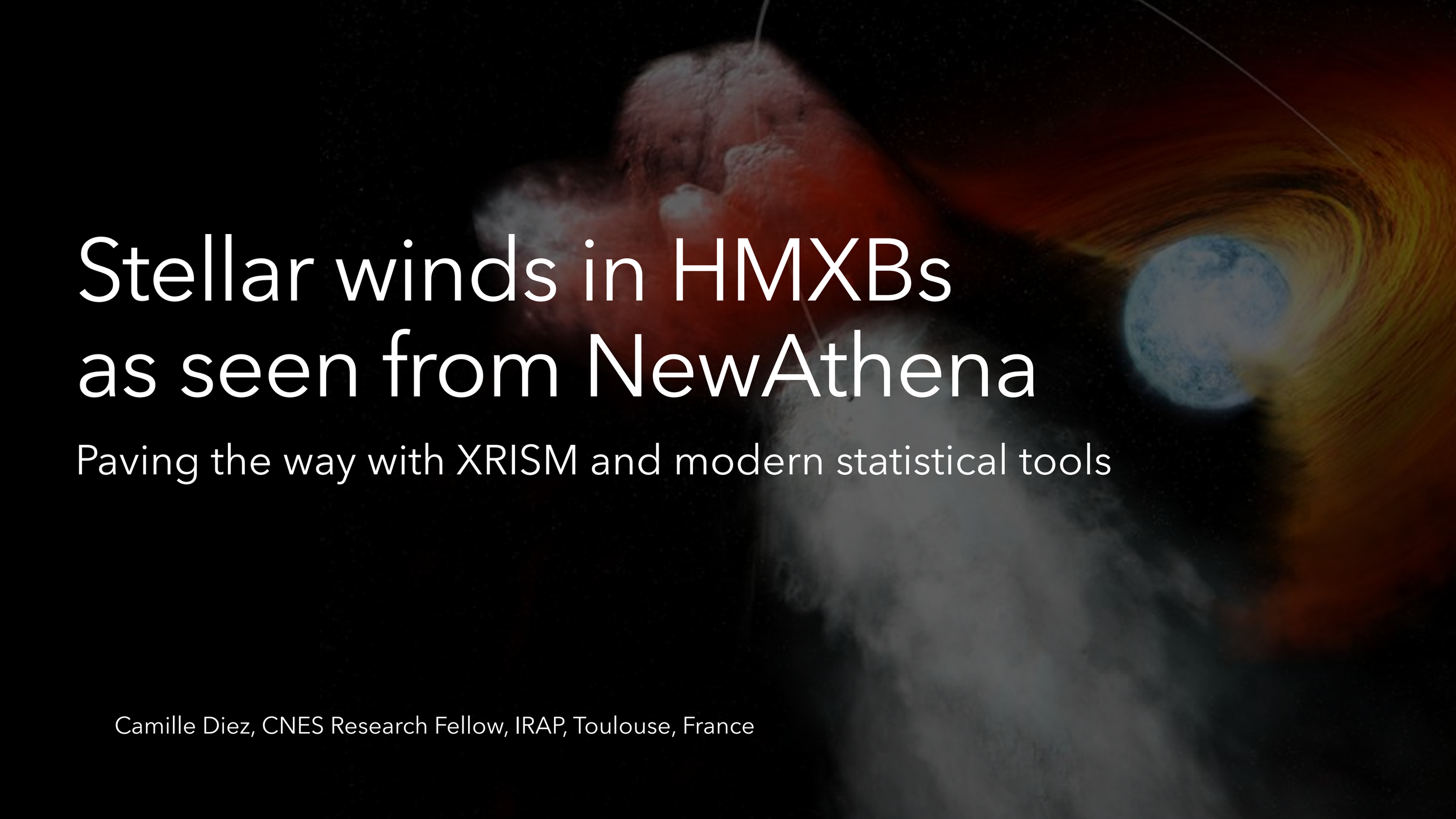

Stellar winds in HMXBs as seen from NewAthena

Paving the way with XRISM and modern statistical tools

Camille Diez, CNES Research Fellow, IRAP, Toulouse, France

Outline

- Introduction — • *Stellar winds* • *Observations* • *Microcalorimeters* •
- Statistical tools — • *Bayesian inference* • *jaxspec* •
- Results from XRISM — • *Cross-calibration updates* • *High-res spectro* •
- Perspectives for NewAthena — • *Special Issue* • *Future prospects* •

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Stellar winds in HMXBs

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Compact object (NS or BH) + massive companion star

NS

- $M_\star > 10\,M_\odot$

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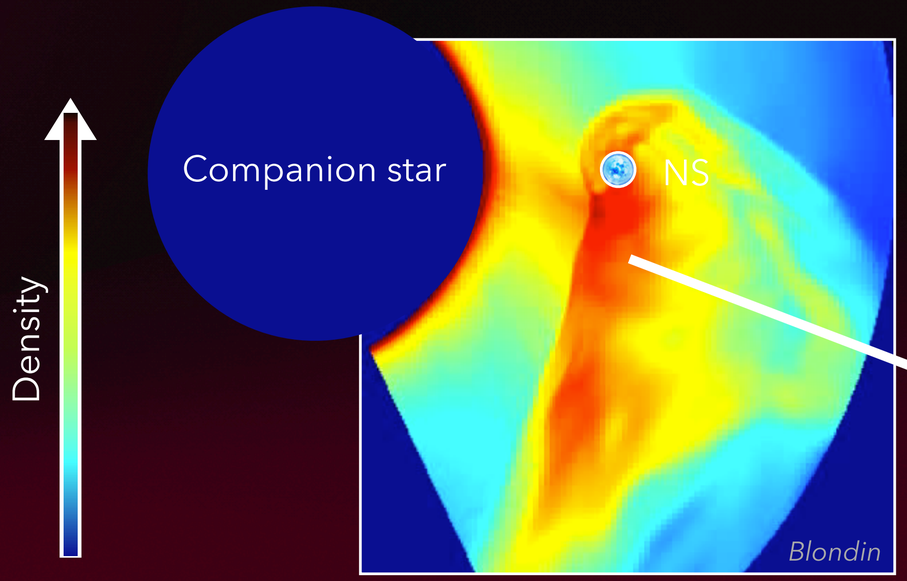
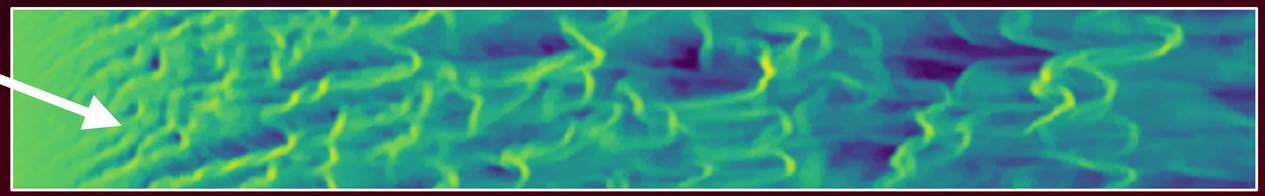


- $M_\star > 10\,M_\odot$
- Accretion from the stellar wind onto the compact object



Complex structure

Stellar winds in HMXBs

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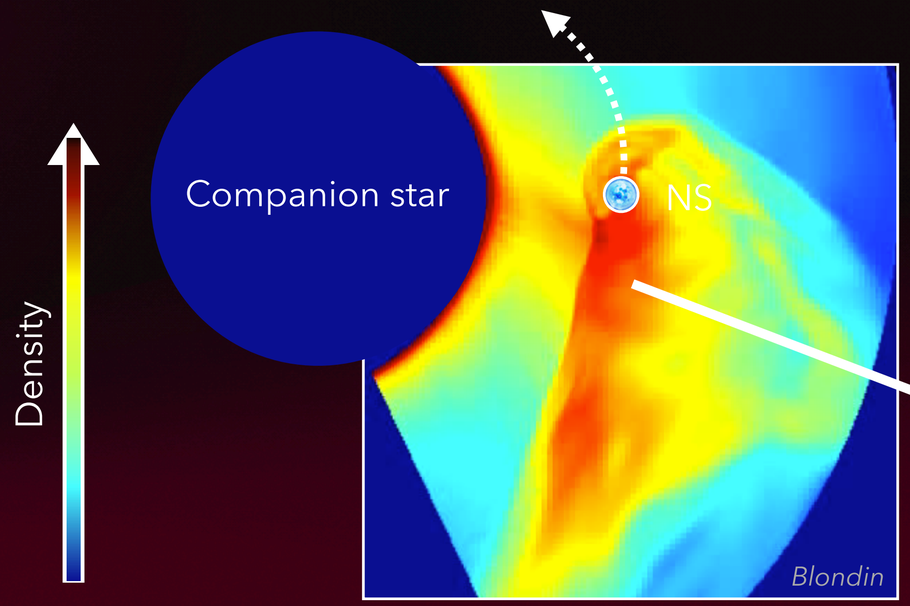

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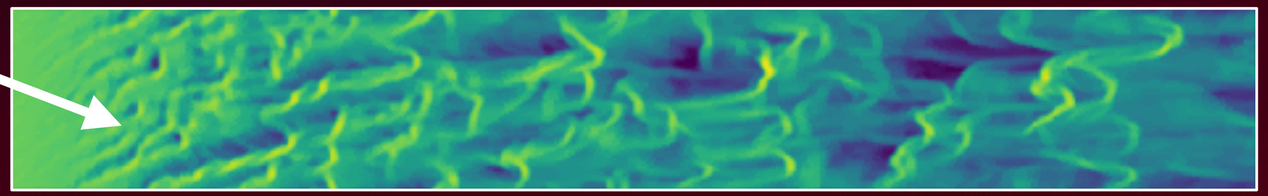


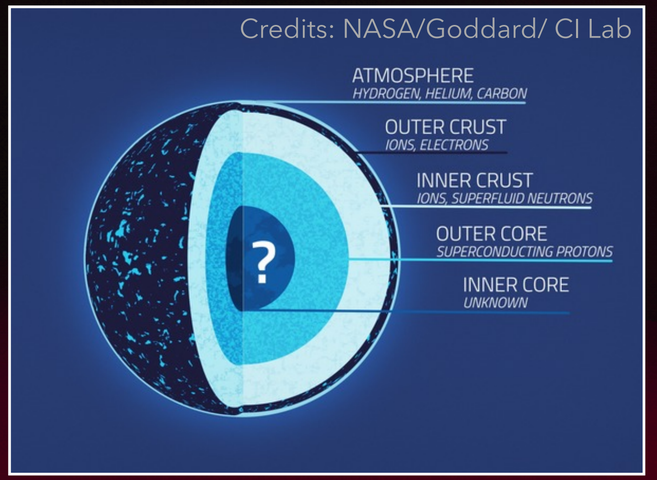
Complex structure

- Inhomogeneous wind (“clumpy”) + accretion/photoionisation wakes
- Velocity perturbations in the wind
- Affects the accretion rate and X-ray emission from the compact object

Motivations

Motivations

- NS = laboratories to study dense matter



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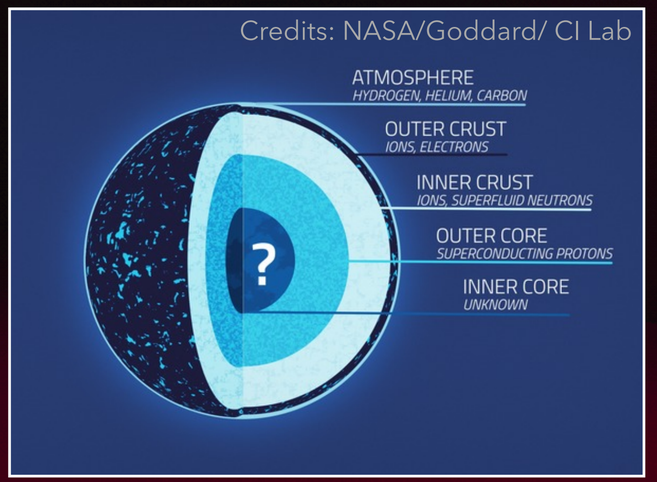
- Study of accretion phenomena around compact objects

(jets, interaction matter/mag. field)



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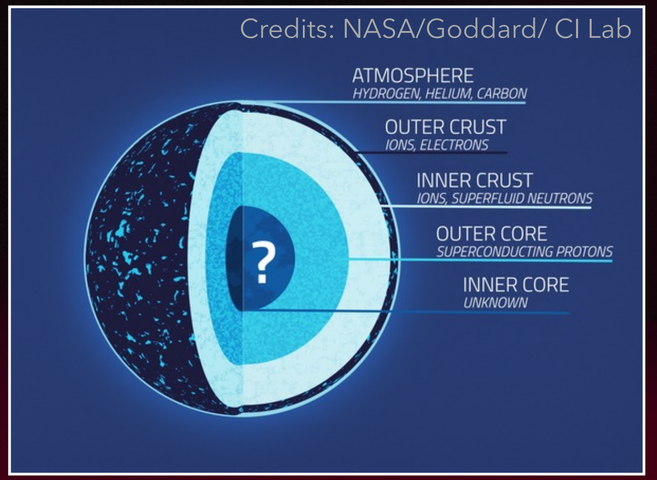

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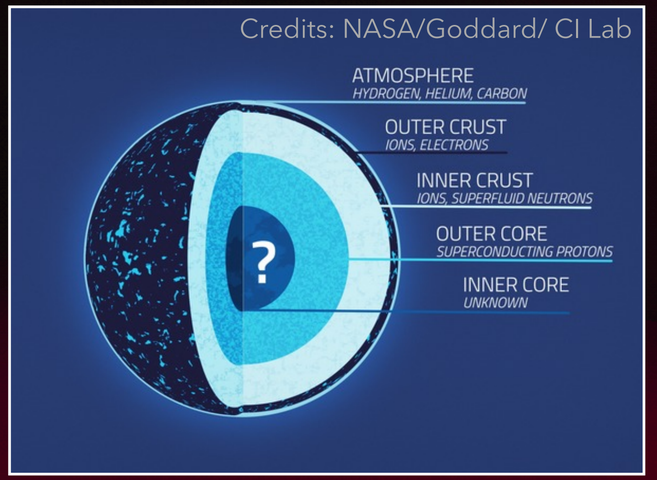

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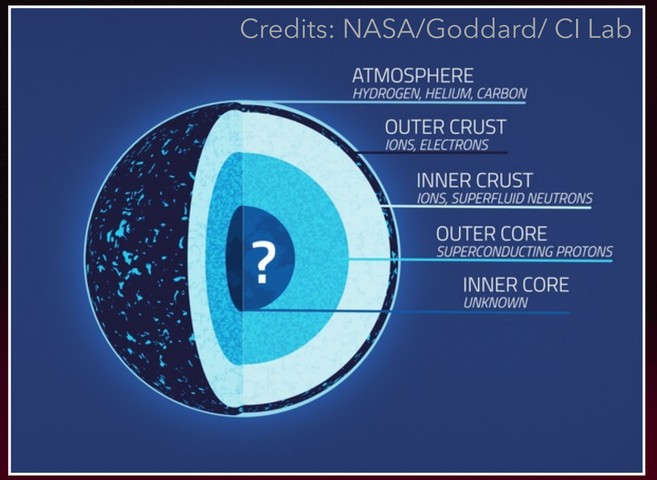
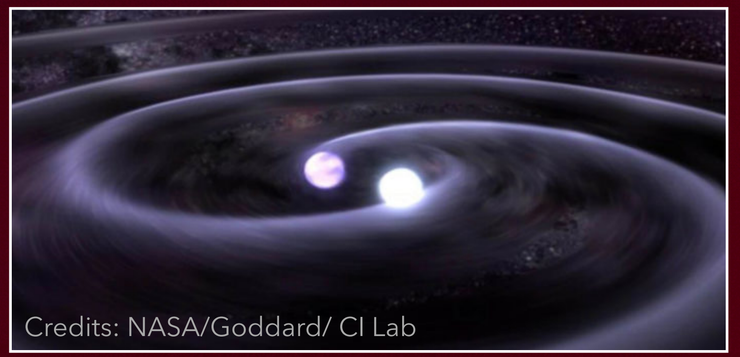
- Tools for studying stellar formation and evolution

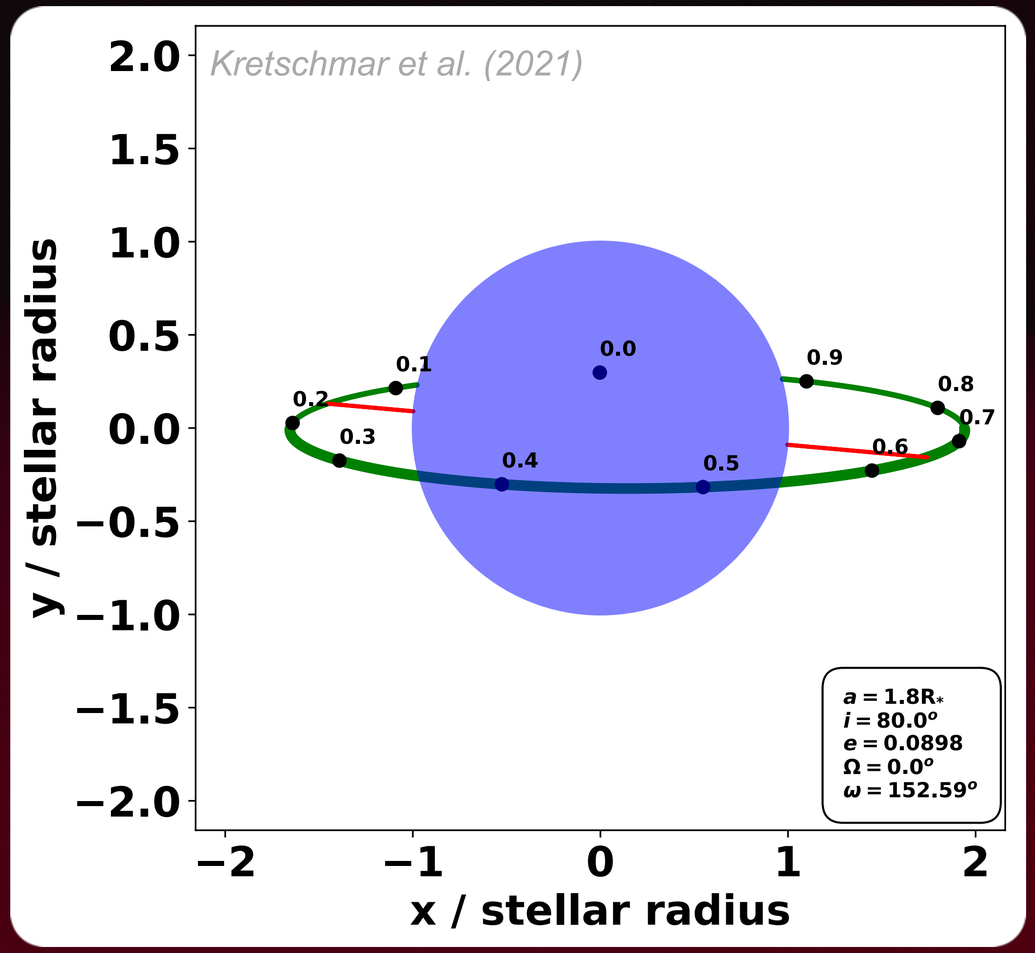
(supernovae + gravitational waves)





An example: Vela X-1

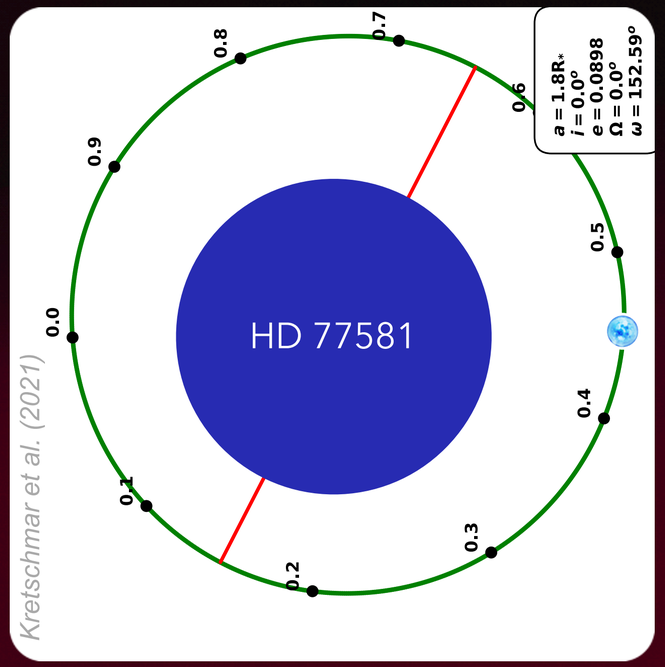
(1)	Distance	$2.42^{+0.19}_{-0.16}$ kpc
(2)	HD 77581 radius $R_\star$	$31^{+4}_{-3}\ R_\odot$
(3)	HD 77581 mass $M_\star$	$21.5 \pm 4.0\ M_\odot$
(4)	Neutron star mass $M_{\rm NS}$	$\sim 1.8\ M_\odot$
(5)	Orbital period $P_{\rm orb}$	8.964357 ± 0.000029 day
(6)	Semi-major axis $a \sin i$	113.89 ± 0.13 lt-sec
(6)	Eccentricity e	0.0898 ± 0.0012
(6)	Longitude of periastron ω	152.59 ± 0.92
(7)	Inclination i	$> 73^\circ$
(8)	Pulse period P	~ 283 sec
(7)	Orbital separation a	$\sim 1.8\ R_\star$



(1) *Bailer-Jones et al. (2018)*
(2) *Joss & Rappaport (1984)*
(3) *Giménez-García et al. (2016)*
(4) *Rawls et al. (2011)*
(5) *Kreykenbohm et al. (2008)*
(6) *Bildsten et al. (1997)*
(7) *van Kerkwijk et al. (1995)*
(8) *McClintock et al. (1976)*

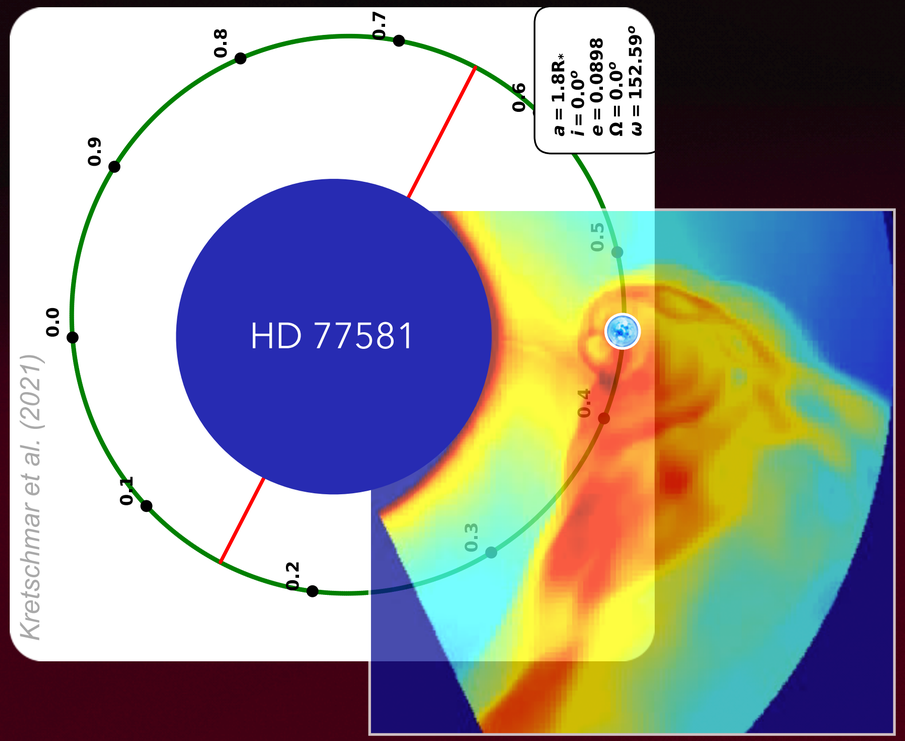
XRISM GO1 campaign: With a key source

Vela X-1

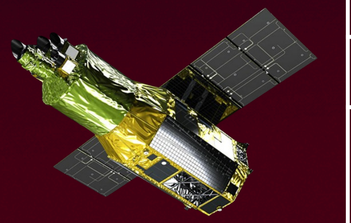


XRISM GO1 campaign: At a key moment

Vela X-1



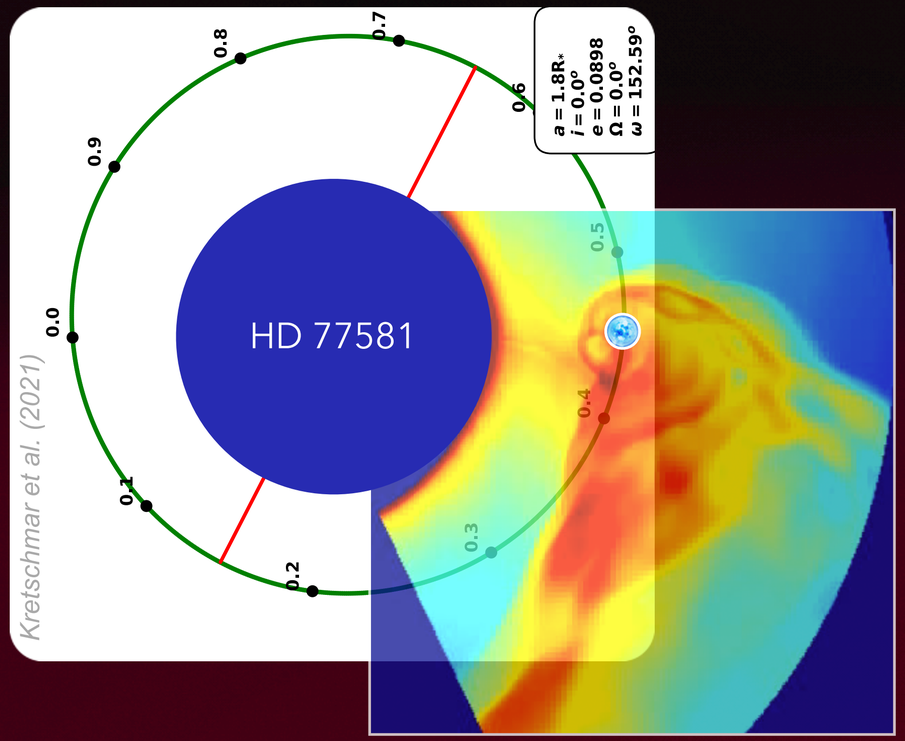
XRISM



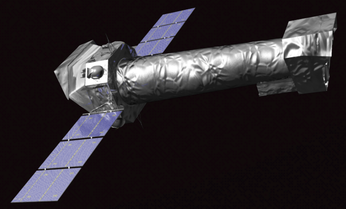
Energy band	0.5-12 keV (soft X-rays)
Launch	7 Sept. 2023
Role in the analysis	High resolution spectroscopy

XRISM GO1 campaign: With simultaneous X-ray coverage

Vela X-1

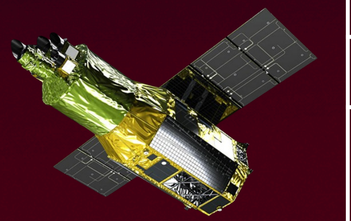


XMM-Newton



Energy band	0.3-12 keV (soft X-rays)
Launch	10 Dec. 1999
Role in the analysis	Spectral analysis of the wind variability

XRISM



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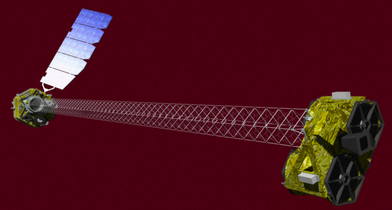
NuSTAR



Energy band	3-79 keV (hard X-rays)
Launch	13 June 2012
Role in the analysis	Constrain the continuum

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Frequentist or Bayesian?

Well, it is up to you, but we chose Bayesian

$$P(\theta \mid X) = \frac{P(X \mid \theta)}{P(X)} P(\theta)$$

θ: parameters
X: observations (per bin)

Slide: courtesy of Simon Dupourqué (IRAP)

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A posteriori of the parameters given the observations

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The probability of observing the dataset given all possibilities

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Turns the likelihood into a posterior distribution

θ: parameters
X: observations (per bin)

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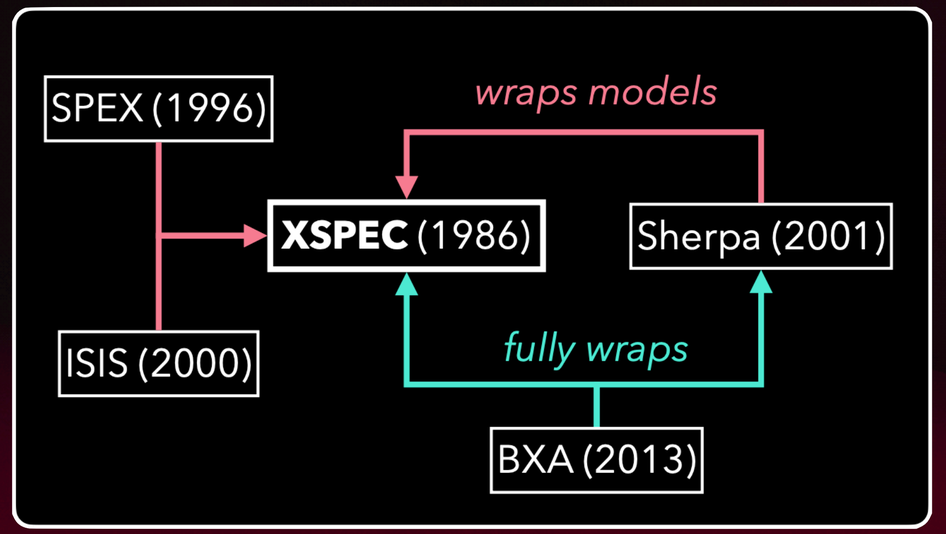
Landscape of X-ray spectral fitting

Words from an ISIS user in transition



Courtesy of Simon Dupourqué (IRAP)

Which one do you use?
Tell us here:

Landscape of X-ray spectral fitting

Words from an ISIS user in transition

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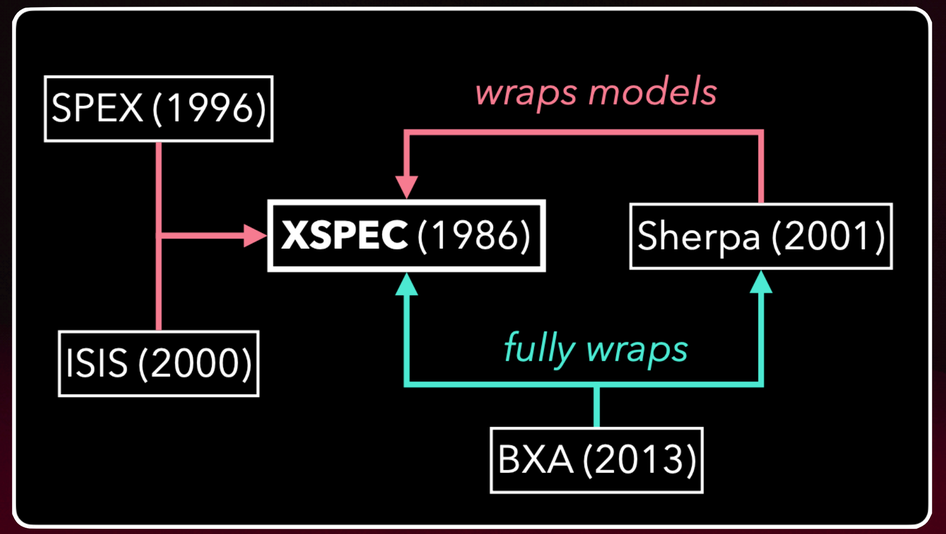
  - MCMC (emcee) or nested sampling (BXA) become slow in high-dimensional parameter space



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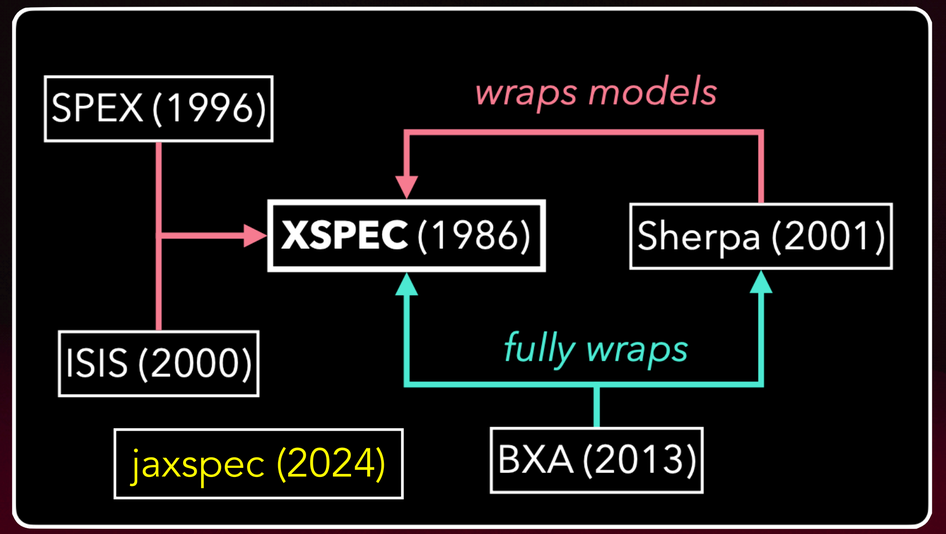
- We propose **jaxspec**
  - `pip install jaxspec`, that's it!
  - based on JAX:
    - enables GPU acceleration
    - differentiation (faster samplers for MCMC)
    - variational inference (assume a distribution guide for your posteriors)



