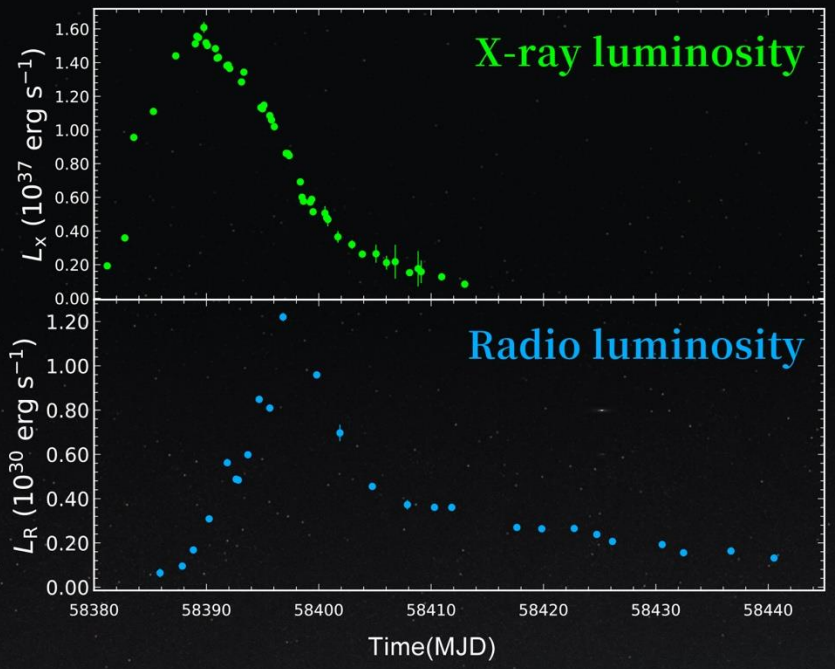
Geometrical & dynamic evolution of the accretion flow in MAXI J1820+070



- You B. et al., 2021, Nat. Comm.
- You B. et al., 2023, Science

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MAXI J1820+070

Collaborators:

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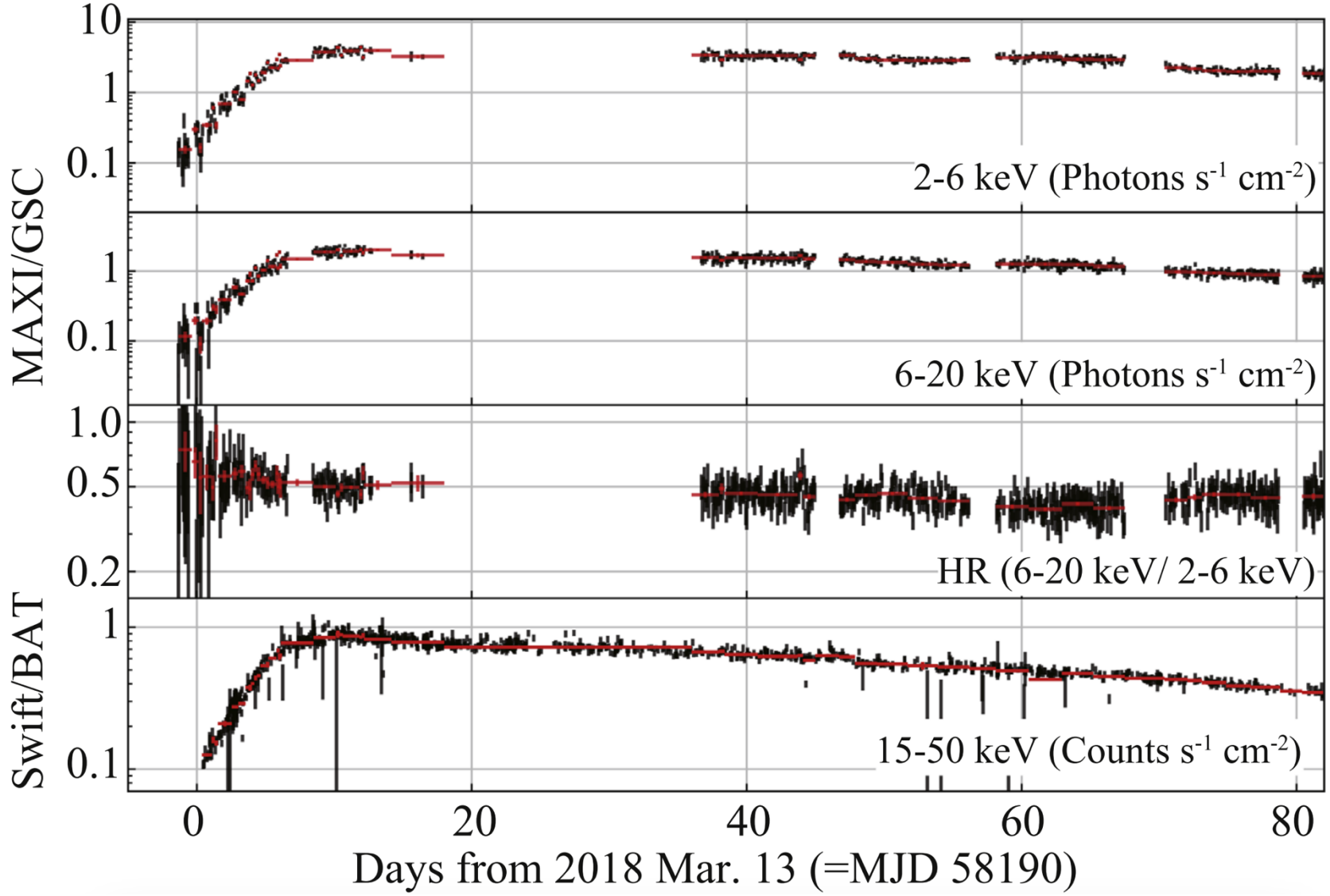
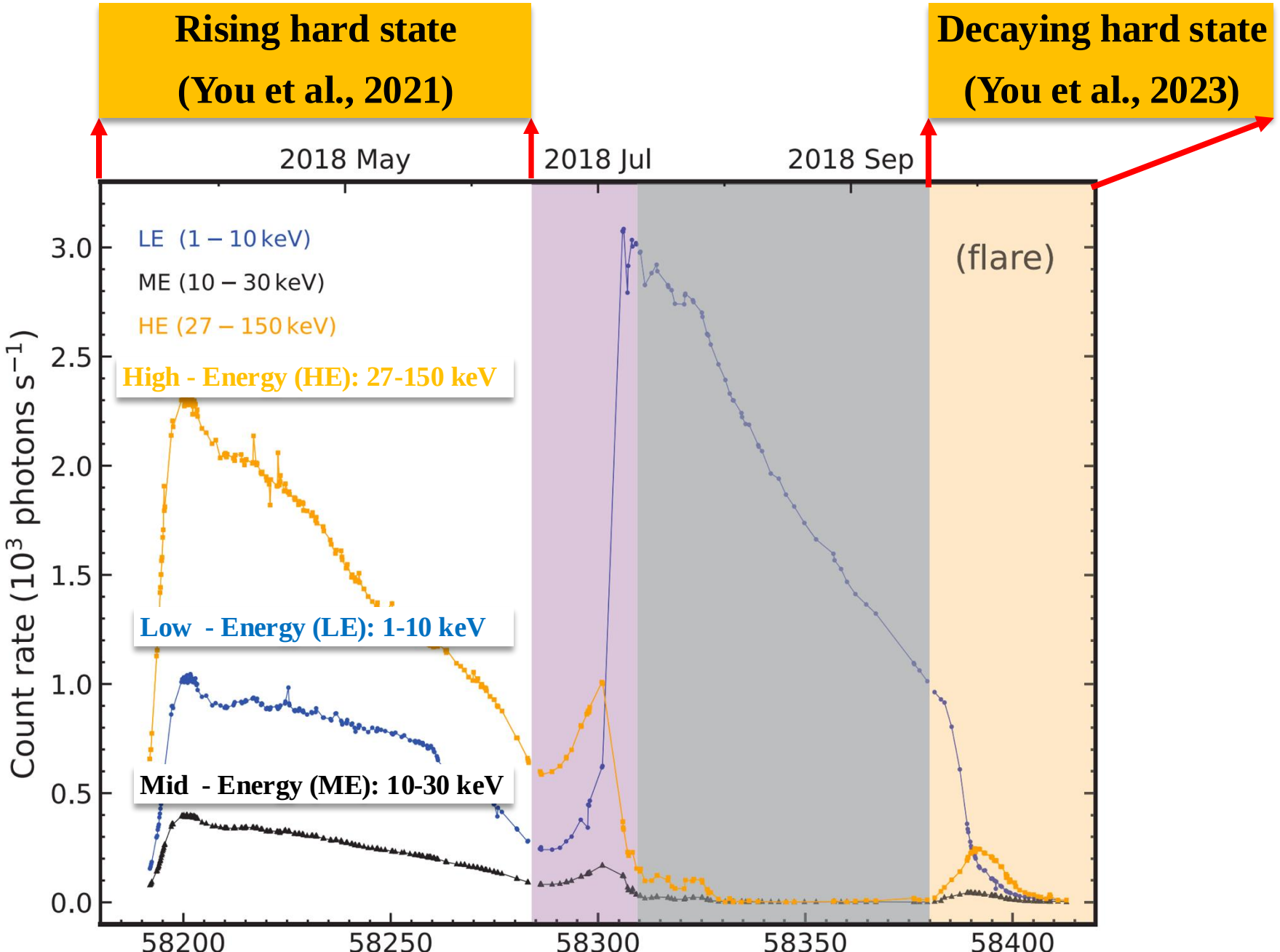
- **The 2018 outburst of J1820+070 by MAXI/Swift**

Kawamuro et al., 2018; Shidatsu et al., 2021



- **The 2018 outburst of J1820+070 by HXMT**



Outline

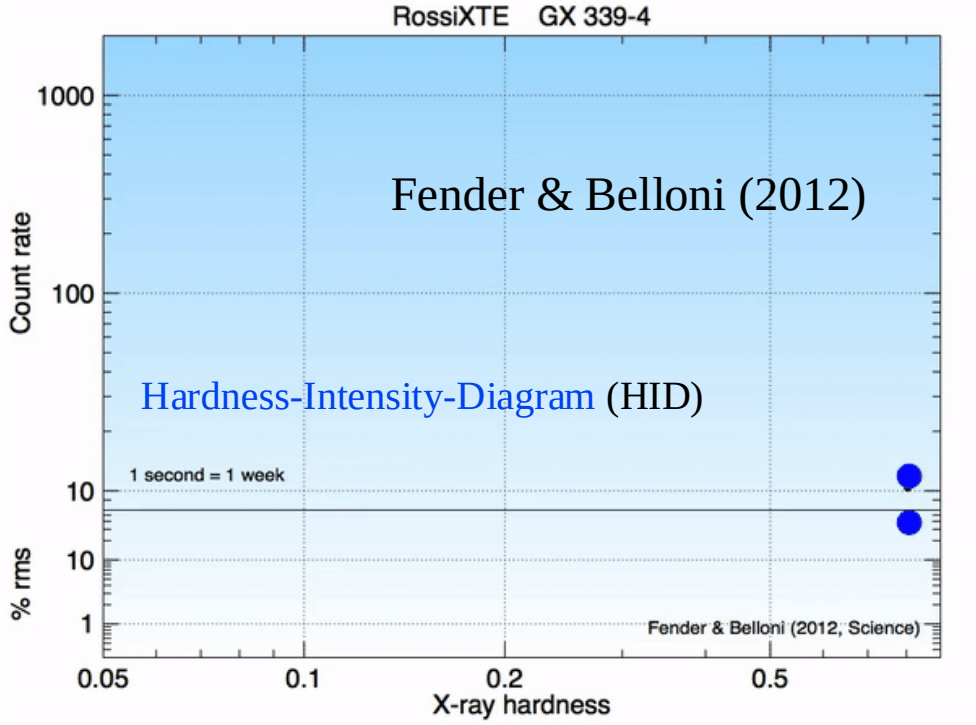
- Some questions of BHXRBs

I. Rising hard state (You et al., 2021)
   - The illumination of the corona on the disk was suppressed, as the disk/corona was contracting over time

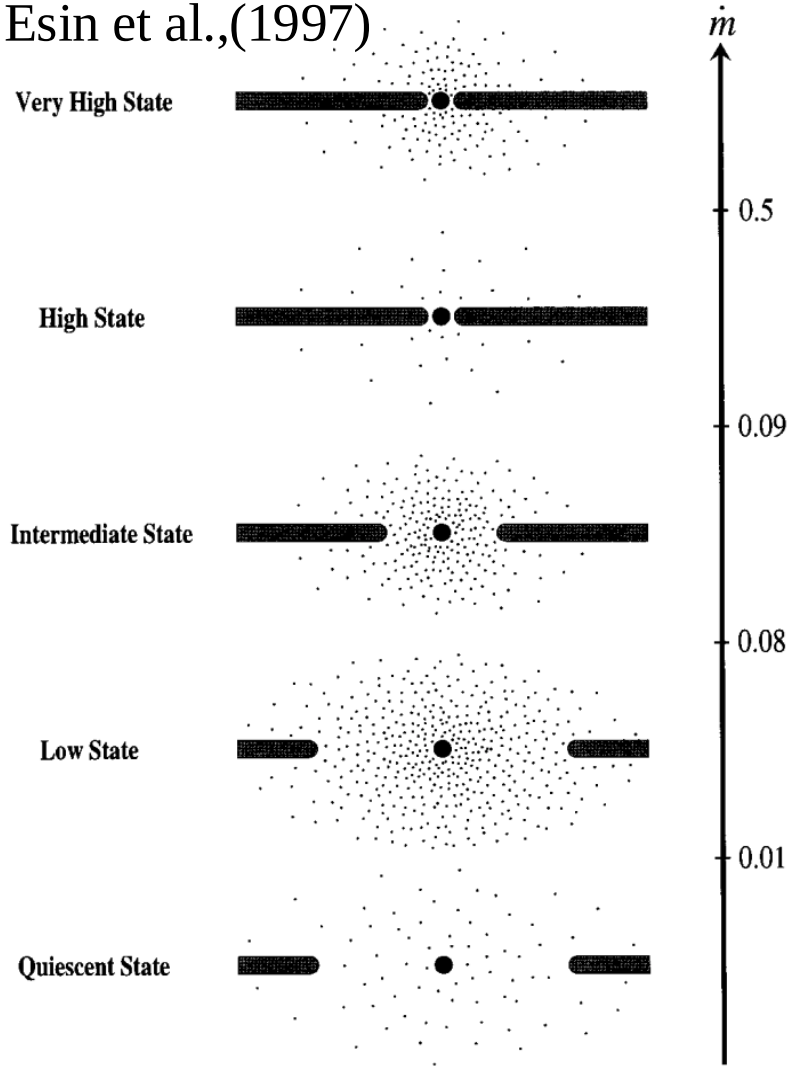
II. Decaying hard state (You et al., 2023)
   - Unprecedented radio-lag (8d) and optical-lag (17d), following X-ray flare

