

Modeling the Unexpected Light Curves of IMBH–TDE EP240222a

Wenkai Li, Ning Jiang, Tinggui Wang, Rongfeng Shen, Erlin Qiao,
Lixin Dai, Di Luo, Dongyue Li, Chichuan Jin, Jiazheng Zhu



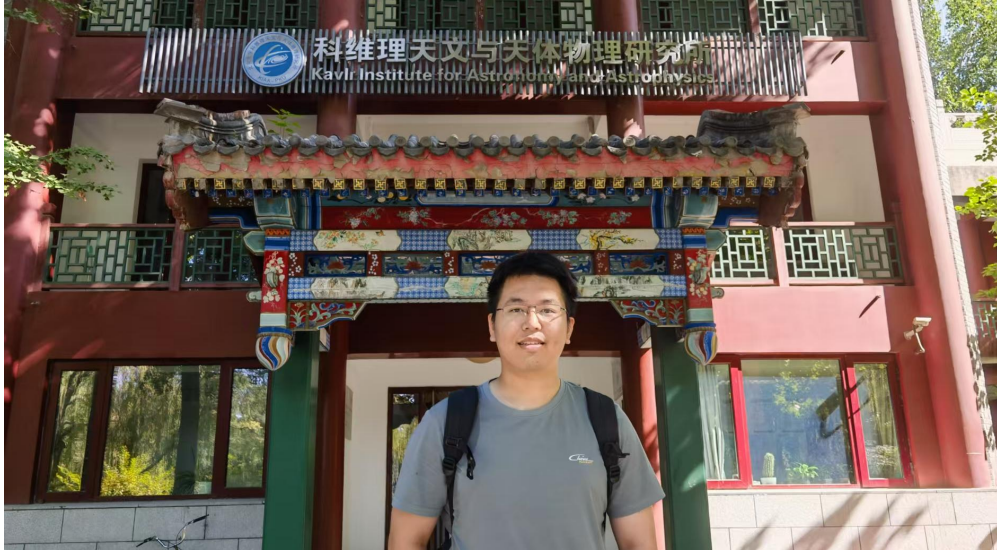
Inefficient Circularization, Delayed Stream–Disk Interaction and Reprocessing: A Five–Stage Model for the IMBH–TDE EP240222a



MS-IMBH-TDE: Slow Rise
WD-IMBH-TDE: Fast Rise
Stream-Disk Interaction: Turning Point

Self-Introduciton

Wenkai Li (李文楷)



USTC Undergraduate

Advisor: Ning Jiang, Ann Zabludoff

Current Research Focuses:

Tidal Disruption Events (TDEs)

Intermediate-mass Black Holes (IMBHs)

Post-Starburst Galaxies (PSBs)

Research Interest:

Various Astrophysical Phenomena :D

Hobby:

Star Party, Travel, Daily Photography

All Kinds of Sports: Cue Sports,
Armrestling etc. (after my ACL injury)



Astronomy Photographer of the Year (shortlist, 2017)



JUPITER AND ITS MOONS

Kevin Li (China), aged 14
Shenzhen, Guangdong Province, China, 4 April 2017

I took this photo when Jupiter was in a favourable opposition on 4 April, on the balcony of my home in Shenzhen, China. Jupiter is one of my favourite planets, not only because of its changeable cloud band and the Great Red Spot but also because of its four famous moons. The buildings in front of my balcony were a big challenge for this photograph. My parents were also 'big challenges' for me, since I had to go to school the next day, so they wanted me to go to bed early! The seeing was great, so I used a Barlow 3X lens with a ZWO ASI120MM camera on my Sky-Watcher BKP 150/750 telescope. The Sky-Watcher EQ3-D

mount can't 'go-to', so I had to find Jupiter manually. Because I used a monochrome camera, I used LRGB (luminance, red, green and blue) filters in order to show colour. For processing, I used AutoStakkert!2 to stack them. Then, I used Registax 6 to sharpen the image. After that, I used Astra Image to combine the LRGB. I also used it to wavelet sharpen and de-noise. I processed Jupiter and its moons individually. Finally, I used Adobe Photoshop to combine Jupiter and its moons. I love this photo because if you look at the picture carefully, you can see that the Jupiter and its moons are colourful!

Sky-Watcher 150 mm f/5 reflector telescope at f/15, Barlow x3 lens, Sky-Watcher EQ3-D mount, ZWO ASI120MM camera, stacked from multiple exposures



RAY CRATER LANGRENUS

Kevin Li (China), aged 14
Shenzhen, Guangdong Province, China, 1 April 2017

I took this photo during a clear dusk on the balcony of my home in Shenzhen, China. The Sun had gone down just about an hour ago. I had to take the photo so early because the Moon was about to be blocked by skyscrapers! So I prepared quickly and started to take the picture at once. The Moon is the closest celestial body to Earth. It is fantastic and mysterious! Although I have observed it many times, I will never grow tired of it. Luckily,

the seeing was fantastic at that time, so I tried to use Barlow 2X and Barlow 3X lenses together on my telescope for the first time! I shot about 2,000 frames and used AutoStakkert!2 to align them, and chose about 50% to stack. Then, I used Registax 6 to sharpen the image. After that, I used Astra Image to wavelet sharpen and de-noise. In addition, Adobe Photoshop CS5 was used to lift brightness. Because the focal length was large and the seeing was good, the details of the Ray Crater Langrenus seem very impressive. I will try to take a far more detailed picture next time!

Sky-Watcher 150 mm f/5 reflector telescope at f/30, Sky-Watcher EQ3-D mount ZWO ASI120MM camera, stacked from multiple exposures

Content

- ABC for IMBHs
- ABC for TDEs
- IMBH-TDEs
- IMBH-TDE (EP240222a) Model
- Summary

ABC for IMBHs

An important and rarely found class of black holes (BHs).

Observed Mass Ranges of Compact Objects



Neutron Star



Stellar Black Hole



Intermediate Mass Black Hole



Supermassive Black Hole



$1e2-1e5$ solar mass

White Dwarf

Stellar-mass BH

few candidates some candidates sufficient evidence SMBH

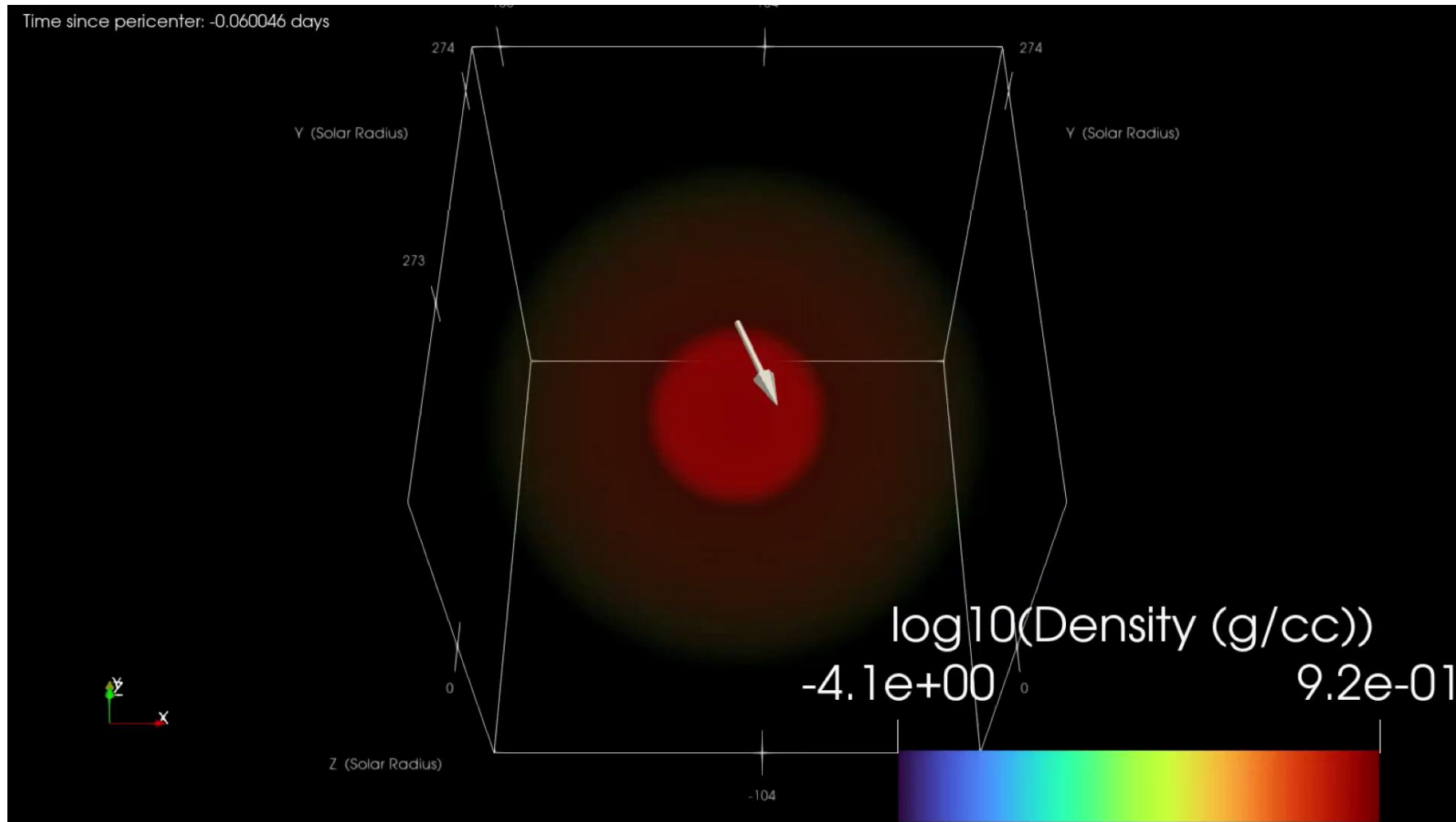


Object Mass
(Relative to the Sun)

ABC for TDEs

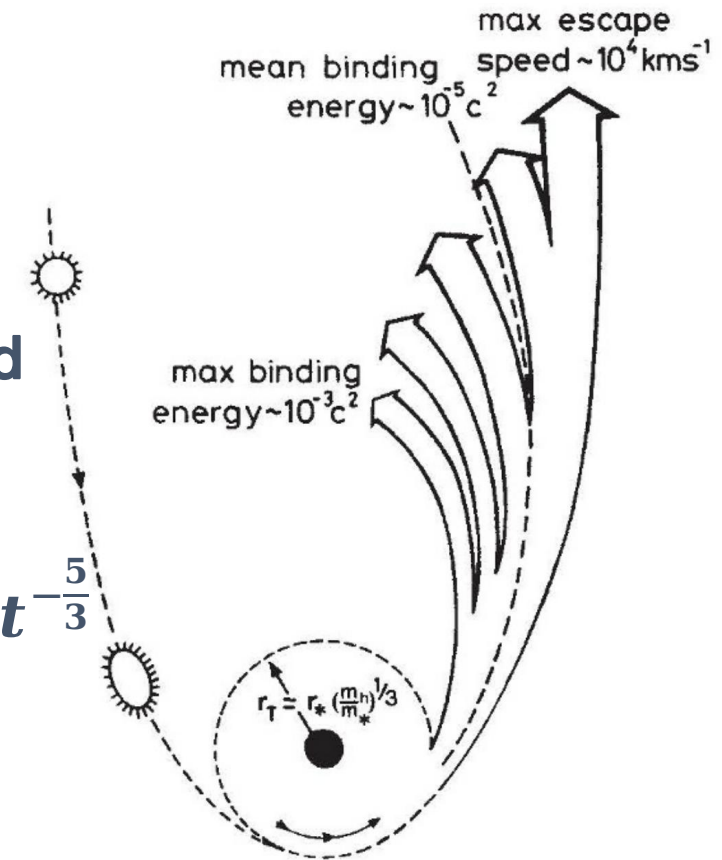
A star disrupted by a black hole (BH).

Intuitive Simulation Animation

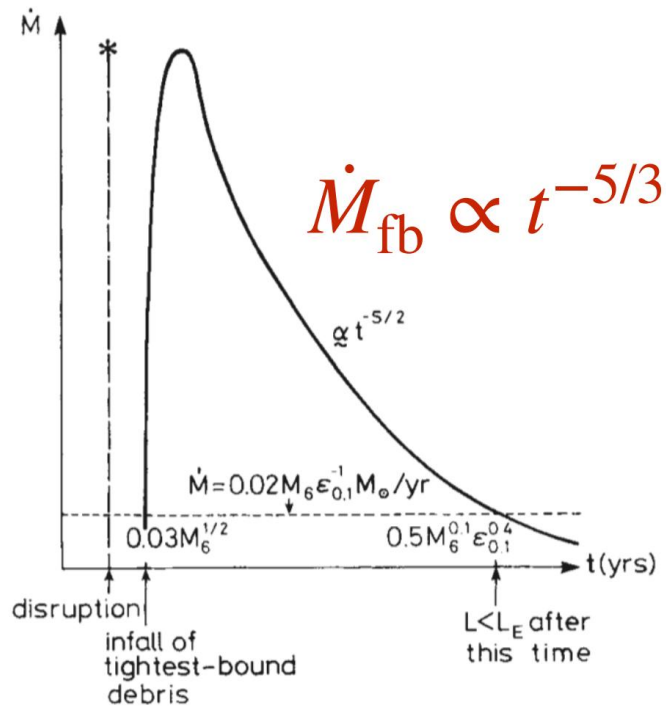


Classical Model

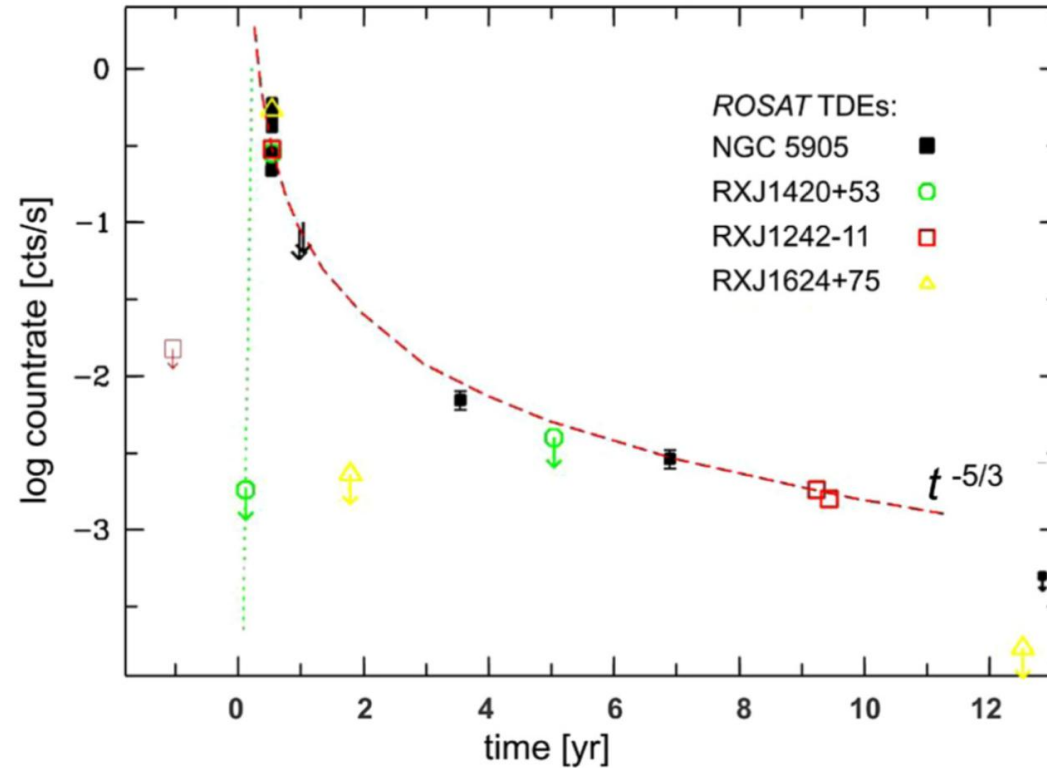
1. Stellar scattered to SMBH (loss cone)
2. Tidal stretching & compression
3. Pericenter radius < tidal radius \rightarrow disruption
4. Near-parabolic \rightarrow ~50% bound, ~50% unbound
5. Quick circularization? & quick accretion?
6. $L \propto \dot{M}_{acc} \propto \dot{M}_{fb}$ & $\frac{dE}{dM} = Const \rightarrow L \propto t^{-\frac{5}{3}}$
(timescale: months–years)
7. Multi-color BB disk? \rightarrow (UV/soft X-ray)



Classical Model

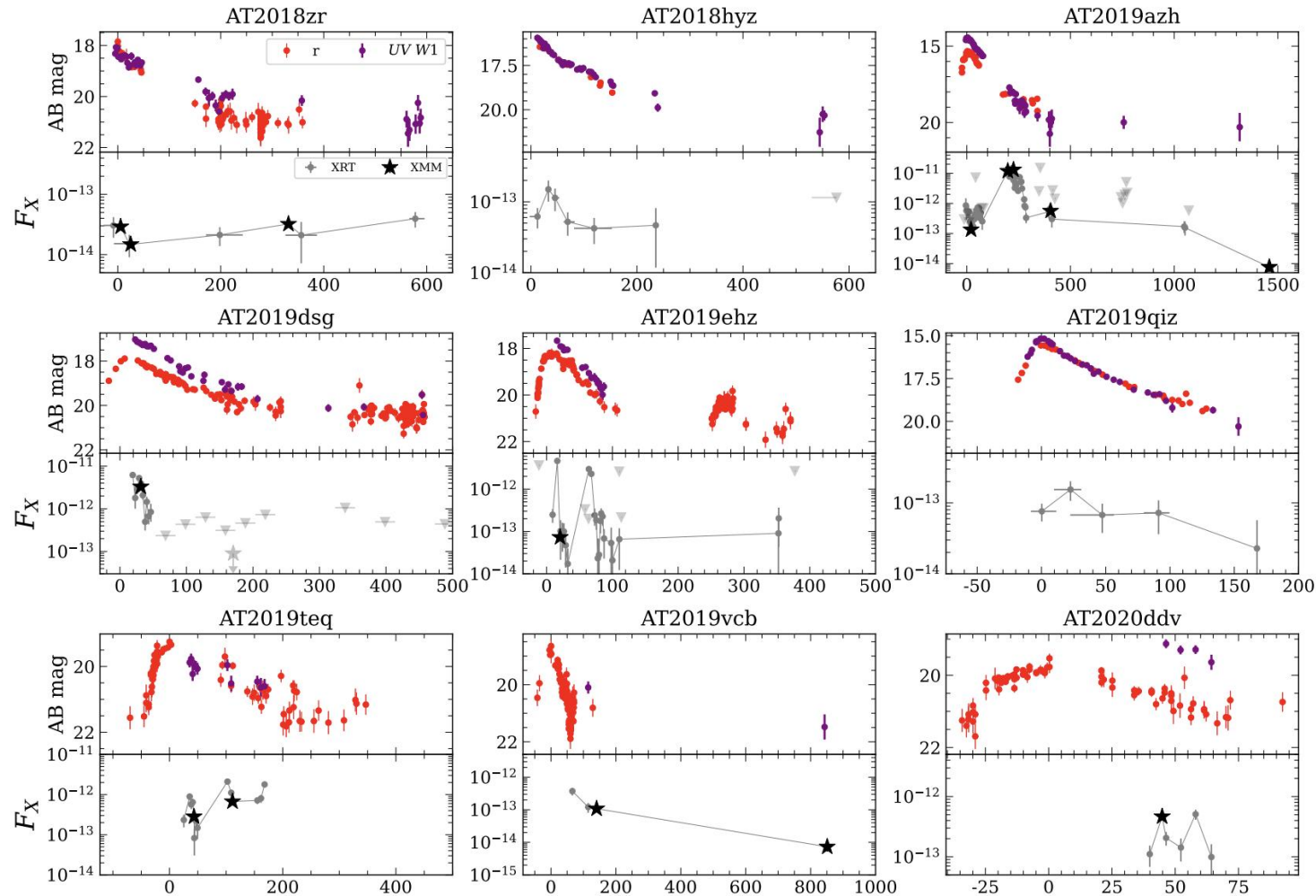


M. Rees, 1988



S. Komossa, 2015

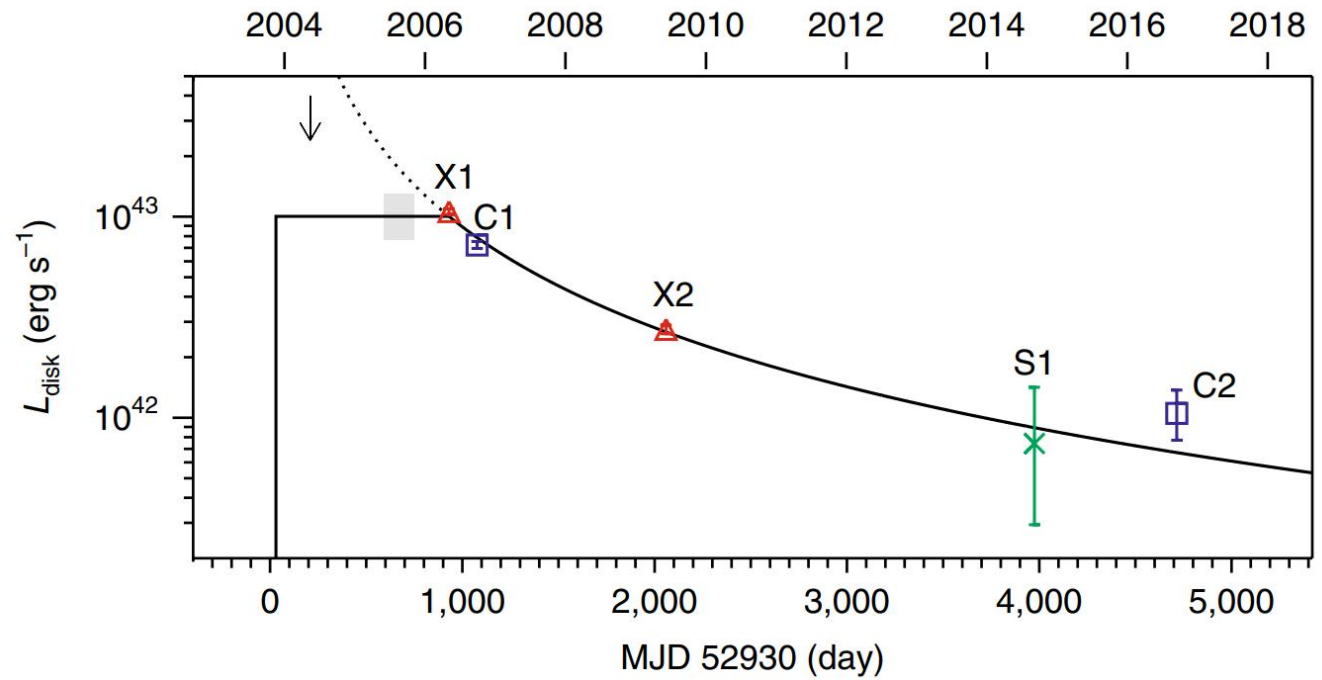
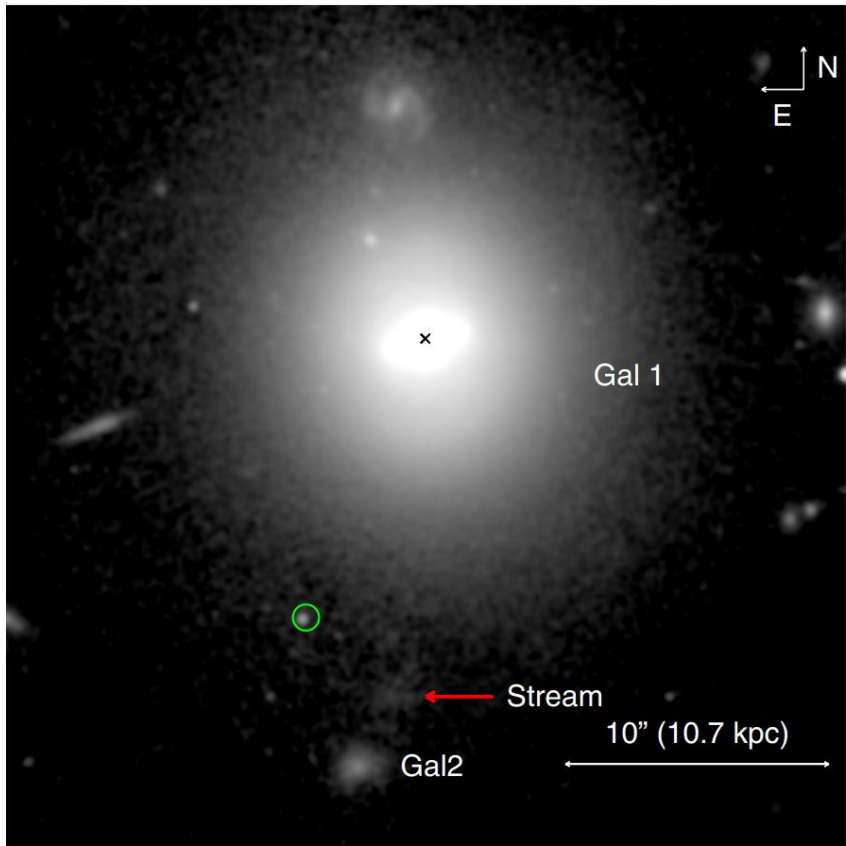
Real Light Curves (Intuitive Impression)



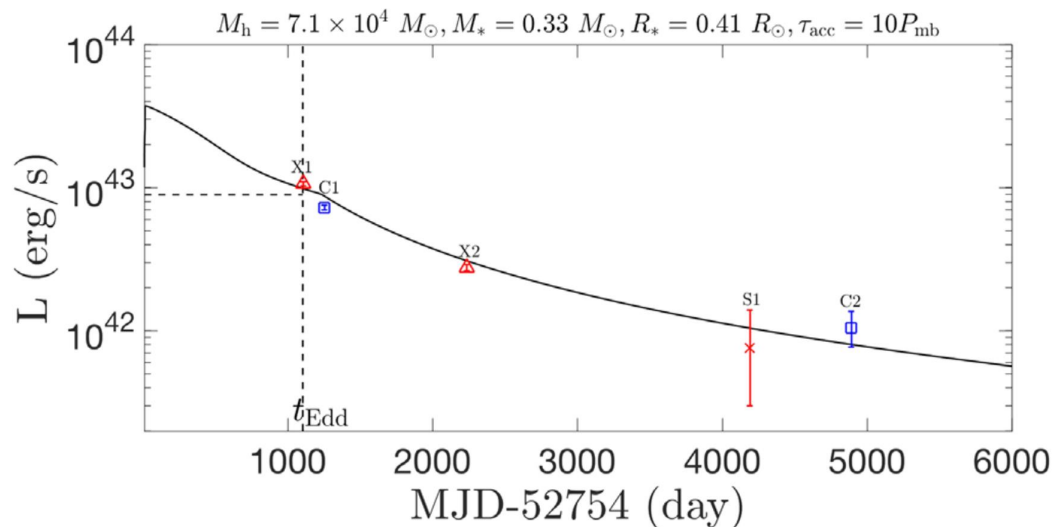
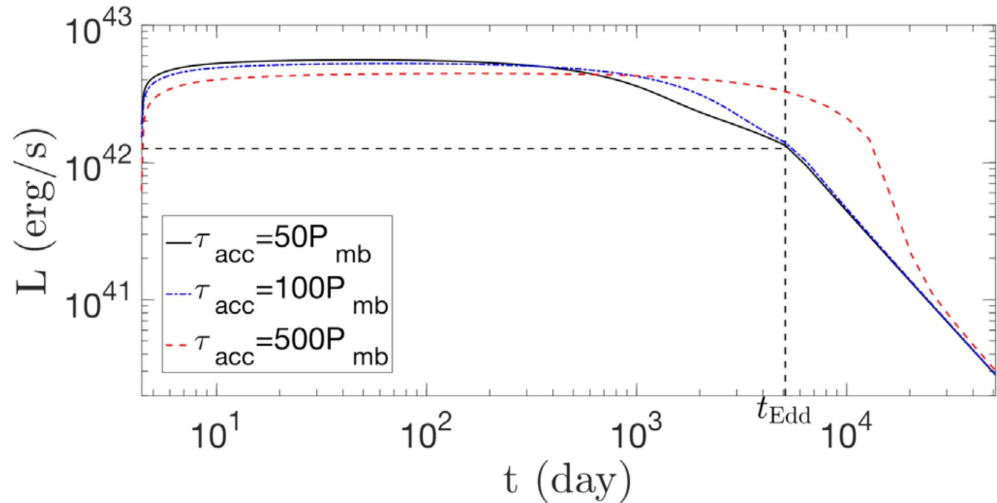
IMBH-TDEs

A very new and interesting field.

