Michela Rigoselli

Astrosiesta 22/03/18

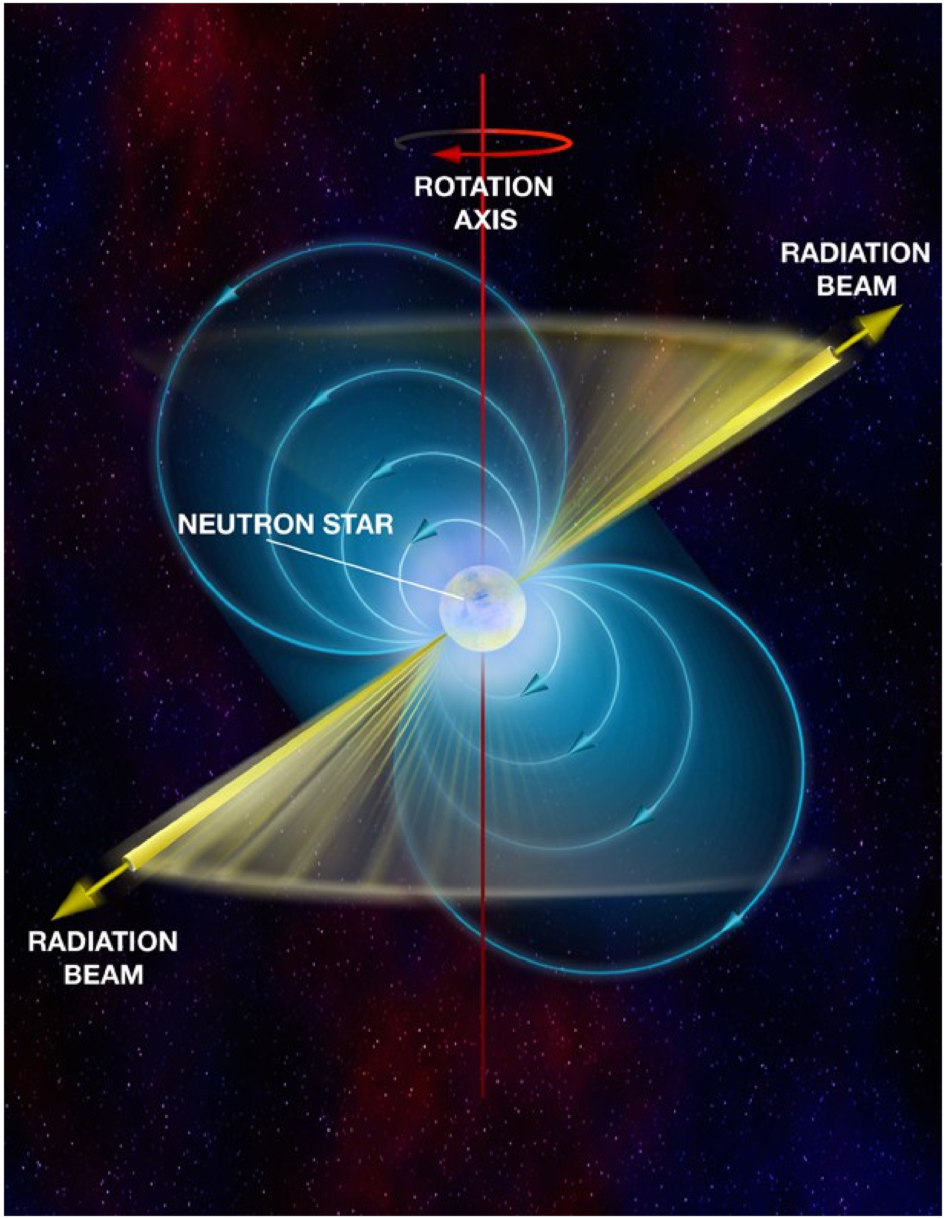
A new X-ray look into four old pulsars

Rotation-Powered Pulsars

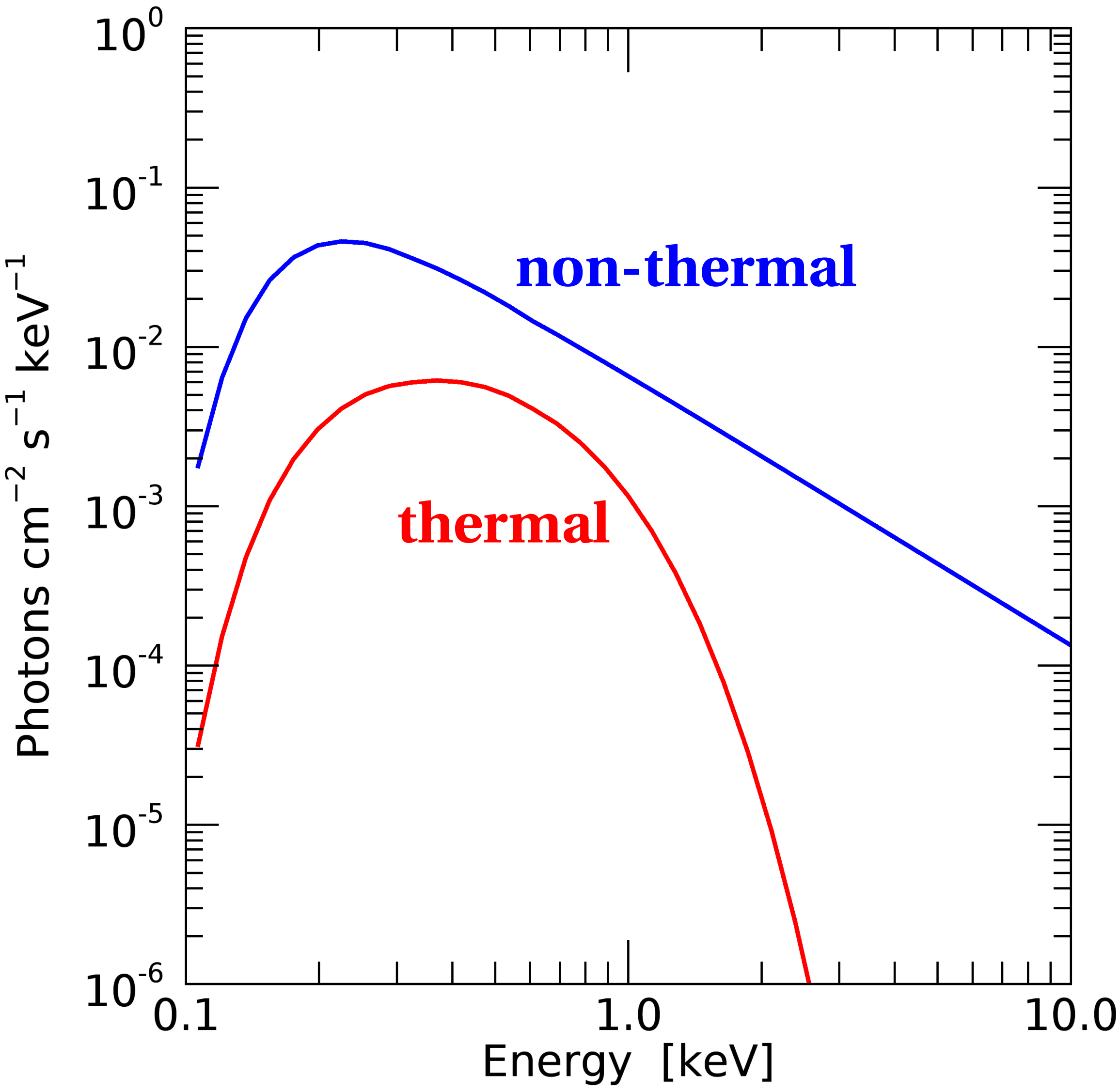
- Lighthouse emission
  from radio to gamma

- Rotating neutron stars
  $P = 1.5\,\mathrm{ms} - 10\,\mathrm{s}$
  $\dot{P} = 10^{-18} - 10^{-12}\,\mathrm{s\,s^{-1}}$
  characteristic age $\tau_c = P/2\dot{P}$

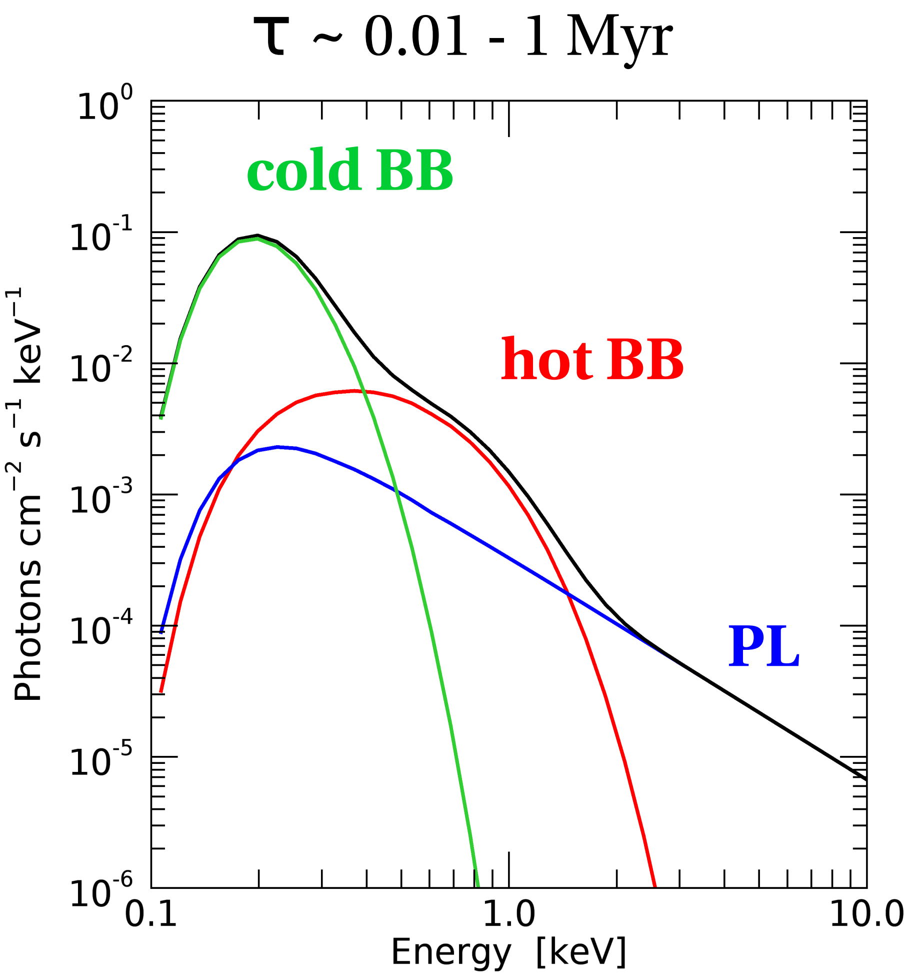
- Powered by rotational energy
  $\dot{E}_{\rm rot} = d\left(\frac{1}{2}I\Omega^2\right)/dt = 4\pi^2 I\dot{P}P^{-3}$
  $\dot{E}_{\rm dip} = \frac{2}{3c^3}|\ddot{\mathbf{m}}|^2 \sim (B_{\rm dip}R^3P^{-2})^2$
  $B_{\rm dip}\,(0.1 - 5\,\mathrm{Myr}) \sim 10^{12}\,\mathrm{G}$