- Summary

Some questions of BHXRBs

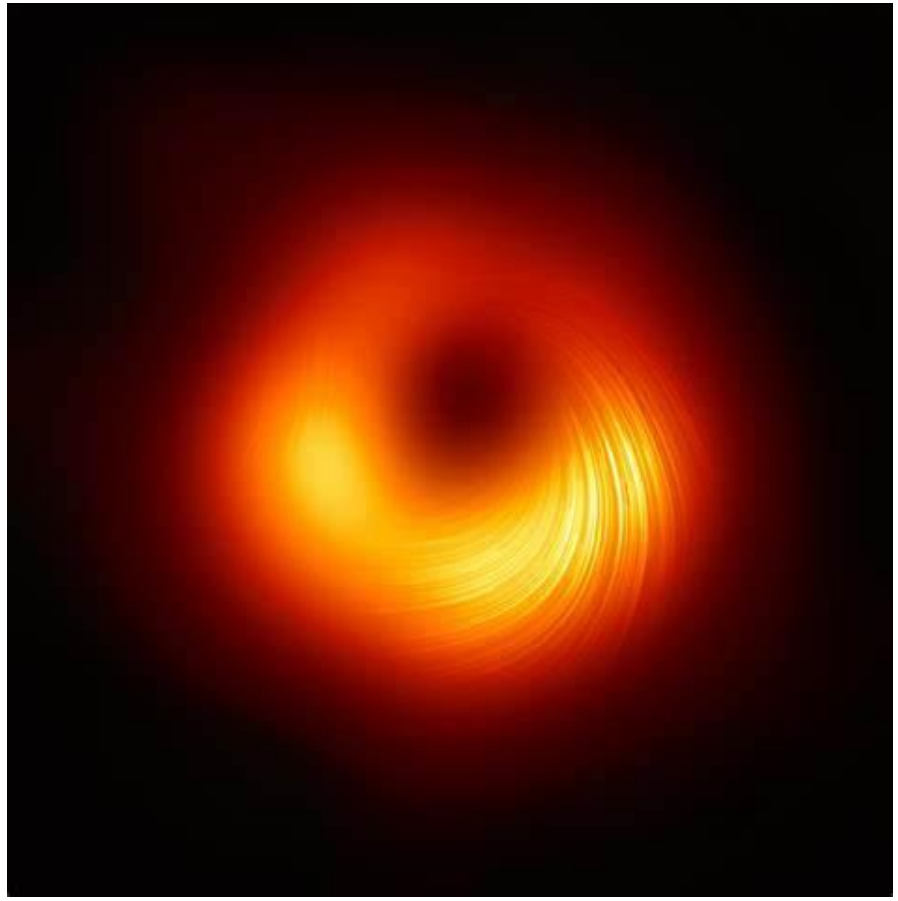


Esin et al.,(1997)



- **The geometrical evolution of XRB was proposed**
- **But, the observational evidence is rare.**

Magnetically Arrested Disk（MAD）



- **Does MAD exist in BHXRB ? How is MAD formed ?**

MAD in M87 **EHT (2021)： 1-30 G**

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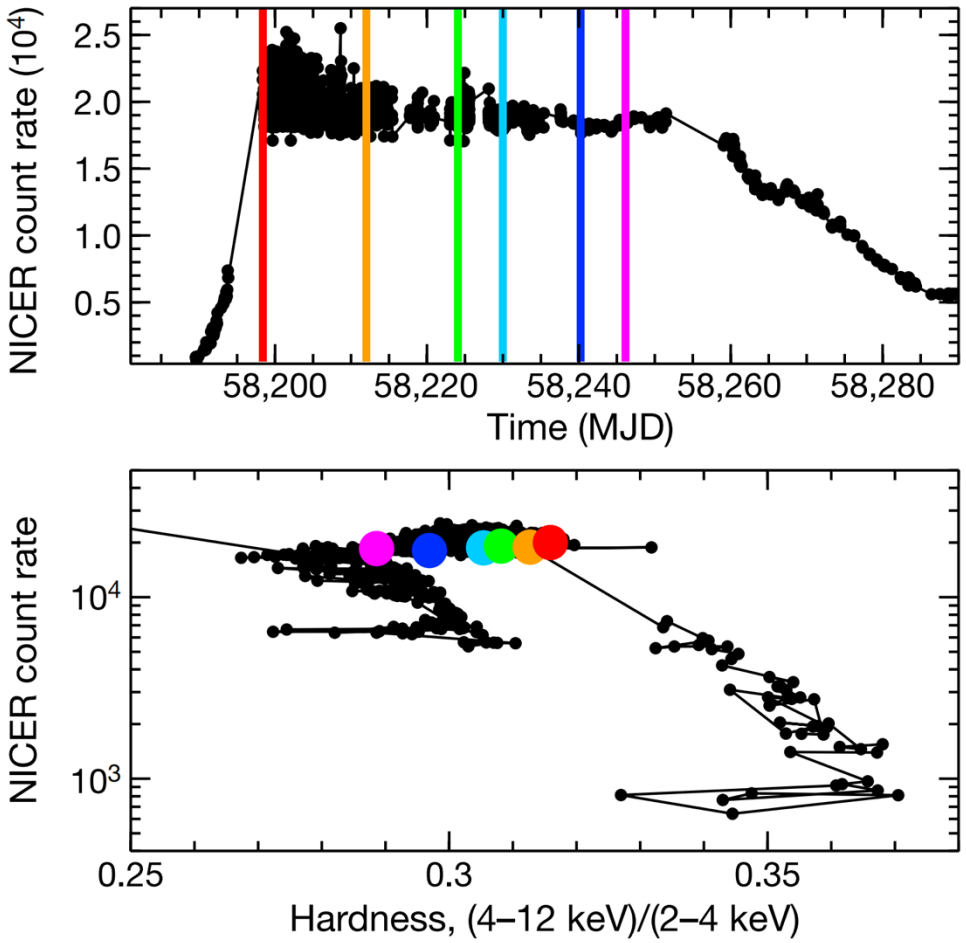
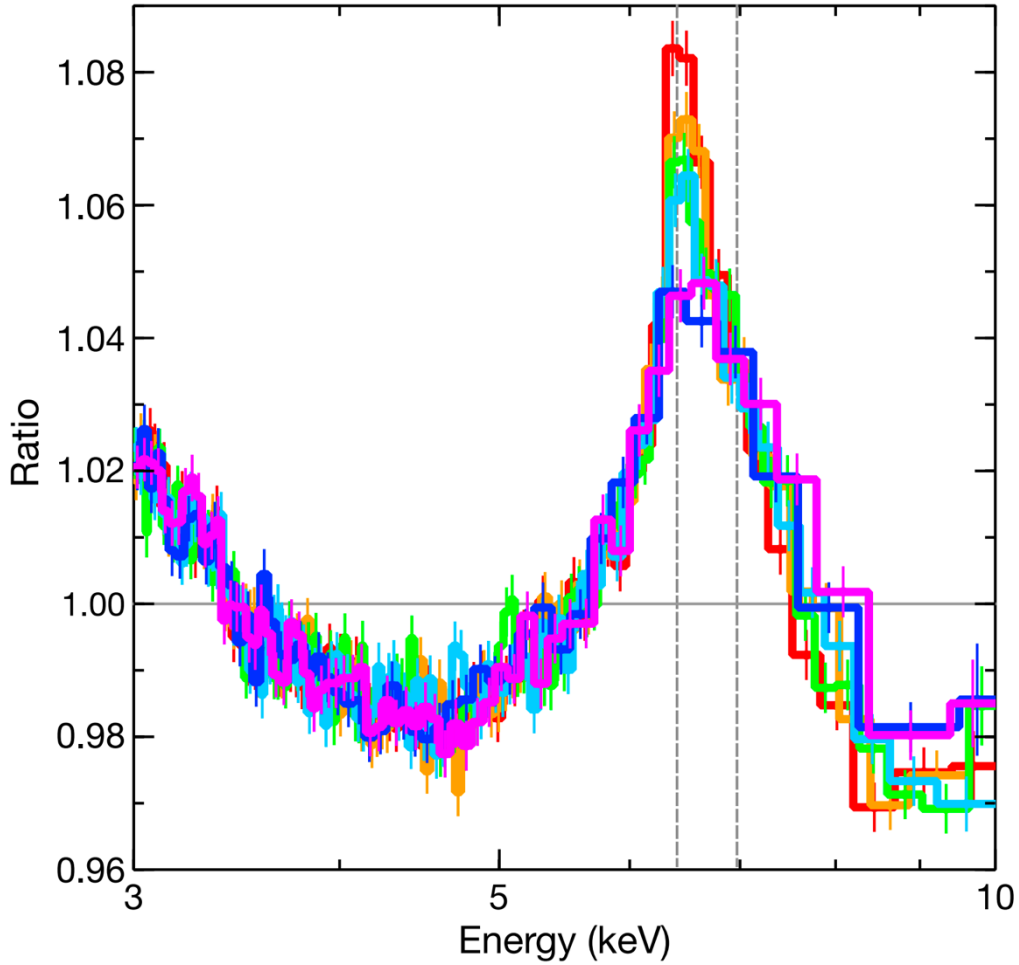
- Summary

(I) Rising hard state

Kara et al.,(2019)

Spectral analysis: iron line remains remarkably constant

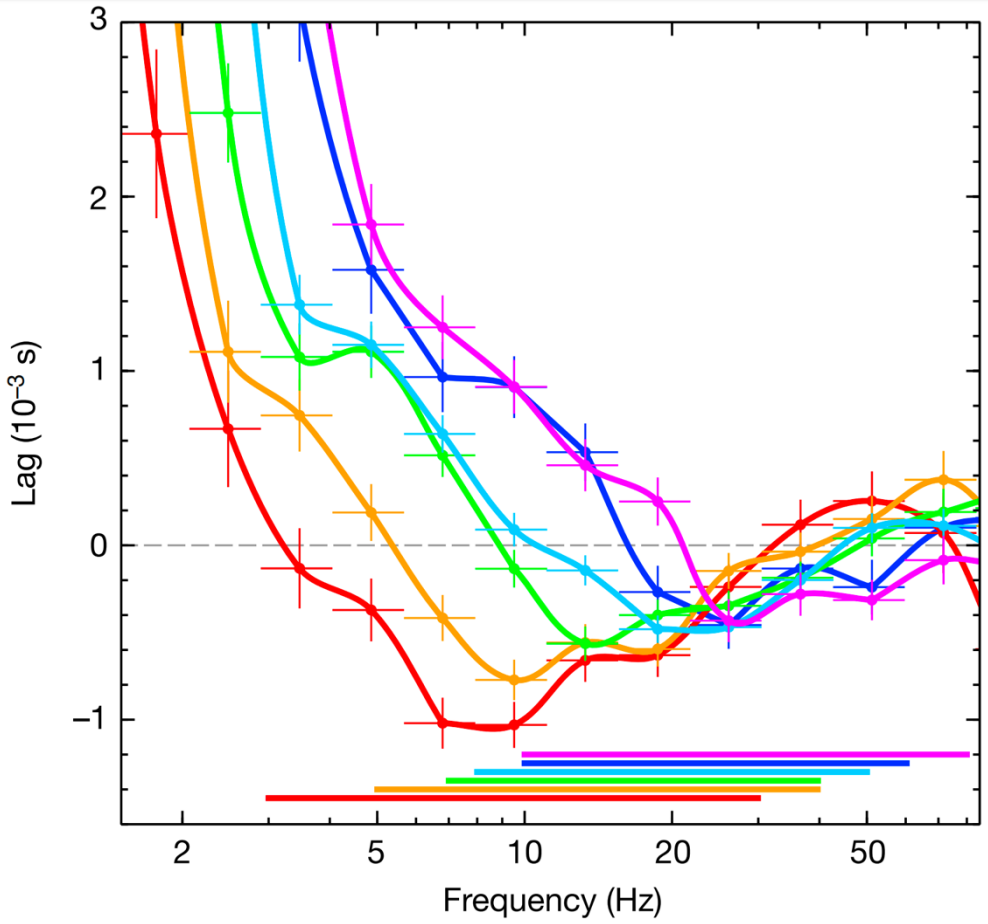




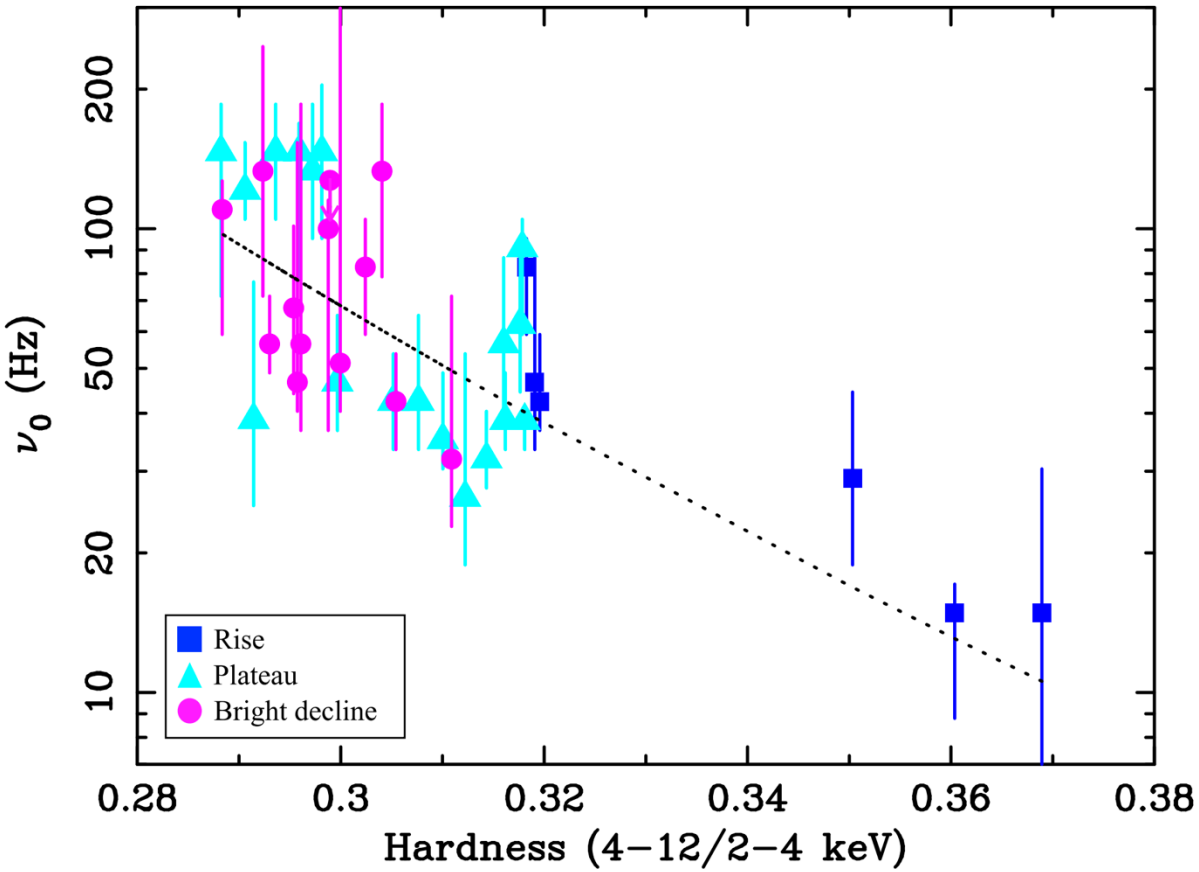
(I) Rising hard state

Timing analysis: Time-evolution of the lag(f)

