Recent results on Magnetars

Sandro Mereghetti

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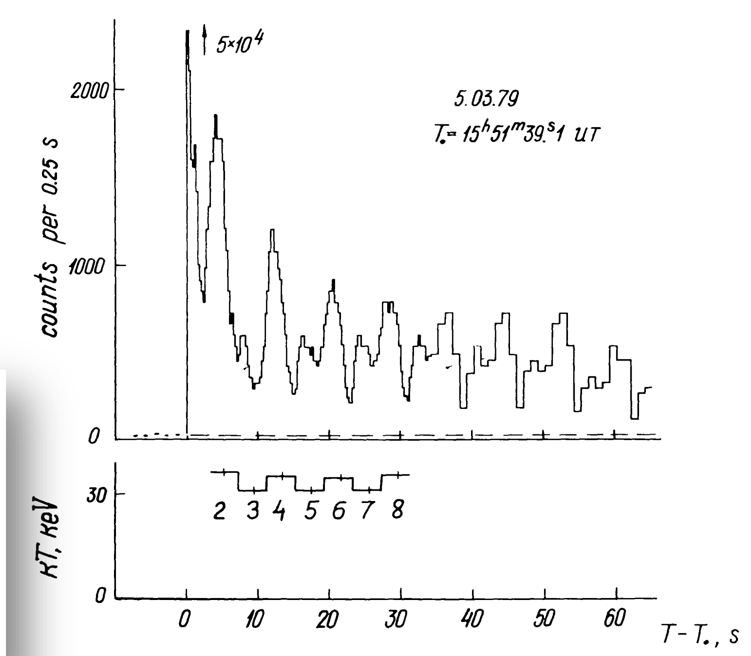
with the “Italian Magnetar Group”:

A. Tiengo, P. Esposito, N. Rea, R. Turolla, S. Zane, L.Nobili, L. Stella, G.L. Israel, D. Götz, ...

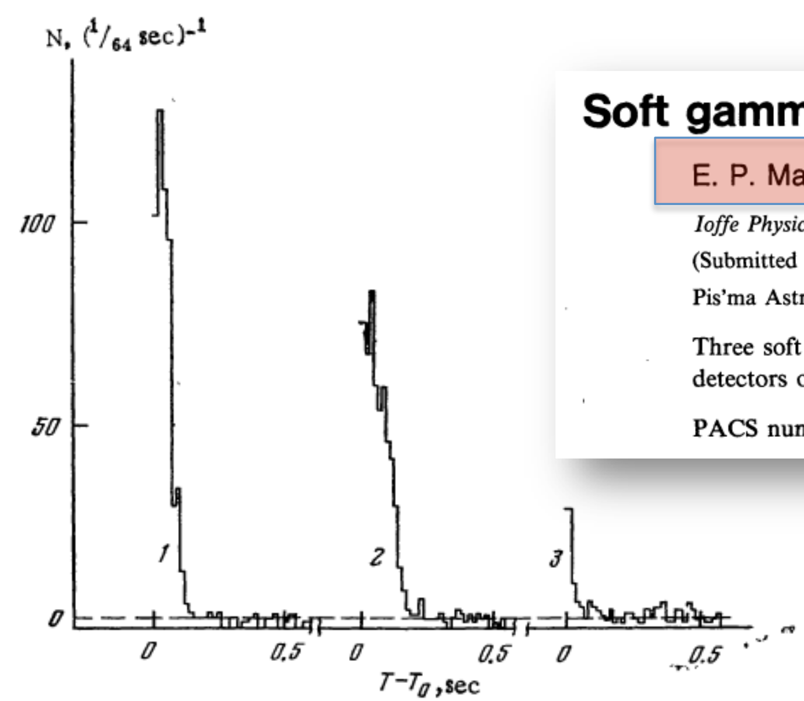
Soft Gamma-ray Repeaters

Discovered in 1979 as **transient** sources of hard X-ray bursts and giant flares (GF)



THE 5 MARCH 1979 EVENT AND THE DISTINCT CLASS OF SHORT GAMMA BURSTS: ARE THEY OF THE SAME ORIGIN?

E. P. MAZETS, S. V. GOLENETSKII, YU. A. GURYAN, and V. N. ILYINSKII



Soft gamma-ray bursts from the source B1900+14

E. P. Mazets, S. V. Golenetskii, and Yu. A. Gur'yan

Ioffe Physics and Technology Institute, USSR Academy of Sciences, Leningrad

(Submitted September 11, 1979)

Pis'ma Astron. Zh. 5, 641–643 (November–December 1979)

Three soft γ-ray bursts from the same source were recorded on 1979 March 24, 25, and 27 by the γ-ray detectors of the Cone experiment aboard the Venera 11 and Venera 12 space probes.

PACS numbers: 97.60.Gb, 98.70.QY

The coordinates of the flaring X-ray pulsar are superimposed on the Large Magellanic Cloud. Moreover, the small source location region contains the N49 supernova remnant in the LMC. Estimates of the energetics involved indicate, however, that the source is in our Galaxy, rather close to the Sùn and, hence, cannot be identified with N49. Indeed, if we estimate the source luminosity in the pulsating stage of the 5 March, 1979 event to be 10^{37}–10^{38} erg, which is typical for steady-state X-ray pulsars (Willmore, 1978) and does not exceed the Eddington limit for objects of mass $\sim M_{\odot}$, the distance to it should be 100–300 pc. It is essential that estimates of the total burst energy, $Q \sim 10^{39}$–10^{40} erg, agree well in this case with those of the average energy of most gamma bursts (see Section 8).

Mazets & Golenetskii 1981

Anomalous X-ray Pulsars

Identified in the 90's as a class of **persistent** X-ray pulsars with no signs of binary companions and $L_x >> dE_{rot}/dt$

THE VERY LOW MASS X-RAY BINARY PULSARS: A NEW CLASS OF SOURCES?

S. MEREGHETTI[1] AND L. STELLA[2,3]

Received 1994 November 21; accepted 1995 January 9

ABSTRACT

While the distribution of spin periods of high-mass X-ray binaries spans more than four orders of magnitude (69 ms–25 minutes) the few known X-ray pulsars accreting from very low mass companions ($<1\ M_\odot$) have very similar periods between 5.4 and 8.7 s. These pulsars also display several other similarities, and we
...naries (LMXBs) with similar magnetic field
...histories. If they are rotating at, or close to,
...sities of the order of a few times 10^{35} ergs
...ss of LMXBs characterized by lower lumi-
...LMXBs.
...tron — stars: rotation — X-rays: stars

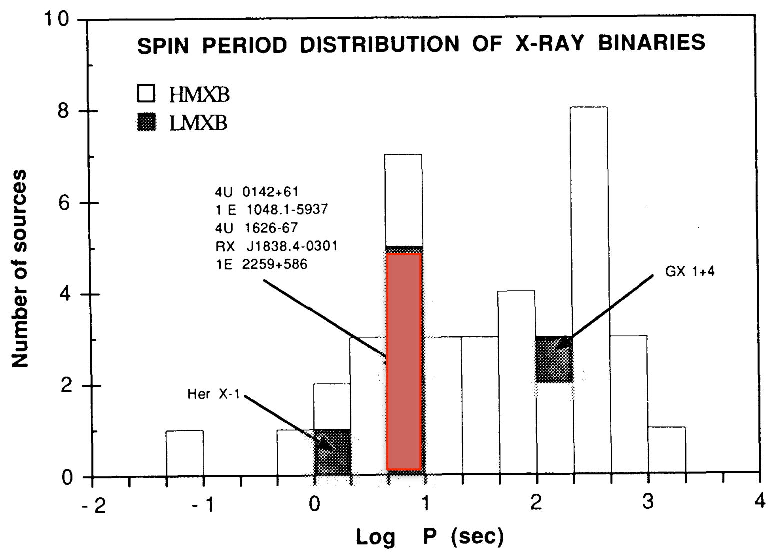


FIG. 1.—The distribution of the spin periods of accreting X-ray pulsars. With the exception of the peculiar systems Her X-1 and GX 1+4, the LMXBs X-ray pulsars have very similar periods between 5.4 and 8.7 s.

Letter to the Editor

On the nature of the 'anomalous' 6-s X-ray pulsars

J. van Paradijs [1,2], R.E. Taam [3], and E.P.J. van den Heuvel [1]

“Historically” two classes of sources:

Mereghetti 2008, Astr. & Astroph. Review 15, 225

- **Soft Gamma-ray Repeaters**
  - Have X-ray counterparts showing all the properties of AXPs
- **Anomalous X-ray pulsars**
  - Most of them emitted “SGR-like” bursts

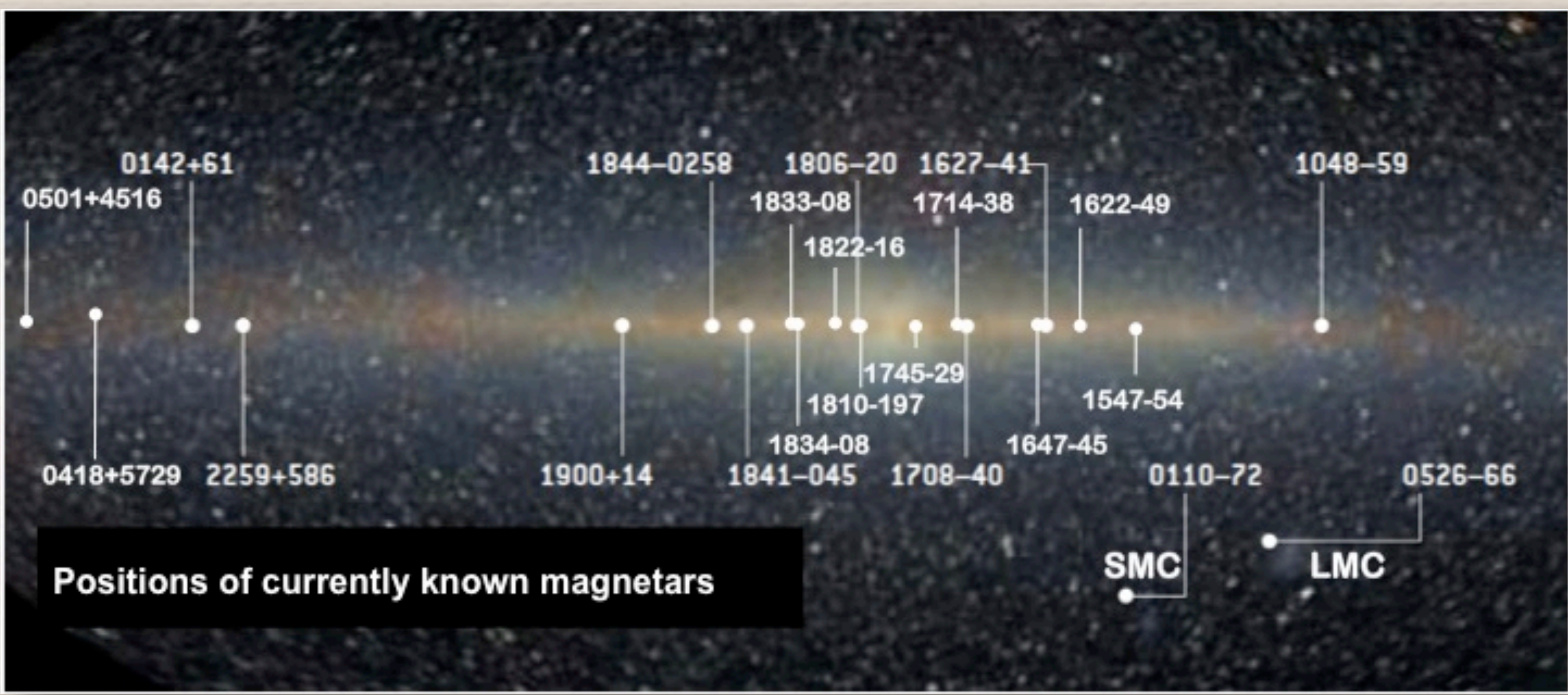
Generally believed that

AXPs = SGRs = (candidate) magnetars

…but see this afternoon session for some alternative models

Thompson
Duncan
Beloborodov
Lyutikov
…

22 confirmed AXP/SGR in the Galaxy and Magellanic Clouds

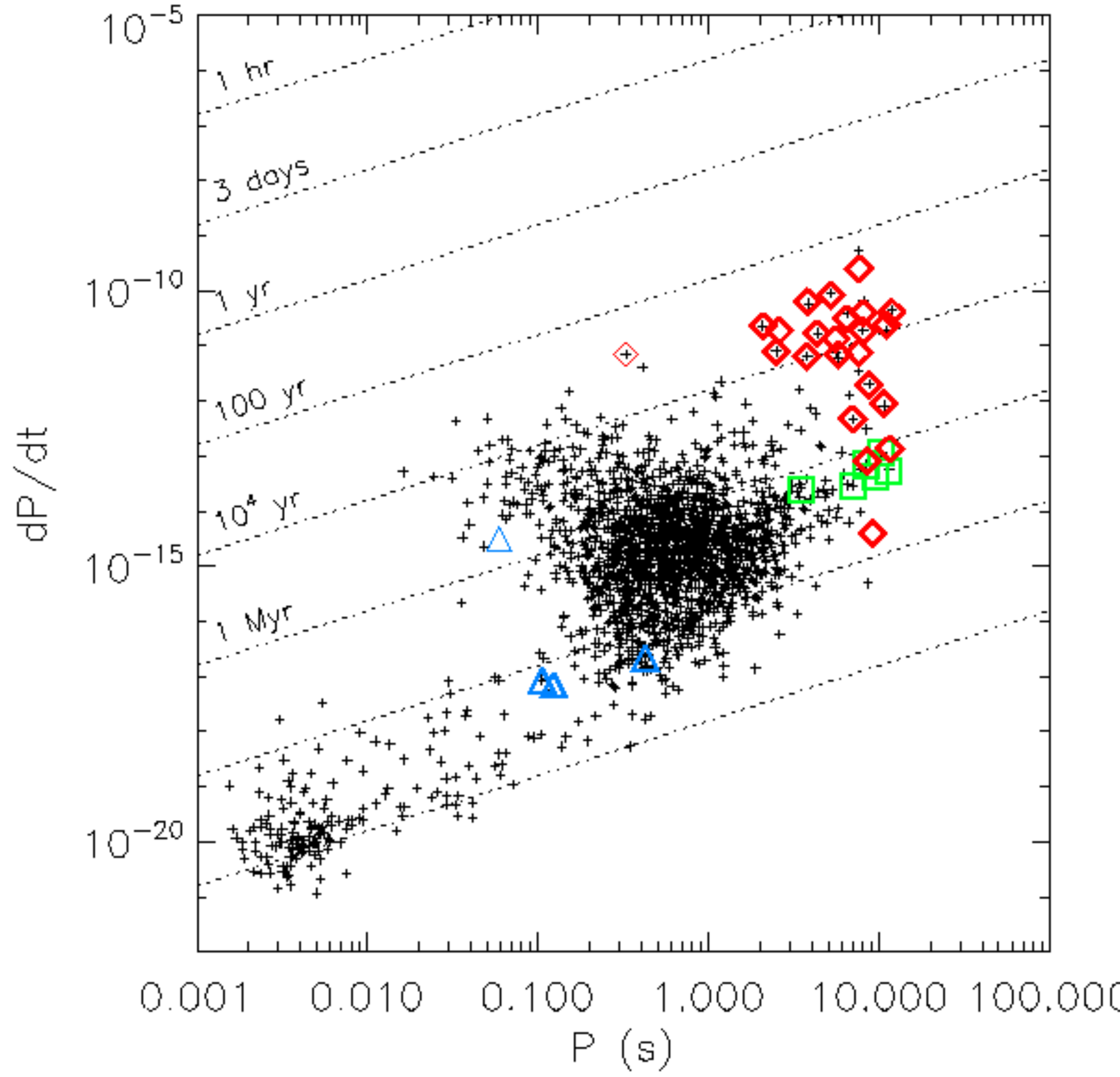


Many associated with SNRs or clusters of massive stars

Many are transient sources

NAME	P (s)	ASSOCIATIONS	RADIO	IR	OPTICAL	X SOFT	X HARD
CXO J0110-72	8.0	SMC				P	
4U 0142+61	8.7			D	P	P	P
1E 1048-59	6.4			D	P	P	D
1E 1547-54	2.1	G327.24-0.13	P	D		P T	P
CXO J1647-45	10.6	Westerlund 1				P T	
RXS 1708-40	11.0			D?		P	P
XTE J1810-197	5.5		P	D		P T	
1E 1841-045	11.8	Kes 73		D?		P	P
1E 2259+586	7.0	CTB 109		D		P	
SGR 0501+45	5.7			D		P T	P
SGR 0526-66	8	LMC , N49				P	
SGR 1627-41	2.6					P T	
SGR 1806-20	7.6	Star cluster	T	D		P	D
SGR 1900+14	5.2	Star cluster	T	D?		P	D
SGR 0418+57	9.1					P T	
PSR J1622-49	4.3	SNR ? G333.9+0.0	P		P	P T	
CXO J1714-38	3.8	CTB 37B				P	
Swift J1822-16	8.4					P T	
SGR 1833-08	7.6					P T	
Swift J1834-08	2.5	W41 ?				P T	
SGR 1745-29	3.8	Near Gal. center	P			P T	P
3XMM 1852	11.6					P T	

