

Using multi-band observations to study X-ray binaries I.

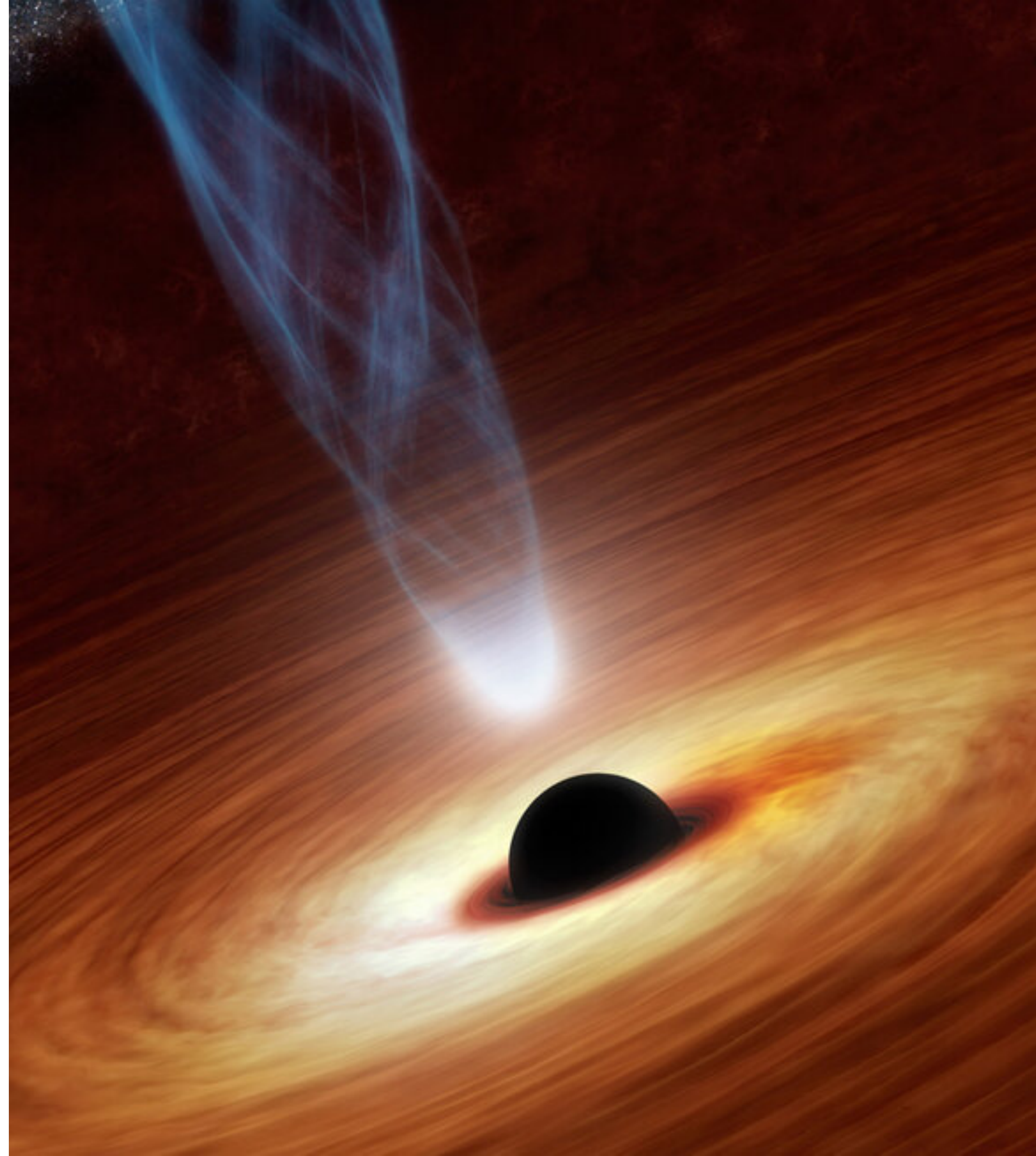
Accretion flows

Alessio **Marino** (he/him)

Postdoctoral fellow
Institute of Space Sciences (ICE-CSIC),
Barcelona, Spain

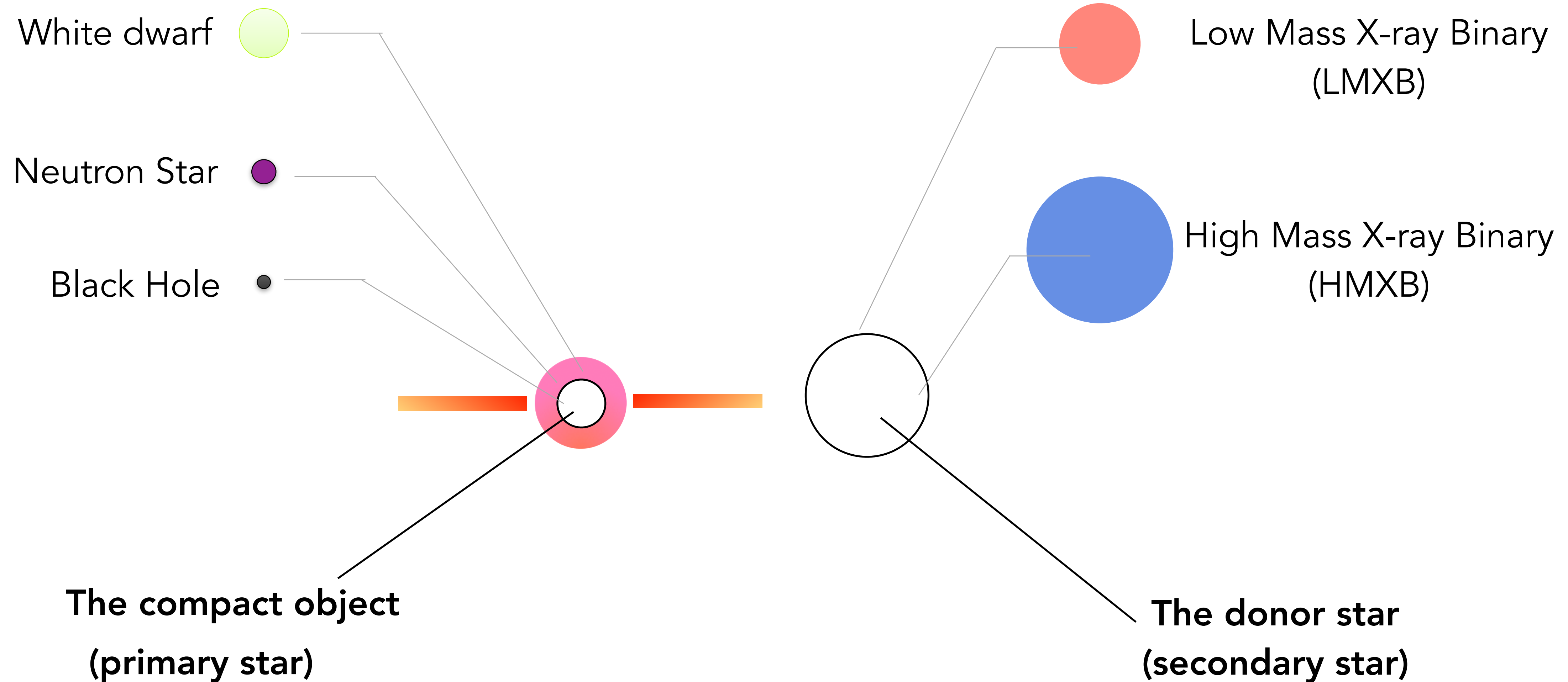
Summary

- ▶ X-ray binaries and matter accretion;
- ▶ The physics of accretion flows;
- ▶ X-ray binaries: spectroscopy and timing;
- ▶ X-ray binaries: multi-band views of their activity;



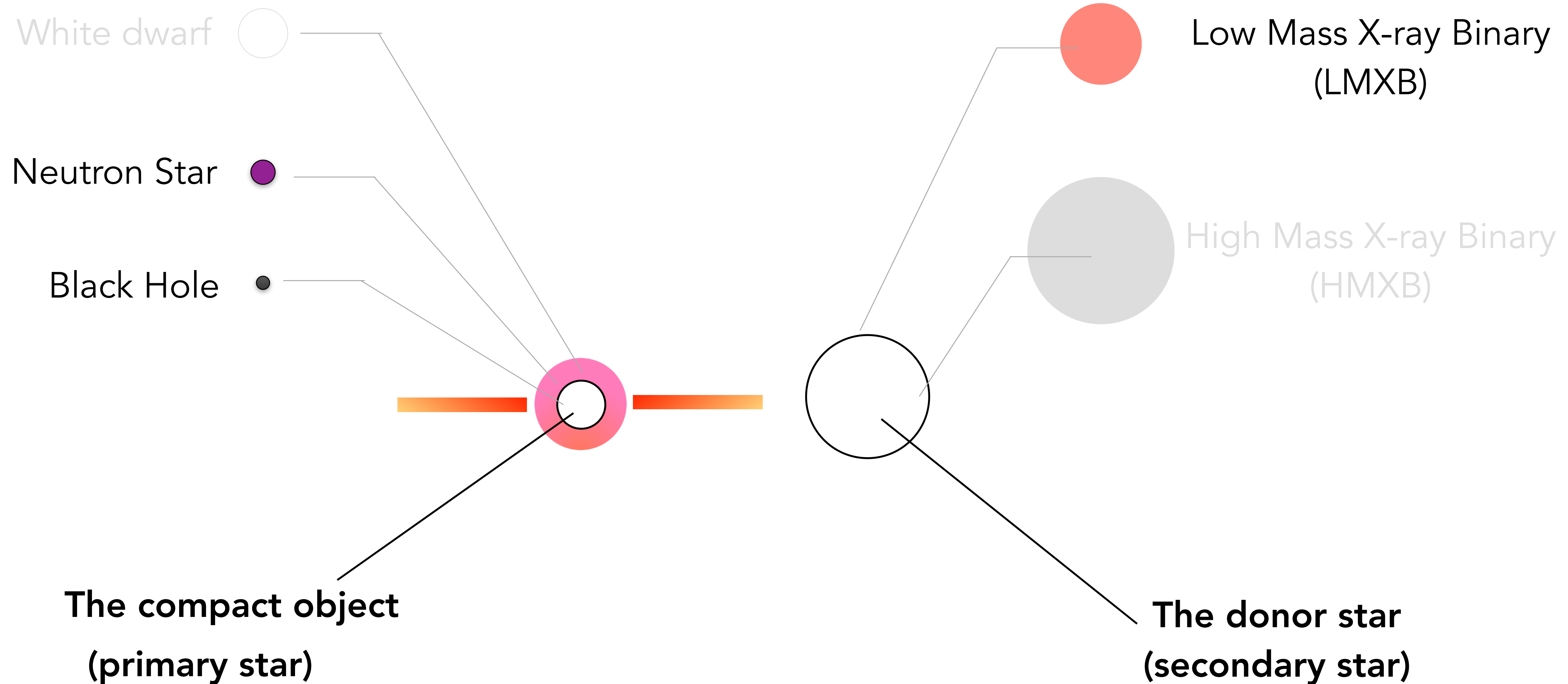
X-ray binaries

- Binary stars composed of a compact object (a BH or a NS) and a companion star of variable mass;



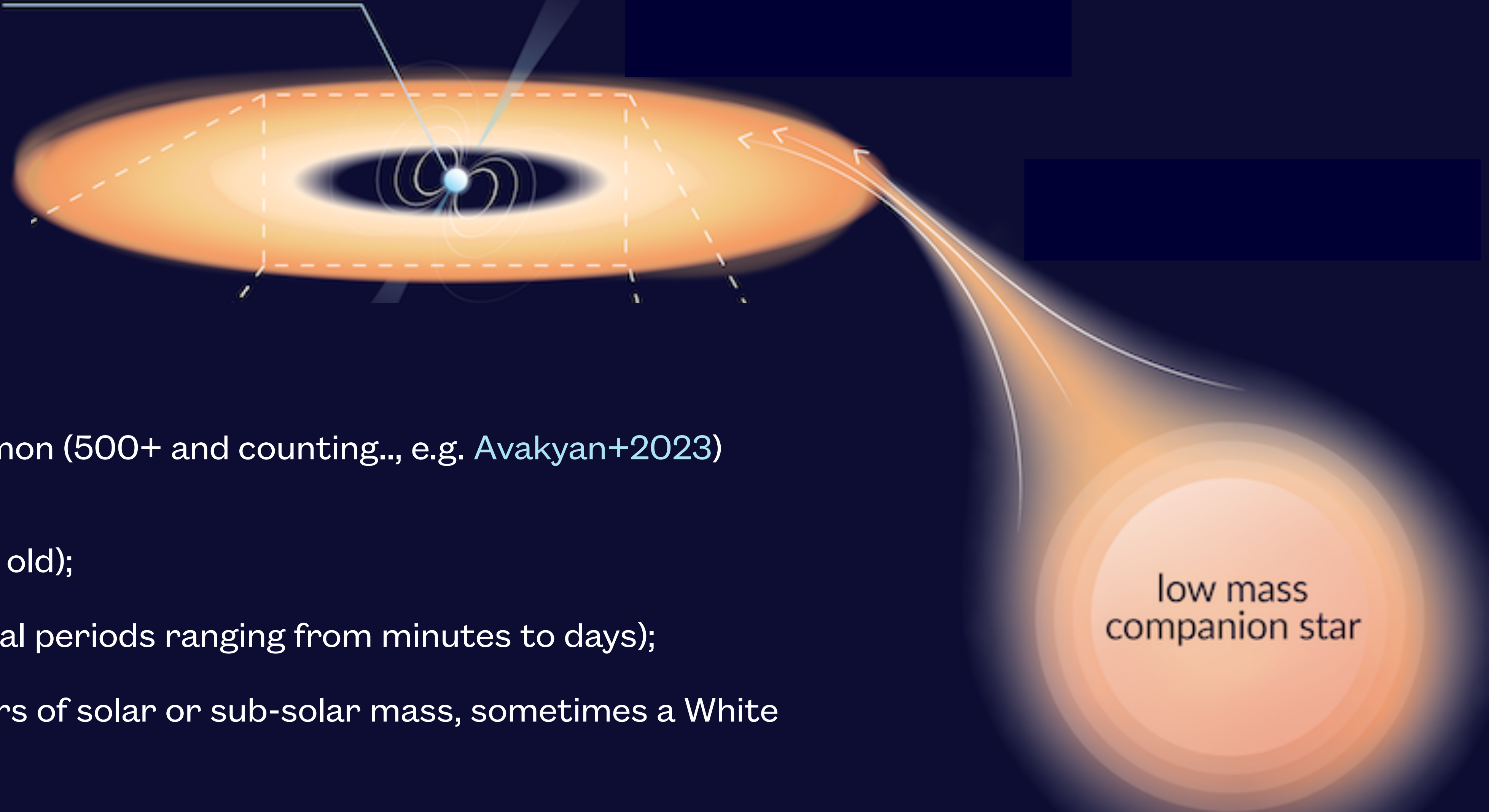
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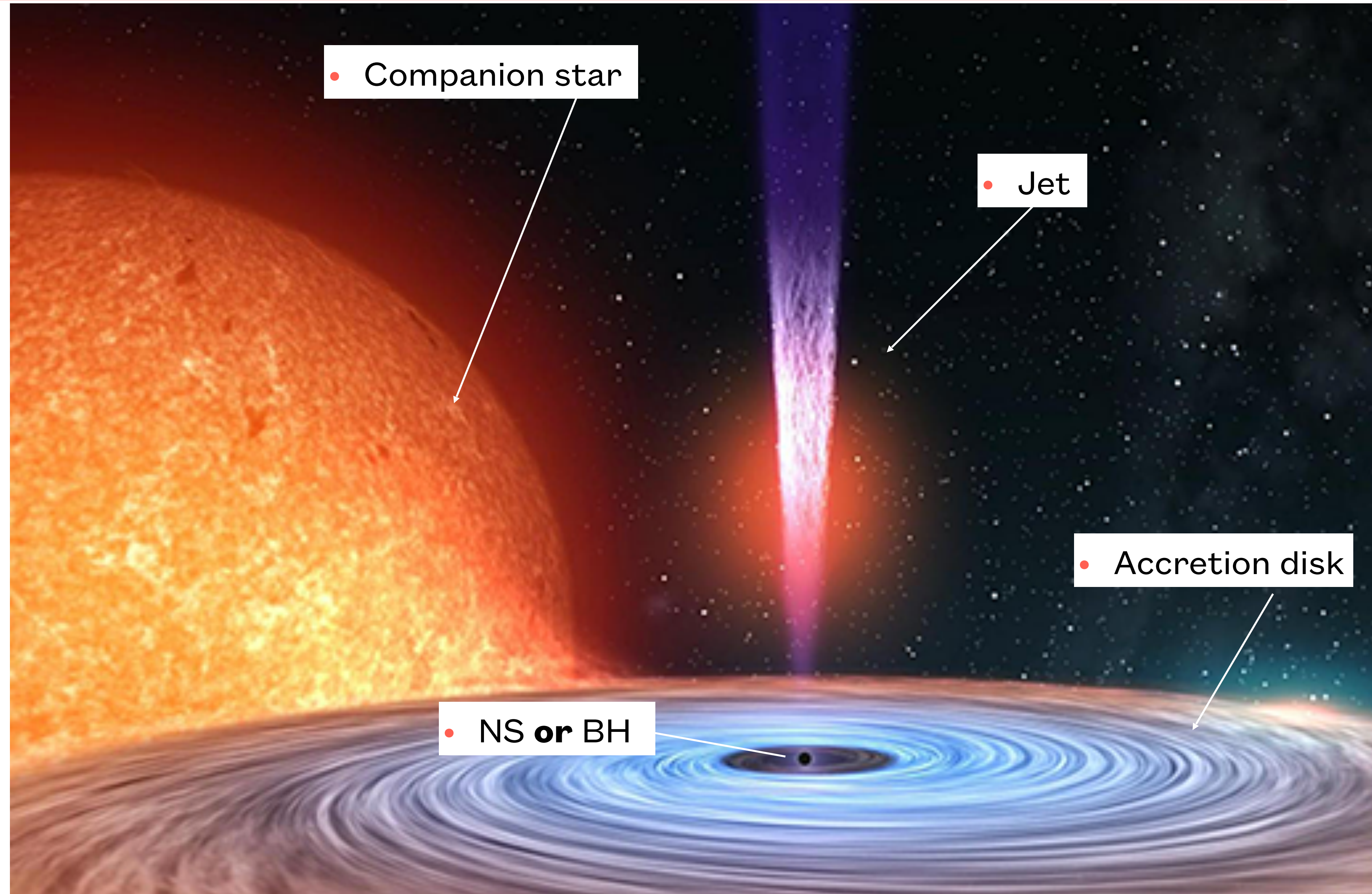


neutron star (or a stellar-mass black hole!)



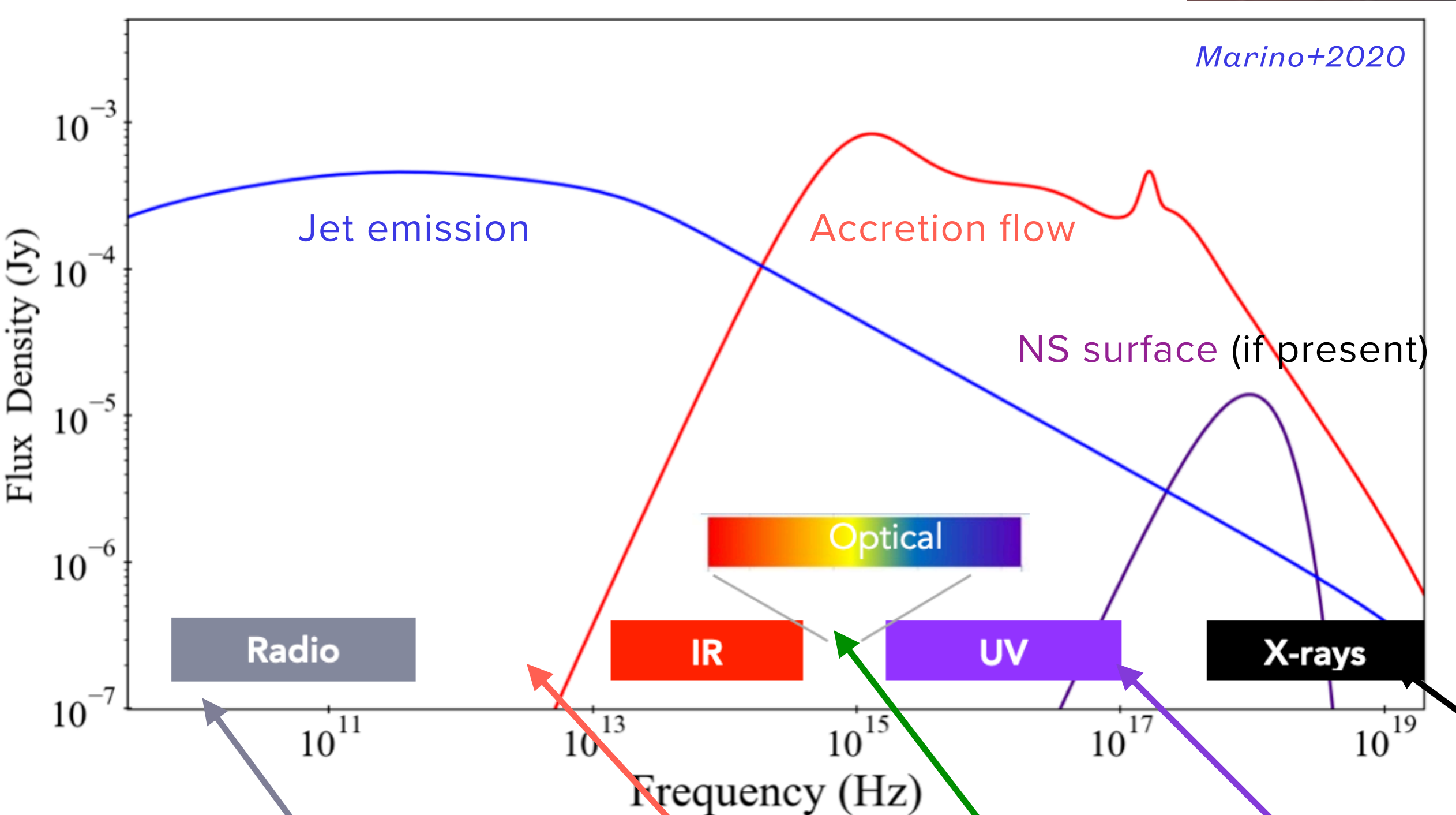
- Relatively common (500+ and counting., e.g. [Avakyan+2023](#)) objects;
- Old (Giga-years old);
- Compact (orbital periods ranging from minutes to days);
- Companion stars of solar or sub-solar mass, sometimes a White Dwarf;

X-ray binaries anatomy



X-ray binaries anatomy at different wavelengths

- **Spectral energy distribution** of a LMXB



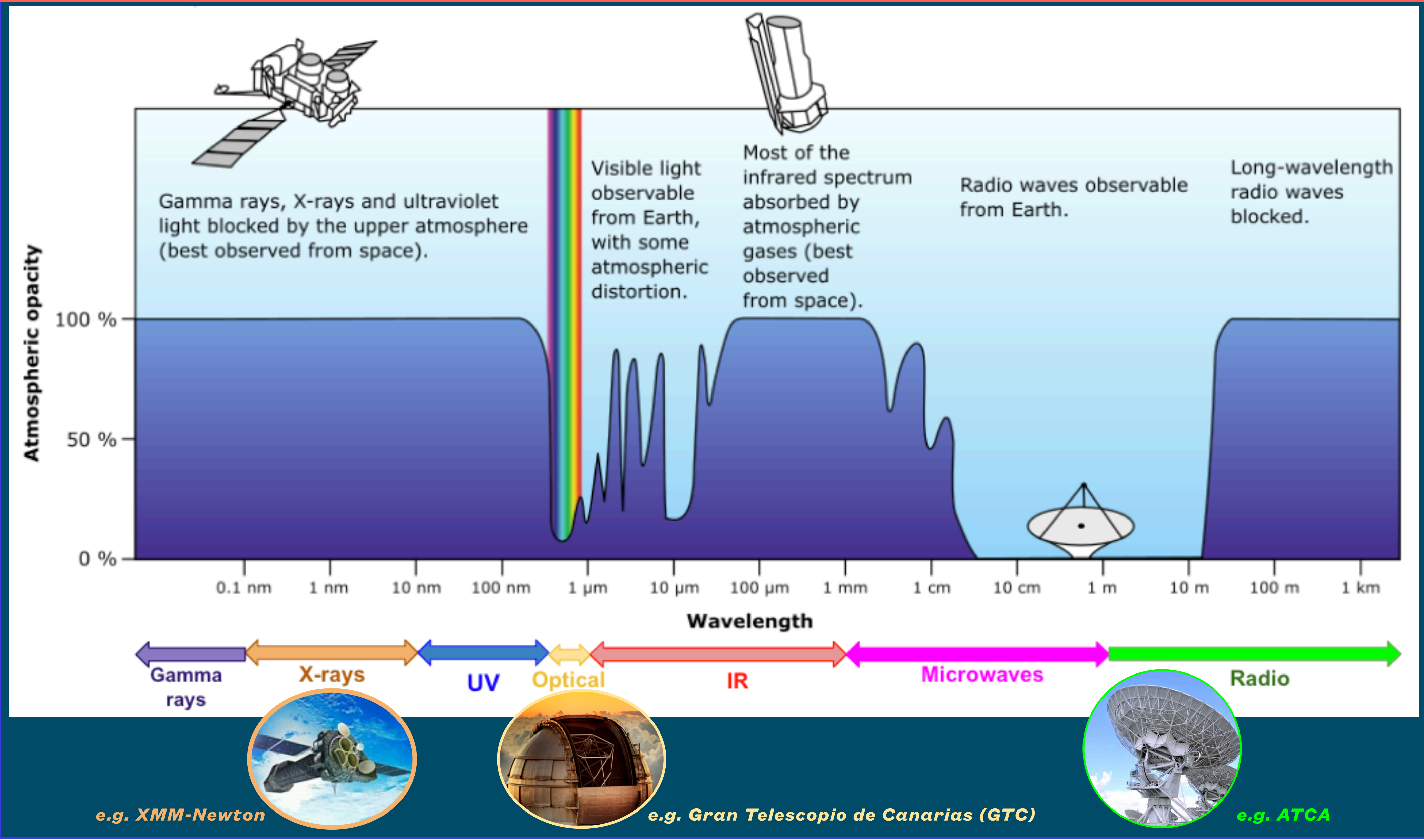
- Companion star

- Jet

- Accretion disk

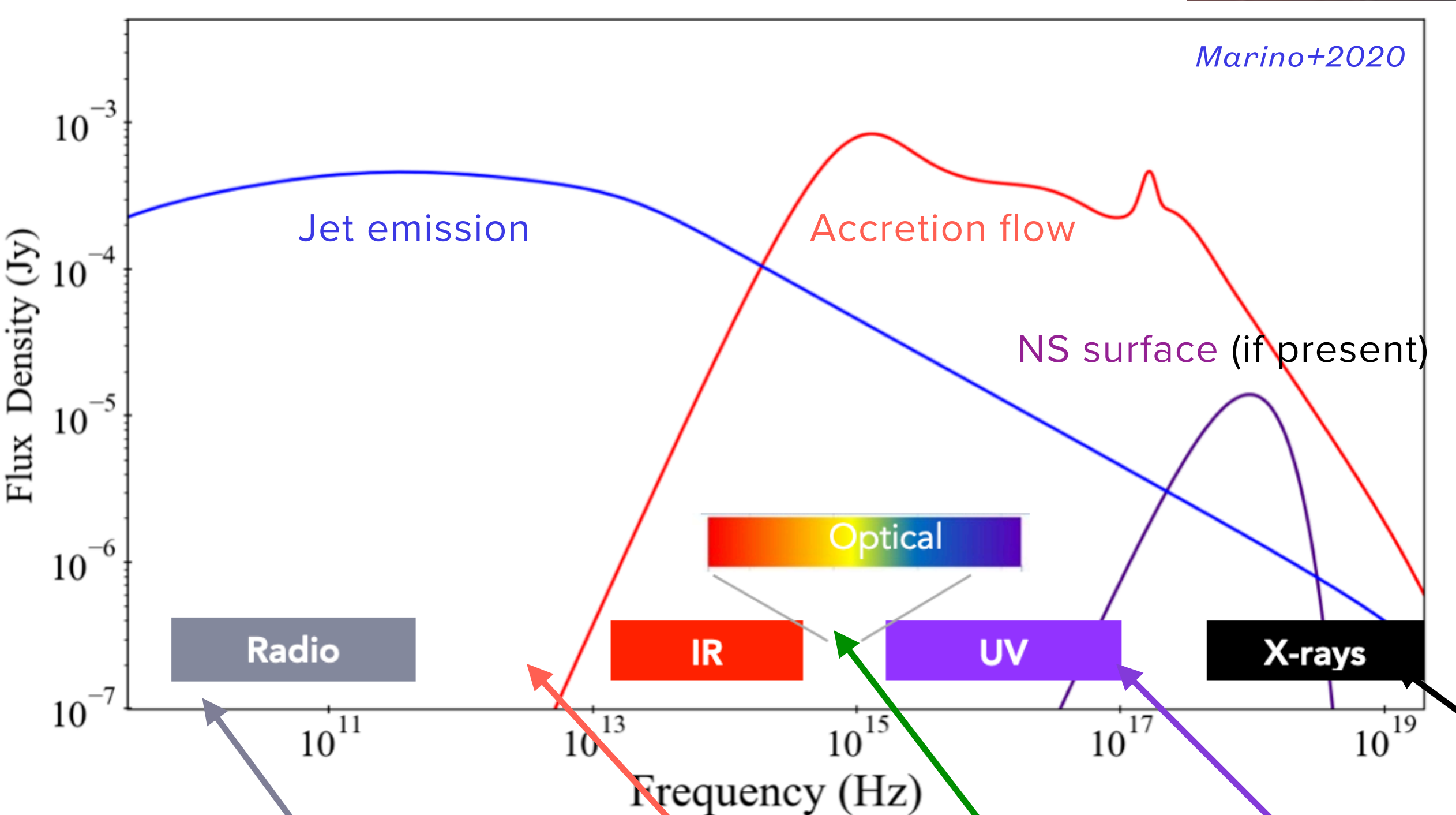
- NS or BH

Observing X-ray binaries at different wavelengths



X-ray binaries anatomy at different wavelengths

- **Spectral energy distribution** of a LMXB



Thursday's lecture!

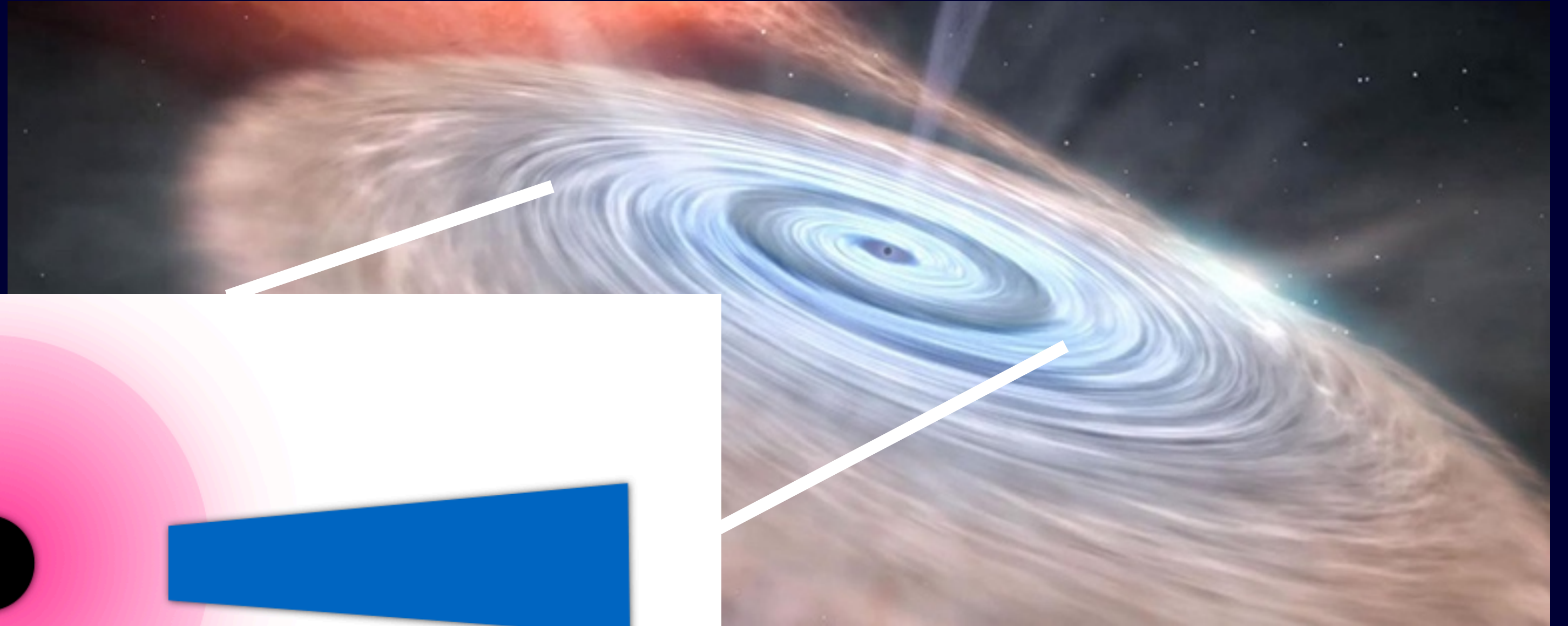
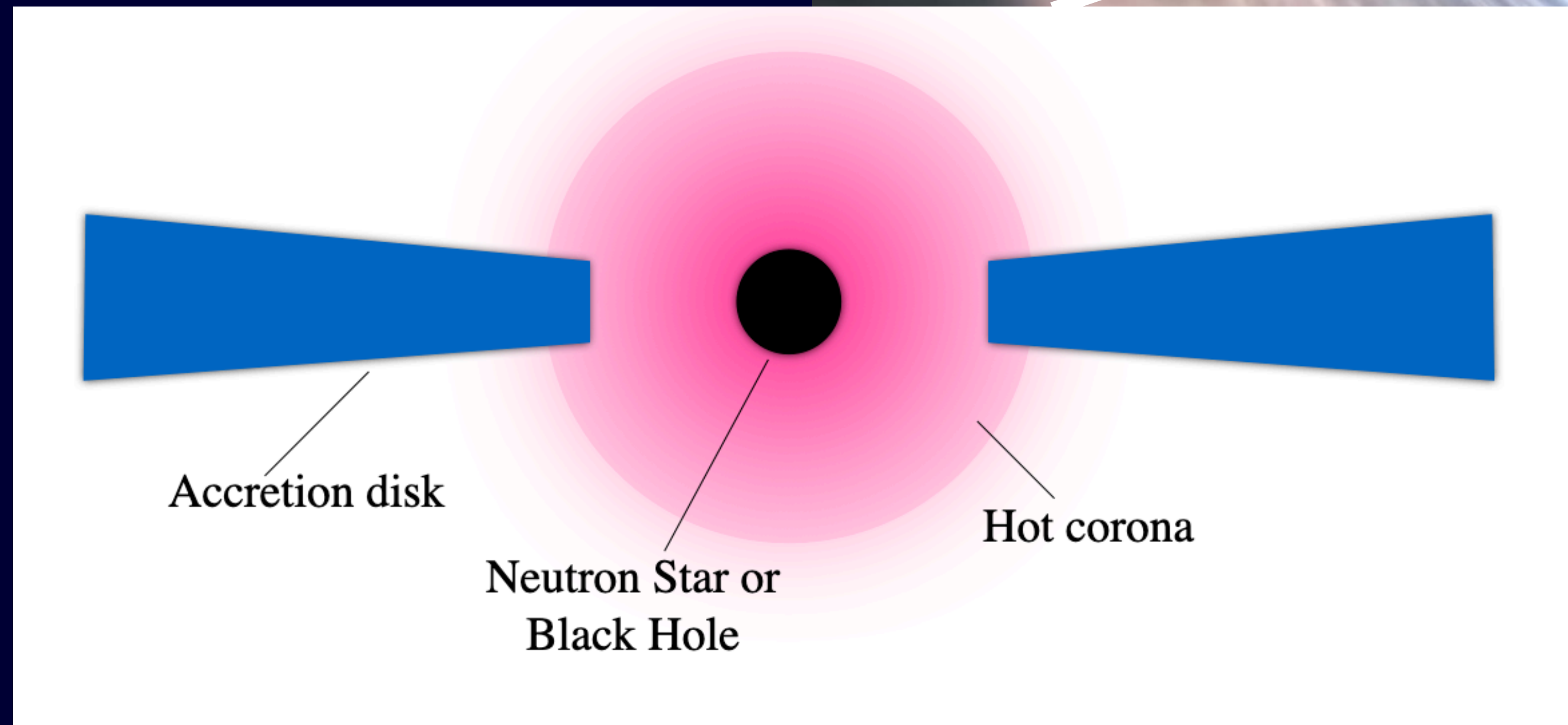
- Jet, winds (outflows)

This lecture!

Accretion disk (inflows)

Accretion flow: what are the main ingredients?

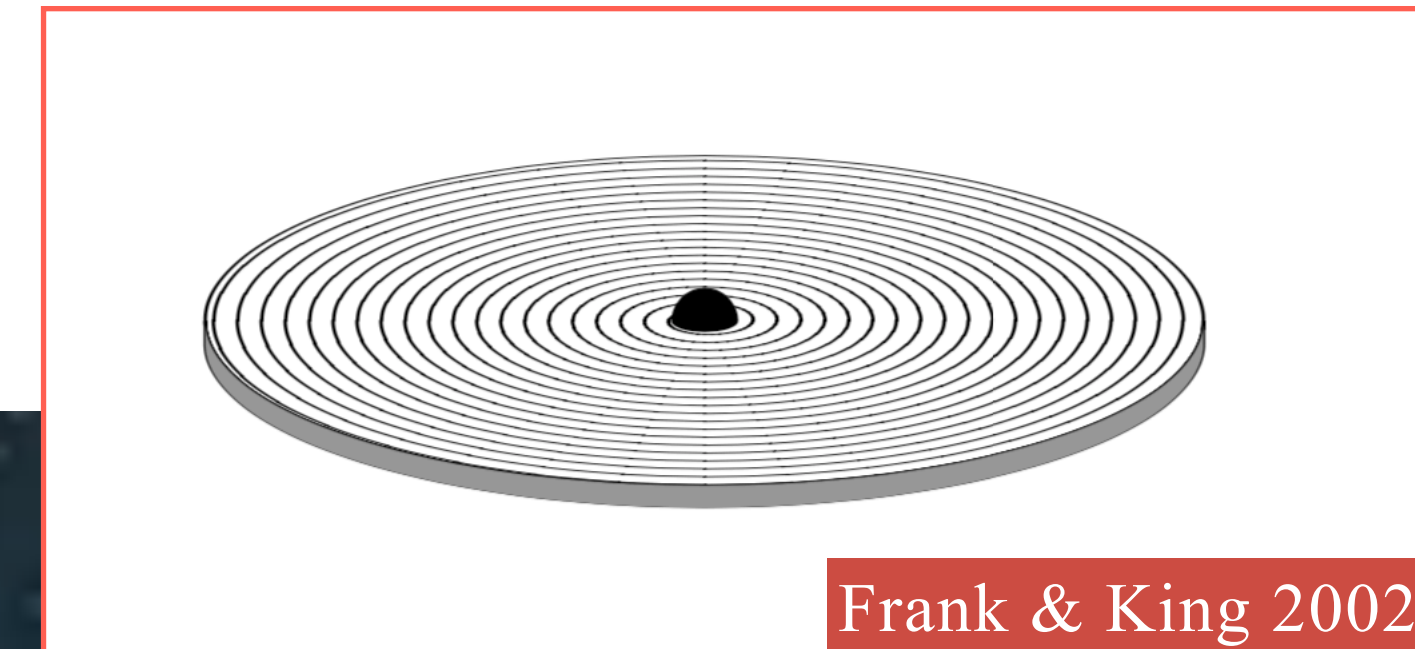
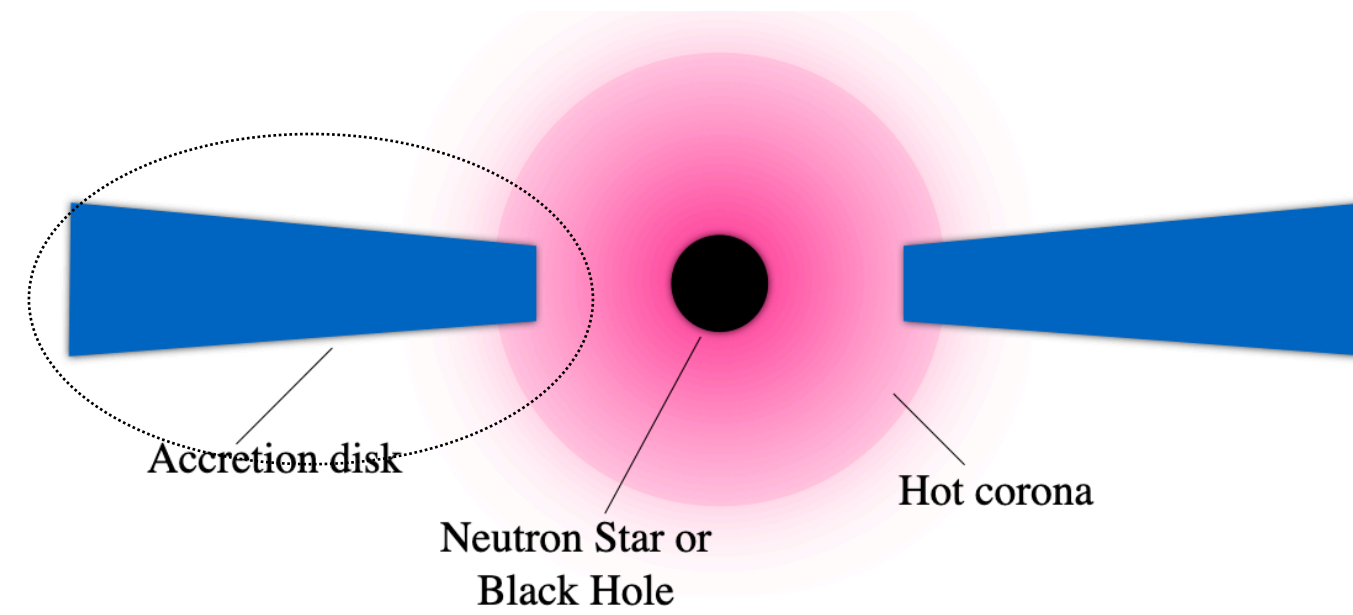
- A schematic view of the inner region of the accretion flow:



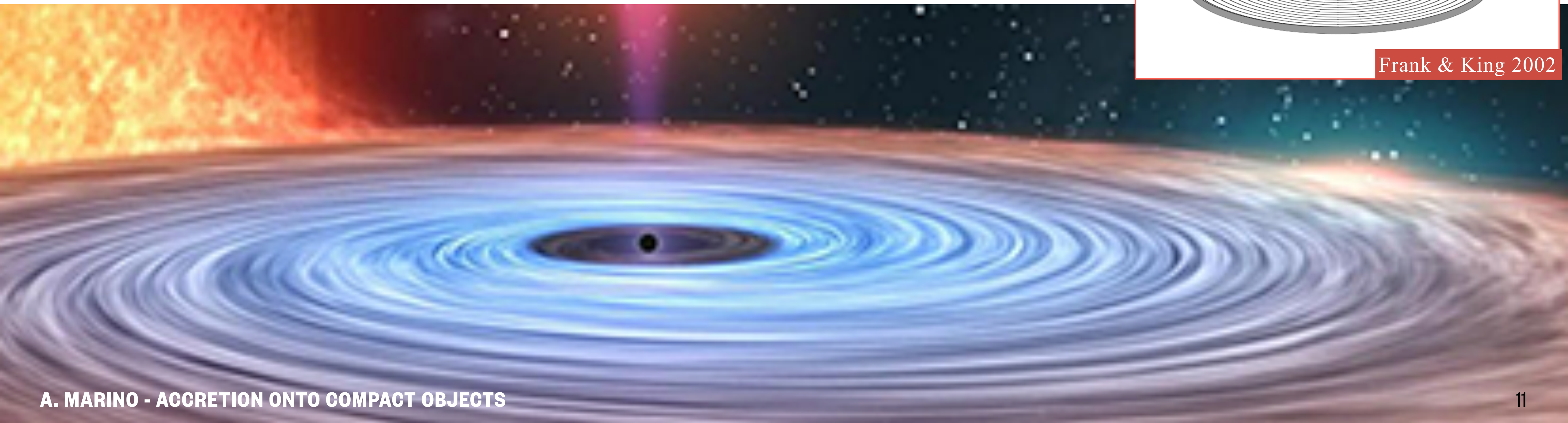


Accretion disks (i)

- Transferred mass has its own orbital angular momentum so it can not fall into straight line onto the compact object;
- It falls around it “in spirals”, building an **accretion disk**.



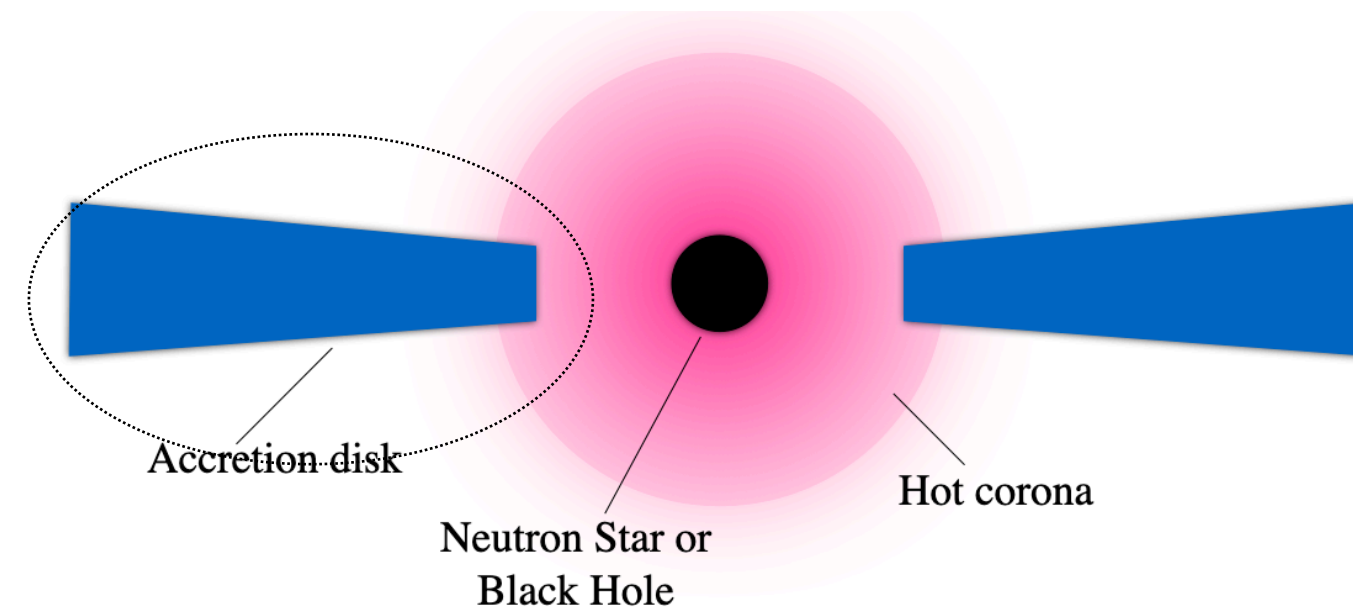
Frank & King 2002



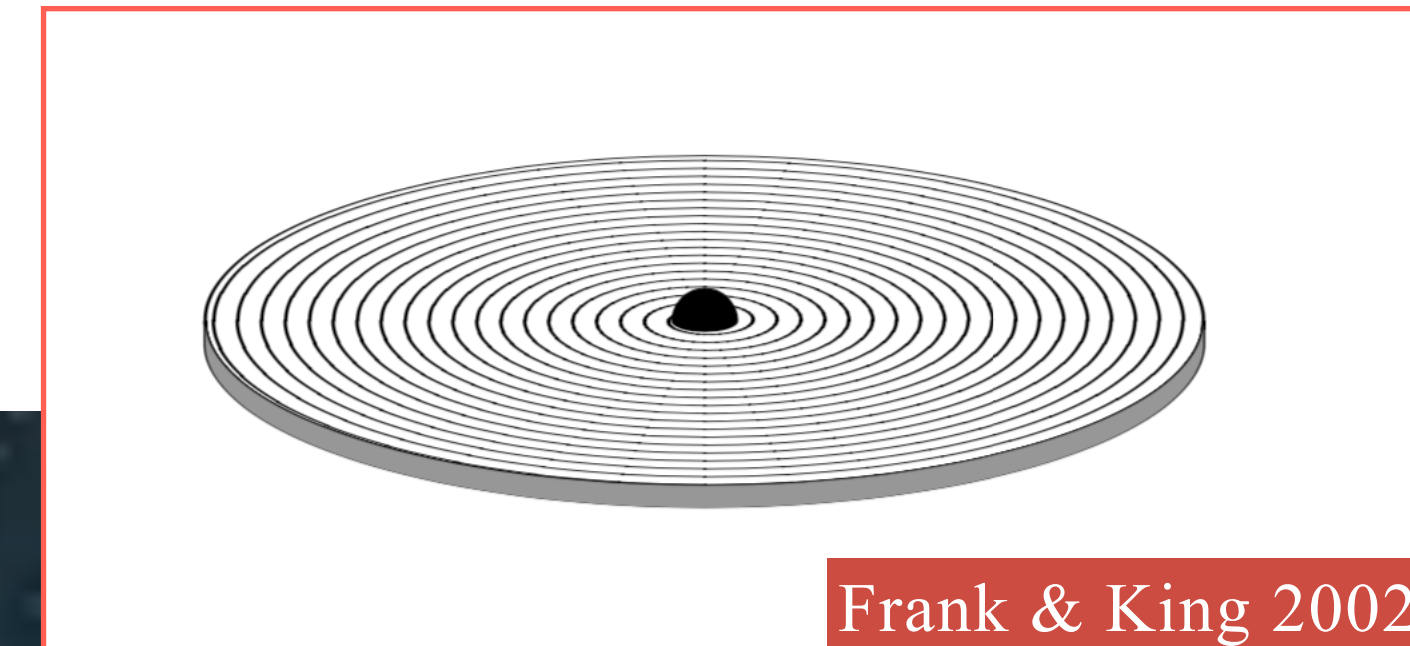


Accretion disks (ii)

- The disk is **geometrically thin, optically thick**.
- Each ring of the disk moves with Keplerian velocity (the closer to the compact object, the faster they rotate);



$$\Omega_K = \left(\frac{GM}{R^3} \right)^{1/2}$$

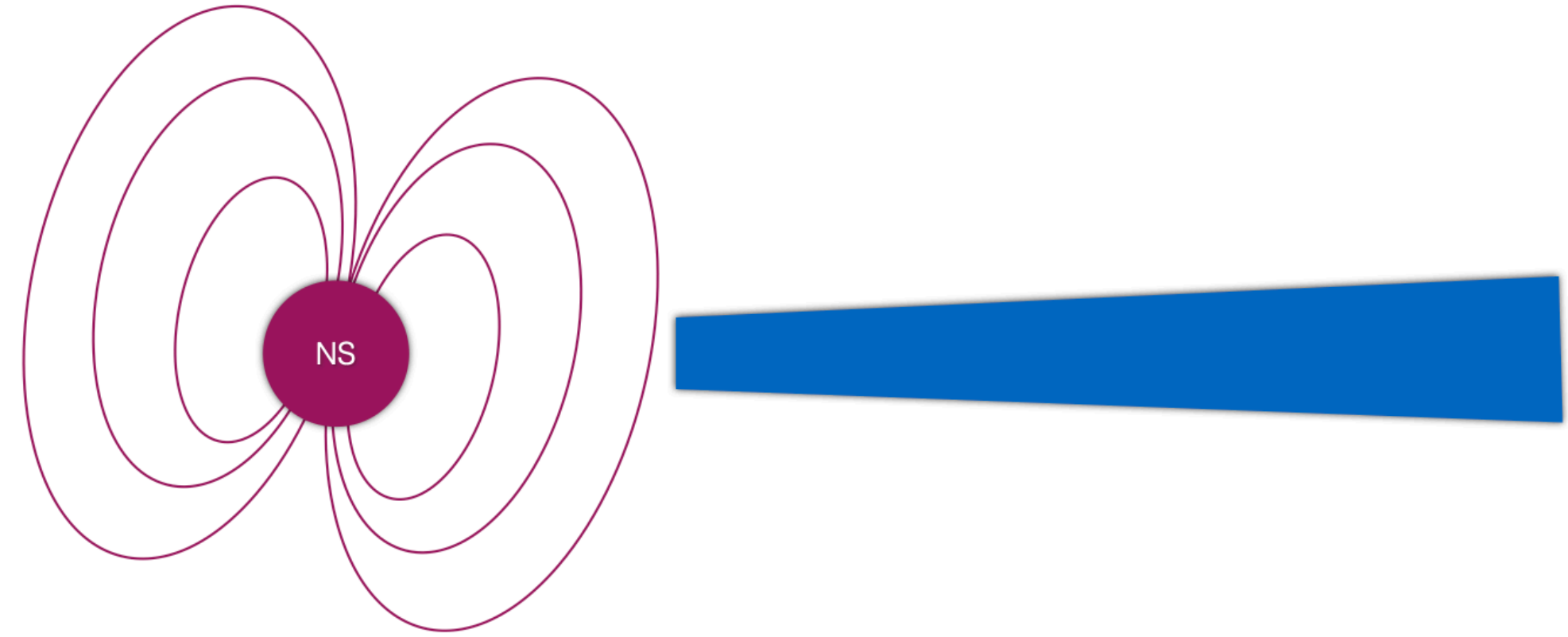


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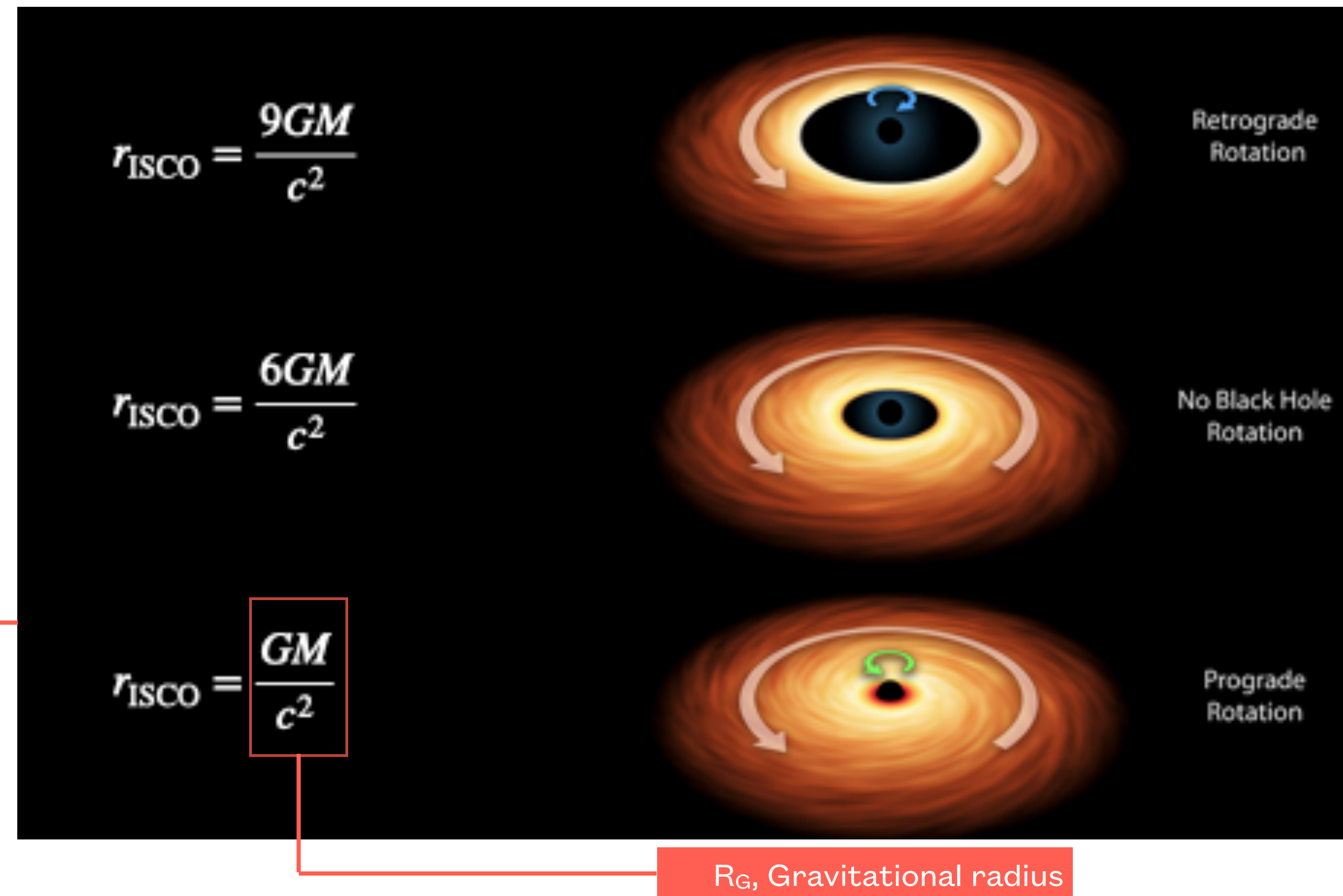


How close can a disk get to the compact object?

- For a magnetised NS, until a radius called **magnetospheric radius**;
- For a weakly magnetised NS, until the NS surface *in principle*;
- For a BH, until a distance called **Innermost Stable Circular Orbit (ISCO)**, whose value depend on the spin of the BH;



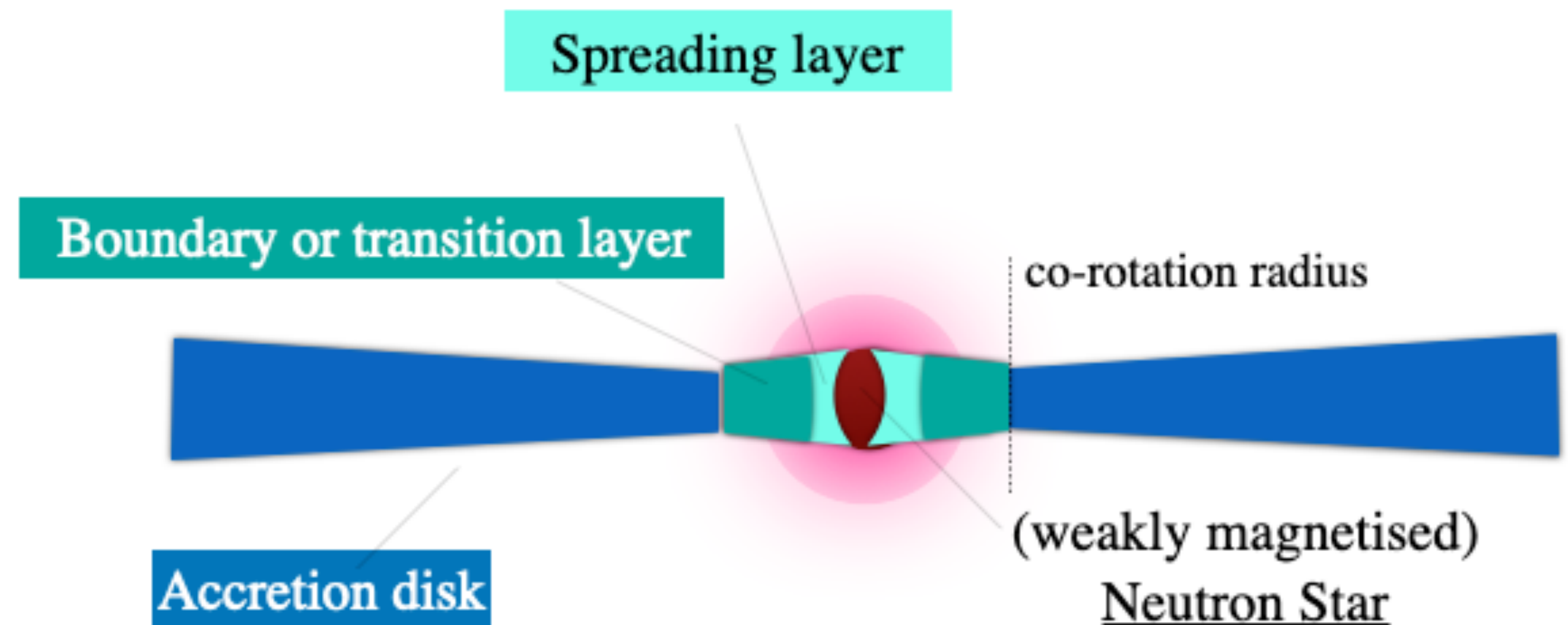
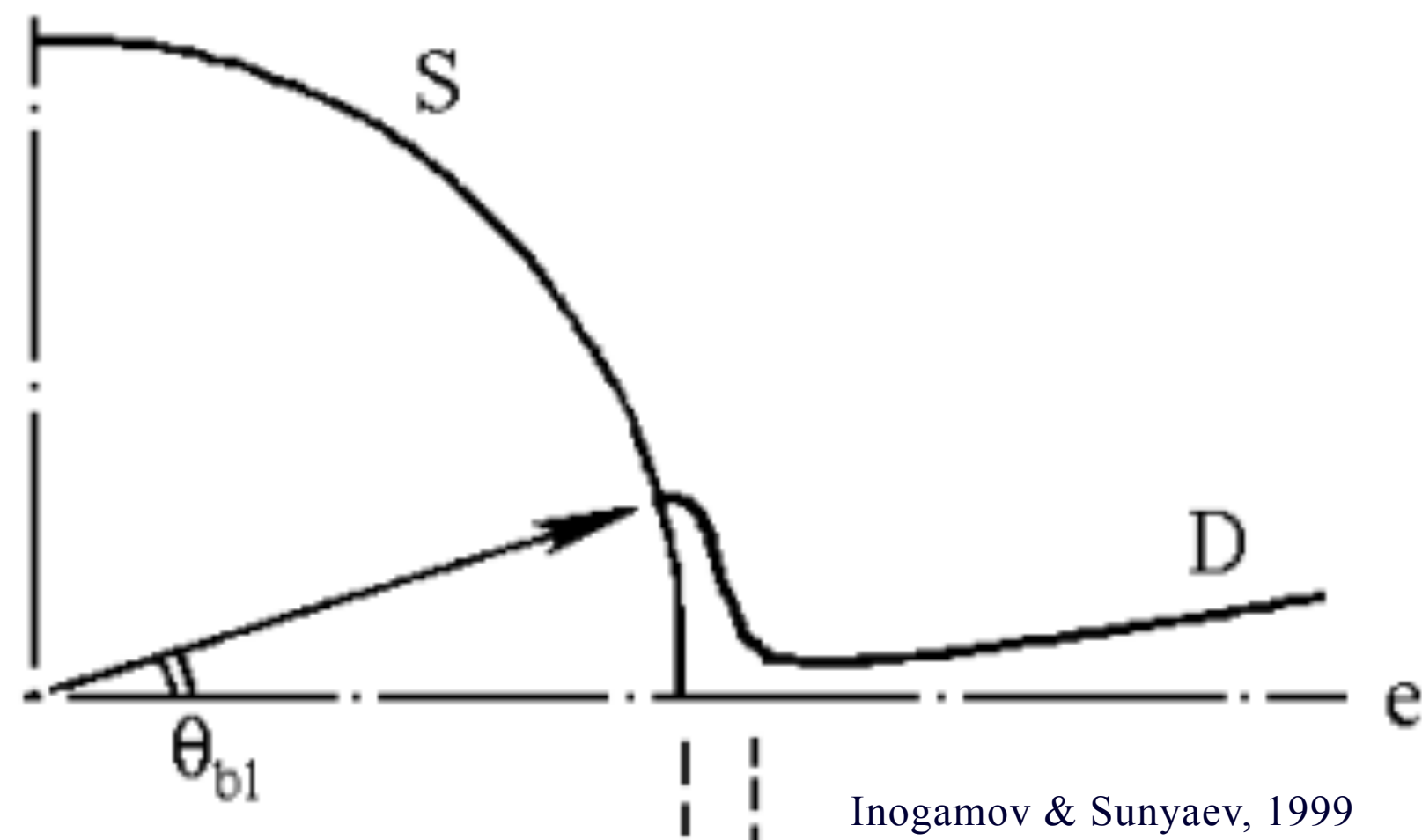
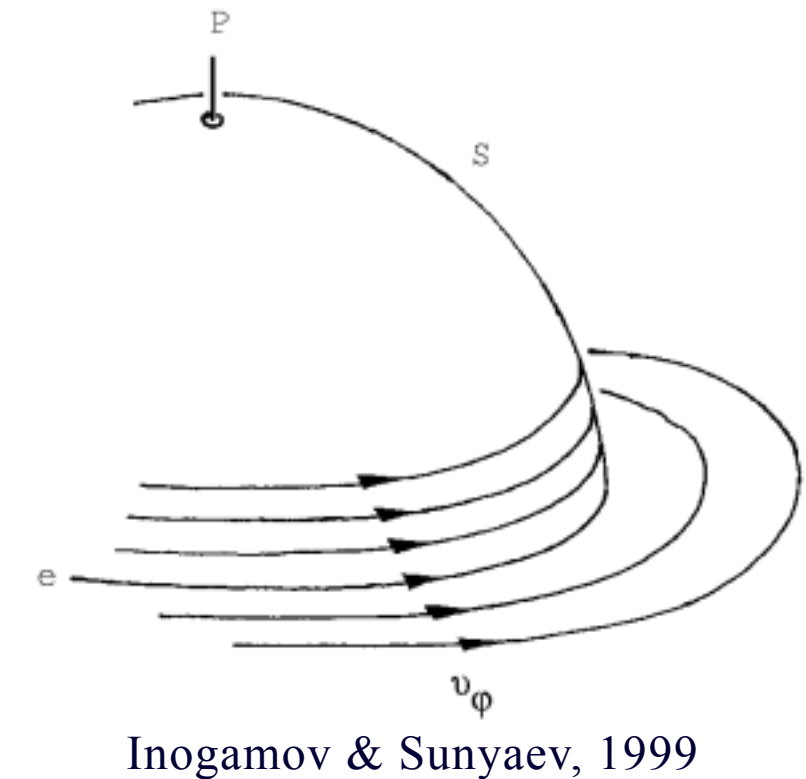
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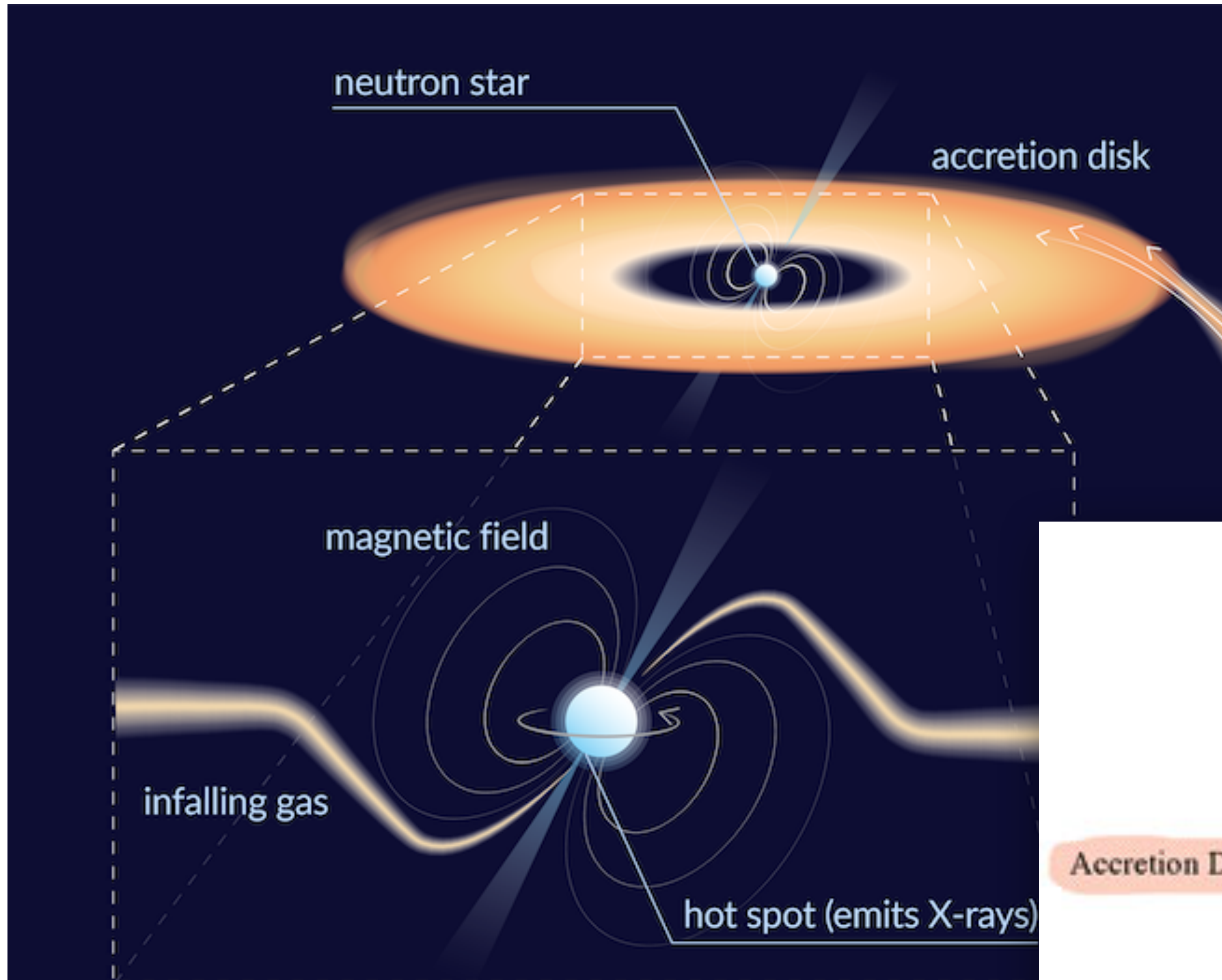
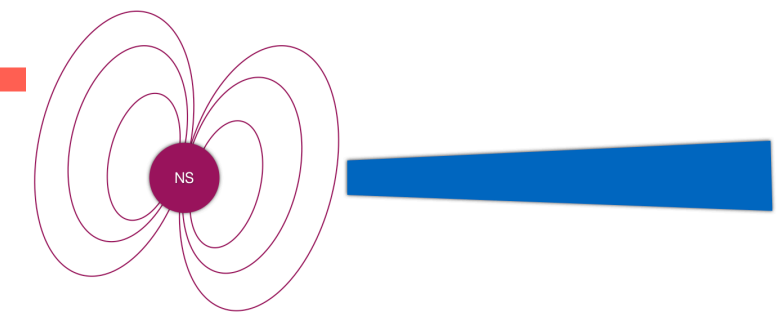
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Getting close to the NS I: boundary, transition and spreading layers

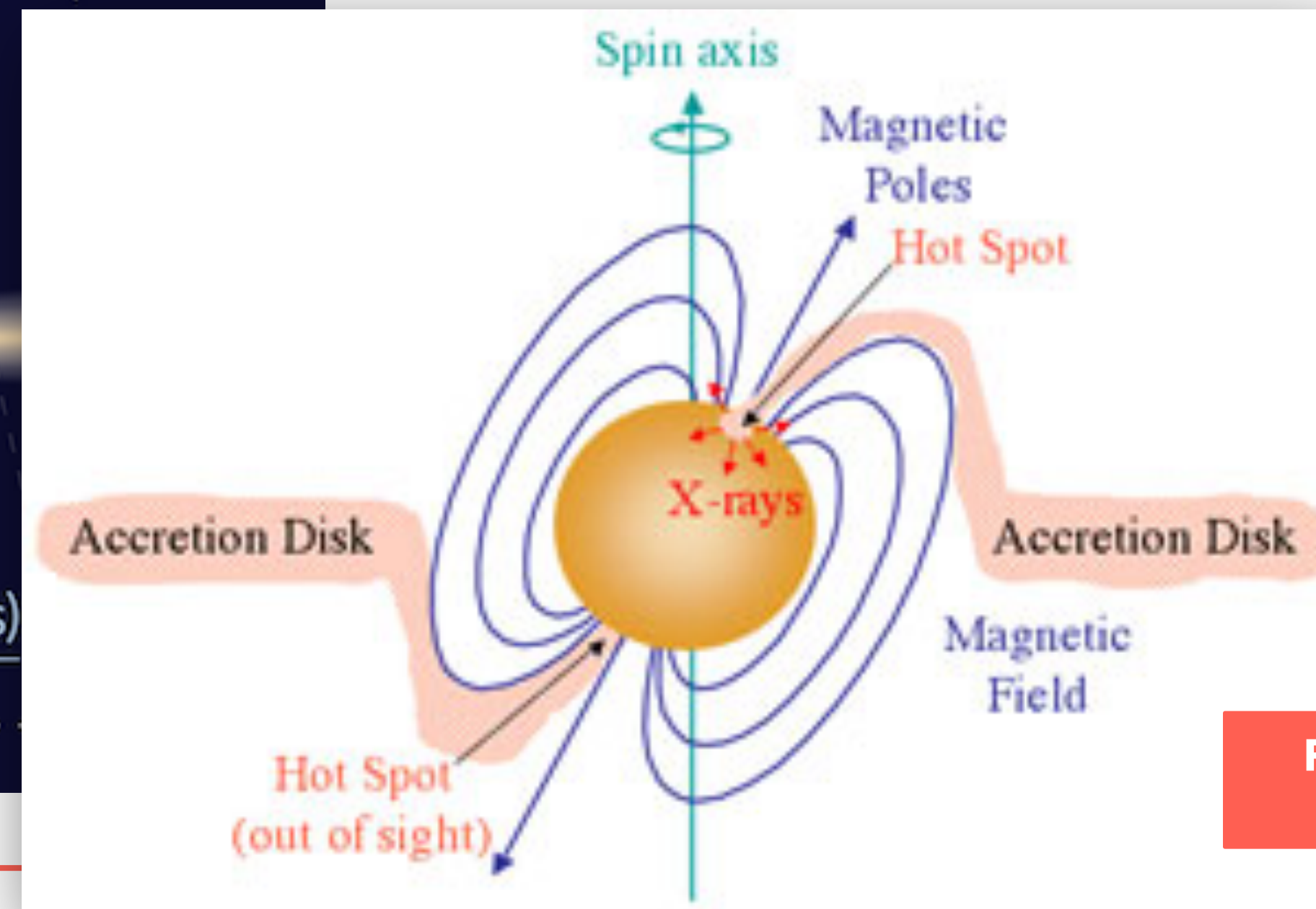
- As the disk approaches the NS, at some radius it will rotate at the same frequency as the NS spin frequency (**co-rotation radius**);
- Beyond that point - and if the magnetic field is not strong enough to channel the material onto the magnetic field lines - the flow slows down and becomes sub-Keplerian: a **boundary layer** in between the disk and the NS forms.



Getting close to the NS II: channeled accretion flow and pulsars



- Inside the magnetospheric radius, matter is channeled onto the magnetic field lines and create hot spots on the NS surface
- These hot spots are typically on the poles and due to this inhomogeneity we see a pulse whenever the pole is directed towards us!
- This is the origin of **X-rays pulsations**;



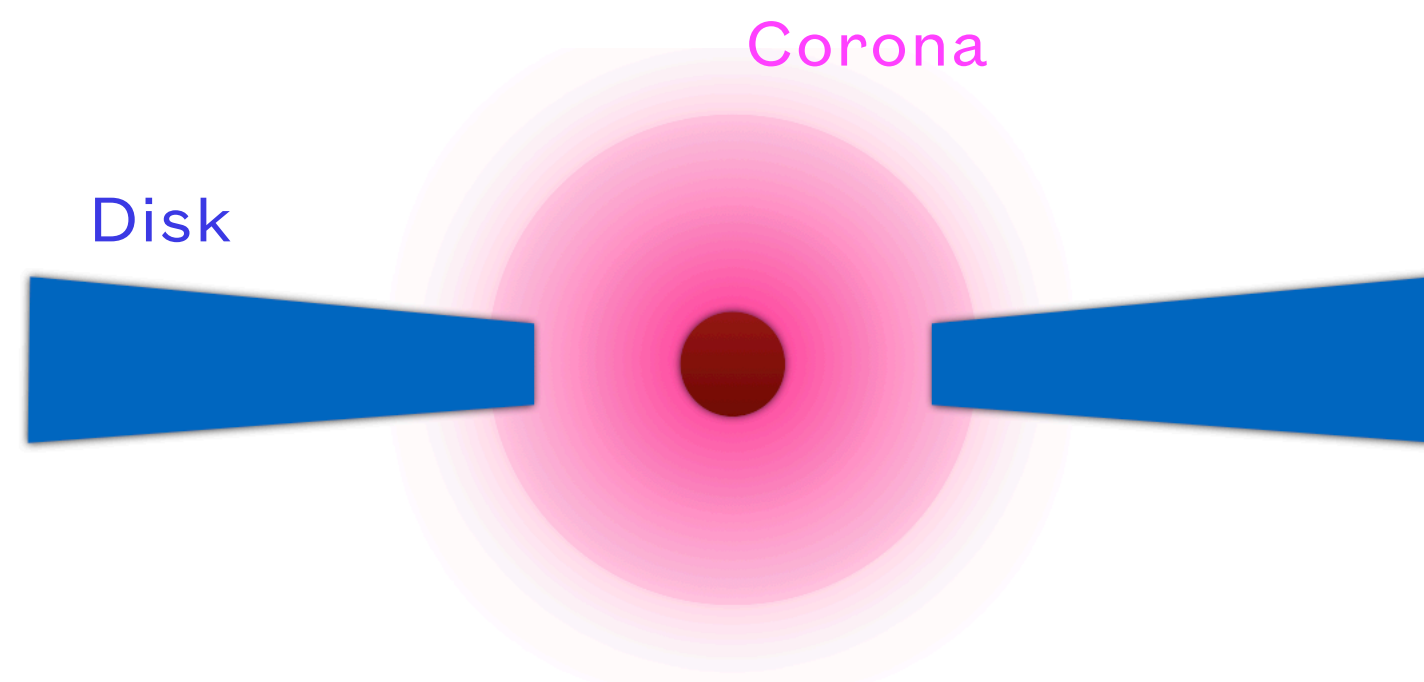
Patruno & Watts 2021; Di Salvo & Sanna 2022; Di Salvo, Papitto, AM+2023; Papitto & Di Martino 2022

Fancy some more? See A. Papitto's lecture!

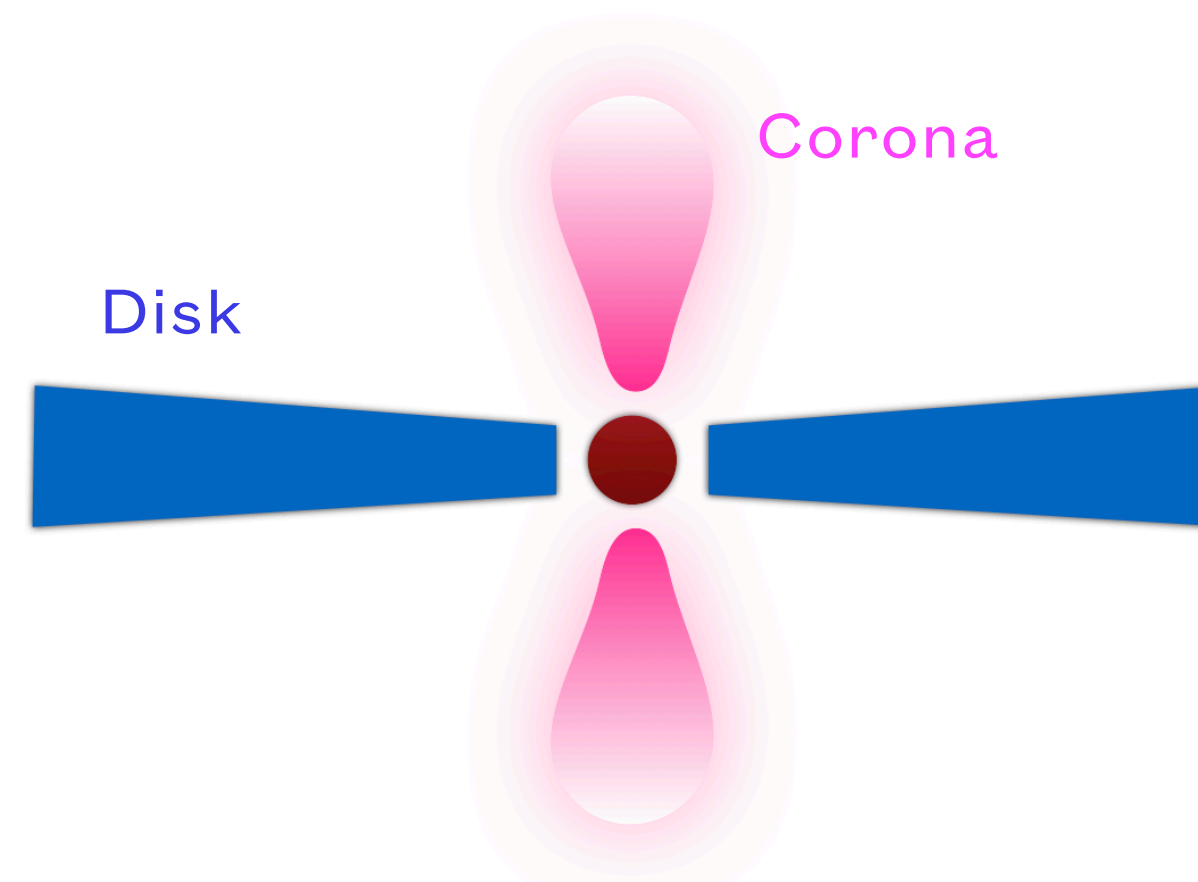


Hot inner flows or coronae

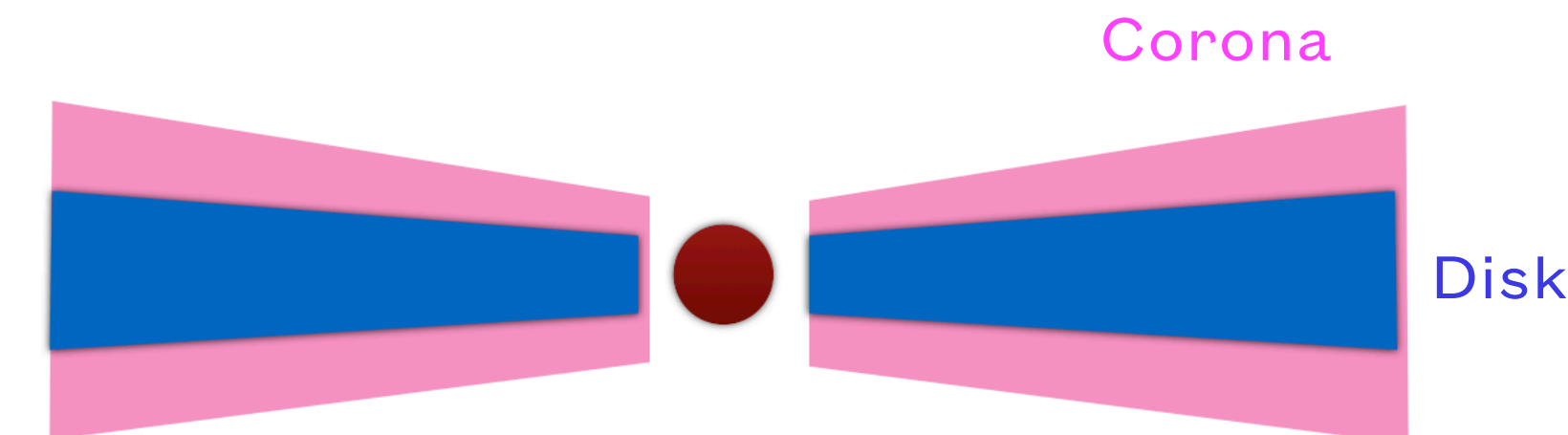
- Another region of the accretion flow is the corona, where the disk evaporates into an **optically thin** cloud of plasma;
- Think of it as a **low density cloud of hot electrons**.
- The geometry of the corona is not established yet, some of the proposed models are:



Spherical model



“Lamppost” model

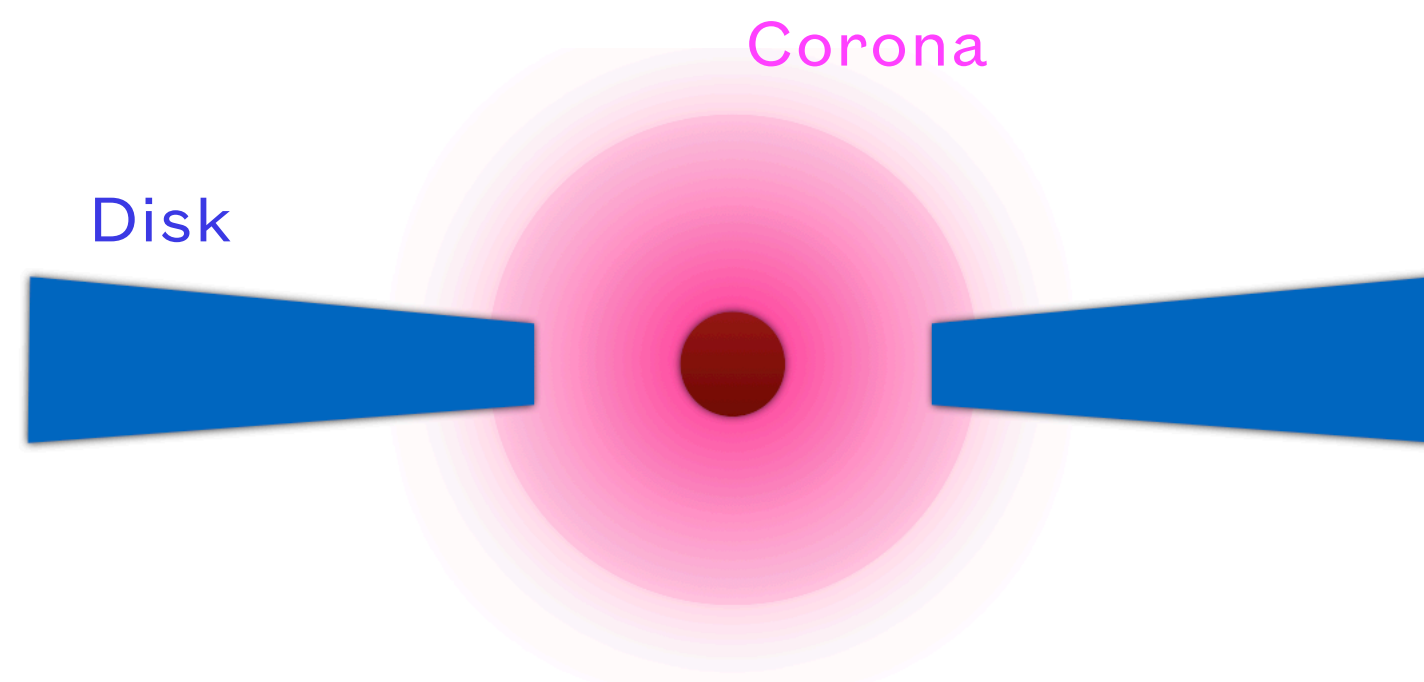


“Slab” model

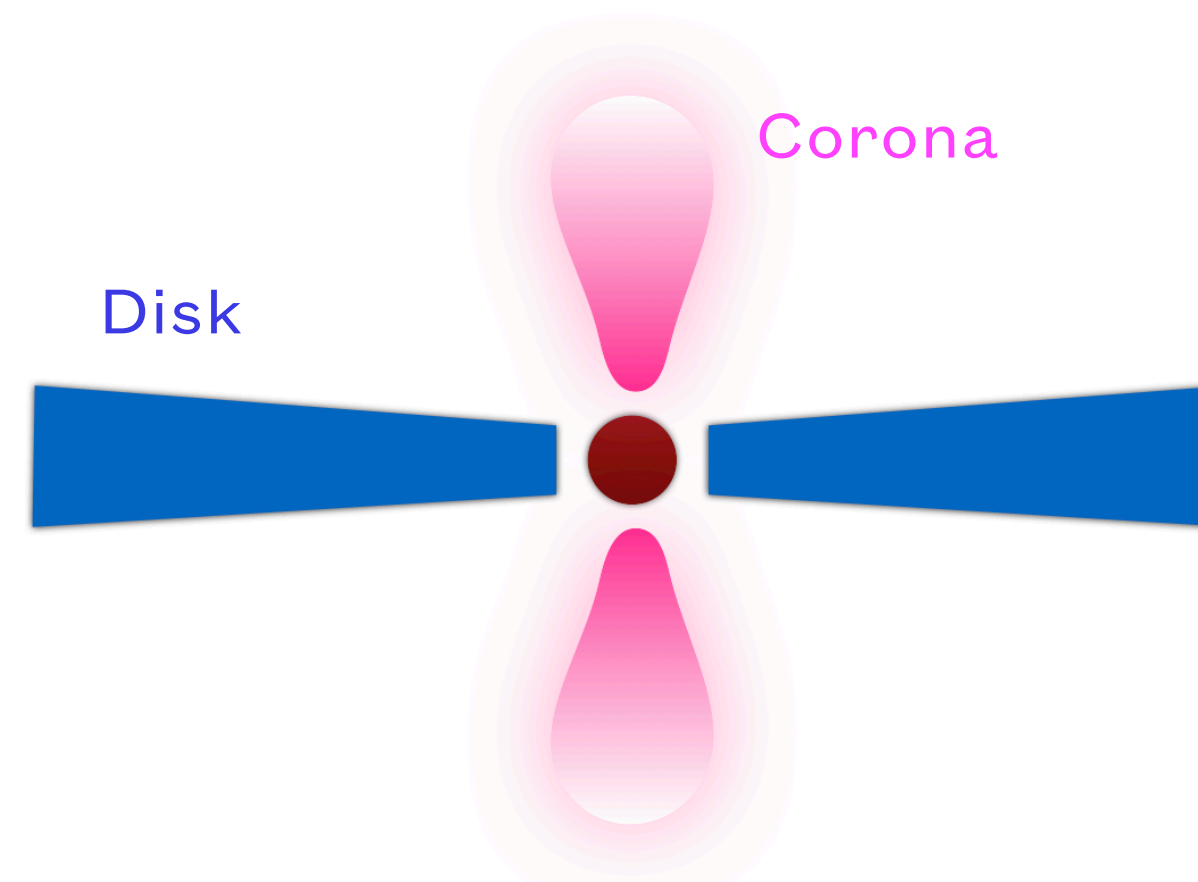


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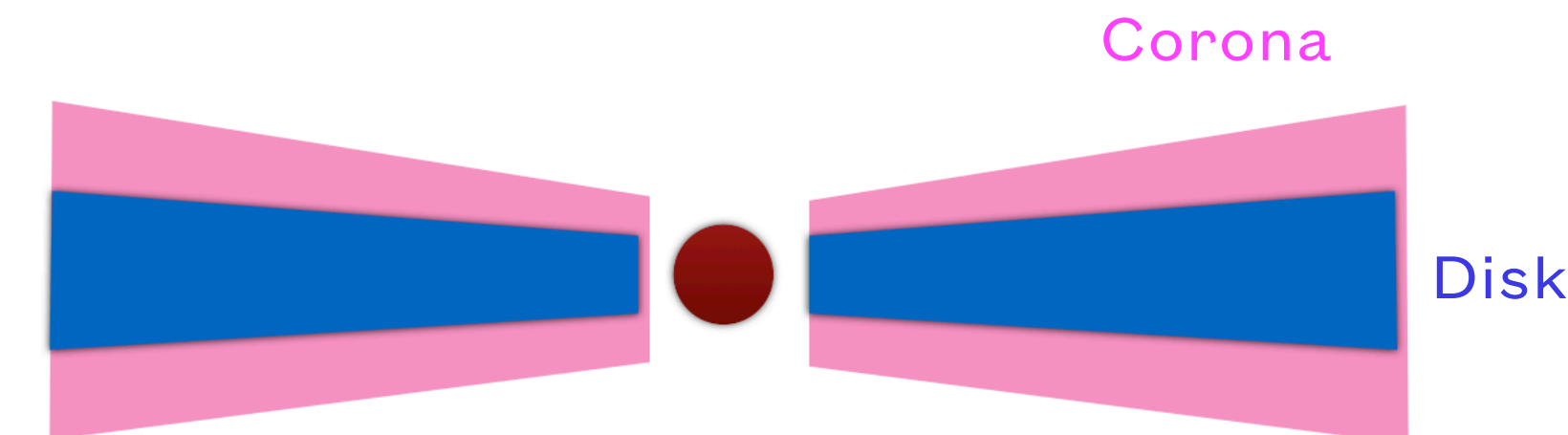
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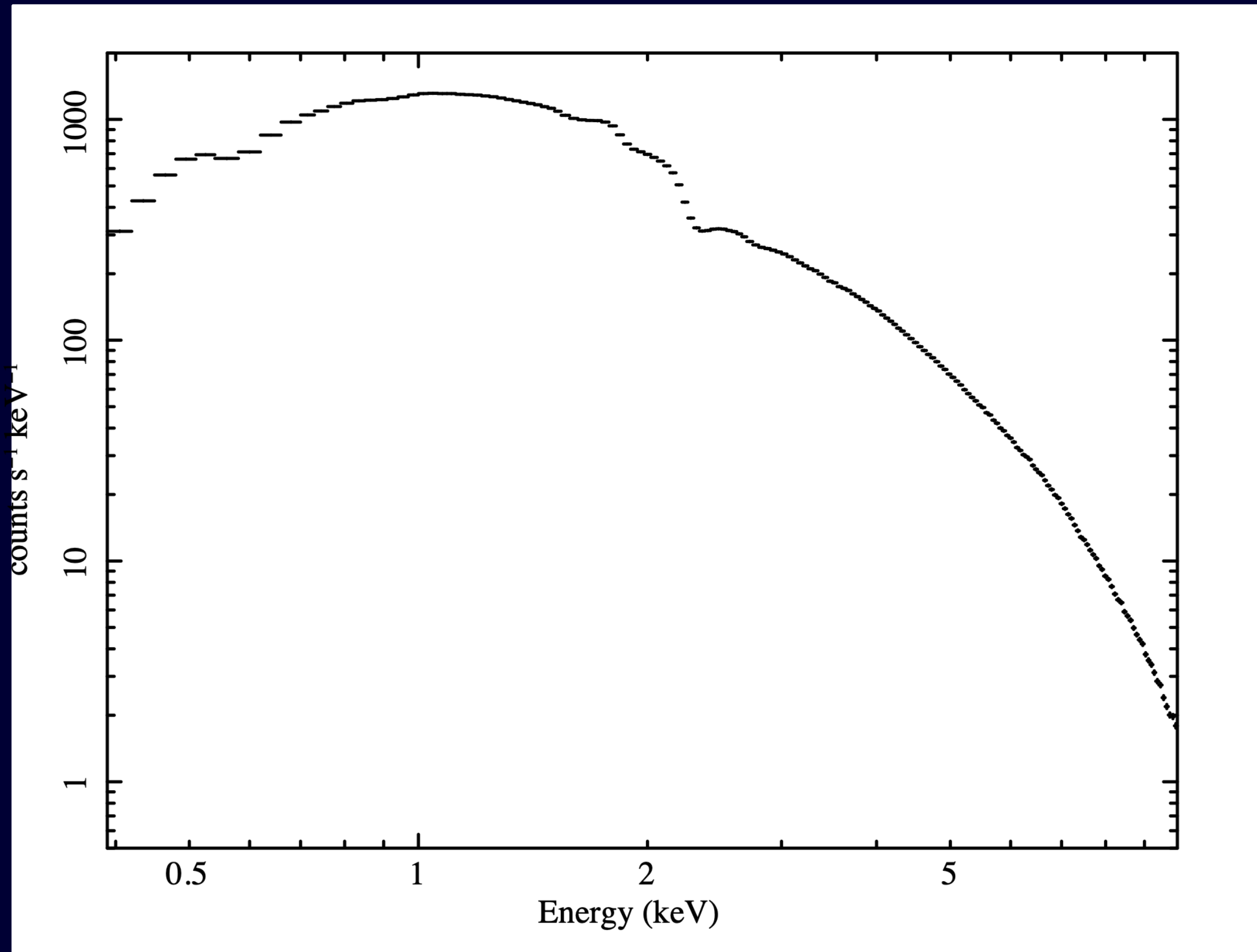
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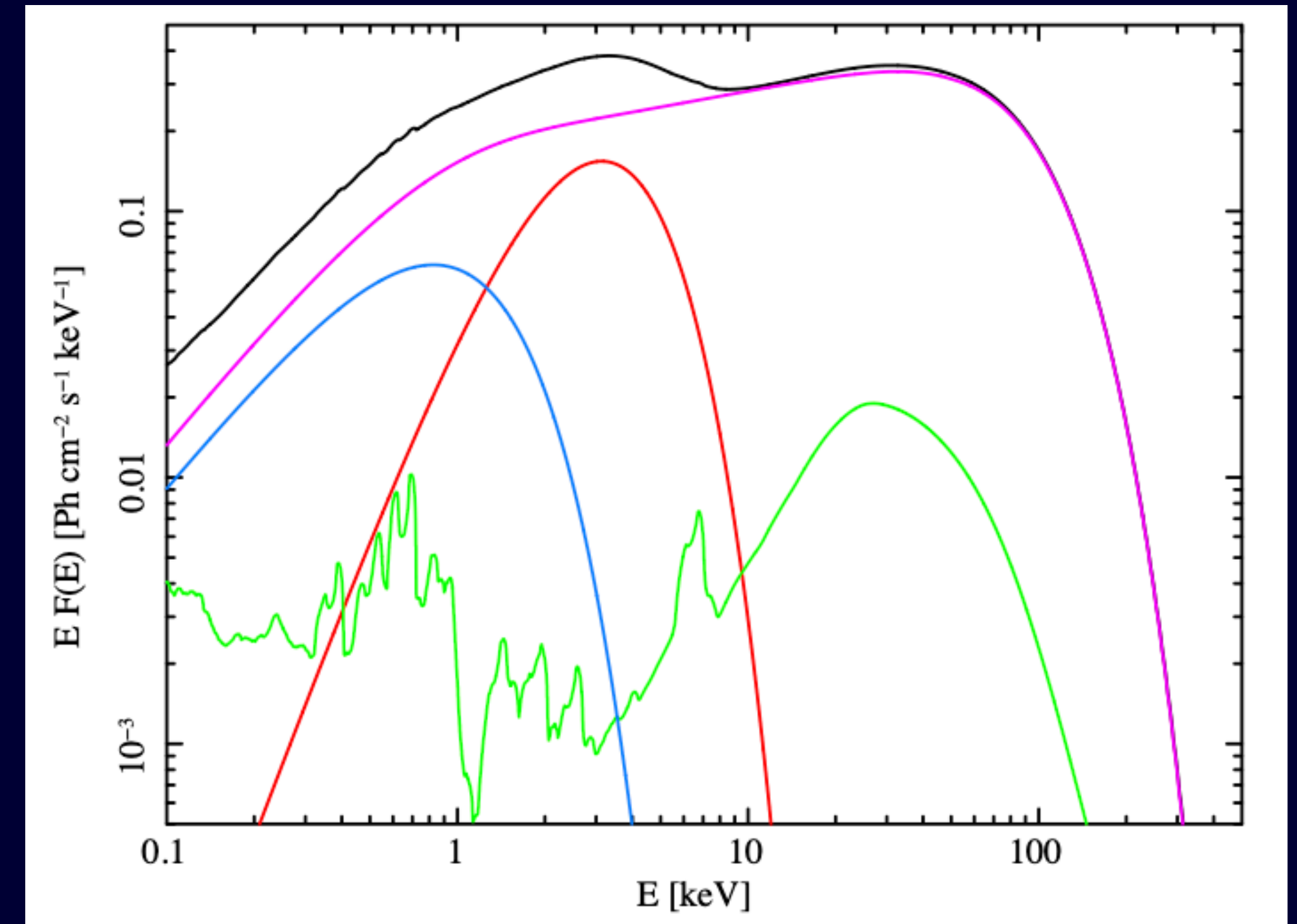
“Slab” model

Spectro-polarimetry helps! See A. Di Marco's lecture!

