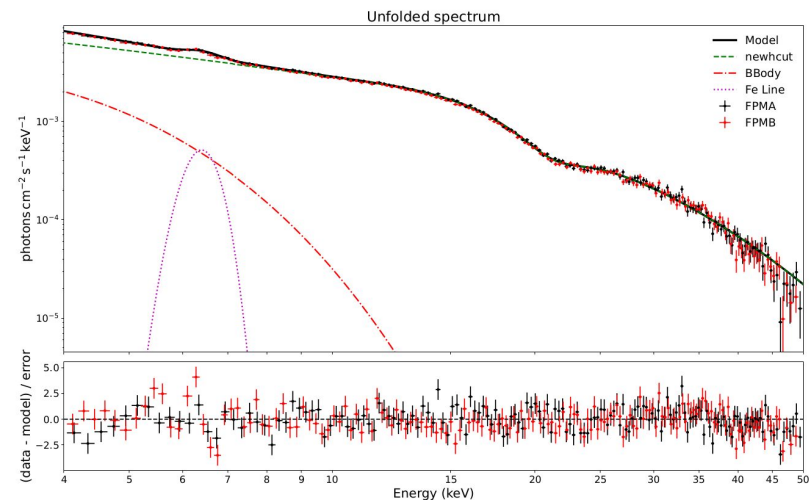


Energy resolved pulse profiles of Vela X-1: Cross-calibrating XMM-Newton and NuSTAR to trace spectral features

Dimitrios K. Maniadakis, Antonino D'Ai, Camille M. Diez, Giancarlo Cusumano,
Elena Ambrosi, Carlo Ferrigno, Ekaterina Sokolova-Lapa, Matteo Lucchini,
Peter Kretschmar, Alessio Anitra, Christian Malacaria, Gabriele A. Matzeu
Ciro Pinto, Jörn Wilms, Felix Fürst

The X-ray spectrum of an accreting pulsar (with NuSTAR)

→ (Absorbed) **Continuum**: up-scattered seed photons via inverse compton scattering + thermal emission

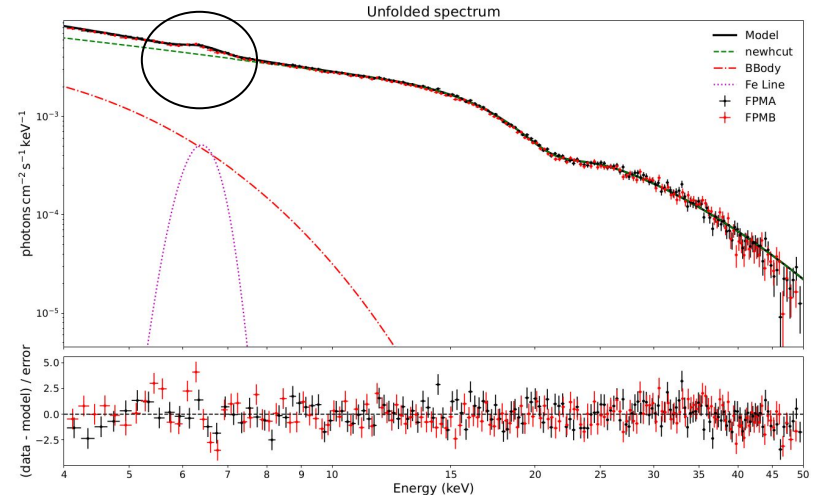


Maniadakis+ 2025

The X-ray spectrum of an accreting pulsar (with NuSTAR)

→ (Absorbed) **Continuum**: up-scattered seed photons via inverse compton scattering + thermal emission

→ **Iron line**: Some X-ray pulsars show iron fluorescence lines at 6.4 keV



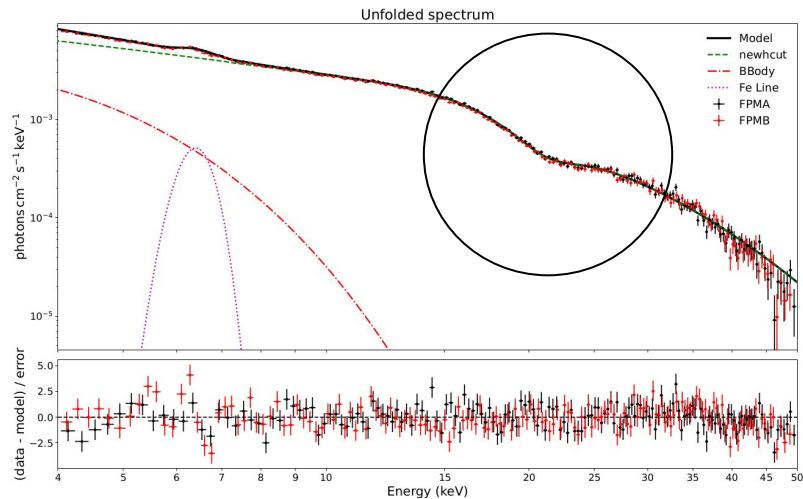
Maniadakis+ 2025

The X-ray spectrum of an accreting pulsar (with NuSTAR)

→ (Absorbed) **Continuum**: up-scattered seed photons via inverse compton scattering + thermal emission

→ **Iron line**: Some X-ray pulsars show iron fluorescence lines at 6.4 keV

→ **Cyclotron lines**: broad absorption features due to the discrete energies that electrons assume under a strong magnetic field



Maniadakis+ 2025

$$E_{\text{cyc}} \approx \frac{n}{(1+z)} 11.6 [\text{keV}] \times B_{12},$$

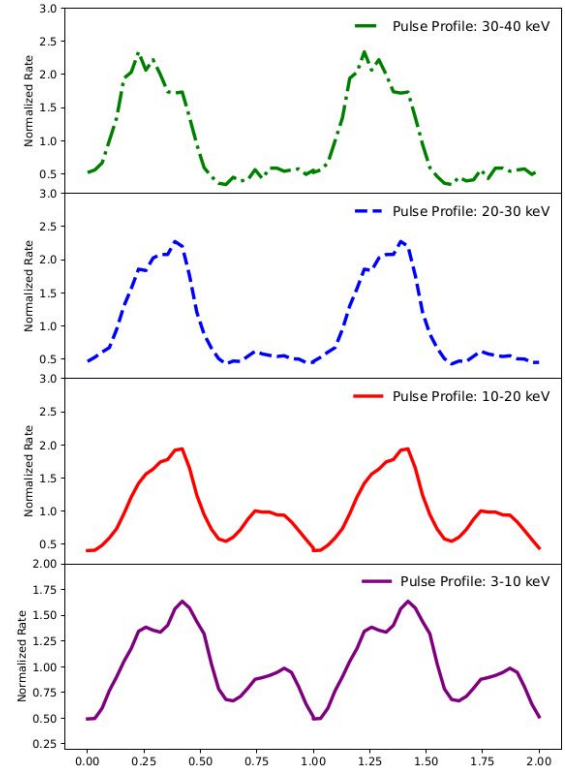
Energy resolved pulse profiles

4U1538-522

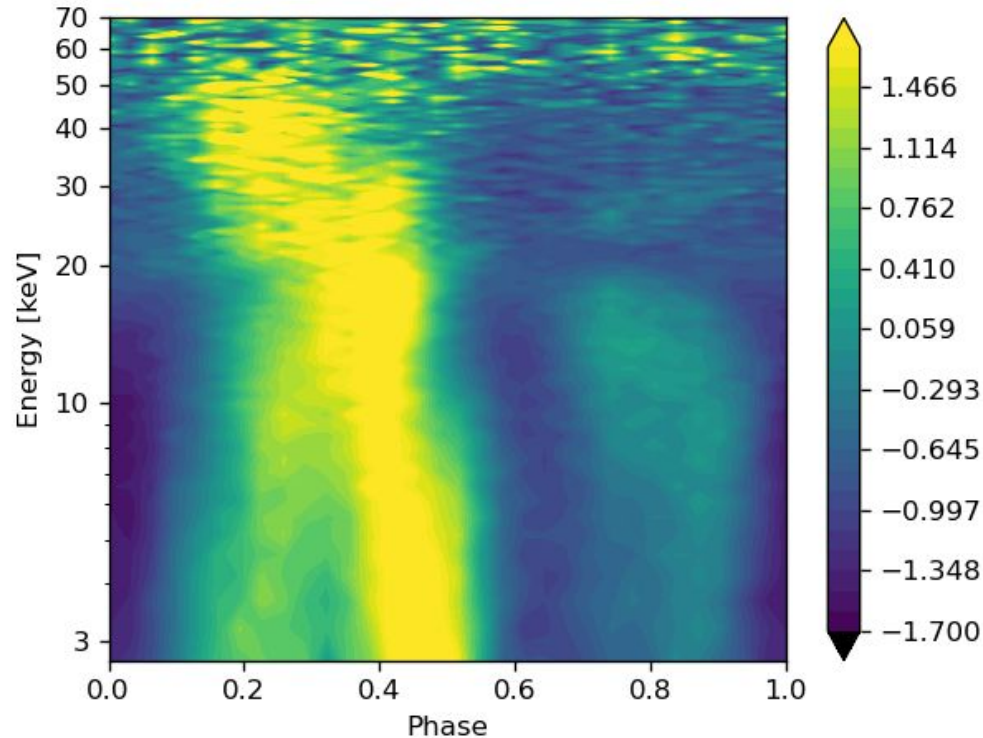
Different pulse profile **for different energy bands**



Energy Resolved Pulse Profiles



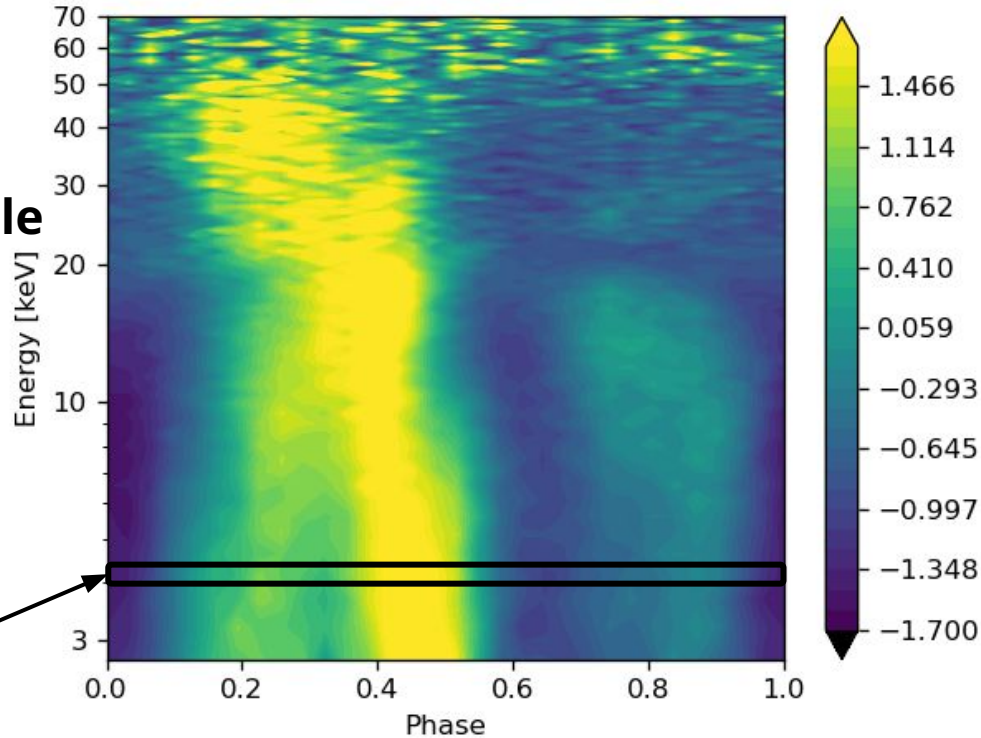
Energy Phase Matrix



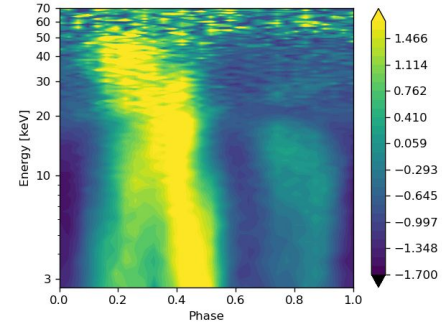
Energy-phase matrix: the matrix of all energy-resolved pulse profiles of each energy bin of your instrument

Energy Phase Matrix

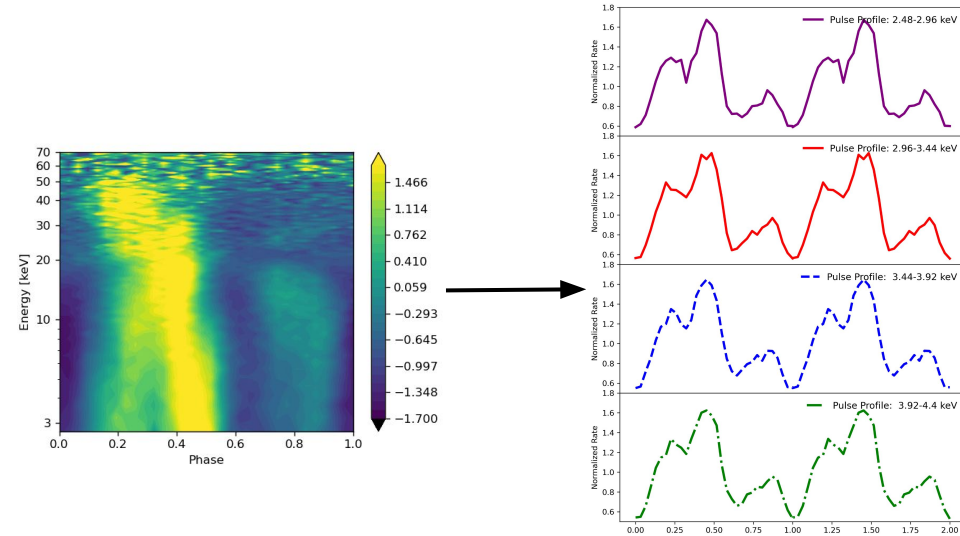
Each line: an energy resolved **pulse profile**



