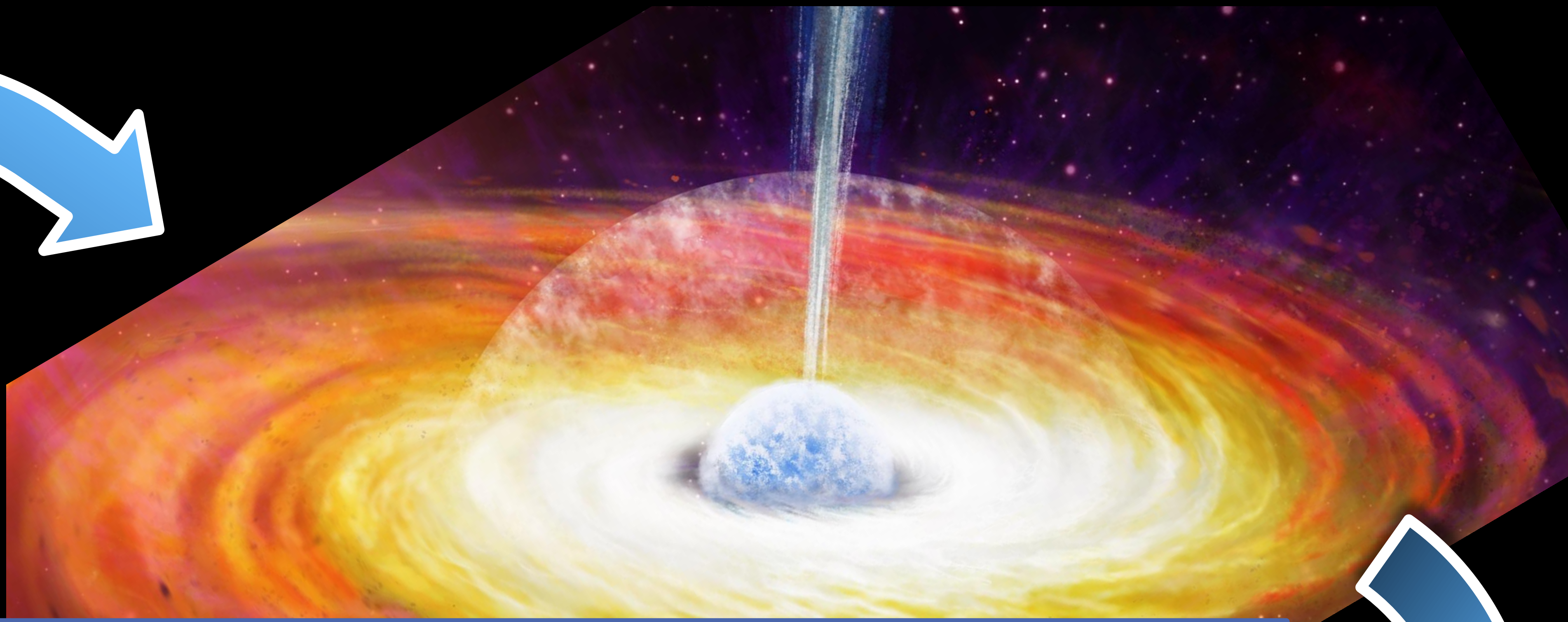
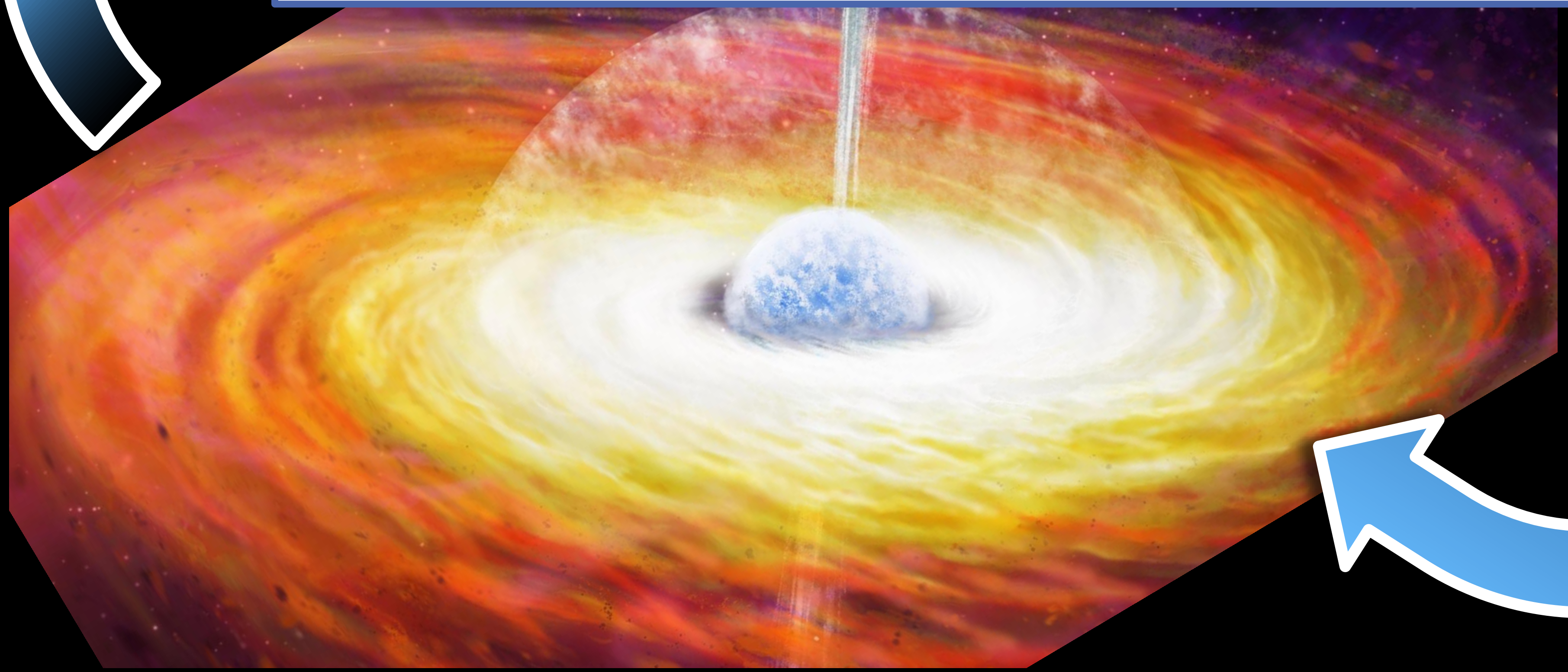
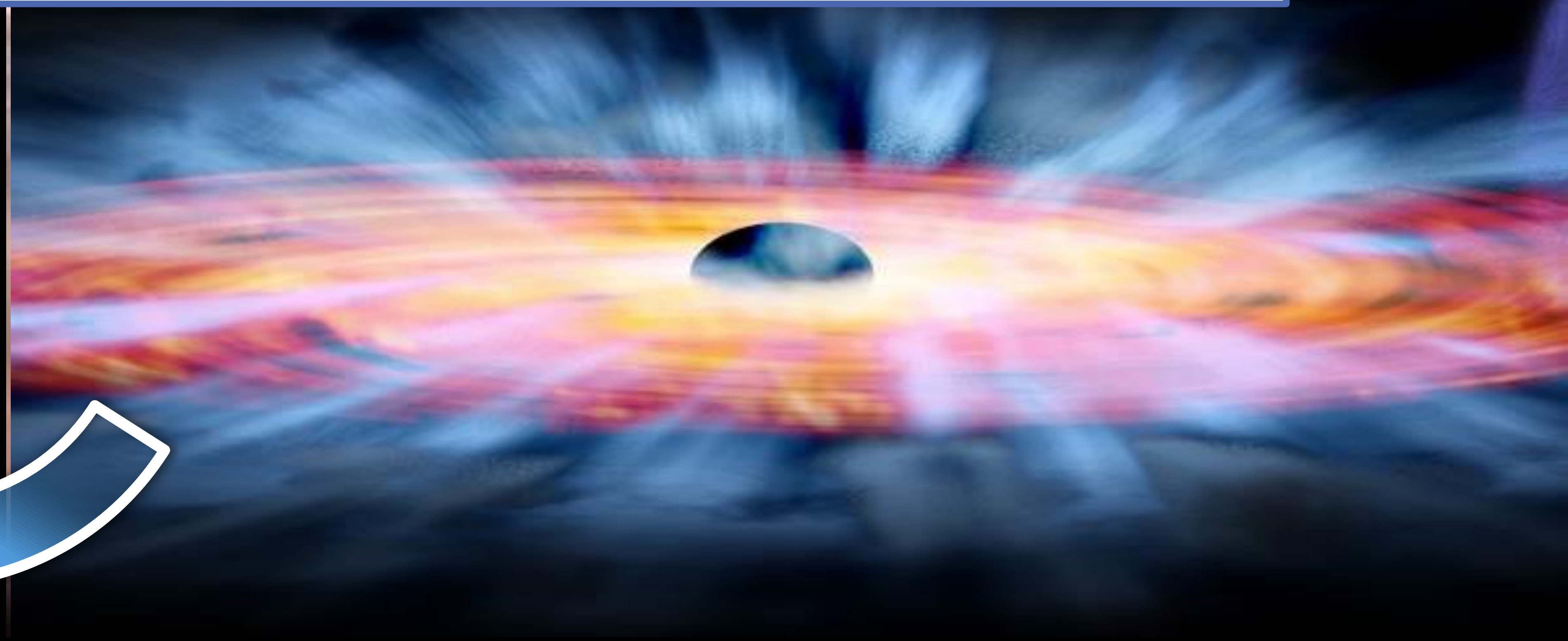
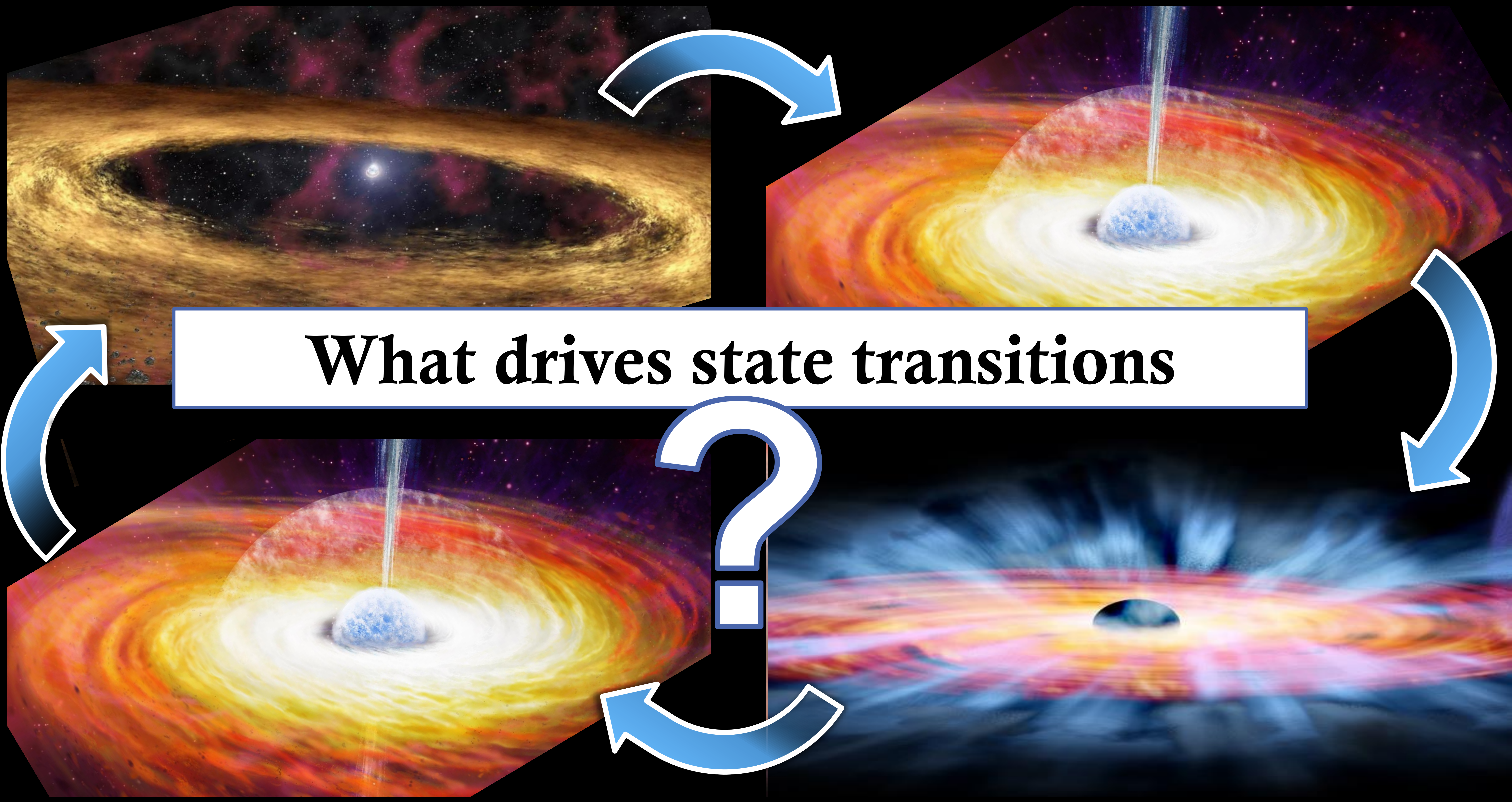
States and Transitions in X-ray Binaries

Nathalie Degenaar, University of Amsterdam



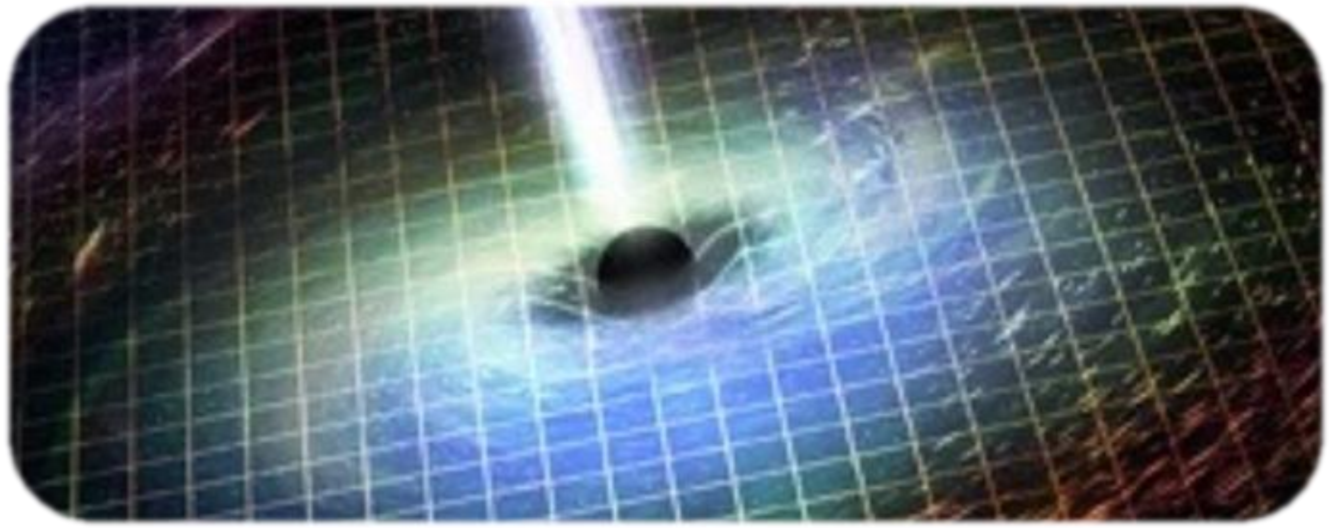


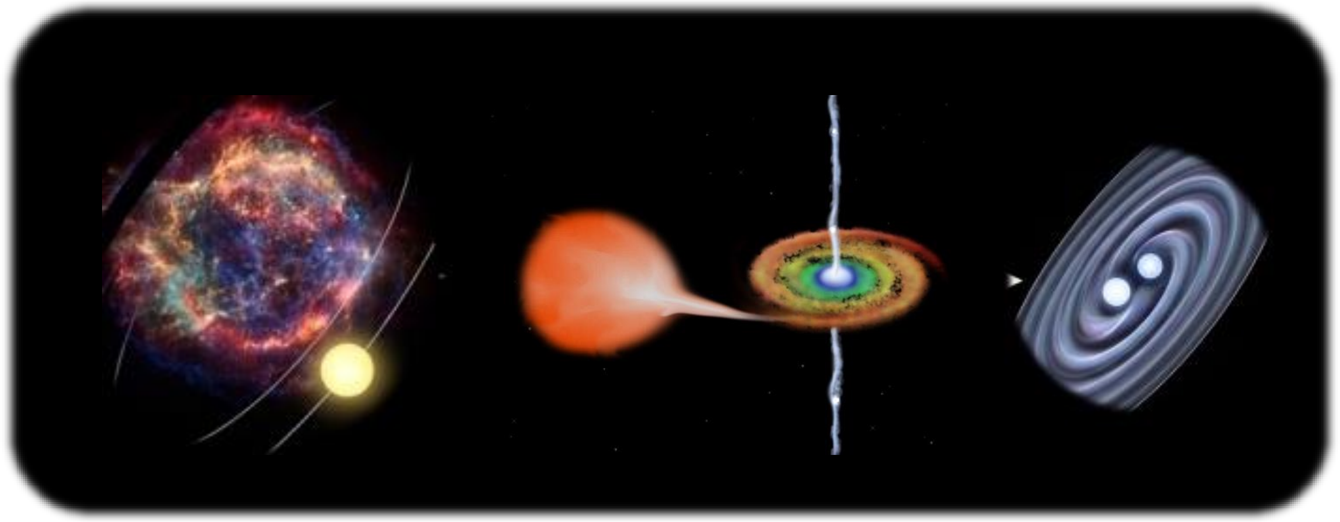



What drives state transitions

What do we want to know?

- **What drives state transitions?**
- **What does it tell us about:**
  - Accretion geometry
  - Jet production
- **What does this imply for:**
  - Measuring masses and spin
  - Binary evolution
  - Impact on environment



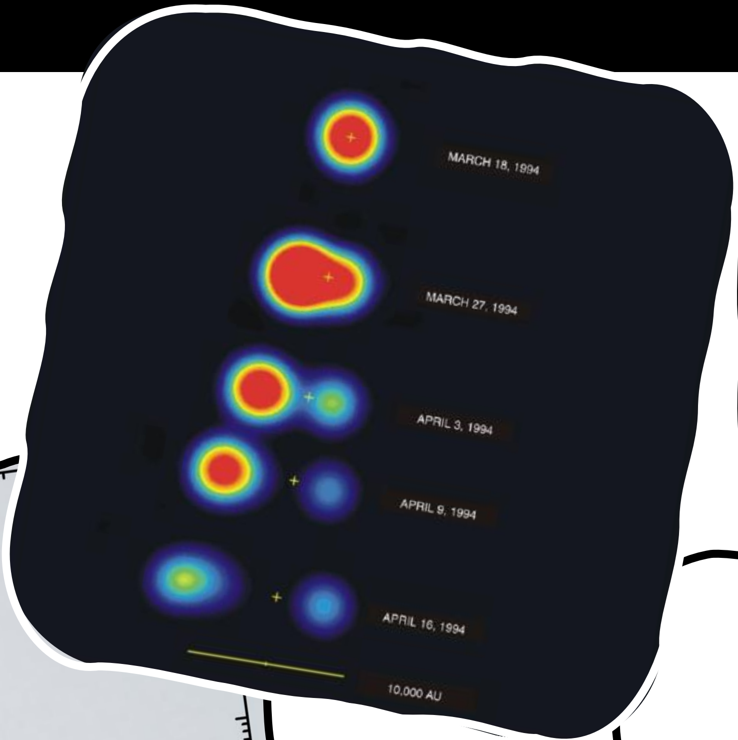


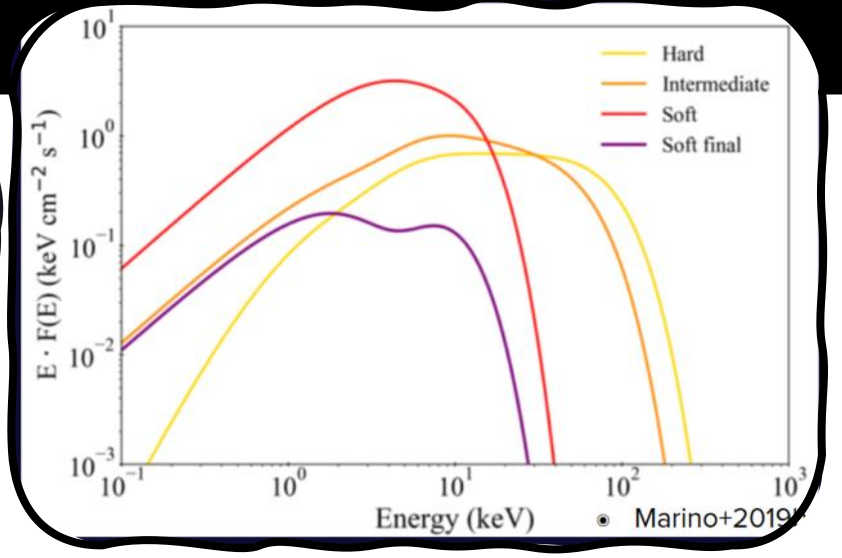
How do we do this?

