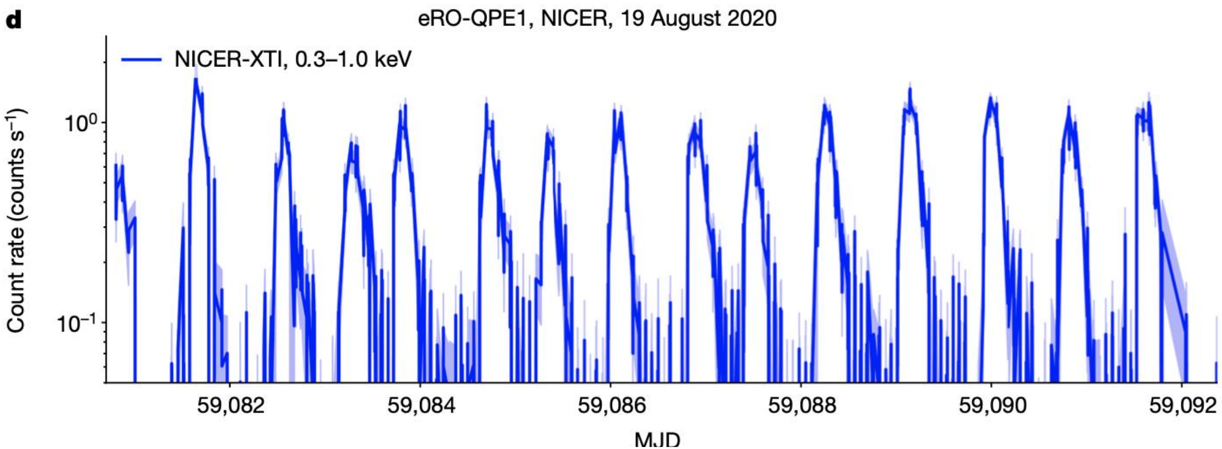
Star-disk Interaction:
Dynamics, Emission, Connection to QPEs

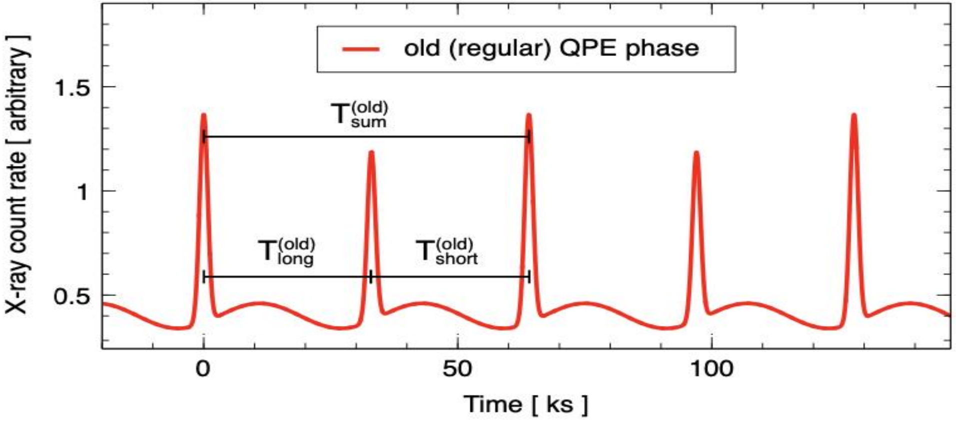
Xiaoshan Huang (黄小珊), Yan-fei Jiang (姜燕飞), Itai Linial
With Re'em Sari, Daichi Tsuna (津名 大地), Phillipe Yao, Eliot Quateart, Tony Piro…

Transient Phenomena and Physical Processes around Super Massive Black Holes
Tsung-Dao Lee Institute, Oct 16, 2024

Quasi-episodical soft X-ray emission from nuclei



(Arcodia et al 2024, Charkraborty et al 2024)



(Miniutti et al 2023)

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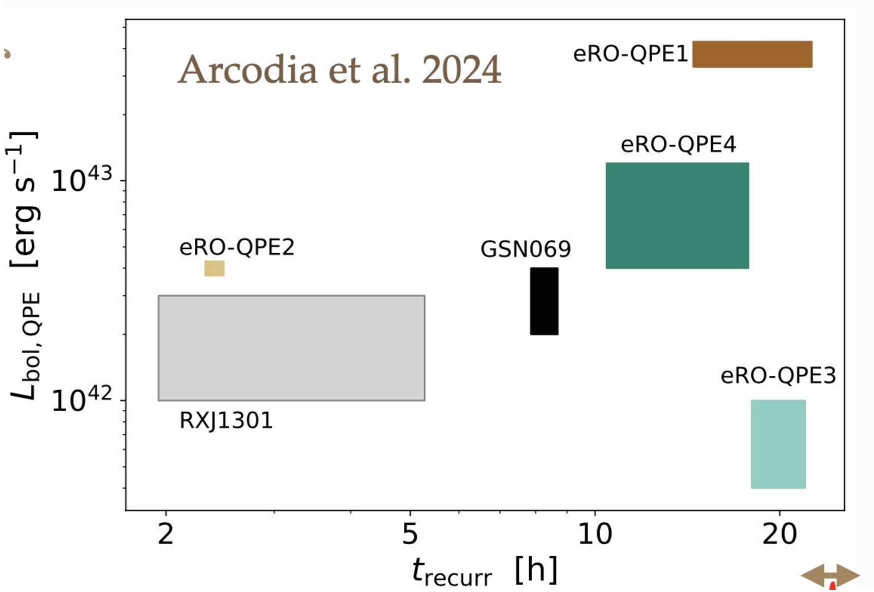
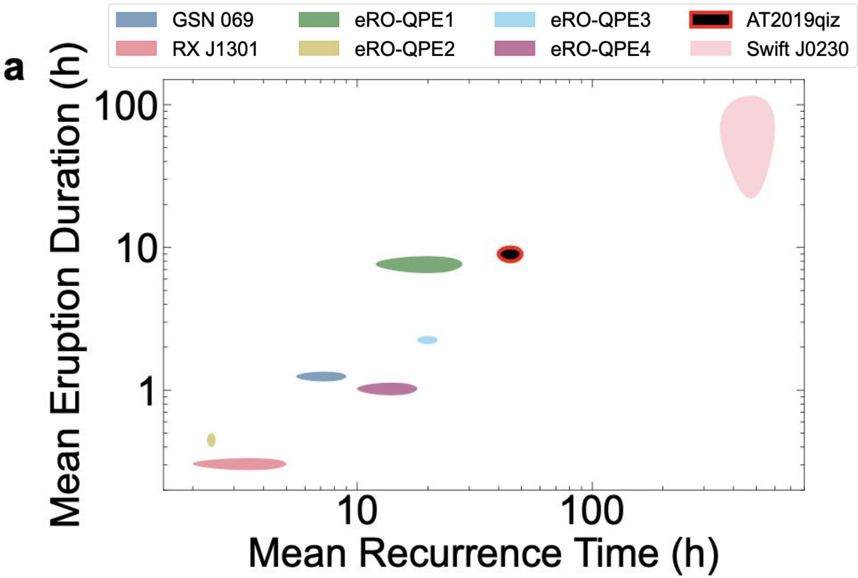
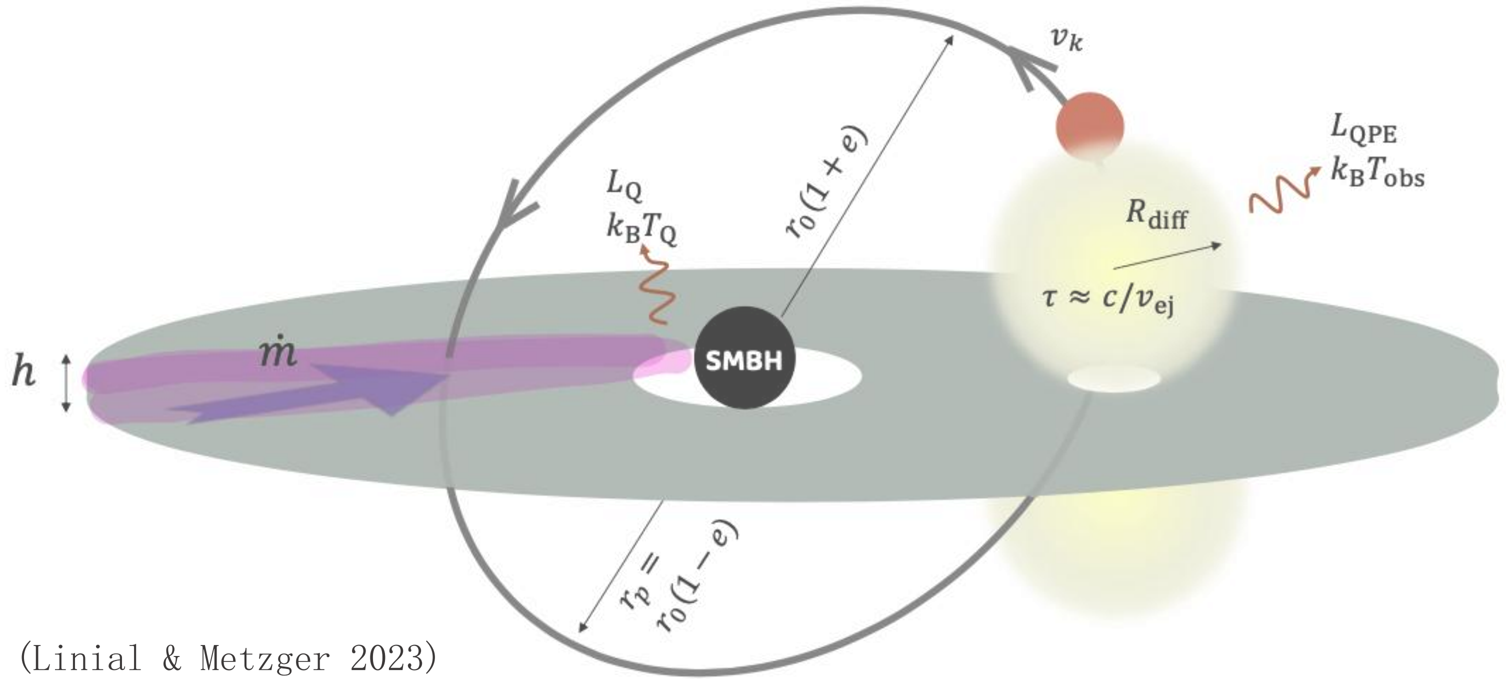


(Arcodia et al 2024)



(Nicholl et al 2024)