Inspecting the innermost regions of accretion flows: spectral analysis



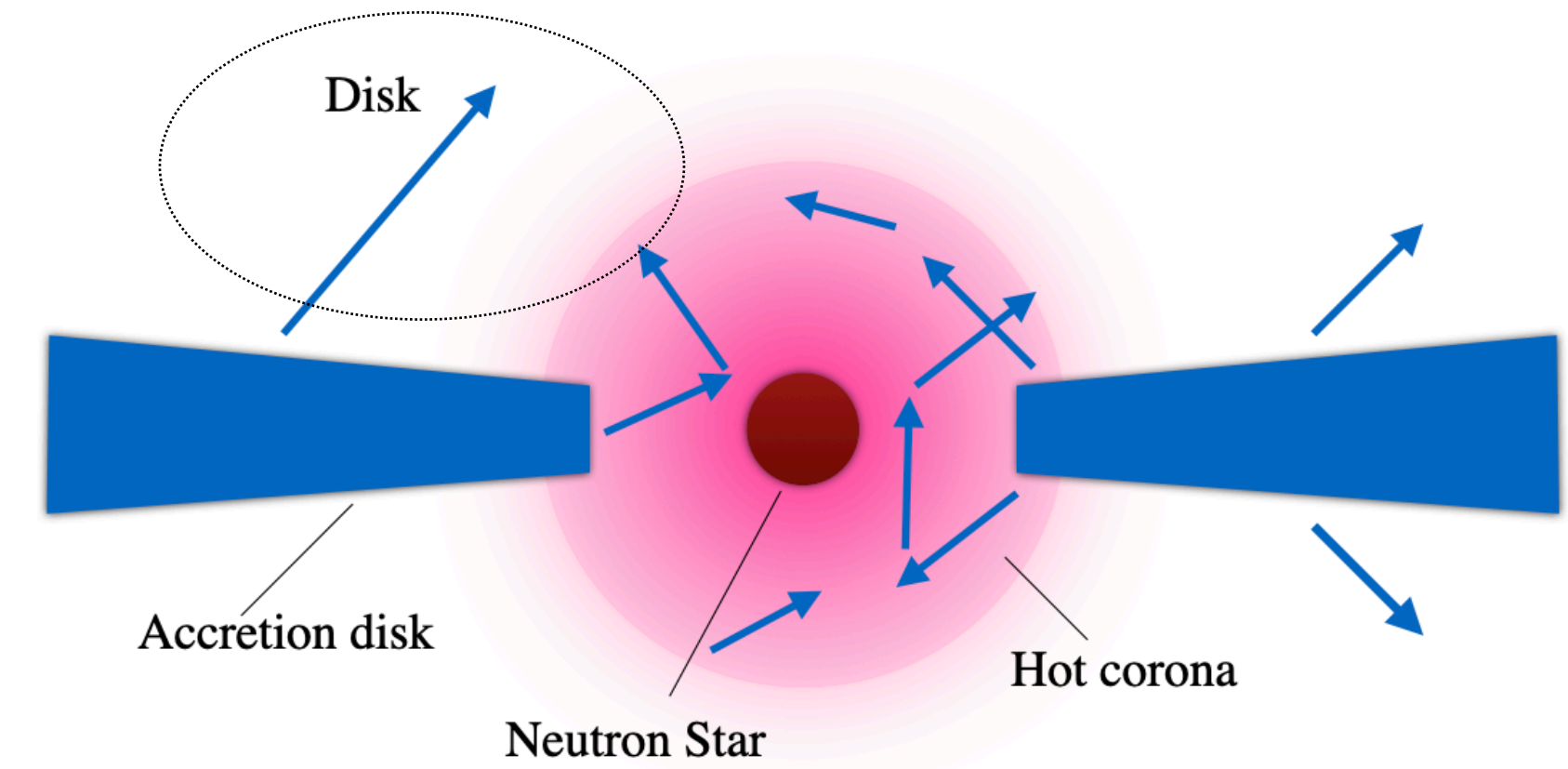
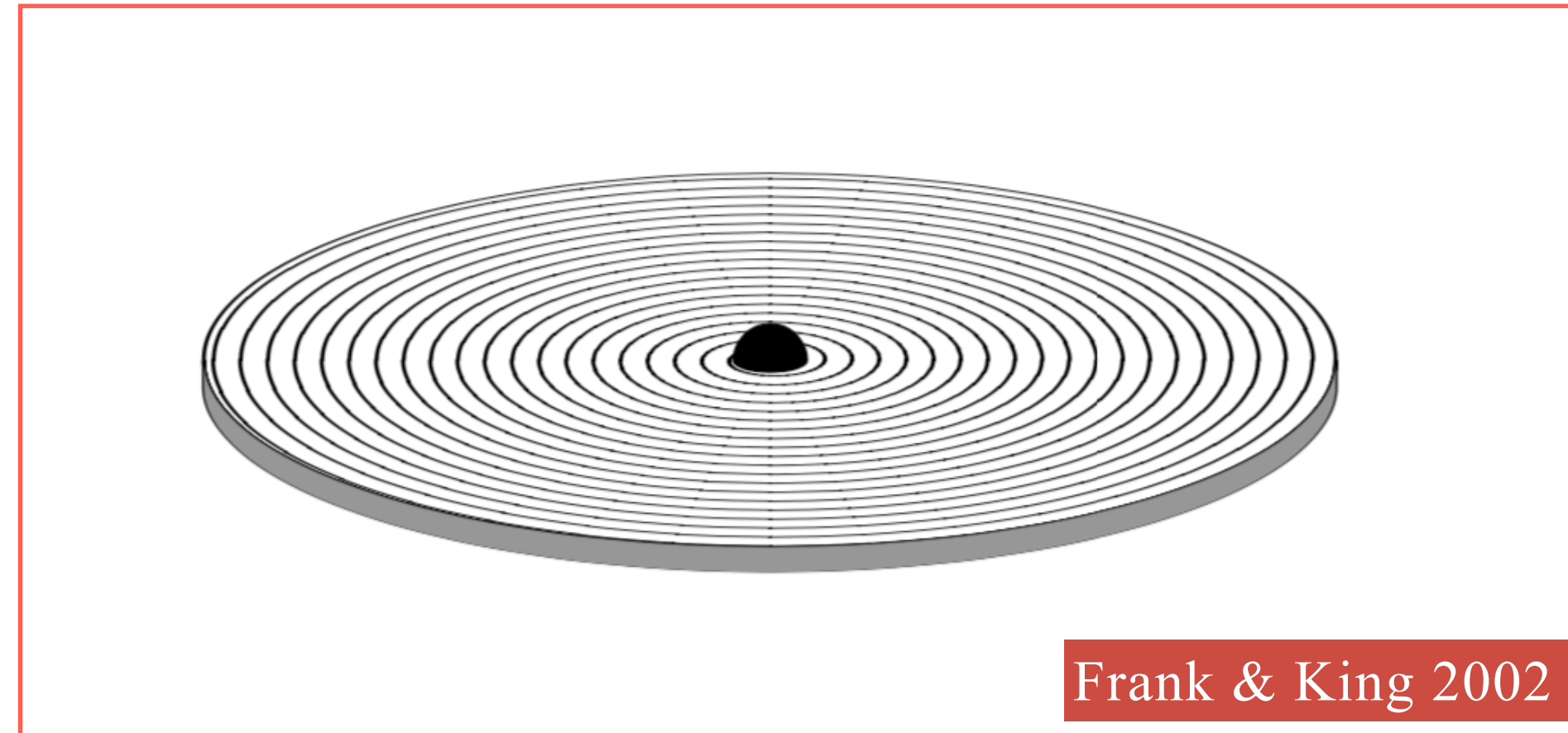
- X-rays energy spectrum of a NS LMXB (*NICER* data)



- Best-fit model for an ideal spectrum: **4** main ingredients

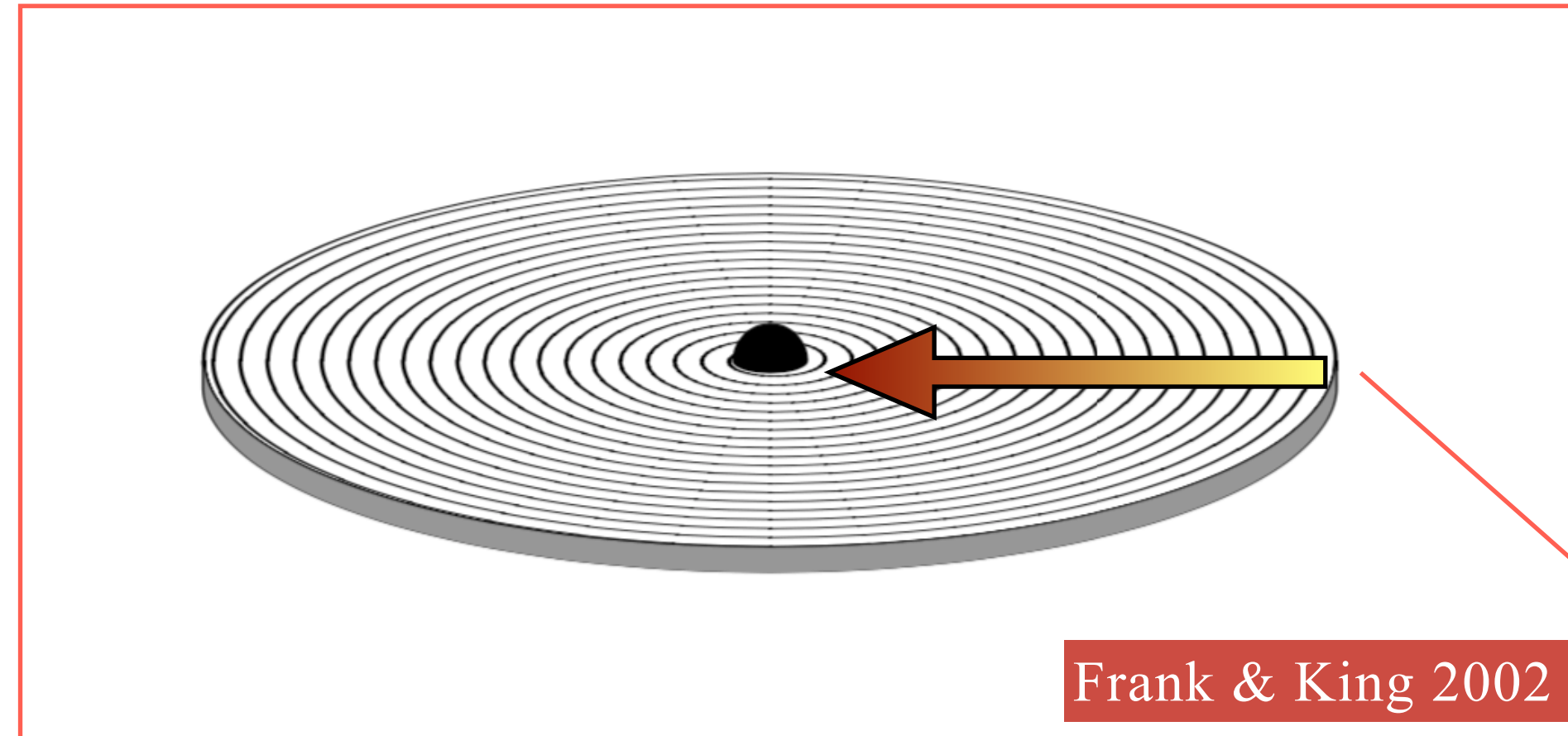
Accretion disks: multi-color disk blackbody

- Consider the disk as made of rings, where each ring emits as a blackbody;

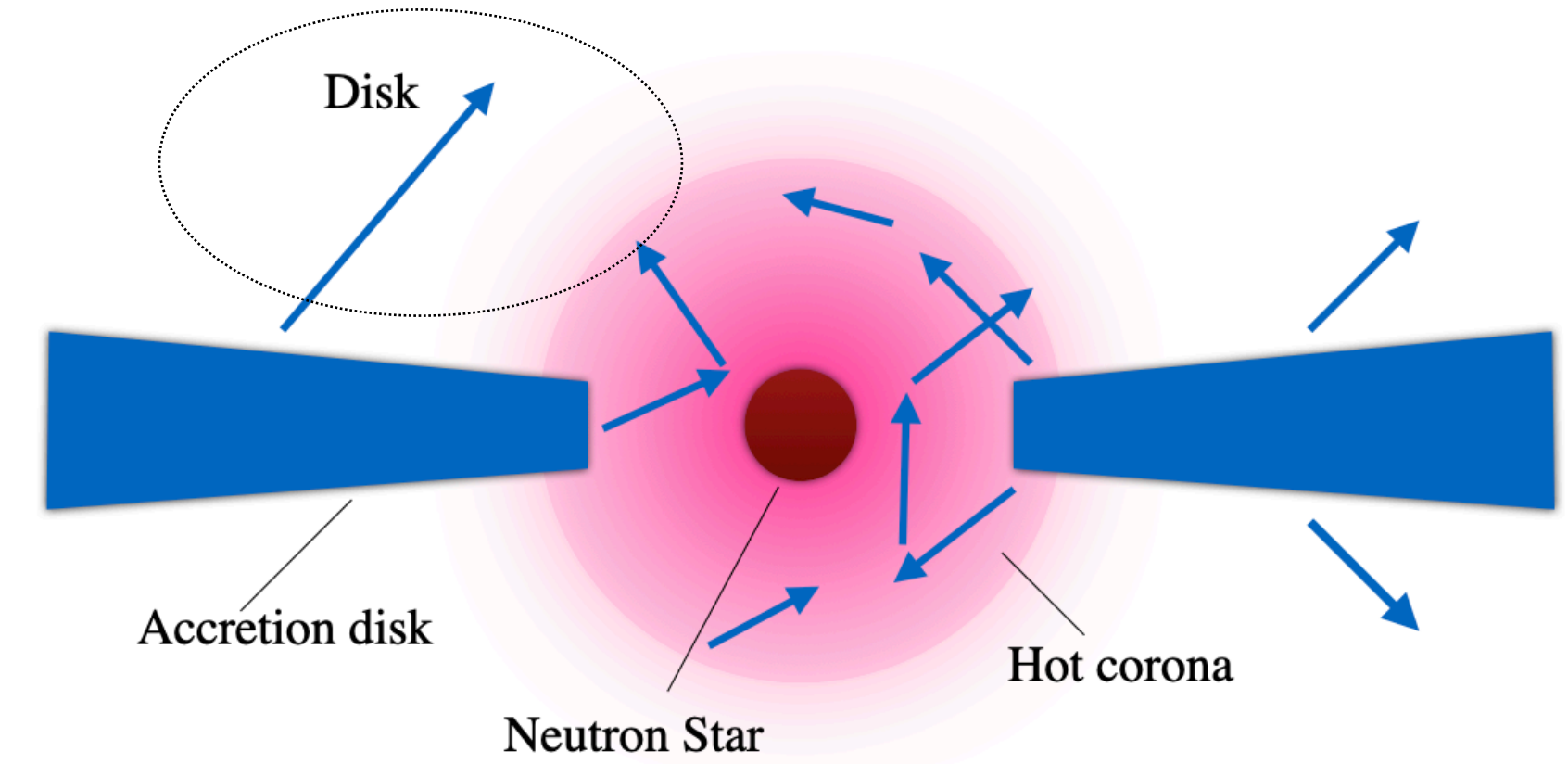


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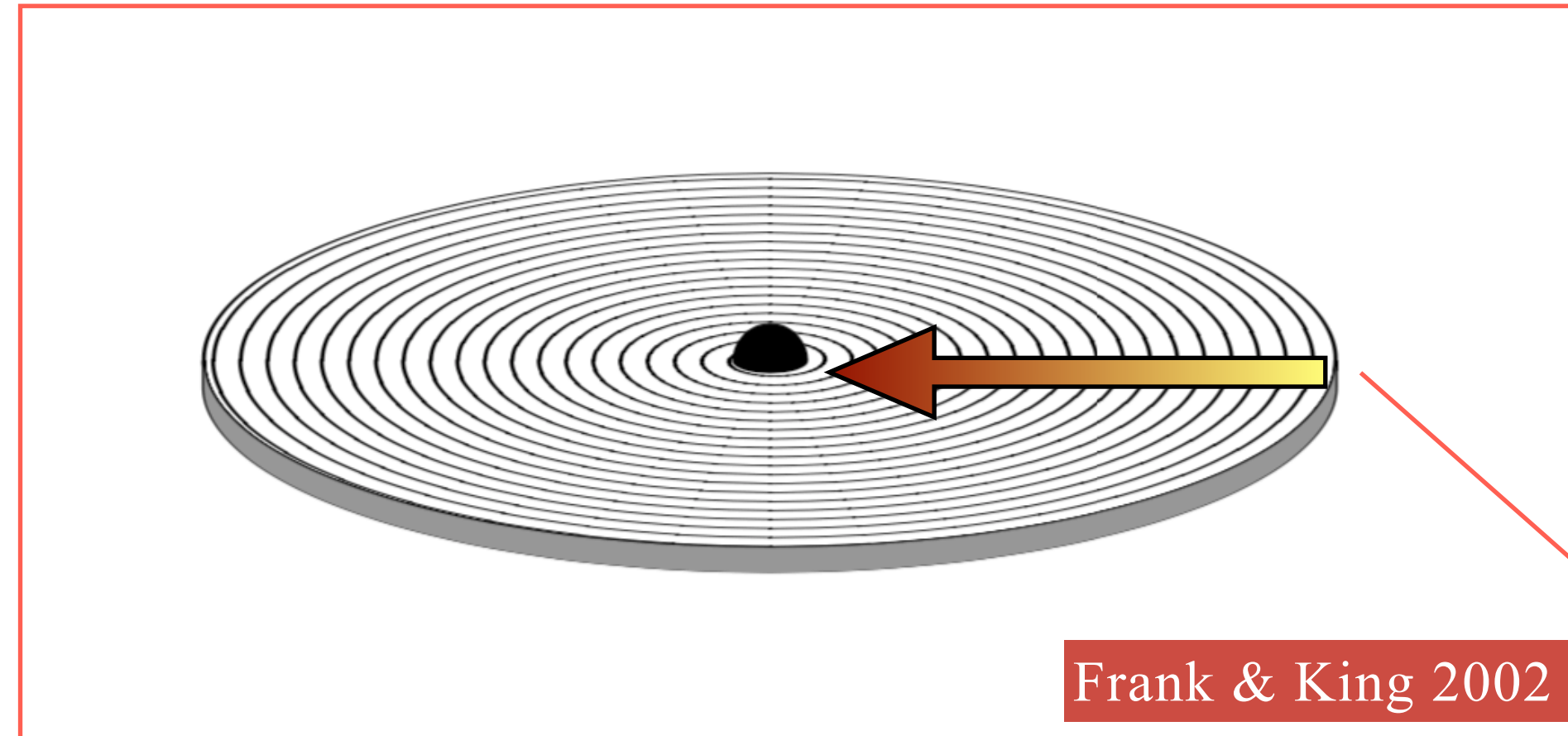


- Temperature $T(R)$ decrease as $R^{-3/4}$;

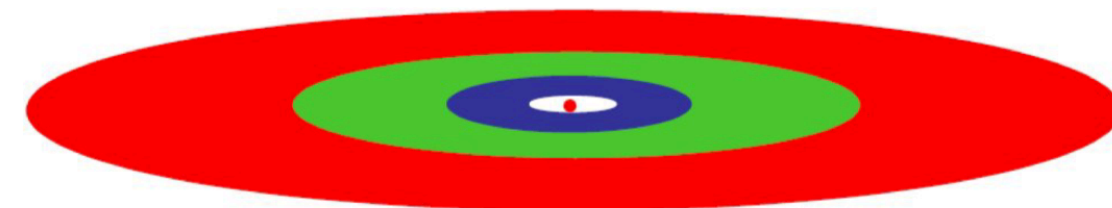
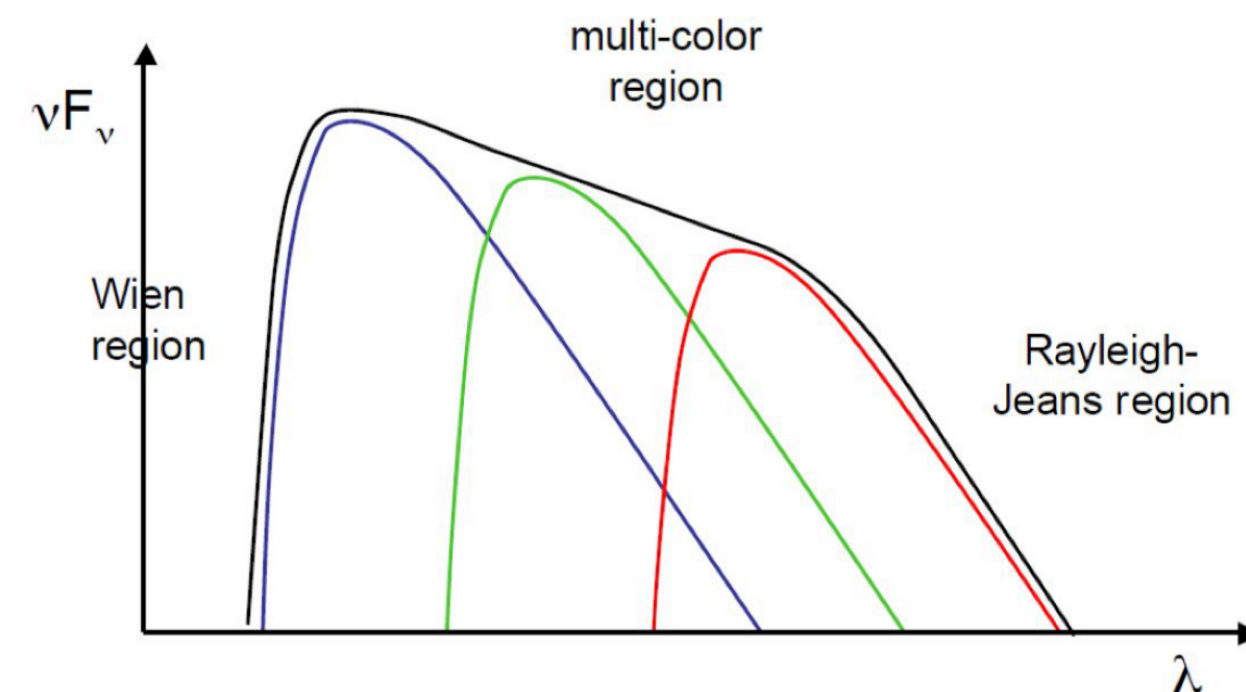
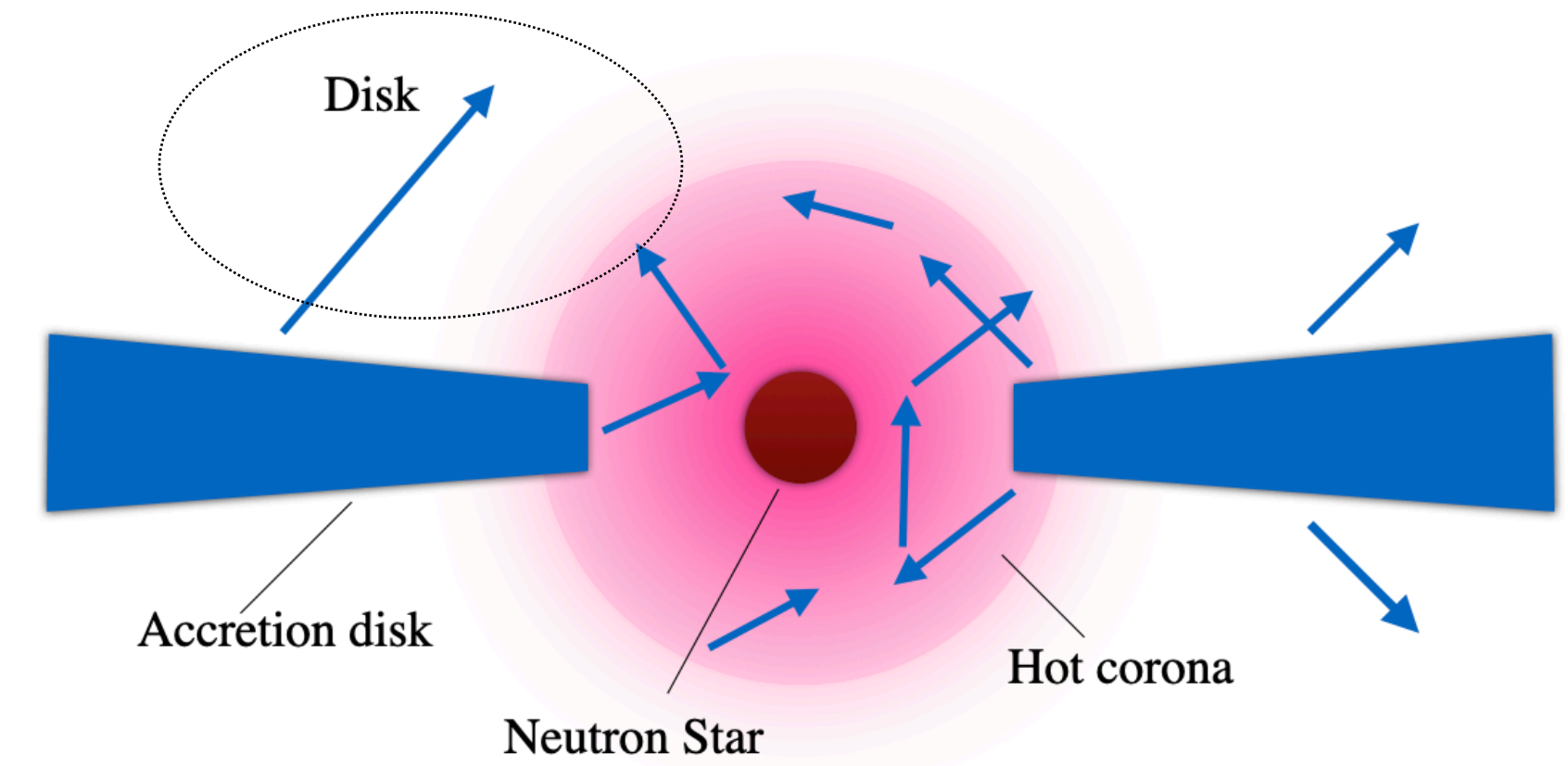


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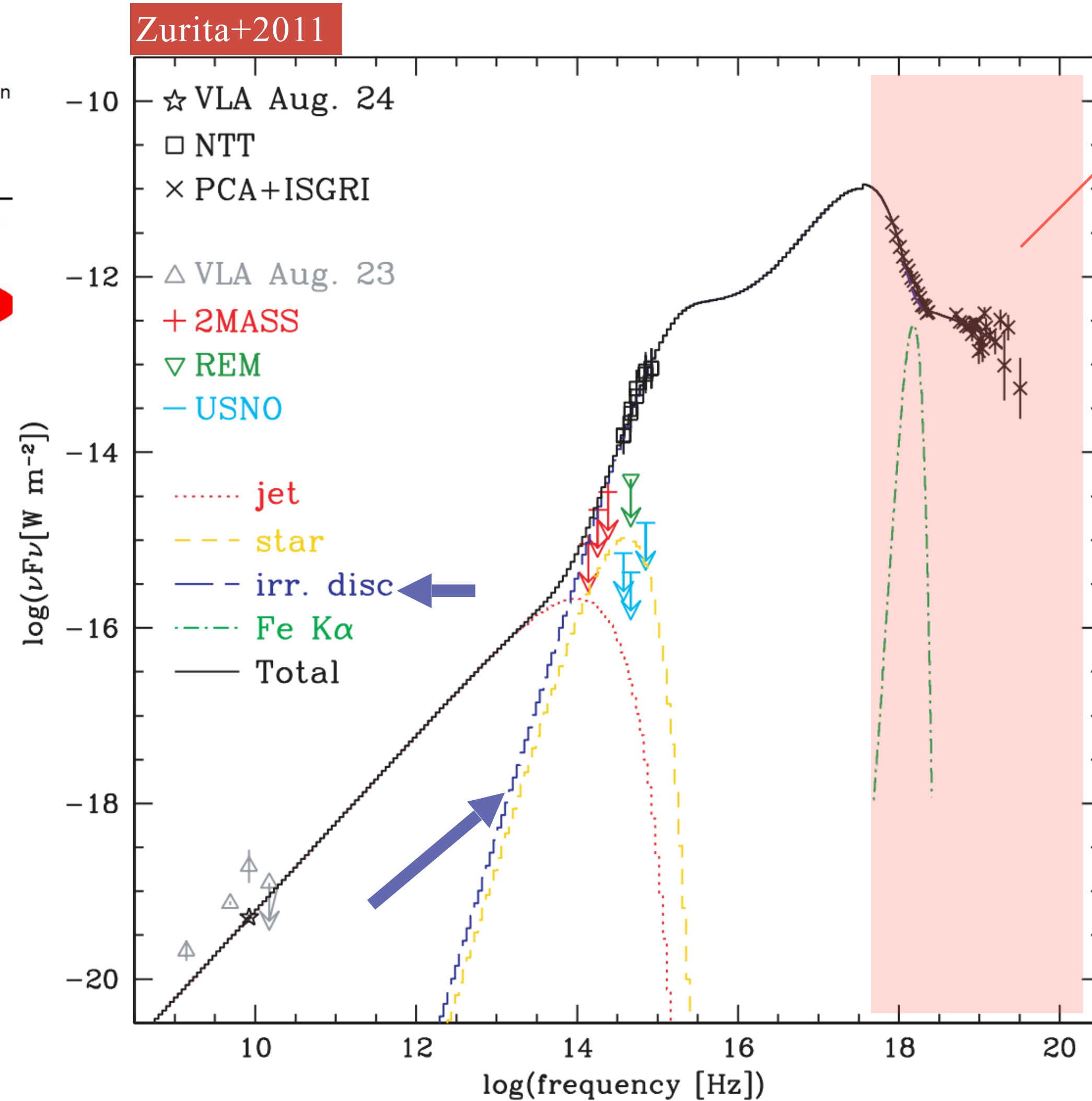
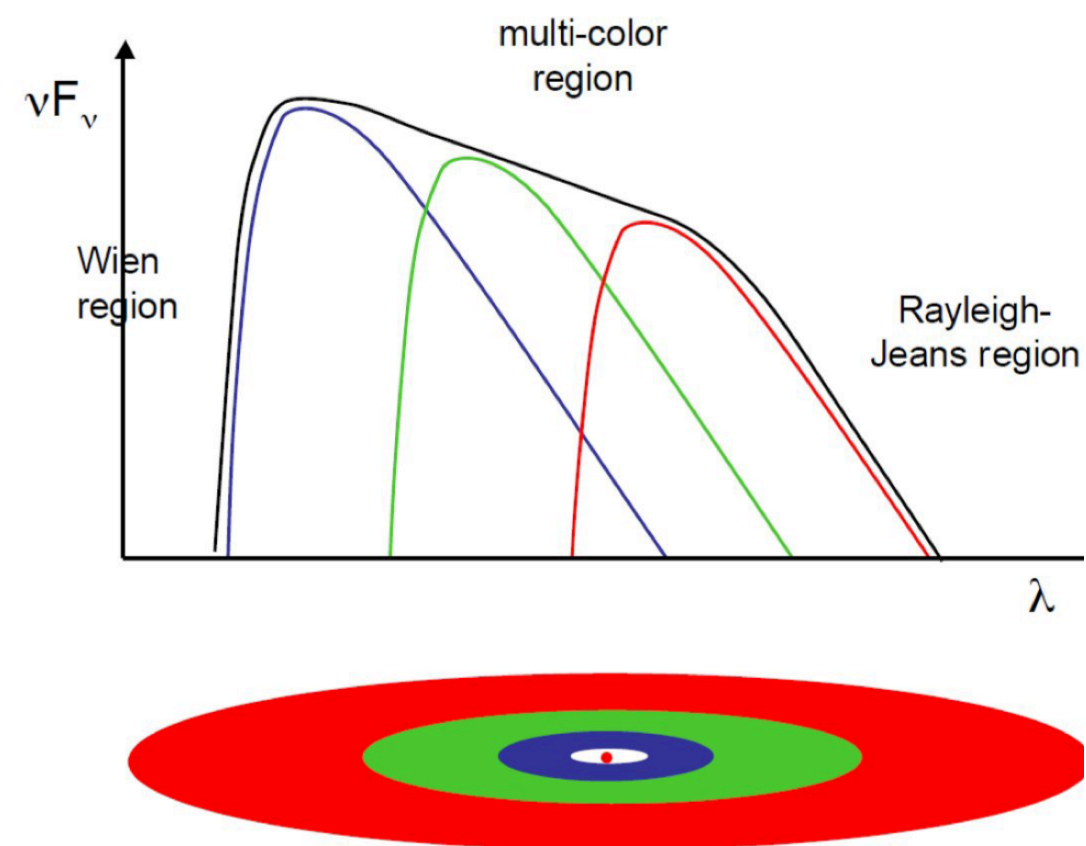
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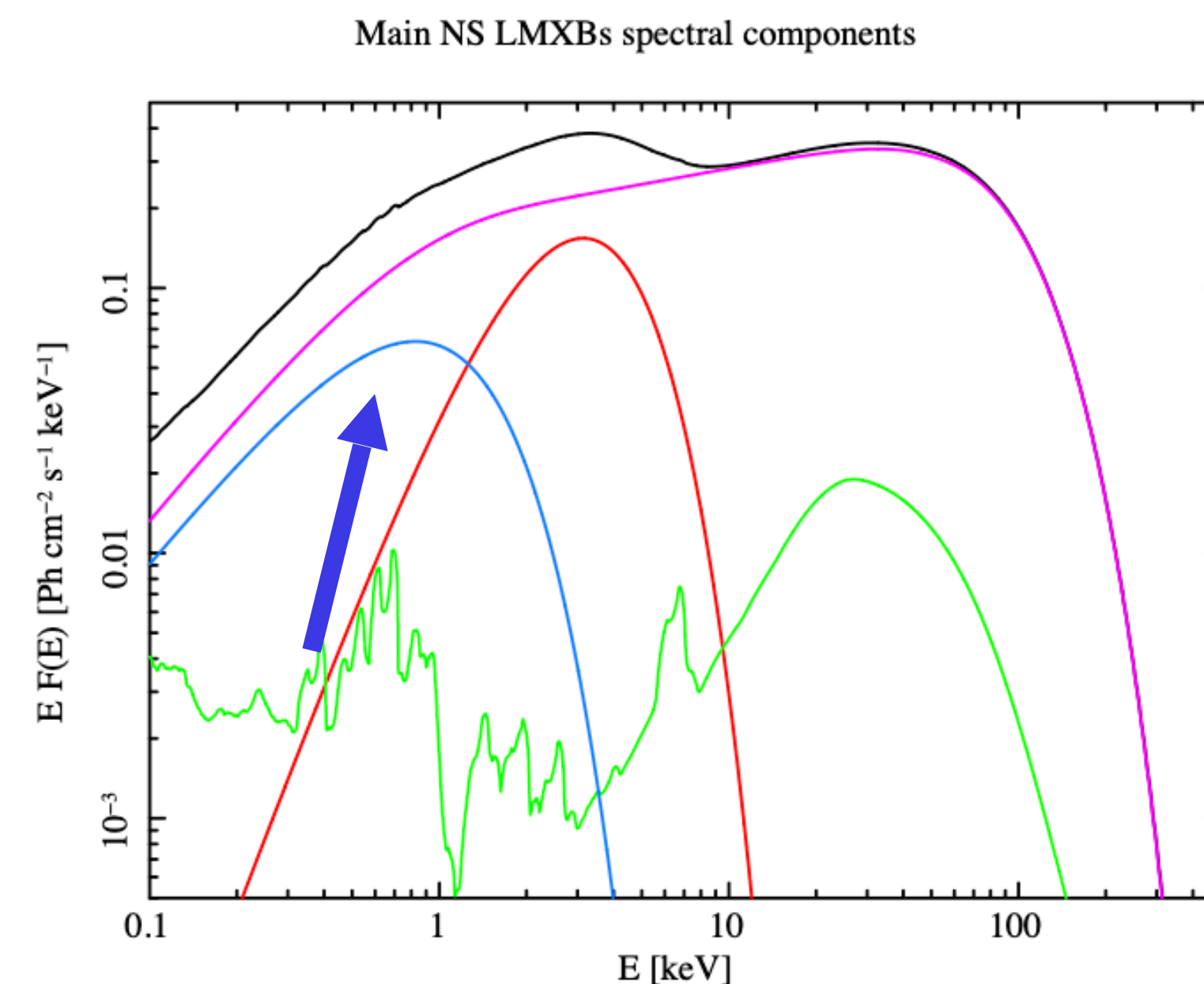
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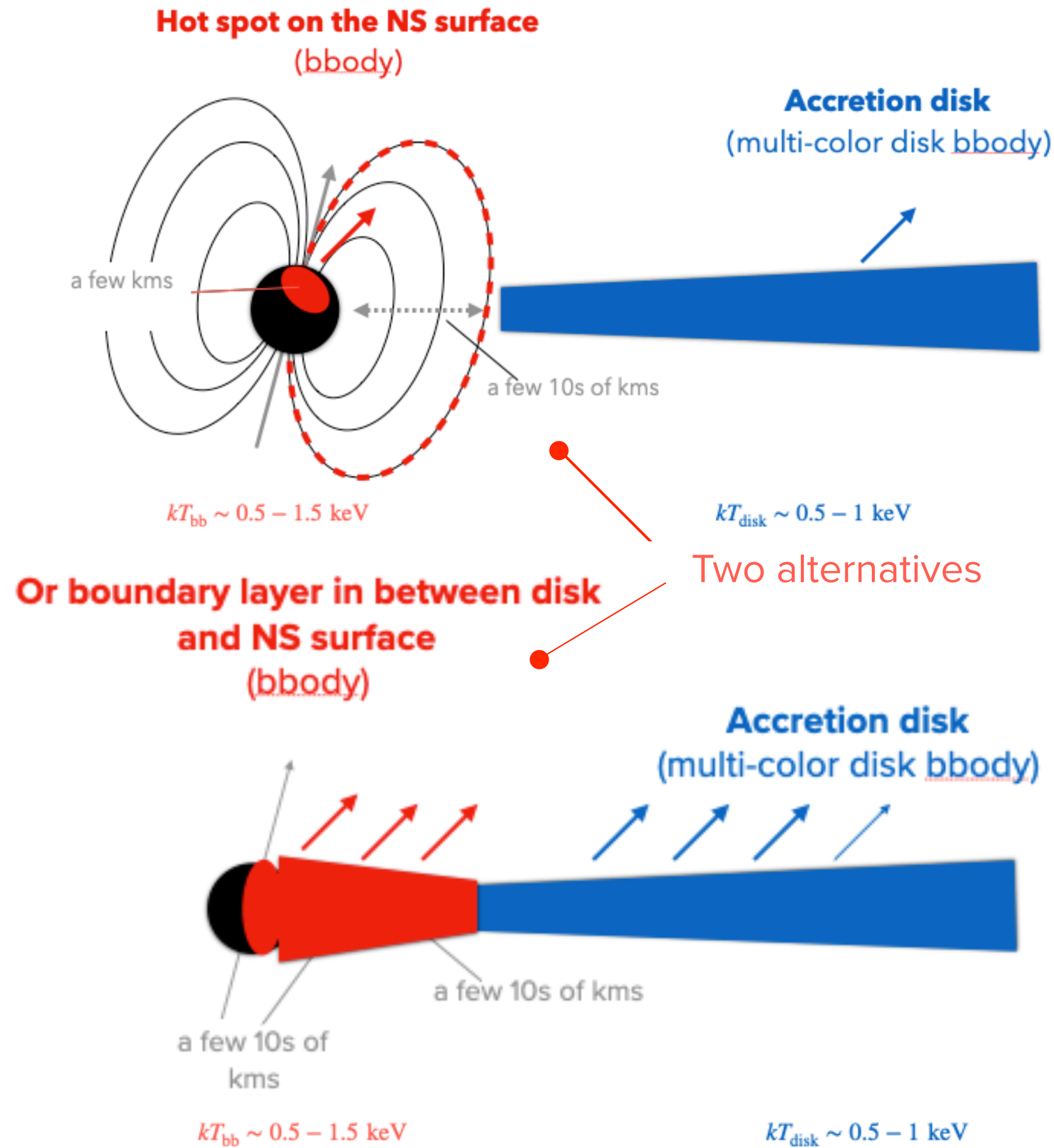
- The superposition of all of these single blackbody spectra is a **multi-color disk blackbody**, which is similar to a blackbody but with a “flatter top”.



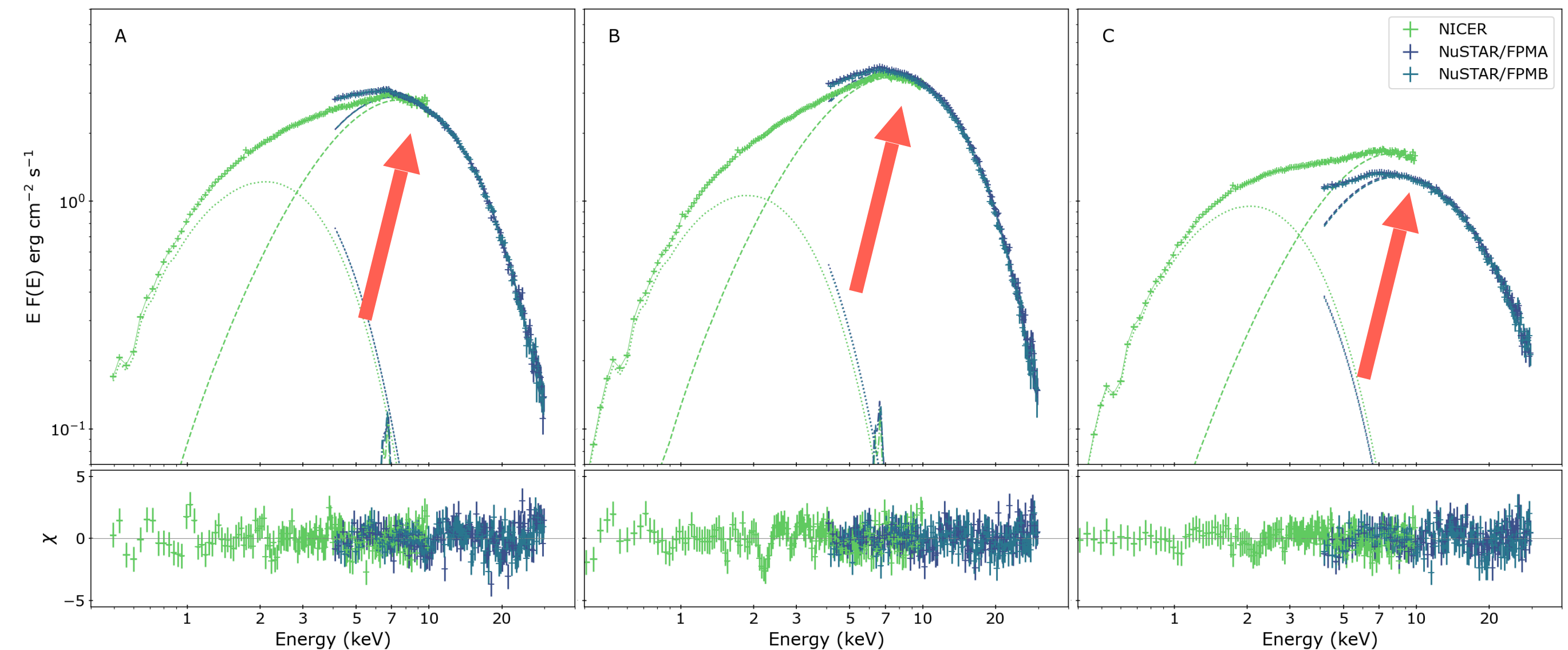
• In the X-rays we only see the inner (hotter) part of the disk (typical temperatures: 0.1-1 keV);



Accretion disks: multi-color disk blackbody

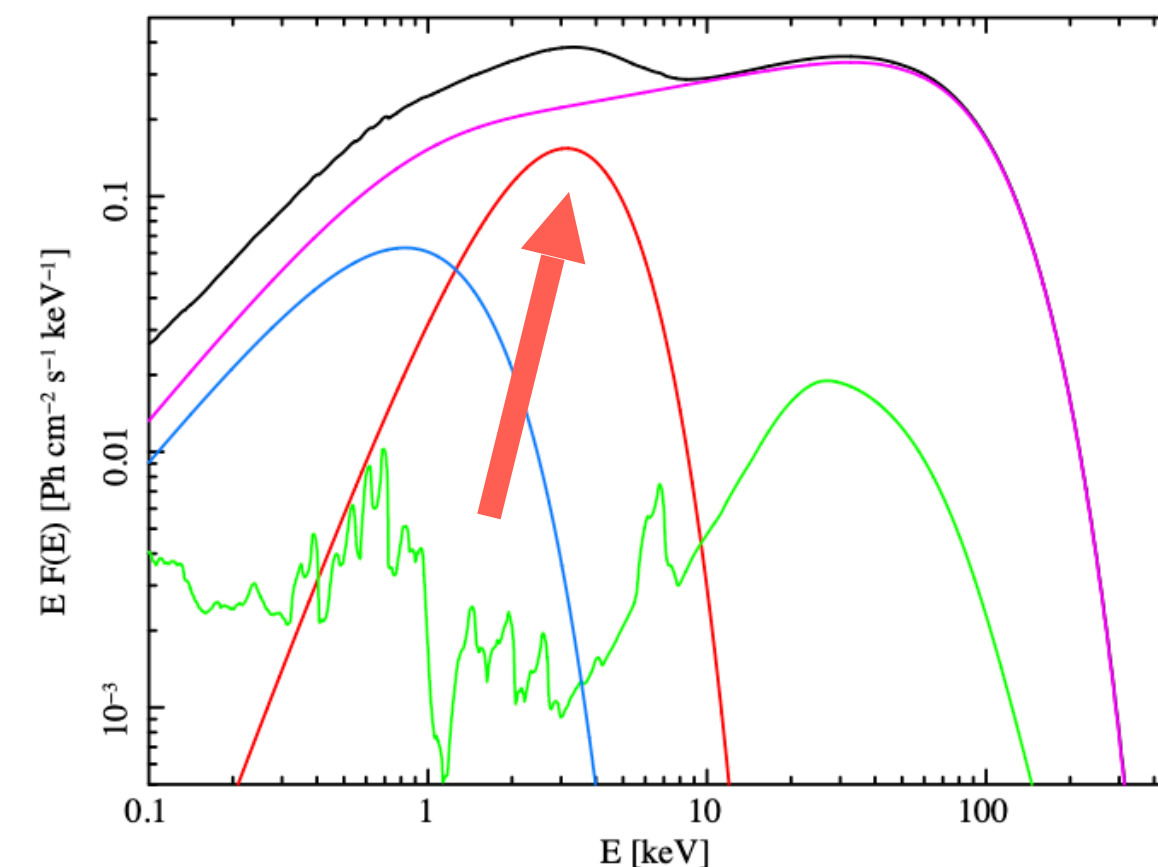


- An additional blackbody is sometimes found in accreting NSs, which depending on the physical size can be attributed to the hot spot or to the spreading / boundary layer;



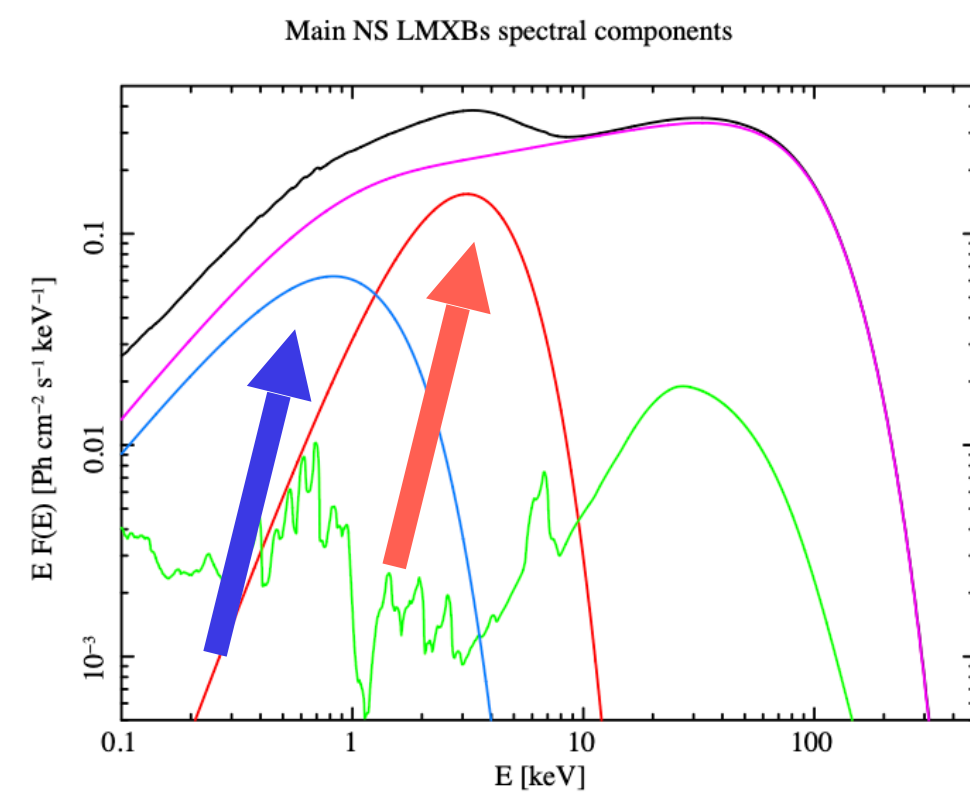
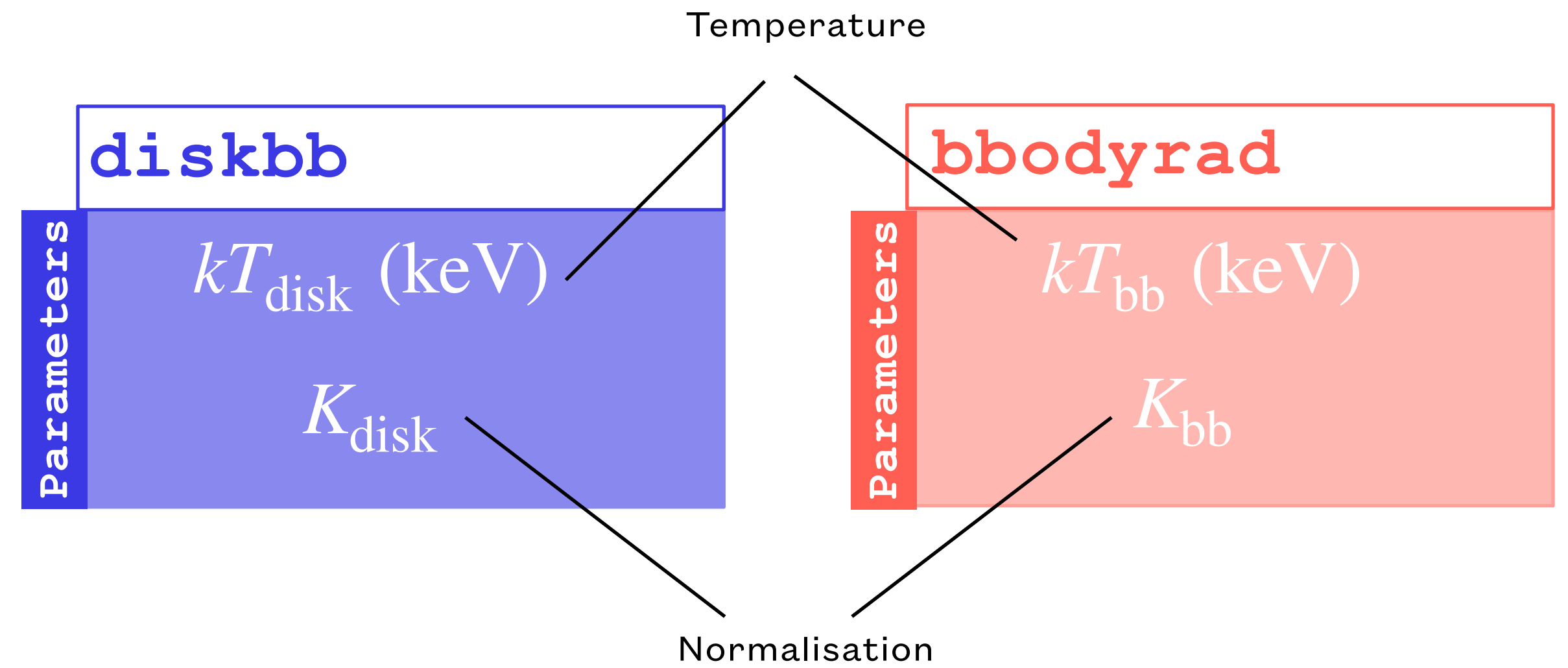
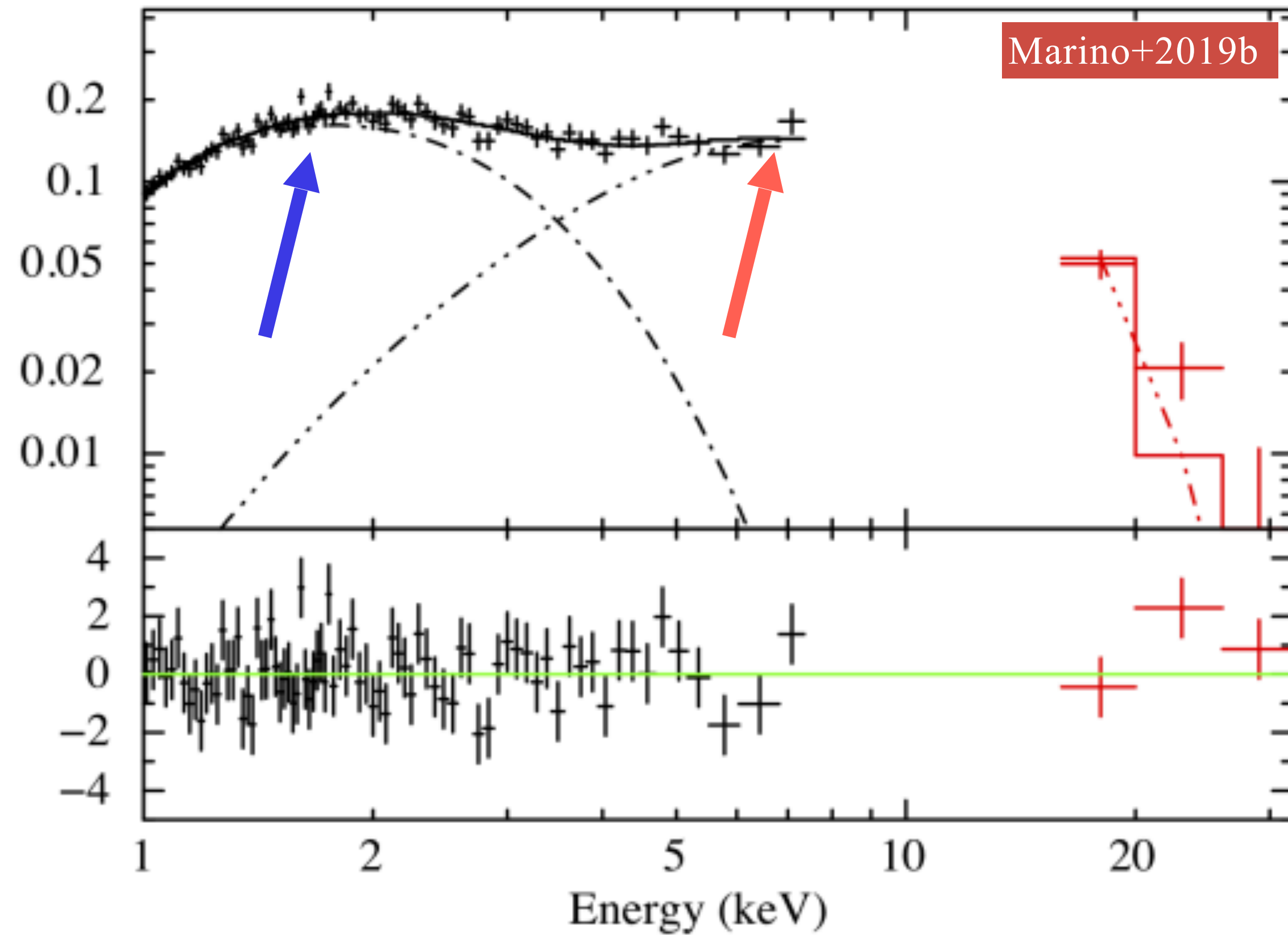
Marino+2023

Main NS LMXBs spectral components

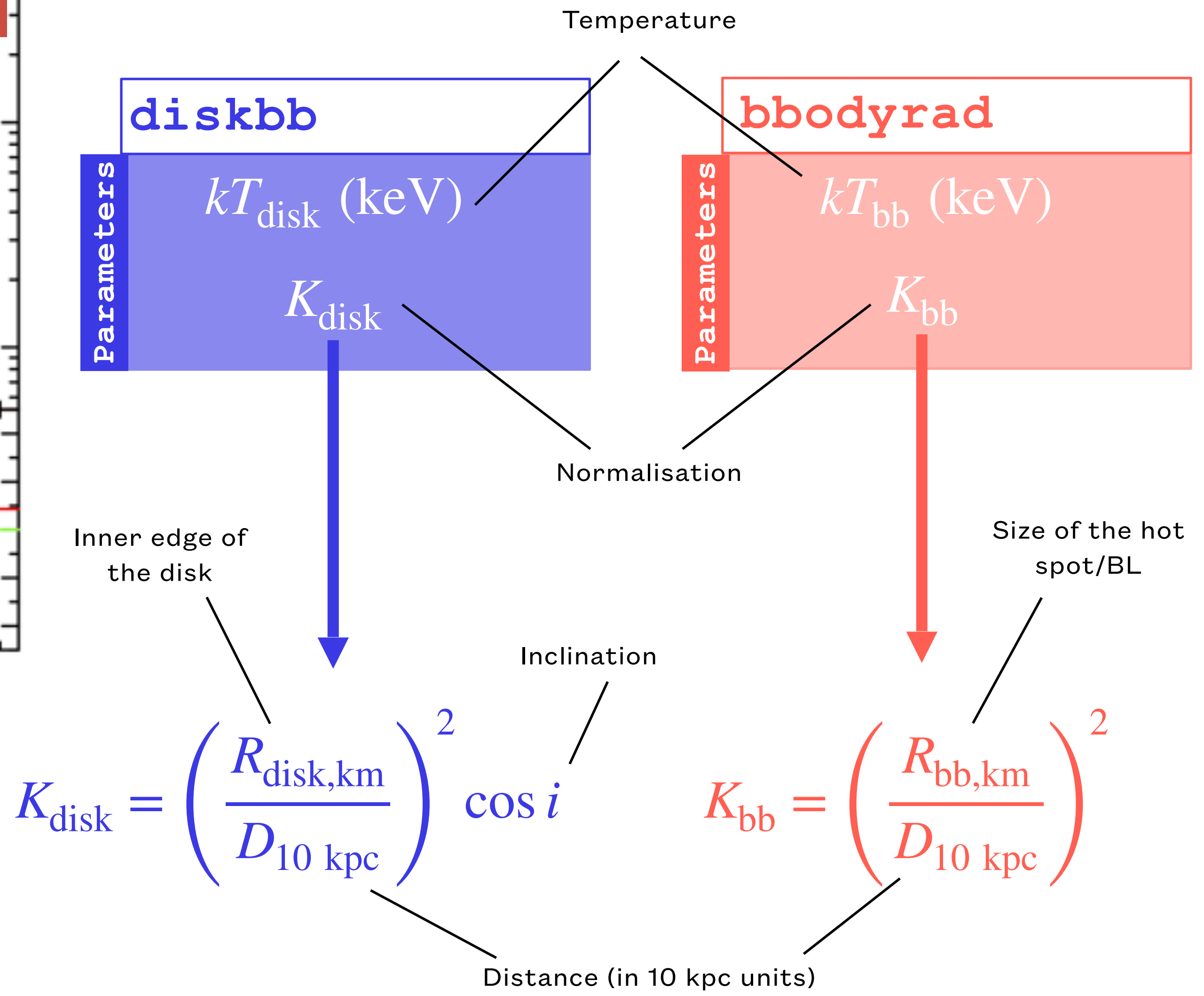
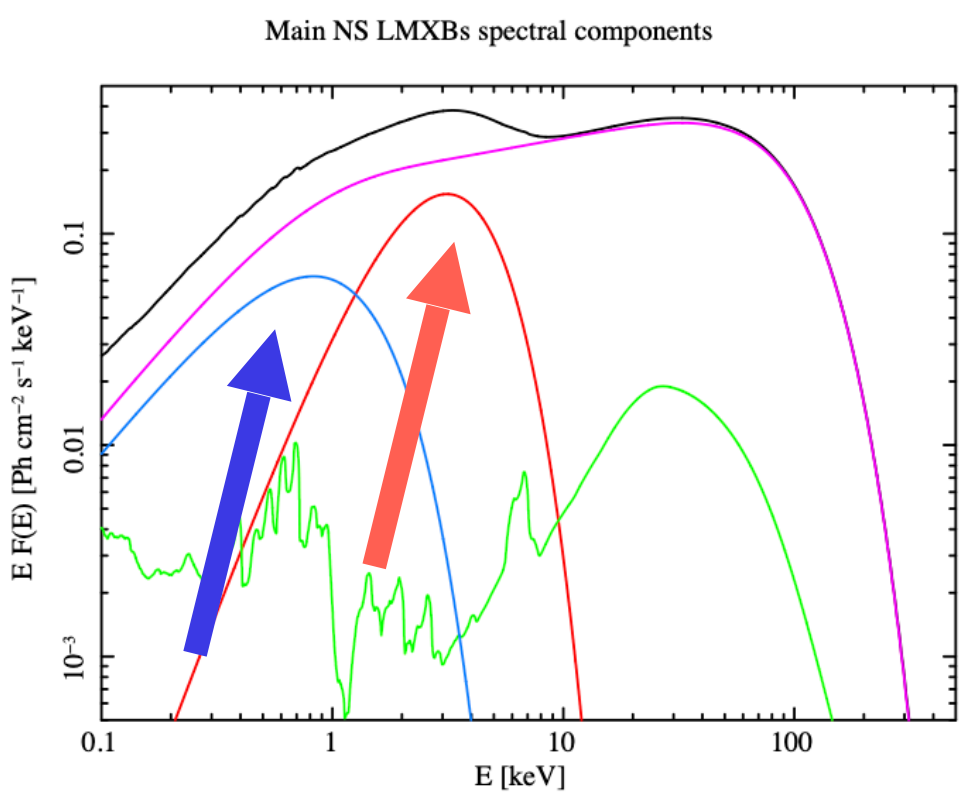
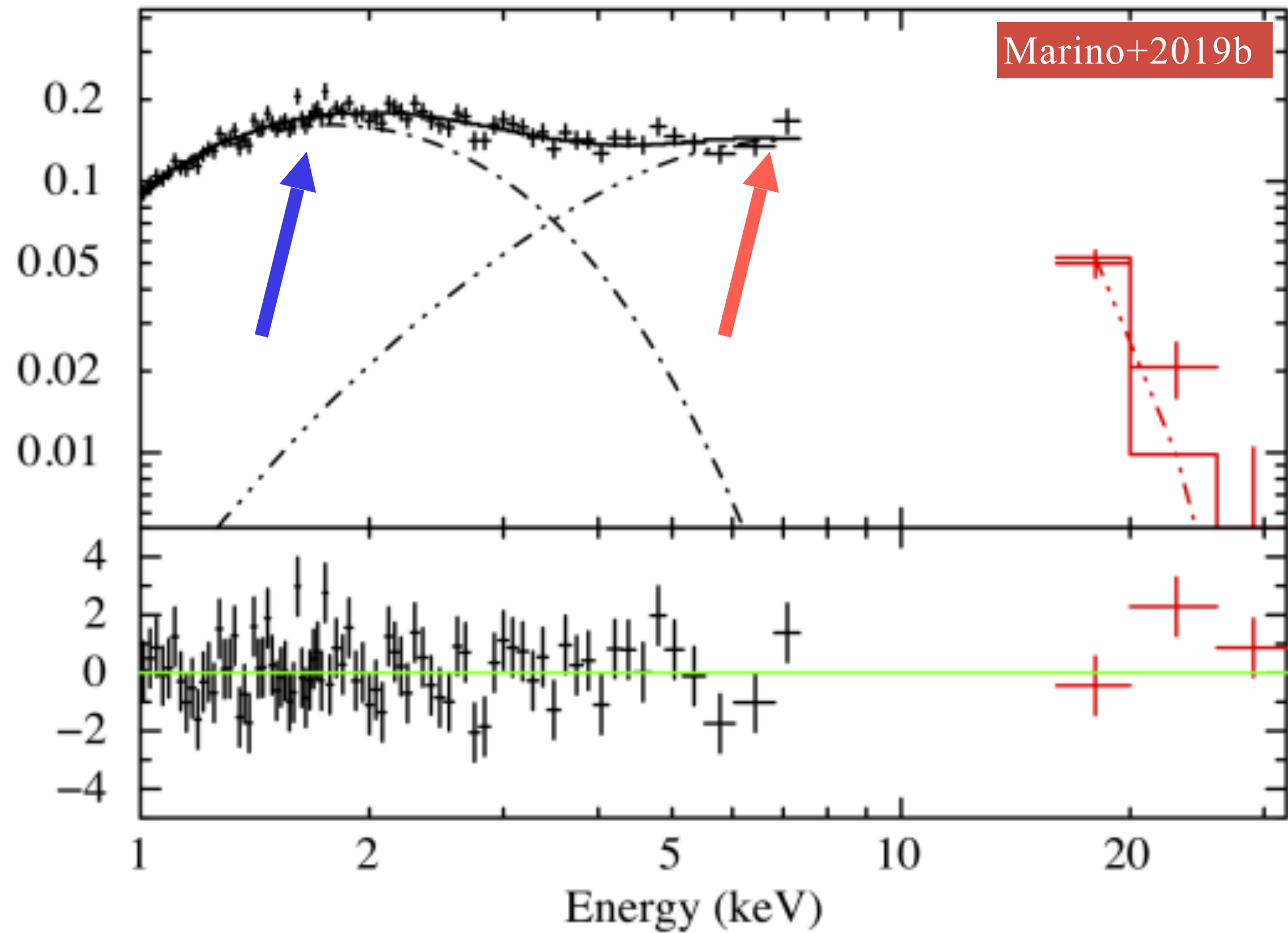


Emission from hot spots and boundary layers (NSs only!)

Simple blackbody / disk blackbody models



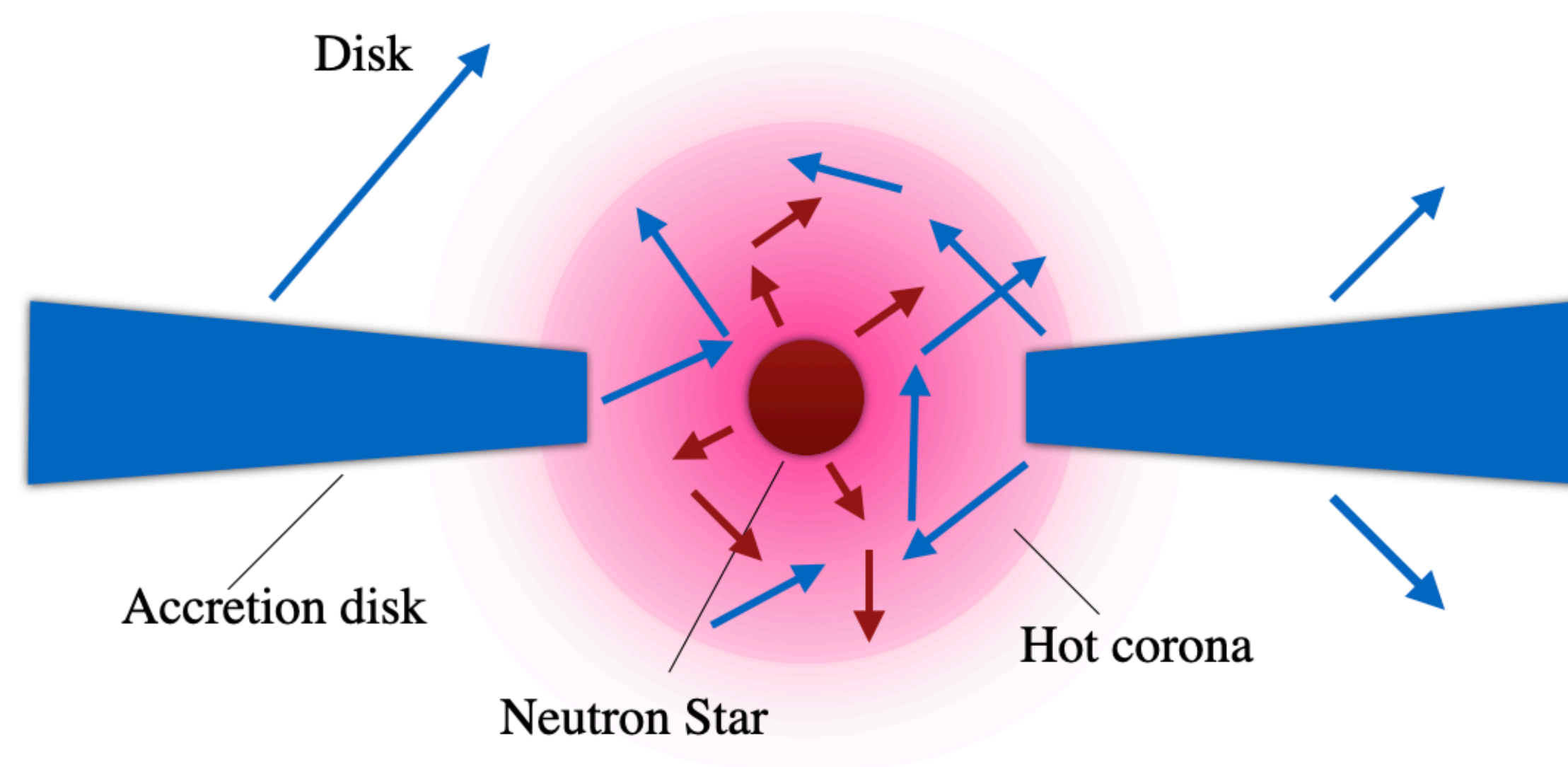
Simple blackbody / disk blackbody models



- The normalisation provides pieces of information on the physical size of the emitting region

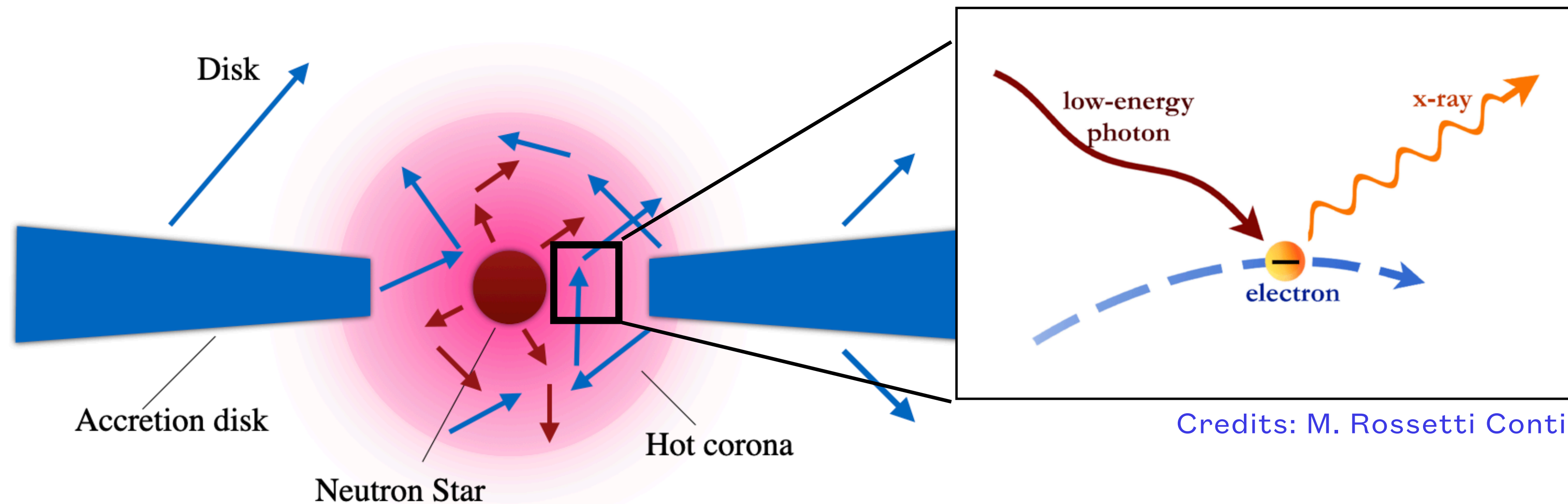
Electron-photon interactions in the hot corona

- Inside the corona, the photons from the disk (and/or from the NS if we have a NS) interact with the electrons. How do they interact?

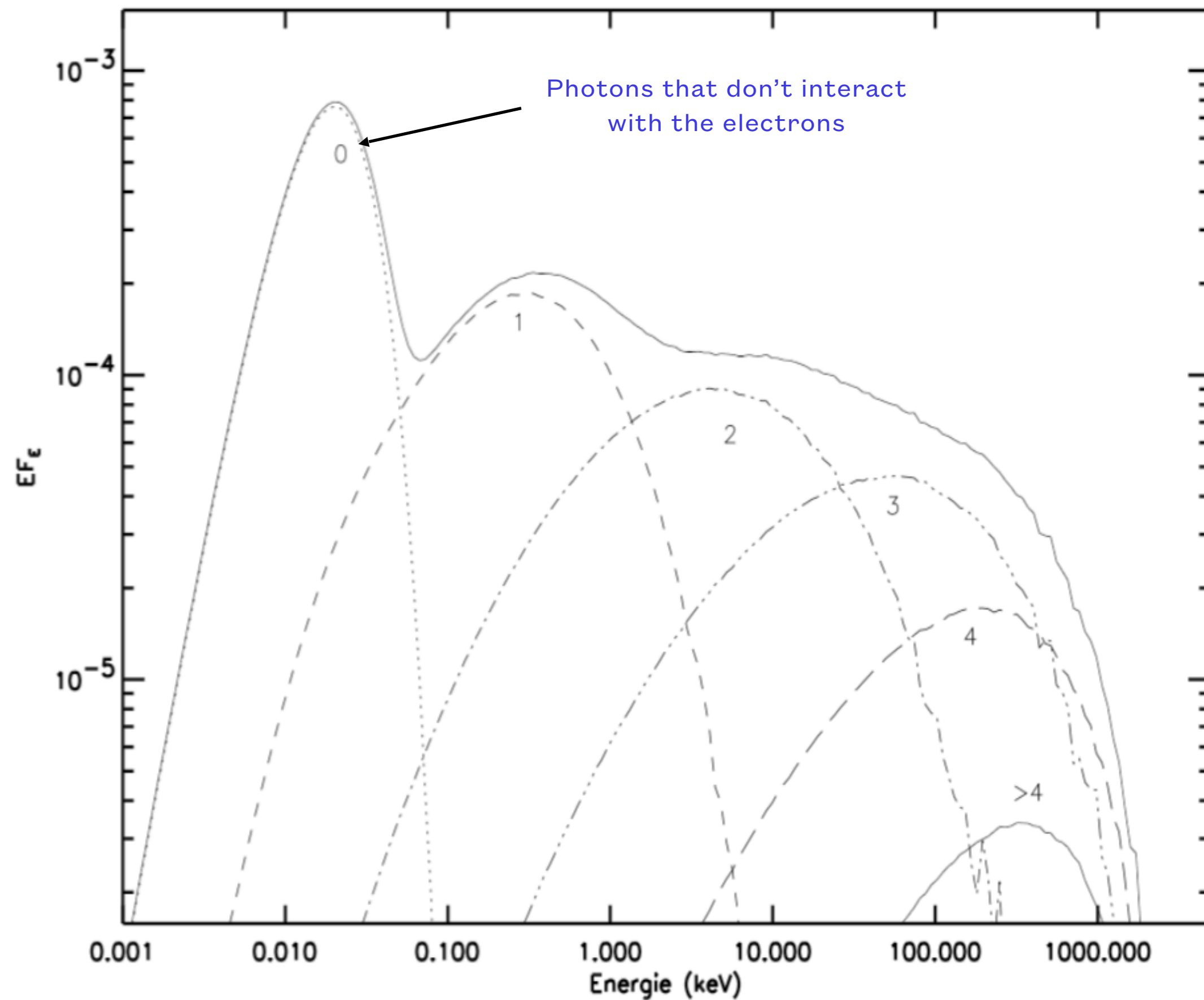


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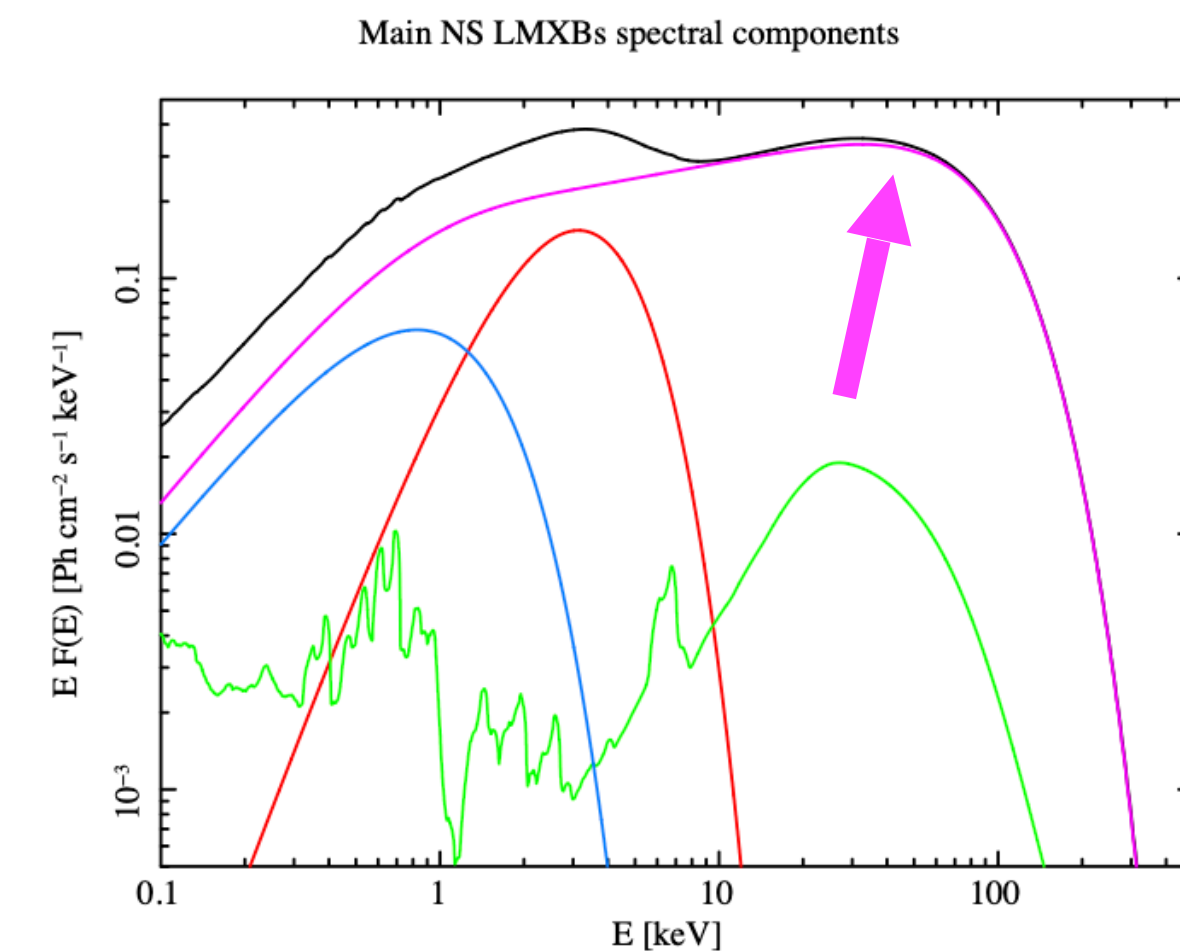
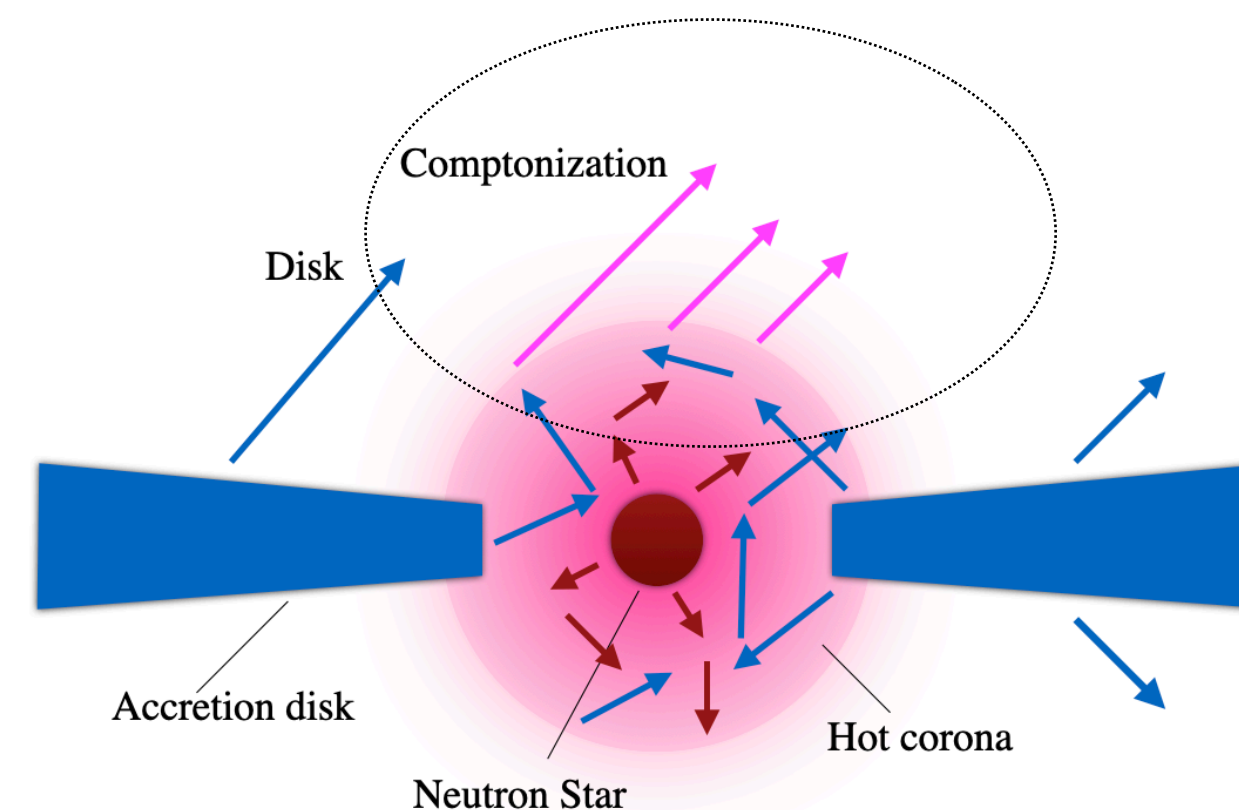
- Inside the corona, the photons from the disk (and/or from the NS if we have a NS) interact with the electrons. How do they interact?
- Photons emitted from the disk/NS are gaining energy from the electrons in the cloud, which are hotter. This process is called **Inverse Compton scattering**.