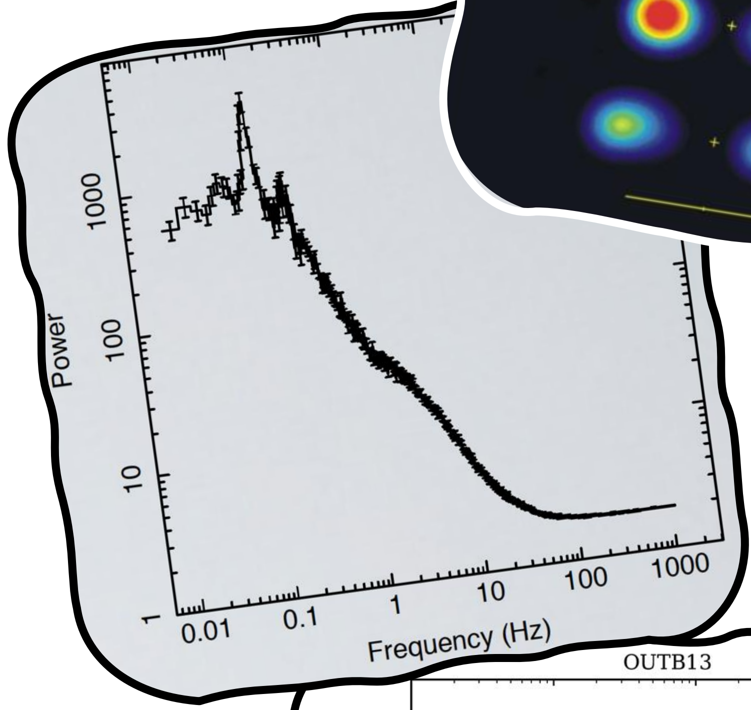
- **What drives state transitions?**

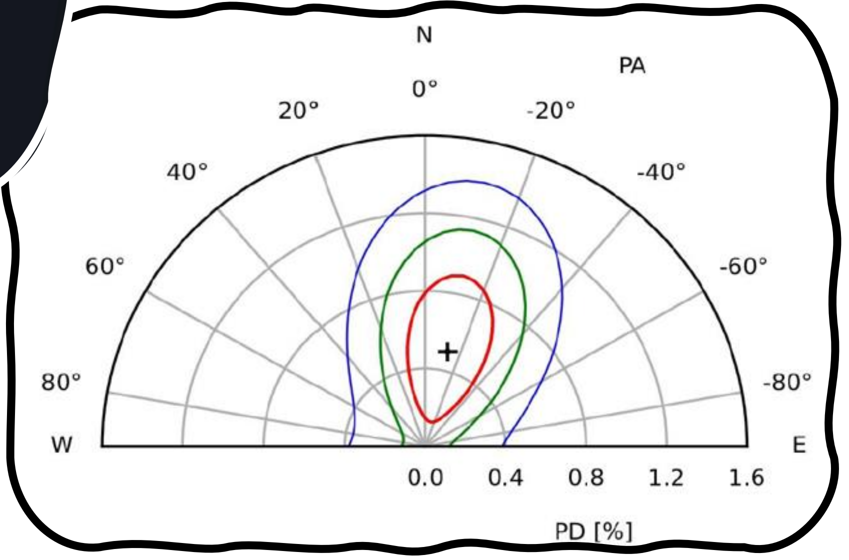
- **Approaches**
  - X-ray Spectroscopy
  - X-ray timing
  - Radio jet behavior
  - Optical/infrared
  - Polarimetry
  - Simulations

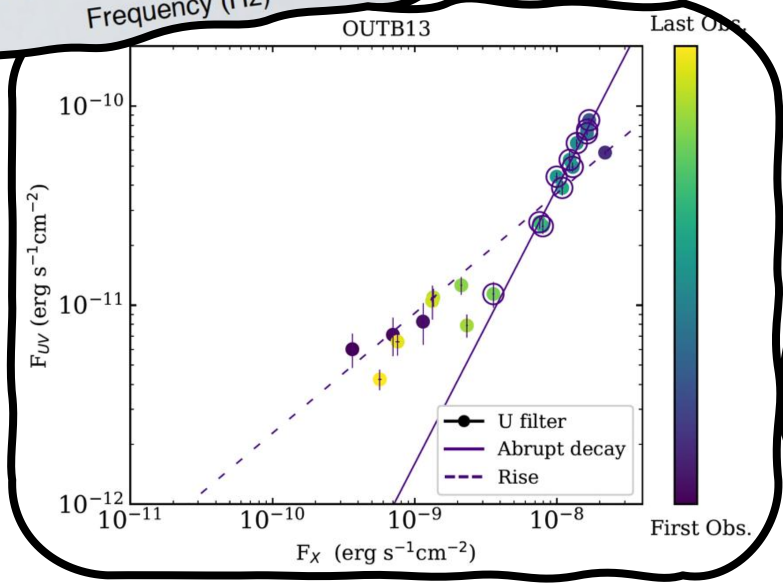
  !! Combinations of above

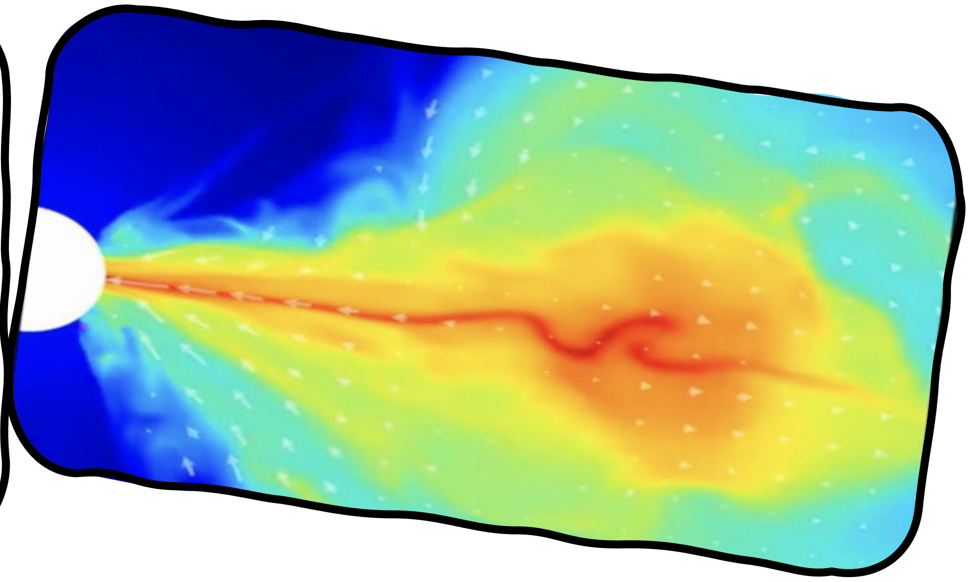




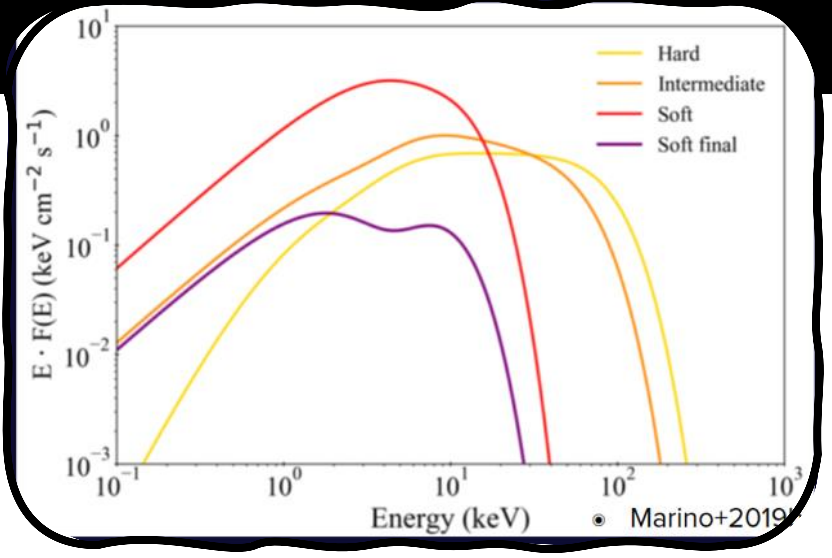








How do we do this?



- **What drives state transitions?**

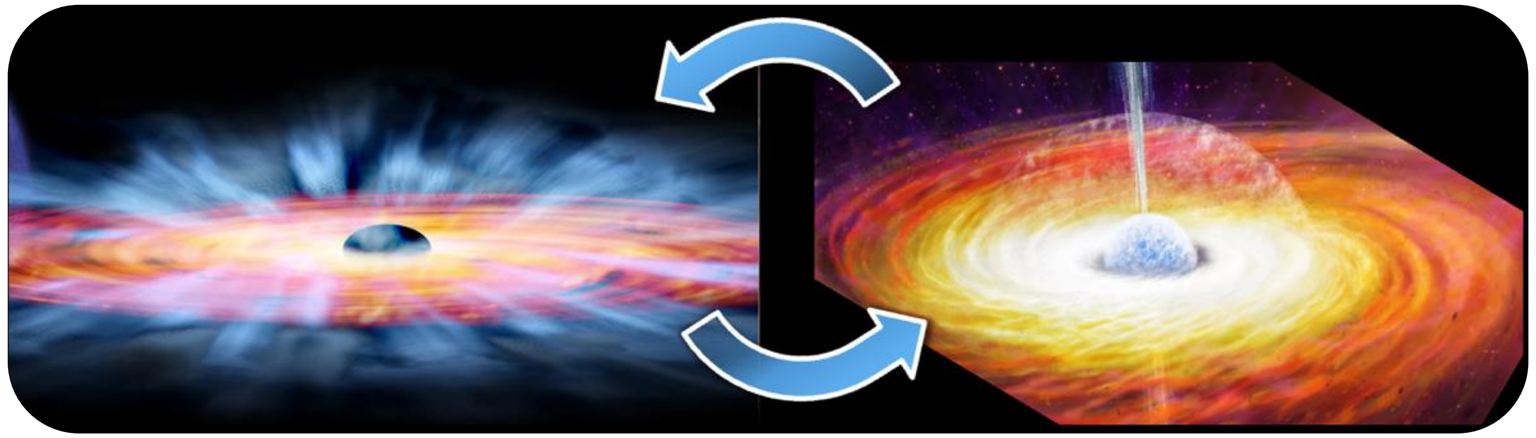
- **Approaches**
  - X-ray Spectroscopy → this talk & **Mastroserio** (**Wed**)
  - X-ray timing → **Vincentelli** & other talks (**Tue**)
  - Radio jet behavior → **Fender** & others (**Wed**)
  - Optical/infrared → **Russell**, **Casella** & others (**Wed**)
  - Polarimetry → **Veledina** & others (**Thu**)
  - Simulations → **Baker**, **Savard** talks (**Mon**, **Wed**)

Plan for this talk

Brief for context: **Spectral components & states**

Broad physical picture

Some questions



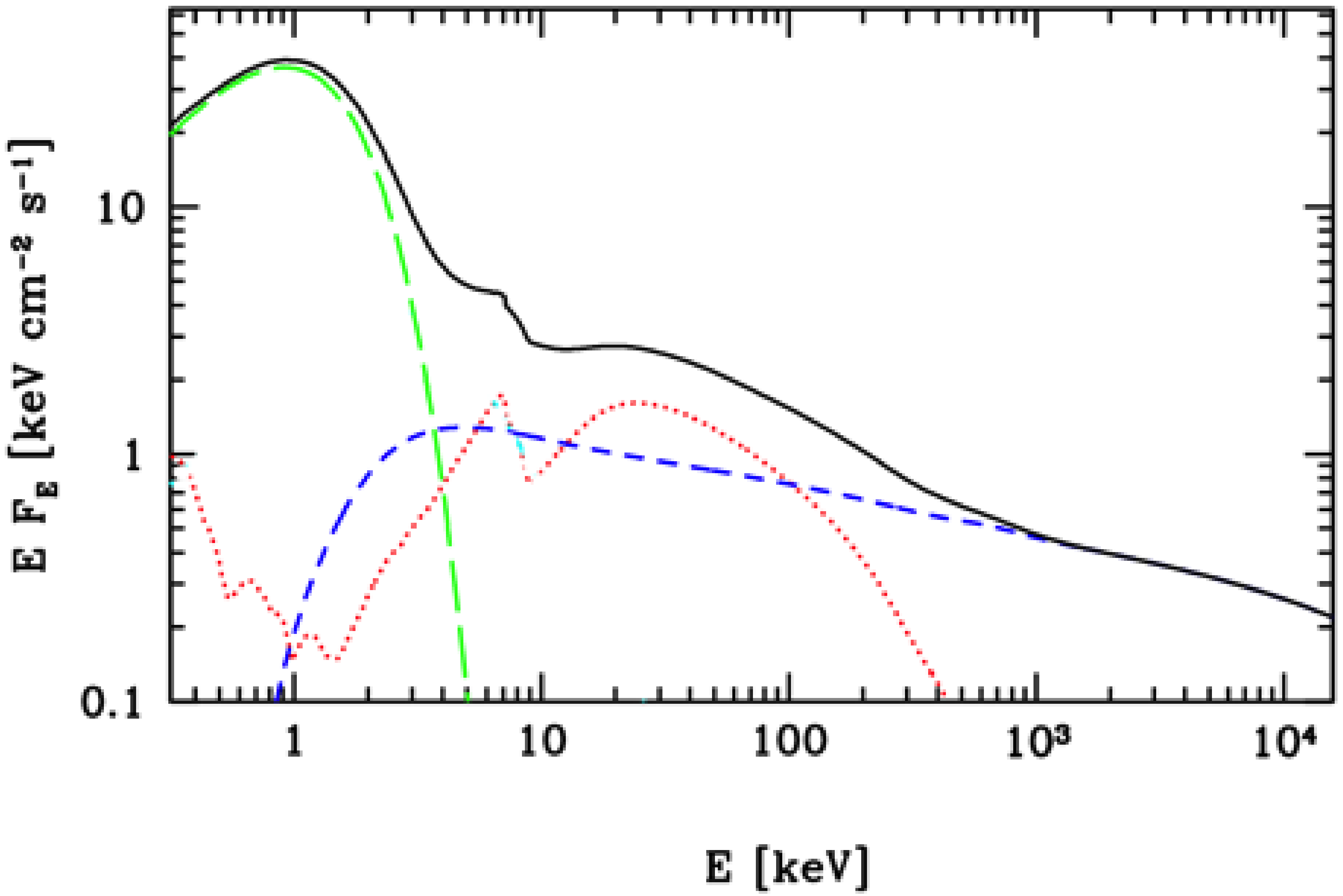
Out of the box: State transition physics with **X-ray bursts**?

