Hard non-thermal X-ray / soft gamma-ray emission from Anomalous X-ray Pulsars

Wim Hermsen
SRON Netherlands Institute for Space Research, Utrecht
&
Astronomical Institute Anton Pannekoek, Univ. of Amsterdam

L. Kuiper, P. den Hartog (SRON)

V. Kaspi, R. Dib (McGill Univ.)

363. Heraeus-Seminar, Neutron Stars and Pulsars, 18 May 2006

SRON
Netherlands Institute for Space Research

Outline

- Introduction
- Observational evidence for luminous pulsed hard X-ray/soft-γ-ray emission from AXPs:

  Kuiper, Hermsen & Mendez 2004, ApJ 613, 1173

  den Hartog, Hermsen, Kuiper, Vink, in 't Zand & Collmar 2006, A&A in press (atro-ph/060)

  Kuiper, Hermsen, den Hartog & Collmar 2006, ApJ in press (astro-ph/0603467)

- Mutiwavelengths campaign on 4U 0142+61
- First theoretical attempts
- Outstanding questions

SRON

- **Introduction**

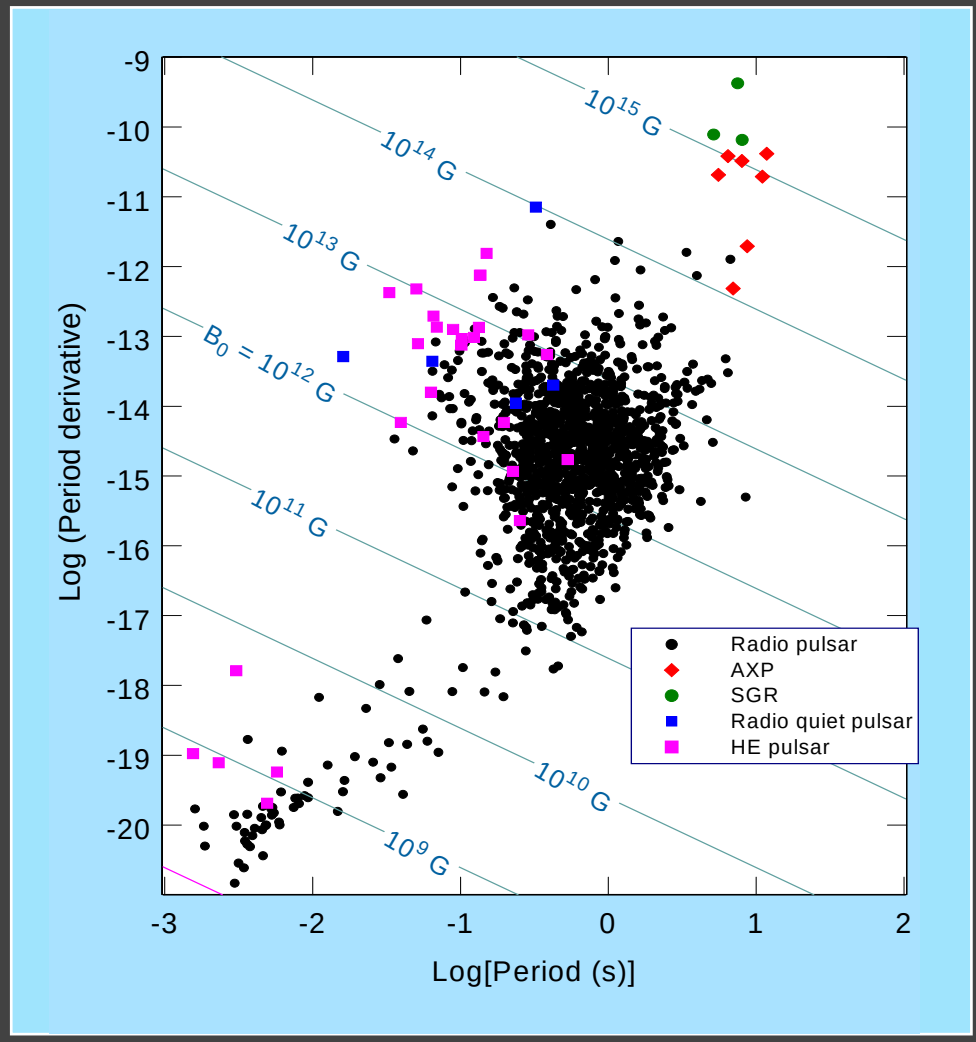
Rotation-Powered Pulsars and Magnetars:

$P–\dot{P}$ diagram with B_s

- ~1500 radio pulsars
- ~30 X-ray pulsars
- 10 γ-ray pulsars
- 7 AXPs
- 3 SGRs

Extreme B fields:

- **AXPs & SGRs $10^{14} – 10^{15}$ G**
- **Millisecond pulsars $10^{8} – 10^{10}$ G**



Magnetar properties (X-ray energies below 10 keV)

	SNR	P (s)	dP/dt (10^{-11}s/s)	B (10^{14}G)	kT(keV) / Γ	L (10^{33} erg/s) (0.2-10keV)
4U 0142+61		8.7	0.2	1.3	0.46 / 3.4	72
1E 2259+586	CTB 109	7.0	0.05	0.6	0.41 / 3.8	17 - 59
1E 1048-5937		6.4	2-3	3.9	0.63 / 2.9	5.3 - 25
1E 1841-045	Kes 73	11.8	4.0	7.1	0.44 / 2.0	110
XTE 1810-197		5.5	1.8	2.9	0.67 / 3.7	10 - 260
RXS J1708-4009		11	2.0	4.7	0.44 / 2.4	190
CXO J0110-72	in SMC	8.0	1.8	3.9	0.38 / 2.0	200
Westerlund 1		10.6	<20	-	0.61	3
AX J1845-0258	G29.6+0.1	7.0	-	-	/ 4.6	5 - 120
SGR 1900+14	G42.8+0.6?	5.2	6.1-20	5.7	0.43 / 2.0	200 - 350
SGR 1806-20	G10.0-0.3?	7.5	8.3-47	7.8	0.6 / 1.4	320 - 540
SGR 0526-66	N49 in LMC	8.0	6.6	7.4	0.53 / 3.1	260
SGR 1627-41	G337.0-0.1?	6.4 ?	-	-	/ 2.9	4 - 100
SGR 1801-23		-	-	-	-	-

SRON

Anomalous X-ray pulsars (status around 2003-2004)
Bright ***Uhuru*** sources: **Are AXPs Magnetars ?**

- **No** rotation powered pulsar — $L_X >> L_{spin\ down}$
- **No** X-ray pulsar in LMXB/HMXB (**no** accretion-powered pulsar) — steady spin-down; no apparent optical counterpart; no periodic Doppler delay in X-ray timing

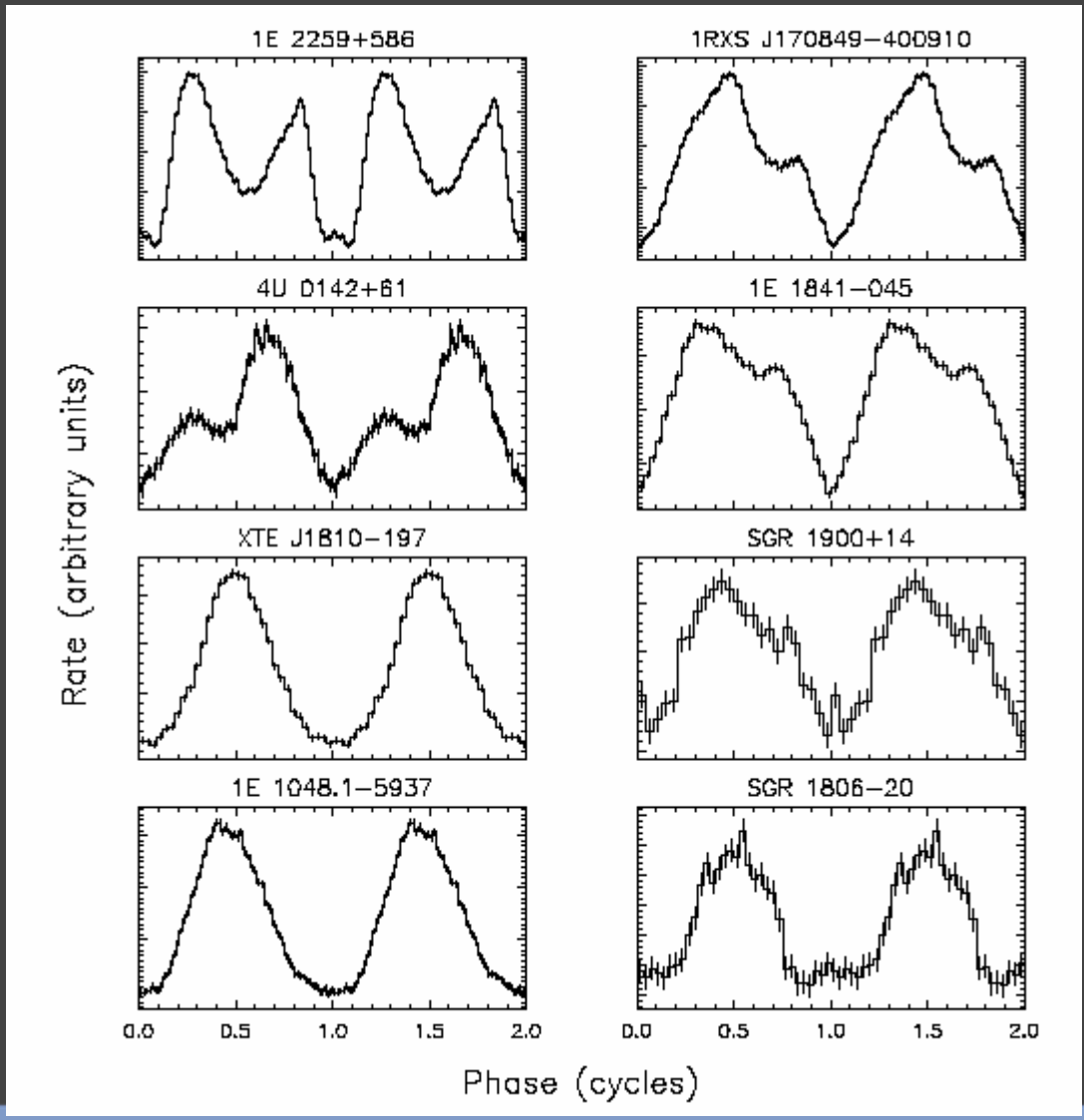
Characteristics:

- ◇ Pulse periods: 5 -12 s
- ◇ "Steady" spin-down like rotation powered pulsars (glitches observed also)
- ◇ X-ray luminosities: $10^{34\text{-}36}$ erg/s (steady, but outbursts also detected; transient AXPs)
- ◇ (very) soft X-ray (0.5-10 keV) spectra: BB (0.35 – 0.6 keV) + PL (2 – 4)
- ◇ Similar to Soft Gamma-Ray Repeaters (glitches; (out)bursts) → **Magnetars**
- ◇ Young population concentrated along galactic plane

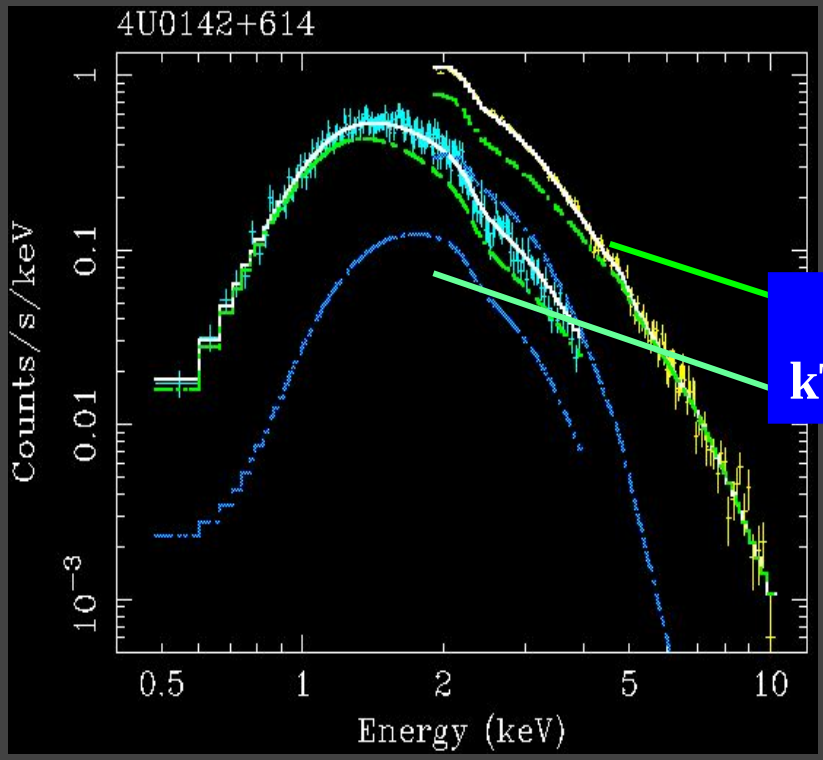
SRON

Quiescent emission pulse profiles of AXPs and SGRs
E<10keV

Woods & Thompson 2004



Soft spectra of AXPs: 4U 0142+614



(Def. power-law photon index: $E^{-\Gamma}$)

Γ=2.5-4
kT=0.4-0.7 keV

Also, variable X-ray fluxes below 10 keV
(Rea et al. 2004, 2005)

Any reason to study AXPs above 10 keV?

