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

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

Università degli Studi di Palermo

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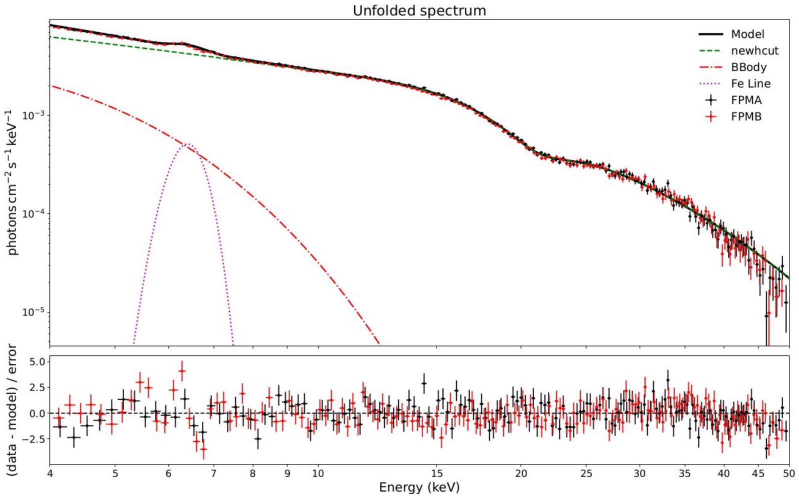
IASF Istituto di Astrofisica Spaziale e Fisica cosmica Palermo

INAF ISTITUTO NAZIONALE DI ASTROFISICA

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

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




Maniadakis+ 2025

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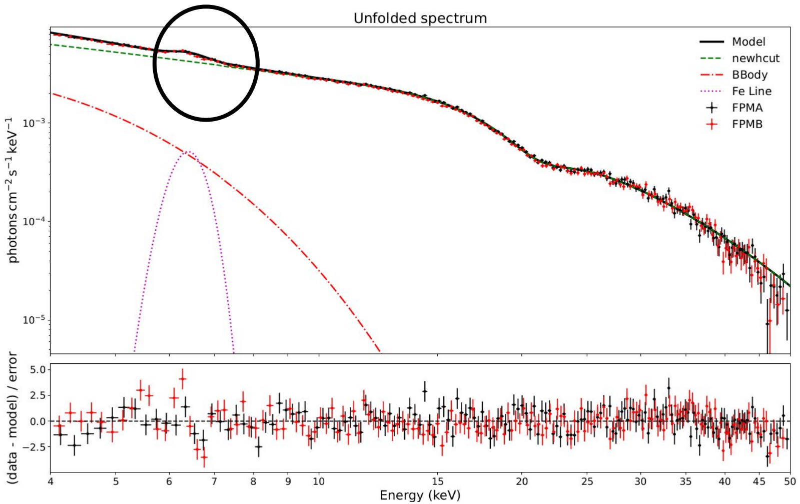


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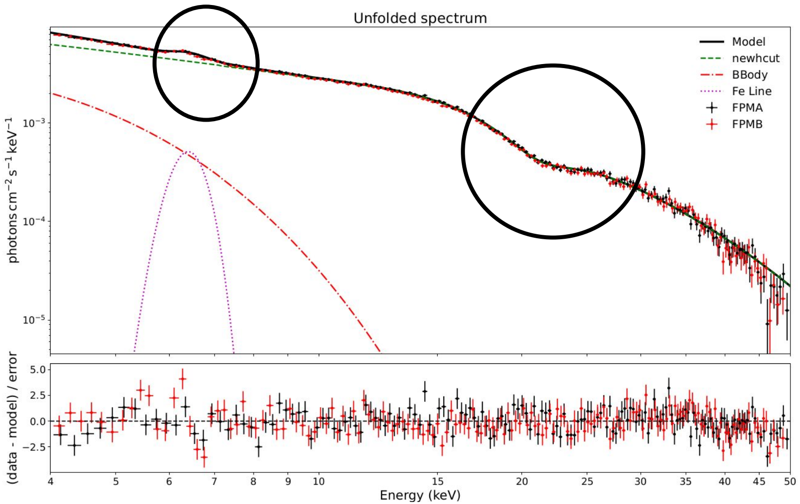


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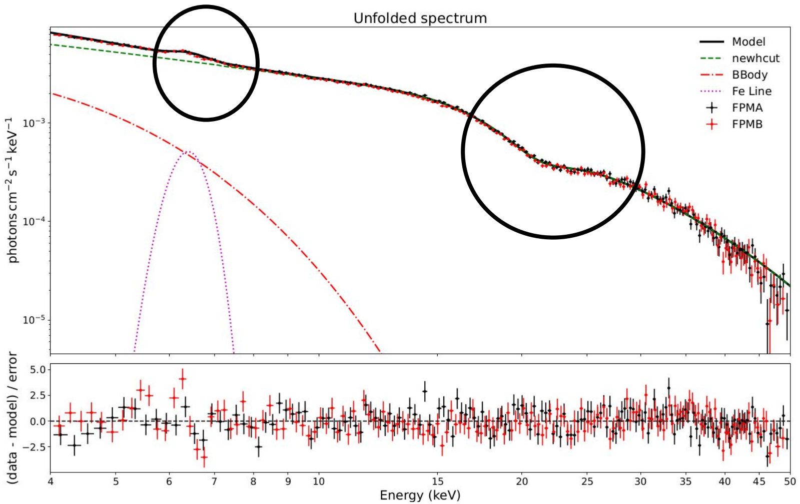


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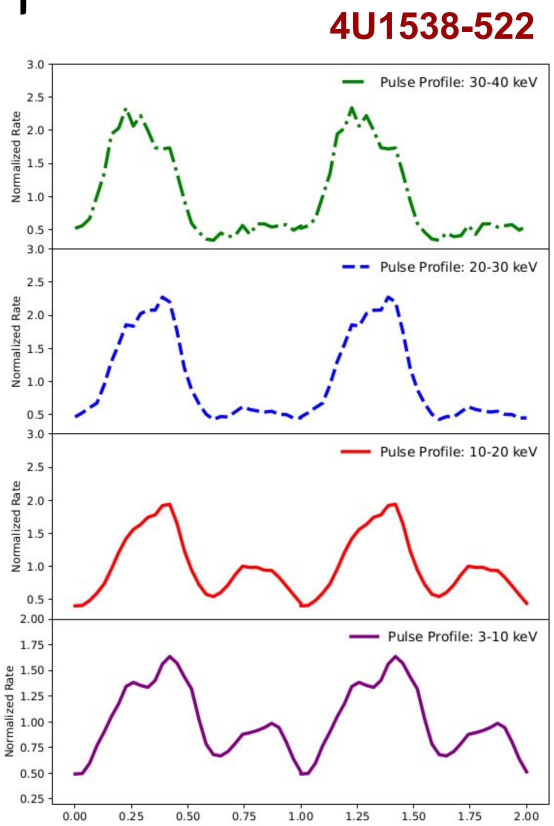
The X-ray spectrum is **not** the only place we look at to study these features in accreting pulsars though...

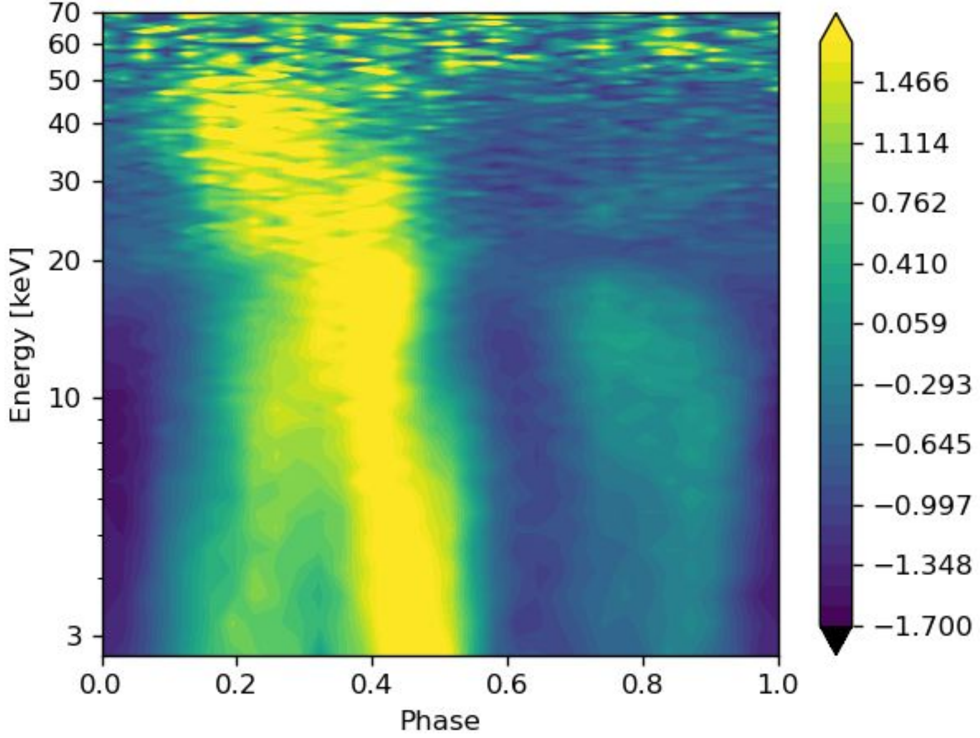
# Energy resolved pulse profiles

Different pulse profile **for different energy bands**

**Energy Resolved Pulse Profiles**



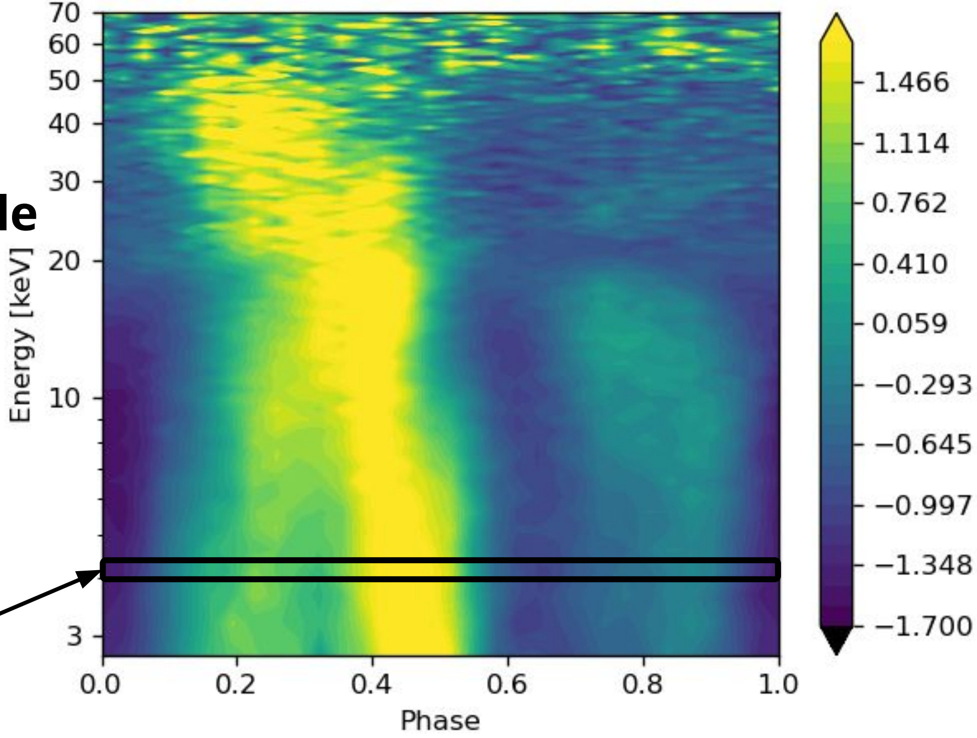
# Energy Phase Matrix



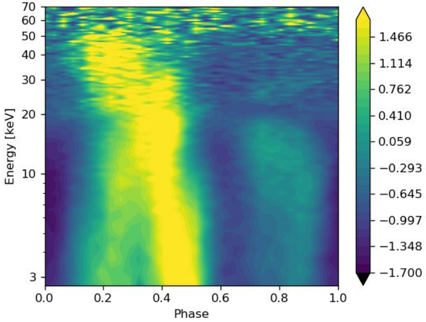

Energy-phase matrix: the matrix of all energy-resolved  pulse profiles of each energy bin of your instrument

# Energy Phase Matrix

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




# Energy Phase Matrix → Pulsed Fraction (PF) Spectrum



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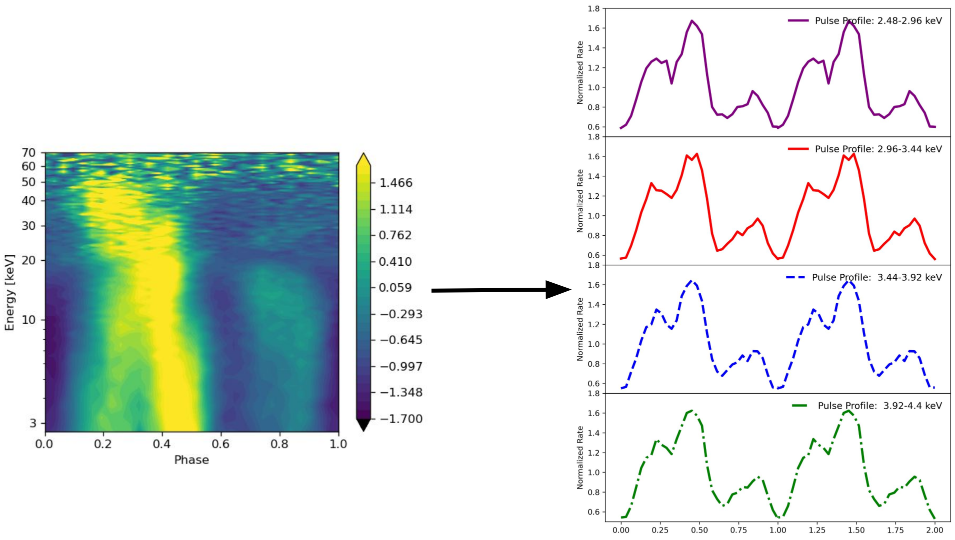