The secret diaries of Tomaso…

Brief: X-ray spectral states & outburst evolution

Ⅰ. Emission components

Example X-ray spectrum

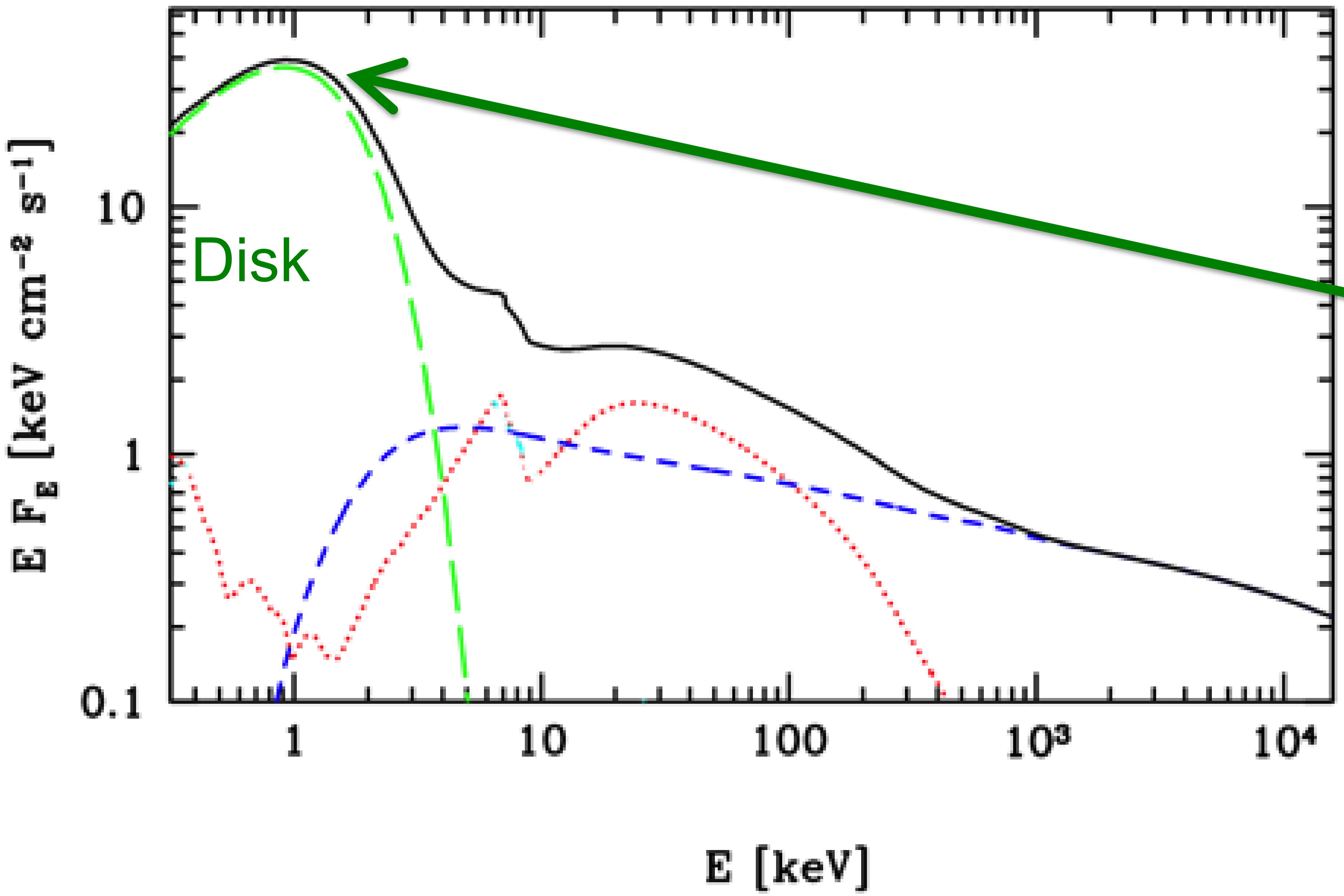


Spectra from Zdziarski & Gierlinski 2004, Cyg X-1

Brief: X-ray spectral states & outburst evolution

Ⅰ. Emission components

Geometrically thin, optically thick accretion disk

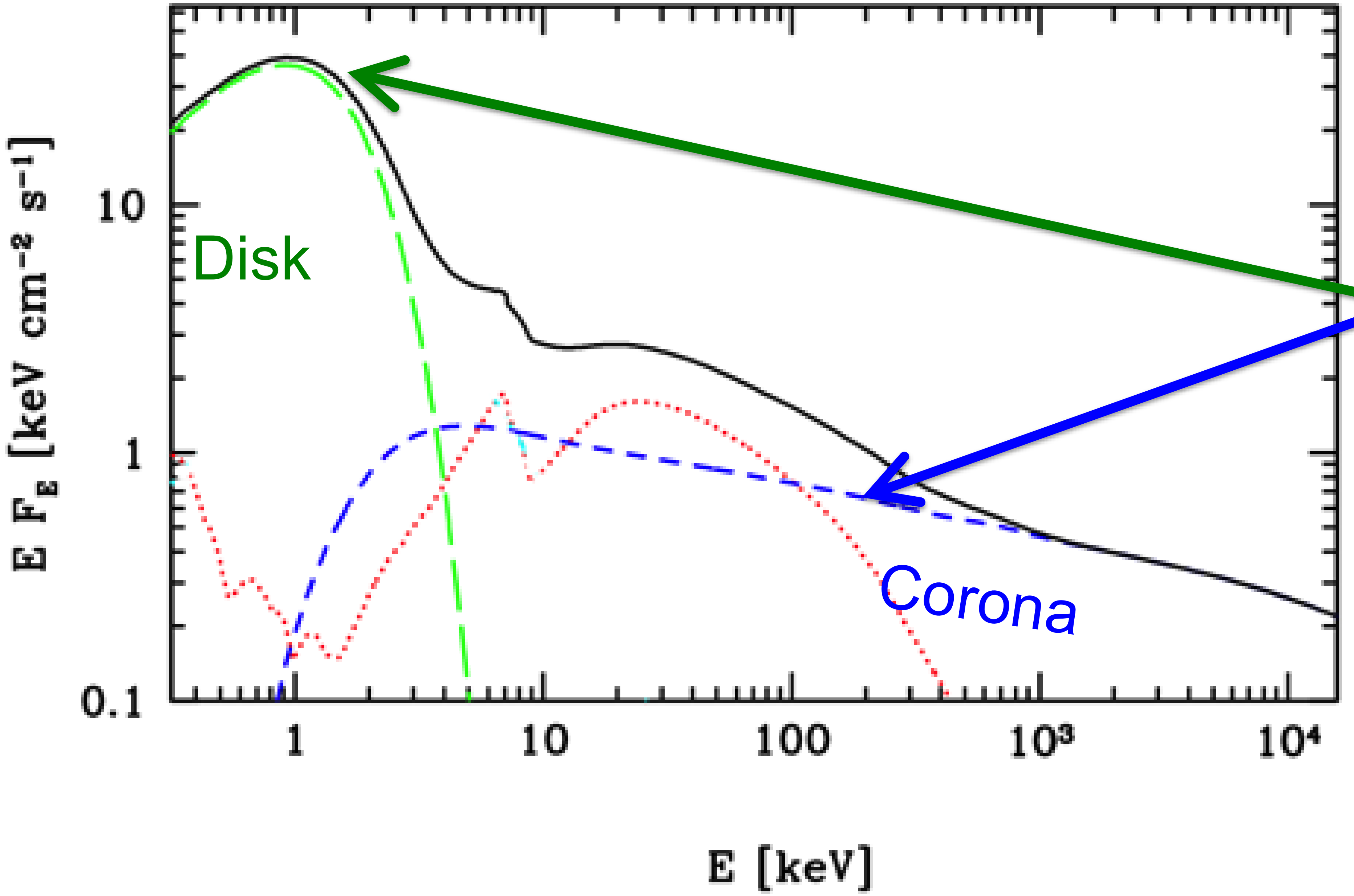


Spectra from Zdziarski & Gierlinski 2004, Cyg X-1

Brief: X-ray spectral states & outburst evolution

I . Emission components

Population of hot electrons: the corona

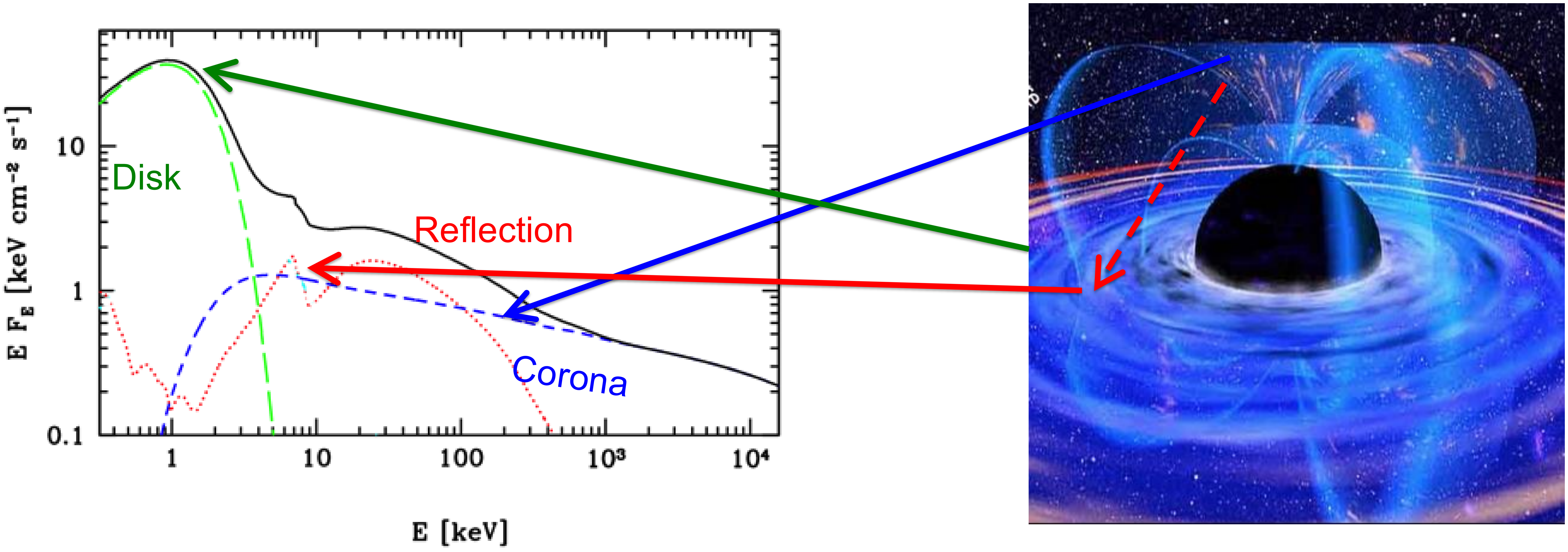


Spectra from Zdziarski & Gierlinski 2004, Cyg X-1

Brief: X-ray spectral states & outburst evolution

Ⅰ. Emission components

X-rays from corona reflecting off the accretion disk

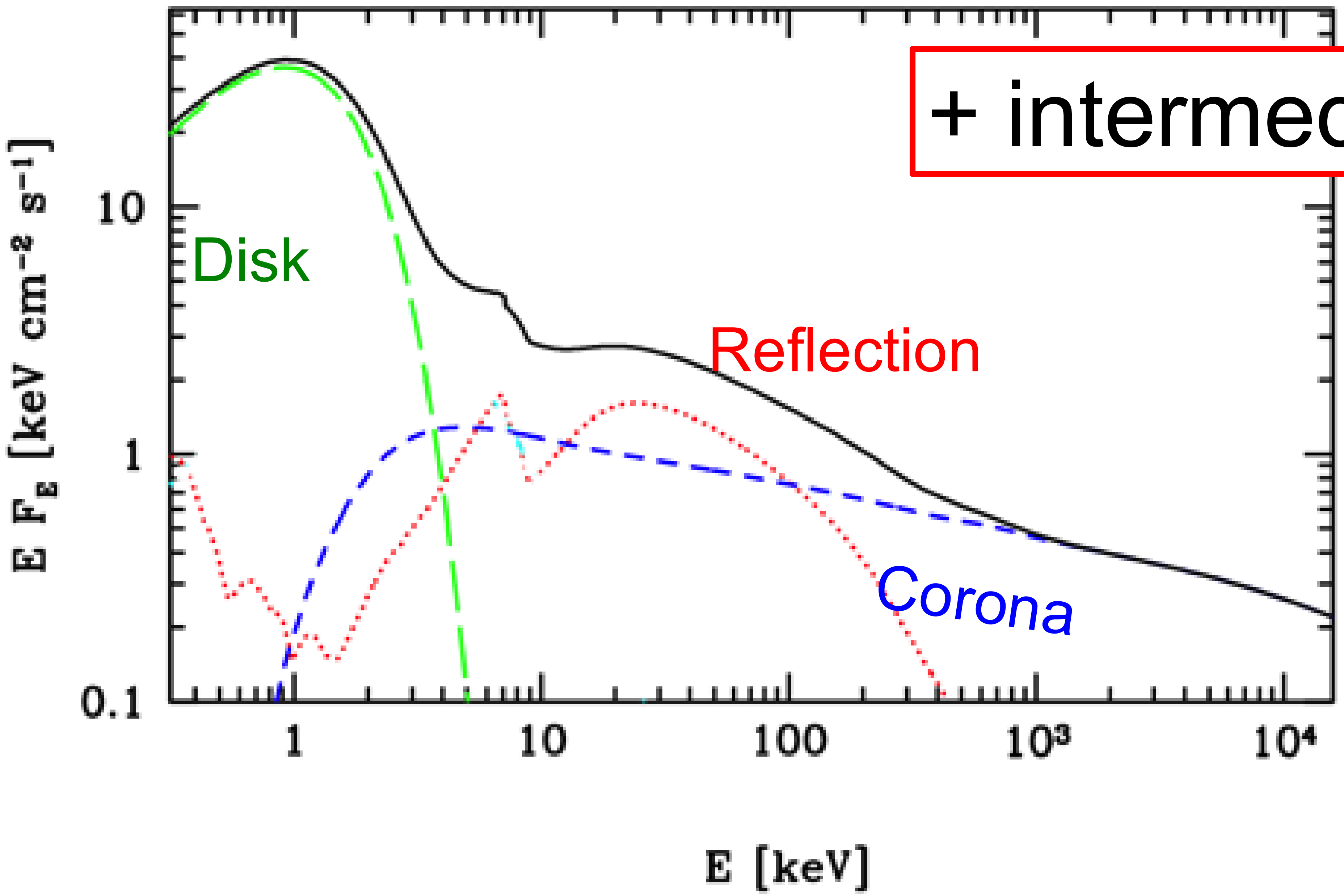


Spectra from Zdziarski & Gierlinski 2004, Cyg X-1

Brief: X-ray spectral states & outburst evolution

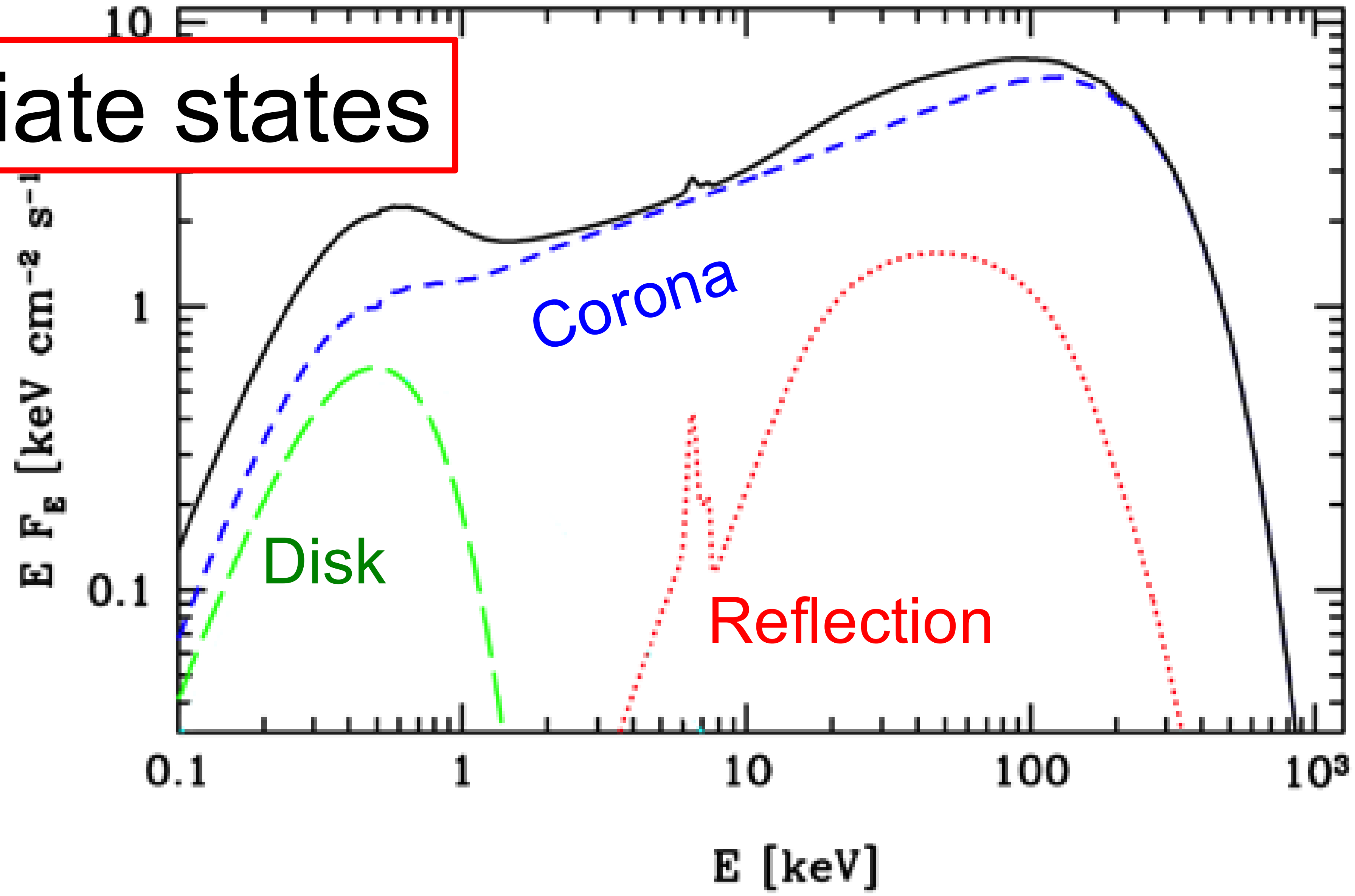
II. Emission components & X-ray spectral states

Soft state (disk dominated)



+ intermediate states

Hard state (corona dominated)

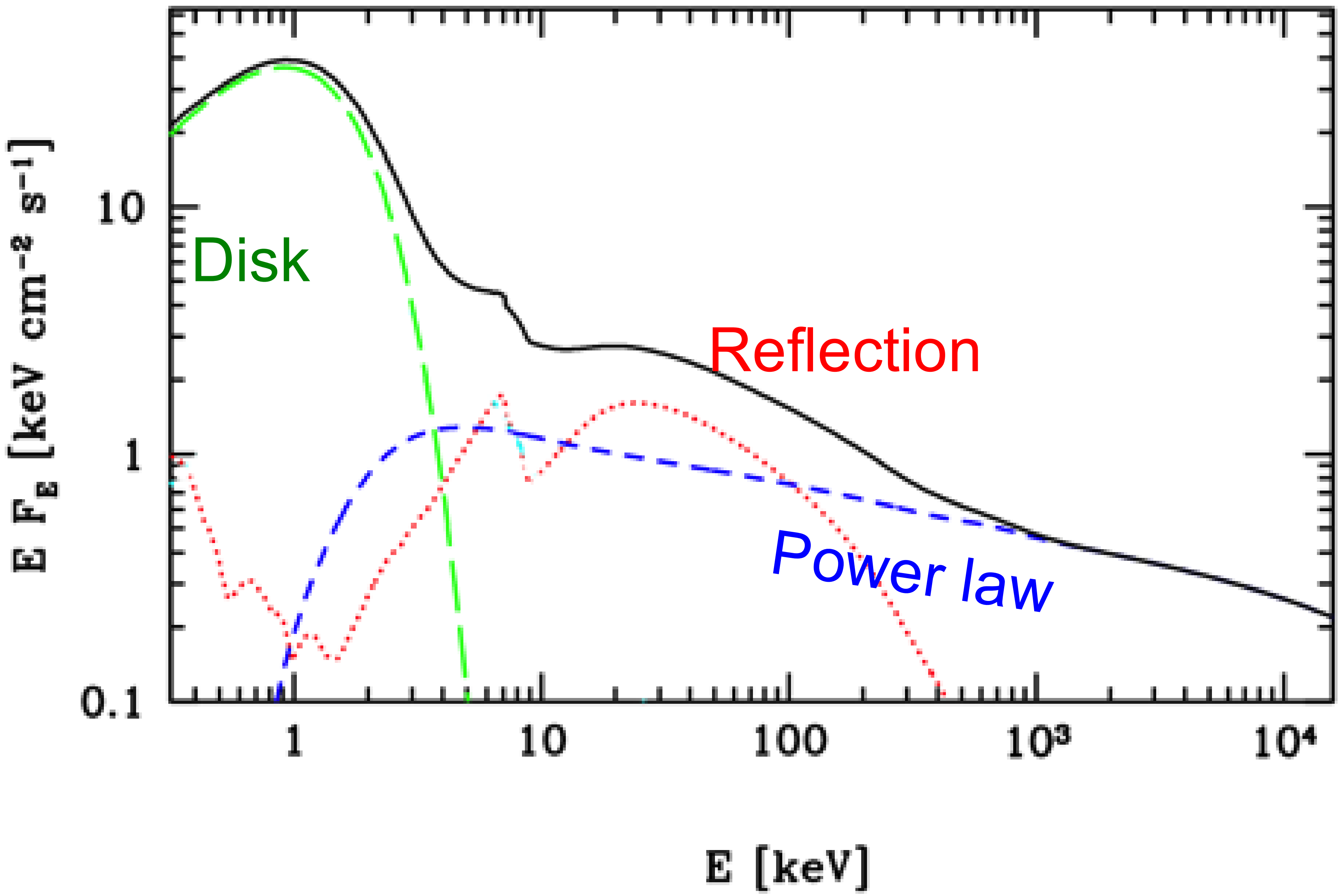


Spectra from Zdziarski & Gierlinski 2004, Cyg X-1

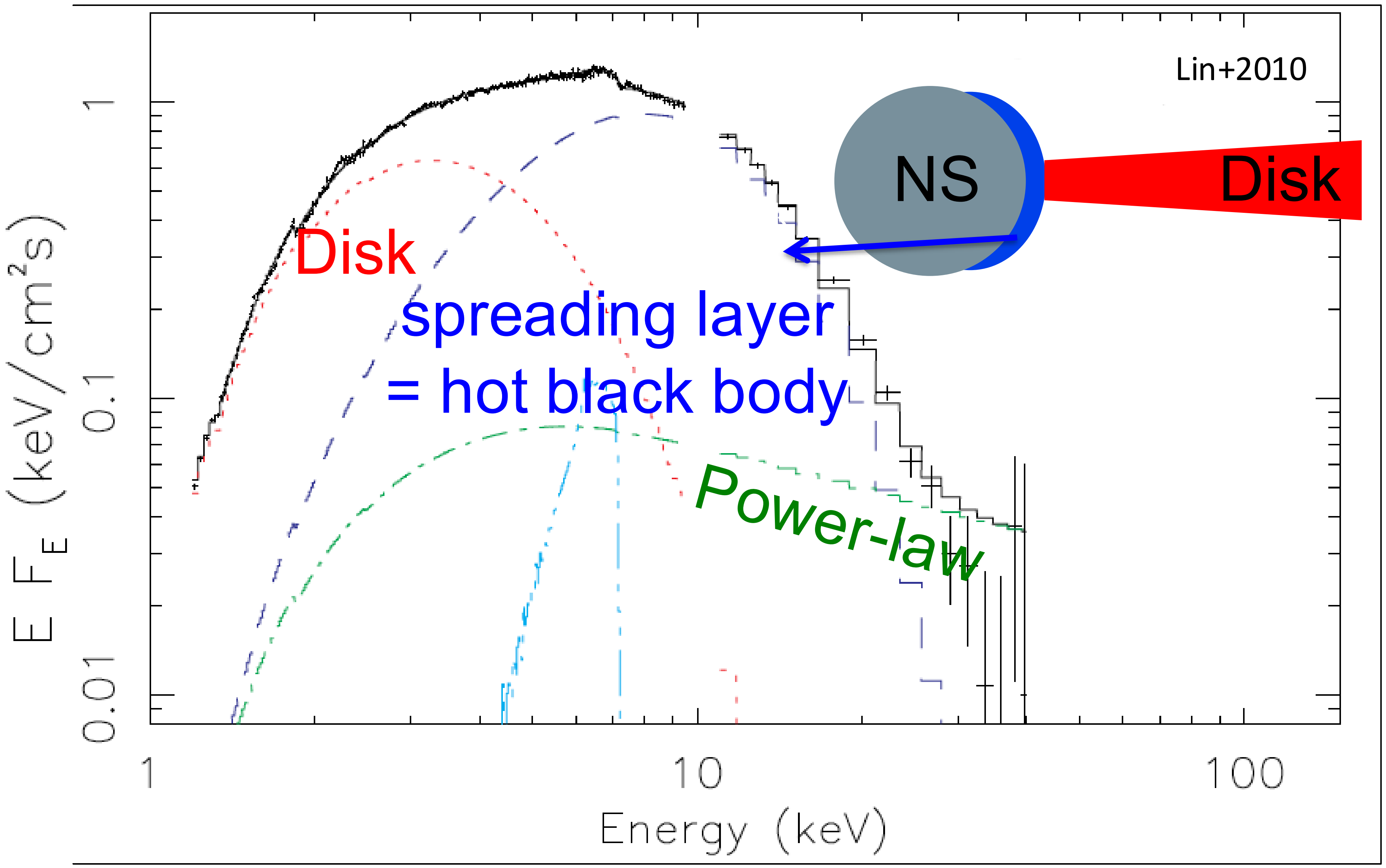
Brief: X-ray spectral states & outburst evolution

II. Emission components & X-ray spectral states

Soft state (disk dominated)



