Recent Progress in Observations of Magnetars

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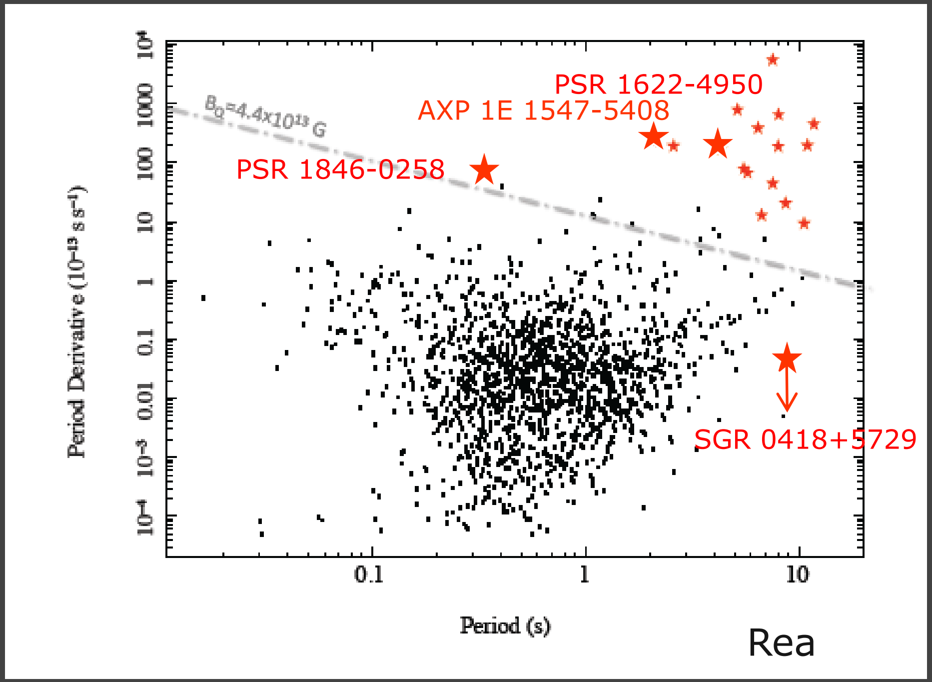
Outline of presentation

- Introduction
- New constraints from RXTE-HEXTE, INTEGRAL-IBIS and Fermi-GBM
- The January 2009 outburst of the "transient" AXP 1E1547.0-5408 / SGR J1550-5418: Evolution of timing and spectral characteristics over 27 months
- Summary

AXP / SGR	Hosts	P (s)	B (10^{14} G)	comments (O=opt, I=IR)
4U 0142+61		8.69	1.3	hard X-rays, O, I
RXS J1708-4009		10.99	4.7	hard X-rays
1E 1841-045	Kes 73	11.77	7.1	hard X-rays
1E 2259+586	CTB 109	6.98	0.5	transient/ hard X-rays, O, I
CXO J0100-72	in SMC	8.02	3.9	
1E 1048-5937		6.4	3.9	transient, O
1E 1547-5408/SGR1550-5418		2.0	2.2	outbursts/radio/ hard X-rays, I
XTE 1810-197		5.5	2.9	transient/radio, O
CXO 1647-4552	in Wes 1	10.61	1.3	outburst, radio
CXO 1714-3810	CTB 37B	3.82	4.8	
SGR 1900+14	OB	5.17	6.5	GF/ hard X-rays /outbursts
SGR 1806-20	OB	7.55	18	GF/ hard X-rays /outburst, I, QPO
SGR 0526-66	in LMC	8.05	7.3	GF
SGR 1627-41		2.59	2.2	outburst
SGR 0501+4516		5.76	2.0	outburst/ transient h**ard-X, O**
SGR 1833-0832		7.56	1.8	outburst
AX J1844-0258	G29.6+0.1	6.97	-	transient , candidate
SGR 0418+5729		9.08	<0.075	outburst
PSR 1622-4950		4.32	2.8	radio, extremely variable; X-ray quiet
(PSR J1846-0258	Kes 75	0.32	0.5	high B-field pulsar, radio quiet)

Challenges in magnetar studies over last decade

1st SGRs = AXPs = magnetars ?
(• Fall-back-disk scenario, e.g. Alpar 2001, Trümper et al. 2011
• Massive rotating WDs, Malheiro et al. 2011
• Quark stars, Xu 2007, Orsaria et al. 2010)



2nd timing characteristics like those of rotation-powered pulsars /radio pulsars ?

3rd Production mechanisms, scenario's of radio, IR, optical, soft X-ray, hard X-ray emissions in bursts, radiative outbursts, persistent emission ?

4th Connection with radio pulsar population ?

- SGR 0418+5729
- PSR 1622-4950
- PSR J1846-0258

Focus of this presentation: persistent soft and hard X-ray emission

Sources with persistent soft and hard X-ray emission:

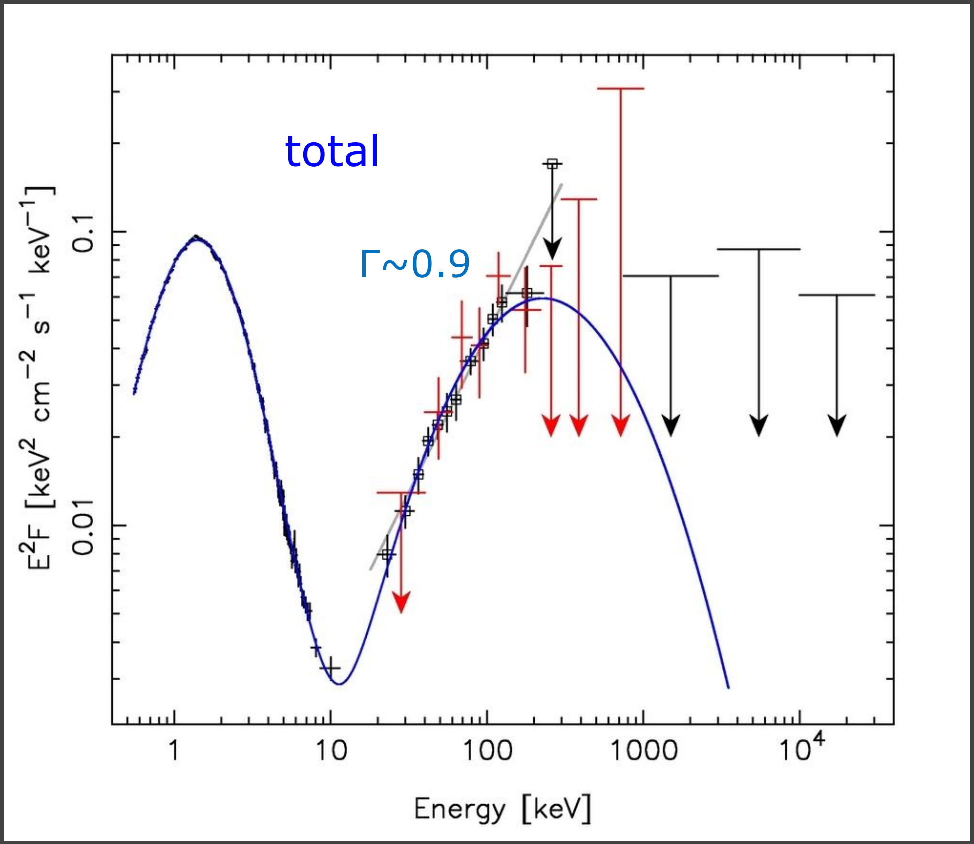
AXP 1E1841-045
AXP 1RXS J1708-4009
AXP 4U0142+614
AXP 1E1547.0-5408 (transient hard X-ray emission)
AXP 1E 2259+586

SGR 1900+14 (Götz et al. 2006)

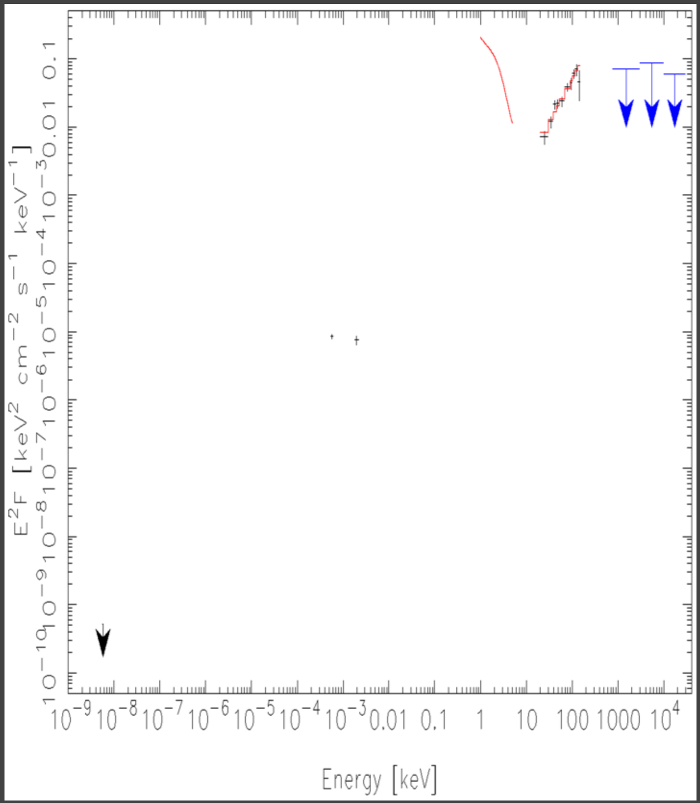
SGR 1806-20 (Mereghetti et al 2005; Molkov et al. 2005)
SGR 0501+4516 (transient hard X-ray emission)

Persistent X-ray emission: **two characteristic peaks in luminosity**,
each exceeding spin-down luminosity 1-3 orders of magnitude

AXP 4U 0142+61



den Hartog, Kuiper, Hermsen et al. 2008

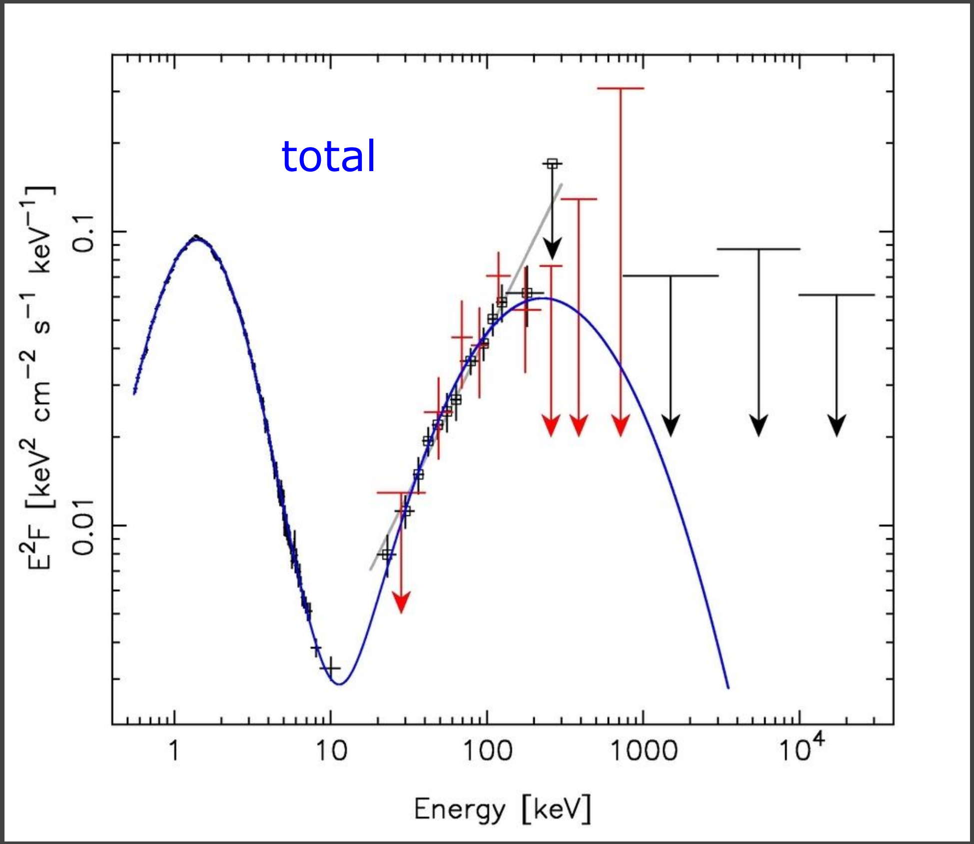


den Hartog et al. 2007

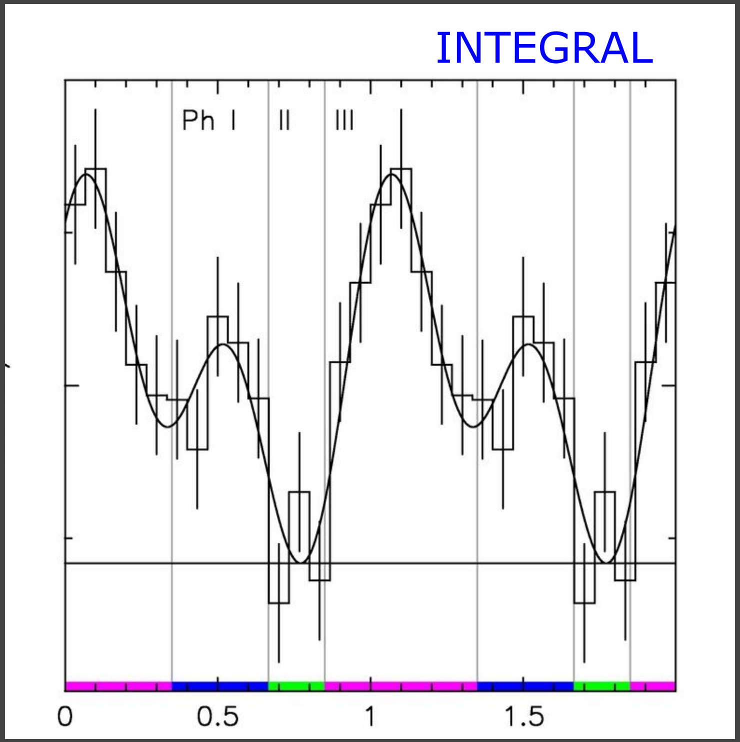
Non-thermal persistent emission above 10 keV discovered with INTEGRAL

Persistent X-ray emission: **two characteristic peaks in luminosity,**
pulsed component up to the highest energies

