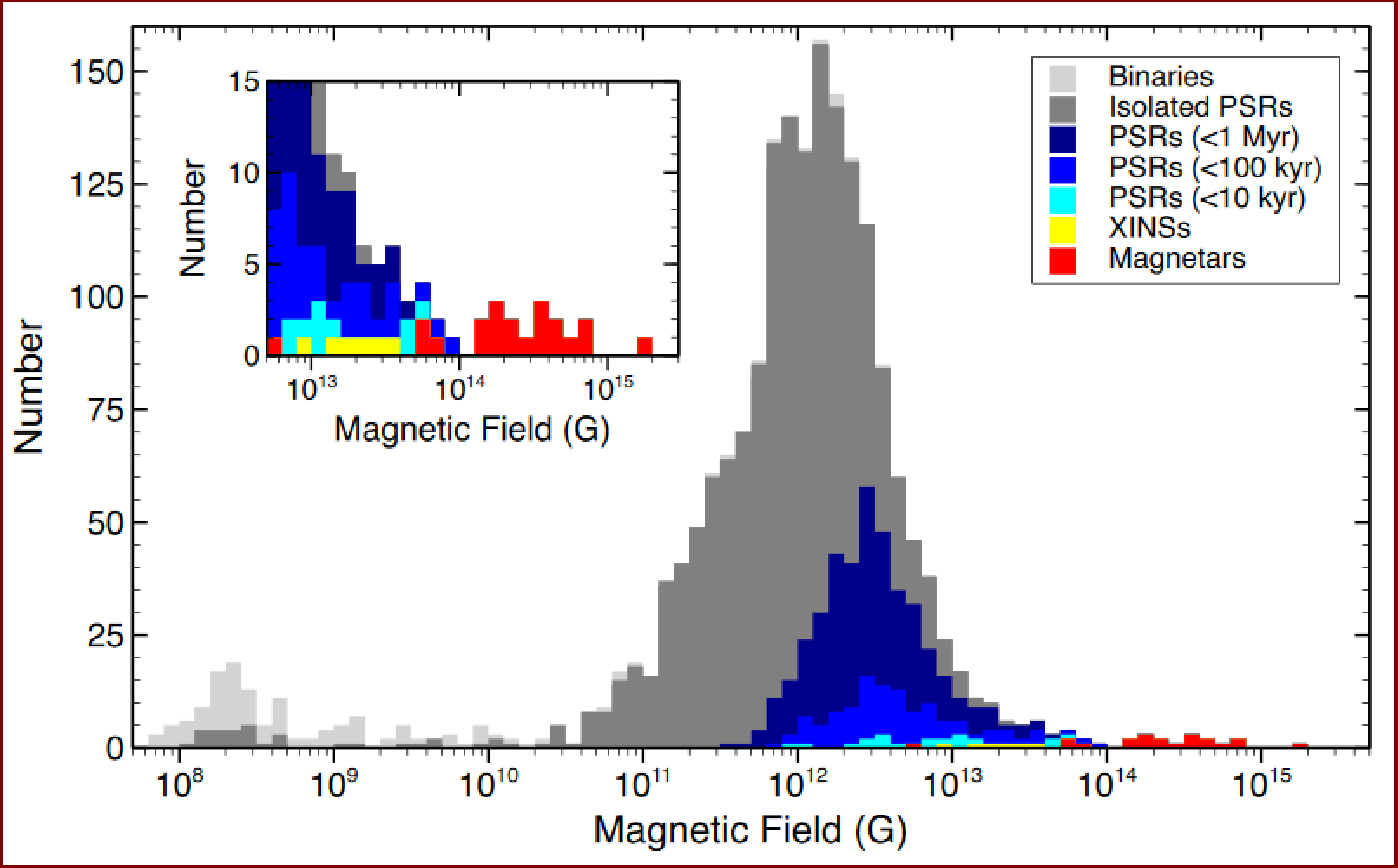
Magnetars: SGRs and AXPs

Magnetic field distribution



Fields from P-Pdot using magneto-dipole formula

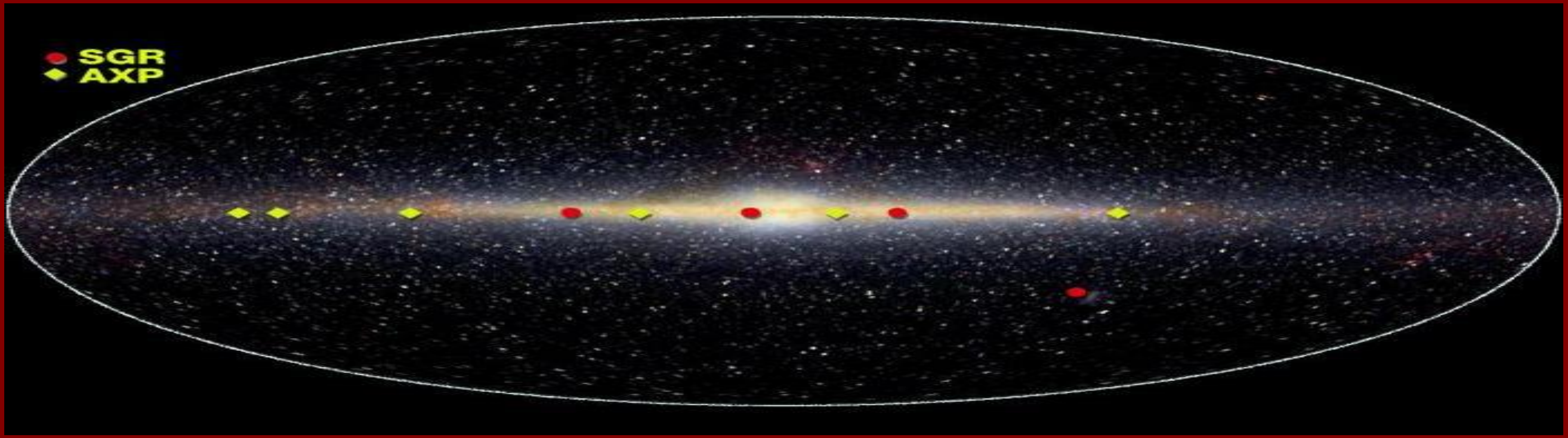
1805.01680 (taken from Olausen, Kaspi 2014)

Magnetars in the Galaxy

- ~24 SGRs and AXPs, plus 6 candidates, plus radio pulsars with high magnetic fields (about them see arXiv: 1010.4592)…
- Young objects (about $10^{3\text{-}5}$ year).

See the latest candidate in 2307.09224

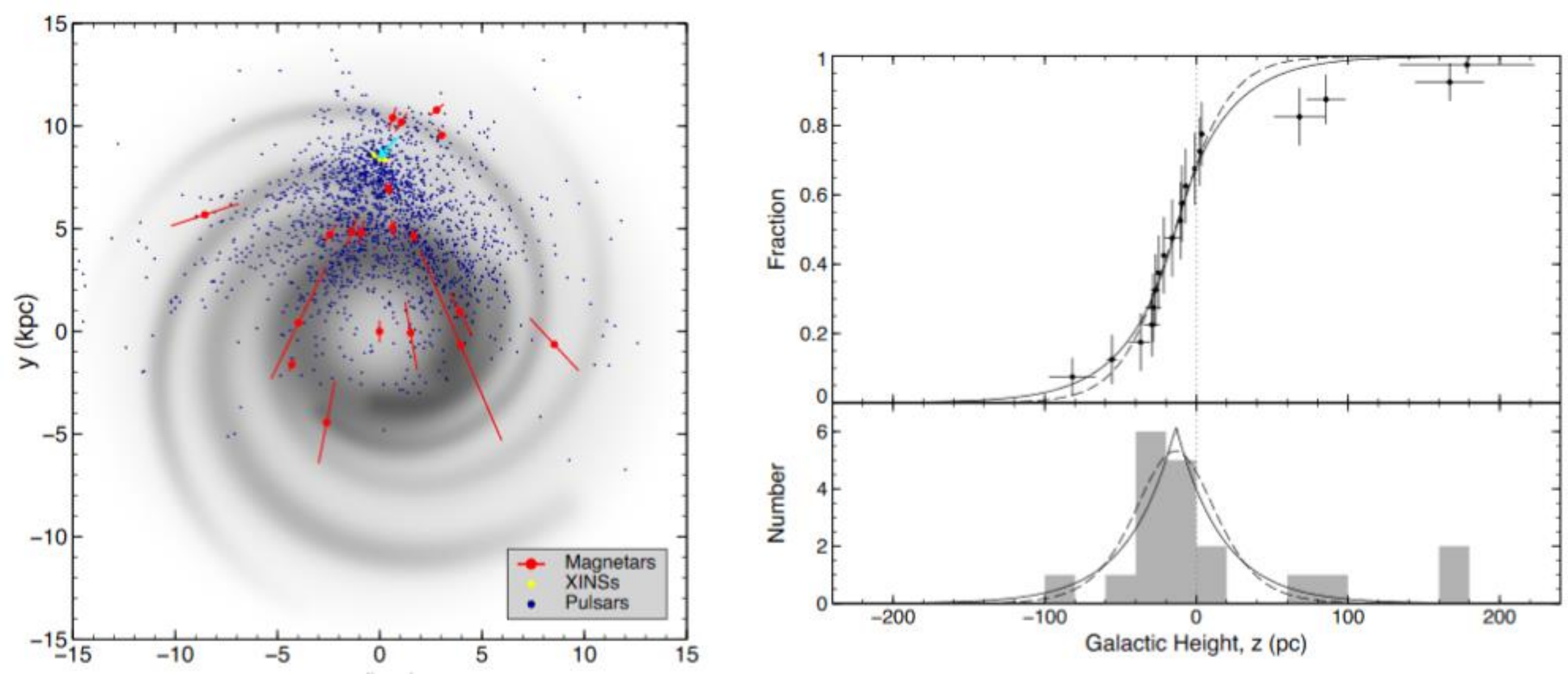
Catalogue: http://www.physics.mcgill.ca/~pulsar/magnetar/main.html



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

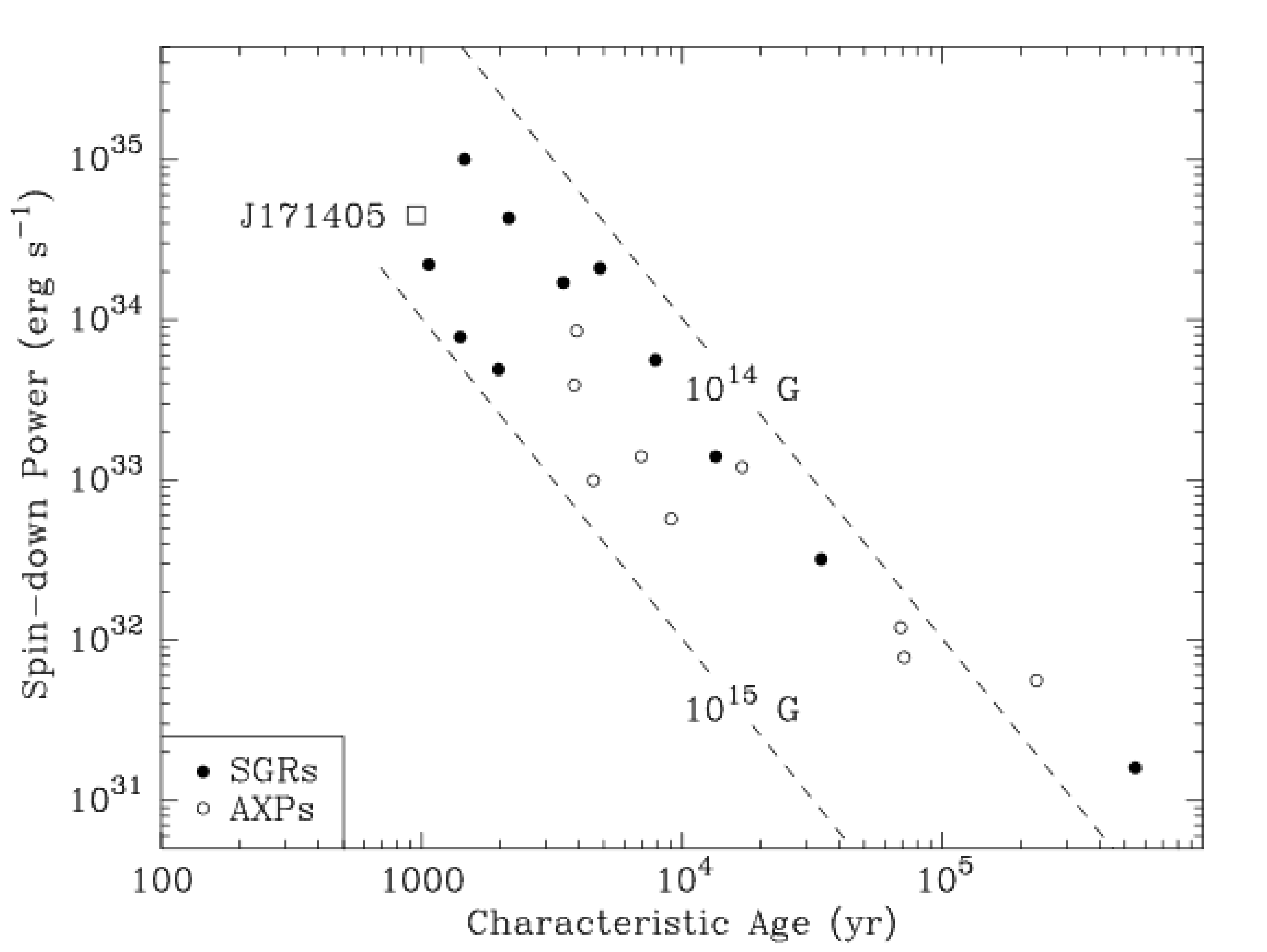
Spatial distribution

Scale height ~20 pc



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

1703.00068



J171405
SGRs
AXPs
10^{14} G
10^{15} G
Spin-down Power (erg s^{-1})
Characteristic Age (yr)
100
1000
10^4
10^5
10^{31}
10^{32}
10^{33}
10^{34}
10^{35}

1907.13267

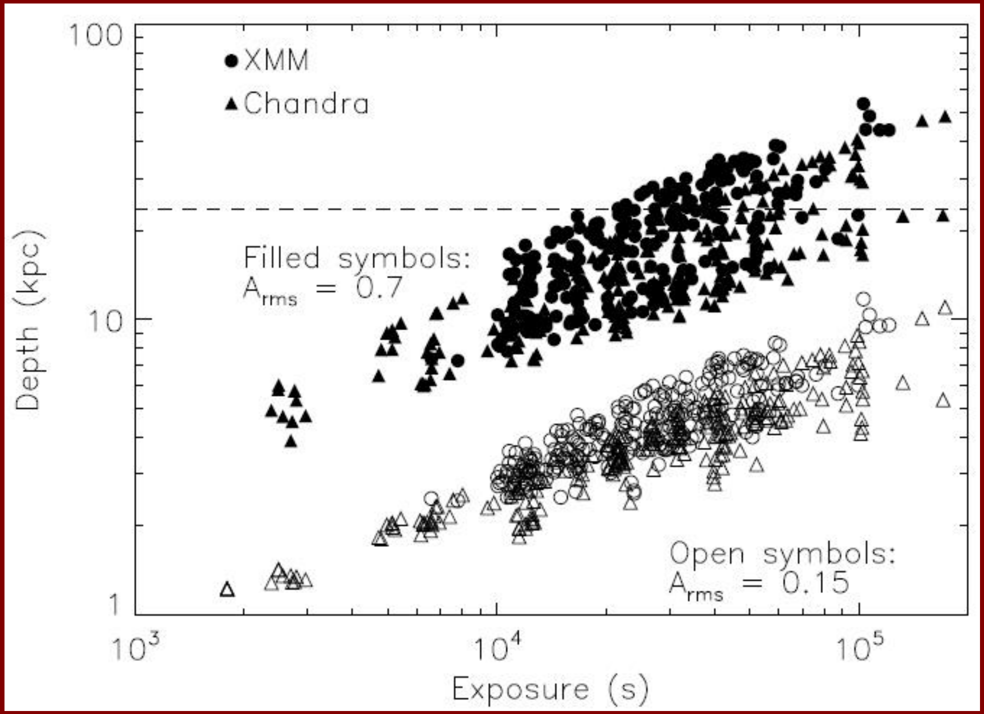
Birth rate of magnetars

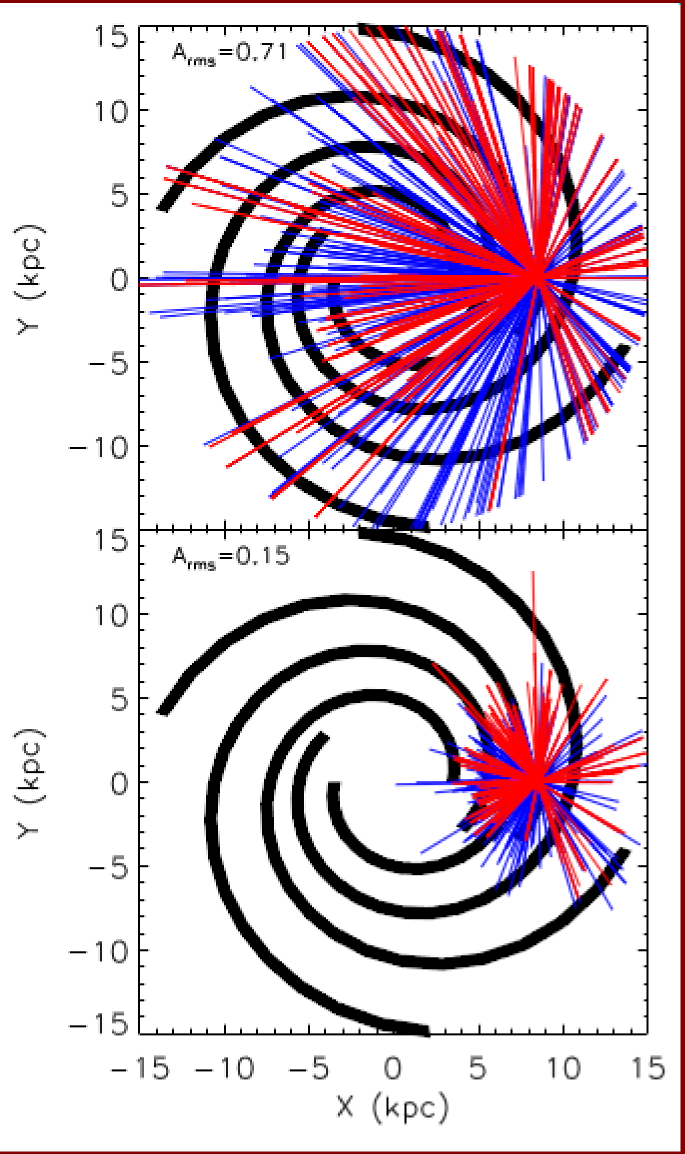
Fraction of magnetars among NSs is uncertain.

Typically, the value ~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 10^{33} A_{rms}=15%)

59^{+92}_{-32} easily detectable (L=10^{35} A_{rms}=70%)

Muno et al. arXiv: 0711.0988

Modeling the population of magnetars

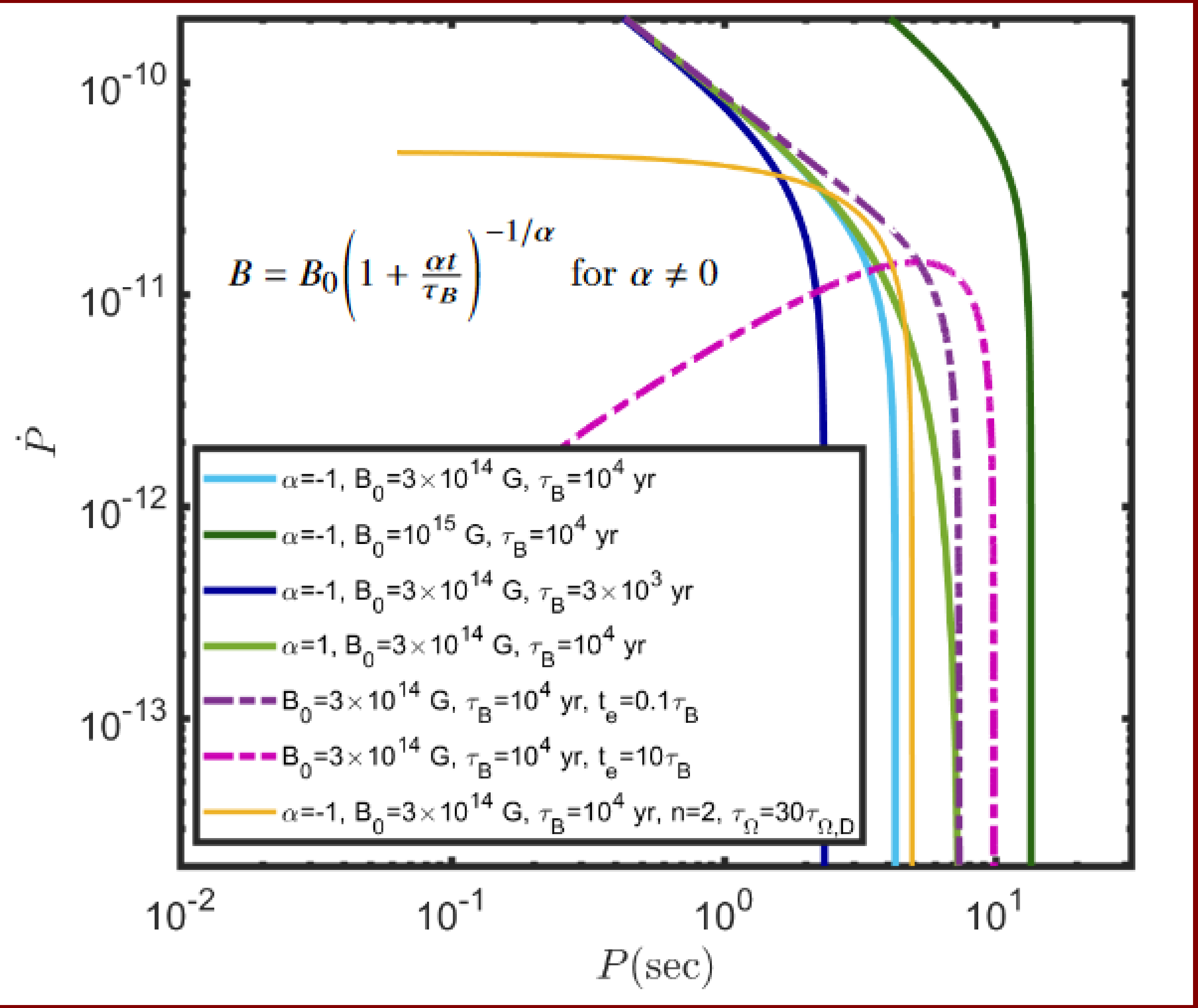
Birthrate 2.3-20 kyr^{-1}

$0.4^{+0.6}_{-0.28}$ of NSs
are born as magnetars

Fields decay in $\sim 10^4$ yrs

Maximum expected
spin period 13 s.

Hyperflares can be
detected by Swift
at ~100Mpc.
Thus, rate $\sim 5\ \mathrm{yr}^{-1}$



1903.06718

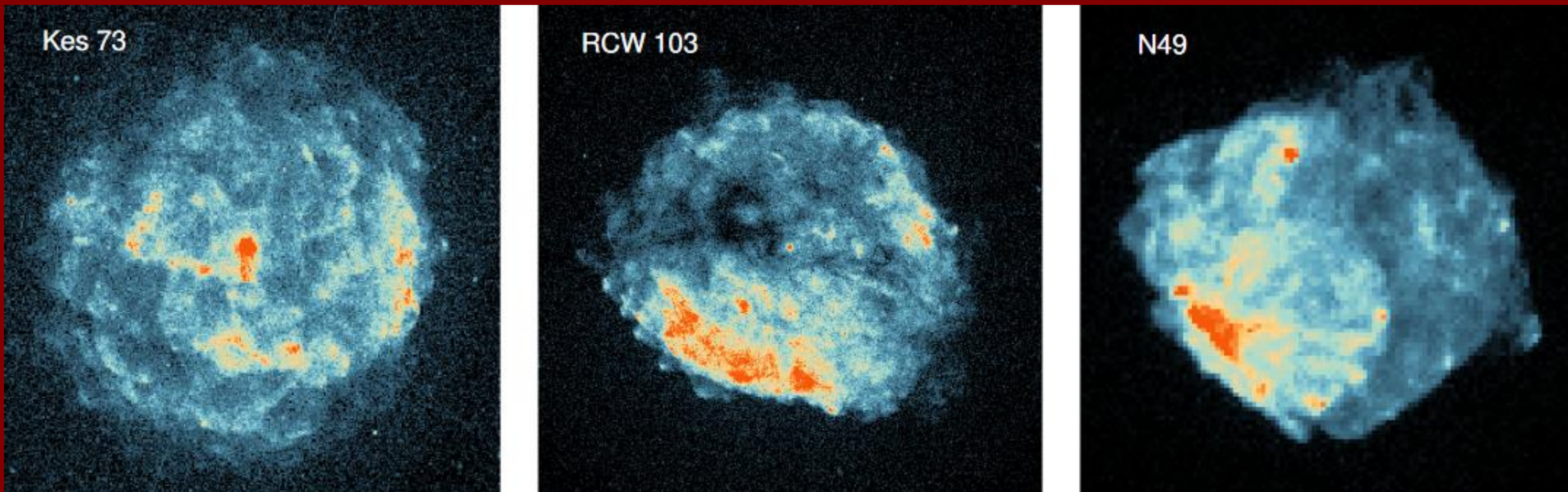
Several of magnetars are related to SNRs.

Many of magnetars show glitches (see 1903.09736).

Name[b]	P (s)	B[c] (10^{14} G)	Age[d] (kyr)	$\dot{E}$[e] 10^{33} erg s^{-1}	D[f] (kpc)	L_X[g] 10^{33} erg s^{-1}	Band[h]
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
SGR 0526−66	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
SGR 1806−20	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	...
SGR 1900+14	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
SGR 0755−2933	...	...	...	...	...	...	...
SGR 1801−23	...	...	...	...	...	...	...
SGR 1808−20	...	...	...	...	...	...	...
AX J1818.8−1559	...	...	...	...	...	...	...
AX J1845.0−0258	6.97	...	...	...	...	2.9	...
SGR 2013+34	...	...	...	...	...	...	...

1703.00068

Supernova remnants of magnetars



n_H (cm^{-3})	$7.3^{+0.5}_{-0.4}$	5.9 ± 0.2	6.6 ± 0.3
M_{SNR} ($M_\odot$)	46^{+3}_{-2}	12.8 ± 0.4	200^{+14}_{-10}
t_{sedov} (kyr)	~ 2.4	~ 2.1	~ 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

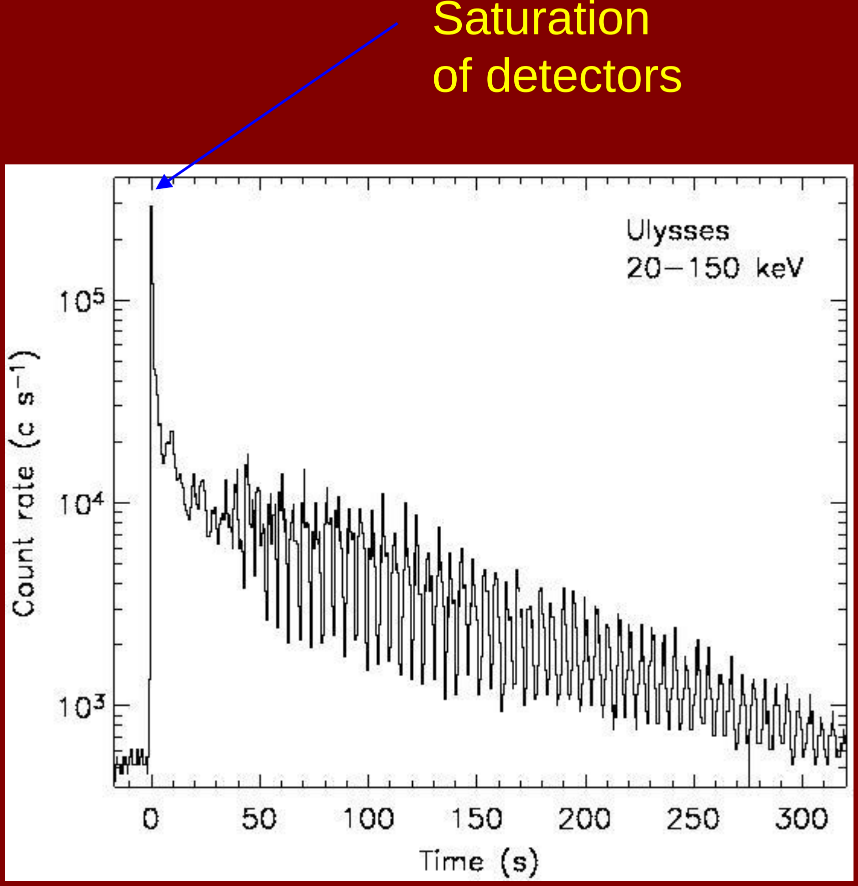
11-15 Msun <13 Msun 13-17 Msun

1909.01922

Fall-back scenario is supported for RCW103

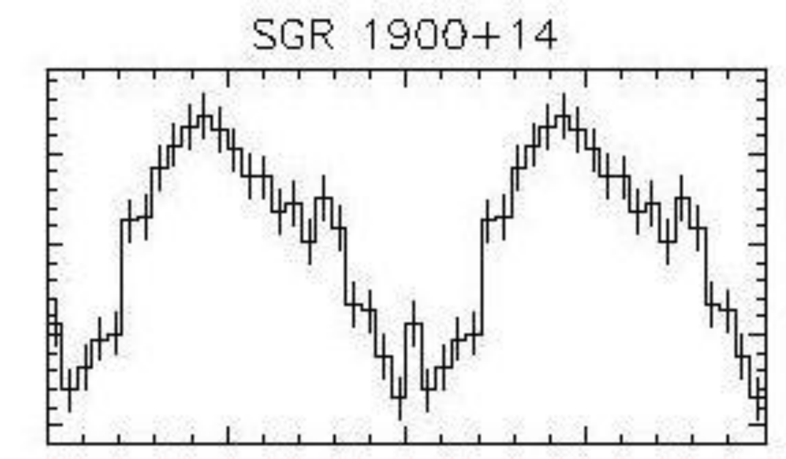
Soft Gamma Repeaters: main properties

- 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 ≈ 5 -10 s
- Huge spindown rates, $\dot{P}/P \approx 10^{-10}\ s^{-1}$



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

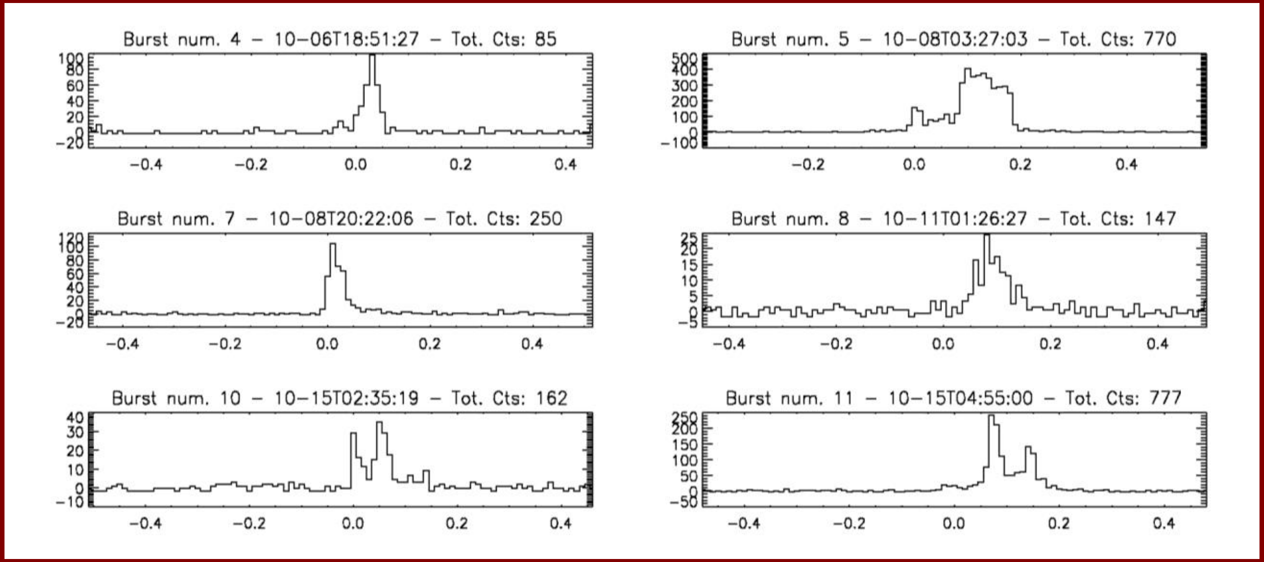


See reviews in Turolla et al. arXiv: 1507.02924
Beloborodov, Kaspi arXiv: 1703.00068

Soft Gamma Repeaters

- Rare class of sources, ~13 confirmed
- Frequent bursts of soft γ-/hard X-rays:

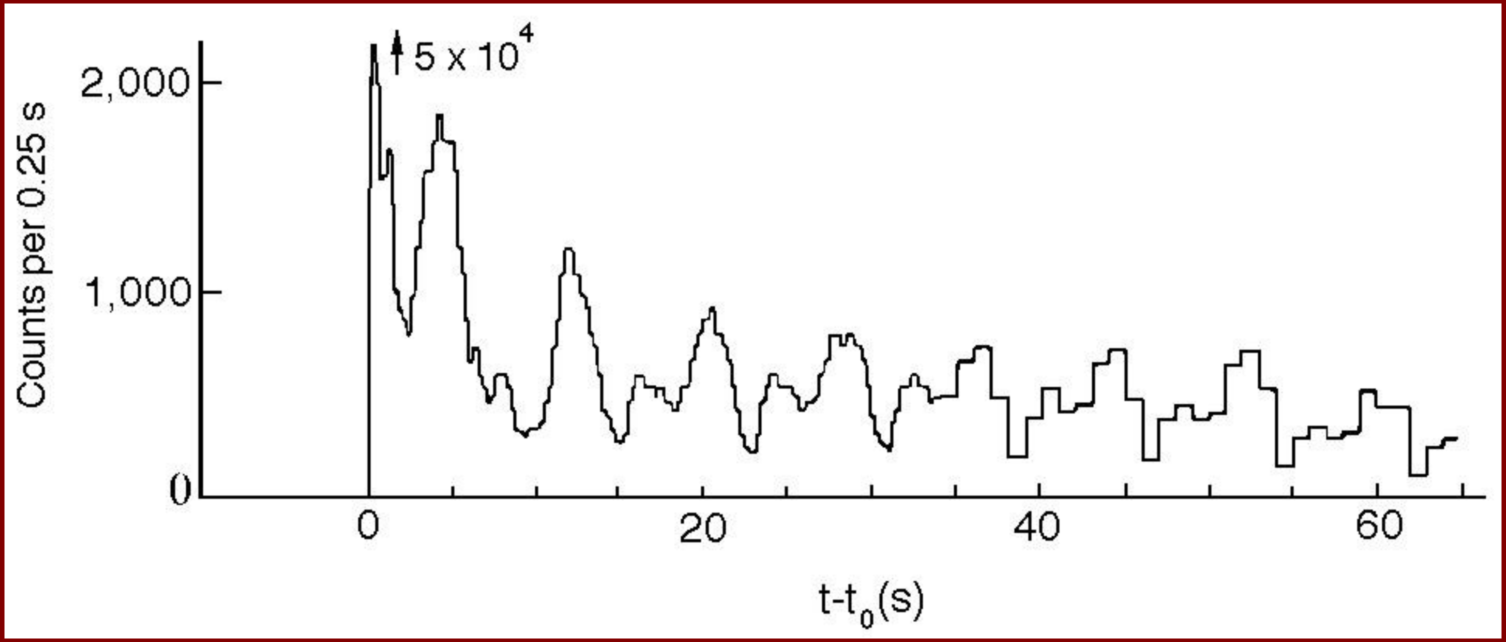
  $L < 10^{42}$ erg/s, duration < 1 s



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

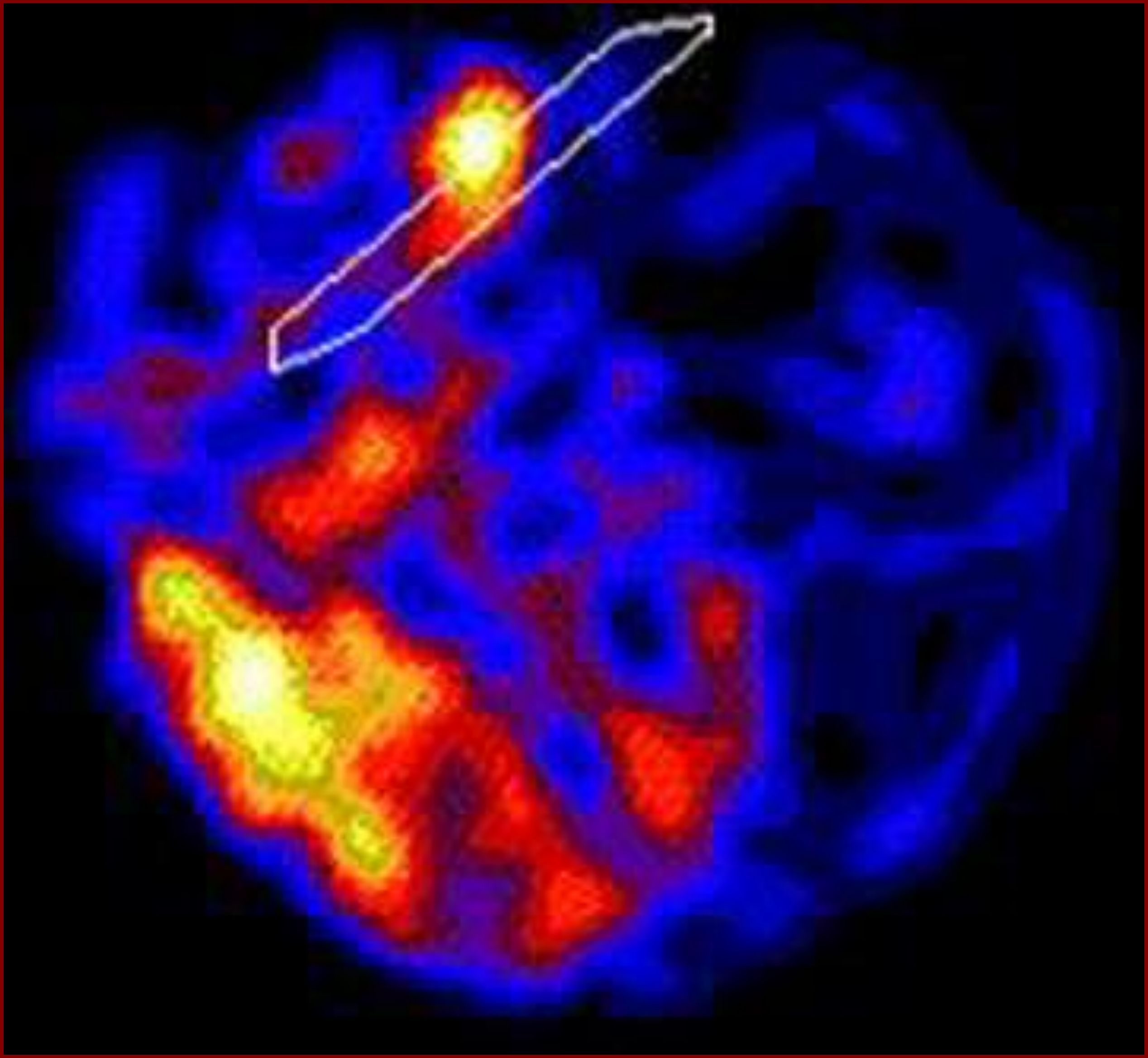
Historical notes

- 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^2



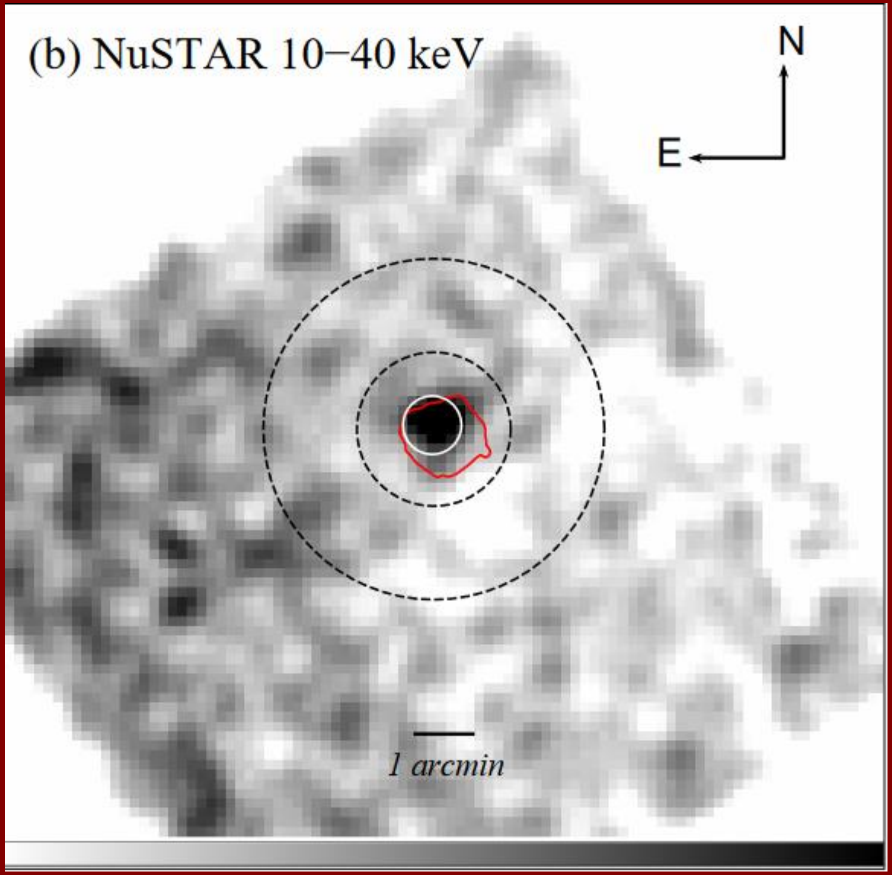
Mazets et al. 1979

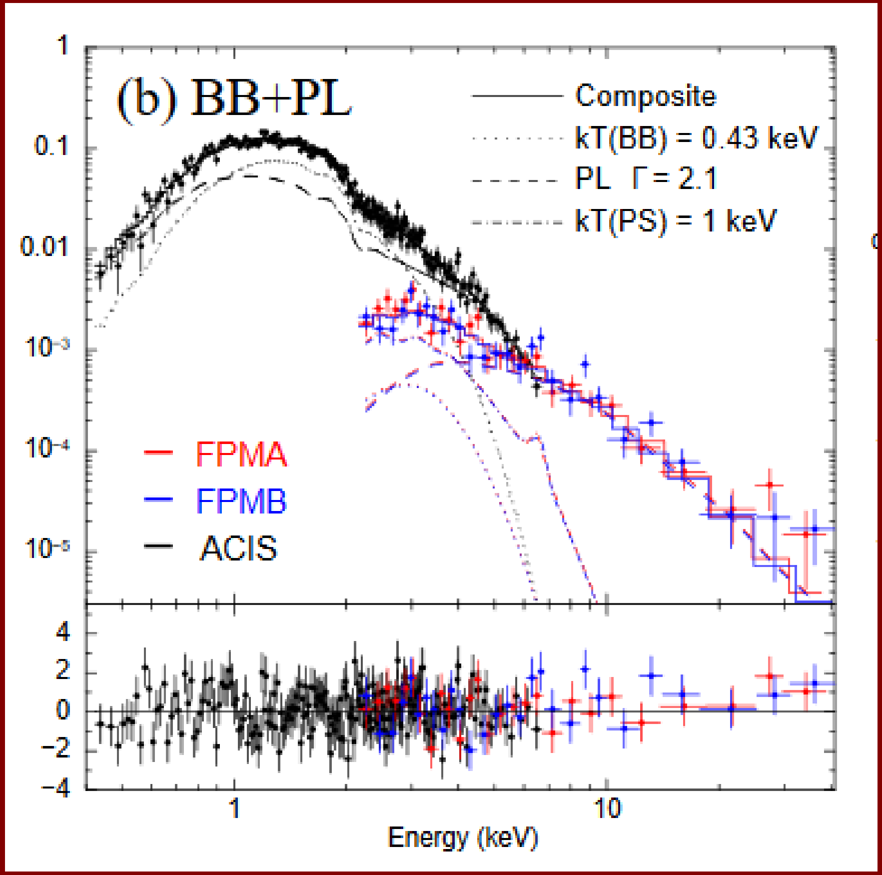
N49 – supernova remnant in the Large Magellanic cloud
(e.g. G. Vedrenne et al. 1979)



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.



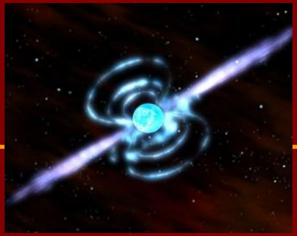


2003.11730

Main types of activity of SGRs

- Weak bursts. $L<10^{42}$ erg/s
- Intermediate. $L\sim10^{42}$–10^{43} erg/s
- Giant. $L<10^{45}$ erg/s
- Hyperflares. $L>10^{46}$ erg/s

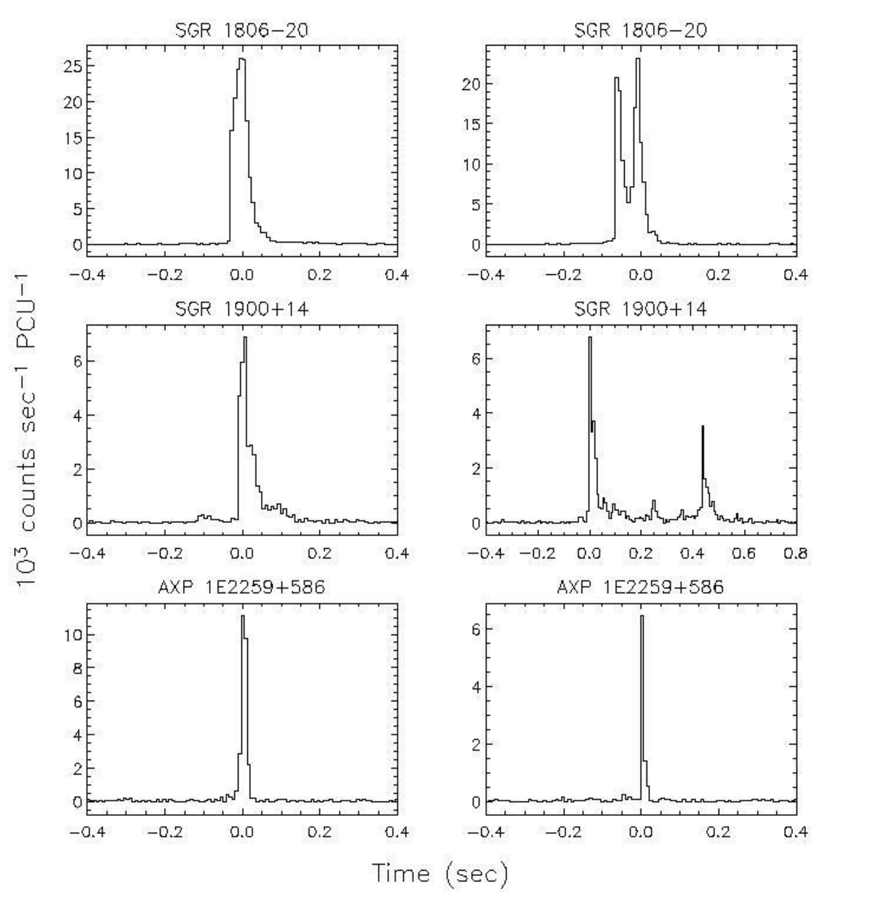
Power distribution is similar to the distribution of earthquakes in magnitude



See the review in Rea, Esposito 1101.4472

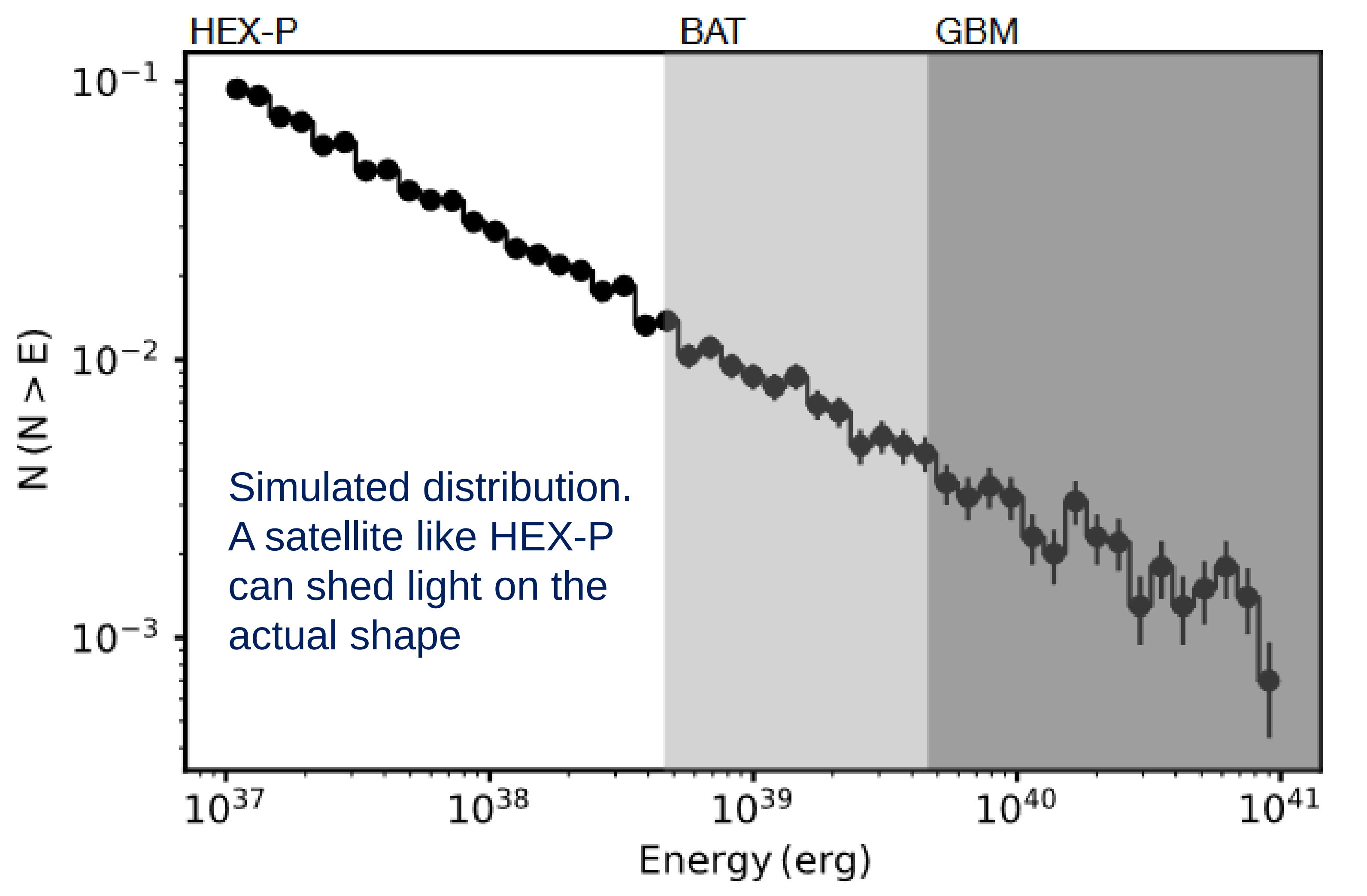
Normal bursts of SGRs and AXPs

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



(from Woods, Thompson 2004)

Log N – log E distribution of weak bursts



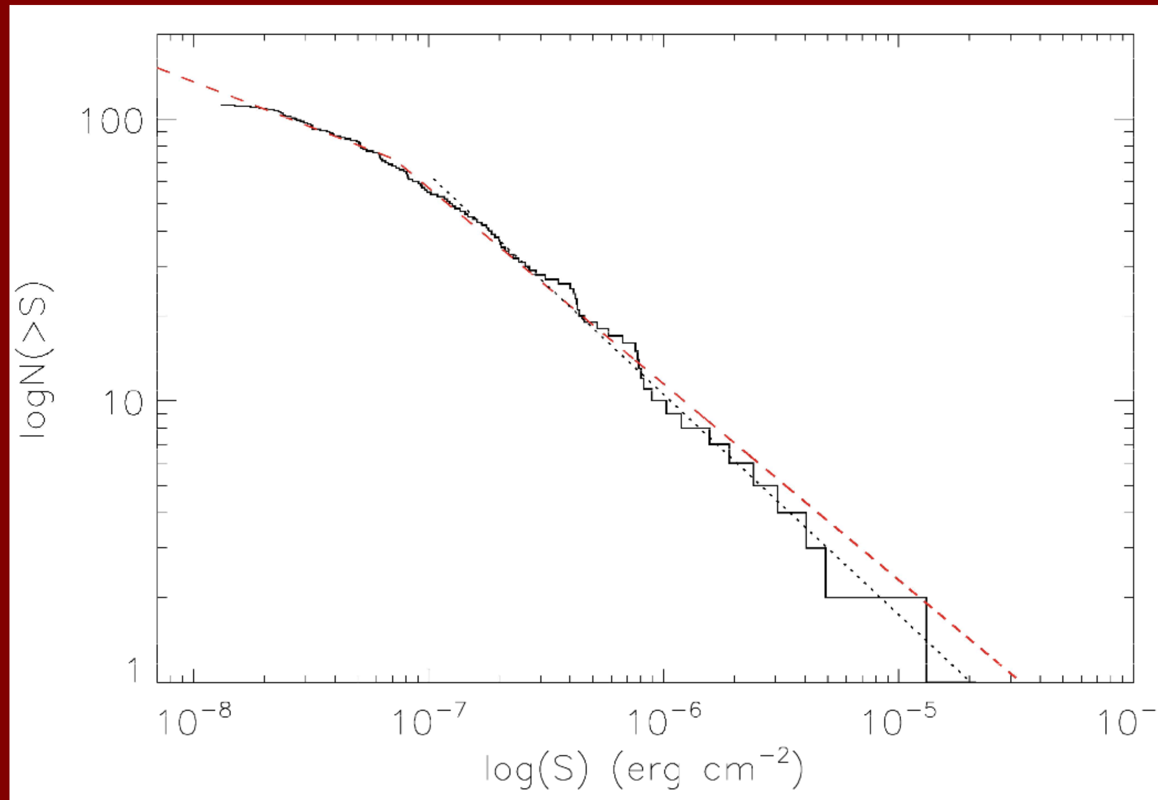
2311.04739

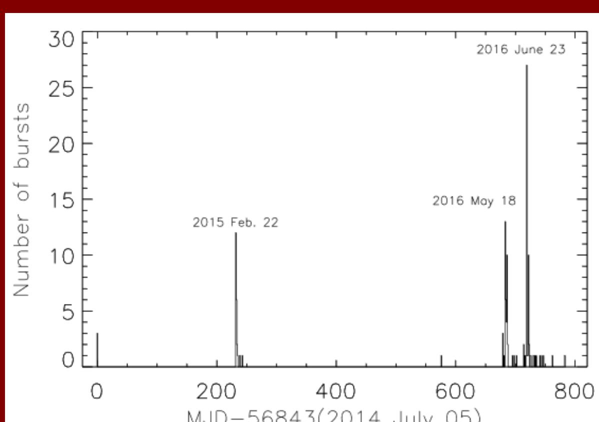
Outbursts

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

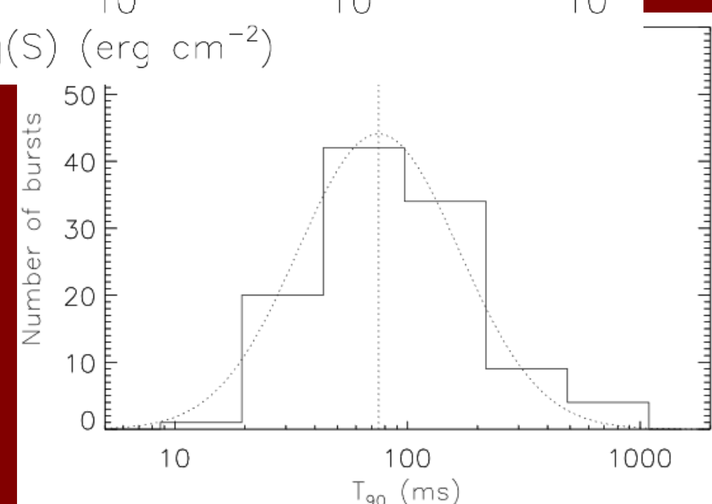
SGR J1935+2154 is the most recurring transient during last years.

