Linking the soft γ-ray pulsar population with the Fermi LAT pulsar population: completing the high-energy picture

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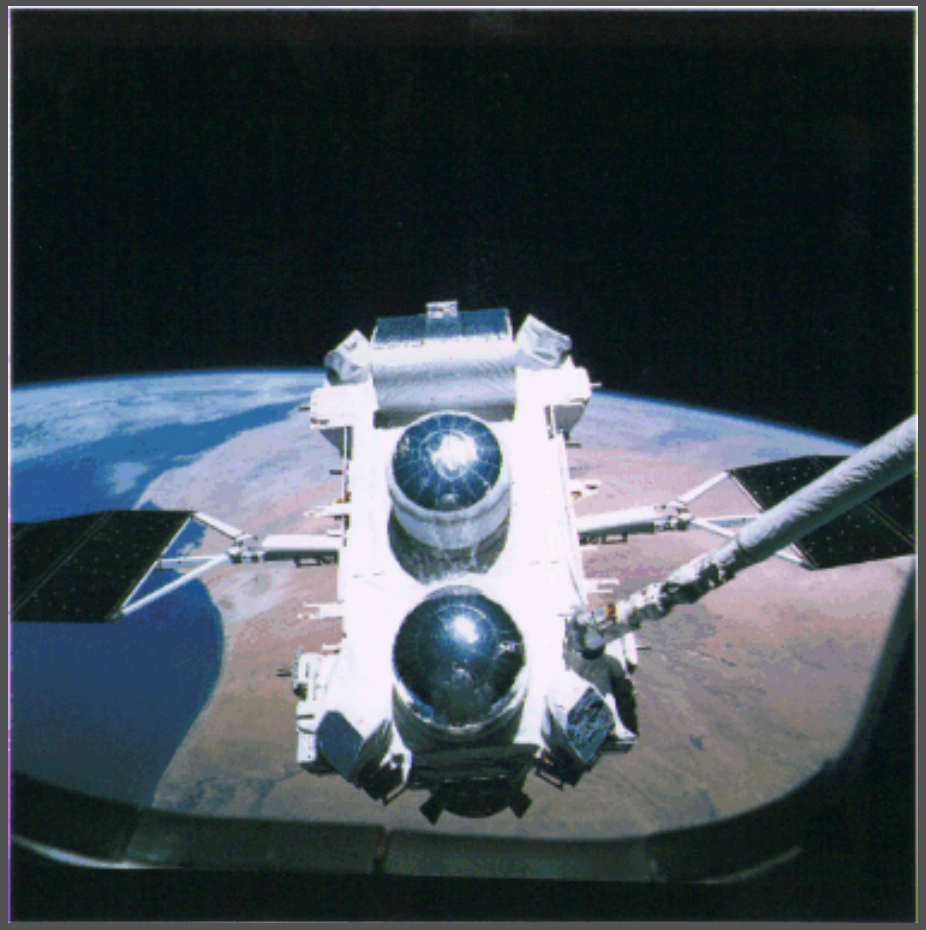
Outline of presentation

- Pre-Fermi status (CGRO); Fermi LAT (>100 MeV) pulsar population
- Observational status of pulsar emission in the hard X-ray / soft γ-ray window (> 20 keV)
  - Increase of sample: How?
    Work horses
  - Current secure member list
  - Update PSR B1509-58 & Vela

    Zoom-in on some recent 'new' members AX J1838.0-0655, PSR J2229+6114 and IGR J18490-0000
- Population comparisons
- Summary & conclusions

Heritage

CGRO: 5 April 1991 – 4 June 2000
(20 keV – 30 GeV)



Only 4 pulsars detected in hard X-ray regime (> 20 keV)….

1) Classical γ-ray pulsars (*SAS-2, COS-B*)

PSR B0531+21 (Crab)
PSR B0833-45 (Vela)

2) Newly discovered high-energy γ-ray pulsars

PSR B1706-44
PSR B1055-52
PSR B1951+32
Geminga
PSR J0218+4232, msp!
PSR B0656+14
PSR B1046-58

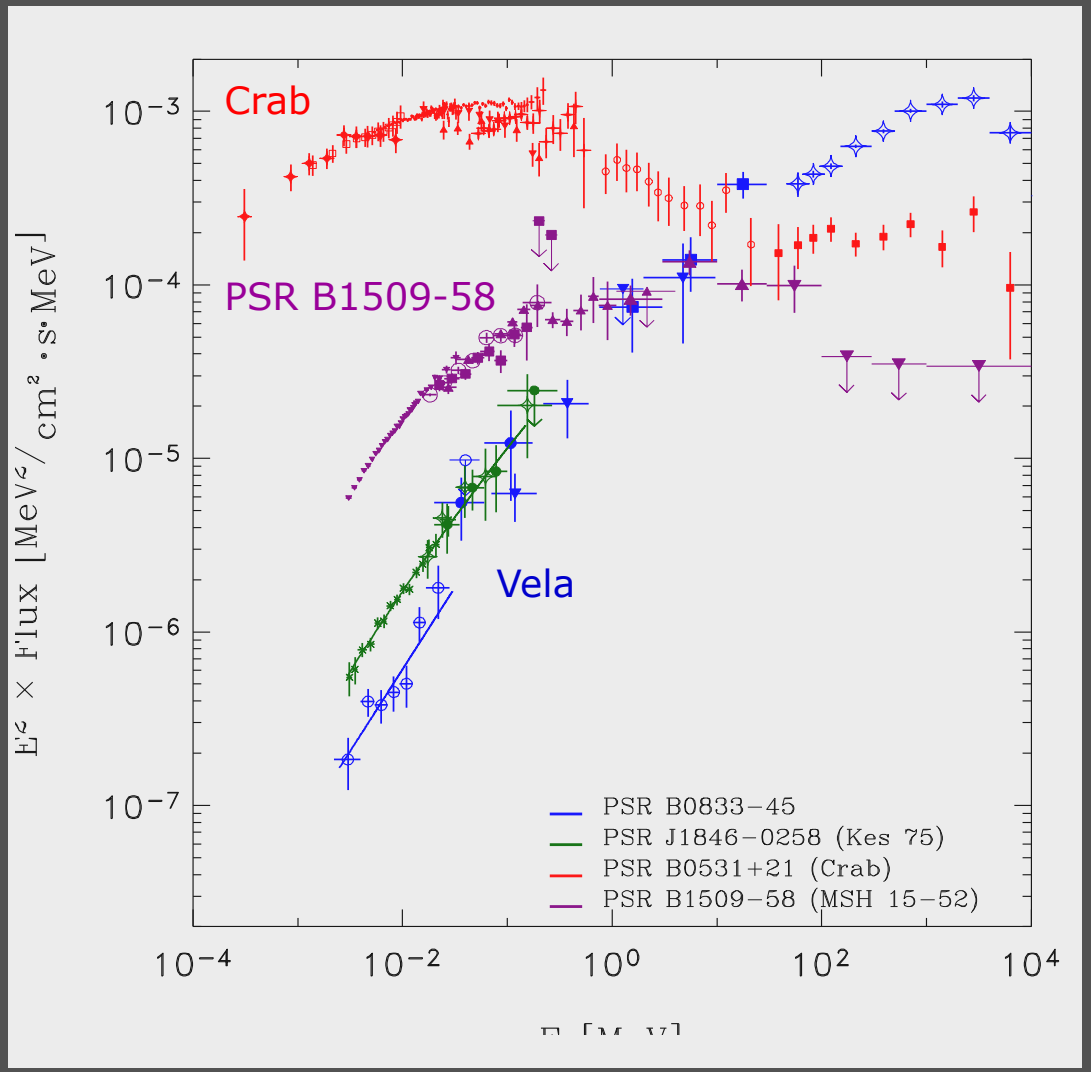
3) Newly discovered soft γ-ray pulsars

PSR B1509-58
PSR B0540-69 (RXTE HEXTE)
(de Plaa, Kuiper, Hermsen 2003)

Spectral Energy Distributions

- Young pulsars, e.g. Crab, PSR 1509-58 reach maximum luminosity below 100 MeV
- Middle-aged Vela and older pulsars reach max. luminosity at GeV energies
- High-energy spectra of young pulsars are different from spectra of older γ–ray pulsars:

  L_X/L_γ larger for young pulsars!



High-energy γ-ray (>100 MeV) pulsar population Fermi LAT findings

Radio-loud : 42

Radio quiet: 35

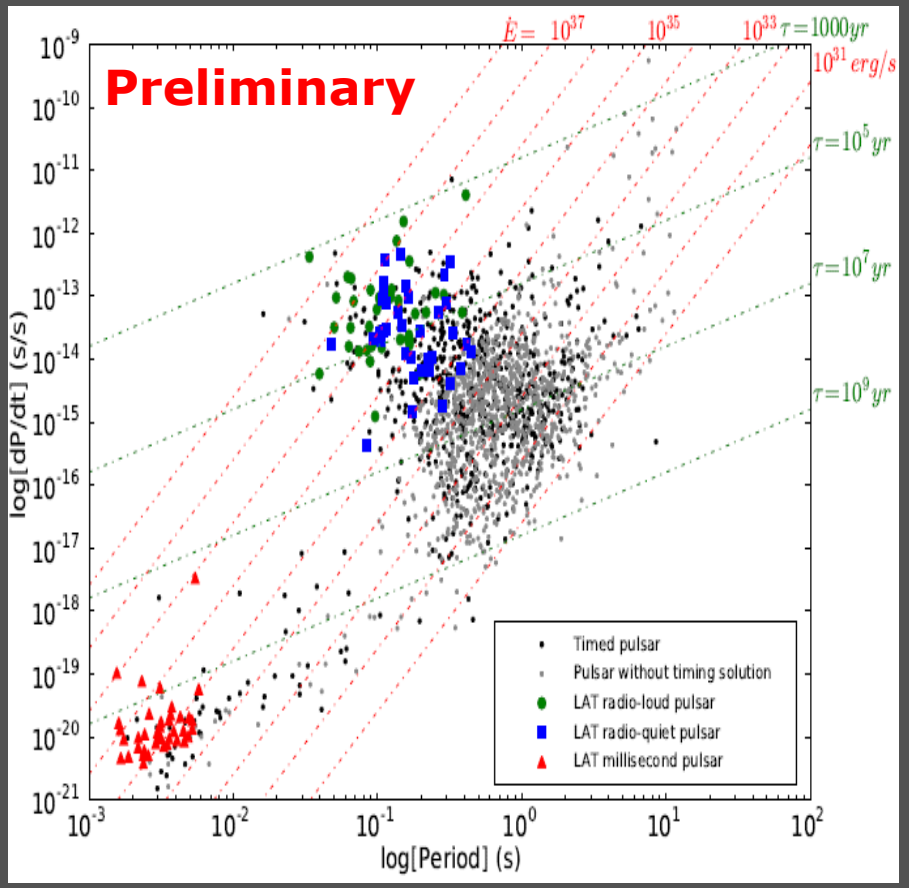
Ms pulsars : 40 (recycled)

Young pulsars: 77 (non-recycled)

Simple exponential cutoff Pl model ➔ Outer-magnetospheric emission

Maximum luminosity at GeV energies!

