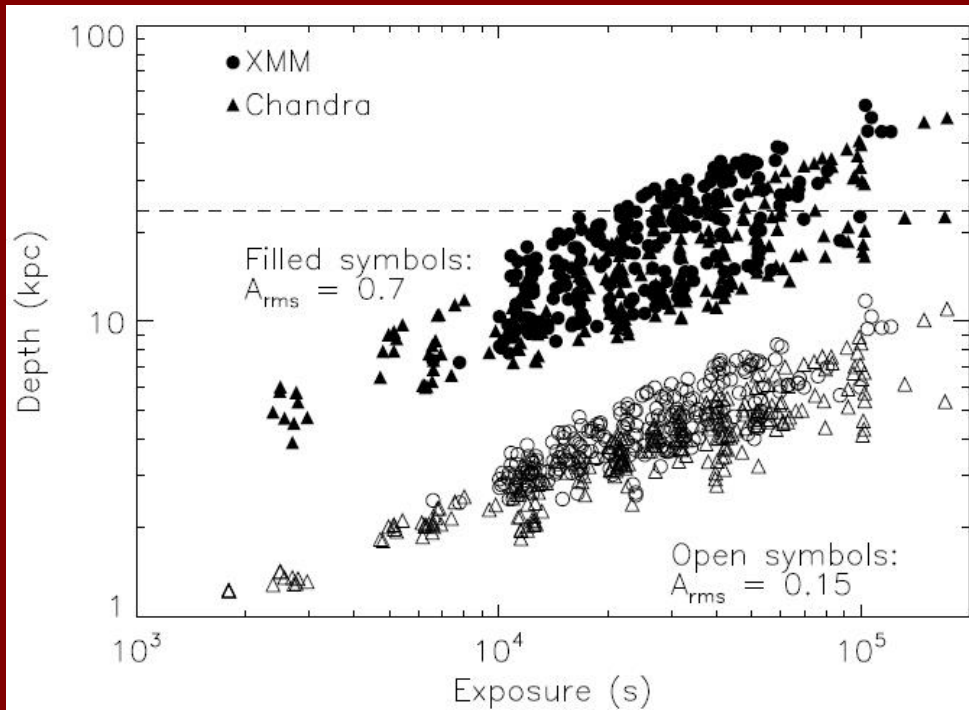
This is supported observationally and theoretically.

Recent modeling favours somehow larger values: 1903.06718.

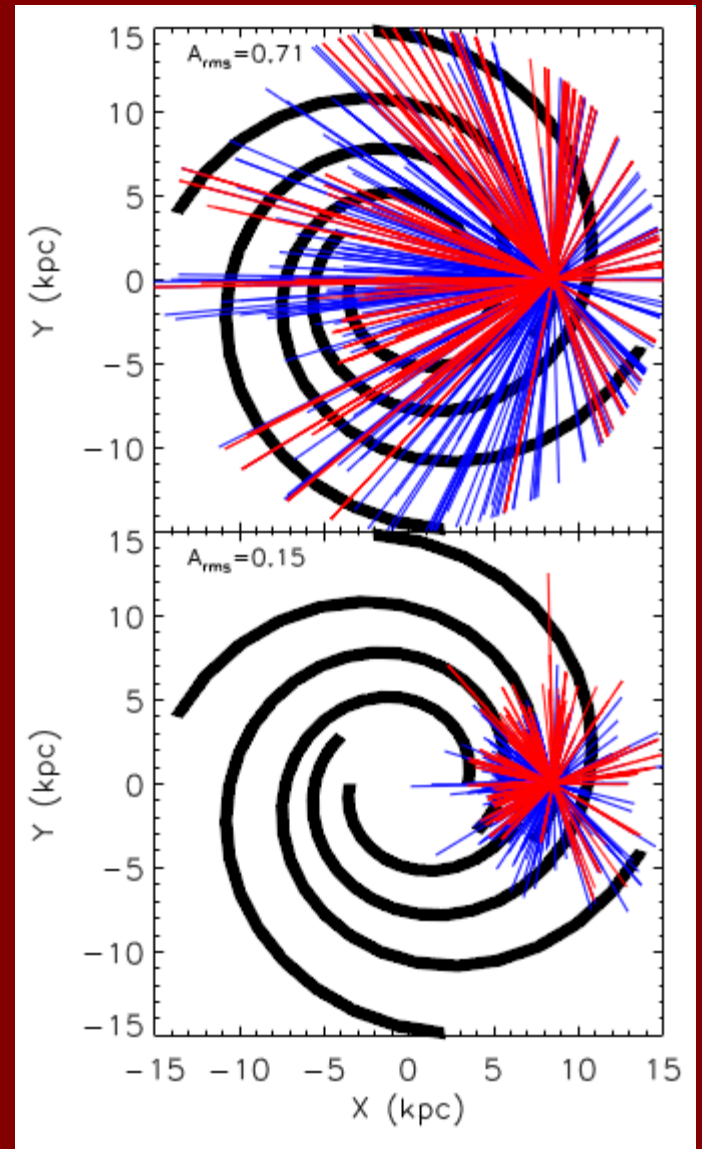
However, the result is model dependent.

In particular, it depends on the model of field decay.

# How many magnetars?



<540 barely-detectable ( $L=3 \cdot 10^{33}$   $A_{\text{rms}}=15\%$ )  
 $59^{+92}_{-32}$  easily detectable ( $L=10^{35}$   $A_{\text{rms}}=70\%$ )



# Population synthesis of magnetars

Birthrate 2.3-20 kyr<sup>-1</sup>

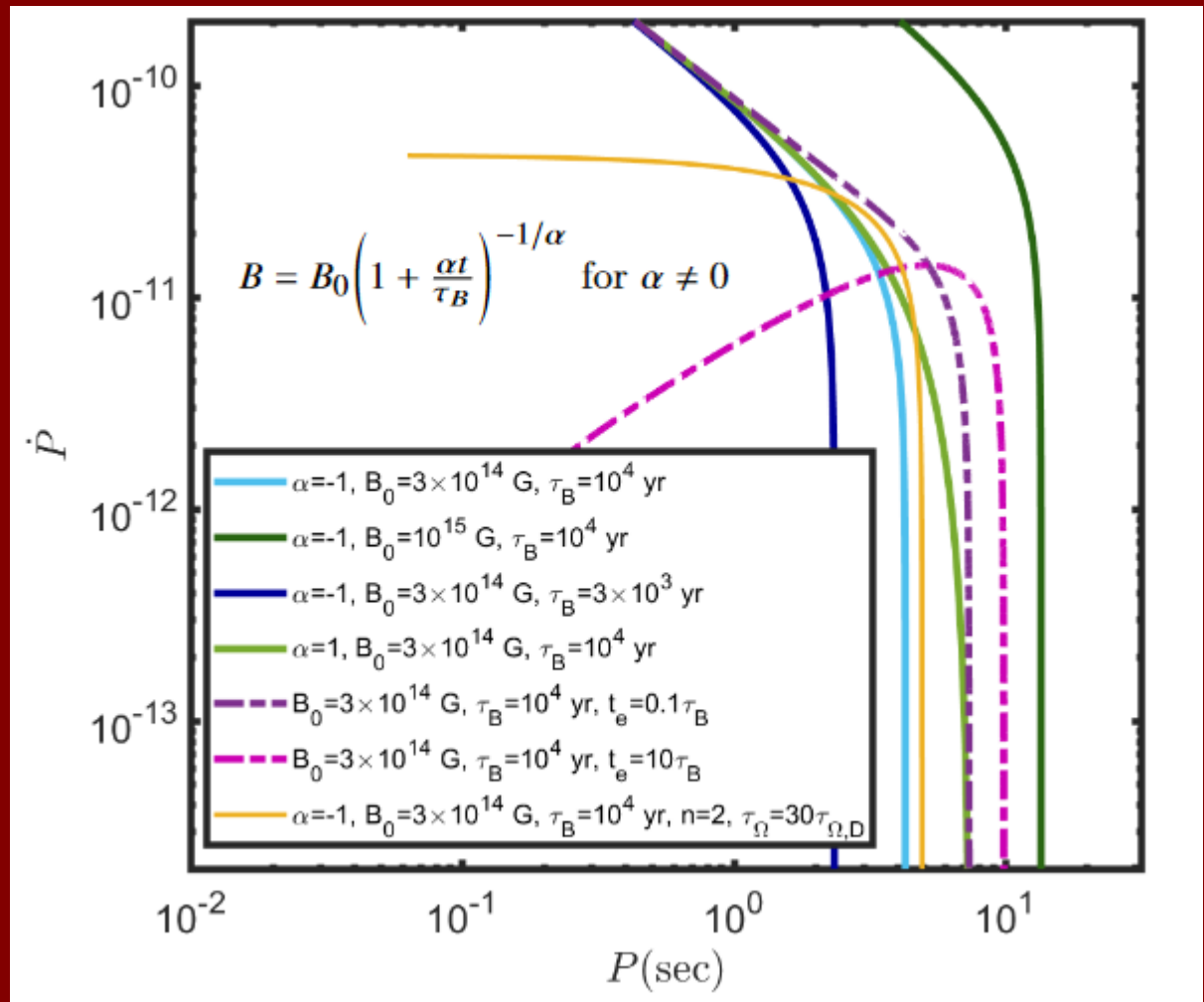
0.4<sup>+0.6</sup><sub>-0.28</sub> of NSs  
are born as magnetars

Fields decay in ~10<sup>4</sup> yrs

Maximum expected  
spin period 13 s.

Hyperflares can be  
detected by Swift  
at ~100Mpc.

Thus, rate ~5 yr<sup>-1</sup>



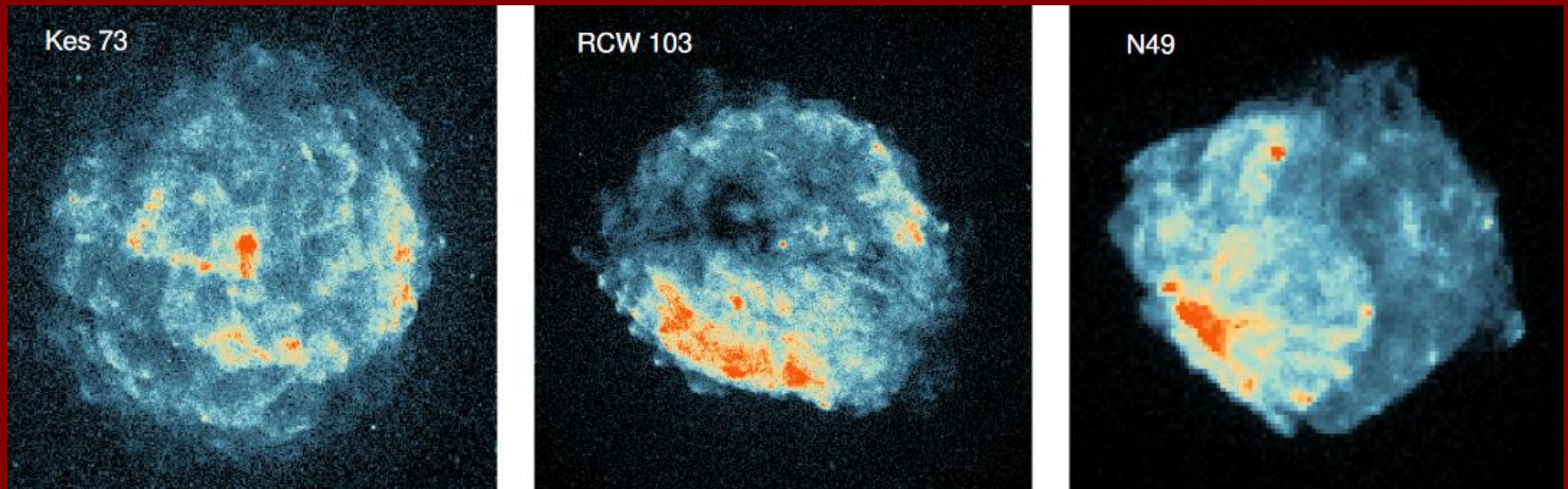


Several of magnetars  
are related to SNRs.

Many of magnetars  
show glitches  
(see 1903.09736).

Name <sup>b</sup>	$P$ (s)	$B^c$ ( $10^{14}$ G)	Age <sup>d</sup> (kyr)	$\dot{E}^e$ $10^{33}$ erg s <sup>-1</sup>	$D^f$ (kpc)	$L_X^g$ $10^{33}$ erg s <sup>-1</sup>	Band <sup>h</sup>
CXOU J010043.1-721134	8.02	3.9	6.8	1.4	62.4	65	...
4U 0142+61	8.69	1.3	68	0.12	3.6	105	OIR/H
SGR 0418+5729	9.08	0.06	36000	0.00021	~2	0.00096	...
SGR 0501+4516	5.76	1.9	15	1.2	~2	0.81	OIR/H
<b>SGR 0526-66</b>	8.05	5.6	3.4	2.9	53.6	189	...
1E 1048.1-5937	6.46	3.9	4.5	3.3	9.0	49	OIR
(PSR J1119-6127)	0.41	4.1	1.6	2300	8.4	0.2	R/H
1E 1547.0-5408	2.07	3.2	0.69	210	4.5	1.3	O?/R/H
PSR J1622-4950	4.33	2.7	4.0	8.3	~9	0.4	R
SGR 1627-41	2.59	2.2	2.2	43	11	3.6	...
CXOU J164710.2-455216	10.6	<0.66	>420	<0.013	3.9	0.45	...
1RXS J170849.0-400910	11.01	4.7	9.0	0.58	3.8	42	O?/H
CXOU J171405.7-381031	3.82	5.0	0.95	45	~13	56	...
SGR J1745-2900	3.76	2.3	4.3	10	8.3	<0.11	R/H
<b>SGR 1806-20</b>	7.55	20	0.24	45	8.7	163	OIR/H
XTE J1810-197	5.54	2.1	11	1.8	3.5	0.043	OIR/R
Swift J1822.3-1606	8.44	0.14	6300	0.0014	1.6	>0.0004	...
SGR 1833-0832	7.56	1.6	34	0.32	...	...	...
Swift J1834.9-0846	2.48	1.4	4.9	21	4.2	<0.0084	...
1E 1841-045	11.79	7.0	4.6	0.99	8.5	184	...
(PSR J1846-0258)	0.327	0.49	0.73	8100	6.0	19	...
3XMM J185246.6+003317	11.56	< 0.41	> 1300	< 0.0036	~7	< 0.006	...
<b>SGR 1900+14</b>	5.20	7.0	0.9	26	12.5	90	H
SGR 1935+2154	3.24	2.2	3.6	17	...	...	...
1E 2259+586	6.98	0.59	230	0.056	3.2	17	OIR/H
<i>SGR 0755-2933</i>	...	...	...	...	...	...	...
<i>SGR 1801-23</i>	...	...	...	...	...	...	...
<i>SGR 1808-20</i>	...	...	...	...	...	...	...
<i>AX J1818.8-1559</i>	...	...	...	...	...	...	...
<i>AX J1845.0-0258</i>	6.97	...	...	...	...	2.9	...
<i>SGR 2013+34</i>	...	...	...	...	...	...	...

# Supernova remnants of magnetars



$n_H$ ( $\text{cm}^{-3}$ )	$7.3^{+0.5}_{-0.4}$	$5.9 \pm 0.2$	$6.6 \pm 0.3$
$M_{\text{SNR}}$ ( $M_{\odot}$ )	$46^{+3}_{-2}$	$12.8 \pm 0.4$	$200^{+14}_{-10}$
$t_{\text{sedov}}$ (kyr)	$\sim 2.4$	$\sim 2.1$	$\sim 4.9$
$E_0$ (erg)	$\sim 5.4 \times 10^{50}$	$\sim 1.0 \times 10^{50}$	$\sim 1.7 \times 10^{51}$
$F_X$ (0.5–7 keV; $10^{-11}$ erg)	2.5	17.4	2.3

11-15 Msun

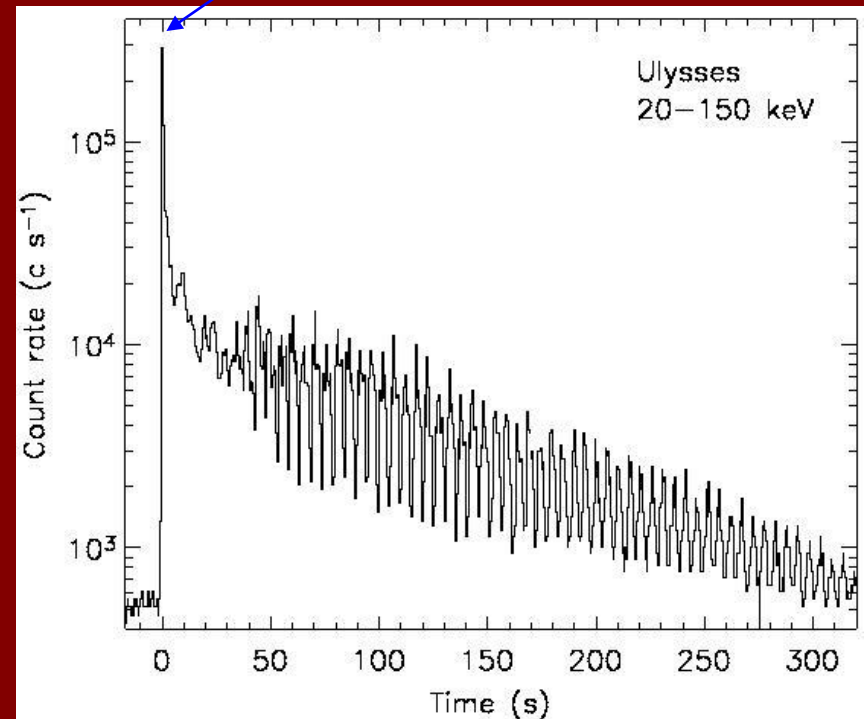
<13 Msun

13-17 Msun

# Soft Gamma Repeaters: main properties

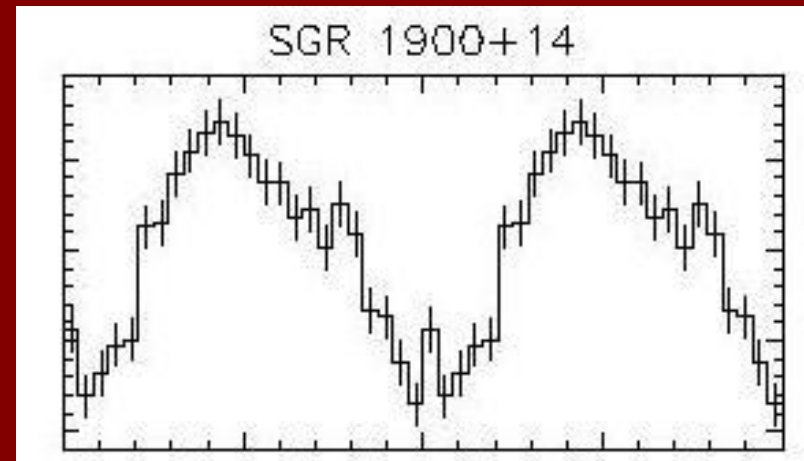
- Energetic “Giant Flares” (GFs,  $L \approx 10^{45}$ - $10^{47}$  erg/s) detected from 3 (4?) sources
- No evidence for a binary companion, association with a SNR at least in one case
- Persistent X-ray emitters,  $L \approx 10^{35}$  -  $10^{36}$  erg/s
- Pulsations discovered both in GFs tails and persistent emission,  $P \approx 5$  -10 s
- Huge spindown rates,  $\dot{P}/P \approx 10^{-10} \text{ s}^{-1}$

Saturation  
of detectors



# SGRs: periods and giant flares

	P, s	Giant flares
■ 0526-66	8.0	5 March 1979
■ 1627-41	2.6	18 June 1998 (?)
■ 1806-20	7.5	27 Dec 2004
■ 1900+14	5.2	27 Aug 1998

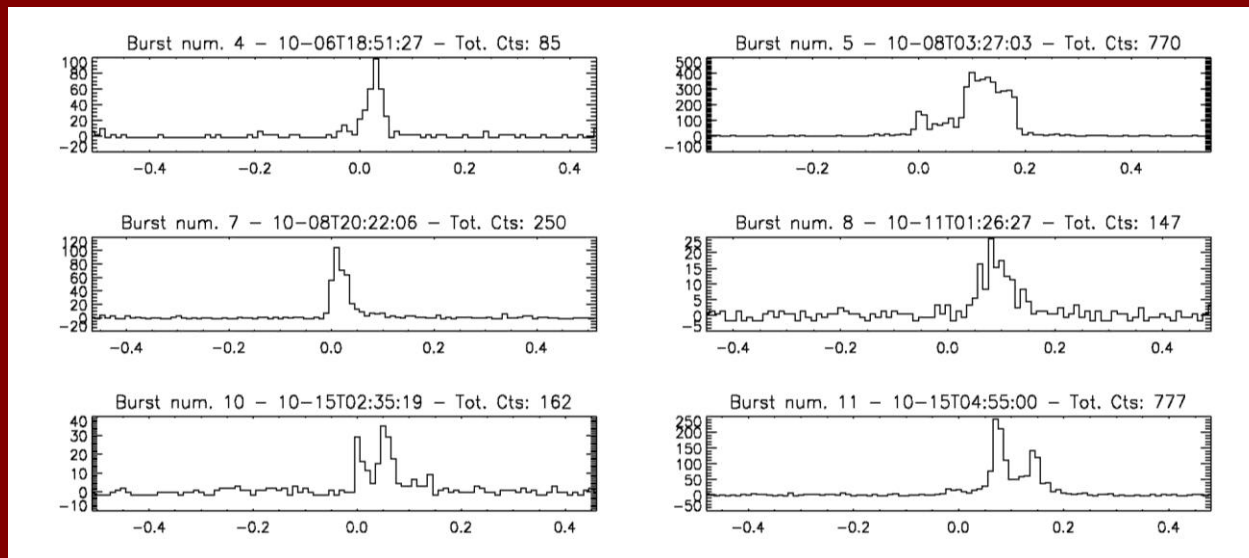


See reviews in Turolla et al. arXiv: 1507.02924

Beloborodov, Kaspi arXiv: 1703.00068

# Soft Gamma Repeaters

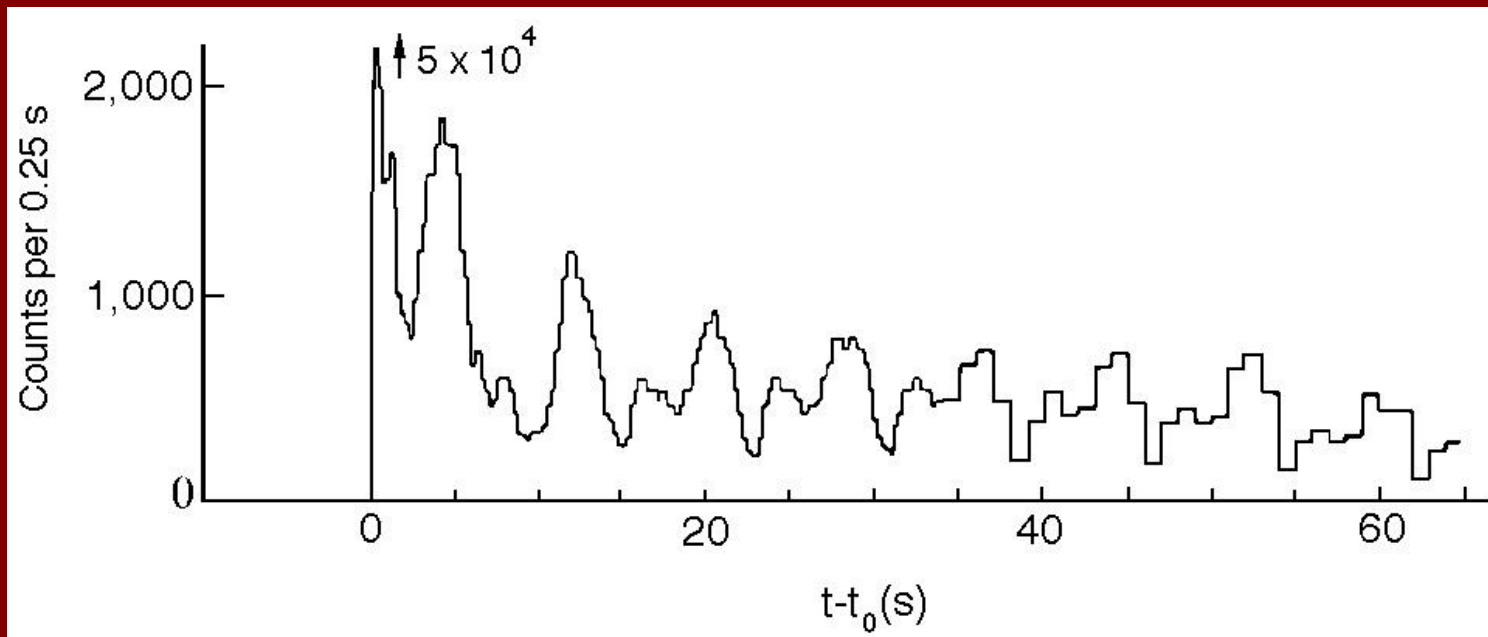
- Rare class of sources, ~13 confirmed
- Frequent bursts of soft  $\gamma$ -/hard X-rays:  
 $L < 10^{42}$  erg/s, duration  $< 1$  s



Bursts from SGR 1806-20 (INTEGRAL/IBIS, Götz et al 2004)

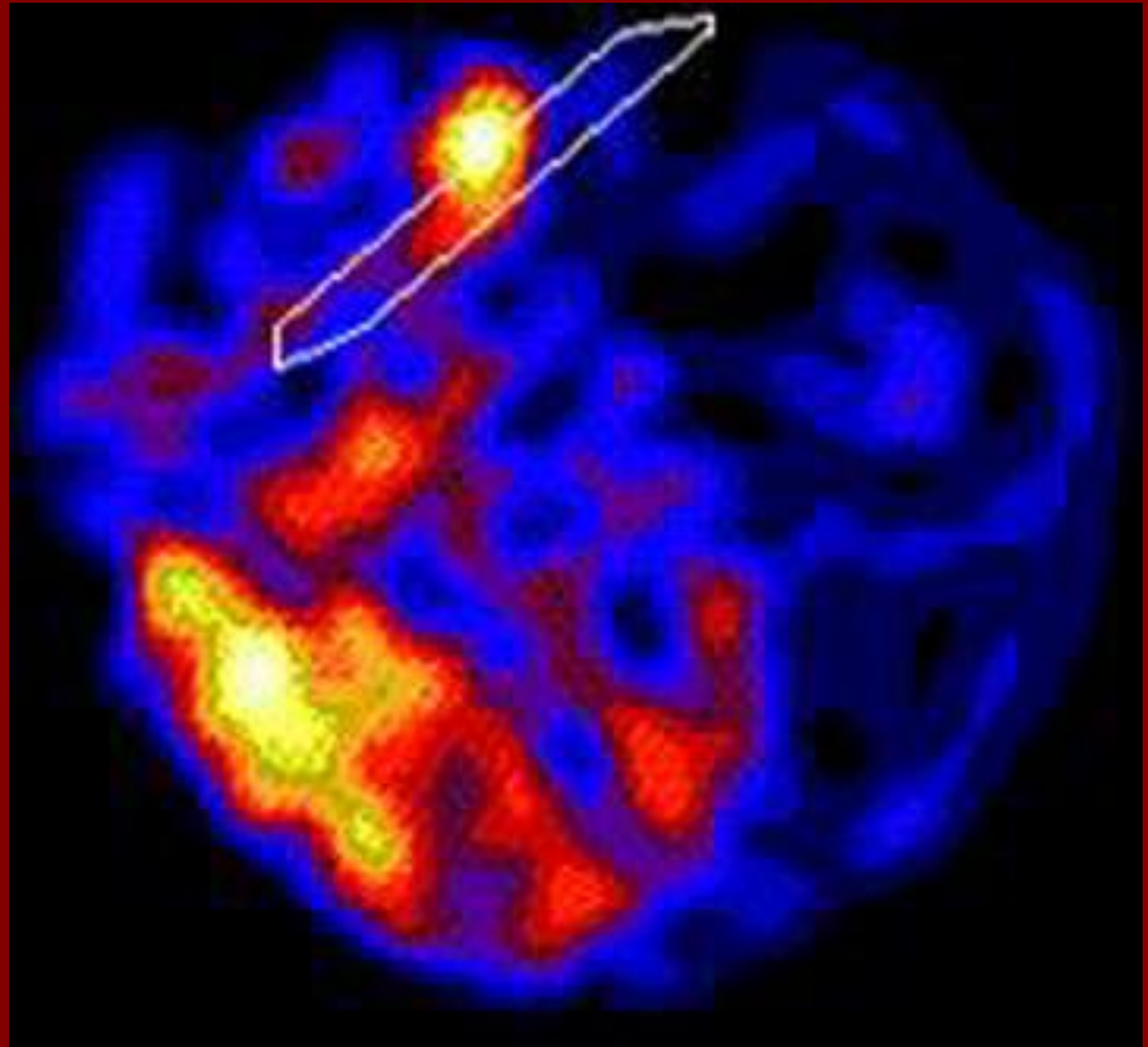
# Historical notes

- 05 March 1979. The "Konus" experiment & Co. Venera-11,12 (Mazets et al., Vedrenne et al.)
- Events in the LMC. SGR 0520-66.
- Fluence: about  $10^{-3}$  erg/cm<sup>2</sup>





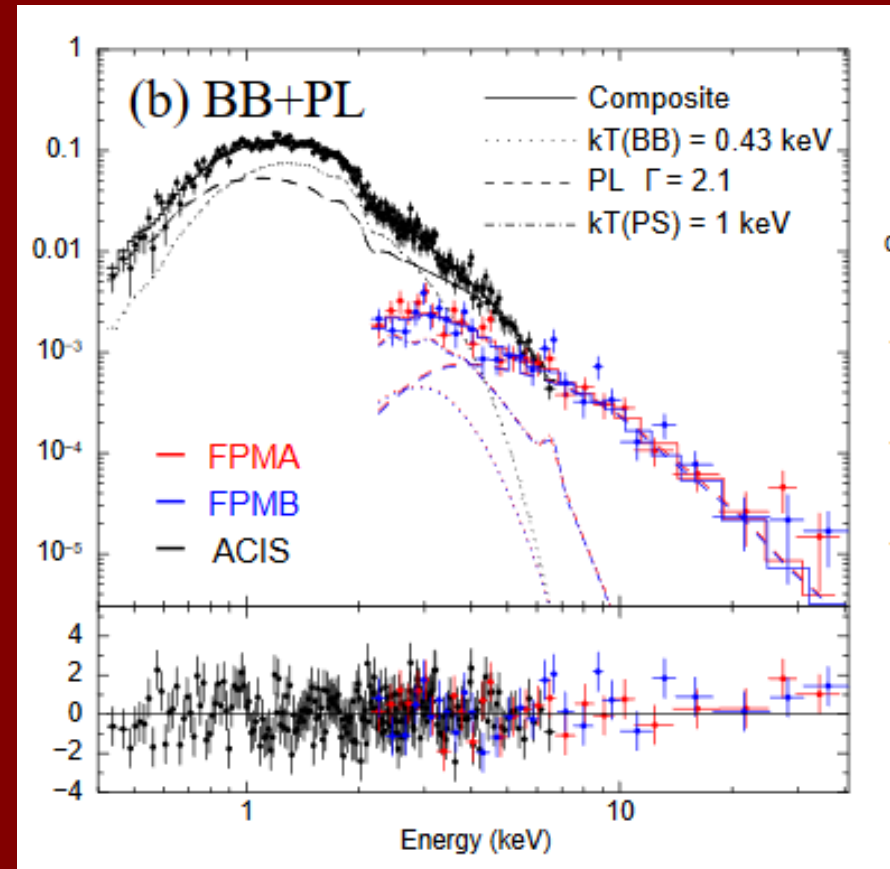
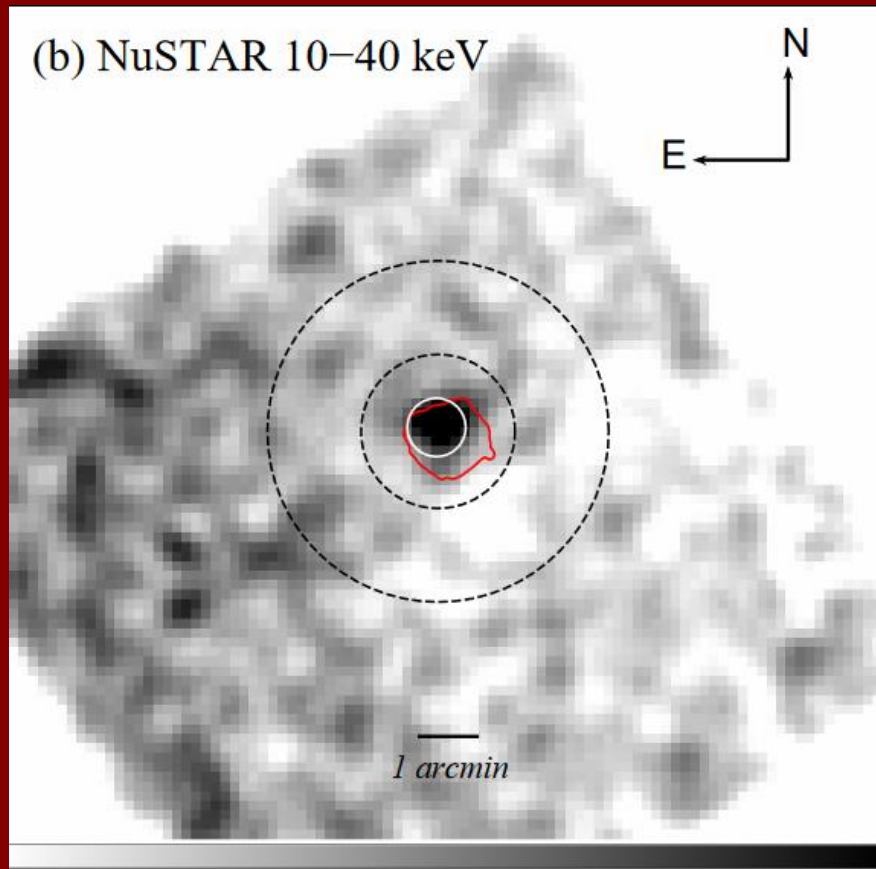
N49 – supernova  
remnant in the  
Large Magellanic  
cloud  
(e.g. G. Vedrenne  
et al. 1979)



# Magnetar on pension?

The source is not active since 1979.

Just in 2020 it was for the first time detected at  $E > 10$  keV in quiescence.

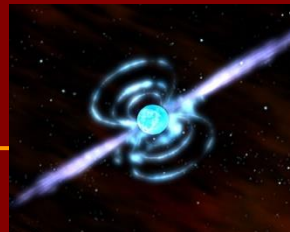




# Main types of activity of SGRs

- Weak bursts.  $L < 10^{42}$  erg/s
- Intermediate.  $L \sim 10^{42} - 10^{43}$  erg/s
- Giant.  $L < 10^{45}$  erg/s
- Hyperflares.  $L > 10^{46}$  erg/s

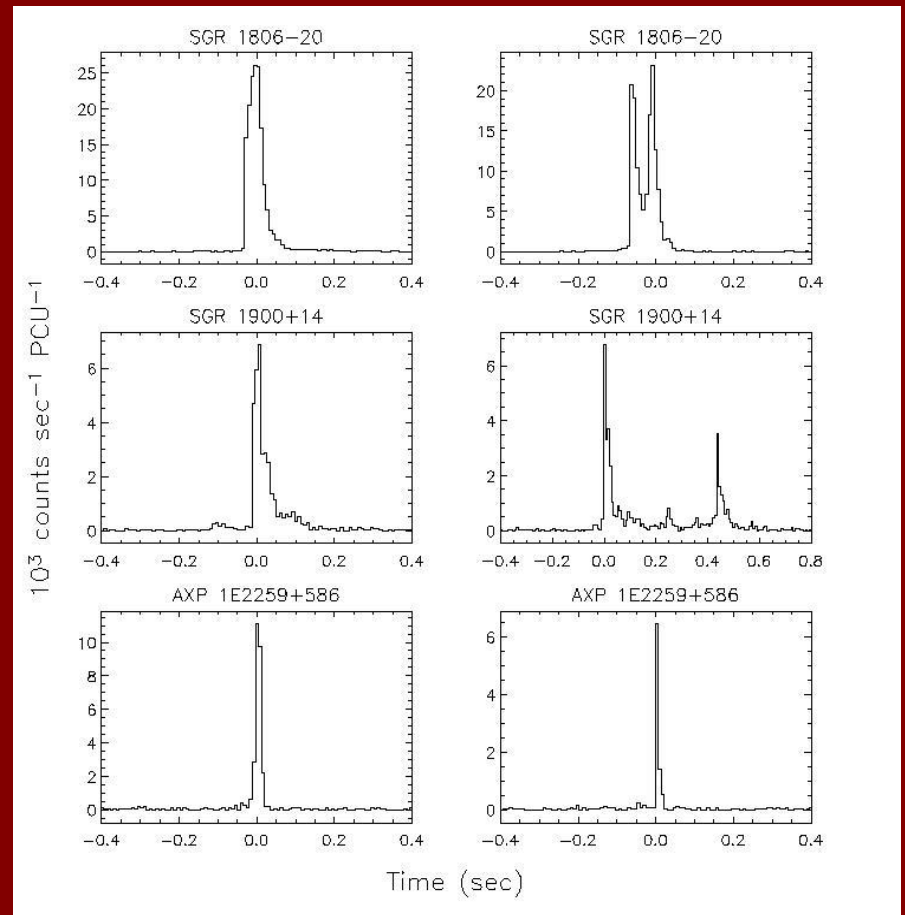
*Power distribution is similar  
to the distribution of earthquakes  
in magnitude*



See the review in  
Rea, Esposito  
1101.4472

# Normal bursts of SGRs and AXPs

- Typical weak bursts of SGR 1806-29, SGR 1900+14 and of AXP 1E 2259+586 detected by RXTE



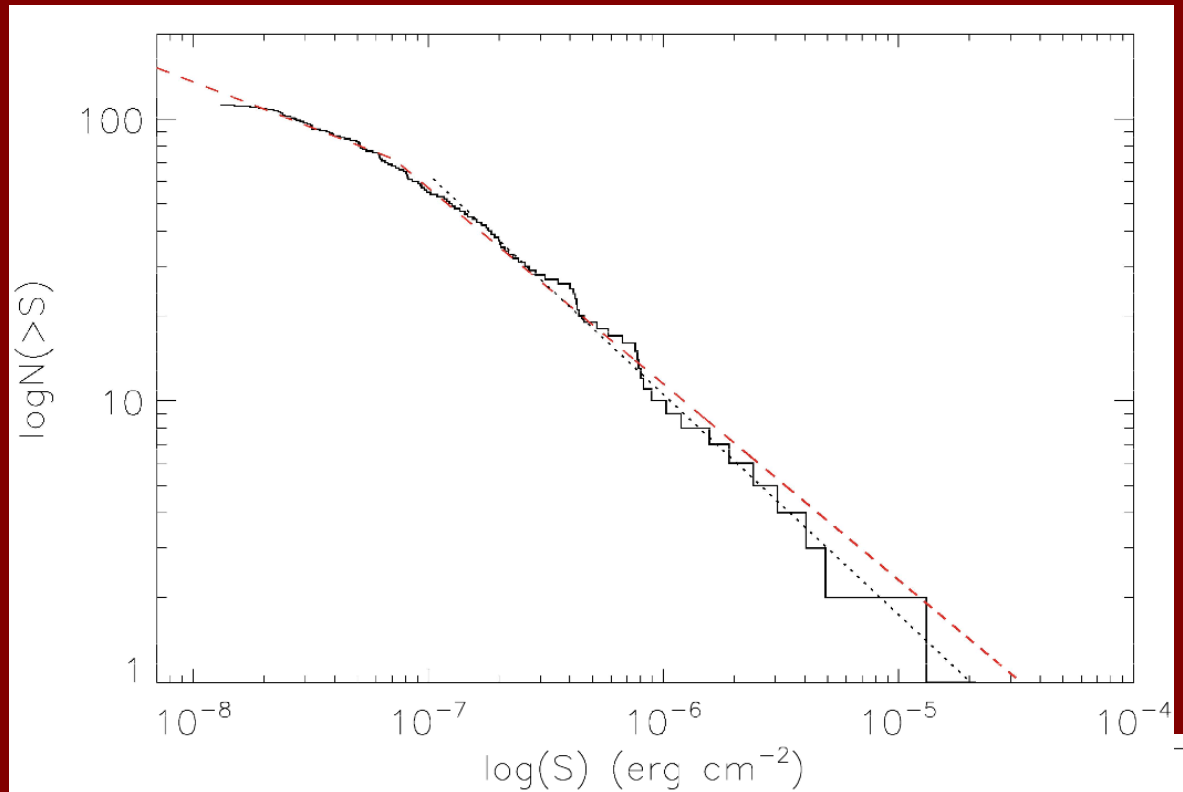
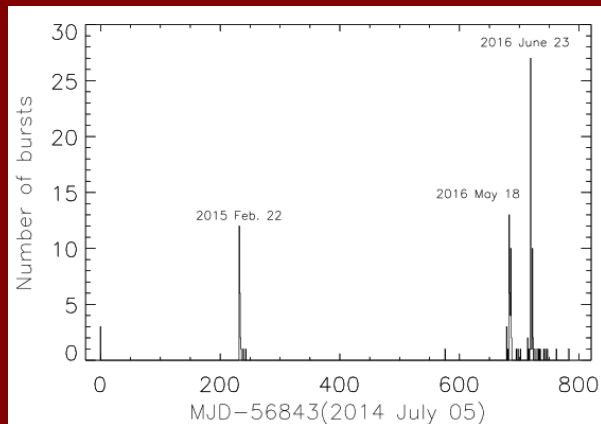
(from Woods, Thompson 2004)

# Outbursts

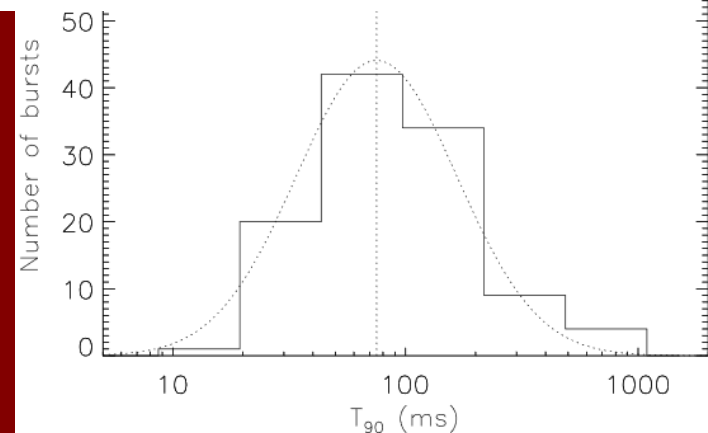
Individual flares often appear during period of activity. They are called *outbursts*.