Energy Phase Matrix \rightarrow Pulsed Fraction (PF) Spectrum



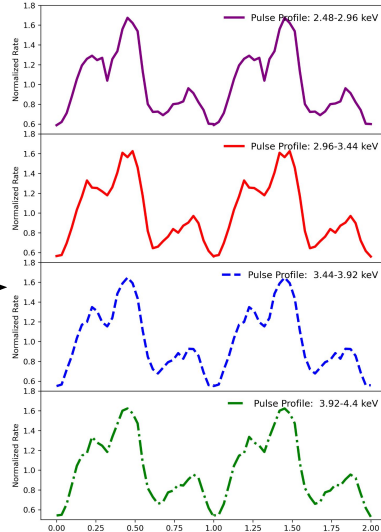
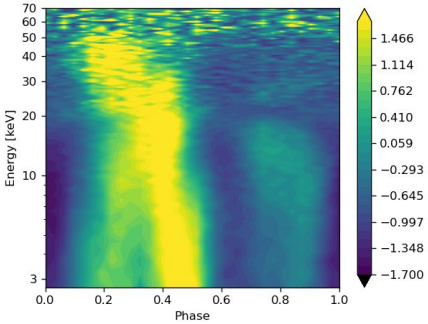
Energy Phase Matrix \rightarrow Pulsed Fraction (PF) Spectrum



•
•
•
•

One pulse profile for **every energy bin!**
(100+ bins for NuSTAR, for a certain minimum SNR)

Energy Phase Matrix → Pulsed Fraction (PF) Spectrum



$$PF_{\text{rms,c}} = \frac{\sqrt{\sum_{i=0}^N [(p_i - \bar{p})^2 - \sigma_{p_i}^2] / N}}{\bar{p}}, \longrightarrow \text{PF} (\sim 2.7 \text{ keV})$$

$$PF_{\text{rms,c}} = \frac{\sqrt{\sum_{i=0}^N [(p_i - \bar{p})^2 - \sigma_{p_i}^2] / N}}{\bar{p}}, \longrightarrow \text{PF} (\sim 3.2 \text{ keV})$$

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$$PF_{\text{rms,c}} = \frac{\sqrt{\sum_{i=0}^N [(p_i - \bar{p})^2 - \sigma_{p_i}^2] / N}}{\bar{p}}, \longrightarrow \text{PF} (\sim 4.2 \text{ keV})$$

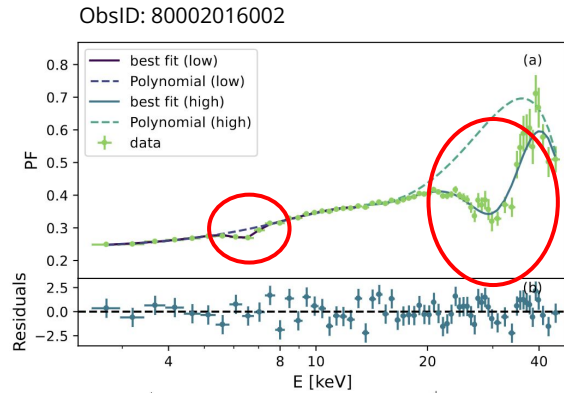
Calculate the **PF on that energy bin** by using the root-mean-square

PF (~ 25 keV)

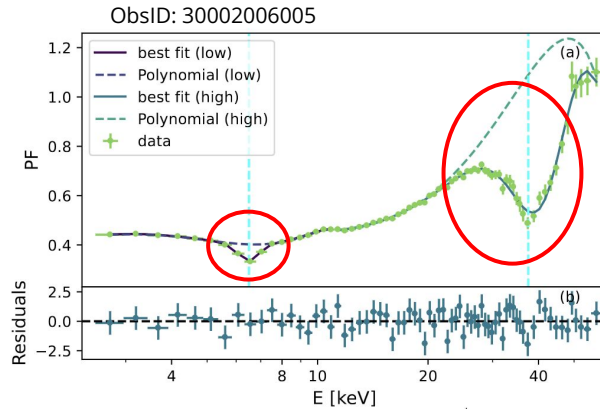
One pulse profile for **every energy bin!**
(100+ bins for NuSTAR, for a certain minimum SNR)

PF spectra: timing signatures of spectral features

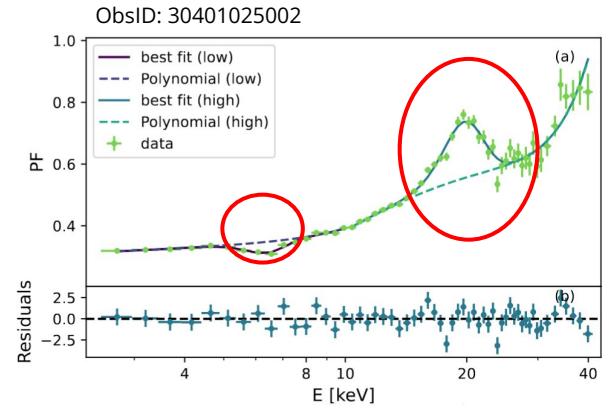
Cep X-4



Her X-1



4U 1538-52

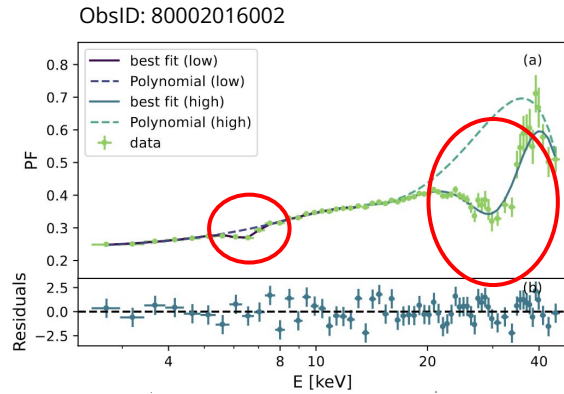


Ferrigno, D'Ai, Ambrosi 2023

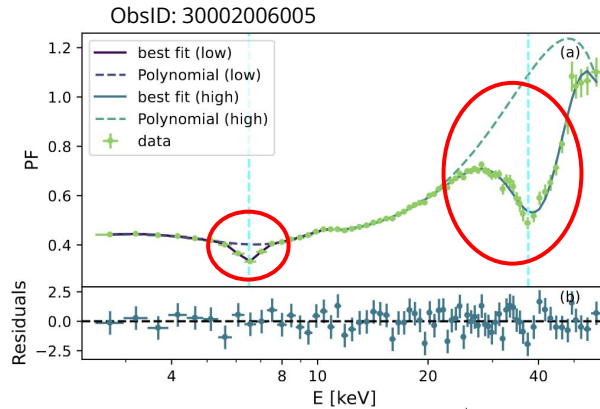
Maniadakis+ 2025

PF spectra: timing signatures of spectral features

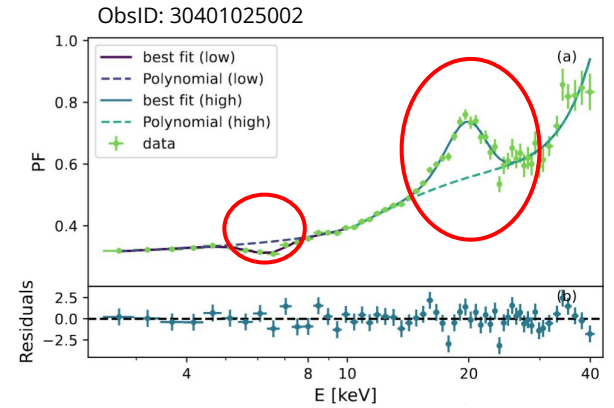
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4U 1538-52



Ferrigno, D'Ai, Ambrosi 2023

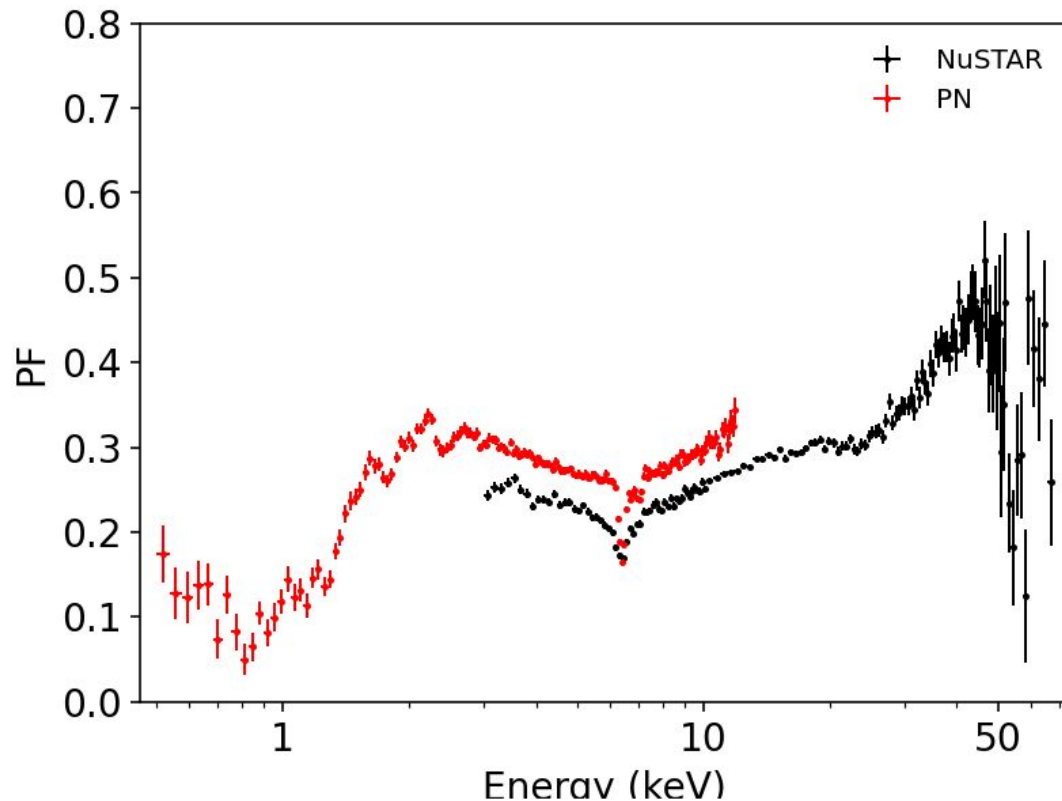
Maniadakis+ 2025

What about other X-ray instruments? How does the PF spectrum look in lower energies? Timing signatures of X-ray lines other than iron line?