Courtesy of Simon Dupourqué (IRAP)

Dupourqué, Barret, Diez et al. 2024

Why a capybara?
Ask for the bonus slides…

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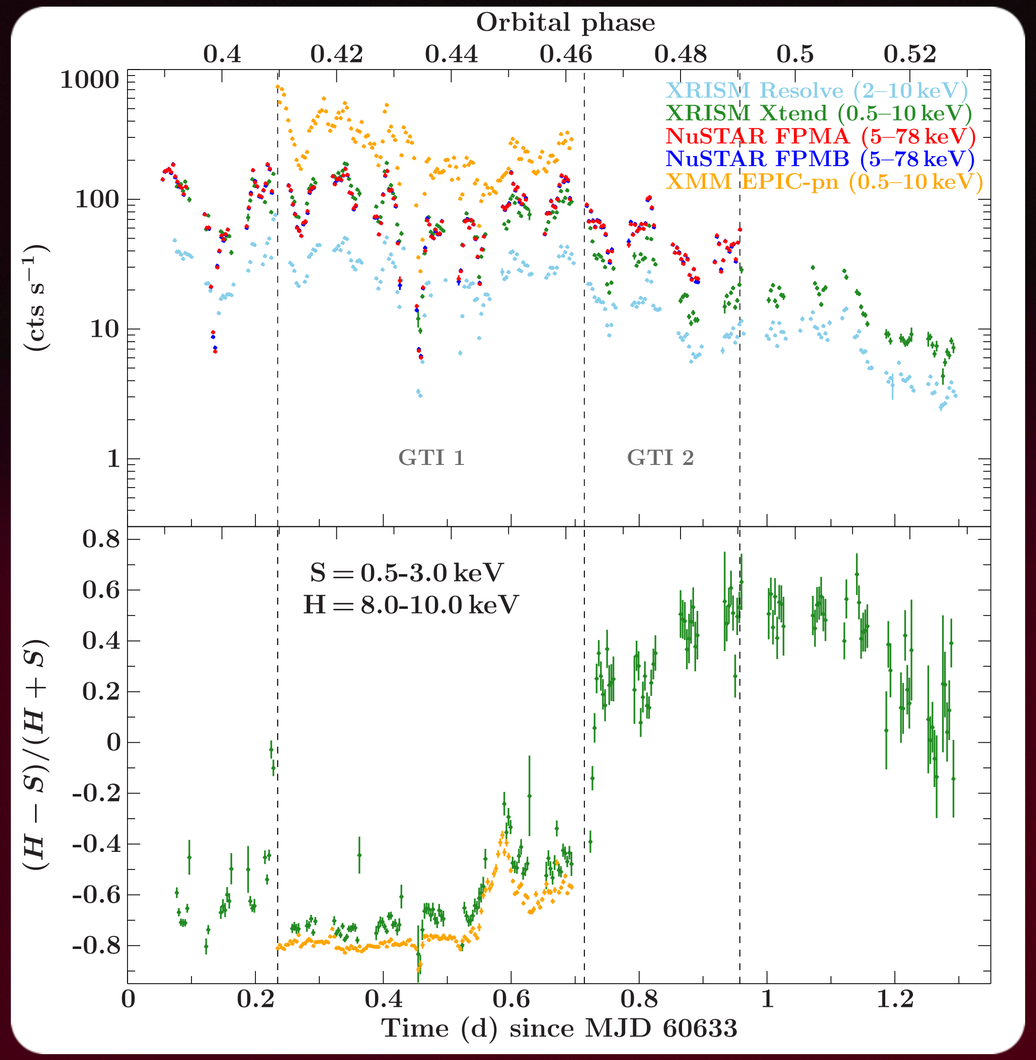
Spectral evolution



Diez et al. 2025

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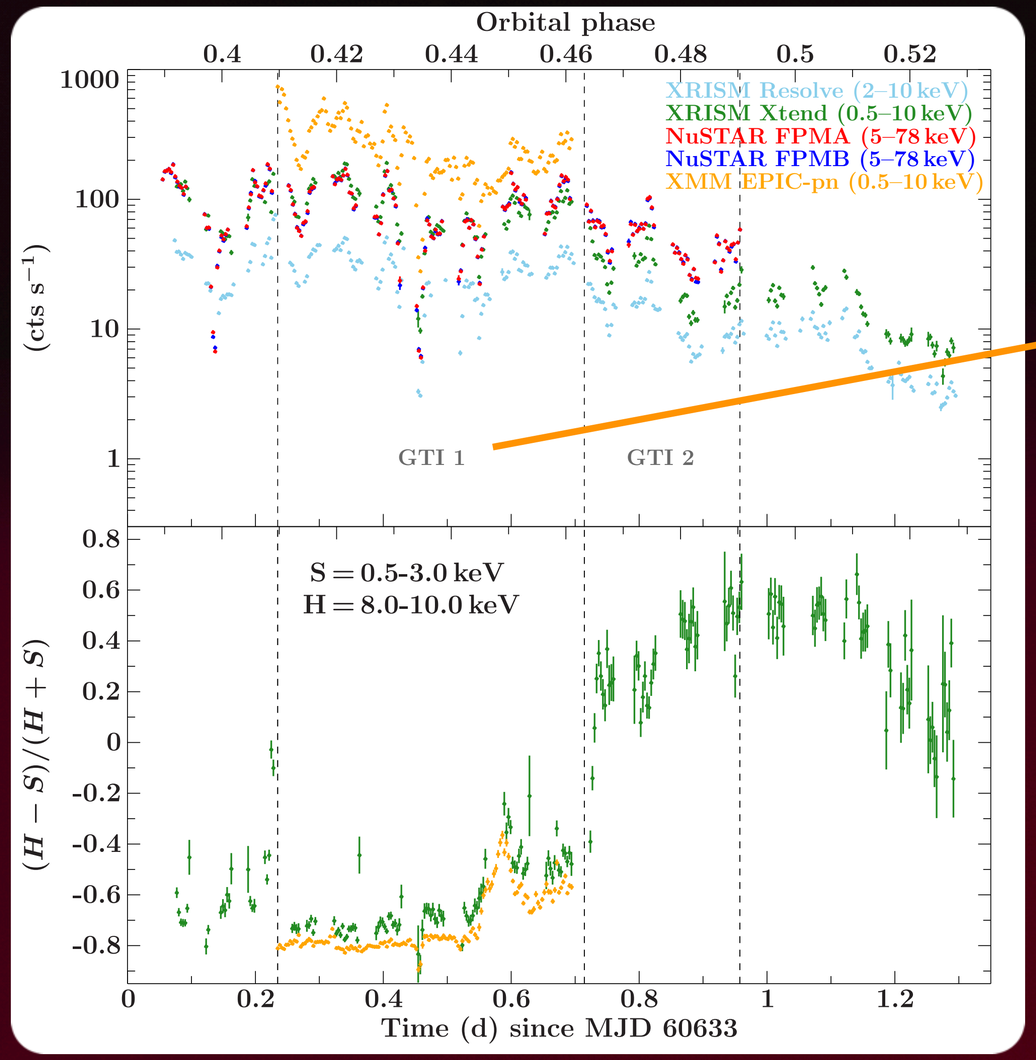

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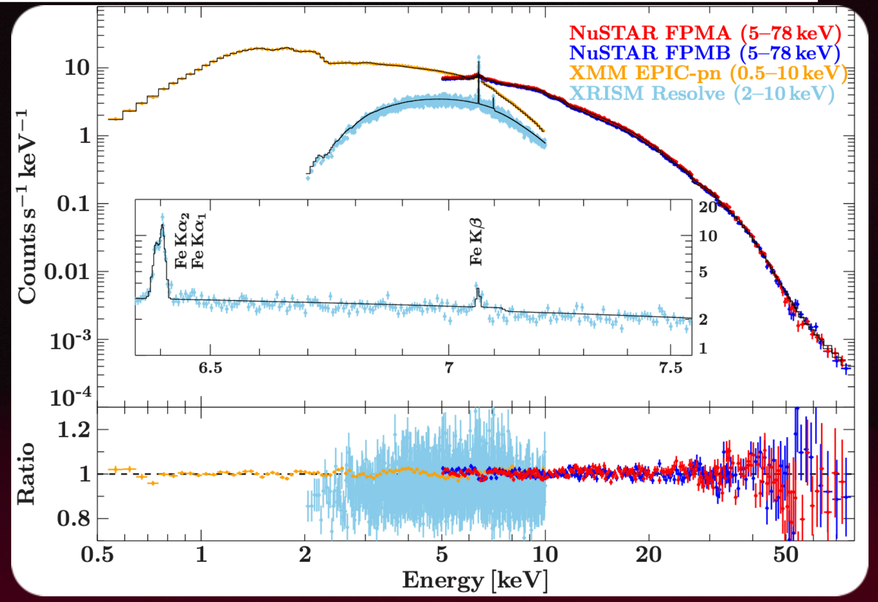

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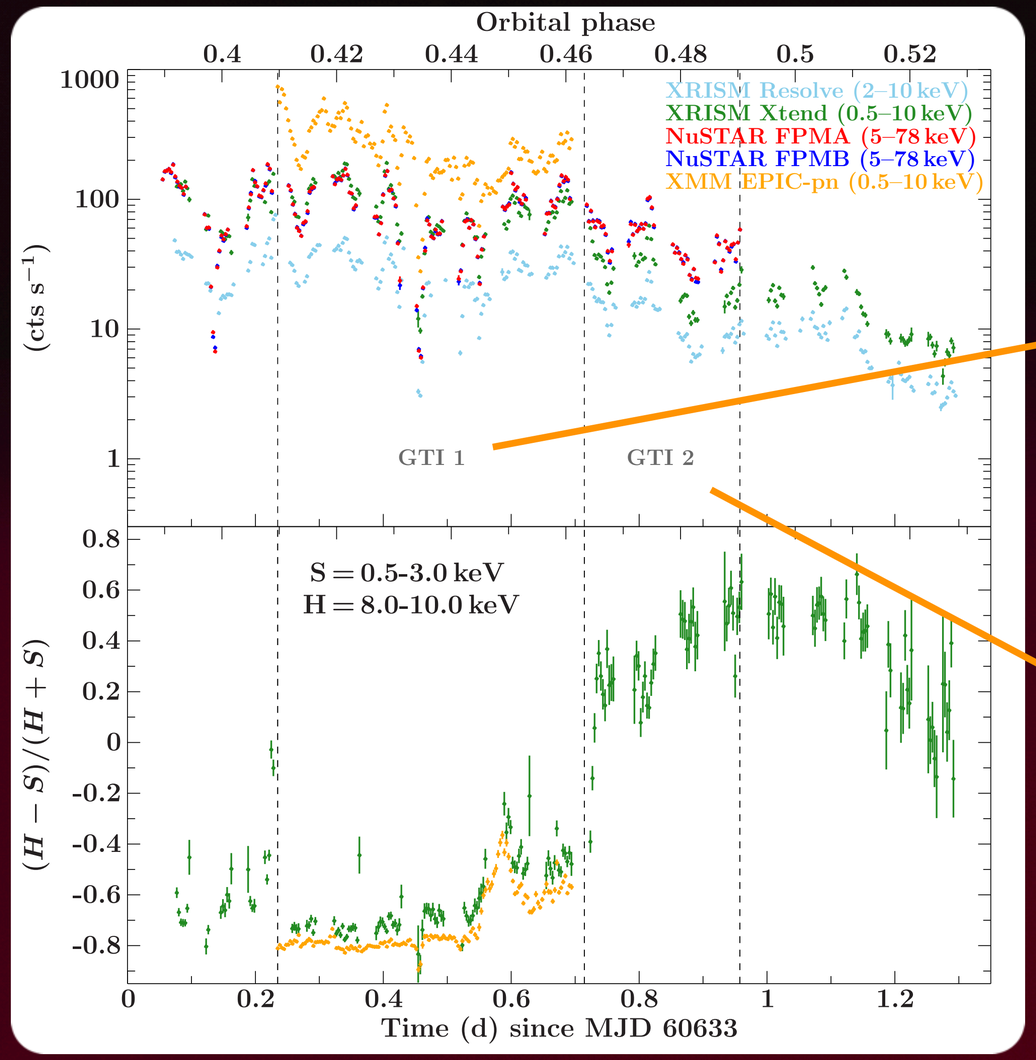

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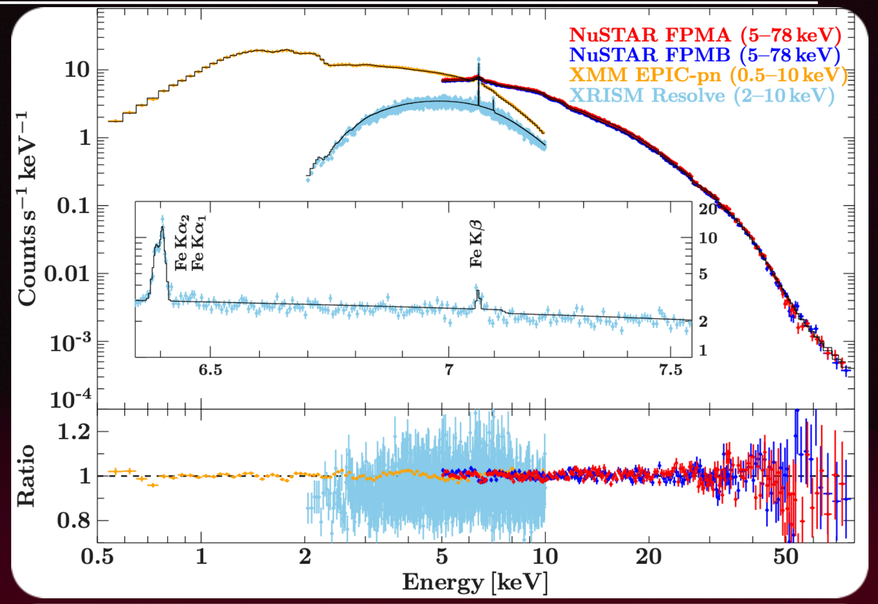
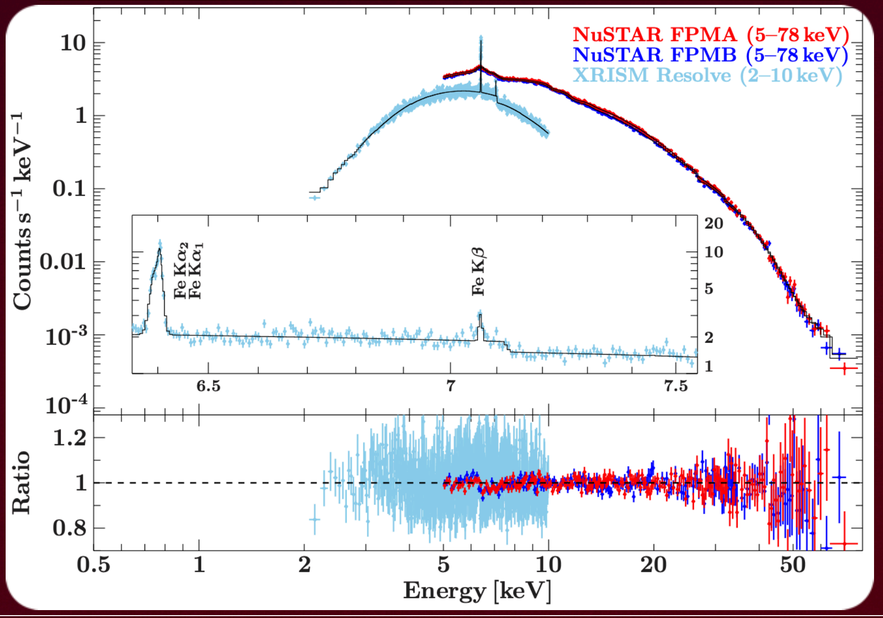
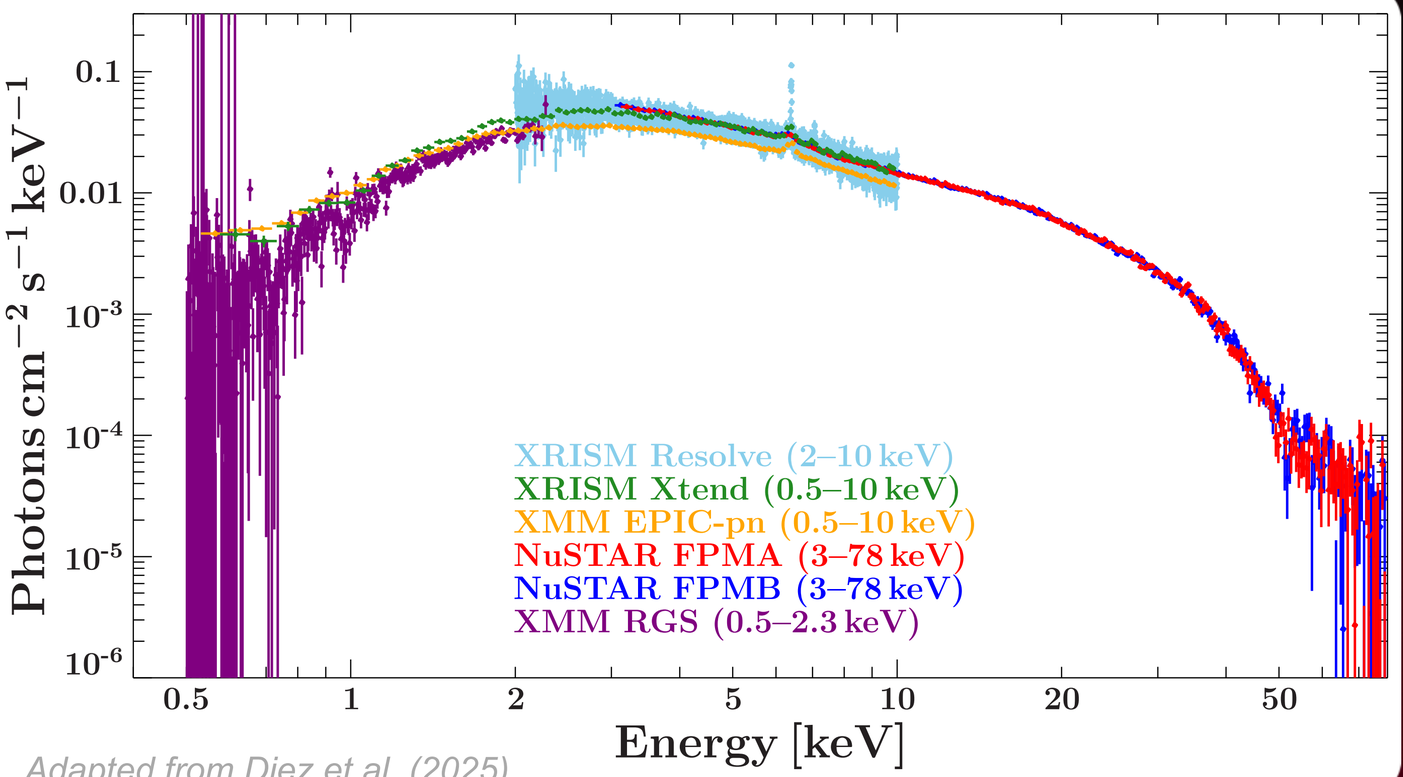




Line search



Adapted from Diez et al. (2025)

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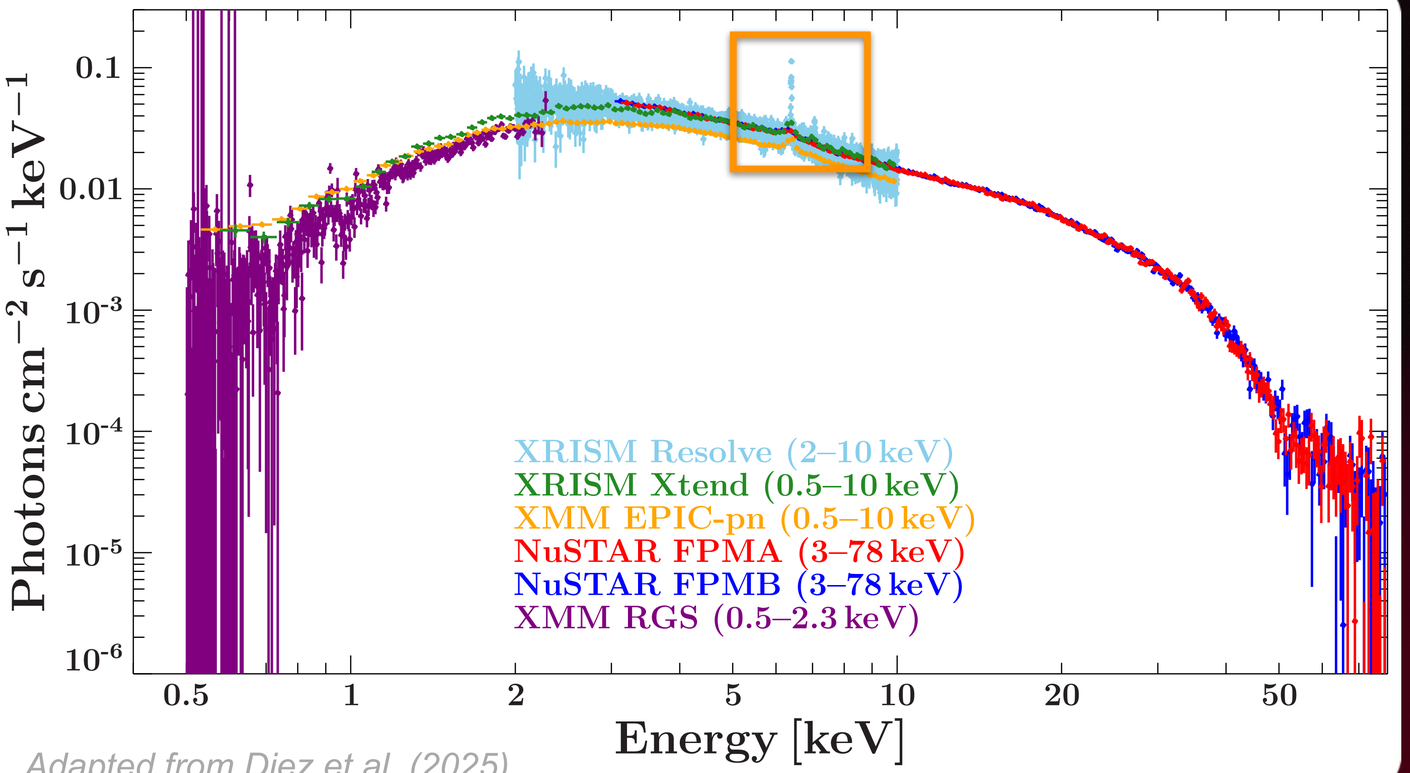

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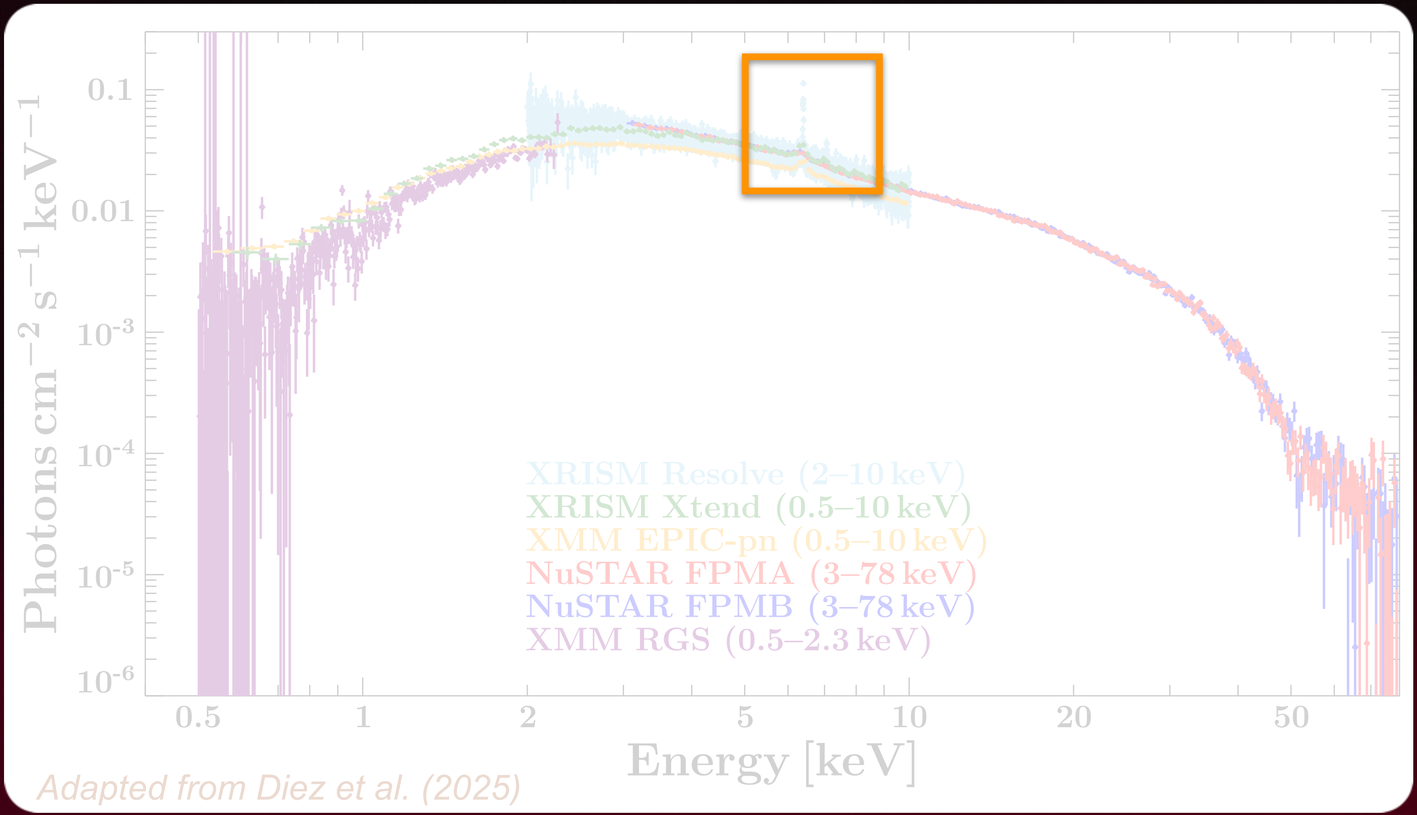
Fe region



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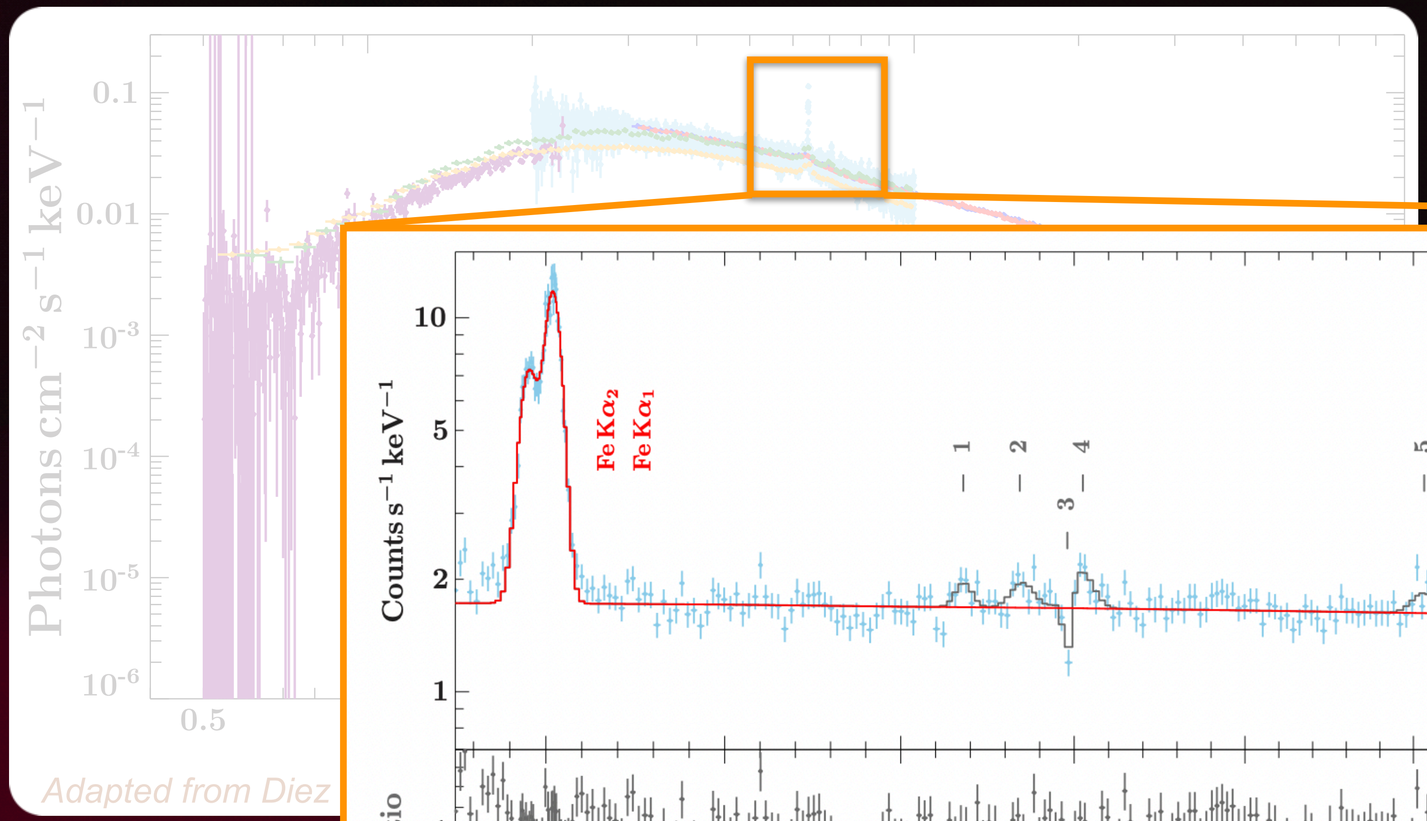