IMBH-TDE Candidate: 3XMM J215022.4-055108



IMBH-TDE Candidate: 3XMM J215022.4-055108



$$\frac{dM_d(t)}{dt} + \dot{M}_{\text{acc}}(t) = \dot{M}_{\text{fb}}(t)$$

$$\dot{M}_{\text{acc}}(t) = \frac{M_d(t)}{t_{\text{acc}}} = \frac{1}{t_{\text{acc}}} \left(e^{-t/t_{\text{acc}}} \int_{t_{\text{fb}}}^t e^{t'/t_{\text{acc}}} \dot{M}_{\text{fb}}(t') dt' \right)$$

$$L_{\text{bol}}(t) \simeq \begin{cases} [1 + \ln(\dot{M}_{\text{acc}}(t)/\dot{M}_{\text{Edd}})] L_{\text{Edd}}, & \dot{M}_{\text{acc}}(t) \gtrsim \dot{M}_{\text{Edd}} \\ (\dot{M}_{\text{acc}}(t)/\dot{M}_{\text{Edd}}) L_{\text{Edd}}, & \dot{M}_{\text{acc}}(t) \lesssim \dot{M}_{\text{Edd}} \end{cases}$$

- **~ 200 eV**
- **Candidate from historical data**
- **No early stage light curves**
- **No spectroscopic confirmation**

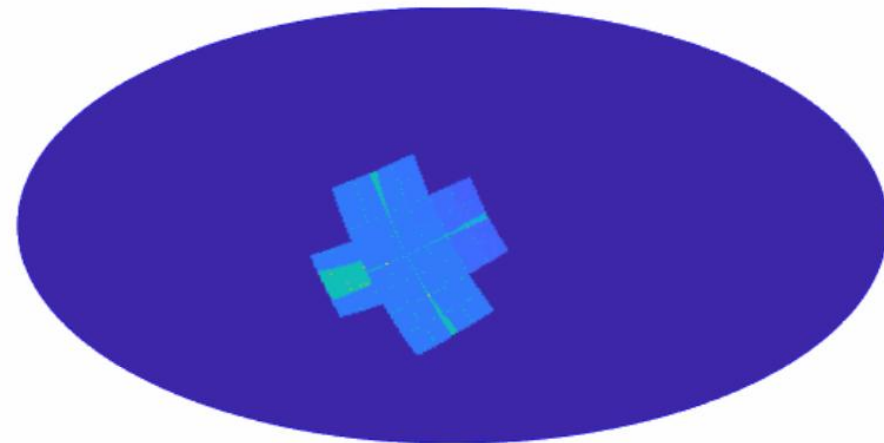
Einstein Probe: X-ray Time-domain Telescope

➤ WXT (0.5–4 keV)

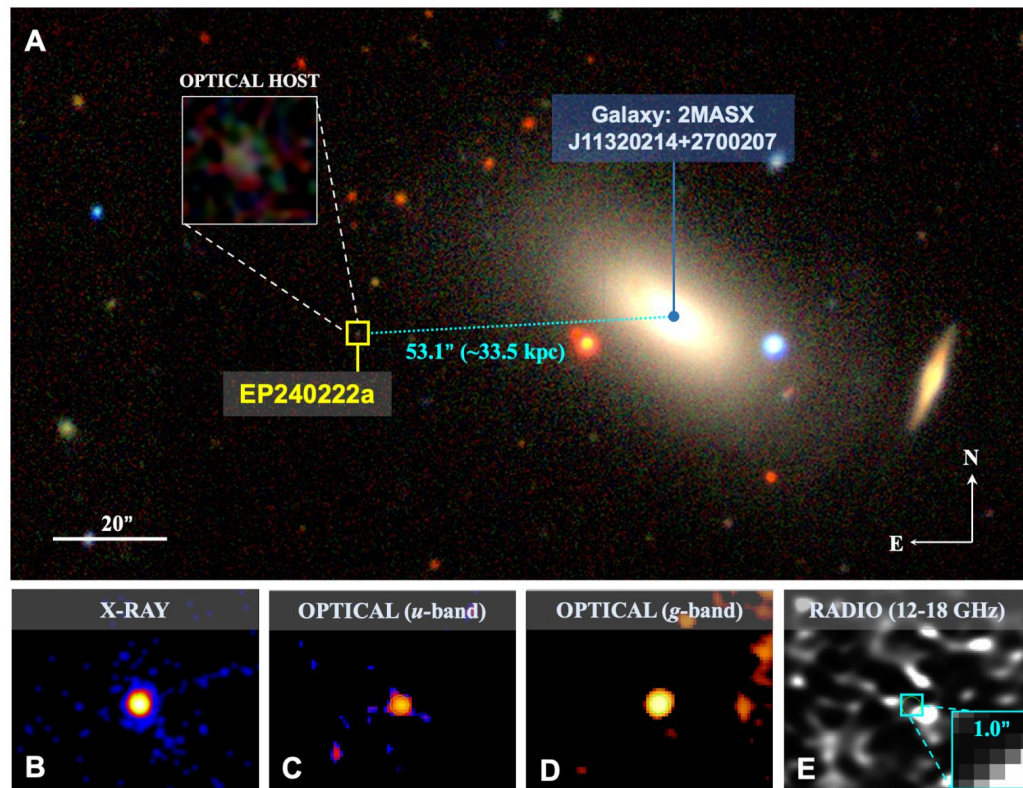
- FOV: 3600 degrees
- Orbit: 600km (5800s/orbit)
- 3 pointings/orbit, ~1200s each
- ~ 1/2 sky covered in 3 orbits (~ 5 hr)
- ~6ks exposure/sky region/day

➤ FXT (0.3–10 keV)

- 2 telescopes
- Similar to eROSITA

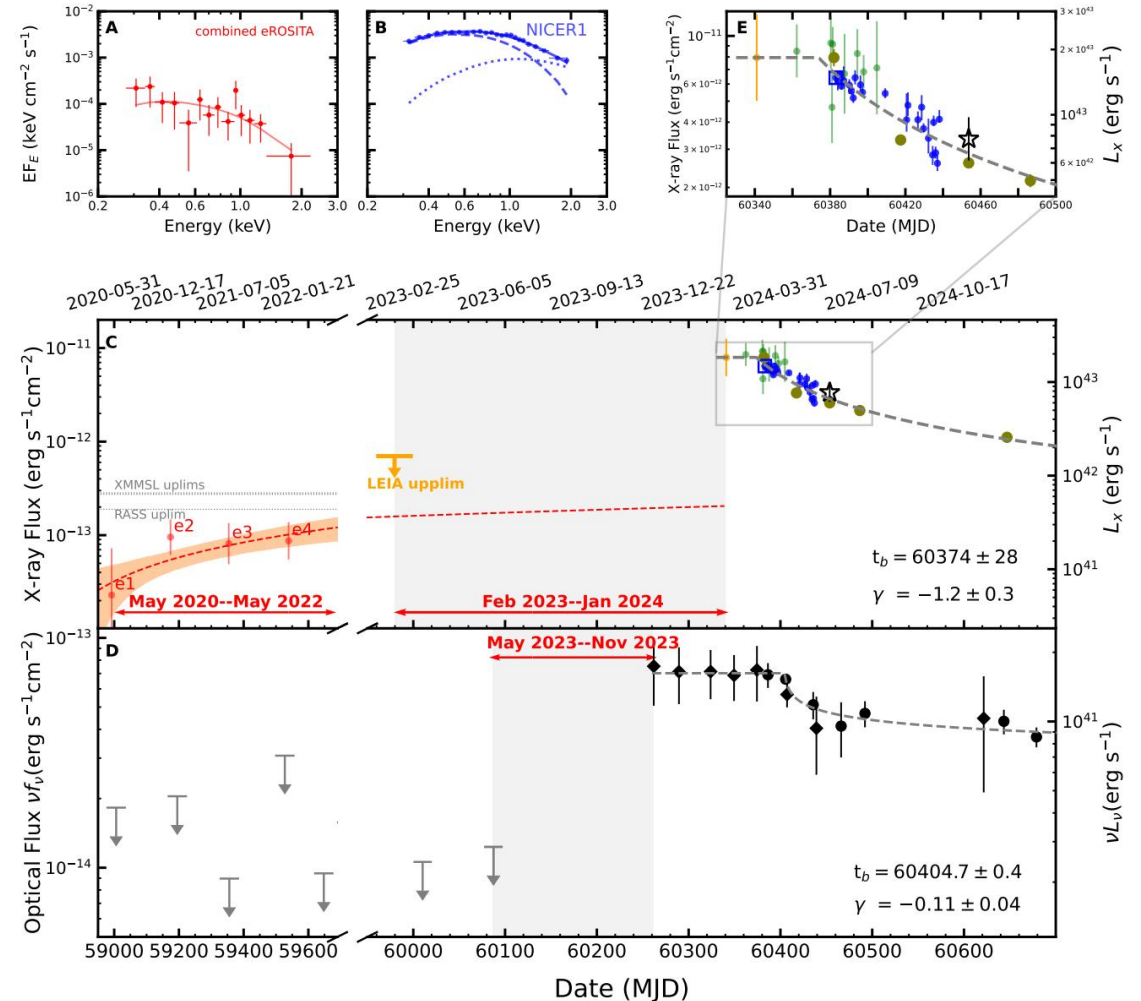
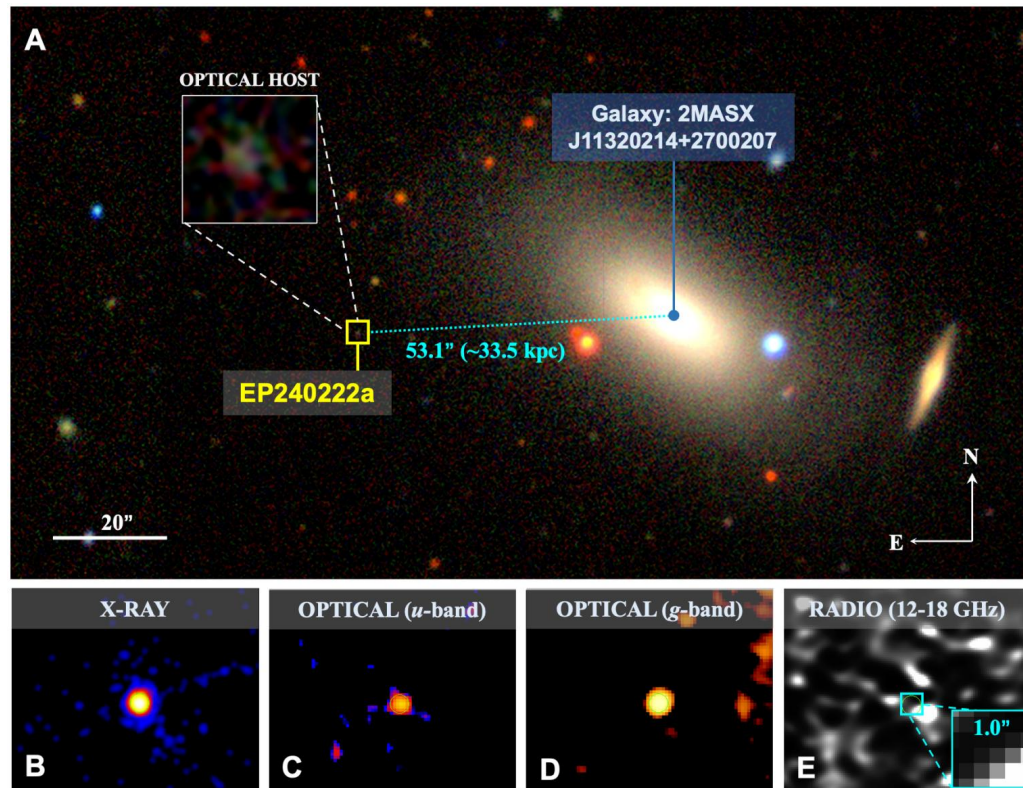


EP240222a: A Confirmed IMBH-TDE



- Real time captured
- Multi-wavelength observed
- Spectroscopic confirmed

EP240222a: A Confirmed IMBH-TDE



Why IMBH?

- Host (dwarf galaxy / globular cluster) Luminosity → BH Mass
- X-ray SED Fitting
 - Blackbody temperature $\sim 160\text{eV}$
 - Inner disk temperature $\sim 200\text{eV}$
- Similar to XMMJ2150 (IMBH-TDE candidate)
- Long Rise (year timescale) → Inefficient Circularization → IMBH

EP240222a: What Can We Learn From Light Curves?

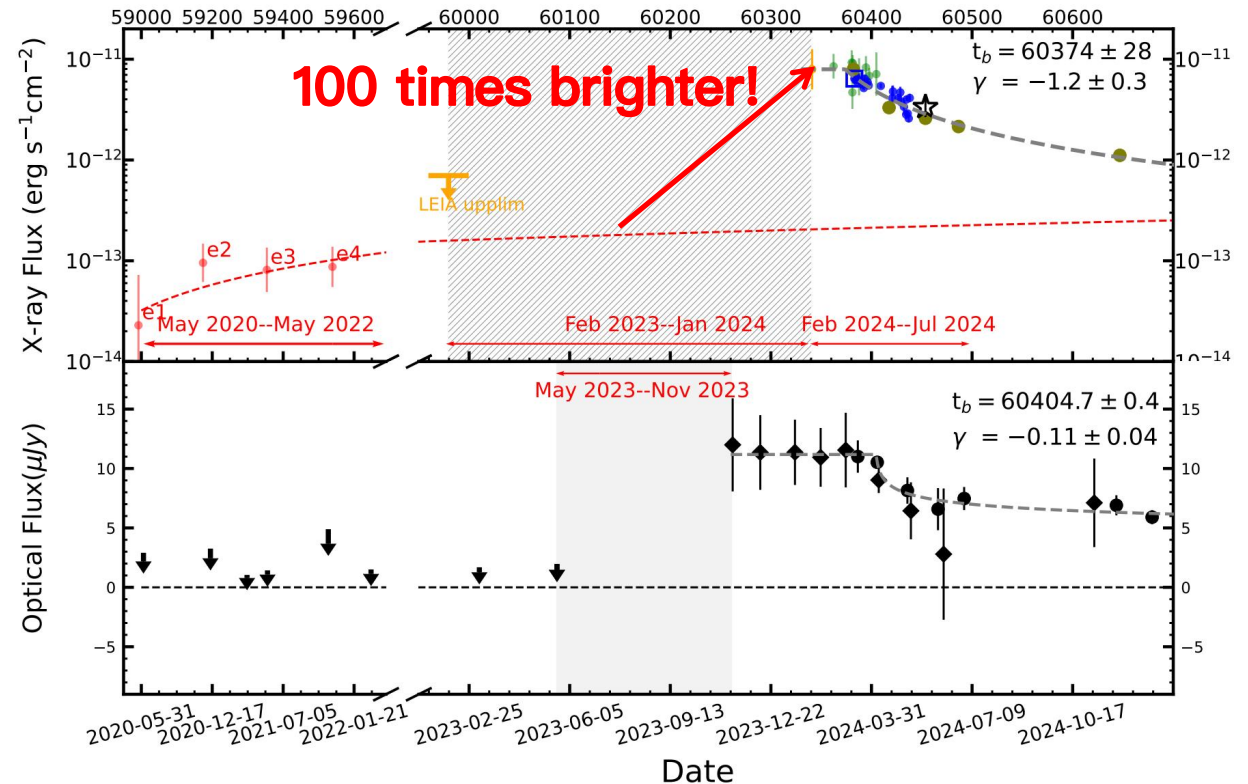
➤ X-ray Emission

- Slow rising stage (~ 3 years)
- Turning point (slow rise → fast rise)
- Plateau stage
- Decline stage

➤ Optical Emission

- Follow X-ray light curves
- 200 times fainter than X-ray
- Delayed & slower decline compared to X-rays

➤ New Model Required!



EP240222a Model

Inefficient circularization,
delayed stream-disk interaction
and reprocessing.

0. Disruption: Two Free Parameters

➤ Stellar Parameters

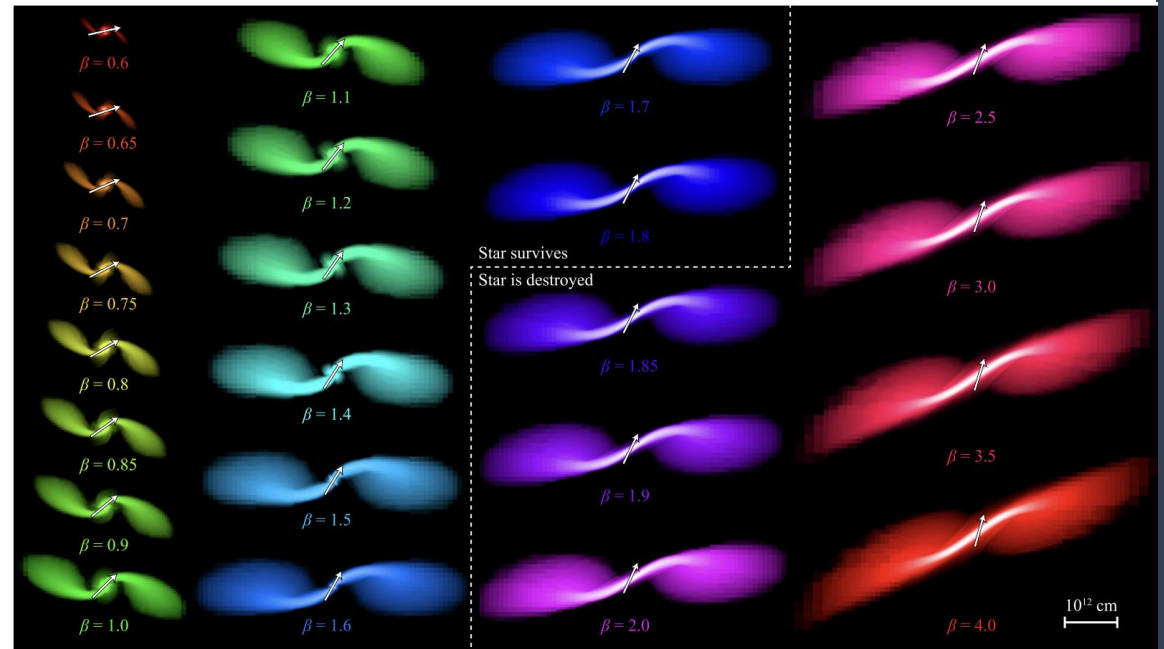
- Stellar mass (M_*)
- Stellar radius (R_*): M_* - R_* relation
- Polytropic index (γ): depend on M_*

➤ Orbital Parameter

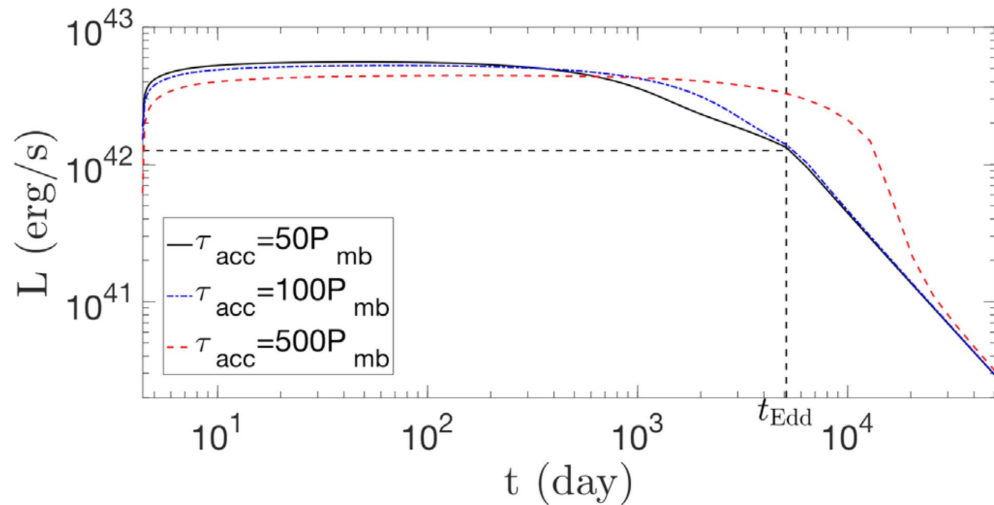
- Penetration factor (β): R_t/R_p

➤ Black Hole Parameters

- Black hole mass (M_{BH}): $\sim 7.7 * 10^4 M_\odot$
- Black hole spin (a_*): ~ 0.98



Recall: Previous IMBH-TDE Model



$$\frac{dM_d(t)}{dt} + \dot{M}_{\text{acc}}(t) = \dot{M}_{\text{fb}}(t)$$

$$L_{\text{bol}}(t) \simeq \begin{cases} [1 + \ln(\dot{M}_{\text{acc}}(t)/\dot{M}_{\text{Edd}})] L_{\text{Edd}}, & \dot{M}_{\text{acc}}(t) \gtrsim \dot{M}_{\text{Edd}} \\ (\dot{M}_{\text{acc}}(t)/\dot{M}_{\text{Edd}}) L_{\text{Edd}}, & \dot{M}_{\text{acc}}(t) \lesssim \dot{M}_{\text{Edd}} \end{cases}$$

➤ Fast Rise

- Ignore circularization timescale

➤ Plateau

- Super-Eddington stage

➤ Power law Decline

- Trace fallback rate

Timescales

$$t_{\text{fb}} = 2\pi \sqrt{\frac{a_0^3}{GM_{\text{BH}}}} \simeq 13 M_5^{1/2} r_*^{3/2} m_*^{-1} \text{ days} \times \begin{cases} \beta^{-3}, & \beta \lesssim \beta_d \\ 1, & \beta \gtrsim \beta_d \end{cases}$$

$$t_{\text{cir}} = \frac{2\epsilon_0 t_{\text{fb}} e_0^2}{\Delta\epsilon_0} \simeq 328 M_6^{-7/6} m_*^{-4/3} r_*^{7/2} \text{ days} \times \begin{cases} \beta^{-4}, & \beta \lesssim \beta_d \\ \beta^{-3}, & \beta > \beta_d \end{cases}$$

$$t_{\text{acc}} \simeq \left(\frac{H}{R}\right)_d^{-2} \alpha^{-1} t_{\text{dyn,c}} \simeq 13 \left(\frac{(H/R)_d}{0.2}\right)^{-2} \left(\frac{\alpha}{0.1}\right)^{-1} \beta^{-3/2} r_*^{3/2} m_*^{-1/2} \text{ days}$$

Timescales

$$t_{\text{fb}} = 2\pi \sqrt{\frac{a_0^3}{GM_{\text{BH}}}} \simeq 13 M_5^{1/2} r_*^{3/2} m_*^{-1} \text{ days} \times \begin{cases} \beta^{-3}, & \beta \lesssim \beta_d \\ 1, & \beta \gtrsim \beta_d \end{cases}$$

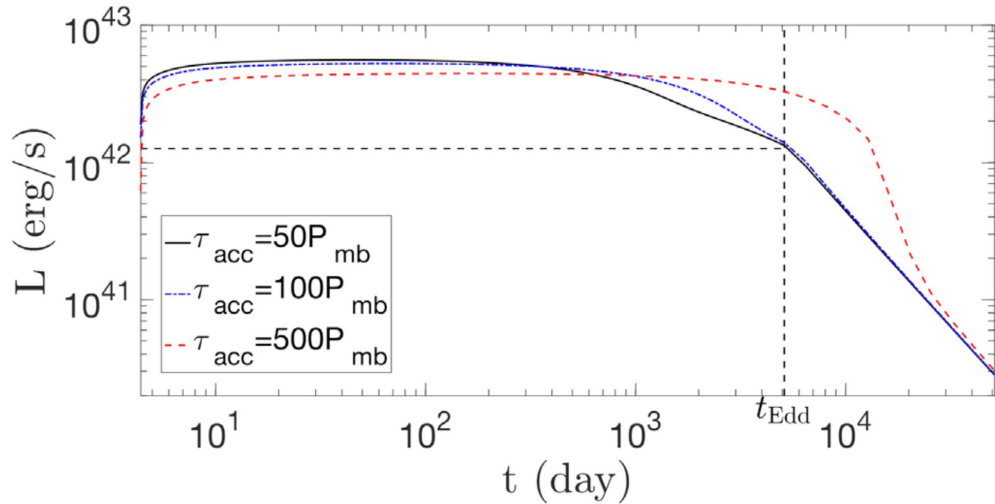
$$t_{\text{cir}} = \frac{2\epsilon_0 t_{\text{fb}} e_0^2}{\Delta\epsilon_0} \simeq 328 M_6^{-7/6} m_*^{-4/3} r_*^{7/2} \text{ days} \times \begin{cases} \beta^{-4}, & \beta \lesssim \beta_d \\ \beta^{-3}, & \beta > \beta_d \end{cases}$$

Be Careful !

- thin stream
- **j conserved**
- **100% eff**

$$t_{\text{acc}} \simeq \left(\frac{H}{R}\right)_d^{-2} \alpha^{-1} t_{\text{dyn,c}} \simeq 13 \left(\frac{(H/R)_d}{0.2}\right)^{-2} \left(\frac{\alpha}{0.1}\right)^{-1} \beta^{-3/2} r_*^{3/2} m_*^{-1/2} \text{ days}$$

Recall: Previous IMBH-TDE Model



➤ **Fast Rise**

- **Ignore circularization timescale**

➤ **Plateau**

- **Super-Eddington stage**

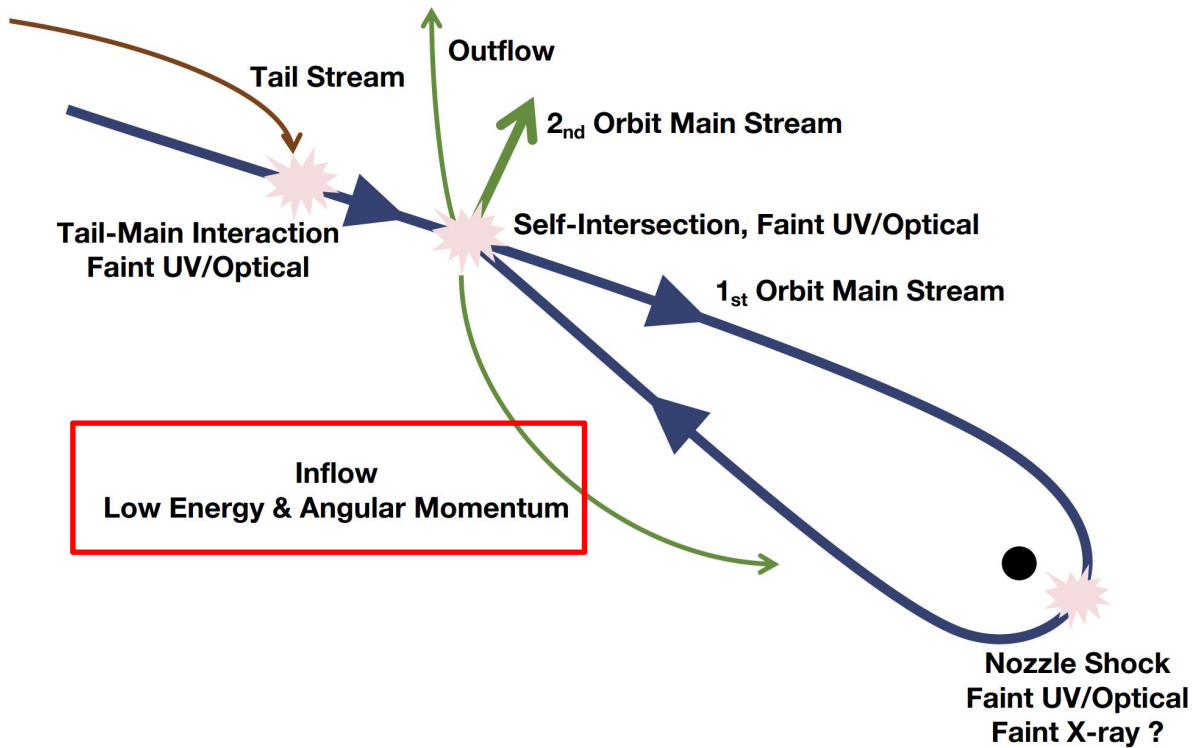
➤ **Power law Decline**

- **Trace fallback rate**

$$\frac{dM_d(t)}{dt} + \dot{M}_{\text{acc}}(t) = \boxed{\dot{M}_{\text{fb}}(t)} \rightarrow \dot{M}_{\text{sup}}(t)$$

$$L_{\text{bol}}(t) \simeq \begin{cases} [1 + \ln(\dot{M}_{\text{acc}}(t)/\dot{M}_{\text{Edd}})] L_{\text{Edd}}, & \dot{M}_{\text{acc}}(t) \gtrsim \dot{M}_{\text{Edd}} \\ (\dot{M}_{\text{acc}}(t)/\dot{M}_{\text{Edd}}) L_{\text{Edd}}, & \dot{M}_{\text{acc}}(t) \lesssim \dot{M}_{\text{Edd}} \end{cases}$$

1. Initial Stage: Inefficient Circularization



1. Initial Stage: Inefficient Circularization

➤ Dissipation channels (**inefficient for IMBHs!**)

- **nozzle shock**

$$\epsilon_{\text{noz}} \simeq \frac{\frac{1}{2} v_{z,\text{max}}^2}{E_c} \simeq 9.3 \times 10^{-6} \beta M_5^{-2/3} m_*^{2/3} \ll 1$$

- **self-intersection of the main stream**

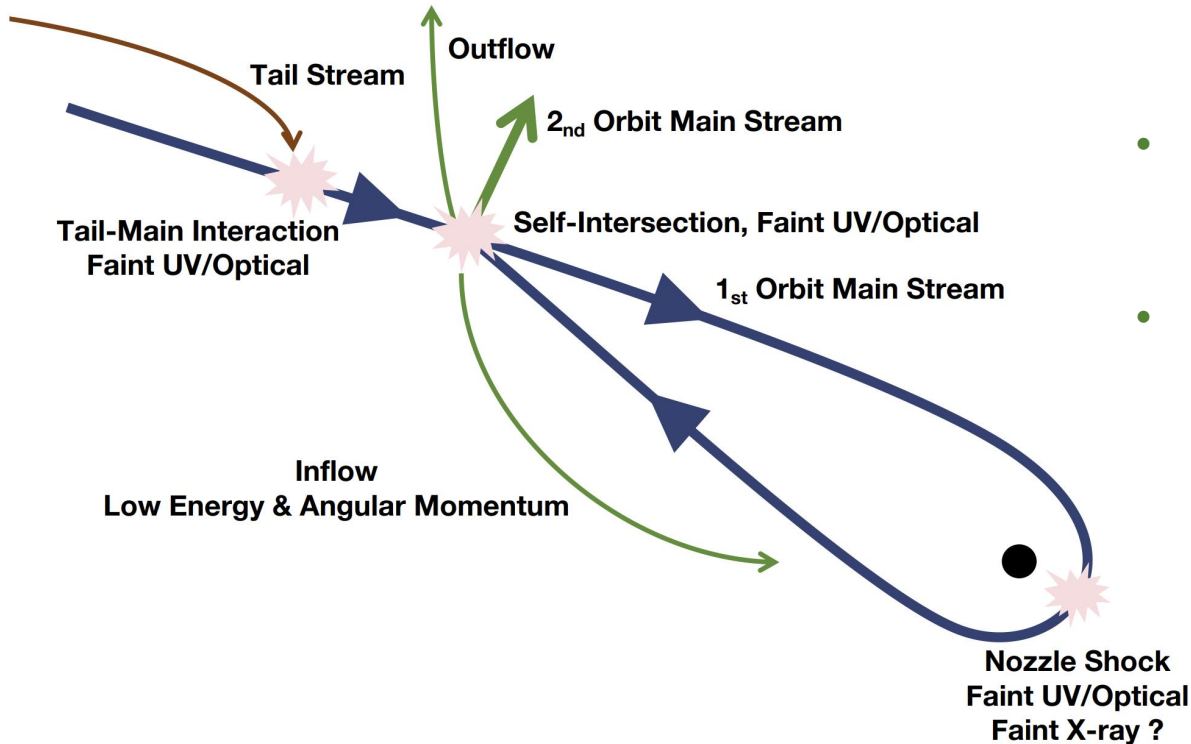
$$\epsilon_{\text{self}} \simeq \frac{\Delta E_0}{E_c} \simeq 4.6 \times 10^{-4} e_0^2 \beta^2 M_5^{4/3} r_*^{-2} m_*^{2/3} \ll 1$$