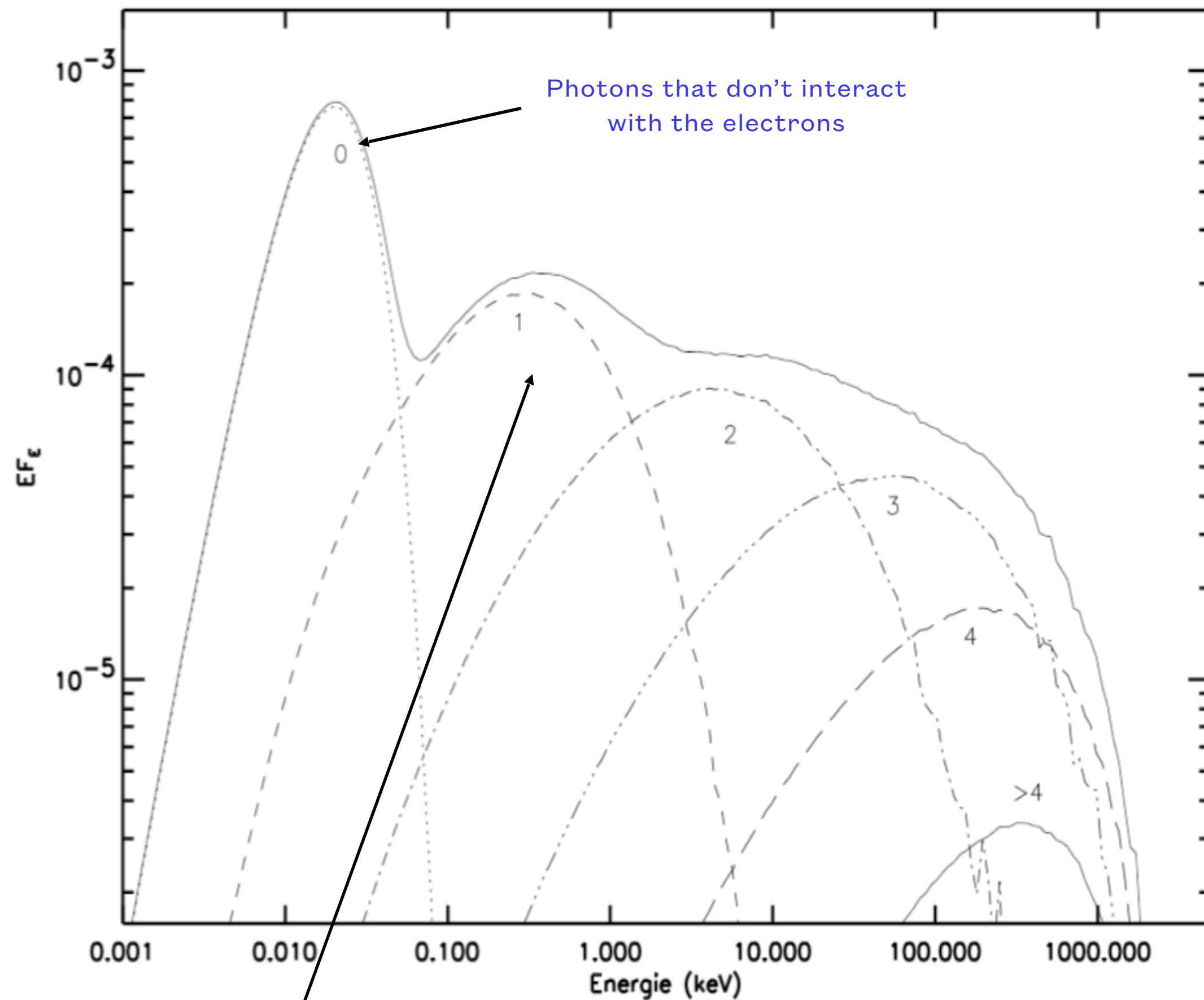
Explaining the emission from the corona: Comptonization spectra



- Since the corona is optically thin, some photons will not interact with any electron in the corona, some will have a few encounters, some will interact a lot.
- The final shape of the spectrum depends on how many times photons on average interact with the electrons in the cloud;
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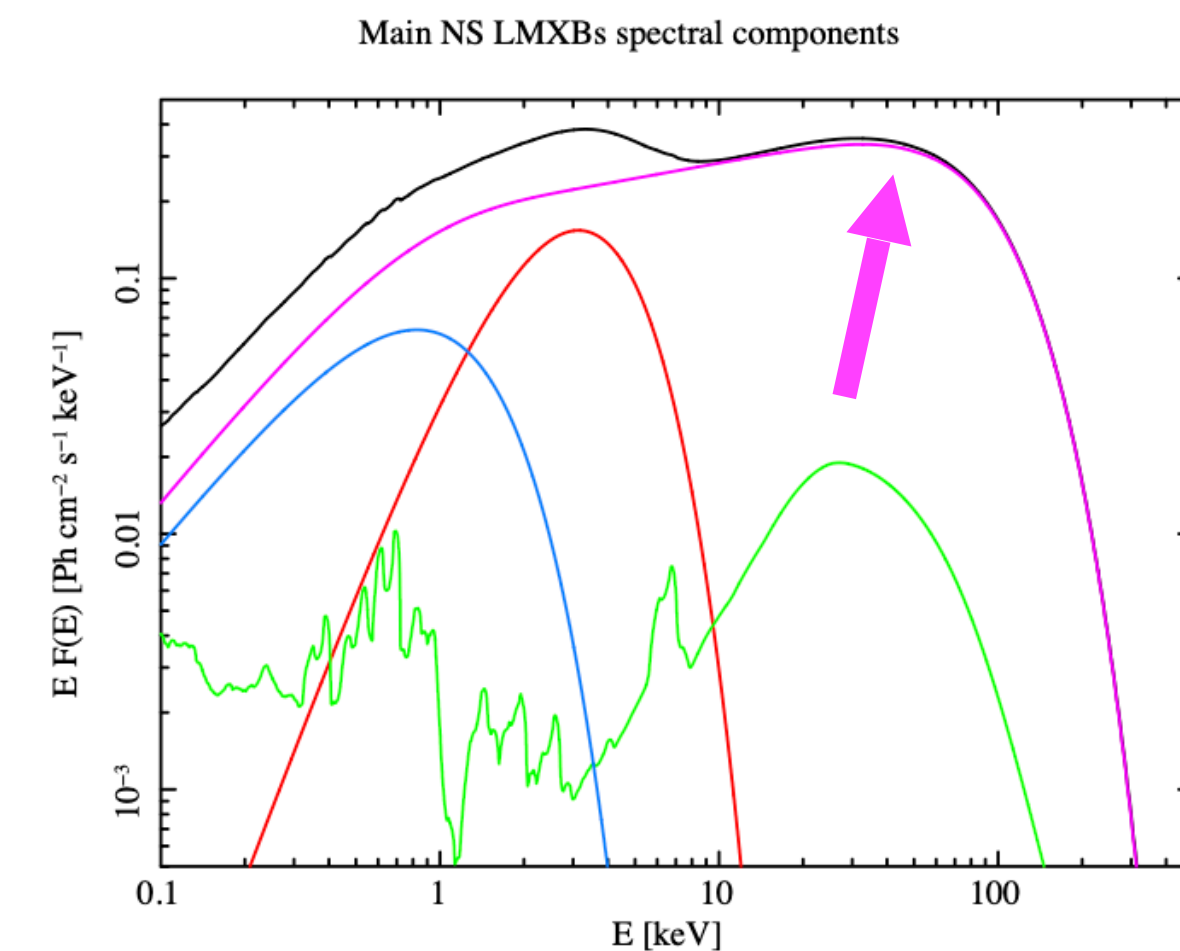
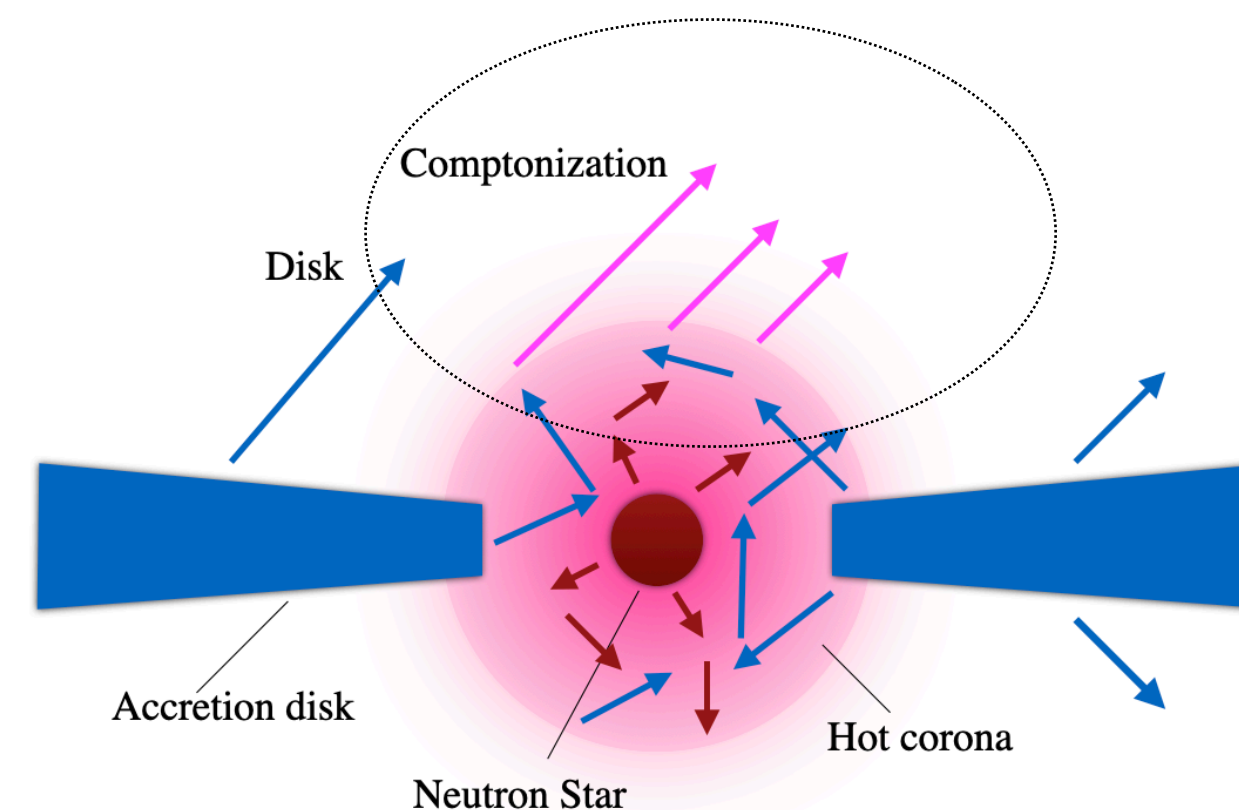


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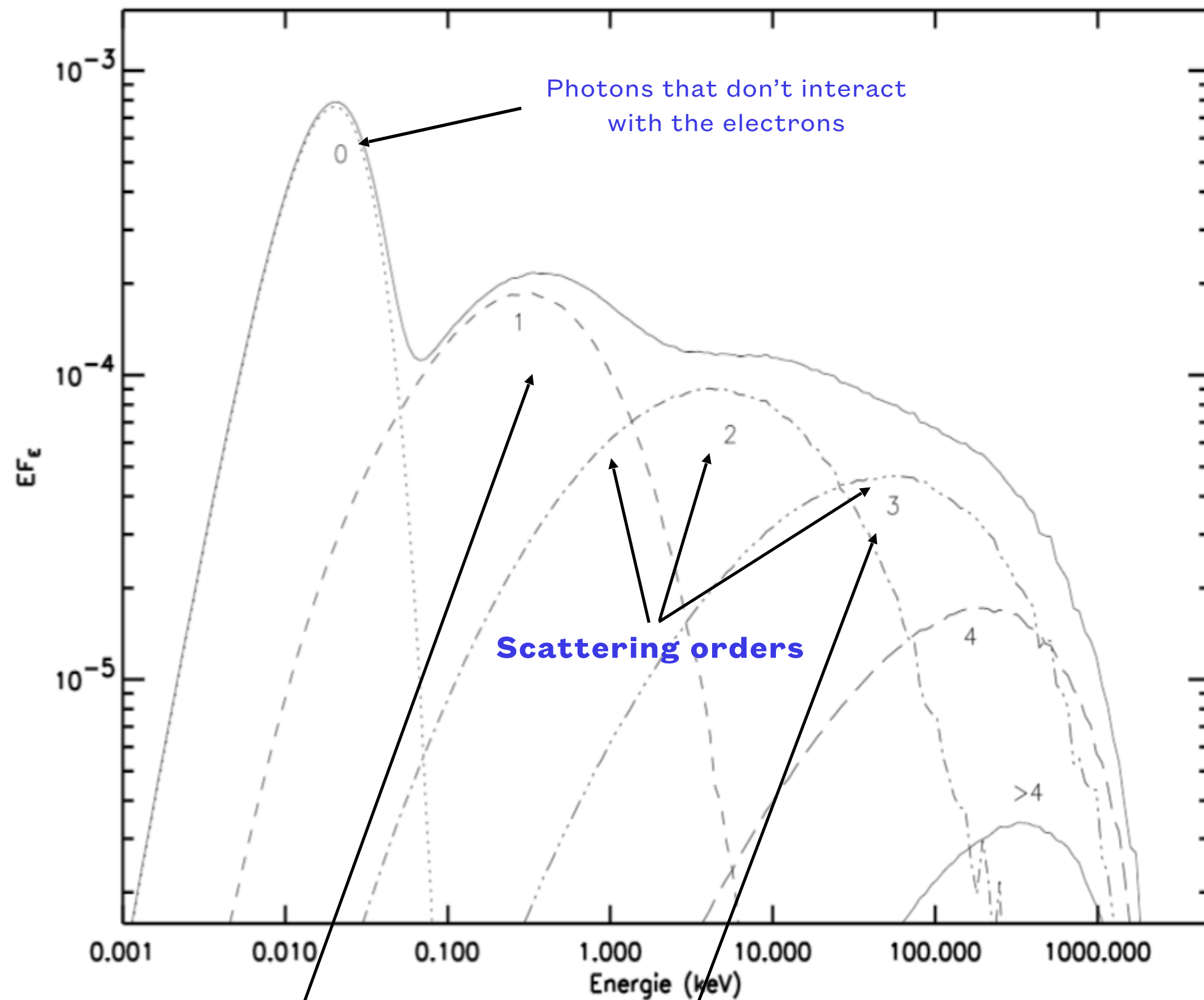


Photons that interact 1 time

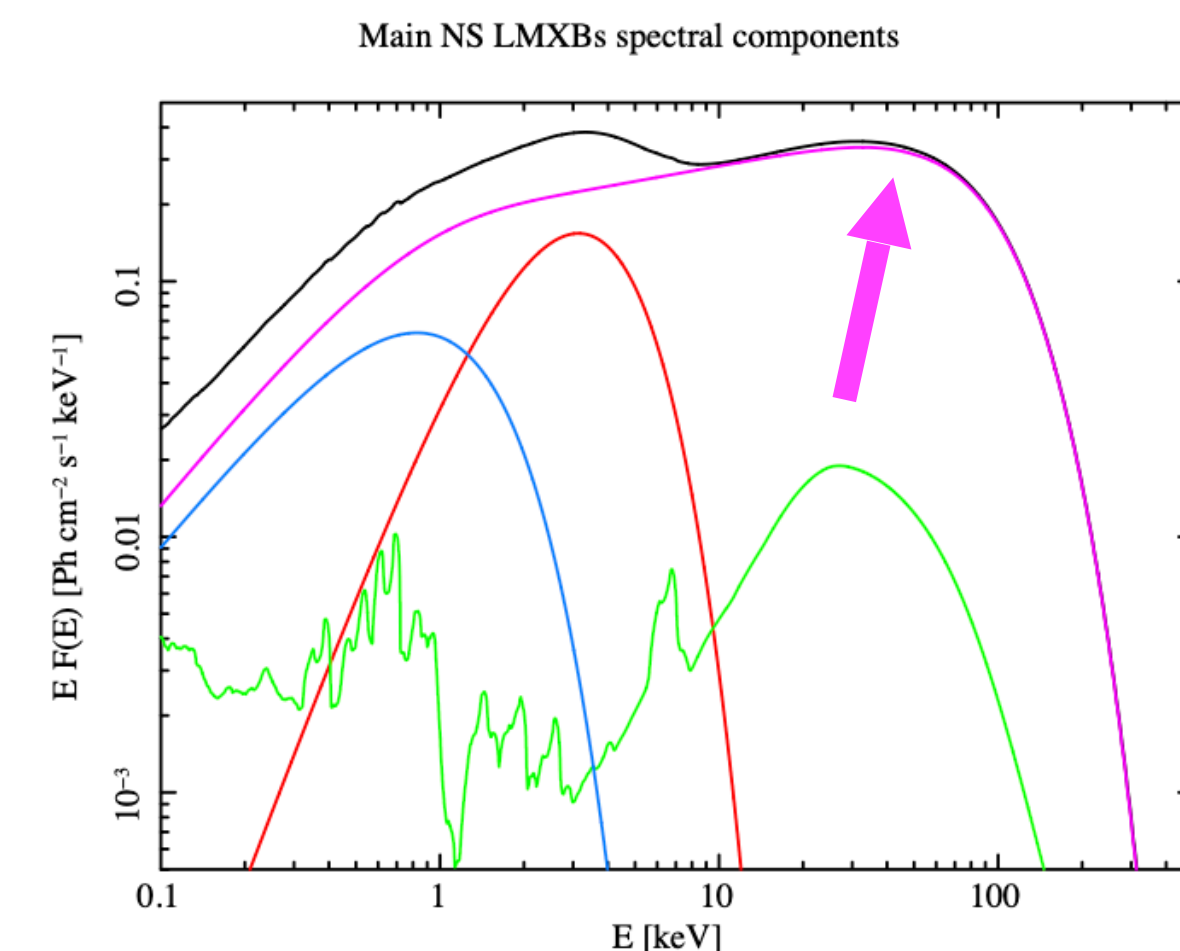
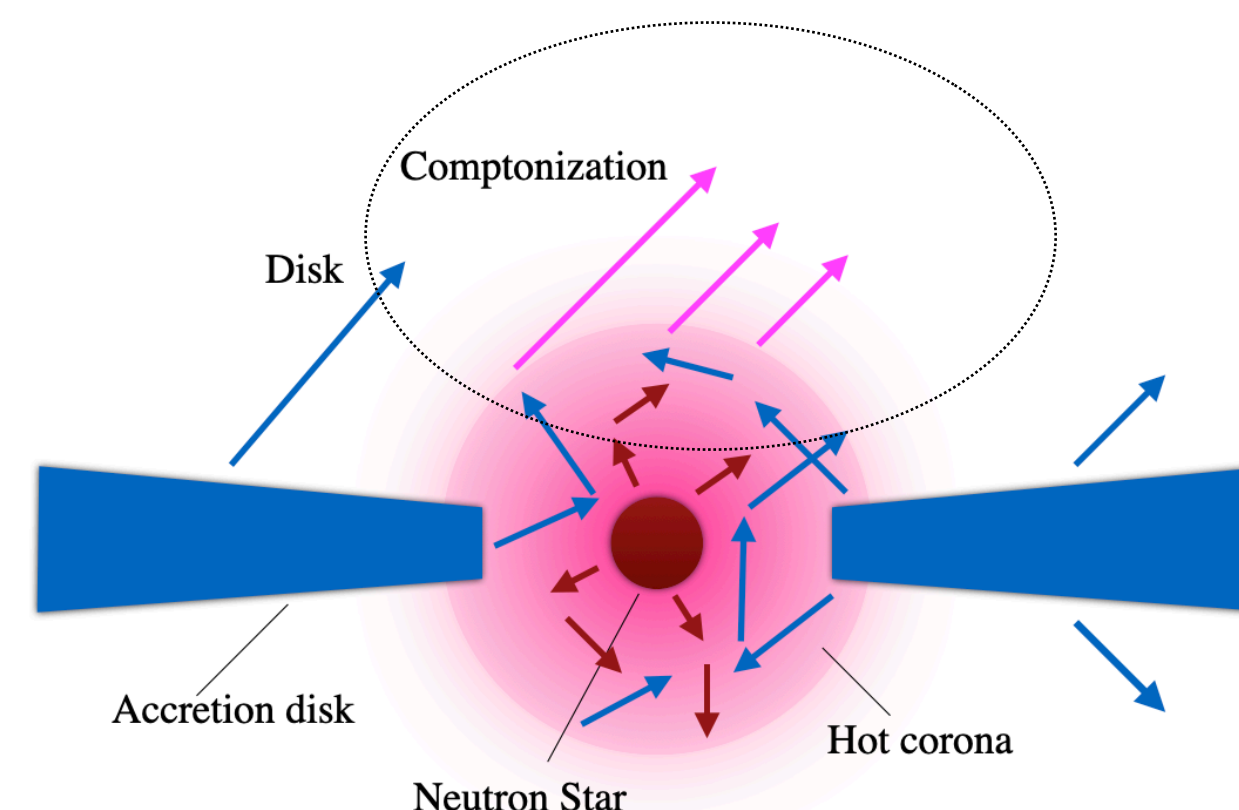
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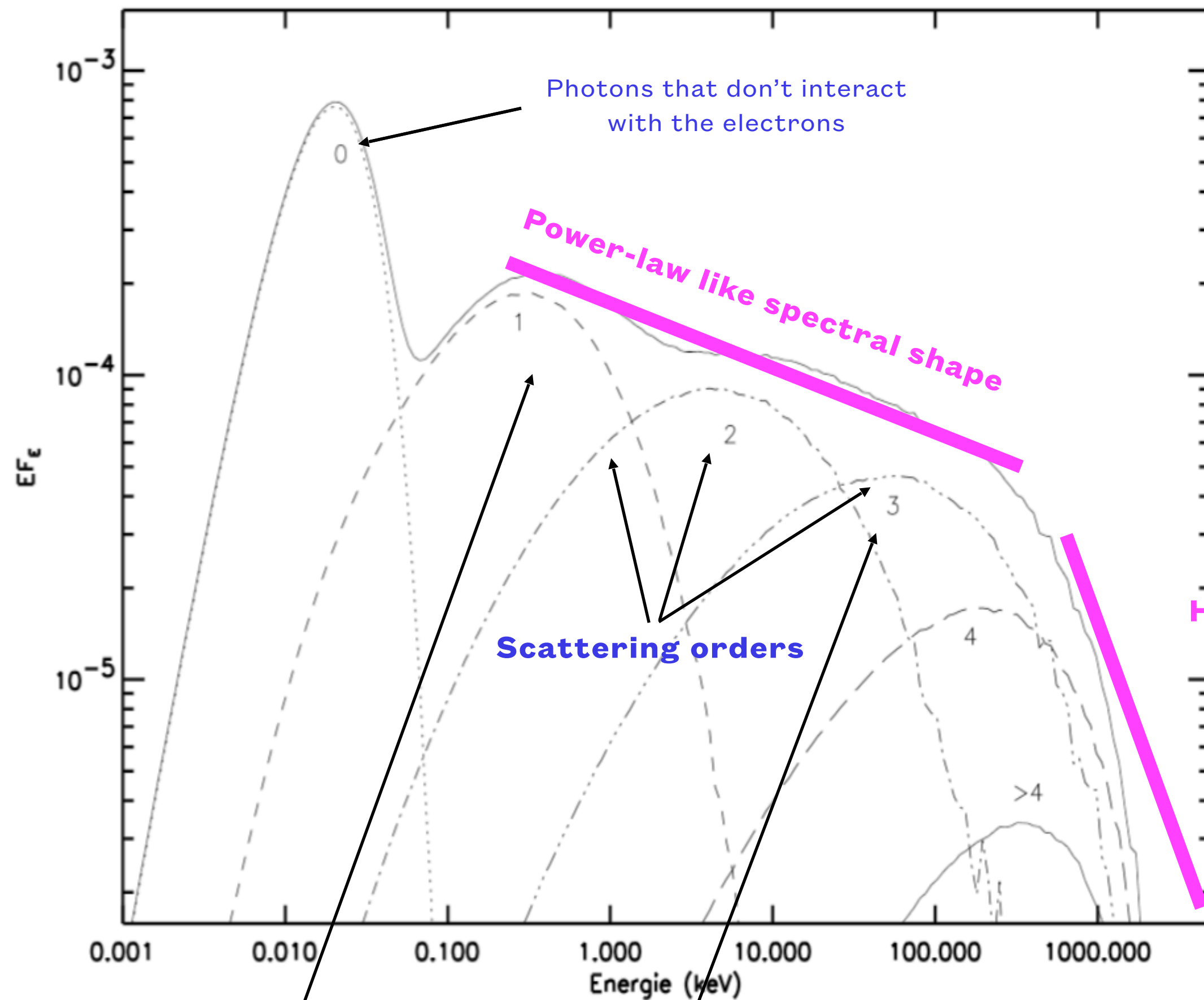
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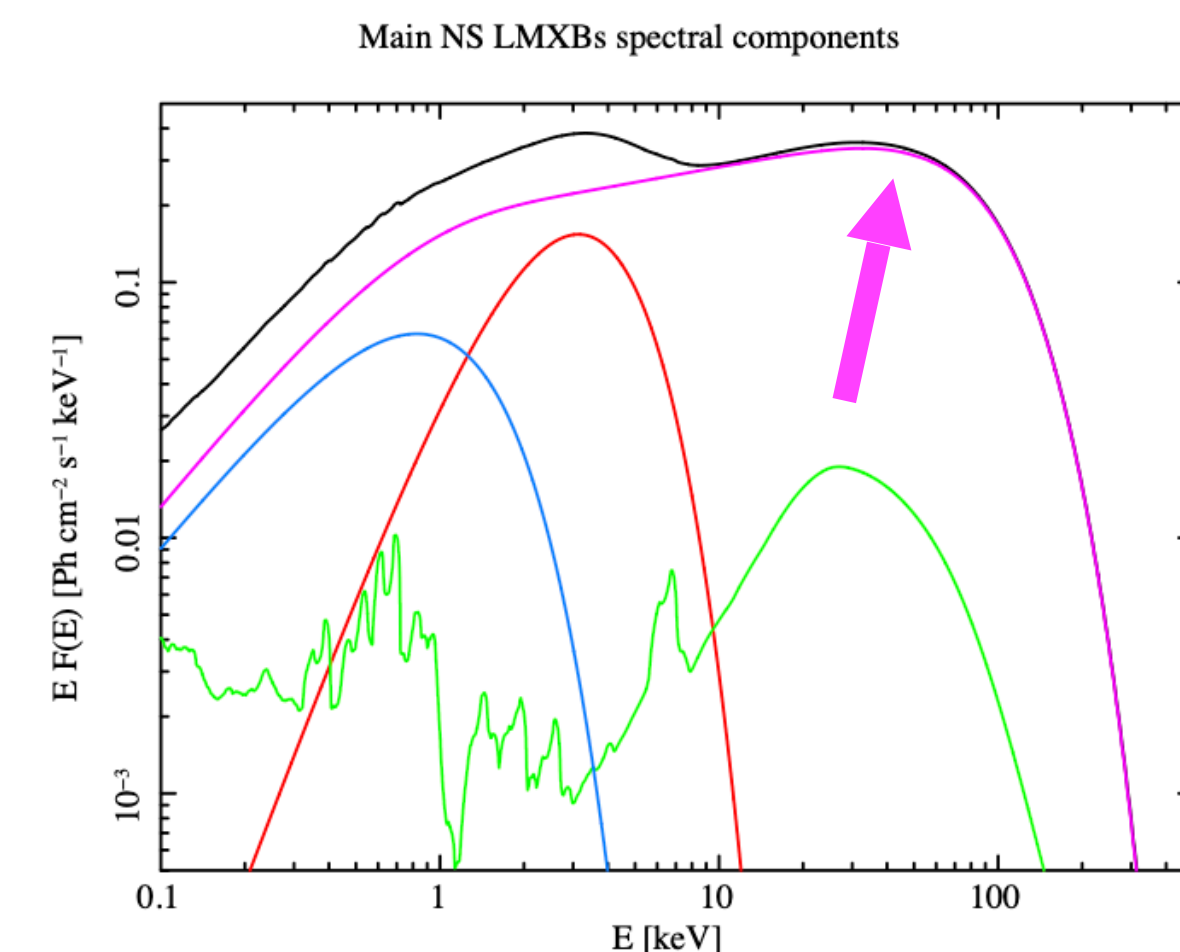
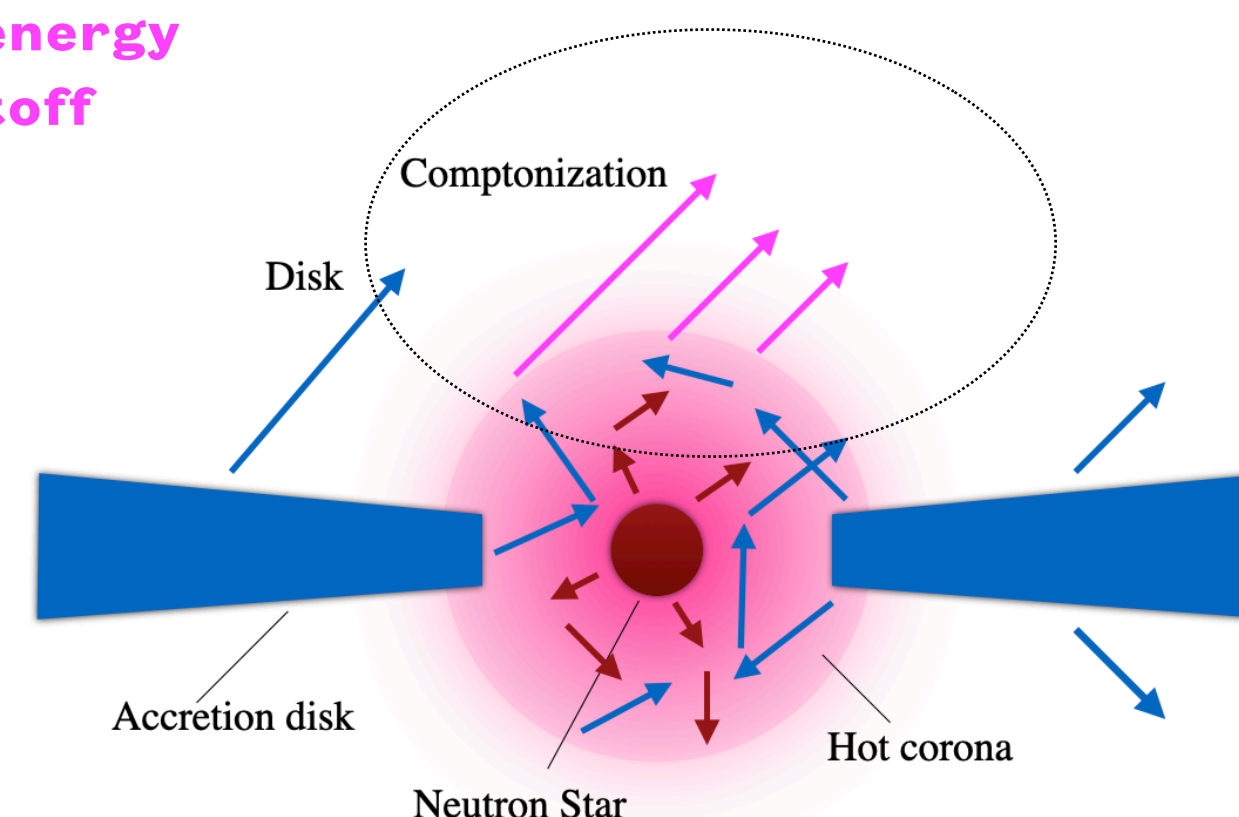
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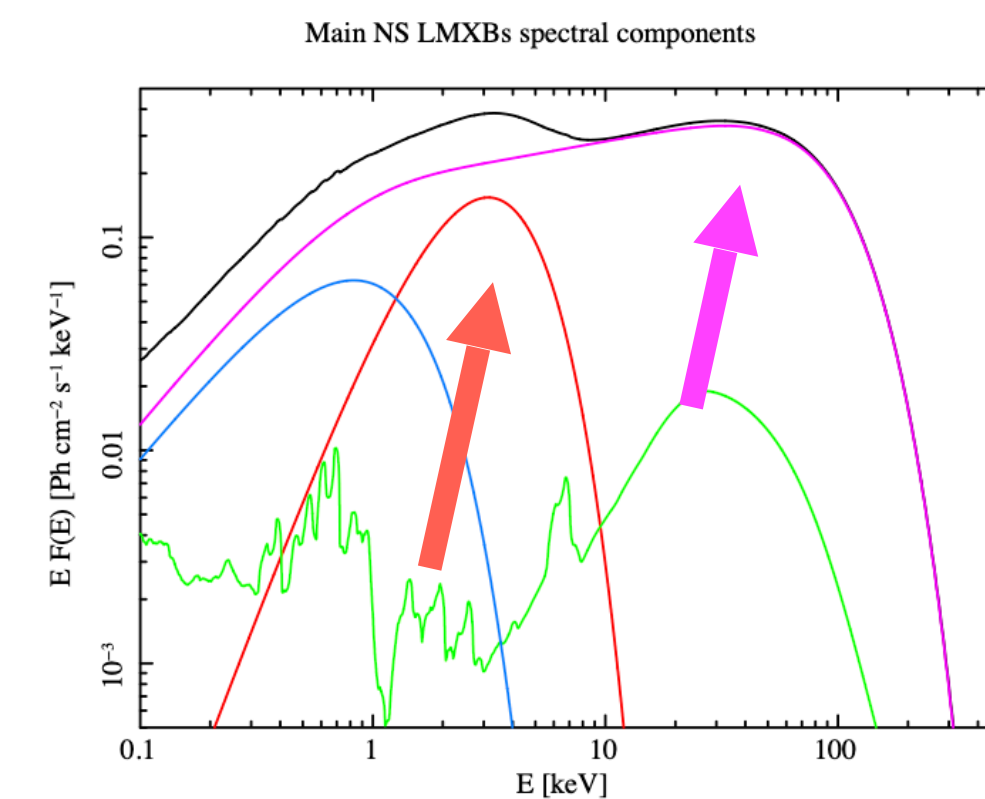
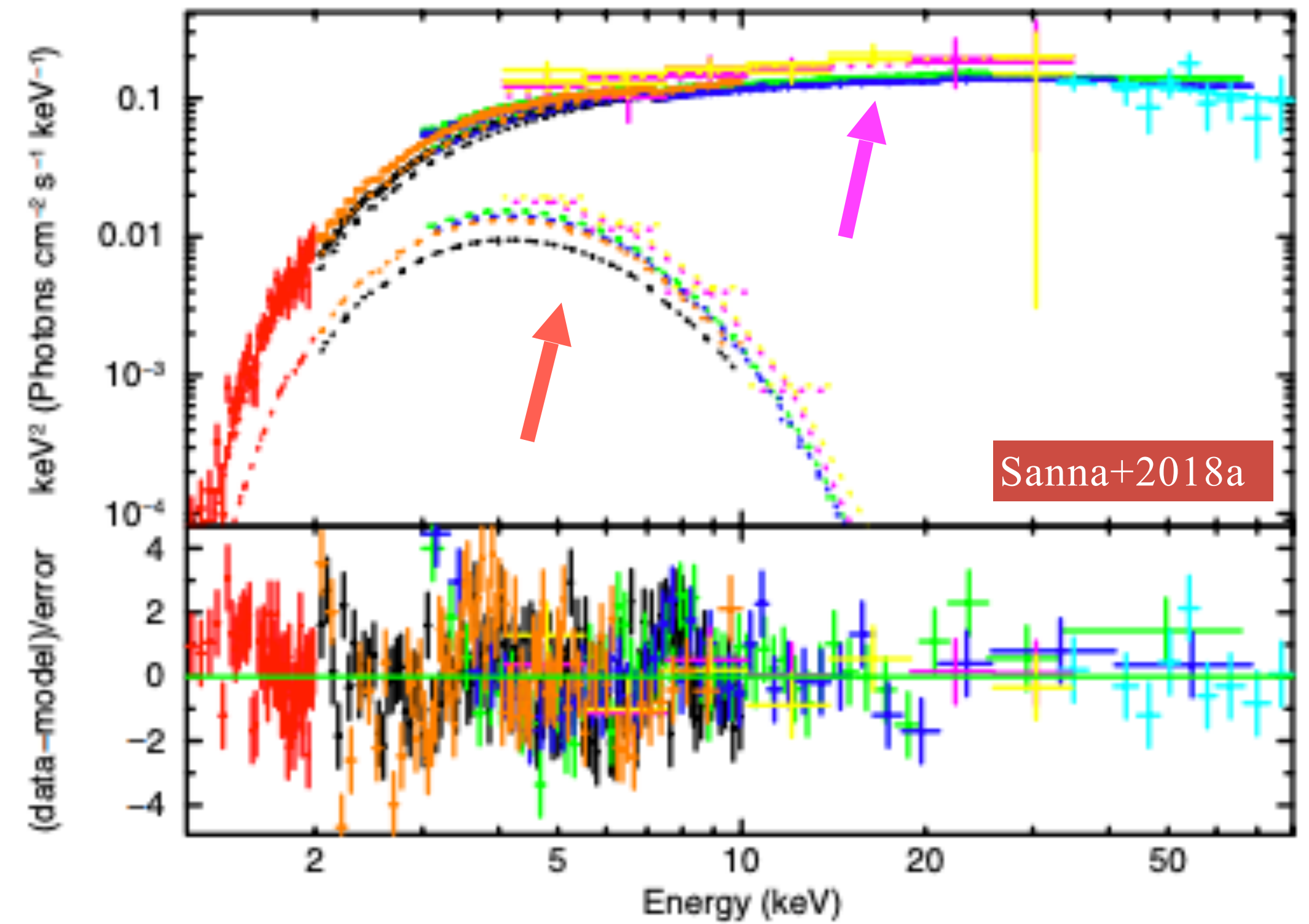
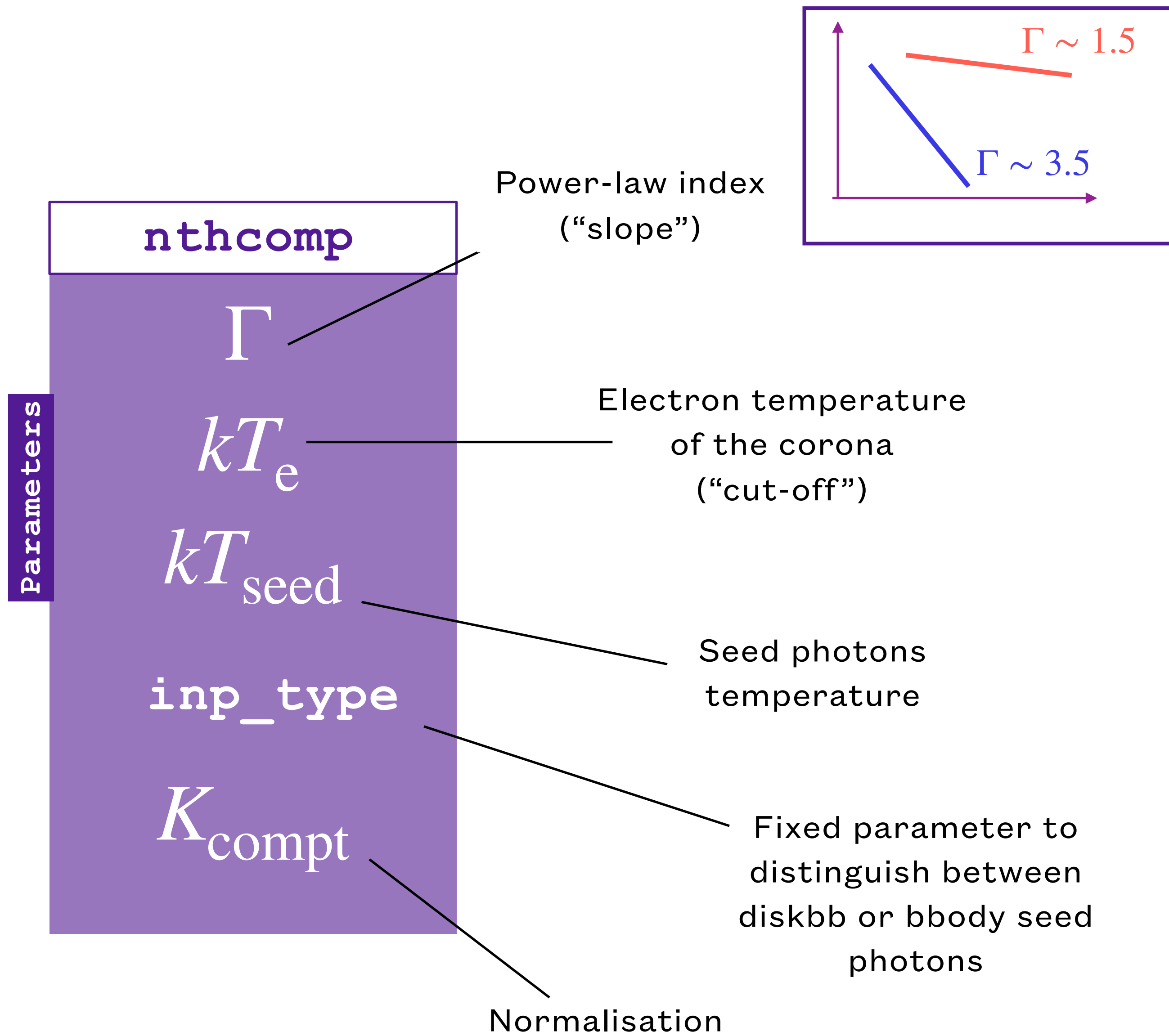
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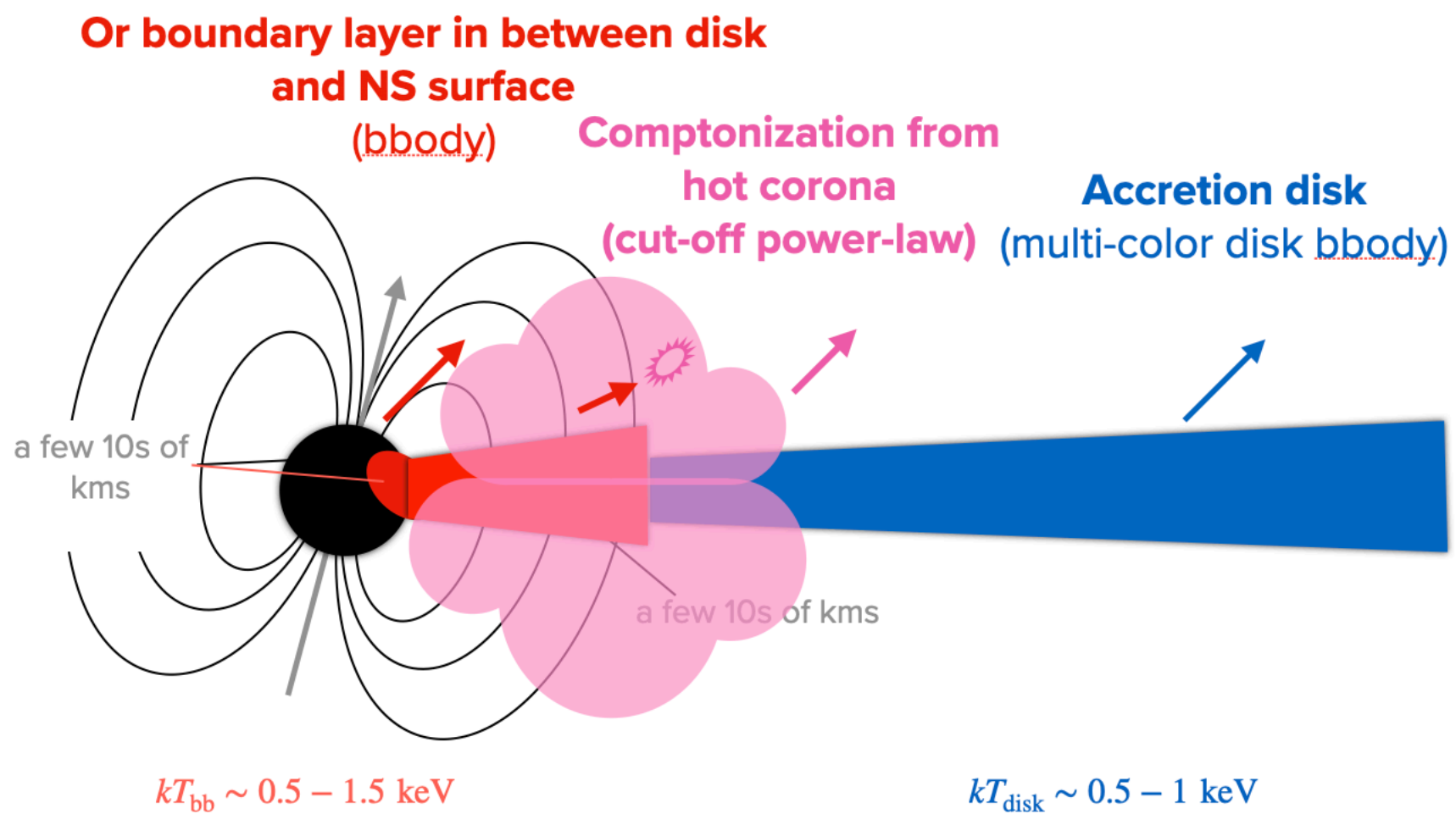
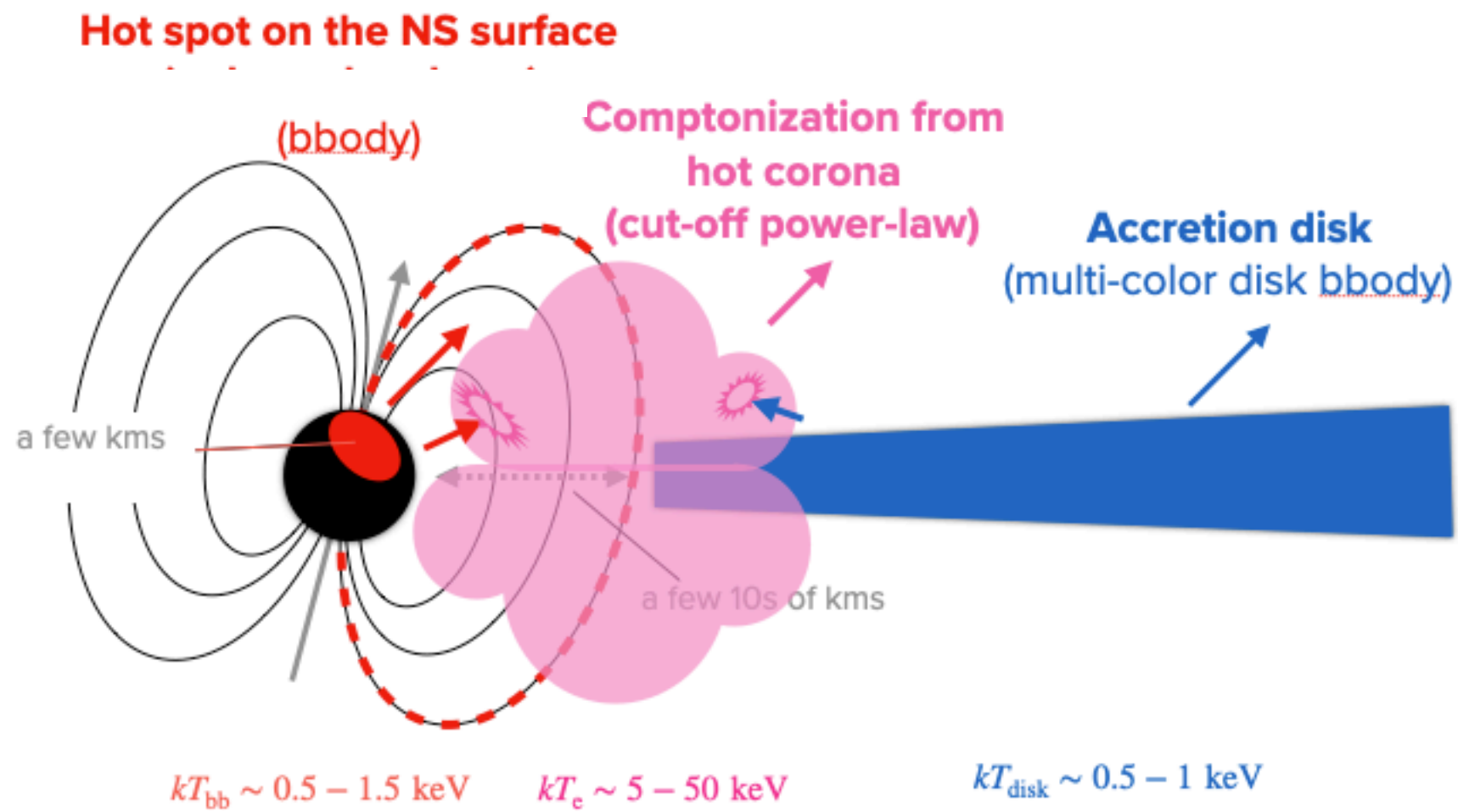
Modelling the emission from the corona: Comptonization spectra



Zdziarski+2020



NEUTRON STARS



Solid surface?



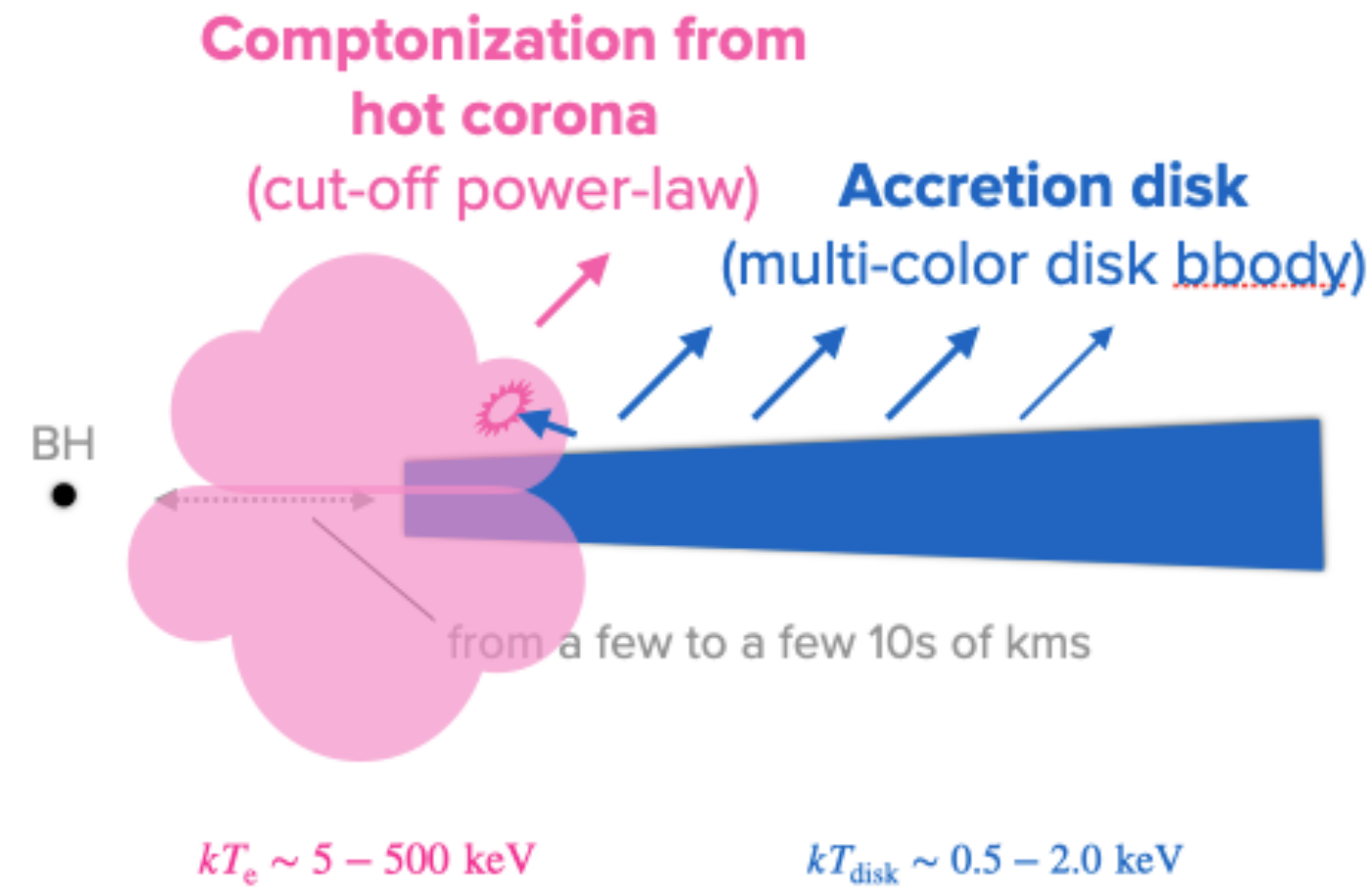
Potential presence of a boundary layer?



Magnetosphere of the accreting star?

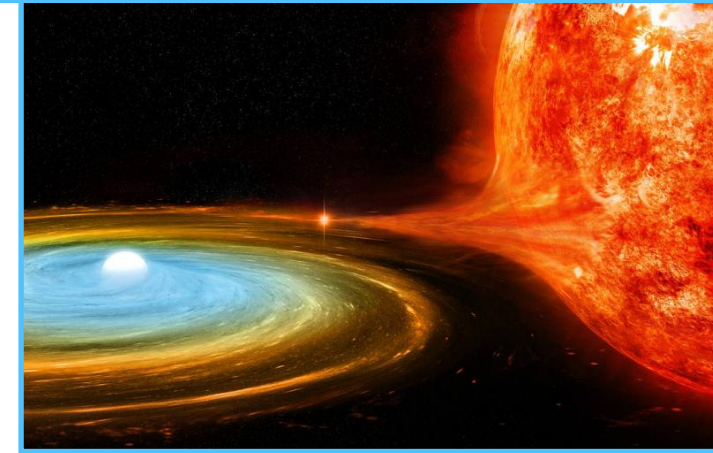
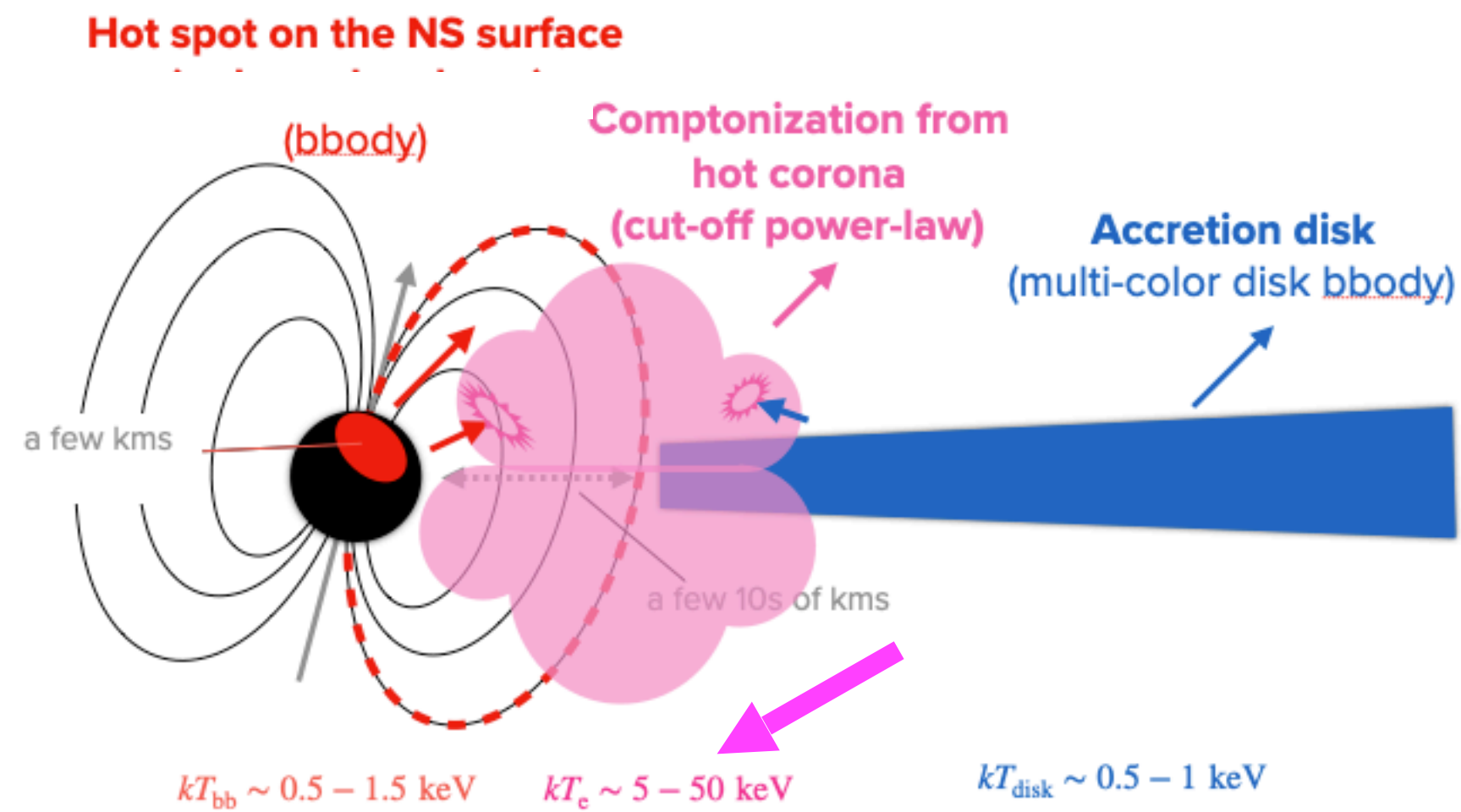


NS vs. BHs: a summary



BLACK HOLES

NEUTRON STARS



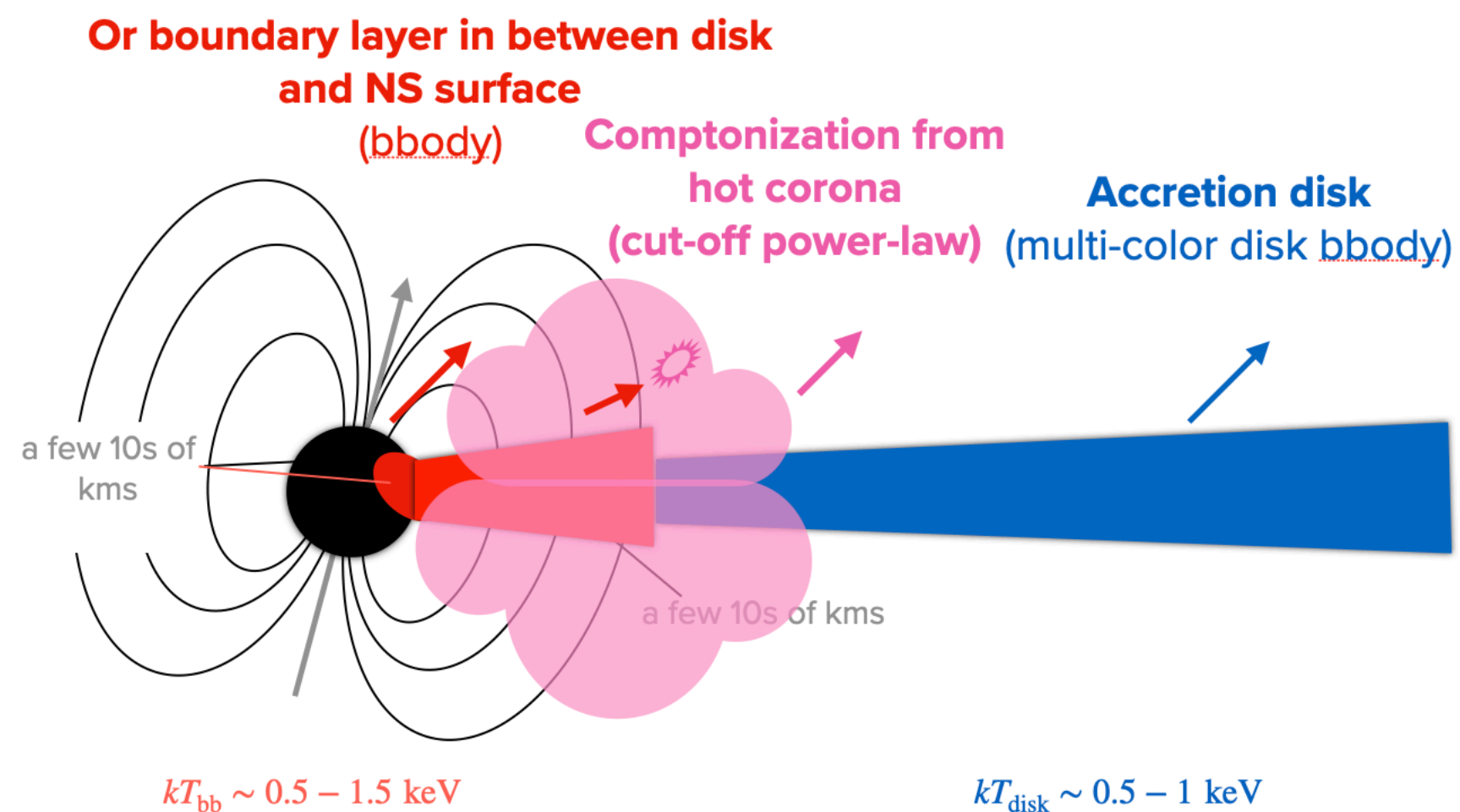
Solid surface?



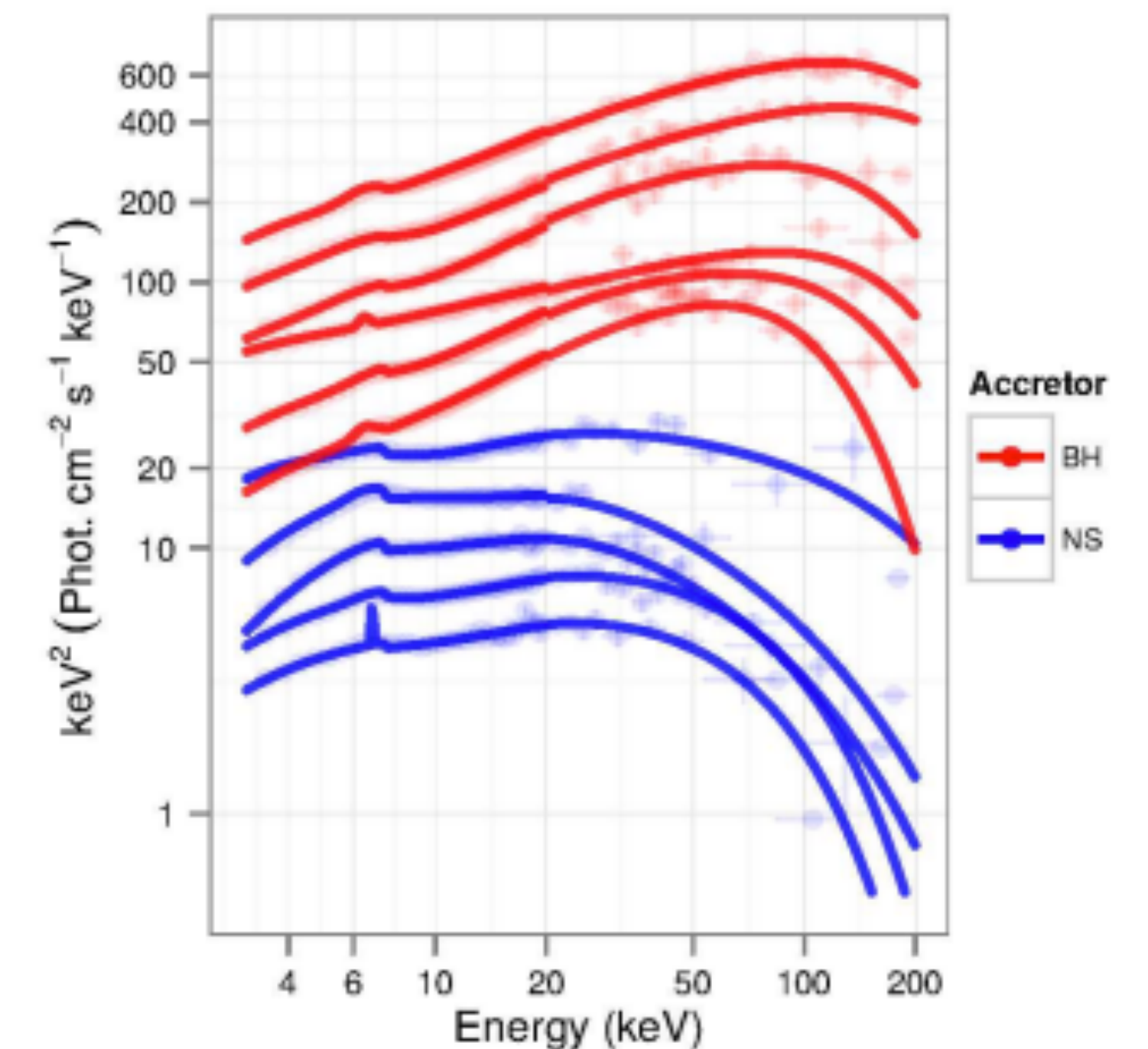
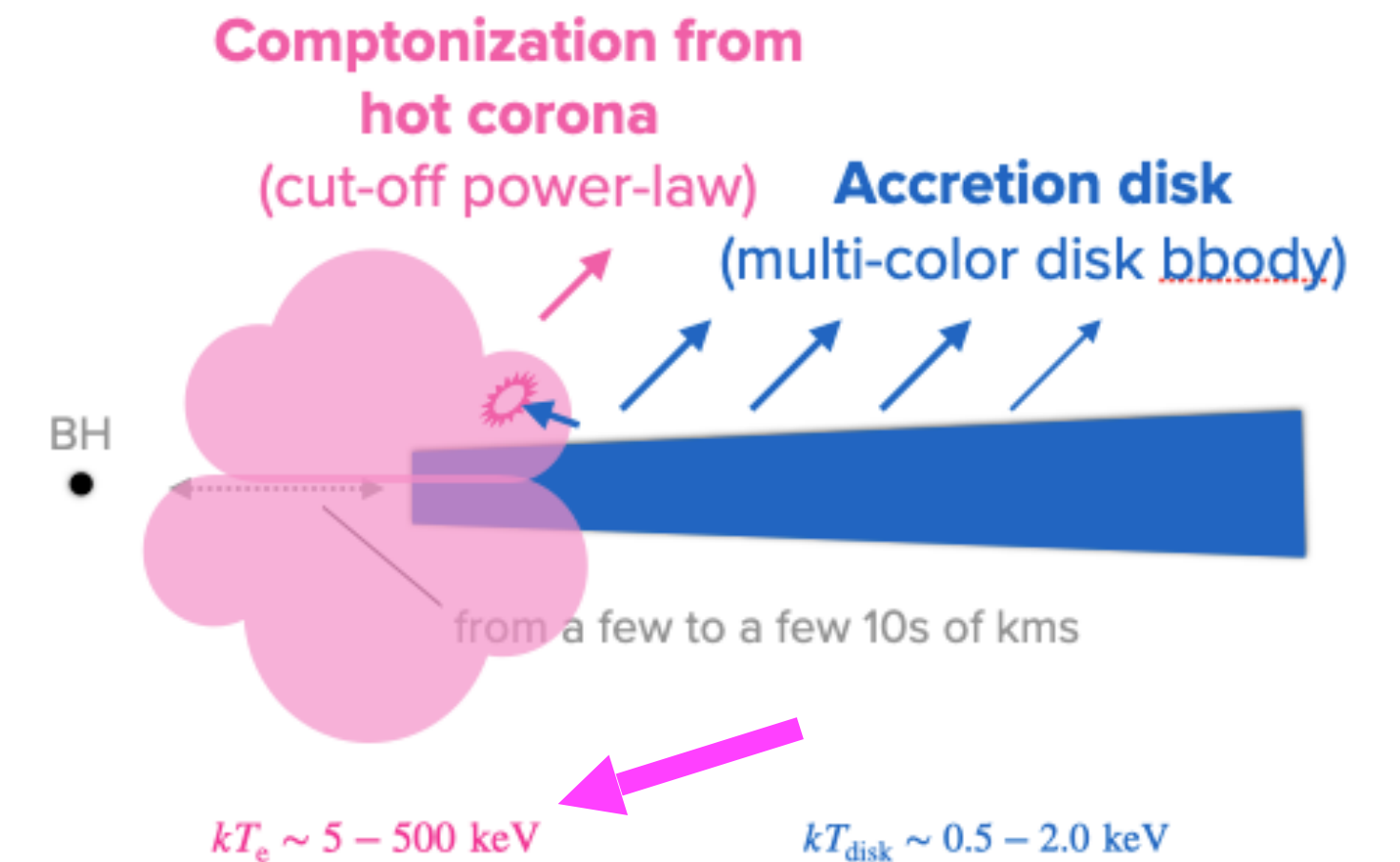
Potential presence of a boundary layer?



Magnetosphere of the accreting star?



NS vs. BHs: a summary



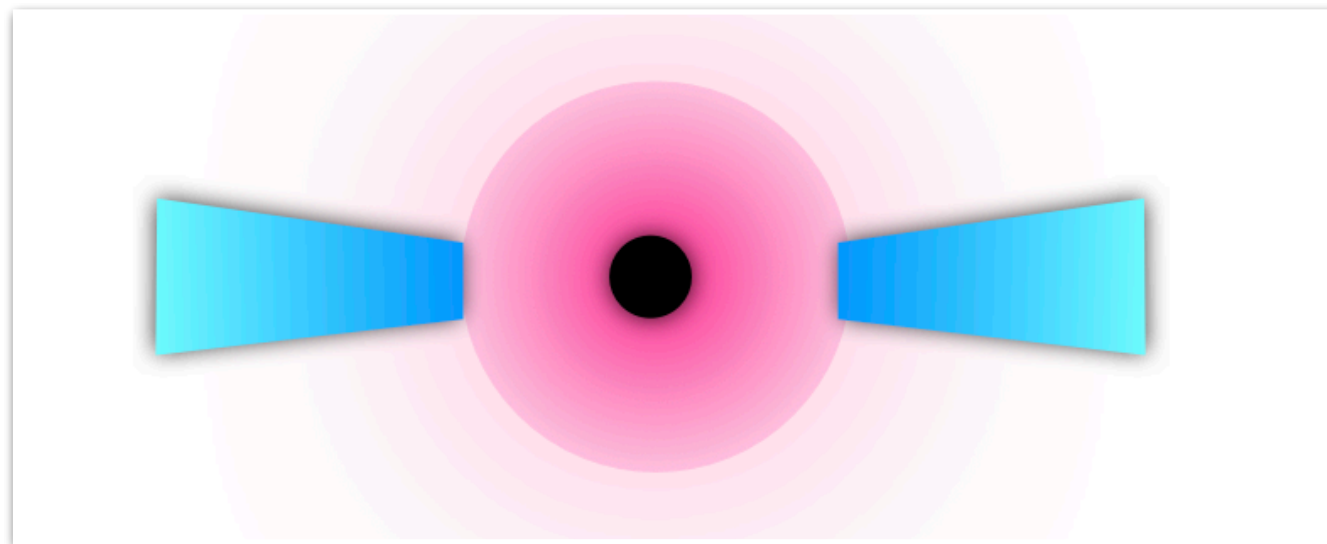
BLACK HOLES

Spectral states

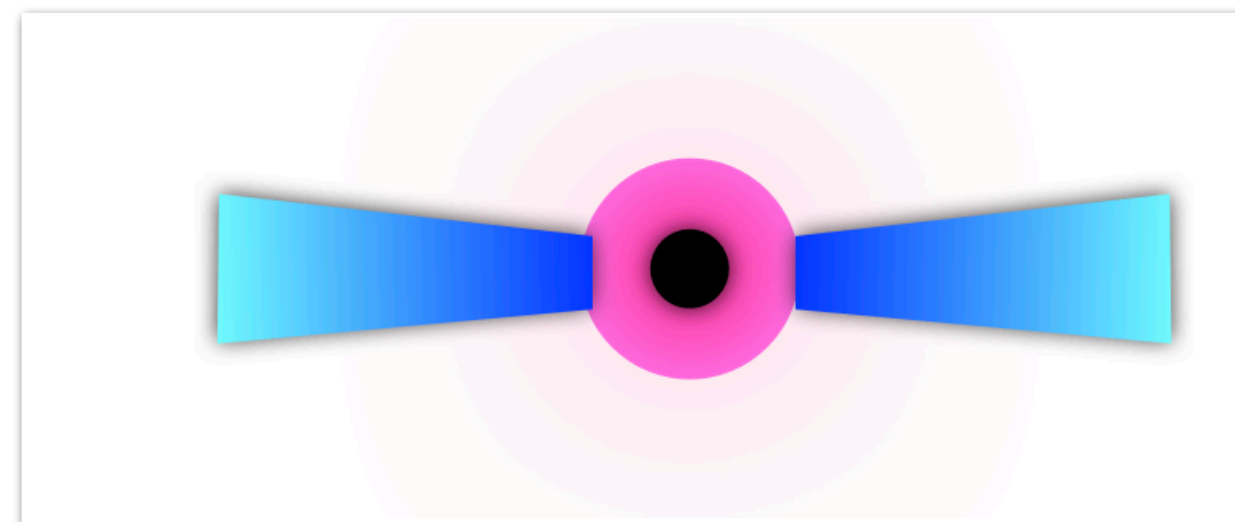
- According to the way those building blocks assemble, we identify three **main spectral states**, most likely connected to changes in the **geometry of the accretion flow**.

THE EXACT GEOMETRY IS STILL MATTER OF DEBATE

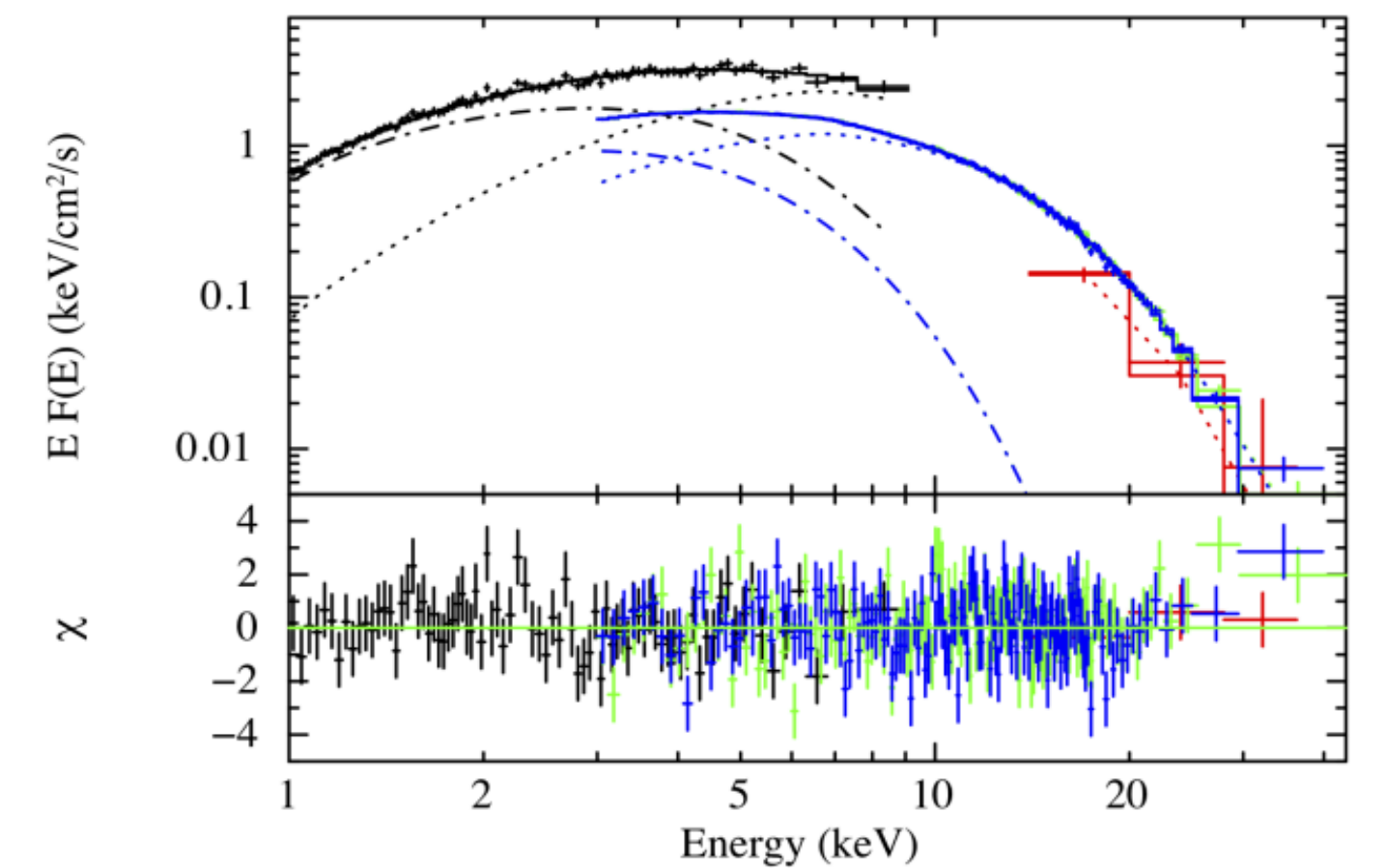
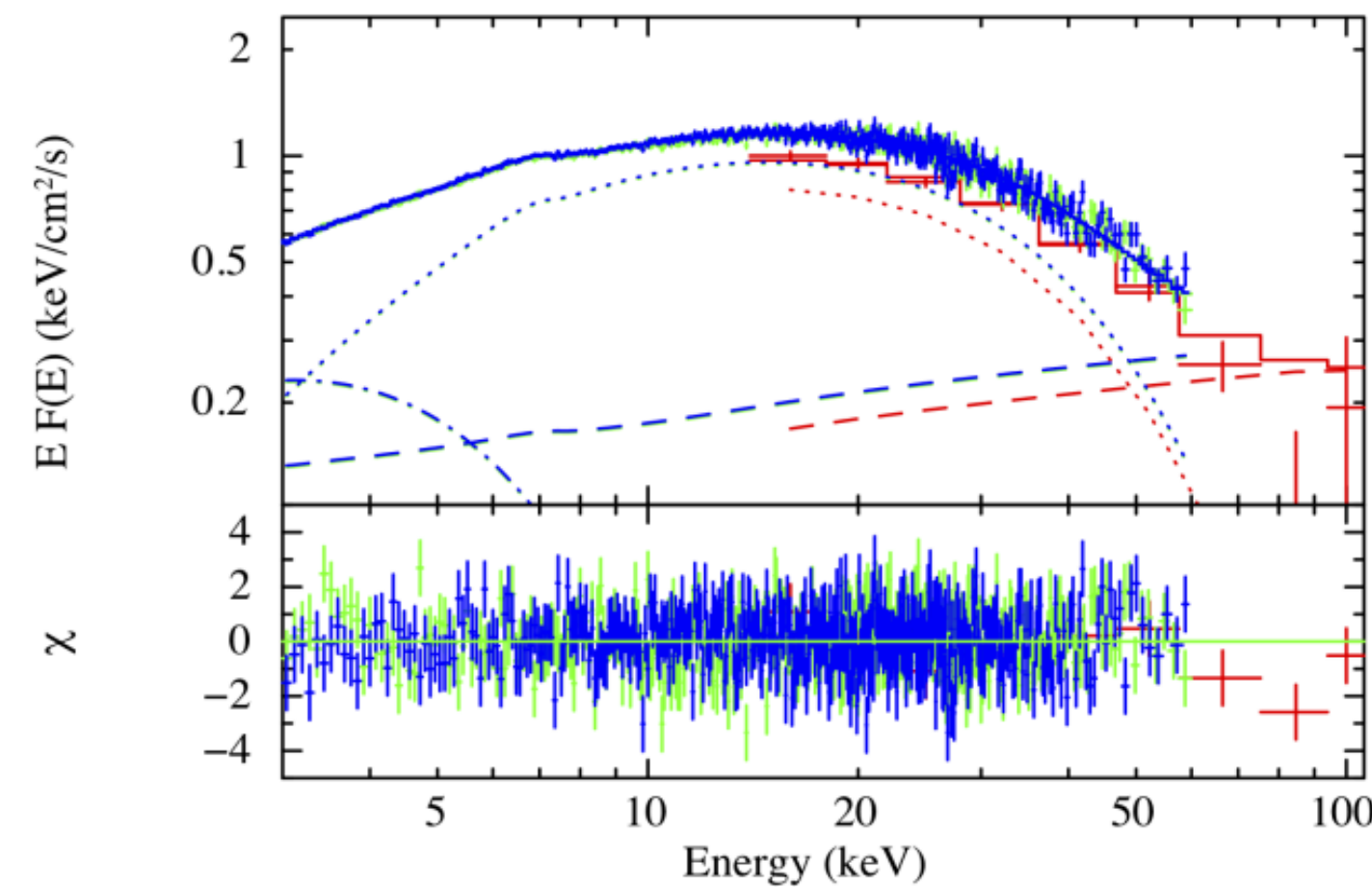
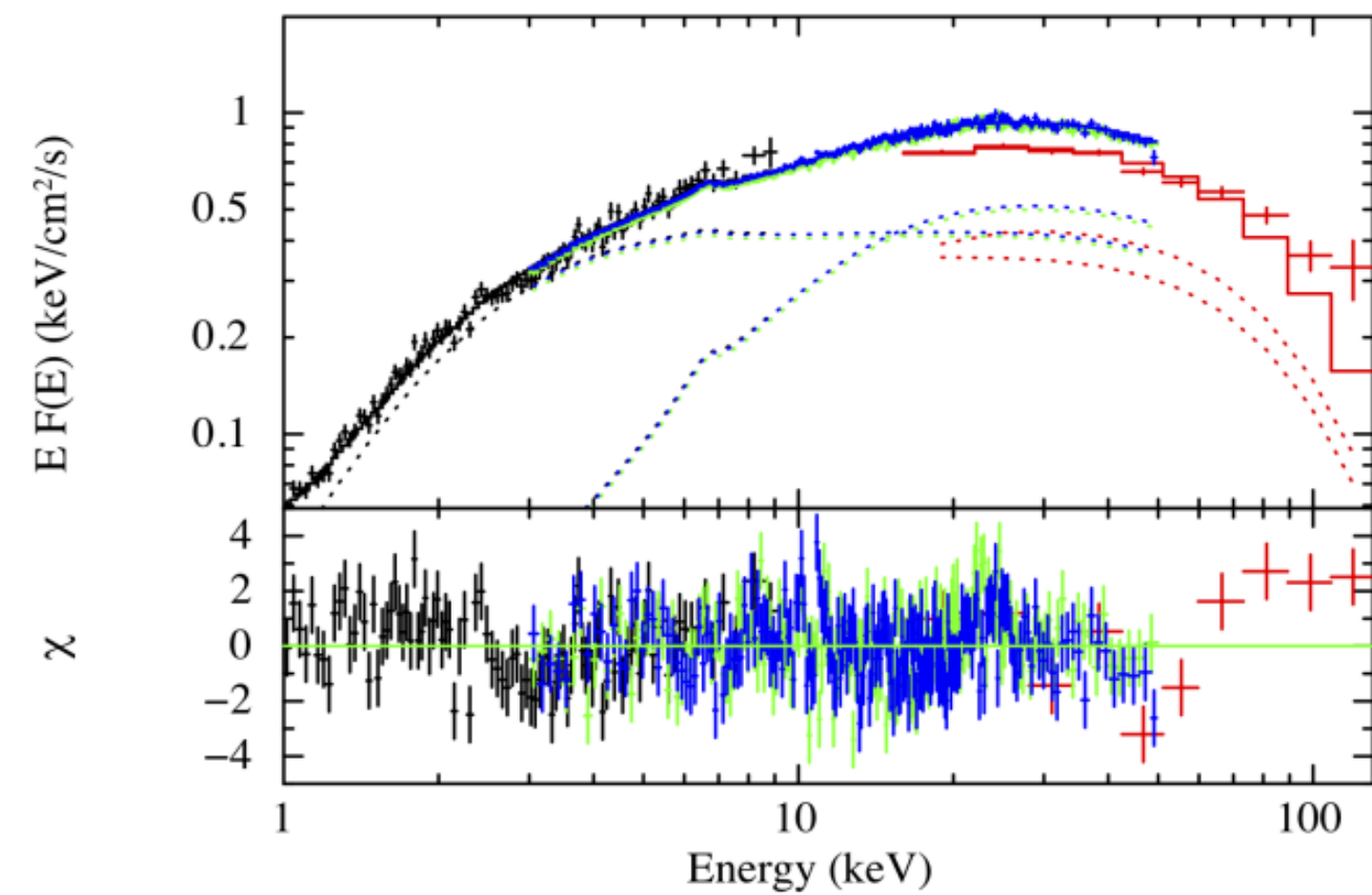
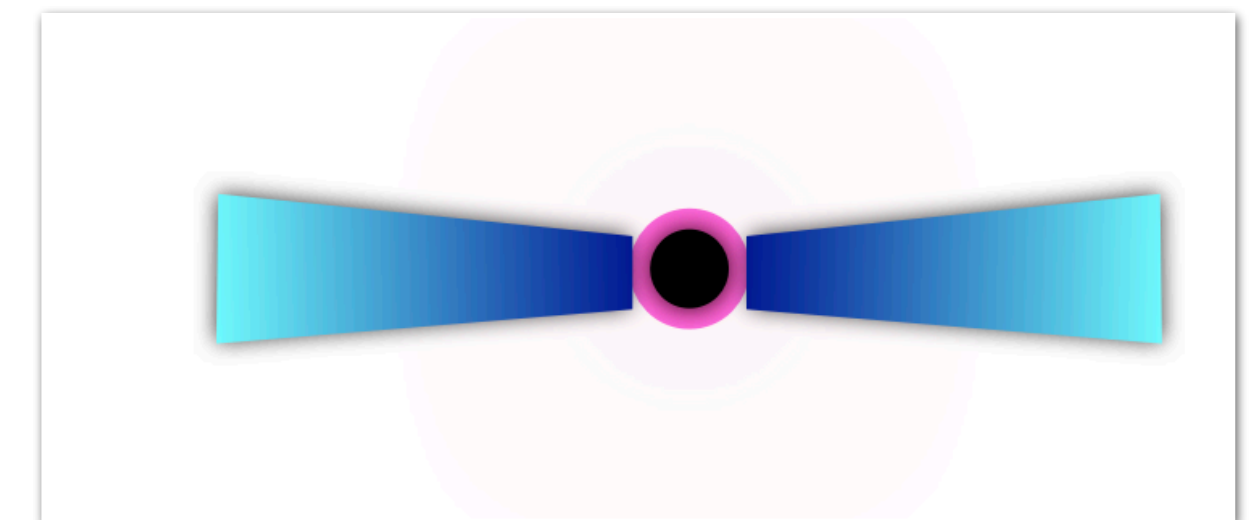
Hard state

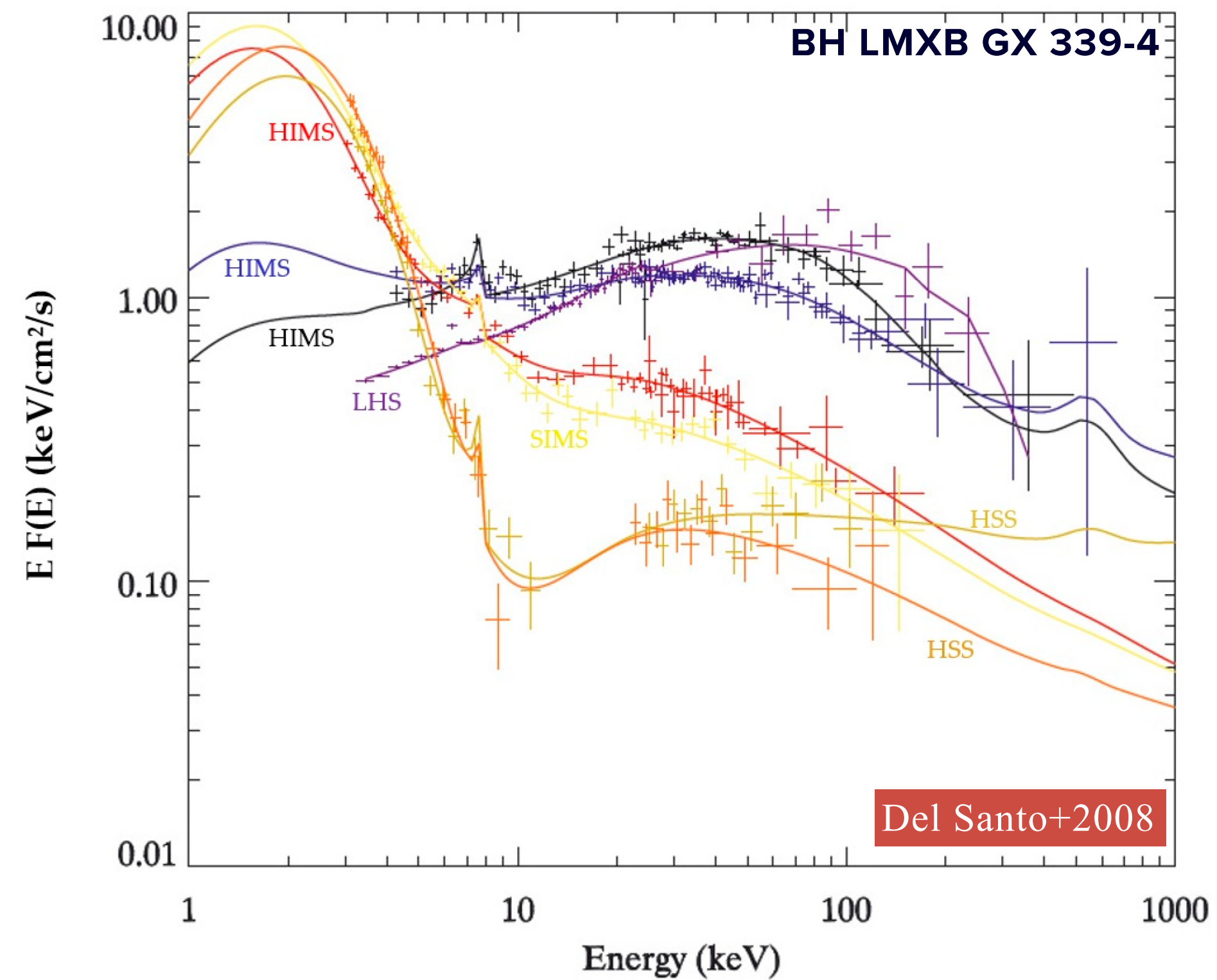
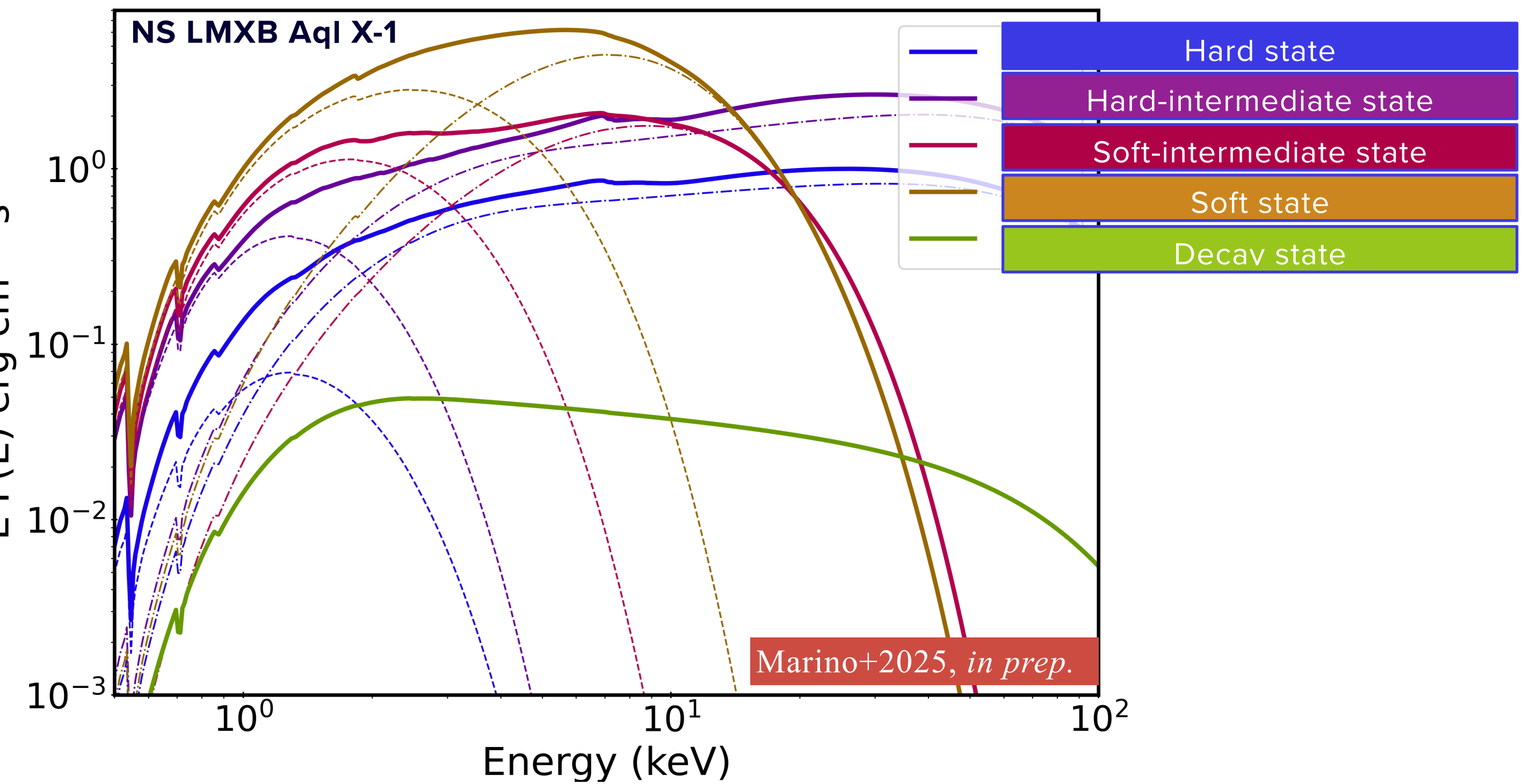


Intermediate state



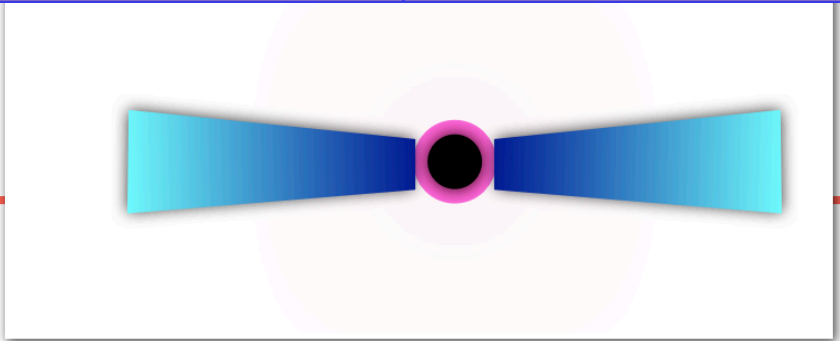
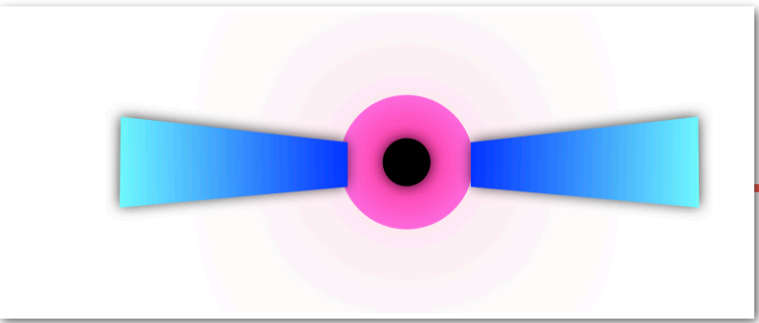
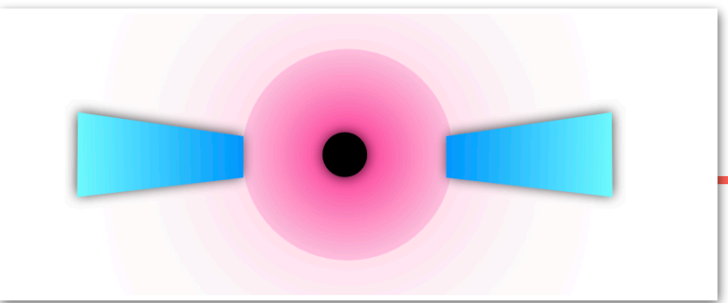
Soft state





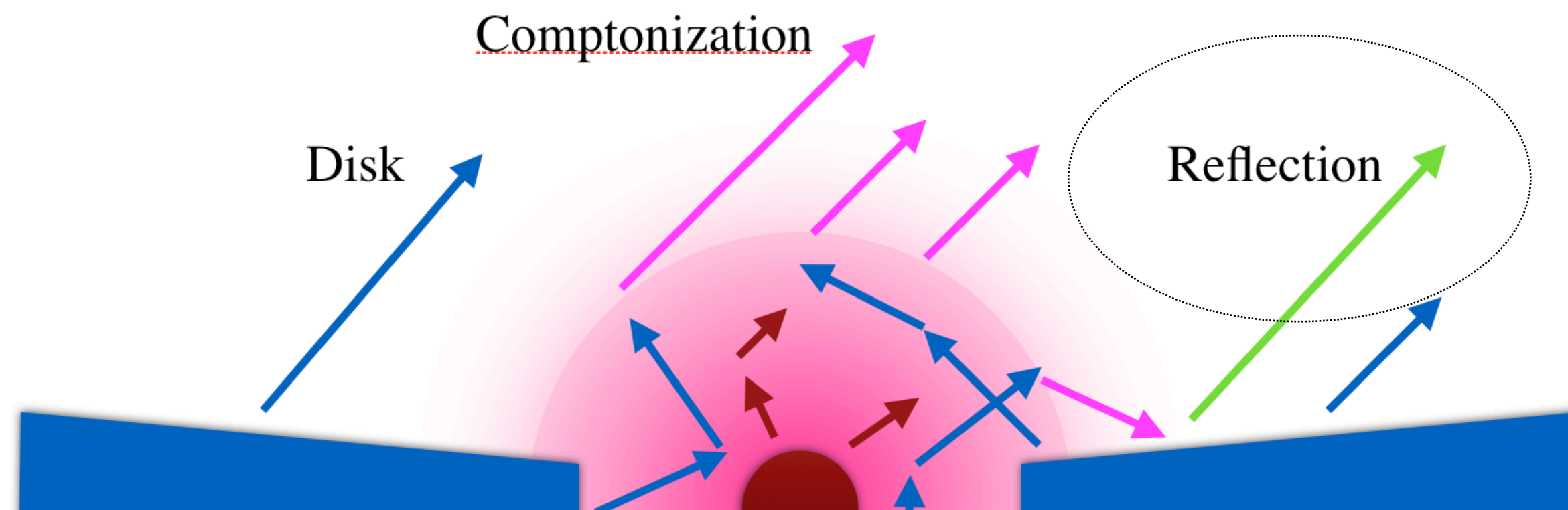
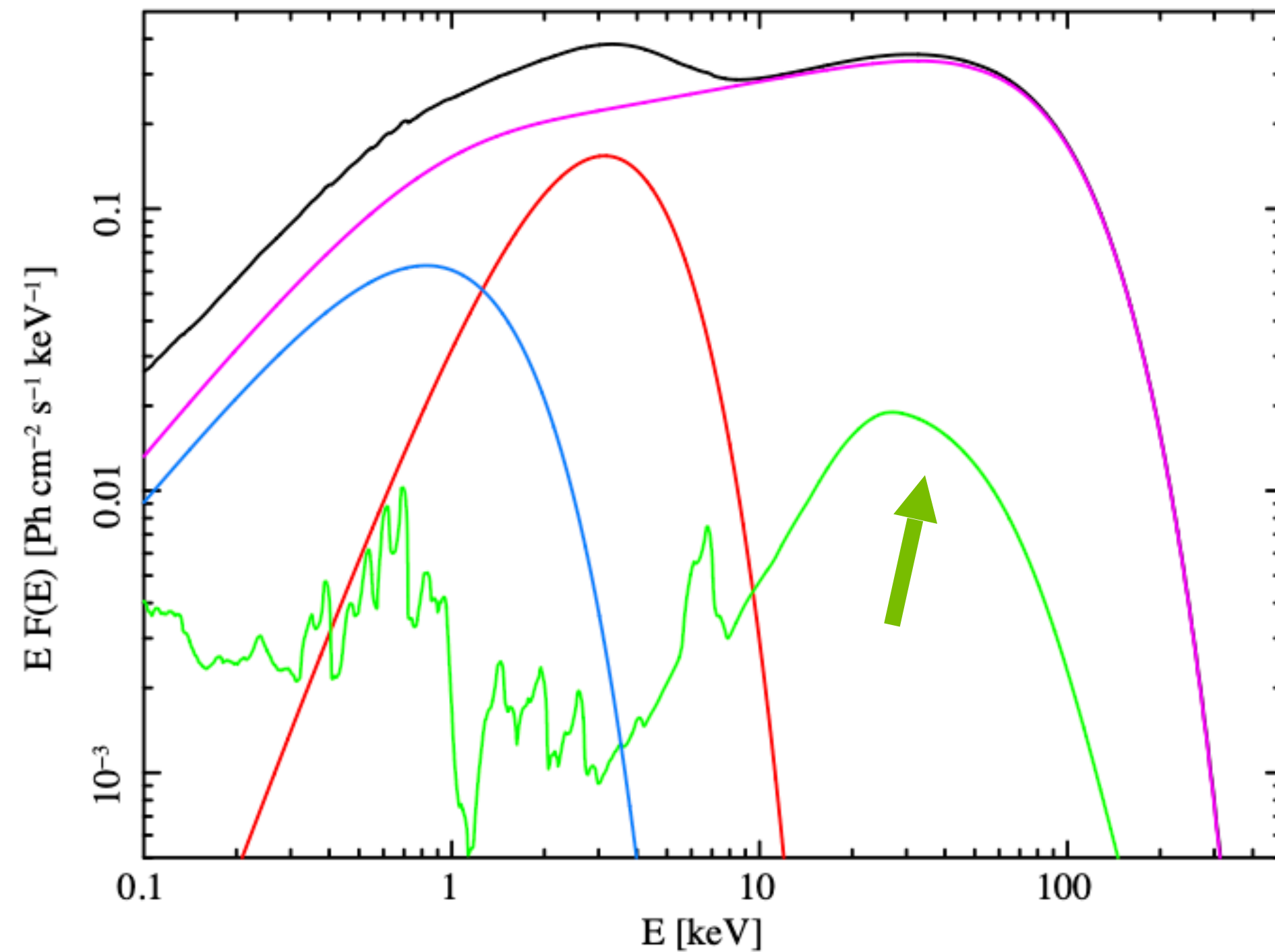
Typical values

Parameter	Hard		Intermediate		Soft	
	BHs	NSs	BHs	NSs	BHs	NSs
Power-law index	1.5-2.0		2.0-3.0		>3.0	
Electron temperature of the corona (kT_e)	>50 keV	10-50 keV	10-50 keV	5-10 keV	1-10 keV	<5 keV
Disk temperature	0.2-0.5		0.6-1.0		1.0-1.5	
Truncated disk?	Most likely		Maybe?		Probably not	
Hot spot/boundary layer temperature	N/A	0.6-1.0	N/A	1.0-1.5	N/A	1.5-2.0