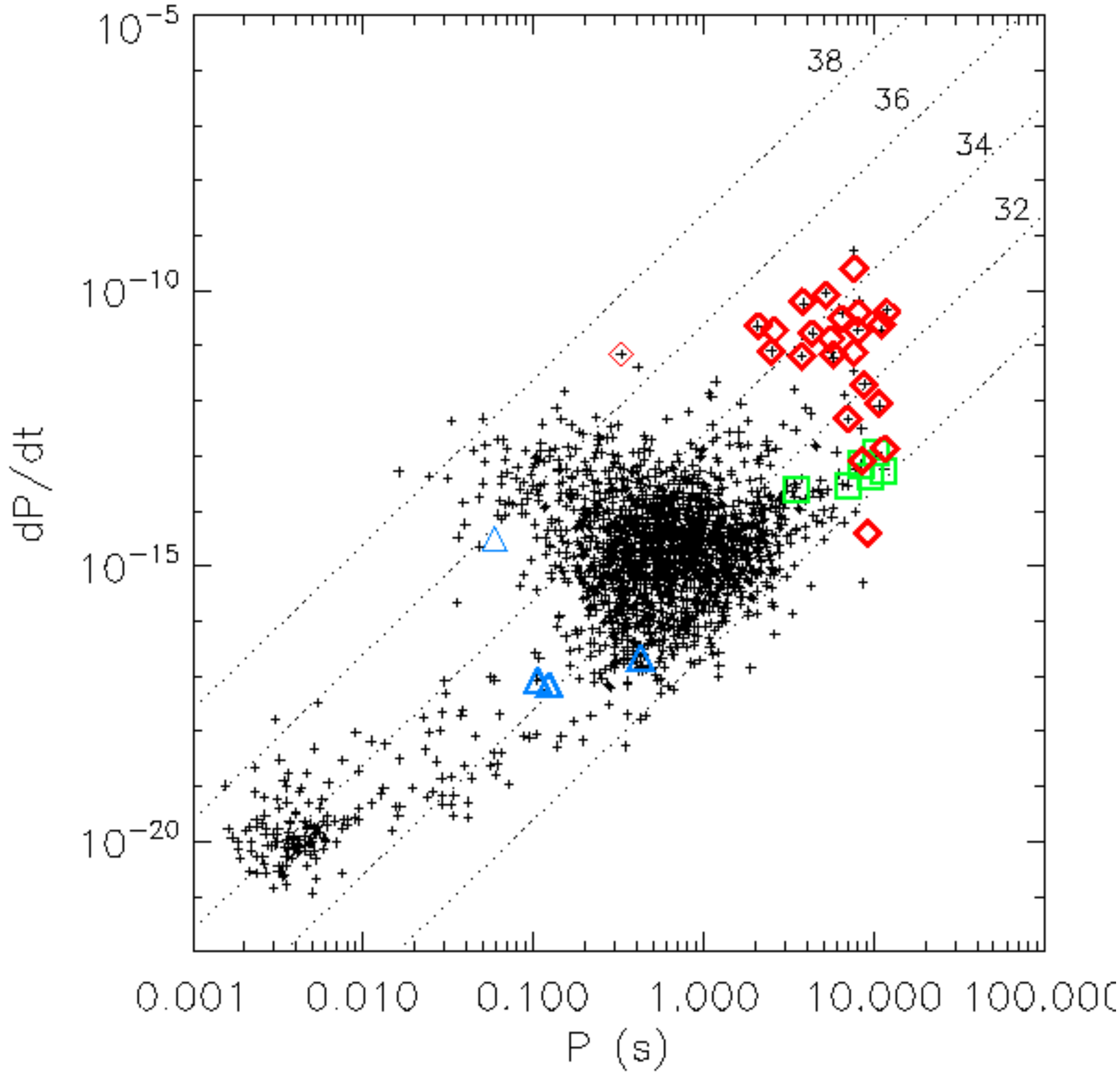
$$\tau = \frac{P}{2\dot{P}}$$



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

$<< L_x$

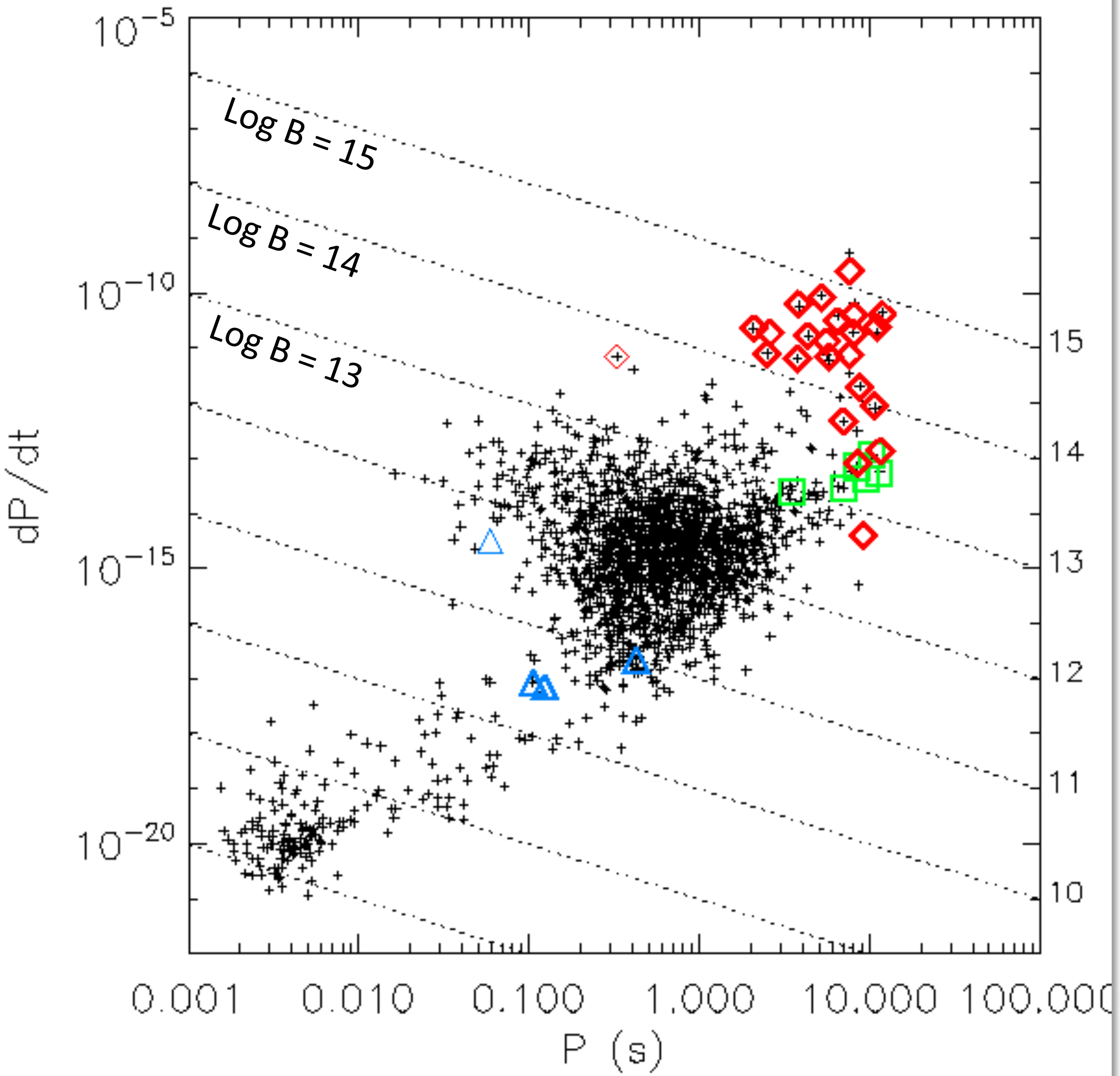
for magnetars



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

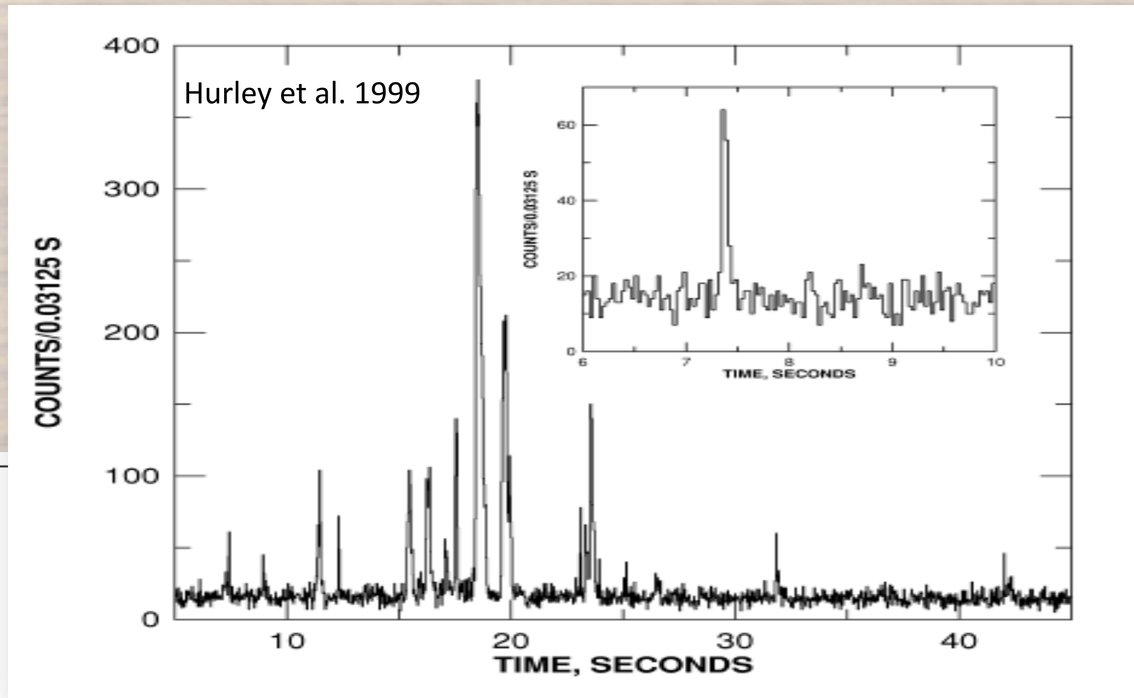
$$\frac{dE}{dt} = \frac{1}{6c^3}B^2R^6\omega^4 sin^2\alpha$$

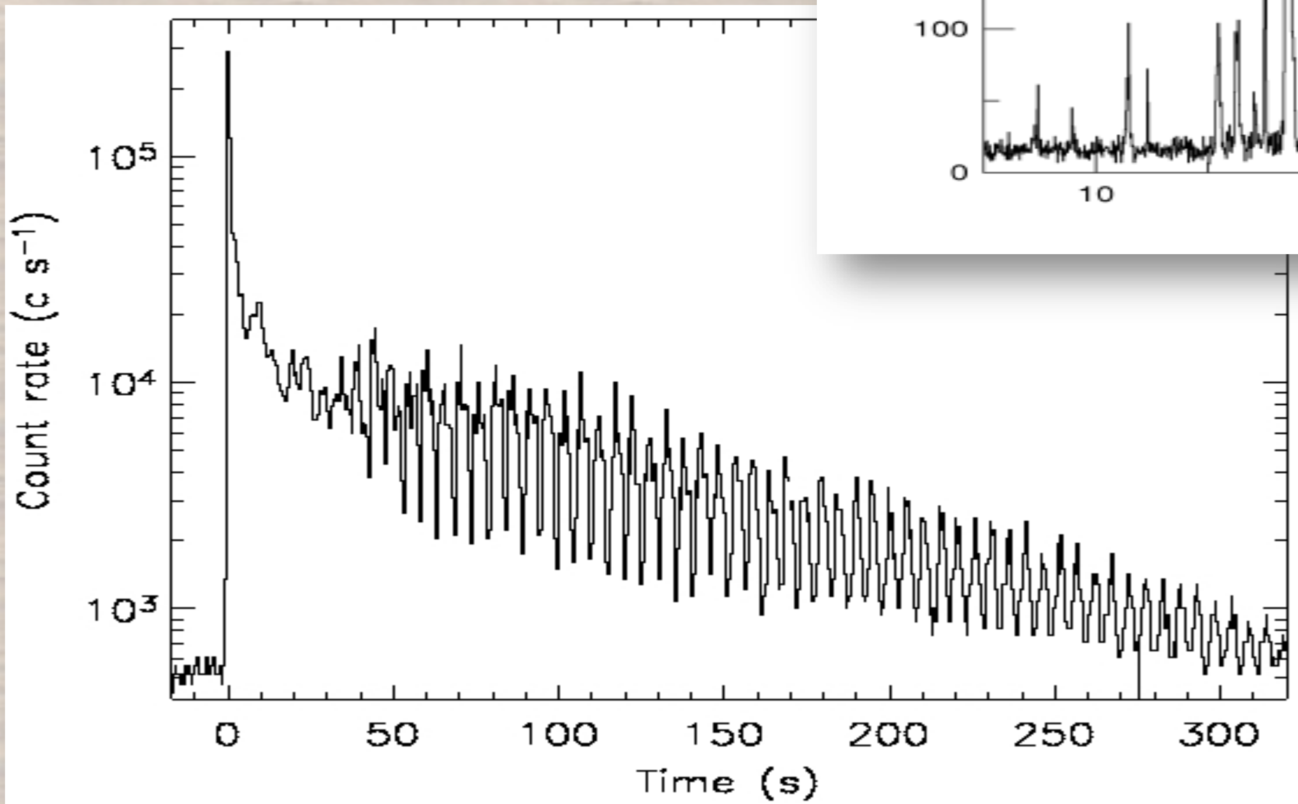
$$B = 3.2 \cdot 10^{19}\sqrt{P\dot{P}}\ \mathrm{Gauss.}$$



Short bursts of soft γ-rays

- $L_x \sim 10^{39\text{-}41}$ erg/s
- kT~30-40 keV
- durations ~0.1-1 s





Giant Flares

- L_x > 10^{44} erg/s
- very rare events (only three observed)
- E ~ few 10^{46} erg