- **tail stream-main stream interaction**

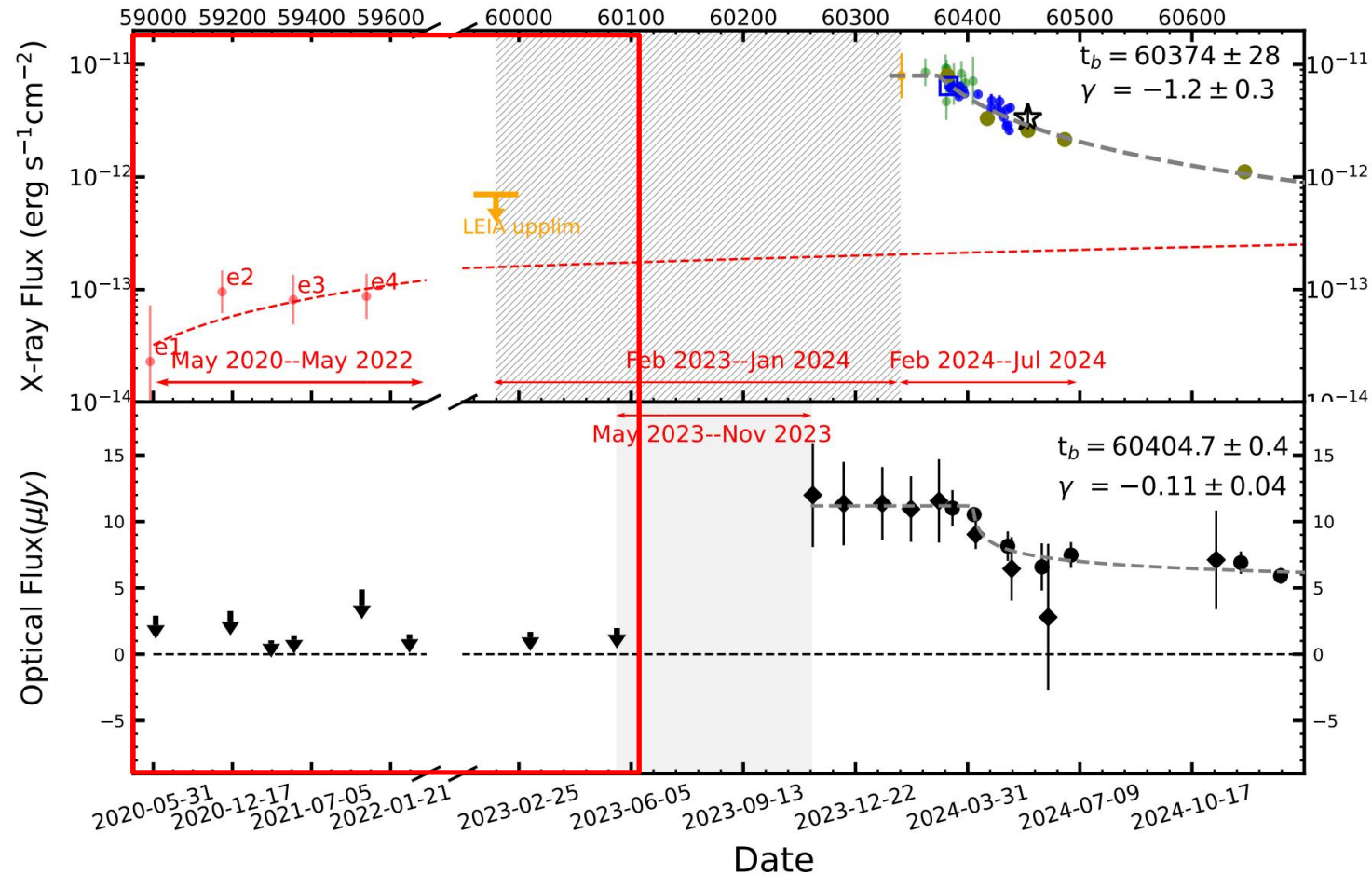
$$\begin{aligned} \epsilon_{\text{tm}}(t) &\simeq \frac{\Delta E_{\text{tm}}}{E_c} \simeq \frac{\dot{M}_{\text{fb}}(t) t_{\text{fb}} E_0}{M_s(t) E_c} \\ &\simeq 4.3 \times 10^{-2} \left(\frac{t}{t_{\text{fb}}}\right)^{-n} \left[1 - \left(\frac{t}{t_{\text{fb}}}\right)^{1-n}\right]^{-1} (n-1)(1+e_0) \\ &\quad \times M_5^{-1/3} m_*^{1/3} \times \begin{cases} \beta, & \beta \lesssim \beta_d \\ \beta^{-1}, & \beta \gtrsim \beta_d \end{cases} \ll 1 \end{aligned}$$

➤ **Self-intersection** → **inflow** & **outflow**

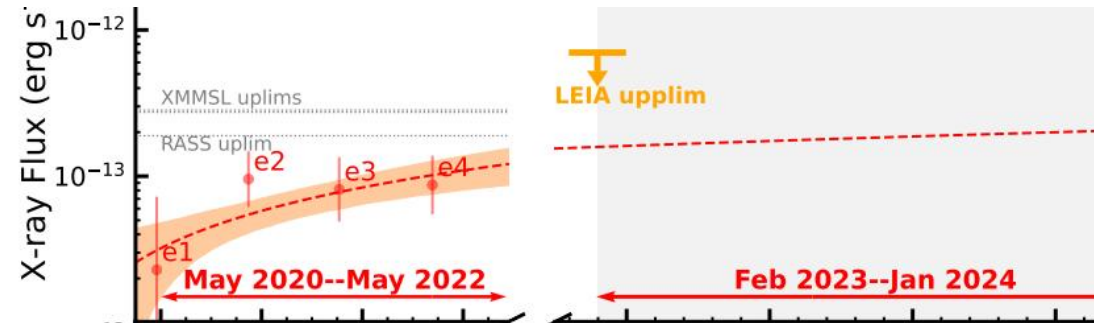
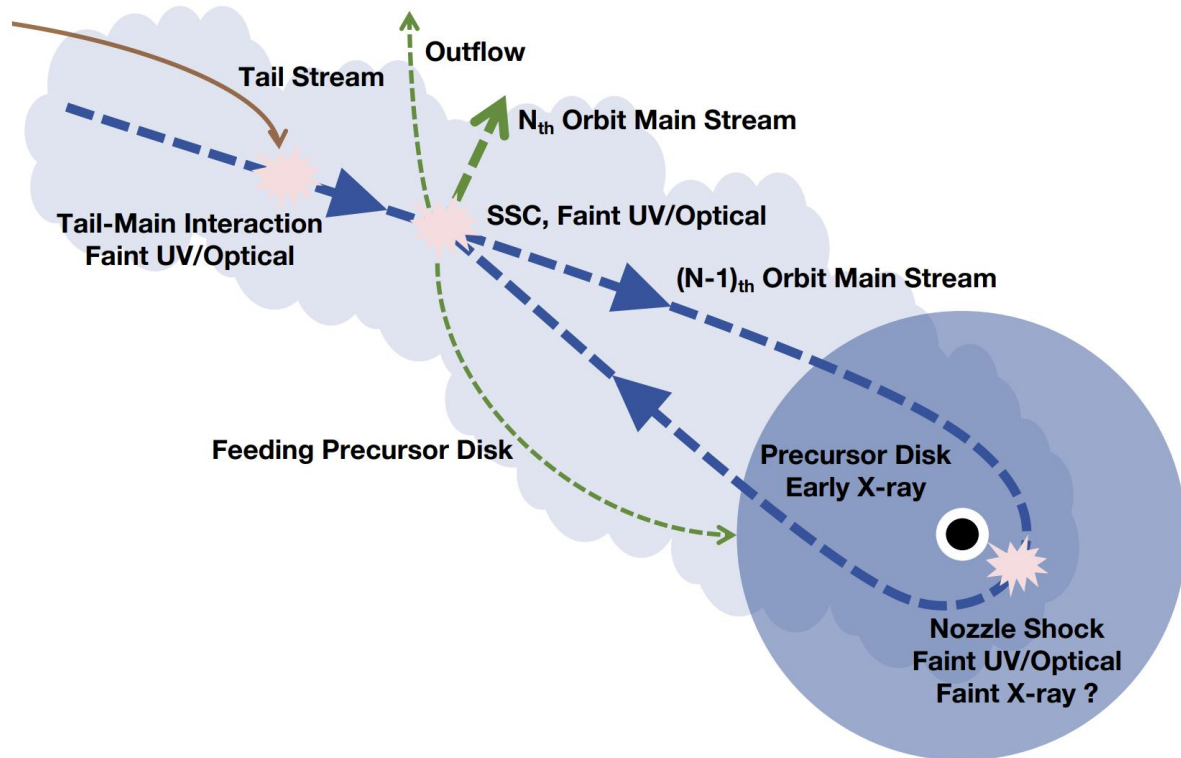
➤ **Timescale: t_{fb}**



2. Slow-Rising Stage



2. Slow-Rising Stage: SSC-Feeding Precursor Disk



- Photon trapped → thick main stream
- Dissipation continue, dominated by SSC (a succession of self-crossings)
- **Inflow** & outflow continue
- **Precursor disk forms** → early X-rays
- **Timescale: years**

Basic Equations for Accretion Disk: Slow-Rising Stage

$$\frac{dM_d(t)}{dt} = \dot{M}_{\text{sup}}(t) - \dot{M}_{\text{acc}}(t)$$

➤ Key equation: mass supply rate

➤ Early accretion timescale

$$\dot{M}_{\text{sup}}(t) \simeq \eta_{\text{sup}}(t) M_s(t) \frac{\dot{E}(t)}{E_c - E_0}$$

• can be longer than late time

• MRI not fully developed → smaller alpha

• low accretion rate → tinner disk

$$\dot{M}_{\text{acc}}(t) = M_d(t) / t_{\text{acc,early}}$$

$$t_{\text{acc}} \simeq \left(\frac{H}{R} \right)^{-2} \alpha^{-1} t_{\text{dyn,c}}$$

$$L_{\text{bol}}(t) \simeq \eta_{\text{mis}} \dot{M}_{\text{acc}}(t) c^2$$

➤ Misaligned disk

$$\eta_{\text{retro}} < \eta_{\text{mis}} < \eta_{\text{align}}$$

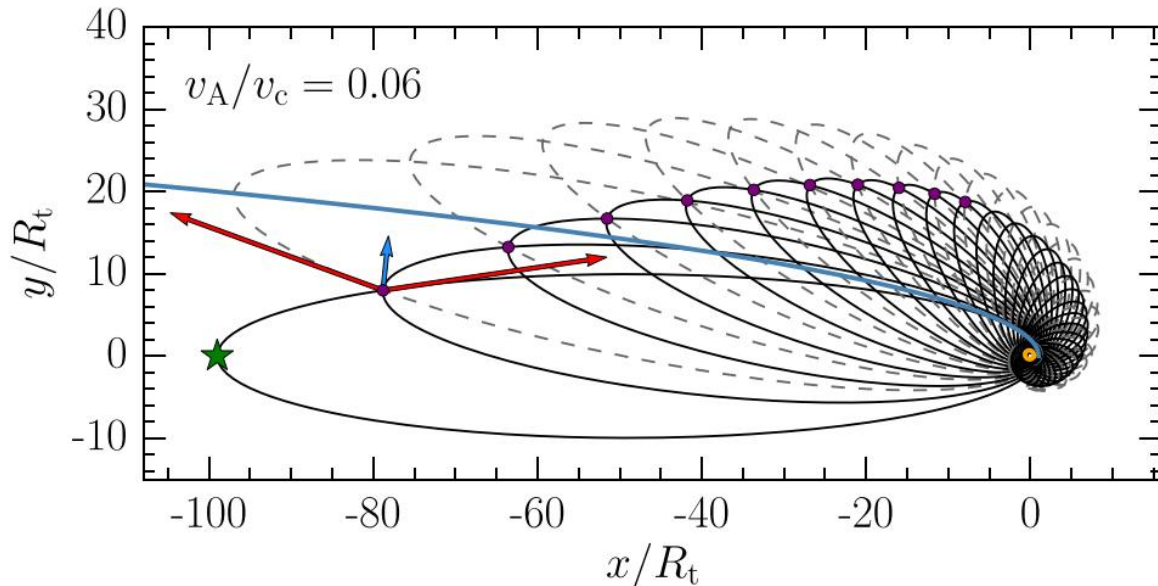
SSC Model with Correction

➤ Assumption: thin main stream

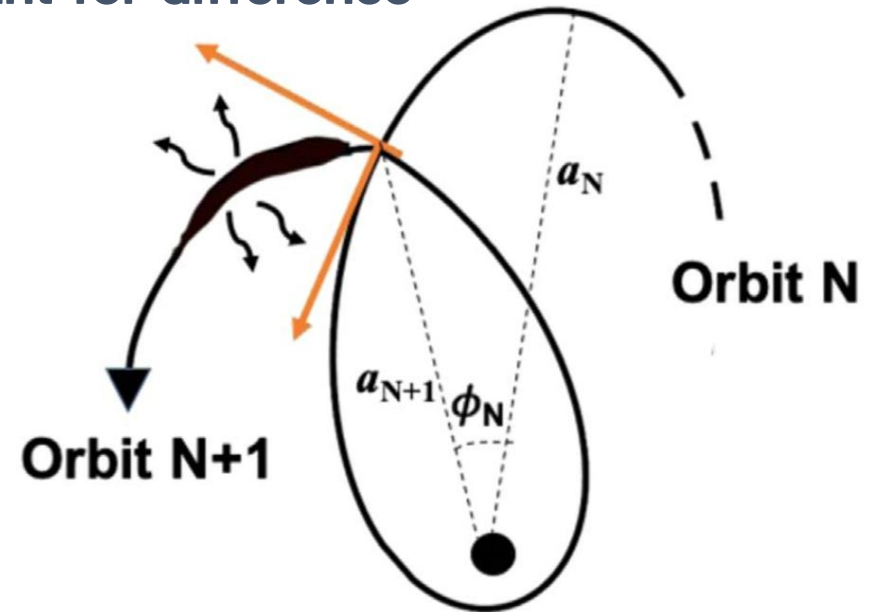
➤ Here: thick main stream

➤ Free parameter $\eta_{\text{self}}(t)$ (can >1) to account for difference

$$\dot{E}_{\text{ideal}}(t) \simeq \frac{\Delta E_0}{t_{\text{fb}}} \frac{1}{e_0^2} \left(1 - \frac{E_{\text{ideal}}(t)}{E_c} \right) \left(\frac{E_{\text{ideal}}(t)}{E_0} \right)^{3/2}$$



C. Bonnerot et al. 2017



J. Chen & R. Shen 2021

Basic Equations for Accretion Disk: Slow-Rising Stage

$$\frac{dM_d(t)}{dt} = \dot{M}_{\text{sup}}(t) - \dot{M}_{\text{acc}}(t)$$

➤ Key equation: mass supply rate

➤ Early accretion timescale

$$\dot{M}_{\text{sup}}(t) \simeq \eta_{\text{sup}}(t) M_s(t) \frac{\dot{E}(t)}{E_c - E_0}$$

• can be longer than late time

• MRI not fully developed → smaller alpha

• low accretion rate → tinner disk

$$\dot{M}_{\text{acc}}(t) = M_d(t) / t_{\text{acc,early}}$$

$$t_{\text{acc}} \simeq \left(\frac{H}{R} \right)^{-2} \alpha^{-1} t_{\text{dyn,c}}$$

$$L_{\text{bol}}(t) \simeq \eta_{\text{mis}} \dot{M}_{\text{acc}}(t) c^2$$

➤ Misaligned disk

$$\eta_{\text{retro}} < \eta_{\text{mis}} < \eta_{\text{align}}$$

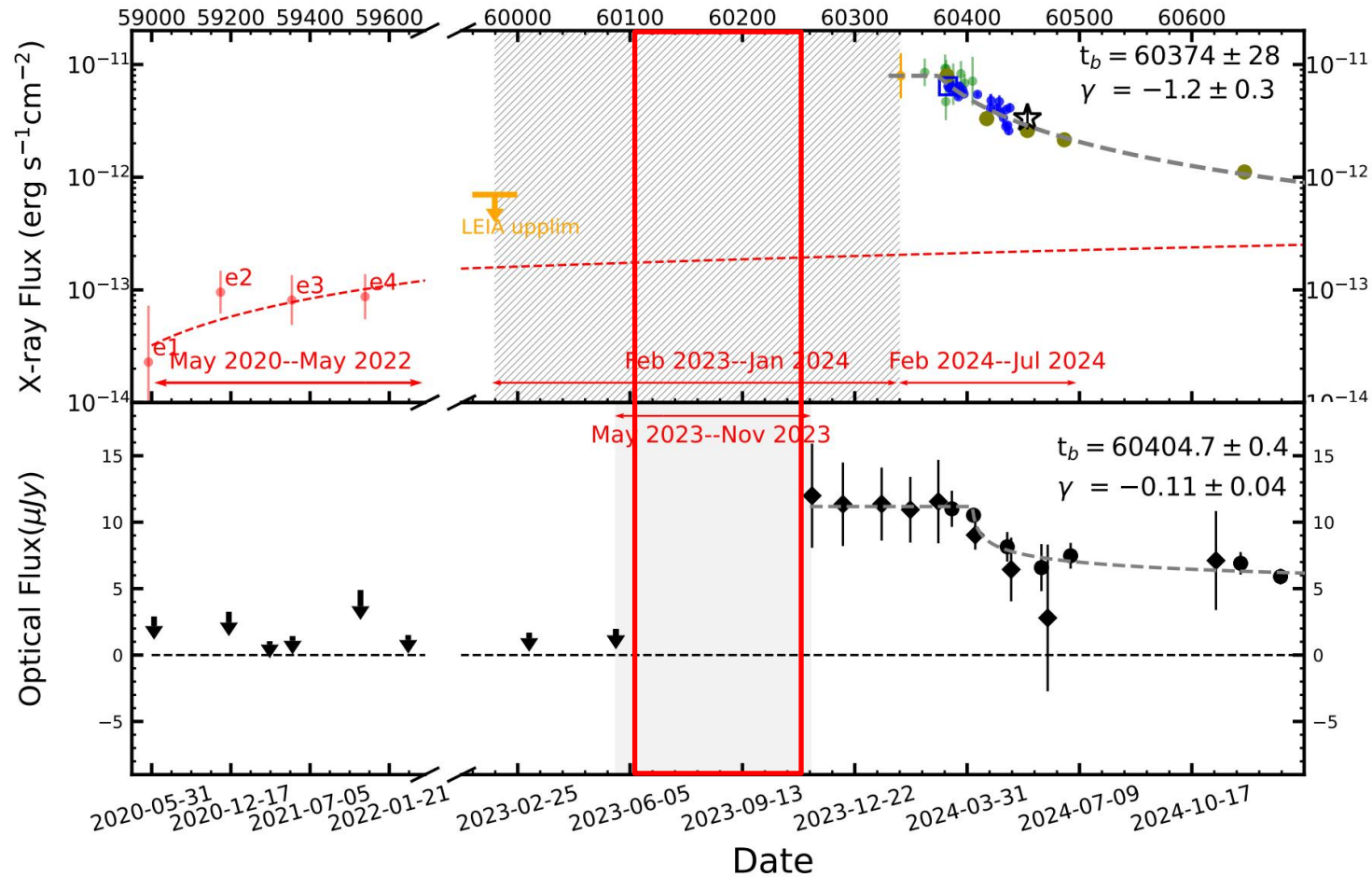
Basic Equations for Accretion Disk: Slow-Rising Stage

$$\dot{M}_{\text{sup}}(t) \simeq \eta_{\text{sup}}(t) M_{\text{s}}(t) \frac{\dot{E}(t)}{E_{\text{c}} - E_0}$$

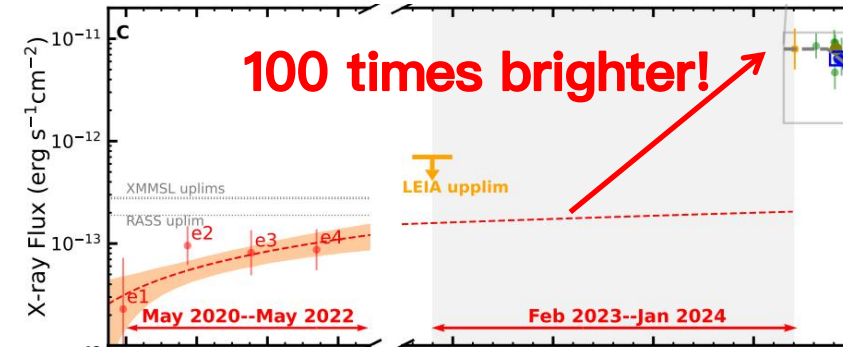
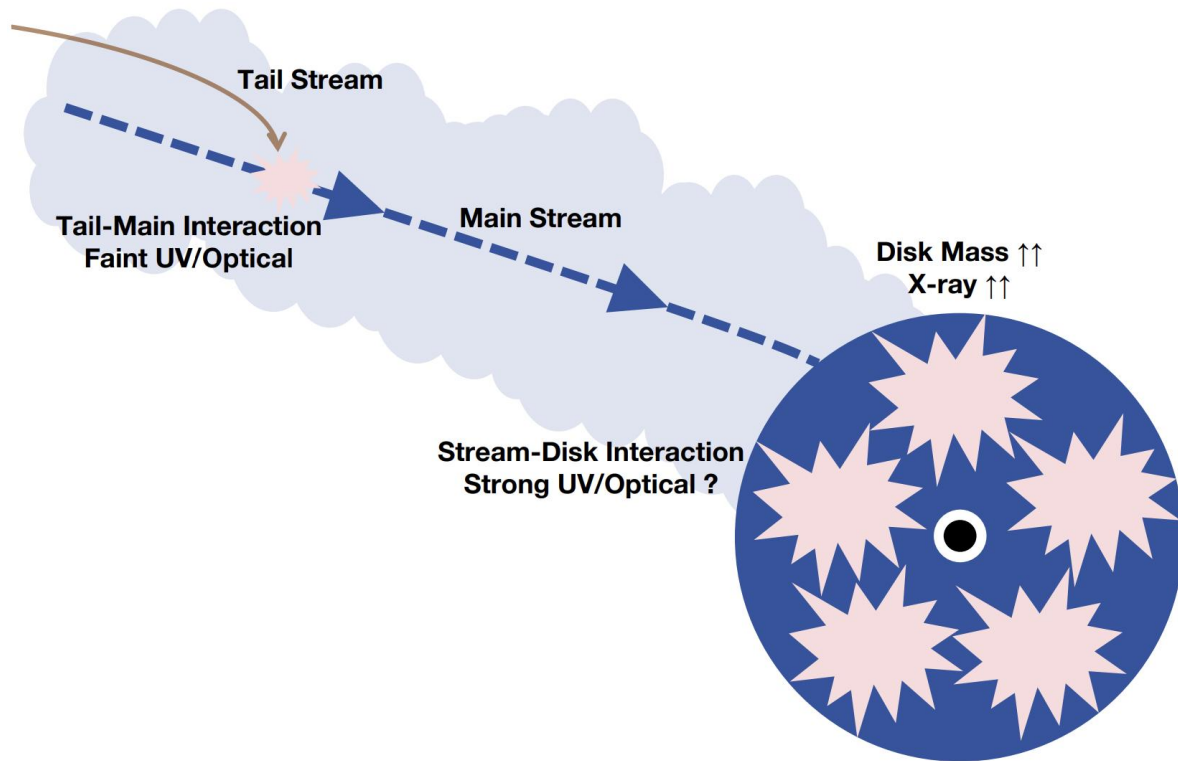
Basic Equations for Accretion Disk: Slow-Rising Stage

$$\begin{aligned}\dot{M}_{\text{sup}}(t) &\simeq \eta_{\text{sup}}(t)M_{\text{s}}(t)\frac{\dot{E}(t)}{E_{\text{c}} - E_0} \simeq \eta_{\text{self}}(t)\eta_{\text{sup}}(t)M_{\text{s}}(t)\frac{\dot{E}_{\text{ideal}}(t)}{E_{\text{c}} - E_0} \\ &\simeq \overline{\eta_{\text{self}}\eta_{\text{sup}}}M_{\text{s}}(t)\frac{\dot{E}_{\text{ideal}}(t)}{E_{\text{c}} - E_0}\end{aligned}$$

3. Fast-Rising Stage

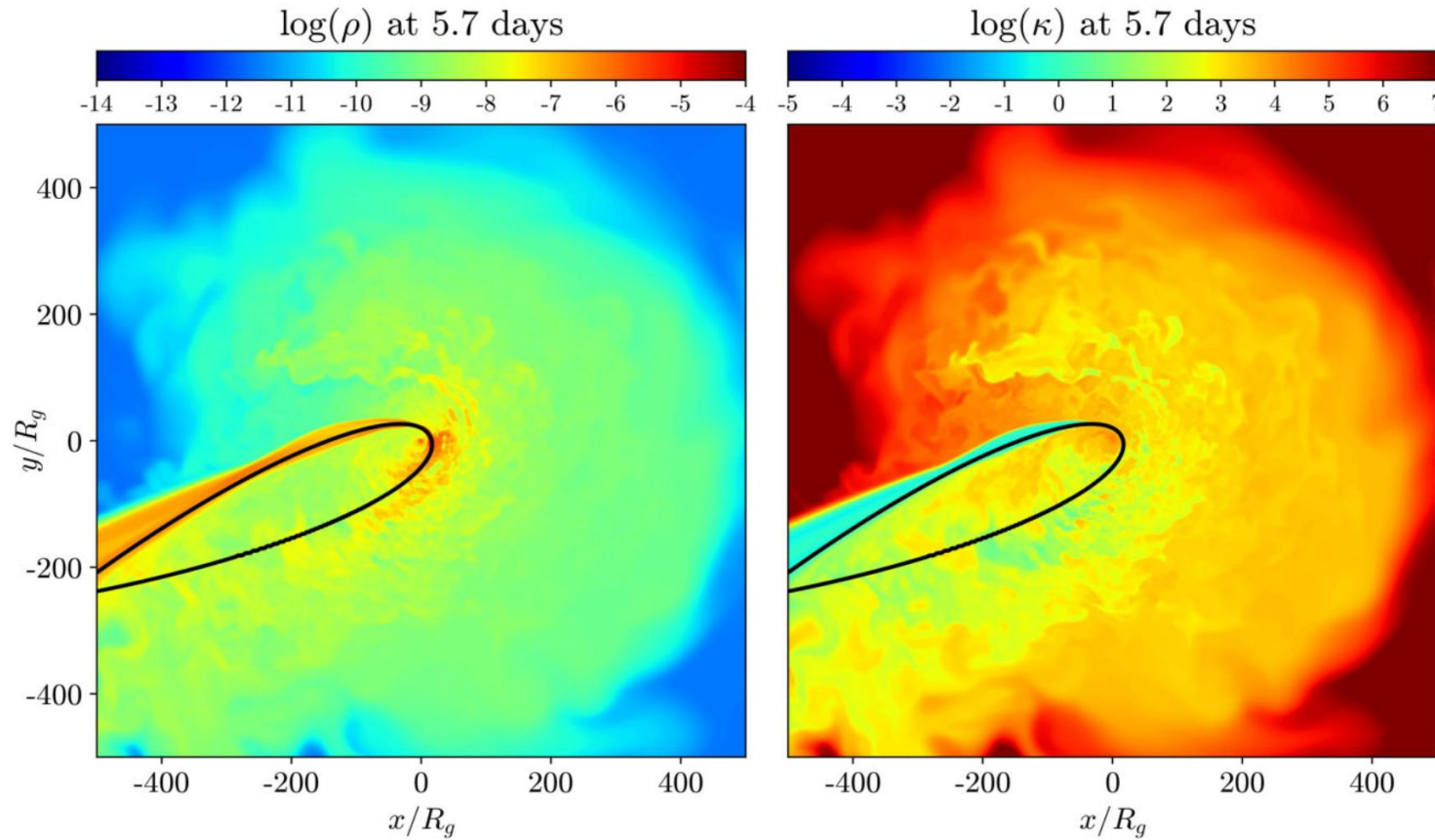


3. Fast-Rising Stage: Stream-Disk Interaction

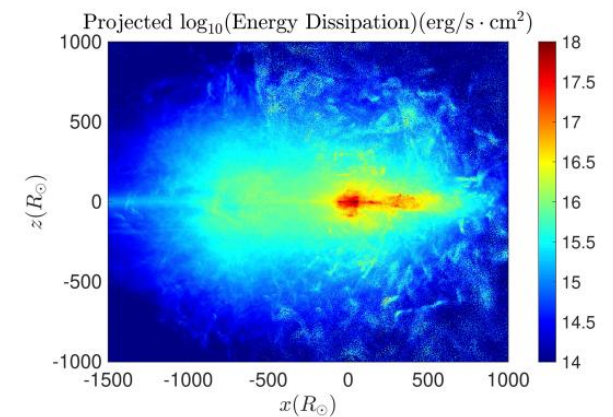
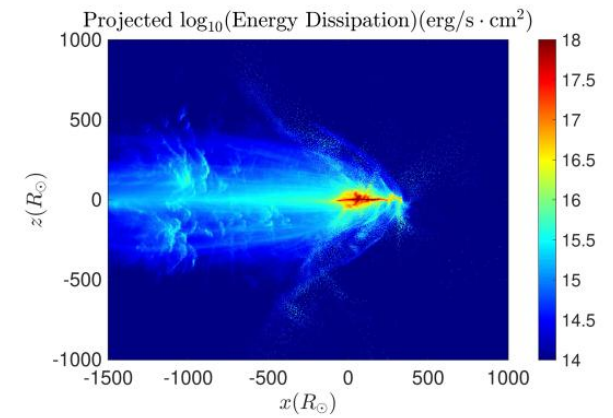
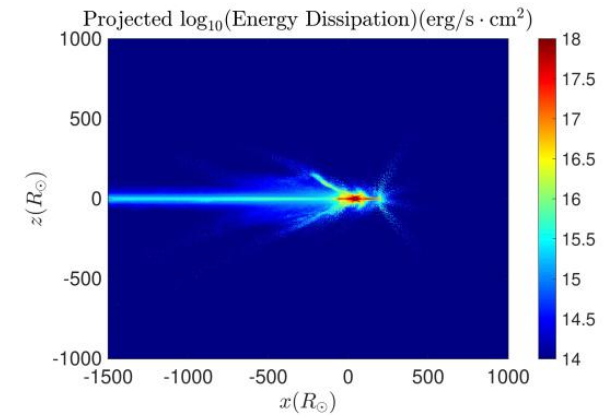


- Momentum flux matching
- Stream-disk interaction
- Runaway circularization ($\sim t_{fb}$)
- Massive disk \rightarrow sharp X-ray rise
- Potential strong UV/optical flares
- Disk aligned with the BH's spin
- Timescale: $< t_{fb}$ or t_{fb}

