PULSARS

X-ray emission properties of old

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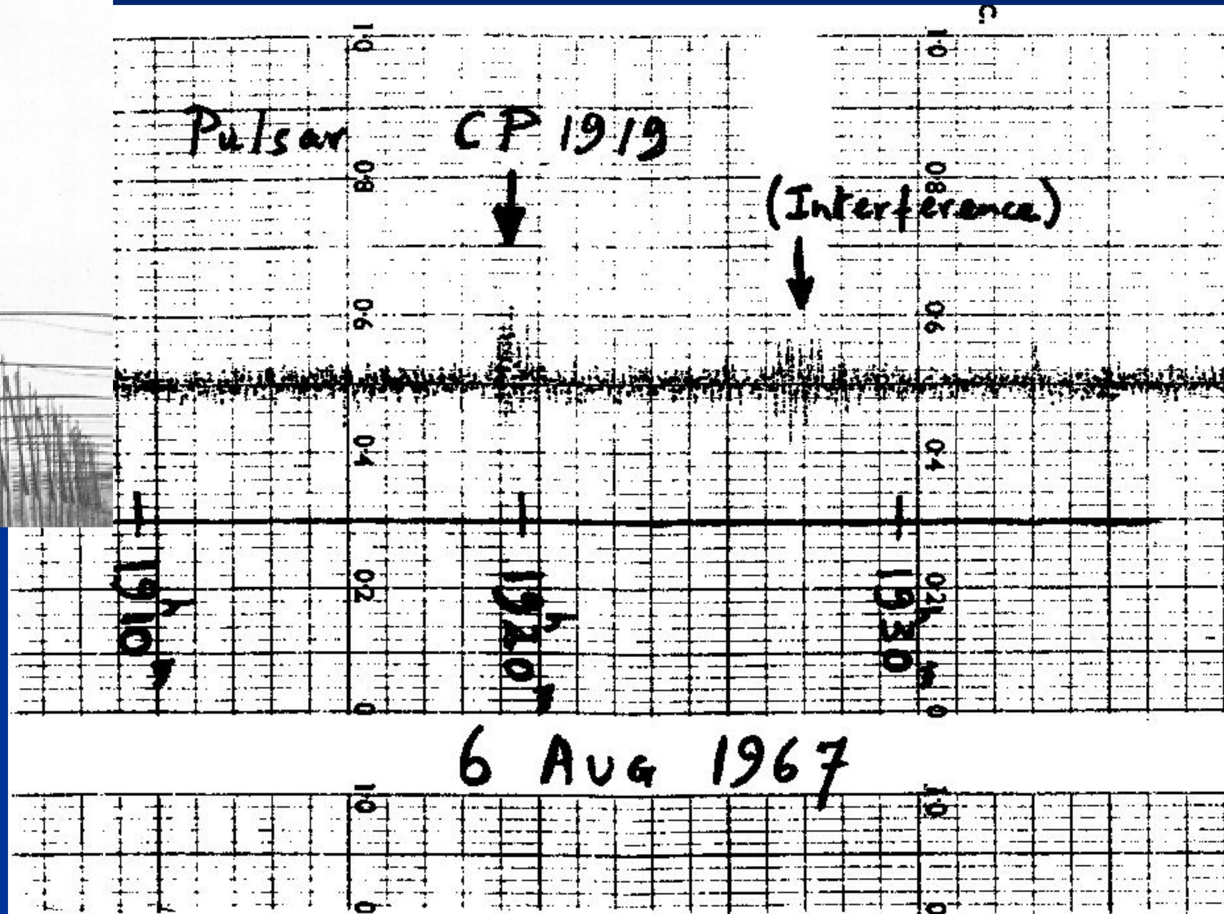
Neutron Stars were discovered 40 yrs ago

Jocelyn Bell-Burnell (1967)



The Neutron Star Zoo

Accretion powered pulsars (e.g. in binaries): ➡ X-ray pulsars

Rotation-powered pulsars: ➡ radio, optical, X-, γ–ray

↳ Pulsar Wind Nebulae: ➡ radio, optical, X-, γ–ray, TeV

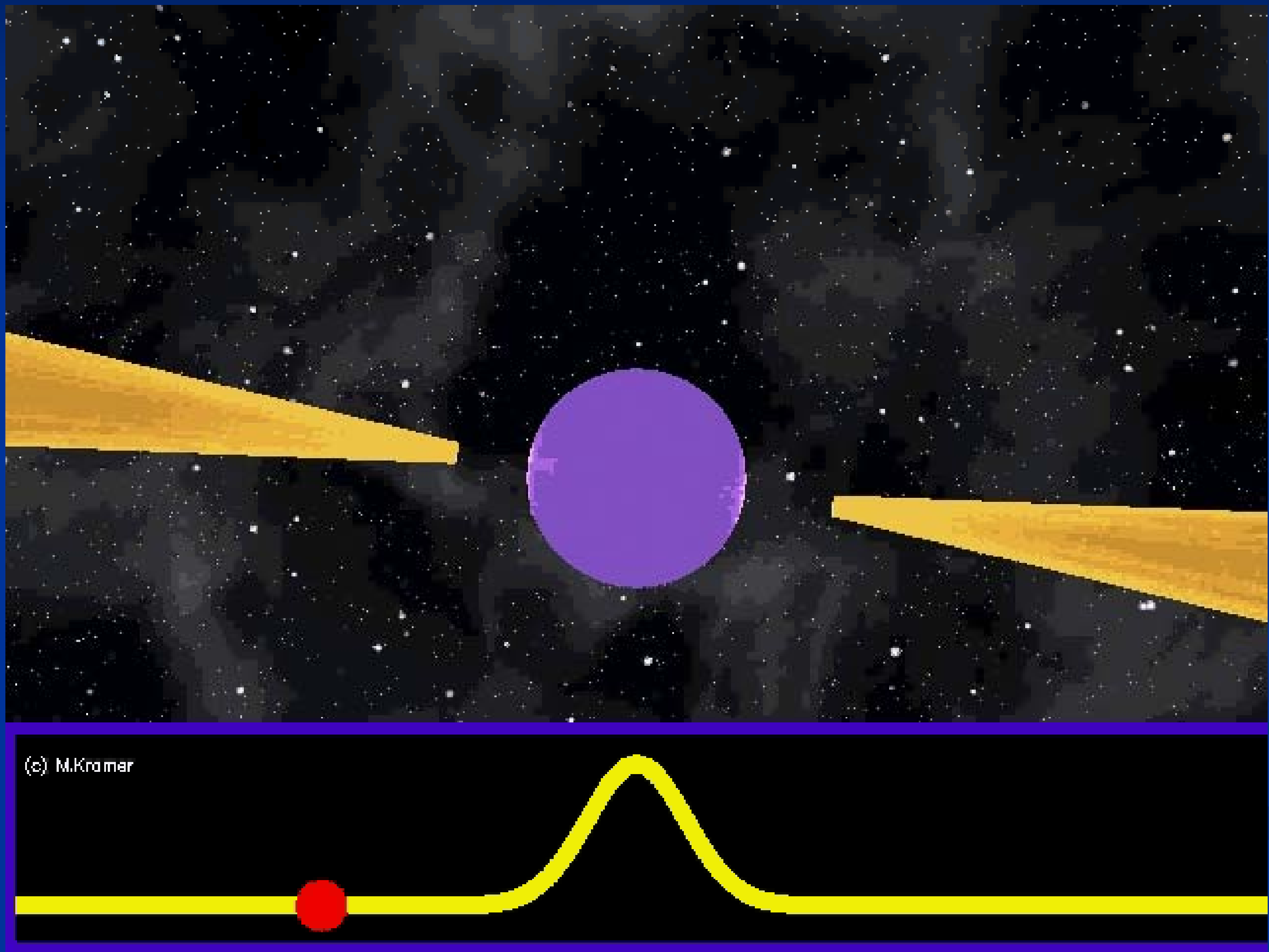
XDINs (X-ray dim isolated neutron stars): ➡ optical, X-ray

Soft Gamma-ray Repeater (SGRs): ➡ optical, X-, γ–ray } Magnetars

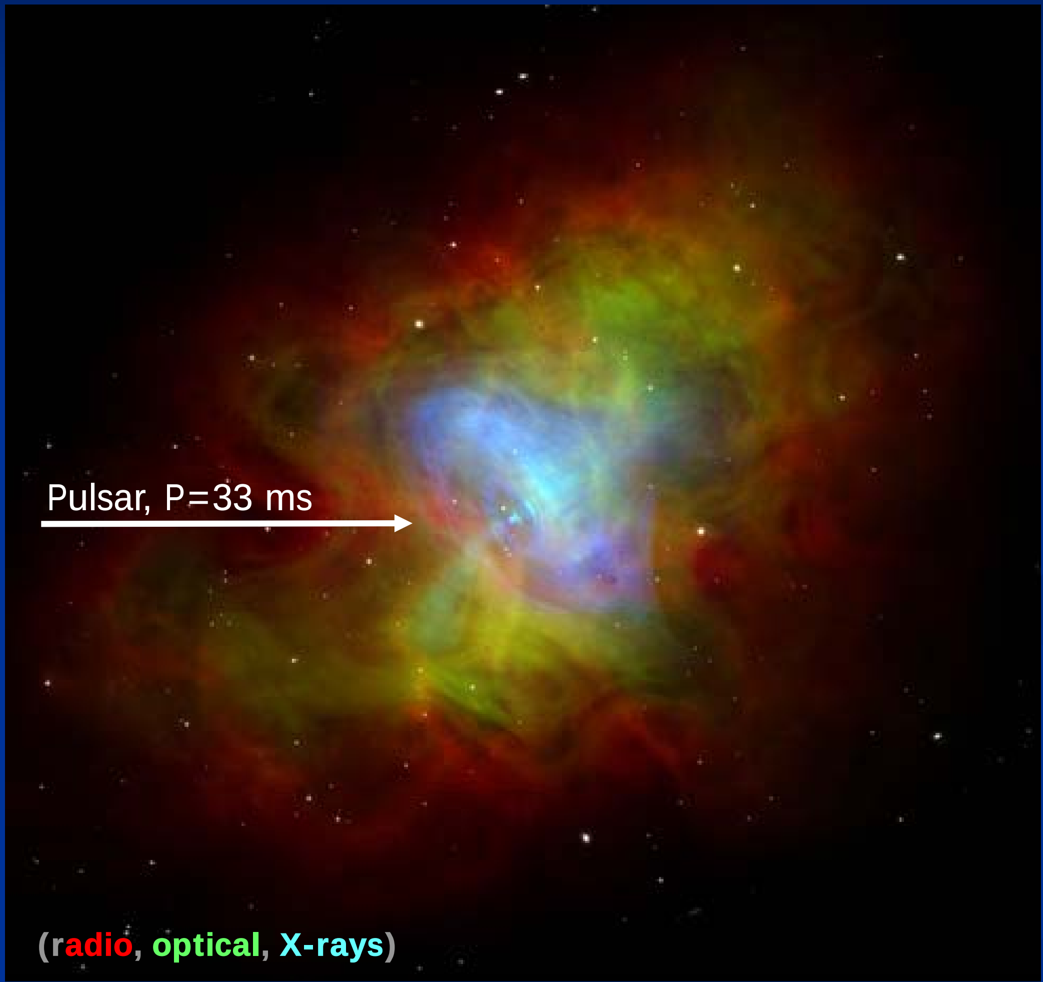
Anomalous X-ray Pulsare (AXPs): ➡ optical, X- ray, (radio) } Magnetars

Central Compact Objects in SNRs (CCOs): ➡ X- ray

Neutron Stars are cosmic lighthouses



The Crab pulsar and supernova remnant (SN 1054)



- $I = 10^{45}$ g cm^2
- $\Omega = 188.11$ rad s^{-1}
- $\dot{\Omega} = -2.37 \times 10^{-9}$ rad s^{-2}
- $E_{rot} = \frac{1}{2}\, I\, \Omega^2 \sim 2 \times 10^{49}$ erg
- $\dot{E} = I\, \Omega\, \dot{\Omega} \sim 4 \times 10^{38}$ erg/s
- $|\, \vec{m}\, | = \frac{1}{2}\, B_p\, R^3$
- $\dot{E} = -\frac{2}{3\, c^3}\, |\, \ddot{\vec{m}}\, |^2$
- $\dot{E} = -\frac{1}{6\, c^3}\, B_p^2\, R^6\, \Omega^4\, \sin^2 \alpha$
- $B_p = 2.1 \times 10^{20} \sqrt{\dot{\Omega}\, /\, \Omega^3}$
- $\tau \equiv -\frac{1}{2}\, \Omega\, /\, \dot{\Omega}$

distance: ~ 6000 LJ, extent ~ 7 x 10 LJ

Rotation-powered Pulsars

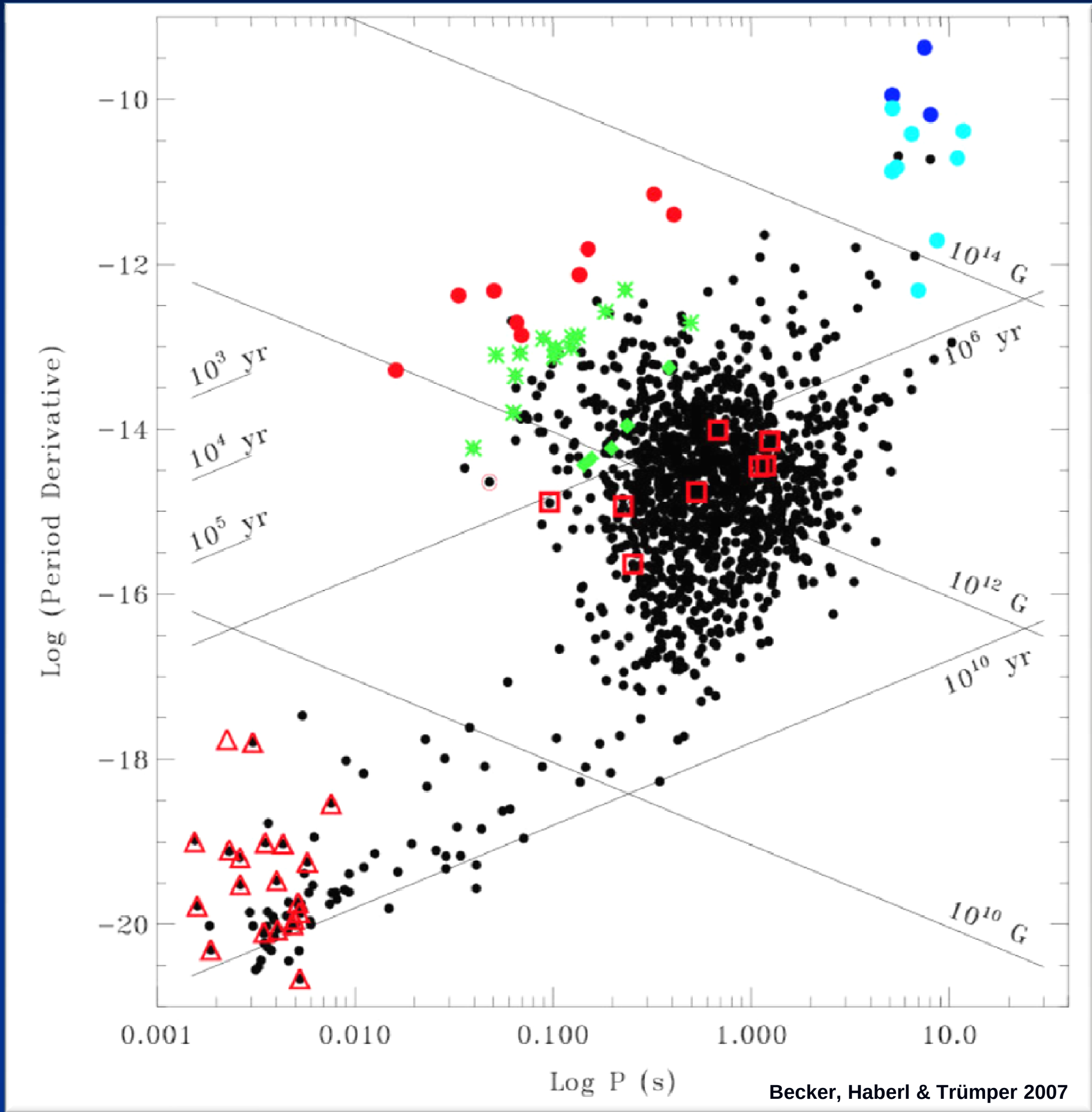
Currently:

- 1765 radio PSRs

  but ONLY

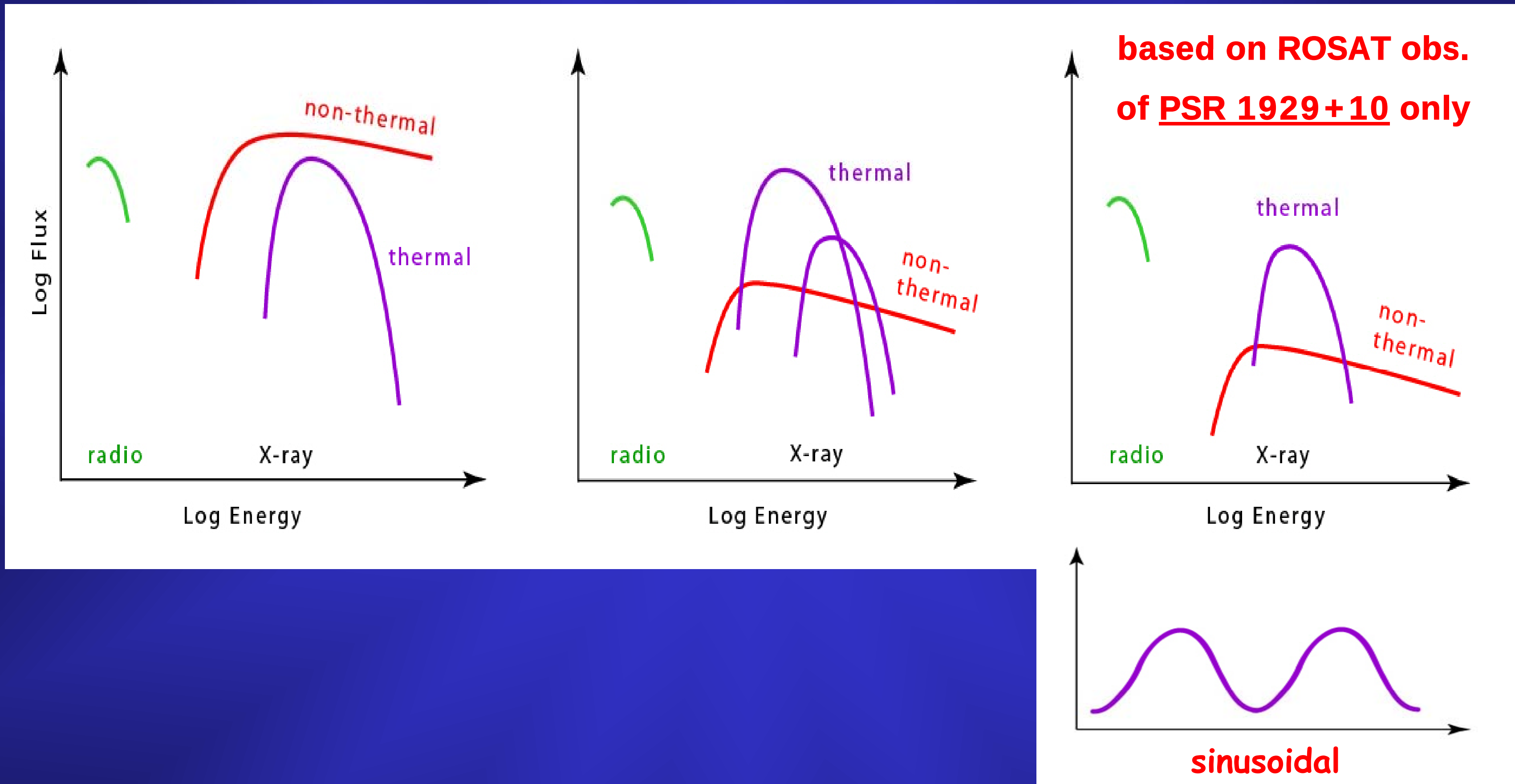
- 7 γ–ray PSRs
- 10 optical PSRs
- 81 X-ray PSRs

Spectral and timing information is available only for ~ 2/3 of them.



X-ray emission properties vary with spin-down age

Crab-like pulsars	Cooling neutron stars	Old pulsars
(< 10^4 yrs)	(~10^5 - 10^6 yrs)	(~10^6 - 10^8 yrs)



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Crab-like pulsars	Cooling neutron stars	Old pulsars
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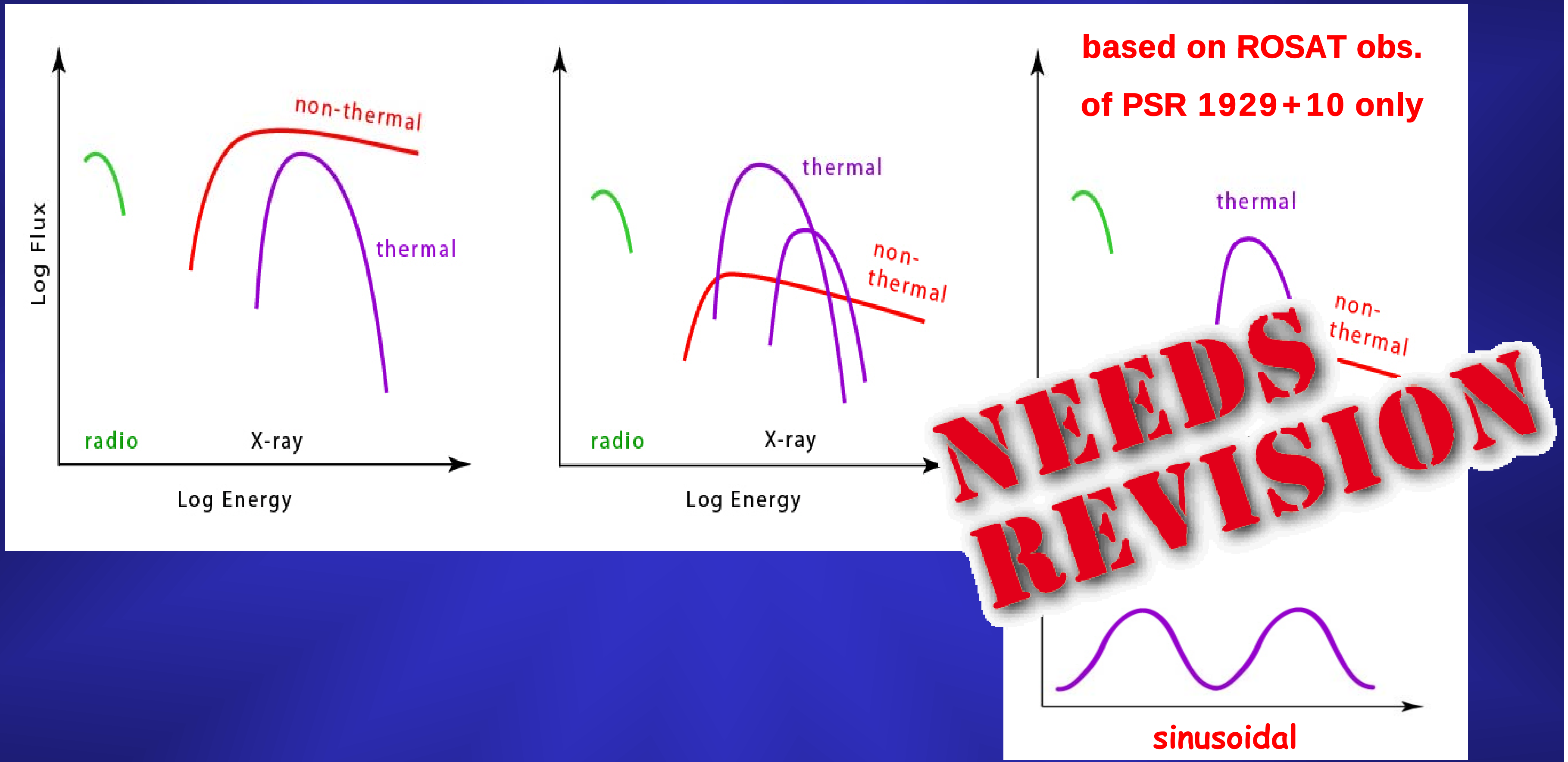
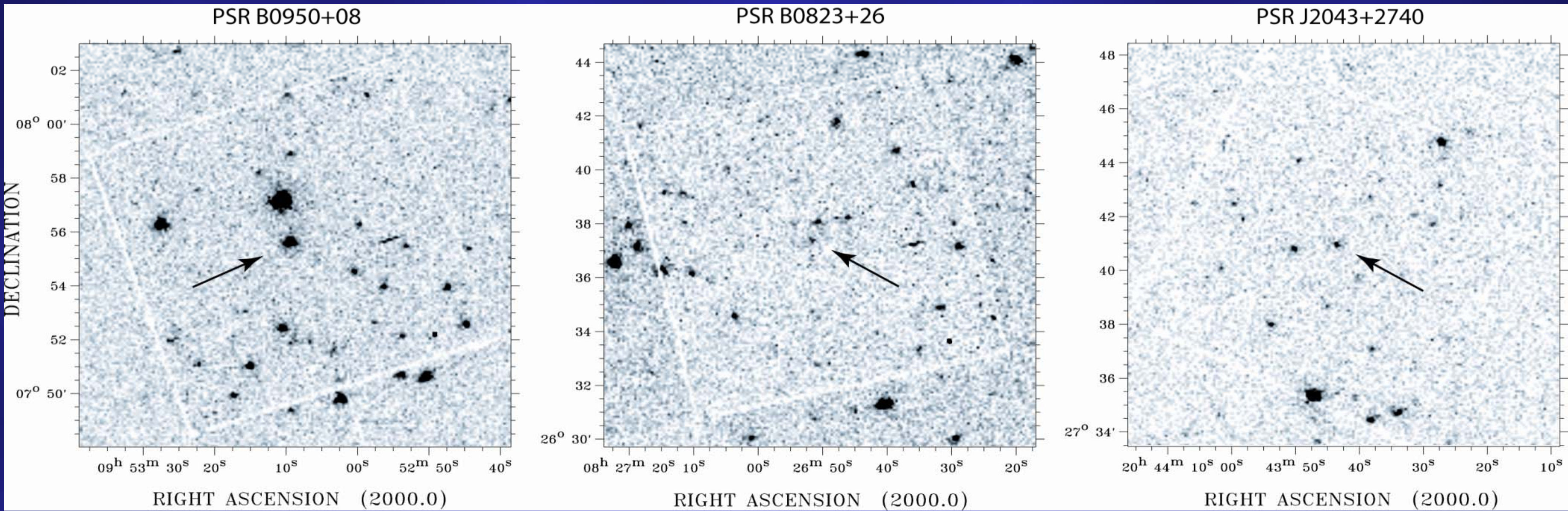


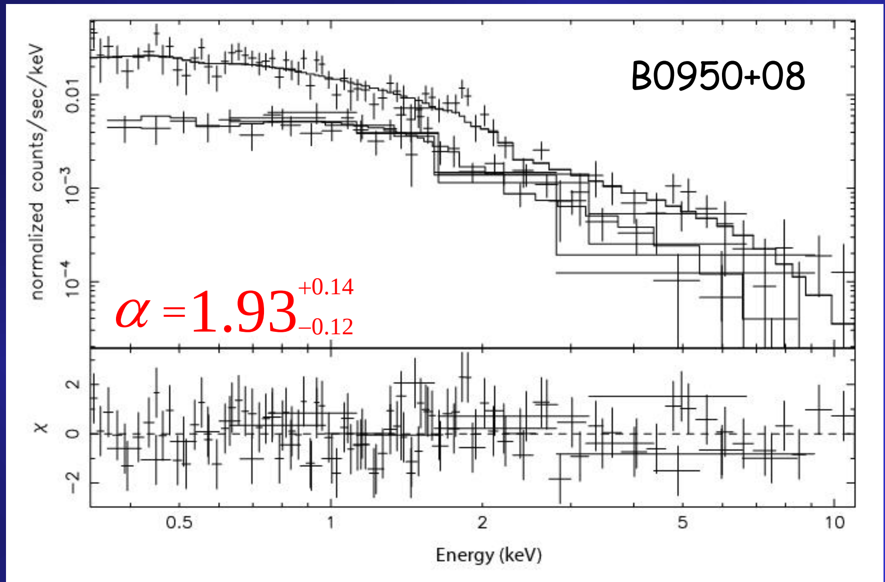
XMM-Newton observations of old pulsars

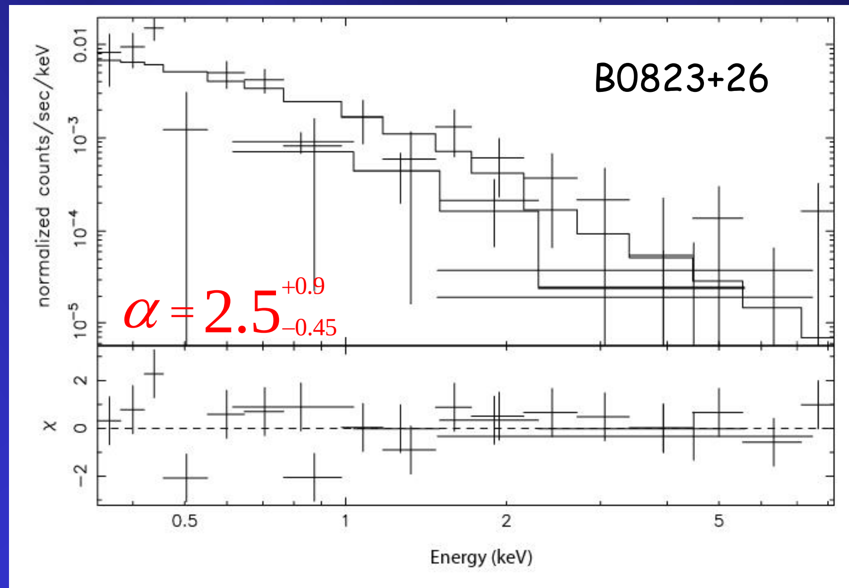


	PSR B0950+08	PSR B0823+26	PSR J2043+2740
τ	~ 17 x 10^6 yrs	~ 5 x 10^6 yrs	~ 1.2 x 10^6 yrs
P	~ 253 ms	~ 530 ms	~ 96 ms
$\dot{E}$	~ 5.6 x 10^{32} erg/s	~ 4.5 x 10^{32} erg/s	~ 5.6 x 10^{34} erg/s
d	~ 255 pc	~ 340 pc	~ 1130 pc
N_H	~ 9.6 x 10^{19} cm^{-2}	~ 60 x 10^{19} cm^{-2}	~ 65 x 10^{19} cm^{-2}