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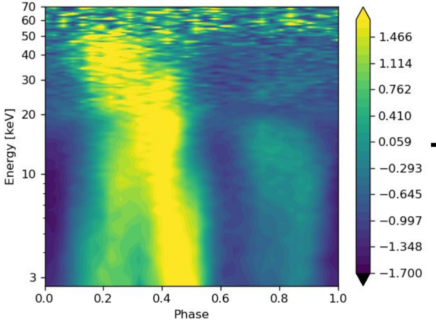
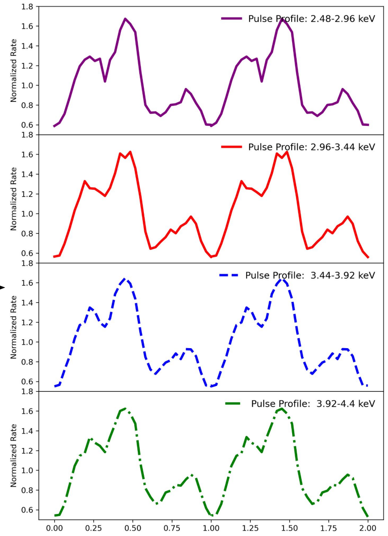
One pulse profile for **every energy bin!**
(100+ bins for NuSTAR, for a certain minimum SNR)

# Energy Phase Matrix ⟶ Pulsed Fraction (PF) Spectrum

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$$PF_{\mathrm{rms,c}} = \frac{\sqrt{\Sigma_{i=0}^{N}\left[(p_i - \bar{p})^2 - \sigma_{p_i}^2\right]/N}}{\bar{p}},$$ → PF (~2.7 keV)

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$$PF_{\mathrm{rms,c}} = \frac{\sqrt{\Sigma_{i=0}^{N}\left[(p_i - \bar{p})^2 - \sigma_{p_i}^2\right]/N}}{\bar{p}},$$ → PF (~4.2 keV)

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PF ( ~ 25 keV)

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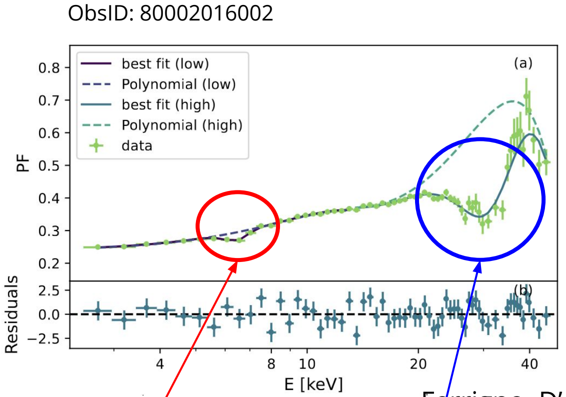
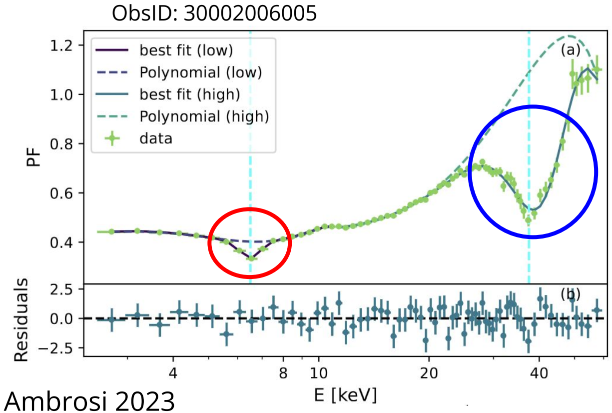
Calculate the **PF on that energy bin** by using the root-mean-square

# Spectral feature signatures!

**Cep X-4**




**Her X-1**

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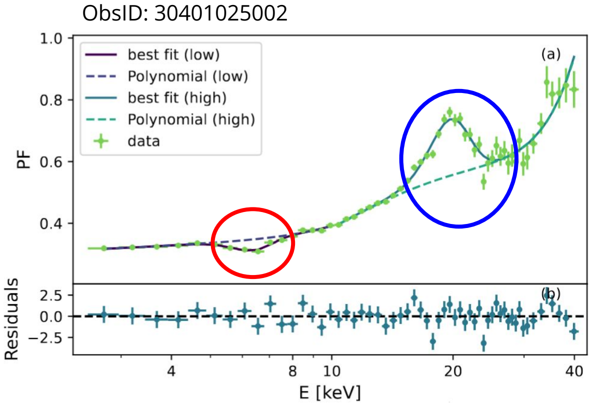
**4U 1538-52**

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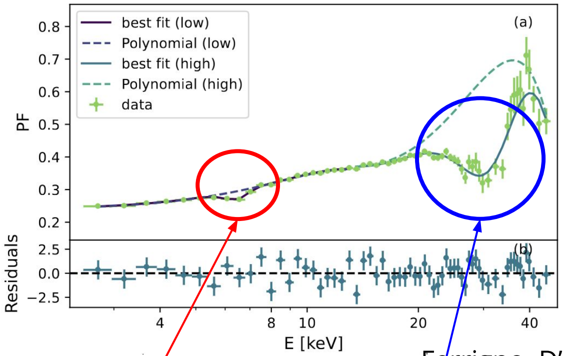
**Iron line**

**Cyclotron line**

# Spectral feature signatures!

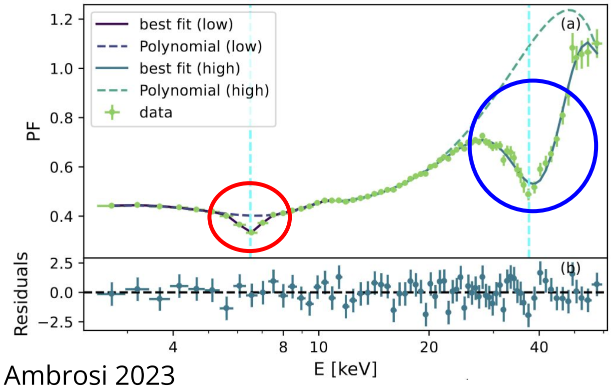
**Cep X-4**

ObsID: 80002016002




**Her X-1**

ObsID: 30002006005

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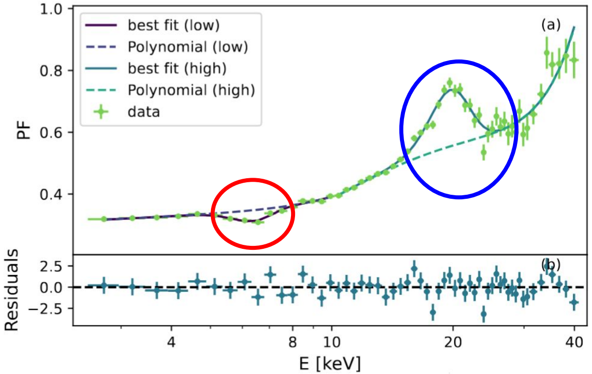
**4U 1538-52**

ObsID: 30401025002

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**Iron line**

**Cyclotron line**

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?

# Spectral feature signatures!

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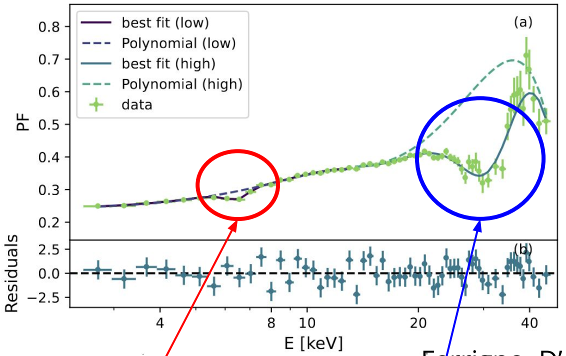


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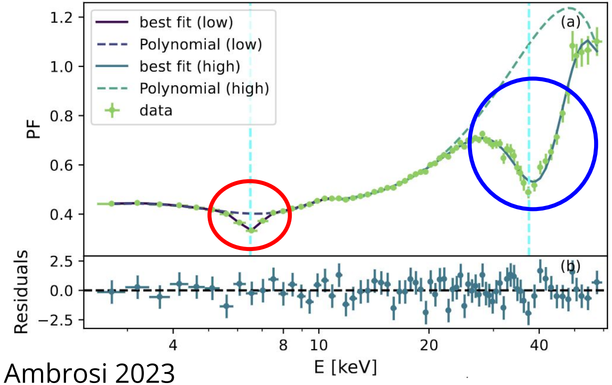


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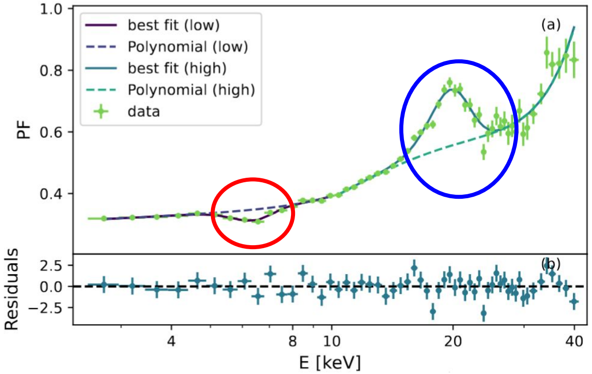


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**Iron line**

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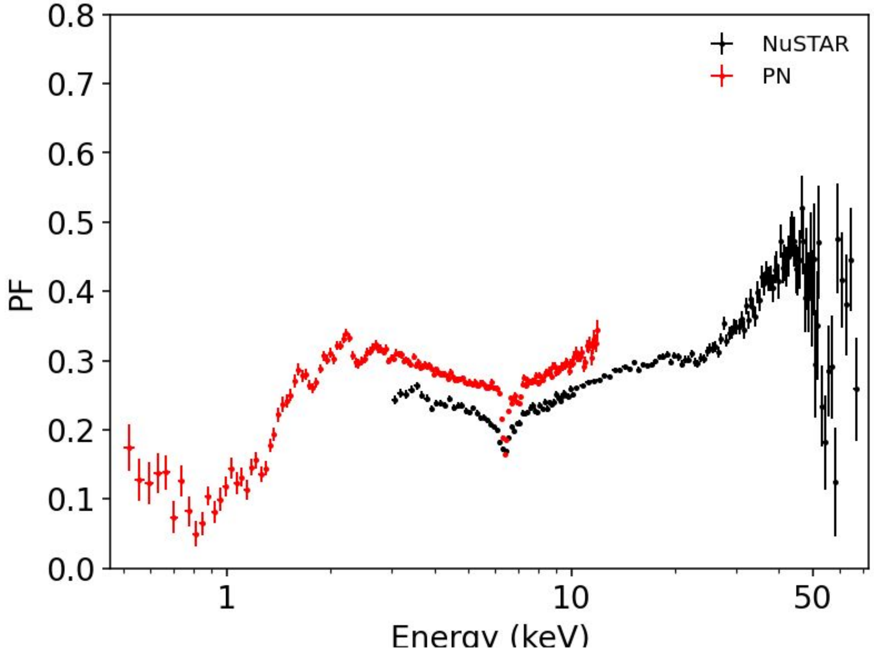
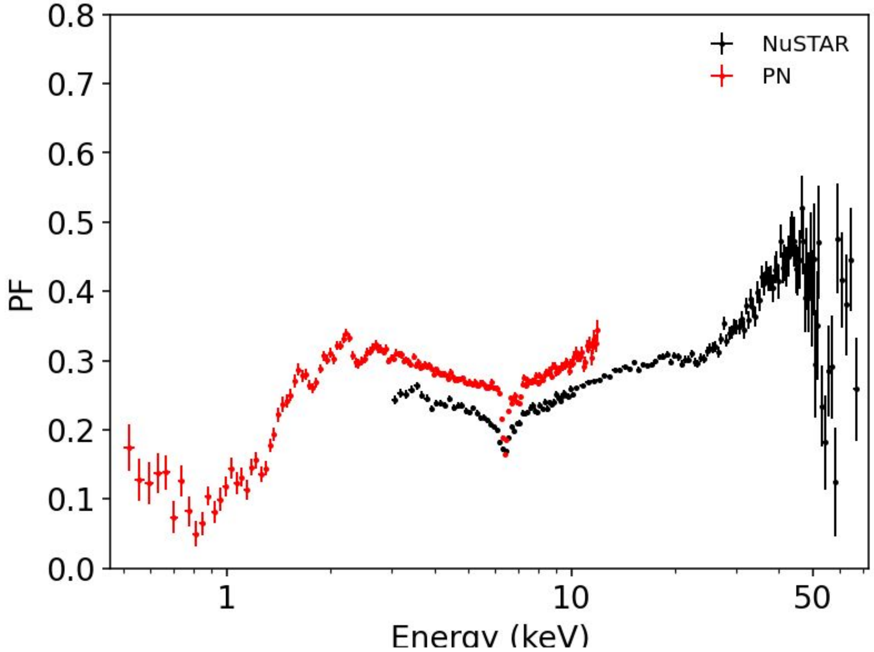
What about other X-ray instruments? How does the PF spectrum look in lower energies? Timing signatures of X-ray lines other than iron line?