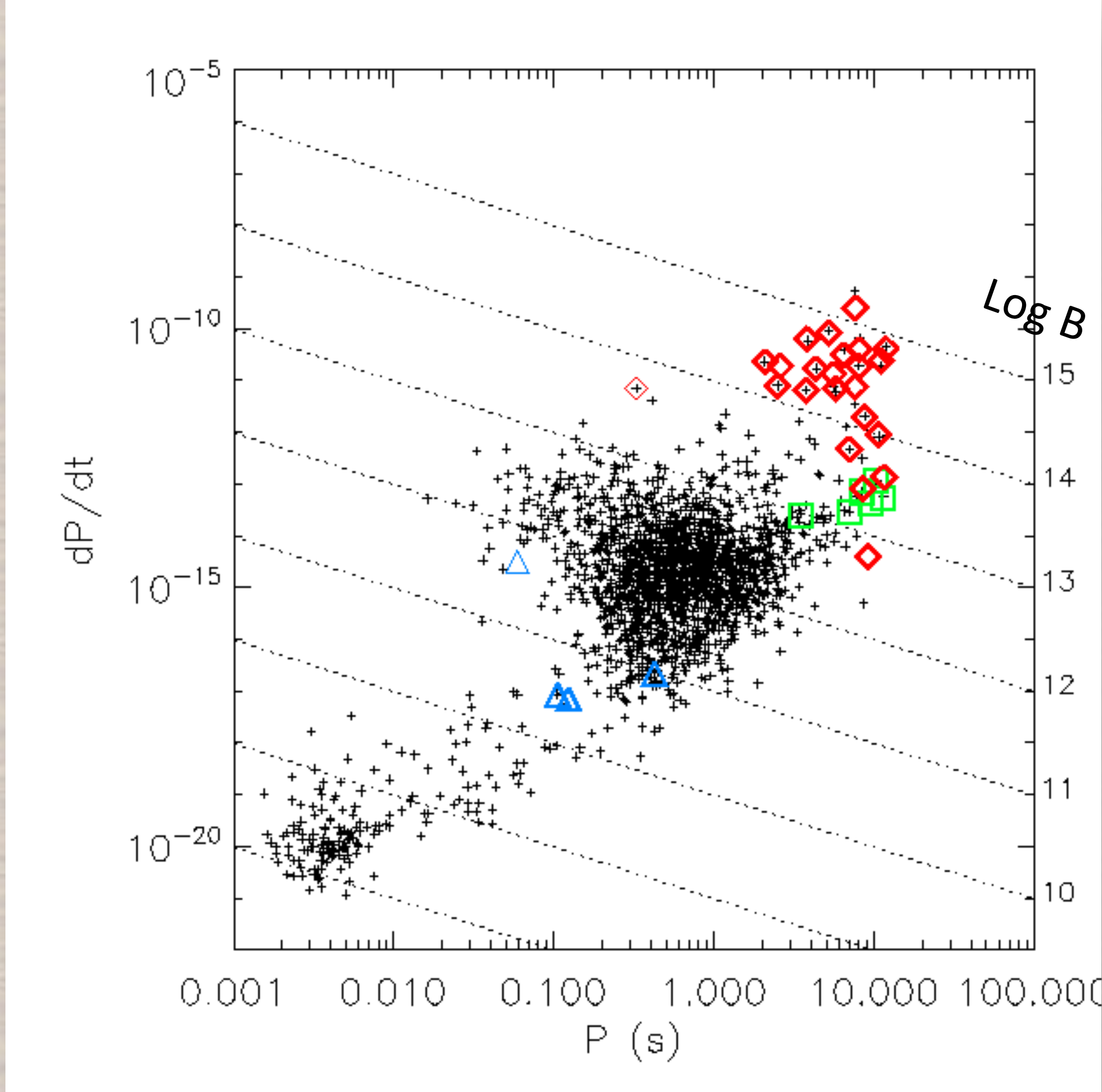
Crustal fractures (Thompson+ 2002) **or magnetic reconnections** (Lyutikov 2003)

Size matters, but it is not all that matters

High B (radio) pulsars

wrt

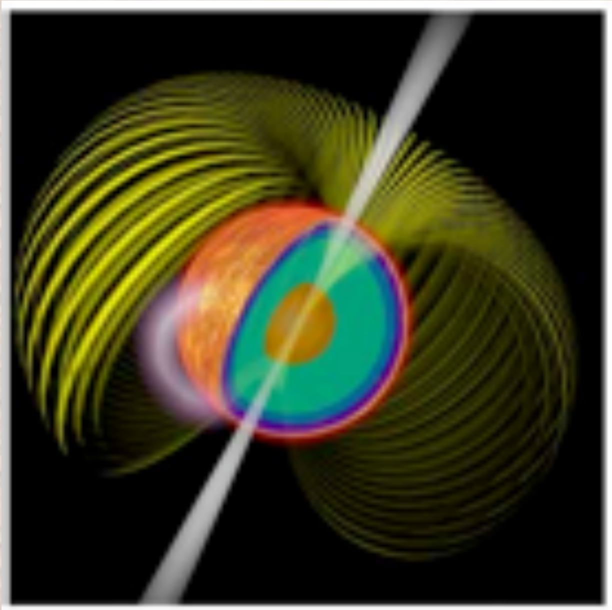
Low B magnetars



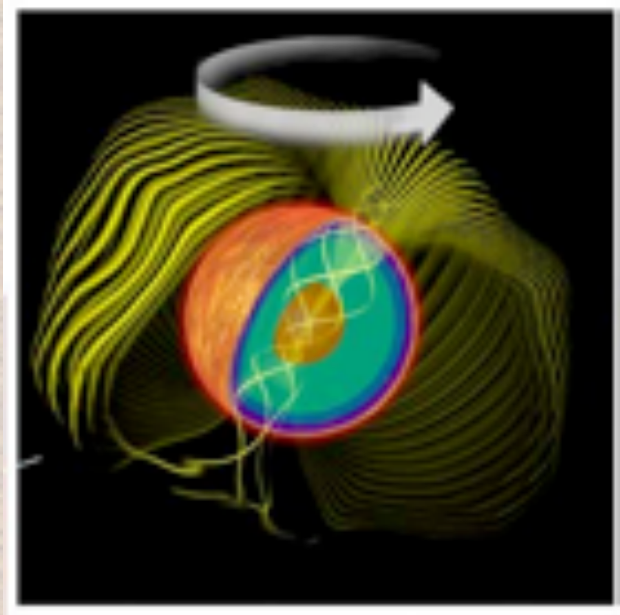
It is **NOT** the dipole magnetic field alone that makes a magnetar

The importance of being twisted

High-*B* radio PSRs



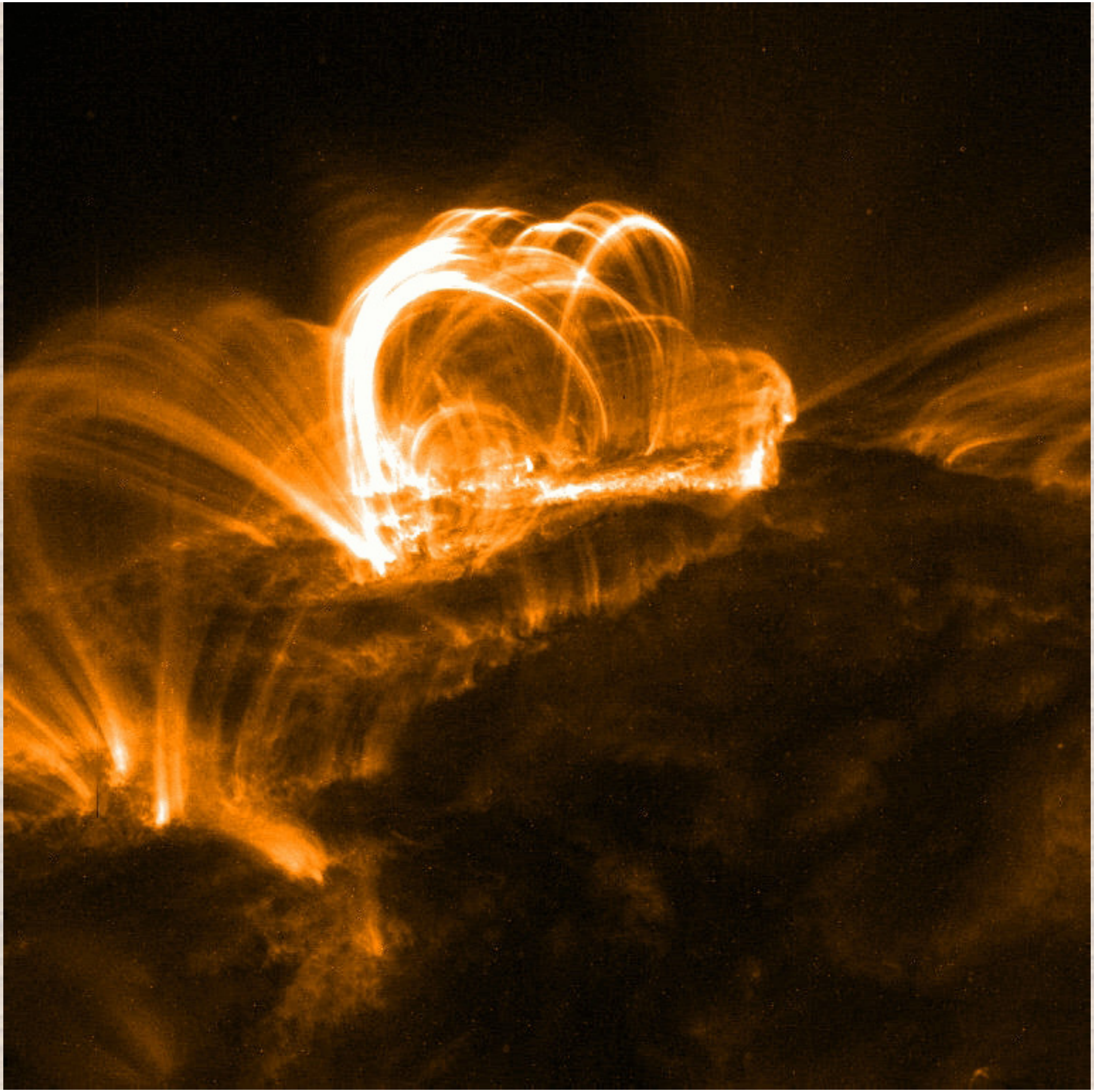
High-*B*



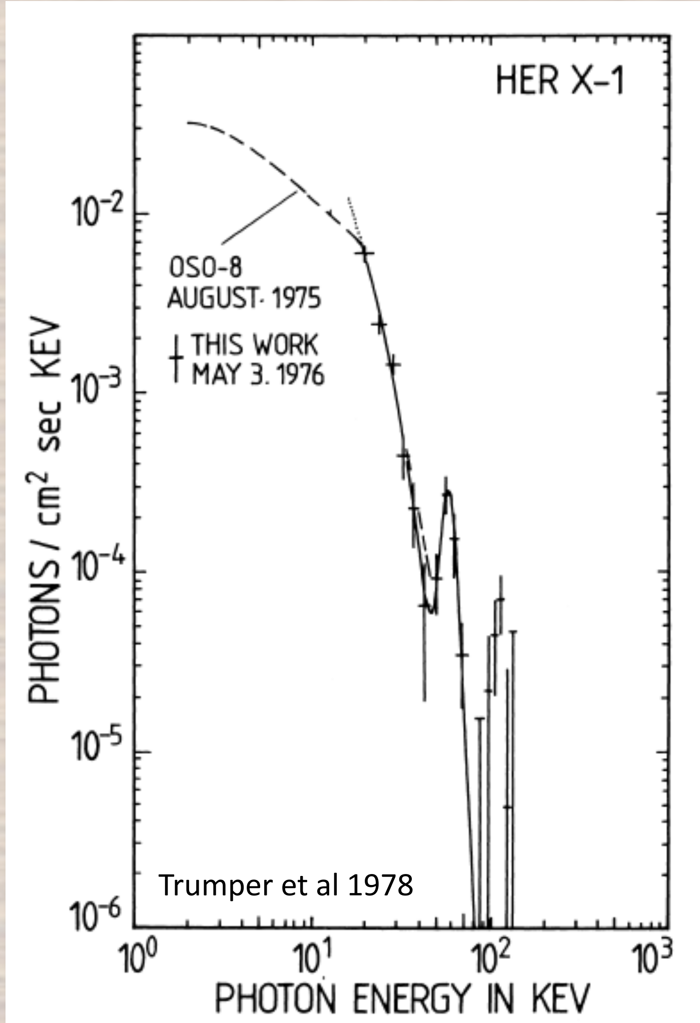
Magnetars

The internal **TOROIDAL** *B* produces the crustal displacements responsible for the bursting/outbursting episodes in AXPs/SGRs

(Thompson & Duncan 1995; Thompson et al 2002; Beloborodov 2009)



A more direct way to estimate B



Cyclotron lines in accreting NS

$$E_{Cycl} \approx 12.6\, Z_g \left(\frac{B}{10^{12}\, G} \right) \; keV \qquad for \;\; electrons$$

$$E_{Cycl} \approx 0.63\, Z_g \left(\frac{B}{10^{14}\, G} \right) \; keV \qquad for \;\; protons$$

$$Z_g = \left(1 - \frac{2GM}{Rc^2} \right)^{1/2} \qquad gravitational \;\; redshift$$

0.7 - 0.85

Reports of CYCLOTRON lines AXPs/SGRs

Source	Energy (keV)	Signif. (σ)	Satellite/Instrument reference	Notes
1E 2259+586	5, 10	-	**GINGA/LAC** Koyama et al. 1987 Iwasawa et al. 1992	Phase-resolv. spectra absorption
SGR 1806-20	5, (7.5, 11.2, 17.5)	3.3	**RossiXTE/PCA** Ibrahim et al 2002,2003	Bursts (precursor), absorption
4U 0142+614	4, 8, 14	-	**RossiXTE/PCA** Gavriil et al 2011	Bursts,emission
XTE 1810-197	12.6	4.5	**RossiXTE/PCA** Woods et al. 2005	Burst (tail) emission
1RXS 1708-40	8.1	2.95	**BeppoSAX/MECS** Rea et al. 2003	Phase-resolv. spectra absorption
SGR 1900+14	6.4	3.7	**RossiXTE/PCA** Strohmayer Ibrahim 2000	Burst, emission
1E 1048-5937	14;13	3.9;3.3	**RossiXTE/PCA** Gavriil et al. 2002 **NuSTAR** An et al. 2014	Bursts,emission

1E1048-5937 - NuStar observation
Emission line at 14 keV in burst tail

An et al. 2014

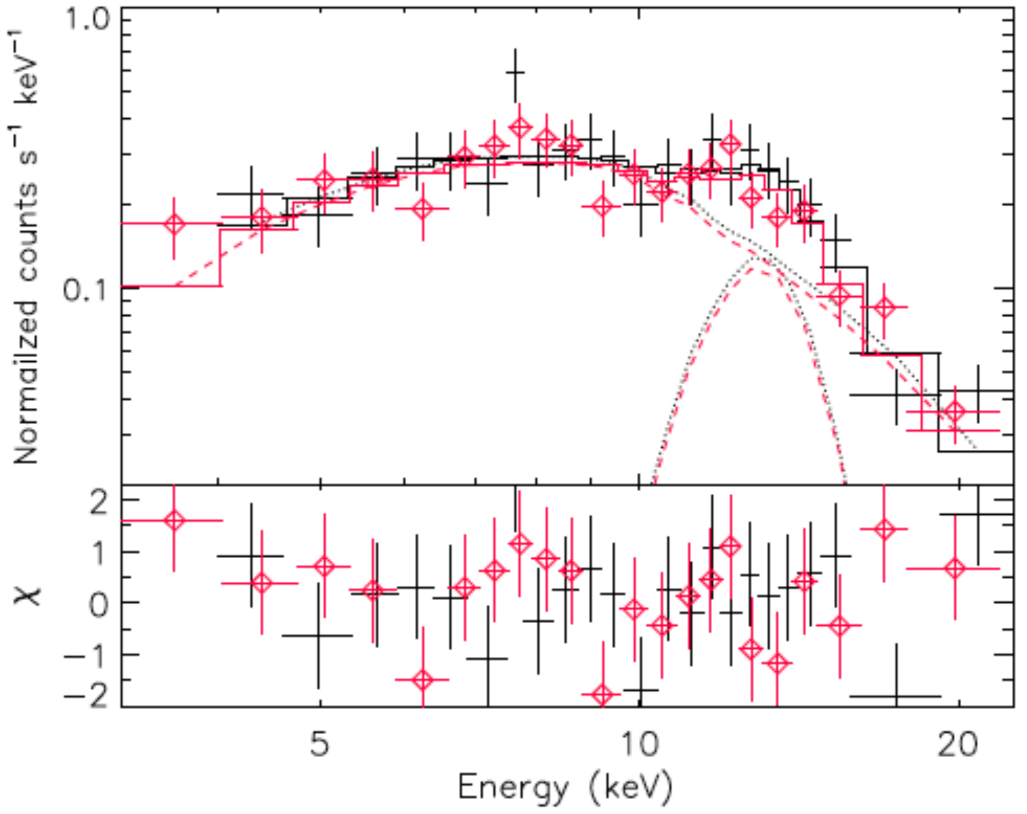


Figure 6. Blackbody plus Gaussian line fit for the 150 s *NuSTAR* spectrum of burst 5.