2nd Fermi LAT Pulsar Catalogue: # 117



Abdo et al. 2013; ApJS 208, 17

Soft γ-ray pulsar population (> 20 keV)

Step 1

Identification of energetic point-sources in supernova remnants (radio), unidentified Fermi LAT/CGRO EGRET (>100 MeV), INTEGRAL (>20 keV) or HESS/VERITAS/Magic (> 300 GeV; TeV regime) error regions by using the sensitive X-ray instruments aboard Chandra, XMM-Newton, [RXTE], NuSTAR and Suzaku

Step 2

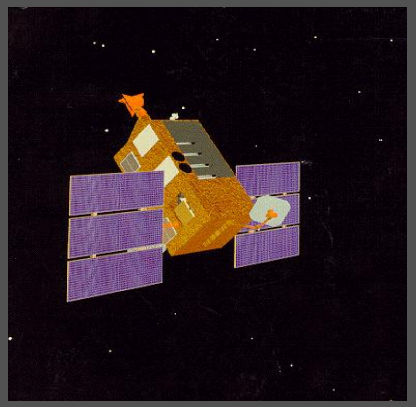
Follow-up with instruments with sensitivity above ~20 keV: Workhorses

With presently available sensitivities long exposures are required, sometimes summing (archival) data collected over years from:

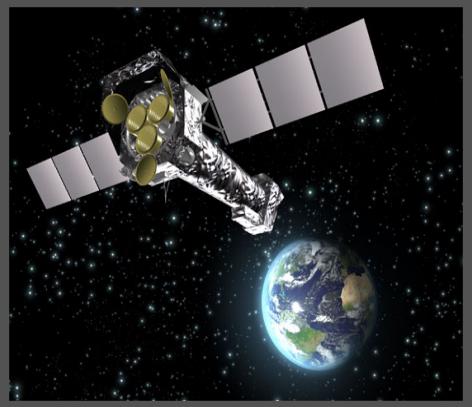
a)	RXTE PCA	(2 - 60 keV; non-imaging)
b)	RXTE HEXTE	(15-250 keV; non-imaging)
c)	INTEGRAL IBIS ISGRI	(15-300 keV; **imaging**)
d)	NuSTAR	(3 - 80 keV; **imaging**)
[e)	Suzaku HXD PIN	(12 - 60 keV; non-imaging)
f)	Swift BAT	(15-150 keV; imaging)]

Good imaging is required to avoid source confusion, particularly in Galactic Plane regions, and to disentangle pulsed and DC (PWN) emission

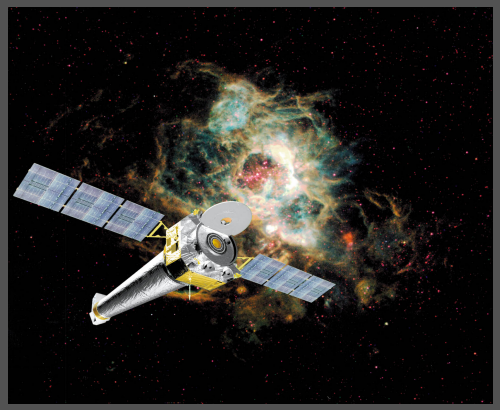
Fleet of high-energy observatories



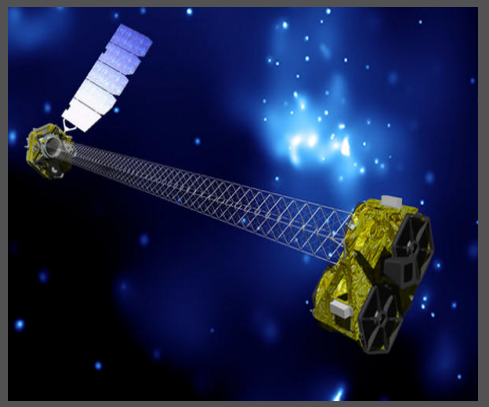
RXTE: 1995-2012



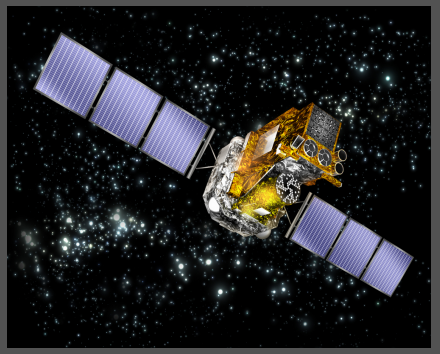
XMM-Newton 1999+



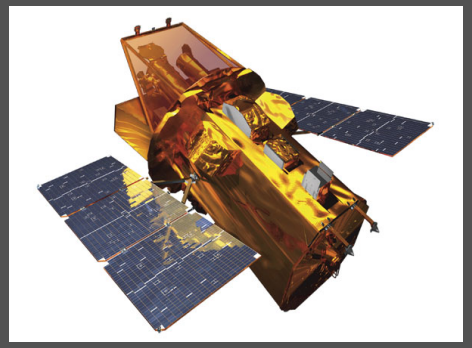
Chandra 1999+



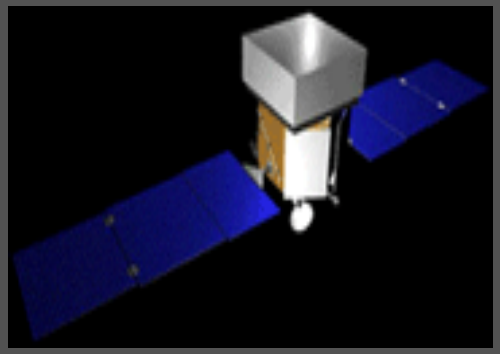
NuSTAR 2012+



INTEGRAL 2002+



SWIFT 2004+



Fermi 2008+

Ground based TeV telescopes: HESS, MAGIC, Veritas, MILAGRO etc.

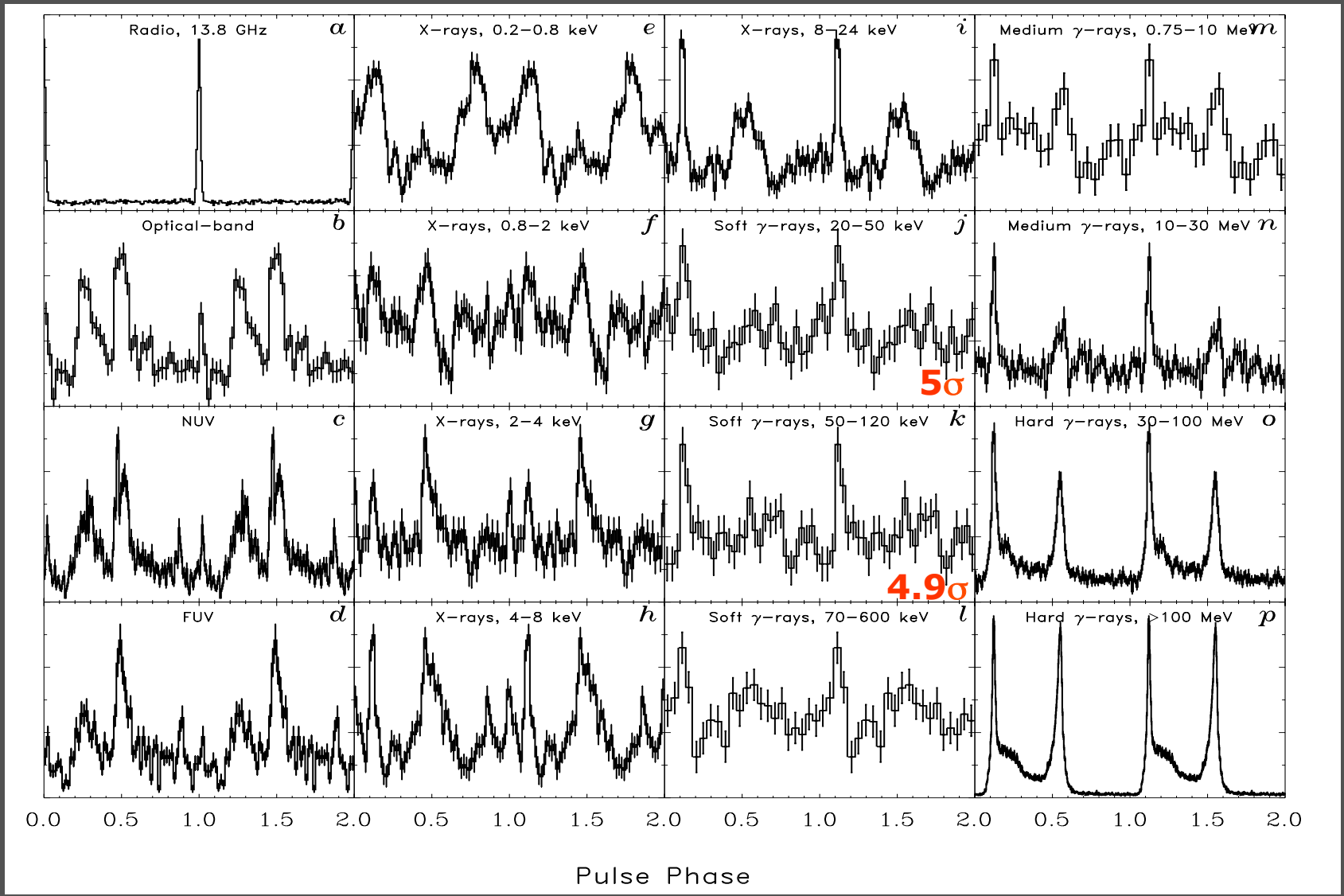
Soft γ-ray pulsar population (> 20 keV): 16 members