Becker, Weisskopf, Tennant et al.(2004)

X-ray emission properties of old pulsars

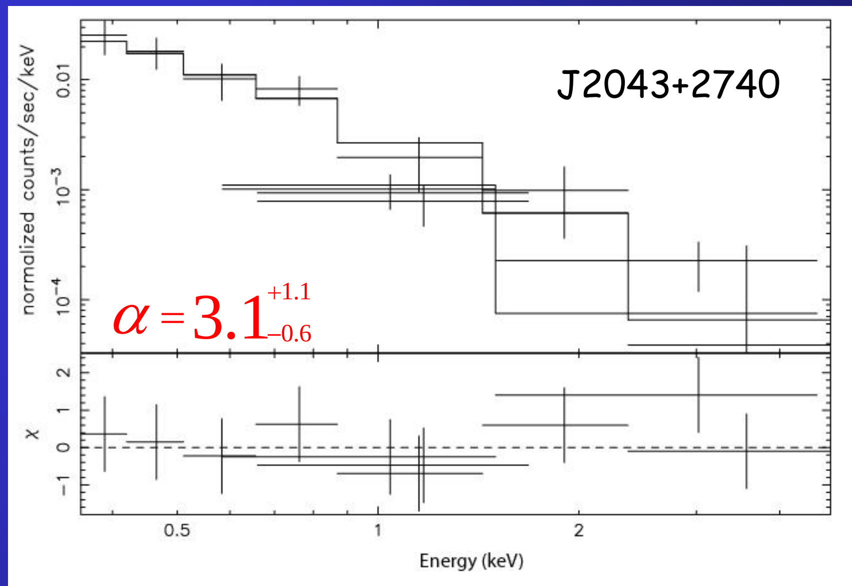




- BB spectra are clearly excluded
- BB+BB doesn't fit as well
- single PL spectrum fits best and is the easiest explanation:

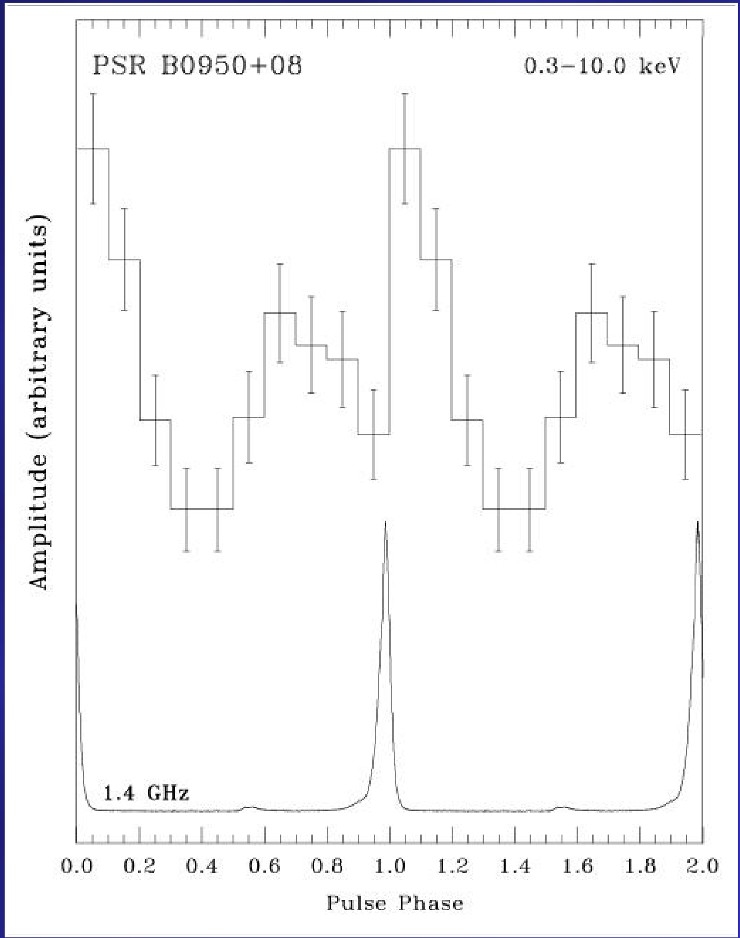
  → non-thermal emission dominates

- in J2043+1740 some thermal contr. possible



Becker, Weisskopf, Tennant et al.(2004)

X-ray emission properties of old pulsars: B0950+08

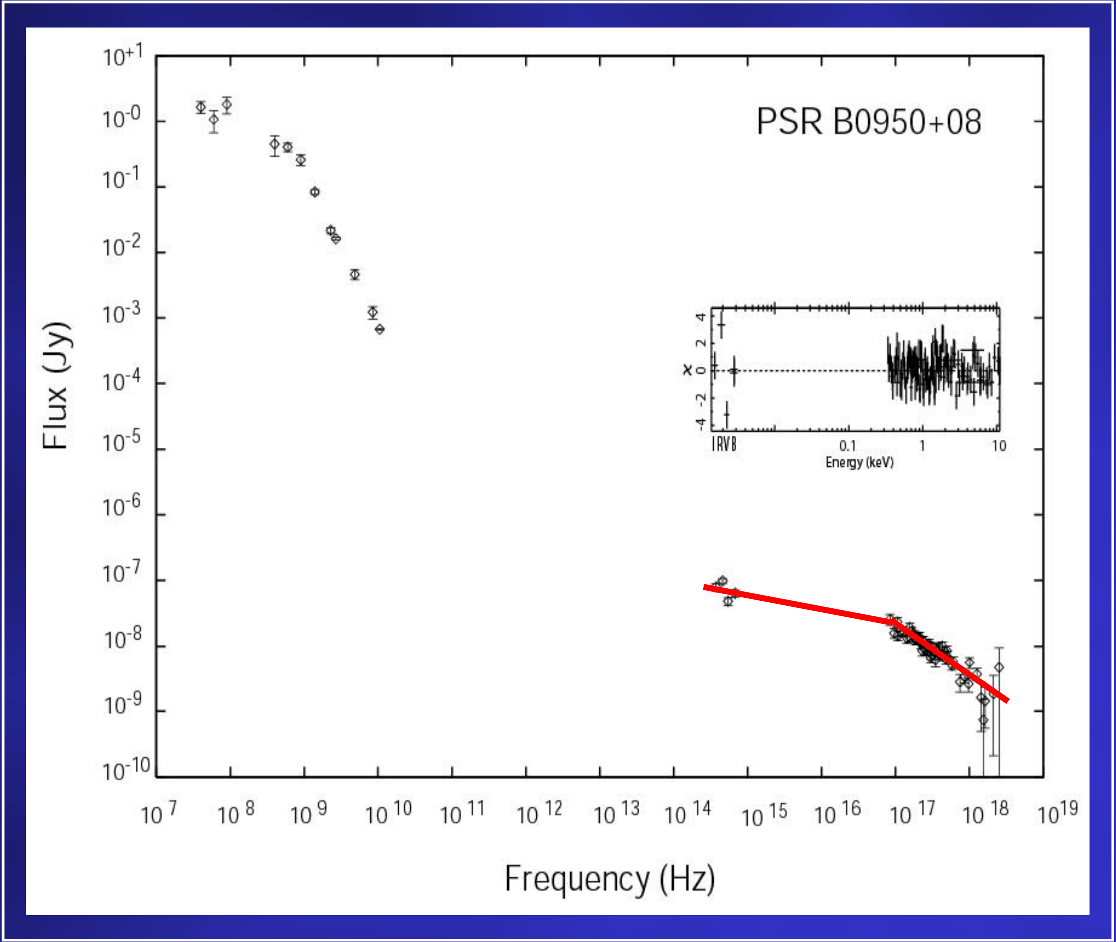


PF = 28 +- 6%, phase separation ~ 144^0

- pulse profile **NOT** sinusoidal
- double peaked pulse profile
- phase separation between X-ray peaks ~ 144^0 the same as for radio pulse and interpulse

Becker, Weisskopf, Tennant et al.(2004)

Multi-wavelength emission spectrum: B0950+08



- Optical to X-ray data:

  → broken power law

$$\alpha_1 = 1.27^{+0.02}_{-0.01}$$

$$\alpha_2 = 1.88^{+0.14}_{-0.11}$$

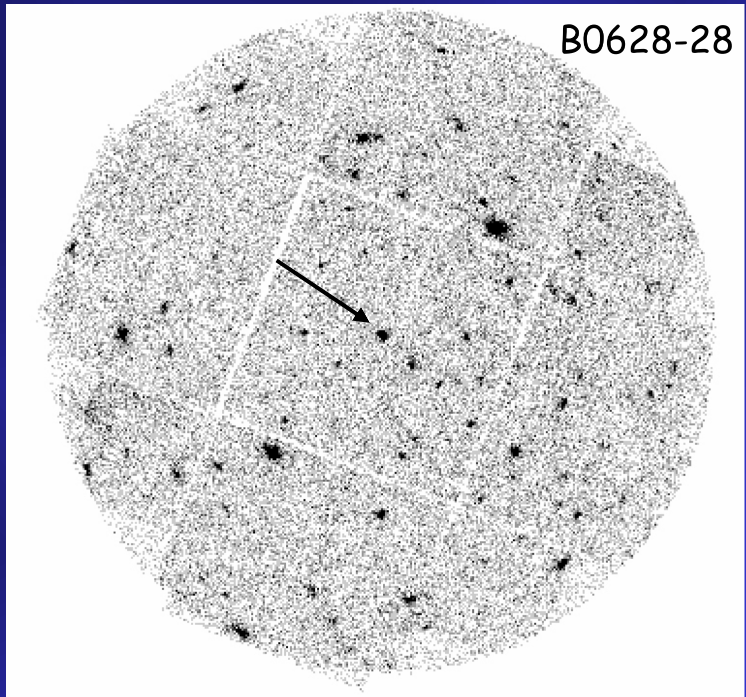
$$E_{break} = 0.67^{+0.18}_{-0.41}$$

Optical data taken with the VLT FORS1 (Zharikov et al. 2003)

Radio data from Malofeev et al.(1994)

Becker, Weisskopf, Tennant et al.(2004)

XMM-Newton observations of old pulsars: B0628-28



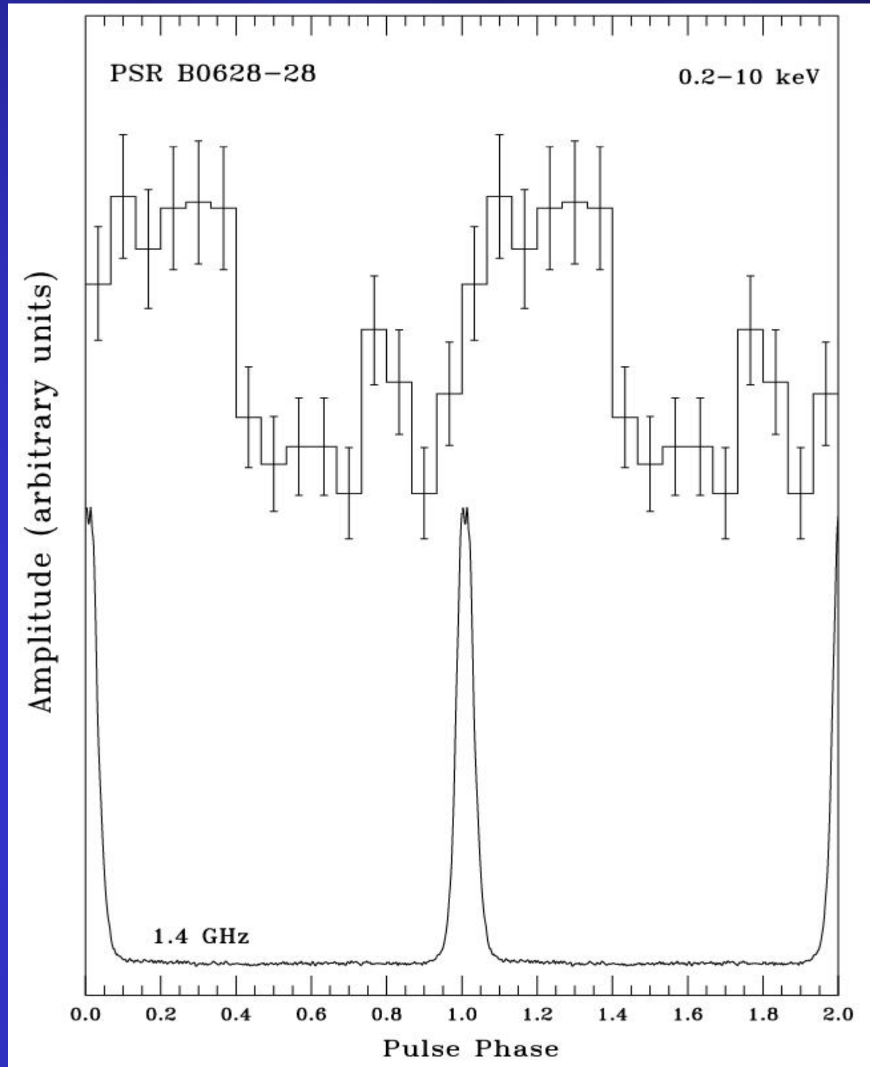
τ ~ 2.75 x 10^6 yrs

P ~ 1.24 s

$\dot{E}$ ~ 1.45 x 10^{32} erg/s

d ~ 1.45 kpc

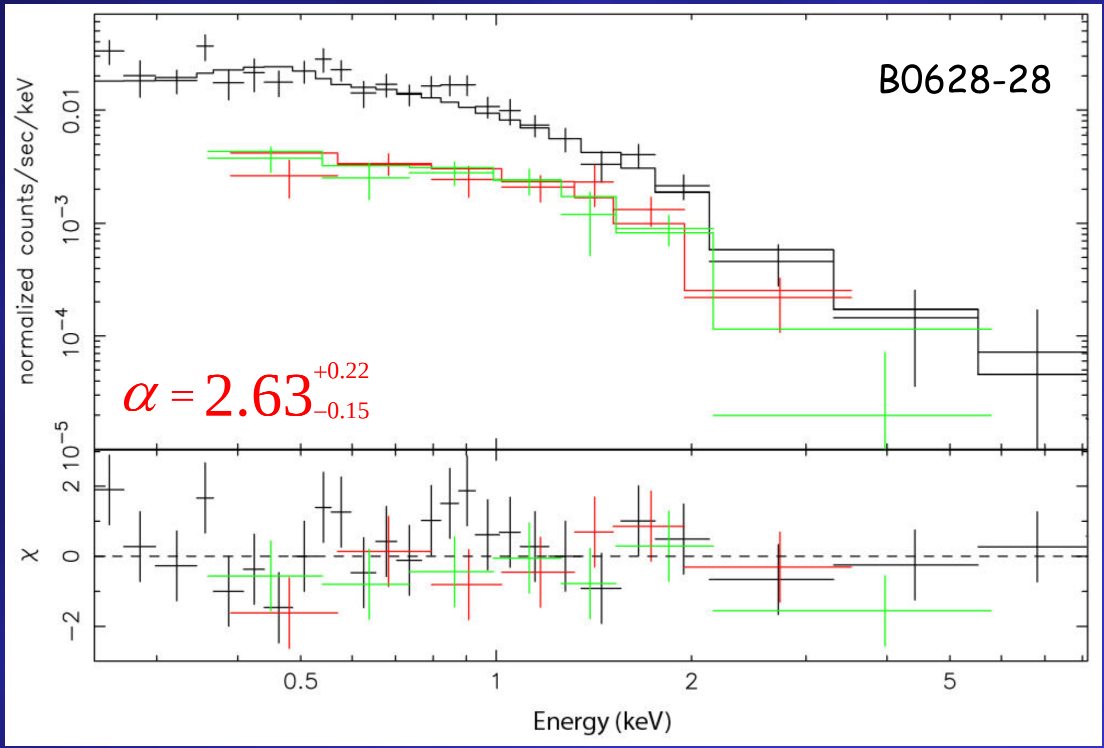
N_H ~ 6 x 10^{20} cm^{-2}



PF = 39 +- 6% (0.2 - 10 keV)