Possible confirmation of similar features seen in the past only with RXTE

LETTER

doi:10.1038/nature12386

A variable absorption feature in the X-ray spectrum of a magnetar

Andrea Tiengo[1,2,3], Paolo Esposito[2], Sandro Mereghetti[2], Roberto Turolla[4,5], Luciano Nobili[4], Fabio Gastaldello[2], Diego Götz[6], Gian Luca Israel[7], Nanda Rea[8], Luigi Stella[7], Silvia Zane[5] & Giovanni F. Bignami[1,2]

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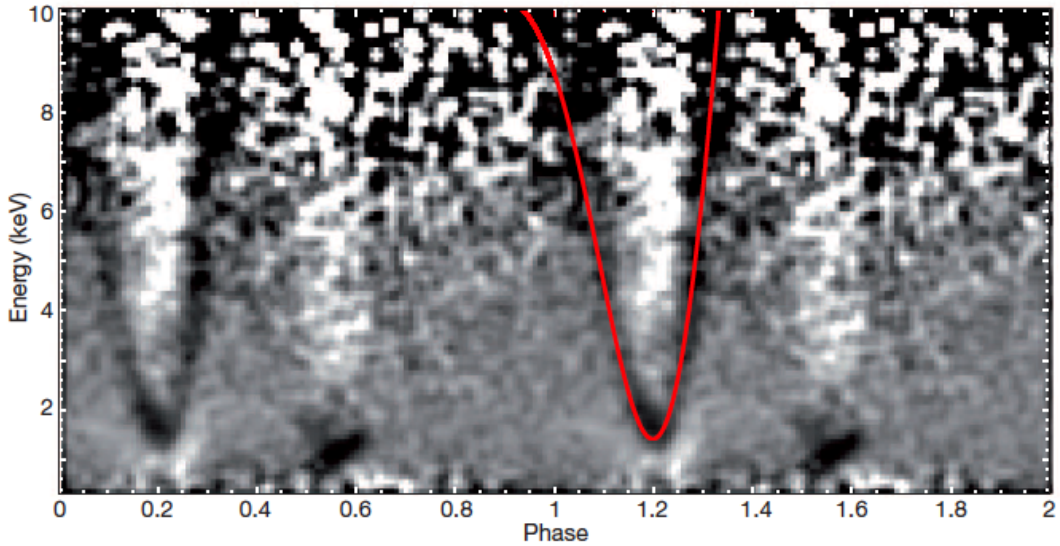
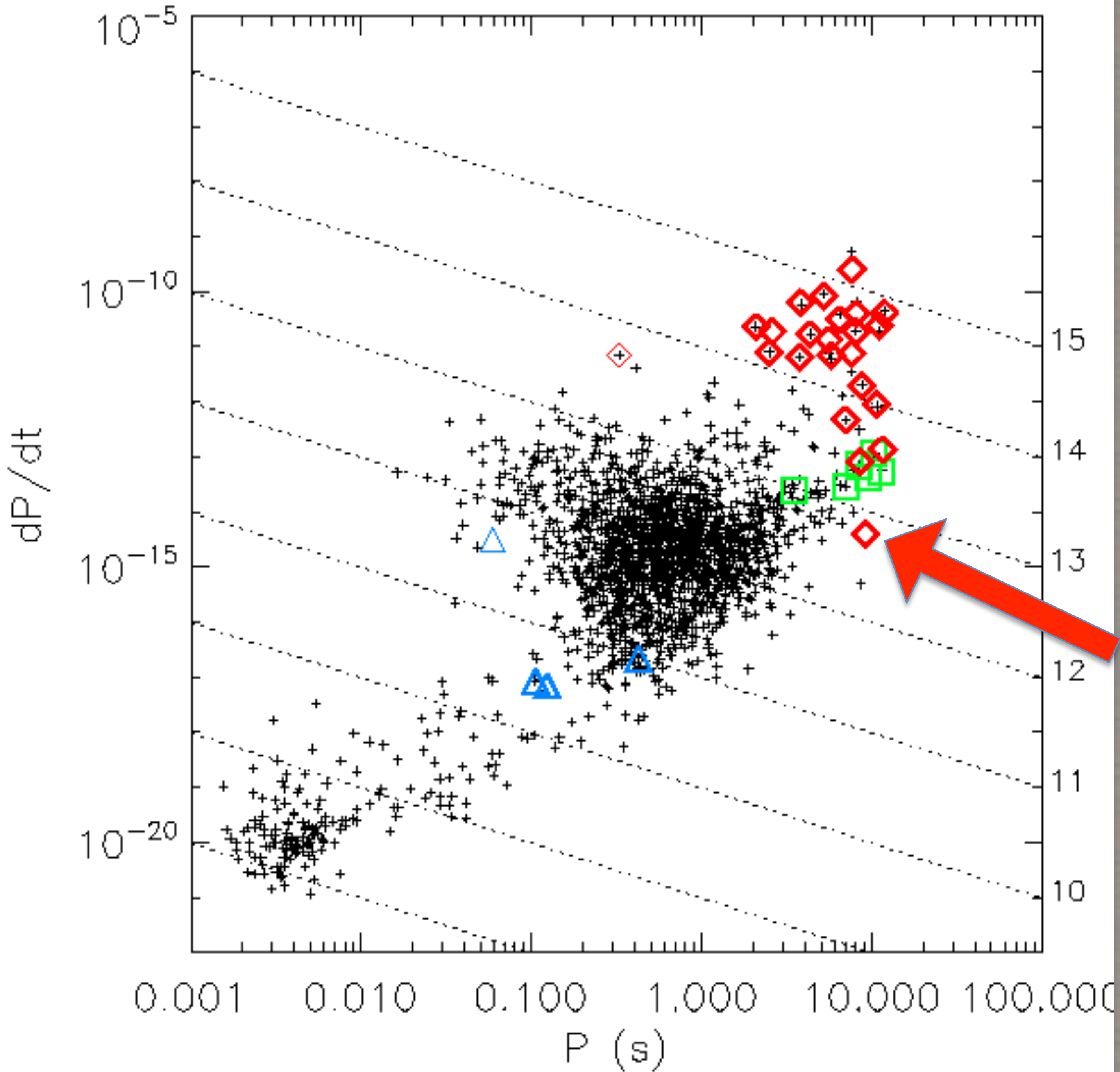
Soft-γ-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are slowly rotating, isolated neutron stars that sporadically undergo episodes of long-term flux enhancement (outbursts) generally accompanied by the emission of short bursts of hard X-rays[1,2]. This behaviour can be understood in the magnetar model[3–5], according to which these sources are mainly powered by their own magnetic energy. This is supported by the fact that the magnetic fields inferred from several observed properties[6–8] of SGRs and AXPs are greater than—or at the high end of the range of—those of radio pulsars. In the peculiar case of SGR 0418+5729, a weak dipole magnetic moment is derived from its timing parameters[9], whereas a strong field has been proposed to reside in the stellar interior[10,11] and in multipole components on the surface[12]. Here we show that the X-ray spectrum of SGR 0418+5729 has an absorption line, the properties of which depend strongly on the star's rotational phase. This line is interpreted as a proton cyclotron feature and its energy implies a magnetic field ranging from 2×10^{14} gauss to more than 10^{15} gauss.



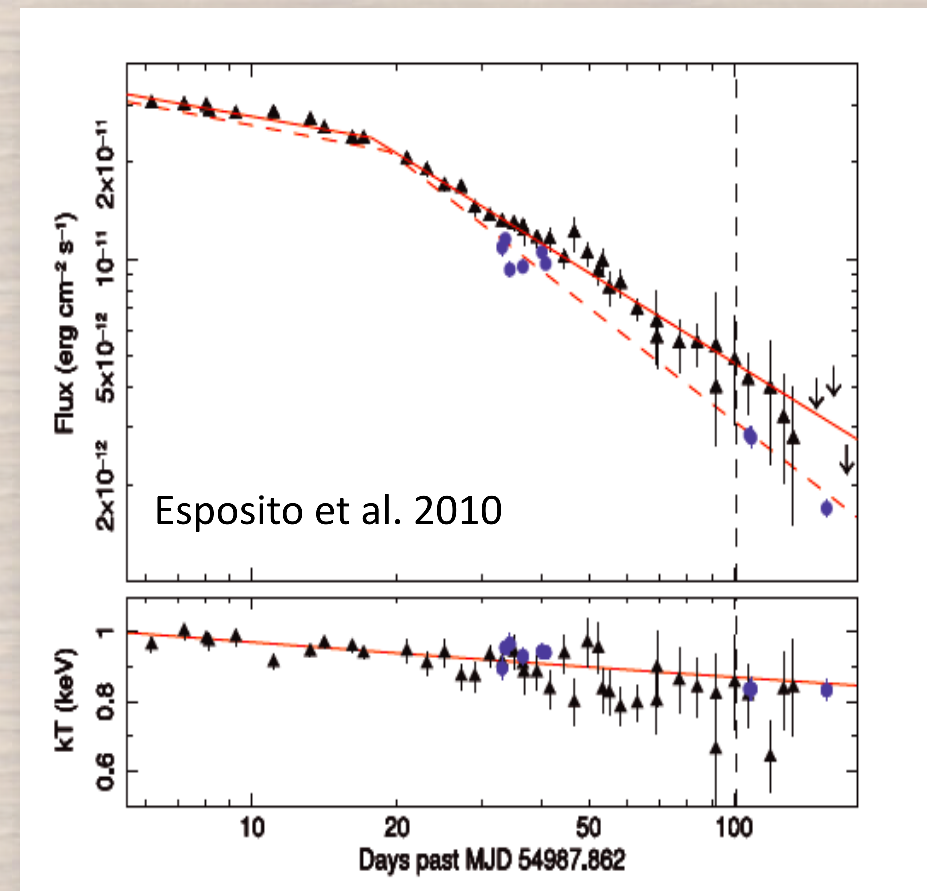


SGR 0418
The magnetar with the smallest Pdot

SGR 0418+5729

- Transient source (June 2009)

  large flux increase + long decay with decreasing kT

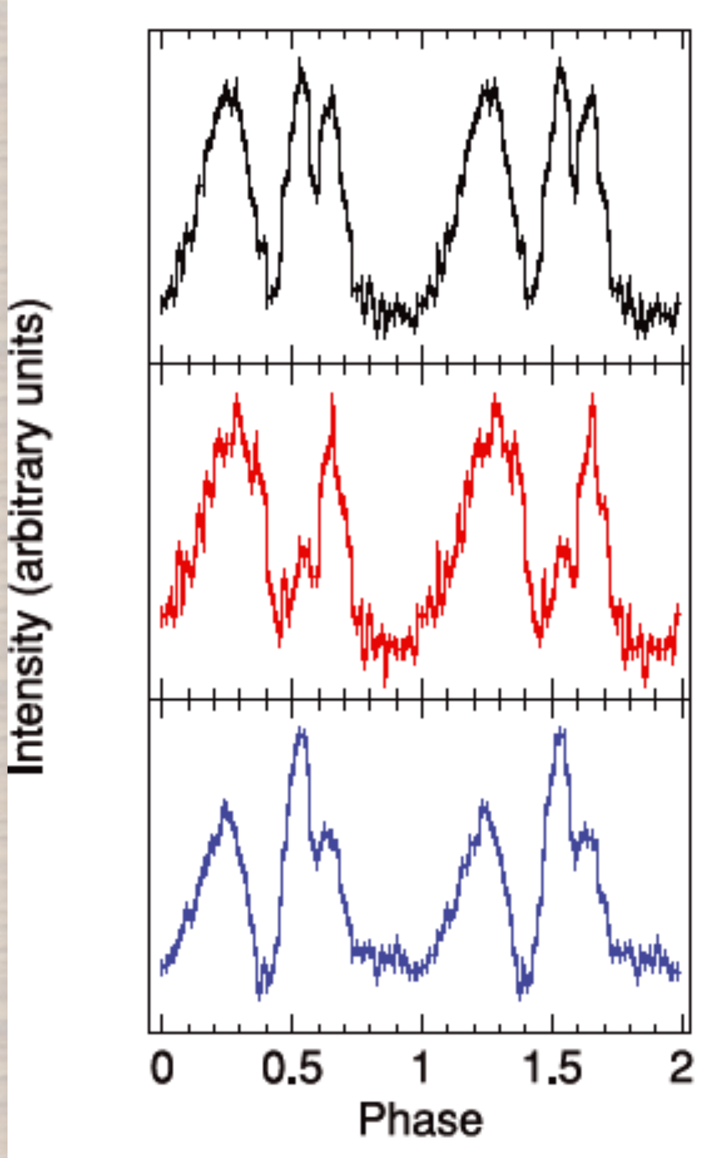


SGR 0418+5729

- Transient source (June 2009)

  large flux increase + long decay with decreasing kT

- P=9.1 s



2-10 keV

2-4 keV

4-10 keV

SGR 0418+5729

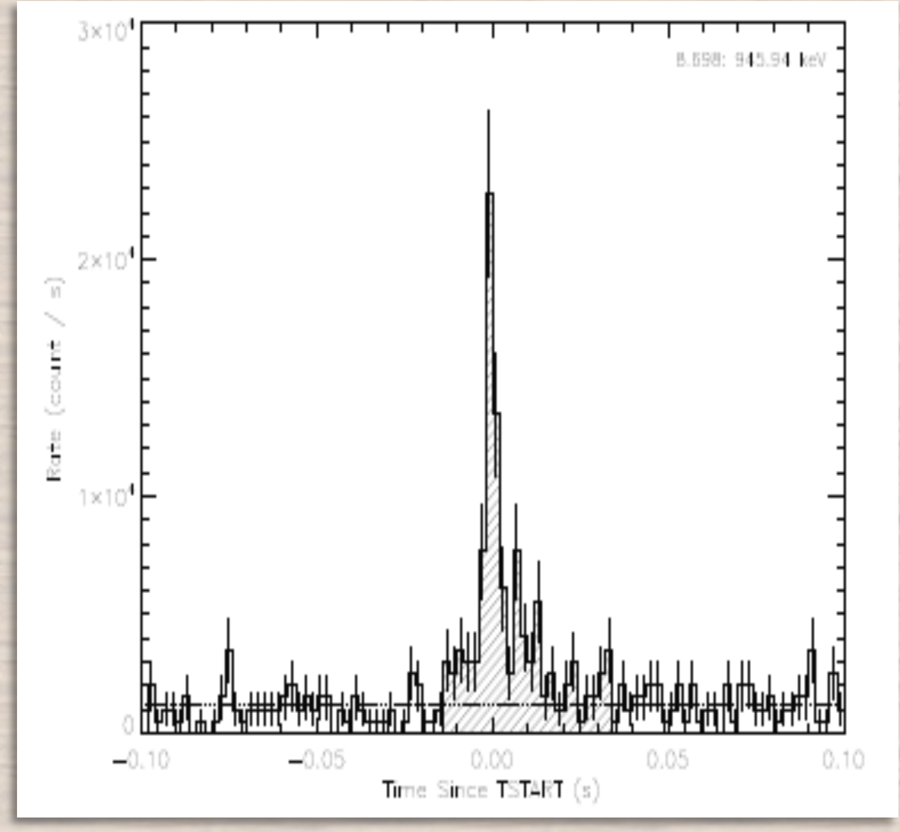
- Transient source (June 2009)

  large flux increase + long decay with decreasing kT

- P=9.1 s

- Emitted two short bursts

van der Horst et al. 2009



SGR 0418+5729

- Transient source (June 2009)

