Spectral Behavior of Cepheus X-4 at Low Luminosity: Cyclotron Line Analysis Challenged by NuSTAR Instrumental Background

Deniz Demirci

Remeis-Observatory & ECAP, FAU Erlangen-Nürnberg

in collaboration with

Katja Pottschmidt, Nicolas Zalot, Ekaterina Sokolova-Lapa, Jakob Stierhof, Philipp Thalhammer, Aafia Zainab, Katrin Berger, Ralf Ballhausen, Alicia Ruoco-Escorial, Christian Malacaria, Felix Fuerst, Nazma Islam, Joel Coley, Peter Kretschmar, Pragati Pradhan, Carlo Ferrigno, and Joern Wilms

CONTENTS

1. Be X-ray Binaries: mass transfer and outburst

Let’s understand the system!

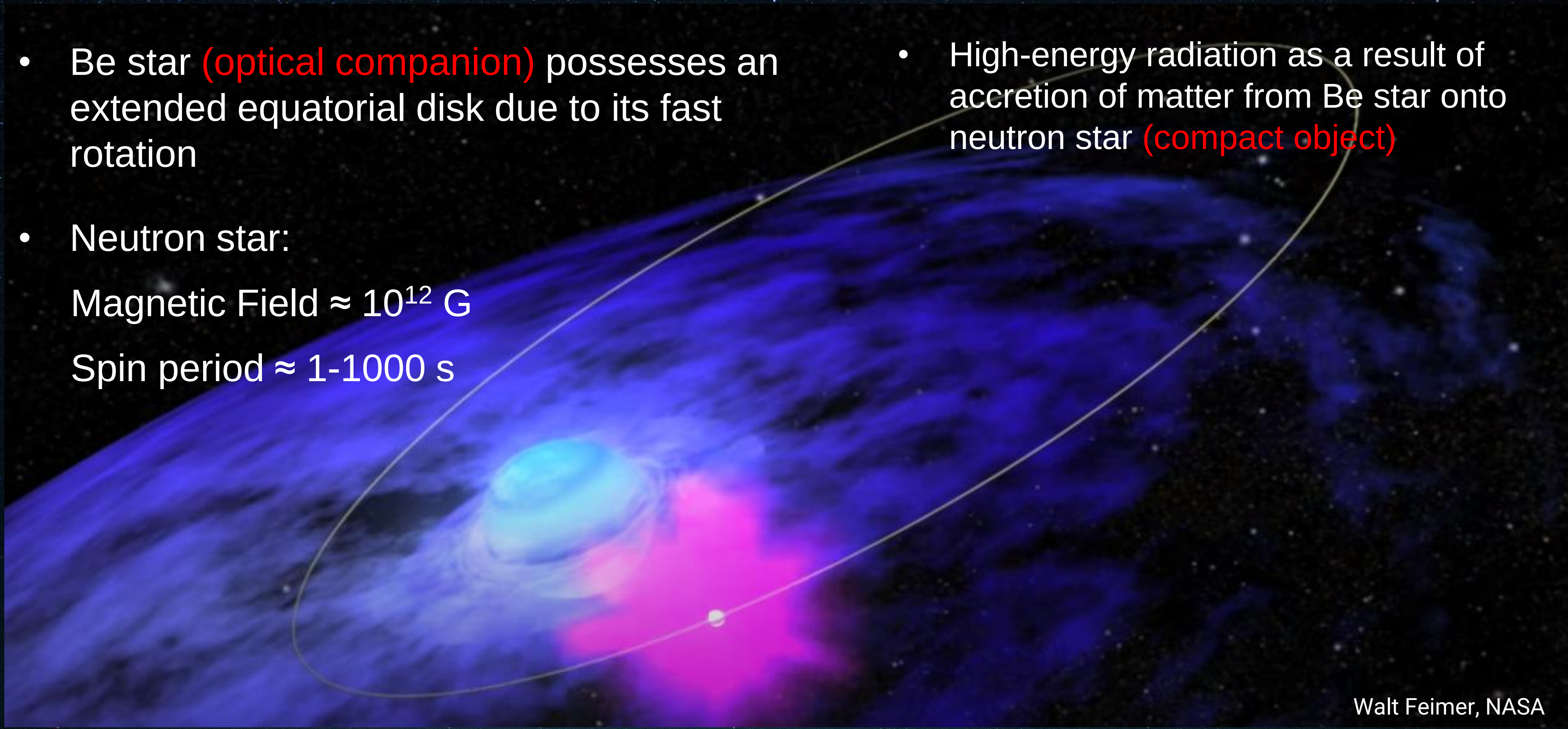
- Be star (optical companion) possesses an extended equatorial disk due to its fast rotation

- Neutron star:

  Magnetic Field ≈ 10^{12} G

  Spin period ≈ 1-1000 s

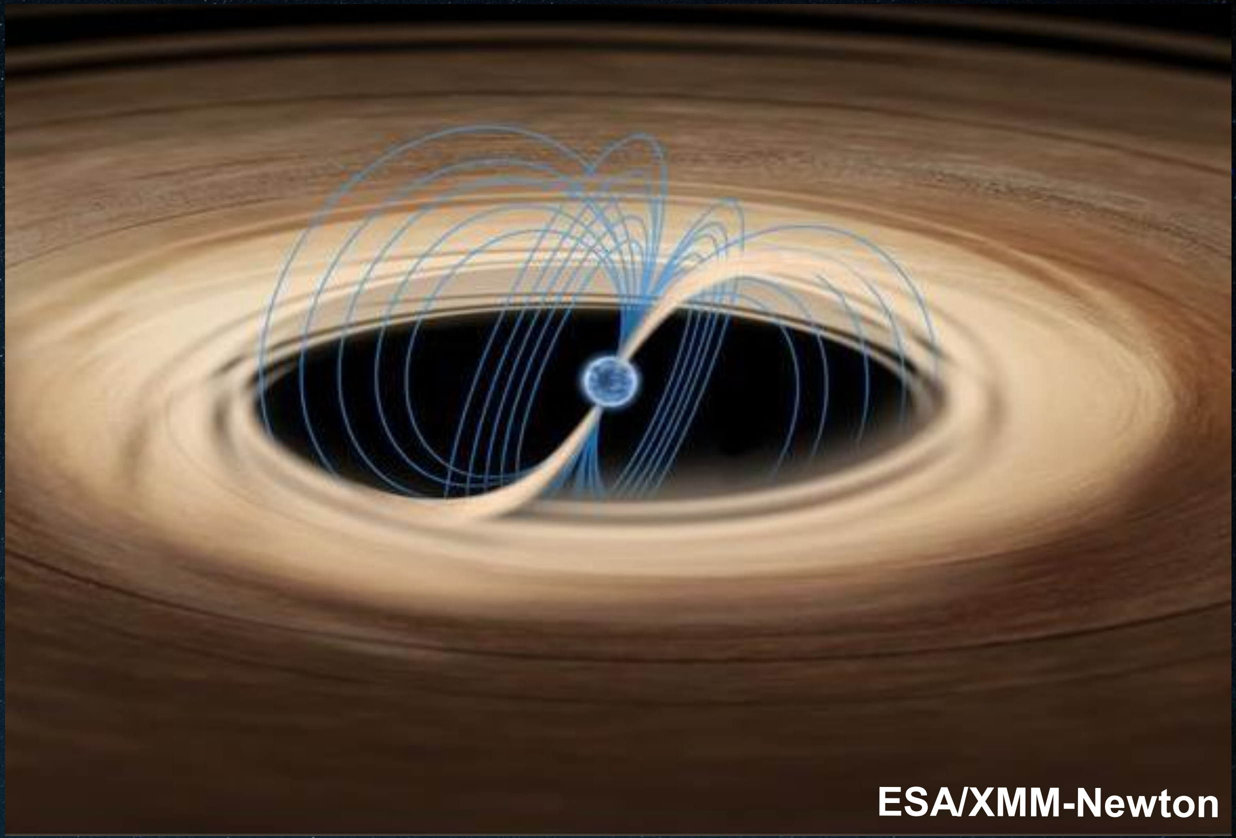
- High-energy radiation as a result of accretion of matter from Be star onto neutron star (compact object)



