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Authors	LA PALOMBARA, NICOLA, SIDOLI, Lara, Esposito, P., Pintore, Fabio, Tiengo, A., MEREGHETTI, Sandro
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High-resolution spectral analysis of transient pulsars in the SMC

*N. La Palombara
(IASF Milano)*

L. Sidoli, P. Esposito, S. Mereghetti, F. Pintore, A. Tiengo



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INAF



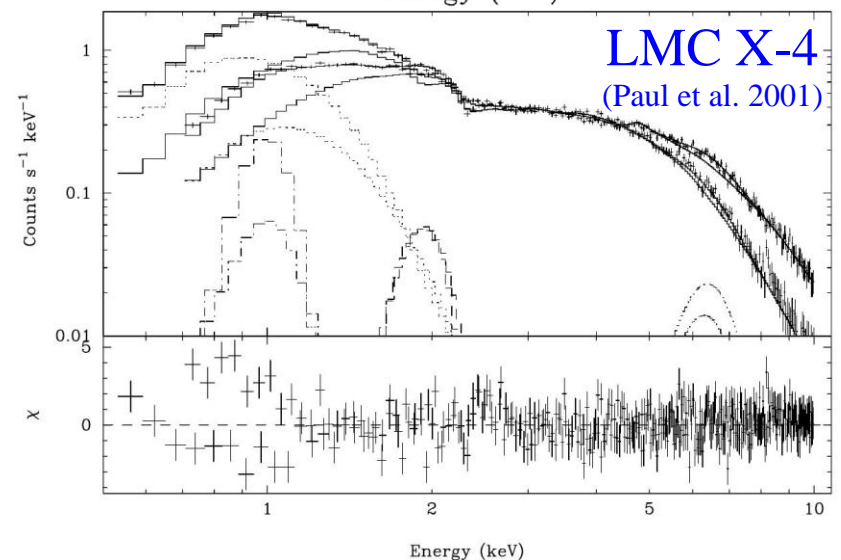
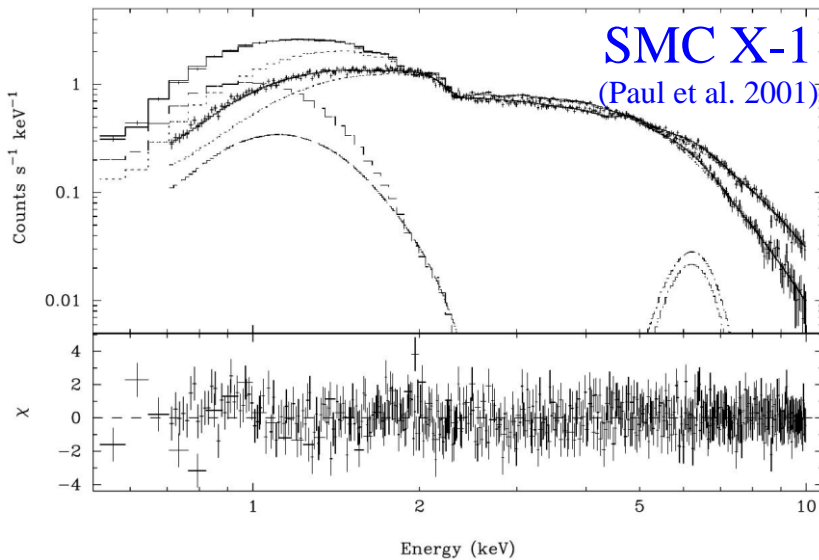
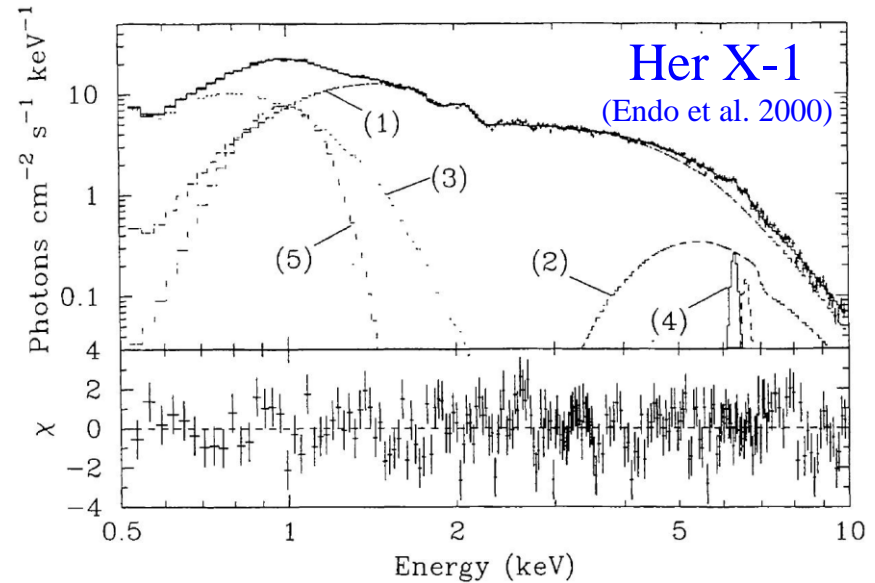
Spectral properties of High Mass X-Ray Binaries

X-ray spectrum between 0.1 and 10 keV:

- usually described with a rather flat power law (photon index $\Gamma \sim 1$) with an exponential cut-off
- often with Fe $K\alpha$ emission line

BUT

several XBPs have a marked **data excess** above the main **power-law** component

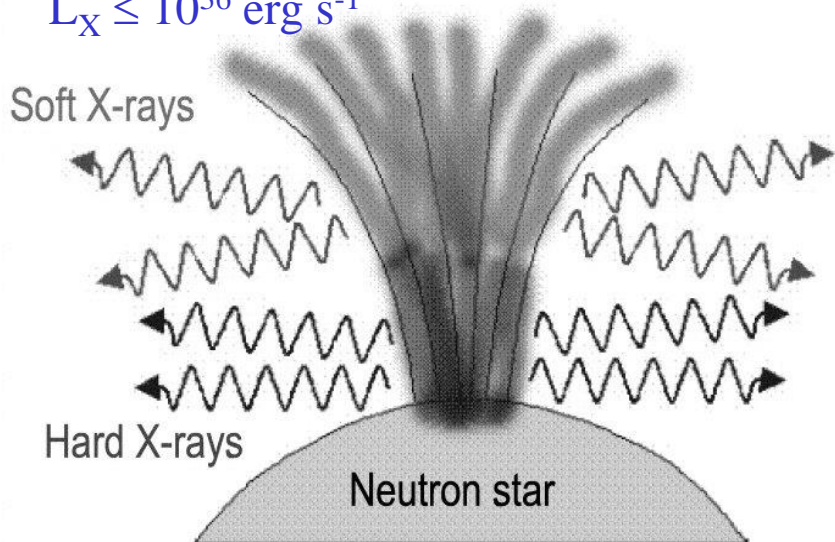


Spectral properties of High Mass X-Ray Binaries

Hickox et al., 2004: the origin of the thermal excess depends on the source luminosity