AXP 4U 0142+61



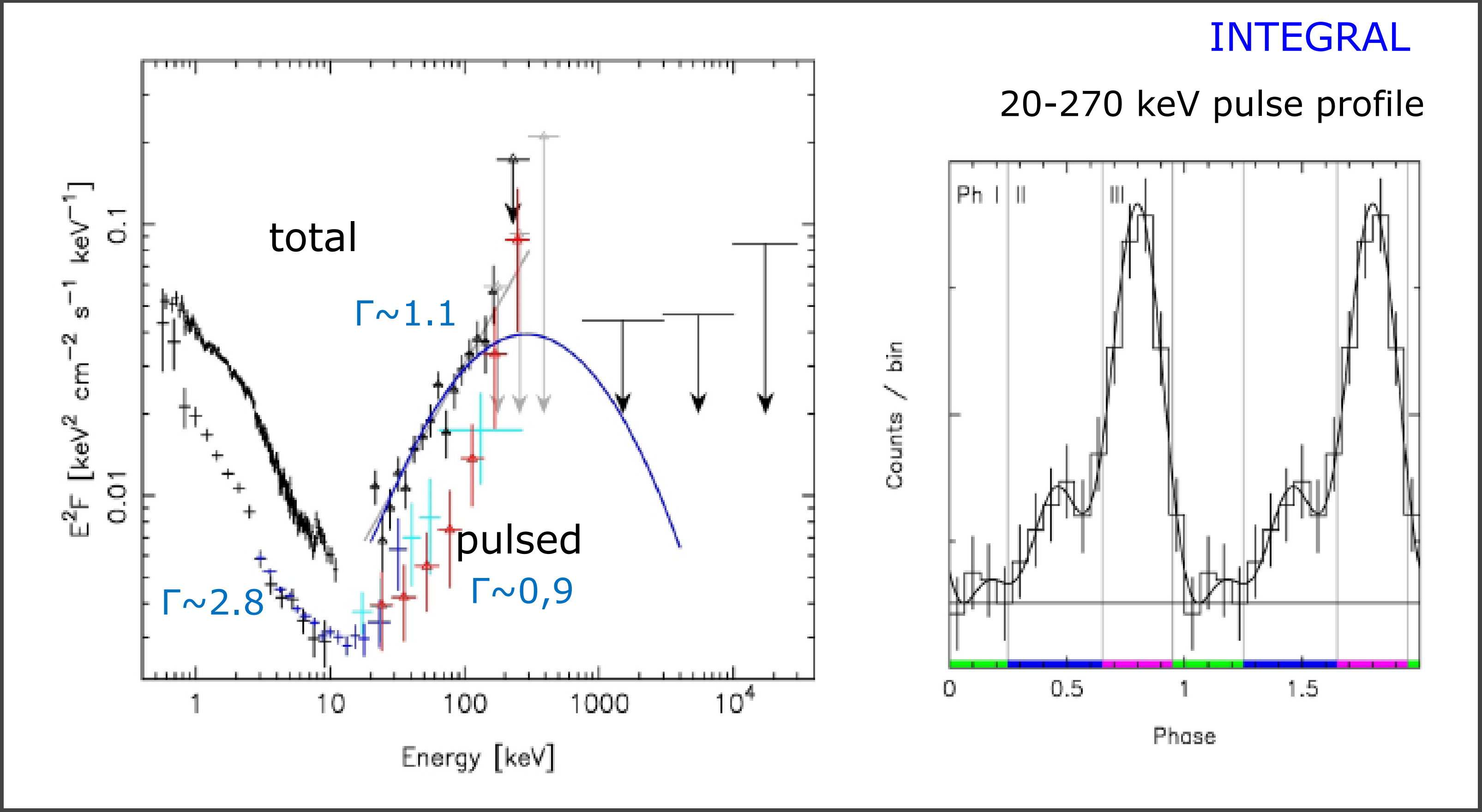
20-160 keV pulse profile



Den Hartog, Kuiper, Hermsen et al. 2008

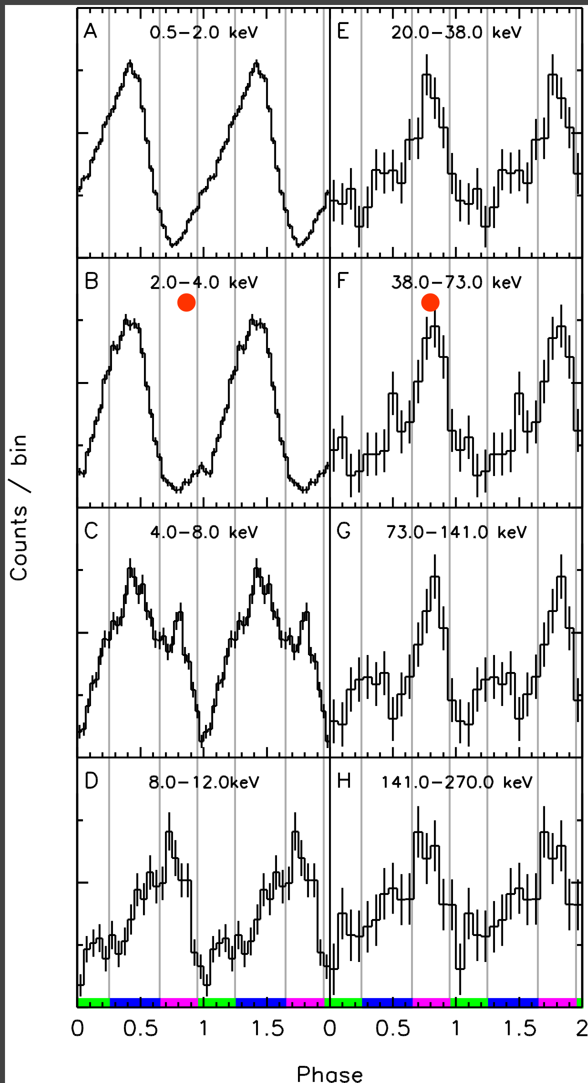
Persistent non-thermal emission

AXP 1RXS J170849-400910

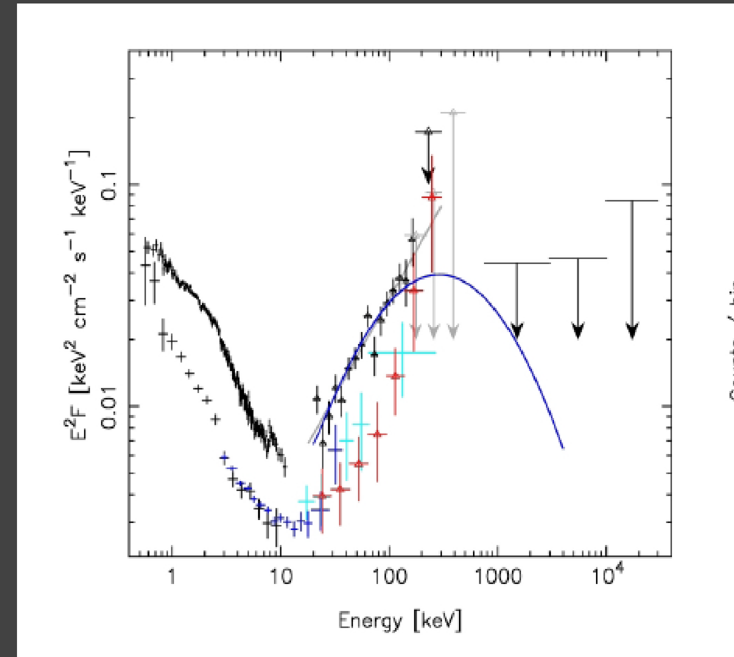


den Hartog, Kuiper, Hermsen 2008

AXP 1RXS J170849-400910



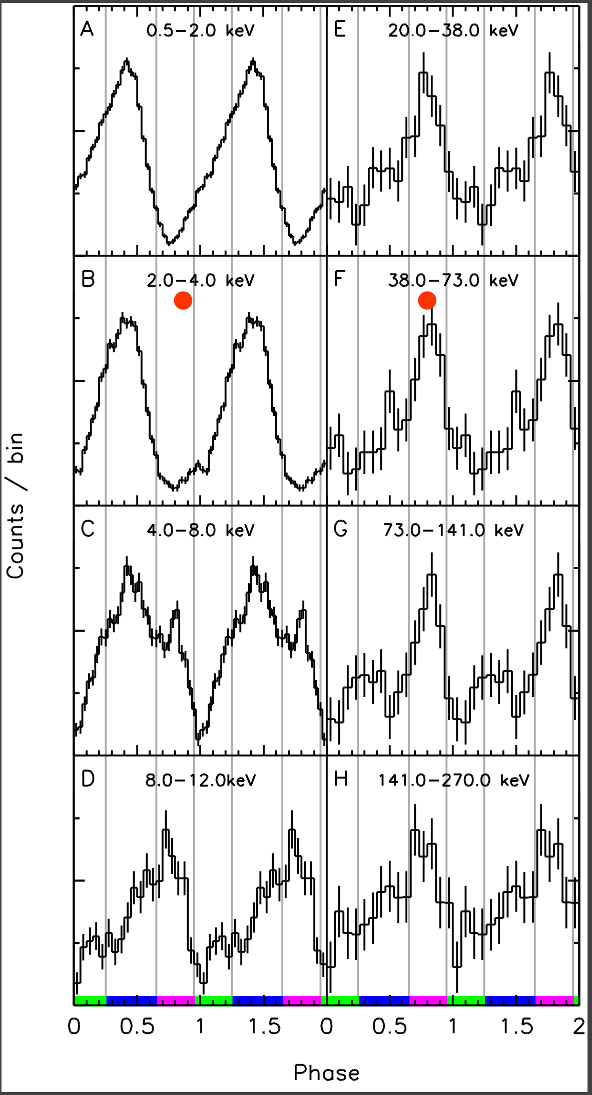
XMM-Newton
&
INTEGRAL

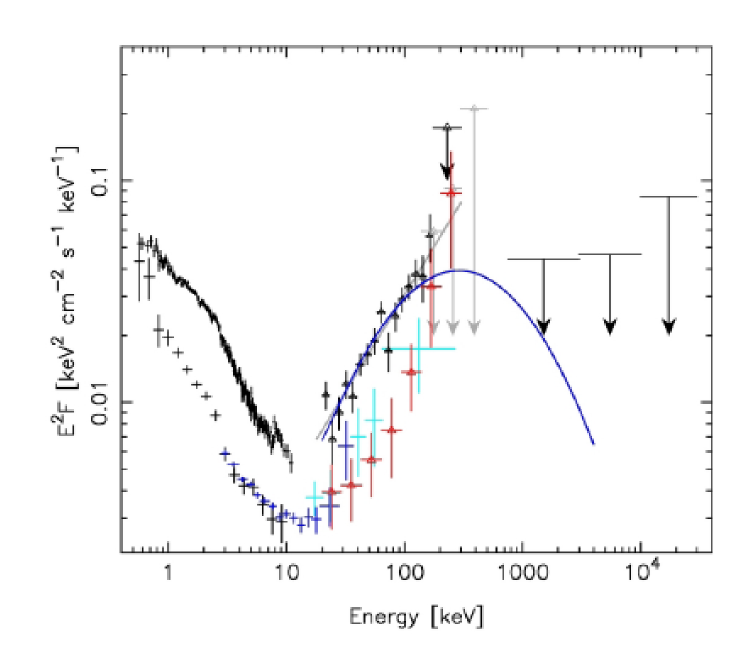


Persistent soft pulse and hard pulse separated in pulse phase:

➡ Different components produced in different sites of the magnetosphere with energy source being the high B field.

AXP 1RXS J170849-400910





Persistent emission below ~10 keV)

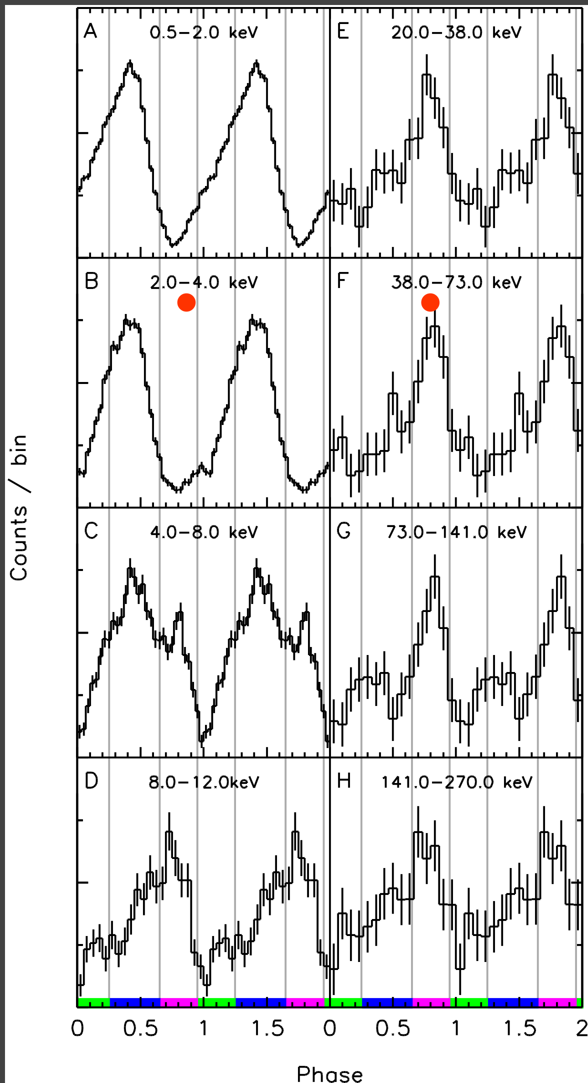
- BB (kT~0.3-0.6 keV + power law index ~2-4) or
- two BBs (kT_1~0.3 keV, kT_2 ~0.6 keV)

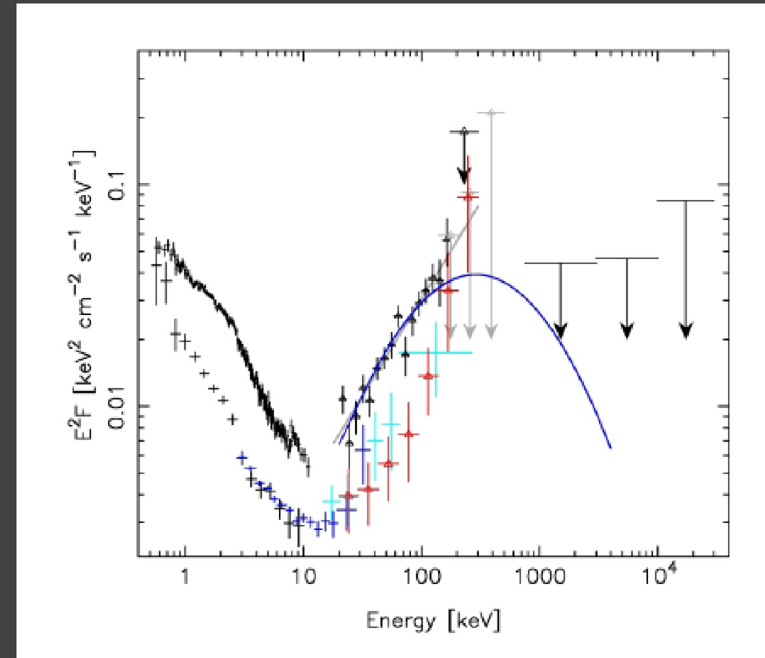
  e.g. Rea et al. 2007; Güver et al. 2007, 2008

- Resonant cyclotron scattering

  e.g. Thompson, Lyutikov & Kulkarni, 2002
  Lyutikov & Gavrill, 2006
  Fernandez & Thompson, 2007
  Rea et al. 2008
  Nobili et al. 2008
  Zane et al. 2009,2010

AXP 1RXS J170849-400910



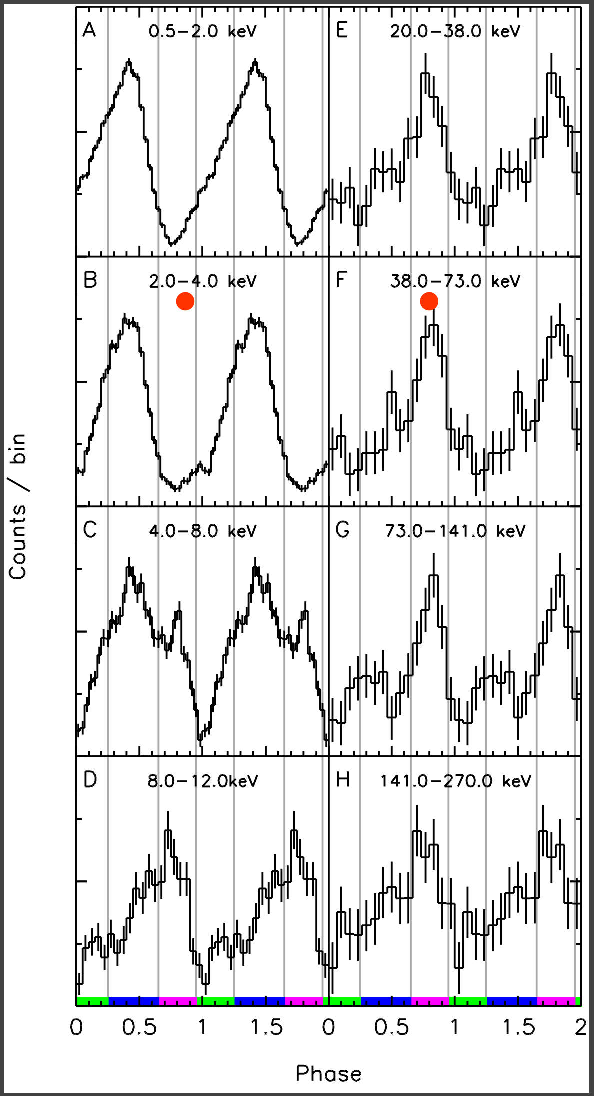


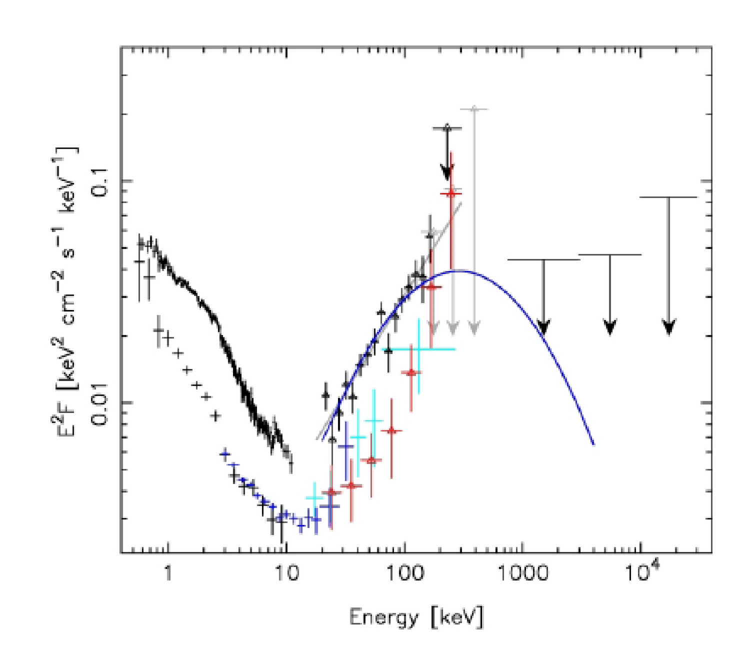
Persistent non-thermal emission above ~20 keV:

From RXTE, INTEGRAL, Swift, Suxaku observations spanning more than 10 years

- Stable (pulsed) flux over > 10 year within ~20%
- Stable (in shape and phase) pulse profile over > 10 year

AXP 1RXS J170849-400910





For persistent non-thermal emission above ~20 keV:

NO AGREED physical model (scenario) yet !