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





See the review in Rea, Esposito 1101.4472

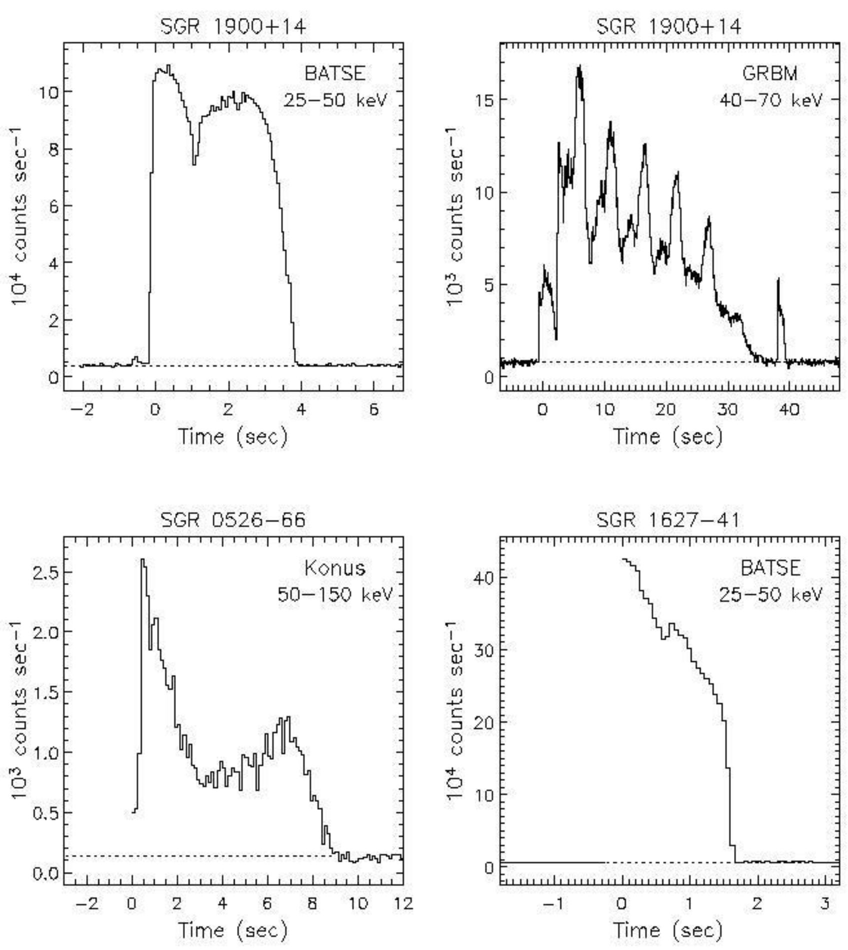


2003.10582

Intermediate SGR bursts

Examples of intermediate bursts.

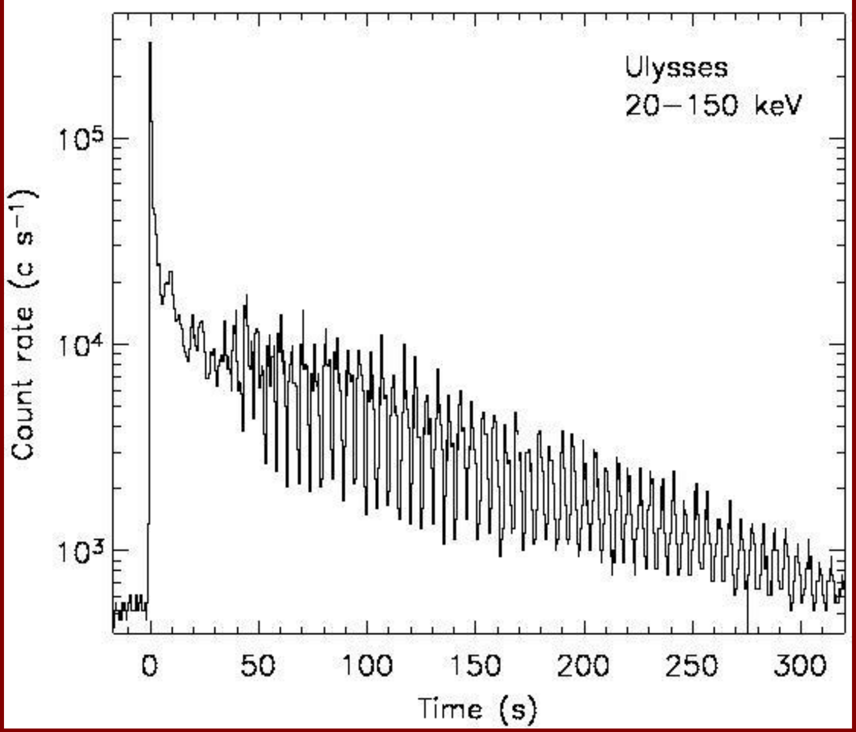
The forth (bottom right) is sometimes defined as a giant burst (for example by Mazets et al.).



(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 10^{44} erg/s
- $E_{TOTAL}>10^{44}$ erg

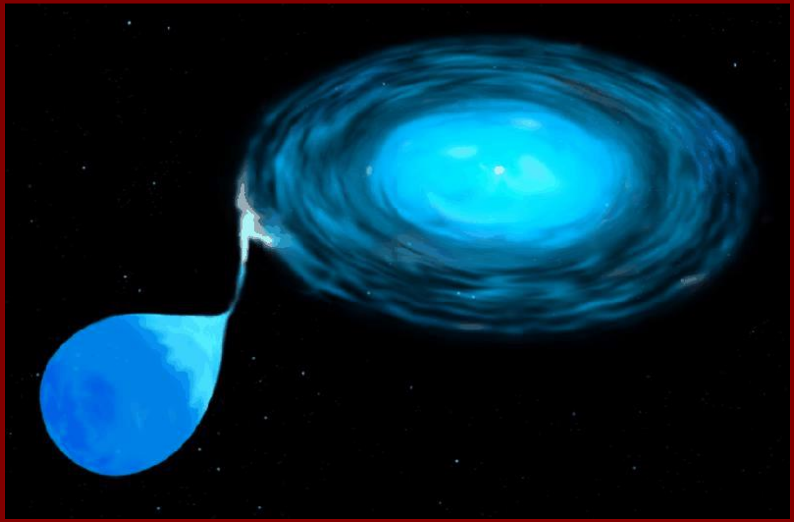


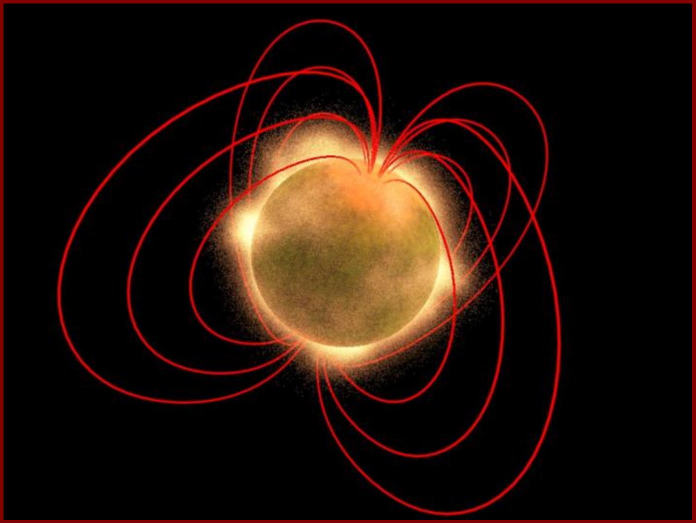
Hurley et al. 1999

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

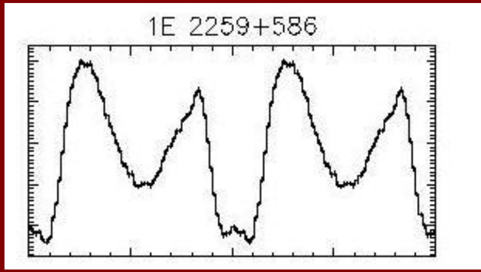
- Fourteen sources known:

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 $P \approx 2$ -12 s
- Large spindown rates, $\dot{P}/P \approx 10^{-11}$ s^{-1}
- No evidence for a binary companion, association with a SNR in several cases

Known AXPs

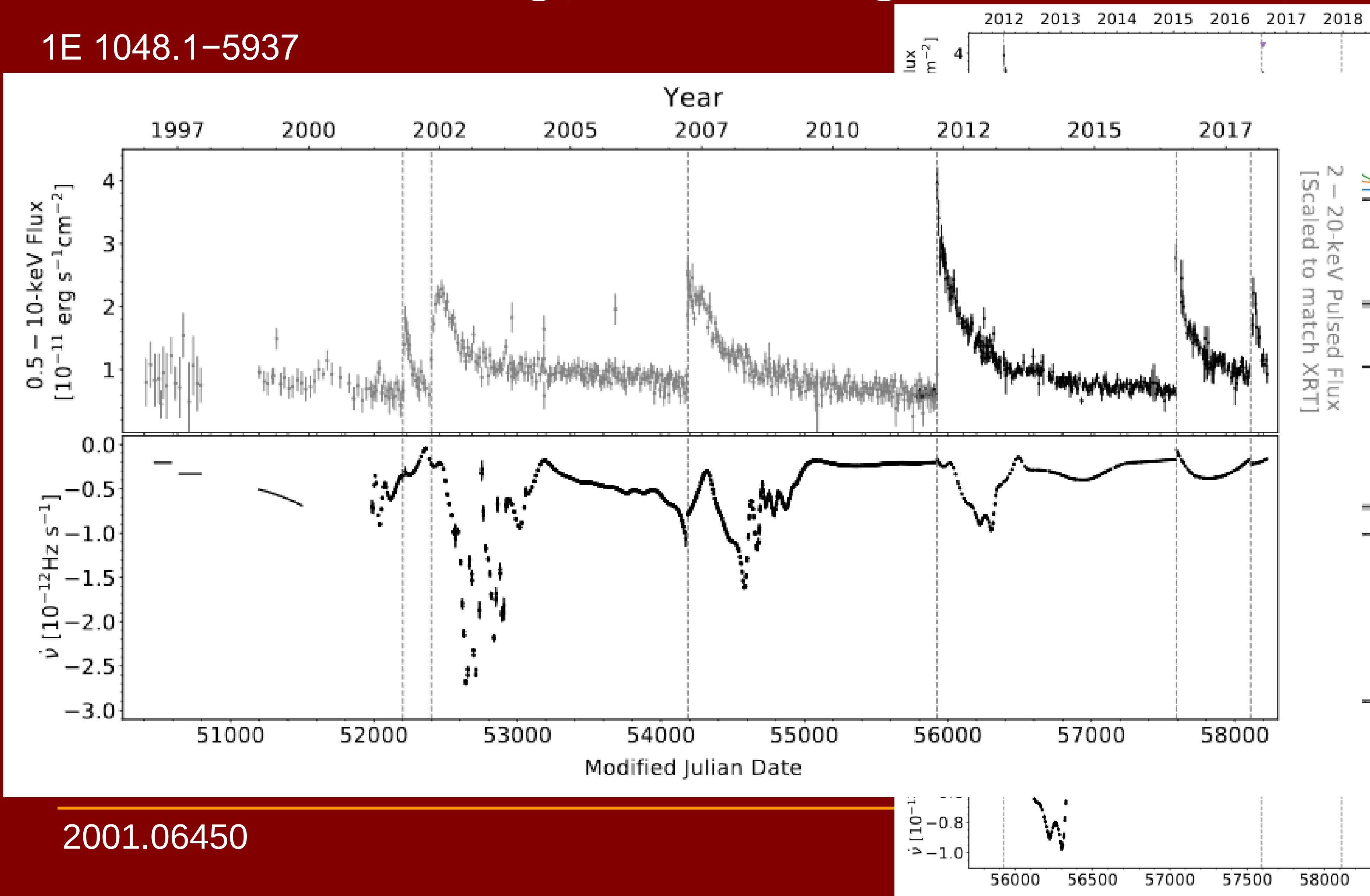
Sources	Periods, s
CXO 010043-7211	8.0
4U 0142+61	8.7
1E 1048.1-5937	6.4
1E 1547.0-5408	2.1
CXOU J164710-4552	10.6
1RXS J170849-40	11.0
XTE J1810-197	5.5
1E 1841-045	11.8
AX J1845-0258	7.0
PSR J1622-4950	4.3
CXOU J171405.7-381031	3.8
1E 2259+586	7.0



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

Phenomenology of a magnetar activity

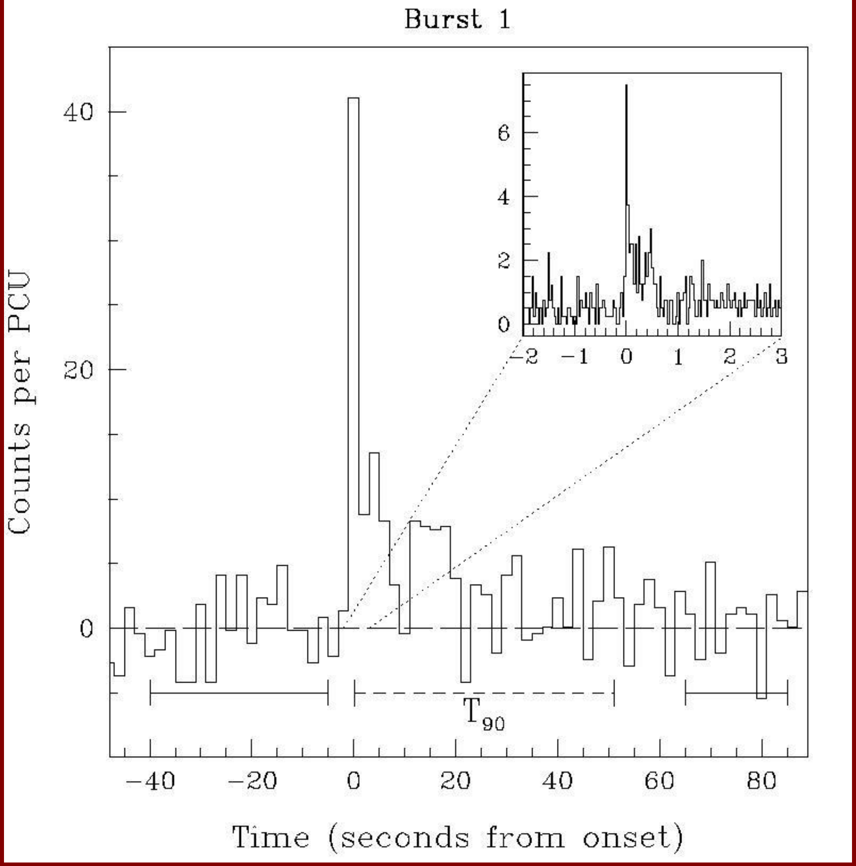
1E 1048.1−5937



2001.06450

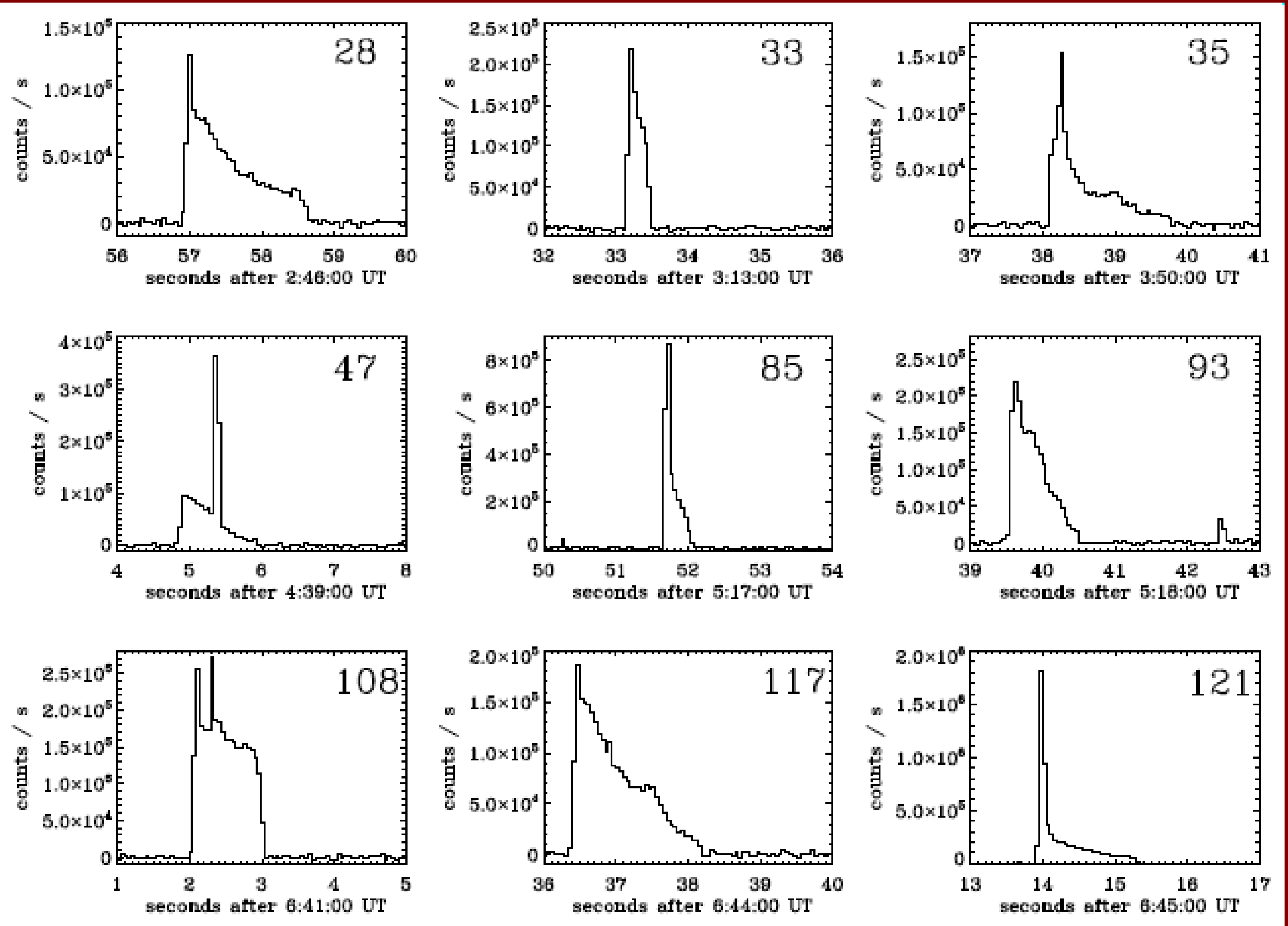
Are SGRs and AXPs brothers?

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



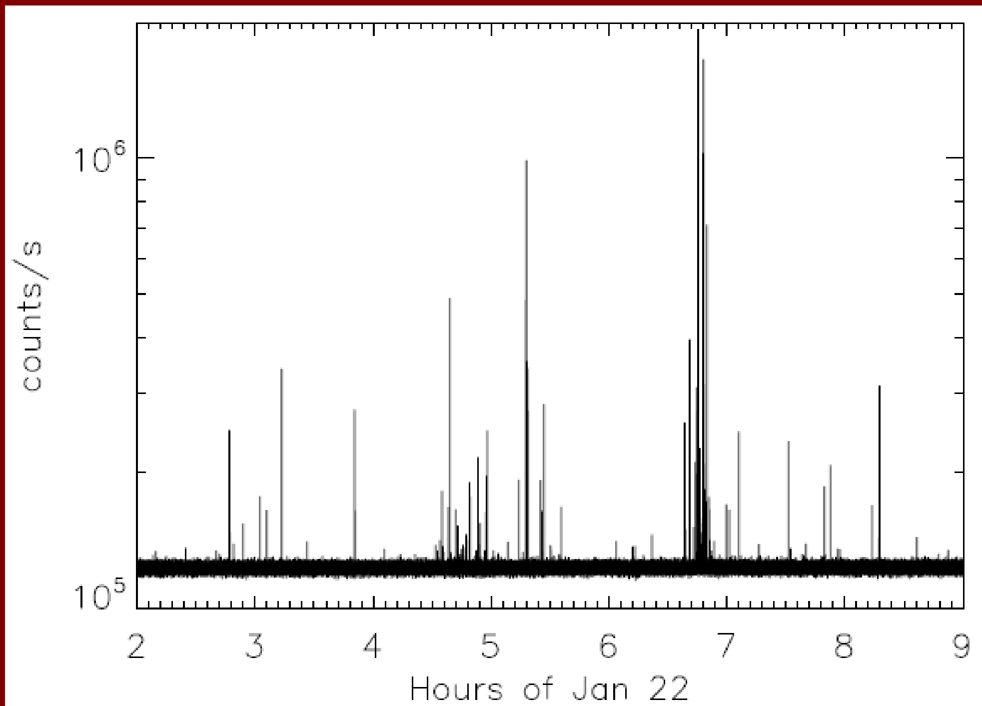
Gavriil et al. 2002

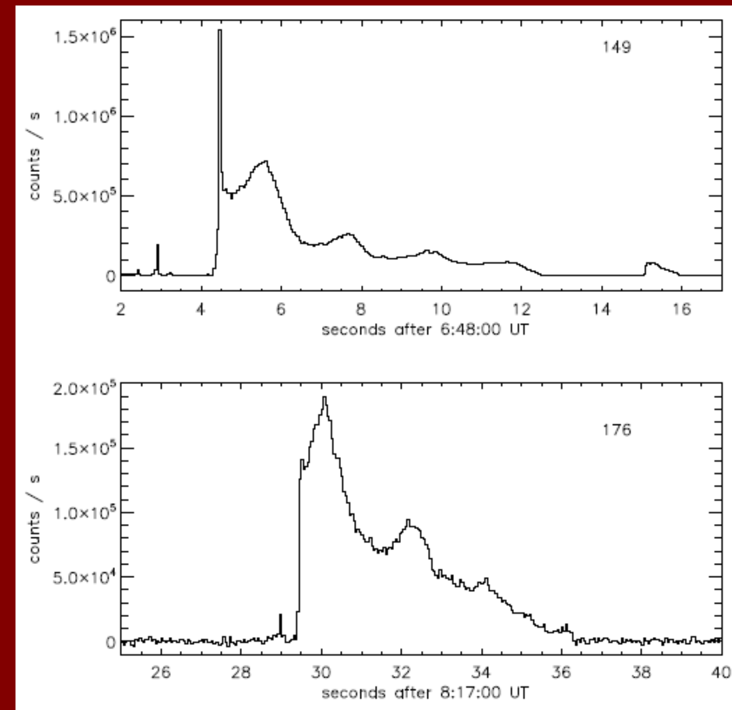
Bursts of the AXP 1E1547.0-5408



0903.1974

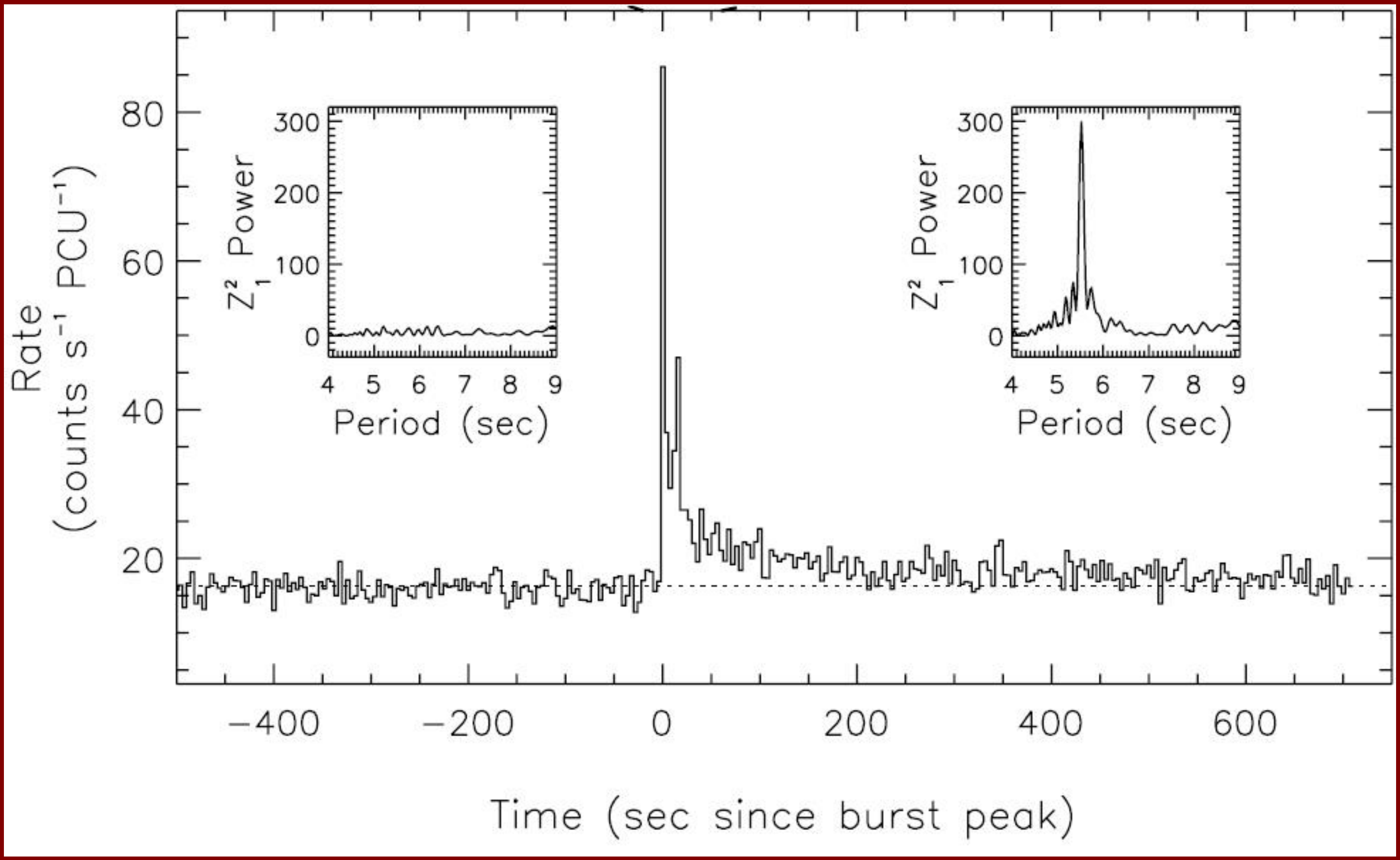
Bursts of the AXP 1E1547.0-5408





Some bursts have pulsating tails with spin period.

Unique AXP bursts?



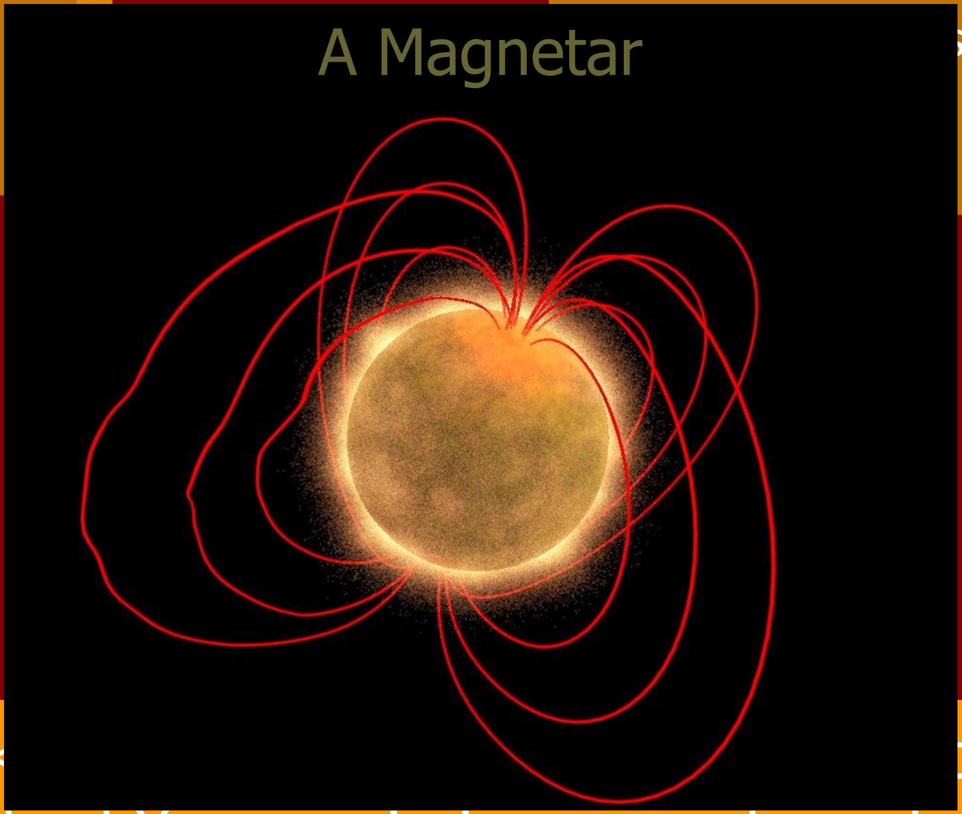
Bursts from AXP J1810-197. Note a long exponential tail with pulsations.

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

A Tale of Two Populations ?

SGRs: bursting X/γ-ray sources

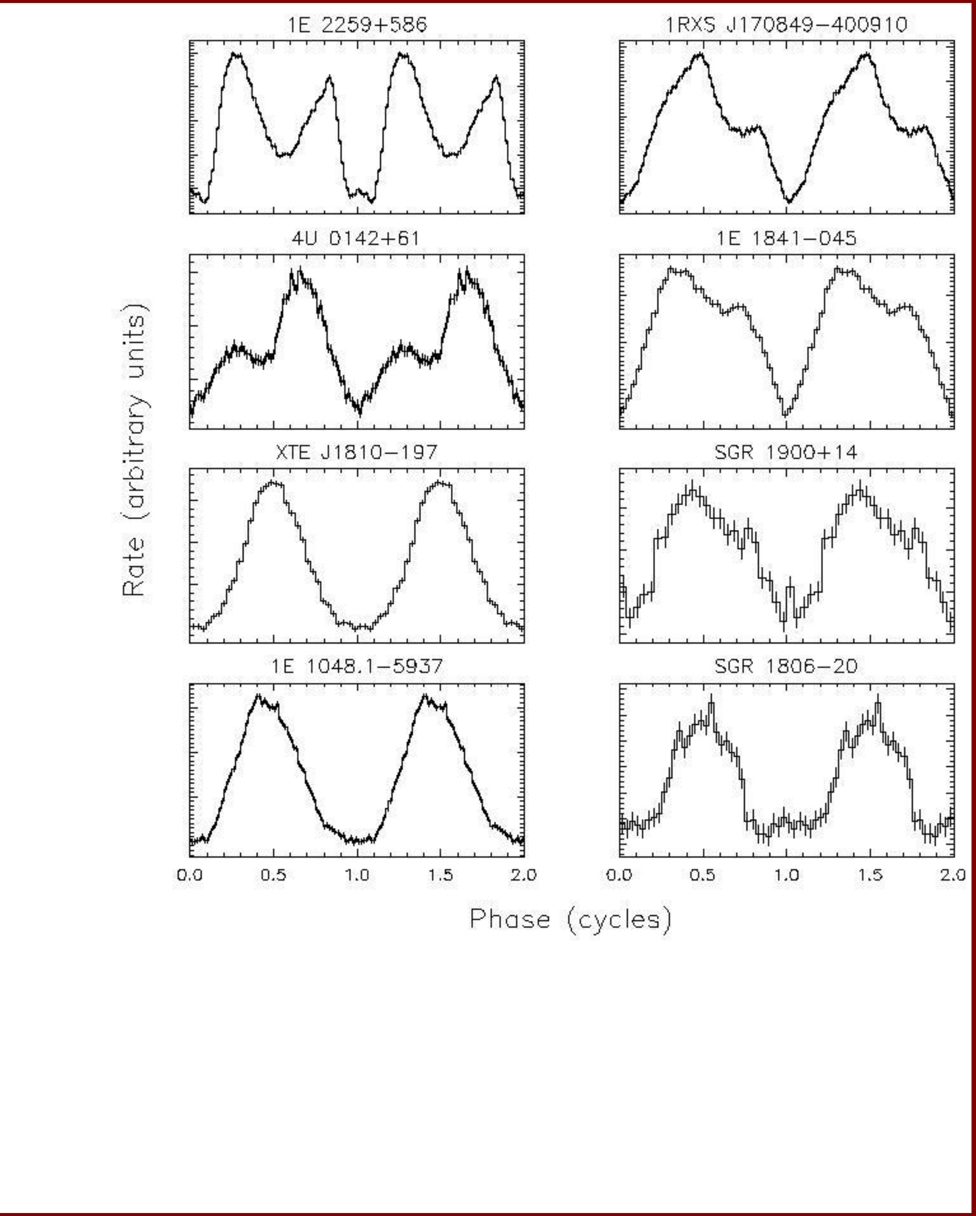
ss

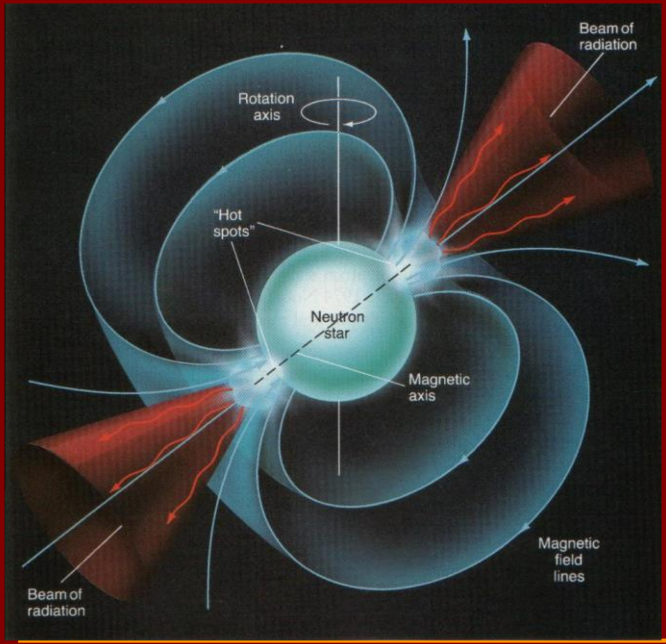


R < ... ct

Pulsed X-ray emission: a neutron star

Pulse profiles of SGRs and AXPs



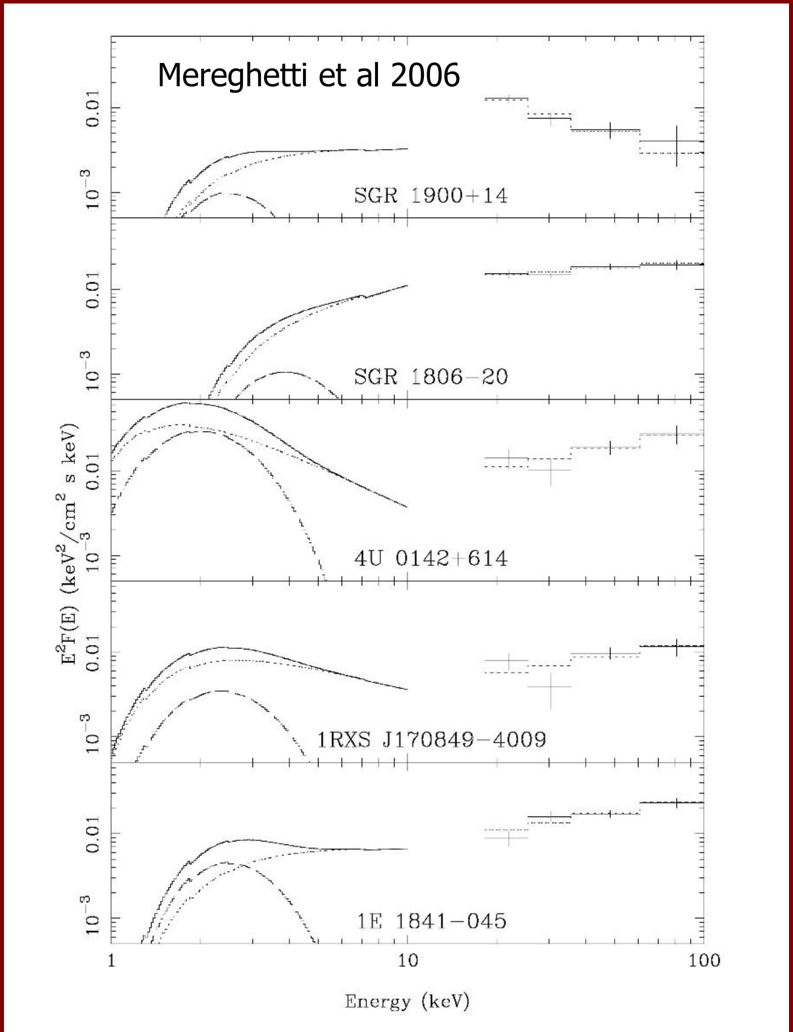


Hard X-ray Emission

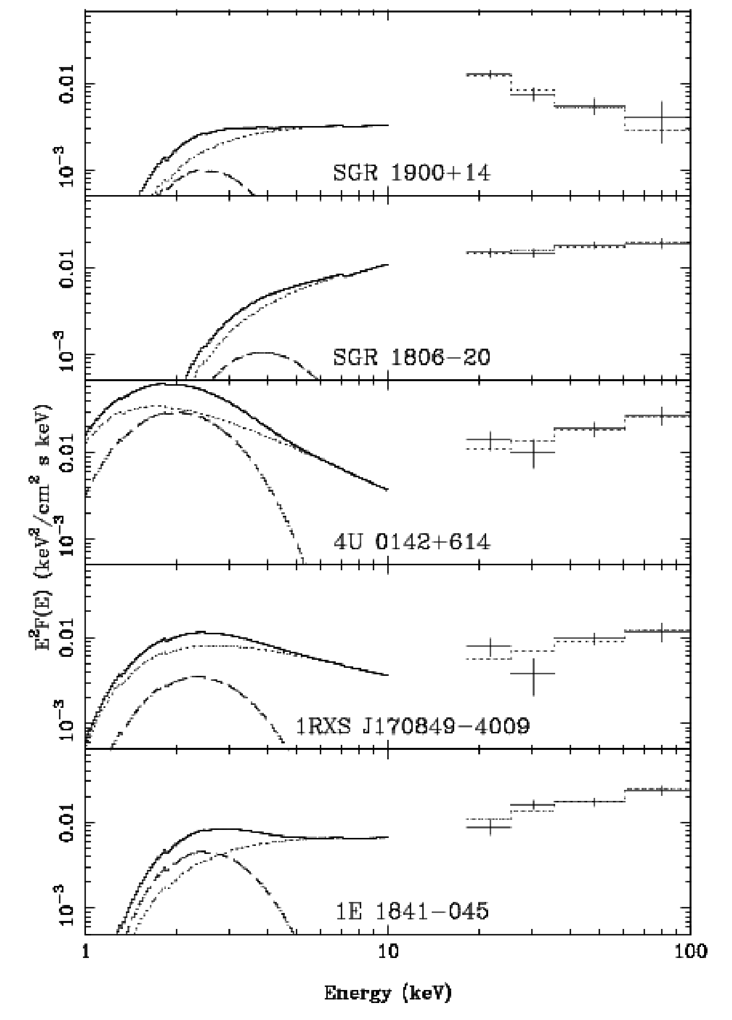
INTEGRAL revealed substantial emission in the 20 -100 keV band from SGRs and APXs

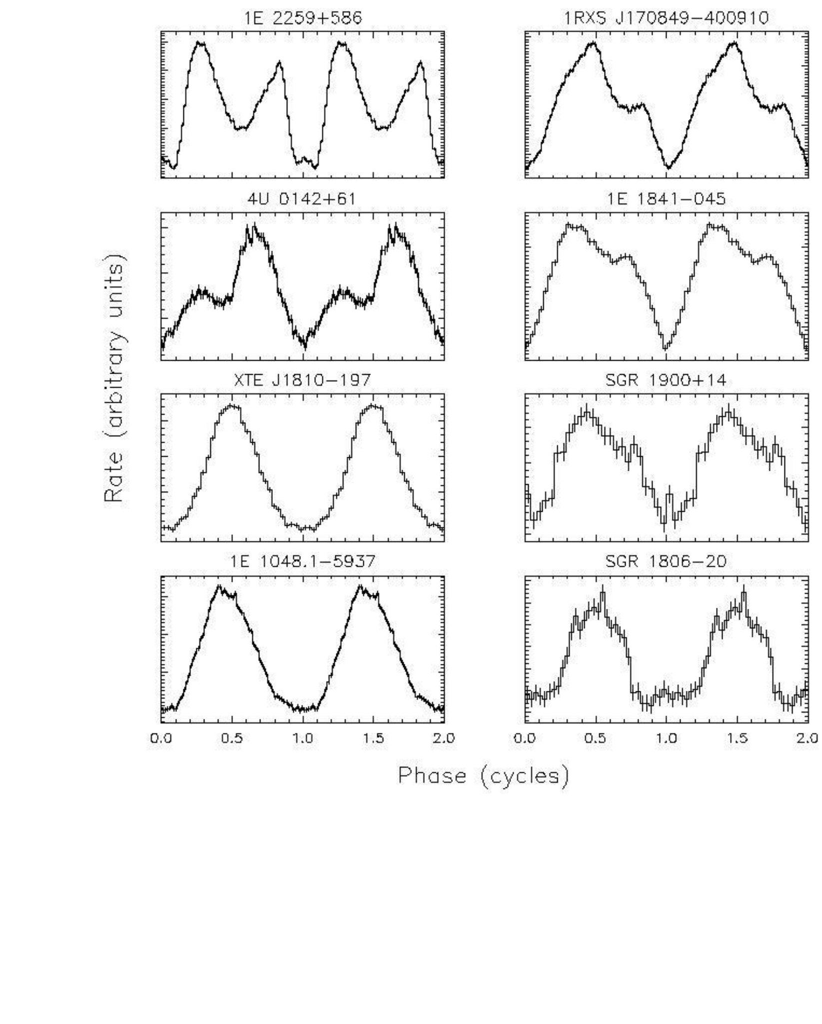
Hard power law tails with $\Gamma \approx 1\text{-}3$
(see 1712.09643 about spectral modeling)

Hard emission pulse



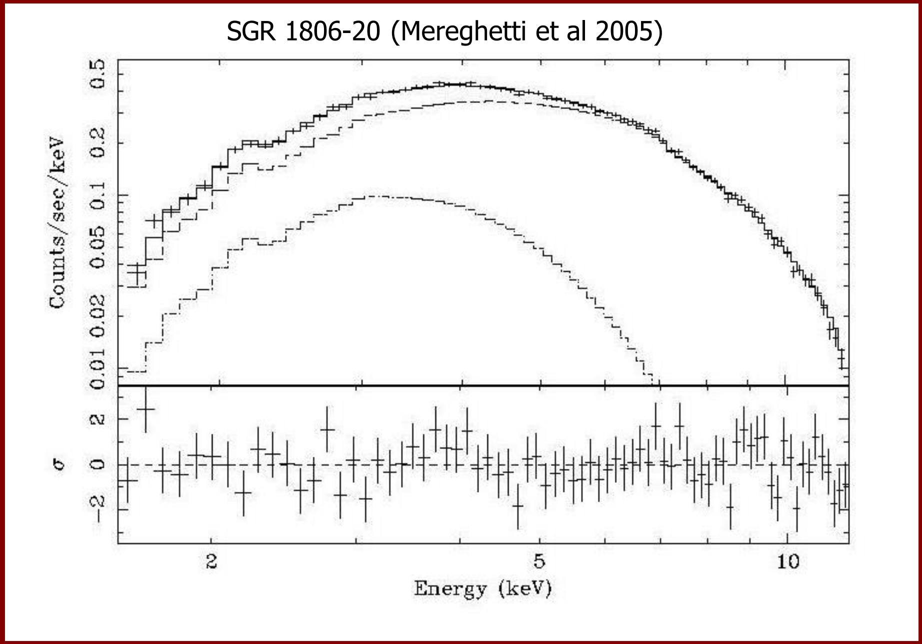
SGRs and AXPs

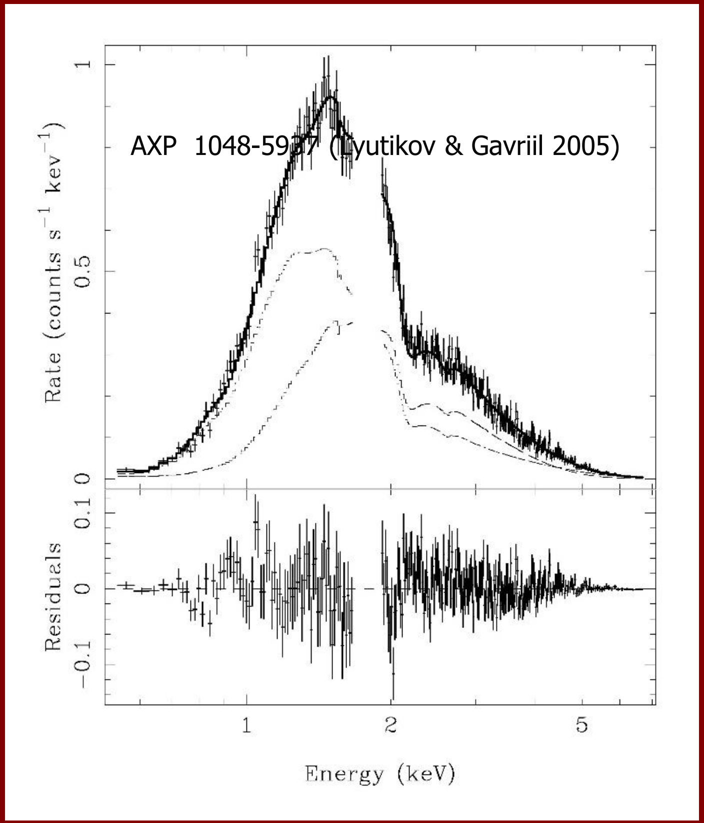




SGRs and AXPs soft X-ray Spectra

- 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

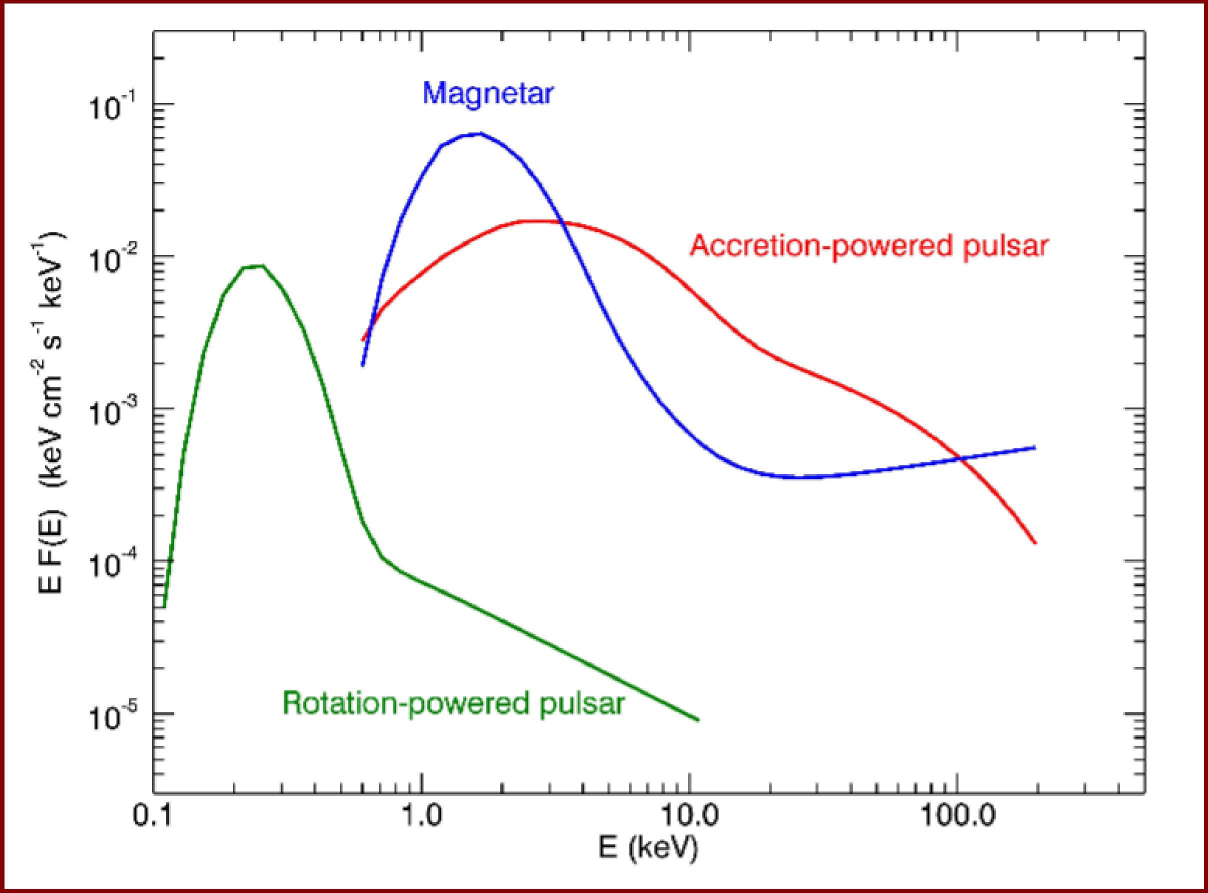
- kT_{BB} ~ 0.5 keV, does not change much in different sources
- Photon index $\Gamma \approx 1 - 4$,