Walt Feimer, NASA

Mass transfer and outburst

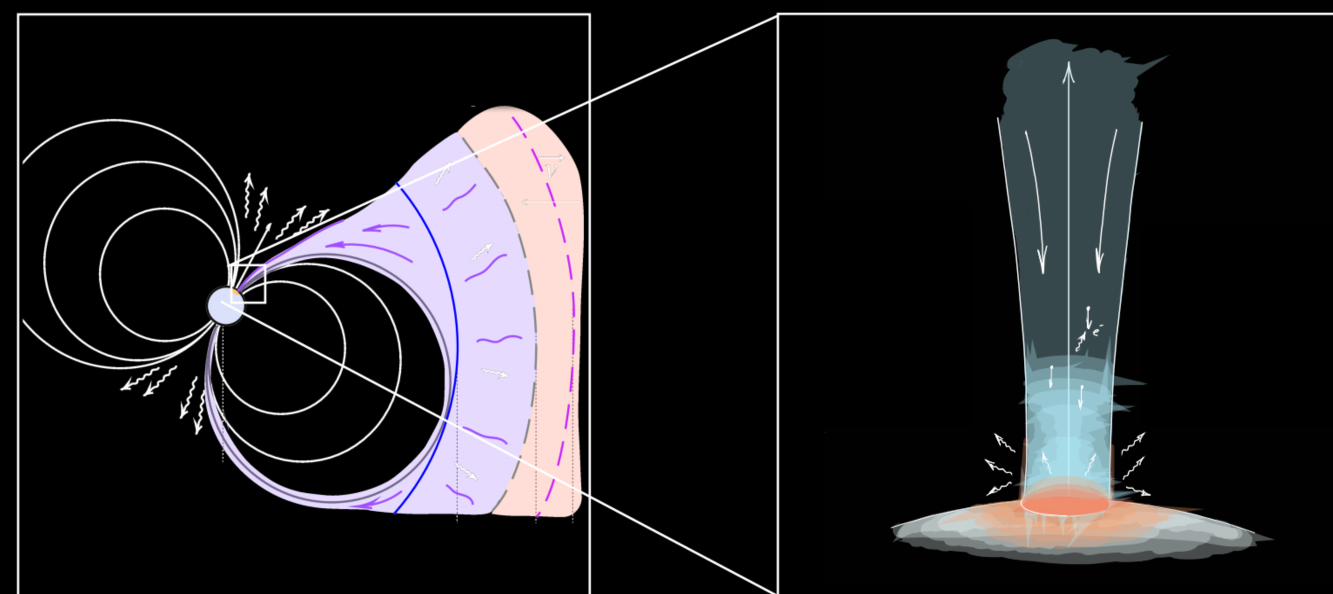
- Periastron → Neutron star passes close to the disk
- Formation of accretion disk due to angular momentum of accreted material
- Kinetic energy of infalling flow is converted into powerful X-ray radiation



Accretion Channel

- Matter follows the magnetic field lines onto the magnetic poles
  → Different mechanisms of deceleration, depending on the mass accretion rate

- High mass-accretion rates (outburst) → Radiative shock occurs and forms the accretion column



Courtesy of E. Sokolova-Lapa

Cyclotron lines

- Strong magnetic field affects the electron motion→ Quantization onto the Landau levels perpendicular to the magnetic field

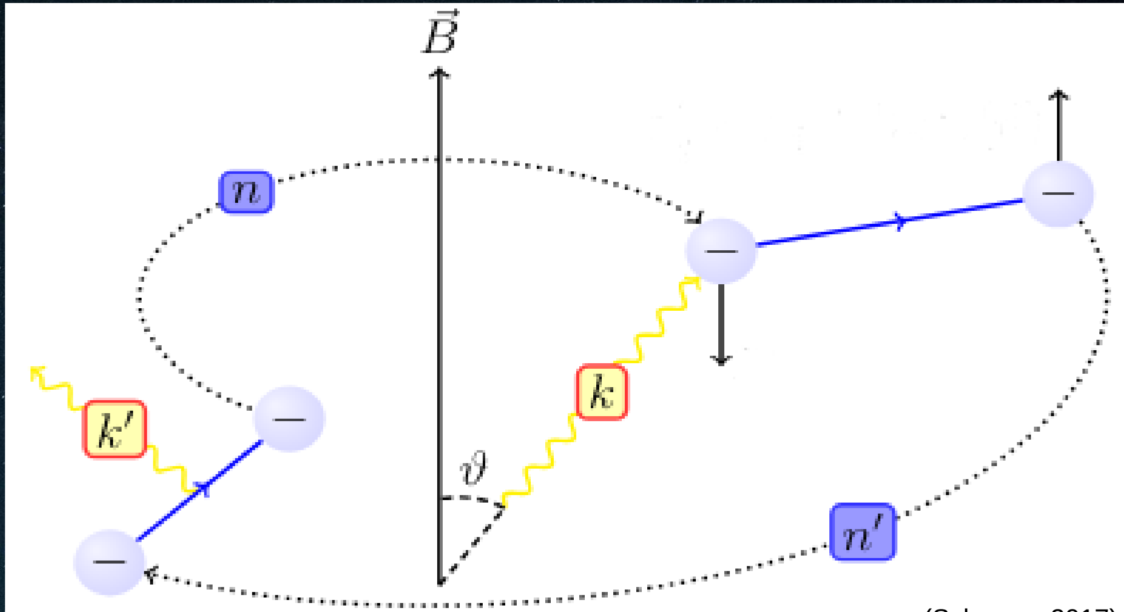
- Formation of the cyclotron lines in the spectra → absorption line of the complex shapes . (majority of them observed X-ray pulsar)

- Energies are proportional to the magnetic field → strength measurement

$$E_{Cyc} \approx \frac{1}{(1+z)} 11.6[keV] \times B_{12}$$

$\mathcal{Z}$: gravitational Redshift

B_{12}: in unit of 10^{12} Gauss



(Schwarm 2017)