SRON

- **Observational evidence for luminous pulsed hard X-ray/soft-γ-ray emission from AXPs**

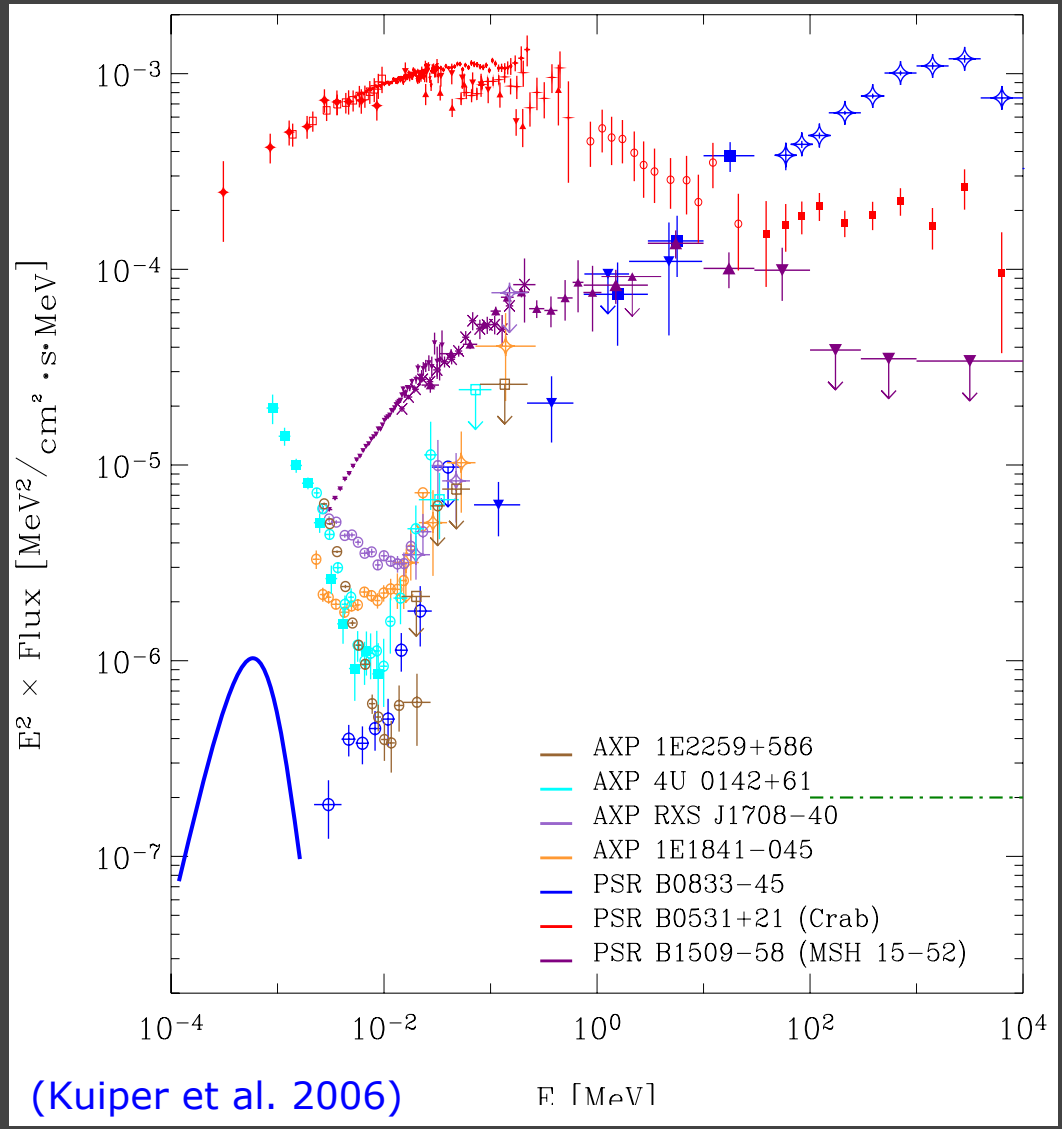
SRON

Anomalous X-ray Pulsars are hard X-ray sources

X-ray – Gamma-ray

pulsed spectra

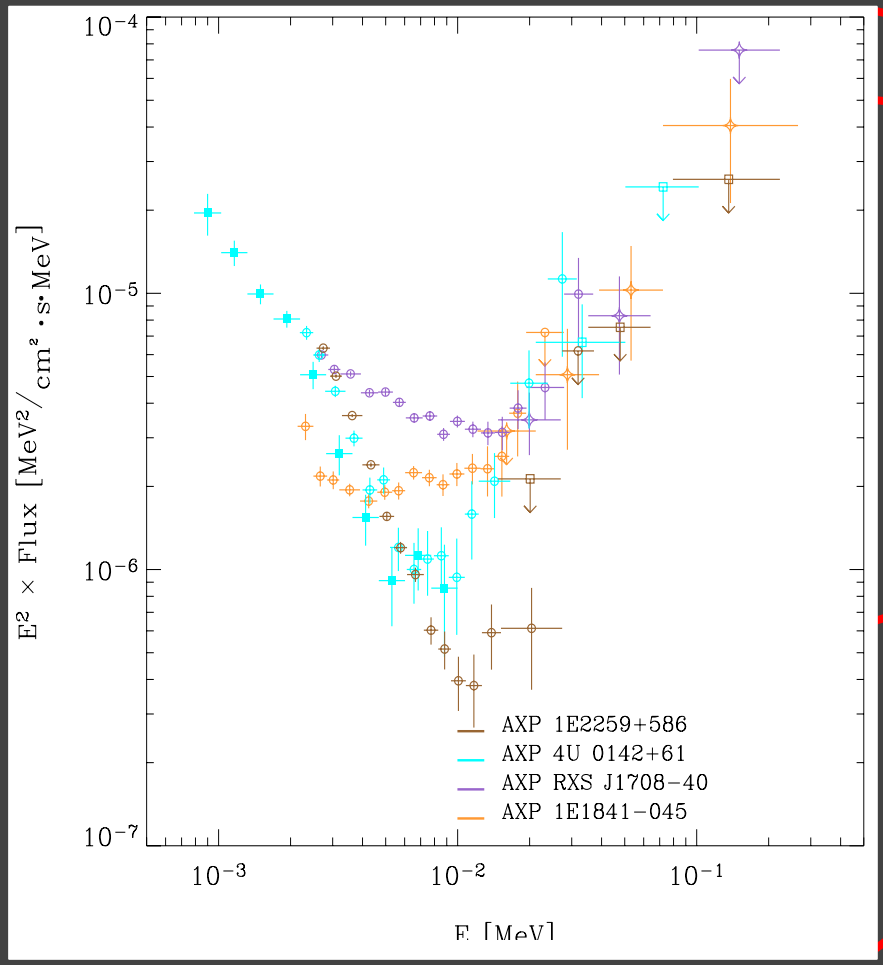
AXPs > 10 keV &
Young Pulsars

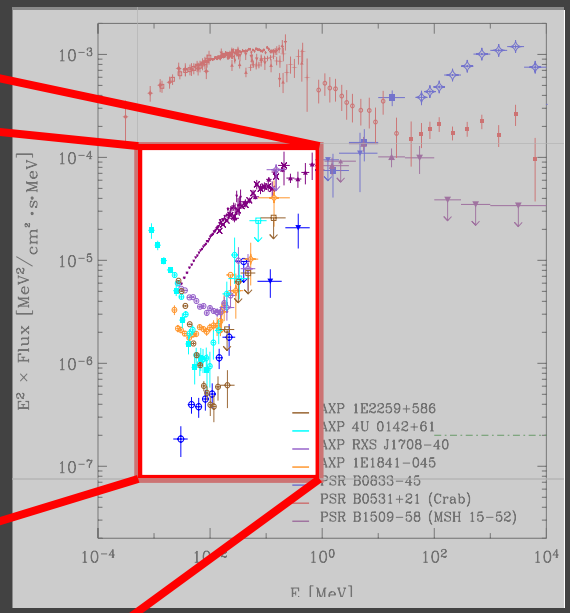


(Kuiper et al. 2006)

SRON

Anomalous X-ray Pulsars are hard X-ray sources





$L_{\text{hard tail}} > L_{\text{rotation power}}$

$\sim 10^{35} : \sim 1.3 \times 10^{32}$ (erg s^{-1})
[20—100 keV]

SRON

AXPs discovered > 10 keV

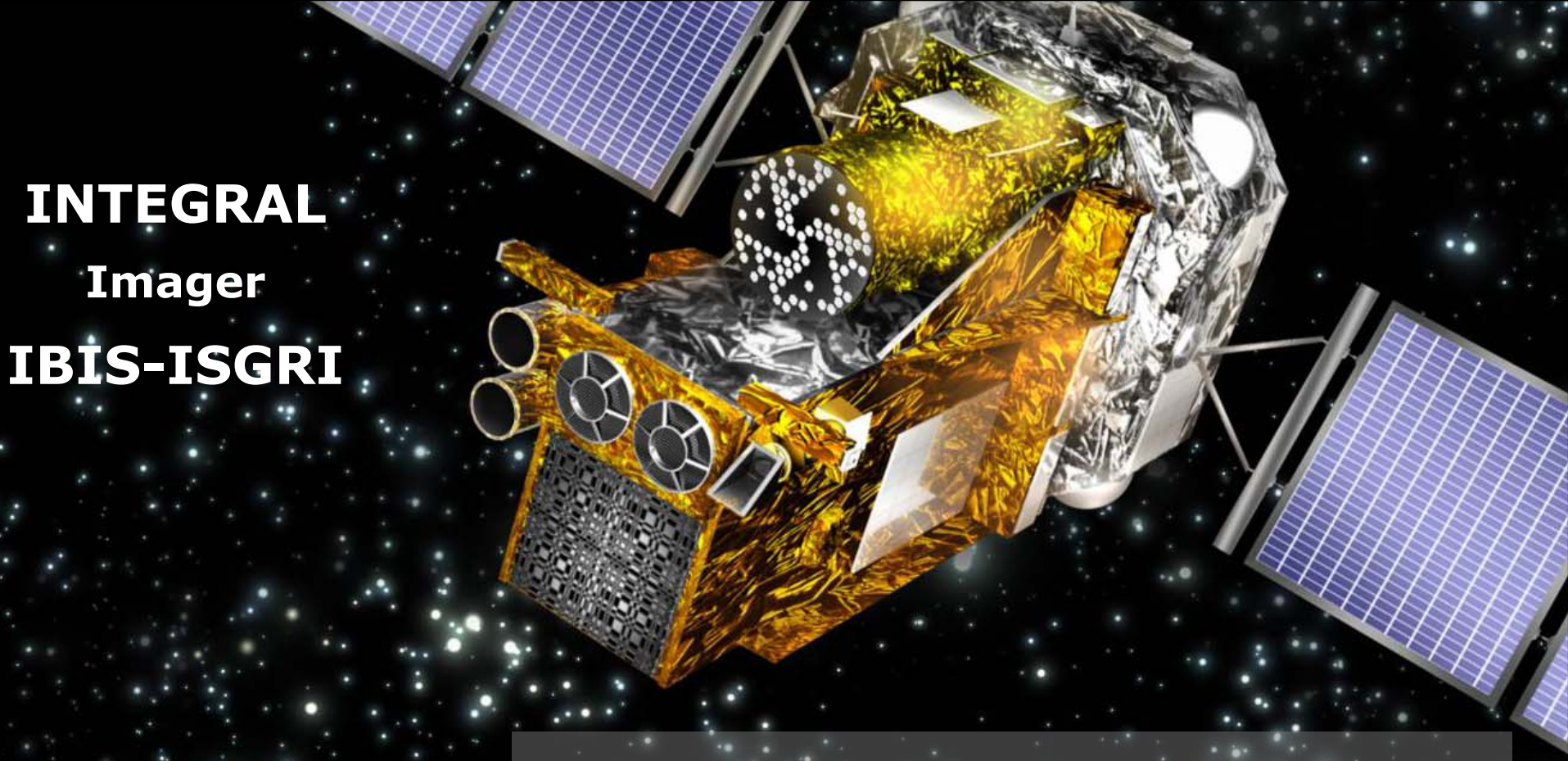
- 1E 1841-045 (Molkov et al. 2004), (Kuiper, Hermsen & Mendez 2004)
- 1RXS J170849-400910 (Revnivtsev et al. 2004), (Kuiper et al. 2006)
- 4U 0142+61 (den Hartog et al. 2006), (Kuiper et al. 2006)
- 1E 2259+586 (Kuiper et al. 2006)

