X-ray Emission from Millisecond Pulsars
(solitary or non-accreting)

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Isolated Neutron Stars: from the Interior to the Surface,
London, April 24-28, 2006

Rotation-powered Millisecond Pulsars (MSPs):

short and stable spin periods, $P<10$ ms, $dP/dt \approx 10^{-21} - 10^{-19}$ s/s
(126 radio MSPs according to the ATNF catalogue)

72 in close binaries → spun up by accretion → recycled pulsars

very old objects, $\tau_{char}=P/(2dP/dt) \approx 1 - 10$ Gyr

very low surface magnetic fileds, $B \propto (P\, dP/dt)^{1/2} \approx 10^8 - 10^9$ G,
due to Ohmic decay and (possibly) accretion-induced decay

except radio, X-ray band is the main source of information on MSPs via:

- nonthermal (magnetospherc) emission
- thermal radiation from small hot spots on neutron star surface around pulsar magnetic poles — polar caps (PCs)

  $R_{pc} \approx [2\pi R^3/cP]^{1/2} = 2\,[P/5\text{ ms}]^{-1/2}$ km, $T_{pc} \approx 0.5$-5 MK

- the rest surface is too cold, < 0.1 MK, for X-ray band but can be seen in UV (Kargaltsev et al. 2004)
- emission from pulsar-wind nebulae

MSPs with available X-ray information

Nonthermal emission:

PSR	P	d	τ	Log dE/dt	pbin
	ms	kps	Gyr	erg/s	day
B1937+21	1.6	3.6	0.2	36.04	∞ = solitary
B1957+20	1.6	2.5	1.5	35.20	0.4
J0218+4232	2.3	2.7	0.5	35.38	2.0
B1821-24	3.1	3.1	0.03	36.34	∞
J0751+1807 ?	3.5	1.2	7.1	33.86	0.3
J1012+5307 ?	5.3	0.4	4.9	33.67	0.6

Power-law spectra, sharp pulses, large pulsed fractions (>50%)

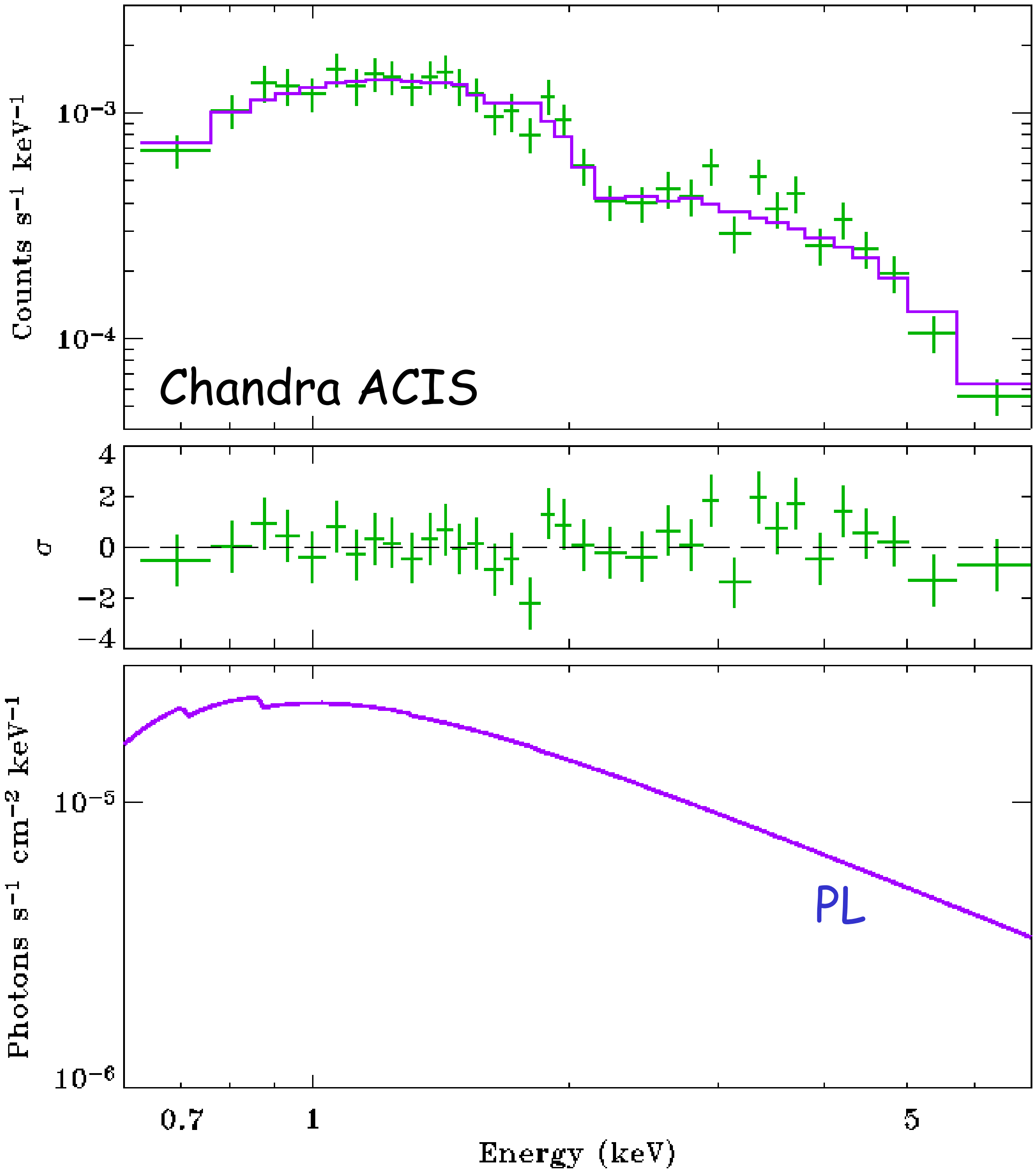
Thermal emission:

J0030+0451	4.9	0.3	7.7	33.53	∞
J2124-3358	4.9	0.3	3.8	33.83	∞
J1024-0719	5.2	0.4	4.4	33.72	∞
J0437-4715	5.8	0.14*	1.6	33.58	5.7

Blackbody-like spectral components, broad pulses

* - parallax

PSR B1821-24



Solitary MSP in M28:

single PL spectrum

$\Gamma \approx 1.2$

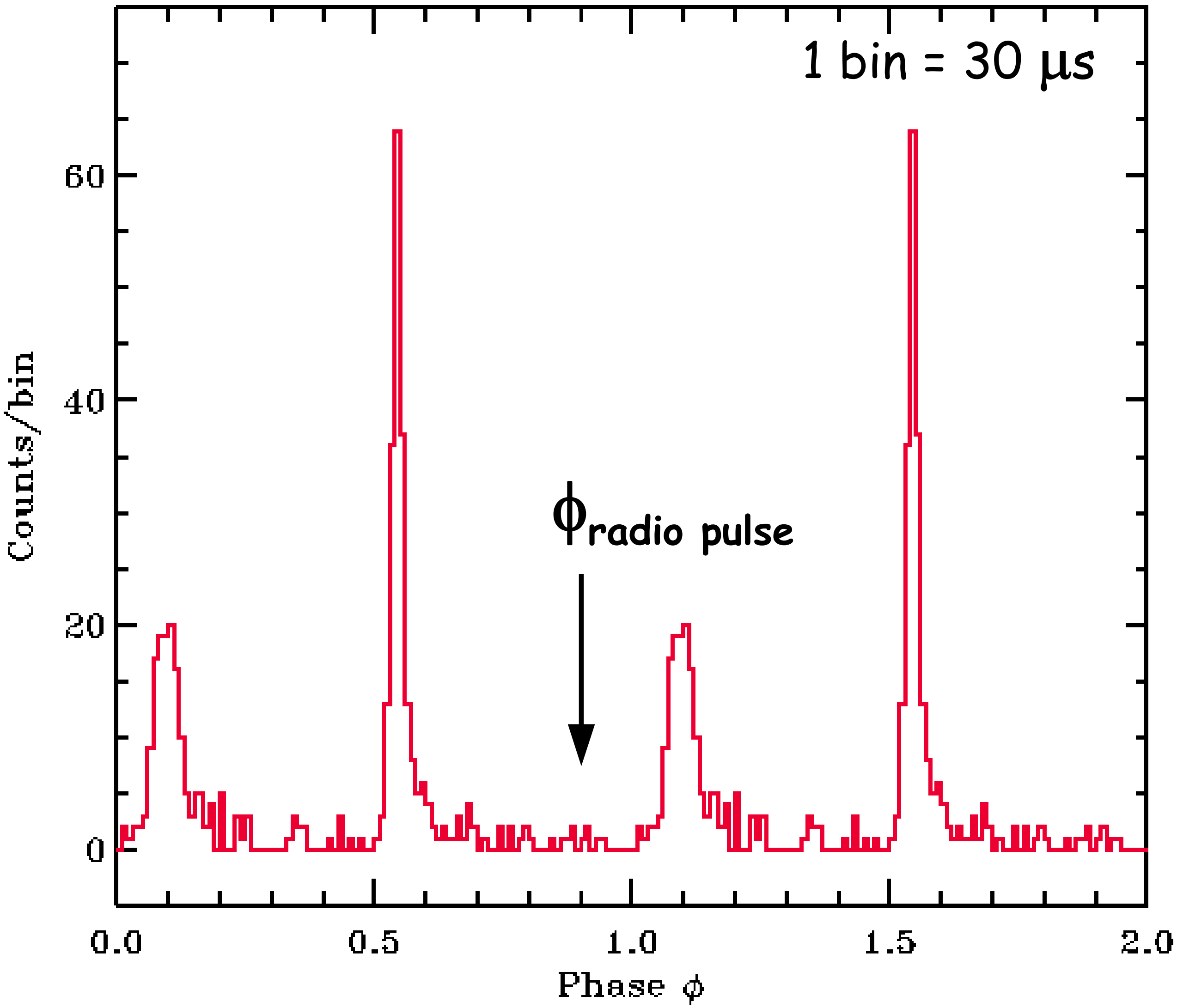
$L_X \approx 4.8 \times 10^{32}$ erg/s =