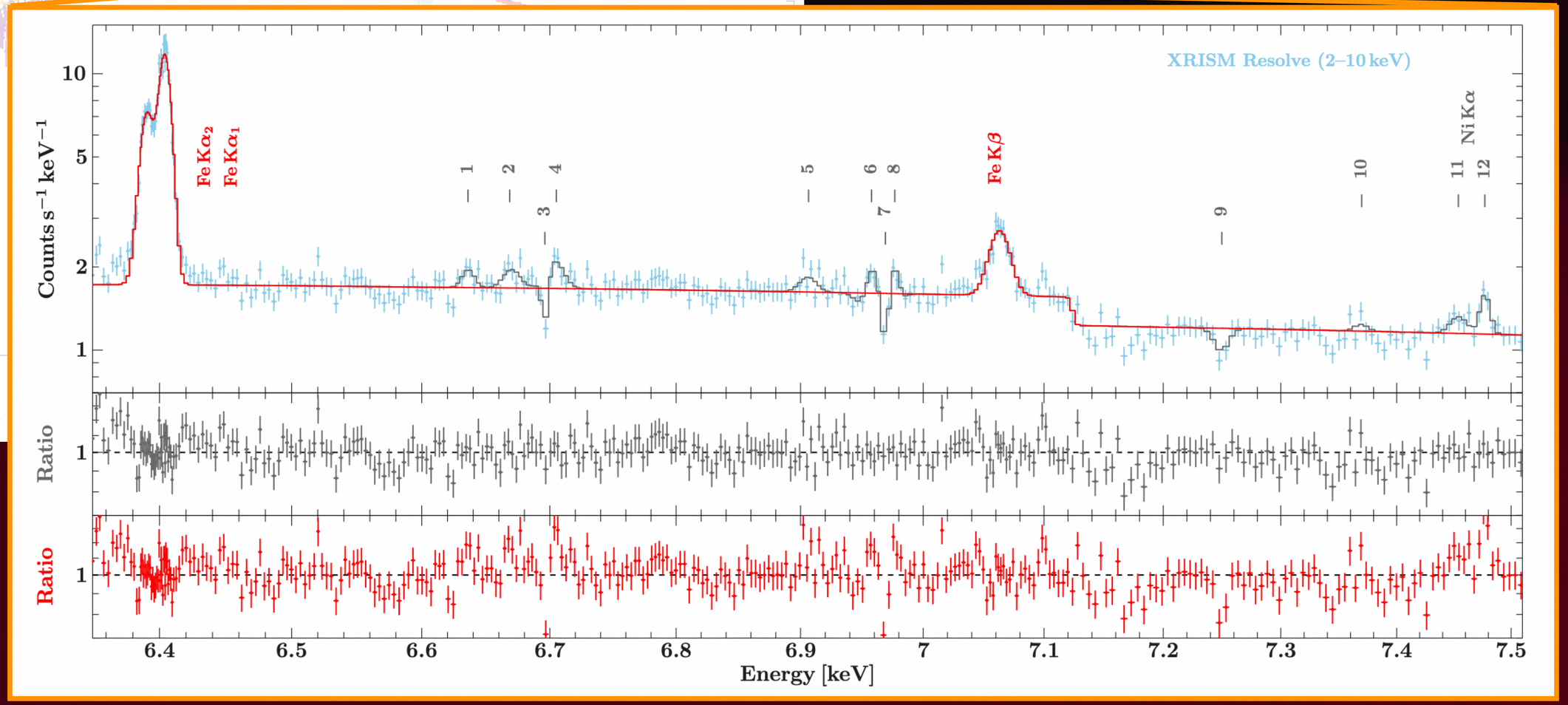

Diez et al. 2025

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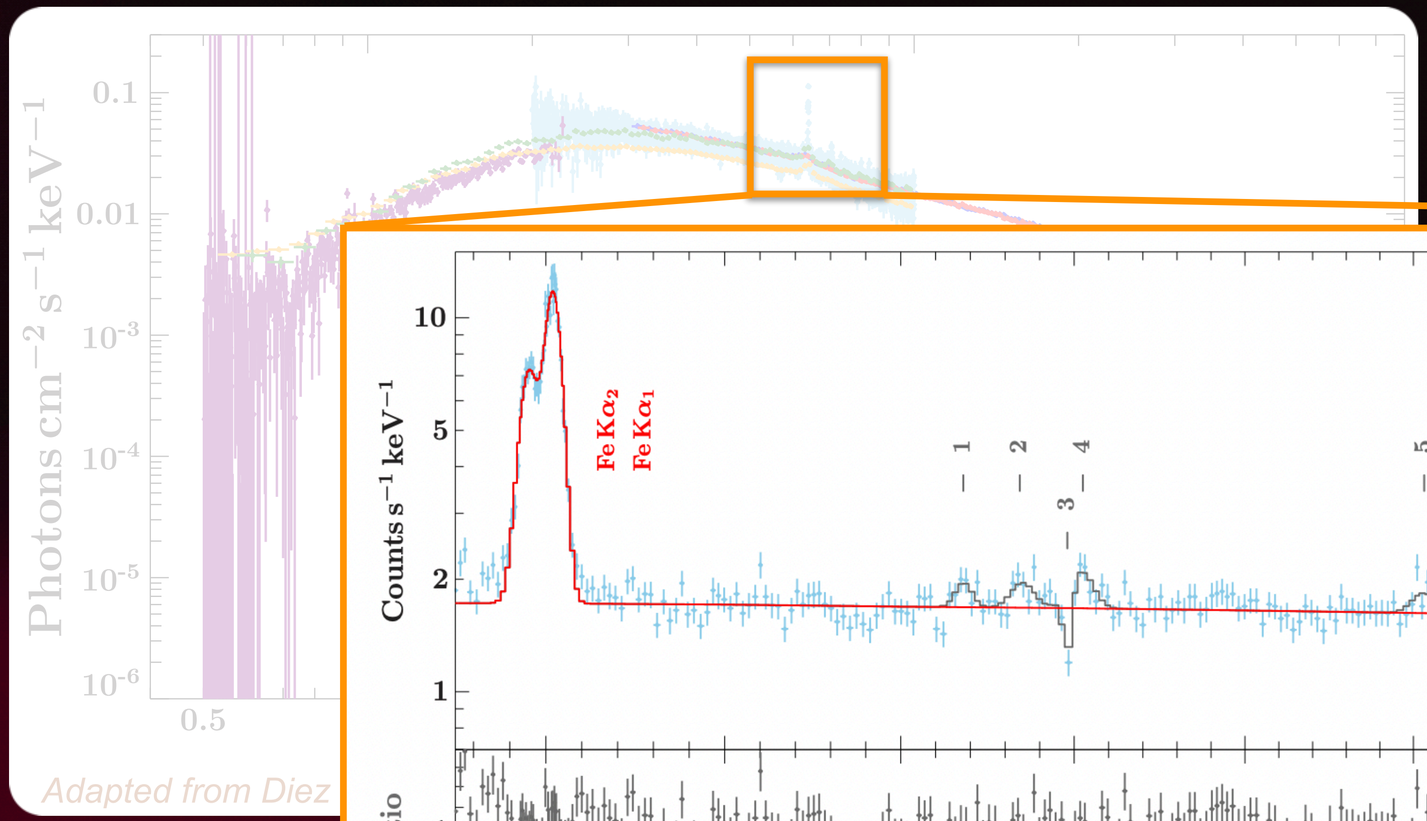

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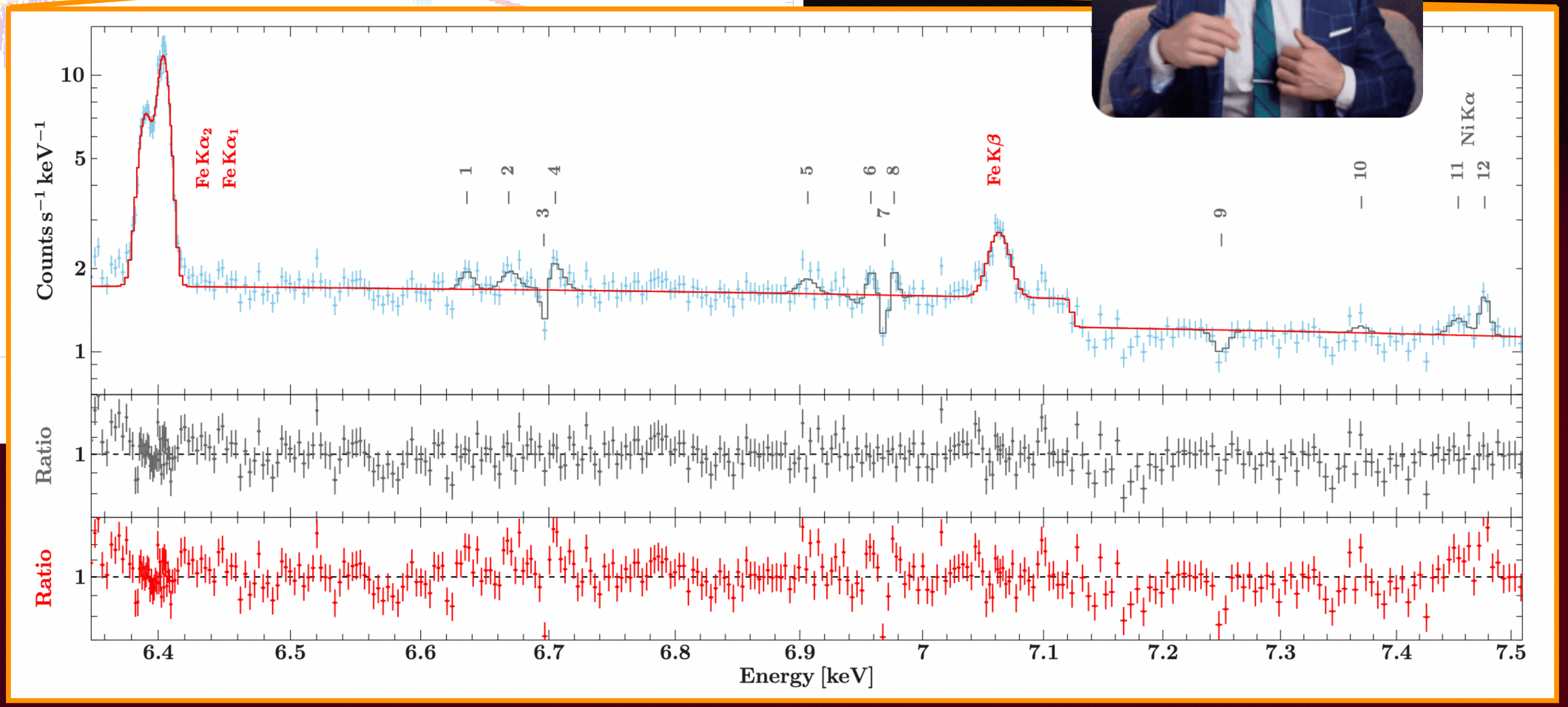
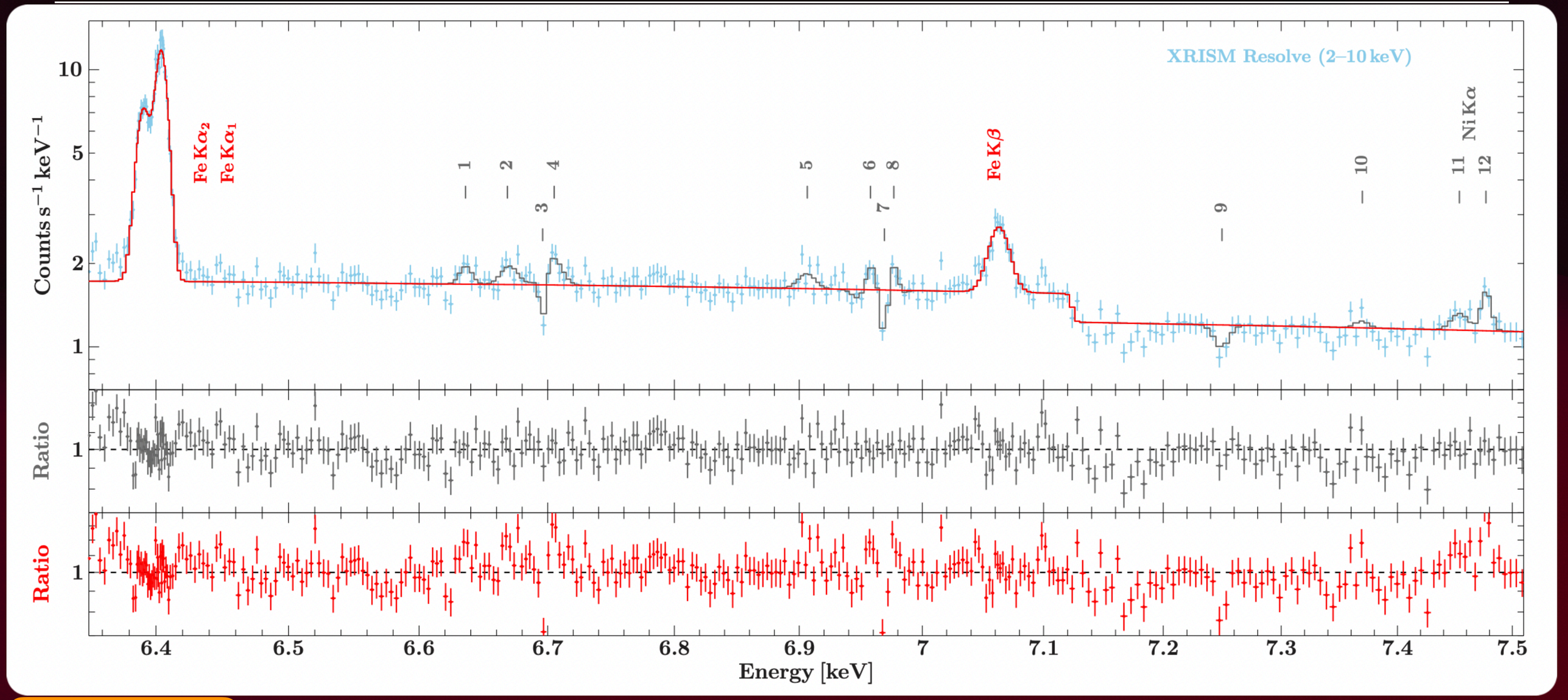


Diez et al. 2025

High-resolution spectroscopy



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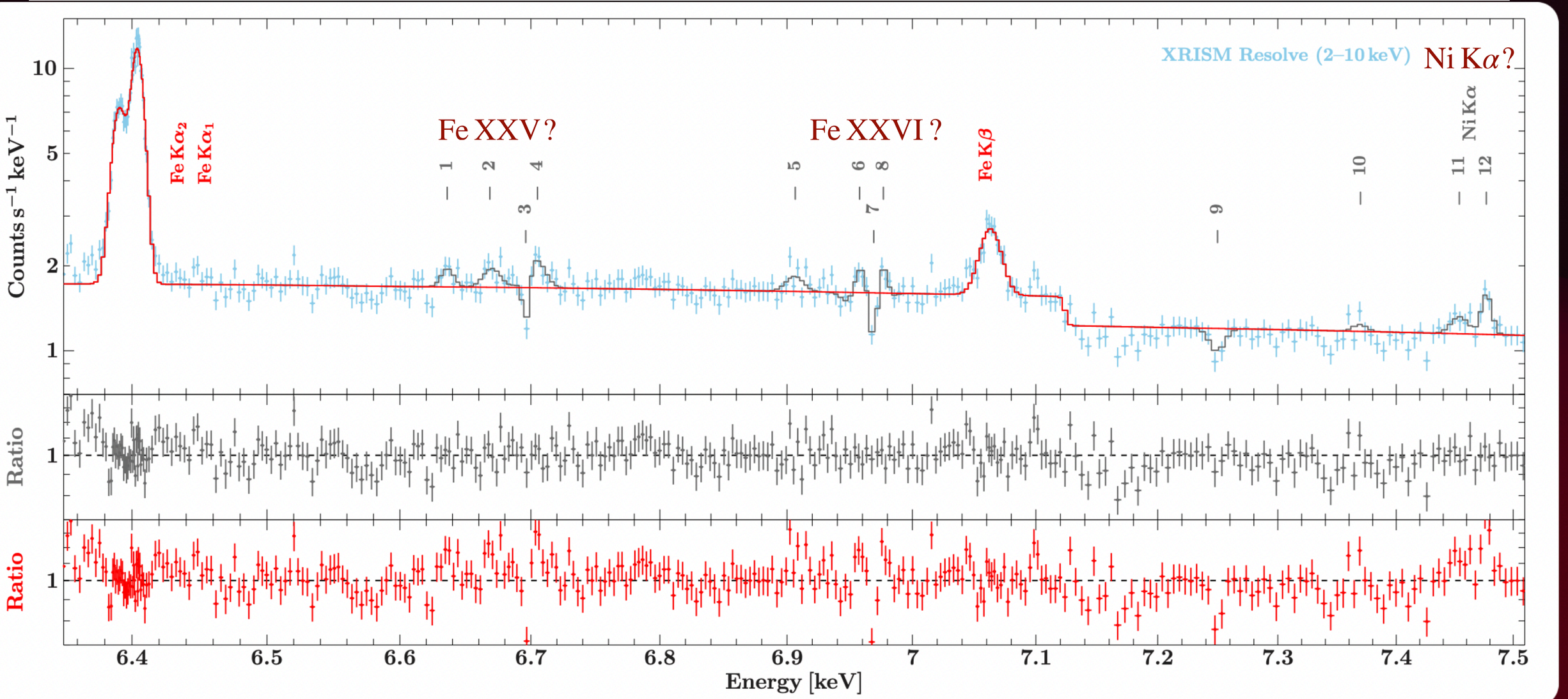

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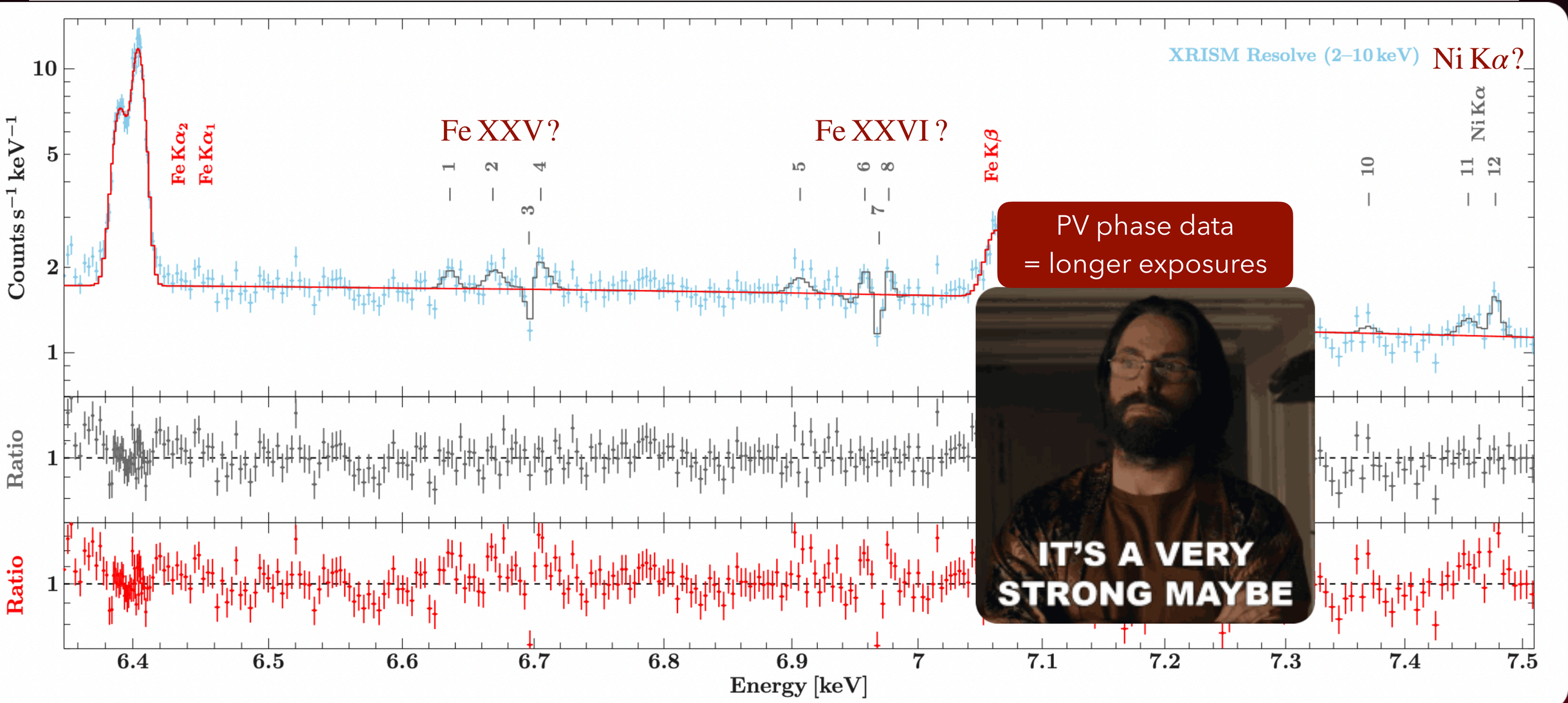
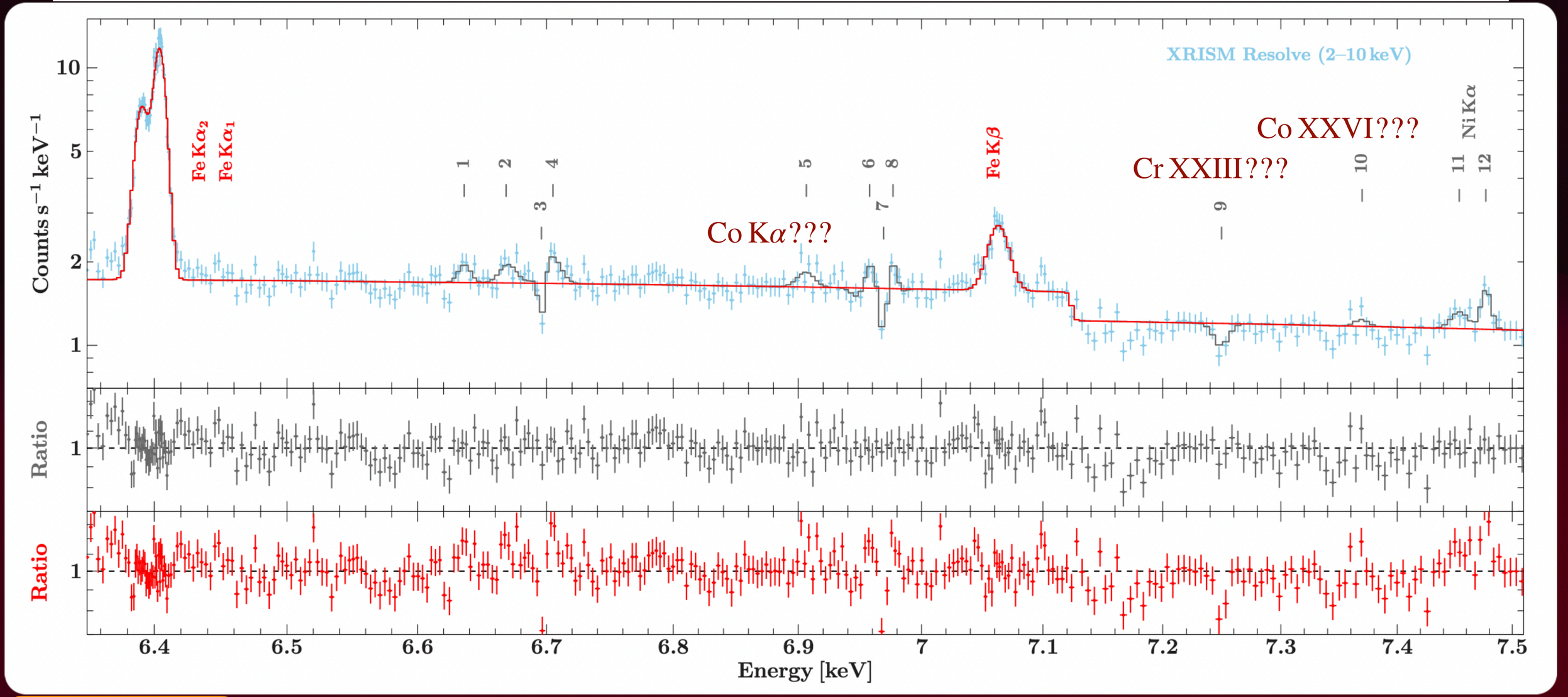


Diez et al. 2025

High-resolution spectroscopy



Diez et al. 2025

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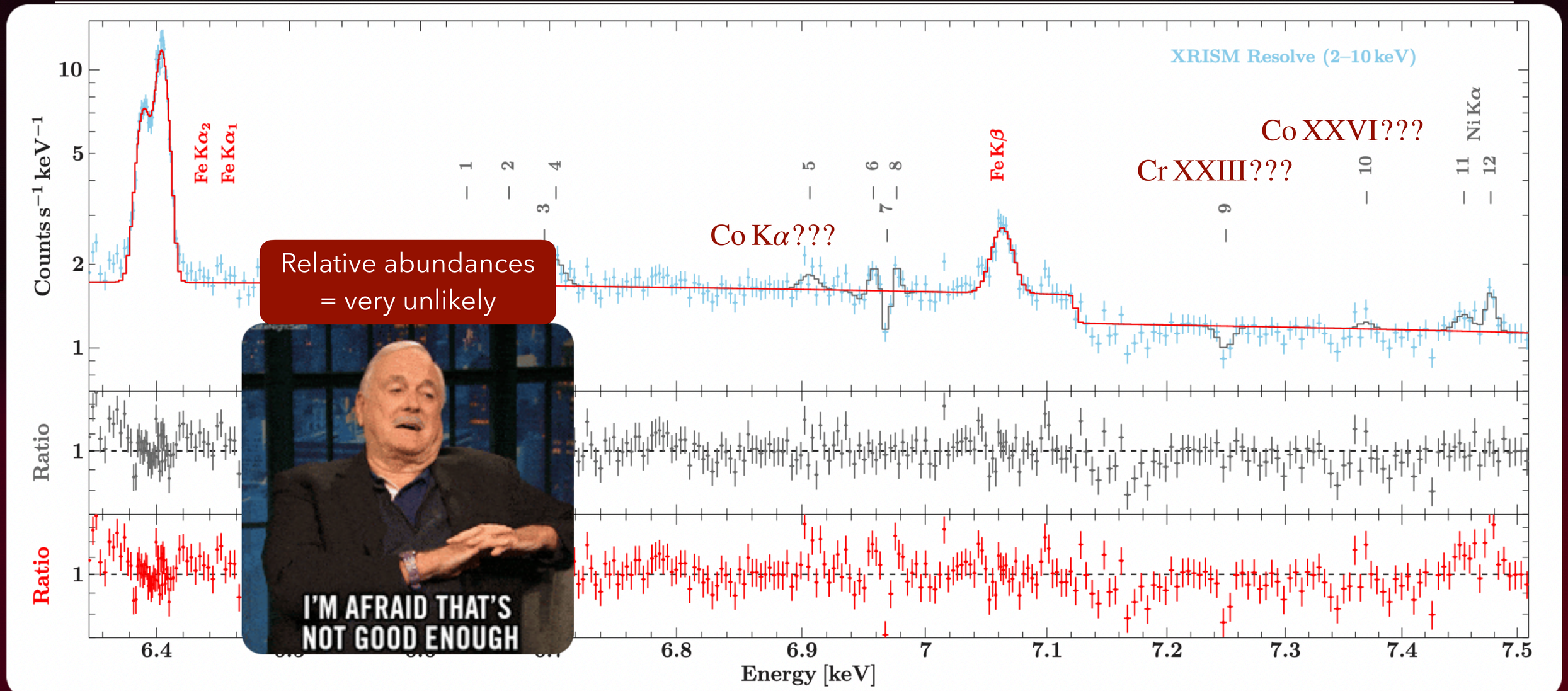

Diez et al. 2025

Outcomes

- High-resolution spectroscopy with XRISM/Resolve
  → first detection of the Fe Kα doublet in Vela X-1
  → wind velocities consistent with theoretical estimates in the inner region where the neutron star is located
  → be conservative when analysing your data at low S/N

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We found Cobalt in Vela X-1!

C. M. Diez[1,⋆], S. Dupourqué[2], M. Zhou (周孟磊)[3], E. Quintin[1], G. A. Matzeu[4], F. Fürst[1], P. Kretschmar[1], R. Amato[5], and C. Malacaria[5]

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Well, most probably no…

First look at Vela X-1 with XRISM

A simultaneous campaign with *XMM-Newton* and NuSTAR

C. M. Diez[1,⋆], S. Dupourqué[2], M. Zhou (周孟磊)[3], E. Quintin[1], G. A. Matzeu[4], F. Fürst[1], P. Kretschmar[1], R. Amato[5], and C. Malacaria[5]

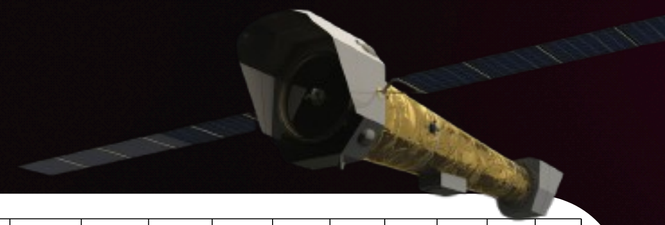
Outline

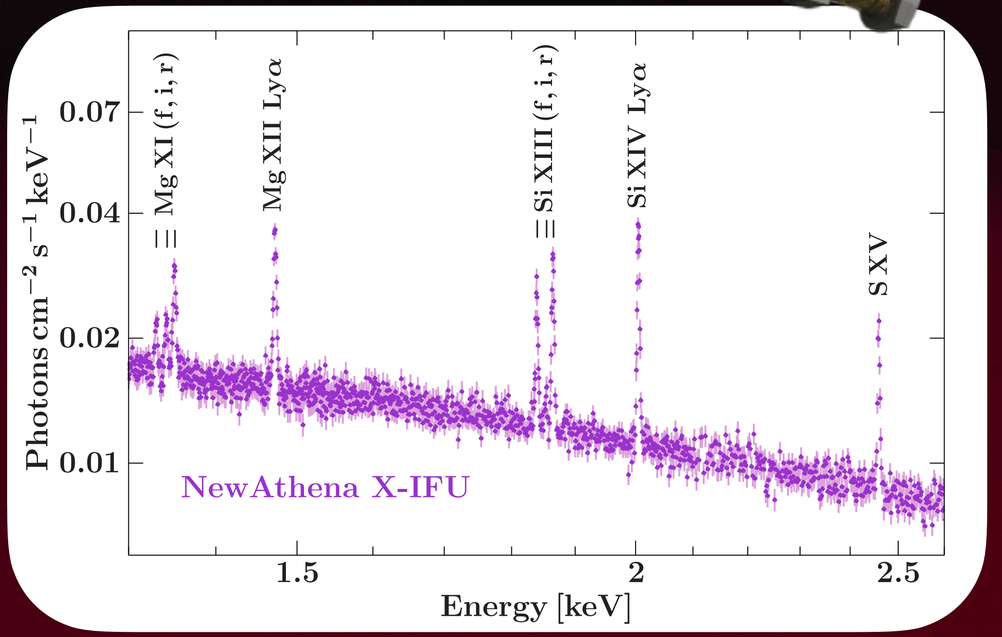
- Introduction • *Stellar winds • Observations • Microcalorimeters •*
- Statistical tools • *Bayesian inference • jaxspec •*
- Results from XRISM • *Cross-calibration updates • High-res spectro •*
- Perspectives for NewAthena • *Special Issue • Future prospects •*

Perspectives for NewAthena

Special Issue

- 5 merged abstracts, total of 40+ authors
- *Mapping the environments around compact objects in binaries with NewAthena*
- Why NewAthena for stellar wind studies?
  → low energy coverage
  → unprecedented spectral and spatial resolution
  → for short exposure times!

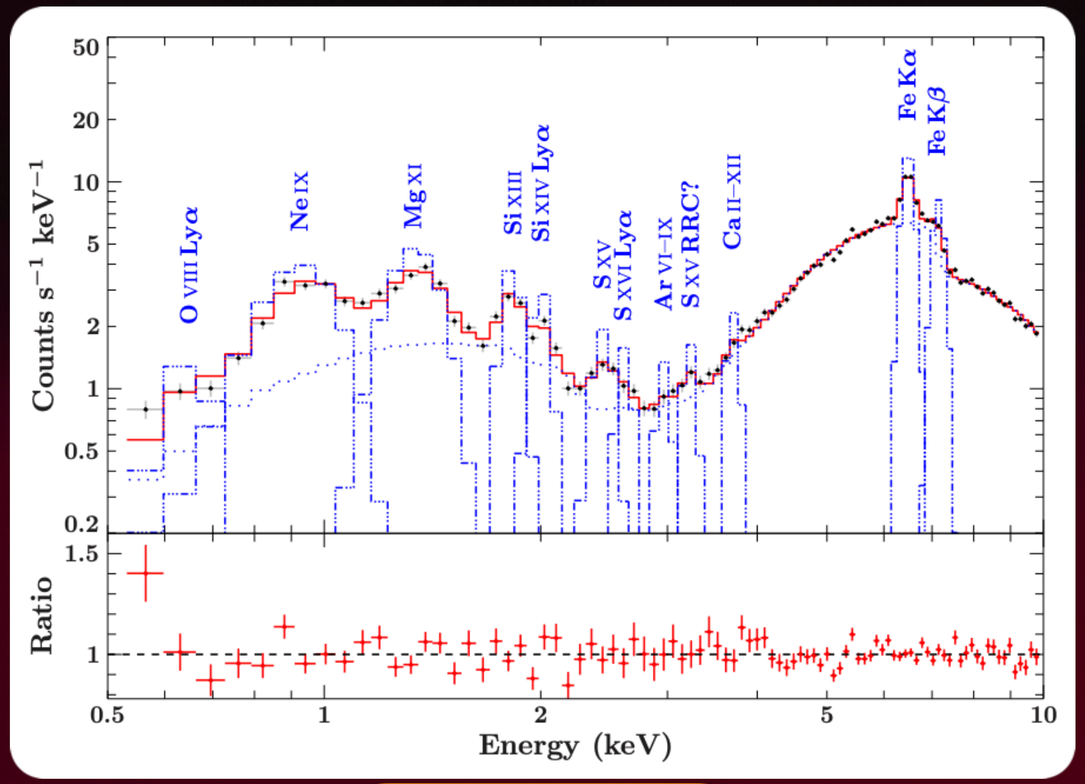




5 ks!