SRON

INTEGRAL

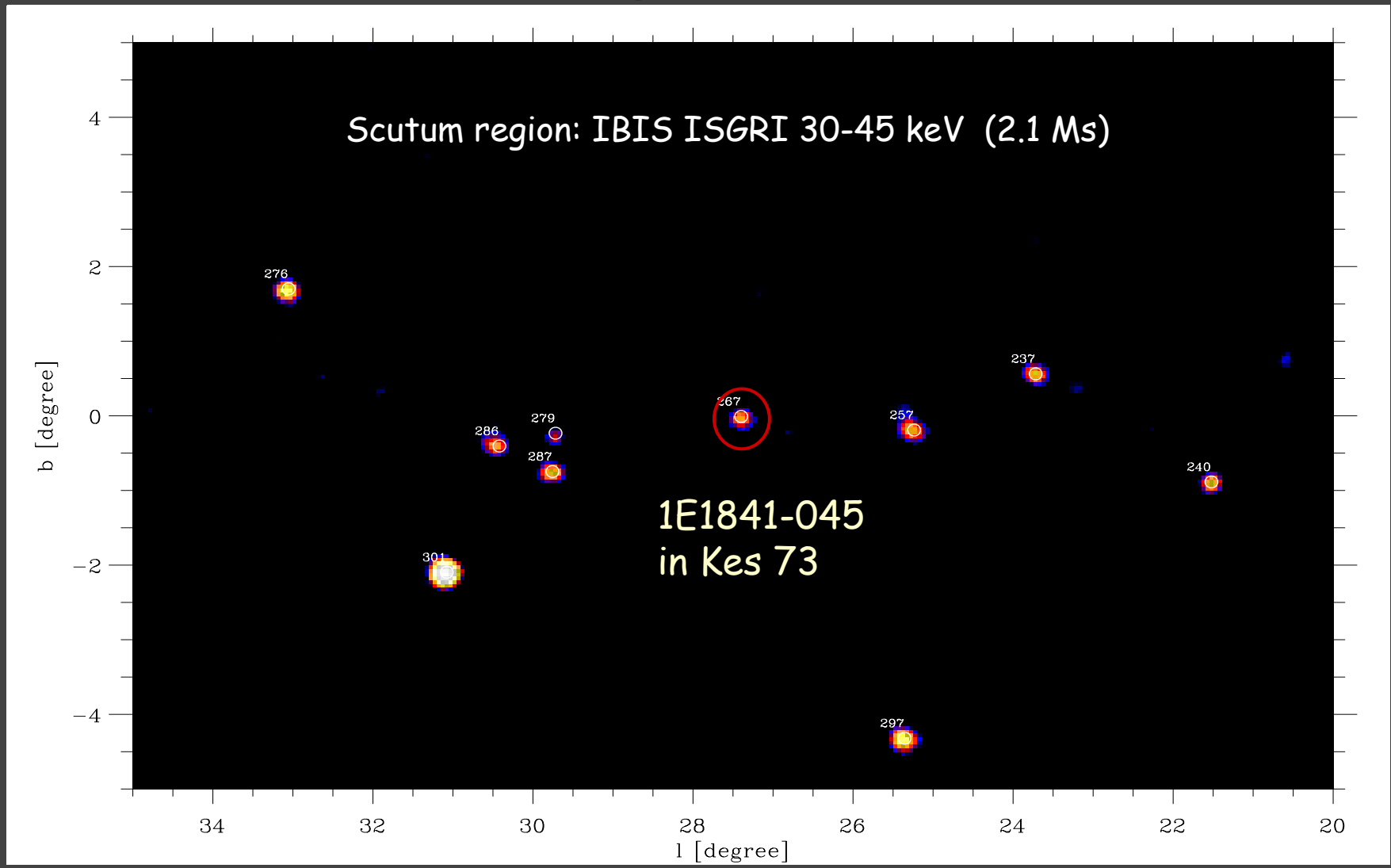
Imager

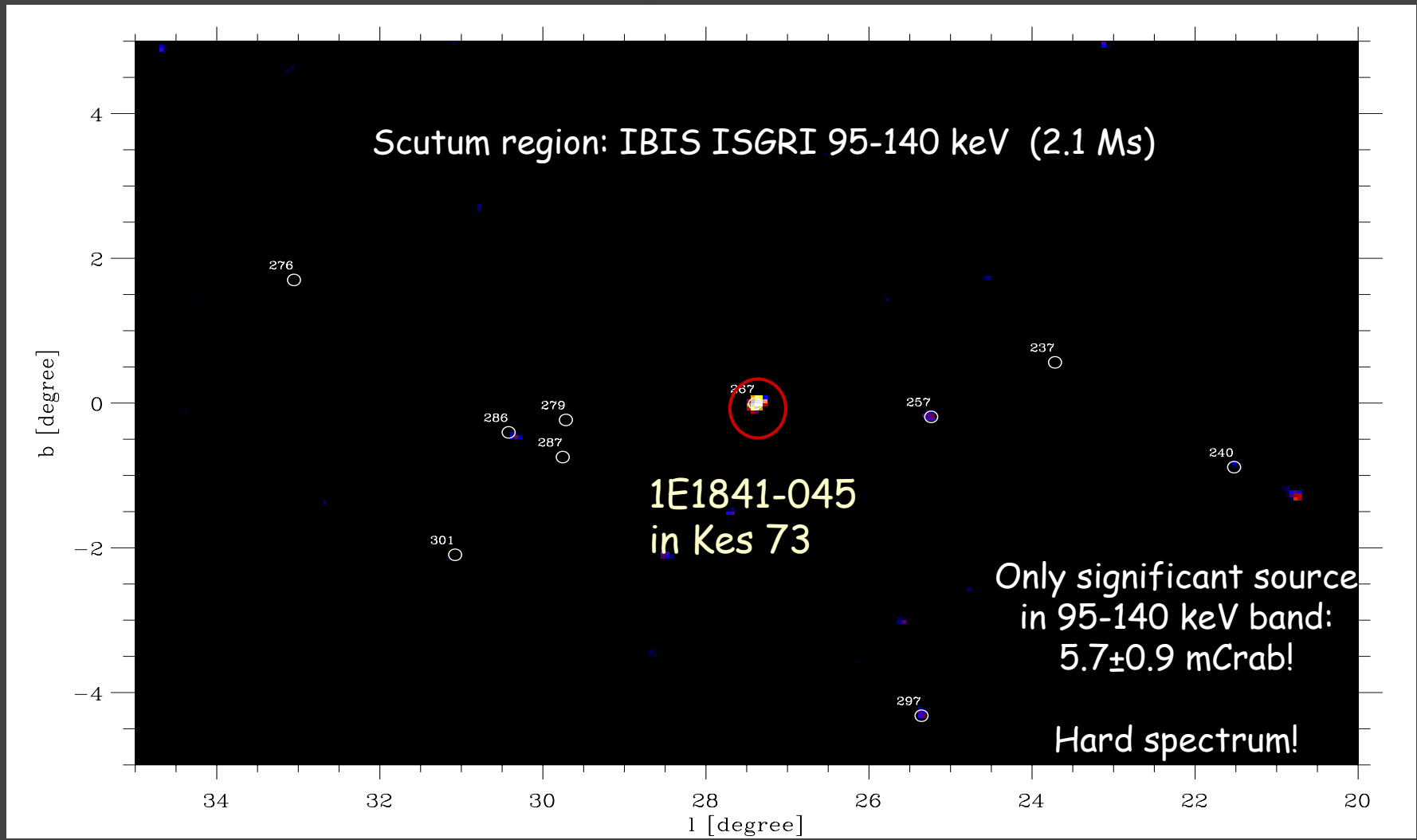
IBIS-ISGRI



Energy range:	20 keV - ~300 keV
Field of view:	9° x 9° (fully coded)
	19° x 19° (partially coded)
Angular resolution:	12′ (FWHM)
Point-source location accuracy:	30″ – 3′

AXP research at soft γ-rays triggered by the detection of a point source in a IBIS ISGRI 18-60 keV map at SNR Kes 73 (Molkov et al. 2004)

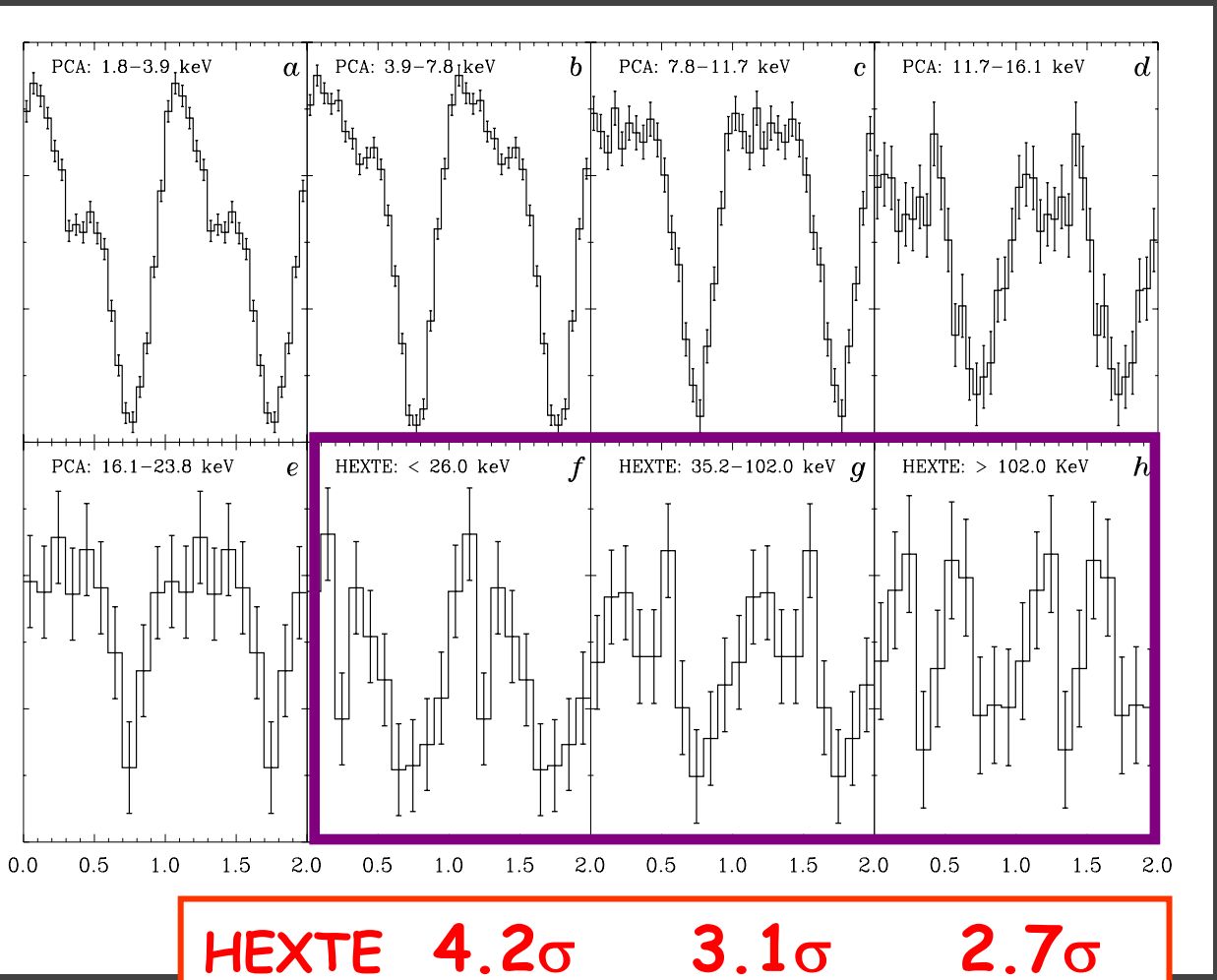



1E 1841−045/Kes 73 Revs. 49−249 : 95 − 140 keV
2003−03−10T10:16:16 − 2004−10−27T22:11:00
GTI exposure : 2073.48 ks
Scutum region: IBIS ISGRI 95-140 keV (2.1 Ms)
1E1841-045
in Kes 73
Only significant source
in 95-140 keV band:
5.7±0.9 mCrab!
Hard spectrum!
276
237
267
279
257
286
287
240
301
297
b [degree]
l [degree]
4
2
0
−2
−4
34
32
30
28
26
24
22
20

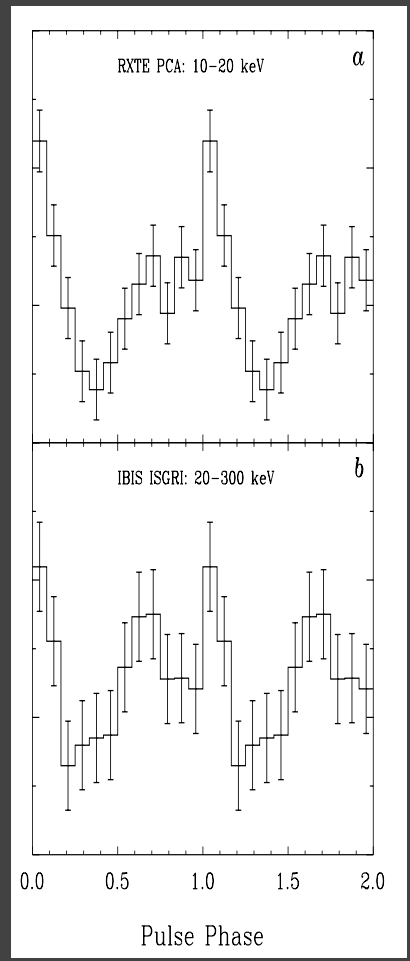
Archival RXTE PCA/HEXTE data
Kuiper, Hermsen & Mendez 2004, ApJ 613, 1173