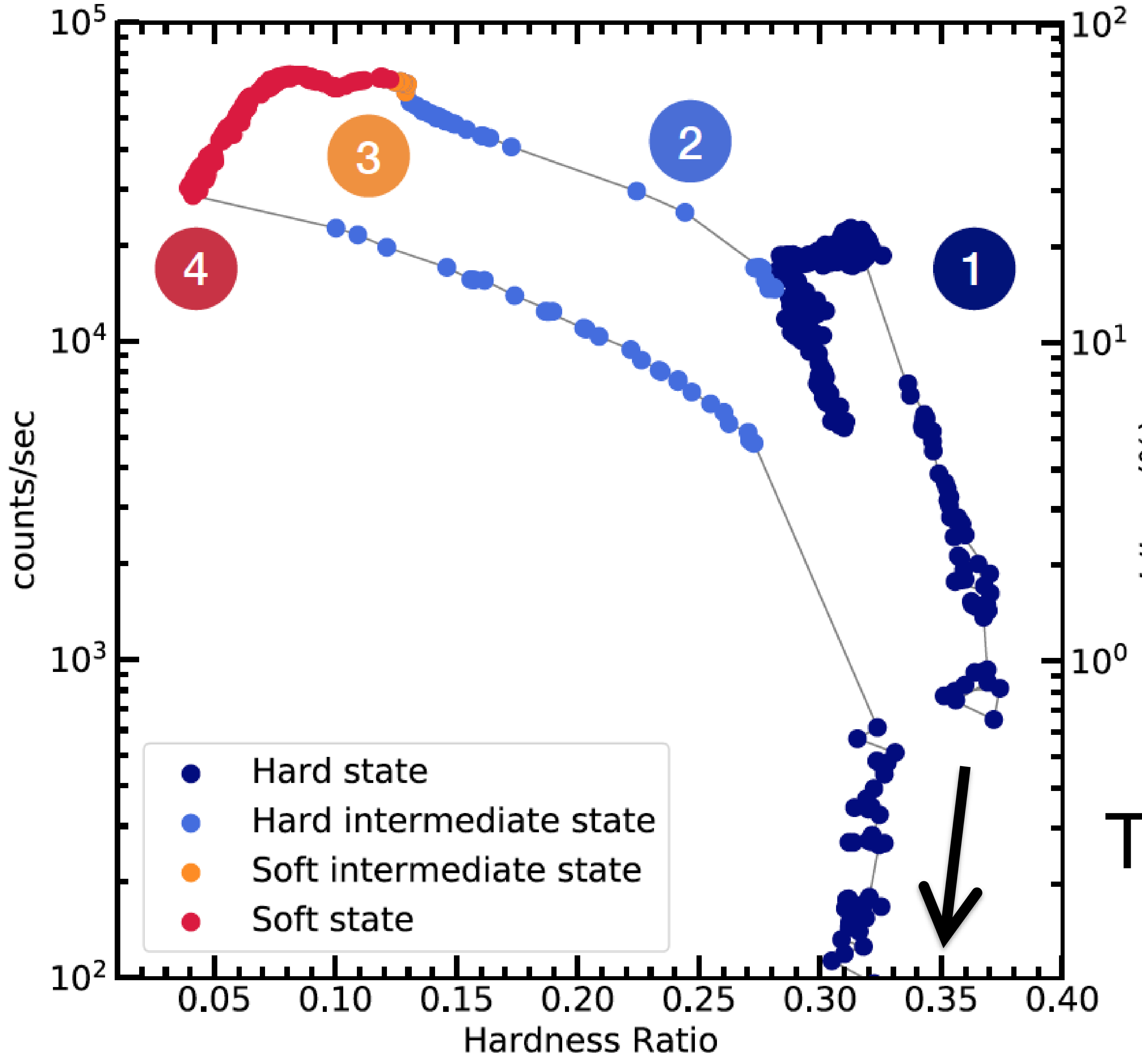
Neutron star: extra component



Spectra from Zdziarski & Gierlinski 2004, Cyg X-1; Lin+2009

Brief intro: X-ray spectral states & outburst evolution

III. Outburst evolution of states & connection with outflows



1 = hard state

4 = soft state

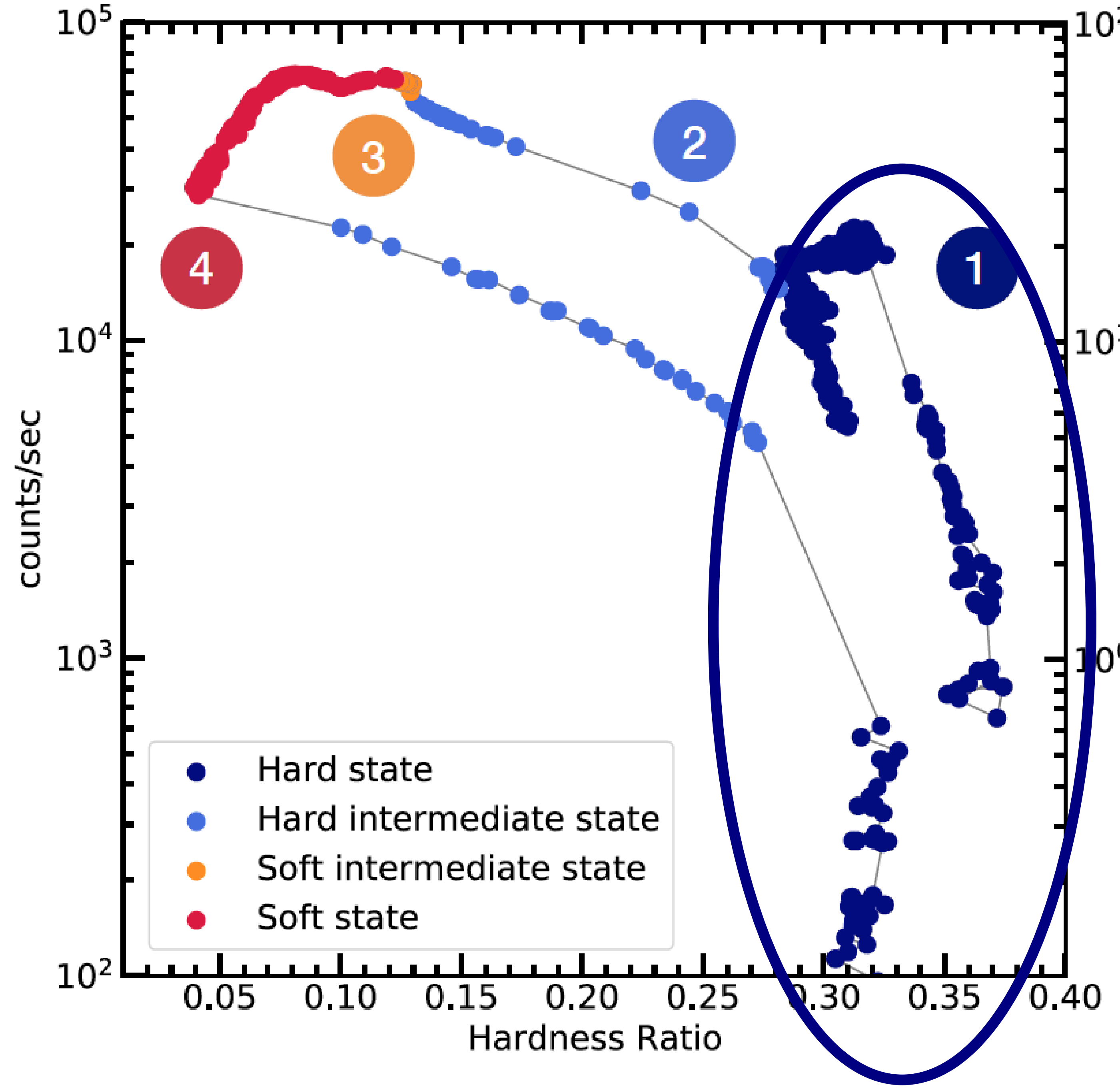
2 & 3 = intermediate states

To quiescence

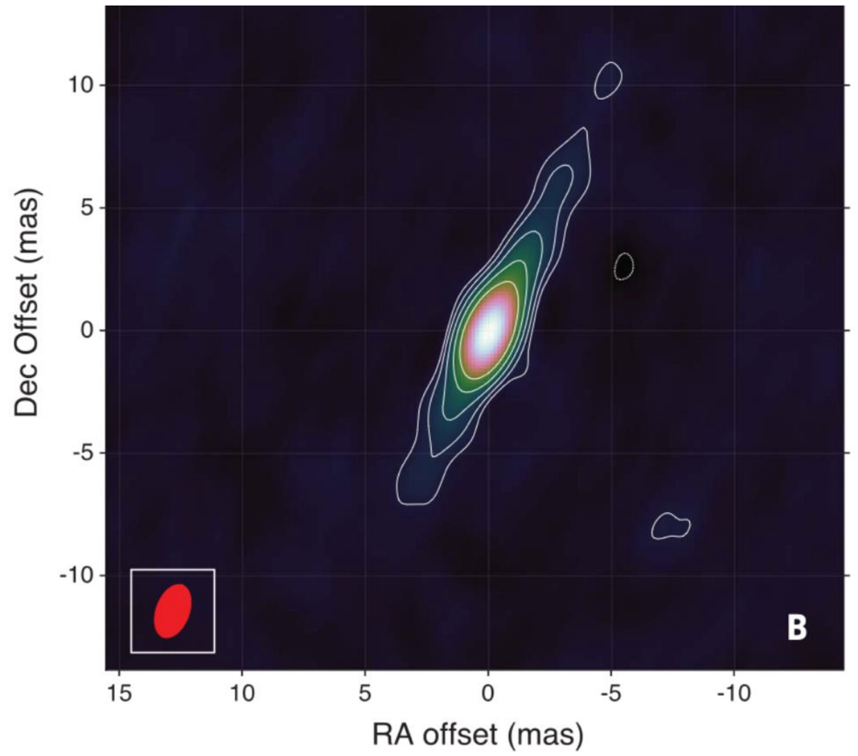
Hardness-Intensity diagram MAXI J1820+070 (NICER): Kalemci+2022, Jingyi Wang

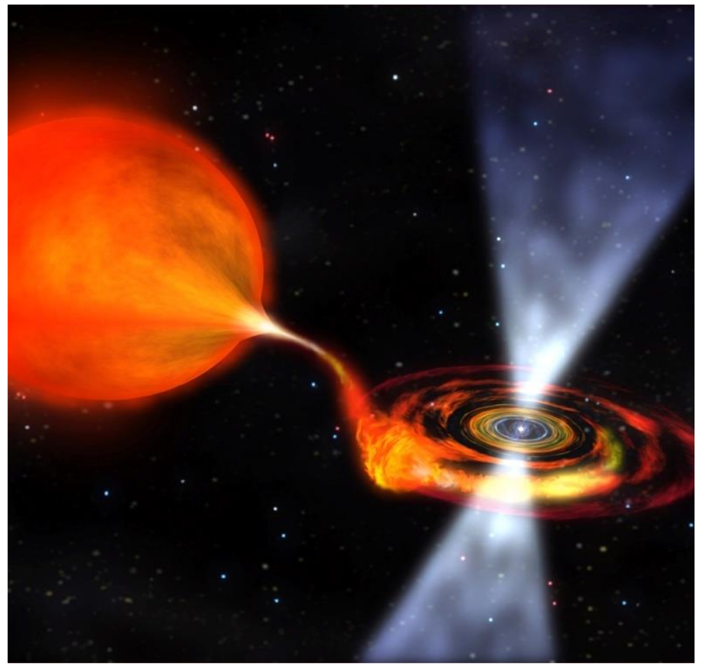
Brief intro: X-ray spectral states & outflows

III. Outburst evolution of states & connection with outflows



<u>Hard state</u>:
Steady radio jet

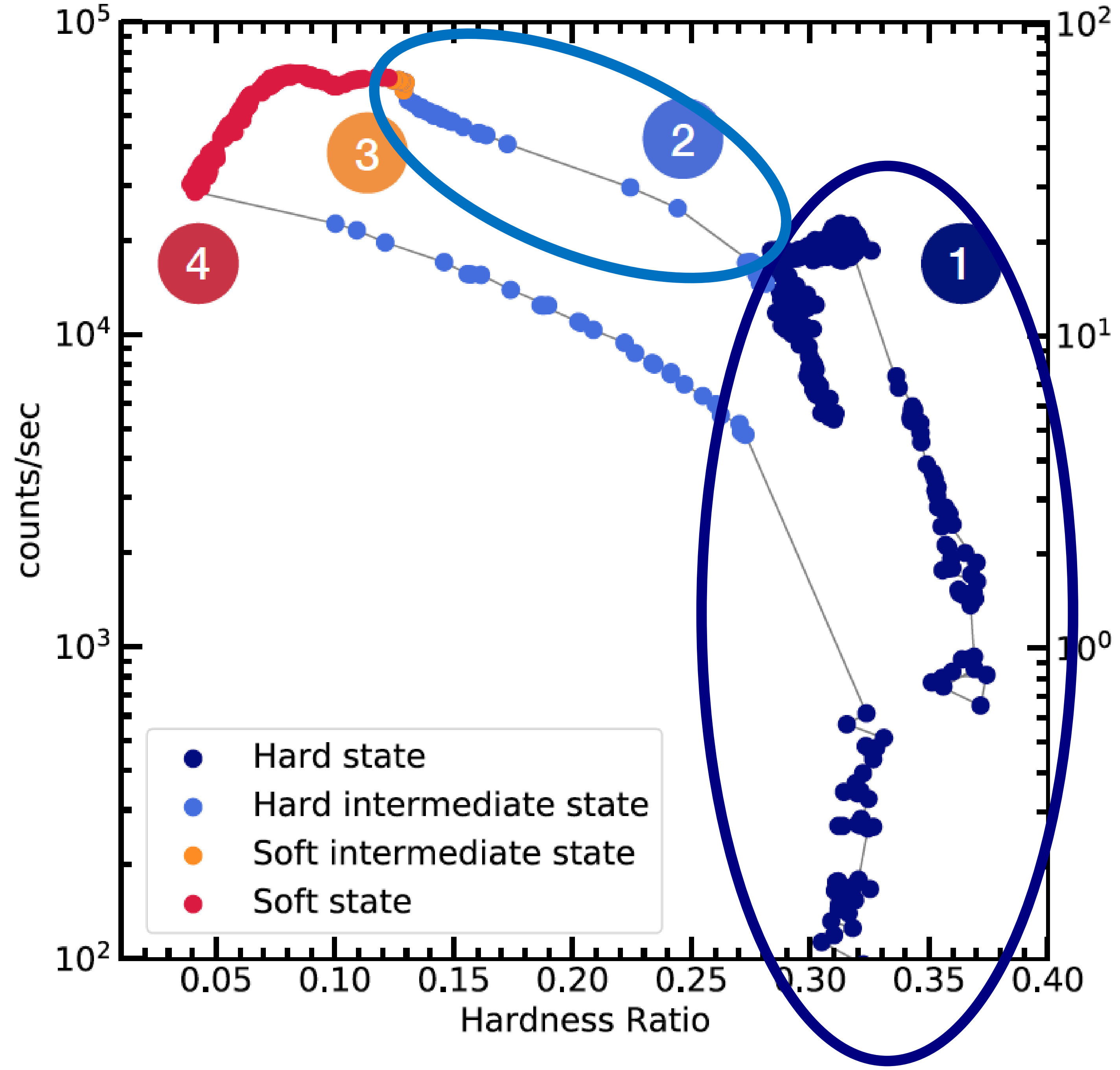




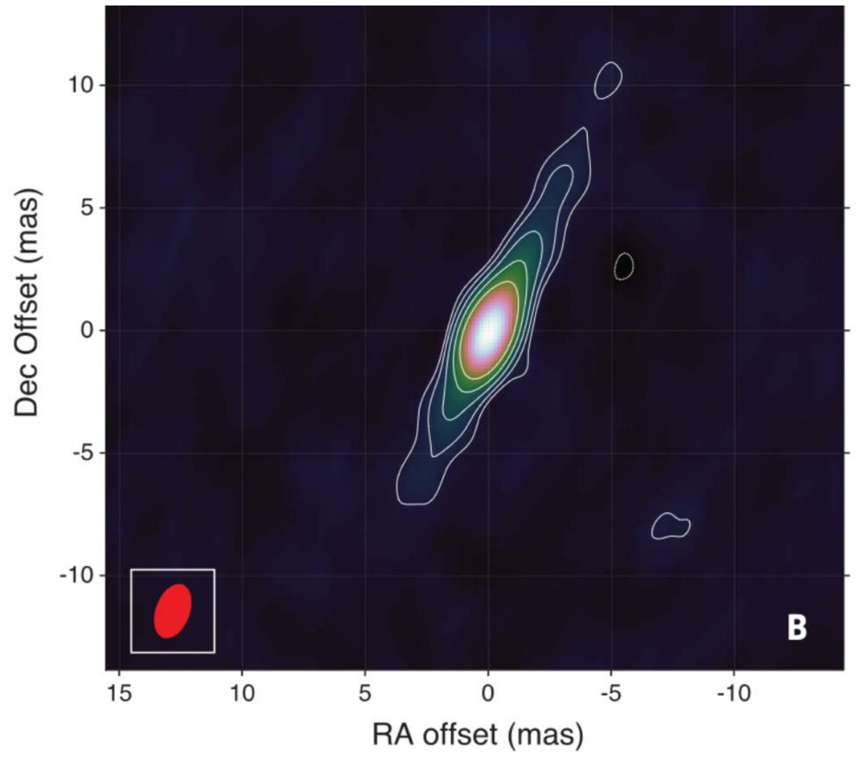
Miller-Jones 2021

Brief intro: X-ray spectral states & outflows

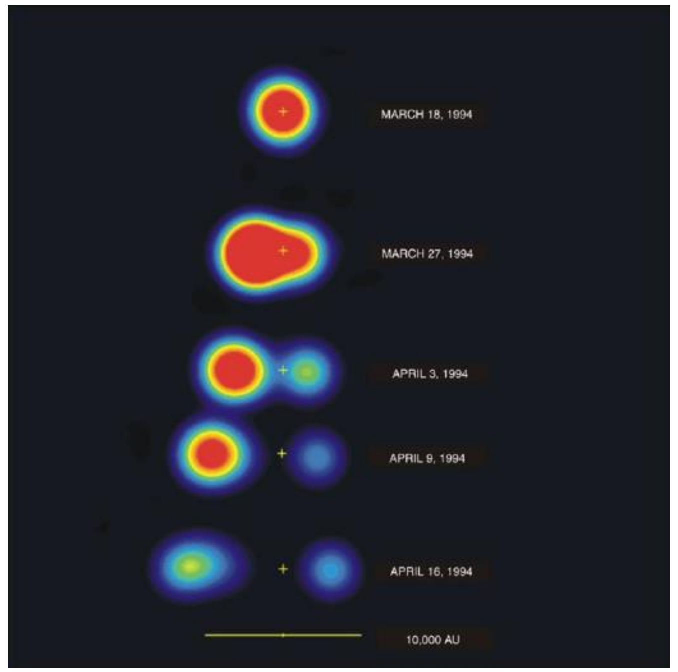
IV. Connection with outflows: Type of outflow depends on state



Hard state:
Steady radio jet



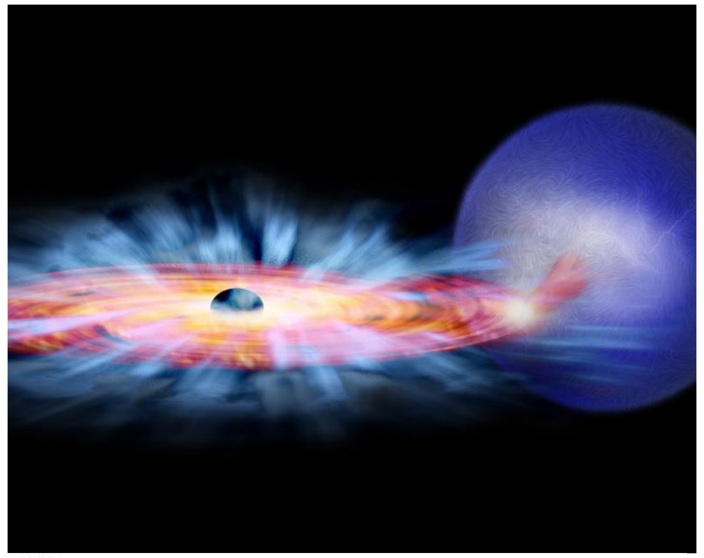
Intermediate :
Steady jet off
Jet ejection

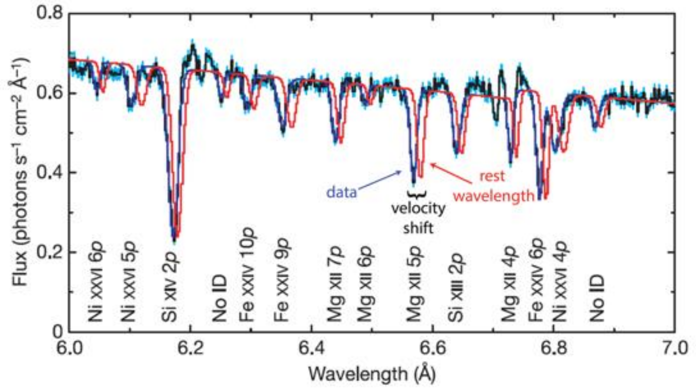


Miller-Jones 2021; Mirabel & Rodriguez 1995

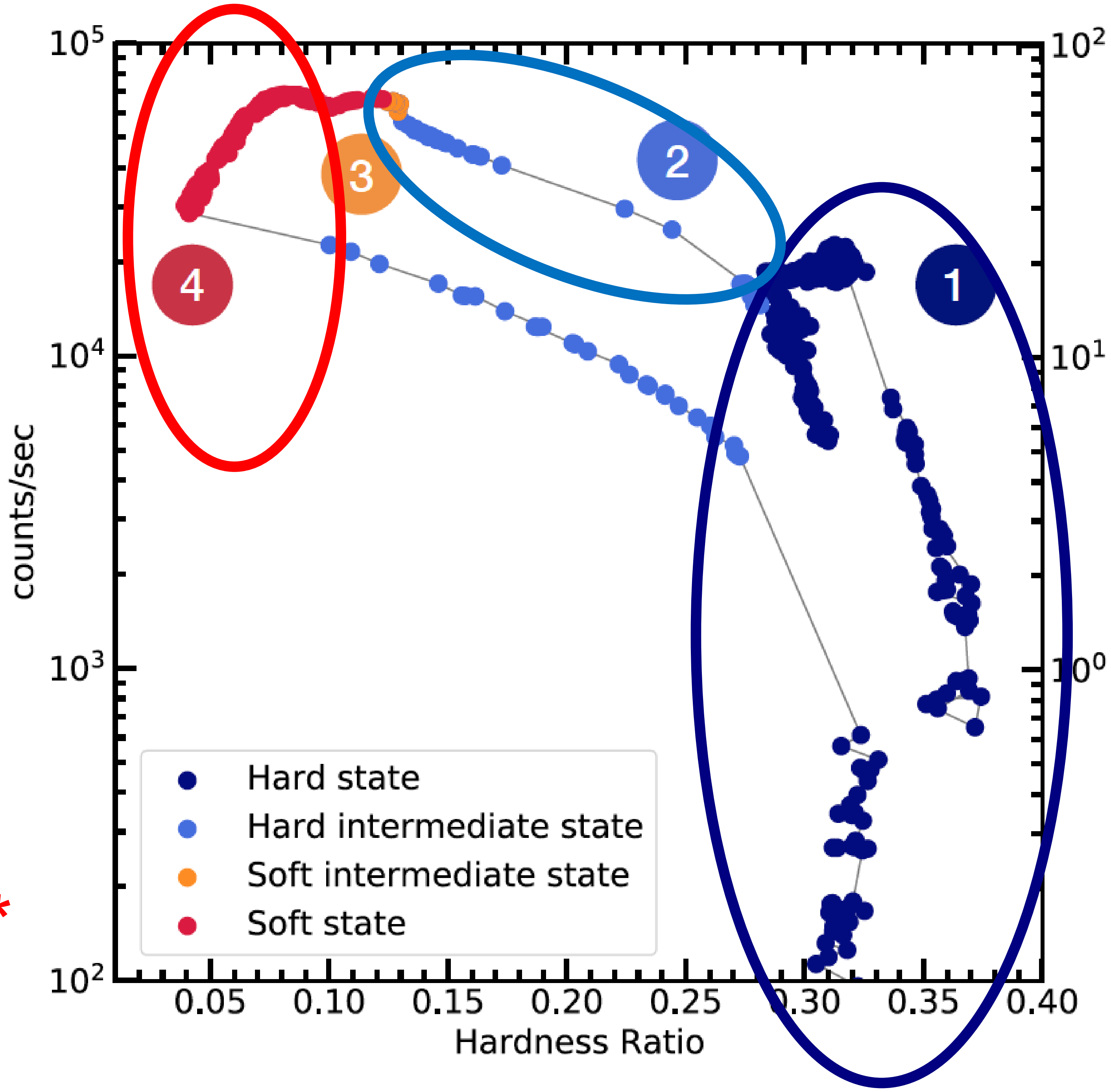
Brief intro: X-ray spectral states & outflows

IV. Connection with outflows: Type of outflow depends on state

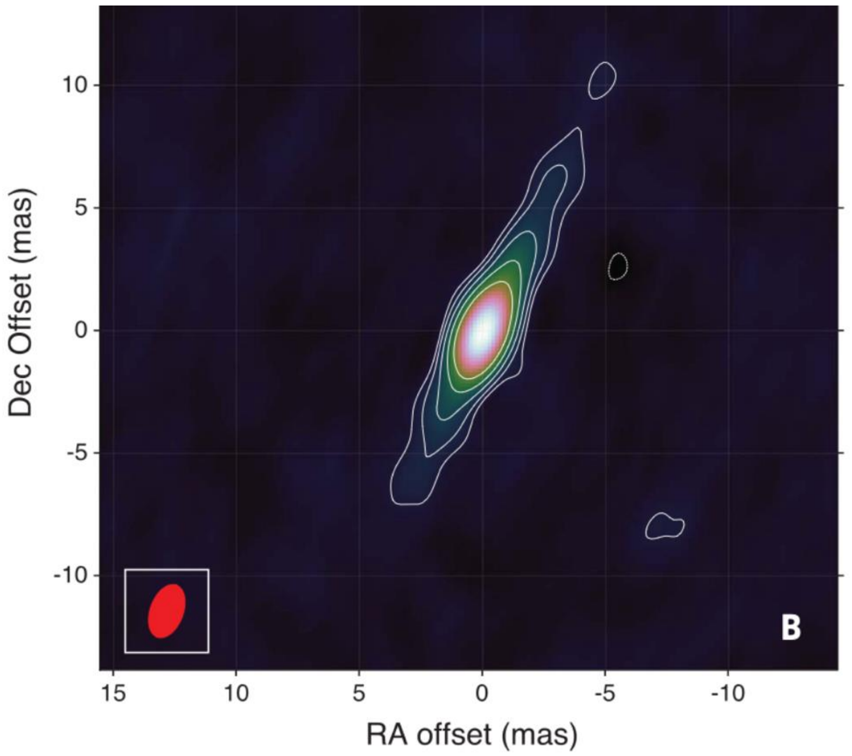




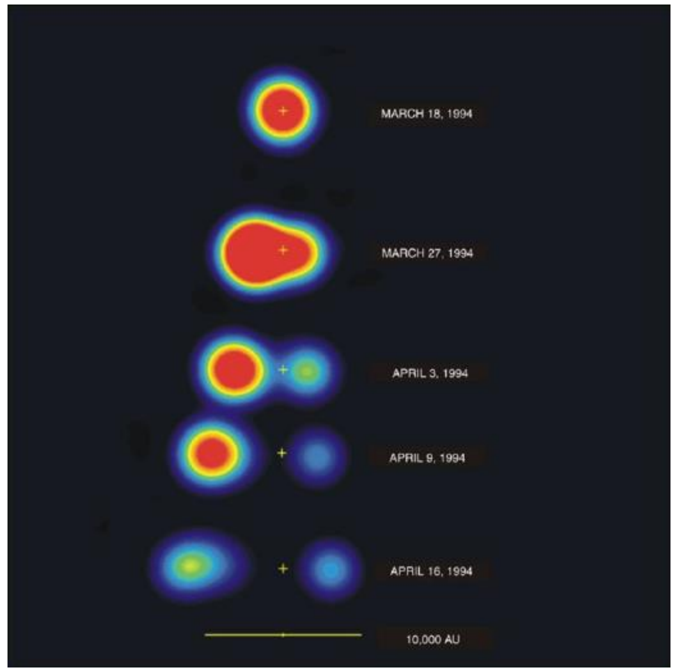
Soft state
X-ray disk wind*
(talk Done)