SGR J1935+2154 is the most recurring transient during last years.

127 bursts in 2-3 years.  
This amount allows detailed statistical studies.



See the review in  
Rea, Esposito  
1101.4472

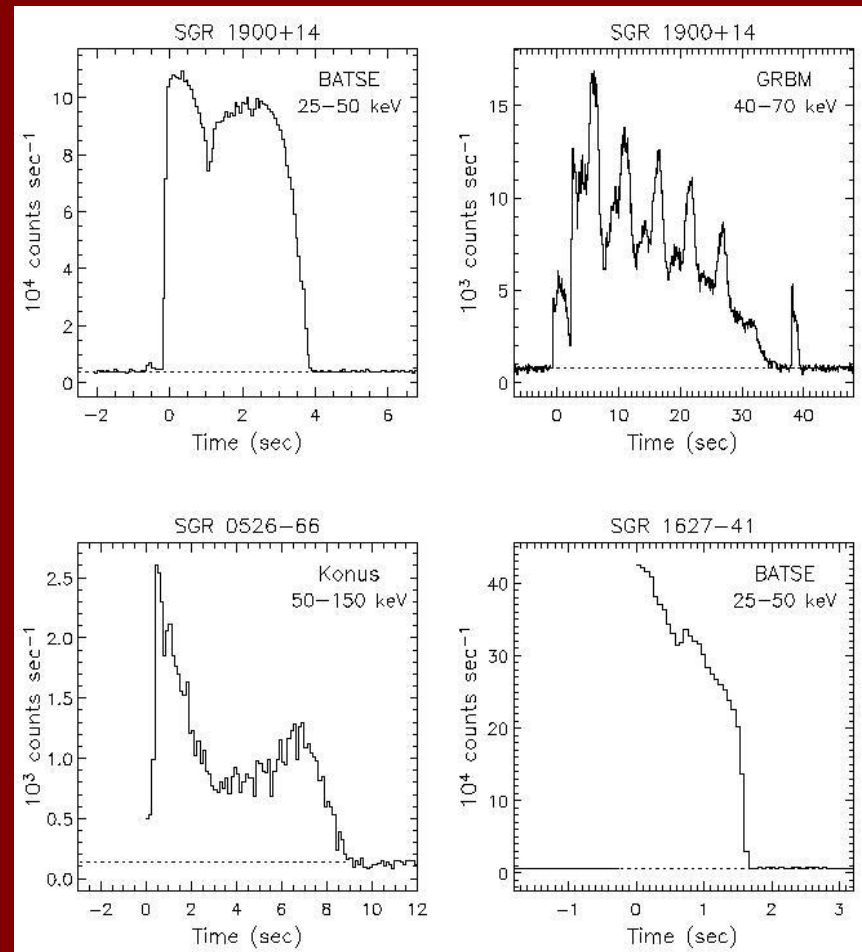


2003.10582

# Intermediate SGR bursts

Examples of intermediate bursts.

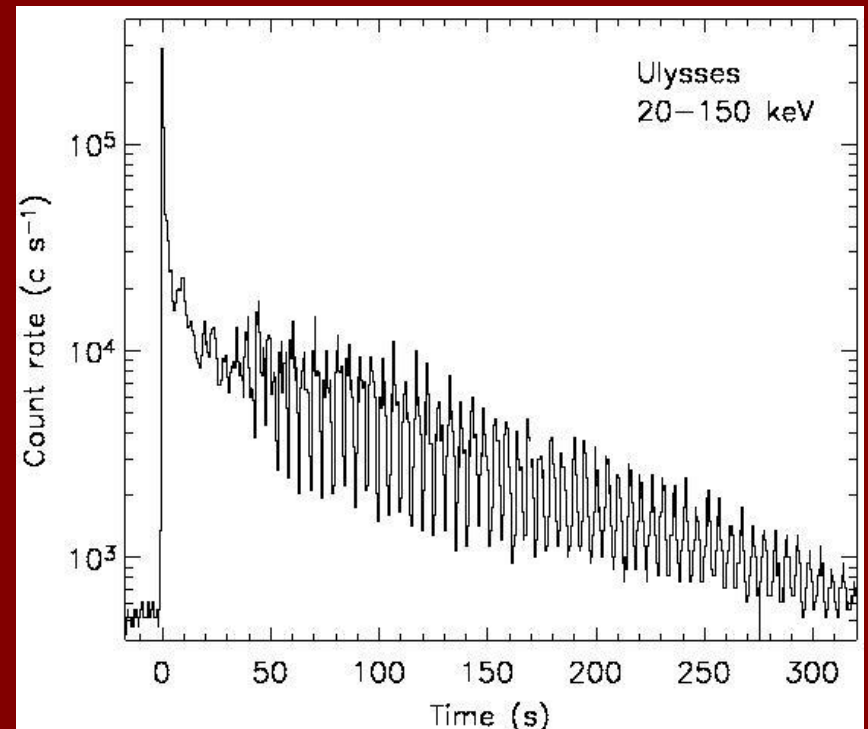
The forth (bottom right) is sometimes defined as a giant burst (for example by Mazets et al.).



(from Woods, Thompson 2004)

# Giant flare of the SGR 1900+14 (27 August 1998)

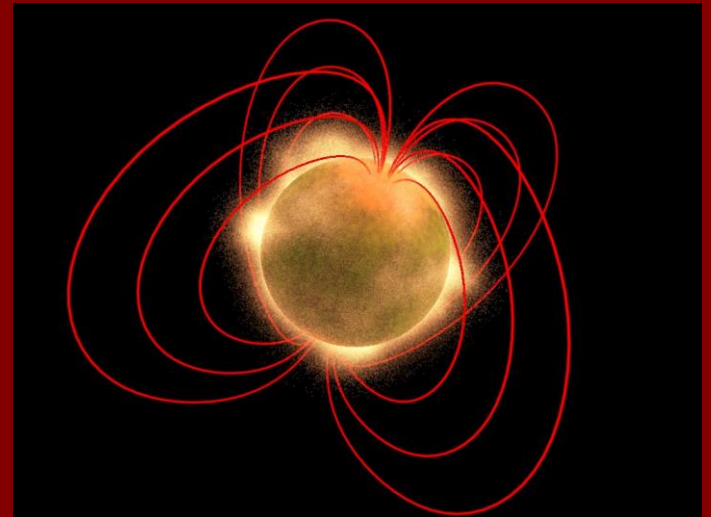
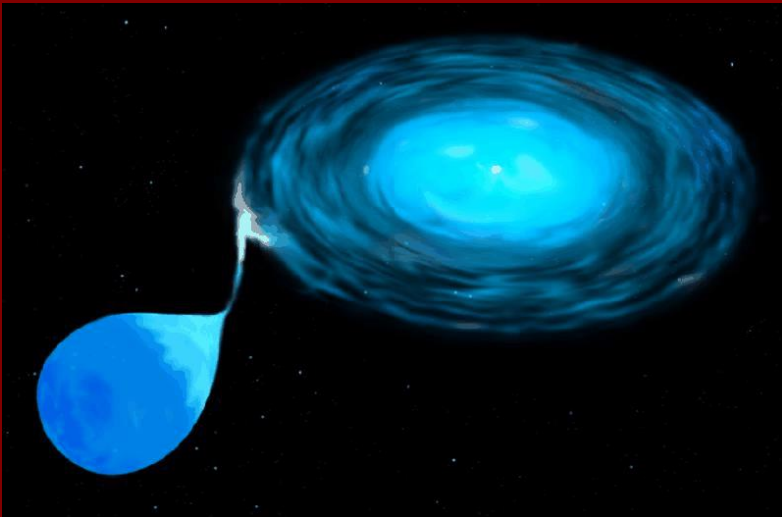
- Ulysses observations  
(figure from Hurley et al.)
- Initial spike 0.35 s
- $P=5.16$  s
- $L > 3 \times 10^{44}$  erg/s
- $E_{\text{TOTAL}} > 10^{44}$  erg



# Anomalous X-ray pulsars

Identified as a separate group in 1995.  
(Mereghetti, Stella 1995 Van Paradijs et al.1995)

- Similar periods (5-10 sec)
- Constant spin down
- Absence of optical companions
- Relatively weak luminosity
- Constant luminosity



# Anomalous X-ray Pulsars: main properties

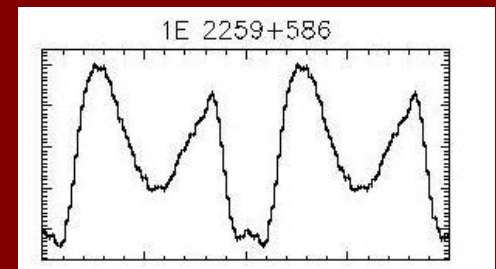
- Fourteen sources known:  
1E 1048.1-5937, 1E 2259+586, 4U 0142+614,  
1 RXS J170849-4009, 1E 1841-045, 3XMM J185246.6+003317,  
CXOU 010043-721134, AX J1845-0258,  
CXOU J164710-455216, XTE J1810-197,  
1E 1547.0-5408, PSR J1622-4950, CXOU J171405.7-381031
- Persistent X-ray emitters,  $L \approx 10^{34} - 10^{35}$  erg/s
- Pulsations with  $P \approx 2 - 10$  s (0.33 sec for PSR 1846)
- Large spindown rates,  $\dot{P}/P \approx 10^{-11} \text{ s}^{-1}$
- No evidence for a binary companion, association with a SNR in several cases

# Known AXPs

Sources

Periods, s

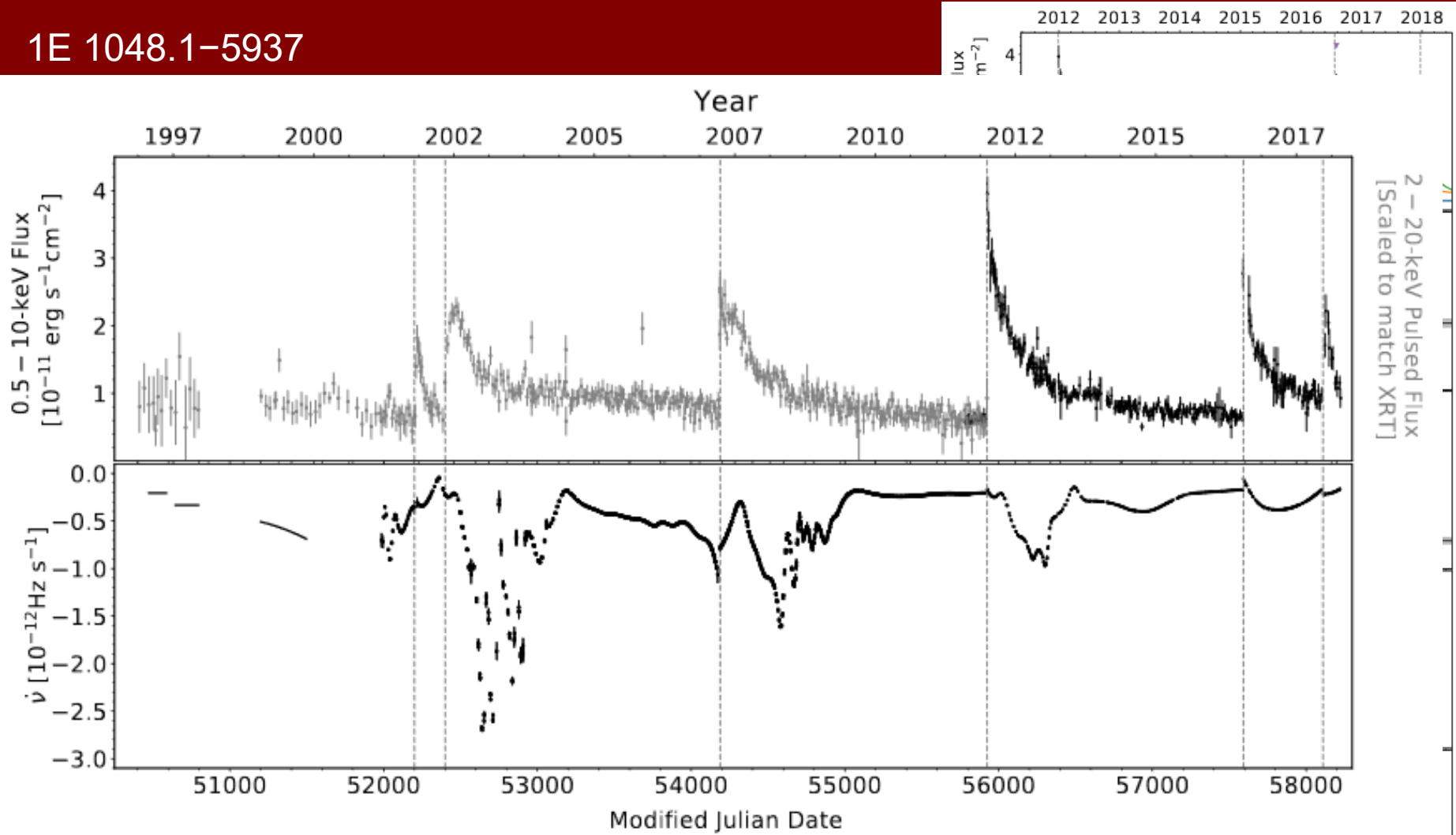
CXO 010043-7211	8.0
4U 0142+61	8.7
1E 1048.1-5937	6.4
1E 1547.0-5408	2.1
CXOU J164710-4552	10.6
1RXS J170849-40	11.0
XTE J1810-197	5.5
1E 1841-045	11.8
AX J1845-0258	7.0
PSR J1622-4950	4.3
CXOU J171405.7-381031	3.8
1E 2259+586	7.0



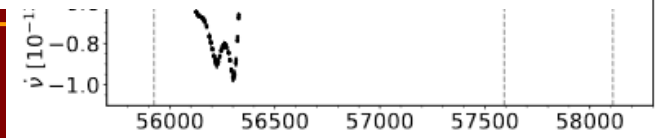


# Phenomenology of a magnetar activity

1E 1048.1-5937

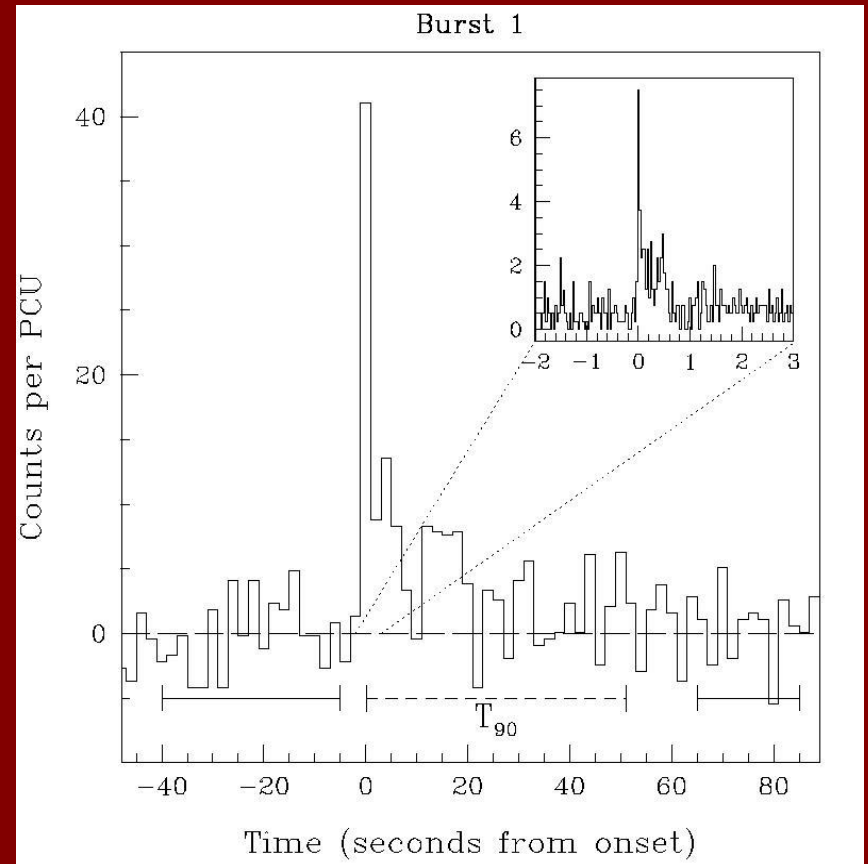


2001.06450

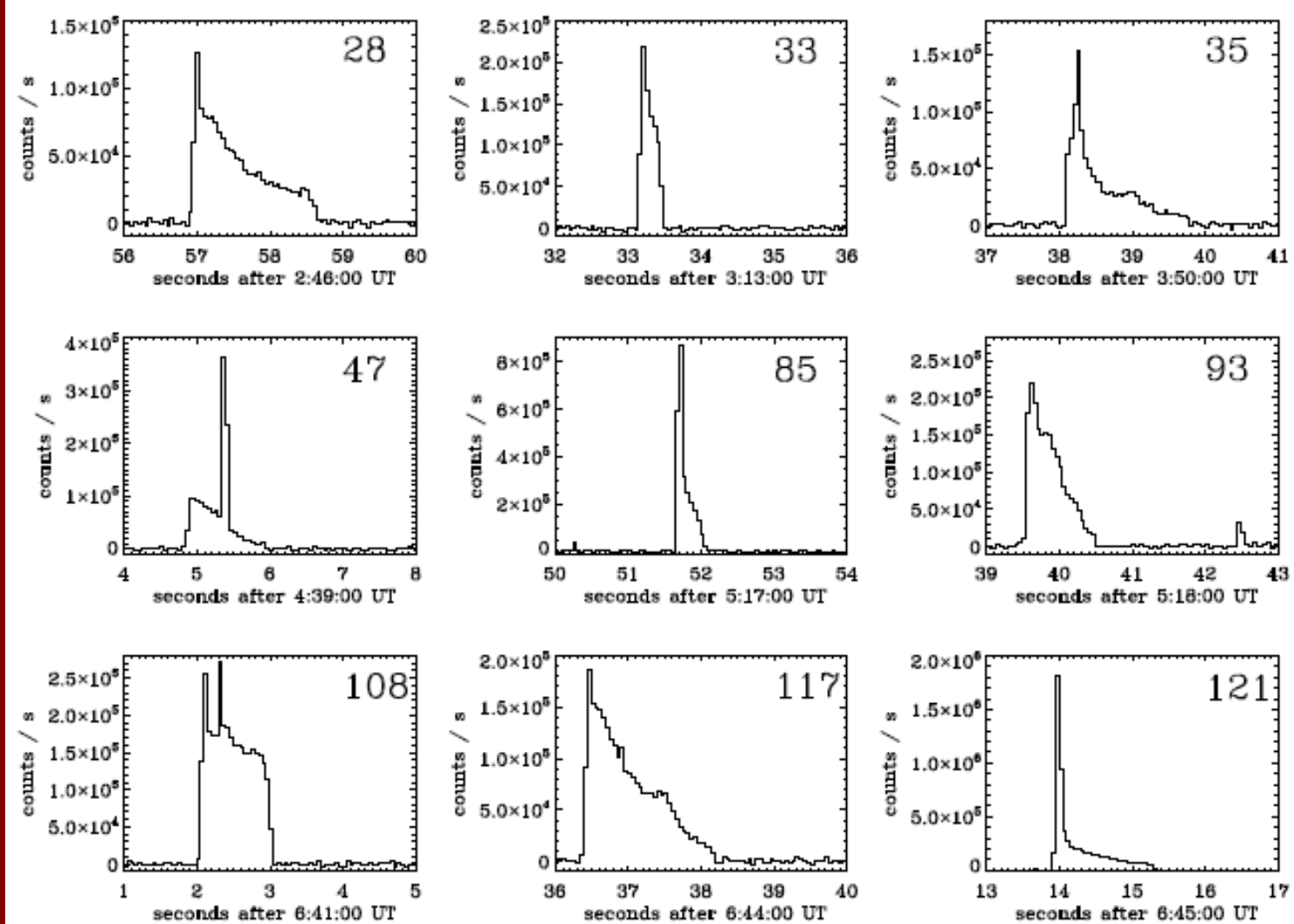


# Are SGRs and AXPs brothers?

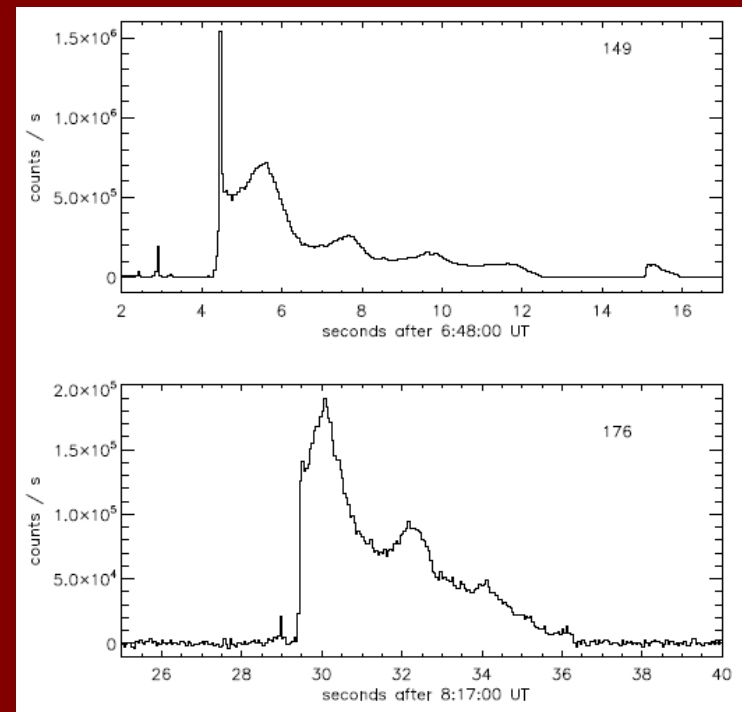
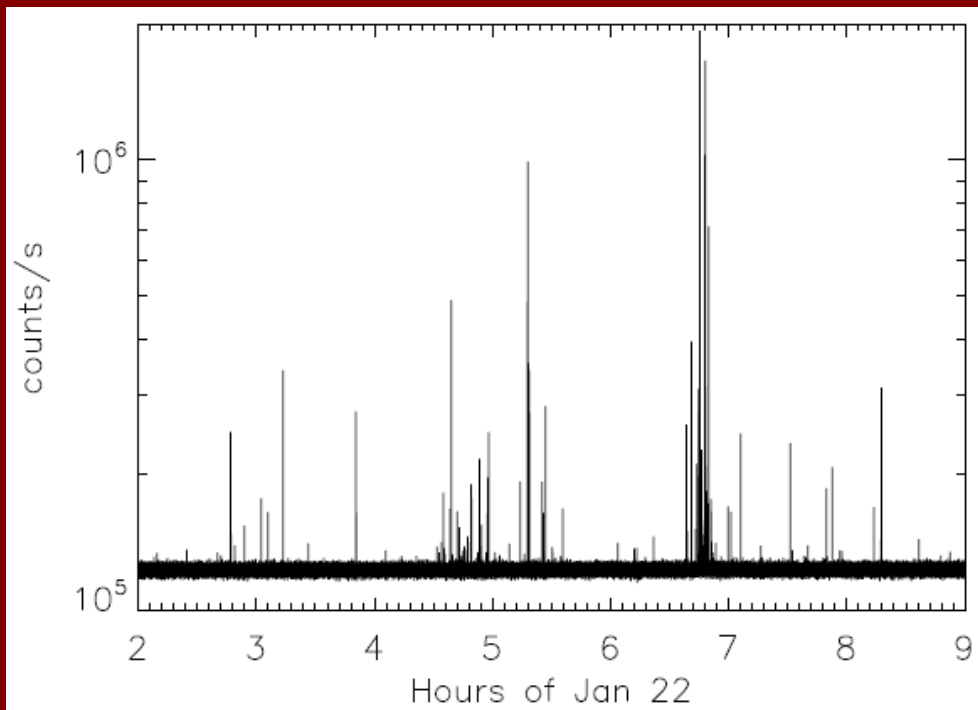
- Bursts of AXPs (more than half burst)
- Spectral properties
- Quiescent periods of SGRs (0525-66 since 1983)



# Bursts of the AXP 1E1547.0-5408

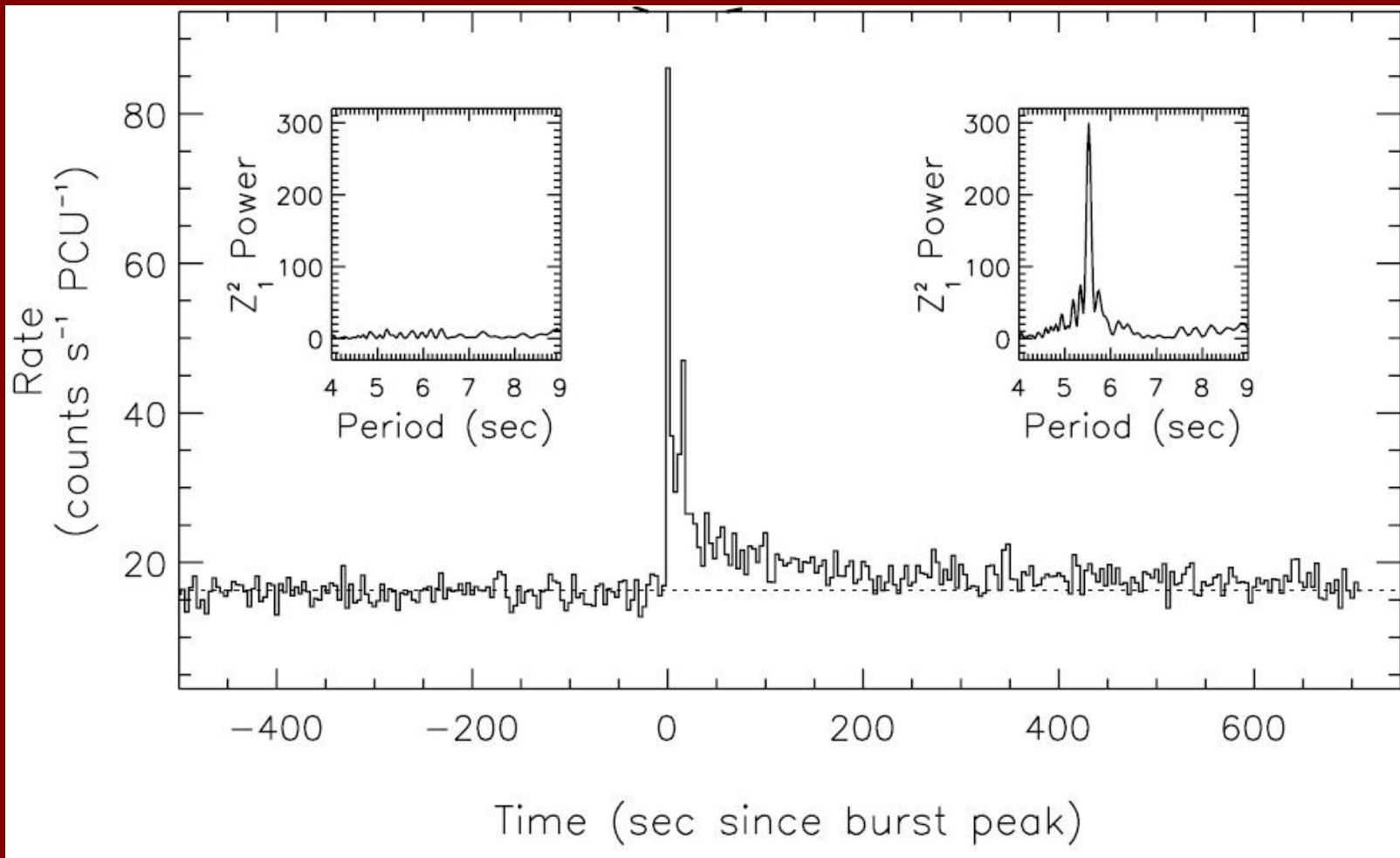


# Bursts of the AXP 1E1547.0-5408



Some bursts have pulsating tails with spin period.

# Unique AXP bursts?



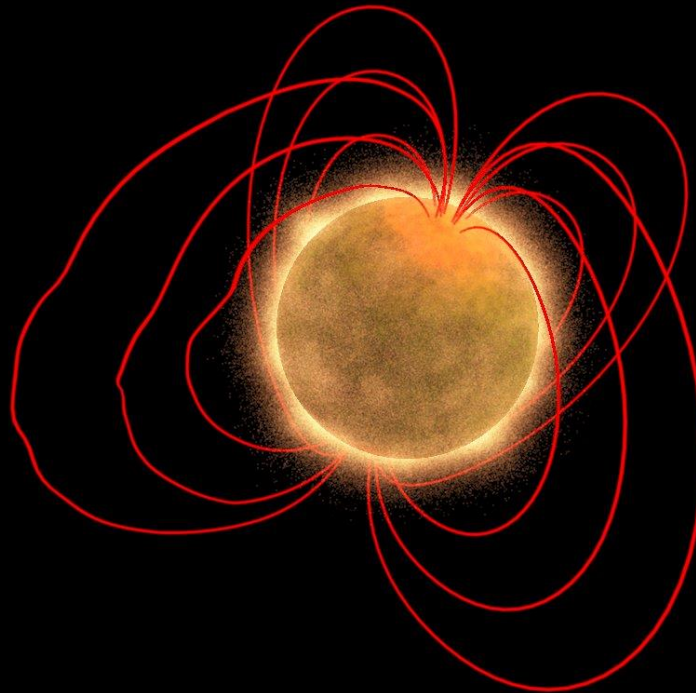
Bursts from AXP J1810-197. Note a long exponential tail with pulsations.

(Woods et al. 2005 astro-ph/ astro-ph/0505039)

# A Tale of Two Populations ?

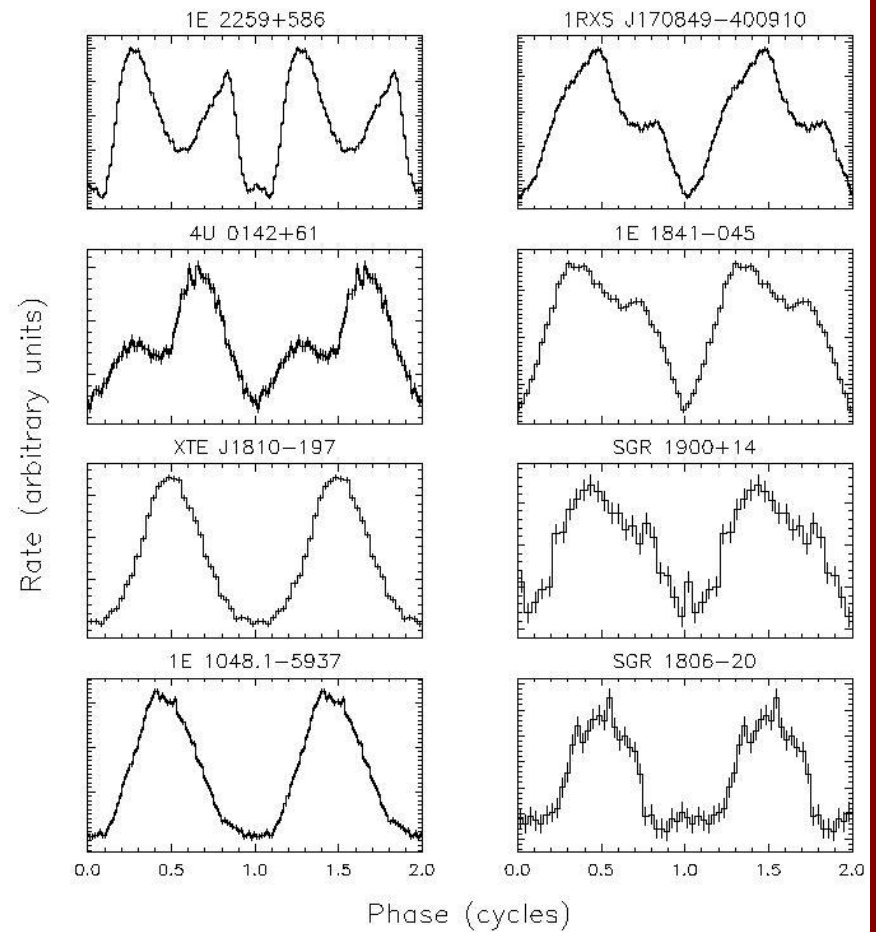
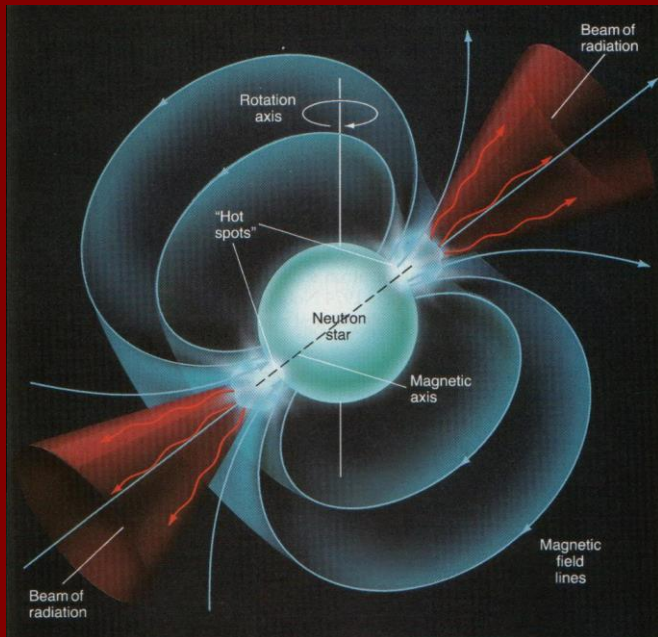
SGRs: bursting  
X/γ-ray sources

A Magnetar



R < 10 km  
Pulsed X-ray emission: a neutron star

# Pulse profiles of SGRs and AXPs

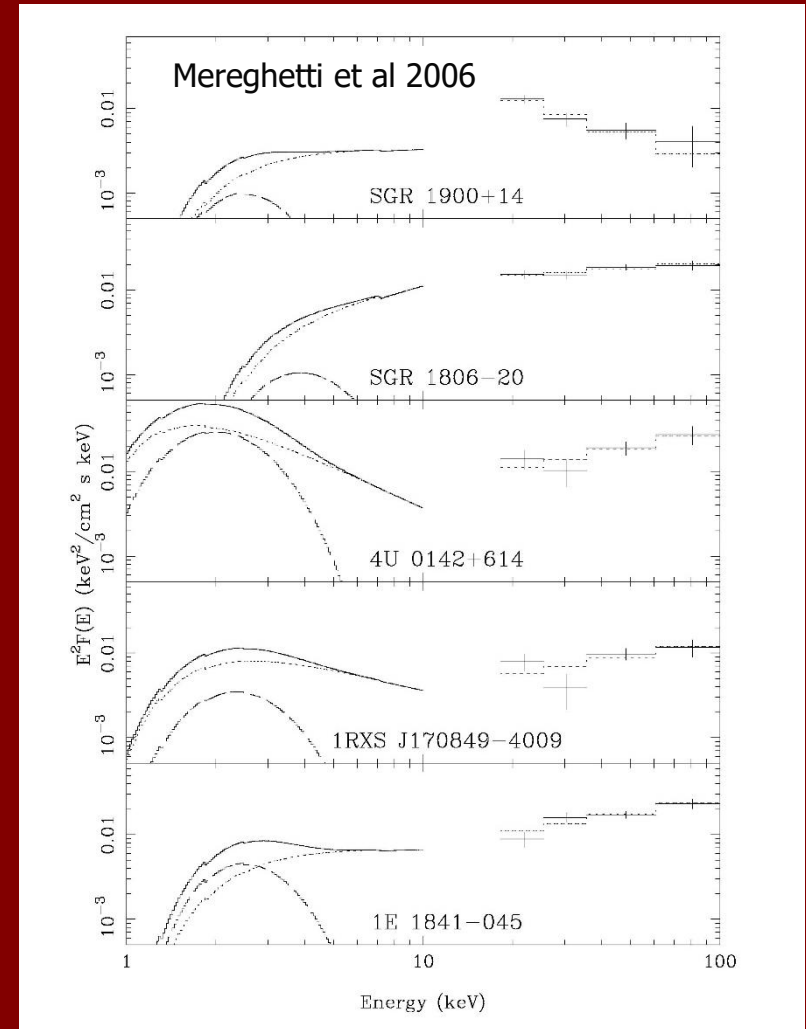


# Hard X-ray Emission

INTEGRAL revealed  
substantial emission in  
the 20 -100 keV band  
from SGRs and APXs

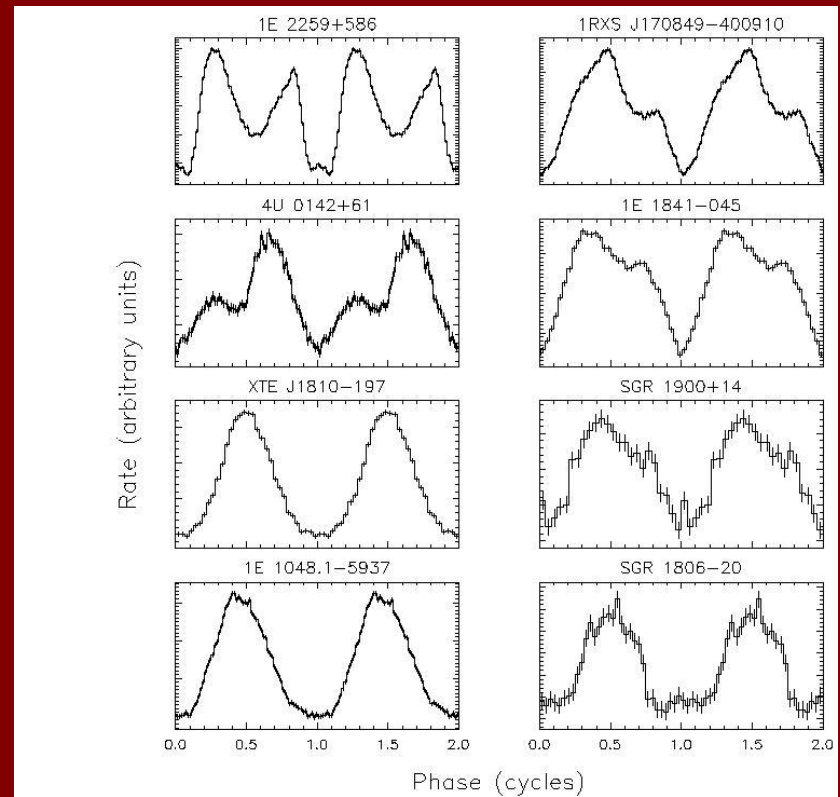
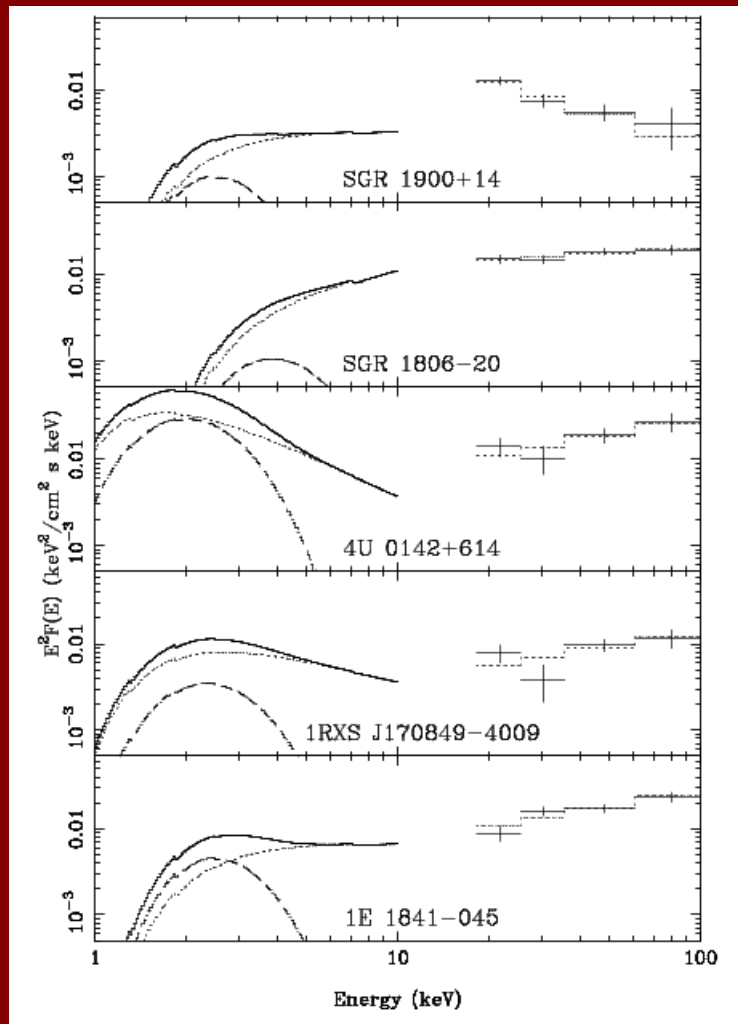
Hard power law tails  
with  $\Gamma \approx 1-3$   
(see 1712.09643 about  
spectral modeling)