**Extension to XMM-Newton...**

# Pulsed fraction spectrum of XMM vs NuSTAR




# Pulsed fraction spectrum of XMM vs NuSTAR





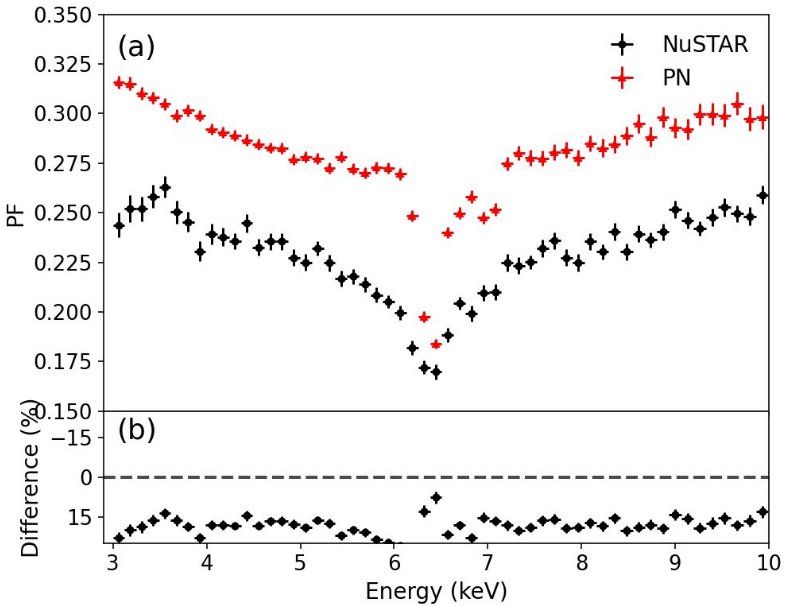
We have to investigate why…

# 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

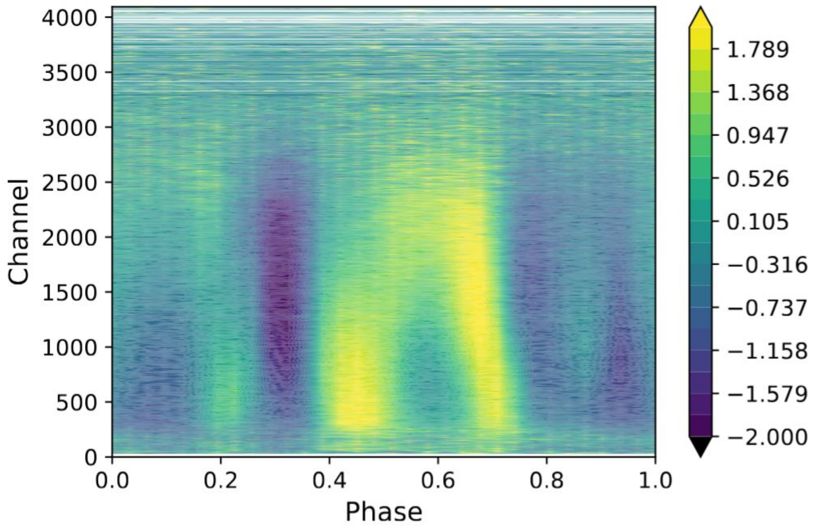
→ cross-calibrating issues between EPIC-pn and NuSTAR are known (e.g Fuerst+ 2022)




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

# Construction of the channel-phase matrix

1. Read from the event file, for each event: a) Channel b) Time
2. tag every photon with a phase bin and create the historgram $H_{ij}$ (i = channel, j = phase bin )
3. Calculate the exposure of each phase bin → count-rates




EPIC-pn data / Timing mode.
Source: Vela X-1
ObsID: 30501003002

# Construction of the energy-phase matrix

What we usually do: channel $\rightarrow$ energies with a linear relationship between channels and energies.

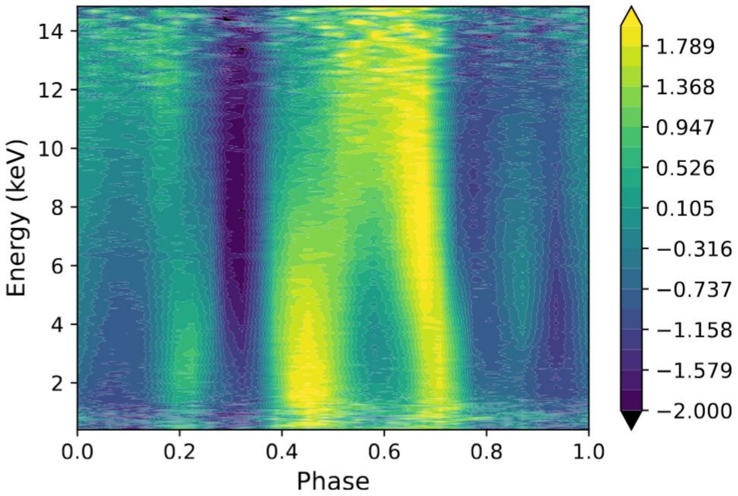
# Construction of the energy-phase matrix

What we usually do: channel → energies with a linear relationship between channels and energies.

**Better**: Go from channels to energies (and from count-rates to fluxes) by unfolding:

We used *nDspec** to pass from the channel-phase matrix to the energy-phase matrix, which uses Houck et al (2000) (ISIS):

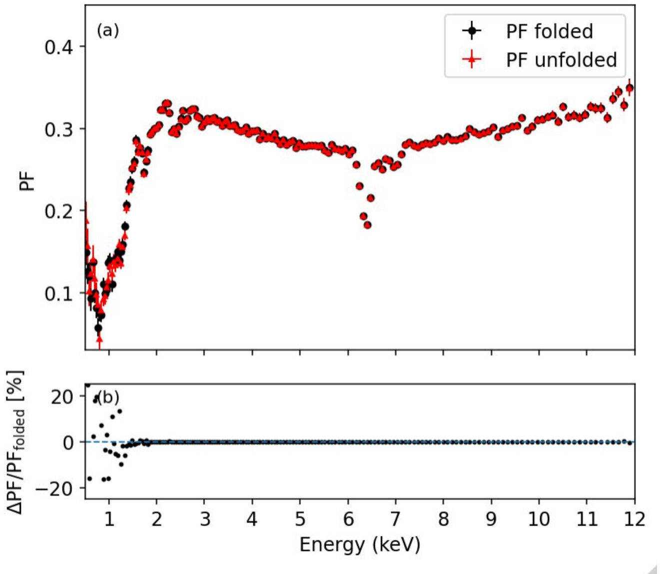
$$F(h) = \frac{C(h) - B(h)}{t \int_{\Delta E(h)} R(h,E)\, A(E)\, dE}$$

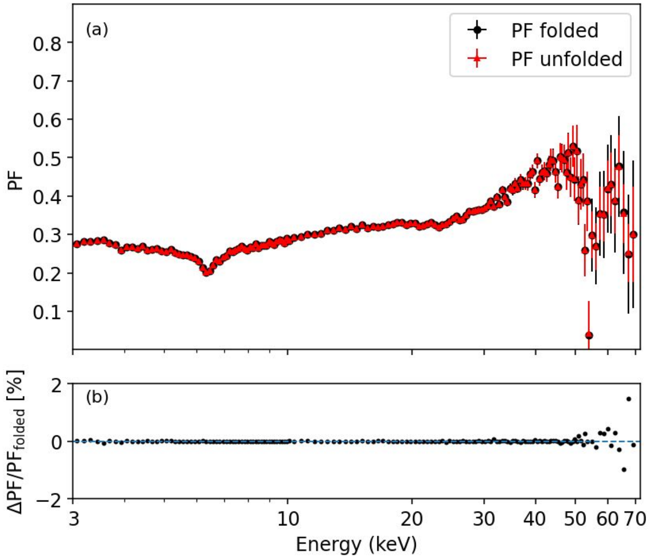



*https://github.com/nDspec/nDspec

# 1) Effect of redistribution on PF spectra

# Redistribution effects




EPIC-pn: some effects under 2 keV

NuSTAR: almost zero effects

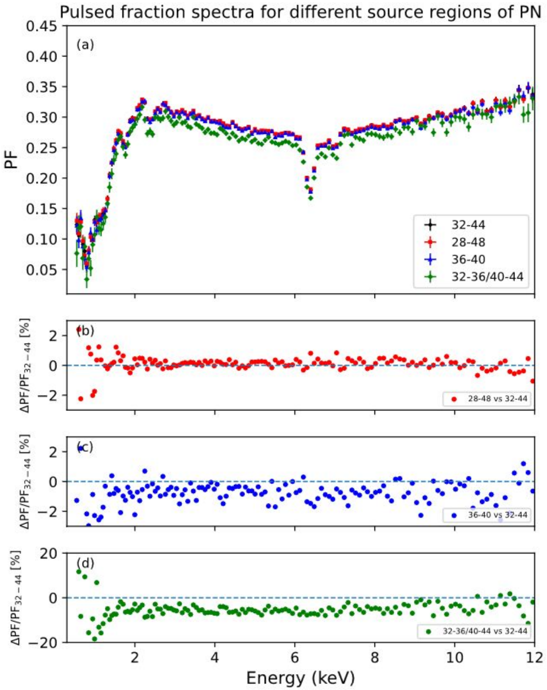
We use the PF spectrum to quantify the effect on pulse profiles

# 2) Effect of source region selection on PF spectra

# Source region selection

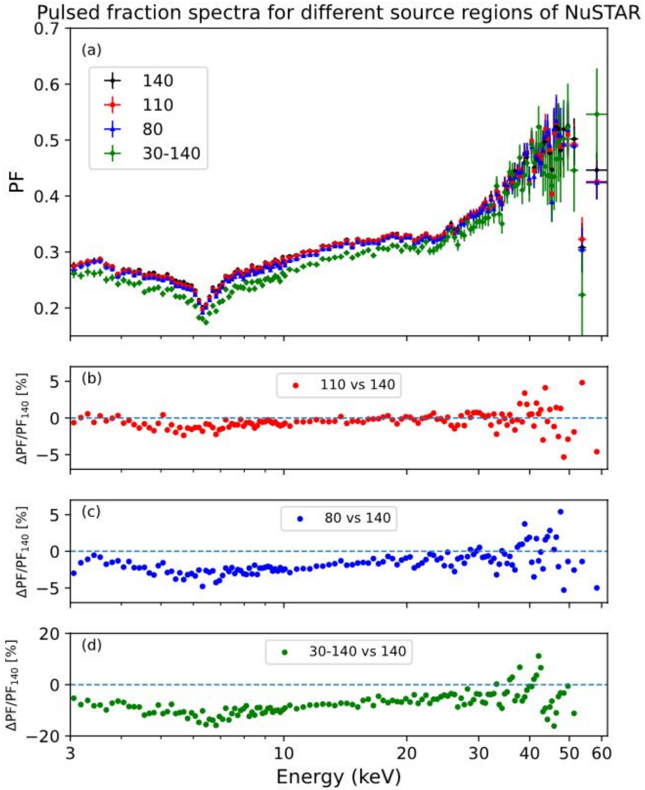
**EPIC-pn/Timing mode**: columns, central 4 columns piled-up (Diez+23)
**FPMA, FPMB**: 2D imaging, no pile-up

- We test the effect of the pile-up columns
- They don't cause significant energy-dependent variations on the PF values
- Neglecting them reduces all PF values, almost uniformly



# Source region selection

- We test also different extraction regions for FPM
- Excluding the source center also reduces the PF
- Therefore, the PF reduction in EPIC-pn is due to removing the central source region, not pile-up
- For both NuSTAR and EPIC-pn, we use the region giving the highest PF