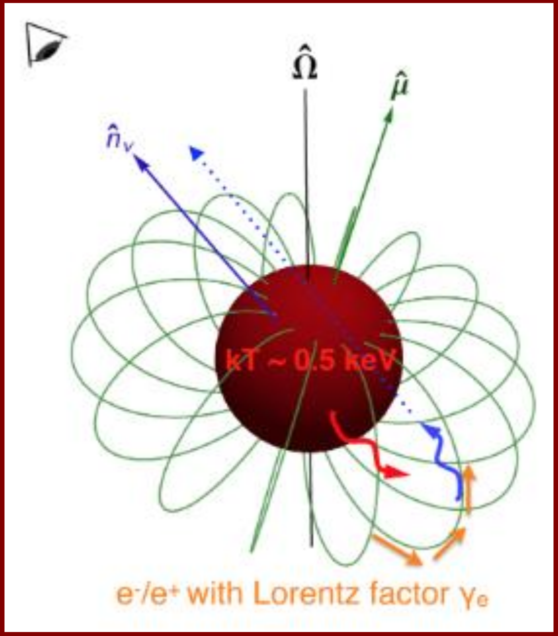
  AXPs tend to be softer
- SGRs and AXPs persistent emission is variable (months/years)
- Variability is mostly associated with

  the non-thermal component

Magnetar spectra in comparison

1503.06313

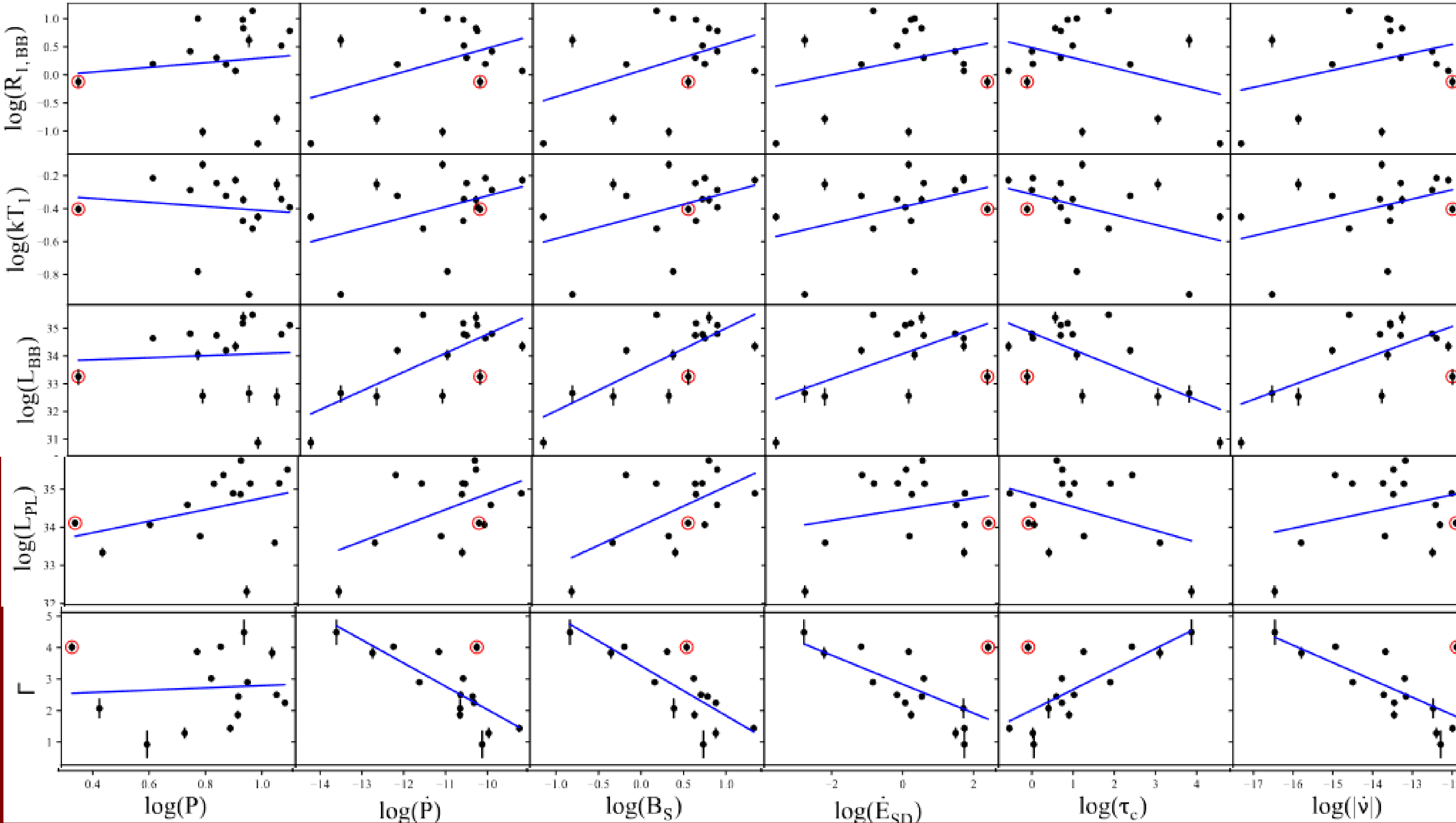




1903.05648

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

Correlation between various parameters

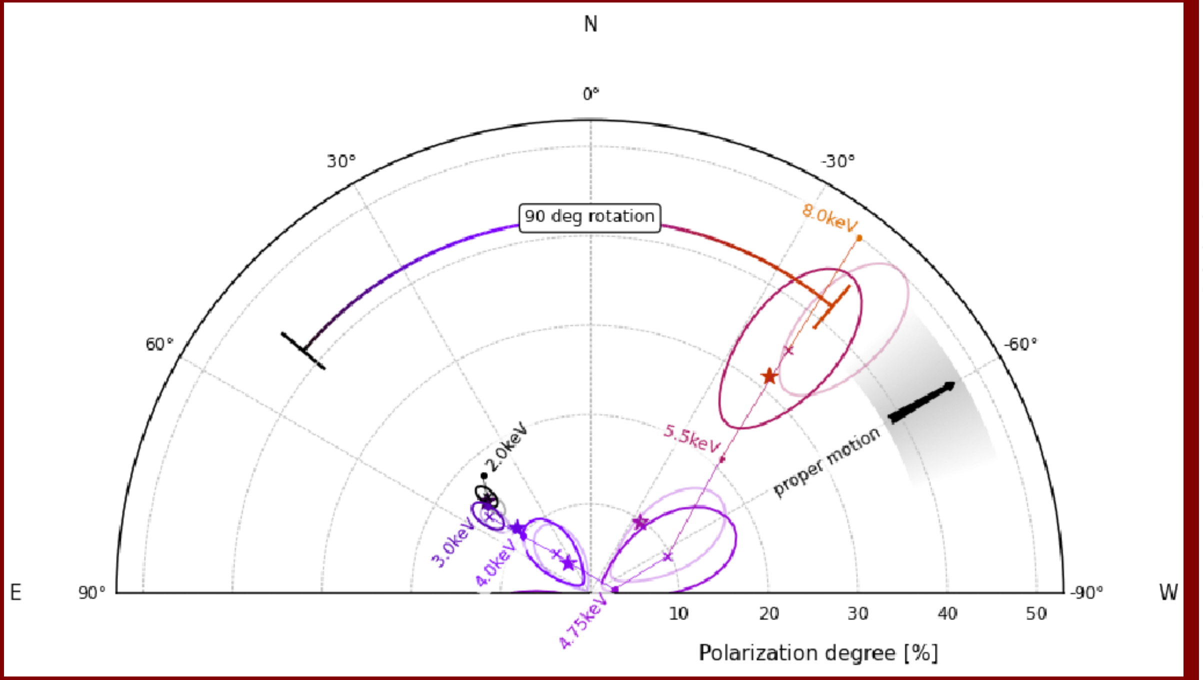


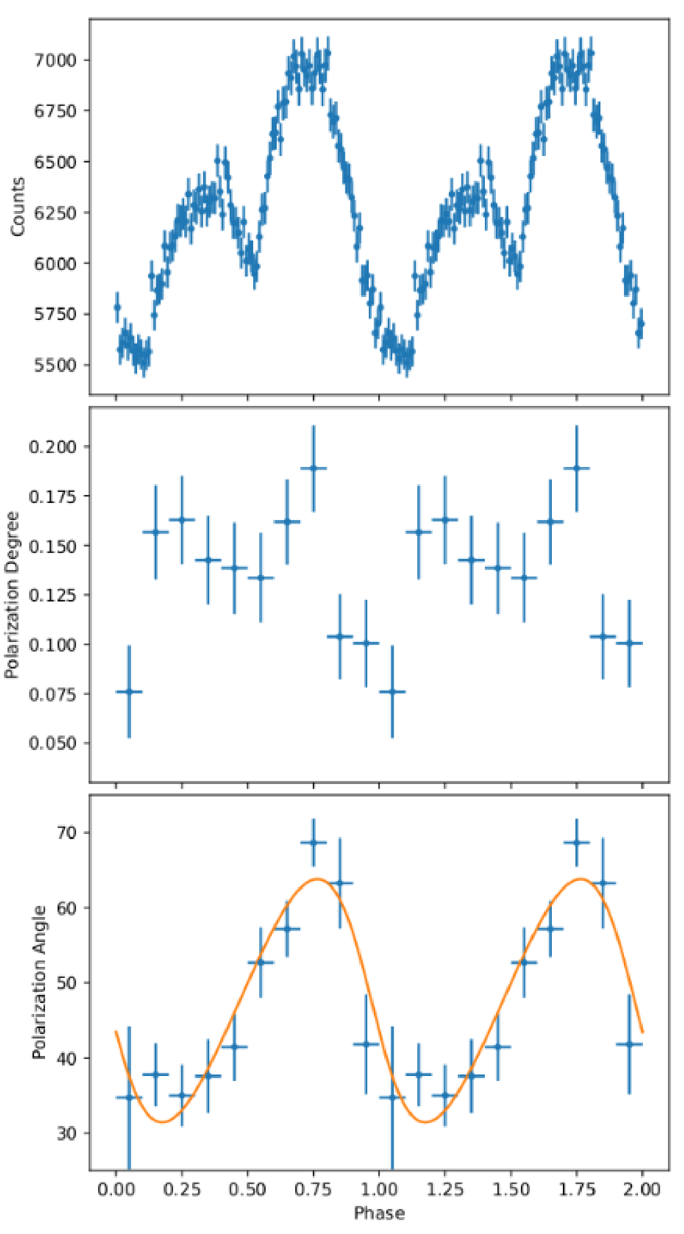
2303.13765. See also for L_{PL}-kT-R_{BB} correlation

Polarization of a magnetar emission

4U 0142+61
IXPE observations
Average linear polarization 12%

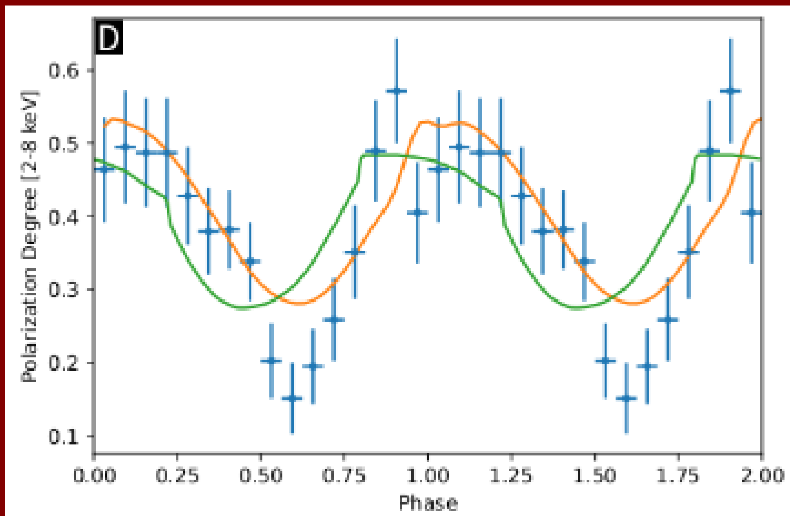
See a review in 2402.05622

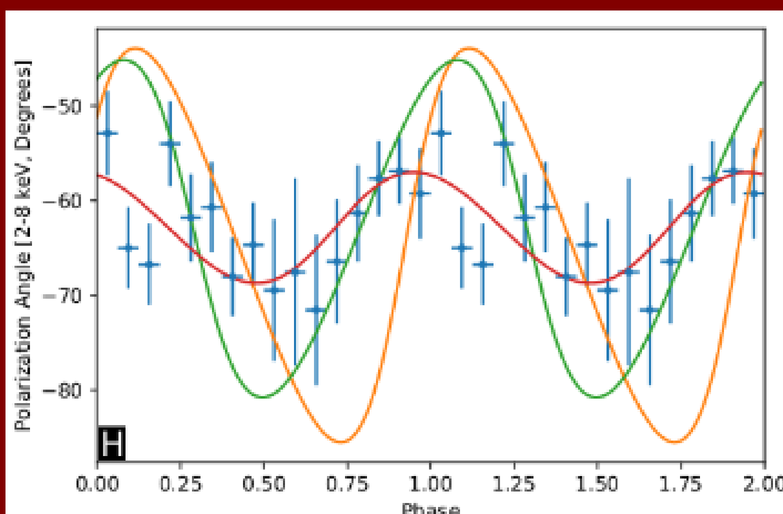


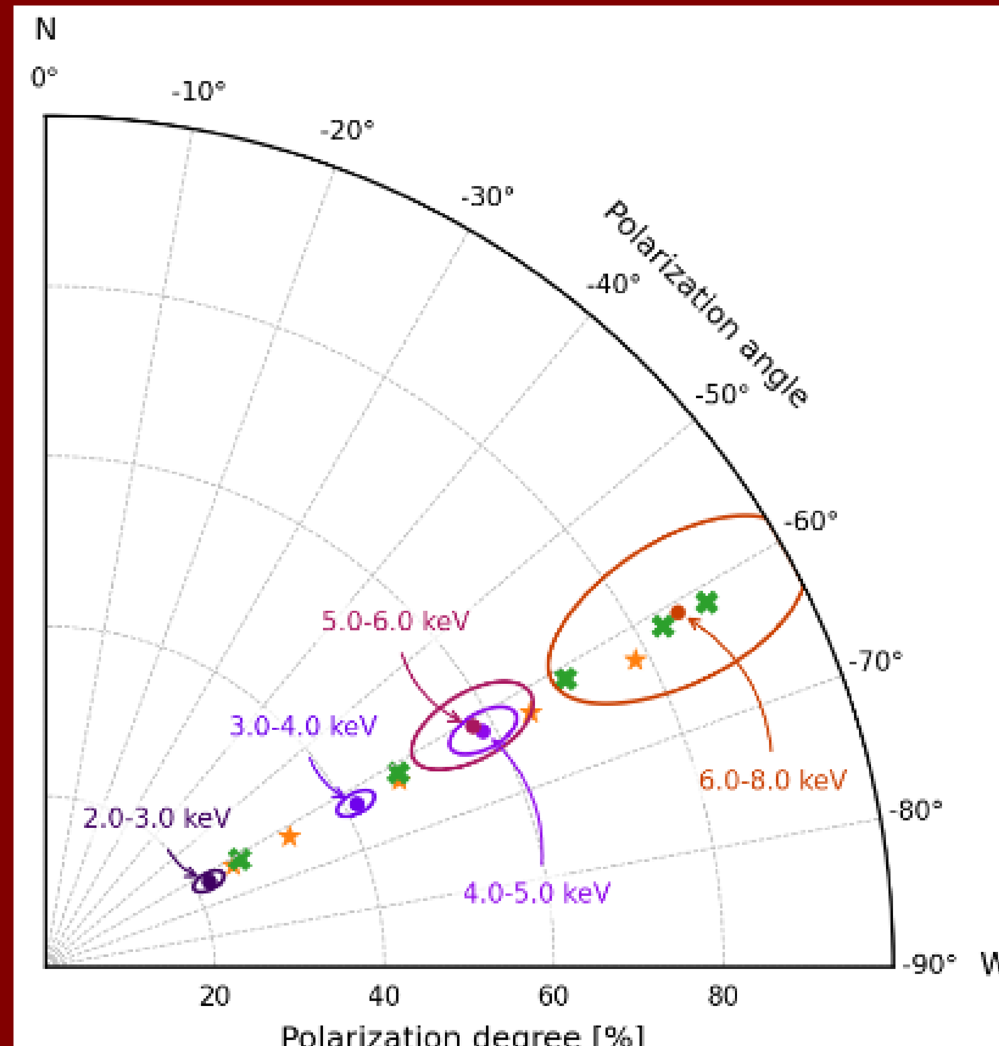


2205.08898

Polarization in 1RXS J170849.0-400910

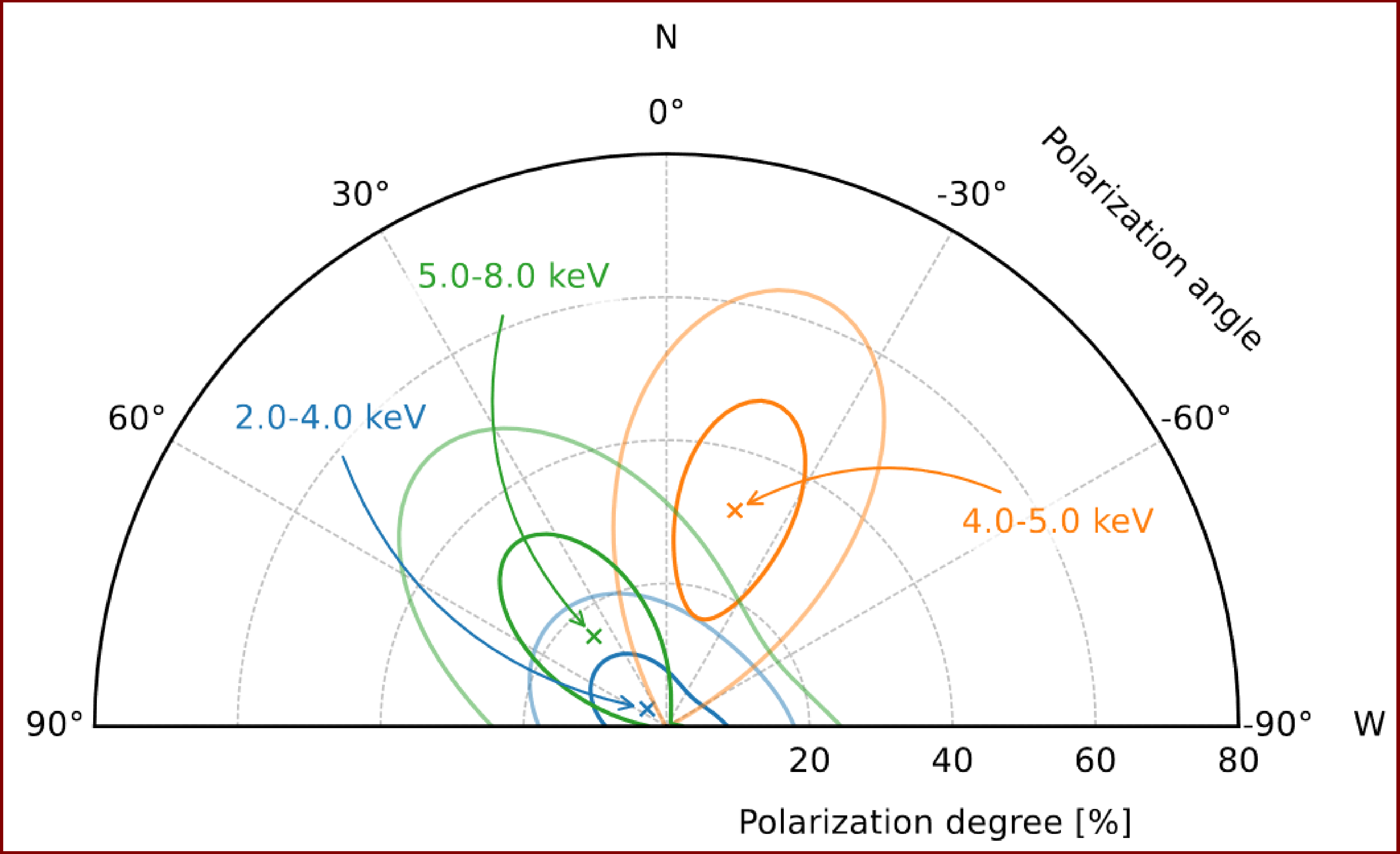






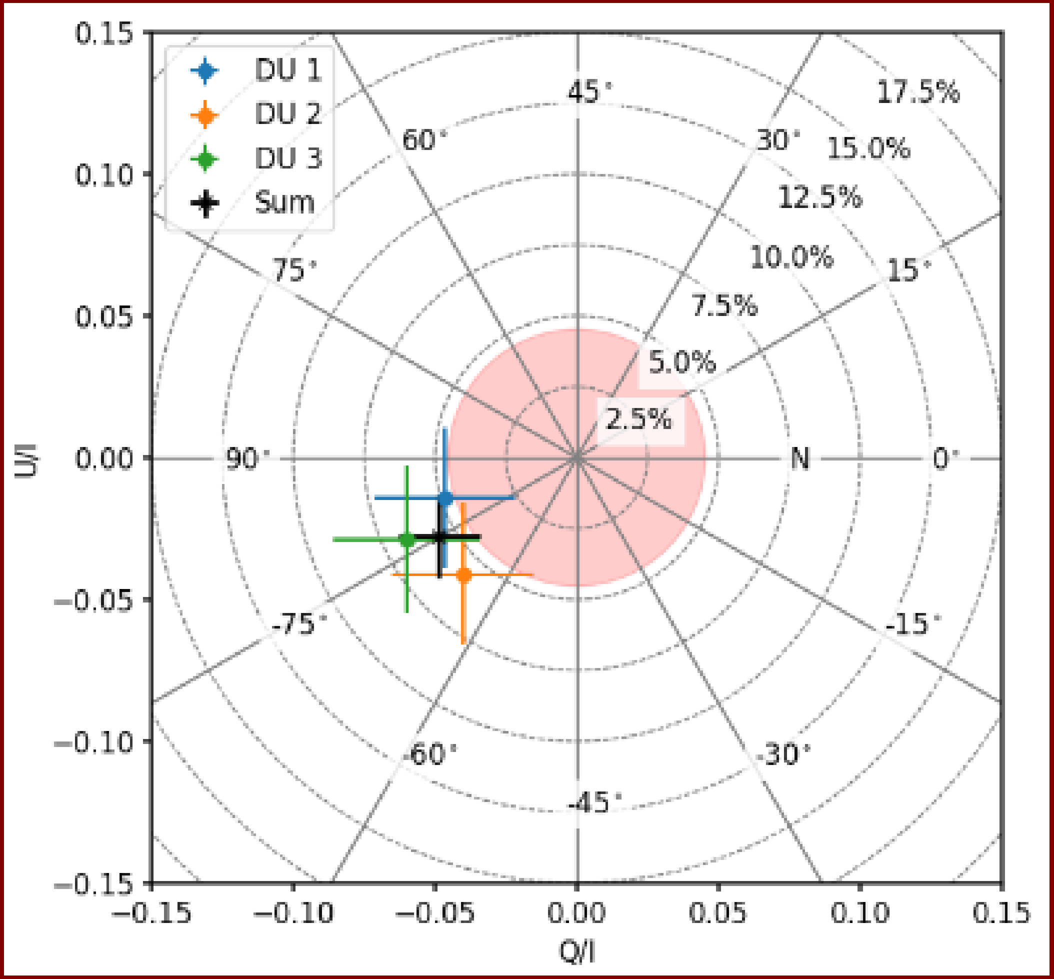
2301.12919

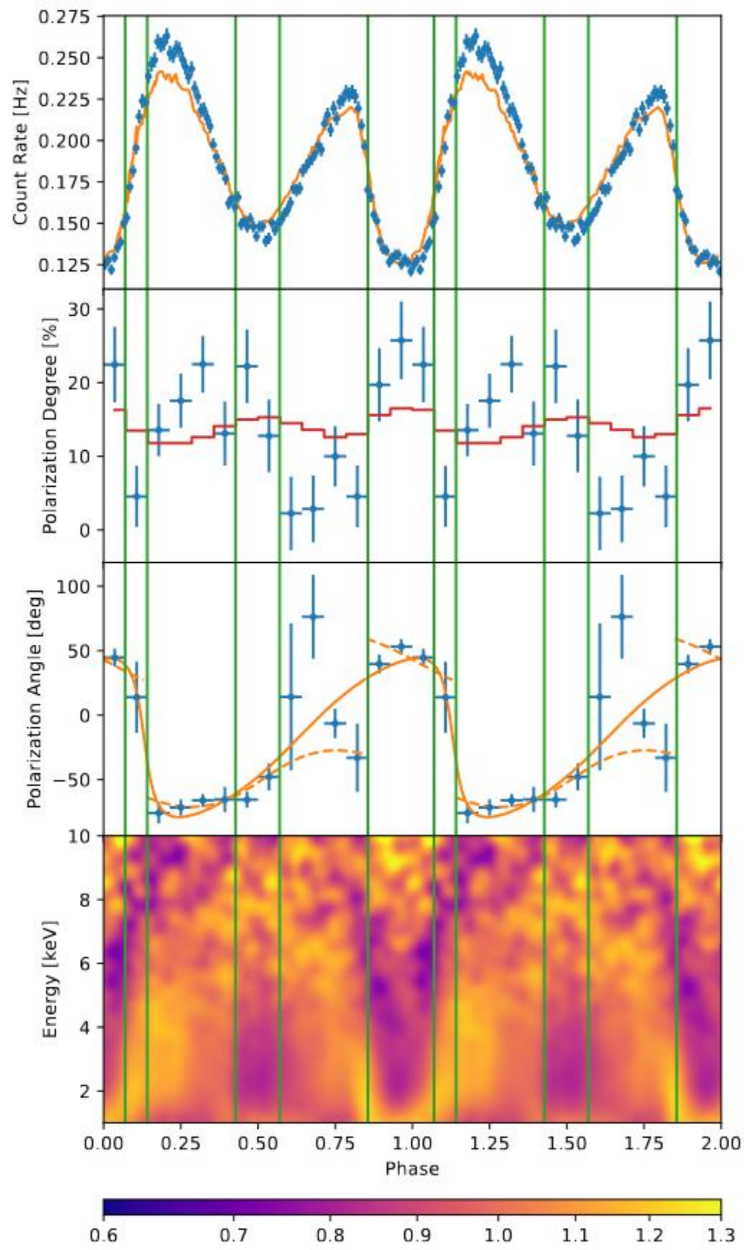
Polarization of SGR 1806–20



2308.01238

Polarization of 1E 2259+586





Polarization due to propagation in a strong magnetic field loop >10^{15} G.

2311.03637

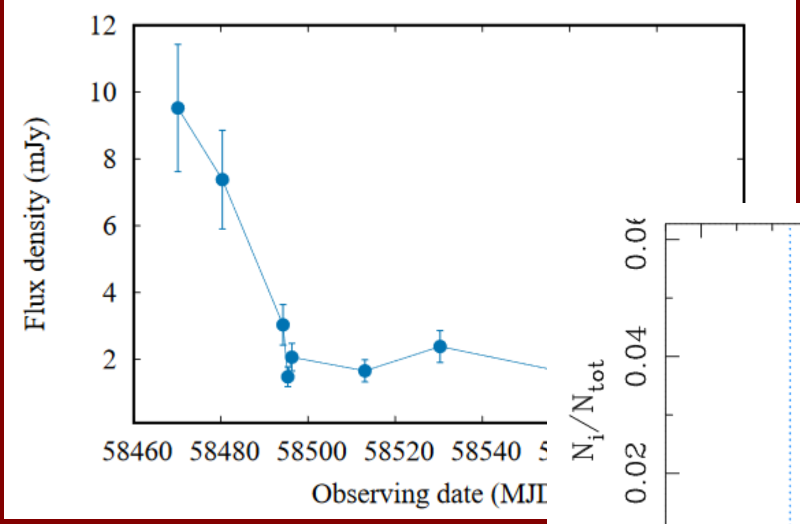
Magnetars can behave like radio pulsars

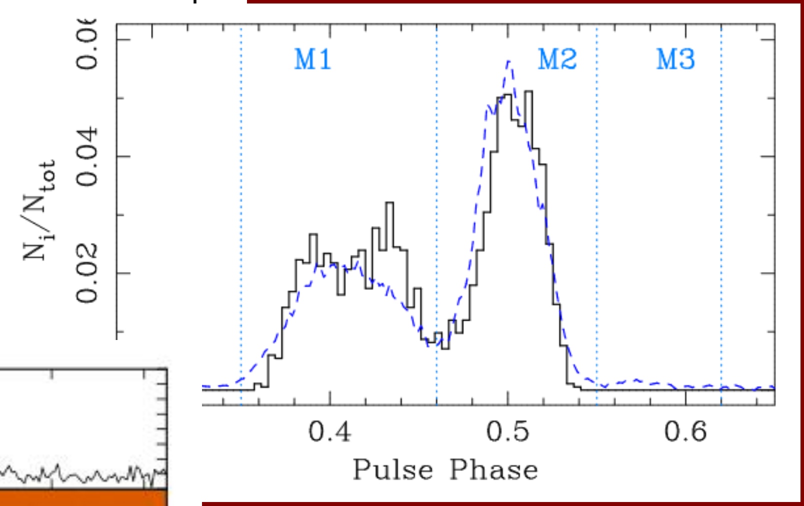
XTE J1810−197

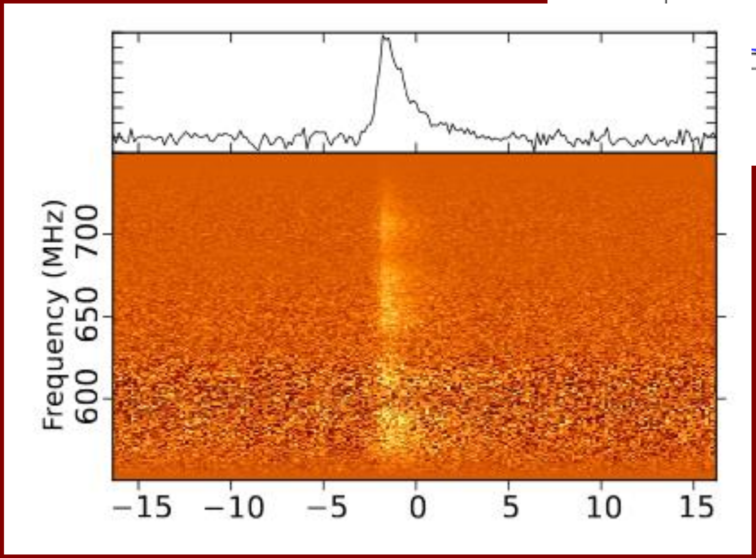
Was the first magnetar to show PSR-like radio emission (see lecture 1)

Activity in radio is transient.

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





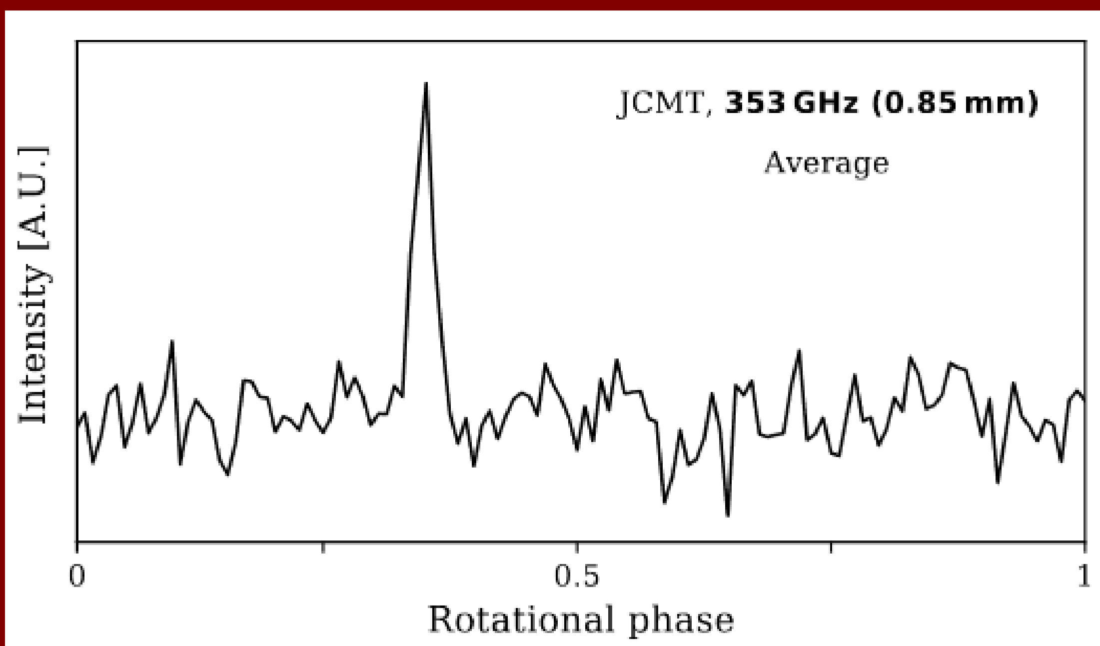


1908.04304

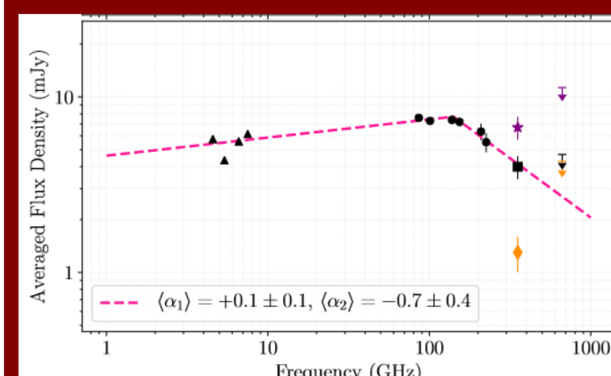
Sub-mm detection of pulsations

XTE J1810−197
James Clerk Maxwell Telescope

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



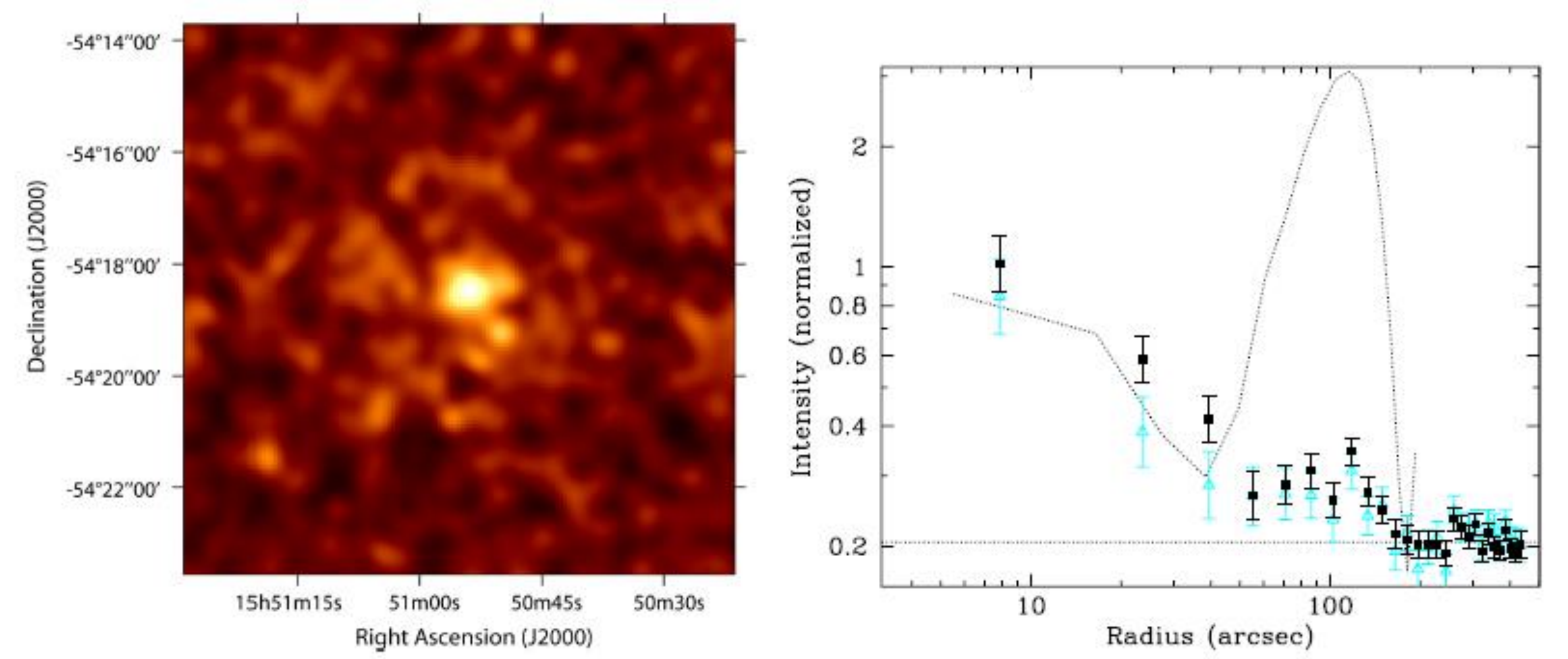
Spectral break at ~200 GHz



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
and 2402.05647 for recent upper limits.

Young and fast magnetar with radio

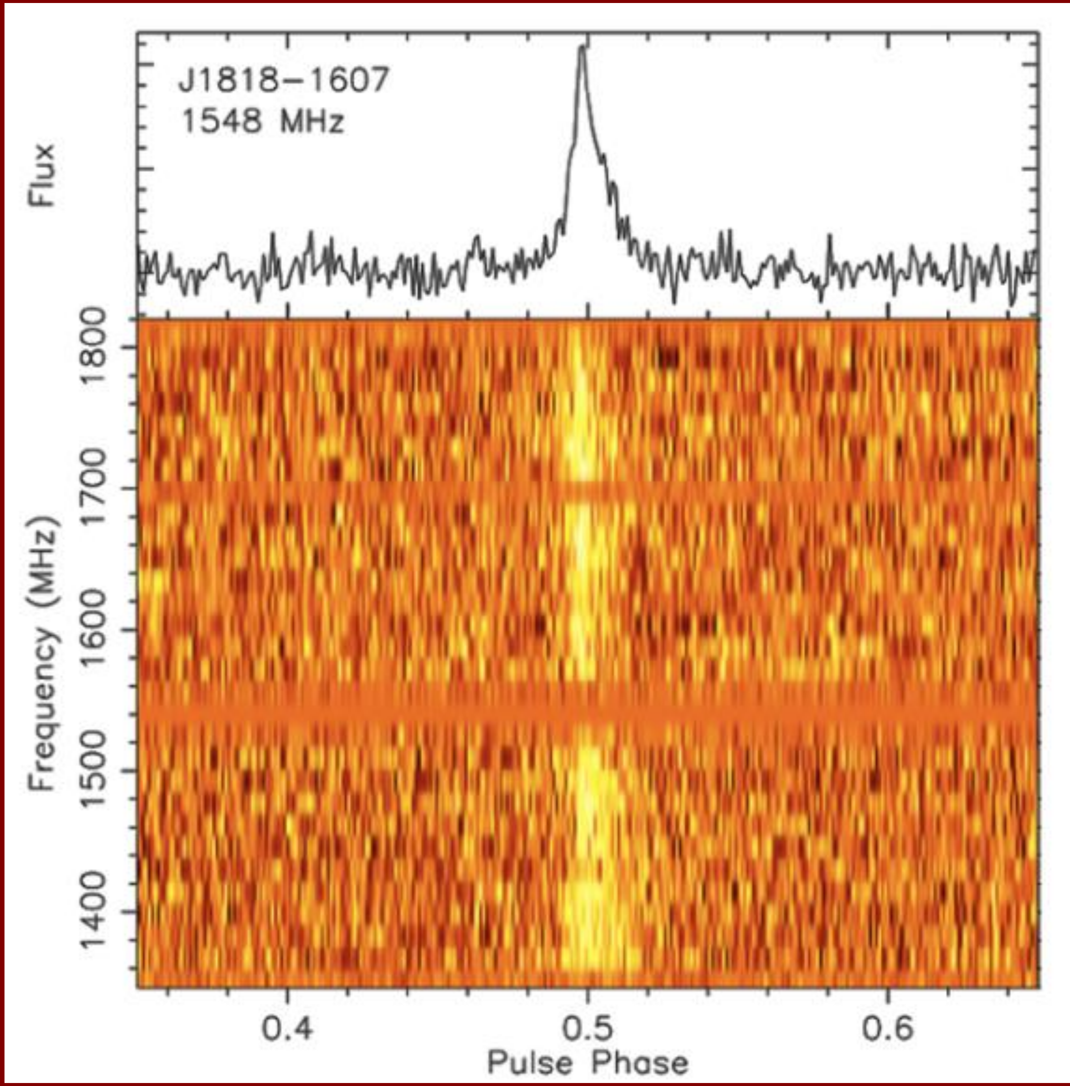
Swift J1818.0–1607
Discovered in March 2020
due to burst and outburst.

Spin period 1.36 s.

Characteristic age 240 yrs.

Radio pulses.

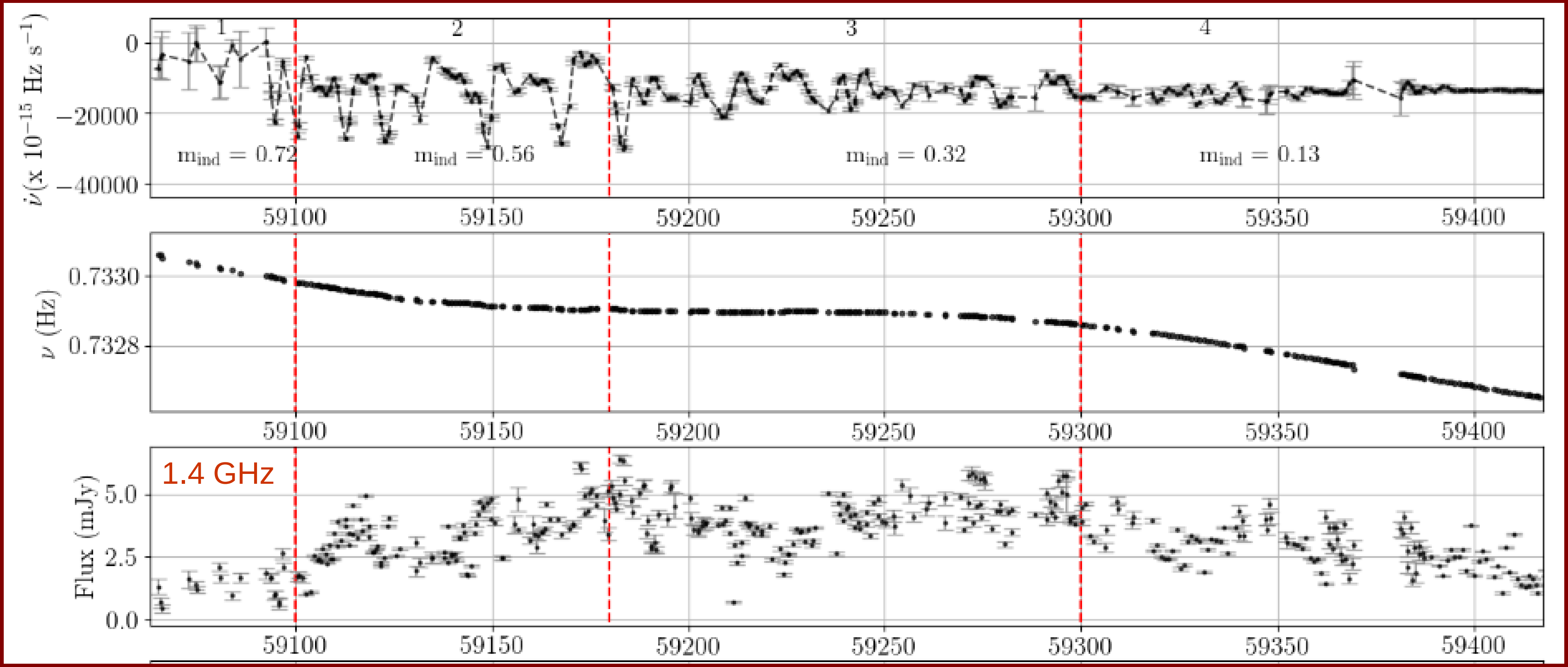
Weak quiescent emission.



2004.04083

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

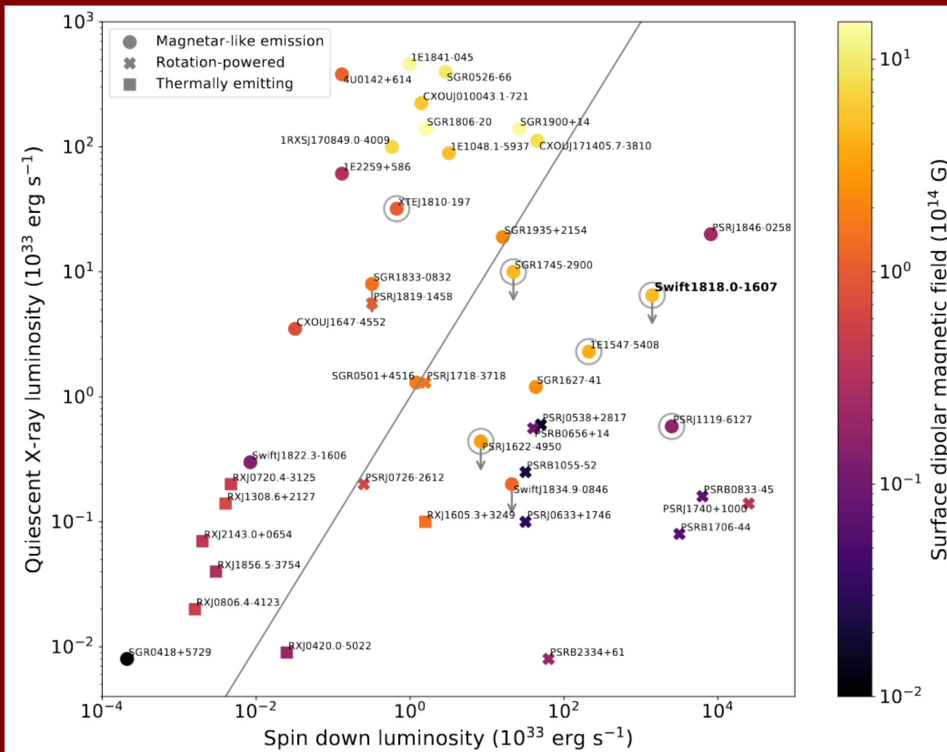
Complicated behavior of Swift J1818



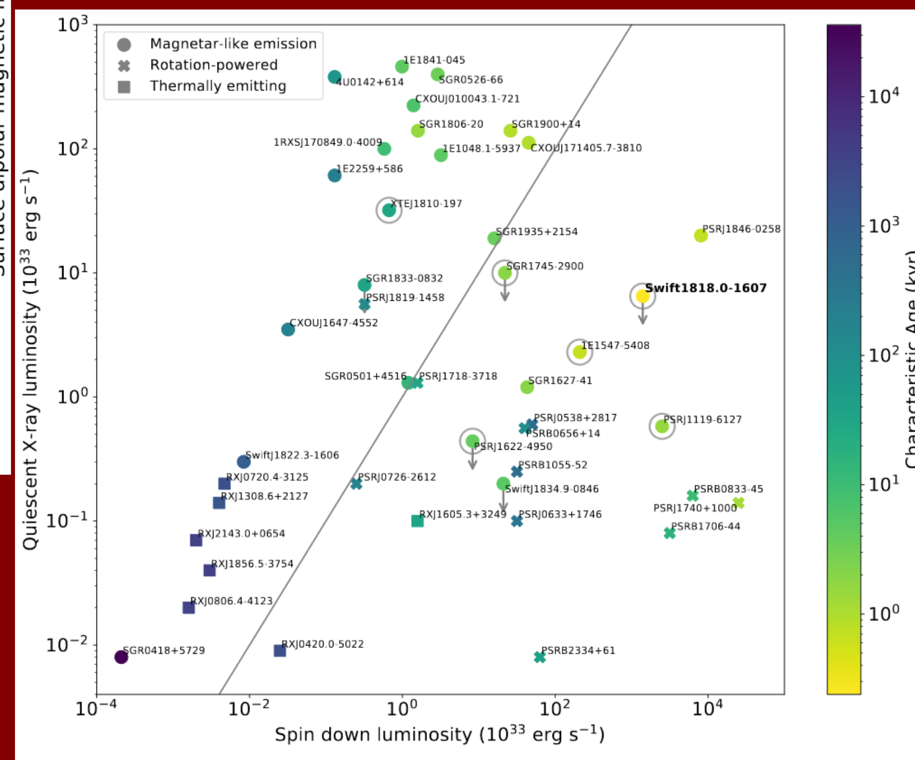
Pulse profile in radio is also changing with time

2202.07548

Edot$_{rot}$-L$_{quiescent}$

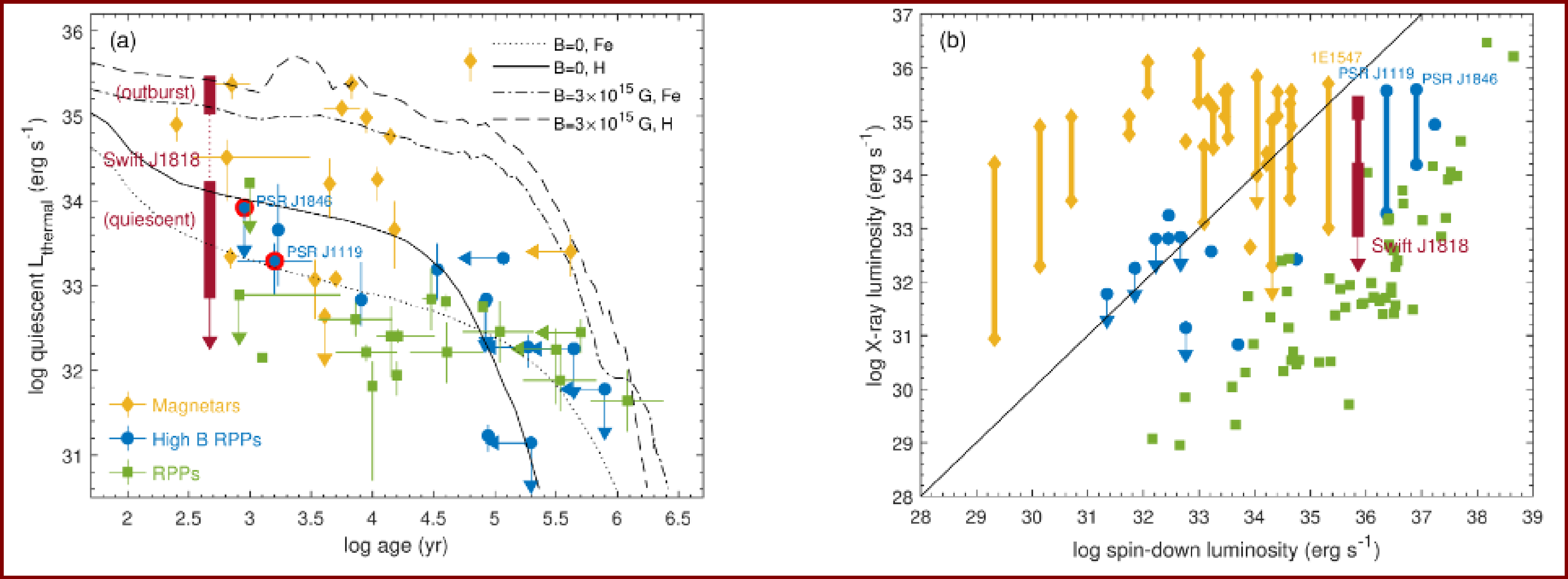


Circles – radio loud



2004.04083

Links between magnetars and PSRs



Swift J1818.0−1607
Fastest rotation: 1.36 sec.
Small characteristic age.
Strongly variable Pdot.
Strong glitch and anti-glitch.

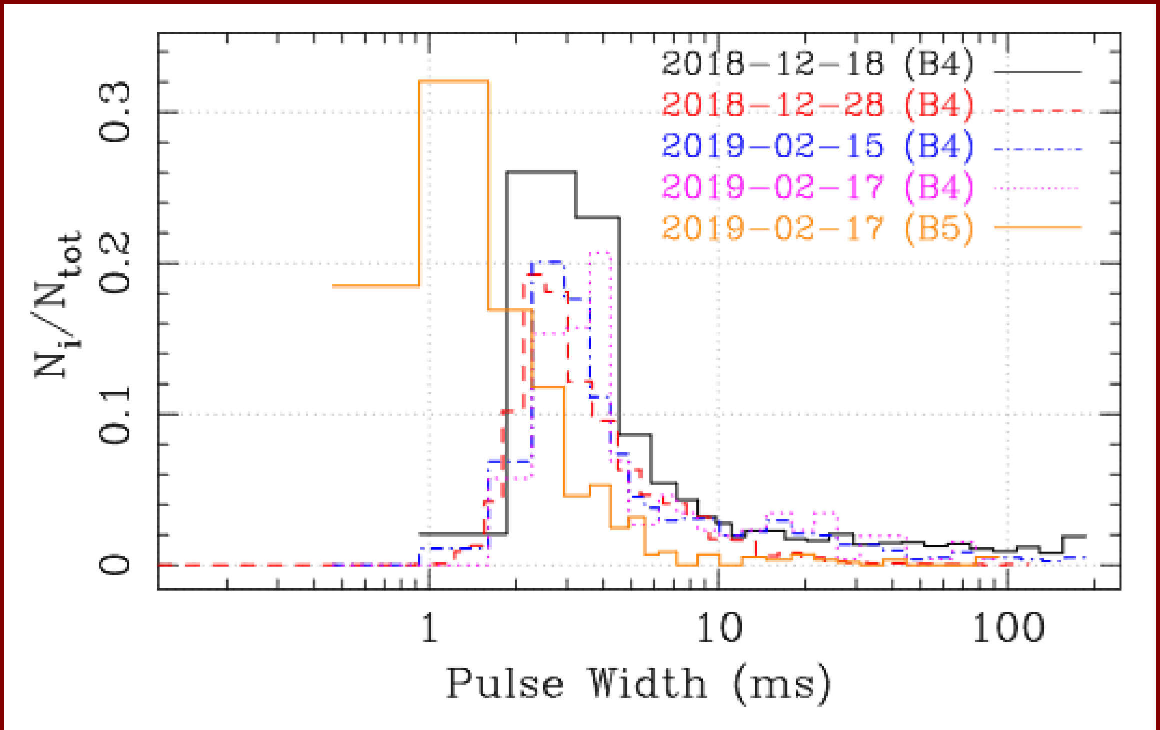
Two high B RPPs that show magnetar-like behaviors are marked by red circles.

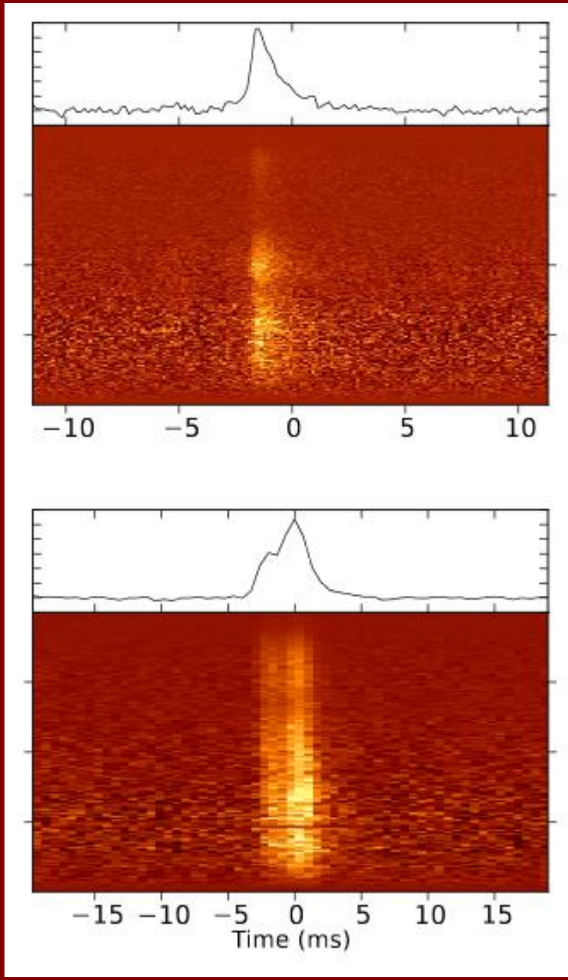
2009.00231

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.

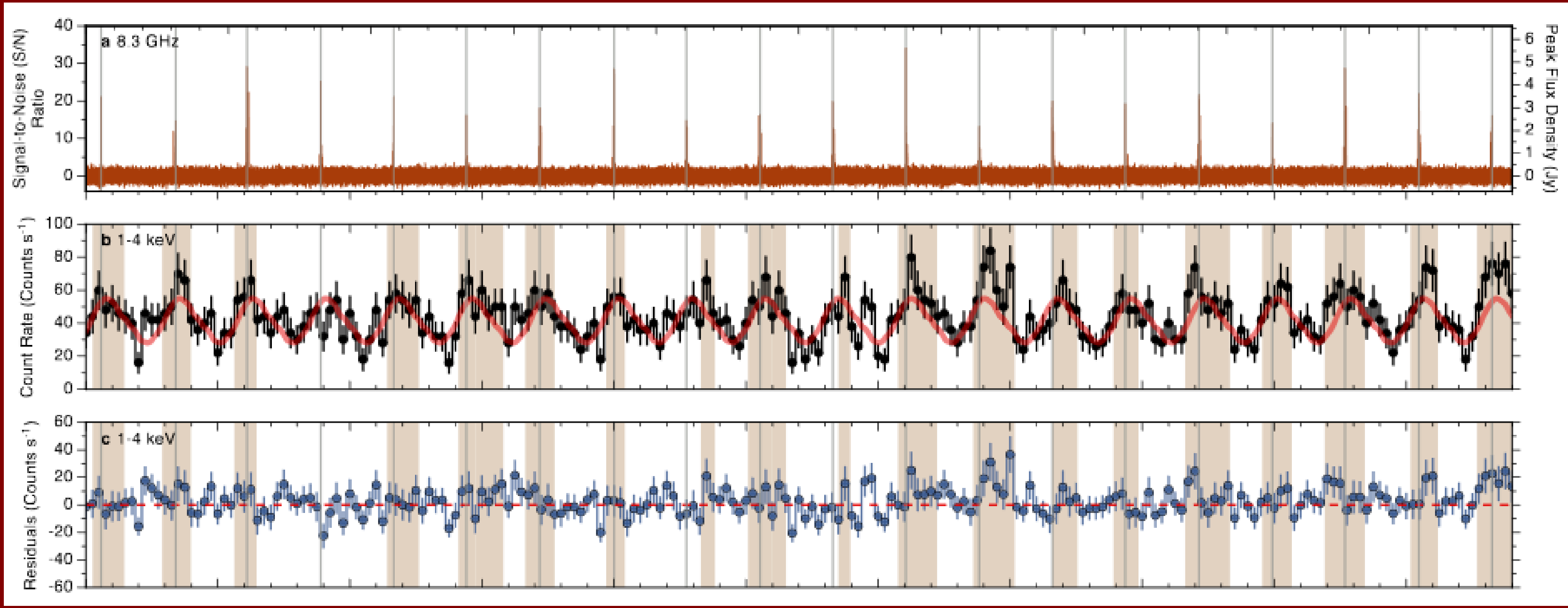




The first parallax for magnetar XTE J1810−197 was measured recently due to radio observations, 2008.06438.