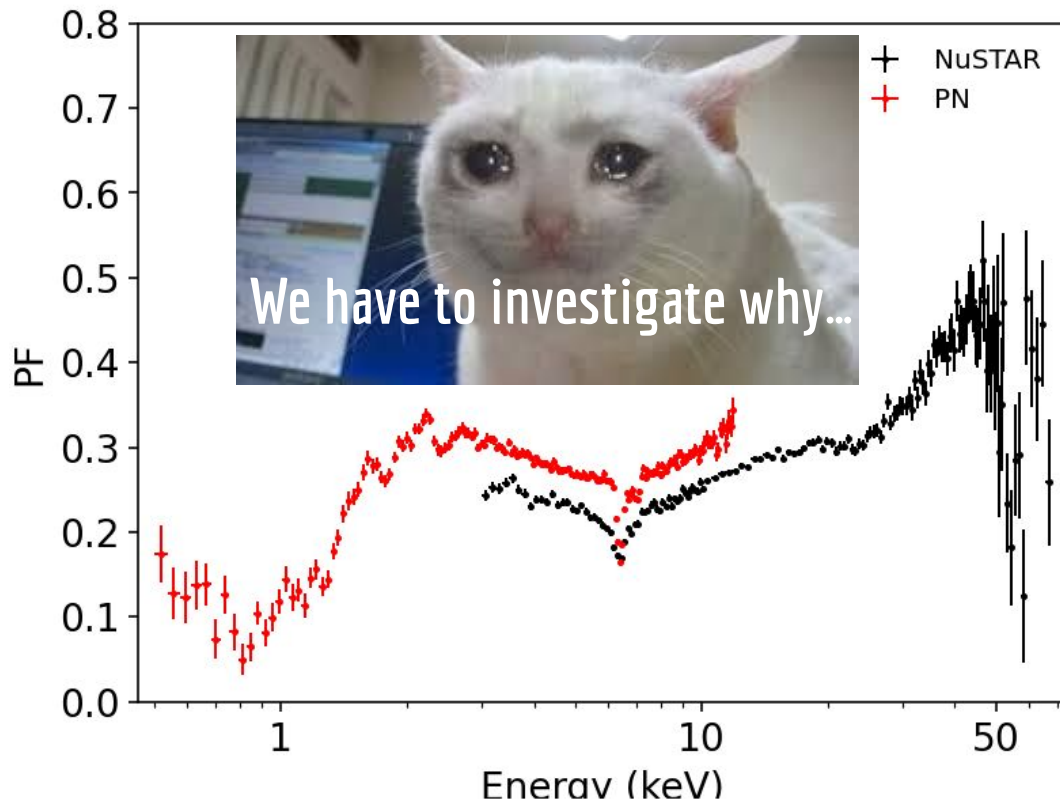
→ **Extension to XMM-Newton**

Pulsed fraction spectrum of Vela X-1: Simultaneous observations of XMM/NuSTAR

Pulsed fraction spectrum of Vela X-1: Simultaneous observations of XMM/NuSTAR



Pulsed fraction spectrum of Vela X-1: Simultaneous observations of XMM/NuSTAR

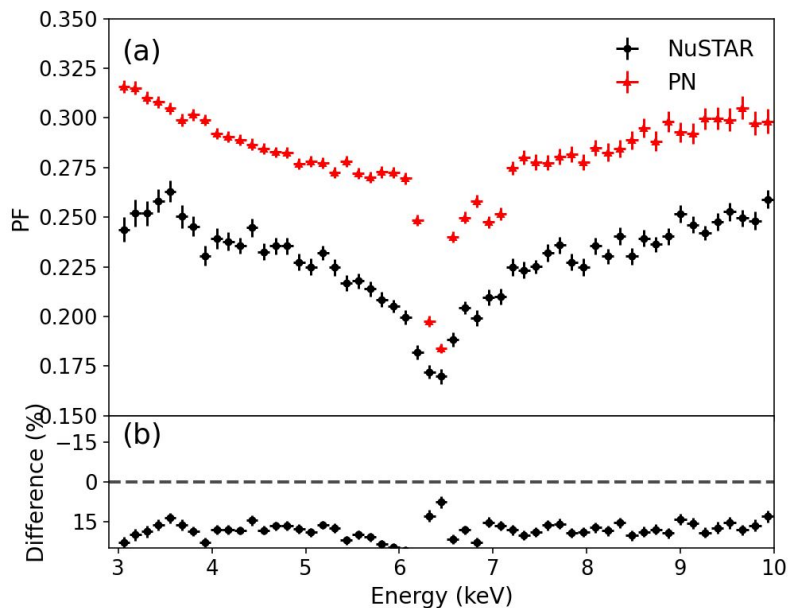


Pulsed fraction spectrum of XMM vs NuSTAR

→ Using a coarse energy binning to compare bin by bin the PF values

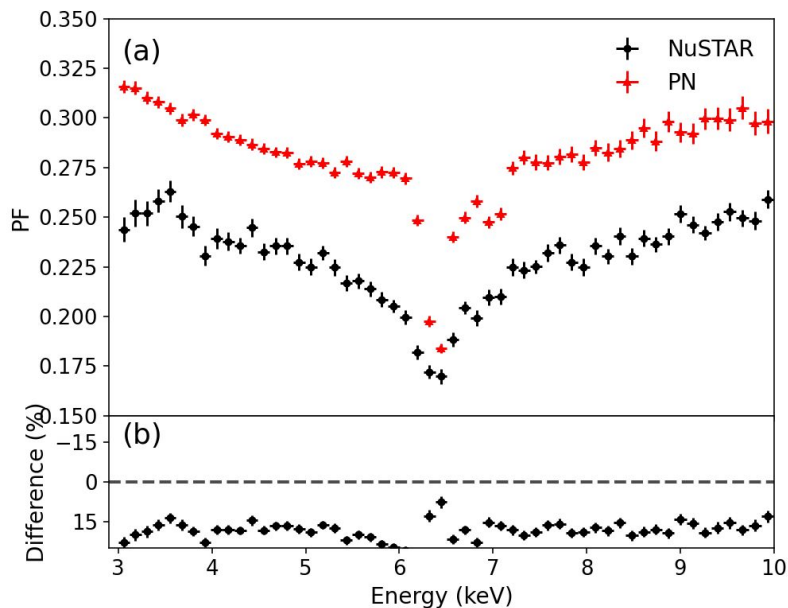
→ There's a huge ~20% difference

→ cross-calibrating issues between EPIC-pn and NuSTAR are known (e.g Fuerst+ 2022)



Pulsed fraction spectrum of XMM vs NuSTAR

- Using a coarse energy binning to compare bin by bin the PF values
- There's a huge ~20% difference
- cross-calibrating issues between EPIC-pn and NuSTAR are known (e.g Fuerst+ 2022)



We use the PF spectrum as a **cross-calibration tool** between NuSTAR and EPIC-pn to assess the effect of different instrumental characteristics

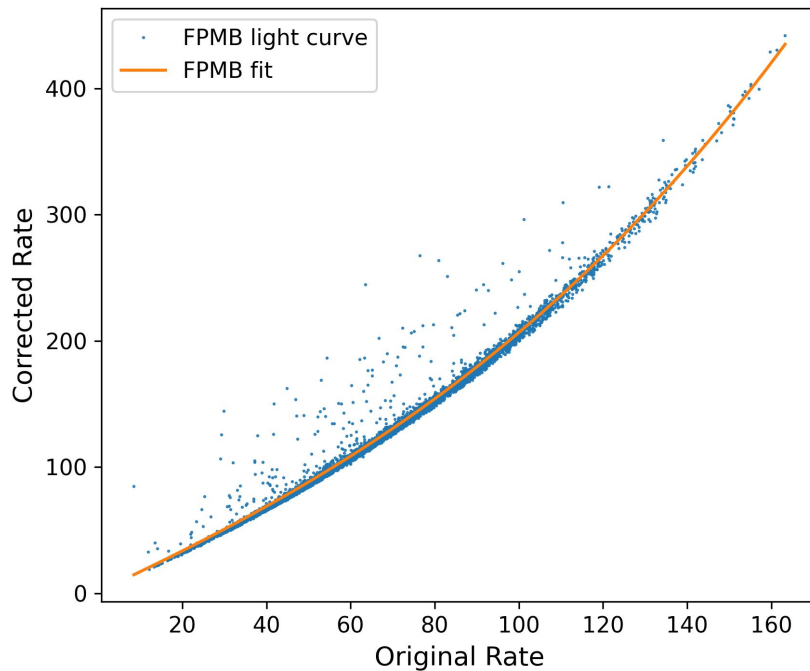
Count-rate correction of NuSTAR

We correct the count-rate of each phase bin from livetime effects, PSF and vignetting

→ We construct a R_{orig} vs R_{corr} plot from the lightcurve file

→ We fit with a polynomial

→ We use that function to correct the count-rates

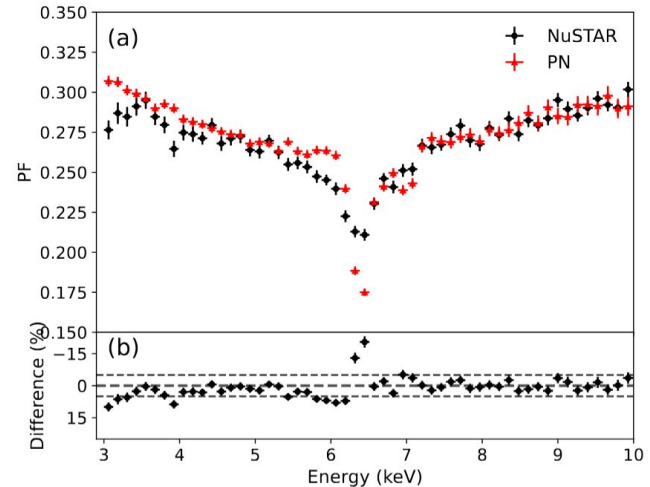
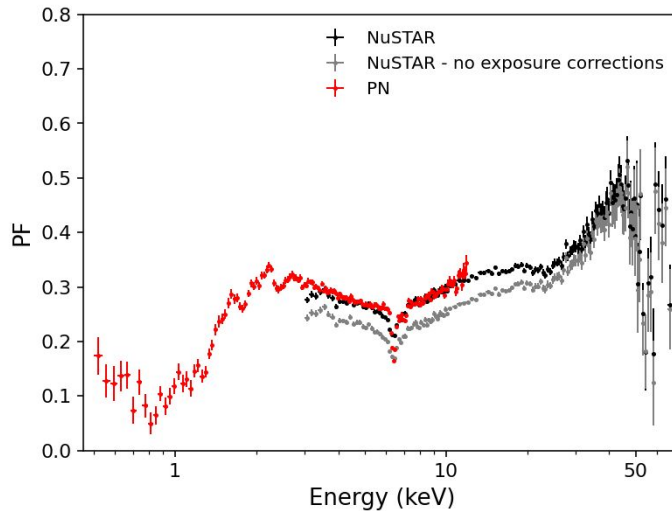


Corrected PF spectrum

Other effects taken into account :

- **redistribution** effects (used ISIS approach to unfold the energy-phase matrices)
- **consistent source region** selection for both instruments
- **backscale** correction

Residual differences at the iron line region reflects the different energy resolution

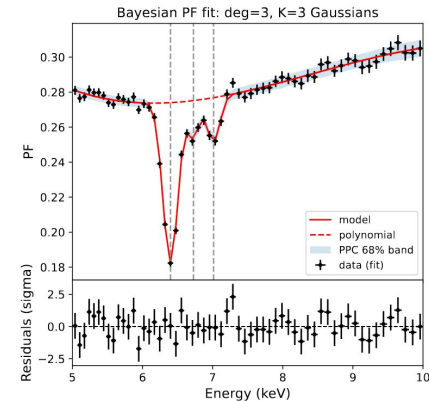
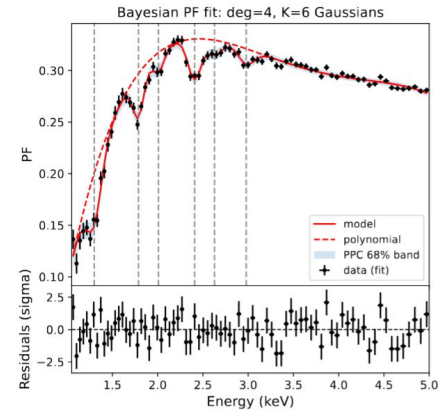


Scientific results with EPIC-pn

Scientific results with EPIC-pn: many dips!

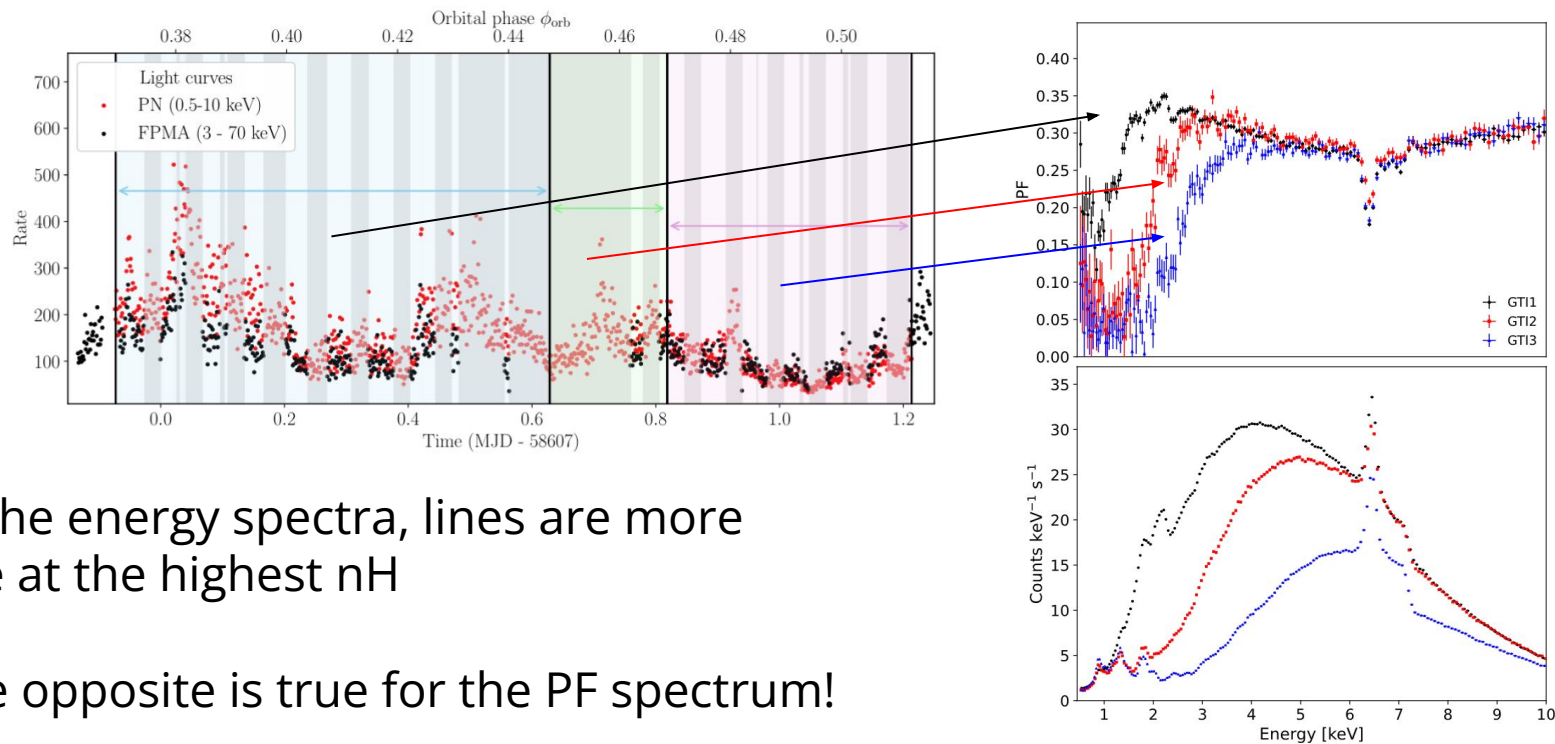
Bayesian fitting: We use the already known spectral information as Gaussian priors

- Mg XI (f,i,r): $E_{\text{ref}} = 1.338 \text{ keV} \rightarrow E_{\text{pf}} = 1.30 \pm 0.01 \text{ keV}$
- Si XIII (f,i,r): $E_{\text{ref}} = 1.823 \text{ keV} \rightarrow E_{\text{pf}} = 1.79 \pm 0.01 \text{ keV}$
- Si XIV Ly α : $E_{\text{ref}} = 2.0049 \text{ keV} \rightarrow E_{\text{pf}} = 2.01 \pm 0.02 \text{ keV}$
- S XV (f,i,r): $E_{\text{ref}} = 2.439 \text{ keV} \rightarrow E_{\text{pf}} = 2.41 \pm 0.01 \text{ keV}$
- S XVI Ly α : $E_{\text{ref}} = 2.6207 \text{ keV} \rightarrow E_{\text{pf}} = 2.63 \pm 0.03 \text{ keV}$
- Ar VI-IX: $E_{\text{ref}} = 2.9661 \text{ keV} \rightarrow E_{\text{pf}} = 2.98 \pm 0.02 \text{ keV}$
- Fe K α : $E_{\text{ref}} = 6.4 \text{ keV} \rightarrow E_{\text{pf}} = 6.399 \pm 0.005 \text{ keV}$
- **Fe XXV: $E_{\text{ref}} = 6.7 \text{ keV} \rightarrow E_{\text{pf}} = 6.73 \pm 0.03 \text{ keV}$**
- Fe K β : $E_{\text{ref}} = 7.06 \text{ keV} \rightarrow E_{\text{pf}} = 7.01 \pm 0.02 \text{ keV}$



Not seen in the X-ray spectrum!