name	period (ms)	age (kyr)	$^{10}\log(L_{sd})$	radio	pulse shape	photon index	Fermi LAT	TeV PWN
PSR B0531+21 (Crab)	33.5	1.23	38.66	bright	two pulses	curved	yes	yes
PSR B0540-69 (N158A in LMC)	50.5	1.7	38.18	very dim	structured broad	curved	no	...
PSR B0833-45 (Vela)	89	11	36.84	bright	multiple sharp	1.1	yes	yes
PSR B1509-58 (MSH 15-52)	150	1.6	37.26	bright	single broad	curved	yes	yes
PSR J1846-0258 (Kes 75)	324	0.72	36.91	quiet	single, broad	1.20(1)	no	yes
PSR J1811-1925 (G11.2-0.3)	65.0	24.0	36.81	quiet	single, broad	1.11(1)	no	no
PSR J1617-5055	69.0	8.0	37.20	very dim	single, broad	1.42(2)	no	?
PSR J1930+1852 (G54.1+0.3)	136	2.9	37.08	very dim	single, broad	1.21(1)	no	yes
PSR J0205+6449 (3C58)	65.7	5.4	37.43	very dim	two sharp pulses	1.1(1)	yes	yes
PSR J2229+6114 (G106.6+2.9)	51.6	10.5	37.34	weak	two pulses	1.11(3)	yes	yes
AX J1838.0-0655	70.5	23.0	36.75	quiet	structured broad	1.12(1)	no	yes
IGR J14003-6326	31.2	12.7	37.71	dim	broad	1.95(4)	no	no
IGR J18490-0000	38.5	42.8	36.99	quiet	broad	1.37(1)	no	yes
PSR J0537-6910 (N157B)	16.1	4.9	38.69	quiet	single, sharp	1.57(1)	no	yes
PSR J2022+3842 (G76.9+1.0)	48.6	8.9	37.47	very dim	two sharp pulses	1.20(2)	no	no
PSR J1813-1749 (G12.82-0.02)	44.7	5.6	37.75	quiet	single, broad	1.30(3)	no	yes

New candidate: PSR J1640-465 206 ms, 3.3 kyr, 36.64, single broad, 1.2, no, yes (HESS J1640-465)

(NuStar discovery; Gotthelf et al. 2014)

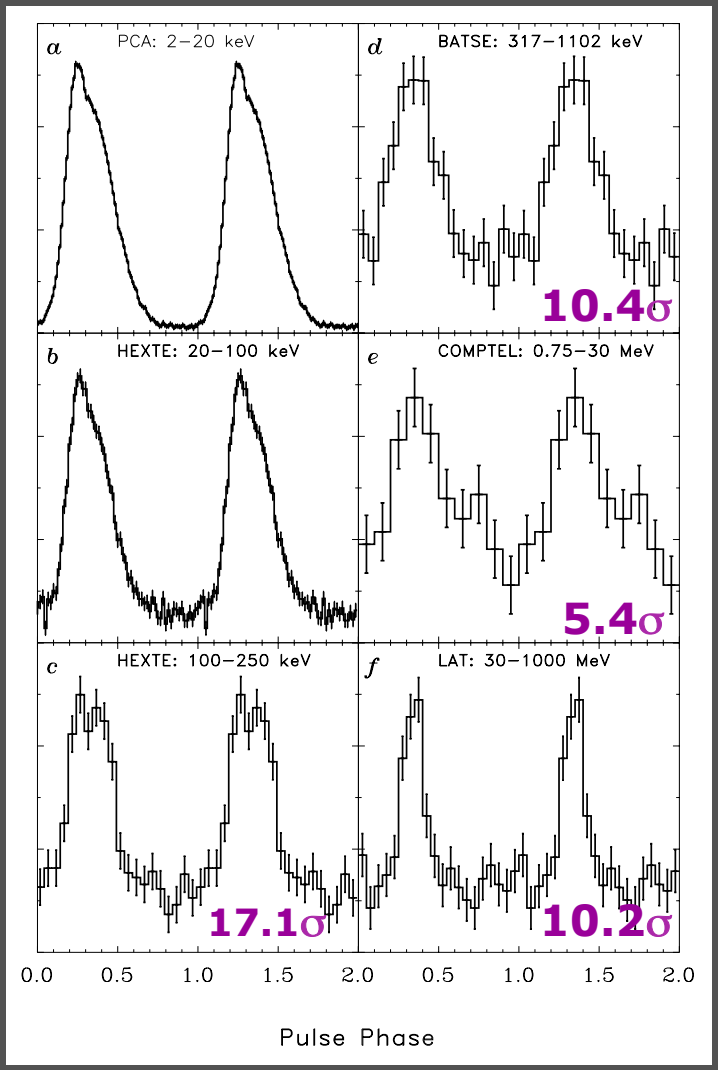
PSR B0833-45: Pulse profile morphology from radio ➔ high energy γ-rays

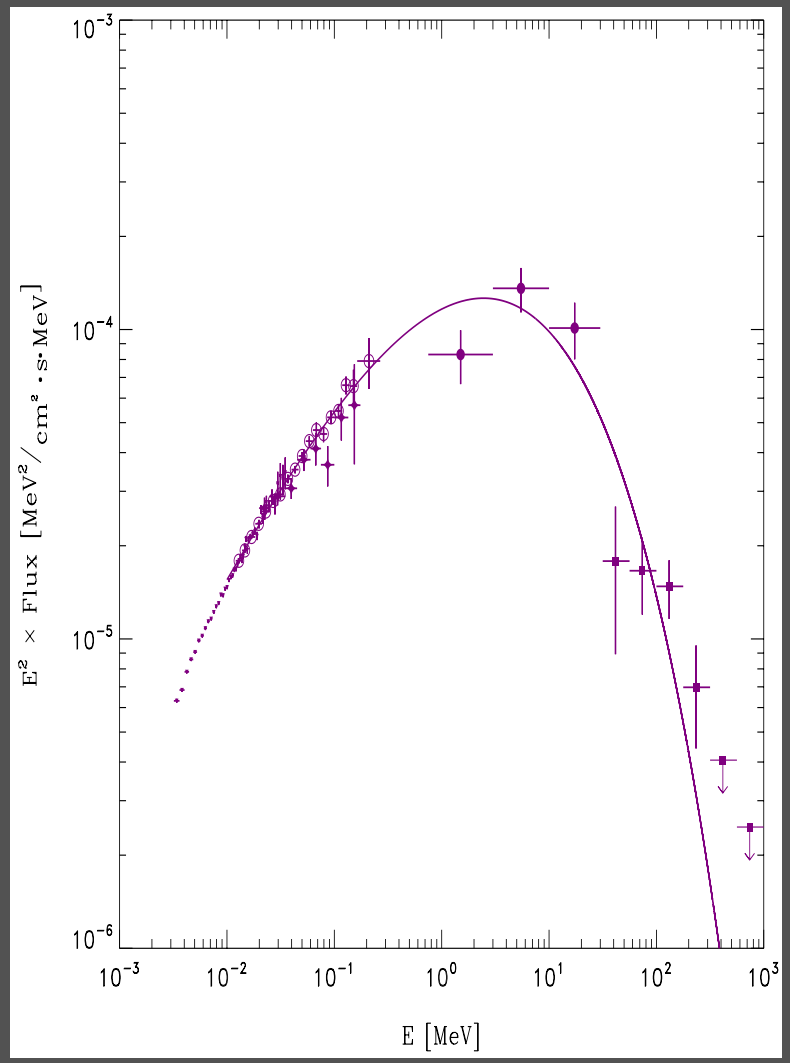


ISGRI:6.1 Ms eff. Exp.

Very complex pulse profile with many emission structures!