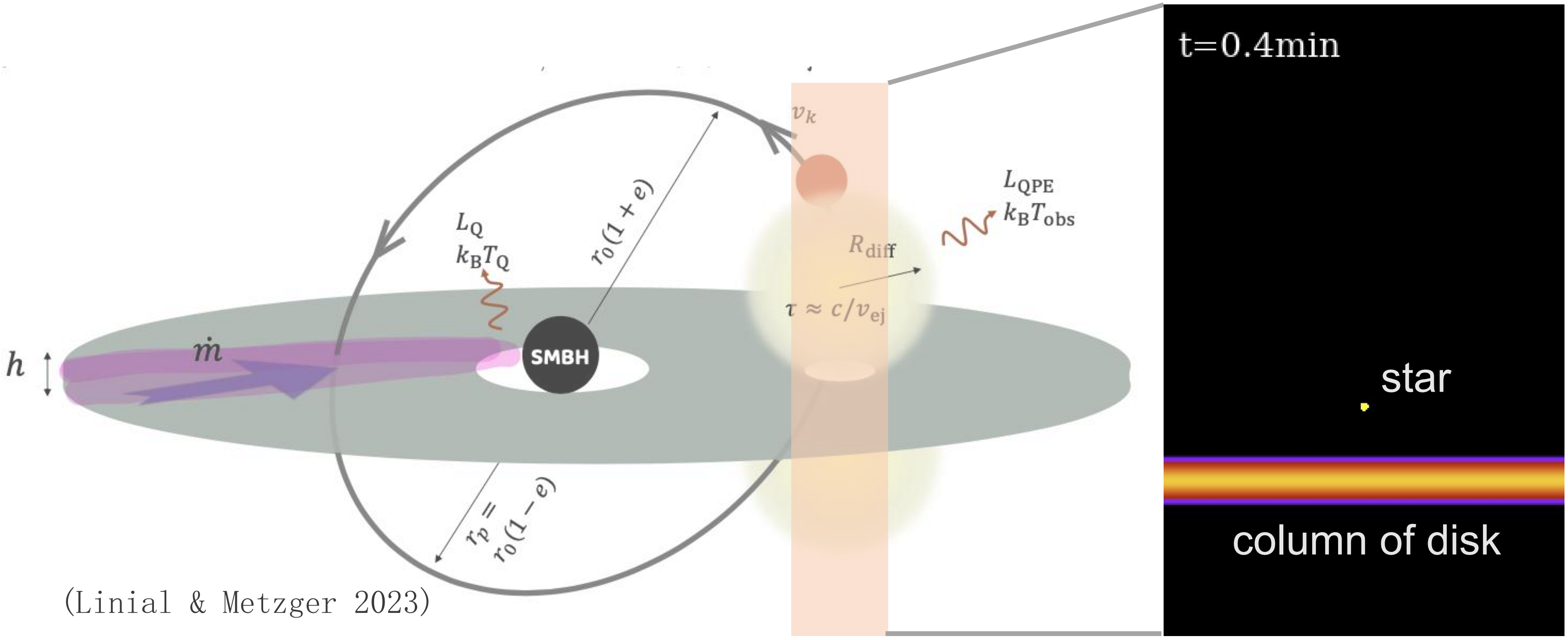
Star orbiter model for QPEs



(Linial & Metzger 2023)

Simulation Set-up

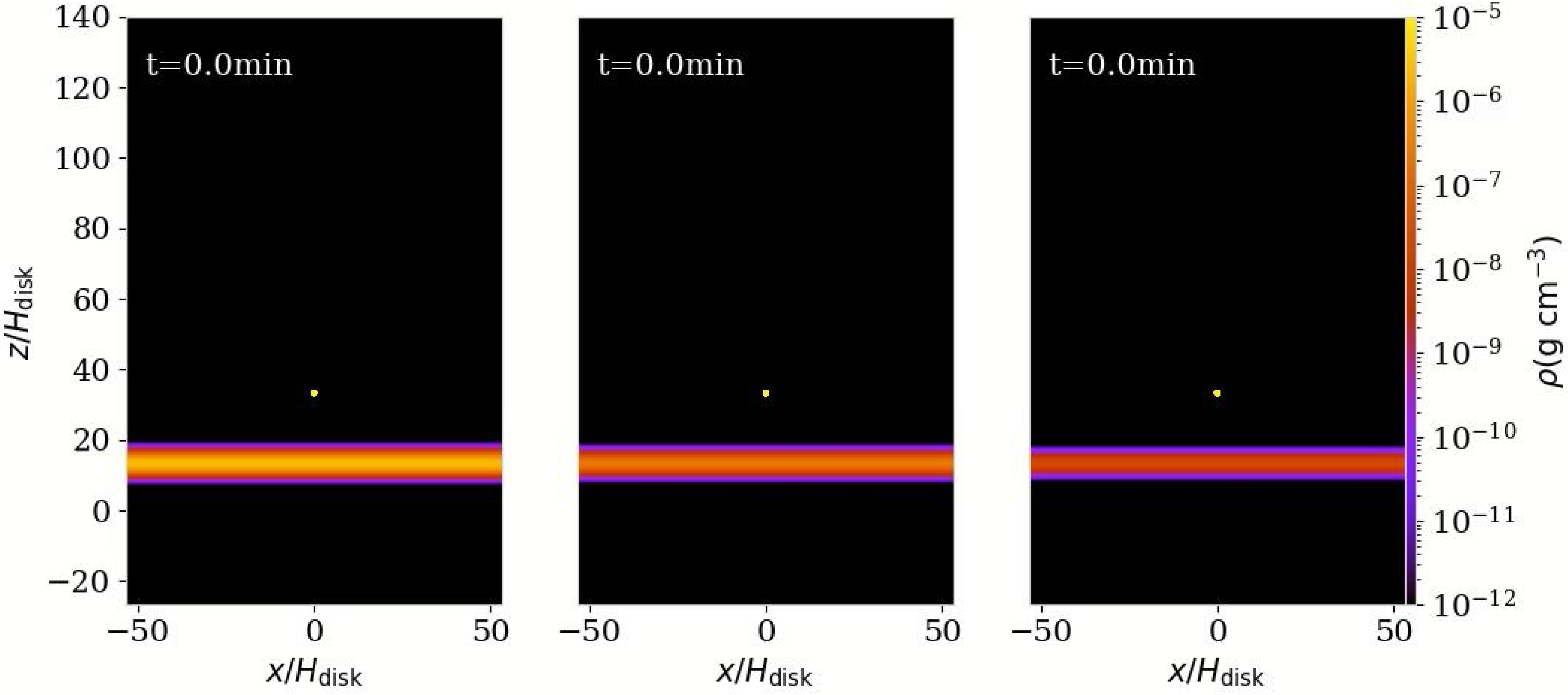
$M_* = M_\odot,\ R_* = R_\odot$



$H_{disk} = R_*\ ,\ v = 0.1c$

star disk interaction

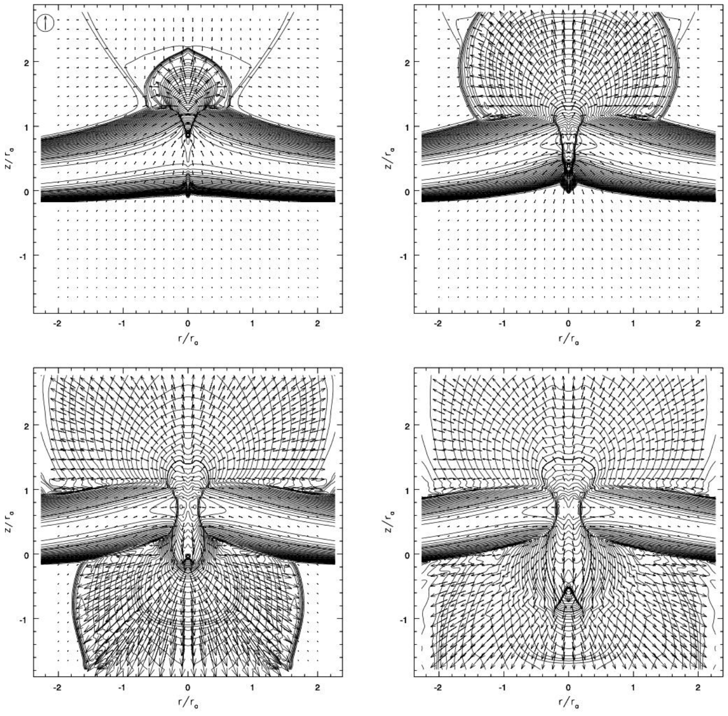
disk surface density



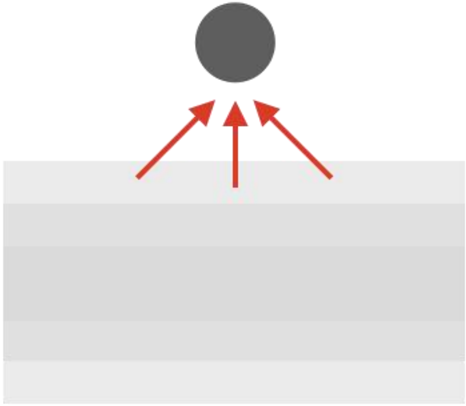
$\Sigma_{disk} \sim 10^5\ g/cm^2$ $\Sigma_{disk} \sim 10^4\ g/cm^2$ $\Sigma_{disk} \sim 10^3\ g/cm^2$

1. Bow Shock between Star and Disk

Compact object: perturbed idealized disk



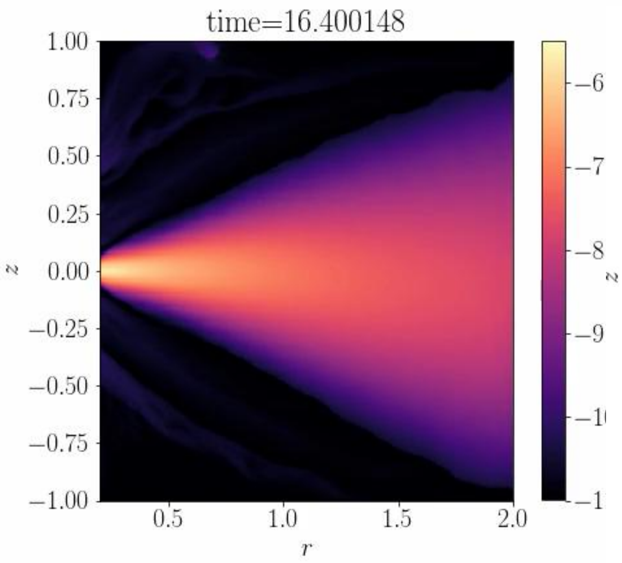
Compact object:
Gravity pull



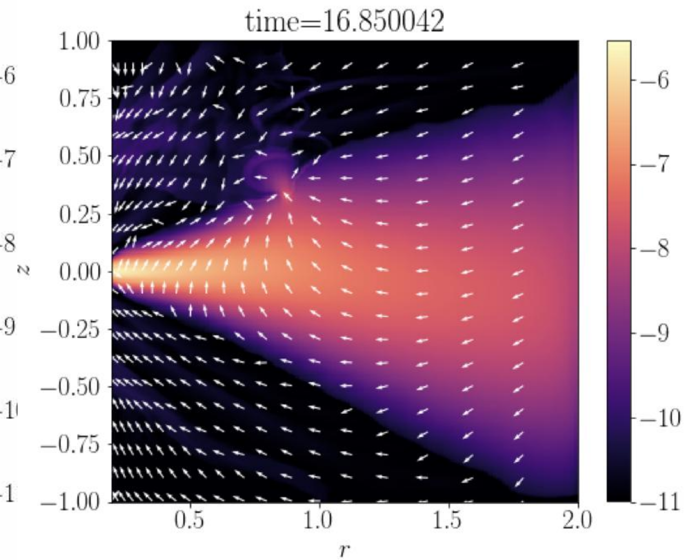
Density contours: a disk crossed by a perturber with mass (Ivanov et al 1998)

1. Bow Shock between Star and Disk

Compact object: perturber through thick disk, M_{pertb}/M_{acc}=0.2

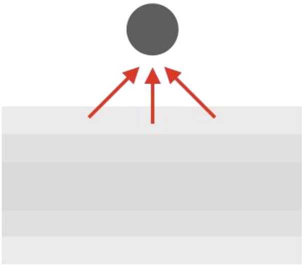


Disk density (side view)