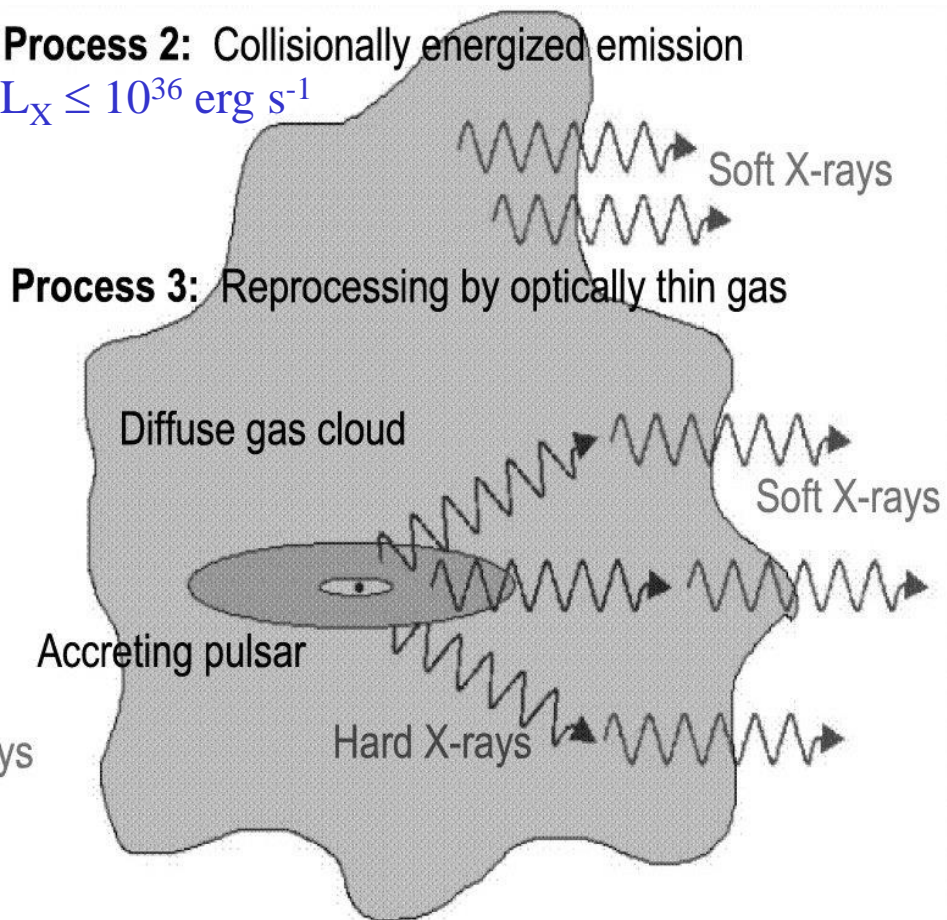
Process 1: Emission from the accretion column

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



Process 2: Collisionally energized emission

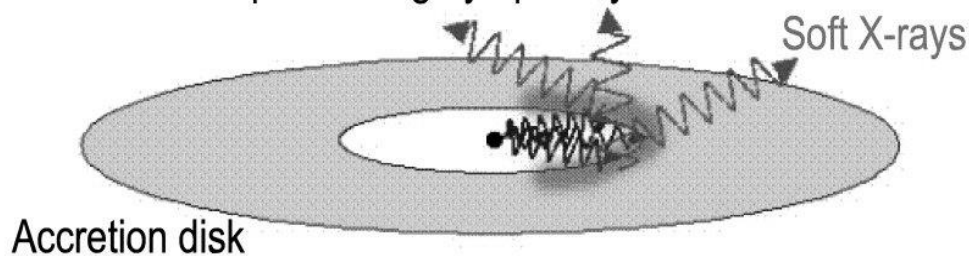
$$L_X \leq 10^{36} \text{ erg s}^{-1}$$



Process 3: Reprocessing by optically thin gas

Process 4: Reprocessing by optically thick material

$$L_X \geq 10^{38} \text{ erg s}^{-1}$$



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



Spectral properties of High Mass X-Ray Binaries

$L_X \geq 10^{38} \text{ erg s}^{-1}$:	reprocessing of hard X-rays by the optically thick accretion material	SMC X-1, LMC X-4, Cen X-3, RX J0059.2-7138, XTE J0111.2-7317
$L_X \leq 10^{36} \text{ erg s}^{-1}$:	emission by photoionized or collisionally heated gas or thermal emission from the accretion column	Vela X-1, AX J0103-722, RX J0101.3-7211 4U 1626-67, X Per
$L_X \sim 10^{37} \text{ erg s}^{-1}$:	either or both the above processes are possible	Her X-1, A0538-66, EXO 053109-6609.2



Spectral properties of High Mass X-Ray Binaries

Hickox et al., 2004:

‘a soft spectral component is a very common, if not ubiquitous,
feature intrinsic to accreting X-ray pulsars’

BUT

the debate about its origin remains open

Study of Galactic sources affected by the interstellar absorption in the Galactic plane



only in few cases it is possible to detect and investigate the soft excess



Transient BeXRBs in the SMC

Ideal site to investigate the *soft* spectral component in the HMXRBs:

- Several (> 100) sources
 - $L_X \sim 10^{38} \text{ erg s}^{-1}$ in outburst
 - $N_H < 10^{21} \text{ cm}^{-2}$
 - Small uncertainties on the source distances \Rightarrow reliable estimate of L_X
- } High count statistics at low energies

Program of ToO observations with *XMM-Newton*



4 sources observed in *outburst*:

- RX J0059.2-7138 (March 2014) \Rightarrow Sidoli et al. 2015, MNRAS 449, 3710
- SMC X-2 (October 2015) \Rightarrow La Palombara et al. 2016, MNRAS 458, L74
- IGR J01572-7259 (May 2016) \Rightarrow La Palombara et al., in preparation
- SXP 59 (April 2017)



RX J0059.2-7138

1993:

- discovered with ROSAT, with $L_x \sim 3 \times 10^{38} \text{ erg s}^{-1}$ (Hughes 1994)
- pulse period of 2.76 s (pulsed fraction $PF \sim 37 \%$) measured with ASCA (Kohno, Yokogawa & Koyama 2000)
- observation of a spectral soft component (Kohno, Yokogawa & Koyama 2000)

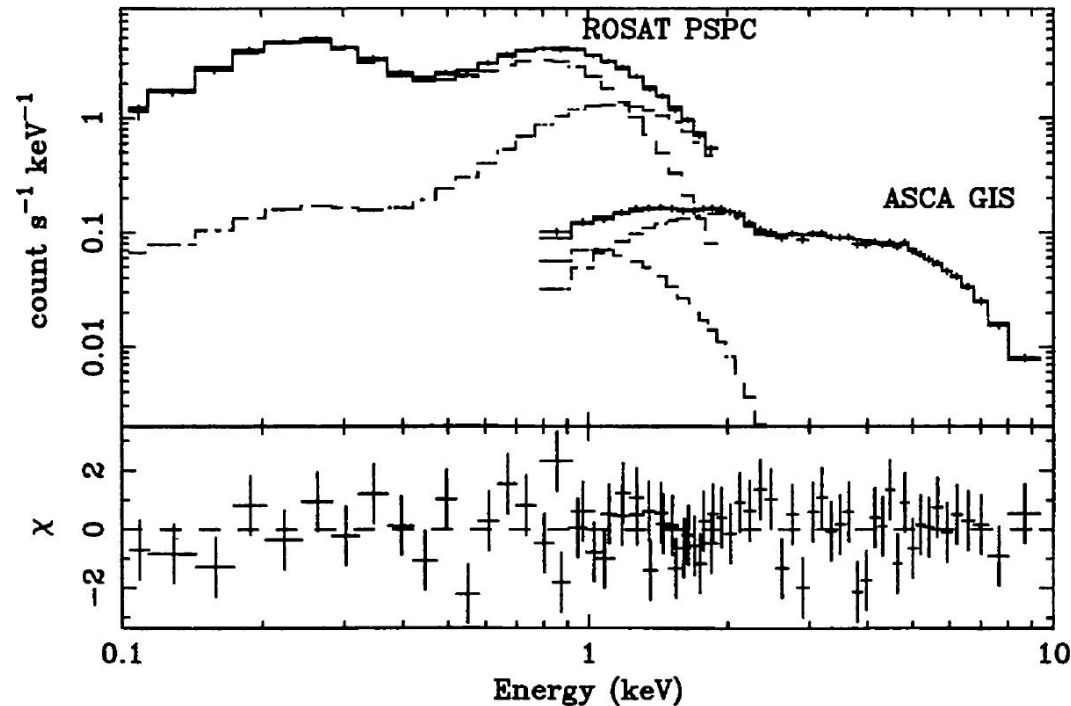
December 2013: first observation of an *outburst* since 1993,

with $L_x \sim 7 \times 10^{37} \text{ erg s}^{-1}$

(ATel 5756, Krimm et al. 2014)