Orbital-phase-resolved soft EPIC-pn PF spectra



→ In the energy spectra, lines are more visible at the highest nH

→ The opposite is true for the PF spectrum!

PF spectra as a cross-calibration and science tool

- The PF spectrum can be used as a **cross-calibration tool between instruments**, as **a way of investigating the dominant effects that affects the shapes of the pulse profiles**.

Example: The count-rate correction in the case of EPIC-pn / NuSTAR

- **PF drops in energies of multiple soft X-ray line**, potentially even on lines that are not visible in phase-averaged energy spectra

Bonus: No need for the very model-dependent phase-resolved spectroscopy!

PF spectroscopy in the newAthena era

	NewAthena / Athena X-IFU	EPIC-pn
Spectral resolution	~4 eV (goal 3 eV) @ 7 keV	~150 eV @ 6 keV
Timing resolution	~10 μ s	30 μ s (Timing mode)
1 keV effective area	~5800 cm ²	~1200–1500 cm ²
7 keV effective area	~880 cm ²	~600–800 cm ²

PF spectroscopy in the newAthena era

- PF spectroscopy: from phenomenology to **precise line-resolved measurements**
- The PF of individual lines **can constrain the geometry and location of the emitting regions**
- Differences in PF between lines and elements **may disentangle multiple emission sites**
- **Cross-calibration:** PF spectra can be used in the same way as a cross-calibration diagnostic between newAthena and other X-ray missions

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NewAthena will transform PF spectroscopy from broad-band studies to detailed line-resolved analyses

Thank you

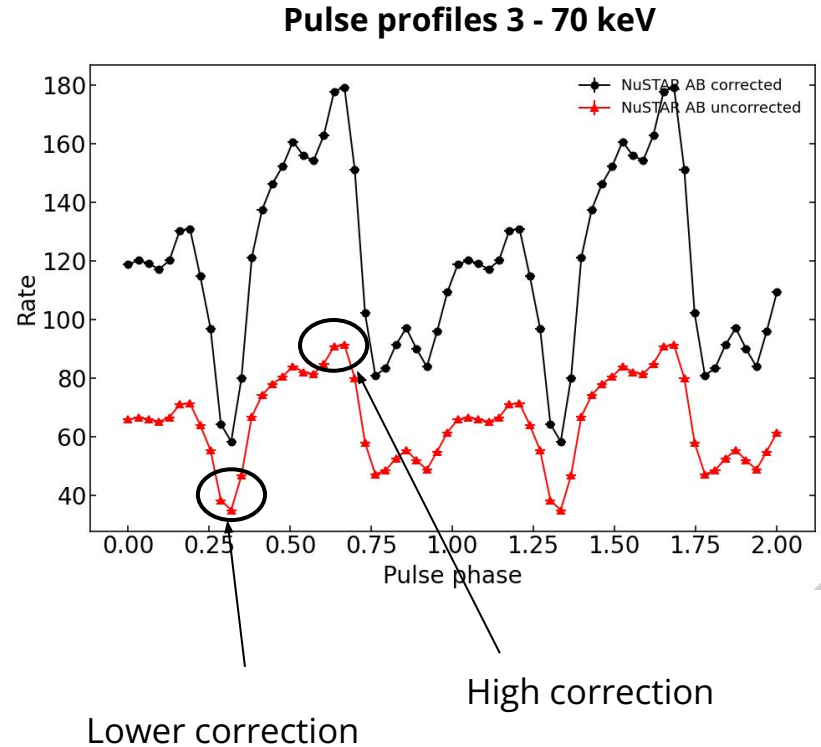
BACKUP SLIDES

Count-rate correction of NuSTAR

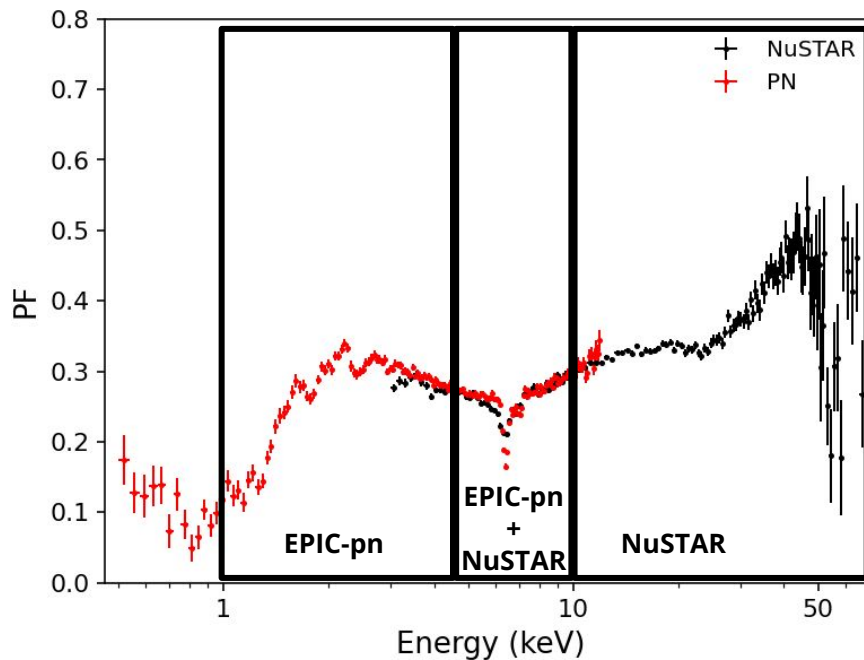
The correction on each phase bin is count-rate dependent:

- **larger count-rate** of a phase bin means a **larger correction** on that phase bin
- pulse profile shape changes (its being *stretched*)
- **PF increases**

→ In EPIC-pn, the correction is ~ 0 :
the relationship R_{corr} vs R_{orig} is linear which results to a rescaling of the pulse profile



Modeling the PF spectrum



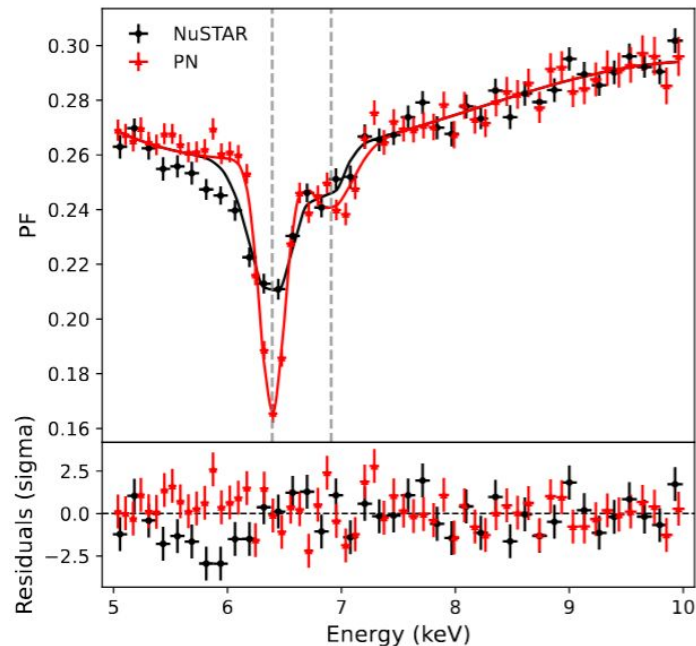
→ 1 - 5 keV: EPIC-pn data → Bayesian fitting

→ 5 - 10 keV: Simultaneous least-squares fitting of NuSTAR/EPIC-pn strictly simultaneous data

→ 10 - 70 keV: least-squares fitting of NuSTAR data

Energy range: 5 - 10 keV: NuSTAR/EPIC-pn data / least-squares

- Centroid energies tied
- Widths free
- $\chi^2 = 128$ (85)
- Fe K α : $E_{\text{pf}} = 6.393 \pm 0.005$ keV
- Fe K β ...?: $E_{\text{pf}} = 6.91 \pm 0.03$ keV



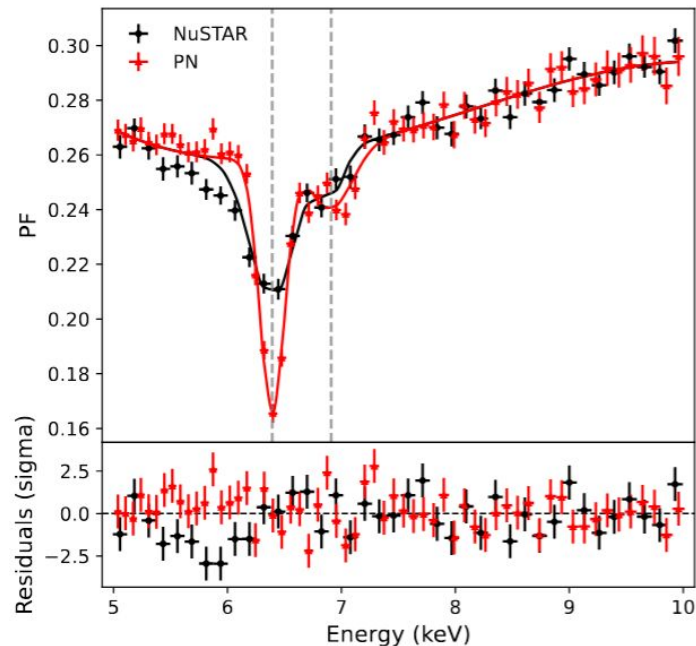
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Residuals at the NuSTAR data (~6 keV):

- Different energy resolution can not be taken into account completely just by leaving the widths vary



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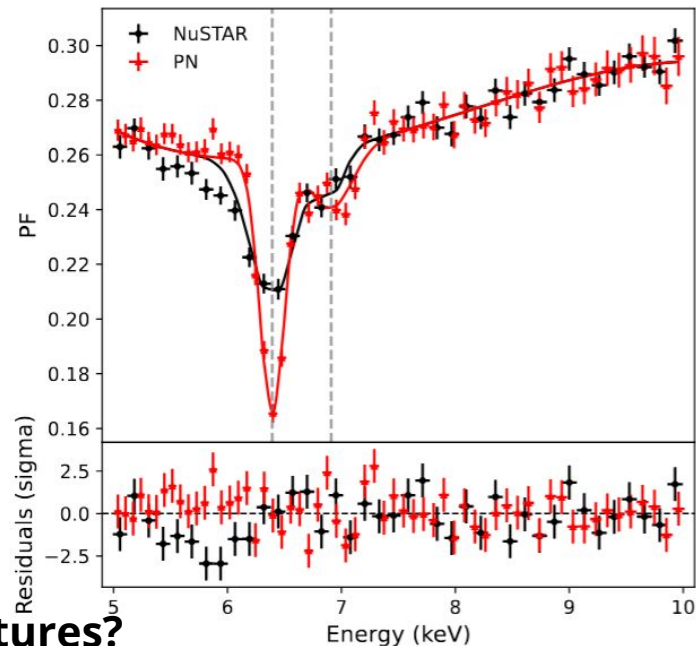
- Fe K α : $E_{\text{pf}} = 6.393 \pm 0.005$ keV
- **Fe K β ...? : $E_{\text{pf}} = 6.91 \pm 0.03$ keV**

Residuals at the NuSTAR data (~6 keV):

- Different energy resolution can not be taken into account completely just by leaving the widths vary

Residuals at the EPIC-pn data (~7 keV):

- 6.9 keV gaussians seems like trying to fit **two features?**
- We decide to conduct a Bayesian fitting to the full signal of EPIC-pn to investigate..

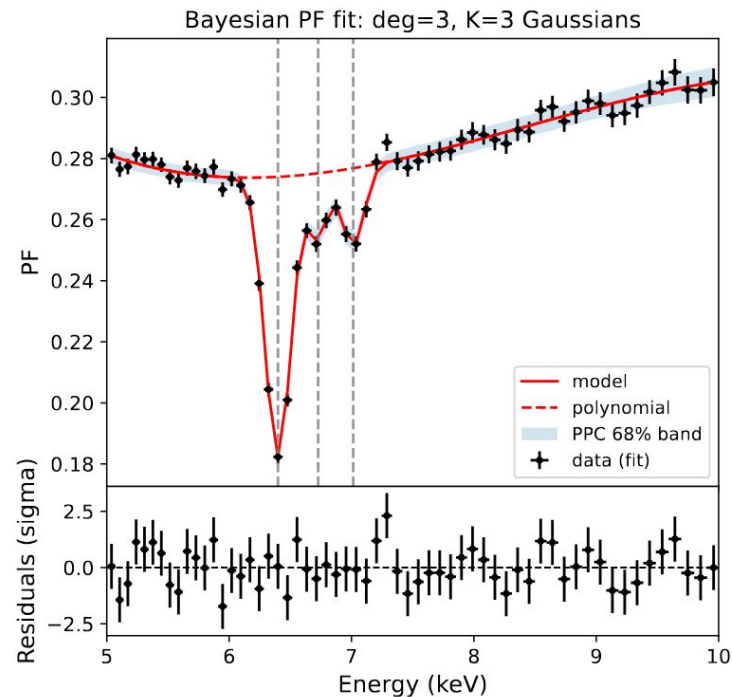


Energy range: 5 - 10 keV: EPIC-pn data / Bayesian fitting

We use all exposure this time...

There are indications in previous works for the Fe XXV triplet at ~ 6.7 keV (Amato+2021, Diez+2025).