RXTE/INTEGRAL Contemporaneous
Kuiper, Hermsen, den Hartog, Collmar 2006, ApJ

1E 1841-045



HEXTE 4.2σ 3.1σ 2.7σ

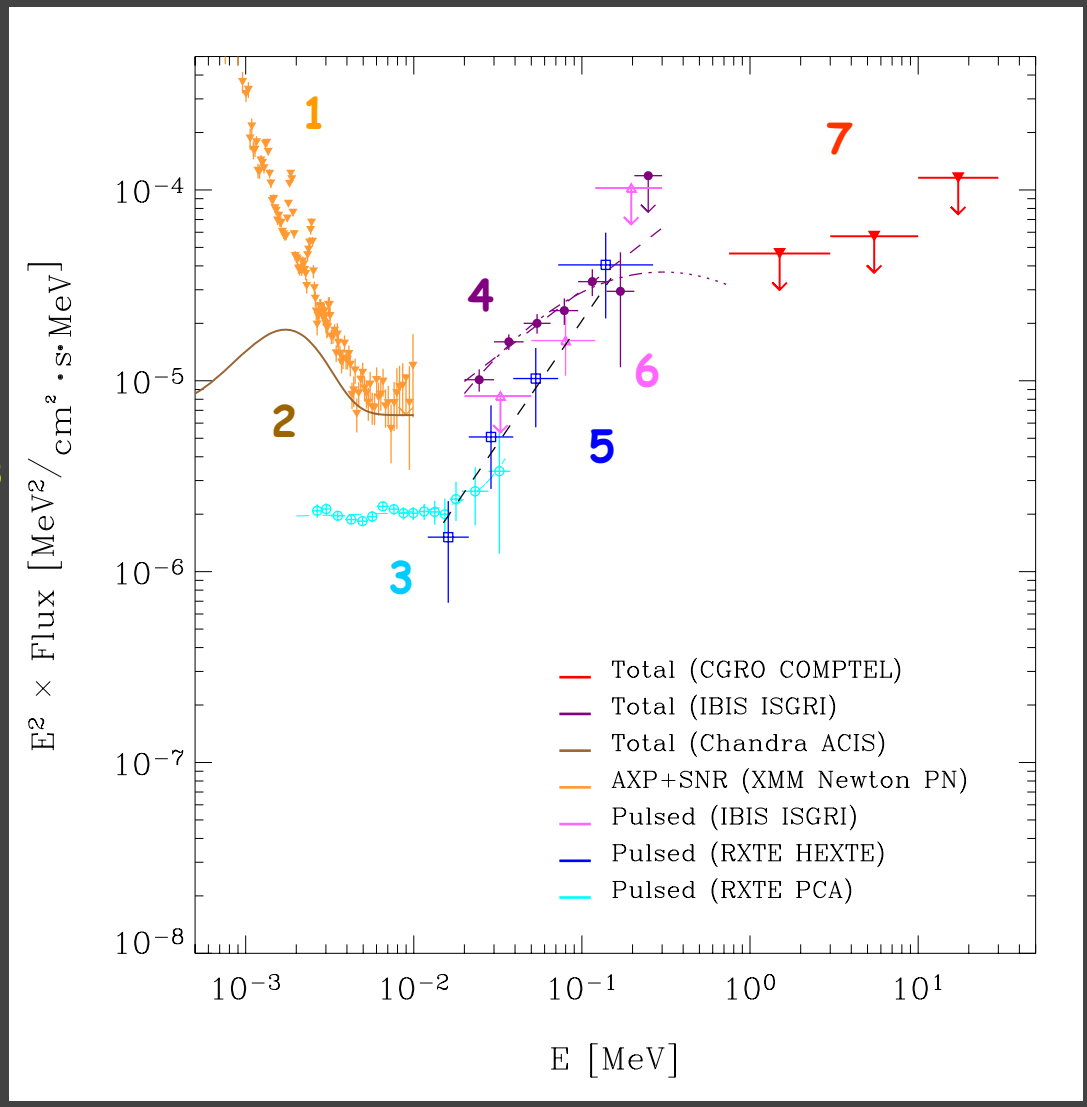


High Energy Spectra SNR Kes 73 and AXP 1E 1841-045

1 Kes 73 +
1E 1841-045
XMM-Newton

2 Total
1E 1841-045
Chandra
(Morii et al. 2003

3 Pulsed
1E 1841-045
RXTE/PCA



Total:
Γ_h=1.44±0.45

4 Kes 73? +
1E 1841-045
IBIS ISGRI
Γ = 1.32±0.11

5 Pulsed
1E 1841-045
RXTE/HEXTE

6 Pulsed
1E 1841-045
IBIS ISGRI

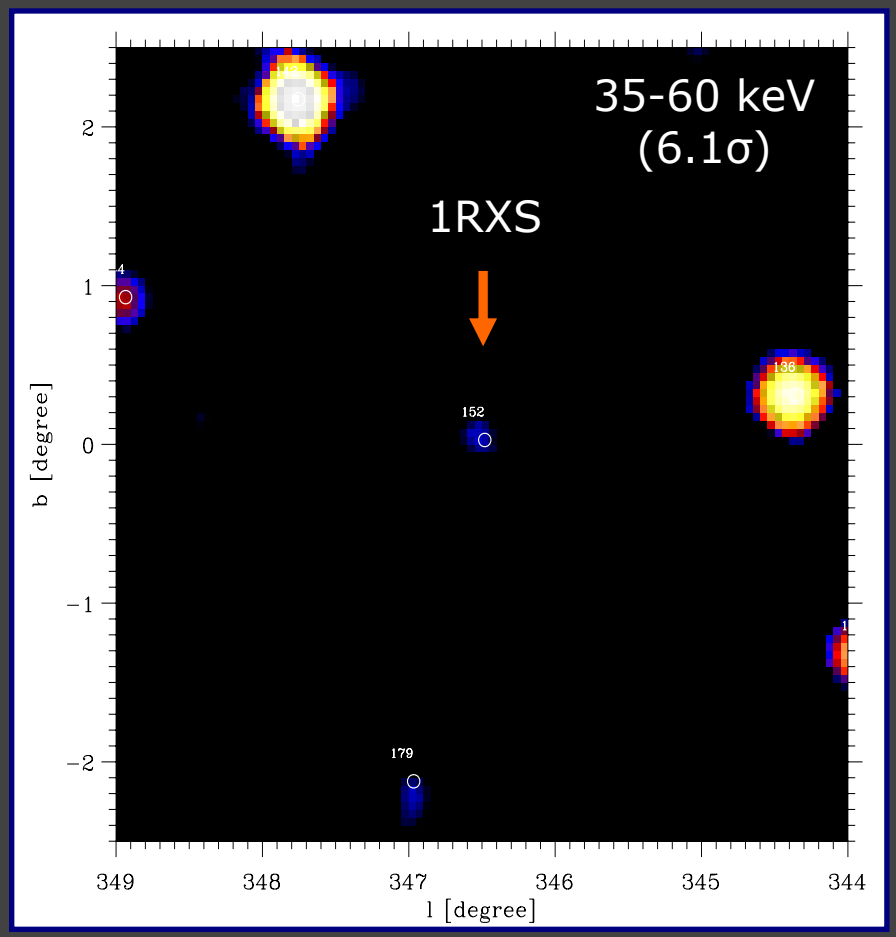
7 Total
1E 1841-045
COMPTEL

Pulsed:
Γ_h=0.72±0.15

SRON

1RXS J170849.0-400910

4U 1700-377



Discovery >18 keV reported by
Revnivtsev et al. 2004

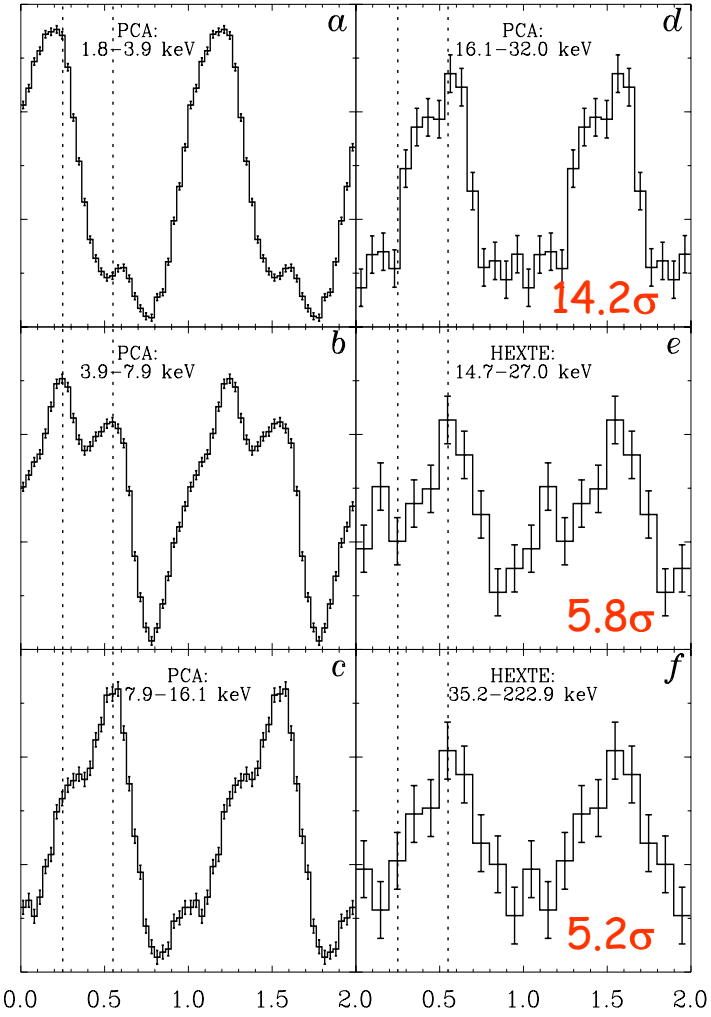
OAO 1657-415

IBIS ISGRI
Revs. 36-106
1.92 Ms

SRON

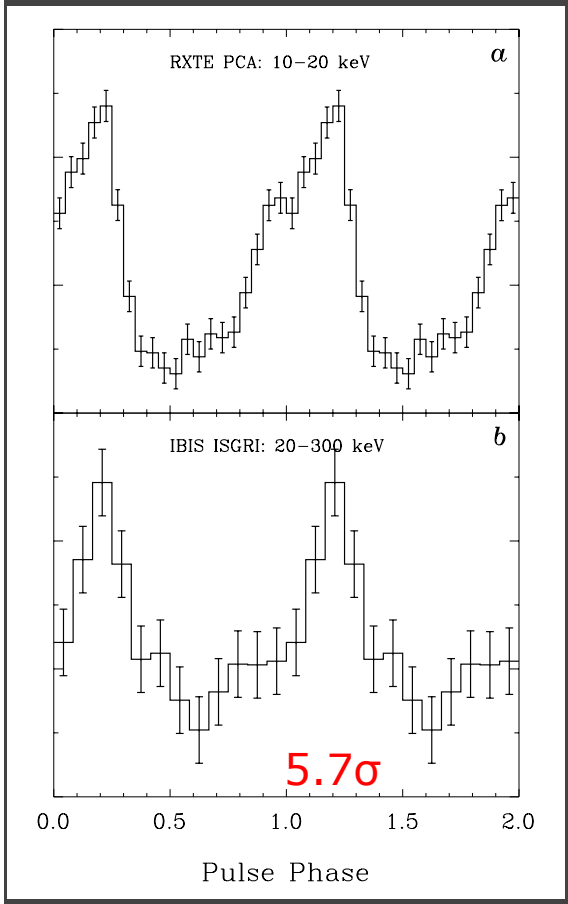
1RXS J170849.0-400910

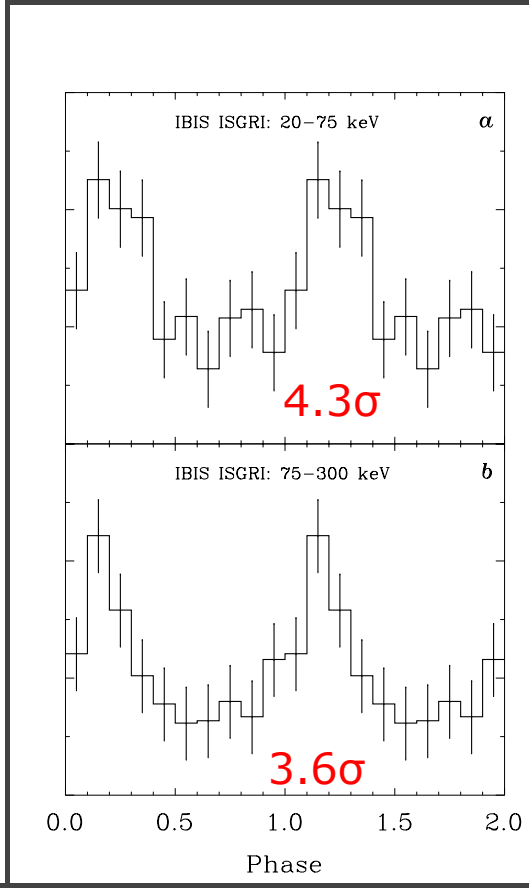
RXTE PCA/HEXTE



INTEGRAL IBIS ISGRI

RXTE PCA / IBIS ISGRI





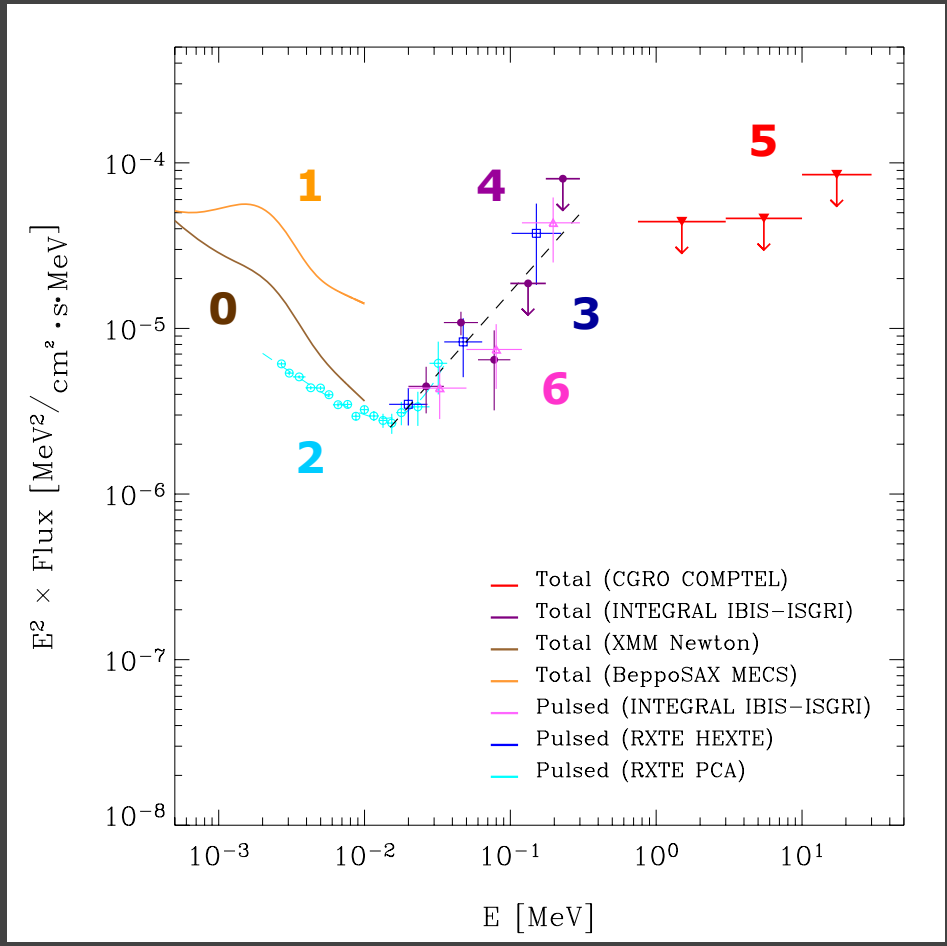
1RXS J170849.0-400910

0 Total
XMM Newton
(Rea et al. 2005)

1 Total
BeppoSAX
(Rea et al. 2003)

2 Pulsed
RXTE PCA

$\Gamma_s = 2.6 \pm 0.01$
$\Gamma_h = -0.12 \pm 0.07$



3 Pulsed
RXTE/HEXTE

4 Total
6 Pulsed
INTEGRAL

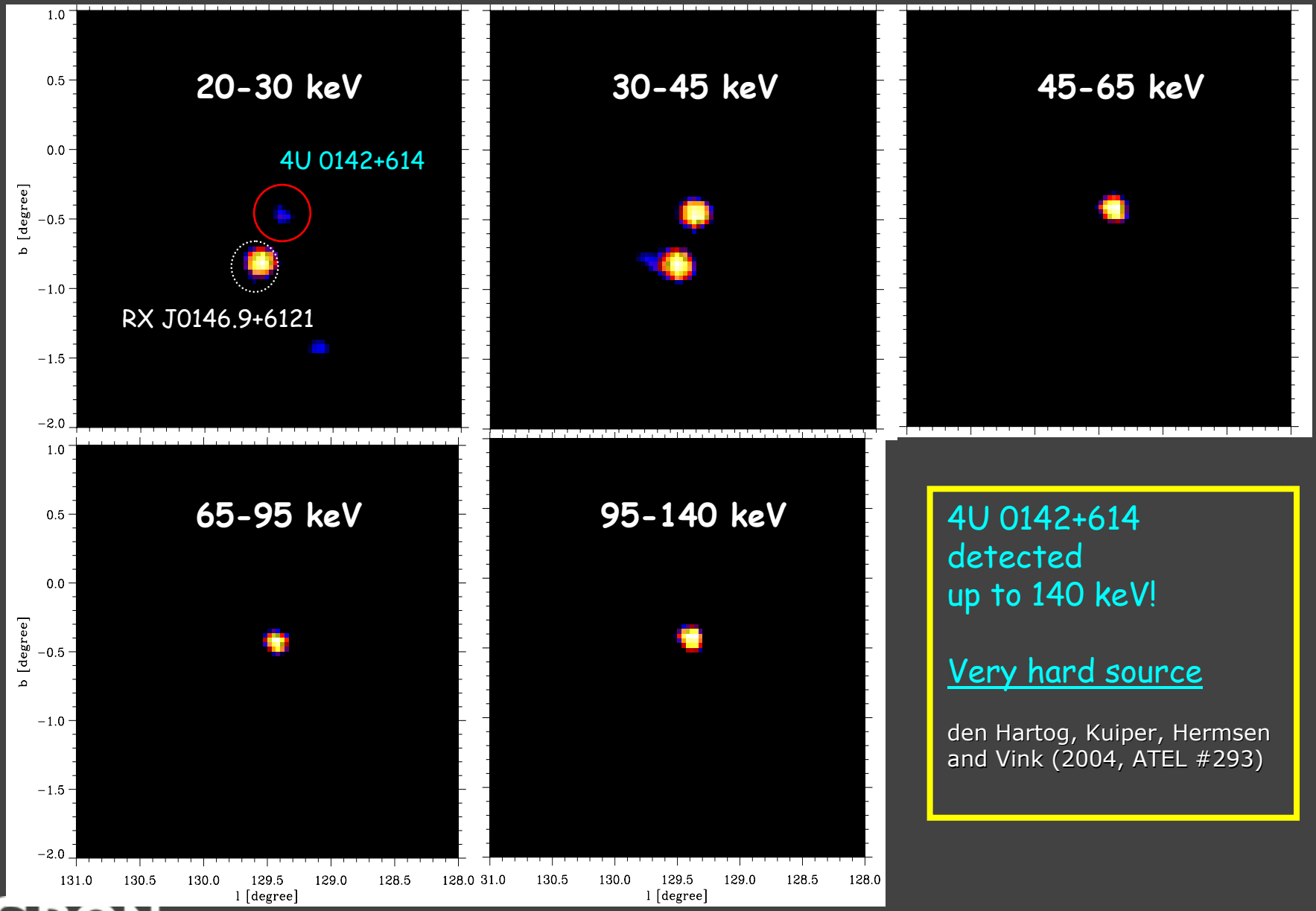
5 Total
CGRO COMPTEL

Pulsed spectrum
10-100 keV:
$\Gamma_h = 1.01 \pm 0.12$

Above 10 keV: Pulsed fraction 100%
But time variable below 10 keV? (see also poster by Sutaria)