Stream-Disk Interaction



Z. Andalman et al. 2022



E. Steinberg & N. Stone 2024

Basic Equations for Accretion Disk: Fast-Rising Stage

$$\frac{dM_d(t)}{dt} = \dot{M}_{\text{sup}}(t) - \dot{M}_{\text{acc}}(t)$$

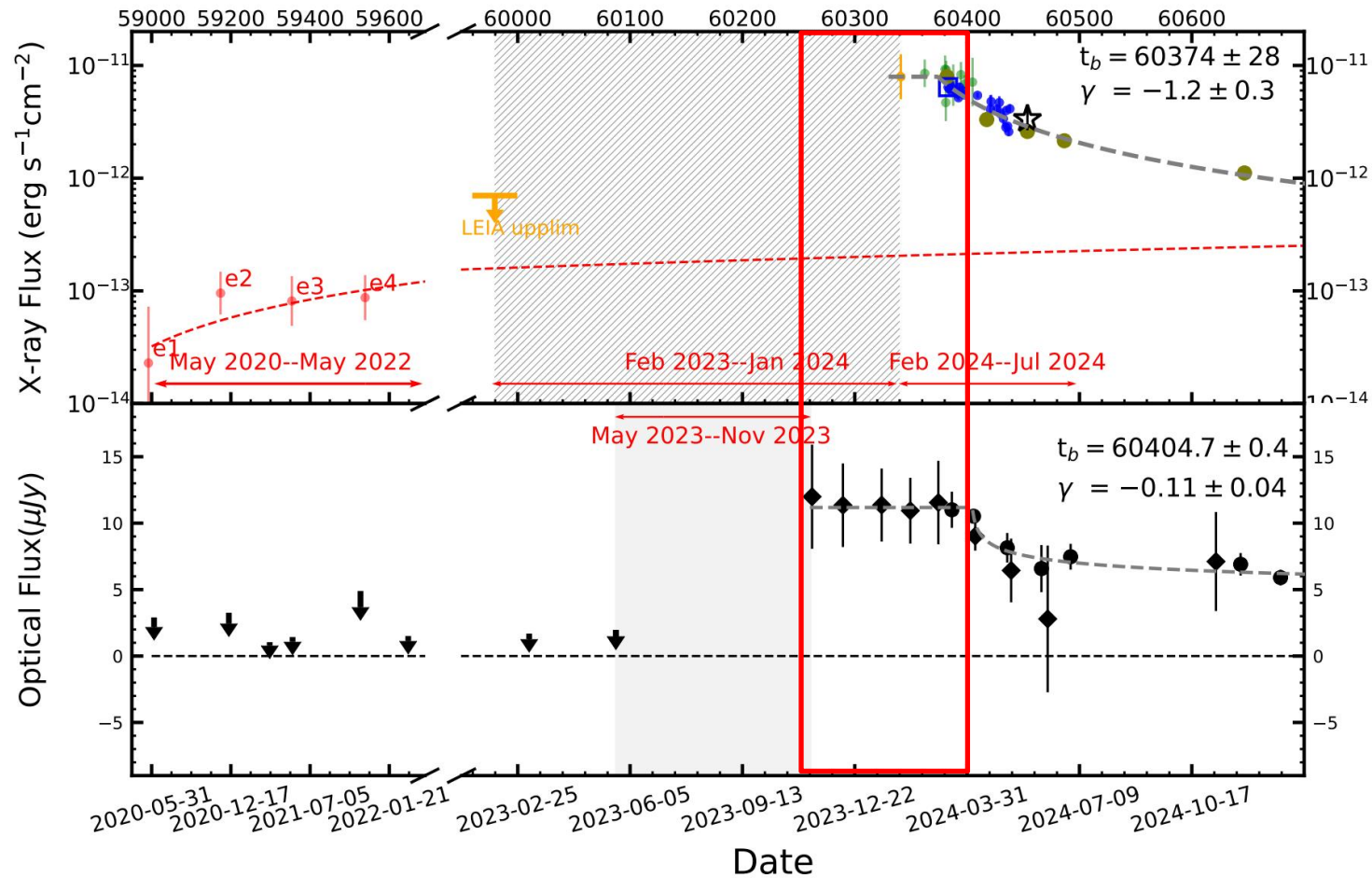
$$\dot{M}_{\text{sup}}(t) \simeq \frac{M_s(t)}{t_{s,N}} + \dot{M}_{\text{fb}}(t)$$

$$\dot{M}_{\text{acc}}(t) = M_d(t)/t_{\text{acc,late}}$$

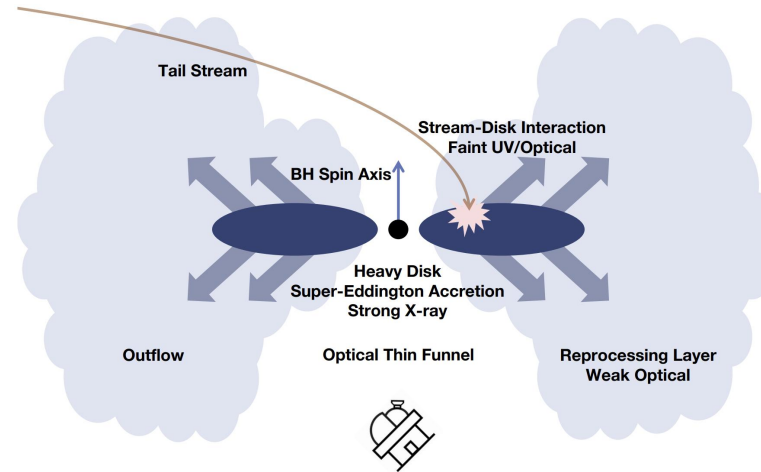
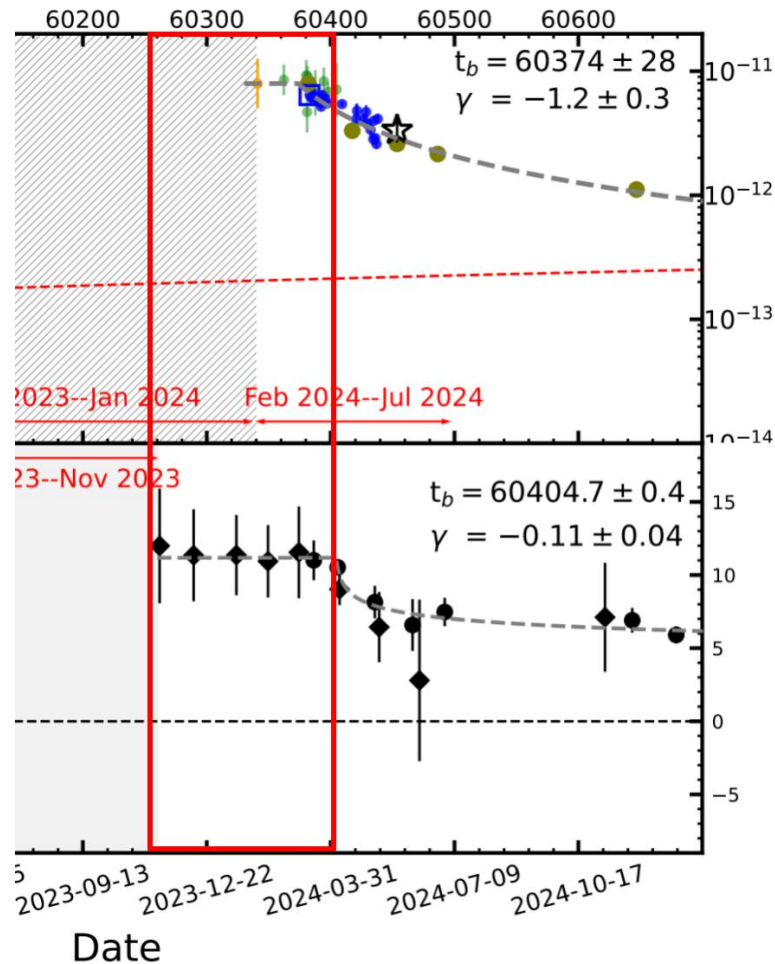
$$L_{\text{bol}}(t) \simeq \begin{cases} [1 + \ln(\dot{M}_{\text{acc}}(t)/\dot{M}_{\text{Edd}})] L_{\text{Edd}}, & \dot{M}_{\text{acc}}(t) \gtrsim \dot{M}_{\text{Edd}} \\ (\dot{M}_{\text{acc}}(t)/\dot{M}_{\text{Edd}}) L_{\text{Edd}}, & \dot{M}_{\text{acc}}(t) \lesssim \dot{M}_{\text{Edd}} \end{cases}$$

- Mass supply dominated by main stream (stream–disk interaction)
- Late accretion timescale (shorter)
- Accretion rate \gg Eddington rate
- Luminosity is “throttled” $\rightarrow L_{\text{bol}} \sim L_{\text{edd}}$
- **outflow & advection**
- Accretion efficiency = `eta_align`

4. Plateau Stage

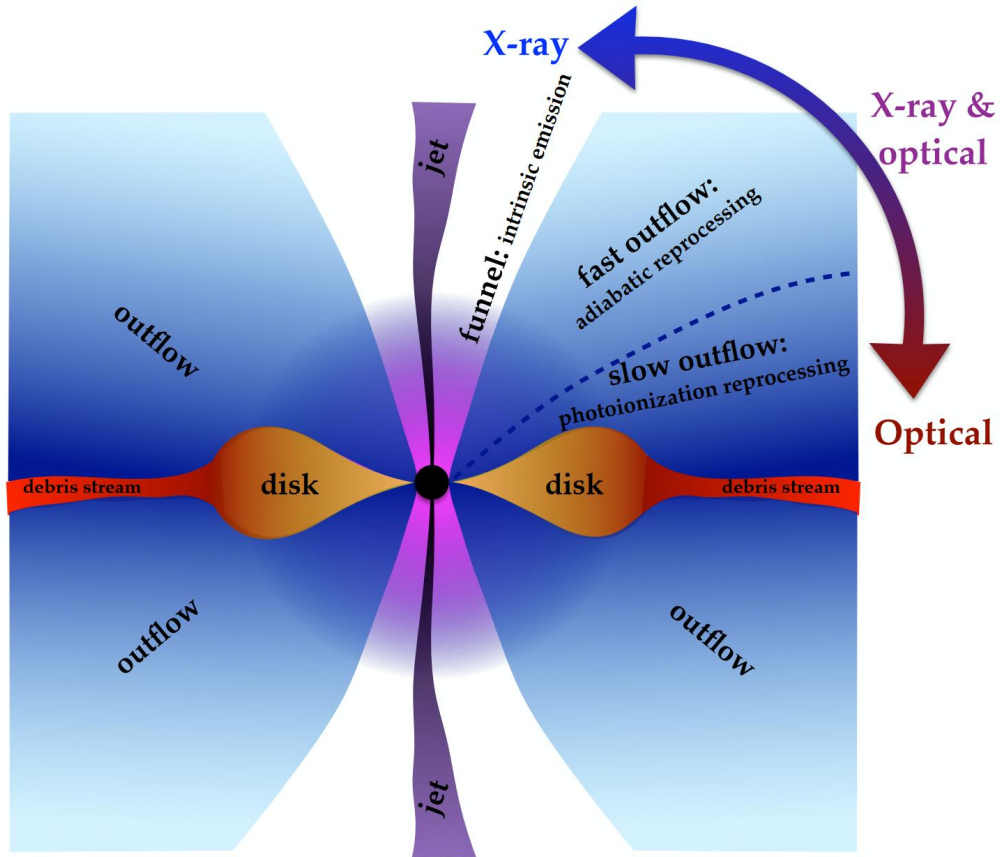


4. Plateau Stage: Super-Eddington Accretion

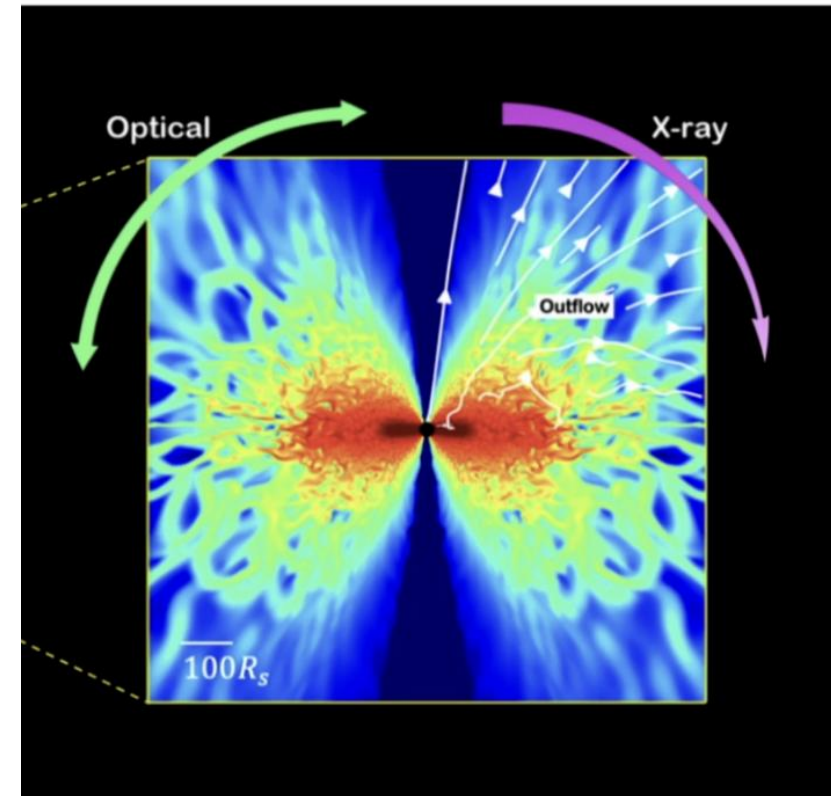


- Massive disk → super-Eddington
- $L_{bol} \sim L_{Edd}$ (outflow & advection)
- Polar funnel → line of sight to X-rays
- Weak optical (reprocessed X-rays)
- Timescale: $t_{acc,late}$

Unified Model for TDEs



L. Dai et al. 2018



E. Qiao et al. 2025

Basic Equations for Accretion Disk: Plateau Stage

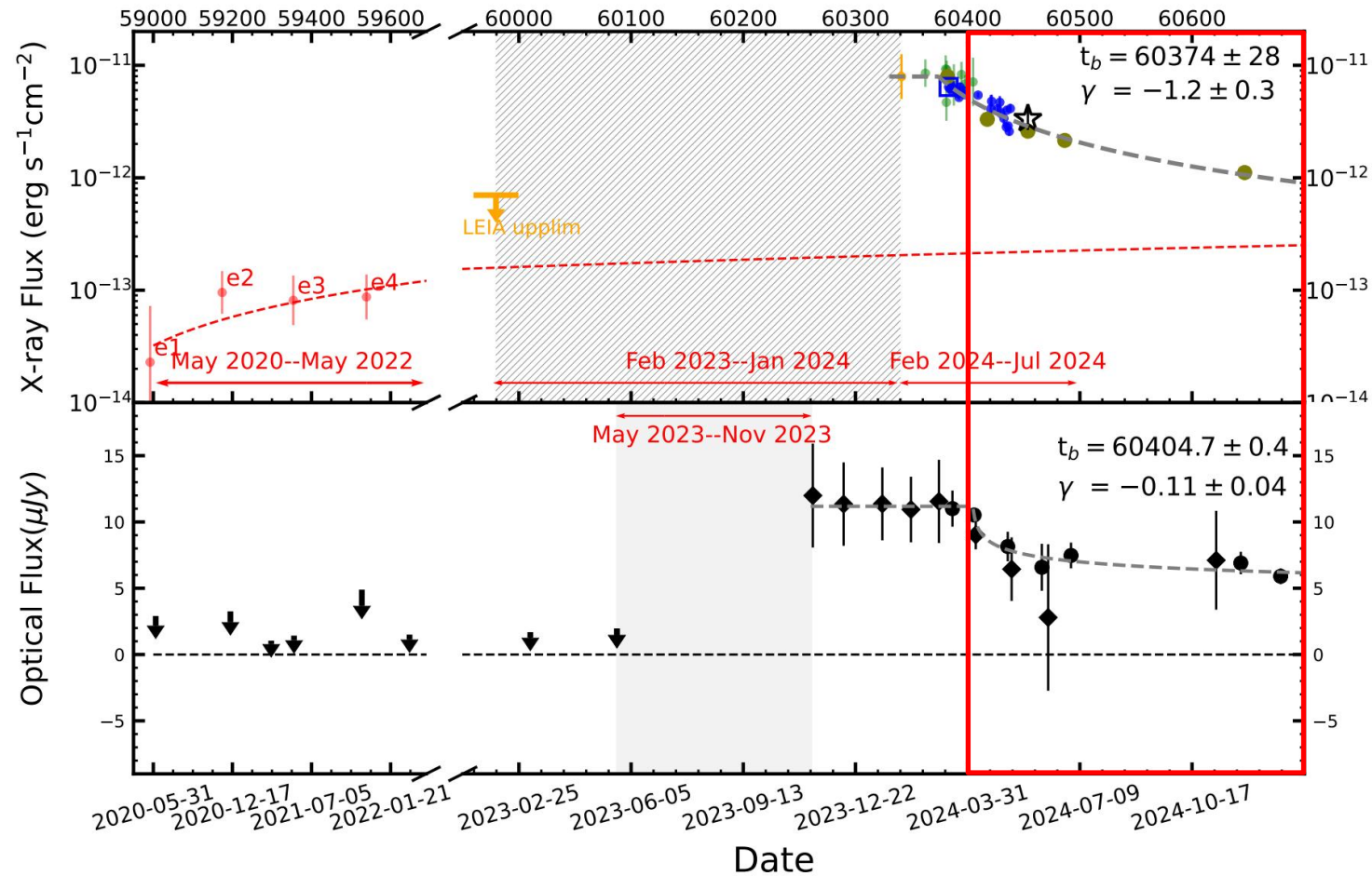
$$\frac{dM_d(t)}{dt} = \dot{M}_{\text{sup}}(t) - \dot{M}_{\text{acc}}(t)$$

$$\dot{M}_{\text{sup}}(t) \simeq \dot{M}_{\text{fb}}(t)$$

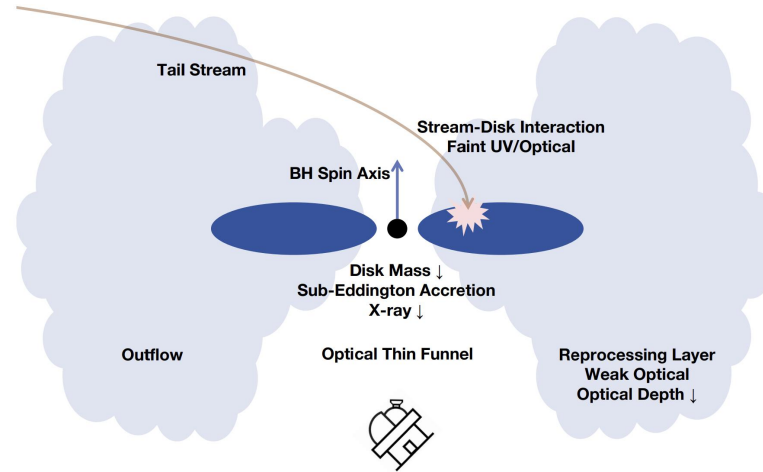
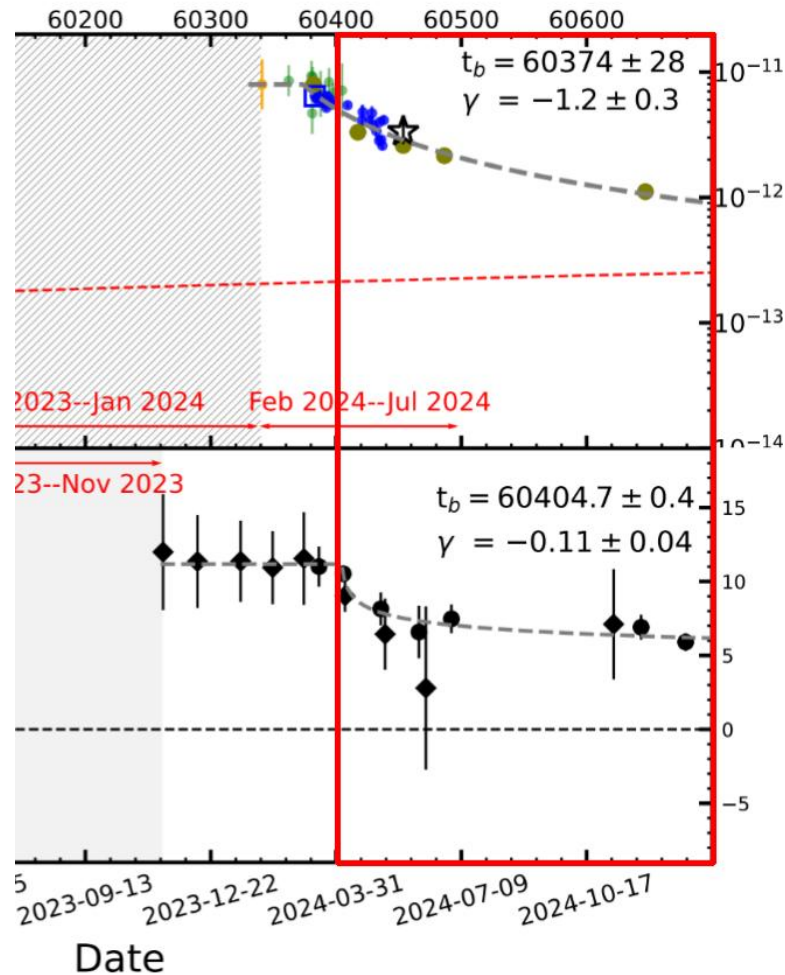
$$\dot{M}_{\text{acc}}(t) = M_d(t)/t_{\text{acc,late}}$$

$$L_{\text{bol}}(t) \simeq \begin{cases} [1 + \ln(\dot{M}_{\text{acc}}(t)/\dot{M}_{\text{Edd}})] L_{\text{Edd}}, & \dot{M}_{\text{acc}}(t) \gtrsim \dot{M}_{\text{Edd}} \\ (\dot{M}_{\text{acc}}(t)/\dot{M}_{\text{Edd}}) L_{\text{Edd}}, & \dot{M}_{\text{acc}}(t) \lesssim \dot{M}_{\text{Edd}} \end{cases}$$

5. Decline Stage



5. Decline Stage: Sub-Eddington Accretion



- Delayed & slower optical decline → reprocess
- Disk mass depletes → sub-Eddington acc
- Outflow ceases
- Optically thin layer (not yet reached)
- Timescale: years

Basic Equations for Accretion Disk: Decline Stage

$$\frac{dM_d(t)}{dt} = \dot{M}_{\text{sup}}(t) - \dot{M}_{\text{acc}}(t)$$

$$\dot{M}_{\text{sup}}(t) \simeq \dot{M}_{\text{fb}}(t)$$

$$\dot{M}_{\text{acc}}(t) = M_d(t)/t_{\text{acc,late}}$$

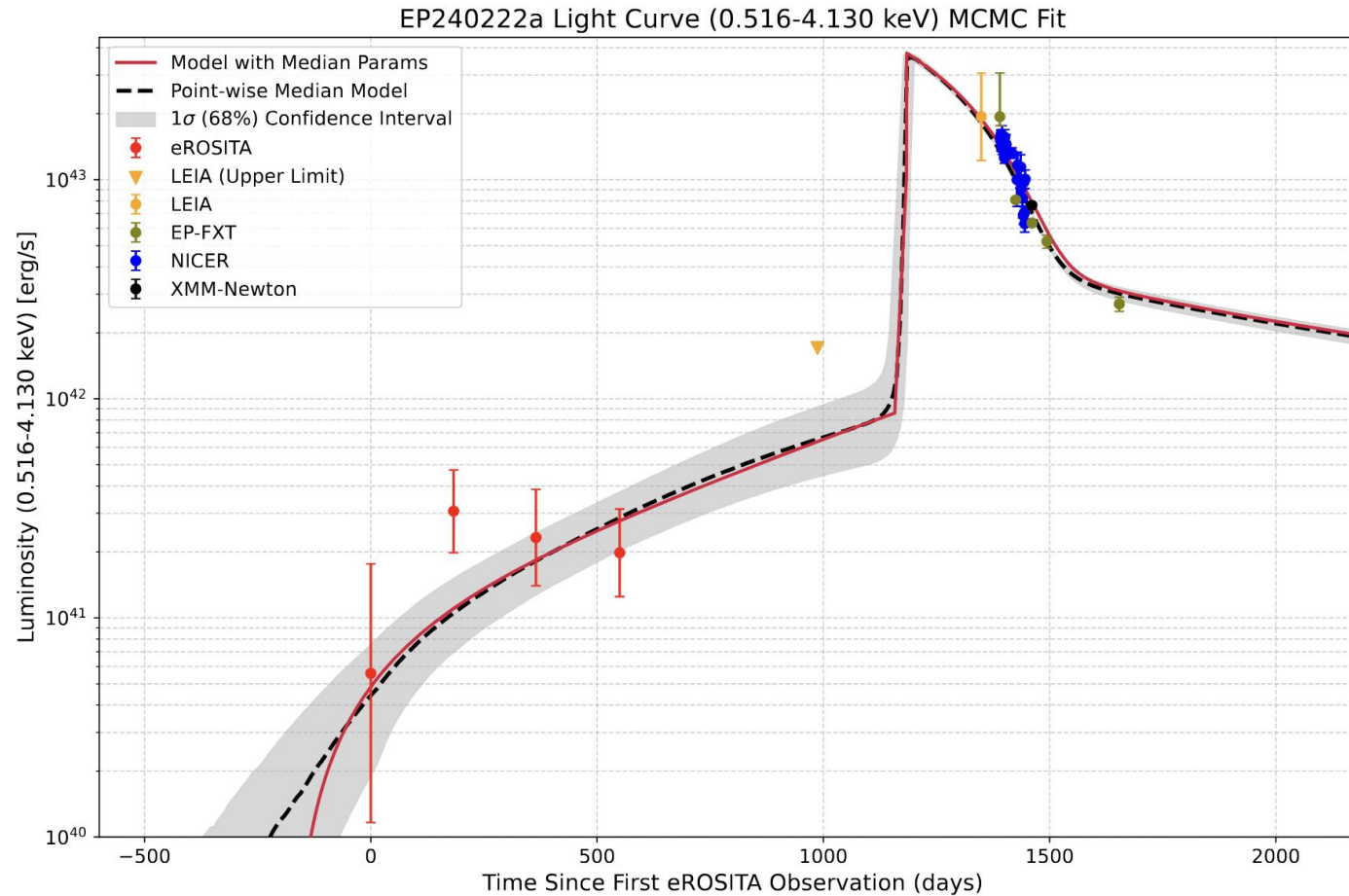
$$L_{\text{bol}}(t) \simeq \begin{cases} [1 + \ln(\dot{M}_{\text{acc}}(t)/\dot{M}_{\text{Edd}})] L_{\text{Edd}}, & \dot{M}_{\text{acc}}(t) \gtrsim \dot{M}_{\text{Edd}} \\ (\dot{M}_{\text{acc}}(t)/\dot{M}_{\text{Edd}}) L_{\text{Edd}}, & \dot{M}_{\text{acc}}(t) \lesssim \dot{M}_{\text{Edd}} \end{cases}$$

Fitting

Free Parameters

1. **Stellar Mass**, $\log_{10}(M_*/M_\odot)$: $[-1.097, 0.477]$.
2. **Penetration Factor**, $\log_{10}(\beta)$: $[-0.301, 0.477]$.
3. **Efficiency Factor**, $\log_{10}(\eta) \equiv \log_{10}(\overline{\eta_{\text{self}}\eta_{\text{sup}}}\eta_{\text{mis}})$: $[-6, 1]$.
4. **Early Accretion Timescale**, $\log_{10}(t_{\text{acc,early}}/t_{\text{dyn,c}})$: $[0, 9]$.
5. **Late Accretion Timescale**, $\log_{10}(t_{\text{acc,late}}/t_{\text{dyn,c}})$: $[0, 4]$.
6. **Critical Time**, $t_{\text{crit}} - t_0 \in [950, 1300]$ days.
7. **Time Offset**, $t_0 \in [0, 1000]$ days.