# 3) Effect of count-rate corrections on PF spectra

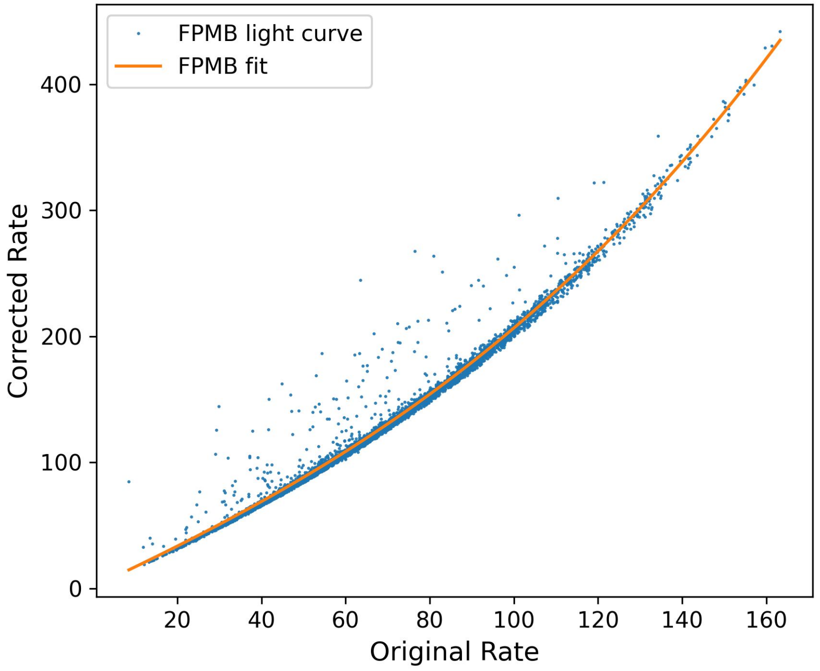
# Count-rate correction of NuSTAR

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



# 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**

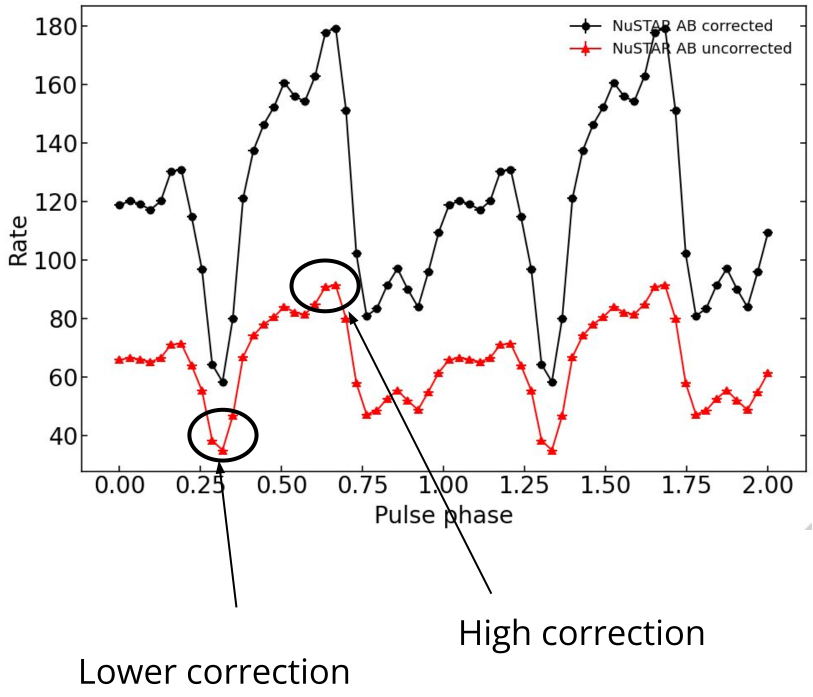
→ pulse profile shape changes (its being *stretched*)

→ **PF increases**

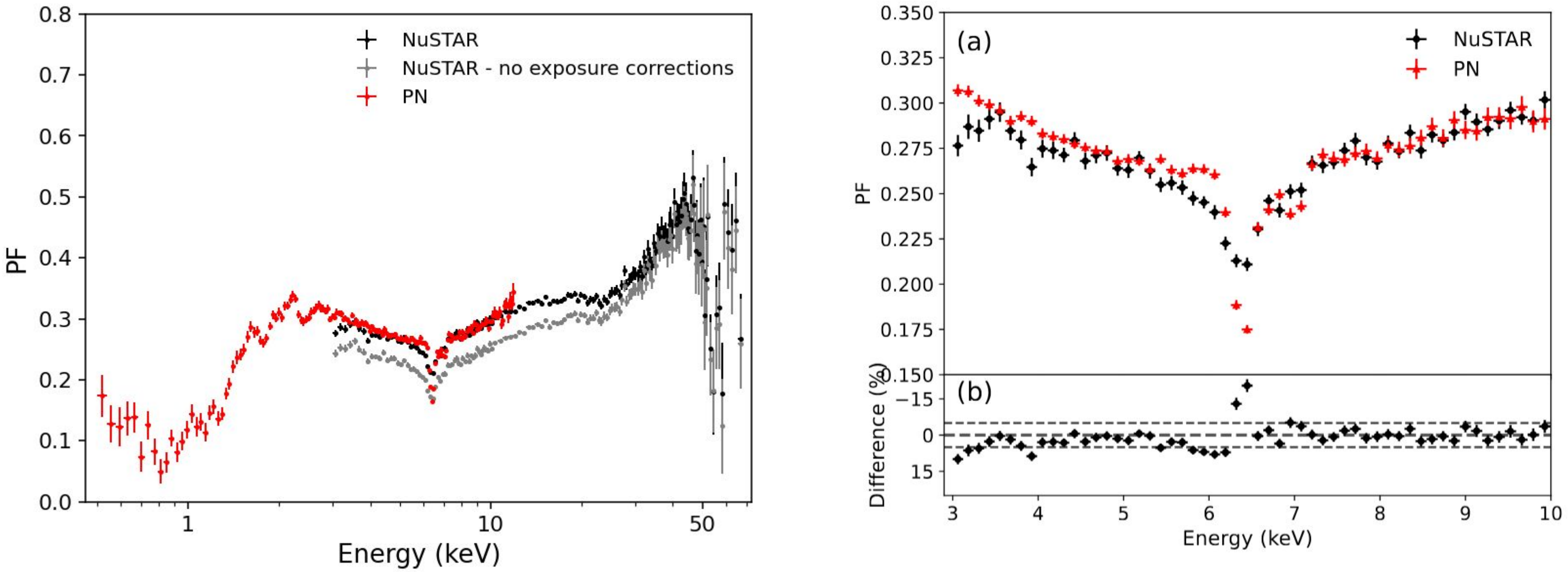
→ In EPIC-pn, the correction is ~0:

the relationship $R_{corr}$ vs $R_{orig}$ is linear which results to a rescaling of the pulse profile

**Pulse profiles 3 - 70 keV**



# Corrected PF spectrum




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

# PF spectrum as a cross-calibration tool

- Inter-mission cross-calibration between two instruments is usually built upon X-ray spectra

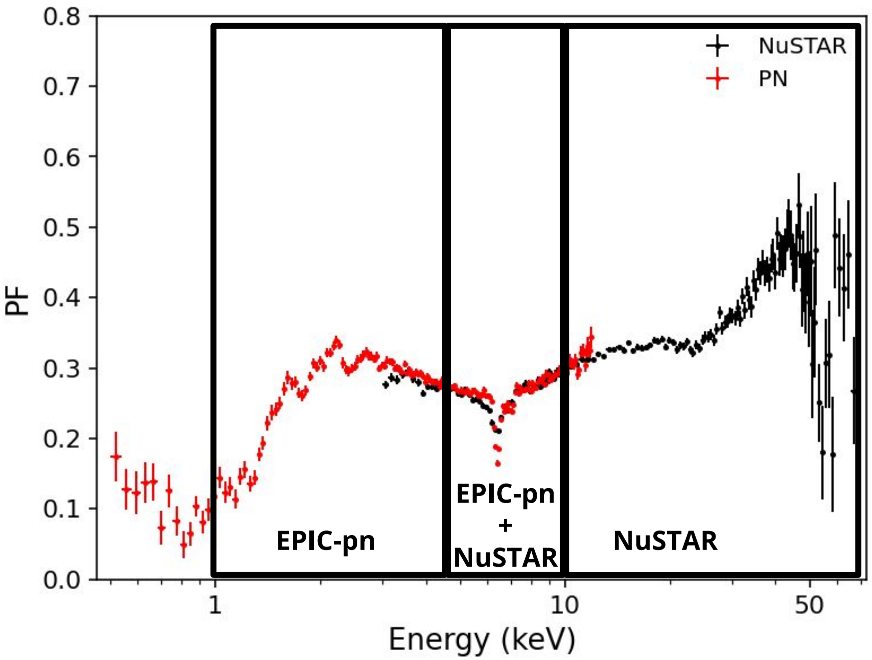
- We introduce the PF spectrum as a quantitative, complementary cross-calibration diagnostic for comparing energy-resolved pulse profiles between instruments.

- For EPIC-pn and NuSTAR, we find that the dominant correction is the NuSTAR livetime/count-rate correction: the differences are $\lesssim$5% in the overlapping 3-10 keV energy range, with remaining differences mainly in the iron line region due to the difference in energy resolution

# Thank you!

# Modeling the joint NuSTAR/EPIC-pn 1 - 70 keV PF spectrum

# Modeling the PF spectrum

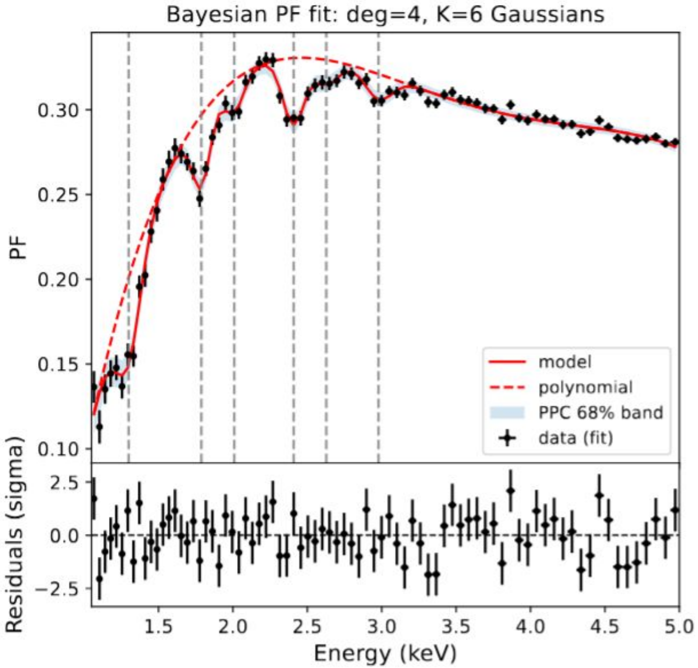



→ 1 - 5 keV: EPIC-pn data → Bayesian fitting
→ 5 - 10 keV: Simultaneous least-squares fitting of NuSTAR/EPIC-pn strictly simultaneous data
→ 10 - 70 keV: least-squares fitting of NuSTAR data

# Energy range: 1 - 5 keV: EPIC-pn data / Bayesian fitting

Gaussian priors:
- centroid energies
- widths of lines: energy resolution

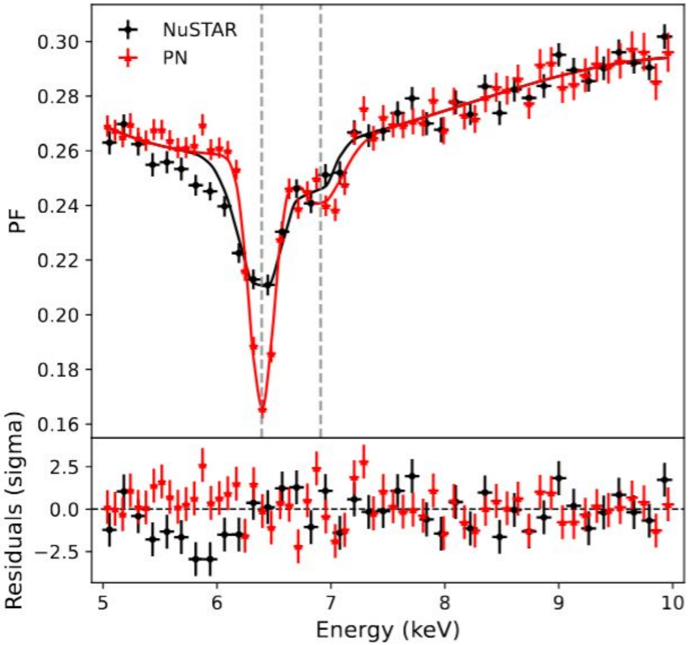
- Mg XI (f,i,r): $E_{ref}$ = 1.338 keV → $E_{pf}$ = 1.30 ± 0.01 keV
- Si XIII (f,i,r): $E_{ref}$ = 1.823 keV →$E_{pf}$ = 1.79 ± 0.01 keV
- Si XIV Lyα: $E_{ref}$ = 2.0049 keV → $E_{pf}$ = 2.01 ± 0.02 keV
- S XV (f,i,r): $E_{ref}$ = 2.439 keV → $E_{pf}$ = 2.41 ± 0.01 keV
- S XVI Lyα: $E_{ref}$ = 2.6207 keV → $E_{pf}$ = 2.63 ± 0.03 keV
- Ar VI–IX: $E_{ref}$ = 2.9661 keV → $E_{pf}$ = 2.98 ± 0.02 keV



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

- Centroid energies tied
- Widths free
- $\chi^2 = 128$ (85)

- Fe Kα: $E_{pf} = 6.393 \pm 0.005$ keV
- Fe Kβ...? : $E_{pf} = 6.91 \pm 0.03$ keV