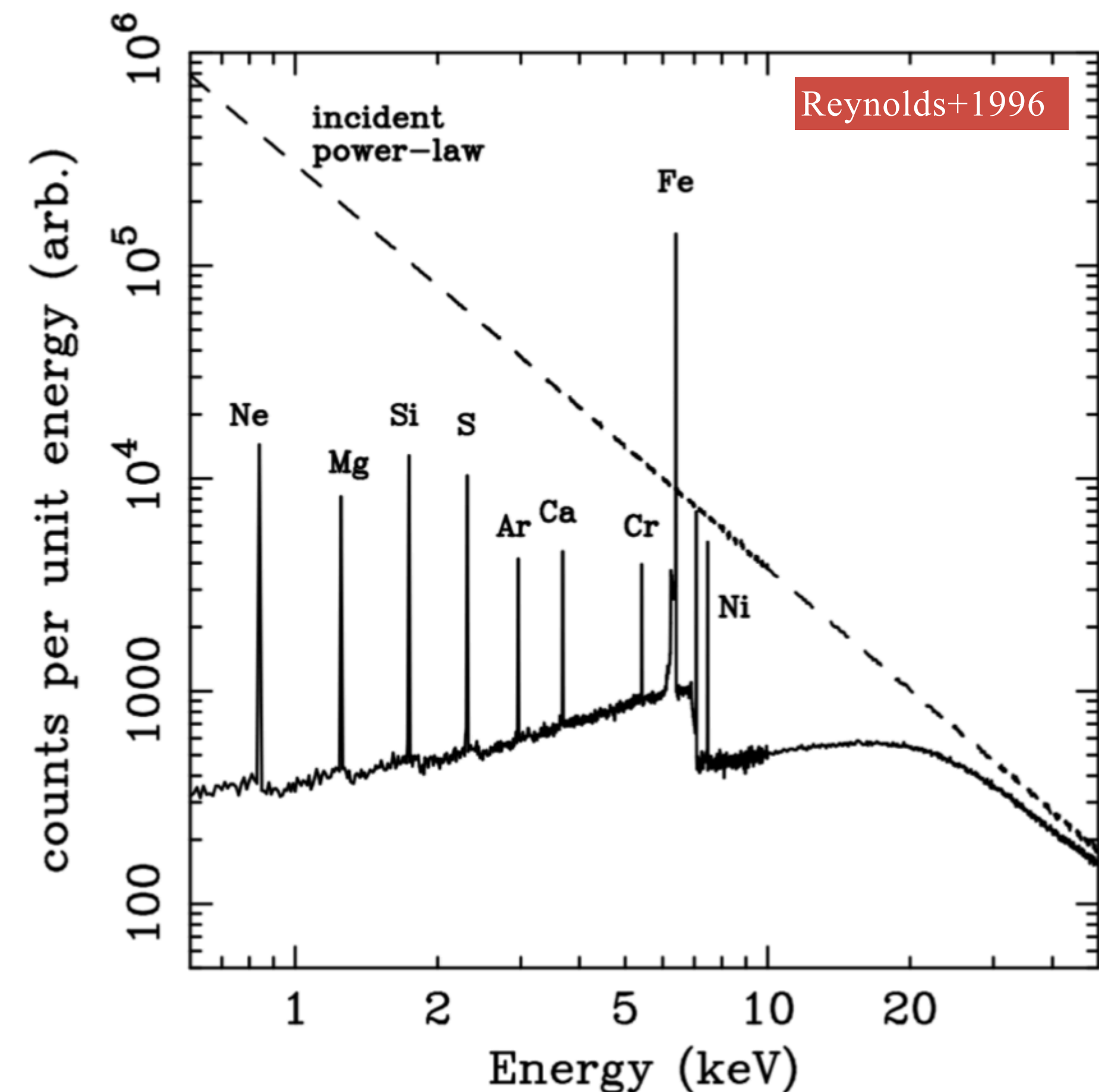


Reflection spectra

Main NS LMXBs spectral components



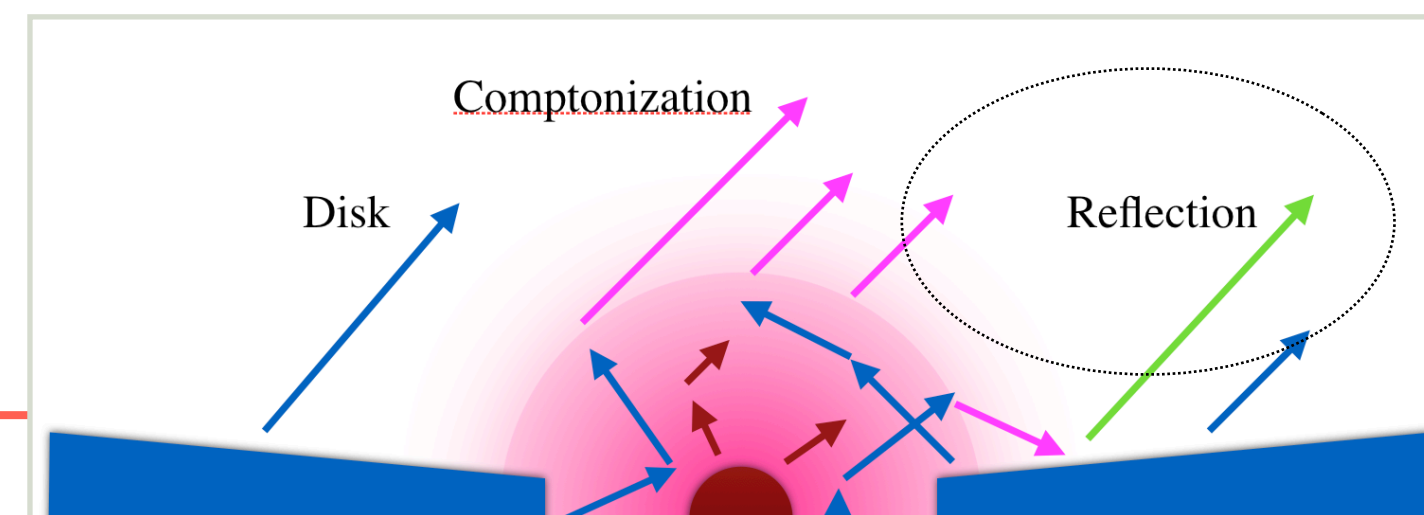
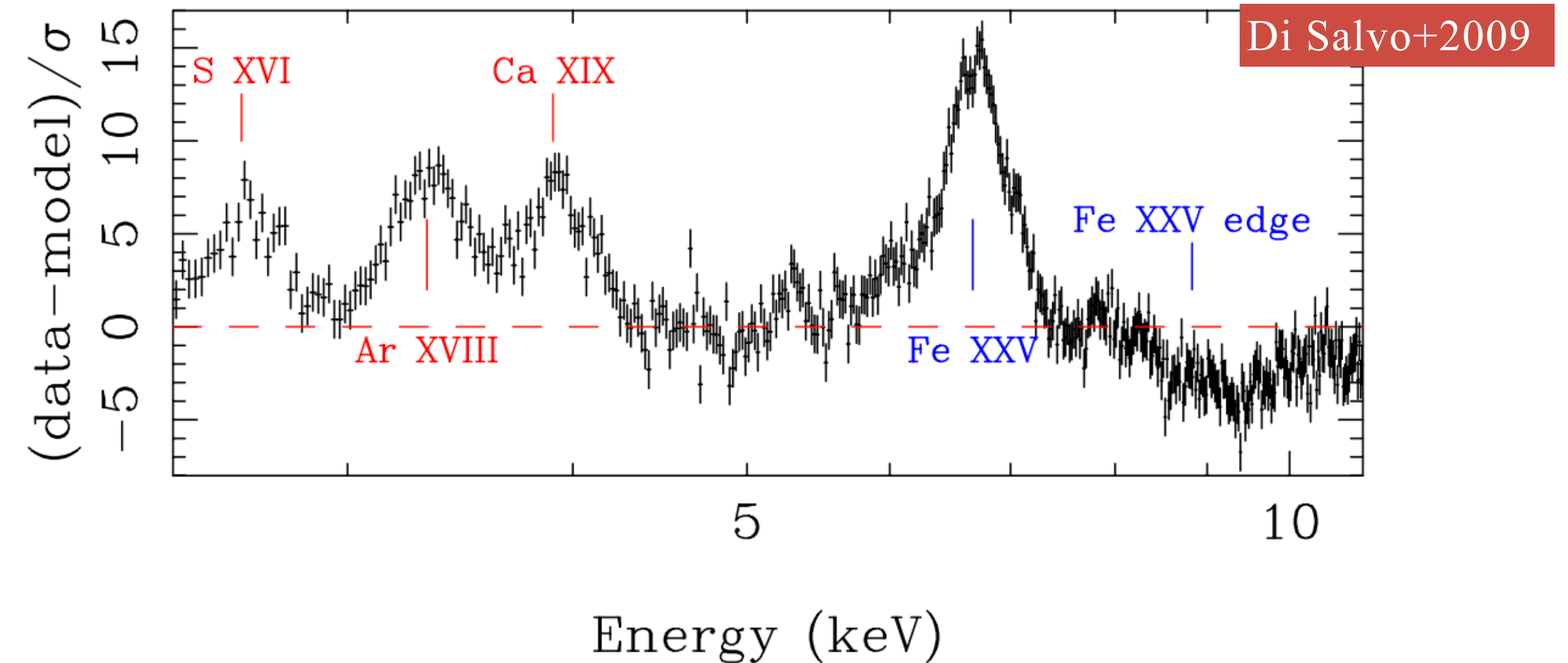
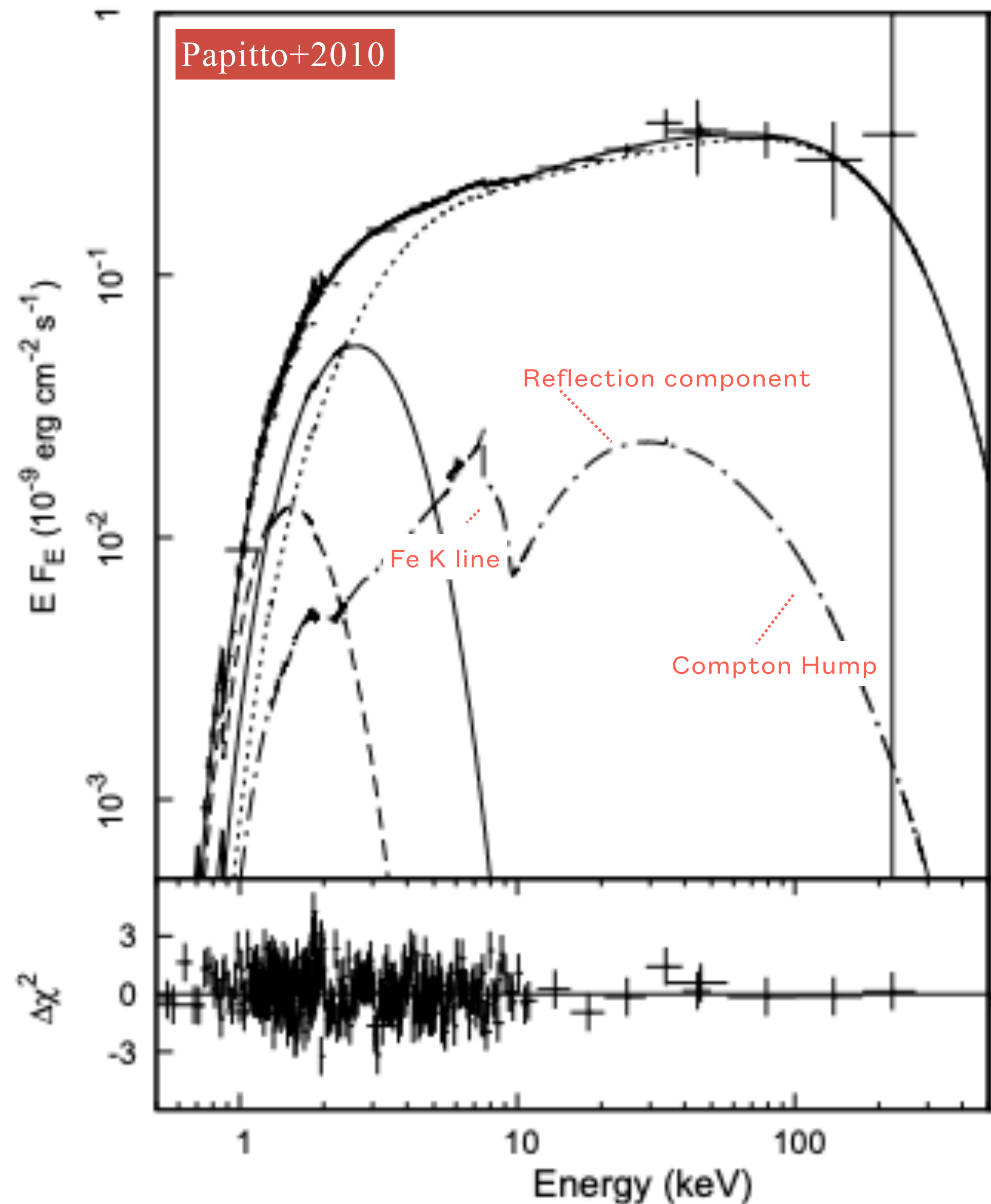
- A fraction of the Comptonisation spectrum hitting the disc undergoes a reprocessing and arises a **reflection component**;





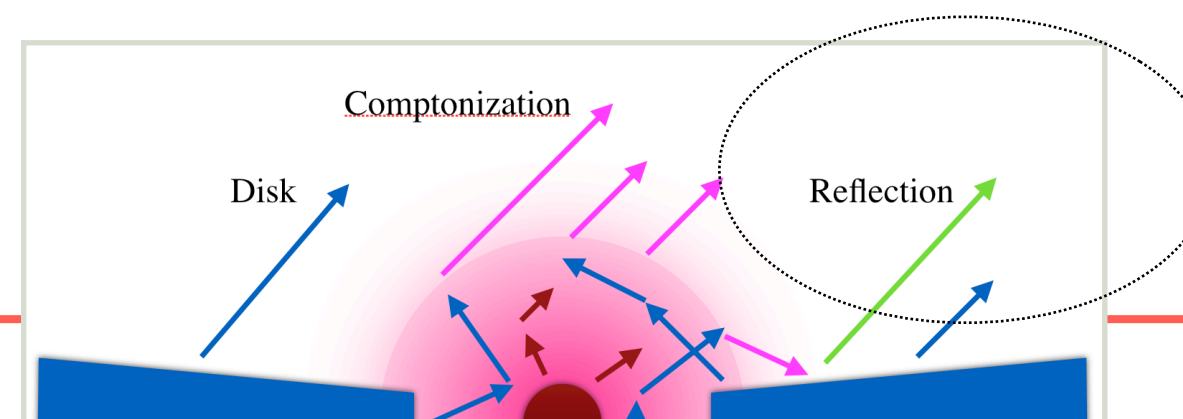
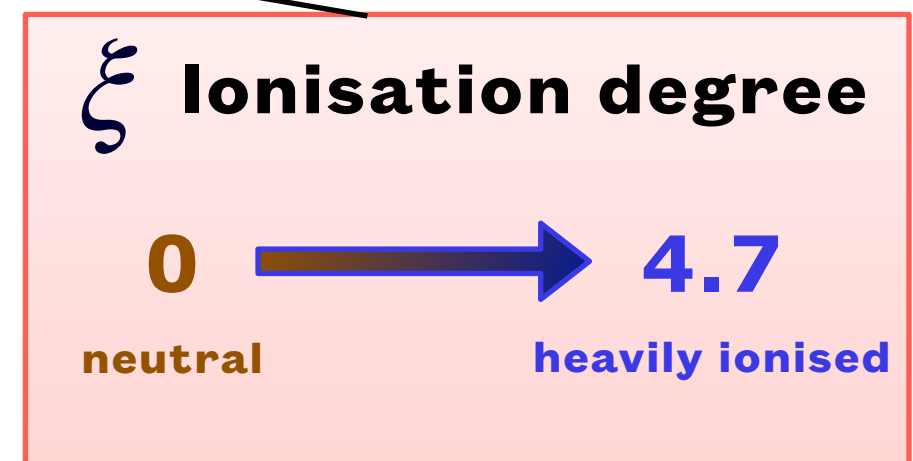
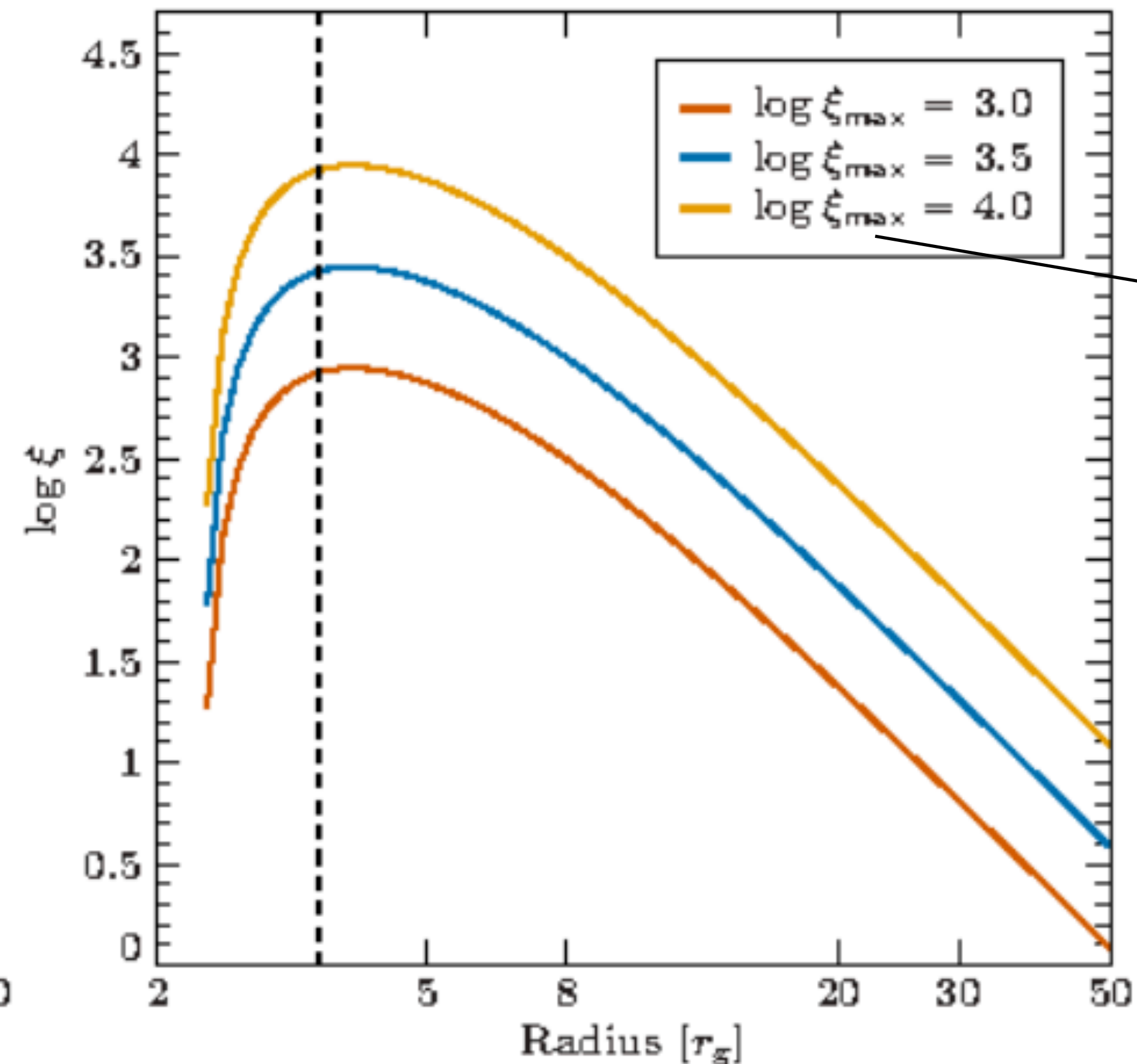
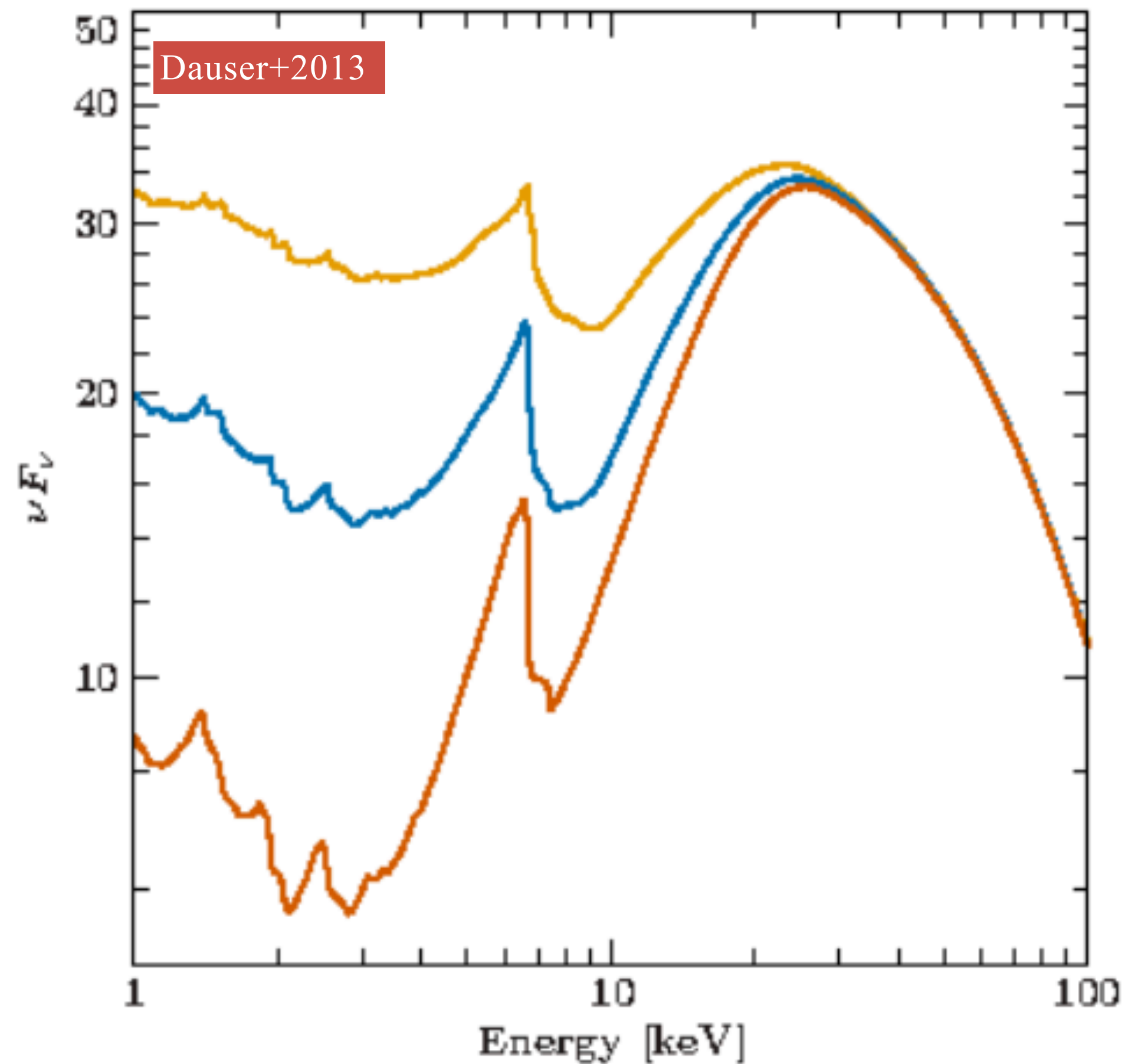
Reflection spectra

- A fraction of the Comptonisation spectrum hitting the disc undergoes a reprocessing and arises a **reflection component**;
- Most prominent features: a Compton hump (at about 10-30 keV), a fluorescence Fe K line at about 6-7 keV and several other discrete features and absorption edges;



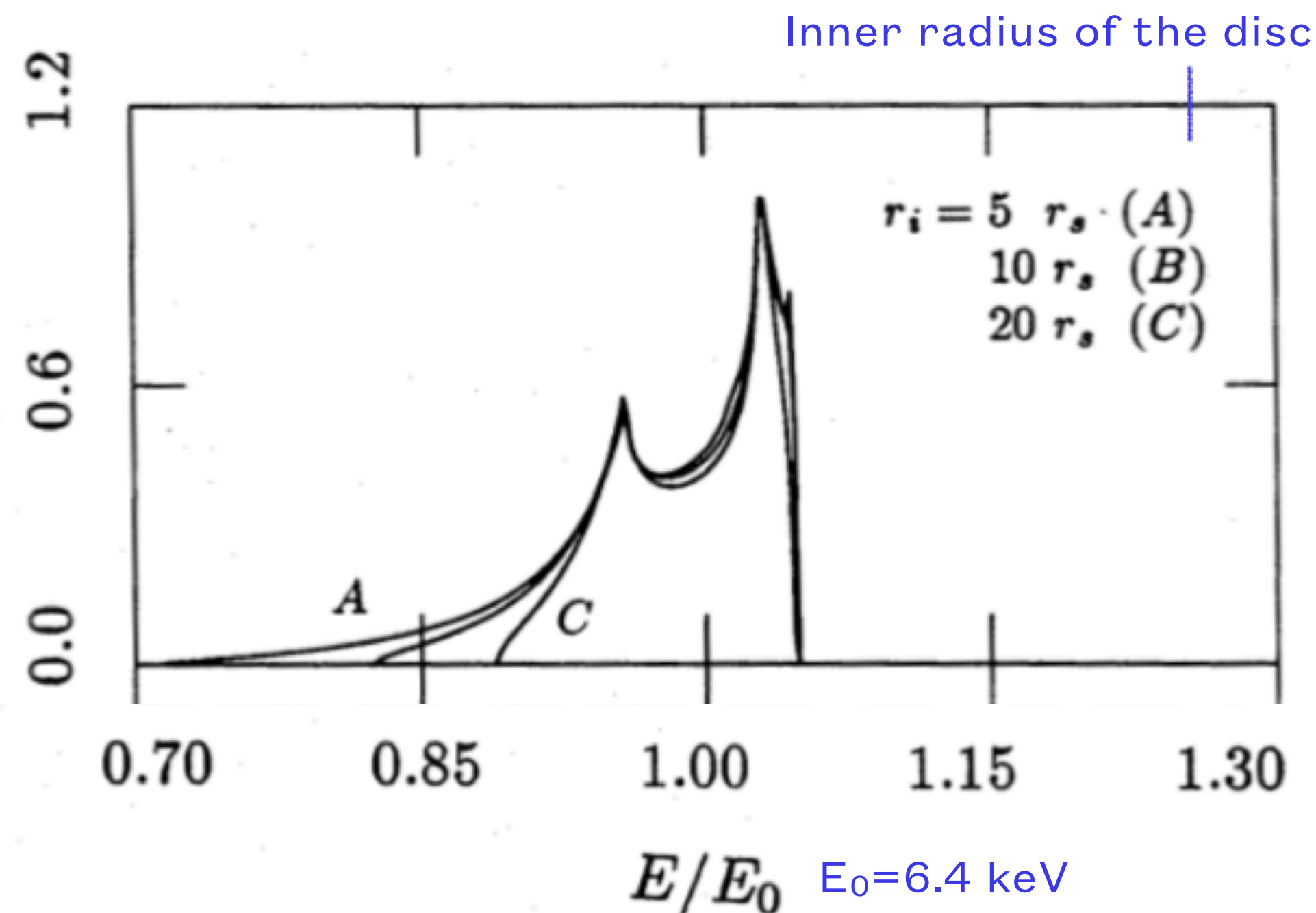
Reflection spectra

- The shape of the overall reflection spectrum is influenced by **the inclination of the system, the ionisation of the disc, the amount of radiation intercepted by the disc..**



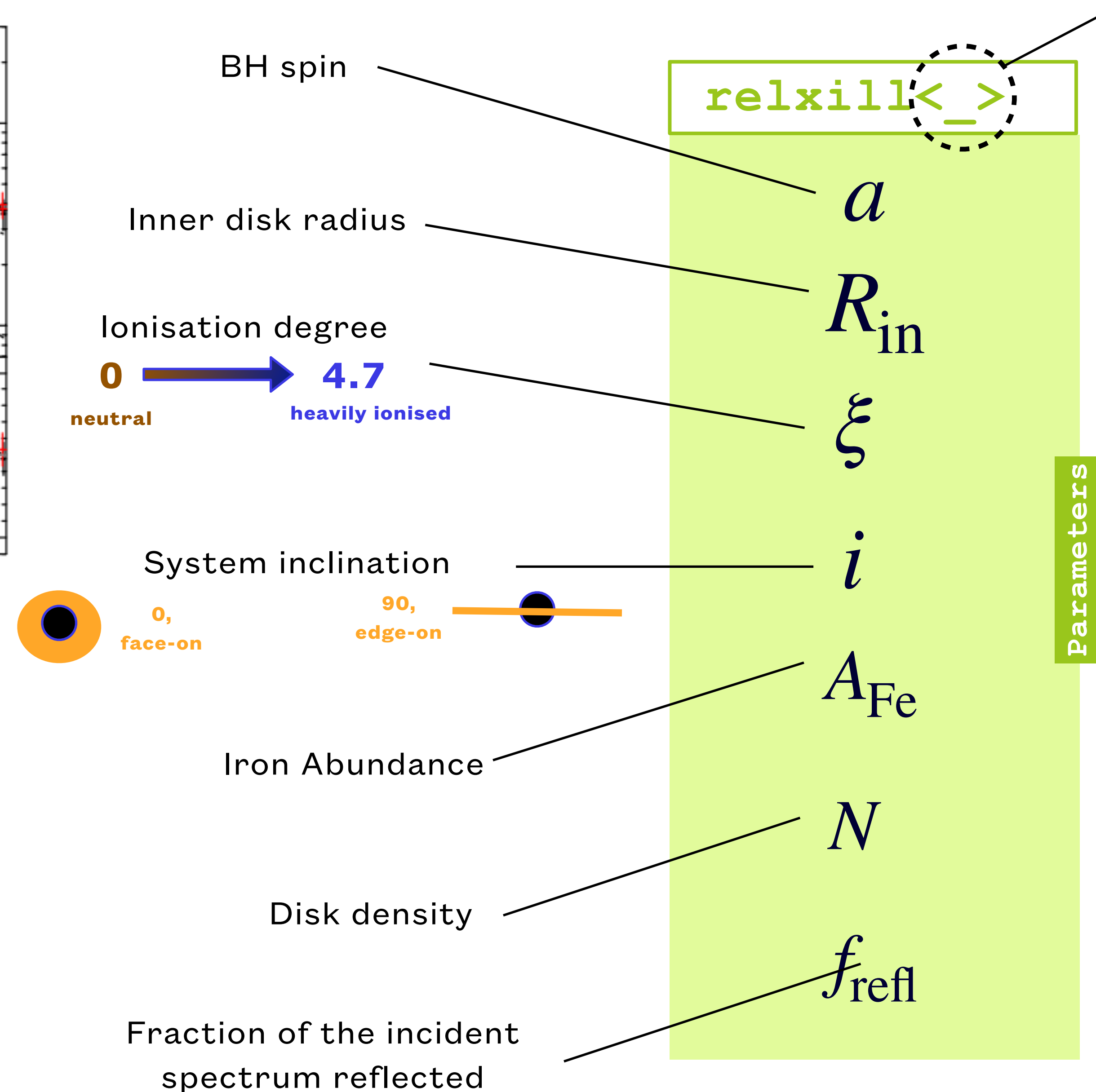
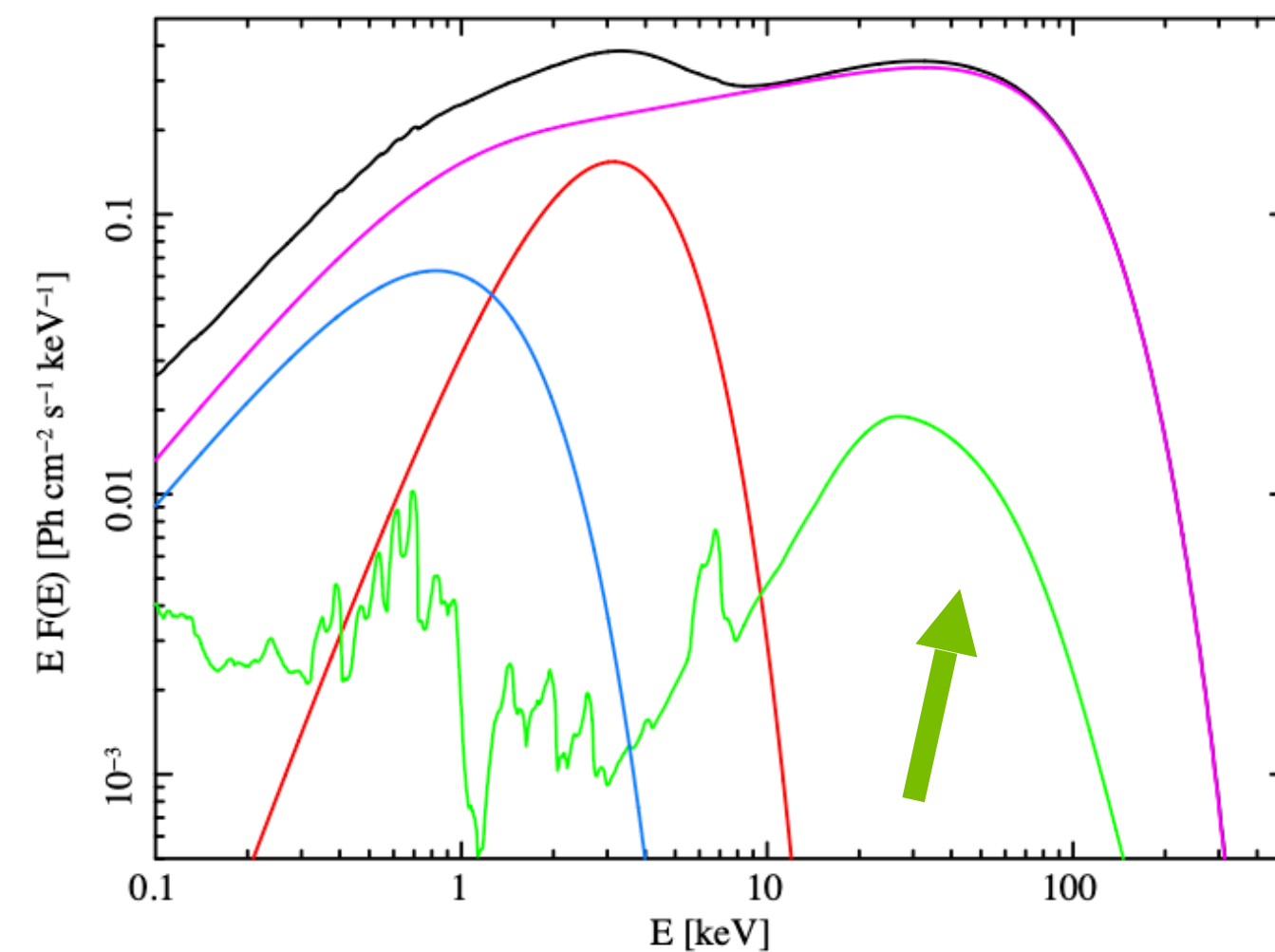
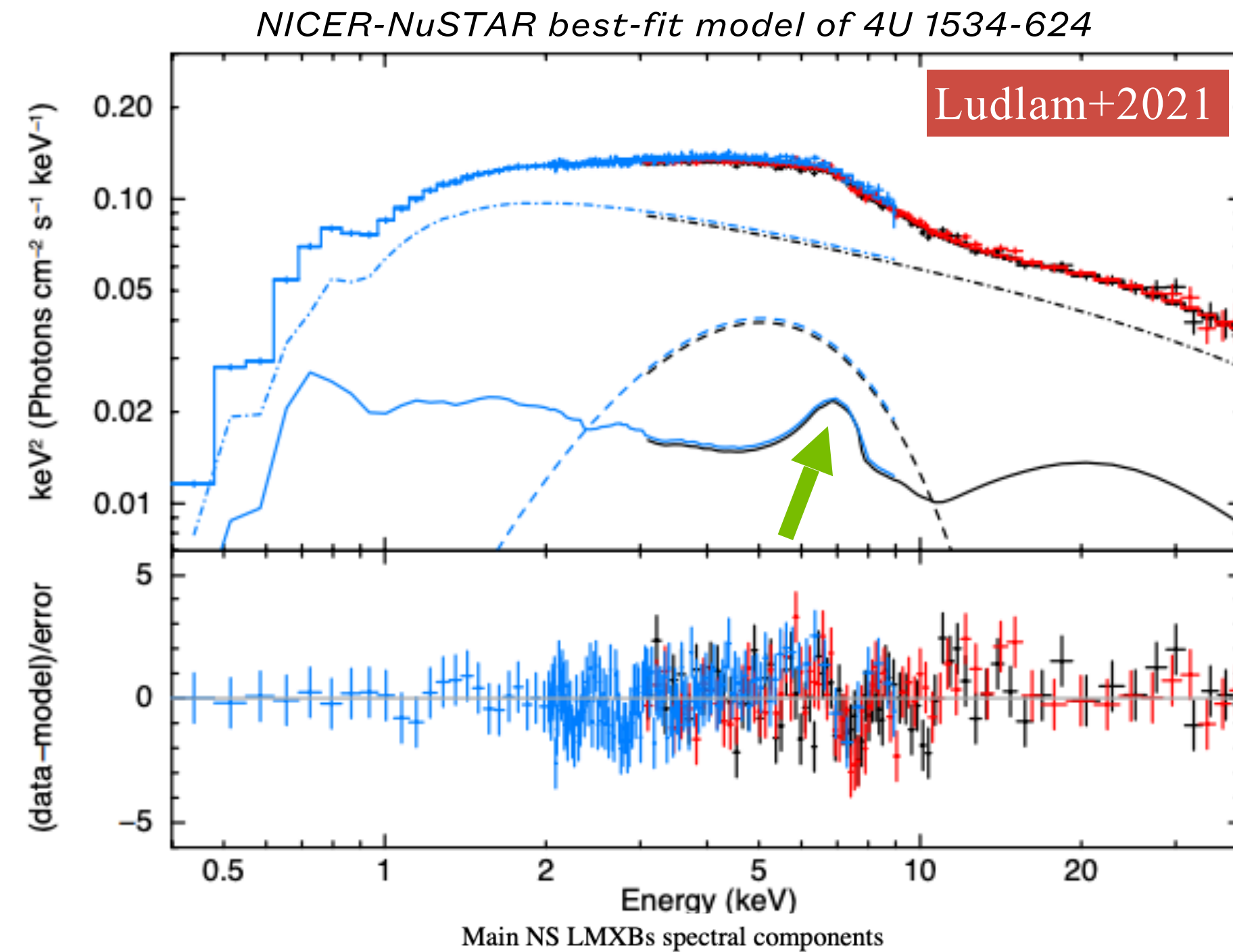
Studying the Fe line

A diagnostics for the innermost regions of the accretion flow



- A fluorescence line emitted by atoms or ions of Fe (transition from $n=2$ to $n=1$ after photoionisation);
- The profile of this line is altered by several effects, in particular by how rapidly material moves at the inner edge of the disk (Doppler broadening + relativistic effects);
- Modelling the profile of this line allows to measure the **inner radius of the disk**, with several applications.



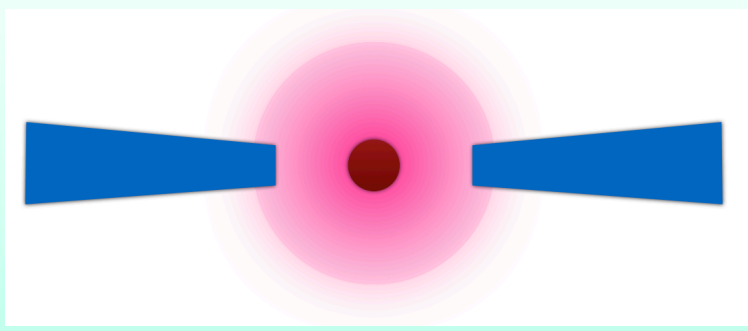


Dauser+2010, 2013, 2014, 2022 ;
Garcia+2010, 2014, 2016, 2023...

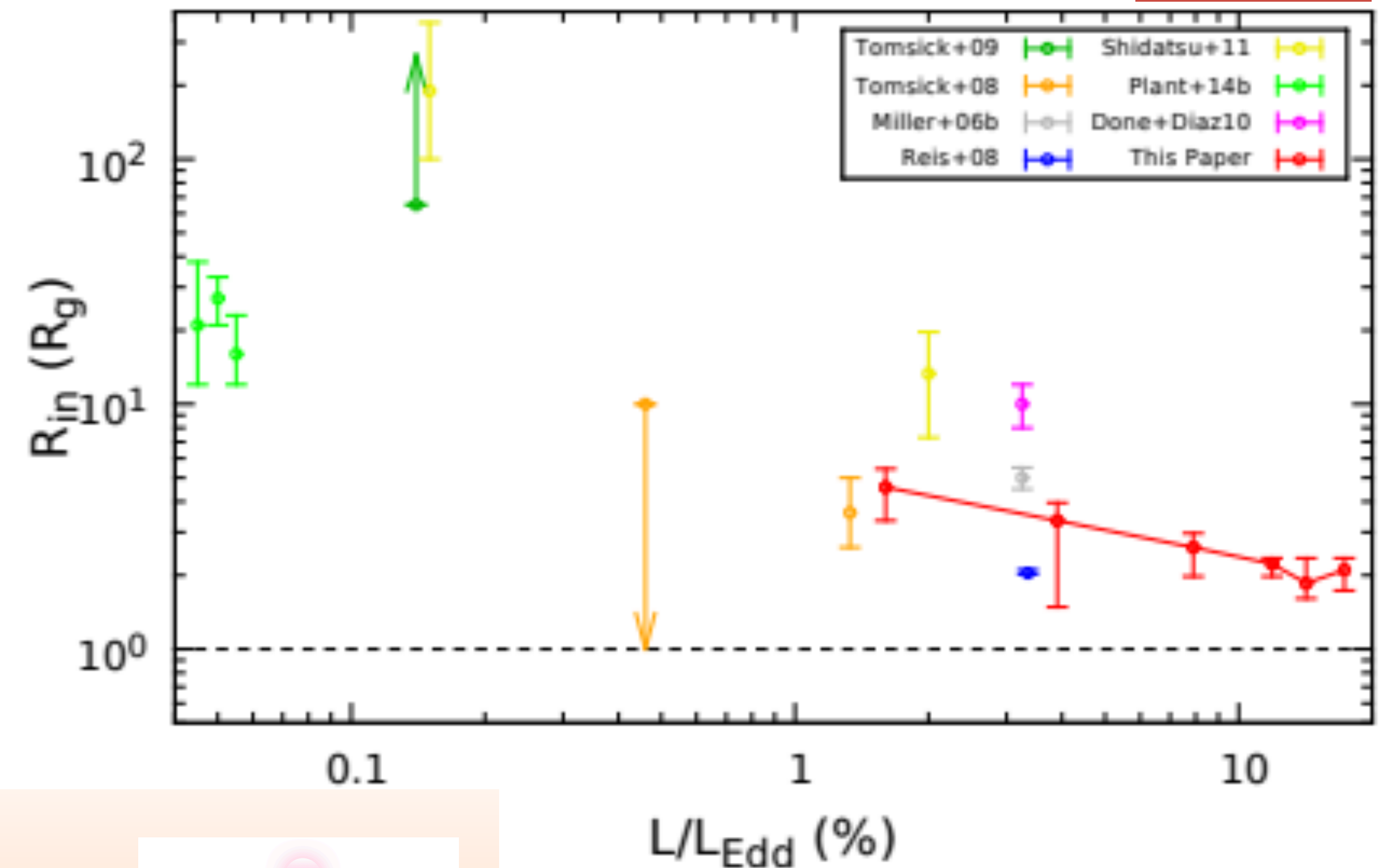
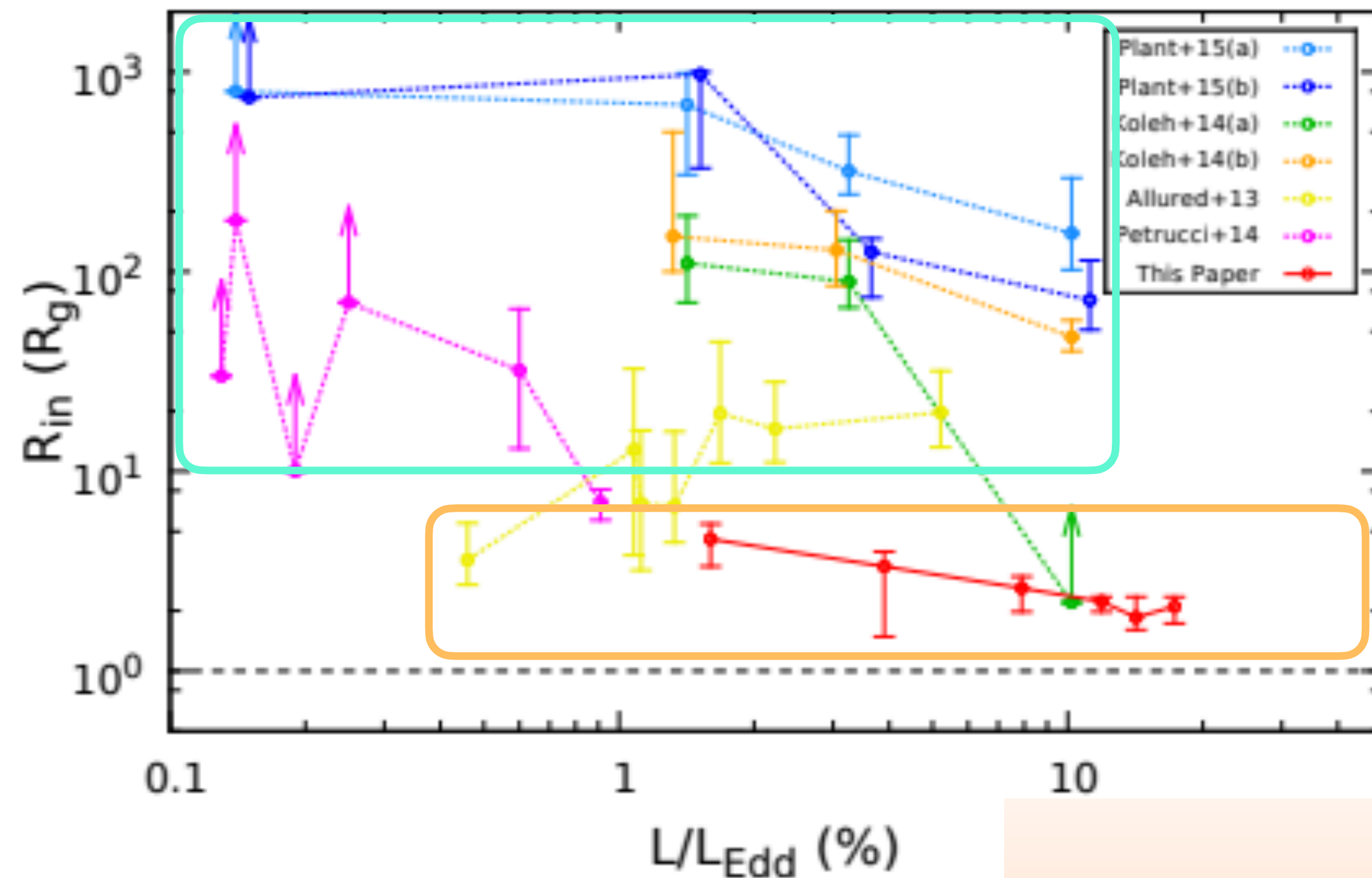
The inner edge of the disk i: *Geometry of the accretion flow*

- Measuring the inner edge of the disk gives the opportunity to determine the accretion flow configuration of the system;

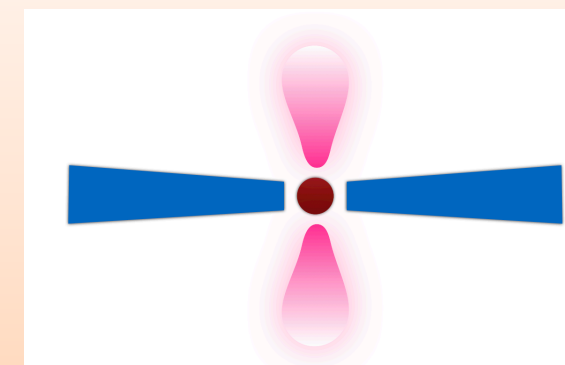
Truncated disk +
hot inner flow



Garcia+2015



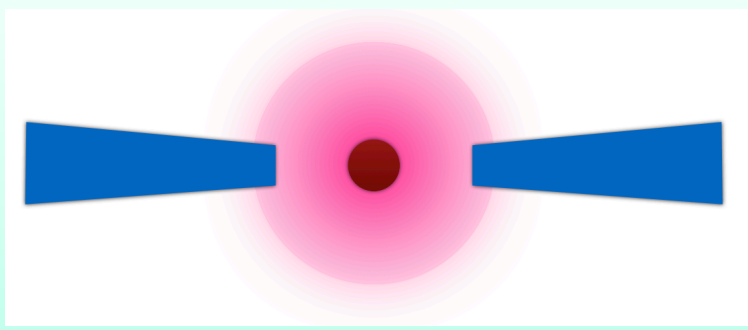
Untruncated disk +
lamppost corona



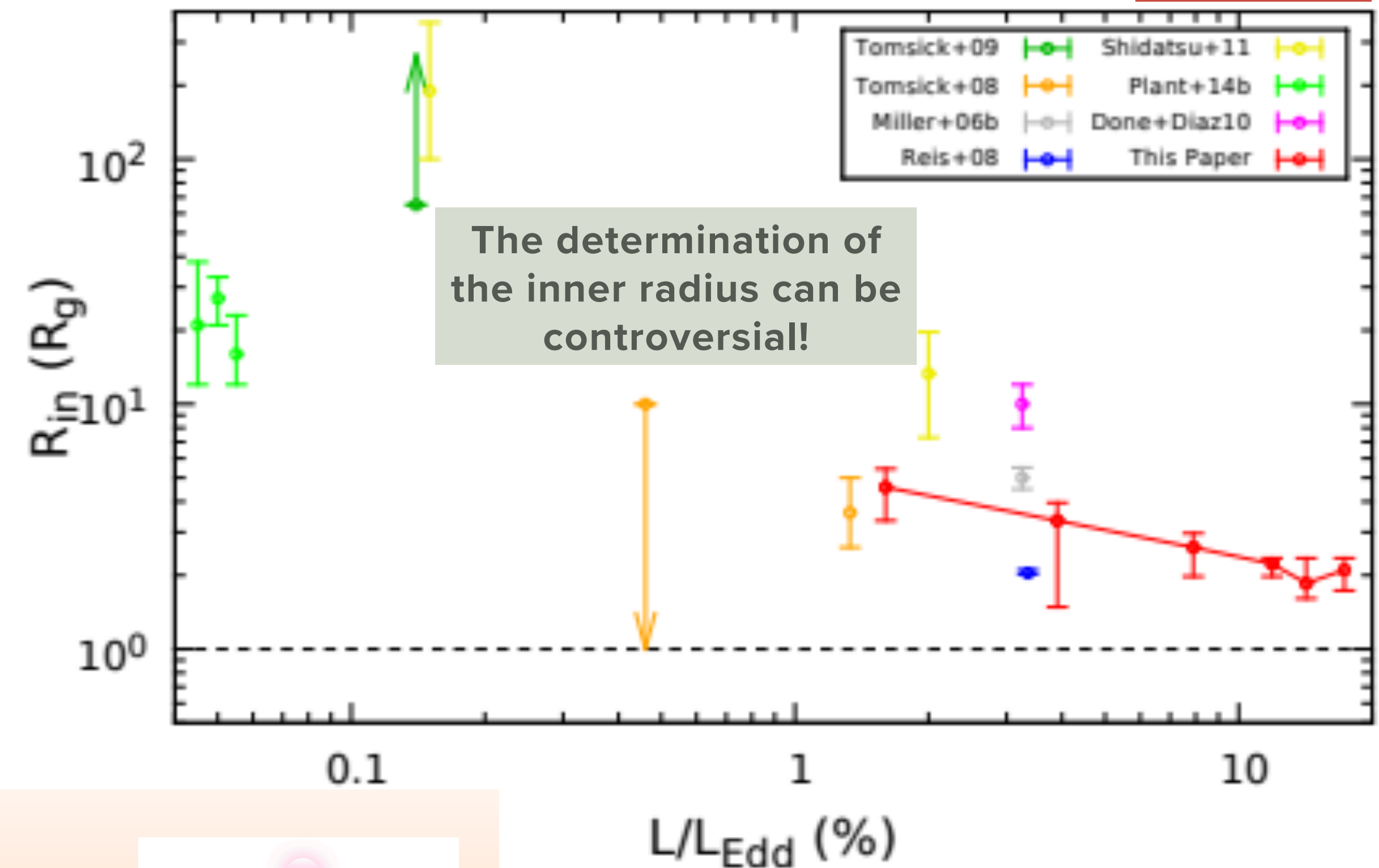
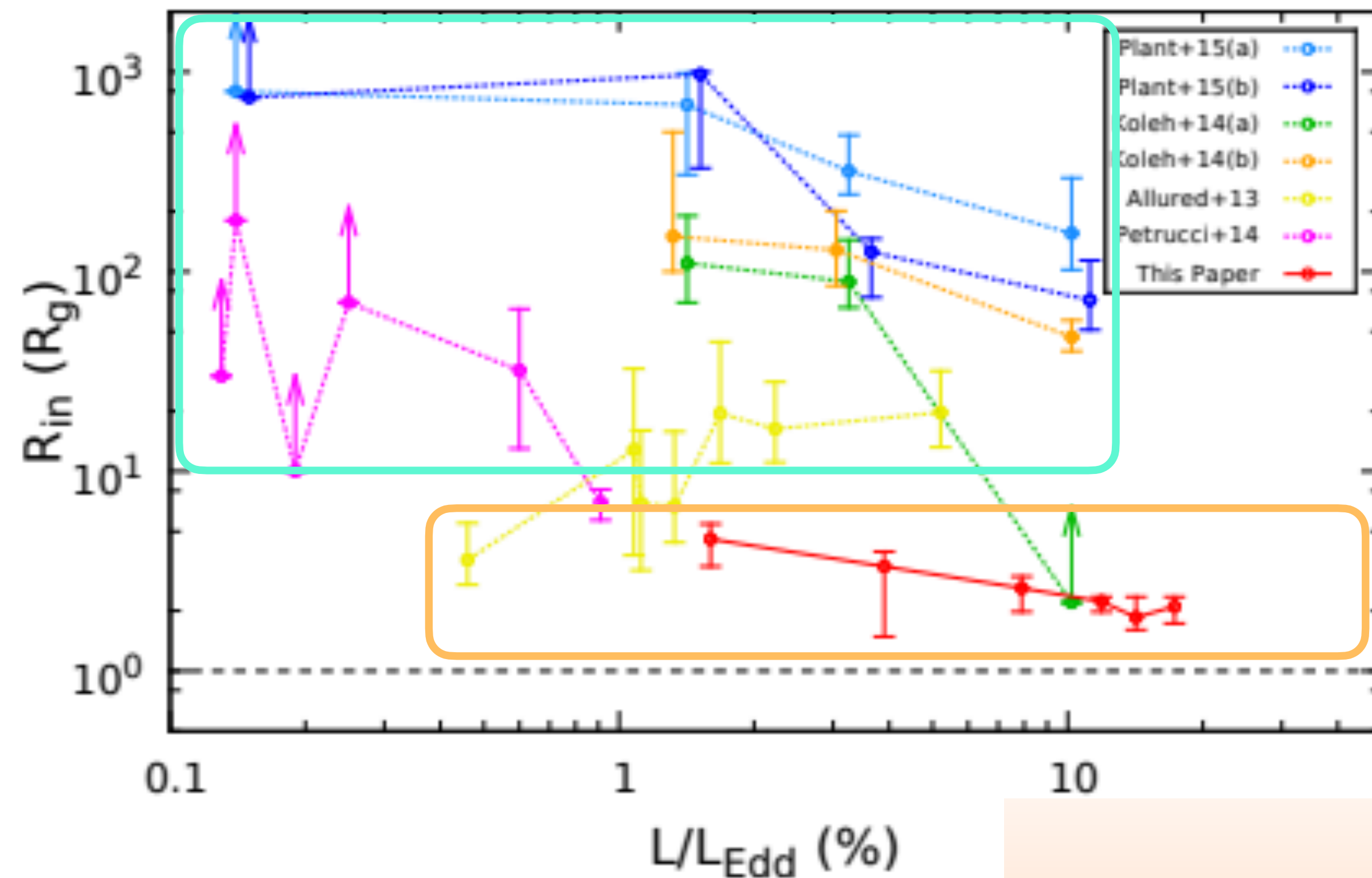
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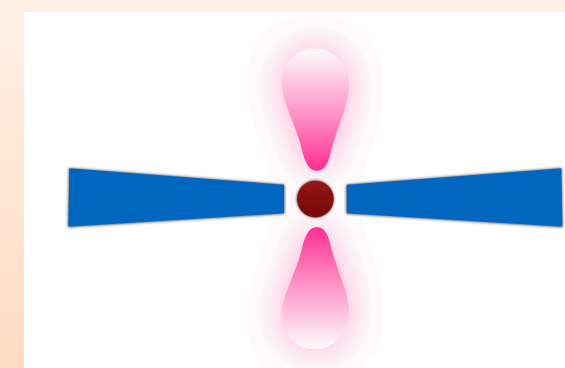
Truncated disk +
hot inner flow



Garcia+2015

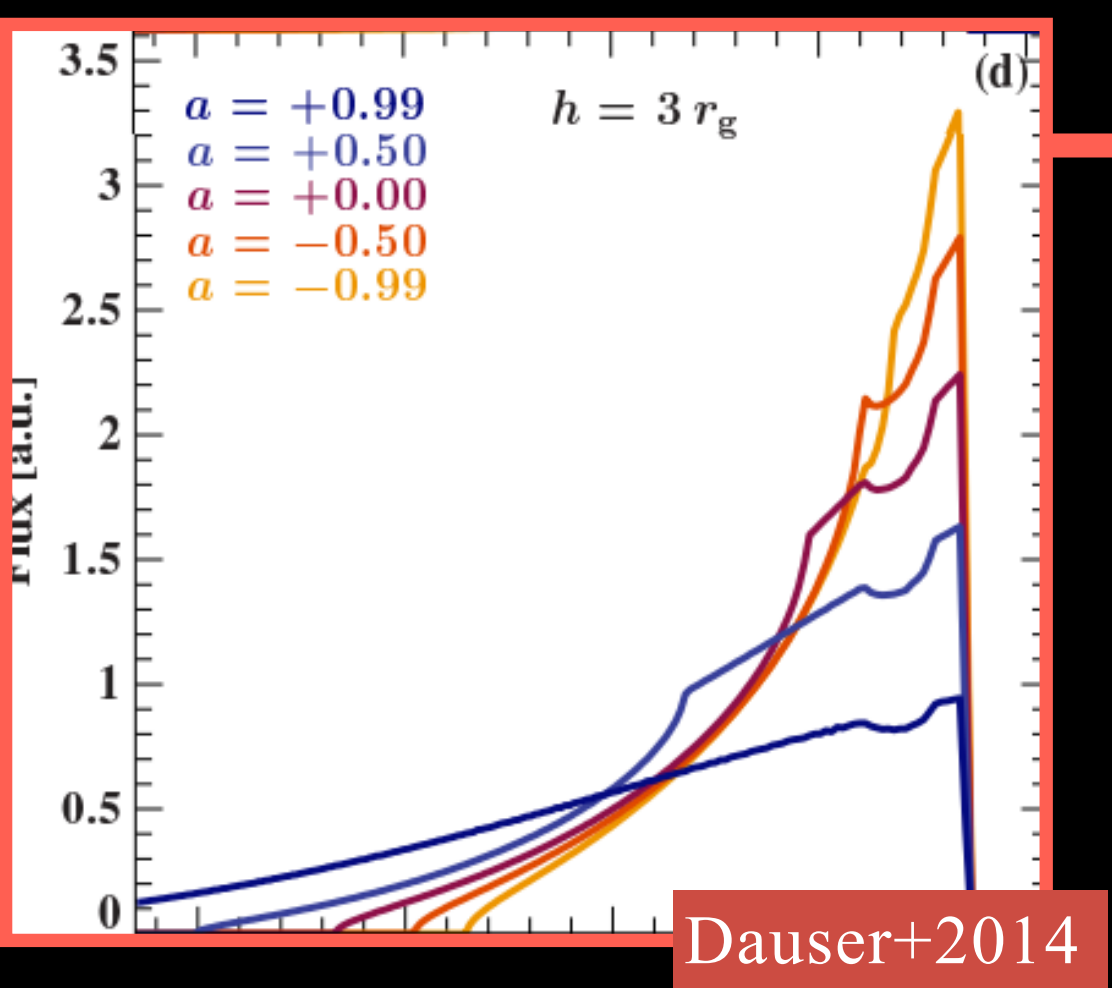


Untruncated disk +
lamppost corona

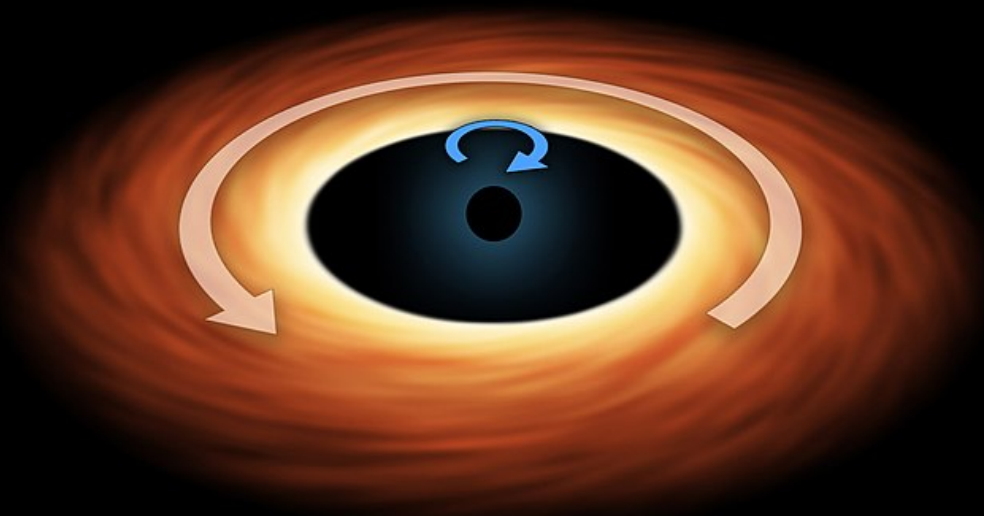


The inner edge of the disk ii: *Black hole spins*

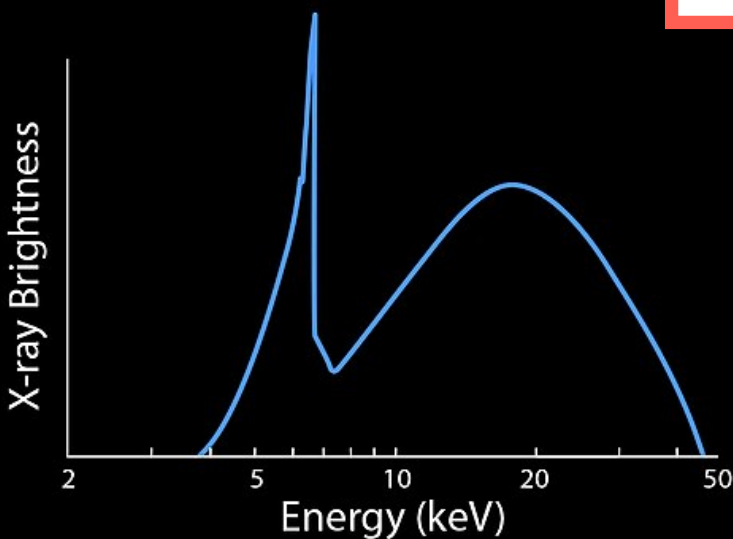
- For untruncated disks, the exact value of the inner edge allows to **measure the spin of the Black Hole**.
- The closest that a disk can get to the BH is indeed the **Innermost Stable Circular Orbit (ISCO)**;



$$r_{\text{ISCO}} = \frac{9GM}{c^2}$$

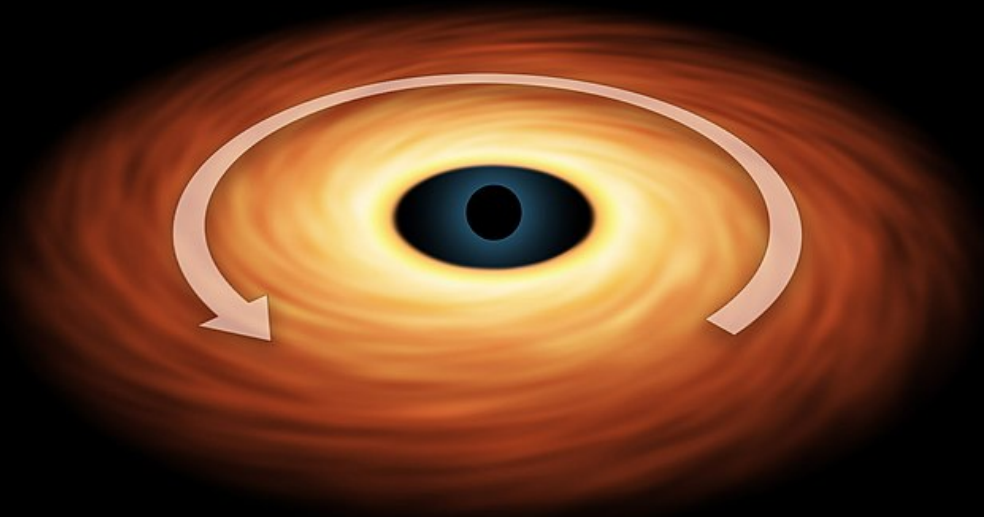


Retrograde Rotation

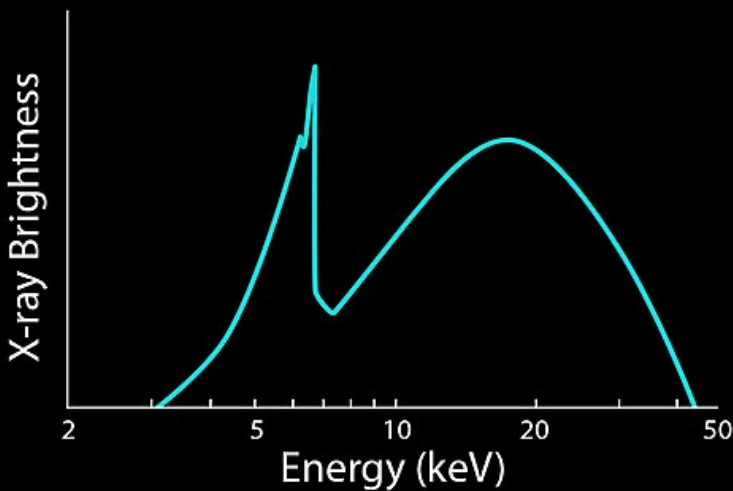


(Maximally rotating)

$$r_{\text{ISCO}} = \frac{6GM}{c^2}$$

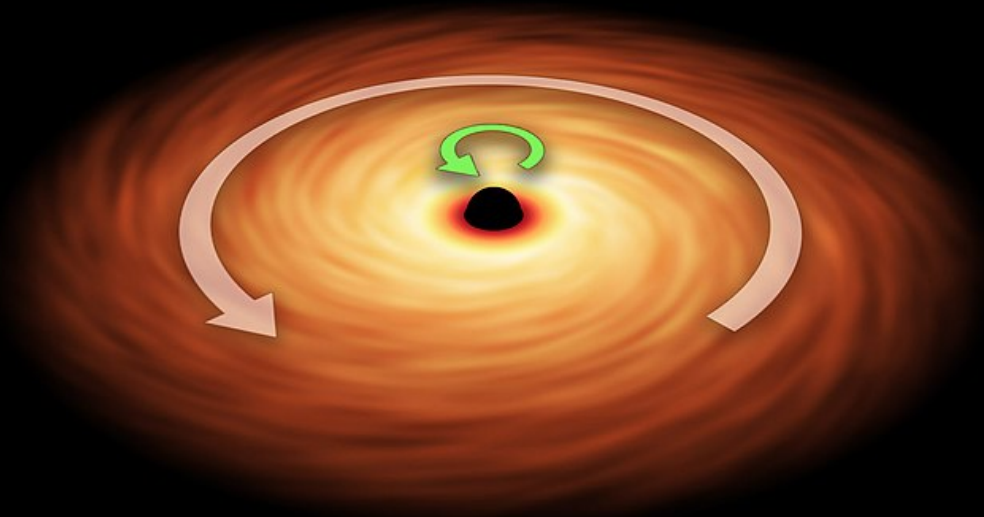


No Black Hole Rotation

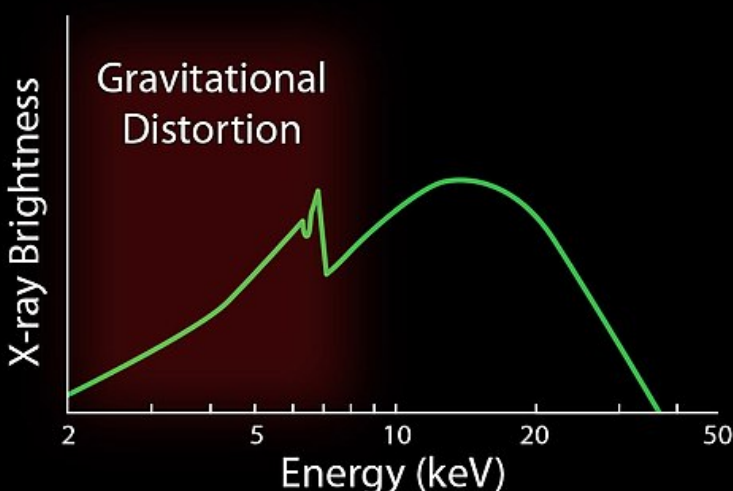


(Non-rotating)

$$r_{\text{ISCO}} = \frac{GM}{c^2}$$



Prograde Rotation

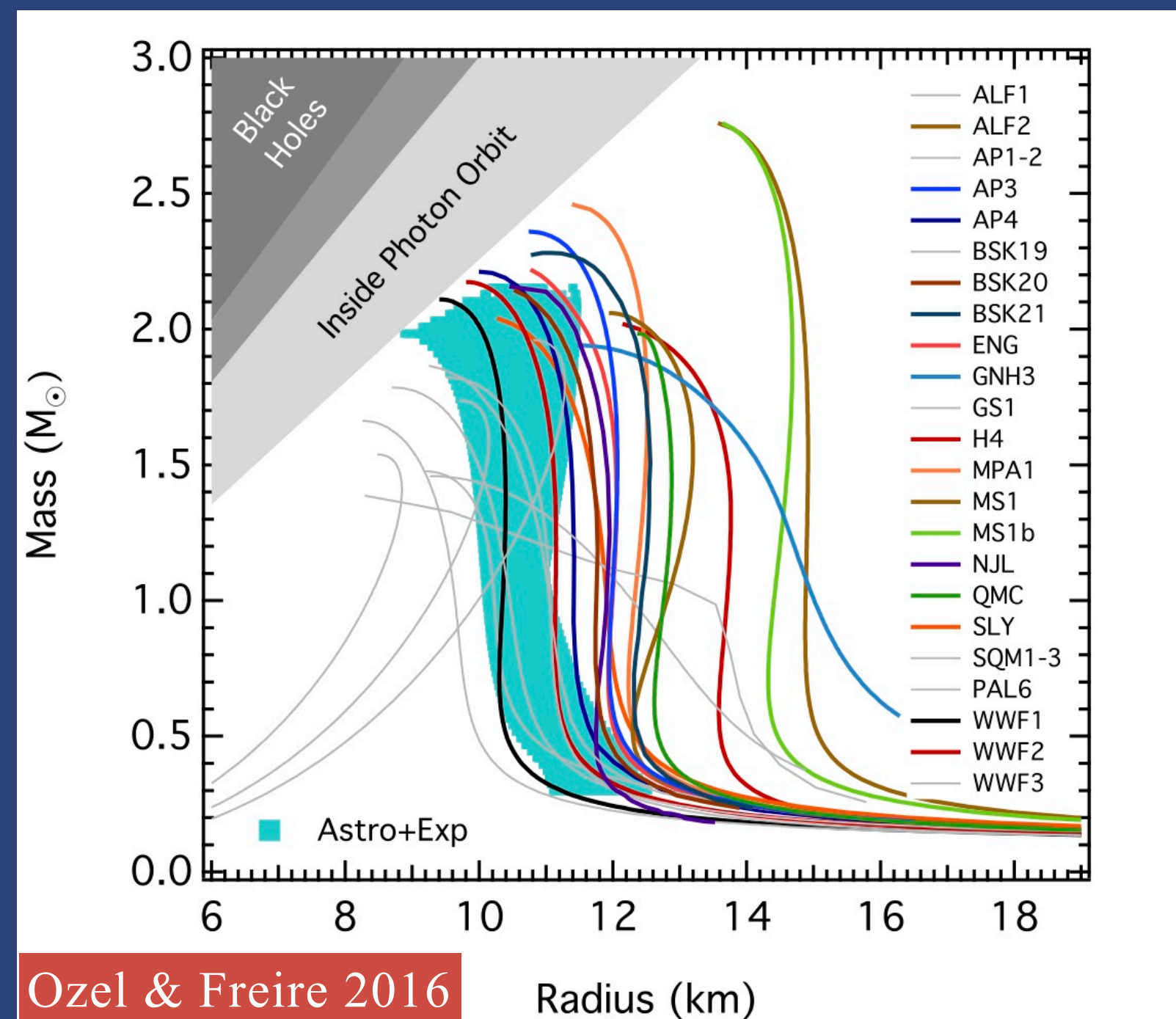


(Maximally rotating)



The inner edge of the disk iii: *Constraints on the EoS*

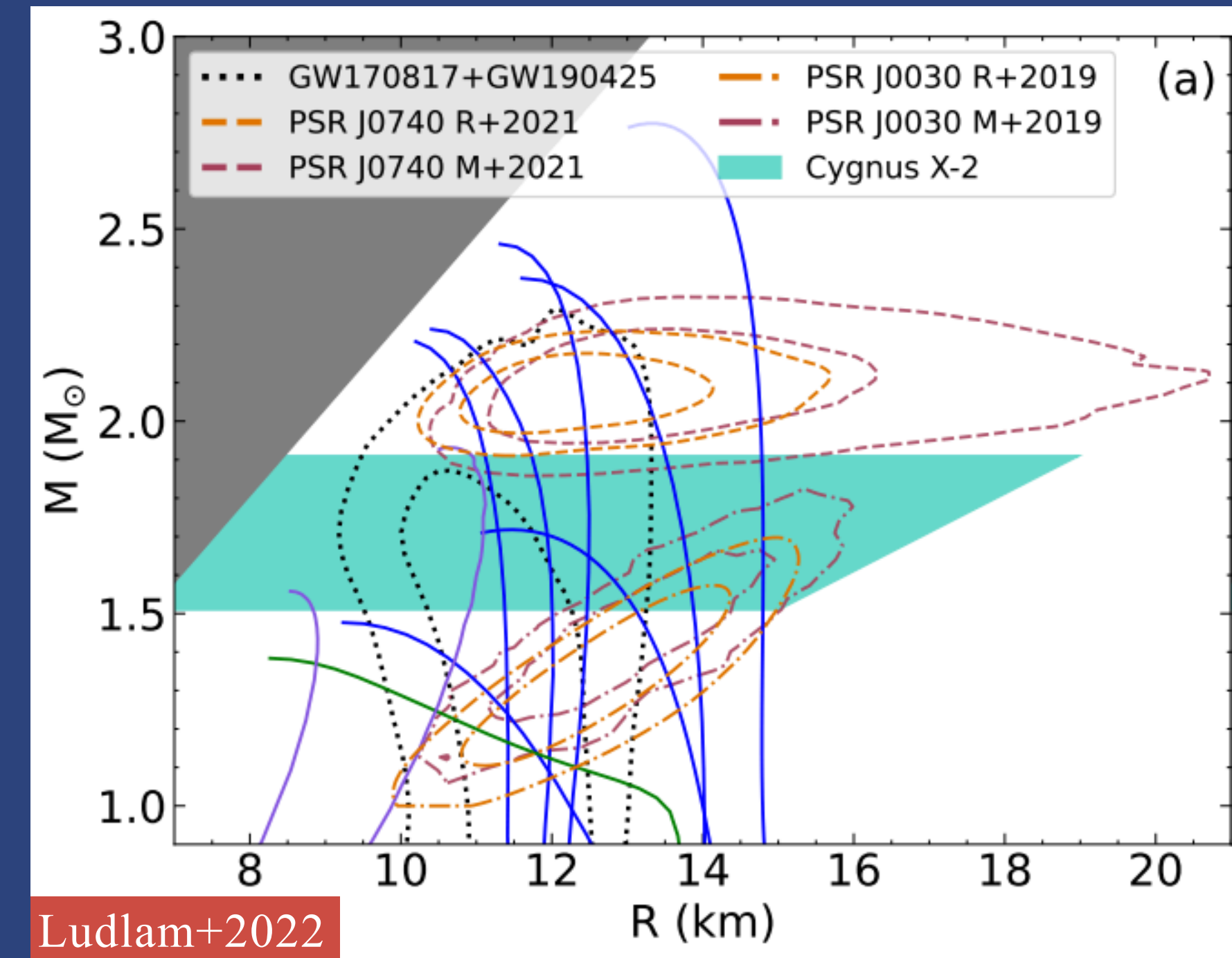
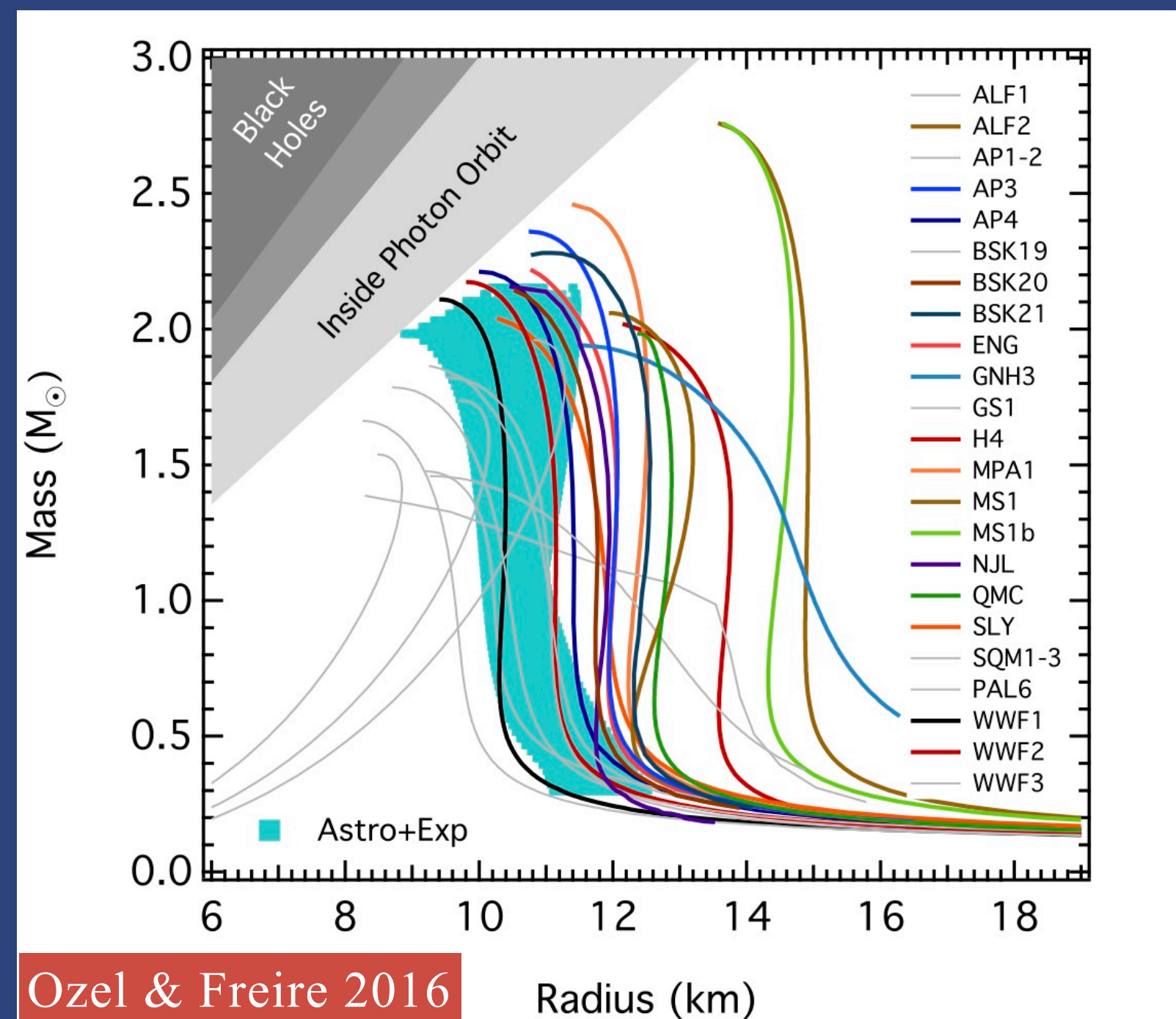
- Finding the right EoS is a goal of modern astrophysics.
- Any EoS can be expressed as a relation between Mass and Radius of the NS;
- How can we measure them?



The inner edge of the disk iii: Constraints on the EoS

Constraints on the NS radius of Cyg X-2 from the spectral analysis

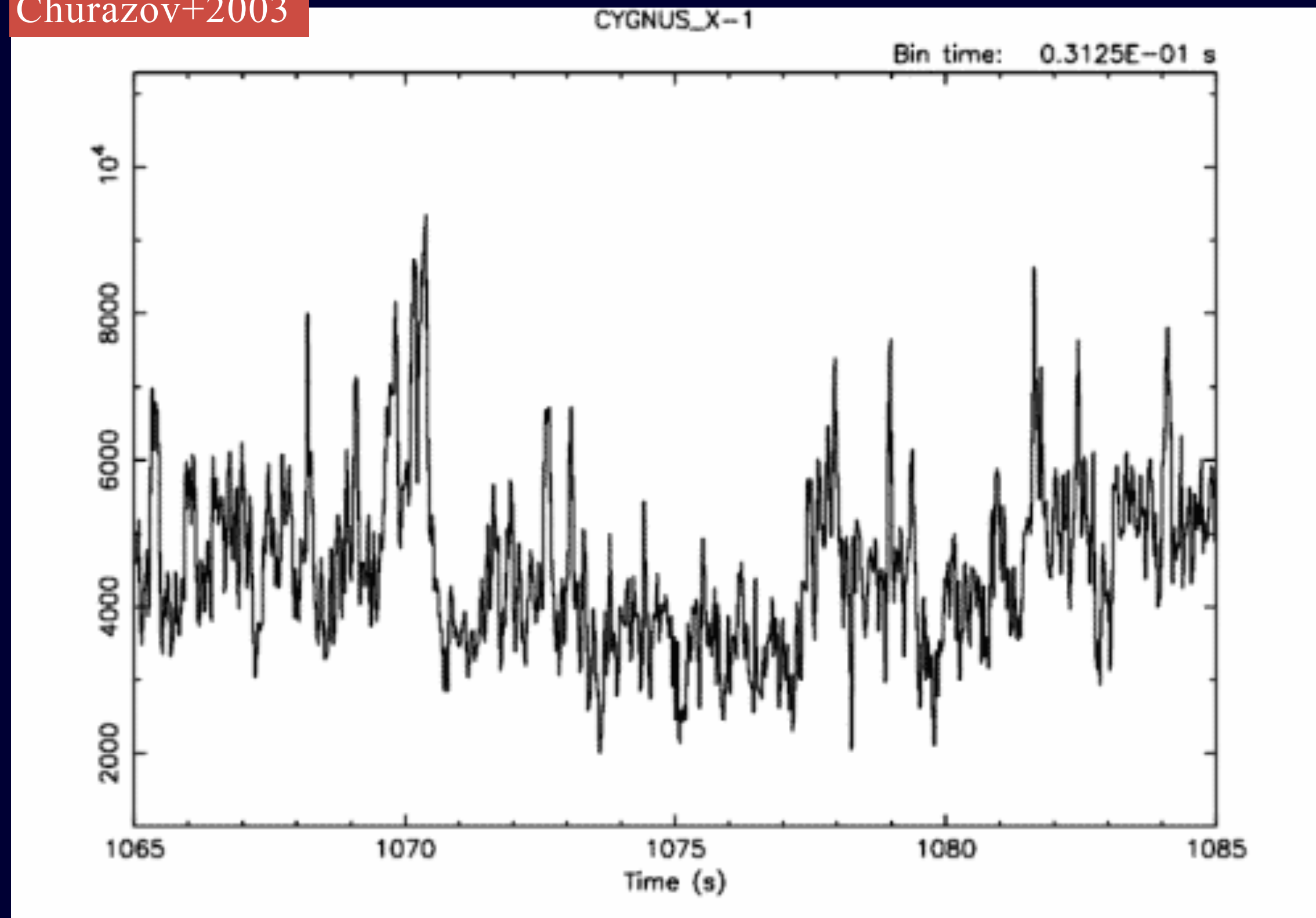
- Finding the right EoS is a goal of modern astrophysics.
- Any EoS can be expressed as a relation between Mass and Radius of the NS;
- How can we measure them?



- The inner radius of the disk is an upper limit on the NS radius!
- Spectral analysis of the reflection component and in particular of the Fe K line can be used as a tool to constrain the Equation of State of the Ultra-dense matter);

Inspecting the innermost regions of accretion flows: (incoherent) timing analysis

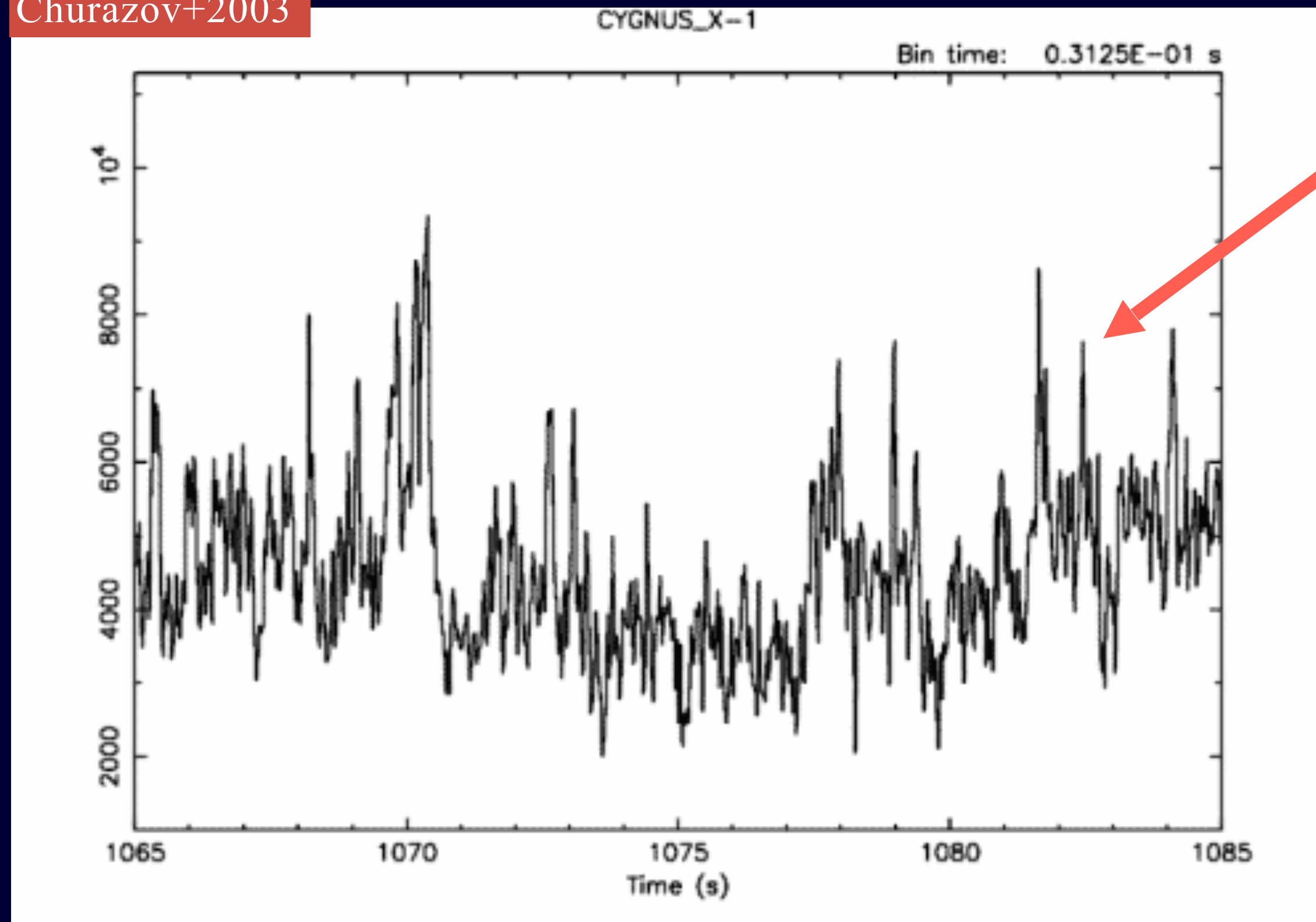
Churazov+2003



- Short-term light curve of the BH XRB Cyg X-1

Inspecting the innermost regions of accretion flows: (incoherent) timing analysis

Churazov+2003



Very variable over different time-scales!