Normalized velocity vector

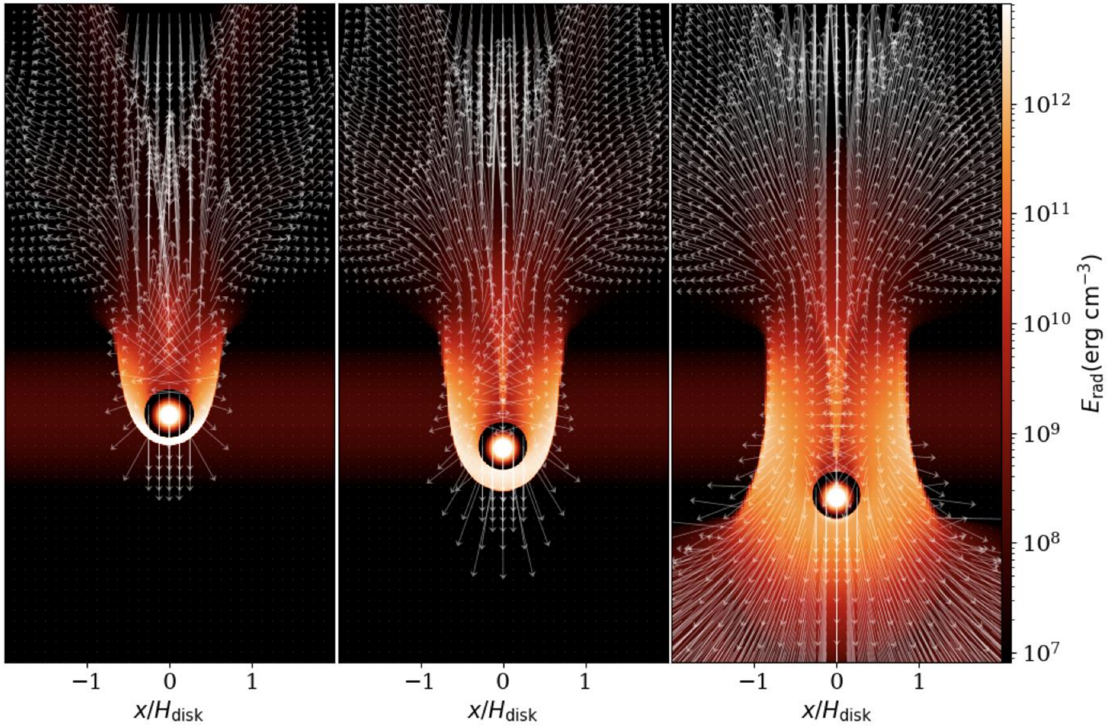
Compact object:
Gravity pull



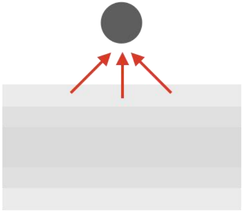
Thick Accretion Disk Perturbed by a Secondary Black Hole
Sierra Dodd, Enrico Ramirez-Ruiz + @ UCSC + Xiaoshan, *in prep*

1. Bow Shock between Star and Disk

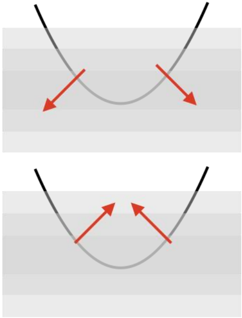
Formation of ”backward” velocity



Compact object:
Gravity pull



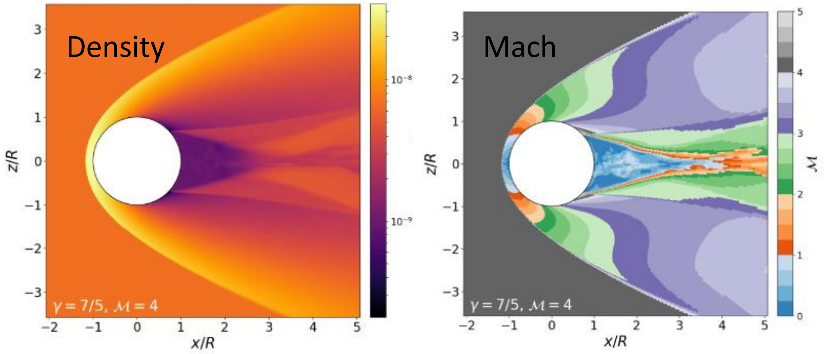
Bow shock:
velocity reflection
at shock front



Colored: Radiation energy density
Arrow: velocity direction in “lab” frame

1. Bow Shock between Star and Disk

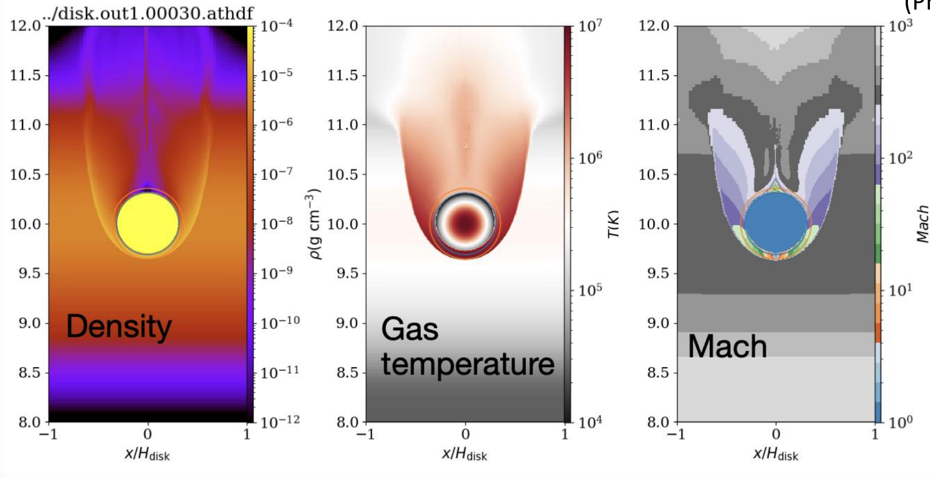
Before star reaches disk mid-plane:

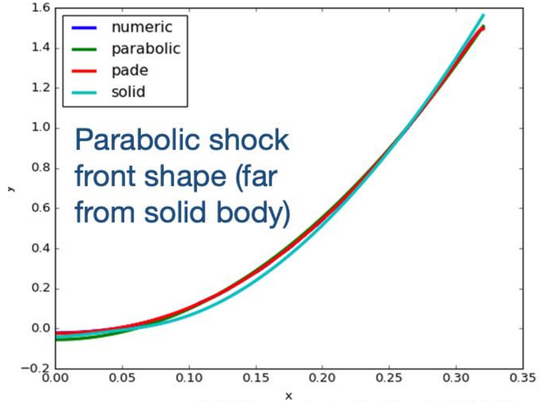


Mach=4, gamma=7/5

(Prust&Bildsten 2023)

In star-disk interaction





(Yalinewich & Sari 2016)

1. Bow Shock between Star and Disk

A Star, A Solid Body, A Compact Object…

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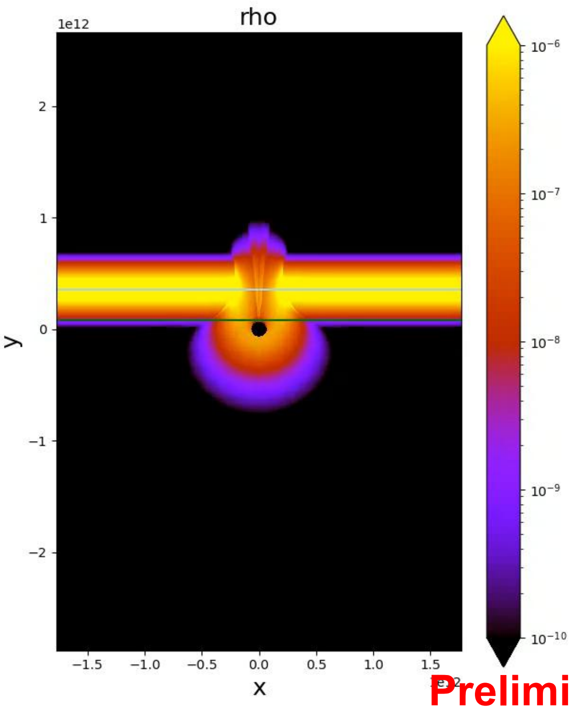
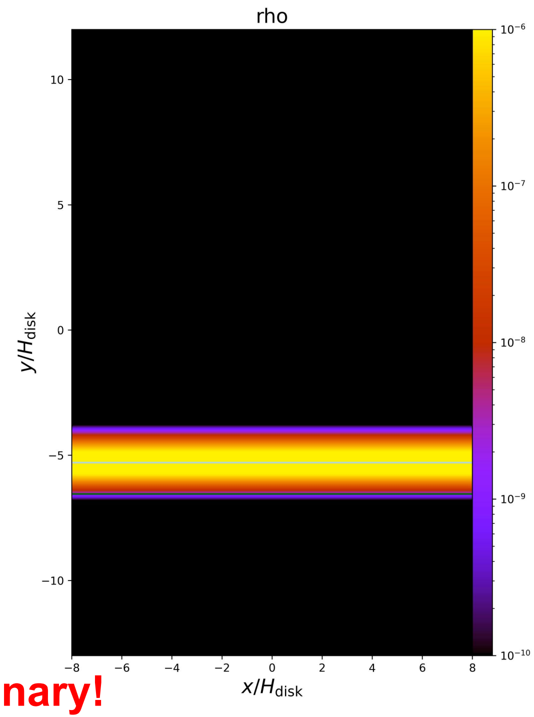
A Star, A Solid Body, A Compact Object…





Preliminary!