Recent attempts:

- Bahring & Harding (2007); resonant magnetic Compton upscattering
- Beloborodov & Thompson 2007, Beloborodov, 2009; acceleration in a twisted corona
- Pavan et al. 2009; multipolar force-free magnetospheres
- Trümper et al. 2010; accretion from a fall-back disk

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New developments (1)

- Increased statistics on the time-averaged pulse profiles and spectra for RXTE-HEXTE and INTEGRAL-IBIS

(Kuiper, Ter Beek, Hermsen, 2011, in prep.)

Example: RXTE HEXTE and INTEGRAL ISGRI update for 4U0142+614

4U 0142+614

HEXTE exposure increase since Kuiper et al. (2006)

103.6 ks → 515.9 ks

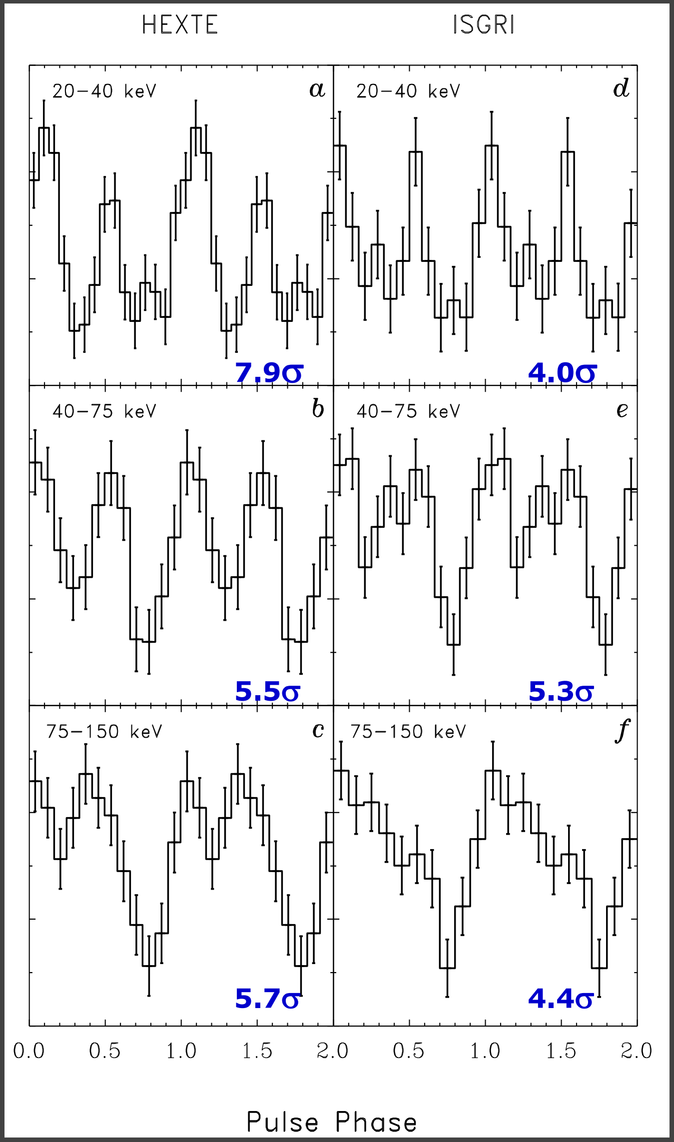
20-50 keV: 3.4σ
50-100 keV: 2.1σ

Now,

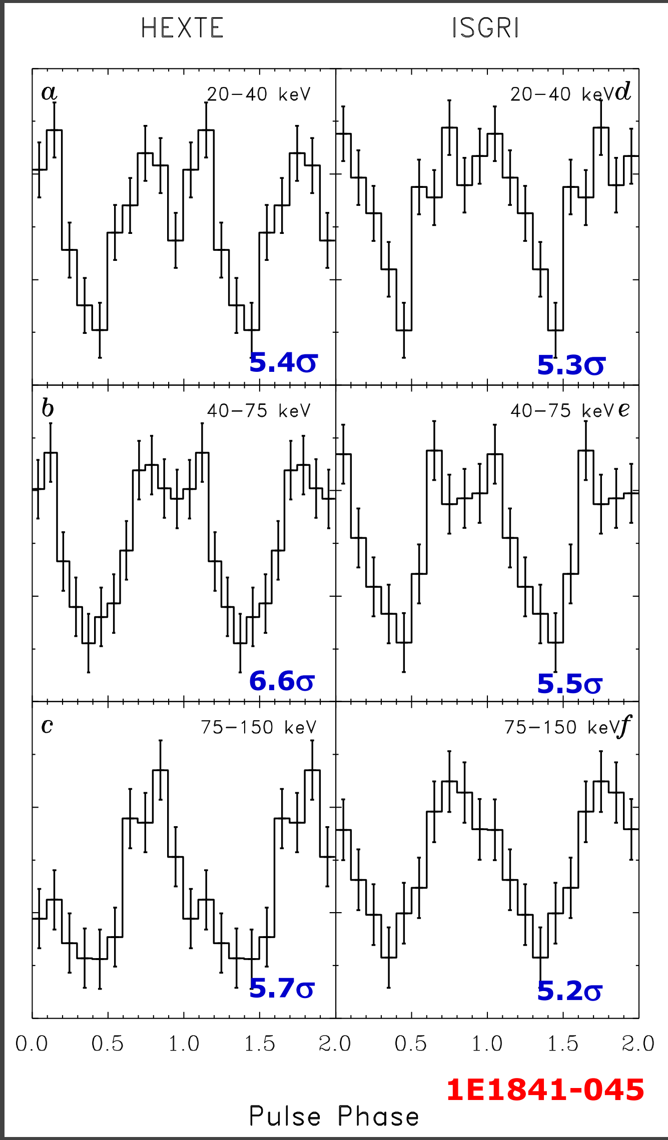
20-40 keV: 7.9σ

ISGRI exposure increase only moderately since den Hartog et al. (2008)

2.1 Ms → 3.2 Ms



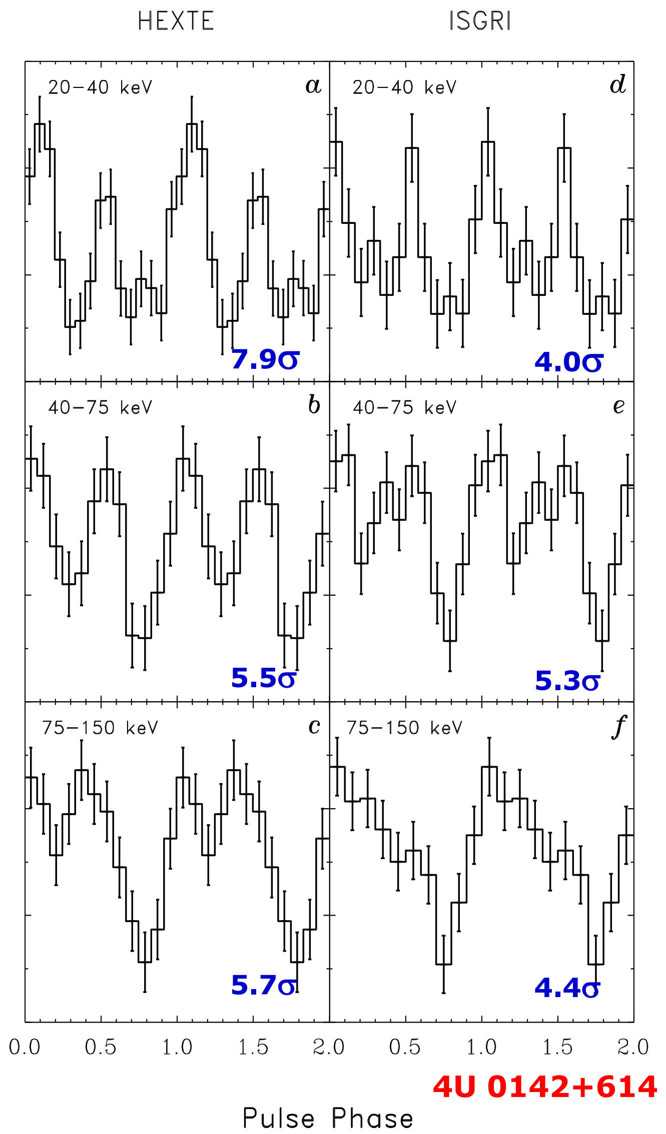
RXTE HEXTE and INTEGRAL ISGRI updates for 1E1841-045 and 4U0142+614



Multi-years profiles (~10 yrs average)

Pulses in stable phase intervals

Be careful in interpreting variations in shape
(low statistics!)



New developments (2)

- First results from 2.3 years of FERMI-GBM monitoring

(Kuiper, Ter Beek, Hermsen, 2011, in prep.)

Fermi GBM data selection and analysis

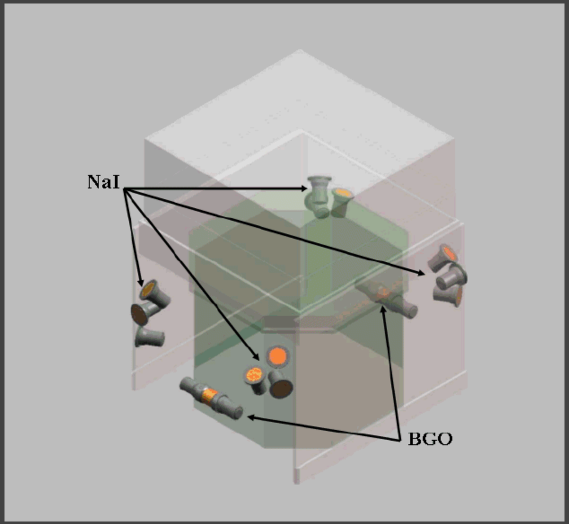
- Timing Analysis for those AXPs with established HE-emission and with valid contemporaneous phase-coherent timing solutions (RXTE monitoring): 1E1841-045, 4U 0141+614, 1RXS J1708-4009 and 1E1547.0-5408

- Only CTIME data (256 ms; 8 energy channels, 8 -2000 keV) from 12 NaI detectors are used → source angle selections

- Remove short-duration events like bursts/flares

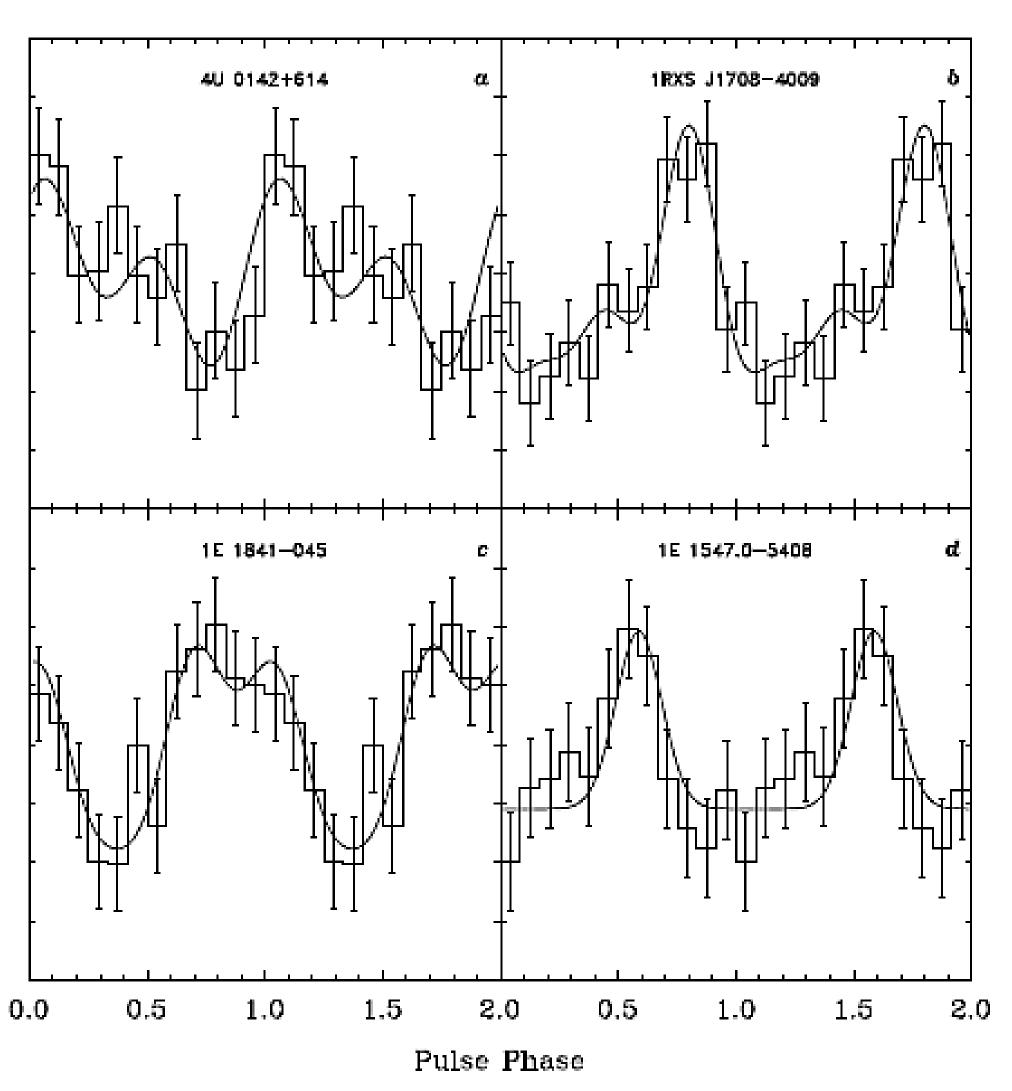
- Optimise event selections

- Phase folding of selected bary-centered count-rate data on proper timing model (Aug. 2008 – Dec. 2010; 2.3 y)