Hard state:
Steady radio jet



Intermediate :
Steady jet off
Jet ejection

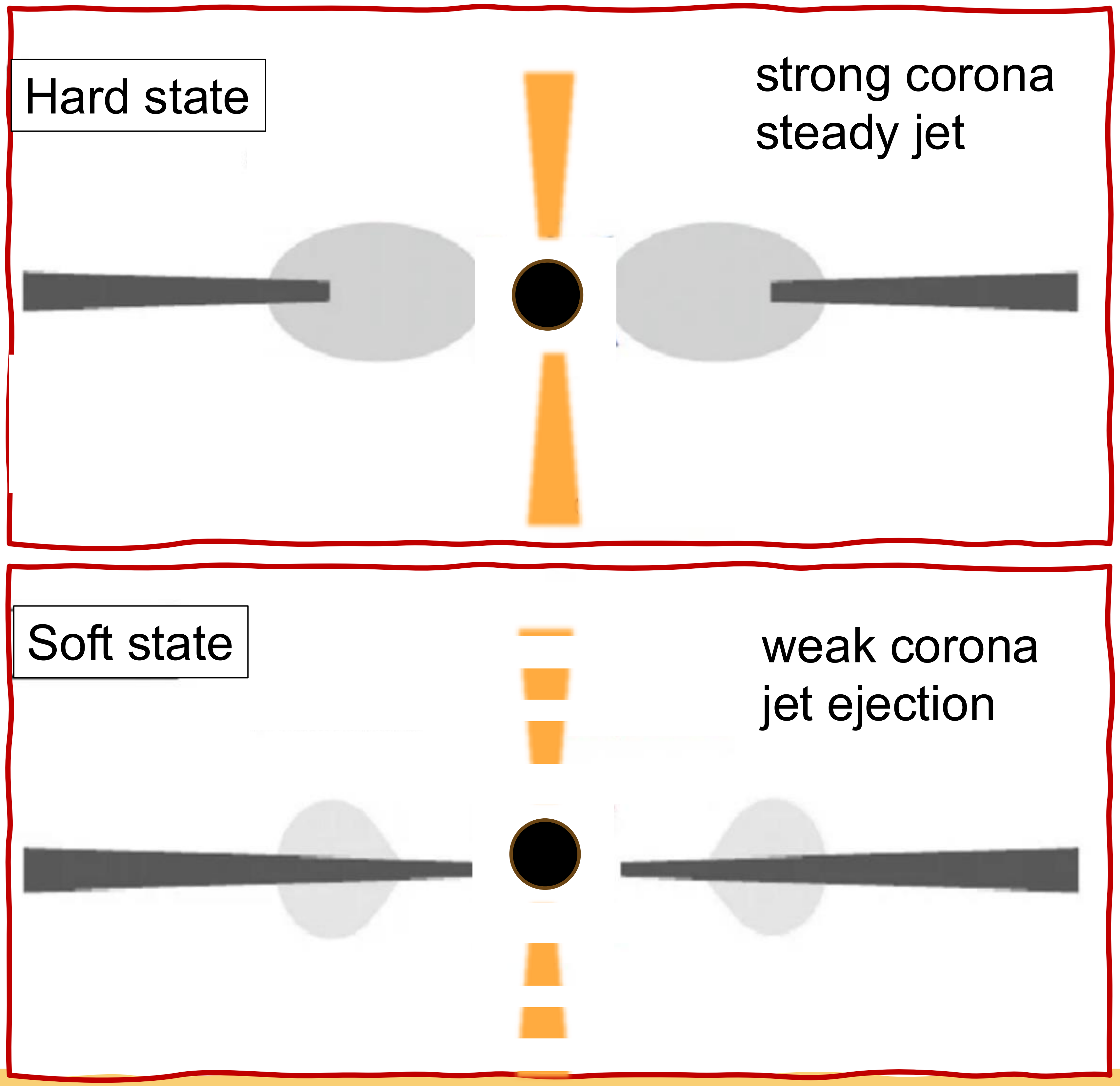


*For optical/infrared disk winds → **Munoz Darius** + other talks (**Wed**)

Standard picture behind observed evolution

- **Hard → soft state**
  - Disk hotter, moves in
  - Corona cooler, weaker
  - Jet ejected

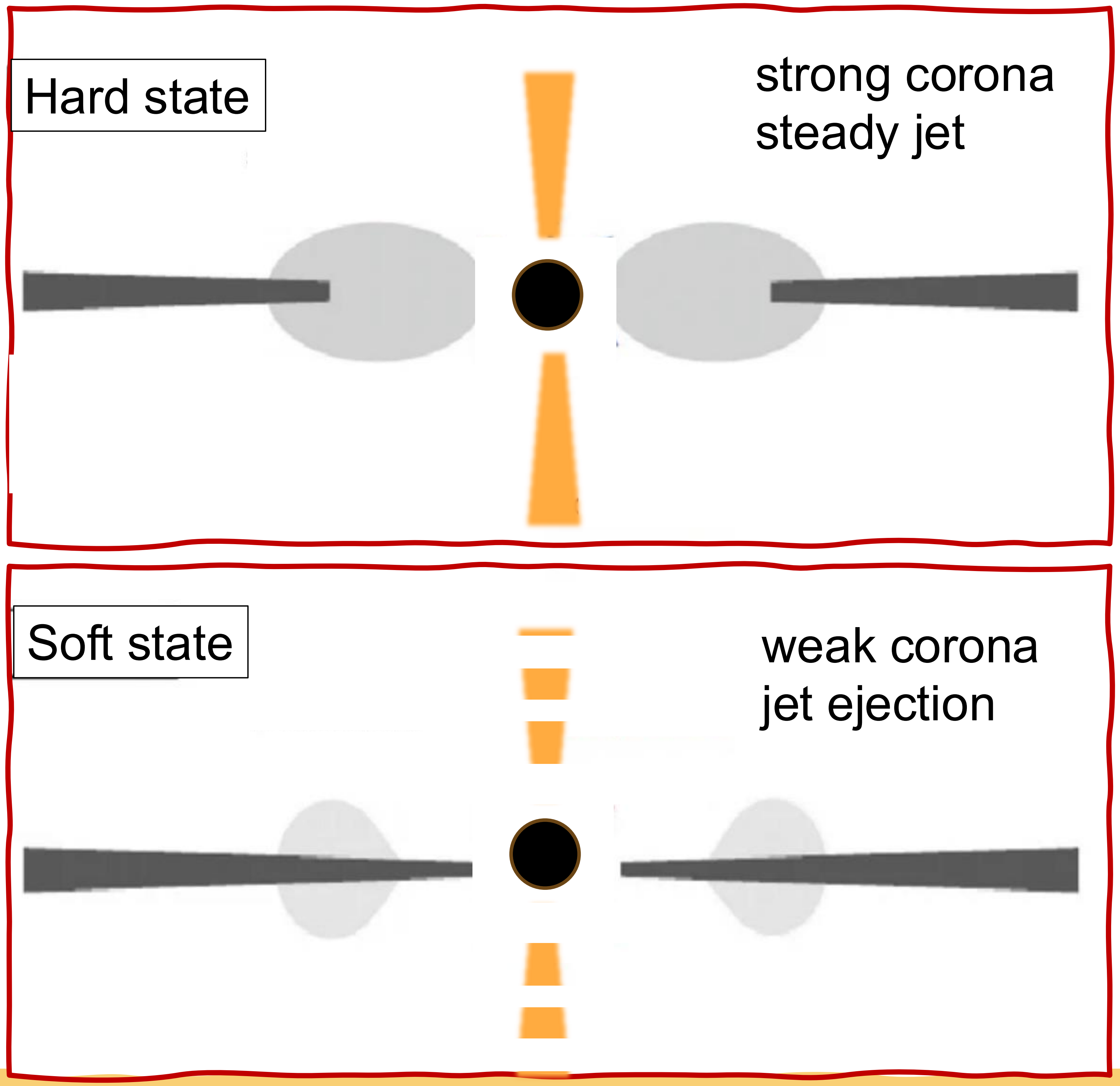
- Are all changes driven by the same process or does one follow another?



Standard picture behind observed evolution

What drives state transitions?

- Do the corona and the disk interact?
- What causes ejection of the compact jet?
- What is radiation doing?



Out of the box

Thermonuclear bursts as laboratories for state transition physics?

The secret diaries of Tomaso (2015)

Team's mission:
Using bursts on neutron stars to explore properties of accretion flows

Accretion Disks and Coronae in the X-Ray Flashlight

Nathalie Degenaar[1,2] · David R. Ballantyne[3] · Tomaso Belloni[4] · Manoneeta Chakraborty[5] · Yu-Peng Chen[6] · Long Ji[7] · Peter Kretschmar[8] · Erik Kuulkers[9] · Jian Li[10] · Thomas J. Maccarone[11] · Julien Malzac[12,13] · Shu Zhang[6] · Shuang-Nan Zhang[6]

Space Sci Rev (2018) 214:15
DOI 10.1007/s11214-017-0448-3

ISSI-Beijing Team "Disks and coronae in the X-ray flashlight" (photo by P. Kretschmar)

The secret diaries of Tomaso (2015)

What drives state transitions?

- How do the corona and disk interact?

- What causes ejection of the compact jet?

- What role plays radiation?

Can bursts provide clues?

- Brief: What are bursts

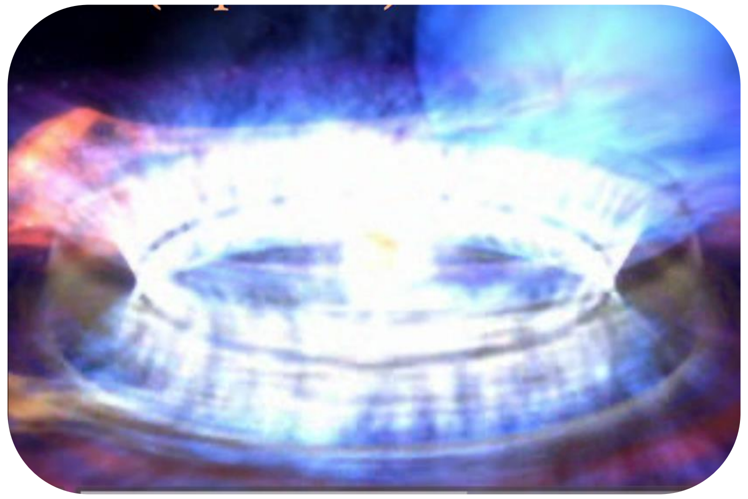
- Burst impact on disk
- Burst impact on corona

  → from observations and simulations

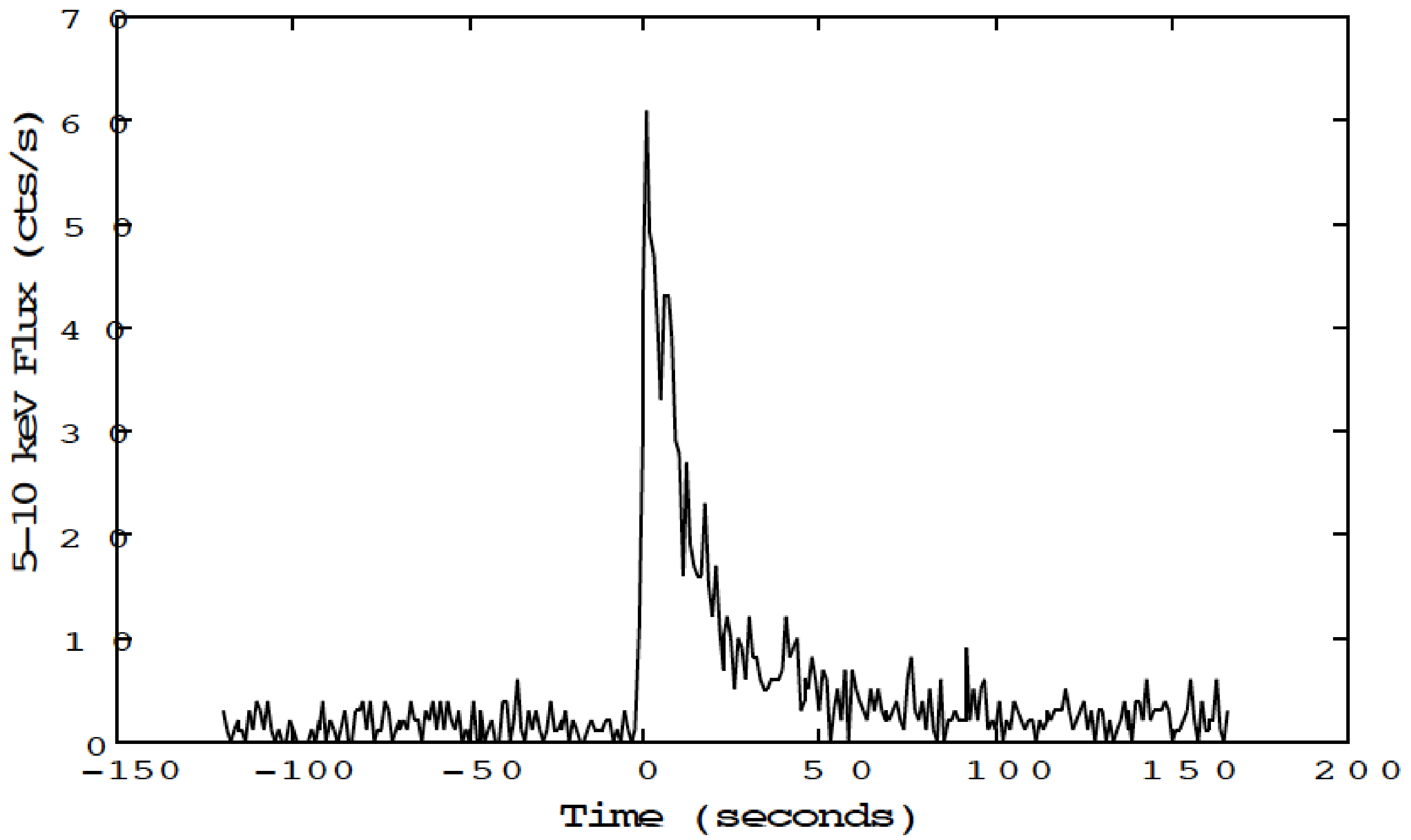
- Burst impact on jets

Why turn to thermonuclear bursts?

Thermonuclear runaway on neutron star surface
→ Explosion, burst of X-rays

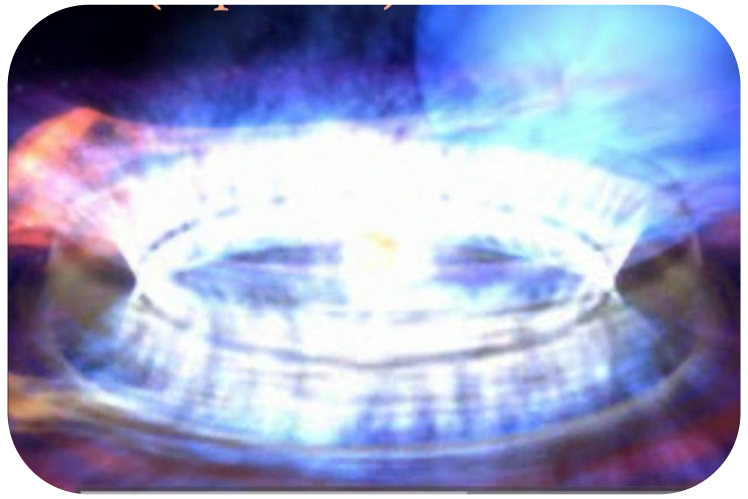


Bright:~10^{38} erg/s
Soft: black body of ~2.5 keV
Brief: ~1 min



From Boirin+2007, EXO 0748-676 (XMM-Newton)

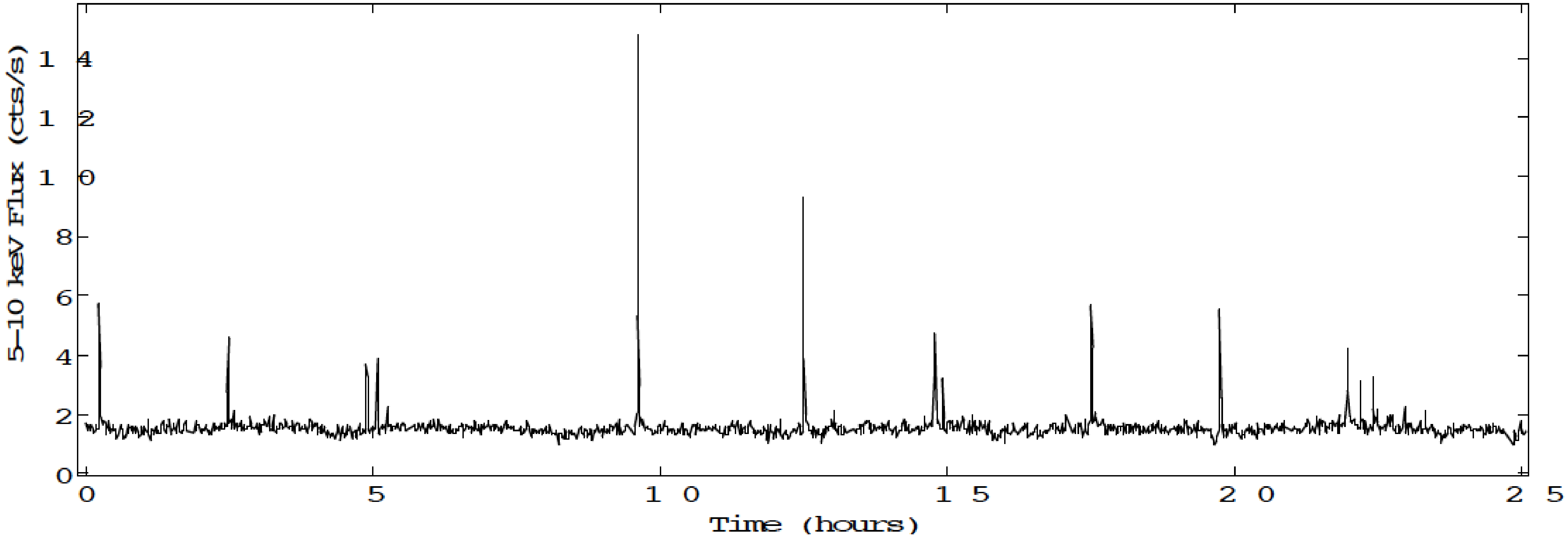
Why turn to thermonuclear bursts?



Thermonuclear runaway on neutron star surface
→ Explosion, burst of X-rays

Bright:~10^{38} erg/s
Soft: black body of ~2.5 keV **+ highly repeatable!**
Brief: ~1 min

→ probe impact of flood of radiation on accretion flow

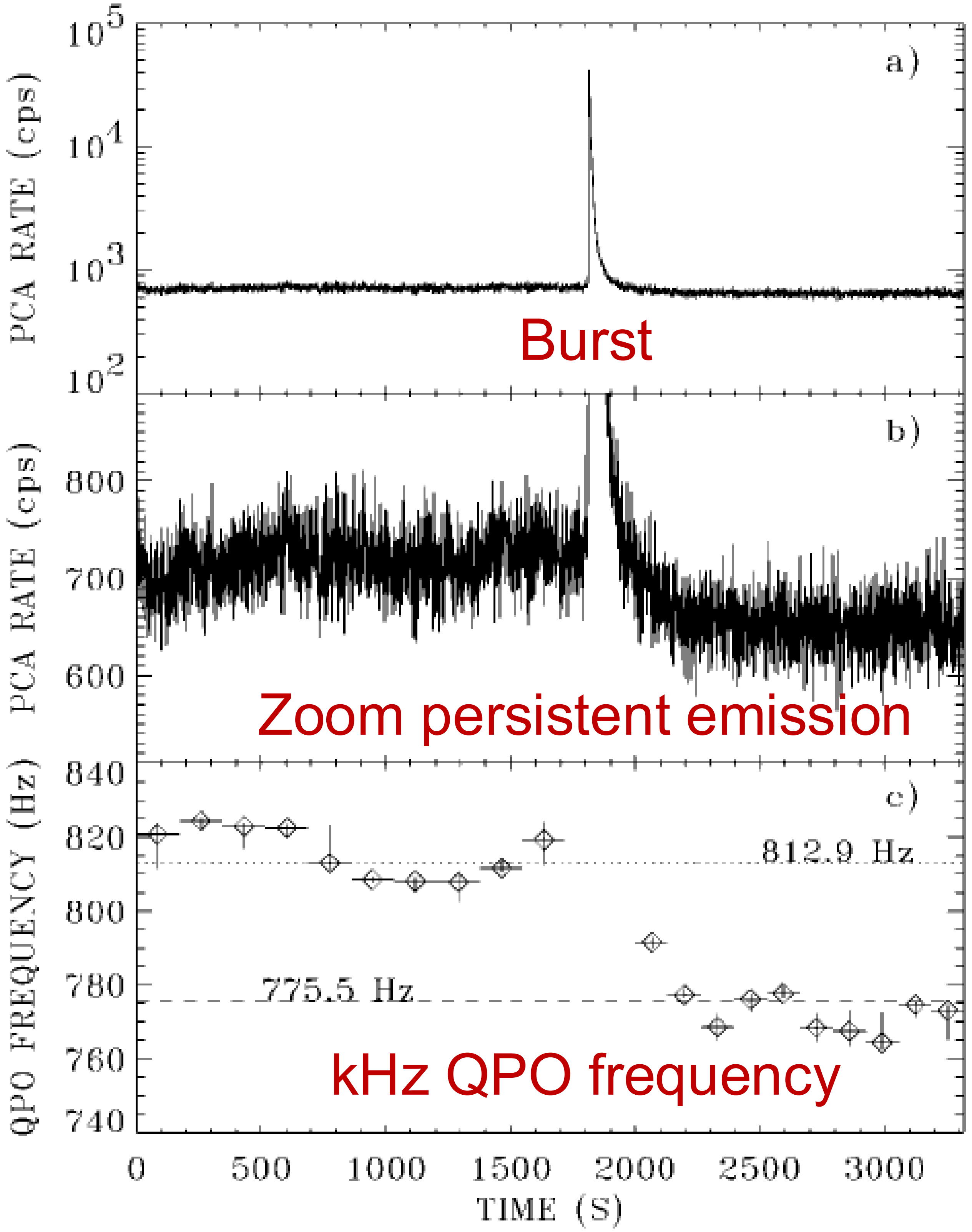


From Boirin+2007, EXO 0748-676 (XMM-Newton)

Impact of bursts on the disk: QPOs

1. Clues from QPOs

Example 1: Drop in QPO frequency
and persistent accretion emission:
→ inner disk pushed out / blown away?