Becker, Jessner, Kramer et al.(2005)

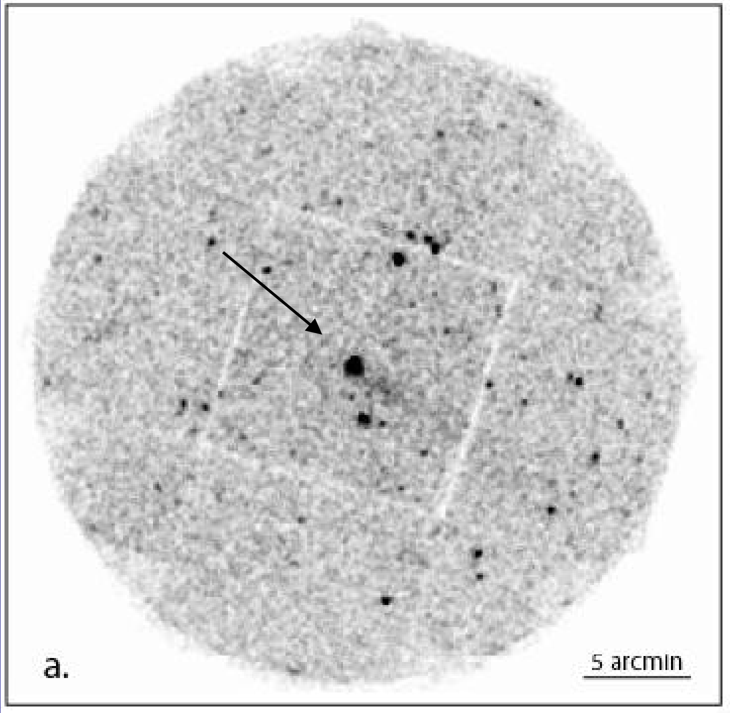
XMM-Newton observations of old pulsars: B0628-28

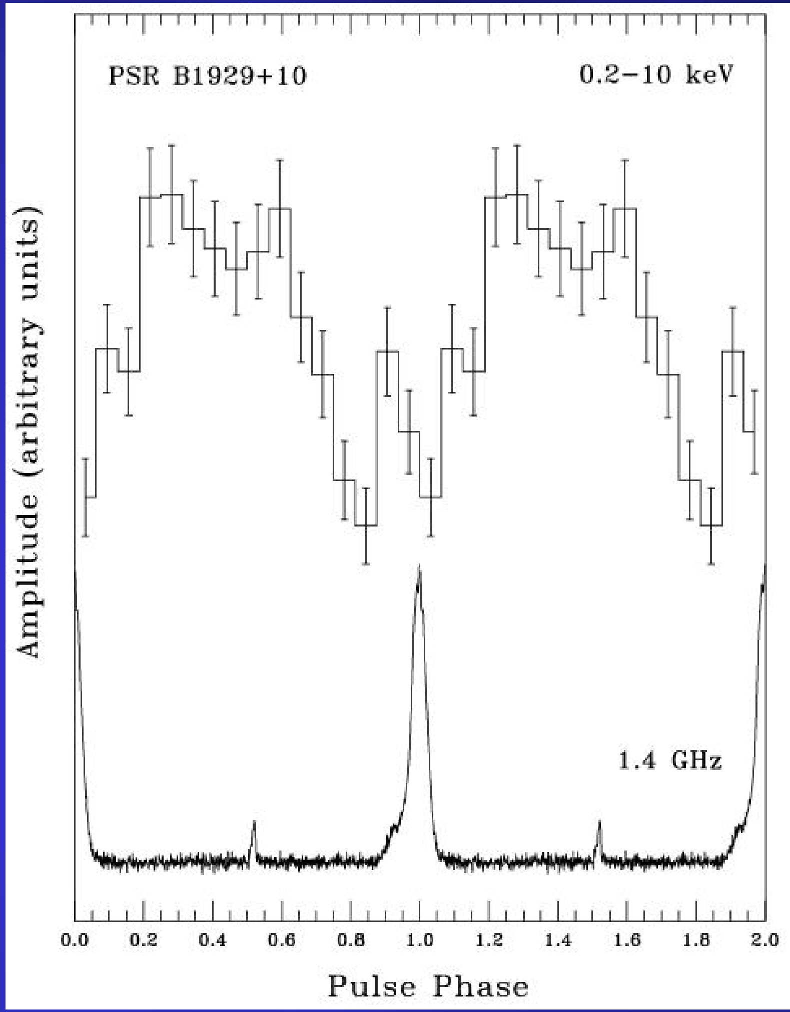


- BB spectra are clearly excluded
- single PL spectrum fits best
  → non-thermal emission dominates
- ~ 20% thermal contrib. possible

Becker, Jessner, Kramer et al.(2005)

X-ray emission properties of old pulsars: B1929-10





τ ~ 3.1 x 10^6 yrs

P ~ 226 ms

$\dot{E}$ ~ 3.9 x 10^{33} erg/s

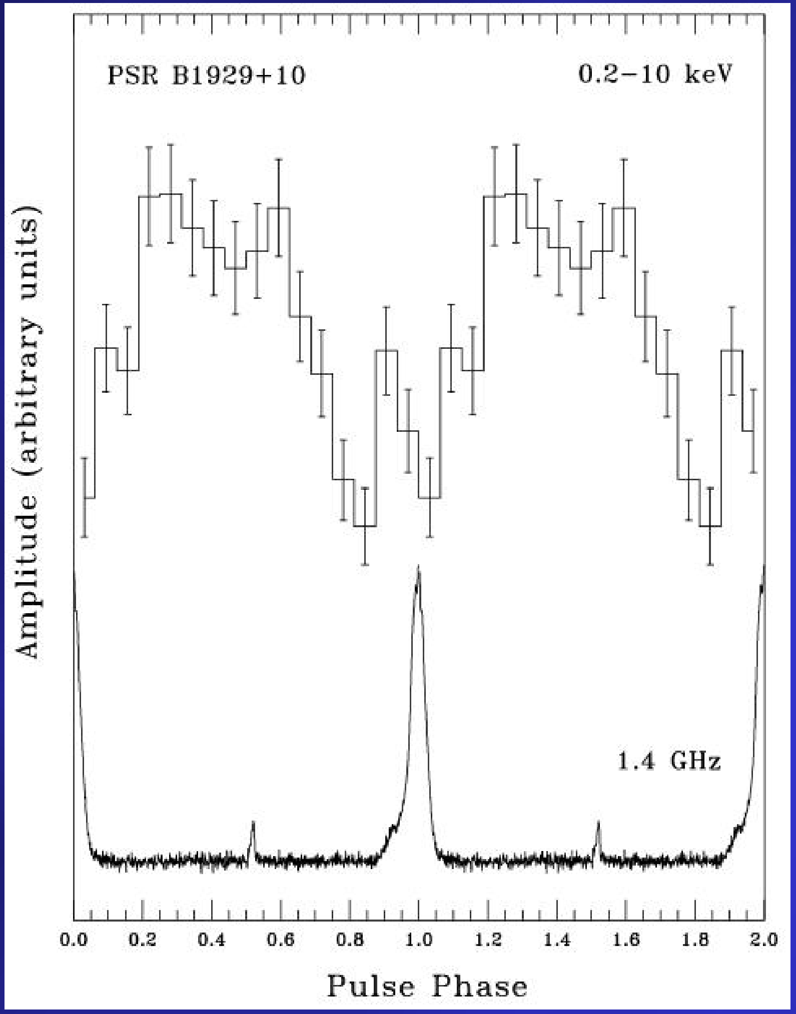
d ~ 3.178 pc

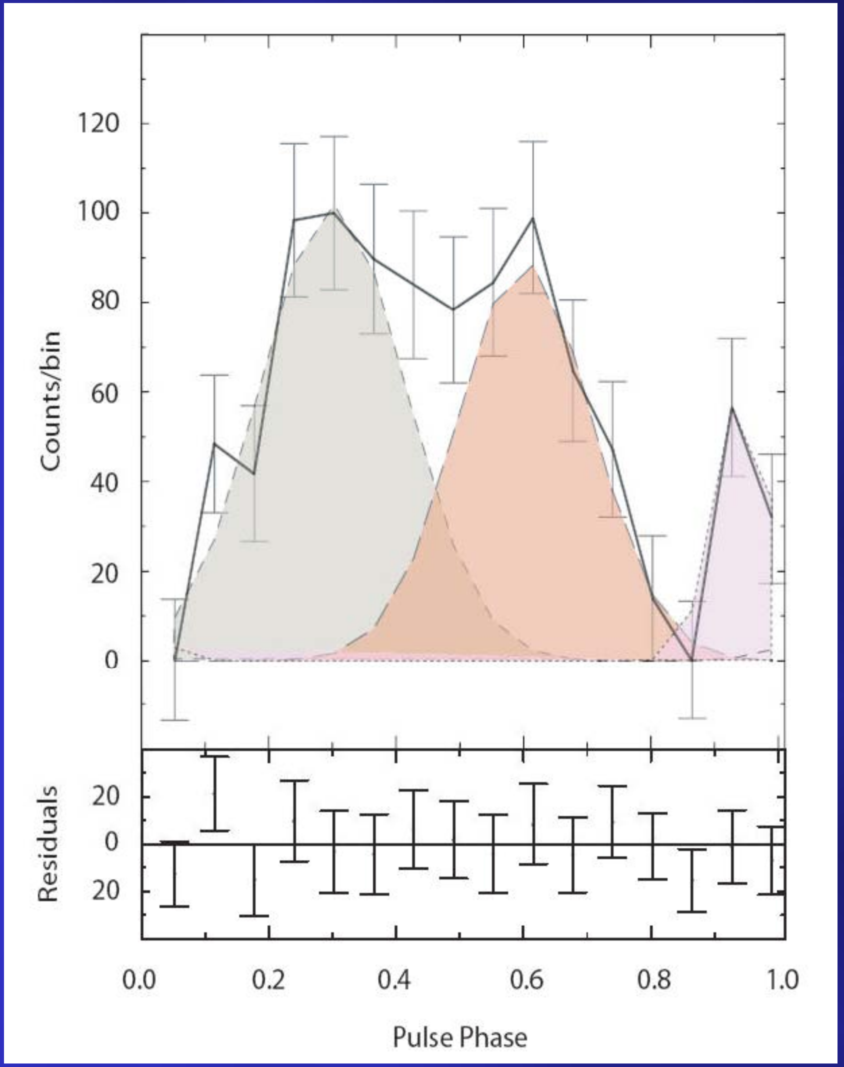
N_H ~ 6 x 10^{20} cm^{-2}

PF = 32 +- 4% (0.2 - 10 keV)

Becker, Kramer, Jessner et al.(2006) / astro-ph-0506545

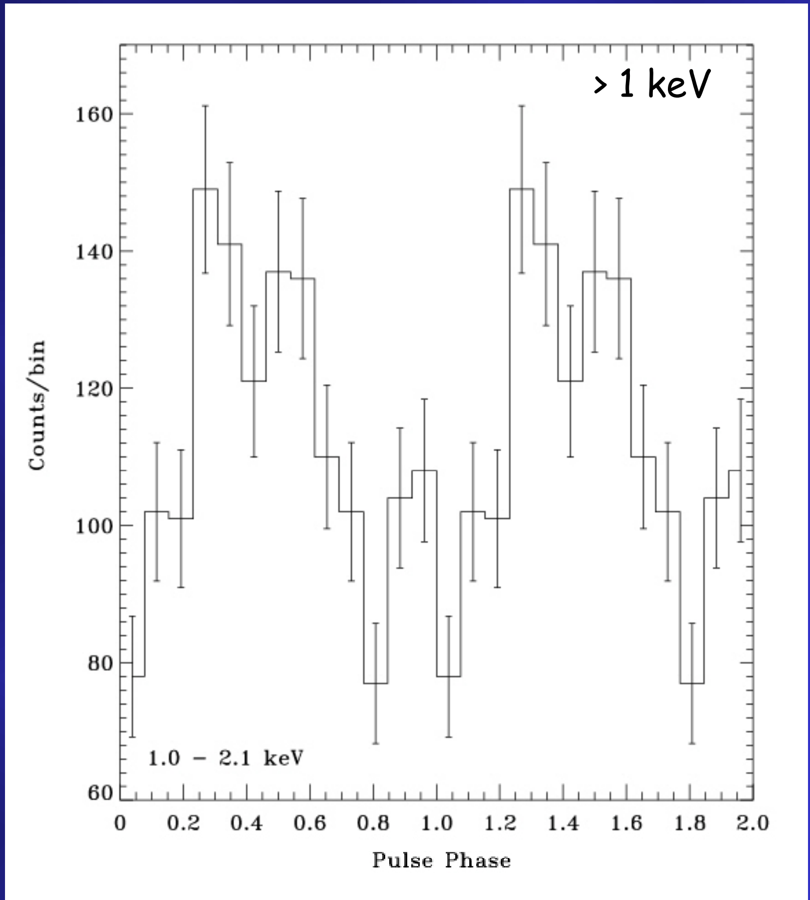
X-ray emission properties of old pulsars: B1929-10