= 0.2×10^{-3} dE/dt

(0.2 - 10 keV)

(Becker et al. 2003)

PSR B1821-24

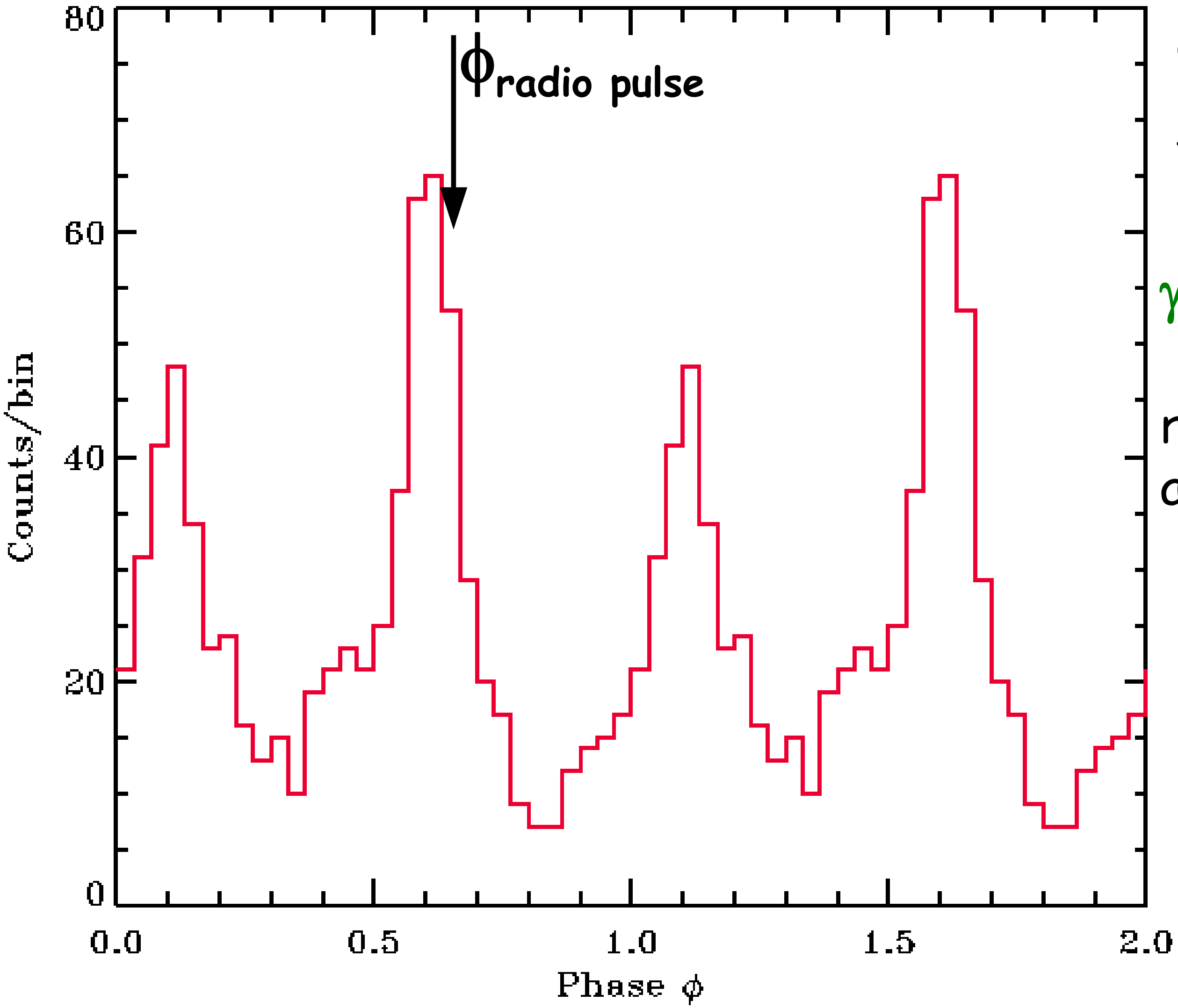


double-peak structure

$f_p \approx 85\%$

Chandra HRC (Rutledge et al. 2004)

PSR J0218+4232



double-peak structure

$f_p \approx 64\%$

γ−ray pulsar

radio, X- and γ−ray pulses are nearly co-aligned

XMM MOS:
single PL spectrum
$\Gamma \approx 1.1$
$L_X \approx 4.0 \times 10^{32}$ erg/s =
= 1.7×10^{-3} dE/dt

Chandra HRC (Kuiper et al. 2002)

Two fastest-spinning MSPs:

B1937+21 — ASCA (Takahashi et al. 2001), SAX (Nicastro et al. 2003), RXTE (Cusumano et al. 2003)

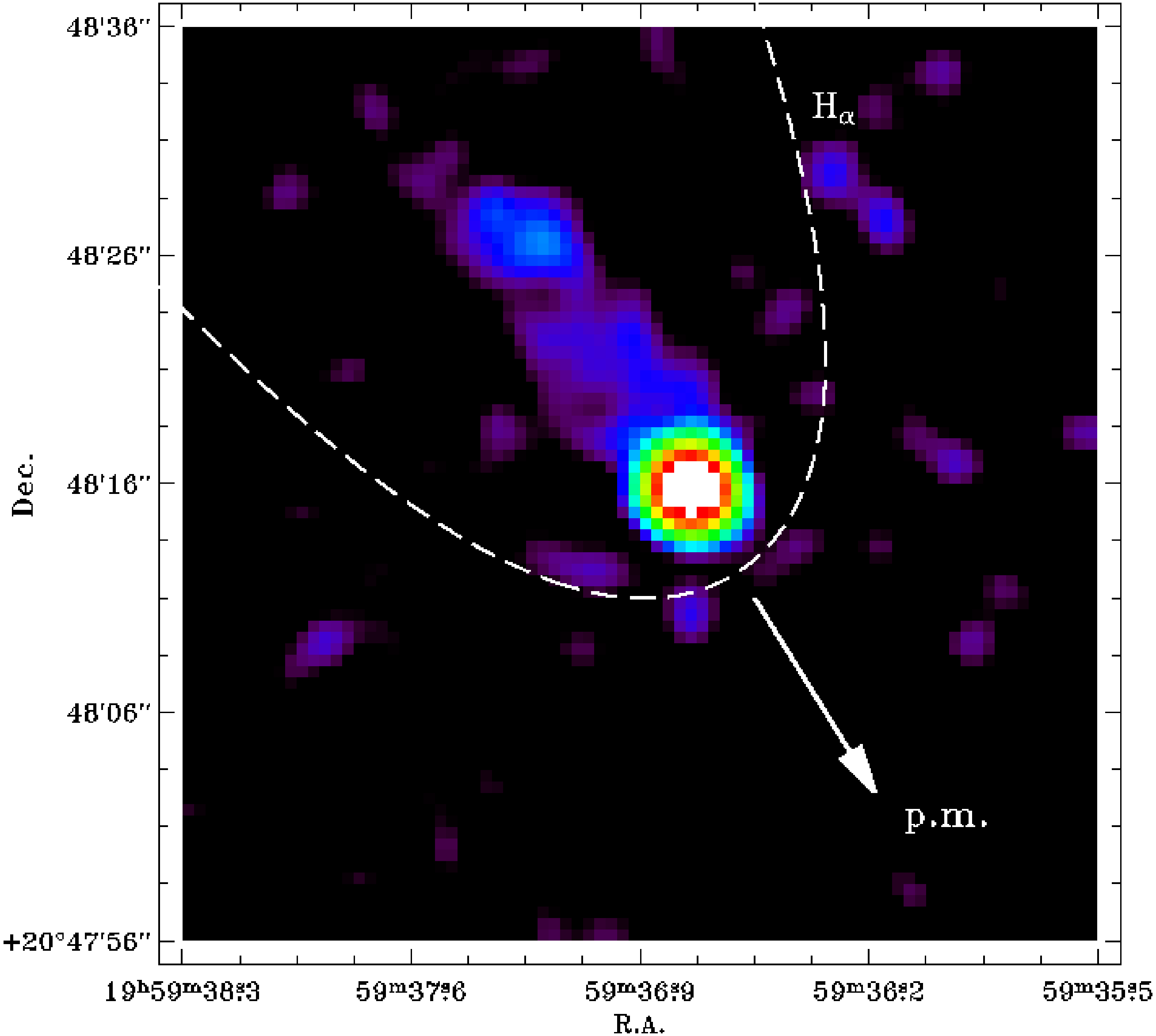
B1957+20 (eclipsing, "black widow") — Chandra (Stappers et al. 2003)