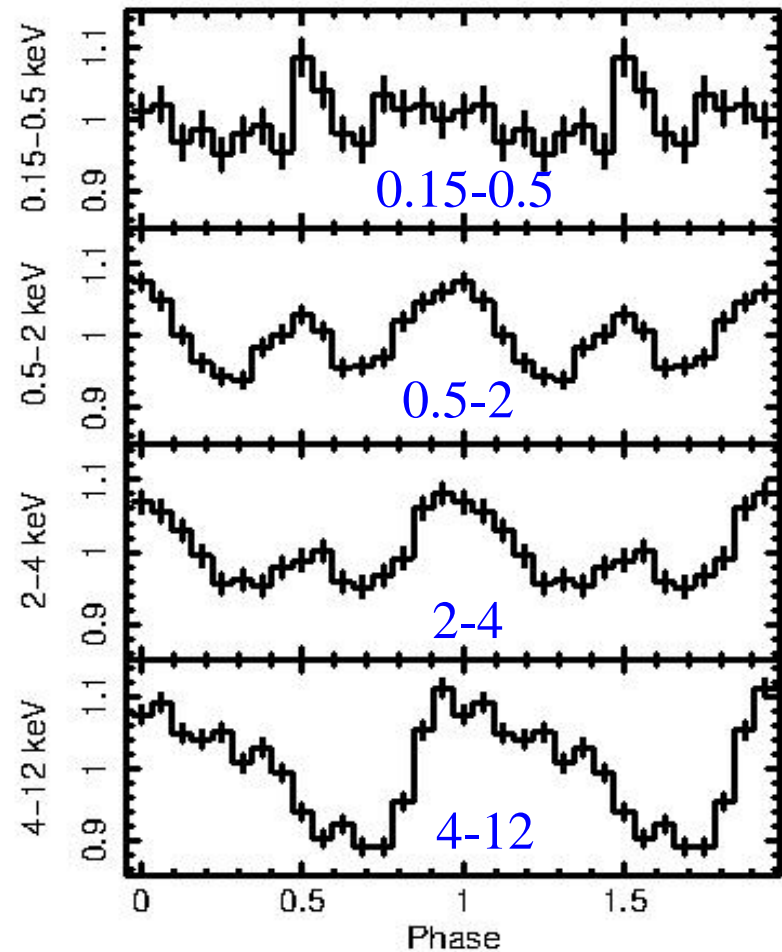
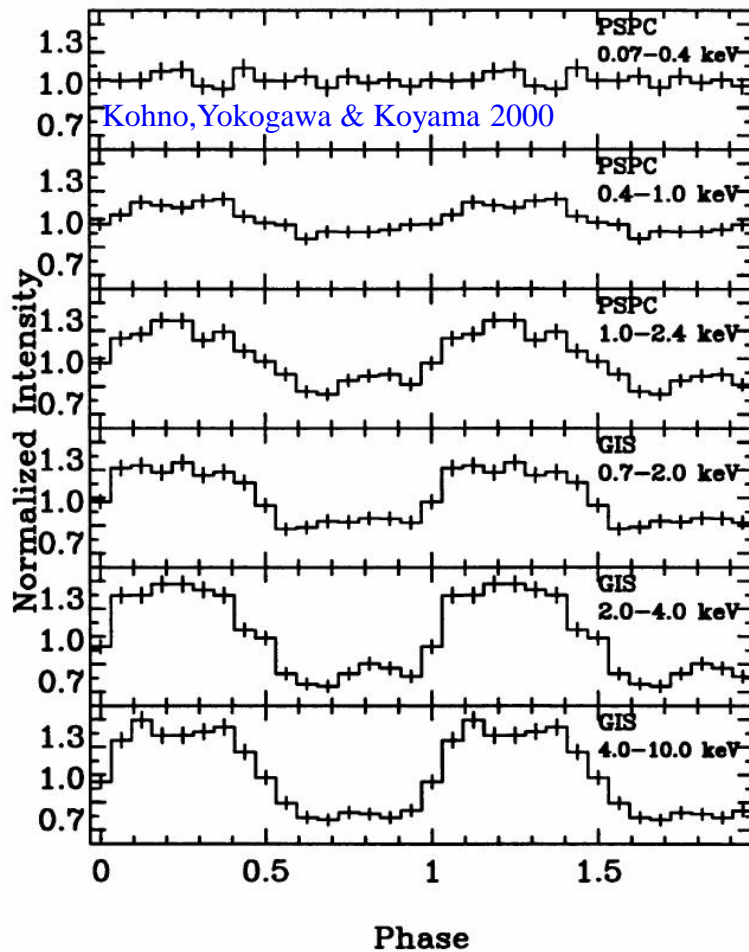
XMM-Newton observation (20 ks)





XMM-Newton observation of RX J0059.2-7138: timing analysis

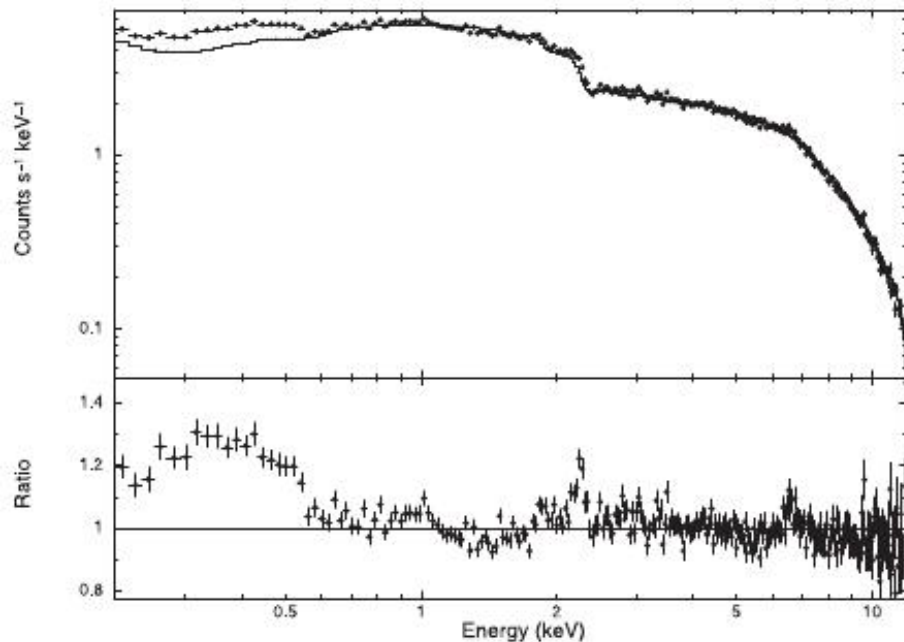
2013: $L_x \sim 7 \times 10^{37}$ erg s⁻¹, detection of pulsed emission also at $E < 0.5$ keV, $PF \sim 9\%$



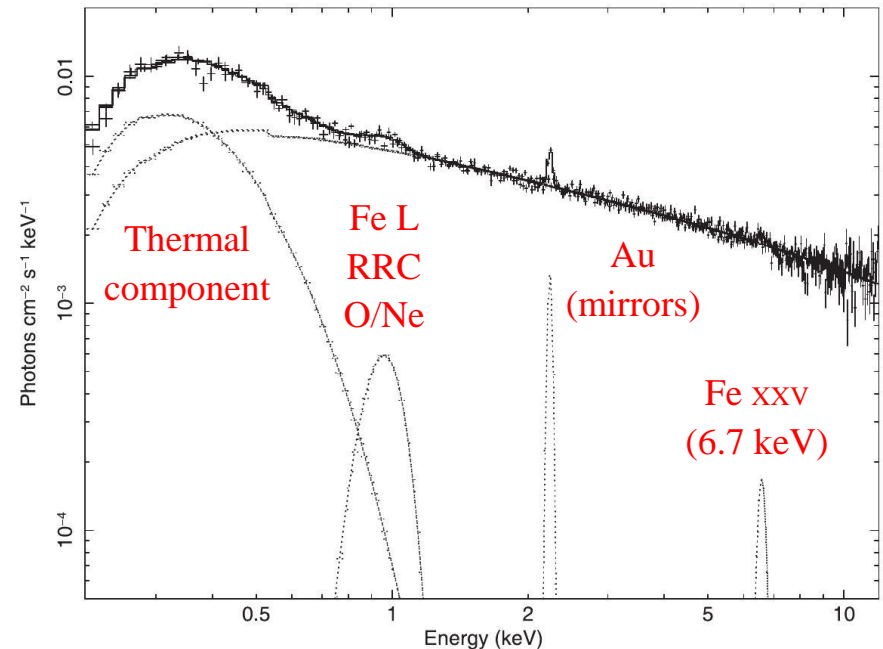
XMM-Newton observation of RX J0059.2-7138: EPIC spectrum

EPIC spectrum:

- Significant SE which dominates the PL emission at $E < 0.5$ keV
- $L_{SE} \sim 1.5\%$ of L_{TOT} ($\sim 44\%$ in 1993)
- SE fit with either a BB ($kT_{BB} = 93$ eV, $R_{BB} \sim 350$ km) or a thermal plasma model (MEKAL: $kT_{ME} = 210$ eV, $R_{ME} > 6 \times 10^5$ km, $A < 0.007$)