Hard emission pulse



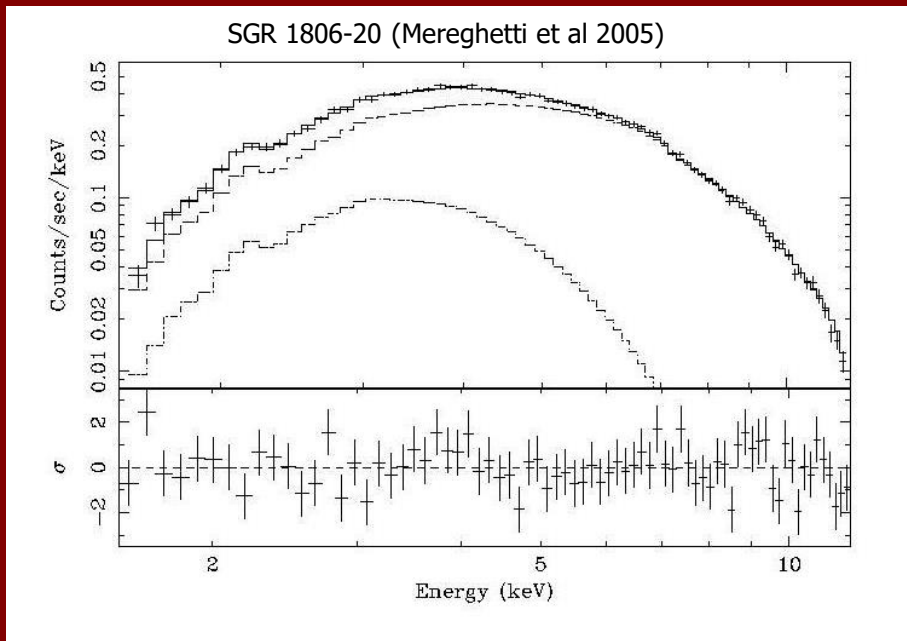


# SGRs and AXPs

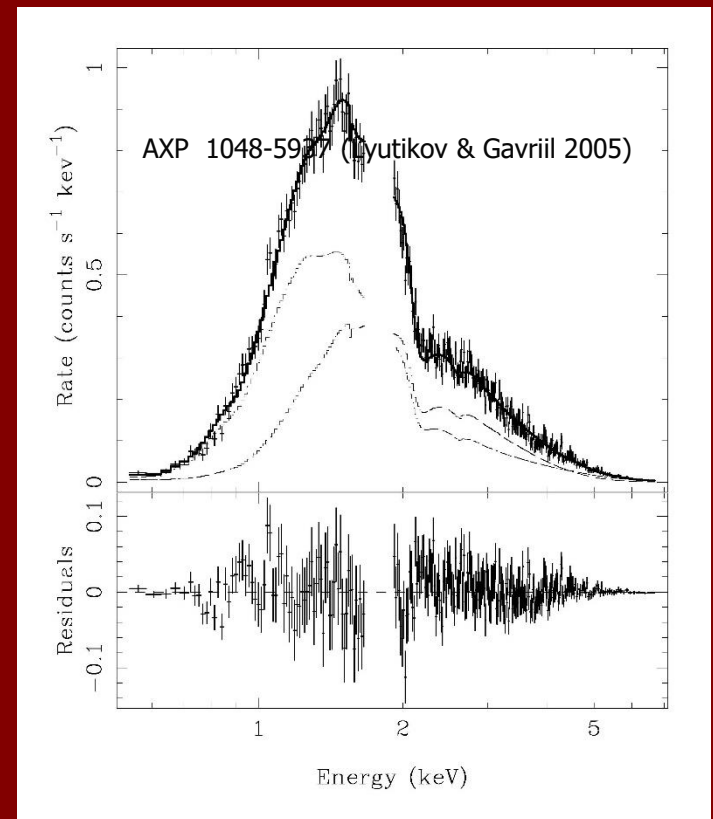


# SGRs and AXPs soft X-ray Spectra

- 0.5 – 10 keV emission is well represented by a blackbody plus a power law



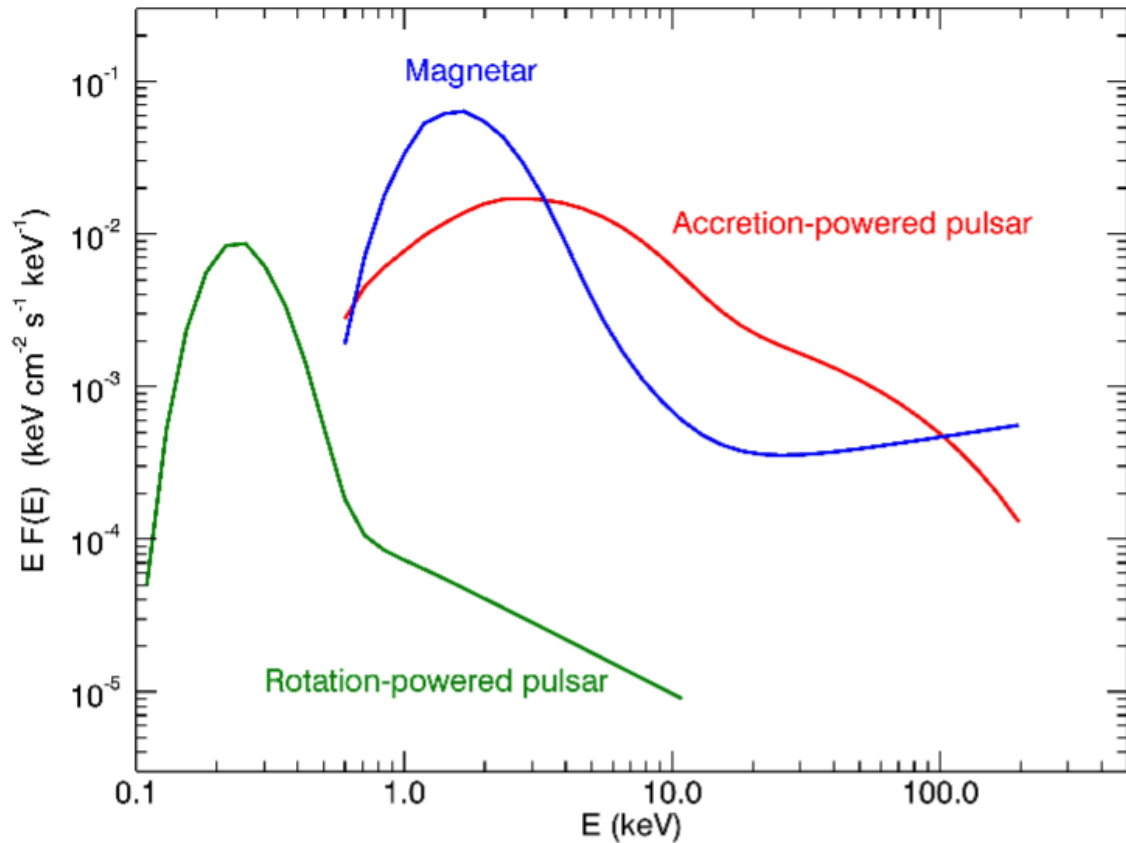
See also discussions in:  
arXiv: 1001.3847, 1009.2810



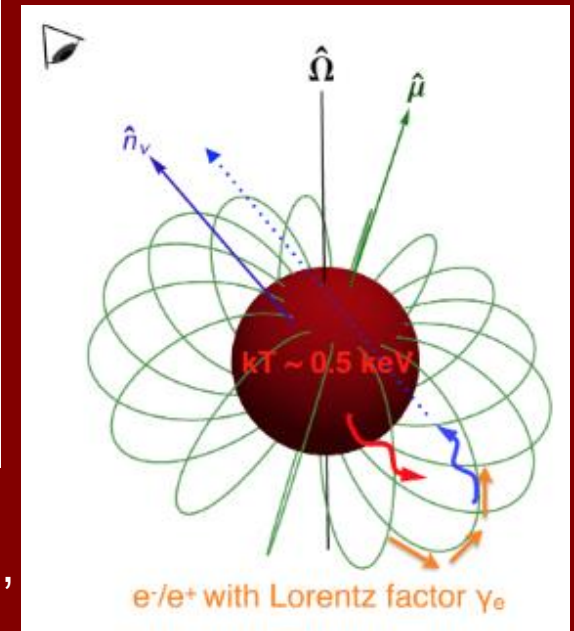
# SGRs and AXPs soft X-ray Spectra

- $kT_{\text{BB}} \sim 0.5 \text{ keV}$ , does not change much in different sources
- Photon index  $\Gamma \approx 1 - 4$ ,  
AXPs tend to be softer
- SGRs and AXPs persistent emission is variable (months/years)
- Variability is mostly associated with the non-thermal component
- About polarization see 2001.07663

# Magnetar spectra in comparison



Hard tails can be due to upscattering of thermal photons from the surface in the magnetosphere, see e.g. 2012.10815.



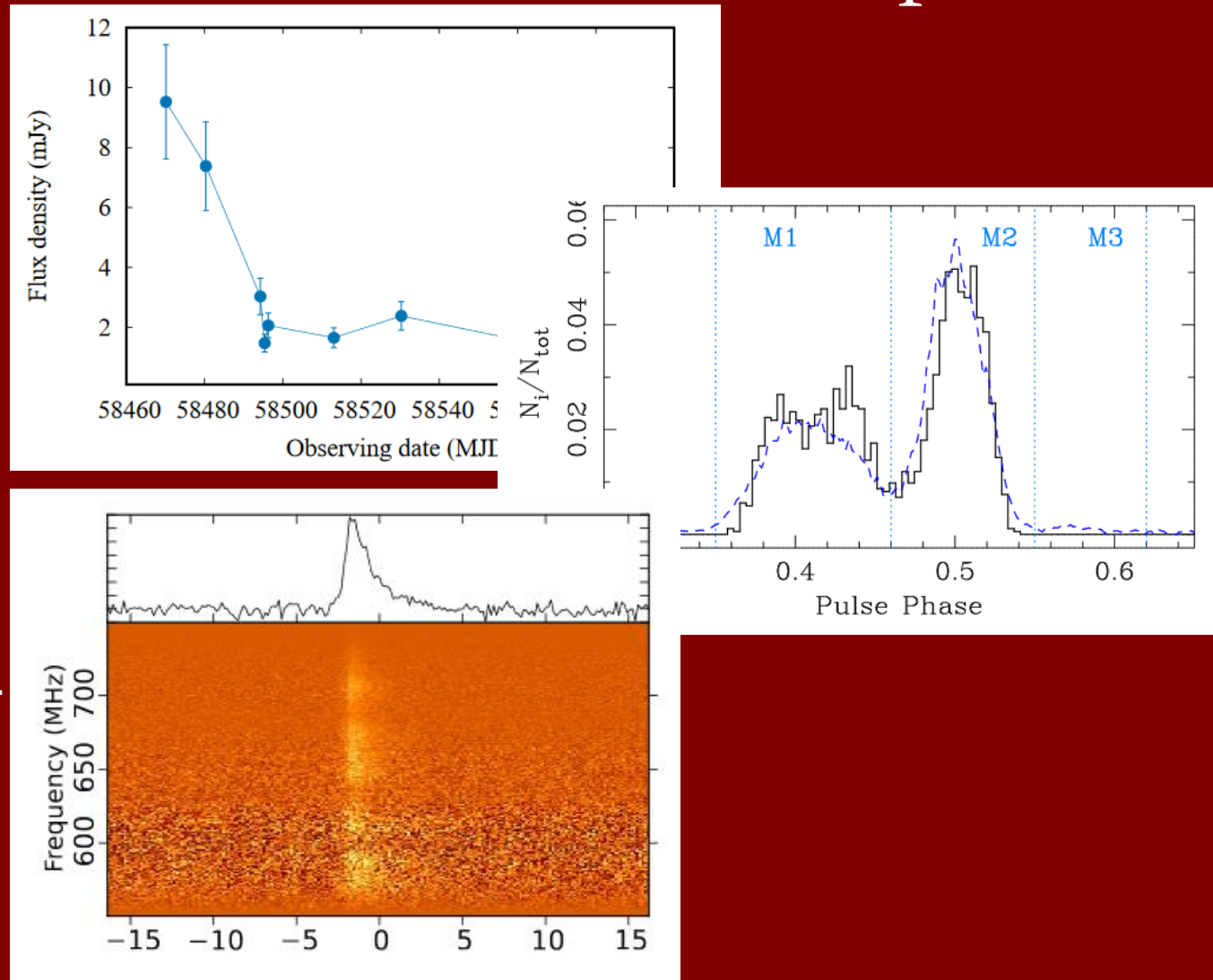
# Magnetars can behave like radio pulsars

XTE J1810-197

Was the first magnetar to show PSR-like radio emission (see lecture 1)

Activity in radio is transient.

Shows short bursts which resemble FRBs (but are much weaker).

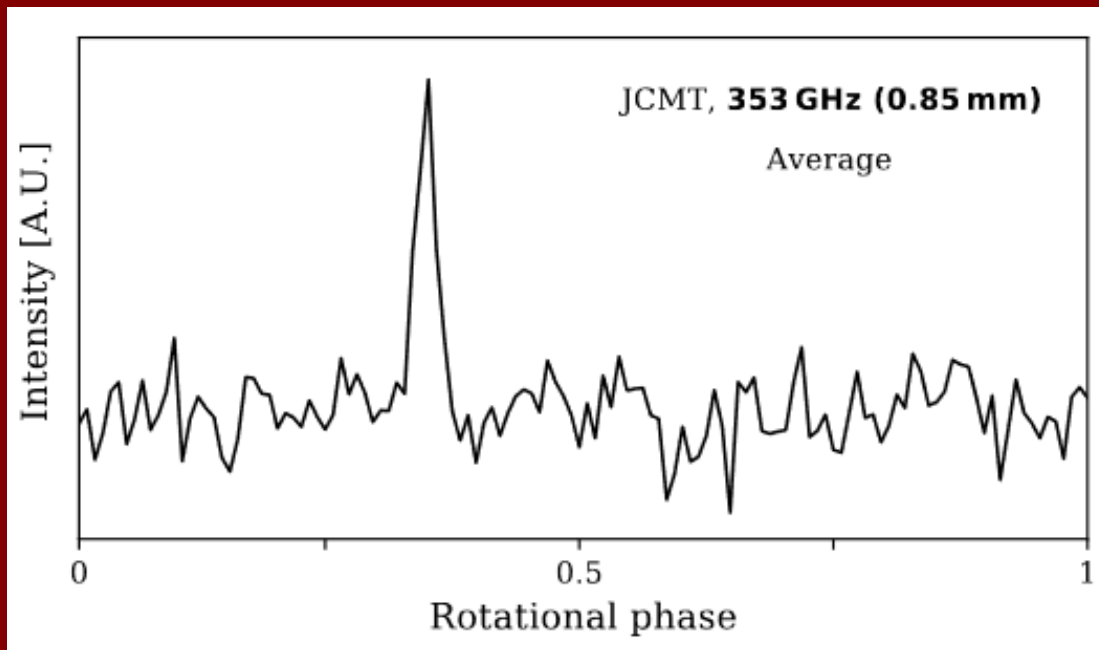


# Sub-mm detection of pulsations

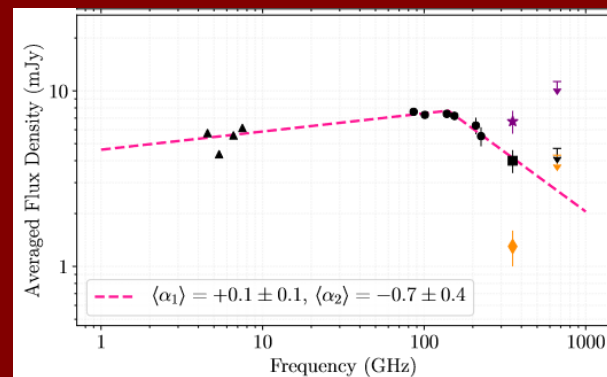
XTE J1810-197

James Clerk Maxwell Telescope

Variable flux at 353 GHz on the time scale of months.  
Only upper limits at 666 GHz.



Spectral break at ~200 GHz

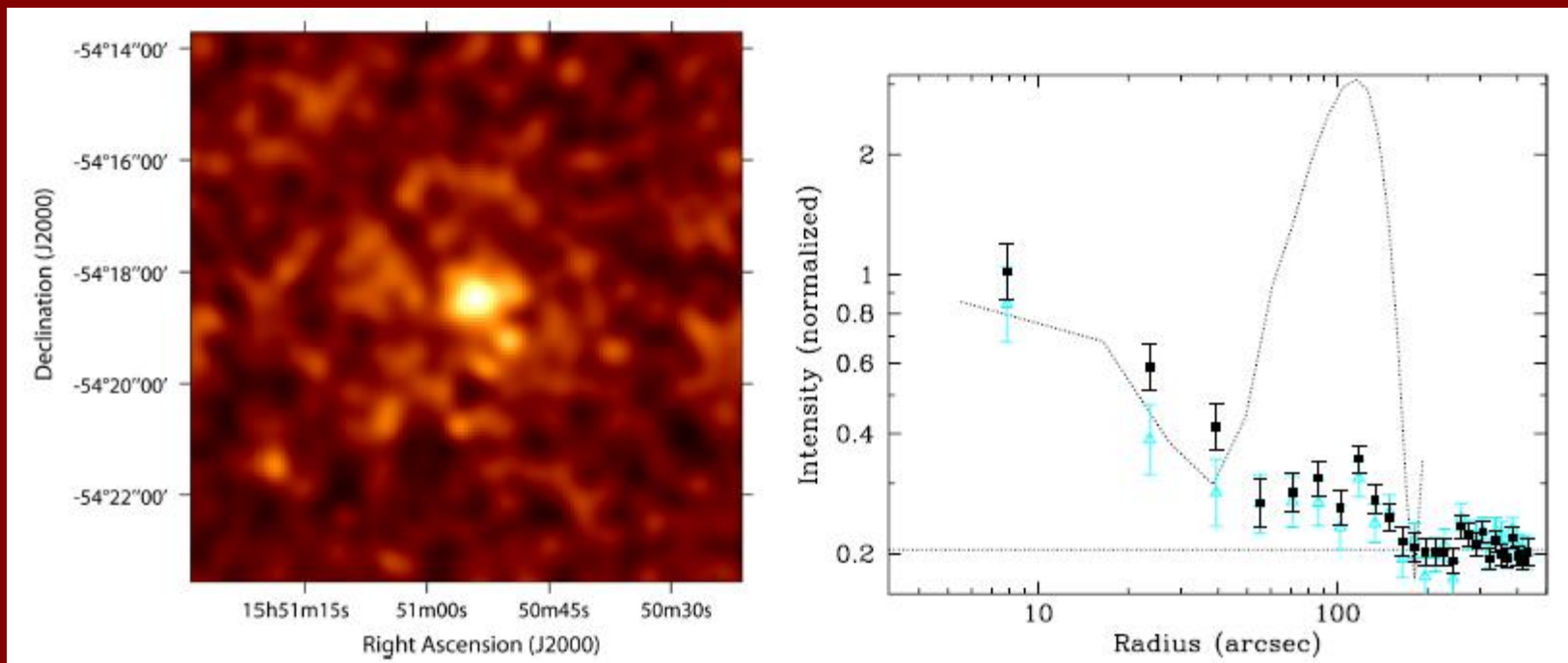


2201.07820

# Similarities between AXPs and PSRs

1E1547.0-5408 – was the most rapidly rotating AXP (2.1 sec) for a long time. The highest rotation energy losses among SGRs and AXPs.

Bursting activity.



Pulsar wind nebulae around an AXP.

0909.3843

See 1902.10712 about radio observations of magnetars.



# Young and fast magnetar with radio

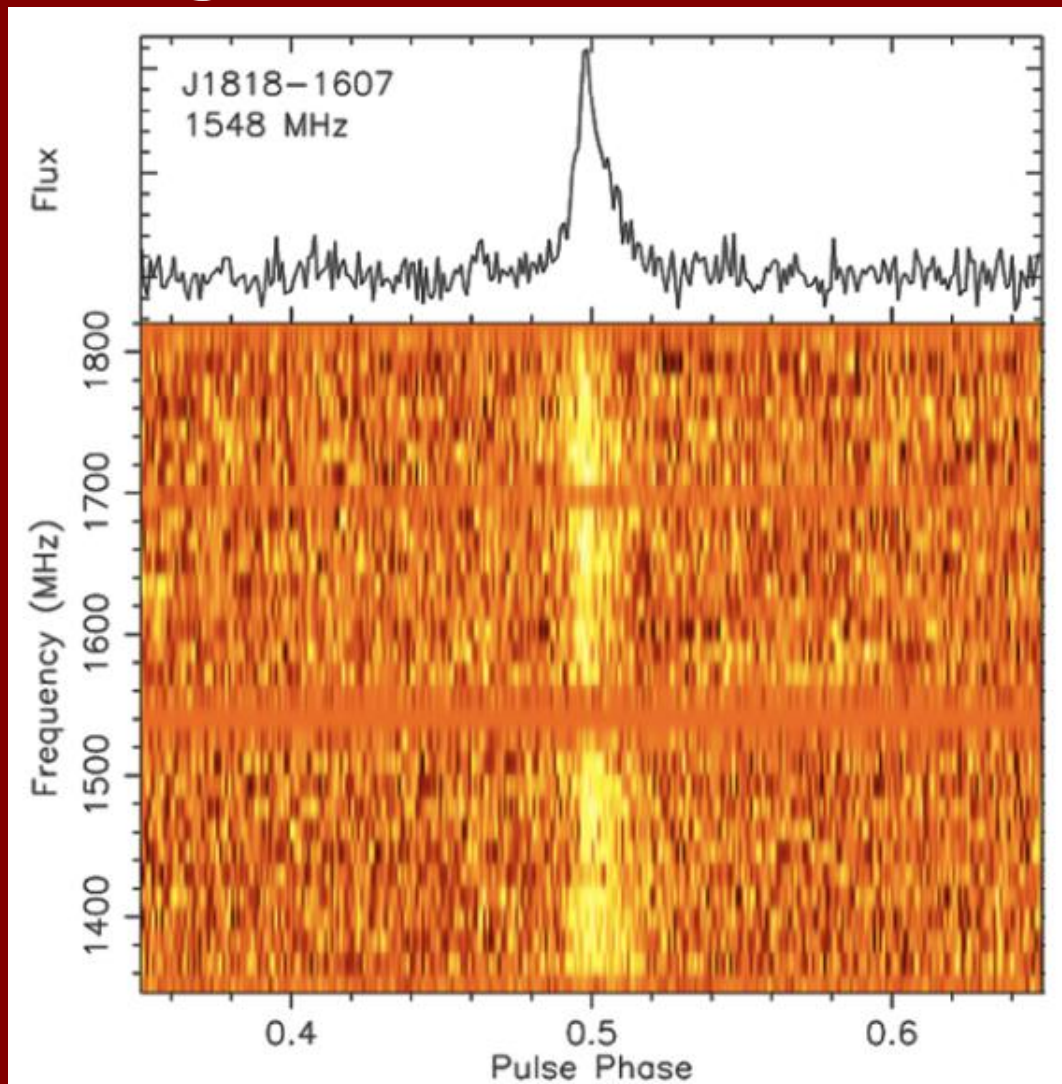
Swift J1818.0–1607  
Discovered in March 2020.

Spin period 1.36 s.

Characteristic age 240 yrs.

Radio pulses.

Weak quiescent emission.

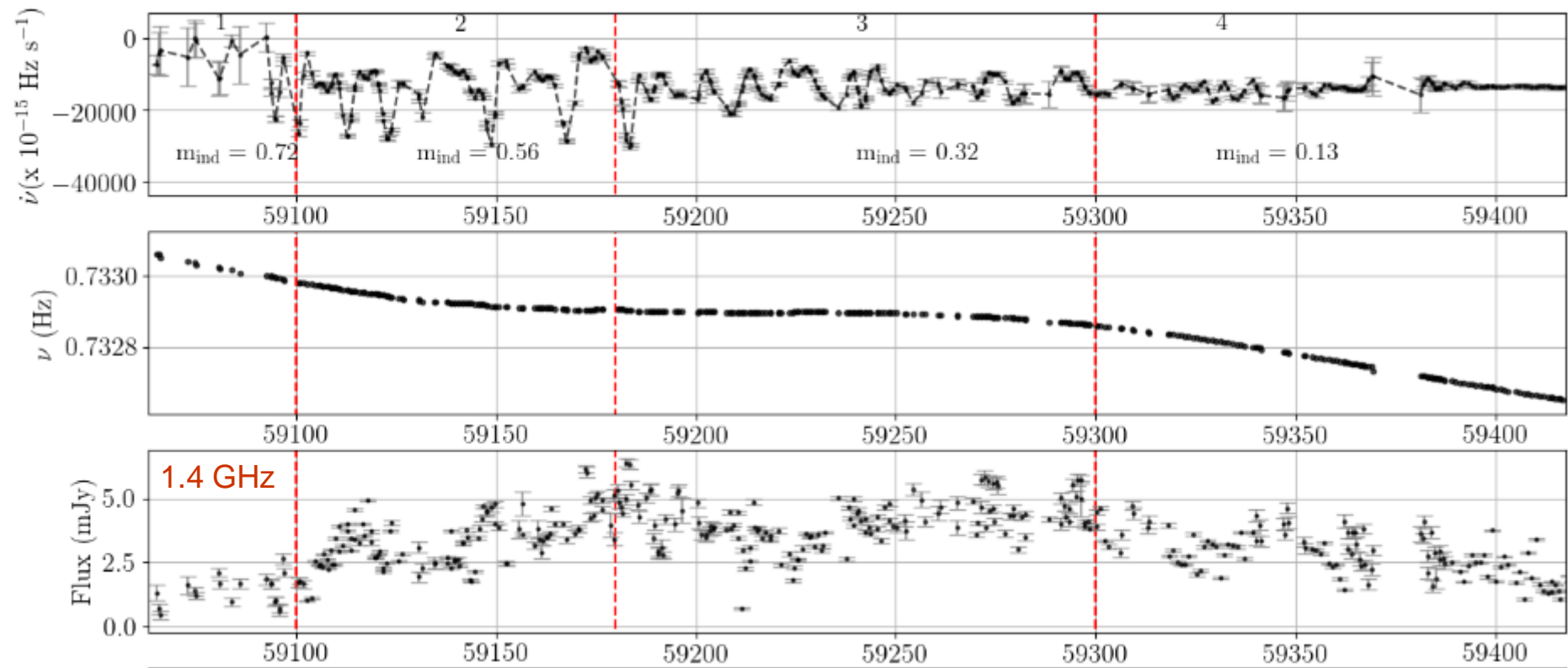


2004.04083

About first radio detection of this source see  
<http://www.astronomerstelegam.org/?read=13577>

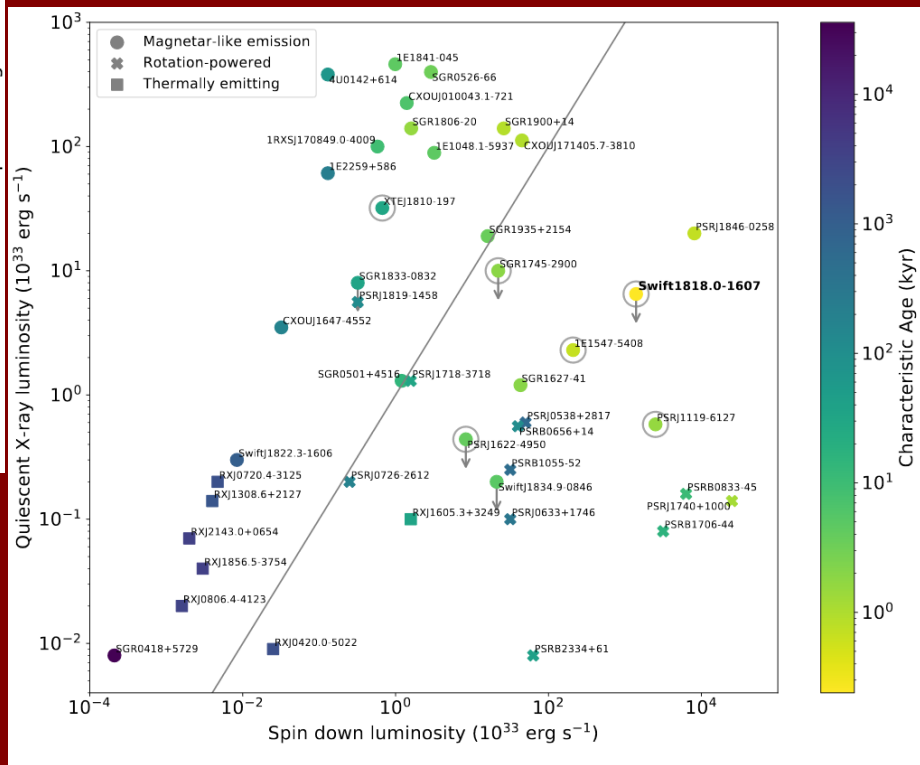
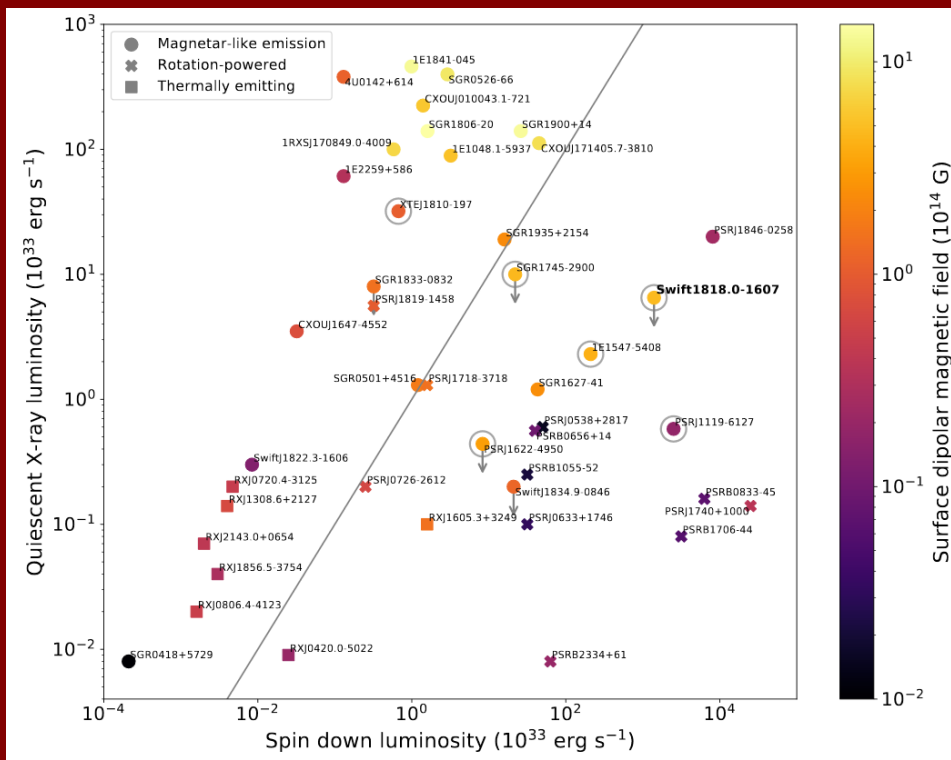


# Complicated behavior of Swift J1818

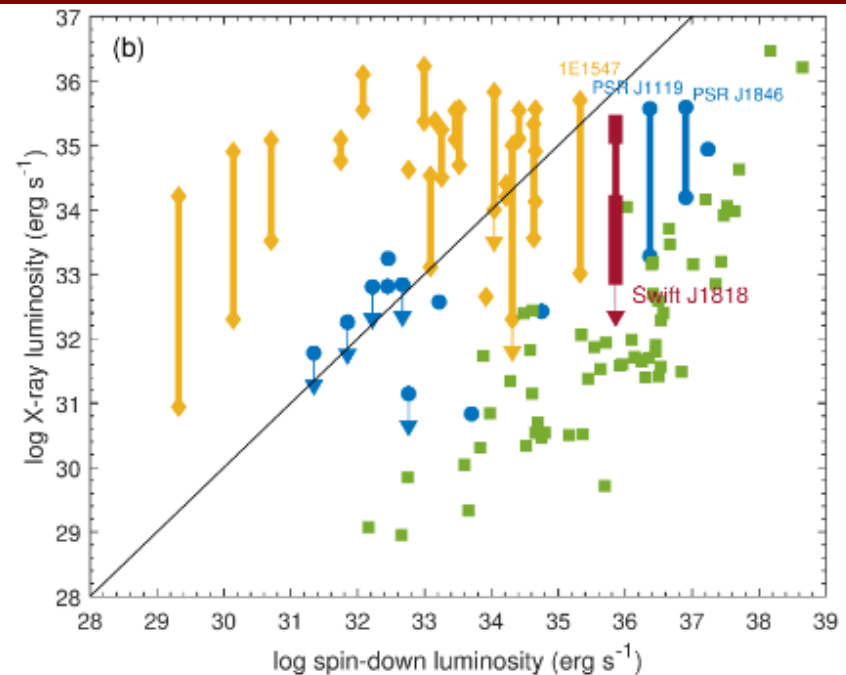
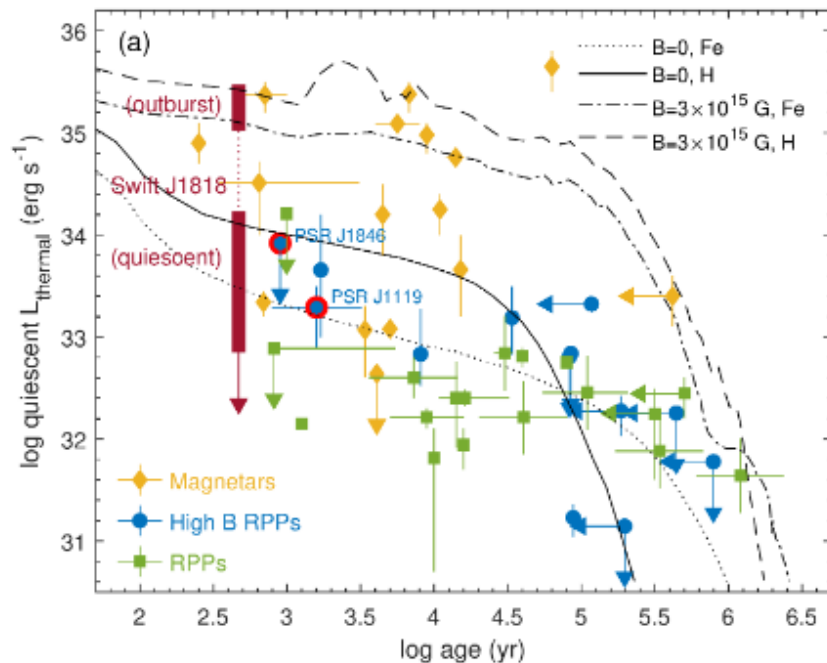


Pulse profile in radio is also changing with time

# $\dot{E}_{\text{rot}} - L_{\text{quiescent}}$



# Links between magnetars and PSRs



Swift J1818.0–1607

Fastest rotation: 1.36 sec.

Small characteristic age.

Strongly variable  $\dot{P}$ .

Strong glitch and anti-glitch.

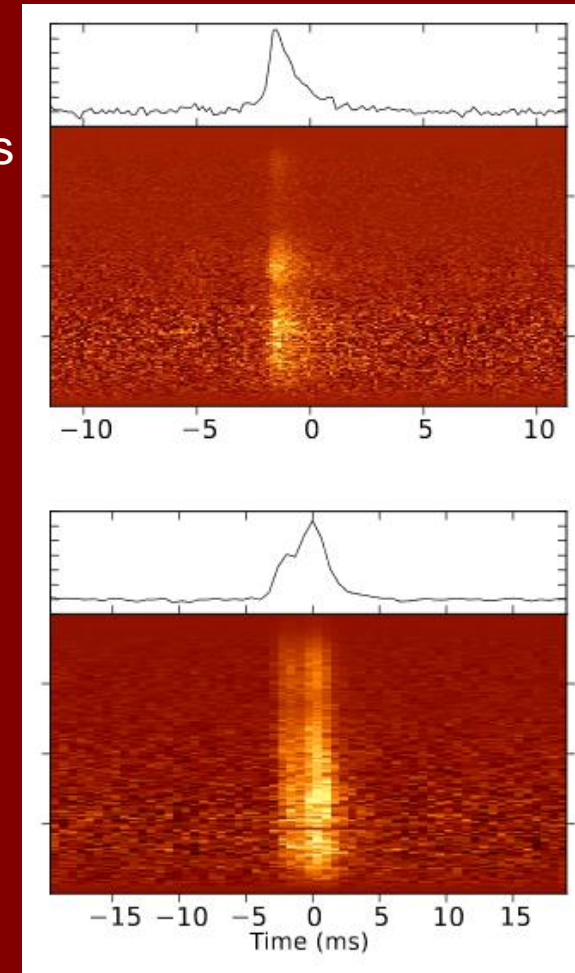
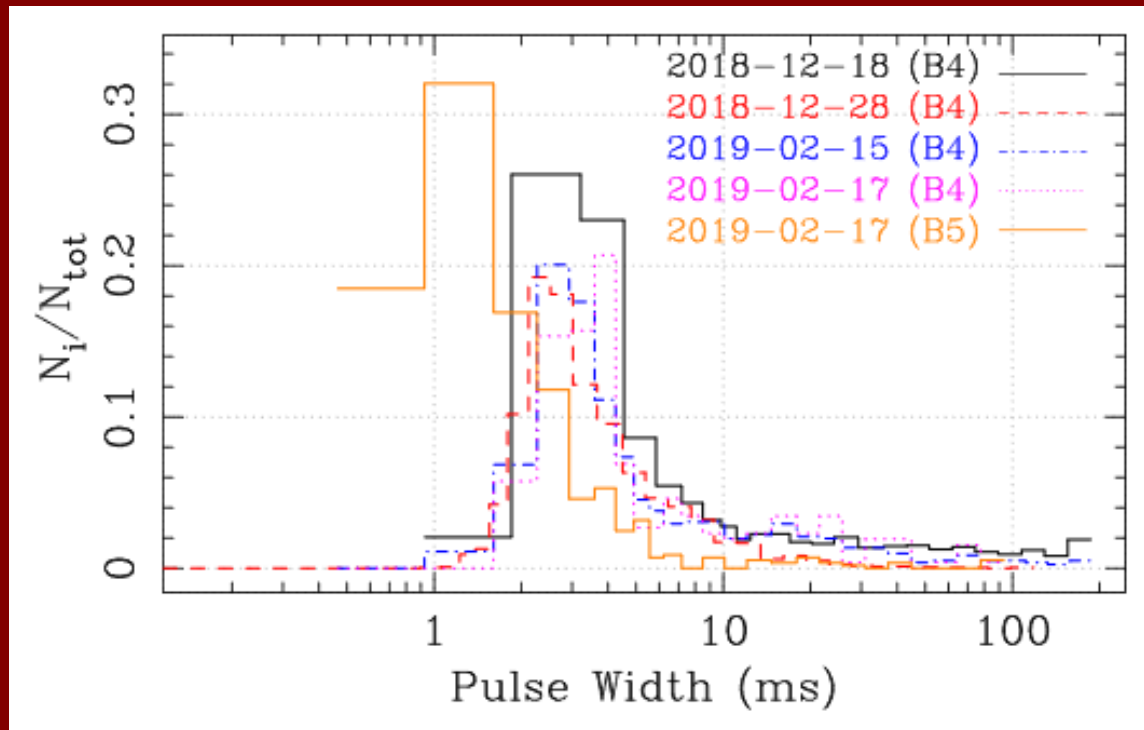
# Bursts from a magnetar

XTE J1810-197

Second period of activity

with radio emission: 2018-2019.

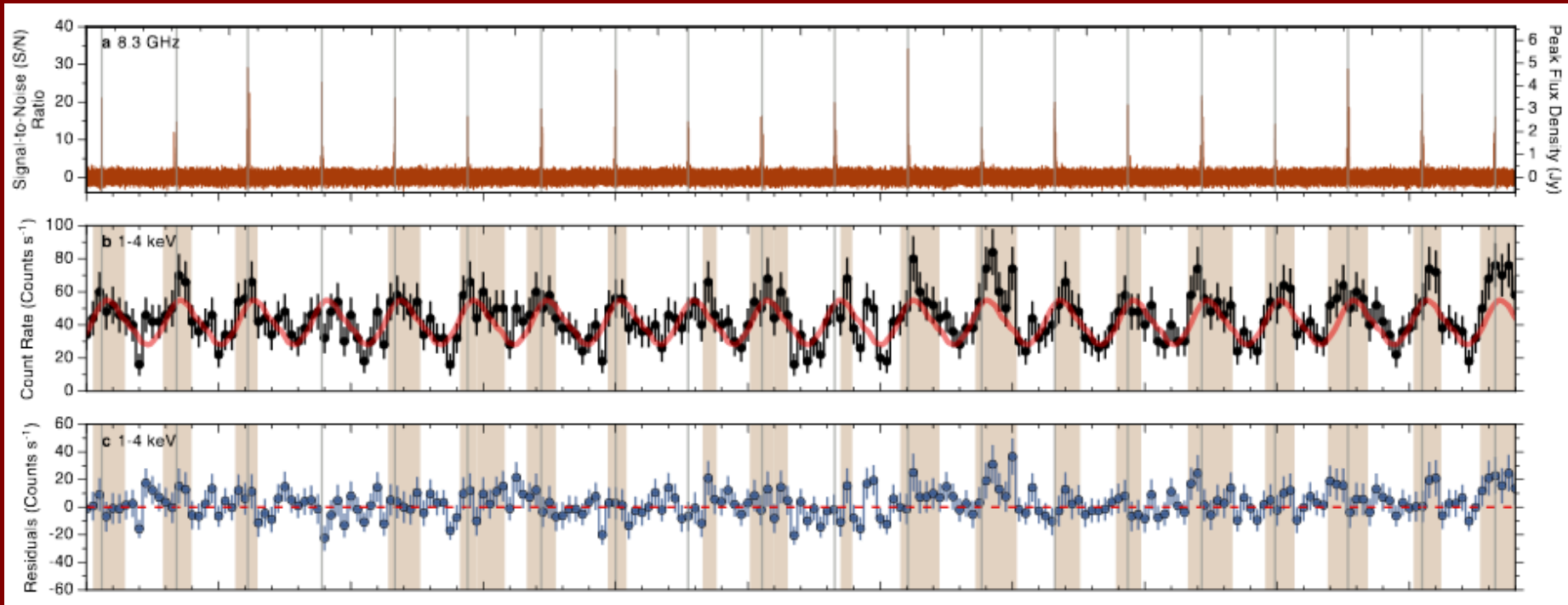
Millisecond scale bursts  
and spectral properties  
similar to FRBs.



The first parallax for magnetar XTE J1810-197 was measured recently due to radio observations, 2008.06438.