Source	Start [MJD]	End [MJD]	Screened exposure (Ms)
4U 0142+614	54690	55496	41.686
1RXS J1708-4009	54690	55516	40.505
1E 1841-045	54690	55524	51.106
1E 1547.0-5408	54855	54890	1.5673

Fermi GBM results on AXPs: data accumulated over 2.3 years



GBM pulse-profiles: Sum of channels 2-4
~27-300 keV

Curves are fits to the INTEGRAL profiles in the corresponding energy window ~27-300 keV

Consistent stable (!) profiles

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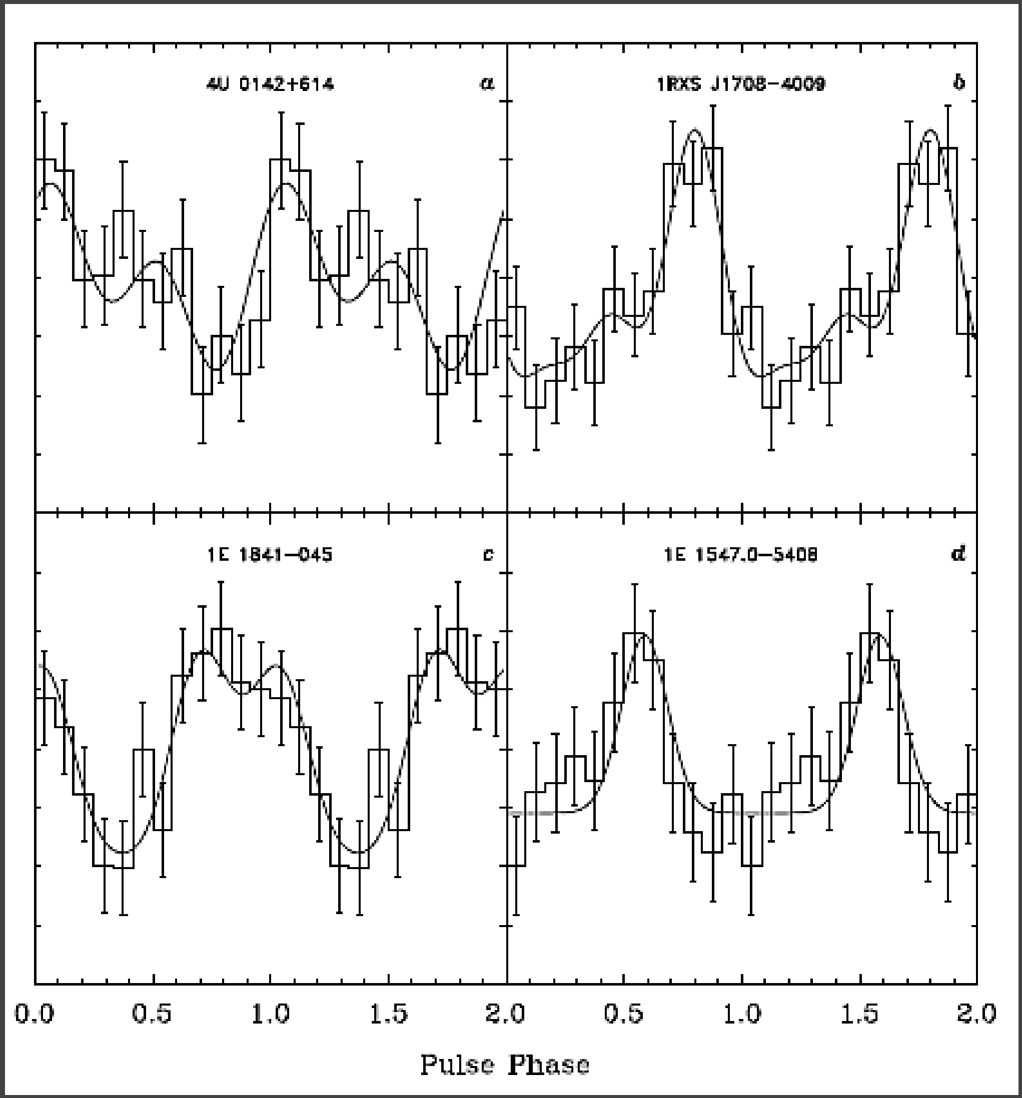
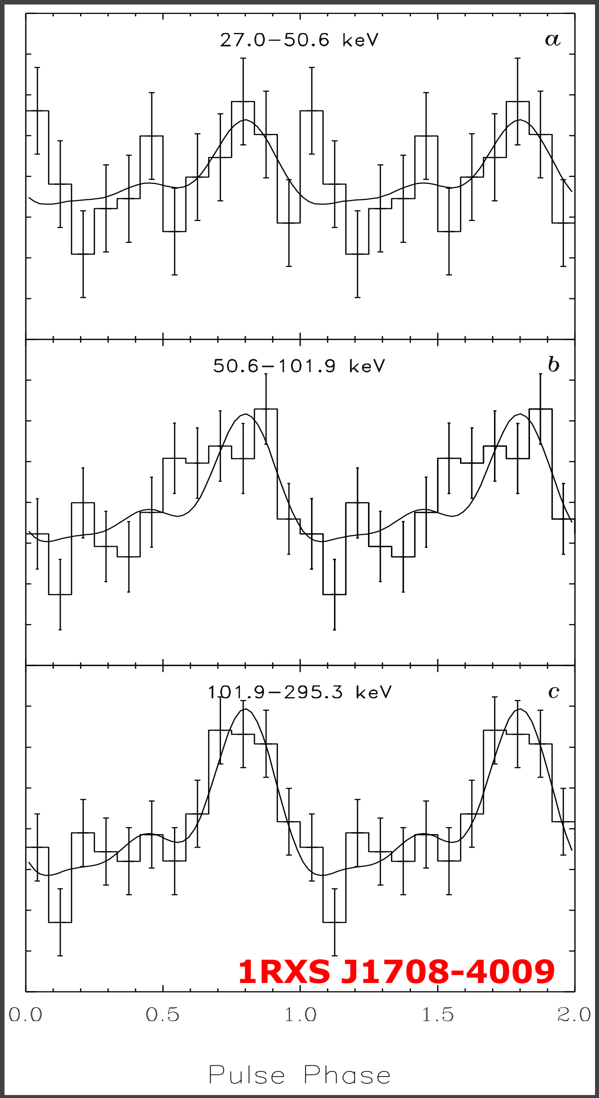
Fermi GBM results on AXPs: data accumulated over 2.3 years





GBM pulse-profiles: Sum of channels 2-4
~27-300 keV

From ① the extracted pulsed count rates per energy channel and ② the angular averaged response information

⇓

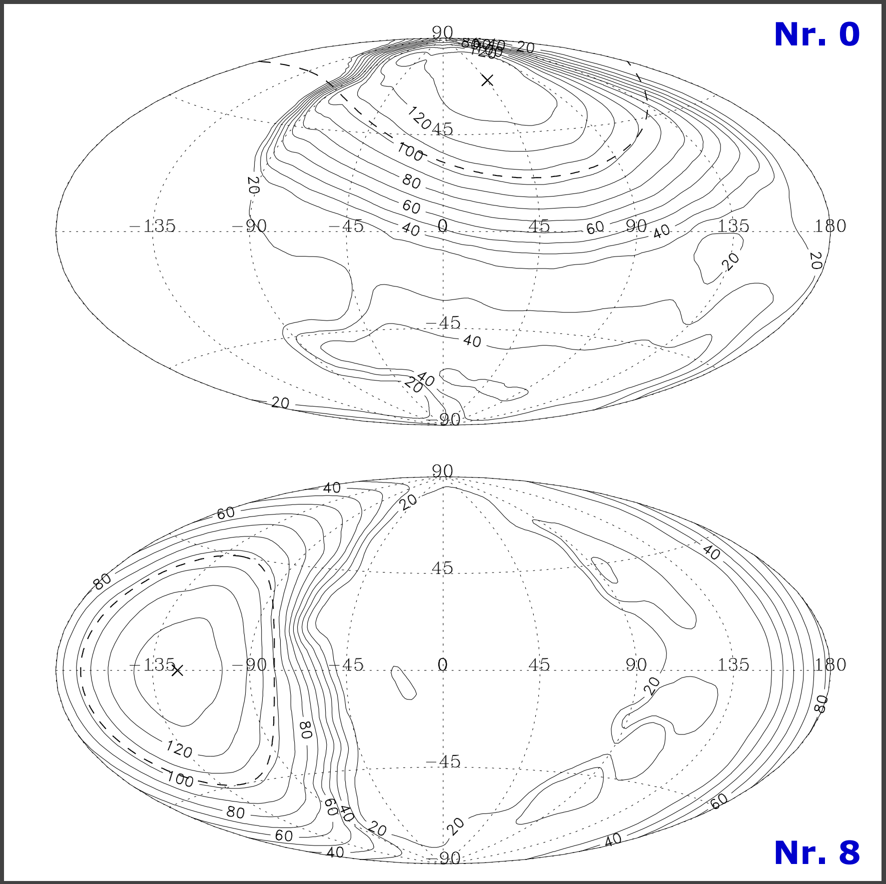
the photon spectrum can be reconstructed adopting certain model shape

Power-law:

$$F(E) = F_0 \cdot (E/E_0)^{\alpha}$$

Power-law with super-exponential cutoff

$$F(E) = F_0 \cdot (E/E_0)^{\alpha} \cdot \exp(-(E/E_c)^2)$$



Simulated instrument response for NaI detectors 0 and 8 (Kippen et al. 2007)

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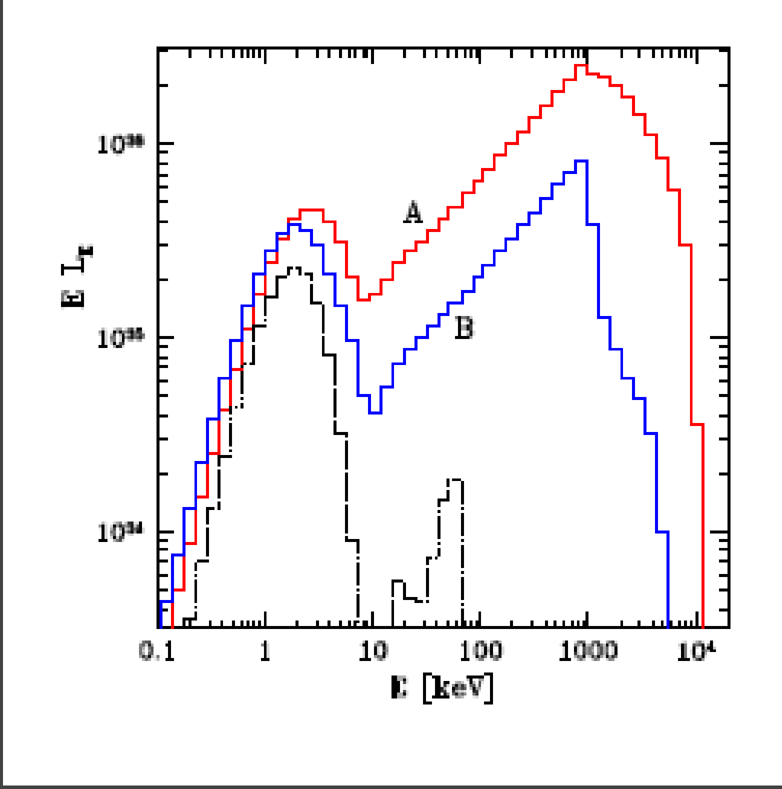
A. Beloborodov (2010)

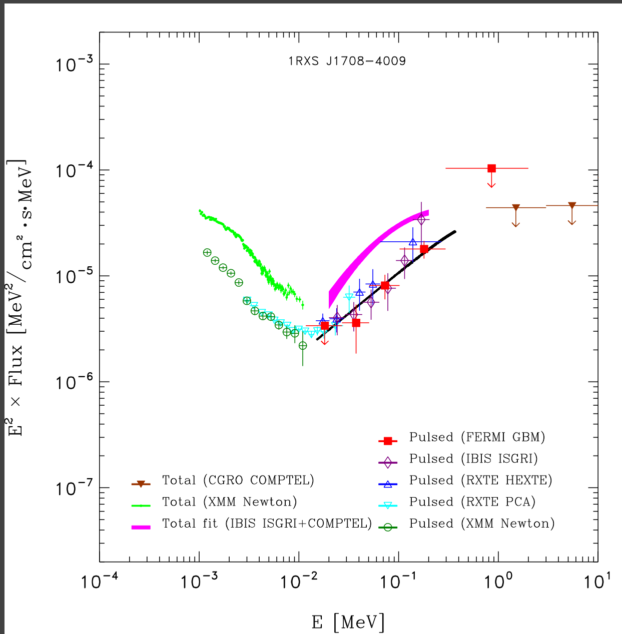
Power-law with
super-exponential cutoff

$$F(E) = F_0 \cdot (E/E_0)^{\alpha} \cdot \exp(-(E/E_c)^2)$$

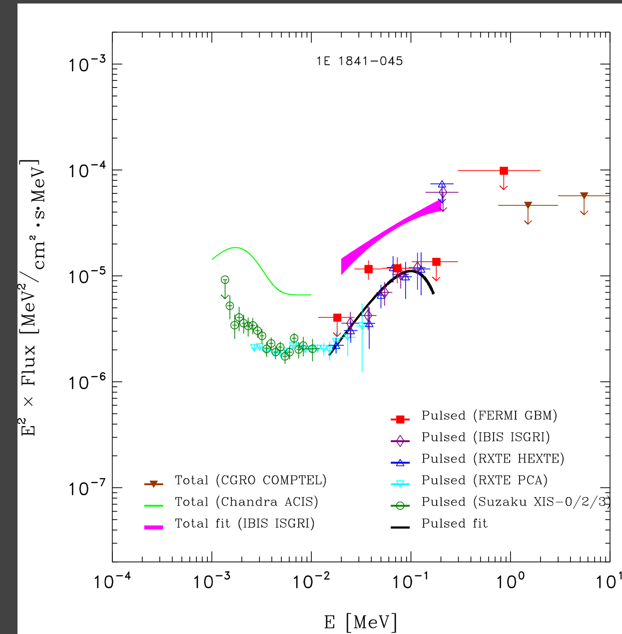
is approximation to model spectrum B



Total and Pulsed high-energy spectra of persistent AXPs



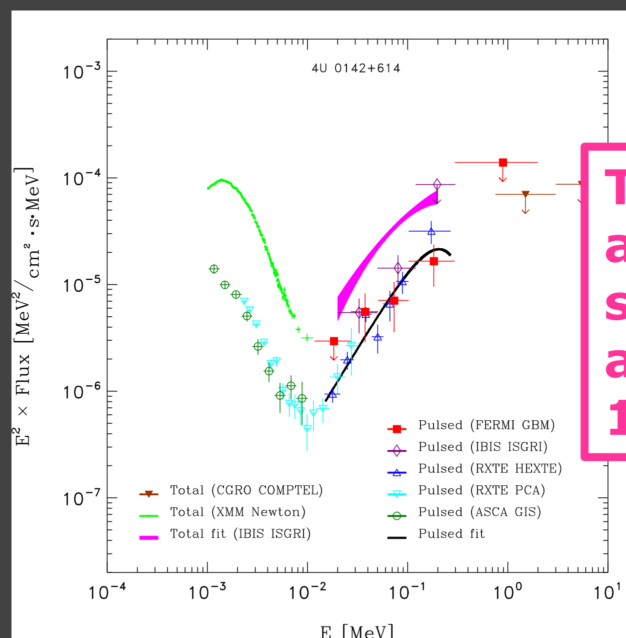
Power-law fit to pulsed spectra above 10 keV acceptable?



