The thermal emission component in low luminosity binary pulsars

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Persistent Be X-Ray Binaries

Classification by Reig & Roche (1999):

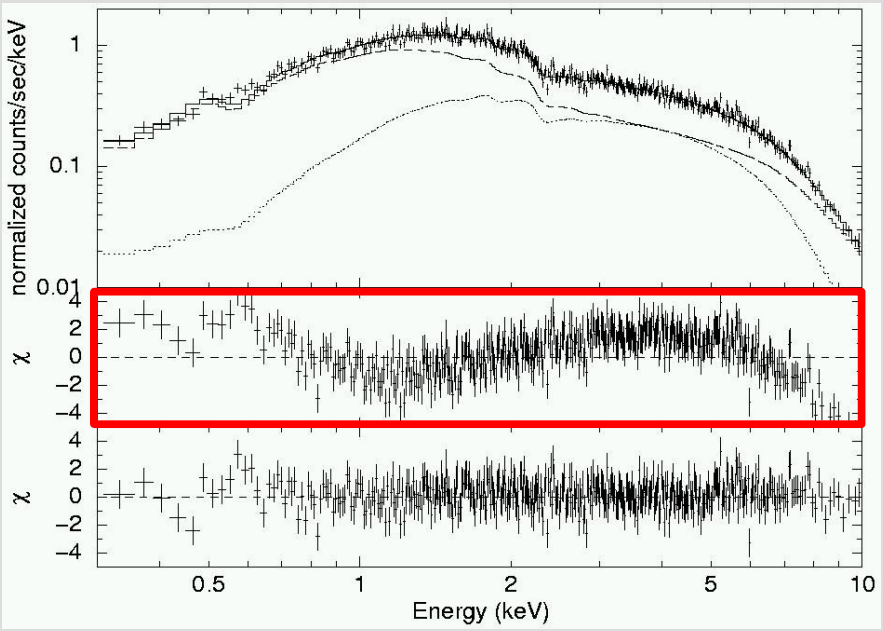
- persistent low luminosity ($L_X \sim 10^{34\text{-}35}$ erg s^{-1}) with small fluctuations
- no outbursts
- long pulse periods ($P_{spin} > 200$ s)
- low cut-off energy (~4 keV instead of 10-20 keV)
- missing or very weak Iron line at 6.4 keV
- $P_{spin} \sim P_{orb}^{\ 2}$ (Corbet 1986)
  => large orbits ($P_{orb} > 100$ d)
  => accretion from low density regions
- no outbursts => low eccentricity
- no tidal circularisation
  => primordial low eccentricity
  => low kick velocity at birth for the NS

XMM observation of two persistent BeXBRs

X-ray source	4U 0352+309	RX J0146.9+6121
Optical counterpart	X Persei	LS I +61^{o} 235
Luminosity (2-10 keV)	~10^{35} erg s^{-1}	~10^{34} erg s^{-1}
Pulse period	839.3 ± 0.3 s	1396.1 ± 0.2 s
Orbital period	250.3 d	?
Orbital eccentricity	0.11	?
Spectral type	O9.5 IIIe	B0 IIIe
Source distance	0.95 kpc	~ 2.5 kpc