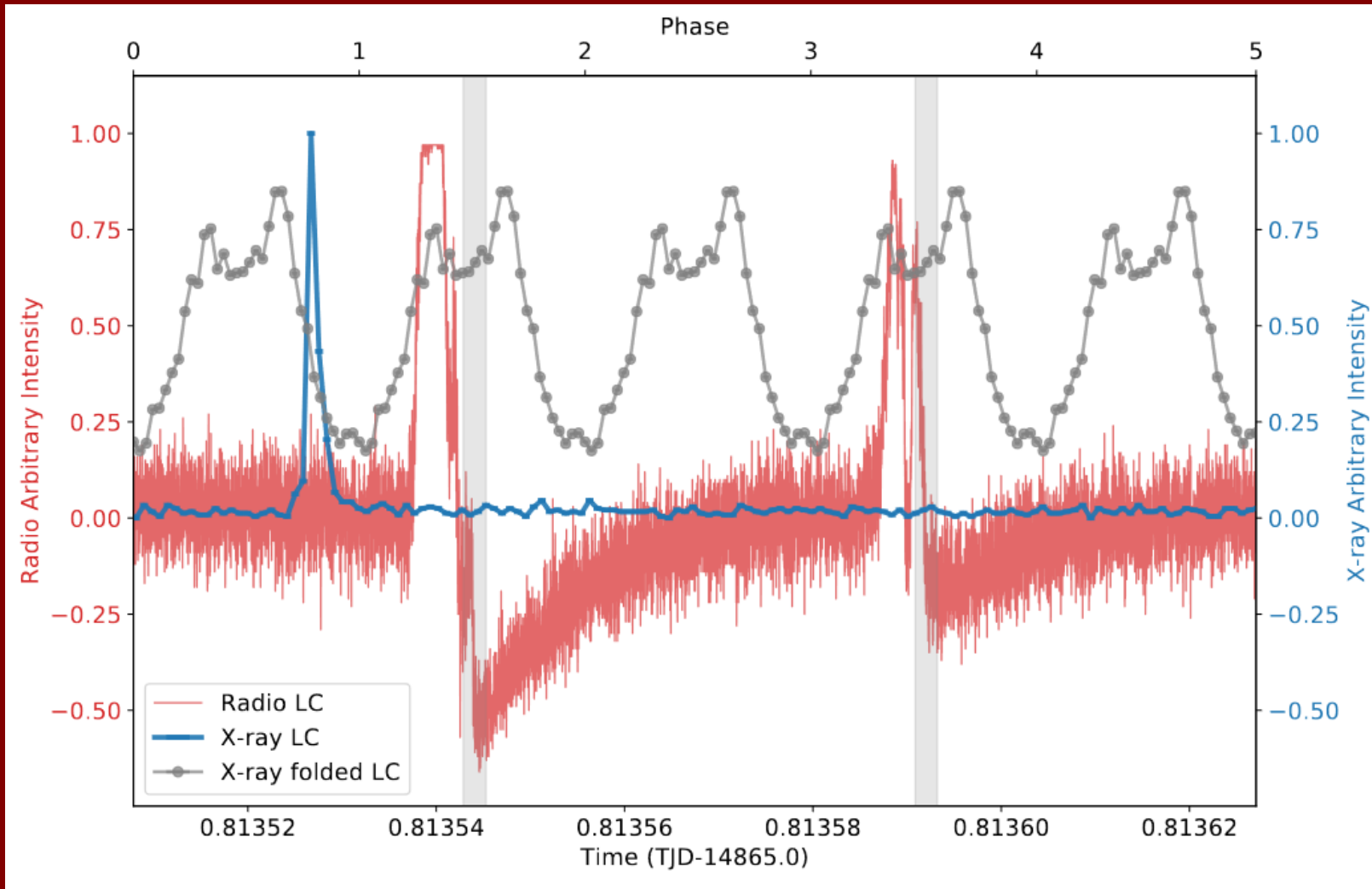
1908.04304. About giant pulses from this source see 2111.01641

# Bursts from XTE 1810



These bursts are not similar to FRBs.

# 1E 1547.0–5408 X-ray and radio bursts



Observations in 2009. Chandra+Swift+Konus-Wind in X-ray and Parkes in radio.

2011.06607

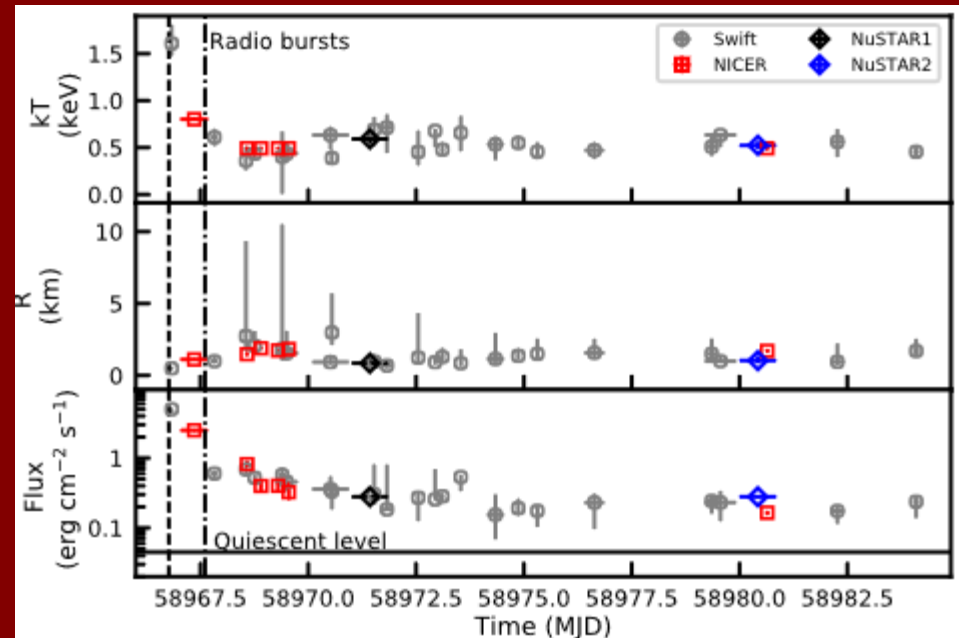
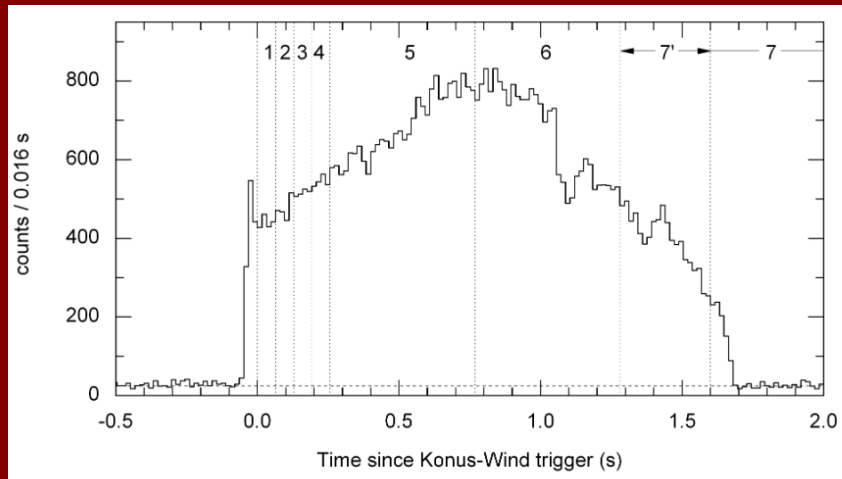
# SGR 1935+2154

Discovered in 2014 (see, Israel et al. 2016).

$P=3.25$  sec

Distance  $\sim 7$ -12 kpc (2005.03517)

Intermediate flare (Kozlova et al. 2016)



Activated in April 2020.

Finally, on April, 28 2020

A simultaneous burst in radio and X/gamma was detected.

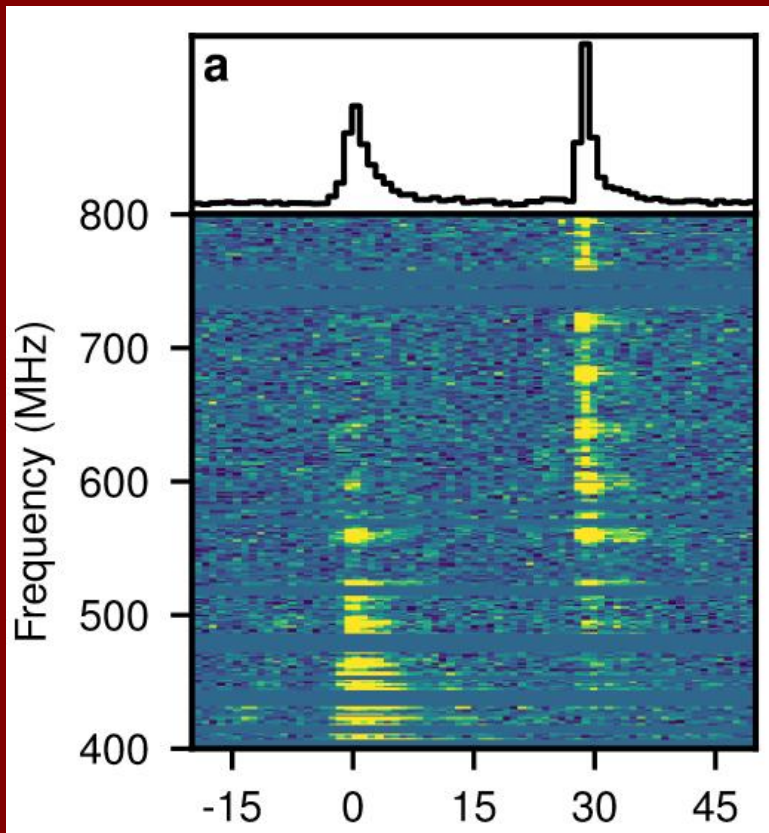
Astronomers telegram: 13681-13769

GCN: 27666-27669

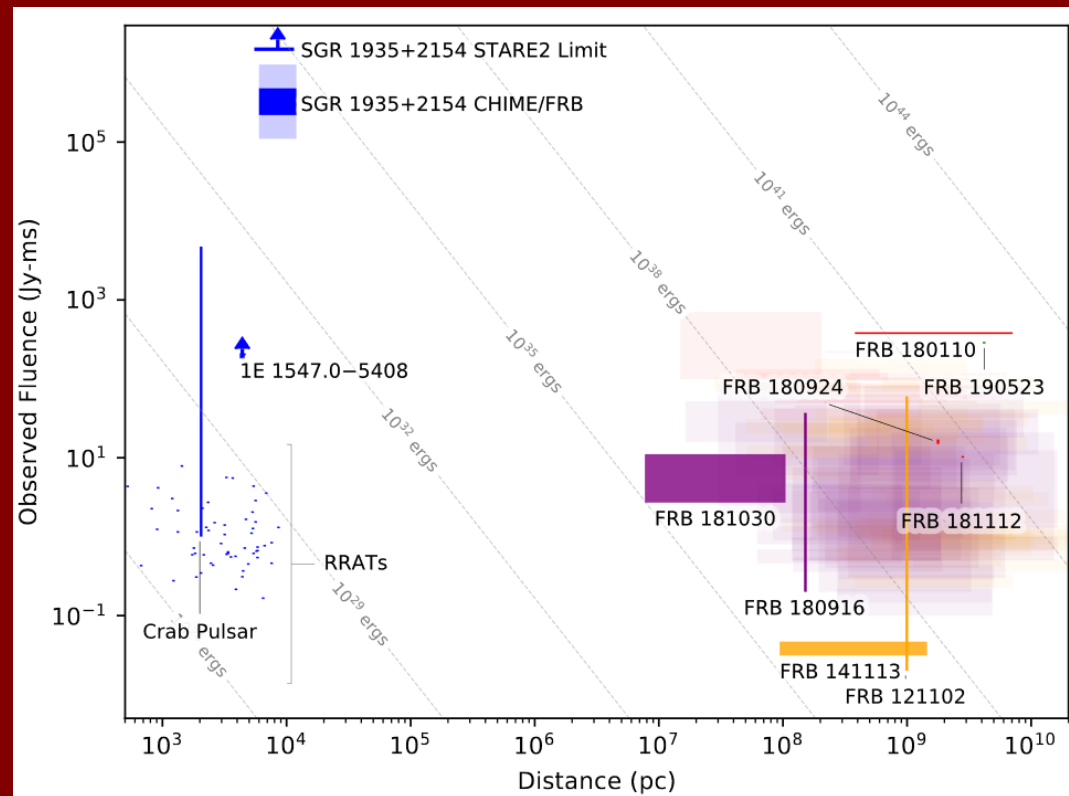
2006.00215



# CHIME data

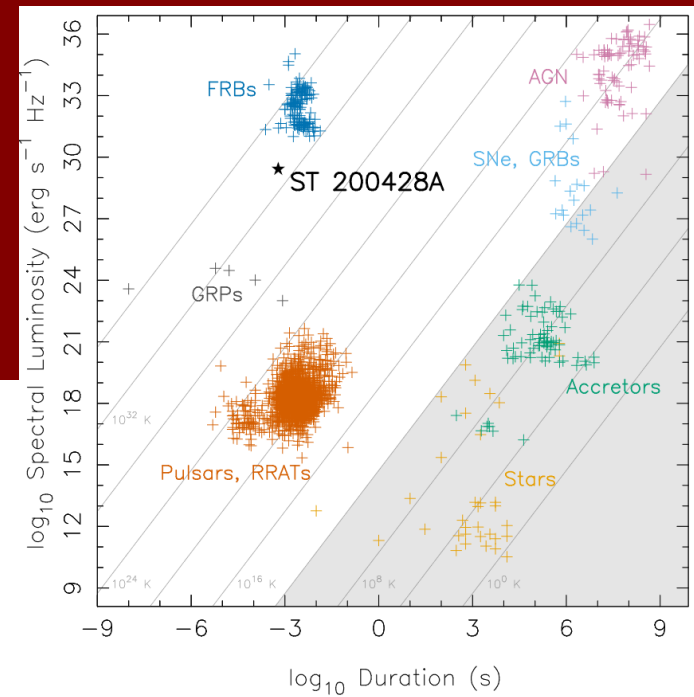
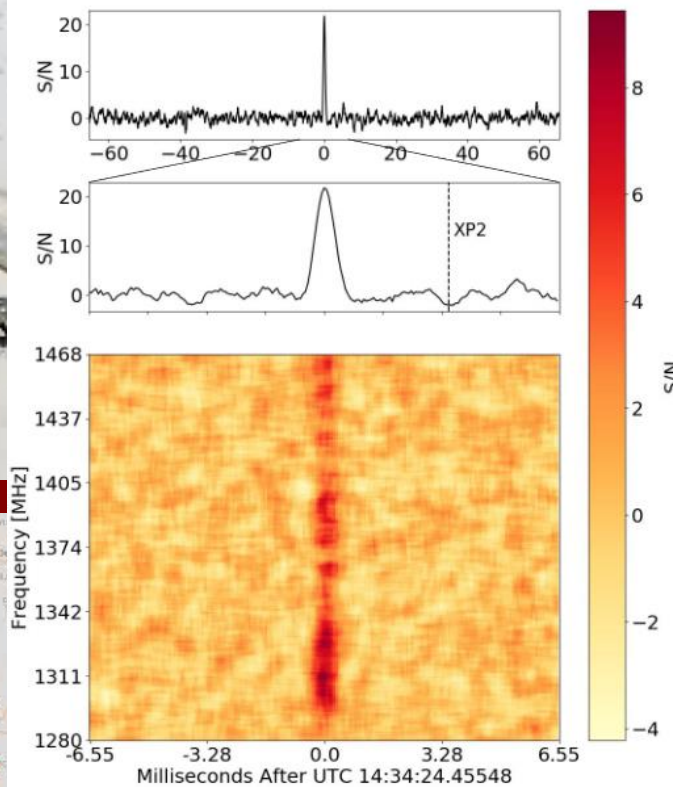


First millisecond radio bursts from a Galactic magnetar very similar (but weaker) to FRBs.





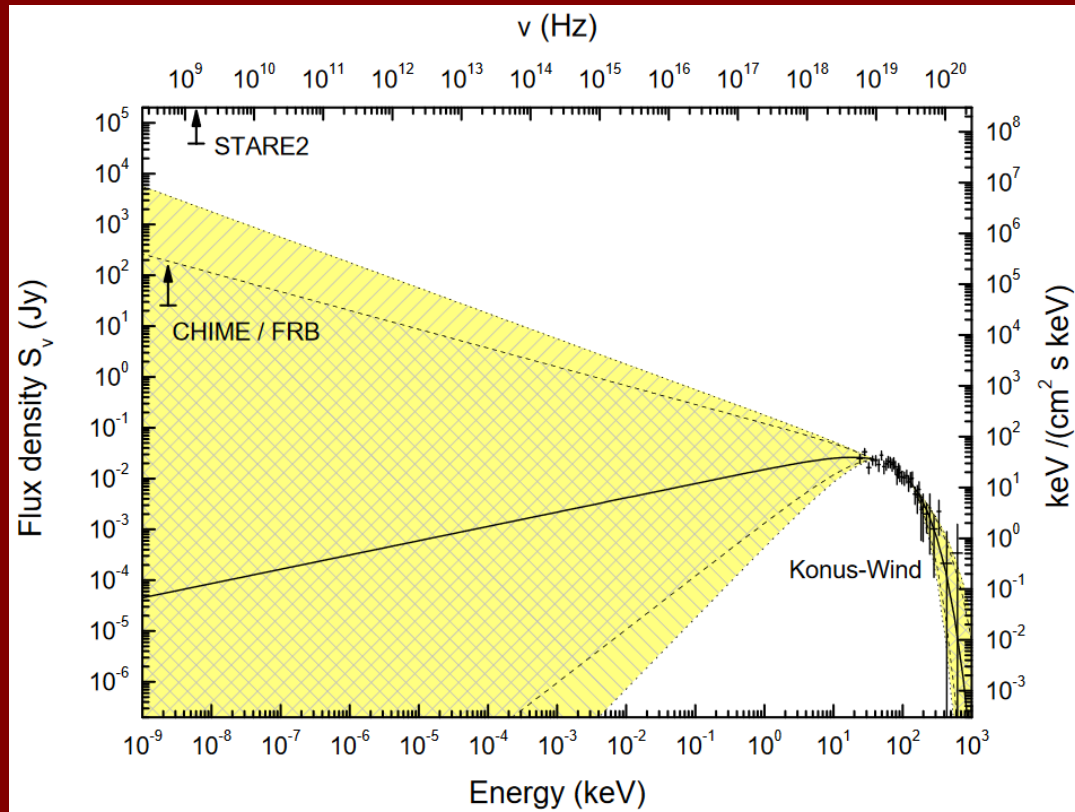
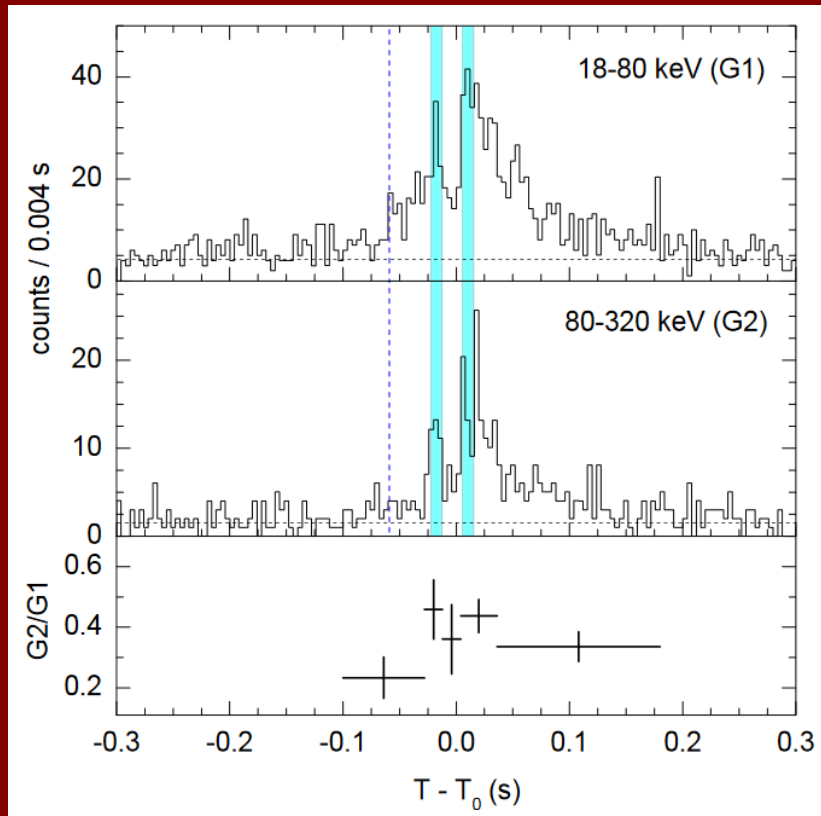
# STARE2 data



Several small-scale instruments at significant distance from each other. Sensitive to short, but very bright bursts.

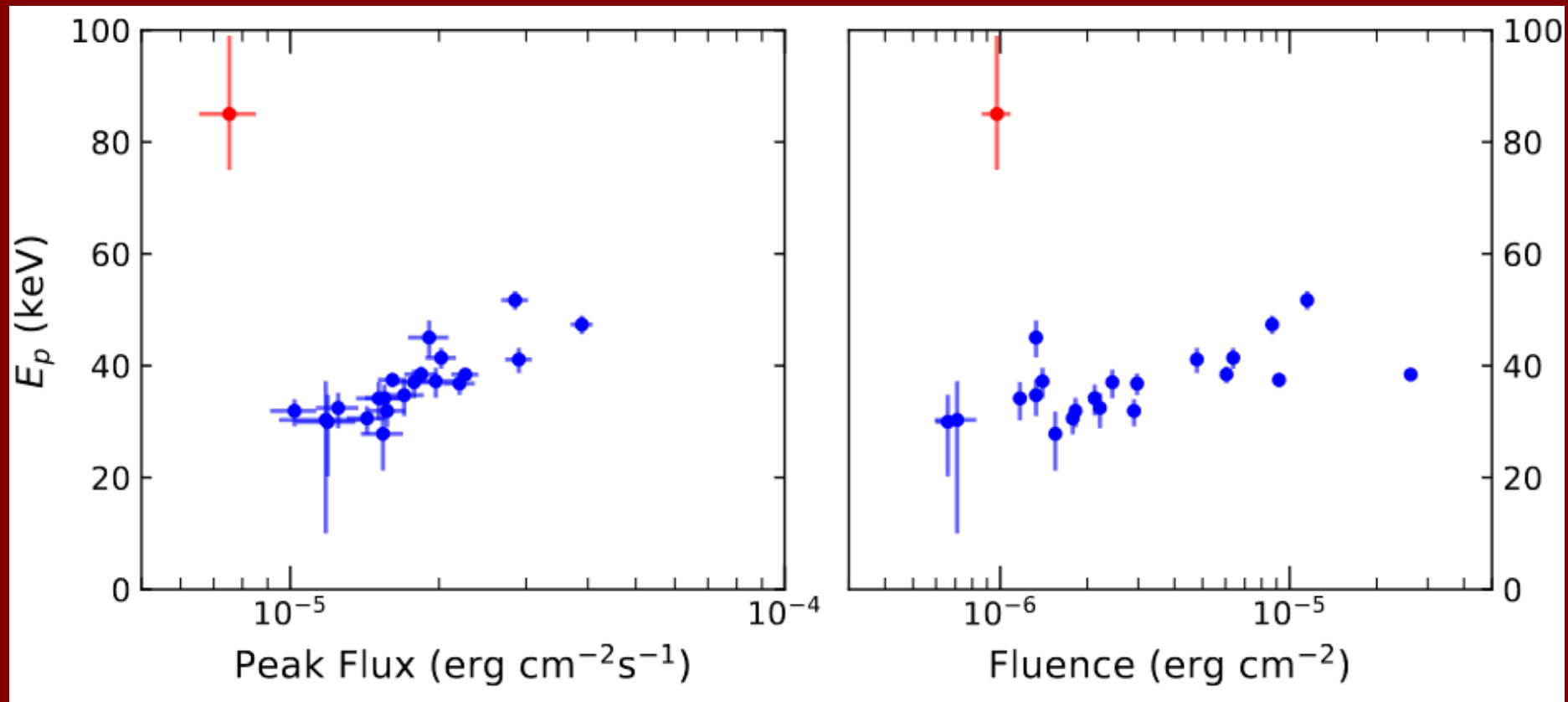
2005.10828

# Konus-Wind data



Radio and X-rays simultaneous.

# Konus-Wind data

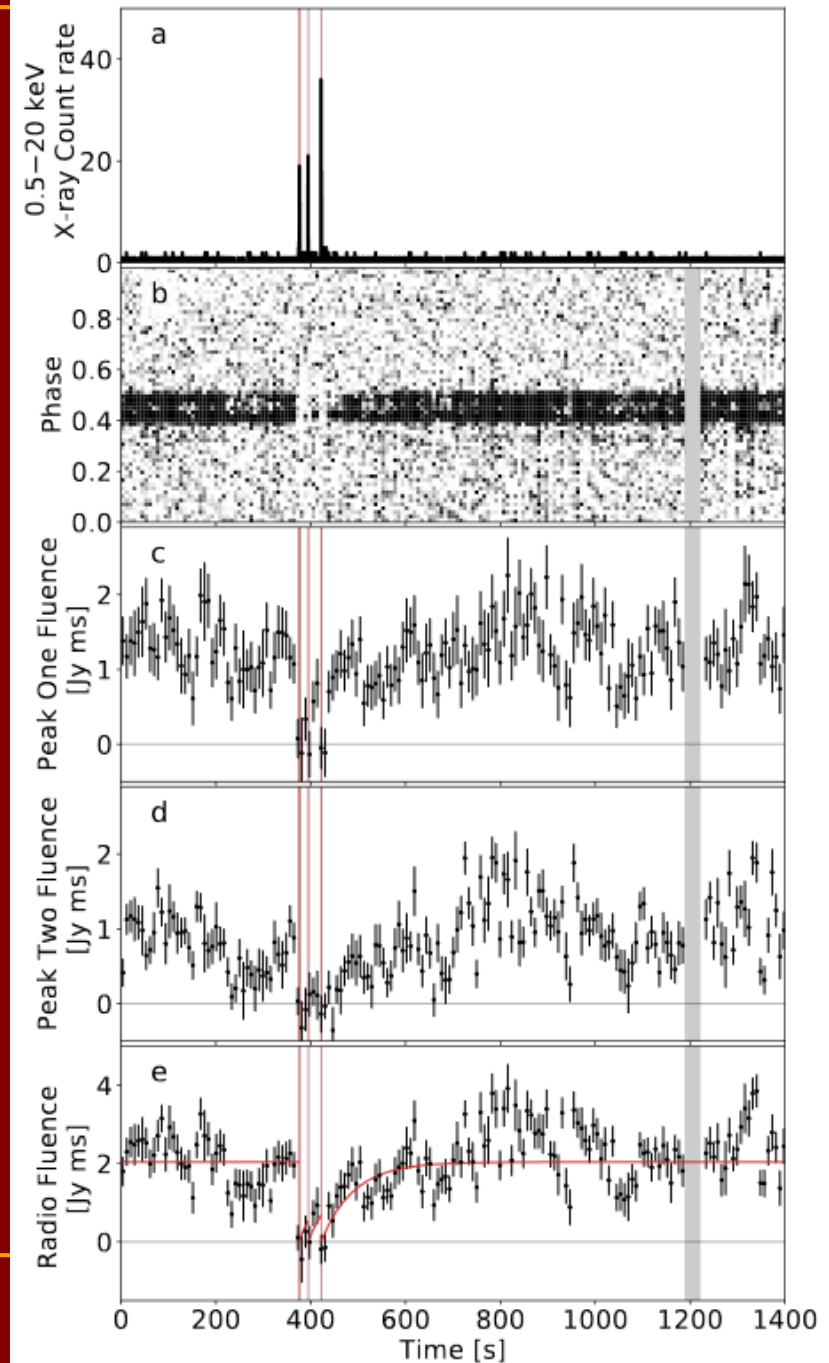


Much different from other flares of the same magnetar

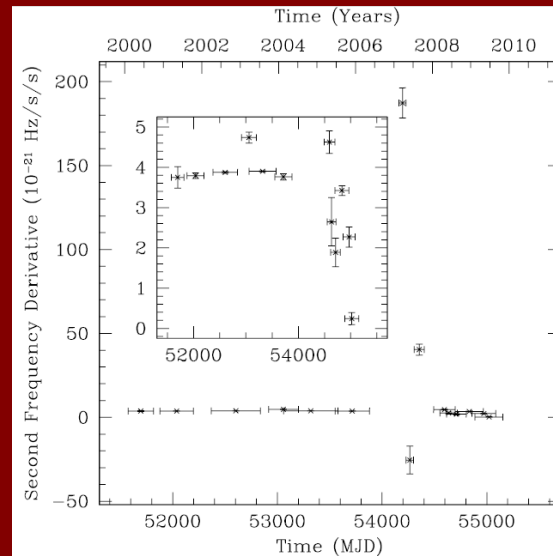
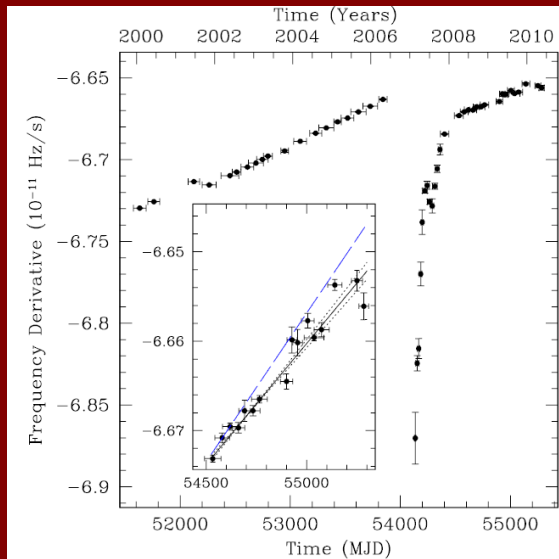
# Suppression of radio during bursts

PSR J1119-6127

The rotationally powered radio emission shuts off coincident with the occurrence of multiple X-ray bursts.



# Postburst properties of PSR J1846-0258



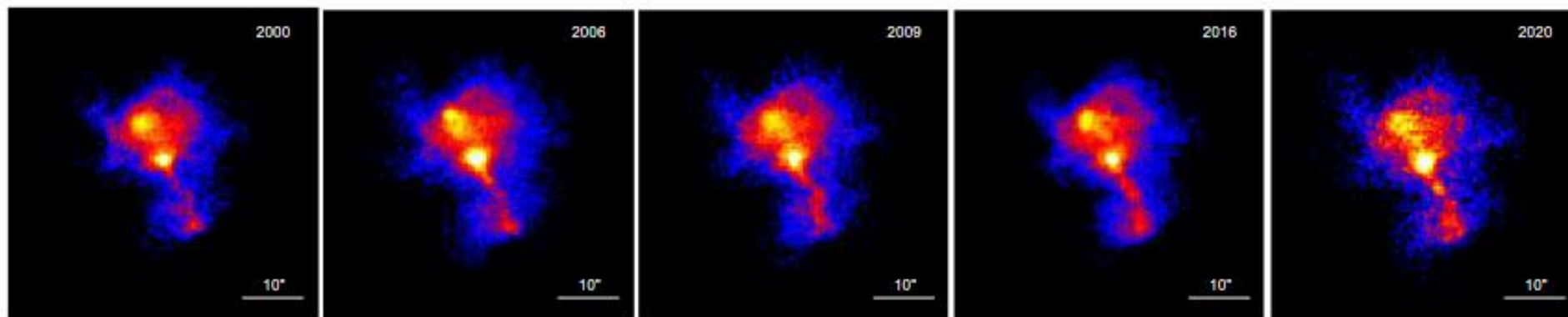
The pulsar showed a glitch.  
A period of magnetar-like activity was started.  
After the burst parameters of the pulsar changed.

$n=2.65 \rightarrow n=2.16$

Timing noise was increased  
(was very small for a magnetar before bursts)



Recent X-ray

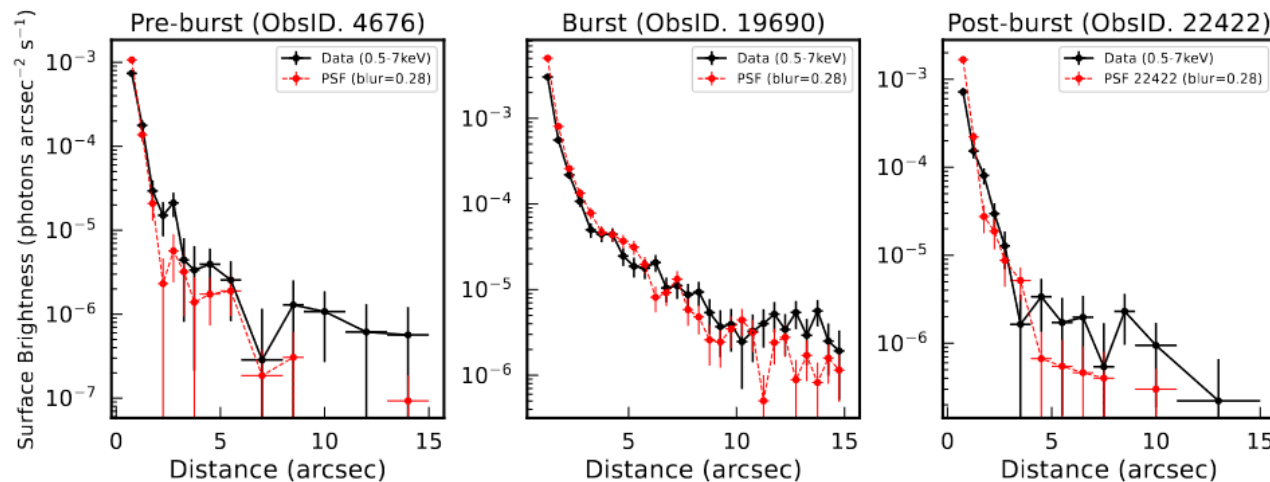
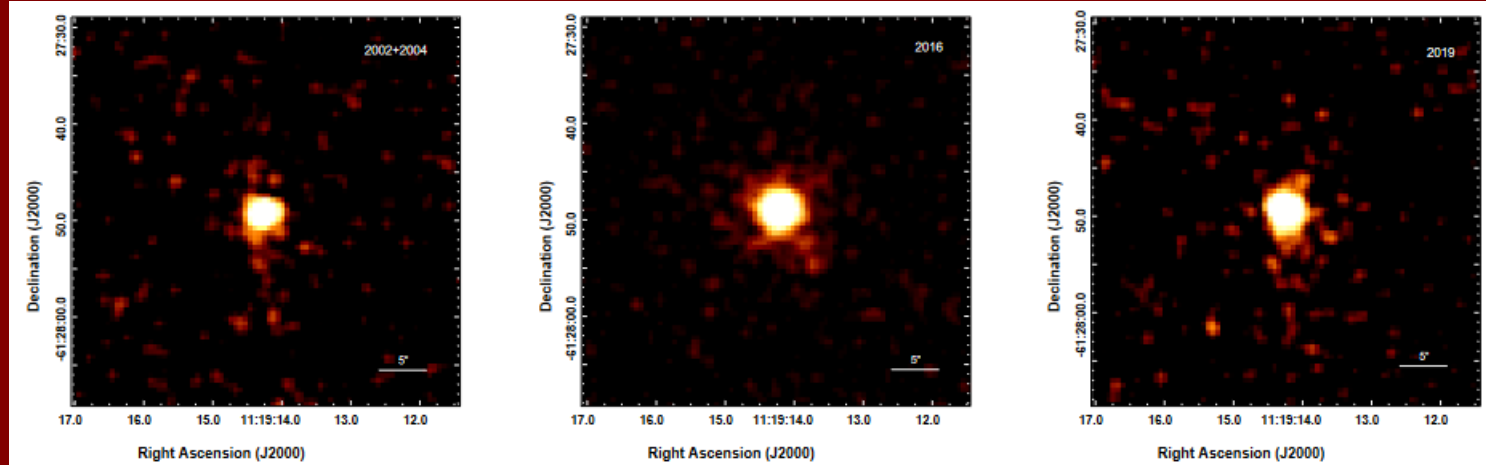


1007.2829, recently re-activated: 2103.12557

# Post-outburst evolution of the pulsar J1119–6127

A young  
rotation-powered  
pulsar.

Magnetar-like  
bursts in 2016.



Chandra observations.

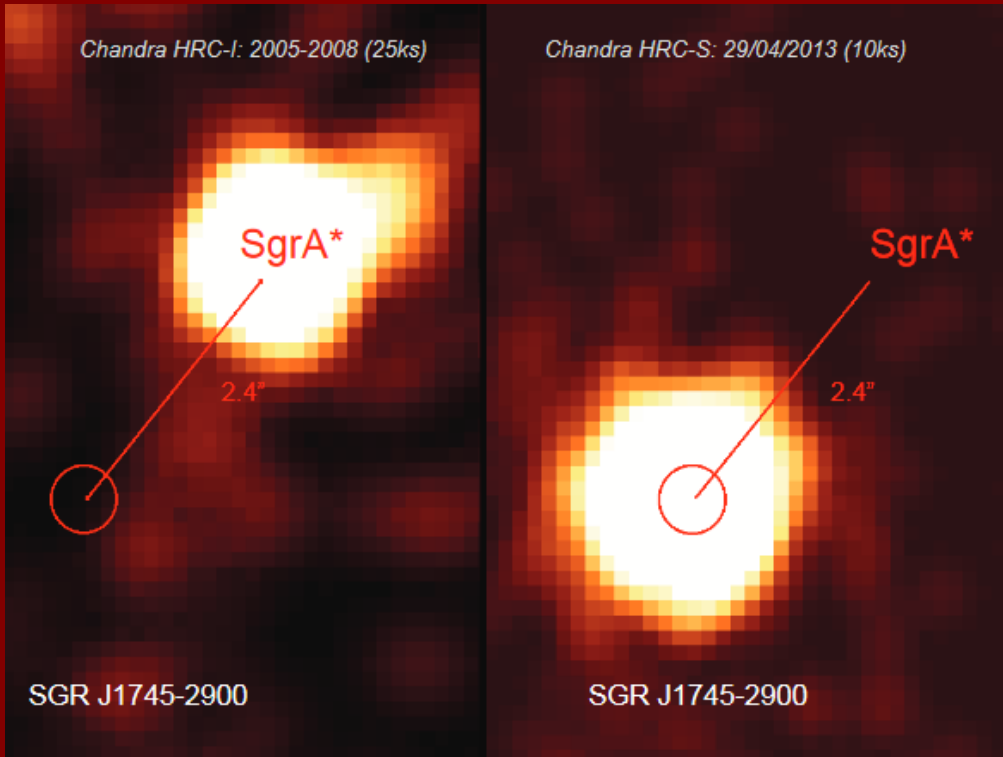
2106.12018



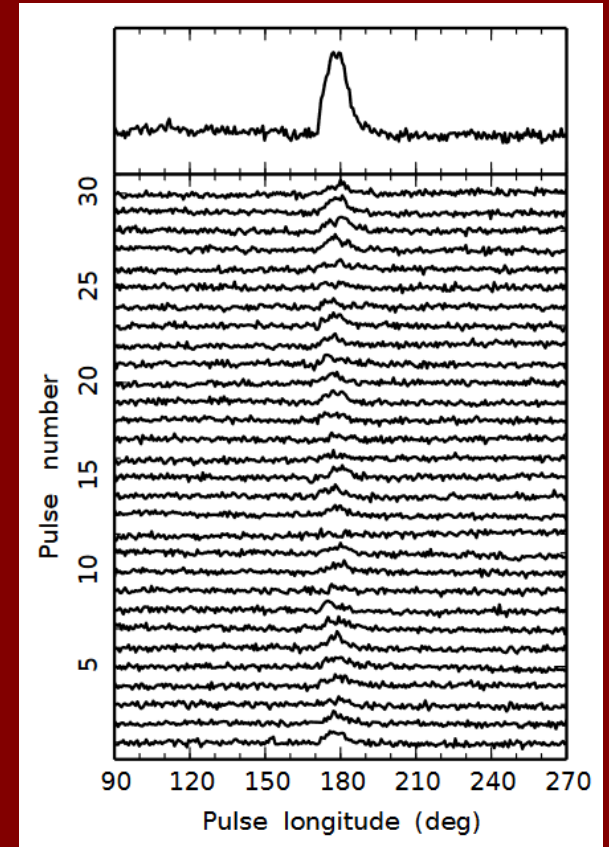
# Galactic center magnetar

SGR/PSR J1745-2900

Radio pulsations detection in 2013  
The largest dispersion measure  
and rotation measure among PSRs.



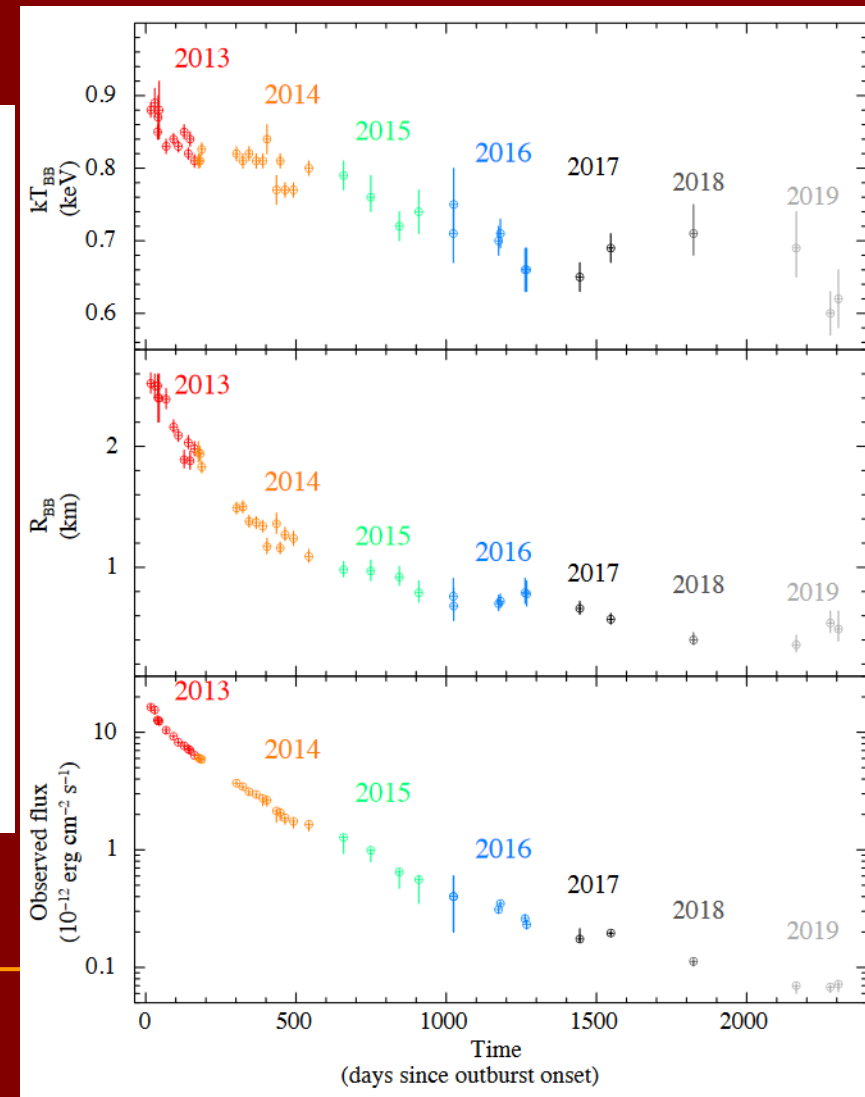
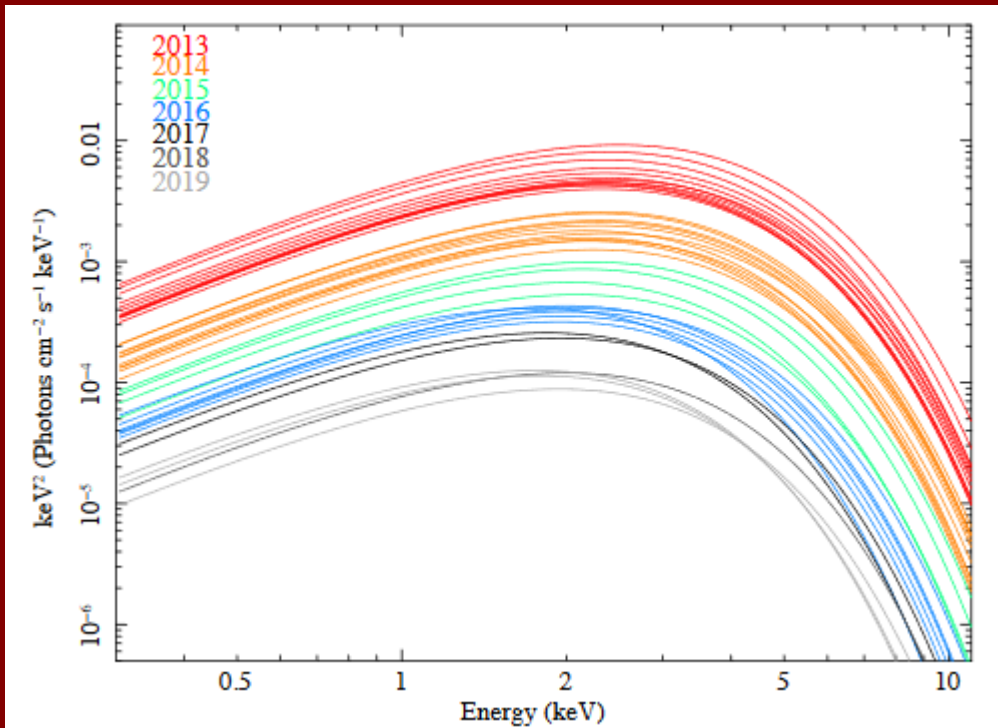
<1 pc from Sgr A\*



1307.6331

1802.07884

# Evolution of the Galactic center magnetar after the outburst in 2013



2003.07235



# Generation of the magnetic field

The mechanism of the magnetic field generation is still unknown.