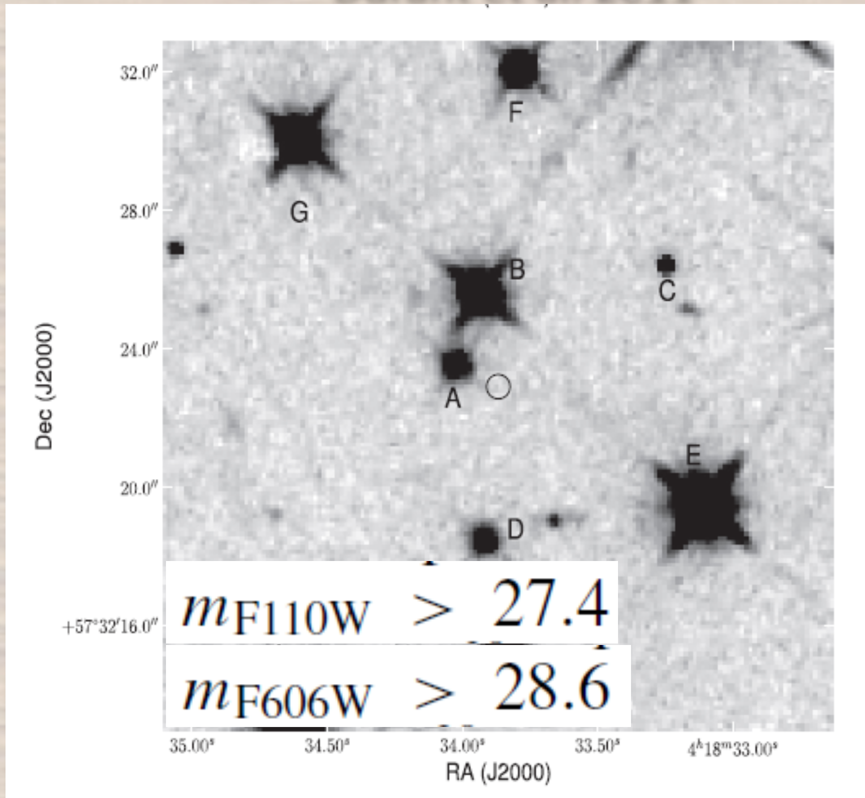
  large flux increase + long decay with decreasing kT

- P=9.1 s

- Emitted two short bursts

- No optical counterpart (b=+5° , low $N_H \approx 10^{21}$ cm^{-2})

Durant et al. 2011

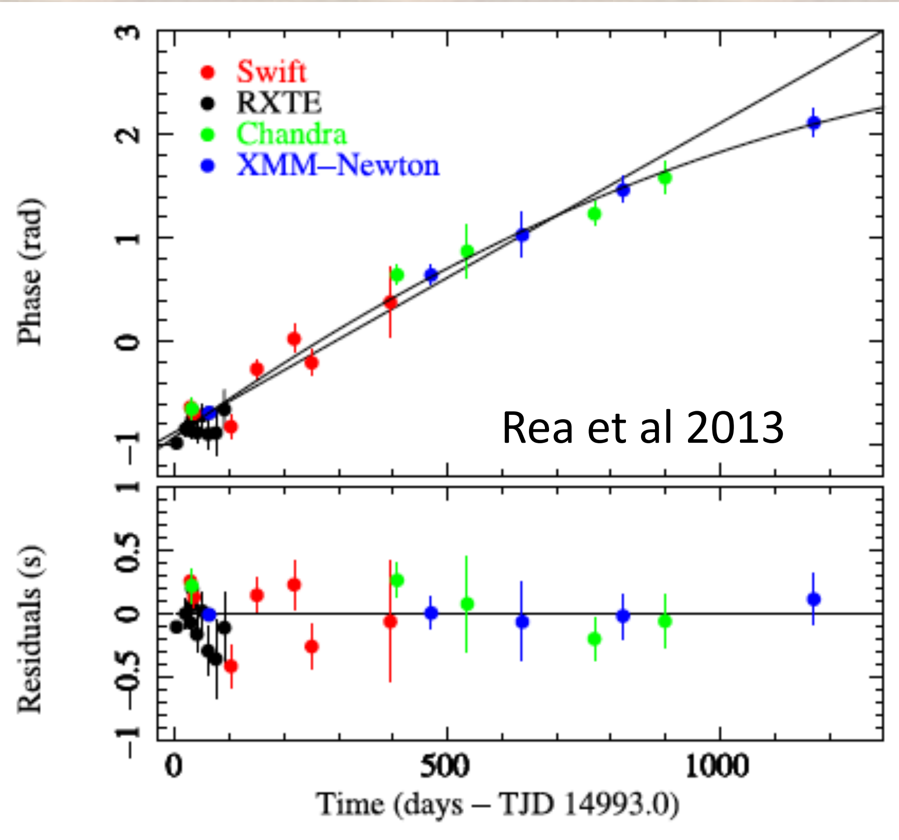


Deep HST observations
V>28.6 J>27.4

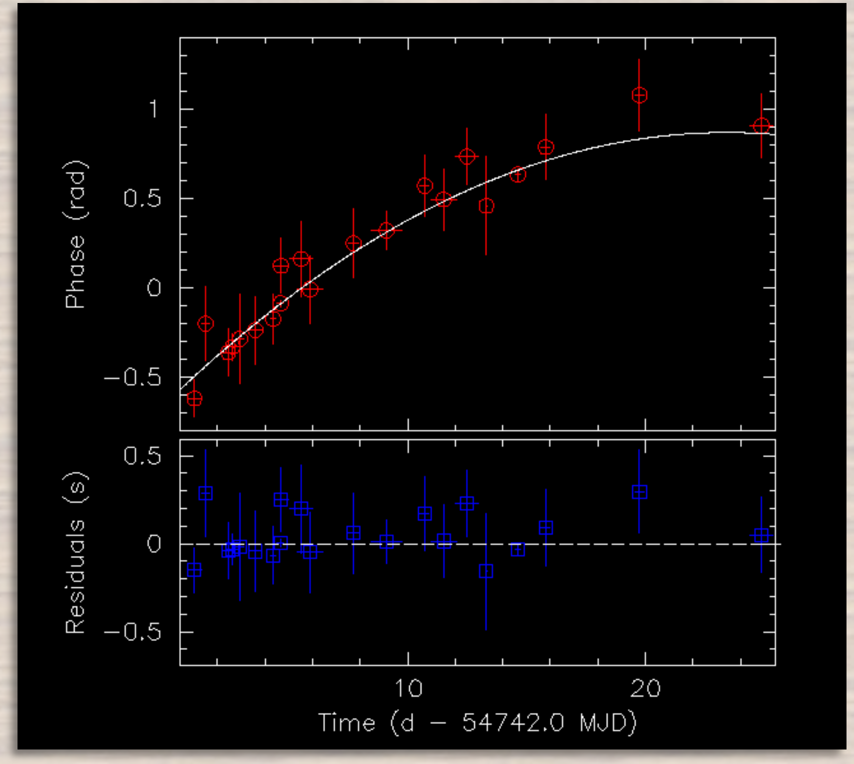
SGR 0418+5729

- Extremely small Pdot = $4x10^{-15}$ s s^{-1} ⇒ $B_{dip} \approx 6x10^{12}$ G

SGR 0418+5729

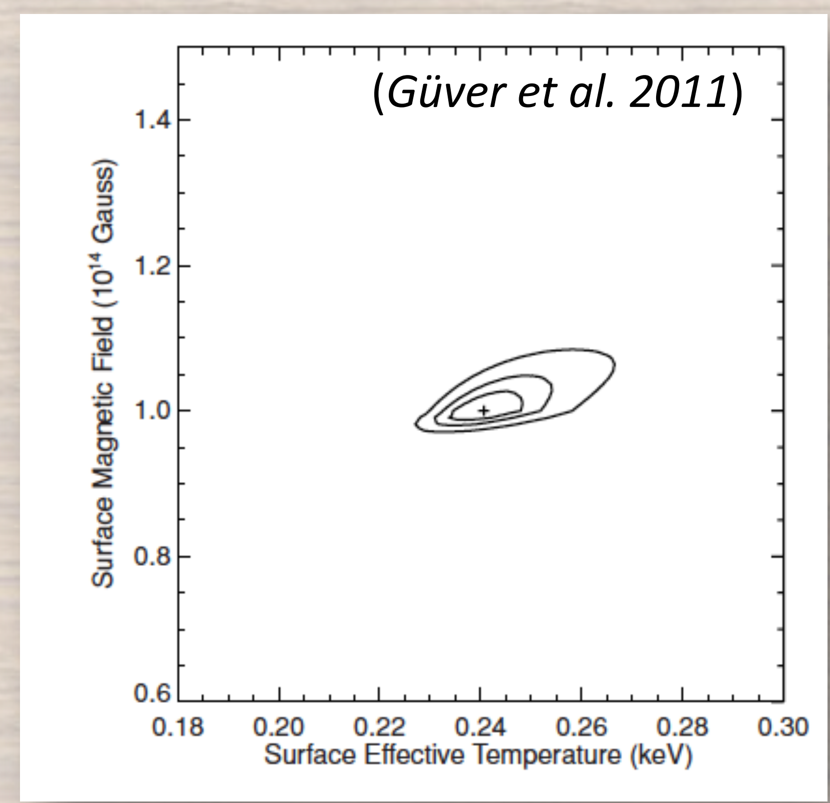


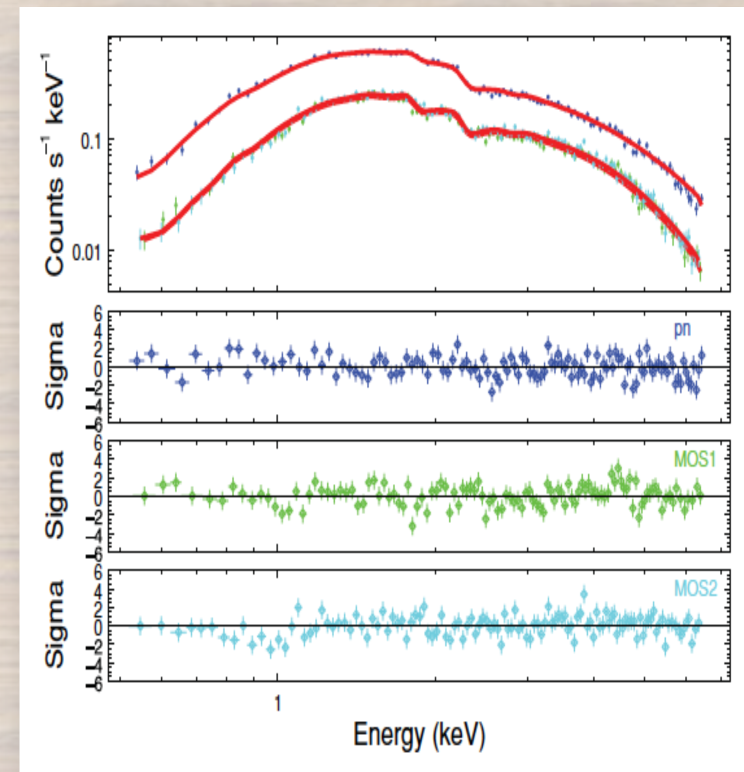
SGR 1833-0832



The high Pdot of ``normal" magnetars is detected after a few days of phase-connected timing

SGR 0418+5729

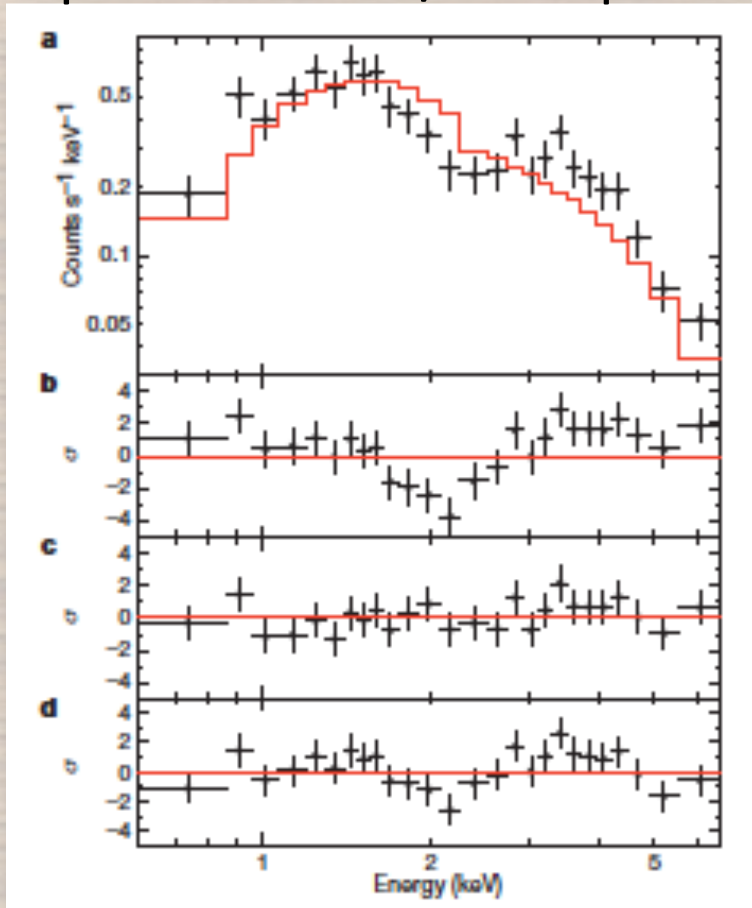




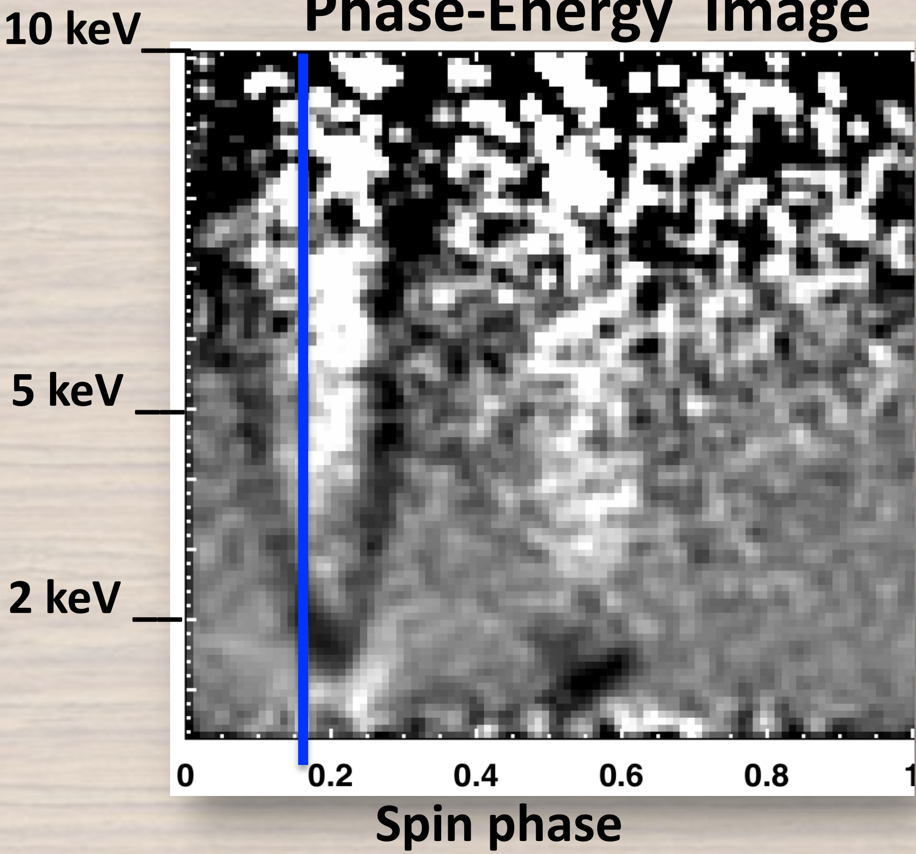
- Spectral fit with magnetized NS atmosphere model → $B=10^{14}$ G
- Strong **MULTIPOLAR** field components on the surface