Kara et al.,(2019)



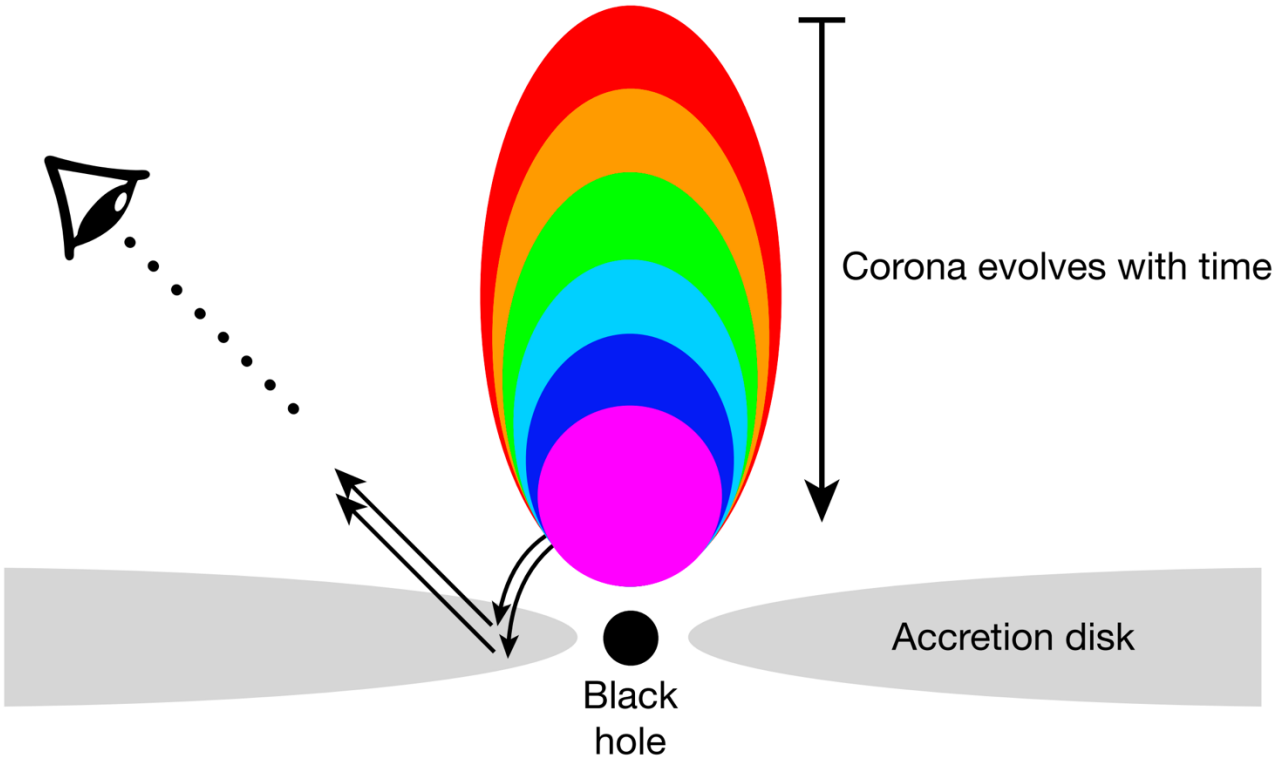
De Marco et al.,(2021)



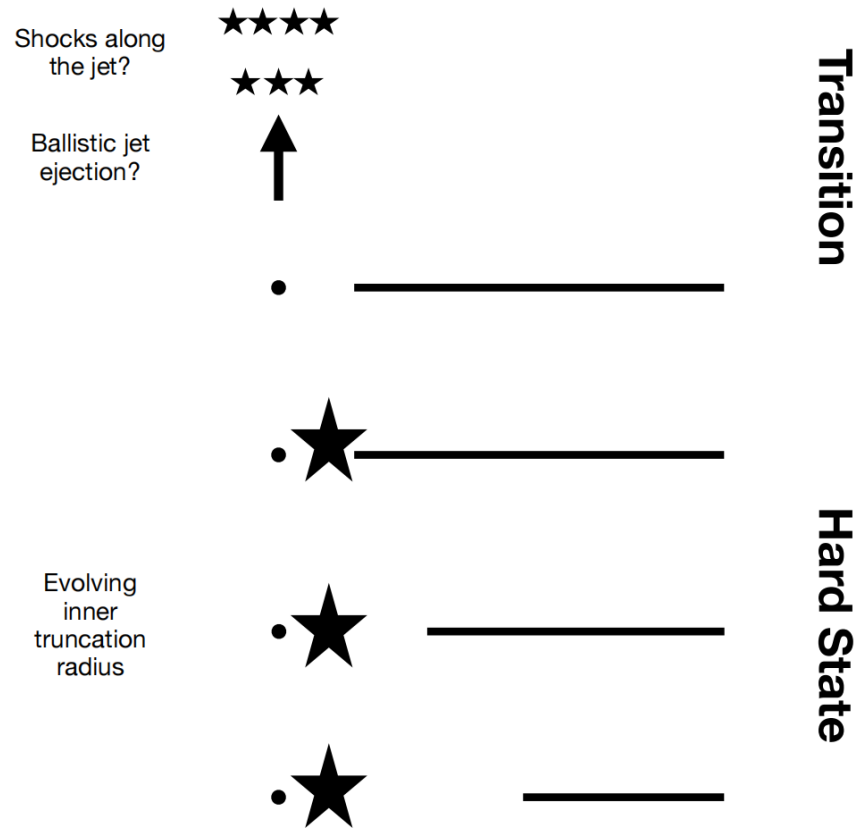
(I) Rising hard state

Spectral +Timing analysis: the geometrical evolution of the accretion flow

Vertically contracting corona (Kara et al., 2019)



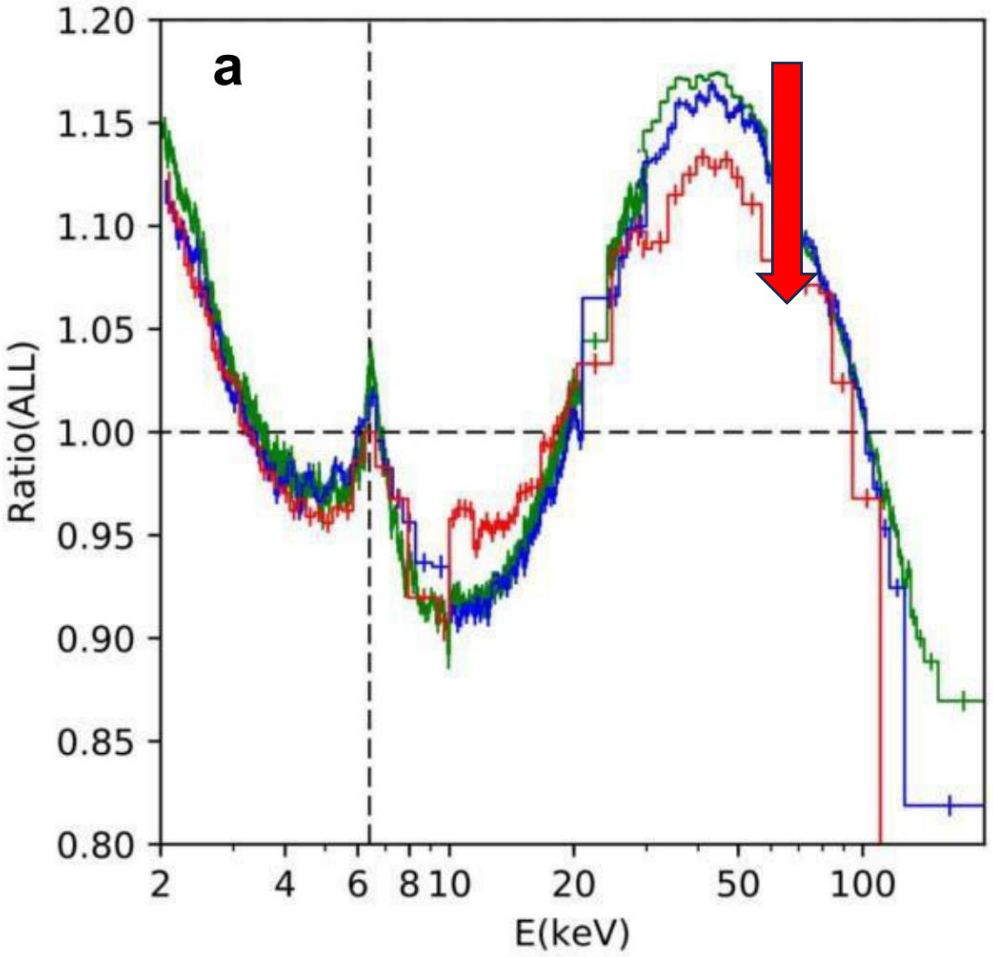
Radially contracting corona (De Marco et al., 2021)



(I) Rising hard state

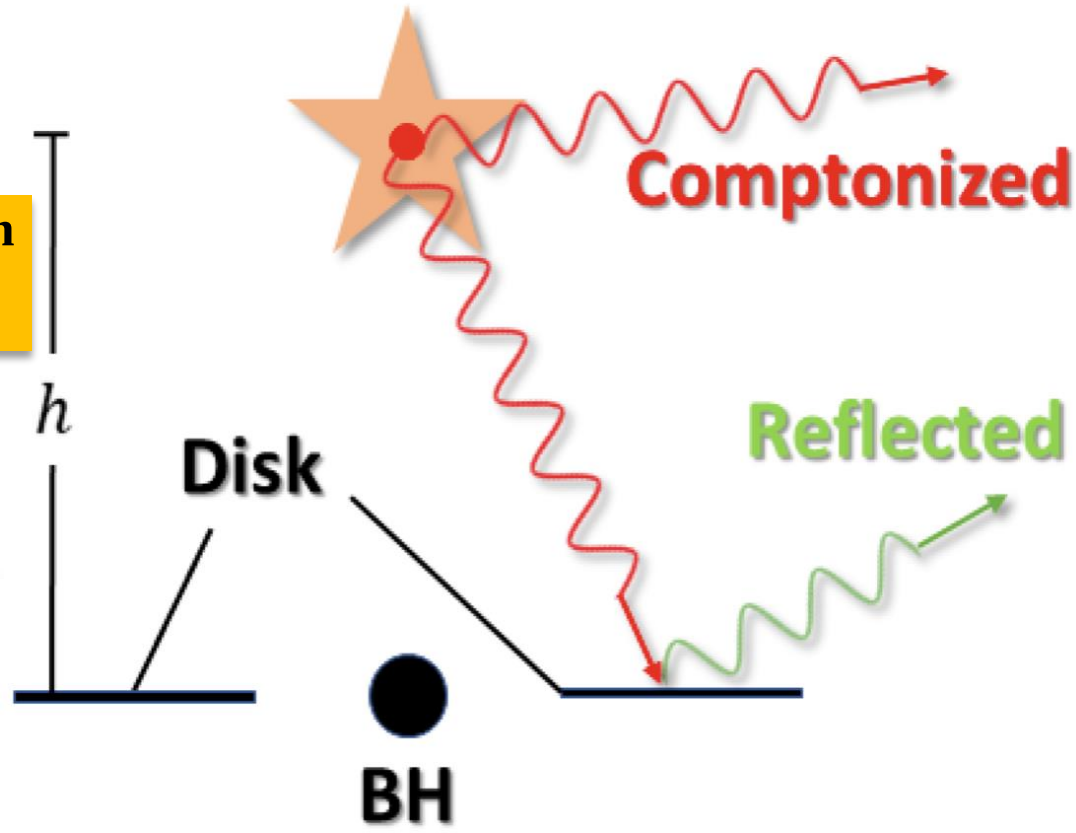
You et al.,(2021)

Spectral analysis: Time-evolution of the illumination and reflection



Reflection fraction in relxill

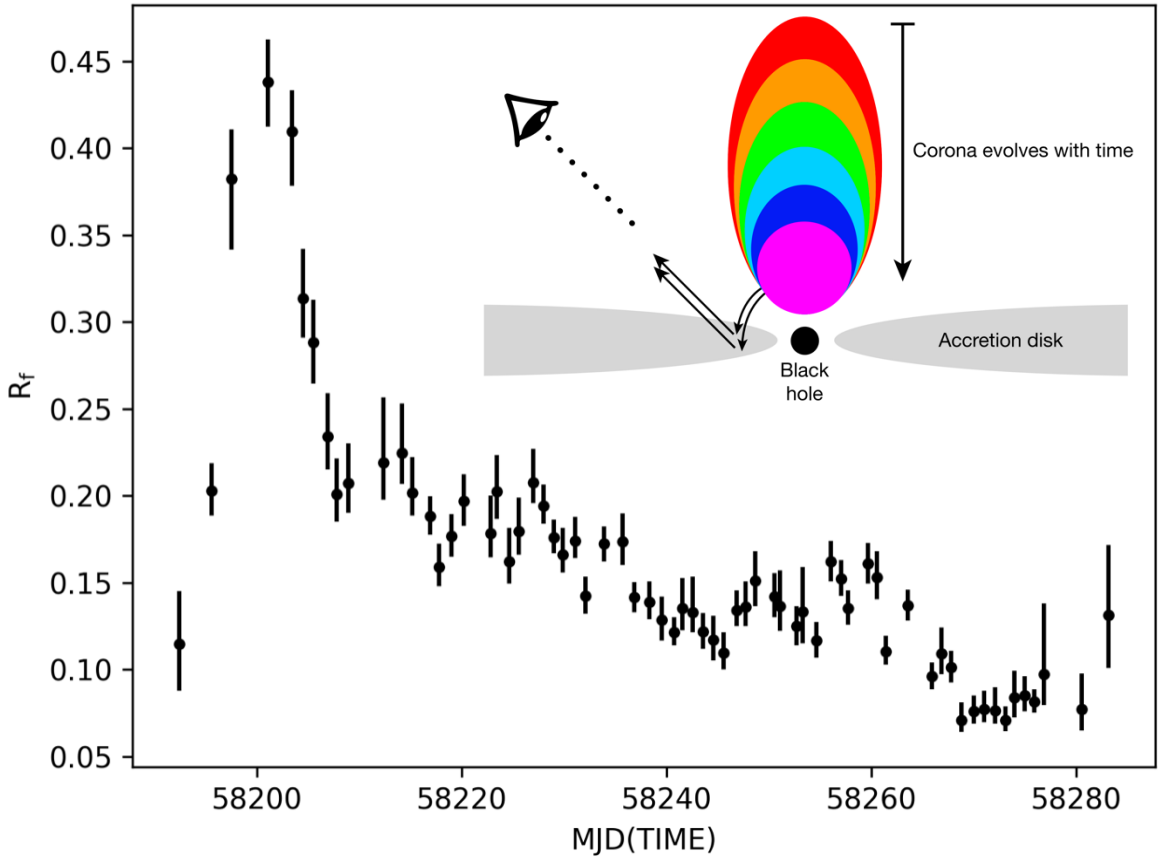
$$R_{\rm f} = \frac{N_{\rm to-disk}}{N_{\rm to-obs}}$$