PSR B1509-58 update: CGRO BATSE, RXTE HEXTE & Fermi LAT

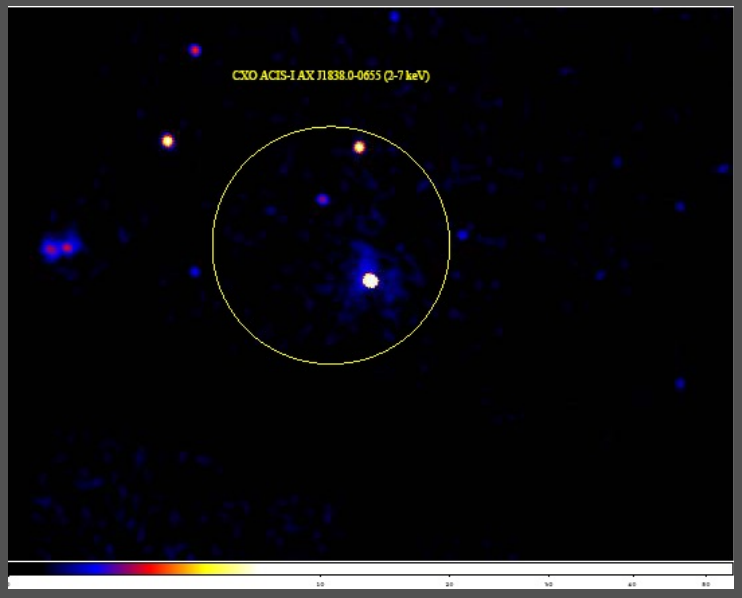


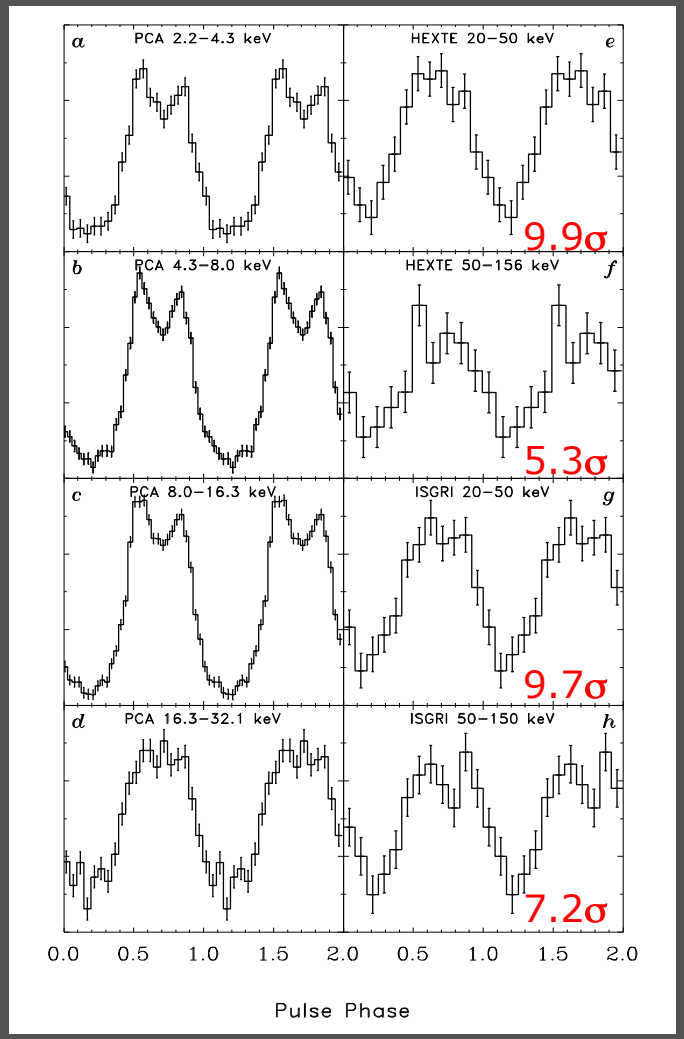


νF_ν spectrum peaks near 2.5 MeV

AX J1838.0-0655

- Discovered in 2008 as an energetic 70.5 ms X-ray pulsar using RXTE PCA data (ATEL #1392; Gotthelf & Halpern (2008))
- Associated with HESS J1837-069
- Characteristic age: 22.6 kyr
- Hard X-ray photon index $\Gamma \sim 1.36(2)$ at 14.2 keV (Kuiper & Hermsen 2014; in prep.)
- Since discovery RXTE monitoring ➡ pulsar ephemeris

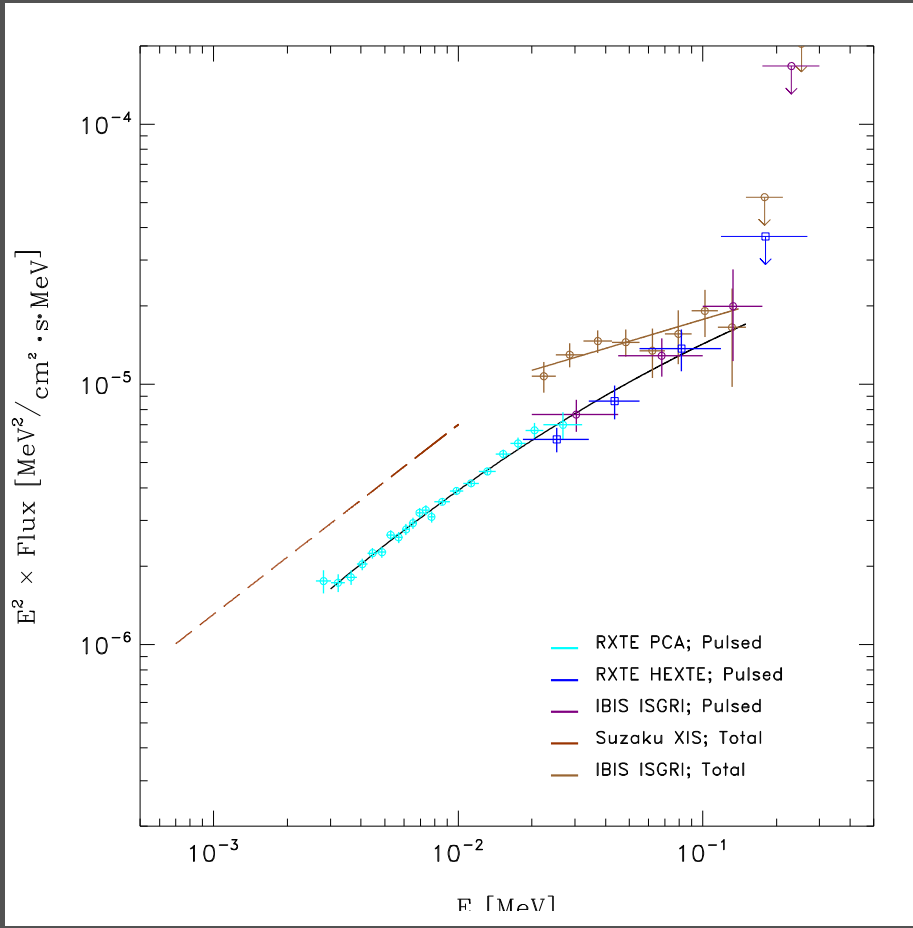


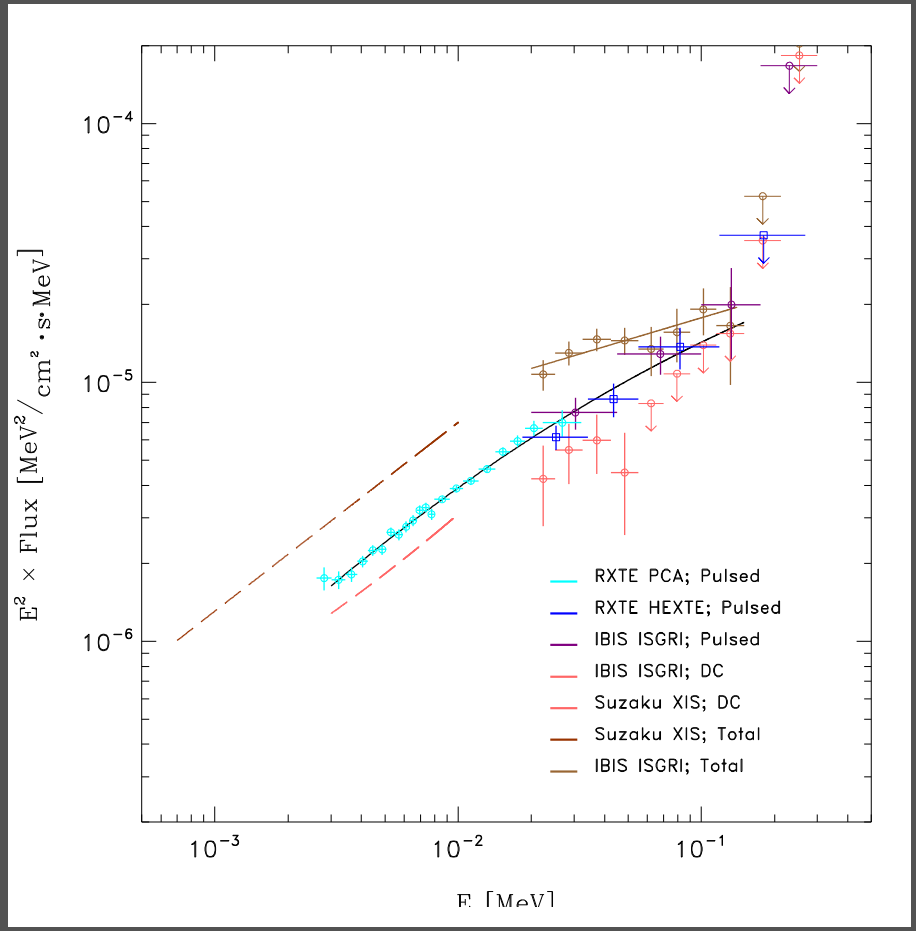


3.3 Ms

Since its discovery a large timing glitch has been detected (Atel #2446; Kuiper & Hermsen)!

Decoupling pulsed/DC spectra
➡ underlying PWN spectrum!





Total emission from AX J1838.0-0655

DC spectrum breaks above ~50 keV

Suzaku XIS 0.7-10 keV (42.2 ks): Γ=1.27±0.11; Anada et al. (2009)
INTEGRAL ISGRI 20-300 keV : Γ=1.72±0.07; this work; consistent with Malizia et al. (2005)

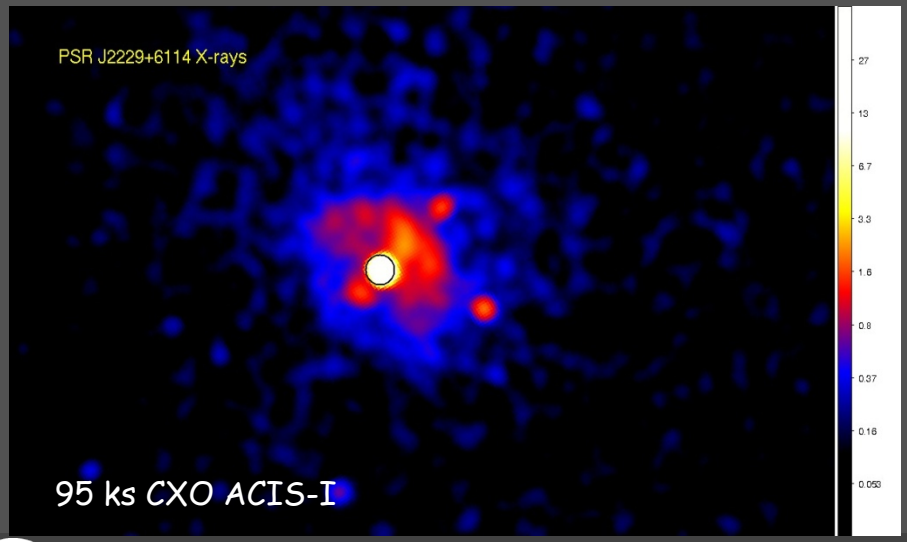
PSR J2229+6114: the energetic young pulsar in 3EG J2227+6122