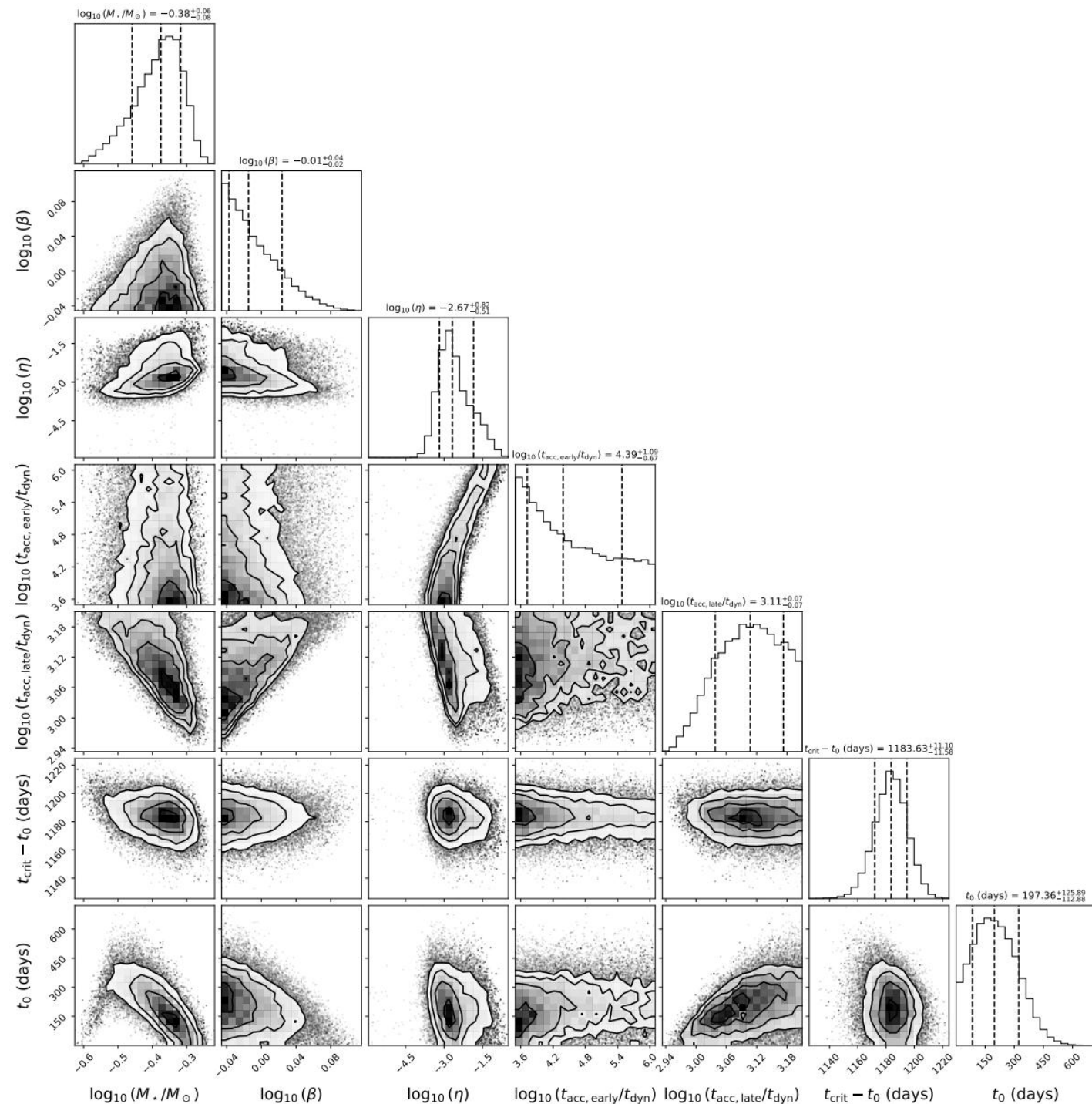
Fitting Results (X-rays)



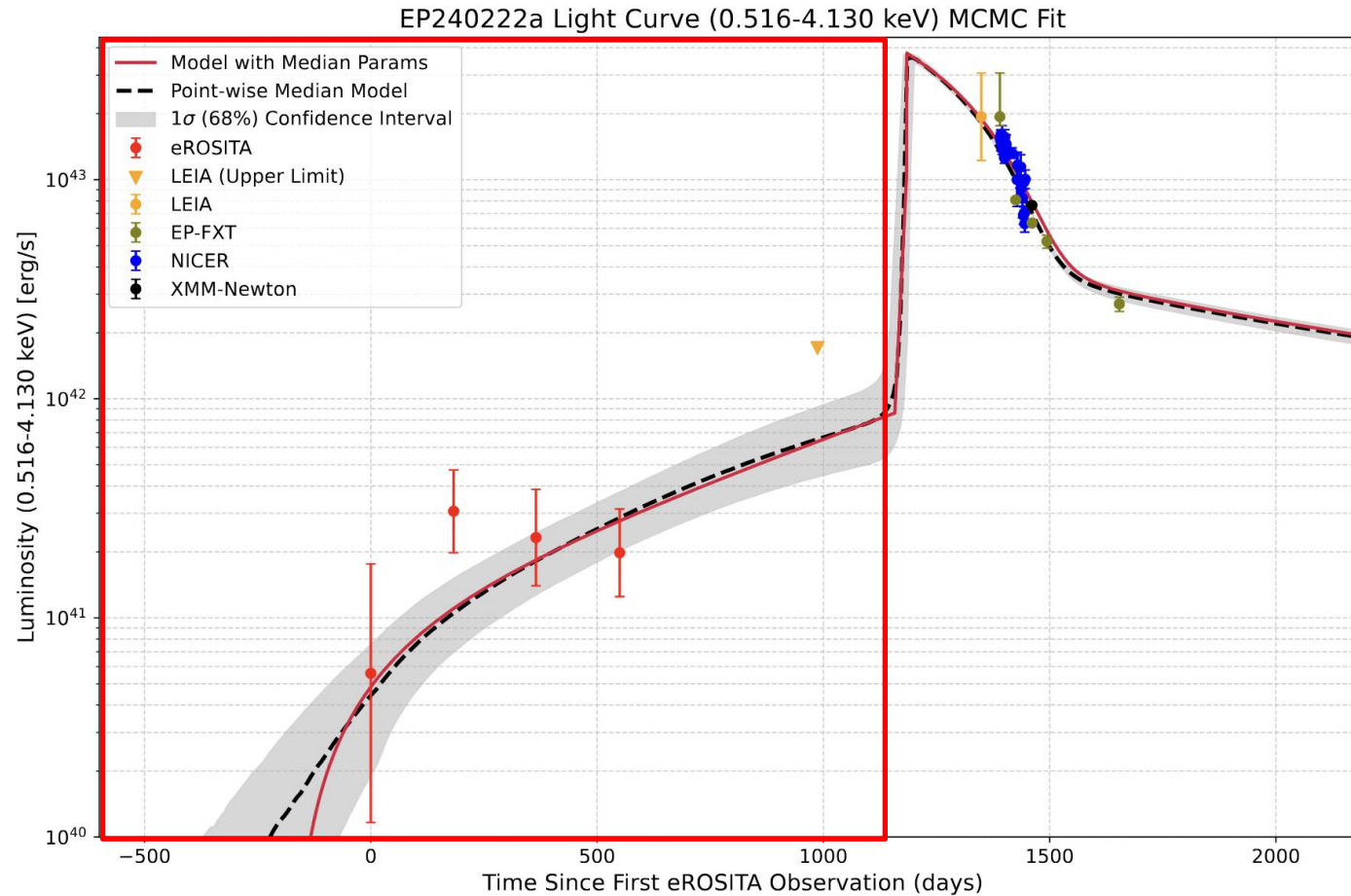
Corner Plot

➤ **Best Model**

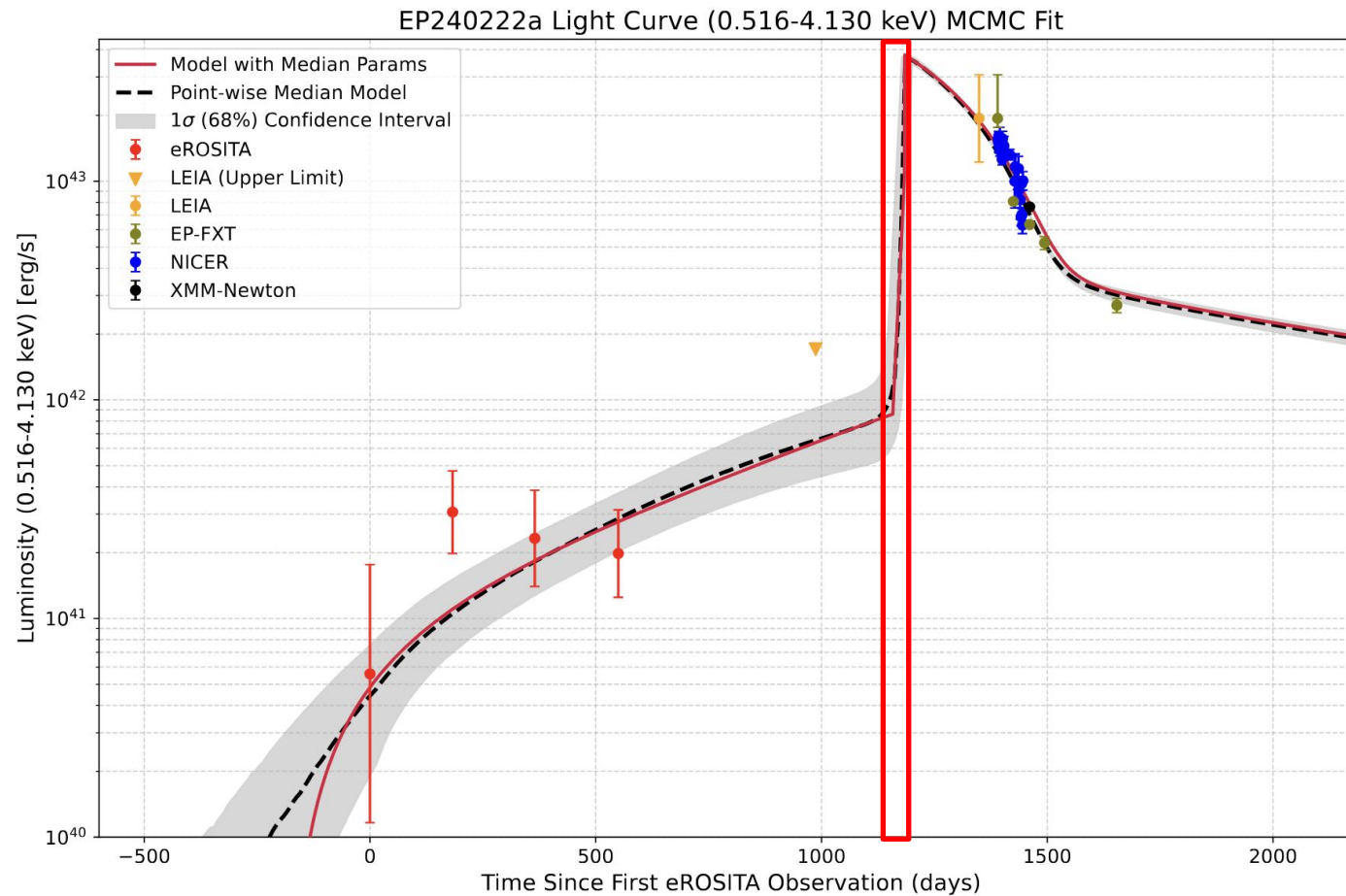
- $M_{\text{star}} \approx 0.4 M_{\text{sun}}$
- $\beta \approx 1.0$



Slow Rise (years)

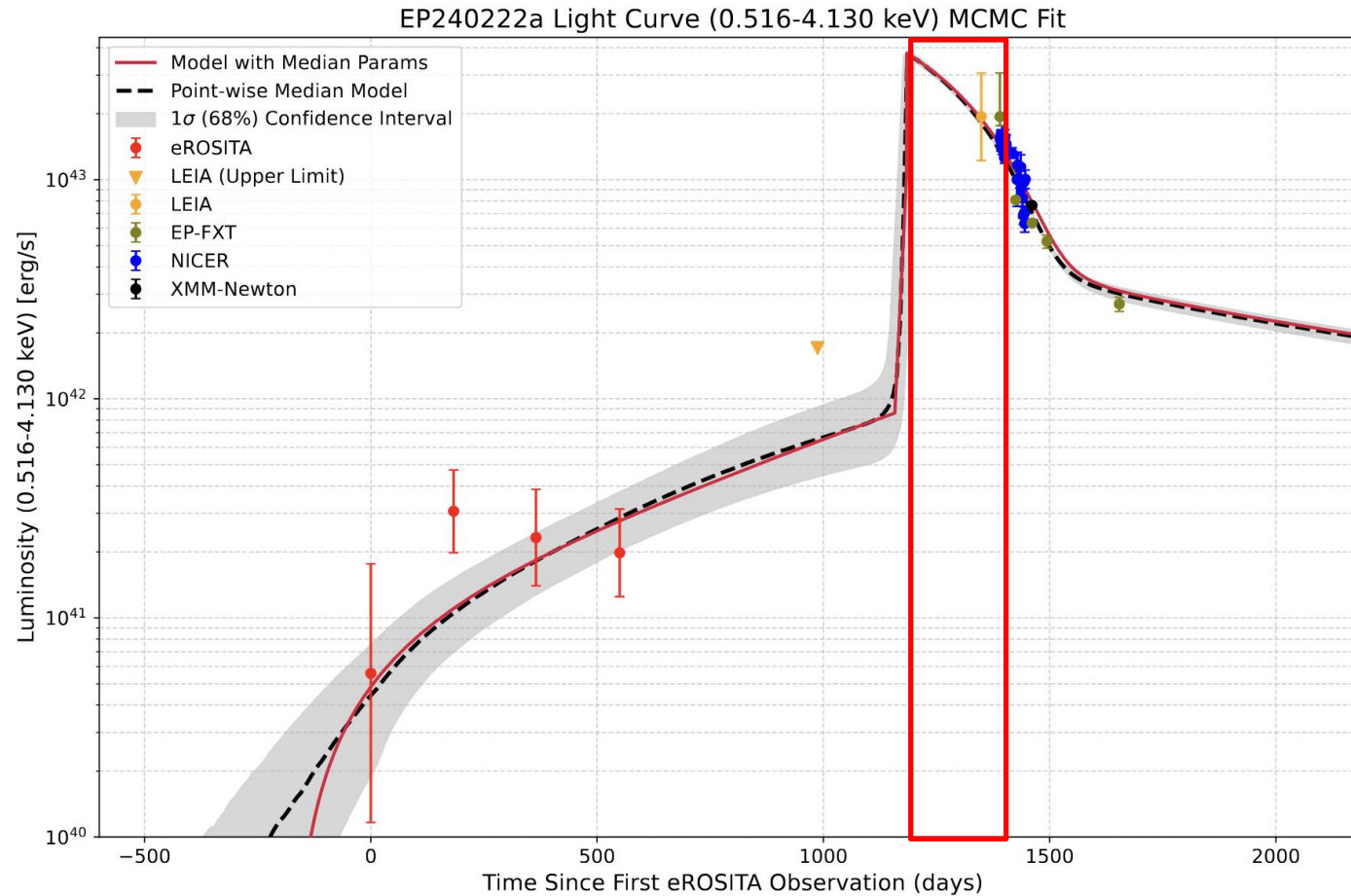


Fast Rise ($<t_{fb}$ or t_{fb})



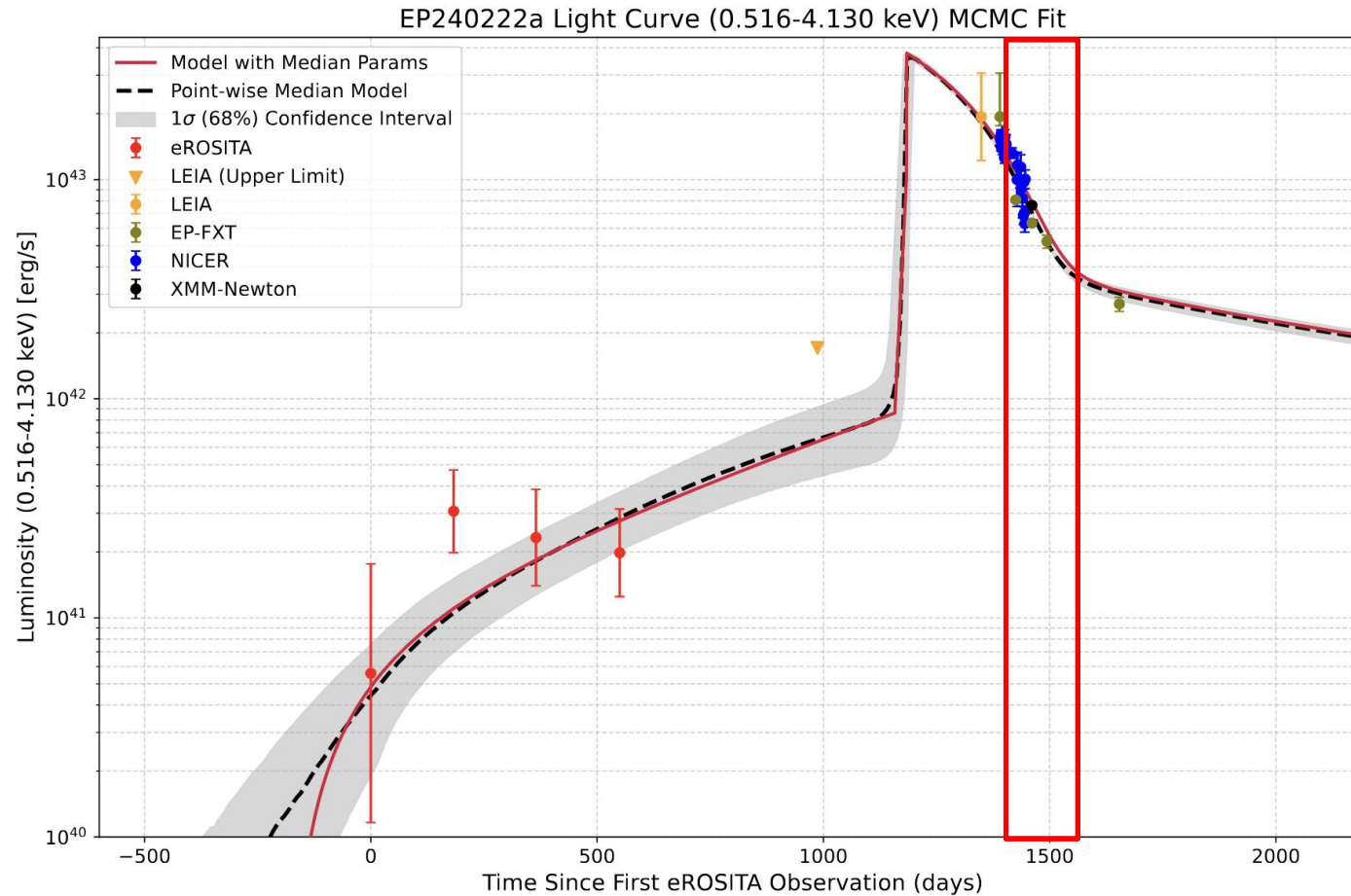
Plateau

$$L_{\text{bol}}(t) \simeq \left[1 + \ln \left(\frac{M_{\text{fb}}}{\dot{M}_{\text{Edd}} t_{\text{acc,late}}} \right) - \frac{t}{t_{\text{acc,late}}} \right] L_{\text{Edd}}$$

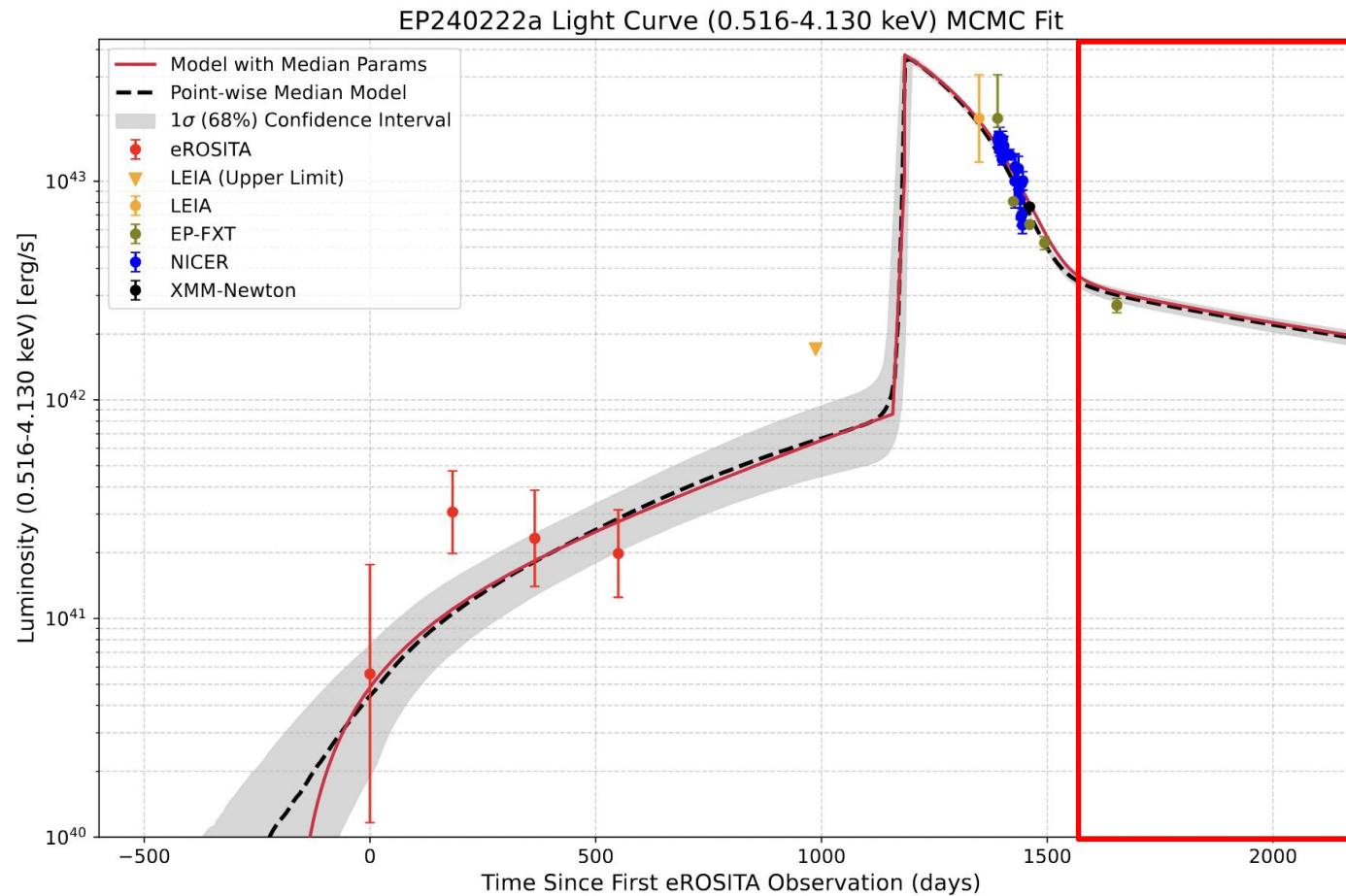


Decline

$$L_{\text{bol}}(t) \simeq \left[1 + \ln \left(\frac{M_{\text{fb}}}{\dot{M}_{\text{Edd}} t_{\text{acc,late}}} \right) - \frac{t}{t_{\text{acc,late}}} \right] L_{\text{Edd}}$$

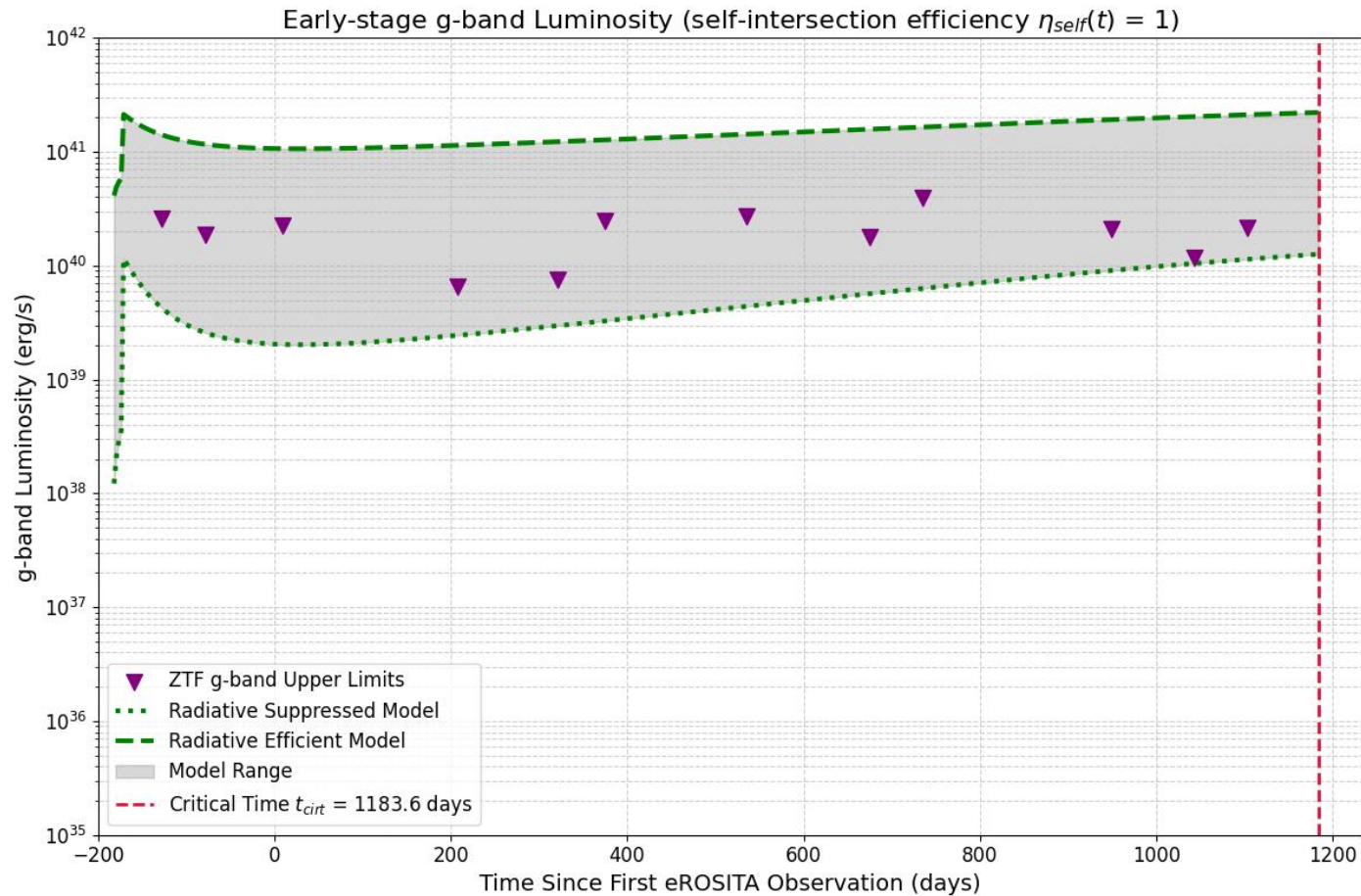


Decline: Power Law

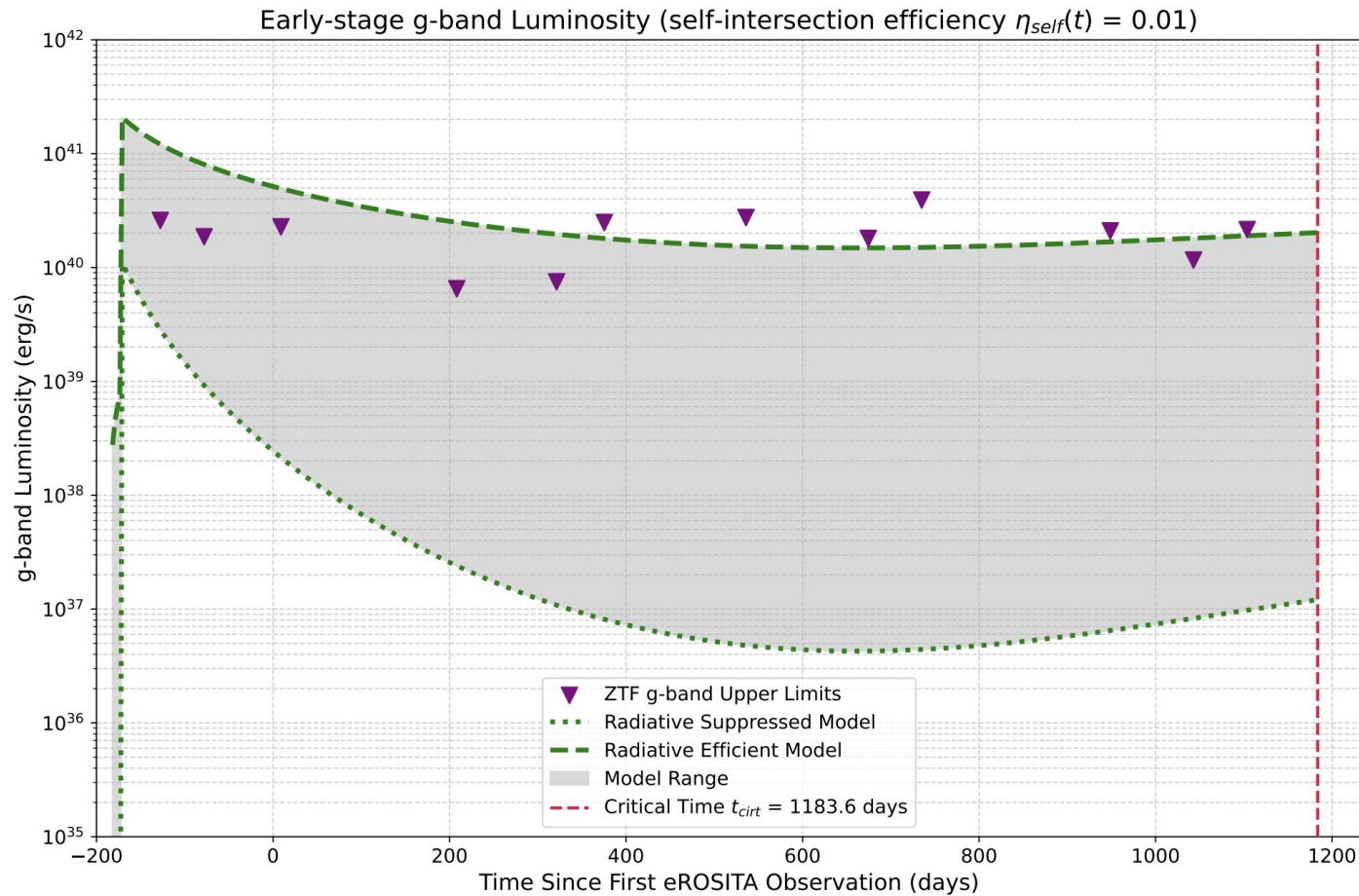


Discussion

Early optical:
$$L_{g,\text{early}}(t) \simeq \frac{M_s(t)\dot{E}(t) + \dot{M}_{\text{fb}}(t) [E_0 - E_{\text{fb}}(t)]}{K_g(t)}$$

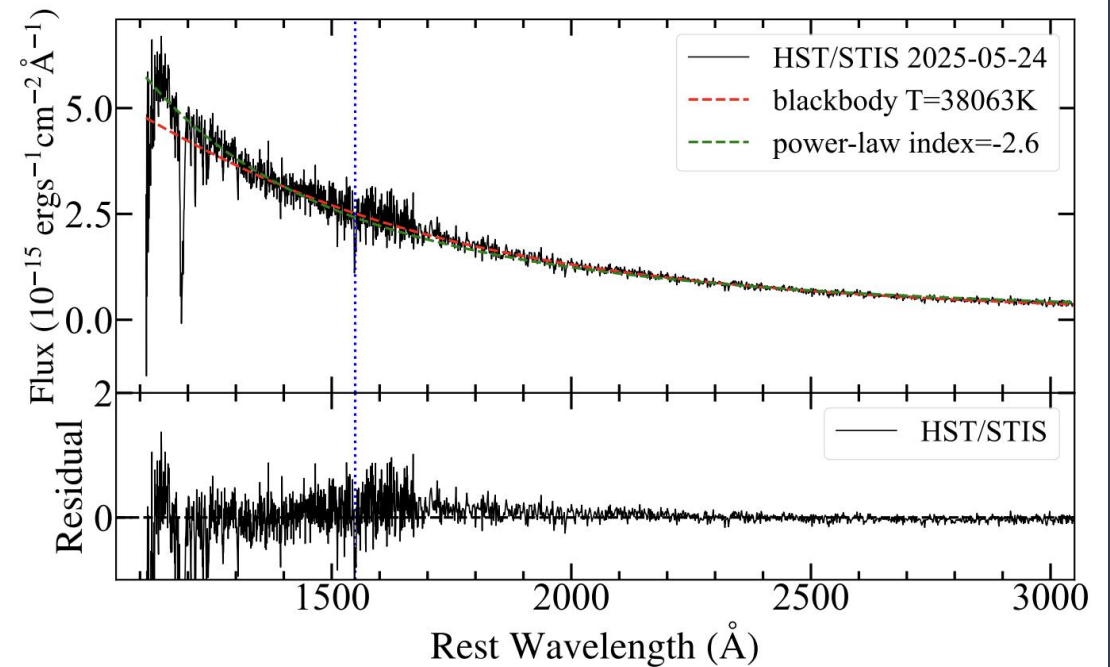
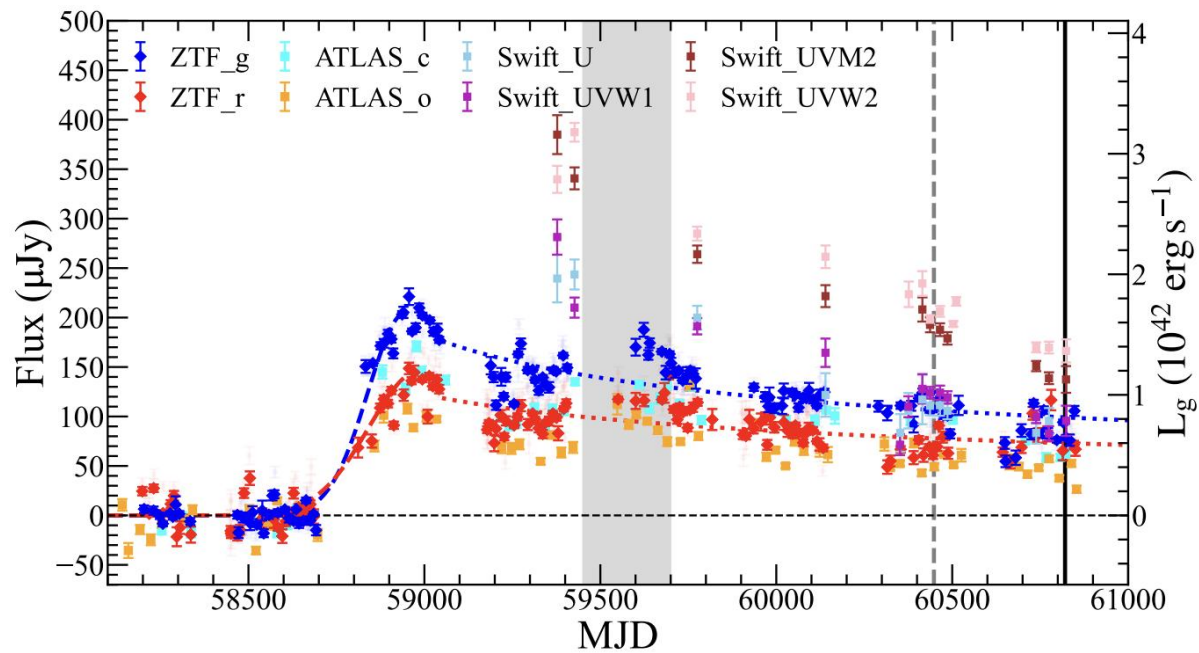