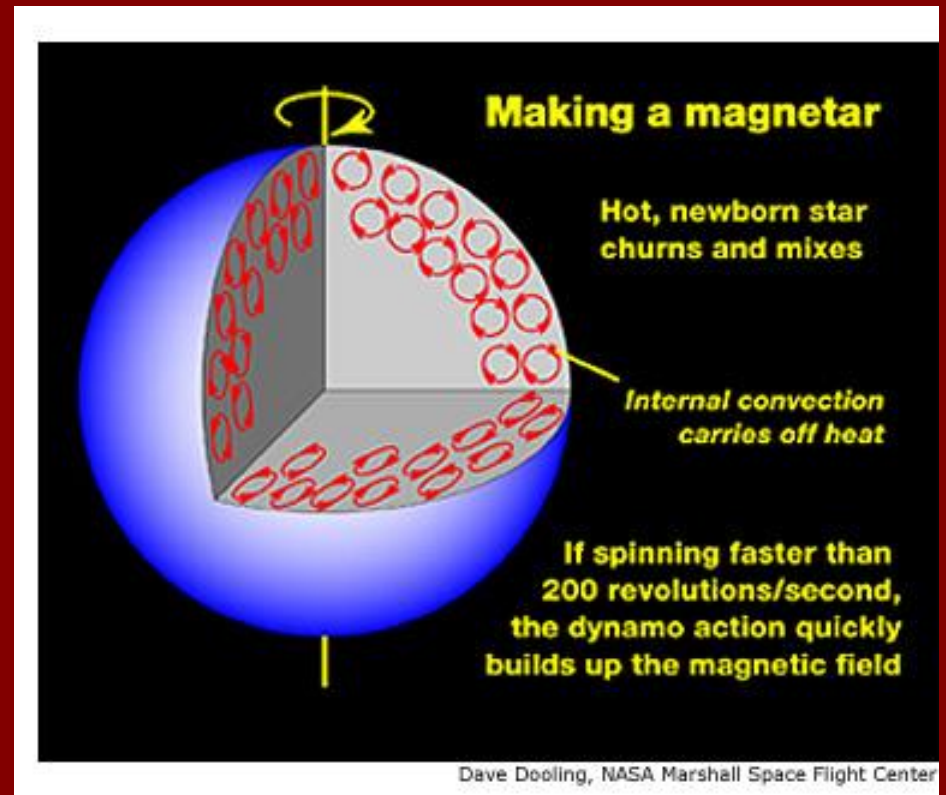
Turbulent dynamo

$\alpha$ - $\Omega$  dynamo (Duncan, Thompson)

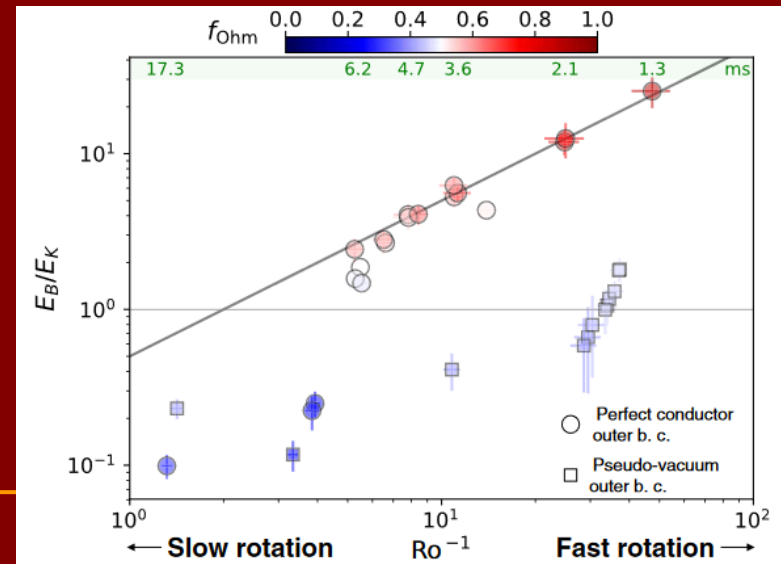
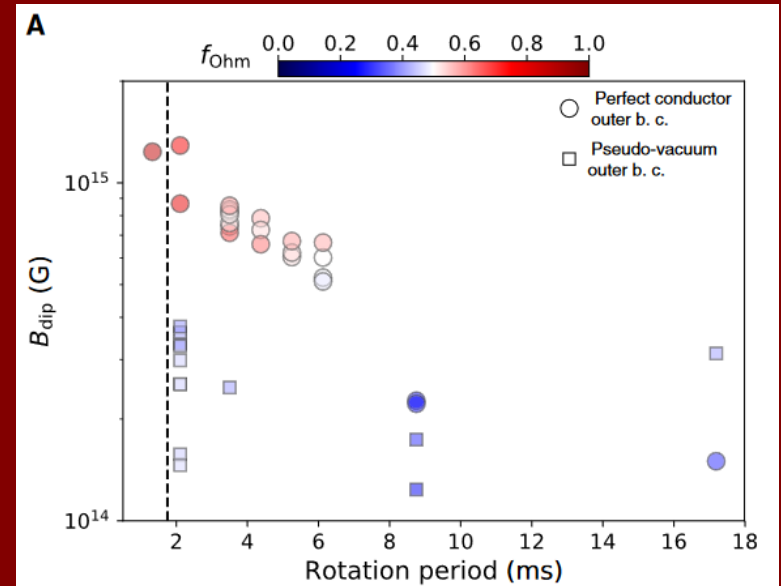
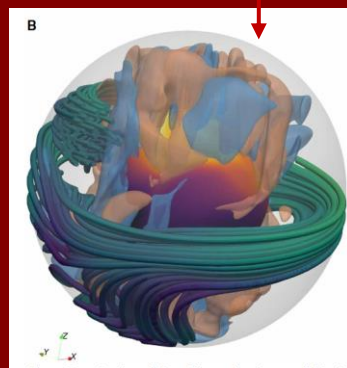
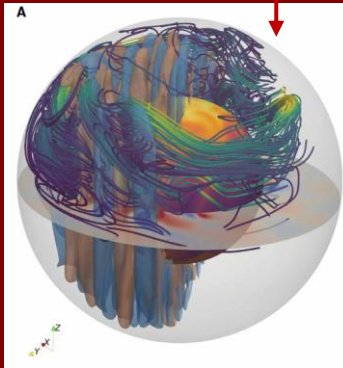
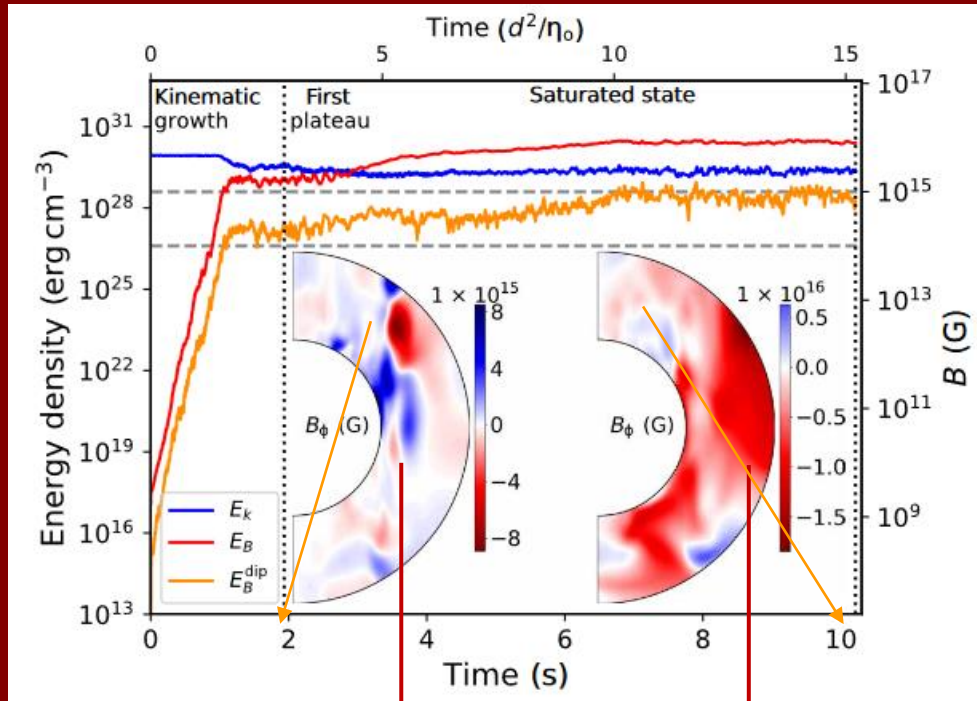
$\alpha^2$  dynamo (Bonanno et al.)

or their combination

In any case, initial rotation of a protoNS is the critical parameter.

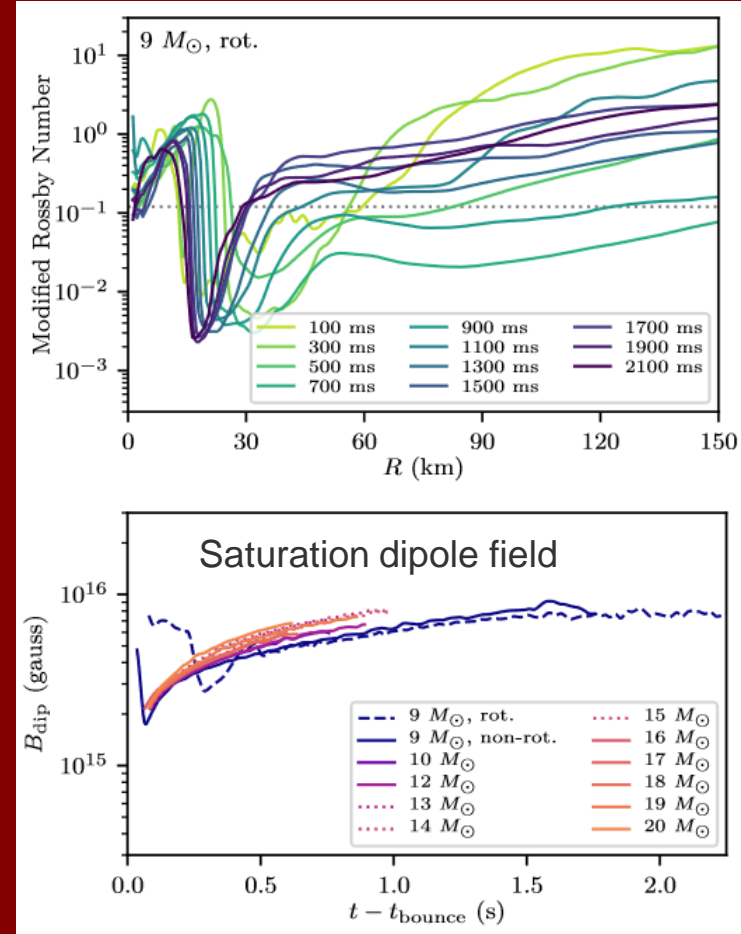
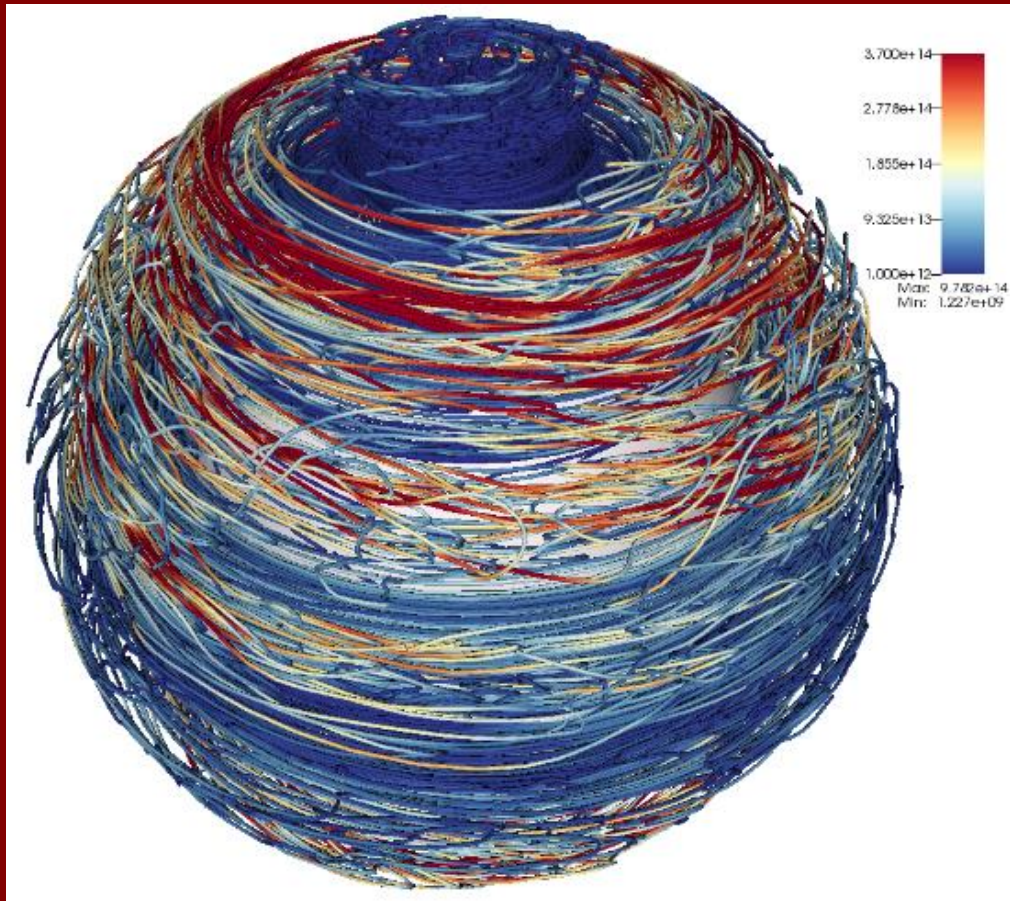


# Numerical model of field amplification



# Detailed numerical modeling

Modern MRI and convective dynamo calculations demonstrate that NS progenitors can provide conditions for generation of strong dipolar field.



# Strong field via flux conservation

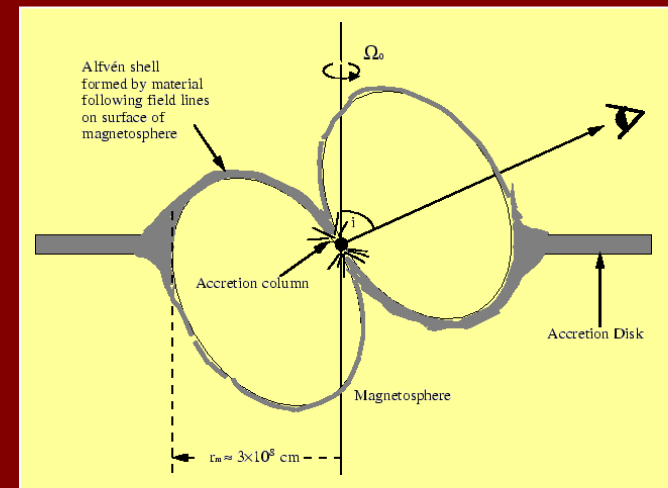
There are reasons to suspect that the magnetic fields of magnetars are not due to any kind of dynamo mechanism, but just due to flux conservation:

1. Study of SNRs with magnetars (Vink and Kuiper 2006, see also 1708.01626). If there was a rapidly rotating magnetar then a huge energy release is inevitable. No traces of such energy injections are found.
2. There are few examples of massive stars with field strong enough to produce a magnetars due to flux conservation (Ferrario and Wickramasinghe 2006)

**Still, these suggestions can be criticized (Spruit arXiv: 0711.3650)**

# Alternative theory

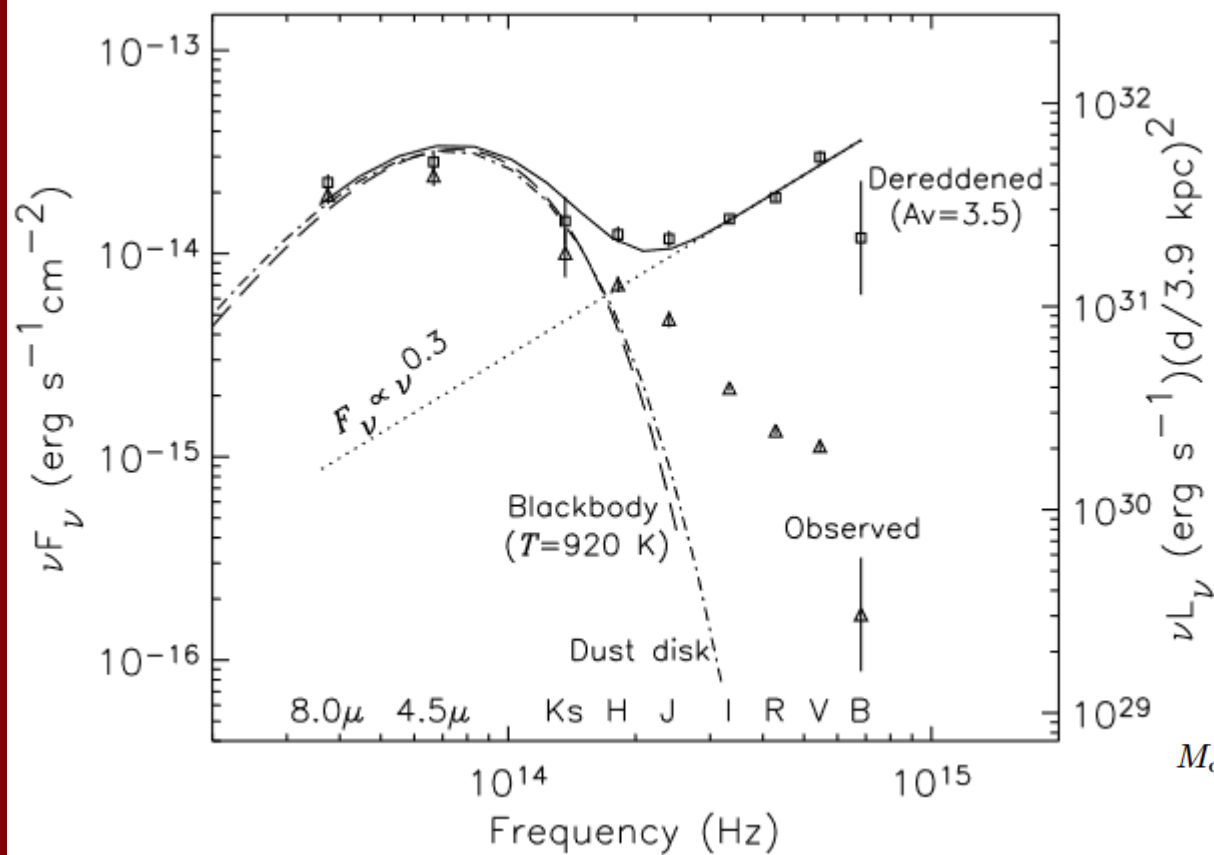
- Remnant fallback disc
- Mereghetti, Stella 1995
- Van Paradijs et al. 1995
- Alpar 2001
- Marsden et al. 2001
- Problems .....
- How to generate strong bursts?
- Discovery of a passive disc in one of AXPs (Wang et al. 2006).  
A new burst of interest to this model.
- Timing noise analysis contradicts accretion (1806.00401)



New arguments against accretion in magnetars: 2009.14064.  
Based on power spectra.



# Fall-back discs

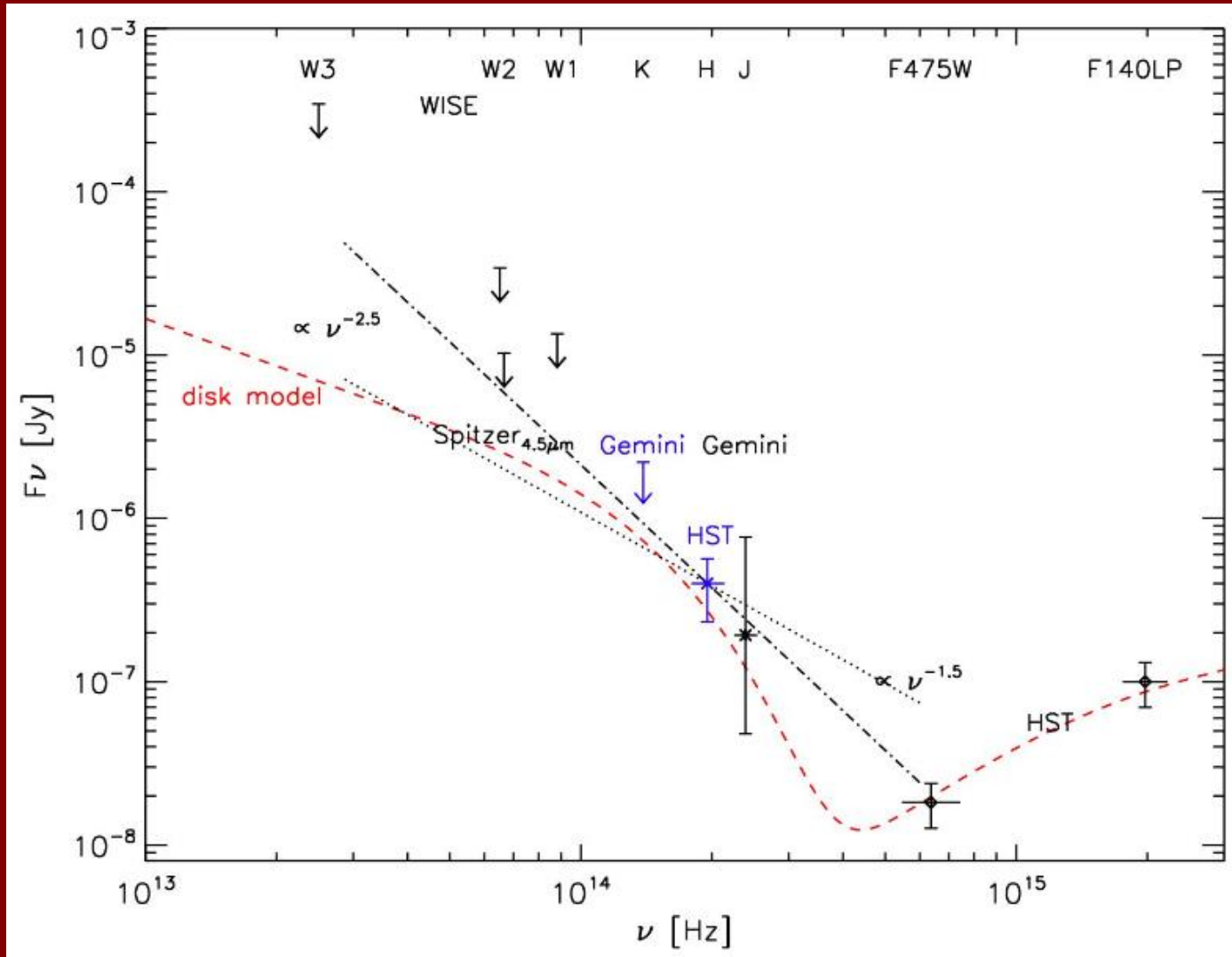


4U 0142+61

$$M_d \lesssim 3 \times 10^{-3} M_\odot \left( \frac{F_{\text{MM}}}{50 \mu\text{Jy}} \right) \left( \frac{d}{3.9 \text{ kpc}} \right)^2 \times \left( \frac{T(r_{\text{out}})}{300 \text{ K}} \right)^{-1} \left( \frac{\kappa_{\text{MM}}}{0.01 \text{ cm}^2 \text{ g}^{-1}} \right)^{-1},$$

$$T(r) \simeq 5,030 \text{ K} (1 - \eta_d)^{2/7} \left( \frac{d}{3.9 \text{ kpc}} \right)^{4/7} \left( \frac{r}{R_\odot} \right)^{-3/7}$$

# A disc around one of the M7

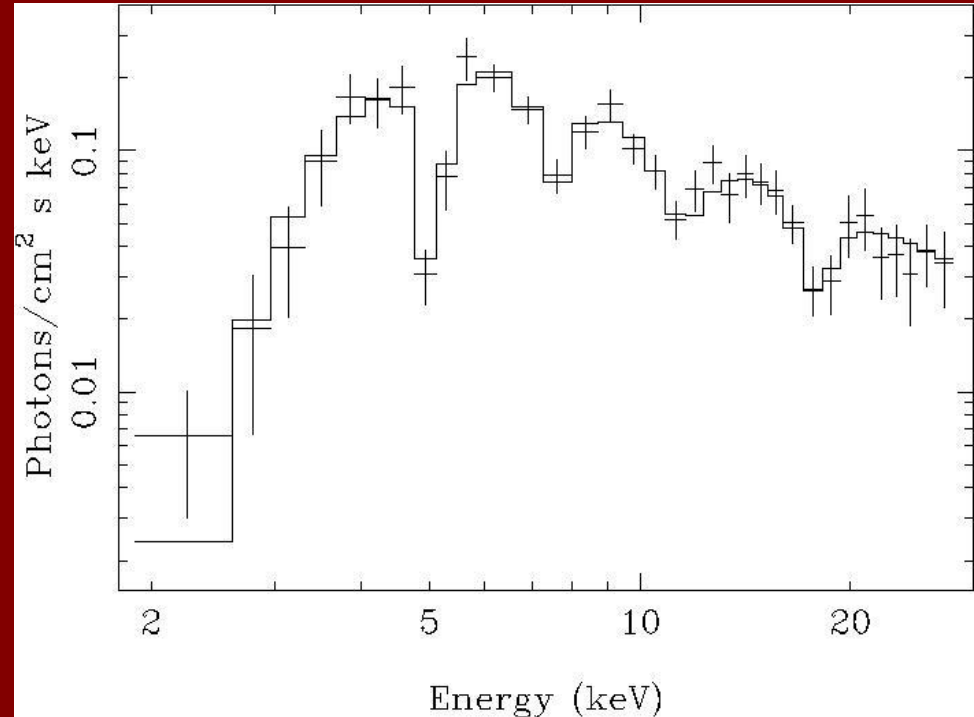


RX J0806.4-4123

Can be a disc,  
and can be a  
nebula.

# Magnetic field estimates

- Spin down
- Long spin periods
- Energy to support bursts
- Field to confine a fireball (tails)
- Duration of spikes (alfven waves)
- Direct measurements of magnetic field (cyclotron lines)

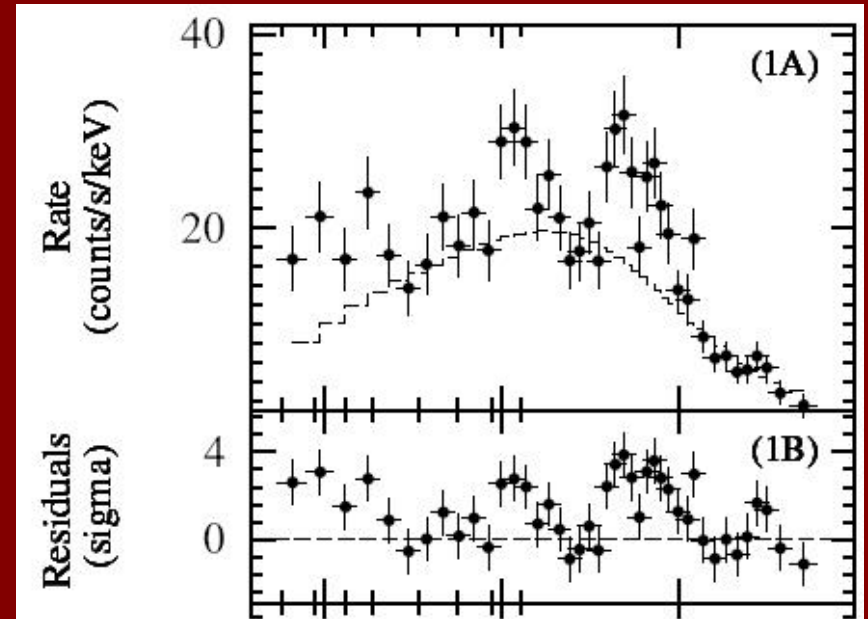
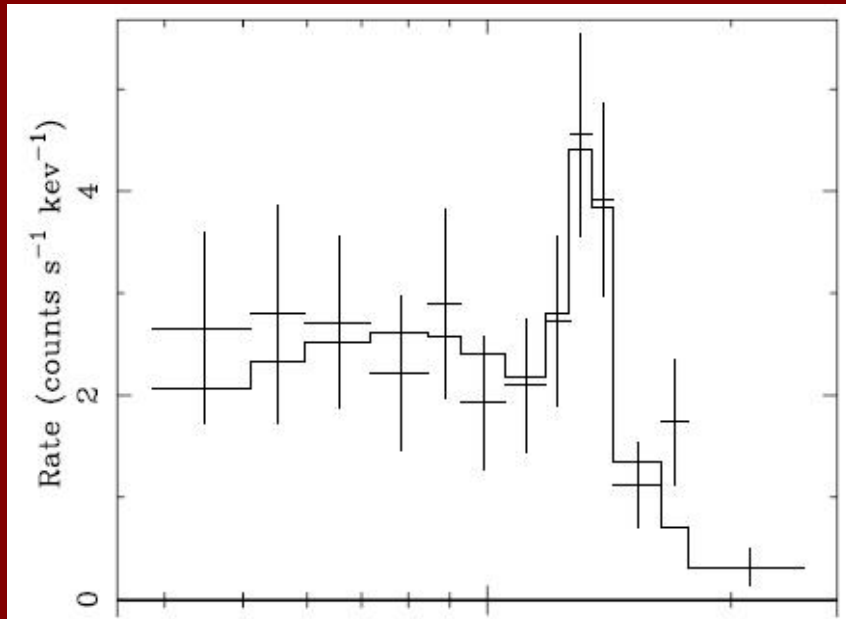


Ibrahim et al. 2002



# Spectral lines claims

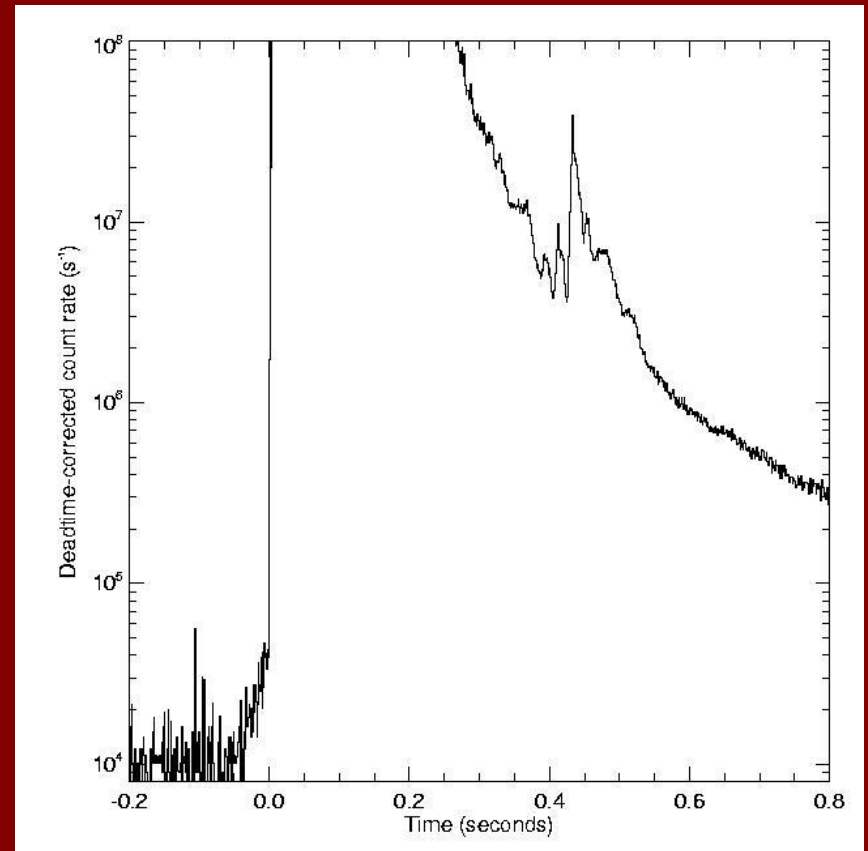
All claims were done for RXTE observations (there are few other candidates).  
All detections were done during bursts.



1E 1048.1-5937 Gavriil et al. (2002, 2004)    4U 0142+61 Gavriil et al. (2007)

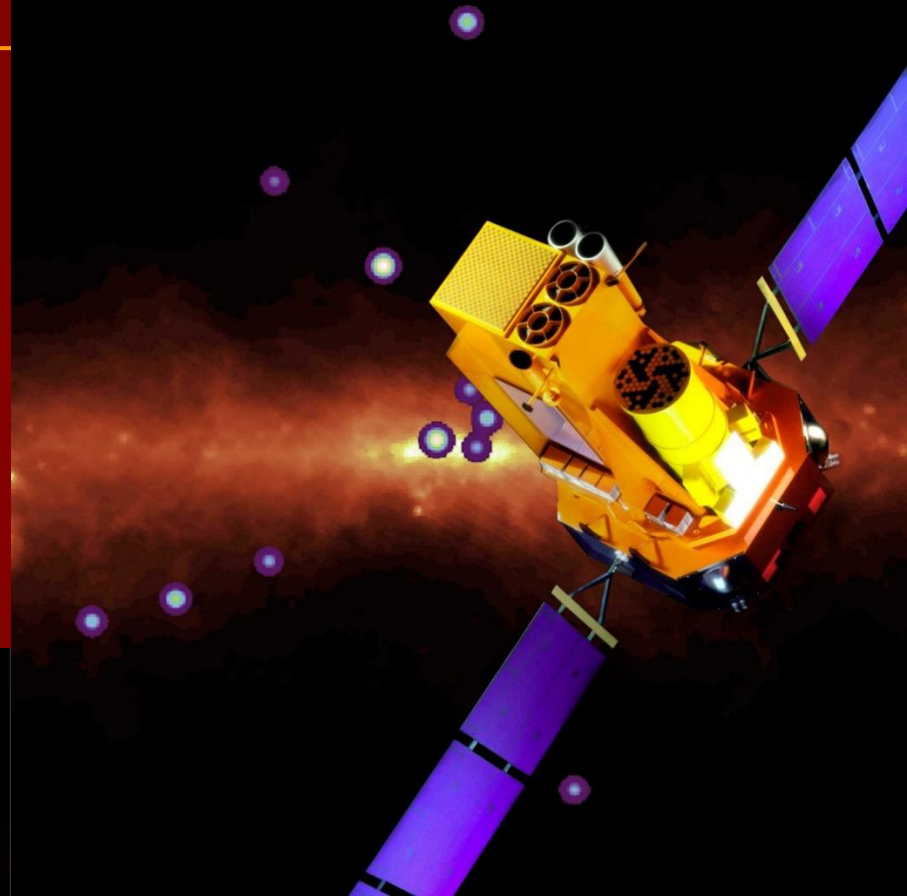
# Hyperflare of SGR 1806-20

- 27 December 2004 A giant flare from SGR 1806-20 was detected by many satellites: Swift, RHESSI, Konus-Wind, Coronas-F, Integral, HEND, ...
- 100 times brighter than any other!