SGR 0418+5729

Spectrum of 1/50 of phase

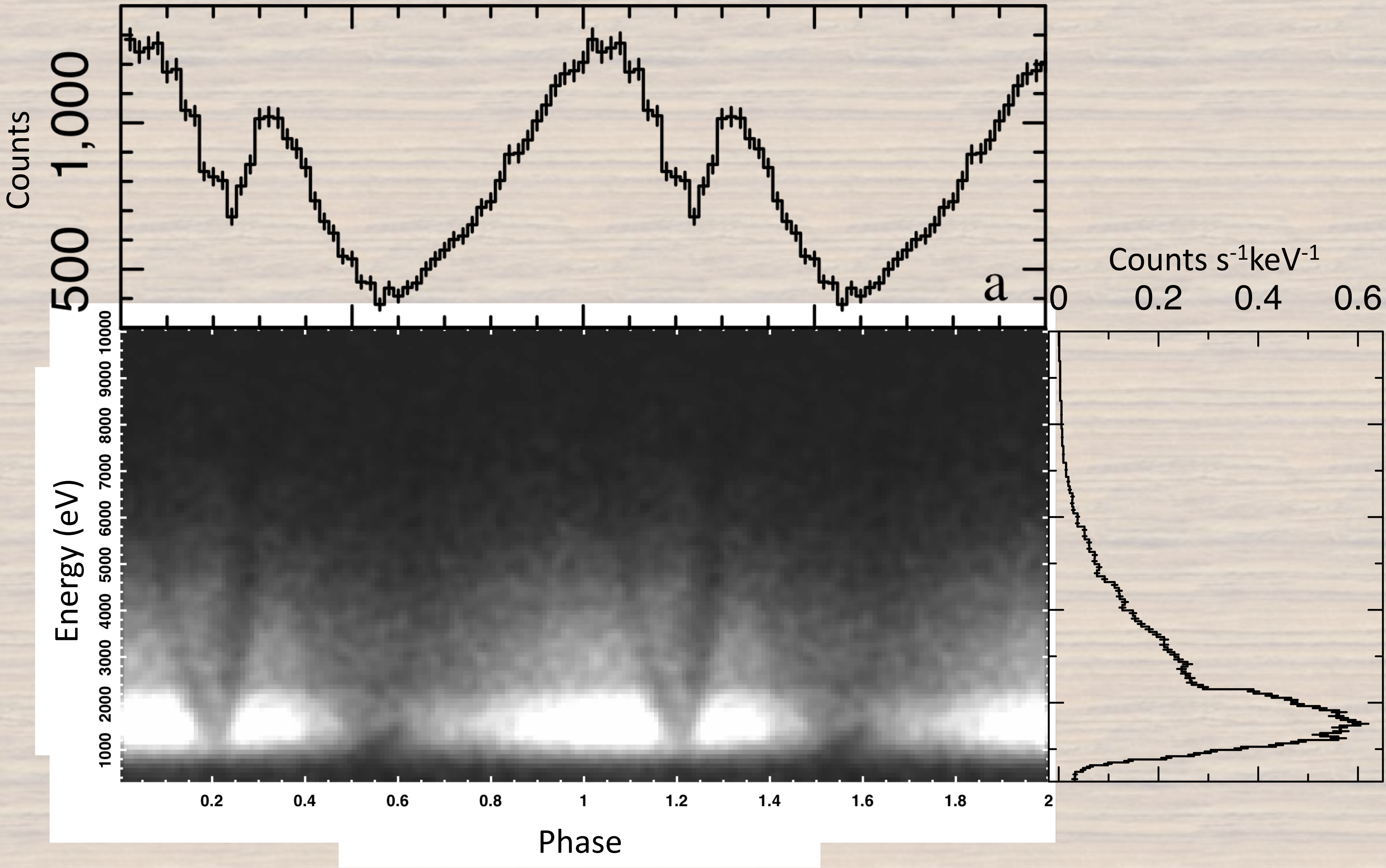


Phase-Energy Image

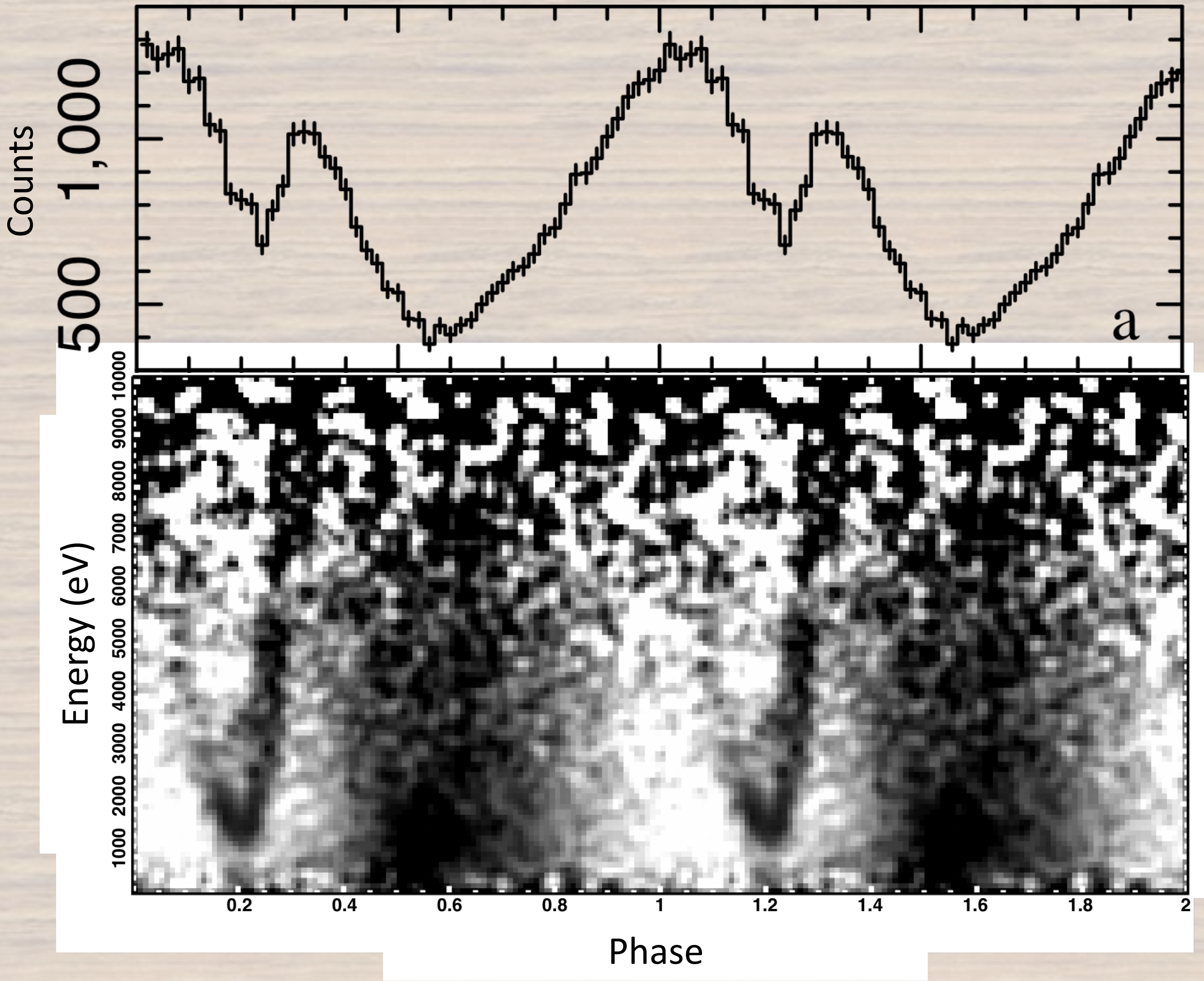


Tiengo et al. 2013, Nature

XMM-Newton/EPIC phase-energy image



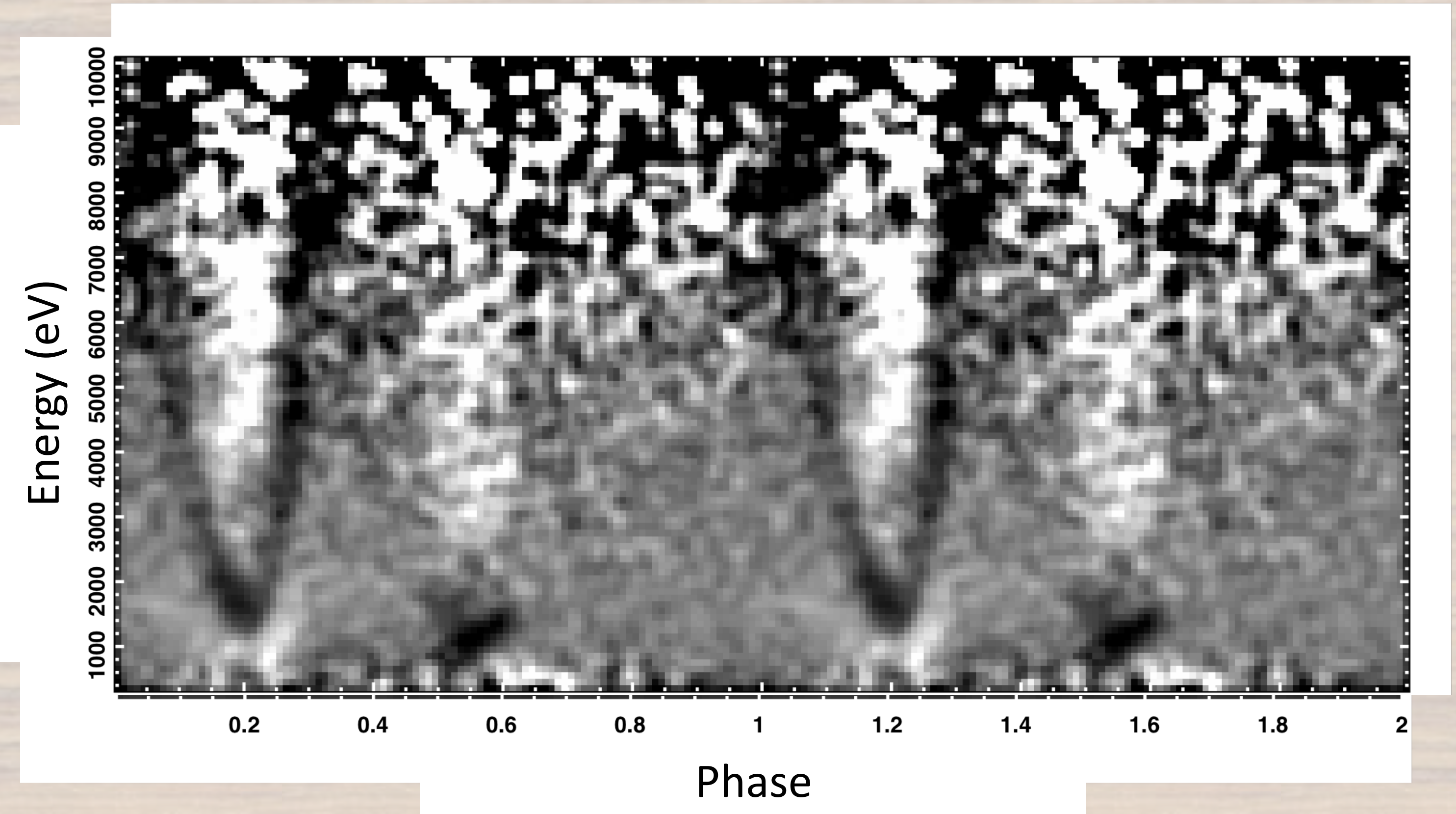
XMM-Newton/EPIC phase-energy image



Normalized to the phase-averaged spectrum

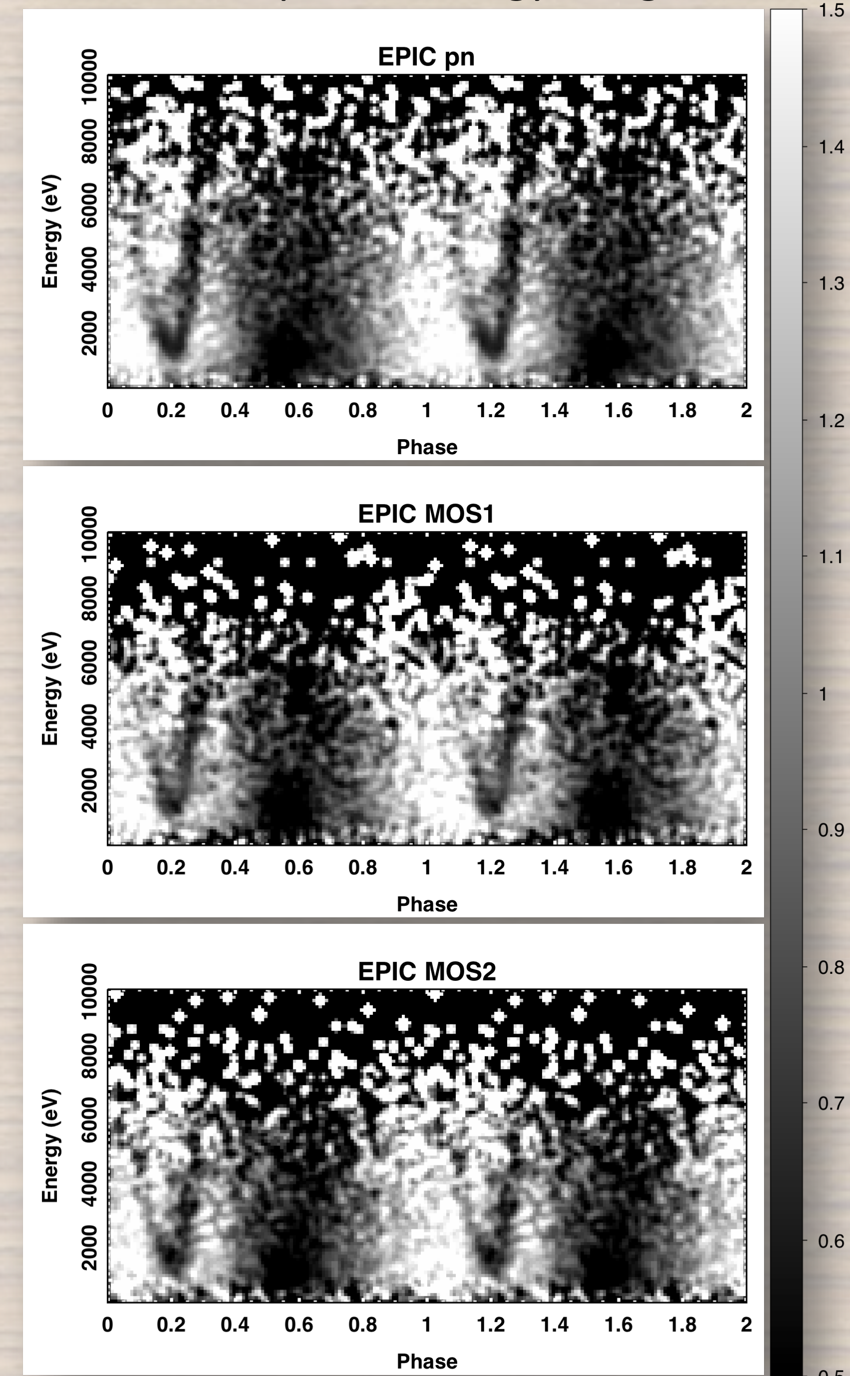
XMM-Newton/EPIC phase-energy image

Normalized to the phase-averaged spectrum AND the energy-integrated pulse profile