Perspectives for NewAthena

Cover low energies where most of the ionised wind is present



Diez et al. 2023

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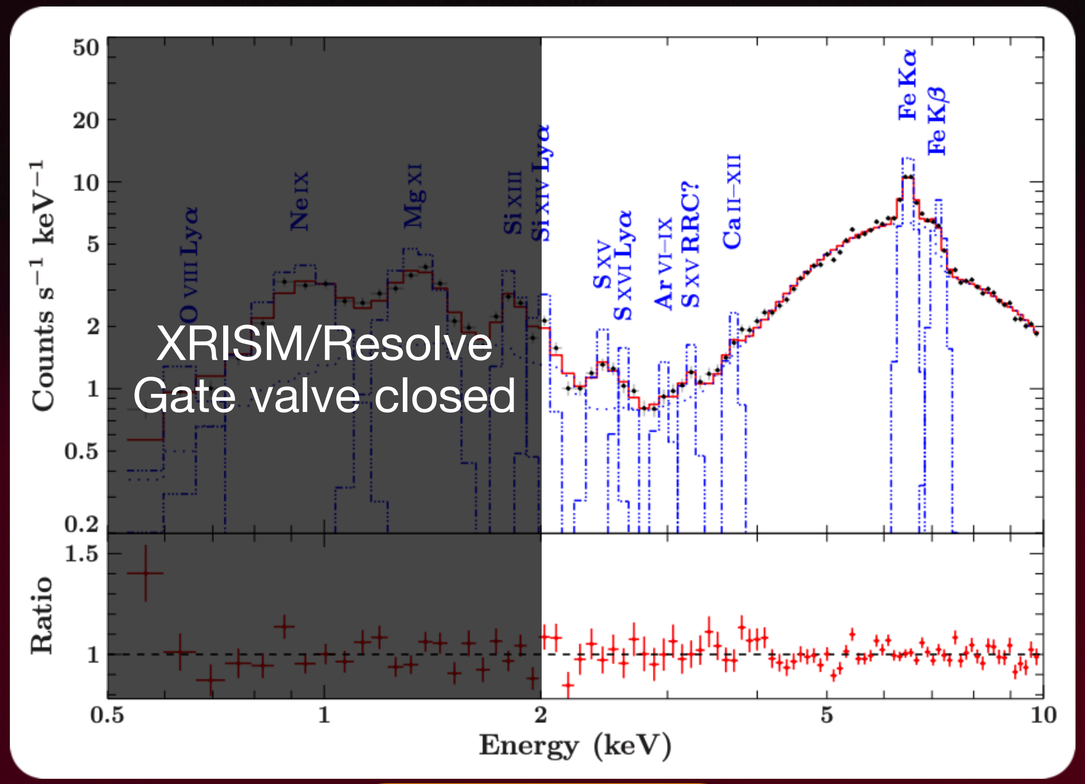

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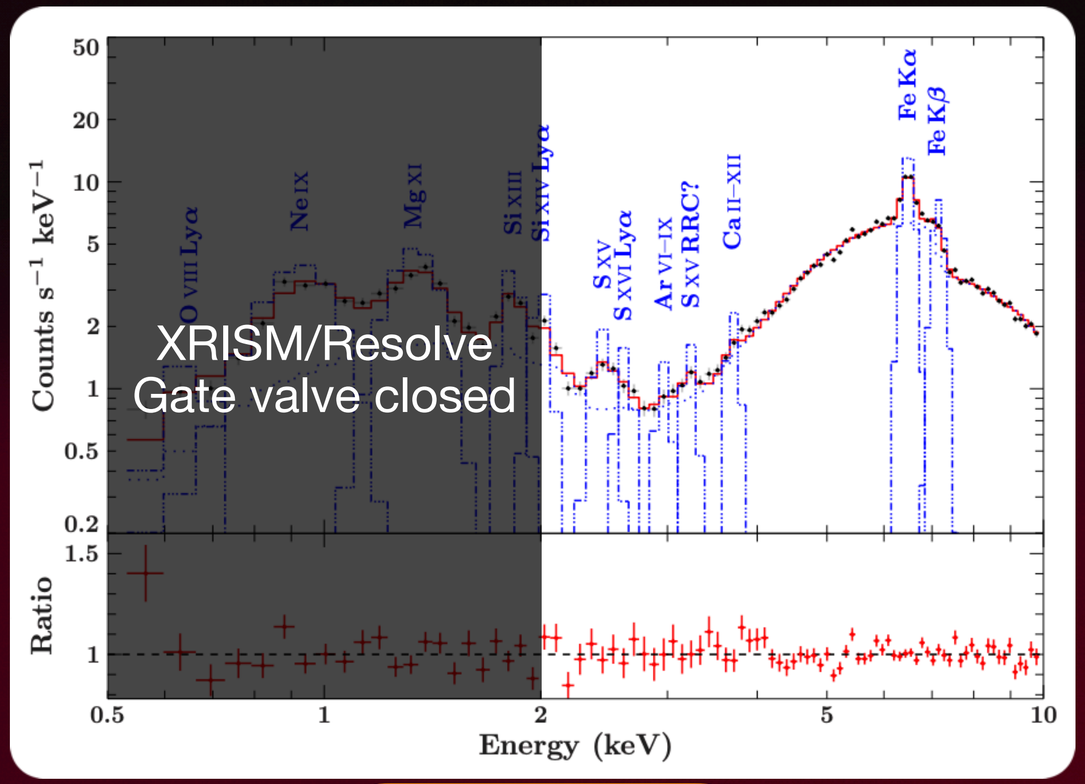

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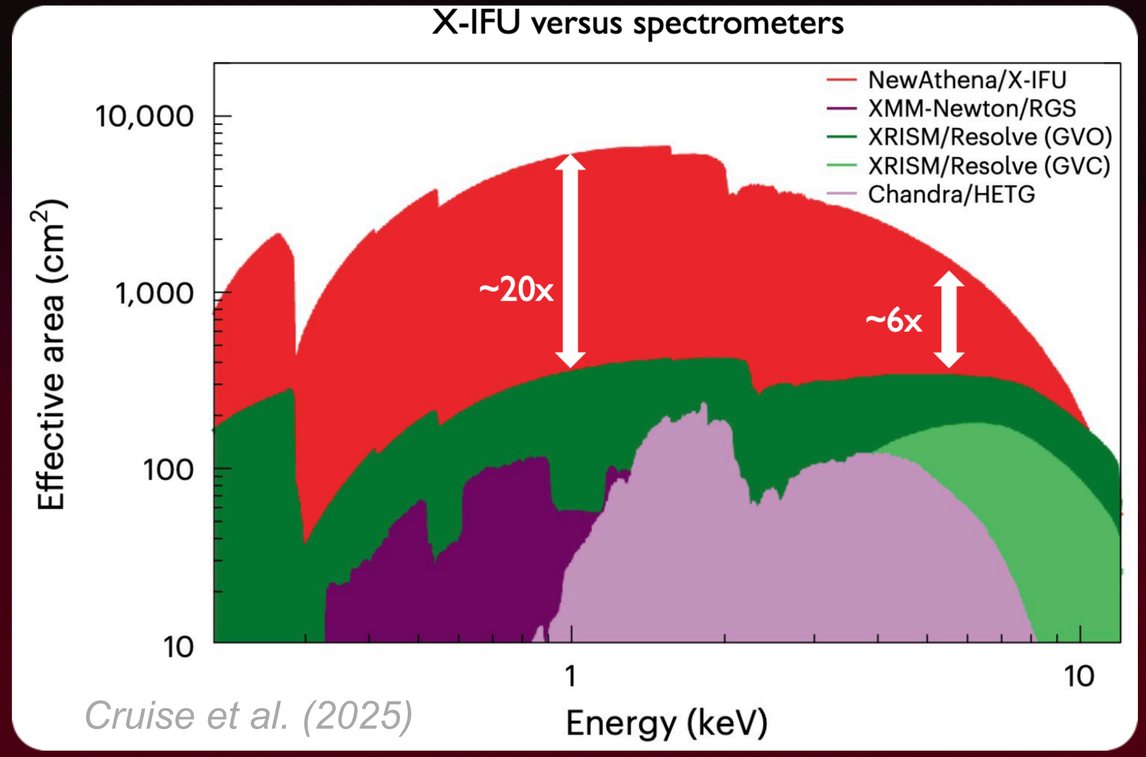
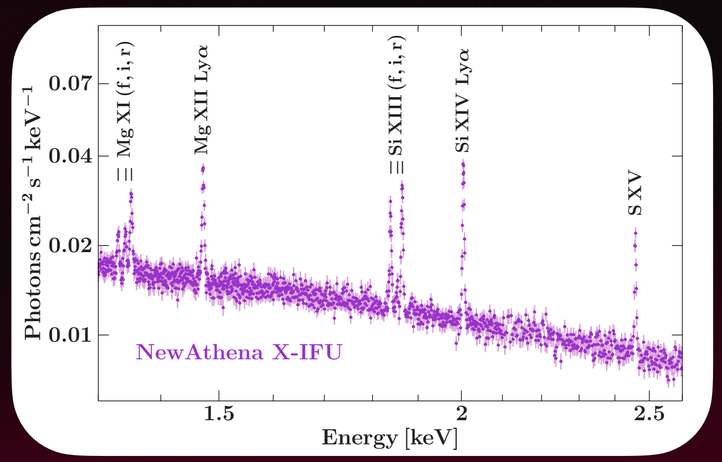


Perspectives for NewAthena

Constraints on $M_{\rm NS}$



Perspectives for NewAthena

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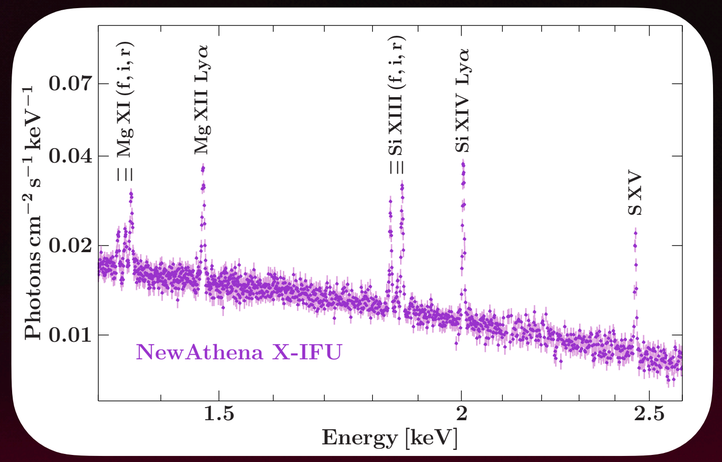

Doppler shifts

$$v_{\mathrm{r}} = c\left(\frac{\lambda_{\mathrm{obs}}}{\lambda_0} - 1\right)$$

Perspectives for NewAthena

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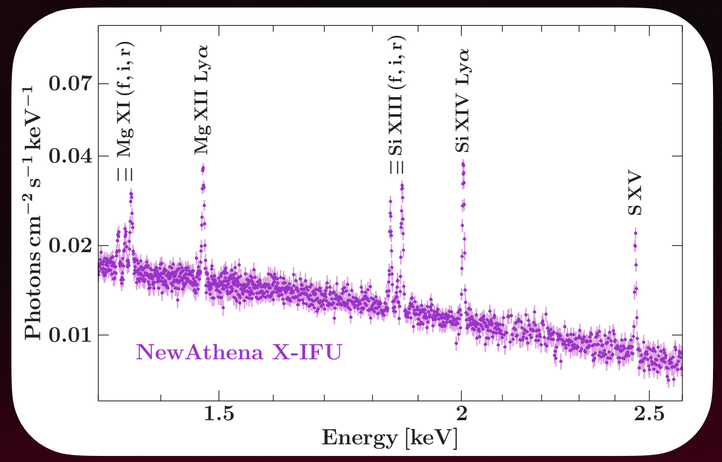

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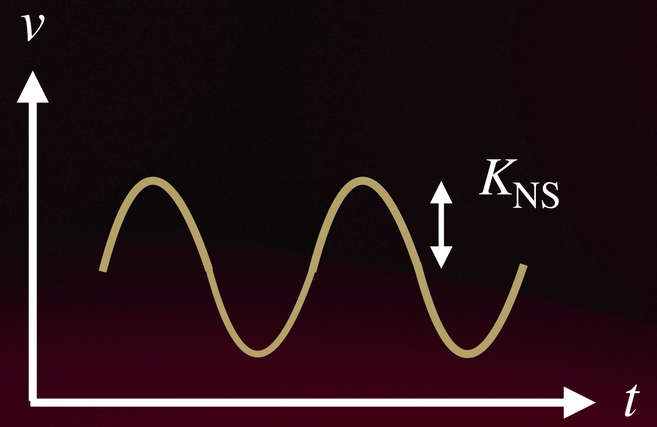

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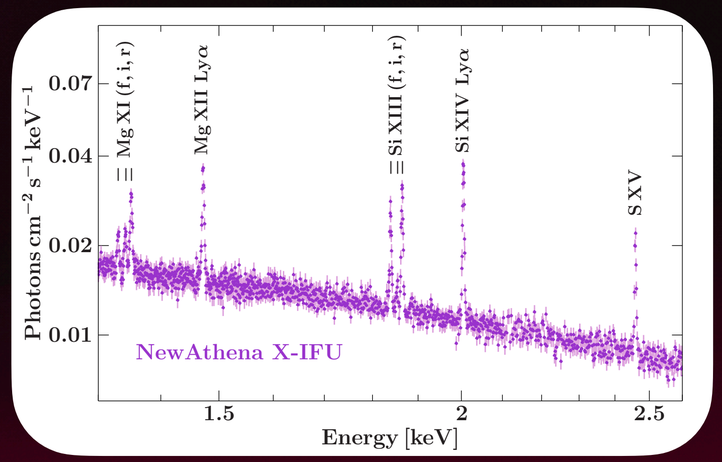

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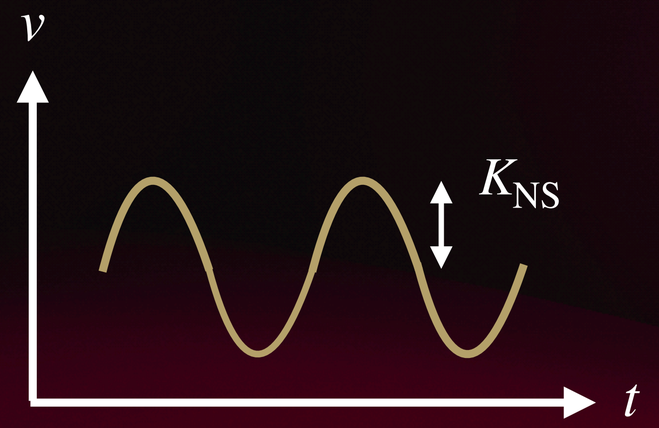

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Ephemeris of the source: P, e, i

Perspectives for NewAthena

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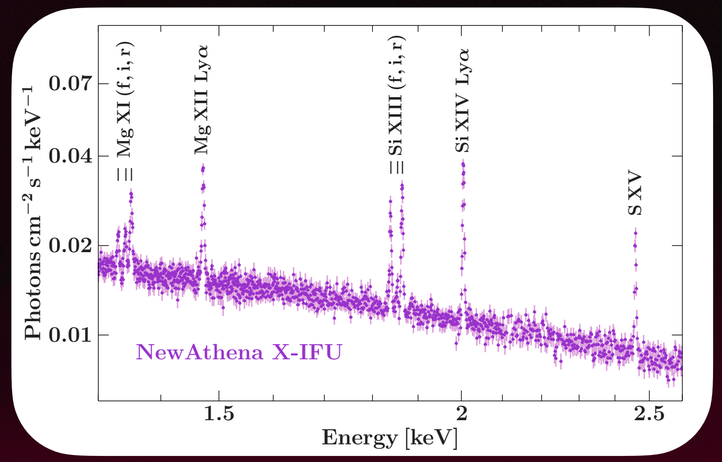

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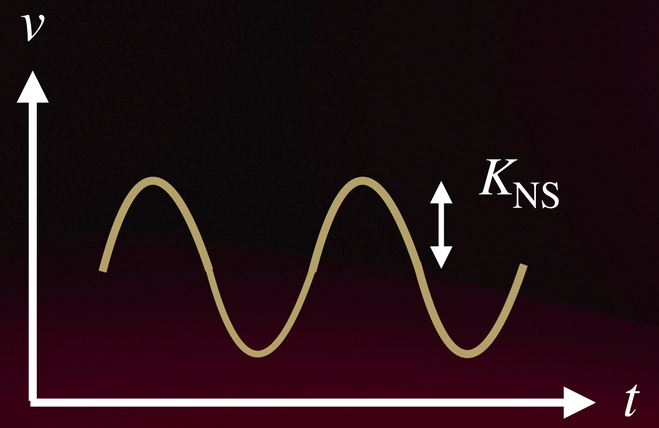

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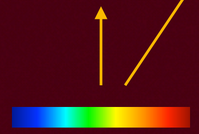

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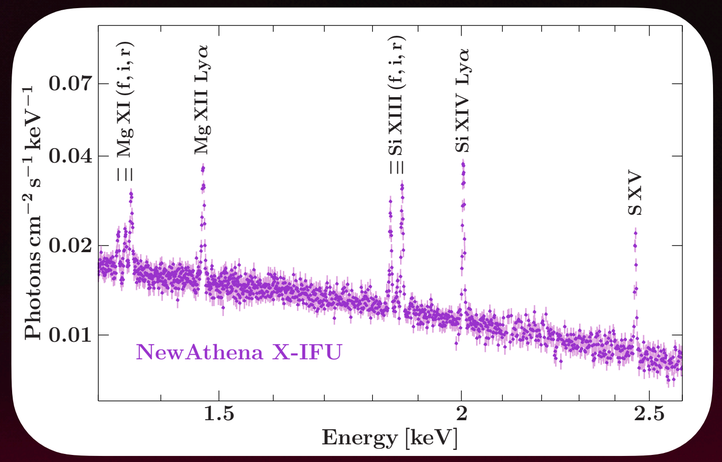

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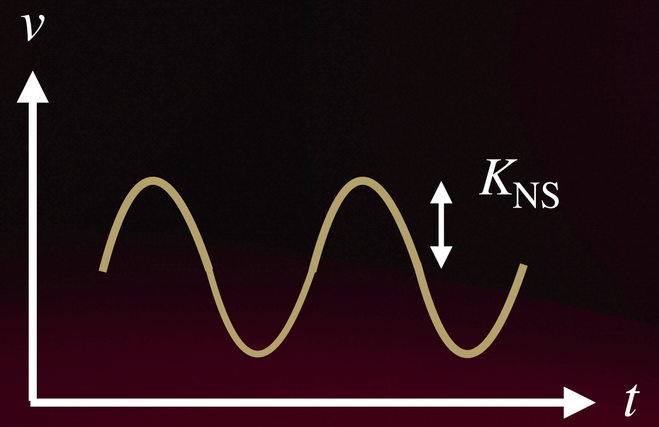

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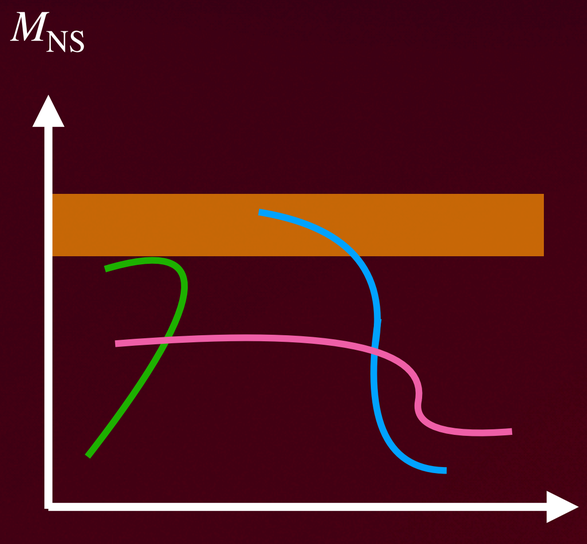

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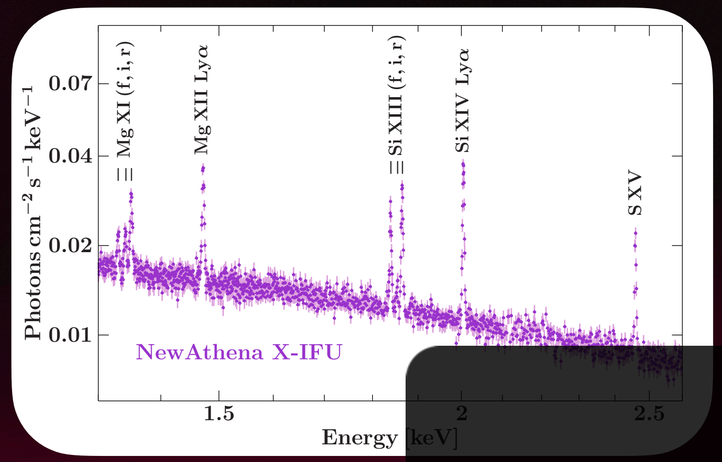

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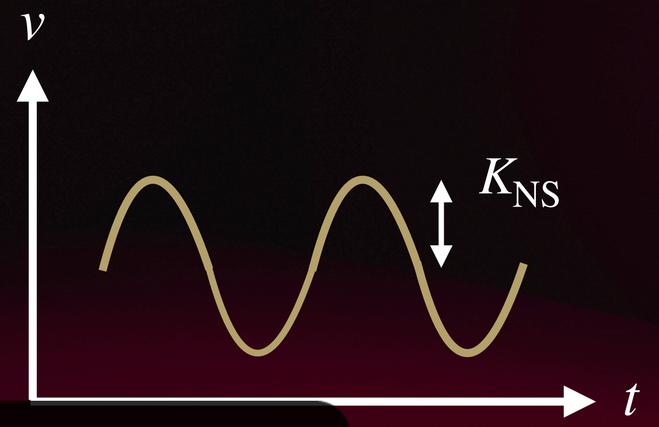
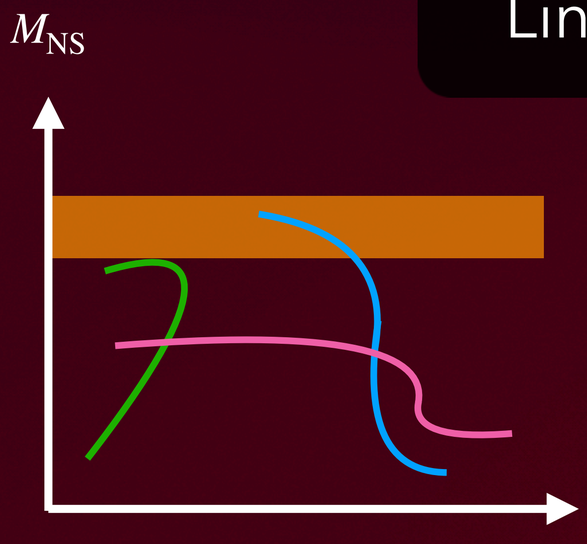


Necessary condition:
Lines need to originate from close to the neutron star



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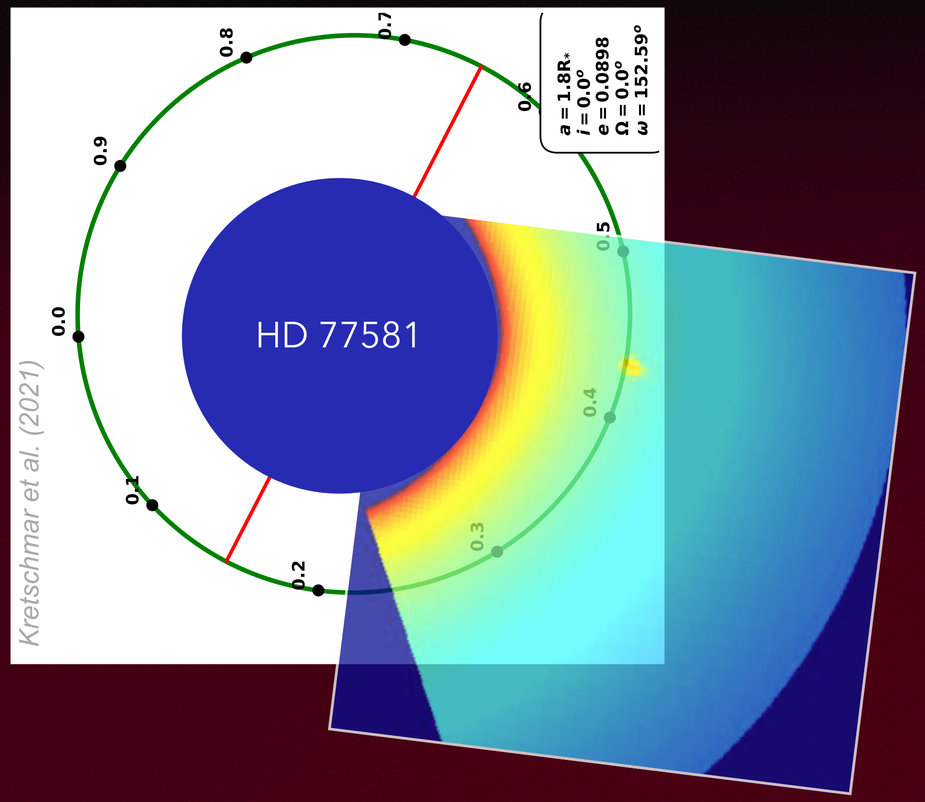
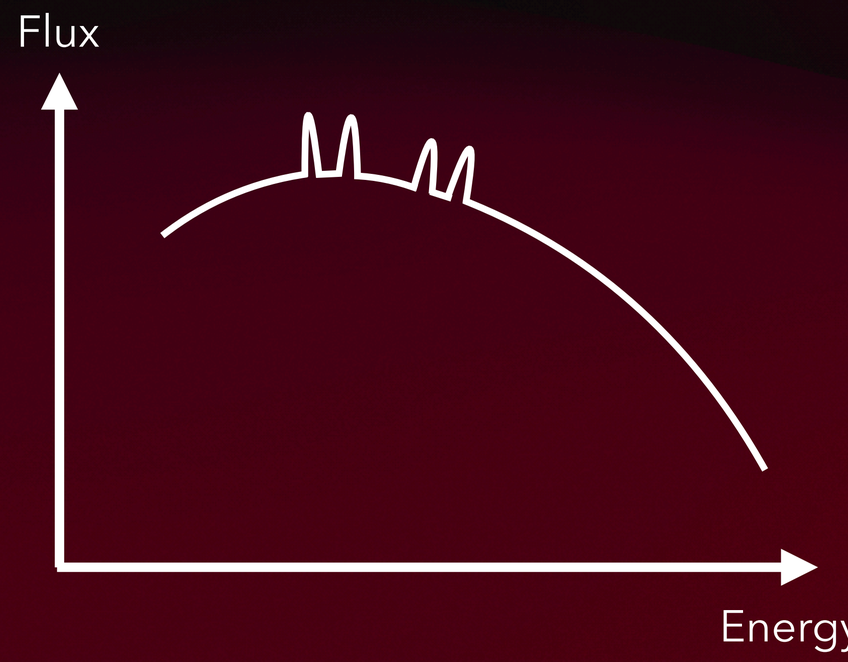
Establish chemical + velocity maps of the accreted material





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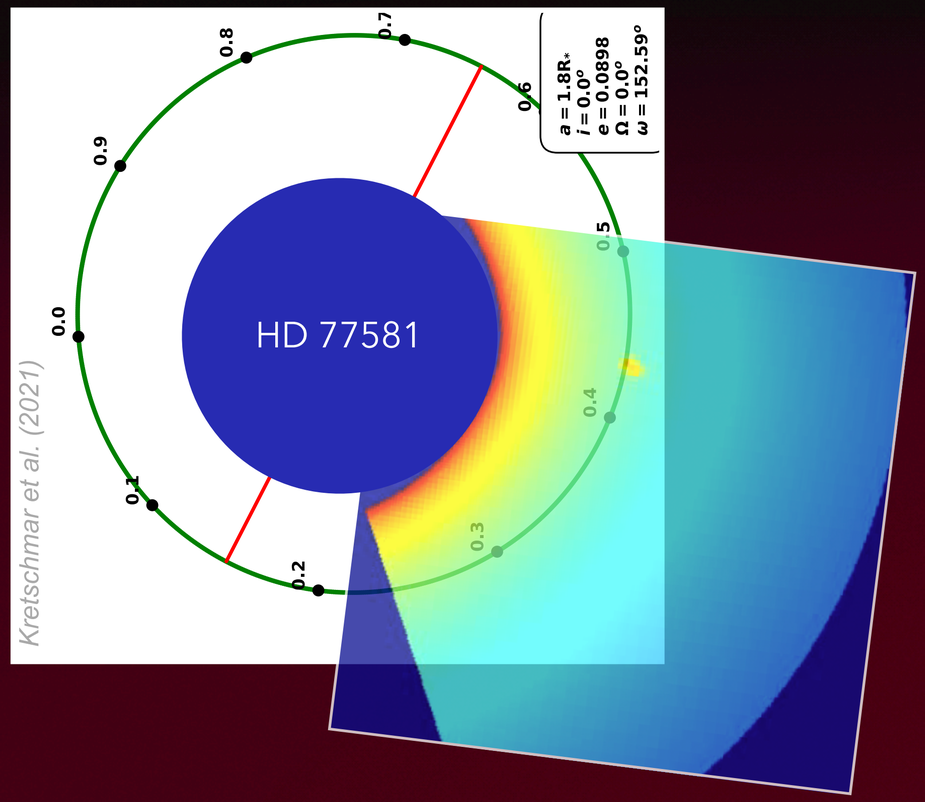

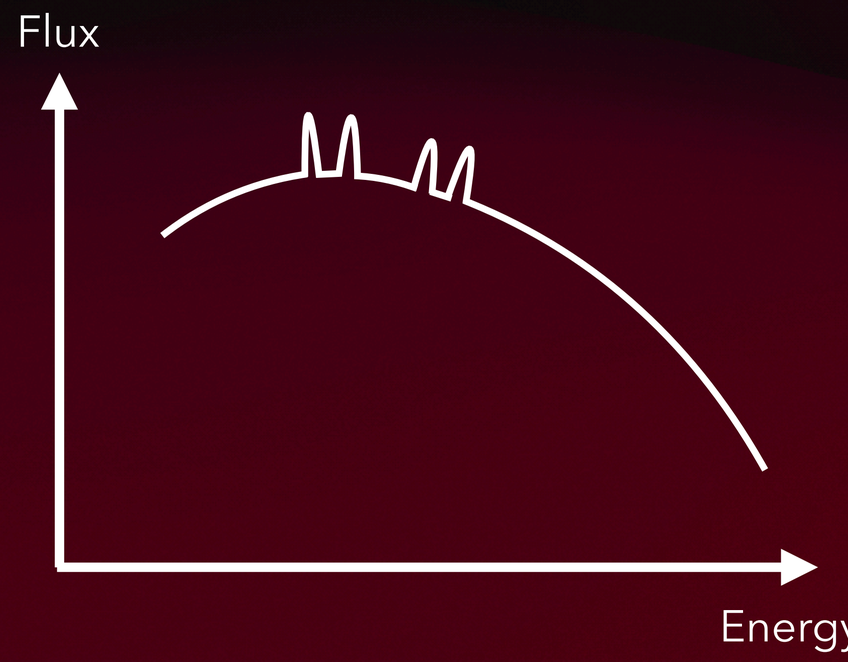

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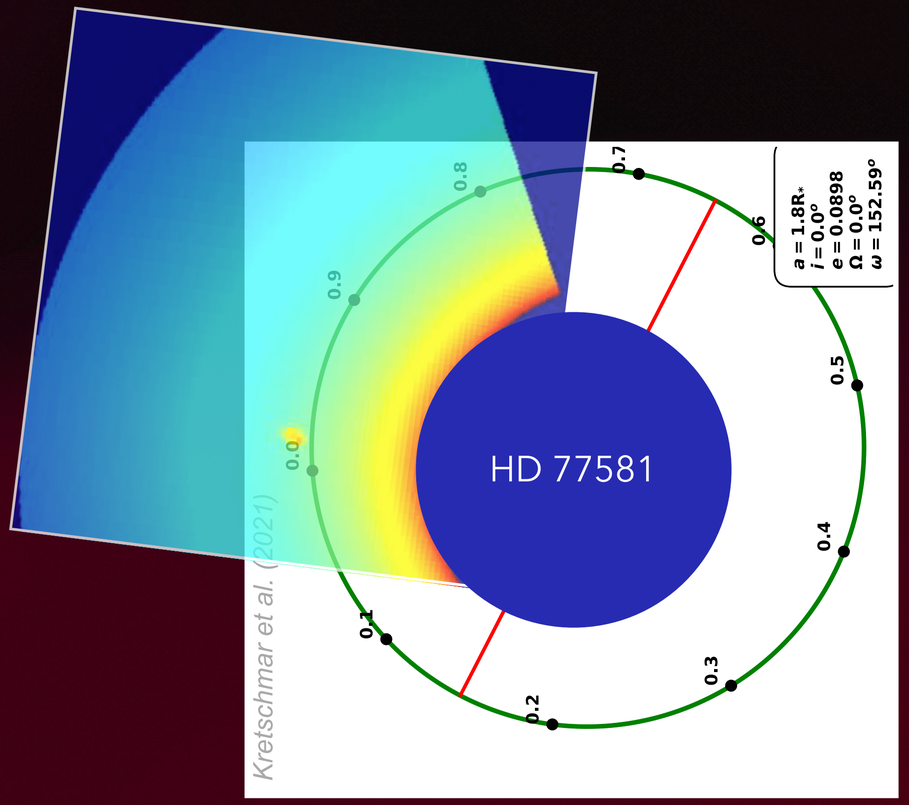