- Short-term light curve of the BH XRB Cyg X-1



Power density spectra (PDS) in X-ray binaries

X-rays
light curve

$x(t)$

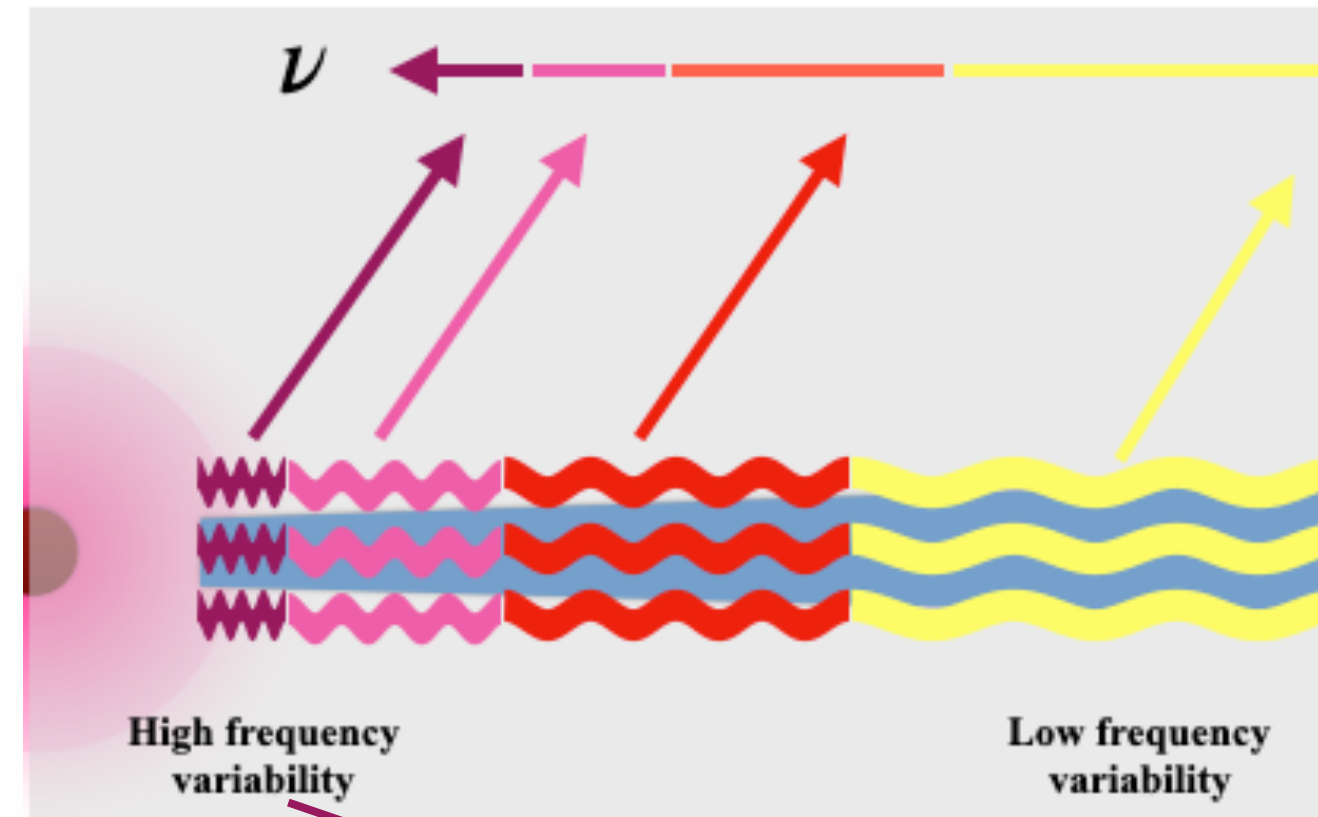
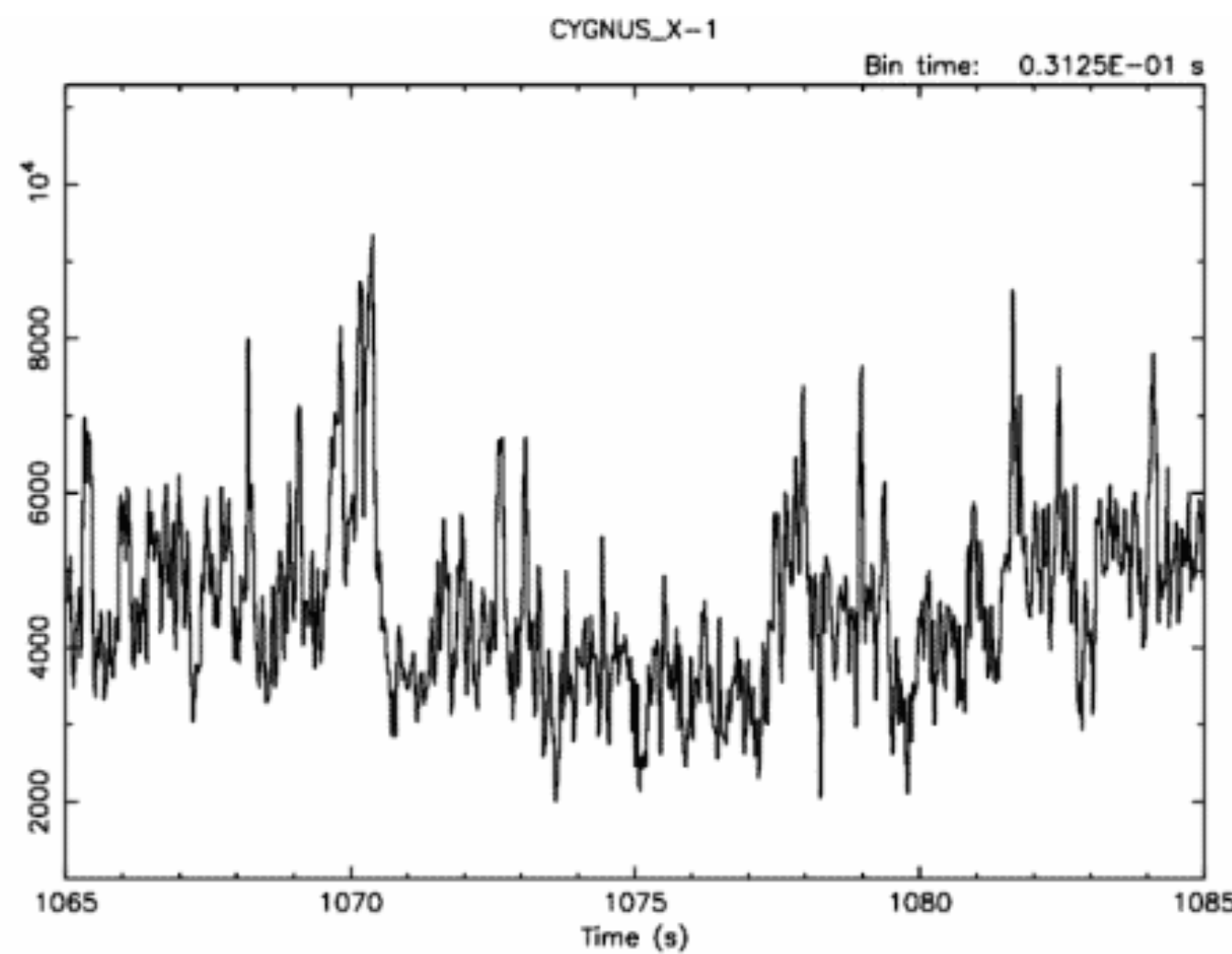
Fourier
transform

$X(\nu)$

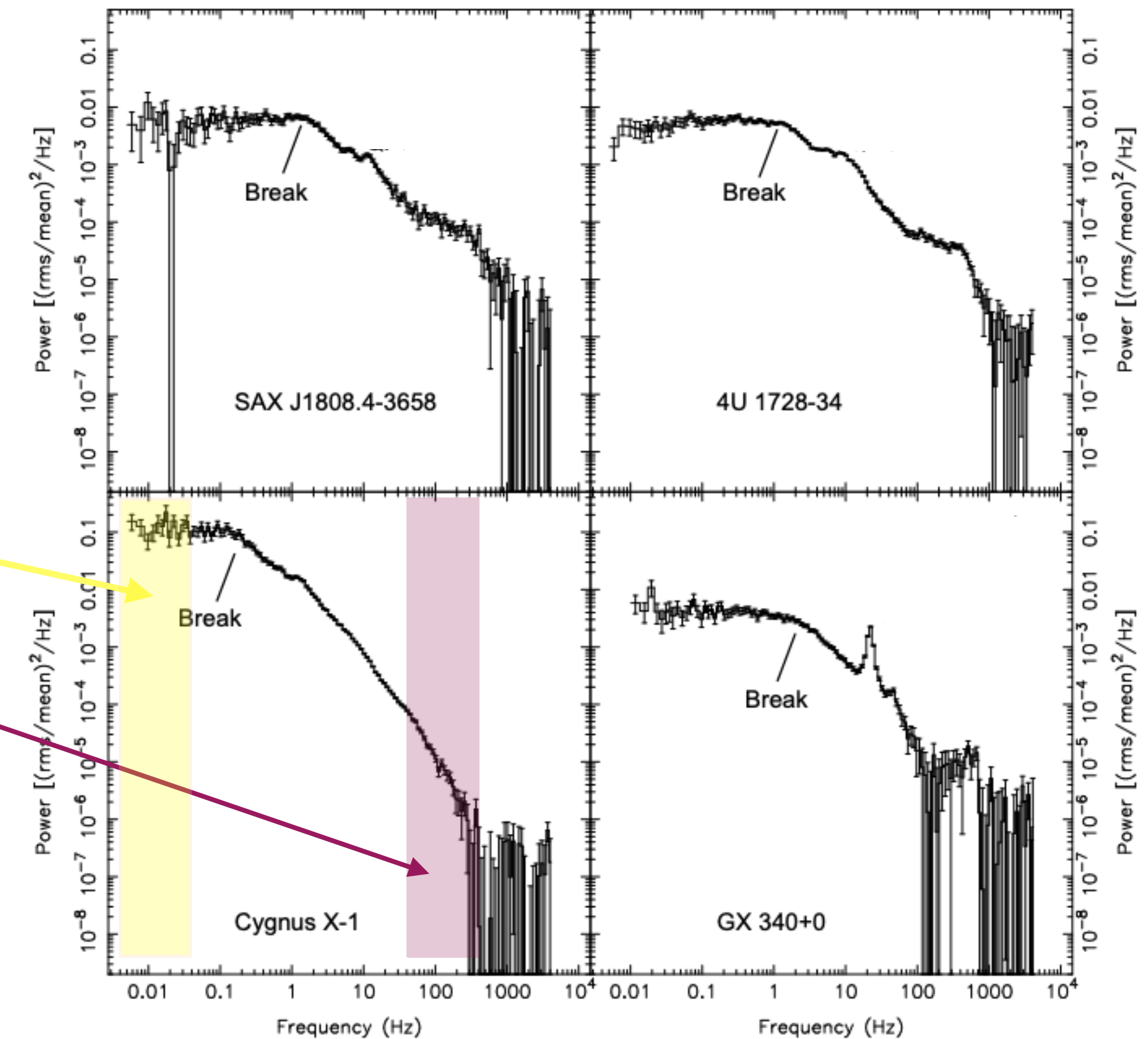
Power
spectrum

$$P(\nu) = |X(\nu)|^2$$

Wijnands & Van der Klis 1999



- The power density spectrum contains information on how “variable” the X-ray emission of a XRB is at different frequency / time-scales;

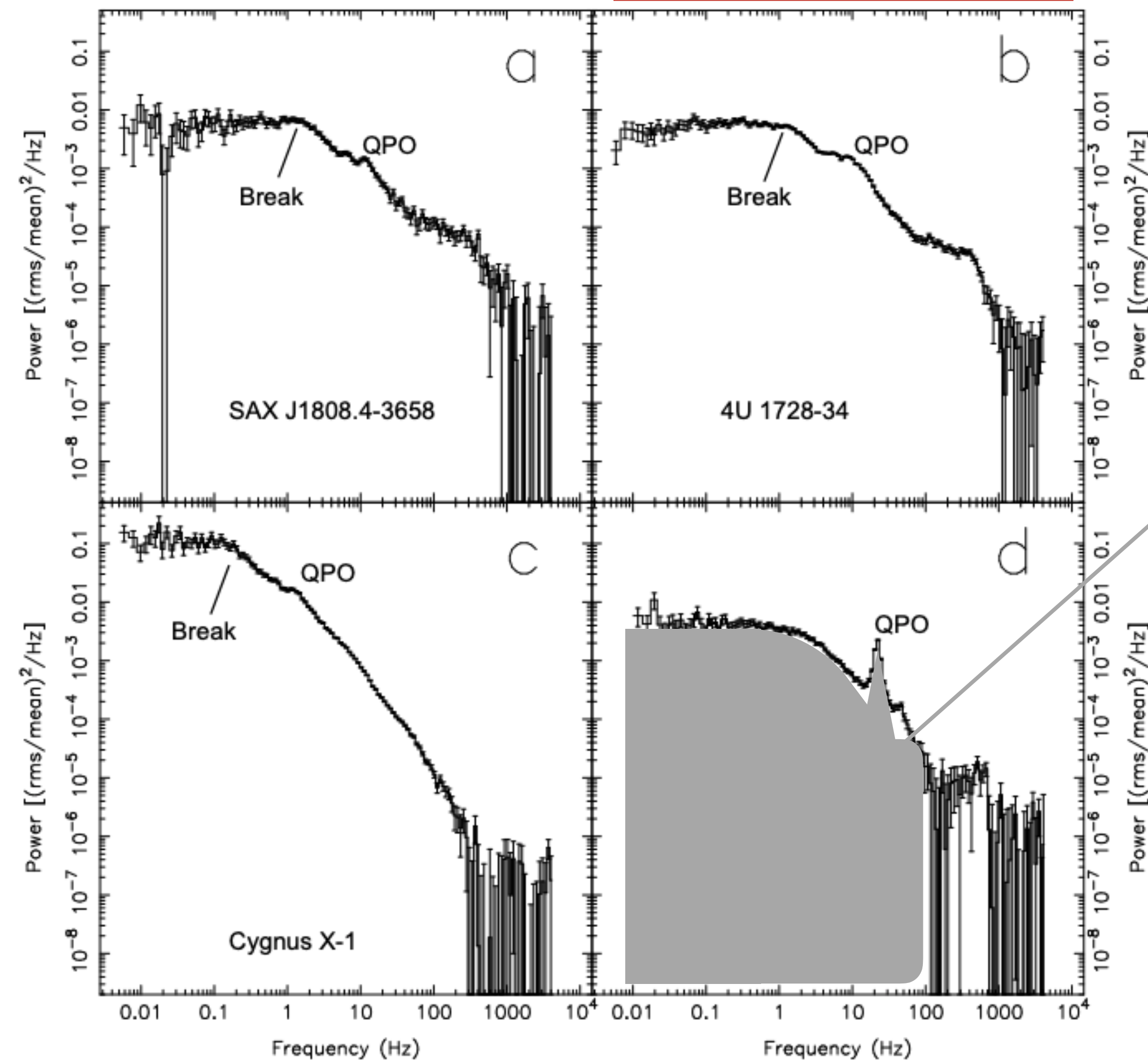


Breaking down a XRB PDS



Wijnands & Van der Klis 1999, Uttley+2004,
Van der Klis 2006, Belloni & Stella 2014

Wijnands & Van der Klis 1999



$$\text{rms/mean} = \left(\int P(\nu) d\nu \right)^2$$

fractional “rms”
amplitude (%)

(a measure of how “noisy”
an observation is)



Breaking down a XRB PDS

Wijnands & Van der Klis 1998

Broadband noise

flat power over a wide range of frequencies

Break

Quasi-periodic Oscillations

Discrete peaks in the PDS, see later ->

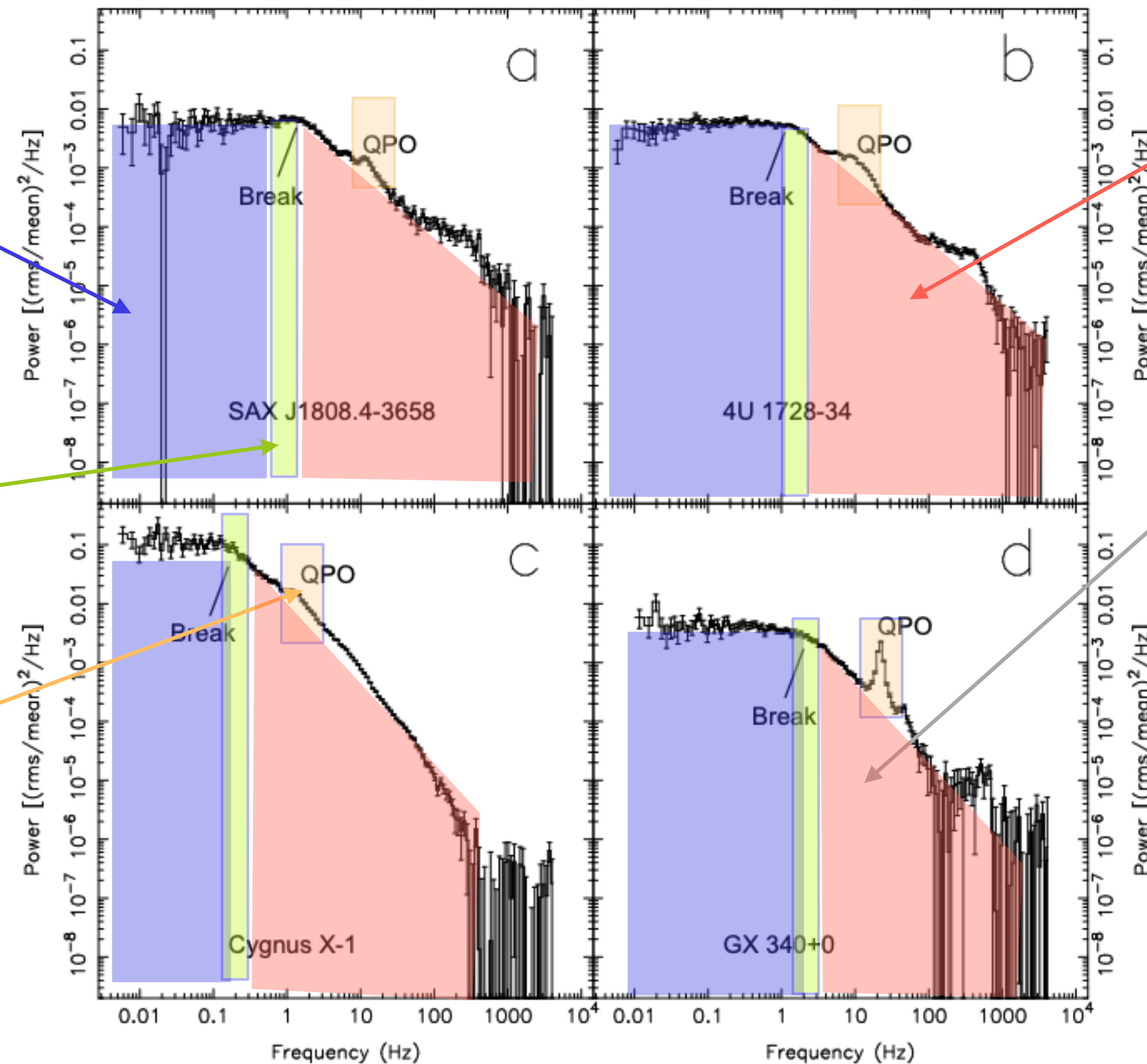
Red noise

Power decreases with frequency as ν^{-2}

$$\text{rms/mean} = \left(\int P(\nu) d\nu \right)^2$$

fractional “rms” amplitude (%)

(a measure of how “noisy” an observation is)



Quasi-periodic oscillations (QPOs) (BHs only)



Strohmayer+1996, van der Klis+1997,
Casella+2005, Belloni+2010, Ingram & Motta 2020

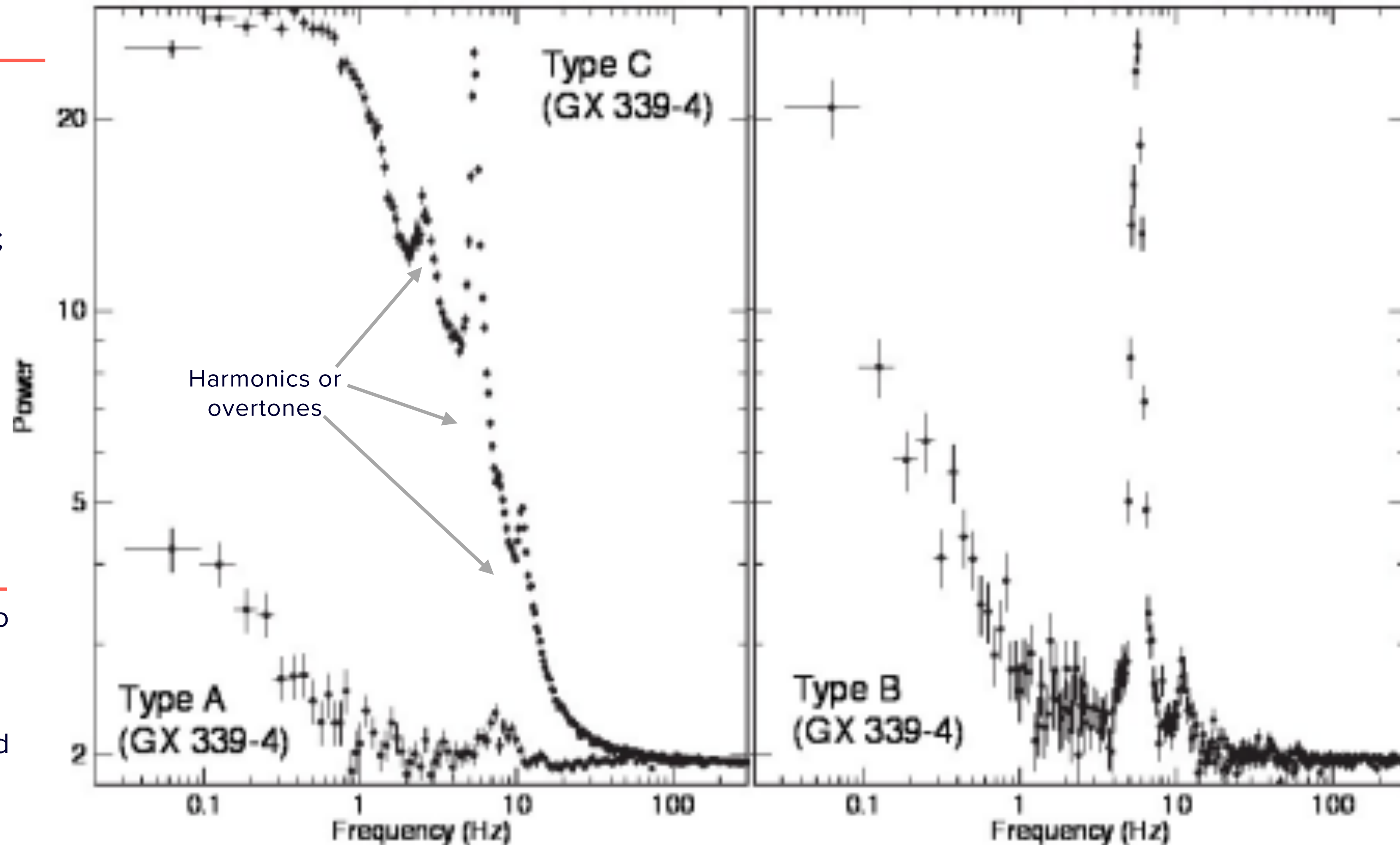
Motta+2011

Type-C

- Centroid frequency from mHz to tens of Hz;
- Narrow, high-amplitude (rms~20%);
- Associated to broadband noise;

Type-A

- Centroid frequency to few to tens of Hz;
- Broad, weak (~1%);
- Very weak broadband noise absent;



Type-B

- Centroid frequency of few Hz;
- Narrow, medium amplitude (~5 Hz);
- Weak broadband noise;

Quasi-periodic oscillations (QPOs) (BHs only)



Strohmayer+1996, van der Klis+1997,
Casella+2005, Belloni+2010, Ingram & Motta 2020

Motta+2011

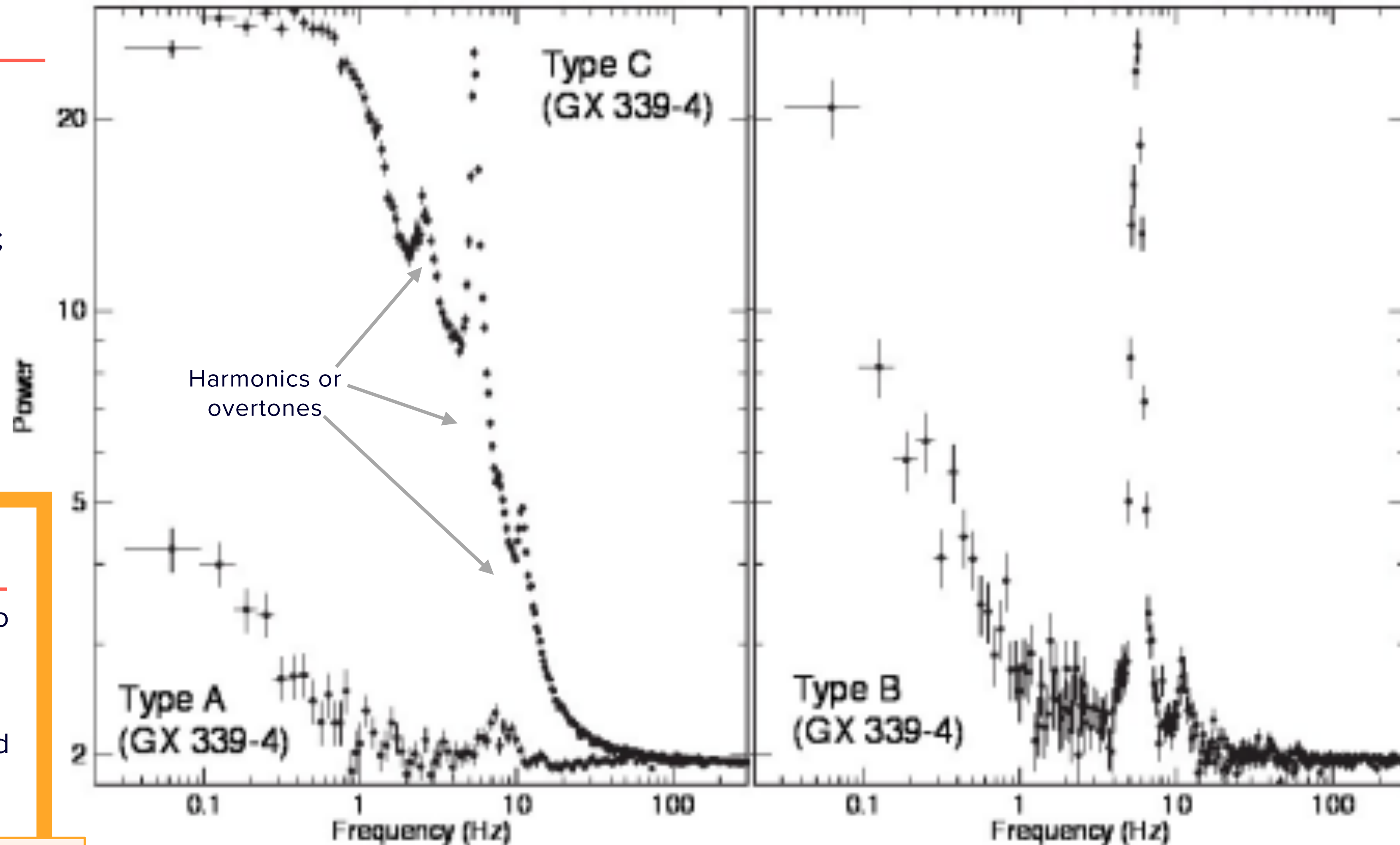
Type-C

- Centroid frequency from mHz to tens of Hz;
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- Associated to broadband noise;

Type-A

- Centroid frequency to few to tens of Hz;
- Broad, weak (~1%);
- Very weak broadband noise absent;

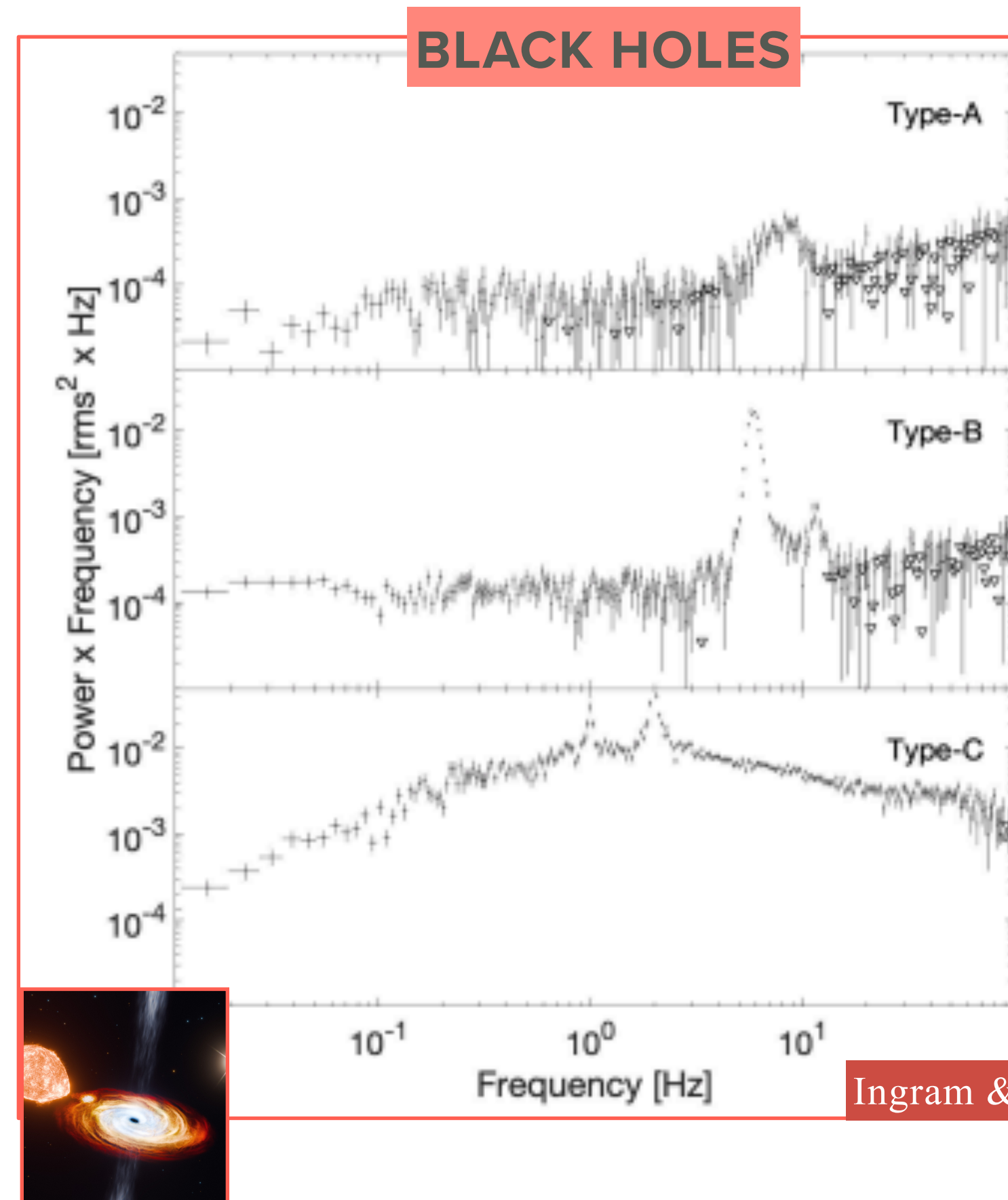
**Controversial! Maybe just
“weird” type-B? (Casella+2005)**



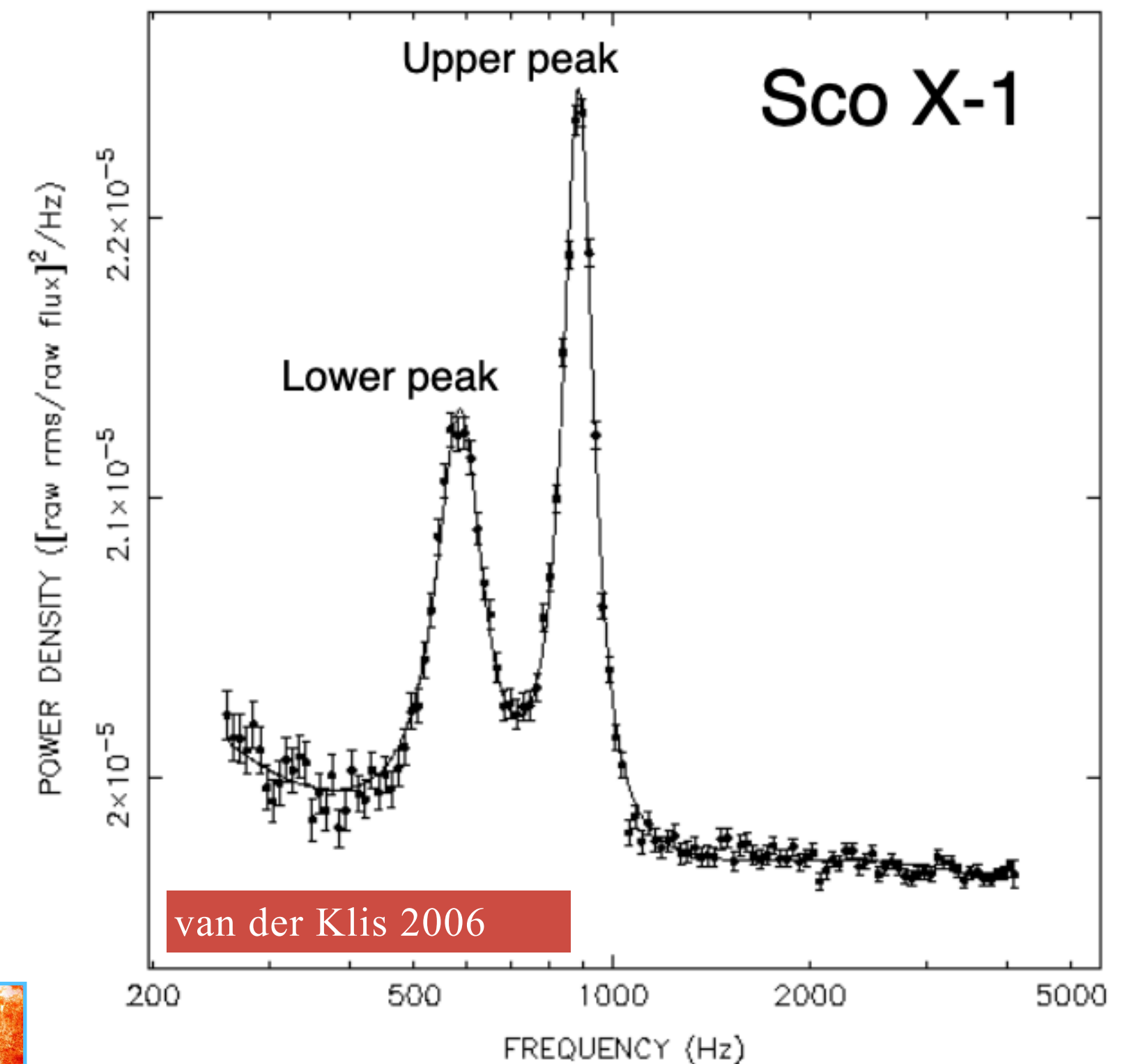
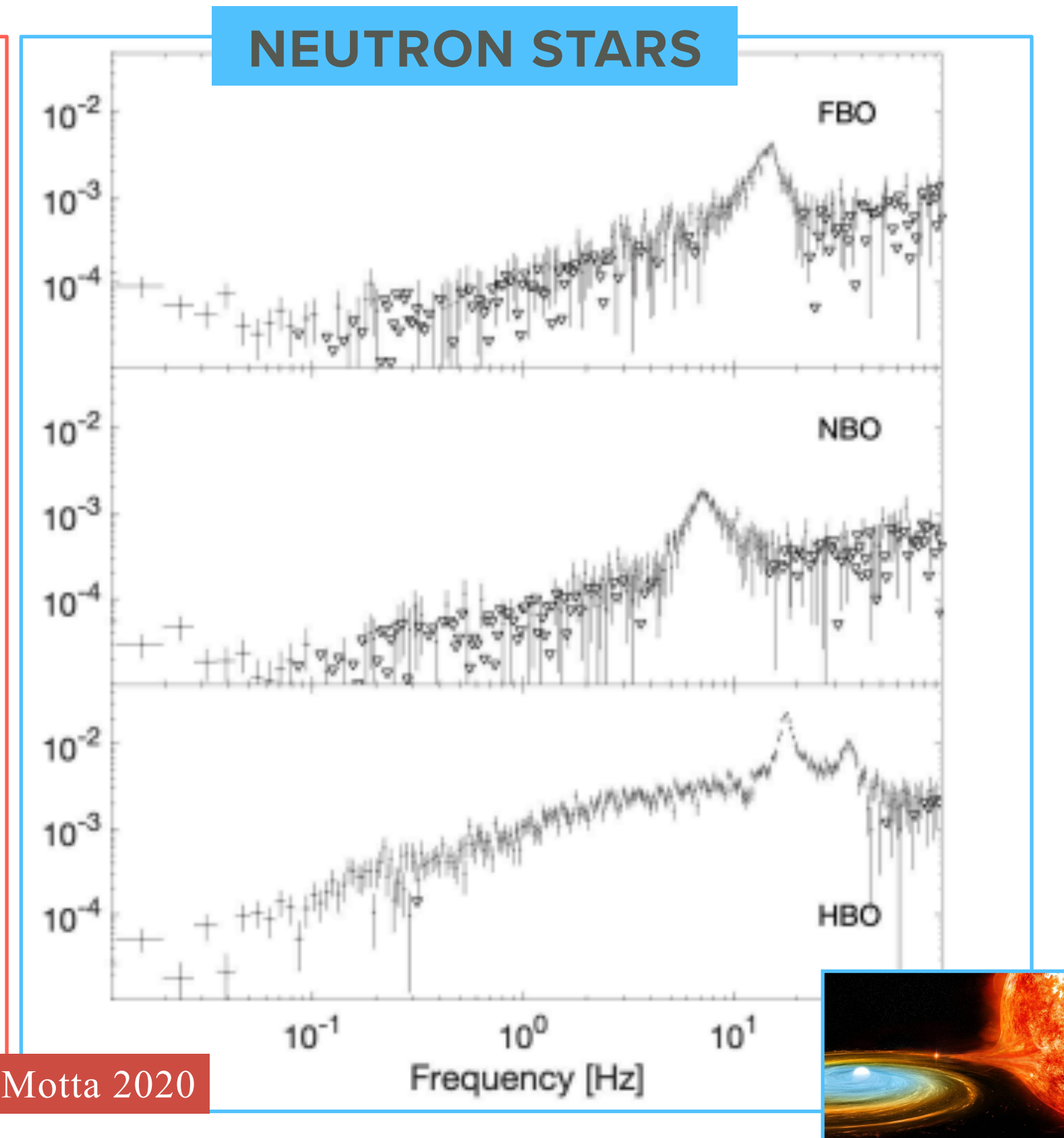
Type-B

- Centroid frequency of few Hz;
- Narrow, medium amplitude (~5 Hz);
- Weak broadband noise;

FBOs, NBOs and HBOs, but also kHz QPOs! (NSs only)



Ingram & Motta 2020



kHz QPOs

- Centroid frequency at hundreds of Hz;
- Narrow, variable amplitudes ($\sim 5\text{-}20\%$);
- Usually they come in pair (the *twin peaks*);

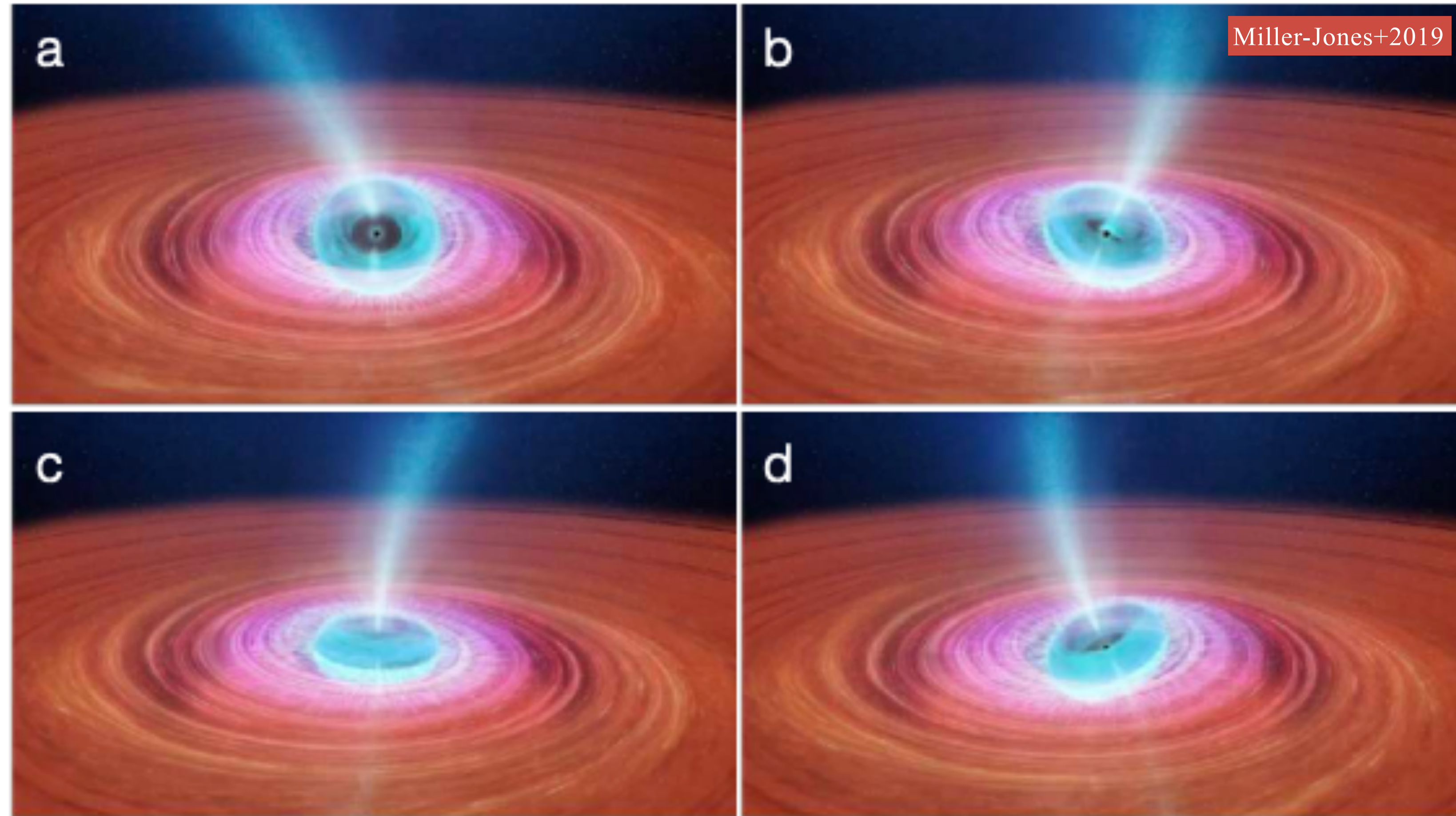
Flaring, Normal, Horizontal Branch Oscillations

- Rough analogous to Type-A, B and C QPOs in BH XRBs;



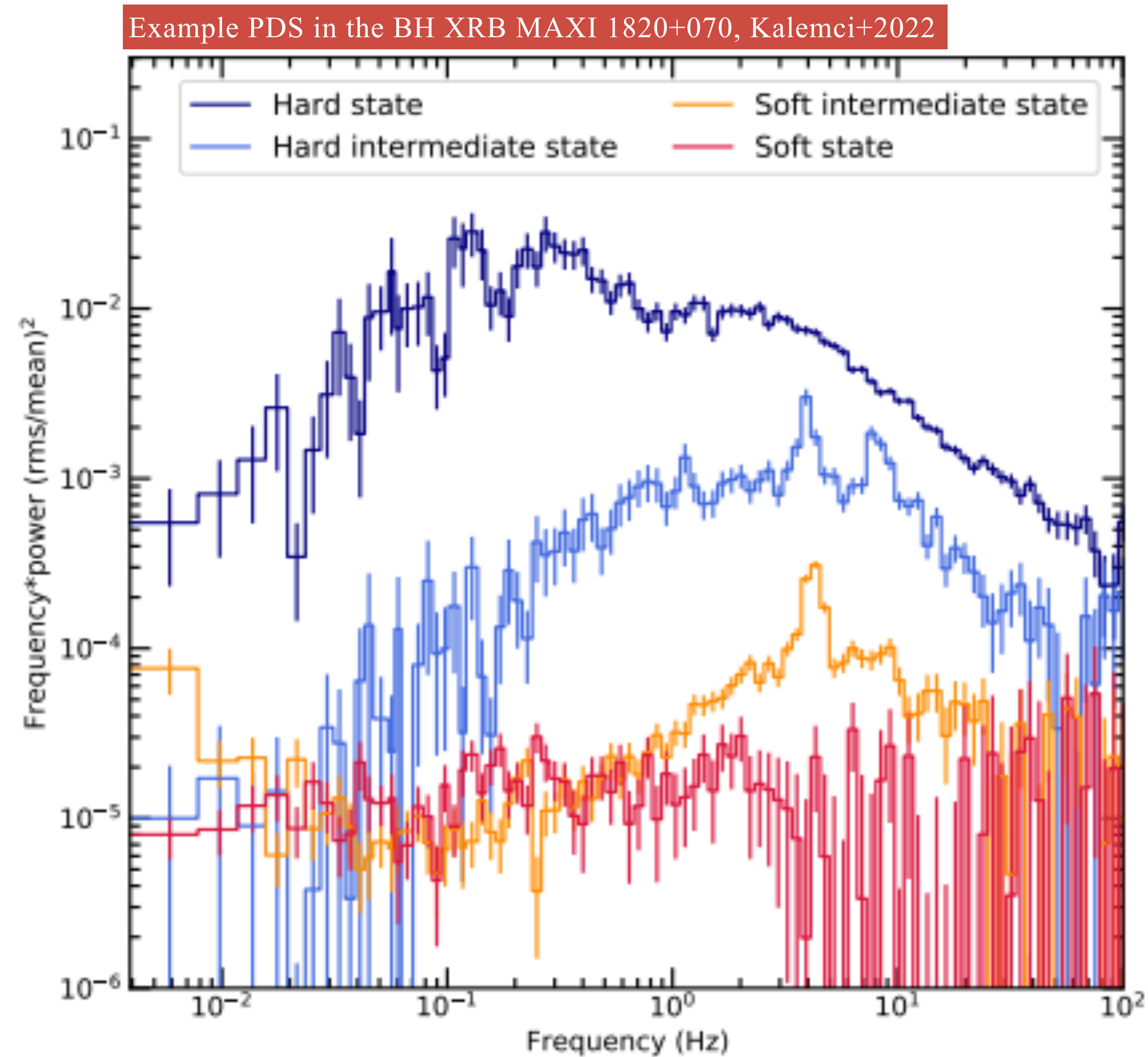
On the QPOs origin;

- Type-C/kHz QPOs: Solid body precession (Lense-Thirring effect) of the inner flow within a truncated disk?
- Type-B QPOs: connected to the launch of discrete jets -> see **Thursday's lecture**;



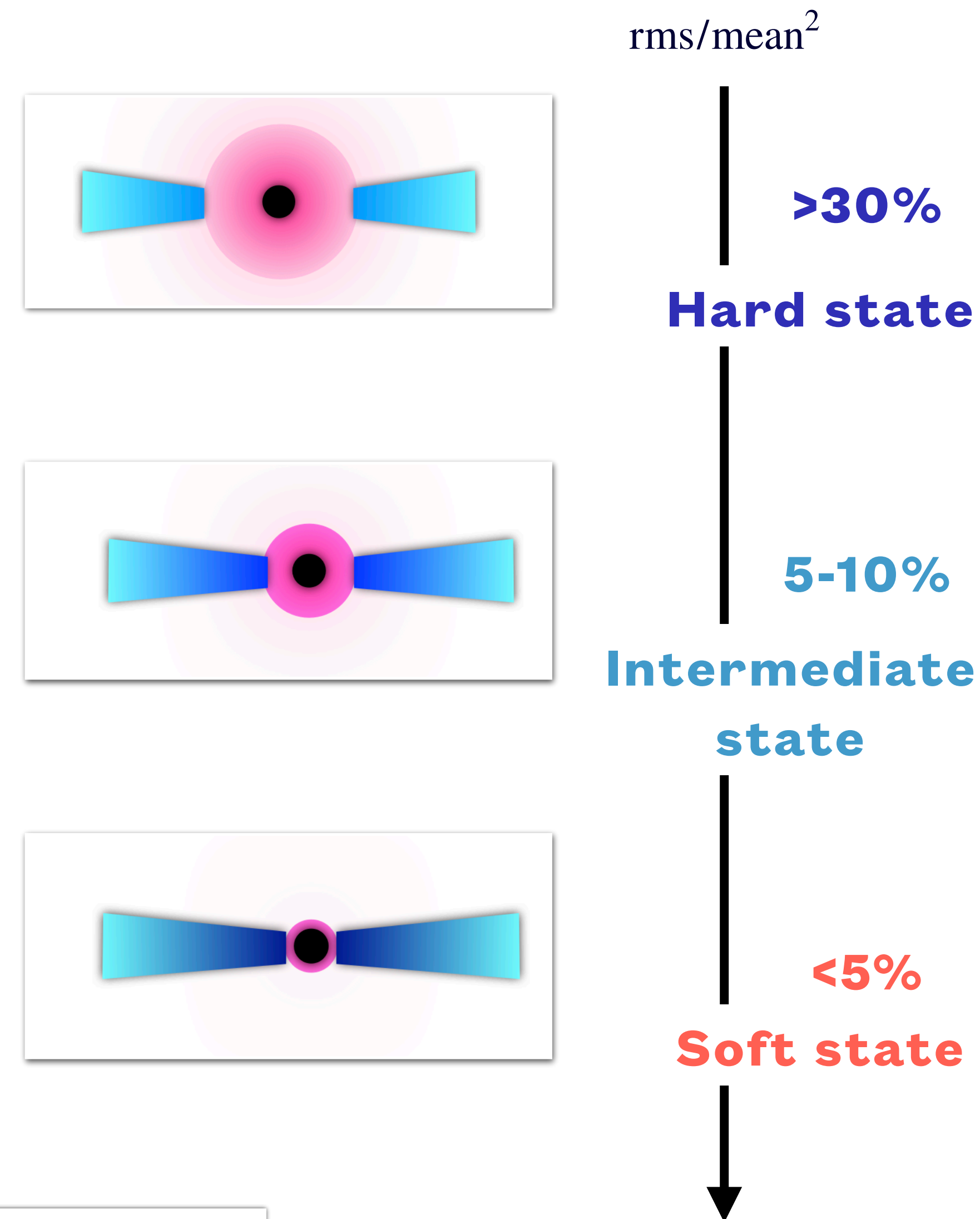
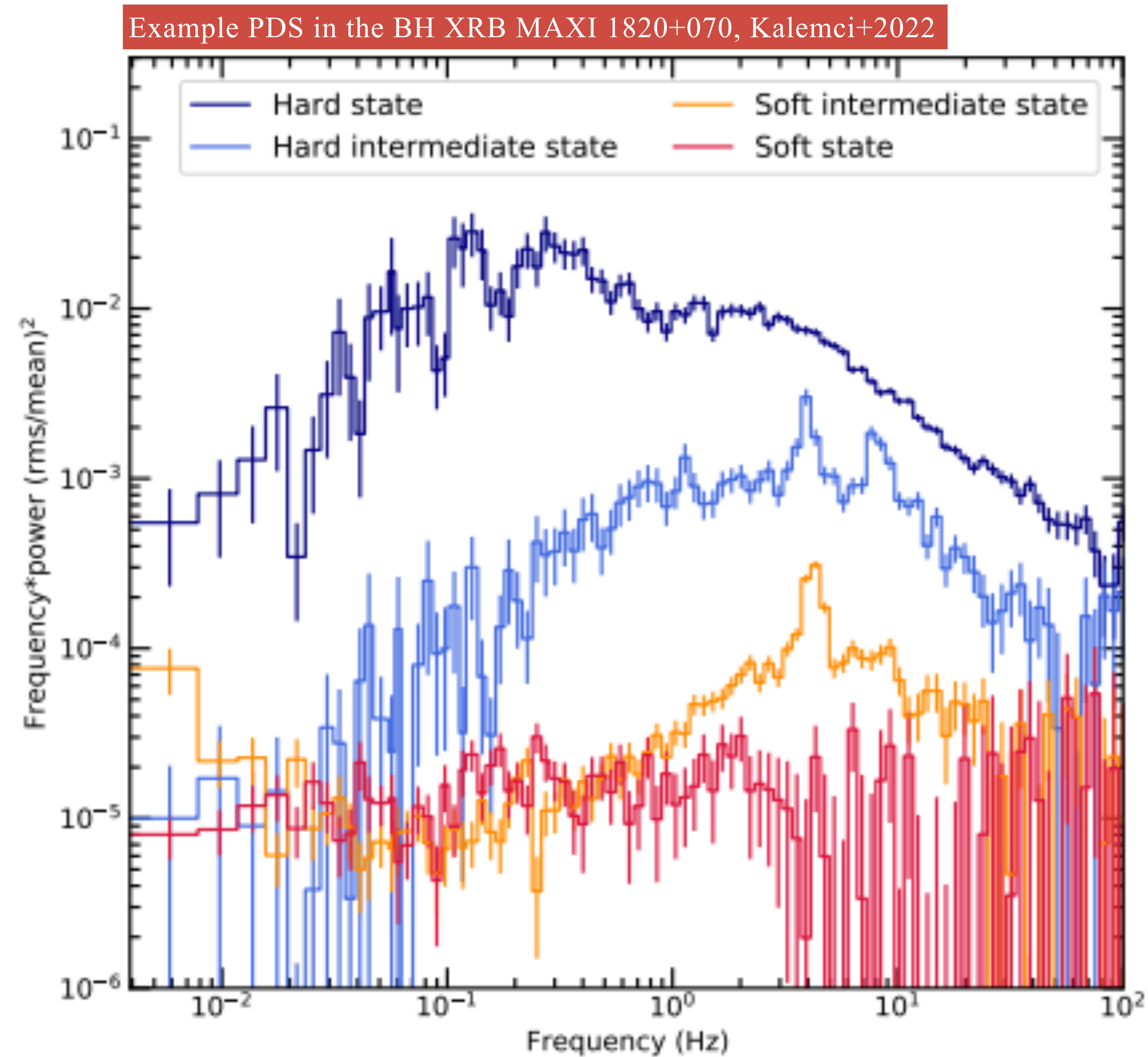
Timing properties and spectral states (i)

- Similarly to energy, PDS also change dramatically with the spectral state in both BH and NS LMXBs.



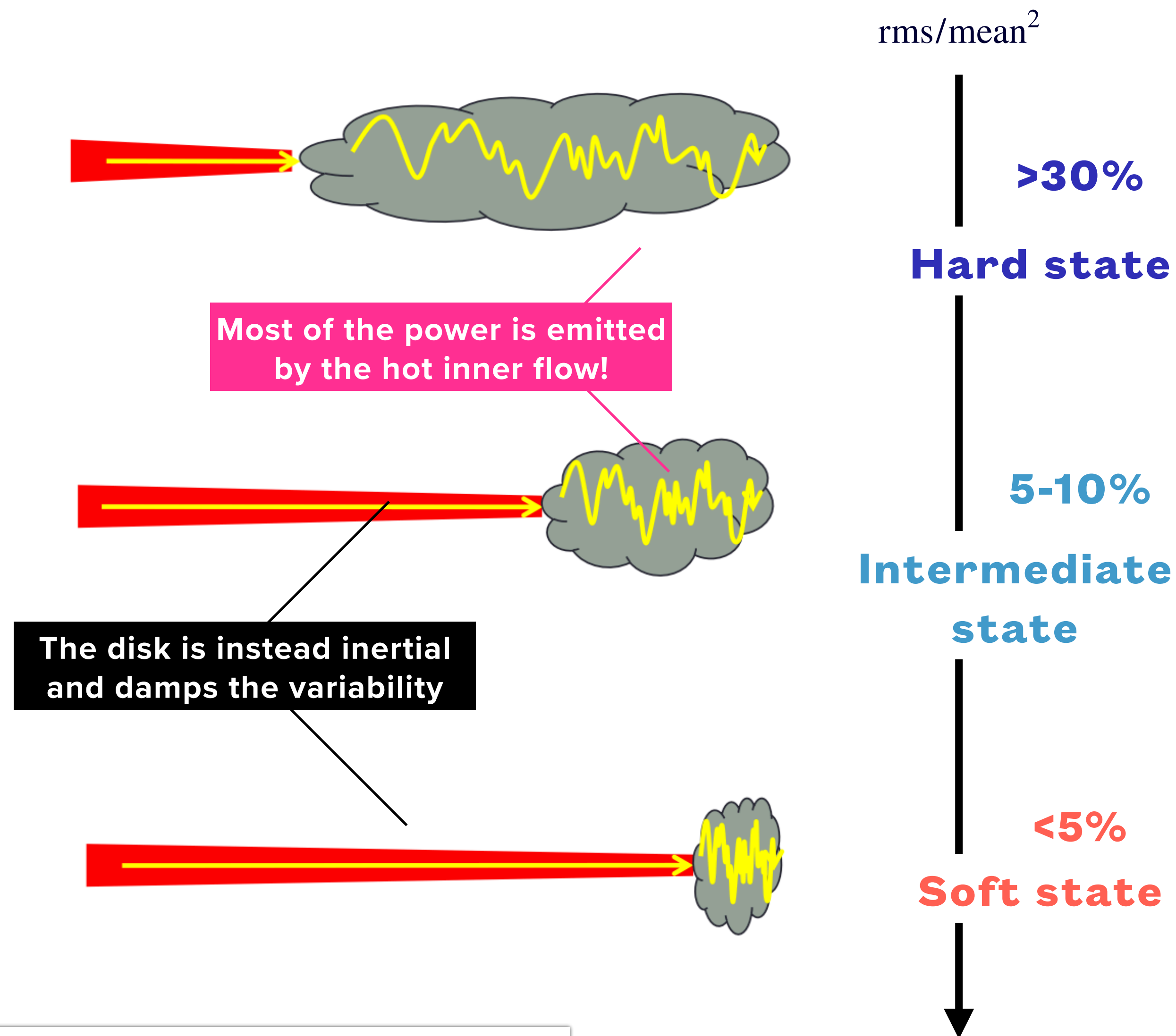
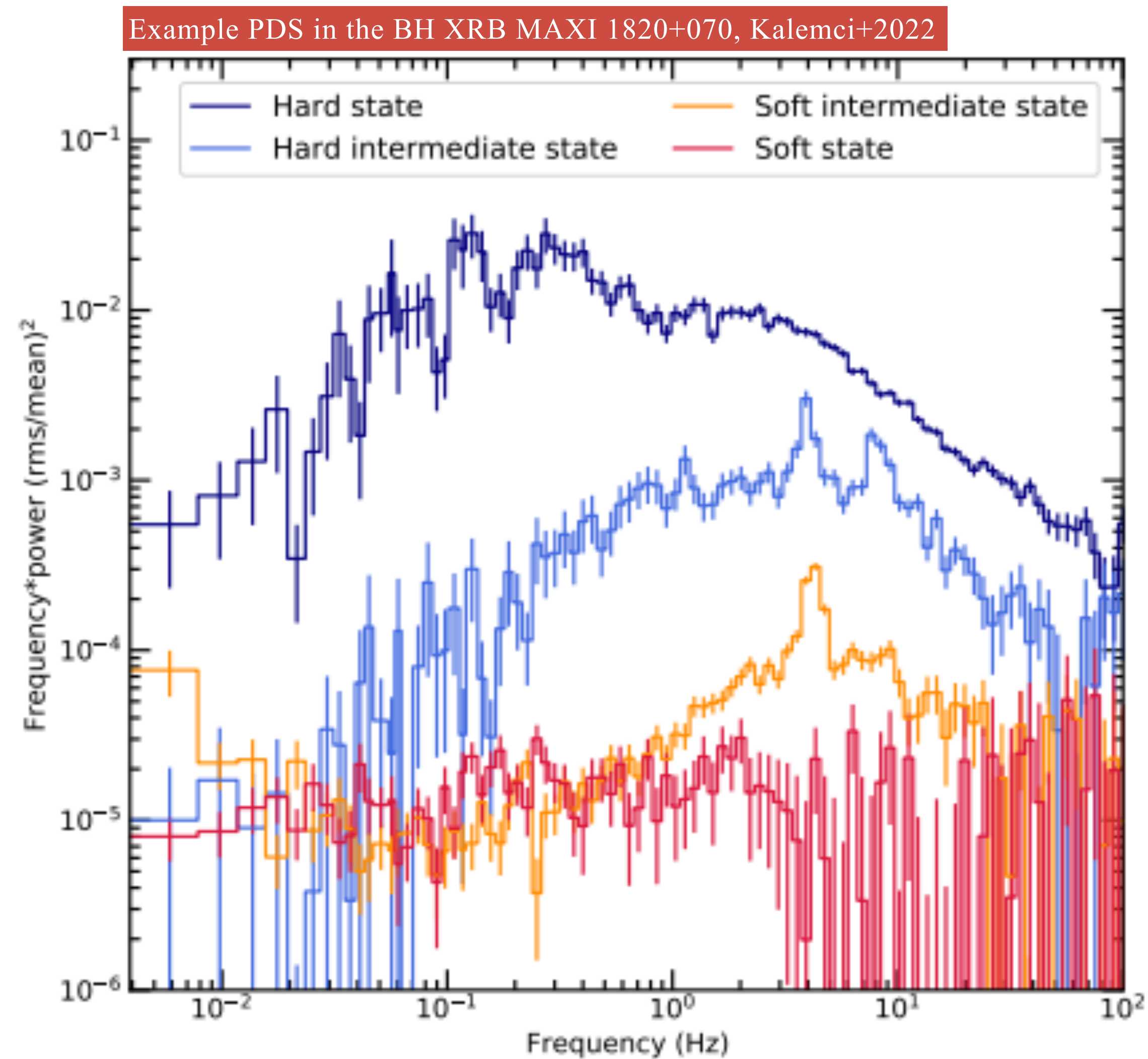
Timing properties and spectral states (i)

- Similarly to energy, PDS also change dramatically with the spectral state in both BH and NS LMXBs.



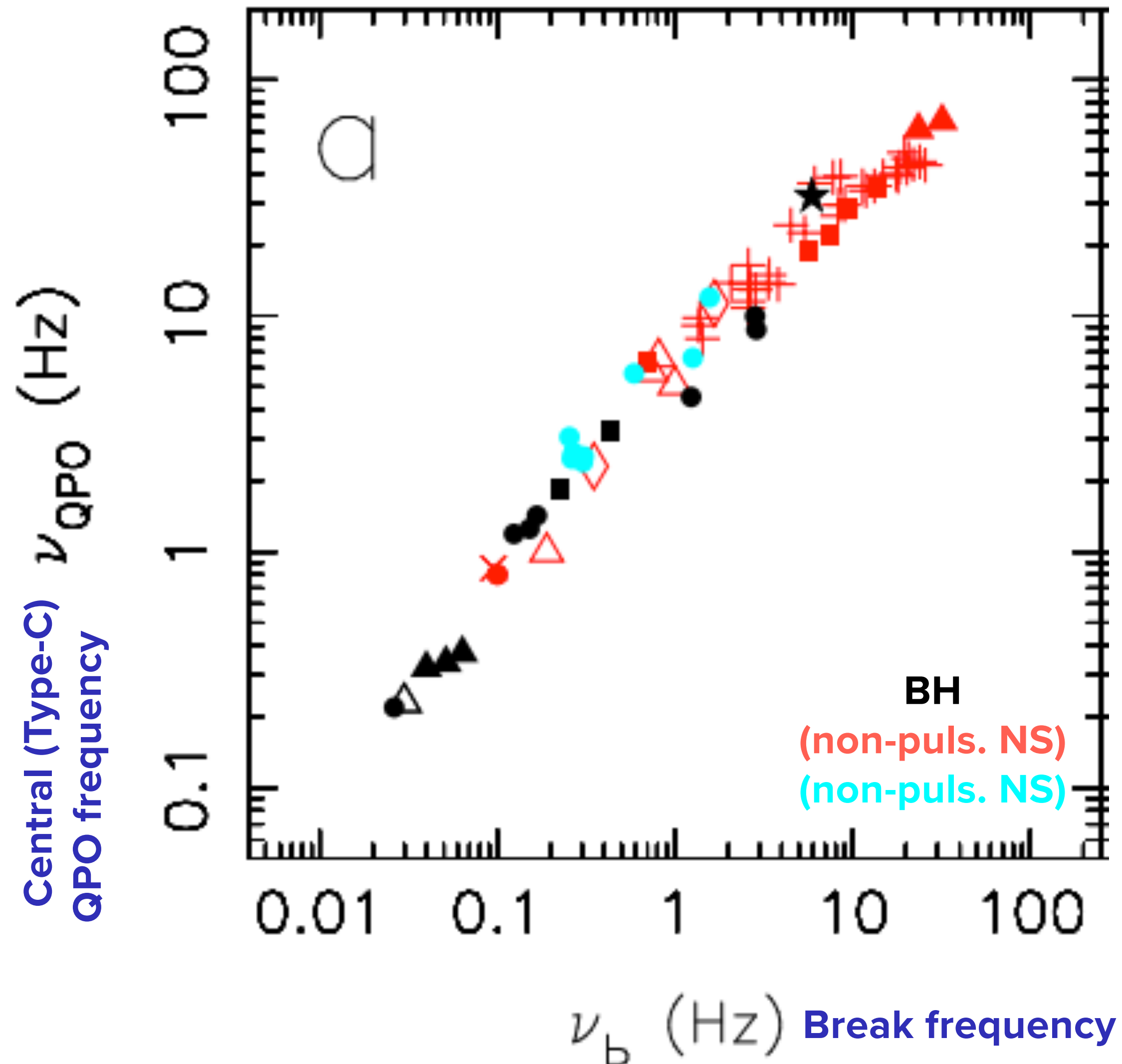
Timing properties and spectral states (i)

- Similarly to energy, PDS also change dramatically with the spectral state in both BH and NS LMXBs.



Timing properties and spectral states (ii)

Wijnands & Van der Klis 1999



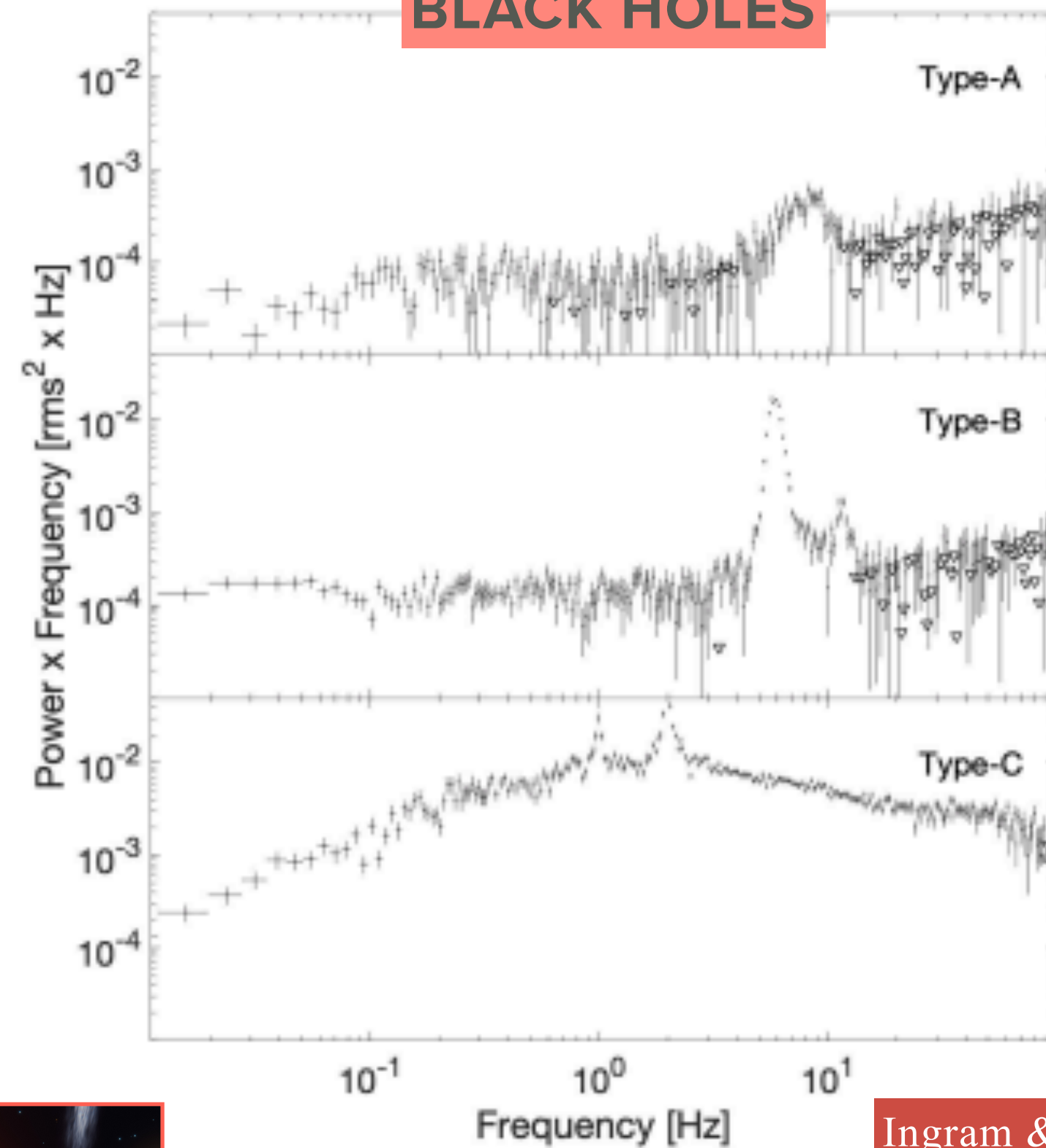
- QPOs (especially Type-C) evolve along with the broadband noise;
- Their frequency correlates indeed with the break frequency of the PDS;

Timing properties and spectral states (iii)

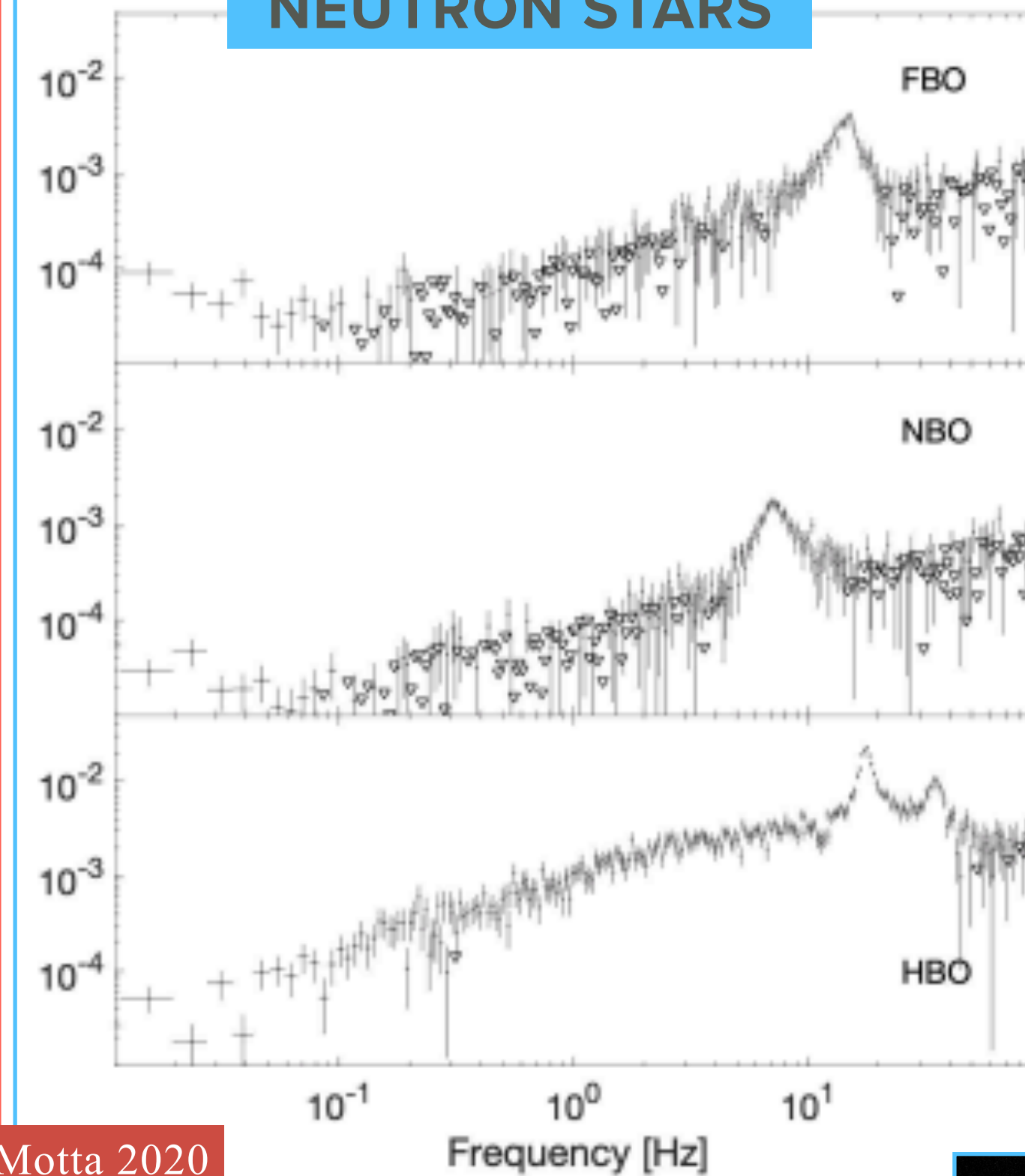


Strohmayer+1996, van der Klis+1997,
Mendez+2006, Belloni+2012,
Kalemci+2022, Ingram & Motta 2020

BLACK HOLES



NEUTRON STARS

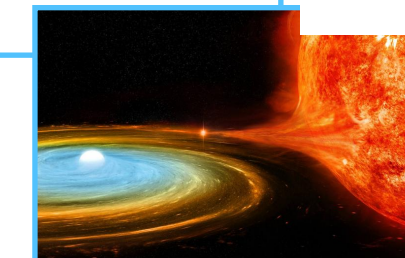


Ingram & Motta 2020

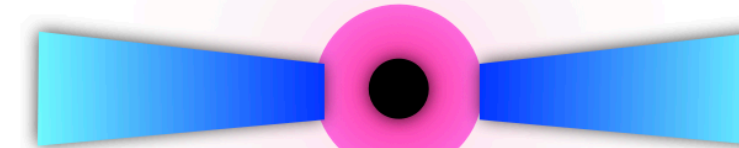
Type-A / FBO → **Soft-intermediate state**

Type-B / NBO → **Soft-intermediate state**

Type-C / HBO → **Predominantly hard**



Soft state



Int. state



Hard state

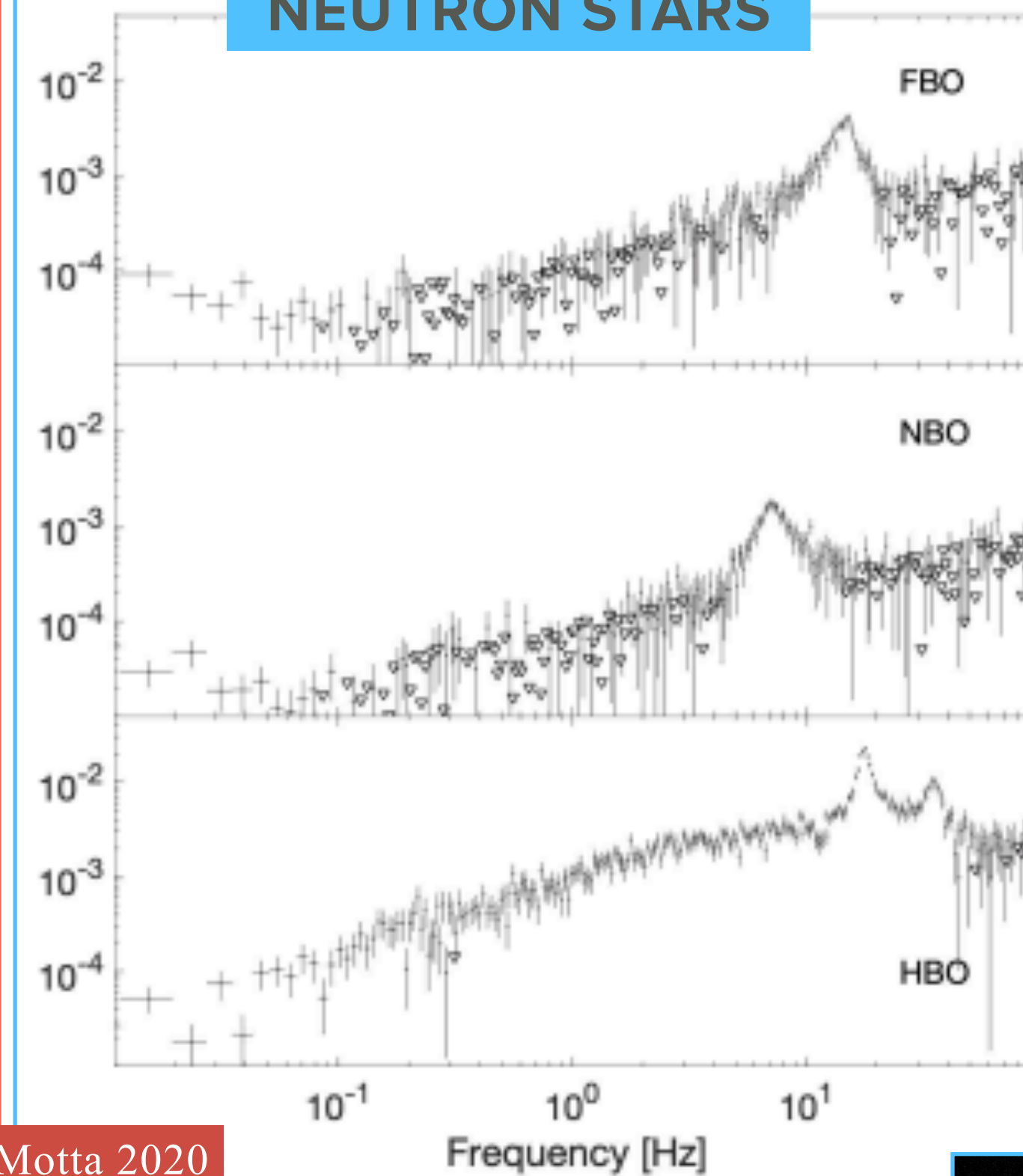
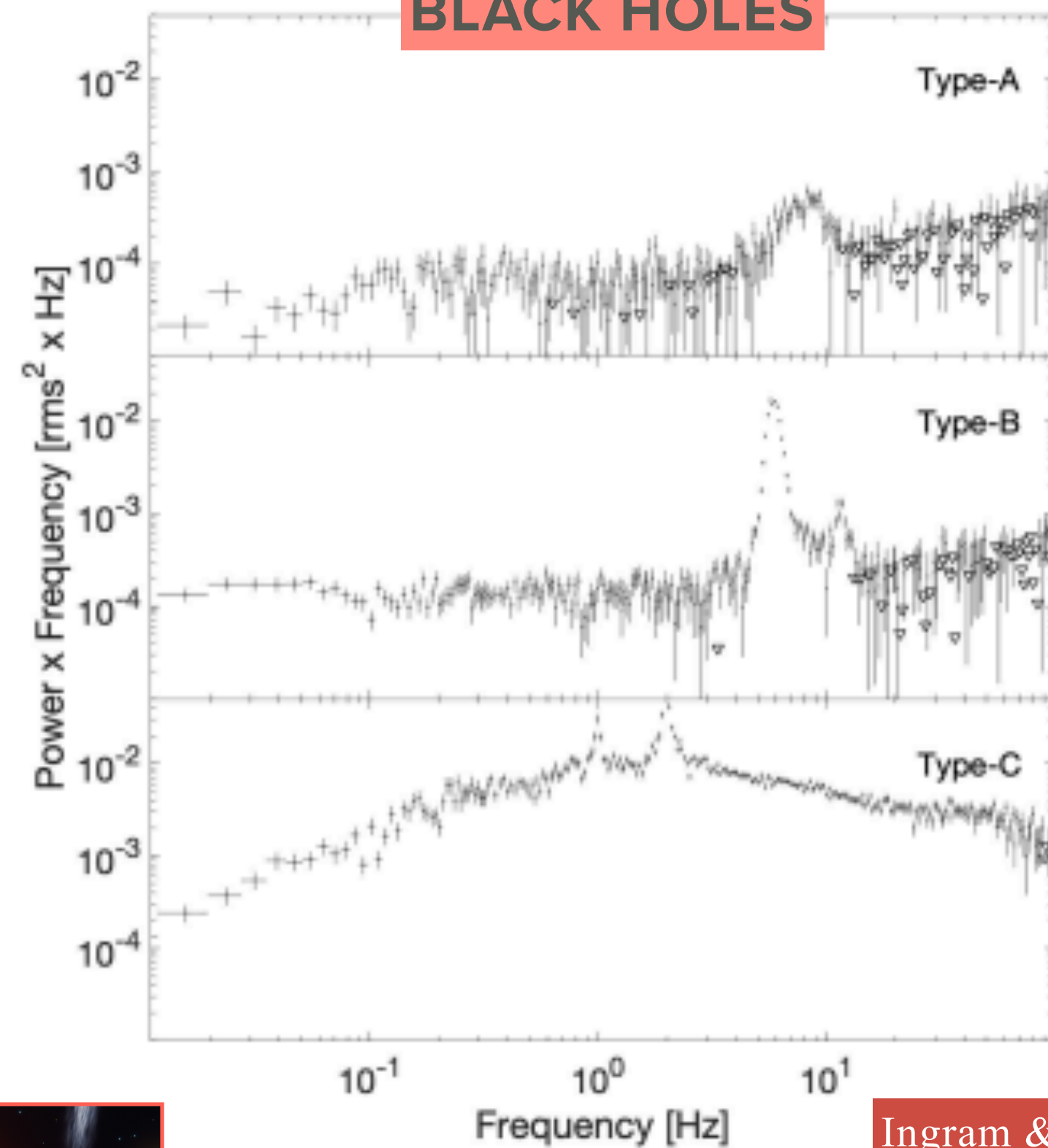
Timing properties and spectral states (iii)



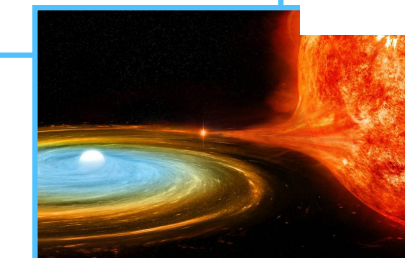
Strohmayer+1996, van der Klis+1997,
Mendez+2006, Belloni+2012,
Kalemci+2022, Ingram & Motta 2020

BLACK HOLES

NEUTRON STARS



Ingram & Motta 2020



Type-A / FBO → **Soft-intermediate state**

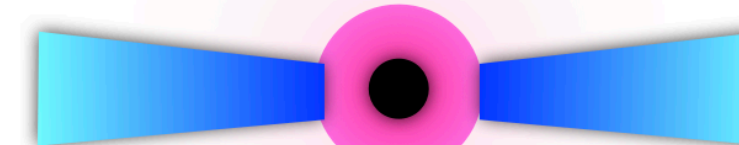
Type-B / NBO → **Soft-intermediate state**

Type-C / HBO → **Predominantly hard**

More about X-rays (incoherent)
timing techniques **this**
afternoon (16:30-18) @ S.
Motta's hands-on session



Soft state



Int. state



Hard state

How do all these properties
evolve with **time**?



Up to which point? The Eddington limit

- There is a point where the radiation produced through accretion has enough energy to prevent matter to be accreted any further.
- This threshold luminosity is called **the Eddington luminosity**. The maximum luminosity that can be reached from X-ray binaries.

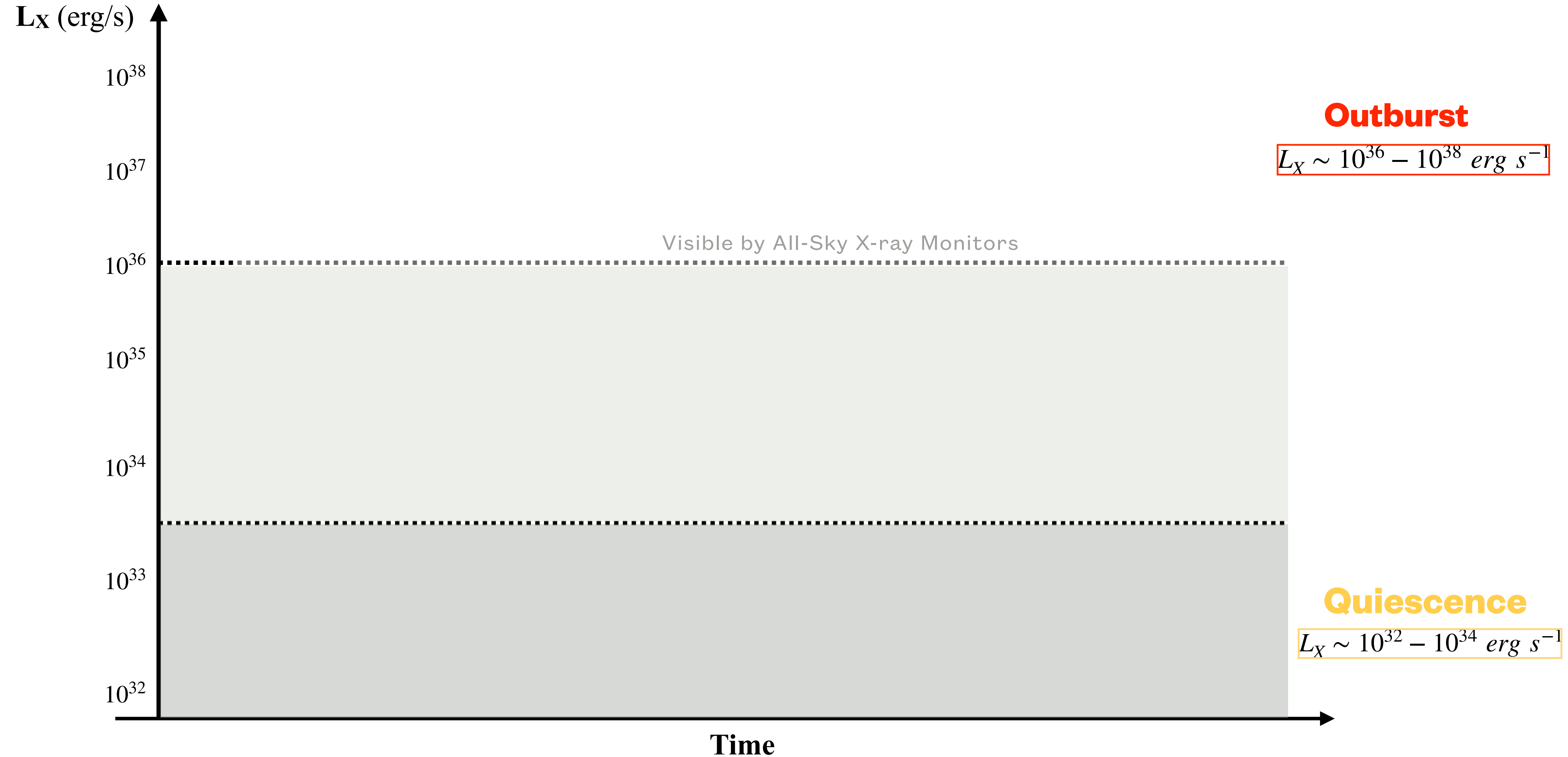
proton mass

$$L_{\text{Edd}} = \frac{4\pi GMm_p c}{\sigma_T} = 1.3 \times 10^{38} \frac{M}{M_{\odot}} \text{ erg s}^{-1} .$$

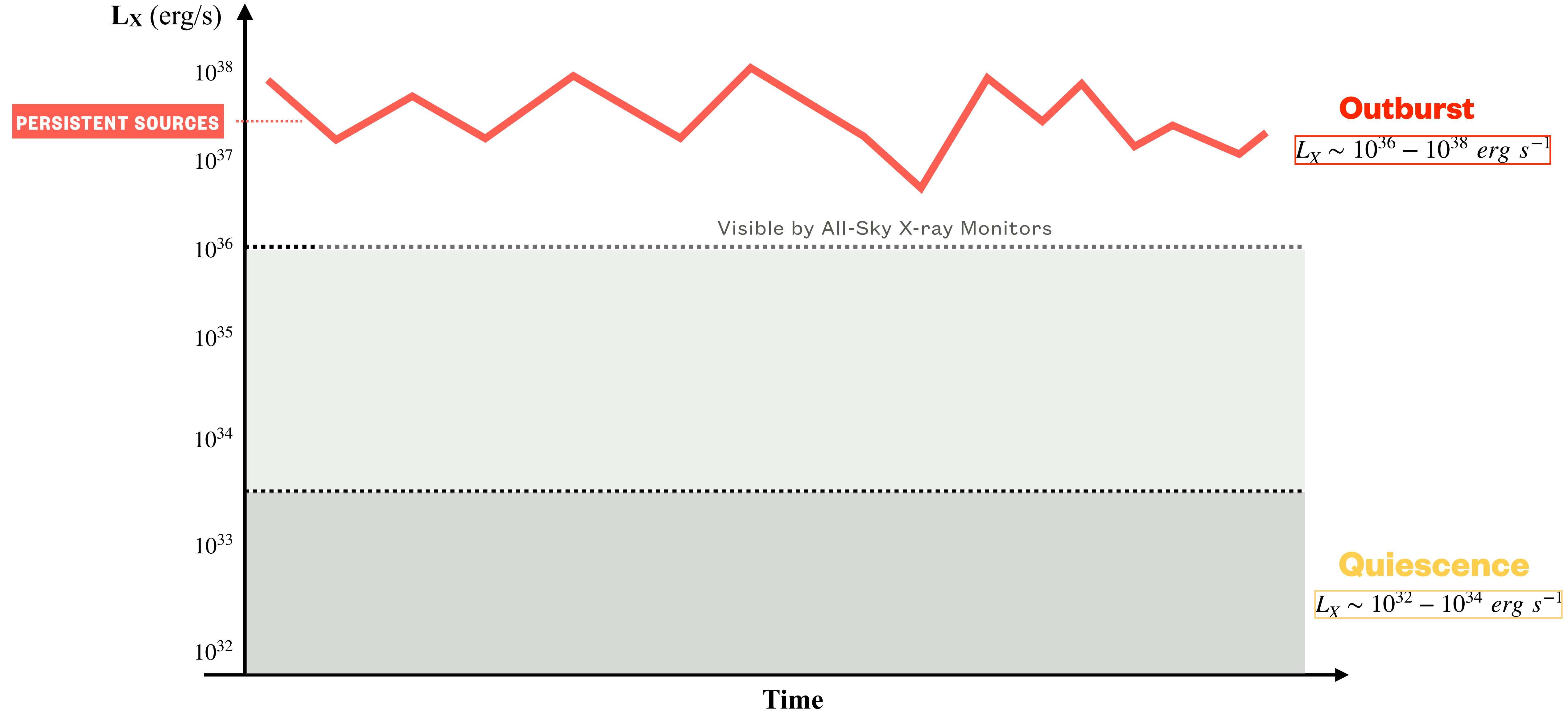
Thomson cross-section

Assumption: accretion is stationary and isotropic, matter is a pure mixture of protons and electrons, electrons and photons interact only through Thomson scattering.

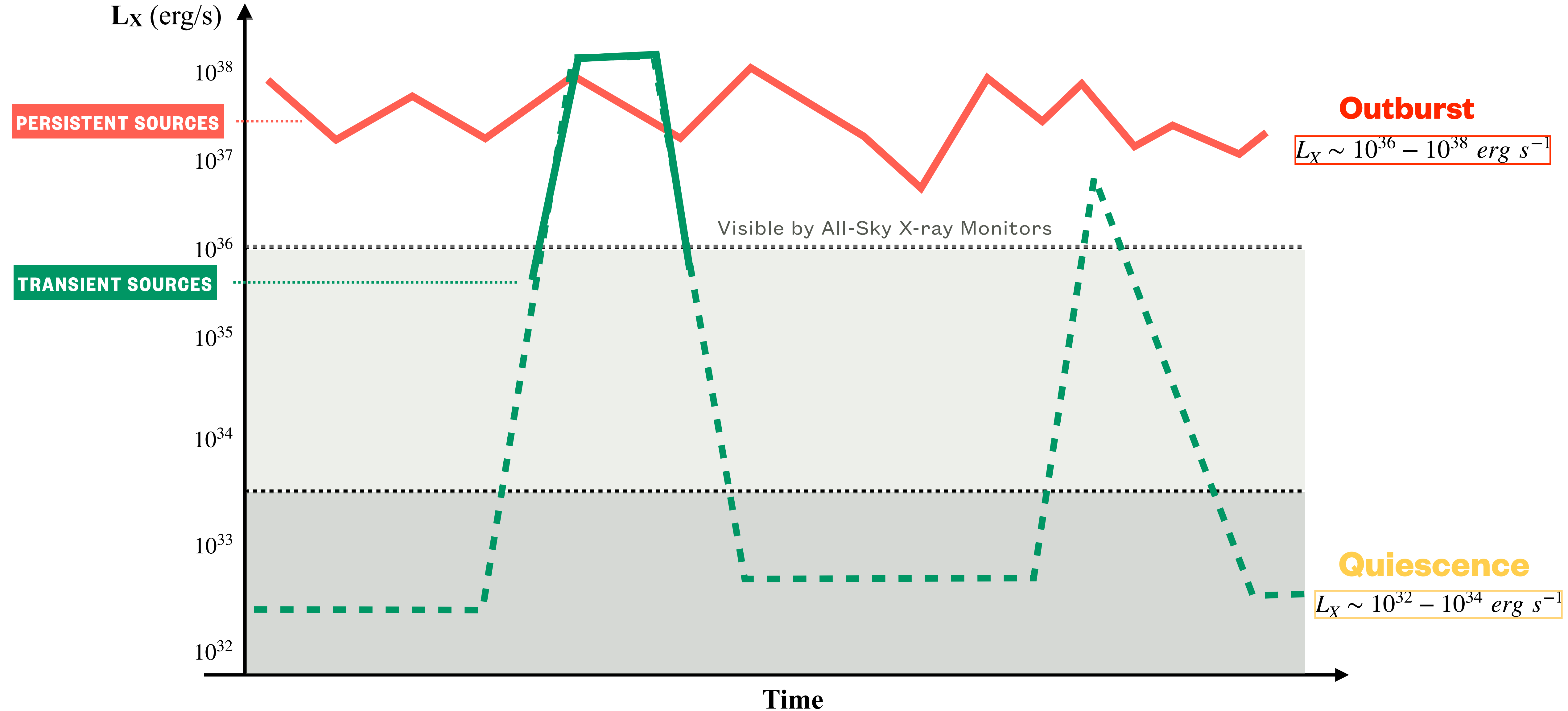
Classifying LMXBs based on their long-term X-ray activity



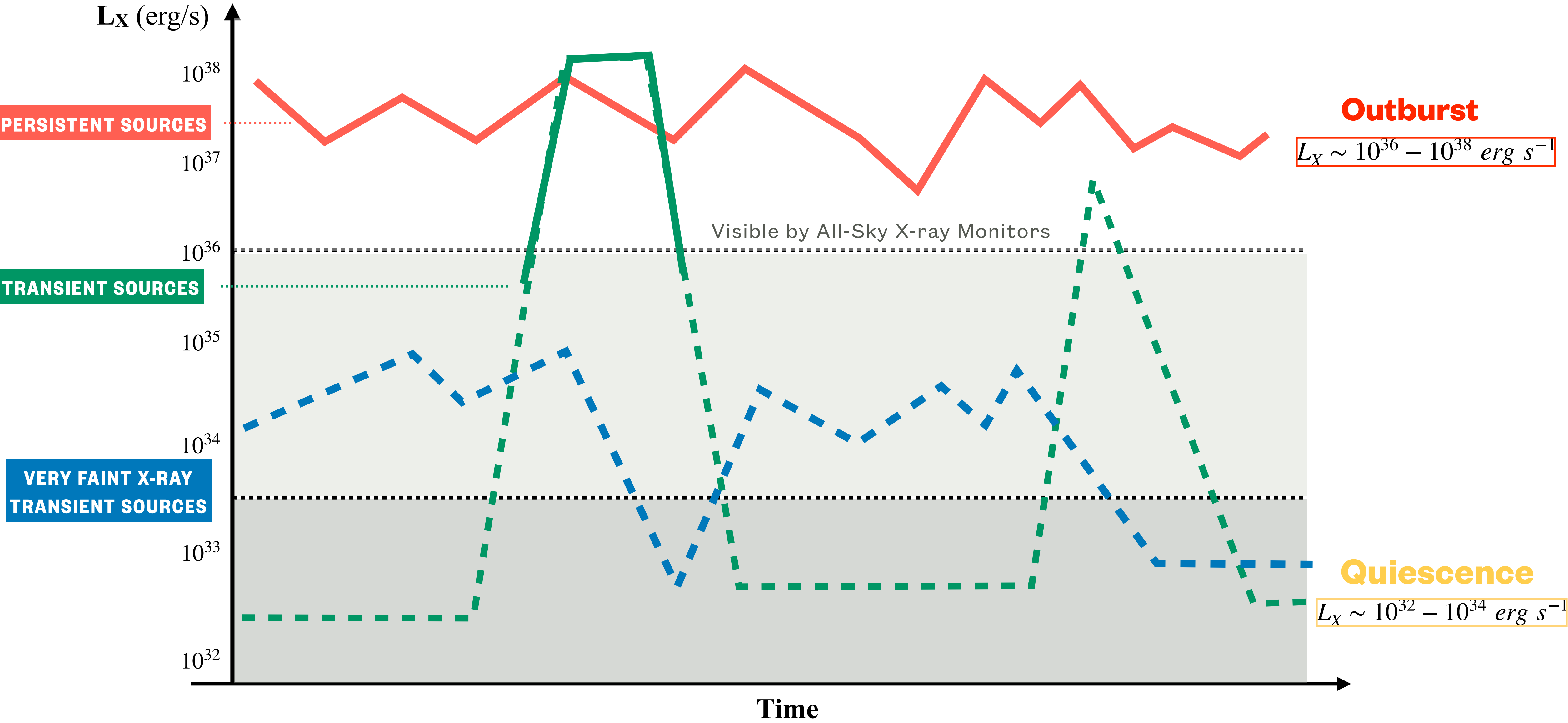
Classifying LMXBs based on their long-term X-ray activity



Classifying LMXBs based on their long-term X-ray activity



Classifying LMXBs based on their long-term X-ray activity

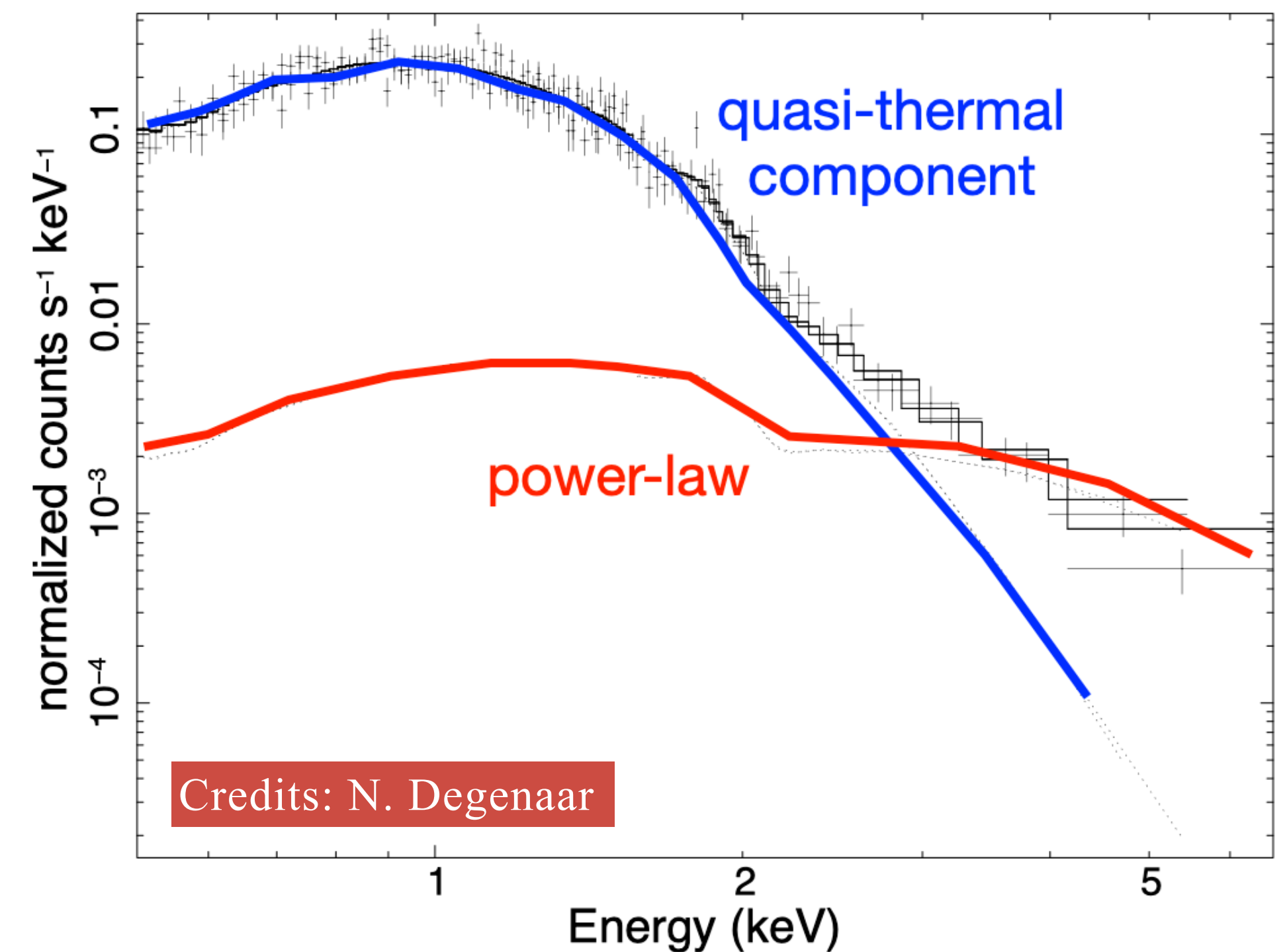
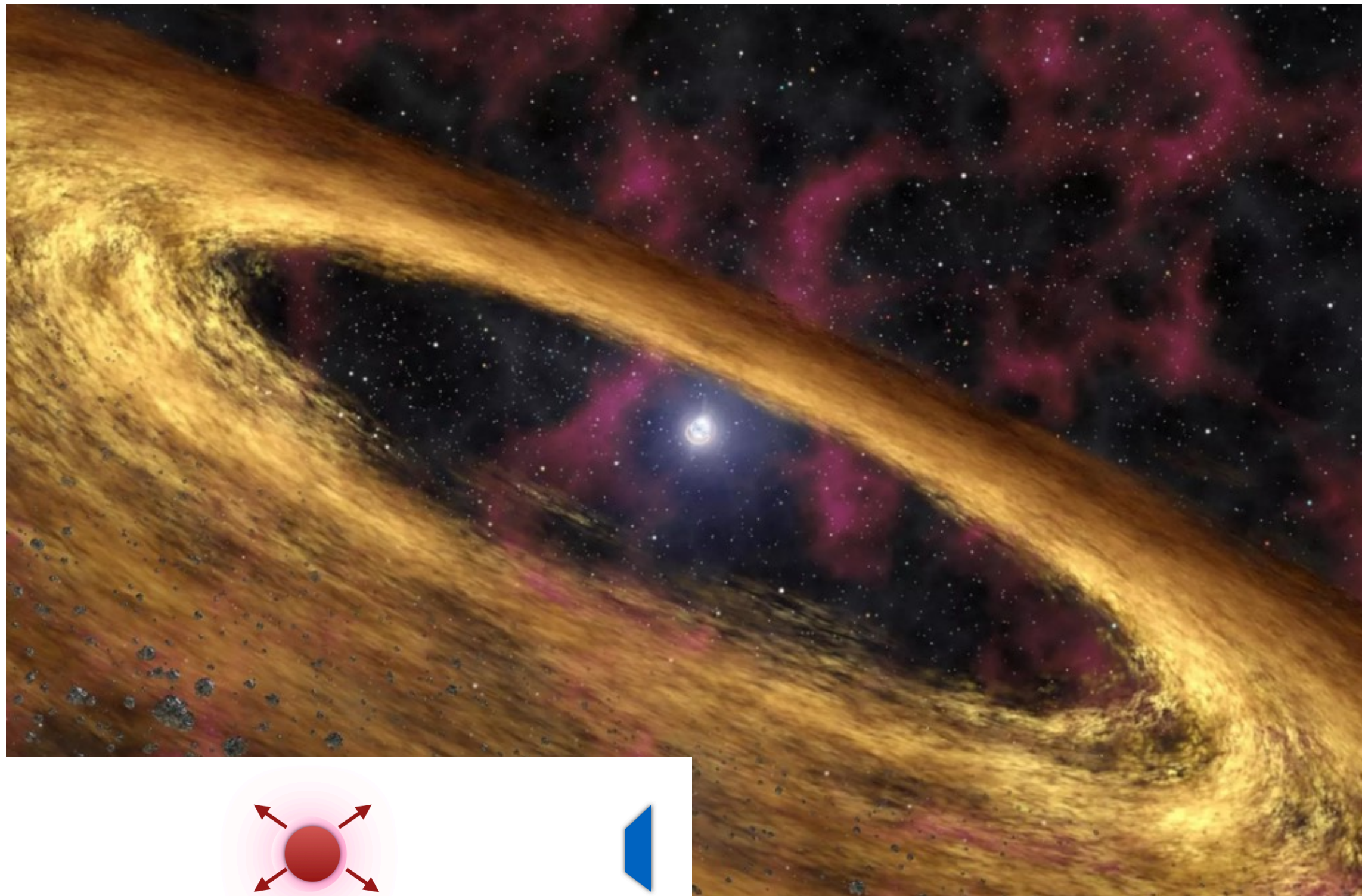
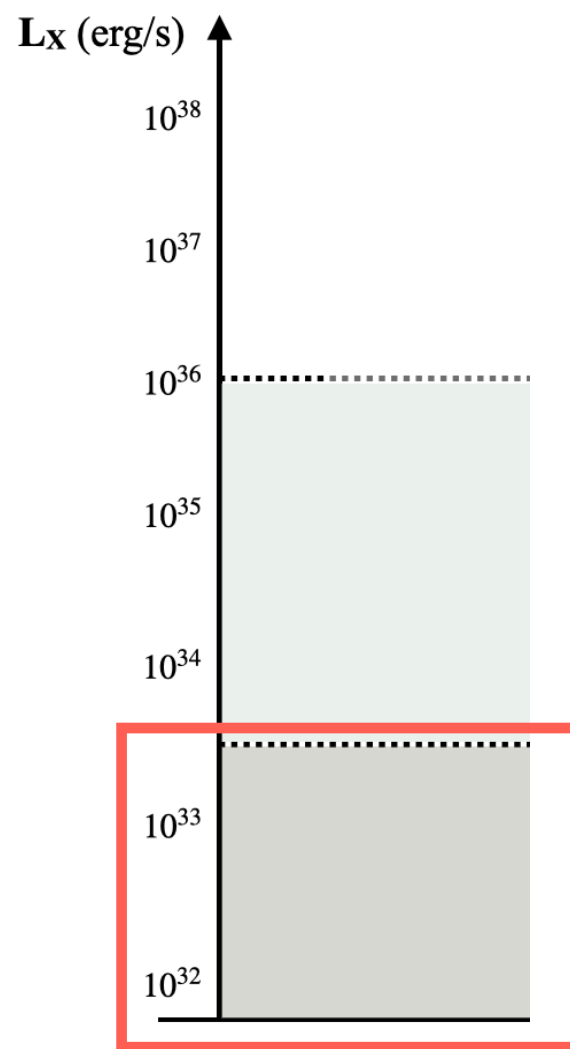