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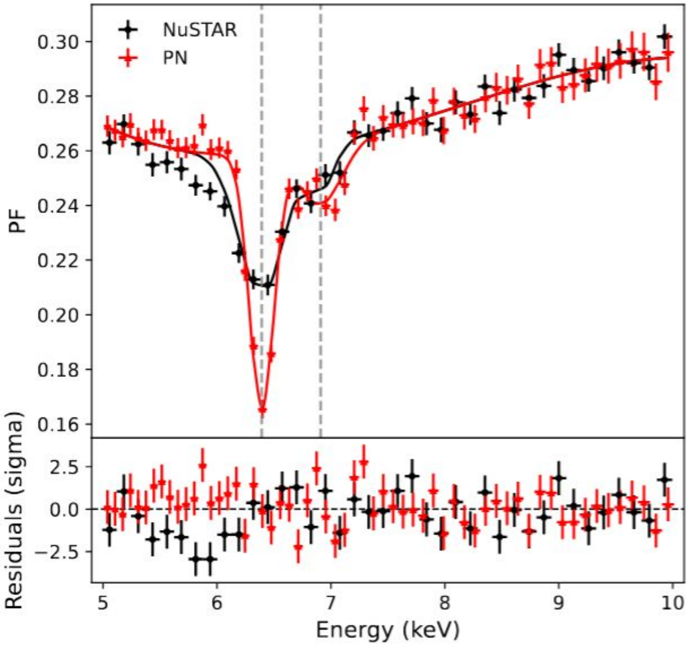
Residuals at the NuSTAR data (~6 keV):

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



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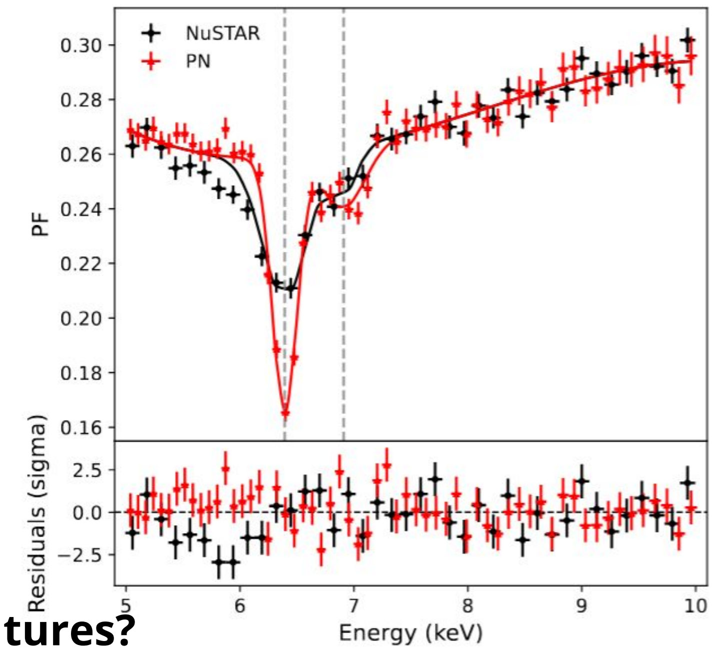



Residuals at the NuSTAR data (~6 keV):
- Different energy resolution can not be taken into account completely just by leaving the widths vary

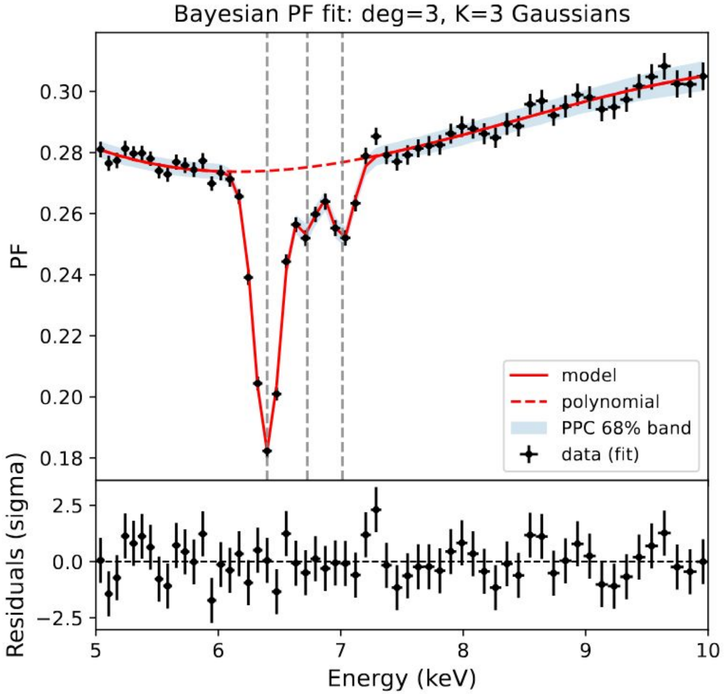
Residuals at the EPIC-pn data (~7 keV):
- 6.9 keV gaussians seems like trying to fit **two features?**
- We decide to conduct a Bayesian fitting to the full signal of EPIC-pn to investigate..

# 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 Kα: $E_{ref}$ = 6.4 keV → $E_{pf}$ = 6.399 ± 0.005 keV
- Fe XXV: $E_{ref}$ = 6.7 keV → $E_{pf}$ = 6.73 ± 0.03 keV
- Fe Kβ: Eref = 7.06 keV → $E_{pf}$ = 7.01 ± 0.02 keV

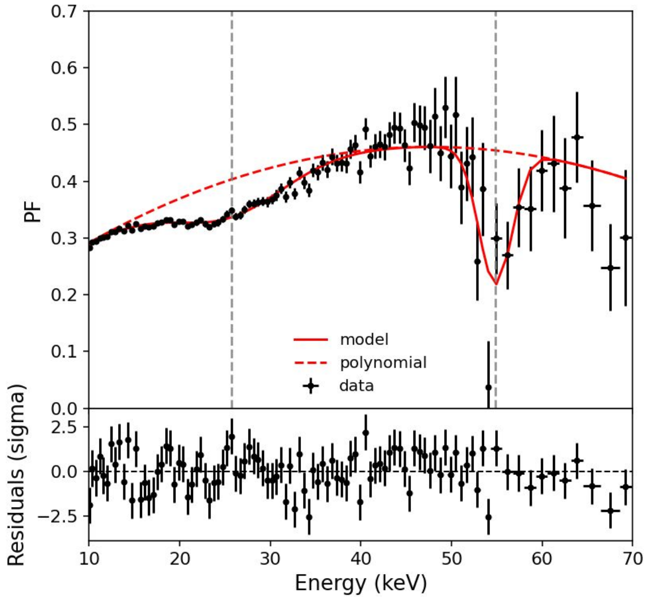


# Energy range: 10 - 70 keV: NuSTAR data / least-squares

- 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)

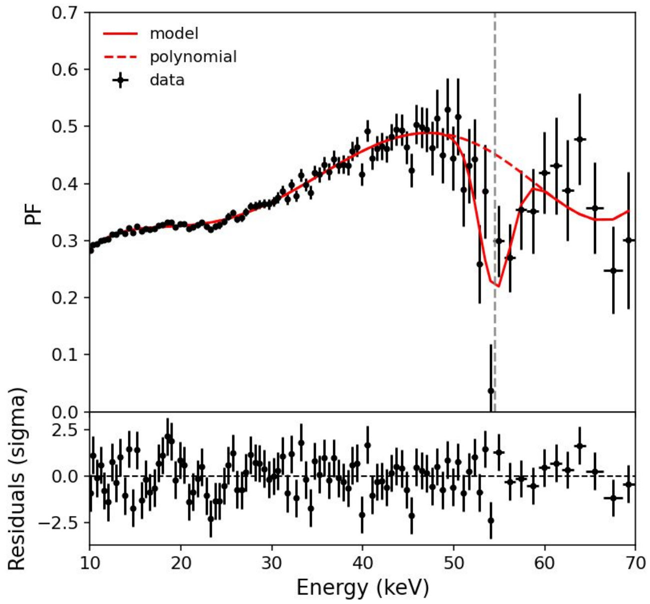


# Energy range: 10 - 70 keV: NuSTAR data / least-squares

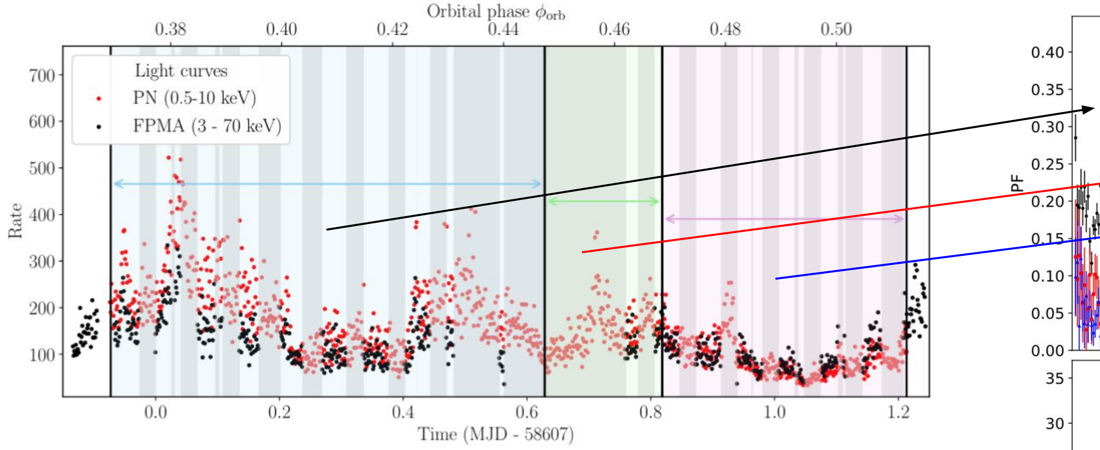
<u>Alternative model:</u>

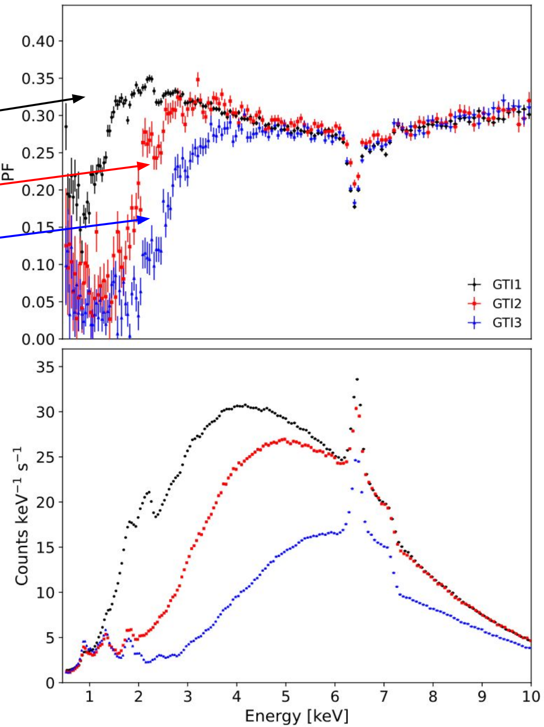
- Polynomial of 5nd degree + 1 gaussian
- $\chi^2 = 97$ (90)
- $E_2 = 54.5 \pm 0.62$, $\sigma_2 = 1.72 \pm 0.56$

Could the 25 keV feature attributed to something else?



# Orbital-phase-resolved soft EPIC-pn PF spectra




→ Dips are the strongest in the first obital-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 → 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

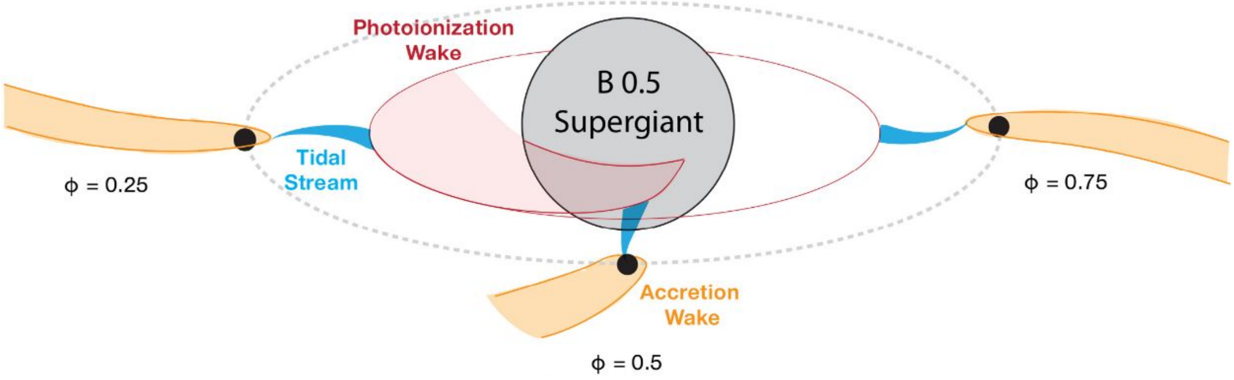
- After taking into account count-rate corrections (+other effects), the pulse profiles of the two instruments match

- The PF spectrum can be used as a cross-calibration tool between instruments

# BACKUP SLIDES

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

- sgHMXB
- L ~ 4e36 erg $s^{-1}$
- M ~ 1.7 - 2.2 Mo
- $M_{donor}$ ~ 23 Mo
- e ~ 0.09
- Porb ~ 8.96 days
- Pspin ~ 283 s