C  
O  
R  
O  
N  
A  
S  
-  
F



Integral

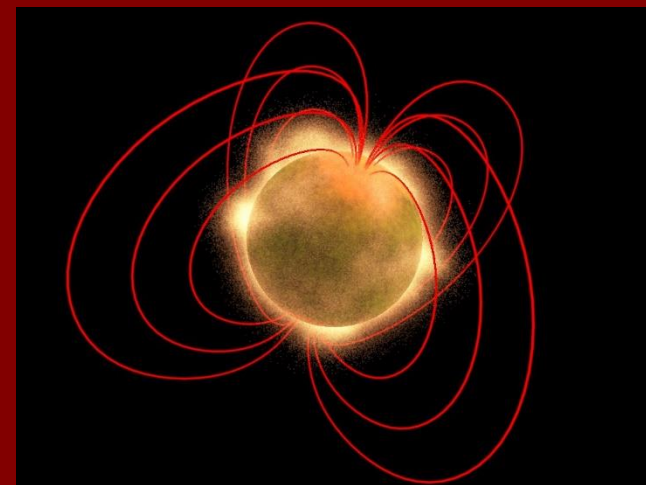


RHESSI

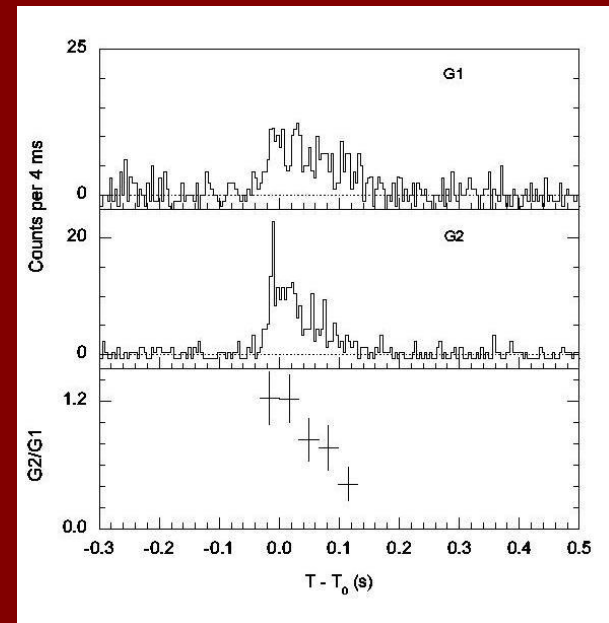
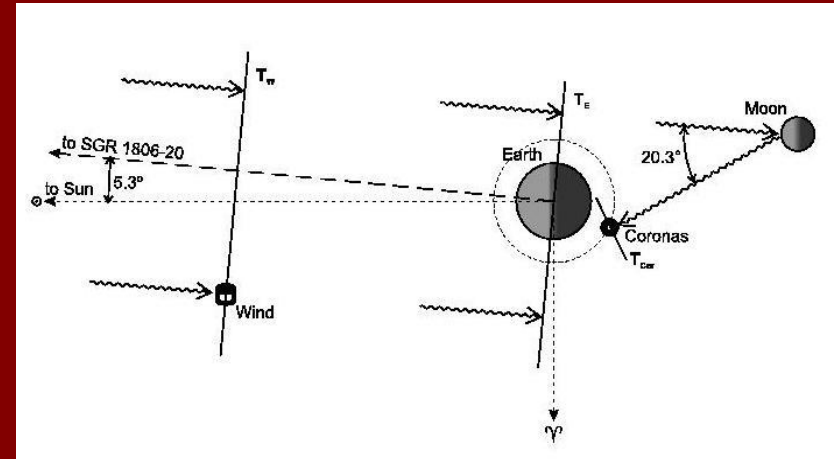
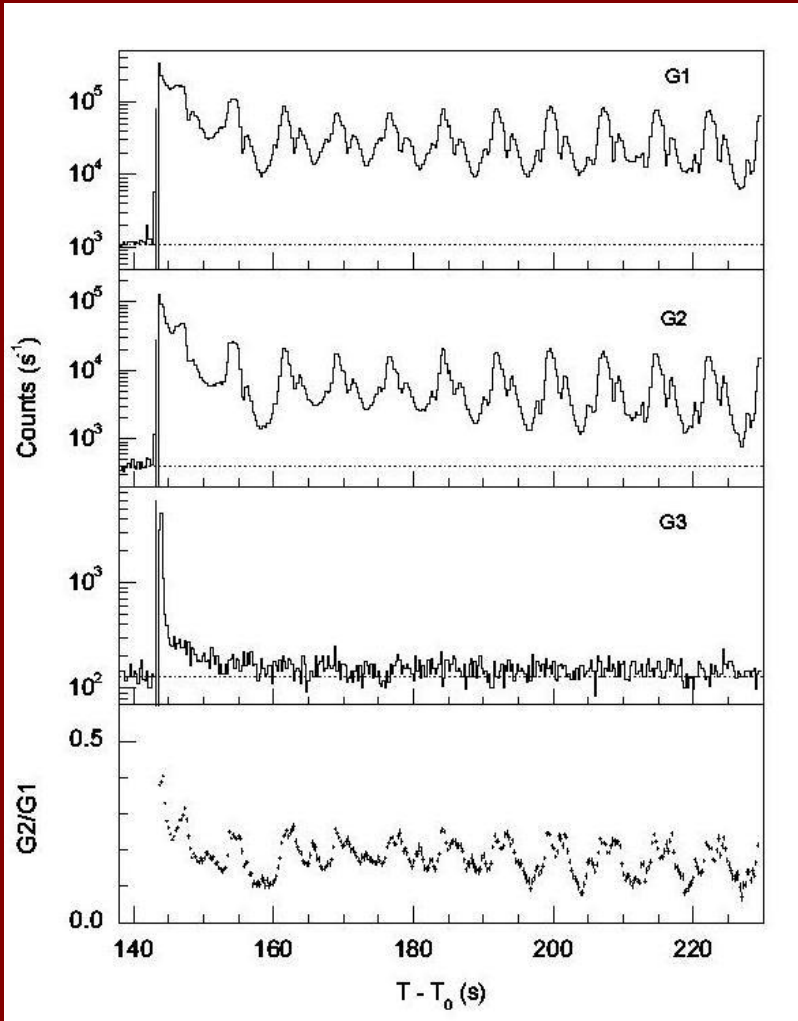
27 Dec 2004:

## Giant flare of the SGR 1806-20

- Spike 0.2 s
- Fluence 1 erg/cm<sup>2</sup>
- $E(\text{spike}) = 3.5 \cdot 10^{46}$  erg
- $L(\text{spike}) = 1.8 \cdot 10^{47}$  erg/s
- Long «tail» (400 s)
- $P = 7.65$  s
- $E(\text{tail}) = 1.6 \cdot 10^{44}$  erg
- Distance 15 kpc — see the latest data in arXiv: 1103.0006

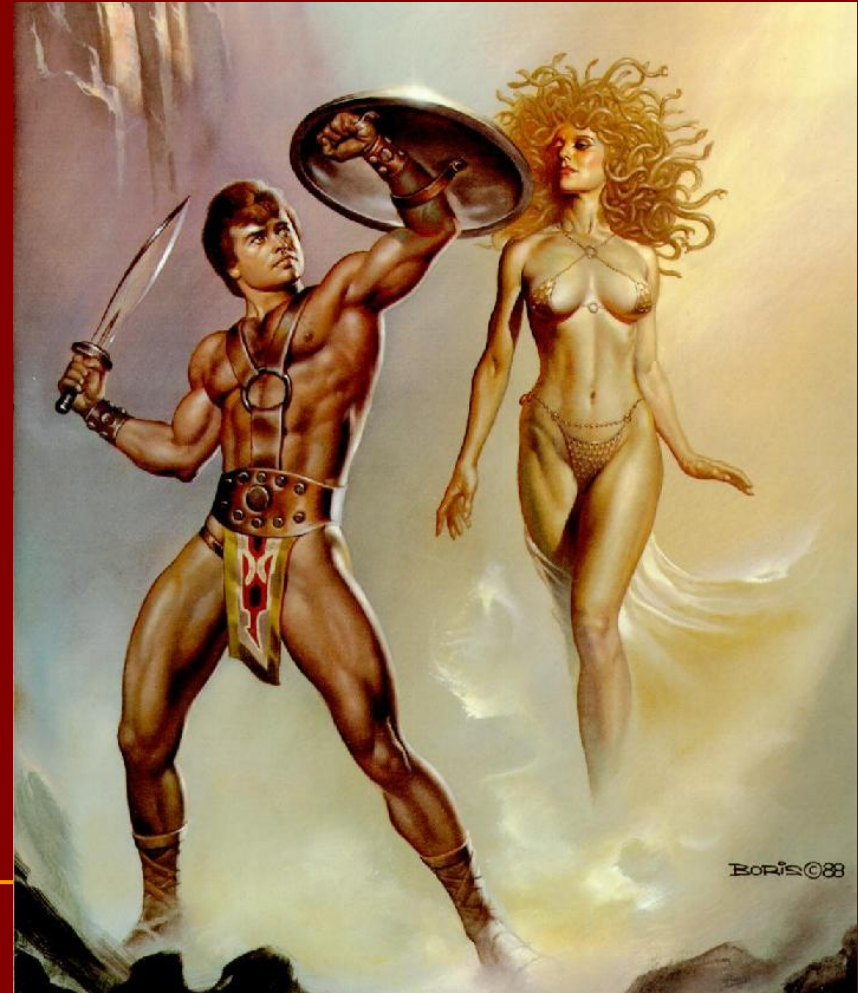


# Konus observations





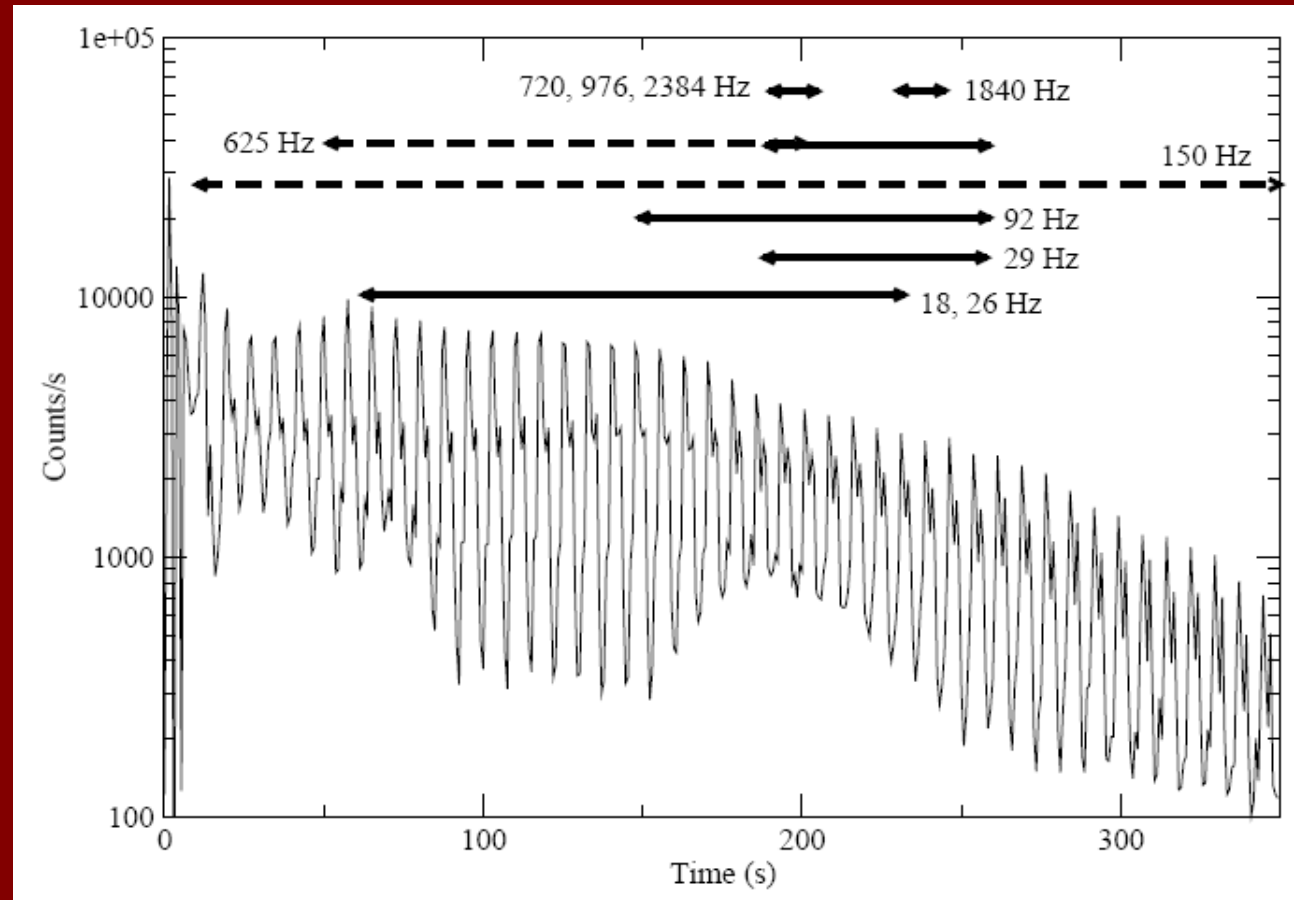
# The myth about Medusa



# QPO in tails of giant flares of SGRs

A kind of quasi periodic oscillations have been found in tail of two events (aug. 1998, dec. 2004). They are supposed to be torsional oscillations of NSs, however, it is not clear, yet.

See 2002.12209 about astroseismology of neutron stars in relation to GW observations.



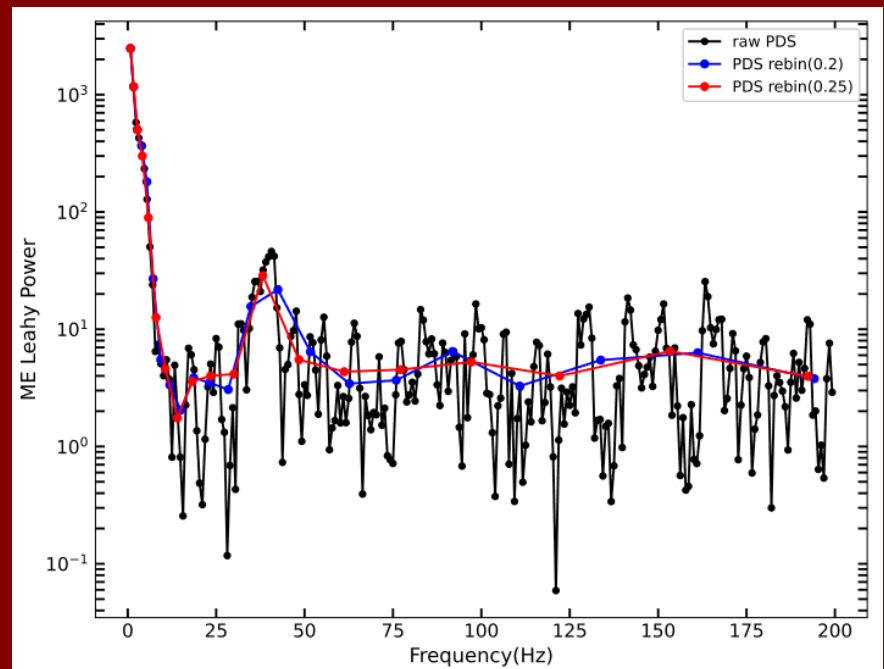
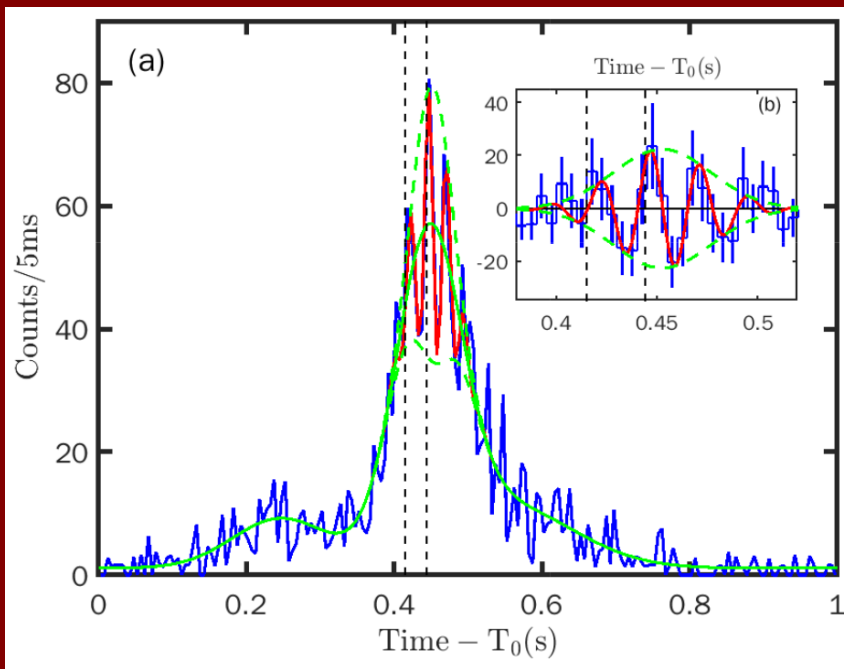
(Israel et al. 2005 astro-ph/0505255,  
Watts and Strohmayer 2005 astro-ph/0608463)

# QPOs in SGR J1935+2154

Insight-HXMT

The pulse that produced the FRB.

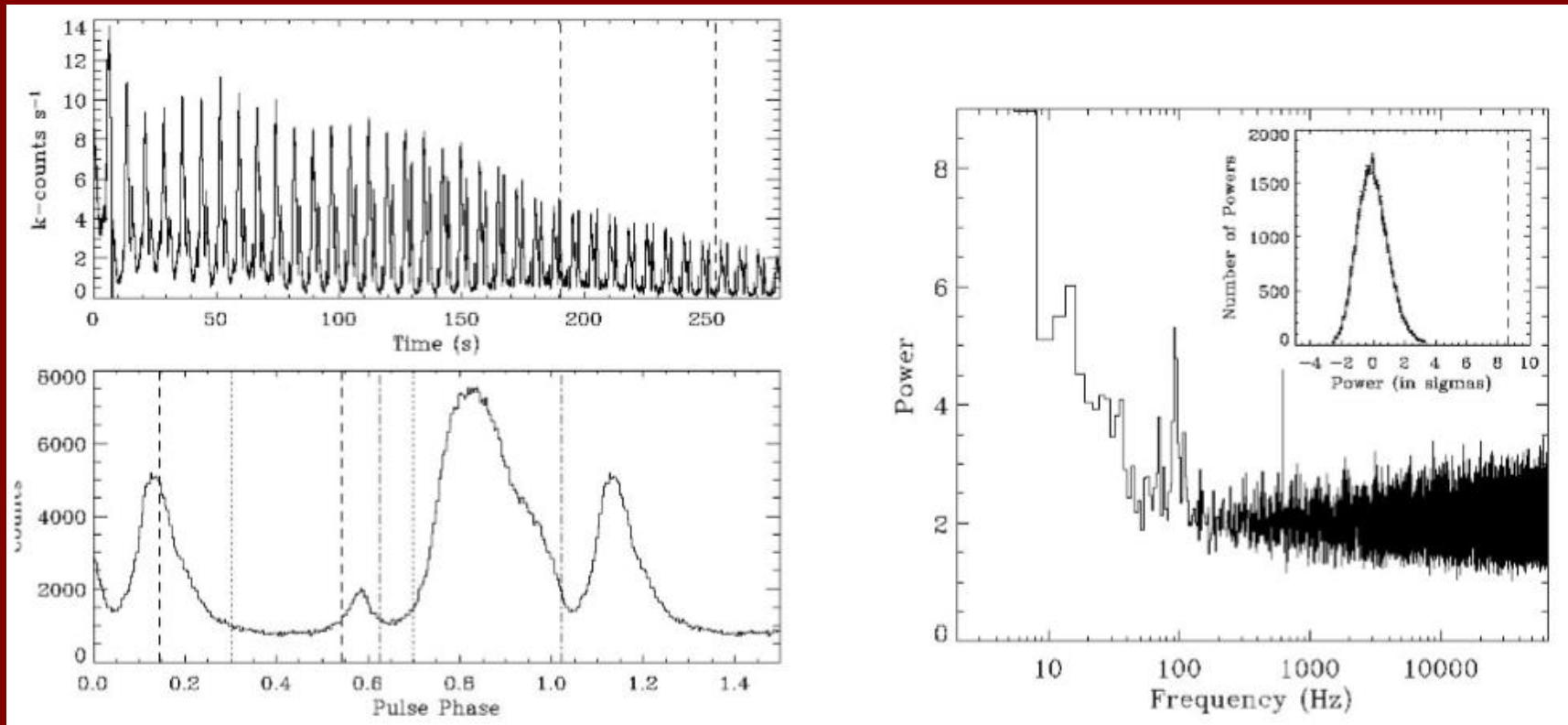
Significance is not high as just three peaks are distinguished in the light curve of the pulse.





# QPO in SGR 1806-20 giant flare

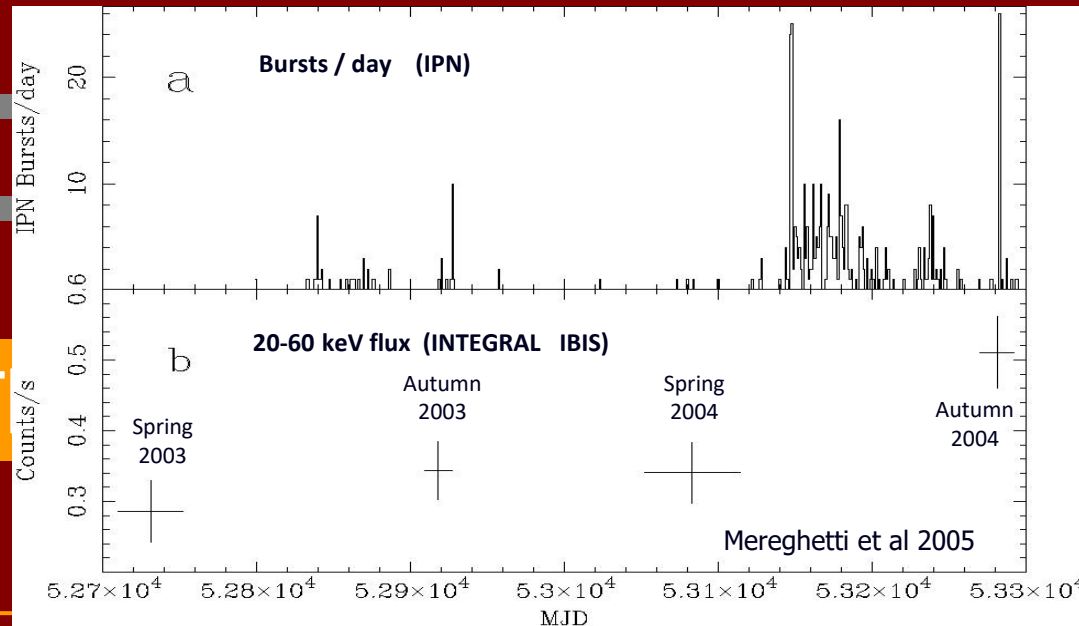
Power spectrum made by averaging nine 3 s segments from the time interval marked by dashed lines in the top left panel. The 92 Hz and 625 Hz QPOs are clearly visible, and the inset illustrates the significance of the 625 Hz feature (from Strohmayer & Watts, 2006)



See fresh analysis in 1808.09483

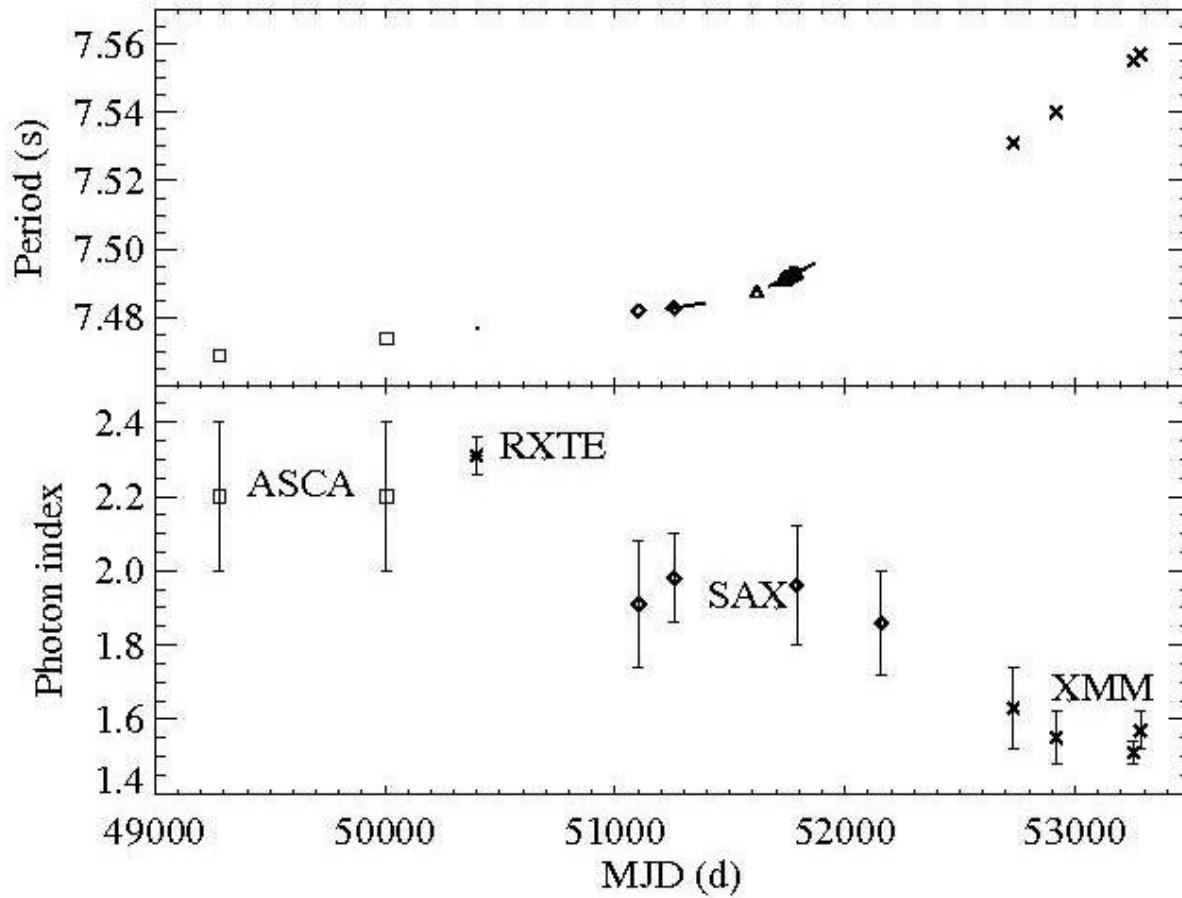
# SGR 1806-20 - I

SGR 1806-20 displayed a gradual increase in the level of activity during 2003-2004 (Woods et al 2004; Mereghetti et al 2005)



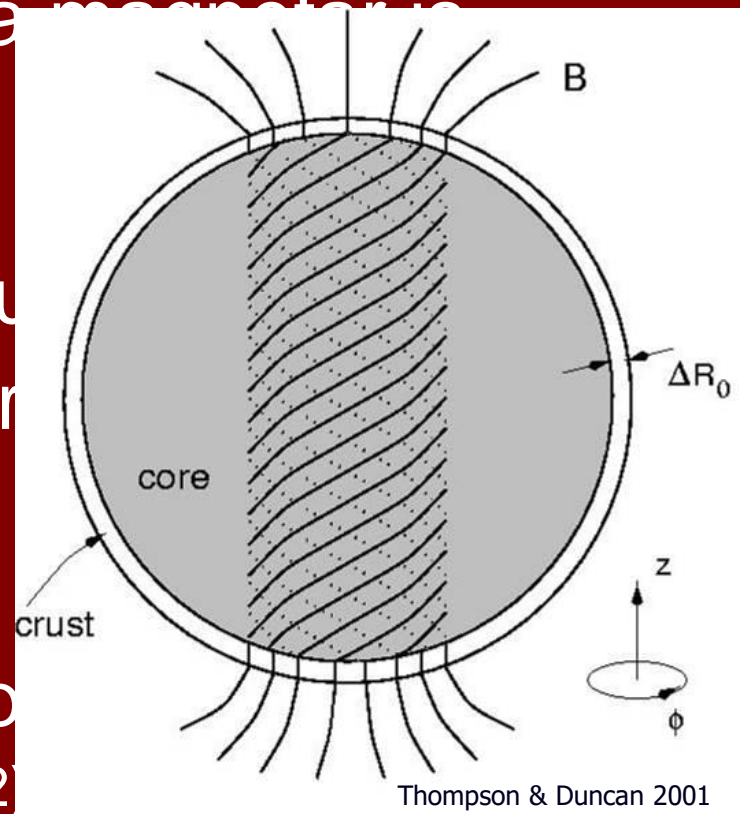
# SGR 1806-20 - II

- Four XMM-Newton observations before the burst (the last one in 2005)
- Pulsar period  $P = 7.56$  s
- $\dot{P} \sim 10^{-12}$  s/s
- Blackbody spectrum with  $kT \sim 100$  eV
- Hard X-ray emission with peak value  $\sim 100$  keV
- The energy of the magnetar is  $\sim 10^{36}$  erg

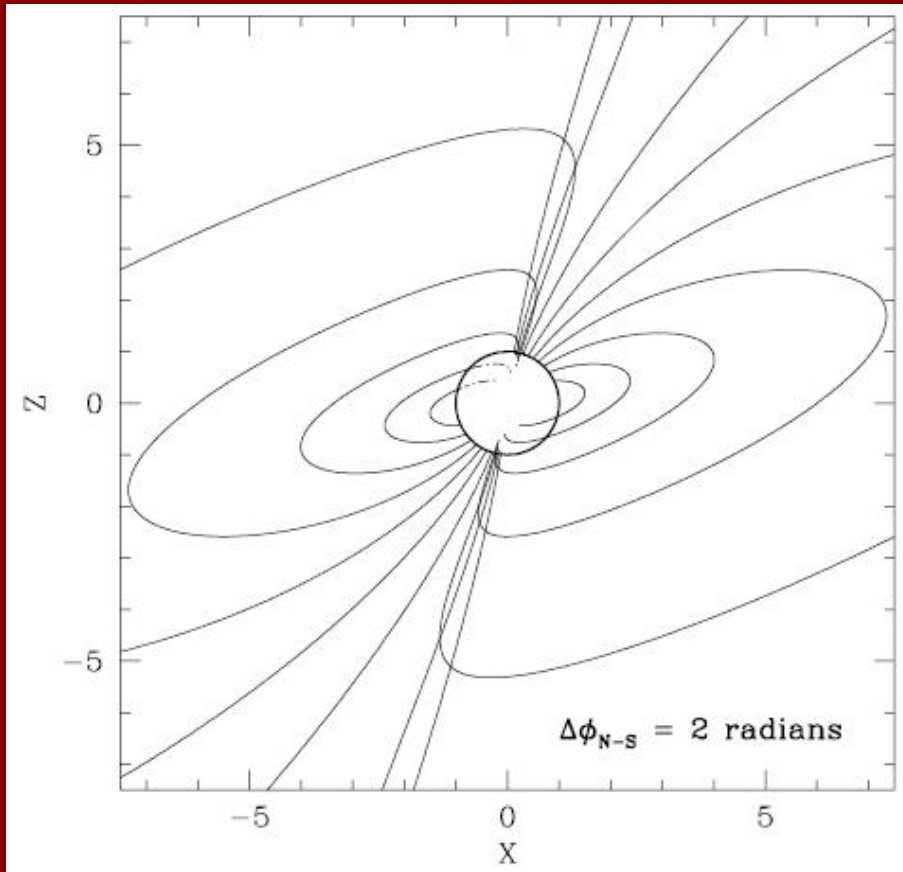


# Twisted Magnetospheres – I

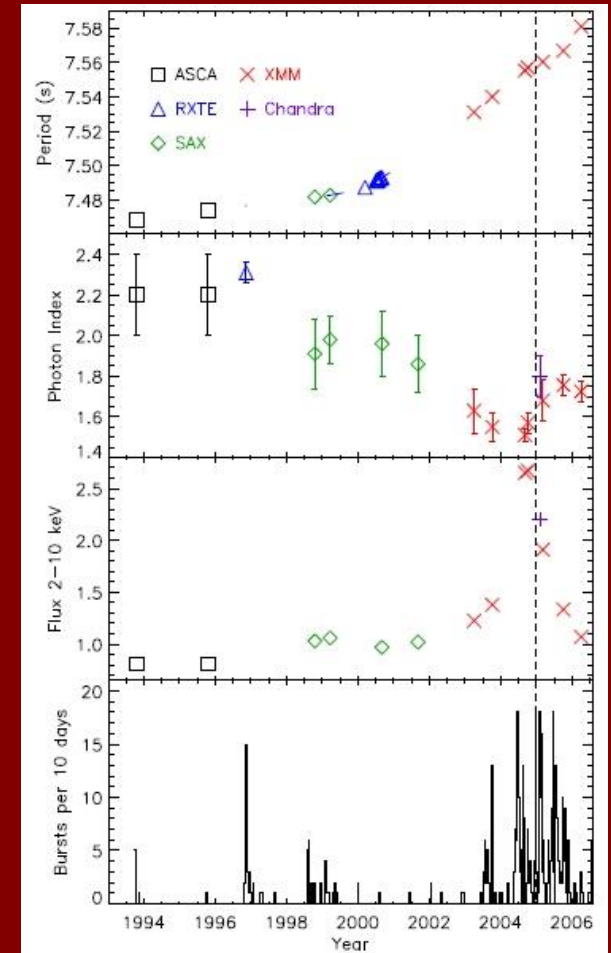
- The magnetic field inside a magnetar is “wound up”
- The presence of a toroidal field induces a rotation of the surface
- The crust tensile strength resists the deformation
- A gradual (quasi-plastic ?) deformation of the crust
- The external field twists up  
(Thompson, Lyutikov & Kulkarni 2002)



# Growing twist

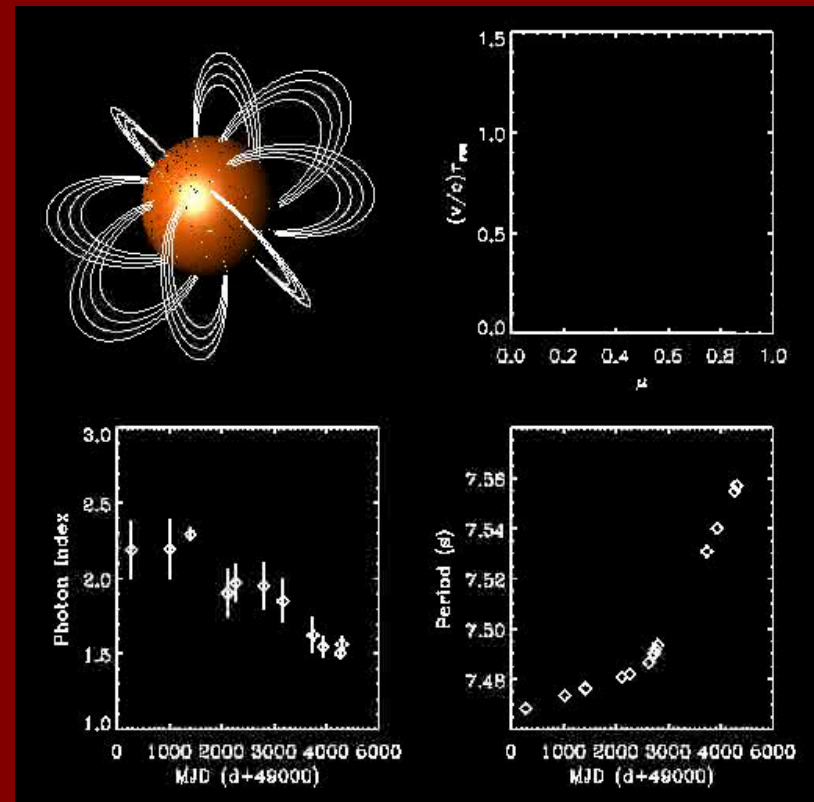


(images from Mereghetti arXiv: 0804.0250)



# A Growing Twist in SGR 1806-20 ?

- Evidence for spectral hardening AND enhanced spin-down
- $\Gamma$ -Pdot and  $\Gamma$ -L correlations
- Growth of bursting activity
- Possible presence of proton cyclotron line only during bursts



All these features are consistent with an increasingly twisted magnetosphere

# Twisted magnetospheres

- Twisted magnetosphere model, within magnetar scenario, in general agreement with observations
- Resonant scattering of thermal, surface photons produces spectra with right properties
- Many issues need to be investigated further
  - Twist of more general external fields
  - Detailed models for magnetospheric currents
  - More accurate treatment of cross section including QED effects and electron recoil
  - 10-100 keV tails: up-scattering by (ultra)relativistic ( $e^\pm$ ) particles ?
  - Create an archive to fit model spectra to observations

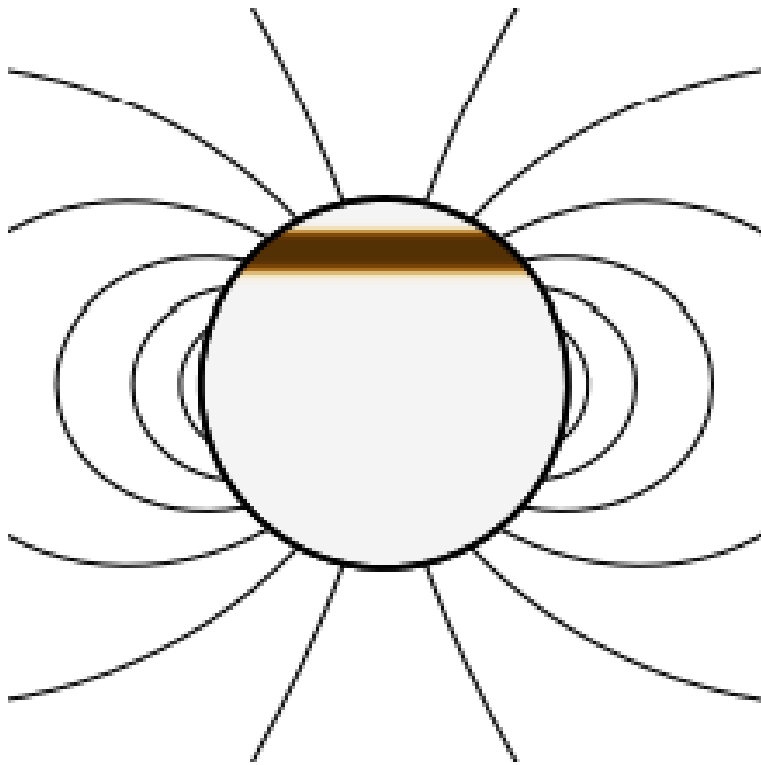
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See, for example, arXiv: 1008.4388 and references therein  
and more recent studies in 1201.3635

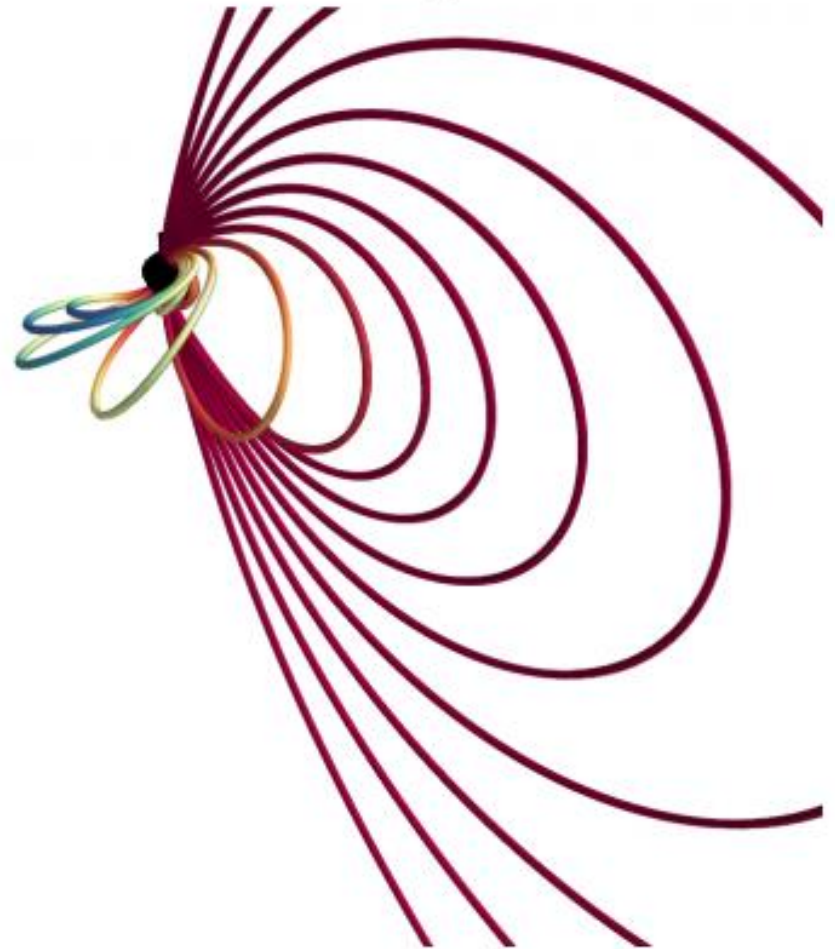


# Non-global twist model

(c) Ring

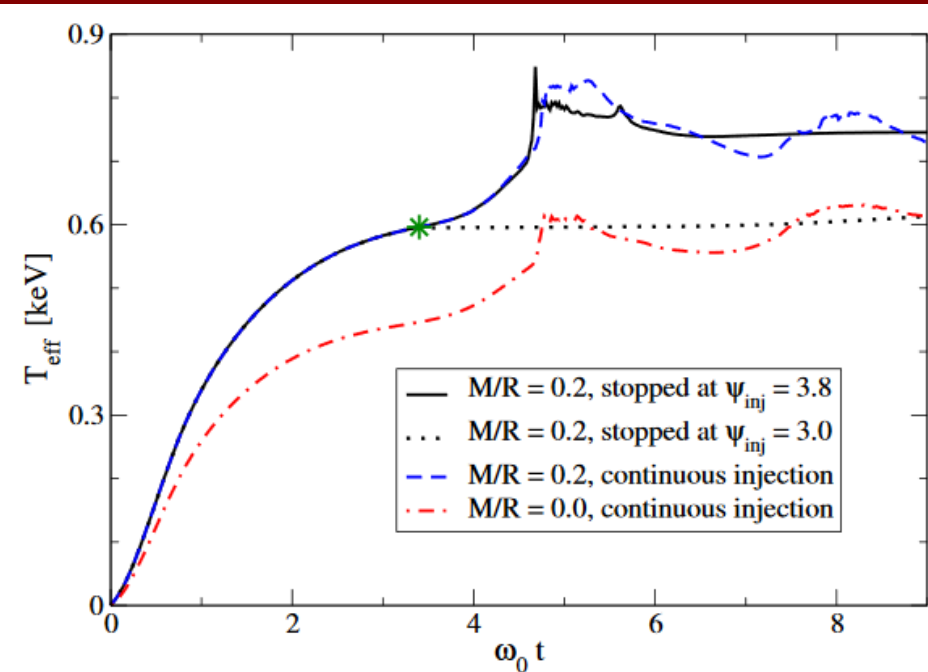
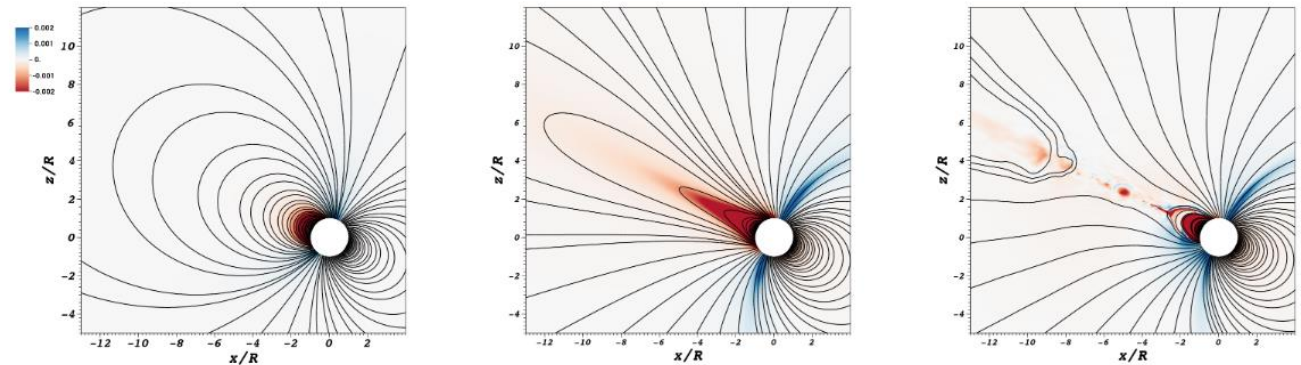
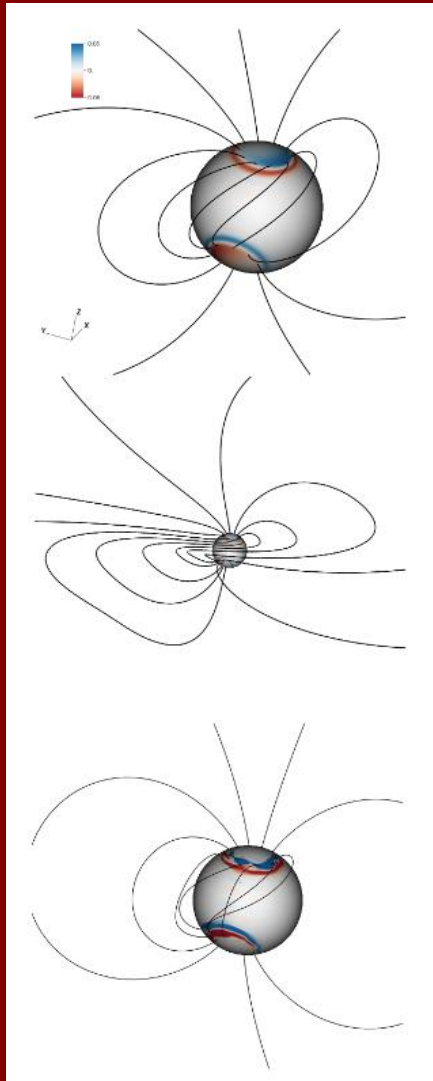


Ring



Energy in the twist:  $\sim l^2 R_{\text{NS}} / c^2$   
Twist decay time  $\sim 1$  yr for typical parms

# Numerical simulation of the twist



See 1807.09021  
about coupling  
between crust and  
magnetosphere.