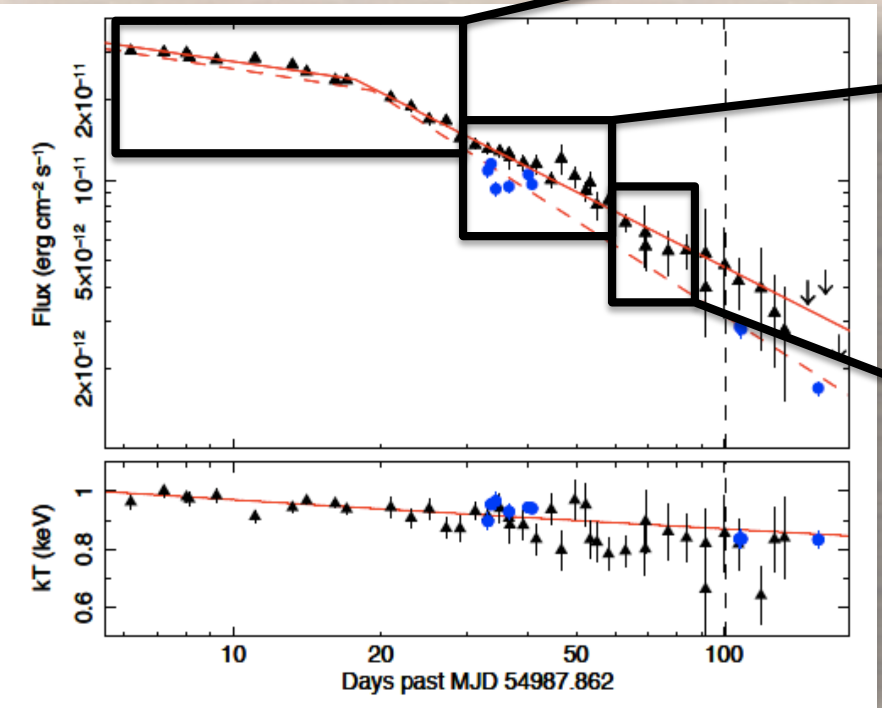


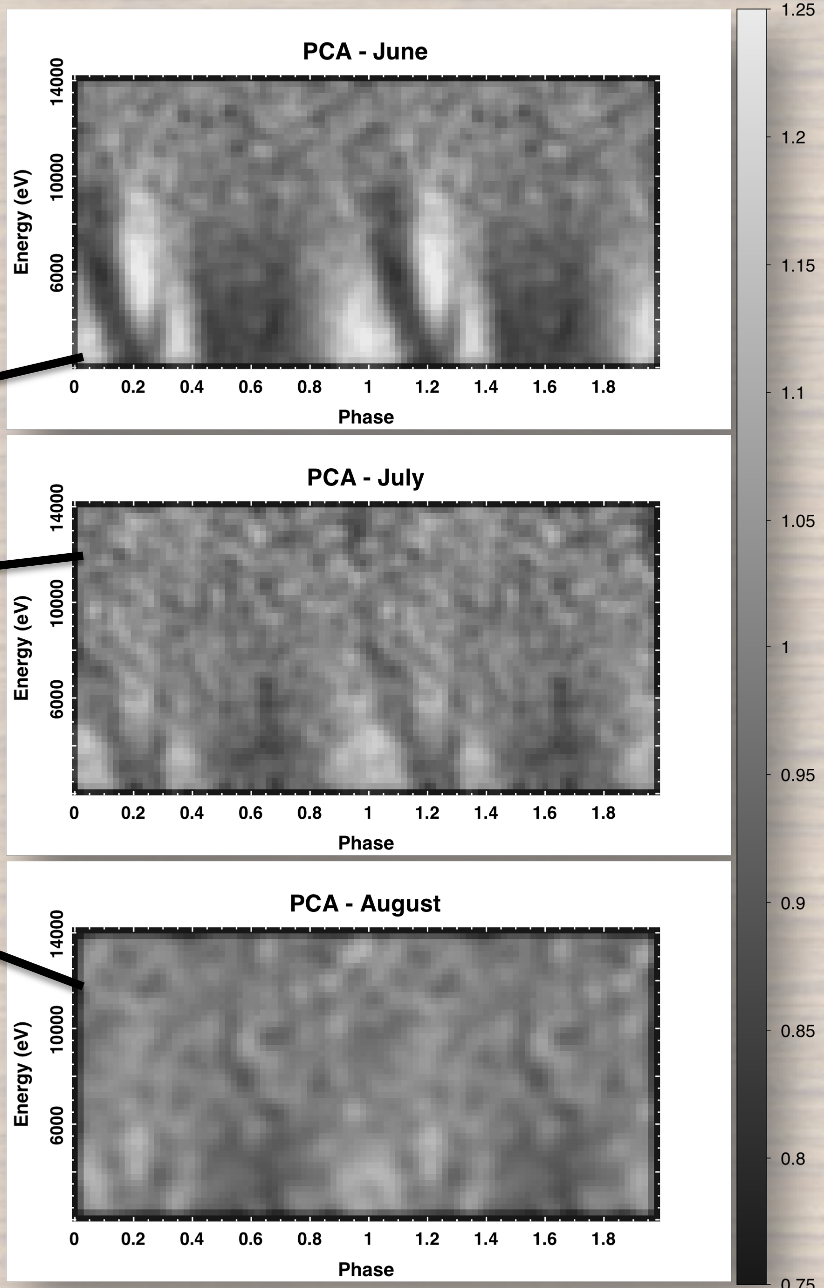
- Same behavior in PN, MOS1 and MOS2 data ⇒ not due to statistical fluctuations or instrumental effects

Normalized phase-energy images



- **Detected also in RXTE data!**
  - line visible up to ~10 keV
  - line was already present at the onset of the outburst





Remarkable feature with unique properties !

- High statistical significance

  (>> any other absorption line reported in isolated NS)

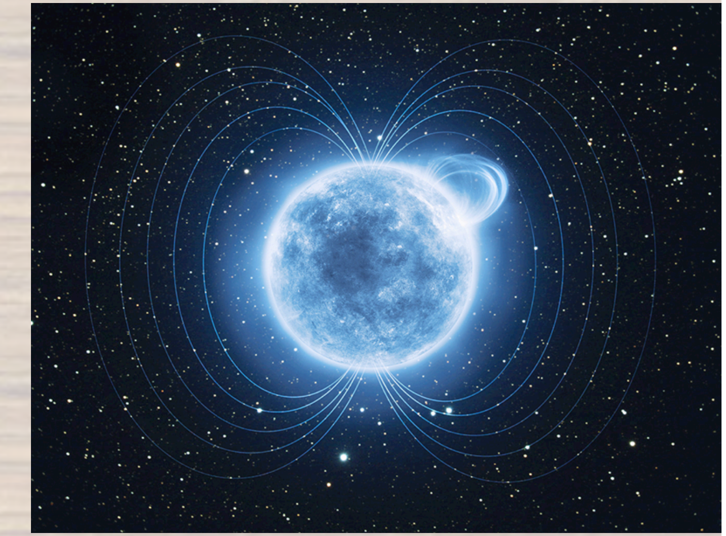
- More than factor 5 variation in line energy (range ~1- 5 keV) in ~1/10 of rotation phase

  never seen before for any NS X-ray line (e.g. cyclotron lines in accreting X-ray binaries)

- Persisted for ~ two months (at least)

We interprete it as a proton cyclotron line in a field of B ≈ (1-10) 10^{14} G

(to be compared to B ≈ 6 10^{12} G inferred from P and Pdot)



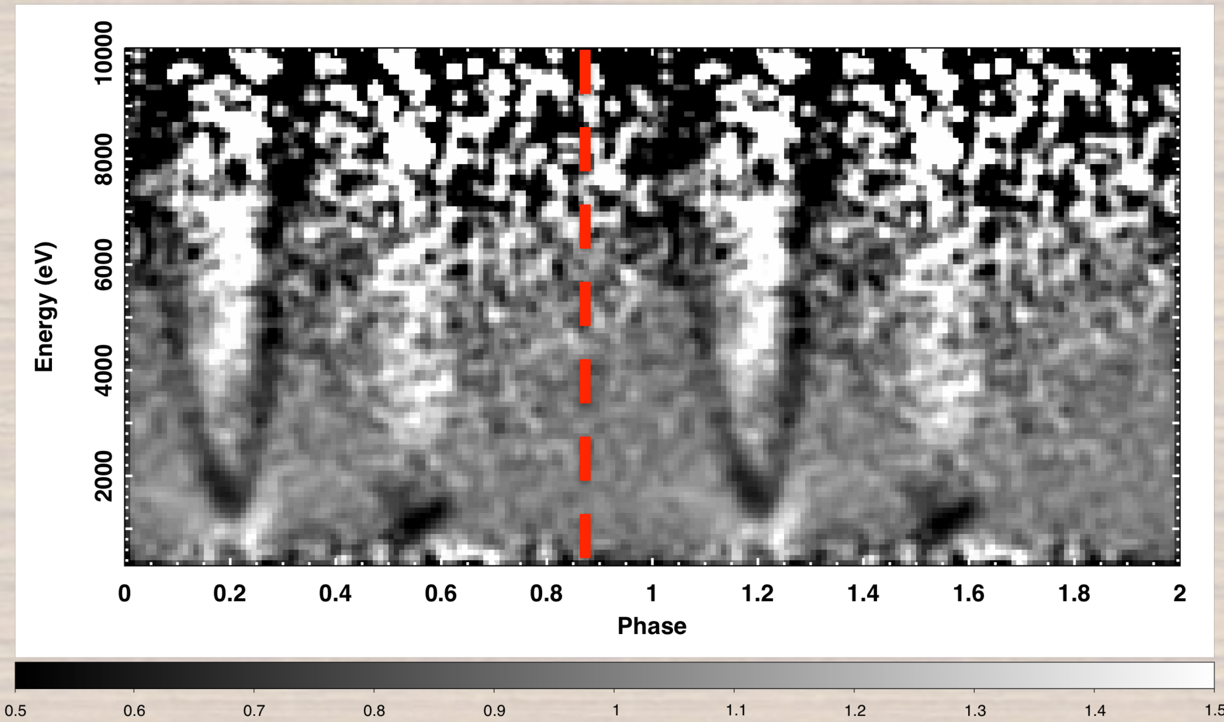
Interpretation within magnetar model

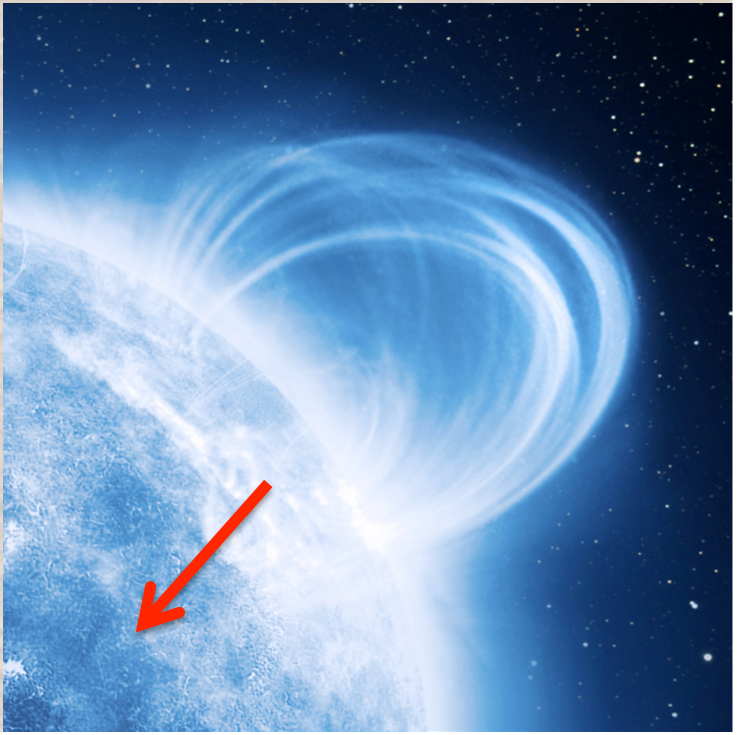
– **PROTON CYCLOTRON**:

- $E_{cycl,p}$= 0.6 B_{14} keV ⇒ **B ~ (2-20) x 10^{14} G** ⇒ **MAGNETAR** field
- We need a **STRONGLY VARIABLE B**, that might vary:
  - along the **SURFACE** (small-scale multipolar B components)

  OR

  ✓ along a **VERTICAL** plasma structure (coronal loop analogy; e.g., *Beloborodov & Thompson 2007; Masada et al. 2010*)





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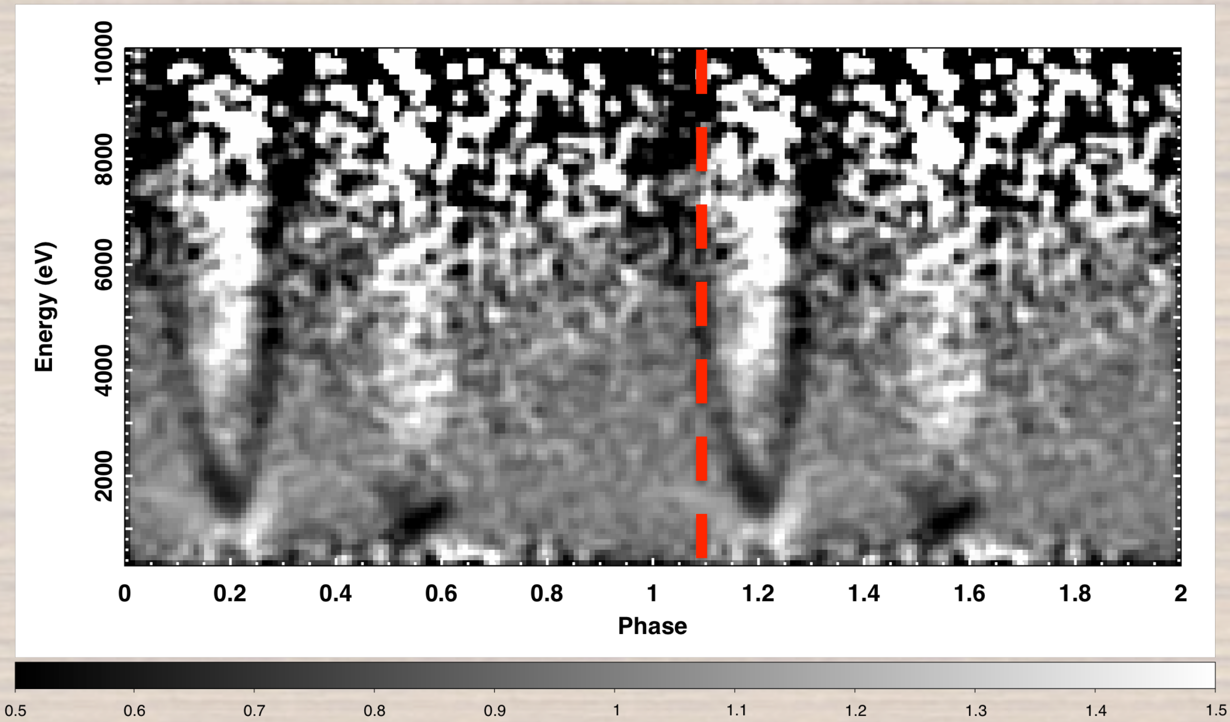