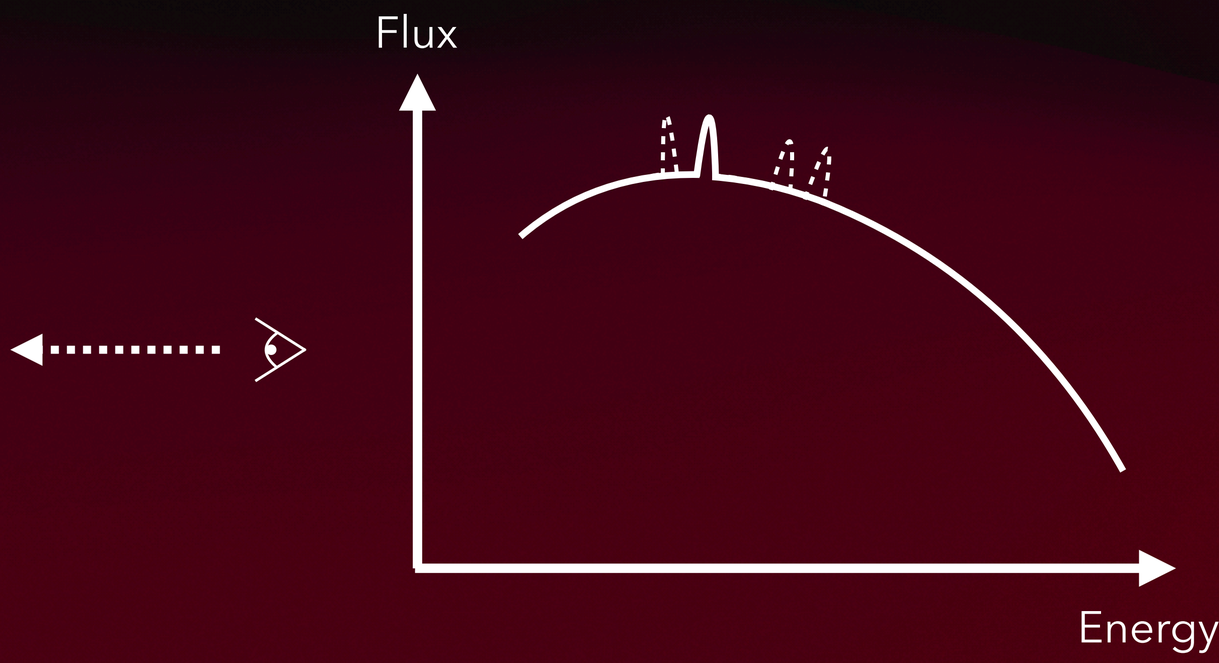

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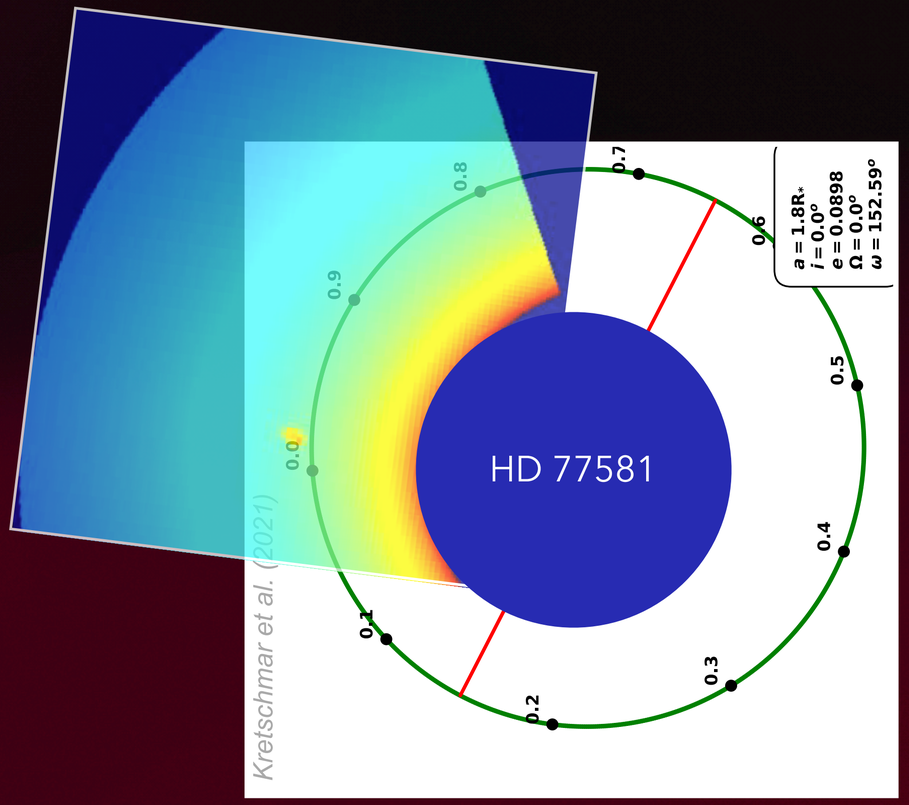

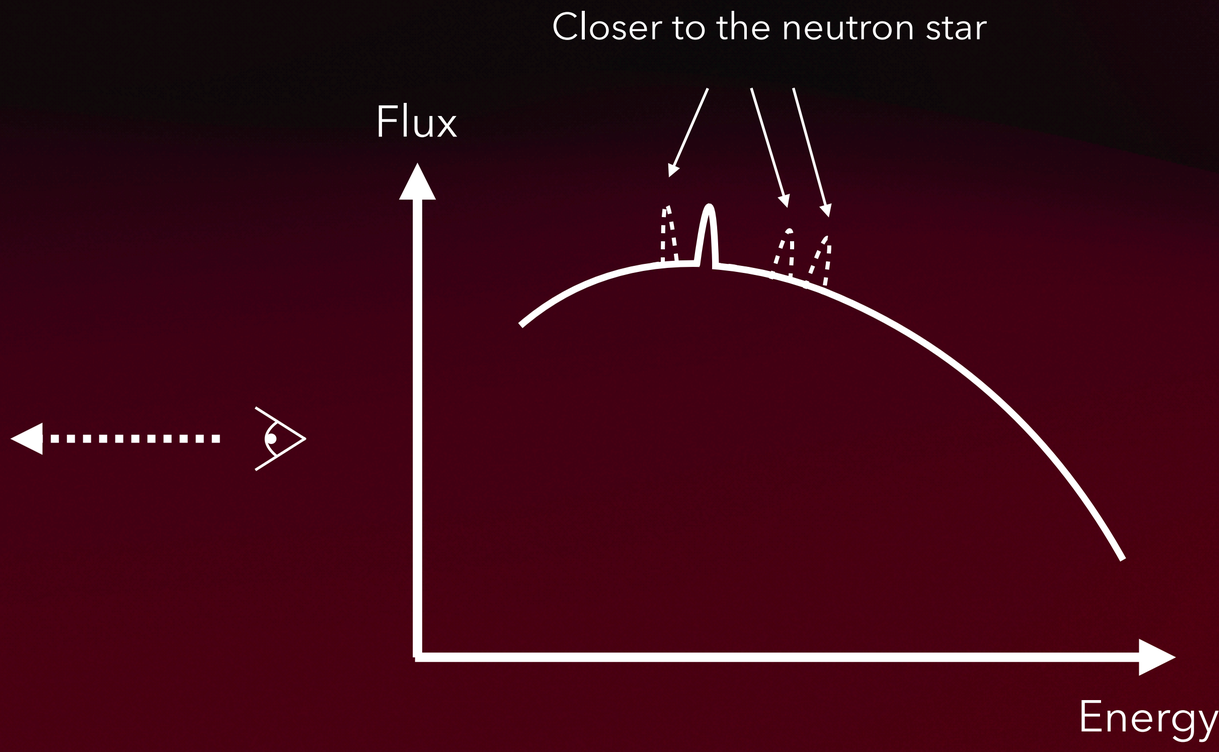

Conclusions

- Stellar winds in NS HMXBs:
  → investigation of massive stars environments
  → magnetic field structure onto NS via, e.g., pulse profile studies (see Dimitris' talk)
  → insights for stellar formation and evolution when combined with studies from more exotic systems (see Aafia's and Iuliia's talks)

- From XRISM/Resolve…
  → most detailed view on stellar winds in HMXBs: wind velocities consistent with theoretical estimates in the inner region where the NS is located
  → constraints on our models

- To NewAthena/X-IFU
  → development of methods for X-ray spectral fitting like jaxspec (+ others: see Graciela's talk)
  → unprecedented spectral and spatial resolution & reduced exposure times for high-resolution and time-resolved spectroscopy

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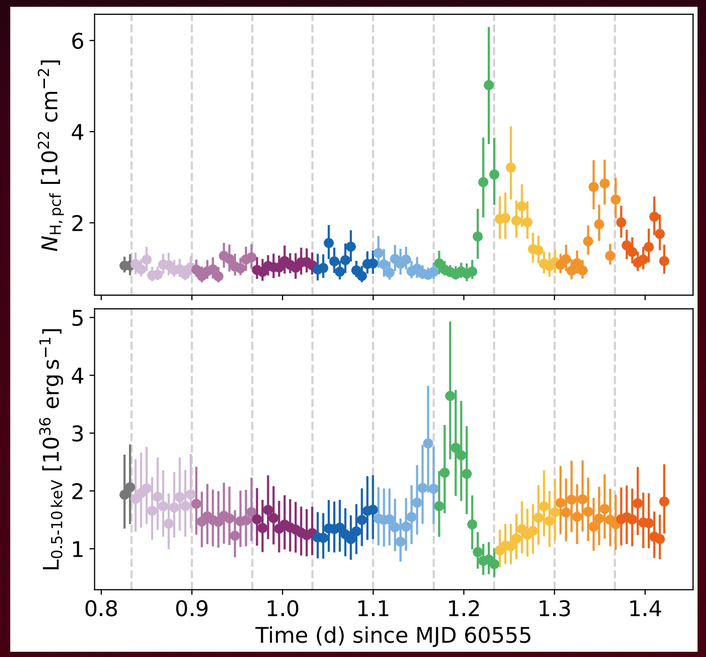
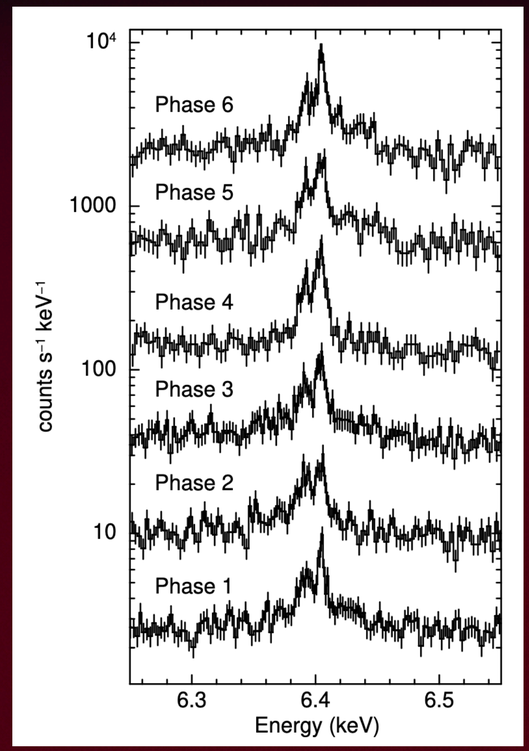
- Back up slides • *Many things I did not have time to talk about* •

What's next?

- Stay tuned:
  - → 4U1538-52: another classical HMXB (XMM+XRISM+NuSTAR) *Diez et al., to be subm.*
  - → 4U1954+31: a rare HMXB with a red supergiant (XMM+SVOM) *Diez et al., in prep.*
  - → 1A1118-61: a BeXRB with a bright outburst (XRISM+XMM+SVOM) *Toshihiro et al., subm.*
  - → AstroWinds SF2A 2026 + COSPAR E1.10/E1.18/E1.20



Diez et al., to be subm.



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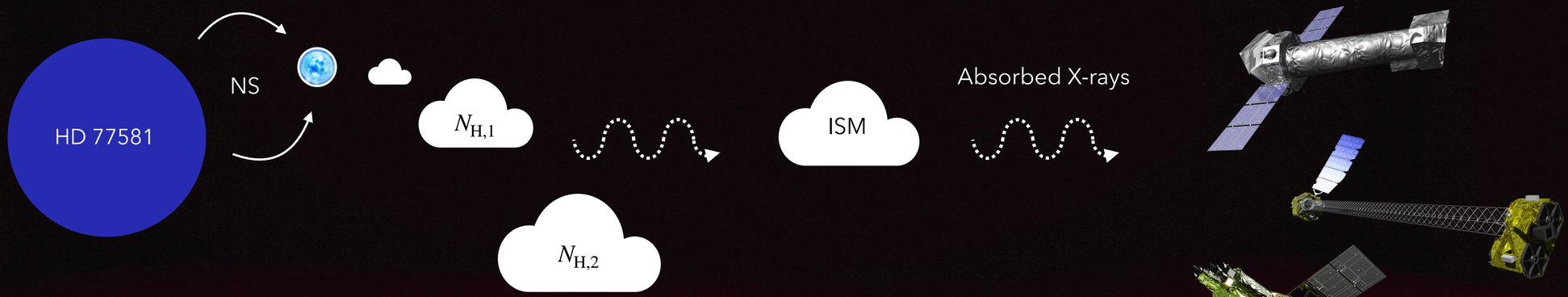

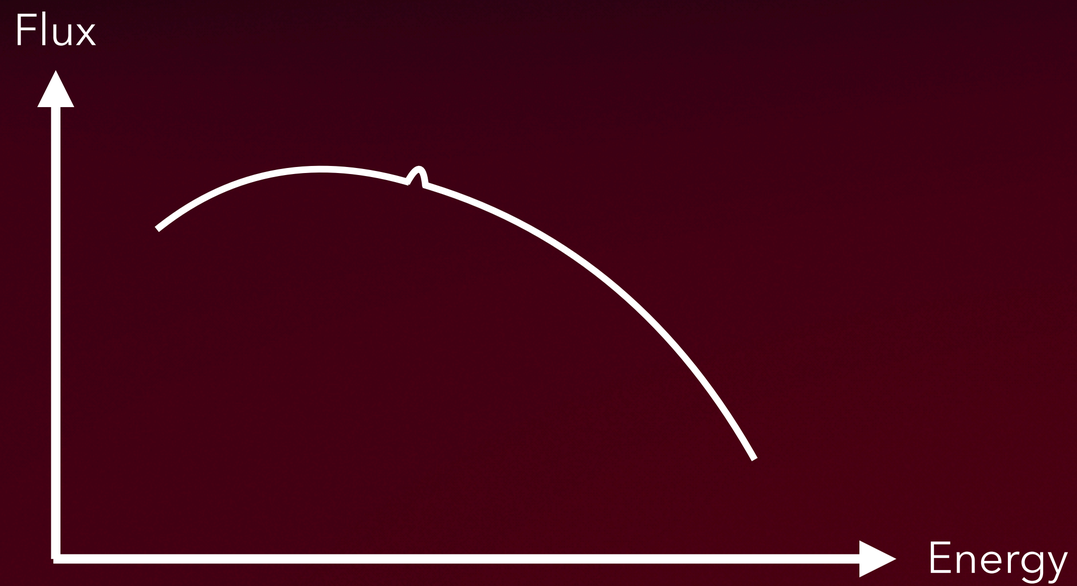

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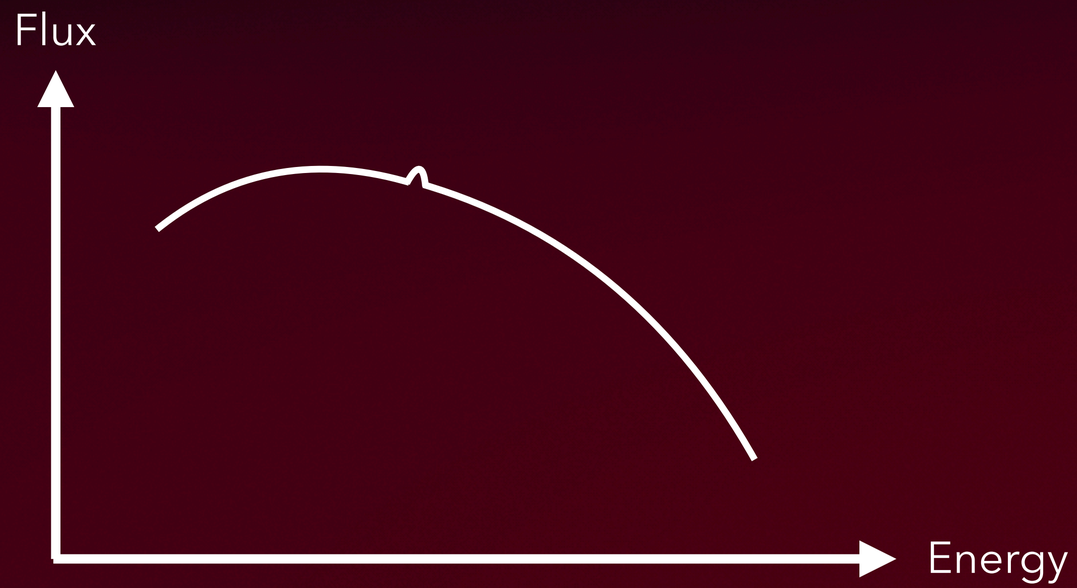

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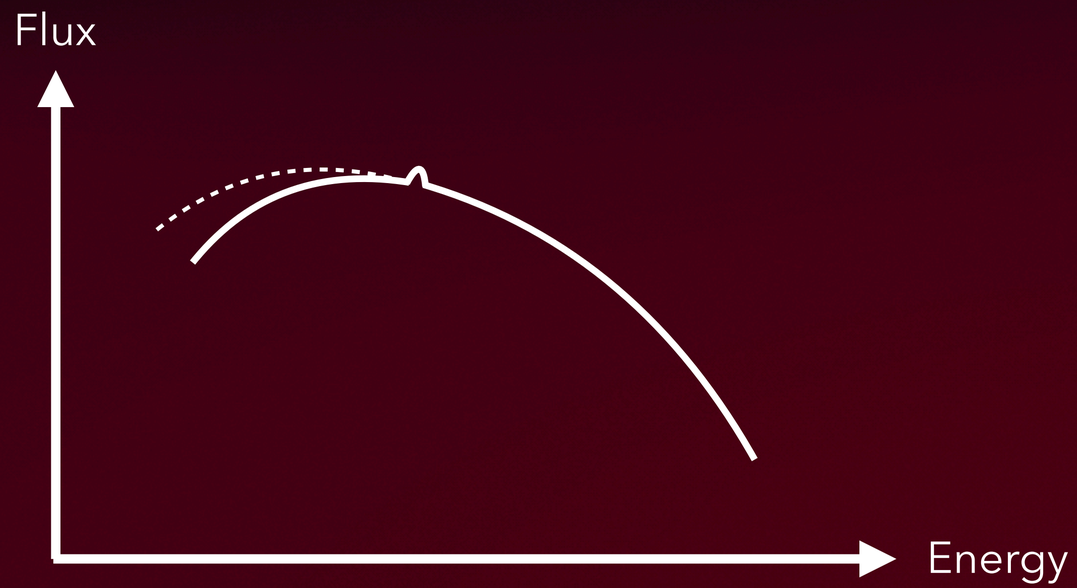

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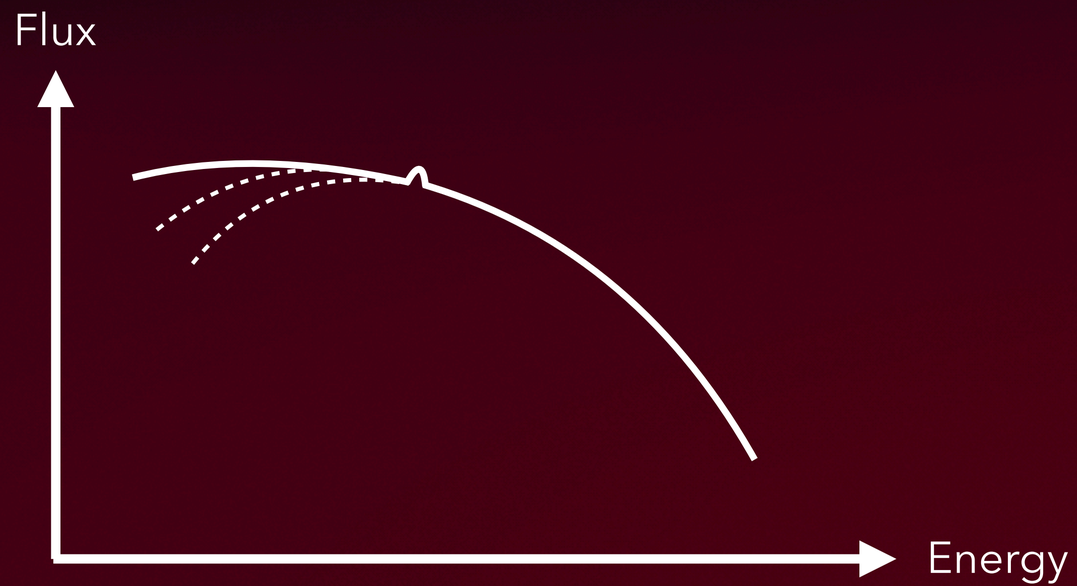

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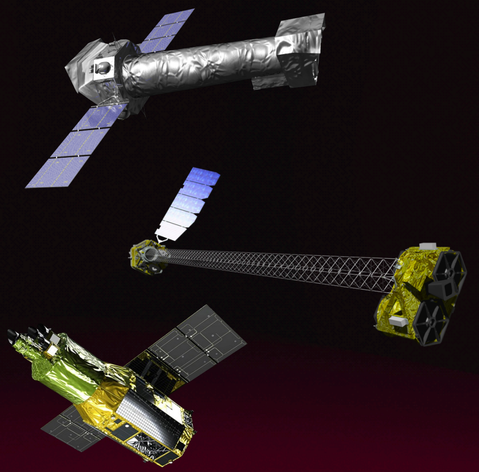
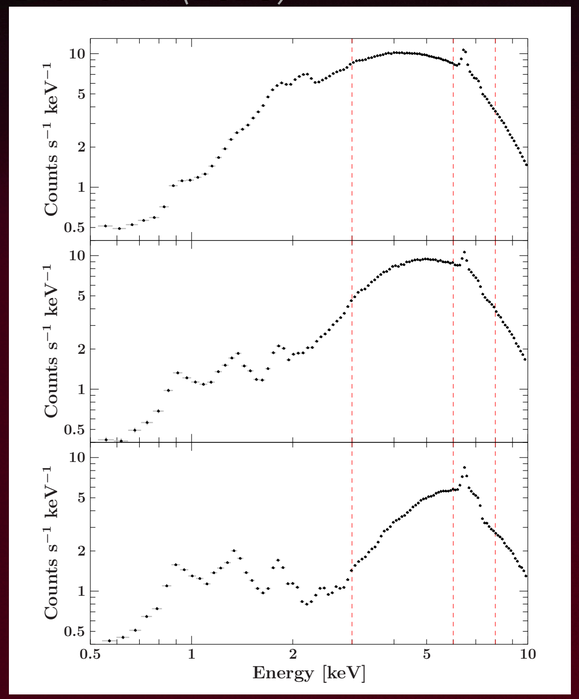
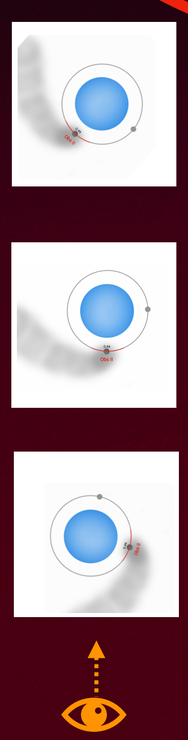


Diez et al. (2023)





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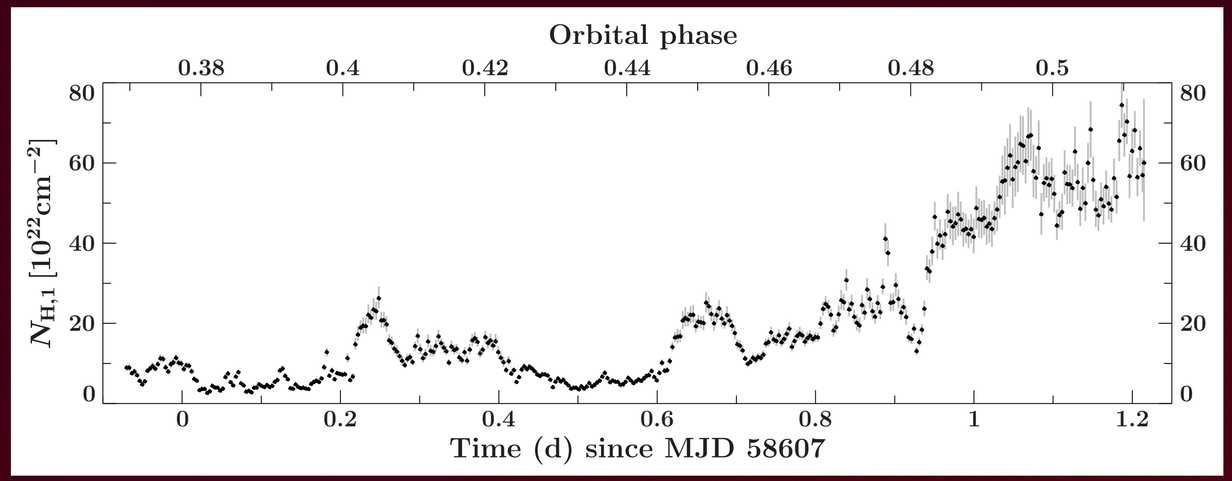

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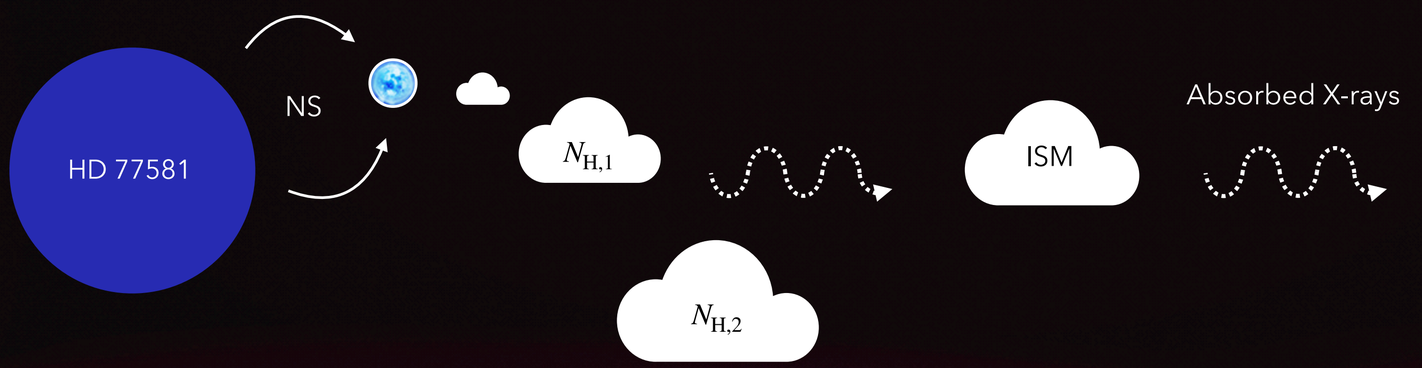
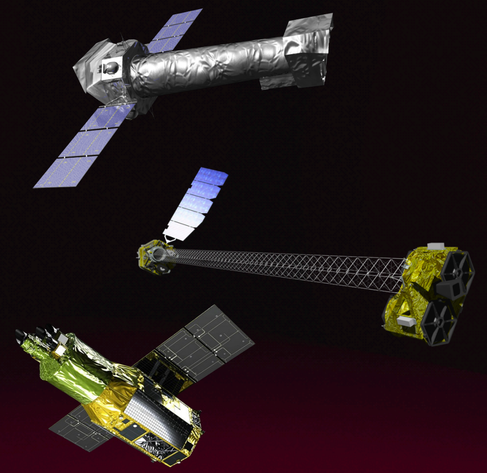
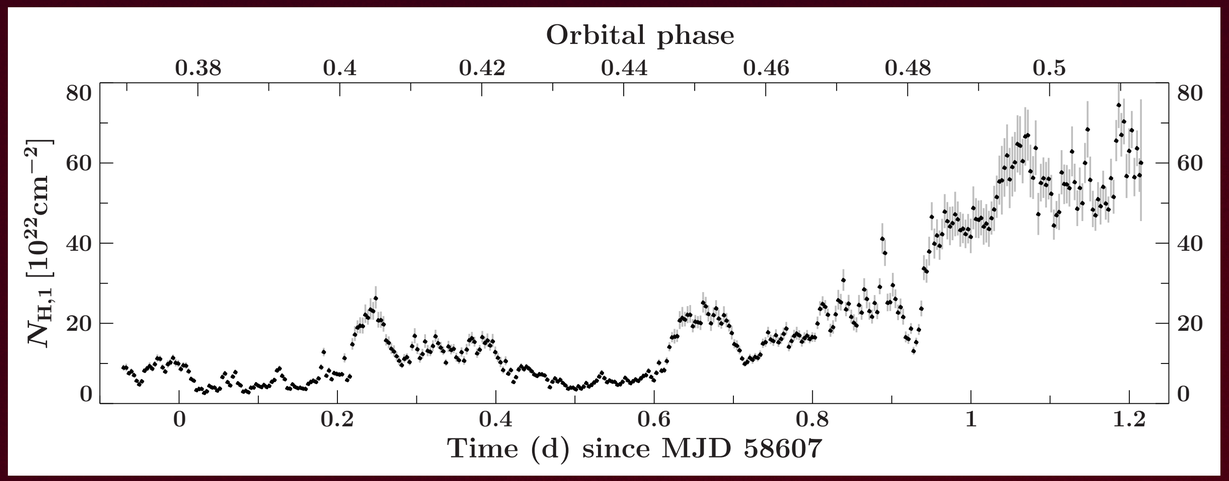
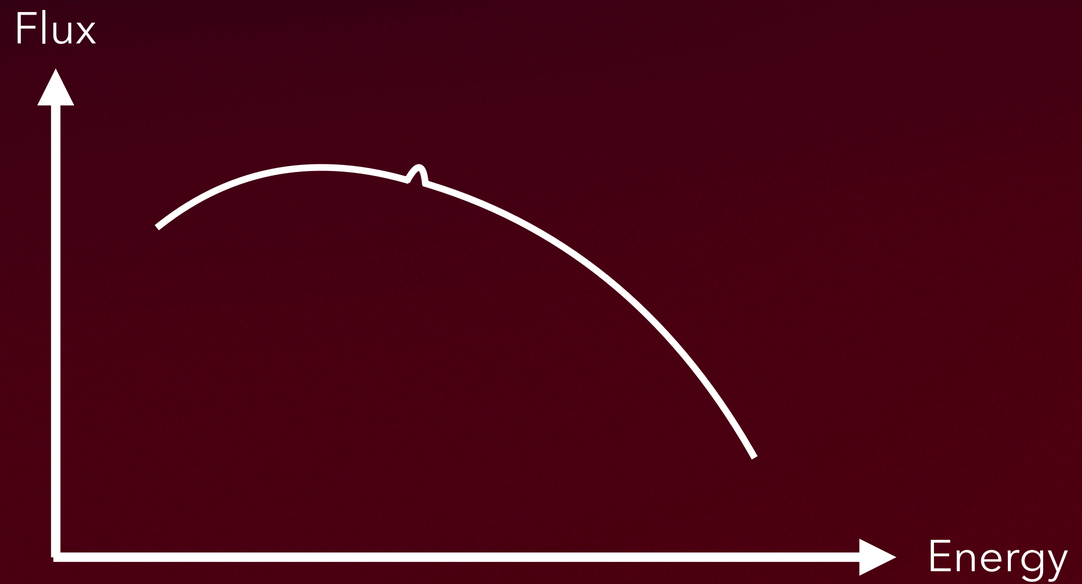