Yu+1999 (Aql X-1)

Impact of bursts on the disk: QPOs

1. Clues from QPOs

Example 2: kHZ QPO disappears after a burst →
talk on Tue morning

10:00 – 10:15 AM (15m)

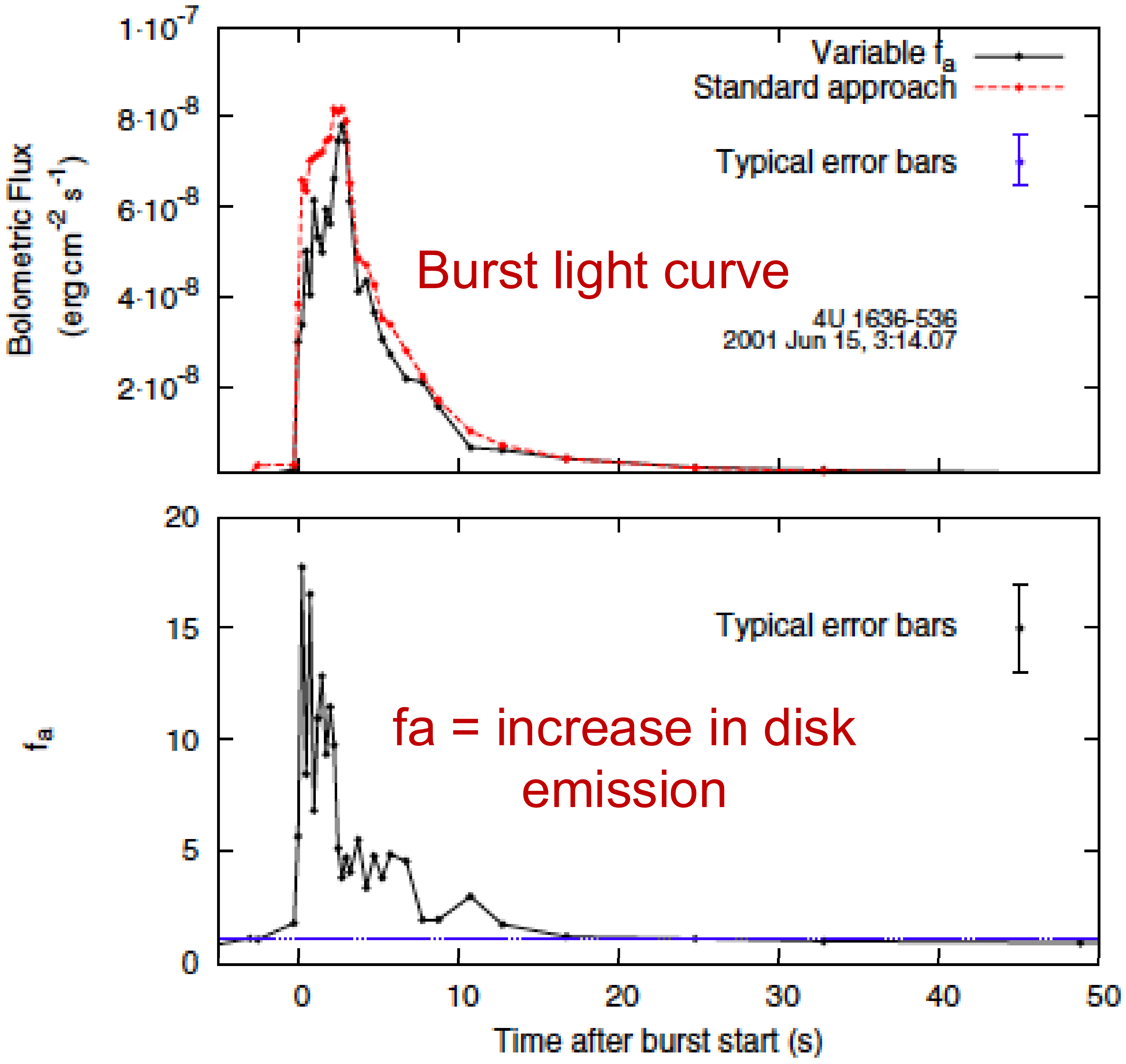
QPOs to track the Disk Restoration signatures after Type-I X-Ray Bursts from 4U 1636−536

Speaker
Suchismito Chattopadhyay

Impact of bursts on the disk: Spectra

2. Clues from spectral modeling

Disk emission increases by factor ~2-20 during a burst
→ disk heated up or accretion rate enhanced?



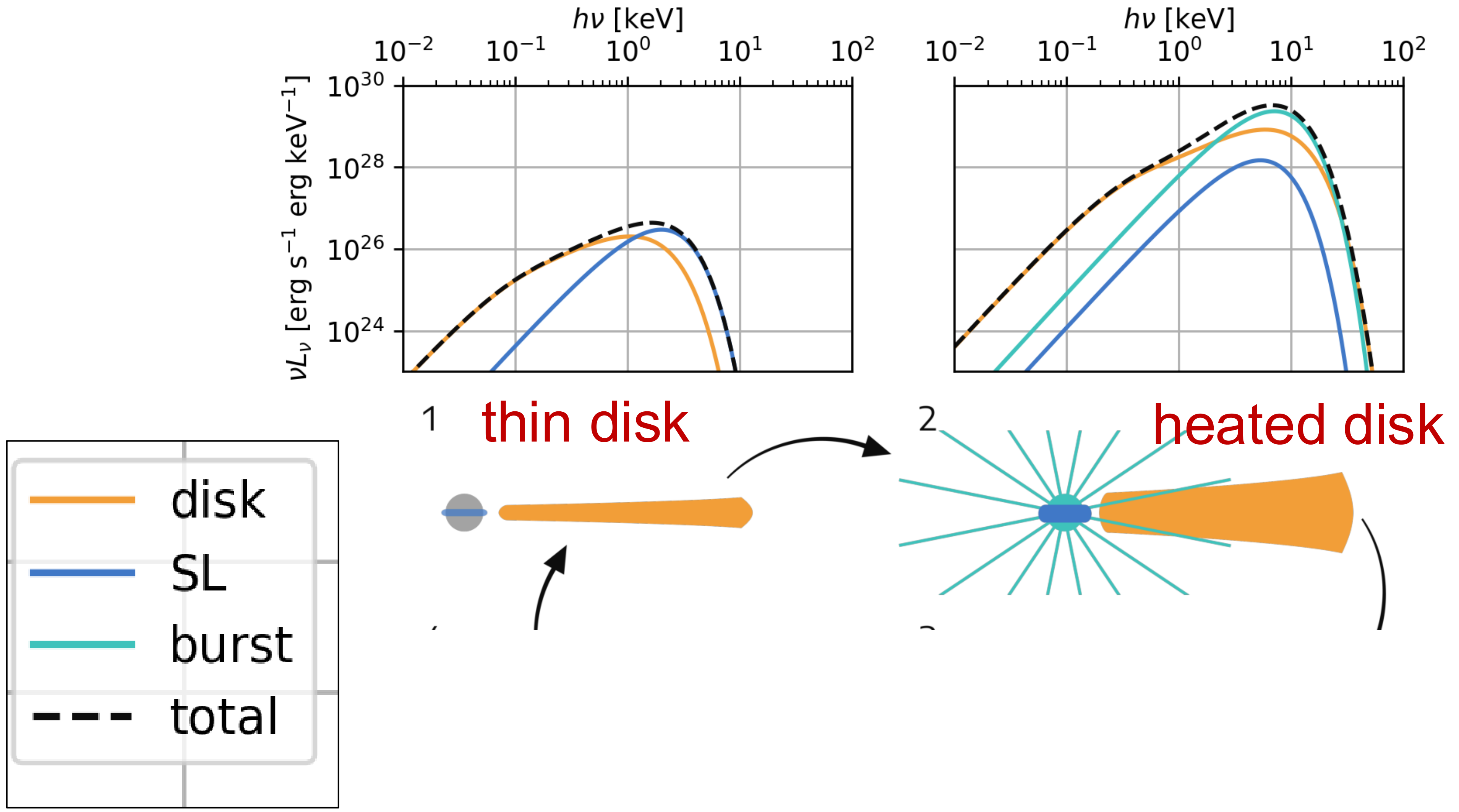
Worpel+2013 (sample study)

Impact of bursts on the disk: Analytical work

3. Answers from simulations

Analytical calculations thin disk

- Disk heats up / puffs up → disk emission increases **explains spectral results**



van de Vosse: poster + Tue flash talk

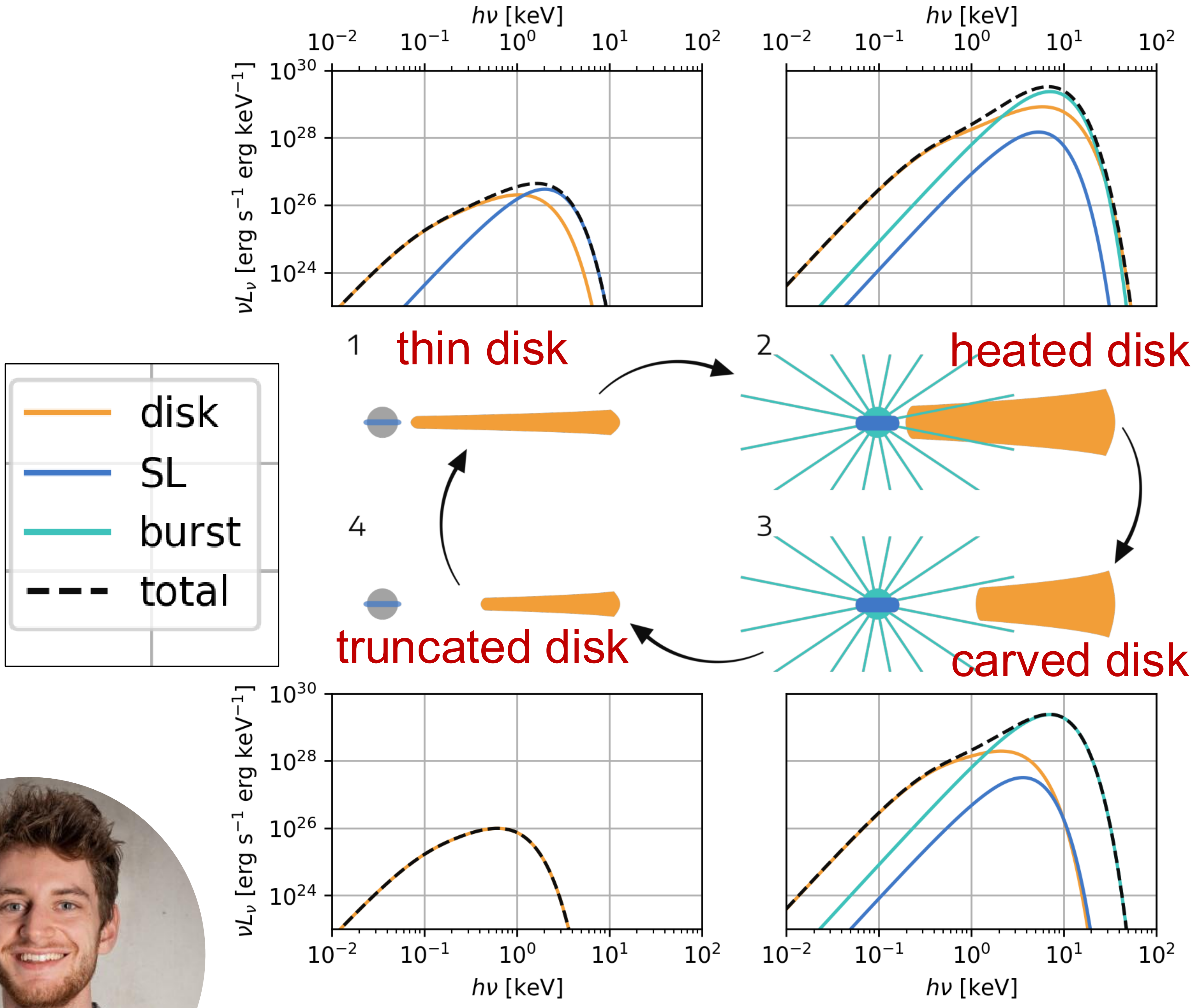
Impact of bursts on the disk: Analytical work

3. Answers from simulations

Analytical calculations thin disk

- Disk heats up / puffs up → disk emission increases **explains spectral results**

- Inner disk is carved out → **explains QPO results**



van de Vosse: poster + Tue flash talk

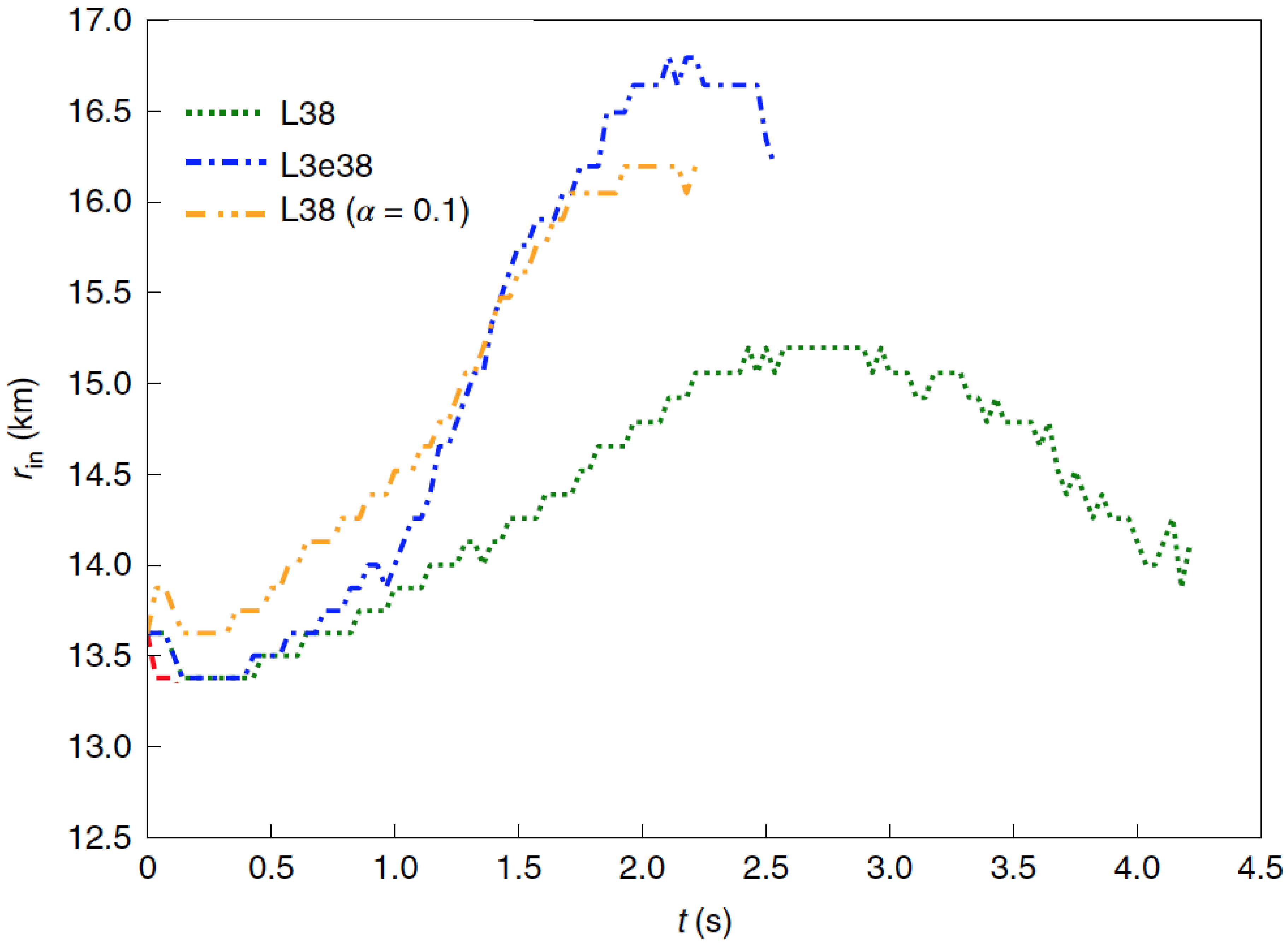
Impact of bursts on the disk: Numerical work

3. Answers from simulations

GR-RHD simulations thin disk

Same trends:

- disk heats up
- inner disk carved out
- mass-accretion enhanced



Change in inner radius depends on disk viscosity α

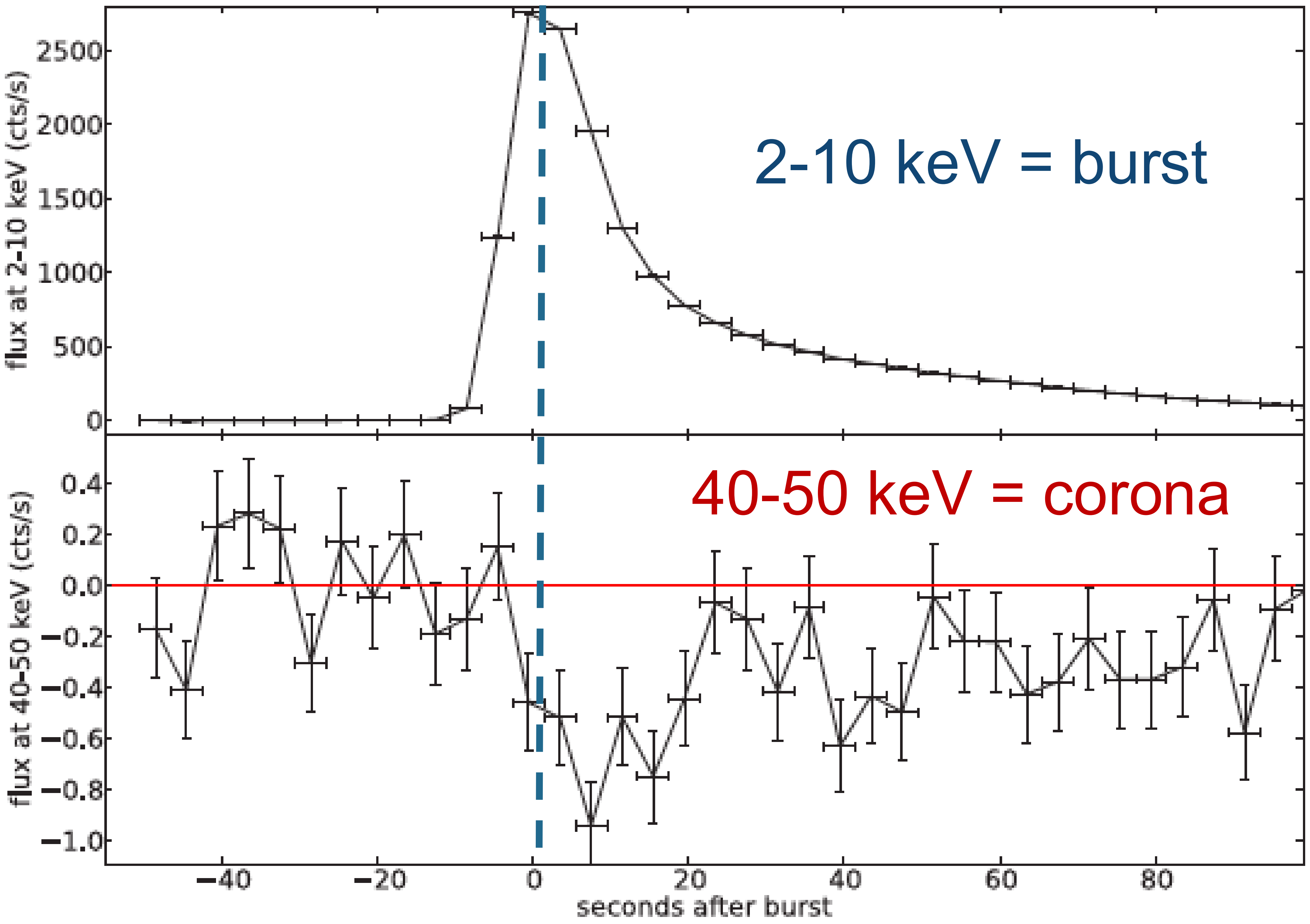
Fragile+2020 (GR-RHD); also Speicher+2024

Impact of bursts on the corona: Light curves

1. Clues from light curves

Hard X-ray emission of the corona drops during bursts

→ Compton cooling by injection of soft photons?