2. Transition into quiescence

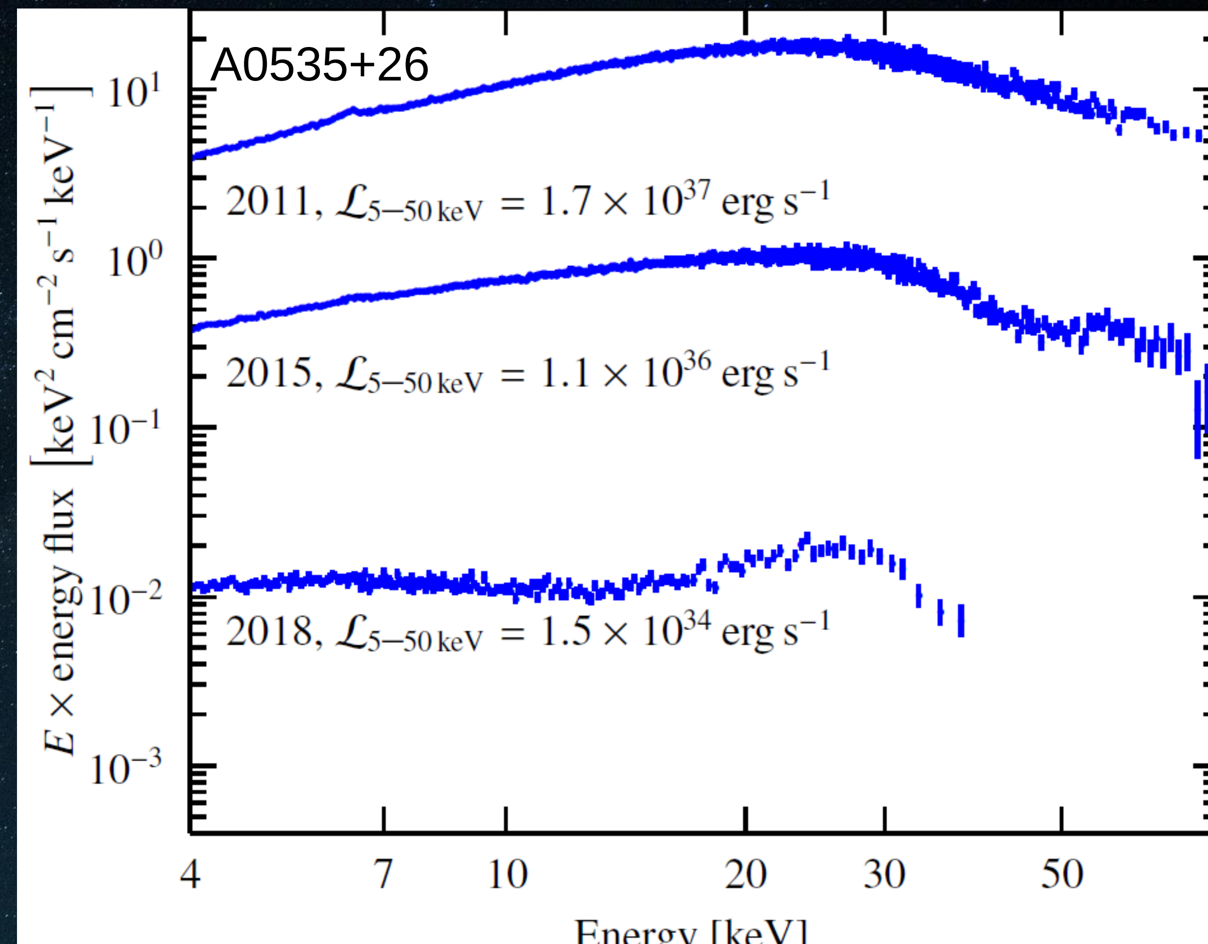
- Direct accretion from the equatorial disk is not possible!
- Accretion onto neutron stars still occurs in quiescence at very low mass-accretion rates

Walt Feimer, NASA

3. Spectral Behavior

- Spectra (continuum and cyclotron line) forms mainly by Compton scattering on falling or thermal electrons
- During transition to quiescence → dramatic spectral change in the broad-band X-ray continuum →

  Two-hump spectra
- At very low mass-accretion rates → matter decelerates in the neutron star atmosphere → Coulomb collisions



(Courtesy of N. Zalot)