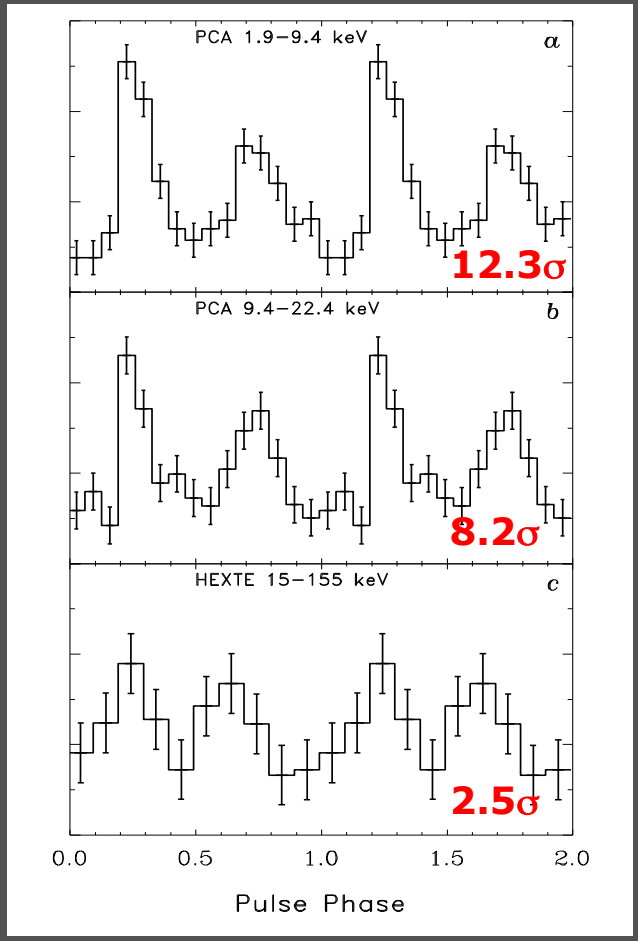
- Discovered by Halpern et al. 2001 in unid. EGRET error region at radio freq. and at X-rays (ASCA): P = 51.6 ms; τ_c=10.5 kyr

  Bright PWN (see below)

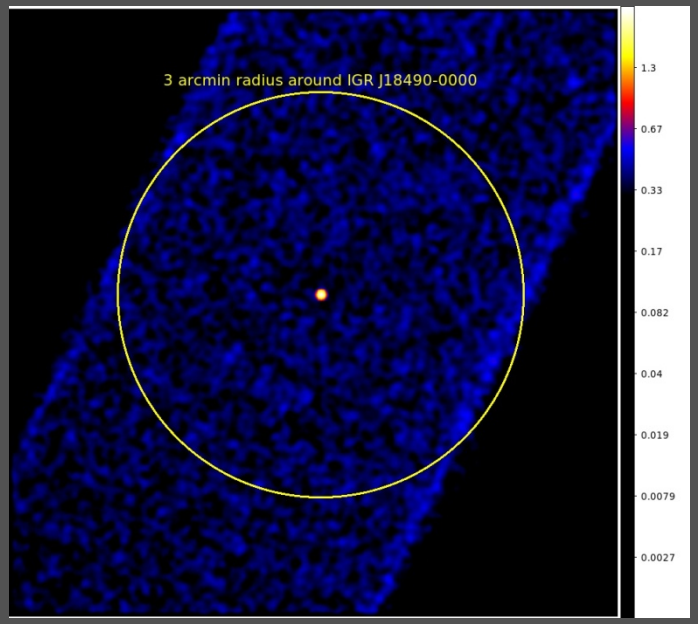
- Pulsations, also detected now by AGILE and Fermi above 100 MeV: a broad asymmetric pulse

- Recent detection of extended TeV emission with Veritas (VER J2227+608) from near environment





Archival RXTE PCA/HEXTE data reveal pulsed emission up to ~30 keV using ~220 ks exposure with hard spectrum, photon index Γ = 1.11(3)



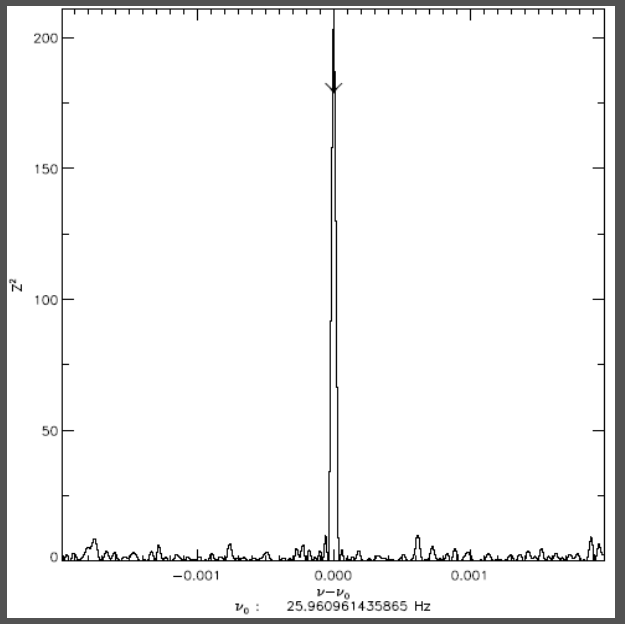
IGR J18490-0000

I) Chandra HRC-SI

Nov. 20, 2011 (25.1 ks)

II) Chandra ACIS-S

Nov. 16, 2012 (22.7 ks)

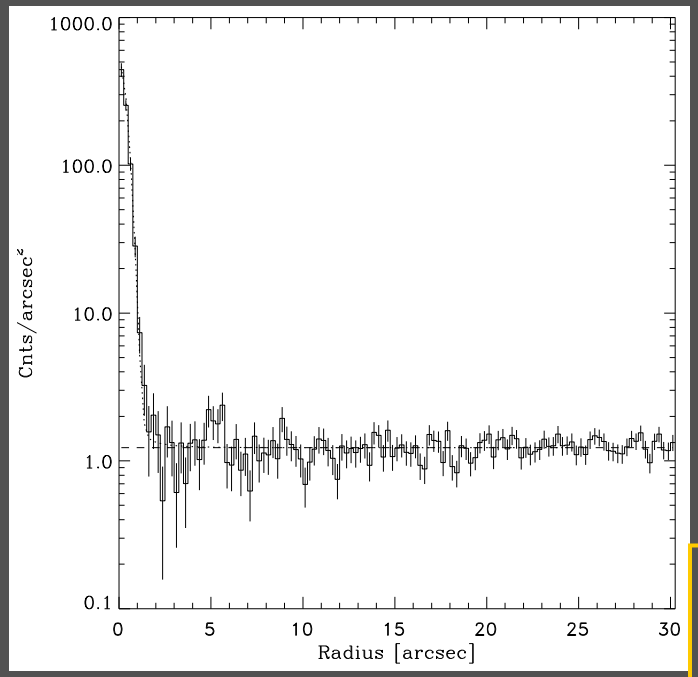


Goals:

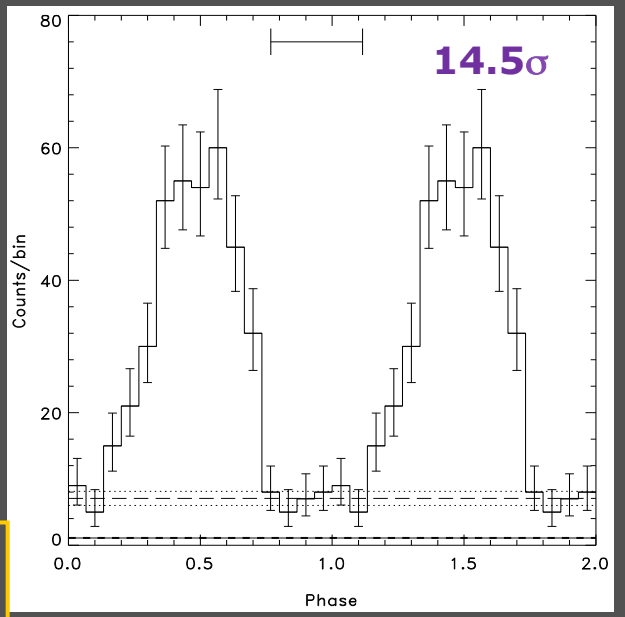
1) Evidence for diffuse emission?

2) Pulsed fraction?

(reported; $P_f \sim 0.25$ PCA based; Gotthelf et al., 2011)