- Fe K α : $E_{\text{ref}} = 6.4$ keV $\rightarrow E_{\text{pf}} = 6.399 \pm 0.005$ keV
- Fe XXV: $E_{\text{ref}} = 6.7$ keV $\rightarrow E_{\text{pf}} = 6.73 \pm 0.03$ keV
- Fe K β : $E_{\text{ref}} = 7.06$ keV $\rightarrow E_{\text{pf}} = 7.01 \pm 0.02$ keV



Energy range: 10 - 70 keV: NuSTAR data / least-squares

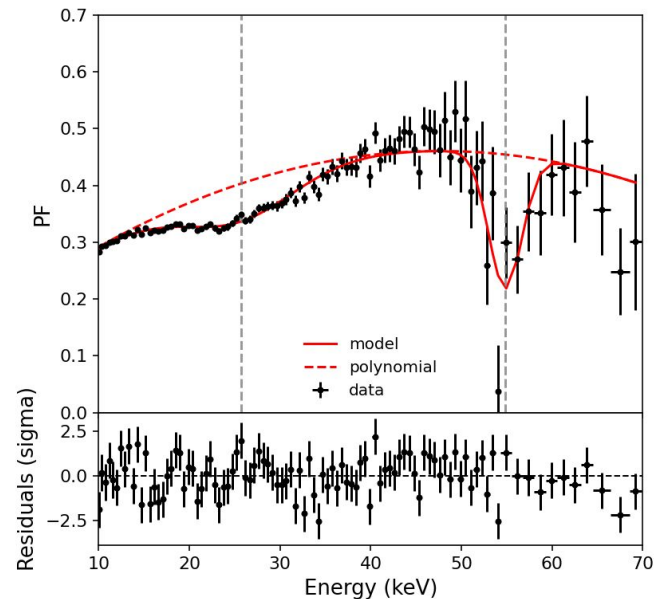
- Polynomial of 2nd degree + 2 gaussians
- $\chi^2 = 107$ (90)

$$E_1 = 25.67 \pm 0.25, \sigma_1 = 5.88 \pm 0.09$$

$$E_2 = 55.05 \pm 0.62, \sigma_2 = 2.09 \pm 0.56$$

Energies compatible with the two known CRSFs, with energies of

$E_1 \sim 23.5$ keV and $E_2 \sim 55$ keV (Fuerst+14, Diez+22, Diez+23)

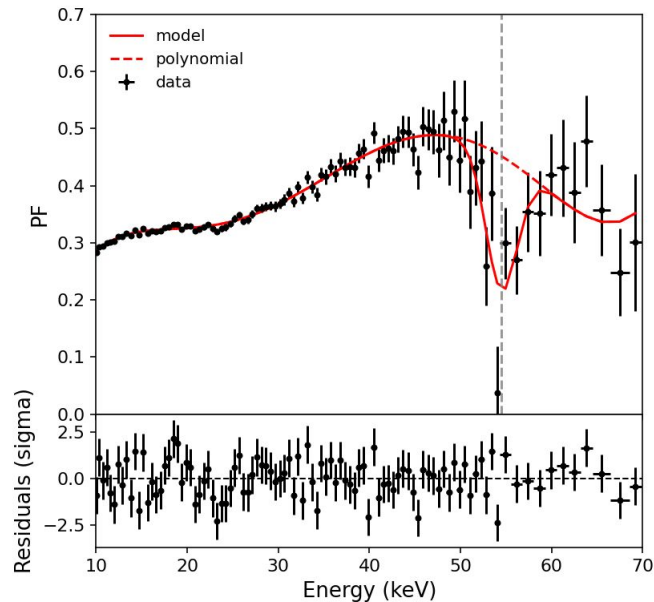


Energy range: 10 - 70 keV: NuSTAR data / least-squares

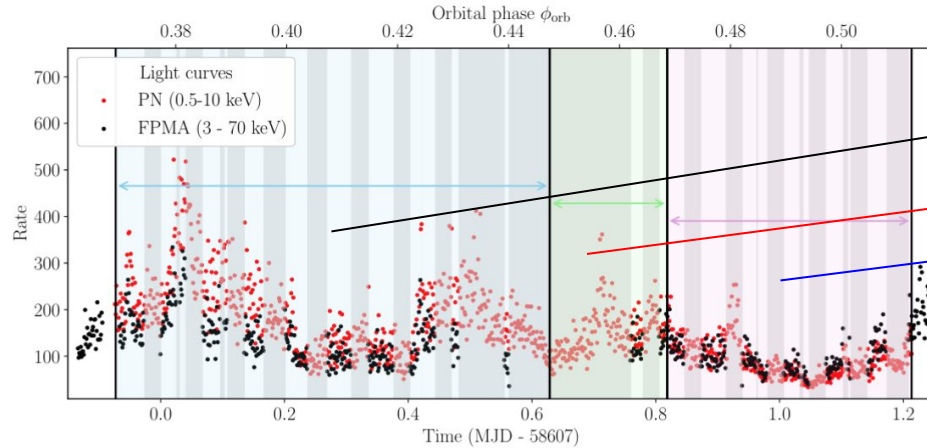
Alternative model:

- Polynomial of 5th degree + 1 gaussian
- $\chi^2 = 97 (90)$
- $E_2 = 54.5 \pm 0.62$, $\sigma_2 = 1.72 \pm 0.56$

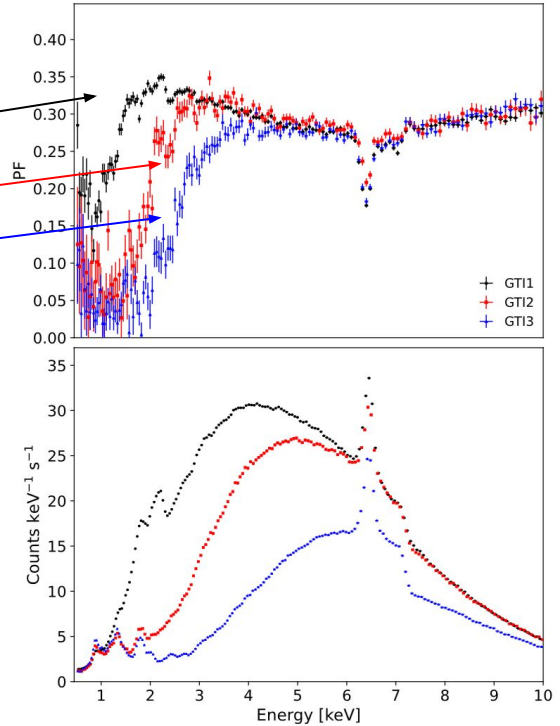
Could the 25 keV feature attributed to something else?



Orbital-phase-resolved soft EPIC-pn PF spectra



→ Dips are the strongest in the first orbital-phase-resolved PF spectrum, before the passage of the accretion wake



Discussion and Conclusions

Modeling of the EPIC-pn PF spectra

- For the first time we observe PF drops in energies that correspond to soft X-ray lines other than the iron line. A PF drop would indicate that most of the flux of the line is not coherent with the pulse period
- An immediate way of checking how much “pulsed” a line is (aka no need to model phase-resolved spectra..)
- Indications of a line (Fe XXV at ~ 6.7 keV) that is not visible in the phase-averaged spectrum of EPIC-pn
- PF line dips are strongest at the first orbital-phase-resolved PF spectrum \rightarrow indicates that the origin of the lines is not the accretion wake but the wind (consistent result with Diez+23)

Modeling of the NuSTAR PF spectra

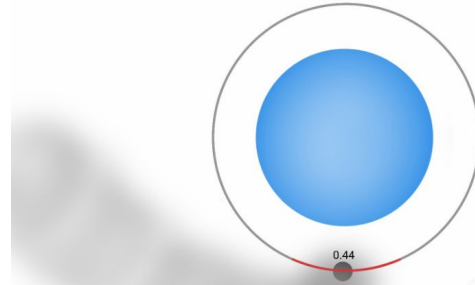
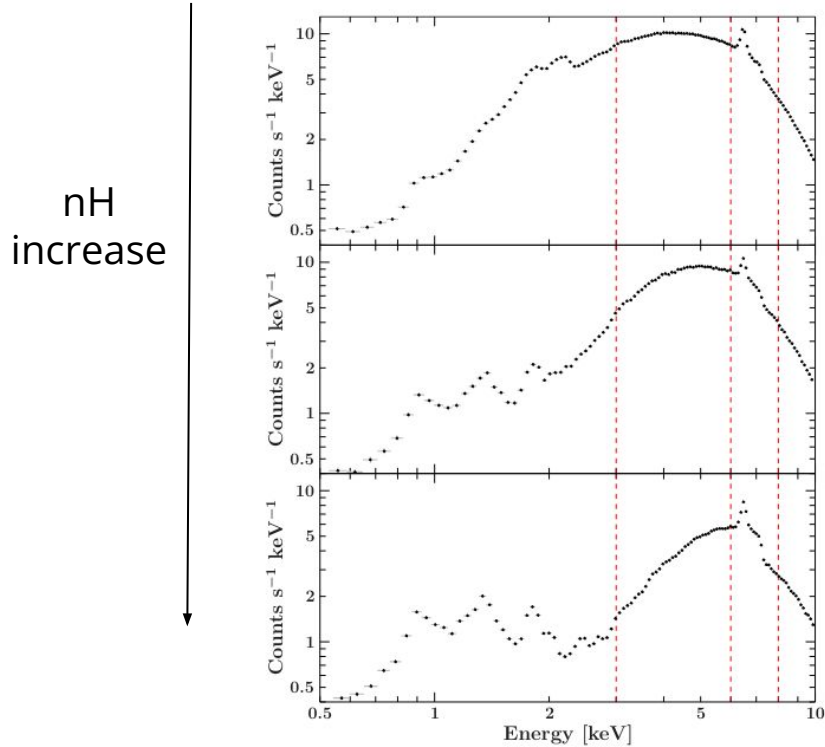
- Two dips that correspond to the two CRSFs
- That indicates that the cyclotron line depth is stronger in phase bins with higher flux (Maniadakis+25)
- The ~ 25 keV feature at the PF spectrum is rather broad and shallow and it can be fitted with a polynomial: it could be an indication of a different origin of the feature

PF spectrum as a cross-calibration tool

- We used the PF spectrum as a cross-calibration diagnostic for the two instruments
- After taking into account count-rate corrections (+other effects), the pulse profiles of the two instruments match
- The PF spectrum can be used as a cross-calibration tool between instruments

Thank you!

Simultaneous EPIC-pn / NuSTAR observations of Vela X-1



Diez+ 2023

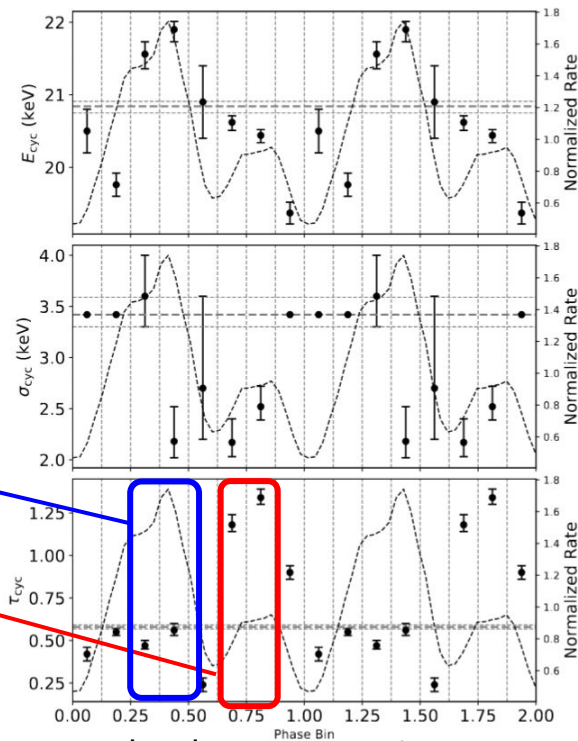
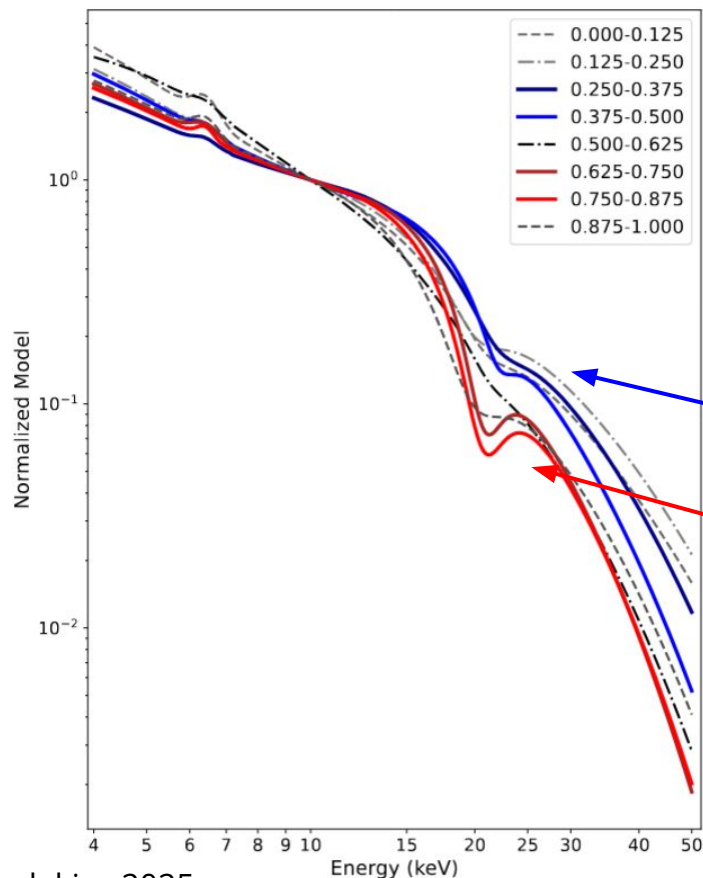
Data taken while accretion wake was *entering* the line of sight