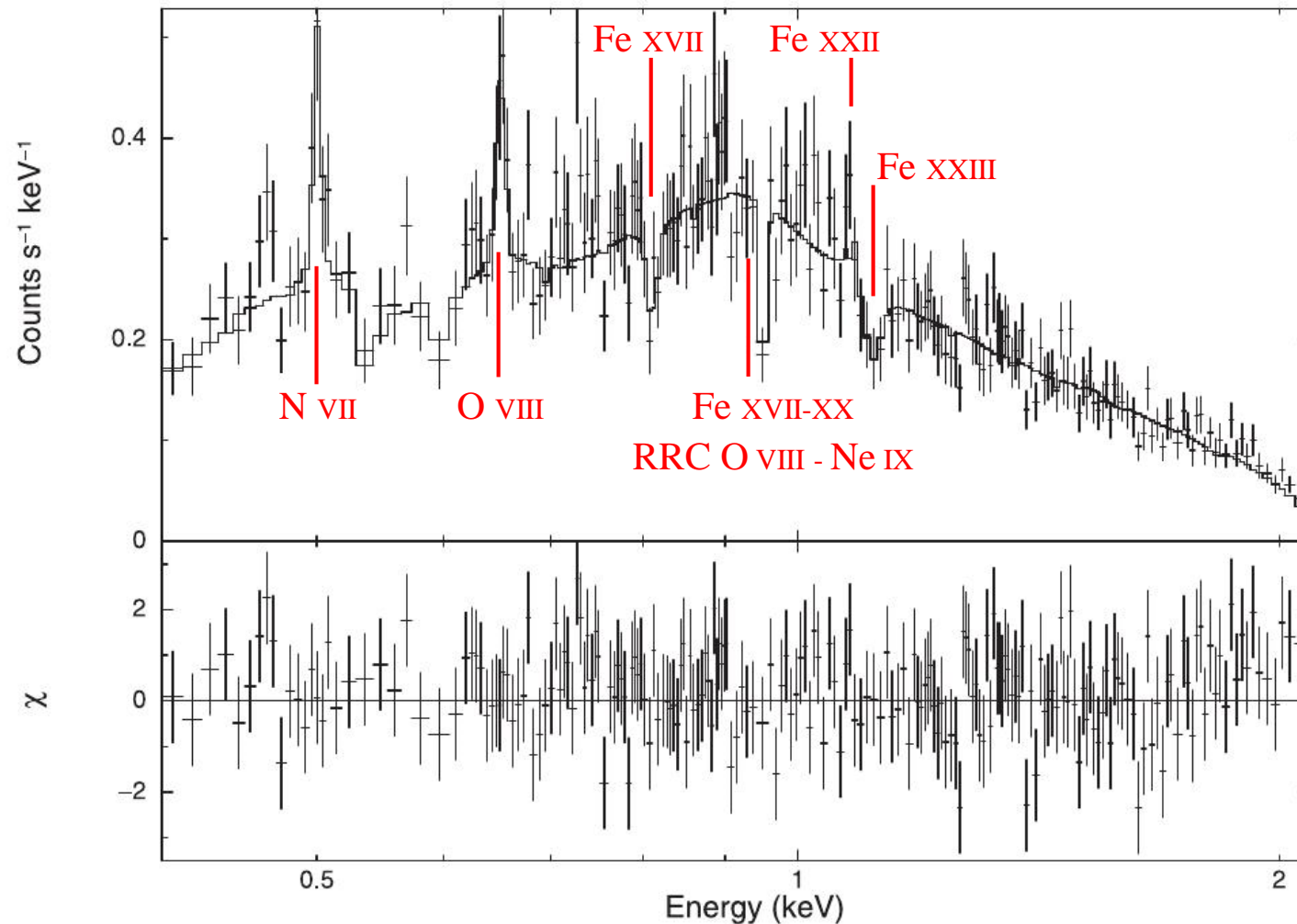
EPIC PN spectrum, PL model



EPIC best-fit model

XMM-Newton observation of RX J0059.2-7138: RGS spectrum

first detection of several absorption and emission lines due to N, O, Ne, and Fe



large residuals if continuum is described with a PL+MEKAL model



SMC X-2

1977: discovered with SAS3 ($L_X = 8.4 \times 10^{37}$ erg s⁻¹; Li, Jernigan & Clark 1977; Clark et al. 1978)

2000: second *outburst* observed with RXTE ($L_X \sim 3 \times 10^{37}$ erg s⁻¹)

⇒ $P_{\text{spin}} = 2.37$ s (Corbet et al. 2001)

2011:

- OGLE: periodic variability of the optical counterpart

($P = 18.62 \pm 0.02$ d, Schurch et al. 2011)

- RXTE: periodic modulation of the pulse period

($P = 18.38 \pm 0.02$ d, Townsend et al. 2011)

September 2015: first observation of an outburst since 2000 (ATel 8088, Negoro

et al. 2015; ATel 8091, Kennea et al. 2015), with $L_X \sim 10^{38}$ erg s⁻¹ ($\sim L_{X, 1977}$)



Swift observations of SMC X-2: timing analysis

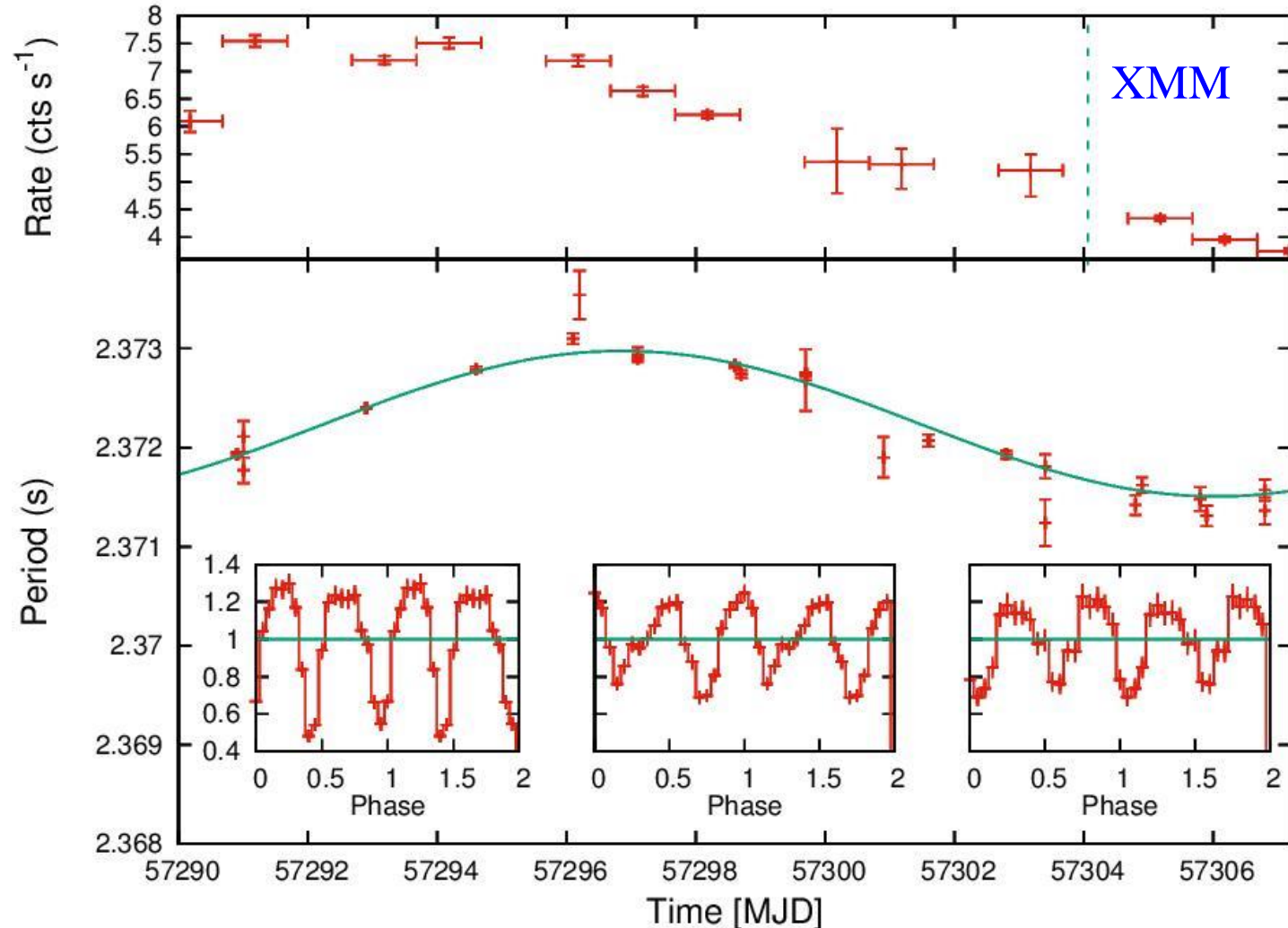
74 observations
with *Swift*/XRT in
Windowed Timing
mode