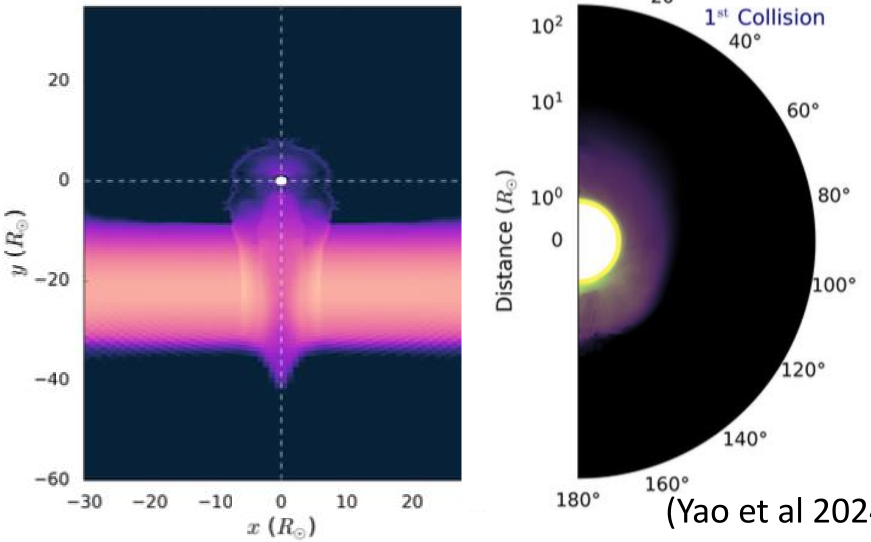
Aftermath of collision between an spherical obstacle and column of disk

Shunquan Huang, Zhaohuan Zhu@ UNLV + Xiaoshan

1. Bow Shock between Star and Disk

A (puffed) Star, A Solid Body, A Compact Object…

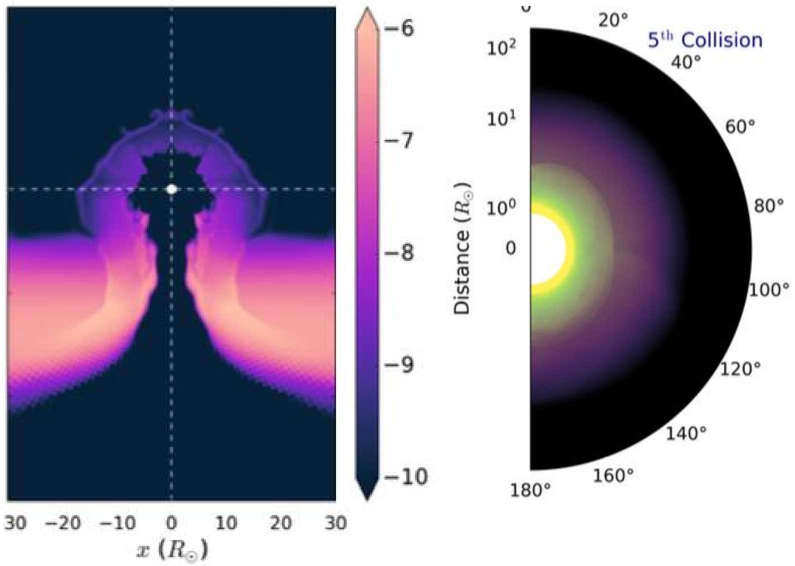
Disk density after impact | Star atmosphere



(Yao et al 2024)

First collision,
A tightly bound star

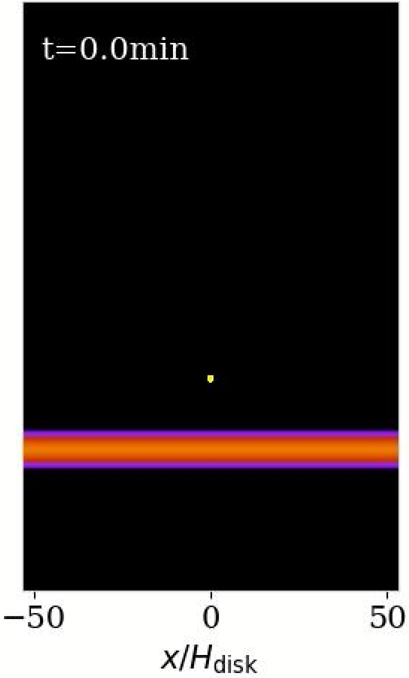
Disk density after impact | Star atmosphere

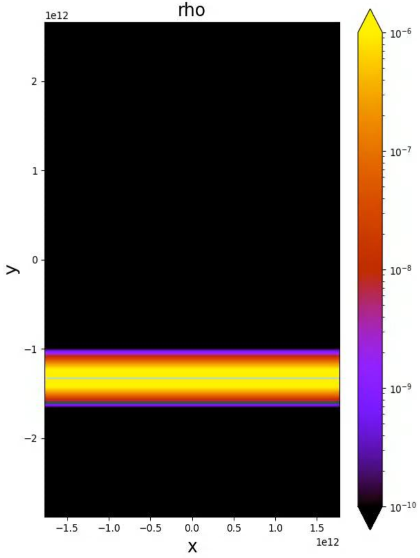


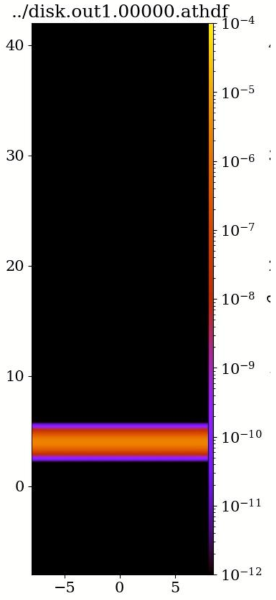
After few collisions
A star with unbound CSM/envelope

1. Bow Shock between Star and Disk

Preliminary!



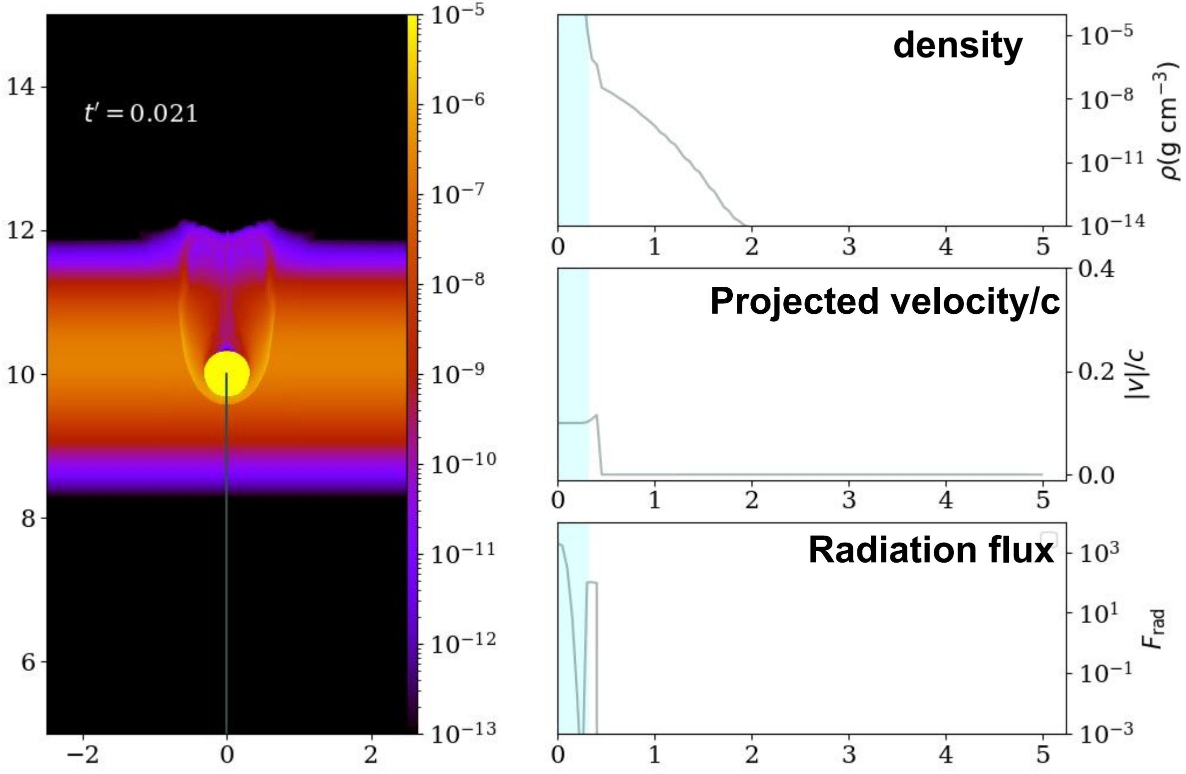




A (solar type) Star, A Solid Body (with R=R*), A Compact Object (M_BH~2000Msun)

2. Shock Break-Out from Disk

After star passing the disk mid-plane…



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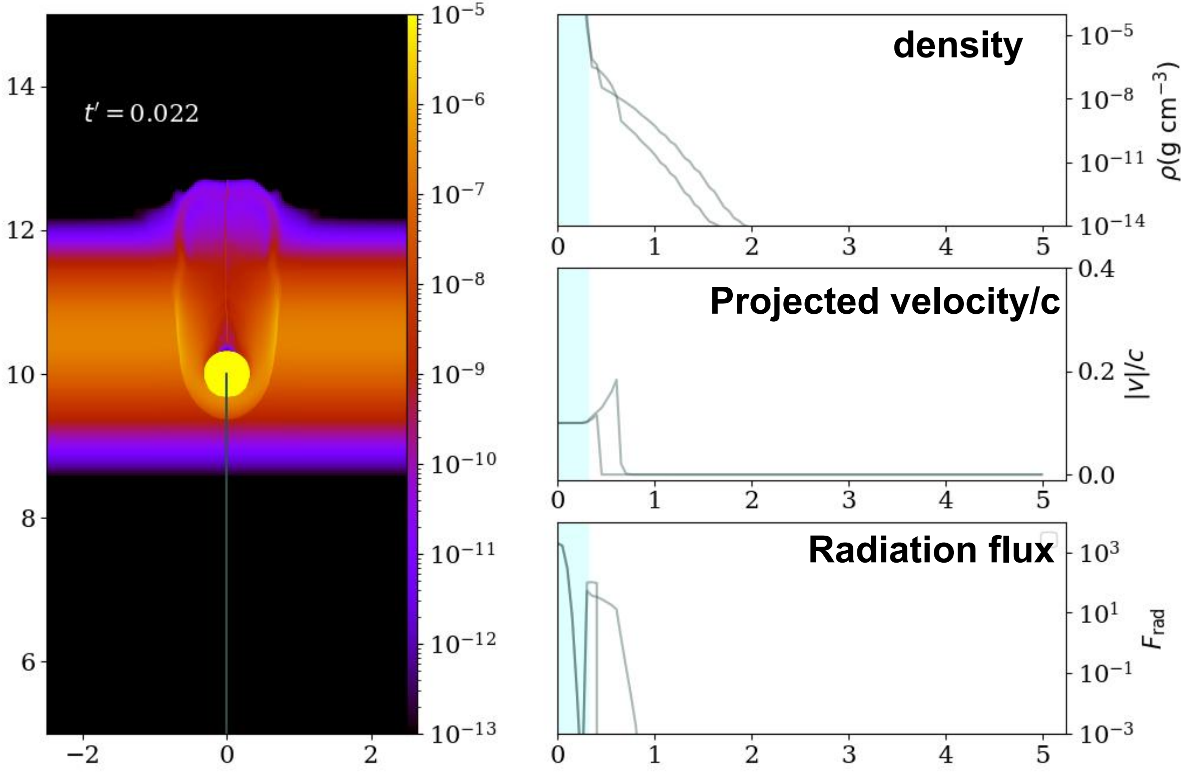