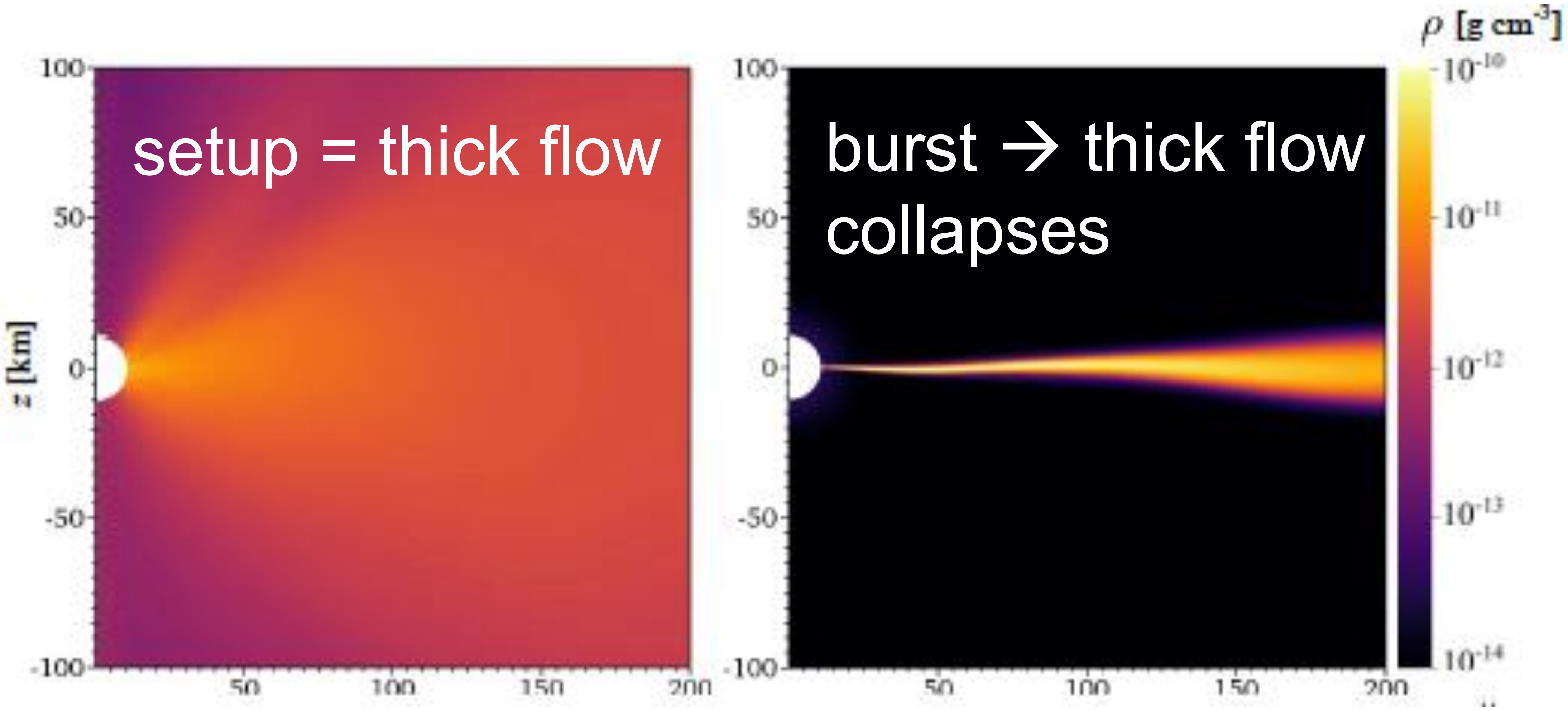
From Chen+2013, Aql X-1 (RXTE, stacked bursts)

Impact of bursts on the corona: Numerical work

2. Answers from simulations

GR-RHD simulations:

- Thick accretion flow collapses
- Mass-accretion rate enhanced

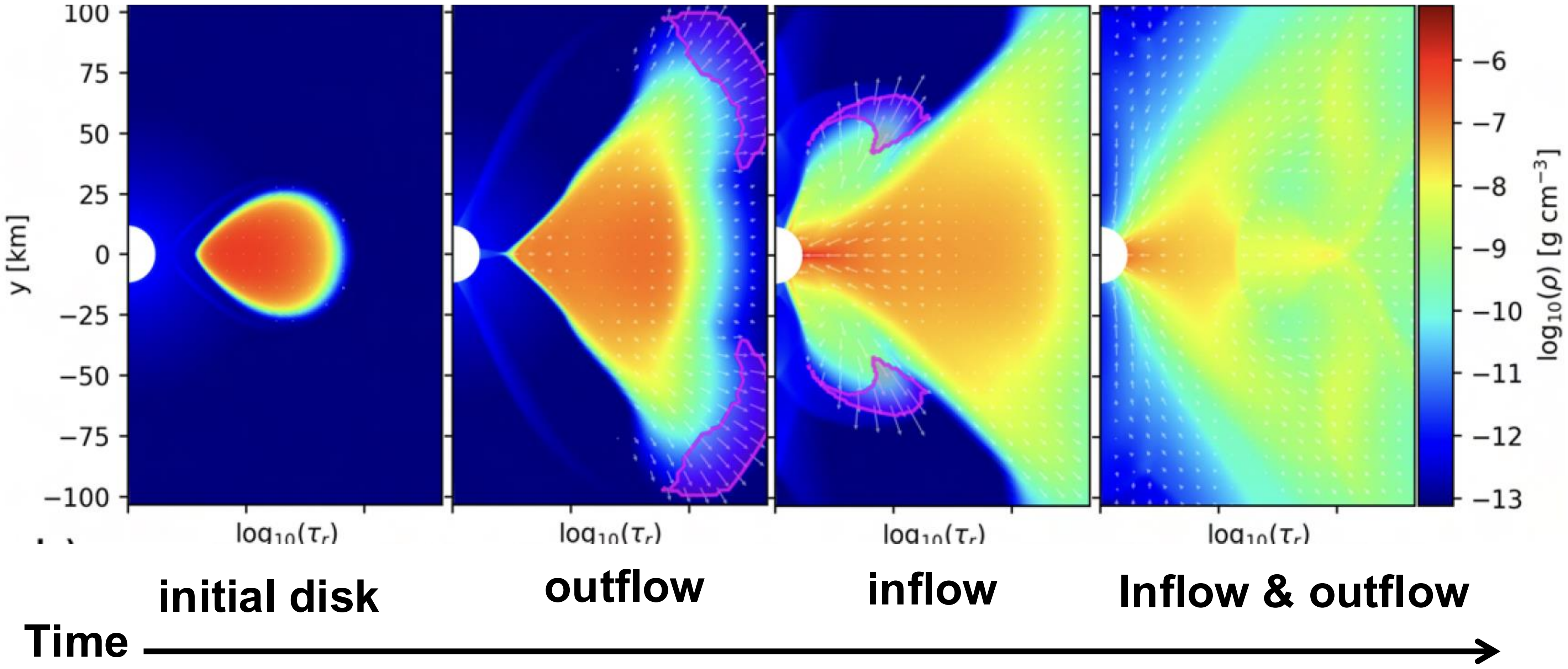


Impact of bursts on the corona: Numerical work

2. Answers from simulations

GR-MHD simulations:

- Outflow from thick flow
- Thick accretion flow collapses
- Mass-accretion rate enhanced



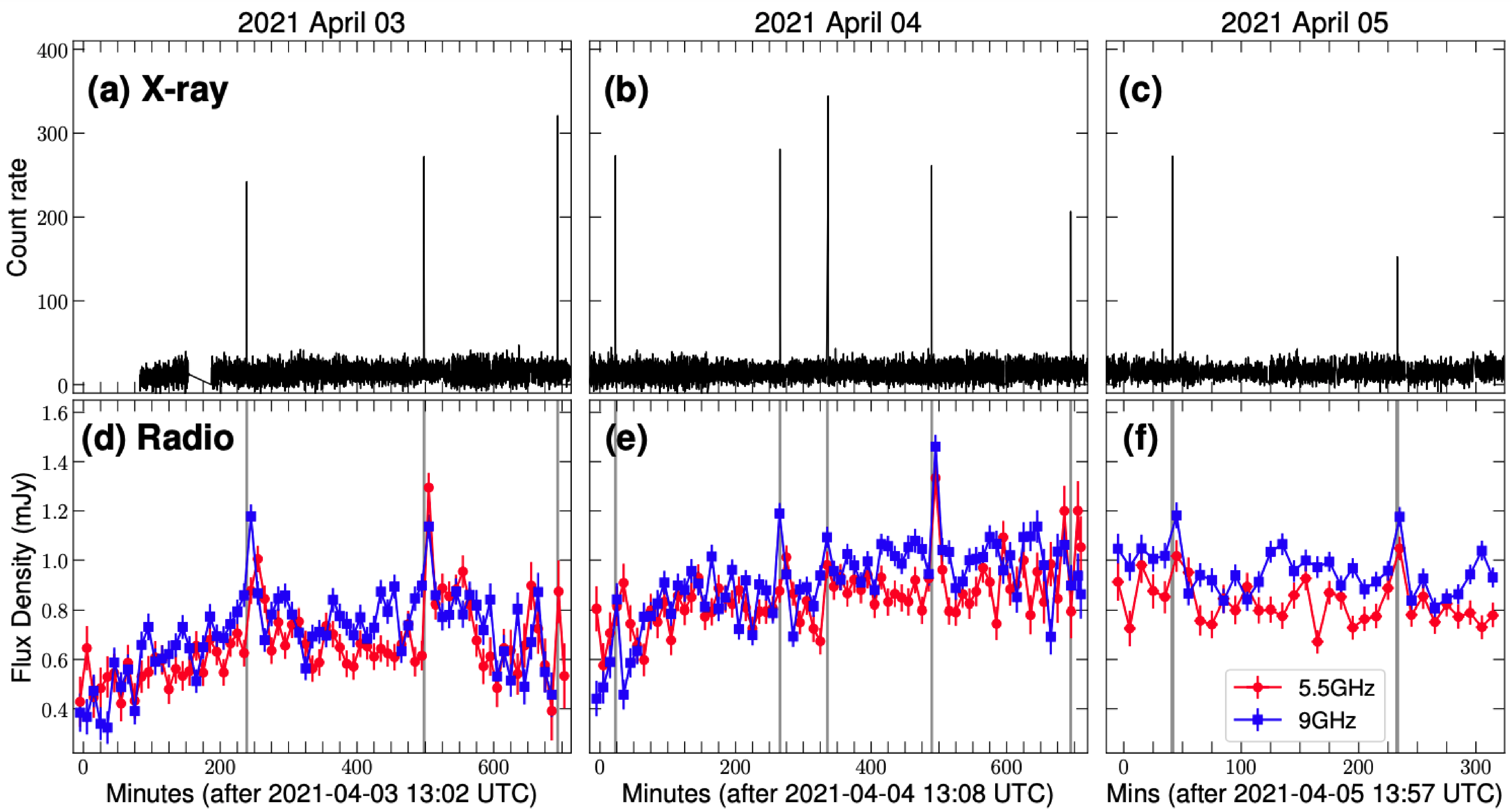
van de Vosse in prep.

Impact of bursts on jets

Observations

Radio jet brightens after bursts → steady jet or mini ejections?

TBD



Russell+2024 (4U 1728-34); also talk by A. Tetarenko on Wed

Recap of the impact of thermonuclear bursts

Thin accretion disk
Heated, carved out, puffs up → enhanced emission and inflow

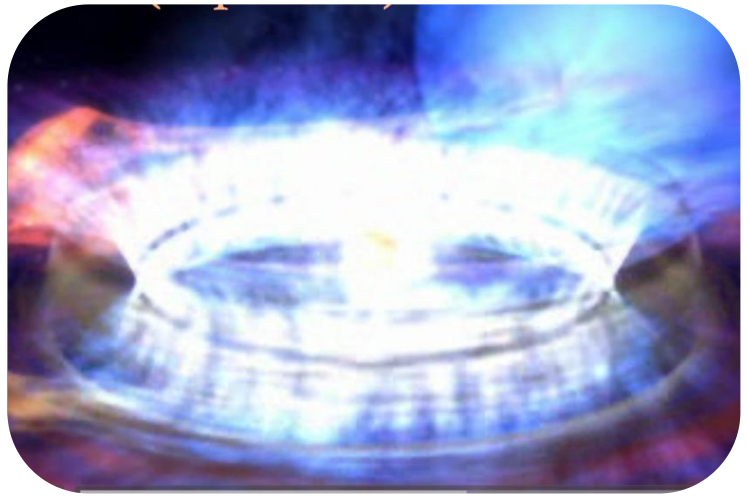
Corona:
Cool, collapse, outflow from flow

Jet:
Radio brightening

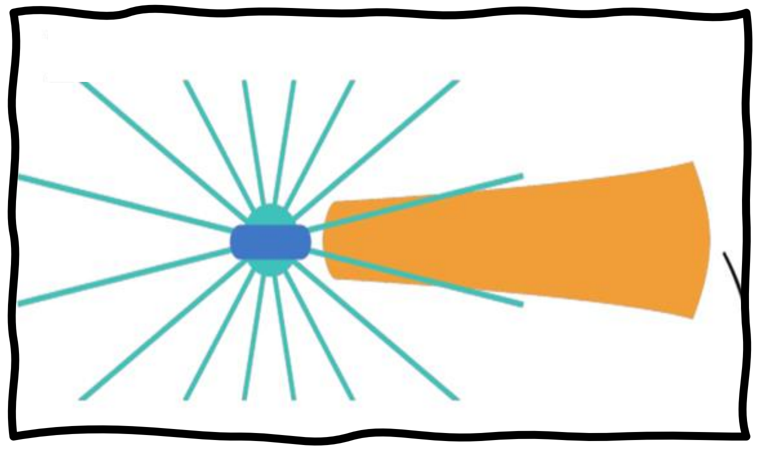
Parameter space to probe impact:

Bursts vary in duration + brightness and occur at different mass-accretion rates

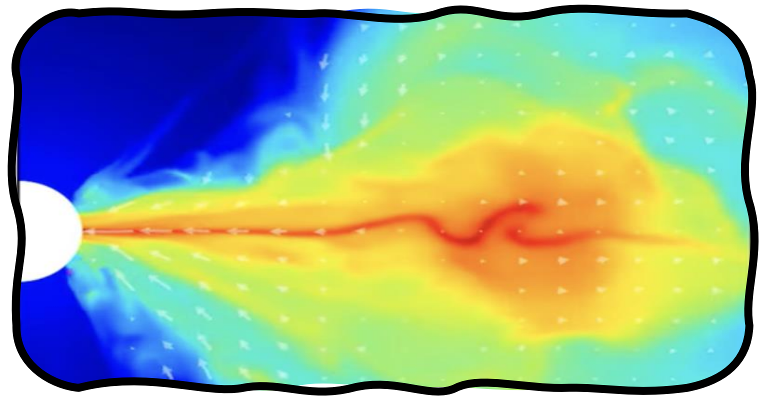
Three Take Aways



I. Thermonuclear bursts → flashes of bright soft X-ray photons



II. Burst cause similar changes as seen during state transitions → mini laboratories?



III. Why interesting: Highly repetitive, easy to measure, timescales doable for simulations

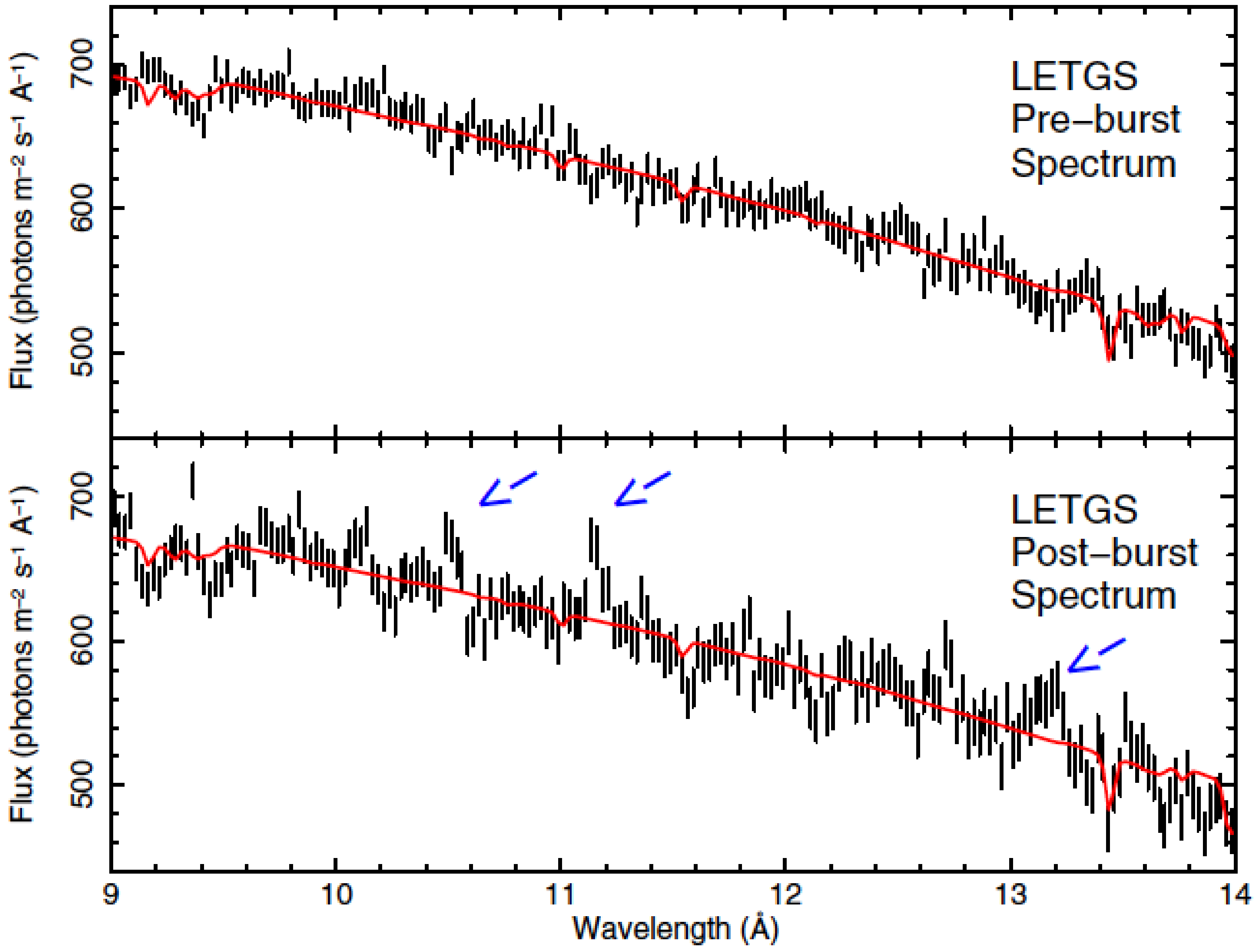
DELETED SCENES

Bursts & Disk winds

Bright burst with RXTE + Chandra

- Emission lines *after* burst
- Blue-shift ~0.1c
- → radiatively driven wind?

Burst of radiation may also amplify an excisiting (thermal) wind?

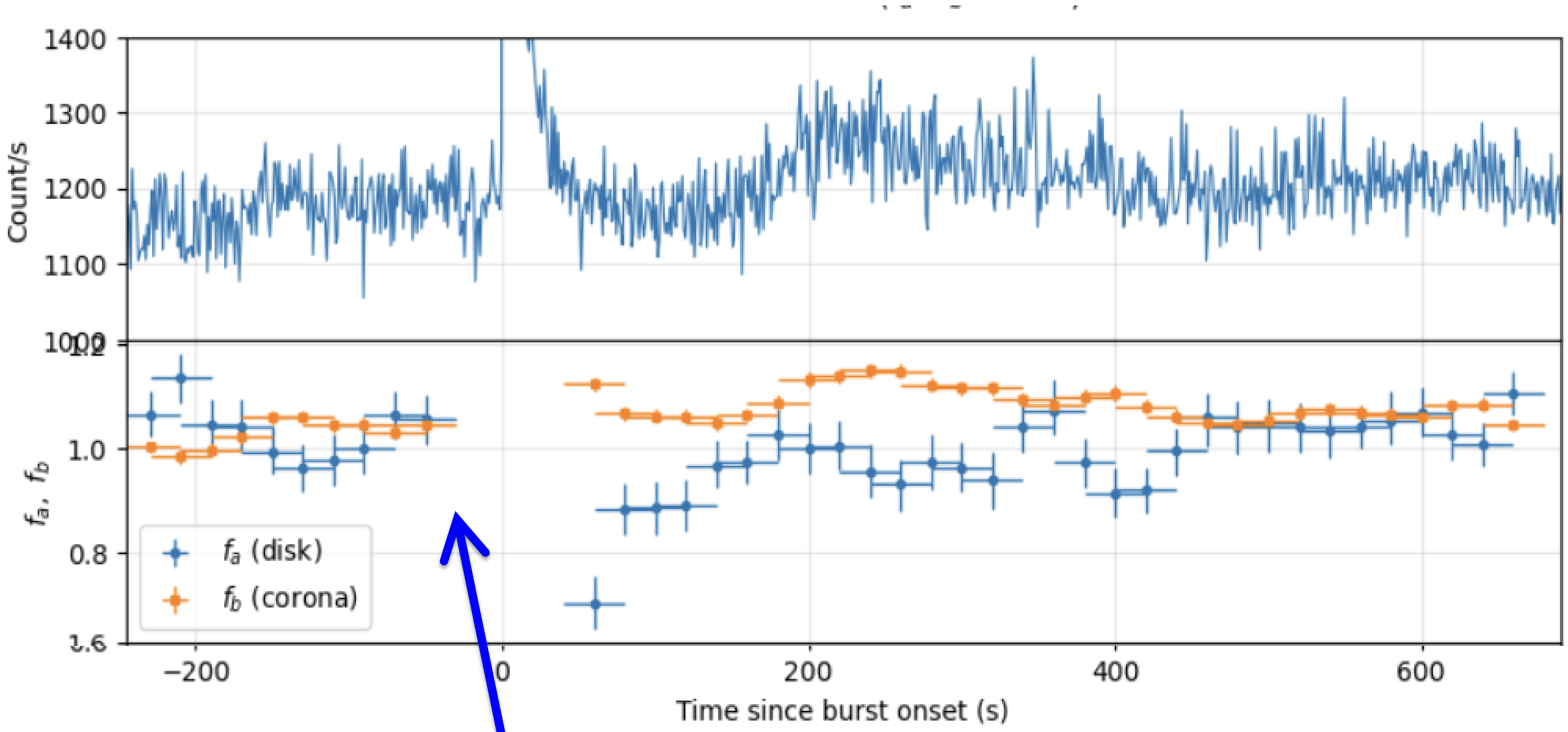


From Pinto+2014, SAX J1808 (Chandra/LETGS + RXTE)

