

Electromagnetic signals from BH-disk collisions

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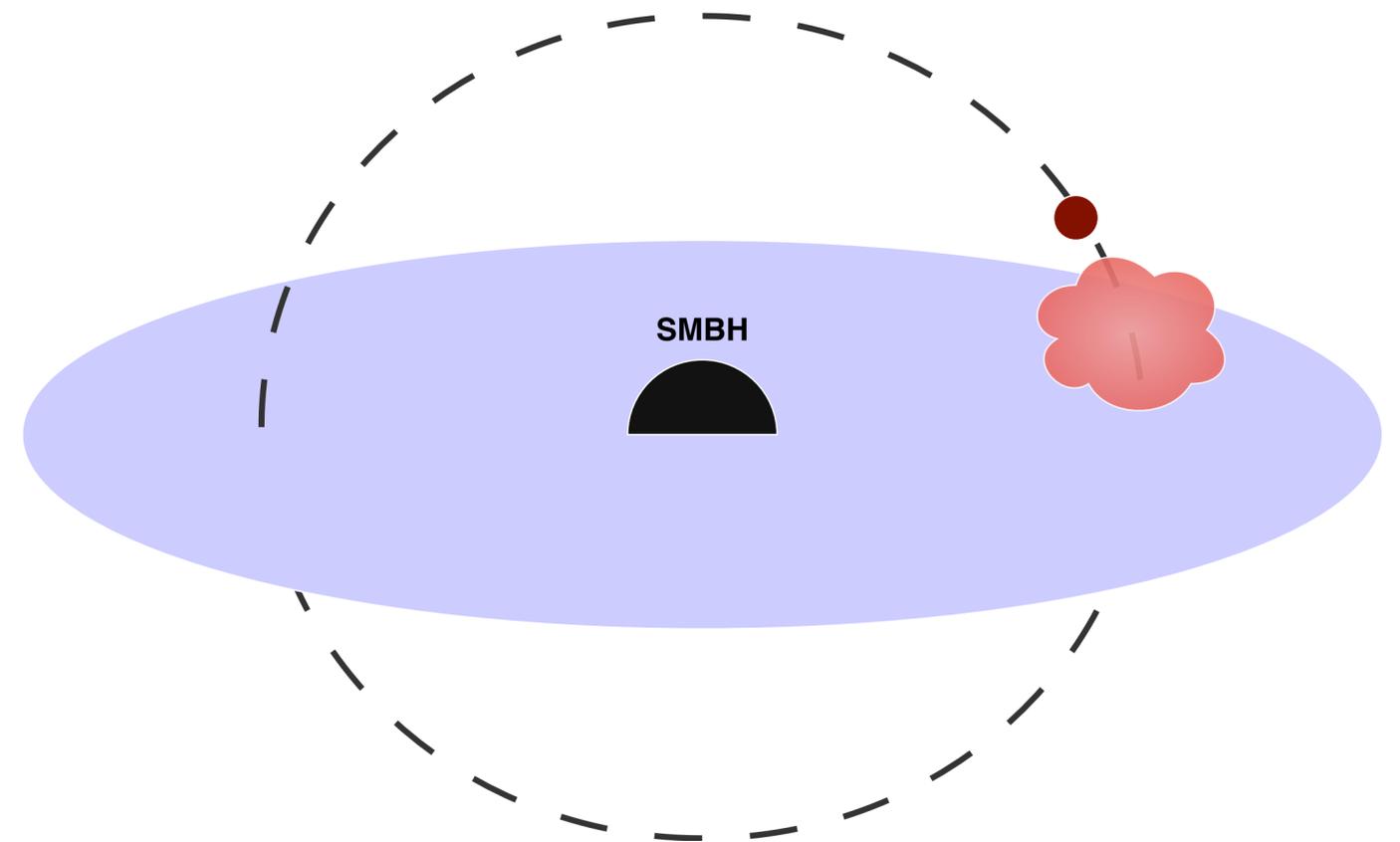
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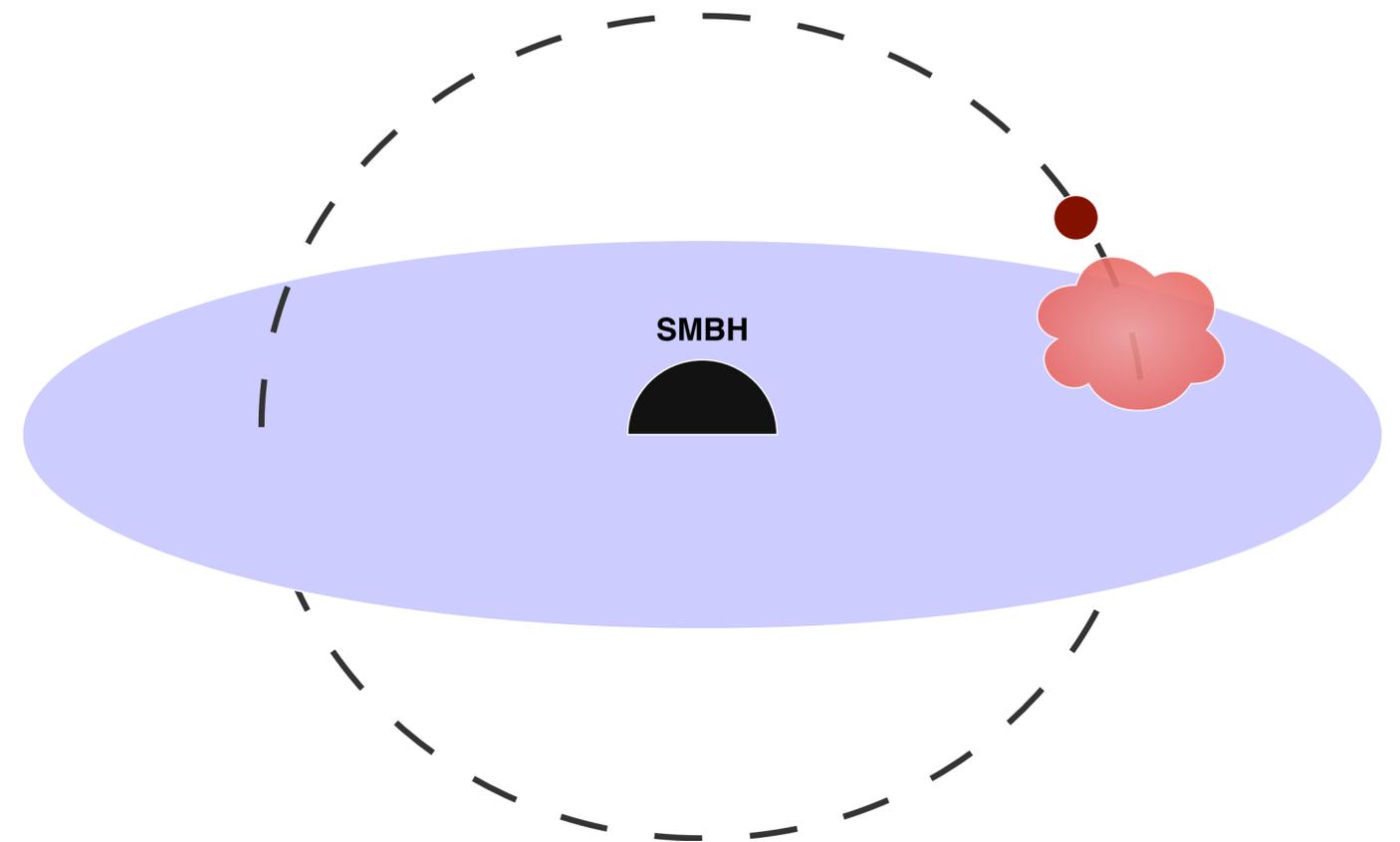
Motivation