1901.08889

$$T_{\text{bb}} \approx 0.18 \text{ keV} \left[ \frac{\Delta r}{1 \text{ m}} \right]^{\frac{1}{4}} \left[ \frac{10^{17} \text{ s}^{-1}}{\sigma_e} \right]^{\frac{1}{4}} \left[ \frac{J}{10^{18} \text{ G/s}} \right]^{\frac{1}{2}}$$

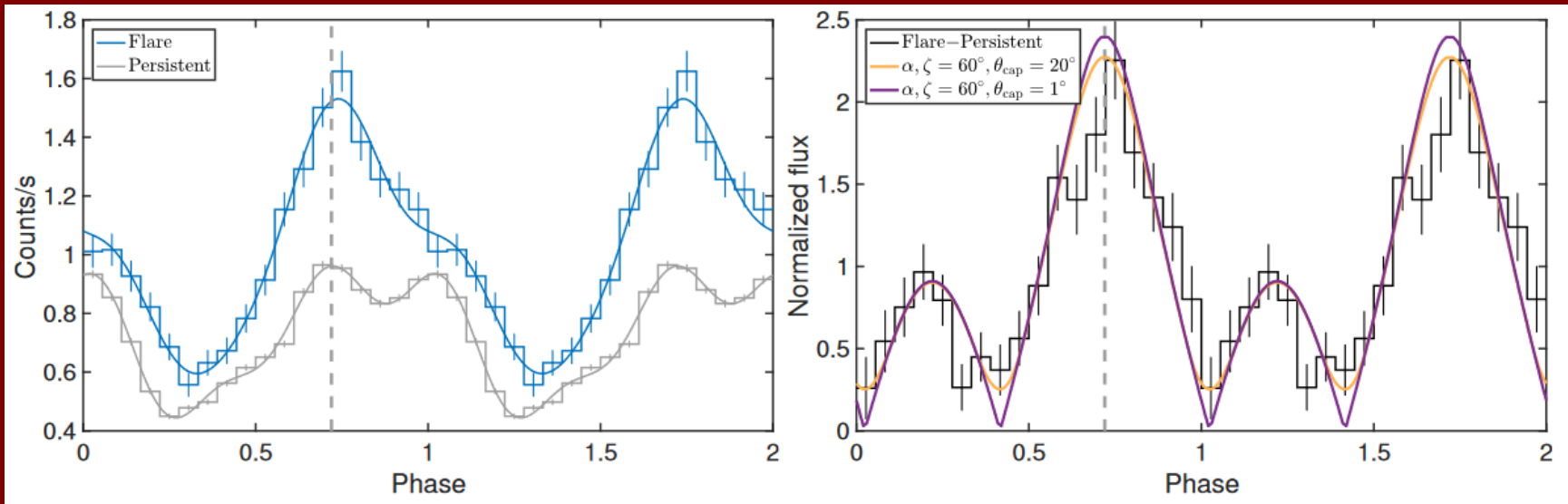
# Antipodal spots heated during a flare

1RXS J1708-40  
NuSTAR

Model	$kT$ (keV)	$\Gamma$	$R$ (m)	$F$ $\text{erg s}^{-1} \text{cm}^{-2}$	$L$ $\text{erg s}^{-1}$
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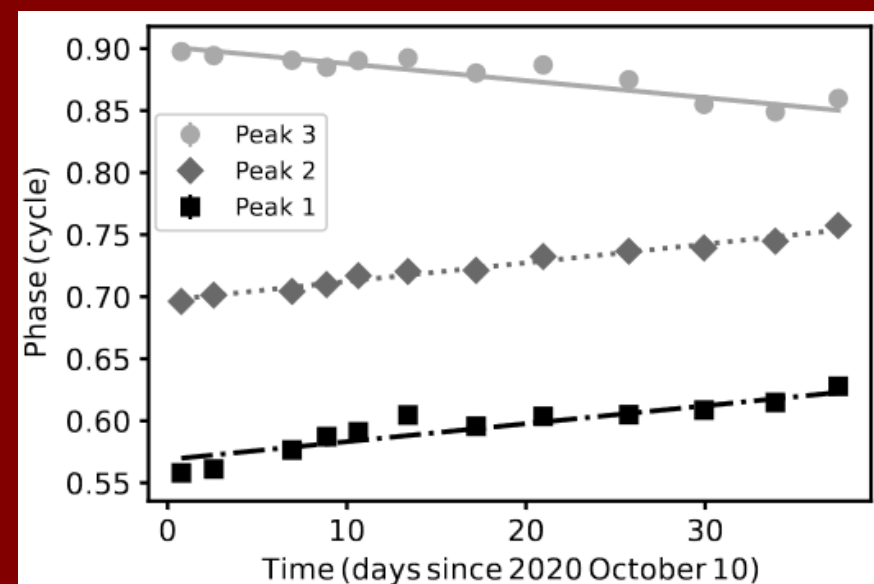
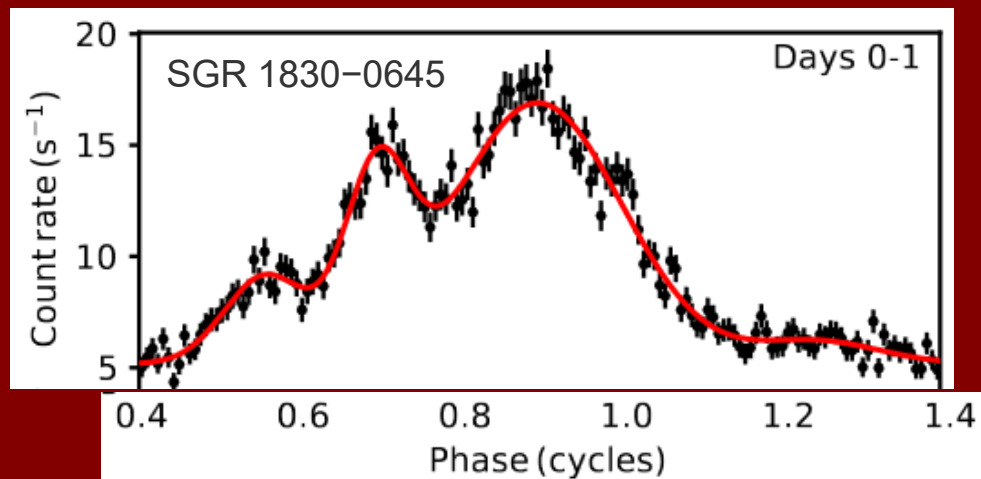
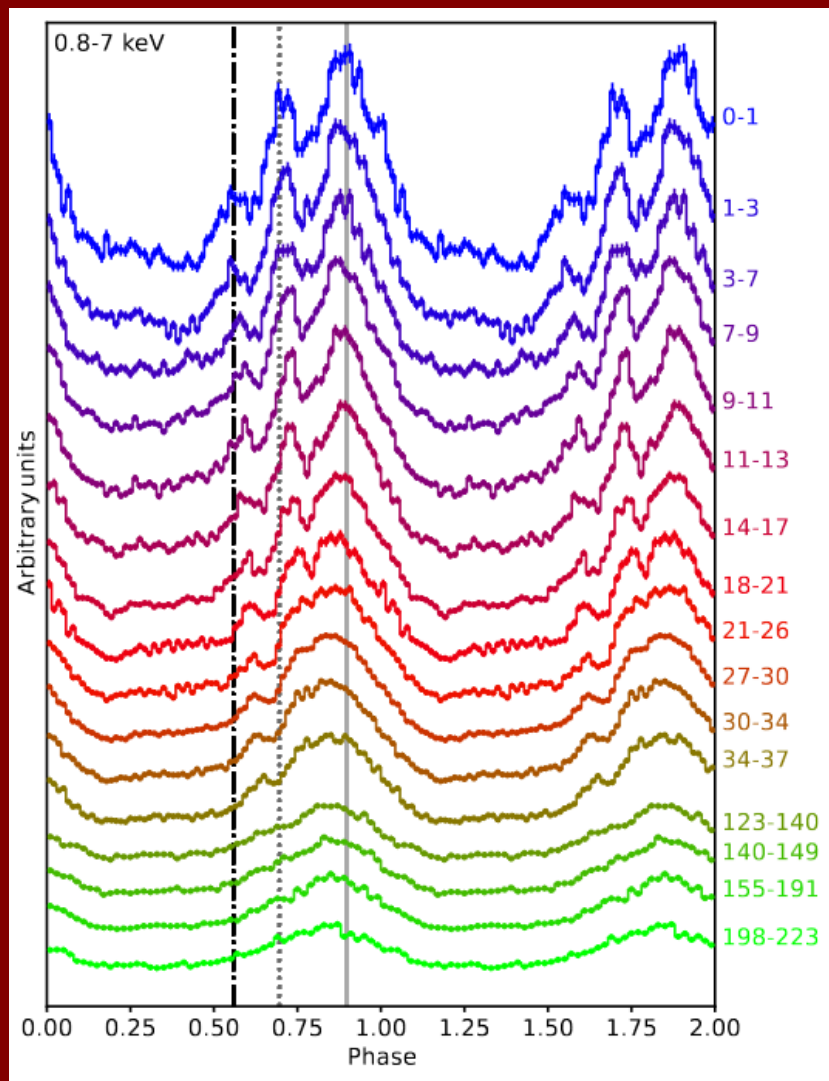
Phase-resolved spectroscopy					
0.06-0.28	BB	$2.3 \pm 0.2$	—	$64^{+17}_{-11}$	$1.4^{+0.2}_{-0.3}$
0.56-0.94	BB	$2.2 \pm 0.1$	—	$105 \pm 10$	$2.9^{+0.4}_{-0.2}$
Rest	BB	$1.8 \pm 0.2$	—	$98^{+30}_{-19}$	$1.1 \pm 0.1$

Antipodal character indicates role of the dipole field.



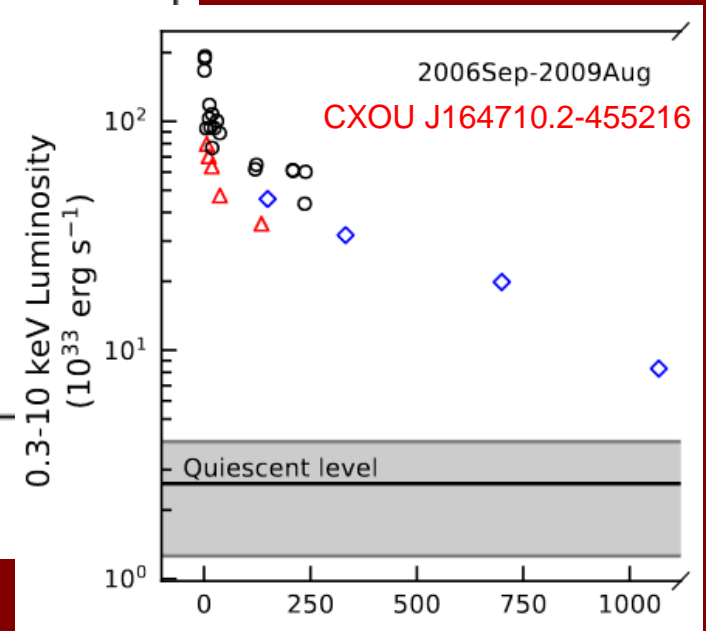
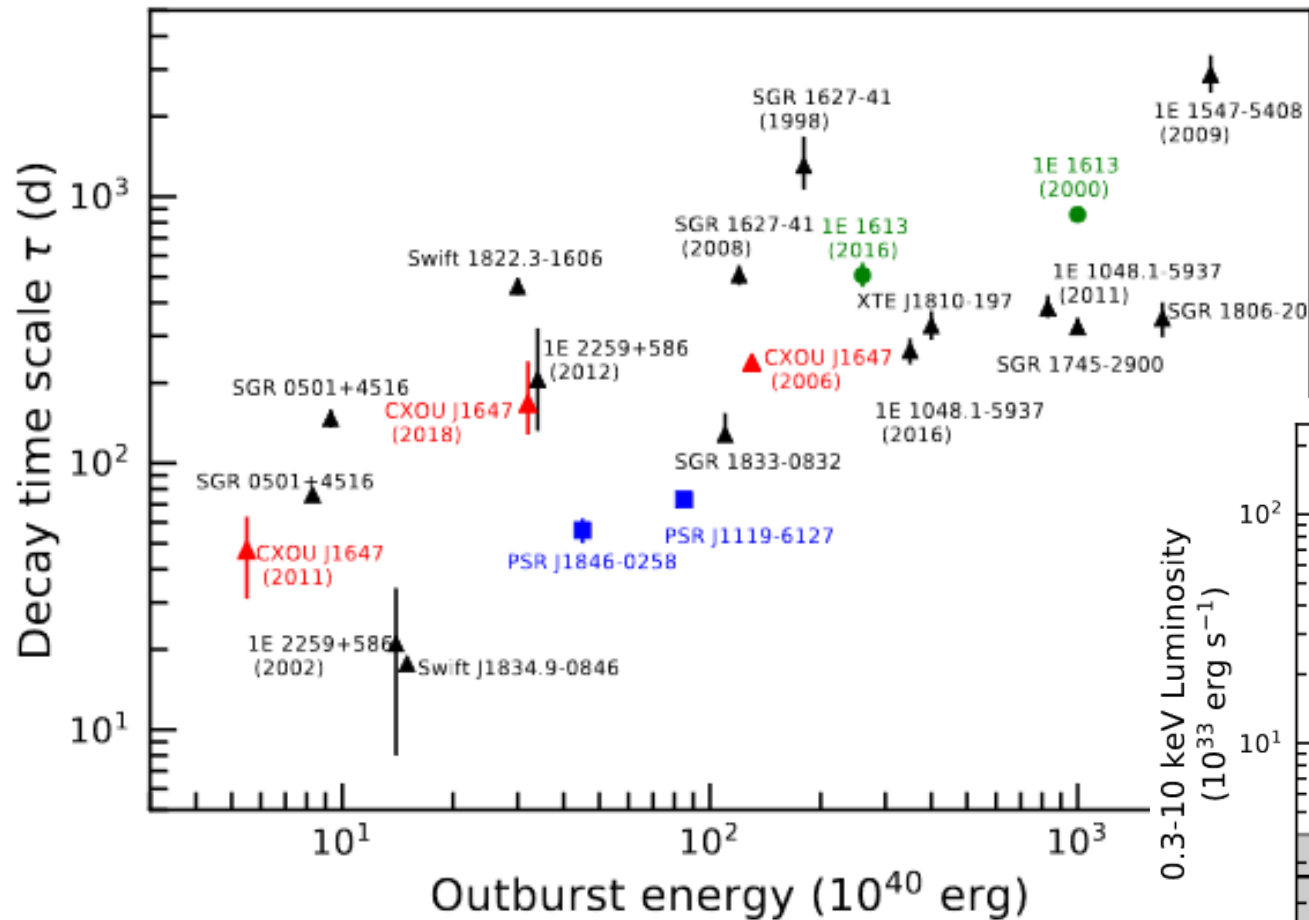
2001.08761

# Pulse profile changes during an outburst



2201.05517 Plastic motion or untwisting?

# Outburst decay vs. released energy



# Optical pulsations

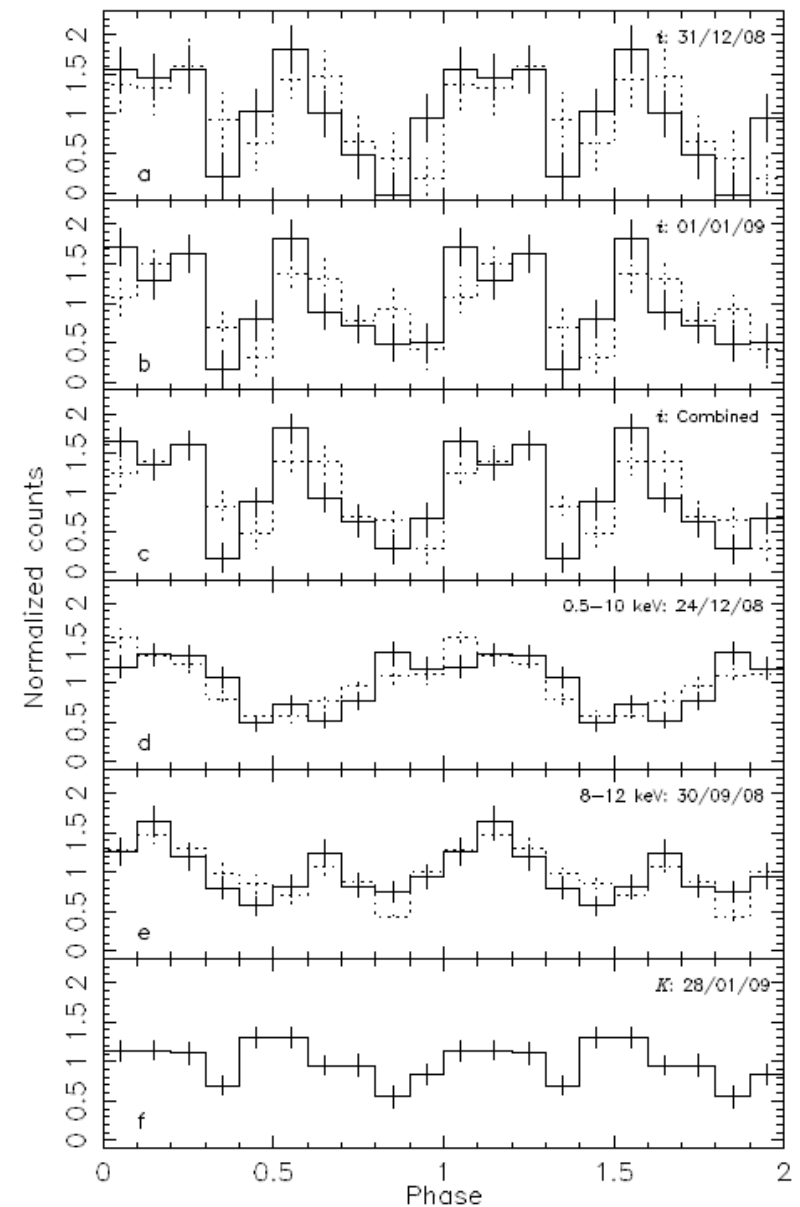
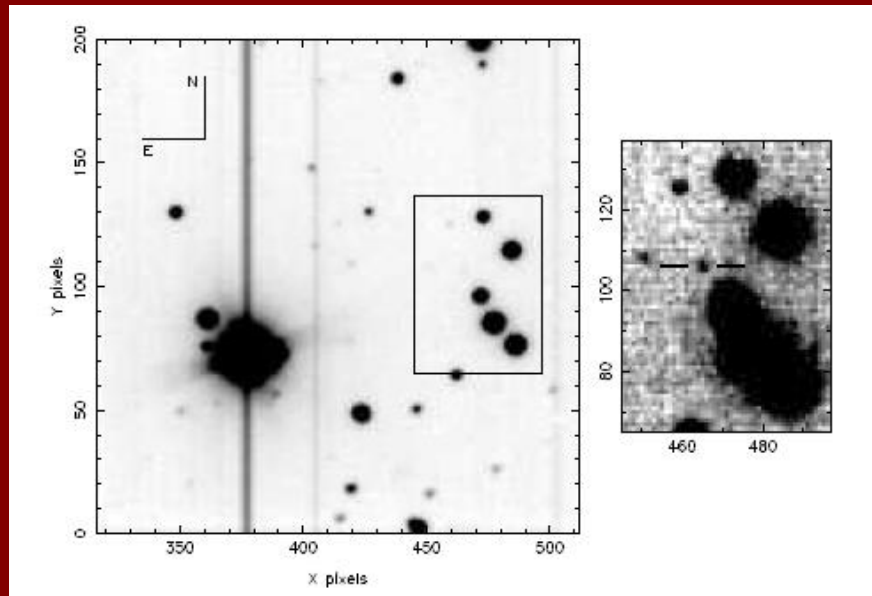
SGR 0501+4516

$P=5.76$  s

$d=0.8$  kpc – the closest!

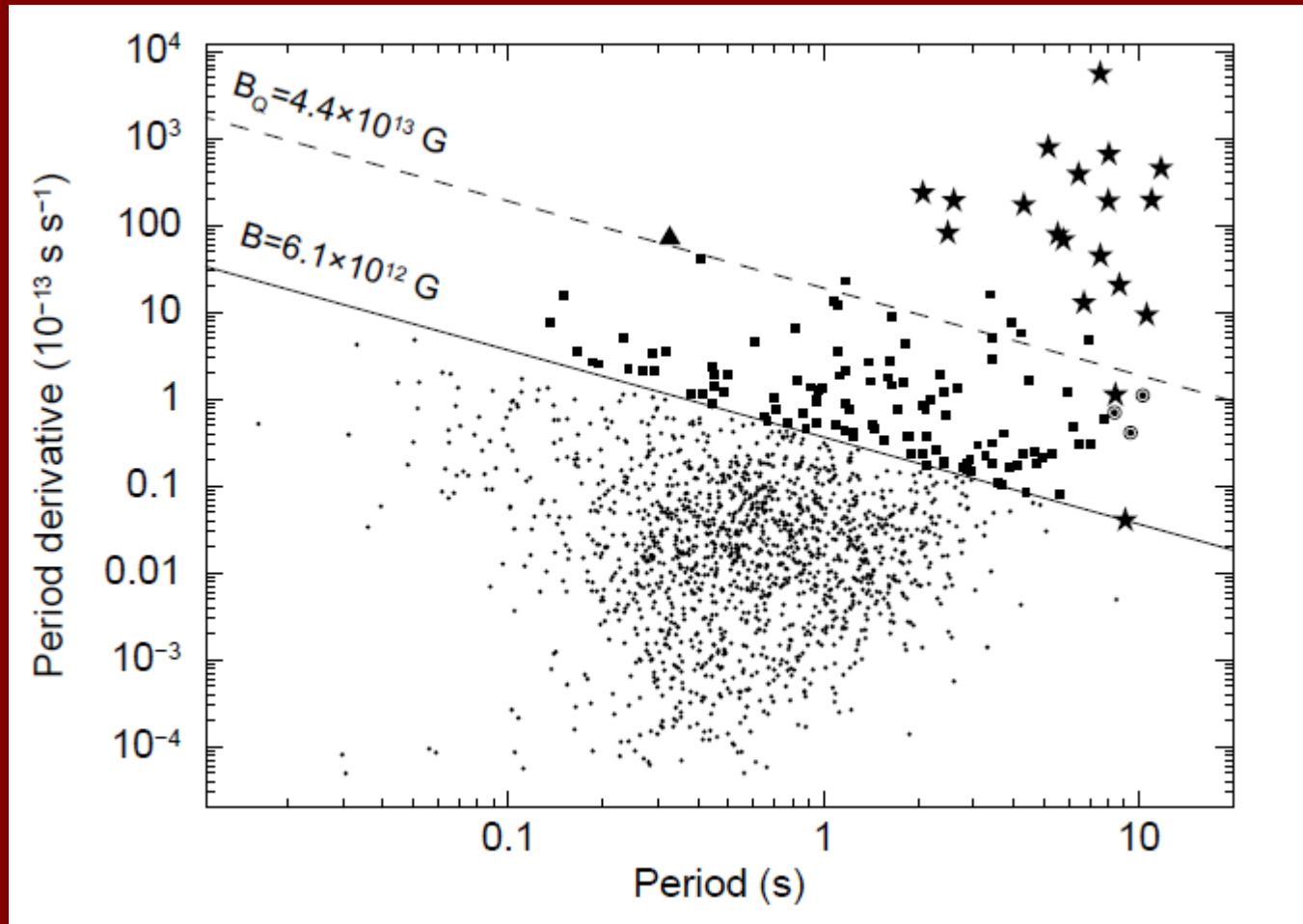
4.2m William Herschel Telescope

Magnetospheric emission?



# Low-field magnetars

SGR 0418+5729 and Swift J1822.3–160



See a review in [arXiv:1303.6052](https://arxiv.org/abs/1303.6052)

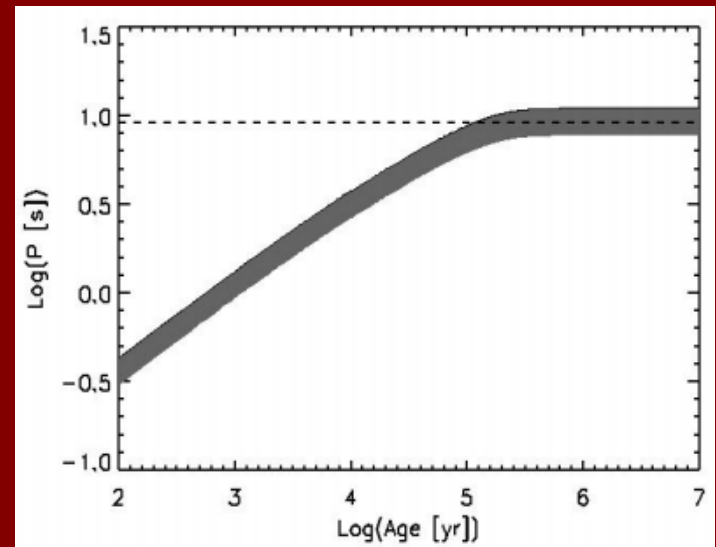
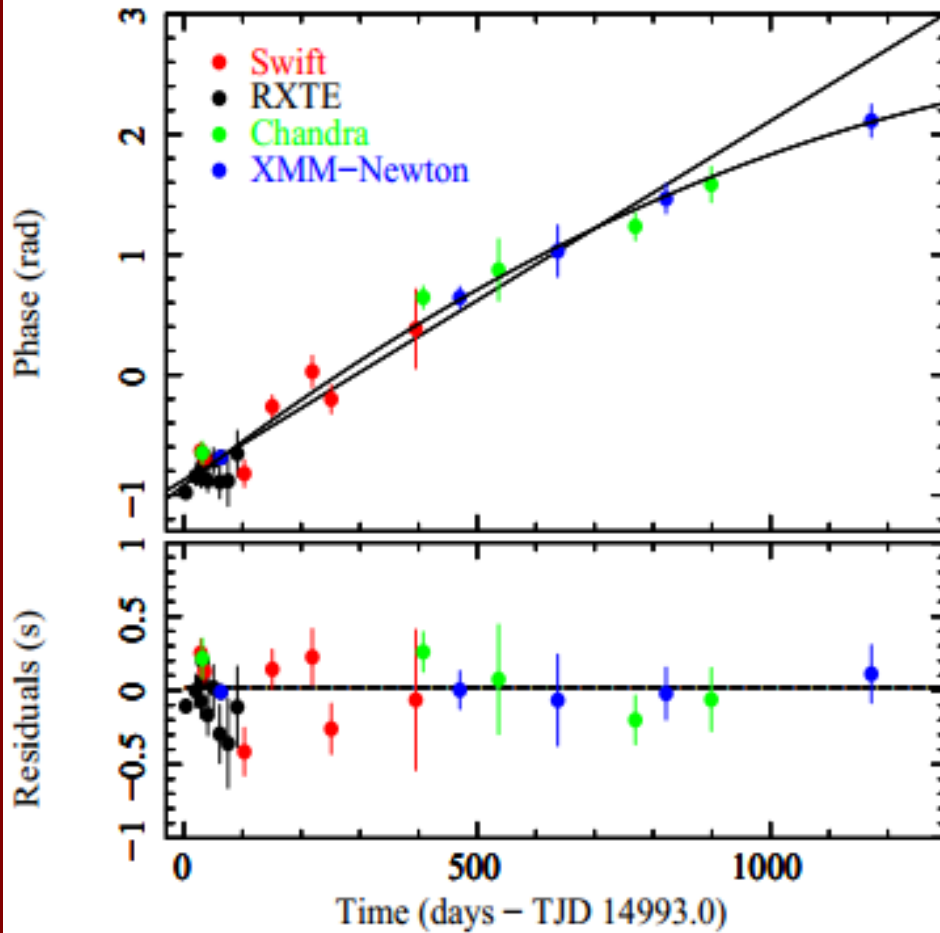


# The first low-field magnetar

SGR 0418+5729

Only after ~3 years of observations it was possible to detect spin-down.

The dipolar field is  $\sim 6 \cdot 10^{12}$  G.

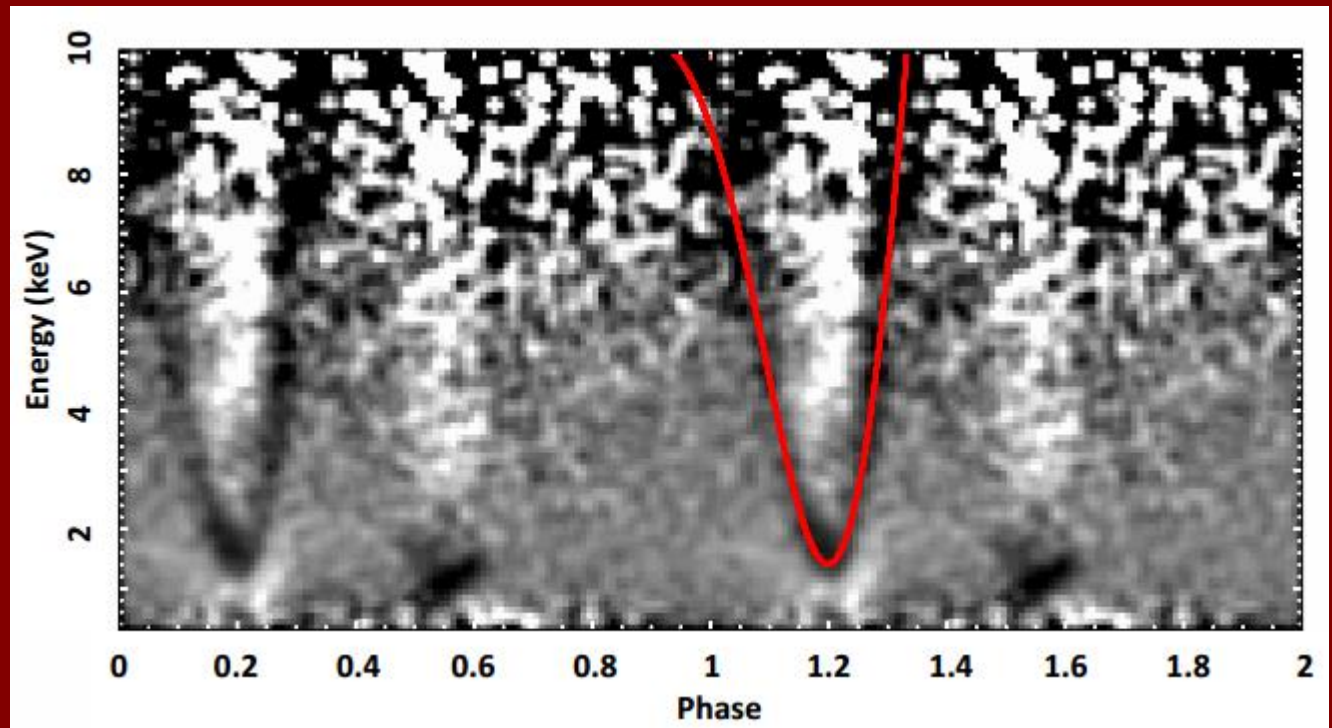


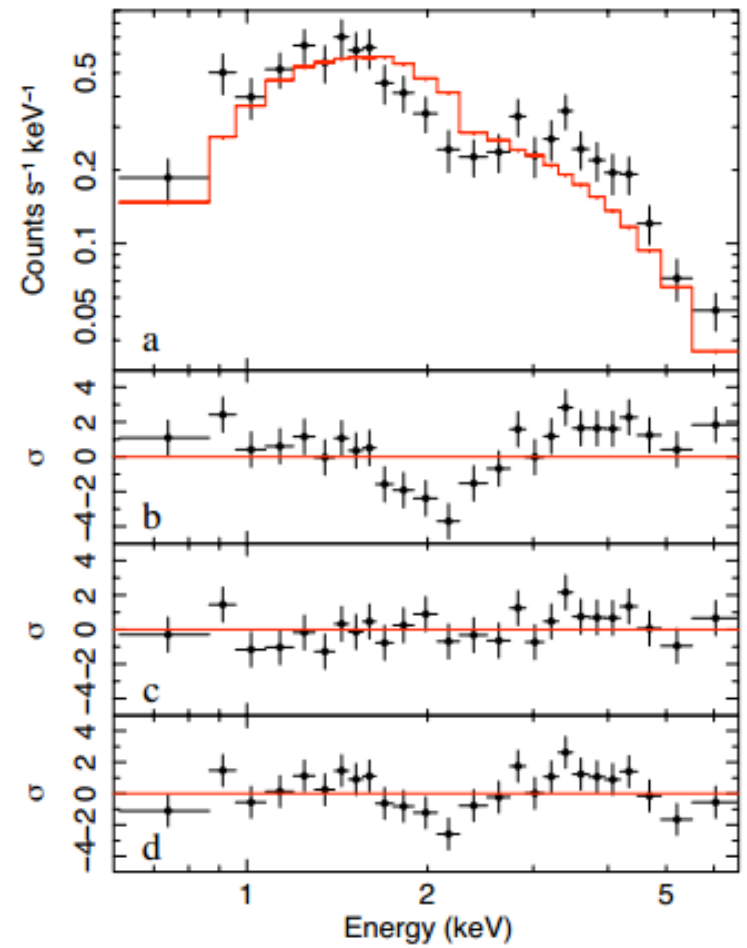
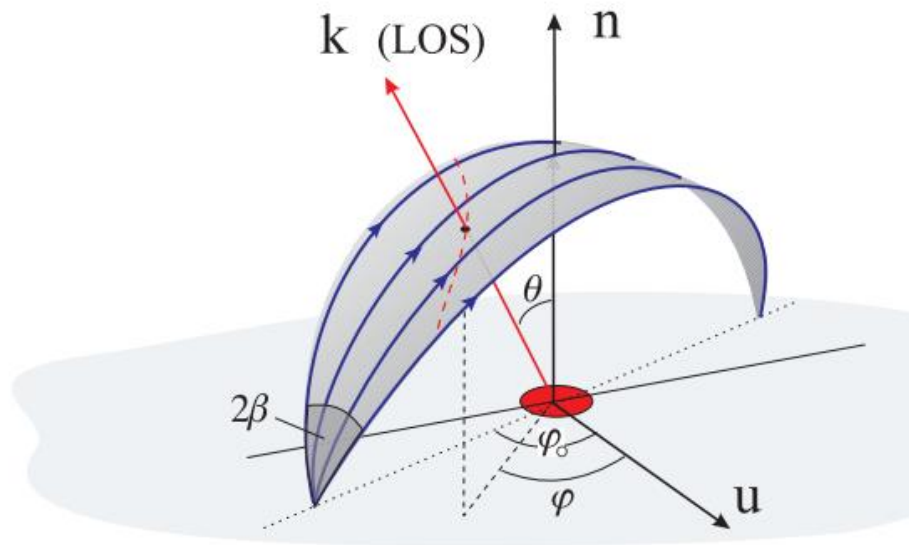
The dipolar field could decay, and activity is due to the toroidal field.

# Large field (at last) ... But multipoles!

XMM-Newton observations allowed to detect a spectral line which is variable with phase.

If the line is interpreted as a proton cyclotron line, then the field in the absorbing region is  $2 \cdot 10^{14} - 10^{15}$  G





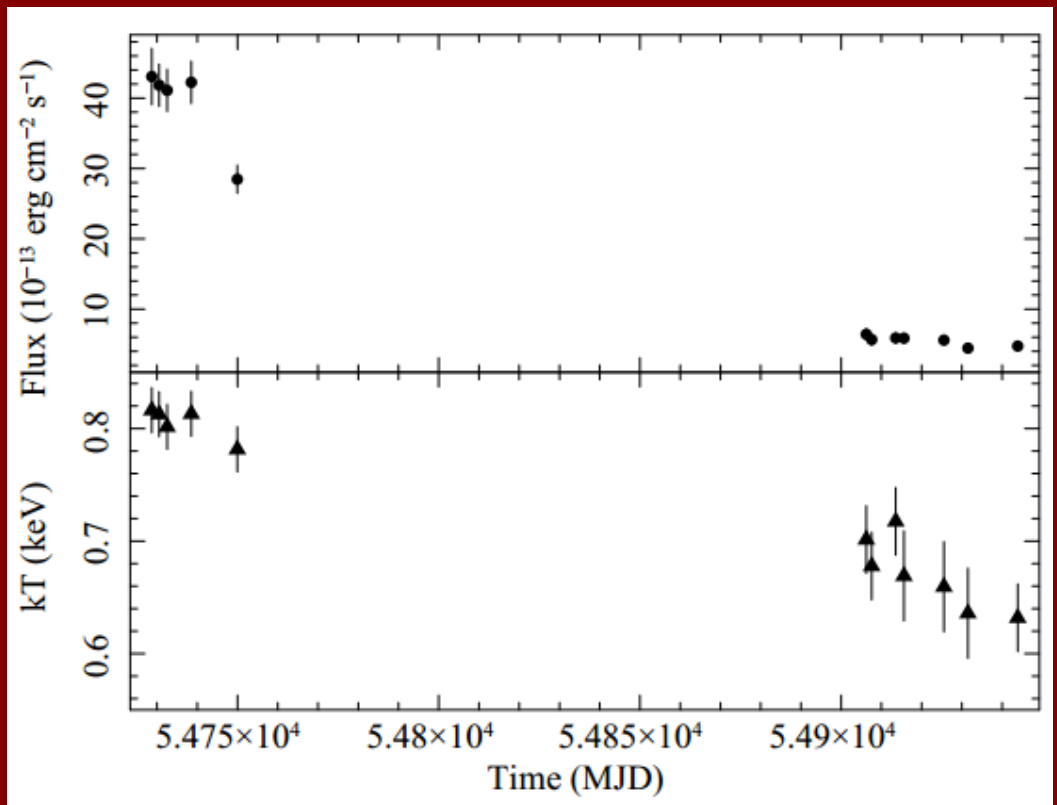
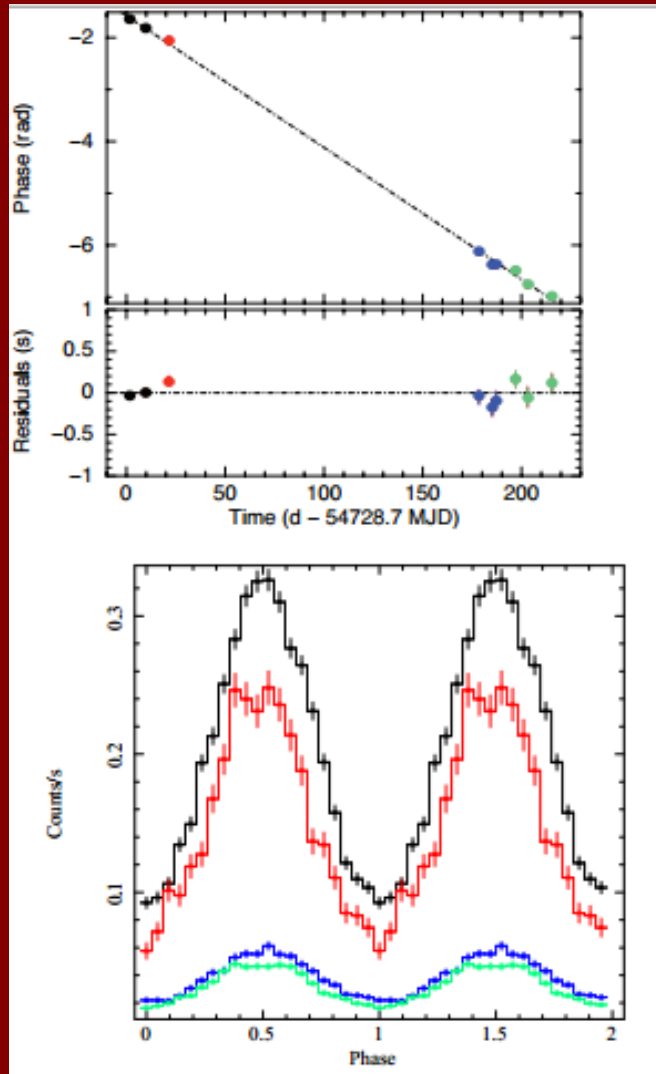
# Another low-field magnetar