Early optical:
$$L_{g,\text{early}}(t) \simeq \frac{M_s(t)\dot{E}(t) + \dot{M}_{\text{fb}}(t) [E_0 - E_{\text{fb}}(t)]}{K_g(t)}$$

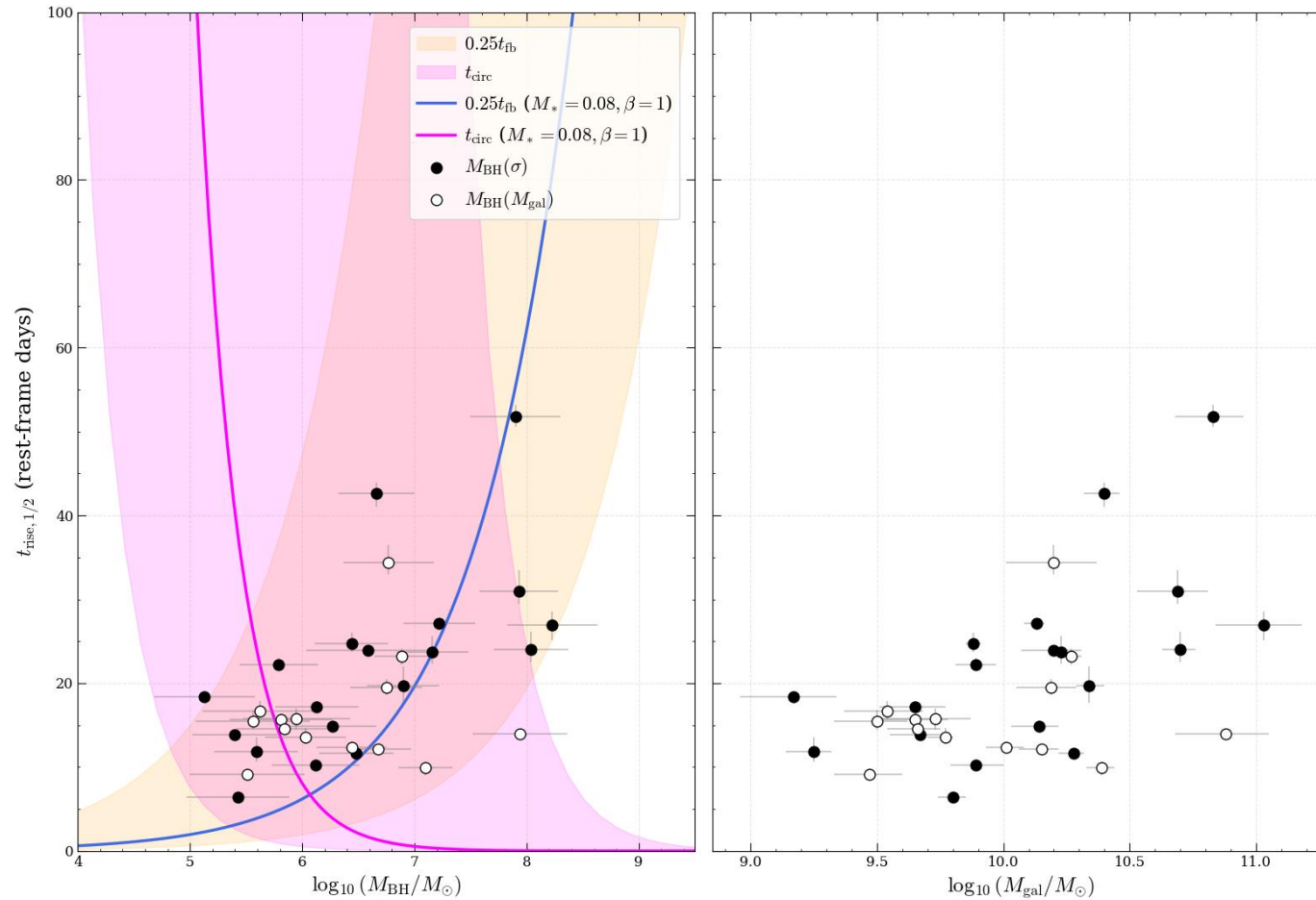


Ansky (most extreme QPE) from an TDE

- **IMBH-TDE?**
- **Post-main sequence star SMBH-TDE**



EP240222a: Far Away in the Upper Left (draft)



WD-IMBH-TDEs: Fast Rise ($\sim t_{\text{fb}}$)

➤ Dissipation channels (**efficient for WD-IMBH-TDEs!**)

- **nozzle shock**

$$\epsilon_{\text{noz}} \simeq \frac{\frac{1}{2}v_{z,\text{max}}^2}{E_c} \simeq 9.3 \times 10^{-6} \beta M_5^{-2/3} m_*^{2/3} \ll 1$$

- **self-intersection of the main stream**

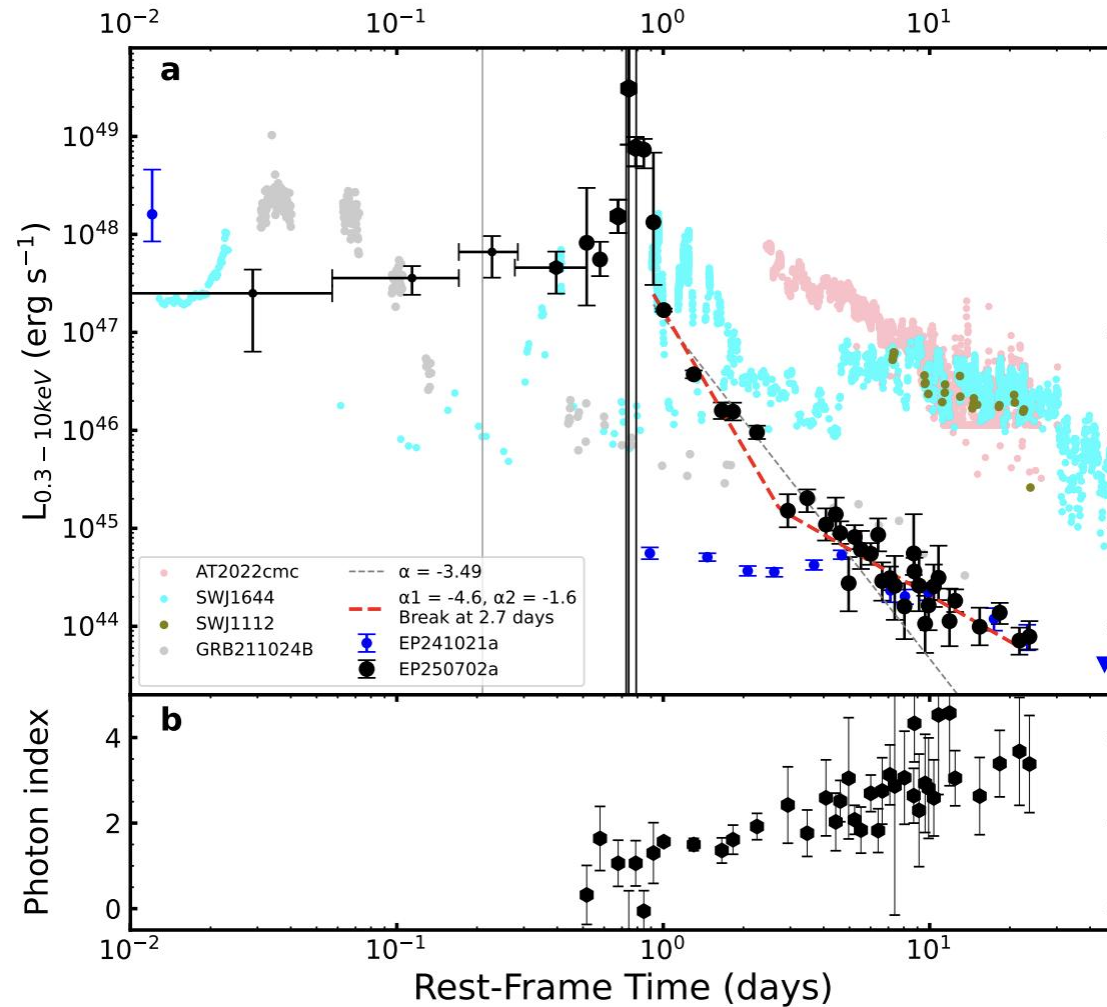
$$\epsilon_{\text{self}} \simeq \frac{\Delta E_0}{E_c} \simeq 4.6 \times 10^{-4} e_0^2 \beta^2 M_5^{4/3} r_*^{-2} m_*^{2/3}$$

- **tail stream-main stream interaction**

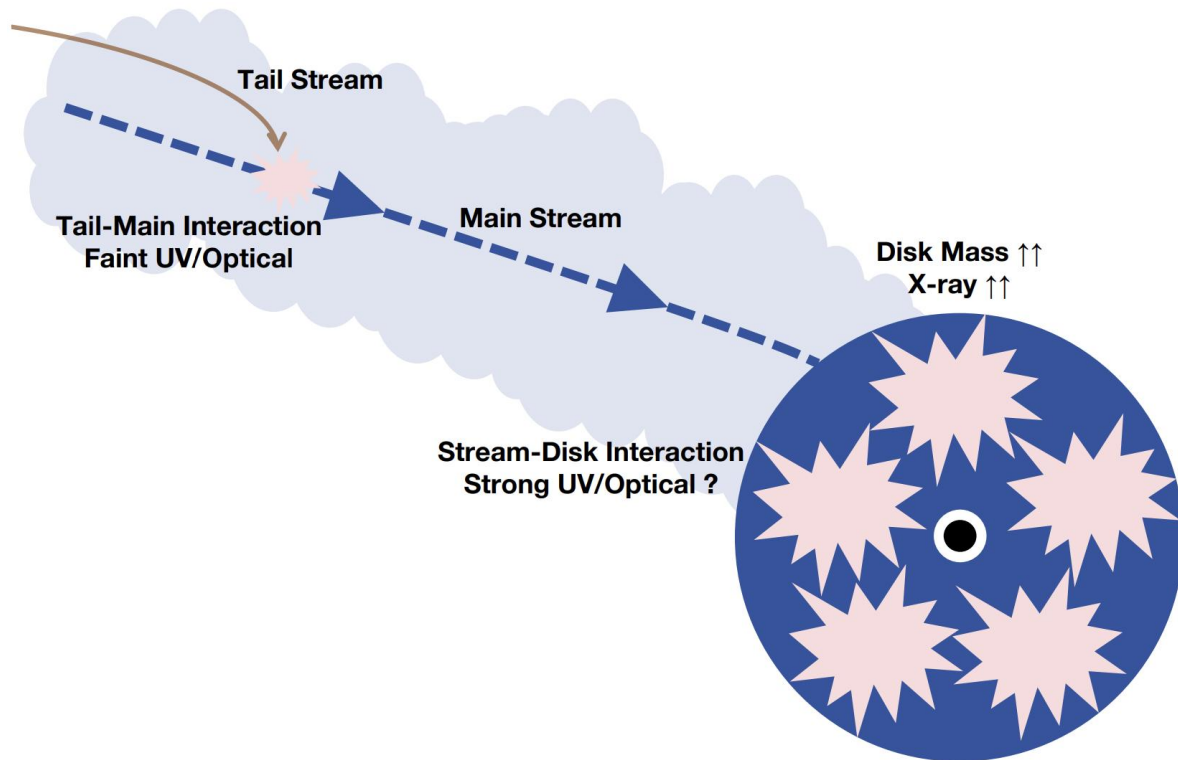
$$\begin{aligned} \epsilon_{\text{tm}}(t) &\simeq \frac{\Delta E_{\text{tm}}}{E_c} \simeq \frac{\dot{M}_{\text{fb}}(t)t_{\text{fb}}E_0}{M_s(t)E_c} \\ &\simeq 4.3 \times 10^{-2} \left(\frac{t}{t_{\text{fb}}}\right)^{-n} \left[1 - \left(\frac{t}{t_{\text{fb}}}\right)^{1-n}\right]^{-1} (n-1)(1+e_0) \\ &\quad \times M_5^{-1/3} m_*^{1/3} \times \begin{cases} \beta, & \beta \lesssim \beta_d \\ \beta^{-1}, & \beta \gtrsim \beta_d \end{cases} \ll 1 \end{aligned}$$

$$t_{\text{acc}} \simeq \left(\frac{H}{R}\right)_d^{-2} \alpha^{-1} t_{\text{dyn,c}} \simeq 13 \left(\frac{(H/R)_d}{0.2}\right)^{-2} \left(\frac{\alpha}{0.1}\right)^{-1} \beta^{-3/2} r_*^{3/2} m_*^{-1/2} \text{ days}$$

Jetted WD-IMBH-TDE Candidate



Critical Moment Check



- Momentum flux matching
- Stream–disk interaction
- Runaway circularization

$$\sqrt{2}\dot{M}_s(t_{\text{crit}}) \left(\frac{H}{R}\right)_{\text{d,early}} \simeq \dot{M}_d(t_{\text{crit}})$$

$$\left(\frac{H}{R}\right)_{\text{d,early}}^3 \alpha_{\text{early}} \simeq \frac{t_{\text{s,N}}(t_{\text{crit}})L_{\text{bol}}(t_{\text{crit}})}{2\sqrt{2}\pi\eta_{\text{mis}}M_s(t_{\text{crit}})c^2}$$

$\log_{10}(t_{\text{acc,early}}/t_{\text{dyn,c}})$ posterior to [3.5, 6.1]

Summary & Take Away Message

- EP240222a is the **first IMBH–TDE** captured in real–time with multi–wavelength observations and spectroscopic confirmation.
- We reveals **inefficient circularization, delayed stream–disk interaction** and **reprocessing** in EP240222a.
- Our results indicate EP240222a was the disruption of a main–sequence star ($M_{\text{star}} \approx 0.4 M_{\text{sun}}$; $\beta \approx 1.0$).
- **MS–IMBH–TDE** (optical, X–rays): **slow rise and/or quasi plateau.**
- **WD–IMBH–TDE** (optical, X–rays): **fast rise.**

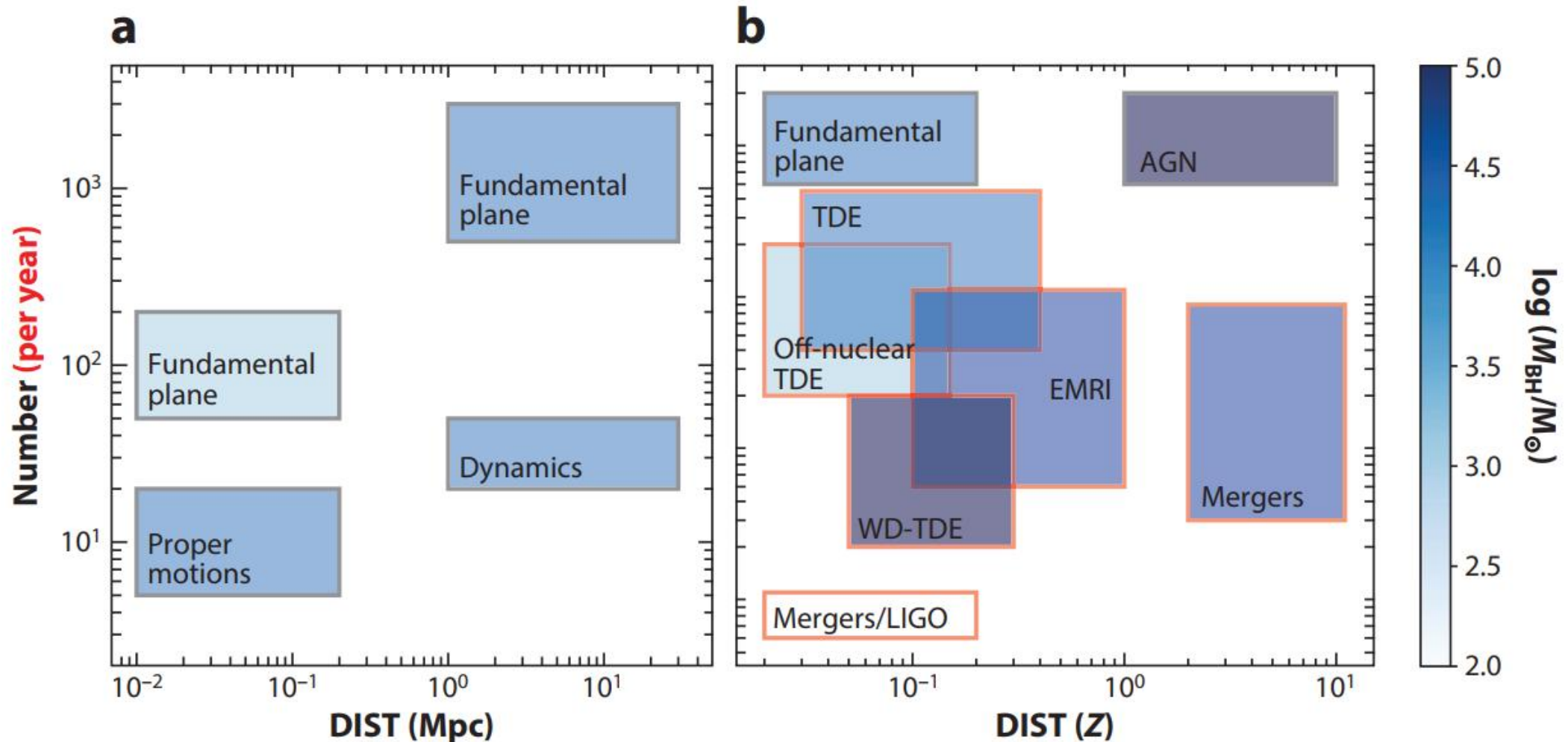
Thanks!

Summary & Take Away Message

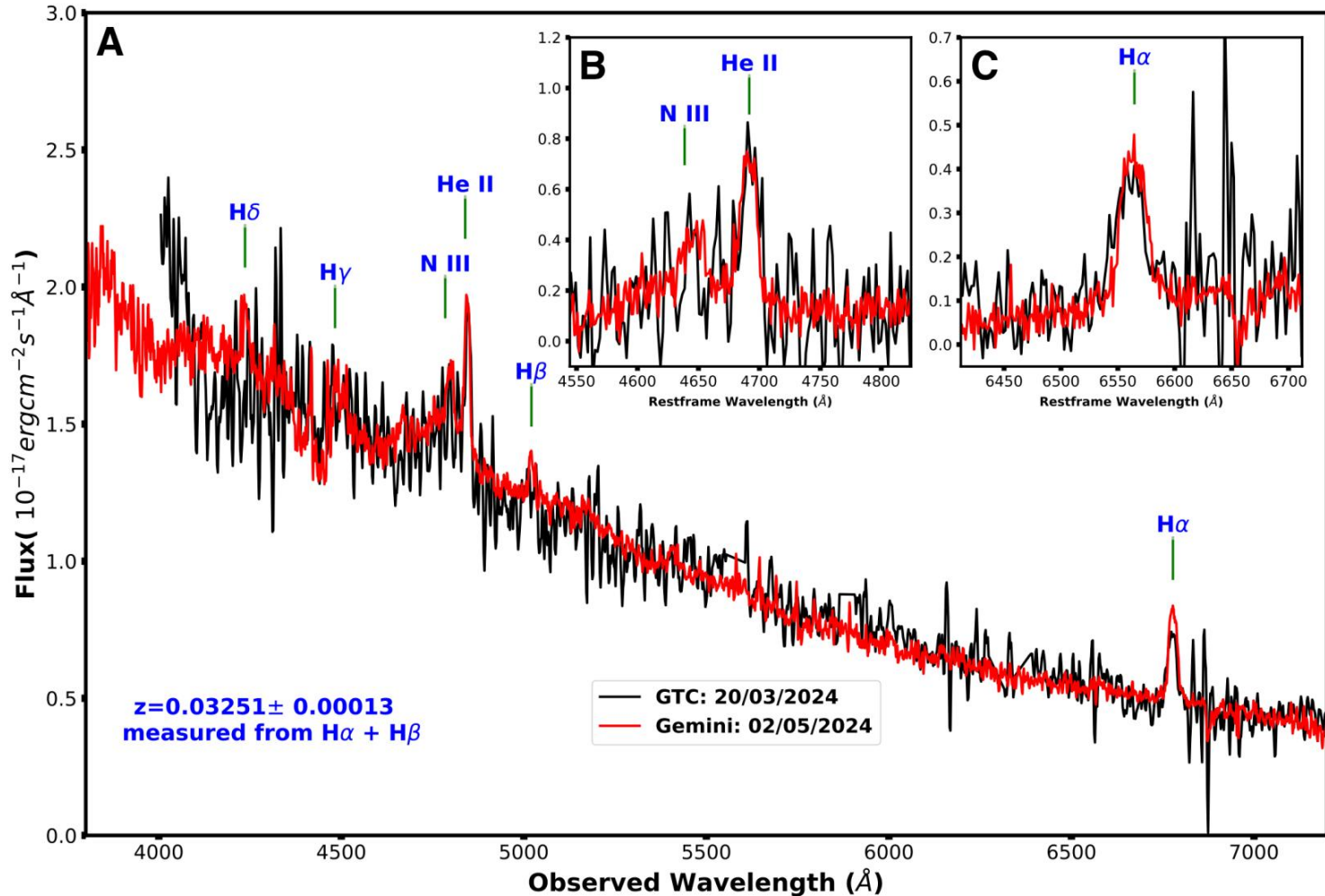
- EP240222a is the **first IMBH–TDE** captured in real–time with multi–wavelength observations and spectroscopic confirmation.
- We reveals **inefficient circularization, delayed stream–disk interaction** and **reprocessing** in EP240222a.
- Our results indicate EP240222a was the disruption of a main–sequence star ($M_{\text{star}} \approx 0.4 M_{\text{sun}}$; $\beta \approx 1.0$).
- **MS–IMBH–TDE** (optical, X–rays): **slow rise and/or quasi plateau.**
- **WD–IMBH–TDE** (optical, X–rays): **fast rise.**

Backup

Using TDE to Find IMBH

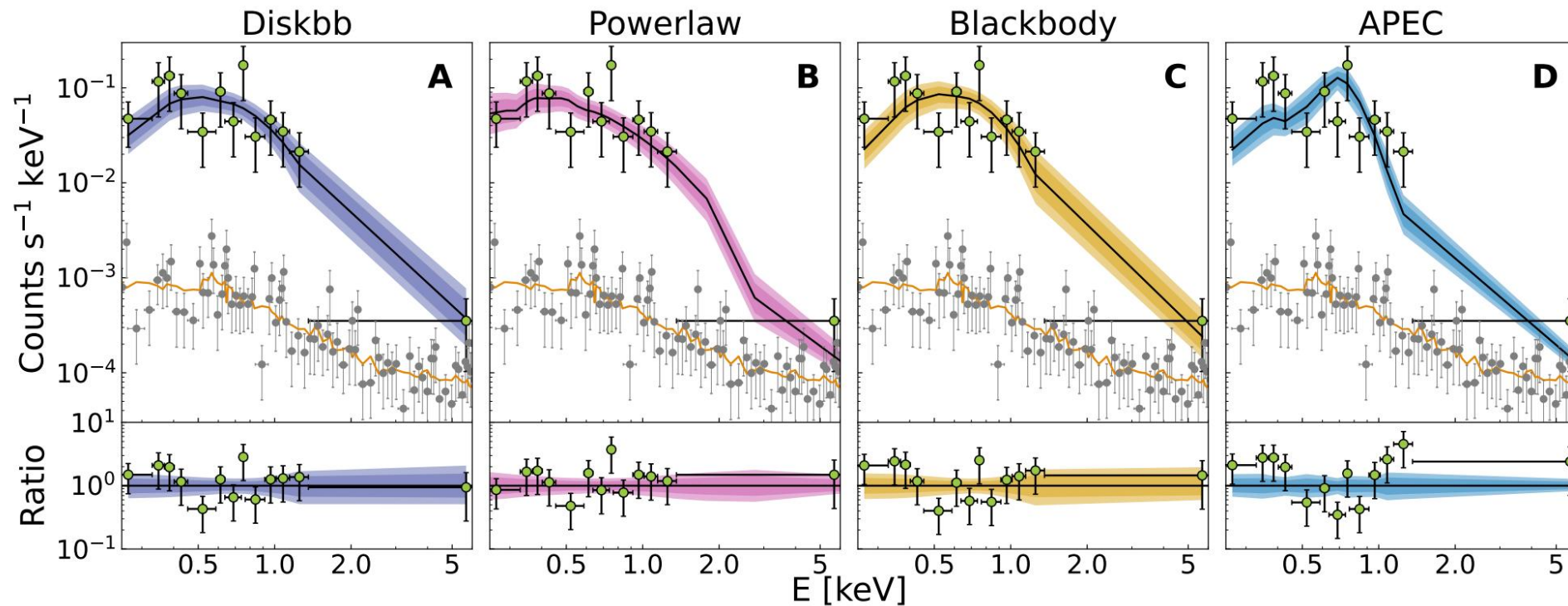


Spectrum: Not as broad as typical TDE (1e4 km/s)

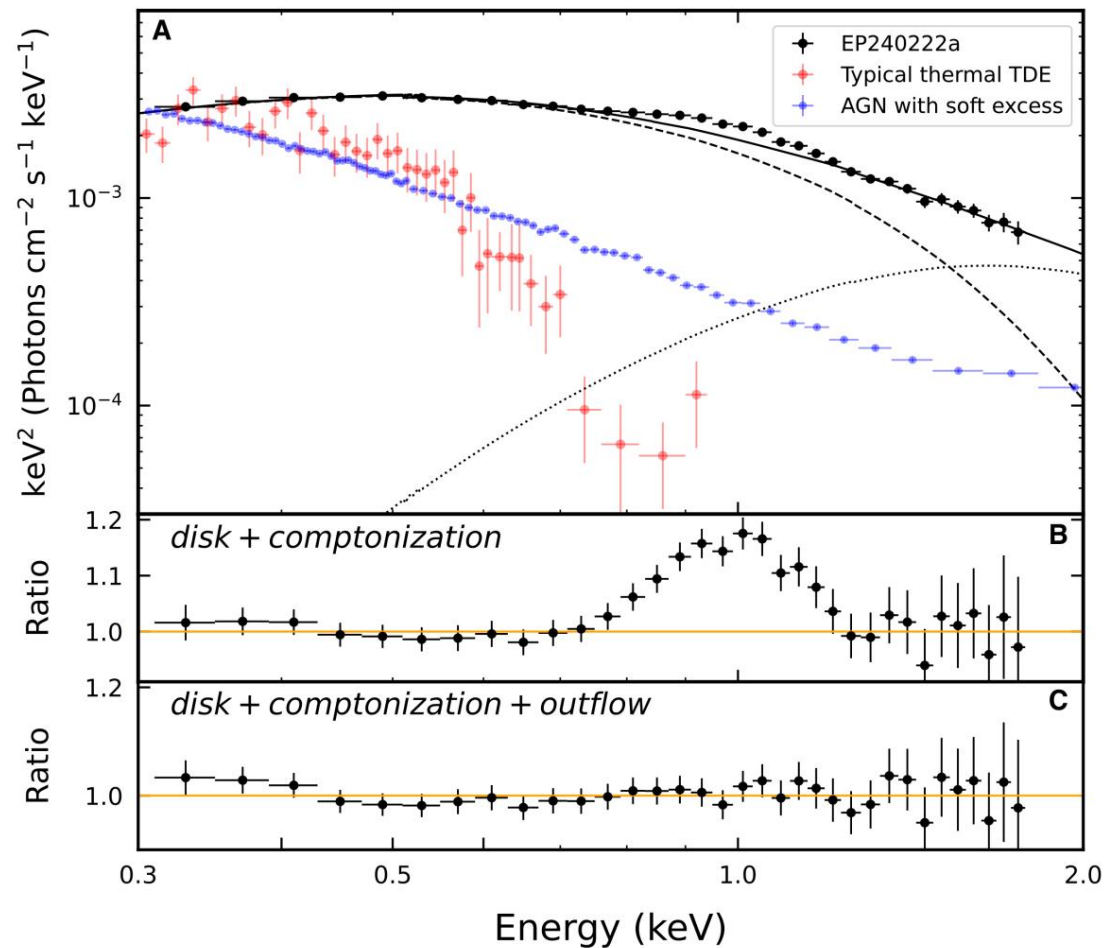


- $z = 0.03251$
- Typical TDE Lines
- No [O III] 4959/5007
- AGN ×
- Kinematics?
- SMBH-TDE ×?
- IMBH-TDE ?
- Electron Scattering?
- SMBH-TDE ✓?
- IMBH-TDE ?