1908.04304. About giant pulses from this source see 2111.01641

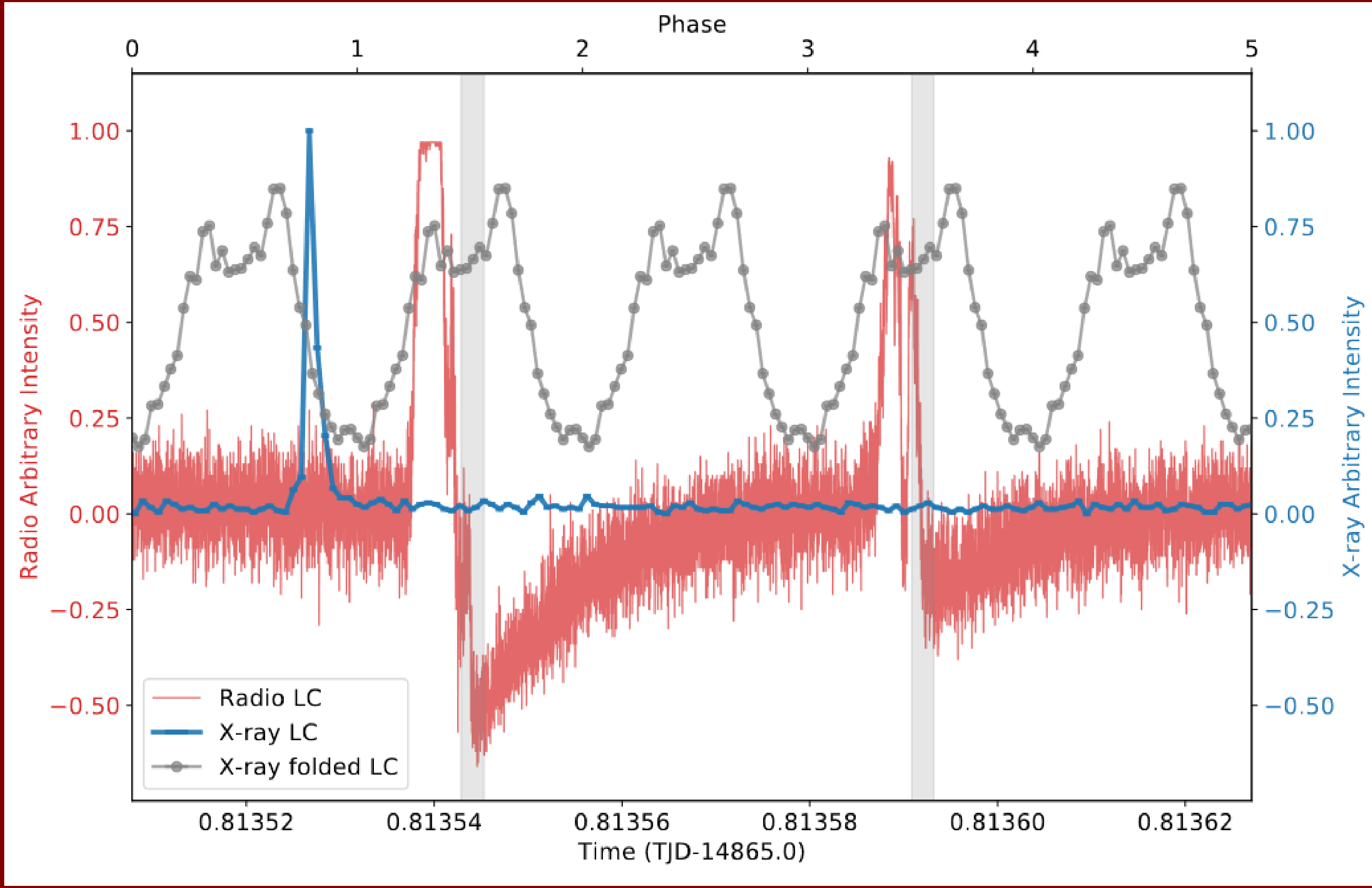
Bursts from XTE 1810



These bursts are not similar to FRBs.

2005.08410

1E 1547.0–5408 X-ray and radio bursts

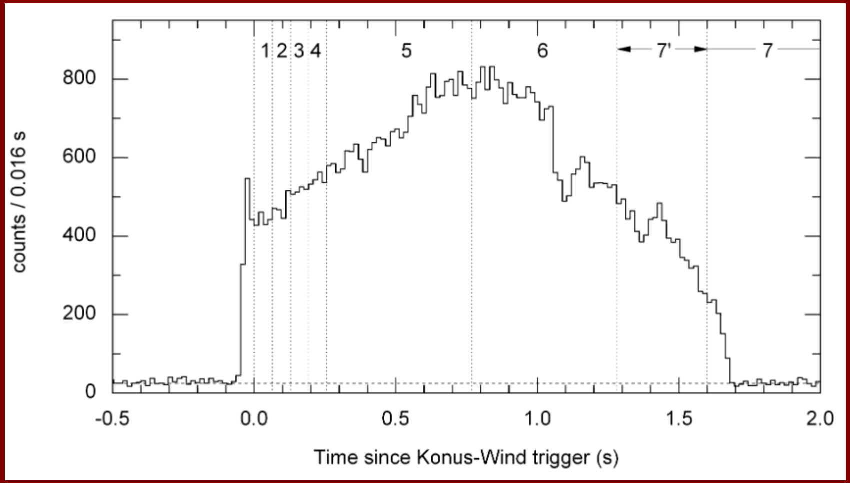


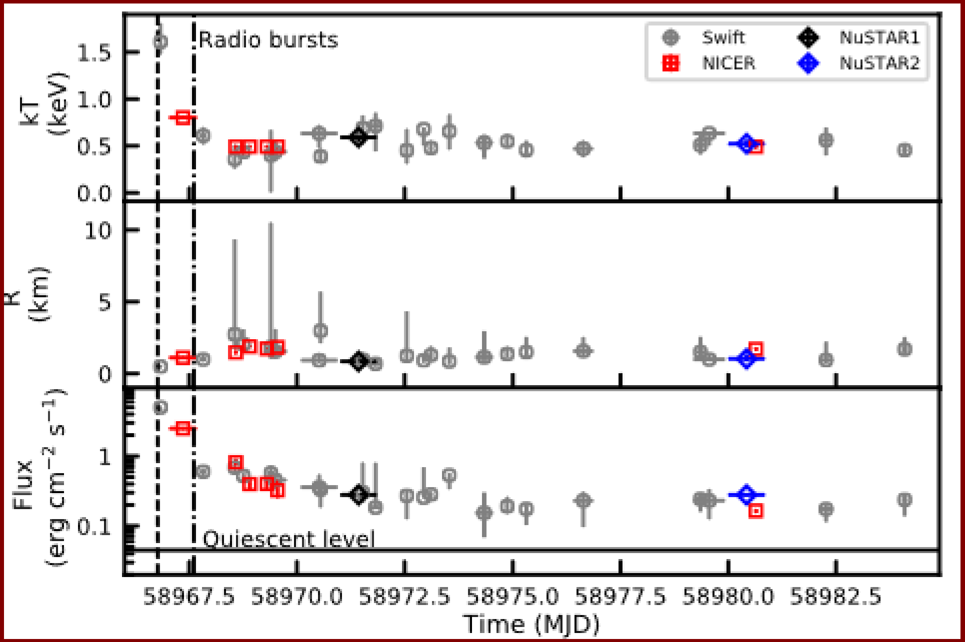
Observations in 2009. Chandra+Swift+Konus-Wind in X-ray and Parkes in radio.

2011.06607

SGR 1935+2154

Discovered in 2014 (see, Israel et al. 2016).
P=3.25 sec
Distance ~7-12 kpc (2005.03517)
Intermediate flare (Kozlova et l. 2016)





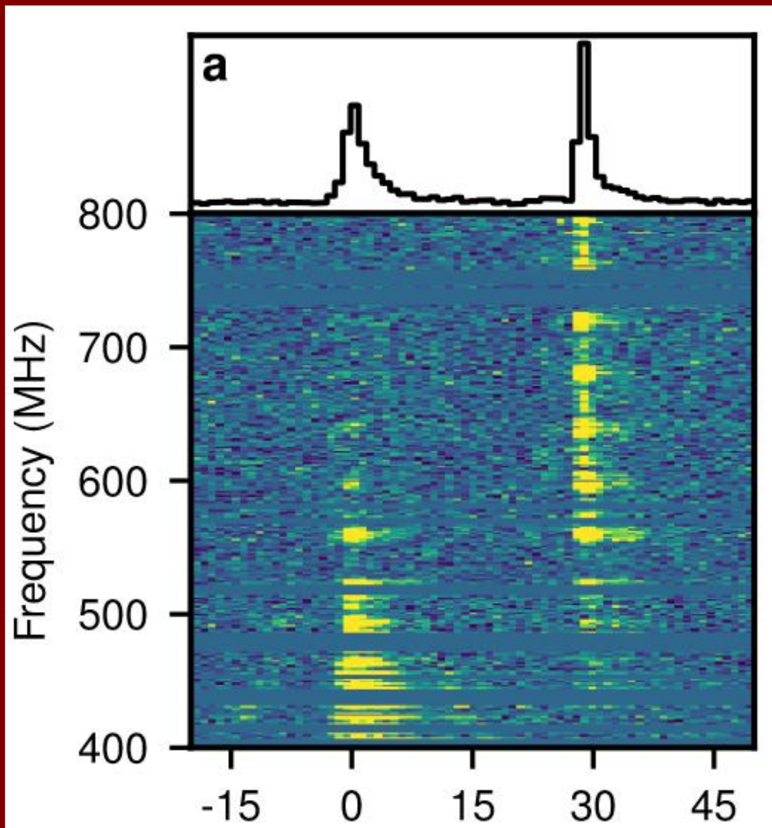
Activated in April 2020.
Finally, on April, 28 2020
A simultaneous burst in radio and X/gamma was detected.

Astronomers telegram: 13681-13769

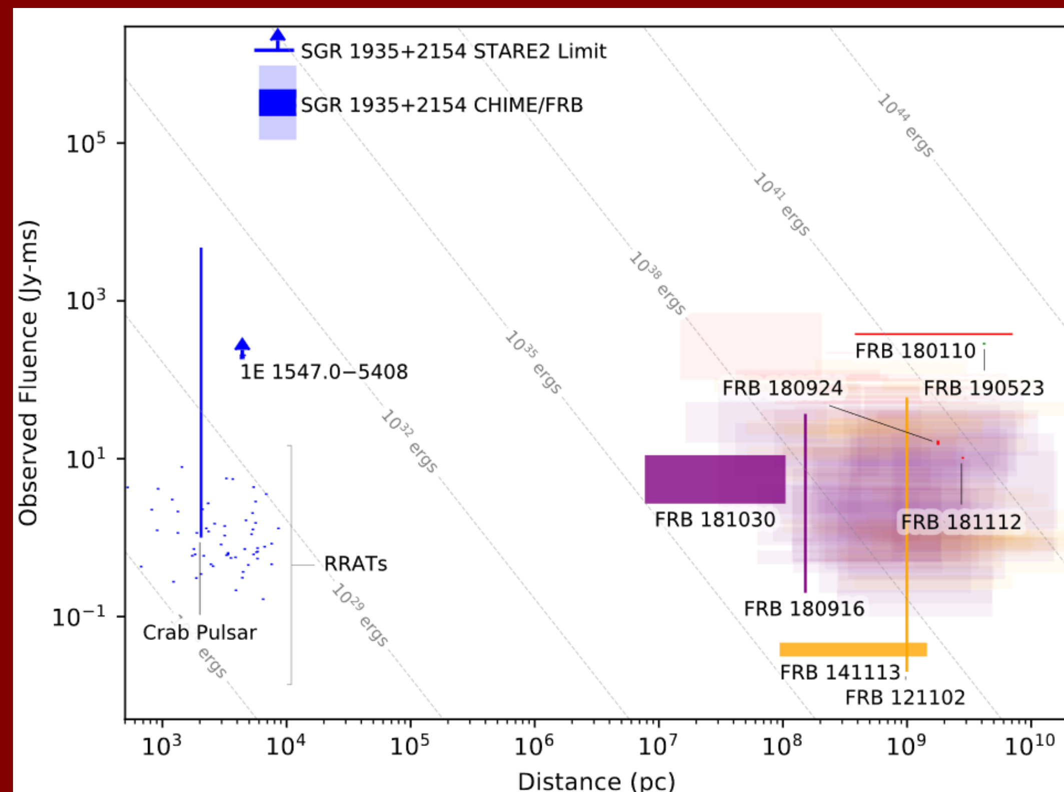
GCN: 27666-27669

2006.00215

CHIME data

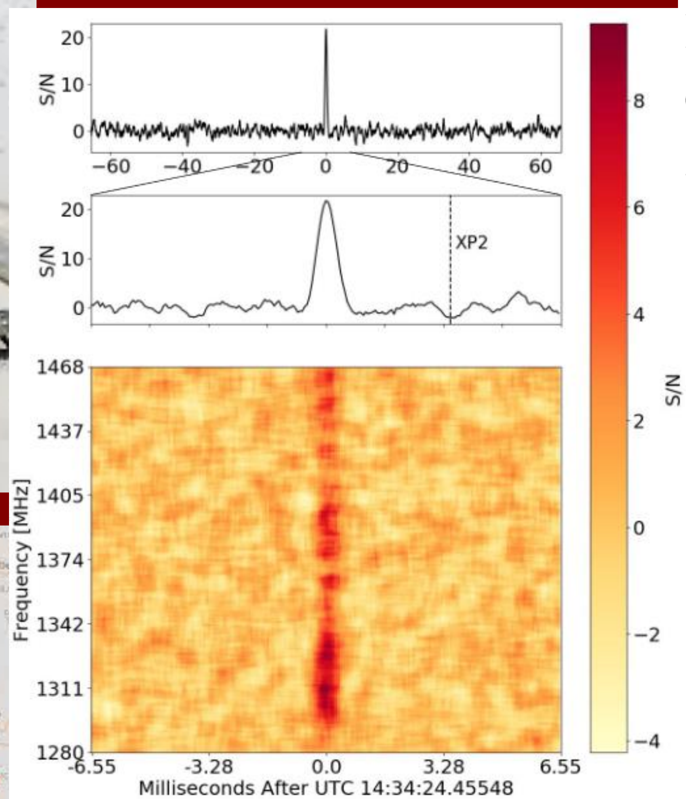


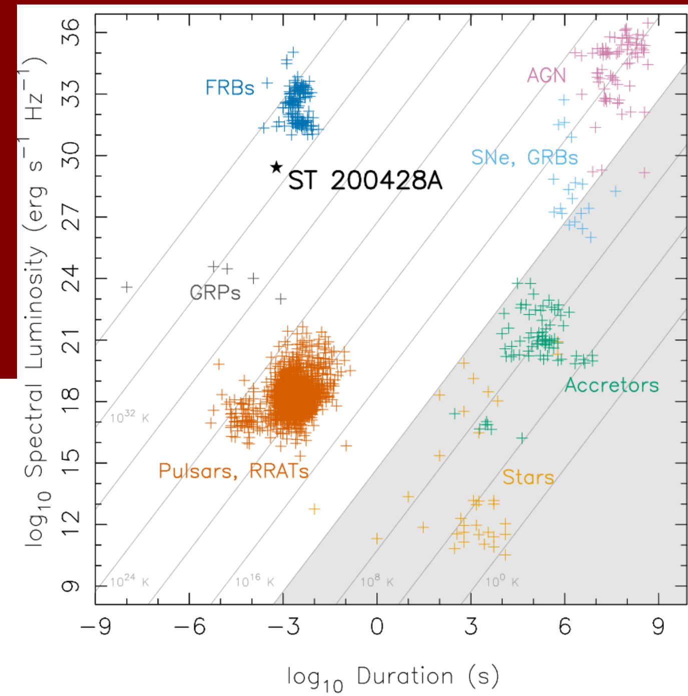
First millisecond radio bursts
from a Galactic magnetar
very similar (but weaker) to FRBs.



2005.10324

STARE2 data

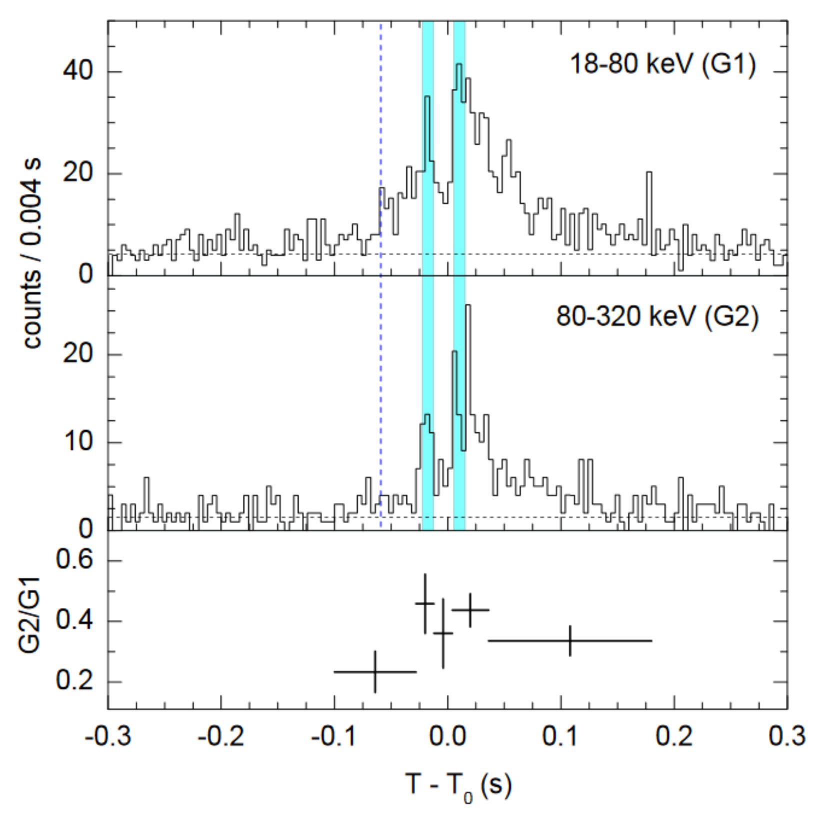


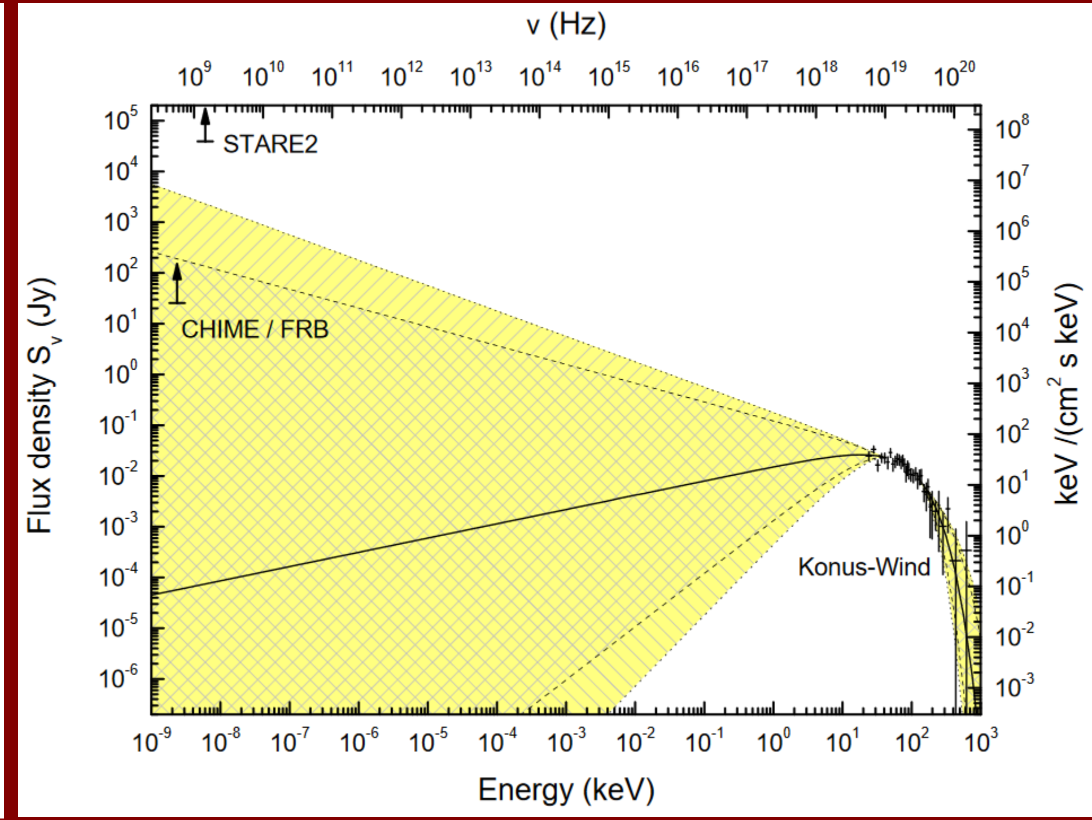


Several small-scale instruments at significant distance from each other. Sensitive to short, but very bright bursts.

2005.10828

Konus-Wind data

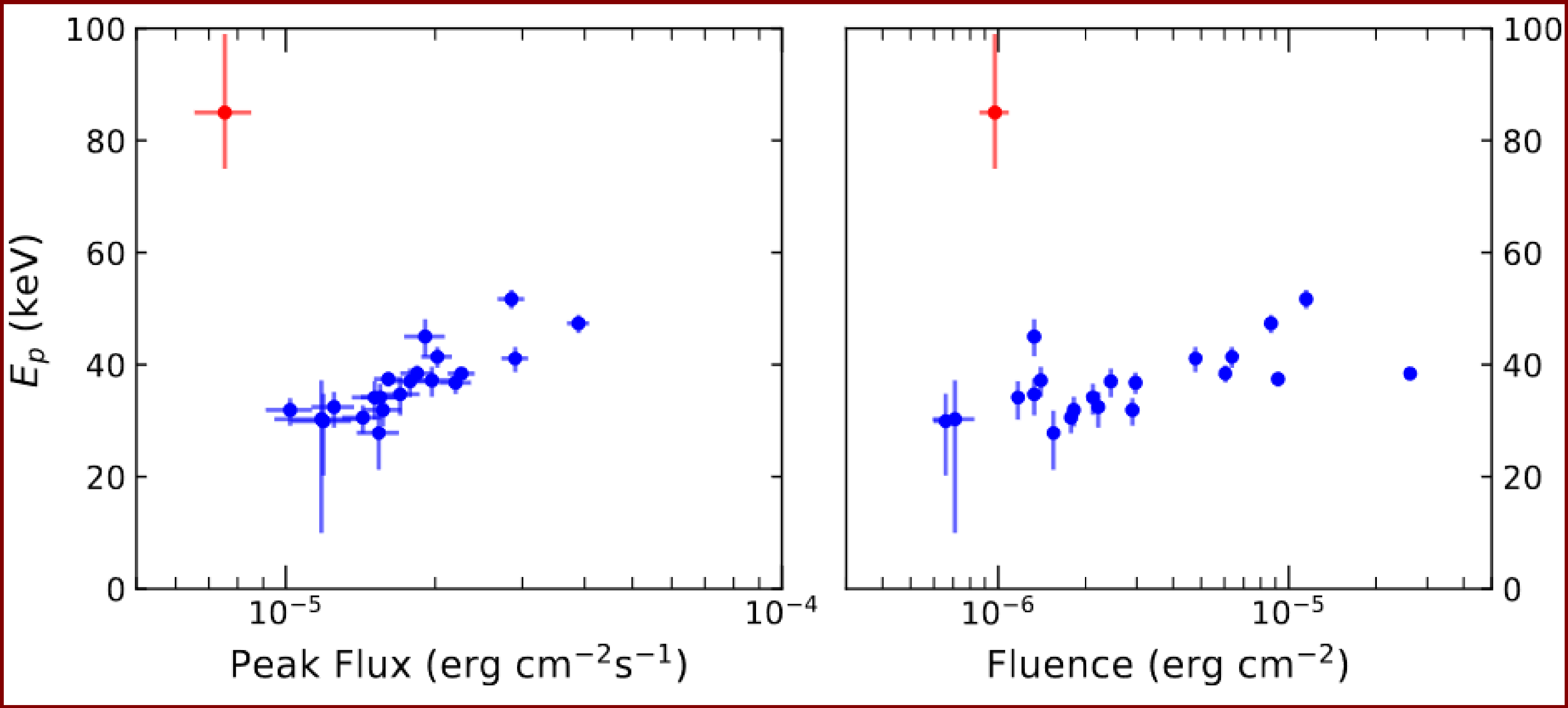




Radio and X-rays simultaneous.

2005.11178

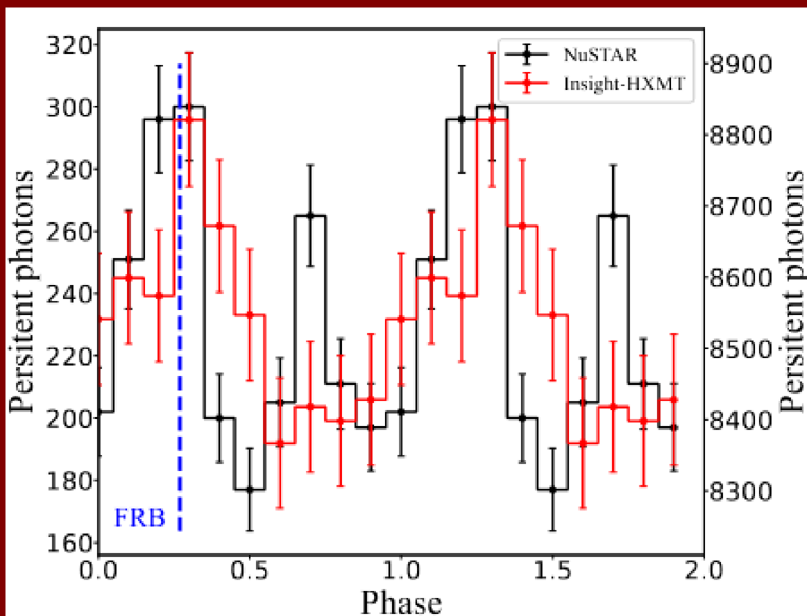
Konus-Wind data

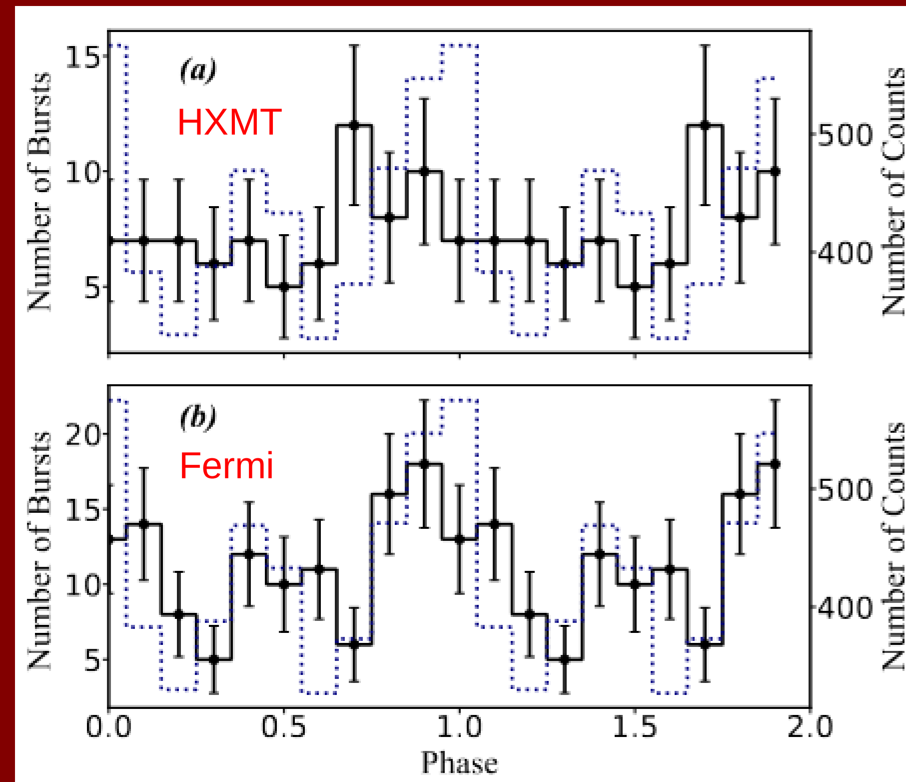


Much different from other flares of the same magnetar

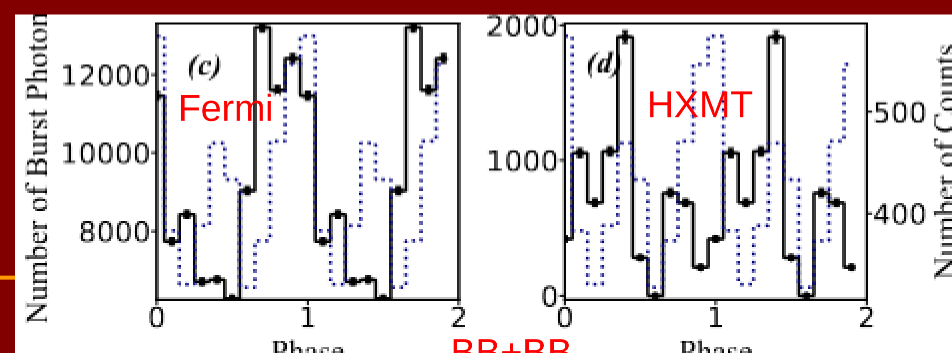
At which spin phases do the bursts appear?

SGR J1935+2154
75 Insight-HMXT
125 Fermi bursts





Phase distribution of bursts is different for bursts with different spectral parameters.

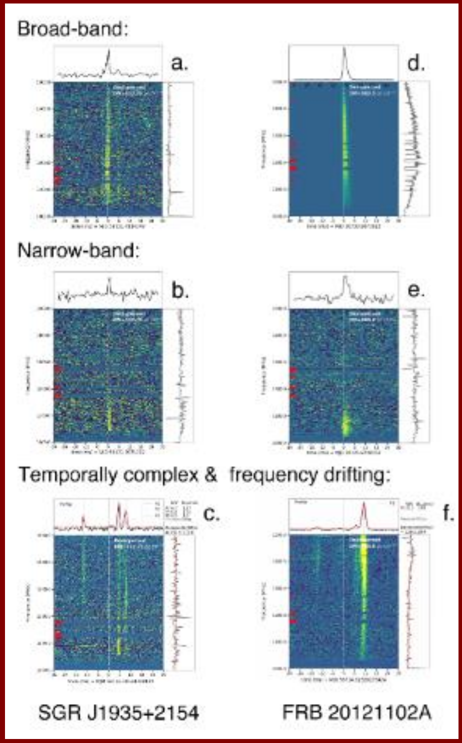


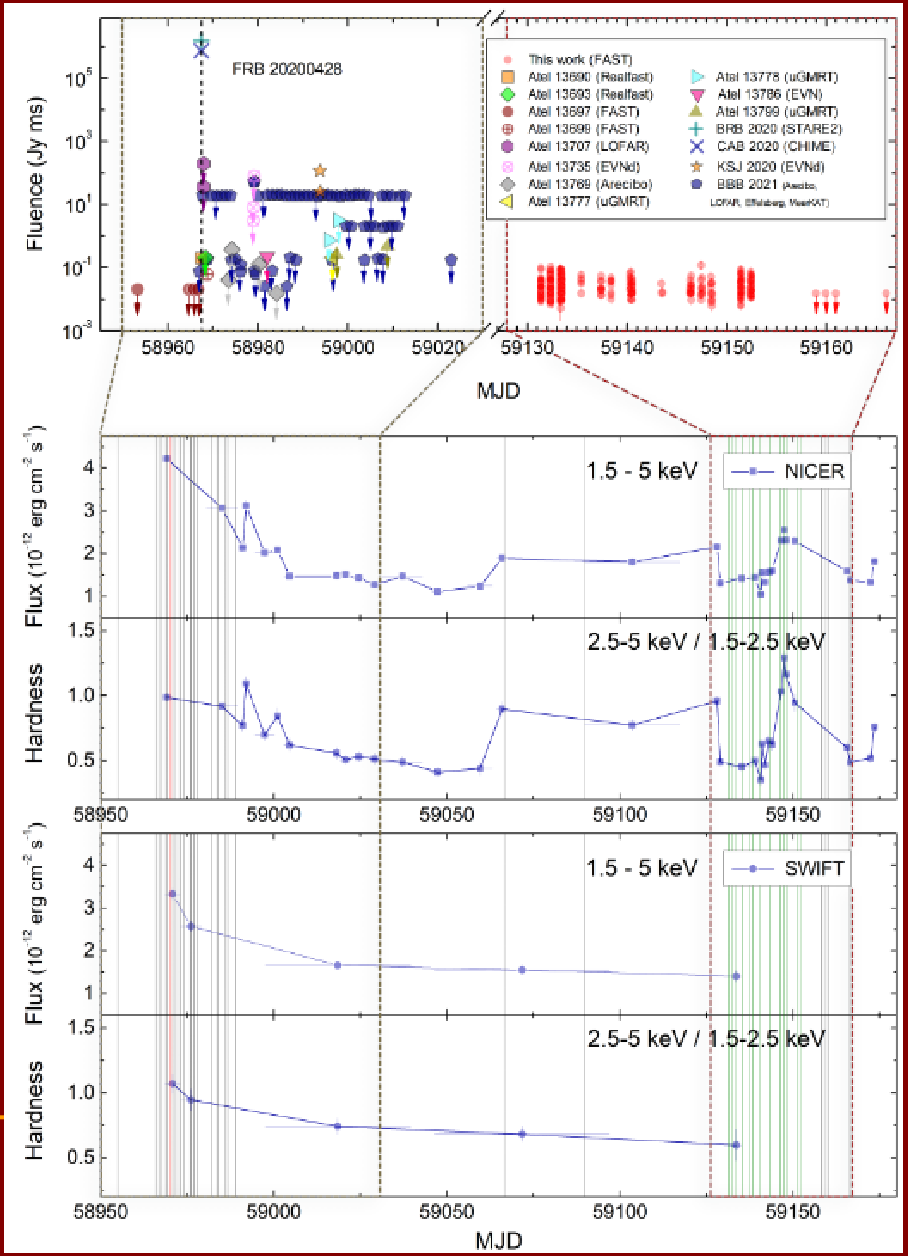
2301.07333

Radio pulses from SGR 1935+2154

Unique properties.
Many similarities with FRBs.

X-ray suppression during
the period of activity in radio.



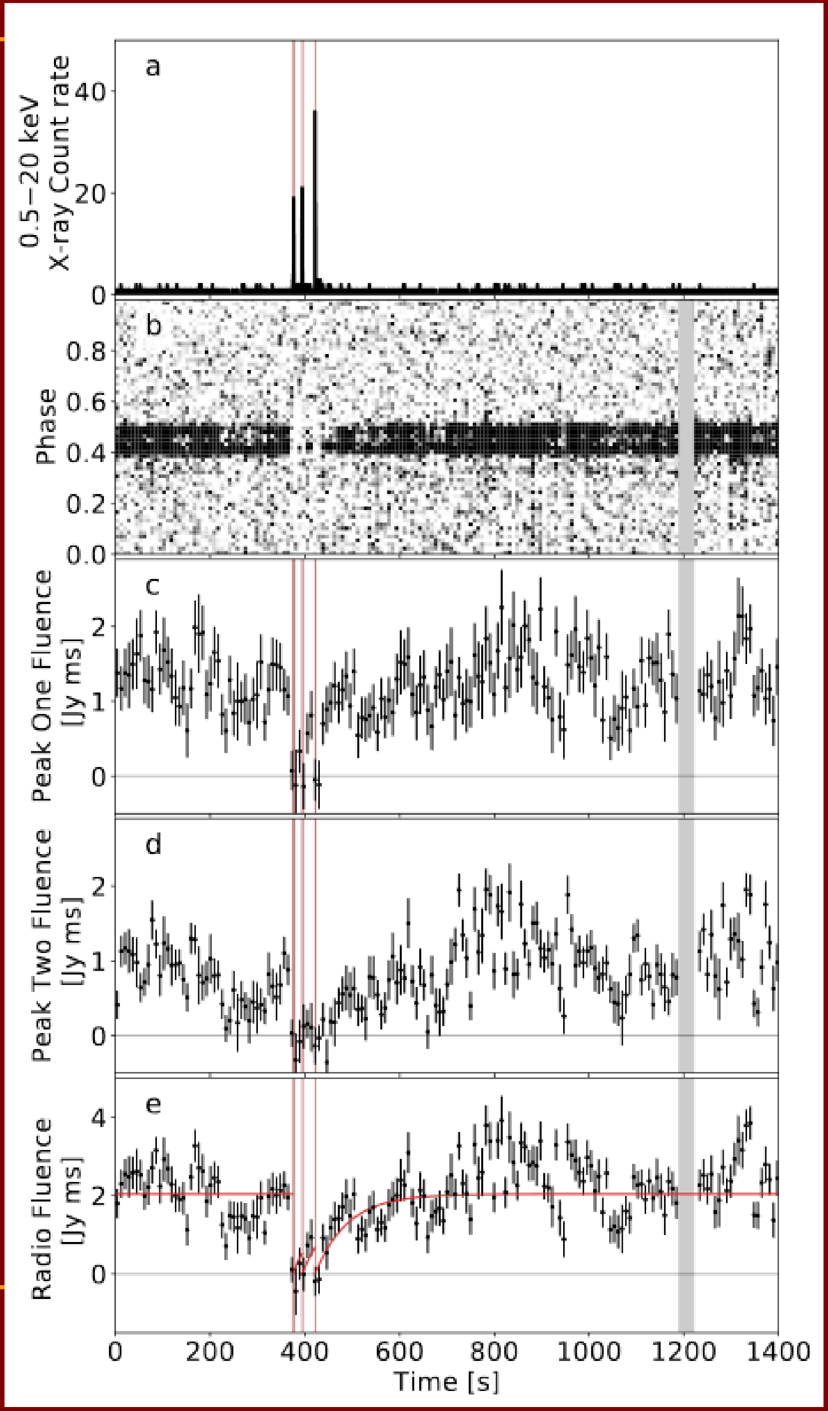


2308.08832

Suppression of radio during bursts

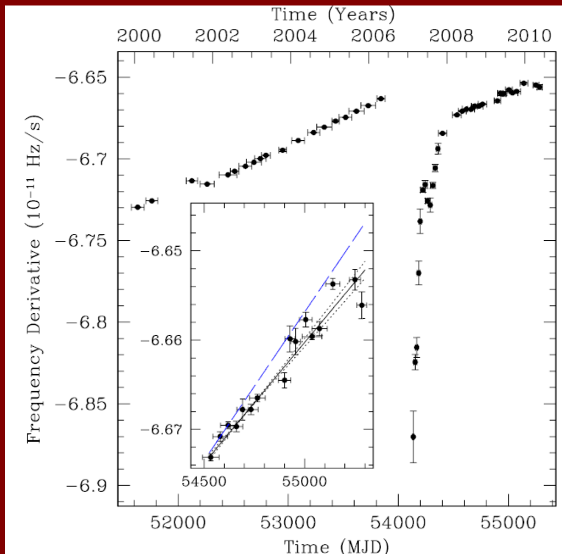
PSR J1119−6127

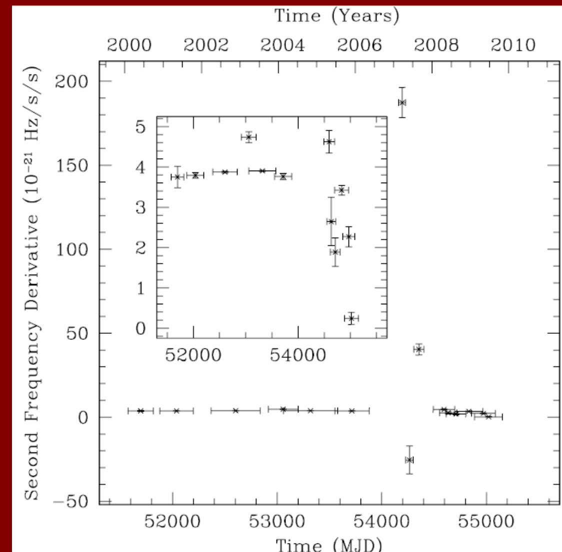
The rotationally powered radio emission shuts off coincident with the occurrence of multiple X-ray bursts.



1710.03718

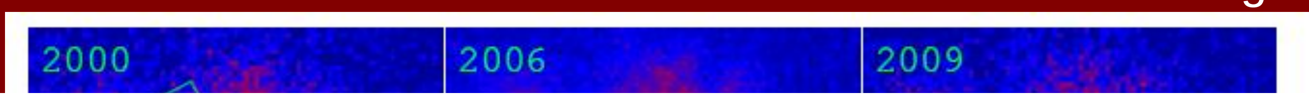
Postburst properties of PSR J1846-0258



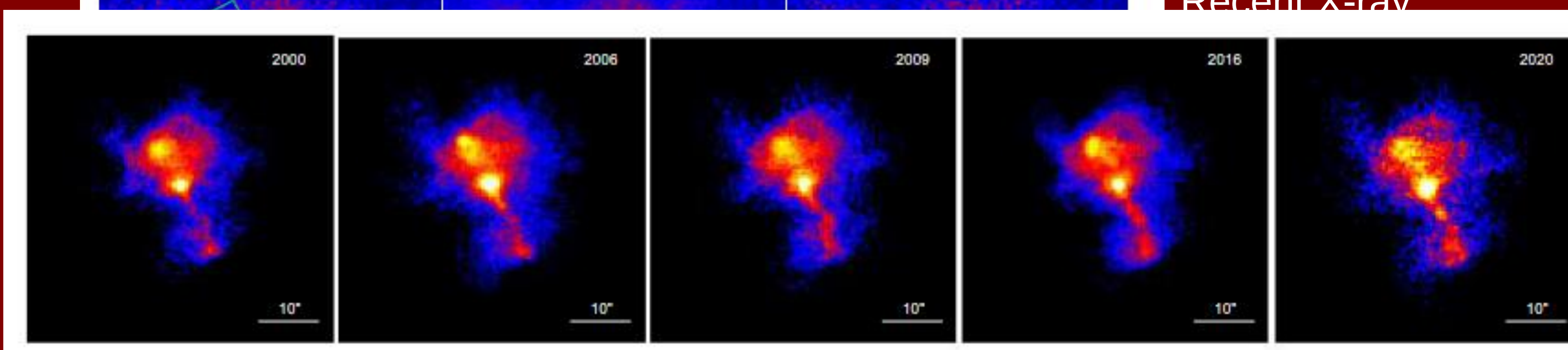


The pulsar showed a glitch.
A period of magnetar-like activity was started.
After the burst parameters of the pulsar changed.

n=2.65 -> n=2.16
Timing noise was increased (was very small for a magnetar before bursts)

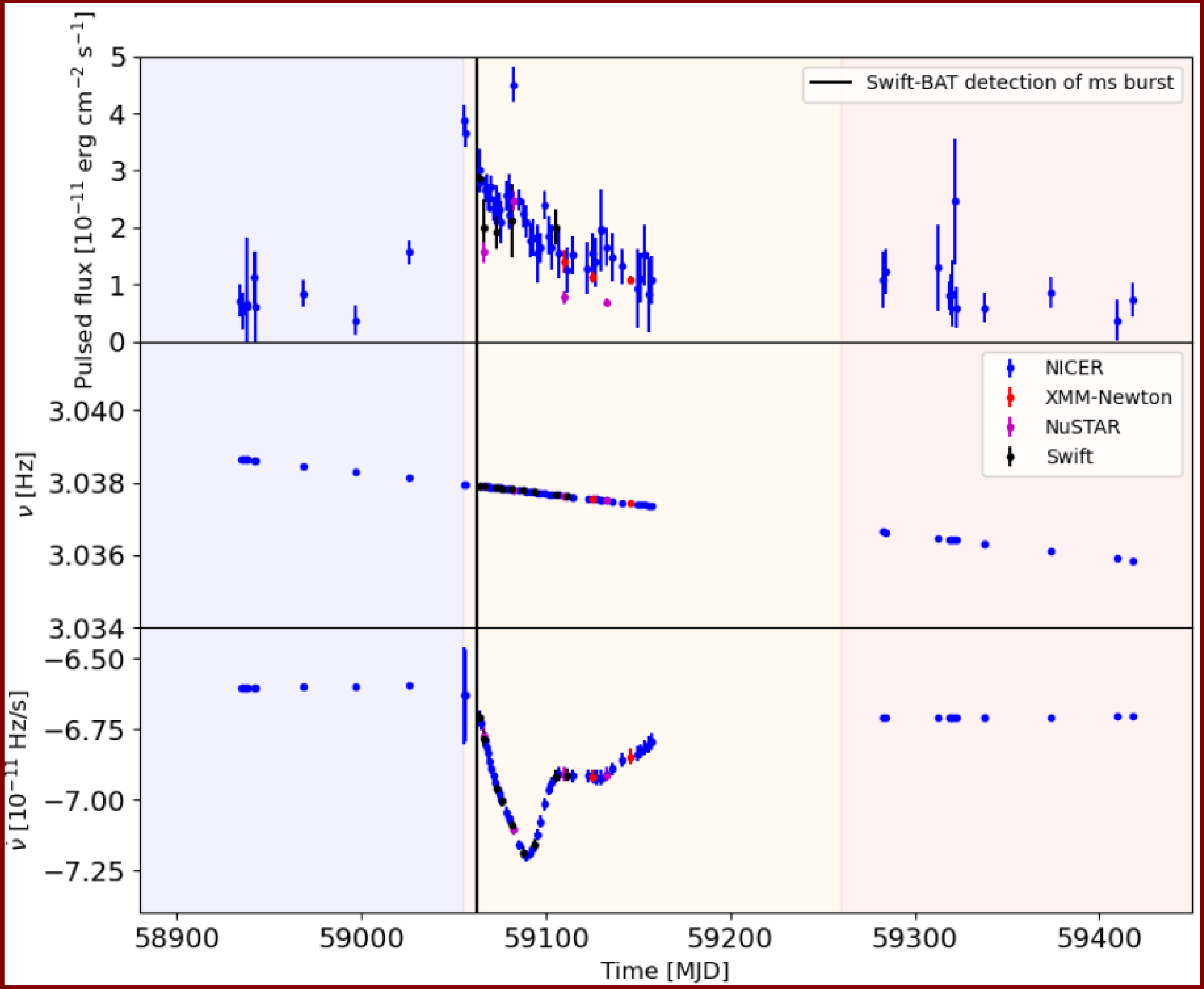


Recent X-ray



1007.2829, recently re-activated: 2103.12557. NICER data 2306.00902

2020 re-activation of PSR J1846 in Kes 75

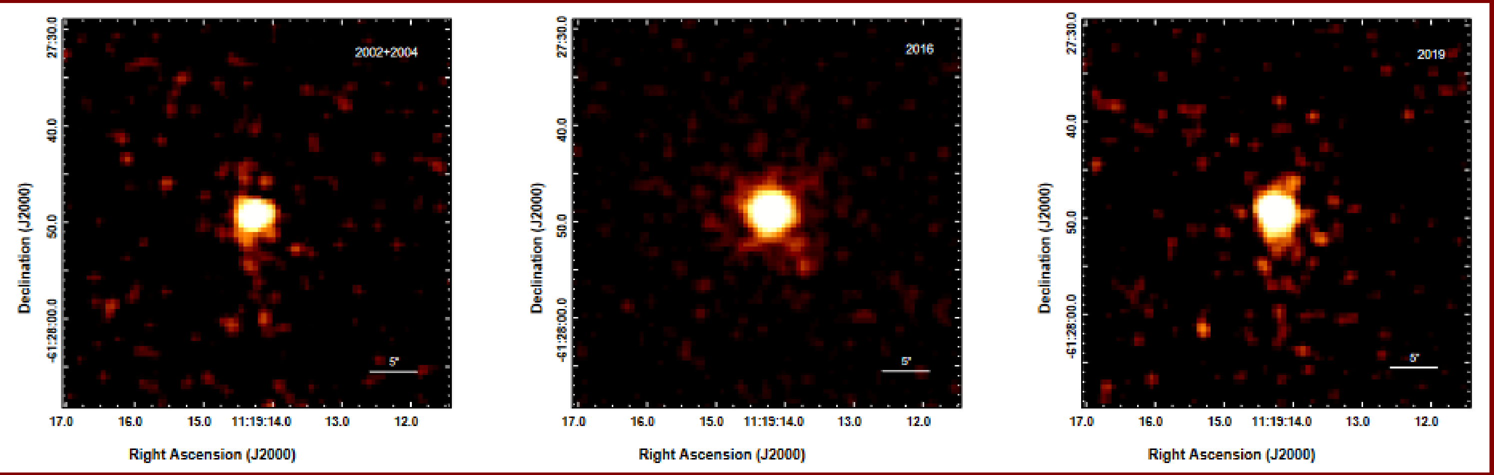


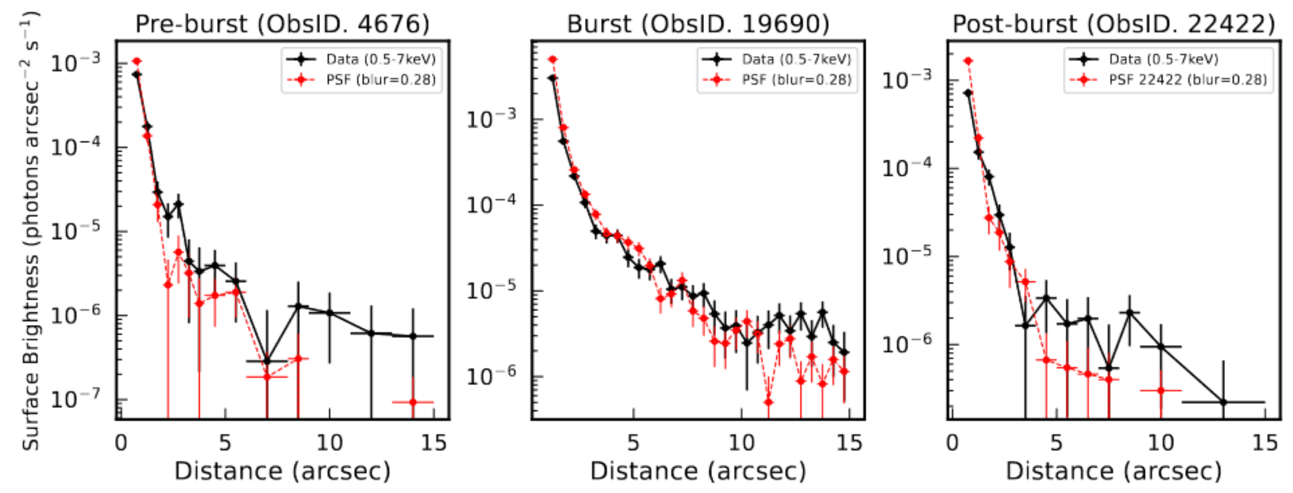
2401.08010

Post-outburst evolution of the pulsar J1119–6127

A young rotation-powered pulsar.

Magnetar-like bursts in 2016.





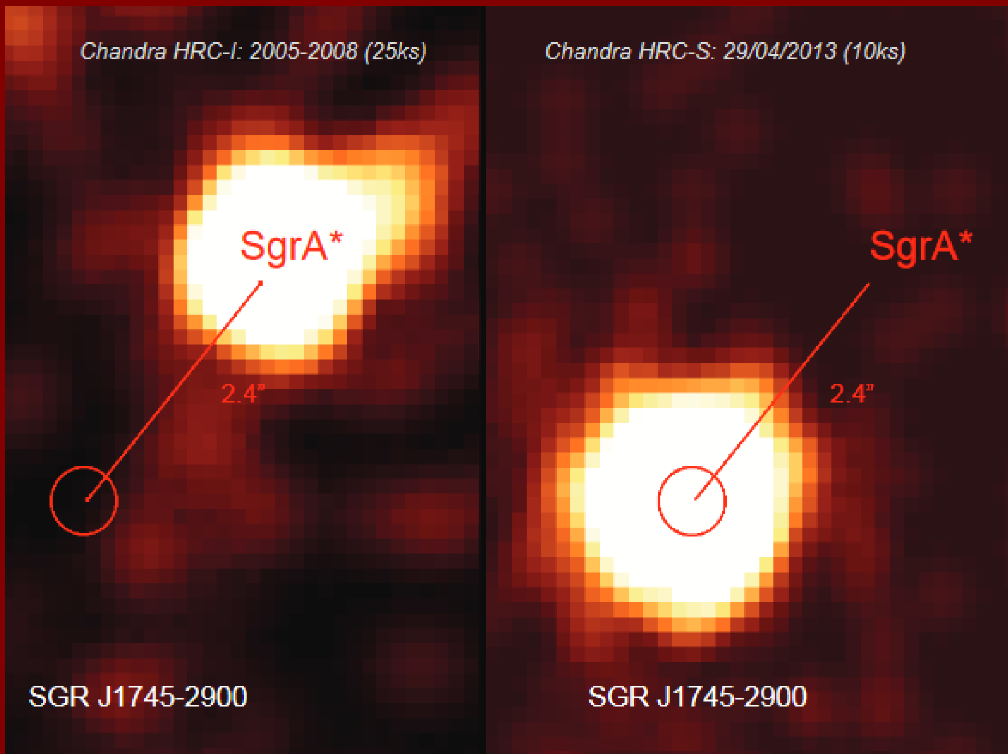
Chandra observations.