3XMM J185246.6+003317

P=11.5 s No spin-down detected after 7 months

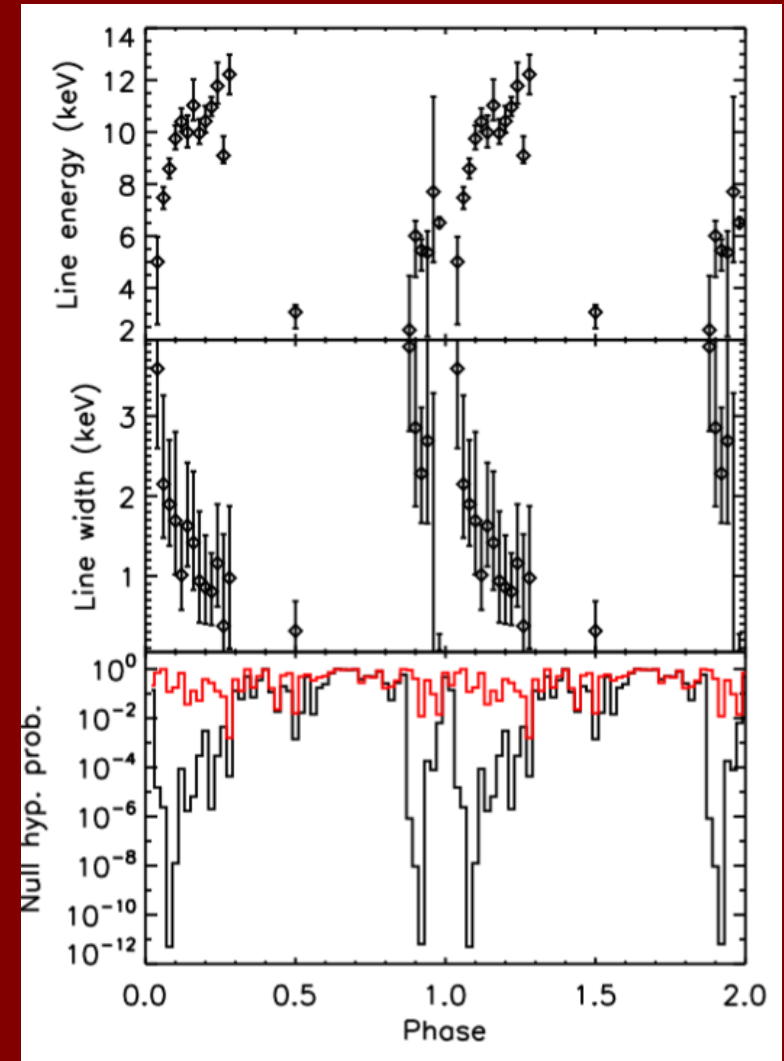
$B < 4 \times 10^{13}$  G

Transient magnetar

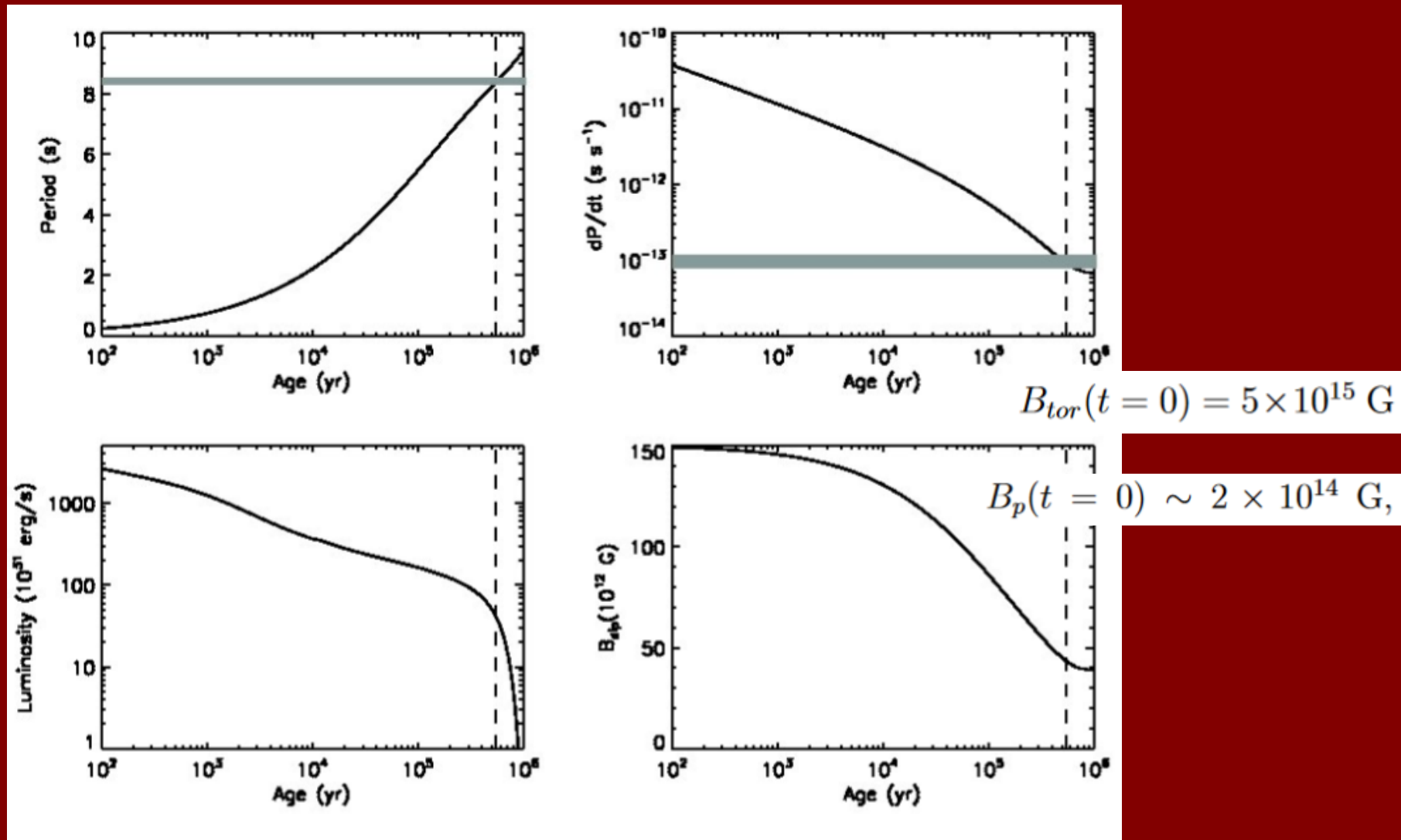


# More lines in low-field magnetars

phase-dependent absorption line



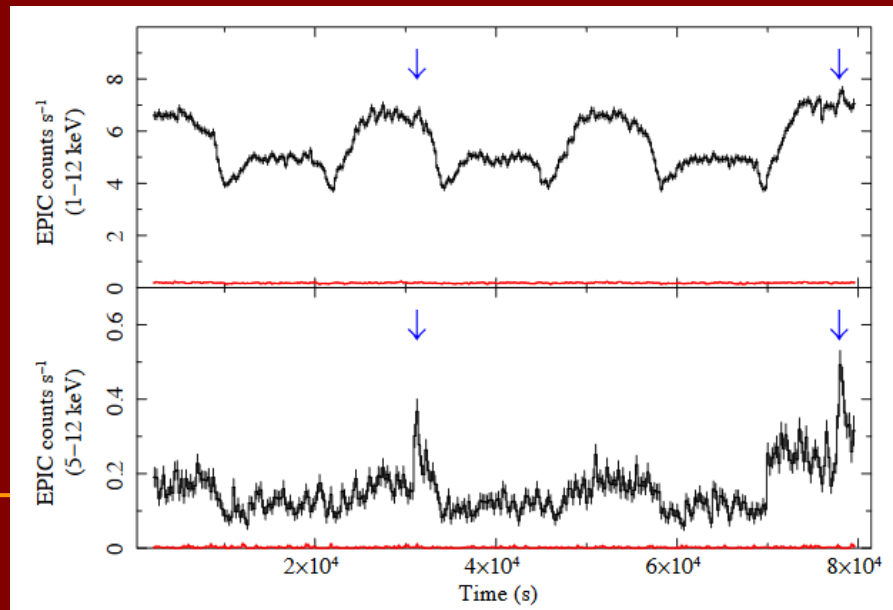
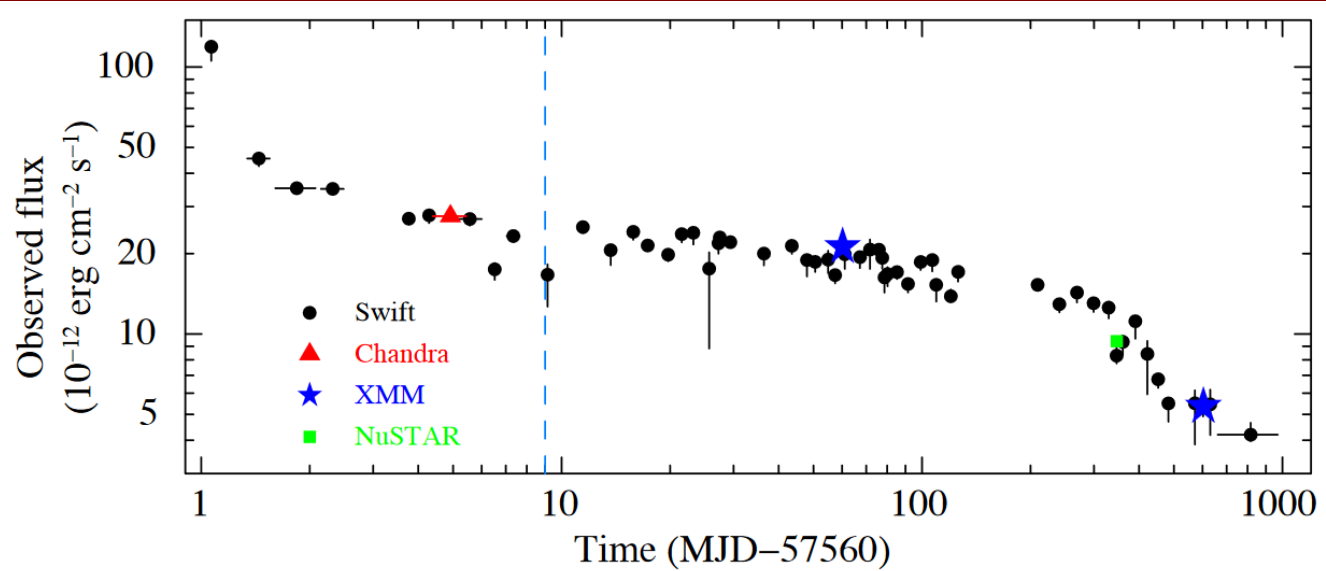
# Old evolved sources?



# RCW103 – a special kind of magnetar



Looked like a CCO  
6.7 hours spin period!  
SGR-like bursts.



1904.05424



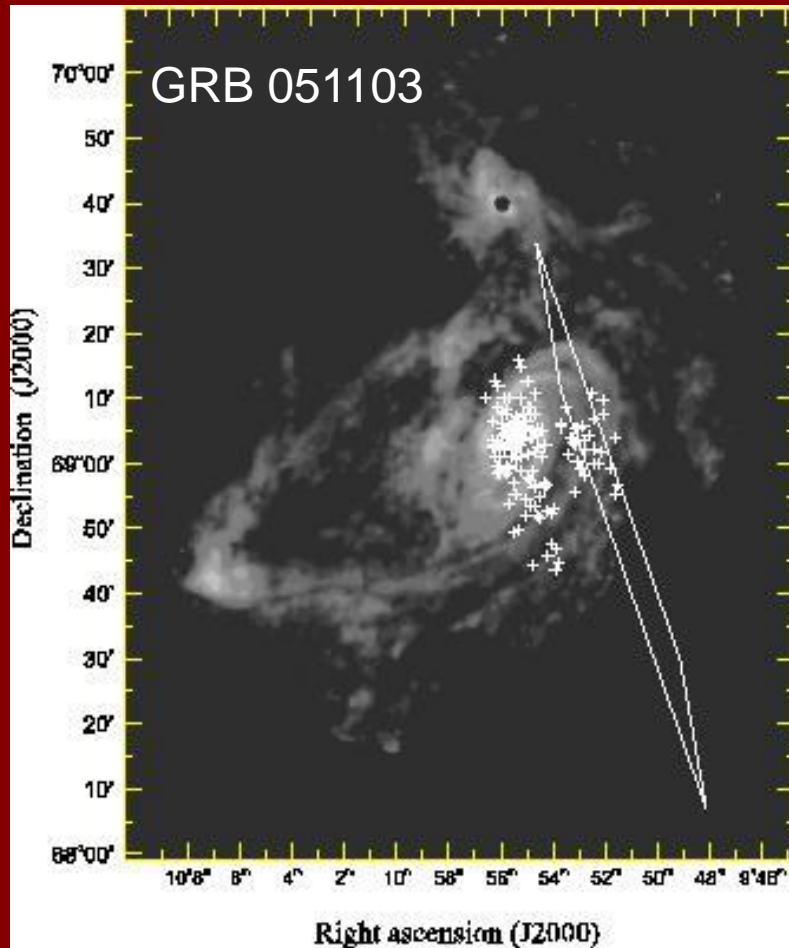
# Extragalactic giant flares

Initial enthusiasm that most of short GRBs can be explained as giant flares of extraG SGRs disappeared.

At the moment, we have a definite deficit of extraG SGR bursts, especially in the direction of Virgo cluster (Popov, Stern 2006; Lazzatti et al. 2006).

However, there are several good candidates.

# Extragalactic SGRs

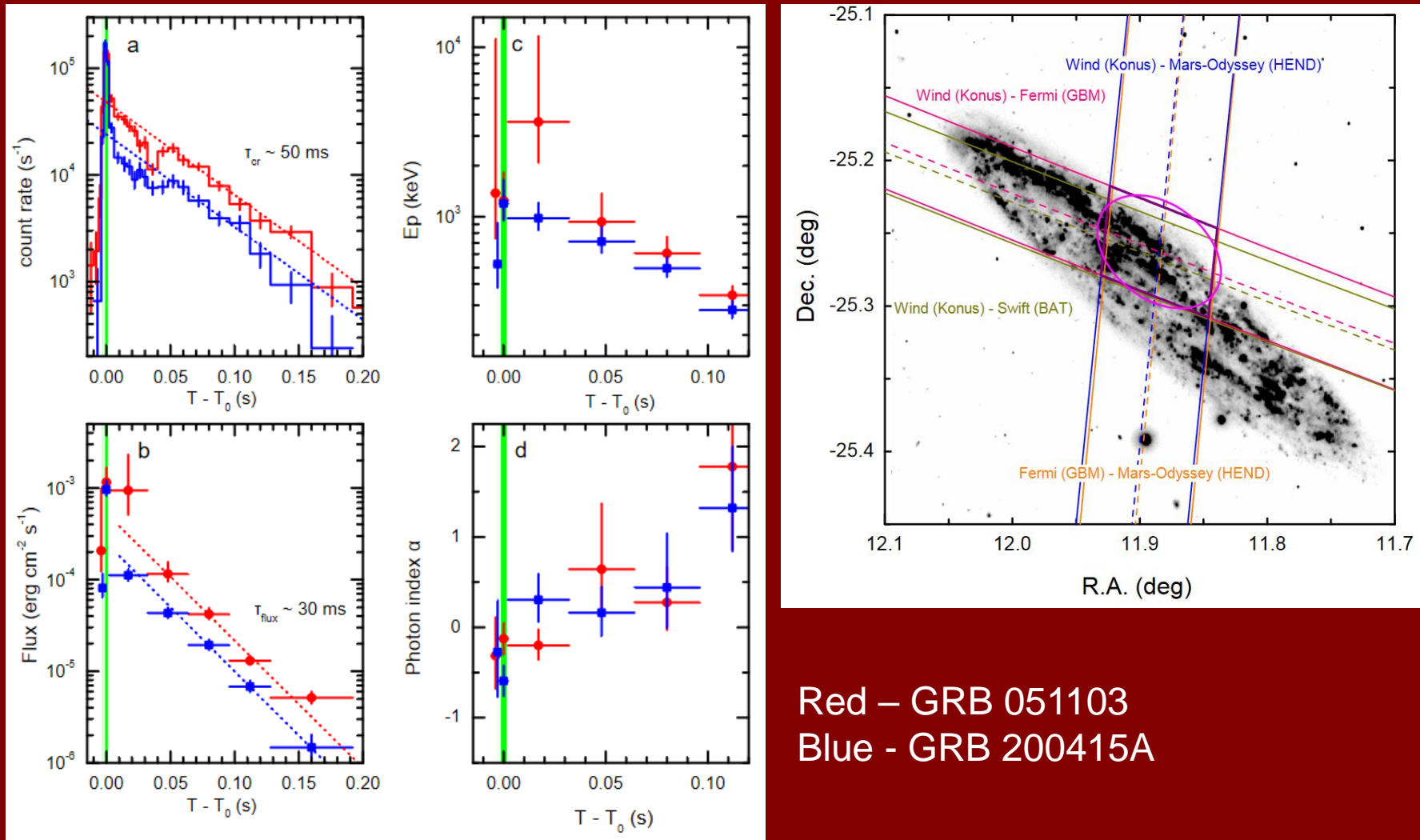


It was suggested long ago (Mazets et al. 1982) that present-day detectors could already detect giant flares from extragalactic magnetars.

However, all searches in, for example, BATSE database did not provide clear candidates (Lazzati et al. 2006, Popov & Stern 2006, etc.).

Finally, recently several good candidates have been proposed by different groups (Mazets et al., Frederiks et al., Golenetskii et al., Ofek et al, Crider ....).

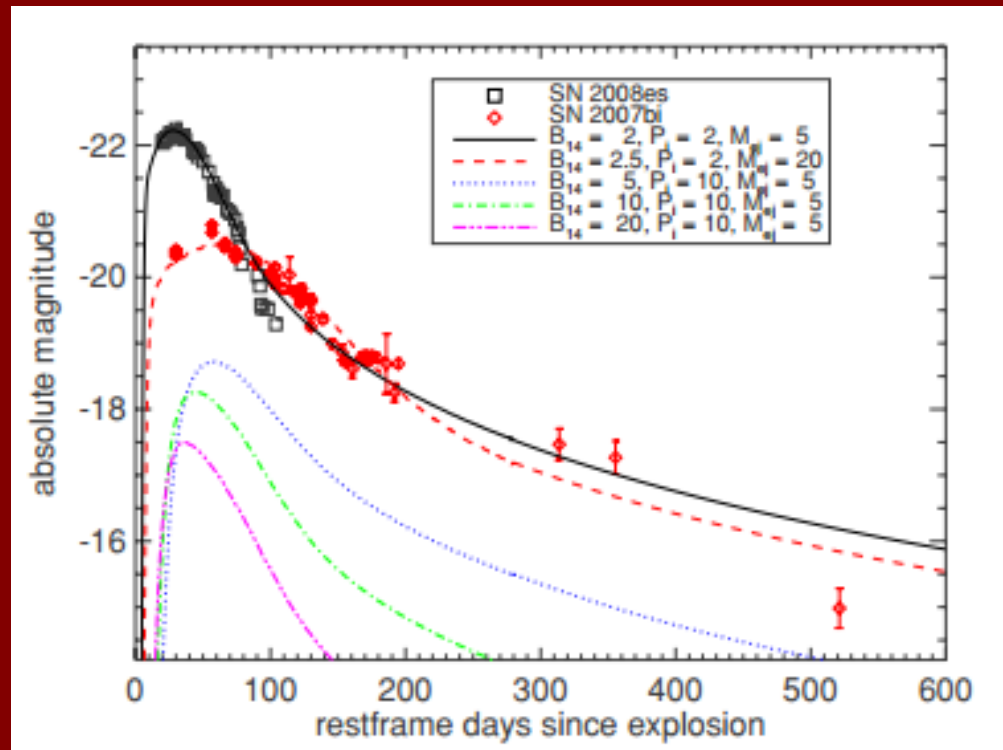
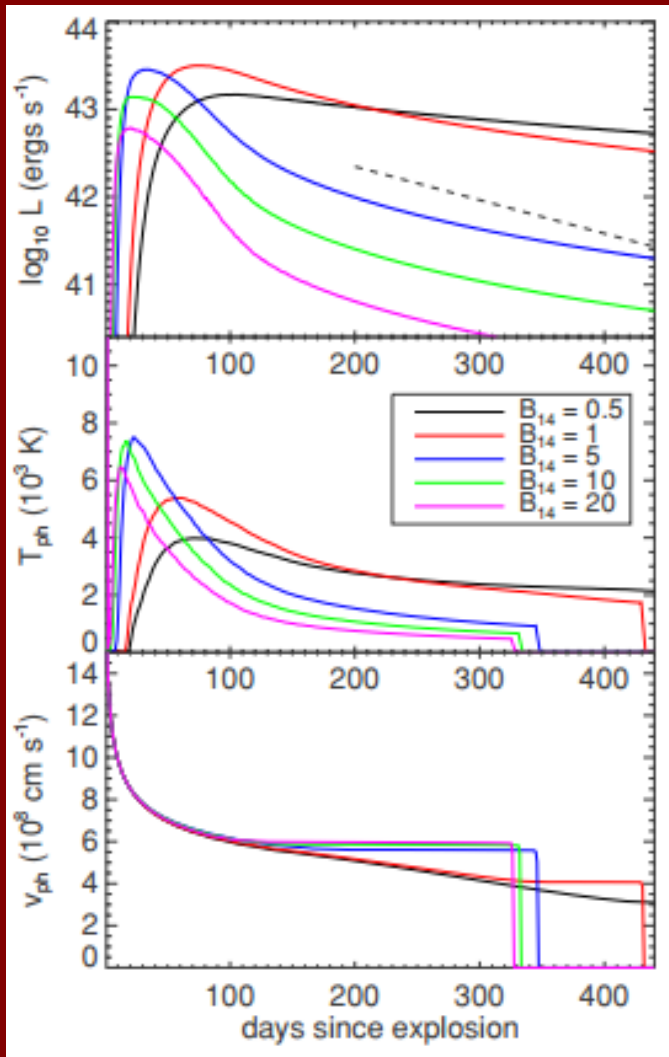
# Magnetar hyperflare in NGC 253



2101.05104, see also 2101.05144, 2008.05097

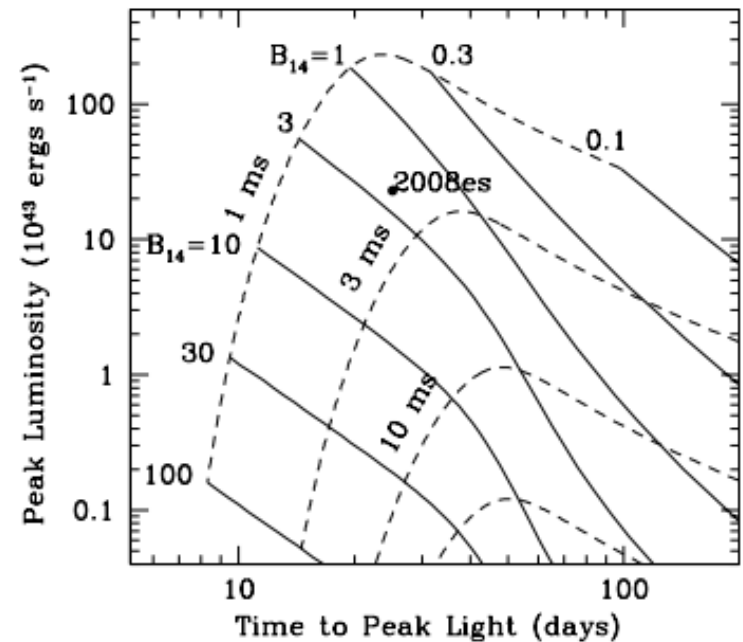
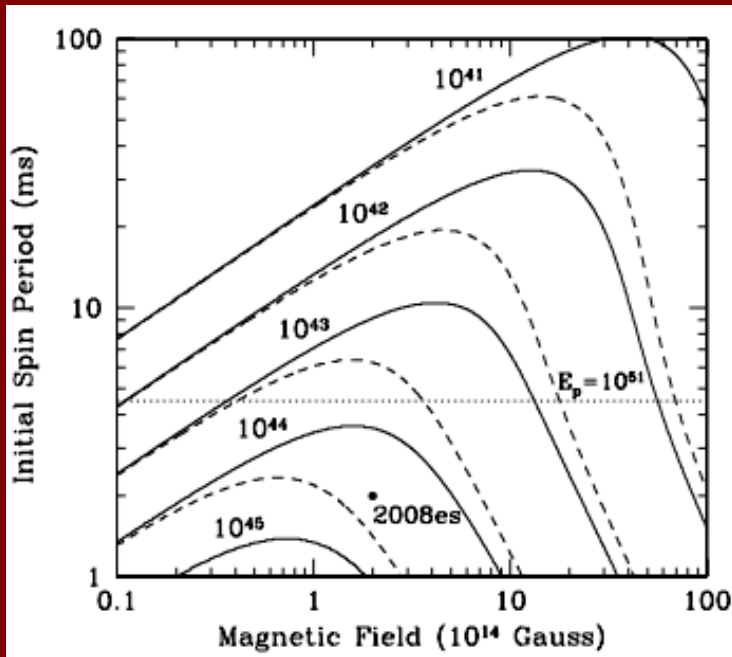
# Magnetars and supernovae

With large field and short spin a newborn NS can contribute a lot to the luminosity of a SN.



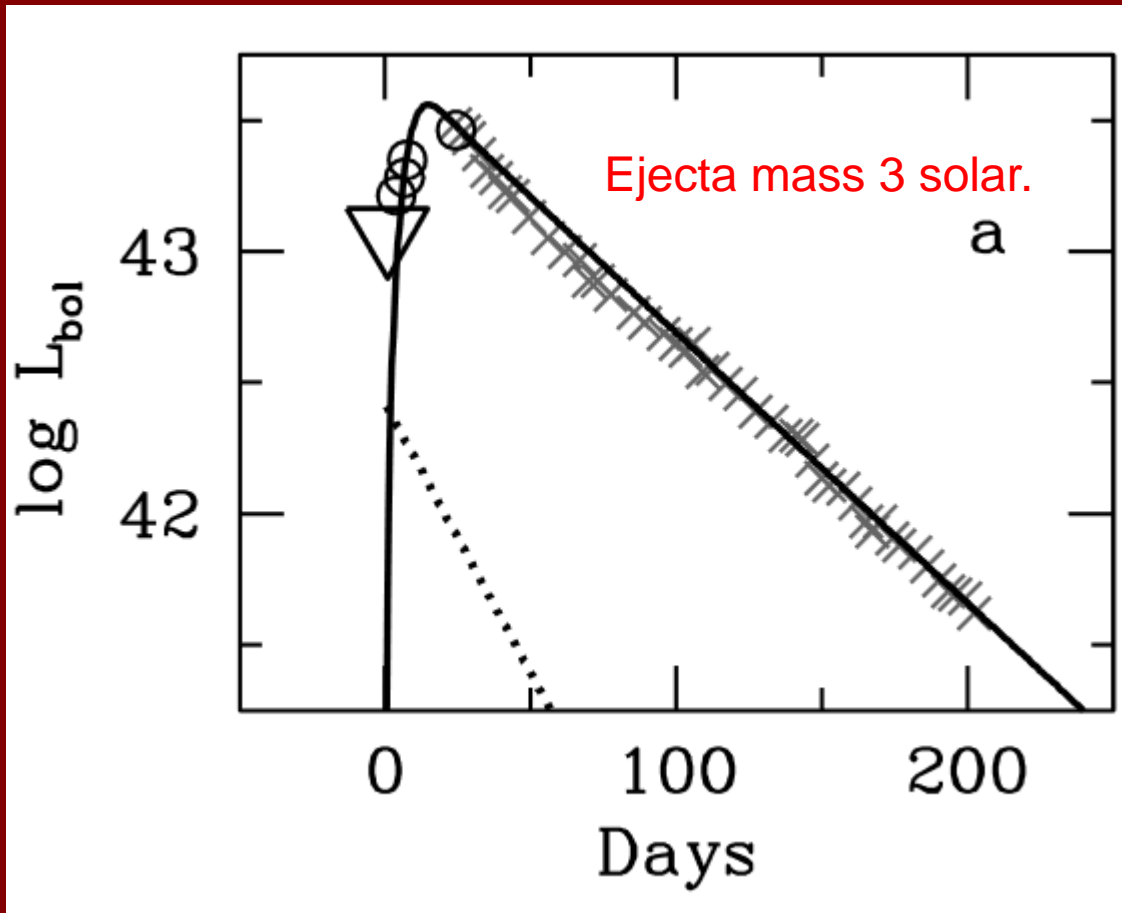
# Parameters needed

For short initial spin periods it is not even necessary to have magnetar scale  $B$ .



About young millisecond magnetars see also 1906.02610, and a review in 2103.10878.

# Young magnetar at the propeller stage



Bolometric light curve of ASASSN-15nx (crosses) and the model (solid line).

$$I\omega\dot{\omega} = -(1/2)\dot{m}(r_m\omega)^2$$

For constant accretion rate:

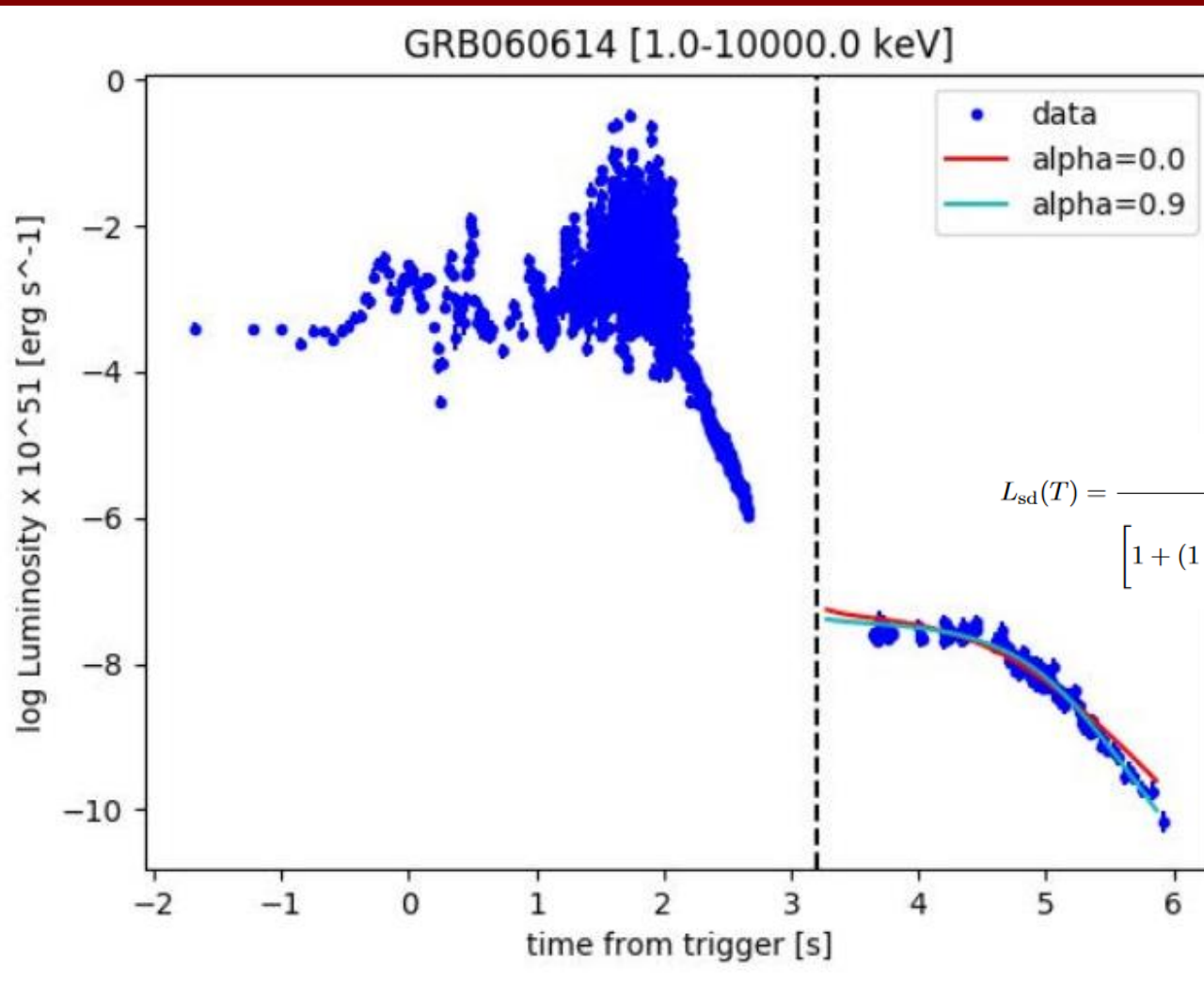
$$\omega = \omega_0 \exp(-bt)$$

$$b = 0.5\dot{m}r_m^2/I.$$

$$L \propto \omega^2 \propto \exp(-2bt)$$

Parameter	Units	Value
$R_{ns}$	km	12
$I$	$10^{45} \text{ g cm}^2$	1
$\mu$	$10^{30} \text{ G cm}^3$	51.8
$P_0$		0.011
$\dot{m}$	$10^{23} \text{ g s}^{-1}$	1.5

# Magnetars and GRBs



$$L_{\text{sd}} = \frac{\mu^2}{c^3} \Omega^4 (1 + \sin^2 \theta)$$

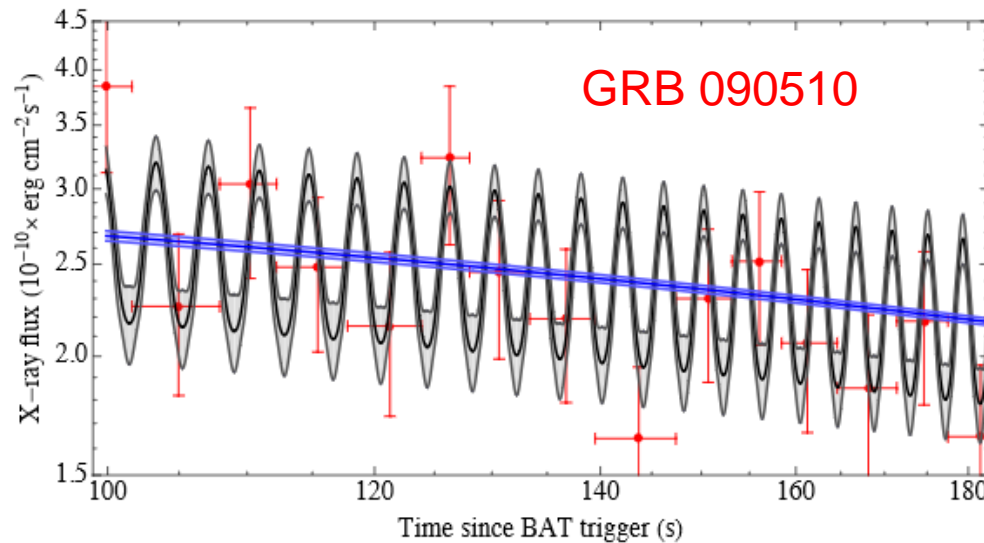
$$L_{\text{sd}}^{(N-1)} = L_{\text{sd}} \left( \frac{\Omega}{\Omega_i} \right)^{-2\alpha}$$

$$n = 3 - 2\alpha.$$

$$L_{\text{sd}}(T) = \frac{L_{\text{sd},i} \frac{2-\alpha}{\left[1 + (1-\alpha) \frac{T}{\tau_i}\right]^{1-\alpha}}}{\tau_i \left[1 + (1-\alpha) \frac{T}{\tau_i}\right]^{1-\alpha}} = \frac{E_{\text{spin},i} \frac{2-\alpha}{\left[1 + (1-\alpha) \frac{T}{\tau_i}\right]^{1-\alpha}}}{\tau_i \left[1 + (1-\alpha) \frac{T}{\tau_i}\right]^{1-\alpha}},$$



# Precessing magnetar in a GRB?

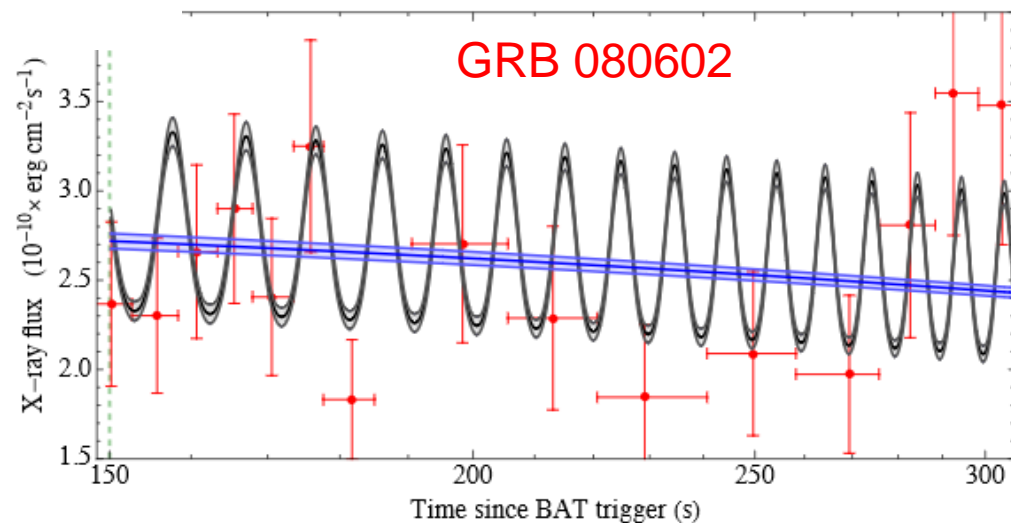


$$L_{\alpha} \approx \frac{B_p^2 R^6 \Omega_0^4}{6c^3} \left\{ 1 + \delta - \delta [\alpha_0 + k \cos(\Omega_p \times t)]^2 \right\} \\ \times \left\{ 1 + \frac{t [1 + \delta (1 - \alpha_0^2 - \frac{1}{2} k^2)]}{\tau_{\text{sd}}} - \frac{k\delta [2\alpha_0 + \frac{1}{2} k \cos(\Omega_p \times t)] \sin(\Omega_p \times t)}{\tau_{\text{sd}} \Omega_p} \right\}^{-2},$$

$\alpha_0$  - initial inclination angle

$$\Omega_p(t) \approx \epsilon \Omega_0 \left( 1 + \frac{t}{\tau_{\text{sd}}} \right)^{-1/2}$$

GRB 090510 – short  
GRB 080602 - long



# What is special about magnetars?

## Link with massive stars

There are reasons to suspect that magnetars are connected to massive stars (astro-ph/0611589, but see 1708.01626).

## Link to binary stars

There is a hypothesis that magnetars are formed in close binary systems (astro-ph/0505406, 0905.3238).

*The question is still on the list.*

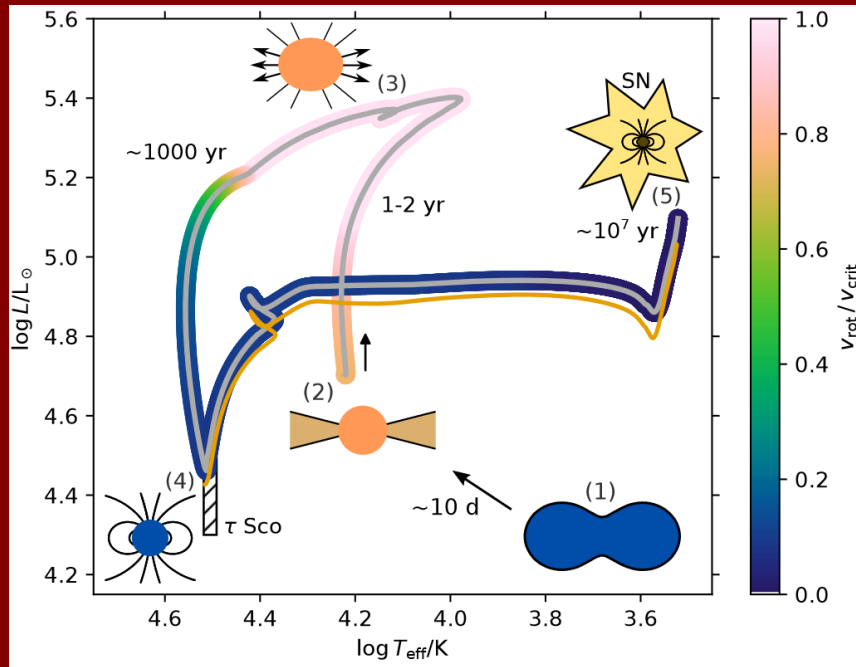


AXP in Westerlund 1 most probably has a very massive progenitor  $>40 M_{\odot}$ . However, recently the age was slightly revised: 2103.02609. ~5-8 Myrs. Older than estimated before.

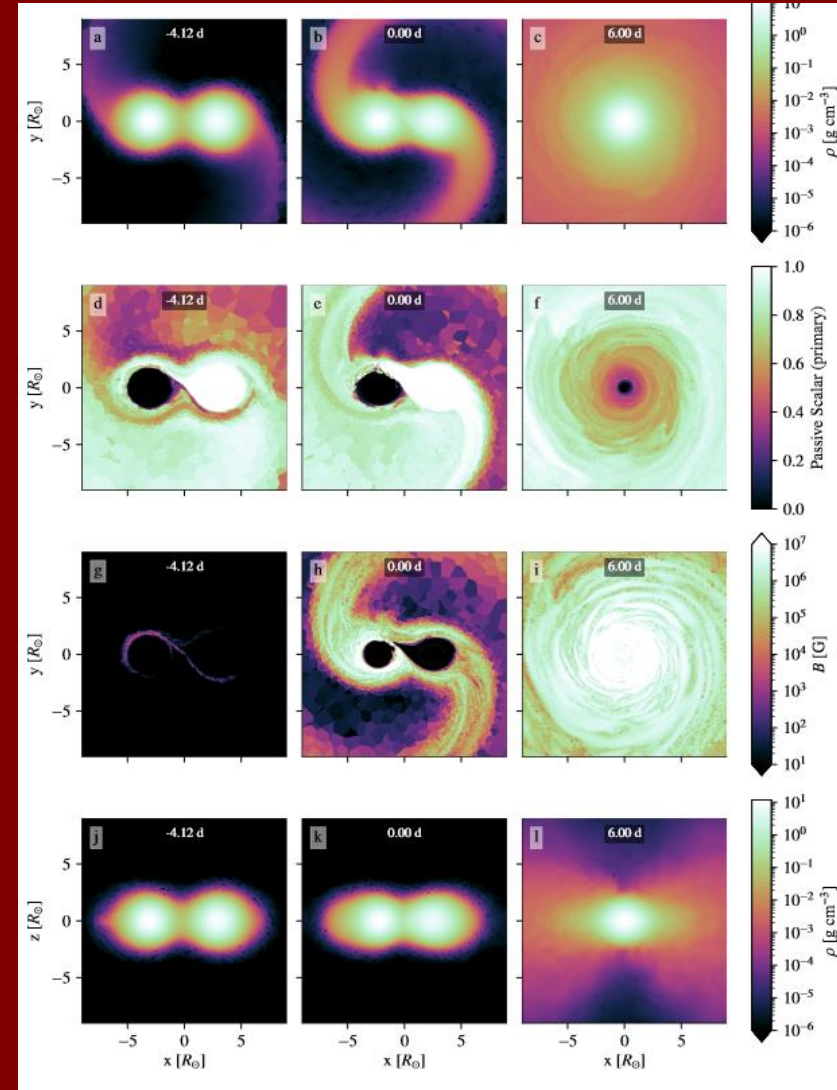
Some candidates for binary companions are proposed in 2203.14947, but up to now these candidates do not look strong enough.

# Magnetic field amplification in binaries

magnetic star  $\tau$  Sco – result of coalescence



If all of the magnetic flux is conserved until core collapse of the merger product, a resulting neutron star of 10 km radius would have a surface magnetic field strength of about  $10^{16}$  G.

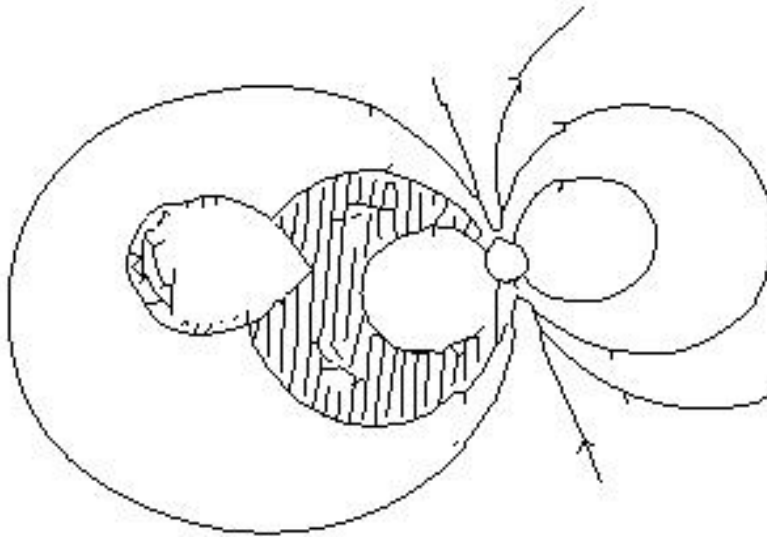


# Are there magnetars in binaries?

At the moment all known SGRs and AXPs are isolated objects.

About 10% of NSs are expected to be in binaries.

The fact that all known magnetars are isolated can be related to their origin, but this is unclear.



If a magnetar appears in a very close binary system, then an analogue of a *polar* can be formed.

The secondary star is inside the huge magnetosphere of a magnetar.

This can lead to interesting observational manifestations.

## Magnetar

[arXiv:0803.1373](https://arxiv.org/abs/0803.1373)

Few candidates have been proposed based on long spin periods and large Pdots:  
1203.1490, 1208.4487, 1210.7680, 1303.5507

# Conclusions

- Two classes of magnetars: SGRs and AXPs
- Similar properties (but no giant flare in AXPs, yet?)
- Hyperflares (27 Dec 2004)
- Transient magnetars
- About 10% of newborn NSs
- Links to PSRs (and others?)
- Twisted magnetospheres

# Papers to read

- Woods, Thompson astro-ph/0406133 – old classical review
- Mereghetti arXiv: 0804.0250
- Rea, Esposito arXiv: 1101.4472 - outbursts
- Turolla, Esposito arXiv: 1303.6052 - Low-field magnetars
- Mereghetti et al. arXiv: 1503.06313
- Turolla, Zane, Watts arXiv: 1507.02924 – Big general review
- Beloborodov, Kaspi arXiv: 1703.00068
- Esposito et al. arXiv: 1803.05716
- Coti Zelati et al. arXiv: 1710.04671 – outbursts
- Gourgouliatos, Esposito 1805.01680 – magnetic fields
- Dall’Osso, Stella 2103.10878 - millisecond magnetars