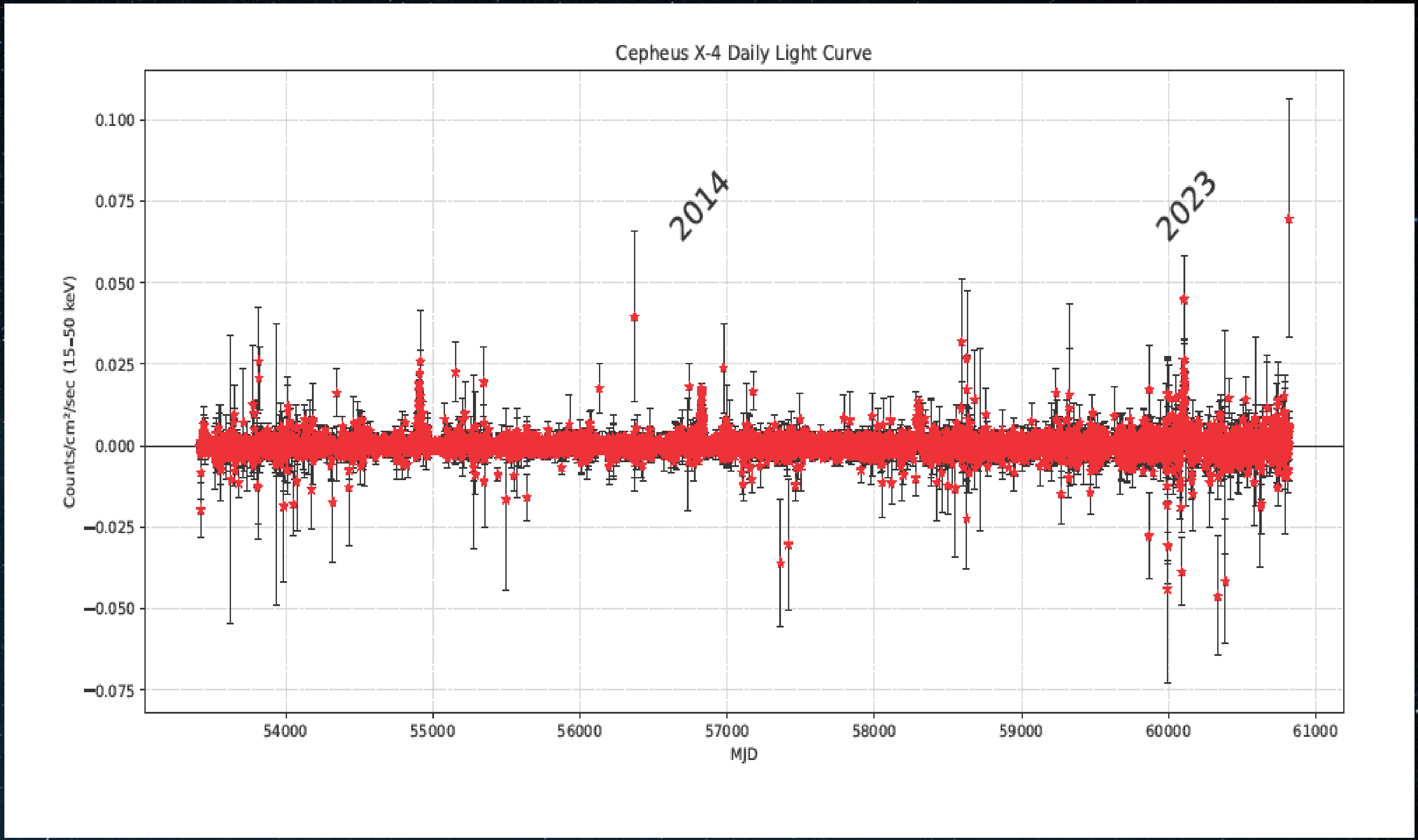
Cepheus X-4

Orbital Period ≈ 20.82 d

Pulsation Period P_s ≈ 66 s

Distance ≈ 7.2 kpc

Outburst Luminosity ≈ 10^{36} - 10^{37} erg/s



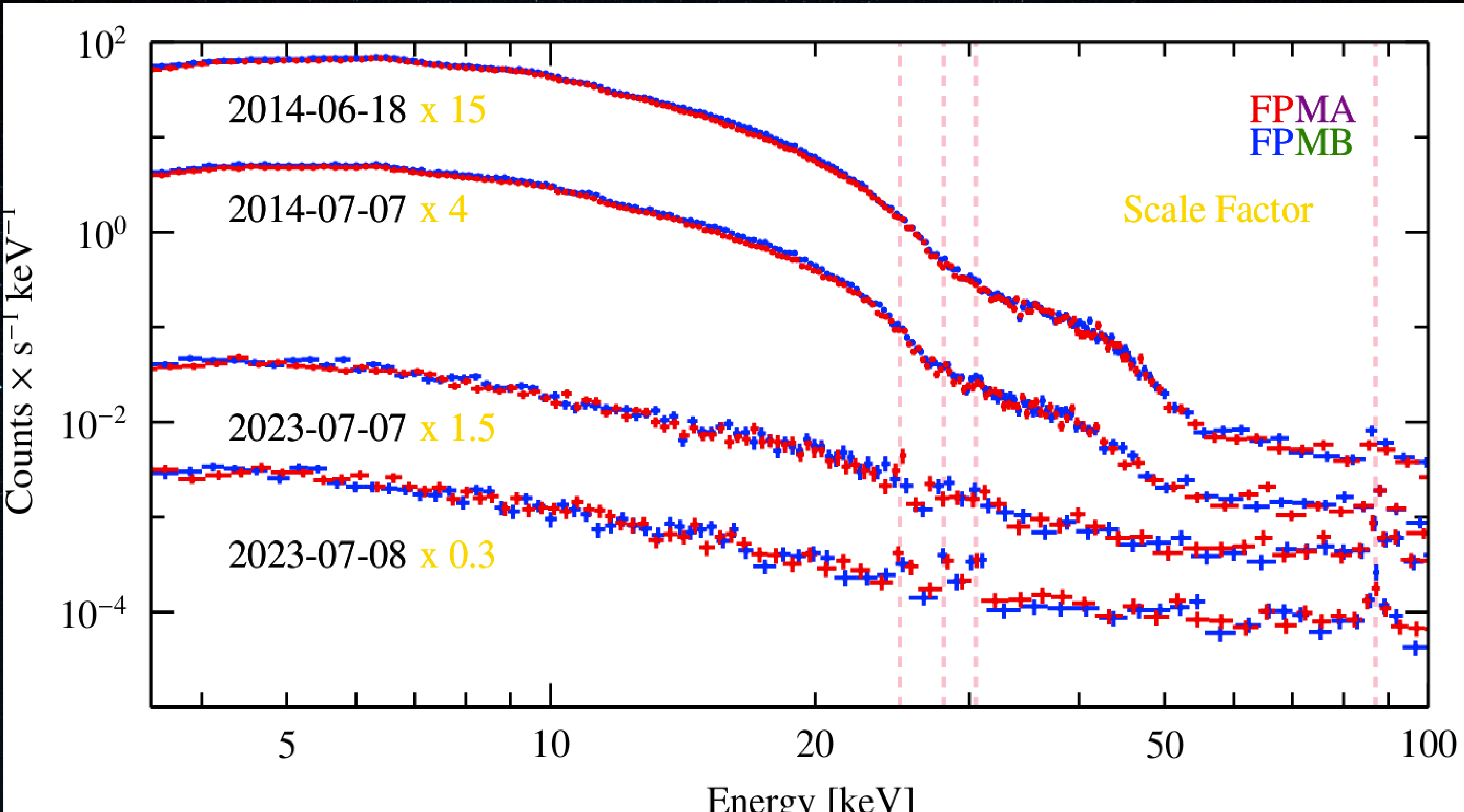
4. Quiescence analysis

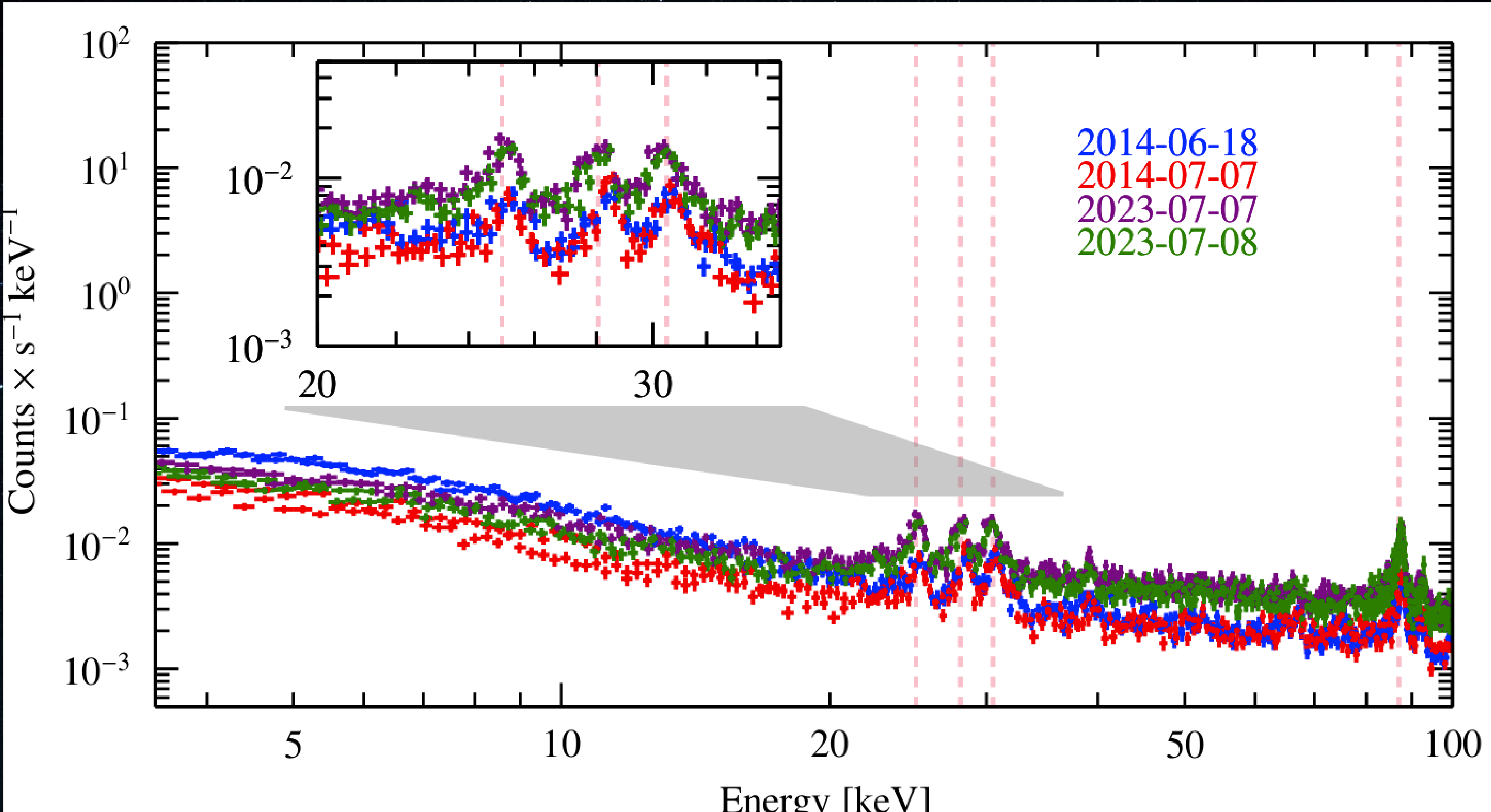
- The source is well studied during outbursts but we focused on low-luminosity state