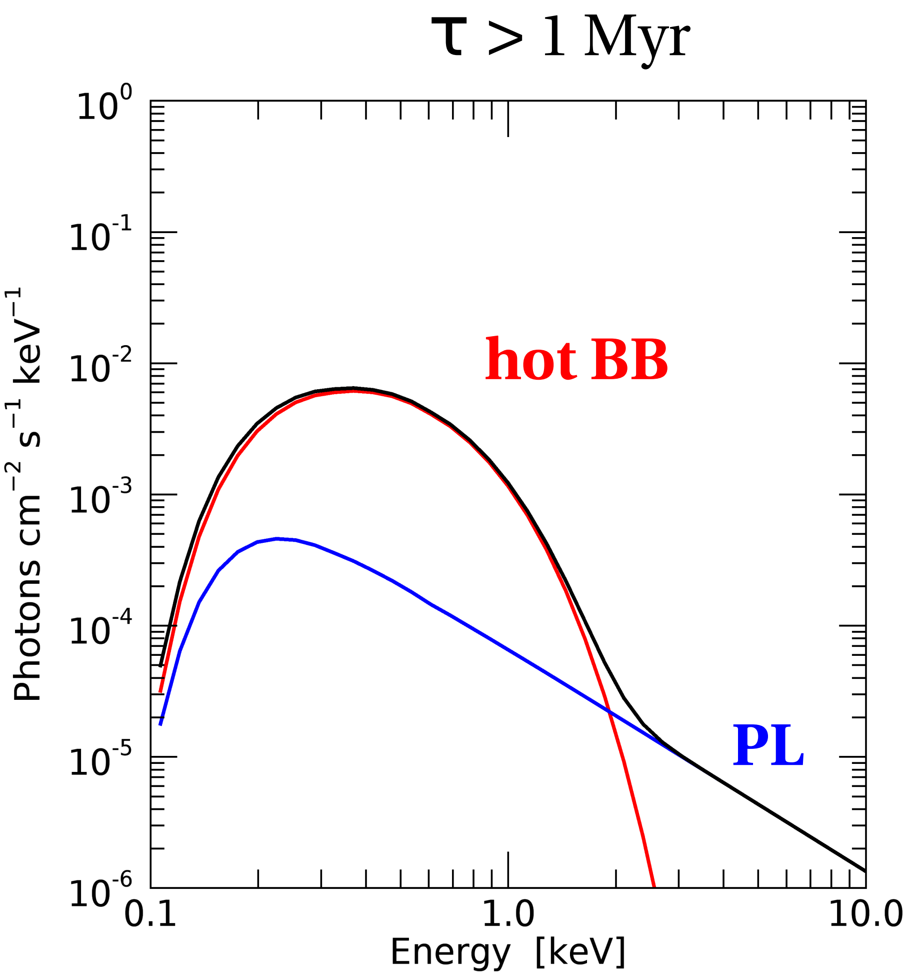


Typical X-ray Spectrum

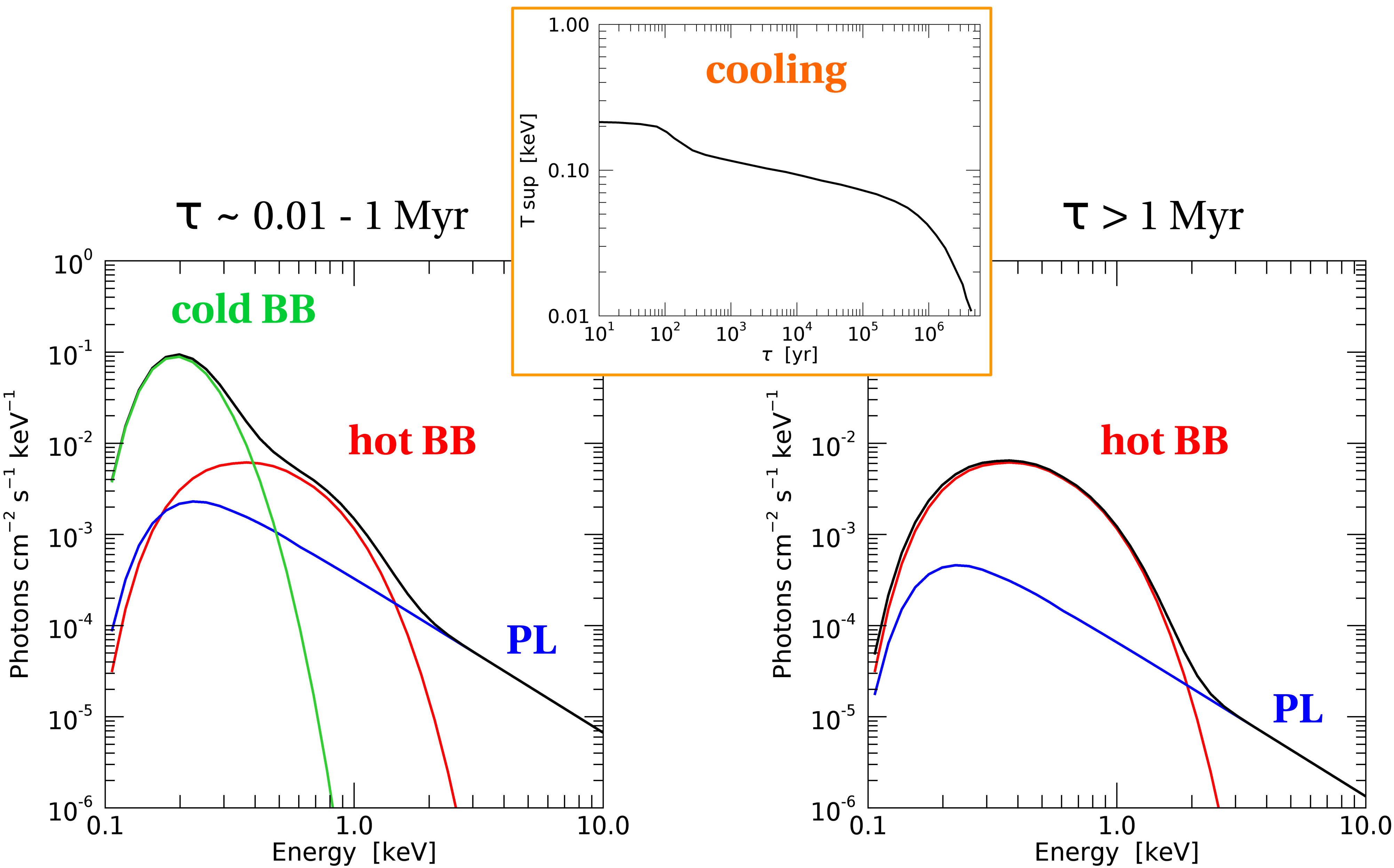


Old Pulsars X-ray Spectrum



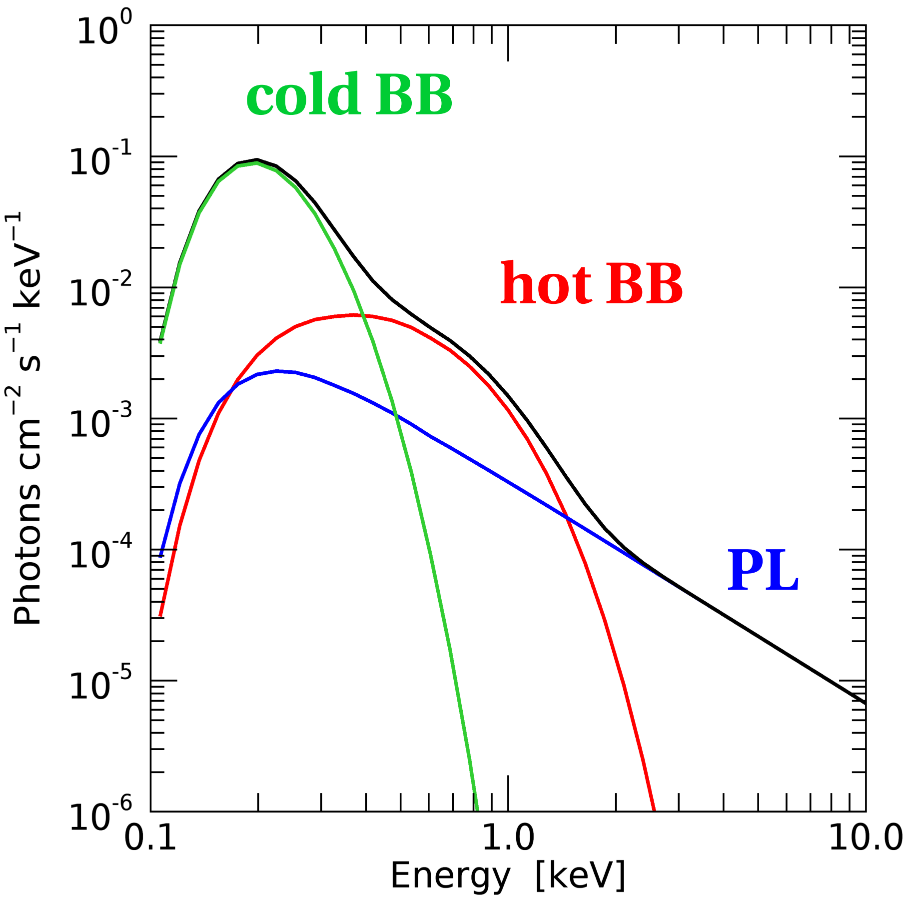


Old Pulsars X-ray Spectrum

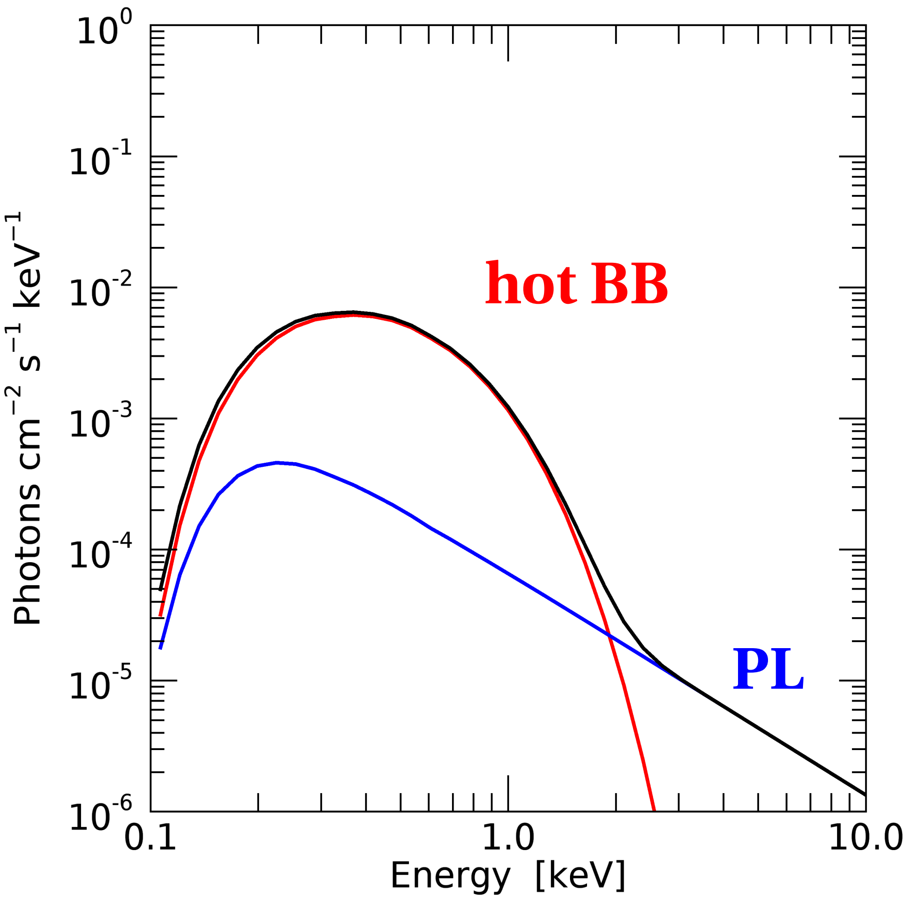


Old Pulsars X-ray Spectrum

τ ~ 0.01 - 1 Myr



τ > 1 Myr

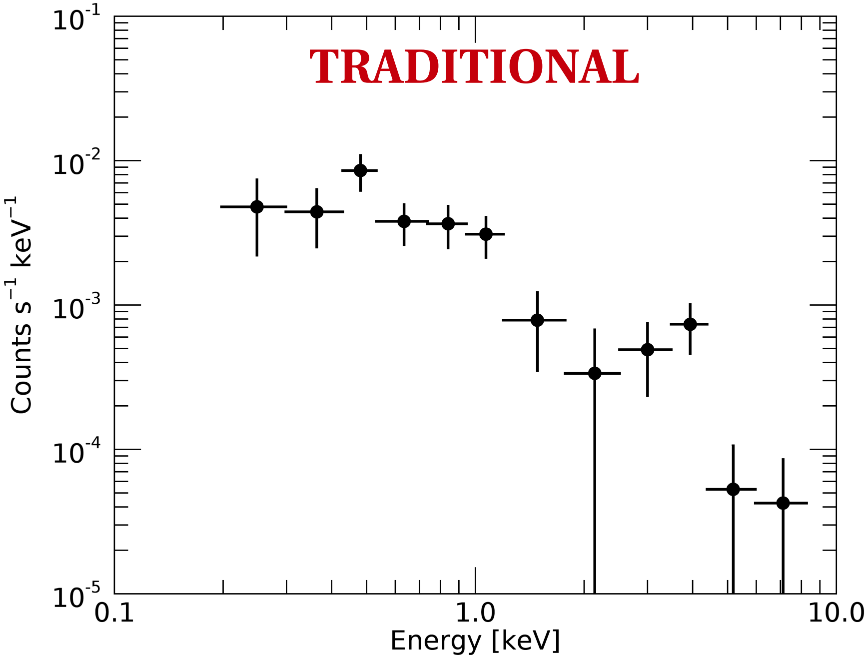


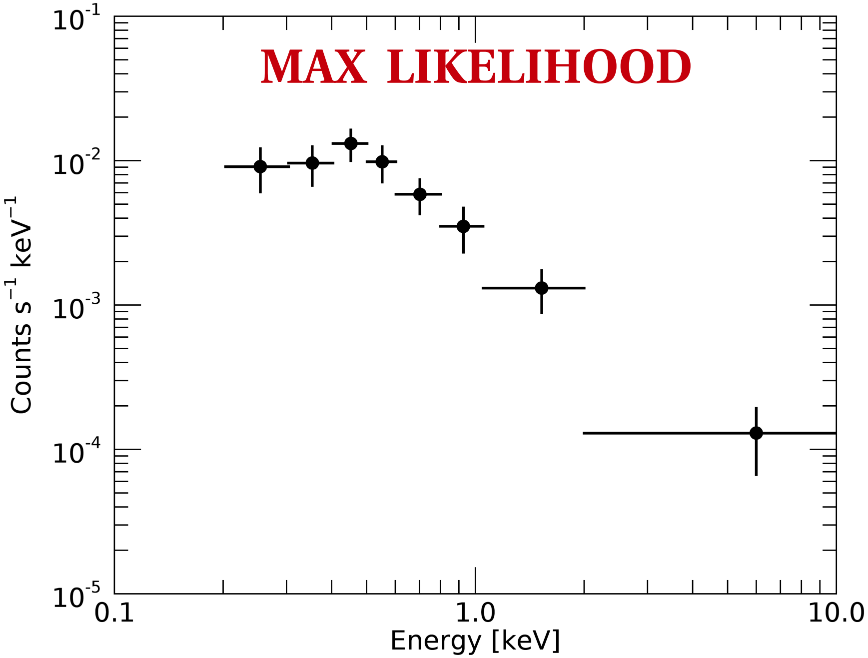
The four Old Pulsars

PSR NAME	P s	$\dot{P}$ 10^{-15} s s^{-1}	B DIP 10^{12} G	C. AGE Myr	COUNTS pn + MOS1/2
PSR B0114+58	0.10	5.85	0.8	0.3	~ 100
PSR B0919+06	0.43	13.73	2.5	0.5	~ 250
PSR B0628-28	1.24	7.12	3.0	3.0	~ 1 000
PSR B1133+16	1.19	3.73	2.1	5.0	~ 900

Maximum Likelihood Method

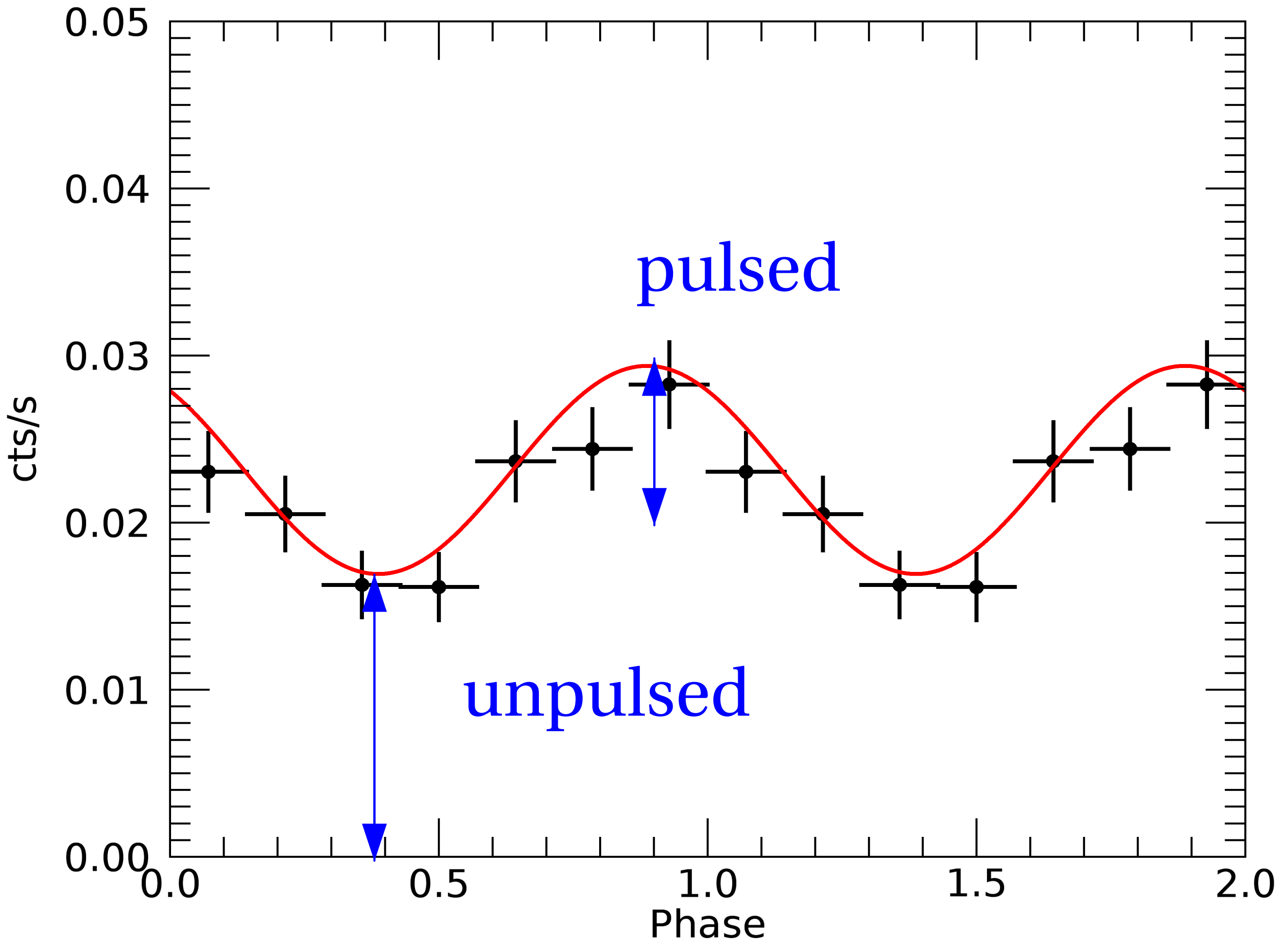
- Very dim sources
- It exploits the knowledge of the PSF and all the counts of the image: makes the best use of the statistics