Phase-averaged spectra - I

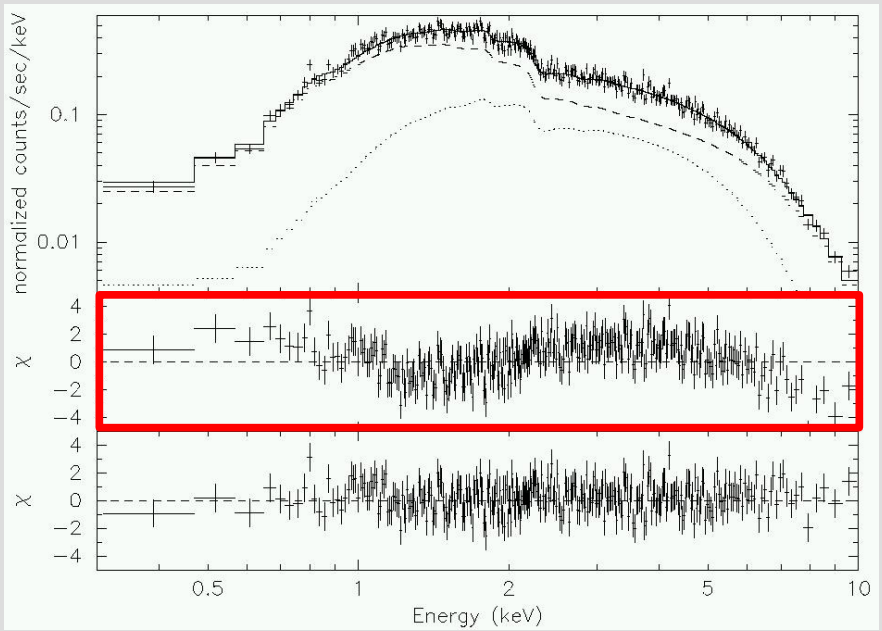
4U 0352+309



La Palombara & Mereghetti, 2007

PL

RX J0146.9+6121

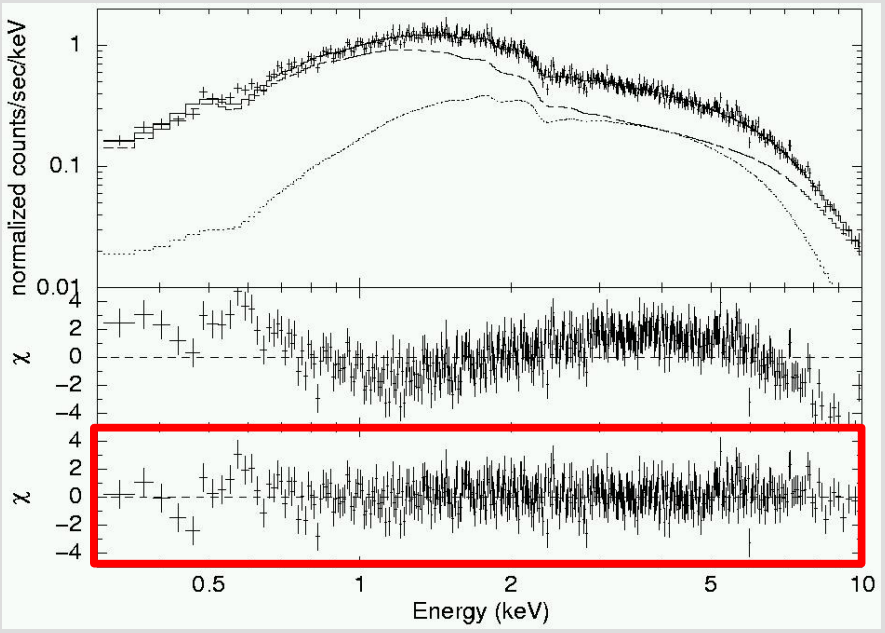


La Palombara & Mereghetti, 2006

=> a single power-law component does not describe the observed spectra

Phase-averaged spectra - II

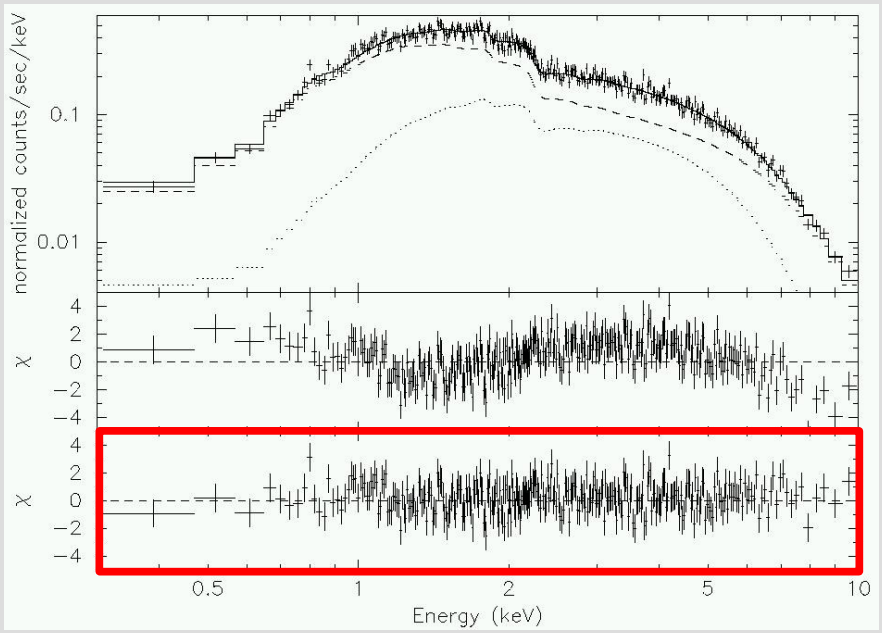
4U 0352+309



La Palombara & Mereghetti, 2007

PL+BB

RX J0146.9+6121



La Palombara & Mereghetti, 2006

=> a single power-law component does not describe the observed spectra

=> the addition of a black-body component improves the fit quality

=> any alternative component is rejected

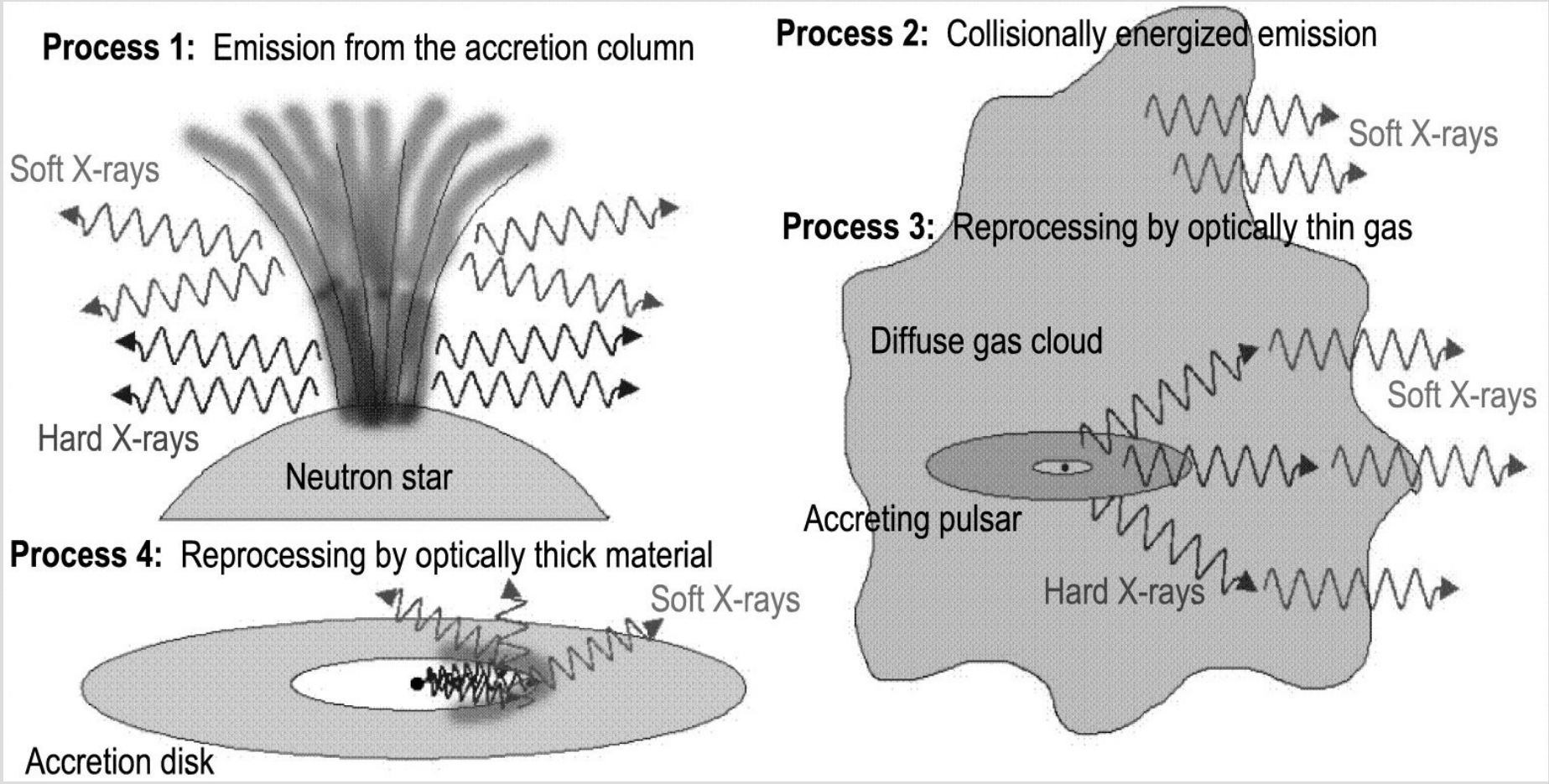
=> no evidence of an Iron line between 6 and 7 keV

Phase-averaged spectra - III

X-ray source	4U 0352+309	RX J0146.9+6121
Luminosity (0.3-10 keV, erg s^{-1})	~1.4×10^{35}	~1.5×10^{34}
Photon index Γ	1.48 ± 0.02	1.34 ± 0.05
Black-body temperature (keV)	1.42 ± 0.03	1.11 ± 0.06
Black-body radius (m)	361 ± 3	140 ± 15
Flux PL (%)	~ 61	~ 76
Flux BB (%)	~ 39	~ 24
Upper Limit EQW Fe (keV)	~ 0.1	~ 0.15

BB component of high temperature and small size as a possible additional common property of persistent BeXRBs

Possible emission processes for the data excess



Hickox et al., 2004

Origin of the thermal excess in 4U 0352+309 and RX J0146.9+6121

- $L_X \leq 10^{36}$ erg s^{-1}

$\Rightarrow$ no reprocessing by optically thick accreting material

- the observed excess can be described only by a black-body model

$\Rightarrow$ no emission by photoionized or collisionally heated gas

- the black-body temperature is high (> 1 keV)

AND

- the emission radius is small (< 0.5 km)

$\Rightarrow$ thermal emission from the neutron star polar caps?

Assuming $M_{NS} = 1.4\ M_{SUN}$, $R_{NS} = 10^6$ cm and $B_{NS} = 10^{12}$ G, we can estimate:

- the accretion rate: $\dot{M} = LR_{NS}/(GM_{NS})$
- the magnetic dipole momentum: $\mu = B_{NS}R_{NS}^{3}/2$
- the magnetospheric radius: $R_m = \{\mu^4/[2GM(\dot{M})^2]\}^{1/7}$
- the accretion column radius: $R_{col} \sim R_{NS}(R_{NS}/R_m)^{1/2}$

Origin of the thermal excess in 4U 0352+309 and RX J0146.9+6121

X-ray source	4U 0352+309	RX J0146.9+6121
Luminosity (2-10 keV)	~ 10^{35} erg s^{-1}	~ 10^{34} erg s^{-1}
Accretion rate	~ 5 x 10^{14} g s^{-1}	~ 5 x 10^{13} g s^{-1}
Magnetospheric radius	~ 9.5 x 10^{8} cm	~ 1.8 x 10^{9} cm
Polar cap radius	~ 330 m	~ 230 m
Black-body radius	361 ± 3 m	140 ± 15 m

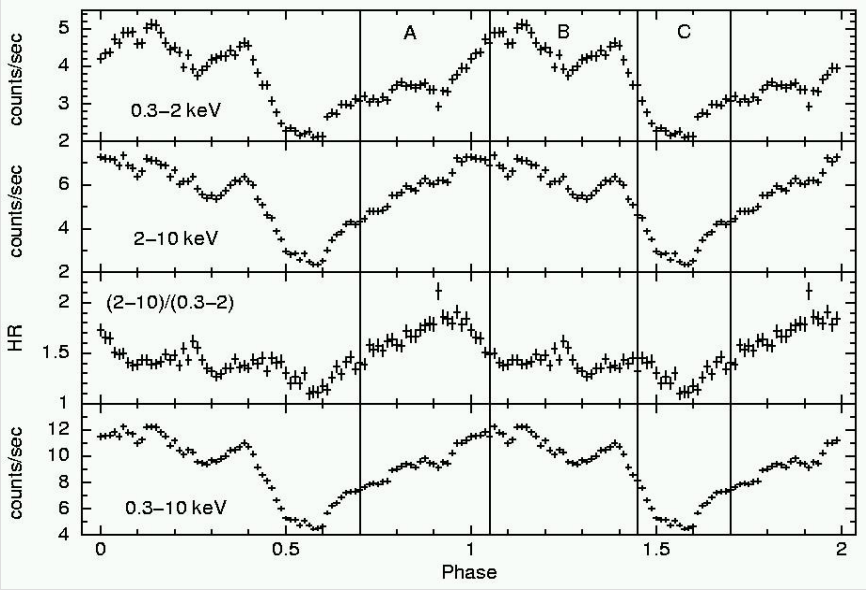
further clue that the BB component is linked to the polar caps…

BUT

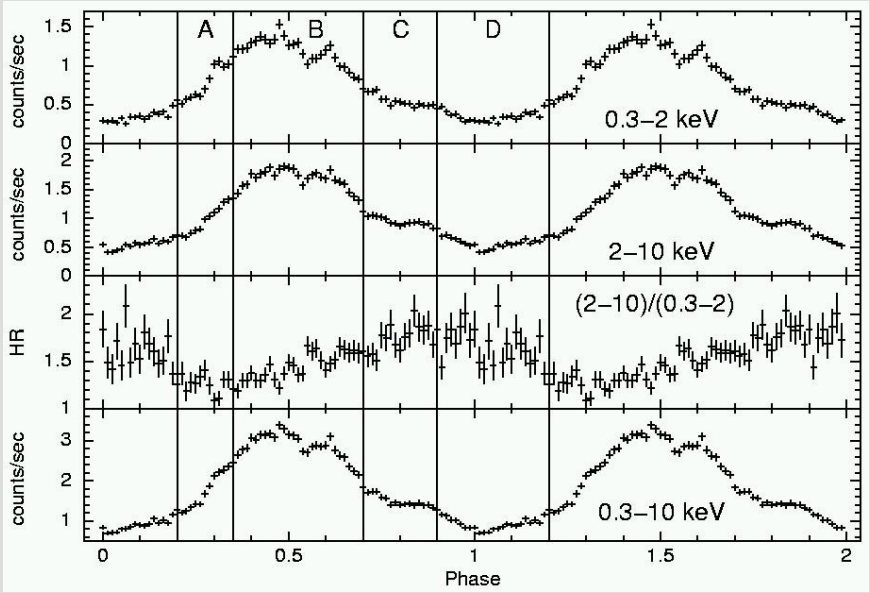
can we prove that the BB component is variable along the pulse phase?