PL spectra with $\Gamma \approx 1.9$, $L_X \approx (1.3, 0.4) \times 10^{-3}\ dE/dt$

pulsed profile of B1937+21 with one very strong, narrow peak (a much weaker second pulse is possible)

pulsations of X-ray flux of B1957+20 to be detected yet

PSR B1957+20



Chandra ACIS

H_α bow-shock

plus

X-ray tail

(Stappers et al. 2003)

PSR J0437-4715

First MSP detected in X-rays (Becker & Trümper 1993), ROSAT:

soft spectrum, pulsed flux with $f_p \approx 35\%$

ROSAT and Chandra data revealed:

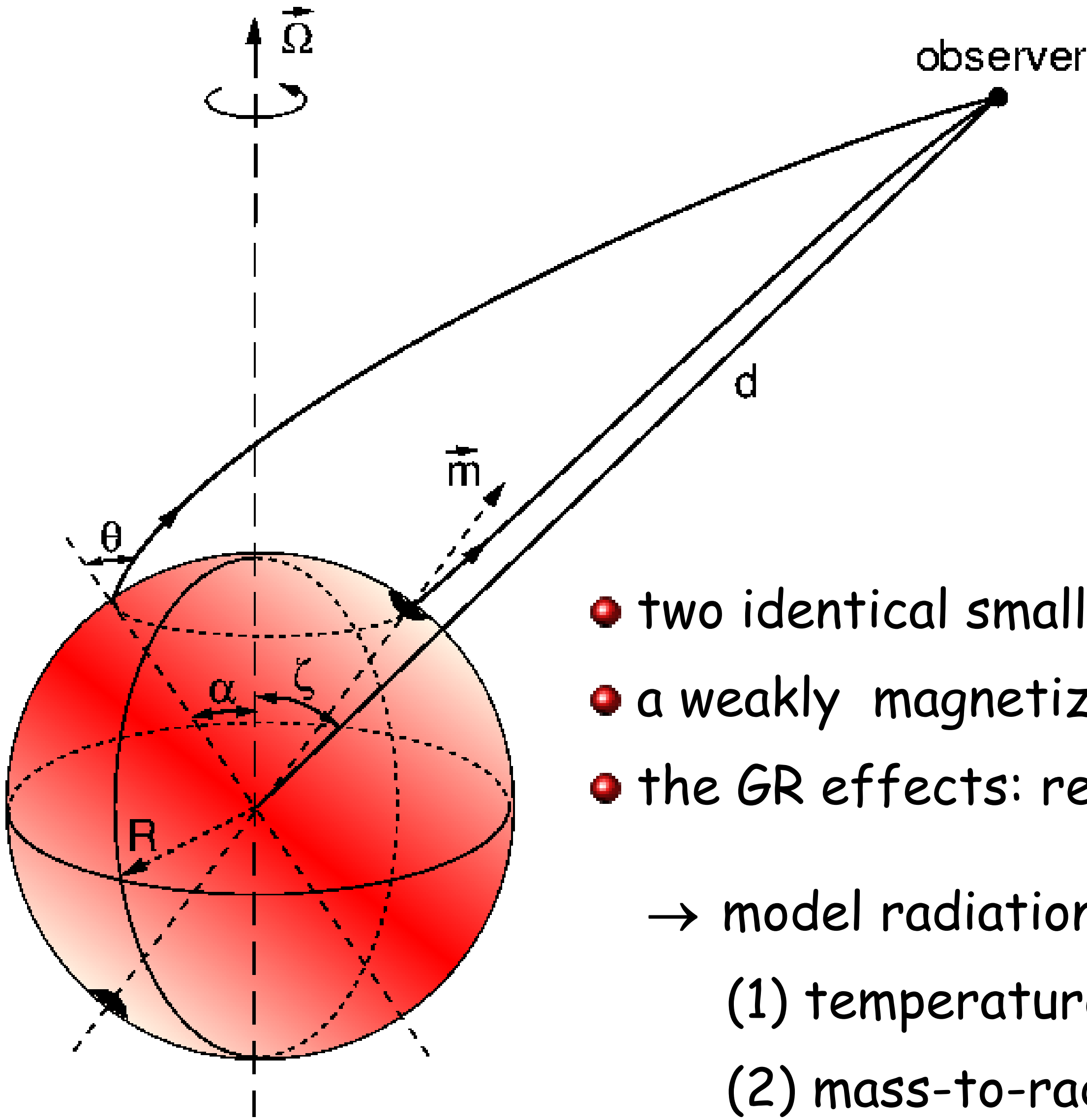
two-component spectrum with

- a soft thermal PC component of a nonuniform temperature decreasing outwards from 2 MK (core) to 0.5 MK (rim)
- nonthermal PL of $\Gamma \approx 1.8$ component prevailing at E>2 keV (Zavlin & Pavlov 1998; Zavlin et al. 2002)

the only MSP detected in UF/FUV (Kargaltsev et al. 2004) $\rightarrow$

$T_{surf} \approx 0.1$ MK

PC model



(Zavlin et al. 1995)

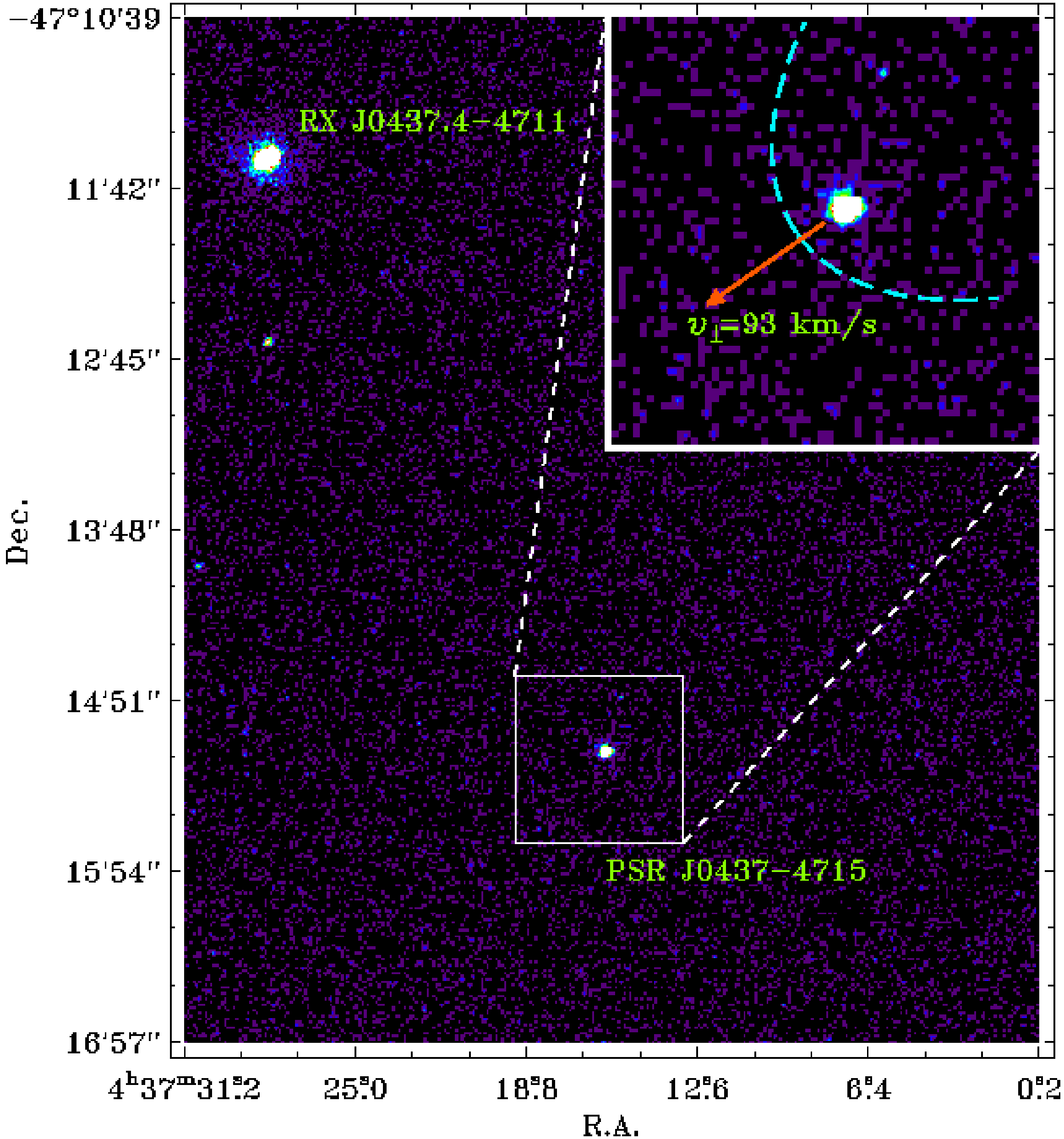
- two identical small spots on magnetic poles
- a weakly magnetized hydrogen atmosphere
- the GR effects: redshift, gravitational bending

→ model radiation depends on

(1) temperature and size of the spots

(2) mass-to-radius ratio, M/R

(3) star geometry — angles α, ζ



H_α bow-shock

and

no X-ray extended emission

Chandra HRC (Zavlin et al. 2002)

XMM observation of PSR J0437-4715:

- neither single nor simple thermal+nonthermal (e.g., BB+PL) model yields a reasonable fit or model parameters ($\Gamma \approx 3$, $n_H \approx 2\times10^{20}$ cm^{-2})
- a two-component thermal plus nonthermal model required, as found from the previous data

the thermal PC model, core+rim:

$T_{core} \approx$ 1.4 MK, $T_{rim} \approx$ 0.5 MK
$R_{core} \approx$ 0.4 km, $R_{rim} \approx$ 2.6 km
$L_{bol} \approx 1.7\times10^{30}$ erg/s = 0.4×10^{-3} dE/dt (for one PC)

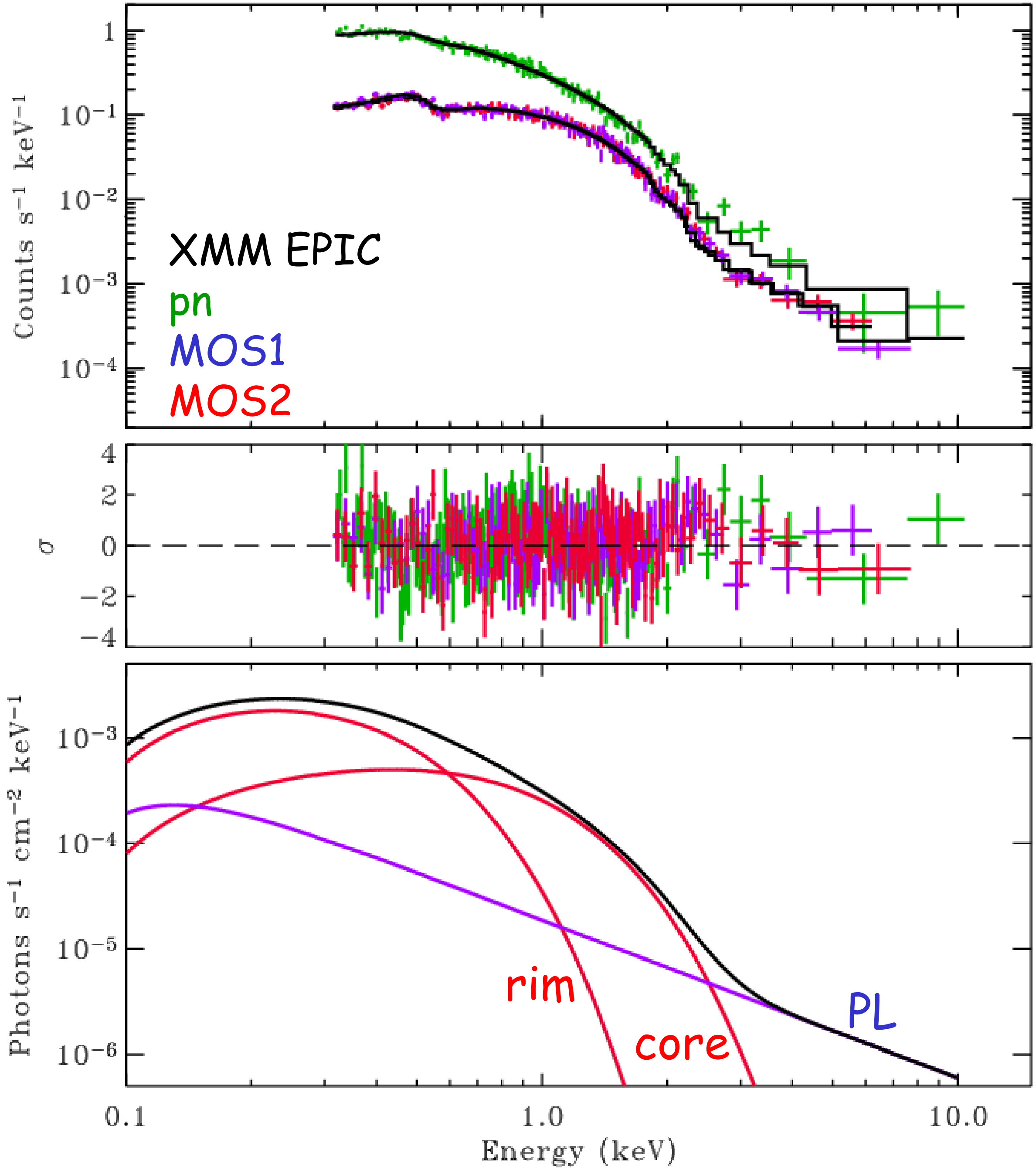
(BB model → smaller radii and higher temperatures)

the nonthermal PL component:

$\Gamma \approx 2.0$, $L_X \approx 0.5\times10^{30}$ erg/s = 0.1×10^{-3} dE/dt

(consistent with the ROSAT+Chandra results)