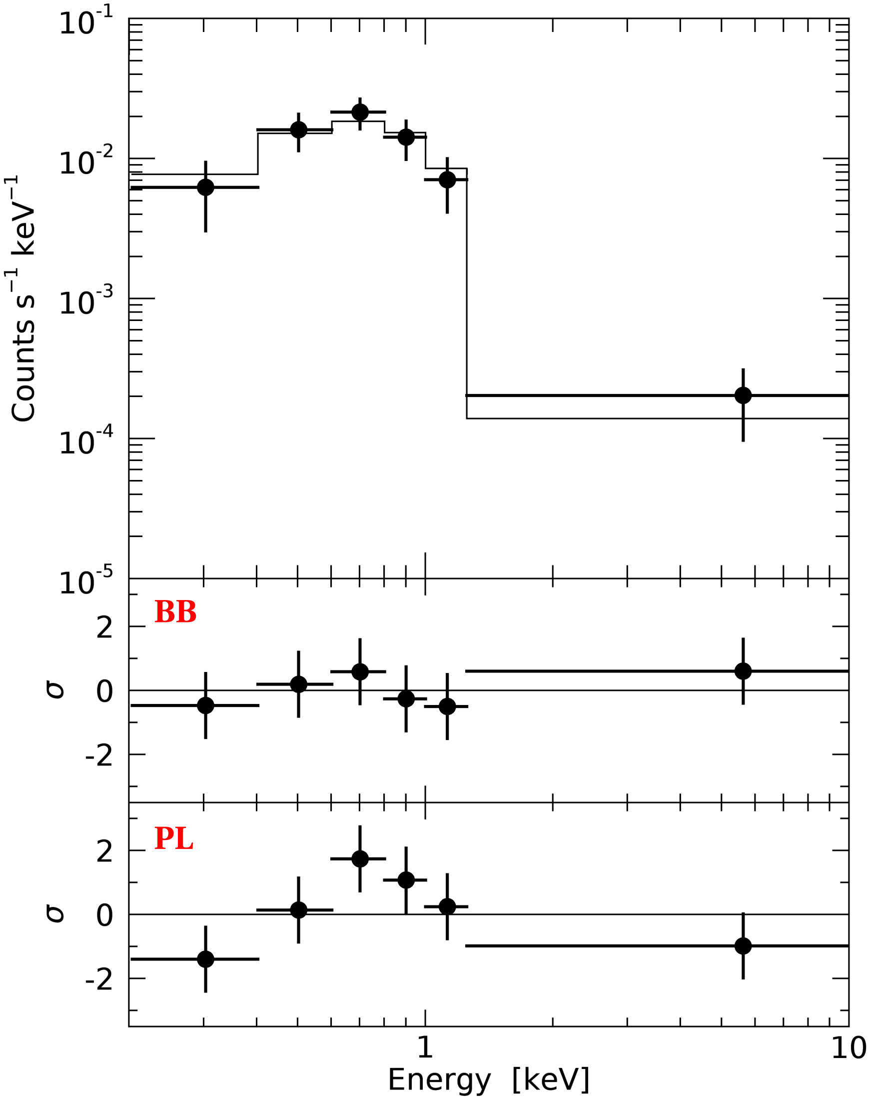


Maximum Likelihood Method

(x,y,t) information: allows to separate pulsed from unpulsed counts → two different spectra



PSR B0114+58



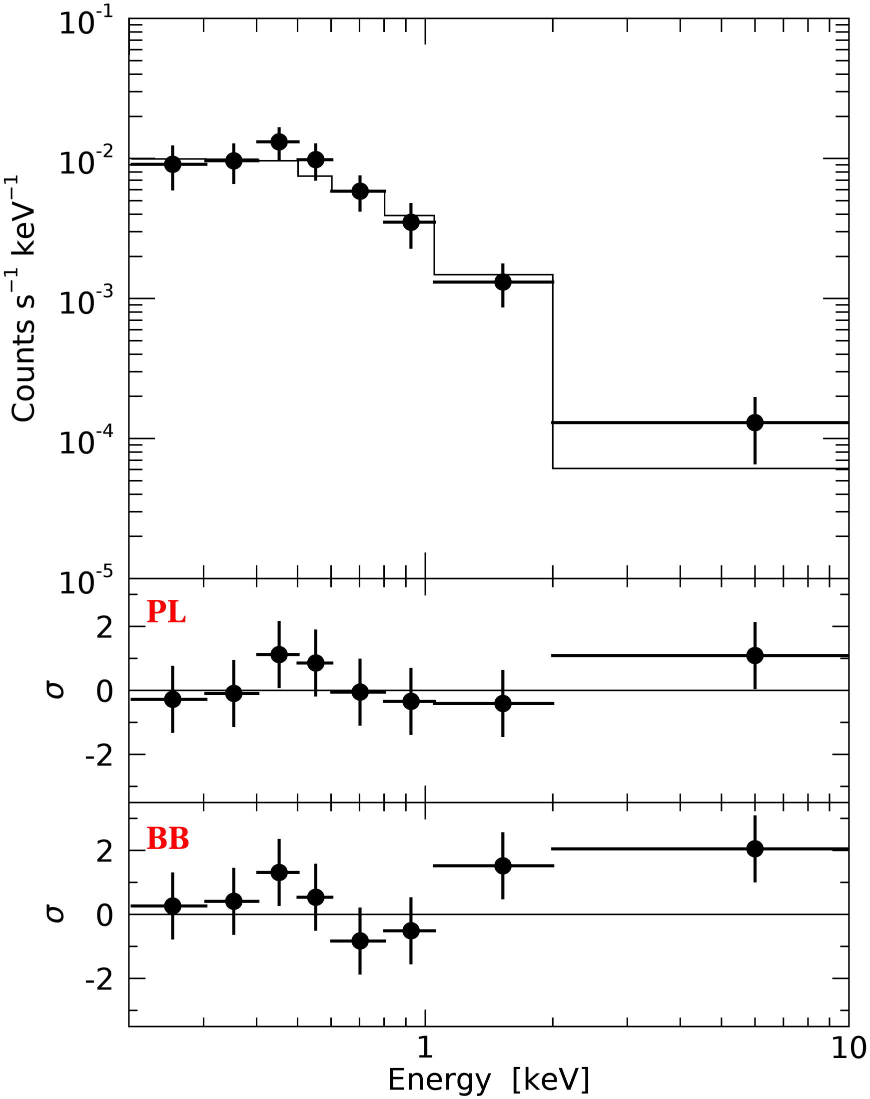
Spectrum fitted for the first time

Absorbed blackbody

$kT = 0.17 \pm 0.02$ keV
$R = 400 \pm 100$ m

Power-law rejected

PSR B0919+06



Best fit:

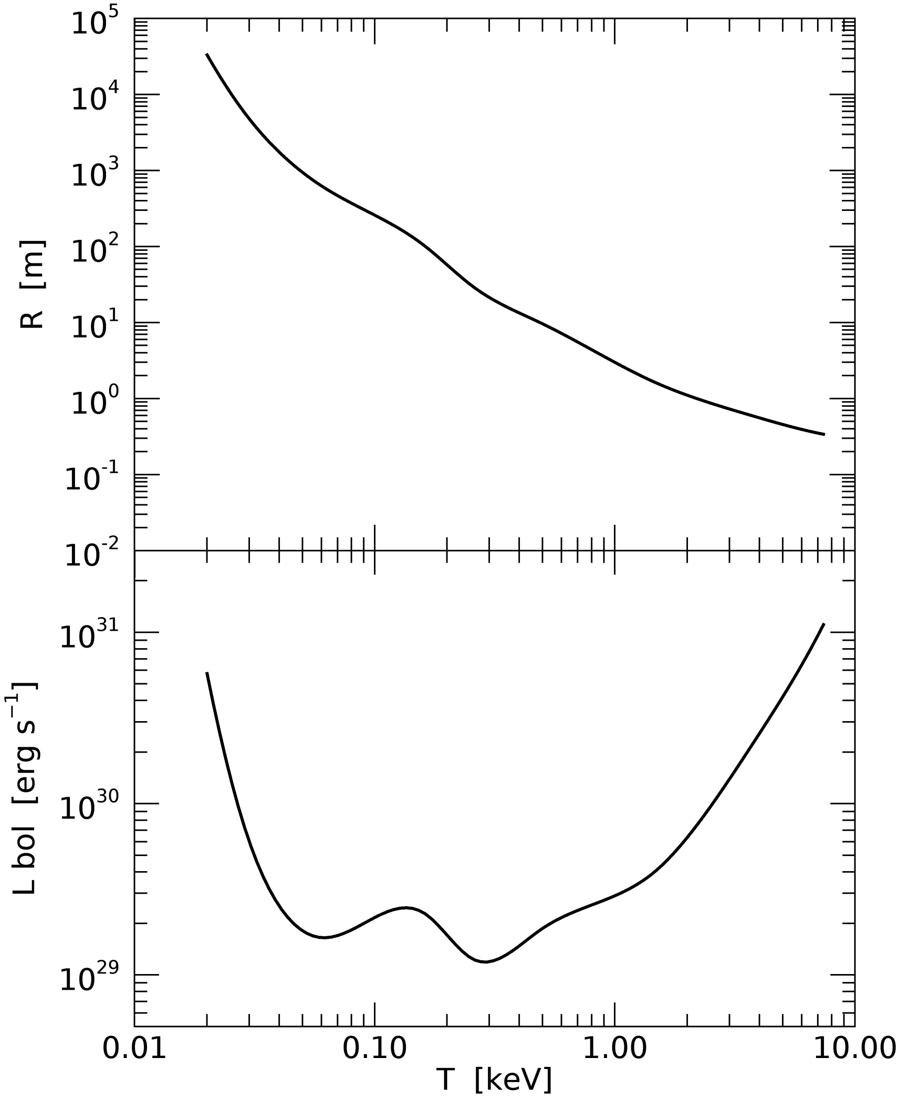
Absorbed power-law

$\Gamma = 3.1 \pm 0.2$

Blackbody rejected

Rigoselli & Mereghetti 2018

PSR B0919+06

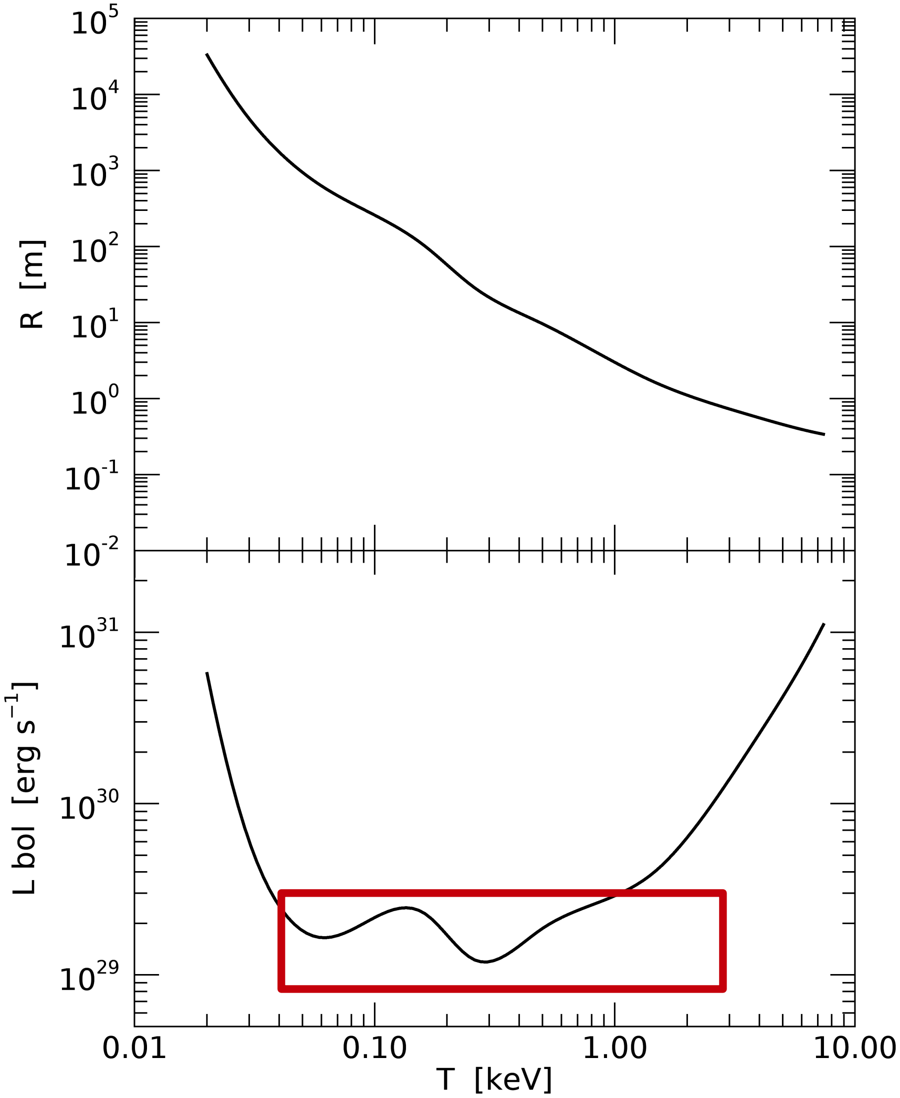


PL+BB model

3σ upper limit on BB

Rigoselli & Mereghetti 2018

PSR B0919+06



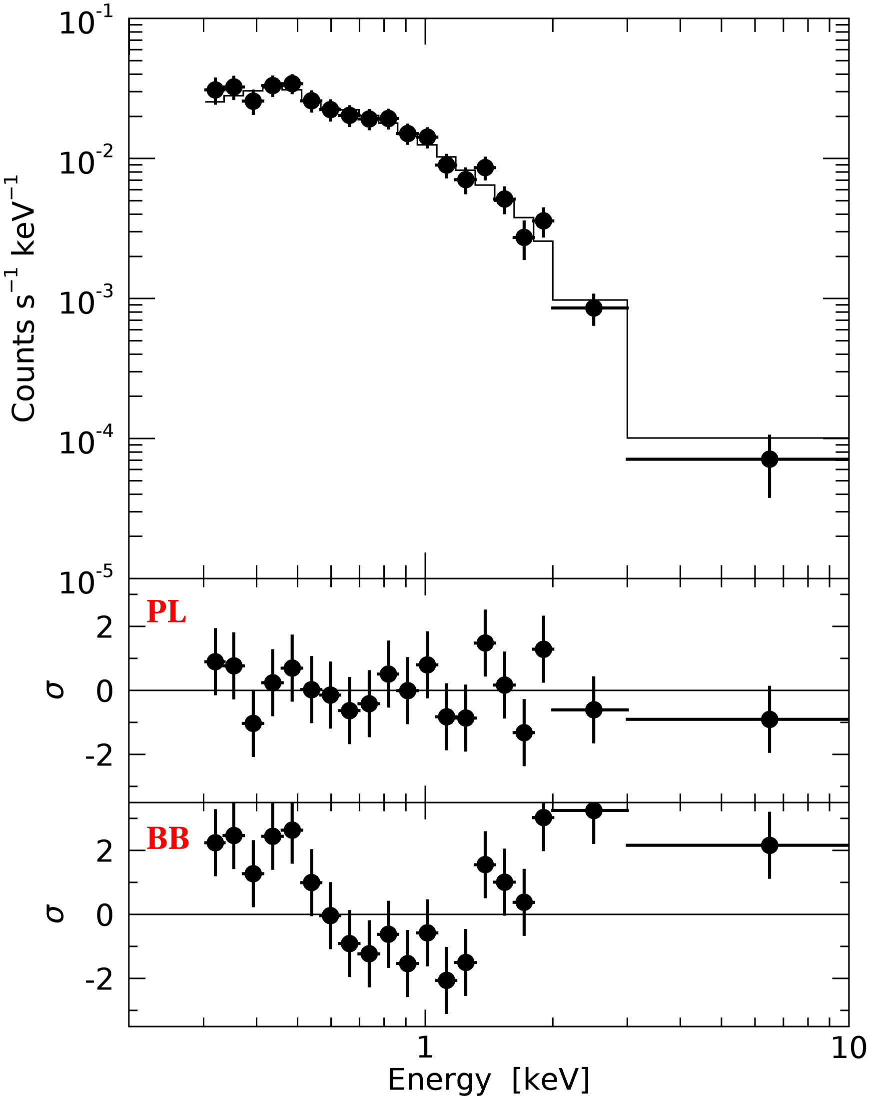
PL+BB model

3σ upper limit on BB

$L_{bol} < 2.4 \times 10^{29}$ erg s^{-1}

Rigoselli & Mereghetti 2018

PSR B0628-28



Best fit:

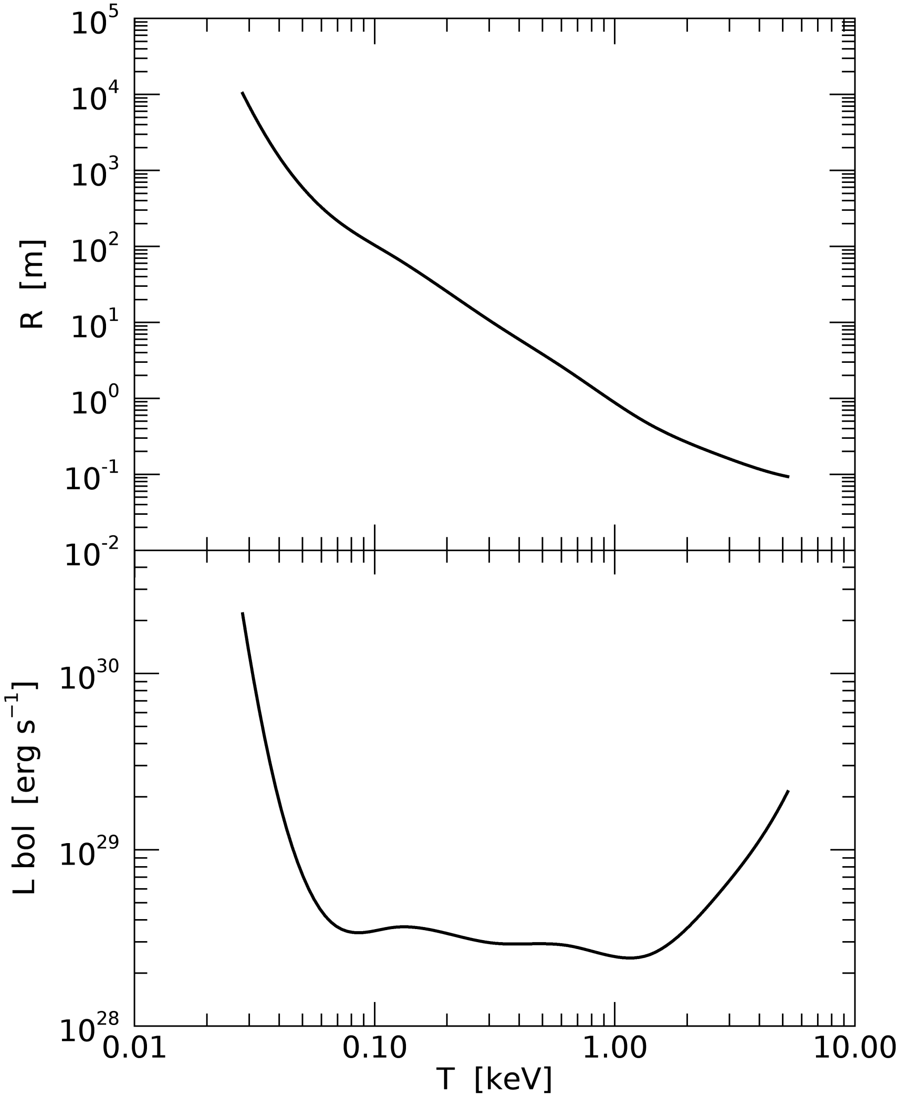
Absorbed power-law

$\Gamma = 2.95 \pm 0.06$

Blackbody rejected

Rigoselli & Mereghetti 2018

PSR B0628-28

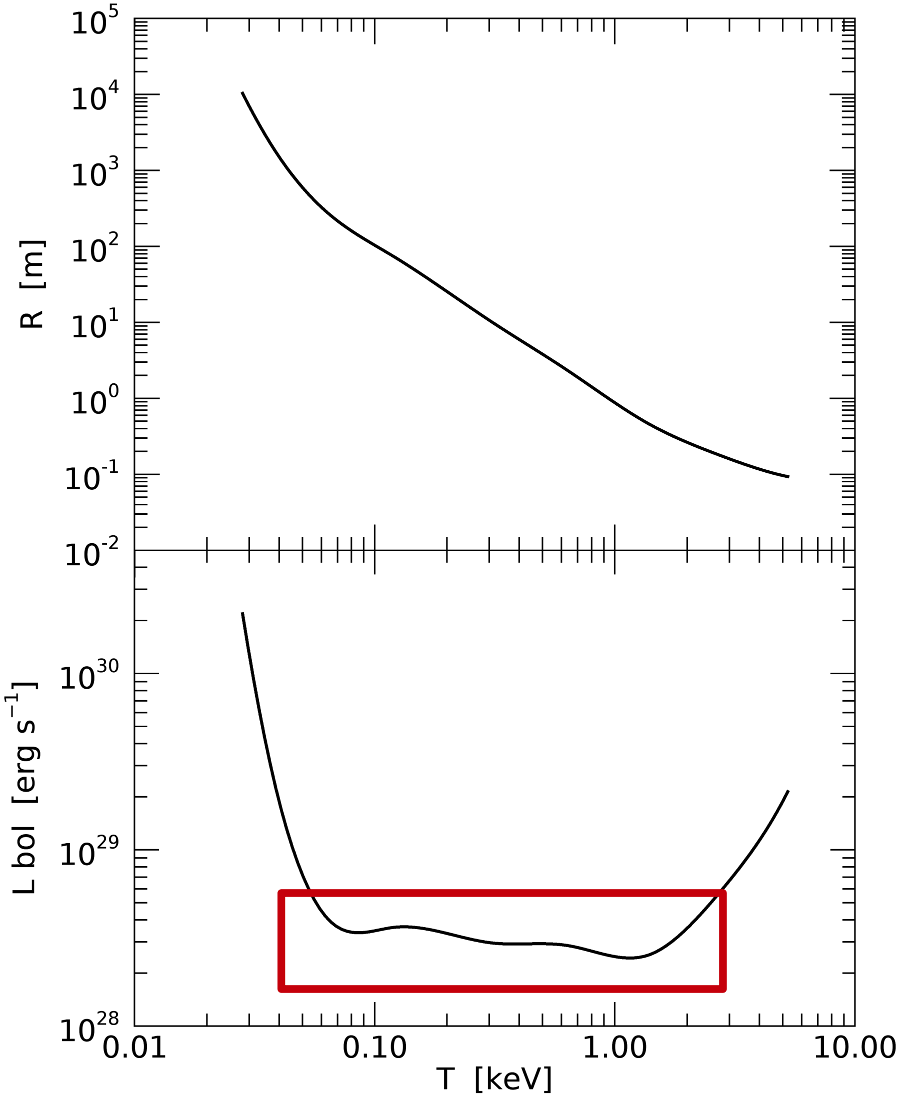


PL+BB model

3σ upper limit on BB

Rigoselli & Mereghetti 2018

PSR B0628-28



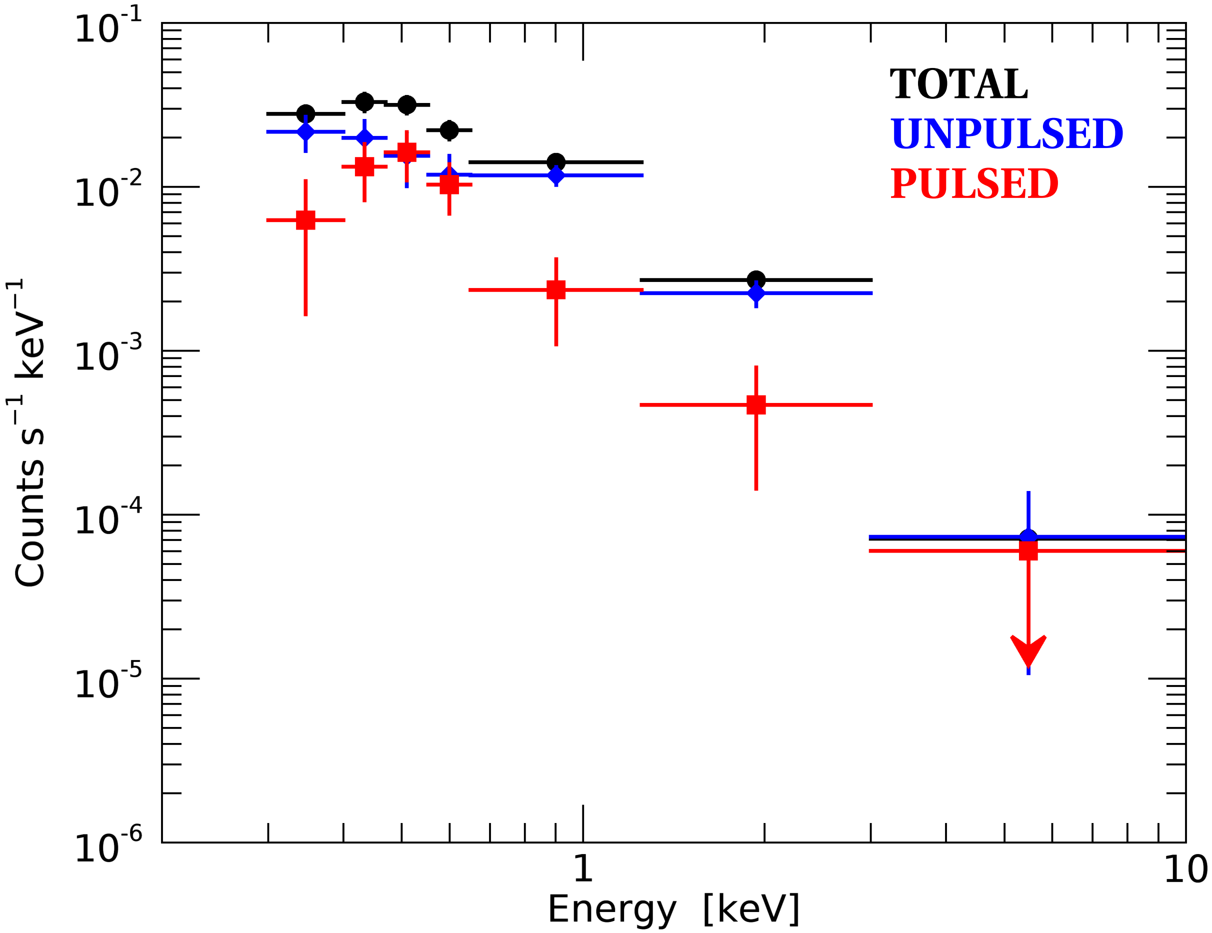
PL+BB model

3σ upper limit on BB

$L_{bol} < 3.2 \times 10^{28}$ erg s^{-1}

Rigoselli & Mereghetti 2018

PSR B0628-28



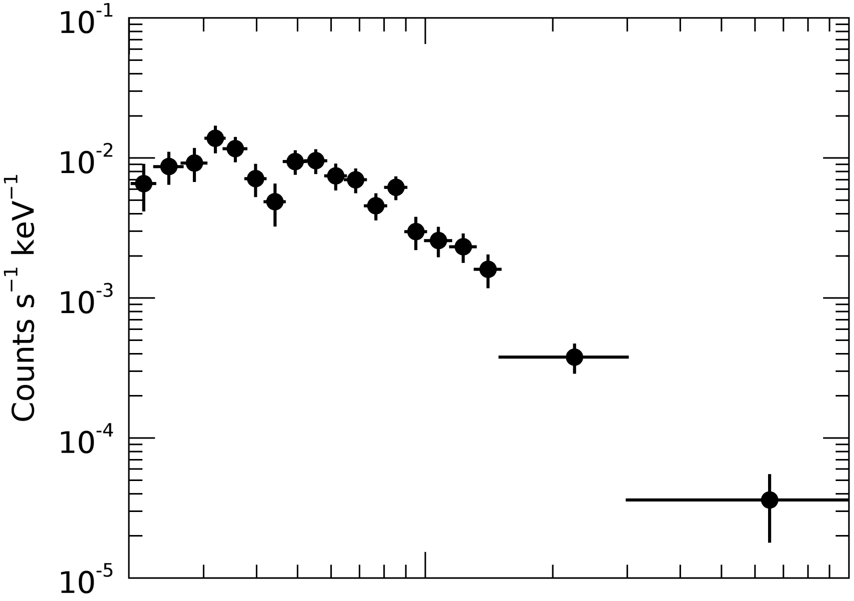
Unpulsed: PL

Pulsed: softer PL or BB with

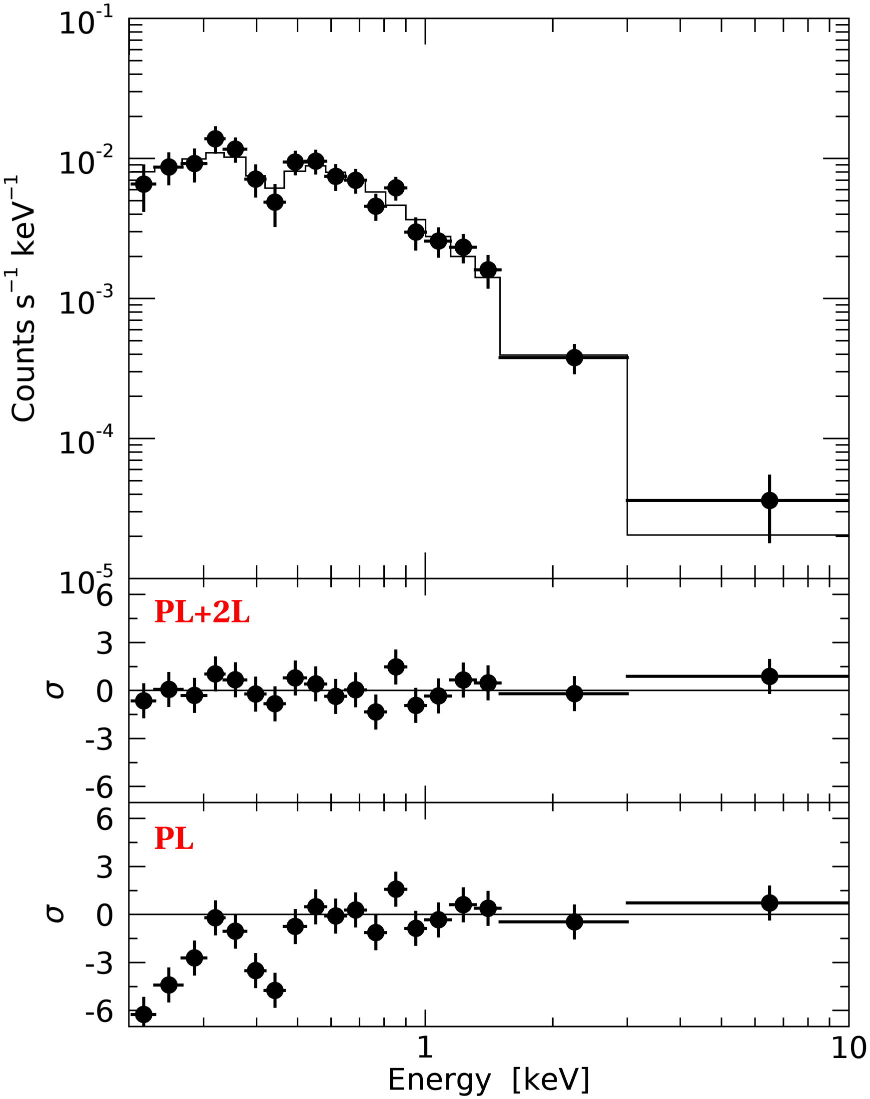
$kT = 0.10 \pm 0.02$ keV
$R = 150 \pm 50$ m

Rigoselli & Mereghetti 2018

PSR B1133+16



PSR B1133+16

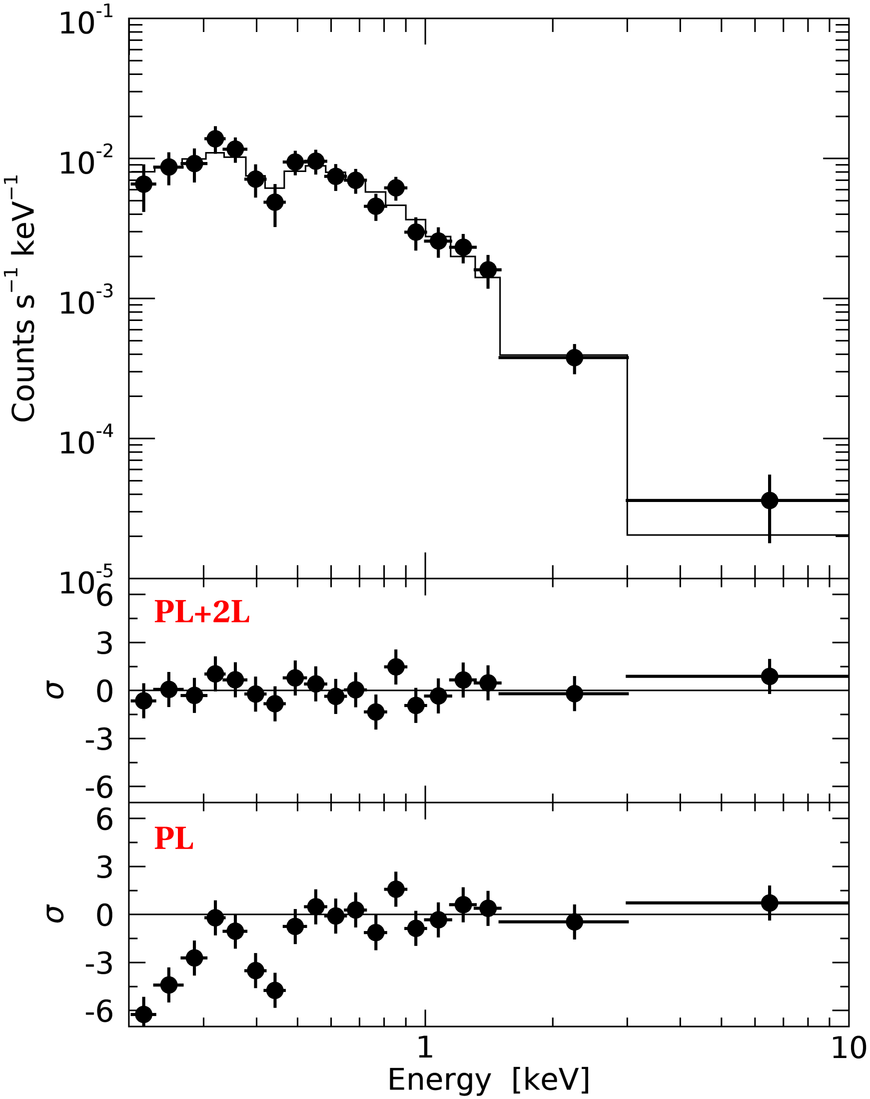


Best fit:

PL + 2 lines
@ 0.22 and 0.44 keV

Rigoselli & Mereghetti 2018

PSR B1133+16



Best fit:

PL + 2 lines
@ 0.22 and 0.44 keV

Harmonically spaced: cyclotron features due to protons

$(B_{sup} \approx 5 \times 10^{13}$ G$)$
$(B_{dip} \approx 2.1 \times 10^{12}$ G$)$

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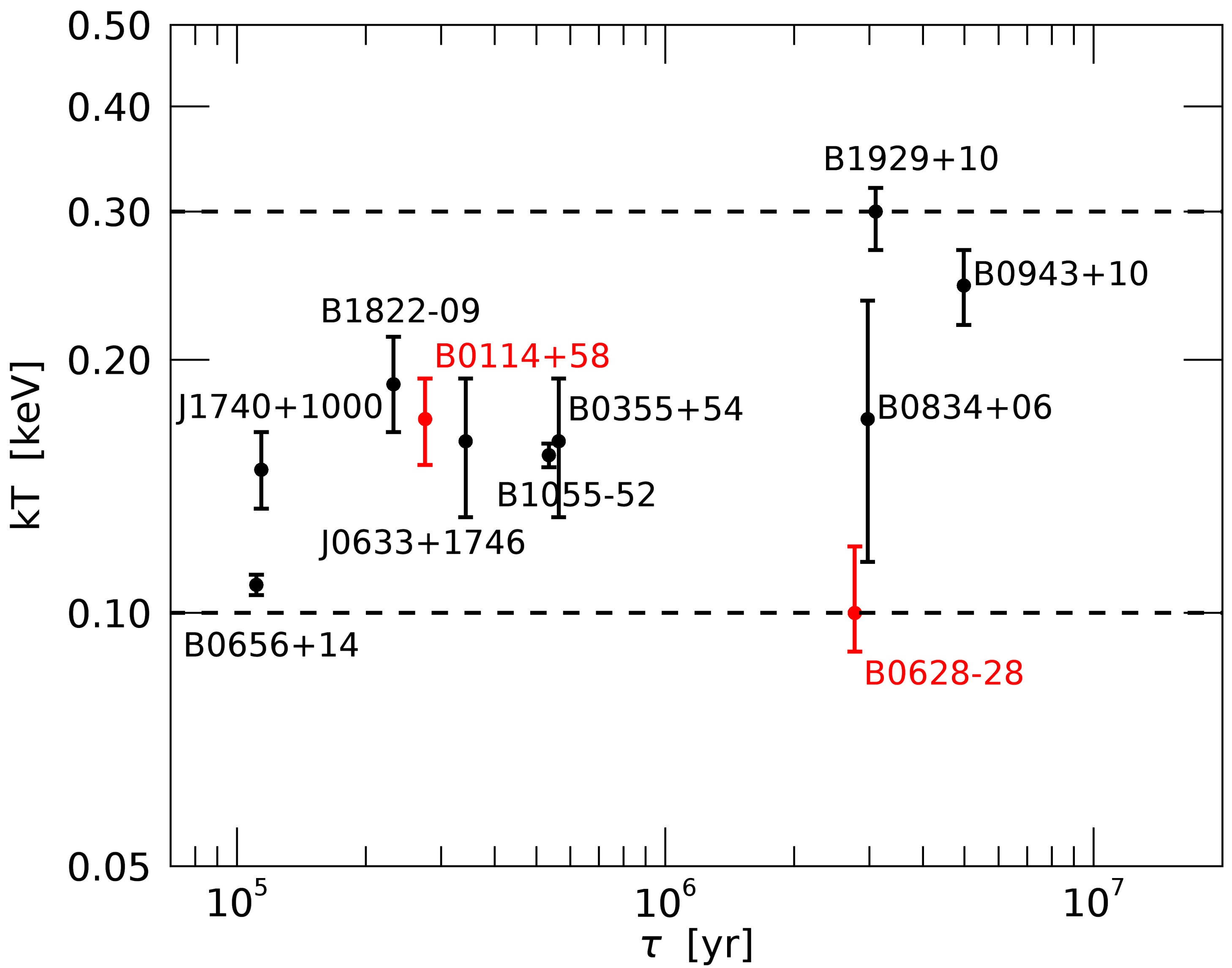
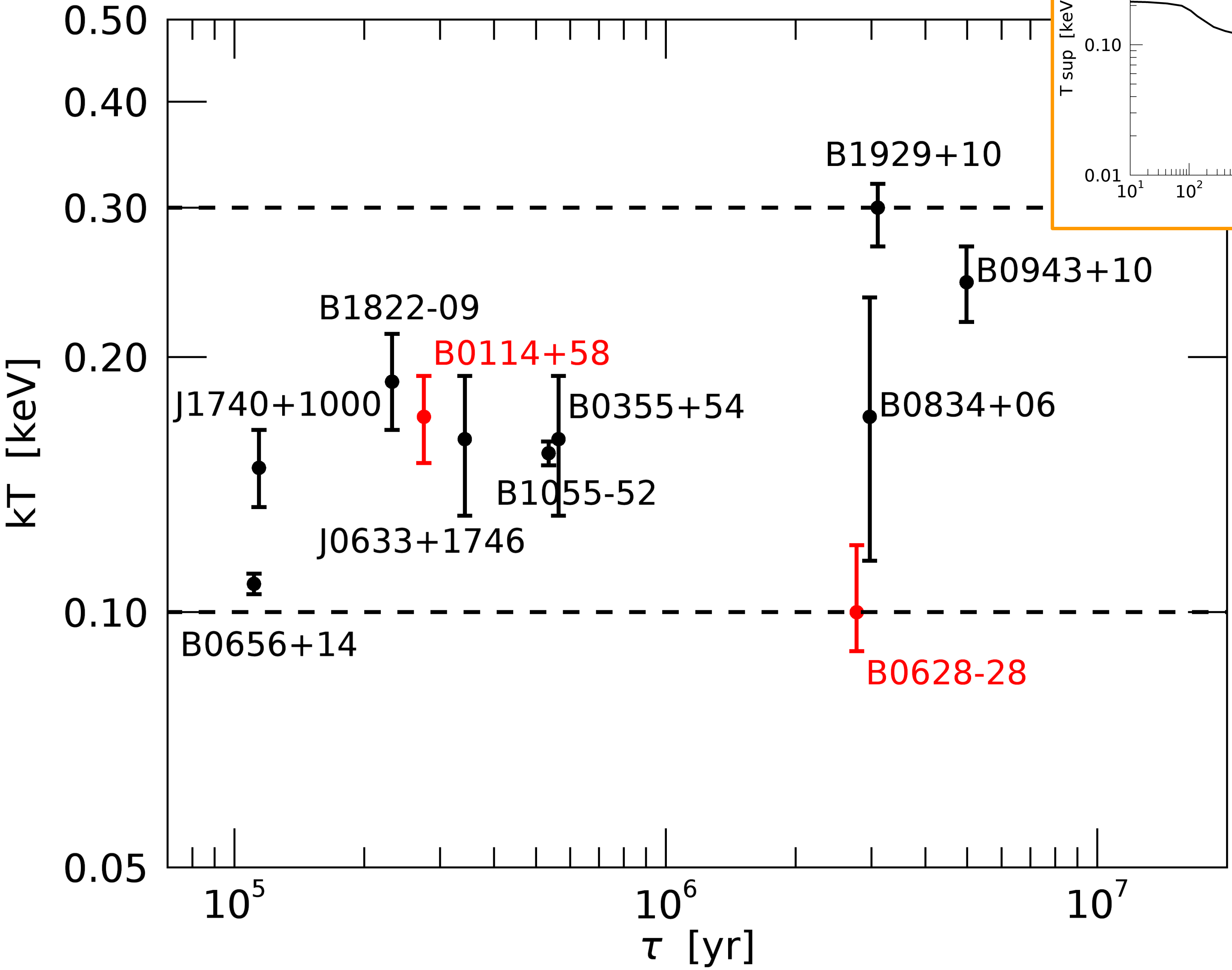
Summary

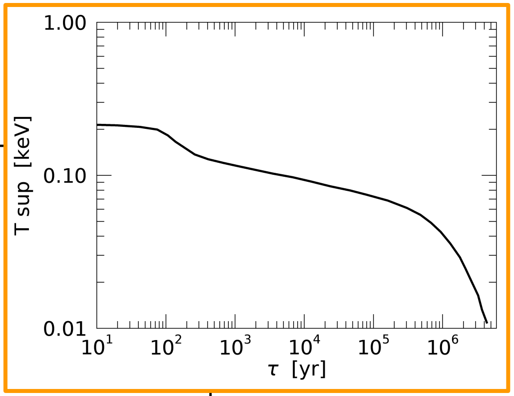
- PSR B0114+58 has a thermal emission from a hot spot
- PSR B0919+06 has a non-thermal emission and an upper limit on the bolometric luminosity
- PSR B0628-28 emission is mainly non-thermal, with a pulsed emission possibly thermal from a hot spot
- PSR B1133+16 spectrum is best described by a power-law plus 2 harmonically spaced lines, interpreted as cyclotron absorption lines