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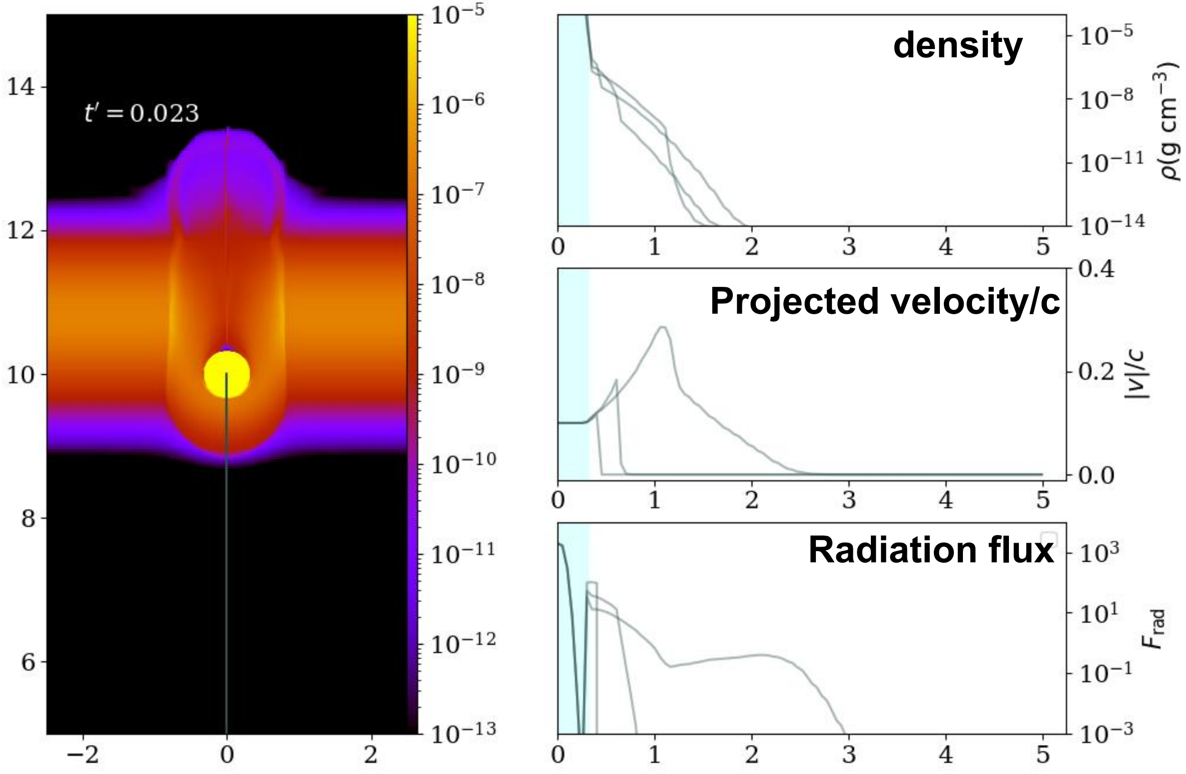

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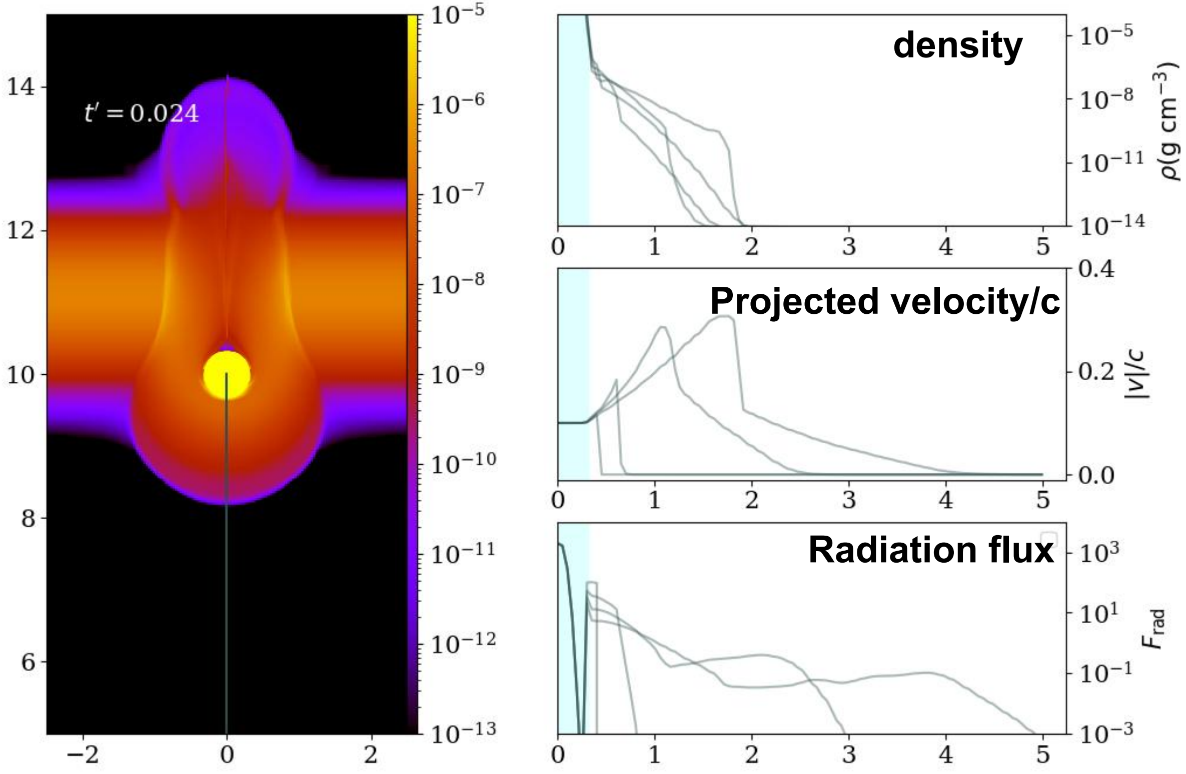

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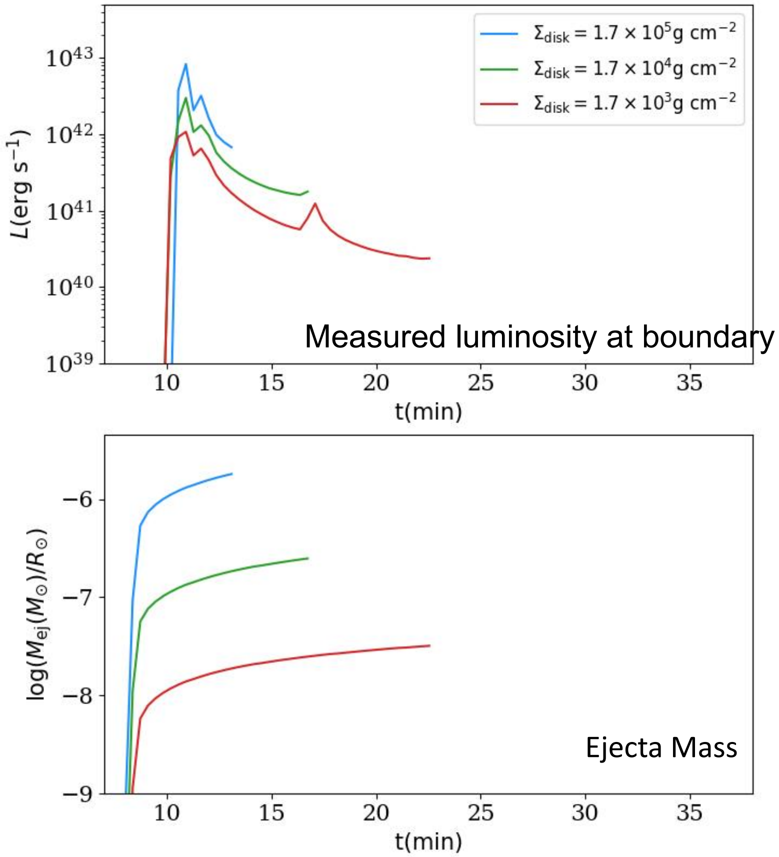

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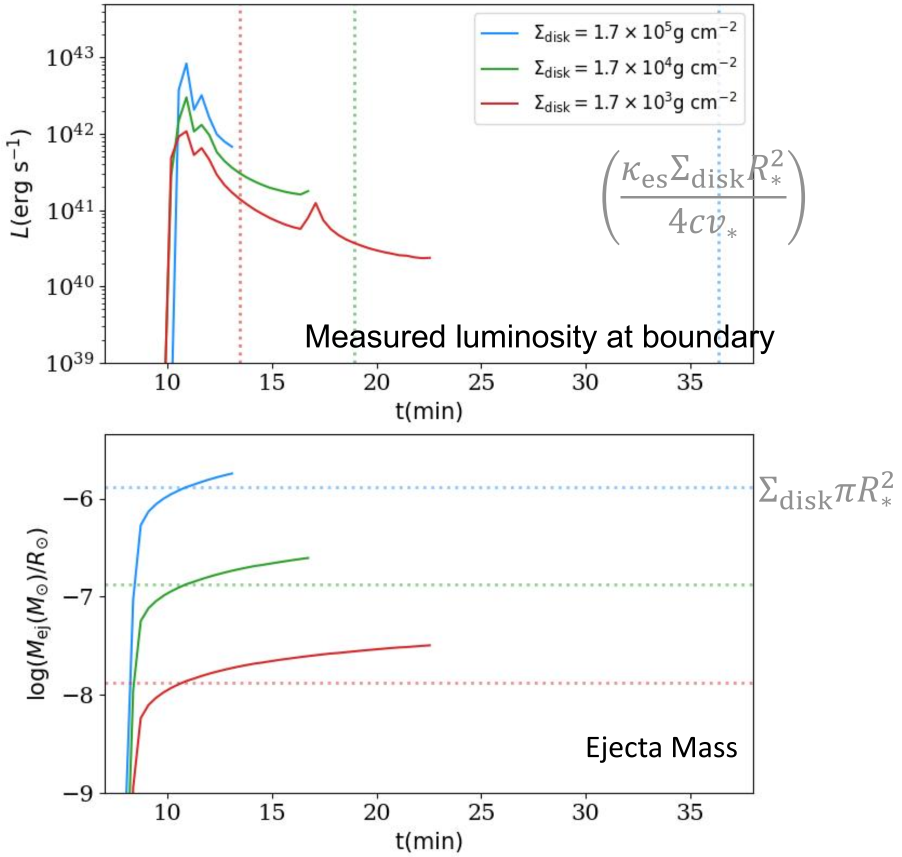

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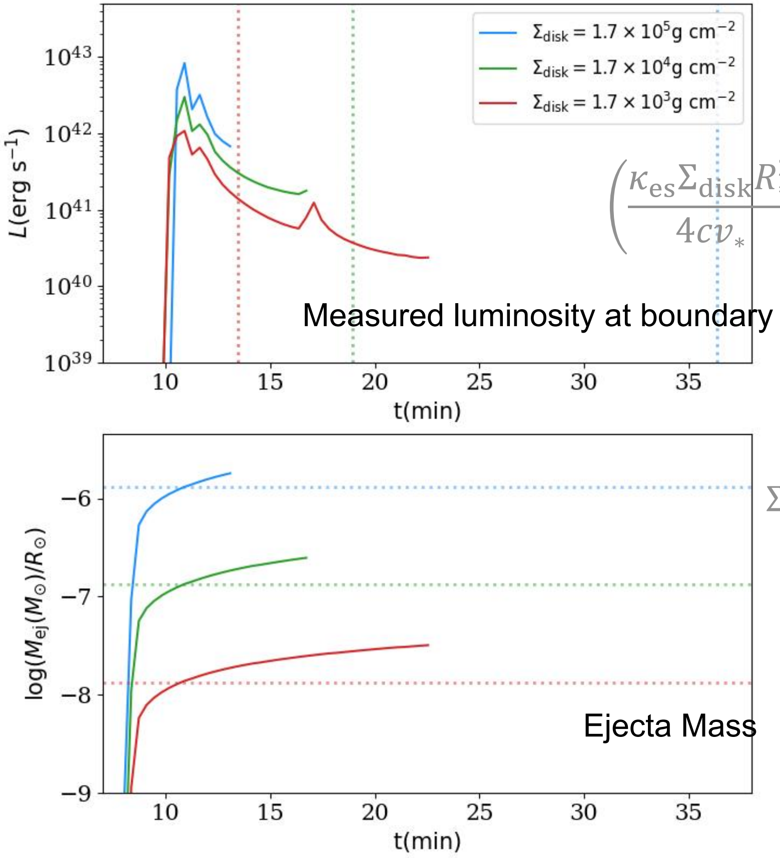
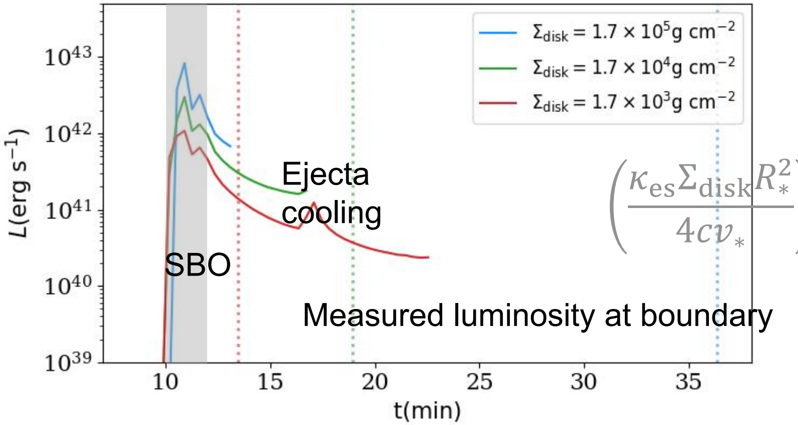