P_{spin} modulations

due to

$P_{\text{orb}} = 18.38 \pm 0.96$ d



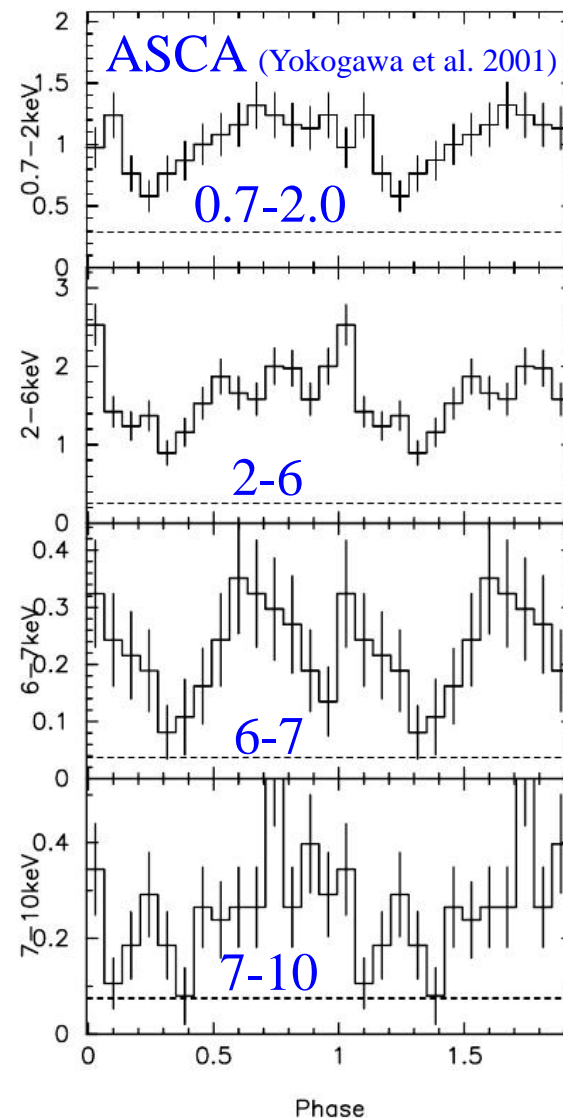
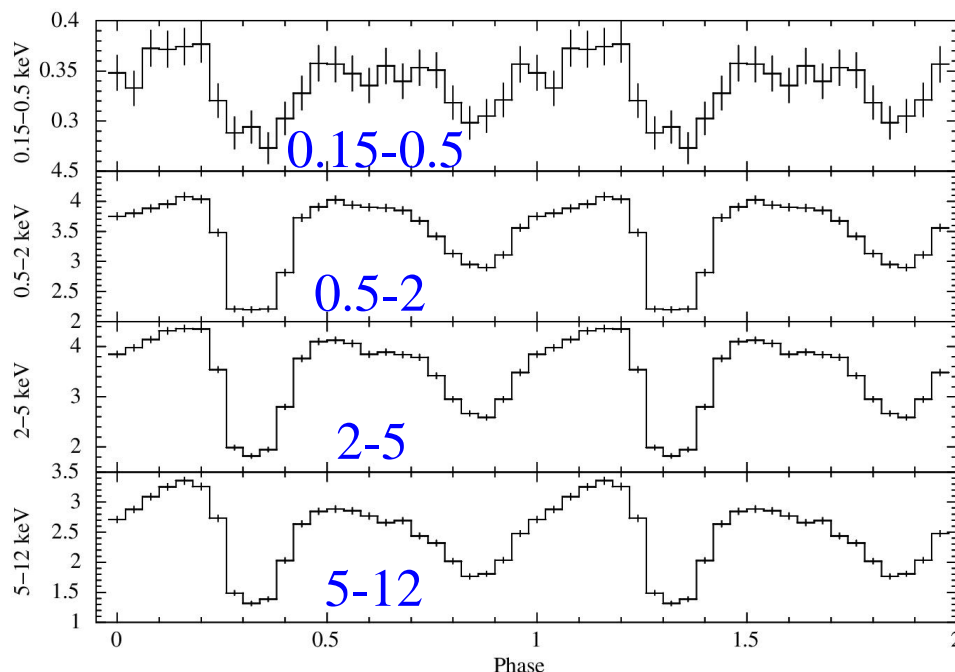


XMM-Newton observations of SMC X-2: timing analysis

XMM-Newton observation (30 ks):

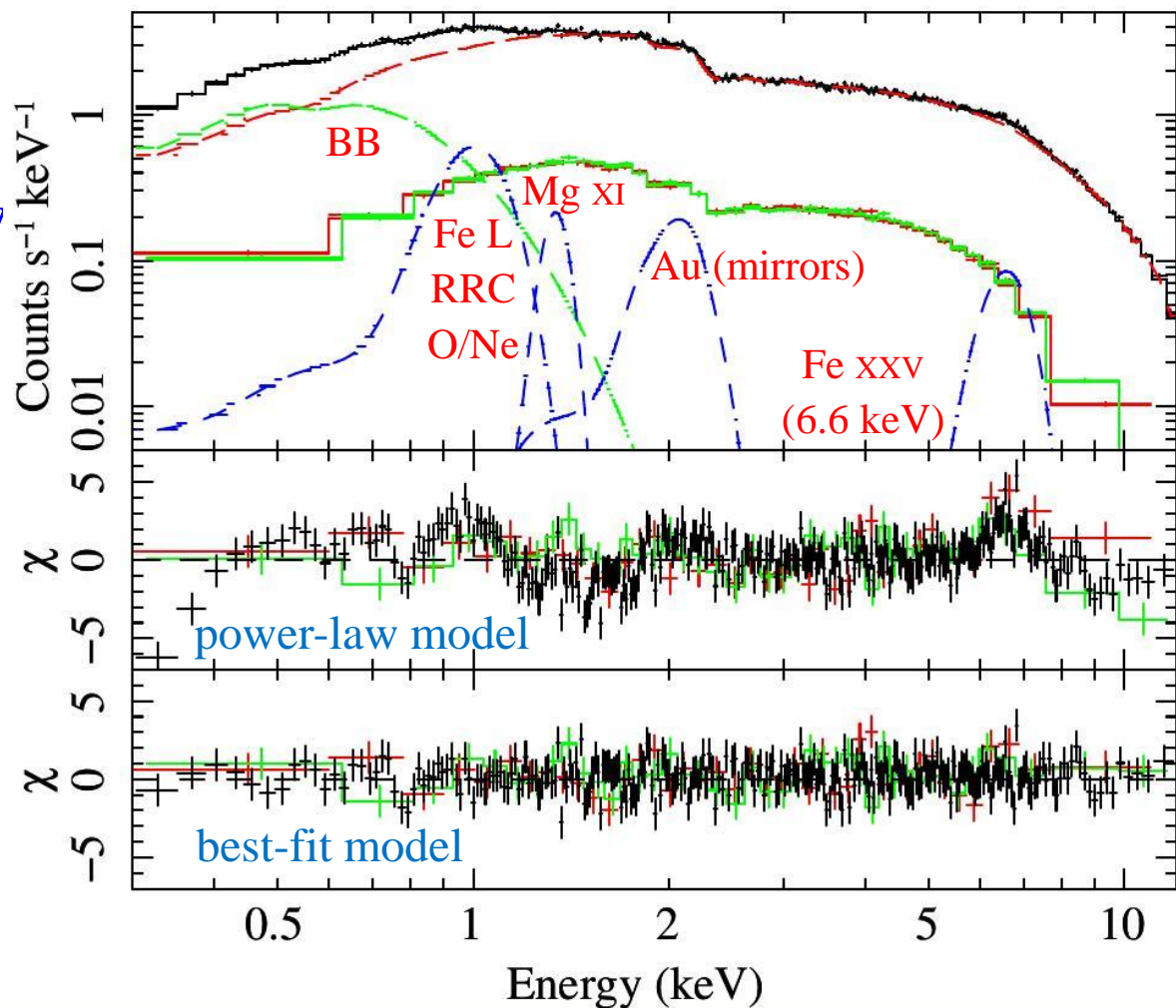
- First detection of pulsed emission also at $E < 0.5$ keV
 - Double-peaked pulse profile also at $E < 0.5$ keV
- at variance with what observed with ASCA
- Pulsed fraction = 30-40 % (as in 2000)