Sleeping beauties: Quiescent LMXBs



e.g. Brown & Bildsten 1998; Degenaar+2011, 2014; Reynolds+2014; Marino+2018

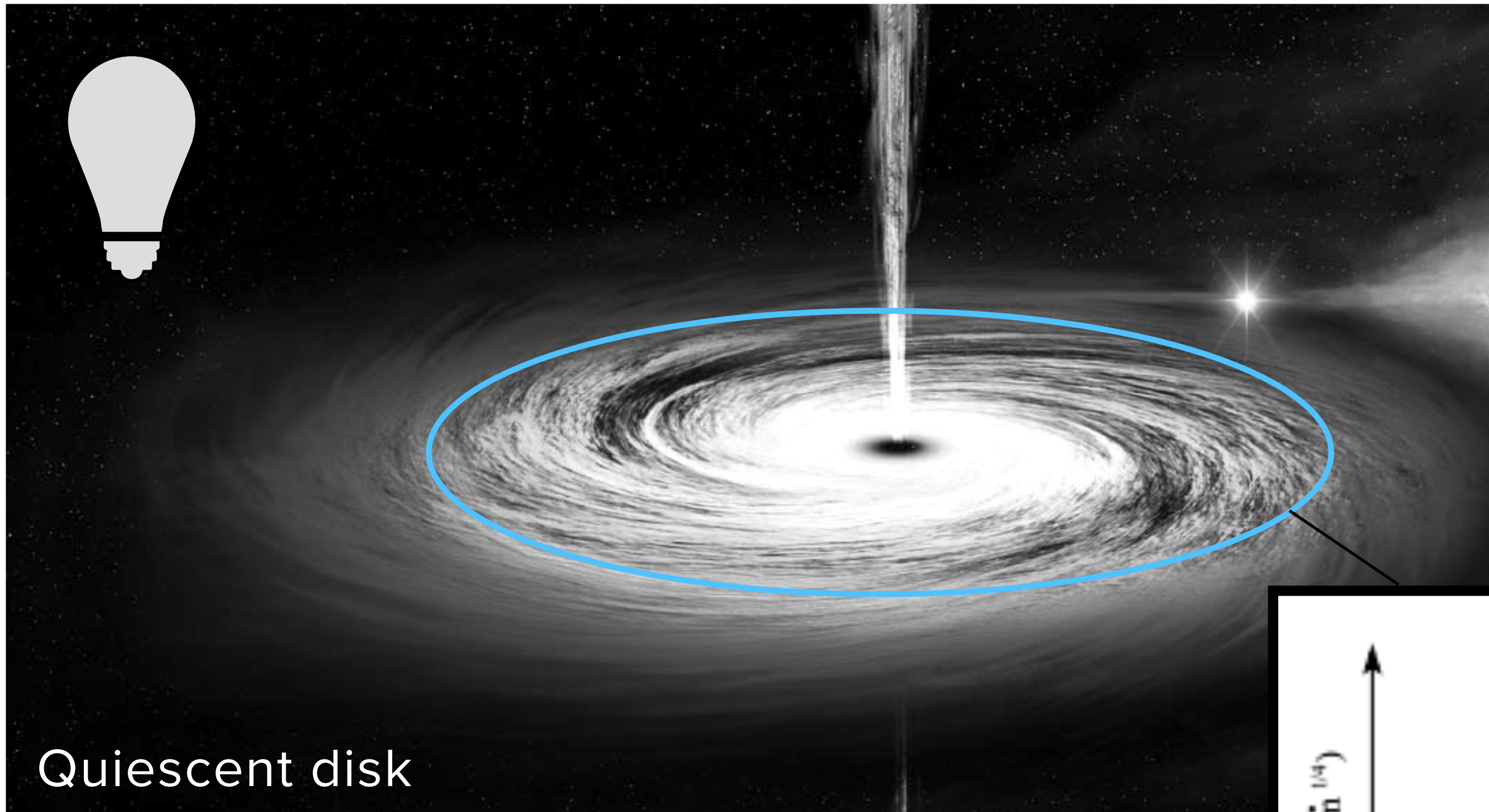
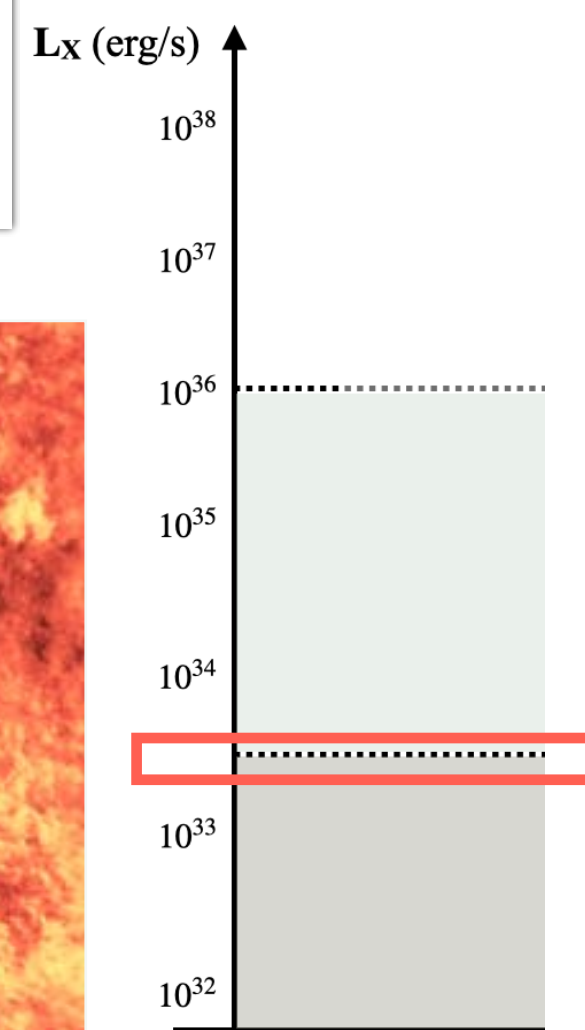
- NS LMXBs are brighter than BHs in quiescence due to the residual emission from the NS surface;
- In both sources, a power-law component is sometimes observed and possibly attributed to residual accretion or, in the case of NSs, of magnetospheric processes;



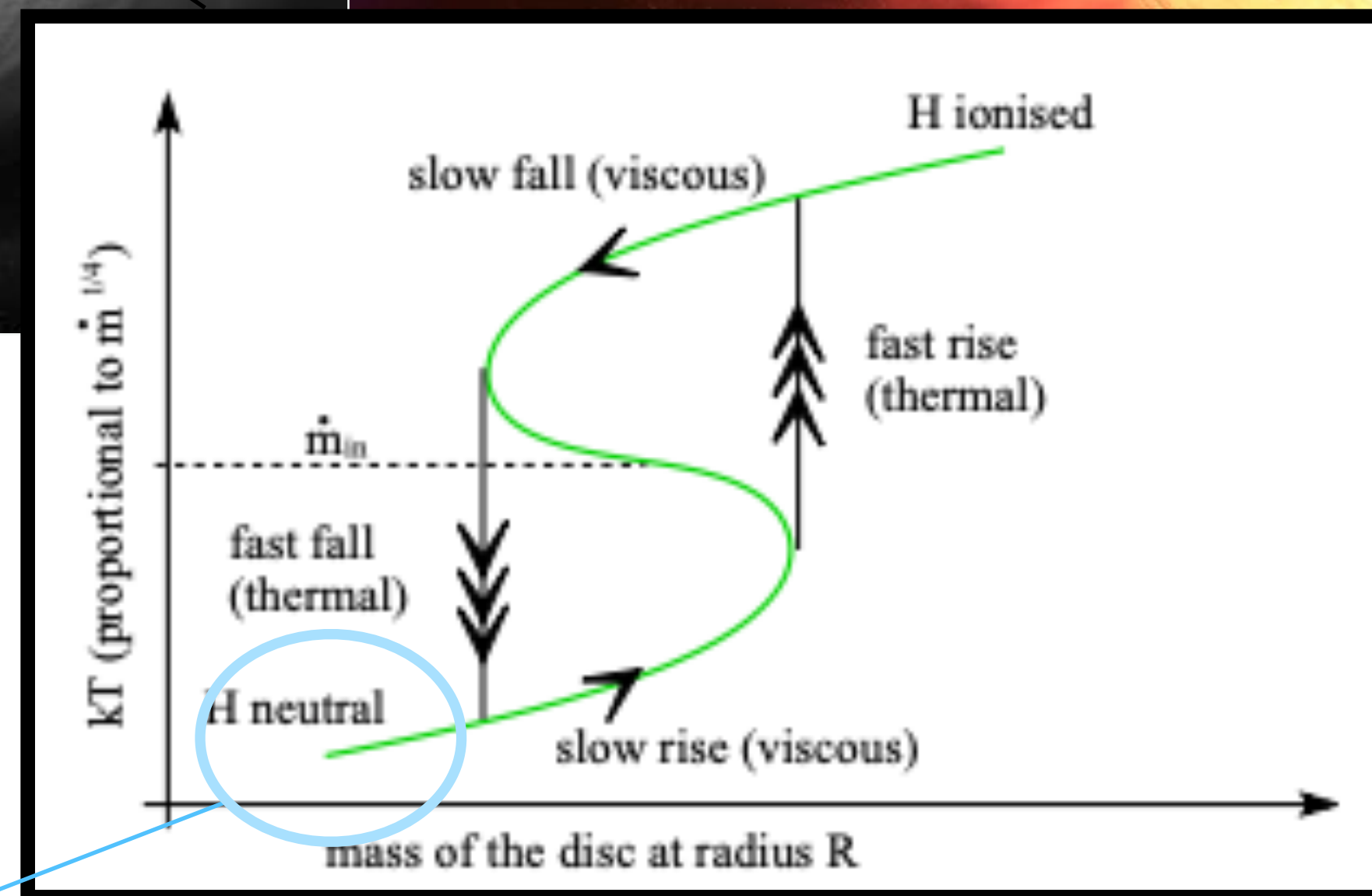
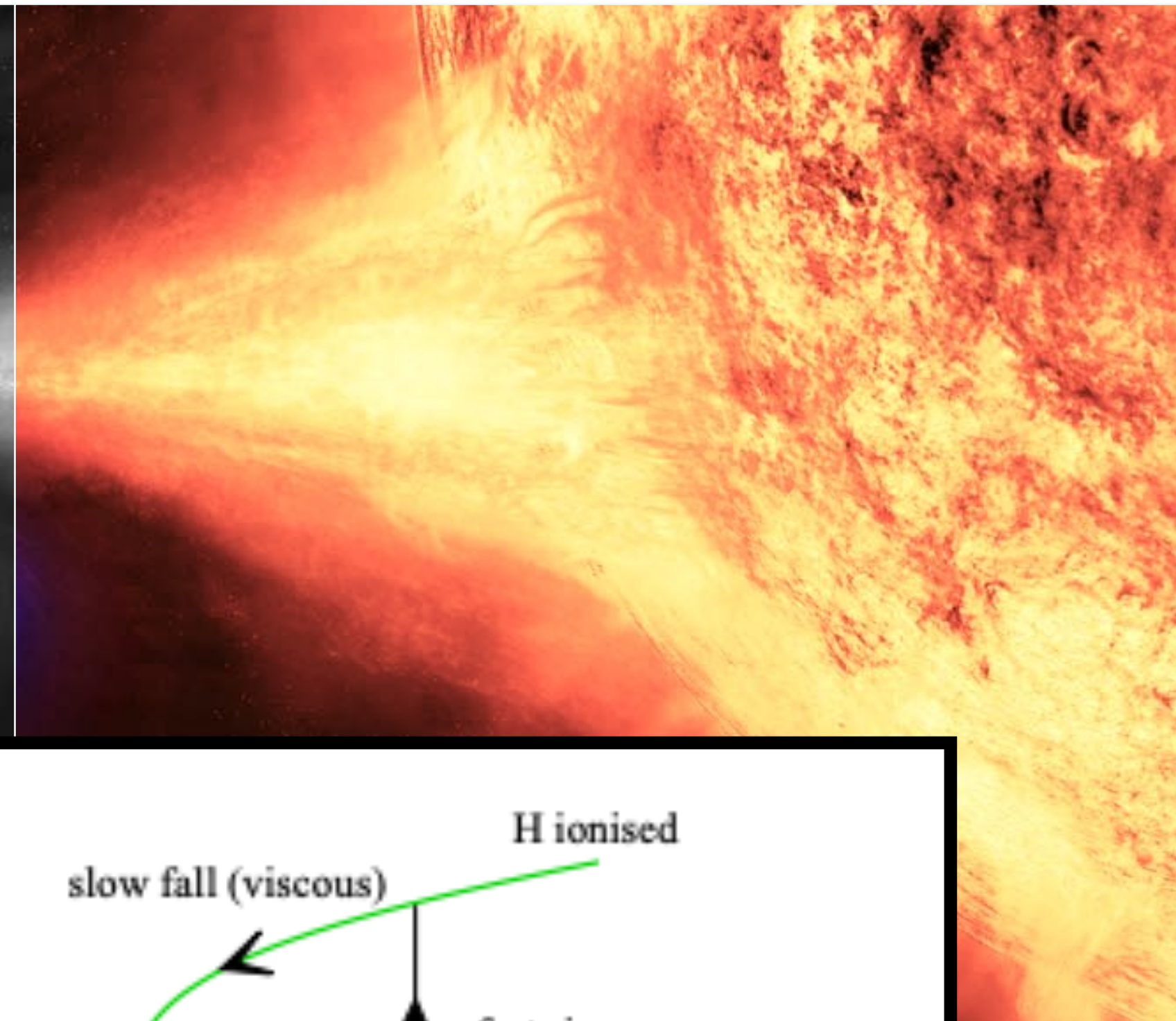
How outbursts start: a local ionisation instability



Meyer+1981; van Paradijs 1996;
Lasota 2001; Dubus+2001;
Coriat+2012; Hammeury 2020



Quiescent disk



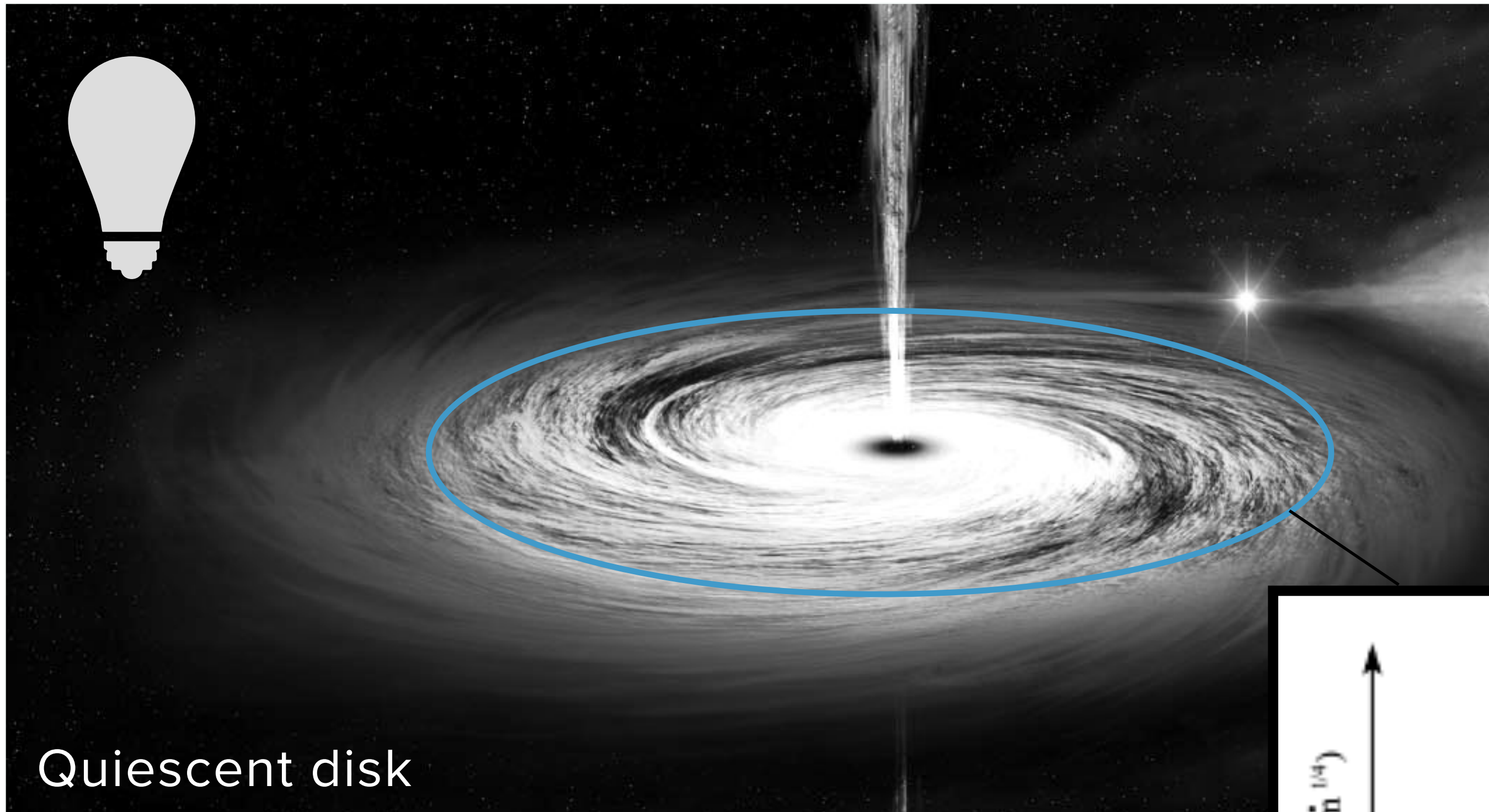
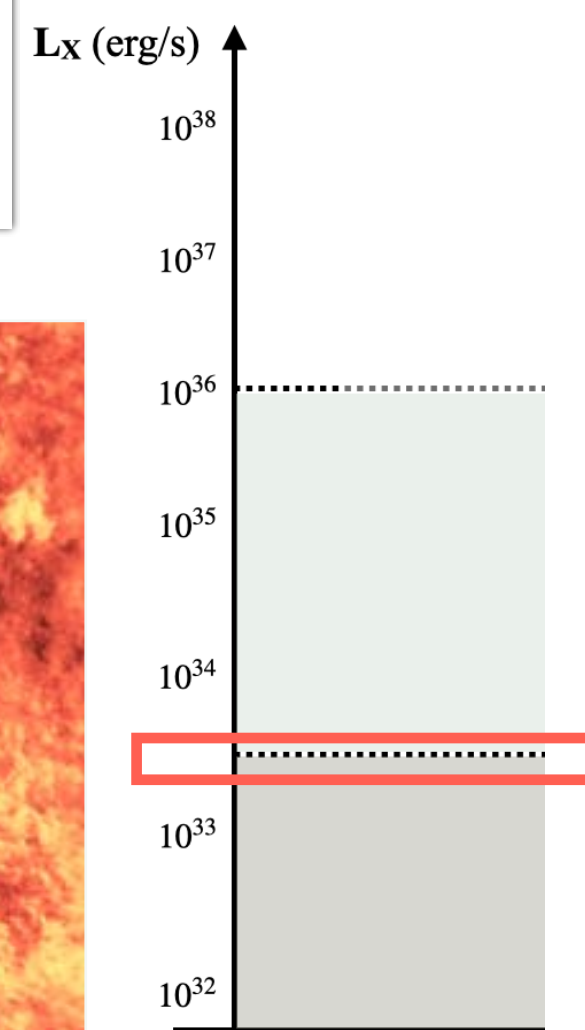
Starting point: matter at a certain radius of the quiescent disk is cold, neutral and transparent;

H-ionisation instability cycle; Done+2007

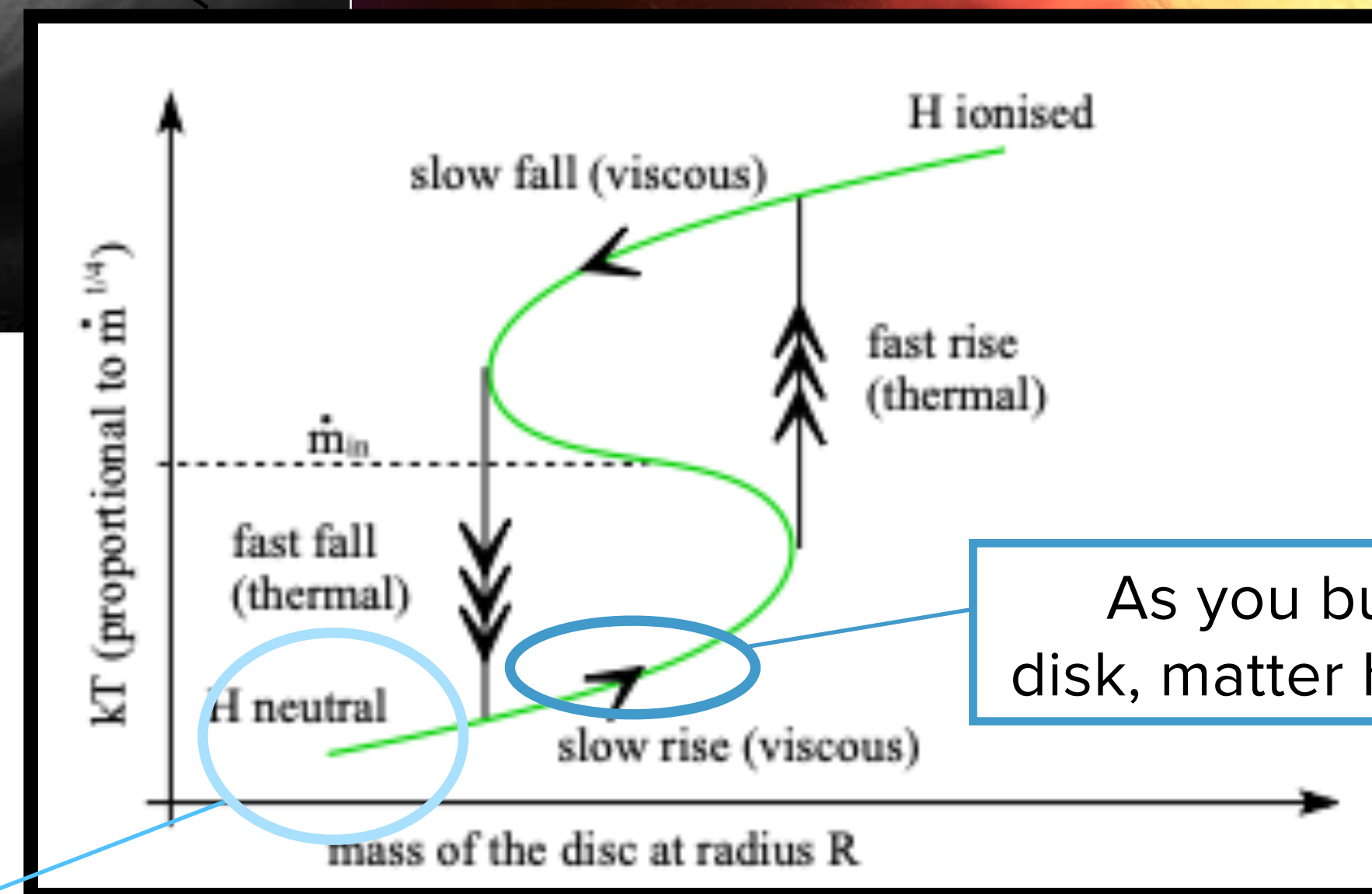
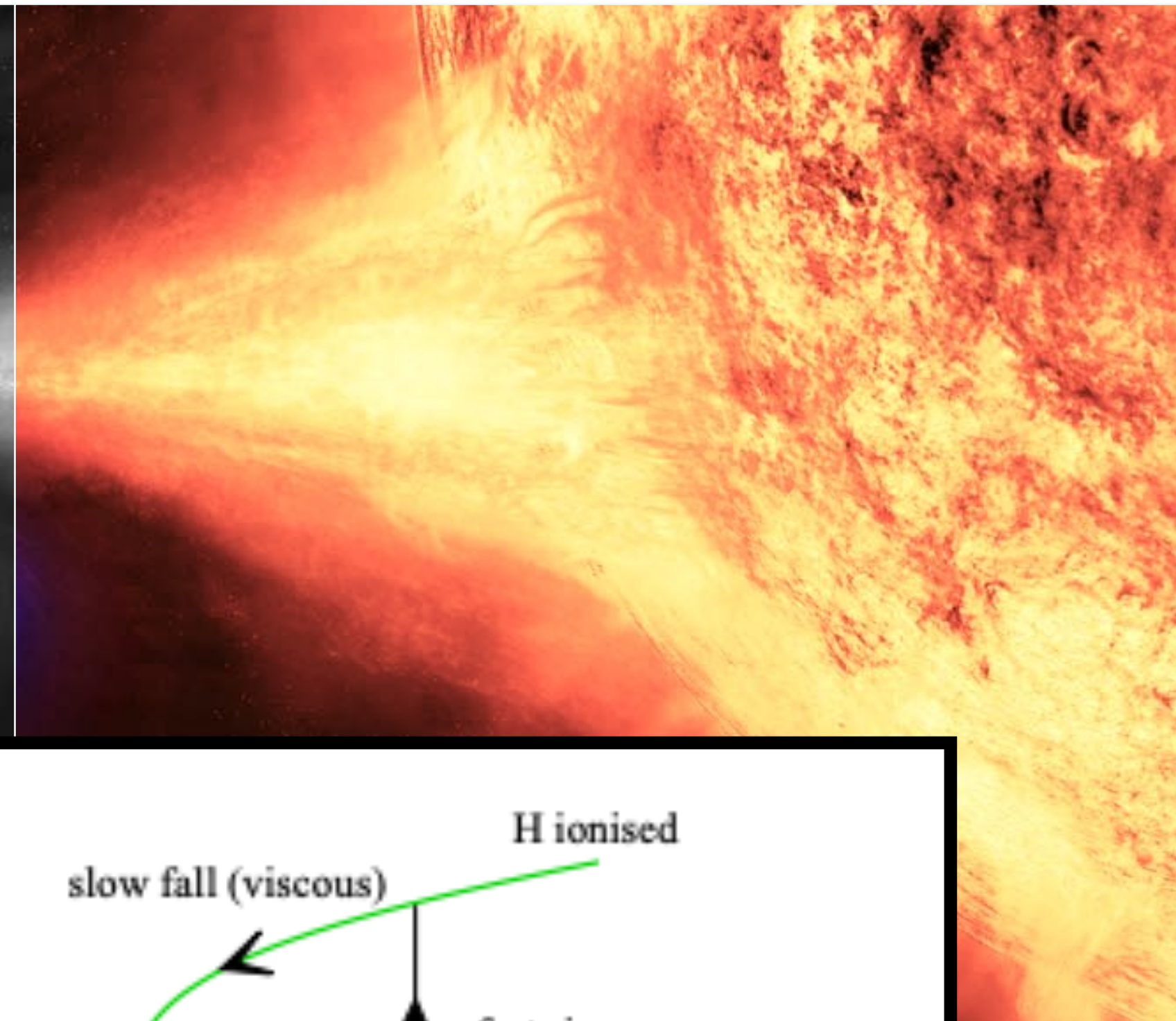
How outbursts start: a local ionisation instability



Meyer+1981; van Paradijs 1996;
Lasota 2001; Dubus+2001;
Coriat+2012; Hammeury 2020



Quiescent disk



Starting point: matter at a certain radius of the quiescent disk is cold, neutral and transparent;

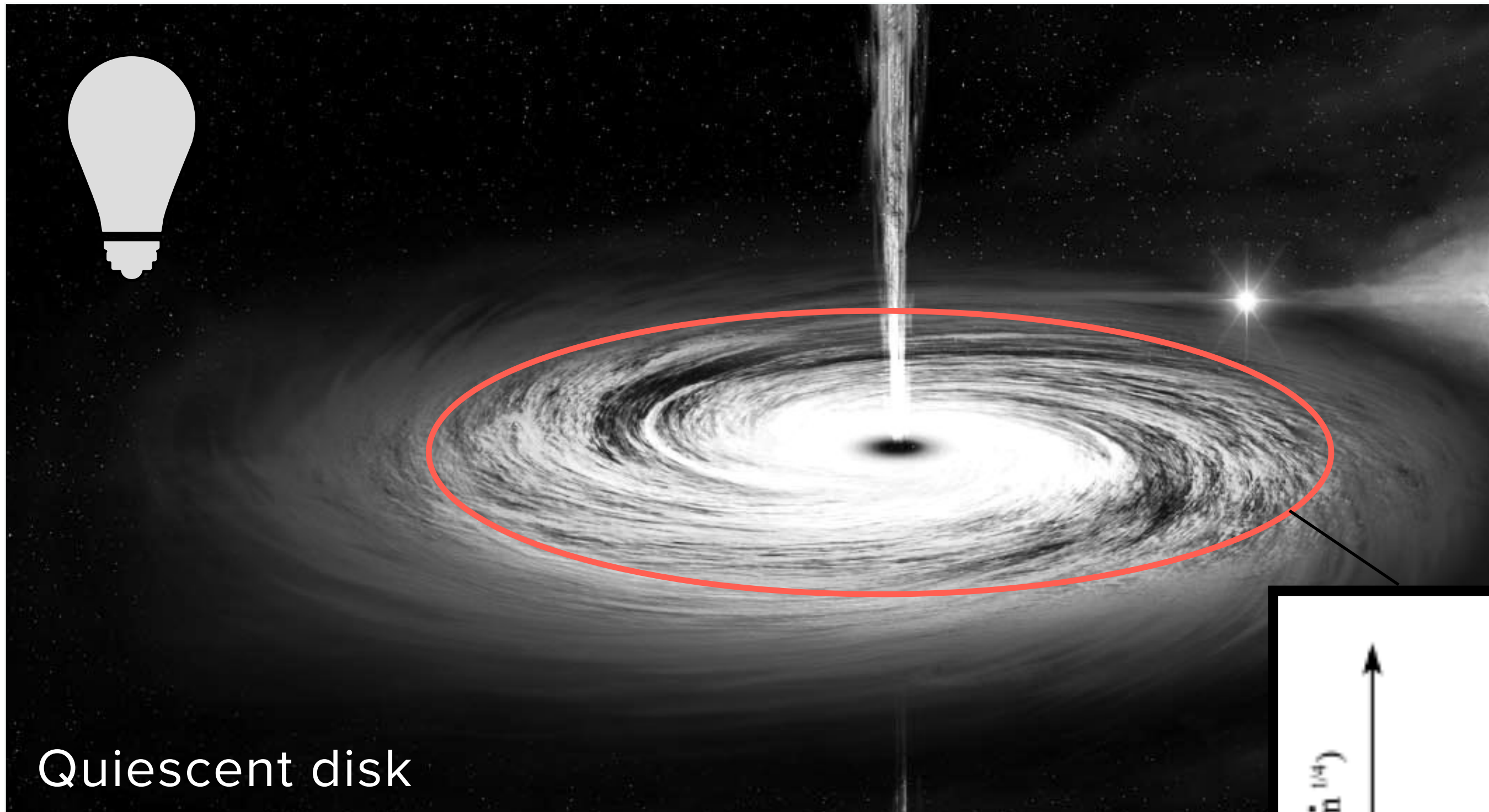
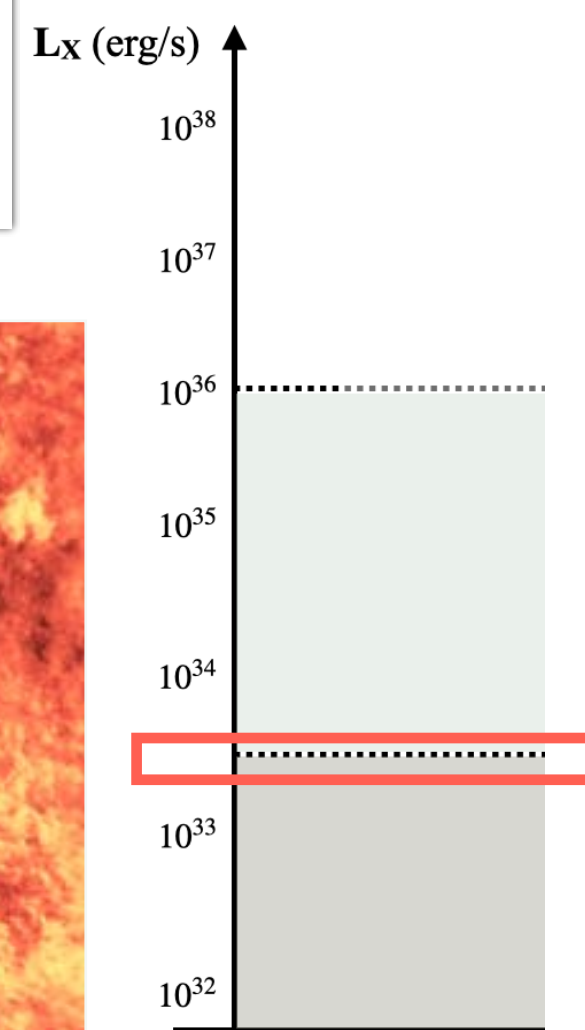
As you build up material in the disk, matter heats up and radiates;

H-ionisation instability cycle; Done+2007

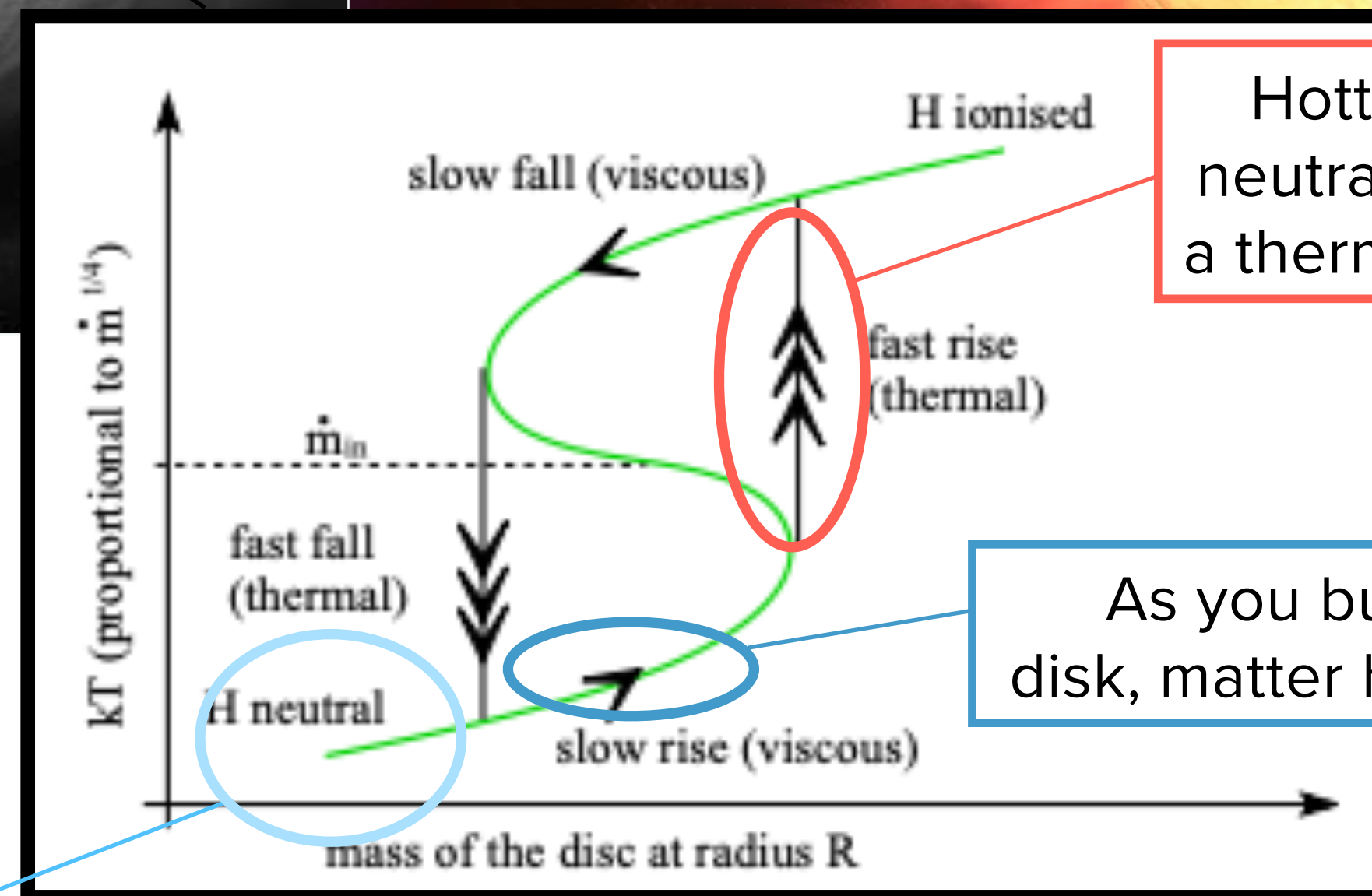
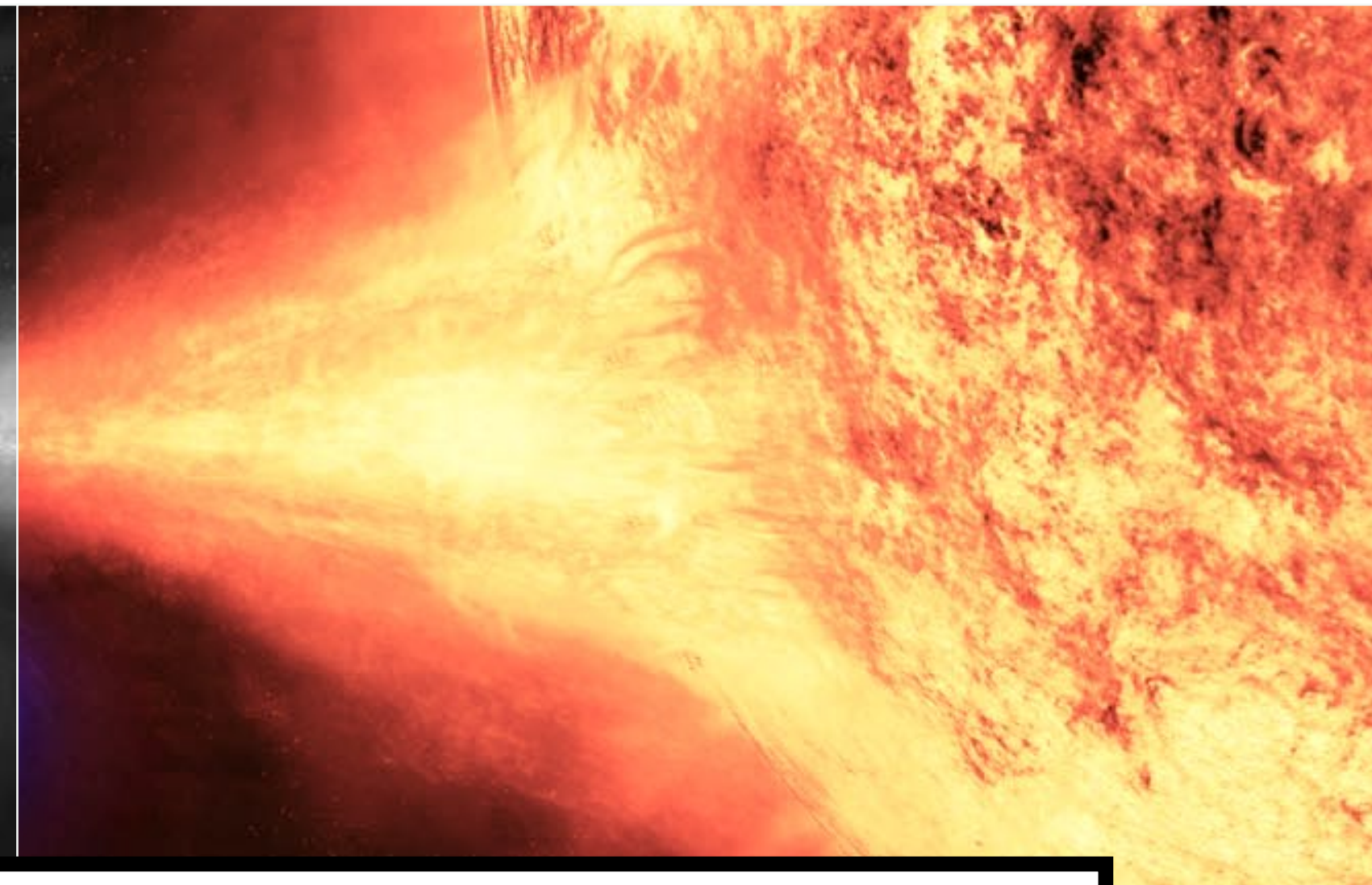
How outbursts start: a local ionisation instability



Meyer+1981; van Paradijs 1996;
Lasota 2001; Dubus+2001;
Coriat+2012; Hammeury 2020



Quiescent disk



Hotter radiation ionises the neutral H, opacity increases, a thermal runaway is initiated

As you build up material in the disk, matter heats up and radiates;

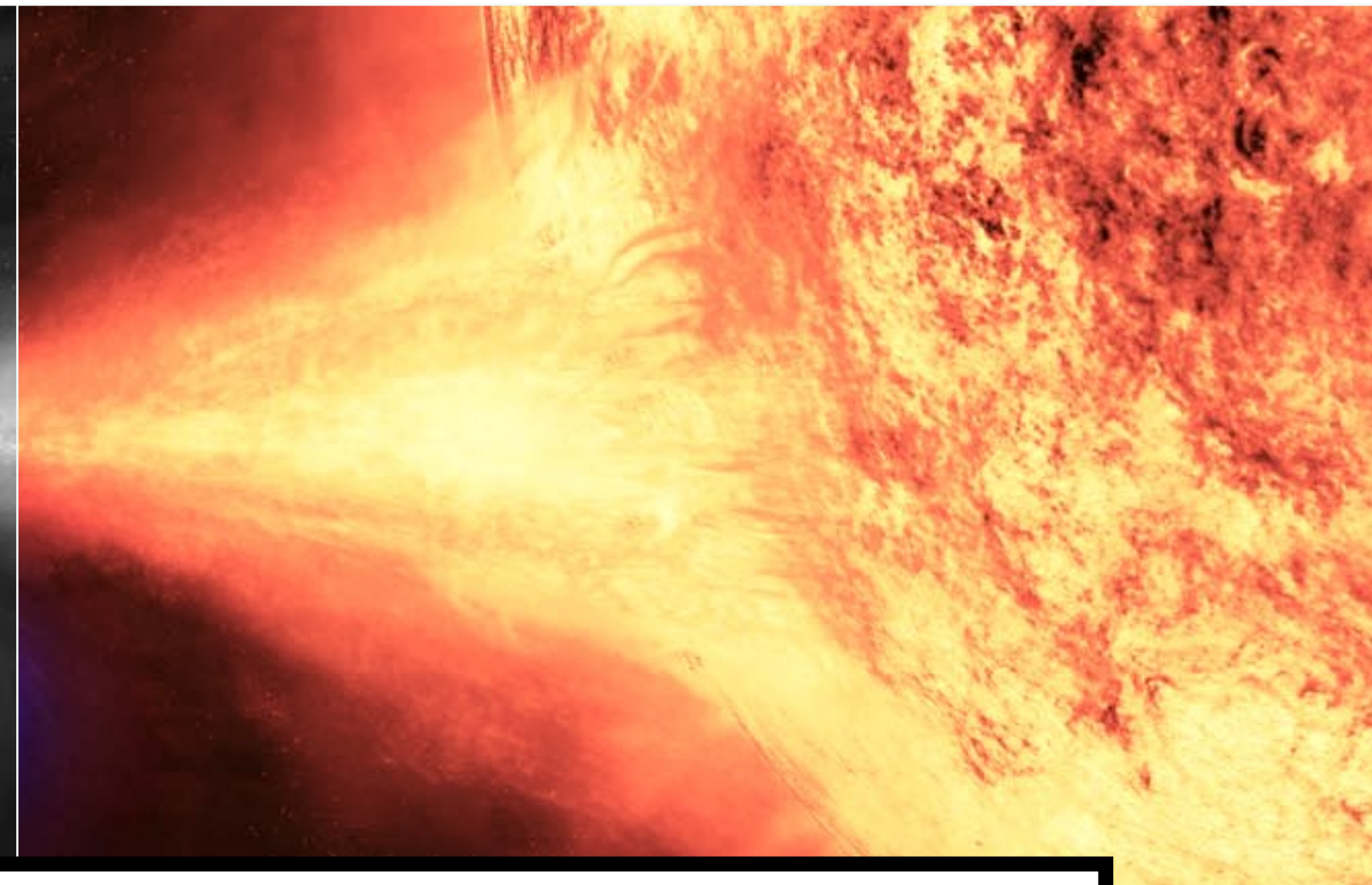
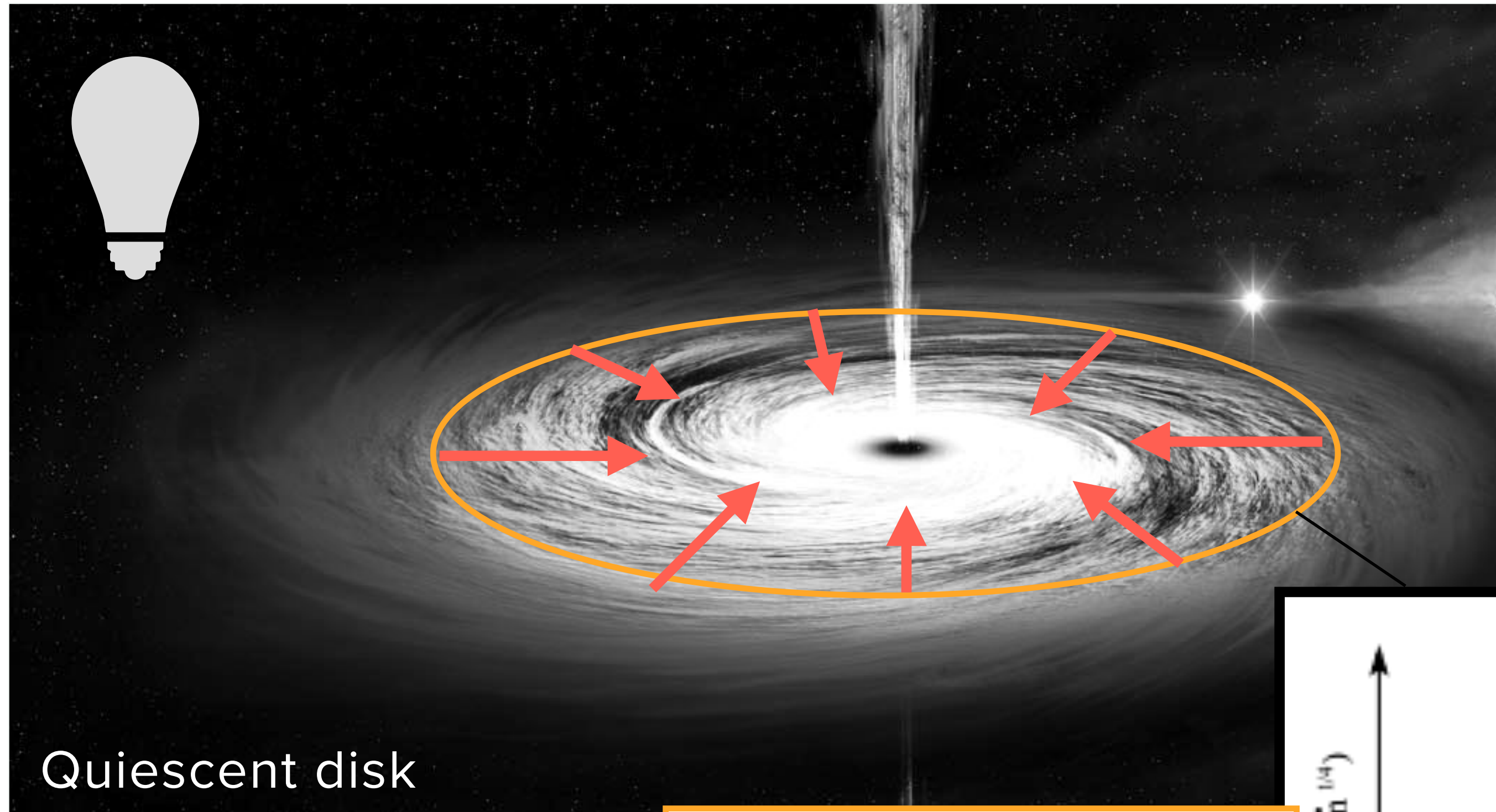
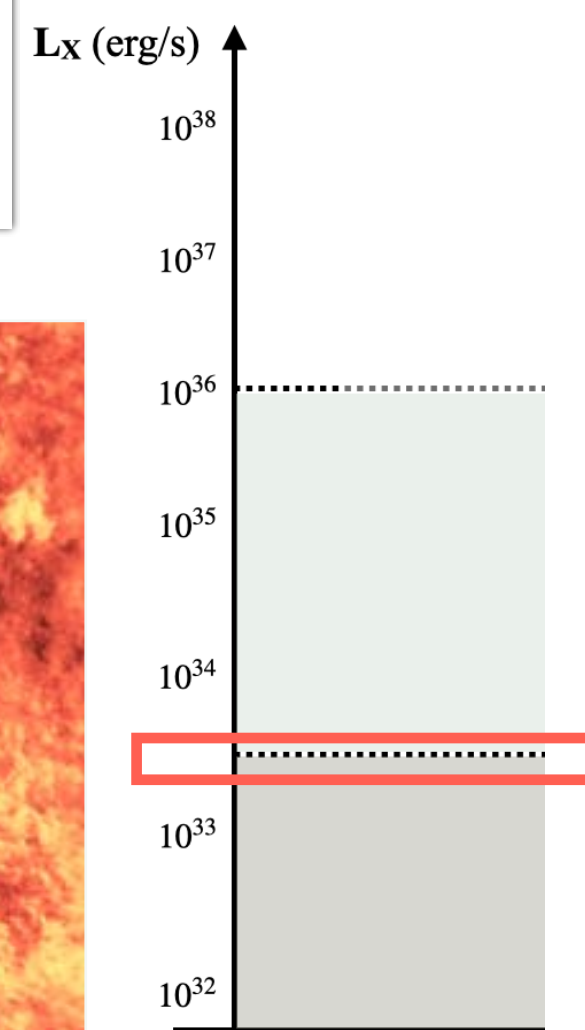
Starting point: matter at a certain radius of the quiescent disk is cold, neutral and transparent;

H-ionisation instability cycle; Done+2007

How outbursts start: a local ionisation instability

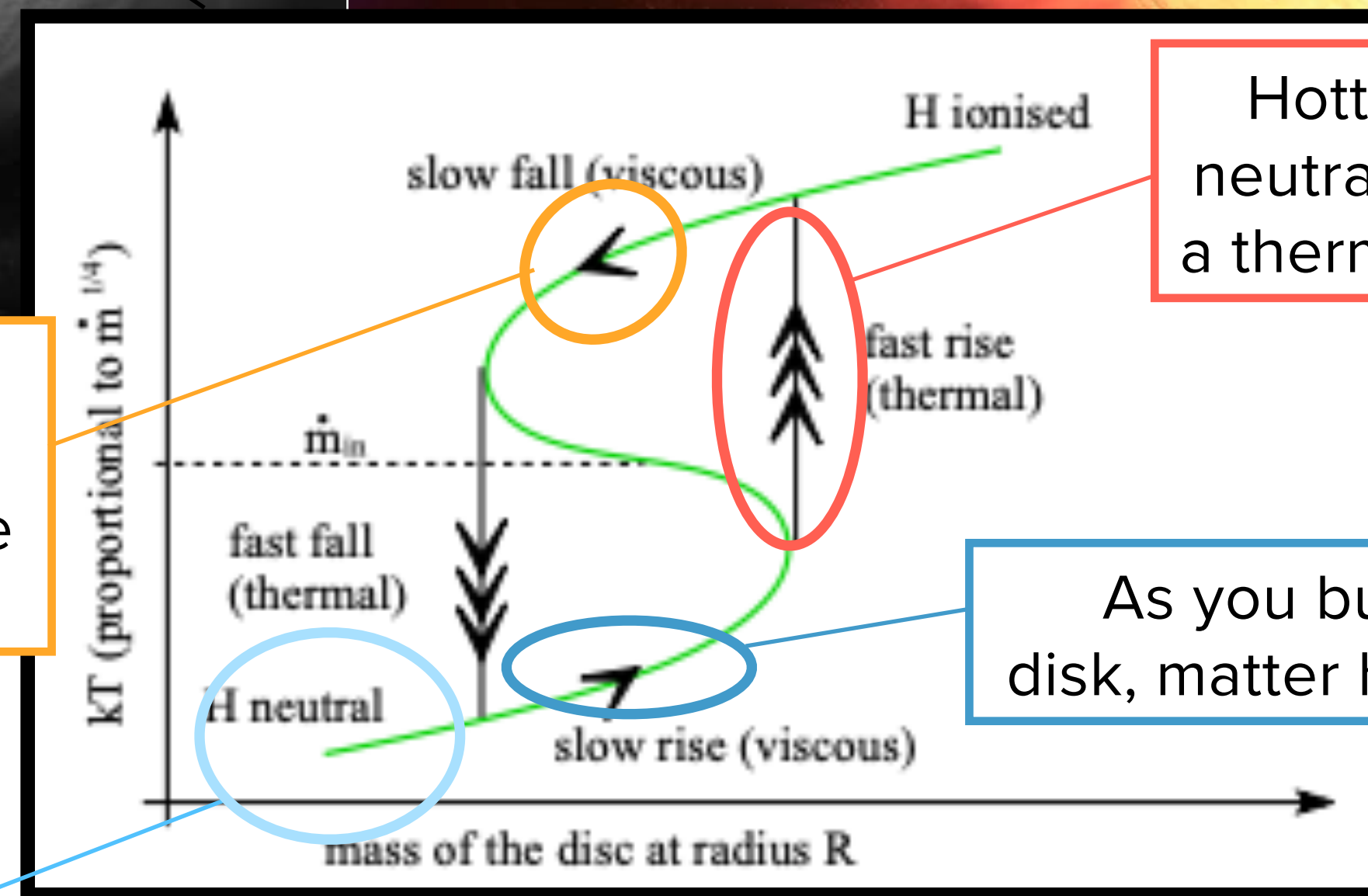


Meyer+1981; van Paradijs 1996;
Lasota 2001; Dubus+2001;
Coriat+2012; Hammeury 2020



Ionised material is accreted more rapidly, reducing the pressure in the annulus; cooling is initiated

Starting point: matter at a certain radius of the quiescent disk is cold, neutral and transparent;



Hotter radiation ionises the neutral H, opacity increases, a thermal runaway is initiated

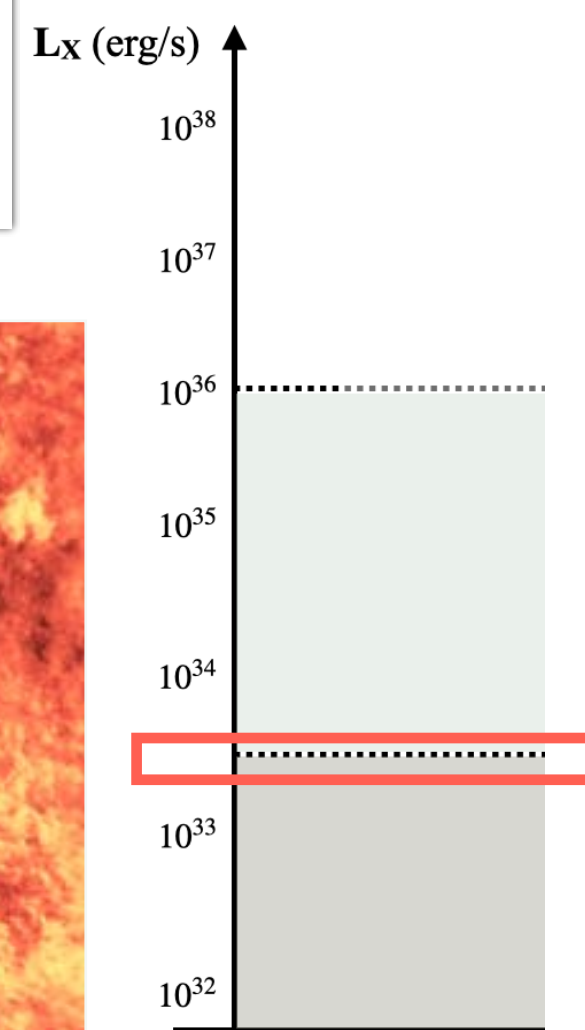
As you build up material in the disk, matter heats up and radiates;

H-ionisation instability cycle; Done+2007

How outbursts start: a local ionisation instability



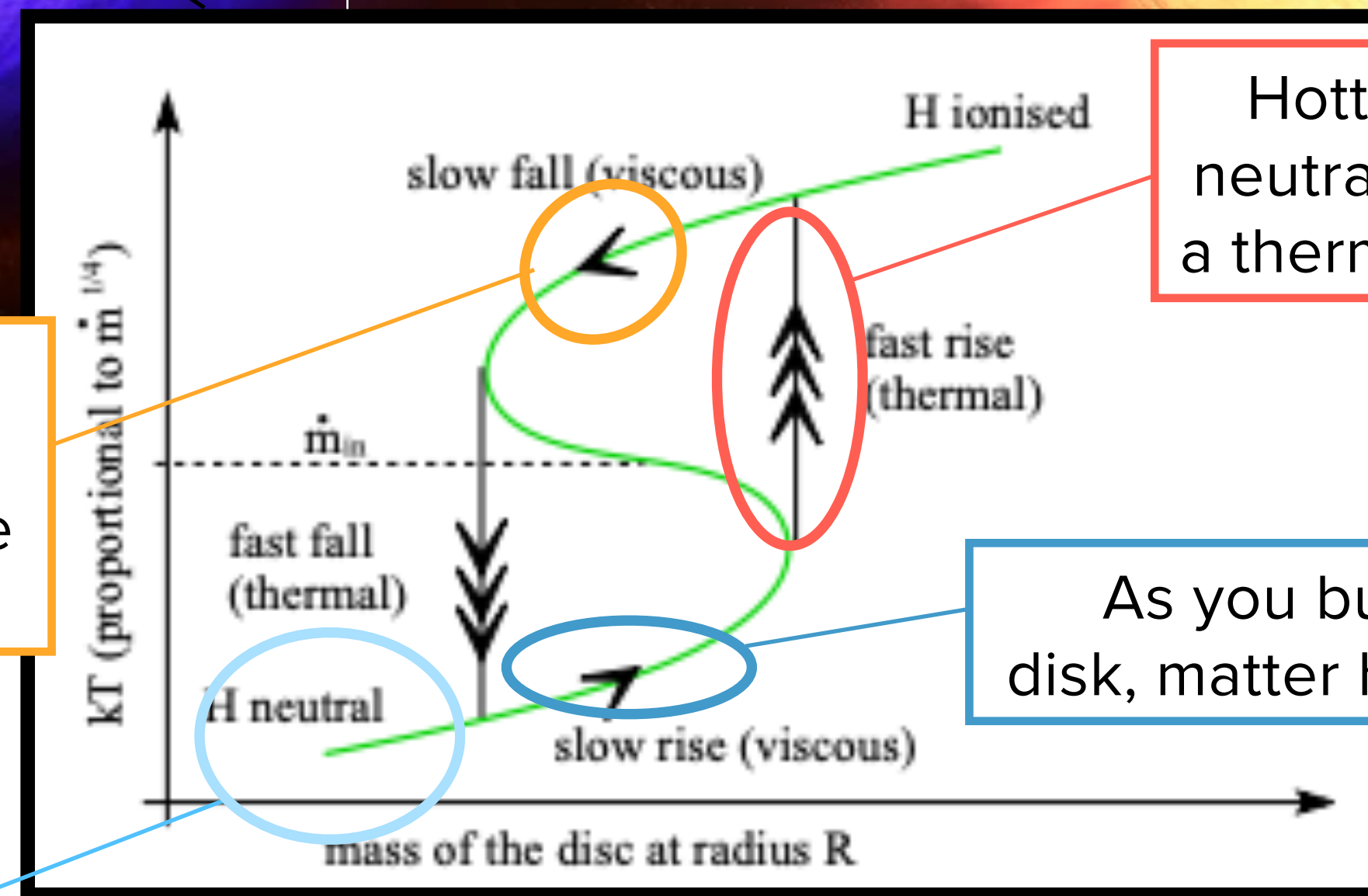
Meyer+1981; van Paradijs 1996;
Lasota 2001; Dubus+2001;
Coriat+2012; Hammeury 2020



An heating front propagates!
An outburst is born

Ionised material is
accreted more rapidly,
reducing the pressure in the
annulus; cooling is initiated

Starting point: matter at a
certain radius of the quiescent disk
is cold, neutral and transparent;



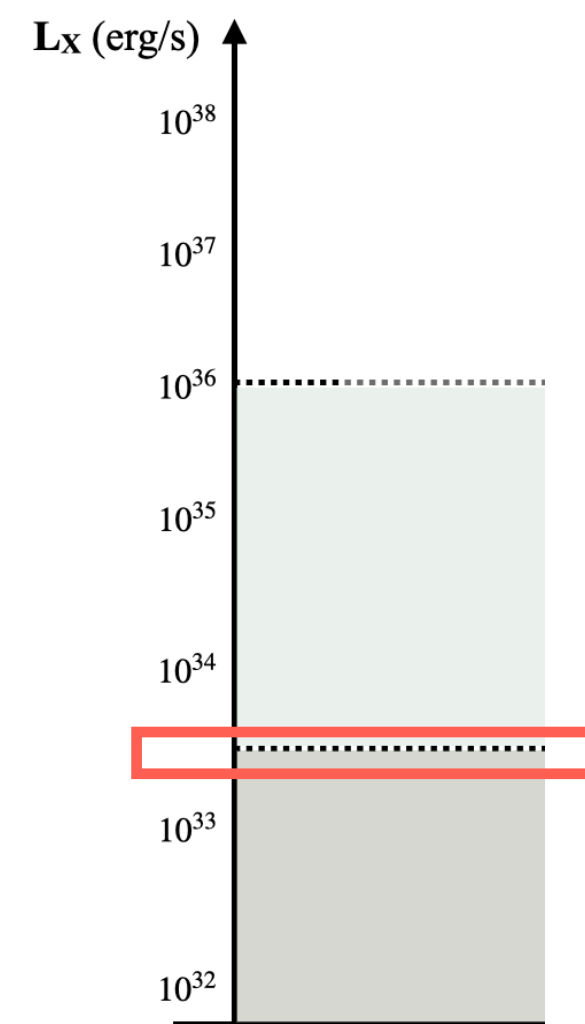
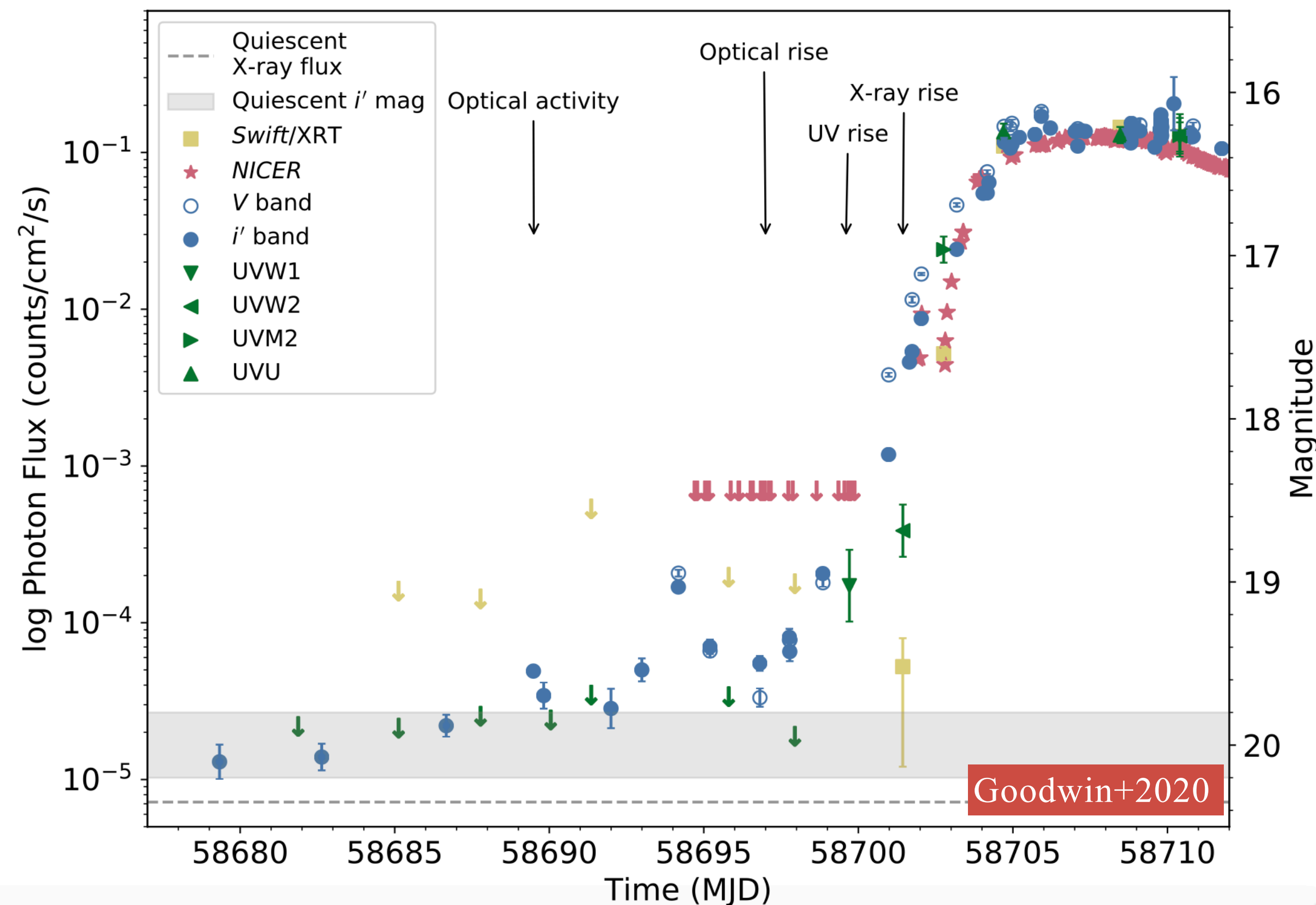
Hotter radiation ionises the
neutral H, opacity increases,
a thermal runaway is initiated

As you build up material in the
disk, matter heats up and radiates;

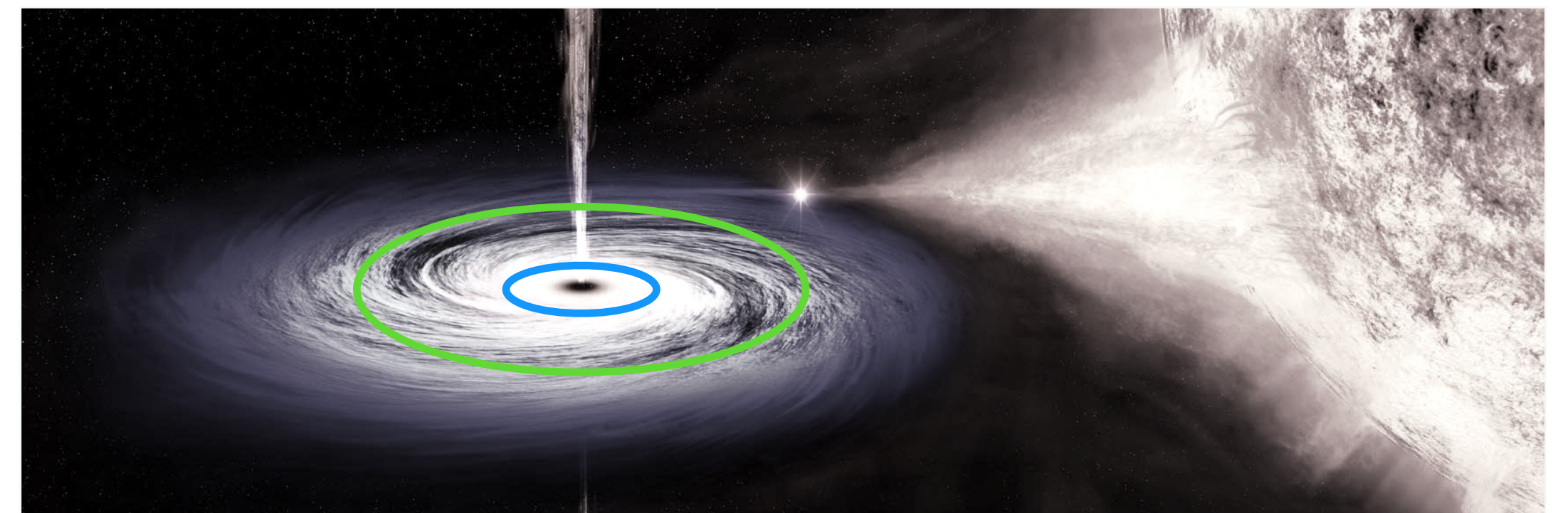
H-ionisation instability cycle; Done+2007

How outbursts start: the disk instability model

- This is the basics of the disk instability model (Lasota 2001), which is known to work well for Cataclysmic Variables (white dwarf accreting from low-mass companion stars);
- In LMXBs it roughly works, with some tweaks due to X-rays irradiation from the central source and the presence of the hot inner flow;

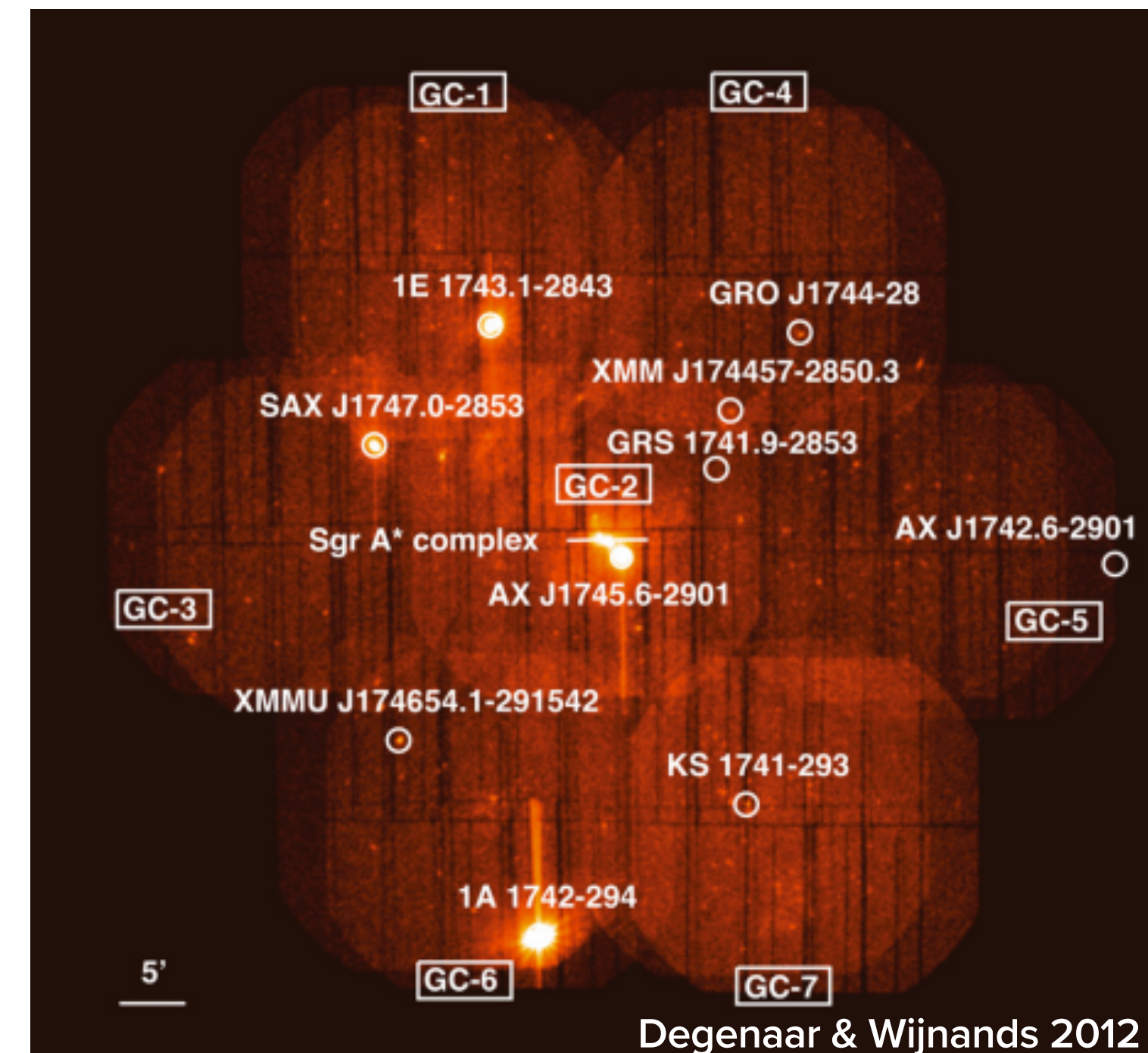
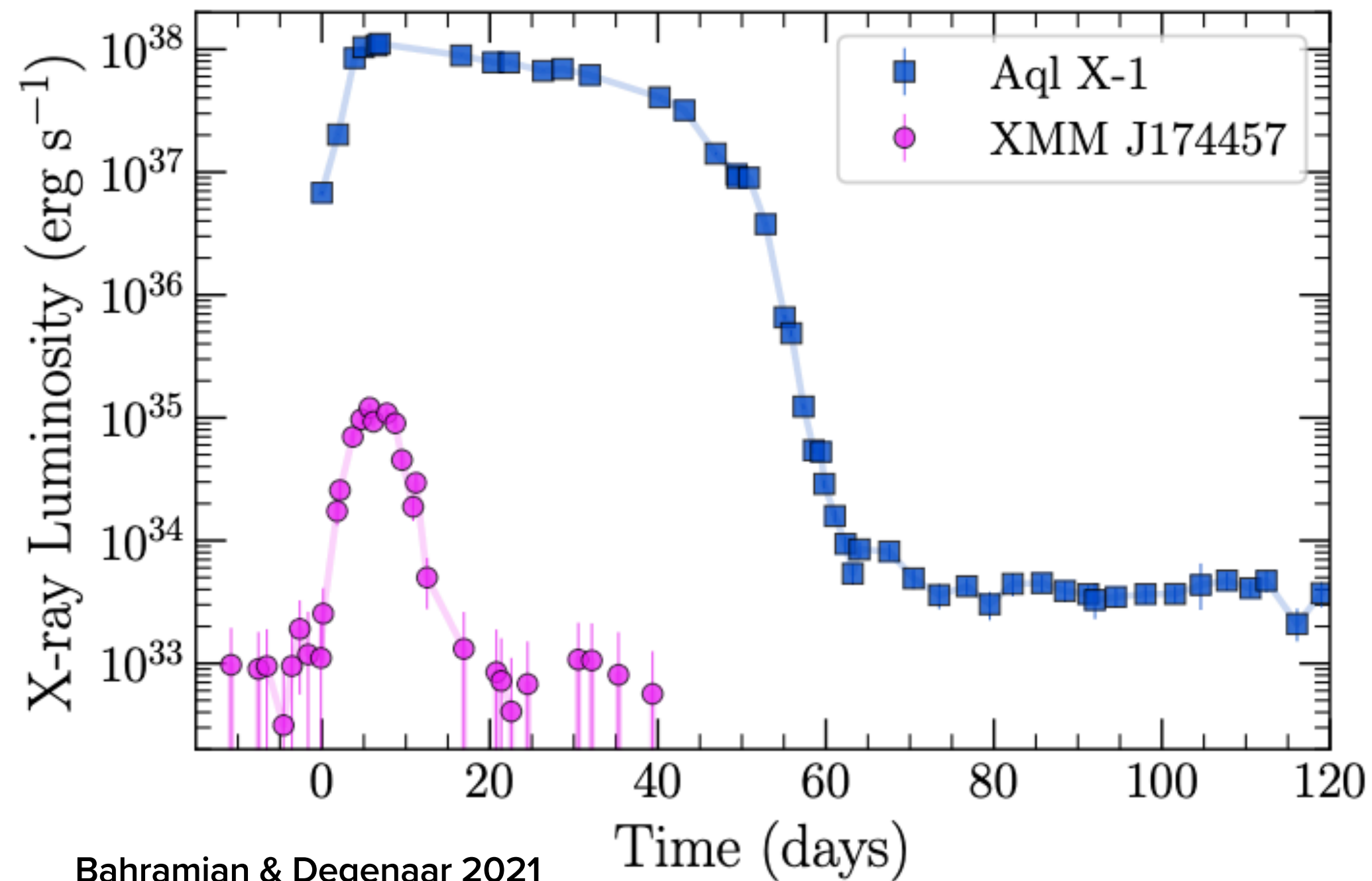
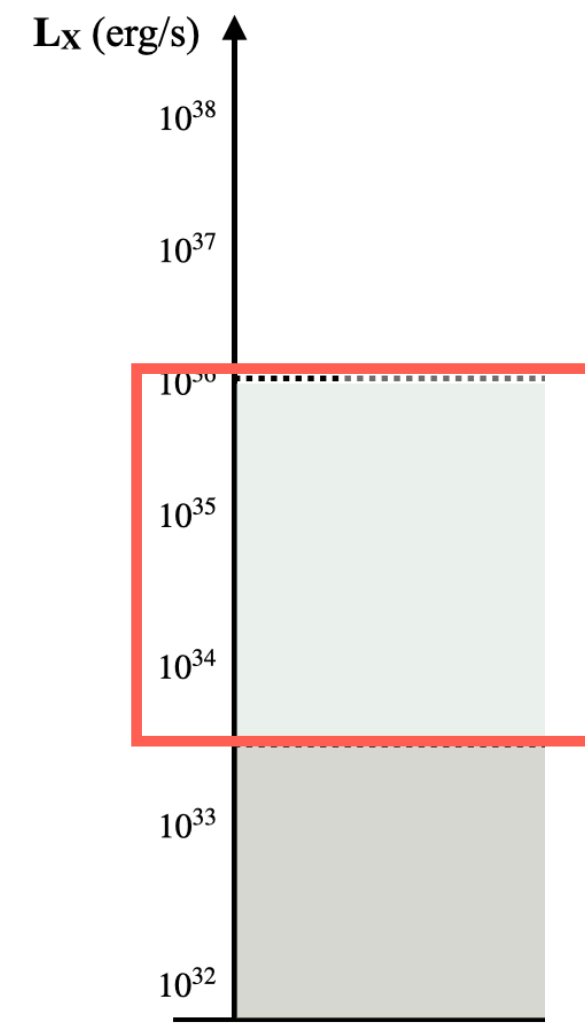


- The DIM in LMXBs could be tested by measuring the delays between the start of the outburst in the optical and X-rays;
- However, this has been so far rarely done;

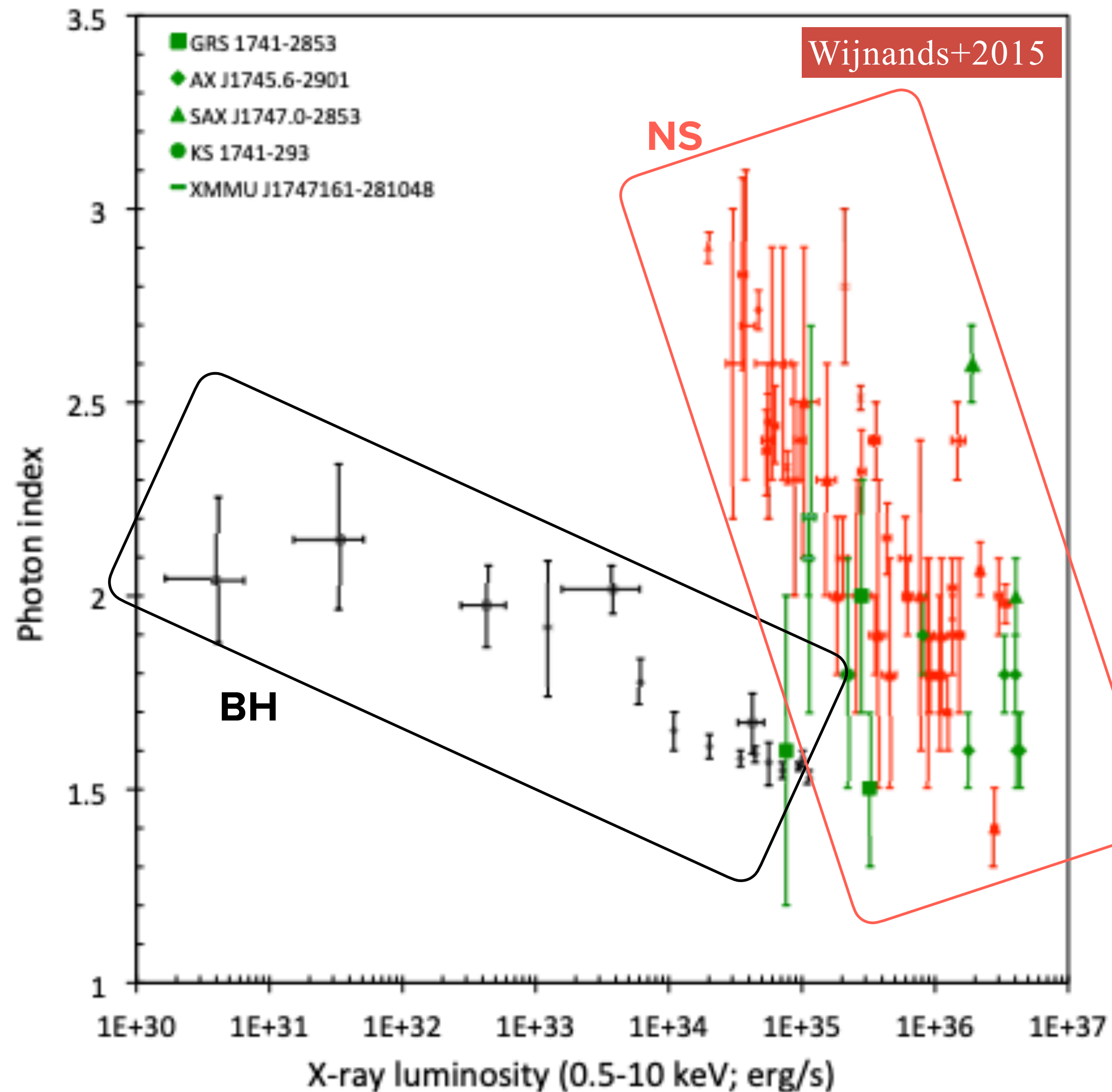


Very faint X-ray transients

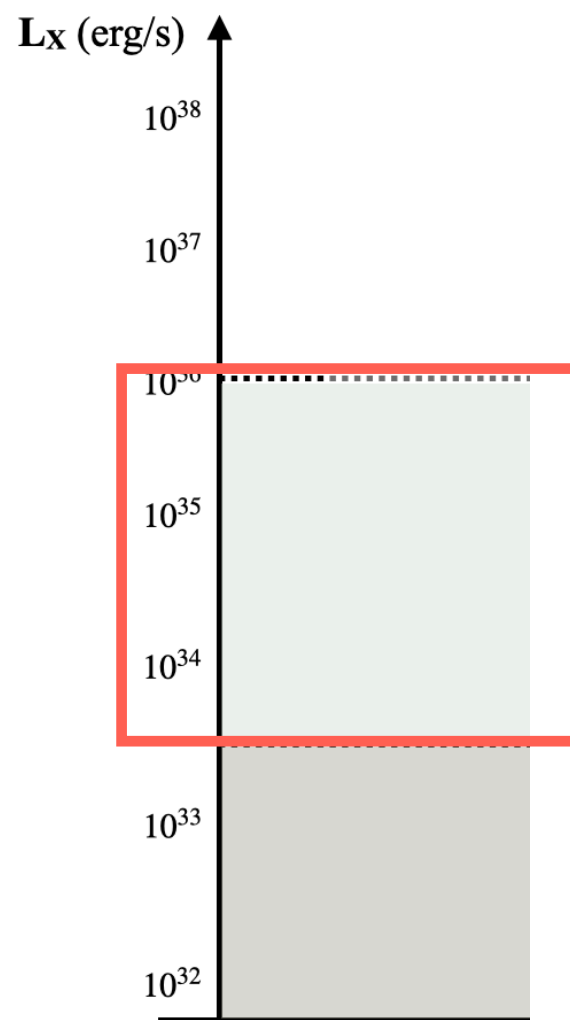
- Transient LMXBs displaying only faint outbursts (peak luminosity below 10^{36} erg/s);
- The majority hosts NSs, but several BHs known (e.g. Corral-Santana+2013);
- Typically discovered during soft X-ray surveys of the Galactic Center with Swift, XMM-Newton or Chandra (Degenaar+2009,2012, Bahramian+2021);



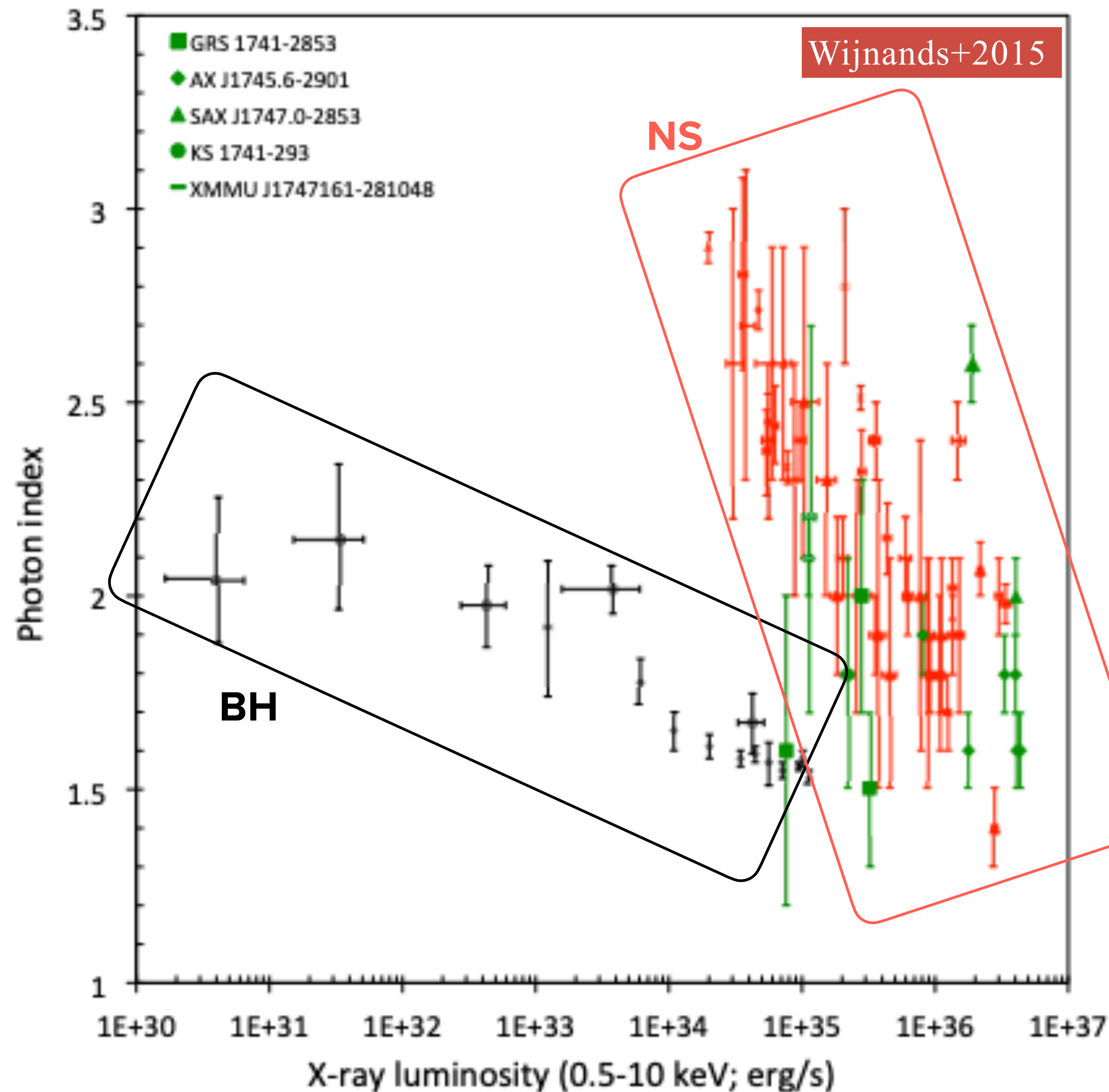
Very faint X-ray transients: *observed properties*



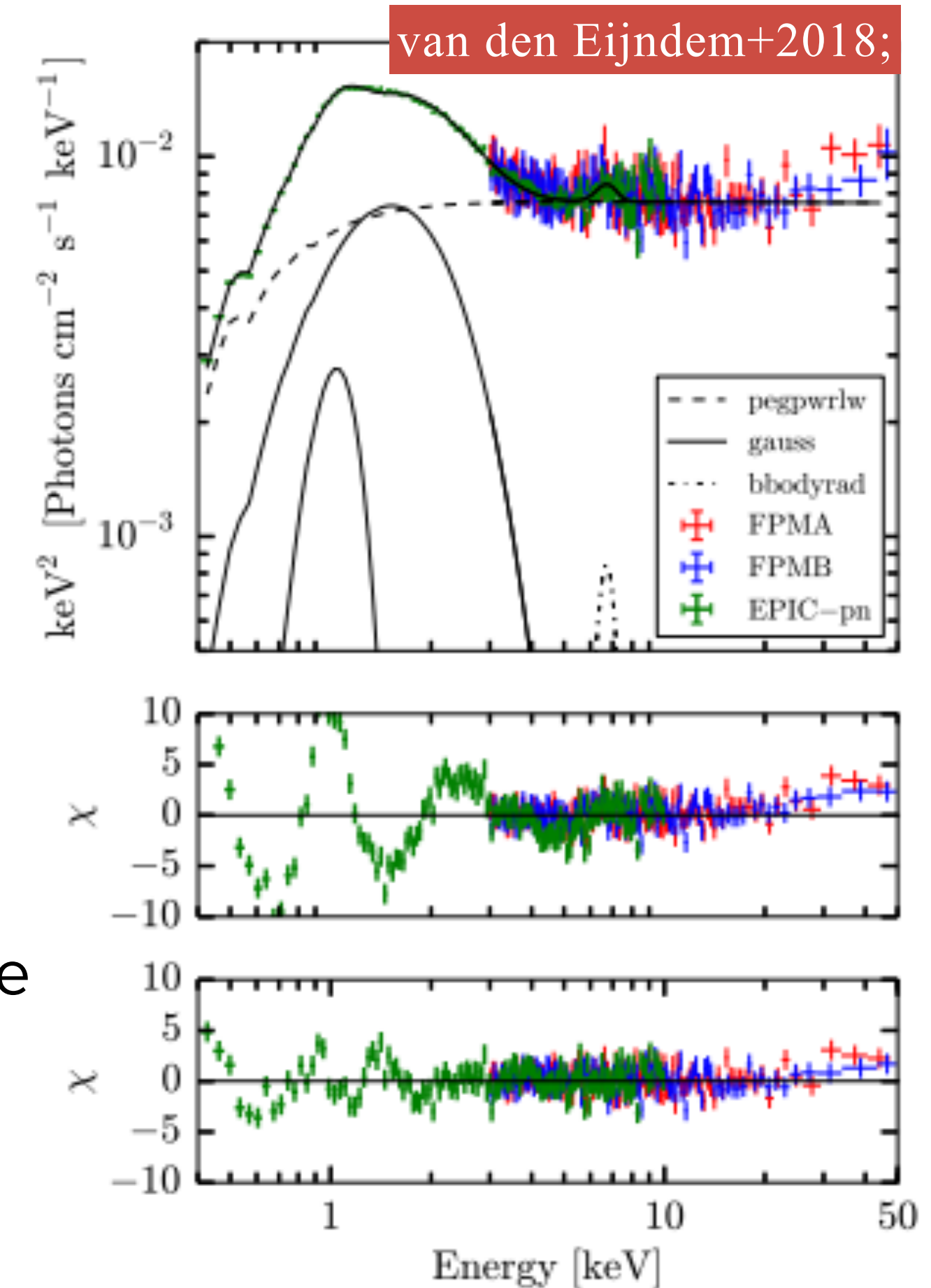
- Statistics is low, but.. Two tracks seem to emerge, with NSs softening much more rapidly and effectively than the BHs;



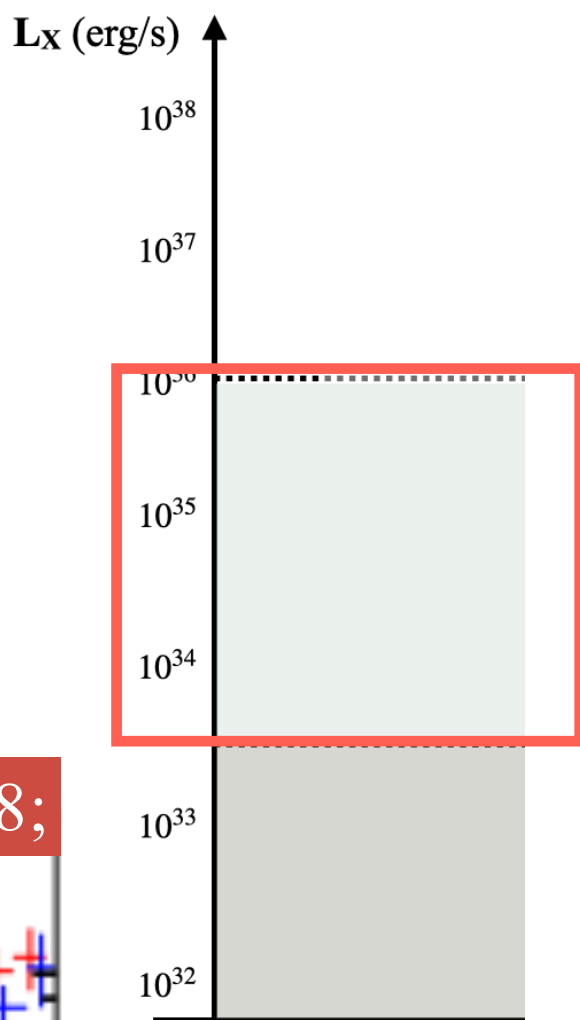
Very faint X-ray transients: *observed properties*



- Statistics is low, but.. Two tracks seem to emerge, with NSs softening much more rapidly and effectively than the BHs;



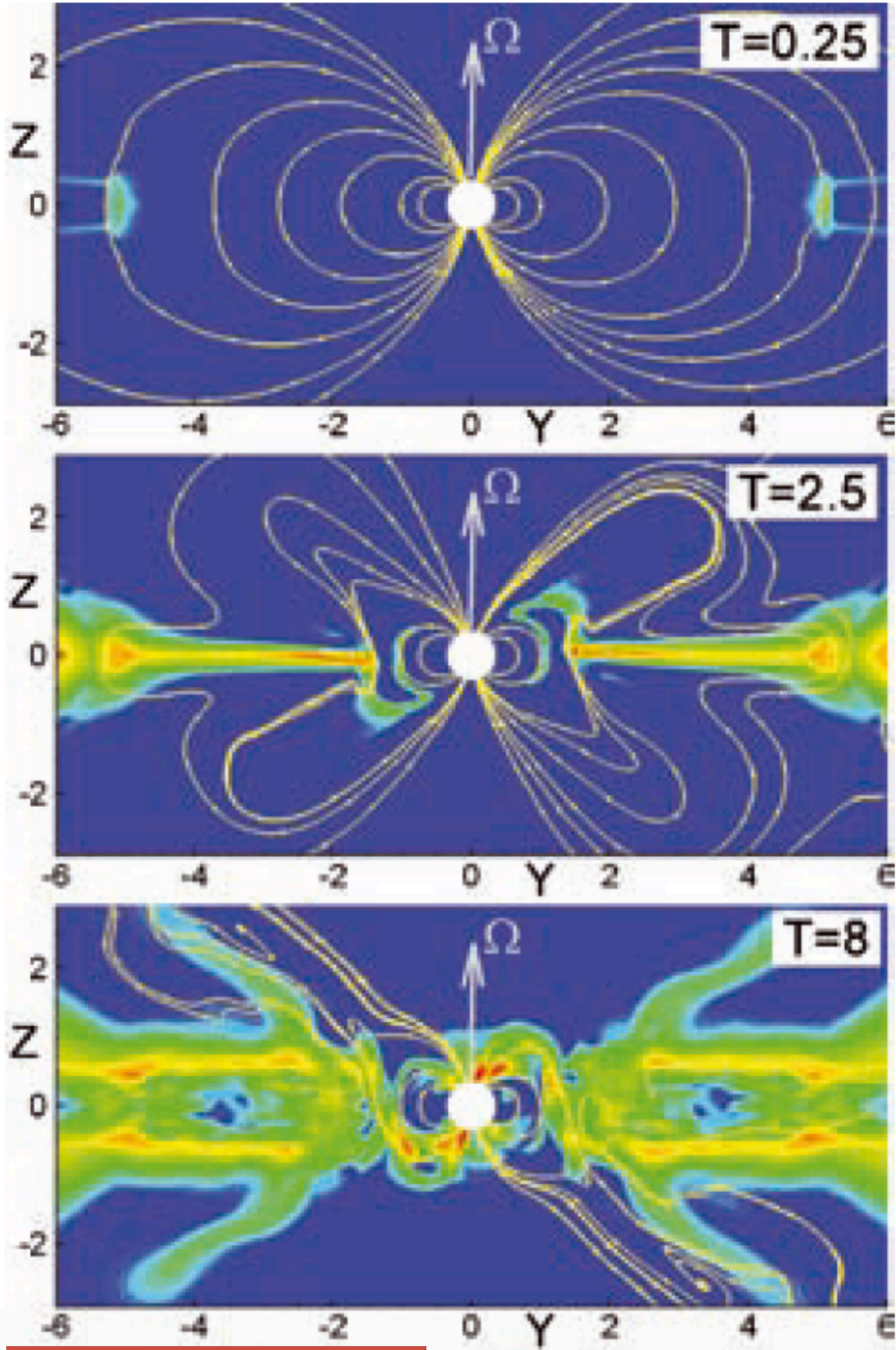
- Spectral properties are similar to hard states (Comptonization-dominated, truncated disk);



Very faint X-ray transients: *what is the origin?*

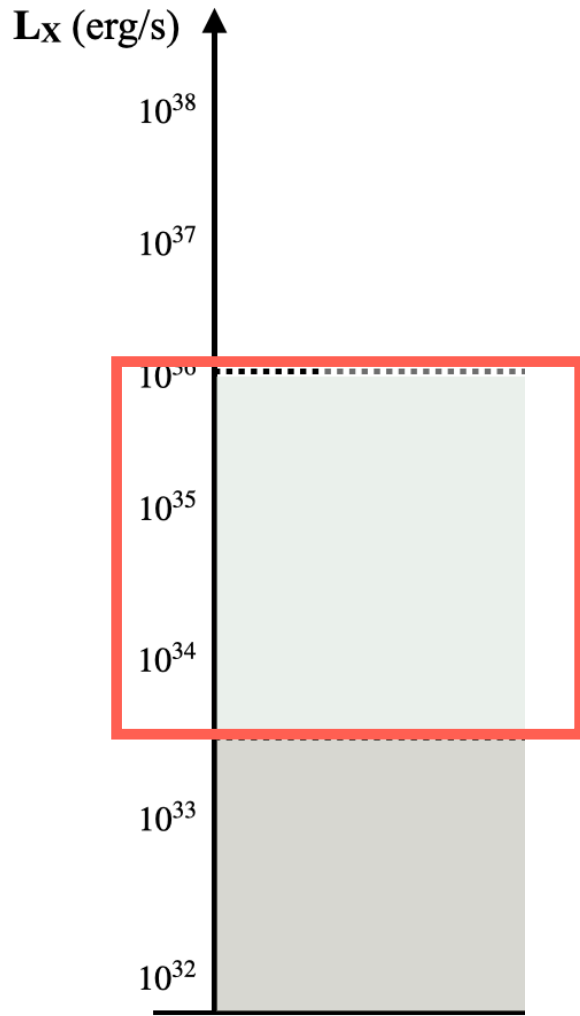


Magnetic propeller?