(I) Rising hard state

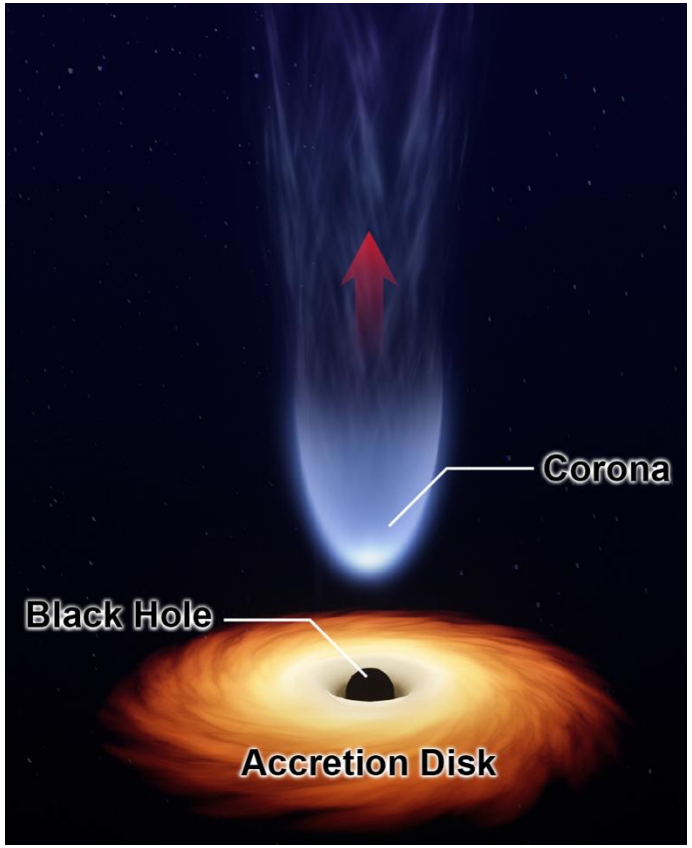
- It turns out the reflection fraction **DECREASES**, as the disk/corona contracts !!!
- It implies that **less** (coronal) photons hit the disk

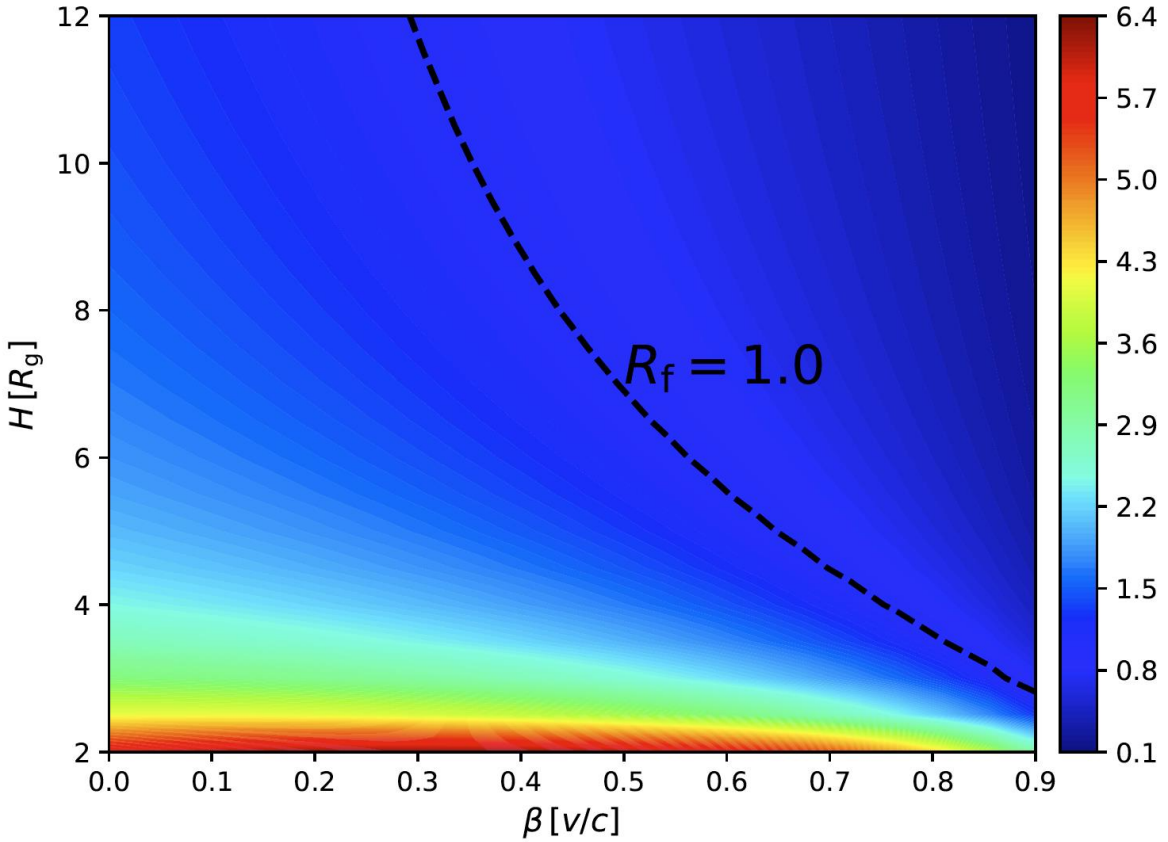
$$R_{\rm f} = \frac{N_{\rm to-disk}}{N_{\rm to-obs}}$$



(I) Rising hard state

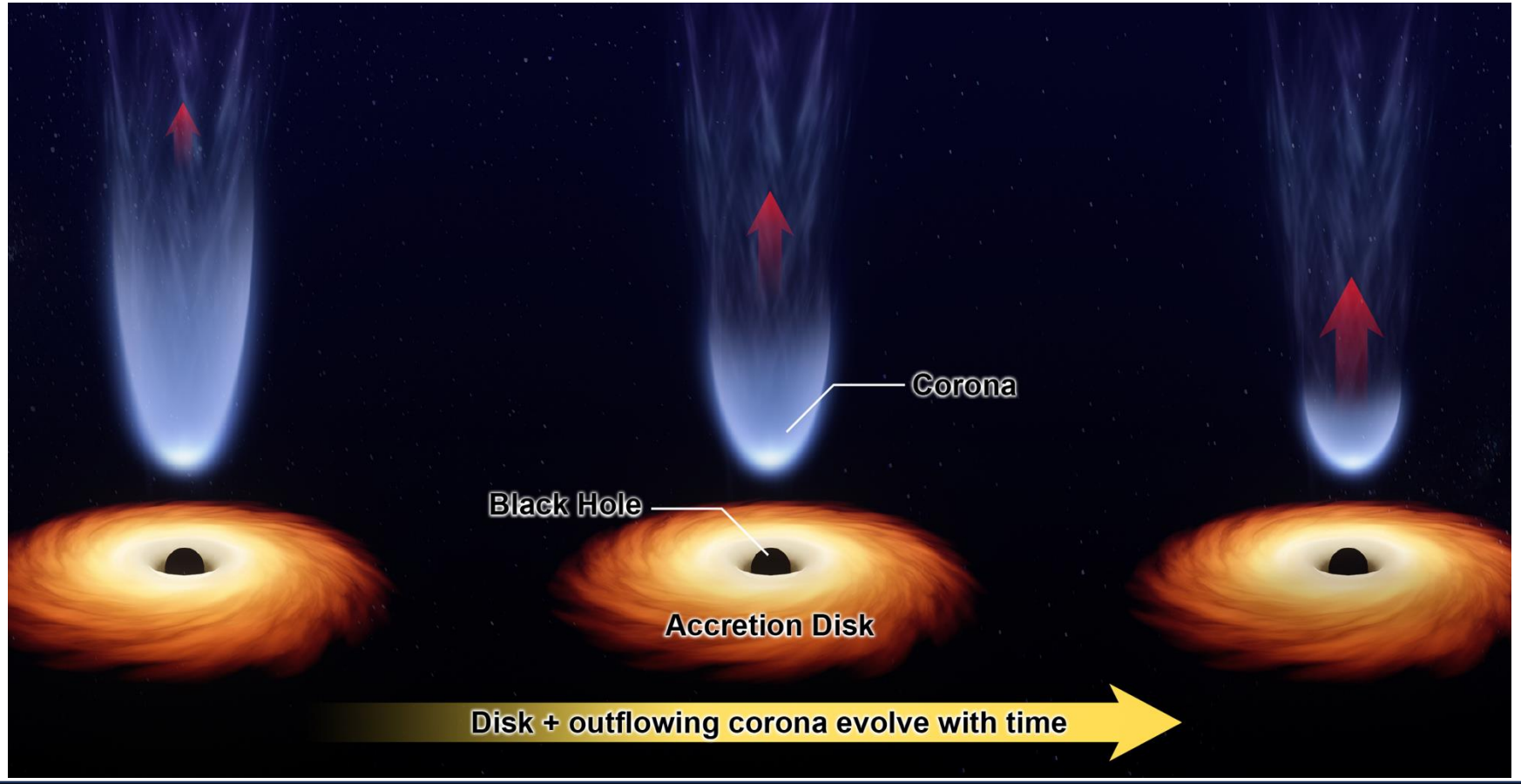
- The light-bending effect and beaming effect determine the irradiation
- R_f depends on both the height and the velocity

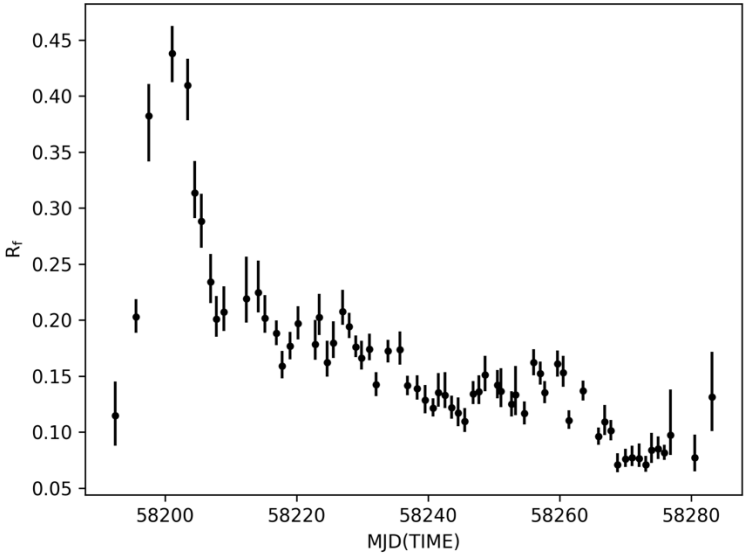




(I) Rising hard state

- **Our solution to the observed decrease in the illumination and reflection:**
  - **The corona is outflowing faster and faster, as the disk/corona is contracting over time**





Outline

- Some questions of BHXRBs

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   - The illumination of the corona on the disk was suppressed, as the disk/corona was contracting over time

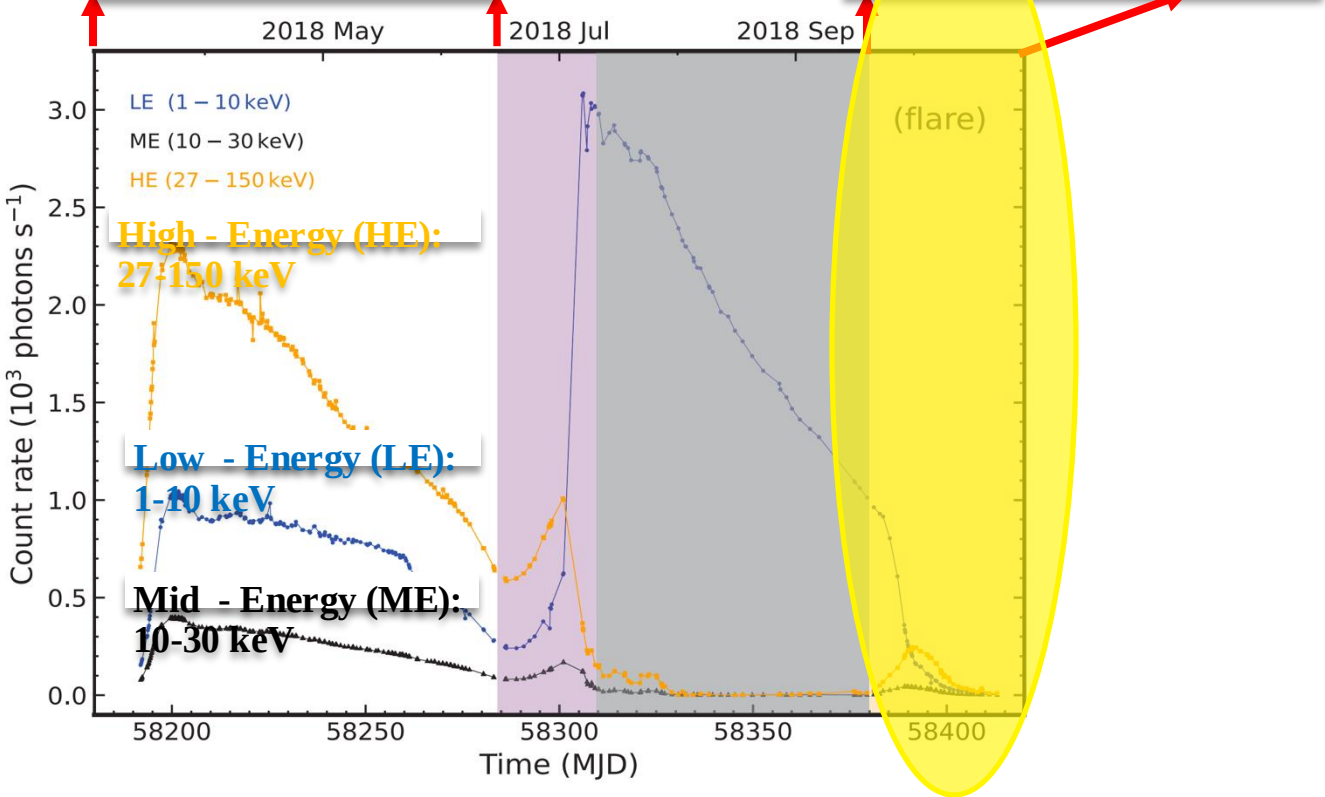
II. Decaying hard state (You et al., 2023)
   - Unprecedented radio-lag (8d) and optical-lag (17d), following X-ray flare