SRON

AXP 4U0142+614; IBIS ISGRI 2.1 Ms Observation

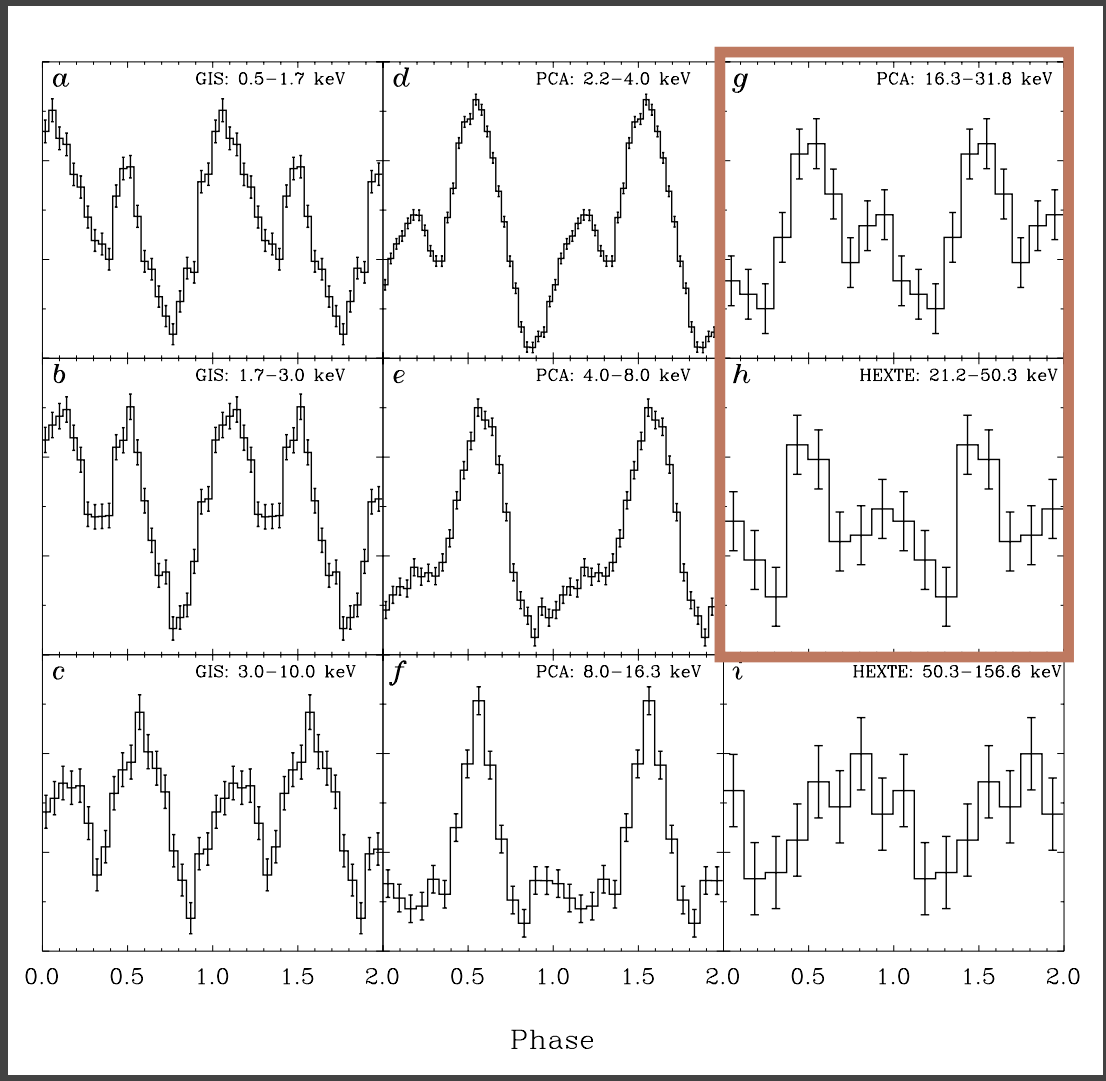


4U 0142+614
detected
up to 140 keV!

Very hard source

den Hartog, Kuiper, Hermsen
and Vink (2004, ATEL #293)

AXP 4U 0142+614; Profiles ASCA GIS, RXTE PCA/HEXTE



5.7σ

3.4σ

2.1σ

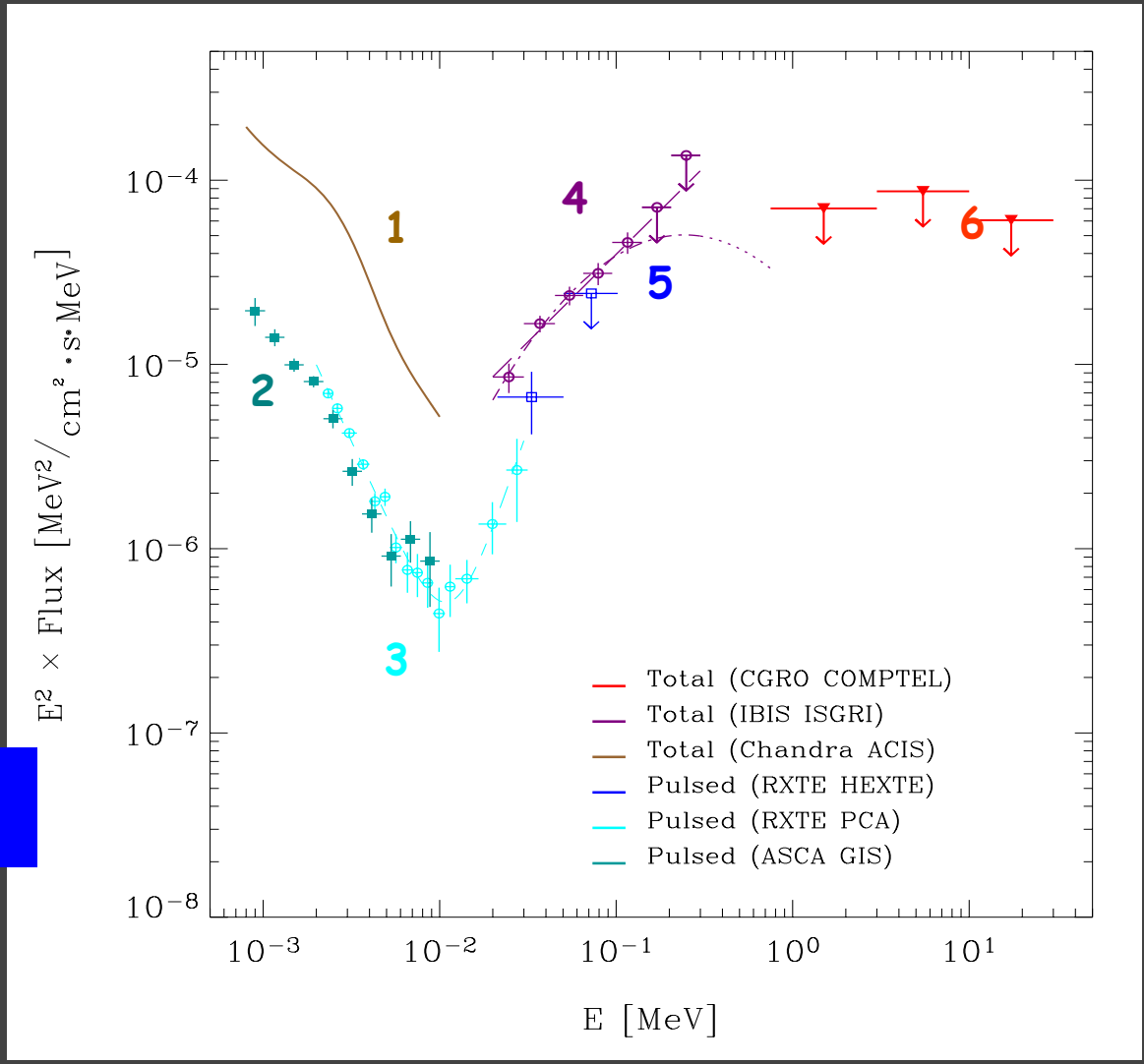
High Energy Spectra of AXP 4U 0142+164

1 Chandra
Total

2 ASCA GIS
Pulsed

3 RXTE PCA
Pulsed

Γ_s=4.09±0.02
Γ_h=-0.80±0.09



4 IBIS ISGRI
Total

Γ_h=1.05±0.11

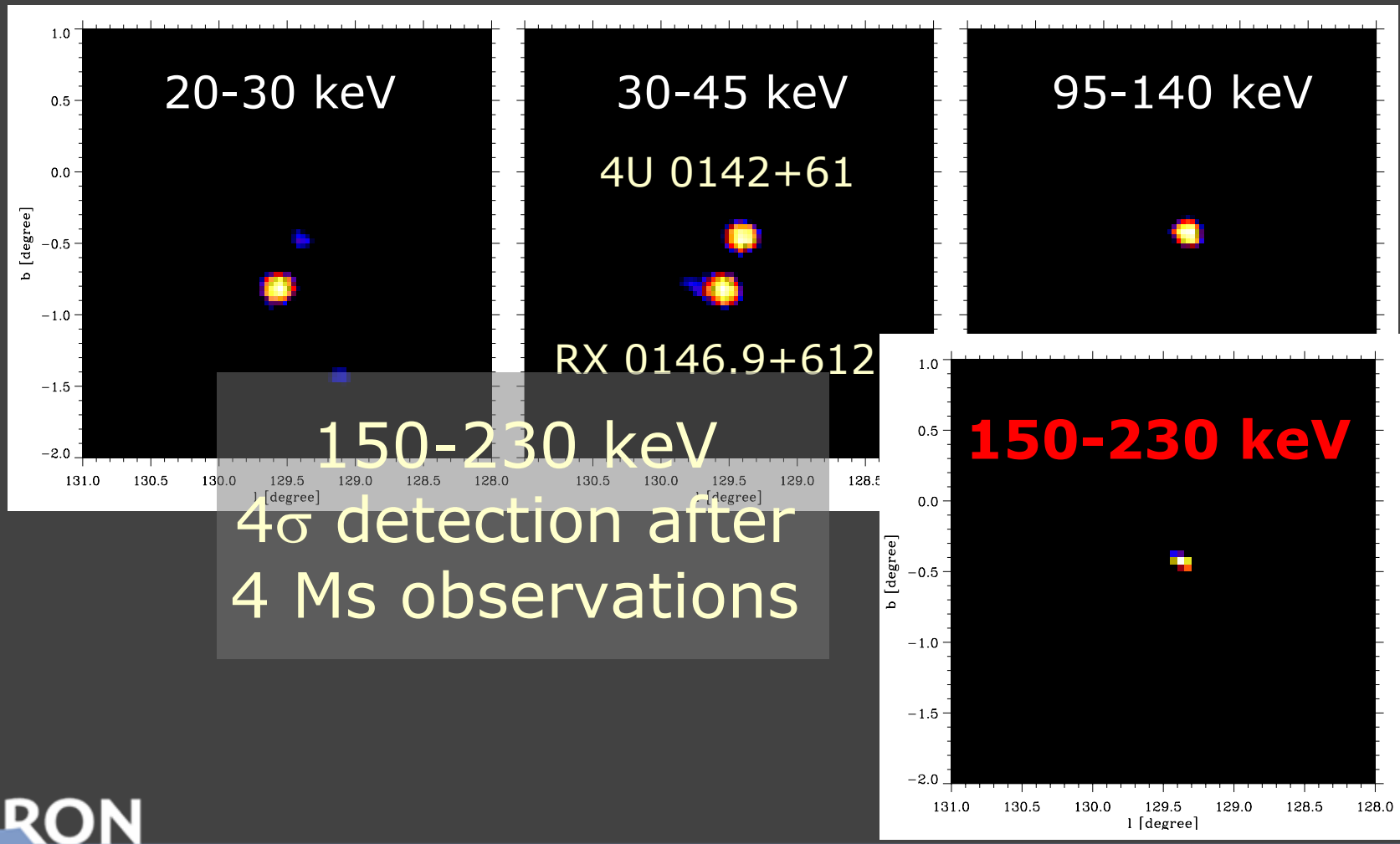
5 RXTE HEXTE
Pulsed

6 CGRO COMPTEL
Total

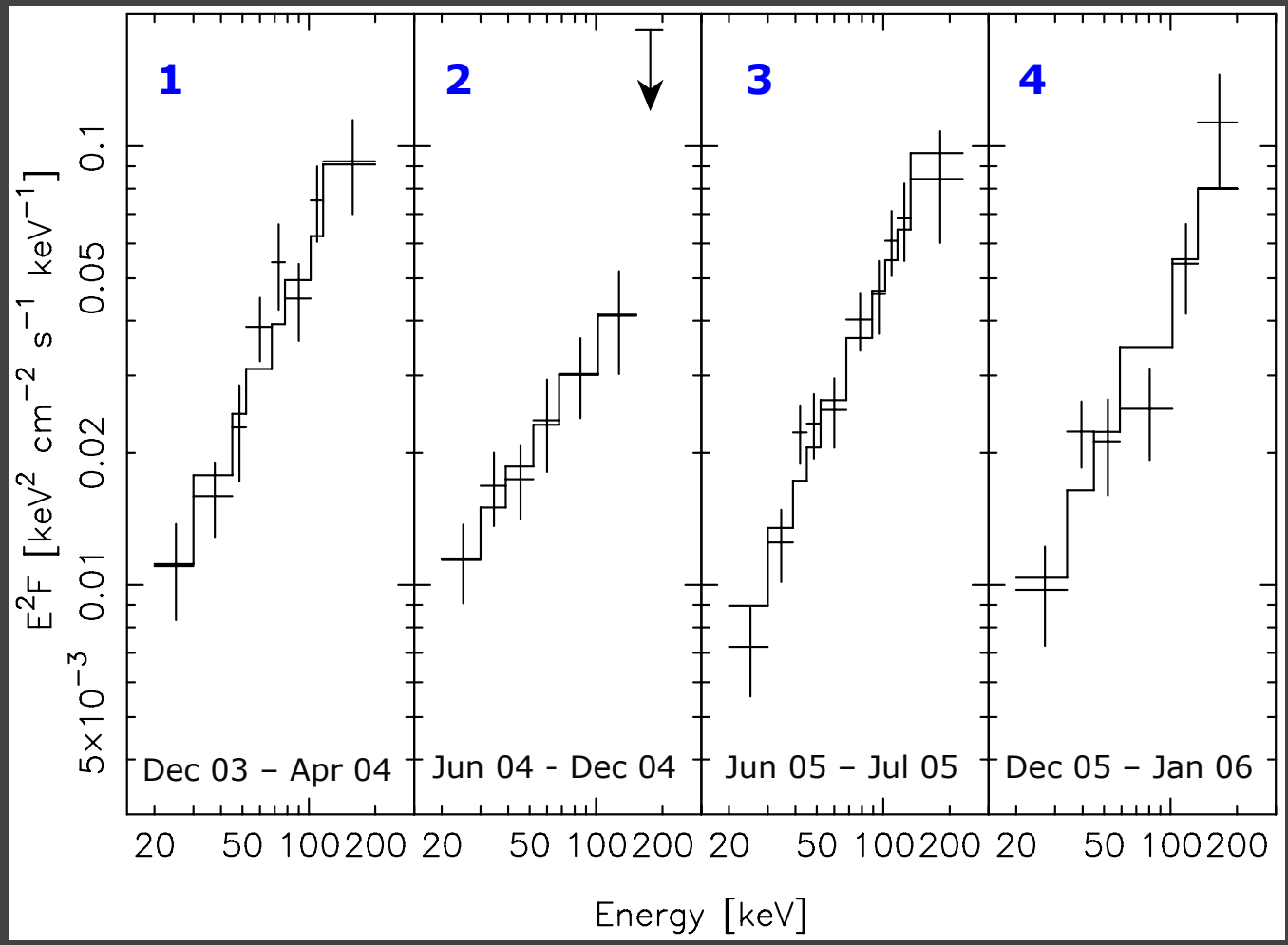
Below 10 keV time variable! Rea et al. (2004, 2005)