2106.12018

Galactic center magnetar

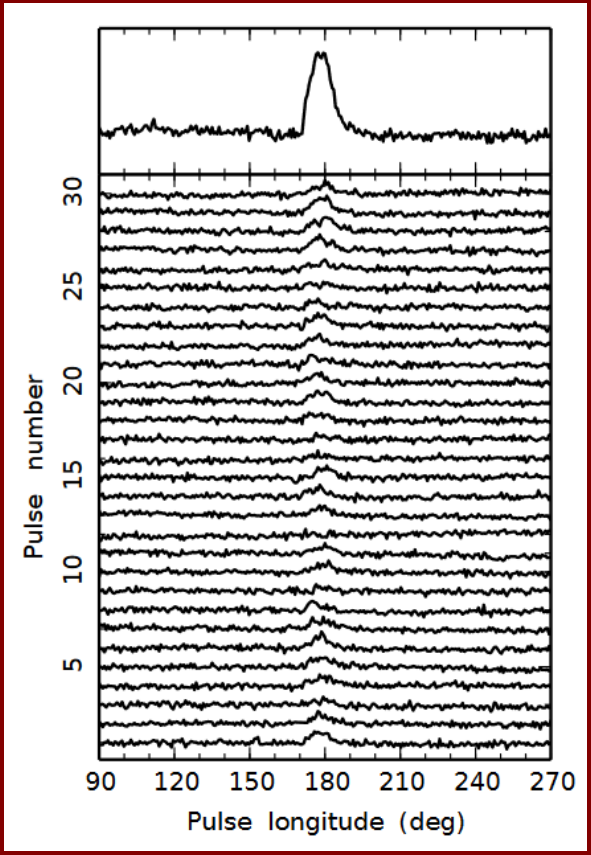
1307.6331

SGR/PSR J1745−2900



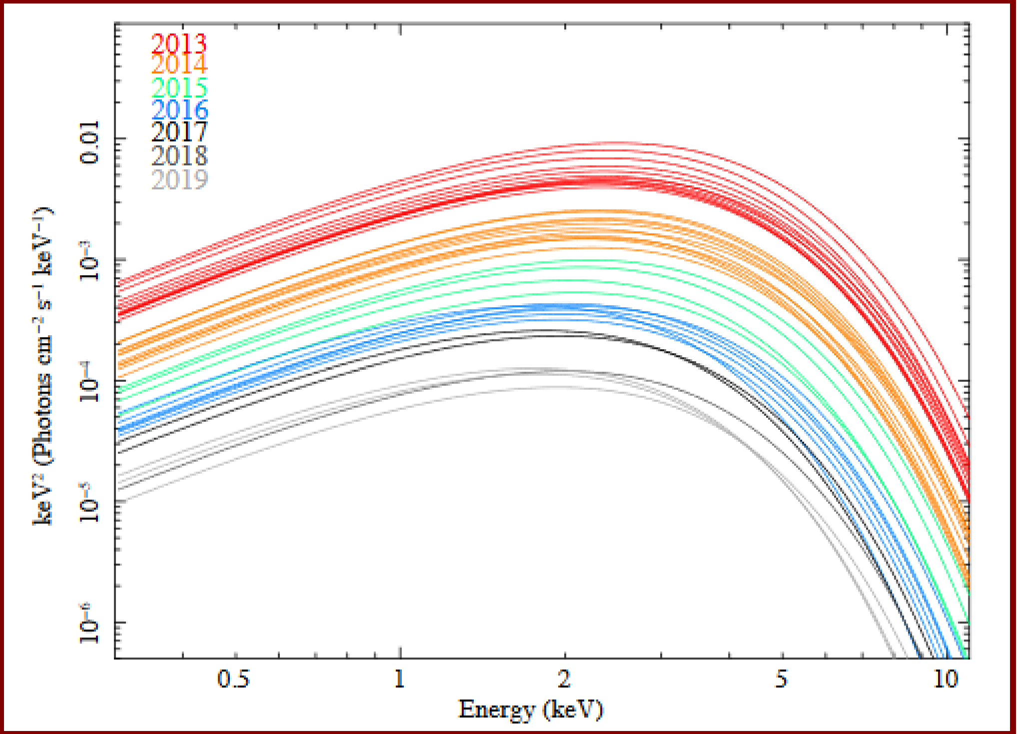
<1 pc from Sgr A*

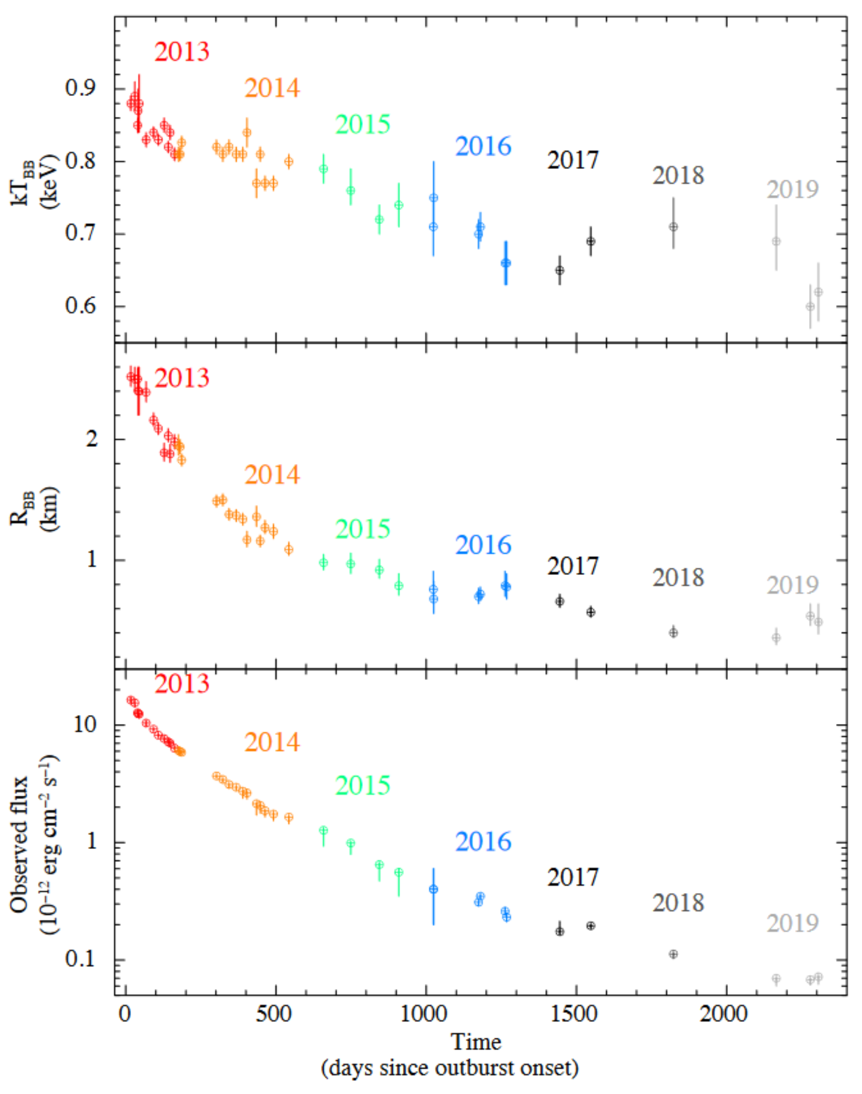
Radio pulsations detection in 2013
The largest dispersion measure and rotation measure among PSRs.



1802.07884

Evolution of the Galactic center magnetar after the outburst in 2013





2003.07235

Generation of the magnetic field

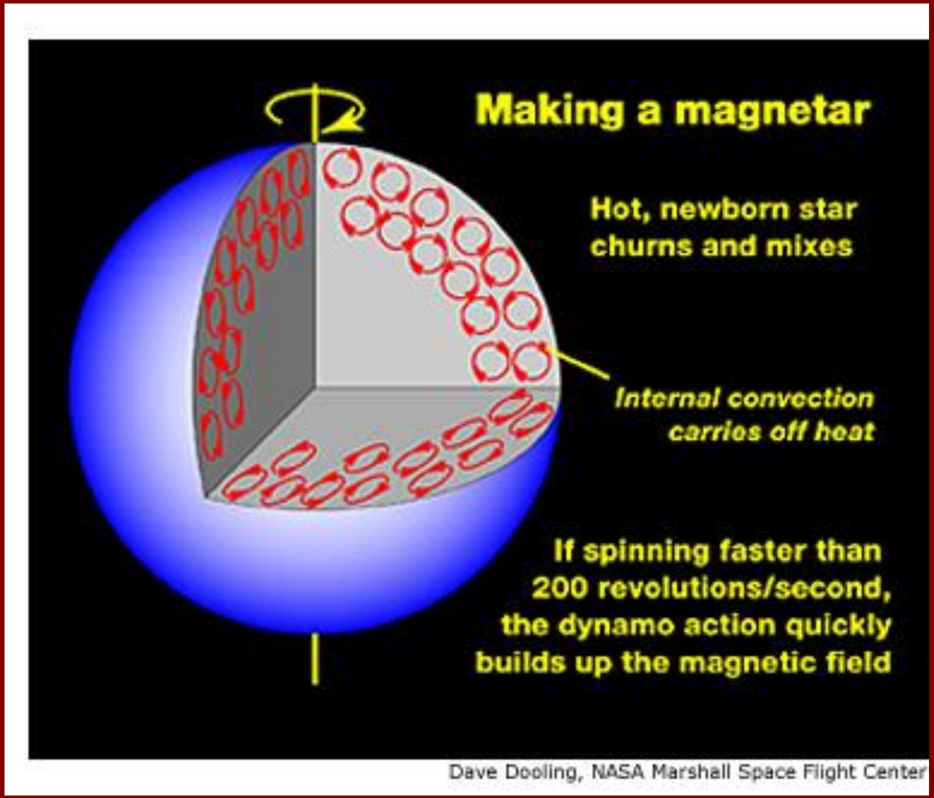
The mechanism of the magnetic field generation is still unknown.

Turbulent dynamo

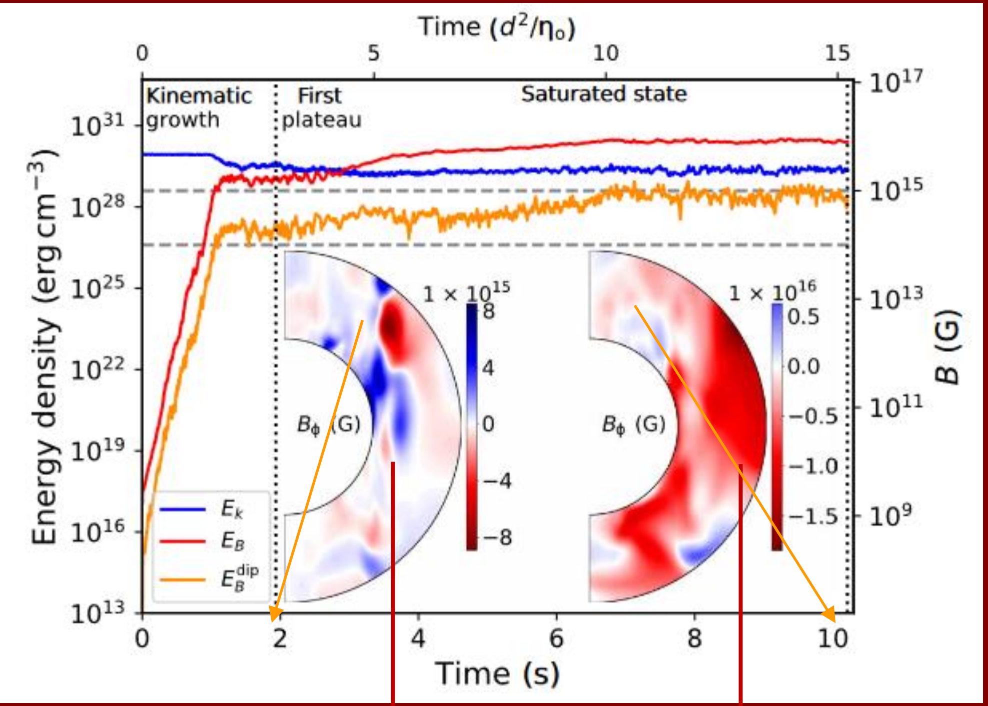
α-Ω dynamo (Duncan,Thompson)
α^2 dynamo (Bonanno et al.)
or their combination

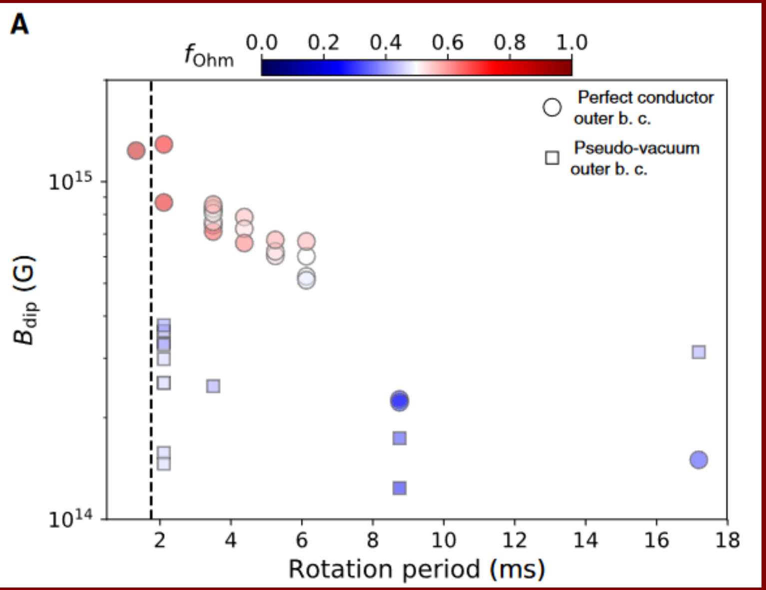
In any case, initial rotation of a protoNS is the critical parameter.

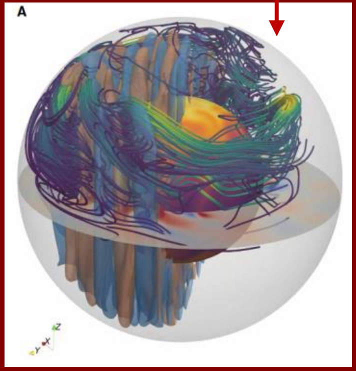
Rapid rotation can also be due to fallback (2206.01269)

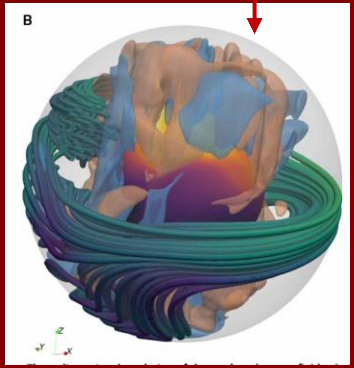


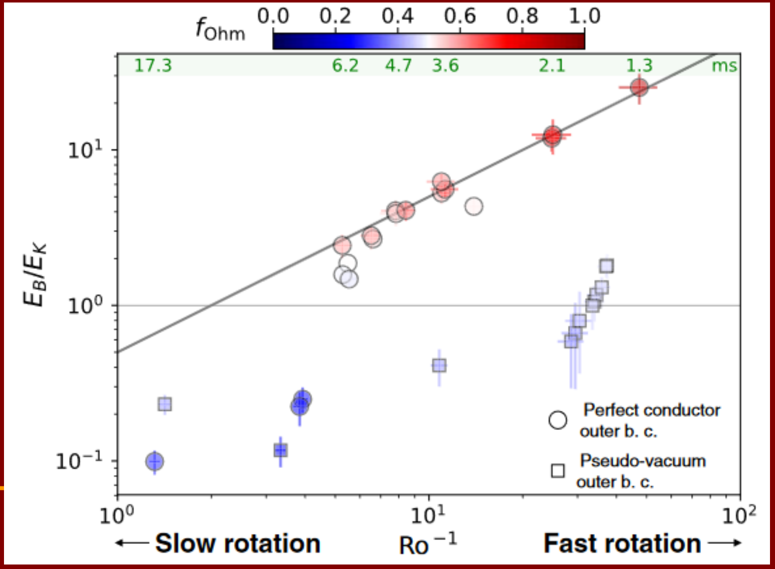
Numerical model of field amplification







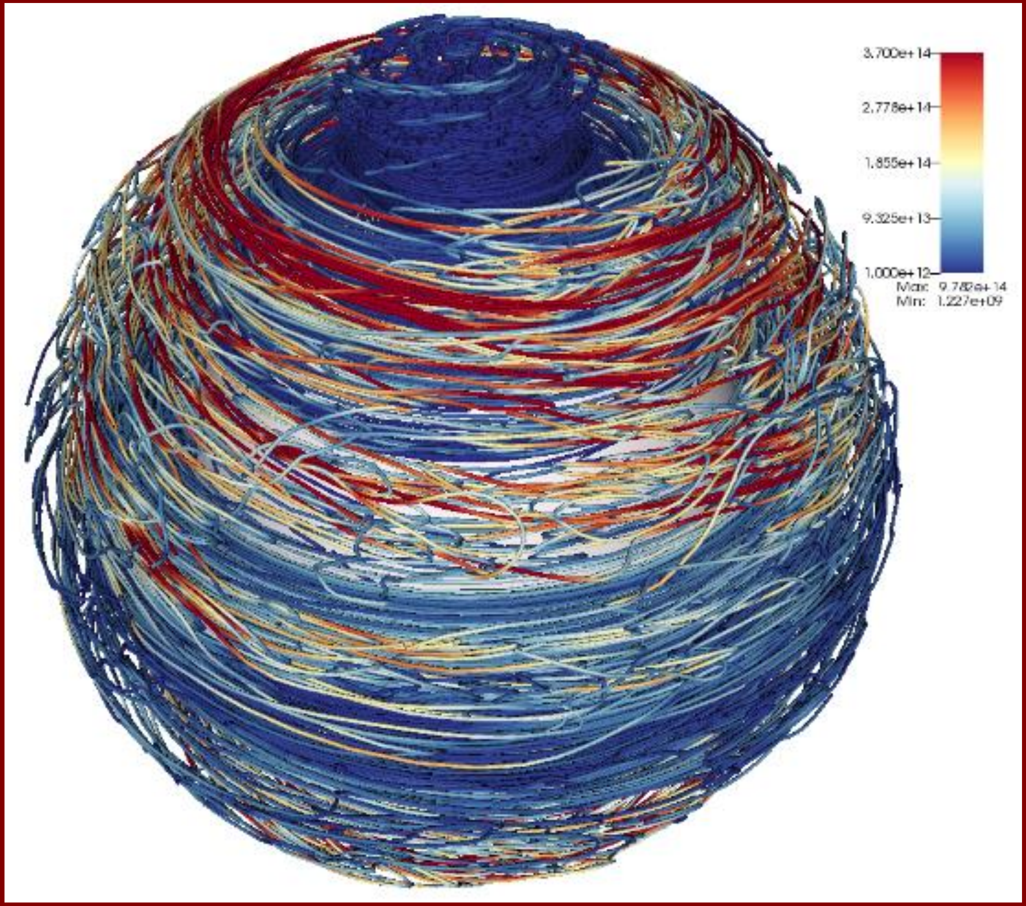


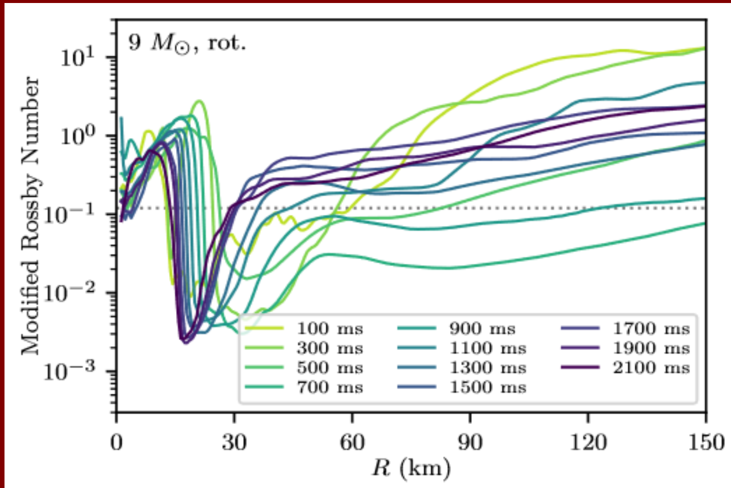


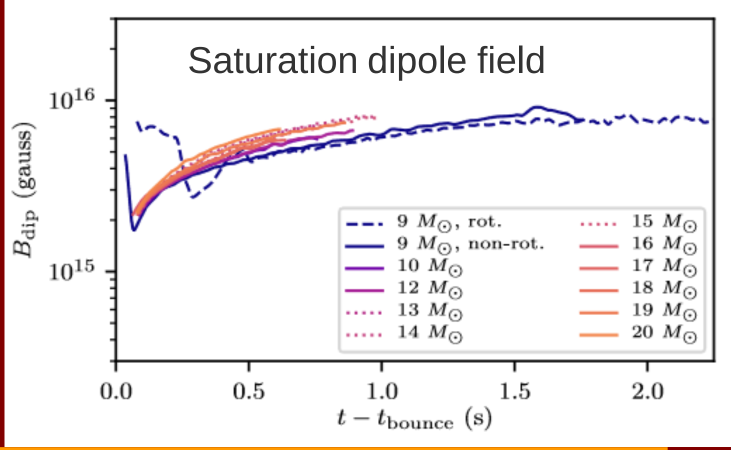
2003.06662

Detailed numerical modeling

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







2111.02148 - MRI

2111.01814 - convection

Strong field via flux conservation

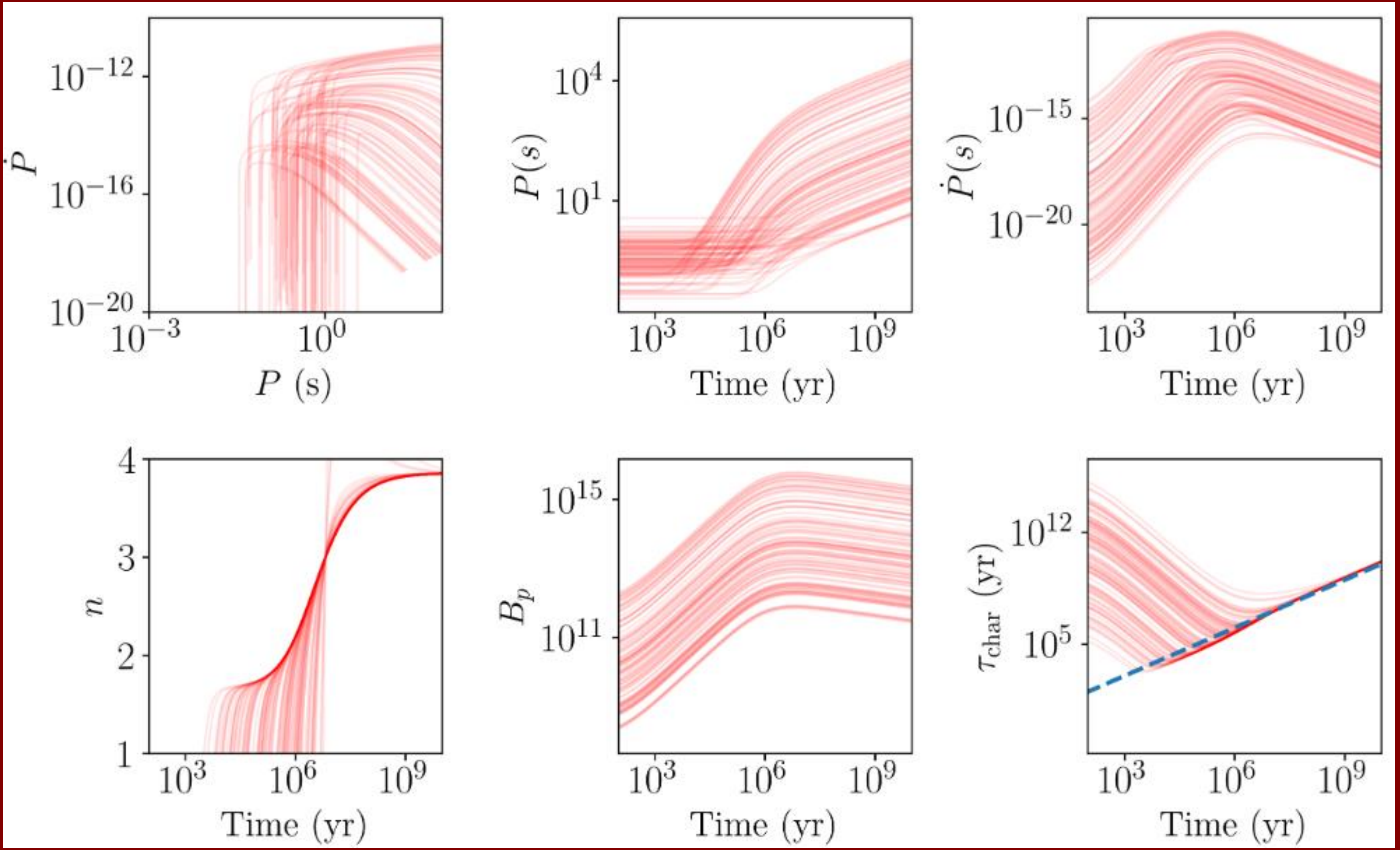
There are reasons to suspect that the magnetic fields of magnetars are not due to any kind of dynamo mechanism, but just due to flux conservation:

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)

Early field growth due to Hall cascade

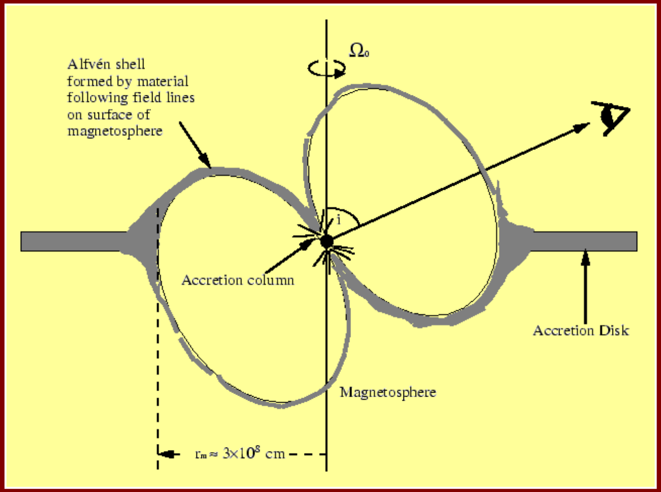


2305.14347 Inverse cascade

$$B_{\rm LS} \propto B_{\rm rms}^{-5} \propto t,$$

Alternative theory

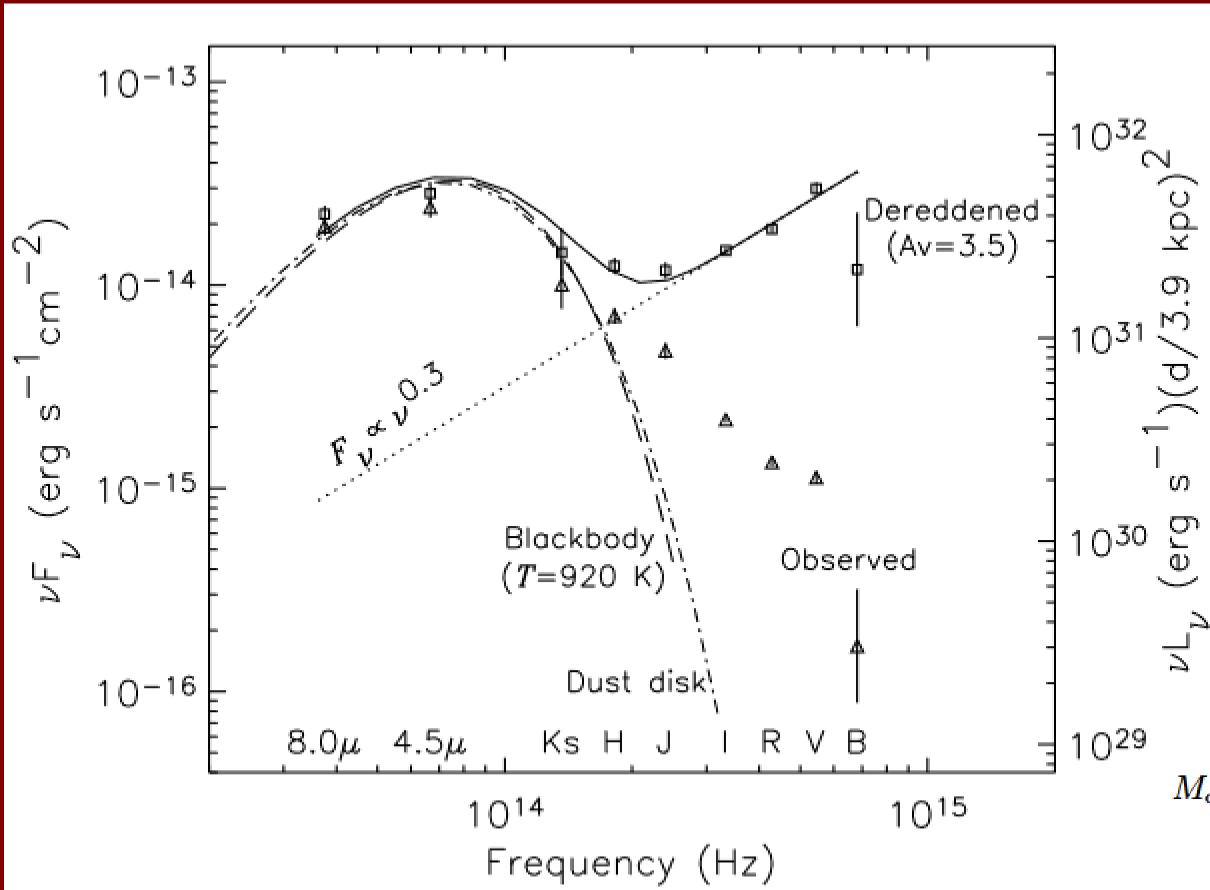
- Remnant fallback disc
- Mereghetti, Stella 1995
- Van Paradijs et al.1995
- Alpar 2001
- Marsden et al. 2001
- Problems …..
- How to generate strong bursts?
- Discovery of a passive
  disc in one of AXPs
  (Wang et al. 2006).
  A new burst of interest
  to this model.
- Timing noise analysis
  contradicts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



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

Fall-back discs

4U 0142+61

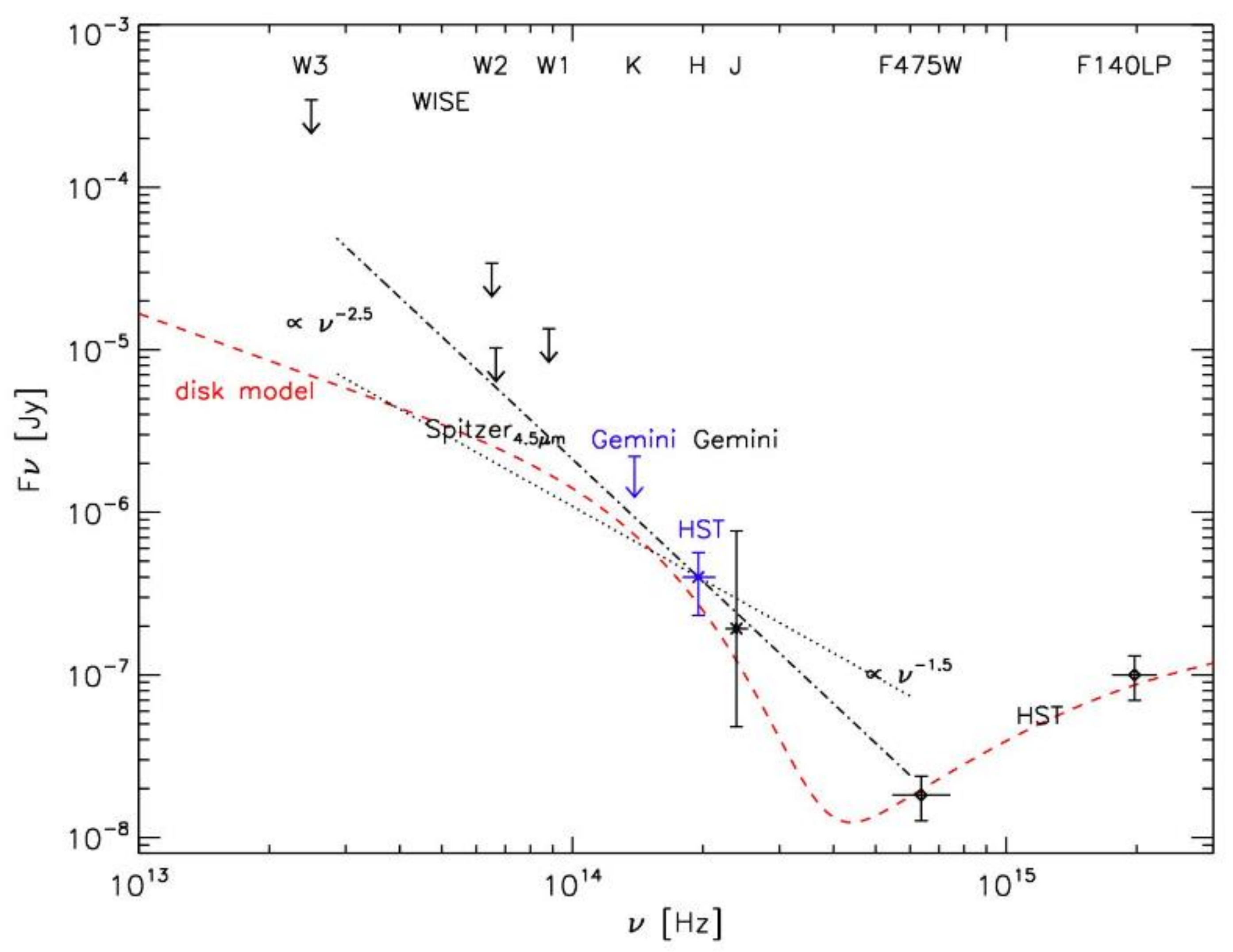


$$M_{\rm d} \lesssim 3 \times 10^{-3}\ M_\odot \left(\frac{F_{\rm MM}}{50\ \mu{\rm Jy}}\right)\left(\frac{d}{3.9\ {\rm kpc}}\right)^2 \times \left(\frac{T(r_{\rm out})}{300\ {\rm K}}\right)^{-1}\left(\frac{\kappa_{\rm MM}}{0.01\ {\rm cm}^2\ {\rm g}^{-1}}\right)^{-1},$$

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

astro-ph/0604076

A disc around one of the M7



RX J0806.4–4123

Can be a disc, and can be a nebula.

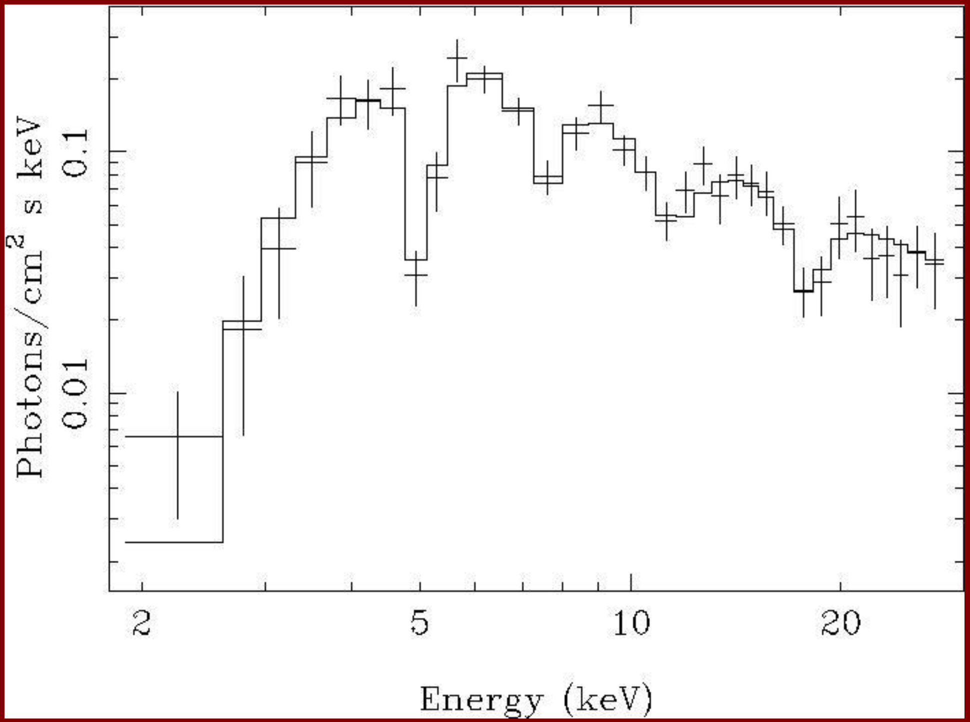
1809.08107

Magnetic field estimates

- Spin down
- Long spin periods

- Energy to support bursts
- Field to confine a fireball (tails)
- Duration of spikes (alfven waves)

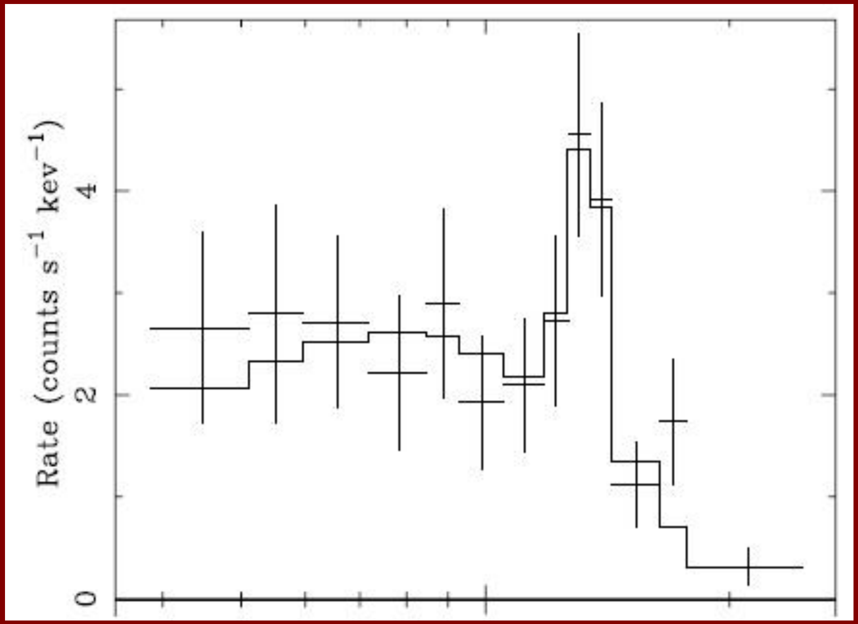
- Direct measurements of magnetic field (cyclotron lines)

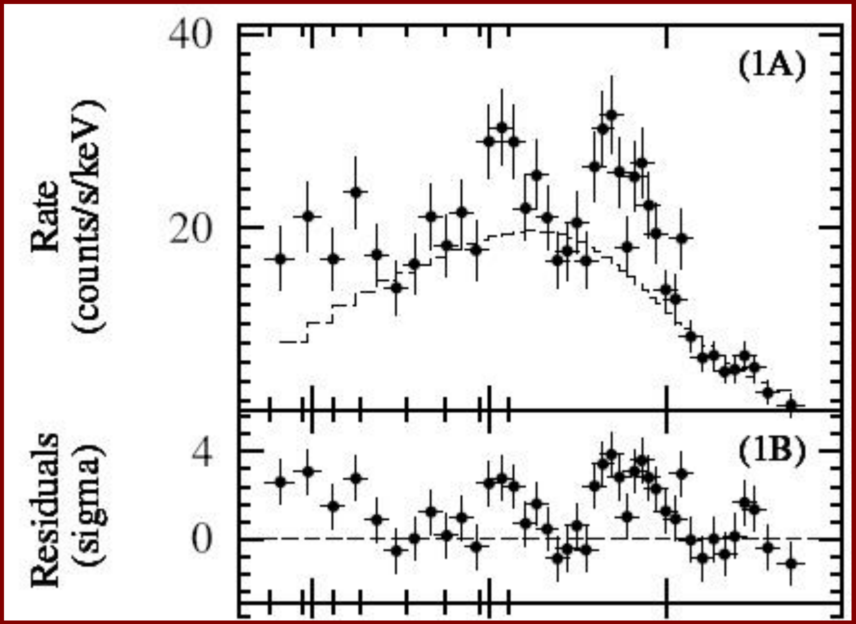


Ibrahim et al. 2002

Spectral lines claims

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

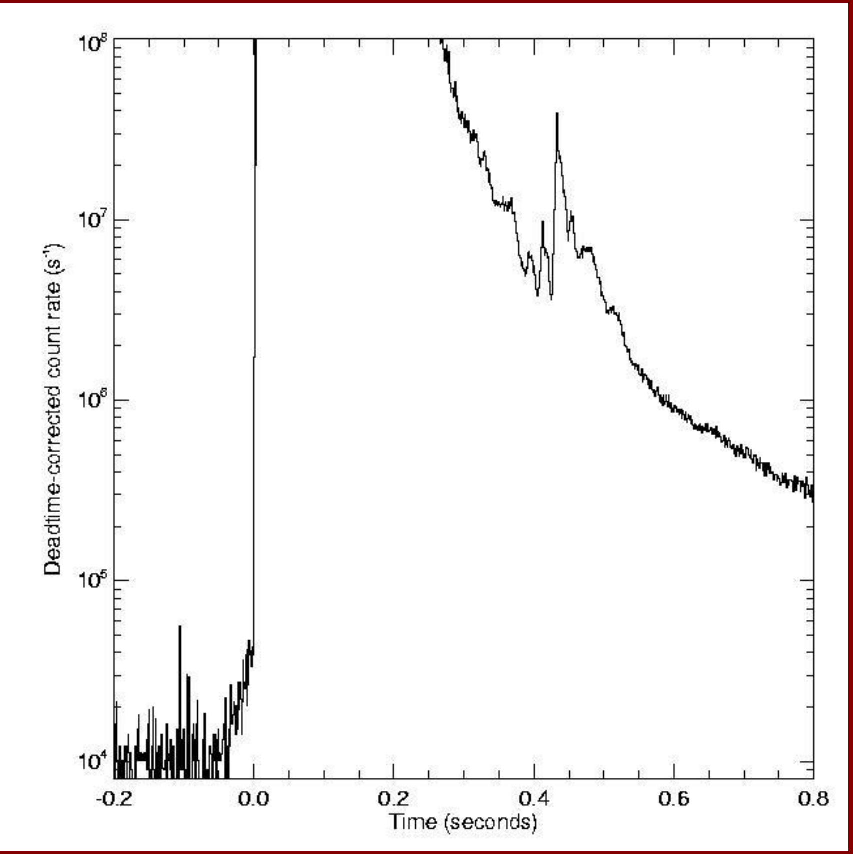




1E 1048.1-5937 Gavriil et al. (2002, 2004) 4U 0142+61 Gavriil et al. (2007)

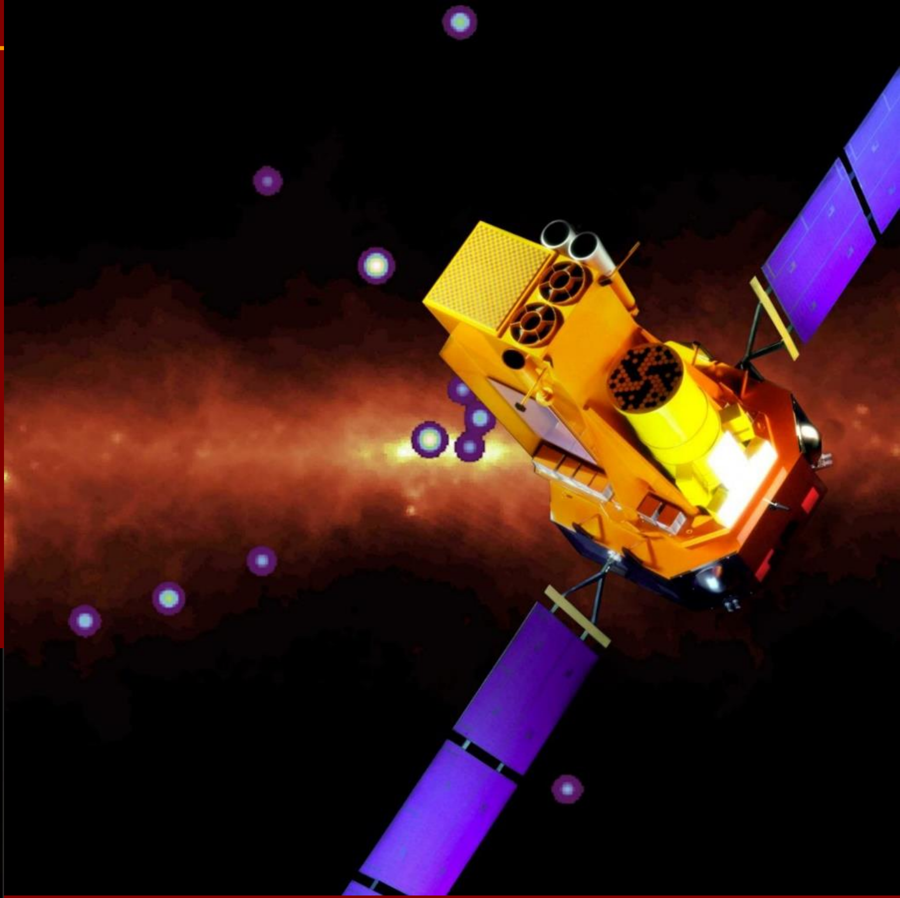
Hyperflare of SGR 1806-20

- 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!



Palmer et al.
astro-ph/0503030

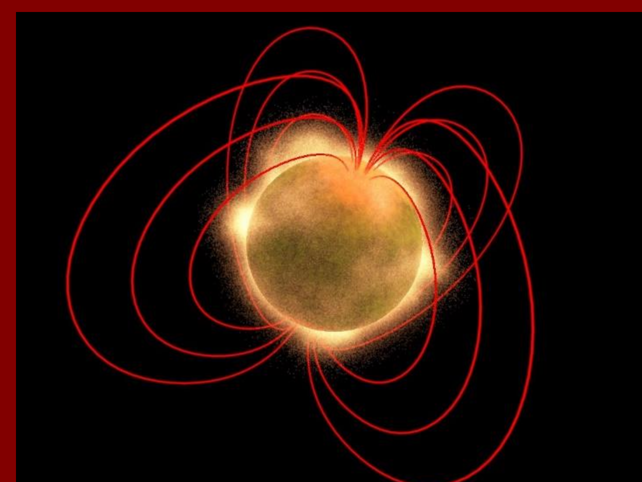
CORONAS-F



Integral

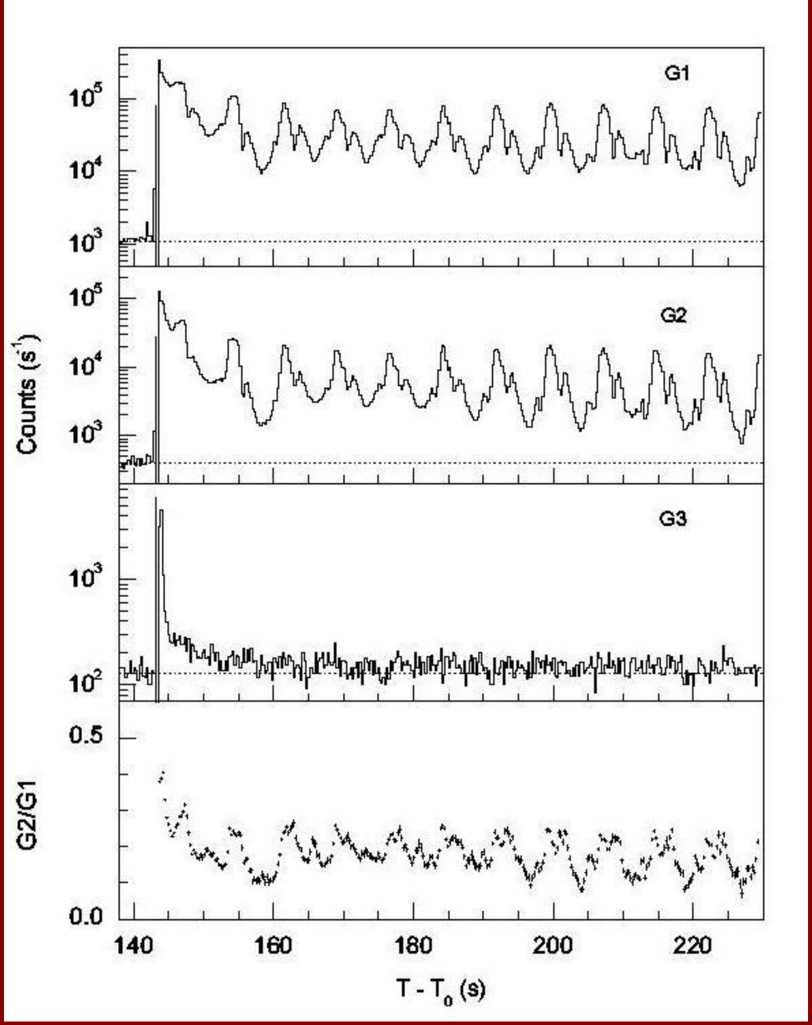
RHESSI

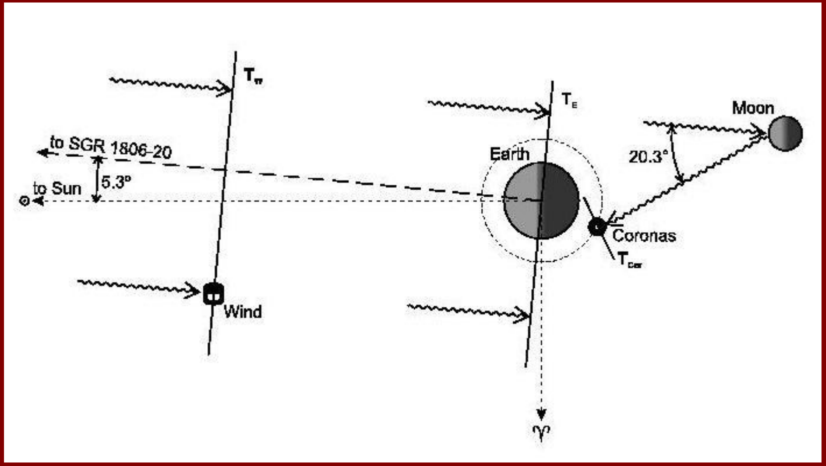
27 Dec 2004:
Giant flare of the SGR 1806-20

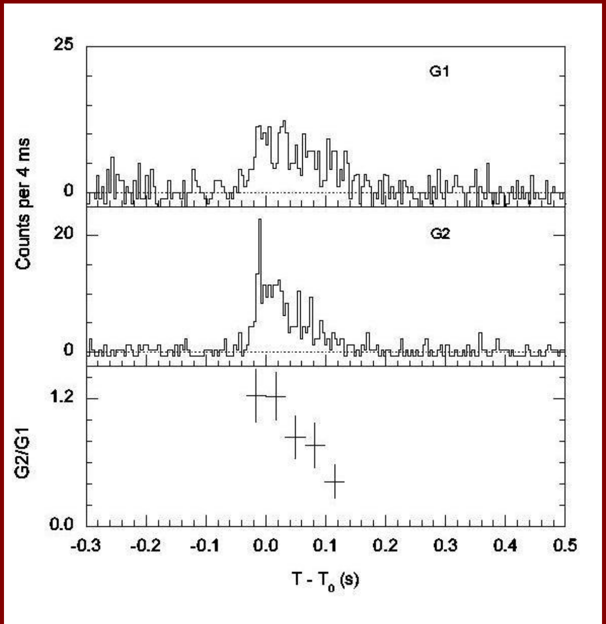


- Spike 0.2 s
- Fluence 1 erg/cm^2
- E(spike)=3.5 10^{46} erg
- L(spike)=1.8 10^{47} erg/s
- Long «tail» (400 s)
- P=7.65 s
- E(tail) 1.6 10^{44} erg
- Distance 15 kpc – see the latest data in arXiv: 1103.0006

Konus observations

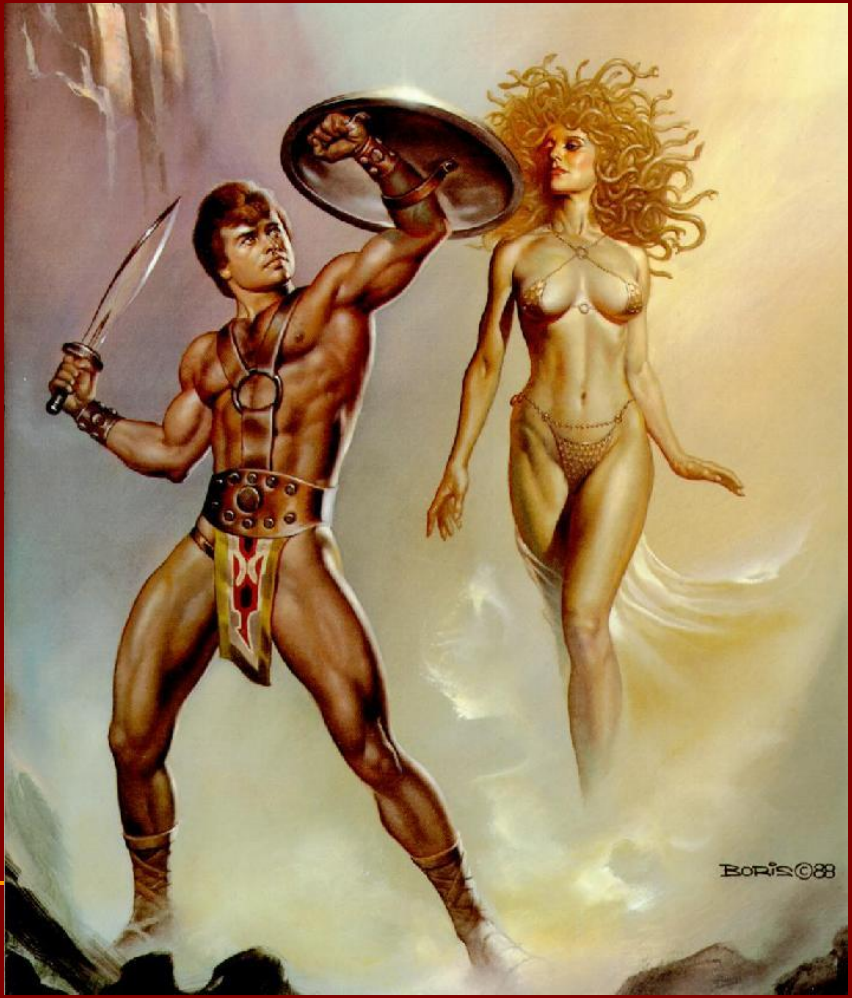






Mazets et al. 2005

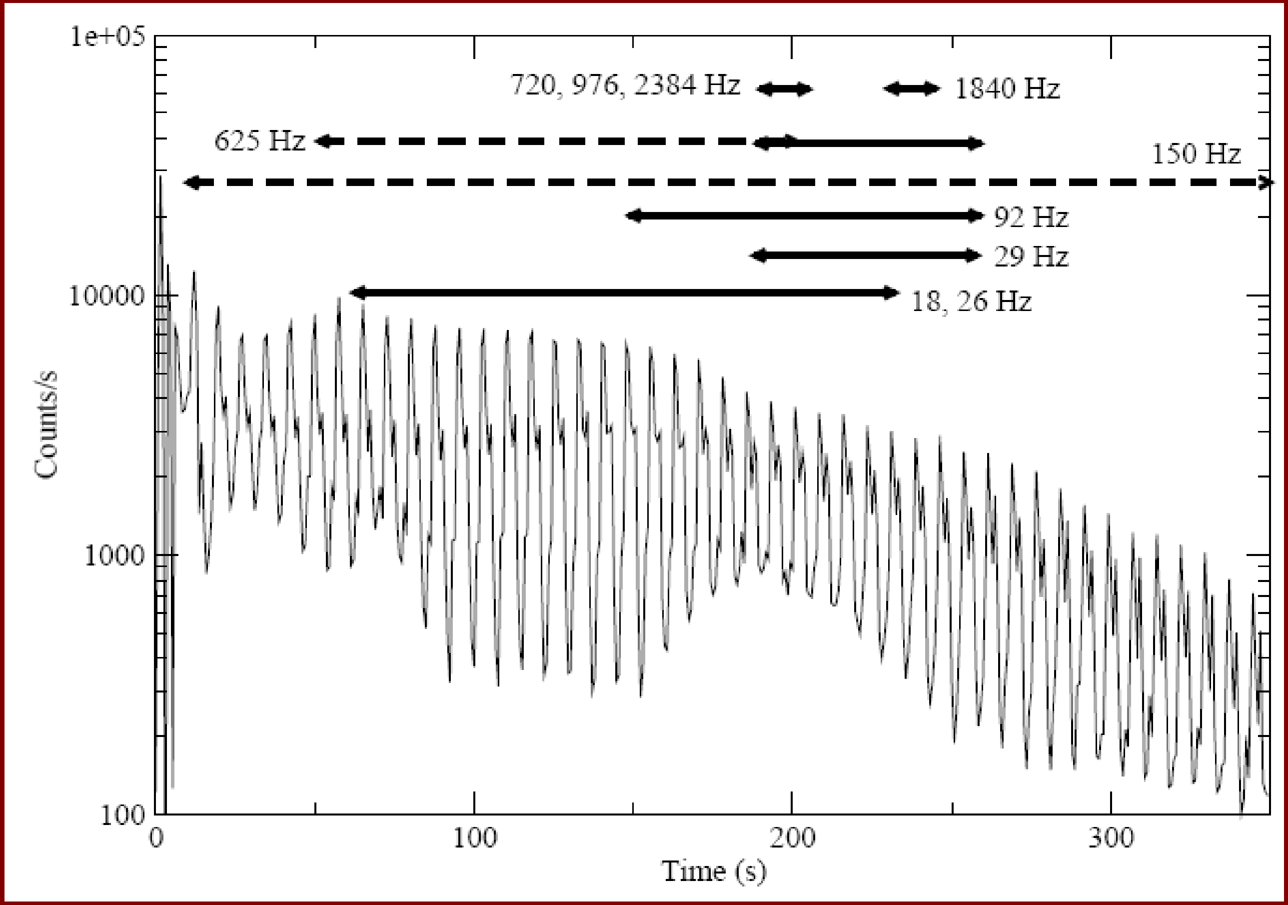
The myth about Medusa



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.