Polar Cap Temperature

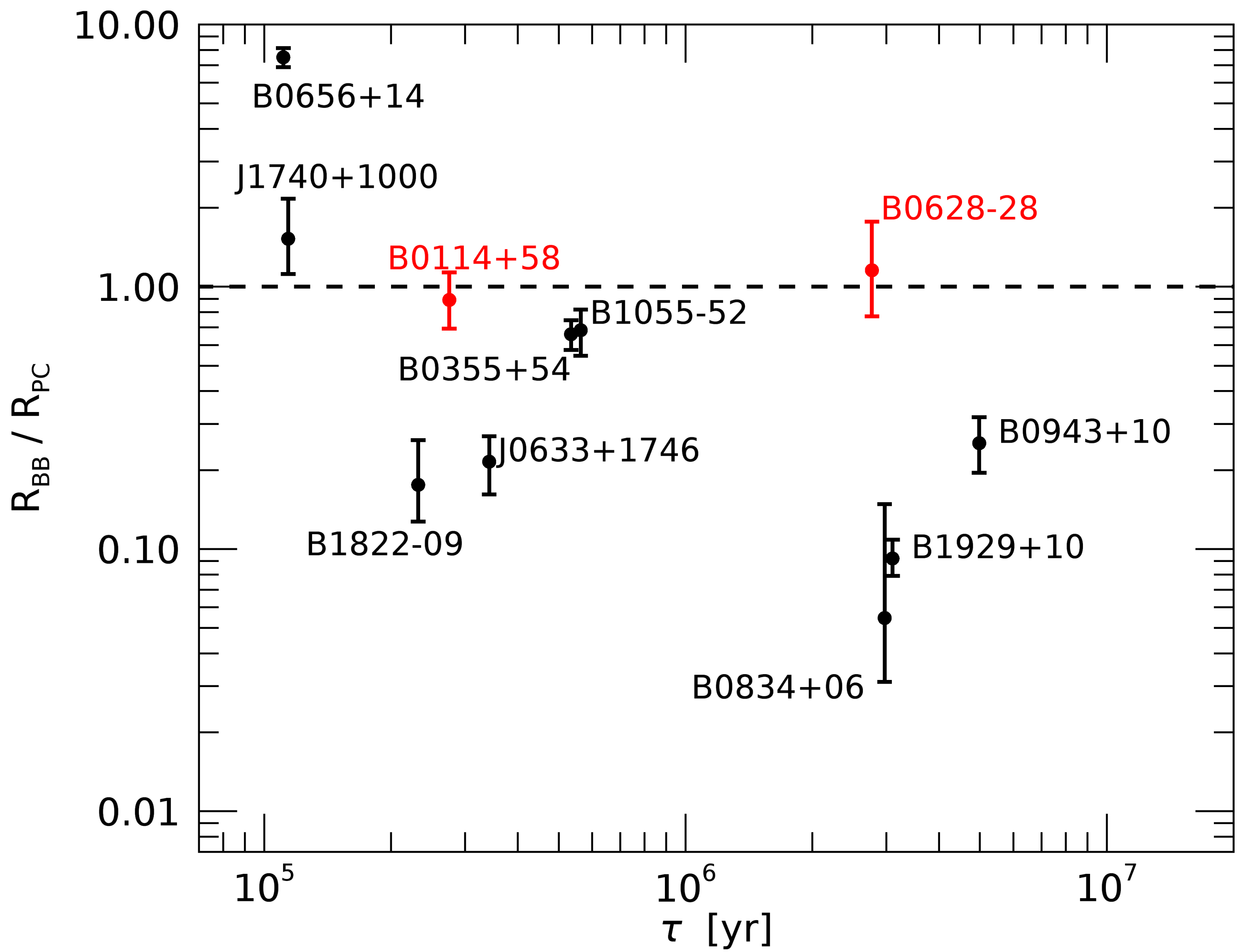


Polar Cap Temperature

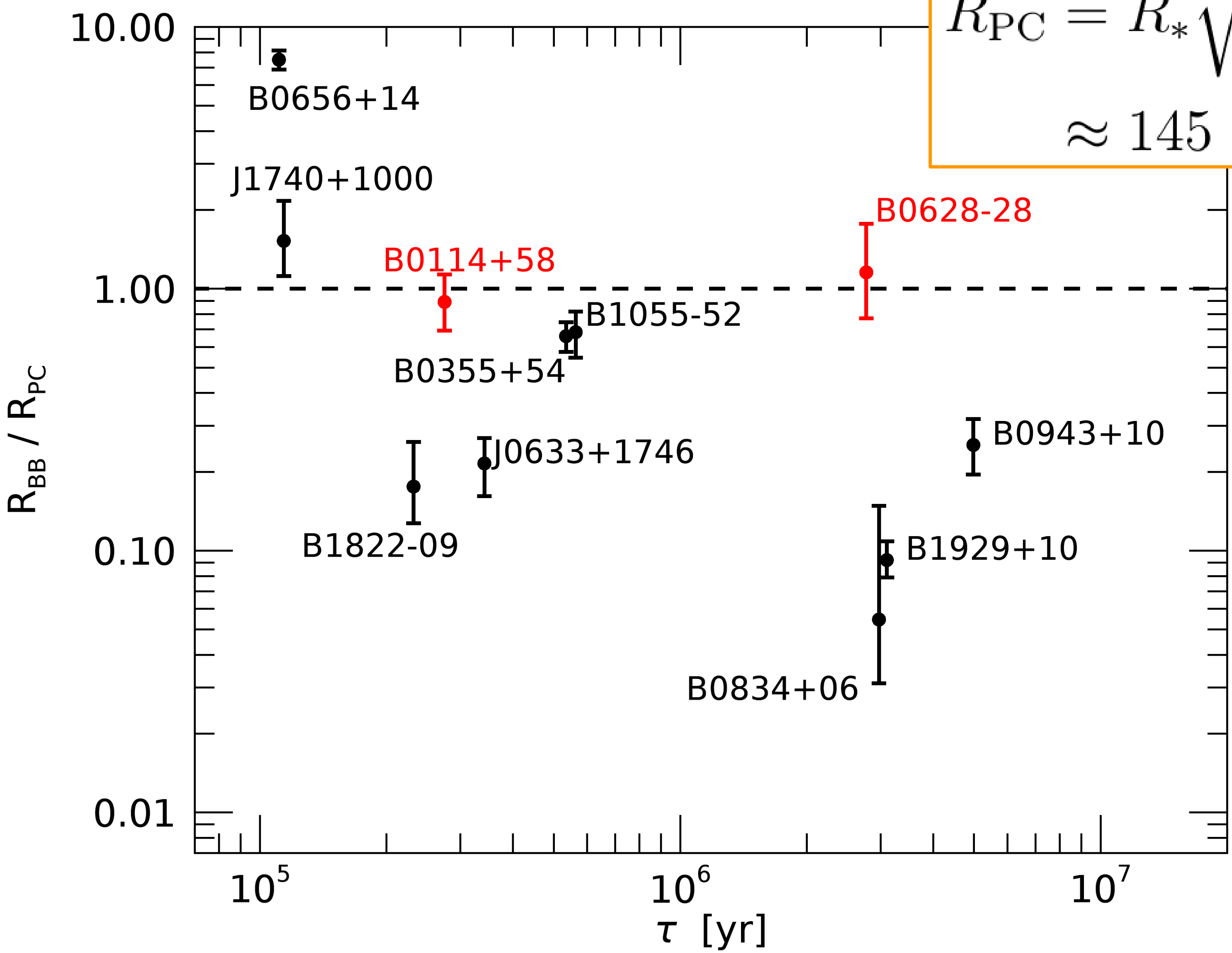




Polar Cap Radius



Polar Cap Radius



$$R_{\rm PC} = R_* \sqrt{\frac{R_* \Omega}{c}}$$
$$\approx 145 \text{ m } P^{-1/2}$$

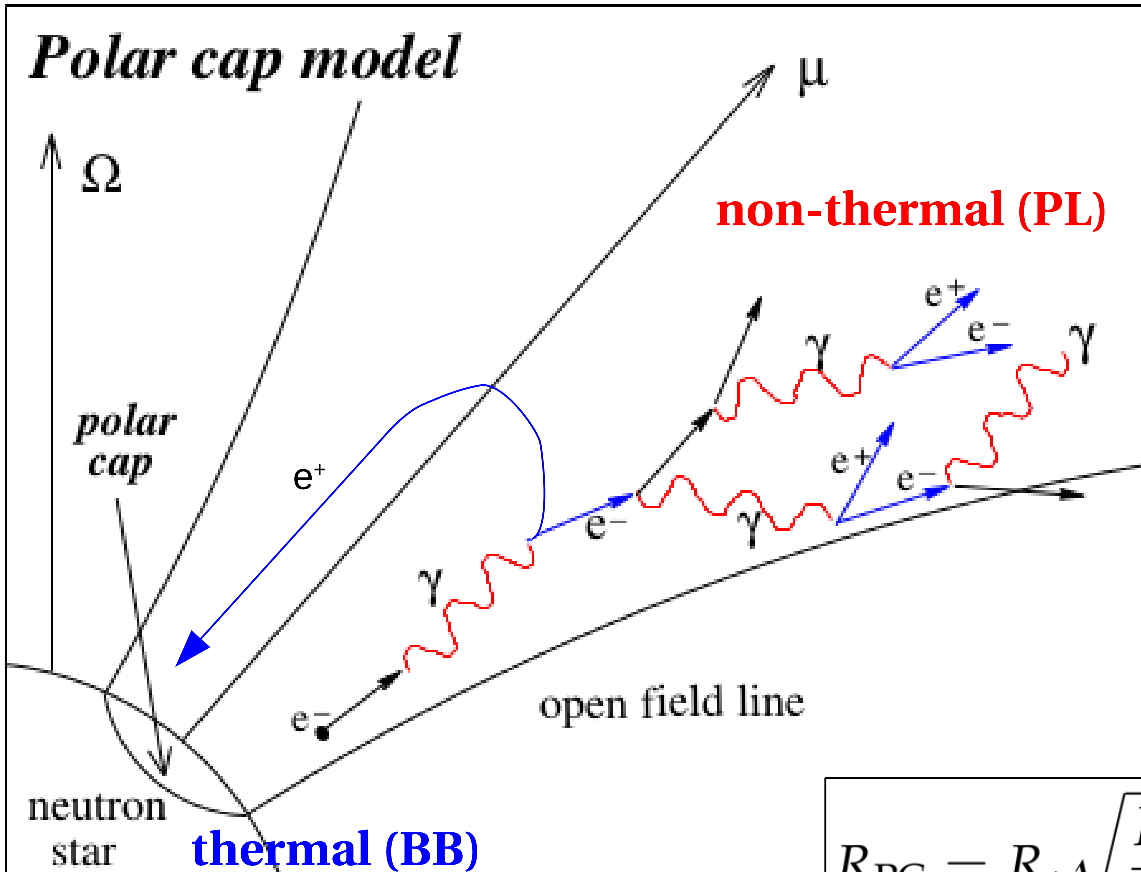
Conclusions

- ML method allows a better spectral analysis of faint sources
- Not all the old ($0.1 < \tau_c < 10$ Myr) RPPs have a thermal emission from a hot spot...
- ...but when it is present, the emission area is consistent with the polar cap
- PSR B1133+16 is the second RPP that shows cyclotron absorption lines *(PSR J1740+1000, Kargaltsev+ 2012)*

The Effects of Polar Cap Heating

Extra Slides

X-Ray Emission



$$R_{\mathrm{PC}} = R_* \sqrt{\frac{R_* \Omega}{c}} \approx 145\,\mathrm{m}\, P^{-1/2}$$

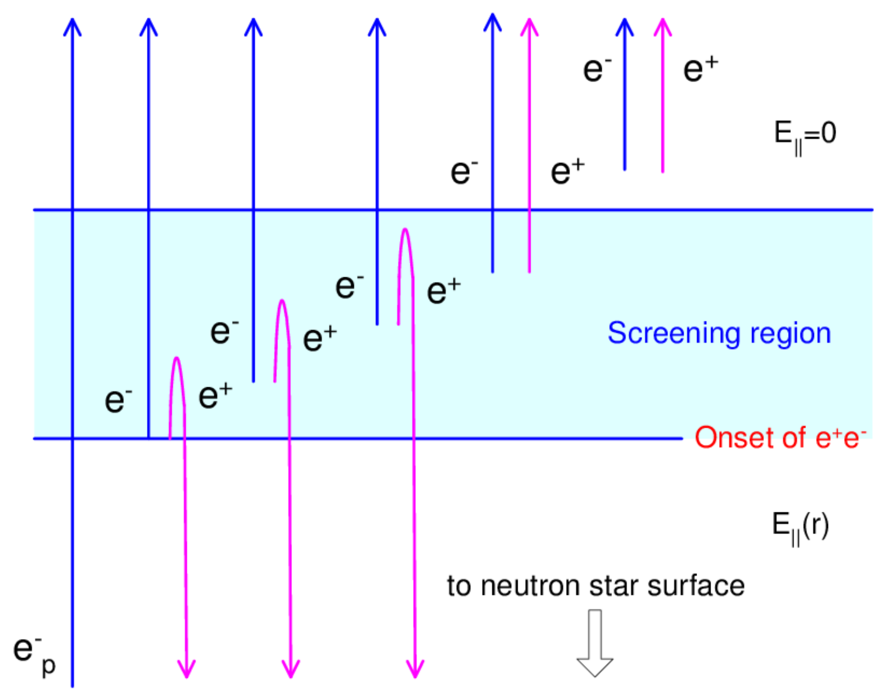
Polar Caps Model

Harding & Muslimov 1998, 2001, 2002

$E_{//}$ accelerates particles until they emit photons and pairs in an avalance process

Accelerated charges towards us → **non-thermal emission**

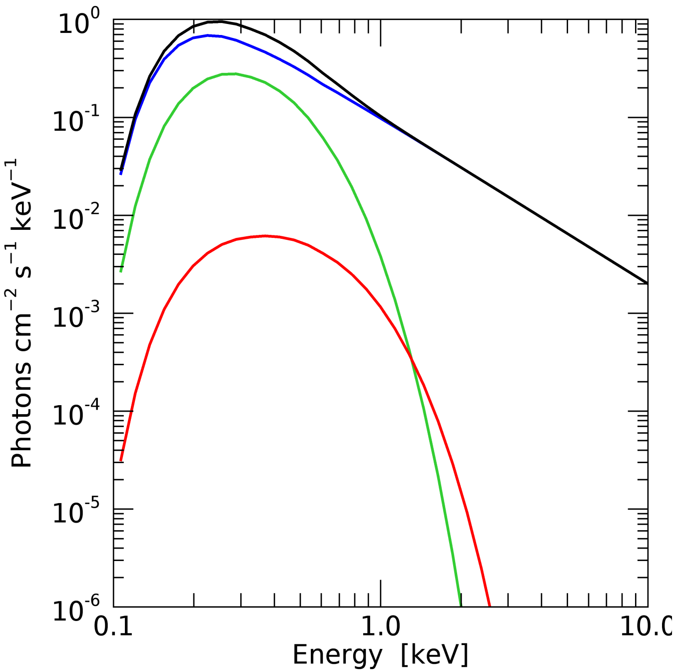
Backflow particles → heating of the polar caps → **thermal emission**