XMM



XMM-Newton observations of SMC X-2: EPIC spectrum

- First observation of the SE
(2-6 % of the total flux)
which dominates at $E < 0.5$ keV
- SE fit with either a BB
($kT_{\text{BB}} \sim 130$ eV, $R_{\text{BB}} \sim 320$ km)
or with emission from
collisionally ionized gas
(APEC, $kT_{\text{APEC}} \sim 1.2$ keV)
- First detection of Fe emission
line

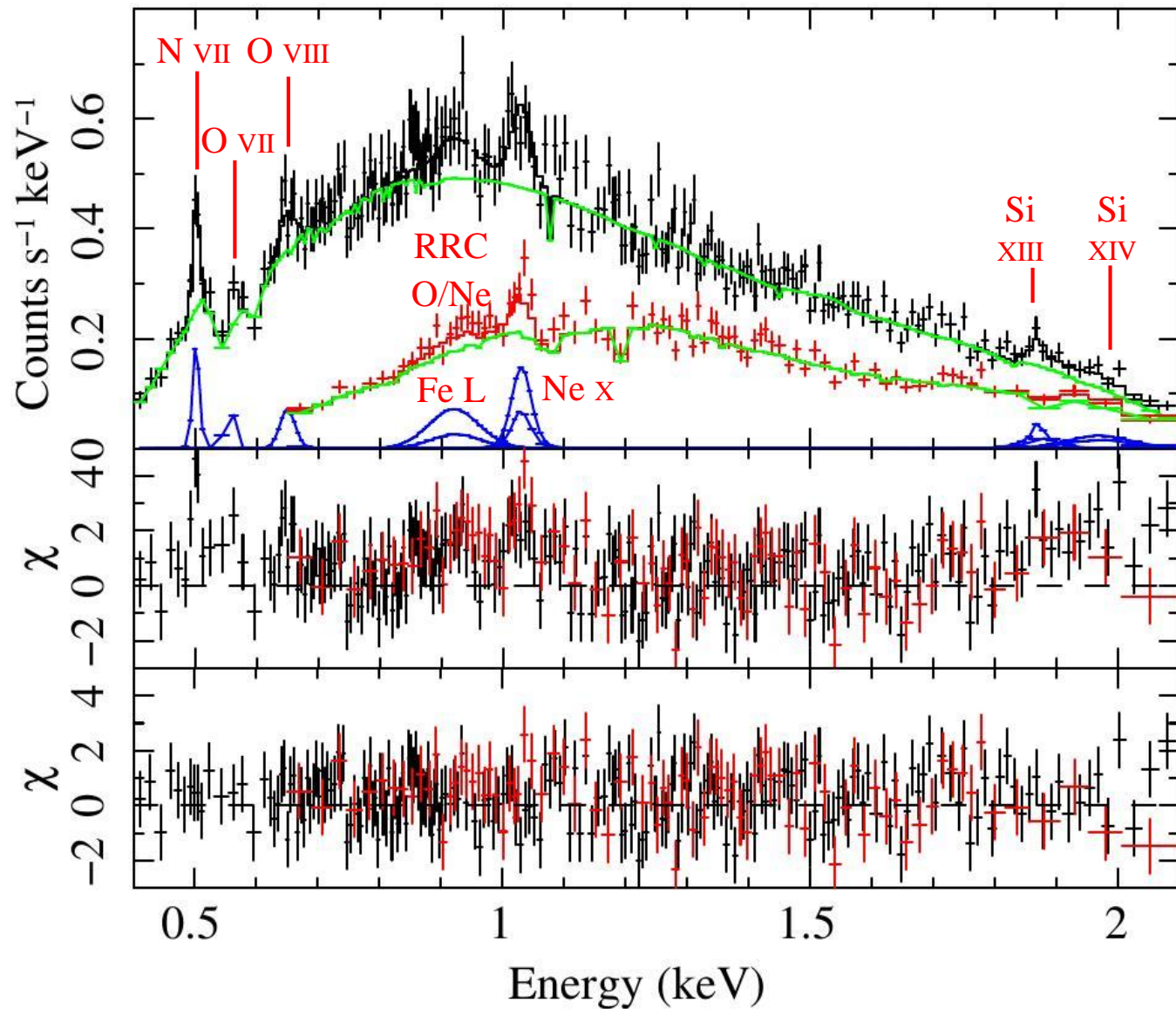




XMM-Newton observations of SMC X-2: RGS spectrum

first detection of several emission lines due to N, O, Ne, Si, and Fe

large residuals in the RGS spectrum if continuum is described with a PL+APEC model





Common properties of RX J0059.2-7138 and SMC X-2

- Characteristics SE: BB model $\Rightarrow kT_{\text{BB}} \sim 0.1$ keV, $R_{\text{BB}} \sim 300$ km, $L_{\text{BB}}/L_{\text{PL}} = 2-3$ %
- Emission lines due to N, O, Ne, Si, and Fe, from matter with very different ionization levels \Rightarrow **not compatible with a single-temperature plasma**
- Large residuals in the RGS spectrum if continuum is described with a PL+MEKAL/APEC model
- SMC X-2: predominance of the forbidden line O VII (f) in the He-like O VII triplet
- High luminosity: $L_{\text{X}} \sim 10^{38}$ erg s⁻¹
- $R_{\text{repr}} \sim 10^8$ cm $\sim R_{\text{m}}$
- $L_{\text{X}} \sim 10^{38}$ erg s⁻¹ $\Rightarrow PF \sim 30-40$ % (RX J0059 in 1993 and SMC X-2 in 2015)



- **soft excess:** reprocessing of the primary emission by the optically thick inner edge of the accretion disc
- **narrow lines:** emission from optically thin photoionized circumsource matter



IGR J01572-7259

2008:

- discovered with INTEGRAL in the Magellanic Bridge (Coe et al. 2008)
 - follow-up observations performed with *Swift* and *RXTE* (McBride et al. 2010)
- ⇒ $P_{\text{spin}} = 11.578 \text{ s}$, hard spectrum ($\Gamma = 0.4$), $L_X = 6.5 \times 10^{35} \text{ erg s}^{-1}$

2013:

- *Swift*/BAT: periodic modulation in the light curve
($P = 35.6 \pm 0.5 \text{ d}$, Segreto et al. 2013)
 - OGLE: periodic variability of the optical counterpart
($P = 35.1 \pm 0.1 \text{ d}$, Schmidtke et al. 2013)
- } ⇒ orbital period

April 2016: detection of an outburst with *Swift*/BAT (ATel 9021, Krimm et al. 2016), with $L_X = 4.1 \times 10^{37} \text{ erg s}^{-1}$