$$\left(\frac{\kappa_{es}\Sigma_{disk}R_*^2}{4cv_*}\right)$$

$$\Sigma_{disk}\pi R_*^2$$

2. Shock Break-Out from Disk

After star passing the disk mid-plane…



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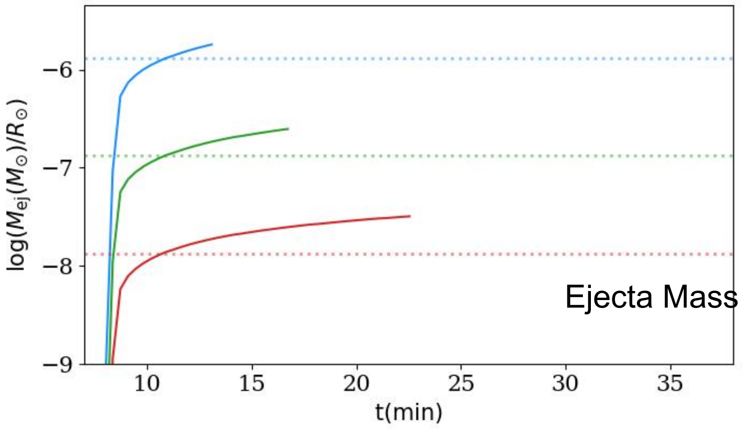

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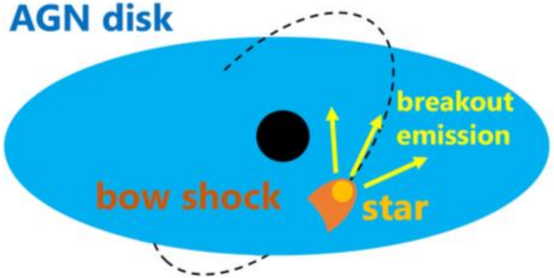
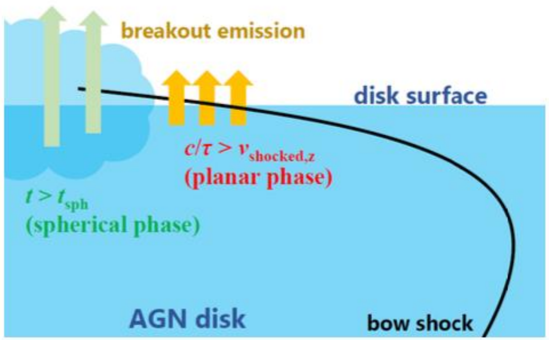


Figure 1. Schematic picture of the breakout emission from the collision between a star and an AGN disk.

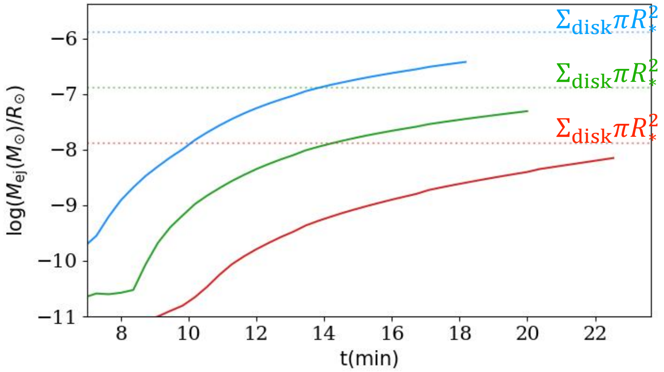


(Tagawa&Haiman2023)

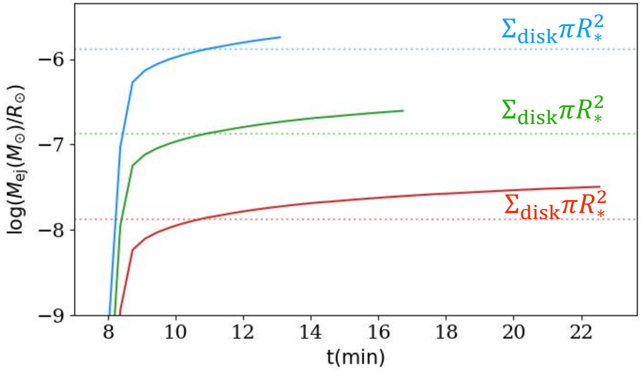
3. Ejecta Cooling Emission

Asymmetric upper and lower ejecta

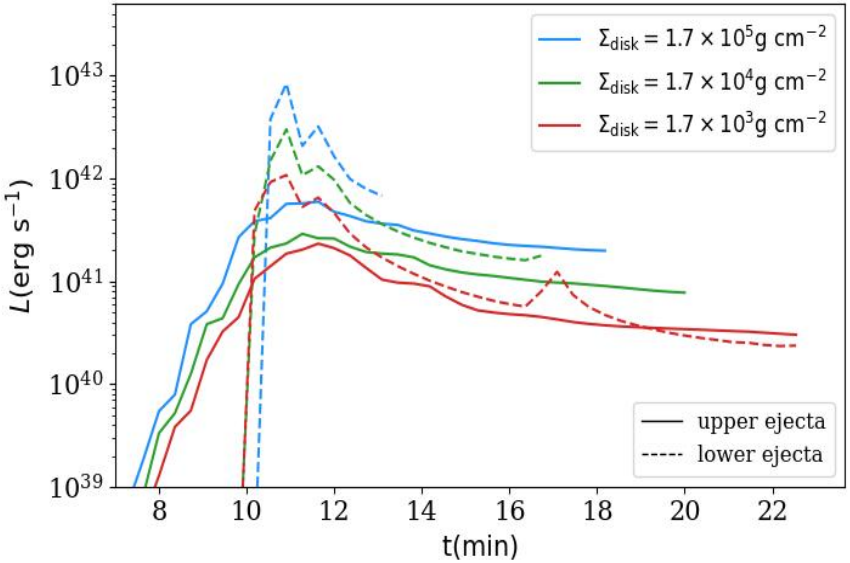
Upper ejecta mass



Lower ejecta mass



Estimated bolometric luminosity



3. Ejecta Cooling Emission

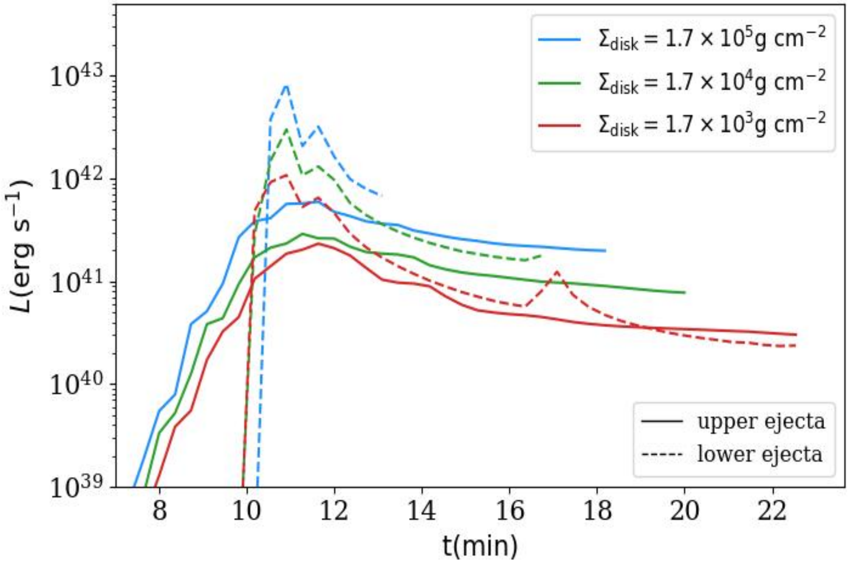
Asymmetric upper and lower ejecta

Potential weak dependency of luminosity on ejecta mass:

$$L_{\rm QPE} \approx \frac{E_{\rm ej}(R_\star^2 h)^{1/3}}{3 v_{\rm ej} P_{\rm QPE}^2} \approx \frac{L_{\rm Edd}}{3} \frac{(R_\star^2 h)^{1/3}}{r_0}$$

(Linial & Metzger 2023)

Estimated bolometric luminosity



4. Spectrum Evolution

What is photon energy distribution?

From *grey* RHD simulation:

The soft X-ray emission ~100eV is harder than ejecta temperature at $\tau = c/v$

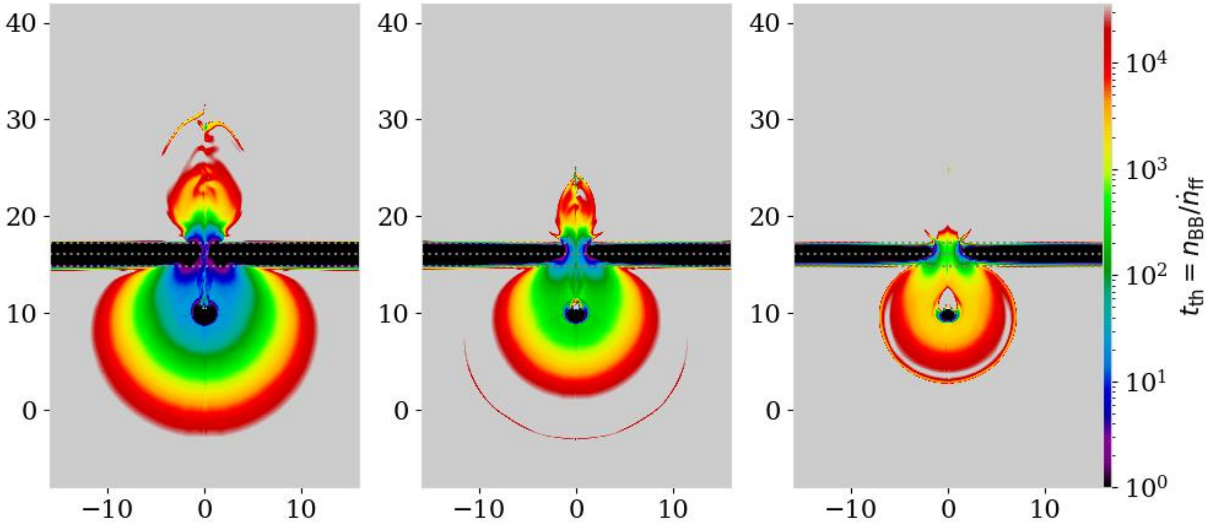
Part of ejecta opacity (Planck and Rosseland mean) > scatter opacity or free-free absorption opacity