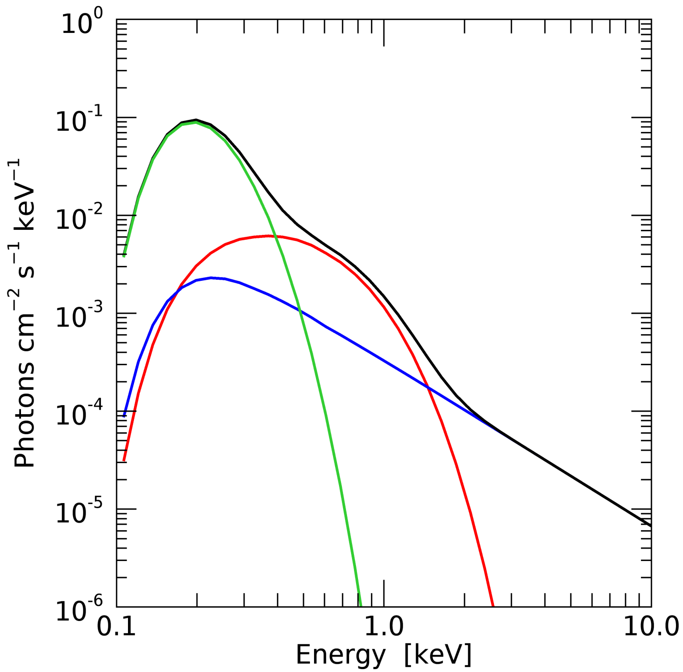
Harding 2007

Typical X-ray Spectra

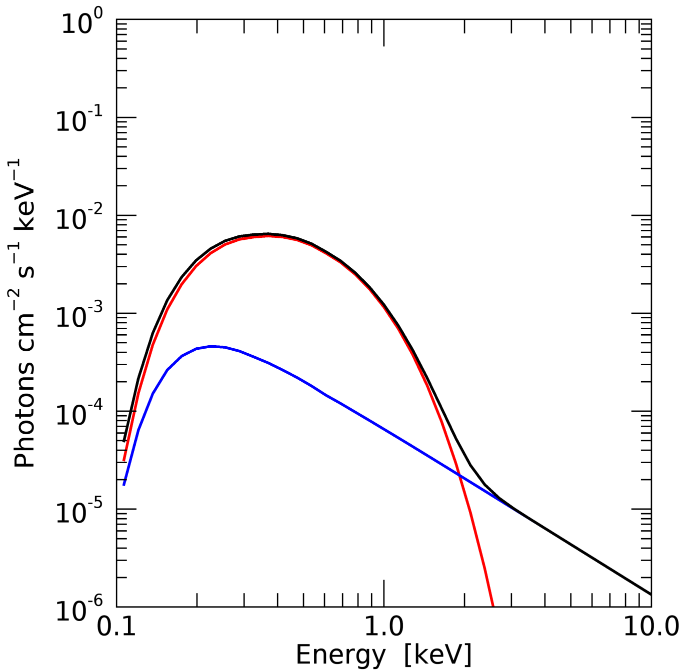
Young Pulsars
< 0.01 Myr



Middle age Pulsars
0.01 - 1 Myr



Old Pulsars
> 1 Myr



Maximum Likelihood Method

Exploits the knowledge of the PSF and all the counts of the image: makes the best use of the statistics

In the pixel *(i,j)* the probability to **measure** N_{ij} counts is

$$P_{ij} = \frac{e^{-\mu_{ij}} \mu_{ij}^{N_{ij}}}{N_{ij}!}$$

where μ_{ij} is the **expectation** value for the pixel *(i,j)* and in this case corresponds to $\mu_{ij} = \sigma \cdot PSF_{ij} + \beta$

Maximum Likelihood Method

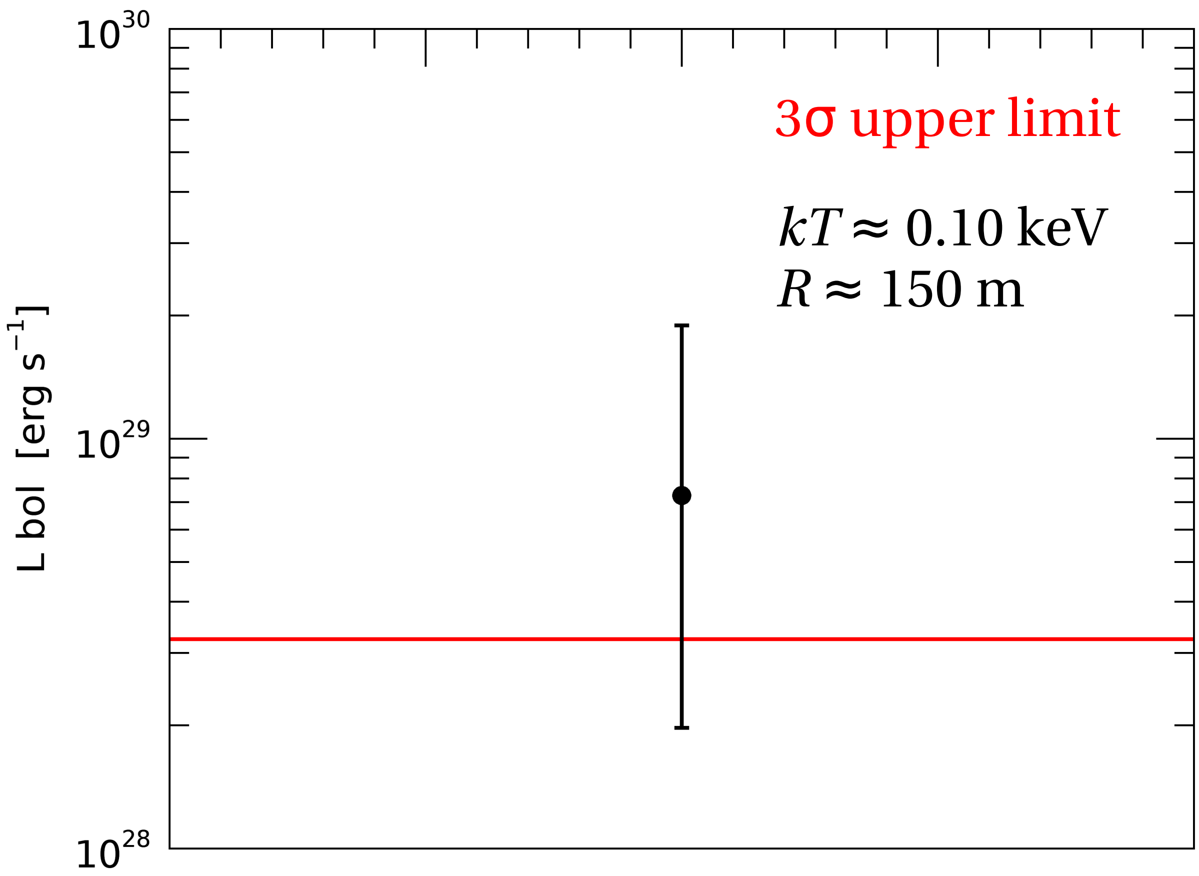
3D *(x,y,t)* approach: the expectation value of bin *(i,j,k)*

$$\mu_{ijk} = (\sigma_u + \sigma_p \cdot \Phi_k) \cdot PSF_{ij} + \beta$$

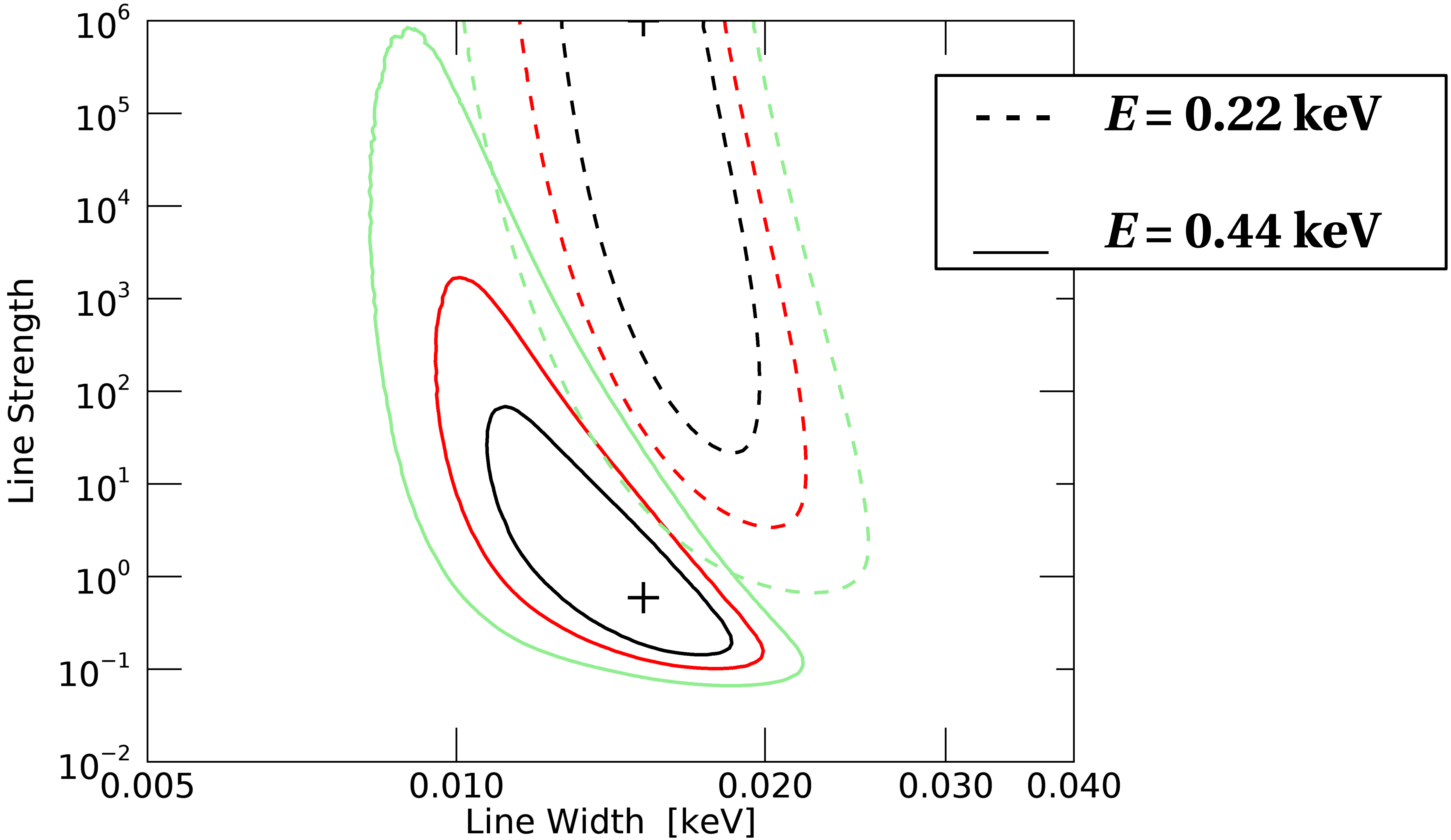
Application: given a pulse profile Φ_k , it separates the unpulsed counts σ_u from the pulsed ones σ_p

Makes possible 3D spectra

PSR B0628-28



PSR B1133+16



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Cyclotron Absorption Lines

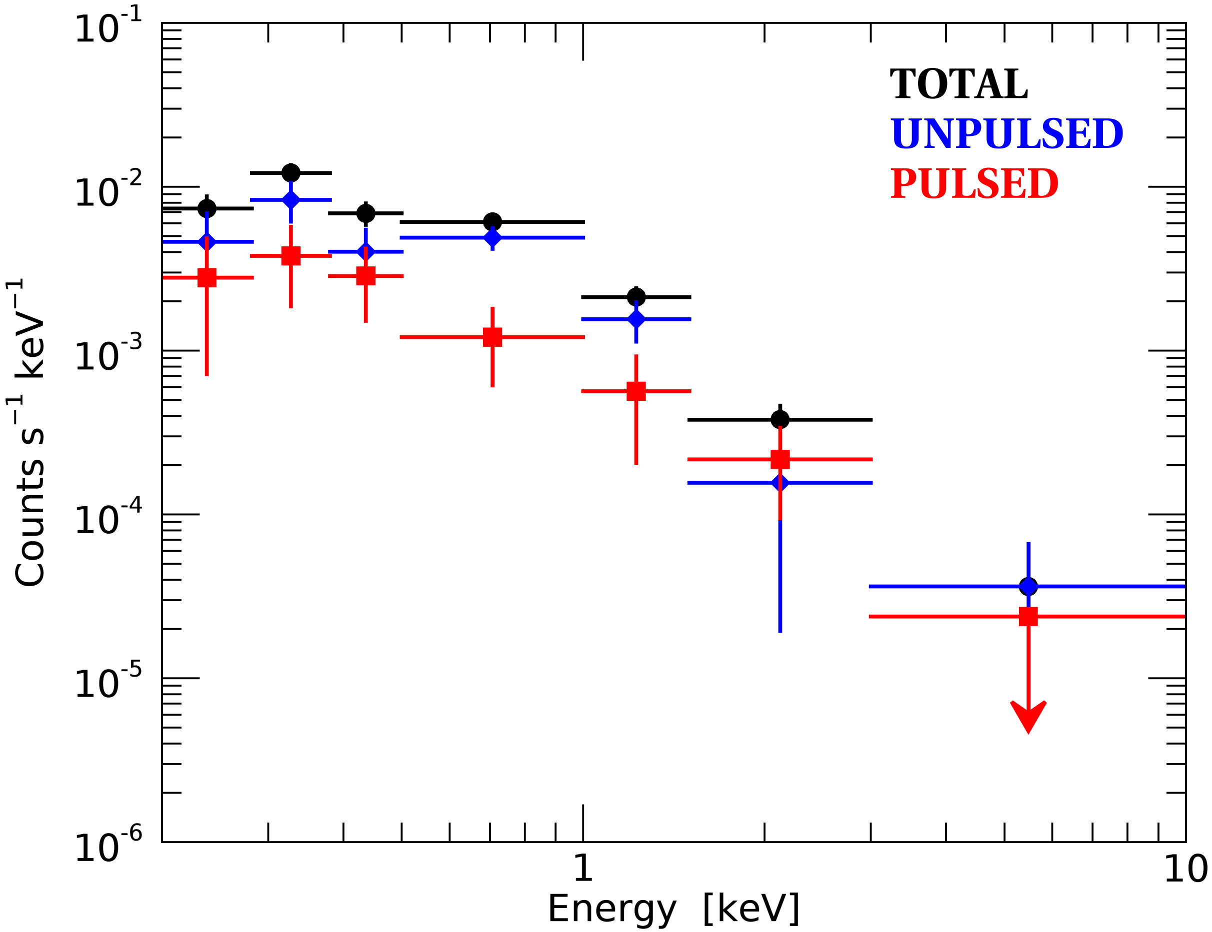
$$B = \frac{E_{\rm cyc}^{\rm obs}}{11.6\ \rm keV} \frac{m}{m_e} \left(1 - \frac{2GM}{Rc^2}\right)^{-1/2} \times 10^{12}\ \rm G$$