Orbital-phase-resolved PF spectroscopy results

Line	E_{ref} (keV)	GTI1			GTI2		
		E_{PF}	σ_{PF}	$\Delta\text{elpd} \pm \text{dSE}$	E_{PF}	σ_{PF}	$\Delta\text{elpd} \pm \text{dSE}$
Mg XI (f,i,r)	$1.338^{+0.012}_{-0.019}$	1.28 ± 0.01	0.06 ± 0.01	16.5 ± 7.0	1.41 ± 0.02	0.06 ± 0.02	7.2 ± 5.0
Si XIII (f,i,r)	$1.823^{+0.014}_{-0.013}$	1.79 ± 0.01	0.04 ± 0.01	21.6 ± 17.0	1.77 ± 0.03	0.10 ± 0.02	15.1 ± 7.2
Si XIV Ly α	2.0049 (fixed)	2.02 ± 0.04	0.06 ± 0.02	1.2 ± 1.9	–	–	–
S XV (f,i,r)	$2.439^{+0.029}_{-0.027}$	2.43 ± 0.01	0.08 ± 0.01	3.7 ± 2.8	2.41 ± 0.03	0.06 ± 0.02	2.7 ± 1.9
Ar VI–IX	2.9661 (fixed)	2.98 ± 0.03	0.07 ± 0.02	27.8 ± 12.6	–	–	–

Spectra of all 8 phase bins Normalized at 10 keV

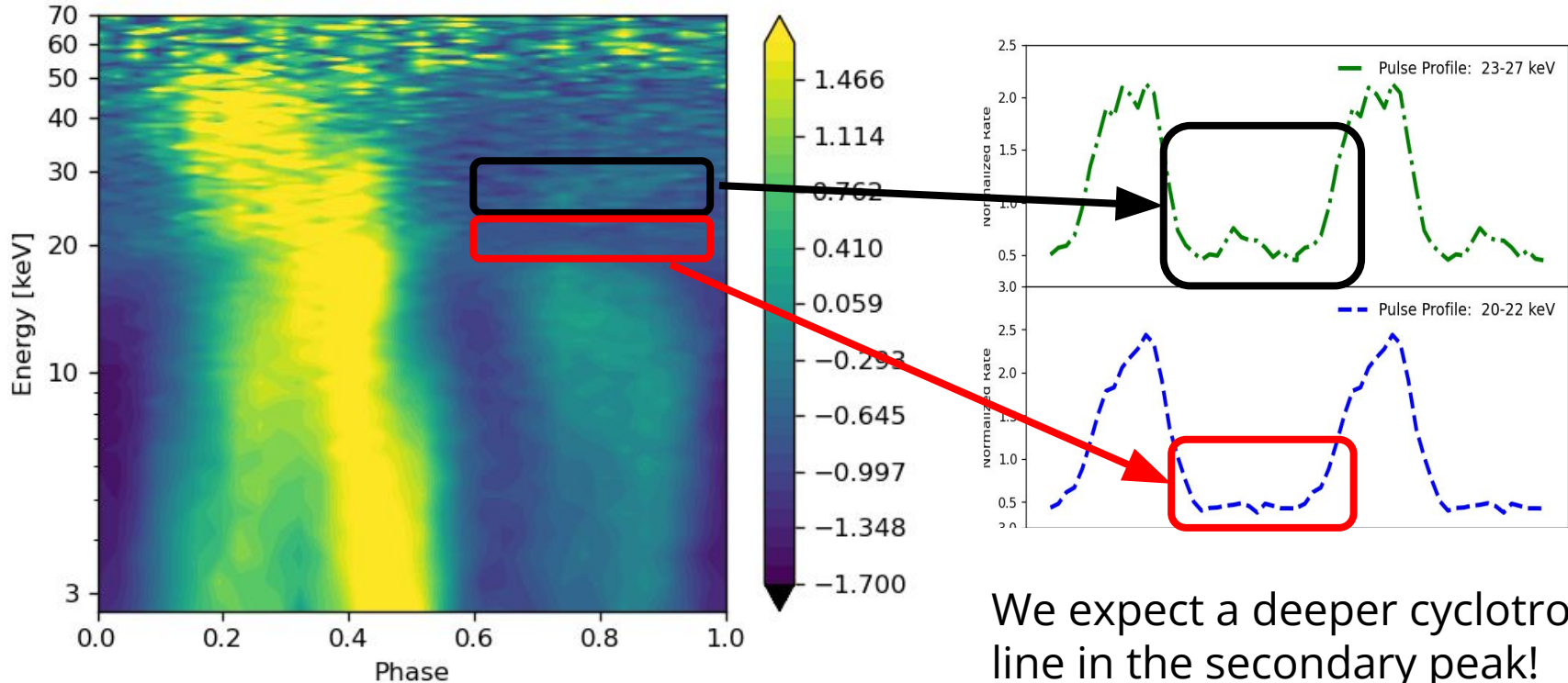
Cyclotron line parameters variation



1. **CRSF deeper** and at lower energies at **secondary** peak
2. Spectrum of **primary** peak has a **higher cut-off energy**

We investigate the matrix and the pulse profiles near the cyclotron line energies

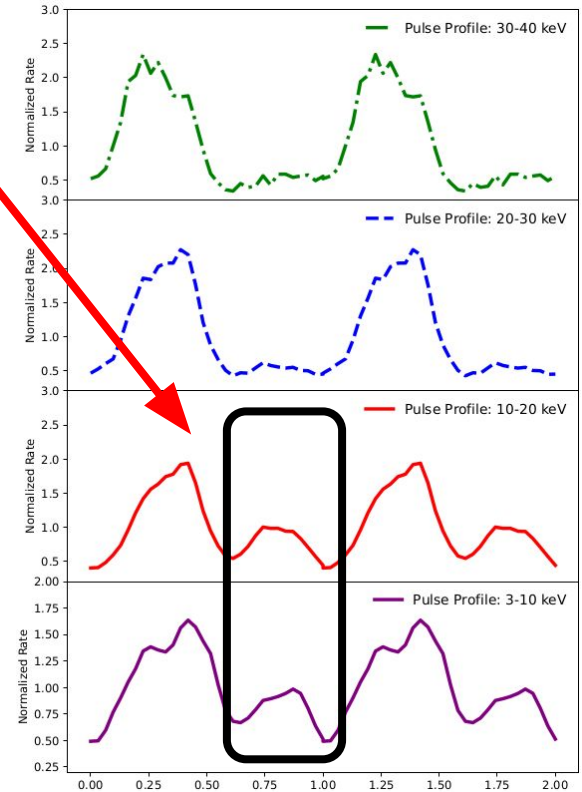
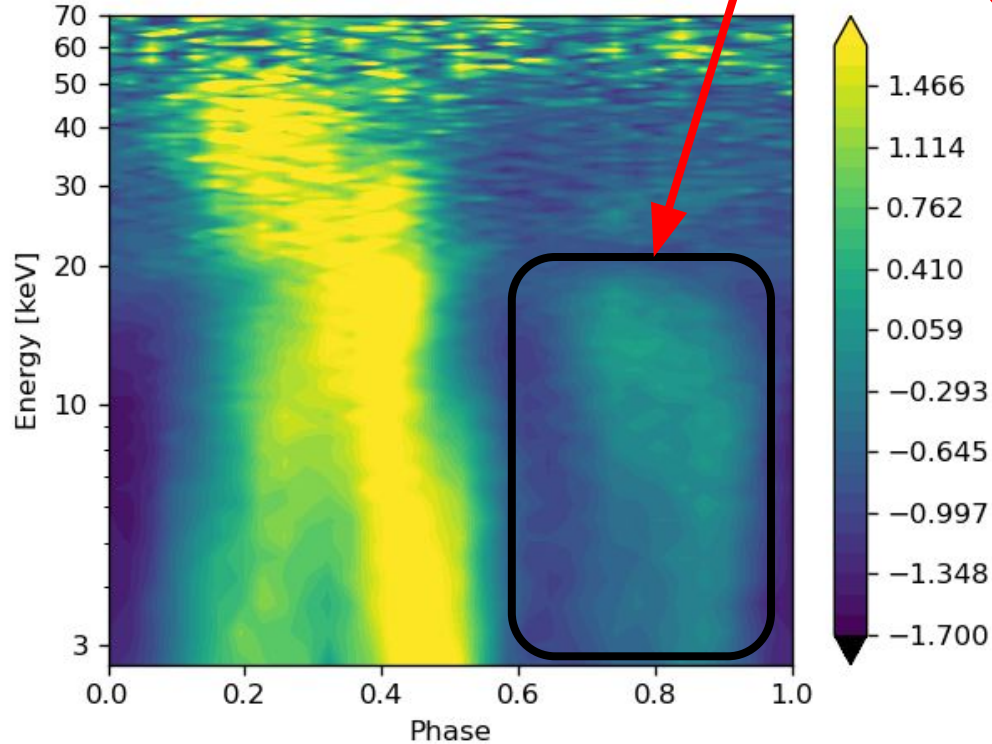
Secondary peak disappears at around 20 keV and reappears after 23 keV



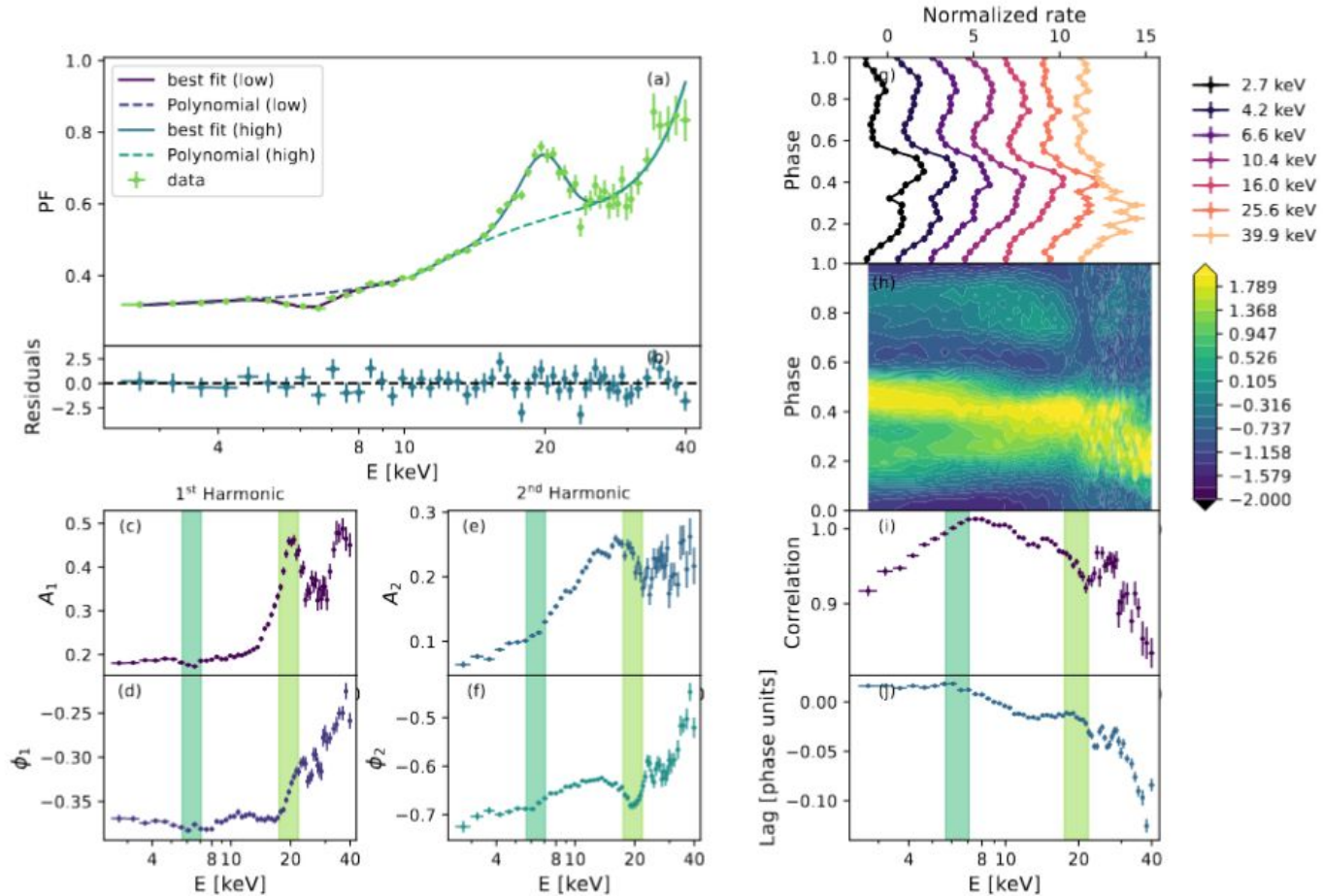
Attention! 2 periods shown in the pulse profile plots but only 1 in the matrix!

Energy Phase Matrix

Secondary peak at 3 - 20 keV



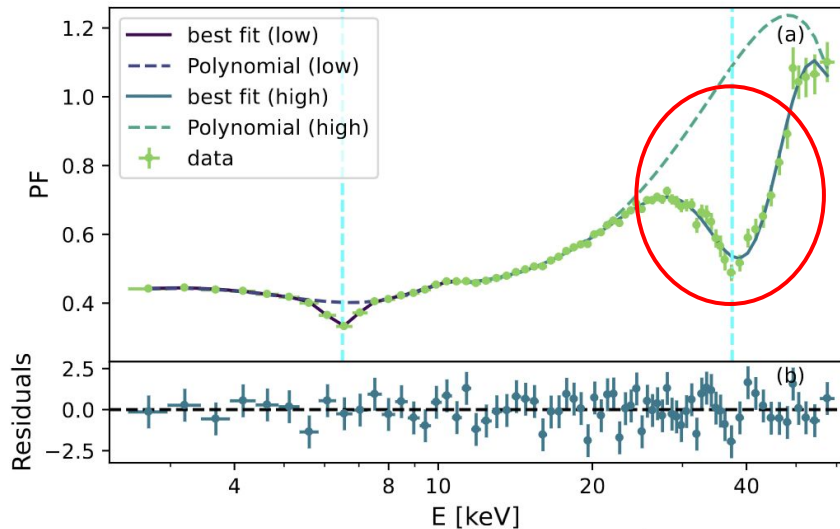
4U 1538-522 30401025002 N = 32 S/N = 15.0



Pulsed Fraction spectrum and cyclotron lines

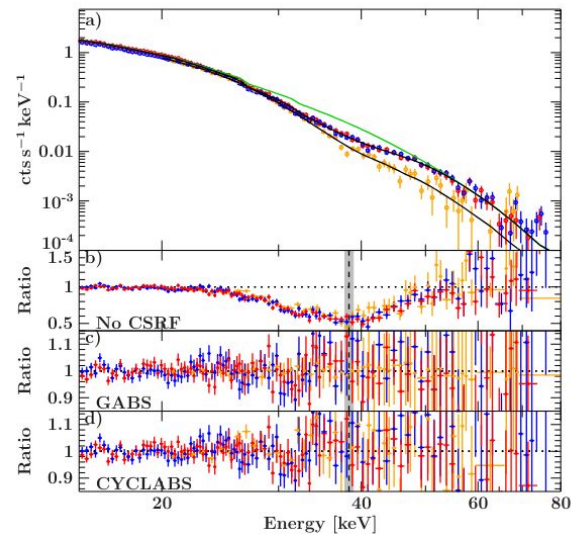
Ferrigno, D'Ai,
Ambrosi 2023

Her X-1



Pulsed Fraction Spectrum: Phenomenological modelling with a polynomial + gauss

Fuerst et al. 2023



Phase-averaged spectrum: the “traditional” spectrum we usually study

cyclotron line in the X-ray phase-averaged spectrum → a dip in the pulsed fraction spectrum!