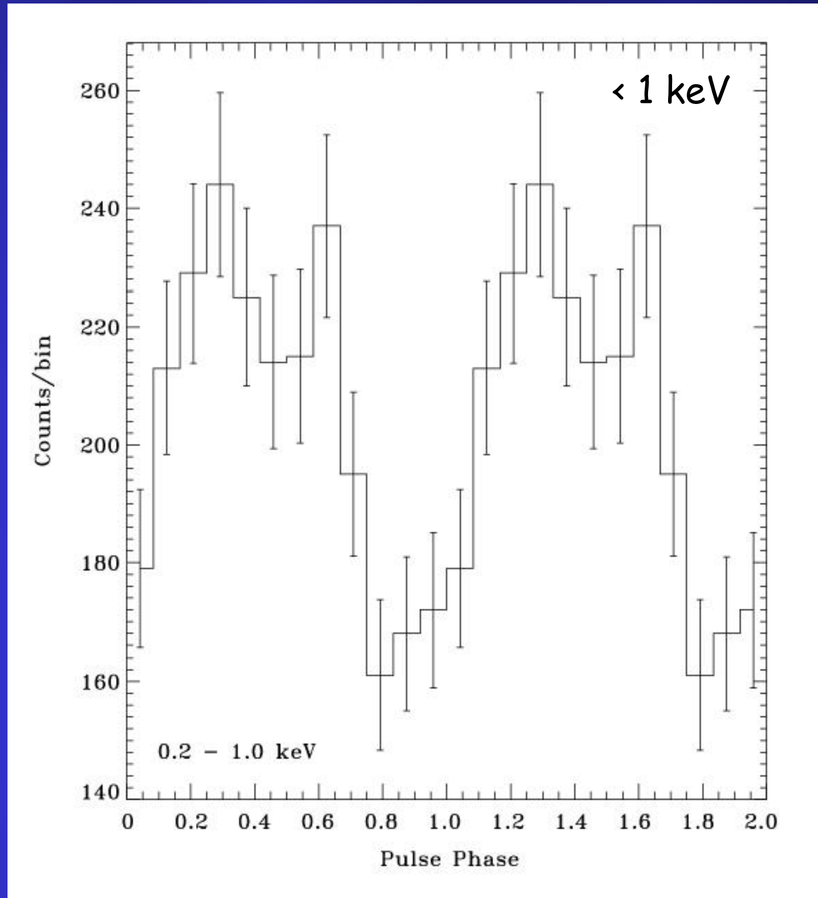




Becker, Kramer, Jessner et al.(2006) / astro-ph-0506545

X-ray emission properties of old pulsars: B1929-10



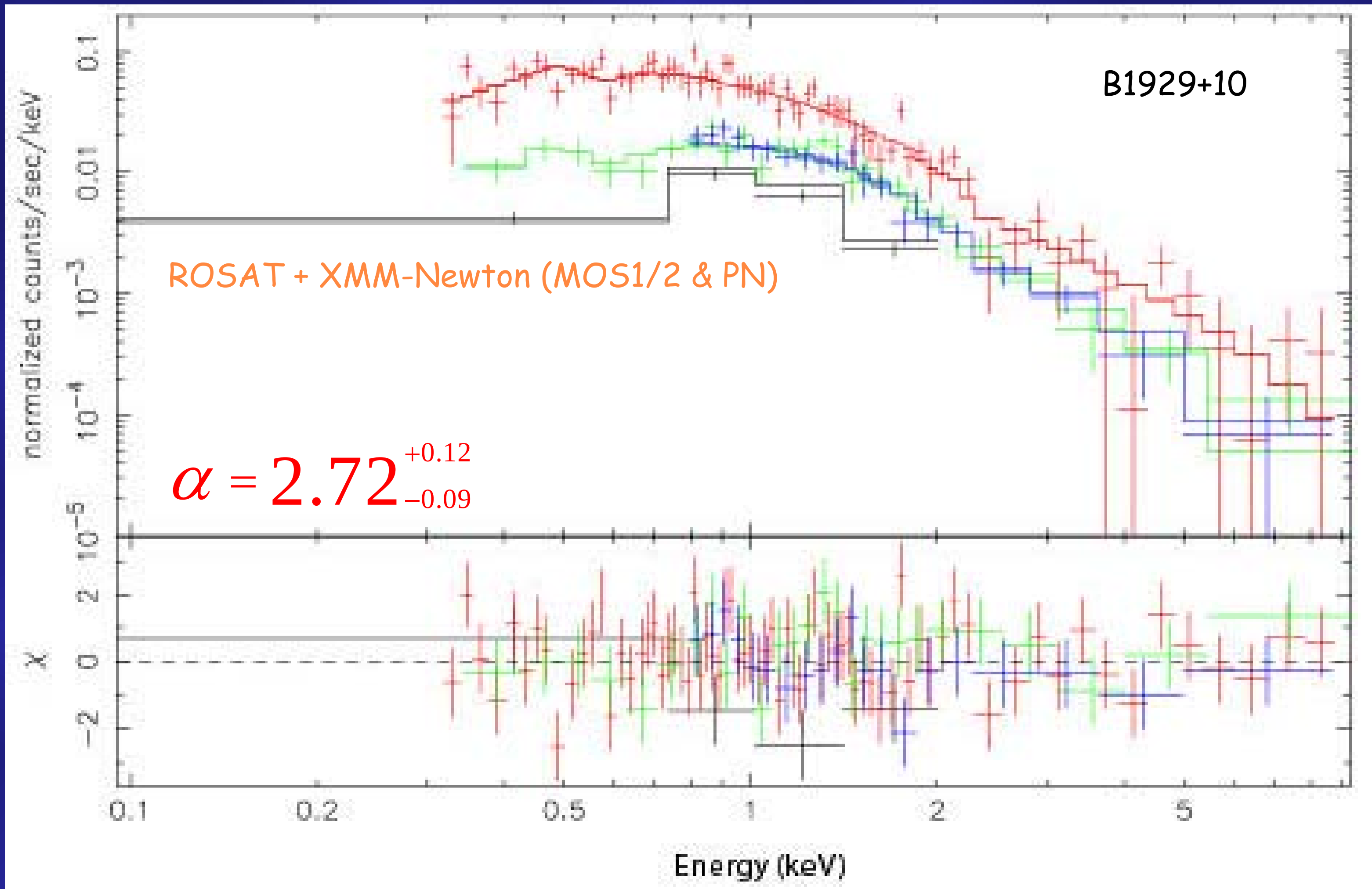


PF = 44 +- 6%

PF = 24 +- 5%

Becker, Kramer, Jessner et al.(2006) / astro-ph-0506545

X-ray emission properties of old pulsars: B1929-10



- BB spectra are clearly excluded
- single PL spectrum fits best
  → non-thermal emission dominates

X-ray emission properties of old pulsars: B1929-10

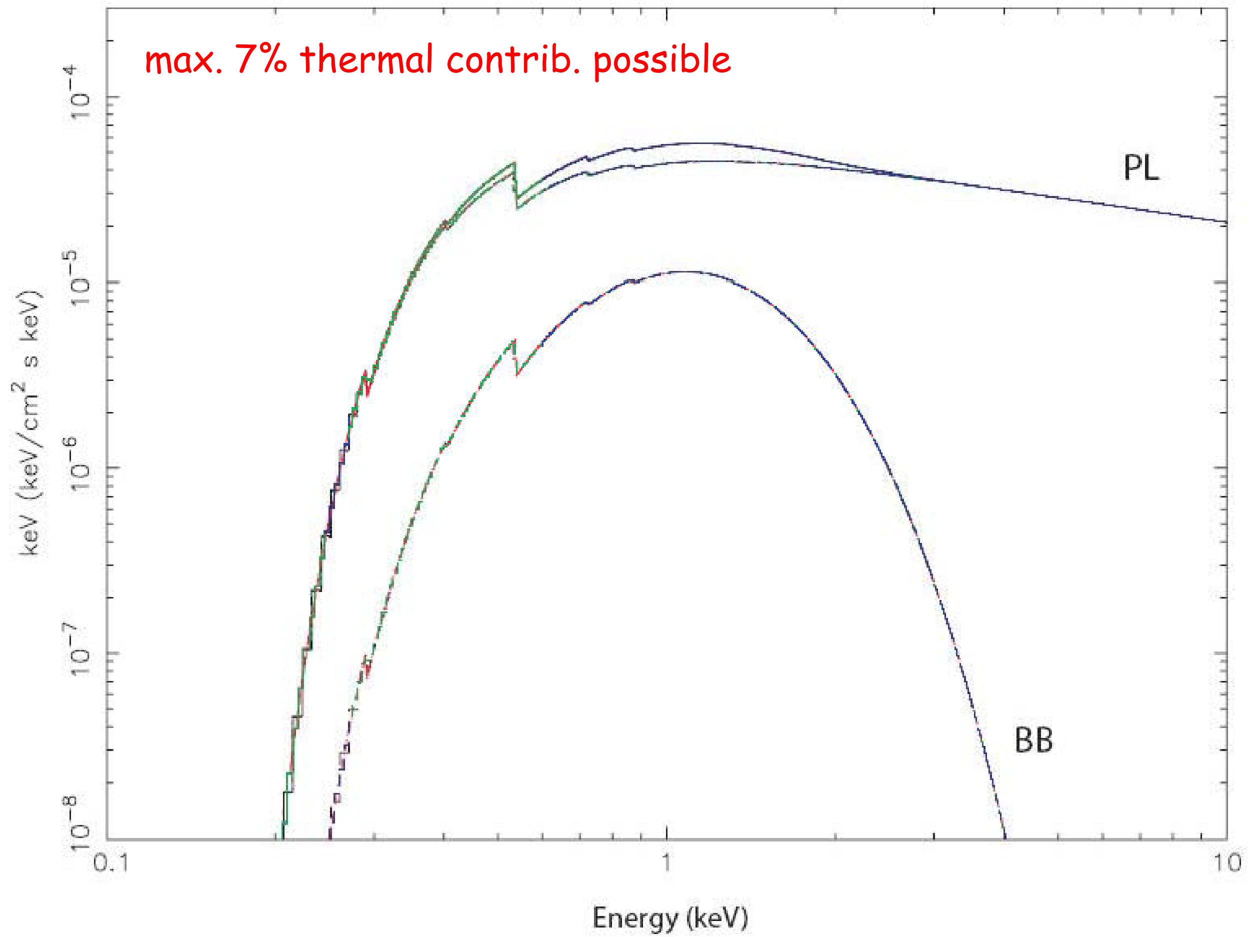
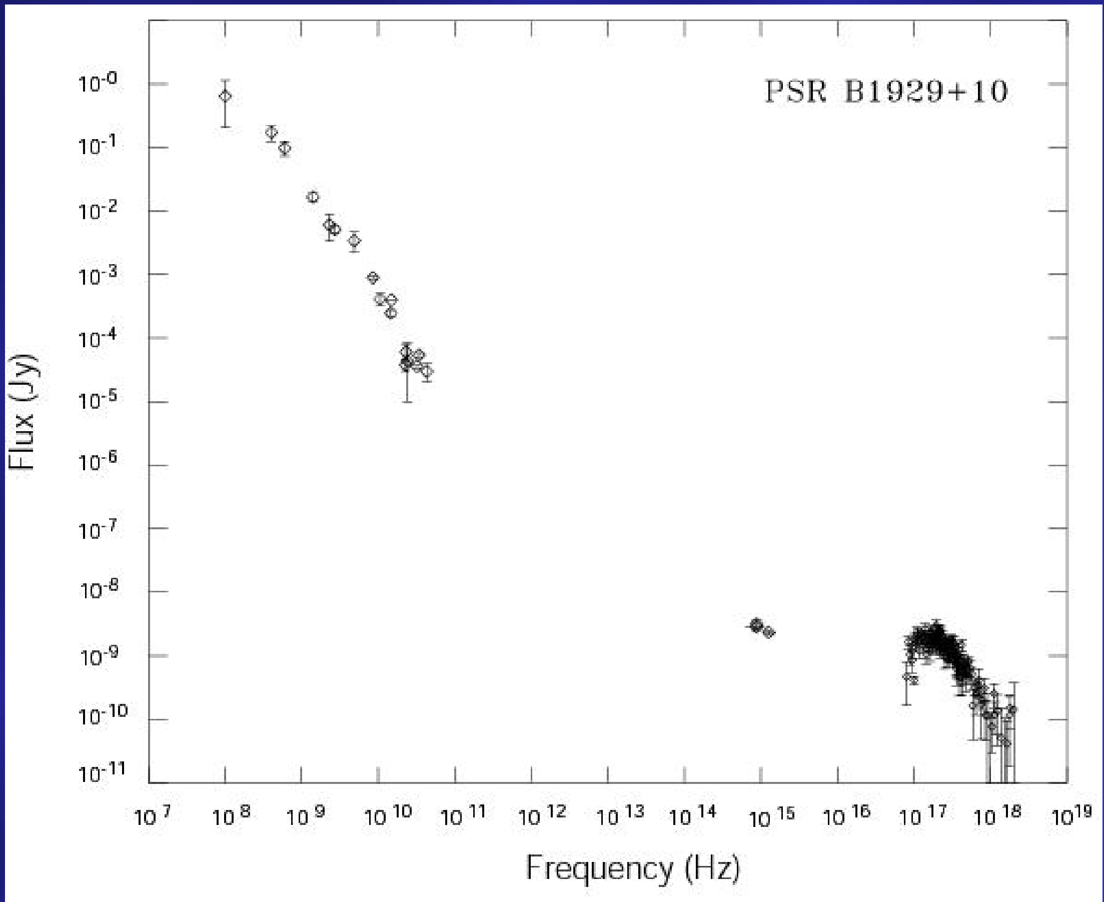


Fig. 12.— Blackbody plus power law spectral components and combined model as fitted to the spectral data of PSR B1929+10.

Becker, Kramer, Jessner et al.(2006) / astro-ph-0506545

Multi-wavelength emission spectrum: B1929+10



- Optical to X-ray data:

  → broken power law

$$\alpha_1 = 1.12^{+0.02}_{-0.03}$$

$$\alpha_2 = 2.48^{+0.06}_{-0.07}$$

$$E_{break} = 0.83^{+0.05}_{-0.03}$$

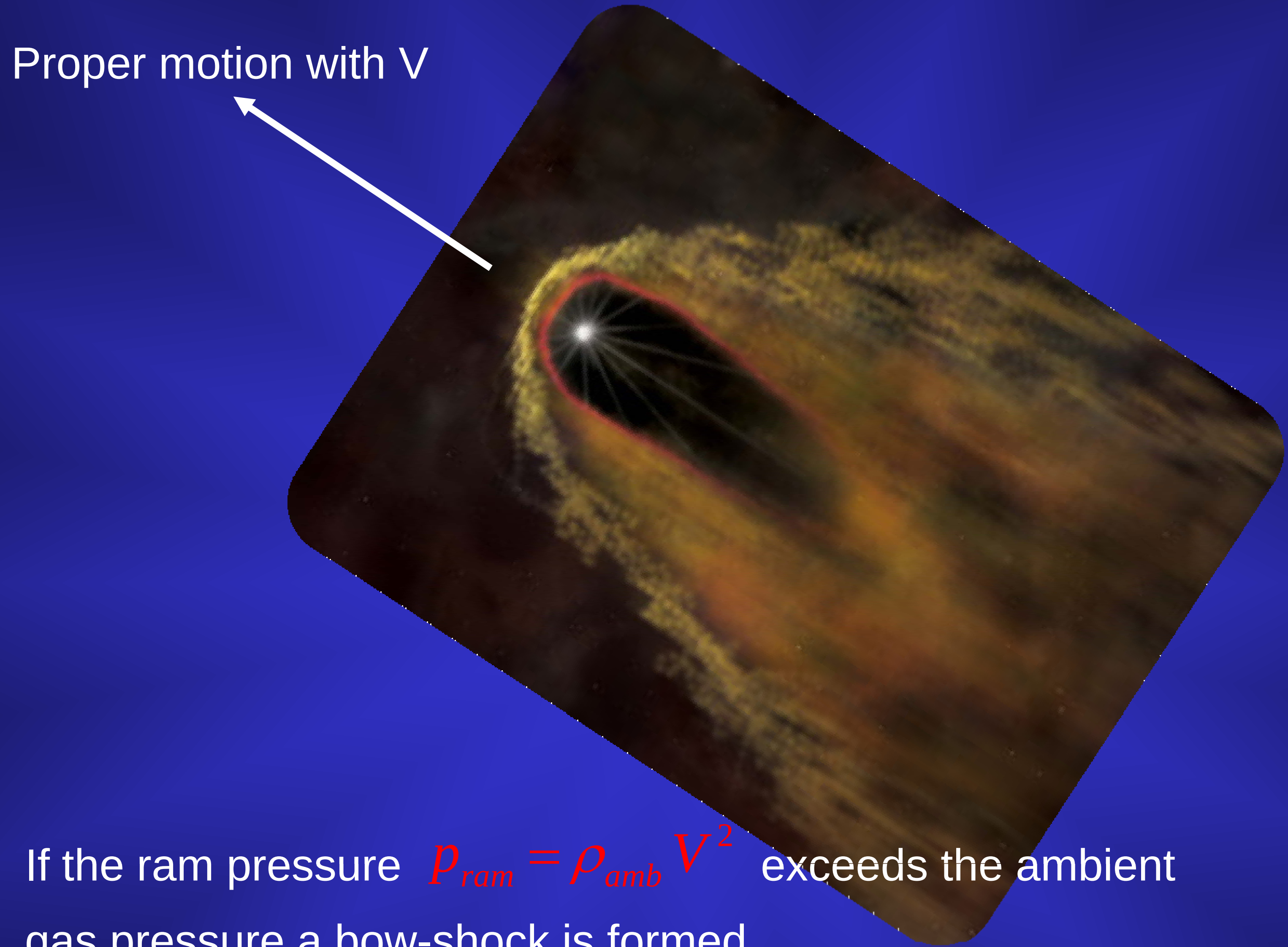
Optical data from Mignani et al.(2002) & Pavlov et al.(1996)