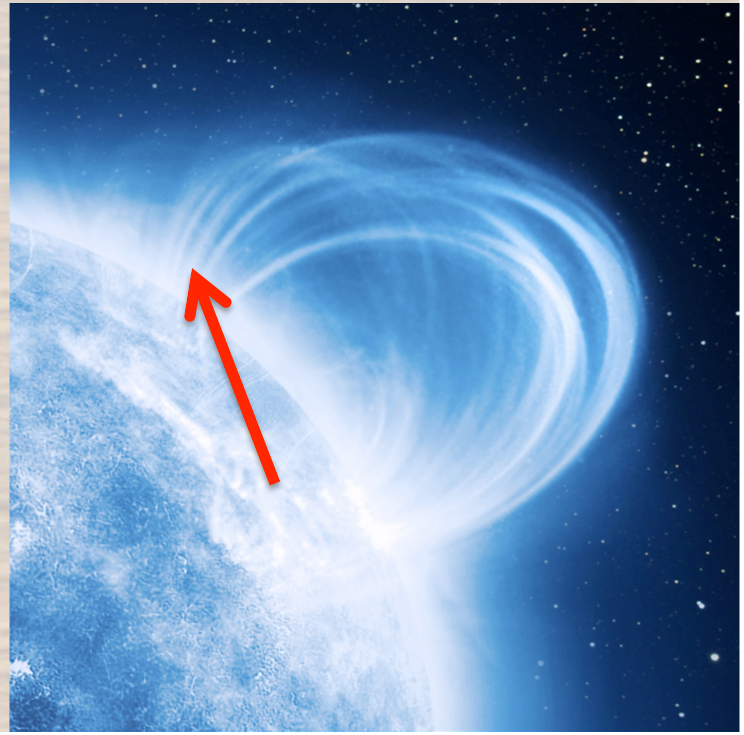

Interpretation within magnetar model

– **PROTON CYCLOTRON**:

- $E_{cycl,p}$= 0.6 B_{14} keV ⇒ **B ~ (2-20) x 10^{14} G** ⇒ **MAGNETAR** field
- We need a **STRONGLY VARIABLE B**, that might vary:
  - along the **SURFACE** (small-scale multipolar B components)

OR

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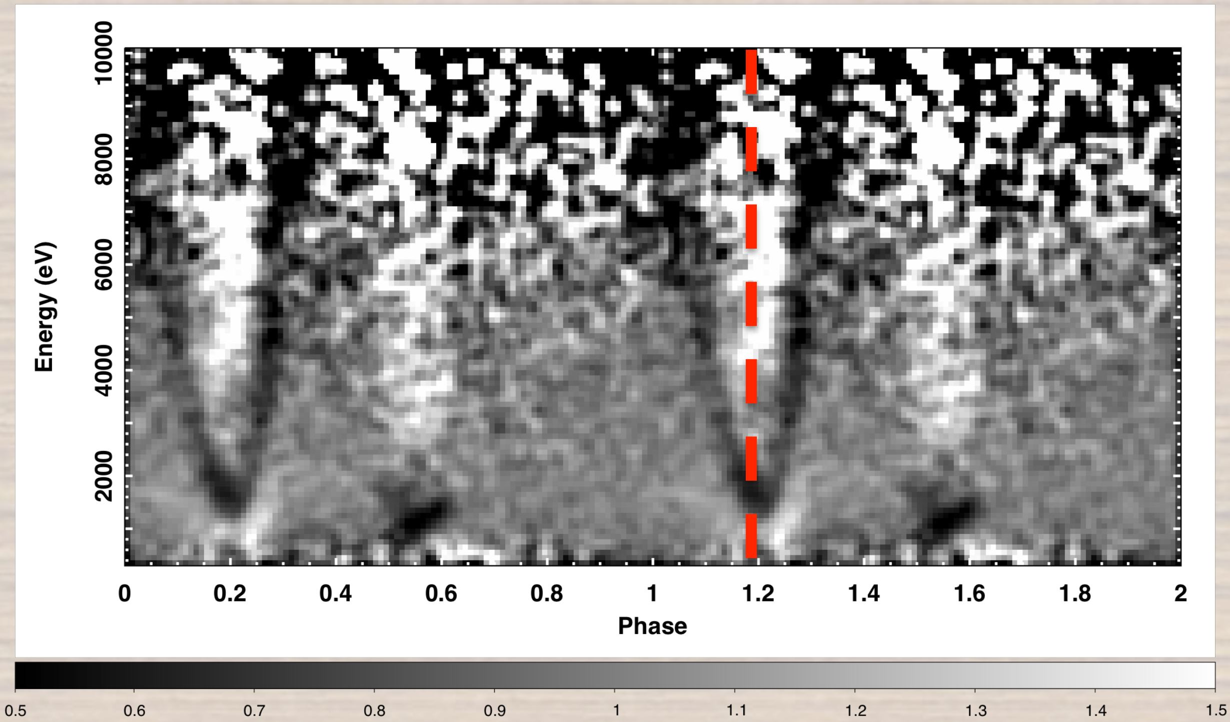

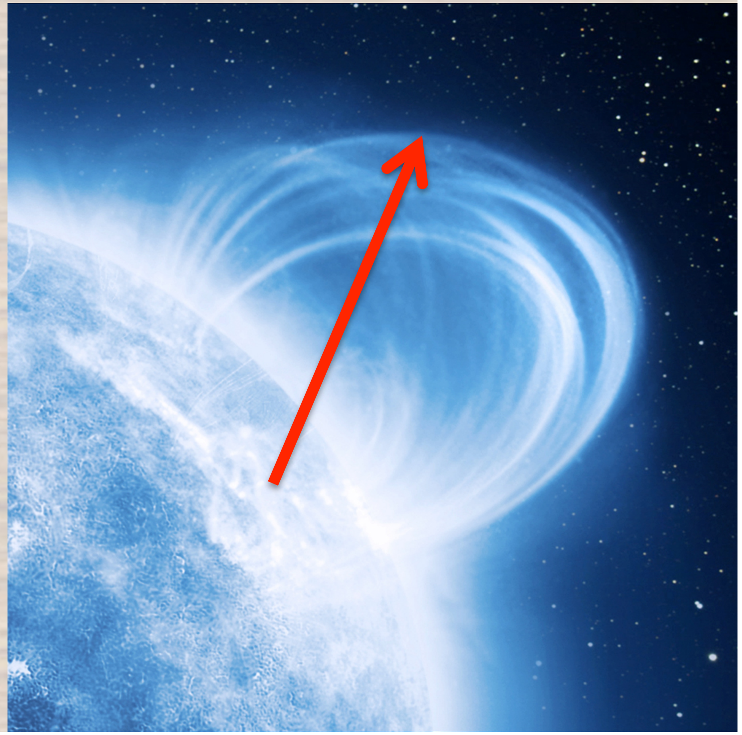

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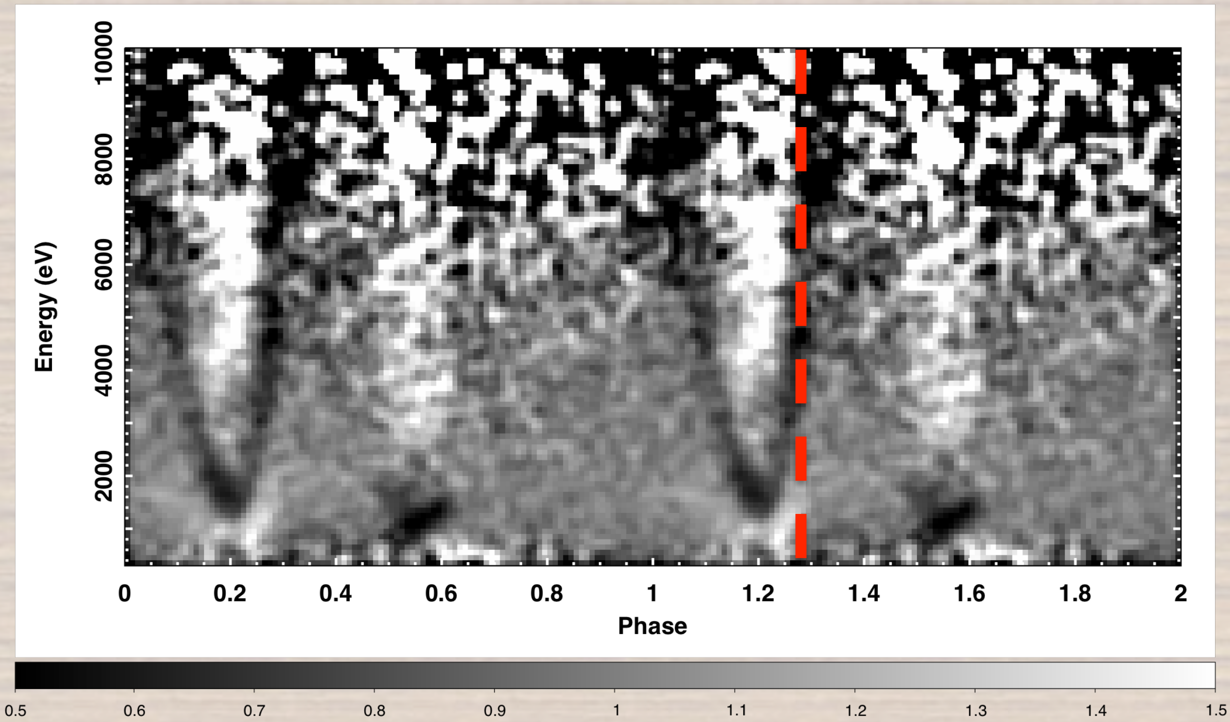
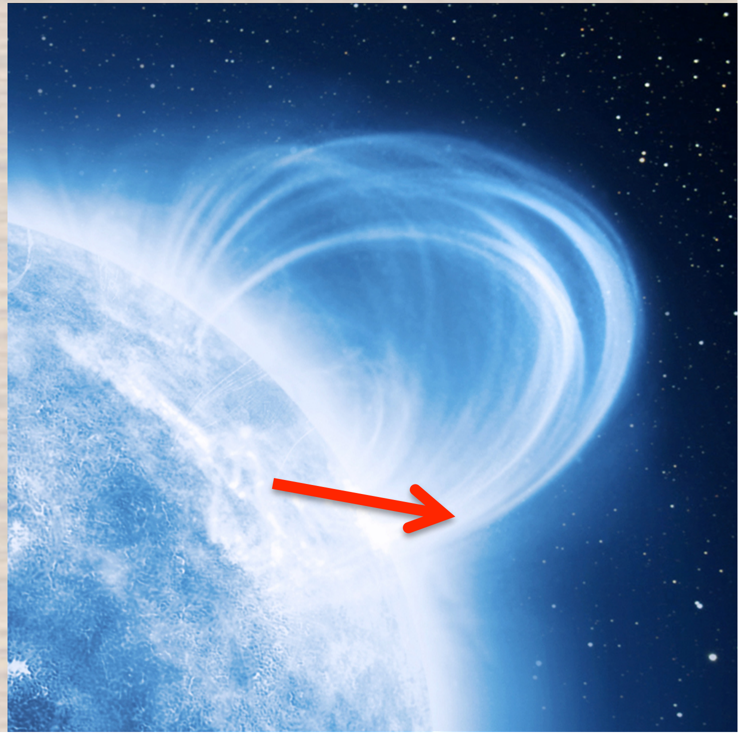
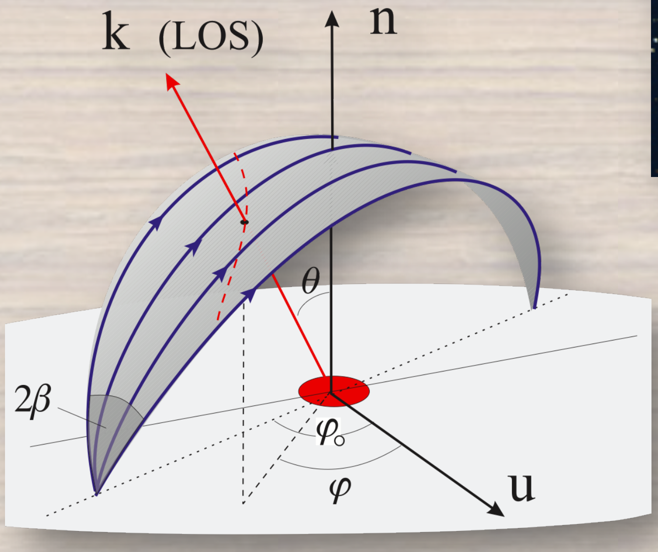
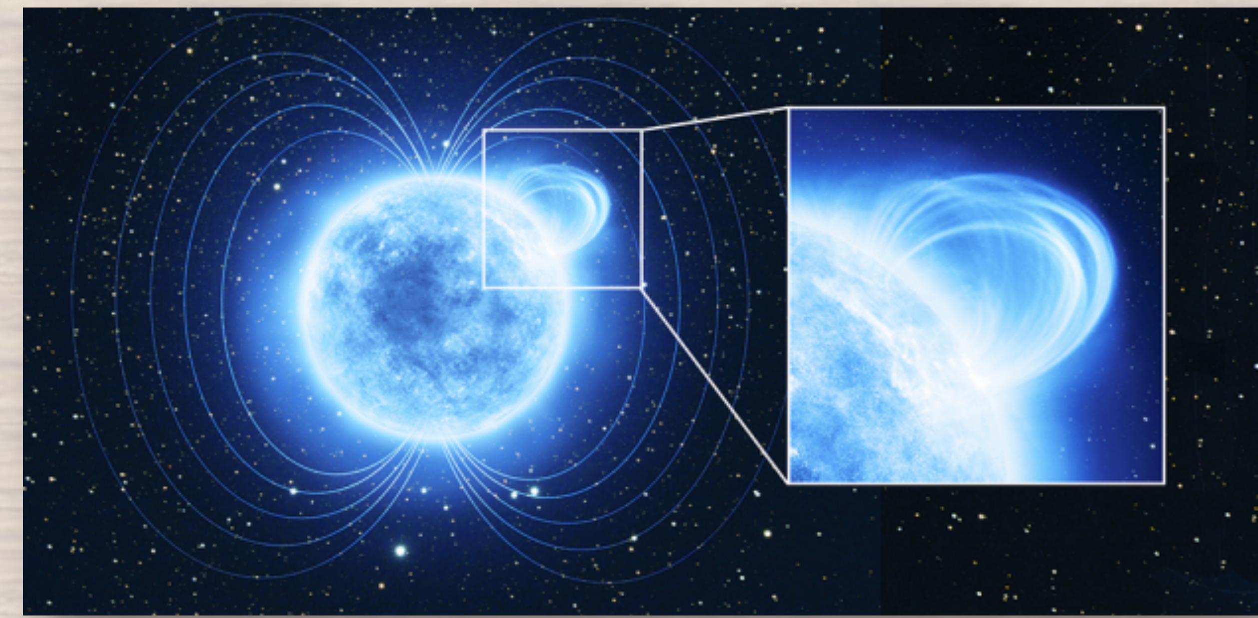




Absorption line at strongly phase-dependent energy in low-Pdot magnetar SGR 0418 (Tiengo+ 2013)





- cyclotron line from protons in small-scale loop with B from ≈2 10^{14} to ≈2 10^{15} G

  wrt dipolar field B≈6 10^{12} G (Rea+ 2013)

Conclusions

What really matters more for the “magnetar behavior” is the geometry (not the intensity) of the external magnetic field

The twisted magnetosphere results from the presence of a strong toroidal field in the neutron star interior

The phase-dependent absorption line in the “low-Pdot magnetar” SGR 0418 supports the presence high-B fields structures close to the NS surface

These are responsible for the “magnetar behavior” even if the dipole field is relatively small

Magnetar-like activity can be present in other classes of NSs