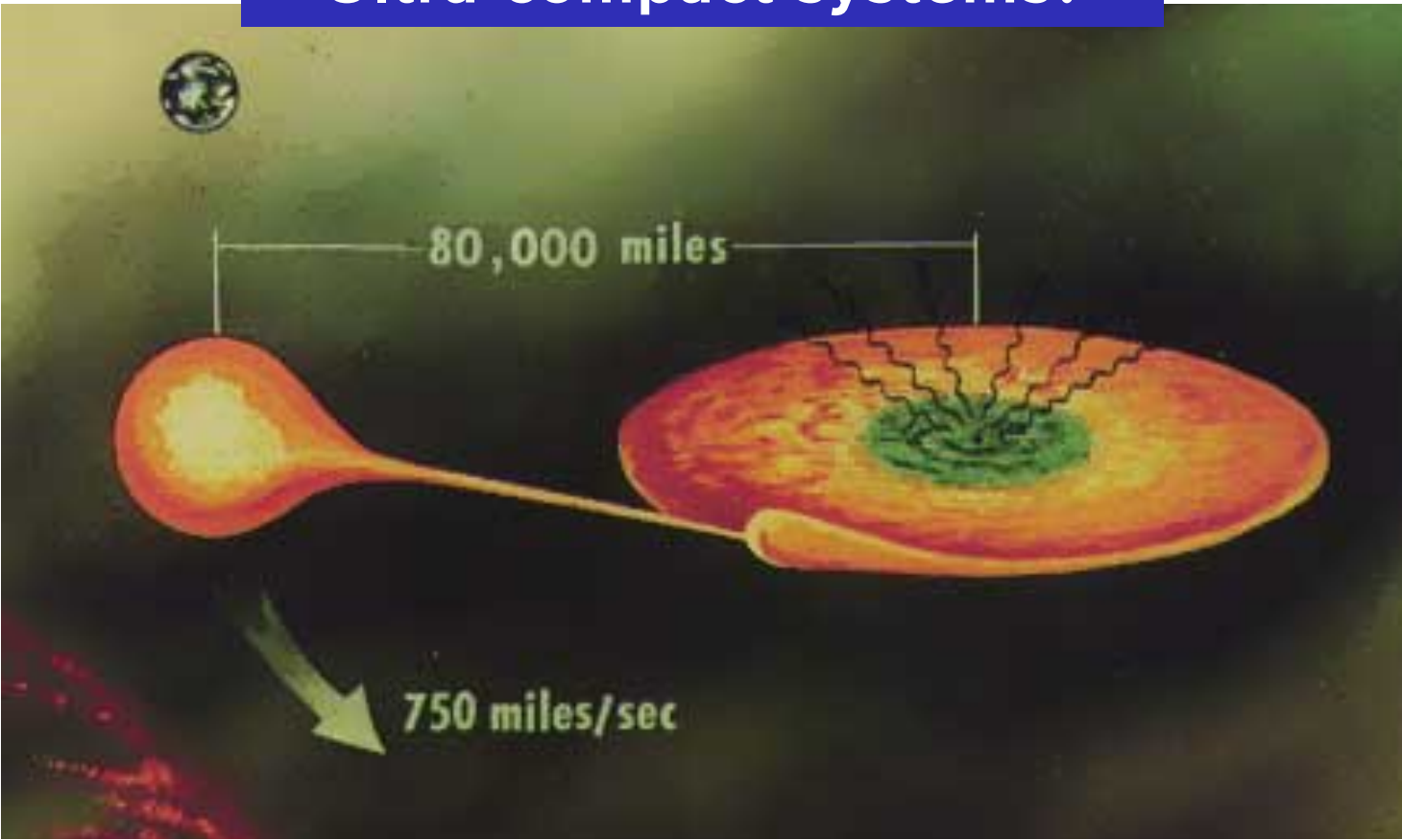


Romanova+2012

Accretion via stellar wind?

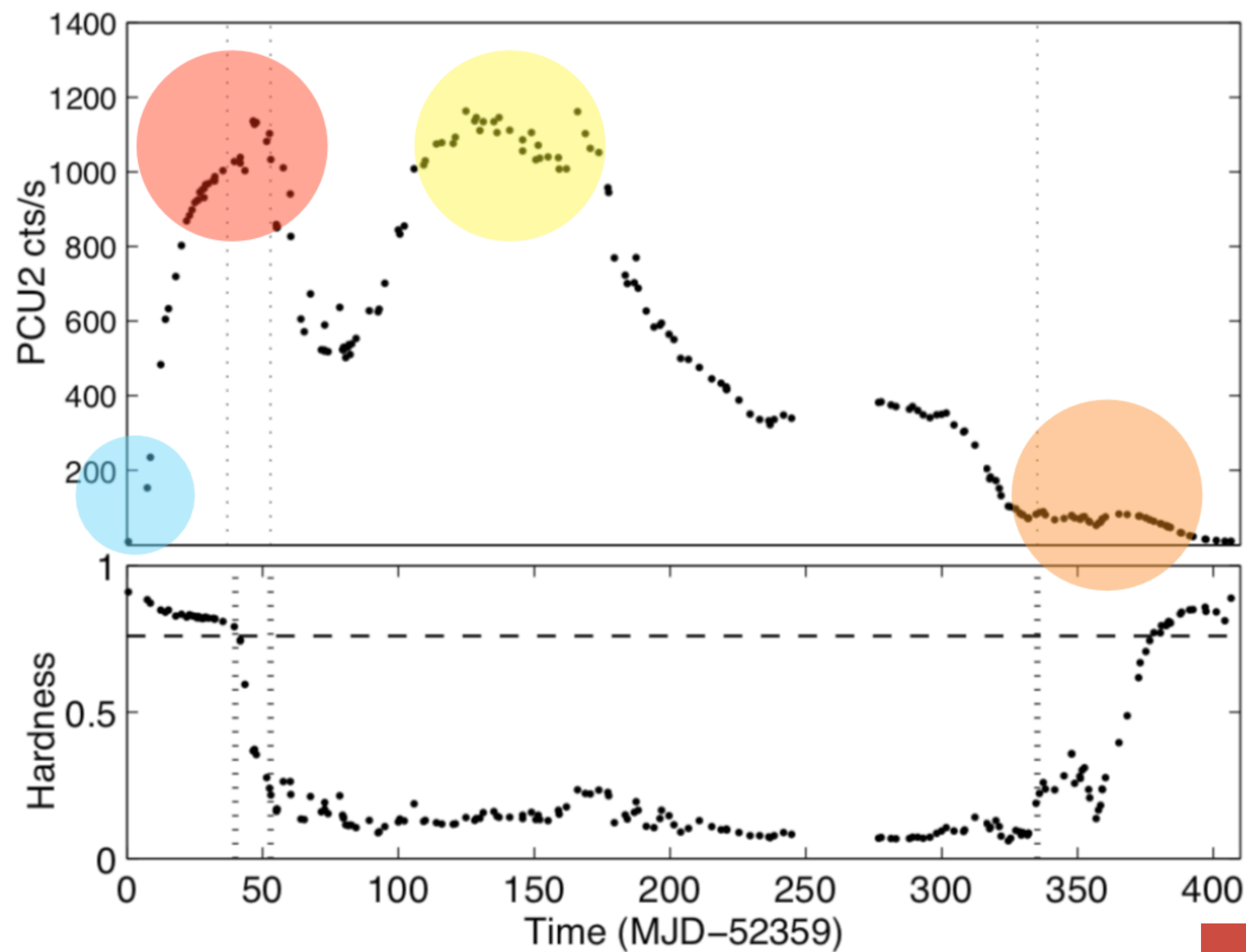


Ultra-compact systems?

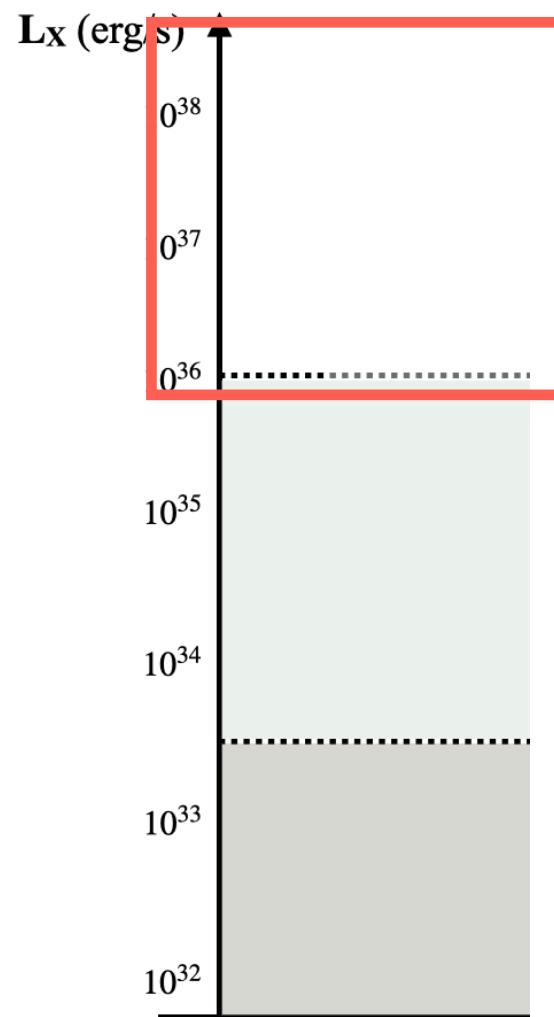
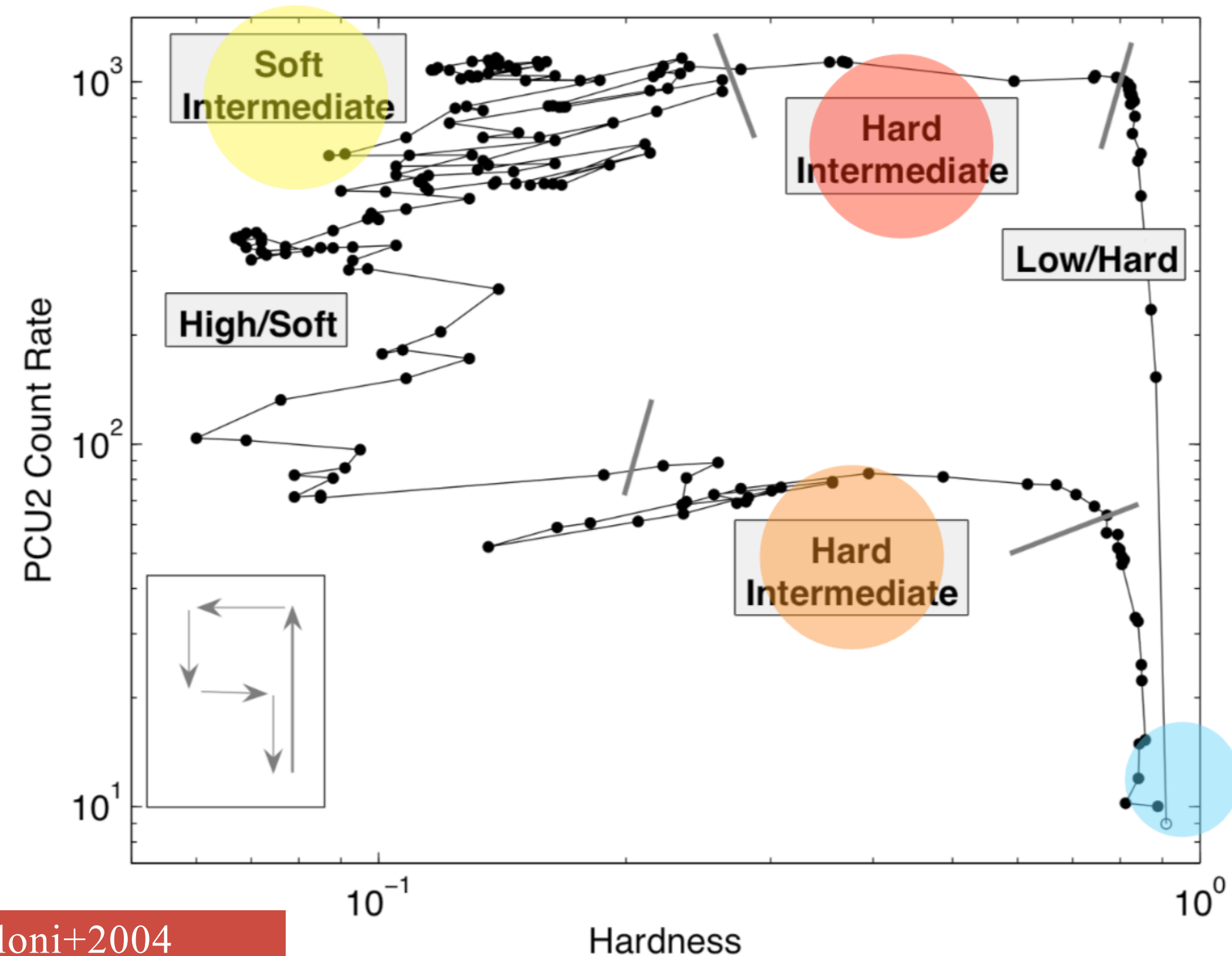


Outbursts: the BHs edition

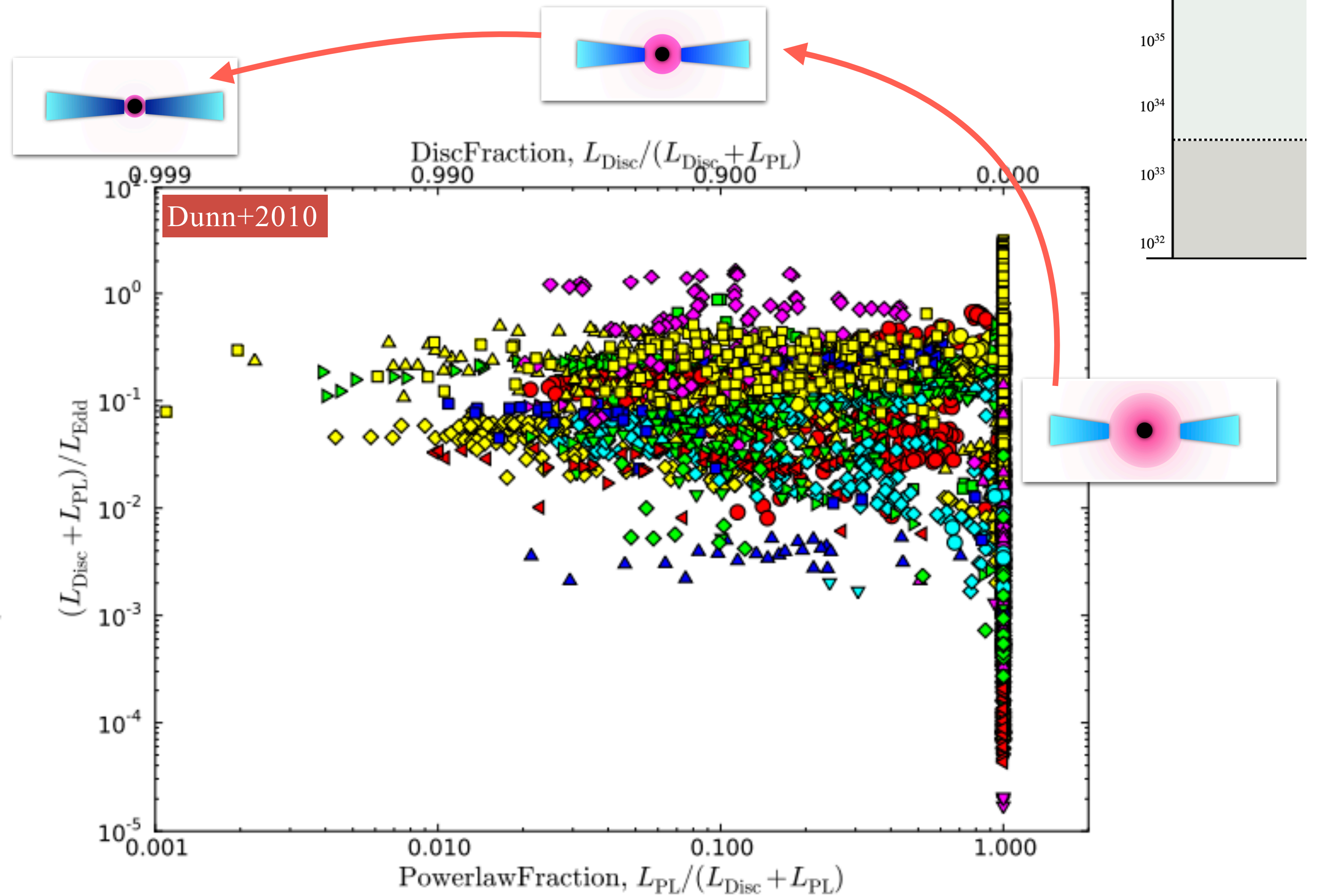
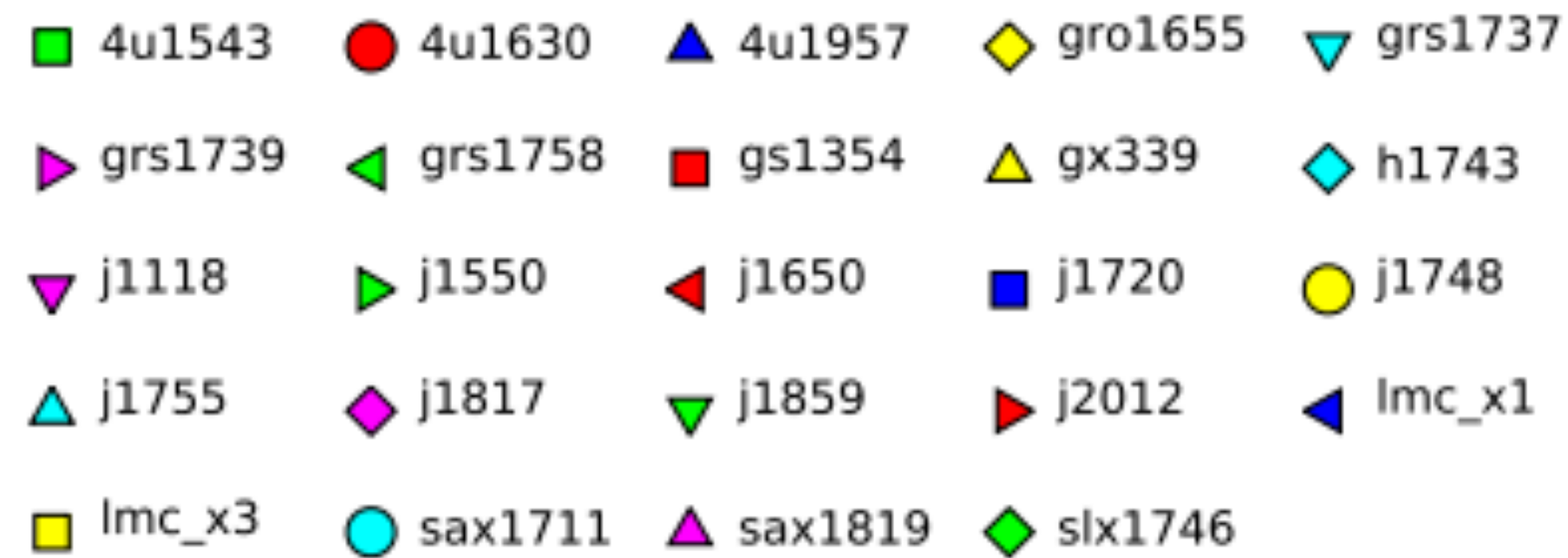
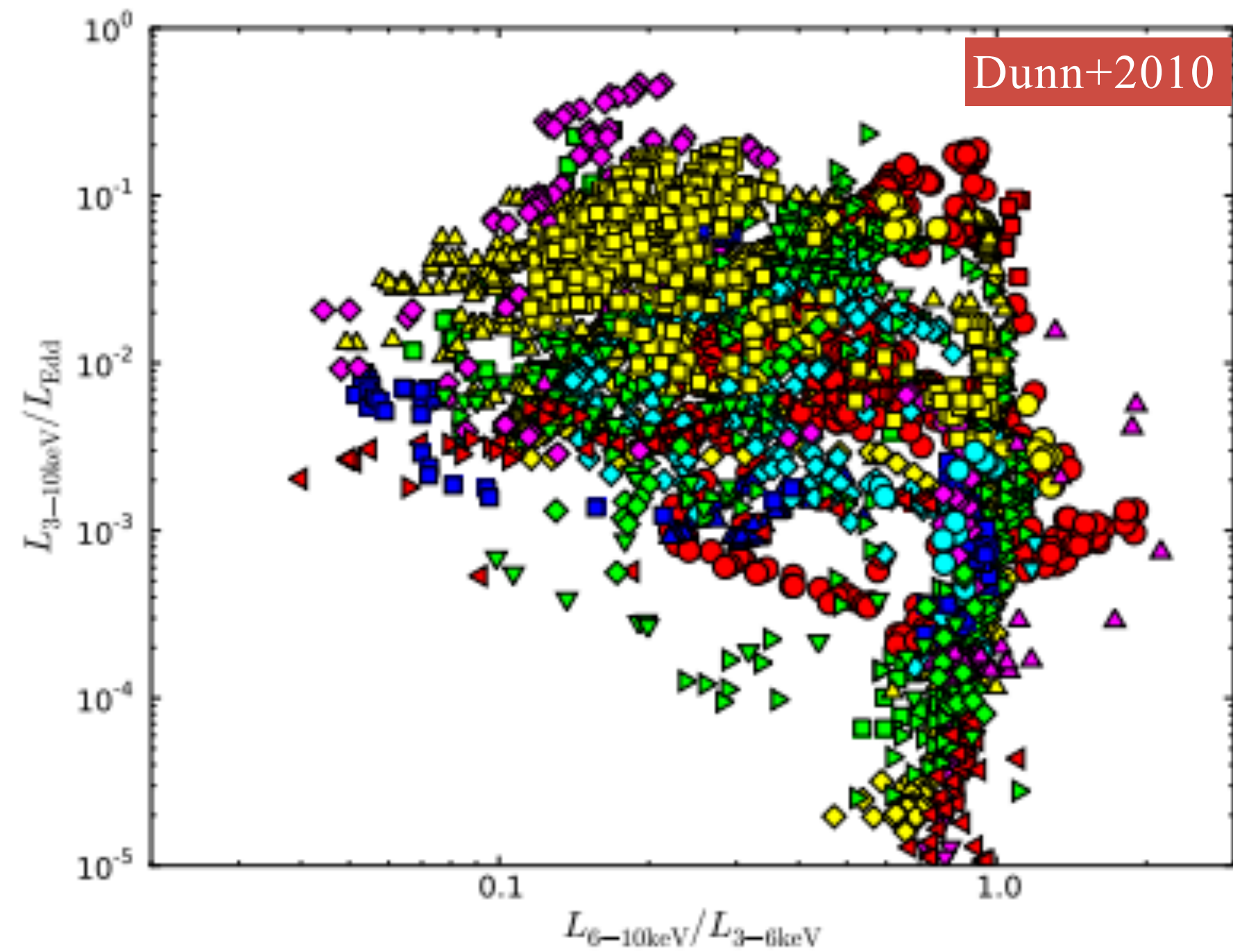
- When in outburst, **BH XRBs** typically evolve in a **Hardness Intensity Diagram** following a specific pattern through the previously mentioned spectral states, a diagram called **q-diagram**.



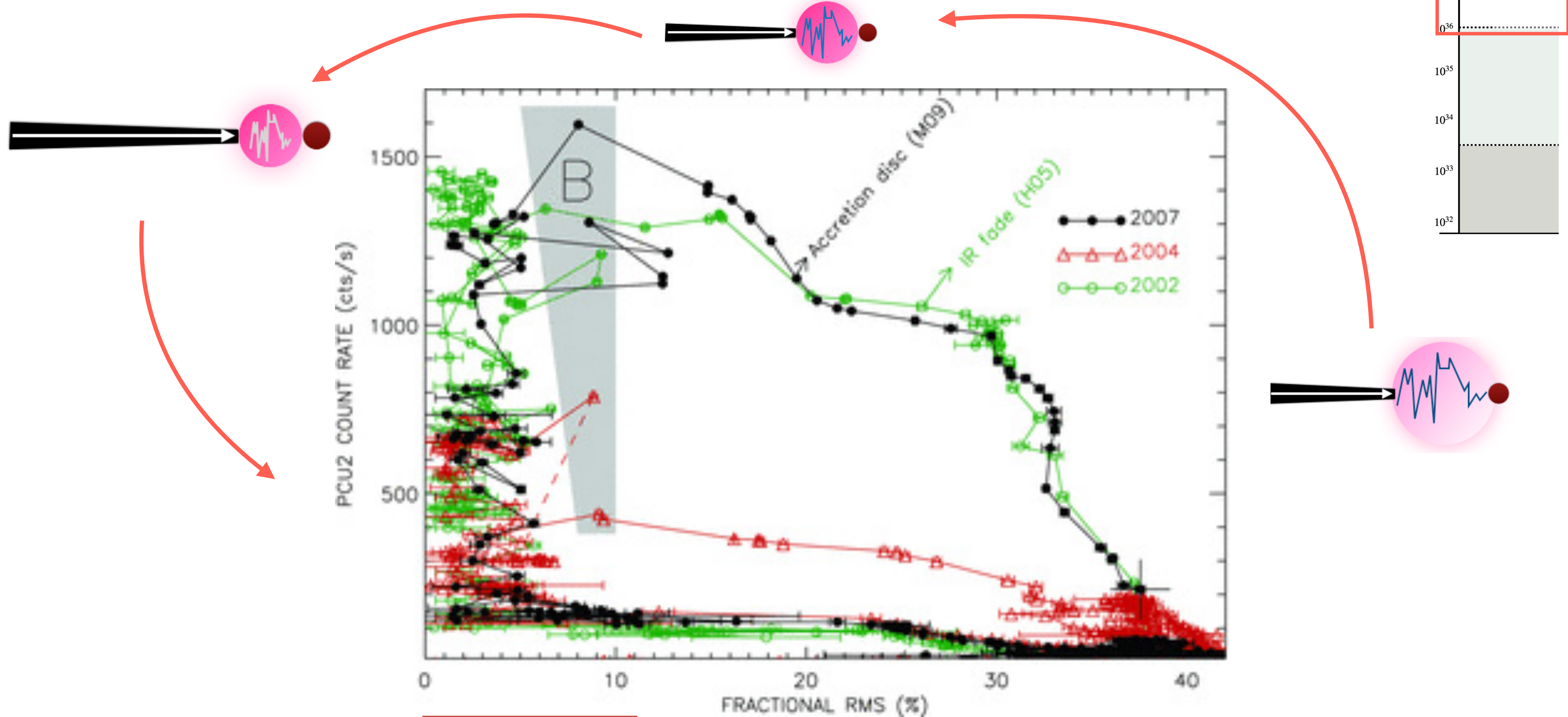
Belloni+2004



Spectral evolution during an outburst (BHs edition)

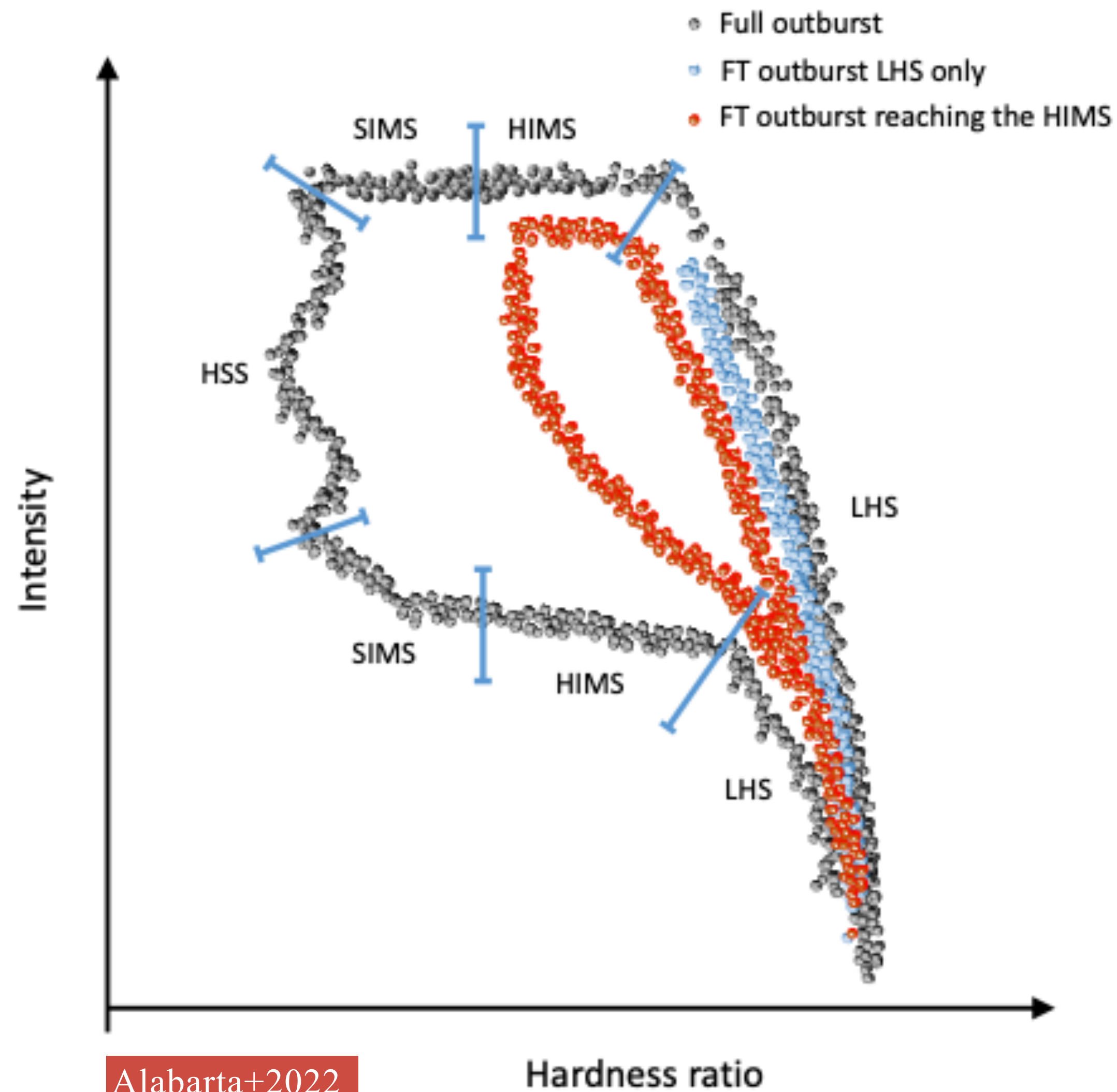


Timing evolution during an outburst (BHs edition)

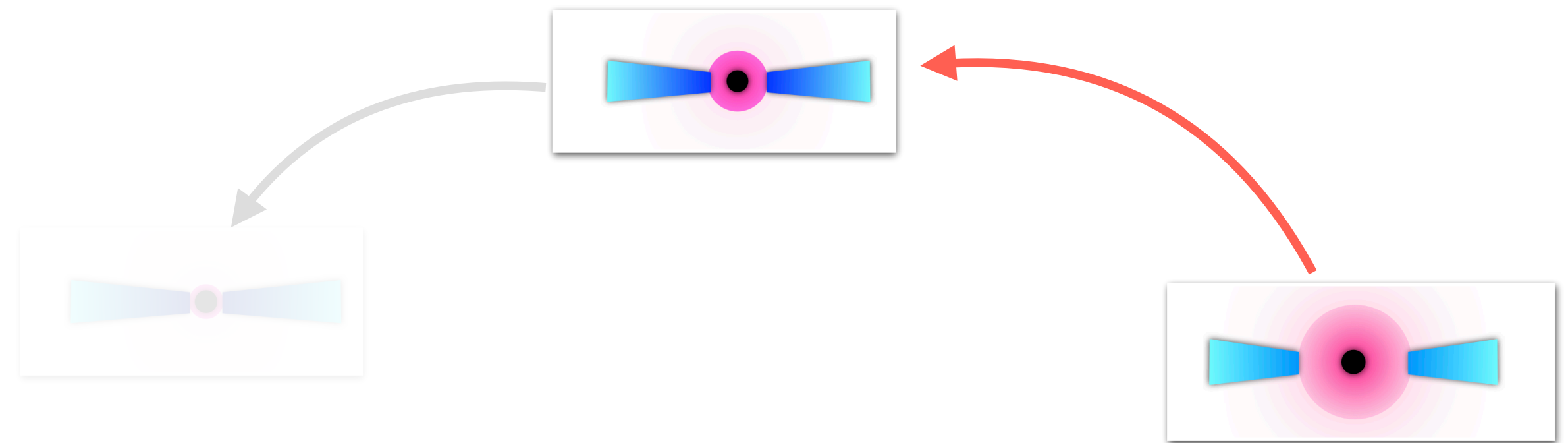
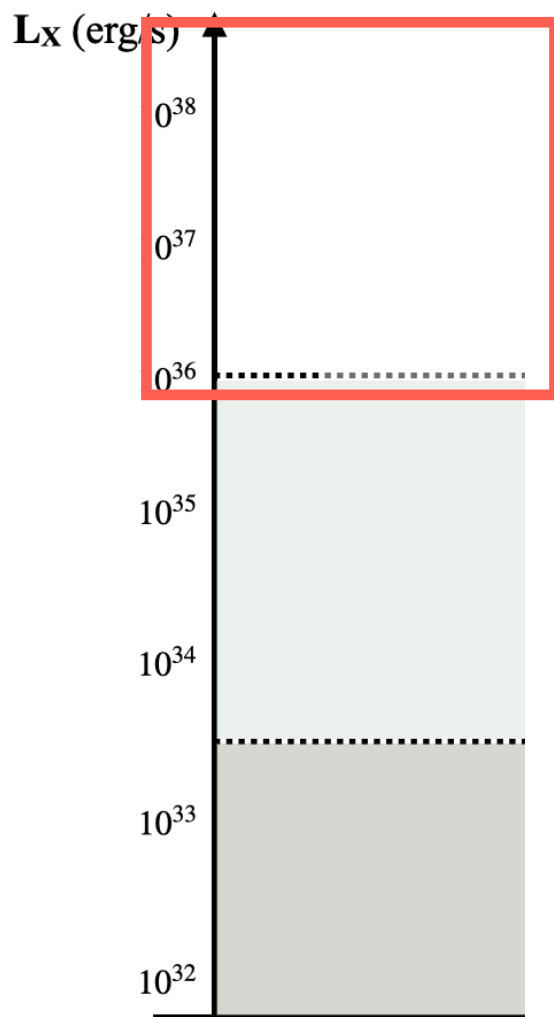


Muñoz-Darias+2011

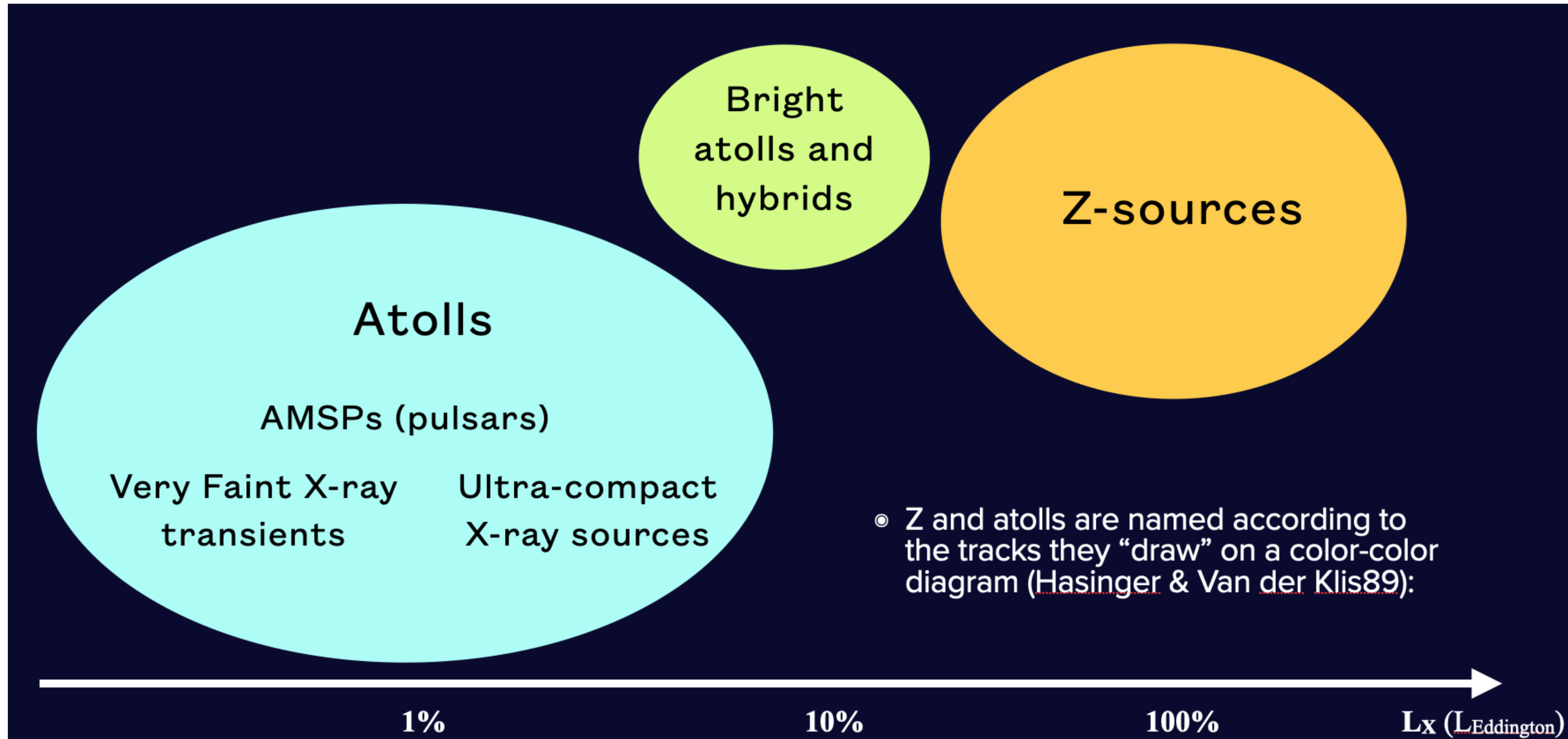
Failed transition outbursts (BHs edition)



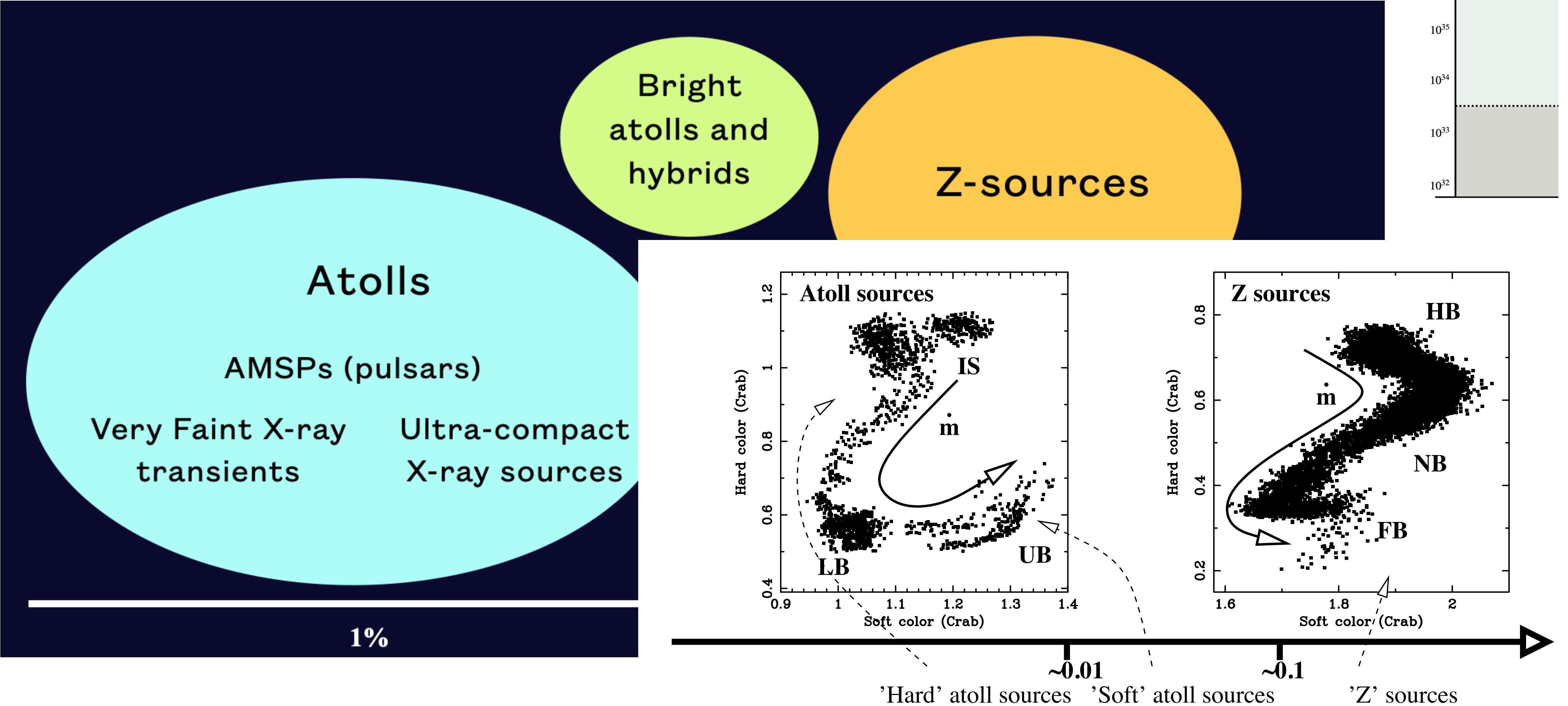
- However q-tracks are not the norm: about 40% (Tetarenko+2016) BH XRBs never show the transition to the soft or soft intermediate state: the **failed transition outburst**.
- **Why?** Is there a critical luminosity that needs to be reached for triggering the transition? Possibly about $0.1 L_{\text{Edd}}$?



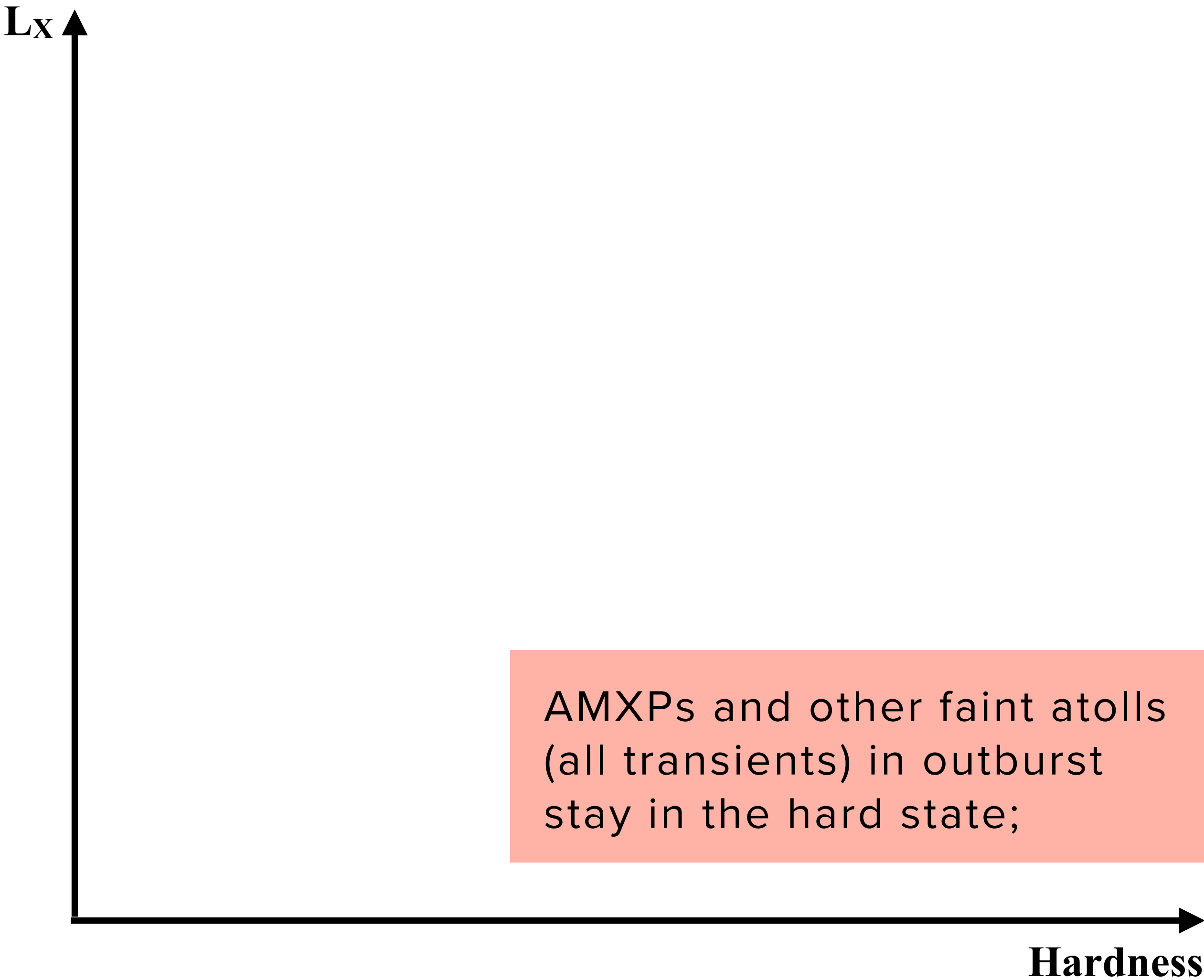
The transient and persistent NS LMXBs zoo



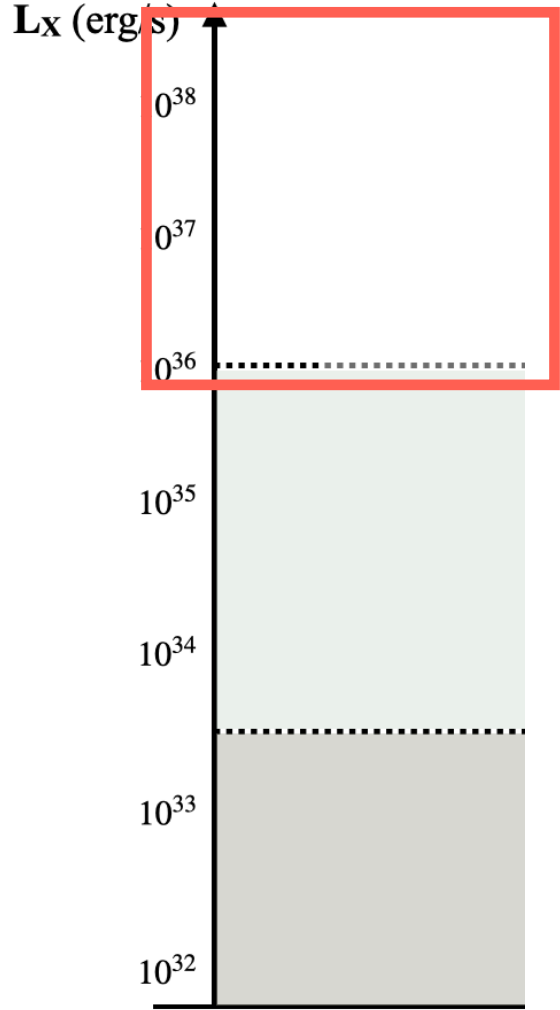
The transient and persistent NS LMXBs zoo



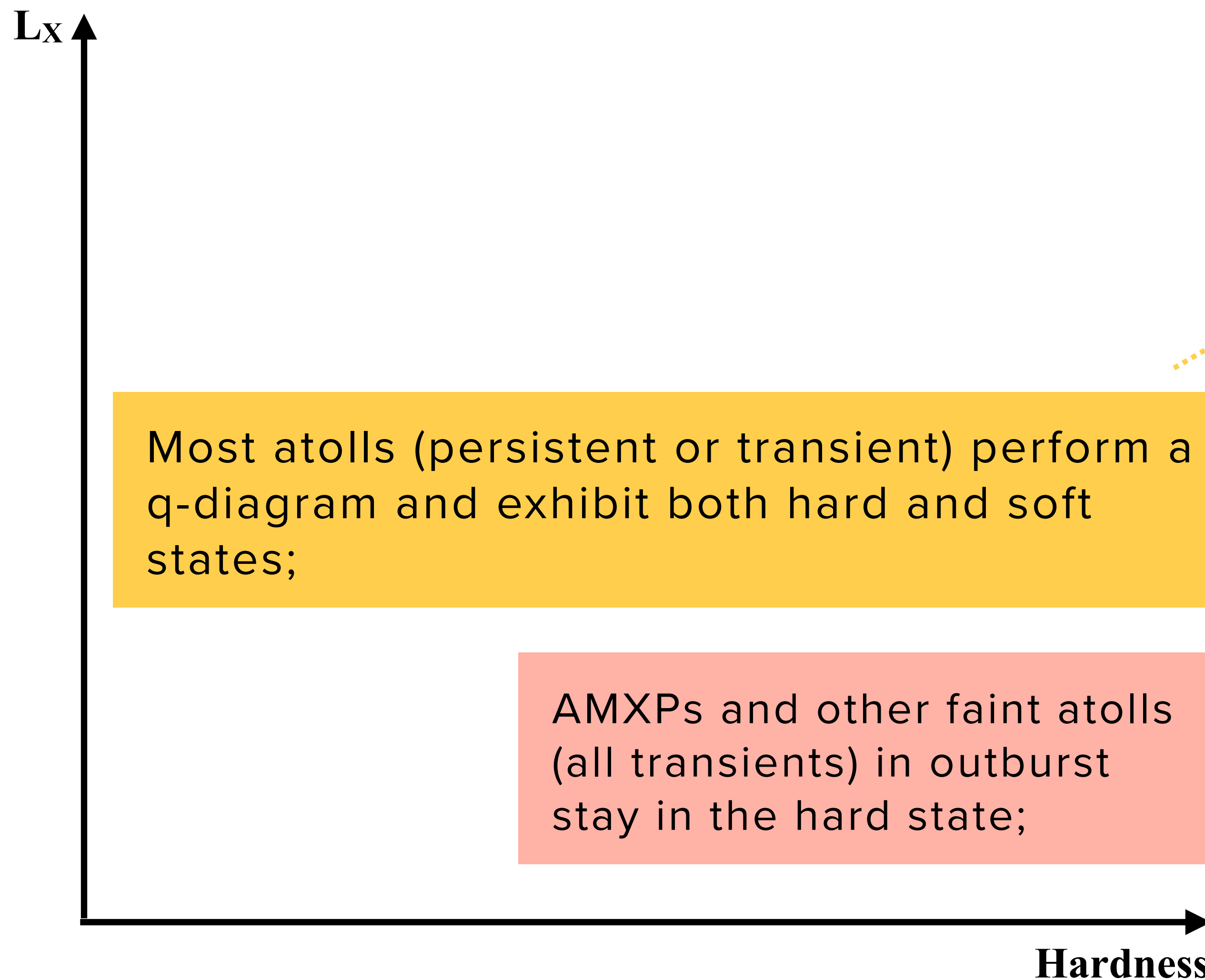
Spectral evolutions for different types of NS LMXBs



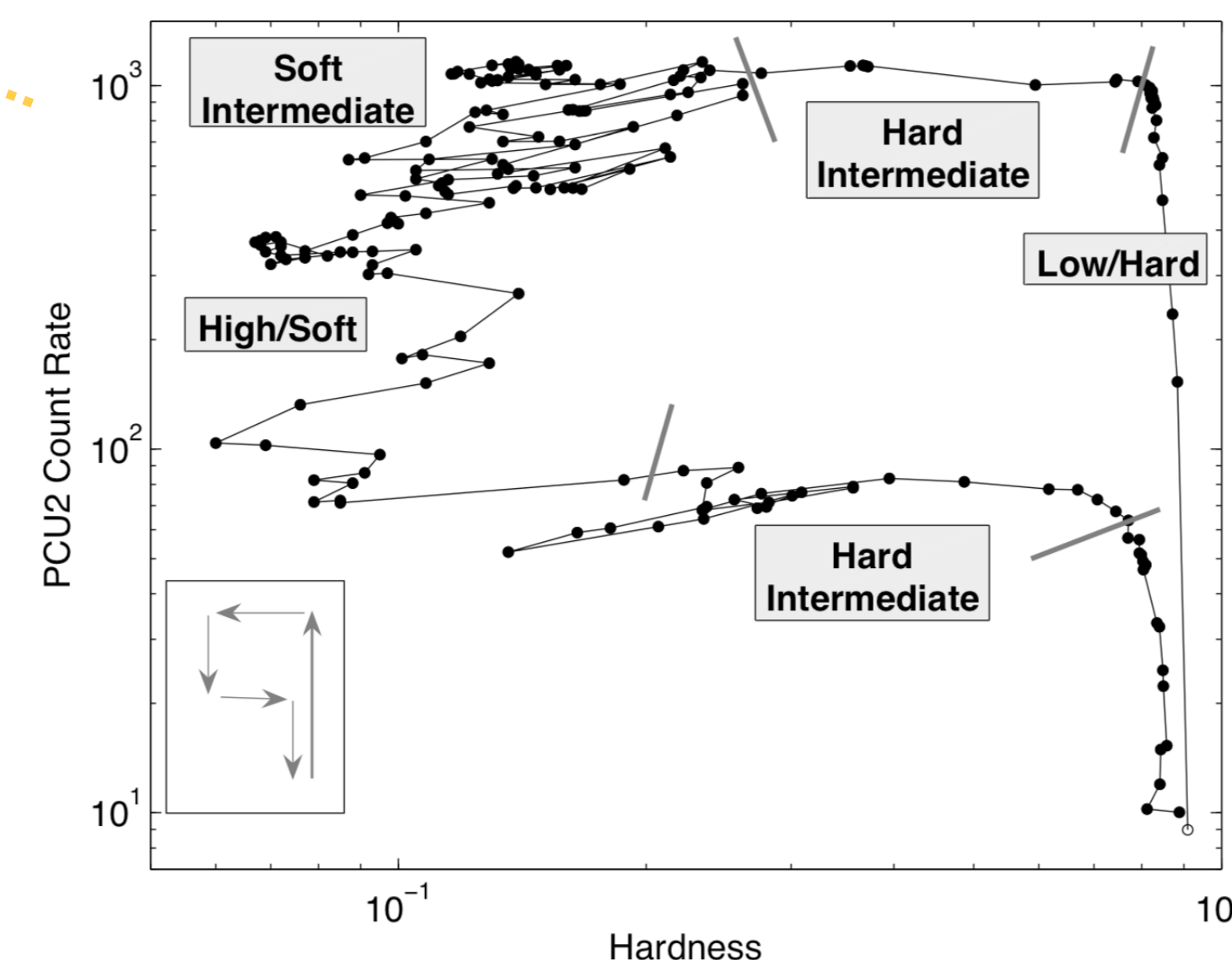
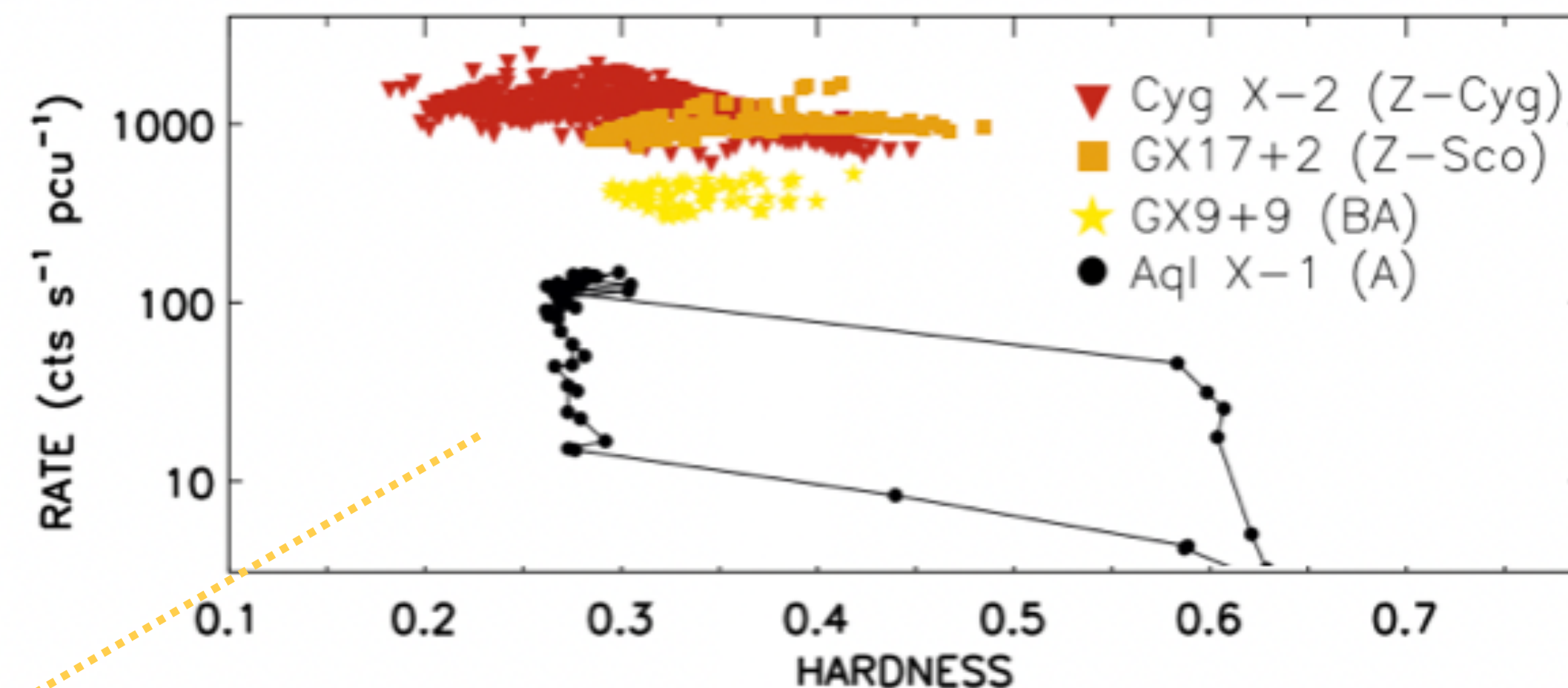
AMXPs and other faint atolls
(all transients) in outburst
stay in the hard state;



Spectral evolutions for different types of NS LMXBs



Observed behaviours for different classes of NS LMXB, [Munoz Darias+14](#)

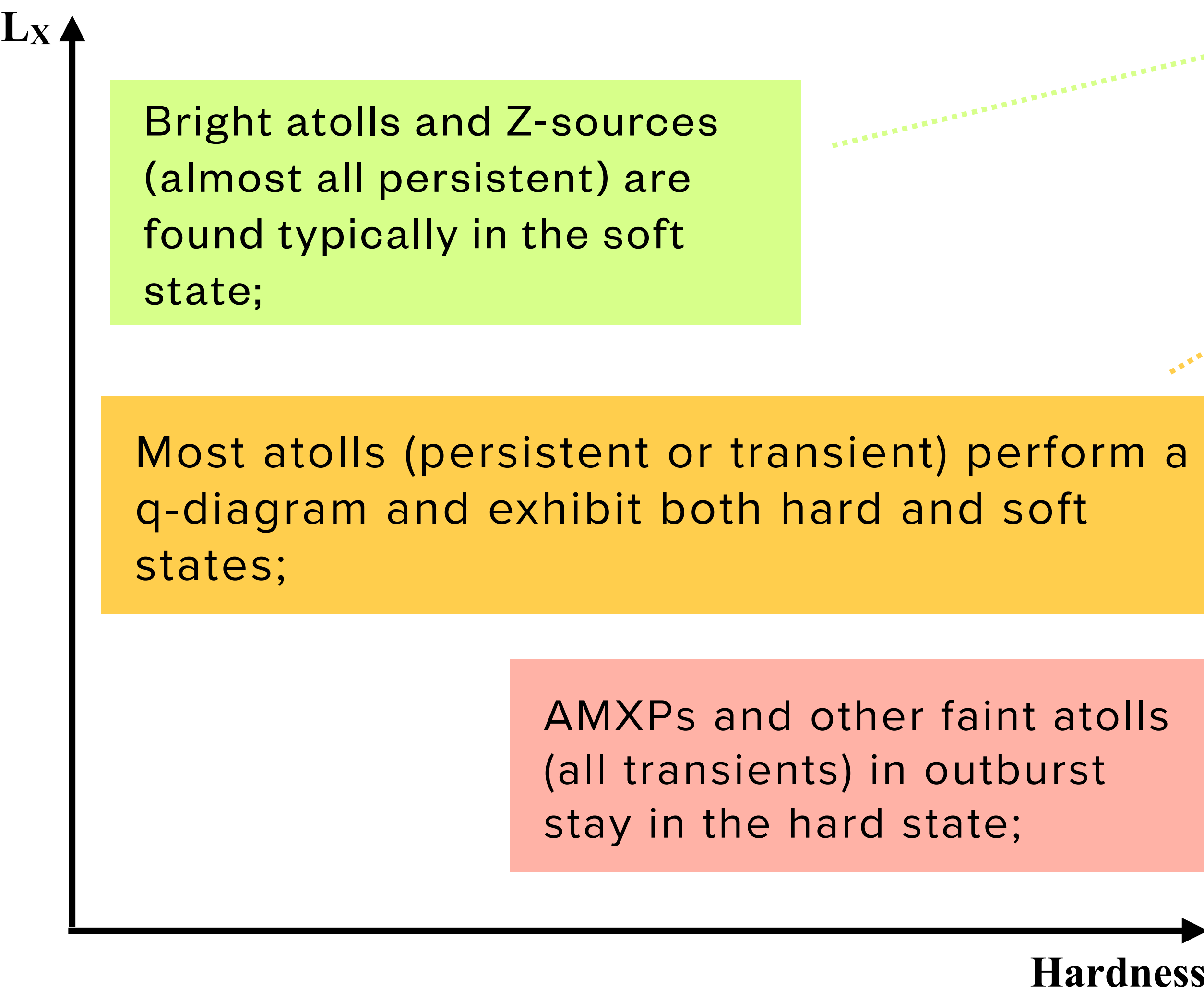


A behaviour similar to BH transients

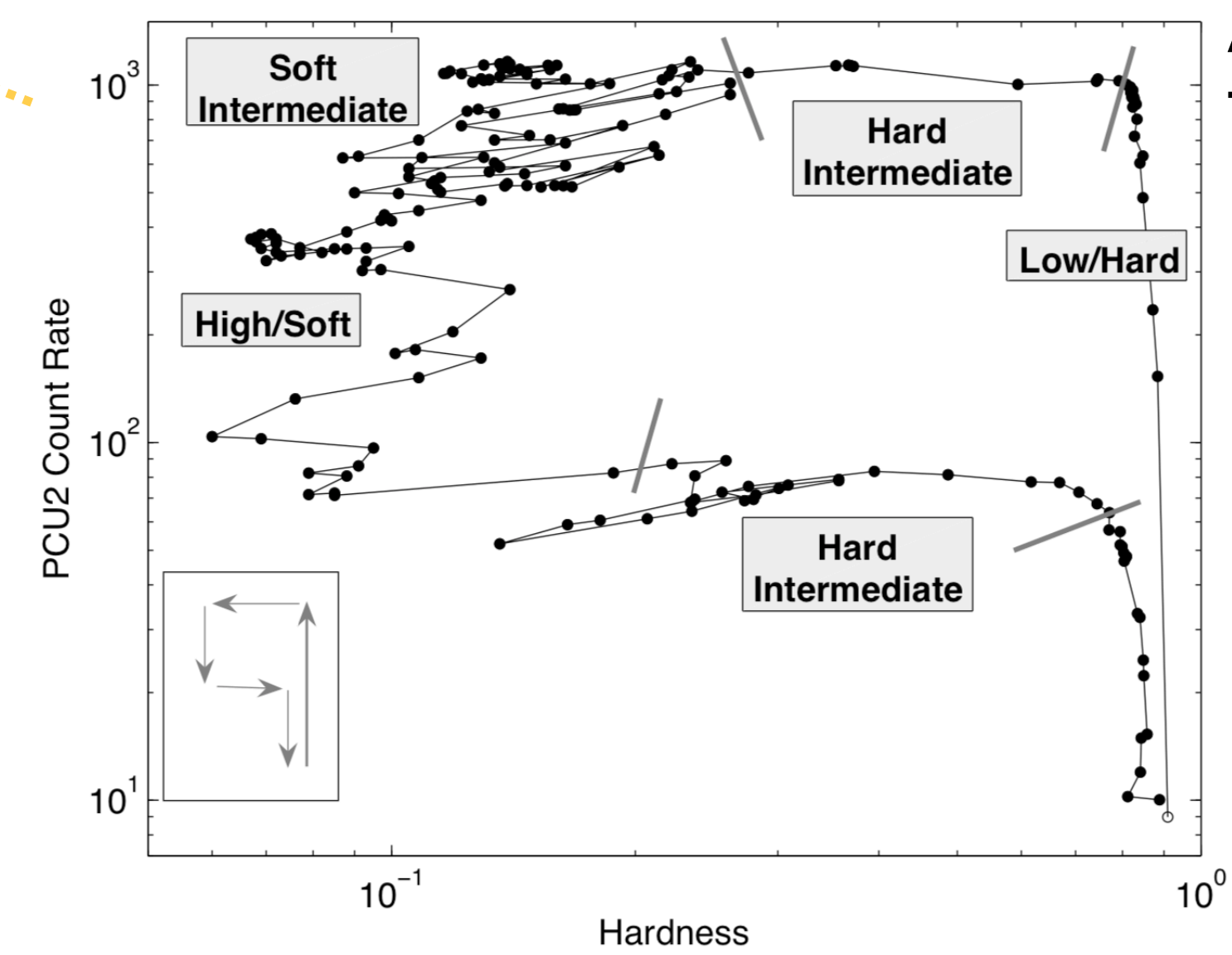
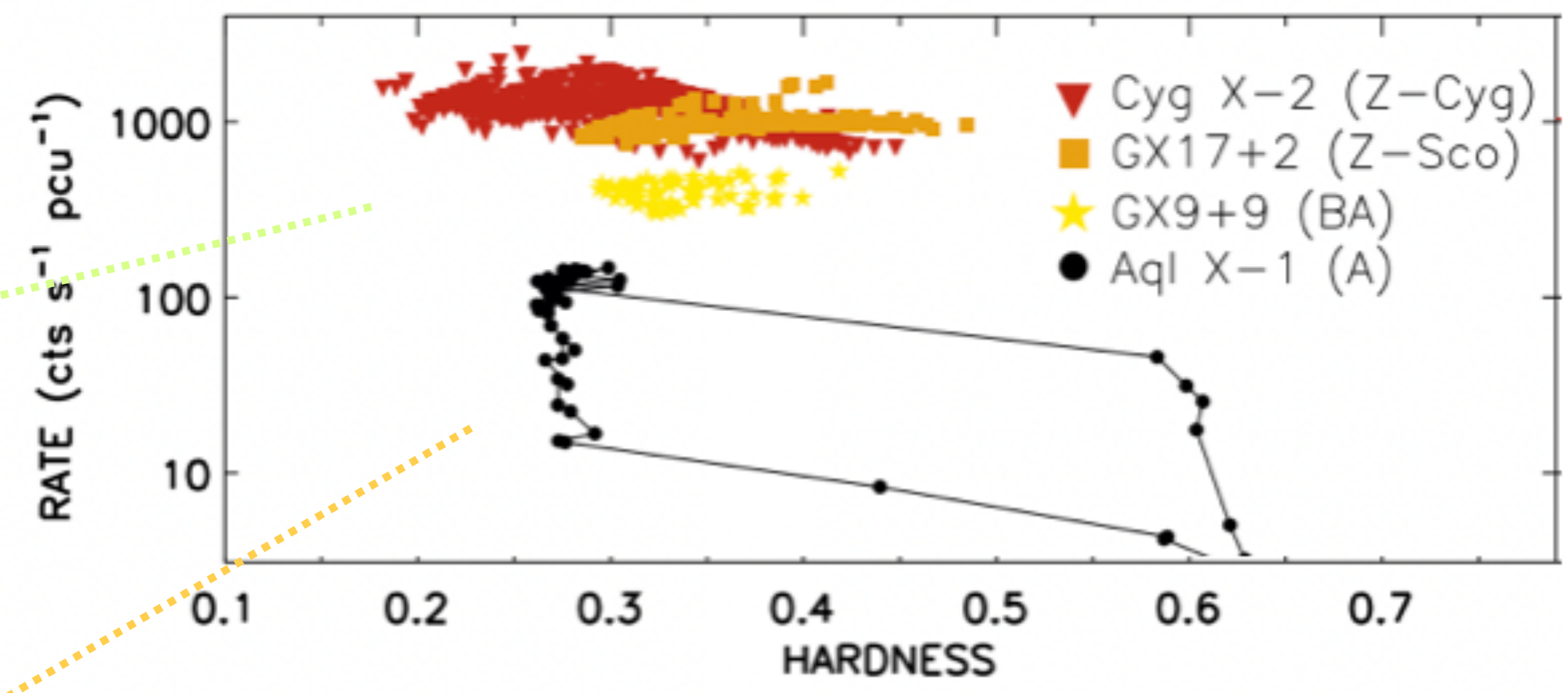
Schematic q-diagram for the BH LMXB GX 339-4, [Belloni+04](#)



Spectral evolutions for different types of NS LMXBs



Observed behaviours for different classes of NS LMXB, [Munoz Darias+14](#)

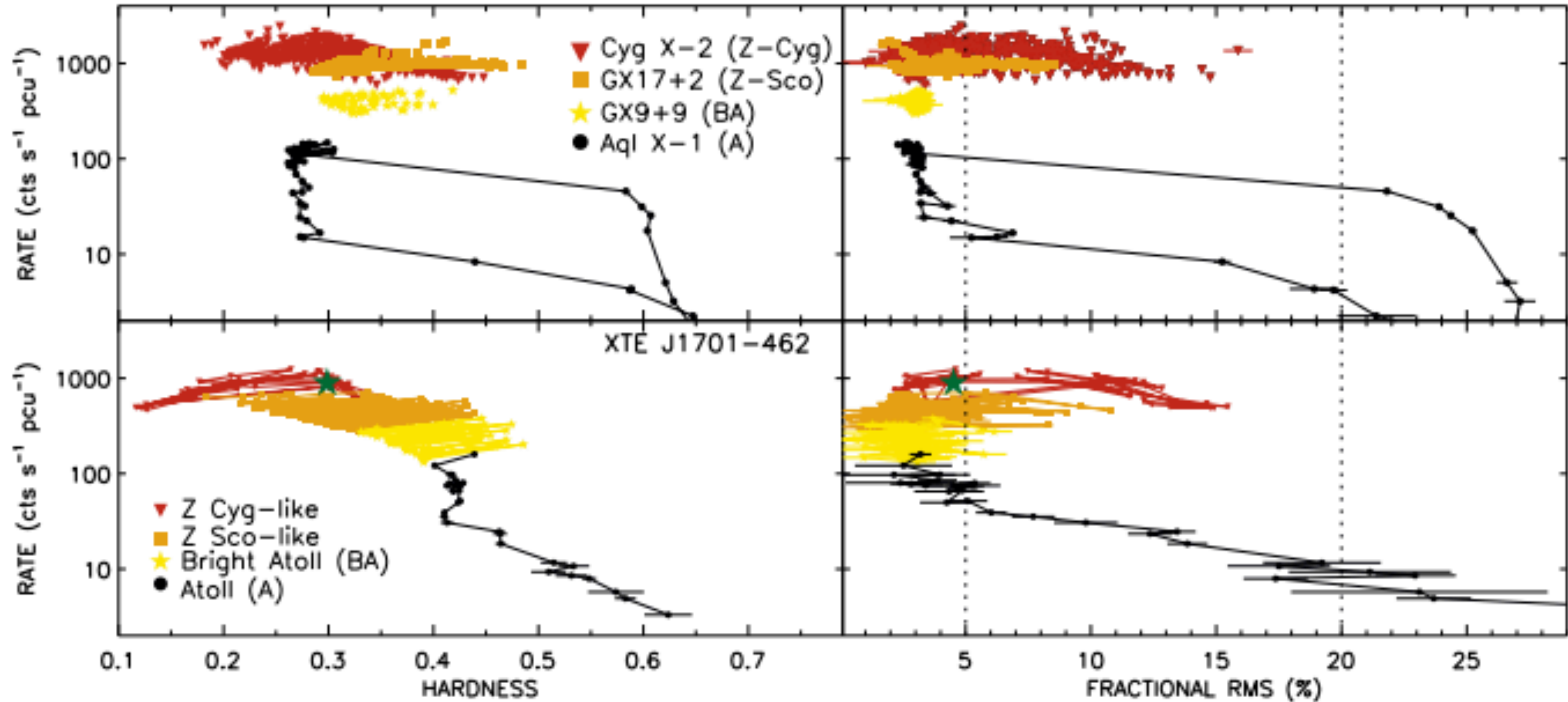


A behaviour similar to BH transients

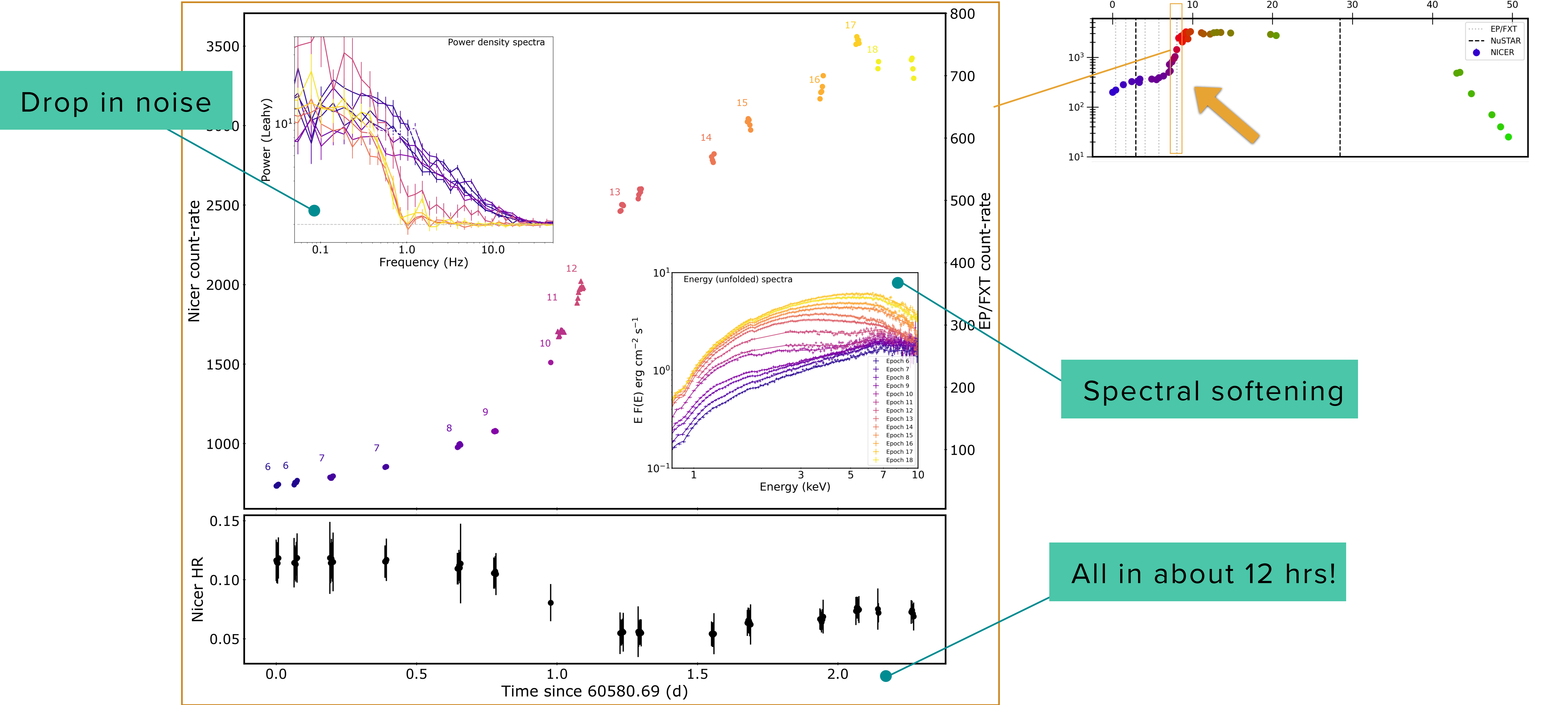
Schematic q-diagram for the BH LMXB GX 339-4, [Belloni+04](#)

Timing evolution of NS LMXBs outbursts

Muñoz-Darias+2014

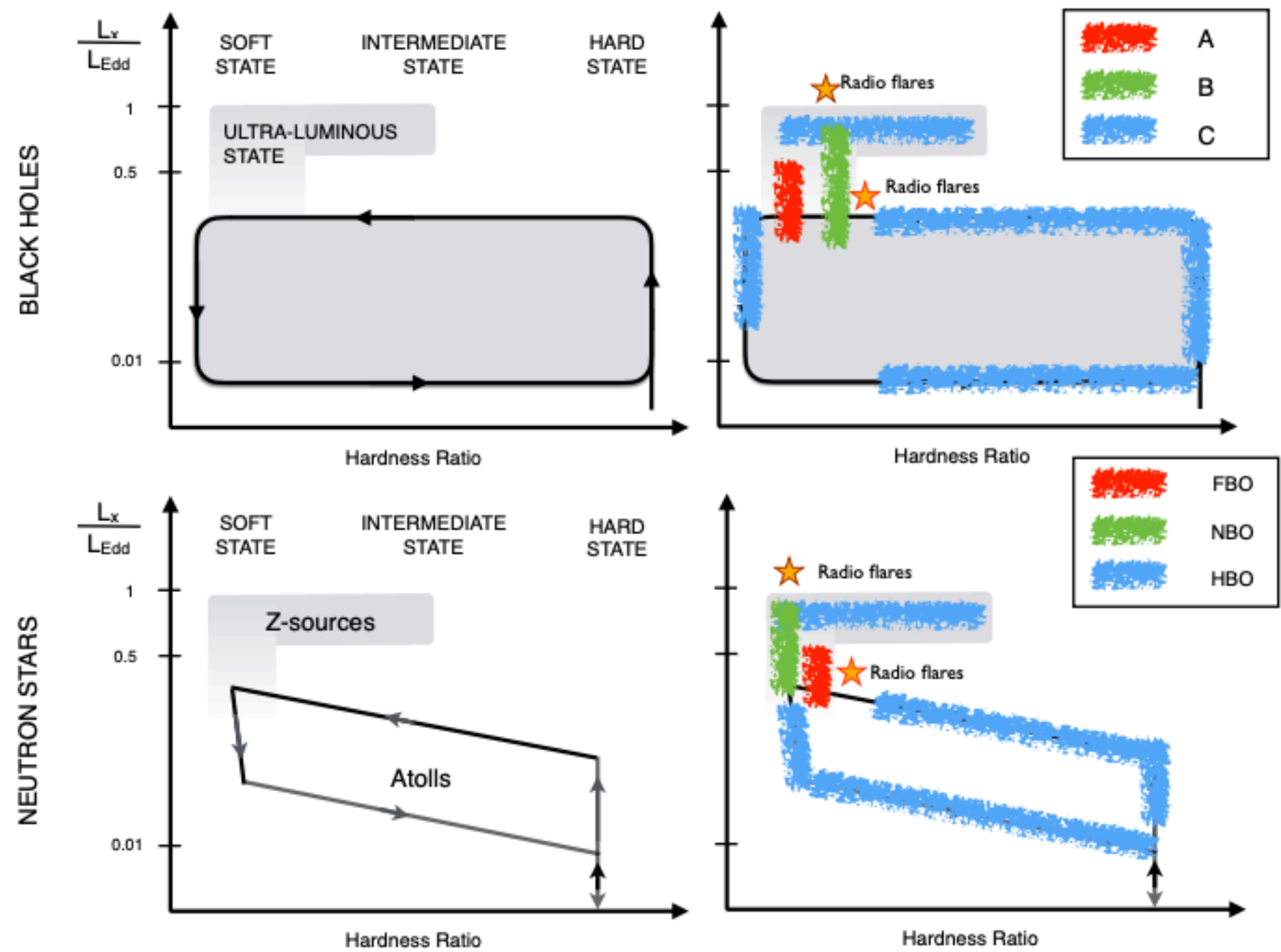


A spectacularly fast state transition “live”: the case of the NS LMXB Aql X-1

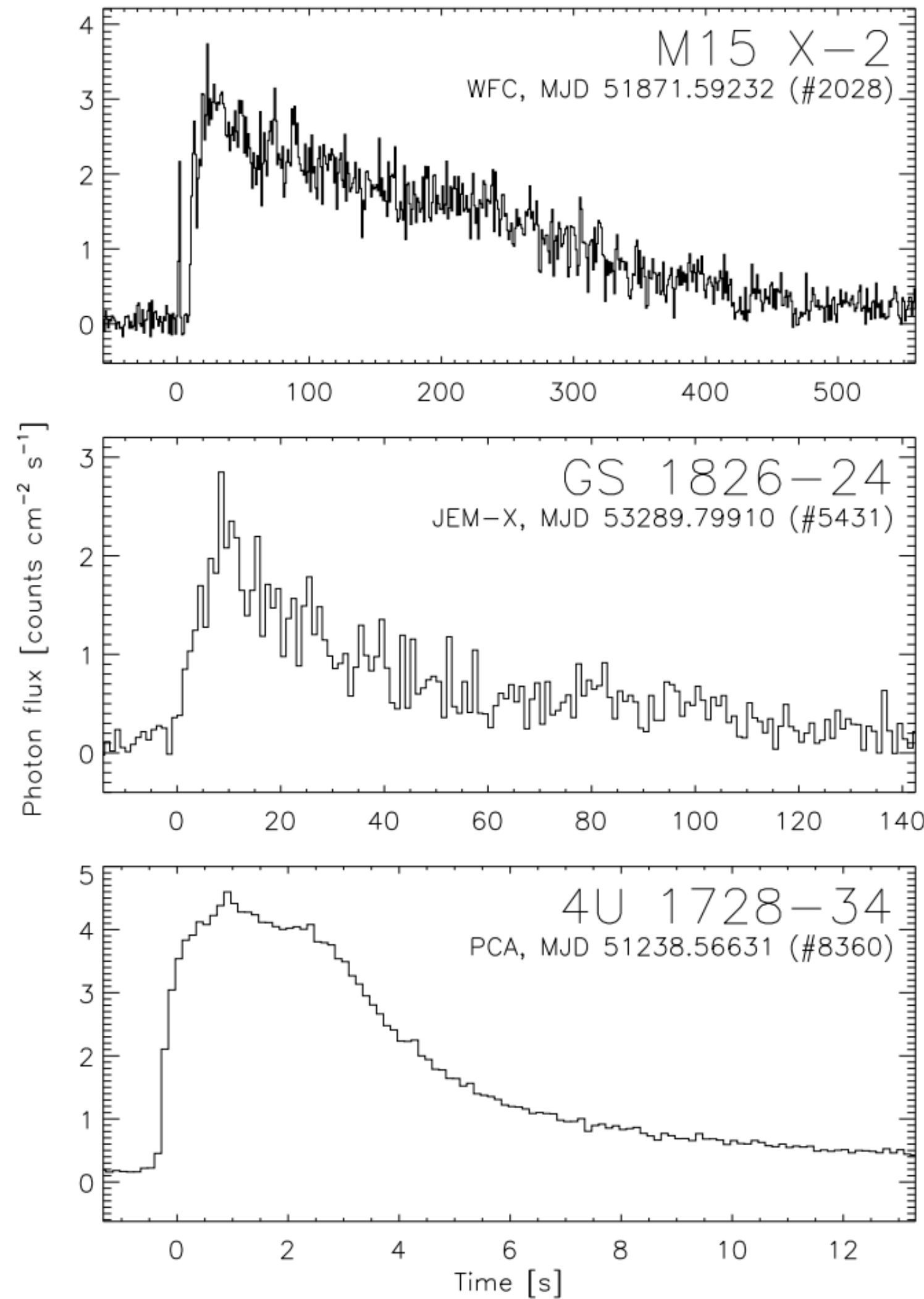


QPOs in the q-diagram(s)

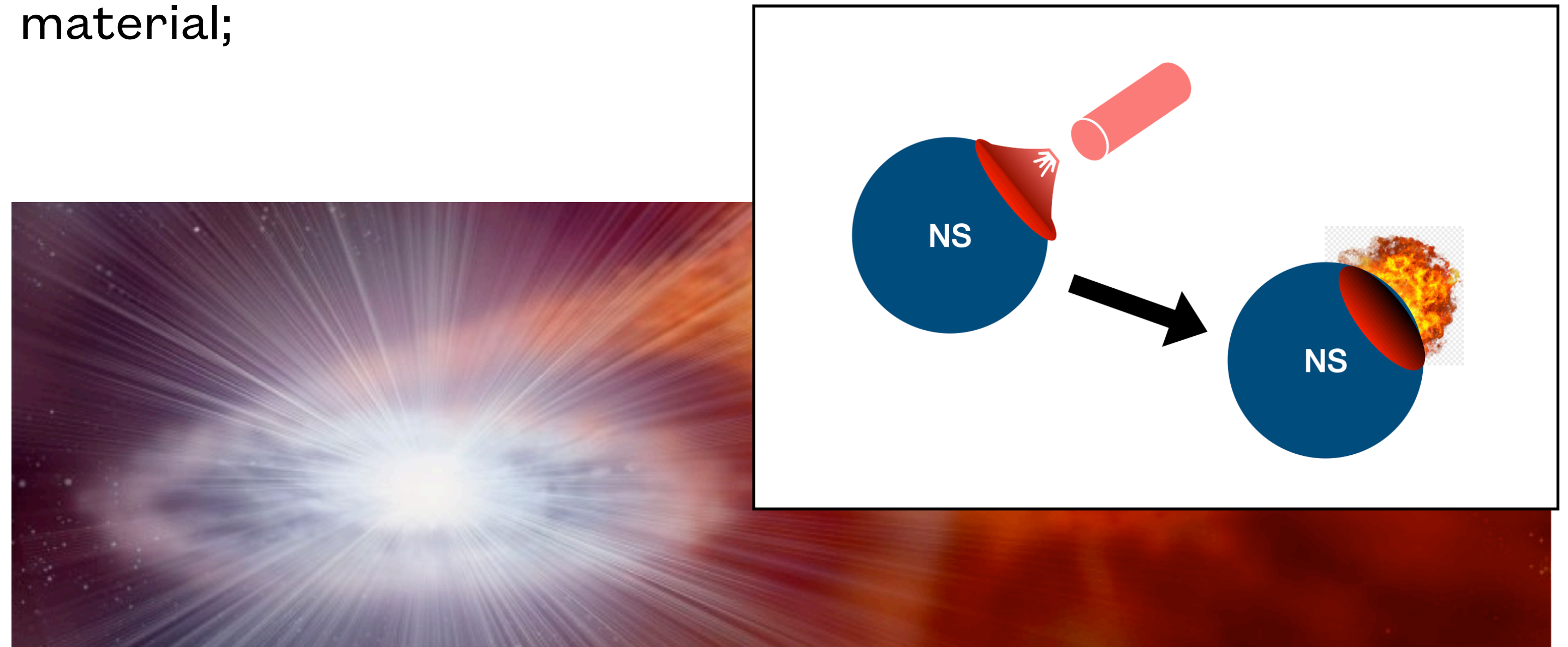
Muñoz-Darias+2014, Ingram & Motta 2020



Accumulating up to the point of ignition: Type-I X-ray bursts



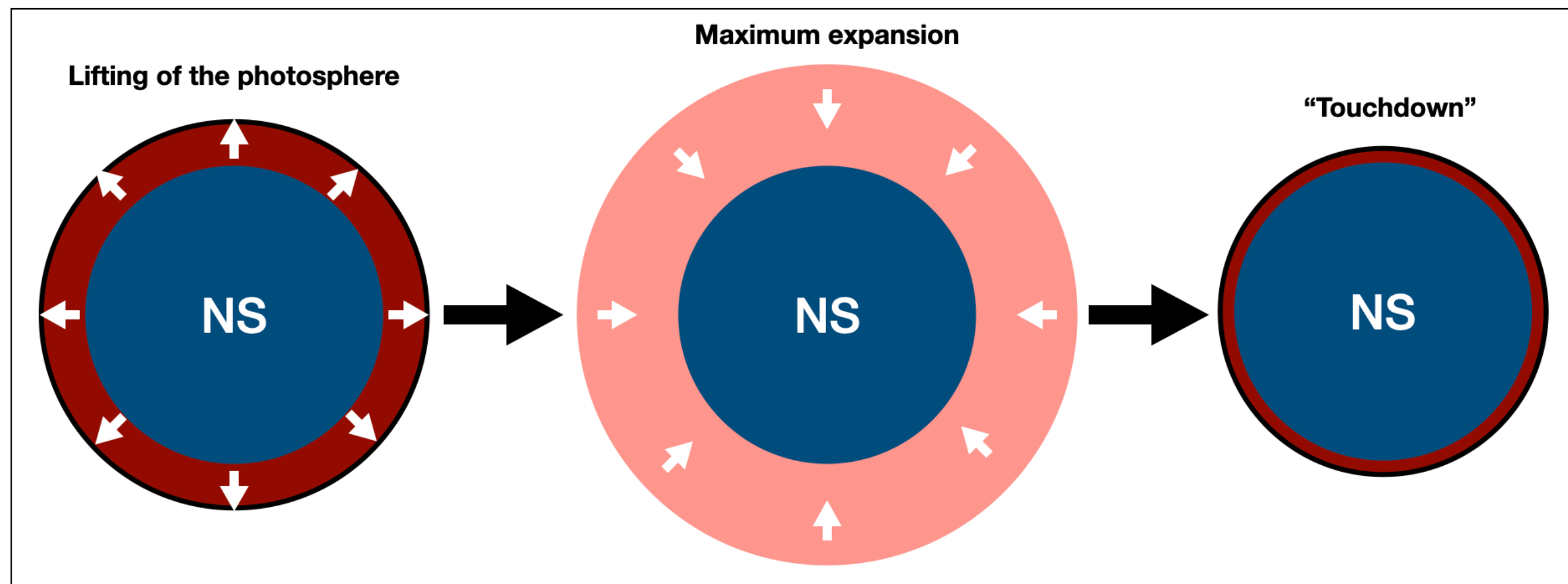
- Thermonuclear explosions occurring due to the piling up of the accreted material on top of the NS surface;
- Signature of the NS nature of the accreting compact object;
- Typically lasting for tens to hundreds of seconds; **intermediate** (minutes) and **superbursts** (hours) also known but more rare;
- Duration connected to the chemical composition of the accreted material;



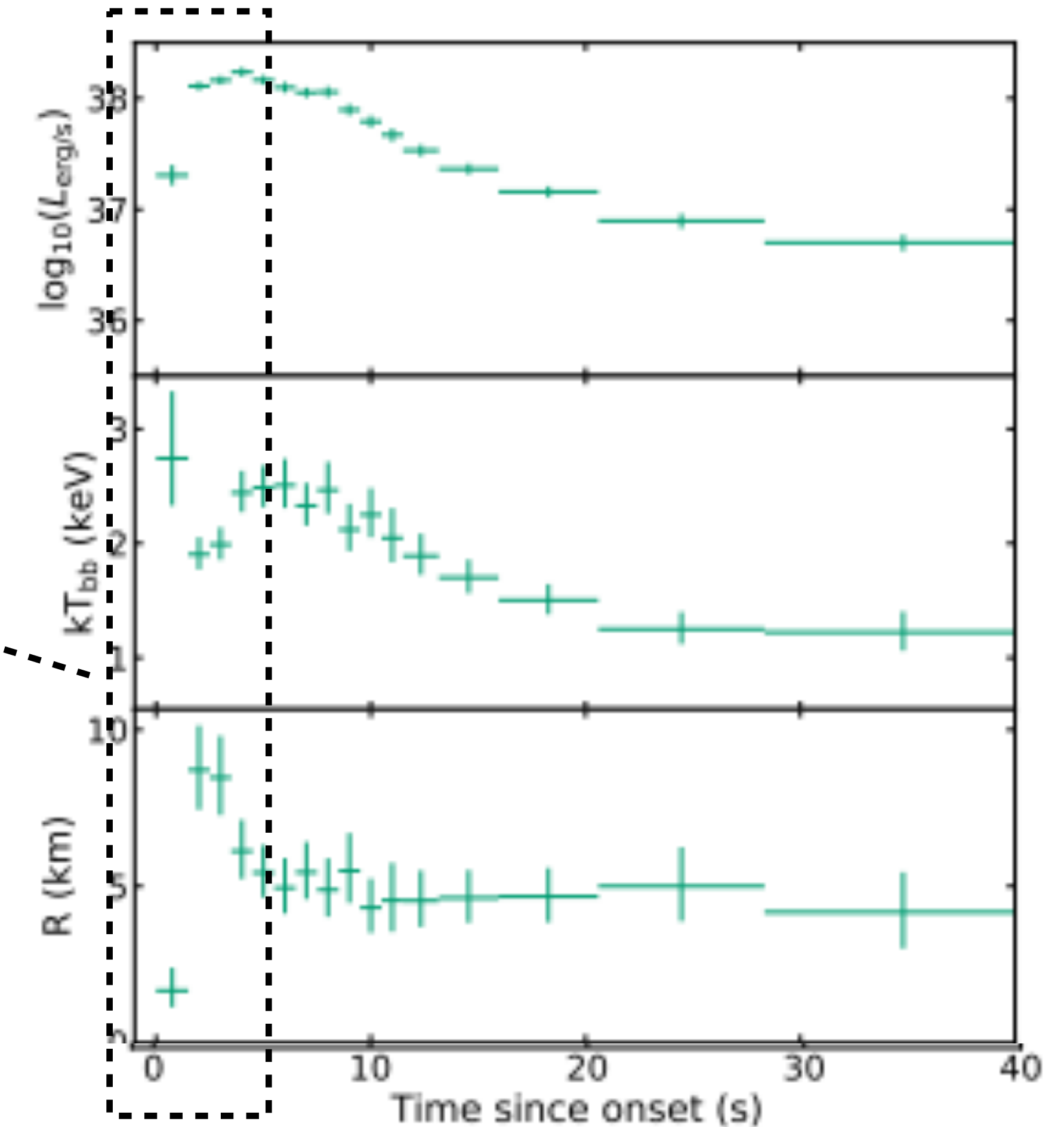
Examples of type-I X-ray bursts with variable durations, [Galloway+20](#)