Folded light curves

4U 0352+309



RX J0146.9+6121



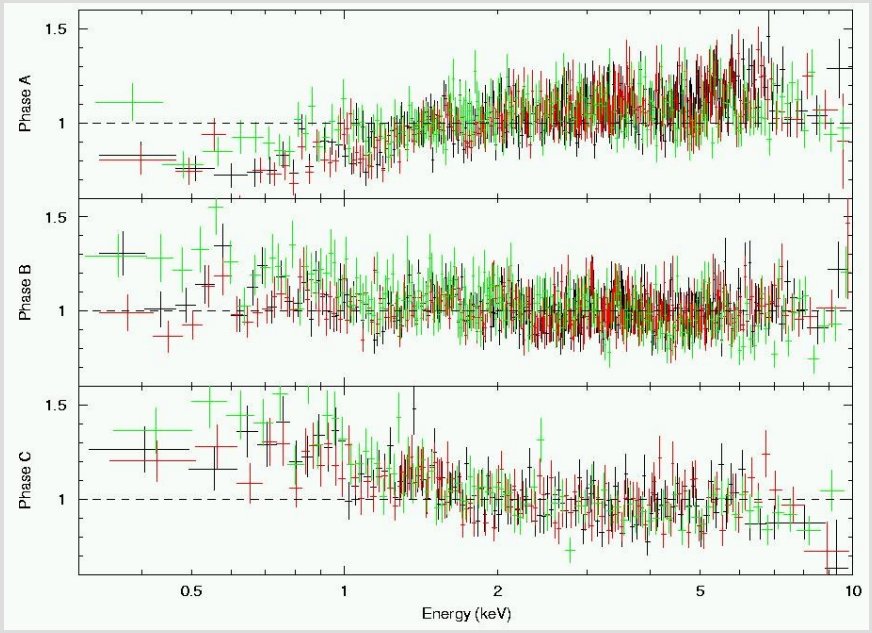
=> the pulse shape is not simply sinusoidal

=> the pulse profile is energy dependent

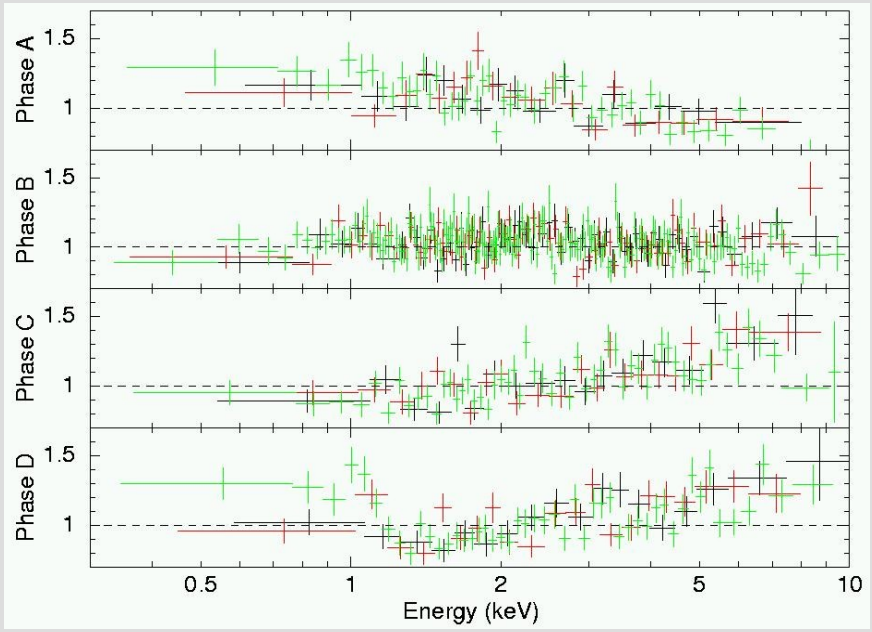
Phase-resolved spectroscopy

Spectra/average-model ratio

4U 0352+309



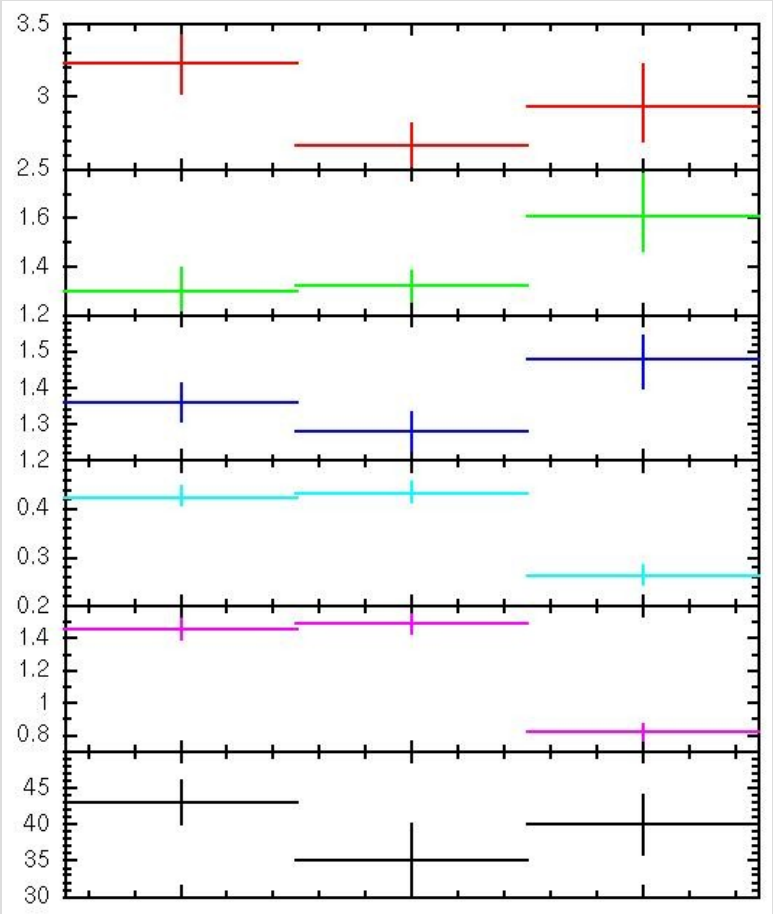
RX J0146.9+6121



spectral variability with the pulse phase

Independent fit of the phase-resolved spectra

4U 0352+309



N_H (10^{21} cm^{-2})

photon index Γ

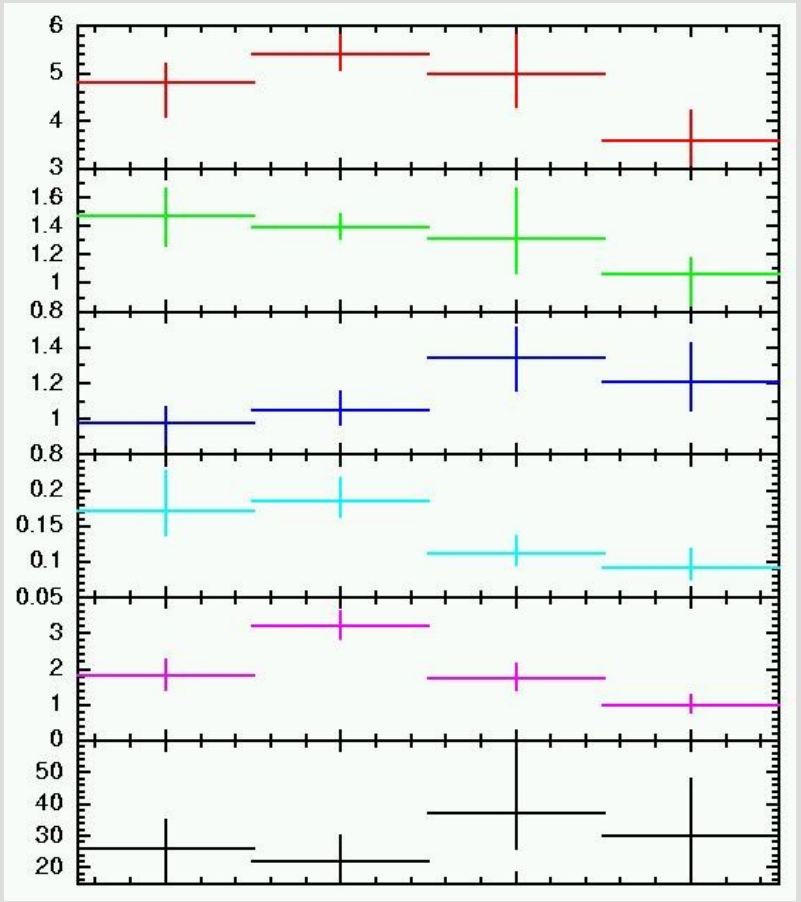
kT_{BB} (keV)