- Unclear whether source is detectable in (deep) quiescence →

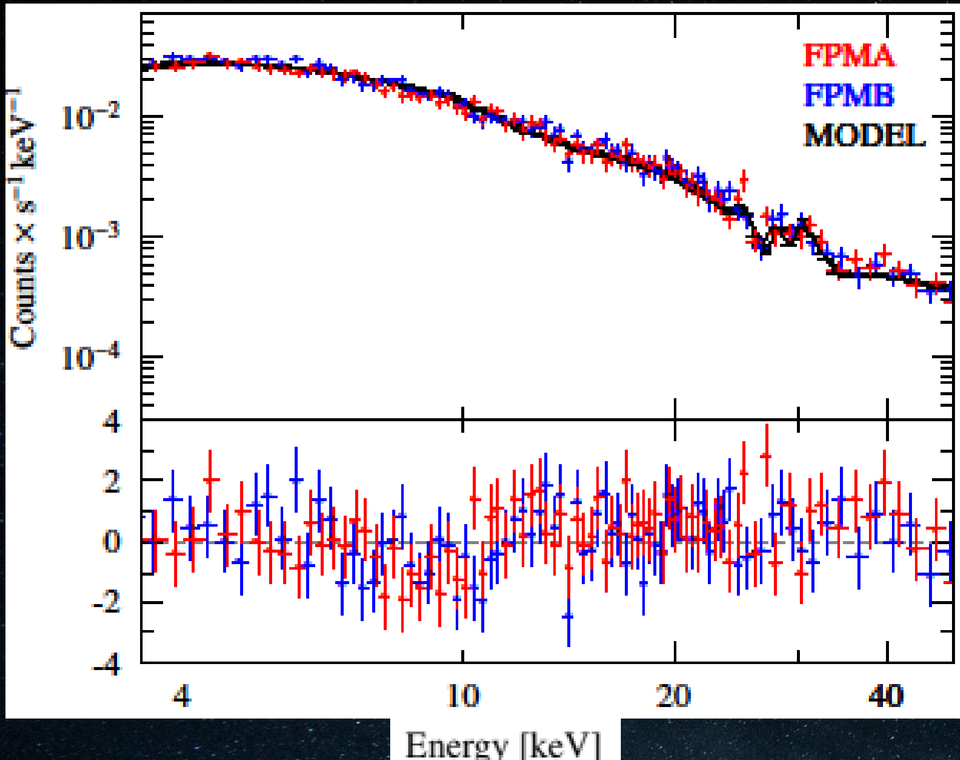
→ We aimed at the latest parts of the outburst decay (thanks to the NuSTAR team)

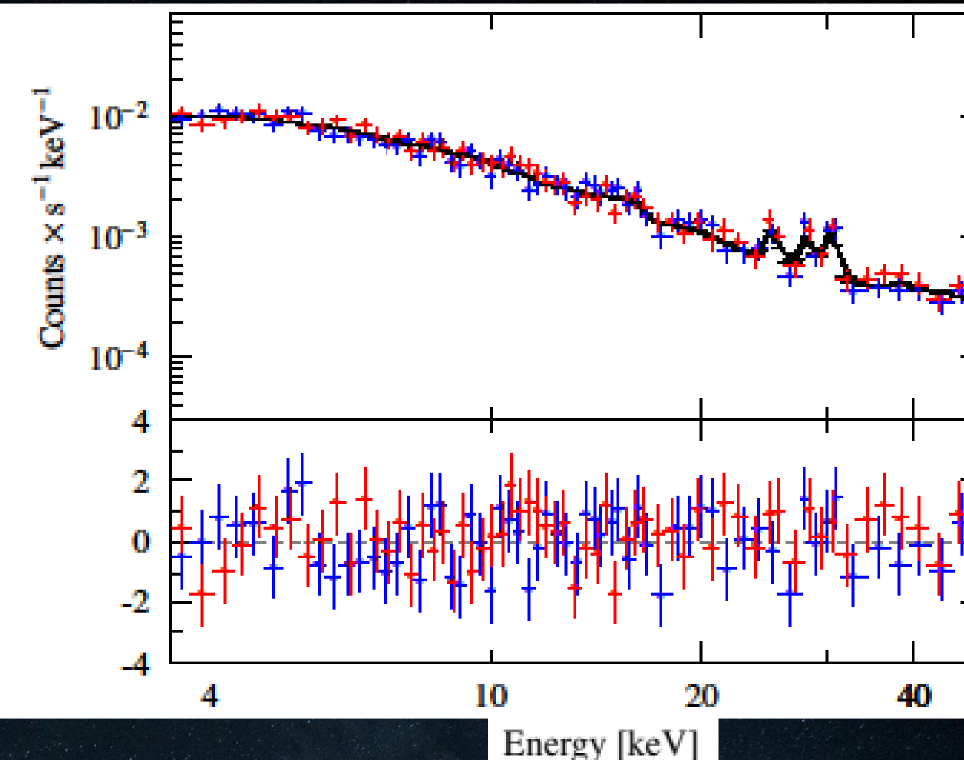
→ Observations at very low luminosities after the 2023 outburst (PI: Ralf Ballhausen), provided valuable hints