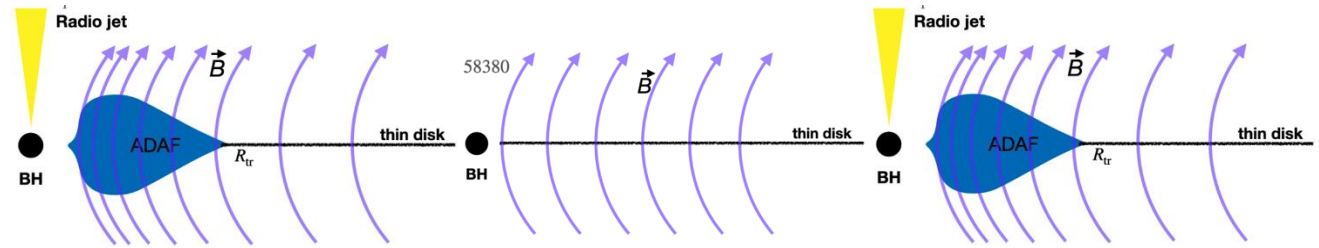
- Summary

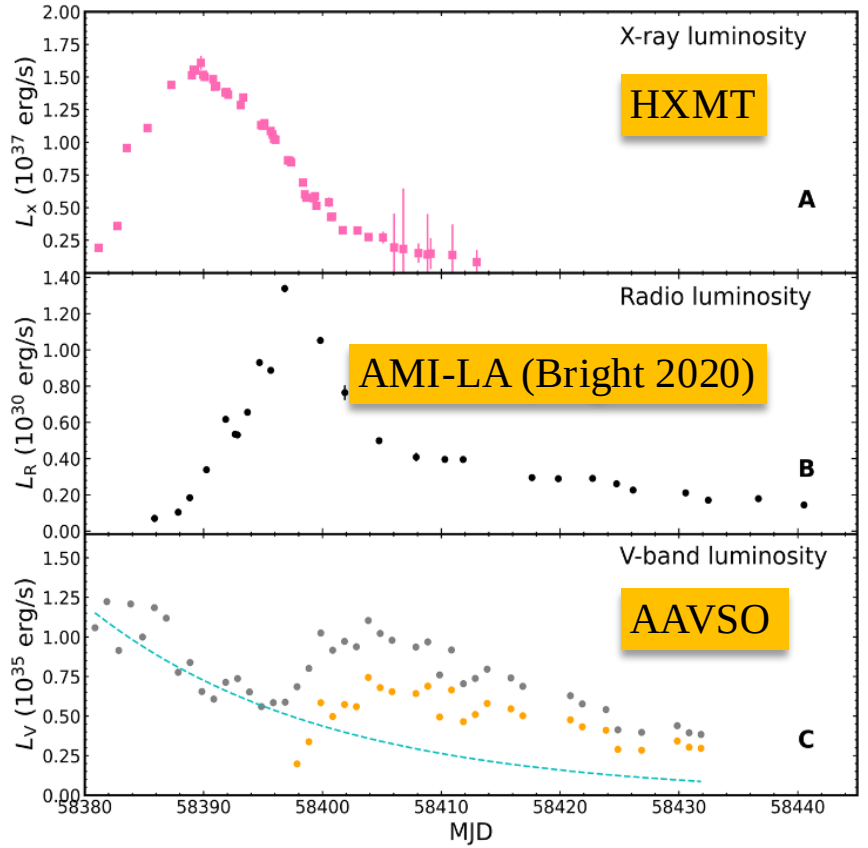
(II) Decaying hard state

Rising hard state (You et al., 2021)

Decaying hard state (You et al., 2023)

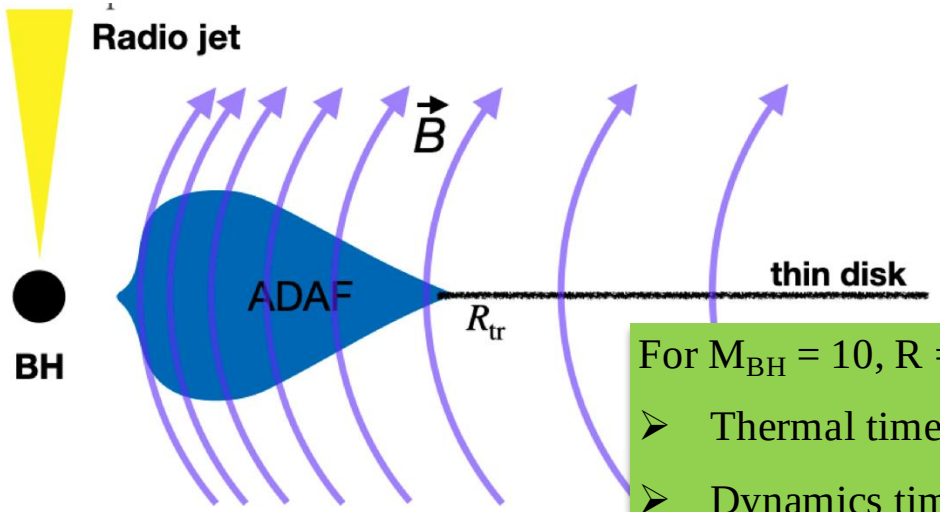






You et al., 2023, Science

Data and analysis



For M_{BH} = 10, R = 10 Rs:

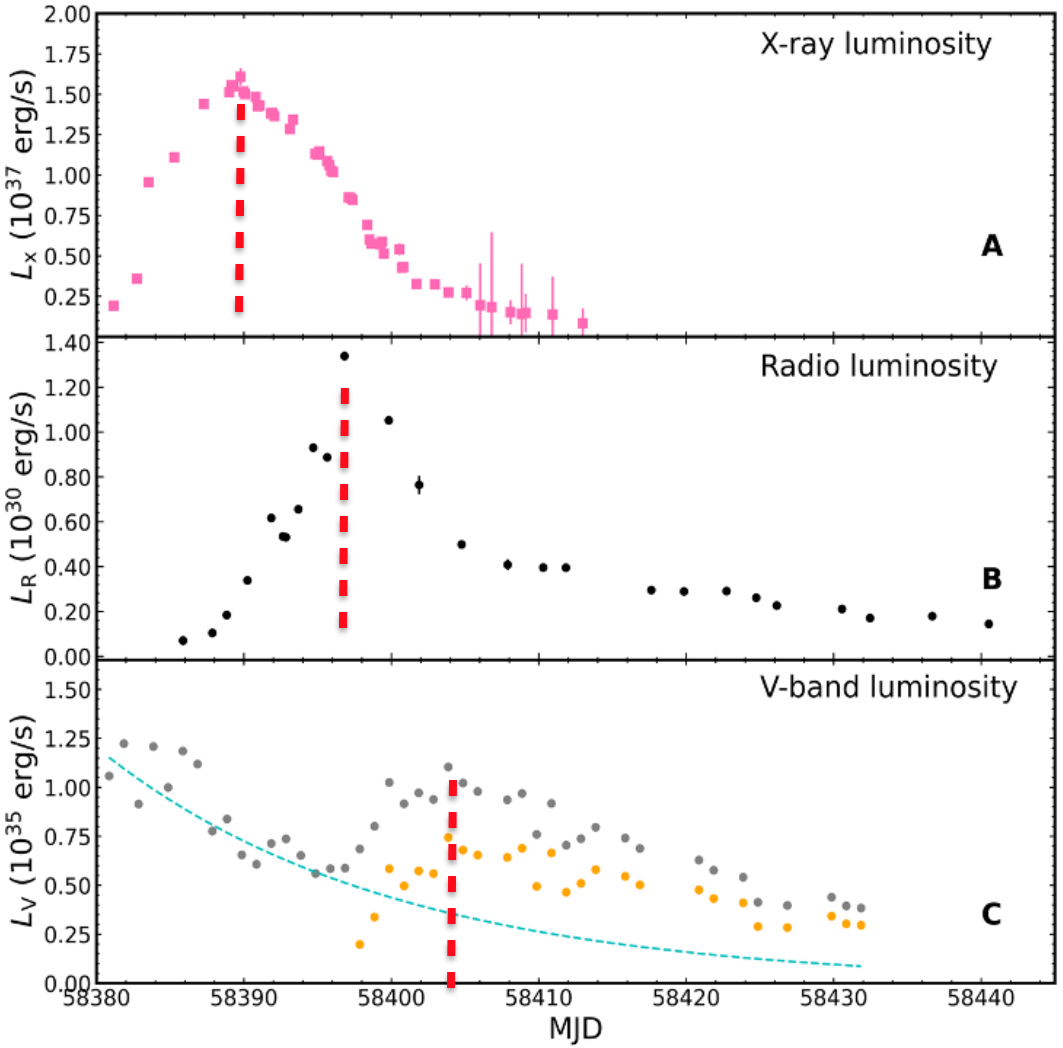
- Thermal timescale: ~ 10^{-7} days
- Dynamics timescale: ~ 10^{-6} days
- Viscous timescale: ~ 10^{-3} days

- Observational highlights:

  - Radio lags X-ray by ~ 8 days !
    - First detection in known BHXRBs

  → **Smoking-gun evidence: X-ray from ADAF, rather than jet !!!**

  - Optical lags X-ray by ~ 15 days !
    - First detection in known BHXRBs



→ **Suggest that Optical from disk, rather than ADAF/jet (possibility of the jet origin; Echiburú-Trujillo et al 2024)**

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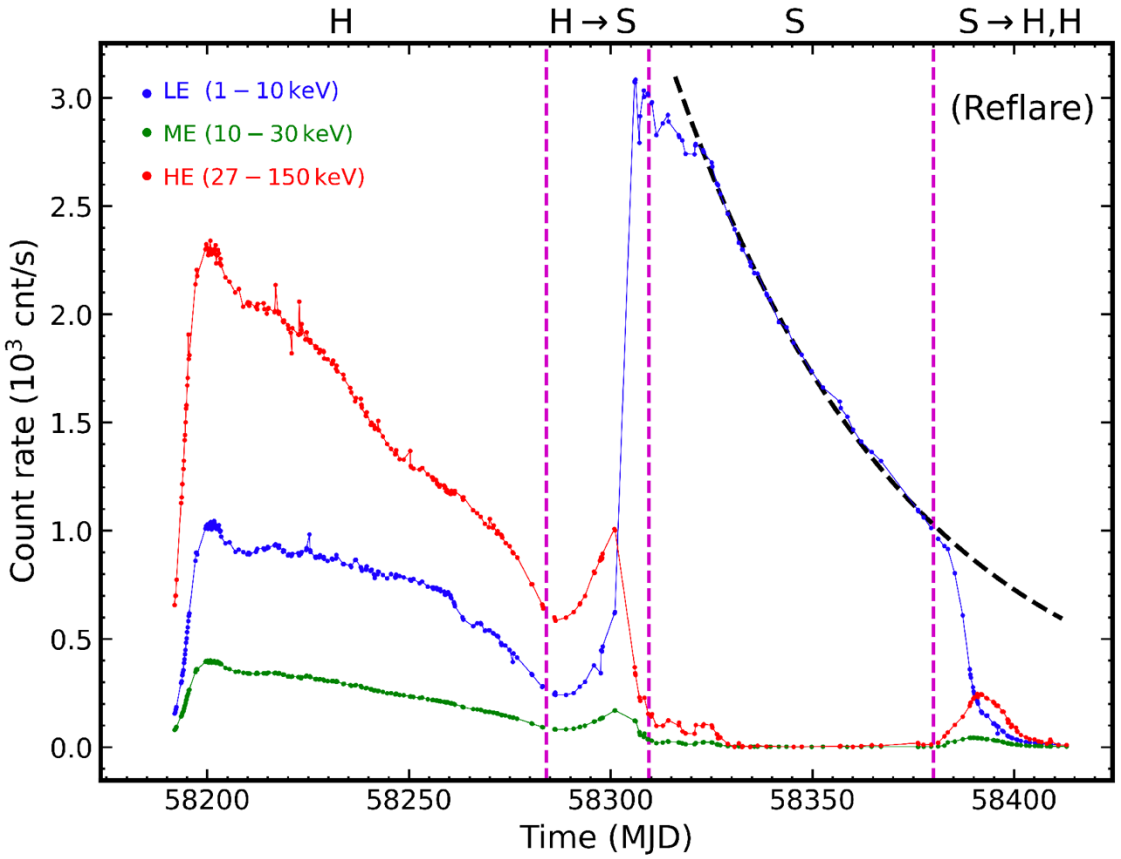
- Summary

Requires to directly answer the mechanism of:
- Hard X-ray Comptonization flare
- Radio flare
- Optical flare (no time in this talk)