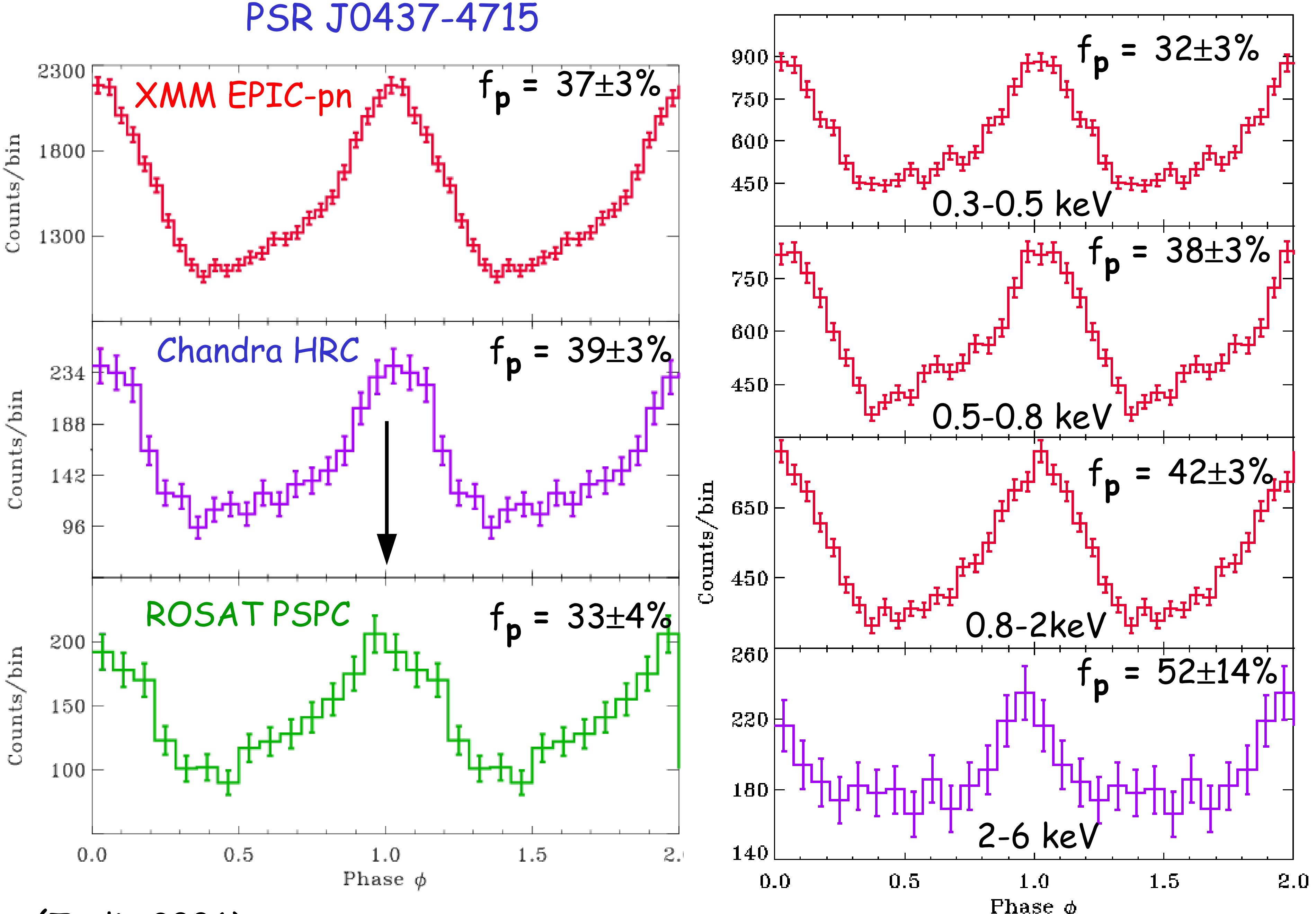
PSR J0437-4715



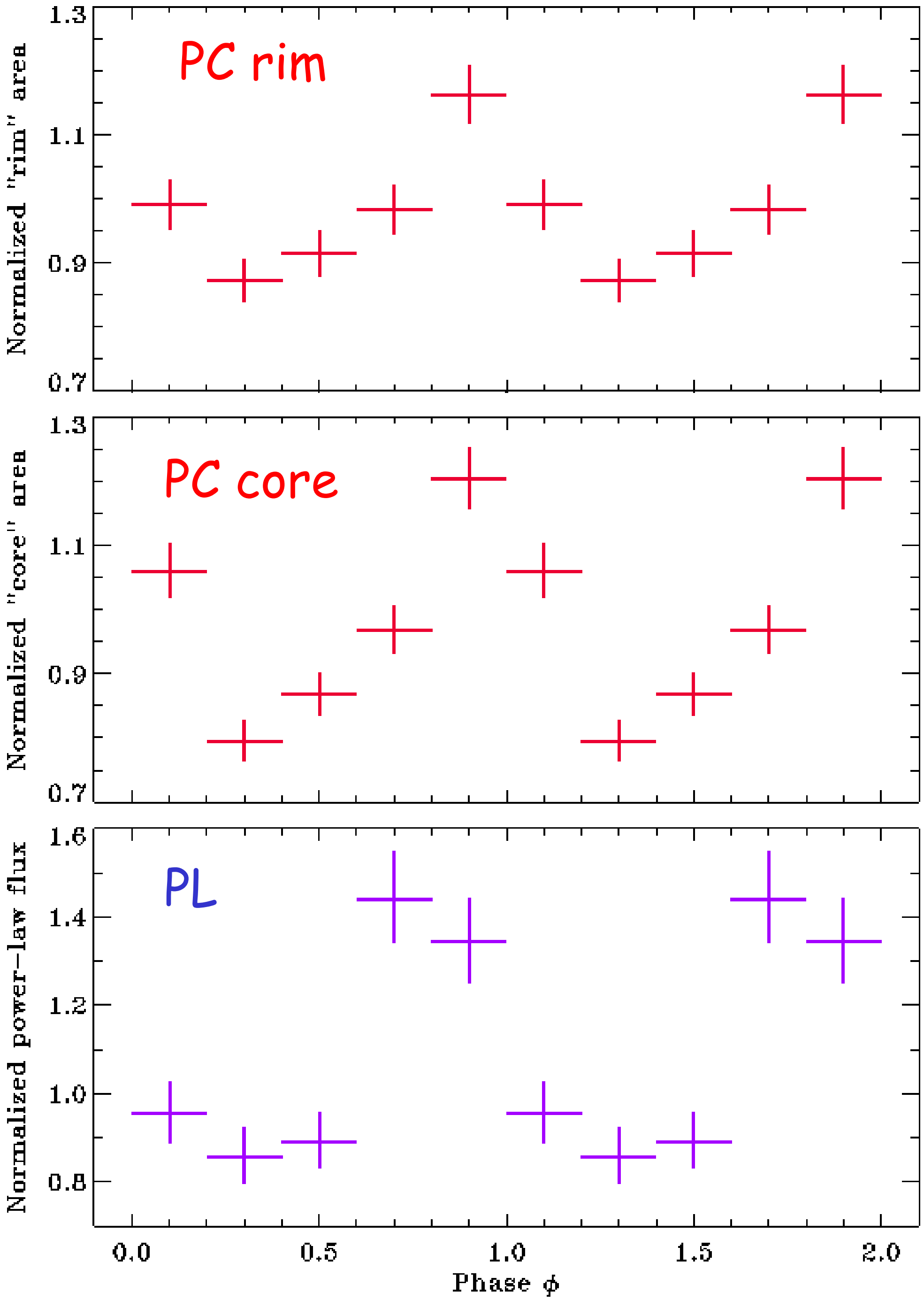
Model fit:
thermal PCs, core+rim, plus
nonthermal PL componets

(Zavlin 2006)

PSR J0437-4715



(Zavlin 2006)



Phase dependence of normalizations of the spectral components of X-rays from PSR J0437-4715

(Zavlin 2006)

PSR J0030+0451

ROSAT (Becker et all. 2000):

pulsations with a double-peaked profile

XMM (Becker & Aschenbach 2002):

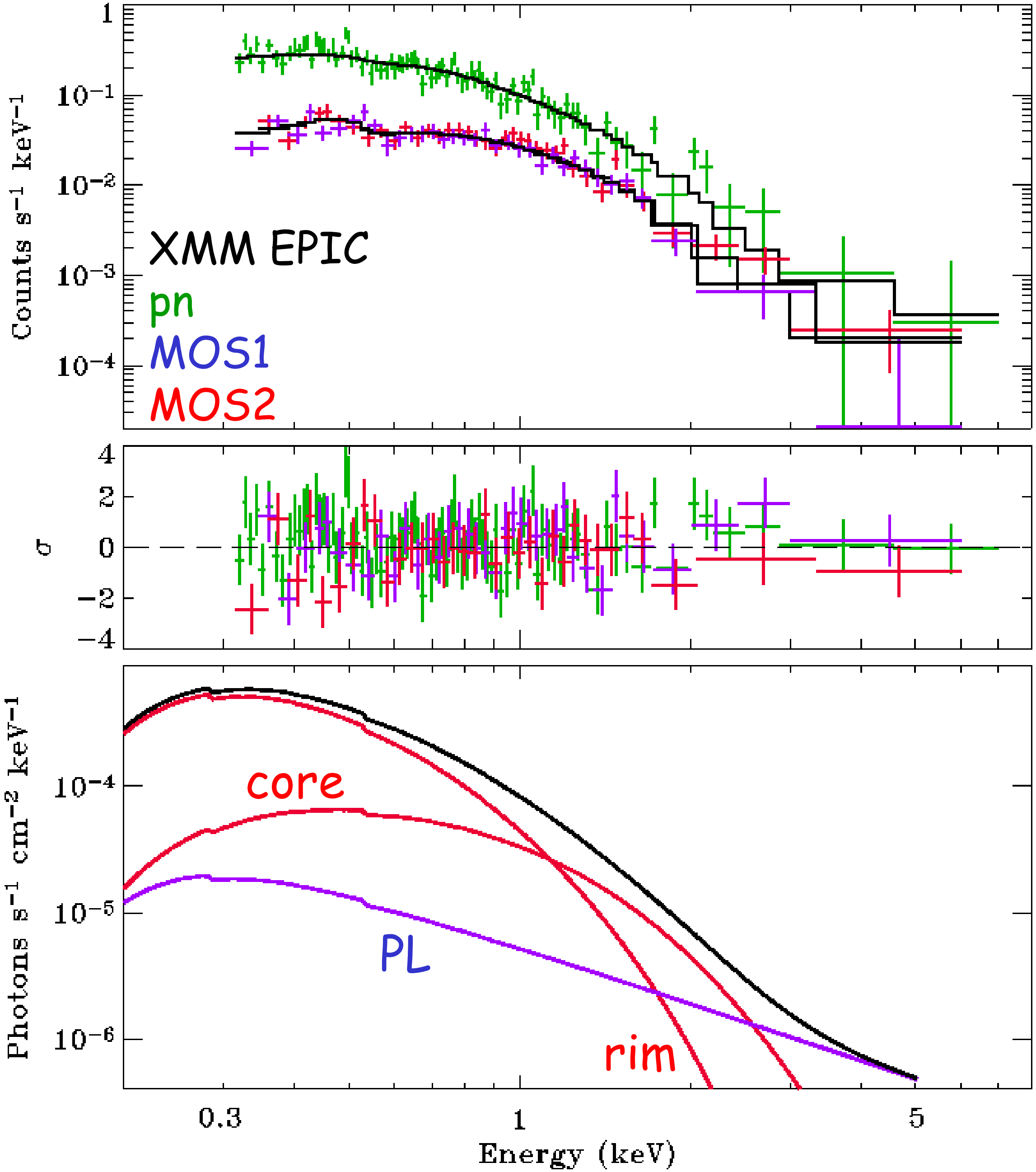
pulsations of $f_p \approx 50\%$, pulsed fraction possibly increasing with E

single PL gives $\Gamma \approx 4$, $n_H \approx 2 \times 10^{21}$ cm^{-2} — unreasonable

single BB does not work

two-component models, BB+PL ($\Gamma \approx 3$) or BB+BB, do

PSR J0030+0451



Model fit:
thermal PCs, core+rim, plus
nonthermal PL componets:

$T_{core} \approx 2.1$ MK, $T_{rim} \approx 0.8$ MK

$R_{core} \approx 0.1$ km, $R_{rim} \approx 1.4$ km

$L_{bol} \approx 1.8\times10^{30}$ erg/s =

$= 0.5\times10^{-3}$ dE/dt

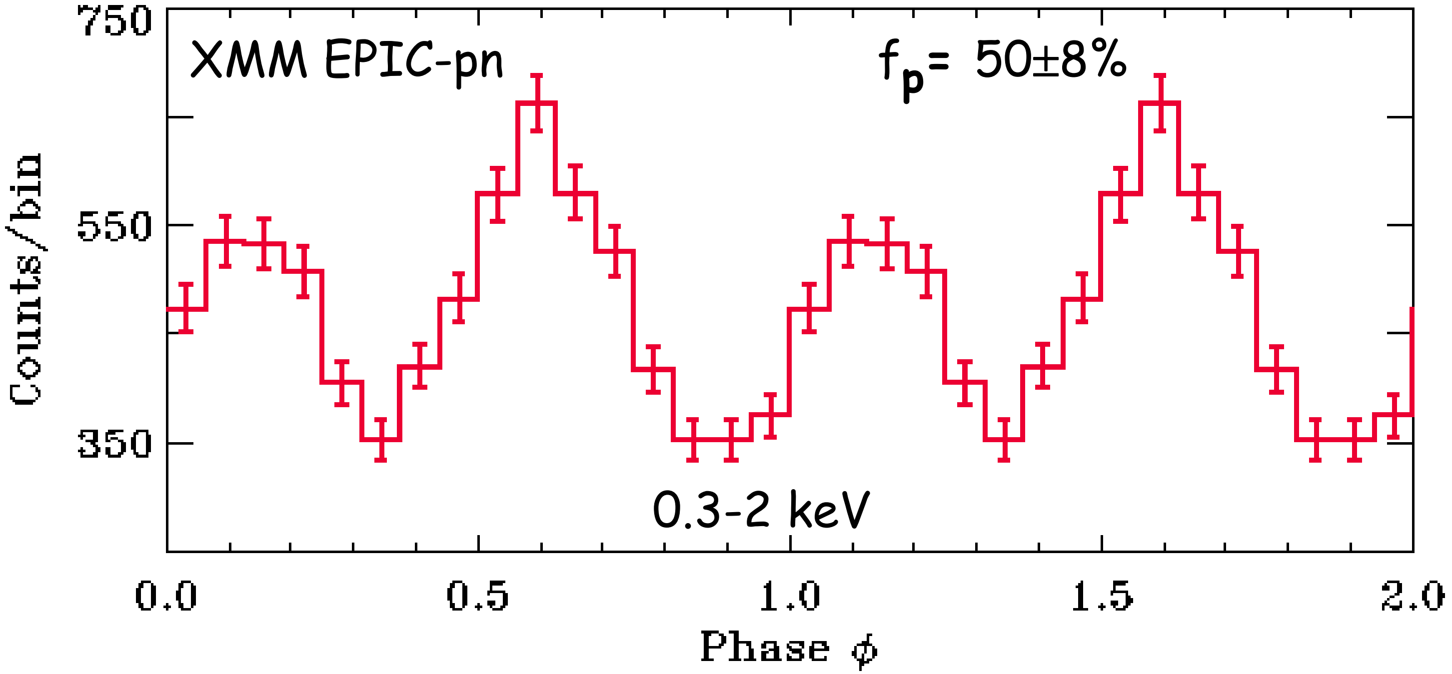
→ similar to J0437-4715

Γ=1.5 (fixed)

$L_X \approx 0.6\times10^{30}$erg/s

$= 0.2\times10^{-3}$ dE/dt

PSR J0030+0451



PSR J2124-3358

ROSAT (Becker & Trümper 1999) :

possible pulsed X-ray emission
no spectral information

ASCA (Sakurai et al. 2001):

no significant pulsations

the spectrum — either a BB model of $T_{BB} \approx 3.6$ MK, $R_{BB} \approx 0.02$ km
or a PL of $\Gamma \approx 3$
$\rightarrow$ the thermal model is more preferable

XMM observation of PSR J2124-3358 :

- the pulsar's spectrum resolved only up to 3 keV
- single PL fit $\rightarrow \Gamma \approx 3.3$, too large absorption $n_H \approx 2\times10^{21}$ cm^{-2}
- single thermal model fit $\rightarrow$ large data excess at E>1.5 keV
- best fit with, thermal+nonthermal, model:

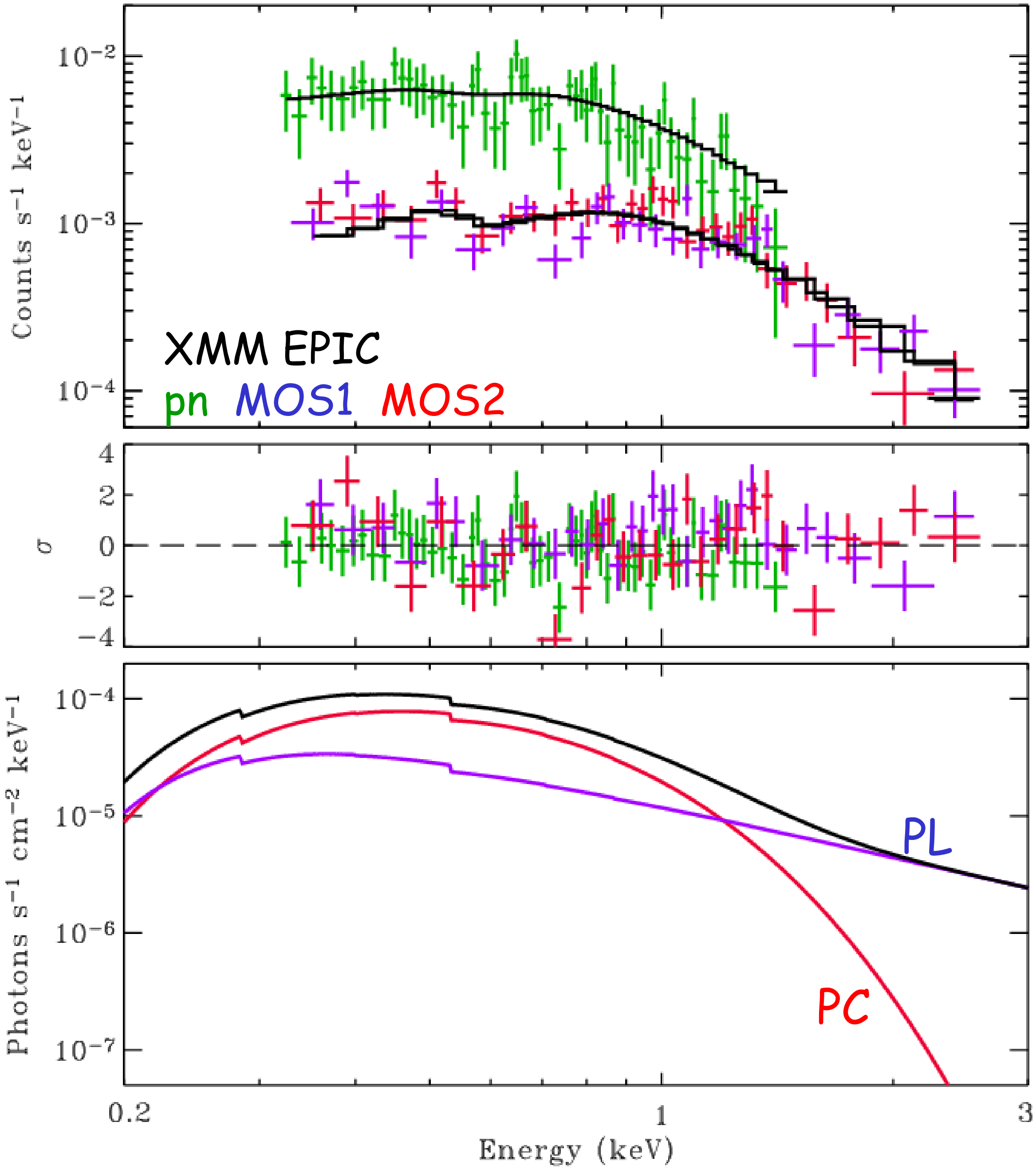
one-temperature PCs —

$T_{pc} \approx$ 1.2 MK, $R_{pc} \approx$ 0.4 km,
$L_{bol} \approx 0.6\times10^{30}$ erg/s = 0.1×10^{-3} dE/dt (for one PC)

the nonthermal, PL component —

Γ =1.5 (fixed), $L_X \approx 0.9\times10^{30}$ erg/s

PSR J2124-3358



Model fit: uniform PCs plus PL

or

pure thermal interpretation:

$T_{core} \approx 2.2$ MK, $T_{rim} \approx 0.5$ MK

$R_{core} \approx 0.1$ km, $R_{rim} \approx 1.9$ km

$L_{bol} \approx 0.9 \times 10^{30}$ erg/s =

= 0.2×10^{-3} dE/dt

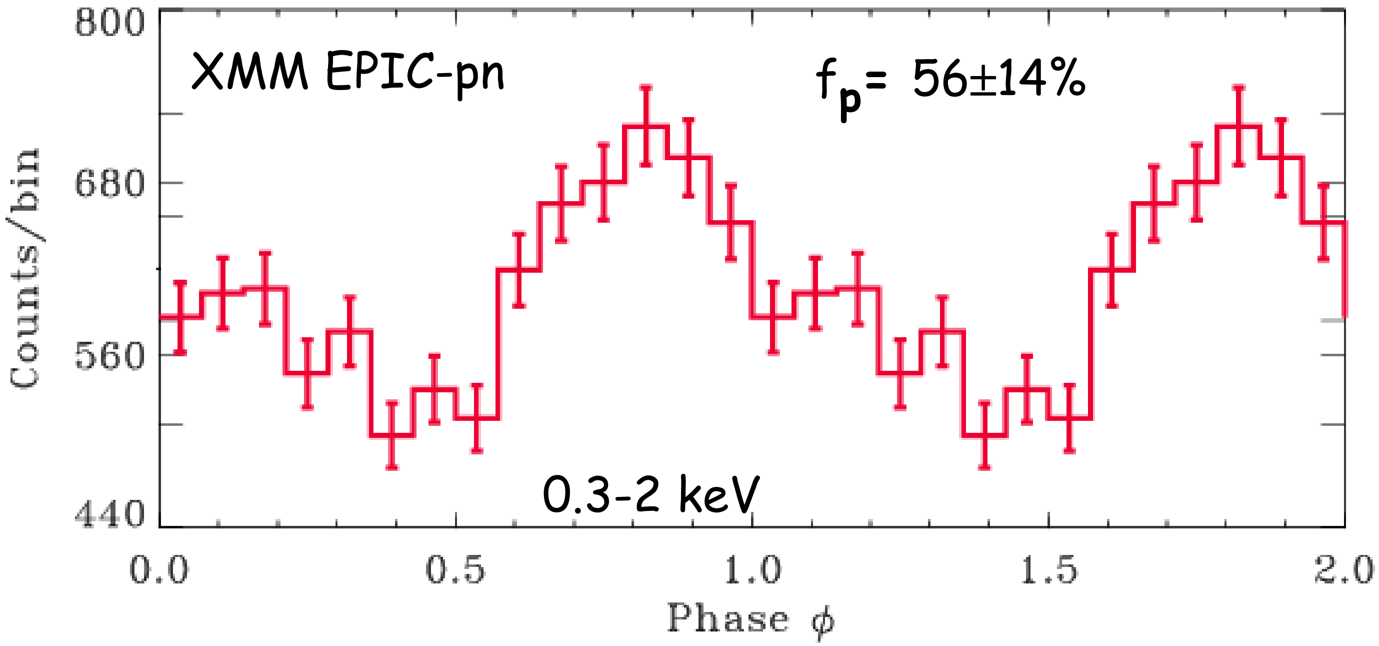
→ similar to J0437-4715

PL: $L_X < 0.1 \times 10^{30}$ erg/s =

= 0.02×10^{-3} dE/dt

(Zavlin 2006)