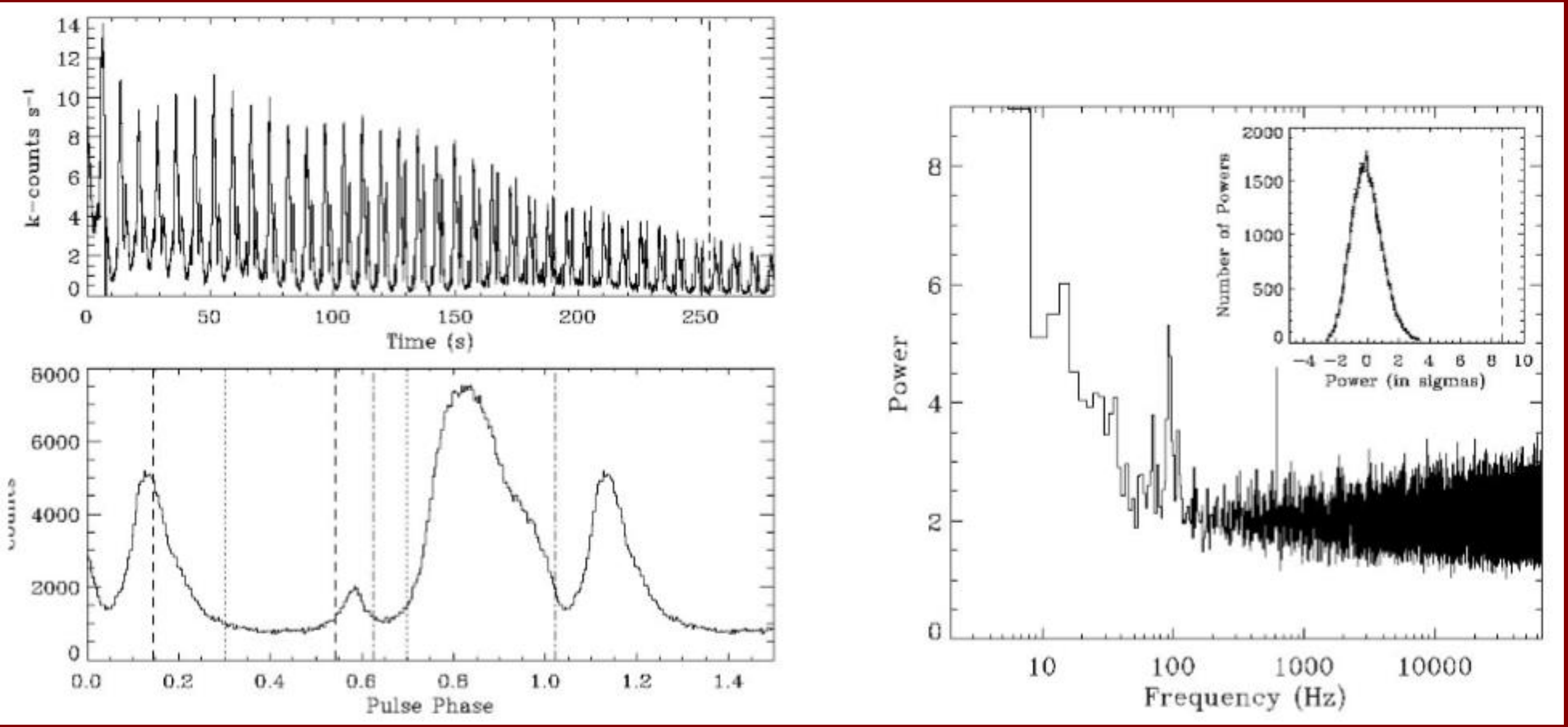
See 2002.12209 about astroseismology of neutron stars in relation to GW observations.



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

QPO in SGR 1806-20 giant flare

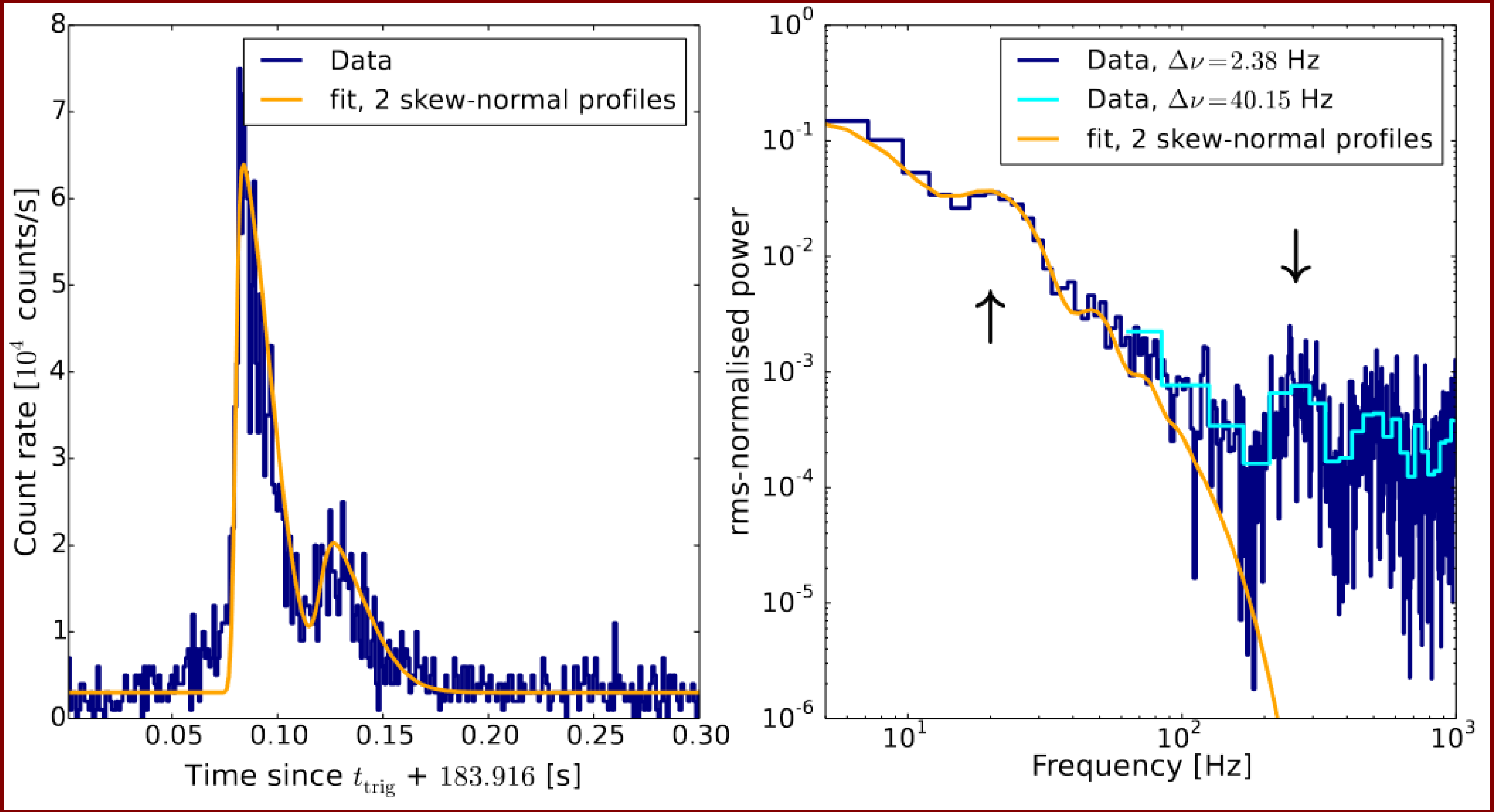
Power spectrum made by averaging nine 3 s segments from the time interval marked by dashed lines in the top left panel. The 92 Hz and 625 Hz QPOs are clearly visible, and the inset illustrates the significance of the 625 Hz feature (from Strohmayer & Watts, 2006)



1507.02924

See fresh analysis in 1808.09483

QPO in SGR J1550-5418



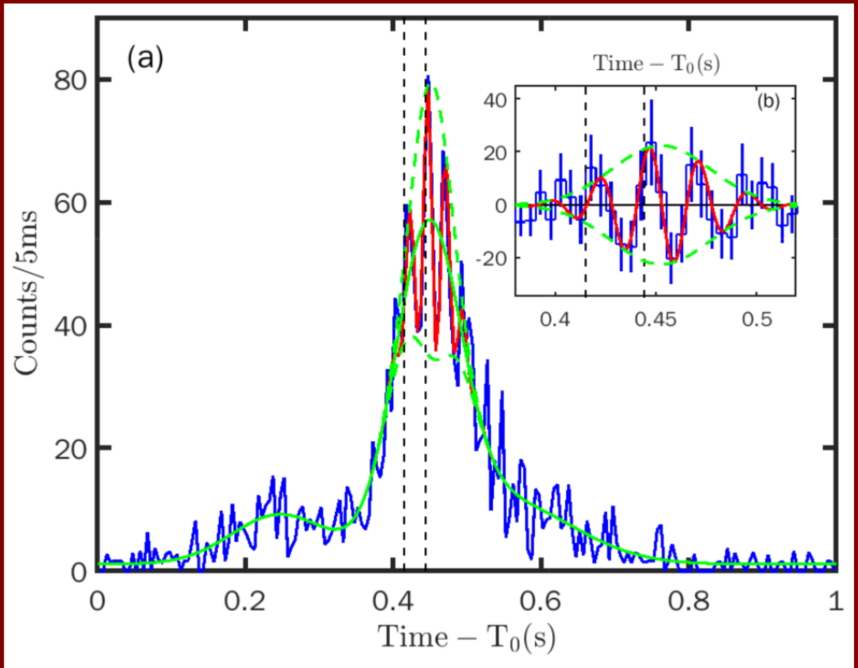
260 Hz (+candidates at ~93 and 127 Hz)

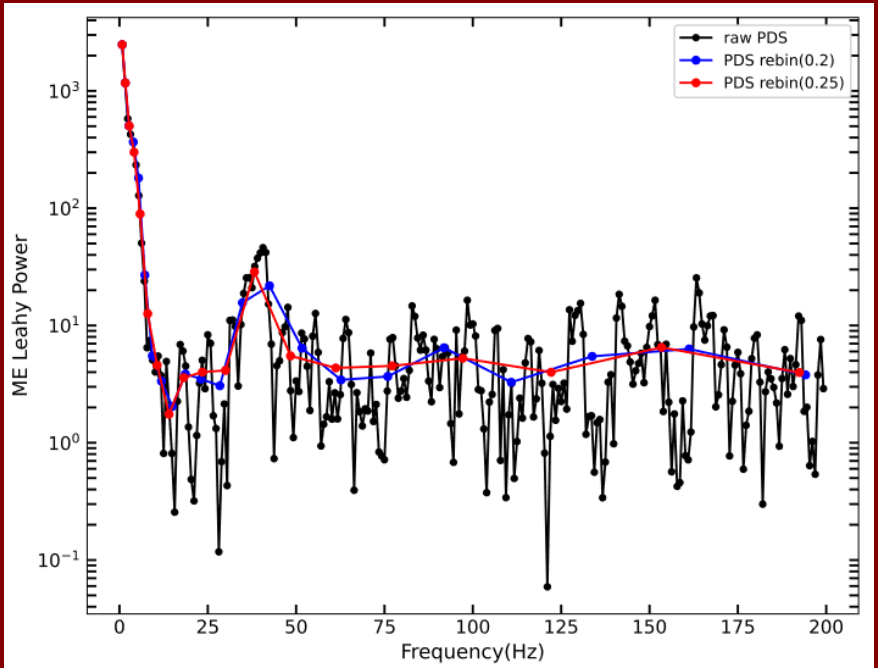
1404.2756

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.

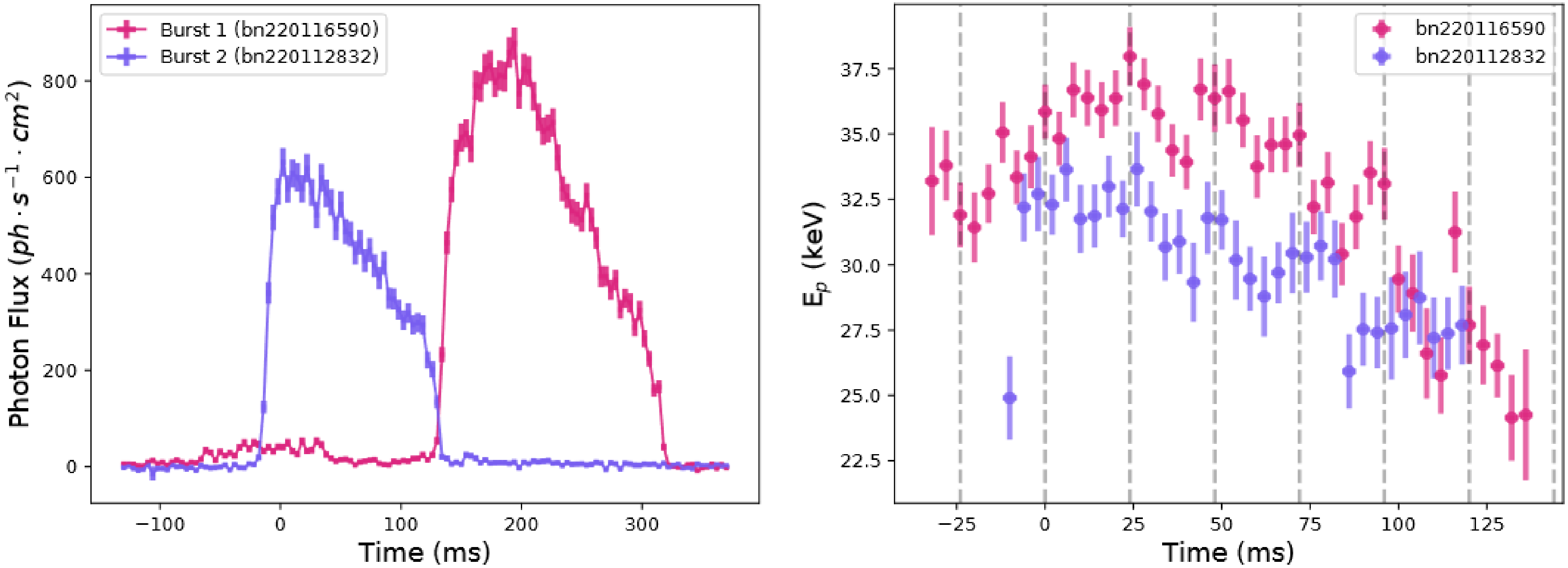




2204.03253

QPO in the peak energy

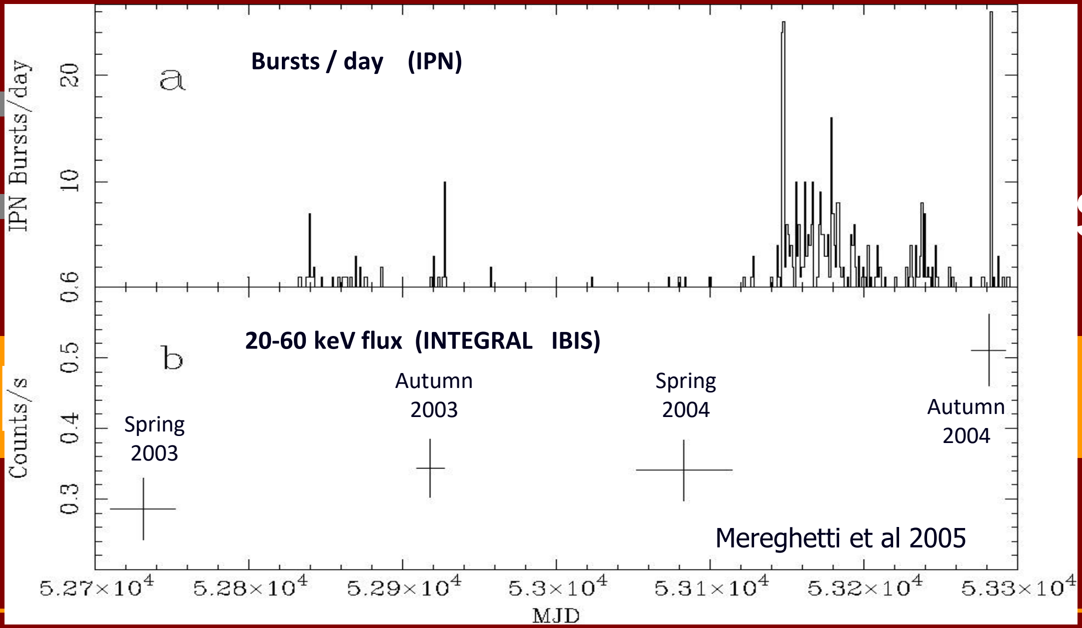
$$F(E) = A\left(\frac{E}{E_{\mathrm{piv}}}\right)^{\alpha} \exp\left[-\frac{(\alpha+2)E}{E_{\mathrm{p}}}\right]$$



2306.08130

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)

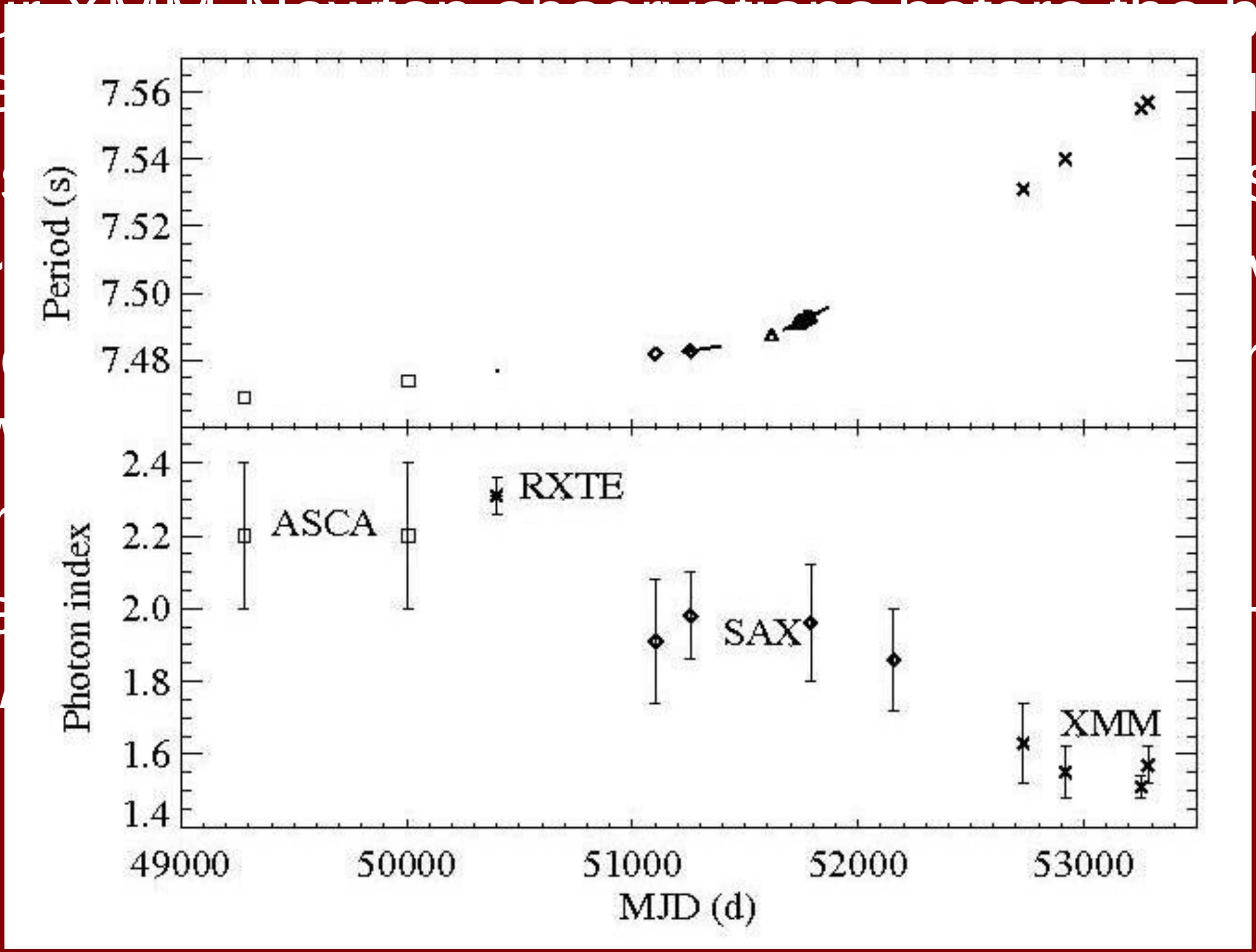


sity

T

SGR 1806-20 - II

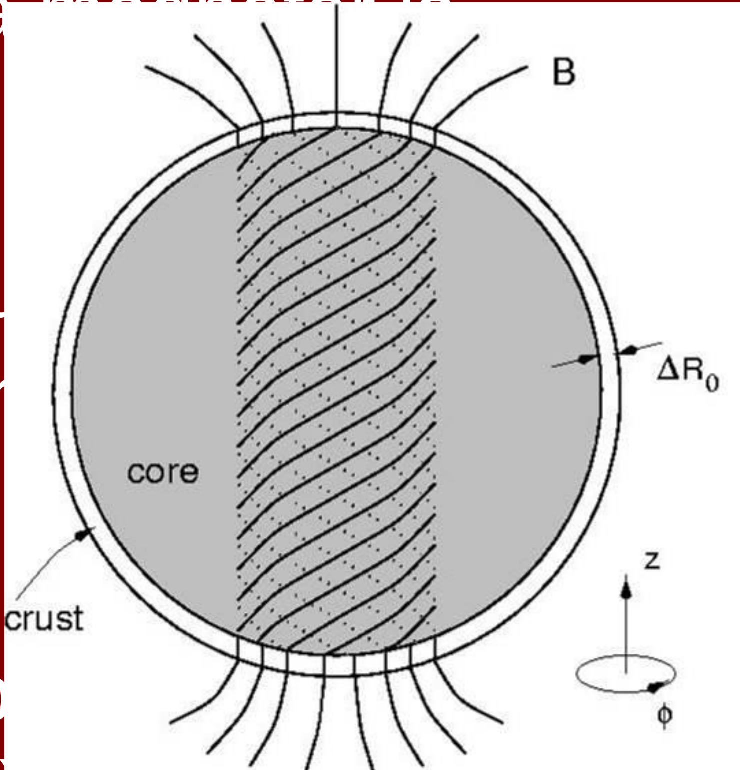
- Fou … urst
  (the … 2005)
- Puls … s
- Ṗ ~ … value
- Blac … rbed
  pow
- Har
- The … ~ 10^{36}
  erg/



Twisted Magnetospheres – I

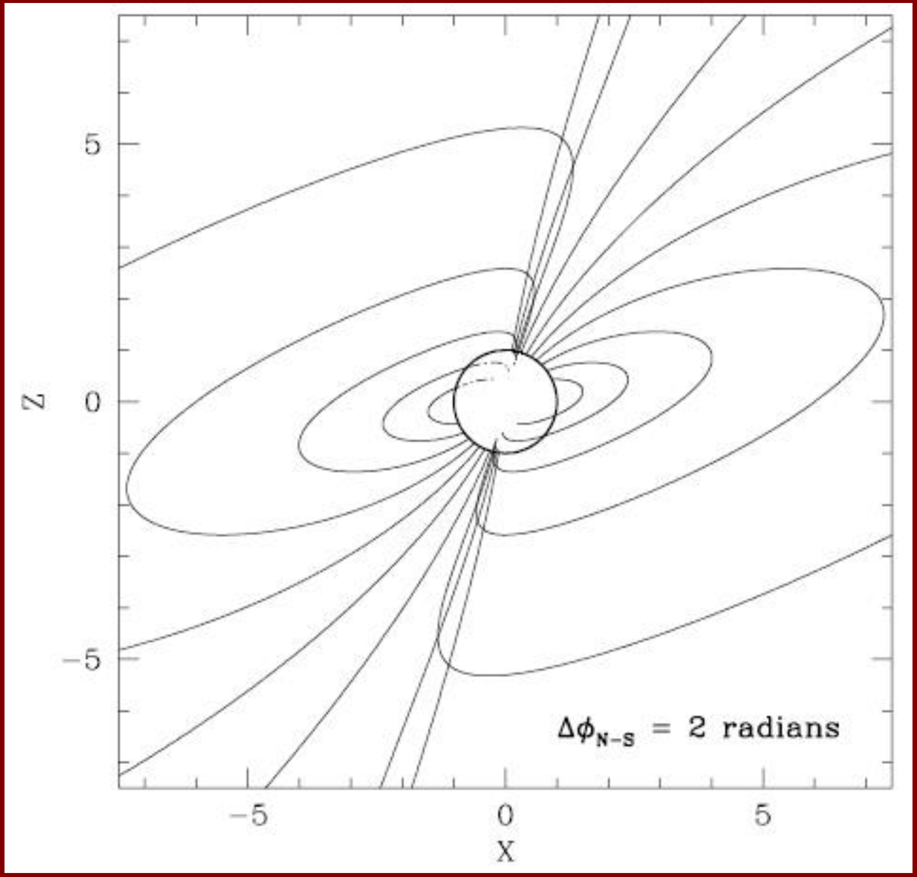
- The magnetic field inside a magnetar is “wound up”
- The presence of a toroidal induces a rotation of the su
- The crust tensile strength r
- A gradual (quasi-plastic ?) crust
- The external field twists up

(Thompson, Lyutikov & Kulkarni 2002)

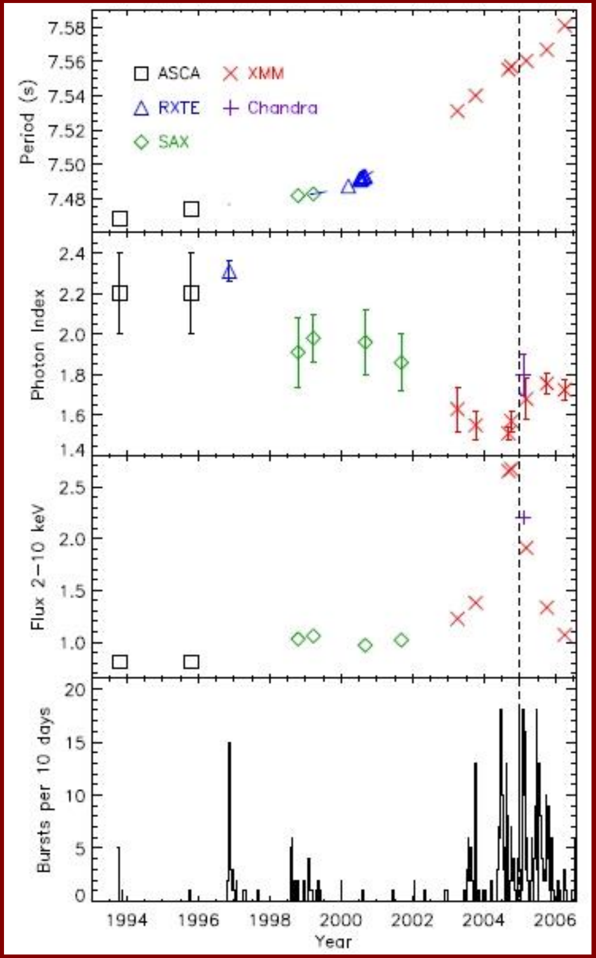


Thompson & Duncan 2001

Growing twist

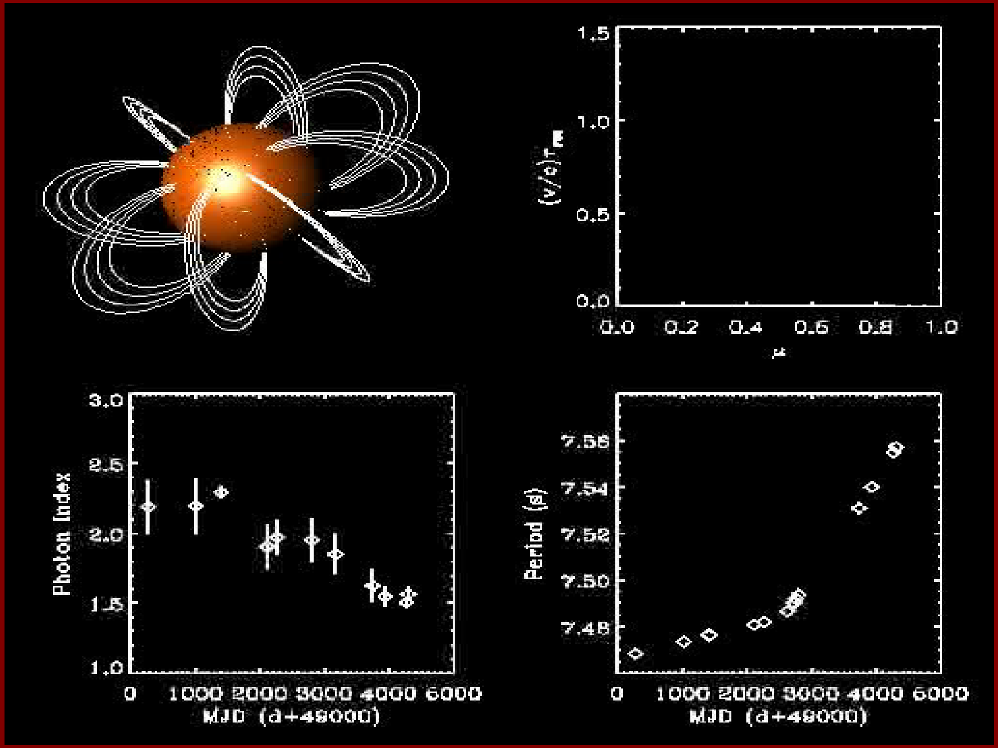


(images from Mereghetti arXiv: 0804.0250)



A Growing Twist in SGR 1806-20 ?

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



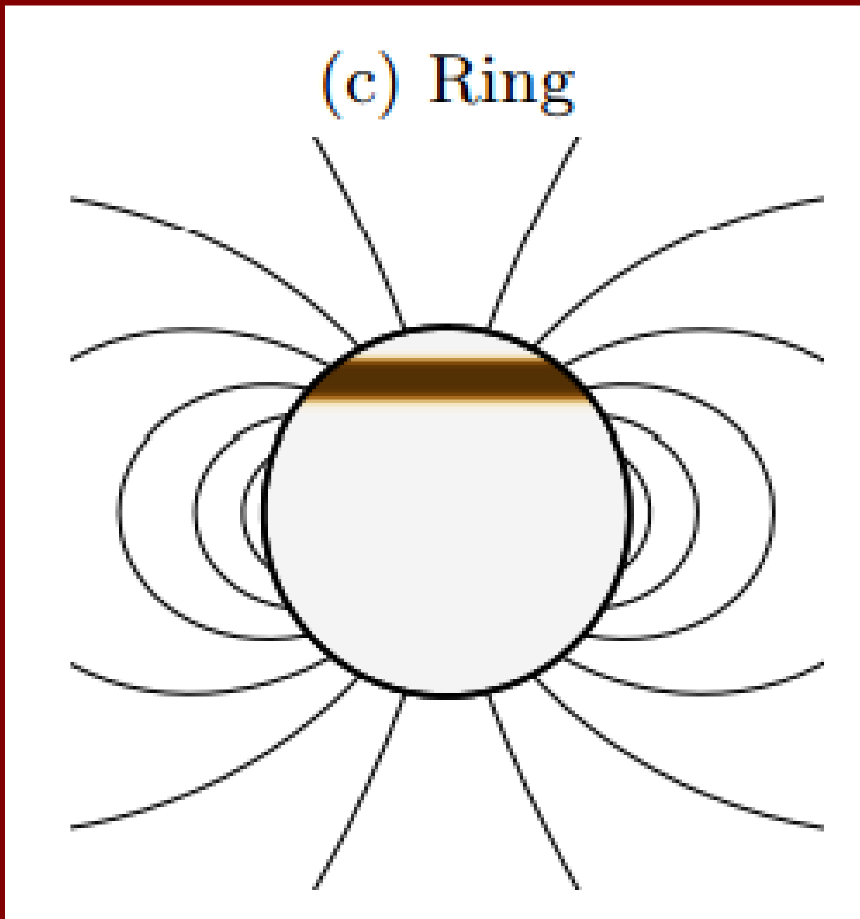
All these features are consistent with an increasingly twisted magnetosphere

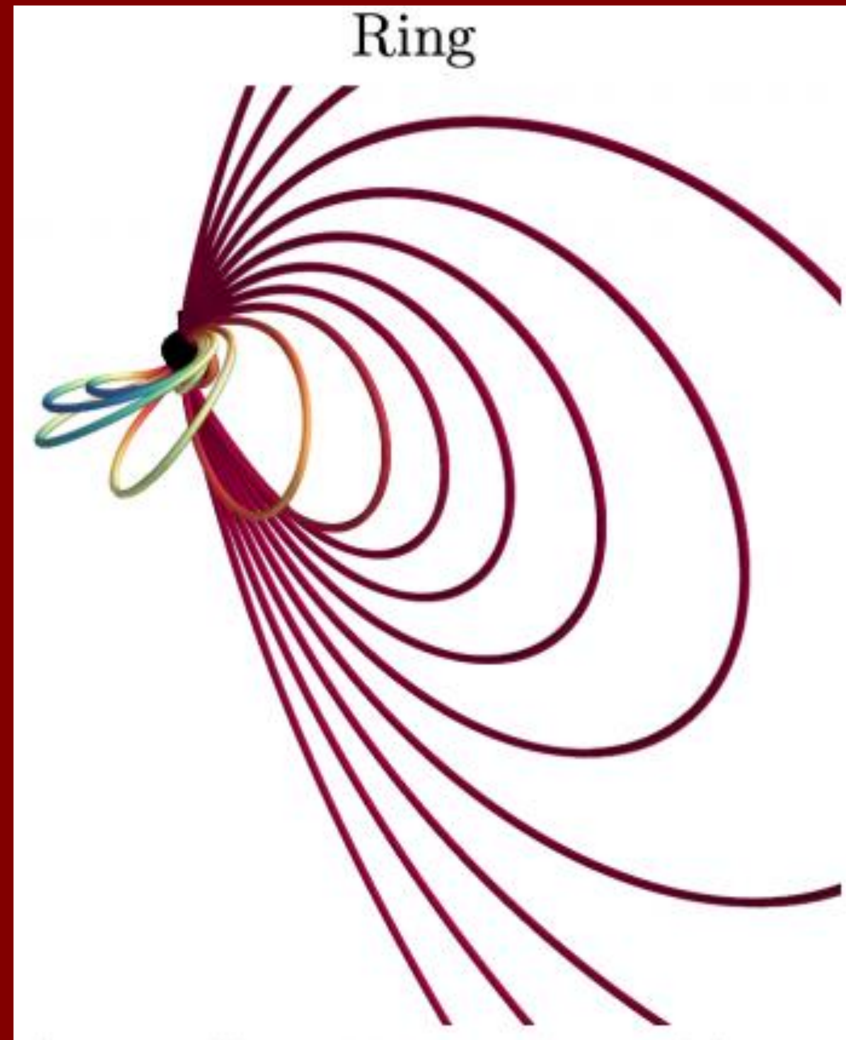
Twisted magnetospheres

- 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

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

Non-global twist model

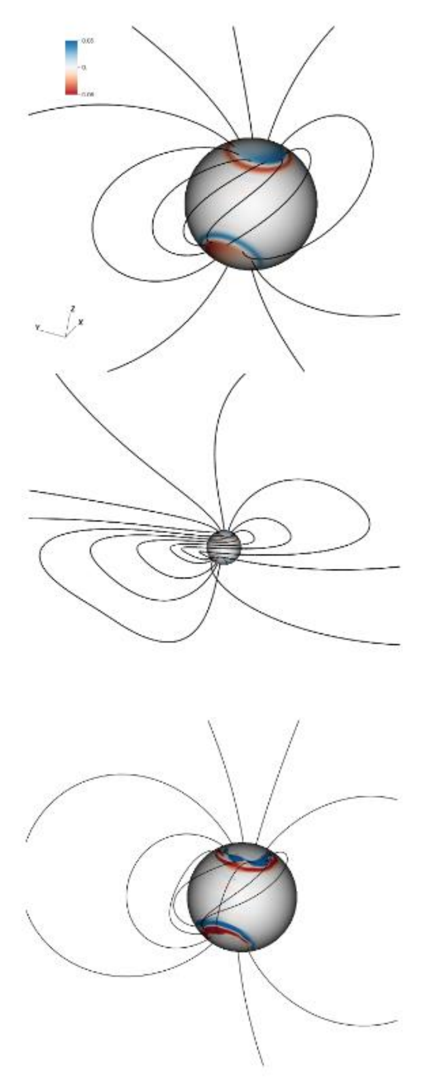


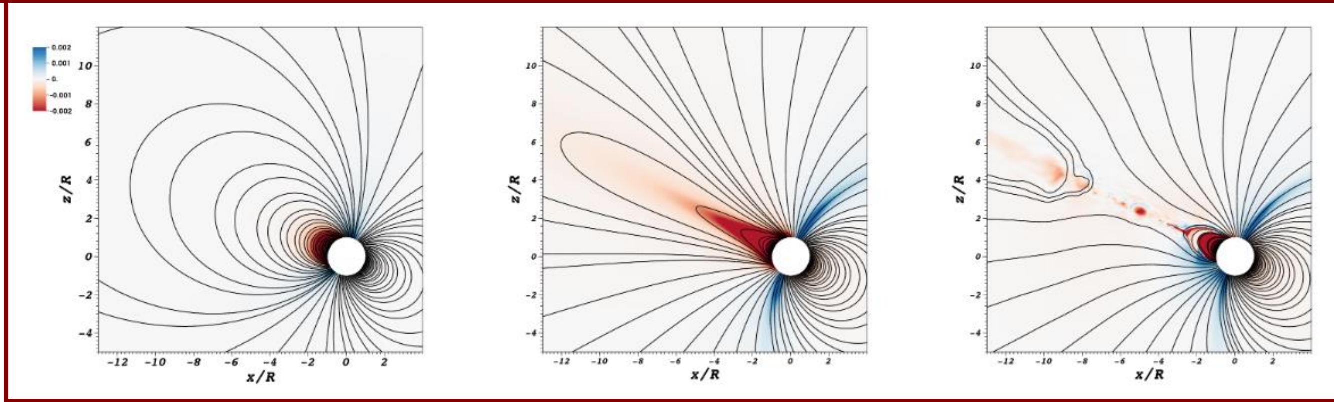


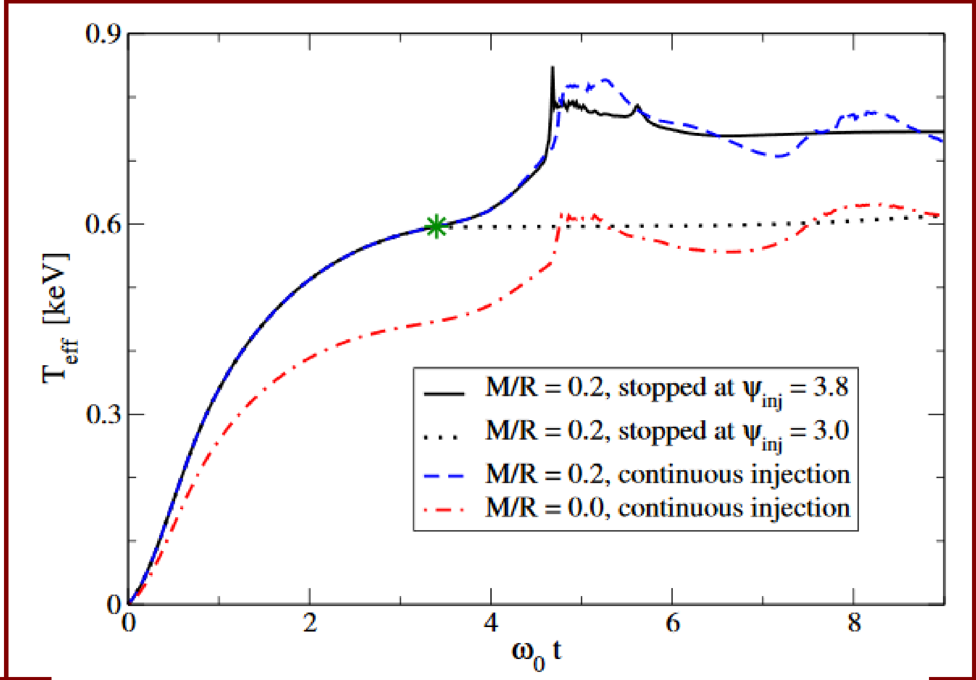
Energy in the twist: $\sim I^2 R_{NS}/c^2$
Twist decay time ~1 yr for typical parms

1306.4335

Numerical simulation of the twist







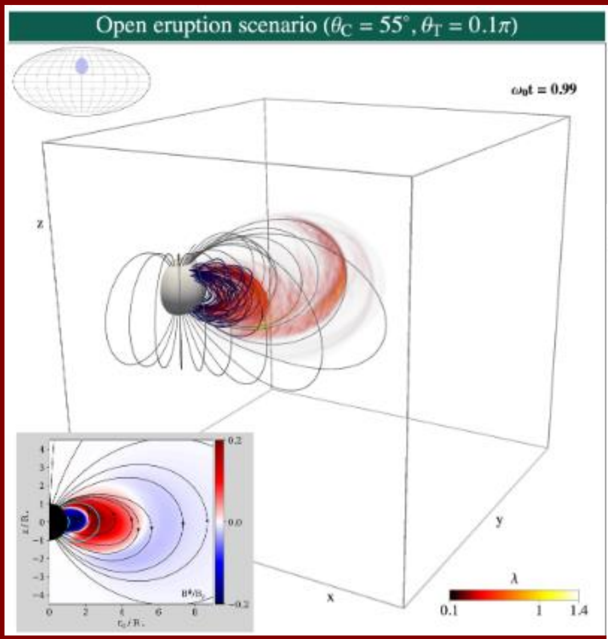
See 1807.09021 about coupling between crust and magnetosphere.

1901.08889

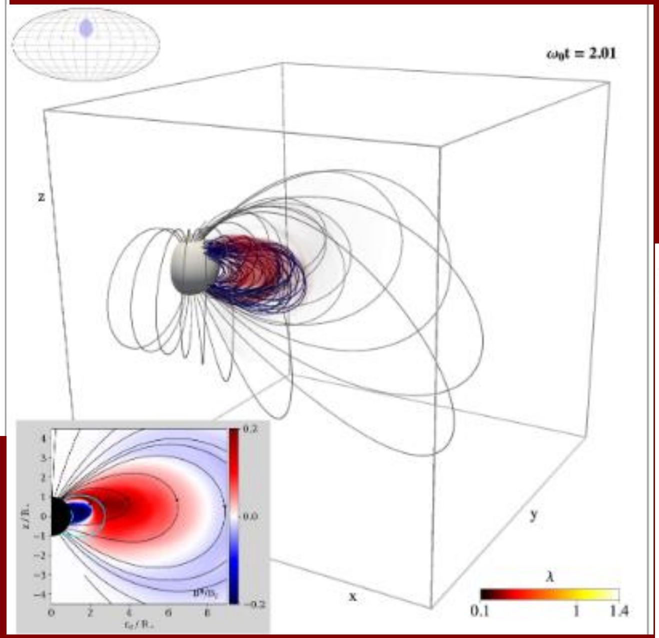
$$T_{\rm bb} \approx 0.18\ {\rm keV} \left[\frac{\Delta r}{1\ {\rm m}}\right]^{\frac{1}{4}} \left[\frac{10^{17}\ {\rm s}^{-1}}{\sigma_e}\right]^{\frac{1}{4}} \left[\frac{J}{10^{18}\ {\rm G/s}}\right]^{\frac{1}{2}}$$

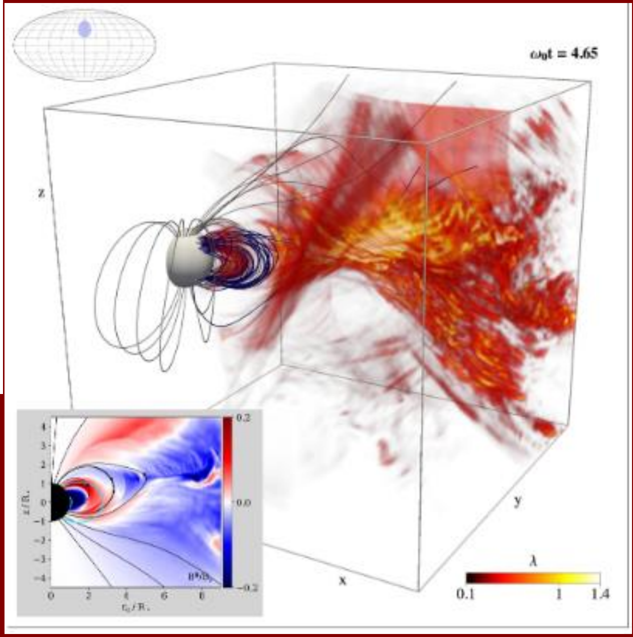
New calculations in 2211.08957

Instabilities and eruptions



non-axisymmetric dynamics of twisted force-free flux bundles in dipolar magnetospheres





The open eruption scenario creates extended flux ropes that can open into large-scale current sheets.

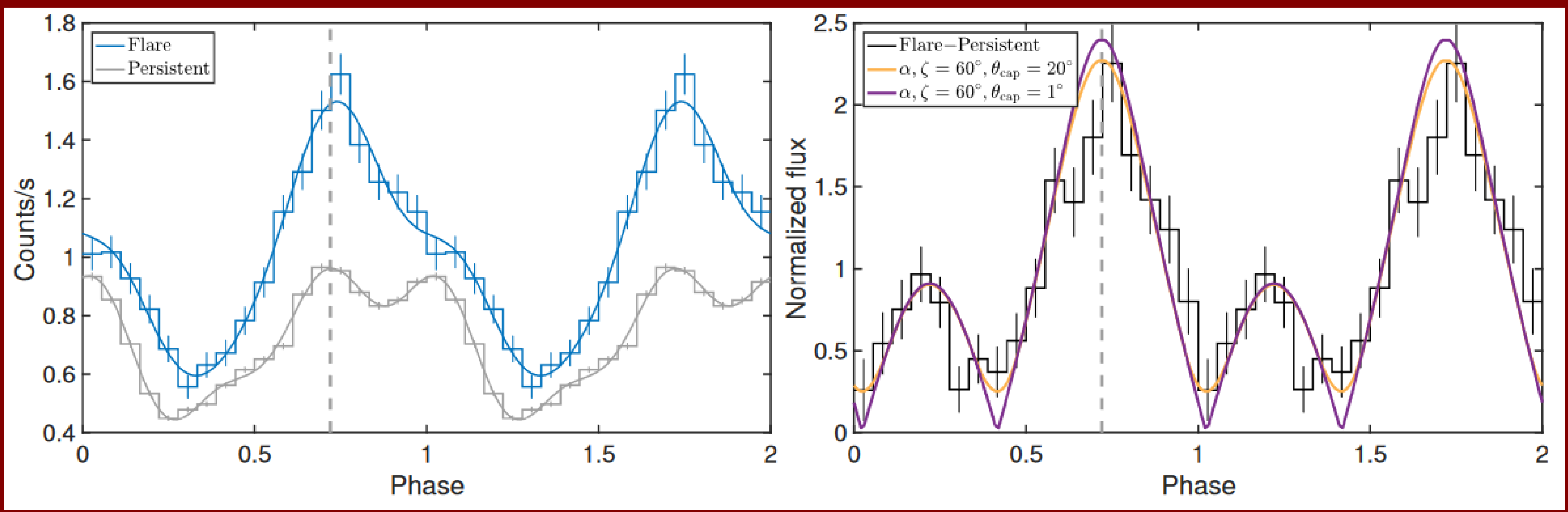
2302.07273

Antipodal spots heated during a flare

1RXS J1708−40
NuSTAR

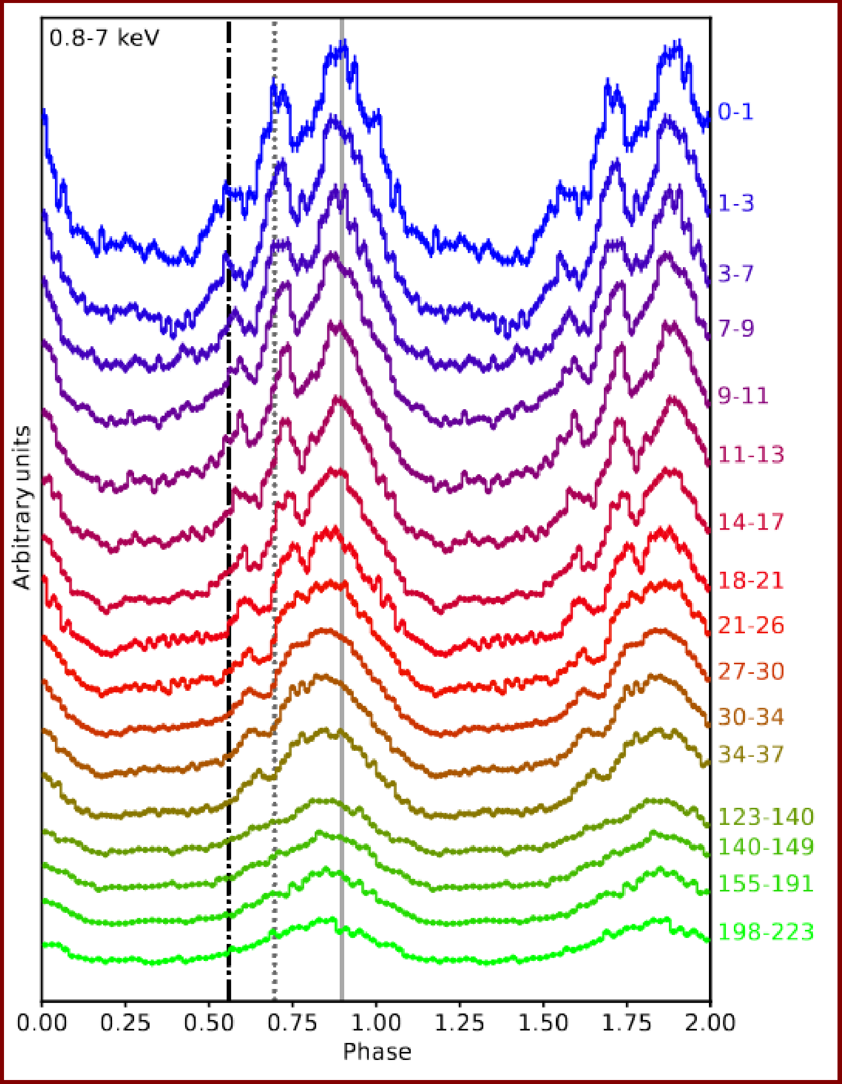
	Model	kT (keV)	Γ	R (m)	F erg s^{-1} cm^{-2}	L erg s^{-1}
Phase-resolved spectroscopy						
0.06-0.28	BB	2.3 ± 0.2	–	64^{+17}_{-11}	8^{+1}_{-2}	$1.4^{+0.2}_{-0.3}$
0.56-0.94	BB	2.2 ± 0.1	–	105 ± 10	17^{+2}_{-1}	$2.9^{+0.4}_{-0.2}$
Rest	BB	1.8 ± 0.2	–	98^{+30}_{-19}	$6.4^{+0.8}_{-0.9}$	1.1 ± 0.1

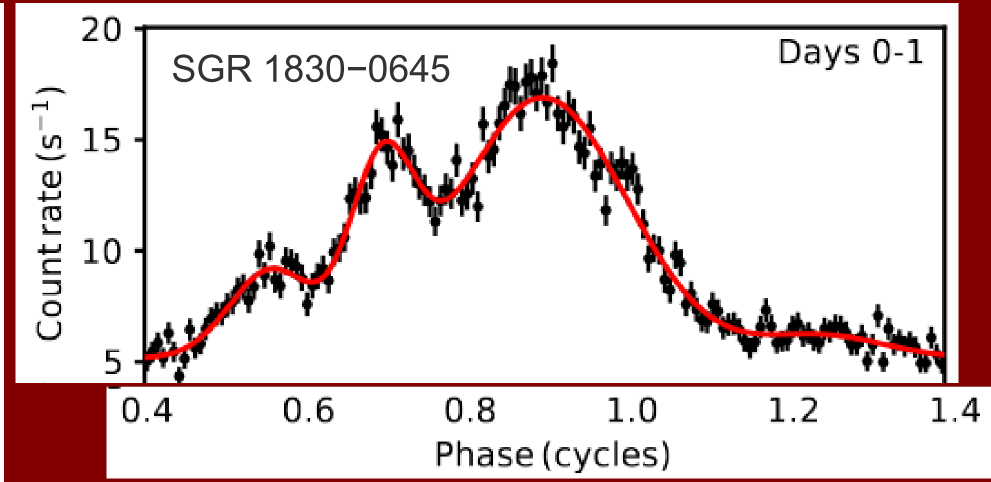
Antipodal character indicates role of the dipole field.