No break required (yet)

Break required

$$F(E) = F_0 \cdot (E/E_0)^{\alpha}$$



Total and pulsed spectra above 10 keV look now similar; pulsed fraction about constant up to 100 keV

Break required

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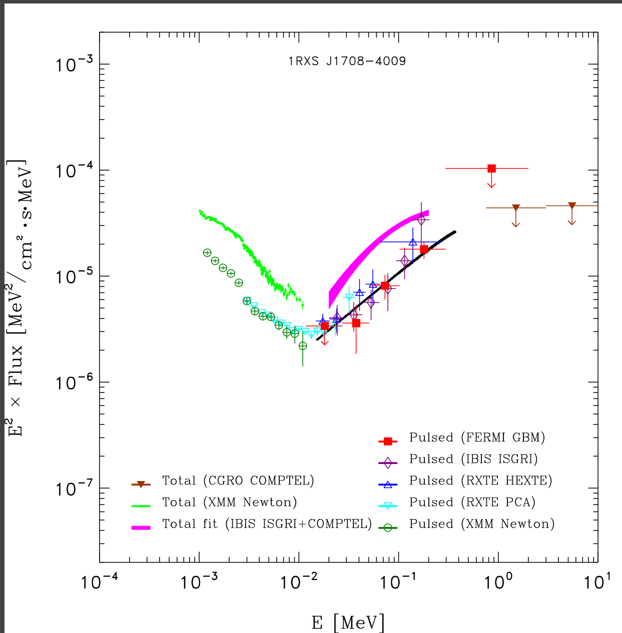
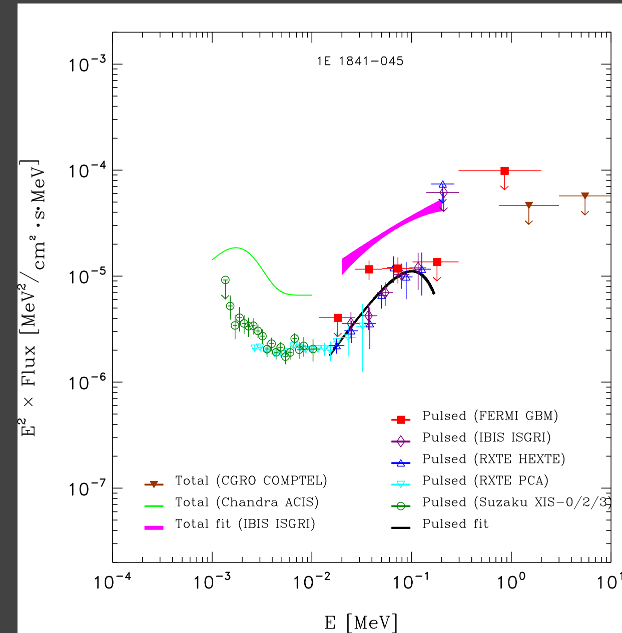
Total and Pulsed high-energy spectra of persistent AXPs

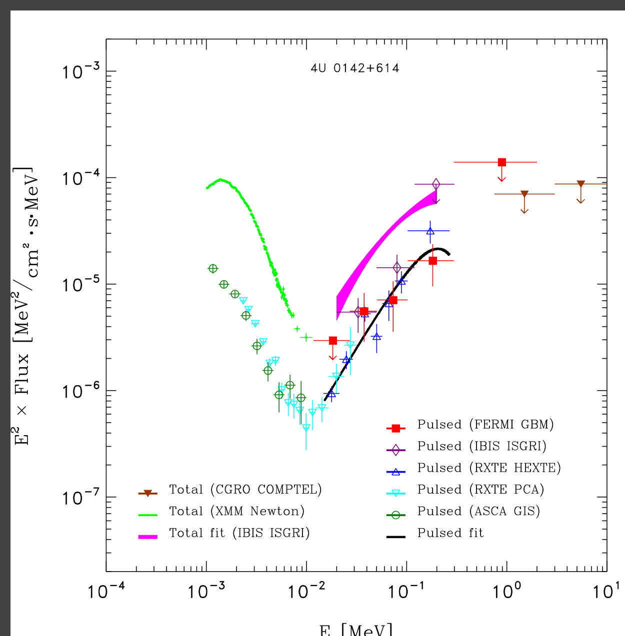


No break required (yet)
Lower limit: 429 keV



Break required at 125^{+26}_{-20} keV

$$F\,(E) = F_0 \cdot (E/E_0)^{\alpha} \cdot \exp(-(E/E_c)^2)$$



Break required at 231^{+64}_{-52} keV

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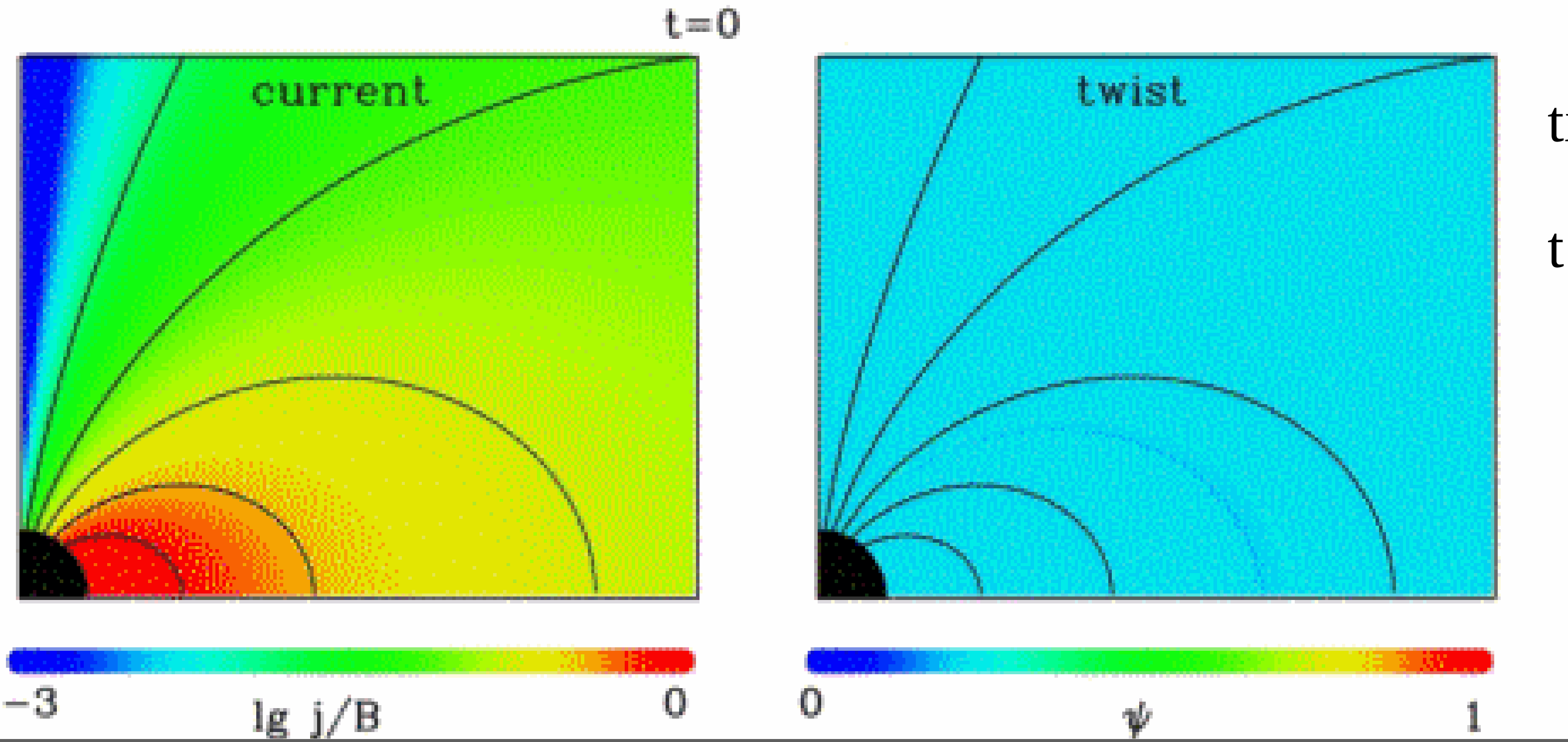


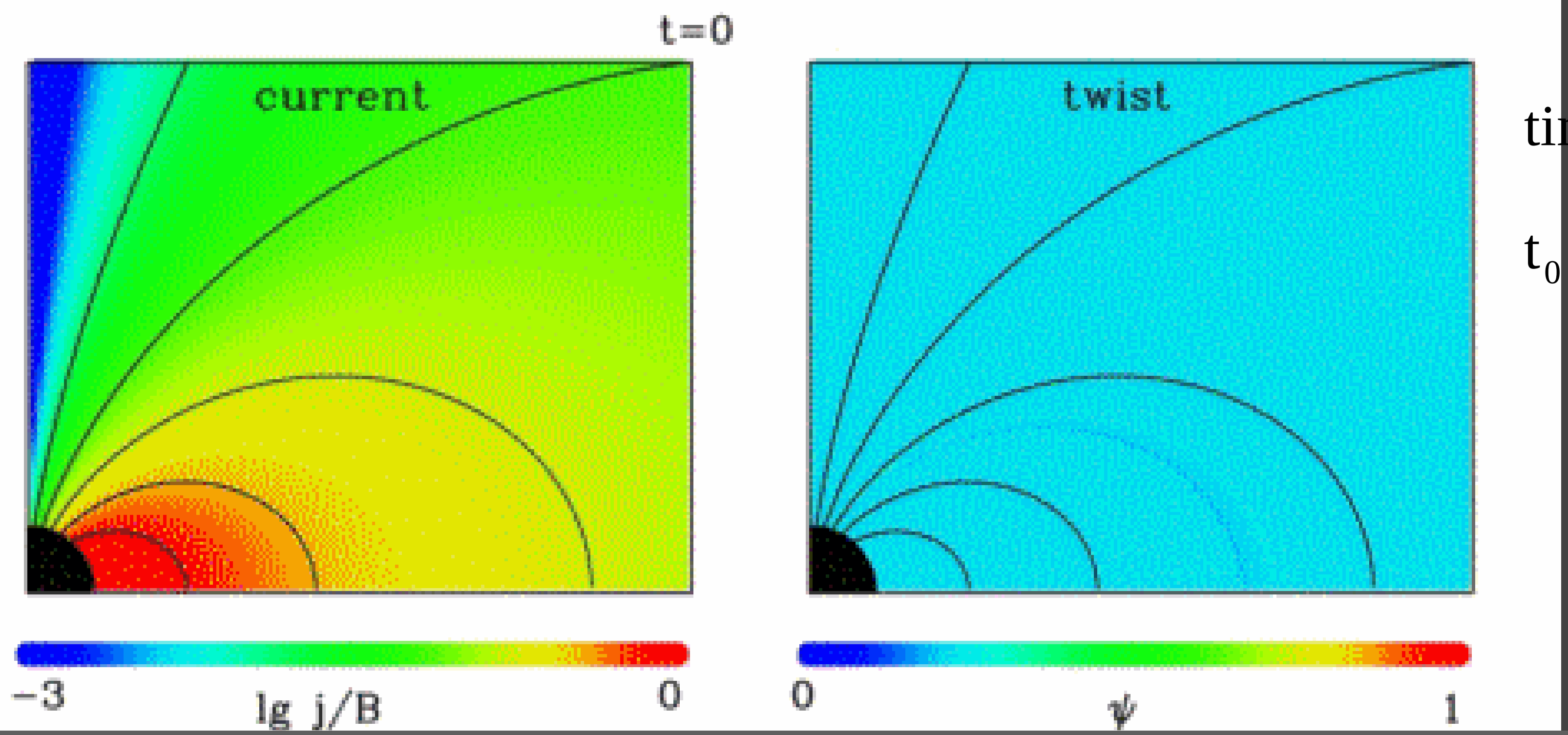
time units:

$$t_0 = \frac{\mu}{cR\bar{V}}$$

Resistive untwisting magnetosphere after a star quake / glitch :
A growing cavity and a shrinking current-carrying bundle of field lines at the pole (“j-bundle”), becoming quasi stable;

Beloborodov, 2009

Prediction: (1) j-bundle produces a shrinking hot spot on the star
(2) A high-multiplicity e+- outflow forms in the j-bundle, producing nonthermal emission from radio to hard X-rays



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Resistive untwisting magnetosphere after a star quake / glitch :
A growing cavity and a shrinking current-carrying bundle of field lines at the pole ("j-bundle"), becoming quasi stable;

Beloborodov, 2009

We need to study a post-outburst decay over the broad energy range including low-energy **and** high-energy X-rays

AXPs, SGRs decaying from an outburst

Energies 1-10 keV

Decays from radiative outbursts (after a timing glitch) could so far only be studied for energies below ~10 keV, e.g.:

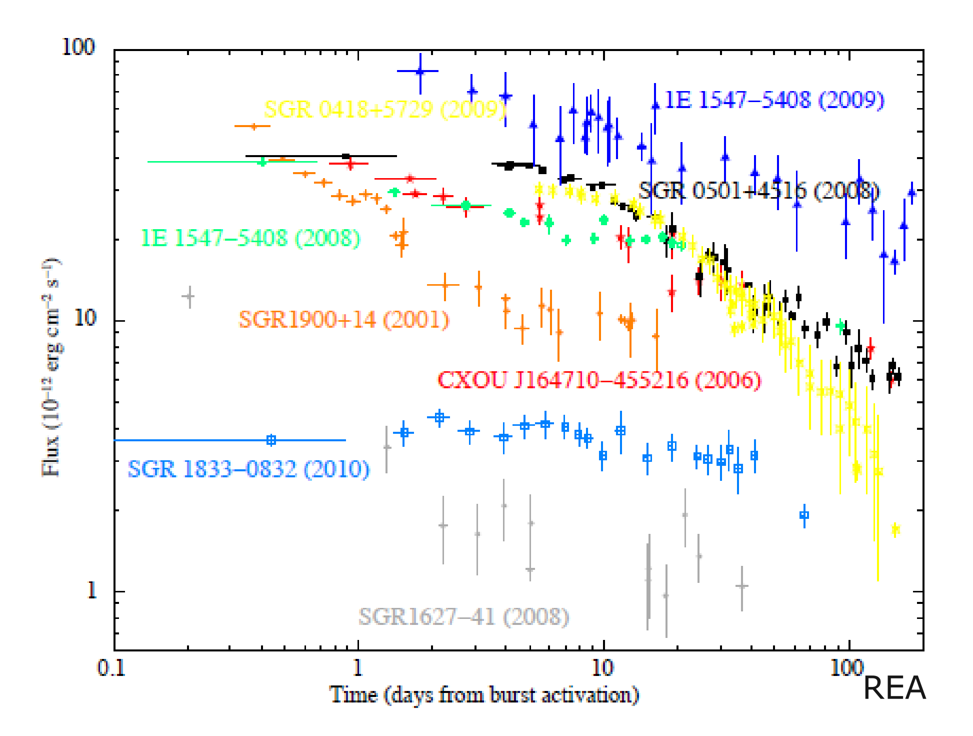
AXP 1E2259+586: Woods et al. 2004

XTE J1810-197: Gotthelf & Halpern 2007

SGR 0501+4516: Rea et al. 2009
Göğüş et al. 2010

SGR J1833-0832: Göğüş et al. 2010
Esposito et al. 2011

SGR 1900+14: Göğüş et al. 2011



AXP 1E 1547.0-5408 / SGR J1550-5418 is the first of which the post-outburst decay can be studied over the broad energy range up to ~300 keV

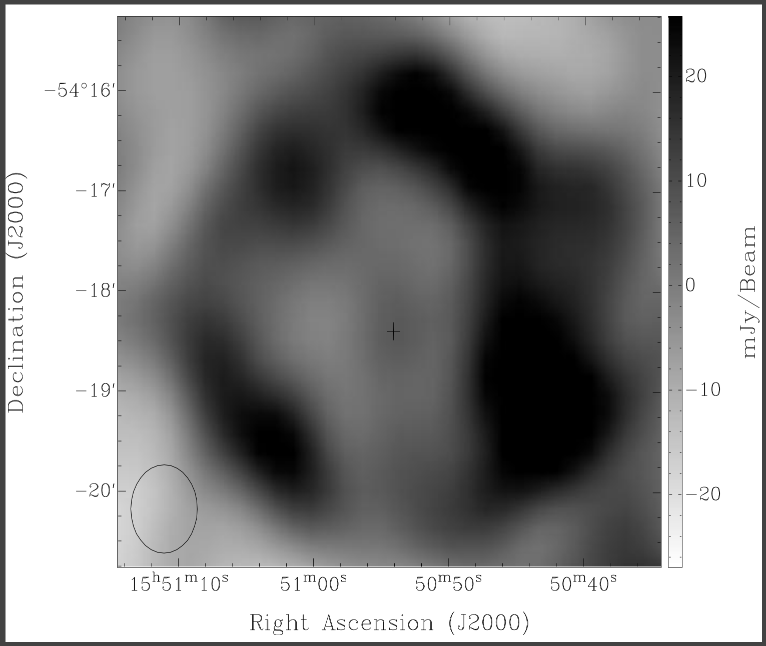
Kuiper, Hermsen, den Hartog and Urama et al. 2011 (in prep.)