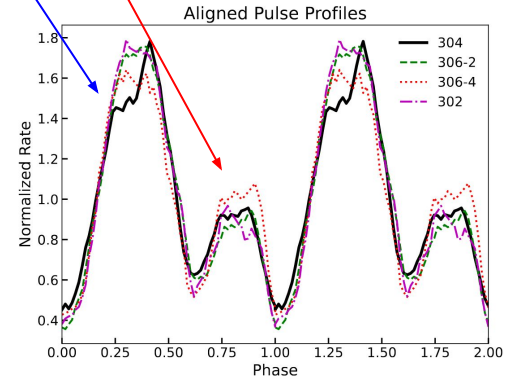
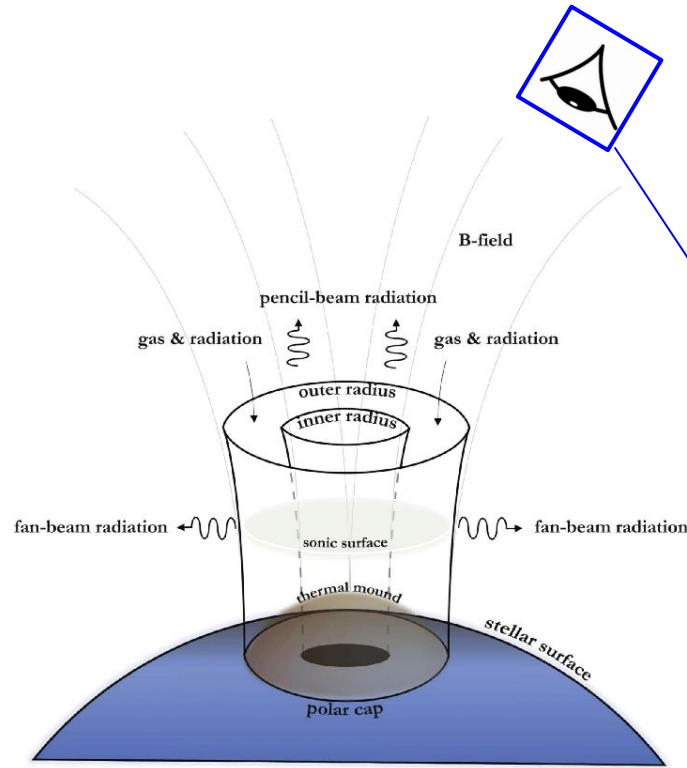
Primary vs Secondary peak

Primary peak:

- Higher flux
- **Smaller** cyclotron cross section

Secondary peak:

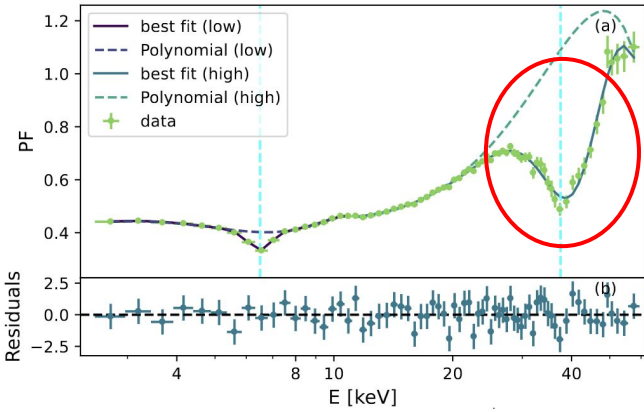
- Lower flux
- **Higher** cyclotron cross section



Opposite simple case: Her X-1

ObsID: 30002006005

Her X-1

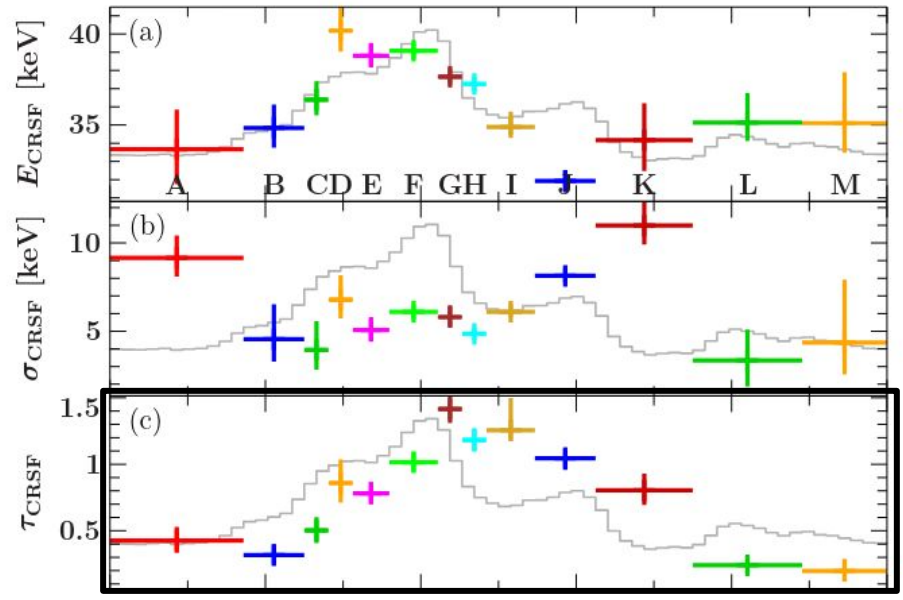


Ferrigno, D'Ai, Ambrosi 2023

Spin-dependent flux VS CRSF depth are correlated

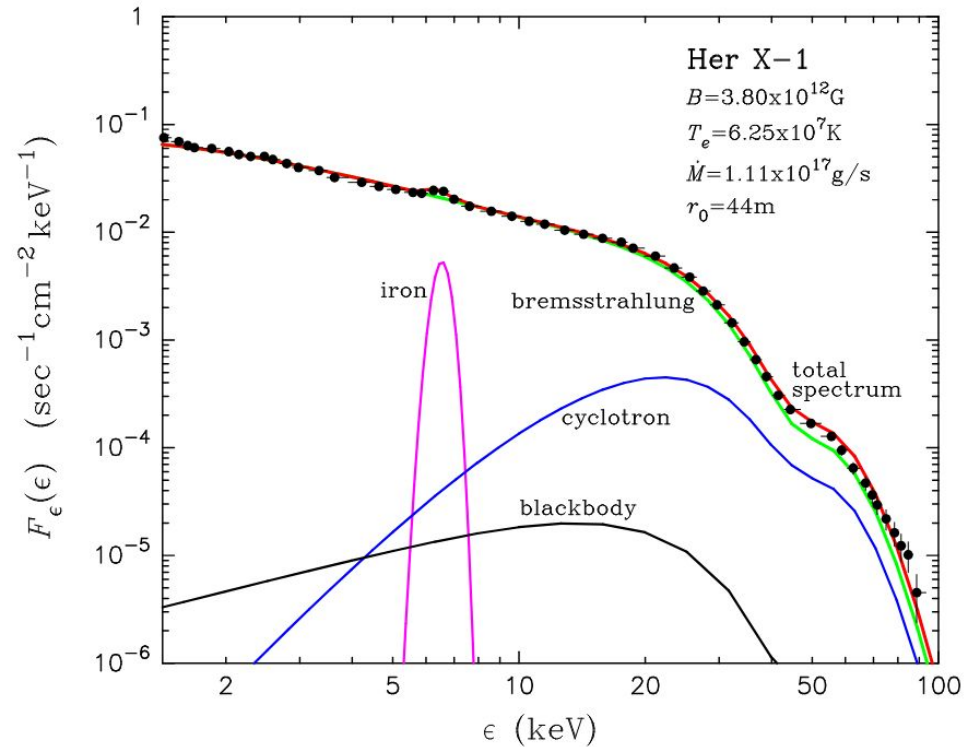
$\tau, F(\varphi) \rightarrow$ correlated

Fürst+2013



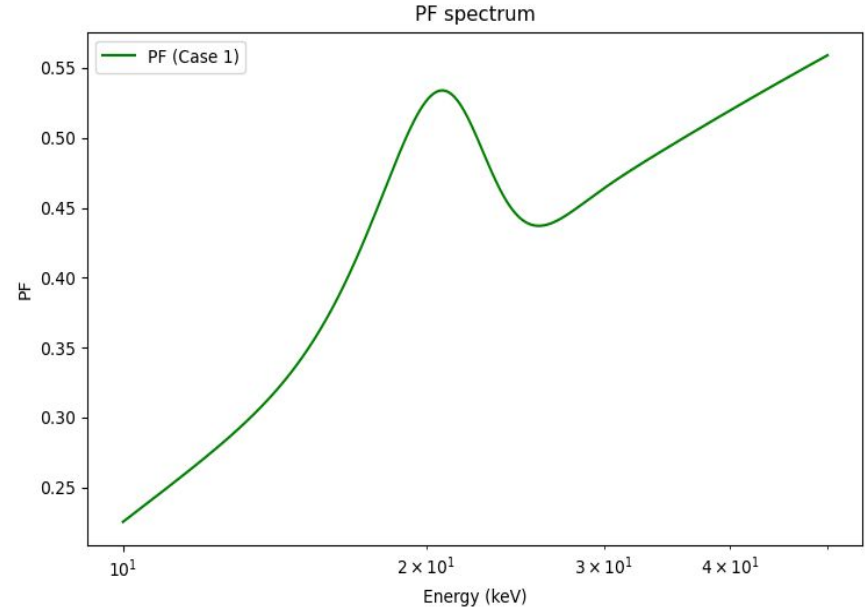
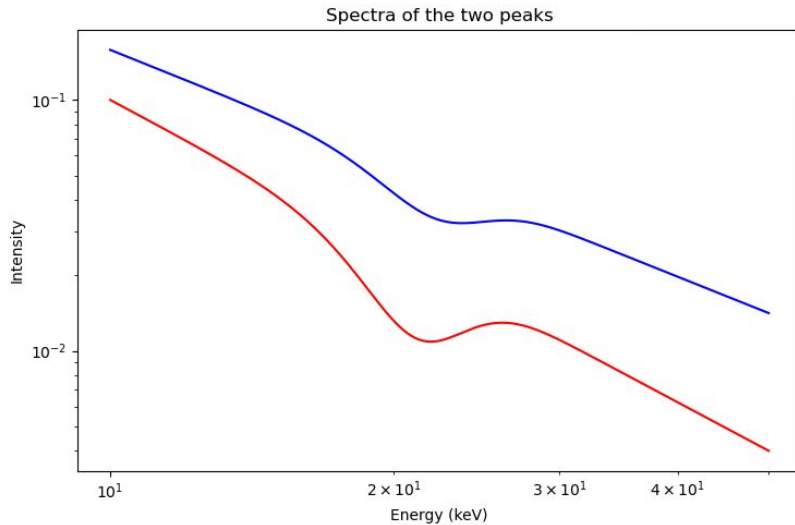
Physical processes with B&W model on Her X-1

(Becker&Wolf 2007)

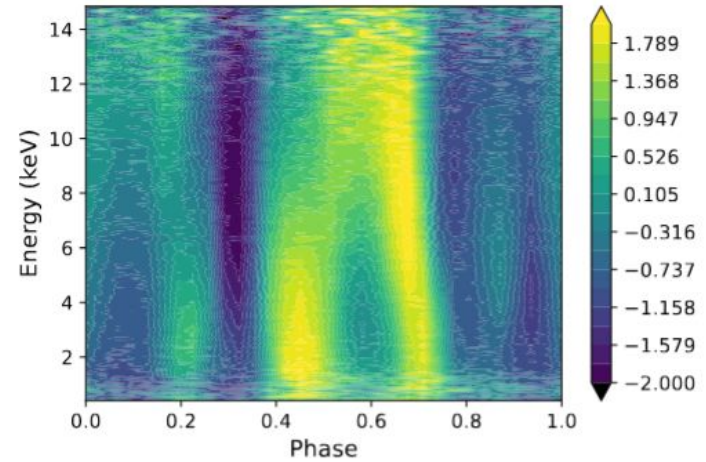
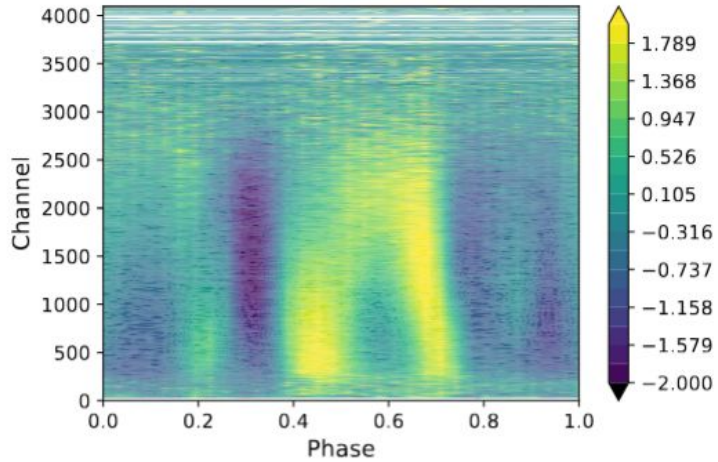