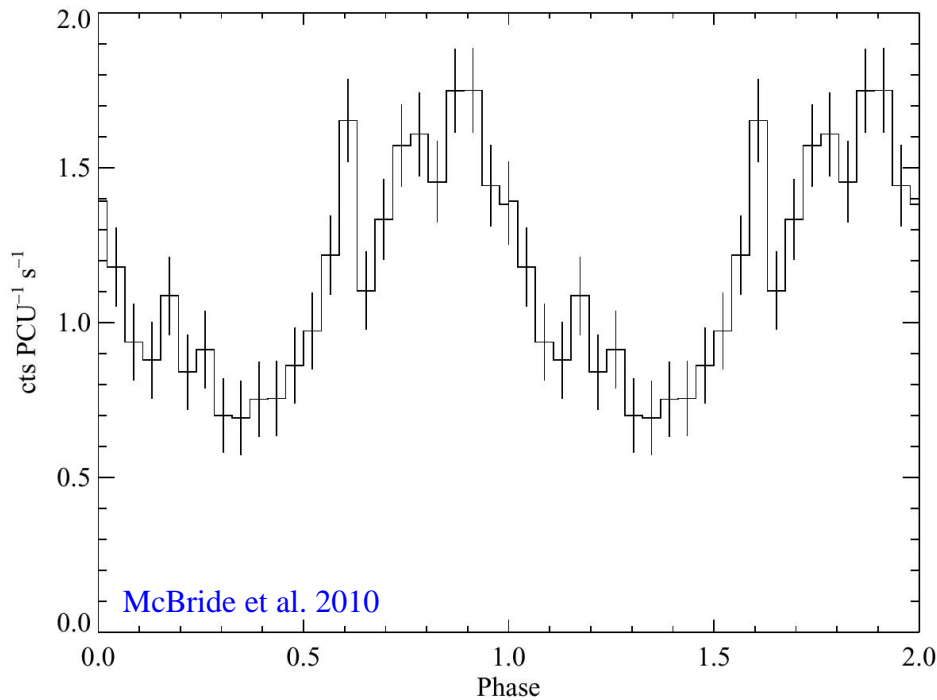
Trigger of a ToO observation with *XMM-Newton* (28 ks)



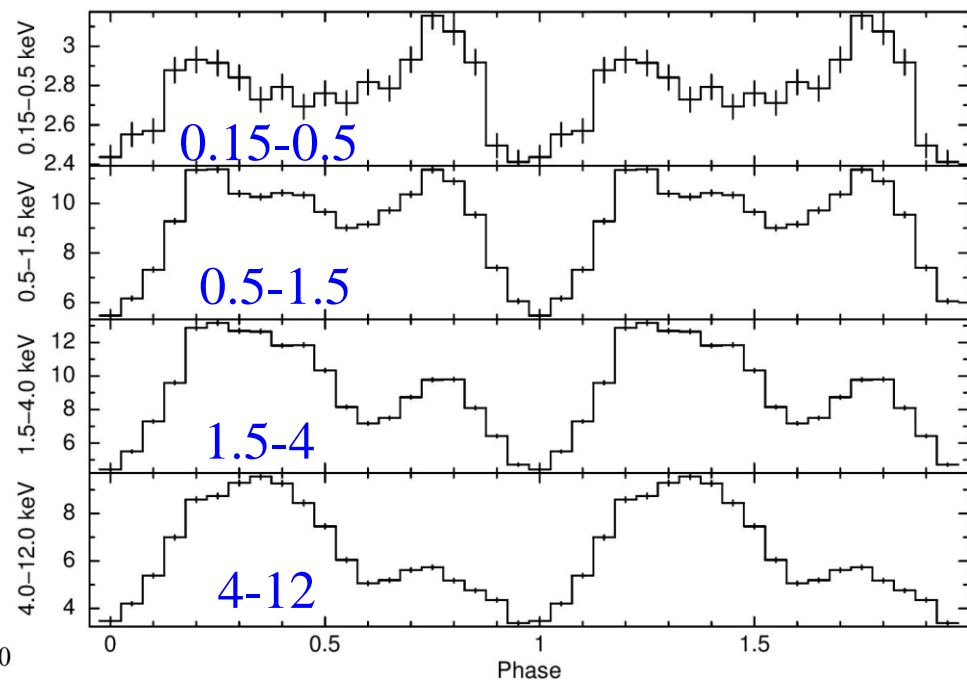
XMM-Newton observation of IGR J01572-7259: timing analysis

- First detection of pulsed emission also at low energies
- Significant energy dependence of the pulse profile
- Pulsed fraction increasing with E ($\sim 15\%$ @ $E < 0.5$ keV, $\sim 45\%$ @ $E > 1.5$ keV)