Early X-ray SED Fitting



X-ray SED



➤ Harder than typical thermal TDE

- IMBH-TDE

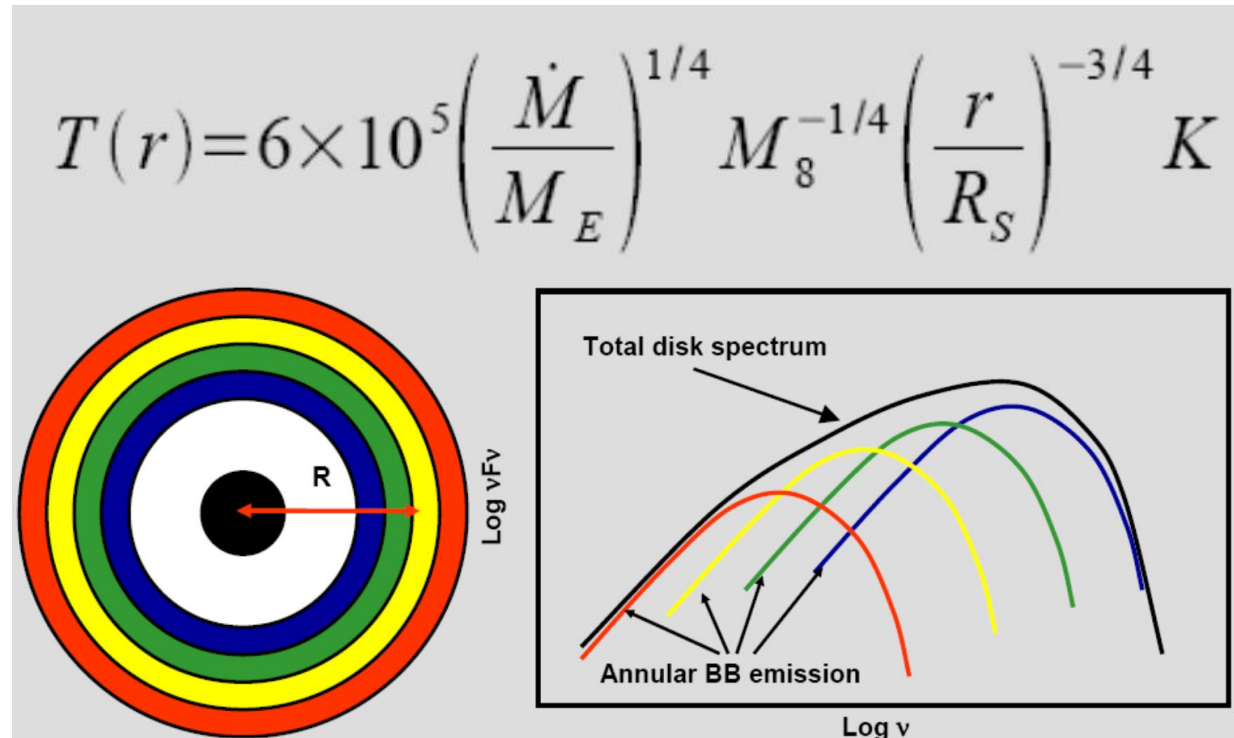
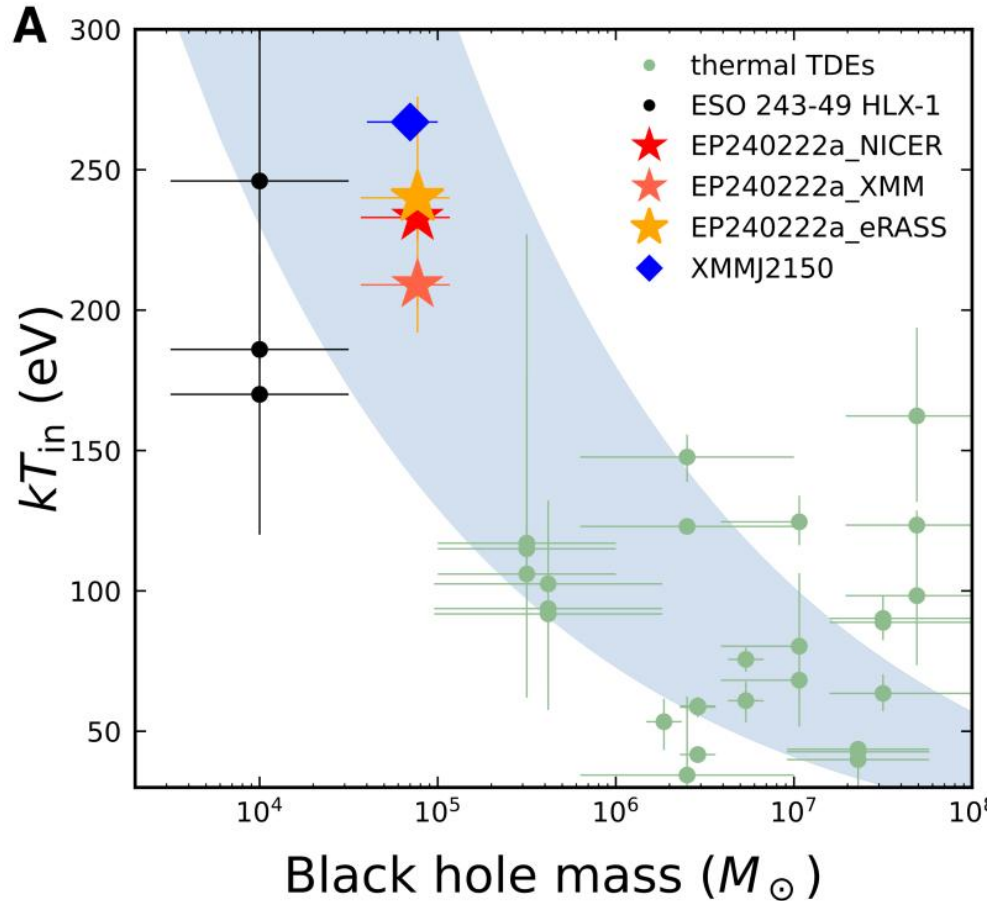
➤ Different from AGN

➤ Outflow signature @ 1keV

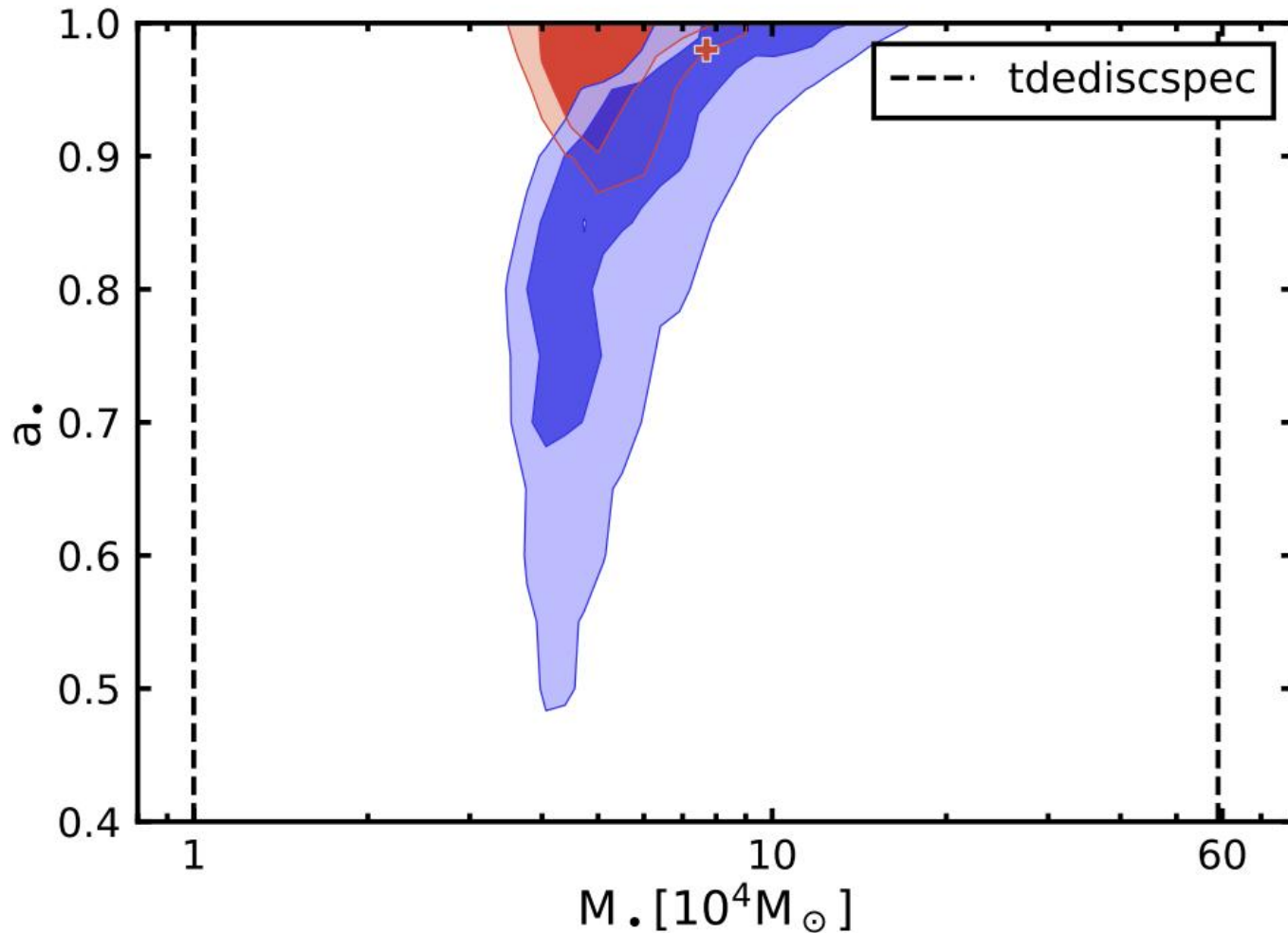
- 0.34c (very fast)

- why no radio?

BH Mass vs Inner Disk Temperature

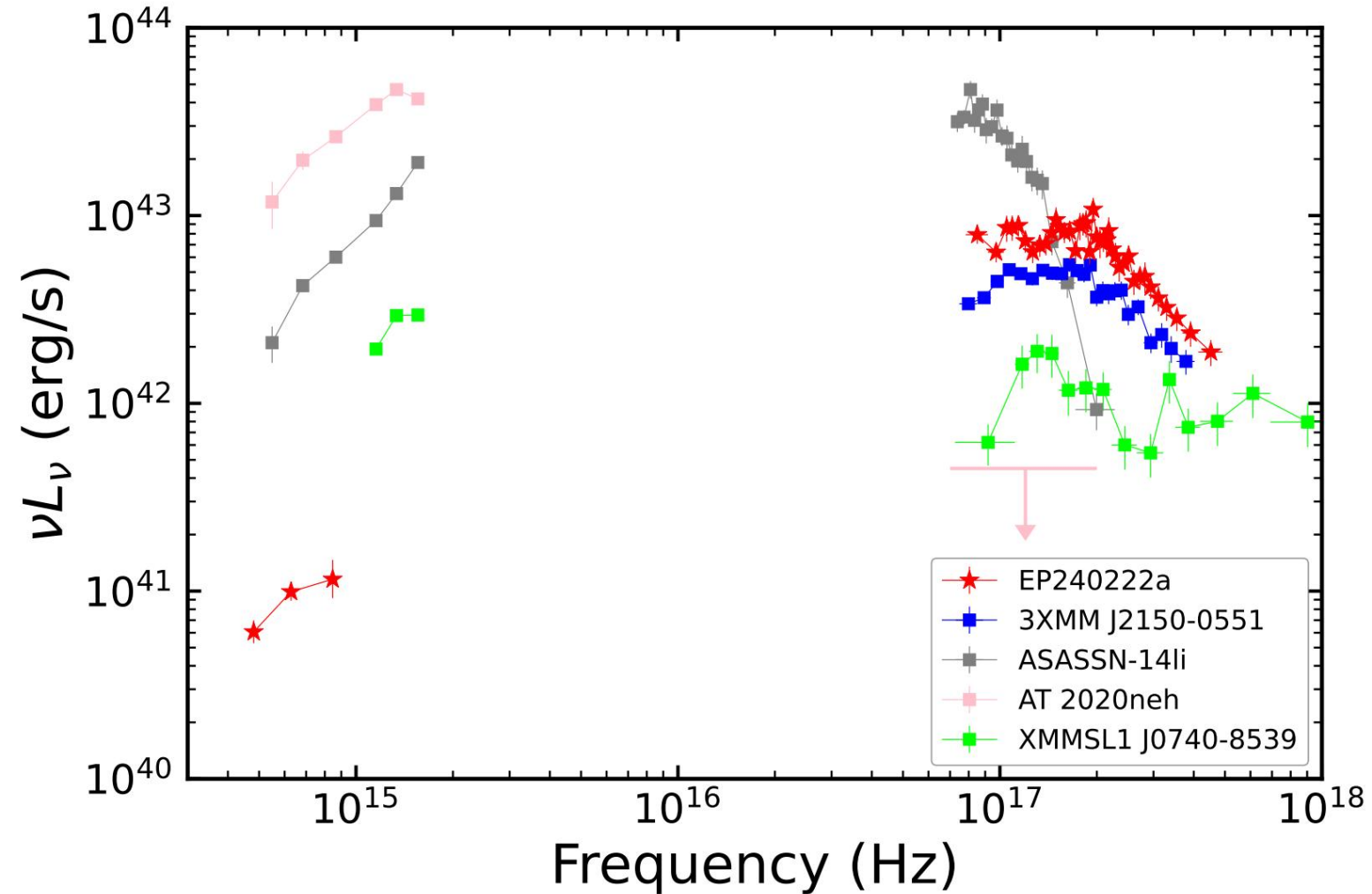


BH Mass & Spin (Sixiang Wen)

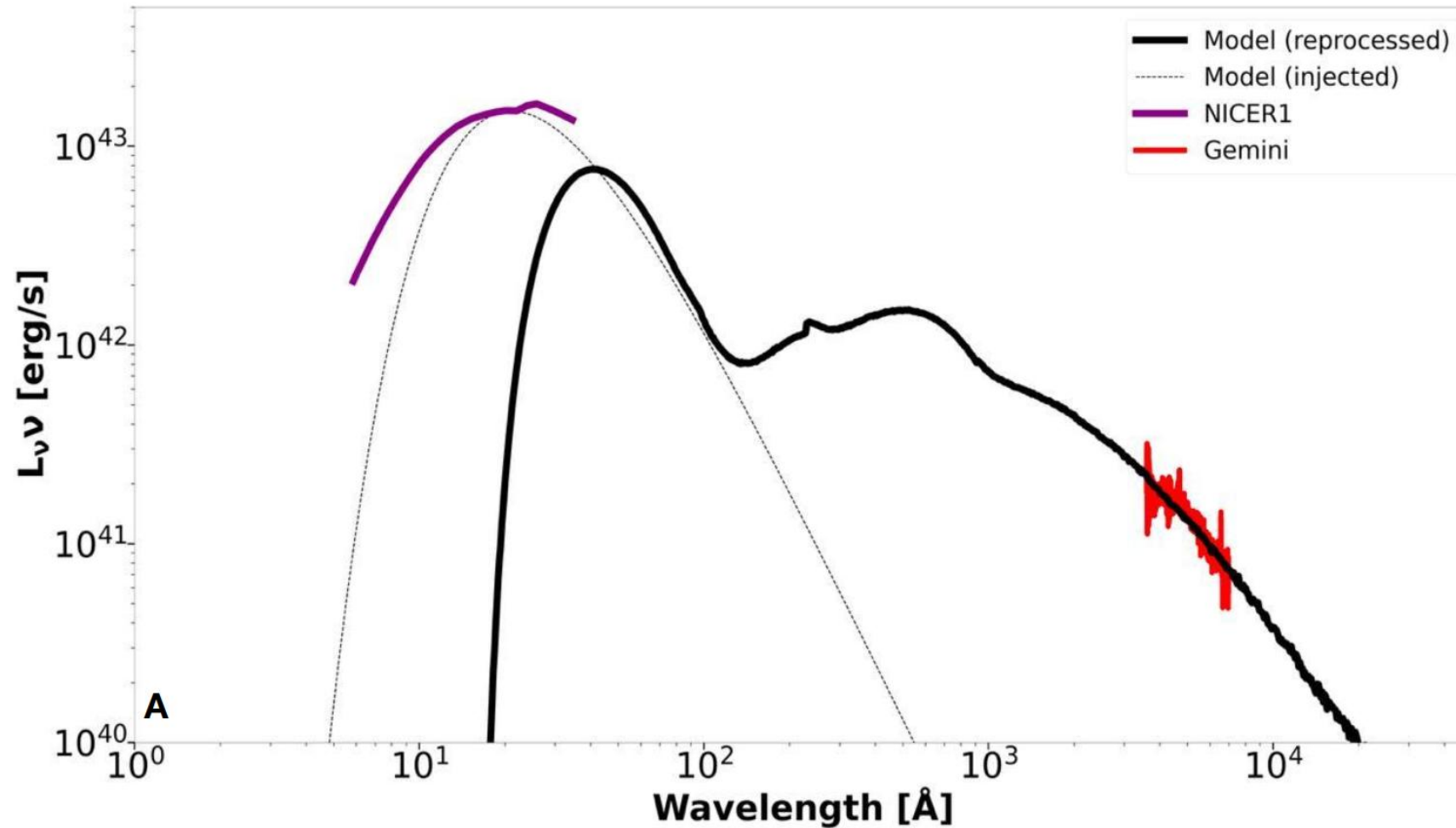


- **BH mass**
- **luminosity**
- **spectrum shape**
- ✓ **BH spin → ISCO**
- **spectrum shape**
- **Multi-epoch → better**

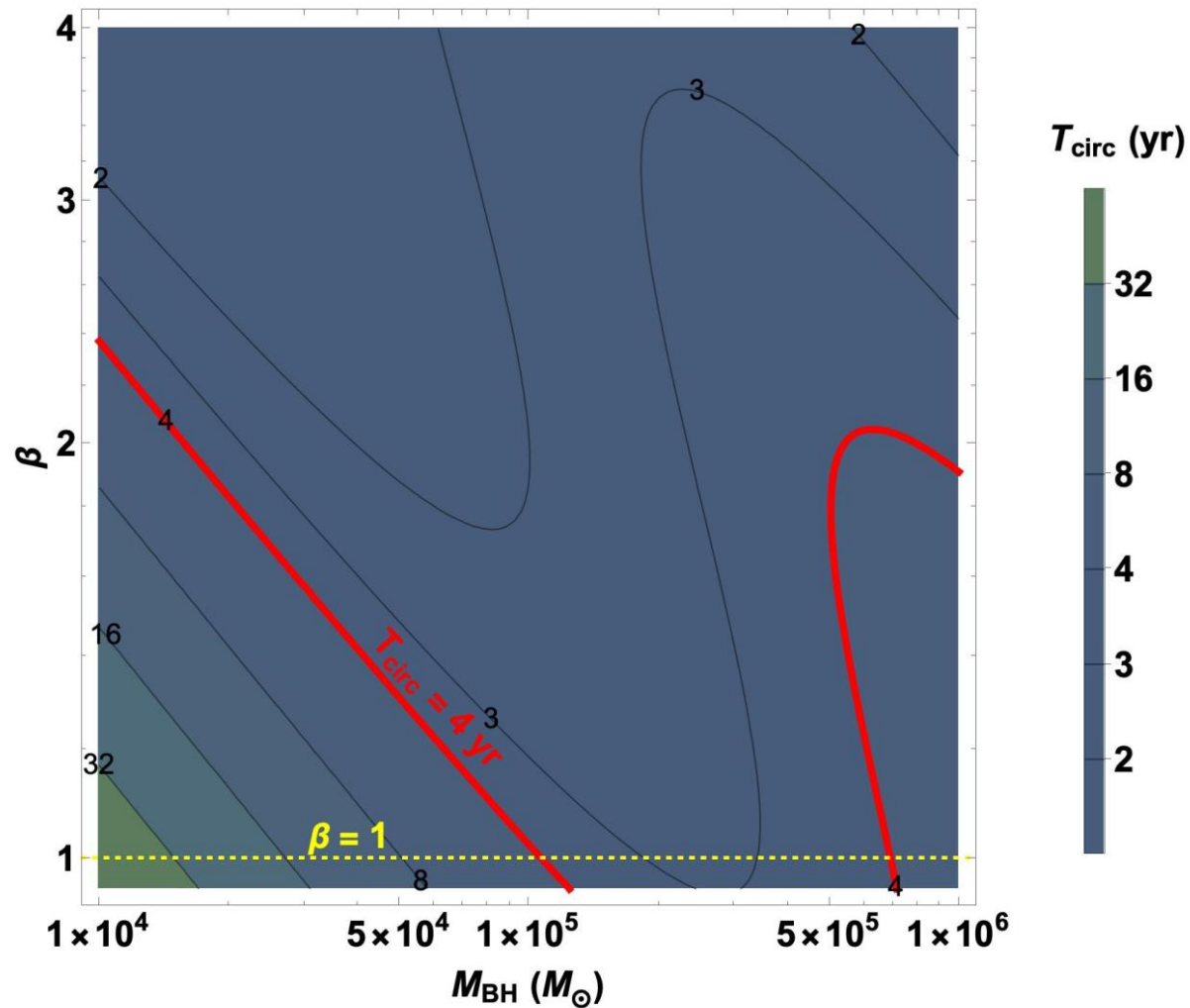
Broad Band SED



Reprocessing Model



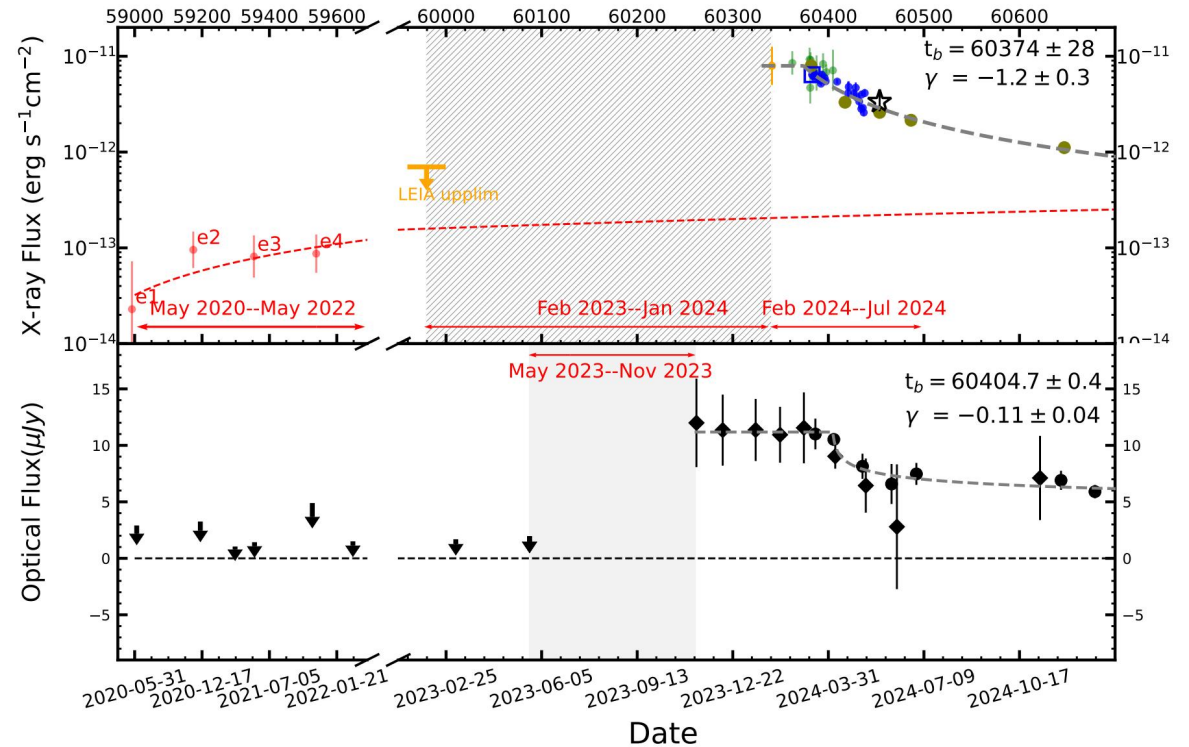
Circularization Timescale



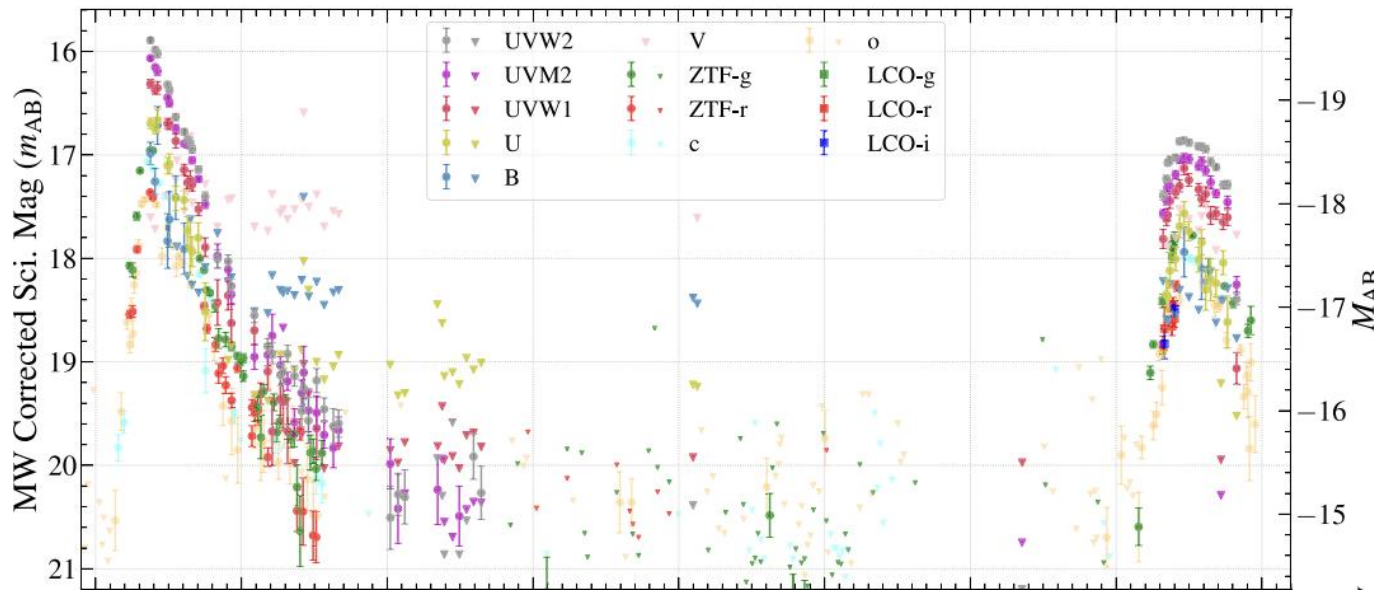
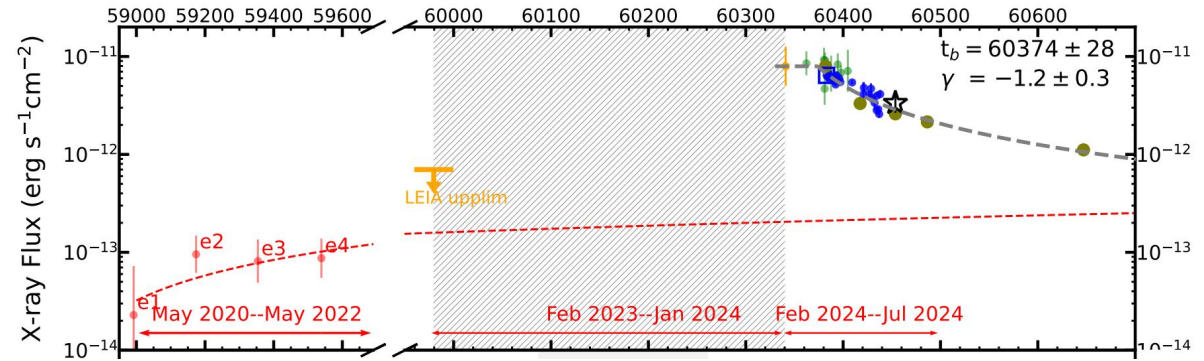
Other Possibilities?

➤ X-rays:

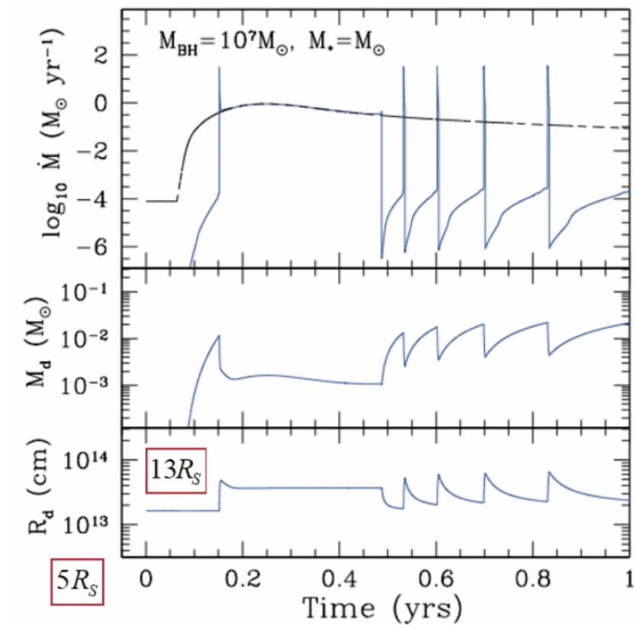
- AGN → not likely
- rpTDE → ?
- pTDE + fTDE → ?
- two distinct TDEs → not likely



Other Possibilities?