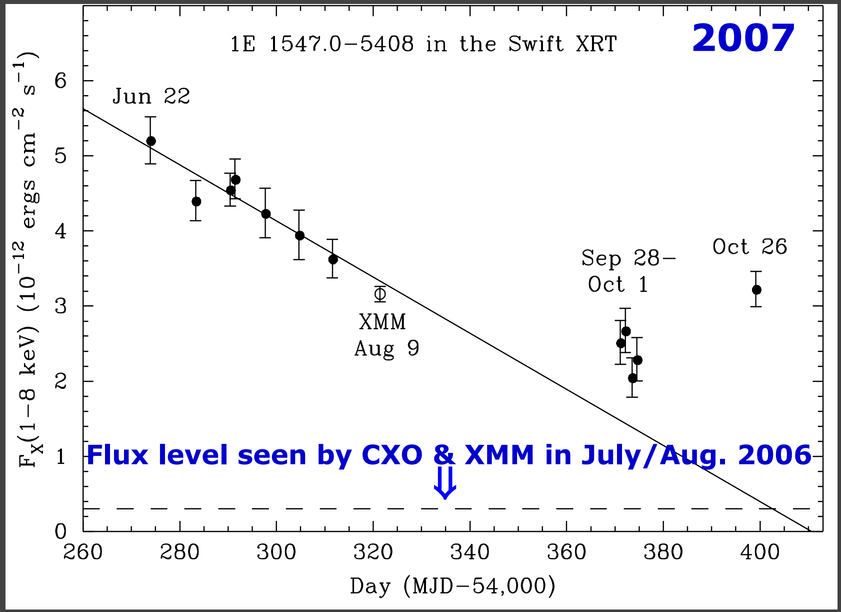
AXP 1E1547.0-5408

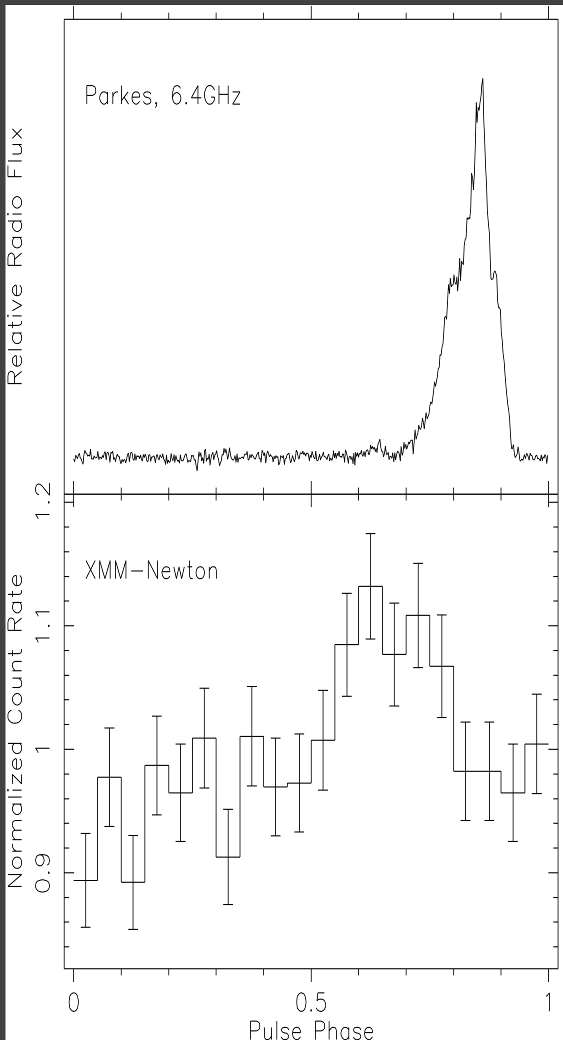
- Discovered in an *Einstein* HRI observation in 1980
- Gelfand & Gaensler (2007) proposed association of a candidate magnetar (X-ray spectrum; variability) and candidate SNR (4′ diameter shell)
- Detection of radio-emitting magnetar, P ~2 s by Camilo et al. (2007) using Parkes data collected on June 8, 2007:

  $B_s \sim 2.2 \times 10^{14}$ G; $\tau \sim 1.4$ kyr

  Noisy timing behaviour.
- SWIFT monitoring and XMM-Newton ToO in June-Oct 2007 ⇒ decay from outburst?; Pulsed X-rays; 7% Pf (Halpern et al. 2008)







Radio/X-ray alignment: X-rays ~ 0.2 ahead

- About 1 year silence from Oct. 2007- Oct. 2008
- On Oct. 3, 2008 several short bursts detected by SWIFT BAT (GCN Circ. 8311)
  Factor ~100 increase in flux (2-10 keV) showing decay; activity till mid Oct. (FERMI GBM)

SGR-like activity commenced on 22 January 2009 initiated strong short burst detected by SWIFT-BAT (GCN Circ. 8833): Many strong bursts detected by several instruments aboard different spacecrafts, SWIFT BAT, INTEGRAL SPI-ACS, FERMI GBM, Konus WIND, Suzaku WAM etc.

In ou
RXTE AL
ISGR al
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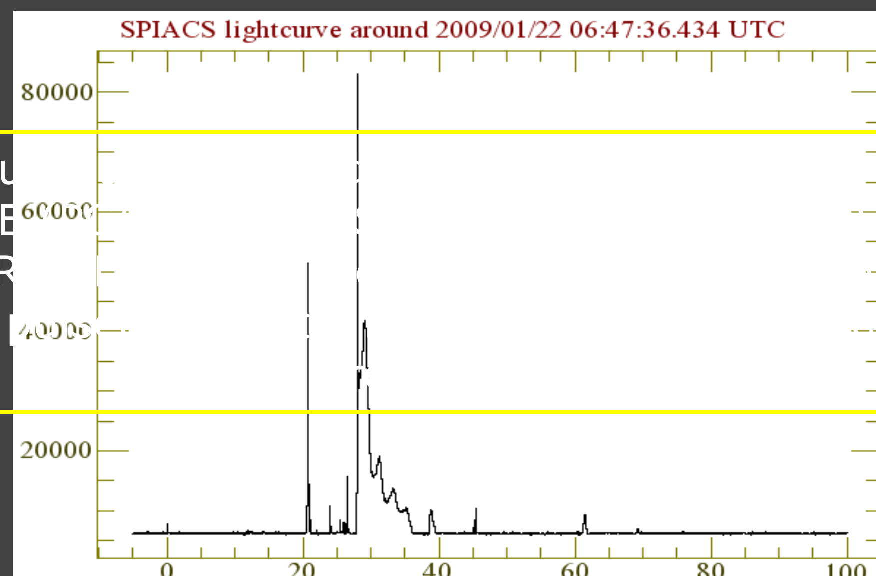
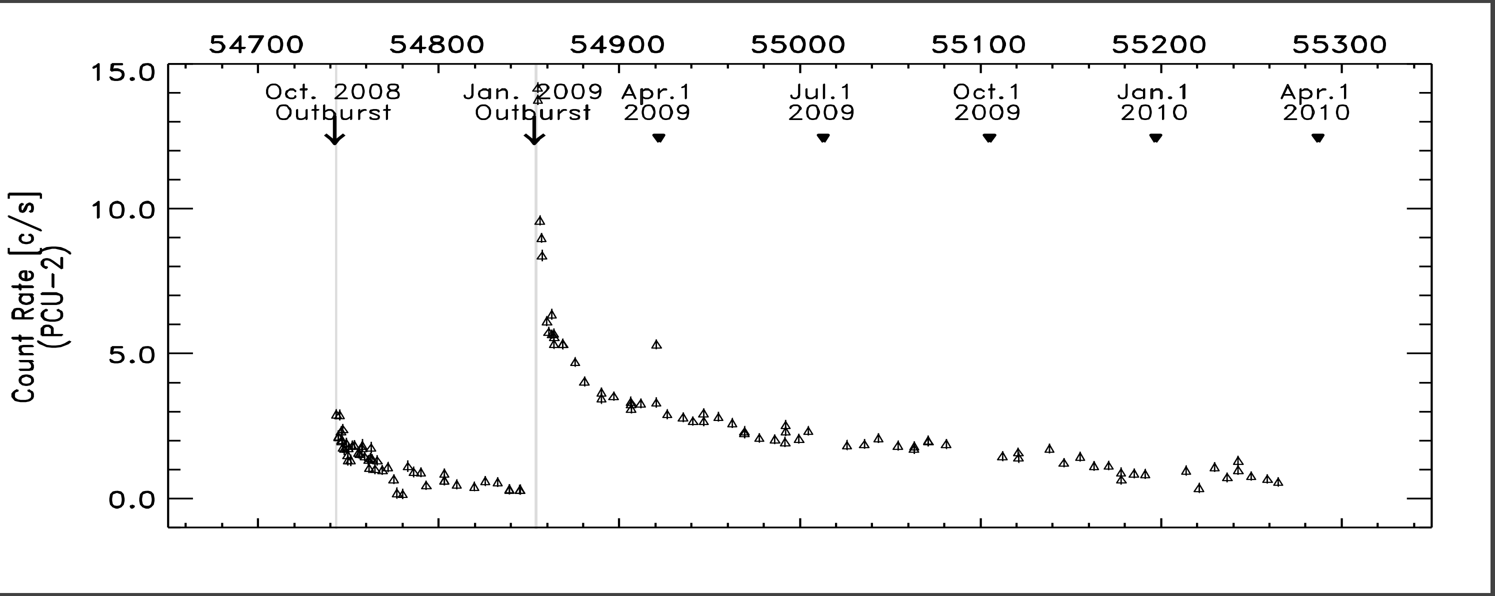


Example of strong burst with pulsating tail

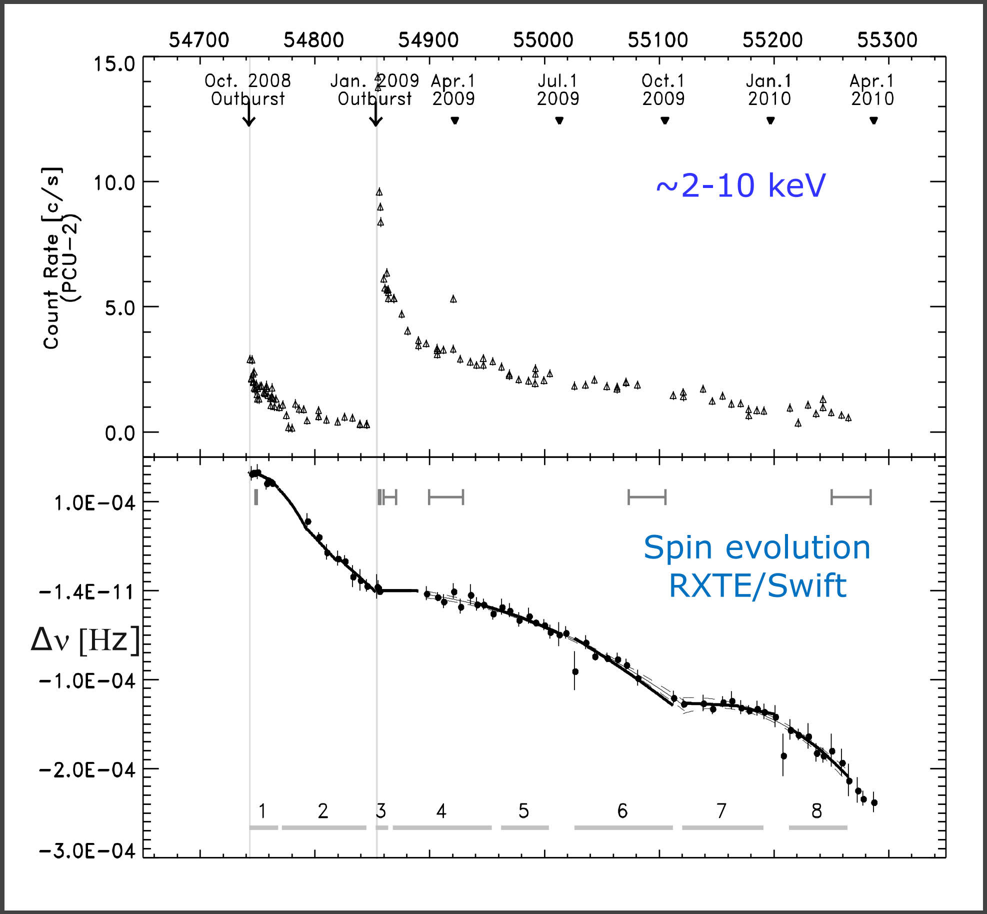
Flux evolution AXP 1E1547.0-5408 at soft X-rays since Oct. 2008 (RXTE PCA)

TOTAL EMISSION , ~2-10 keV

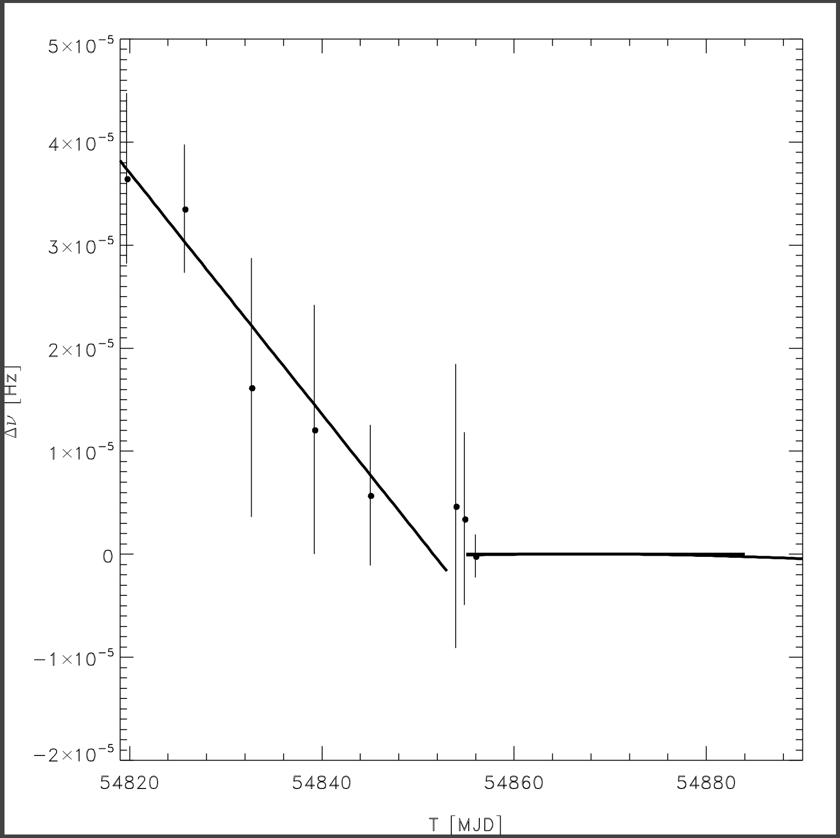


Note: reference level subtracted
2.7 ks Scan obs. May 15, 1997

See also:
Ng et al. (2010)
Israel et al. (2010)
Bernardini et al. (2011)