PSR J2124-3358



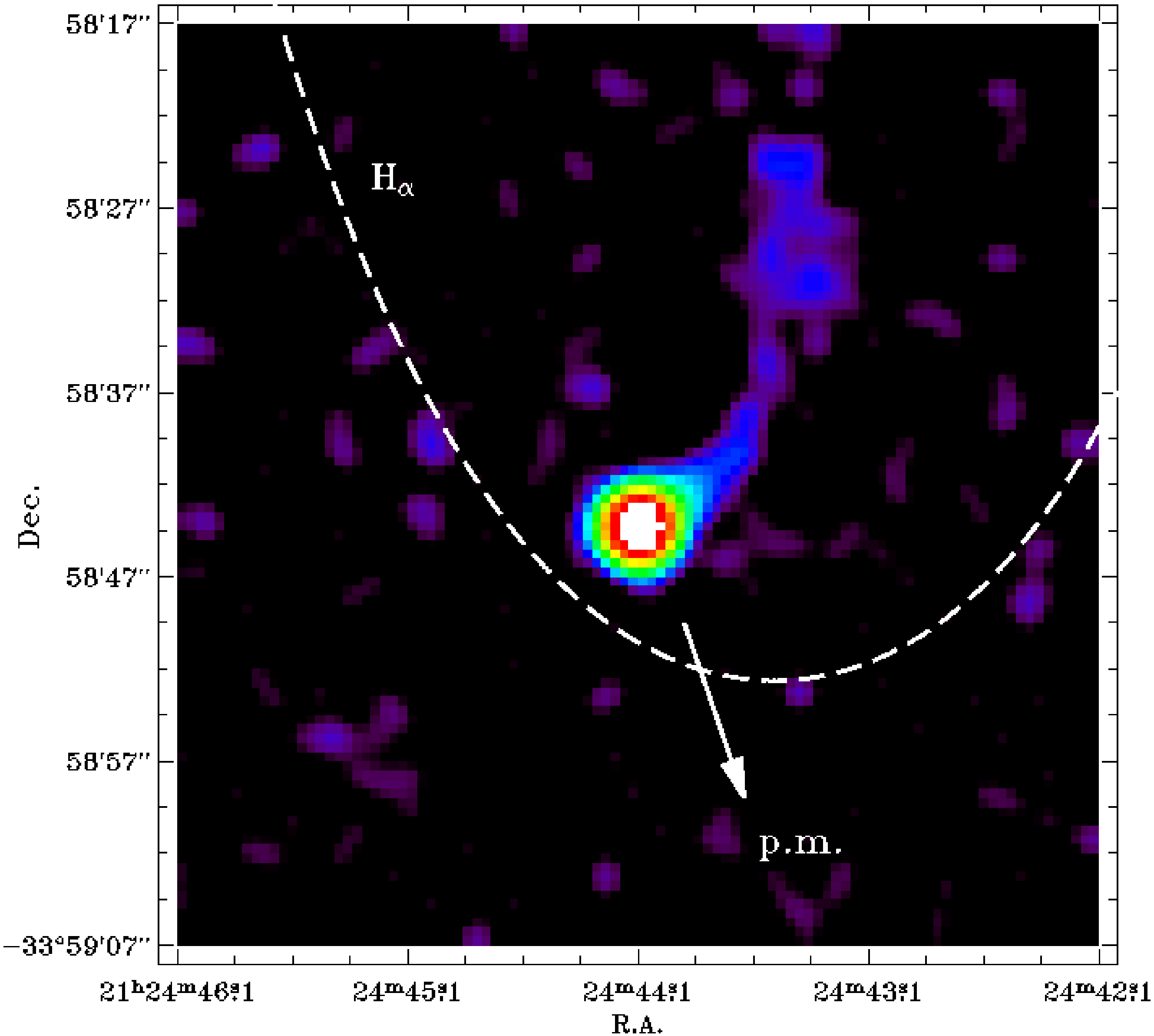
possible double-peaked structure → contributions from two components

or

a single peak of asymmetric shape due to the GR effects,
the Doppler boost (Braje et al. 2000)

(Zavlin 2006)

PSR J2124-3358



H_α bow-shock (Gaensler et al. 2002)

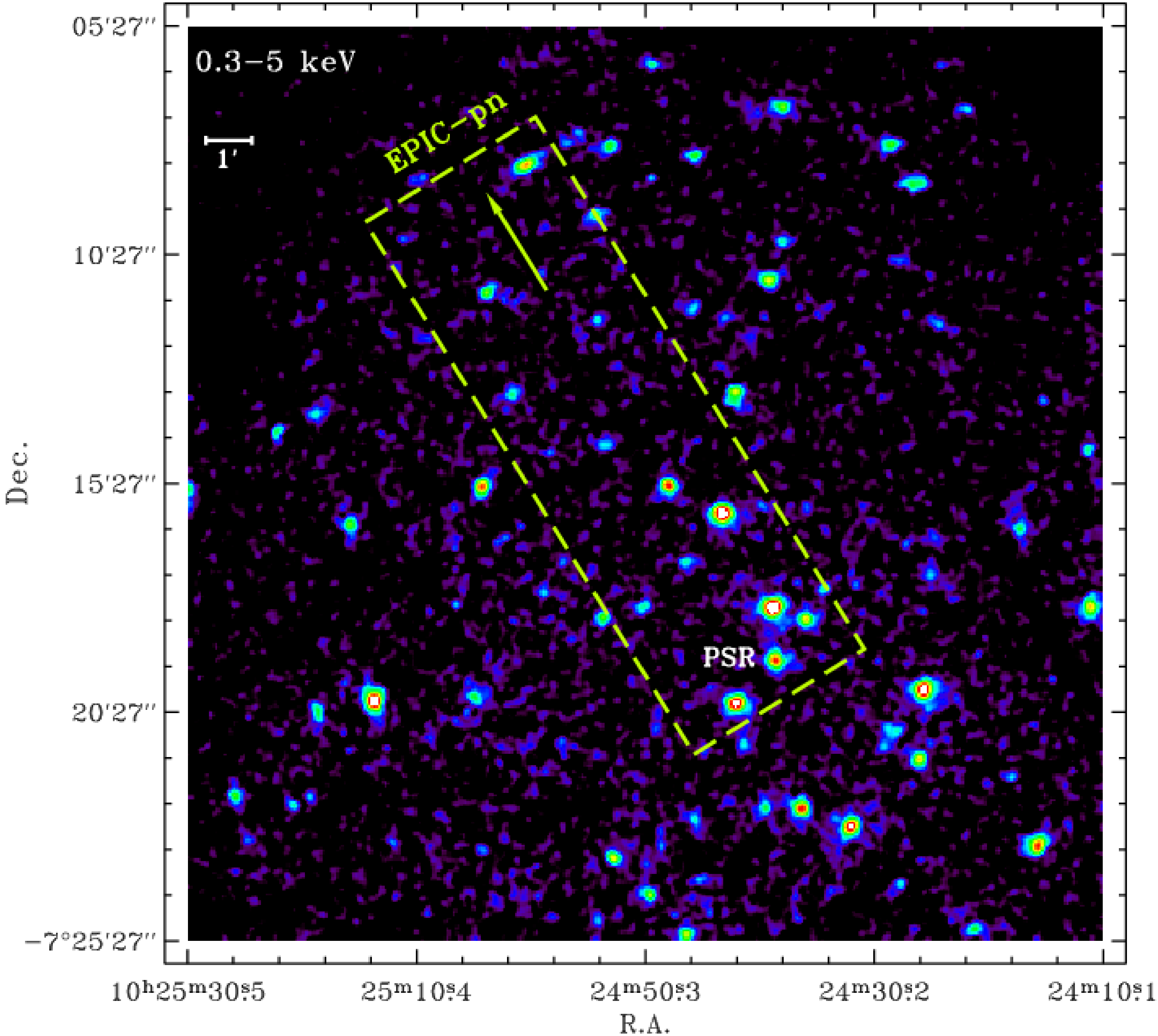
and

X-ray tail

Chandra ACIS (Hui & Becker 2006)

PSR J1024-0719

RO
a



XMM EPIC-MOS data on PSR J1024-0719:

- the pulsar's spectrum resolved only up to 3 keV
- single PL fit $\rightarrow \Gamma \approx 3.5$, too large absorption $n_H \approx 2\times10^{21}$ cm^{-2}
- single thermal model provides an acceptable fit, e.g., PCs:

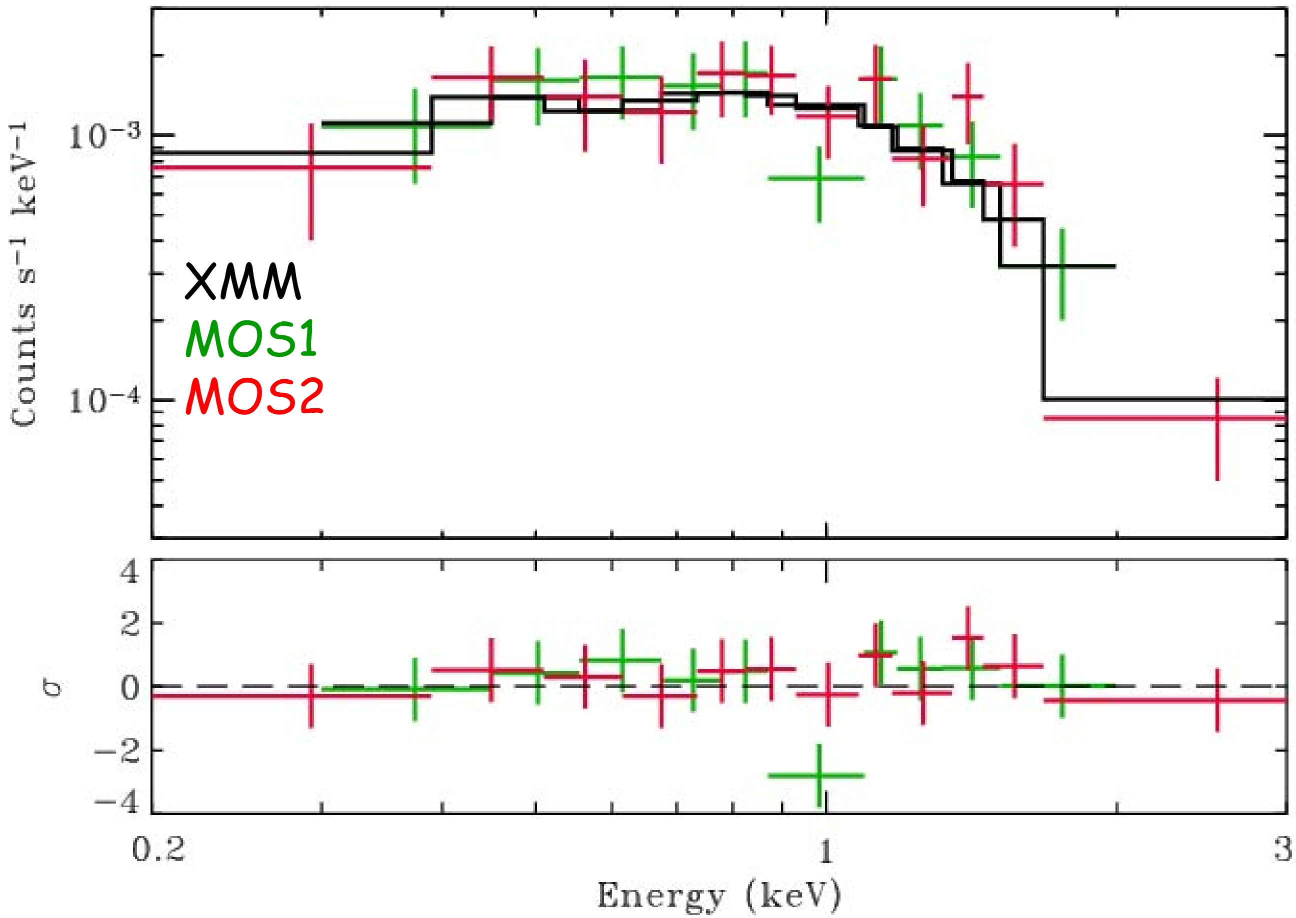
$T_{pc} \approx$ 1.8 MK, $R_{pc} \approx$ 0.1 km,
$L_{bol} \approx 0.2\times10^{30}$ erg/s = 0.04×10^{-3} dE/dt (for one PC)

upper limit on a possible nonthermal component (Γ=1.5):

$L_X < 0.2\times10^{30}$ erg/s = 0.04×10^{-3} dE/dt

PSR J1024-0719

Fit with a pure thermal model

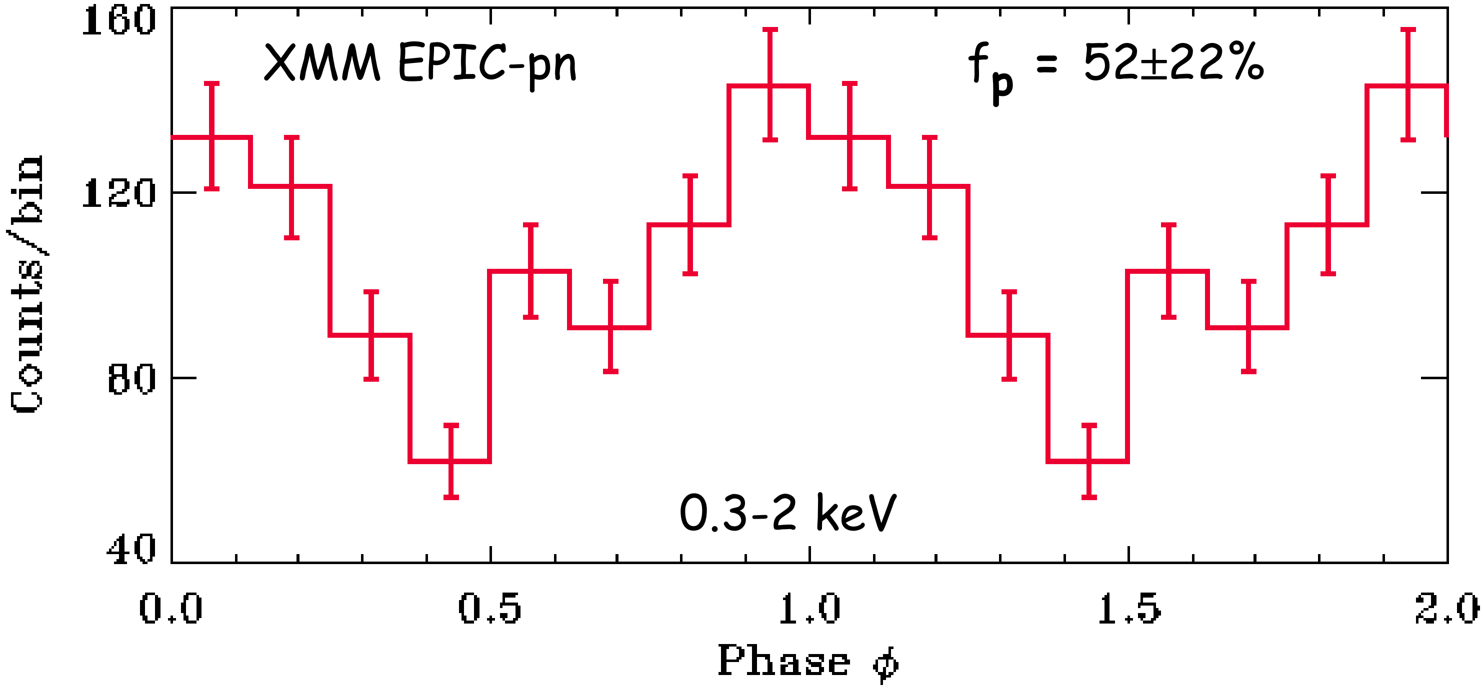


PC "rim" component:

$T_{rim} \approx 0.4$ MK, $R_{rim} \approx 1.1$ km

(Zavlin 2006)

PSR J1024-0719



single broad pulse per period

(Zavlin 2006)

Nonthermal vs. Thermal

Saito et al. 1997

Nonthermal emission:

PSR	dE/dt (10^{33} erg/s)	$B^{LC} = B^{surf} \times (R/R^{LC})^3$ (10^4 G)
B1957+20	1.6×10^2	40
B1937+21	1.1×10^3	102 — close to that in the Crab pulsar
B1821-24	2.2×10^3	74
J0218+4232	2.4×10^2	32

[$R^{LC} = cP/2\pi$]

Thermal emission:

J0437-4715	3.8	3
J0030+0451	7.7	2
J2124-3358	3.8	3
J1024-0719	5.3	2

Conclusions

- in PSRs J0437-15, J0030+0451, J2124-3358, J1024-0719, thermal PC radiation prevails over nonthermal component (plus about 16 more MSPs in Tuc 47)

- measured PC efficiencies, L_{bol} / [dE/dt] = (0.1—0.5) $\times 10^{-3}$,

  (A) are similar to those of some old ordinary pulsars (Zavlin & Pavlov 2004)

  (B) exceed by a factor of 10 predictions of theoretical PC models

  → further elaboration of pulsar models and PC heating mechanisms (curvature radiation, inverse$\dot{E}$Compton scattering)

- fits with the "core+rim" PC model indicate PCs may have nonuniform temperature distributions → models are required

- modeling of observed pulsed profiles to put constraints on M/R and geometry (Pavlov & Zavlin 1997) → models of magnetospheric emission