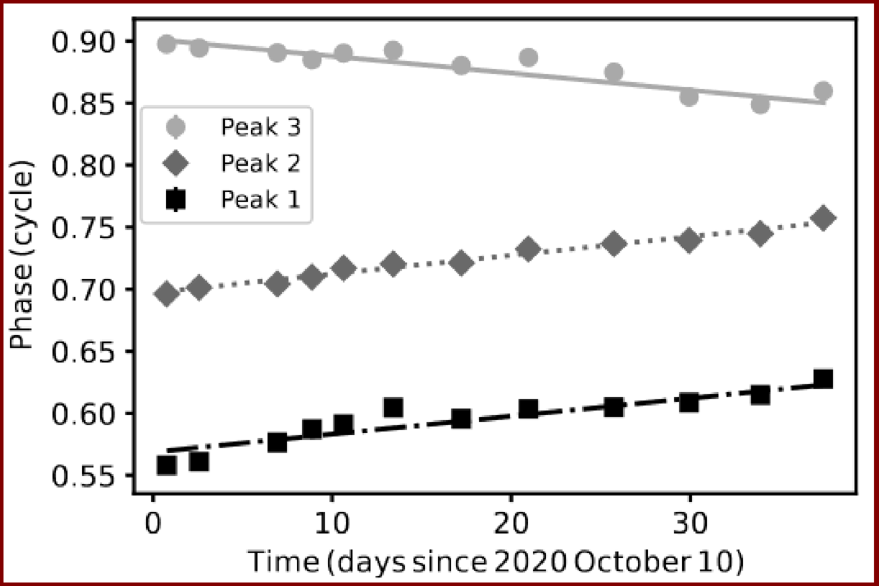


2001.08761

Pulse profile changes during an outburst

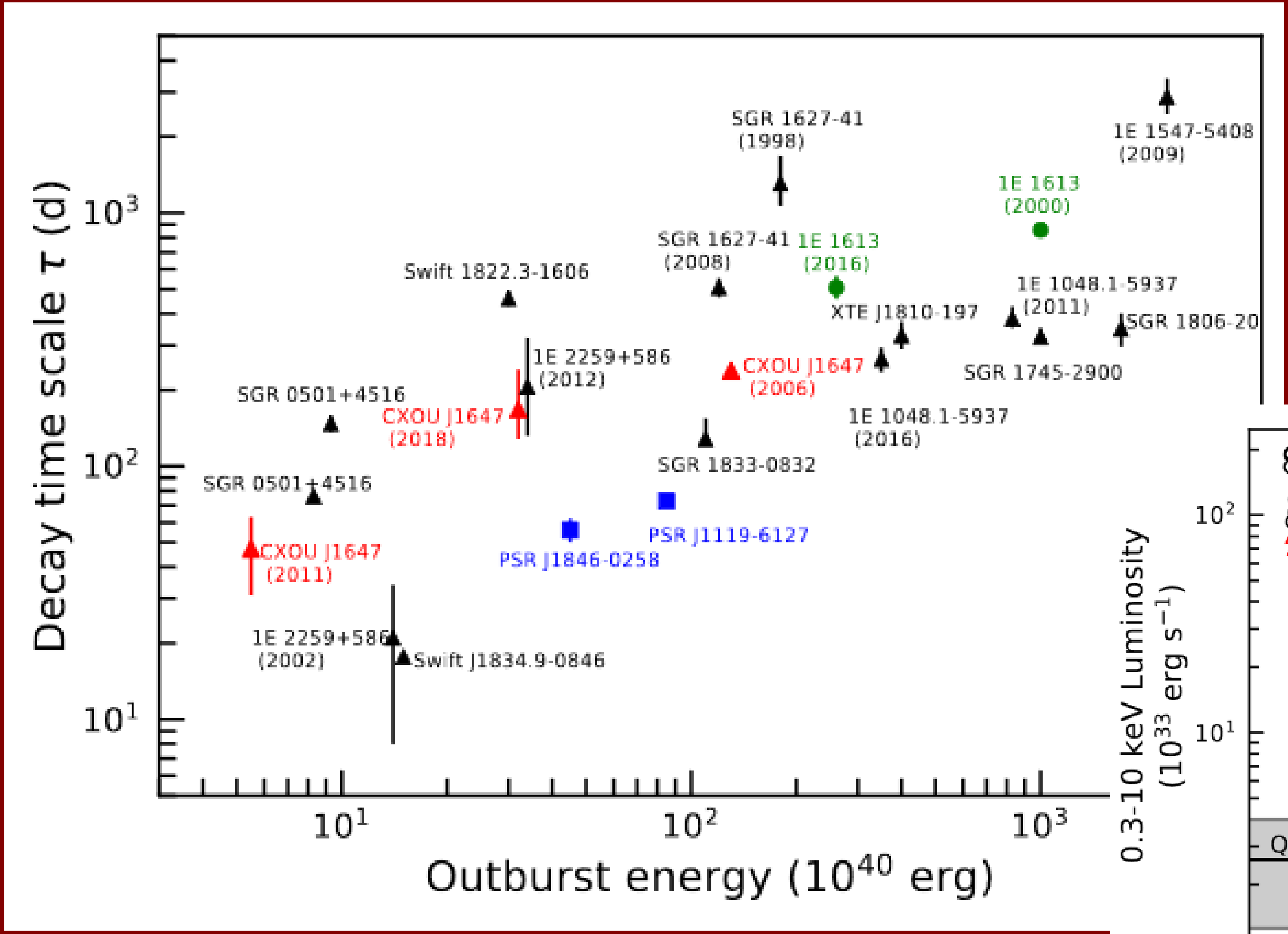


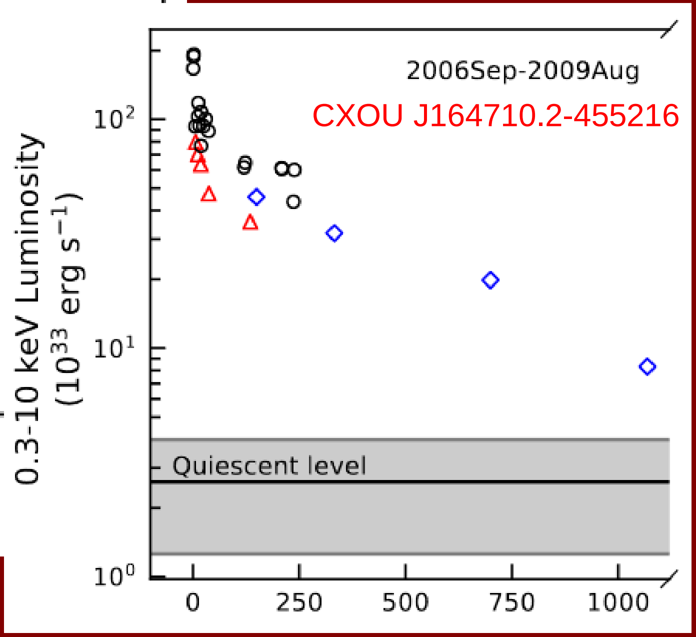




2201.05517 Plastic motion or untwisting?

Outburst decay vs. released energy





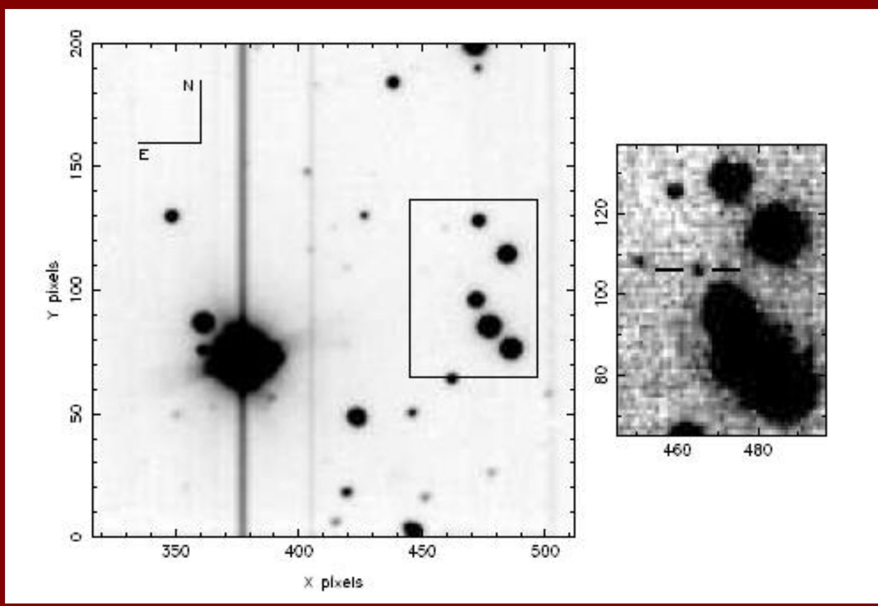
1901.02026

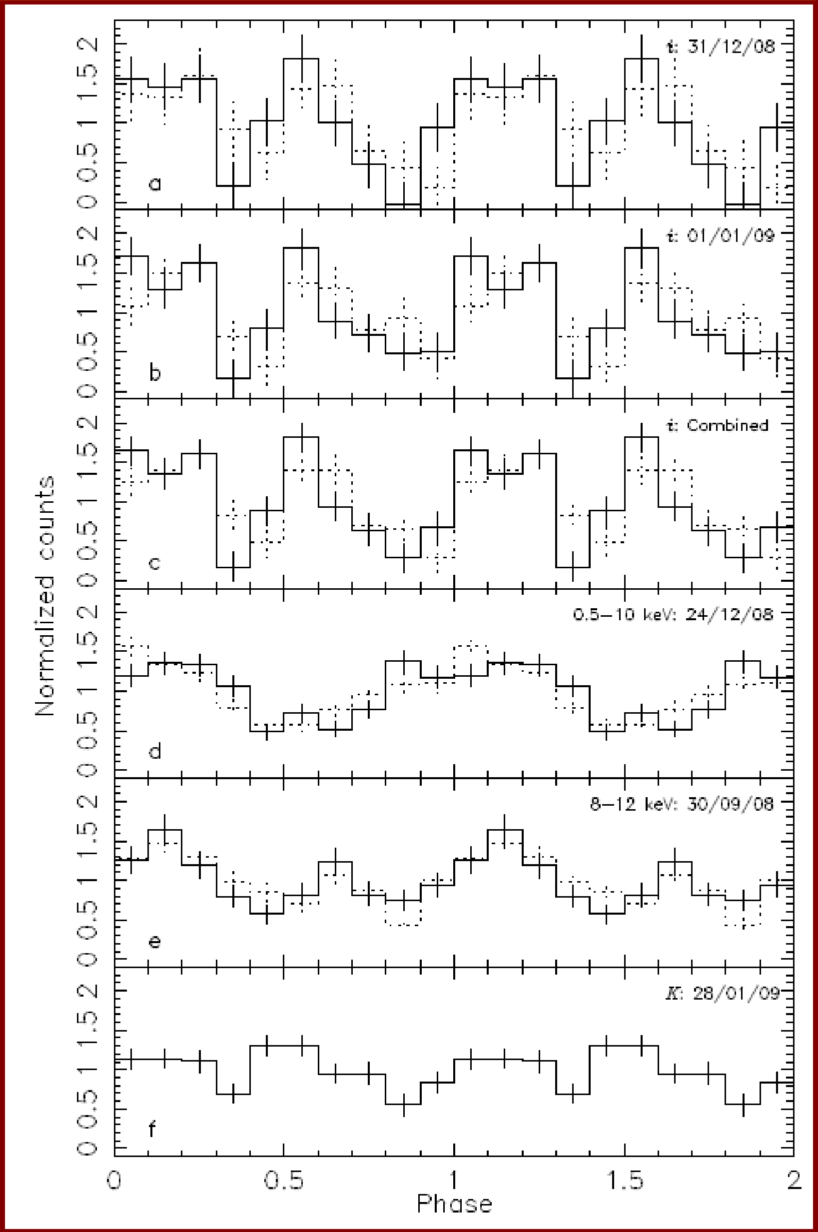
Optical pulsations

SGR 0501+4516
P=5.76 s
d=0.8 kpc – the closest!

4.2m William Herschel Telescope

Magnetospheric emission?



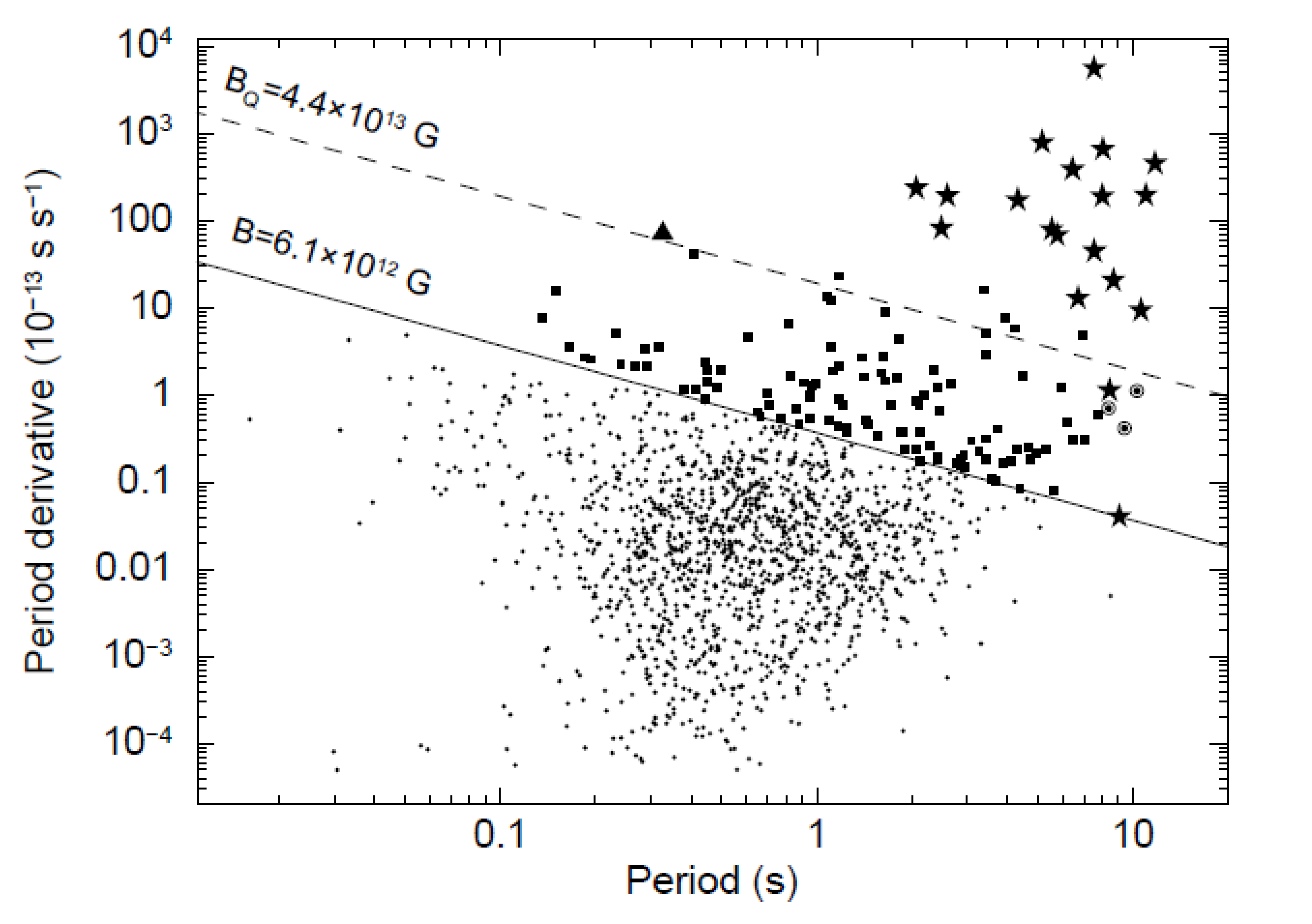


1106.1355

Pulsations are also detected for a few AXPs.

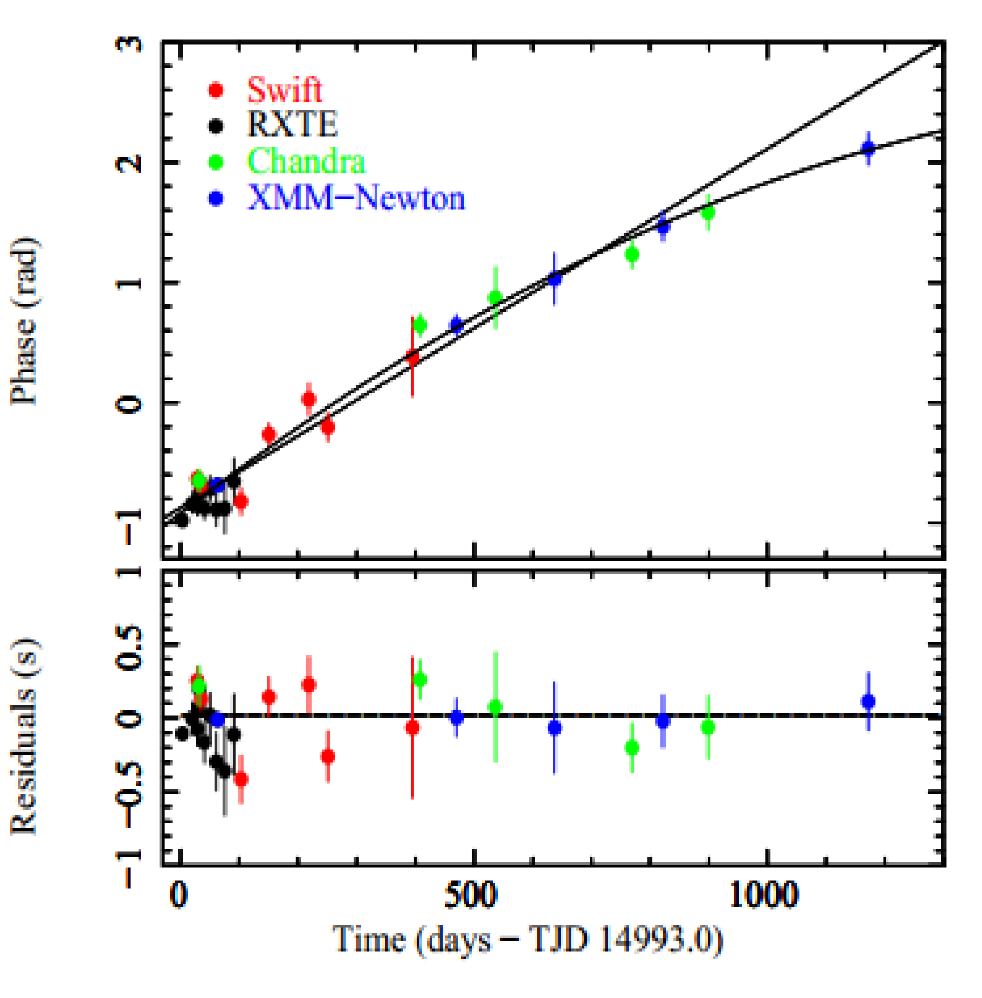
Low-field magnetars

SGR 0418+5729 and Swift J1822.3–160



See a review in [arXiv:1303.6052]

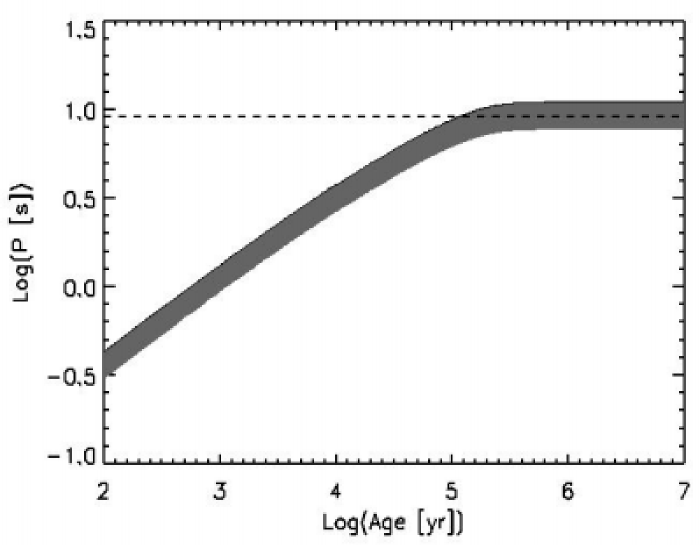
The first low-field magnetar



SGR 0418+5729

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

The dipolar field is ~6 10^{12} G.

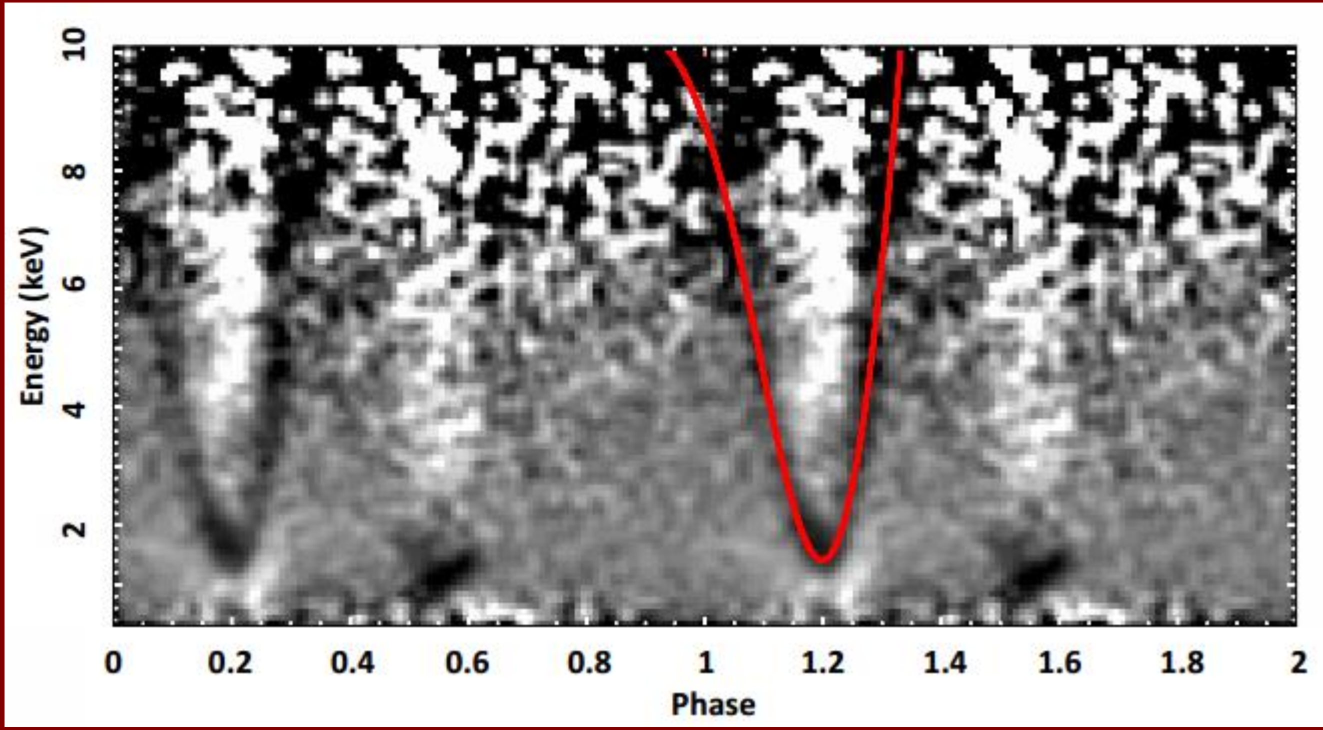


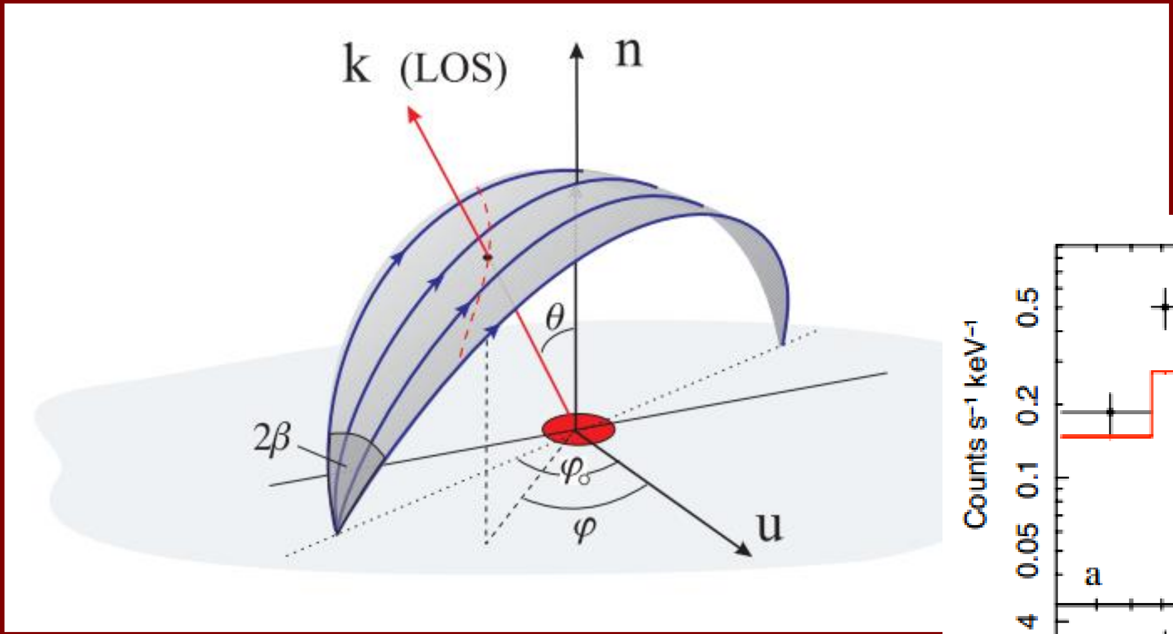
The dipolar field could decay, and activity is due to the toroidal field.

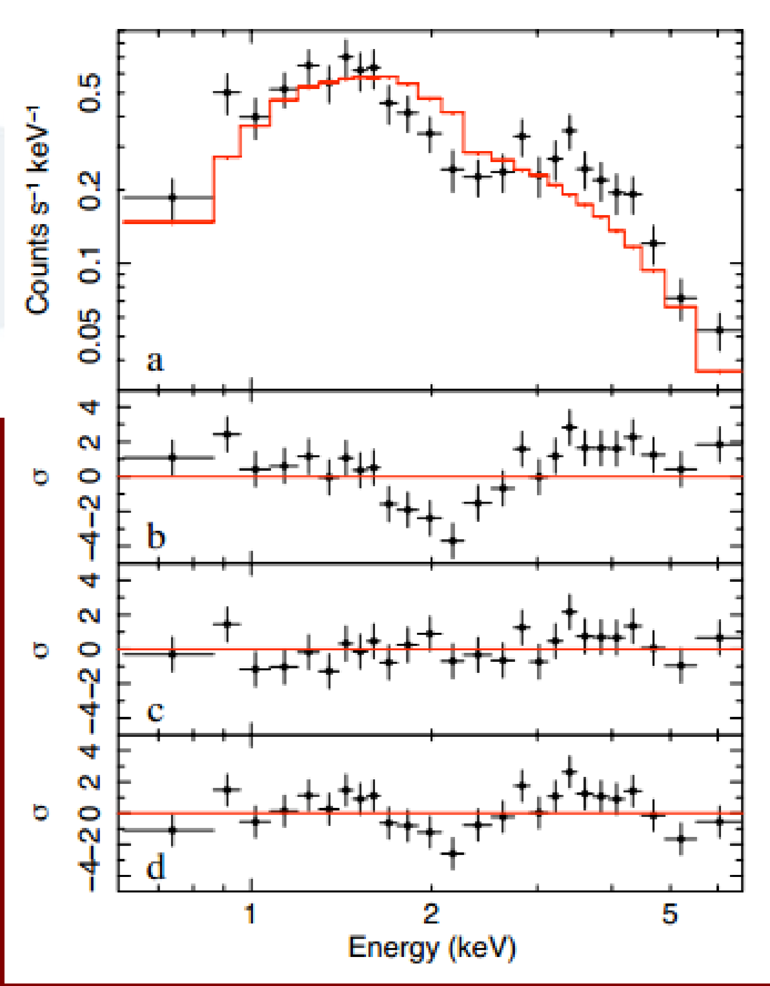
1303.5579

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 $2\ 10^{14} – 10^{15}$ G

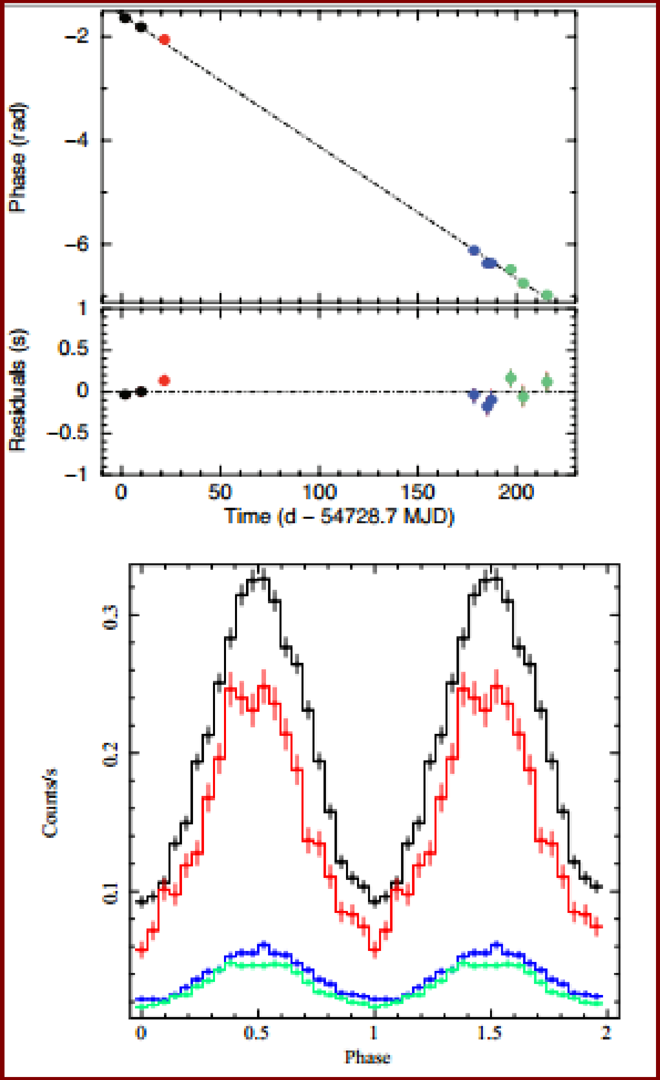



k (LOS)
n
θ
2β
φ₀
φ
u


Counts s⁻¹ keV⁻¹
0.05
0.1
0.2
0.5
a
σ
4
2
0
−2
−4
b
c
d
1
2
5
Energy (keV)

1308.4987

Another low-field magnetar

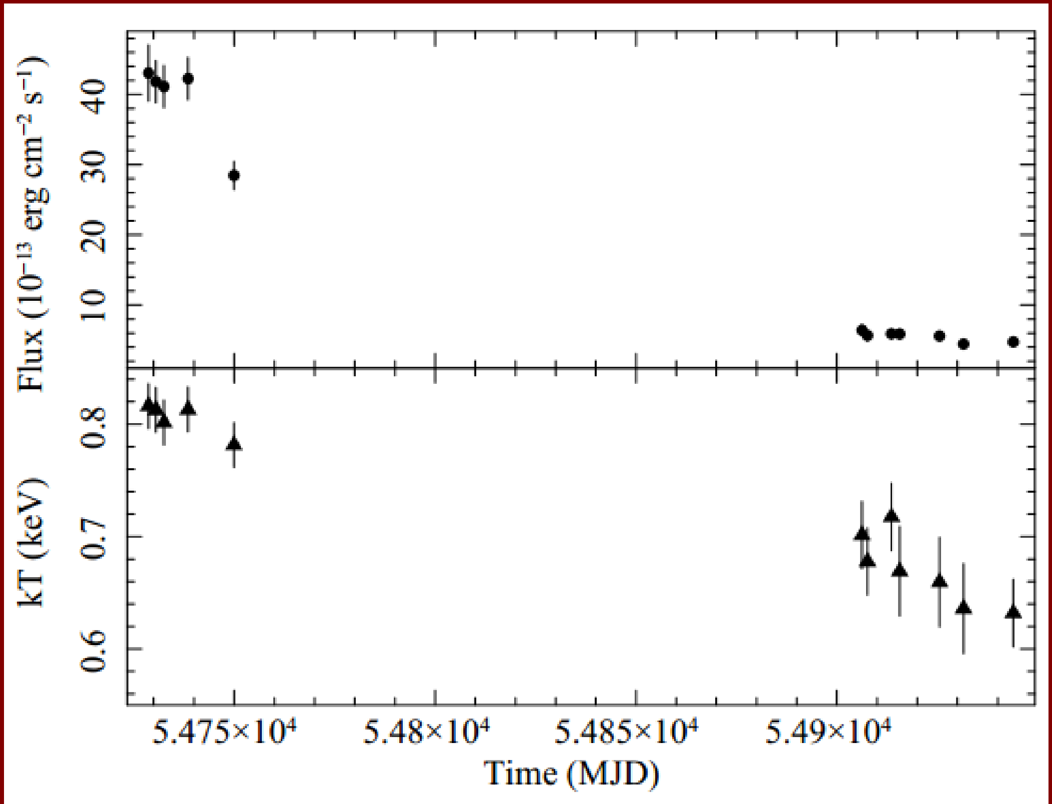


3XMM J185246.6+003317

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

B<4 10^{13} G

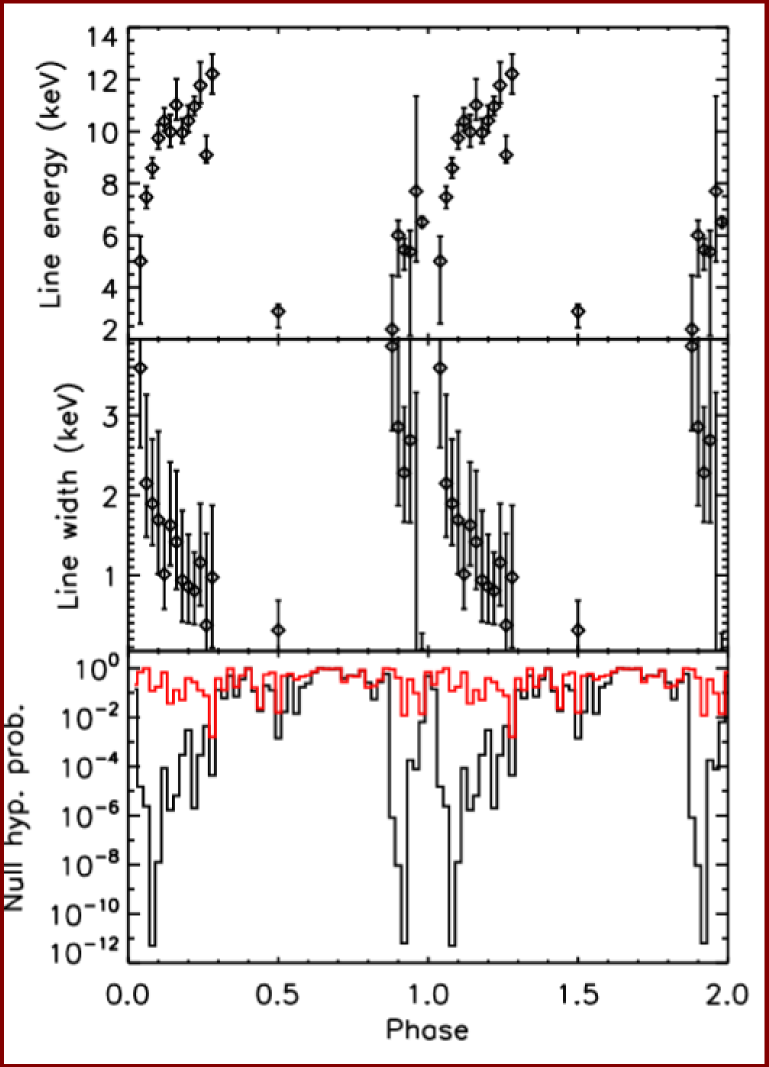
Transient magnetar



1311.3091

More lines in low-field magnetars

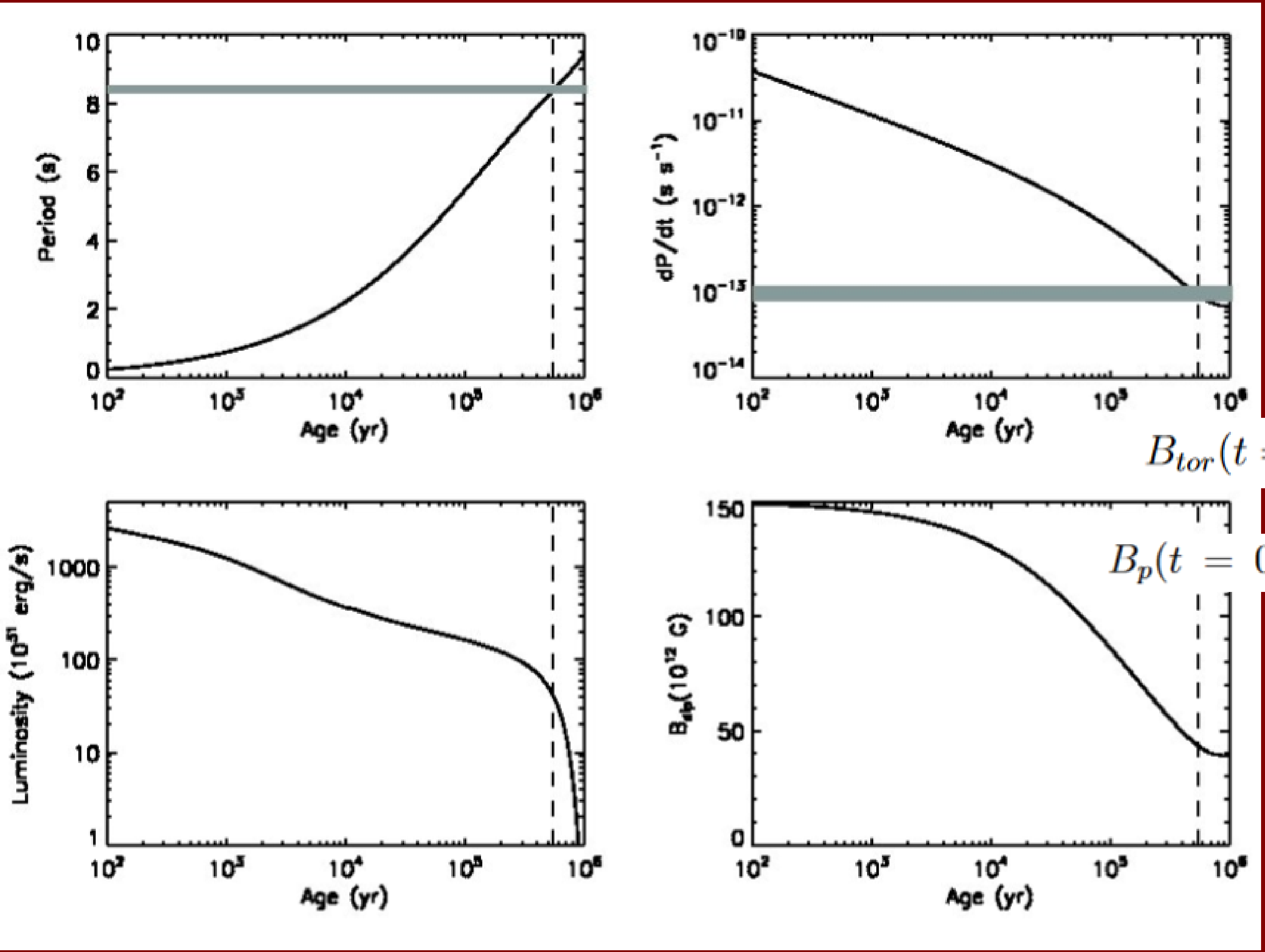
phase-dependent absorption line



SWIFT J1822.3-1606

1510.09157

Old evolved sources?



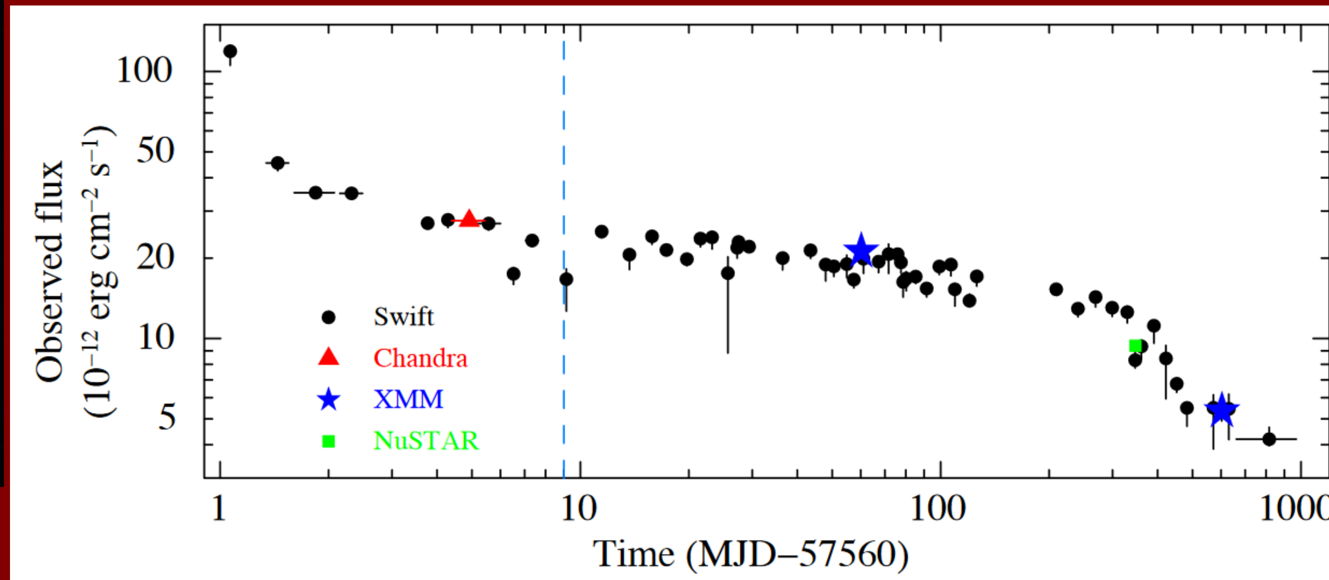
$B_{tor}(t=0) = 5\times10^{15}$ G

$B_p(t = 0) \sim 2 \times 10^{14}$ G,

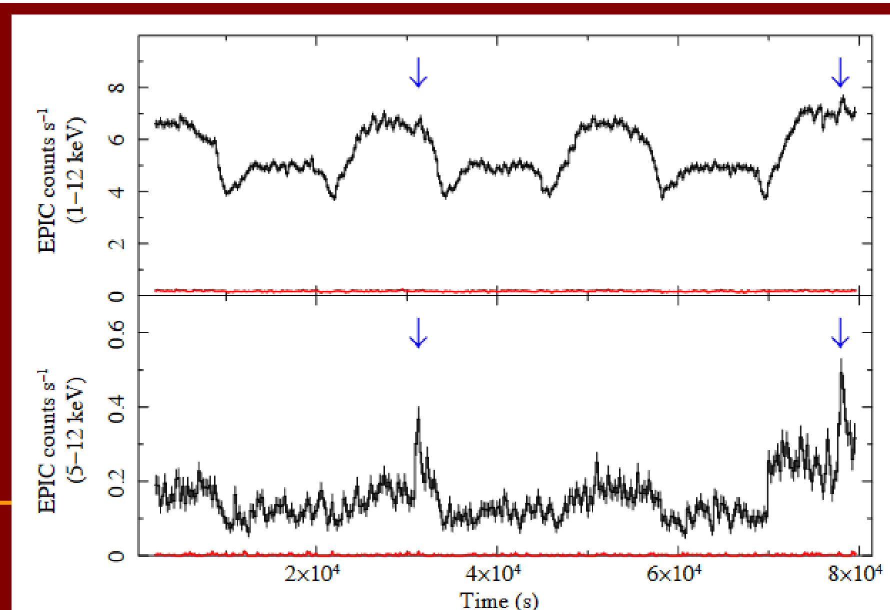
Swift J1822.03–160

1507.02924

RCW103 – a special kind of magnetar



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



1904.05424

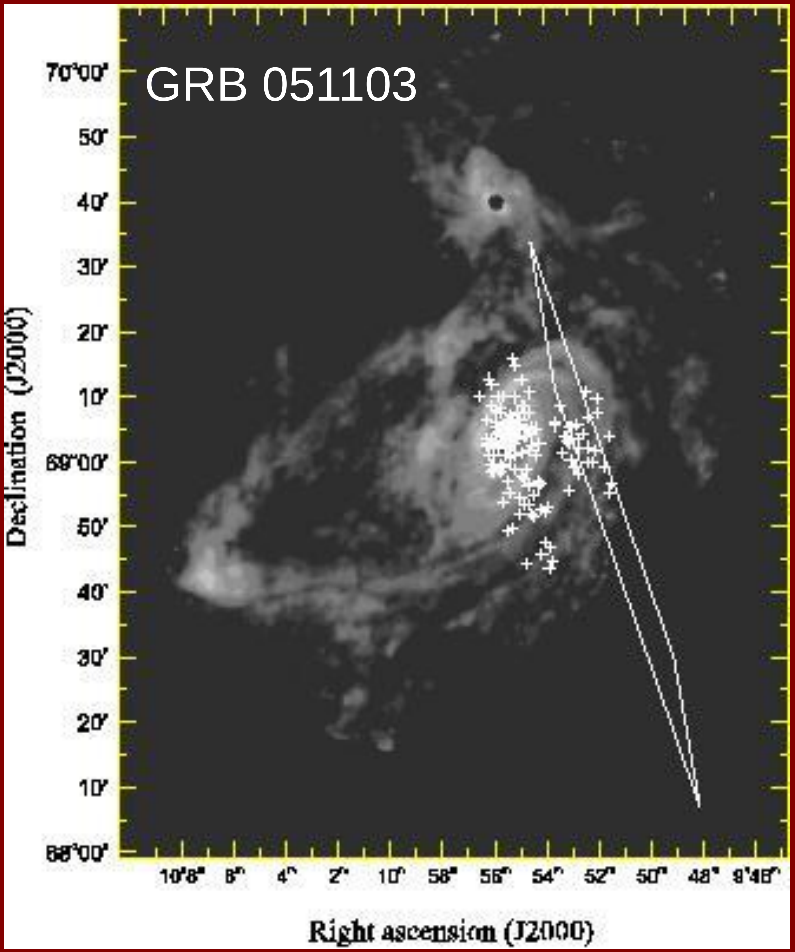
Extragalactic giant flares

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



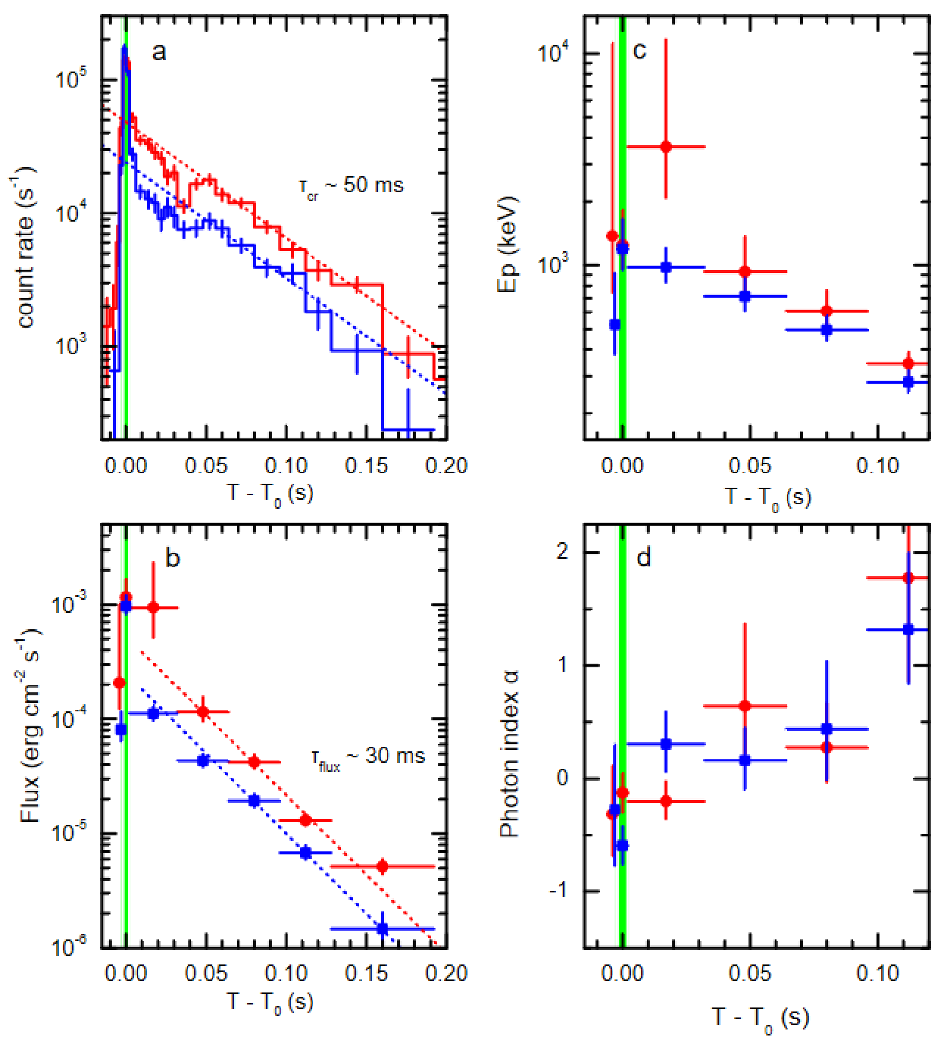
It was suggested long ago (Mazets et al. 1982) that present-day detectors could alredy detect giant flares from extragalactic magnetars.

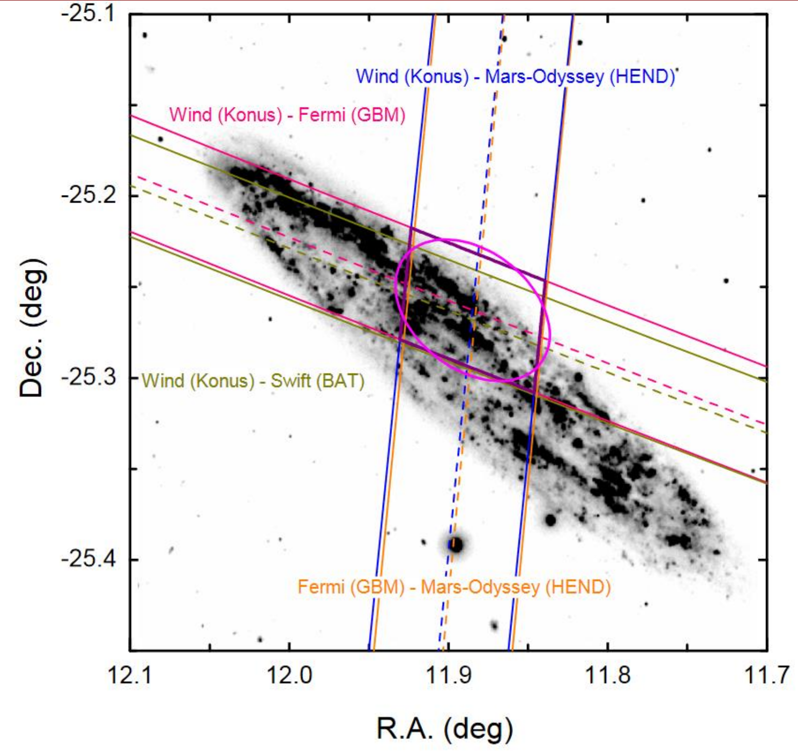
However, all searches in, for example, BATSE database did not provide clear candidates (Lazzati et al. 2006, Popov & Stern 2006, etc.).

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

[D. Frederiks et al. astro-ph/0609544]

Magnetar hyperflare in NGC 253

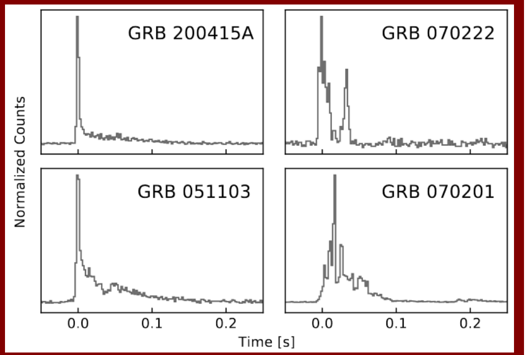




Red – GRB 051103
Blue - GRB 200415A

2101.05104, see also 2101.05144, 2008.05097

Extragalactic hyperflares of magnetars



Four hyperflares of SGRs are identified in near-by galaxies.