R_{BB} (km)

f_{TOT} (<=10^{-9} - 10^{-11}=> erg cm^{-2} s^{-1})

f_{BB}/f_{TOT} (%)

RX J0146.9+6121



Independent fit of the phase-resolved spectra

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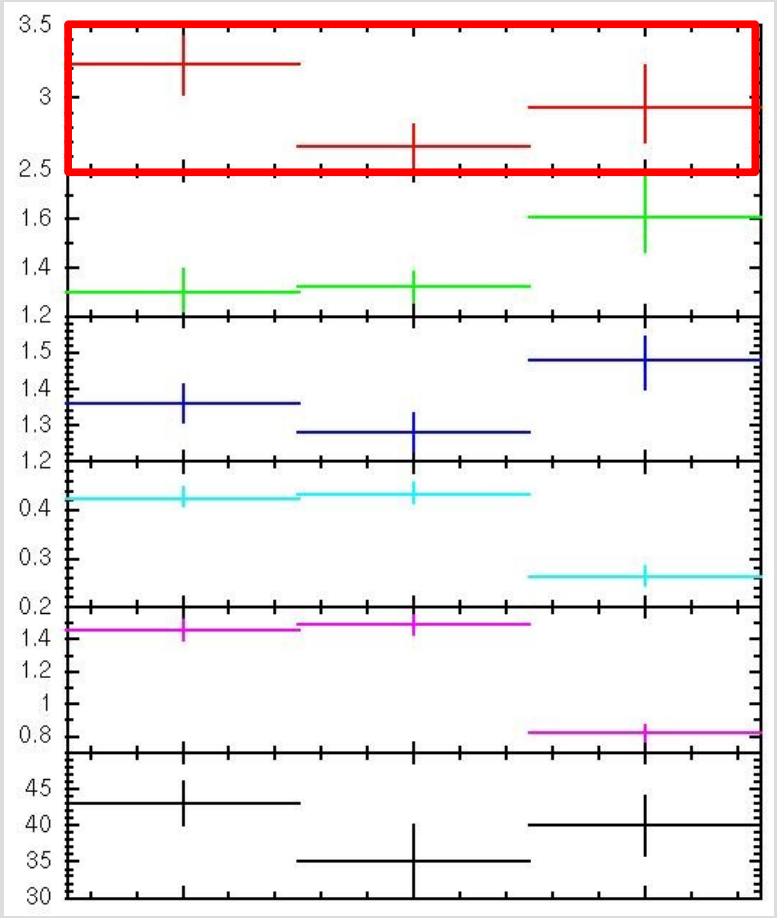
RX J0146.9+6121



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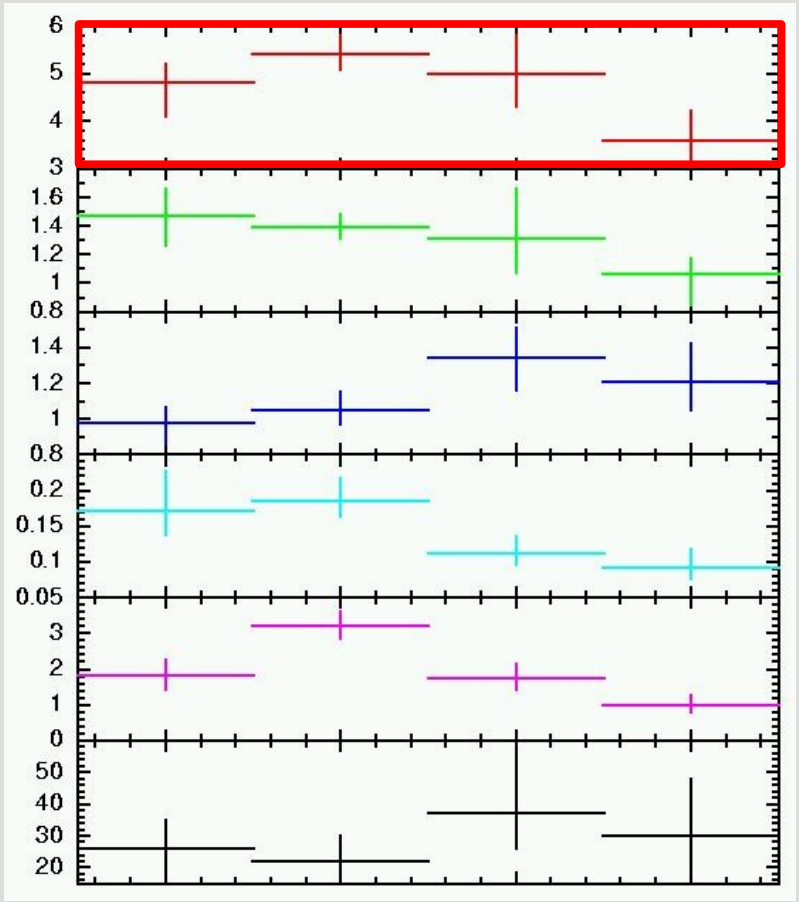
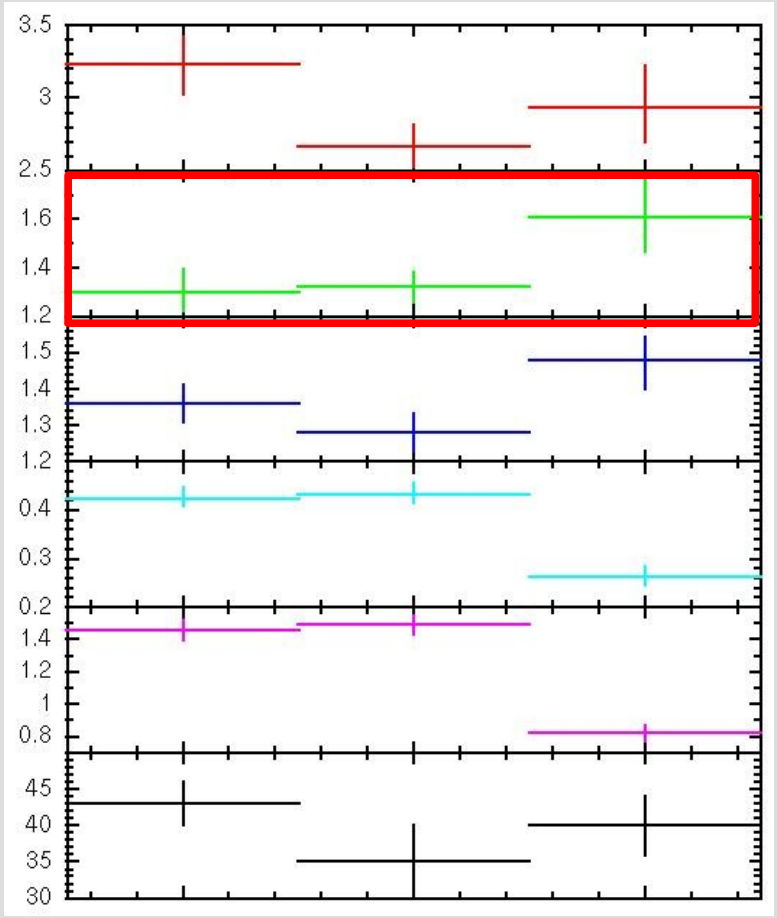