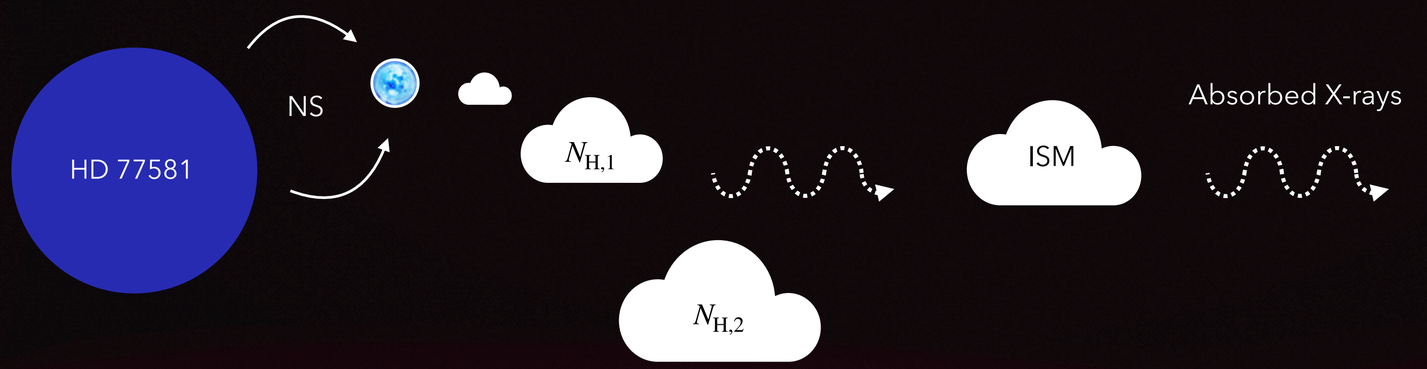


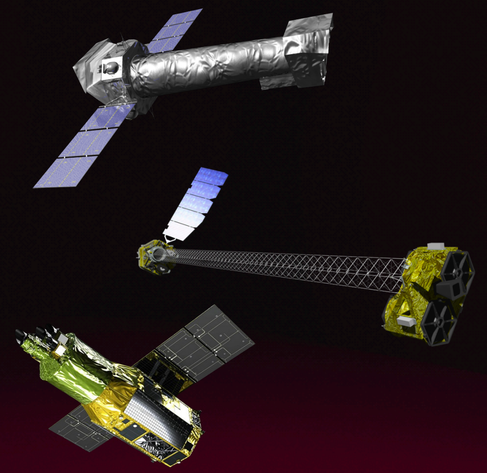


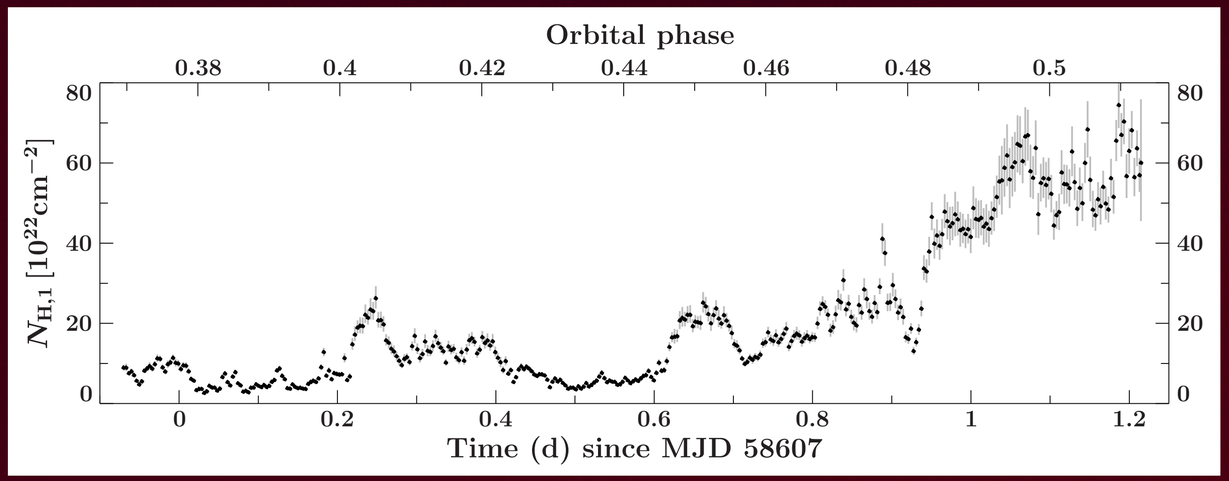


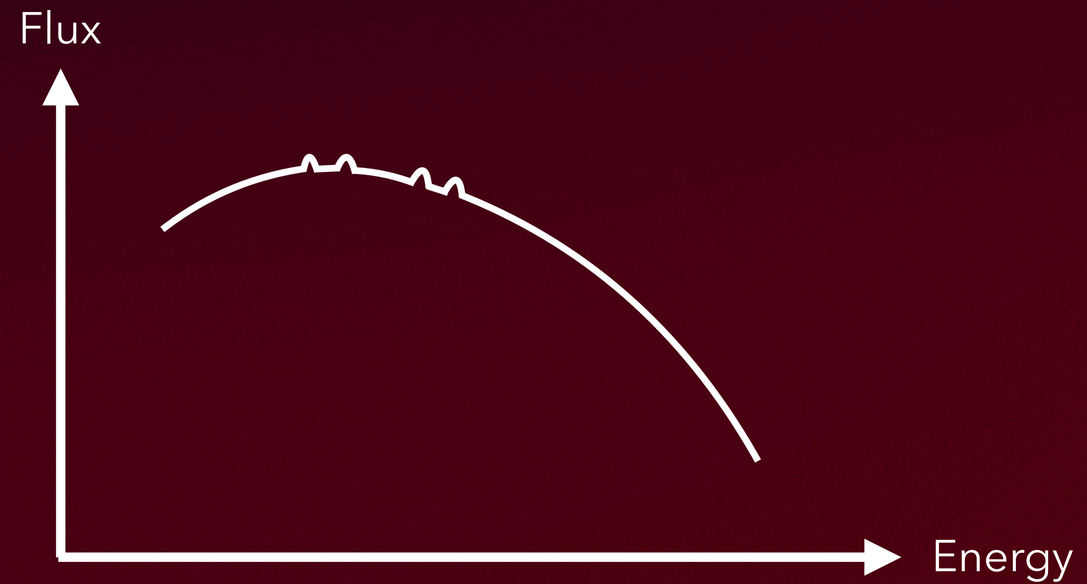
Diez et al. (2023)

What's next?



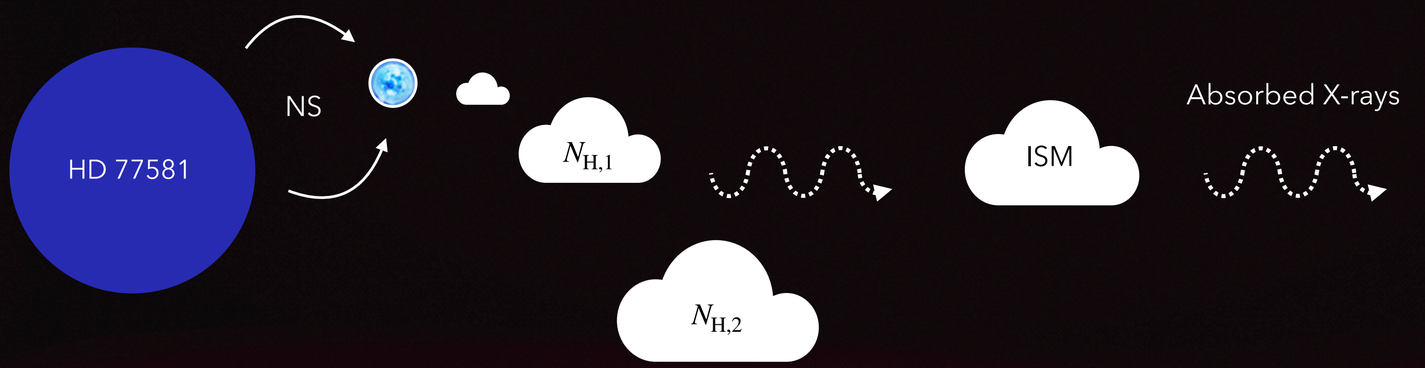


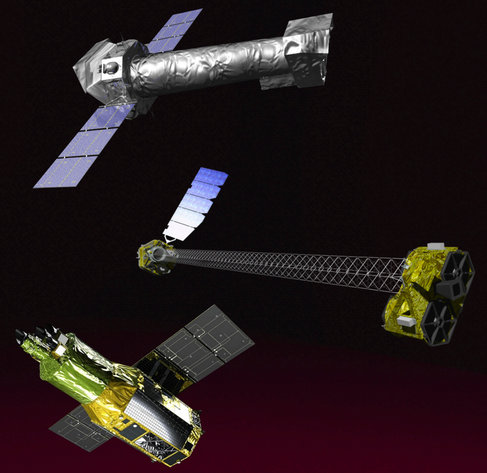


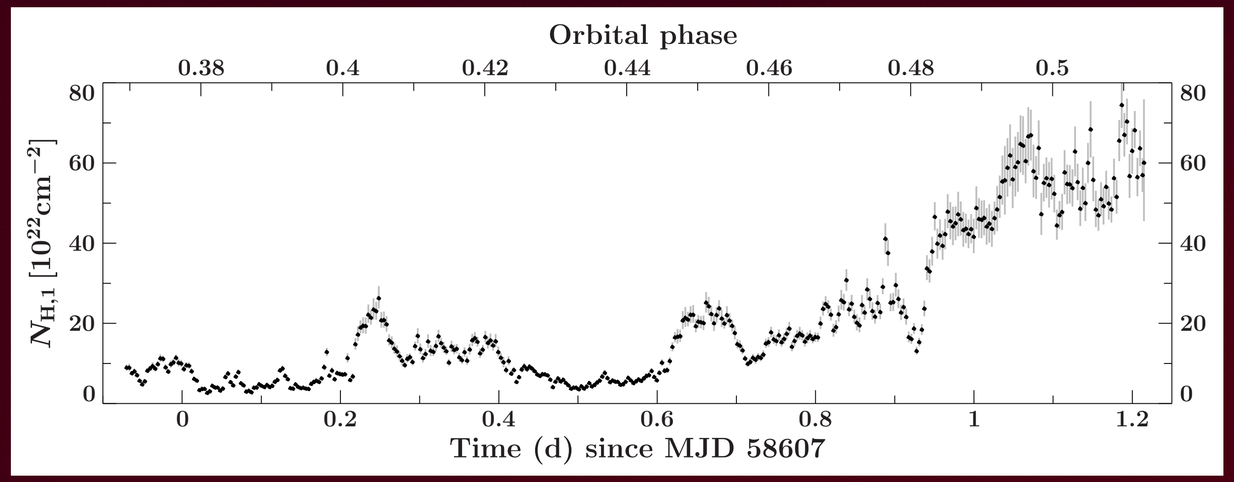


Diez et al. (2023)

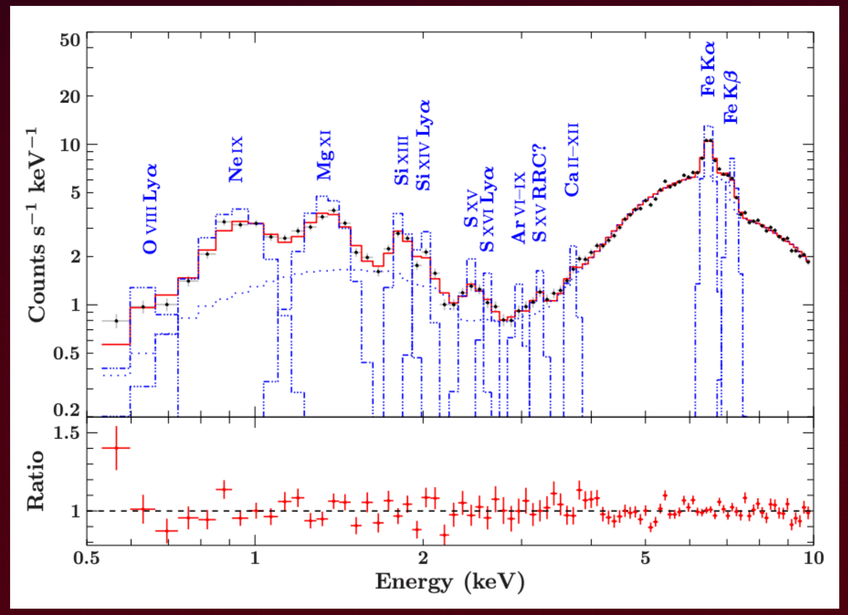
What's next?







Diez et al. (2023)



Diez et al. (2023)

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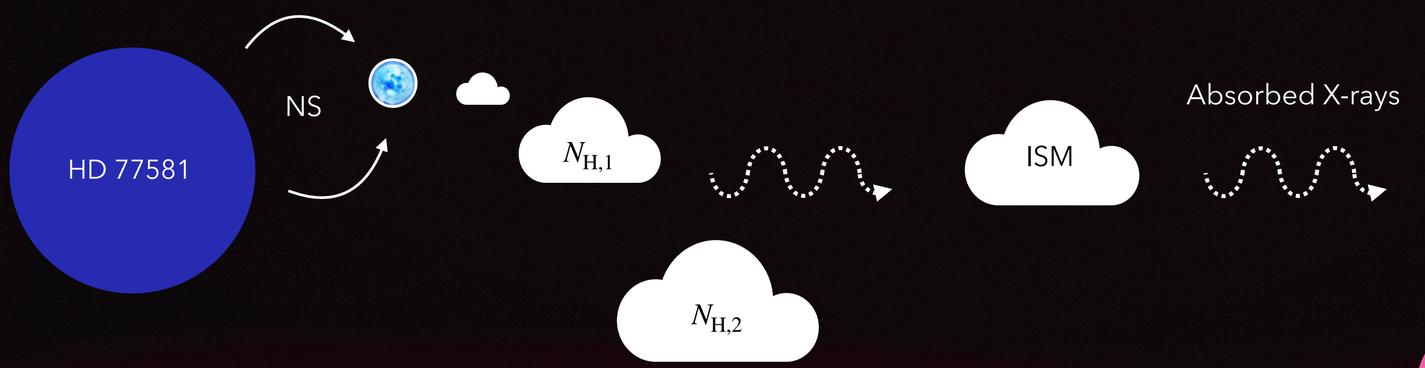
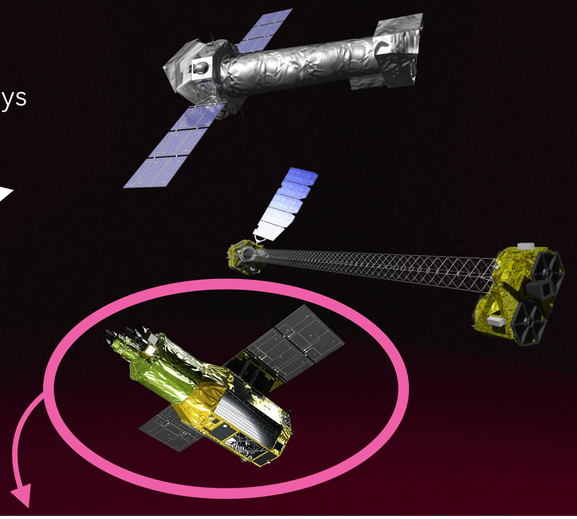
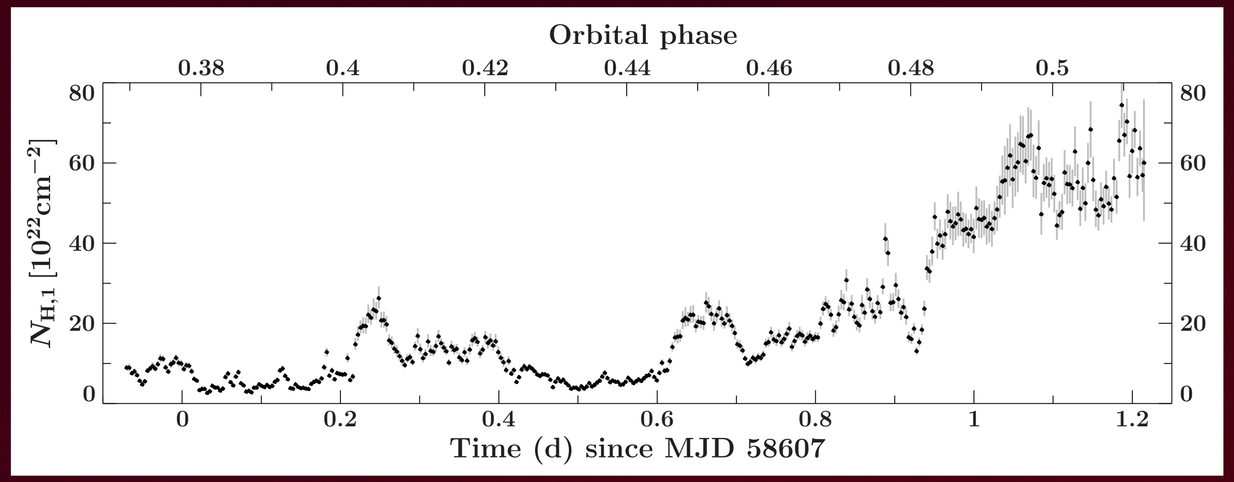
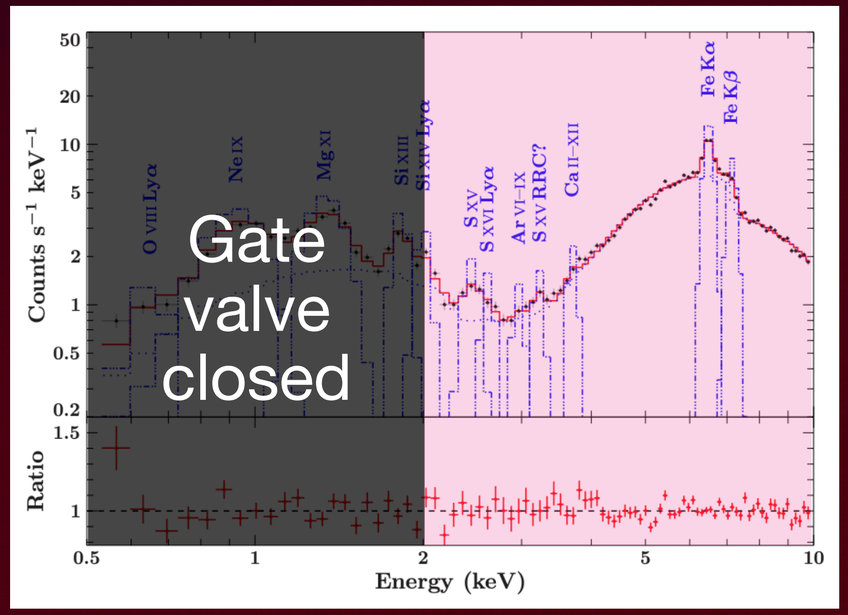




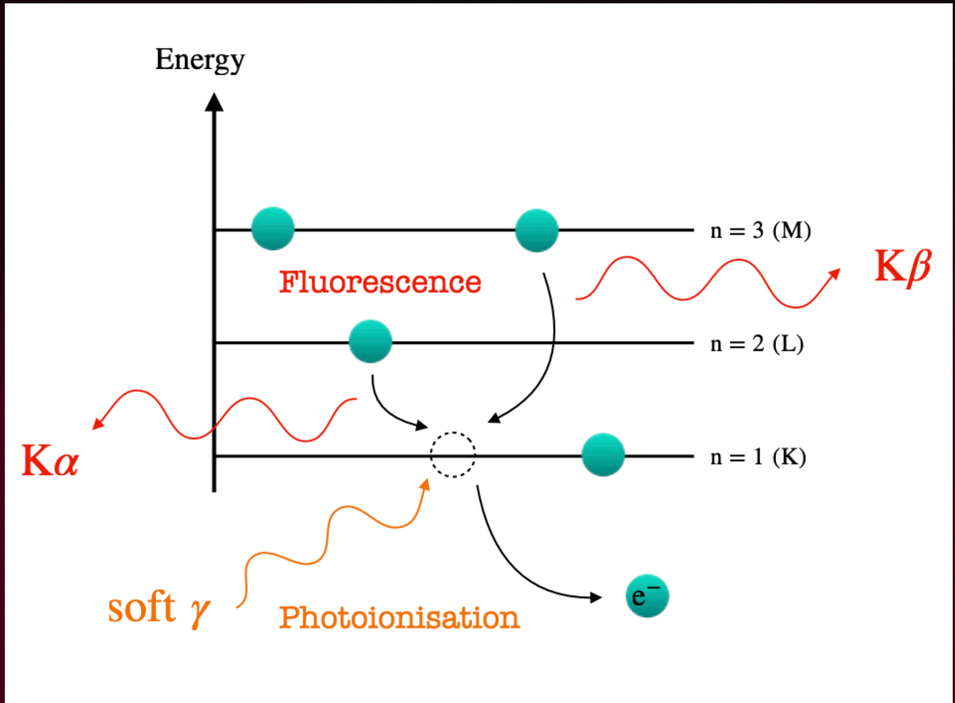


Diez et al. (2023)



Diez et al. (2023)

Emission lines



2. Helium-like Ion

Topic: Ions with 2 electron ("He-like") exist over a wide range of plasma temperatures due to the large ionization potential difference between the 3-electron and 2-electron ions. The n = 2 → 1 transtion of these elements lies in the X-ray band, providing bright lines in the X-ray spectrum.

Fine Structure

The total spin and orbital angular momenta, denoted S and L, are vector sums of the indivudual electrons. $\vec{L} = \sum_i \vec{l}_i \quad \vec{S} = \sum_i \vec{s}_i \quad \vec{J} = \vec{L} + \vec{S}$

$(\mathrm{conf.})^{2S+1}\mathrm{L_J}$ Energy level labeling terminology e.g., $(1s2s)^3P_1$

"Configuration" ignores L and S. "Term" includes the configuration plus total L and total S. "Level" includes the term plus the J

Historical hierarchy of accuracy. → Finer structure

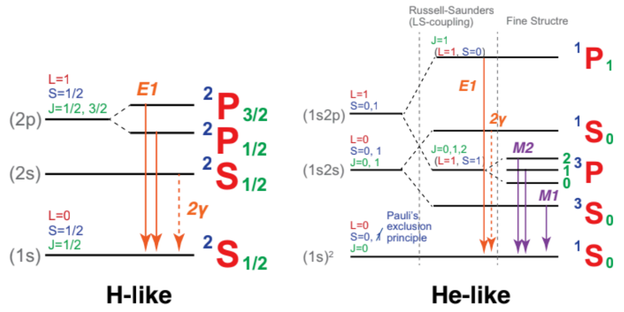


Figure 2.1: Schematic diagram of energy levels of H-like and He-like ions.

Selection rules

Initial and final states of permitted transition. Transitions which do not satitsfy these rules are not slow. (J=0 to J=0 is not allowed)

$$\triangle S = 0, \quad \triangle L = \pm 1, \quad \triangle J = 0, \pm 1$$

He-like Plasma Diagnostics

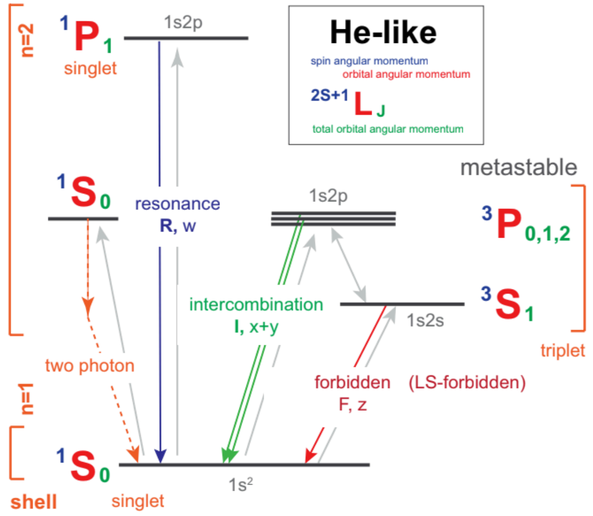
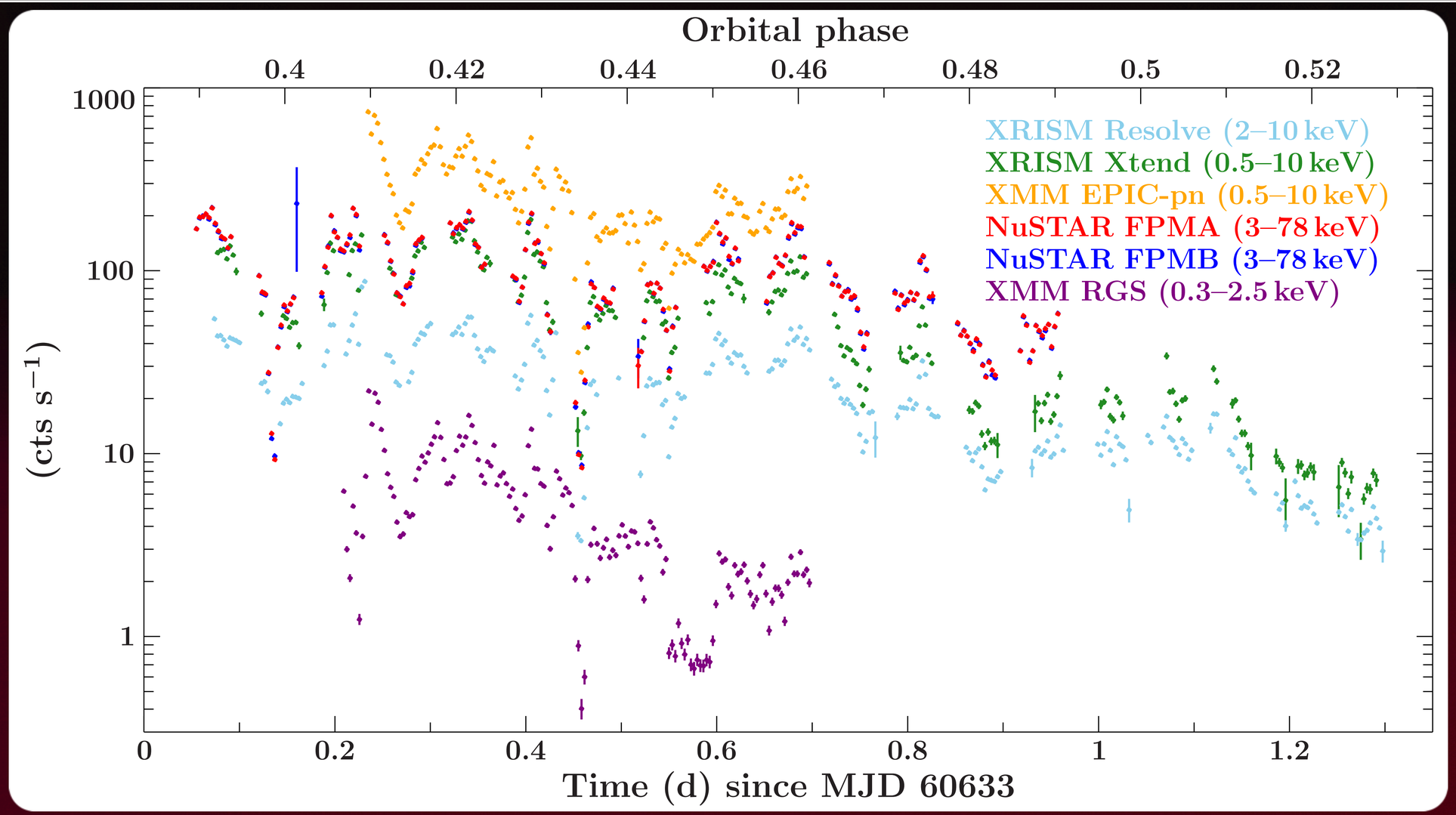


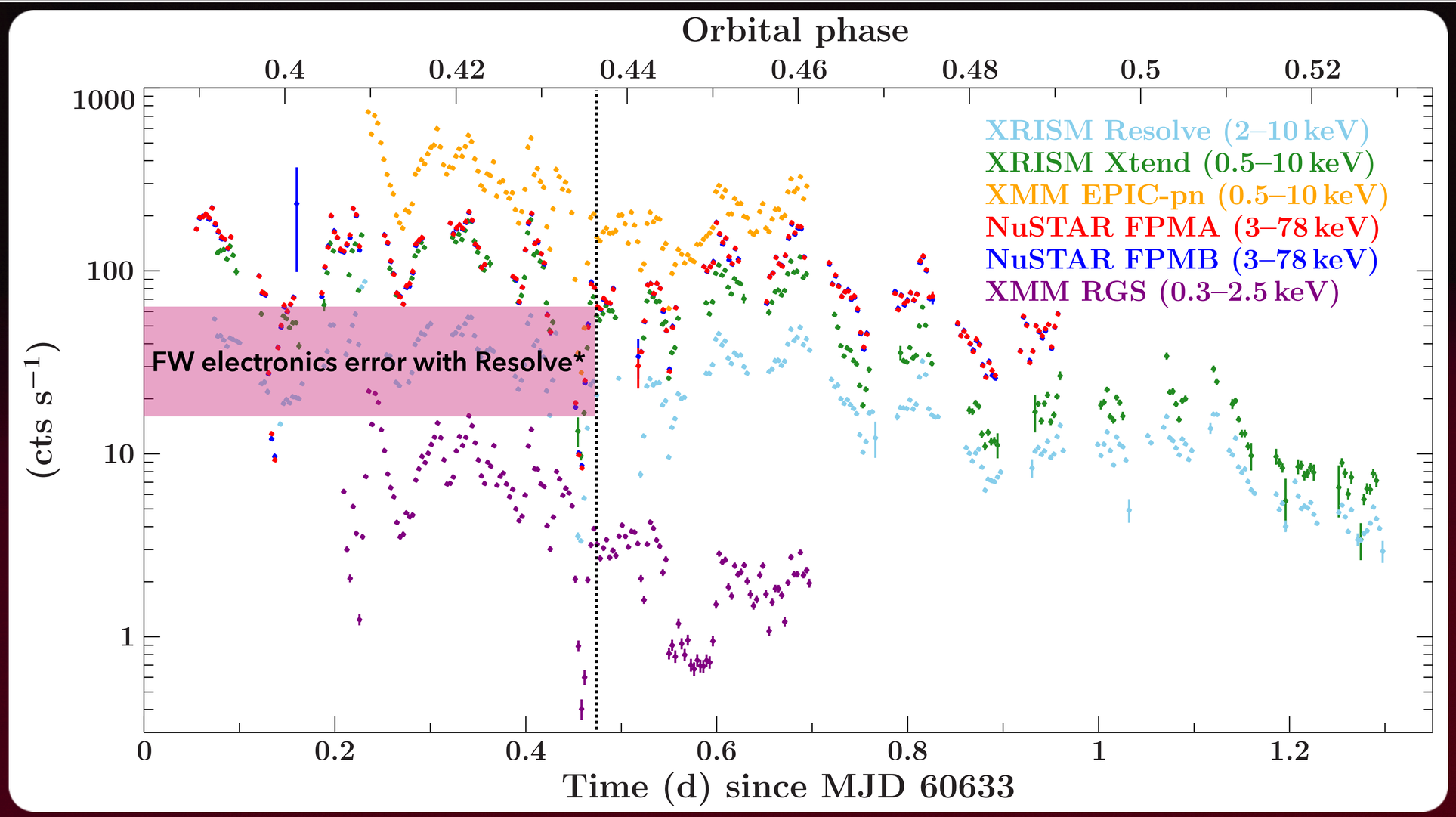
Figure 2.2: Schematic diagram of energy levels of He-like ions.