Photospheric Radius Expansion (PRE) bursts: standard candles

- Certain bursts reach the Eddington Limit at the peak -> **Photospheric Radius Expansion (PRE)**;



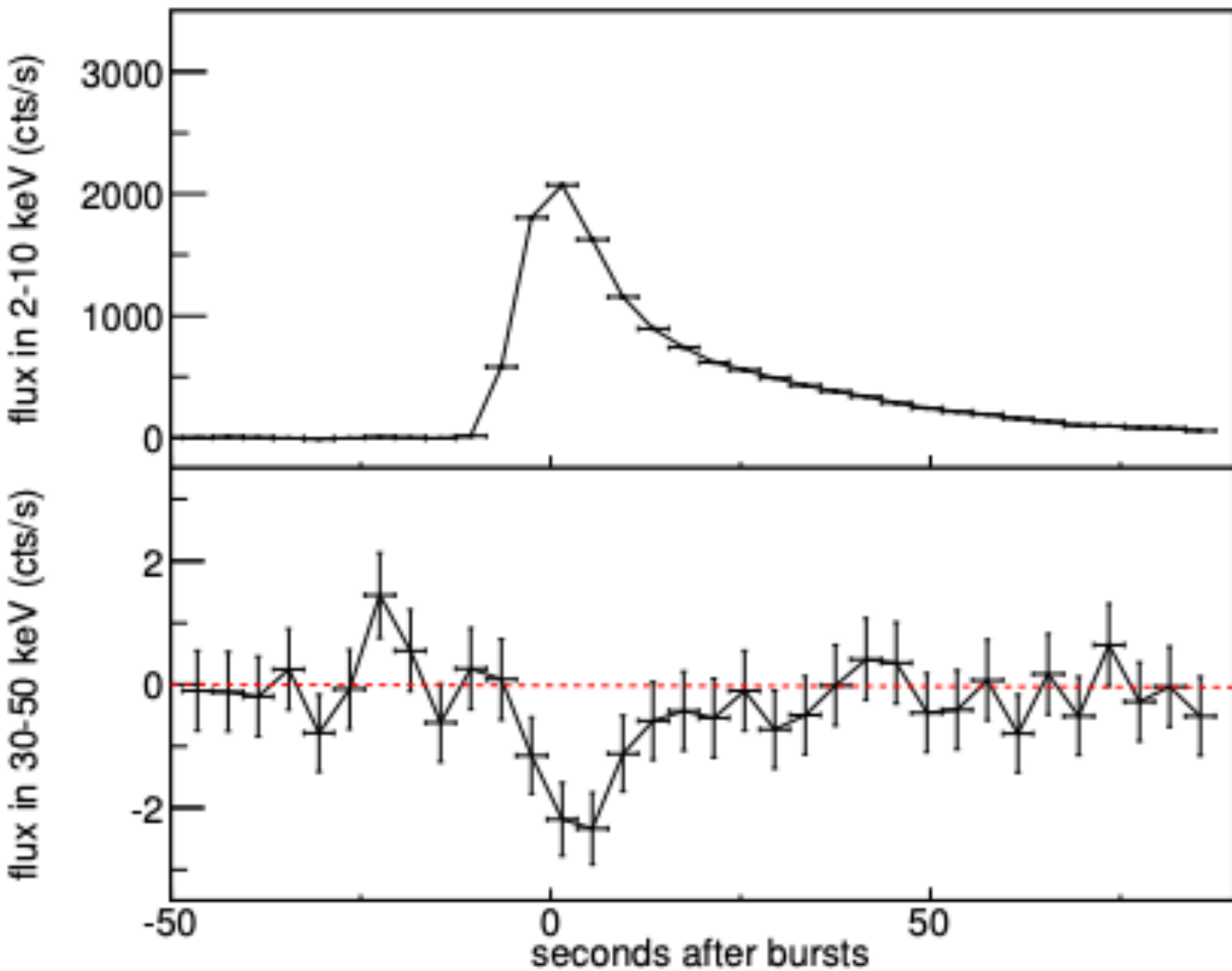
- Proof of PRE bursts from Time Resolved Spectroscopy (increase in radius corresponding to a decrease in temperature);
- Diagnostics for the distance** (most NS LMXBs distances are known thanks to them, e.g. [Galloway+08](#), [Marino+19b](#))



Temperature and radius evolution of a PRE burst, [Pike+21](#)

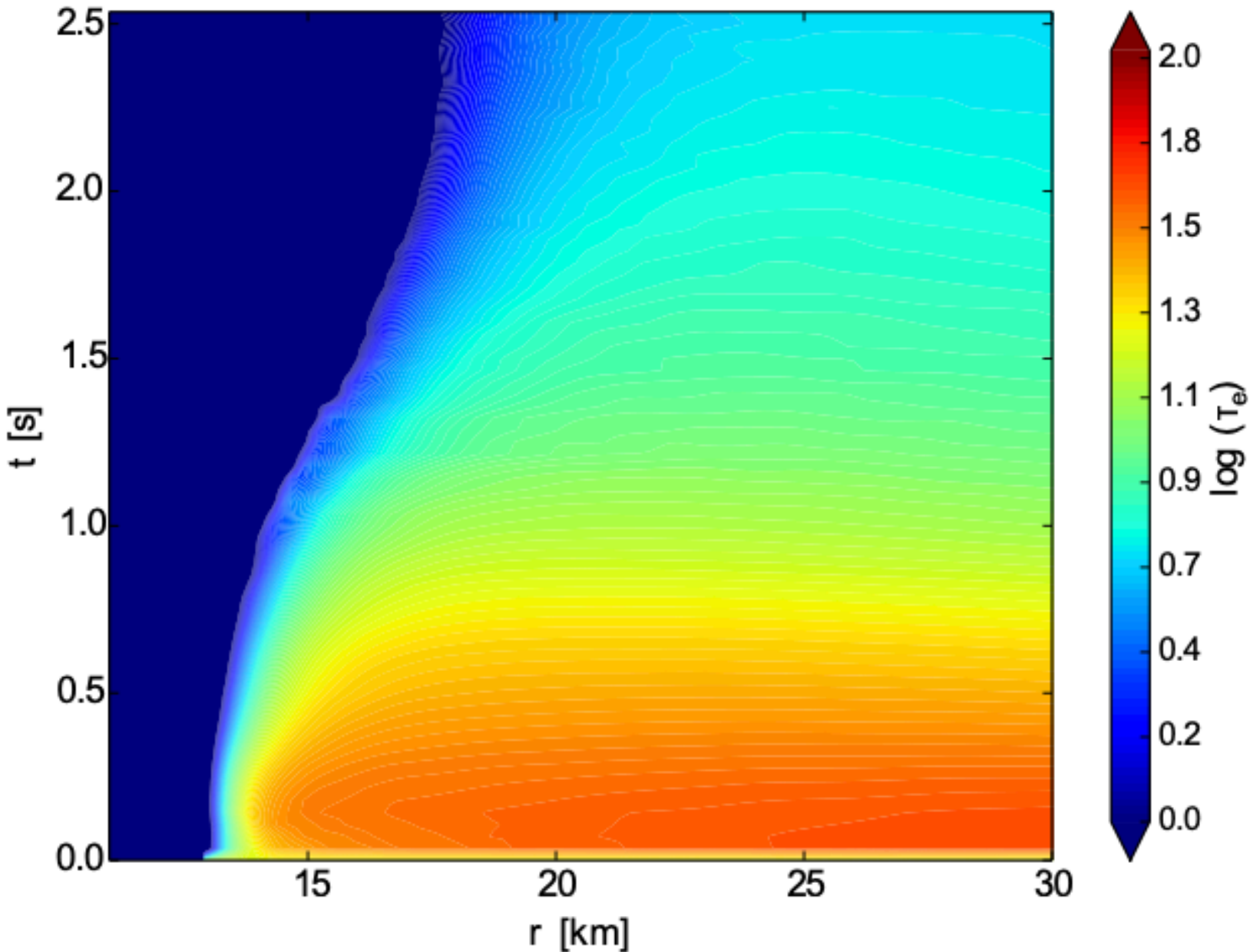
Type-I X-ray bursts and their interaction with the surrounding environment

- Bursts are influenced by the properties (mass accretion rate, spectral state, composition of the accreted fuel) of the accretion flow; but is the surrounding accretion flow influenced by the burst onset?
- Four ways to influence the accretion environment:**
 - * Enhance the continuum emission of an **amplification factor f_a** (Worpel+13,15);
 - * Overall softening of the spectrum (Speicher+20);
 - * Reflection features and/or winds (Degenaar+16, Speicher+21);
 - * Physical alteration of the disc structure (Fragile+20);



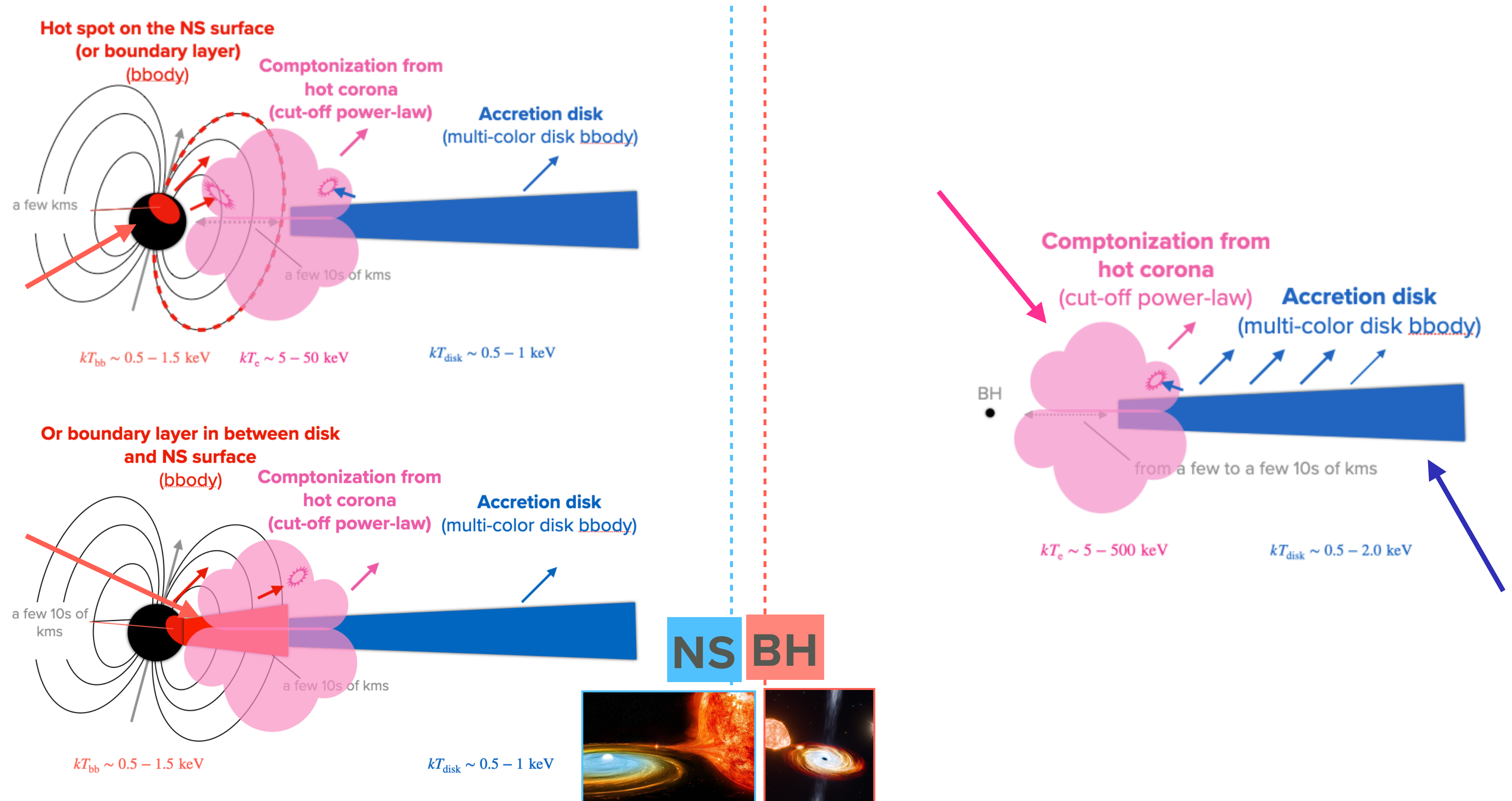
Hard shortage caused by a burst, [Chen+12](#)

Disc radius retreat caused by a burst, [Fragile+20](#)



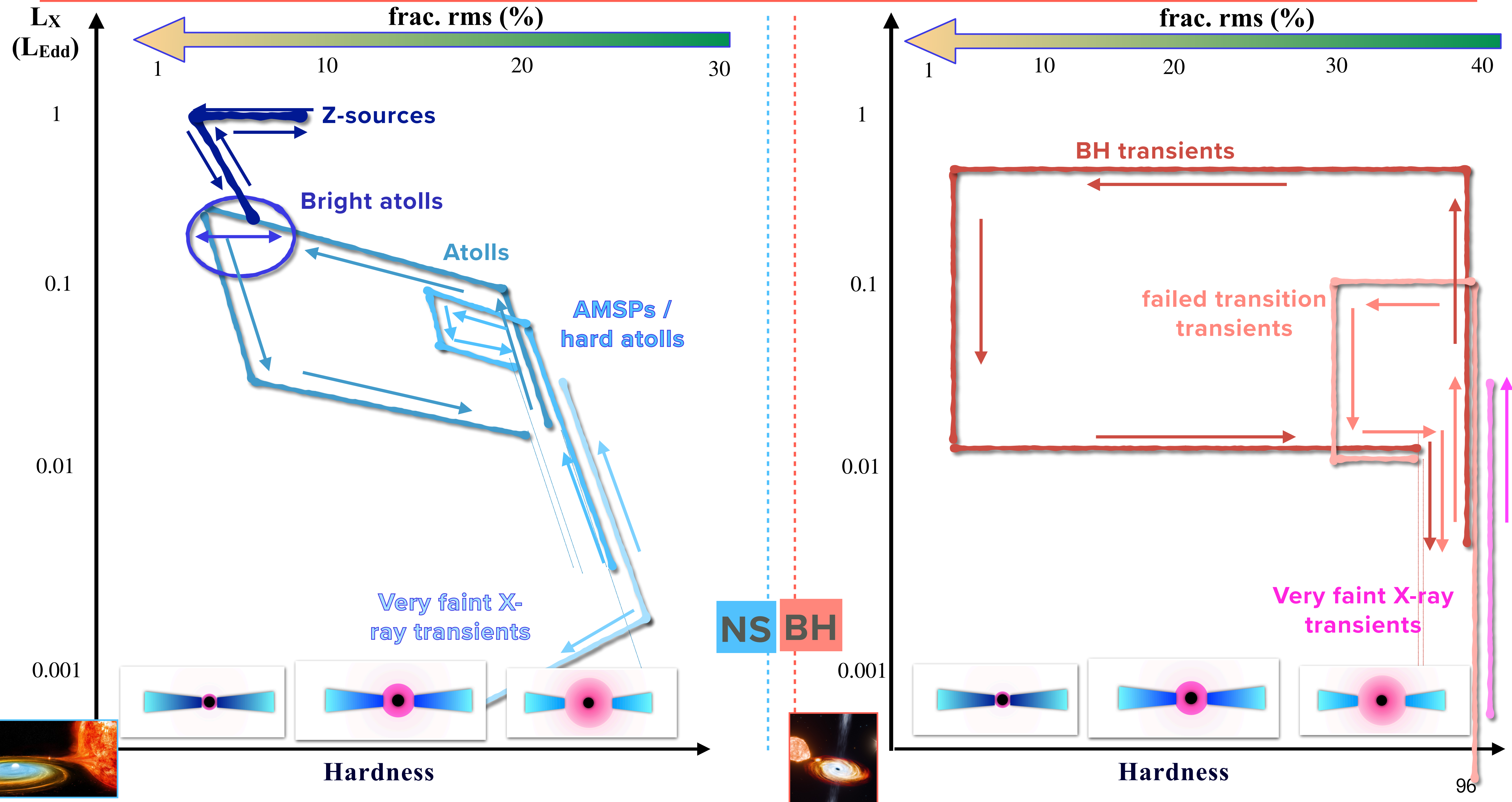
Concluding summary (i)

- The accretion flow surrounding NSs/BHs in LMXBs is composed by several anatomical parts, which imprint distinct spectral and timing signatures in X-rays;



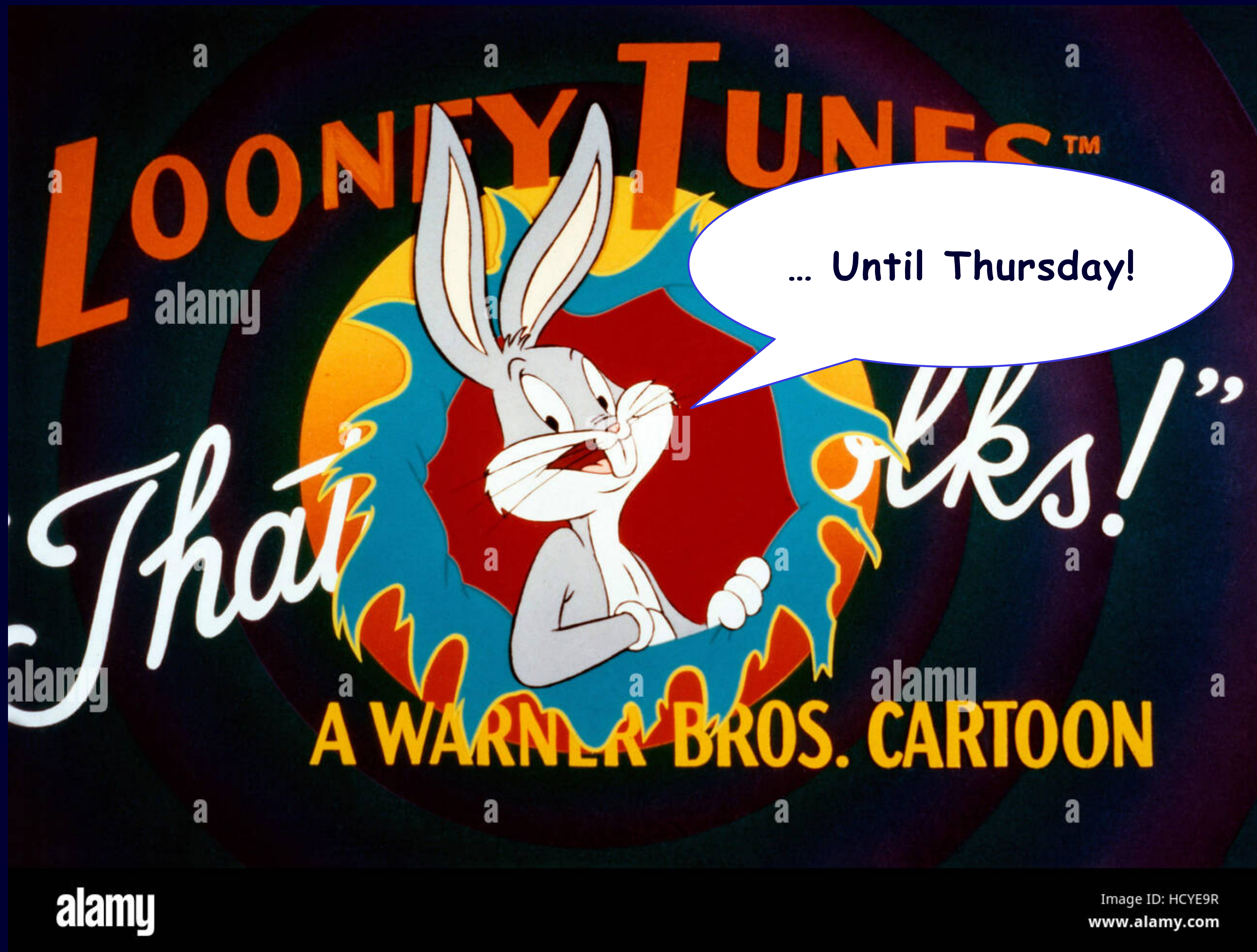
Concluding summary (ii)

- Different types of long-term activities observed;



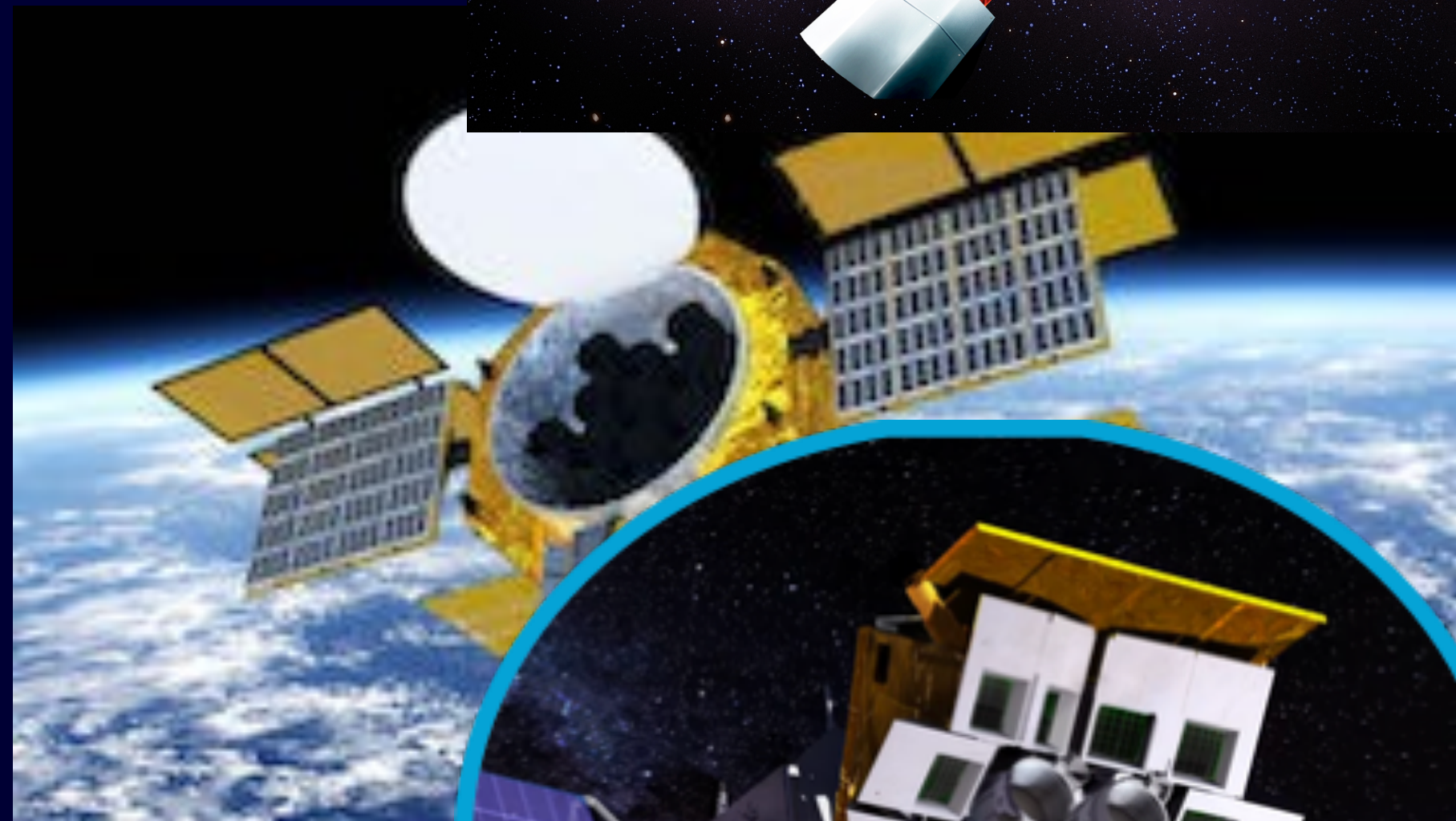
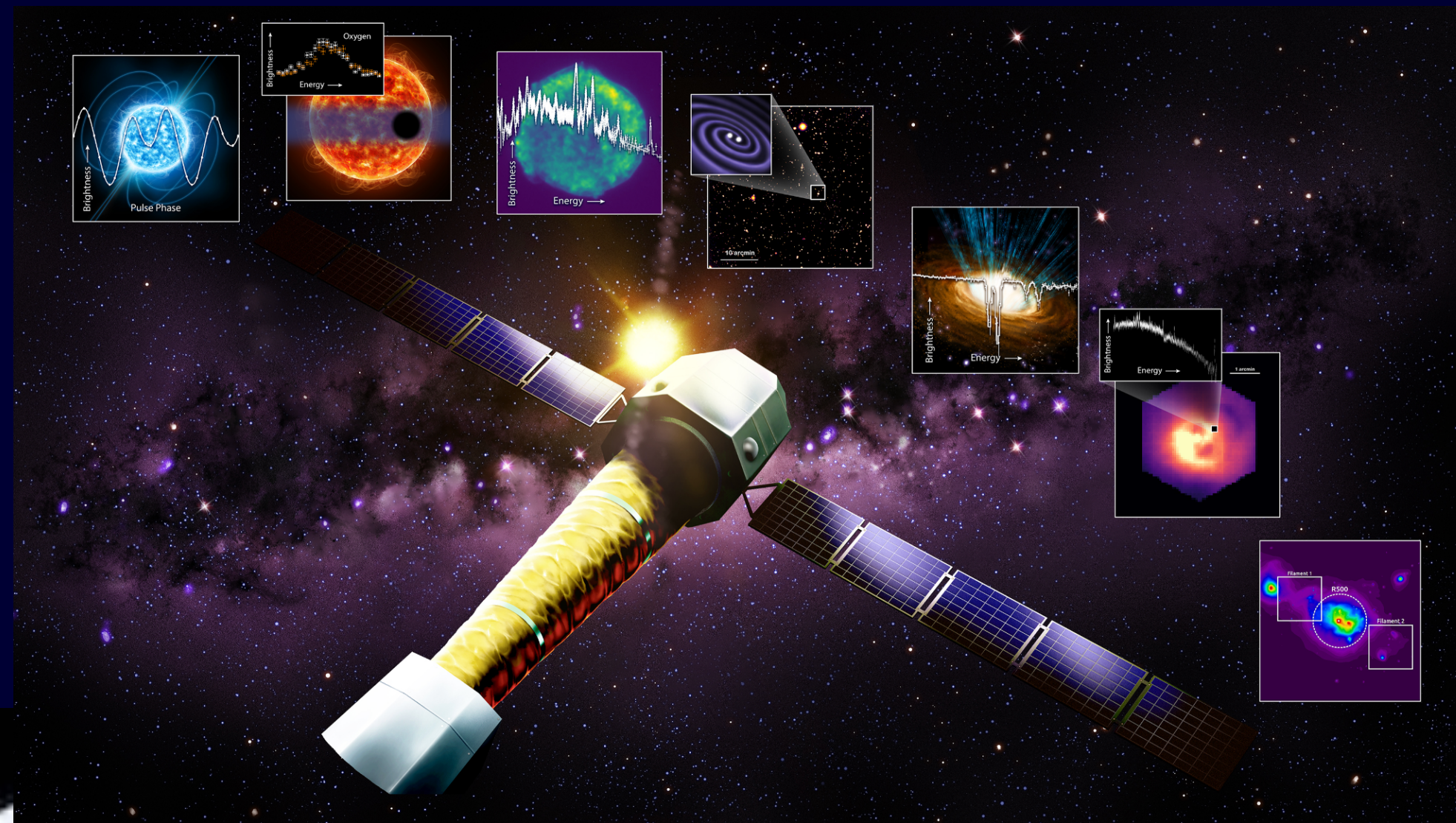


That's all Folks!



alamy

Image ID: HCYE9R
www.alamy.com



What's next?

- A new time-domain X-ray mission, launched in 2024 (Chinese Academy of Sciences, ESA, Max Planck)
- The **WXT** (the monitor) has the best **grasp*** ever - can detect new transients once they get to a few mCrabs!

◉ Slide credits: F. Coti Zelati

Follow-up X-ray Telescope (FXT - 2 detectors)

Wolter-I type ⁺CCD
FoV: 1 deg
Energy: 0.3-10 keV
Eff. Area: 2x300cm² @1keV
Position accuracy: 5-15"

Wide-field X-ray telescope (WXT - 12 modules)

Lobster-eye MPO + CMOS
FoV: 3600 sq deg (1.1 sr)
Energy: 0.5-4 keV
Eff. Area: ~3cm² @1keV
Position accuracy: <3'

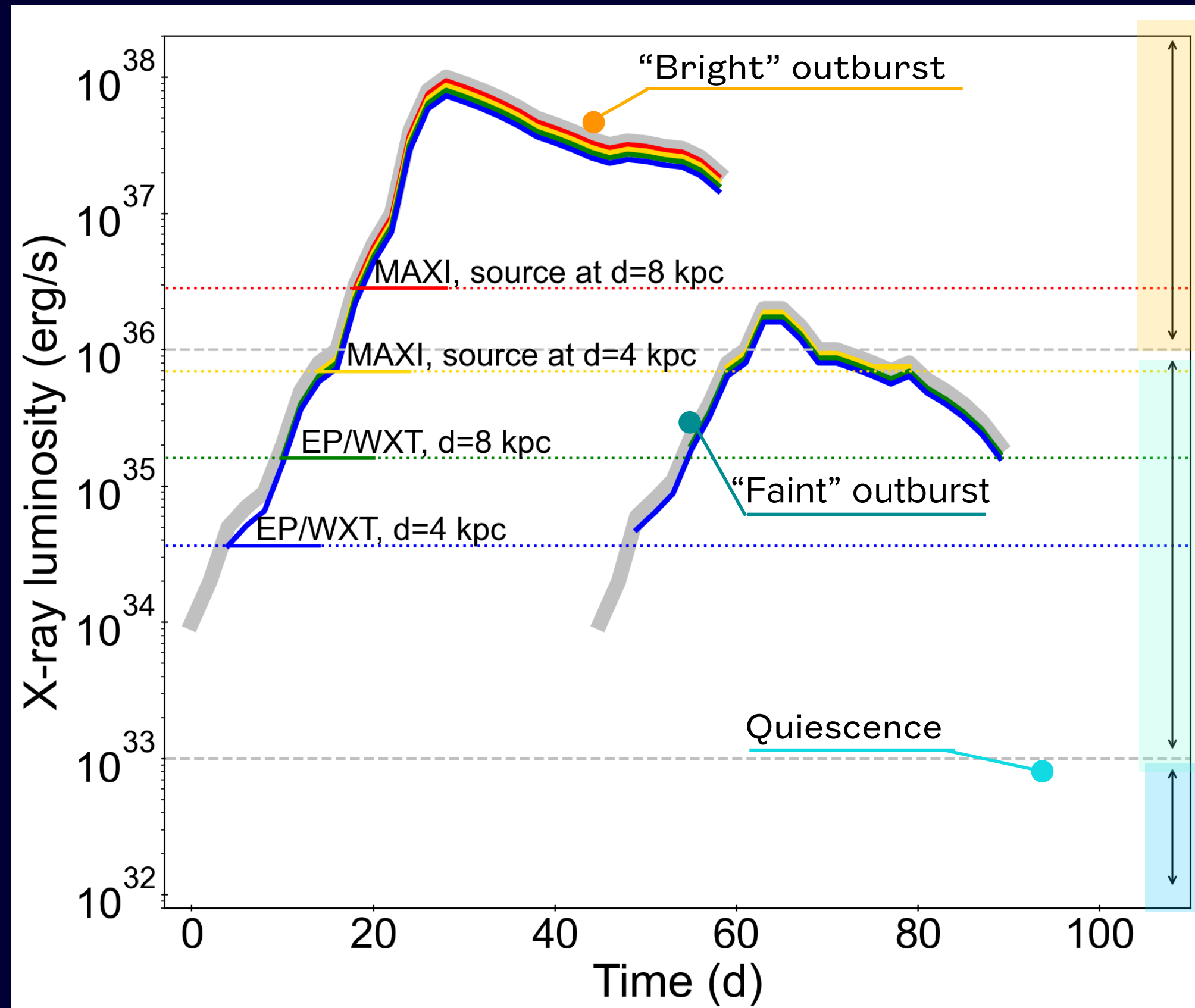
Onboard automated system

- Autonomous slew in 3-5 min
- Fast Alert distribution & ToO upload

Einstein Probe

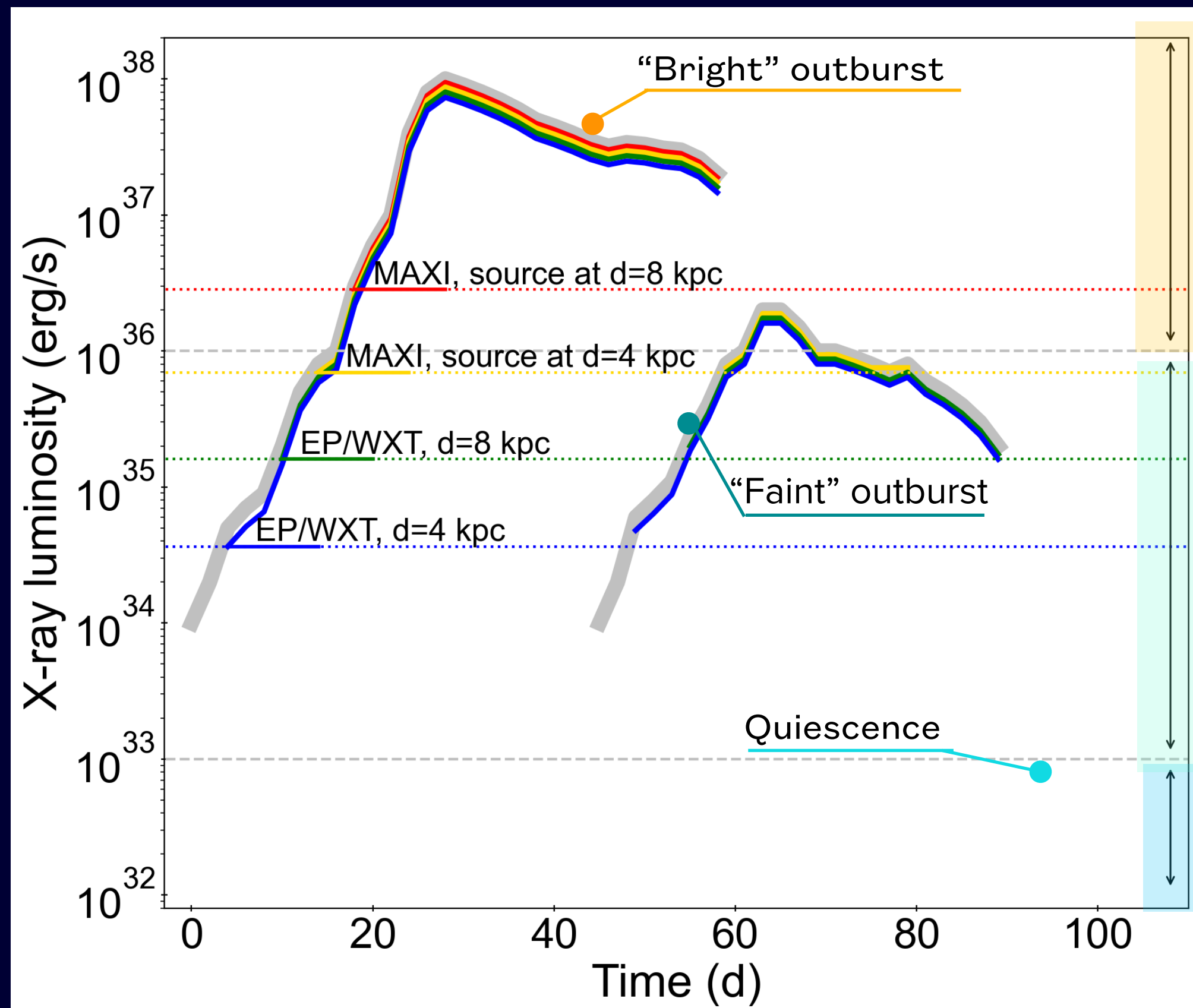
- Hypothetical light curves of two outbursts of a LMXB

Einstein Probe: low-level accretion unveiled



More (bright+**faint**) outbursts, caught earlier on the act!

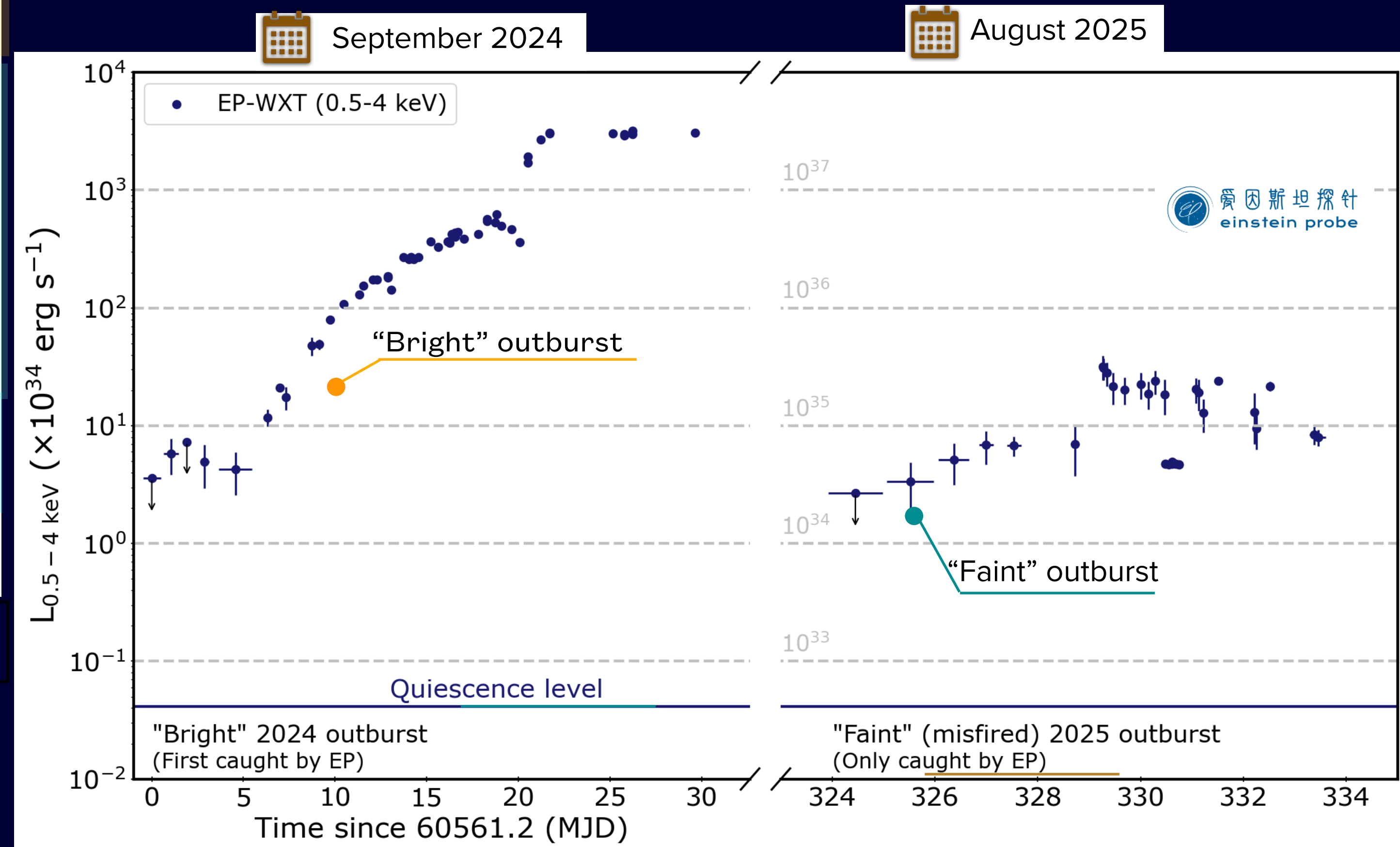
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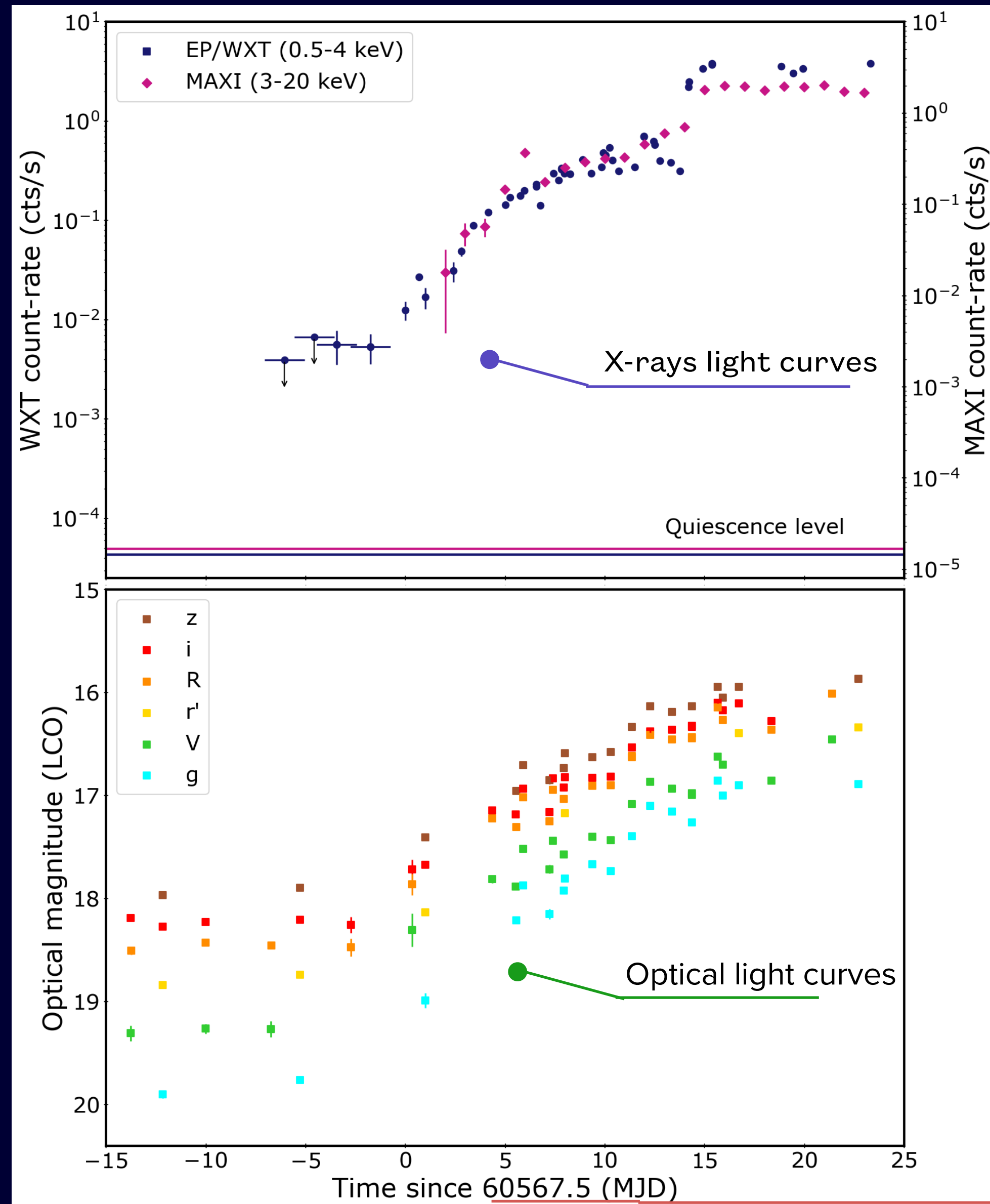
- Real EP light curve of the LMXB Aql X-1



Atels by: Liu+2024, Rout+2024, Russell+2024, Alabarta+2025, Rout+2025;

Einstein Probe: the dawn of the Aql X-1 outburst

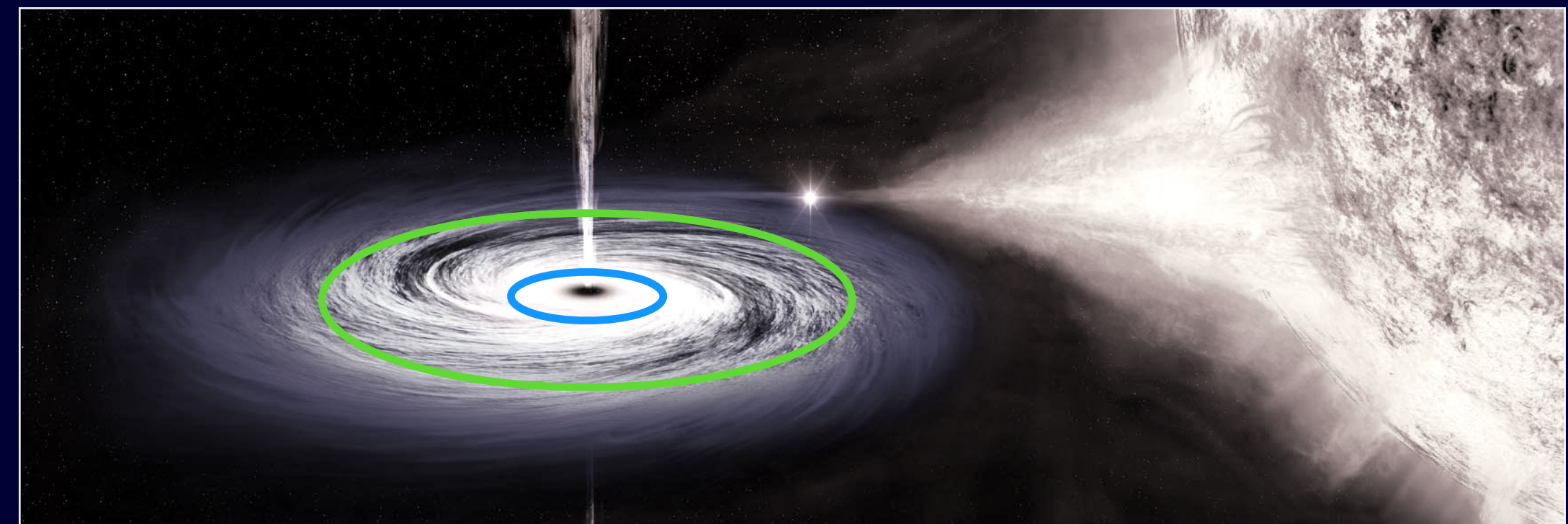
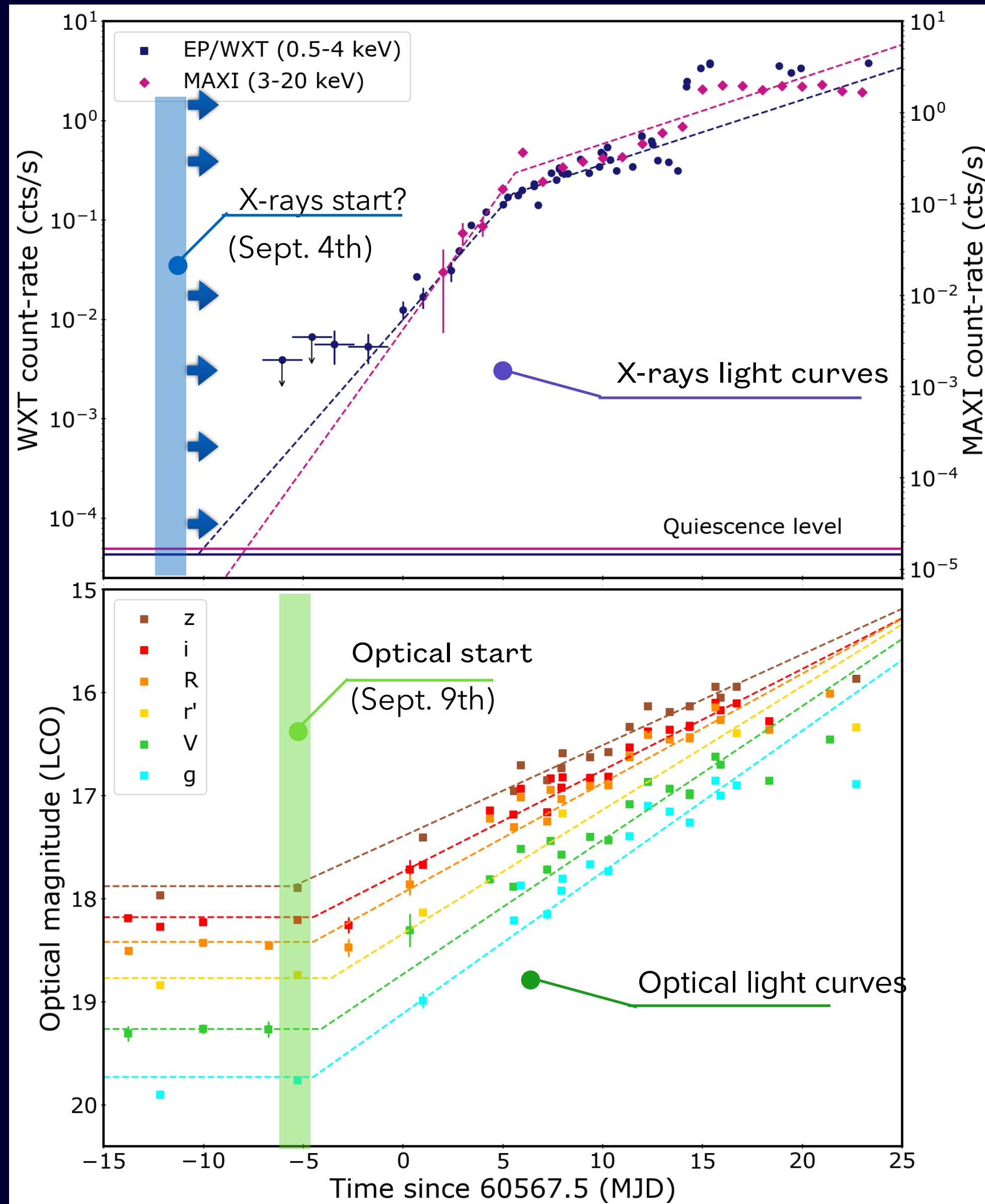
- We were able to observe the onset of the outburst with Einstein Probe, MAXI and Las Cumbres Observatory thanks to the XB-NEWS program (Russell+2019);



The day the outburst was first caught by EP

Einstein Probe: the dawn of the Aql X-1 outburst

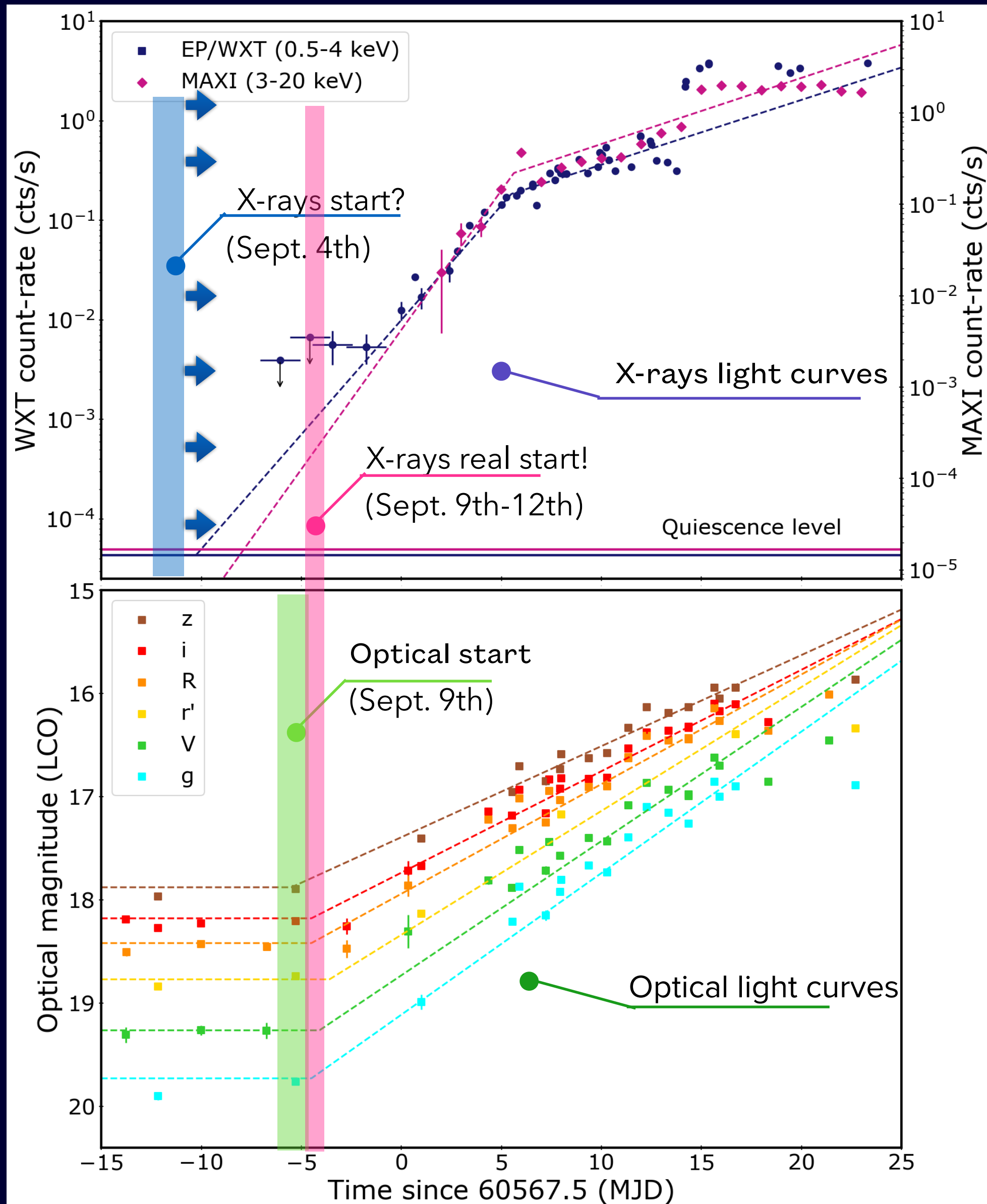
- We were able to observe the onset of the outburst with Einstein Probe, MAXI and Las Cumbres Observatory thanks to the XB-NEWS program (Russell+2019);
- We parametrised the light curves with phenomenological models to individuate the **start time** of the outburst in the different bands;



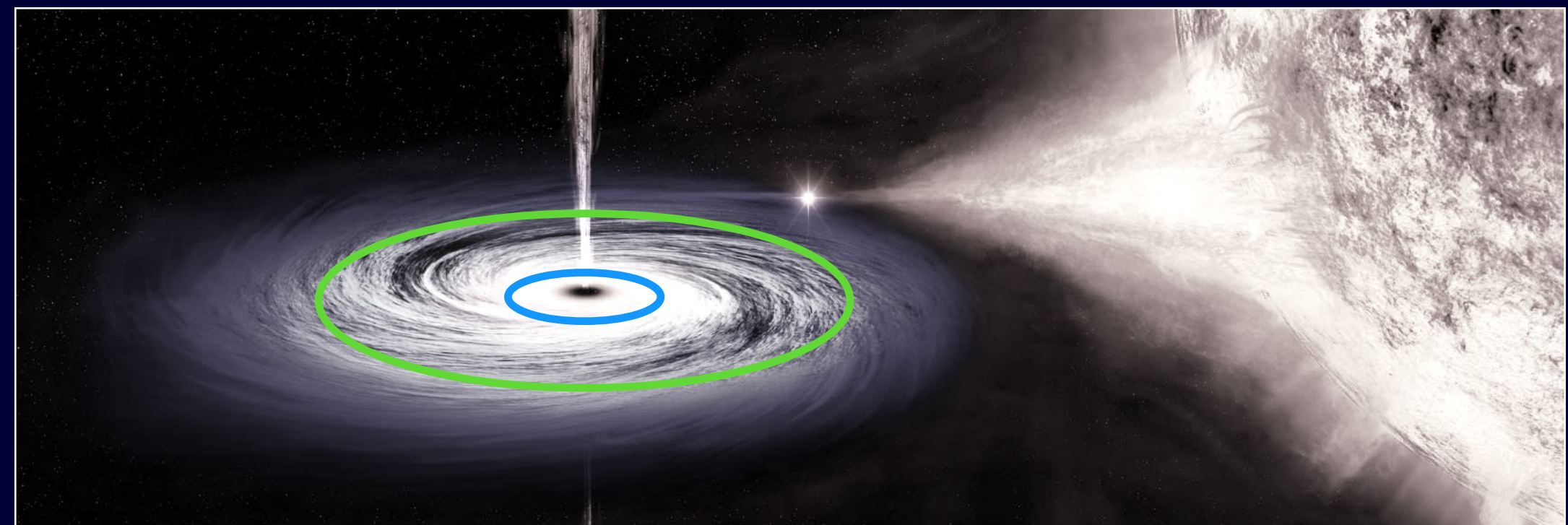
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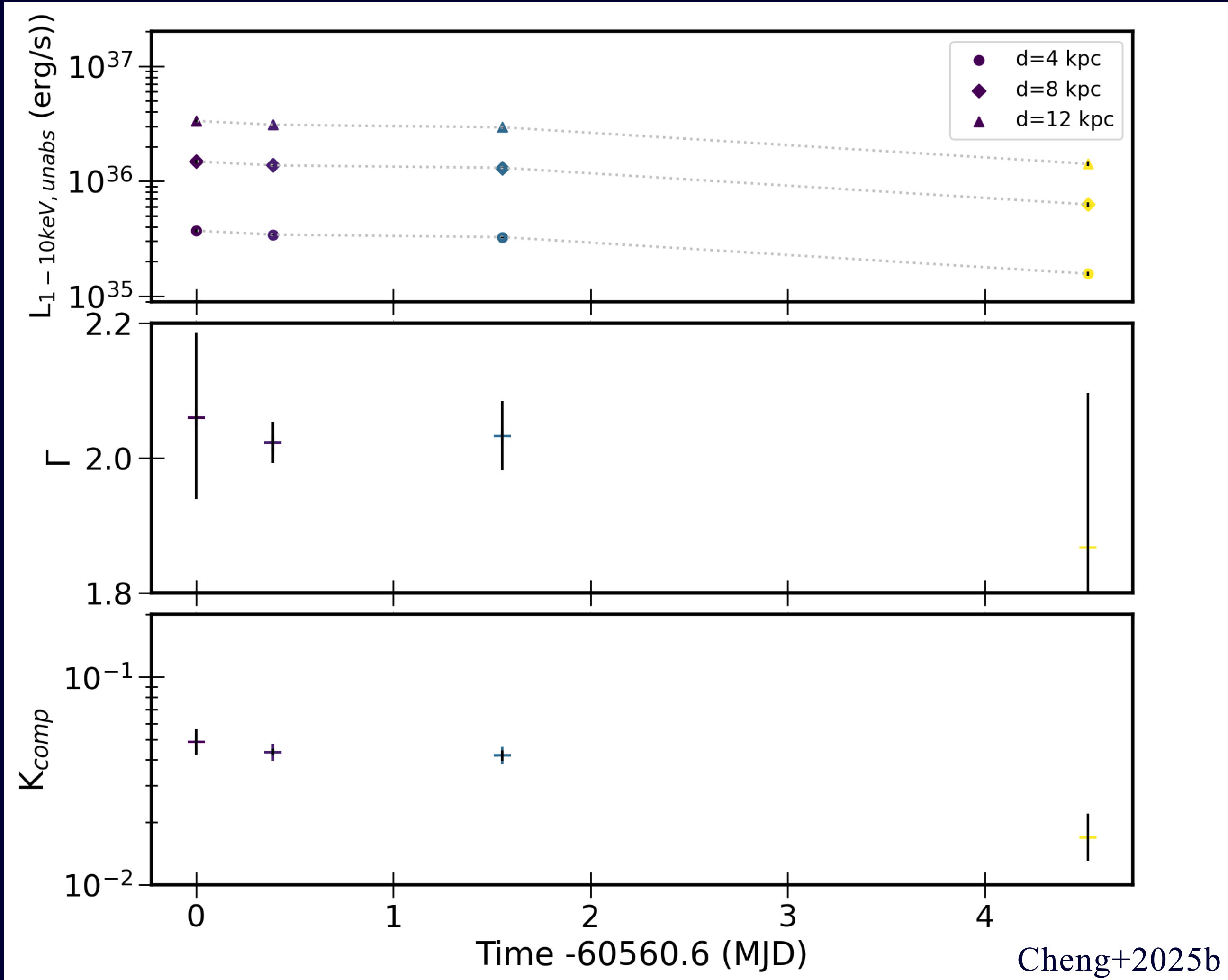
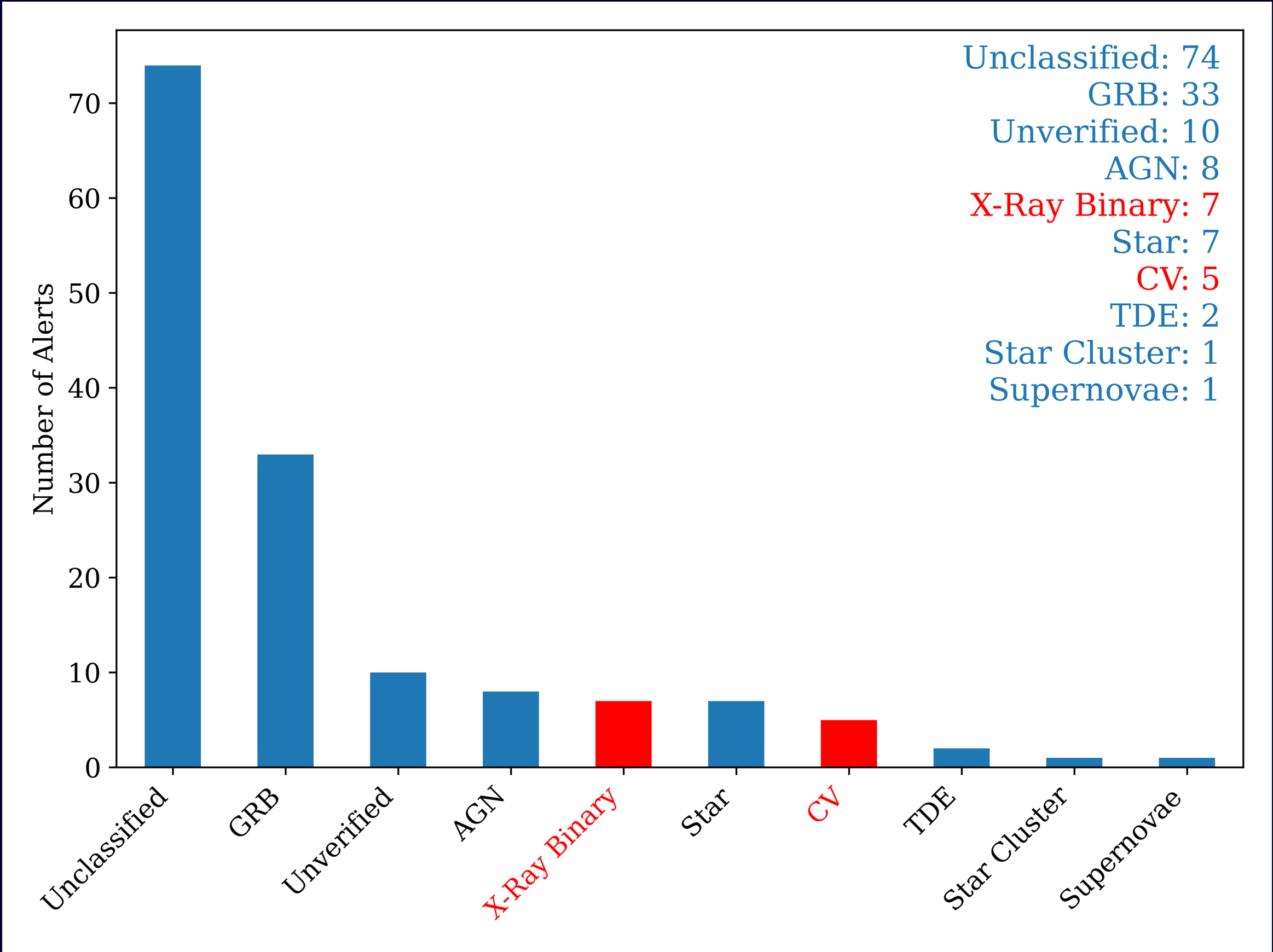


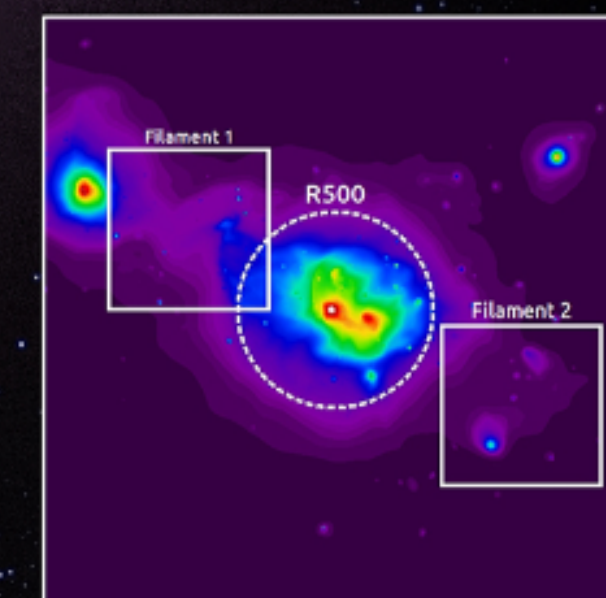
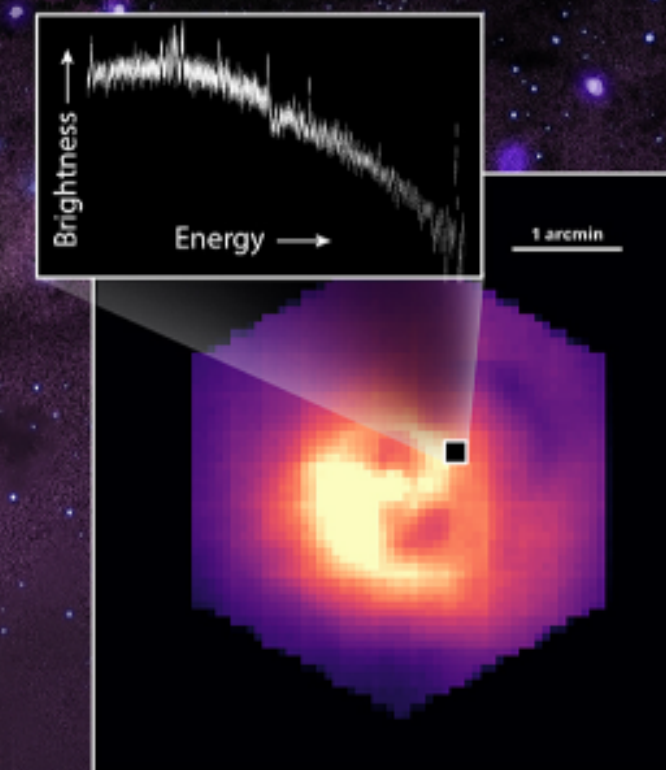
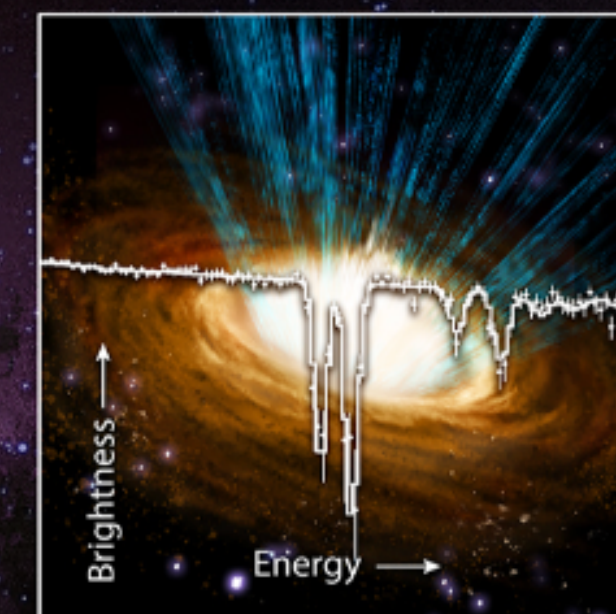
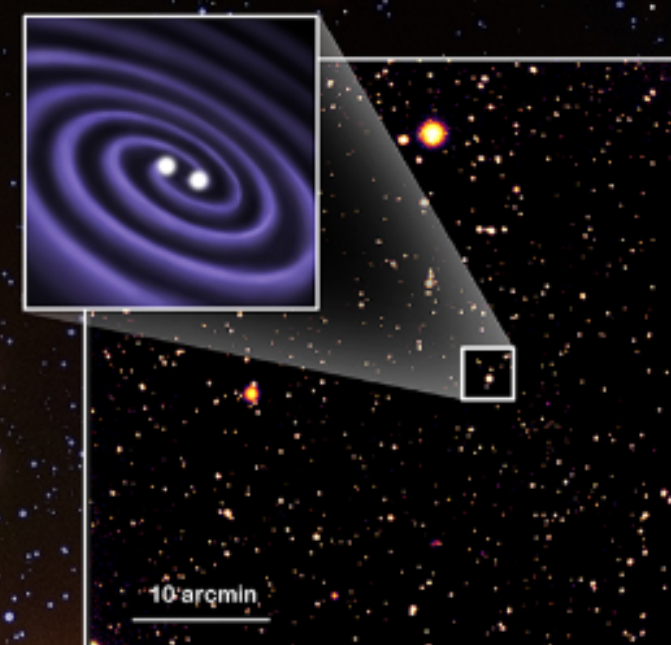
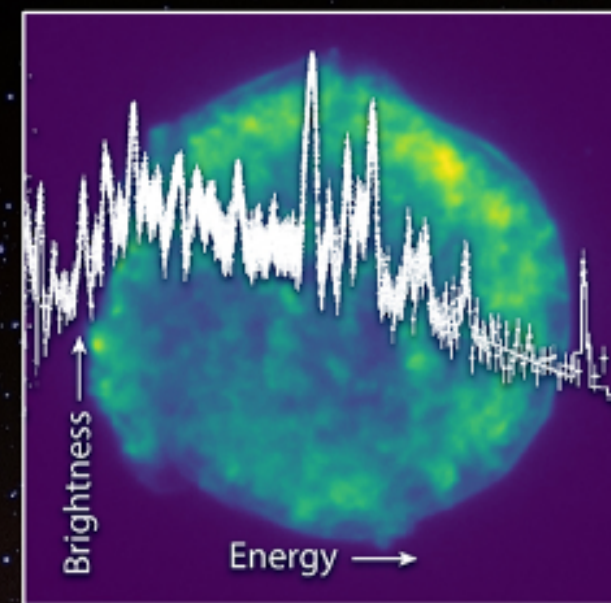
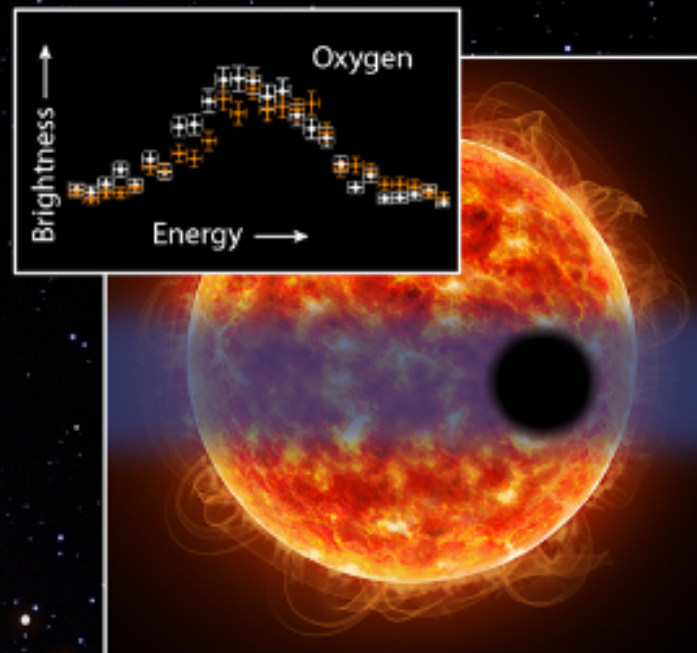
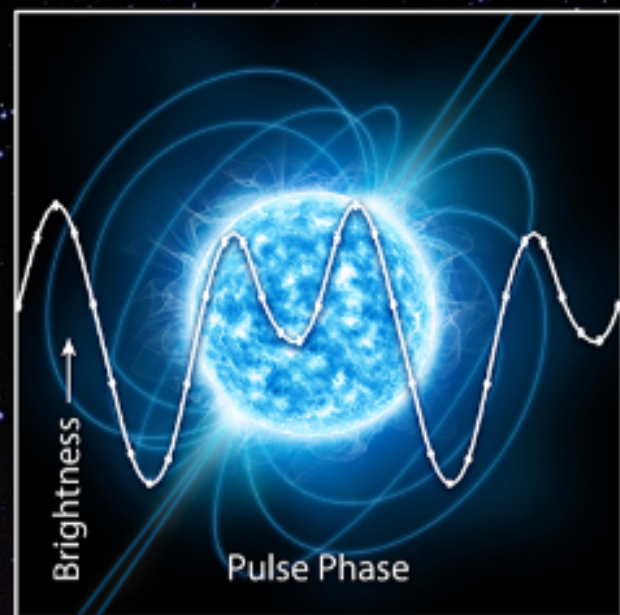
An optical-to-X-rays delay of 3 d or less?



The day the outburst was first caught by EP

Einstein Probe: a population of VFXTs uncovered

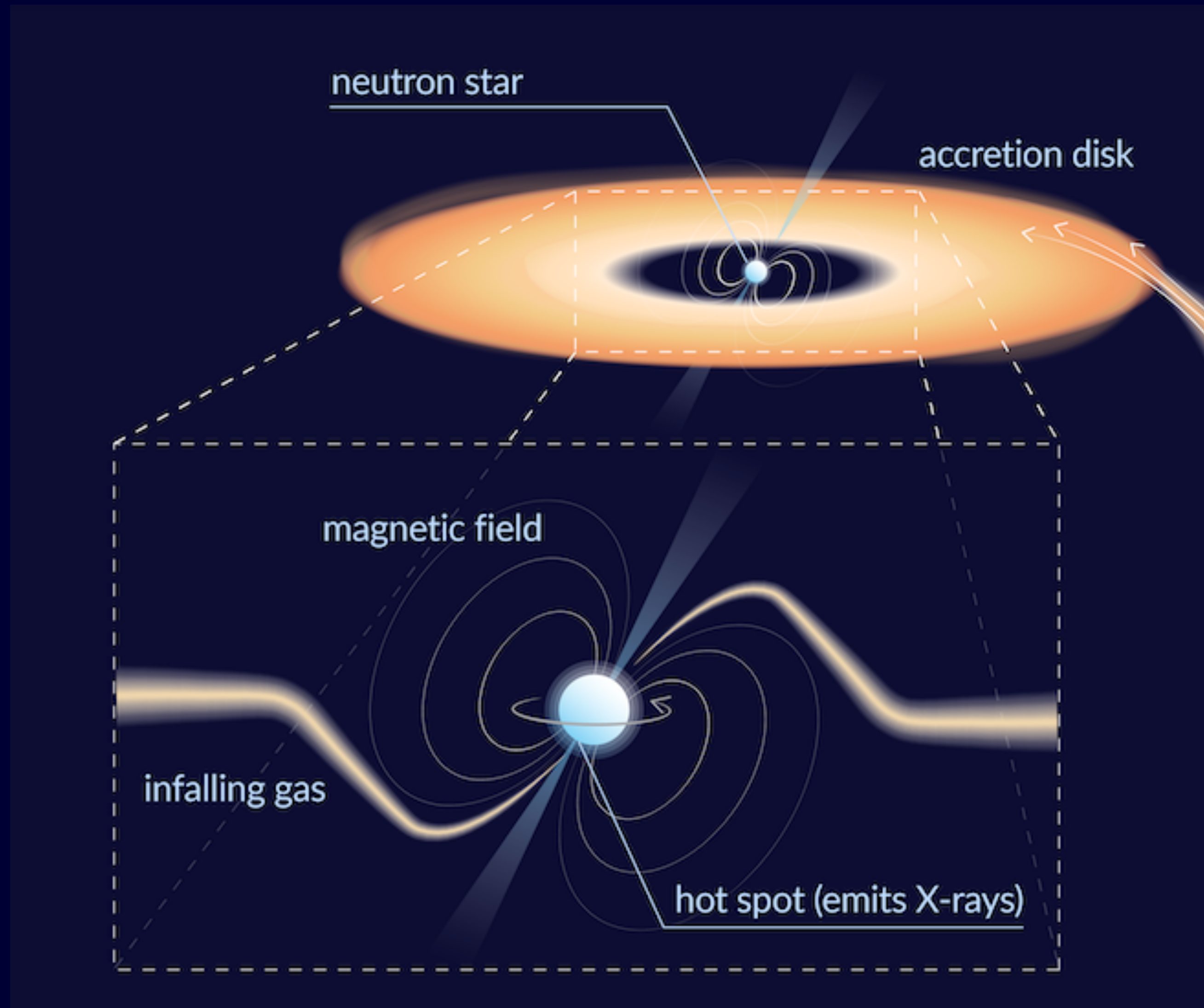
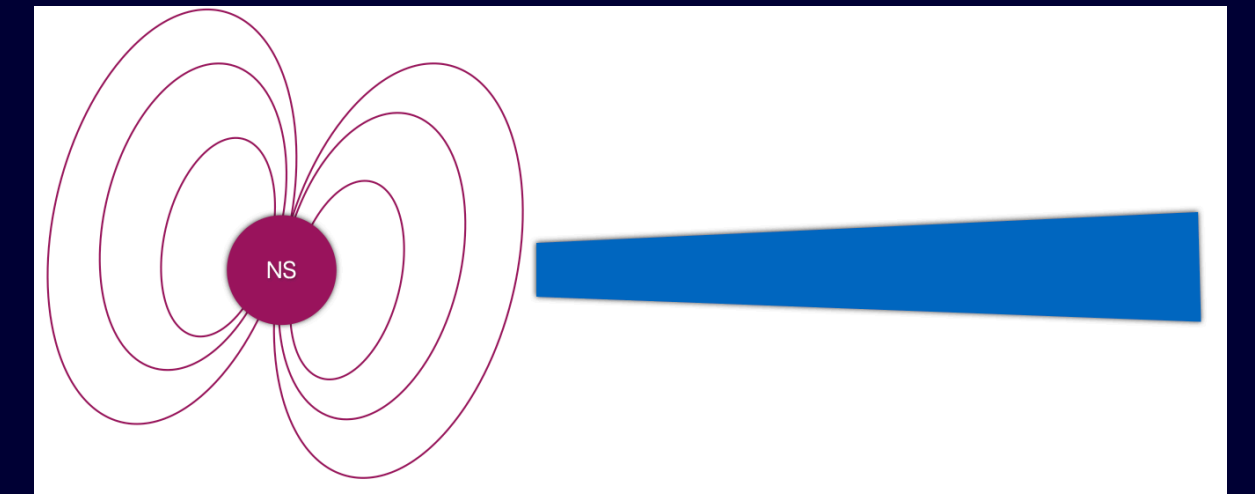




NewAthena

A. MARINO - ACCRETION ONTO COMPACT OBJECTS

Channelled accretion and pulsations (NSs only!)



- Inside the magnetospheric radius, matter is channeled onto the magnetic field lines and create hot spots on the NS surface.
- These hot spots are typically on the poles and due to this inhomogeneity we see a pulse whenever the pole is directed towards us!
- This is the origin of **X-rays pulsations**;

How matter accretion can spin-up a pulsar

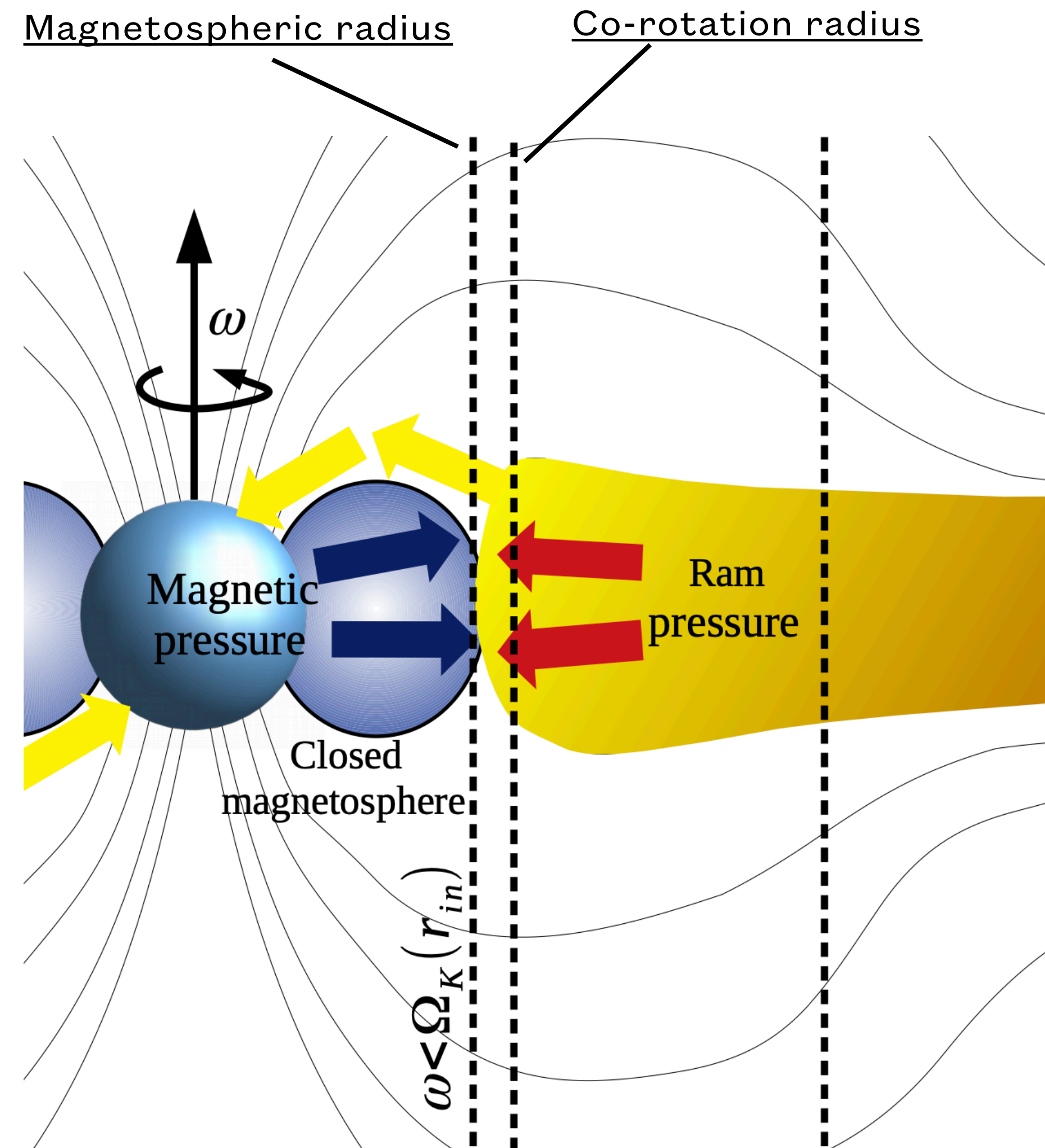
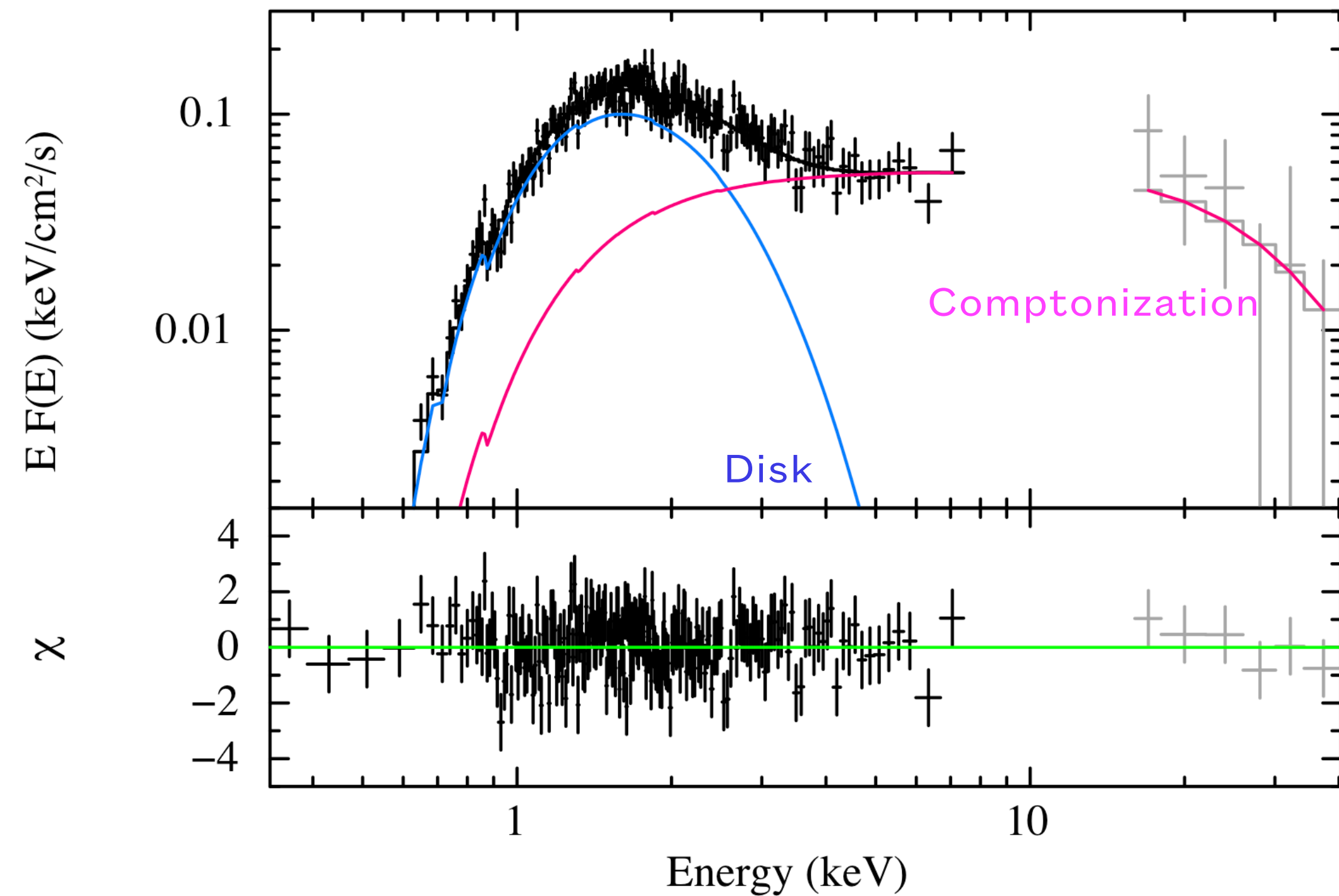


Image by Michele Ronchi

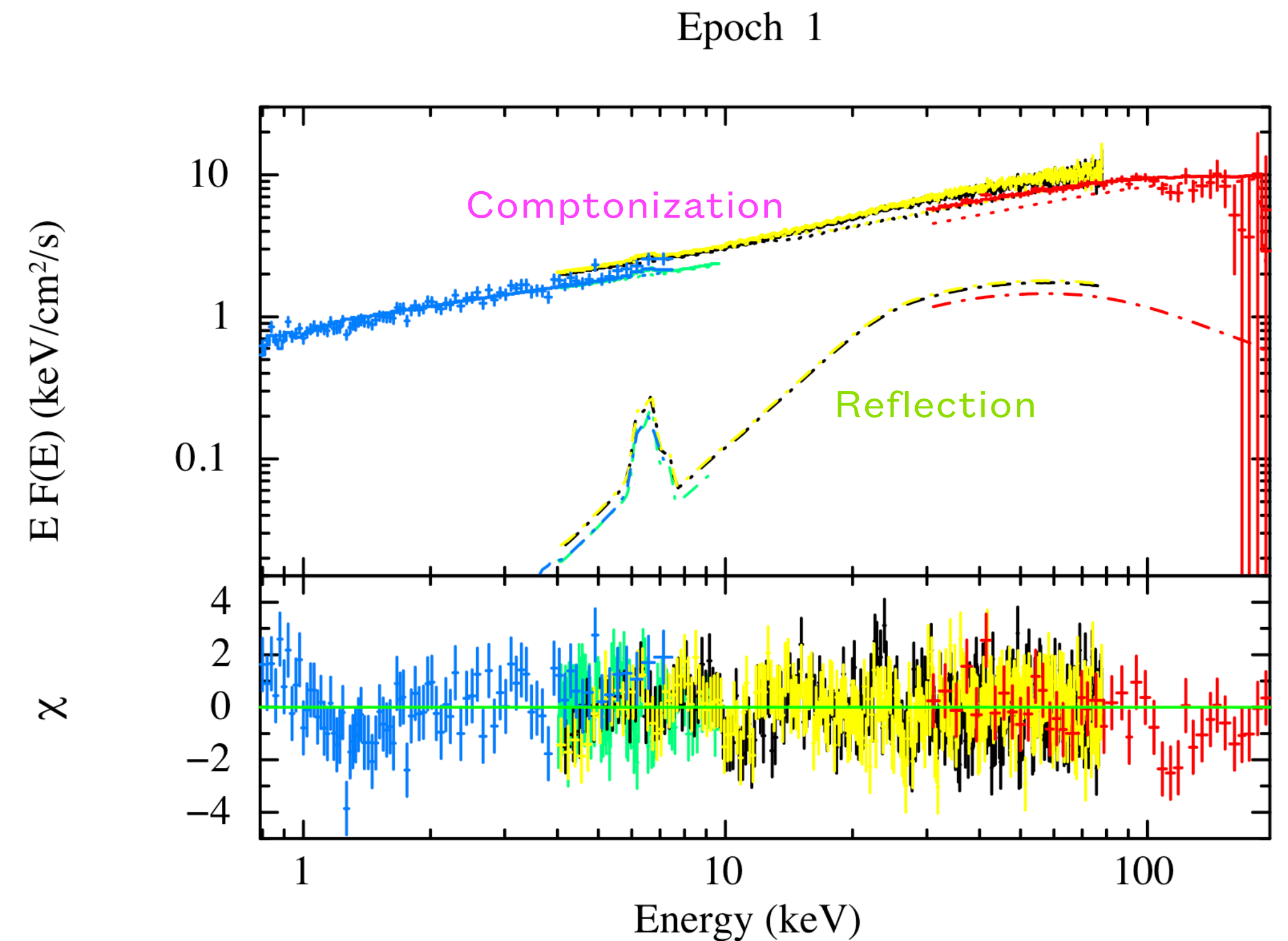
Take into account that:

- In a NS LMXB we can identify a co-rotation radius r_c , the radius where the disc has the same rotational velocity of the NS:
- if $r_c > r_m$
- The disc is faster than the magnetic field and the NS;
 - **The accreting material spins-up the NS!**
 - A very interesting class of pulsating NS LMXBs is composed of **Accreting Millisecond X-ray Pulsars** (AMXPs) where the NS spins extremely rapidly, i.e. with millisecond spin periods.

Some real-life X-ray spectral analysis



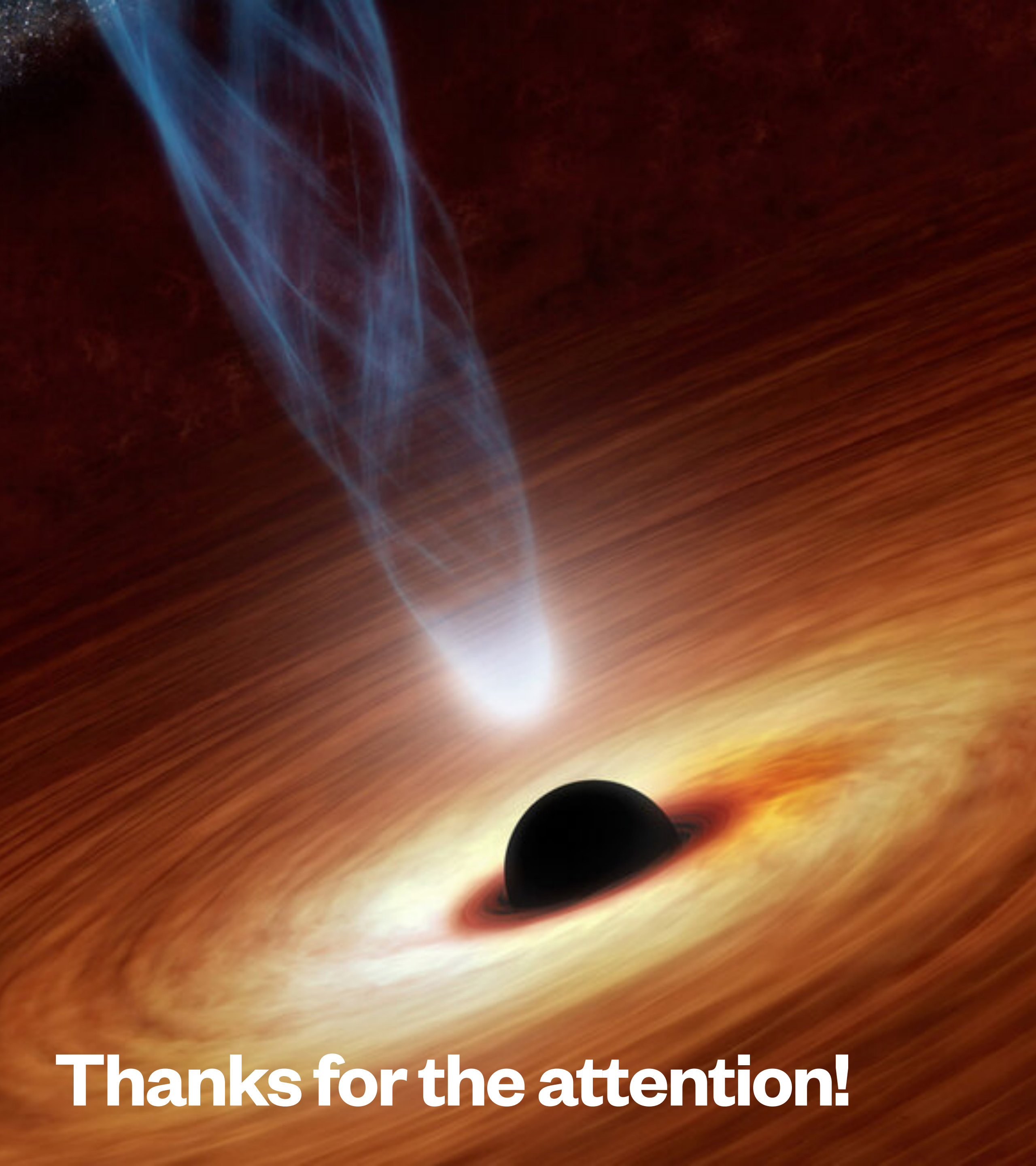
- Example from the Black Hole X-ray Binary MAXI J1810-222 (from [Russell, Del Santo, Marino et al., 2022](#))



- Example from the Black Hole X-ray Binary MAXI J1820-070 (from [Marino et al., 2021](#))

Take-away messages

- ▶ Accretion is a powerful phenomenon that sheds light on the most elusive objects in the cosmo, e.g. black holes and neutron stars;
- ▶ X-ray binaries are natural laboratories to e.g. test General Relativity in strong gravitational fields and to investigate the behaviour of matter inside neutron stars;
- ▶ X-ray spectroscopy is a powerful tool to study the surroundings of accreting compact objects and the compact objects themselves.

A black hole with a bright blue accretion disk and a glowing jet of light.

Thanks for the attention!