SRON

4U 0142+61 w. INTEGRAL IBIS-ISGRI



4U 0142+61: Persistent hard tail

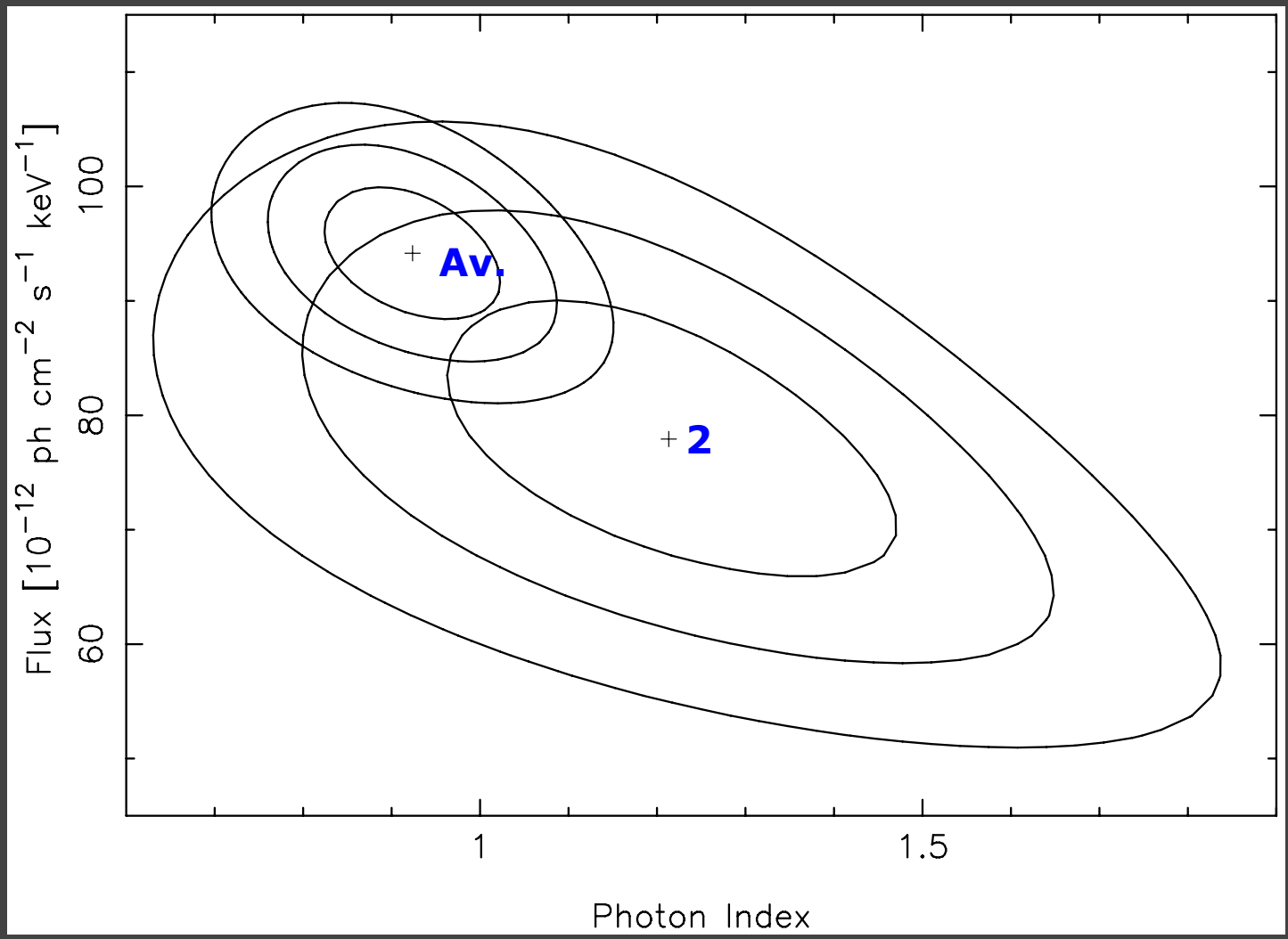


Γ:	0.85 ± 0.14	1.21 ± 0.16	0.79 ± 0.10	0.89 ± 0.17
Flux:	11.3 ± 0.8	7.8 ± 0.8	9.8 ± 0.6	9.5 ± 0.9

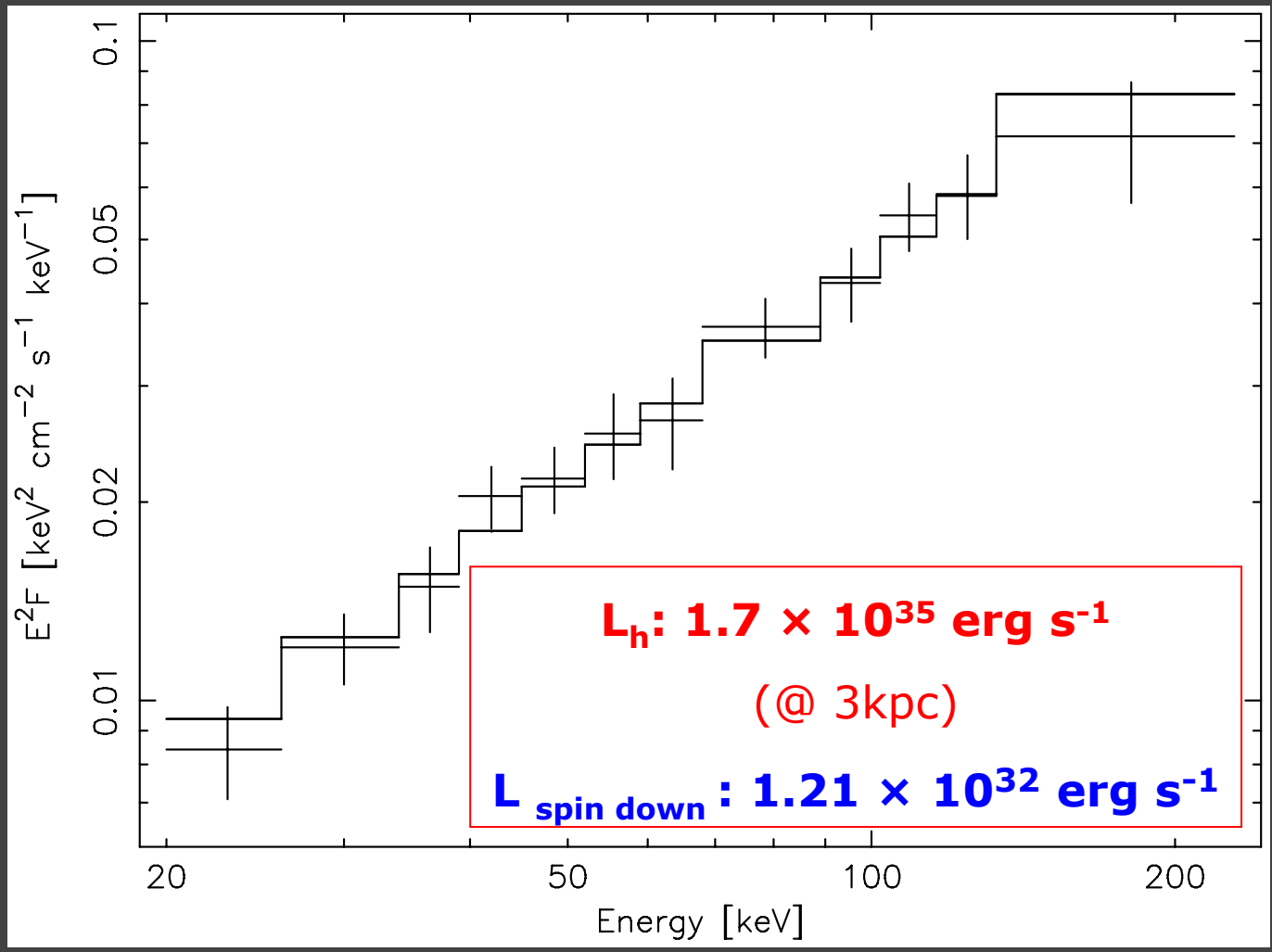
SRON

$\times10^{-11}$ erg cm^{-2} s^{-1} (20-150 keV)

4U 0142+61: No significant variability for E>20 keV



4U 0142+61: Combined INTEGRAL spectrum



Γ = 0.92 ± 0.07 [20-229 keV]

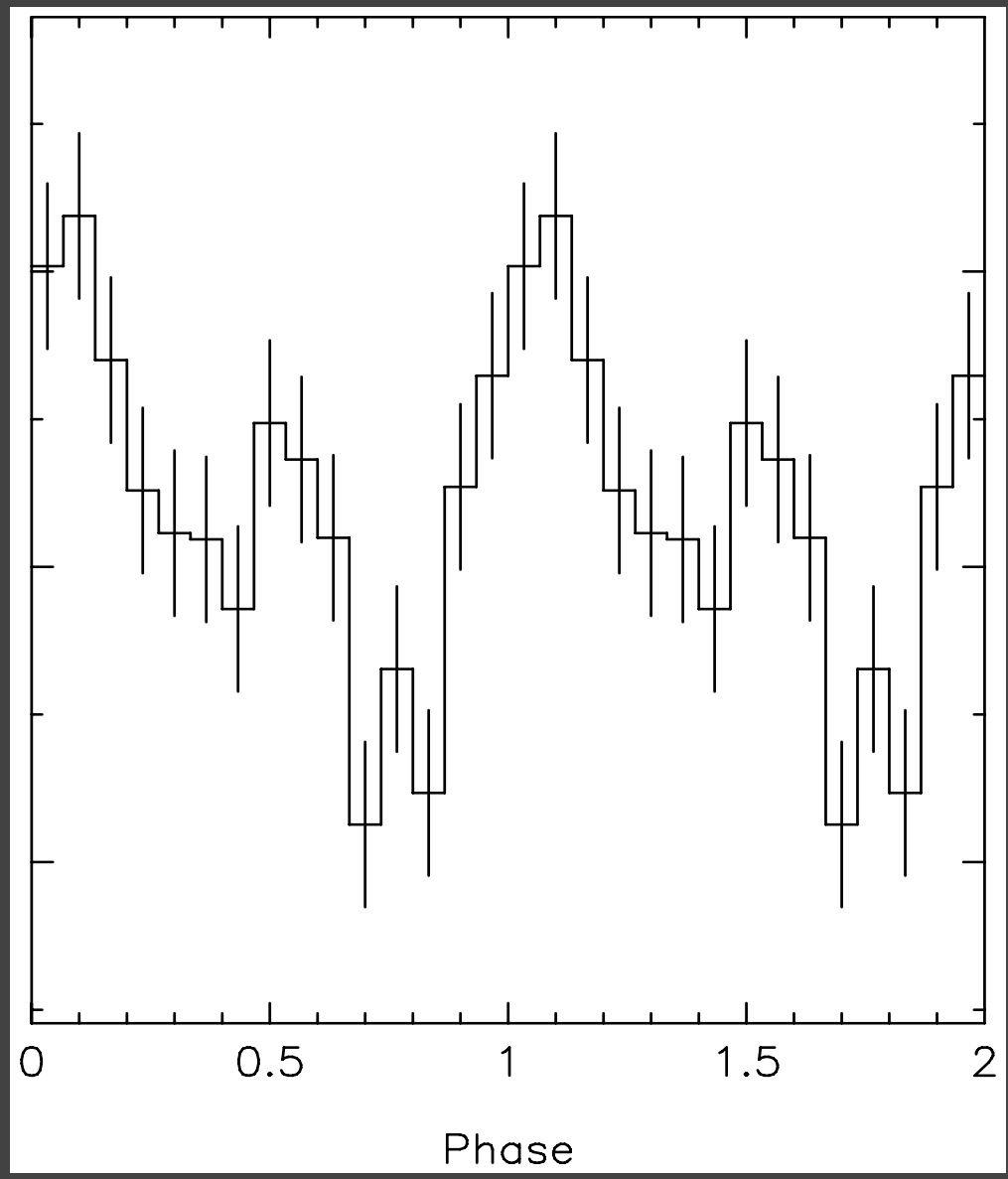
Flux = 15.57± 0.95 ×10^{-11} erg cm^{-2} s^{-1}