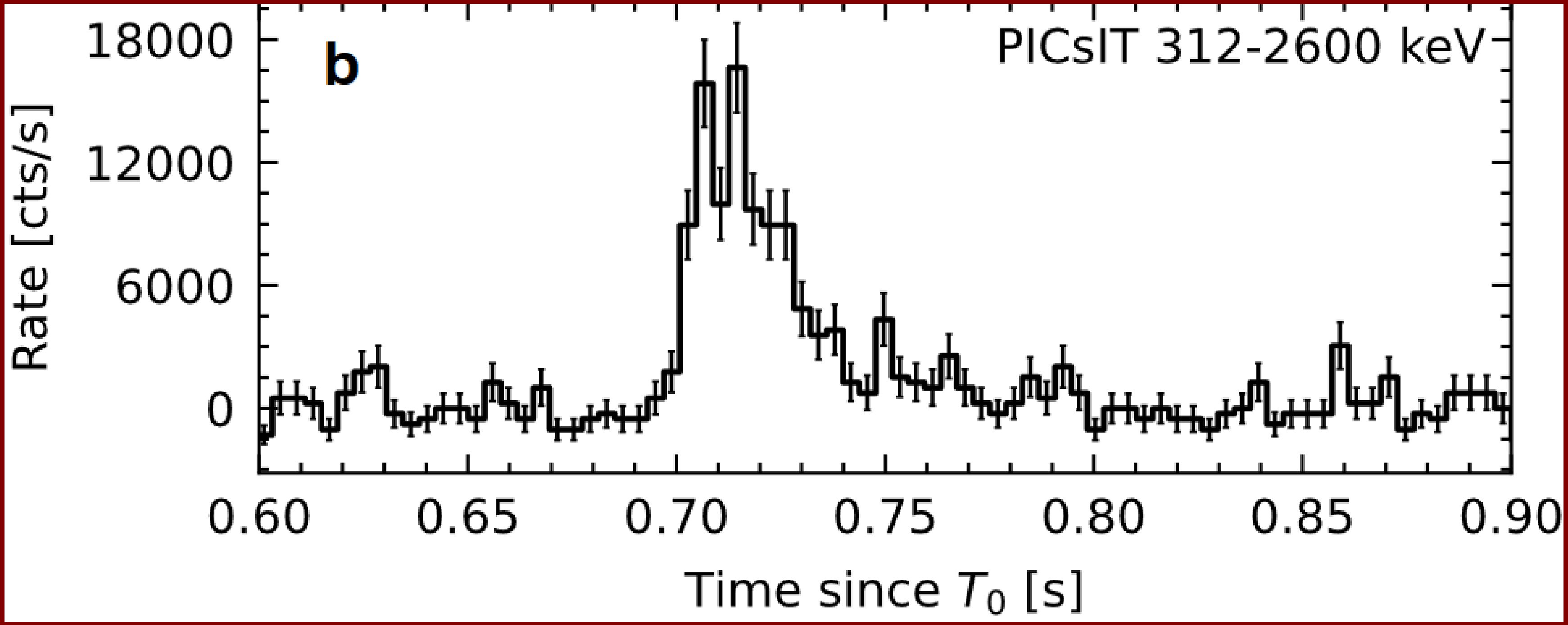
	Known			Extragalactic			
MGF Event	790305B	980827	041227	200415A	070222	051103	070201
Origin							
False Alarm Rate	0	0	0	4.9×10^{-6}	7.8×10^{-6}	1.5×10^{-5}	1.2×10^{-4}
BNS Excl. [Mpc]					6.7	5.2	3.5
Galaxy Properties							
Catalog Name	LMC	MW	MW	NGC253	M83	M82	M31
Distance [Mpc]	0.054	0.0125	0.0087	3.5	4.5	3.7	0.78
SFR [$M_\odot/yr$]	0.56	1.65	1.65	4.9	4.2	7.1	0.4
GRB Properties							
Duration [s]	<0.25	<1.0	<0.2	0.100	0.038	0.138	0.010
Rise Time [ms]	$\sim$2	$\sim$4	$\sim$1	2	4	2	24
$L_{\rm iso}^{Max}$ [10^{46} erg/s]	0.65	2.3	35	140	40	180	12
$E_{\rm iso}$ [10^{45} erg]	0.7	0.43	23	13	6.2	53	1.6
Index			-0.7	0.0	-1.0	-0.2	-0.6
$E_{\rm peak}$ [keV]	500	1200	850	1080	1290	2150	280

Among sGRBs there might be more events of this type, but it is difficult to identify them.

2101.05144

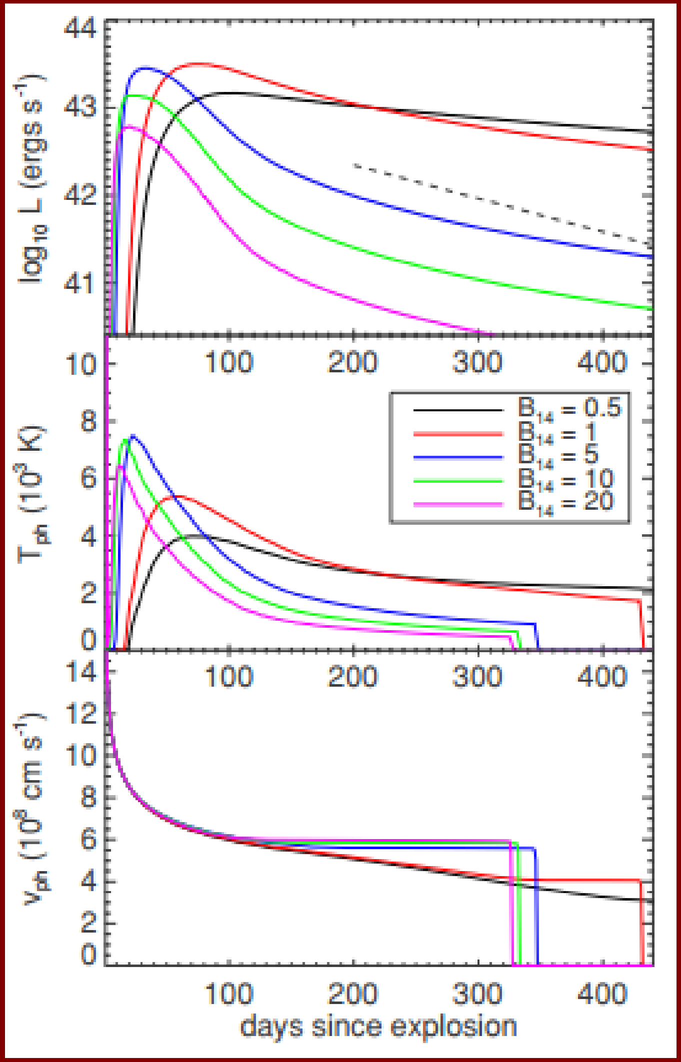
Another flare in M82

GRB 231115A
INTEGRAL detection
Light curve behavior
similar to the SGR 1806-20

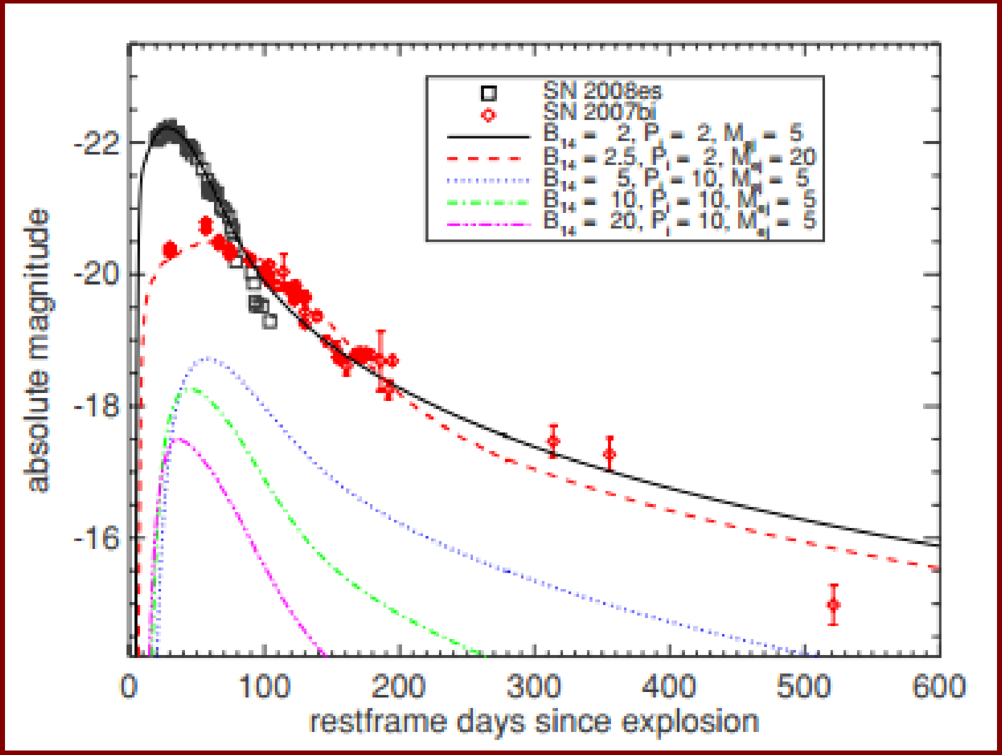


2312.14645, see also 2402.08623

Magnetars and supernovae



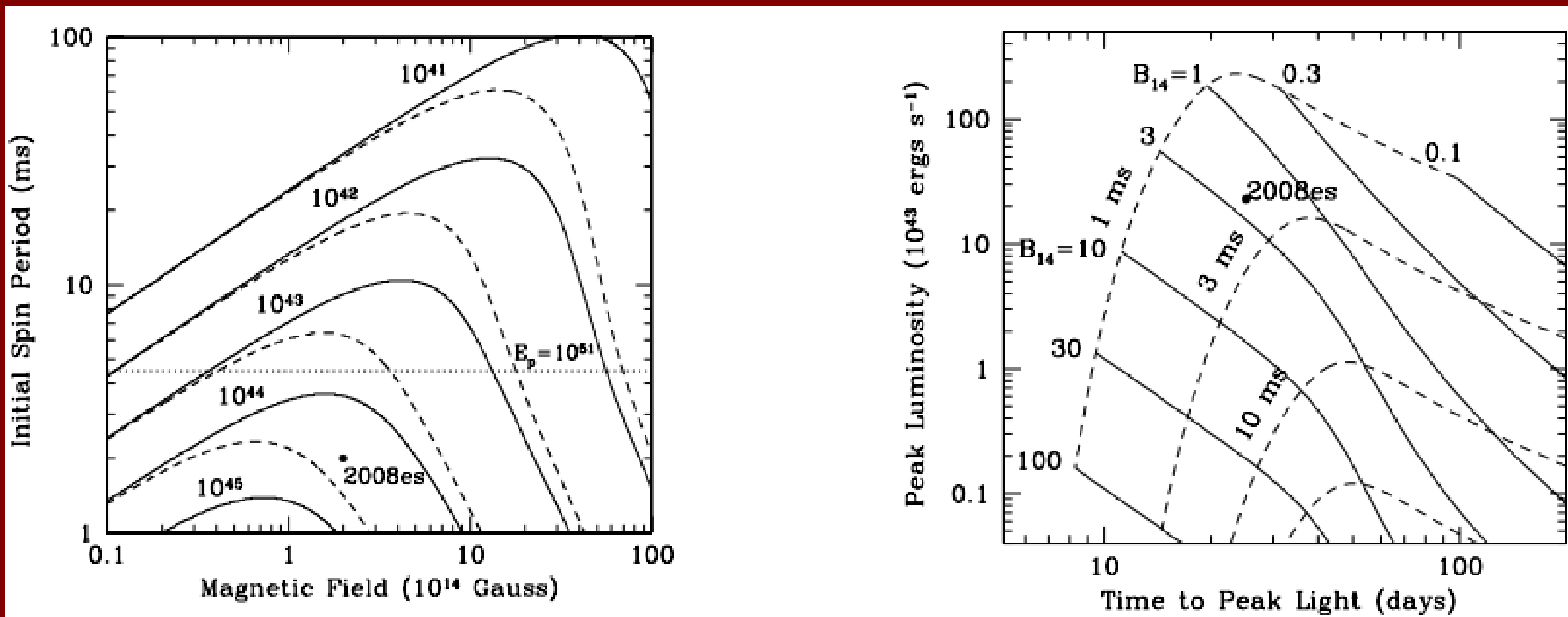
With large field and short spin a newborn NS can contribute a lot to the luminosity of a SN.



KASEN & BILDSTEN (2010)

Parameters needed

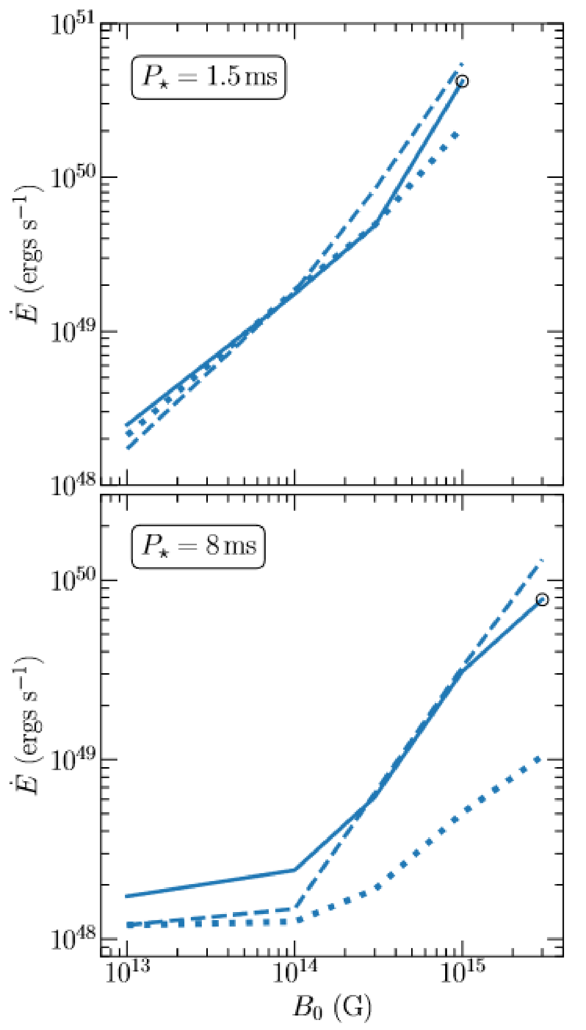
For short initial spin periods it is not even necessary to have magnetar scale B.

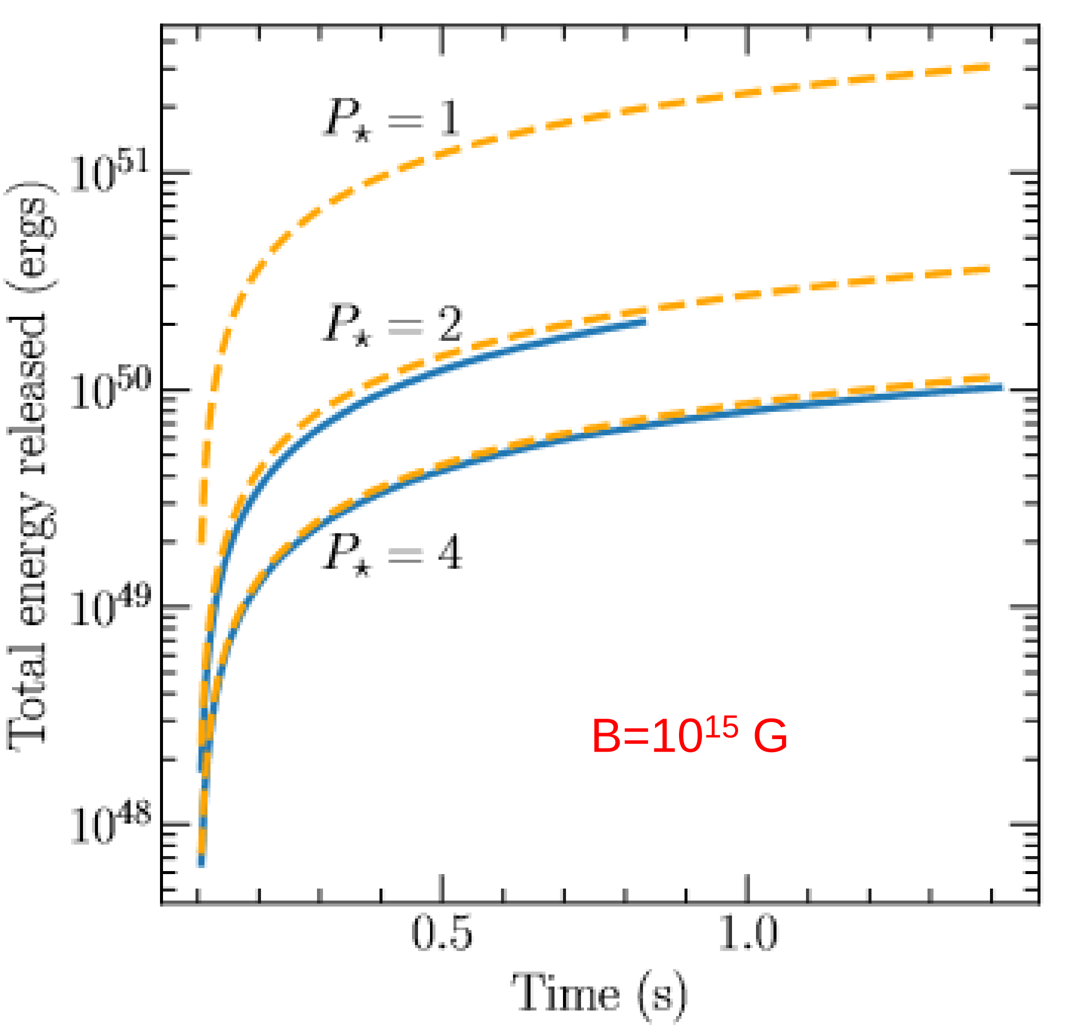


New calculations for GRBs and SLSN are presented in 2305.16412.

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

Powering by a millisecond magnetar

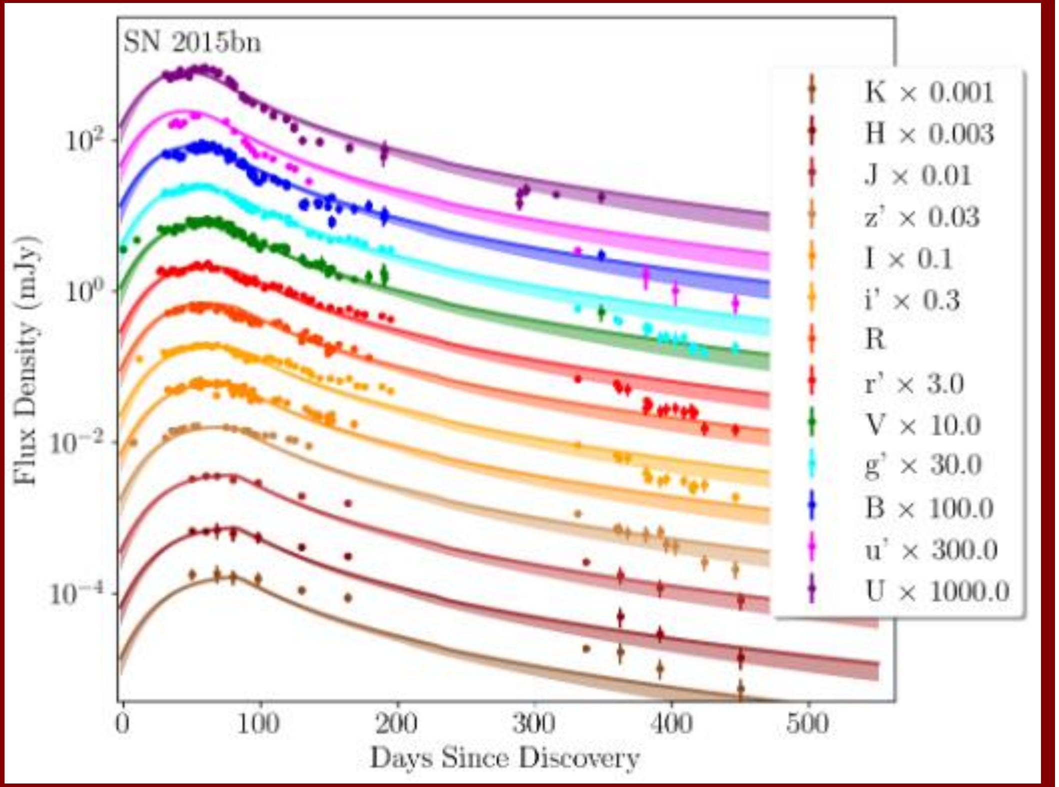


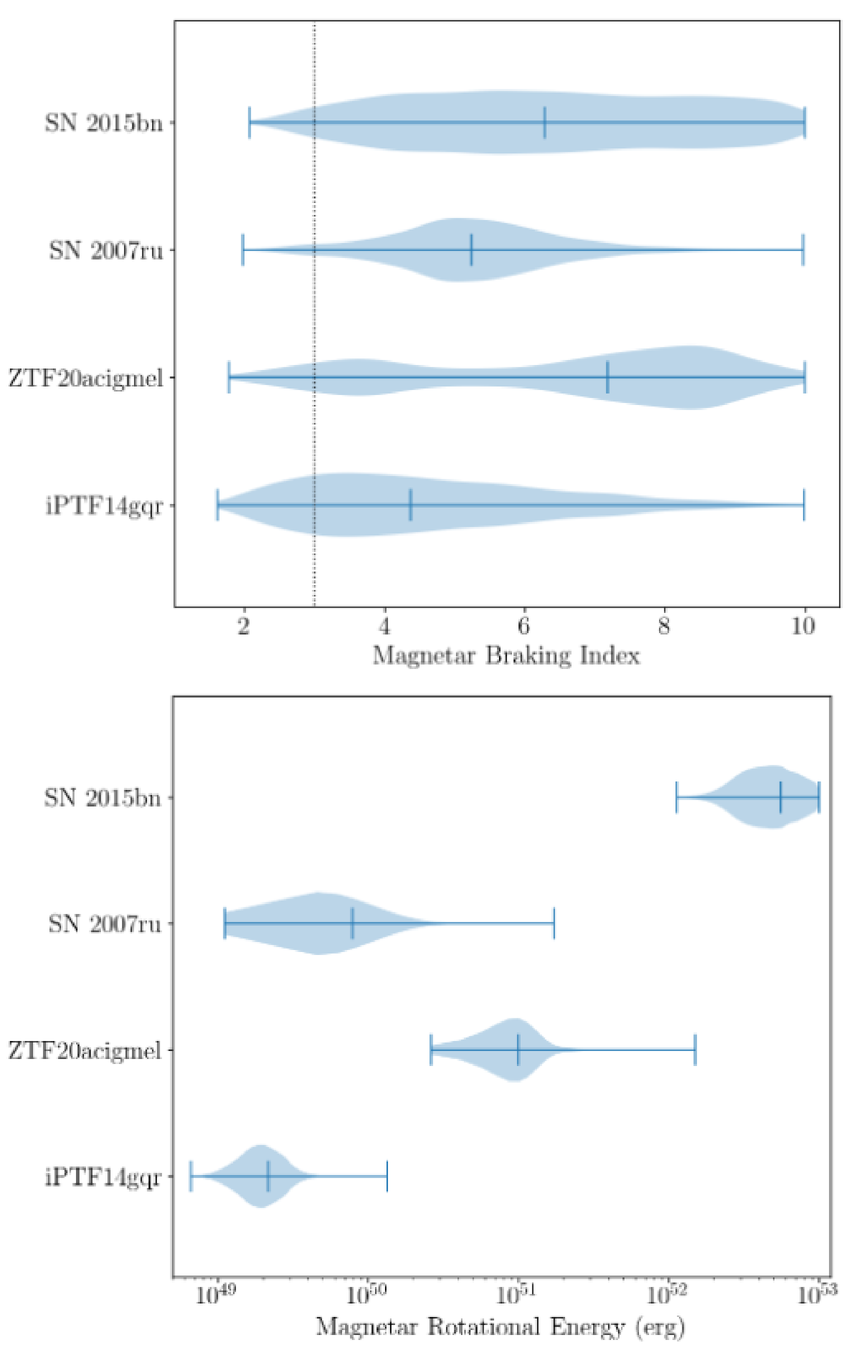


2305.16412

Wind energy

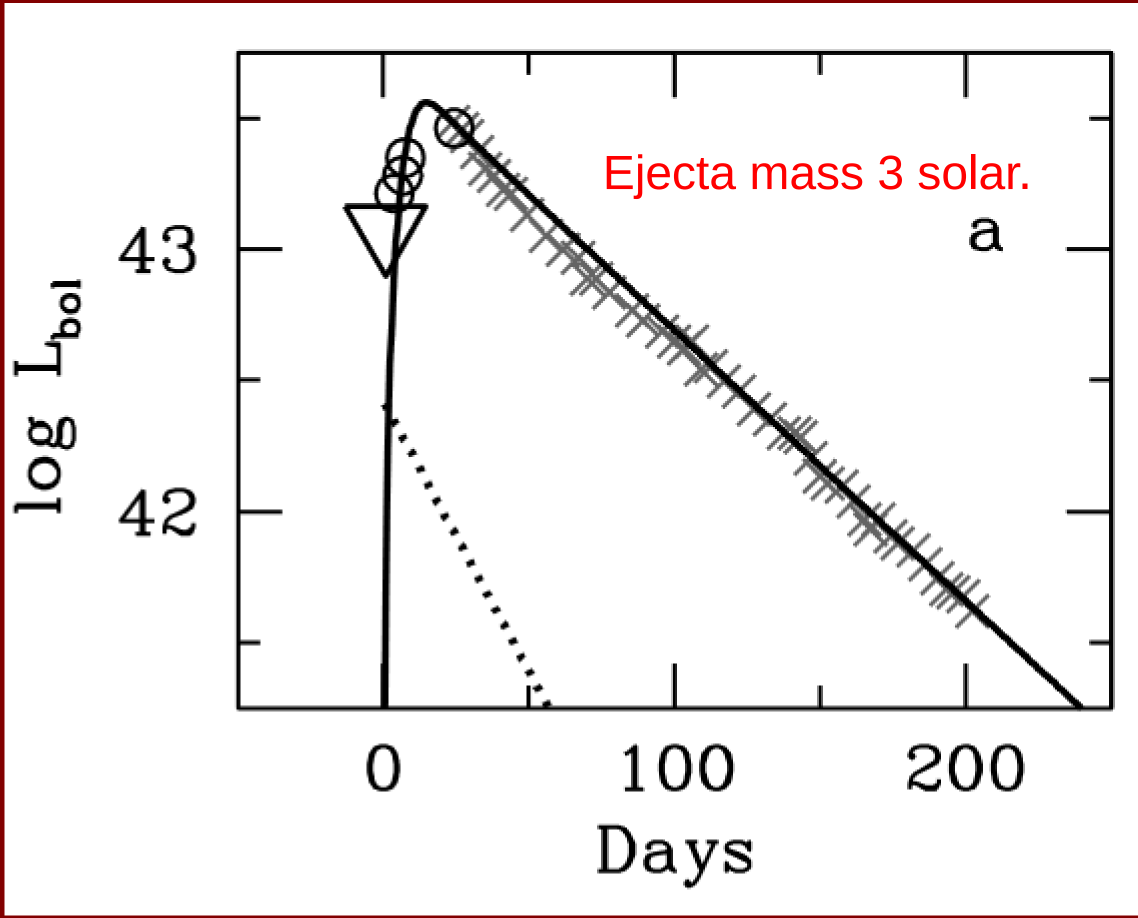
Semi-analytical model





2308.12997

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:

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

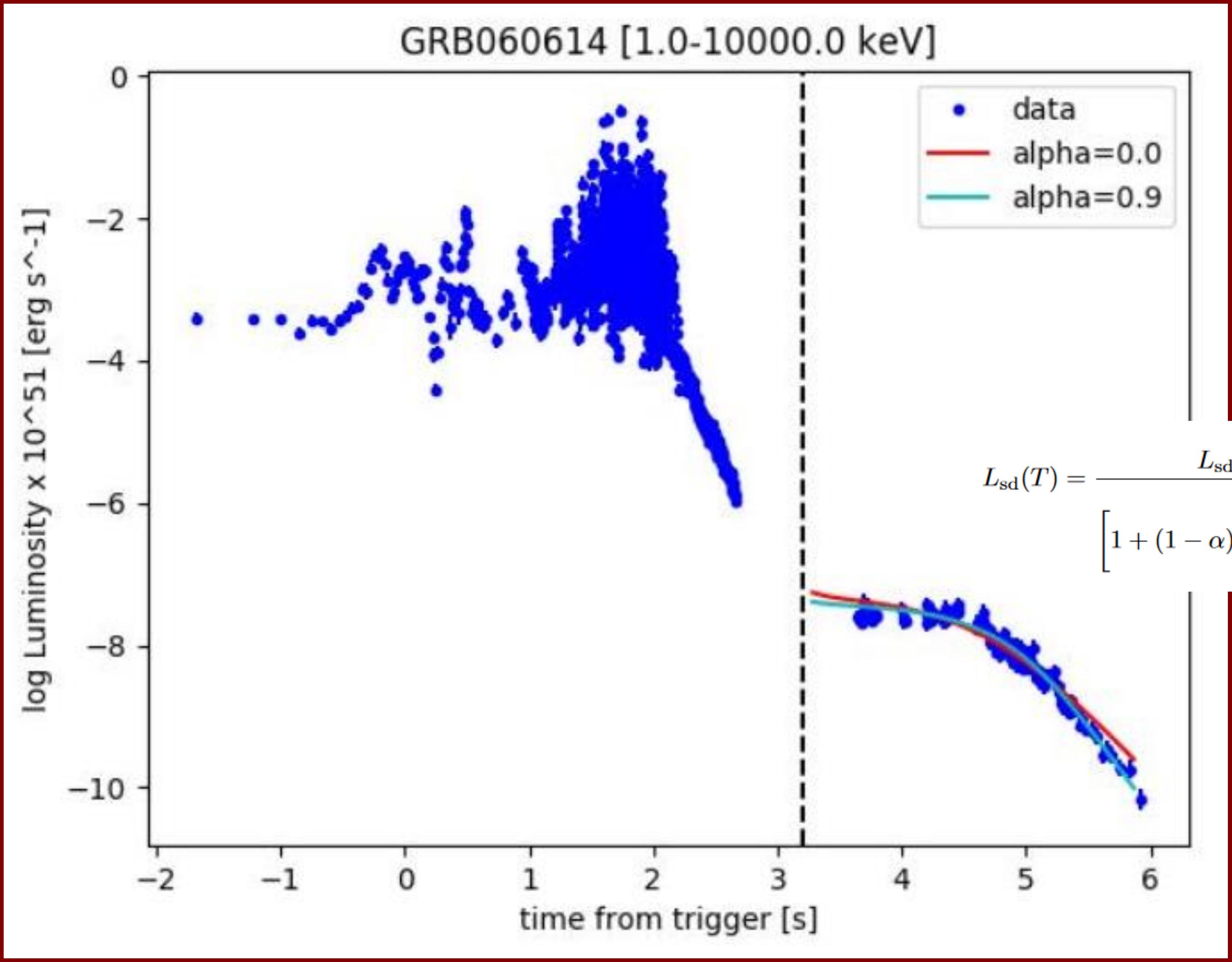
$$b = 0.5\dot{m}r_m^2/I.$$

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

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

1906.12150

Magnetars and GRBs



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

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

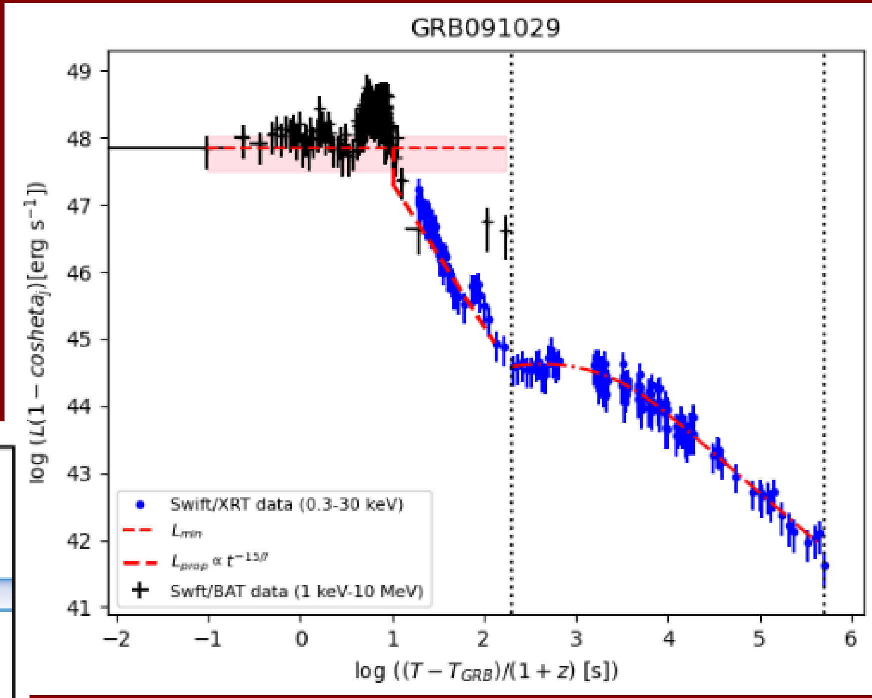
$$n = 3 - 2\alpha.$$

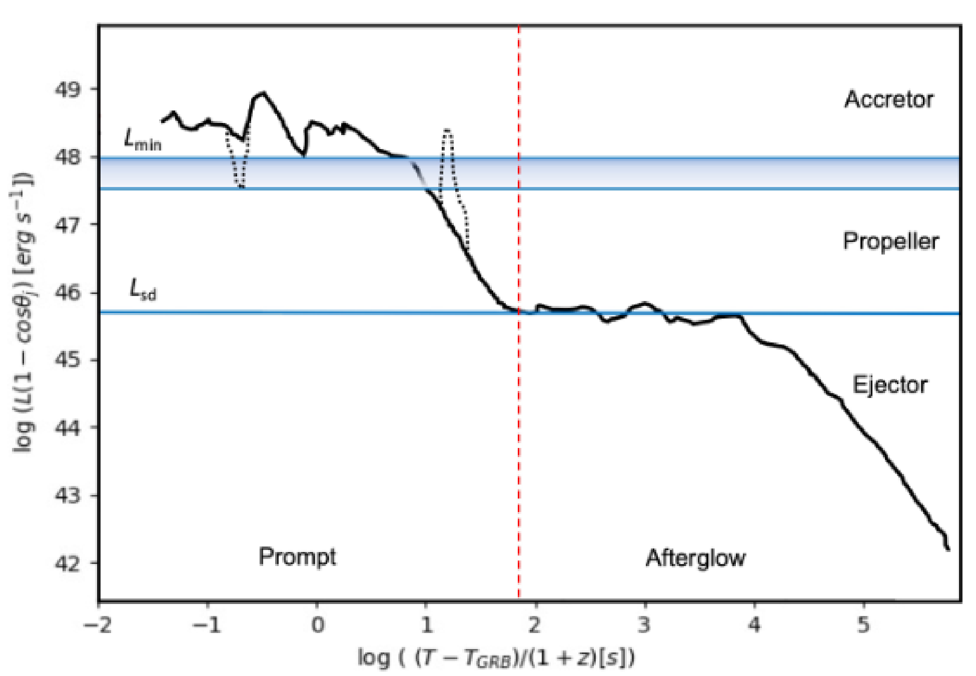
$$L_{\rm sd}(T) = \frac{L_{\rm sd,i}}{\left[1+(1-\alpha)\dfrac{T}{\tau_i}\right]^{\frac{2-\alpha}{1-\alpha}}} = \frac{E_{\rm spin,i}}{\tau_i\left[1+(1-\alpha)\dfrac{T}{\tau_i}\right]^{\frac{2-\alpha}{1-\alpha}}},$$

1804.08652

Plato due to accretion?

The idea: the prompt is powered
by accretion energy
while the afterglow plateau
by the injection of the NS spin energy
into the external shock

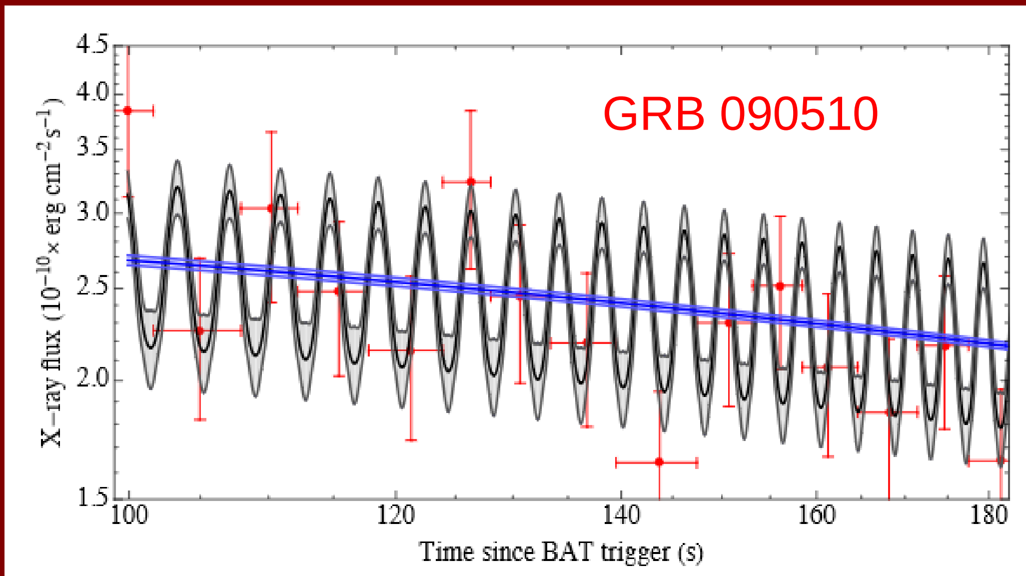




a conversion efficiency of
spin-down power to afterglow emission
~(12%---34%)

2305.00029

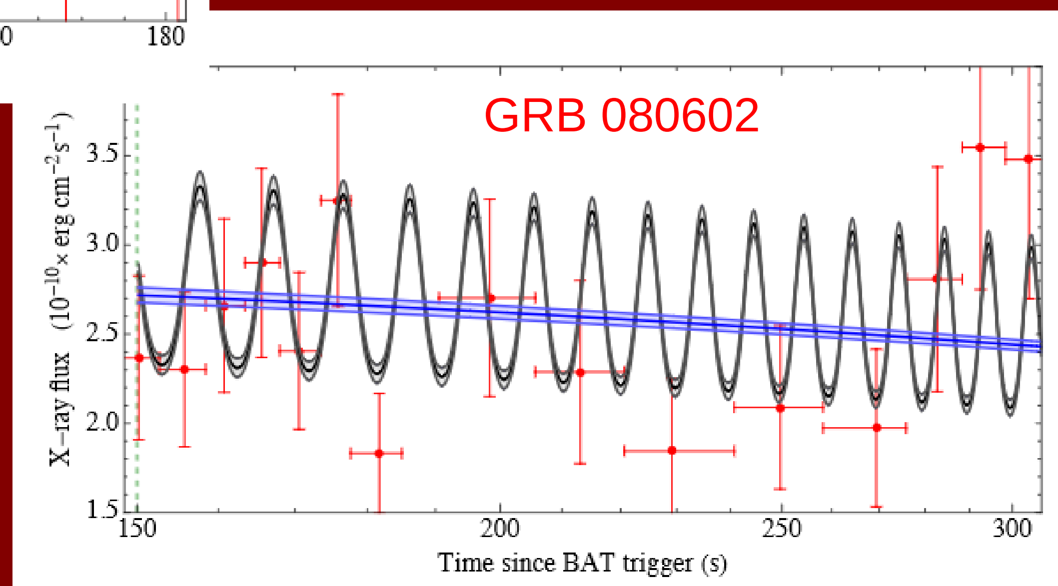
Precessing magnetar in a GRB?



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

α_0 - initial inclination angle

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



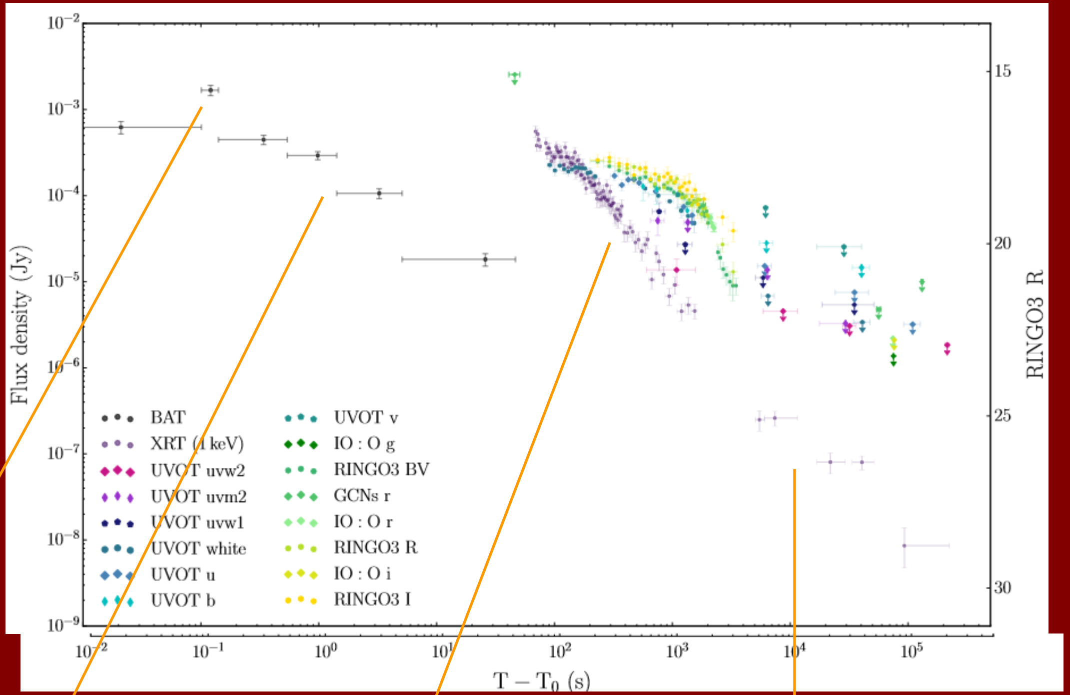
GRB 090510 – short
GRB 080602 - long

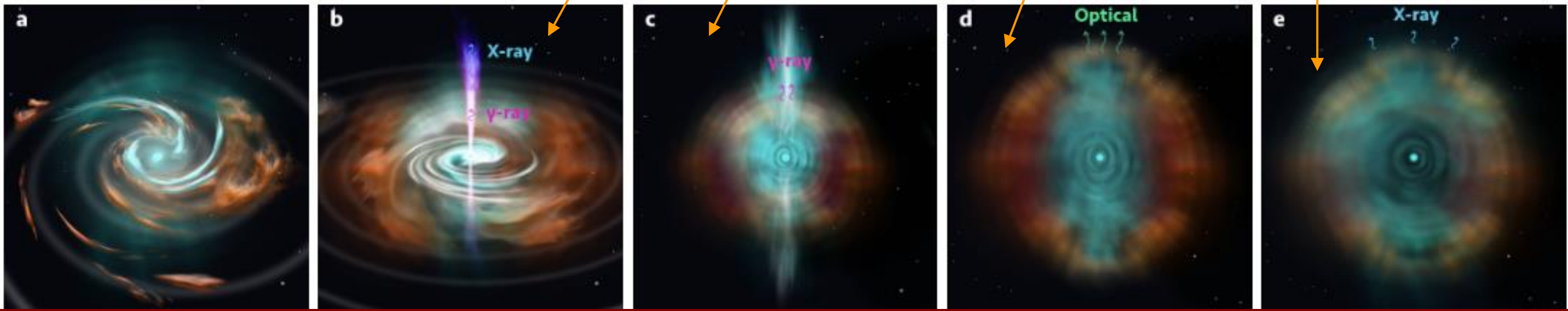
2003.10693

A short GRB with a magnetar formation

GRB 180618A
z=0.55

0.3 sec – initial gamma flare
~45 sec – extended soft gamma
~35 min – optics
~0.5 day – X-rays





2211.05810

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 and 2304.11819).

Link to binary stars

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

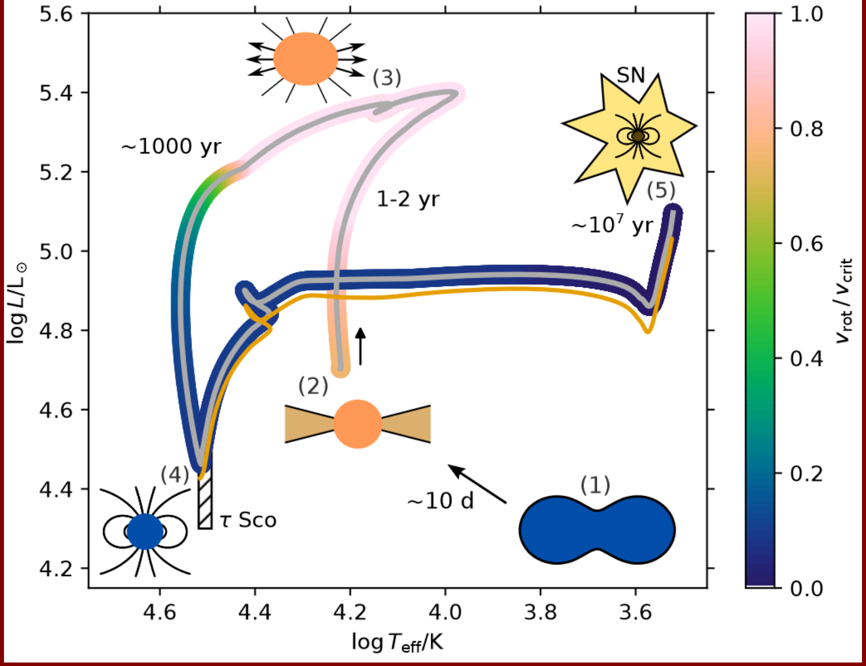
The question is still on the list.

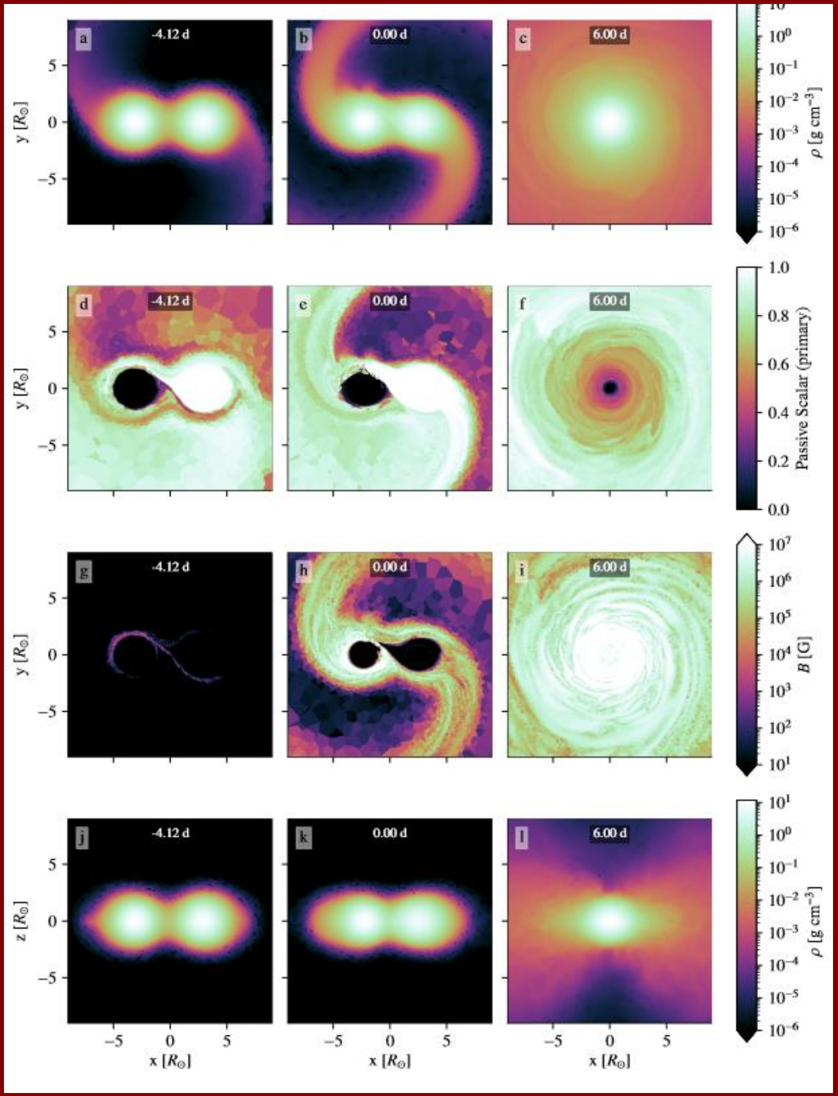
AXP in Westerlund 1 most probably has a very massive progenitor >40 Msolar. However, recently the age was slightly revised: 2103.02609. ~5-8 Myrs. Older than estimated before.

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 τ 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.

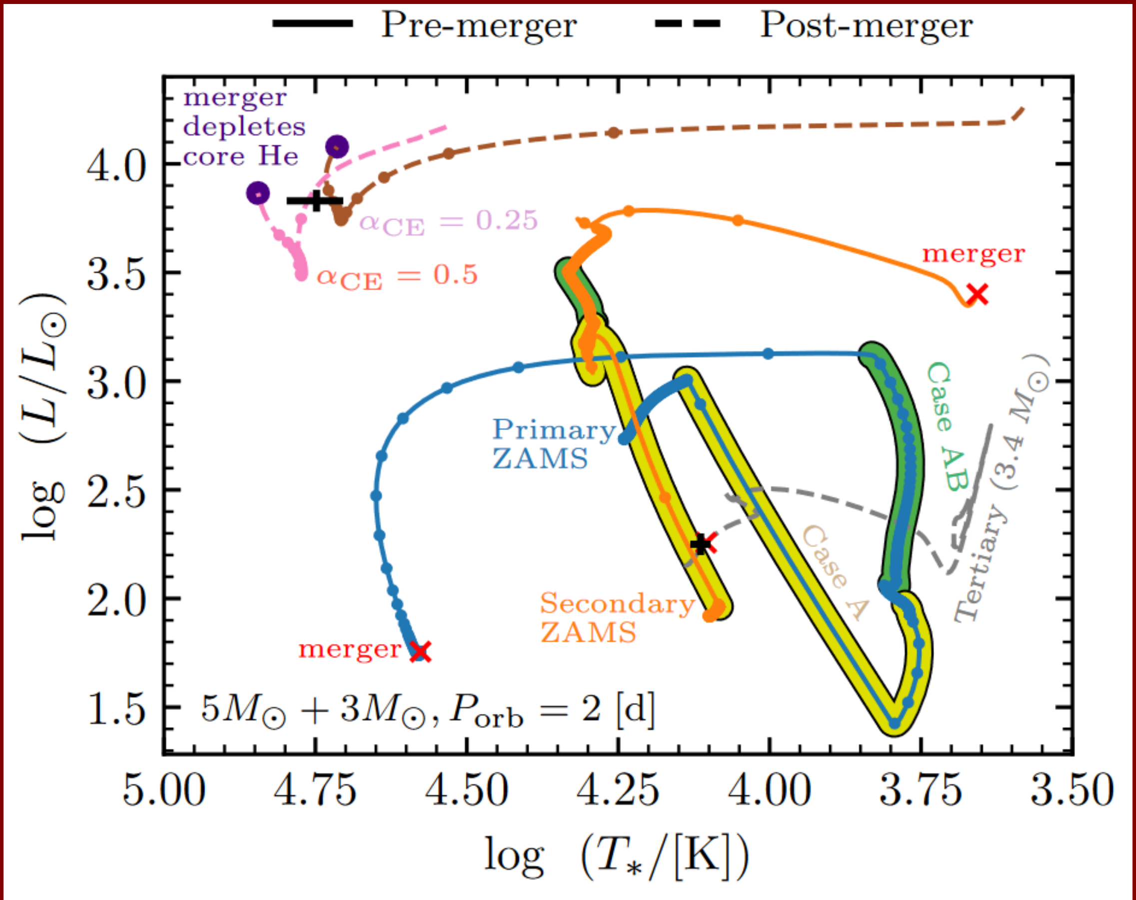
1910.14058

HD45166 – a binary with a WR star

WR + B7V
Orbital period 8200 +/- 200 days
a~9-12 AU

WR: 2 Msun, 43 kGauss
flux conservation will
provide a field $>10^{14}$ G

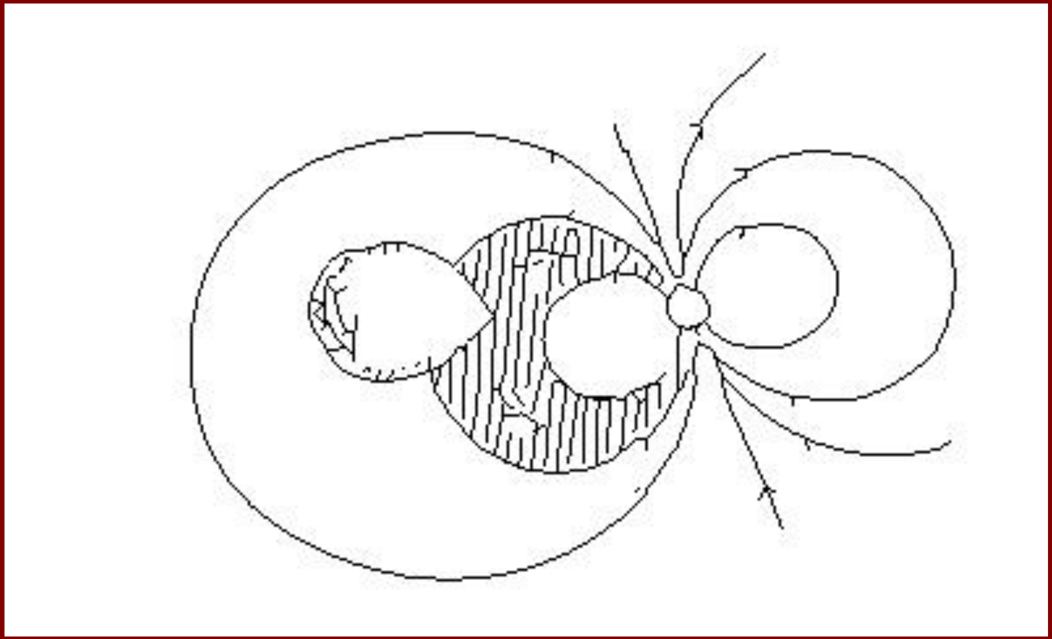
The authors propose that the WR star is a result of a merger of two helium stars.



2308.08591

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.

Magnetor

arXiv: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
- Taverna, Turolla 2402.05622 – polarization in magnetars