2014-06-18 x 15
2014-07-07 x 4
2023-07-07 x 1.5
2023-07-08 x 0.3
FPMA
FPMB
Scale Factor
Counts × s⁻¹ keV⁻¹
Energy [keV]
10^2
10^0
10^{-2}
10^{-4}
5
10
20
50
100



2014-06-18
2014-07-07
2023-07-07
2023-07-08
Counts × s⁻¹ keV⁻¹
Energy [keV]
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
5
10
20
50
100
20
30





1st observation of 2023

$\mathcal{L}_{3.5-50\,keV} \approx 1 \times 10^{35}\, erg/s$

$E_{cyc} = 28.44 \quad d_{cyc} = 10.71$

$\sigma_{cyc} = 1.95 \quad \mathrm{X}^2_{red} = 1.06$

2nd observation of 2023

$\mathcal{L}_{3.5-50\,keV} \approx 3 \times 10^{34}\, erg/s$

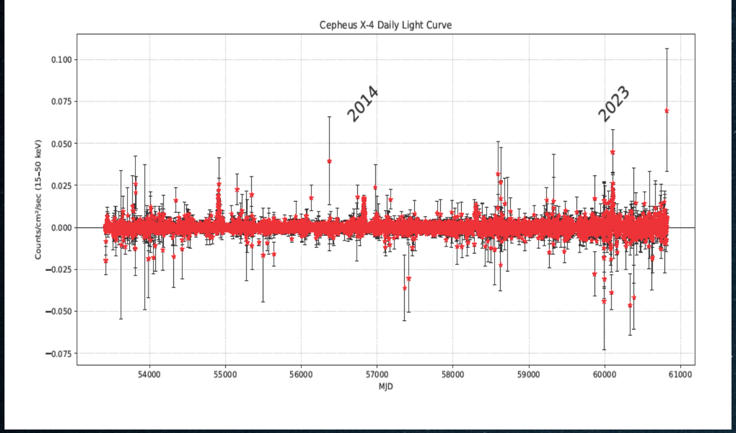
$\mathrm{X}^2_{red} = 0.84$

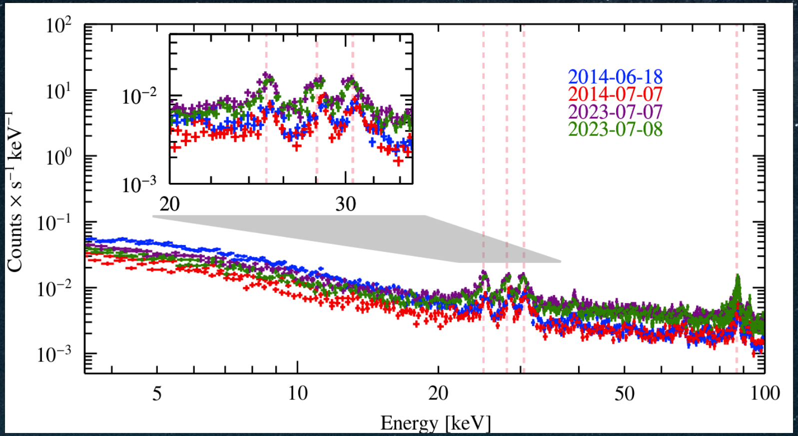
$$\mathbf{DETCONST \times PHABS \times GABS \times (POWERLAW \times FDCUT} + \boldsymbol{GAUSSIAN_{ABS}}) + \boldsymbol{SCALE\ FACTOR} \times$$
$$\mathbf{DETCONST \times (CUTOFFPL + GAUSSIAN_{Cd} + GAUSSIAN_{I} + GAUSSIAN_{Cs} + CONSTANT_{INT})}$$

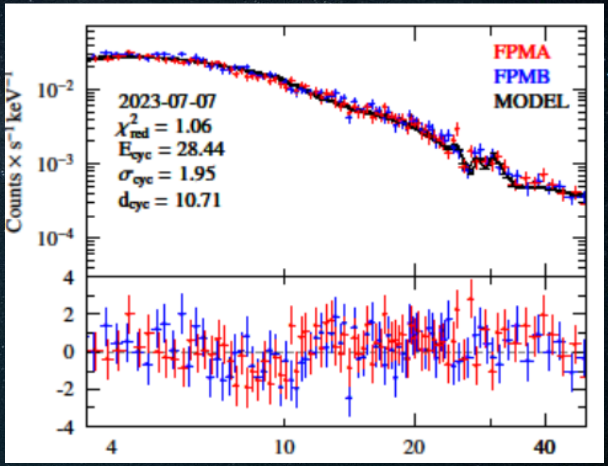
5. Summary

Thank you!

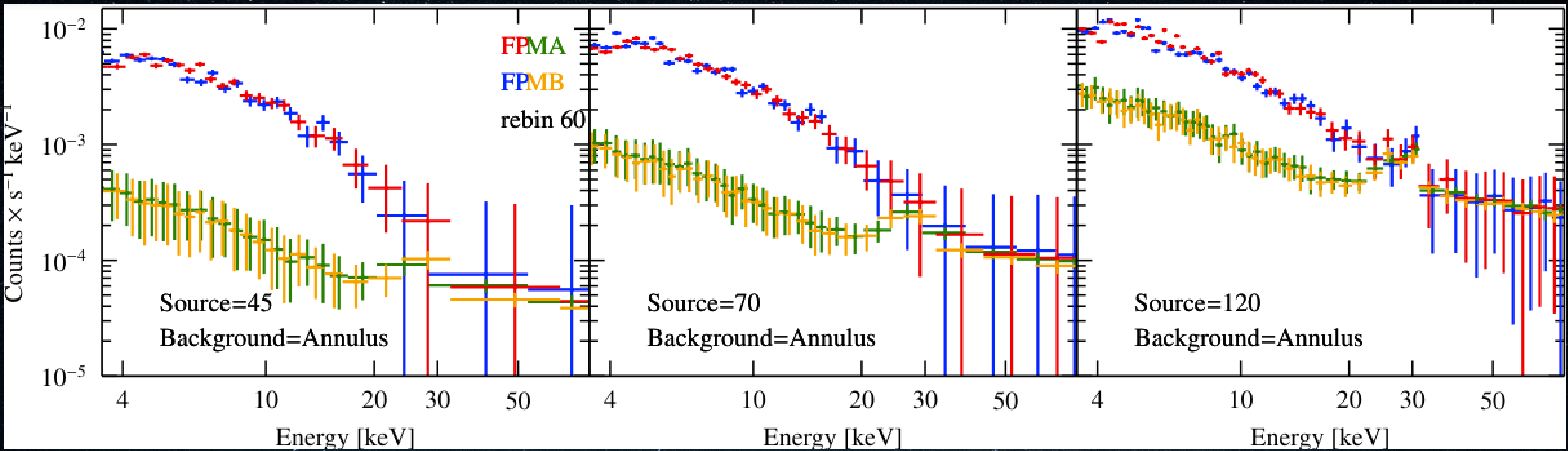
- The study aims to assess the properties of the source at low luminosity levels.
- Background dominates at high energies
- Spectral model suggests a possible cyclotron line at low luminosity, but background effects remain
- It complicated the study of cyclotron line and its variation with luminosity.