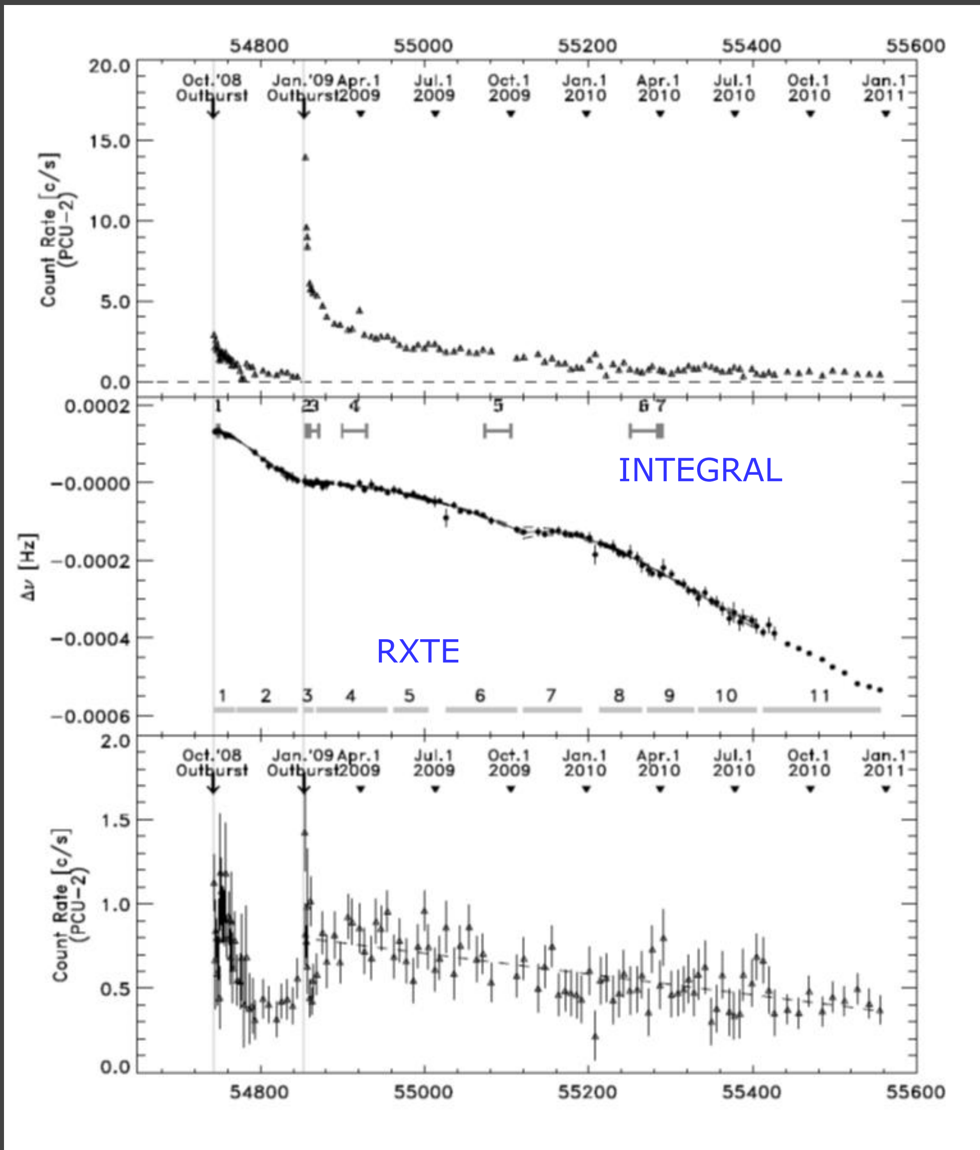
Jan. 22, 2009 radiative outburst accompanied by timing glitch!



No change in flux at 2nd similarly strong glitch in ν and **dν/dt**

Δν/ν ~ 3E-6 ; Δ(dν/dt)/dν/dt = -0.67!!!

Δ(dν/dt) = +12.7(4)E-12 Hz/s



Total flux
2-10 keV

Spin
evolution

Pulsed flux
2-10 keV

Stronger enhanced pulsed flux in Oct. 2008 than in Jan. 2009!

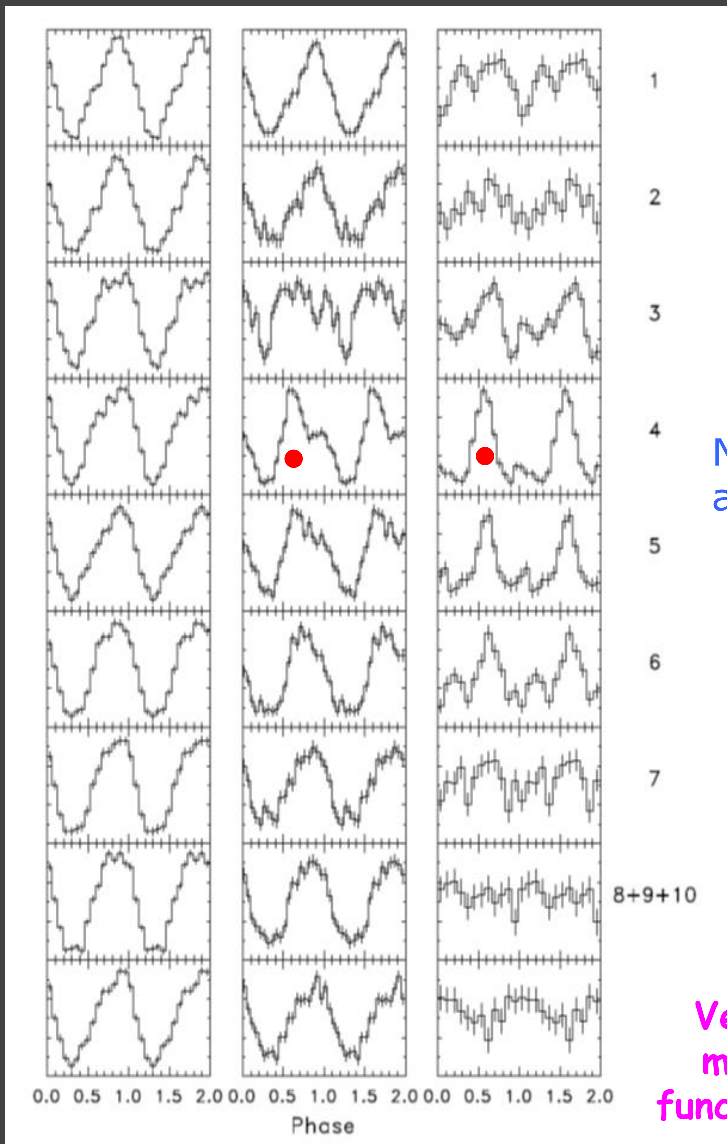
Total soft X-ray flux
and
pulsed soft X-ray flux
evolve very differently

Also no evident change in pulsed flux at 2nd glitch

See also:
Ng et al. (2010)
Israel et al. (2010)
Bernardini et al. (2011)

Pulse profile evolution of 1E1547.0-5408

~2-4 keV ~4-11keV ~11-33 keV



←Oct. 3, 2008 Outburst

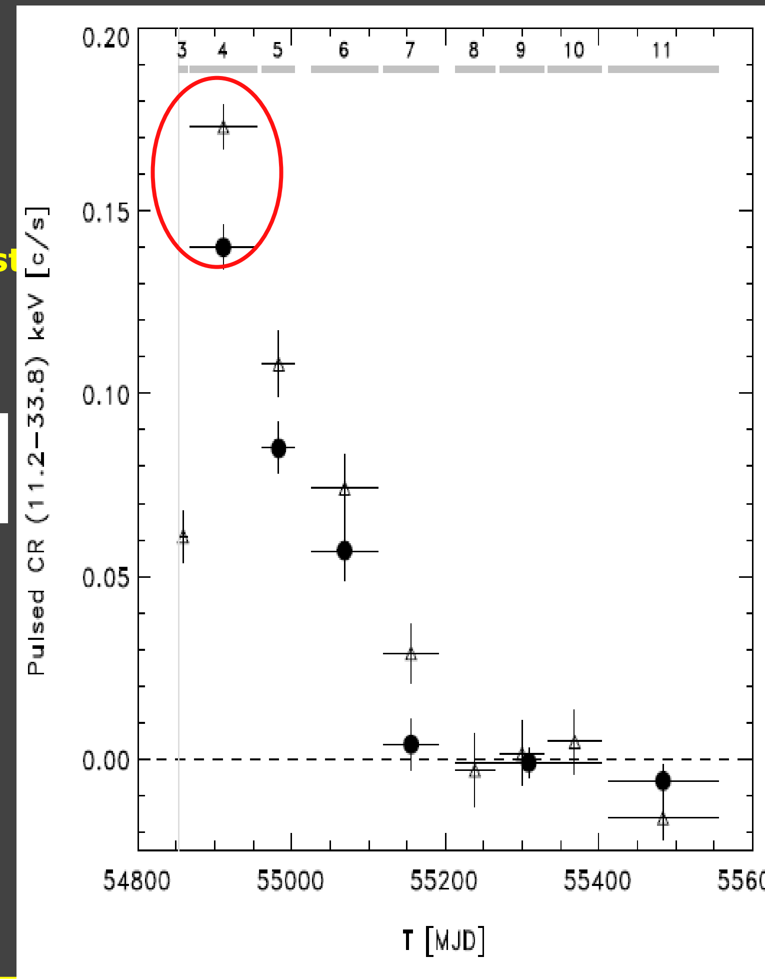
MJD 54743-54768

MJD 54771-54845

←Jan. 22, 2009 Outburst

New pulse ~4-30 keV appears after glitch

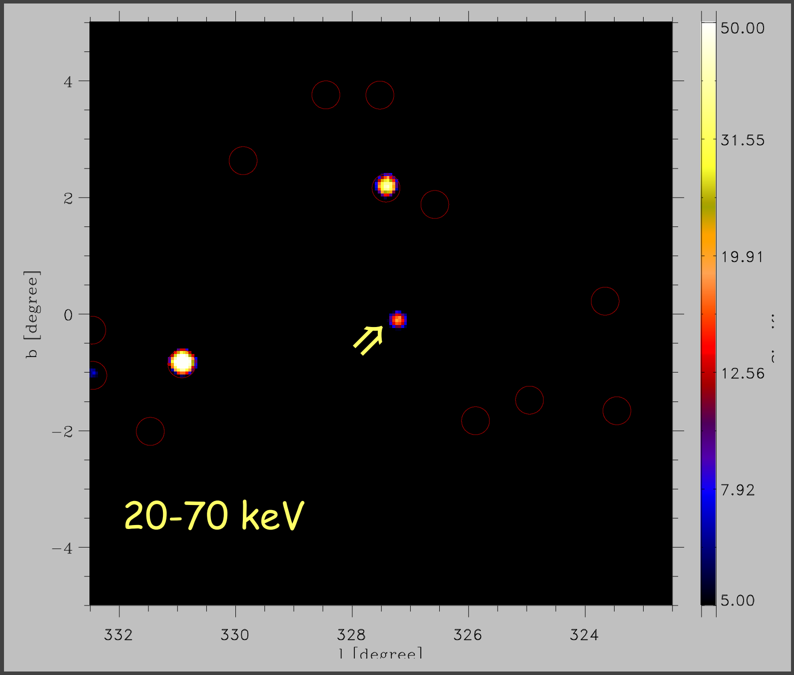
● 4=11 △ 11-33 keV

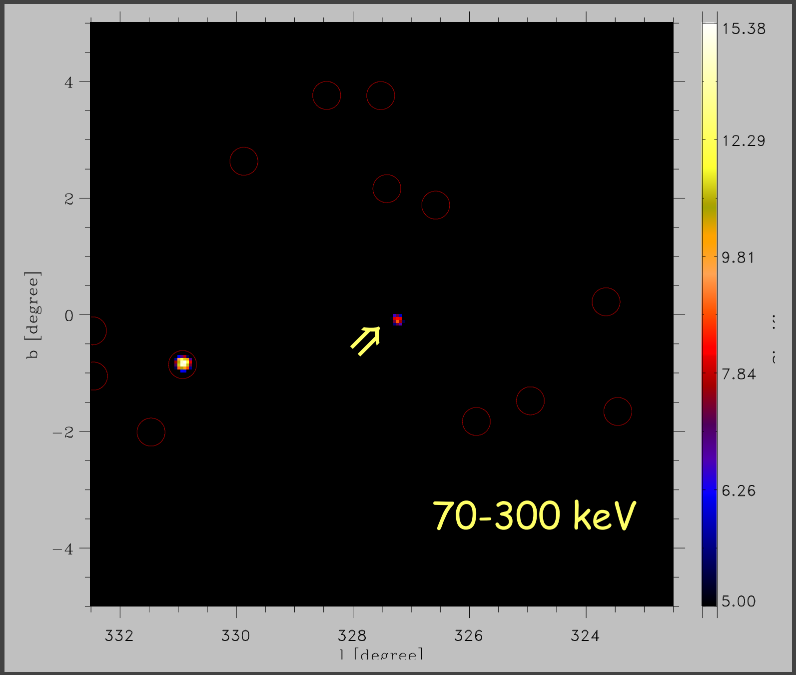


Very different morphology as function of energy!

New pulsed component (~4-30 keV) delayed w.r.t.Jan. 22, 2009 glitch by > 11 days and fades to zero within ~350 days!

1E 1547-5408: Total emission detected with INTEGRAL ISGRI up to ~300 keV
Few days after glitch on 22 January 2009

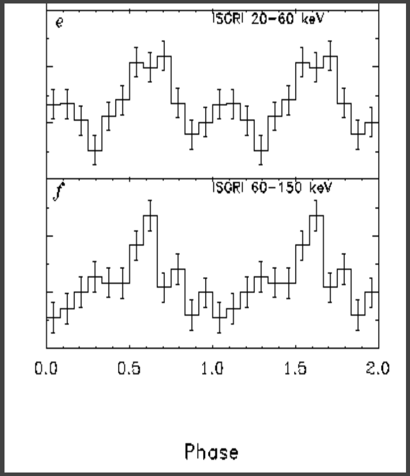




INTEGRAL
Pulsed emission detected
up to ~150 keV

(Atel 1921, Kuiper, Hermsen, den Hartog 2009.
Atel 1922. den Hartog, Kuiper, Hermsen 2009

Confirmed by Suzaku, Enoto et al. 2010)



+ Swift observations for total emission within 13 days after glitch

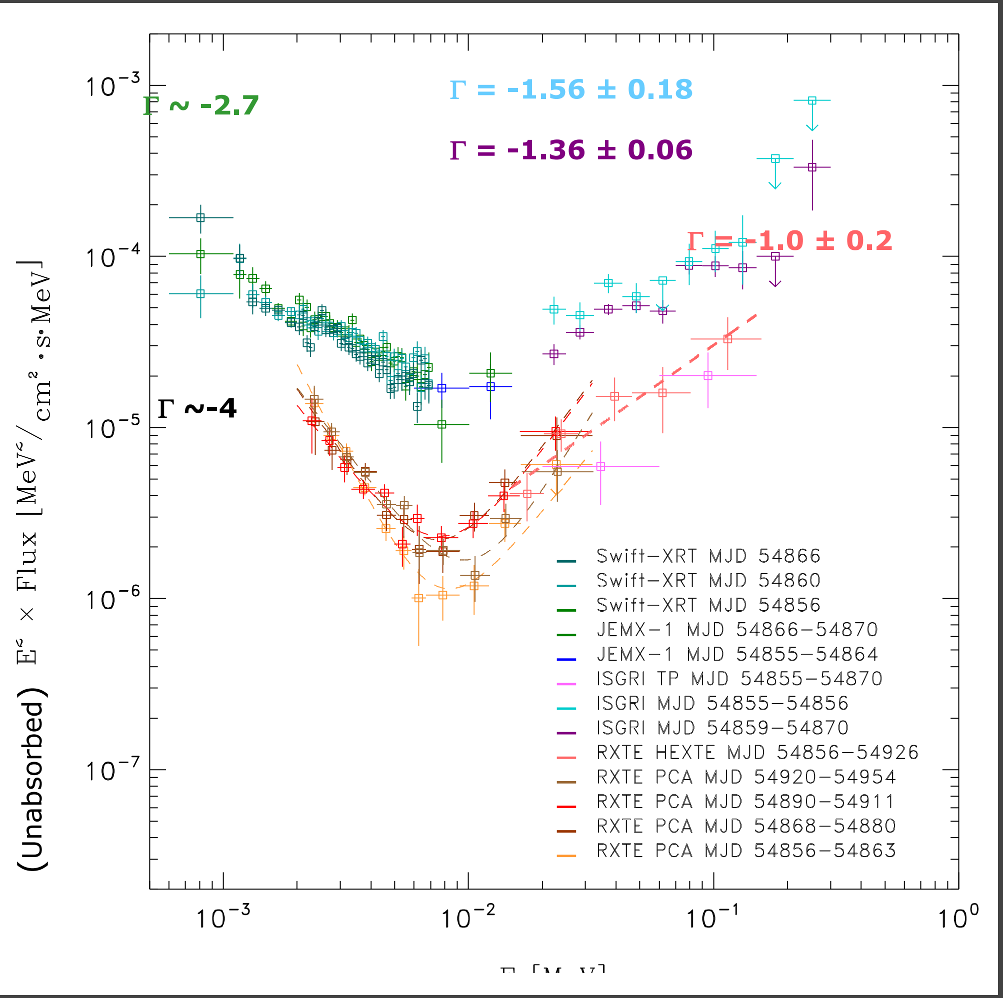
SRON

Spectral evolution of total and pulsed emission 1 – 300 keV during time window of maximum luminosity above 10 keV (up to ~100 days after glitch