A very simple exercise: reproducing the PF

- Just 2 points for every energy bin
- No errors
- **PF = σ / μ** - root mean square **with zero errors (Coefficient of Variation)**



Channel phase \rightarrow Energy phase

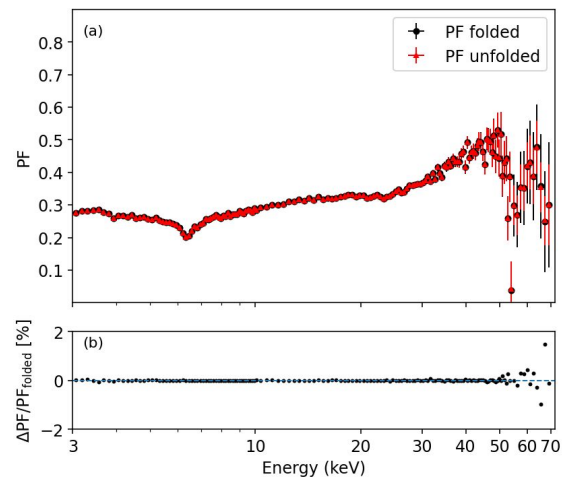
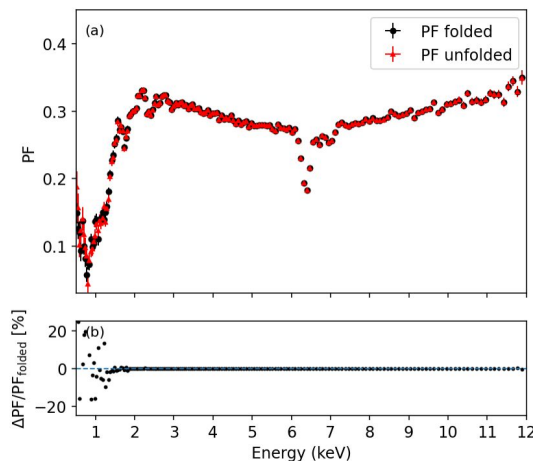


Redistribution effects

→ We used *nDspec** to unfold the energy-phase matrices, which uses Houck et al (2000):

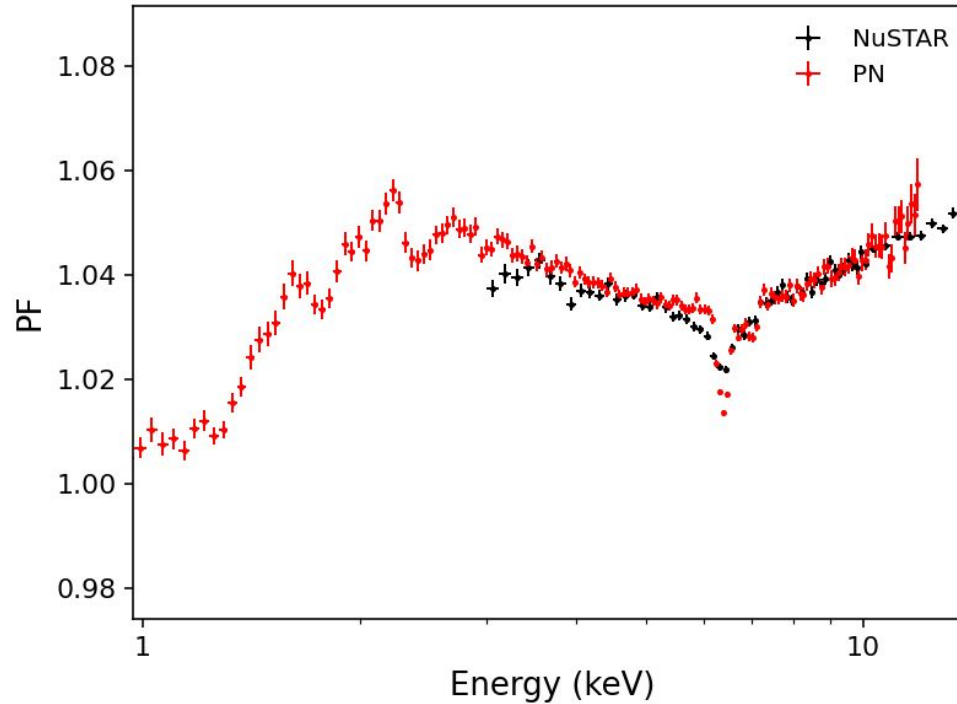
$$F(h) = \frac{C(h) - B(h)}{t \int_{\Delta E(h)} R(h, E) A(E) dE}$$

- NuSTAR: almost zero effects
- EPIC-pn: some effects under 2 keV

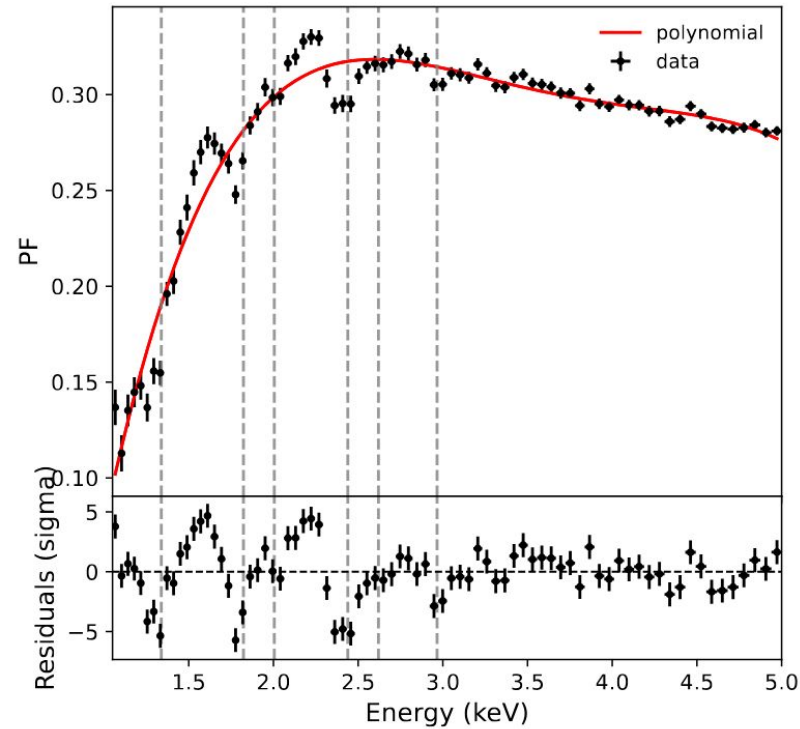


*<https://github.com/nDspec/nDspec>

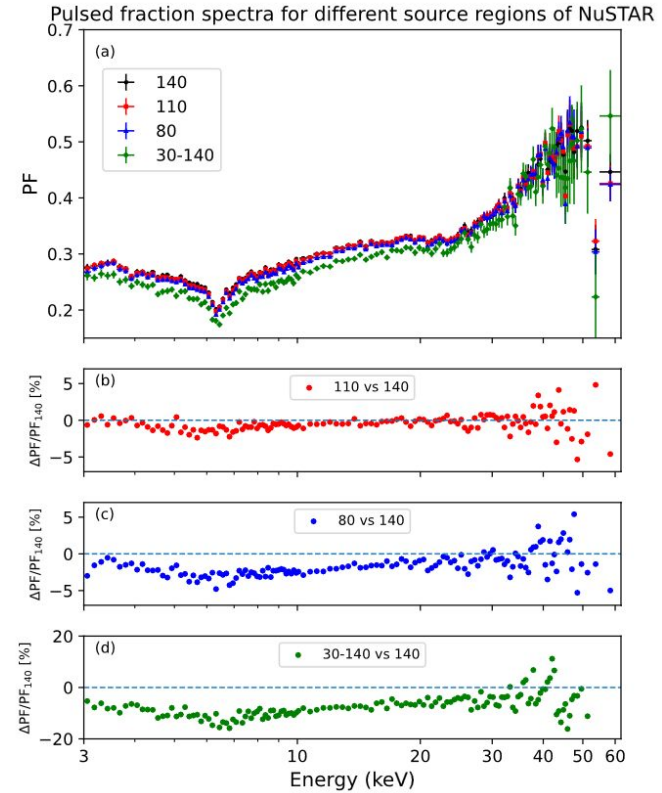
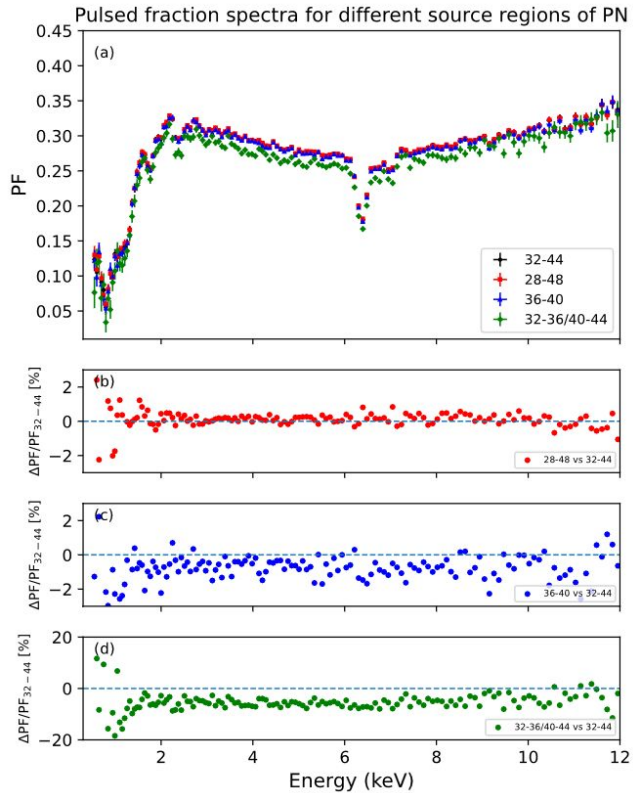
Without subtracting the mean of each pp

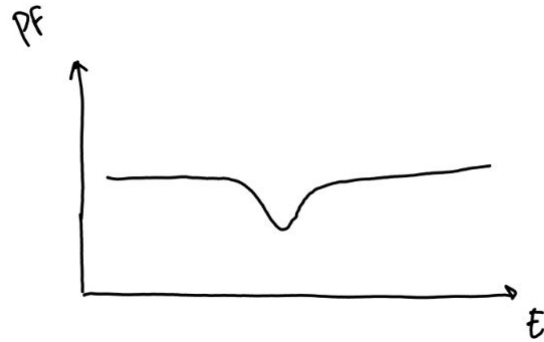
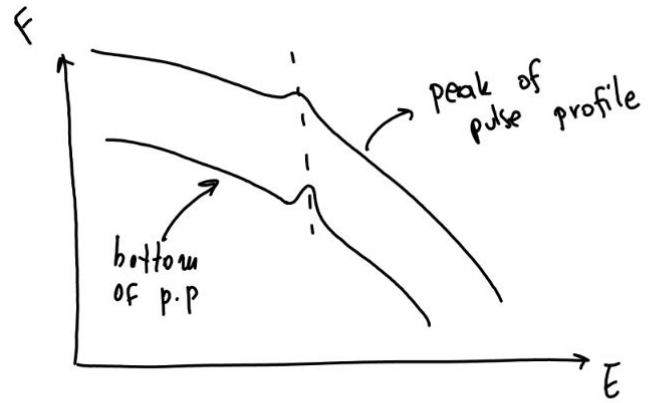


Polynomial used to identify local dips



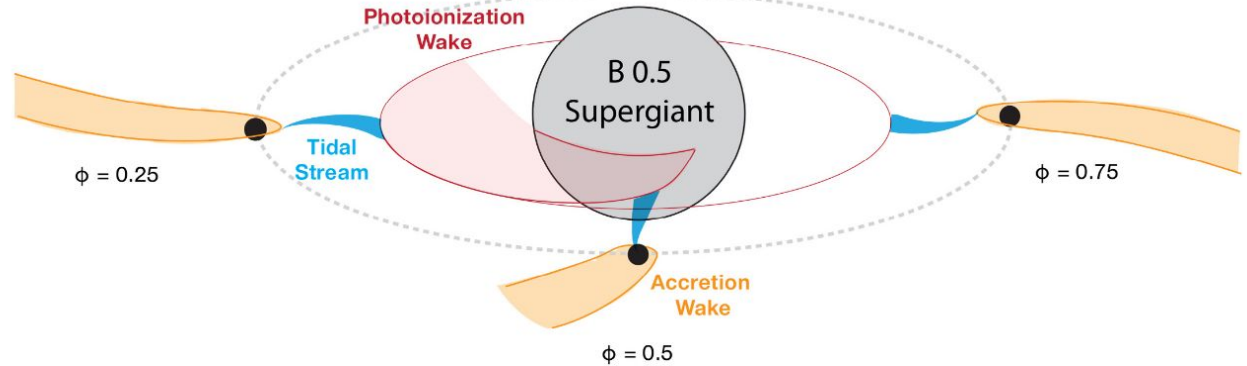
Source region selections





Extension of the methodology to XMM-Newton (EPIC-pn): application to Vela X-1

- sgHMXB
- $L \sim 4e36 \text{ erg s}^{-1}$
- $M \sim 1.7 - 2.2 \text{ Mo}$
- $M_{\text{donor}} \sim 23 \text{ Mo}$
- $e \sim 0.09$
- $P_{\text{orb}} \sim 8.96 \text{ days}$
- $P_{\text{spin}} \sim 283 \text{ s}$



Malacaria+ 2017

→ Archetypal wind accretor with strong n_H modulations with orbital phase, great to study timing signatures of soft X-ray lines in different orbital phases