SRON

4U 0142+61 high-energy pulse profile

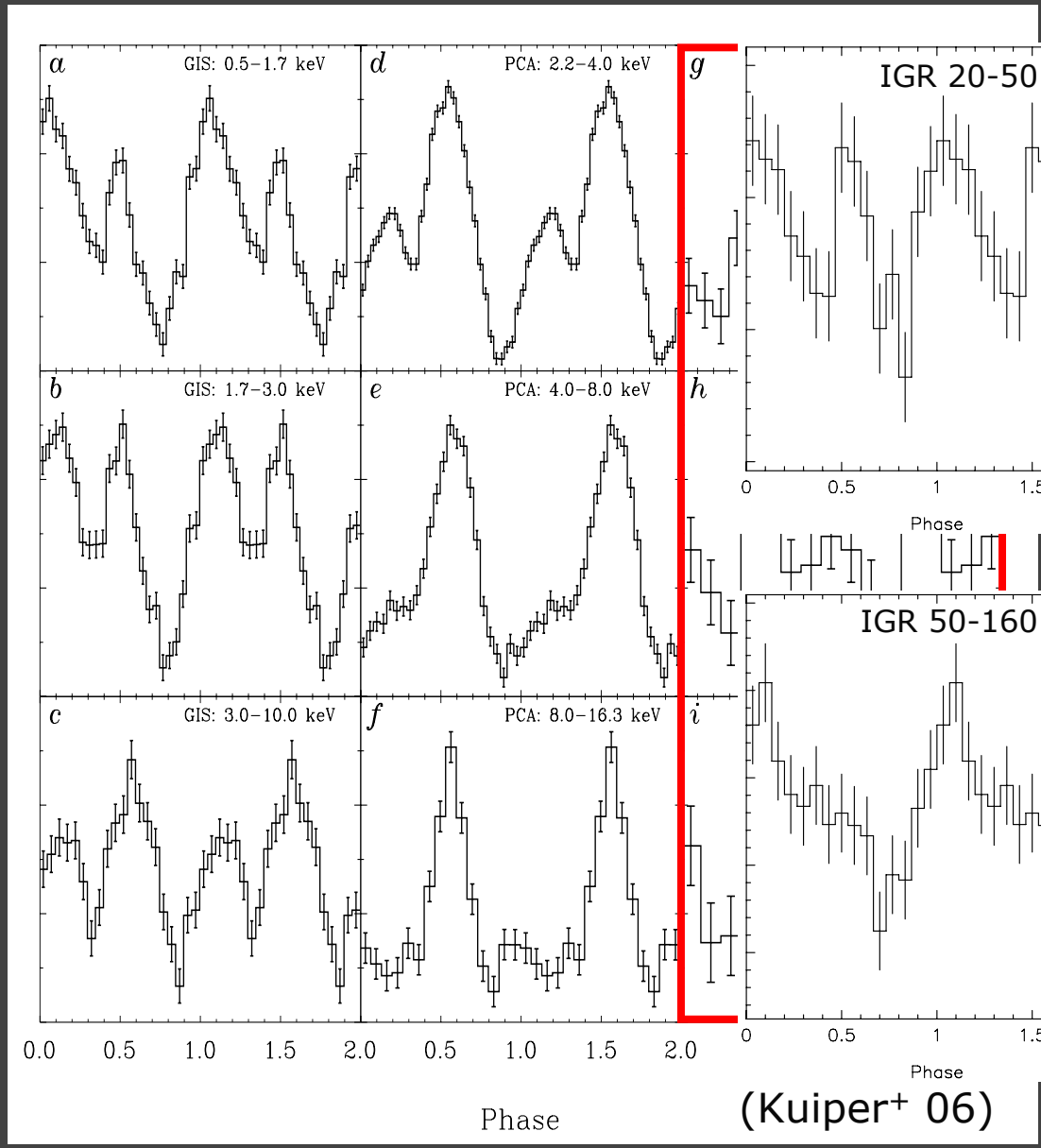
INTEGRAL

20-160 keV: 6.5σ

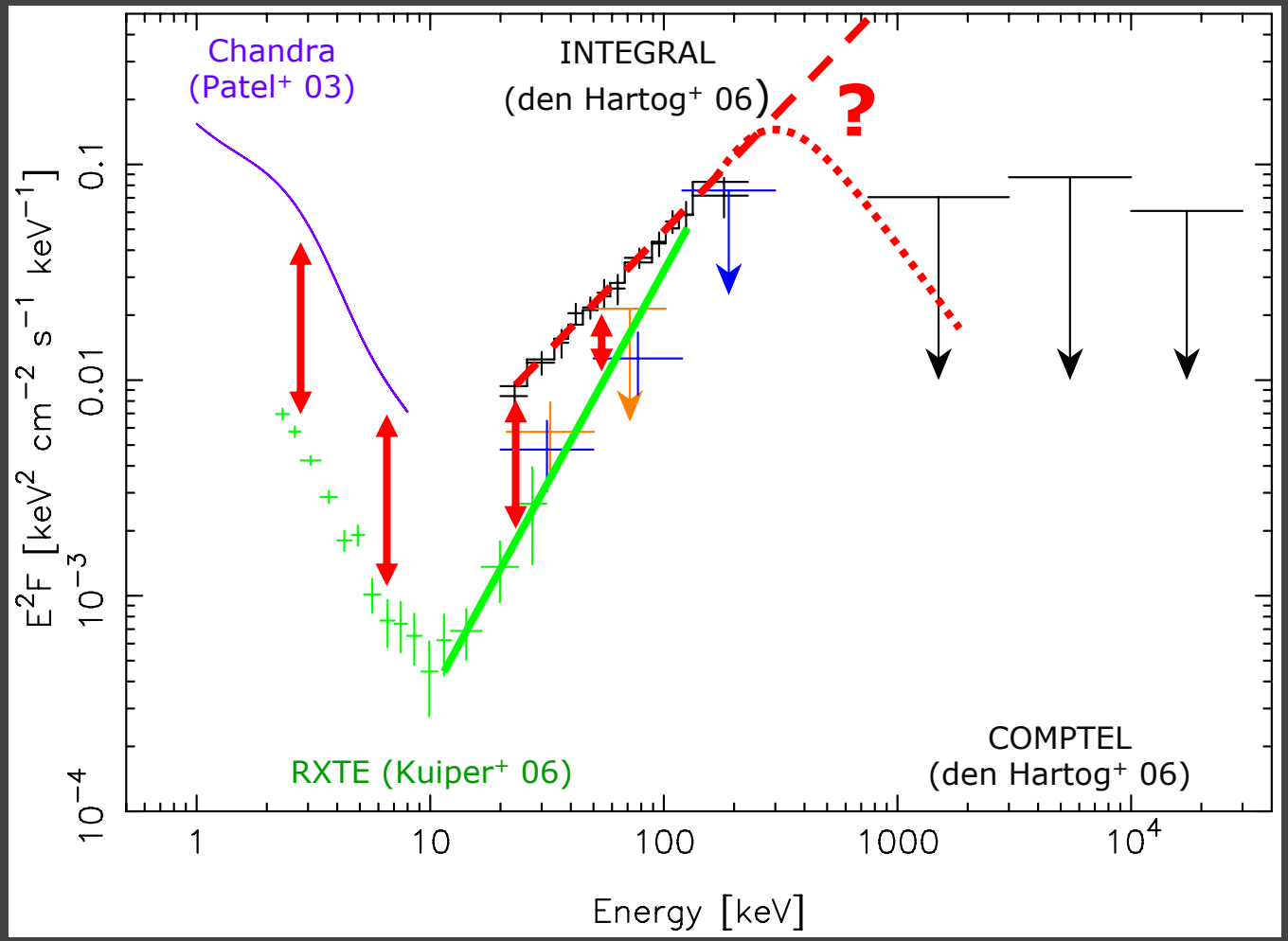


SRON

4U 0142+61 pulse-profile changes with Energy



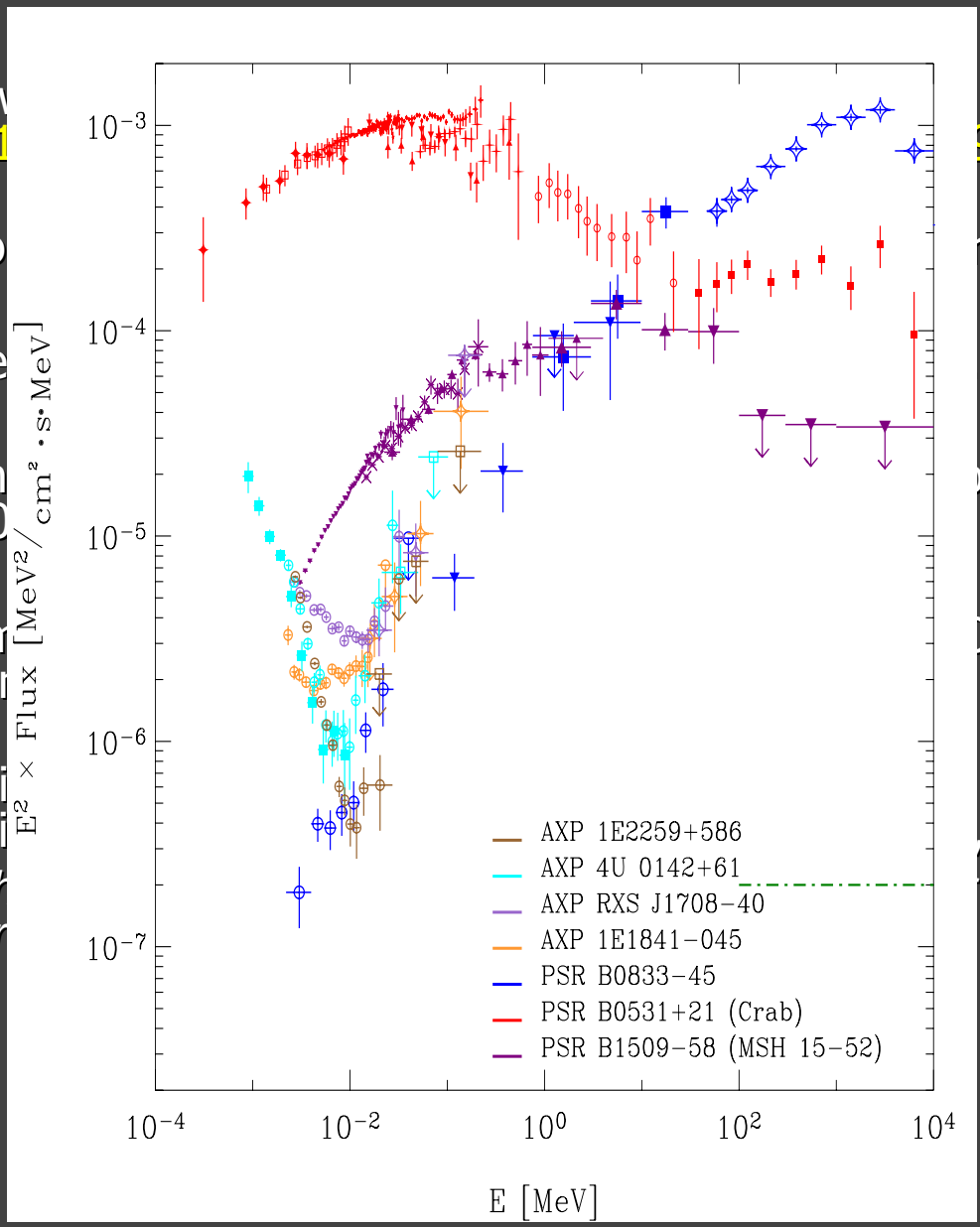
4U 0142+61 – X-ray Spectrum



Conclusions (1) on AXP spectra

- Hard power-law
- Pulsed emissio
- Spectra total e
- Pulsed fraction
  already at ~10
- Hard X-ray lum
  than spin-down
- Still no indicati
  these must exi
  (*unless these h*
  Comptel upper

(4) AXPs:
1E1841-045; 1 9+586)
range -1.0 to 1.0
0 to 1.4
or 1RXS J1708
00 times larger
100 keV, but
s and the



- **Mutiwavelengths campaign on 4U 0142+61**

First (quasi) simultaneous observations from radio to hard X rays

Radio: Westerbork Synthesis Radio Telescope - B. Stappers

NIR/Optical: Gemini North - M. van Kerkwijk & M. Durant

Soft X-rays: Swift - N. Rea & G.L. Israel;

Soft X-rays: RXTE - V. Kaspi & R. Dib (Timing)