Interpretation: X-ray flare



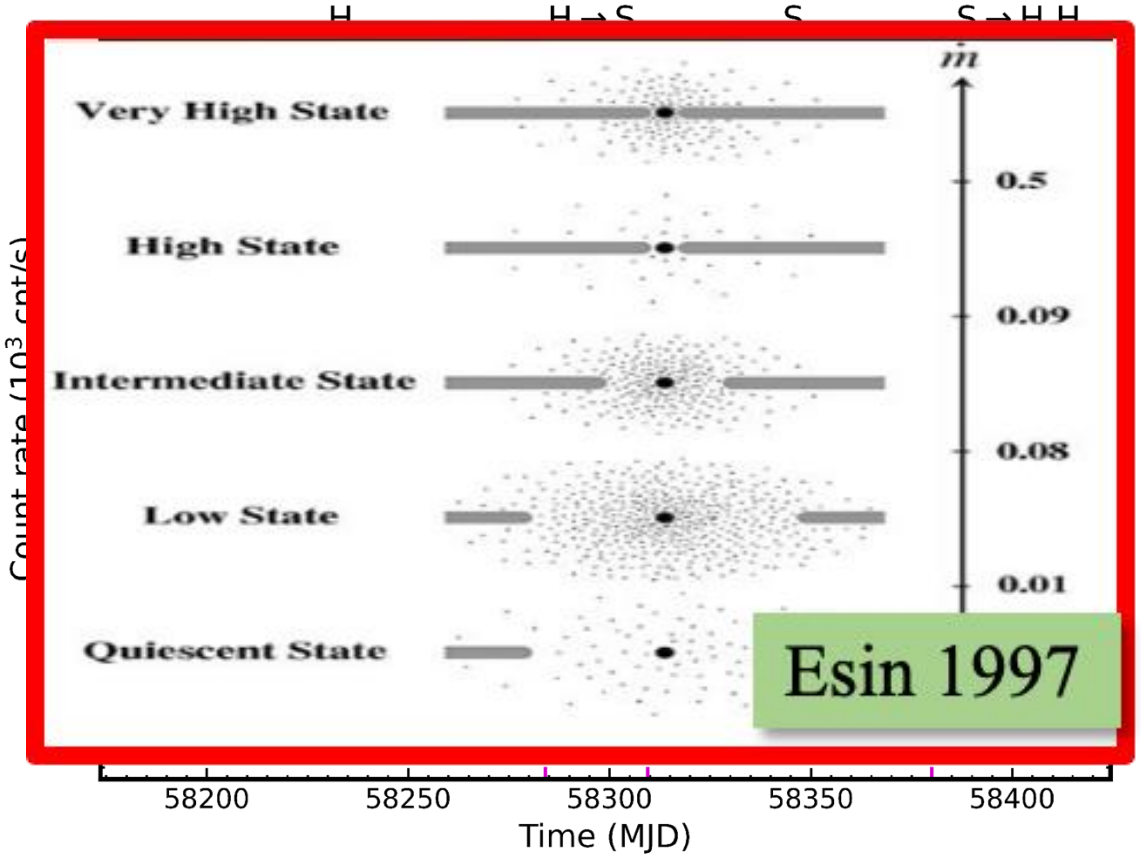
- The disk luminosity $\mathrm{L} = \eta \dot{\mathrm{M}} \mathrm{c}^2$

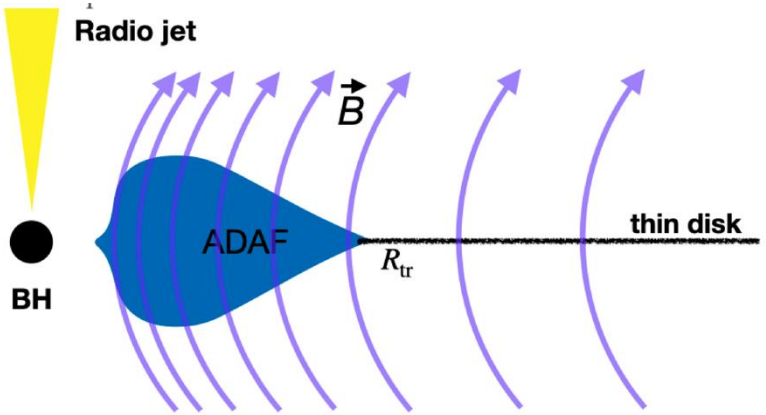
- In the soft state, both the disk luminosity and the mass accretion rate, exponentially decay

$$\exp[-(t - t_\bullet)/\tau]$$

- During the reflare, we assume mdot also follows the same exponential decay, then, $\dot{m}_{\mathrm{d}}(t)$ can be estimated

Interpretation: X-ray flare

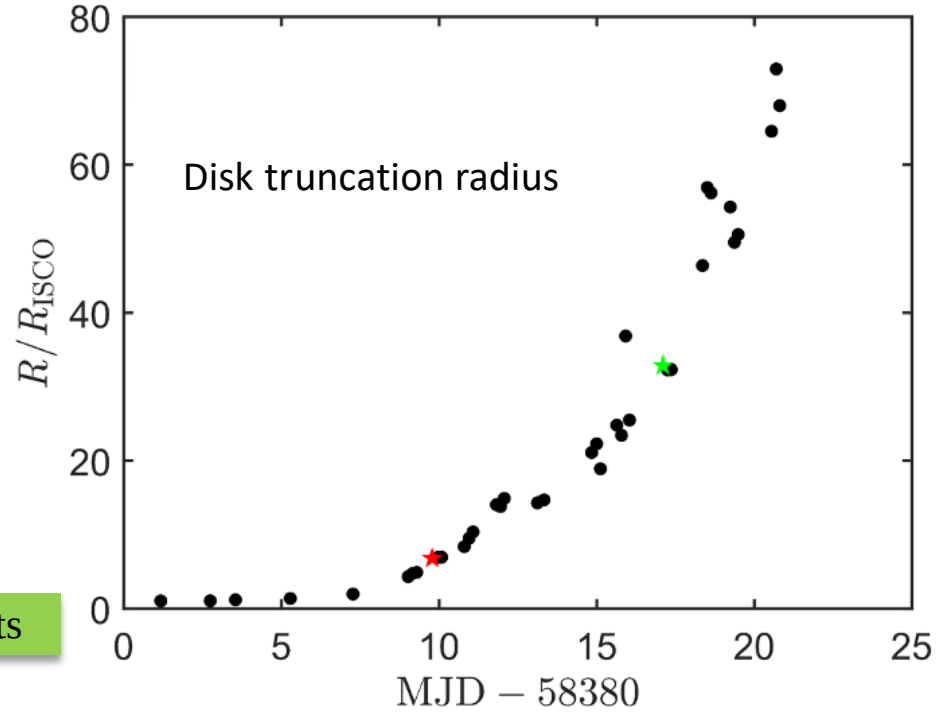




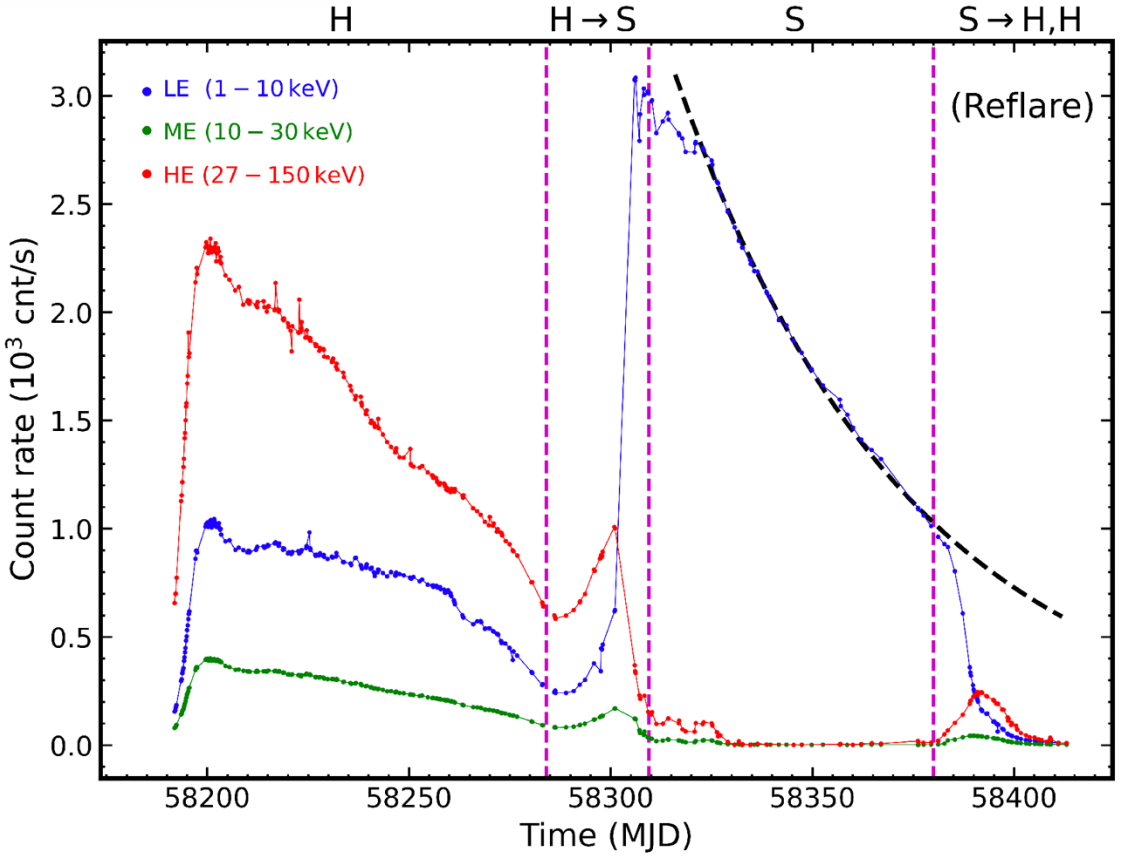
$$L_{\rm d}(t) \propto \frac{\dot{m}_{\rm d}(t)}{R_{\rm tr}(t)} \quad \Rightarrow \quad \frac{R_{\rm tr}(t)}{R_{\rm ISCO}} \simeq \frac{\dot{m}_{\rm d}(t) L_{\rm d}(t_0)}{\dot{m}_{\rm d}(t_0) L_{\rm d}(t)}$$

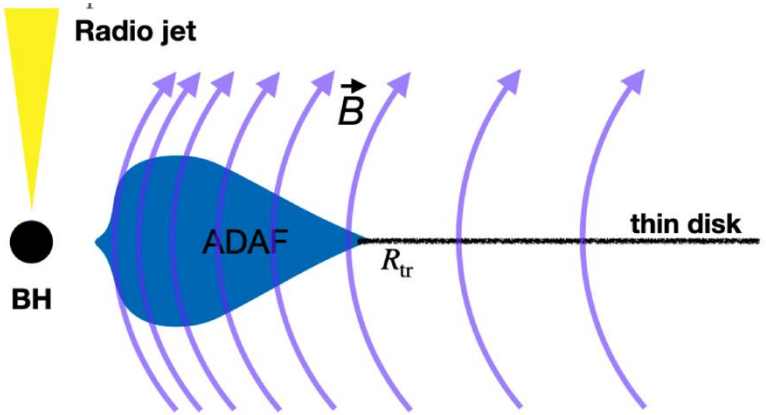
Assuming the disk inner radius = ISCO at t_0 (soft state)

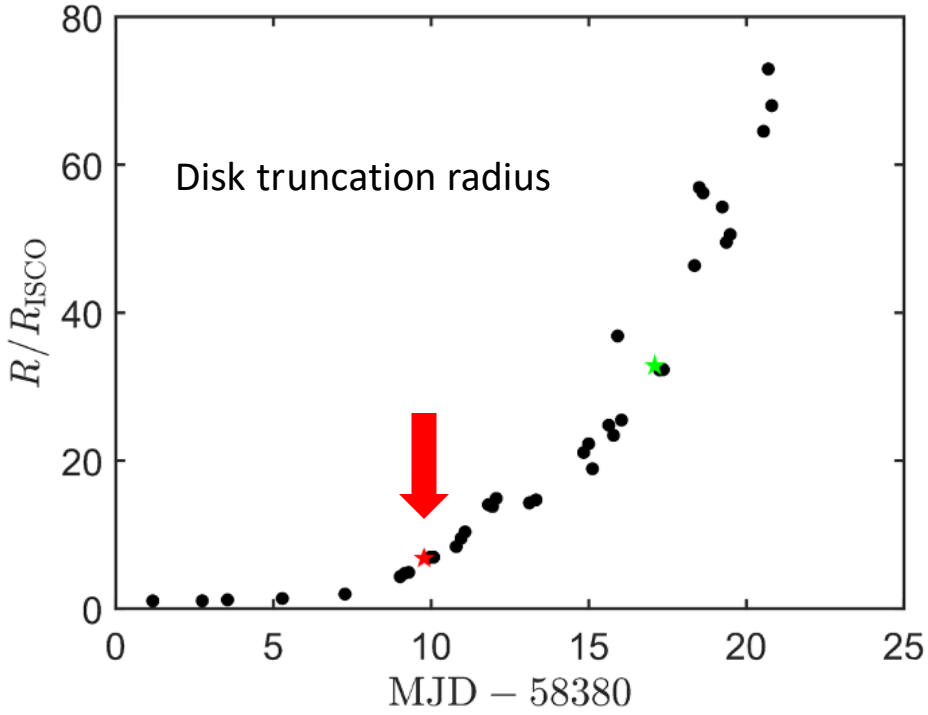
Disk luminosity from spectral fits



Interpretation: X-ray flare







- The Compton luminosity of ADAF:

$$F_X(t) \propto \dot{m}(t) R^{\alpha}(t) \uparrow \downarrow \text{, where } \alpha > 0$$

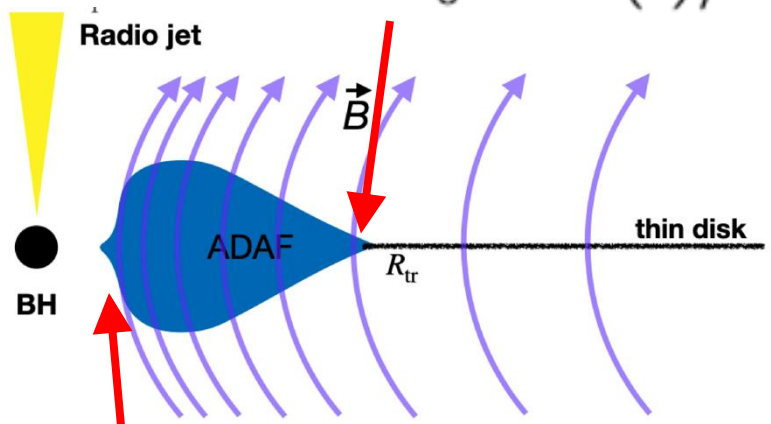
- Rtr increases with time, but Mdot decreases with time, so that hard X-ray flare

➢ After X-ray peaks at ~ MJD 58390, the ADAF keeps expanding !!!