RXTE PCA

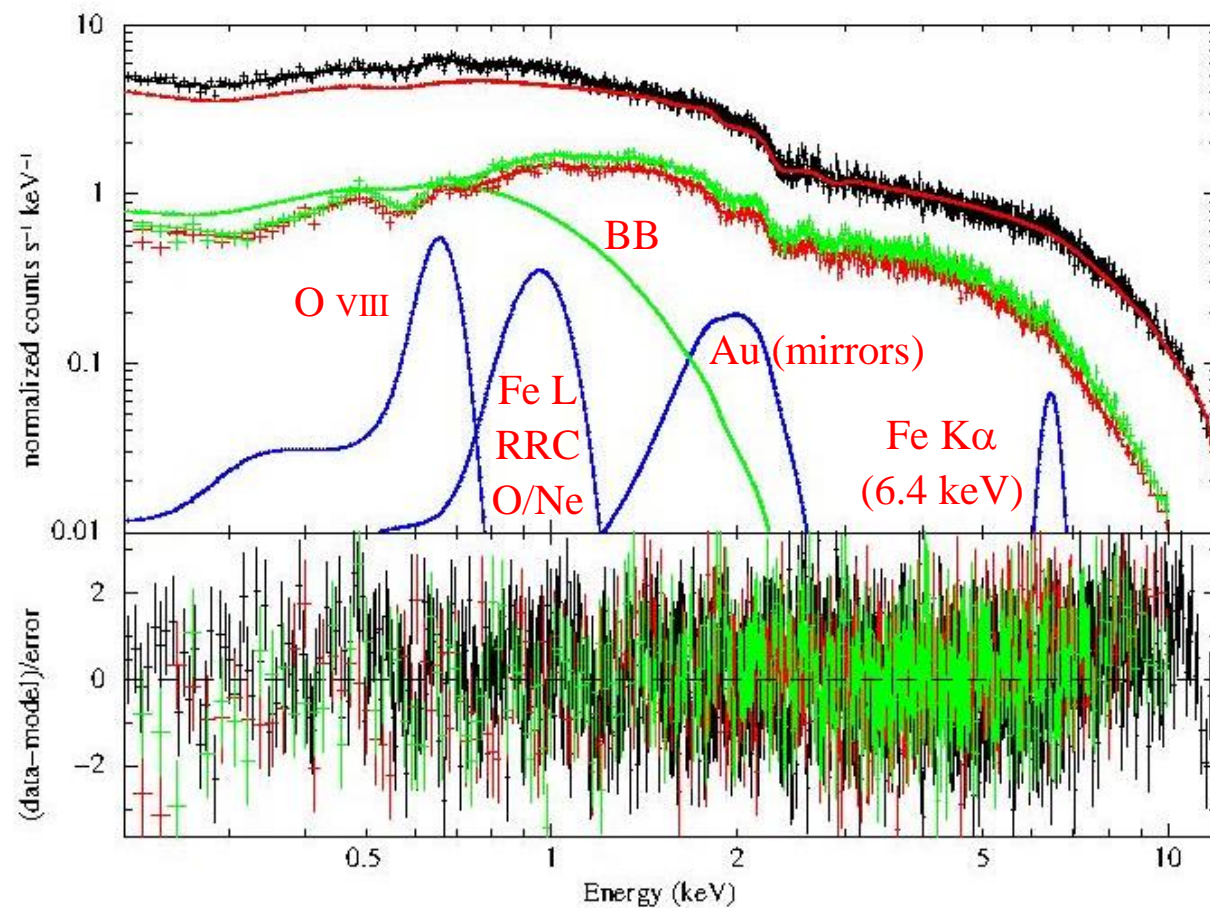


XMM EPIC



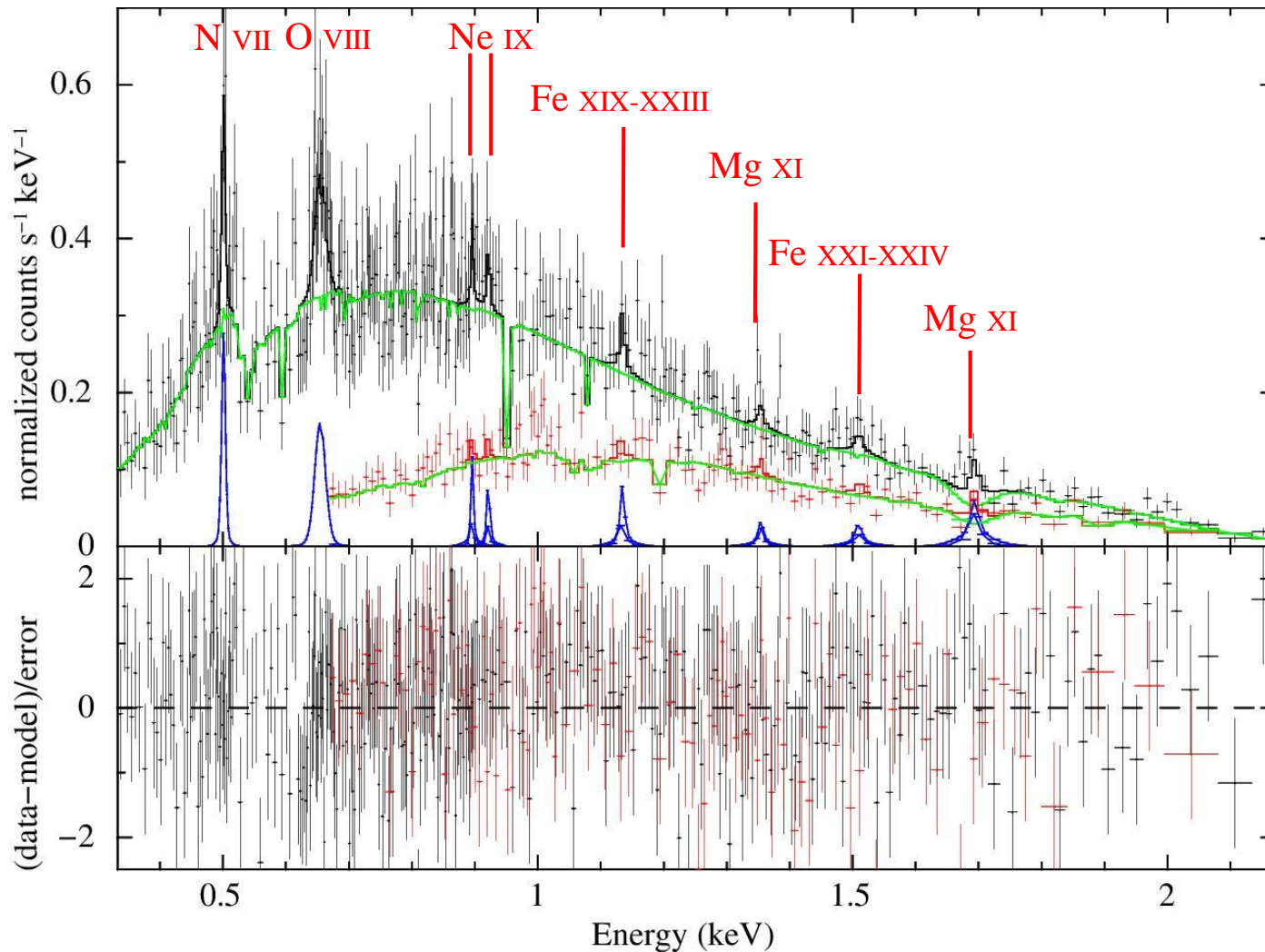
XMM-Newton observation of IGR J01572-7259: EPIC spectrum

- First detection of a faint SE (2-5 % of the total flux)
- SE fit with either a BB ($kT_{\text{BB}} \sim 220$ eV, $R_{\text{BB}} \sim 50$ km) or with emission from collisionally ionized gas (APEC, $kT_{\text{APEC}} \sim 1.1$ keV)
- First detection of O and Fe emission lines



XMM-Newton observation of IGR J01572-7259: RGS spectrum

first detection of several emission lines due to N, O, Ne, Mg, and Fe



large residuals in the RGS spectrum if continuum is described with a PL+APEC model



Origin of the *soft excess* in IGR J01572-7259?

As in the case of RX J0059.2-7138 and SMC X-2:

- SE: BB model $\Rightarrow L_{\text{BB}}/L_{\text{PL}} = 2\text{-}3\%$
- several narrow lines \Rightarrow large residuals in the RGS spectrum if continuum is described with a PL+APEC model

BUT

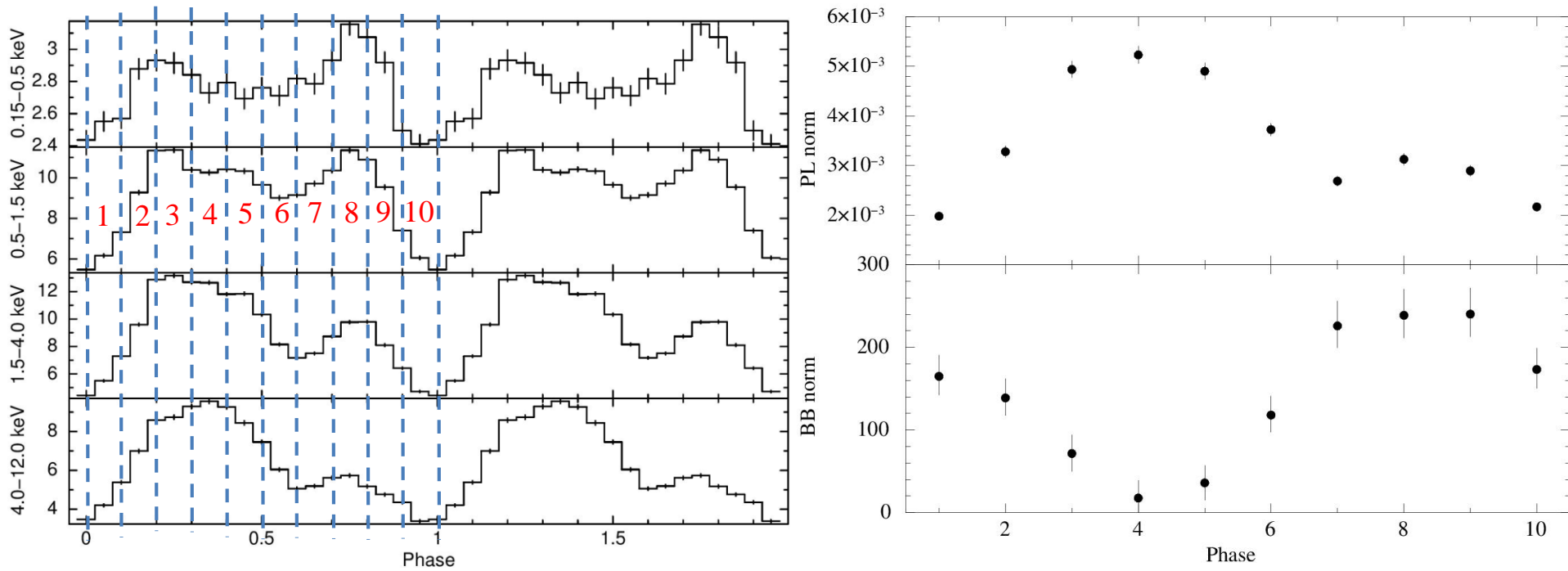
- no strong evidence for very different ionization levels
 \Rightarrow emission from a single-temperature plasma?
- intermediate luminosity ($L_{\text{X}} \sim 3 \times 10^{37} \text{ erg s}^{-1}$)
- $R_{\text{repr}} \sim 3 \times 10^7 \text{ cm} < R_{\text{m}} \sim 10^8 \text{ cm} < R_{\text{cor}} \sim 8.6 \times 10^8 \text{ cm}$





Origin of the soft excess in IGR J01572-7259?

Evidence of a pulsating BB component:



BB due to reprocessing of the primary emission by the inner edge of the accretion disc



Conclusions

For the three observed sources:

- SE + narrow lines
- SE: BB with $kT_{\text{BB}} = 0.1\text{-}0.2$ keV, $R_{\text{BB}} \sim 100$ km $\gg R_{\text{NS}}$, $L_{\text{BB}}/L_{\text{PL}} = 2\text{-}3$ %



reprocessing of the primary emission by optically thick material in the inner region of the accretion disc

- narrow lines due to N, O, Ne, Mg, Si, and Fe: large residuals in the RGS spectrum if continuum is described with a PL+MEKAL/APEC model



emission from optically thin photoionized circumsource matter



Conclusions

For the three observed sources:

- SE + narrow lines
- SE: BB with $kT_{\text{BB}} = 0.1\text{-}0.2$ keV, $R_{\text{BB}} \sim 100$ km $\gg R_{\text{NS}}$, $L_{\text{BB}}/L_{\text{PL}} = 2\text{-}3$ %



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emission from optically thin photoionized circumsource matter

Thanks!