N_H nearly constant along the pulse phase => interstellar absorption

Independent fit of the phase-resolved spectra

4U 0352+309

RX J0146.9+6121



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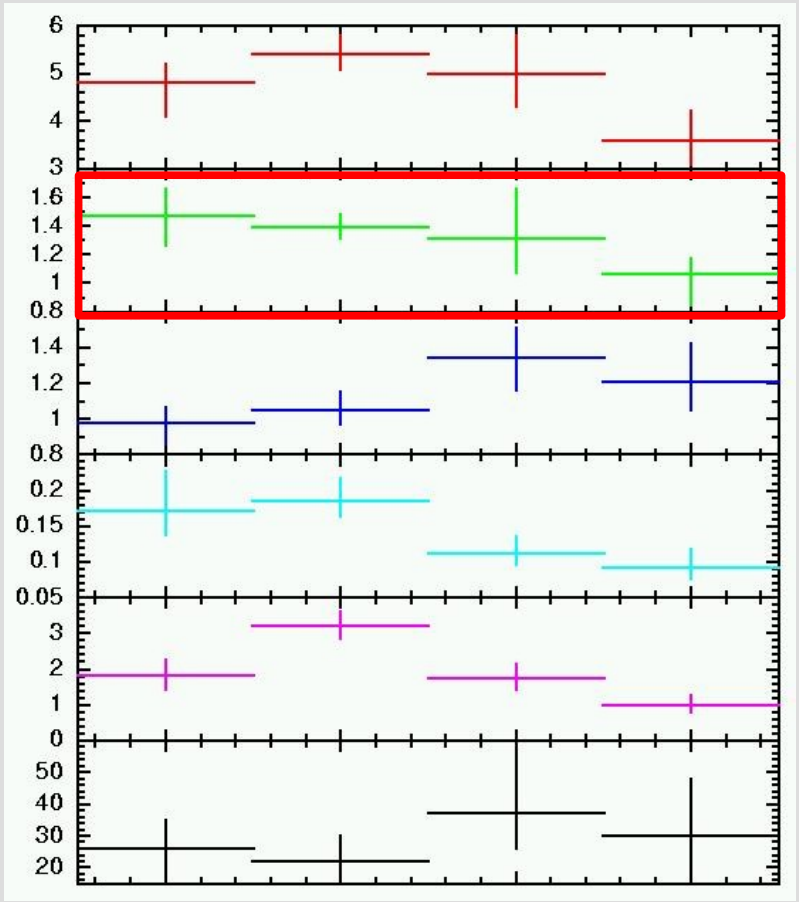


A B C

Phase

A B C D

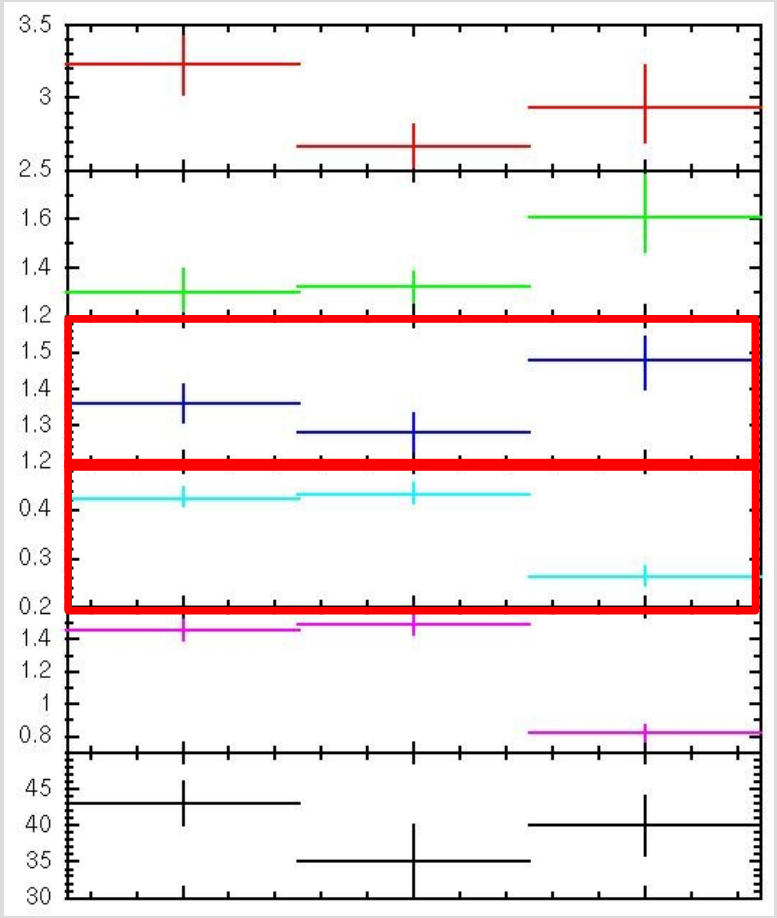
Phase

Γ variations only at the pulse minimum

Independent fit of the phase-resolved spectra

4U 0352+309

RX J0146.9+6121



N_H (10^{21} cm^{-2})

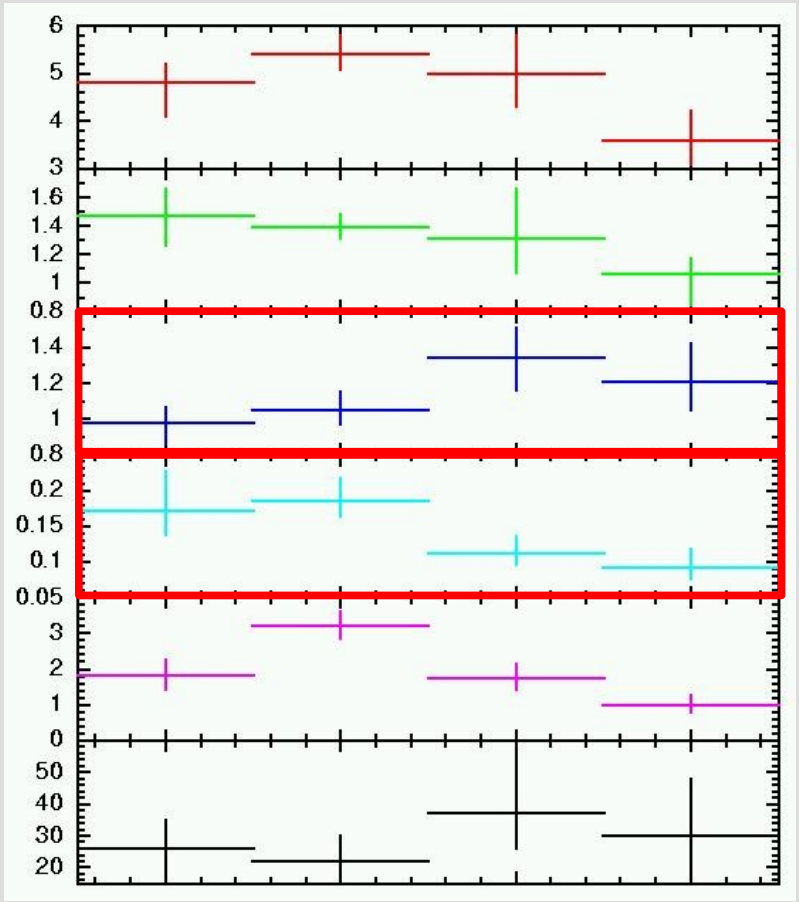
photon index Γ

kT_{BB} (keV)

R_{BB} (km)

f_{TOT} (<=10^{-9} - 10^{-11}=> erg cm^{-2} s^{-1})

f_{BB}/f_{TOT} (%)



A B C

Phase

A B C D

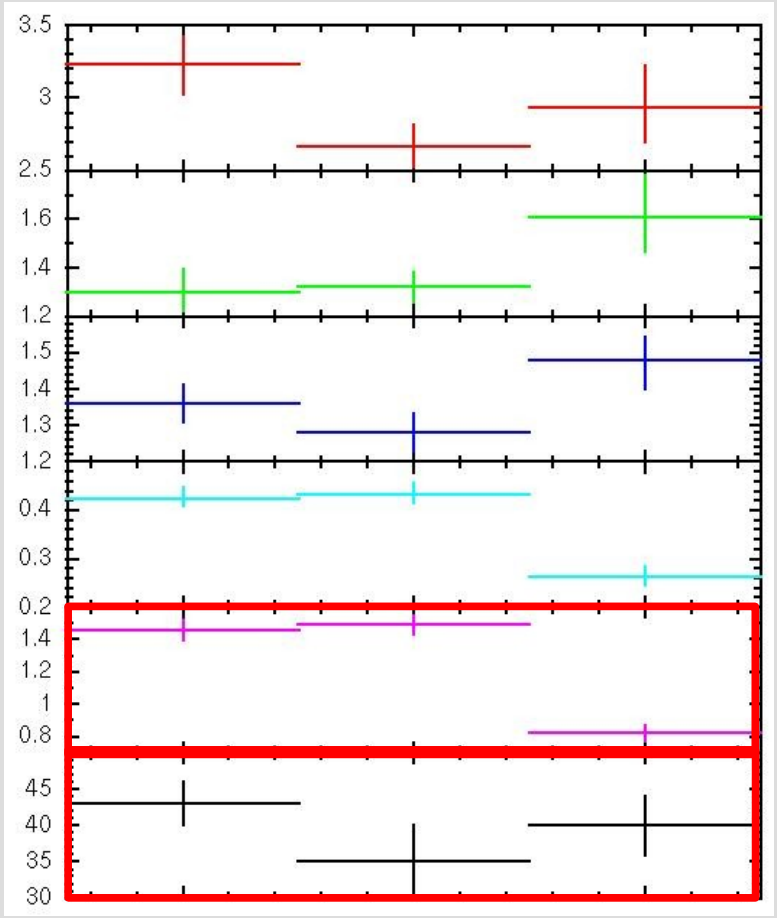
Phase

Significant variations of the BB Temperature and Radius

Independent fit of the phase-resolved spectra

4U 0352+309

RX J0146.9+6121



N_H (10^{21} cm^{-2})