Repeating Partial TDE
Z. Lin et al. 2024

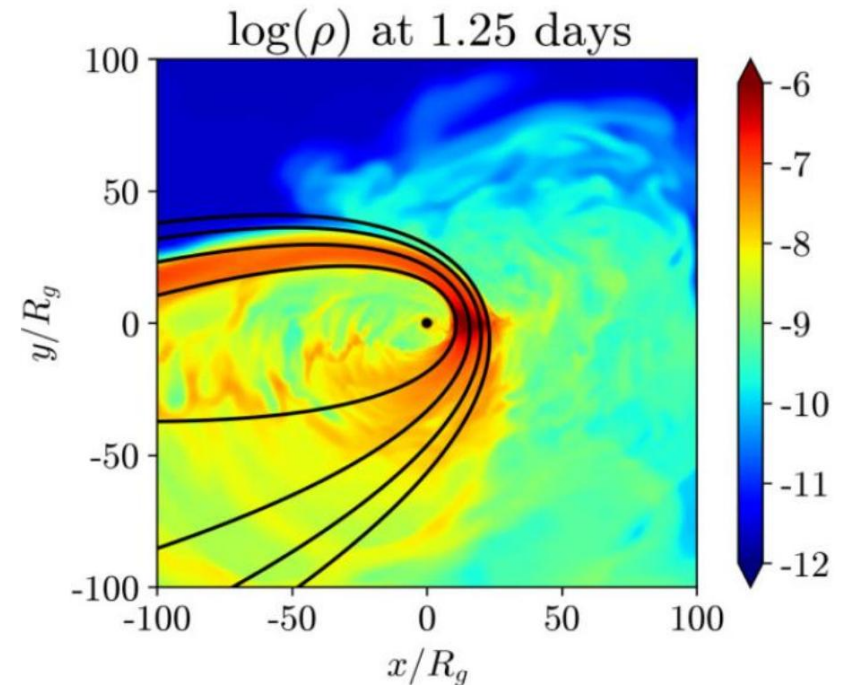


Radiation Pressure Instability
A. Piro & B. Mockler 2024

$R_{\text{eff}} \gg R_{\text{star}}$? In Fact R_{eff} Should $\sim R_p$

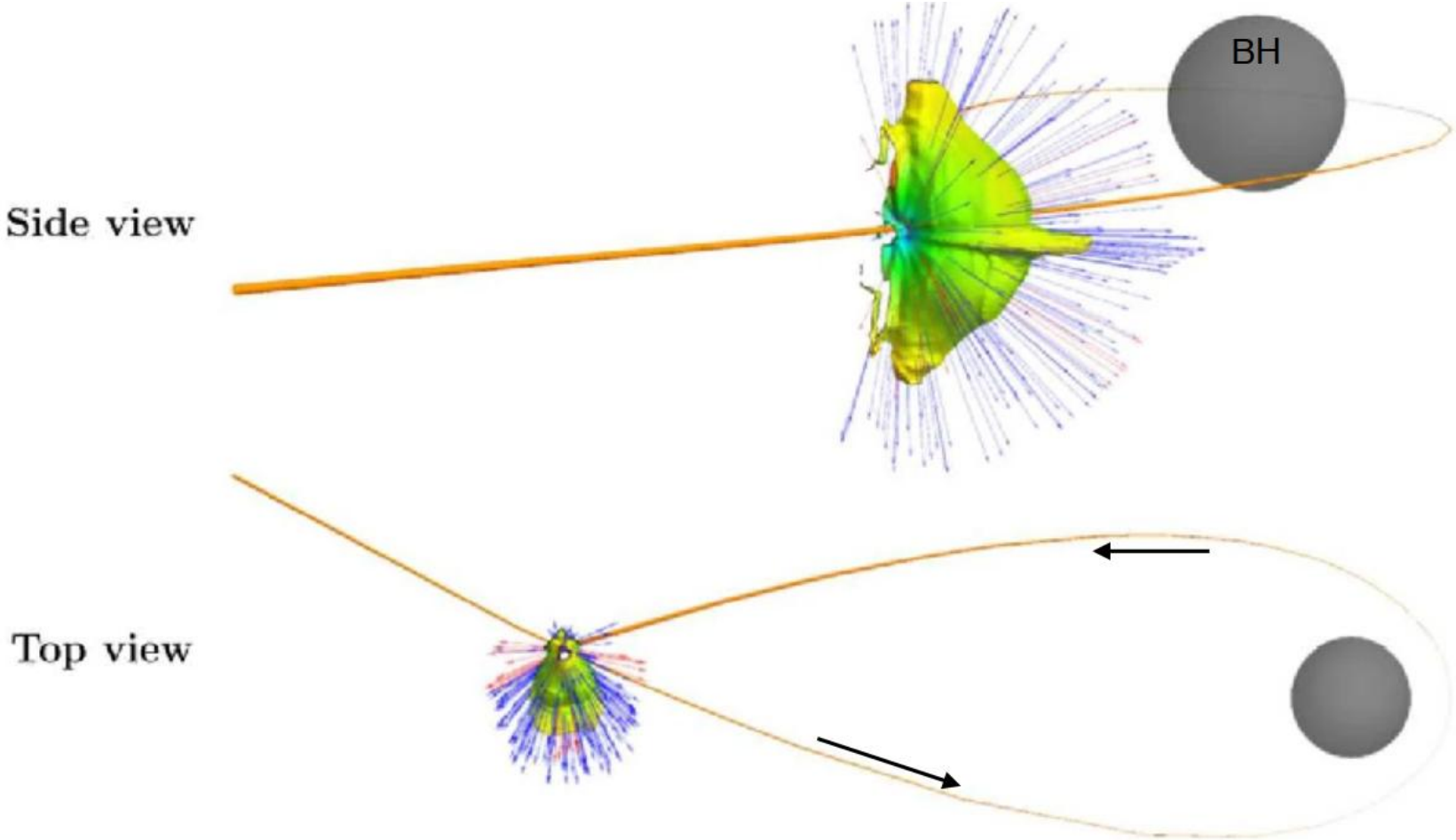
$$\begin{aligned}
 t_{\text{diff}} &\simeq \kappa_{\text{es}} \frac{\Delta M}{4\pi c a_s} \left(\frac{h_s}{w_s} \right) \\
 &\simeq 1.4 \times 10^{-2} \left(\frac{\Delta M}{0.01 M_{\odot}} \right) \left(\frac{h_s}{w_s} \right) \\
 &\quad \times \left(\frac{a_s}{a_0} \right)^{-5/2} \beta^5 M_6^{-7/6} r_*^{-5/2} m_*^{5/3} t_s
 \end{aligned}$$

Diffusion Timescale
 J. Chen & R. Shen 2021

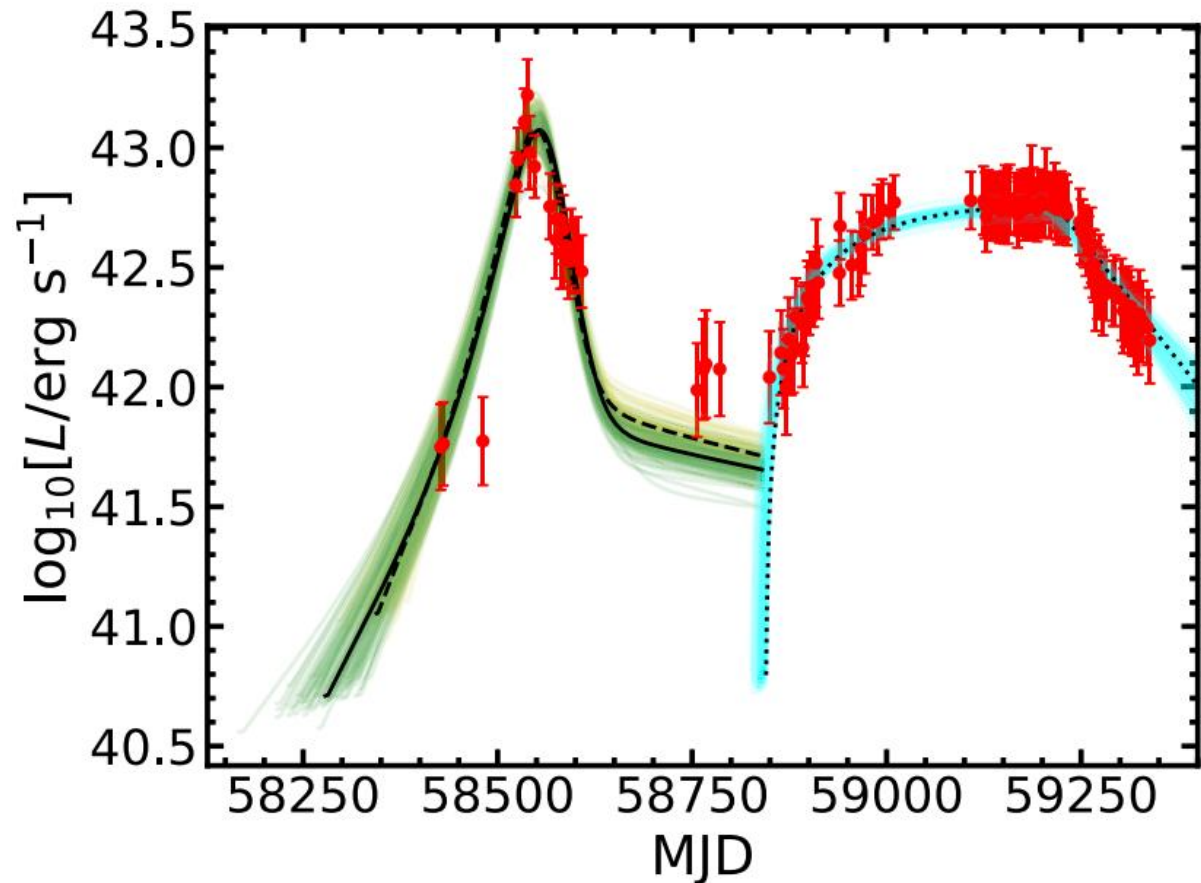
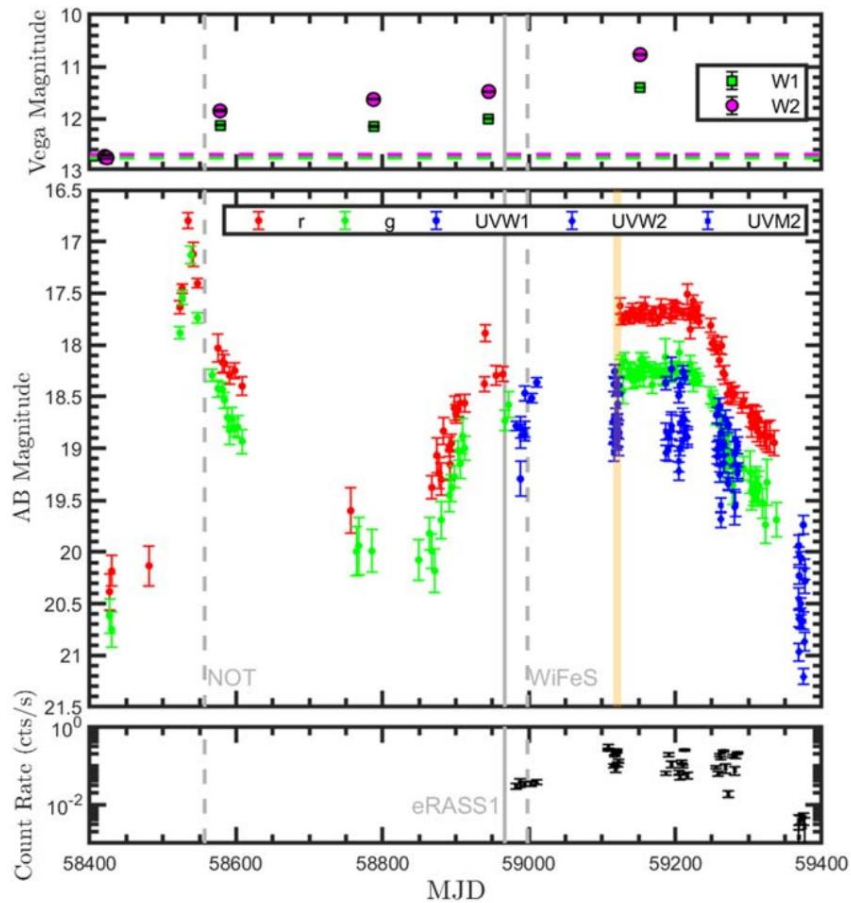


Differential Precession
 Z. Andelman et al. 2022

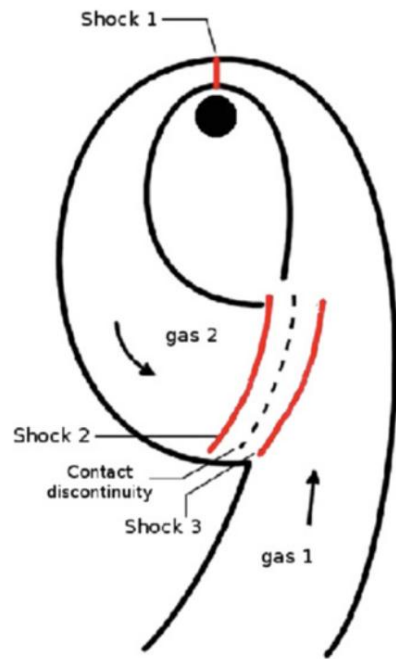
Self-Intersection Induce Outflow



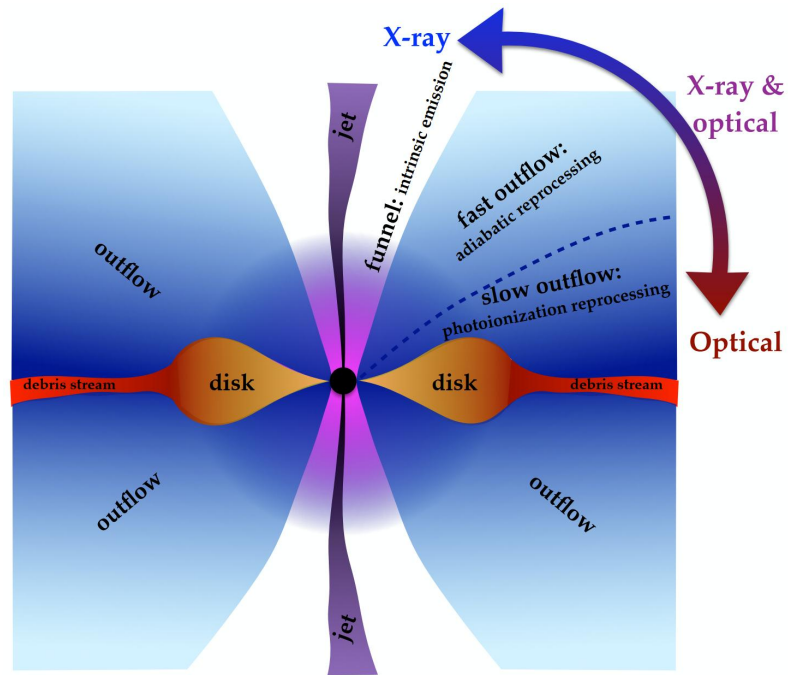
Two Steps Model



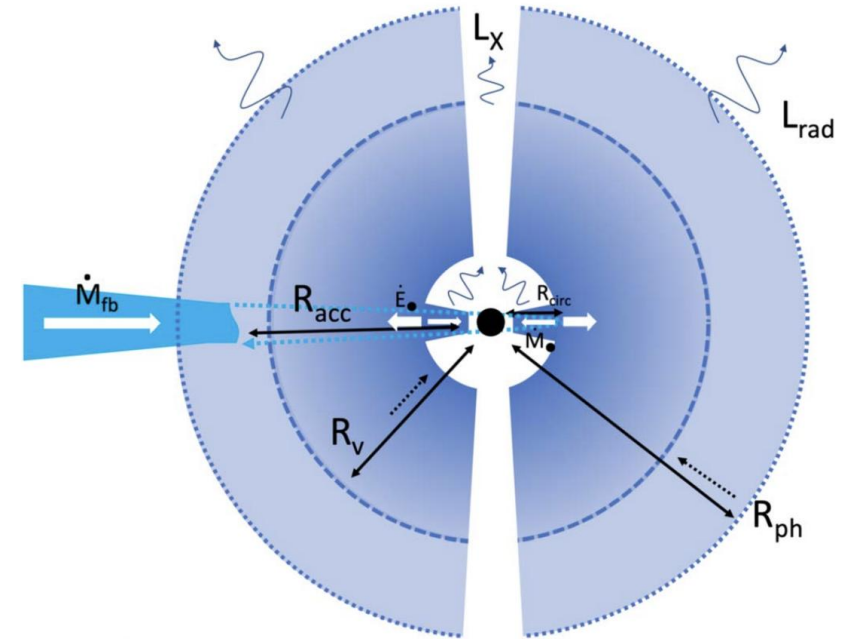
Optical Emission Model



T. Piran et al. 2015

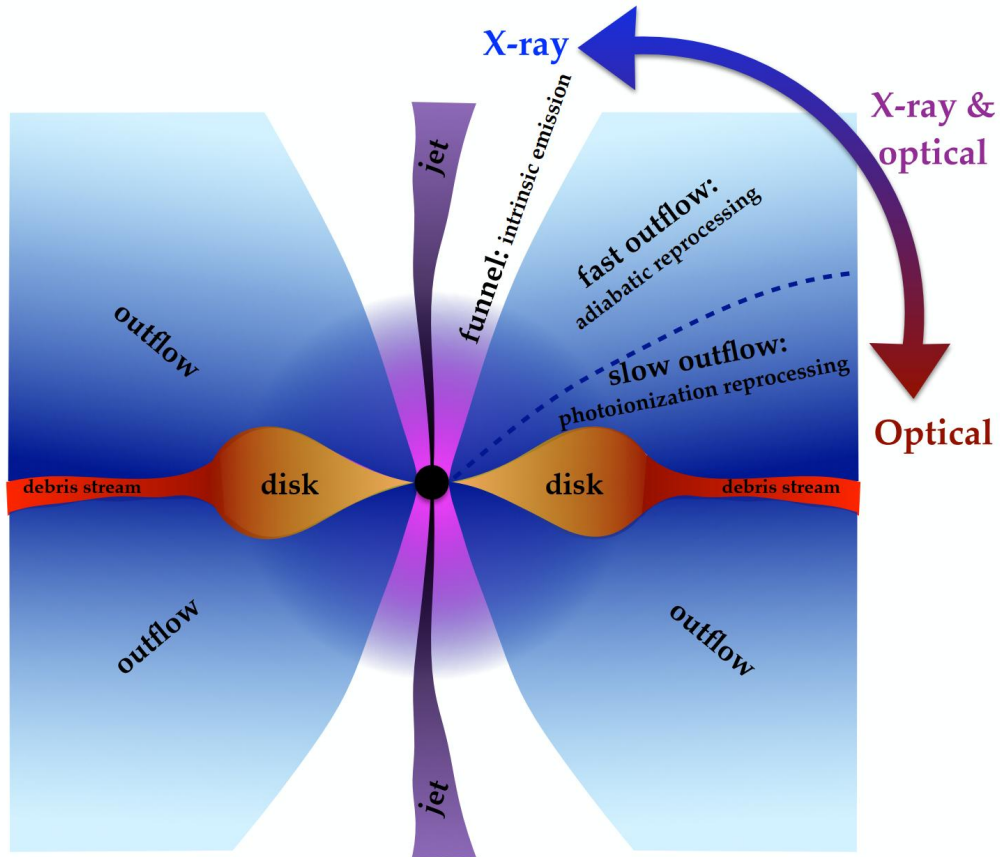


L. Dai et al. 2018

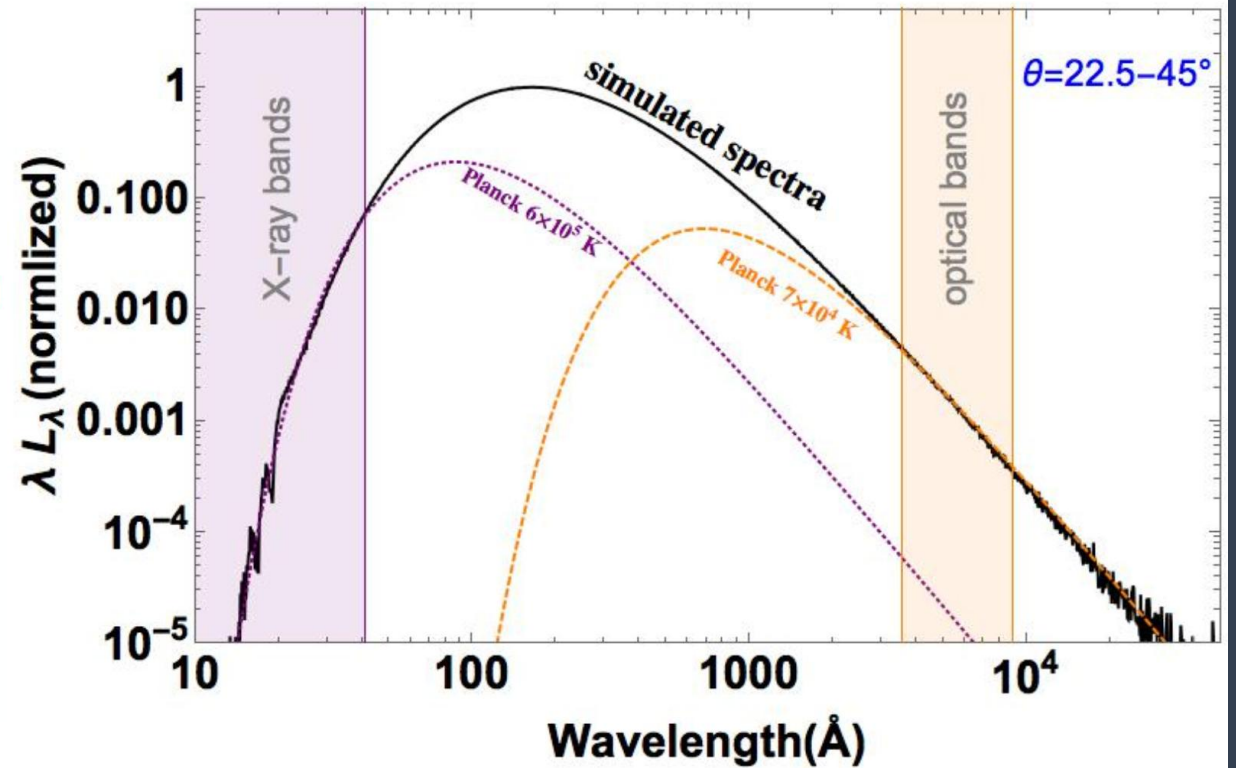


B. Metzger 2022

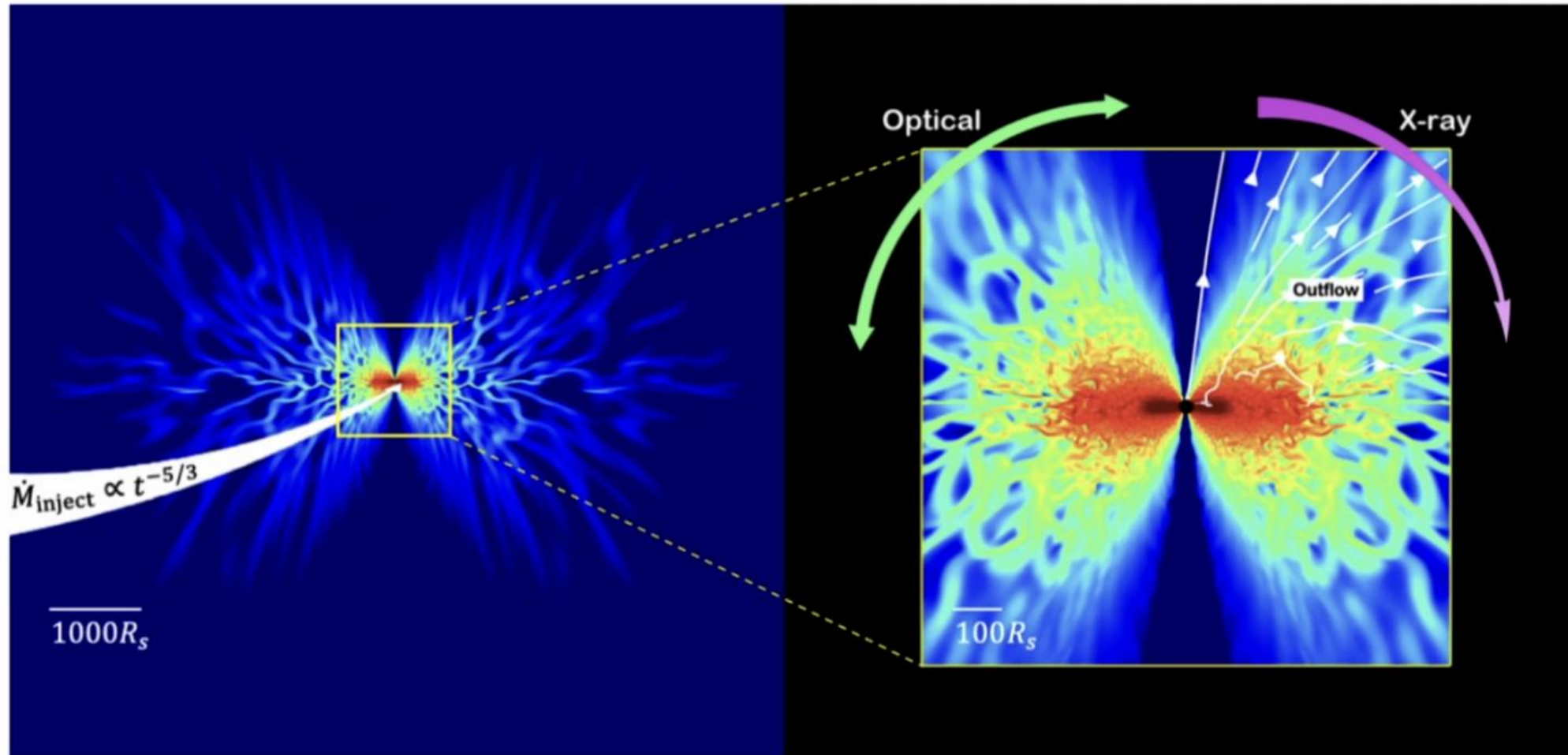
Unified Model



Brighter than black body assumption in UV

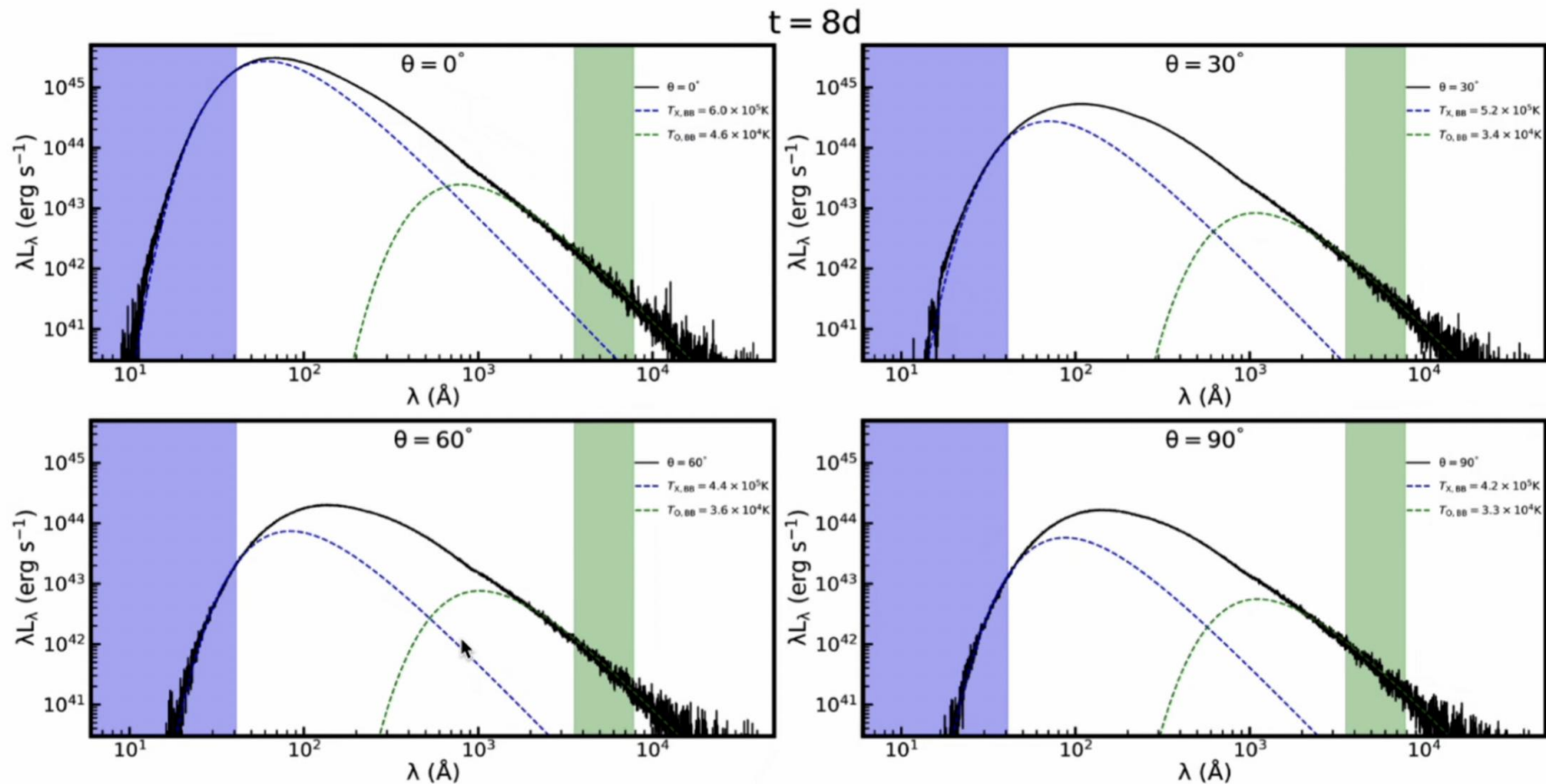


Unified Model

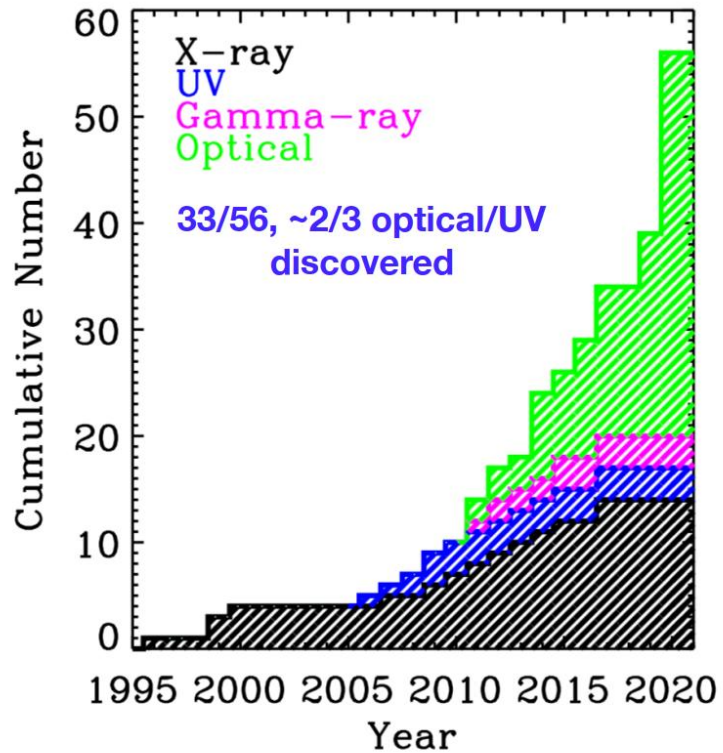


Unified Model

Two blackbody fitting to the spectra

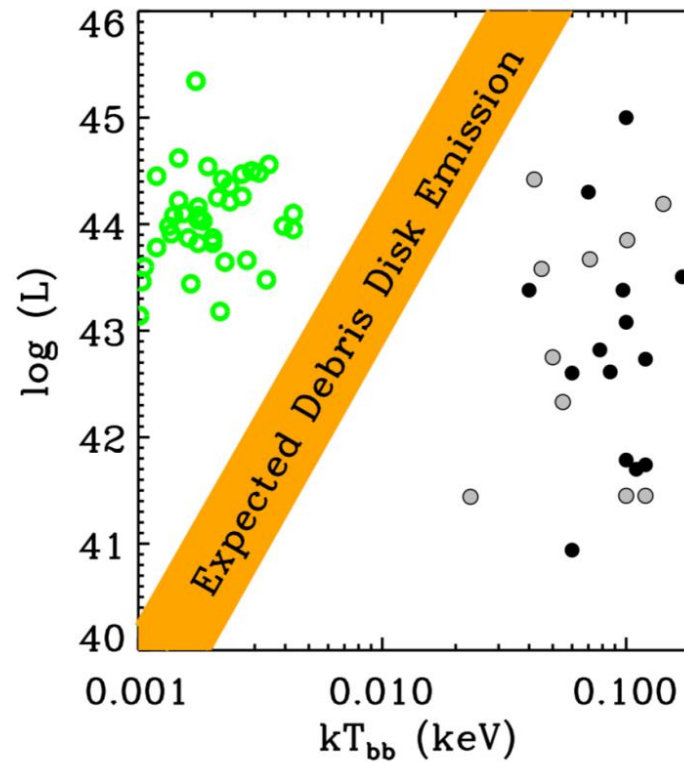


Optical vs X-ray



Gezari 2021, ARA&A, 59, 21

Thermal TDEs



$$L = 4\pi R^2 \sigma T_{bb}^4$$