Interplay between the disk & corona

Spectral modeling

Disk and corona vary in tandem → corona also cooled by disk



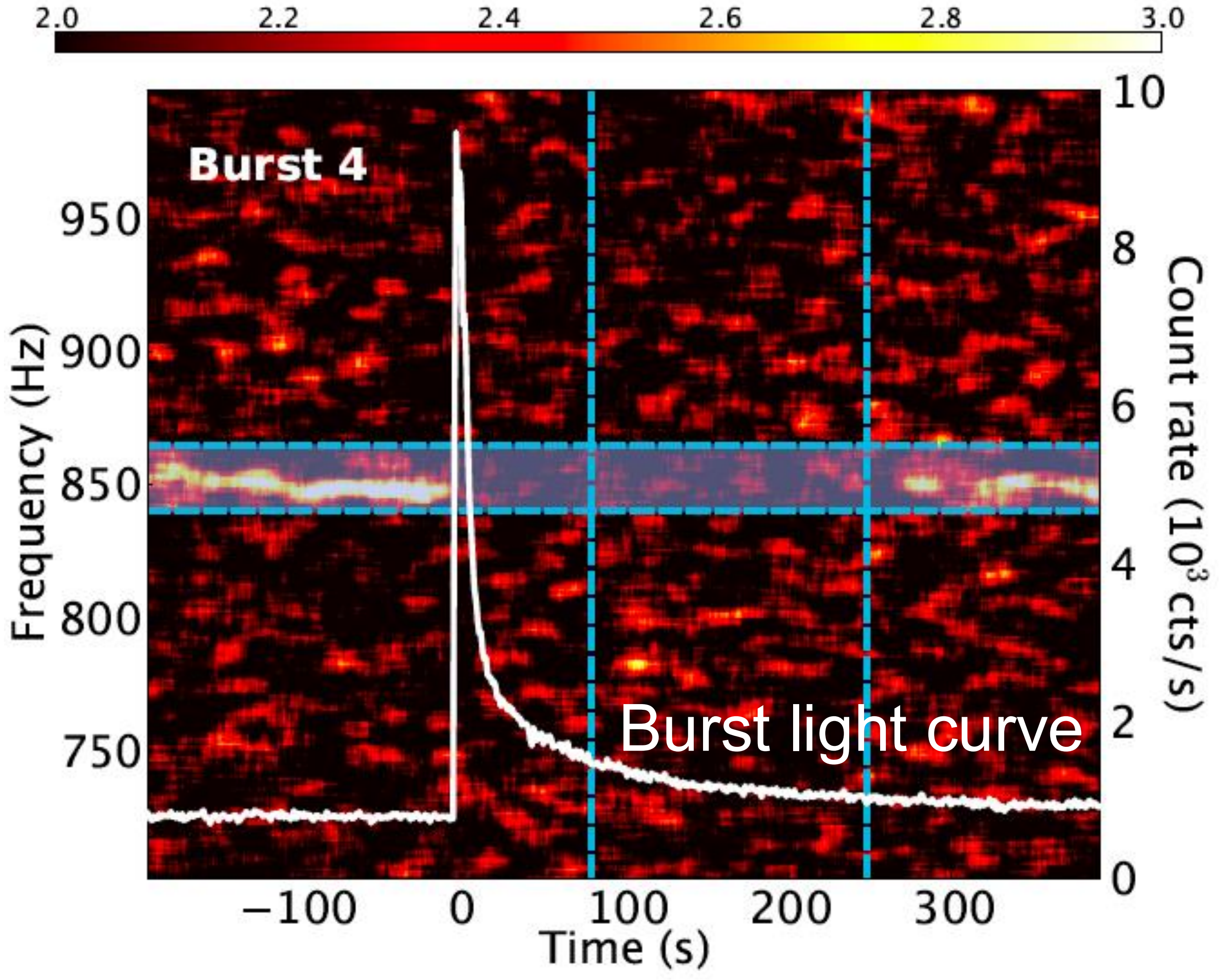
multiplication factor of disk and corona emission

Wei+ in prep (4U1820-30)

Impact of thermonuclear bursts on the disk

1. Clues from QPOs

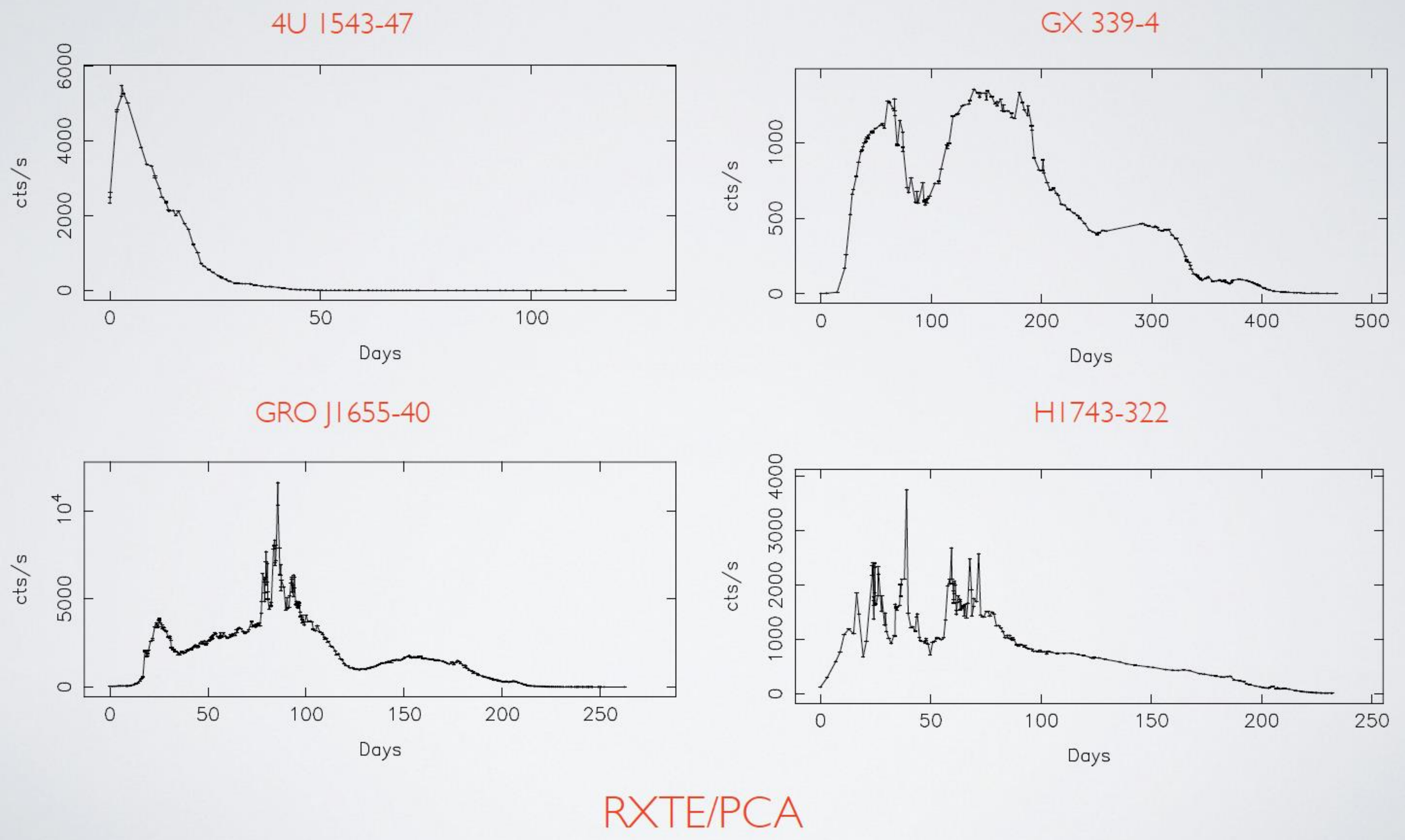
Example 2: kHZ QPO disappears for ~250 s after a burst → inner disk puffed up / shielded from FOV?



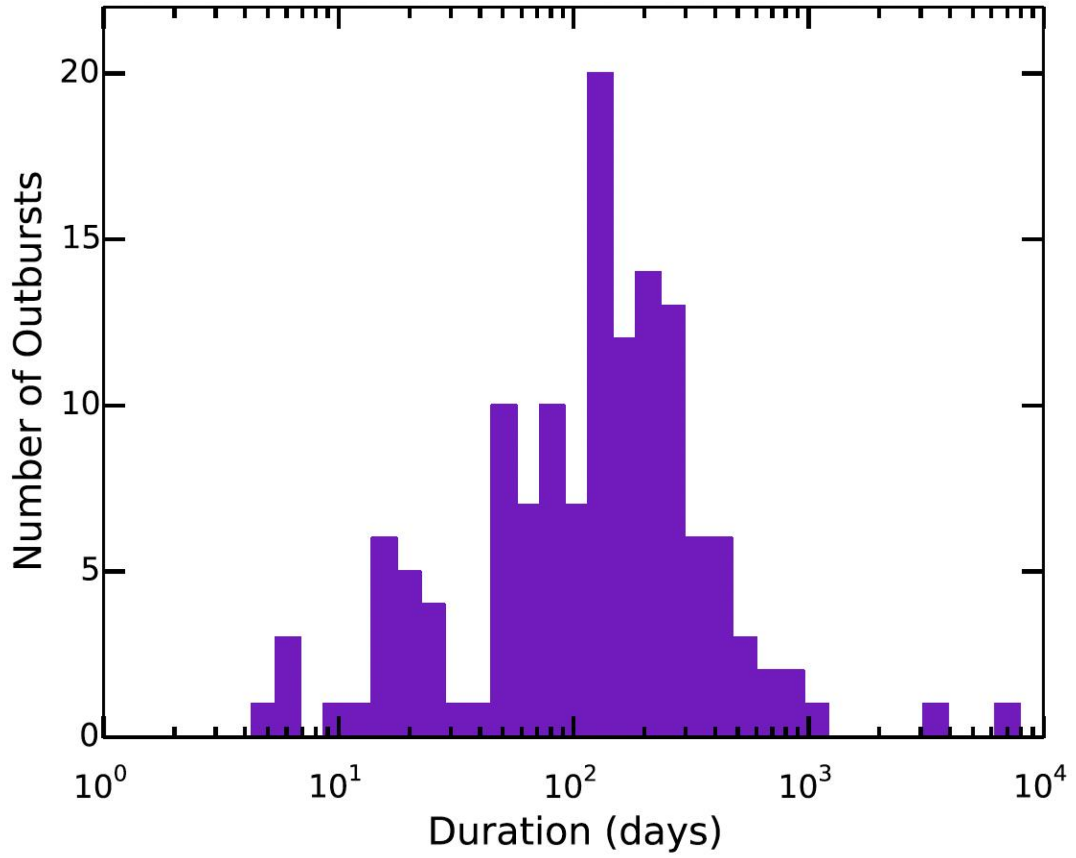
Dynamical power-density spectrum
(+ burst light curve)

Peille+2014 (4U1636-536)

The observations: Large variety outburst profiles



Black hole outbursts

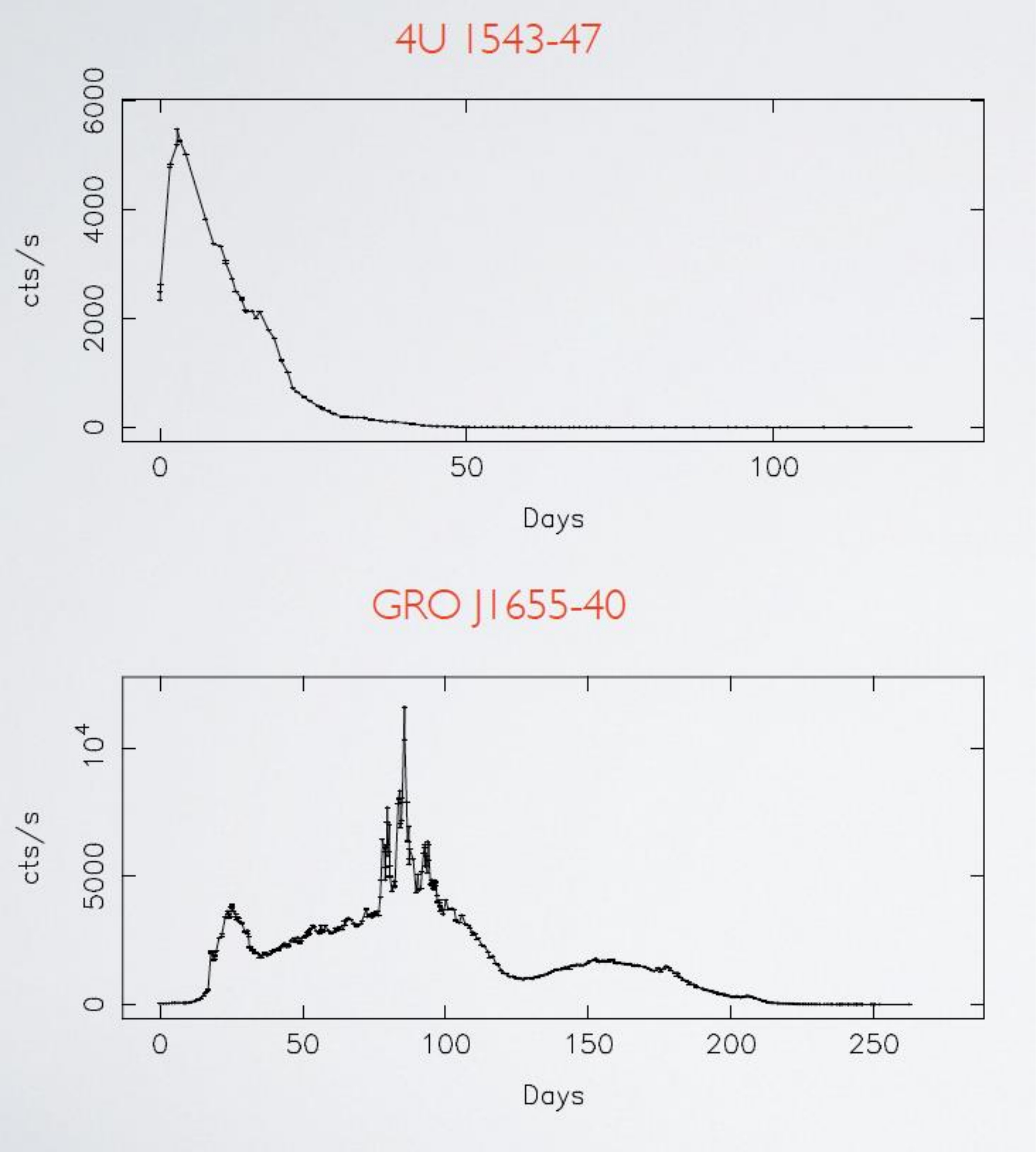


Mean duration ~250 days

Figure courtesy J. Homan

Tetarenko+2016

The observations: Large variety outburst profiles



Complex light curves / decays
→ beyond the disk instability model

- Varying irradiation in outburst

Accretion geometry, disk wind (Tetarenko+2018; 2019)

- Mass and angular momentum loss

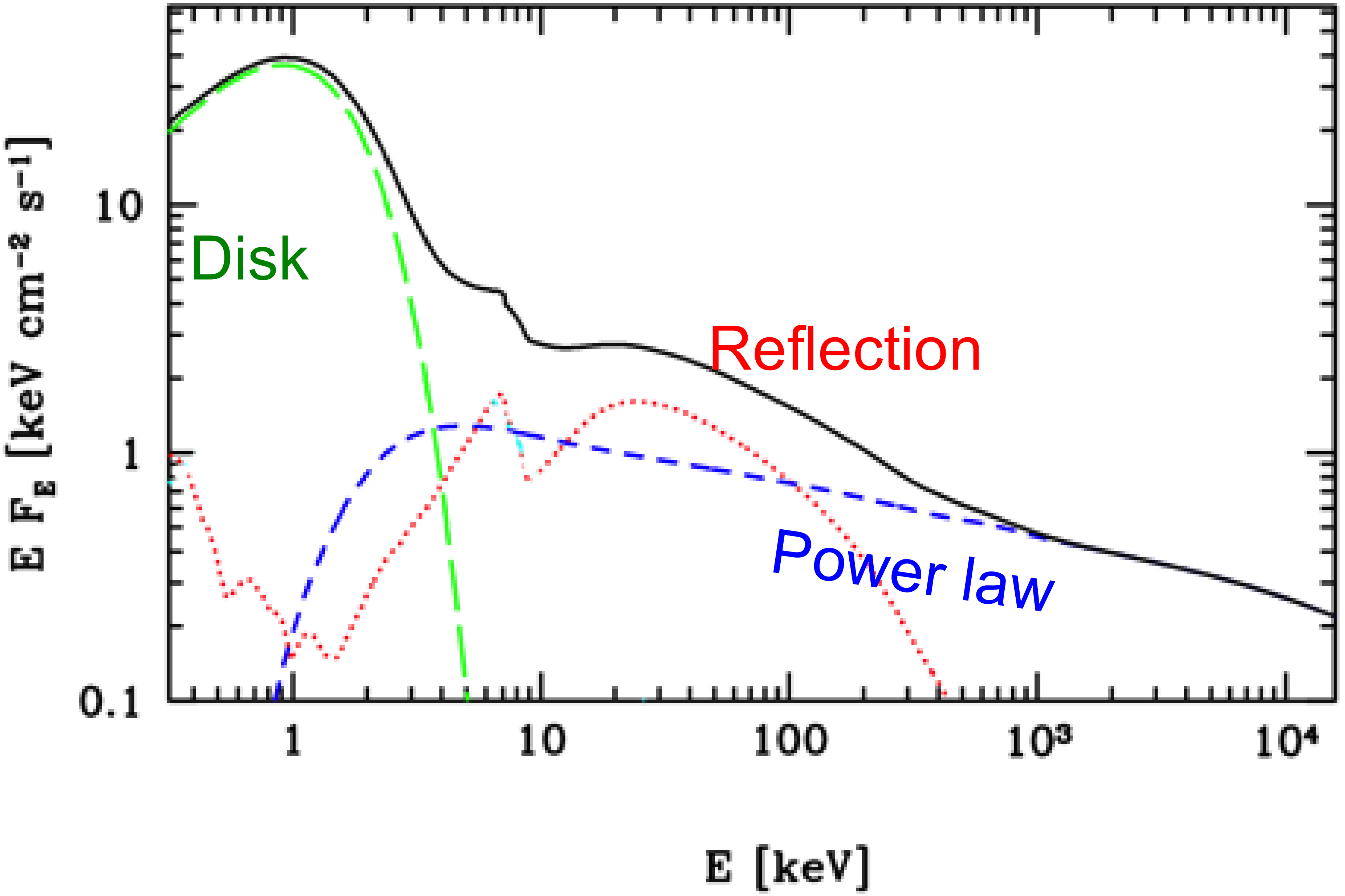
Disk wind (Avaykan+2024)

Figure courtesy J. Homan

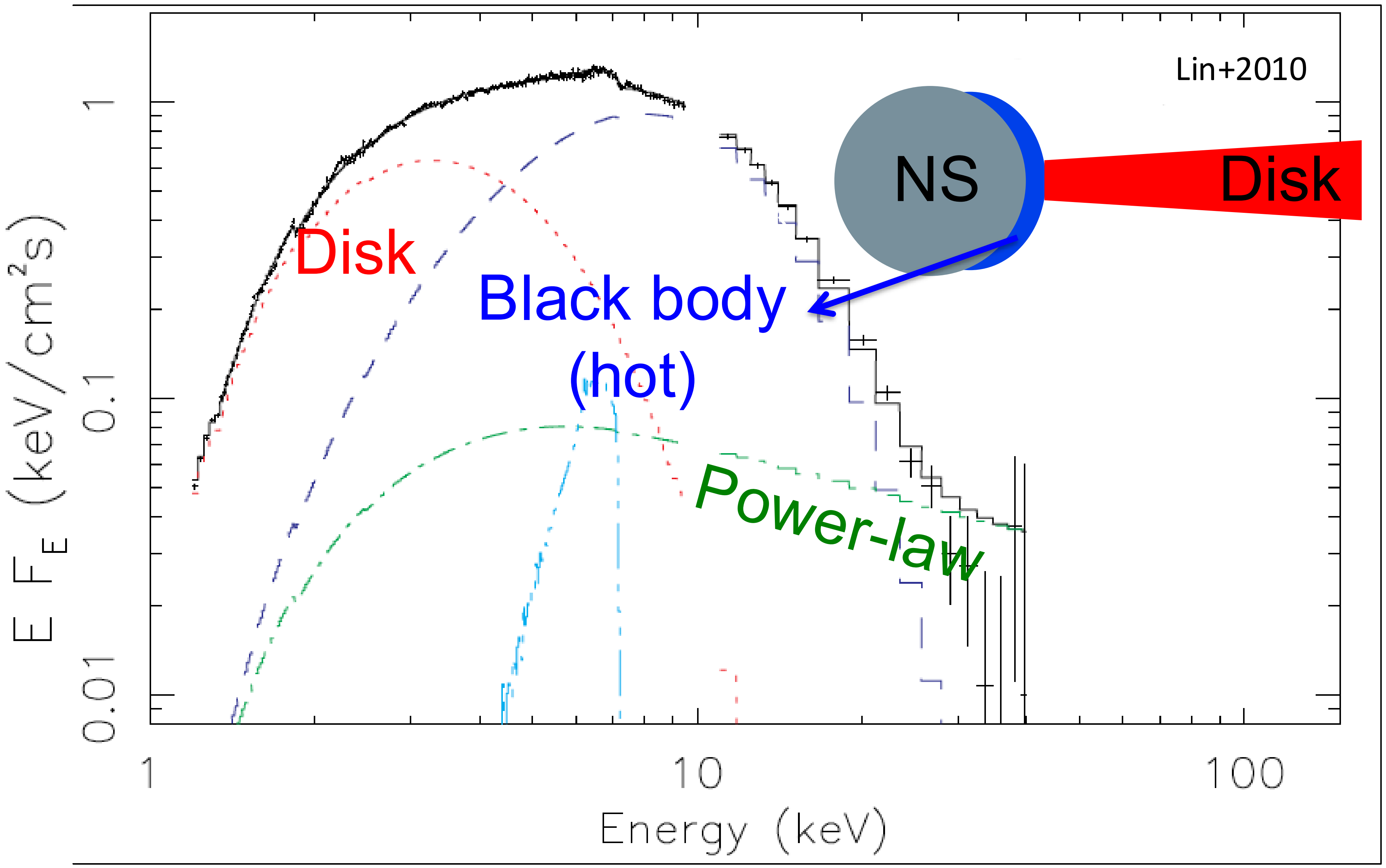
Brief: X-ray spectral states & outburst evolution

II. Emission components & X-ray spectral states

Soft state (disk dominated)



Neutron star (extra component)



Spectra from Zdziarski & Gierlinski 2004, Cyg X-1 (multi-instrument)