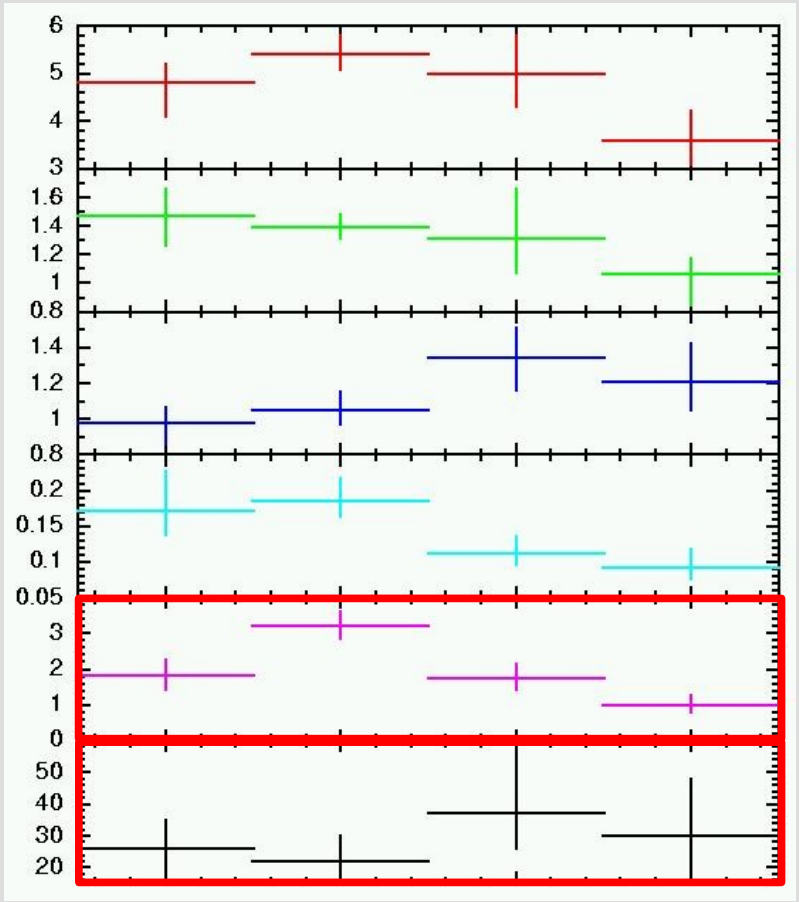
photon index Γ

kT_{BB} (keV)

R_{BB} (km)

f_{TOT} (<=10^{-9} - 10^{-11}=> erg cm^{-2} s^{-1})

f_{BB}/f_{TOT} (%)



A B C

Phase

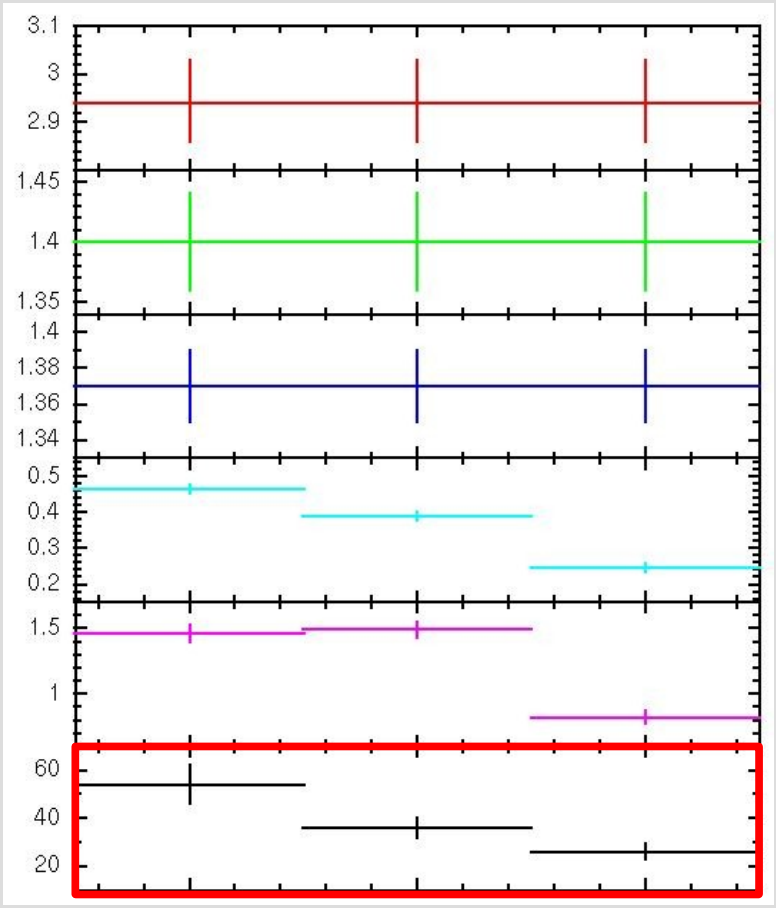
A B C D

Phase

Variations of the total flux, but ~ constant BB fraction along the pulse phase

Fit with forced common values of N_H, Γ and kT_{BB} for all pulse phases

4U 0352+309



N_H (10^{21} cm^{-2})

photon index Γ

kT_{BB} (keV)

R_{BB} (km)

f_{TOT} (<=10^{-9} - 10^{-11}=> erg cm^{-2} s^{-1})

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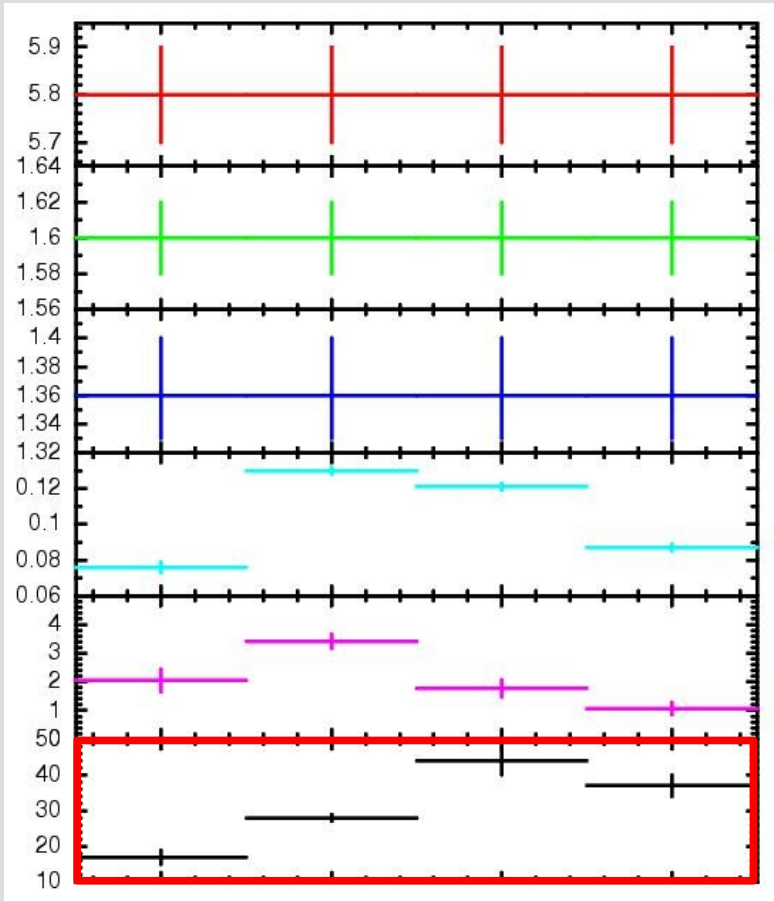
RX J0146.9+6121