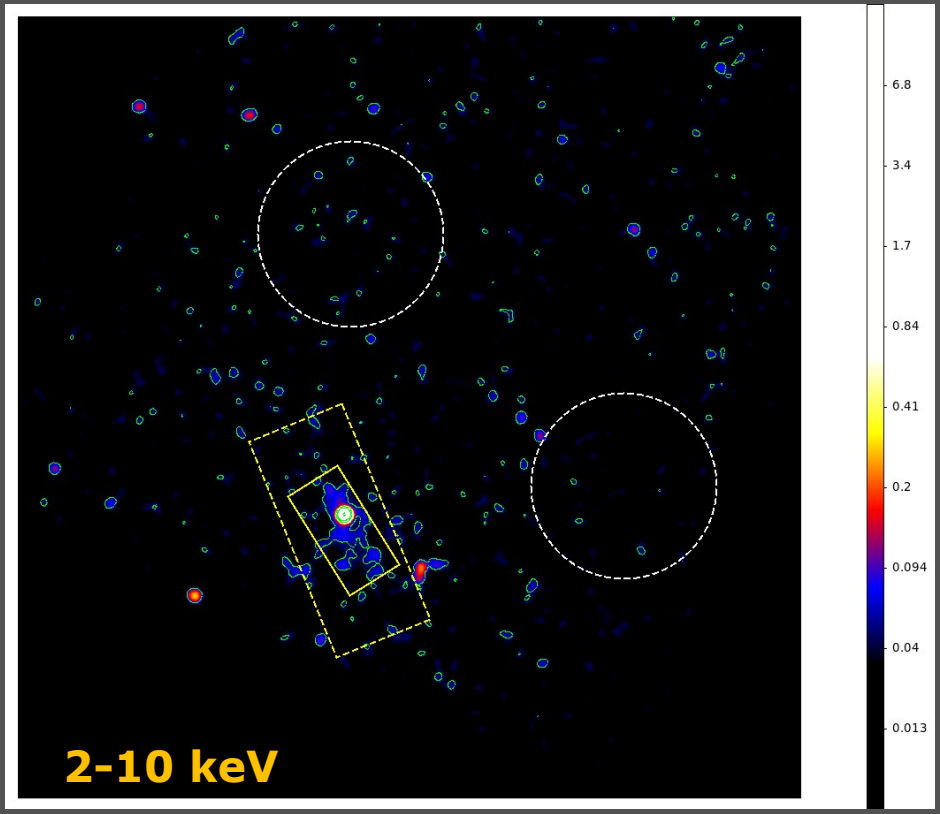


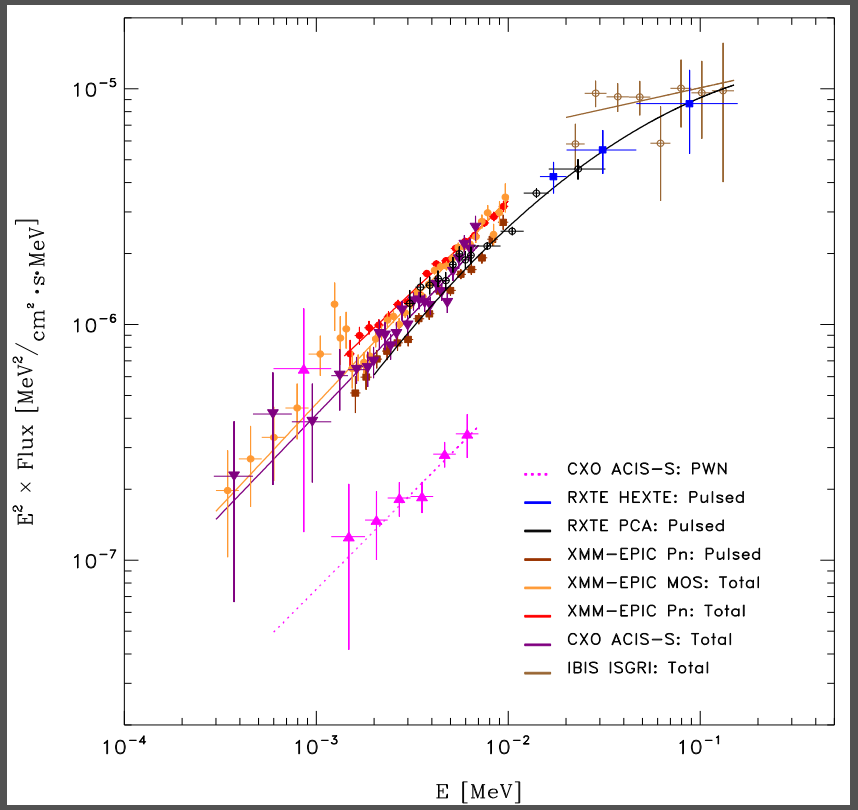
No pronounced diffuse emission seen in HRC-S data



P_f = 0.77 +/- 0.04

IGR J18490-0000: Chandra ACIS-S spatially resolved spectral analysis





2 circular "bg" regions (r = 60") and 2 rectangular "diffuse" PWN emission extraction regions (150" x 65" and 75" x 37.5" minus 5" radius source region) :

Weak, hard PWN emission Γ = 1.18 +/- 0.05

about 5 x weaker than PSR emission

HE-spectrum (Total; unabs.)

ACIS-S (5" source): 1.15 +/- 0.02

EPIC MOS 1+2 : 1.13 +/- 0.01

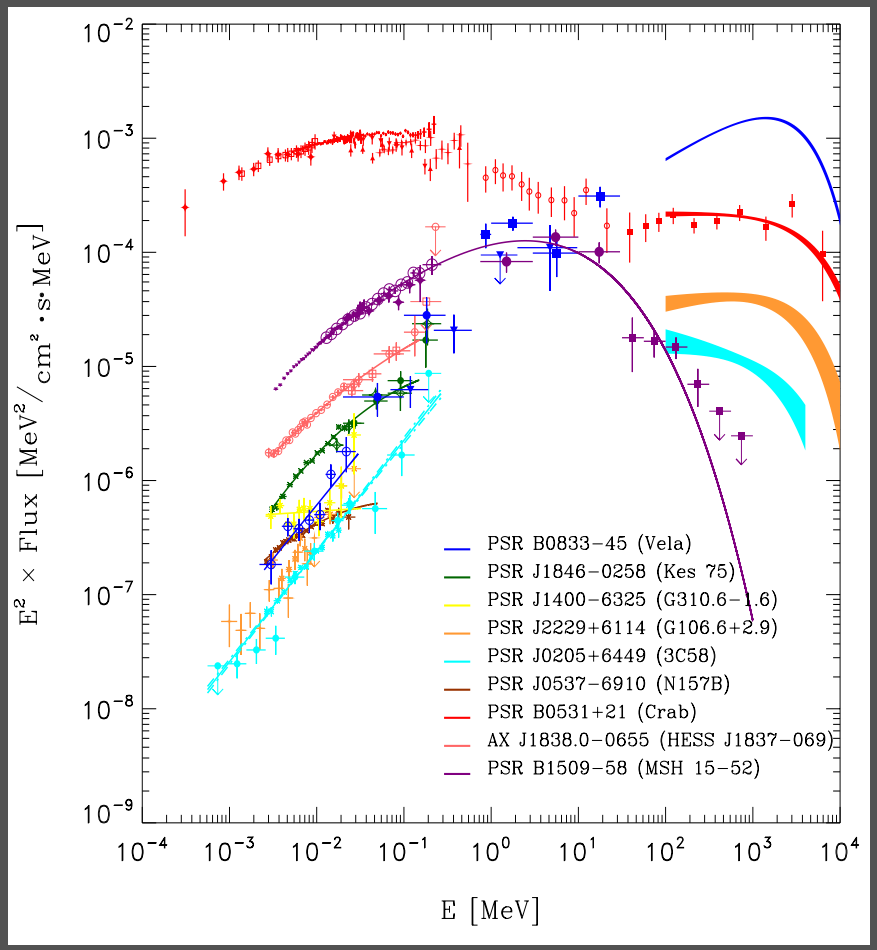
EPIC Pn (SWM) : 1.23 +/- 0.01

Pulsed

EPIC Pn (SWM) : 1.14 +/- 0.01

Soft γ-ray pulsar characteristics

Spectral view (1 keV – 10 GeV)



Maximum luminosity at MeV energies!

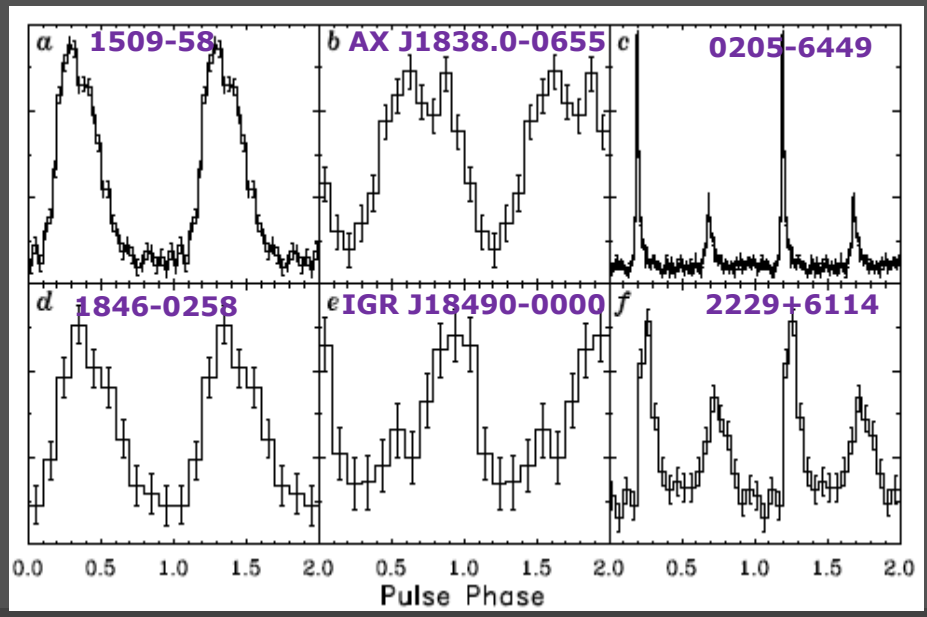
Profile morphology:

Single sharp pulse : #1

Two (sharp) pulses : #4 (3 LAT PSR's)

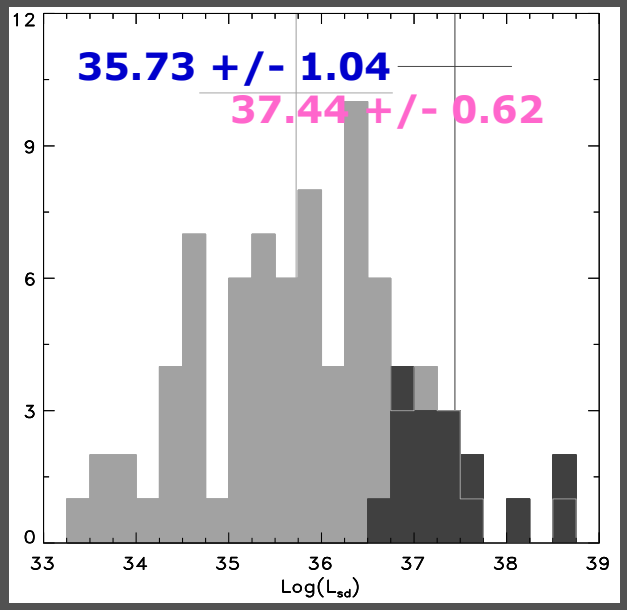
Multiple sharp : #1 (Vela; LAT)