Total emission is high immediately after glitch (Swift < 10 keV and INTEGRAL > 10 keV)

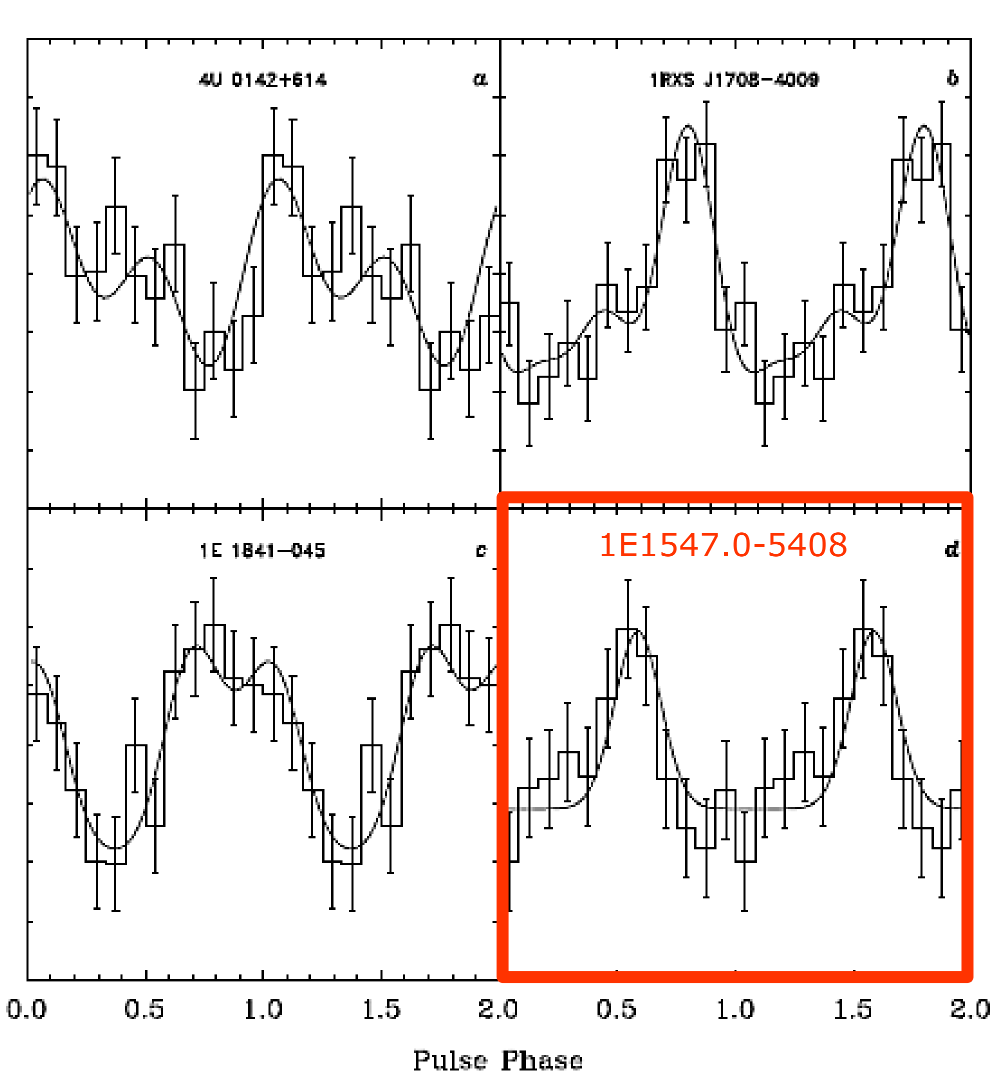
Pulsed emission after glitch:
PCA < 7 keV high immediately
PCA > 7 keV increase delayed by up to ~40 days

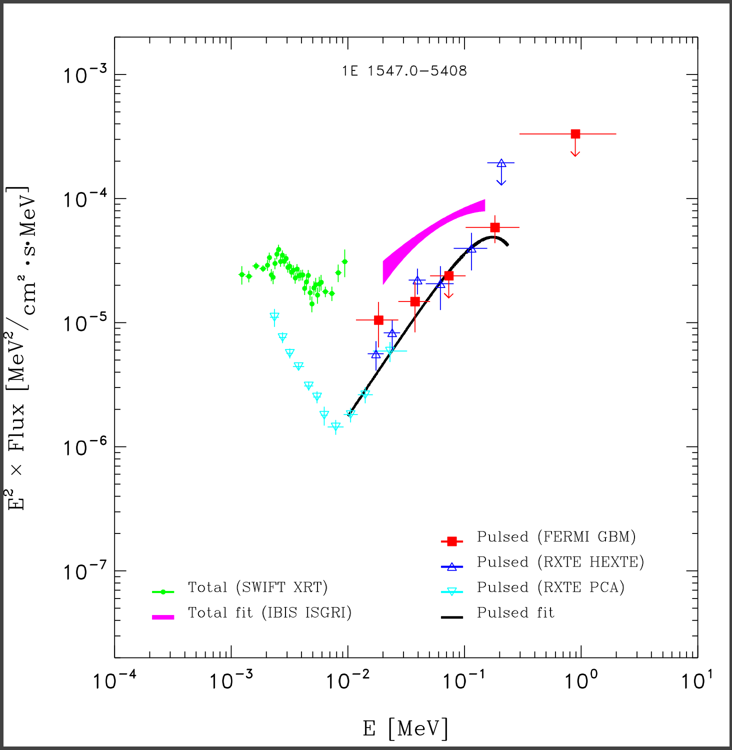
Spectral shape mimics that of persistent emission of AXPs
1E 1841.0-045
4U0142+614
1RXS J1708-40



Also, Suzaku (Enoto et al. 2010), Total HE emission $\Gamma_{total} \sim 1.5$

Transient magnetar 1E1547.0-5408 seen by Fermi/GBM after glich

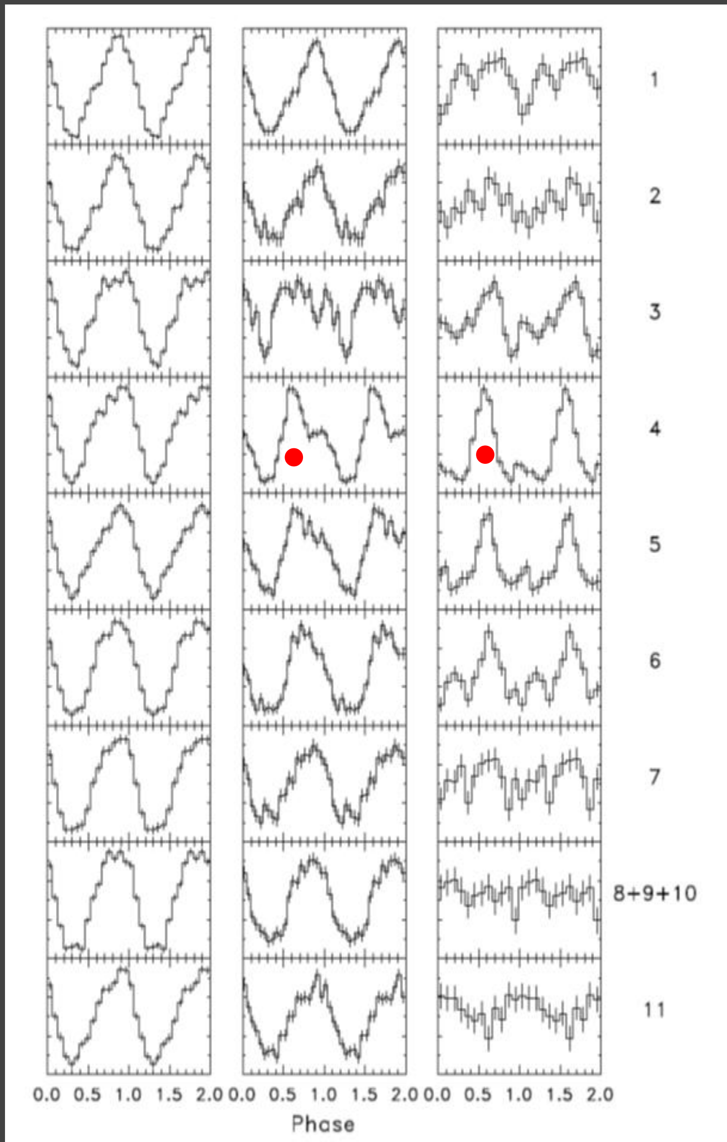




Power-law fit not acceptable:
break required

Pulse profile evolution of 1E1547.0-5408 over >510 days after glitch

~2-4 keV **~4-11keV** **~11-33 keV**



←Oct. 3, 2008 Outburst

MJD 54743-54768

MJD 54771-54845

←Jan. 22, 2009 Outburst

MJD 54853-54864

MJD 54868-54954

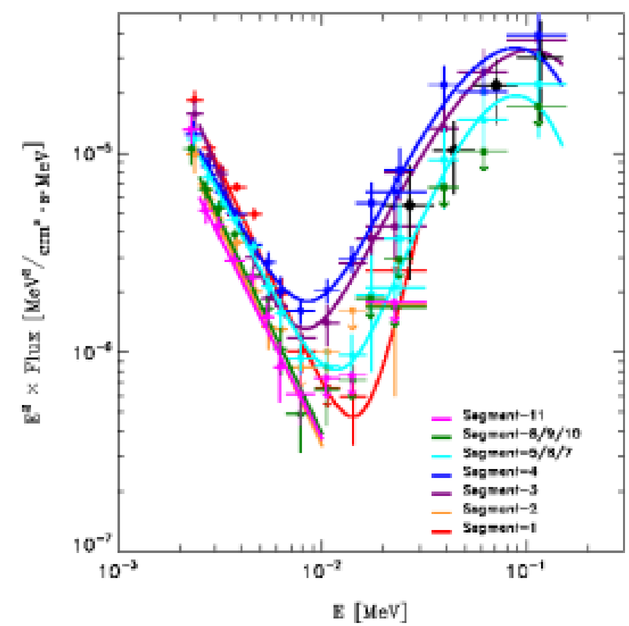
MJD 54962-55004

MJD 55026-55112

MJD 55120-55191

MJD 55213-55264

Evolution pulsed spectra

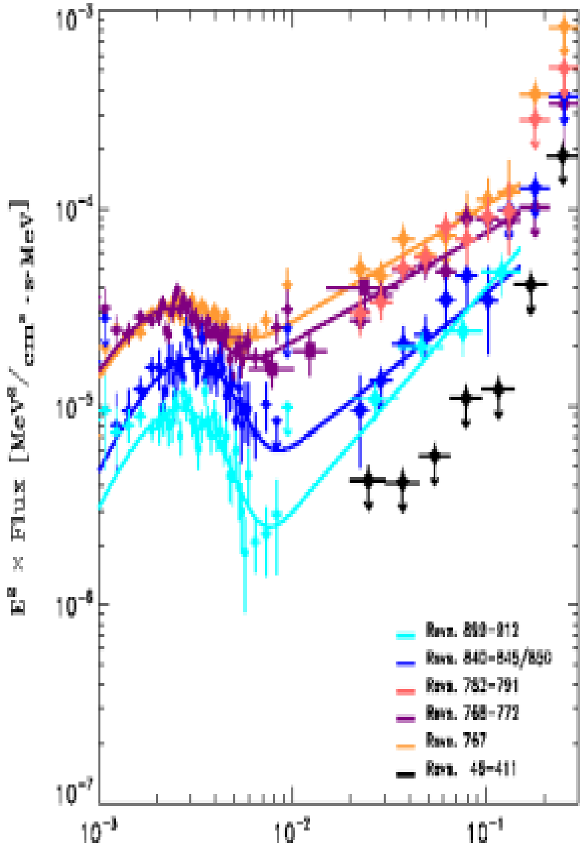


RXTE PCA HEXTE

INTEGRAL

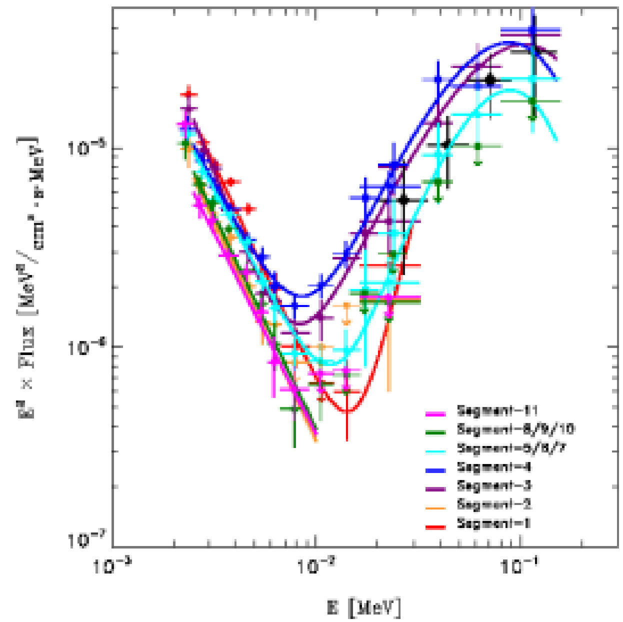
Spectral evolution of 1E1547.0-5408 over >510 days after glitch

Evolution **total** spectra



SWIFT INTEGRAL

Evolution **pulsed** spectra



RXTE PCA HEXTE

INTEGRAL

Spectral shapes similar to that of persistent of AXPs !

SRON

Summary (1)

- A strong glitch detected for AXP 1E1547.0-5408 in January 2009, triggered a radiative outburst and the creation of a new non-thermal hard X-ray pulse in the profile, which decayed to undetectable levels in ~350 days.
- The new pulsed emission above 10 keV reached its maximum ~40 days after the glitch.
- The total soft and hard X-rays and the pulsed soft X-rays reached their maximum flux directly after the glitch
- The total and pulsed X-ray spectra after the glitch resemble the total and pulsed spectra of the persistent emission of AXPs
- A similar second glitch on 17 October 2009 did NOT trigger an outburst

Summary (2)

- Improved statistics of RXTE-HEXTE and INTEGRAL-IBIS data,
  + first results from FERMI-GBM show that the shape of the total and pulsed spectra of the persistent hard X-ray emission from AXPs becomes similar up to ~100 keV

- The pulsed fraction for energies 10–100 keV is in the range 25-40%.

- The total and pulsed hard X-ray spectra require a spectral break, bend above 100 keV

SRON