$$B_e \approx 2.5 \times 10^{10}\ \rm G$$

$$B_p \approx 5 \times 10^{13}\ \rm G$$

$$B(r) = B_{\rm sup}(1 + 3\cos^2\theta_B)(R_*/r)^3$$

PSR B1133+16



Unpulsed: PL + 2L

Pulsed: PL

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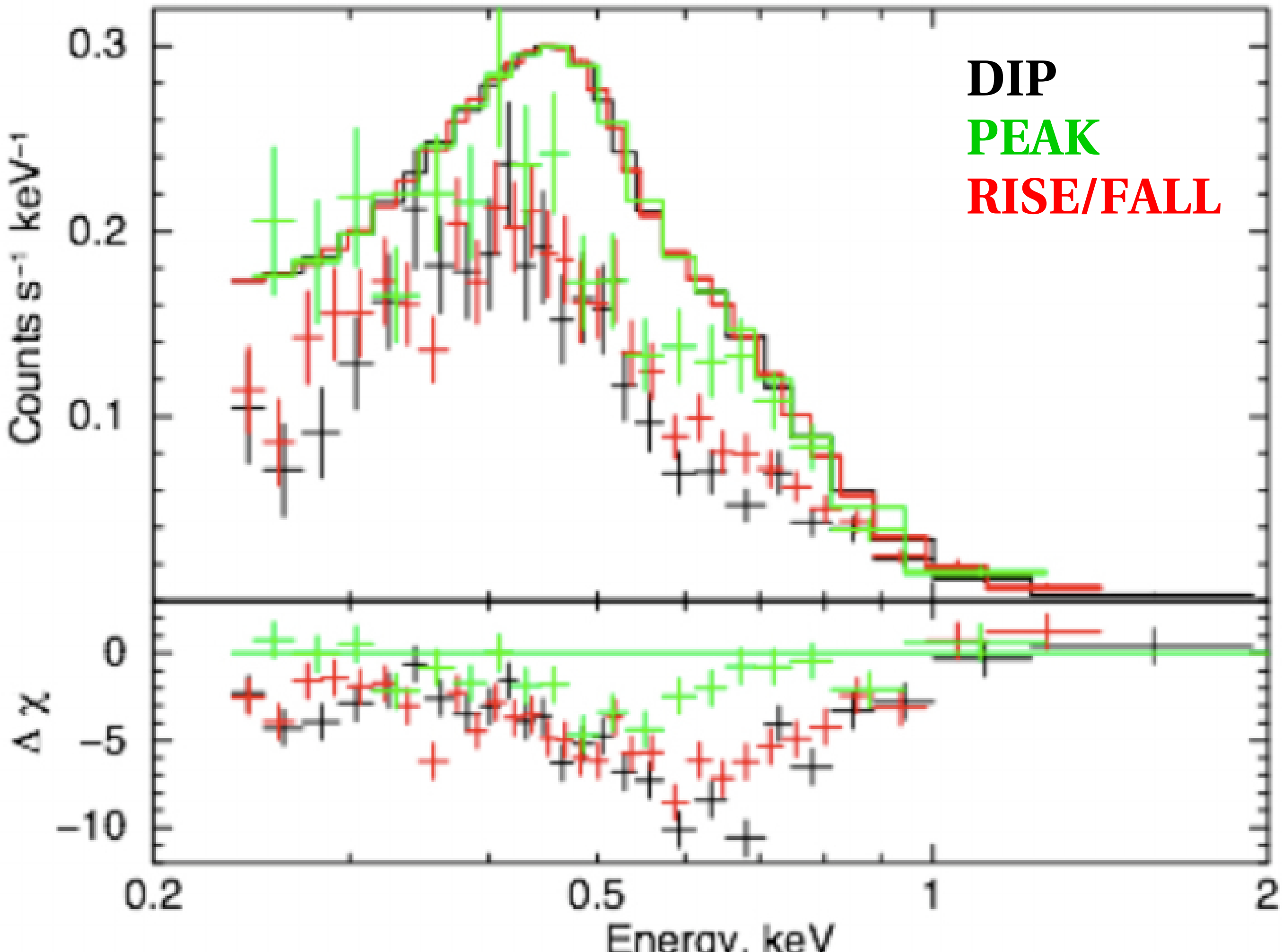
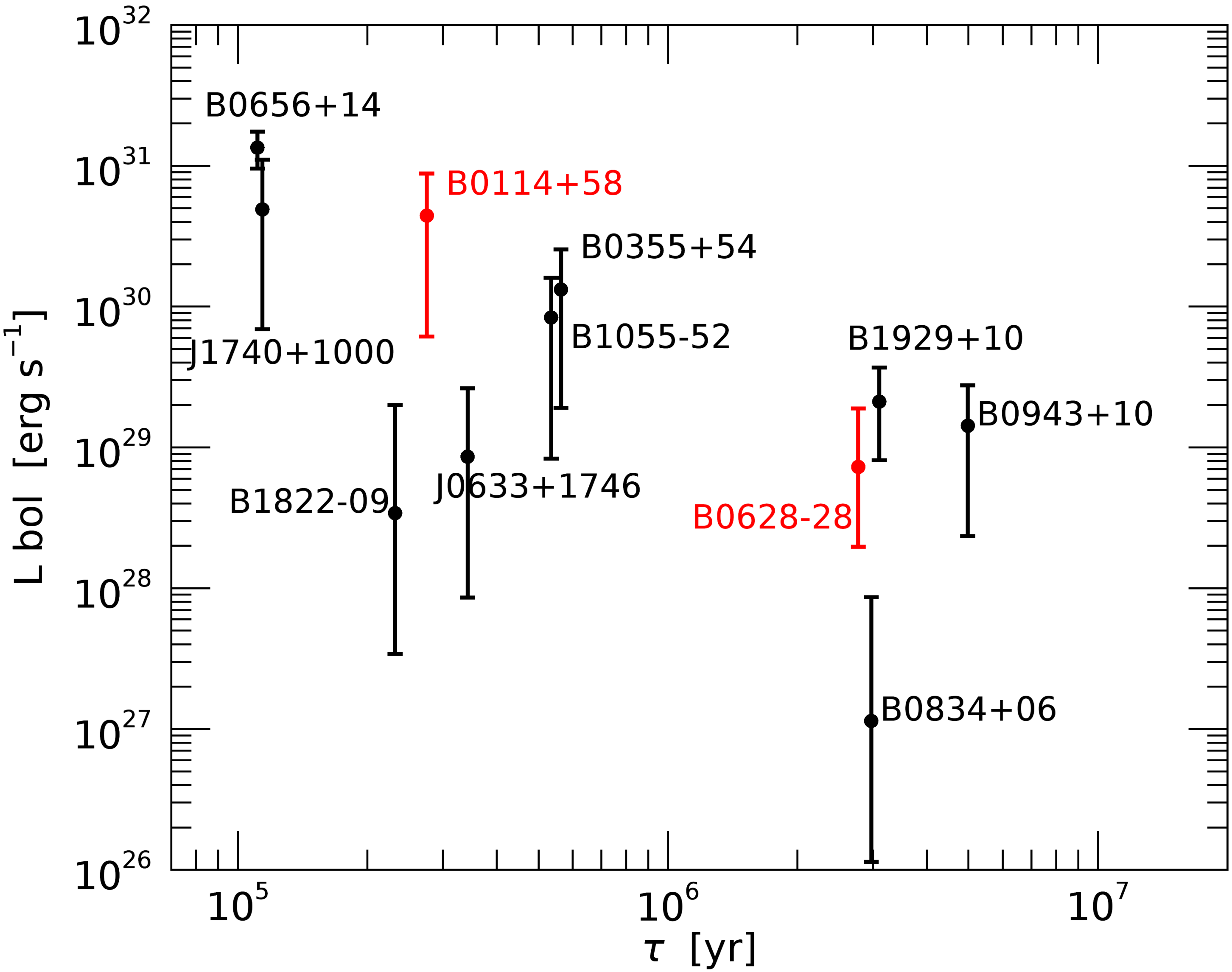
PSR J1740+1000

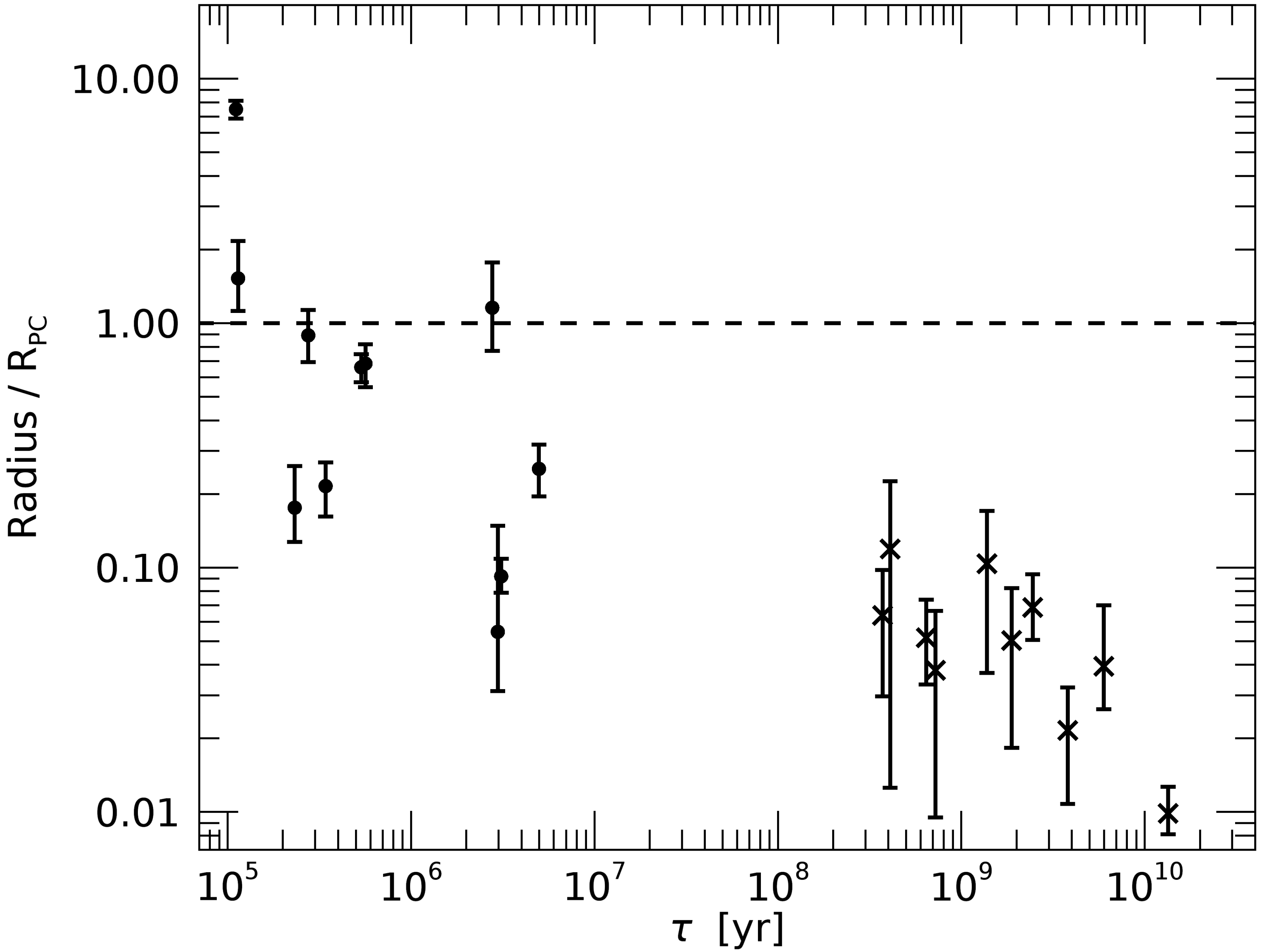


Kargaltsev+ 2012, Science 337, 946

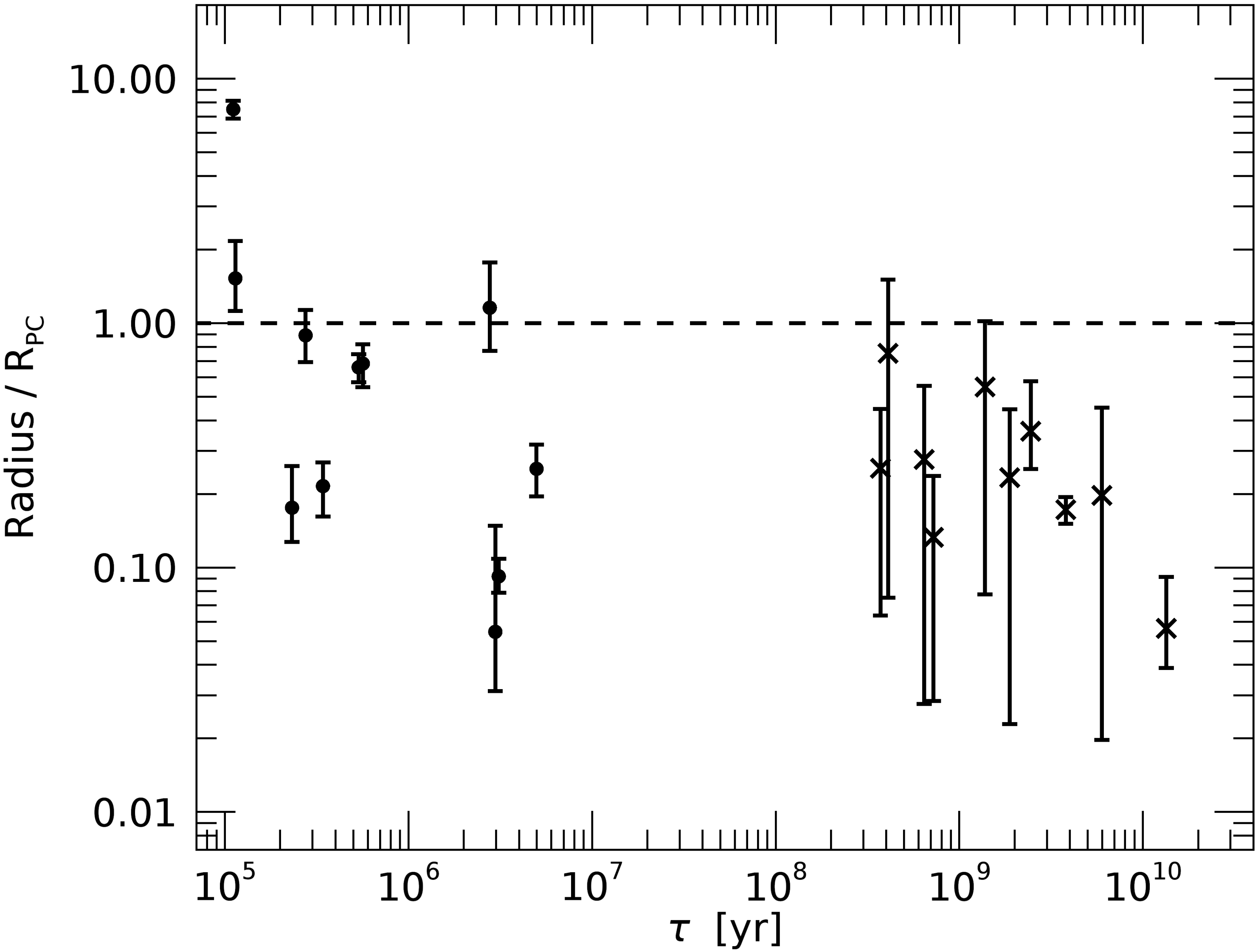
Polar Cap Luminosity



Millisecond Pulsar - BB



Millisecond Pulsar - ATM



Millisecond Pulsar - ATM