Interpretation: Radio flare

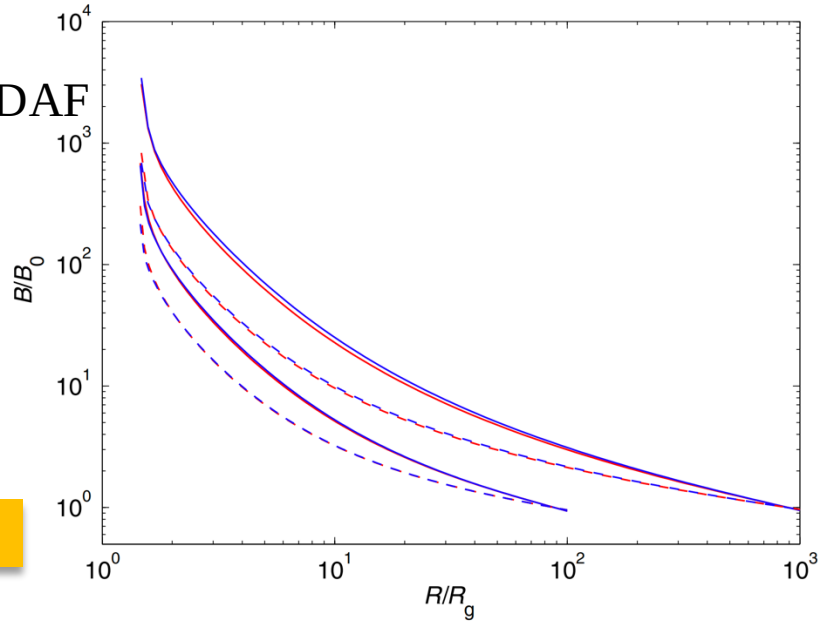
- We consider the magnetic field of the thin disk, which is generated through the inverse-cascade of the dynamo process

$$B_0 \propto \dot{m}(t)/R(t)$$



- Physically, the magnetic field will be efficiently dragged and accumulated within the ADAF due to large radial velocity
- The accumulated magnetic field near the BH are numerically calculated

$$F_{\mathrm{R}}(t) \propto B_{\mathrm{Z}}(t) \propto \dot{m}(t) R^{\beta}(t) \text{, where } \beta > 0$$



➢ Larger ADAF → Stronger B near the BH (size effect; Cao X.W. 2011)

Interpretation: Radio flare

- We consider the magnetic field of the thin disk, which is generated through the inverse-cascac

$$B_0 \propto \dot{m}(t)/R(t)$$

- The magnetic field will be efficiently dragged within the ADAF

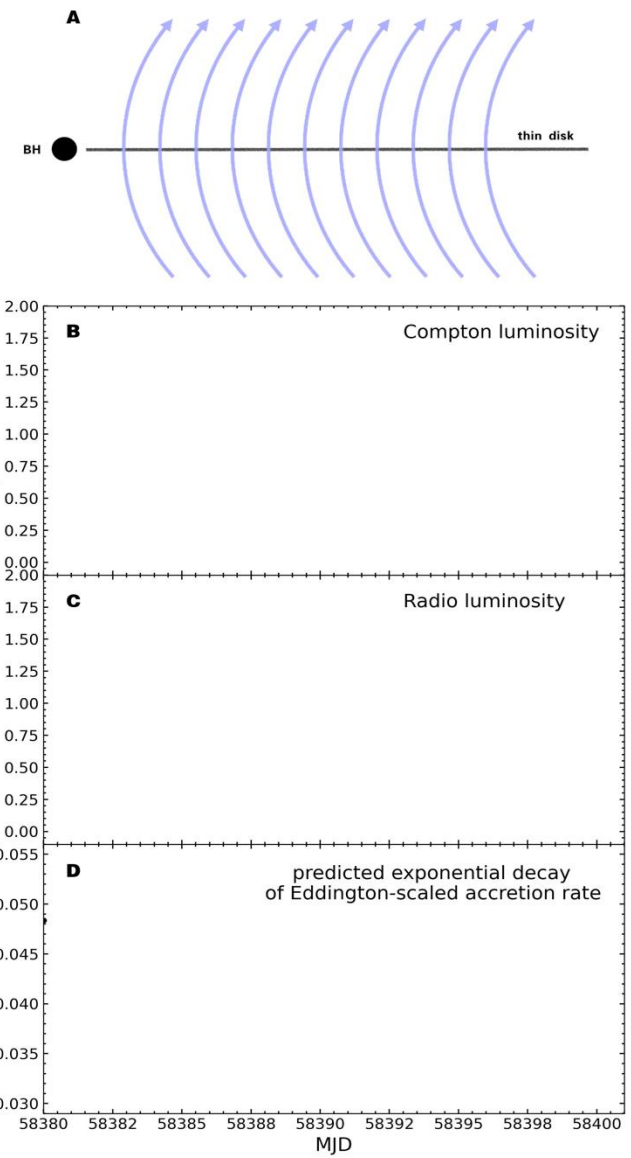
- The accumulated magnetic field near the BH can then be numerically calculated

$$F_{\mathrm{R}}(t) \propto B_{\mathrm{Z}}(t) \propto \dot{m}(t) R^{\beta}(t), \text{ where } \beta > 0$$

➢ Larger ADAF ⟶ Stronger B near the BH

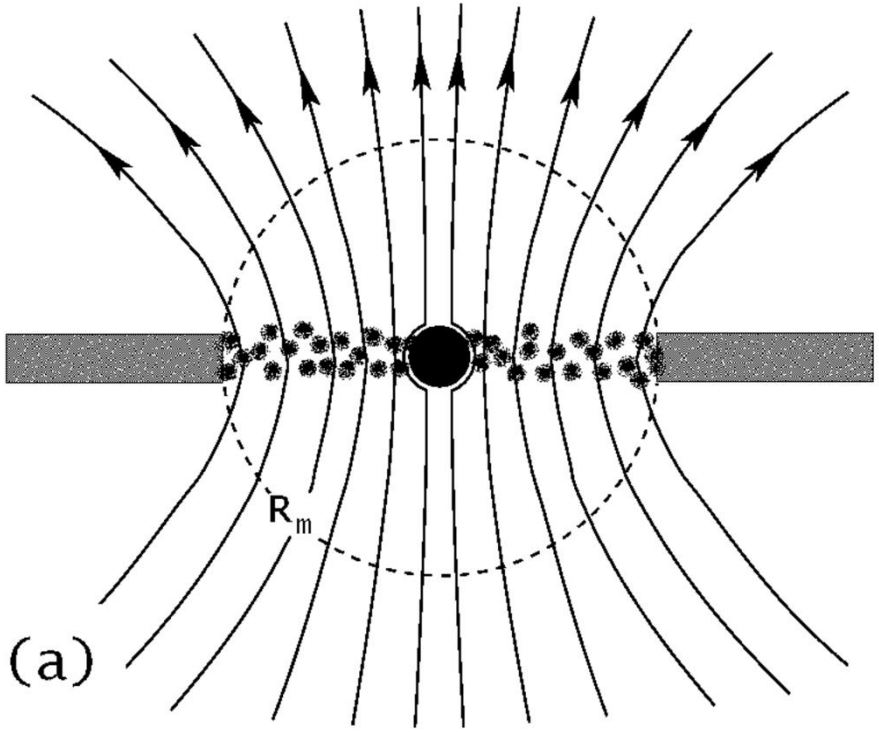
- Recall that, after X-ray peaks, the ADAF keeps expanding
  - Thus, B is continuously amplified due to "size effect", radio emission keeps increasing

- After 8 days, radio peaks !!!, when the decrease in the accretion rate becomes dominant.



Interpretation: MAD

- Magnetically Arrested Disk (Narayan 2003)

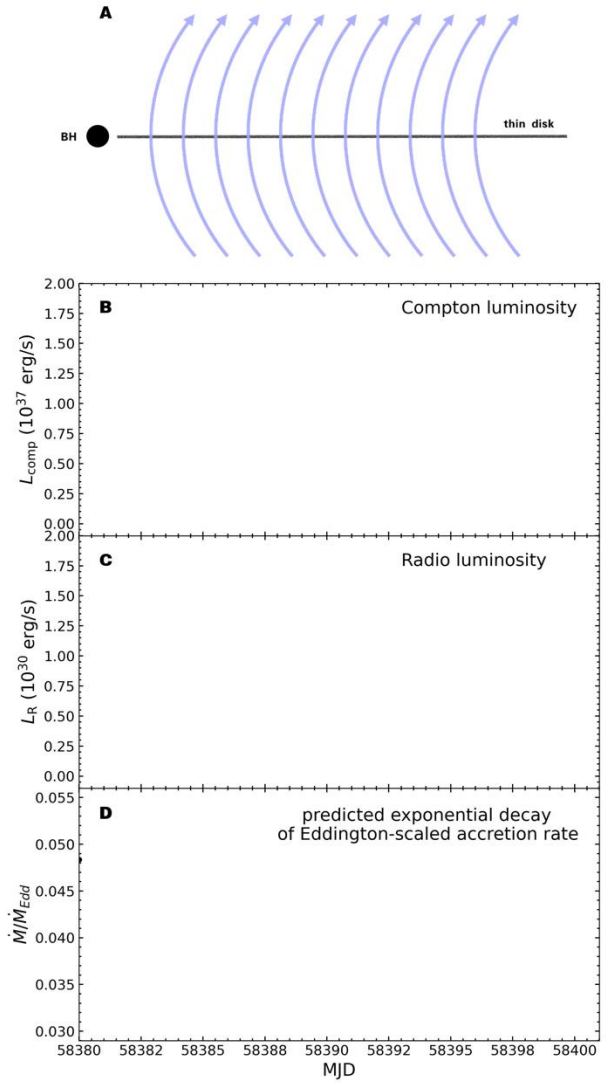


$$GM\Sigma/R^2 \sim 2B_R B_z/4\pi \sim B_z^2/2\pi \longrightarrow B_{\rm MAD} \sim 1.5\times10^9(1-f_\Omega)^{1/2}\epsilon^{-1/2}m^{-1/2}\dot{m}_{\rm ADAF}^{1/2}(R)R^{-5/4}$$

The critical B-field for a MAD

Interpretation: MAD

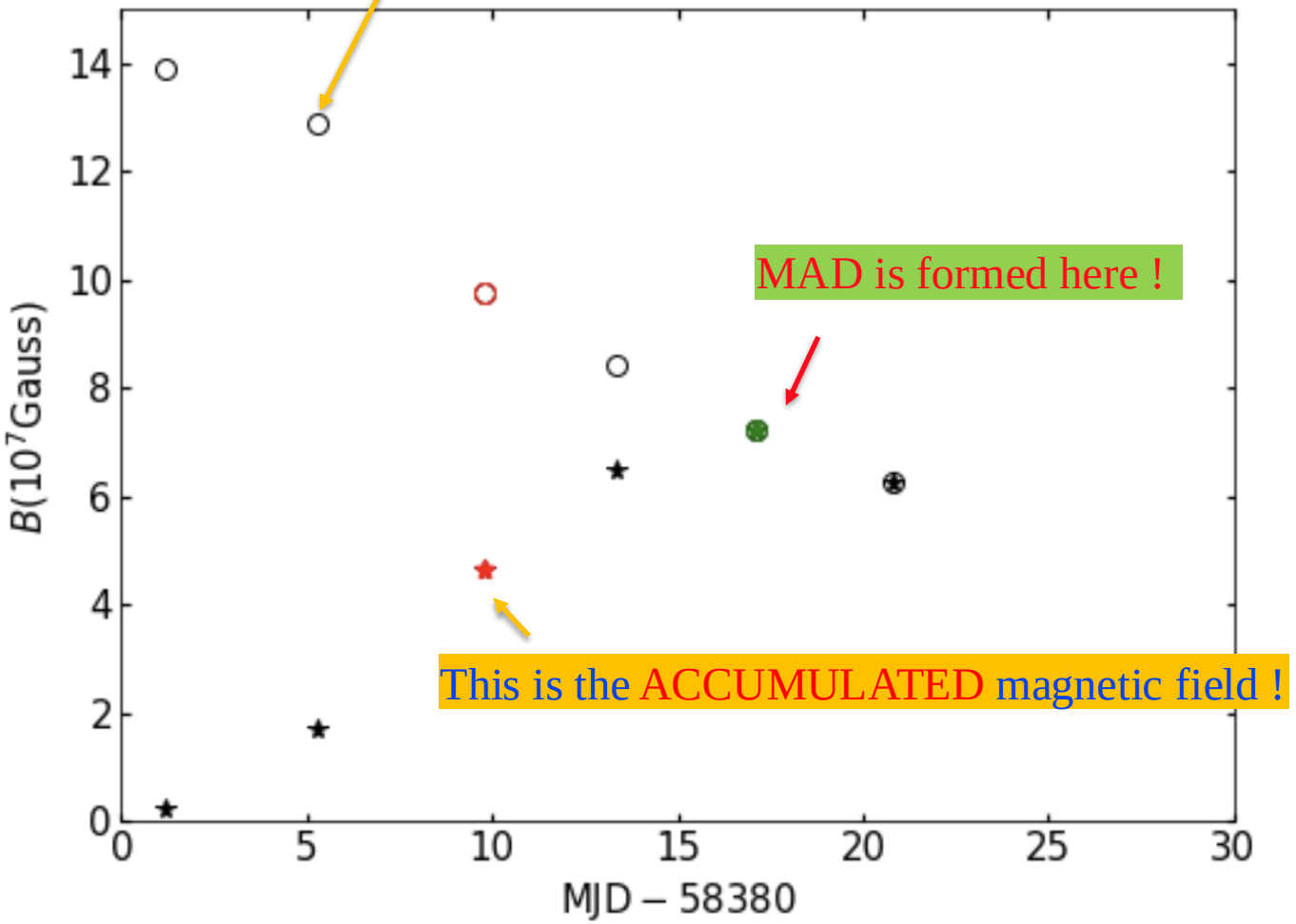
- MAD is being formed during the decaying hard state in MAXI J1820



This is the CRITICAL magnetic field of MAD !

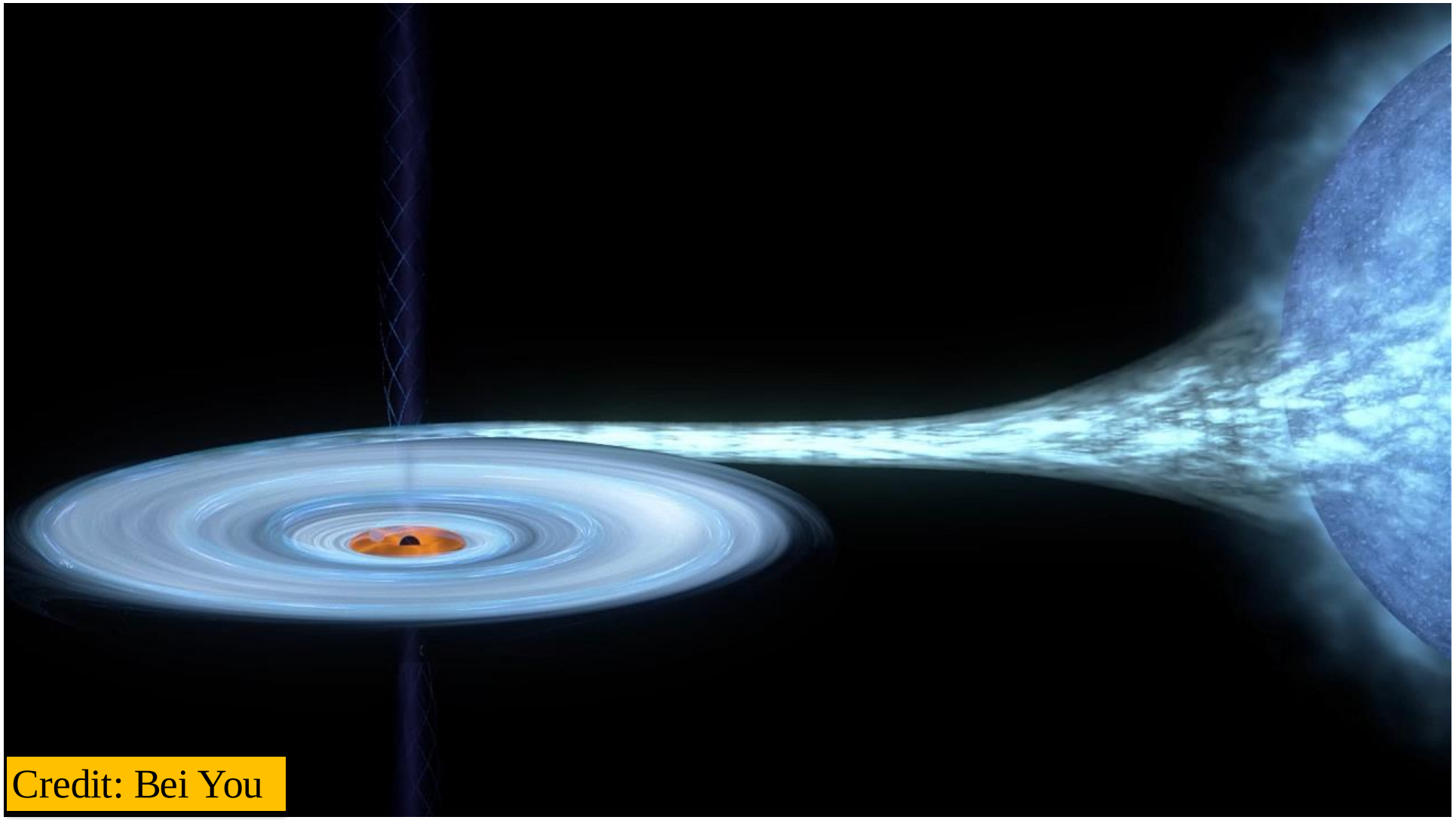
MAD is formed here !