Single (structured) : #10 (1509-58;LAT)
broad pulse



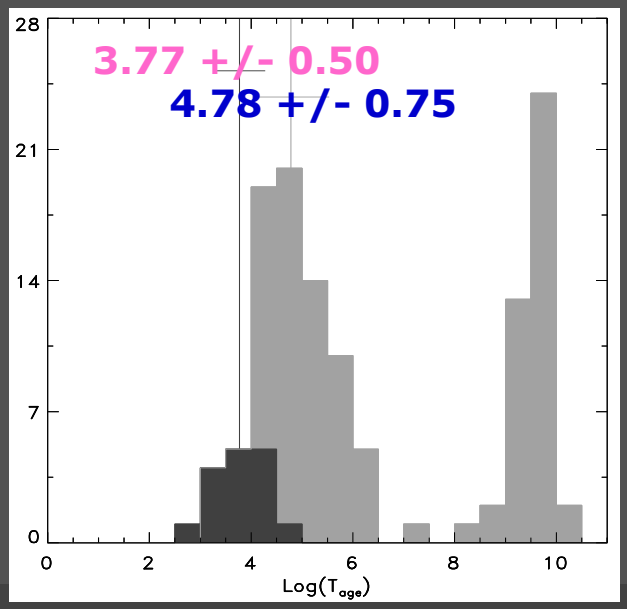
Light grey: Fermi LAT pulsars (77 entries)
Dark grey: Soft γ-ray pulsars (16 entries)

Spin-down luminosity (non-recycled)

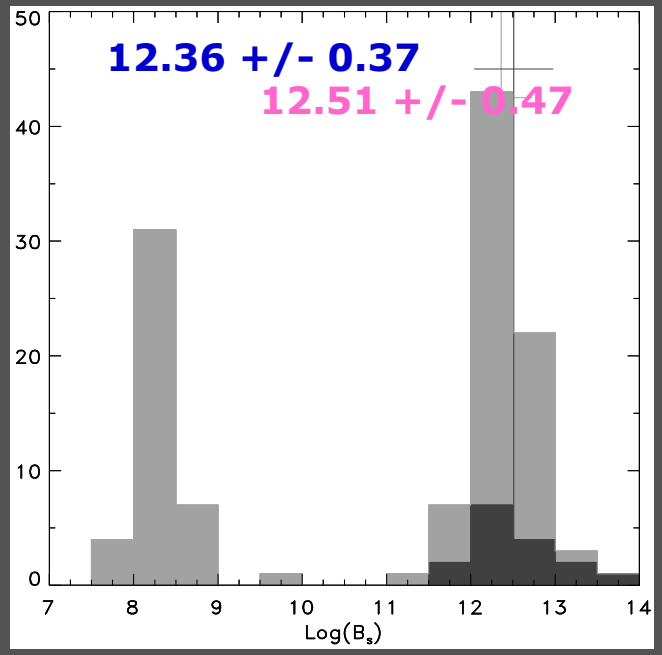


~50 x more energetic

Characteristic age/time scale



~10 x "younger"



Surface magnetic field strength

Comparable distributions!

Summary & Conclusions

- The number of pulsars detected at soft γ-rays has increased to 16 [+1]
  Above 100 MeV now more than 117 pulsars detected by Fermi LAT, only 5 pulsars in both samples…
- The soft γ-ray pulsar population is younger and more energetic than the LAT one
- Soft γ-ray pulsars reach max. luminosity at MeV energies, the LAT pulsars do so in GeV range
- The large majority of the soft γ-ray pulsars has single broad (asymmetric/ structured) pulses contrary to the LAT pulsars, showing mainly double pulses
- Soft γ-ray pulsars are in general associated with bright X-ray/TeV PWNe

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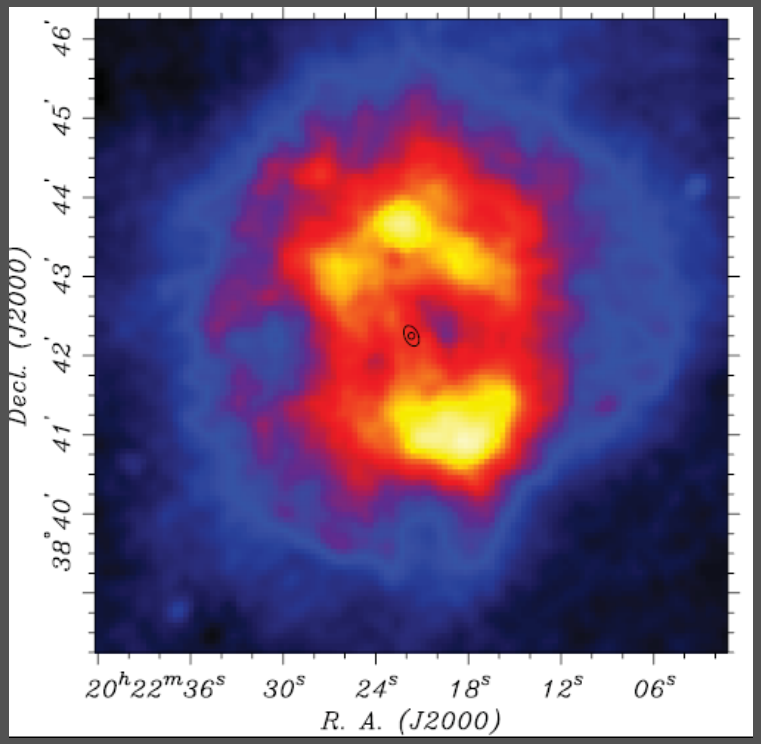
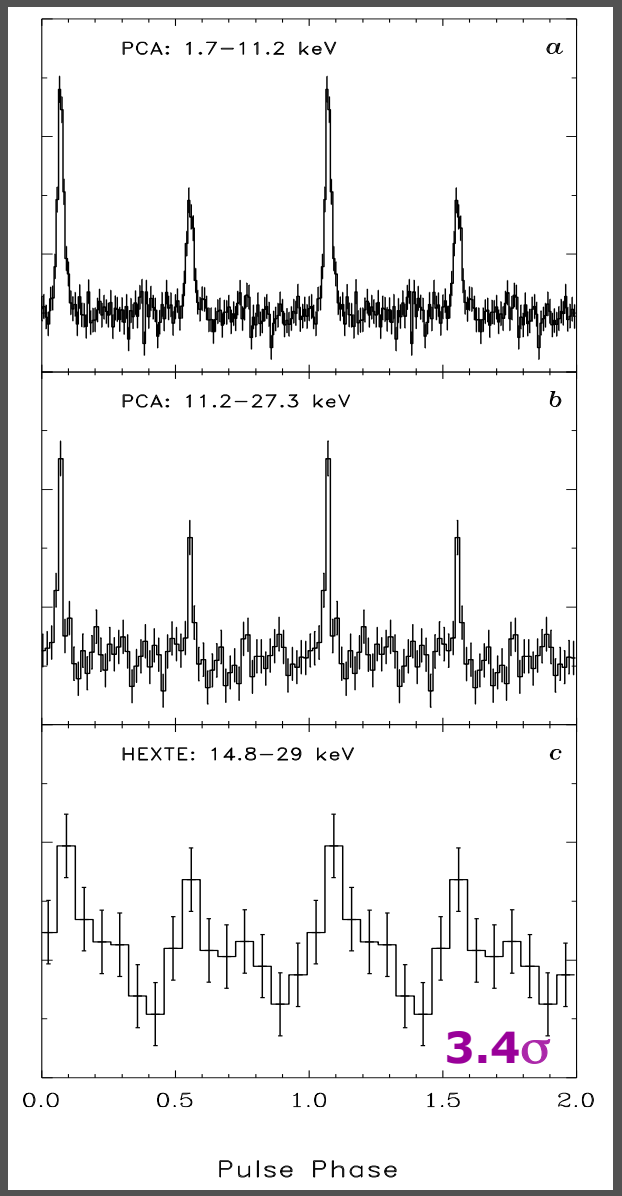
- The current missions sensitive for hard X-rays are not / hardly sensitive enough to detect the "GeV-pulsars" ➡ need more sensitive missions (NuSTAR; Astro-H; AstroSat; LOFT; and MeV missions like e.g. DUAL, GRIPS)
- Open questions: Why no detection of pulsed **non-thermal** X-ray emission (>2 keV) from PSR J1119-6127, (1.6 kyr) PSR J1357-6429 (7.3 kyr) and PSR J1124-5916 (2.9 kyr), while we have Fermi LAT detections and TeV detections of two?

  Instead soft pulsed X-ray emission (< 2 keV; thermal?) has been detected…

  What about: PSR J1833-1034 (G21.5-0.9): LAT plus TeV/soft γ-ray (ISGRI) detection, but NO X-ray pulsations…

PSR J2022+3842 in G76.9+1.0





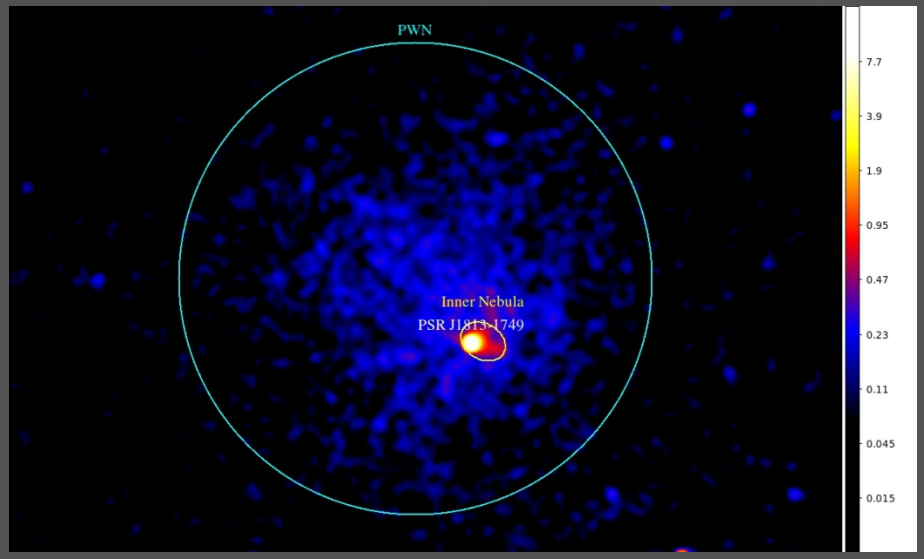
Arzoumanian et al. (2011), ApJ 739, 39

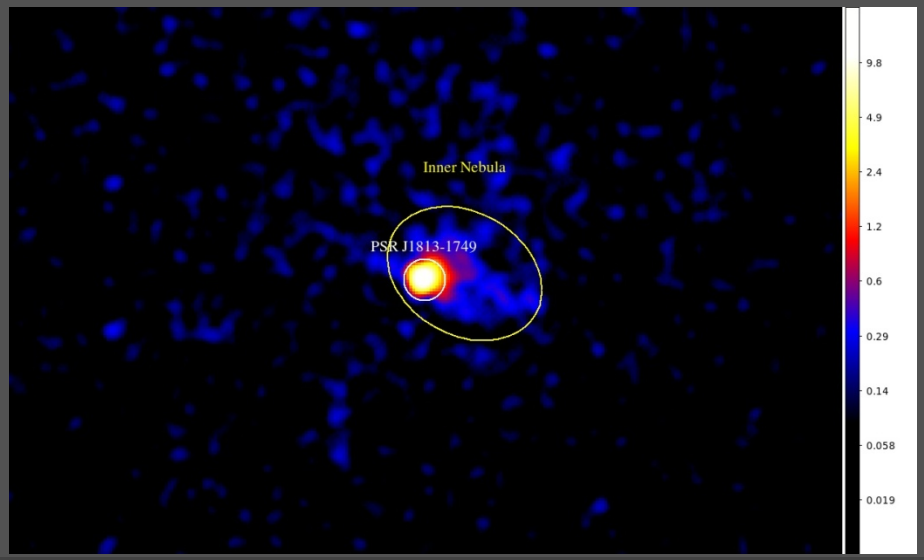
Fast and energetic radio pulsar: P = 48.6 ms,
L_{sd}=3.0E37erg/s