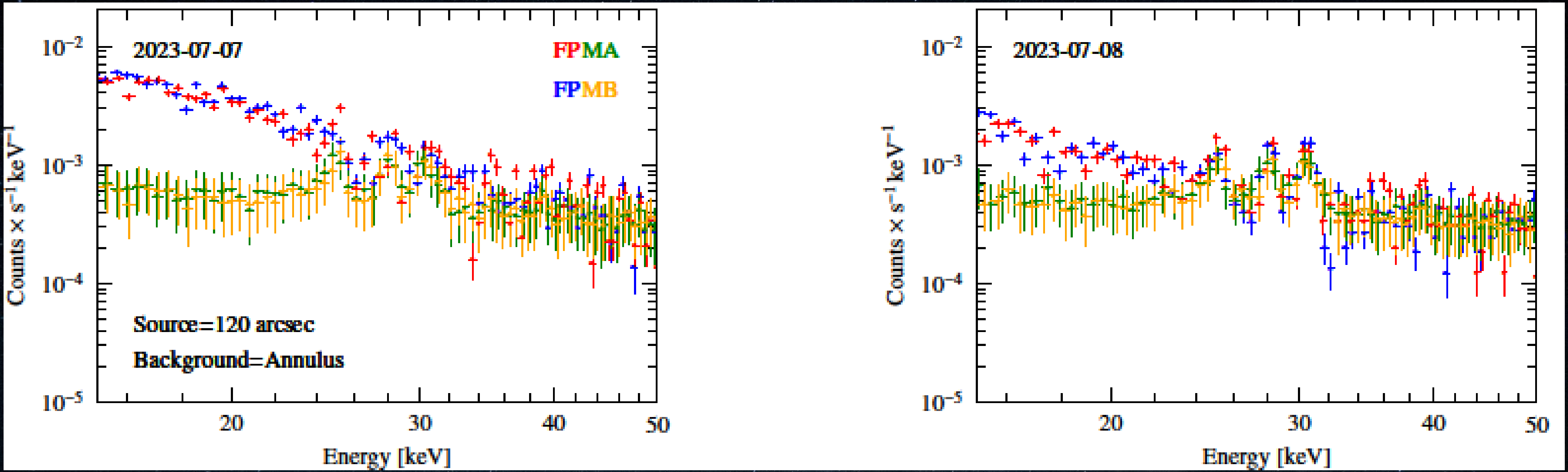




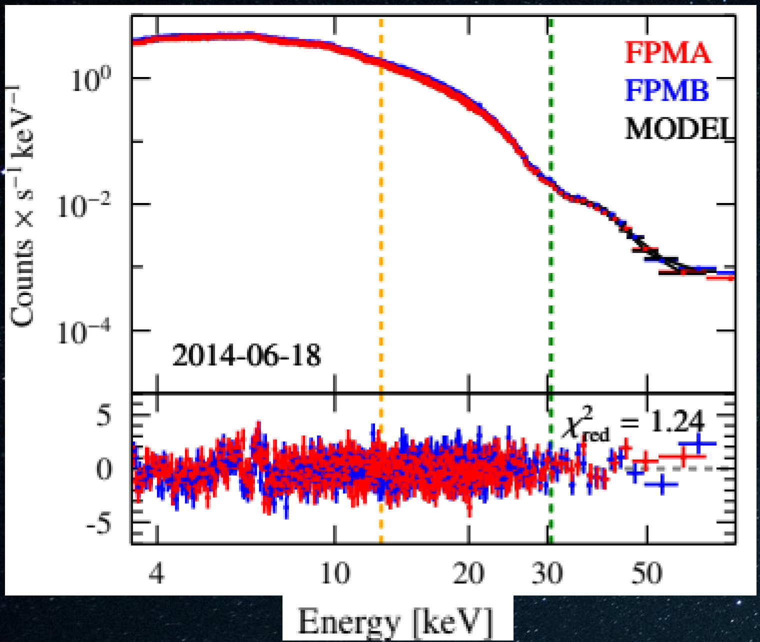
Second Observation of 2023 with different source regions

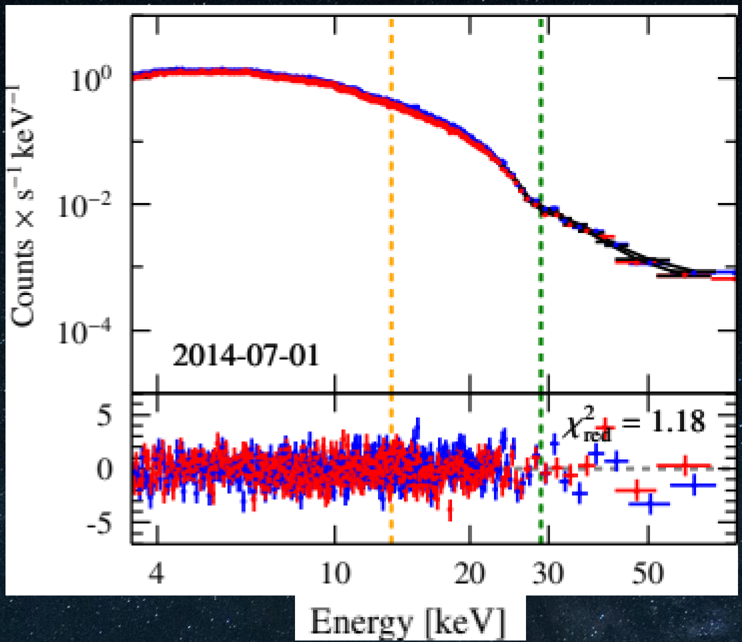


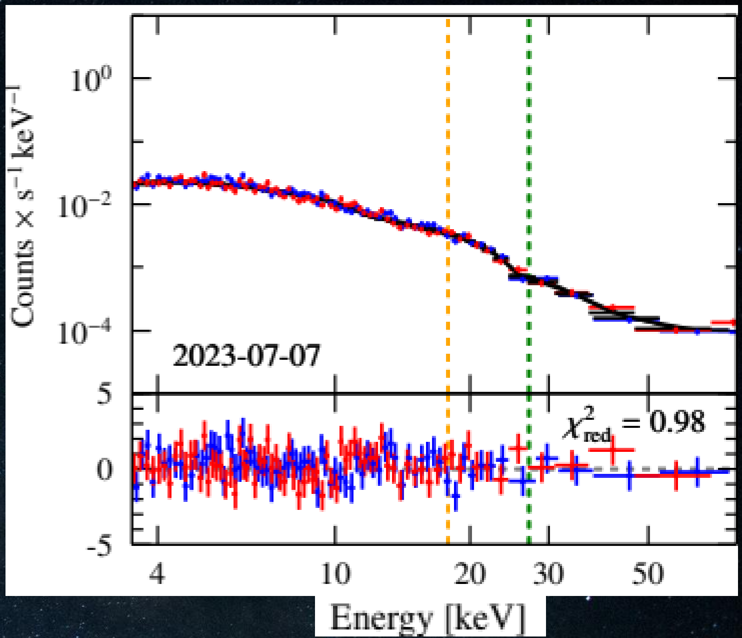
- Shown above are data extractions with differently sized source regions
- High-energy spectrum above 20 keV is highly affected by the background