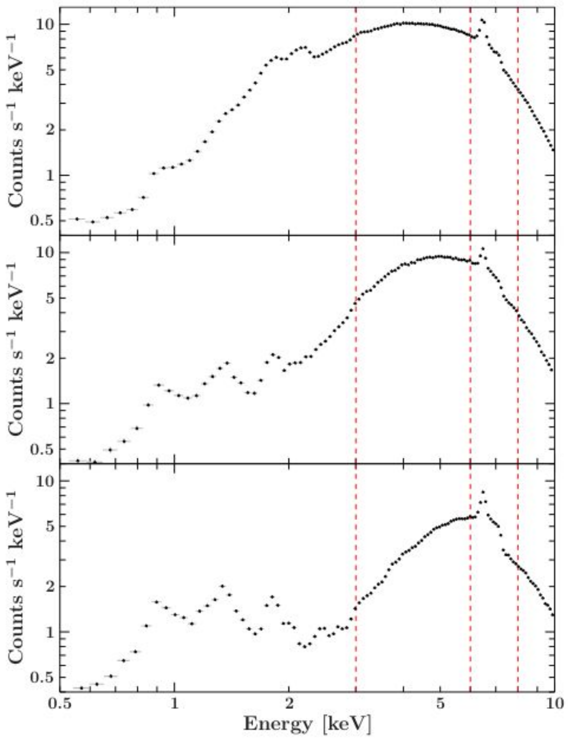


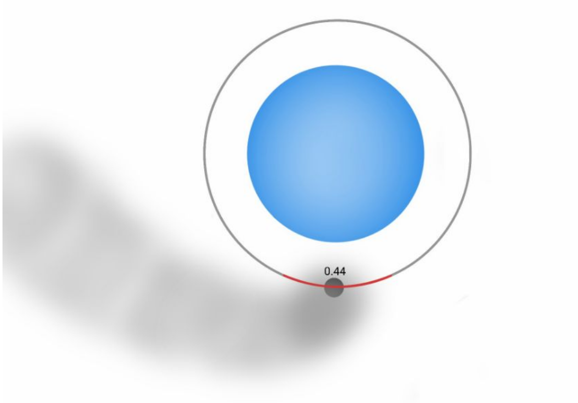

Malacaria+ 2017

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

# Simultaneous EPIC-pn / NuSTAR observations

nH increase



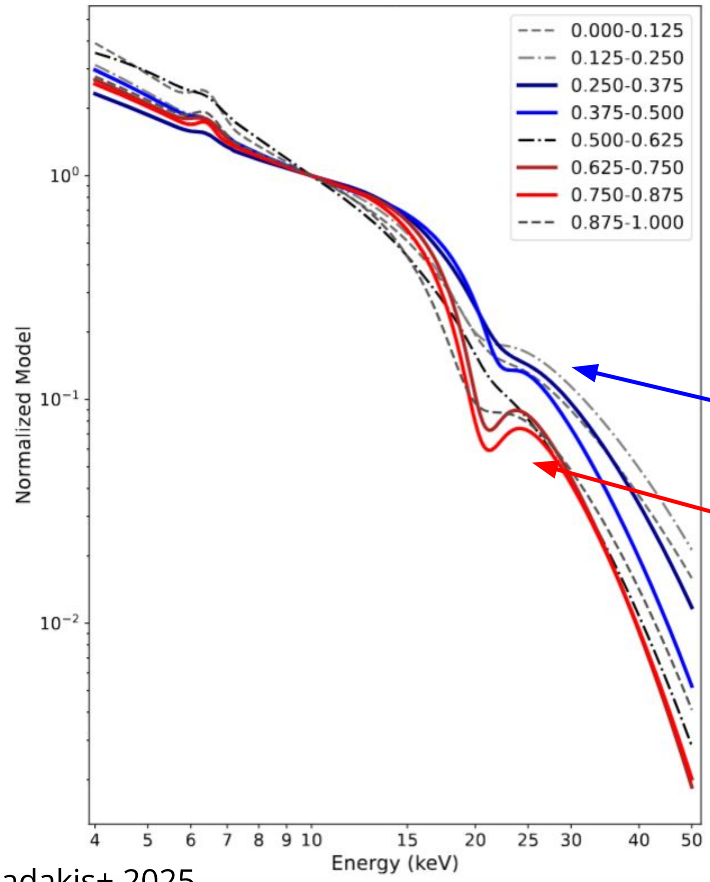

Diez+ 2023

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

# Orbital-phase-resolved PF spectroscopy results

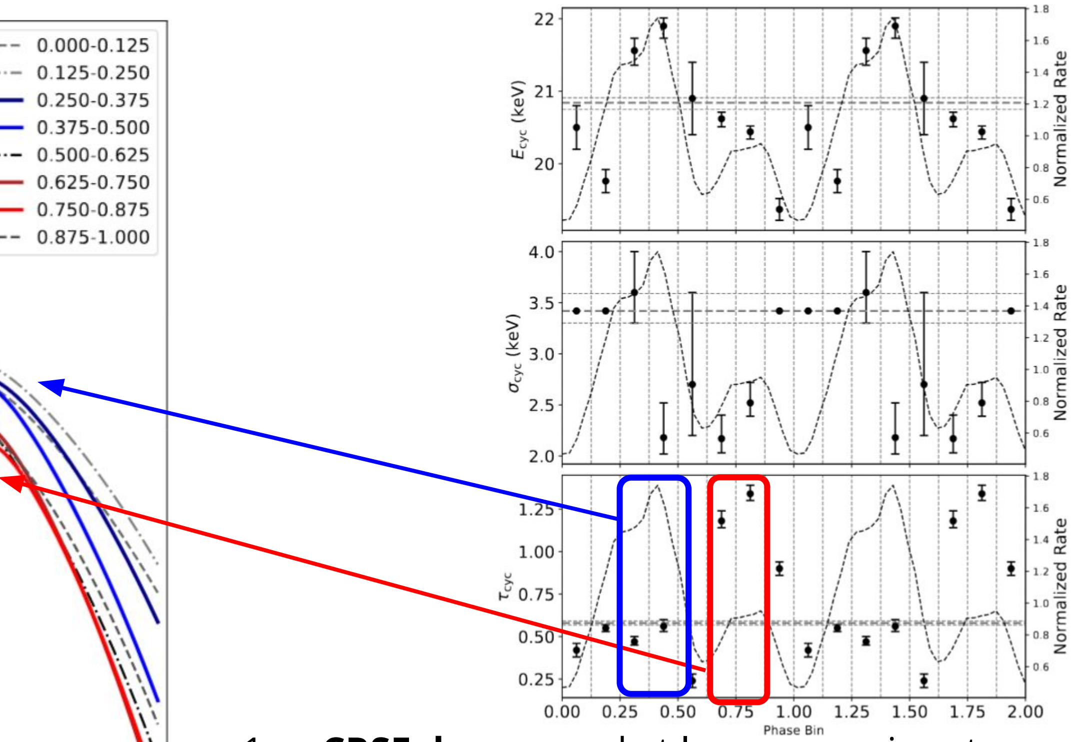
| Line | $E_{\rm ref}$ (keV) | GTI1 | | | GTI2 | | |
|---|---|---|---|---|---|---|---|
| | | $E_{\rm PF}$ | $\sigma_{\rm PF}$ | $\Delta$elpd ± dSE | $E_{\rm PF}$ | $\sigma_{\rm PF}$ | $\Delta$elpd ± dSE |
| Mg XI (f,i,r) | $1.338^{+0.012}_{-0.019}$ | 1.28 ± 0.01 | 0.06 ± 0.01 | 16.5 ± 7.0 | 1.41 ± 0.02 | 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$\alpha$ | 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




Maniadakis+ 2025

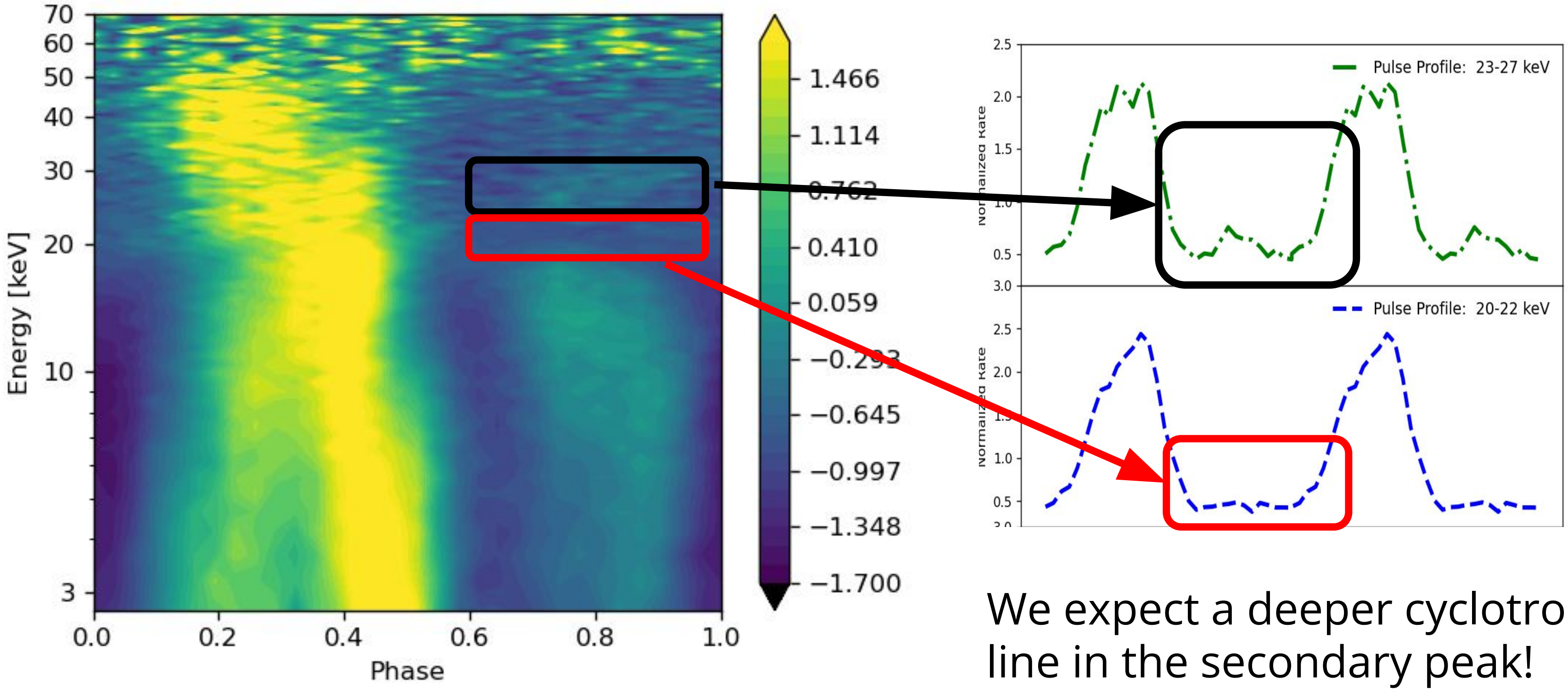
# Cyclotron line parameters variation




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**

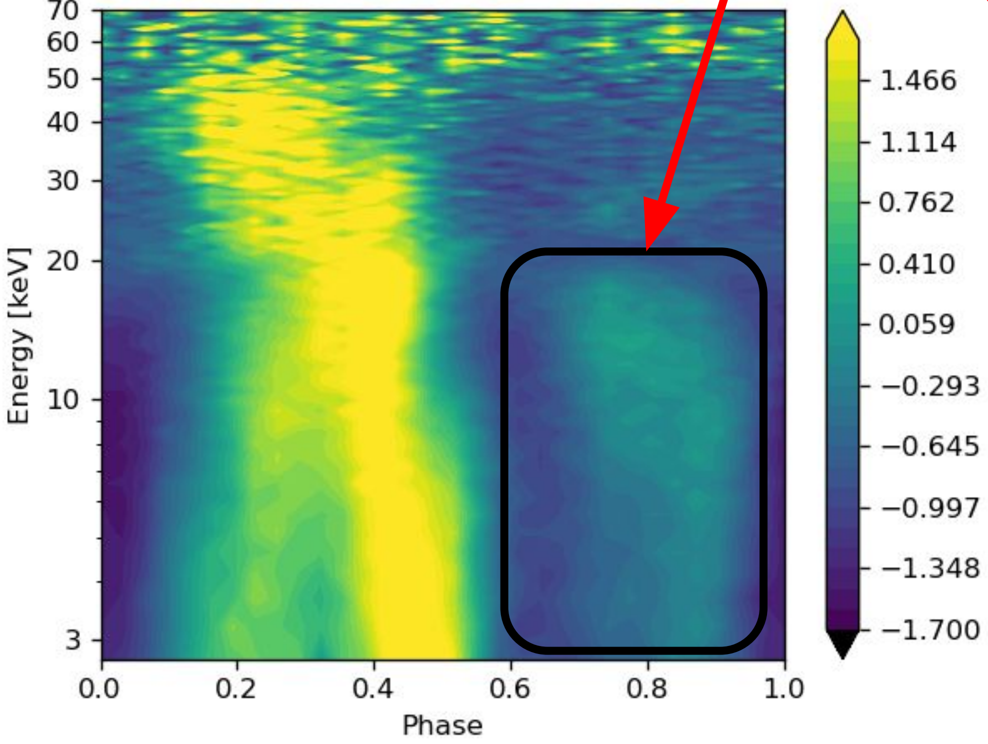


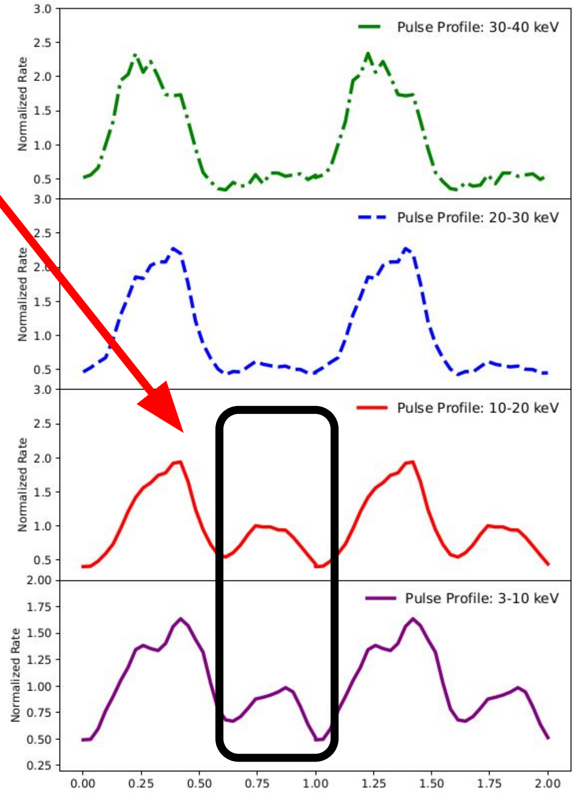

We expect a deeper cyclotron line in the secondary peak!