Lightcurves



Adapted from Diez et al. 2025

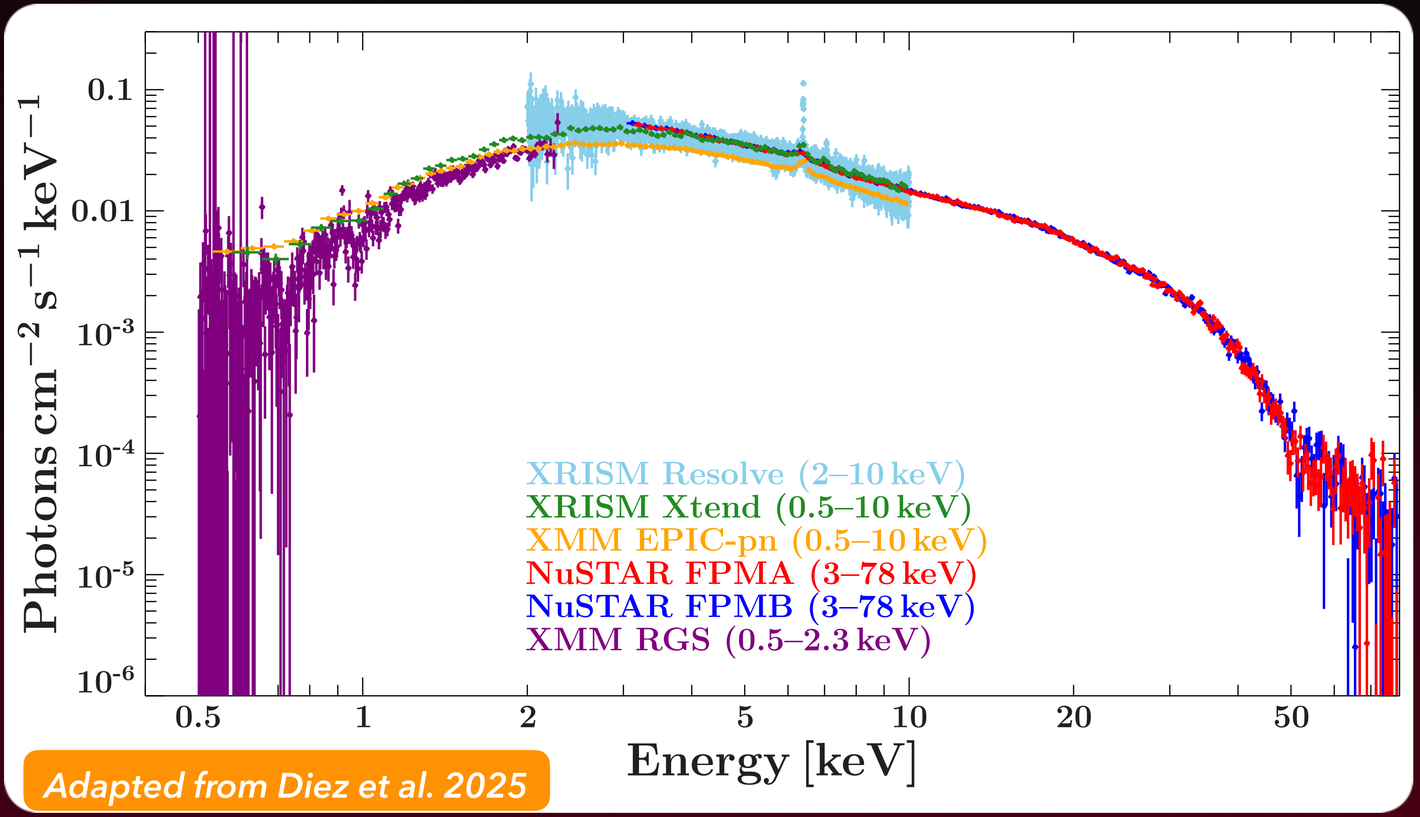
Lightcurves



*Since then, data have been corrected and reprocessed by F. Porter (*Diez et al., in prep.*)

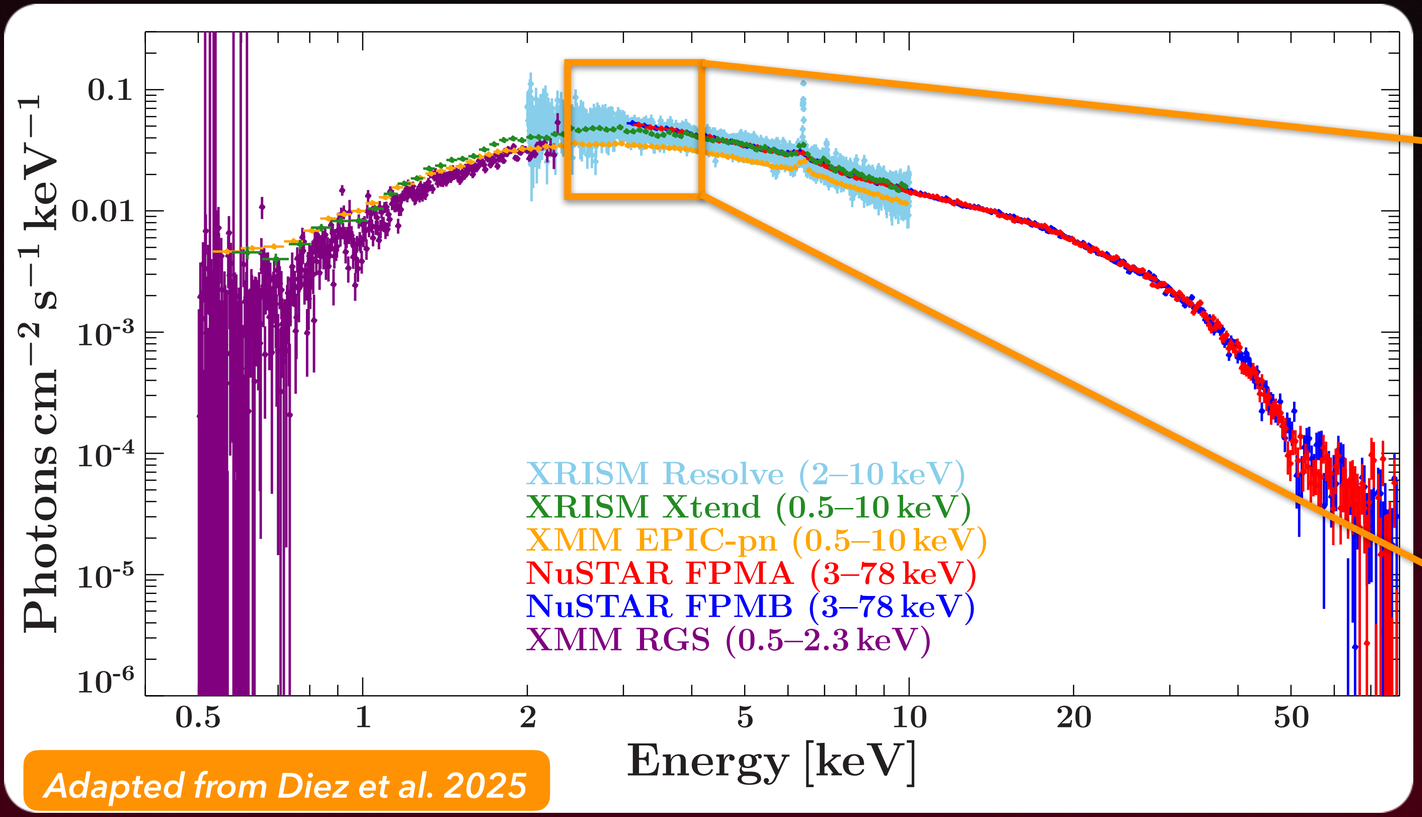
Adapted from Diez et al. 2025

Cross-calibration issues

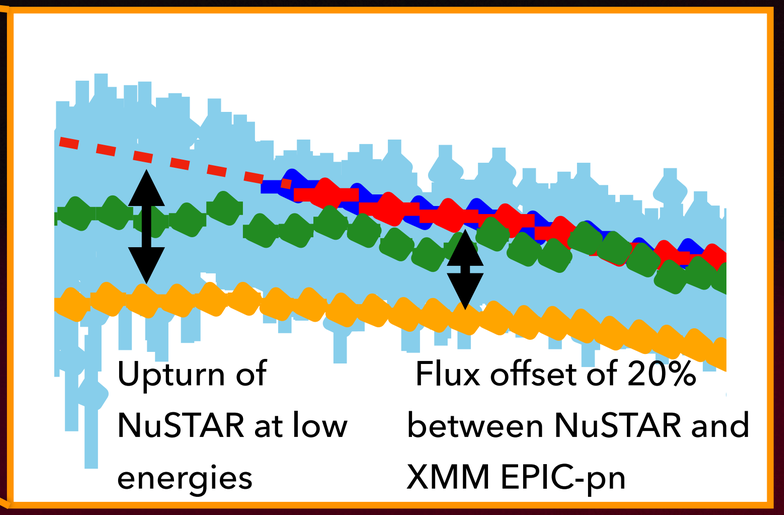


Adapted from Diez et al. 2025

Cross-calibration issues



Adapted from Diez et al. 2025



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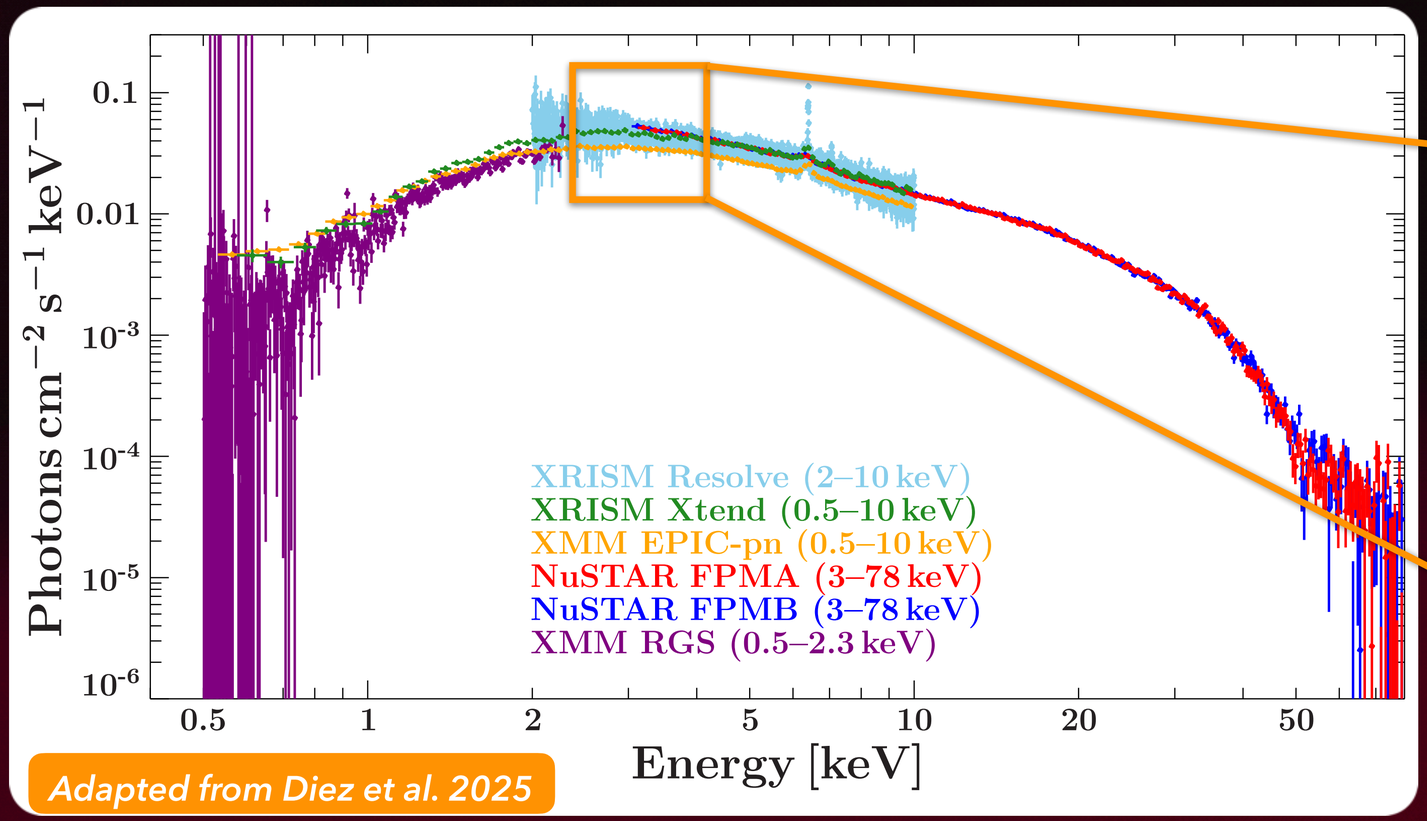
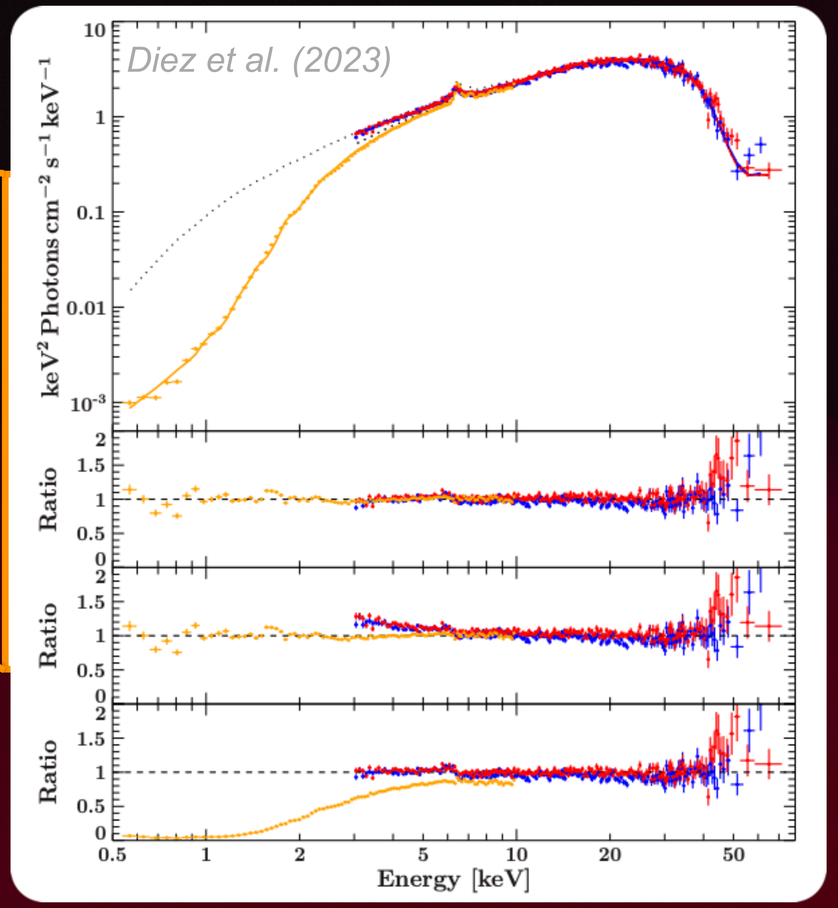
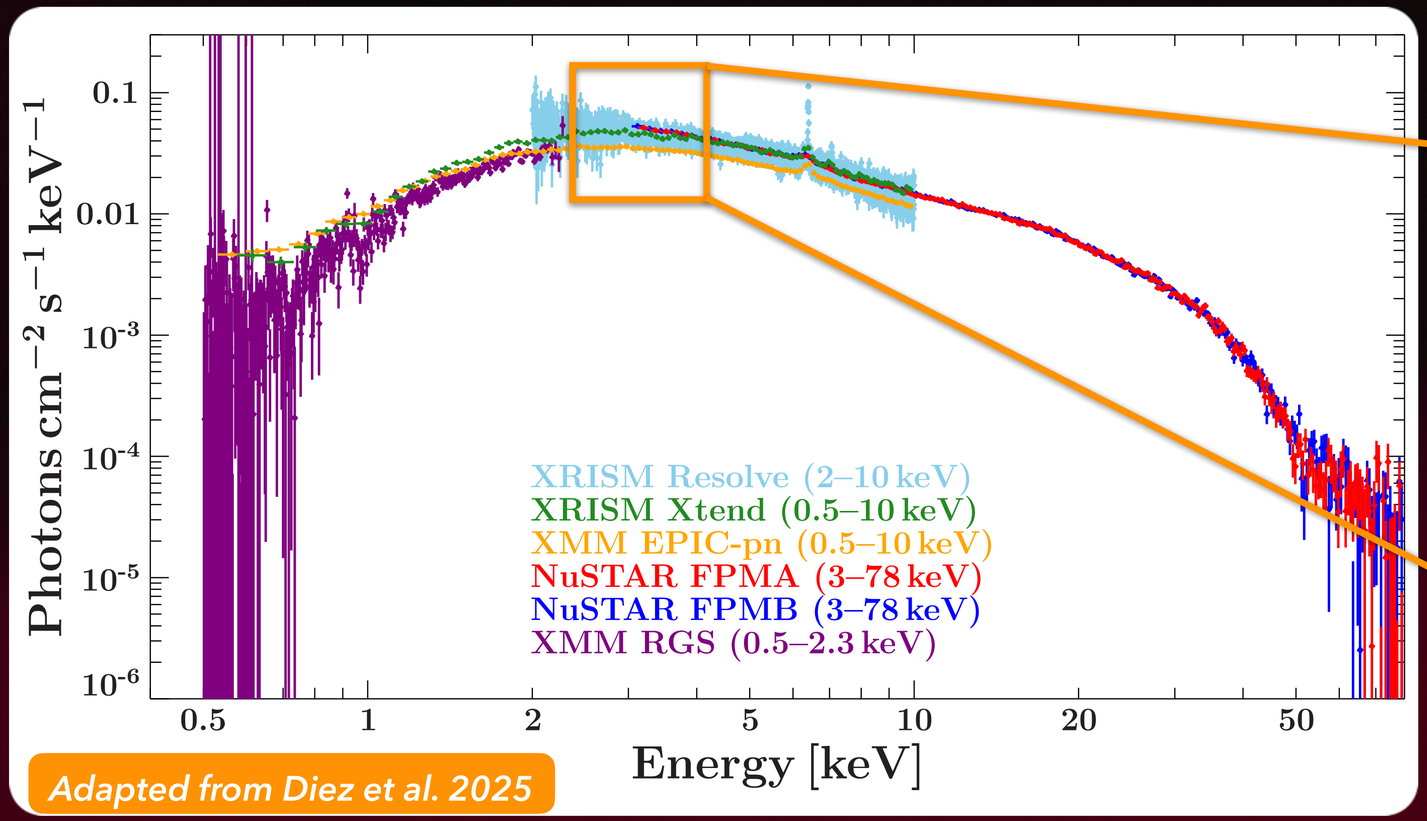


Adapted from Diez et al. 2025



- Already seen in ***Diez et al. 2023*** with Vela X-1 and XMM EPIC-pn/NuSTAR

Cross-calibration issues



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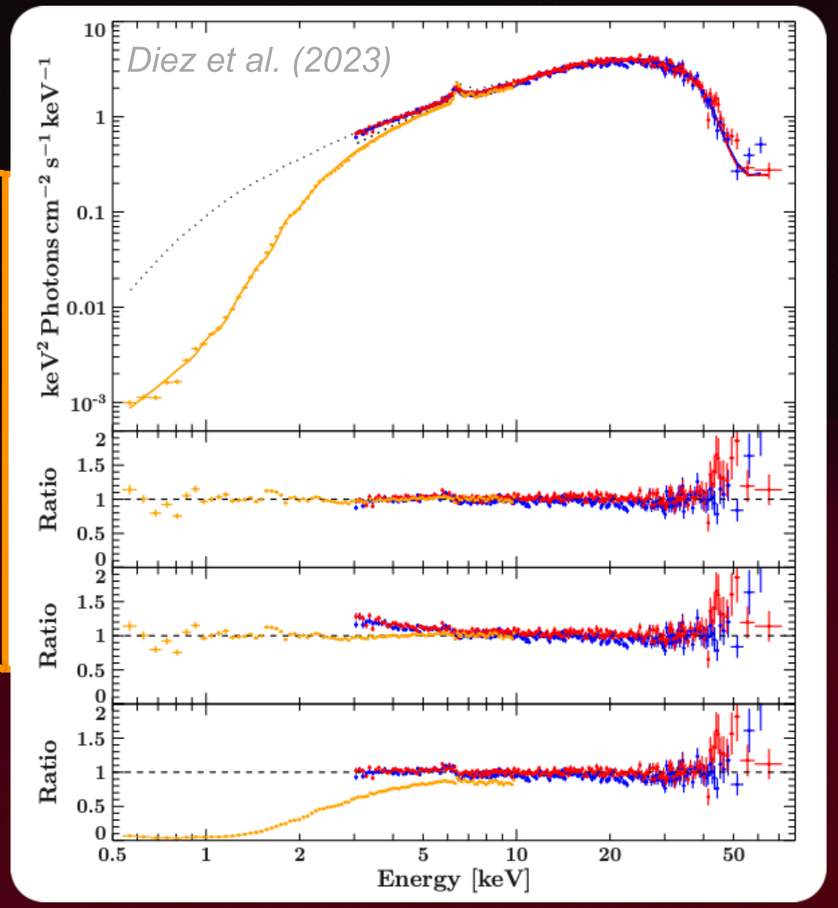
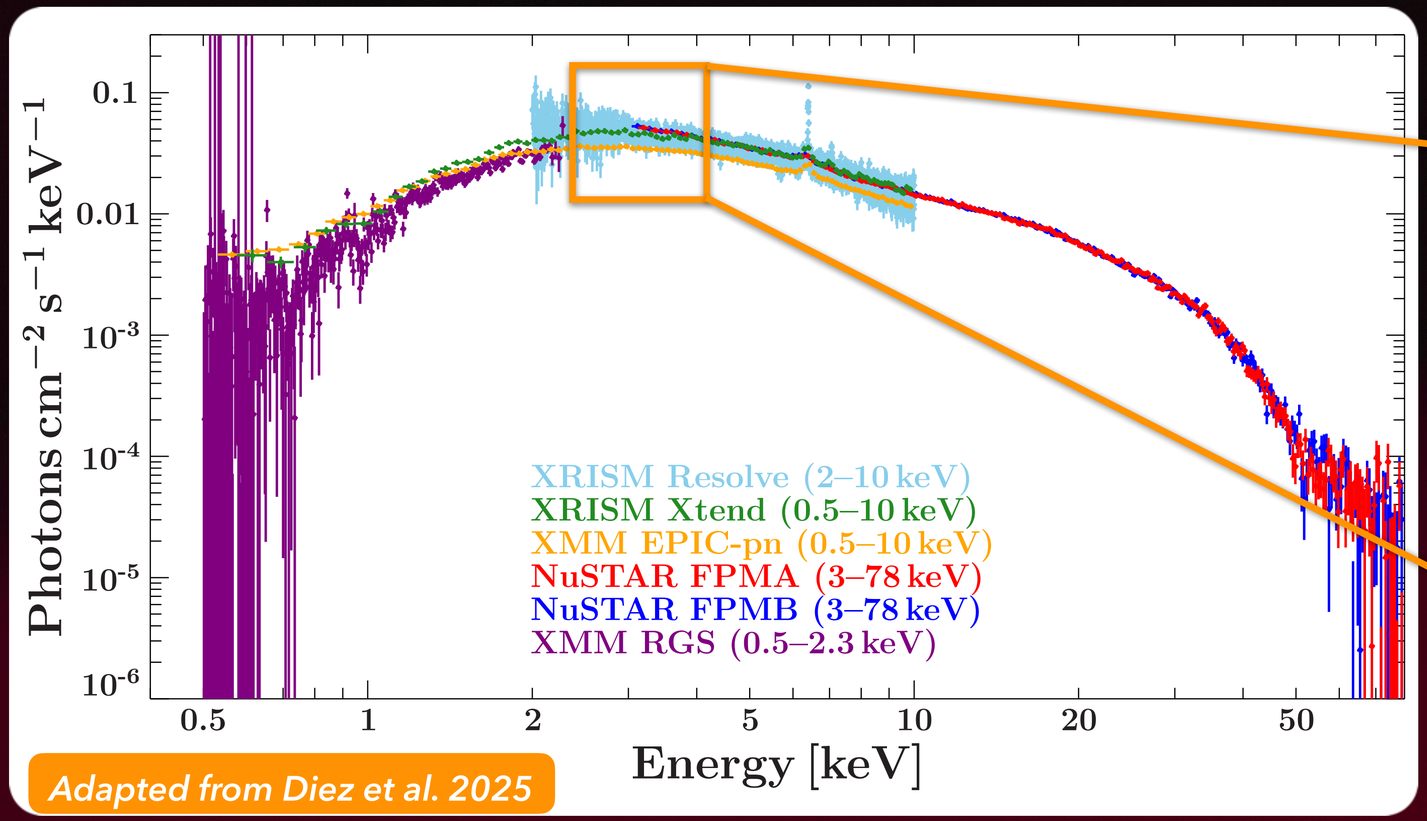


Current solution

- Flux offset: ~20% (in agreement with Madsen et al., 2016)
- Already seen in ***Diez et al. 2023*** with Vela X-1 and XMM EPIC-pn/NuSTAR

Cross-calibration issues



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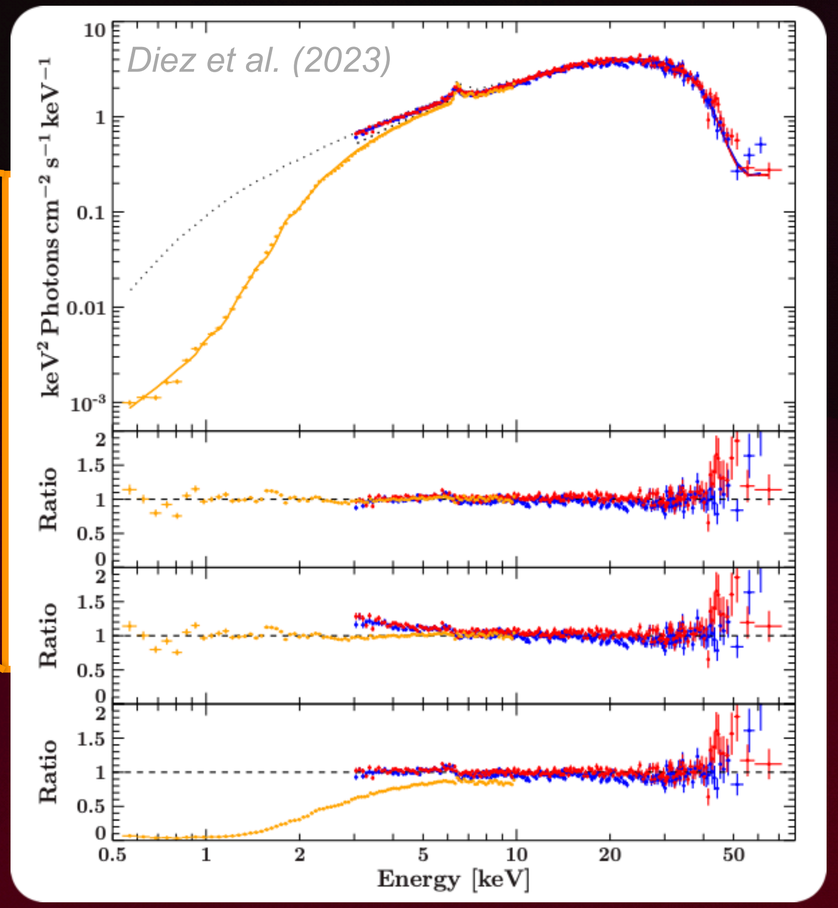


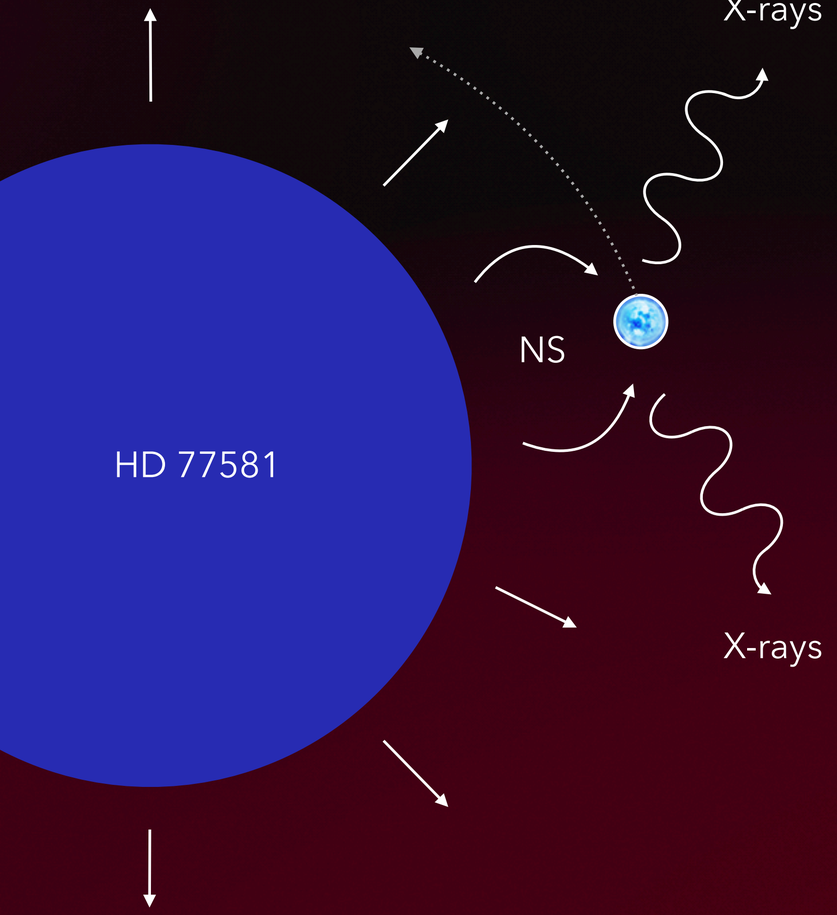
Current solution

- Flux offset: ~20% (in agreement with Madsen et al., 2016)
- Upturn in NuSTAR: ignore energies below 5 keV

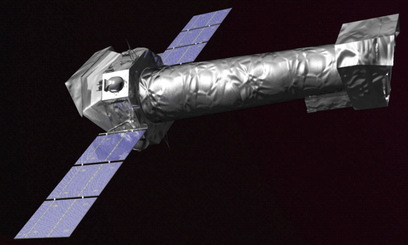
→ Offset reduced to ~13%

- Already seen in ***Diez et al. 2023*** with Vela X-1 and XMM EPIC-pn/NuSTAR

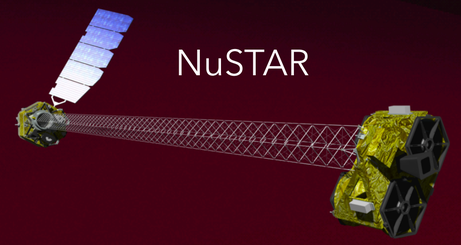
Partial covering model



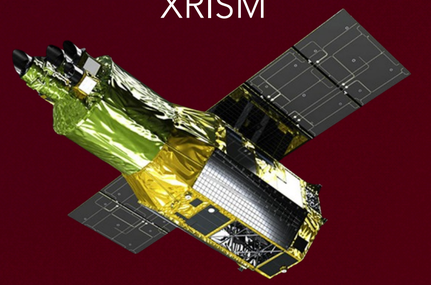
XMM-Newton



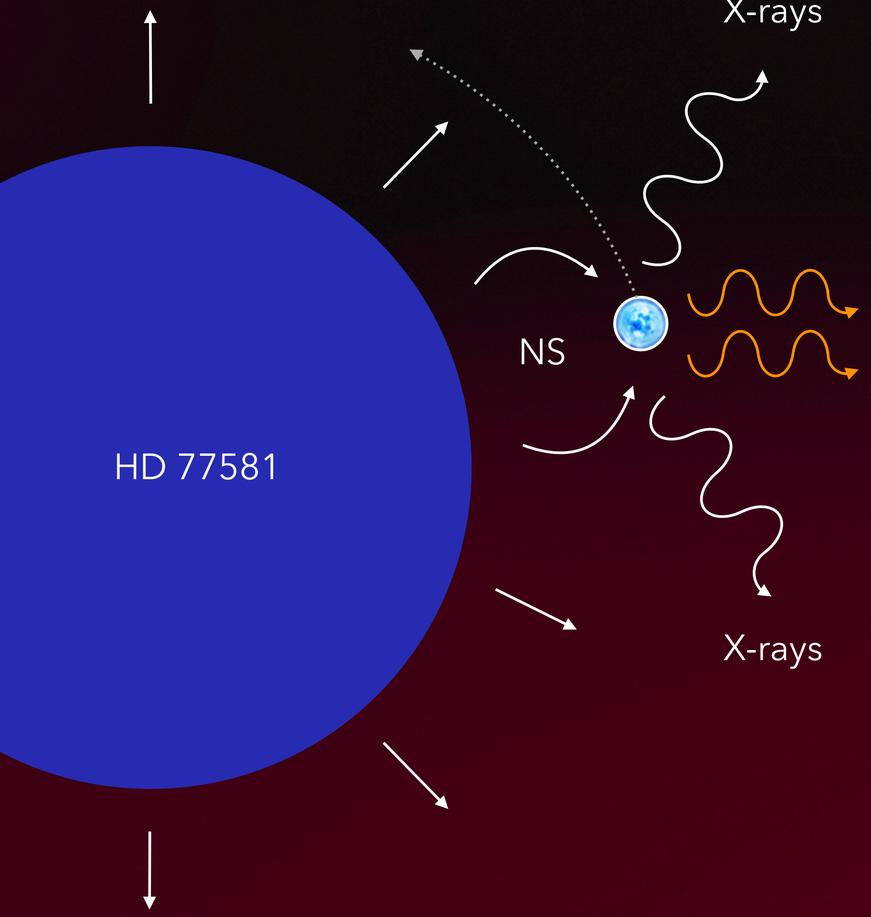
NuSTAR



XRISM



Partial covering model



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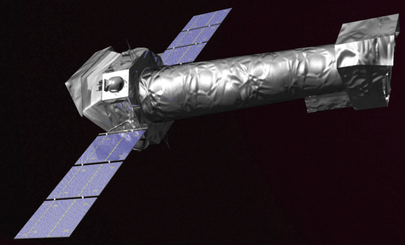

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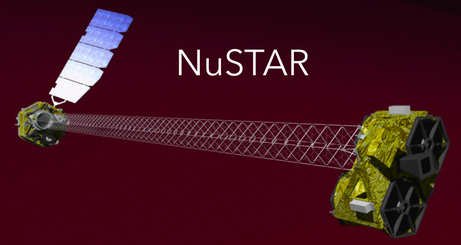
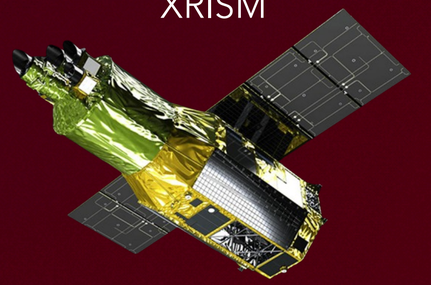