This is the ACCUMULATED magnetic field !



Formation of a MAD

This is what was happening during the decaying hard state of MAXI J1820+070:



Credit: Bei You

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- Summary

TAKE-AWAY MESSAGES

- Observationally, we report (i) weakening of the reflection during the rising hard state; (ii) unprecedented long delays of radio (～ 8 days) and optical flares (～ 15 days), with respect to the hard X-ray flares

(1): Origin of the observed hard X-ray and optical/IR ?

⇨ During the decaying hard state of J1820, hard X-ray from ADAF; probably Optical from disk

(2): How do the accretion flows evolve during the outburst ?

⇨ As mdot decreases, the truncation radius increases, i.e., receding disk

(3): How is the magnetic field transferred towards BH to be strong?

⇨ The B-field generated in the disk is efficiently dragged towards BH, via ADAF

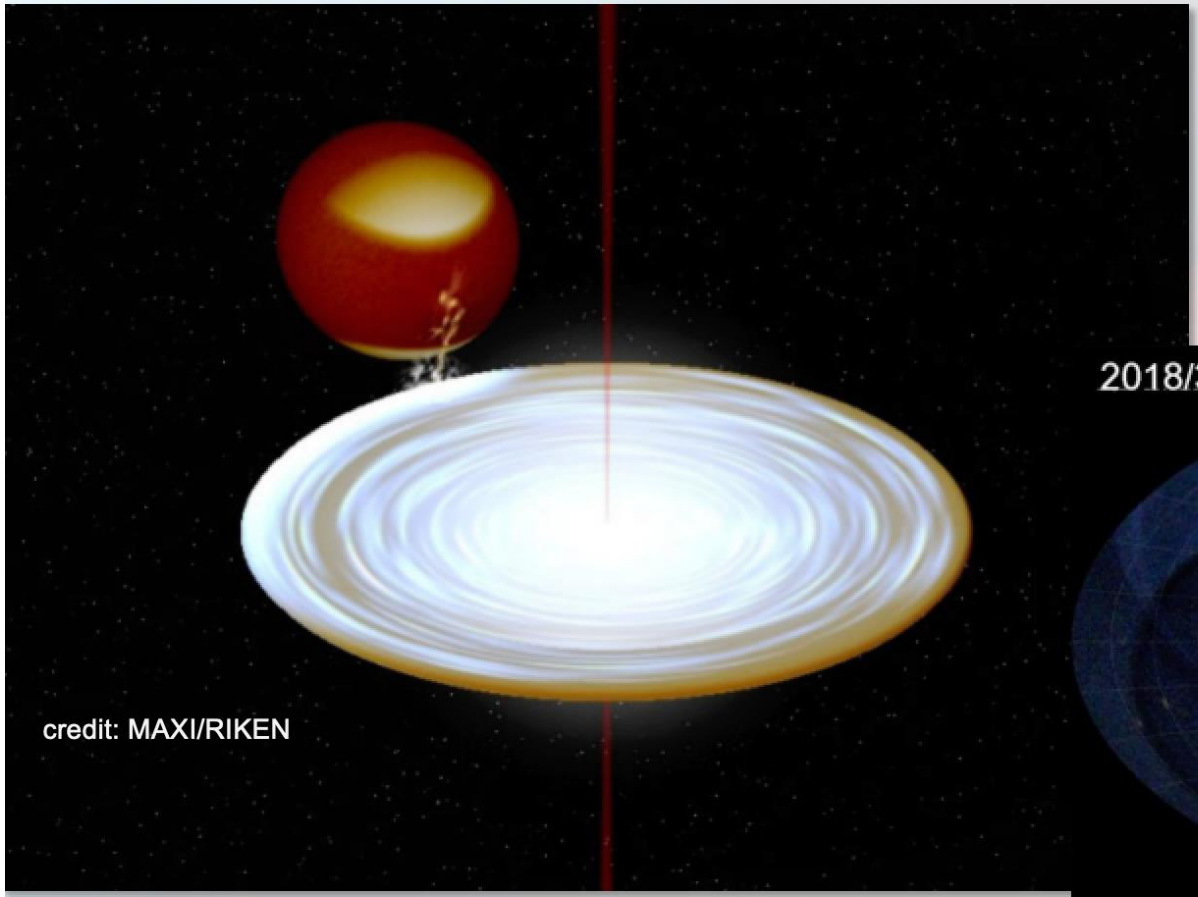
(4): MAD in BHXRB ? How is MAD formed ?

⇨ Yes ! MAD in BHXRB (decaying phase); And, expanding ADAF leads to the forma

Thank you for your attention ! (youbei@whu.edu.cn)

- **The 2018 outburst of J1820+070 by MAXI/Swift**

MAXI J1820+070

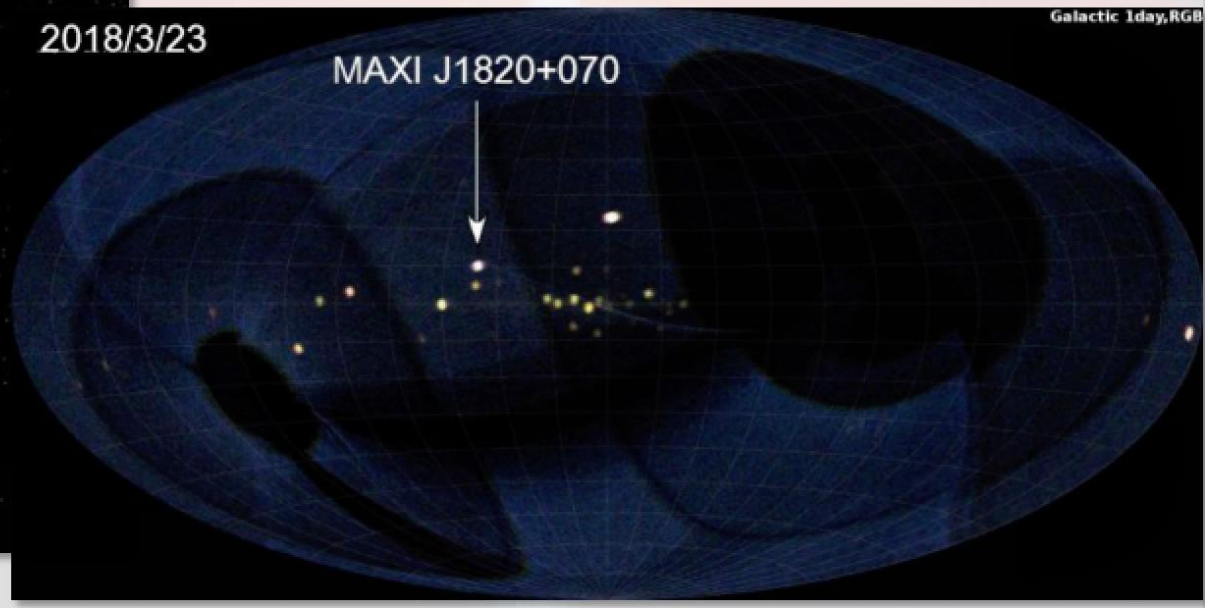


Orbital period = 0.68549 days (Torres et al. 2019)

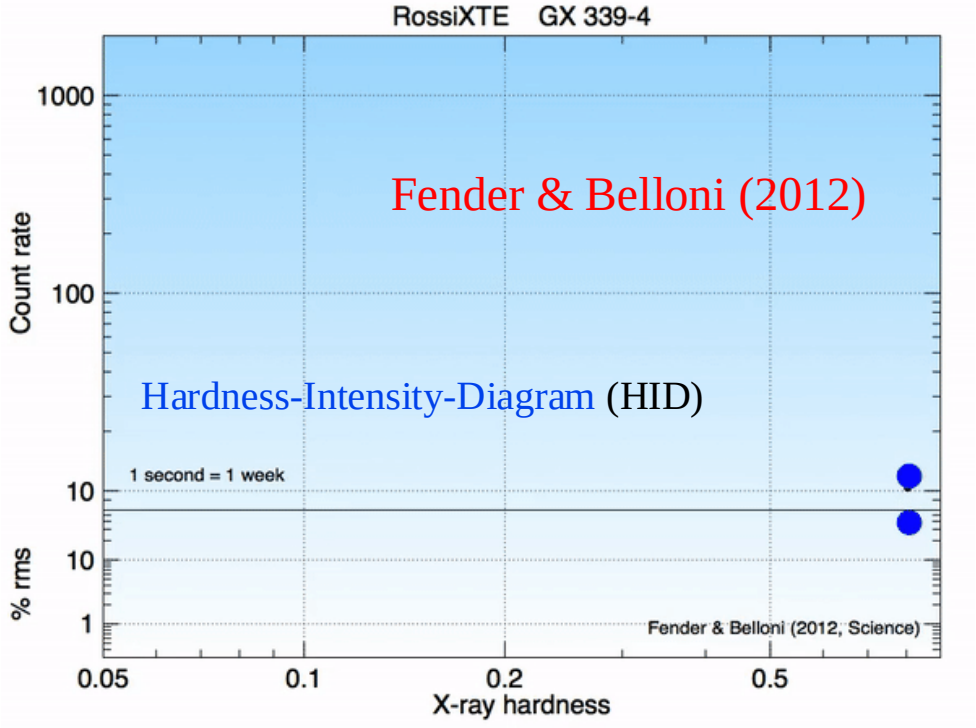
BH mass = 8.48±0.79 $M_{\odot}$ (Torres et al. 2020)

Jet inclination=63 ± 3° (Atri et al. 2020)

Distance = 2.96 ± 0.33 kpc (Atri et al. 2020).



- 100+ papers published, Nature and Science (3+3)



- **The disk wind has been observed and widely studied (Miller et al., 2008; You et al., 2016)**
- **Is the corona outflowing or not ?**

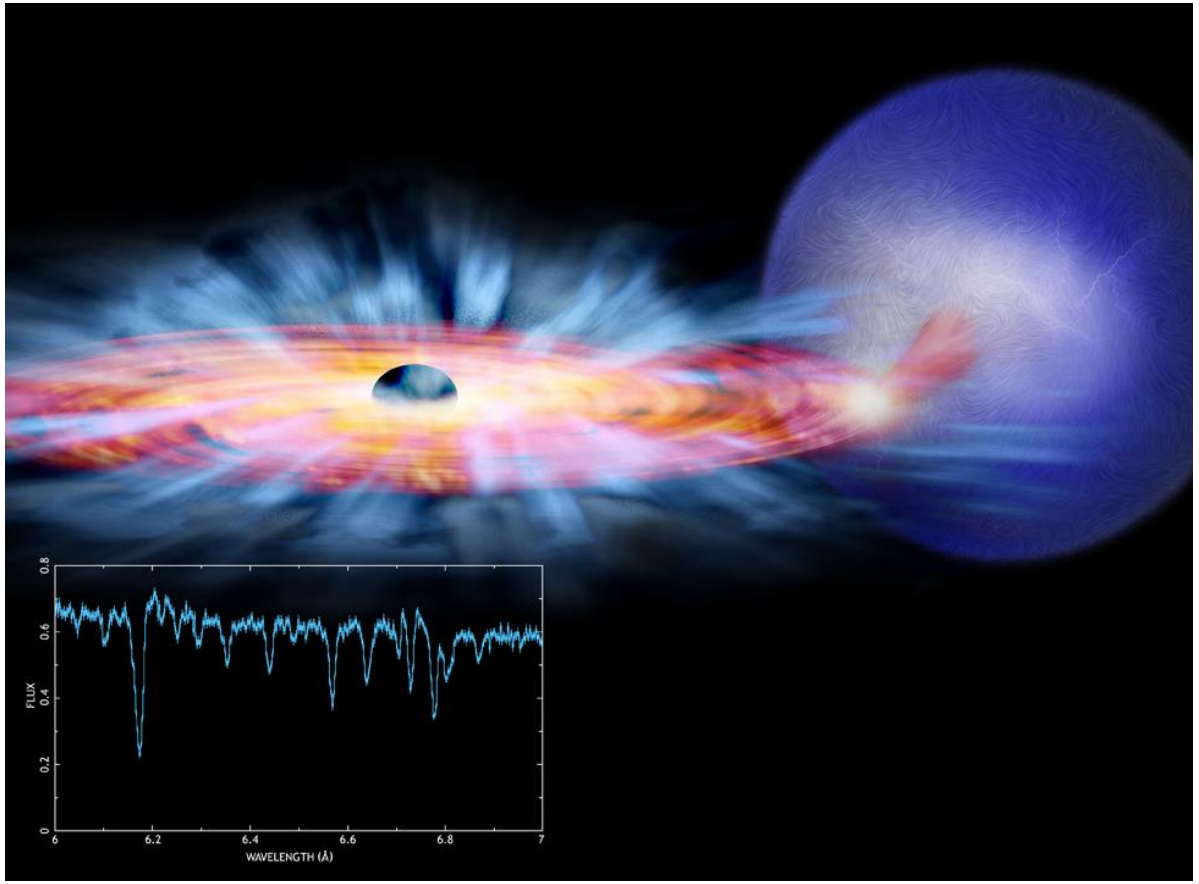


Illustration: NASA/CXC/M.Weiss;
X-ray Spectrum: NASA/CXC/U.Michigan/J.Miller et al.