Radio data by Maron et al.(2000)

Becker, Kramer, Jessner et al.(2006) / astro-ph-0506545

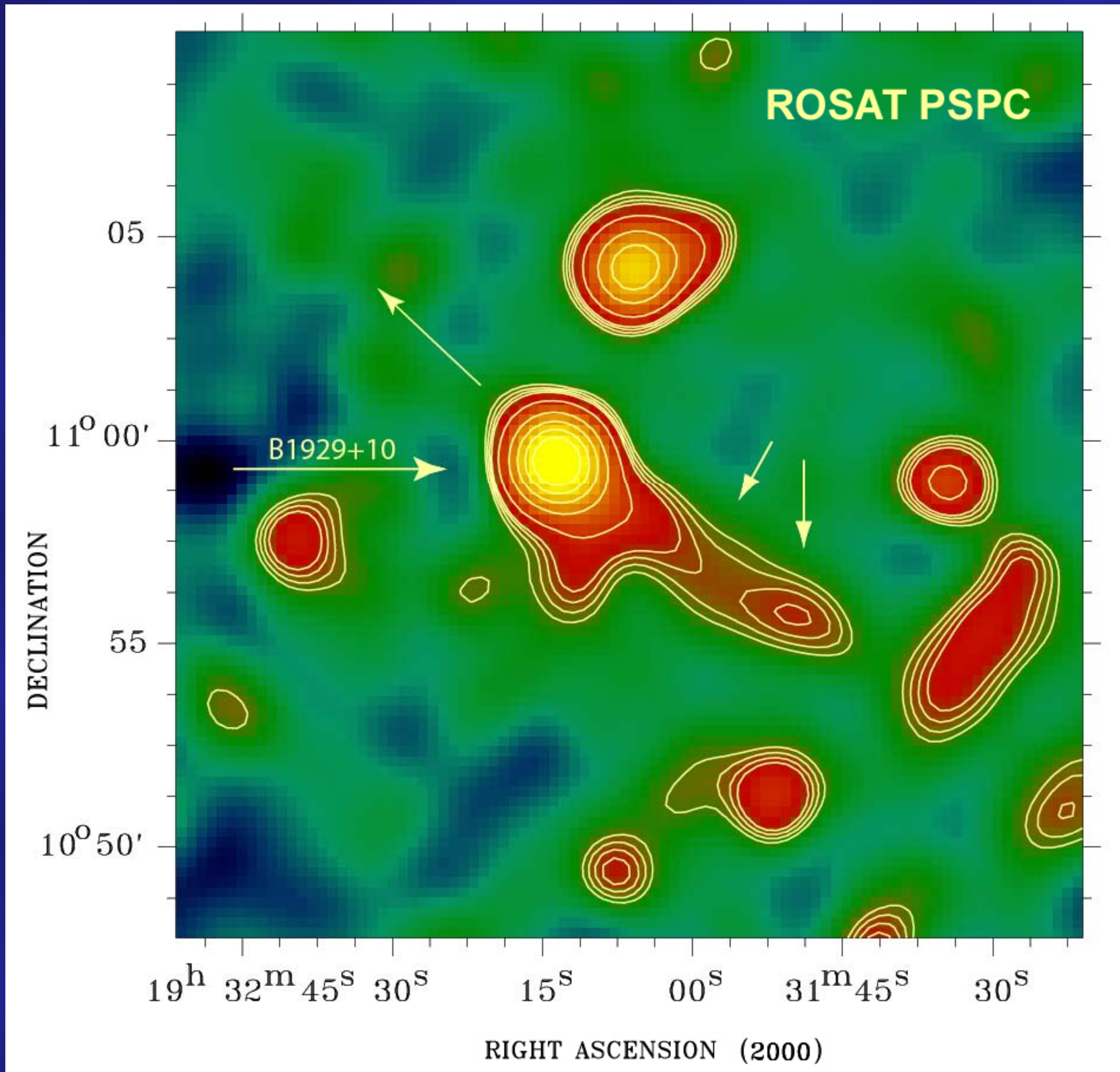
Pulsar Bow-Shocks……

Pulsar bow-shock nebulae



If the ram pressure $p_{ram} = \rho_{amb} V^2$ exceeds the ambient gas pressure a bow-shock is formed

Pulsar bow-shock nebulae: PSR 1929+10

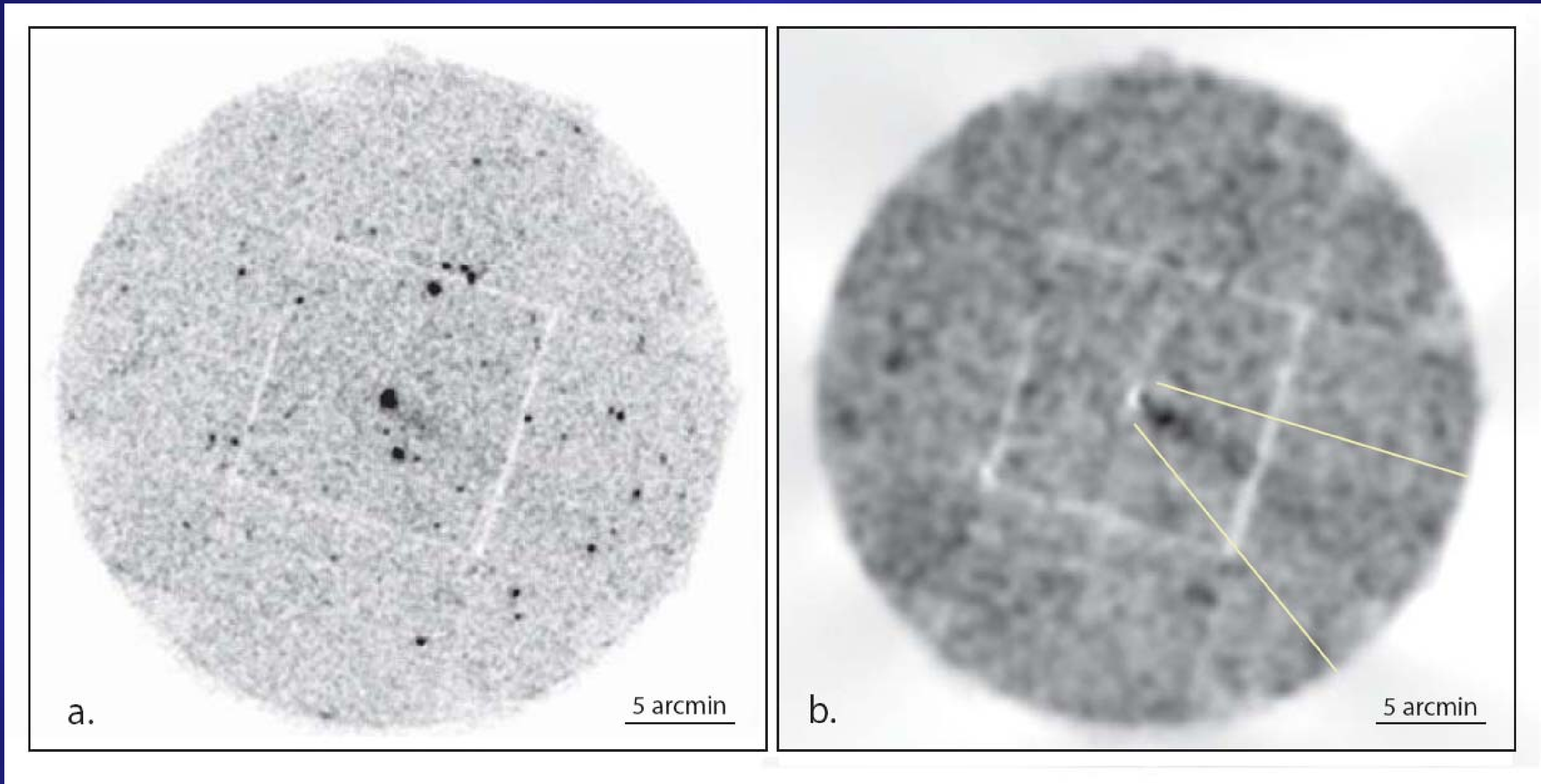


The pulsar is moving at a transverse velocity of 177 km/s

The trail emission is non-thermal and is likely produced from the synchrotron process of highly relativistic electrons in the shocked region between the pulsar wind and the surrounding ISM

Becker, Kramer, Jessner et al.(2006) / astro-ph-0506545

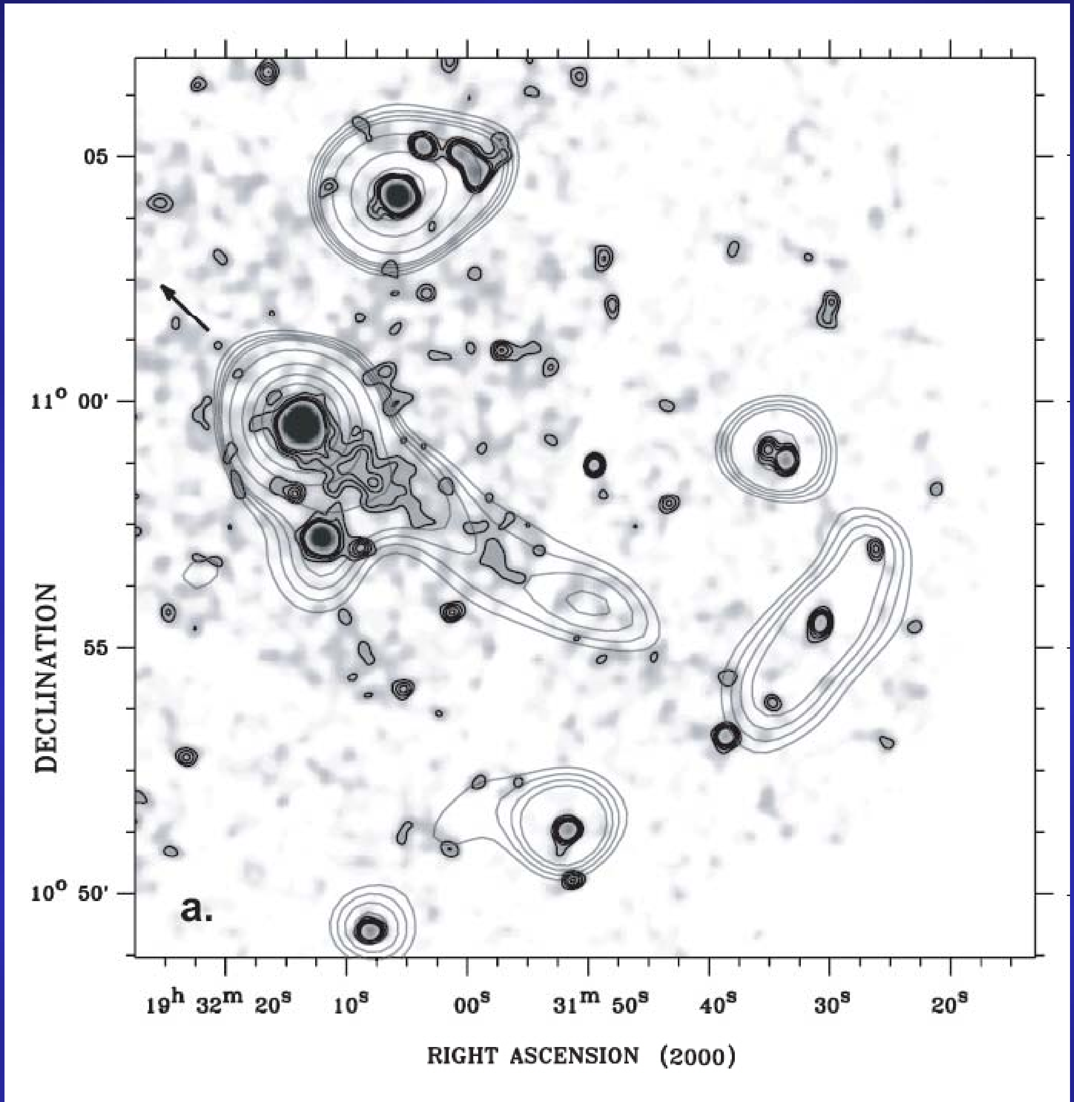
X-ray emission properties of old pulsars: B1929-10



- length of the trail not very well constraint → requires deeper observations !!

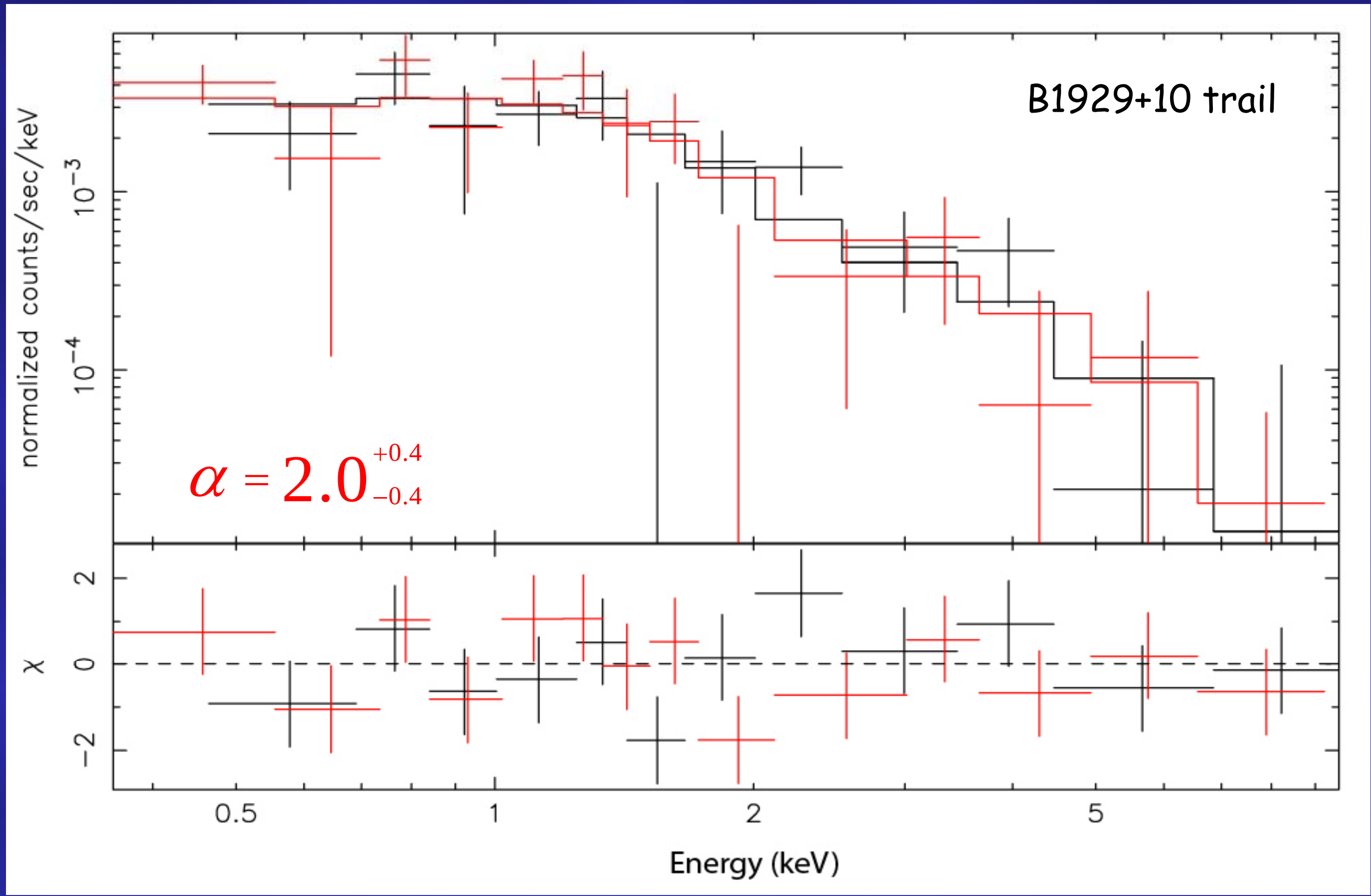
Becker, Kramer, Jessner et al.(2006) / astro-ph-0506545