Two sharp X-ray pulses at 0.484(1)
(see also Arumugasamy et al. 2013)

Hard pulsed X-ray spectrum: Γ = 1.20(2)

A new candidate soft γ-ray pulsar: PSR J1813-1749 in G12.82-0.02 and associated with HESS J1813-178 / IGR J18135-1751





- Putative pulsar and PWN discovered by Helfand et al. (2007) using 30 ks CXO ACIS data (15/09/2006; see left 2 panels).

  X-ray Spectra obtained for point-source ('PSR'; < 2"), Inner Nebula (6" x 8") and PWN (r = 80").

- An energetic 44.7 ms X-ray pulsar was detected by Gotthelf & Halpern (2009) using XMM-Newton EPIC-pn data from a 98 ks obs. performed on 27/03/2009.

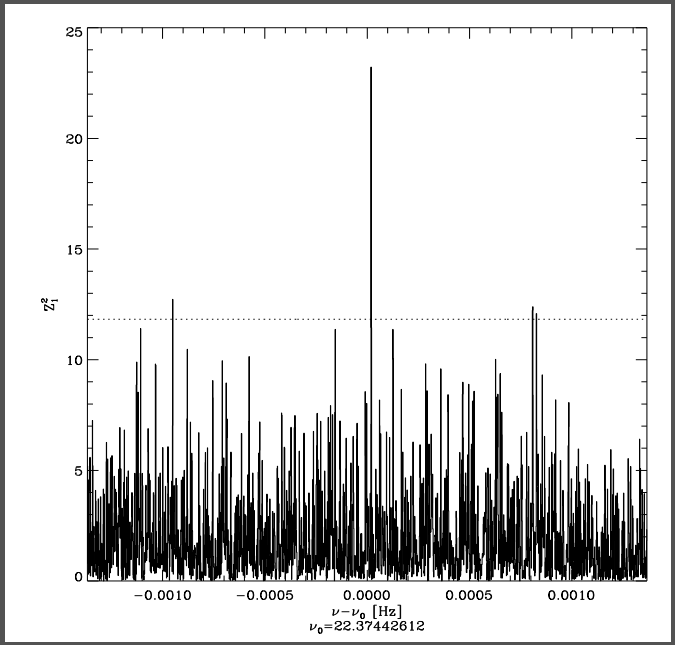
  (broad pulse; hard spectrum > 2 keV)

- Additional XMM and CXO obs. taken in 2011/2012 yielded the spin-down:

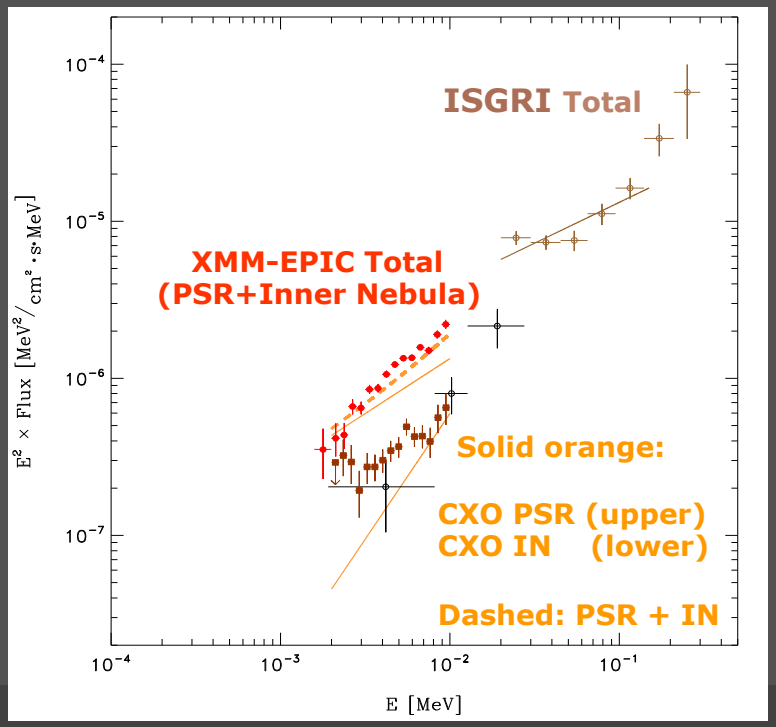
  L_{sd} = 5.6E37 erg/s ; τ = 5.6 kyr

- Revisiting now 125.8 ks RXTE PCA data taken between 16-20 Nov. 2007 with only ONE operational PCU and at 30' offset angle.

A new candidate soft γ-ray pulsar: PSR J1813-1749 in G12.82-0.02 and associated with HESS J1813-178 / IGR J18135-1751

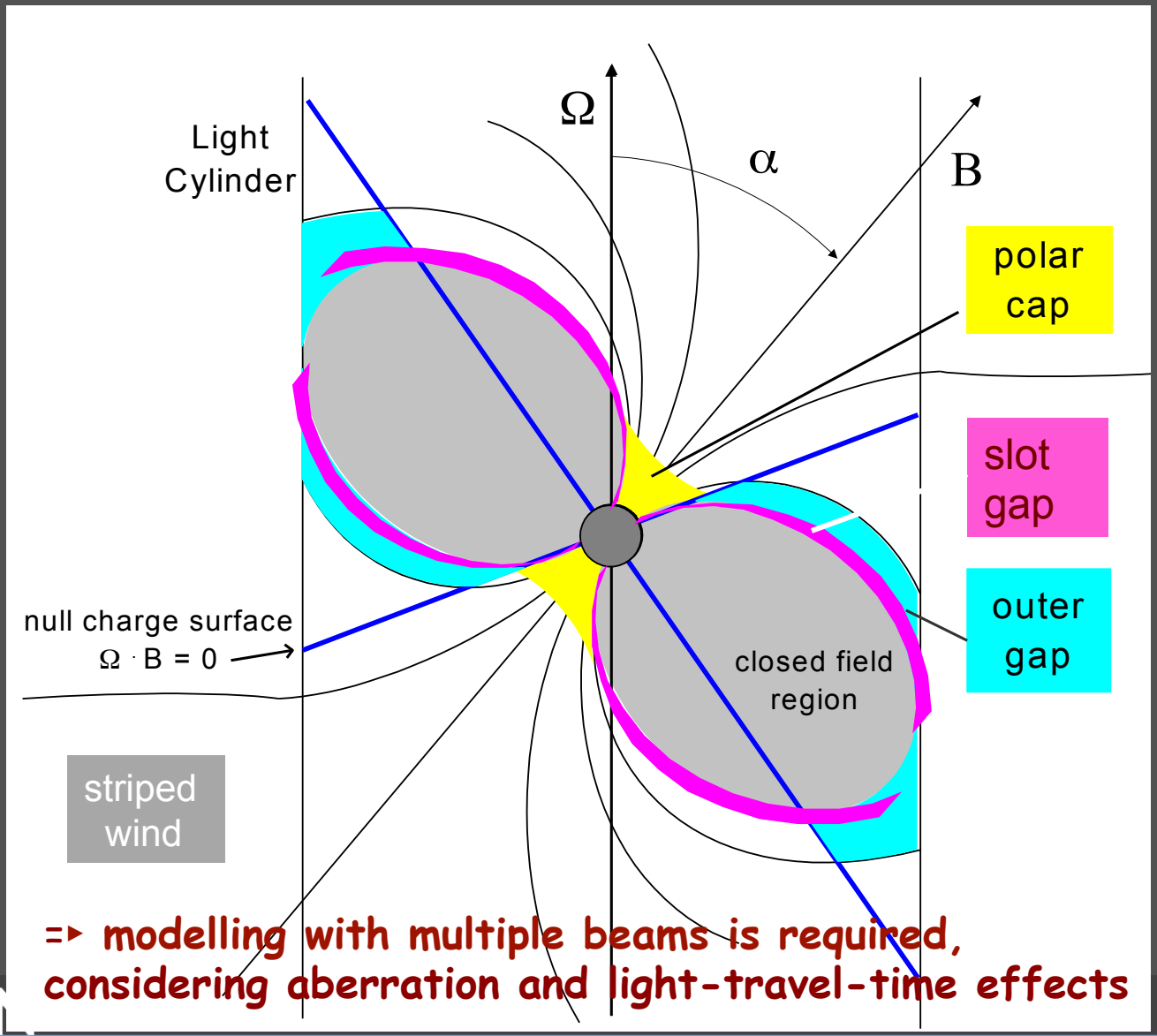


- Restricted period search using 2-20 keV PCA data yielded ~5σ signal (single trial) near predicted period!
- PCA pulsed spectrum (black) consistent with XMM-Newton pulsed spectrum (dark-orange), and >3σ signal for 10-20 keV energy band



Consistent HE-spectral picture!

Geometries of high-energy emission pulsar models



=▸ modelling with multiple beams is required, considering aberration and light-travel-time effects