Hard X-rays: INTEGRAL - W. Hermsen, L. Kuiper, P.R. den Hartog

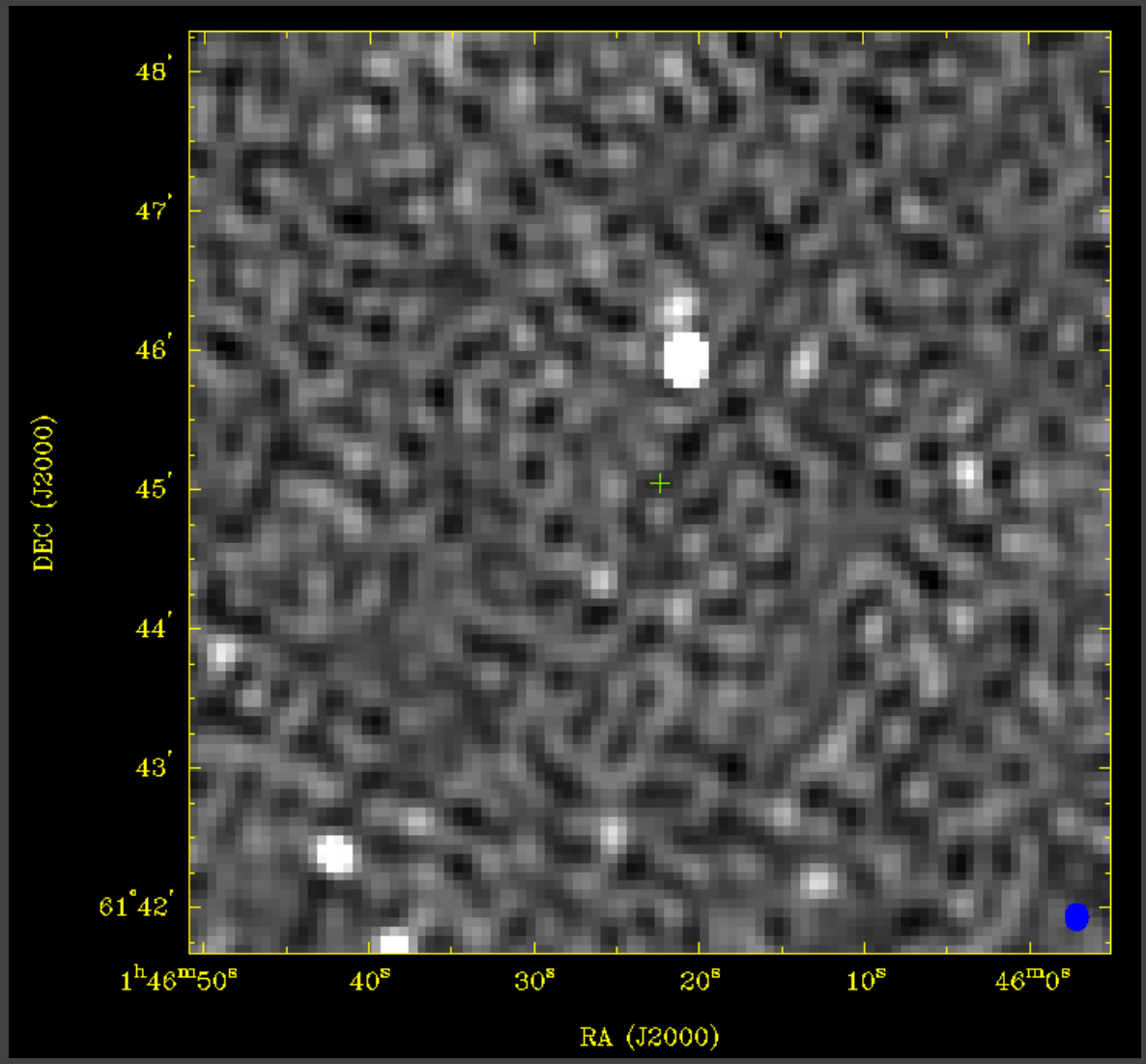
Westerbork Radio Telescope observations

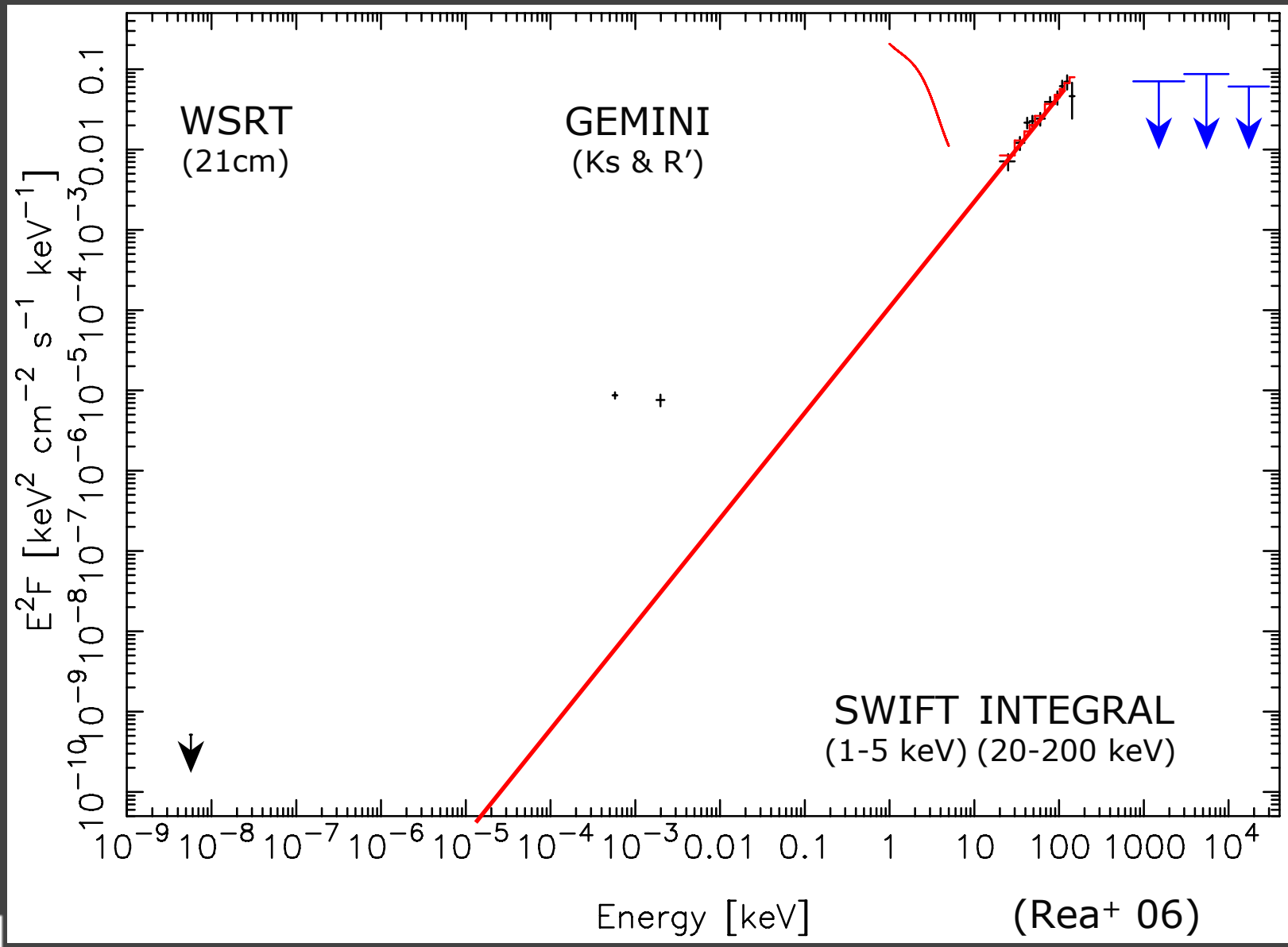
1380 MHz (21 cm)

12 h observation

rms = 30 μJy

'strong' source: 2mJy




WSRT
(21cm)
GEMINI
(Ks & R')
SWIFT INTEGRAL
(1-5 keV) (20-200 keV)
E^2F [keV^2 cm^{-2} s^{-1} keV^{-1}]
10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 0.01 0.1
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 0.01 0.1 1 10 100 1000 10^4
Energy [keV]
(Rea+ 06)

Conclusions (2) on 4U 0142+61

- Detected up to 230 keV with $\Gamma = 0.92$ for total spectrum
- No indication yet for a spectral break
- No detection of long-term time variability over 25-months period
- L(20-230 keV) = 1.7×10^{35} erg s^{-1} , or ~1000 $L_{\text{spin down}}$
- NIR spectral points far above extrapolation hard X-ray power-law spectrum
- Radio upper limit also above extrapolation (not constraining)

SRON

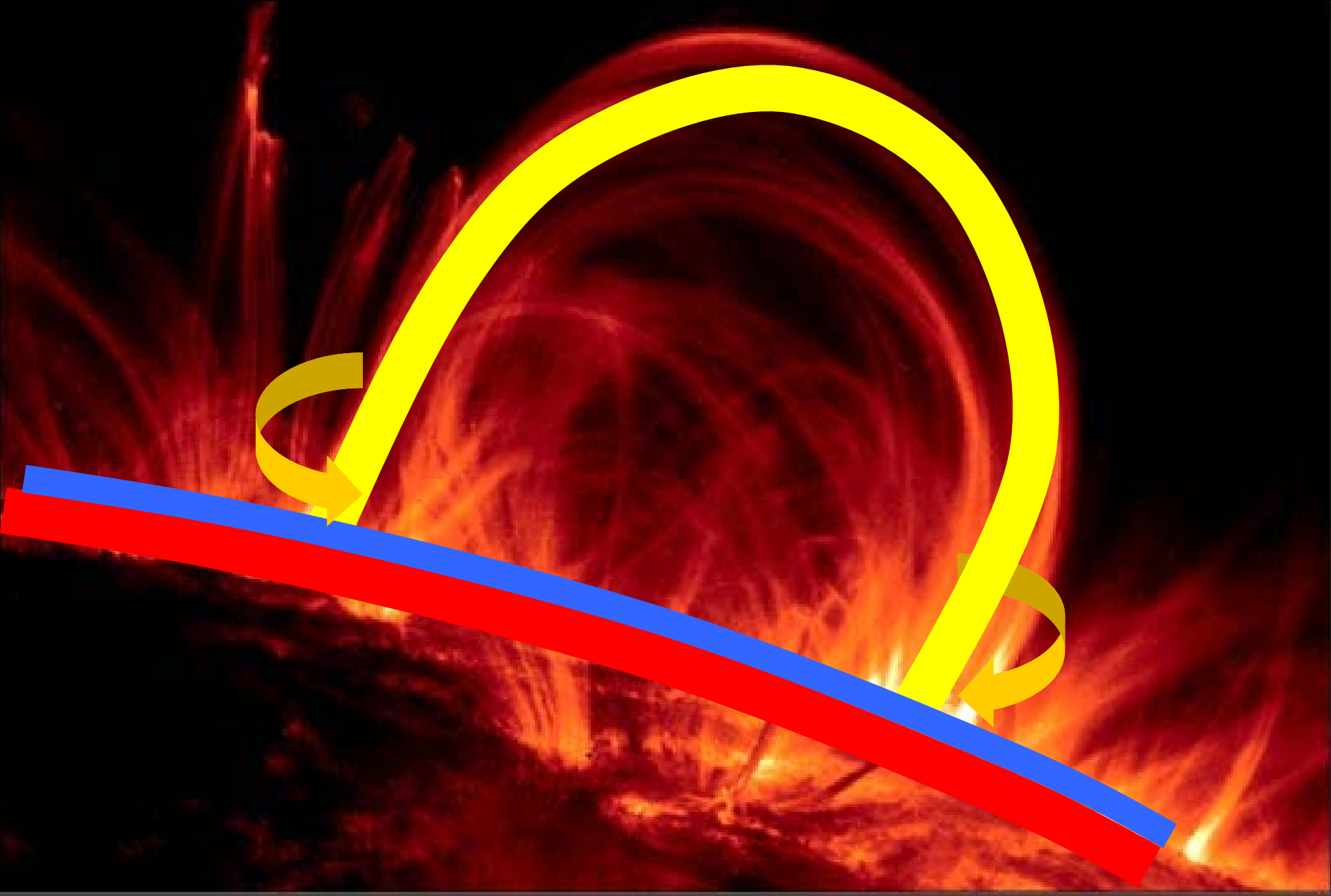
- **First theoretical attempts**

Thompson & Beloborodov 2005, ApJ 634, 565

- Strong $E_{||}$ induced by twisting of field in closed field line region
  - Down-ward beam of current carrying charges excites Langmuir turbulence in surface layers Bremstrahlung photons up to ~100 keV
  - Upscattering of keV photons pair creation synchrotron radiation from electron acceleration at high altitude (~100 km) with peak at ~1 MeV

◊ **Marginally or not consistent with the measured spectra**

◊ **How are pulsations explained?**



SRON Beloborodov & Thompson 2006: Hot coronae around magnetars

- **Magnetosphere is twisted and filled with a plasma corona.**

  The corona can be viewed as a collection of 1D plasma tubes closed to the star. Crust motions in star quakes impart curl(**B**) into the corona.

- **Plasma and electric field in the corona are self-organized**

  a) to maintain the current density **j** dictated by curl(**B**),

  b) to keep voltage along magnetic lines near threshold for pair production:

  $e\Phi \sim \gamma_{res} m_e c^2 \sim 1$ GeV.

- **The corona is made mostly of relativistic e+/- pairs**

  (ions ~ 10%). It is continually lost to the surface and replenished by e+/- discharge. Its density is $\sim n_{min} = j / e c$.

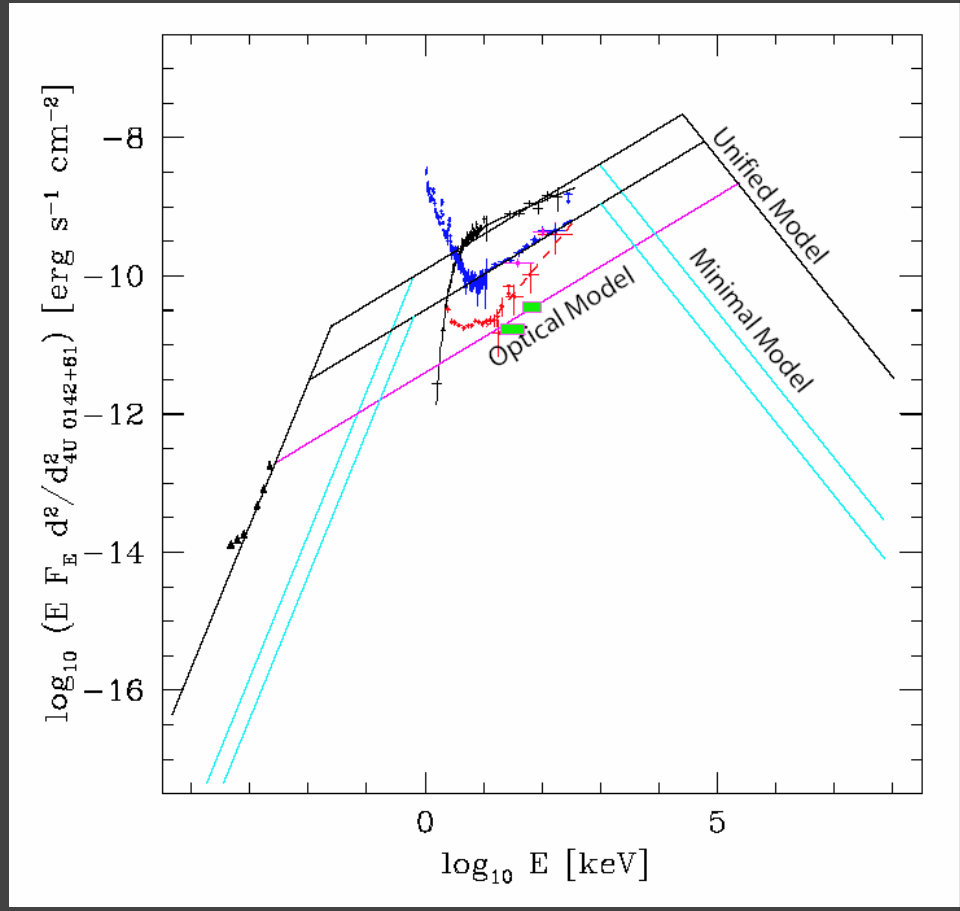
- **Voltage $e\Phi$~1 GeV implies dissipation rate $L=I\Phi \sim 10^{36}$ erg/s.**

  The main sink of the dissipated energy is the surface layer which produces hard X-ray emission. Source of energy – twisted magnetic field.

- **The corona lives 1-10 yr unless new star quakes happen: variability?**

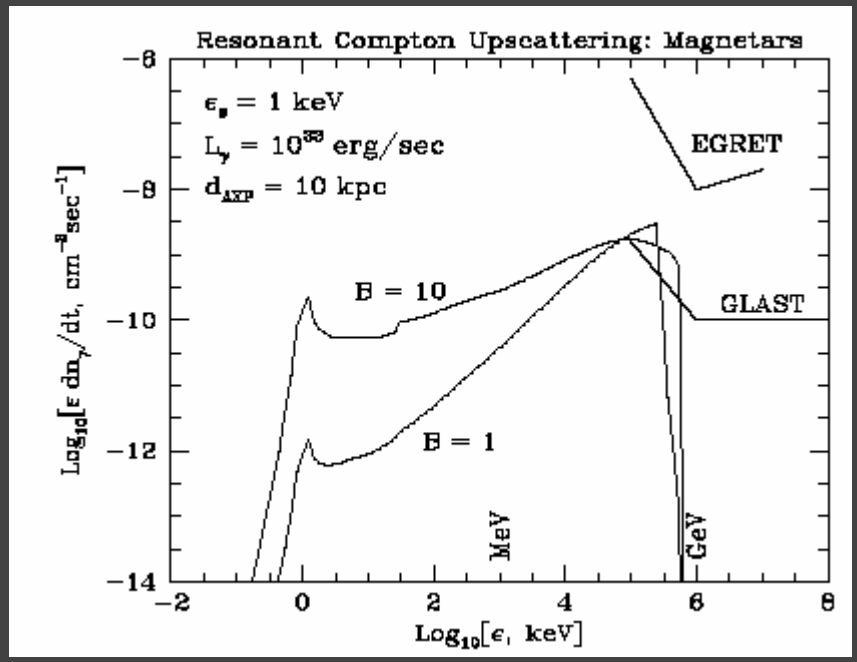
Heyl & Hernquist 2005, ApJ 618, 463; MNRAS, 362, 777

- Fast-mode breakdown wave energy into pairs synchrotron cascade
- No break energy below 1 MeV: not consistent with data



Baring & Harding 2006

- Resonant, magnetic Compton upscattering of thermal X-rays by accelerated particles in open field region
- Source of energy?



Outstanding questions

- Same as long lists in presentations by Hurley and Israel

- More detailed observational results on hard tails:
  - where are the spectral breaks?
  - variabilty similar as for E<10keV?
  - phase-resolved spectroscopy to identify different pulse components
  - cyclotron lines?
  - correlations with IR and optical emissions?
  - really no radio signal?

- Further theoretical modelling!