XRISM



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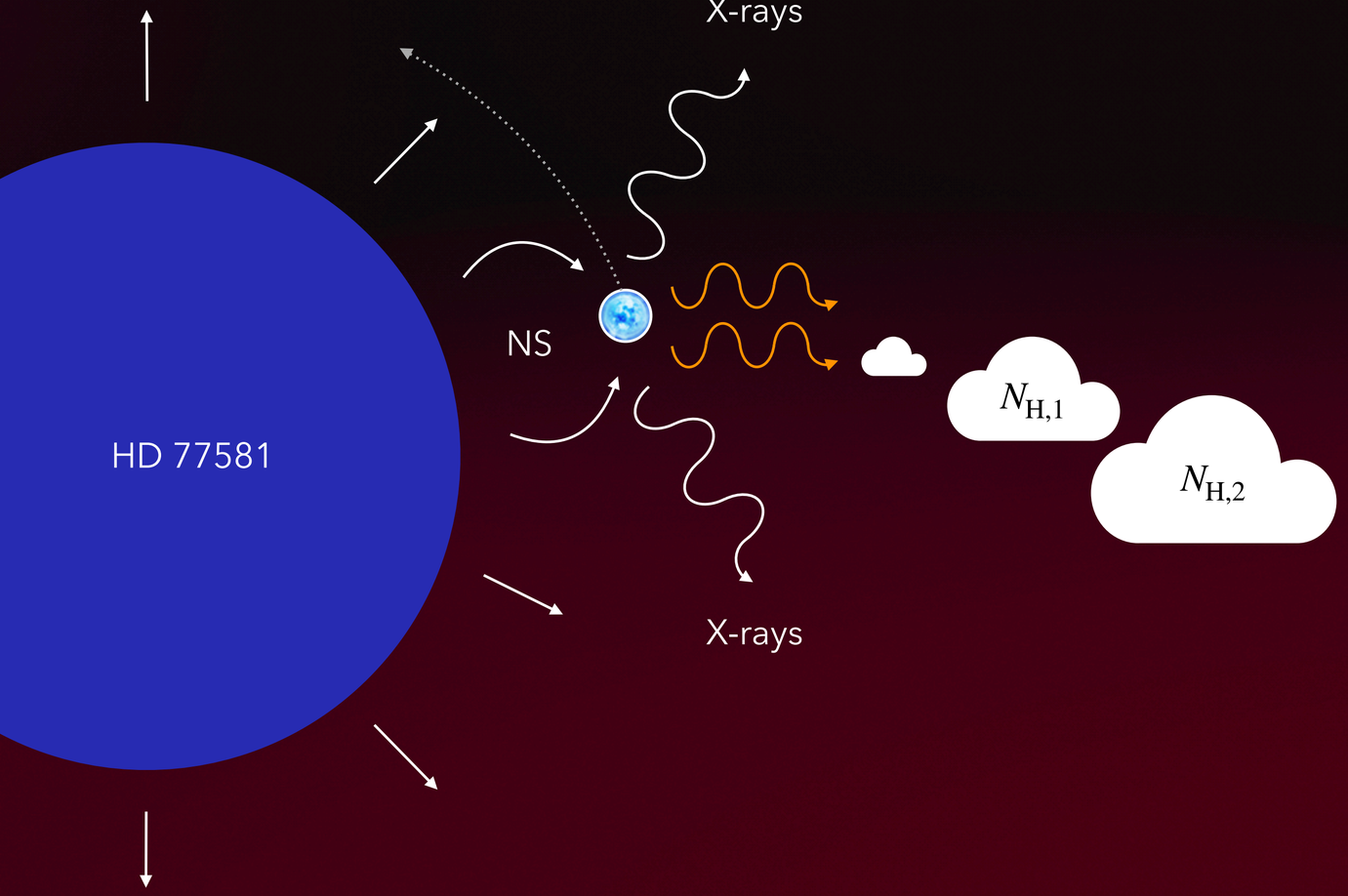
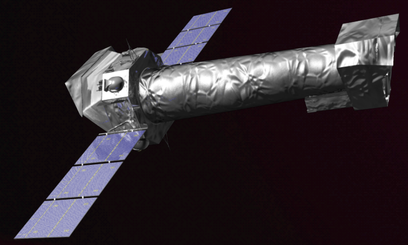


XMM-Newton



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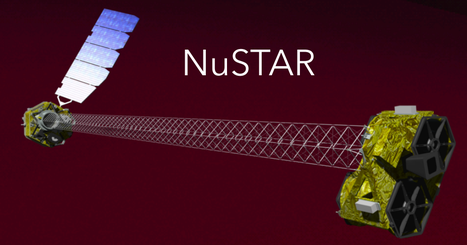

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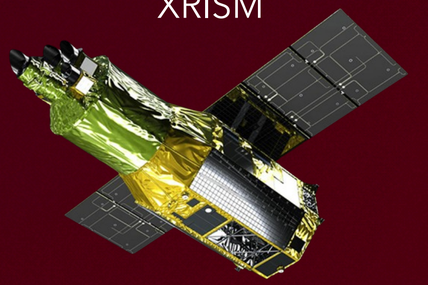

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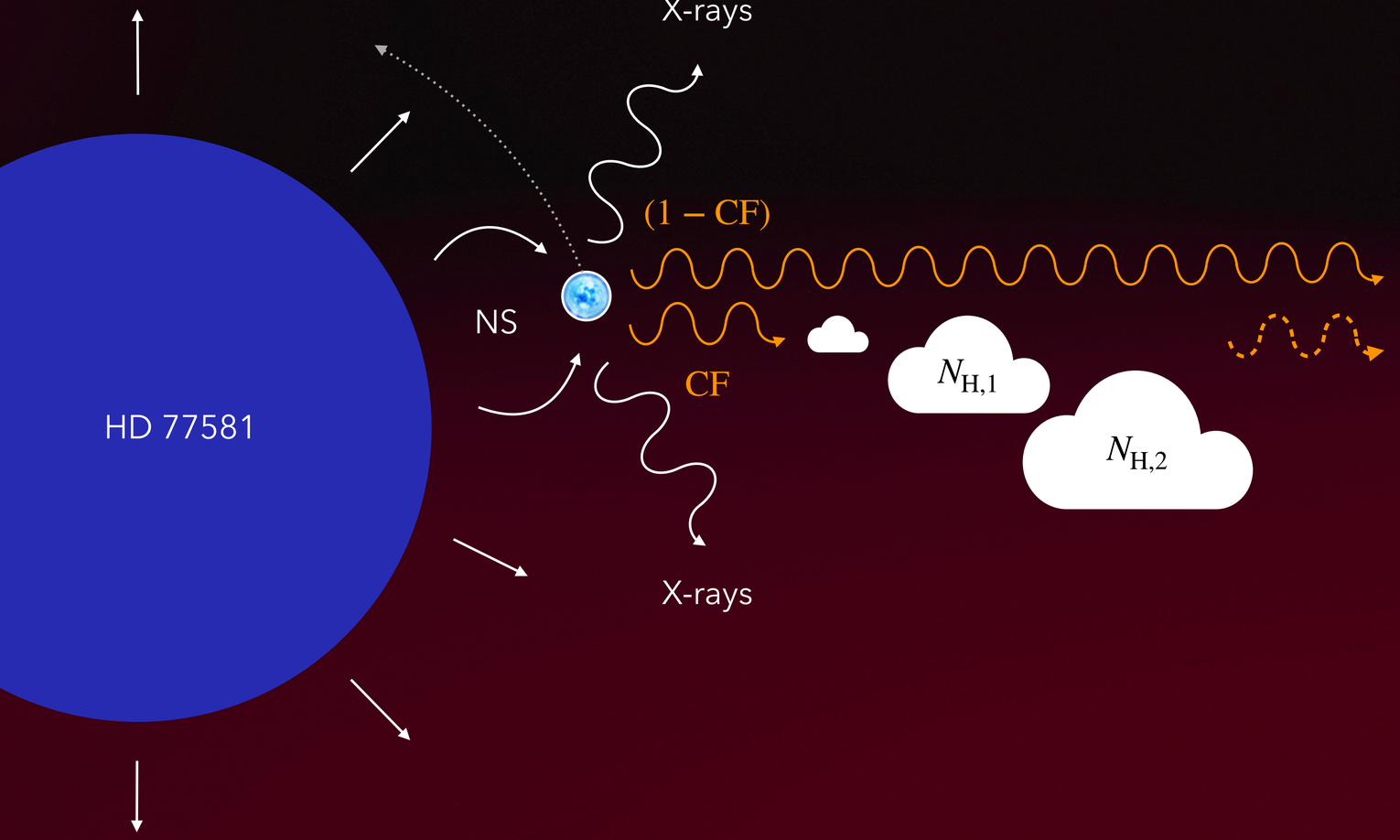
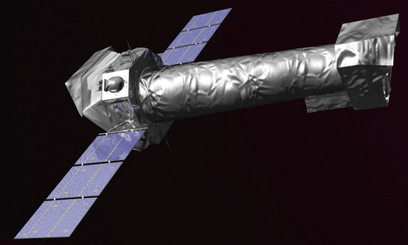
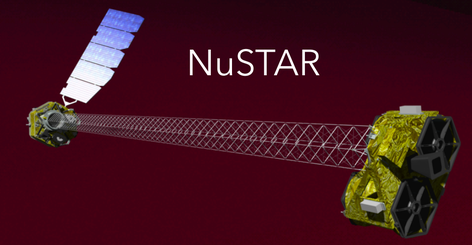


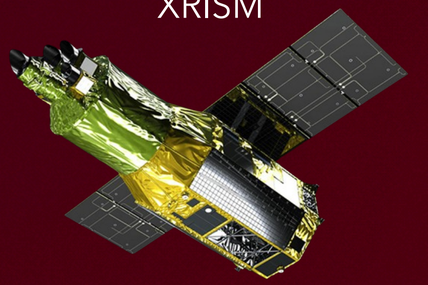
XMM-Newton



NuSTAR



XRISM



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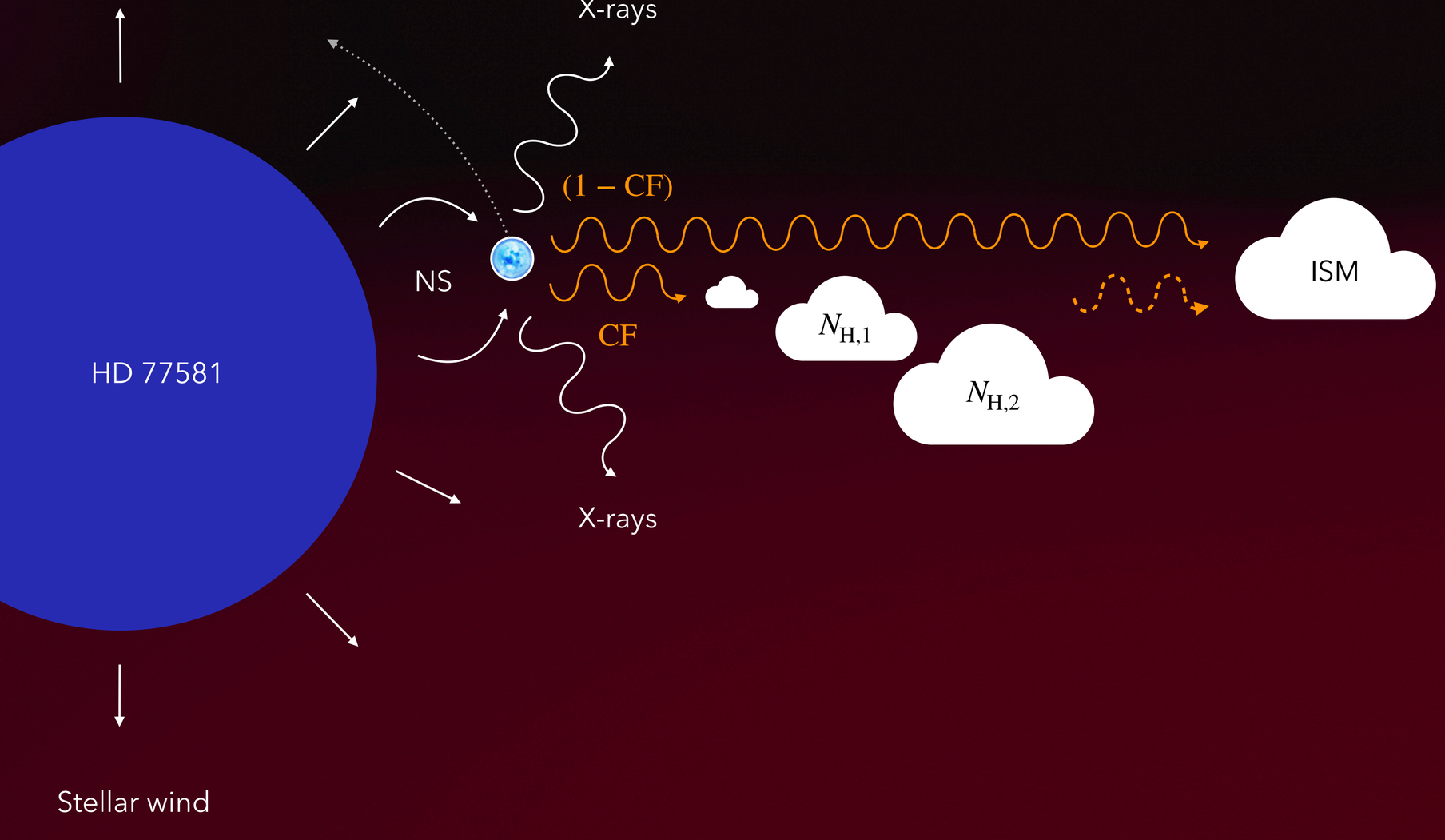
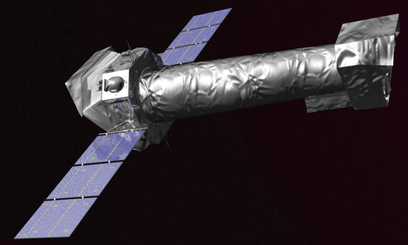


XMM-Newton



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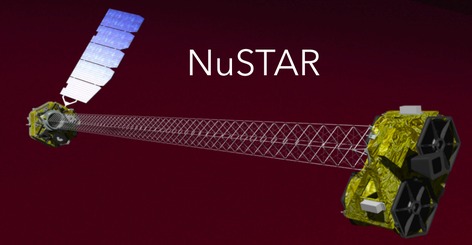
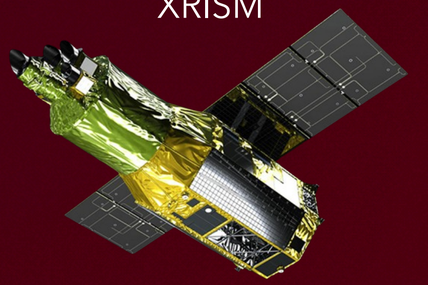
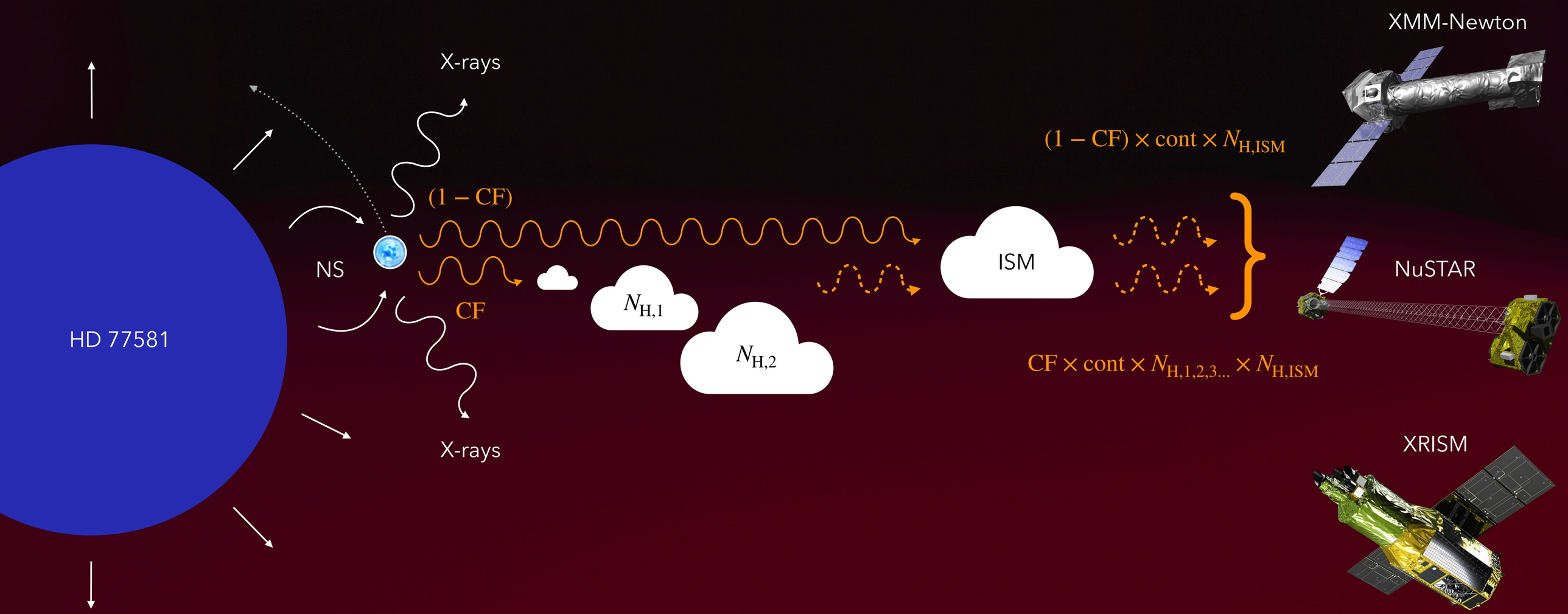


XRISM



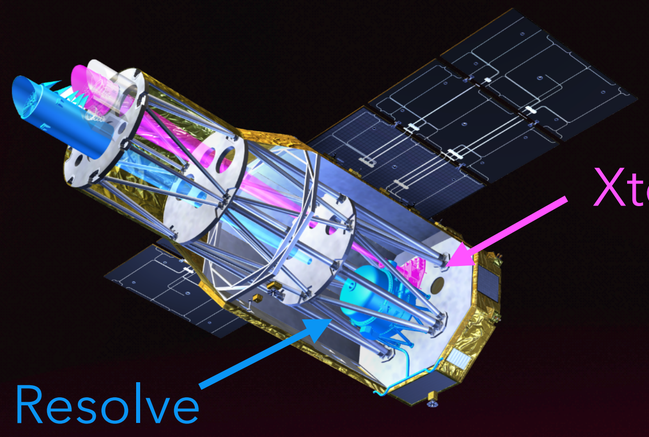
Partial covering model

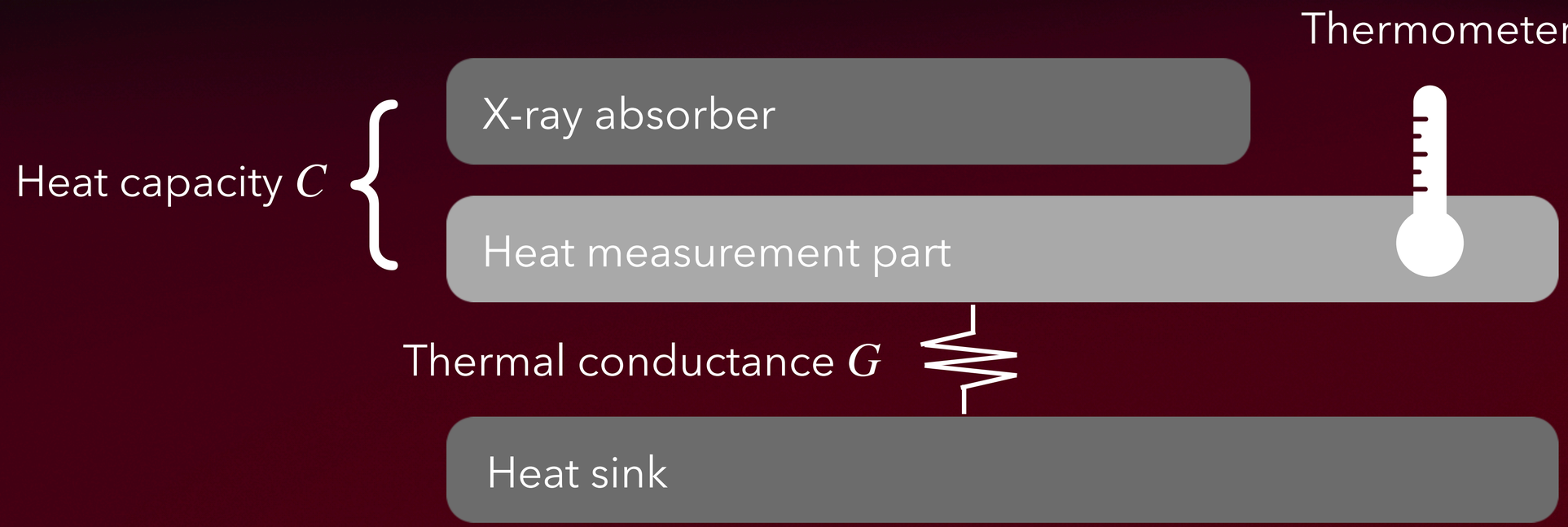


Partial covering model

- Classical for these systems
- Complex model
- XRISM brings additional emission lines

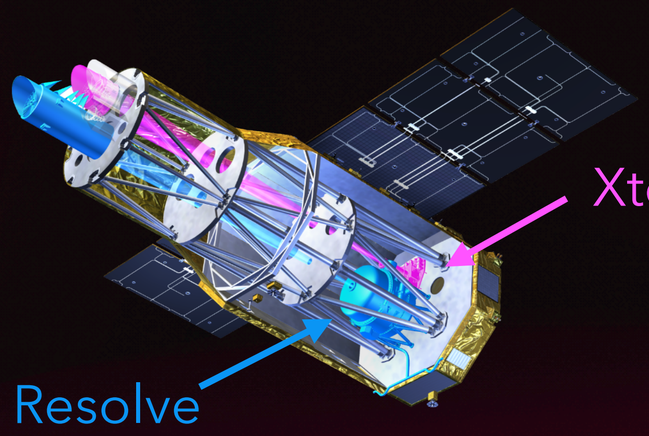
XRISM – Resolve Micro calorimeter





Adapted from www.xrism.jaxa.jp and Sato et al. (2023)

XRISM – Resolve Micro calorimeter



Incoming X-ray E

Thermometer T

Heat capacity C

X-ray absorber

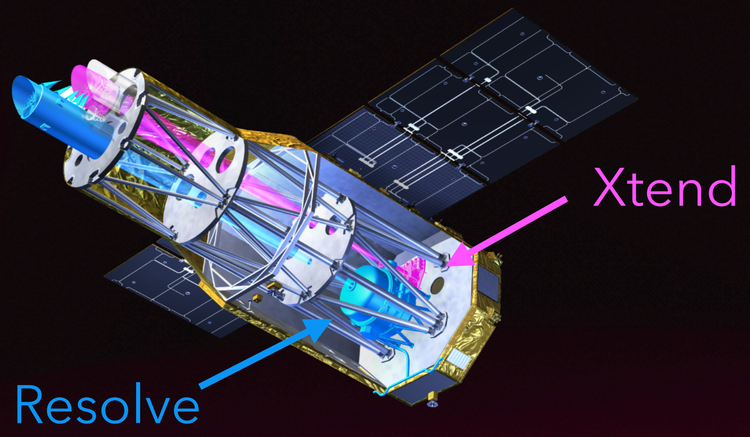
Heat measurement part

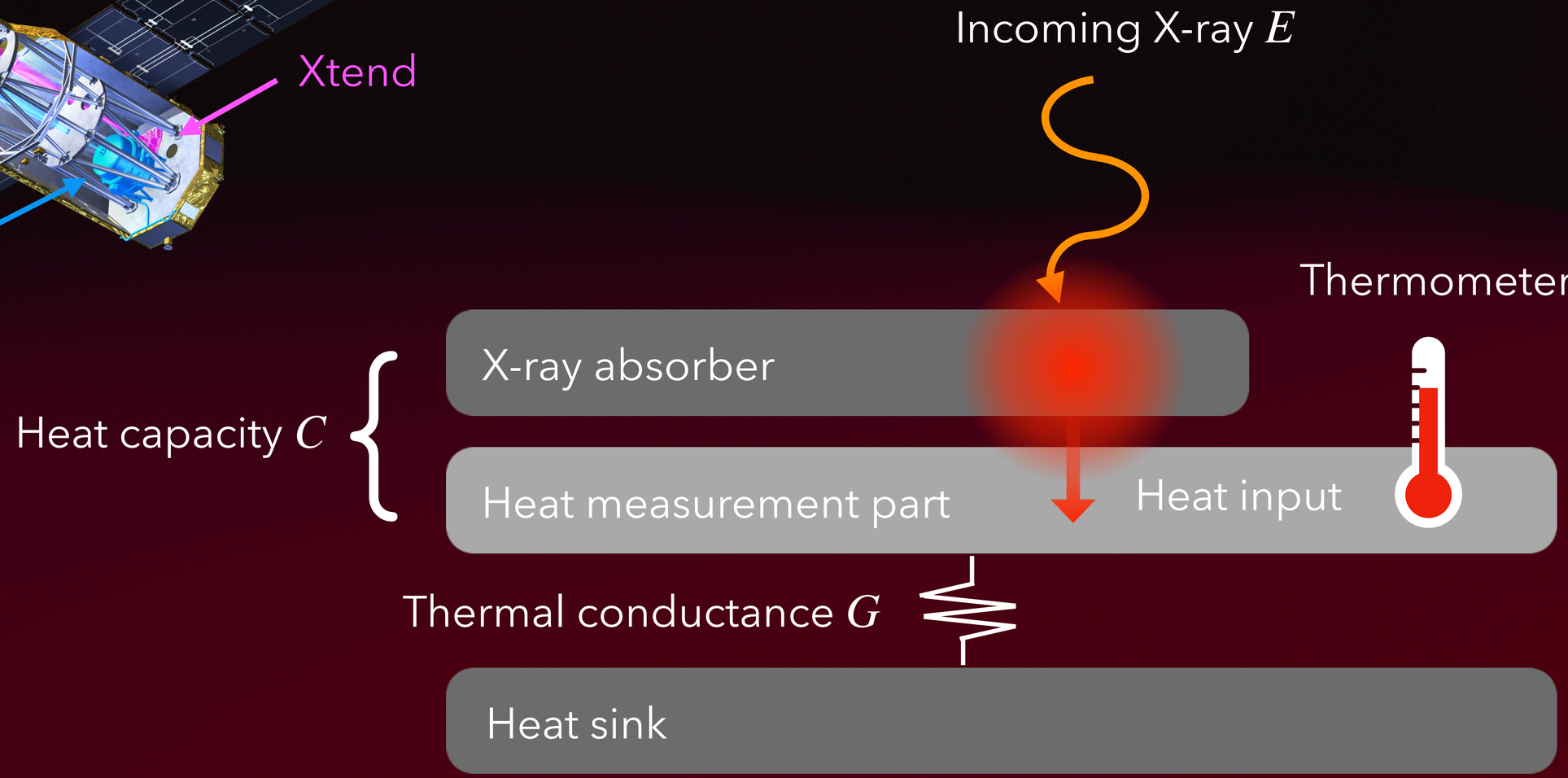
Thermal conductance G

Heat sink

Adapted from www.xrism.jaxa.jp and Sato et al. (2023)

XRISM – Resolve Micro calorimeter





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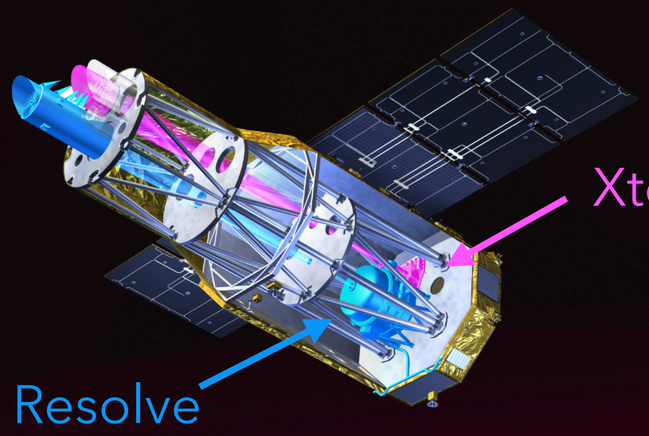
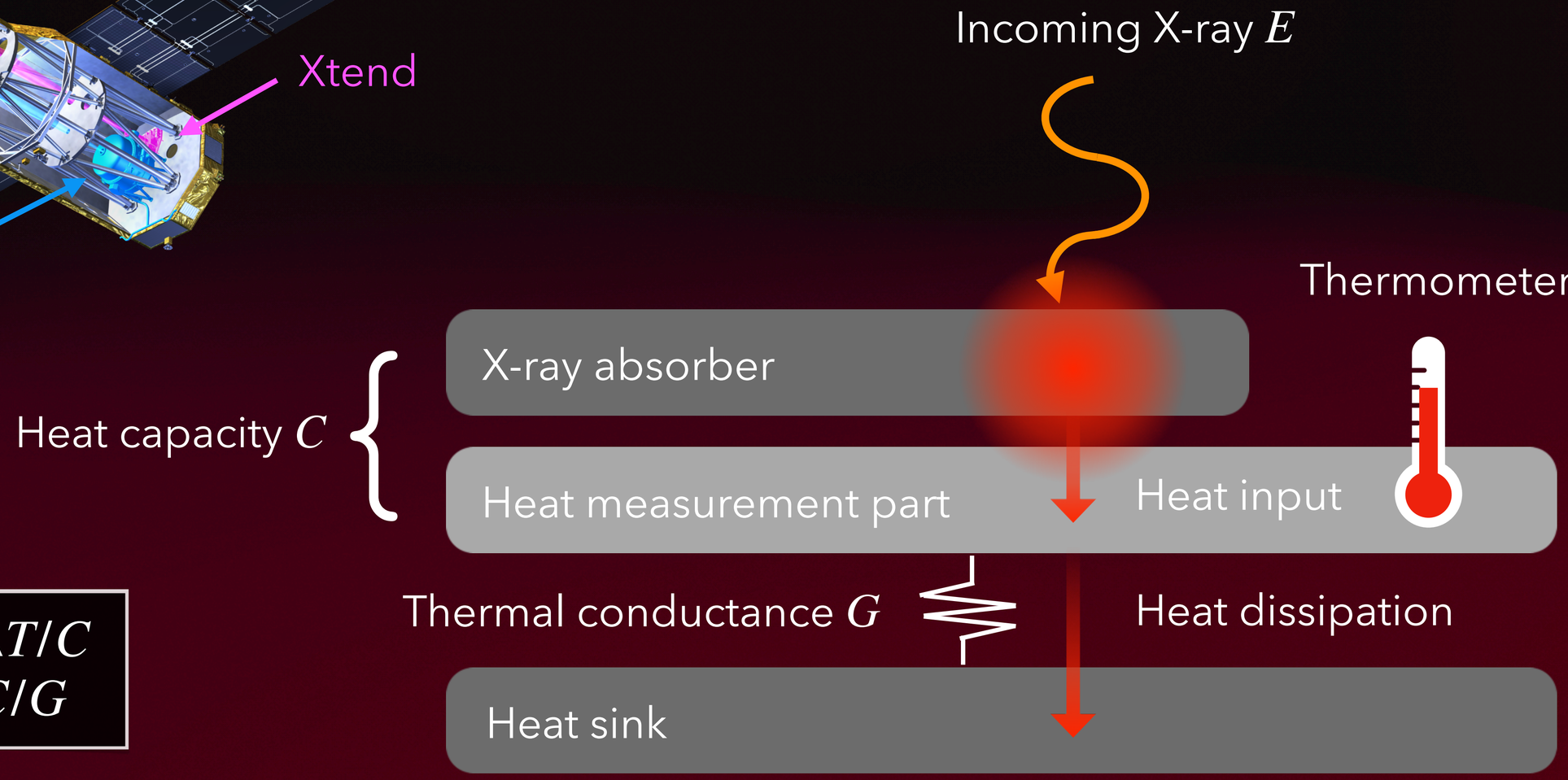
XRISM – Resolve Micro calorimeter





$$E = \Delta T / C$$
$$\tau = C / G$$

Adapted from www.xrism.jaxa.jp and Sato et al. (2023)

Why a capybara?

Because why not?

Seen at CosmoCaixa museum in Barcelona for the 3rd Athena Scientific Conference 2022

The original (unbothered) capybara

The attitude you should adopt towards non-constructive criticism when developing new tools…