# Energy Phase Matrix

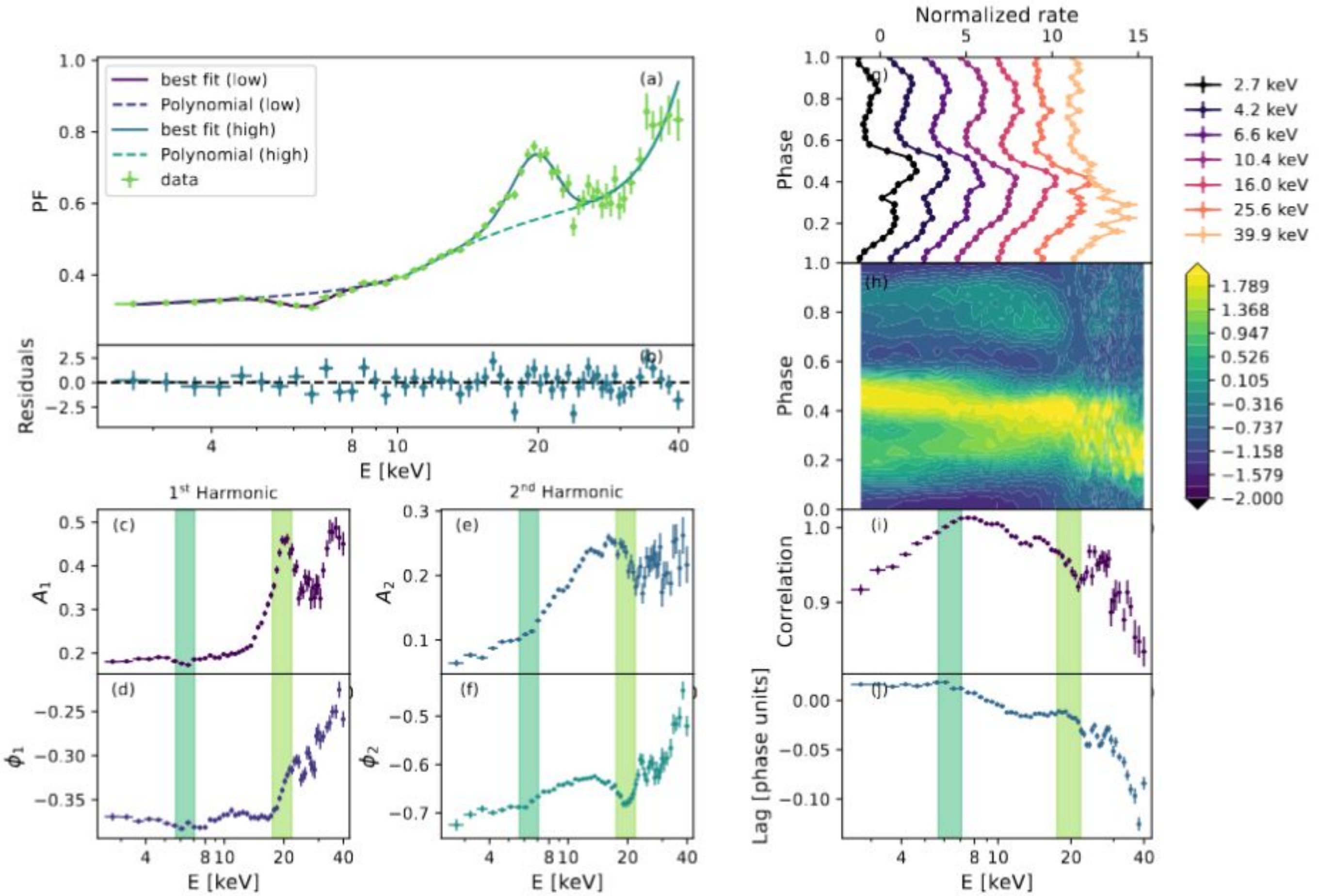
**Attention!** 2 periods shown in the pulse profile plots but only 1 in the matrix!

**Secondary peak at 3 - 20 keV**



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

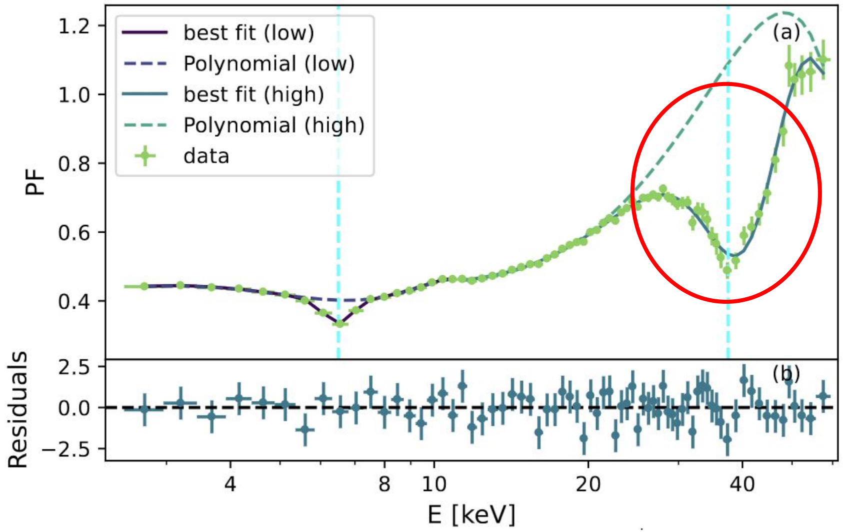


# Pulsed Fraction spectrum and cyclotron lines

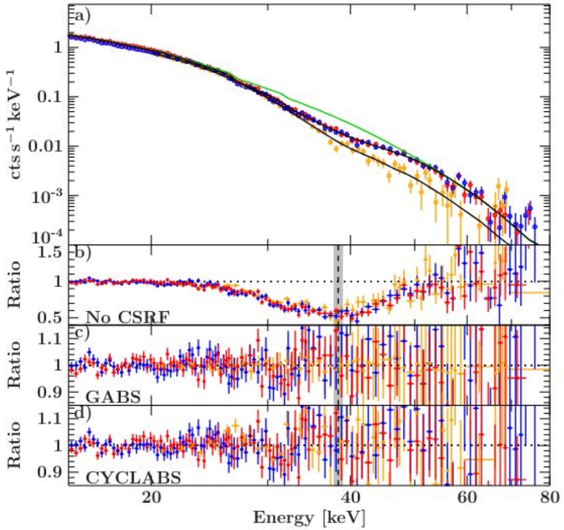
Ferrigno, D'Aì, Ambrosi 2023

**Her X-1**

Fuerst et al. 2023




Pulsed Fraction Spectrum: Phenomenological modelling with a polynomial + gauss



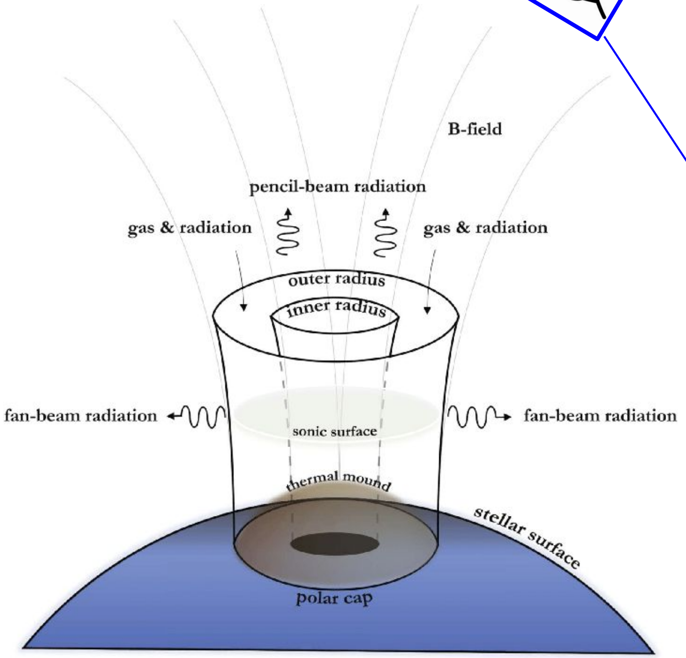

**Phase-averaged spectrum: the "traditional" spectrum we usually study**

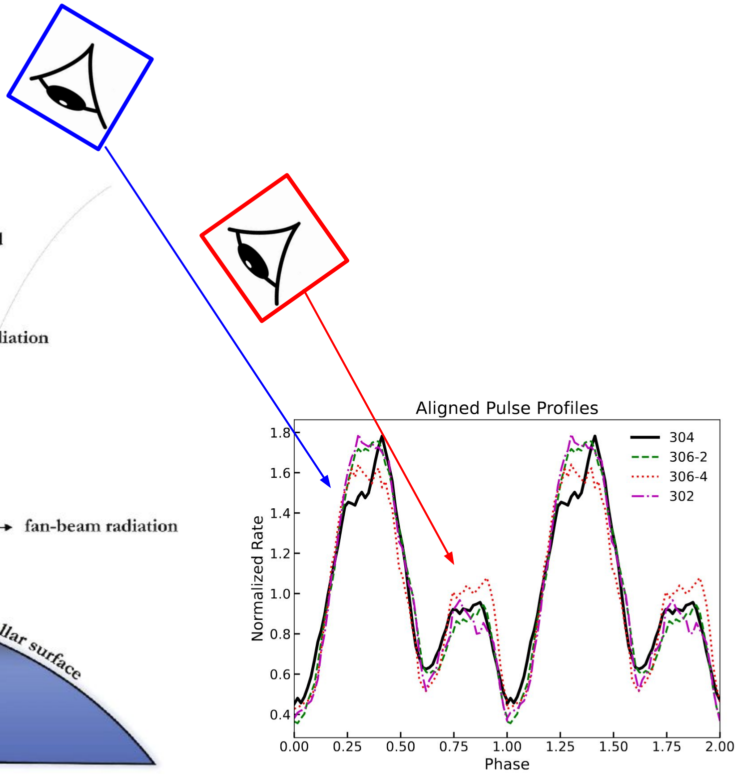
**cyclotron line in the X-ray phase-averaged spectrum → a dip in the pulsed fraction spectrum!**

# Primary vs Secondary peak

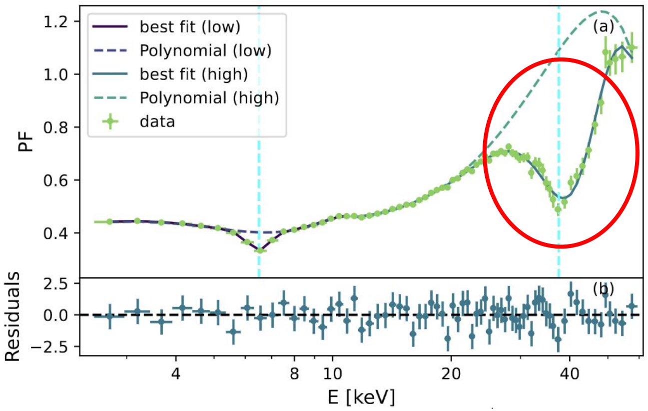
Primary peak:
- Higher flux
- **Smaller** cyclotron cross section