4. Spectrum Evolution

From *grey* RHD simulation: **photon starved ejecta?**

Free-free thermalization time: $t_{th} = \frac{n_{ph,BB}}{\dot{n}_{ff}}$ (Nakar&Sari 2010, Linial&Metzger 2024)

$\Sigma_{disk} \sim 10^5\ g/cm^2$ $\Sigma_{disk} \sim 10^4\ g/cm^2$ $\Sigma_{disk} \sim 10^3\ g/cm^2$



Dependency on temperature & density: $t_{th} \propto \rho^{-2} T^{3.5}$

4. Spectrum Evolution

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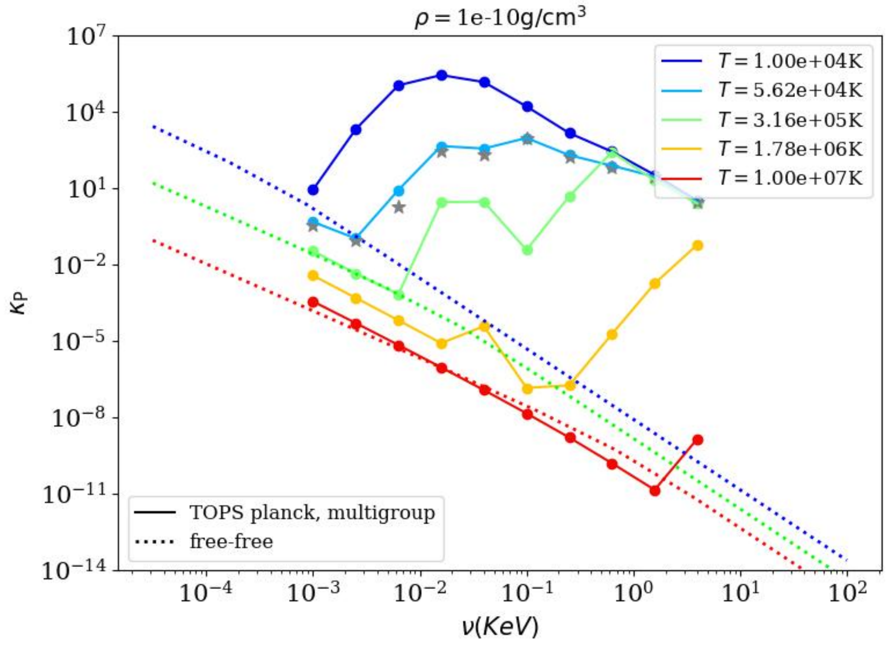
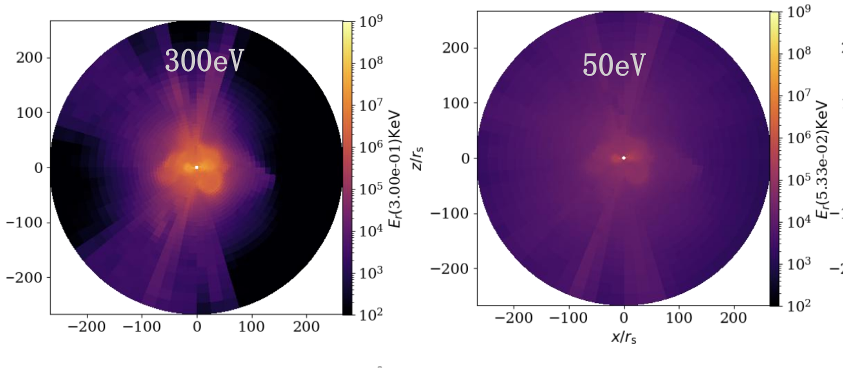


TOPs Opacity (example: Planck mean)

(Jiang 2022)

Multigroup Radiation Hydro in Athena++:
Emission/absorption, scatter, Compton…
Angular resolving, time dependent

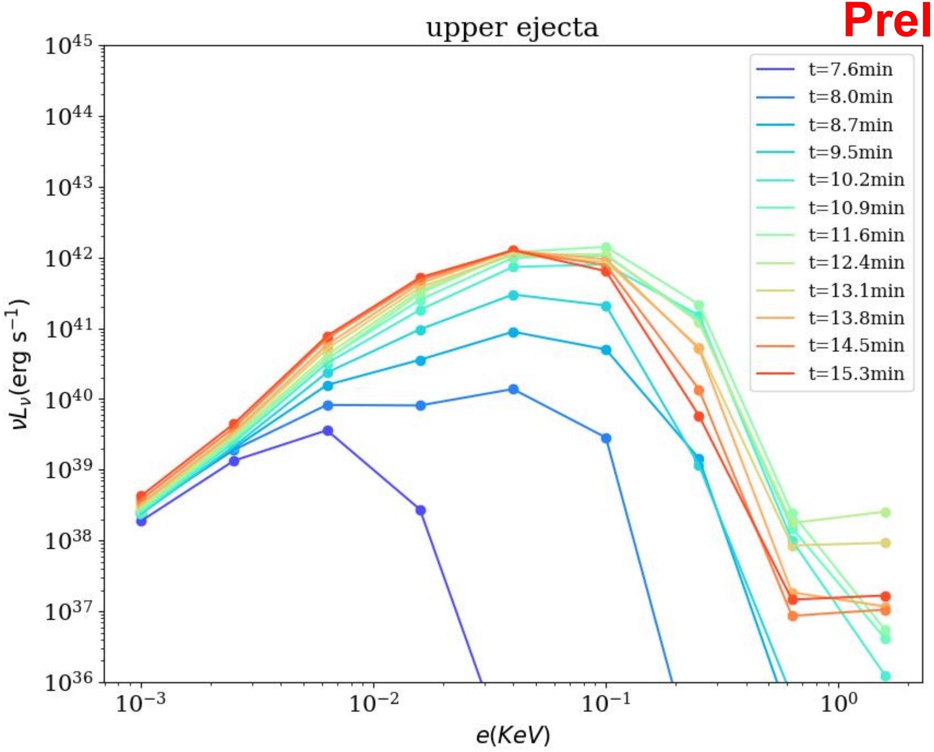


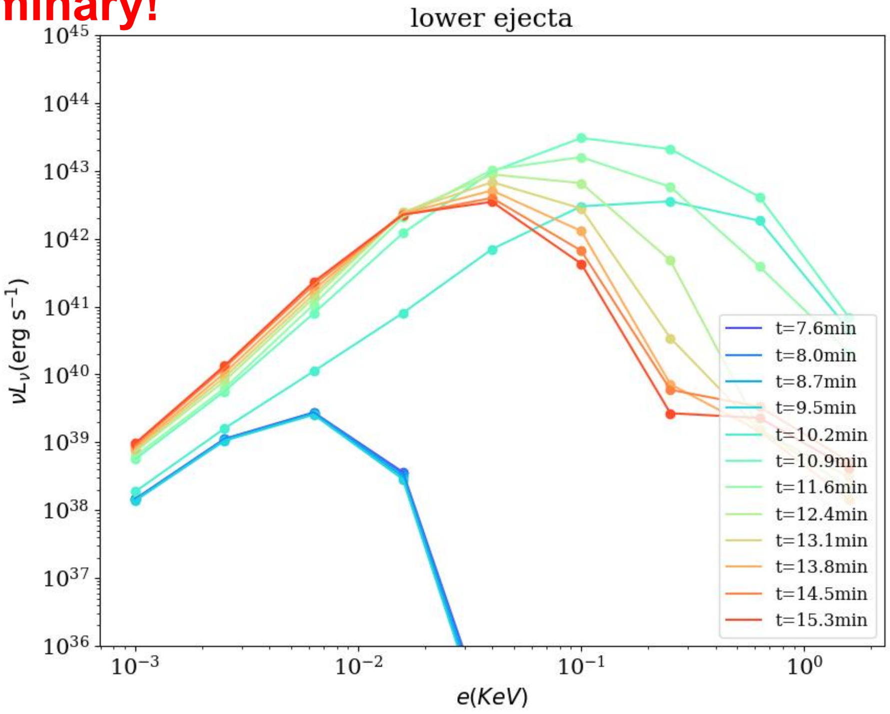
An example application: radiation energy density of TDE disk formation seen in different bands

4. Spectrum Evolution

What is photon energy distribution?

Preliminary!





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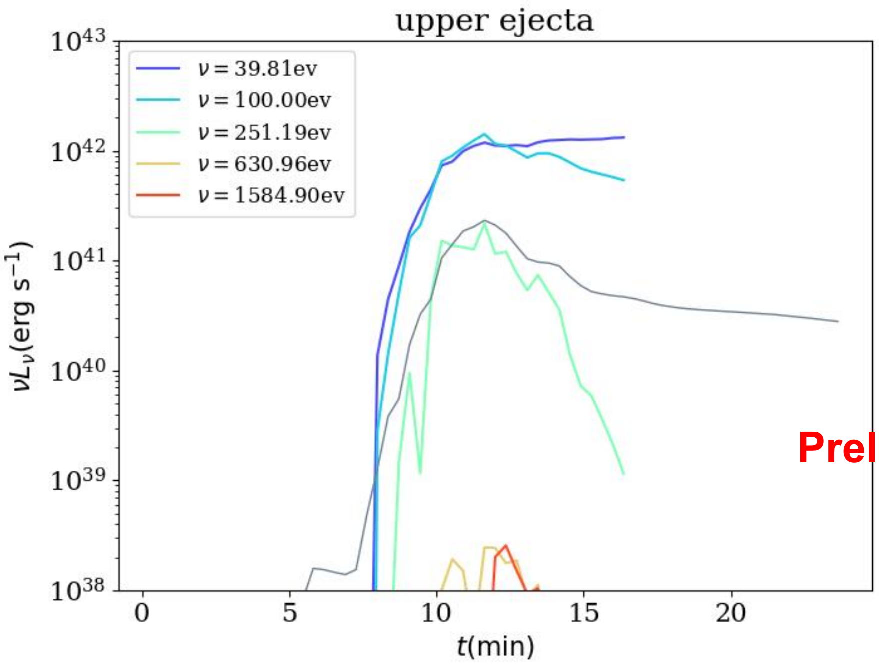
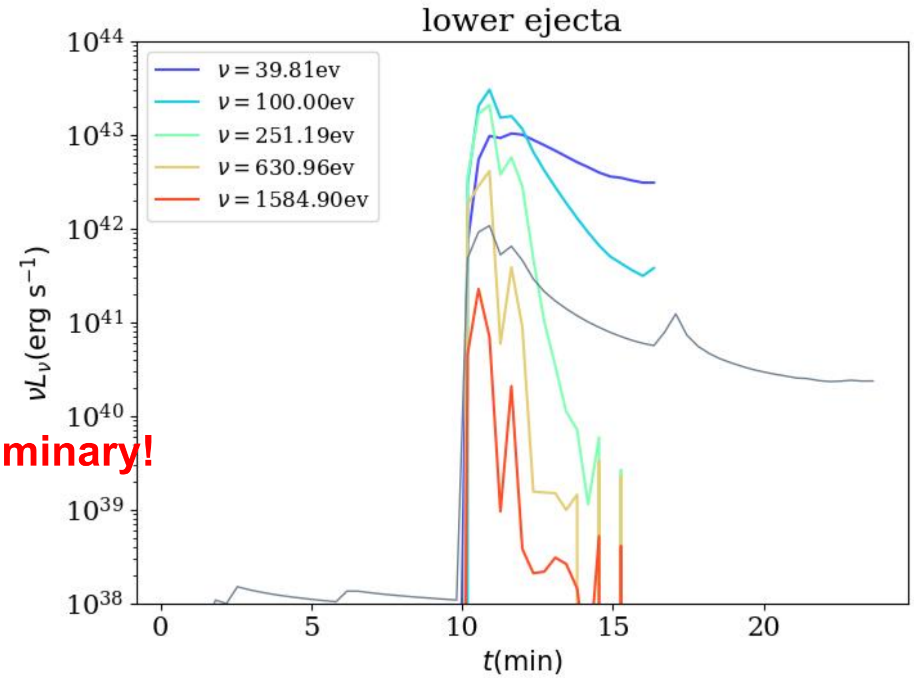
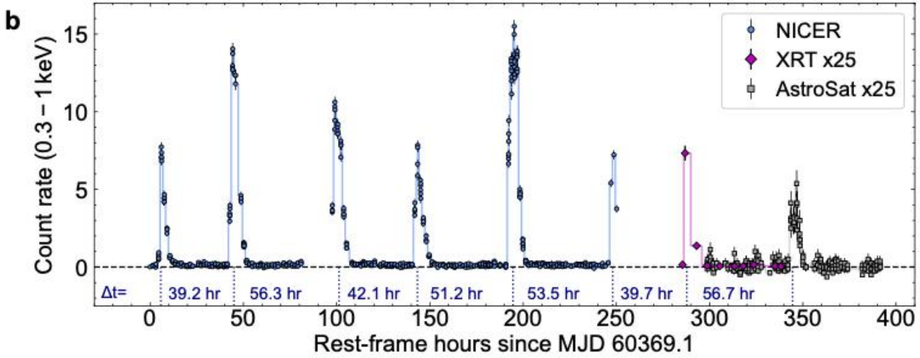