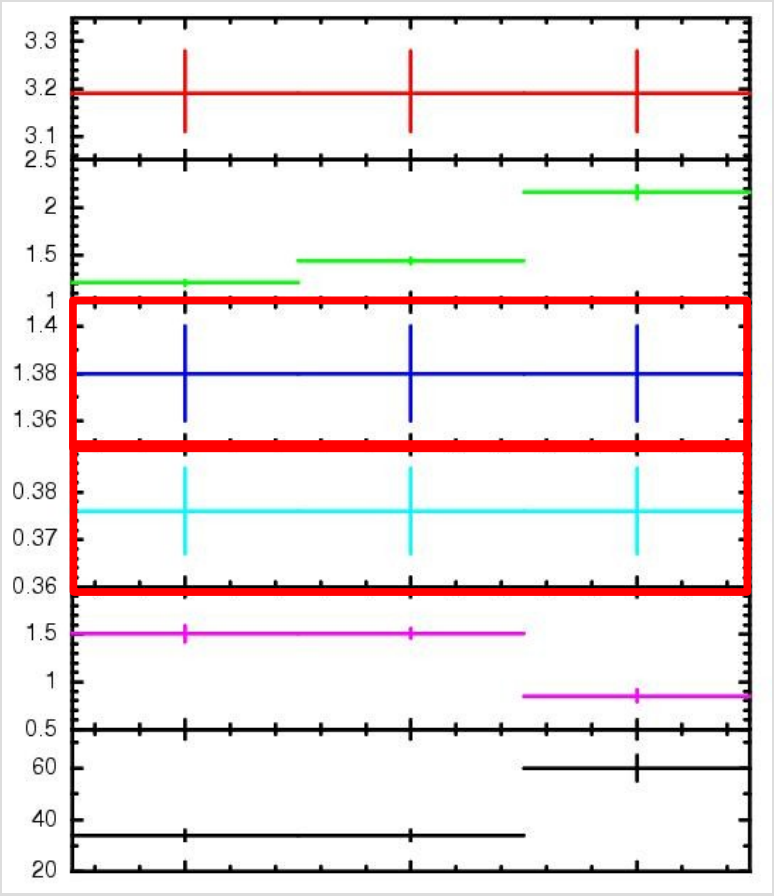


variations in the relative contribution of the PL and BB components

evidence that the BB component is really variable?

Fit with a constant BB component for all the phases

4U 0352+309



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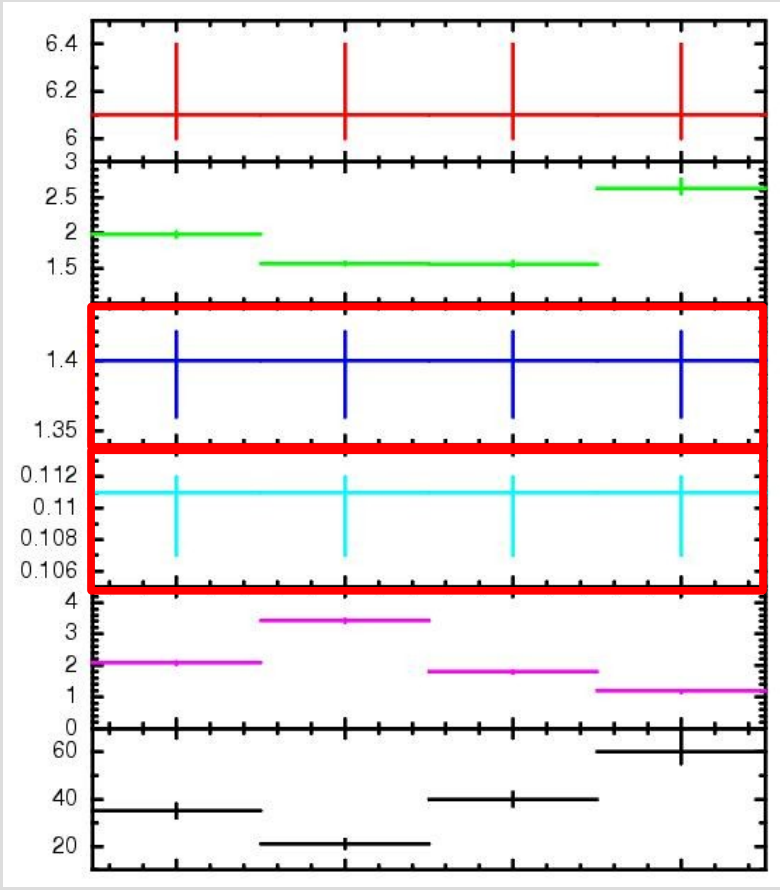
A B C

Phase

RX J0146.9+6121



A B C D

Phase

a constant BB component is not rejected by the data (χ^2 is comparable)

the whole spectral variability can be attributed to the PL component

Soft excess variability: other results...