Secondary peak:
- Lower flux
- **Higher** cyclotron cross section



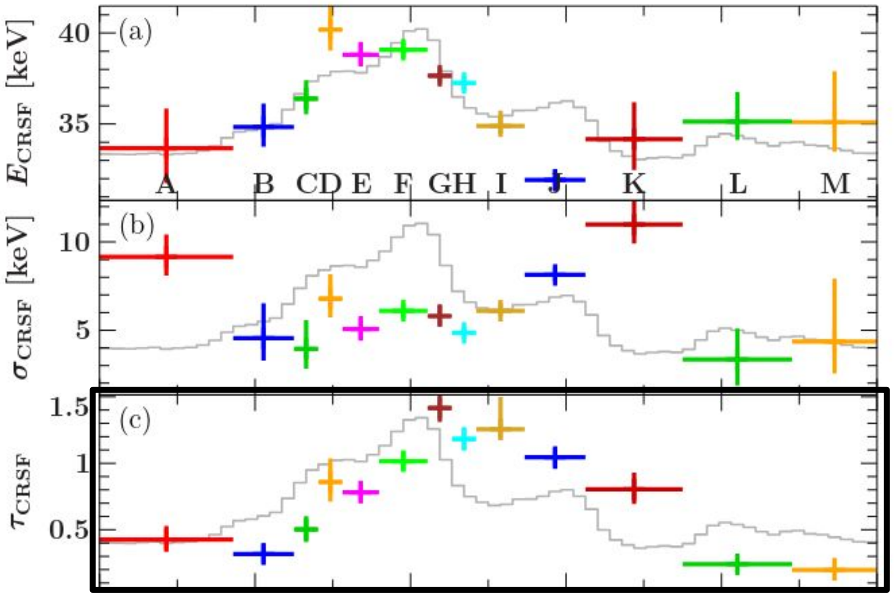



# Opposite simple case: Her X-1




Ferrigno, D'Aì, Ambrosi 2023

Fürst+2013

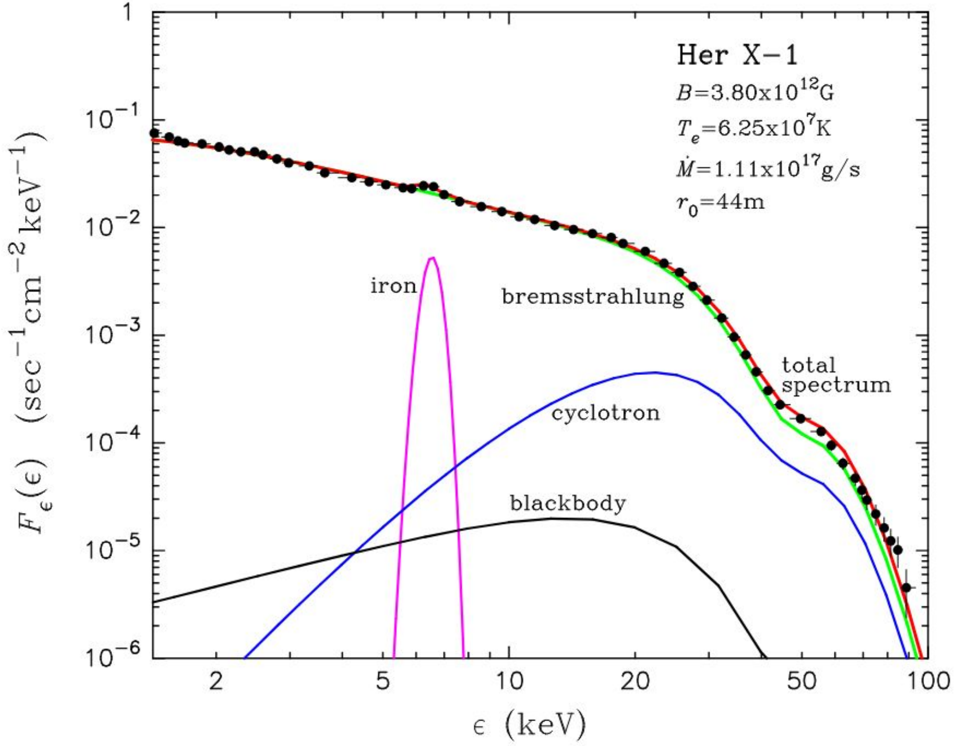



**Spin-dependent flux VS CRSF depth** are **correlated**

τ, F (φ) → correlated

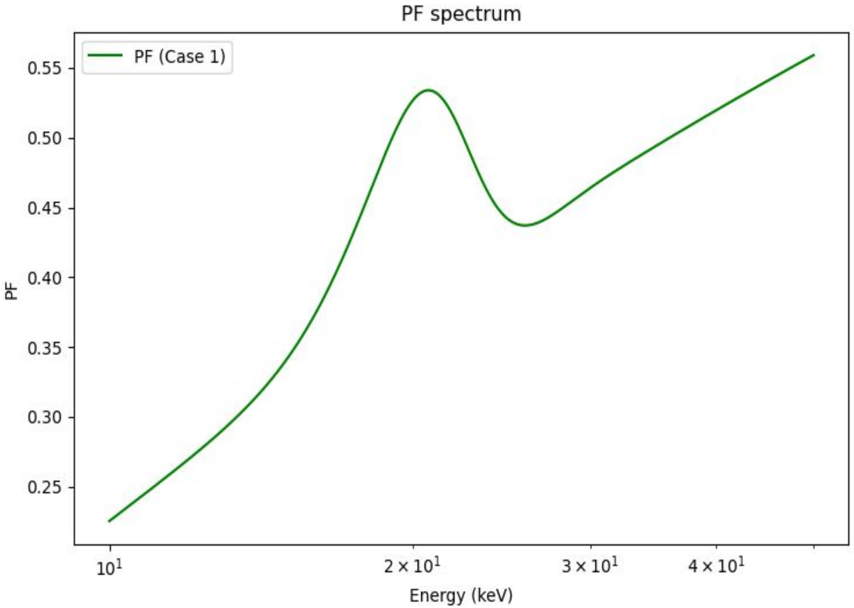
# Physical processes with B&W model on Her X-1

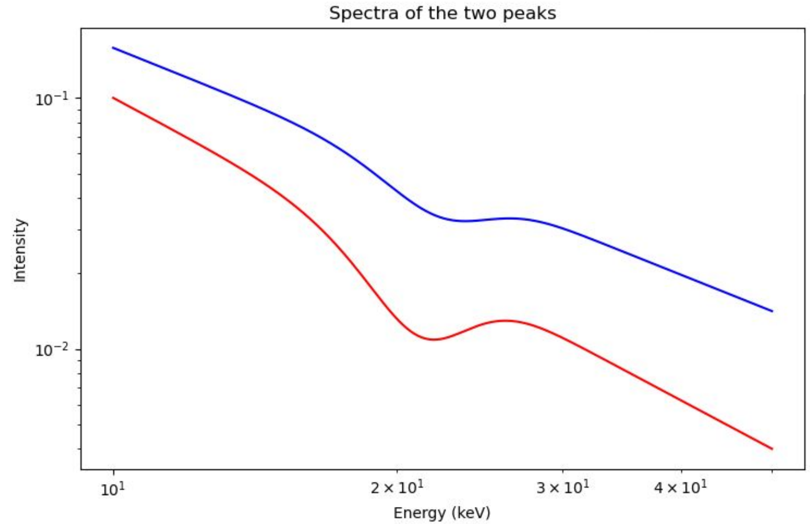
(Becker&Wolf 2007)



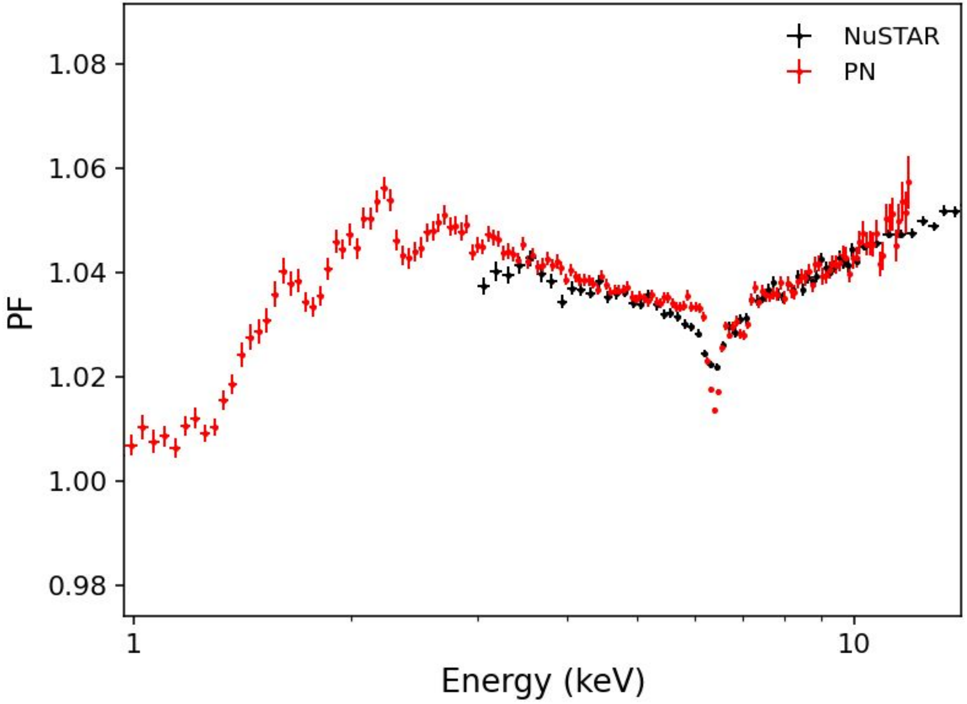
# A very simple exercise: reproducing the PF

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

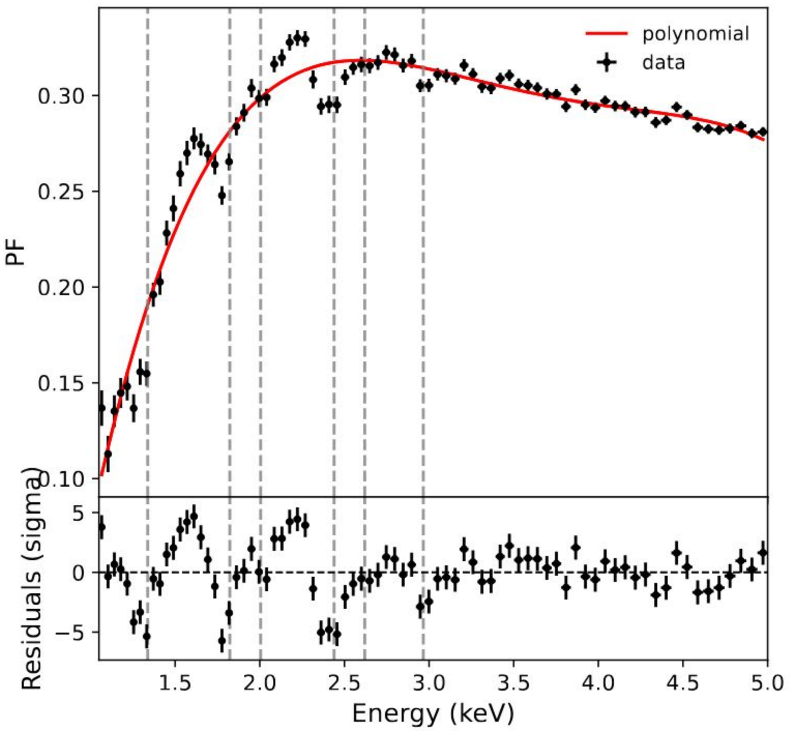


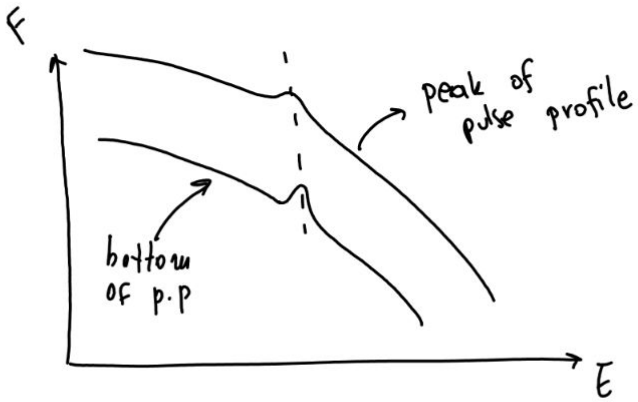



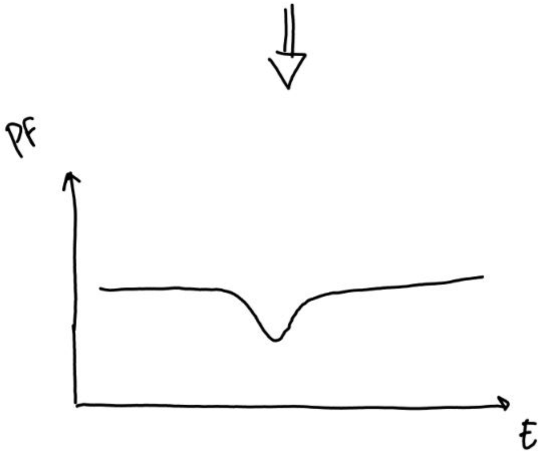
# Without subtracting the mean of each pp



# Polynomial used to identify local dips




F
peak of
pulse profile
bottom
of p.p
E


PF
E