2023-07-07
FPMA
FPMB
Source=120 arcsec
Background=Annulus
Counts × s⁻¹ keV⁻¹
Energy [keV]
2023-07-08
Counts × s⁻¹ keV⁻¹
Energy [keV]

2014 vs 2023 Observations: Outburst vs Quiescence







$\mathcal{L}_{3.5-50\,keV} \approx 6 \times 10^{36}\, erg/s$

First observation of 2014

$E_{gauss} \approx 12.8$ keV

$E_{cyc} \approx 31$ keV

$\Gamma = 1.2$

$\mathcal{L}_{3.5-50\,keV} \approx 1 \times 10^{36}\, erg/s$

(Fürst+ 2017)

Second observation of 2014

$E_{gauss} \approx 13.3$ keV

$E_{cyc} \approx 29$ keV

$\Gamma = 1.1$

$\mathcal{L}_{3.5-50\,keV} \approx 1 \times 10^{35}\, erg/s$

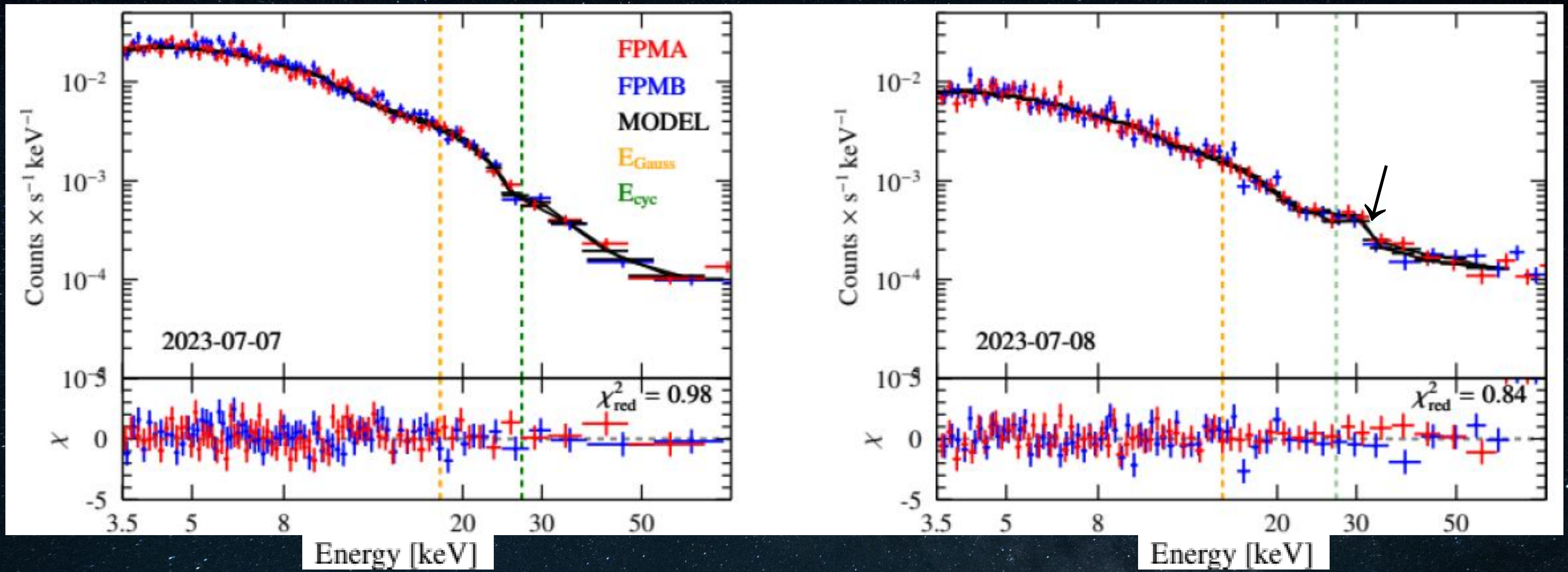
First observation of 2023

$E_{gauss} \approx 18$ keV

$E_{cyc} \approx 27$ keV

$\Gamma = 1.72$

2023 observations: Transition into quiescence



$\mathcal{L}_{3.5-50\,keV} \approx 1 \times 10^{35}\ erg/s$

tbabs(powerlaw*fdcut +egauss)*gabs*

$E_{gauss} \approx$ 18 keV $E_{cyc} \approx$ 27 keV

$E_{cutoff} \approx$ 41 keV $\Gamma = 1.72$

$\mathcal{L}_{3.5-50\,keV} \approx 3 \times 10^{34}\ erg/s$

tbabs*(powerlaw*fdcut+egauss)

$E_{gauss} \approx$ 15 keV **E_{cyc} not detected**

$E_{cutoff} \approx$ 53 keV $\Gamma = 2.00$

Spectral *Model*

Load the dataset

↓

Unassign the background file

↓

Exclude the source dataset

↓

Load the background file as a new dataset

↓

Fit the background model

Freeze the paramaters

↓

Exclude the background dataset

↓

Include the source dataset

↓

Fit the spectral model

detconst*phabs*gabs*(powerlaw*fdcut+gaussian)

detconst*cutoffpl*(gaussian$_{Cd}$ + gaussian$_{I}$ + gaussian$_{Cs}$)

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- The study aims to assess the properties of the source at low luminosity levels.
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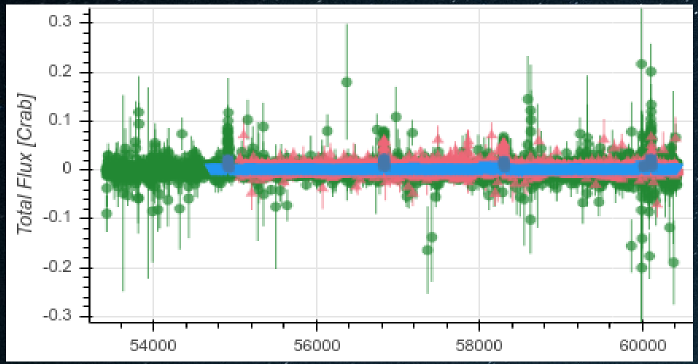

Thank you!