direct PL

absorbed PL

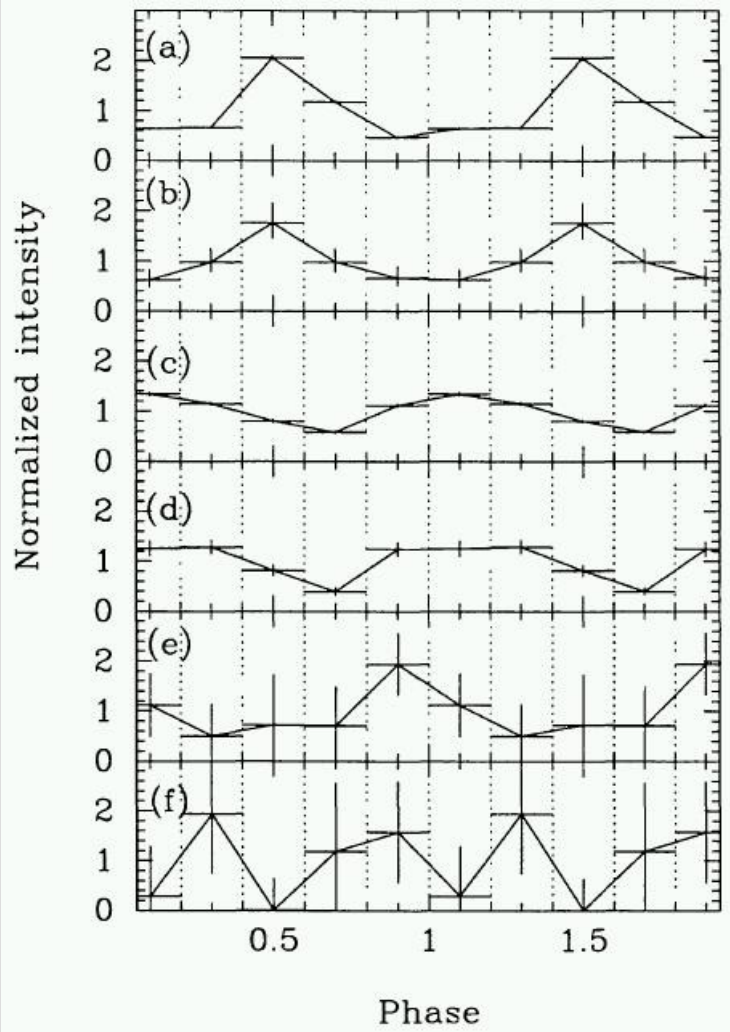
BB

gaussian @ 1keV

gaussian @ 6.4 keV

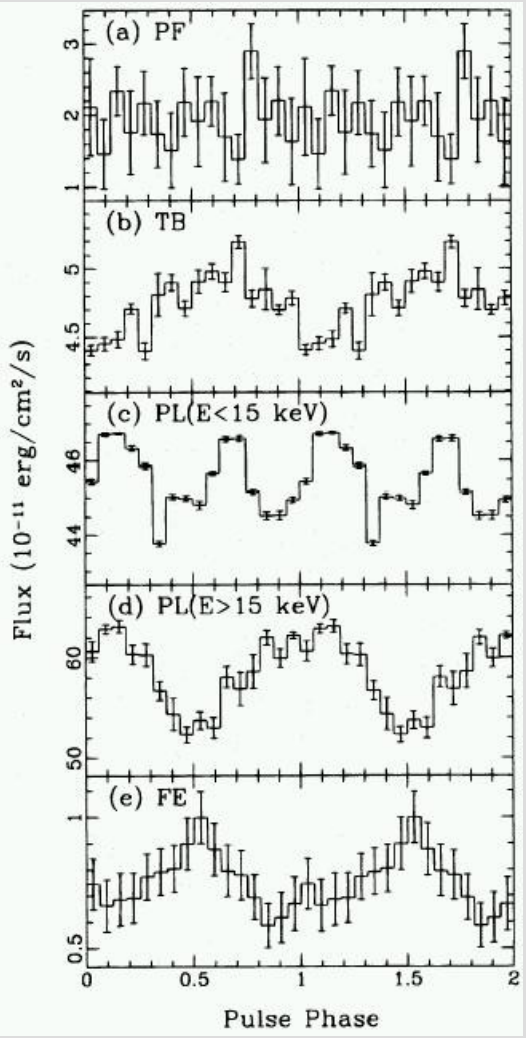
gaussian @ 6.7 keV

Her X-1: common Γ, kT_{BB}, E_{GAU}



Endo et al., 2000, ASCA

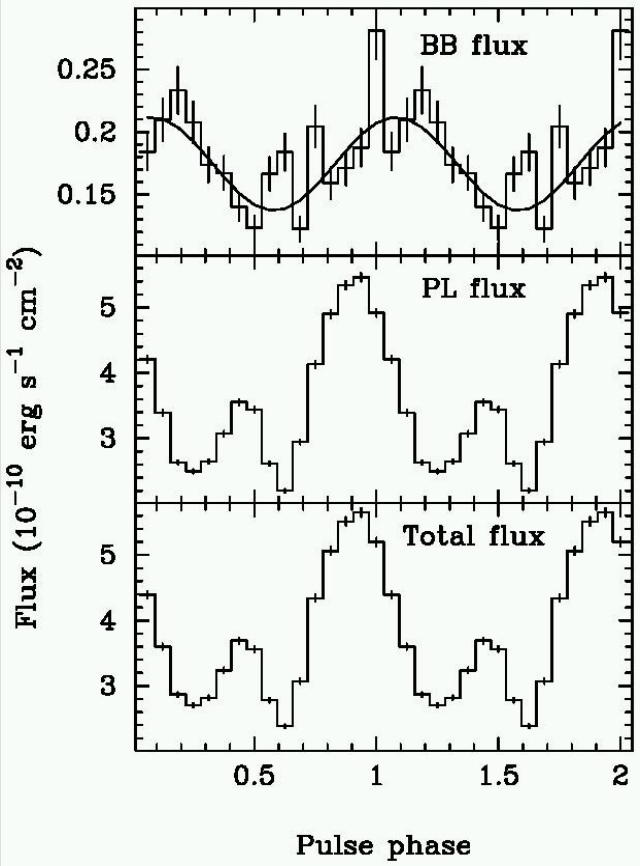
LMC X-4: free parameters



Woo et al, 1996, GINGA+ROSAT

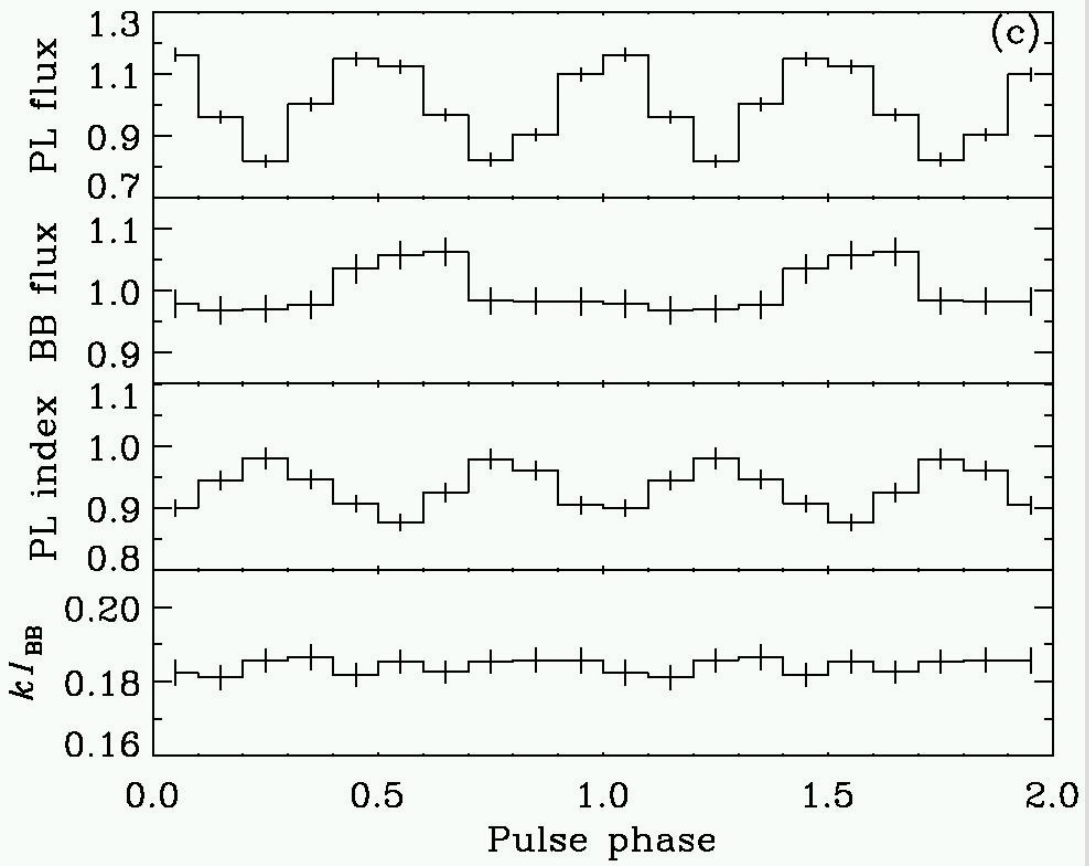
Soft excess variability: other results...

SMC X-1: free parameters



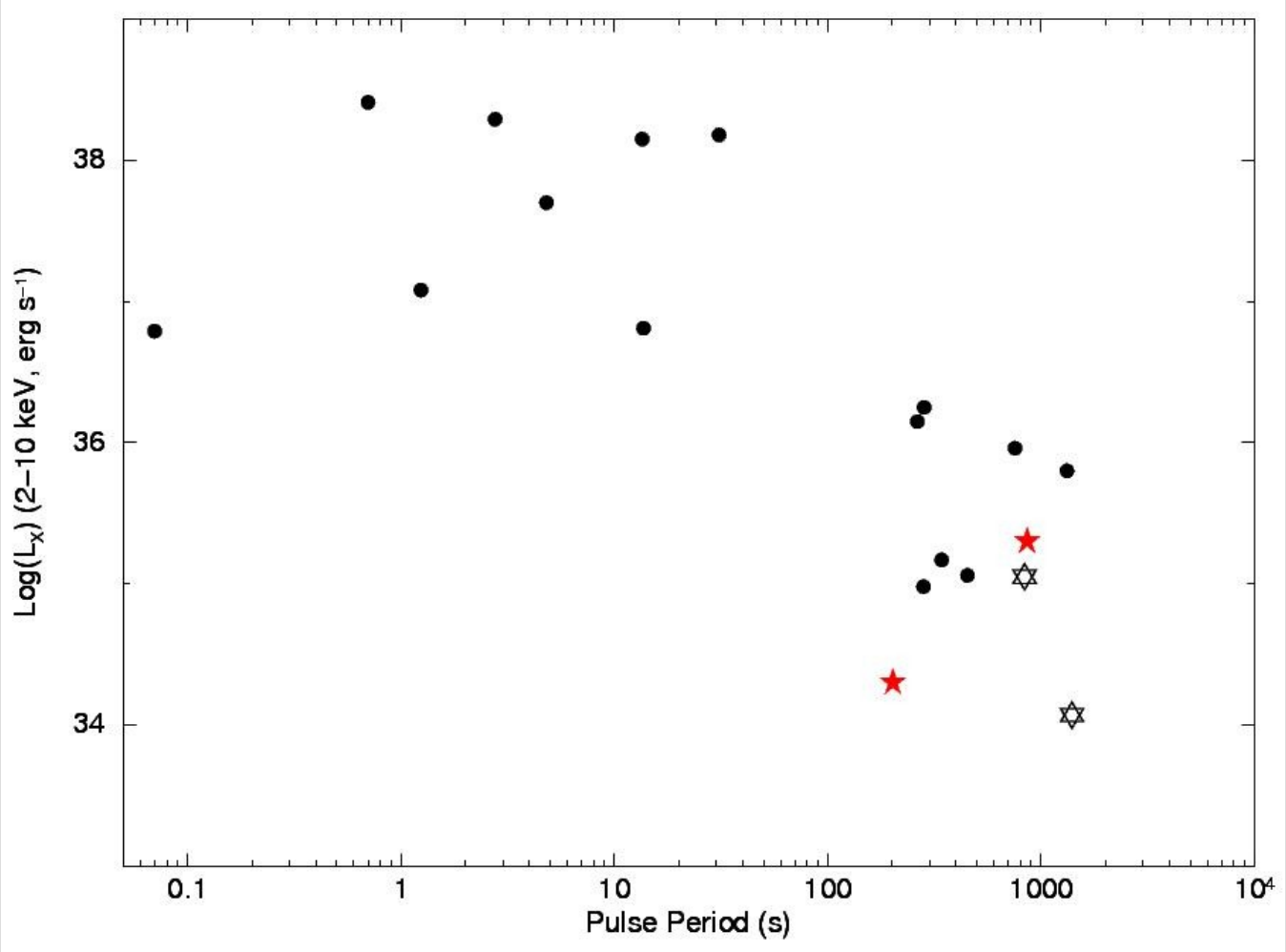
Paul et al., 2002, ASCA

SMC X-1: free parameters



Hickox et al., 2005, CHANDRA

Future perspectives



Other than 4U 0352+309 and RX J0146.9+6121, there are other two confirmed persistent Be binary pulsars:

- RX J0440.9+4431
  P = 202 s
  $L_X \sim 2 \times 10^{34}$ erg s^{-1}

- RX J1037.5-5647
  P = 860 s
  $L_X \sim 2 \times 10^{35}$ erg s^{-1}

We asked XMM observing time to check if the same scenario is applicable

proposal accepted in priority C for XMM AO7

LET'S HOPE...