X-ray emission properties of old pulsars: B1929-10



Becker, Kramer, Jessner et al.(2006) / astro-ph-0506545

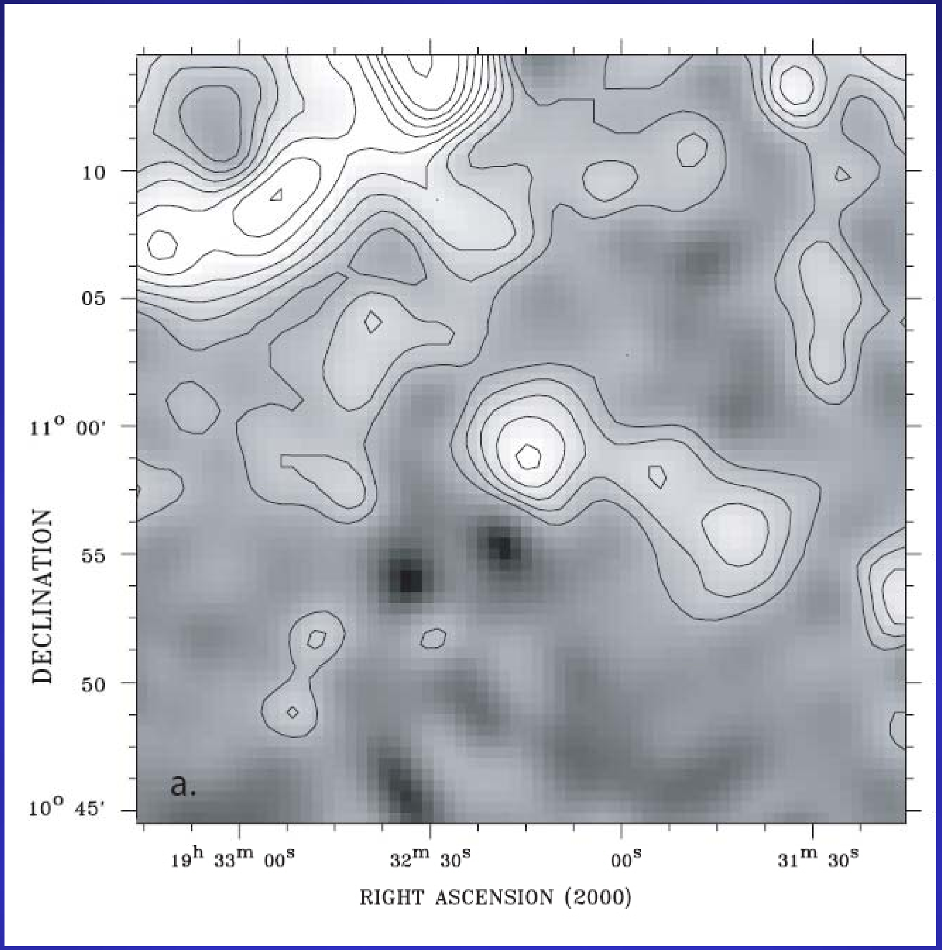
X-ray emission properties of old pulsars: B1929-10



- spectrum non-thermal
- likely from synchrotron processes in the shocked region between pulsar wind and the ISM

Becker, Kramer, Jessner et al.(2006) / astro-ph-0506545

X-ray emission properties of old pulsars: B1929-10

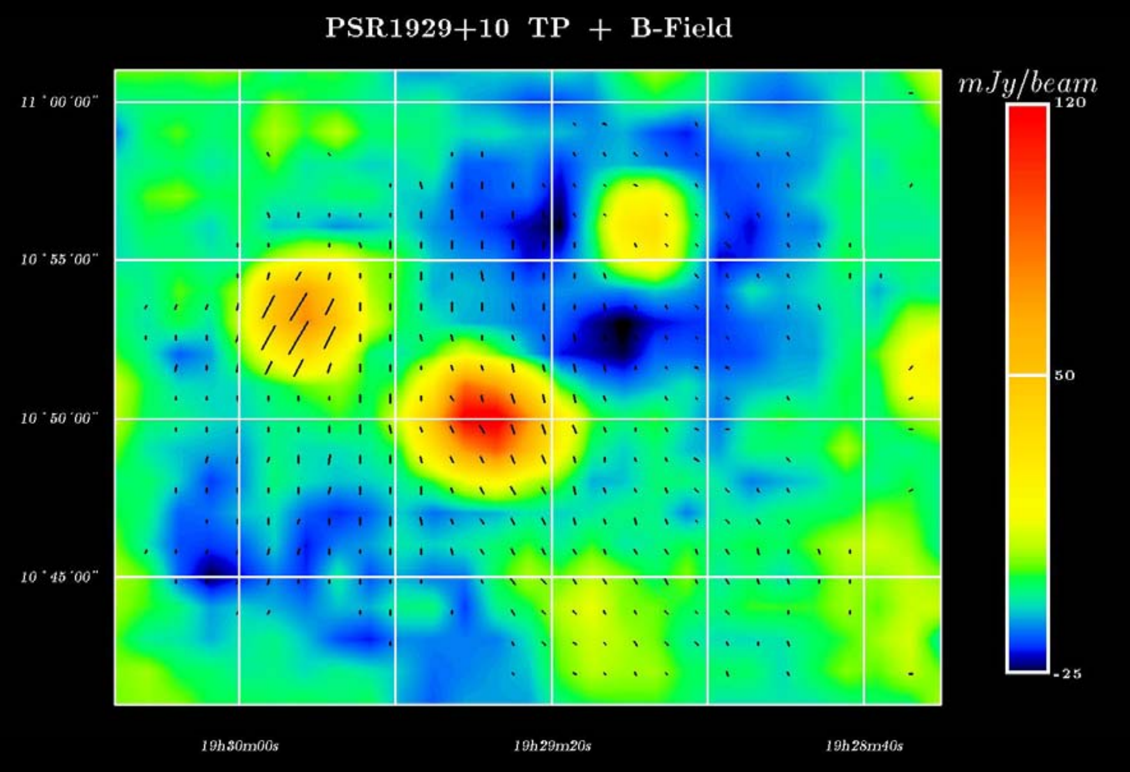


Effelsberg 11cm (2.72 GHz) galactic plane survey

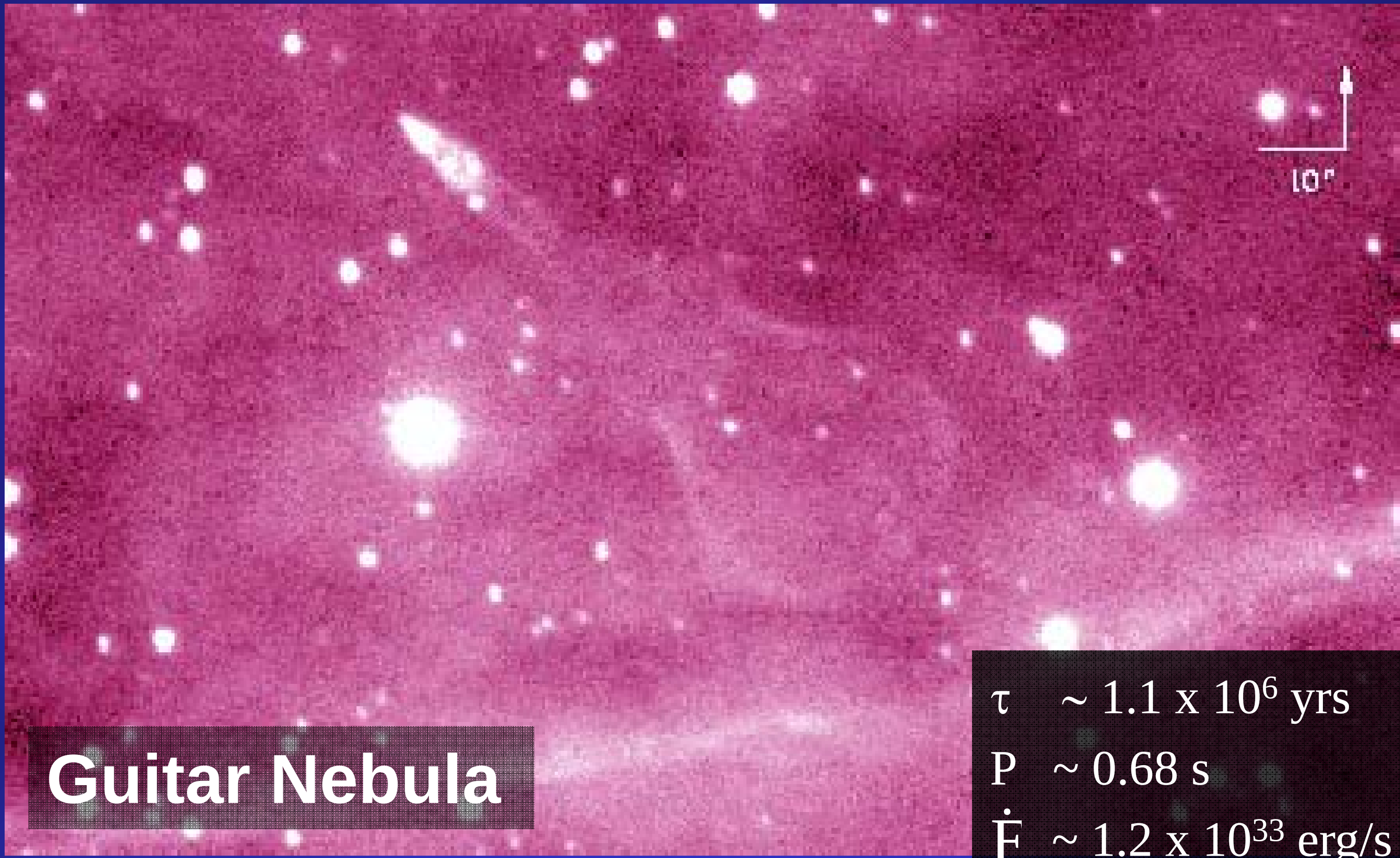
Becker, Kramer, Jessner et al.(2006) / astro-ph-0506545

X-ray emission properties of old pulsars: B1929-10

Effelsberg 6cm, taken in fall 2006



Pulsar bow-shock nebulae: PSR B2224+65



τ ~ 1.1 x 10^6 yrs

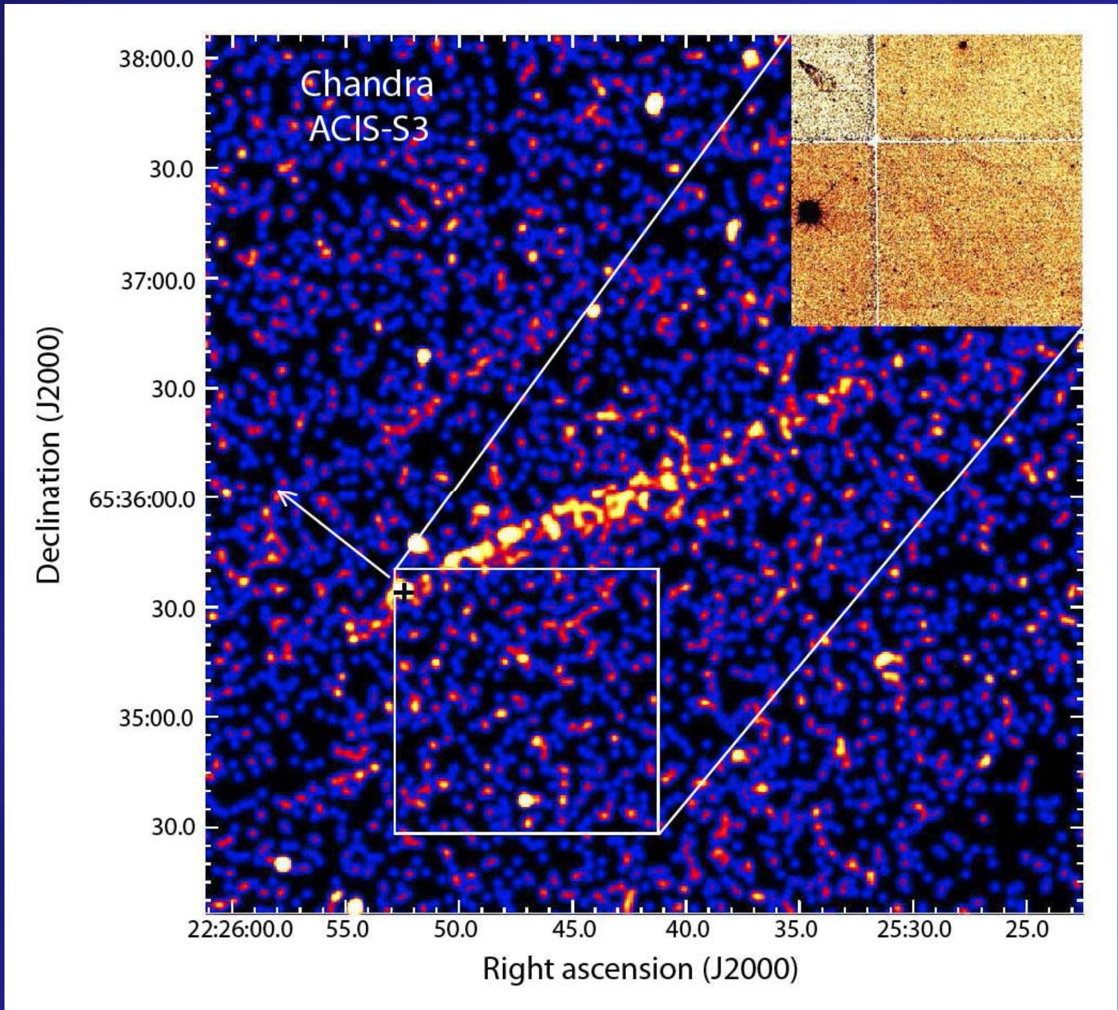
P ~ 0.68 s

$\dot{E}$ ~ 1.2 x 10^{33} erg/s

d ~ 1 kpc

Hui & Becker (2007) / astro-ph-0506545

X-ray emission properties of old pulsars: B2224+65



Extended feature:

non-thermal X-ray spectrum

Photon Index: $\alpha = 0.91^{+0.35}_{-0.24}$

Pulsar emission:

non-thermal X-ray spectrum

Photon Index: $\alpha = 1.58^{+0.43}_{-0.33}$

No radio counterpart of the linear feature in NVSS

Hui & Becker (2007) / astro-ph-0610505

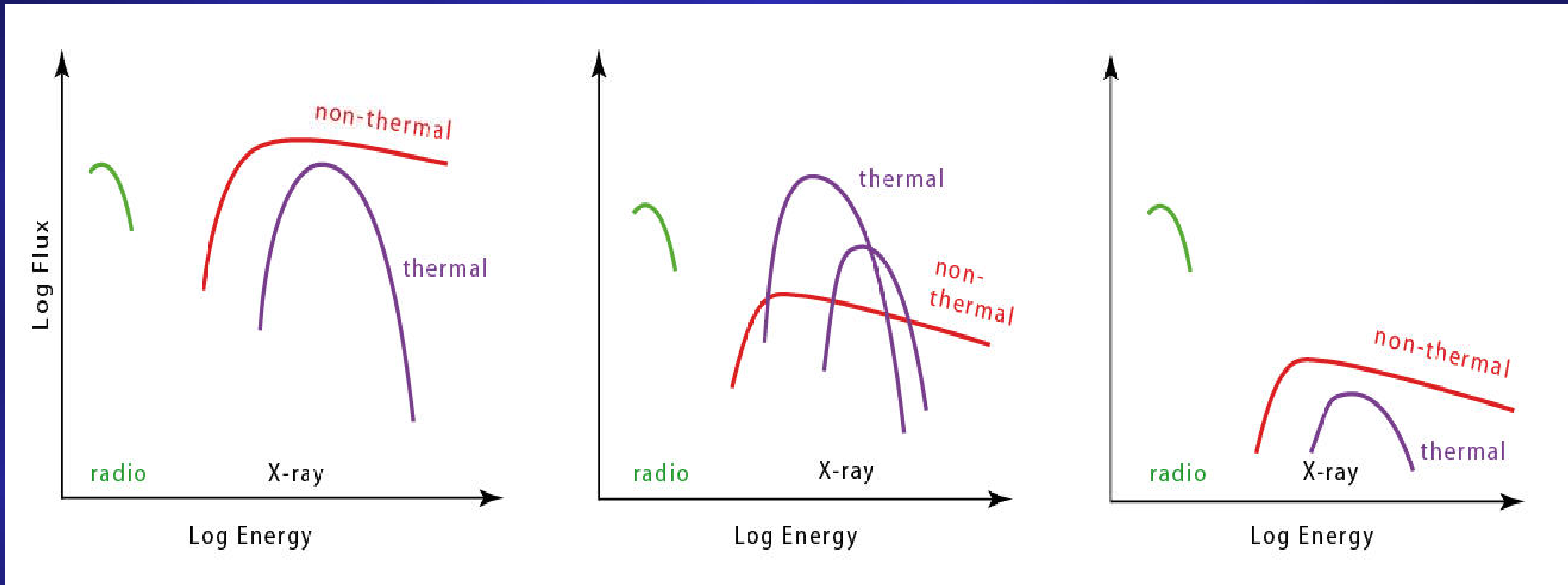
Summary of rot. powered pulsars detected at X

- With EINSTEIN & EXOSAT: 7 radio pulsars detected in X-rays
- With ROSAT, ASCA & BSAX: 33 radio pulsars detected in X-rays
- After ~7 yrs with XMM & Chandra: 81 radio pulsars detected in X-rays

Age τ	Pulsar category	ROSAT/ASCA	XMM/Chandra	Progress
$< 10^4$ yrs	Crab-like	5	9	+4
$10^4 - 10^5$ yrs	Vela-like	9	16	+7
$10^5 - 10^6$ yrs	Cooling NS	5	6	+1
$10^6 - 10^8$ yrs	Old & nearby	3	8	+5
	other	1	2	+1
$> 10^8$ yrs	ms-Pulsars	11	40	+29
	detected #	33	81	+48

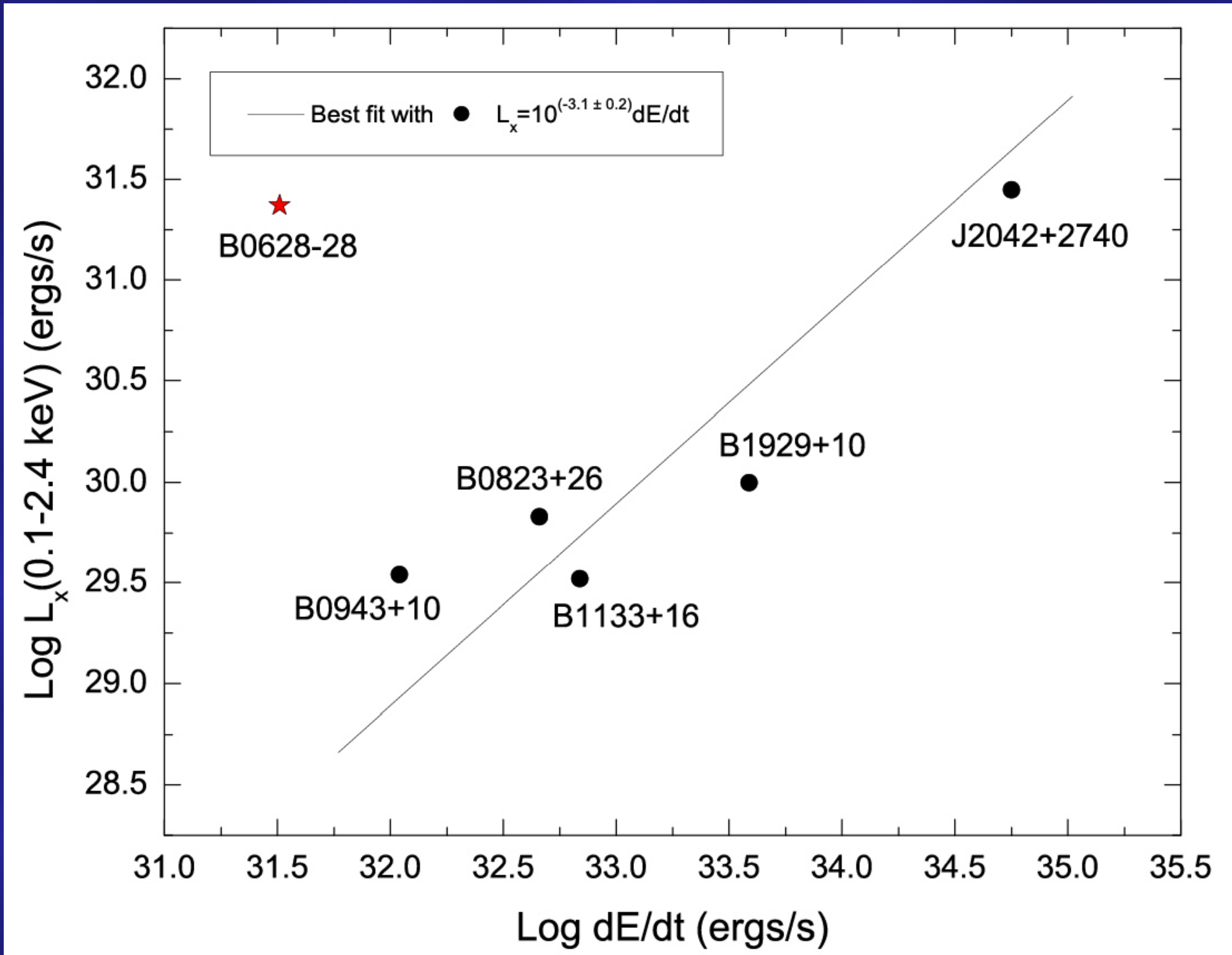
X-ray emission prop. scale with spin-down age

Crab-like pulsars	Cooling neutron stars	Old pulsars
($< 10^4$ yrs)	(10^5 - 10^6 yrs)	(10^6 - 10^8 yrs)



- non-thermal emission dominates in old pulsars / pulse profiles **NOT sinusoidal**
- hot polar cap emission component may decreases along with the cooling surface component ?
- if so, hot polar caps in cooling neutron stars could be formed by anisotropic heat flow due to the presence of the magnetic field rather than by particle bombardment

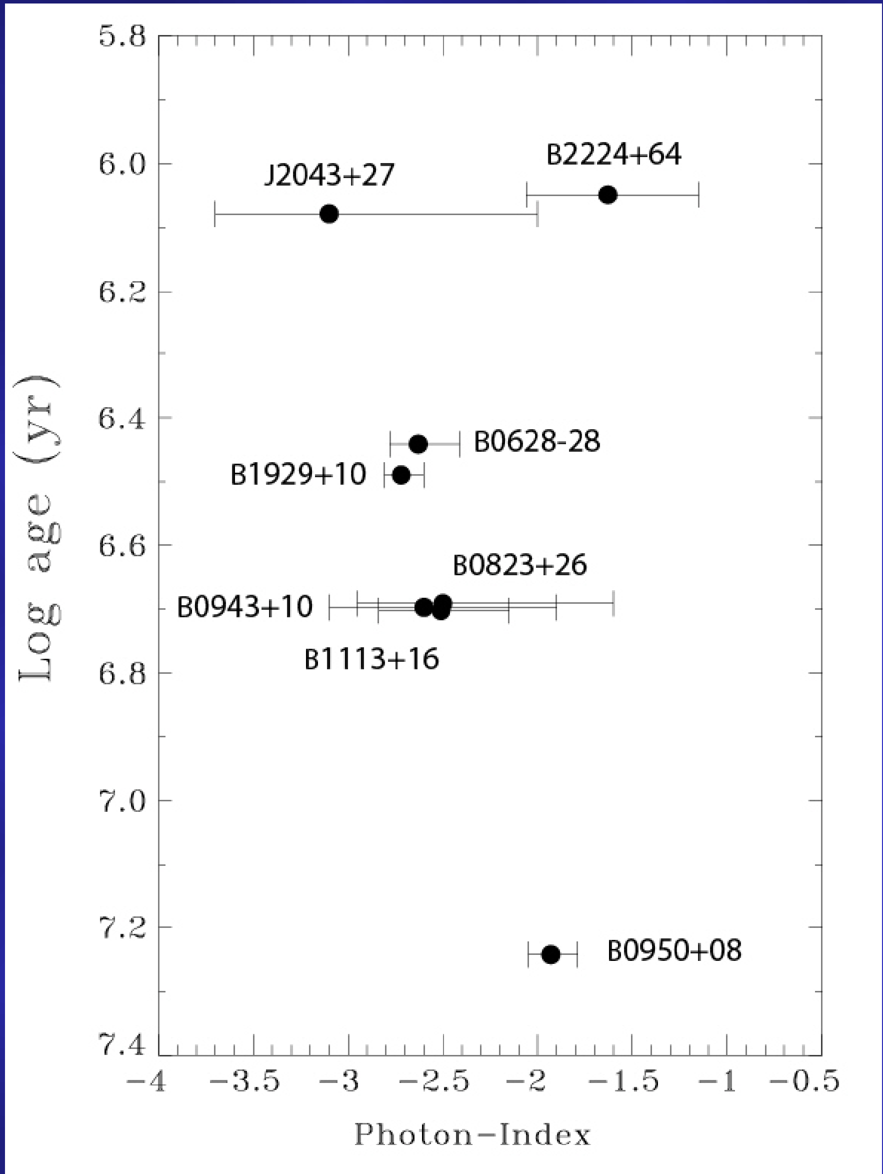
X-ray emission properties of old pulsars



X-ray emission properties of old pulsars

younger

older

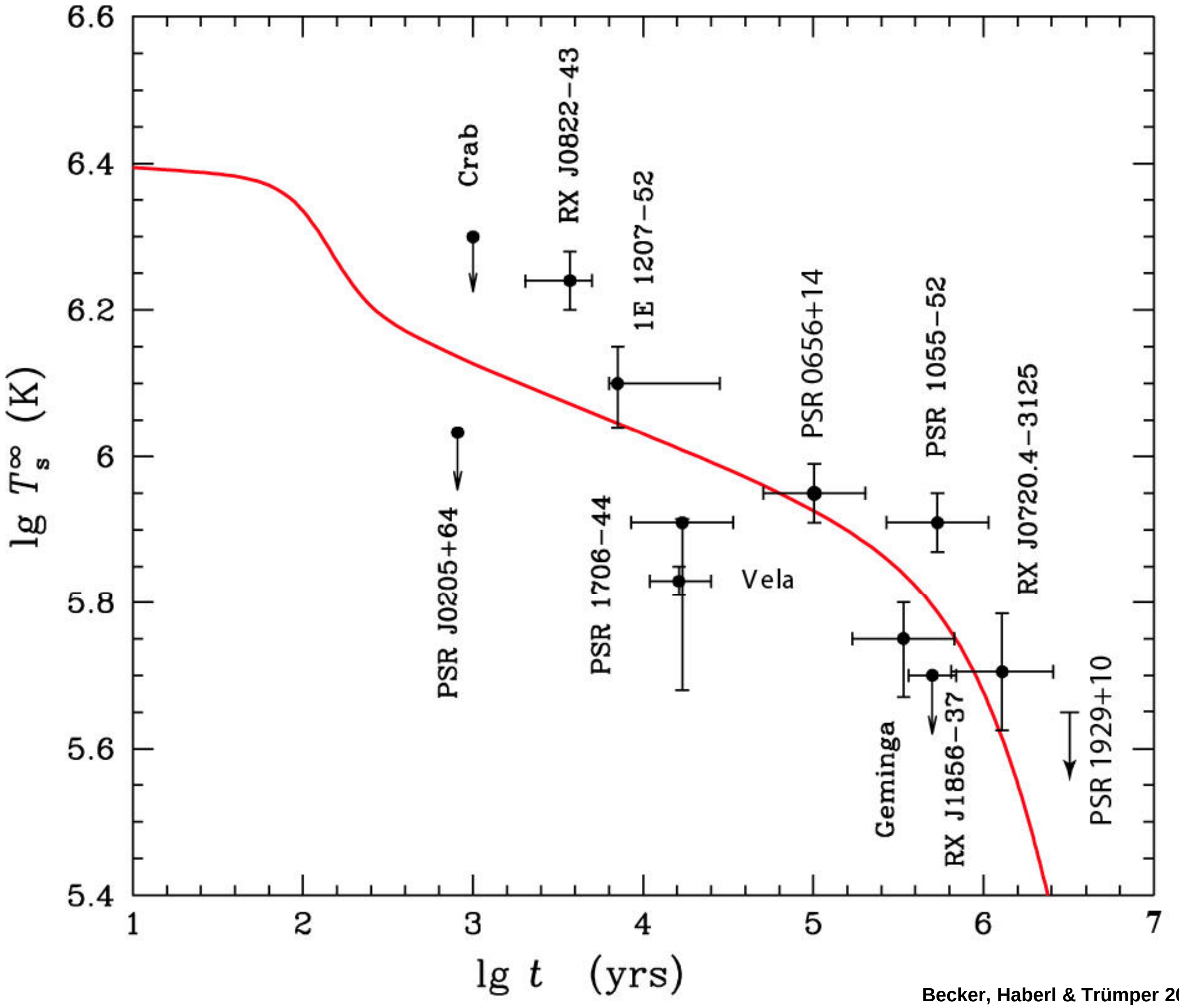


No evidence for a spectral softening with increasing spin-down age for old pulsars

Surface temperature upper limits for R_{NS}=10 km

Pulsar	Spin down age	T_S^∞ 3σ upper limt
B2224+65	1.13 x 10^6 yrs	< 0.68 10^6 k
J2043+2740	1.2 x 10^6 yrs	< 0.62 10^6 k
B0628-28	2.75 x 10^6 yrs	< 0.53 10^6 k
B1929+10	3.1 x 10^6 yrs	< 0.45 10^6 k
B0823+26	5 x 10^6 yrs	< 0.5 10^6 k
B0950-09	17 x 10^6 yrs	< 0.48 10^6 k

Neutron star temperature measurements



Becker, Haberl & Trümper 2007