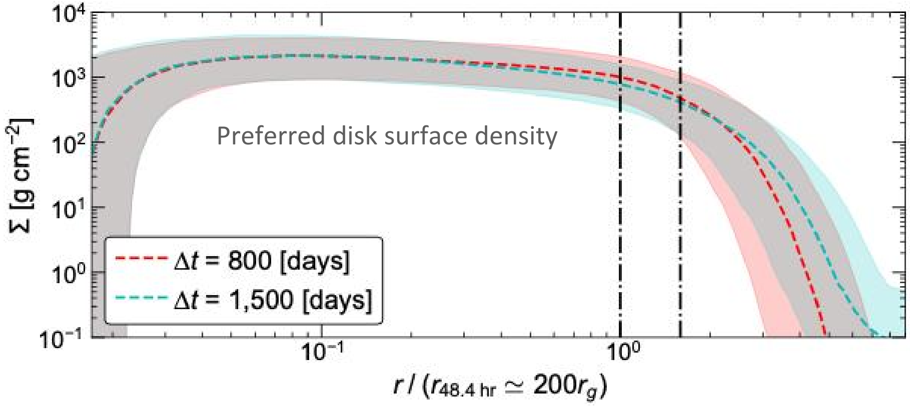
Preliminary!

5. Longer duration events?

Simplified case study of AT2019qiz



(Nicholl et al 2024)



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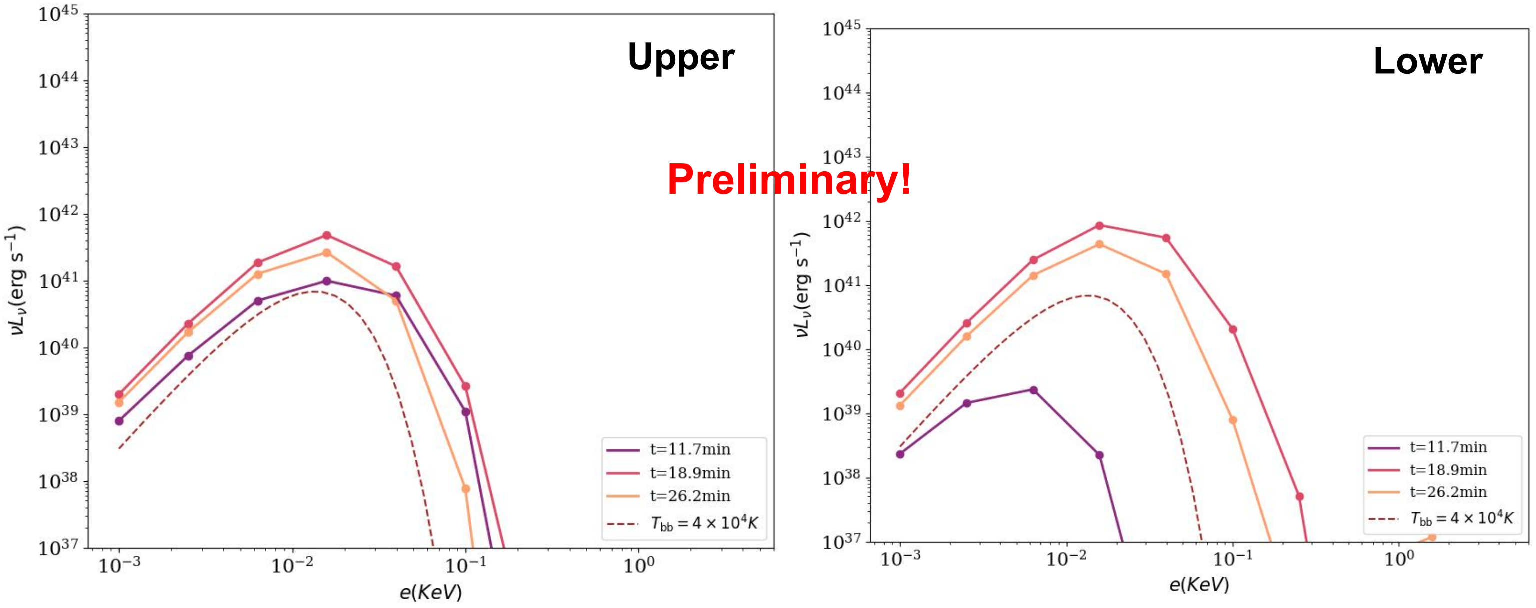

a case study with $M_{\rm BH} = 10^{6.3} M_\odot$, disk surface density $\Sigma_{\rm disk} = 10^4 {\rm g cm^{-2}}$, assume scale height $H_{\rm disk} = R_\odot$ *(could be parameter)*, temperature $T_{\rm disk} = 67eV$

incident velocity $v_* = 0.07c$

-> Ejecta temperature too low, spectrum is mostly thermal

-> What parameter is need ?

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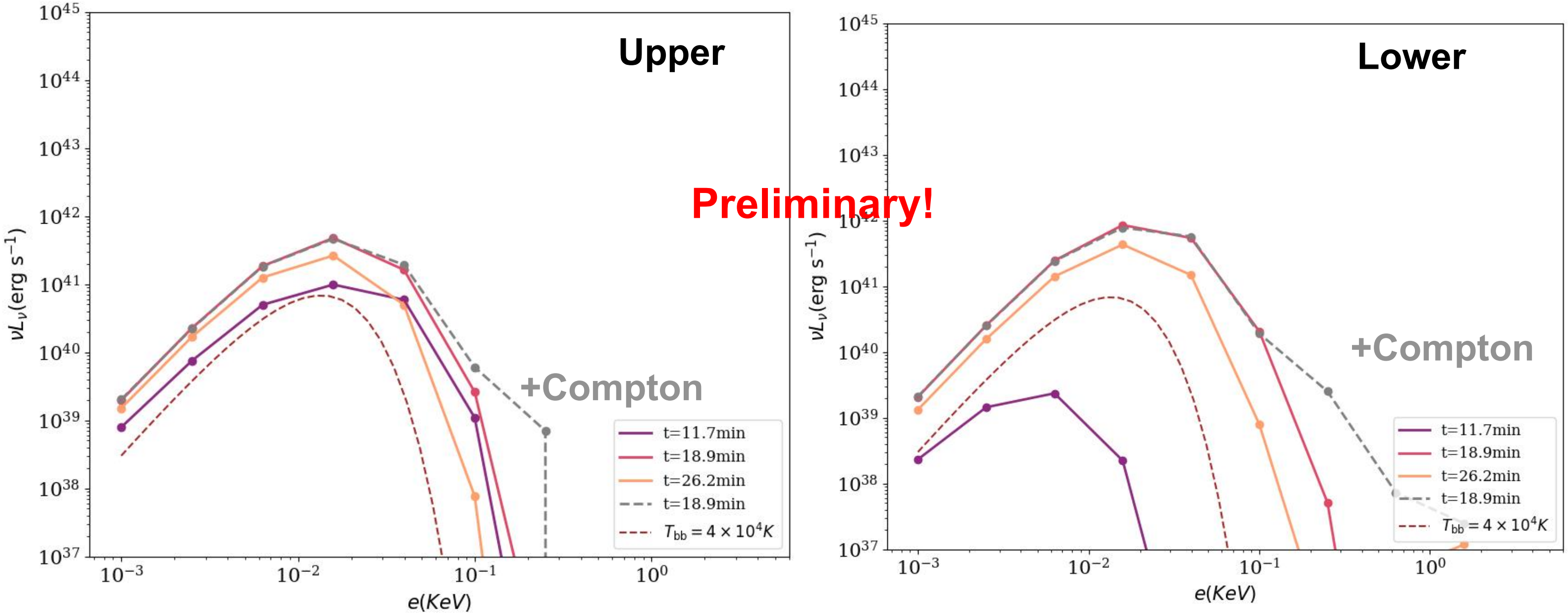

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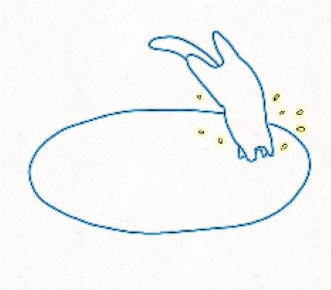
Take aways?



- **Star-disk Collision forms two asymmetric ejecta**
    - **Broken power-law density profile**
        - Flat inner high density region + steep outer low density region
    - **Homologous velocity:**
        - forward > incident velocity
        - Backward ~ half of incident velocity
    - **Non-spherical morphology**
    - **Opacity:**
        - Inner region ($\geq 5 \times 10^5$K): free free ~ absorption <~ scatter
        - Outer region ($\sim 2 \times 10^5$K): free-free < scatter < absorption
- **Ejecta cooling emission:**
    - Bolometric luminosity $L_{bol} \sim 10^{41-43}$ erg/s
    - Diffusion timescale: could show weaker dependency disk surface density due to $\kappa_{abs}(\rho, T)$
- **Beak-out emission** $L_{BO} \geq 10^{42}$ erg/s, faded in minutes
- **Spectral energy:** peaks in UV, can produce soft X-ray excess