- Black holes are expected to be common in galactic nuclei
- Accretion flows: AGN activation, TDEs
- Supersonic collisions: strong shocks + heating



Motivation

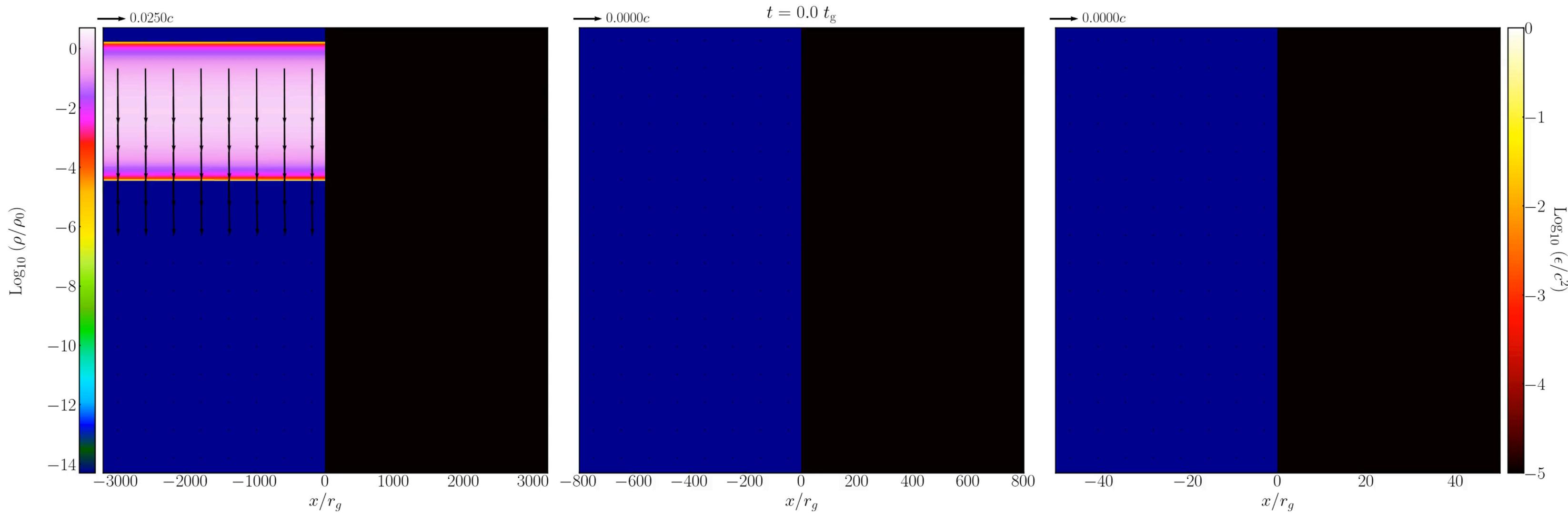
- QPE-like phenomenology
- OJ 287? (Valtonen+2008, Komossa+2023)
- Multimessenger relevance: bounds on LISA-detectable EMRI population



What EM signals are produced in these collisions?

Hydrodynamics

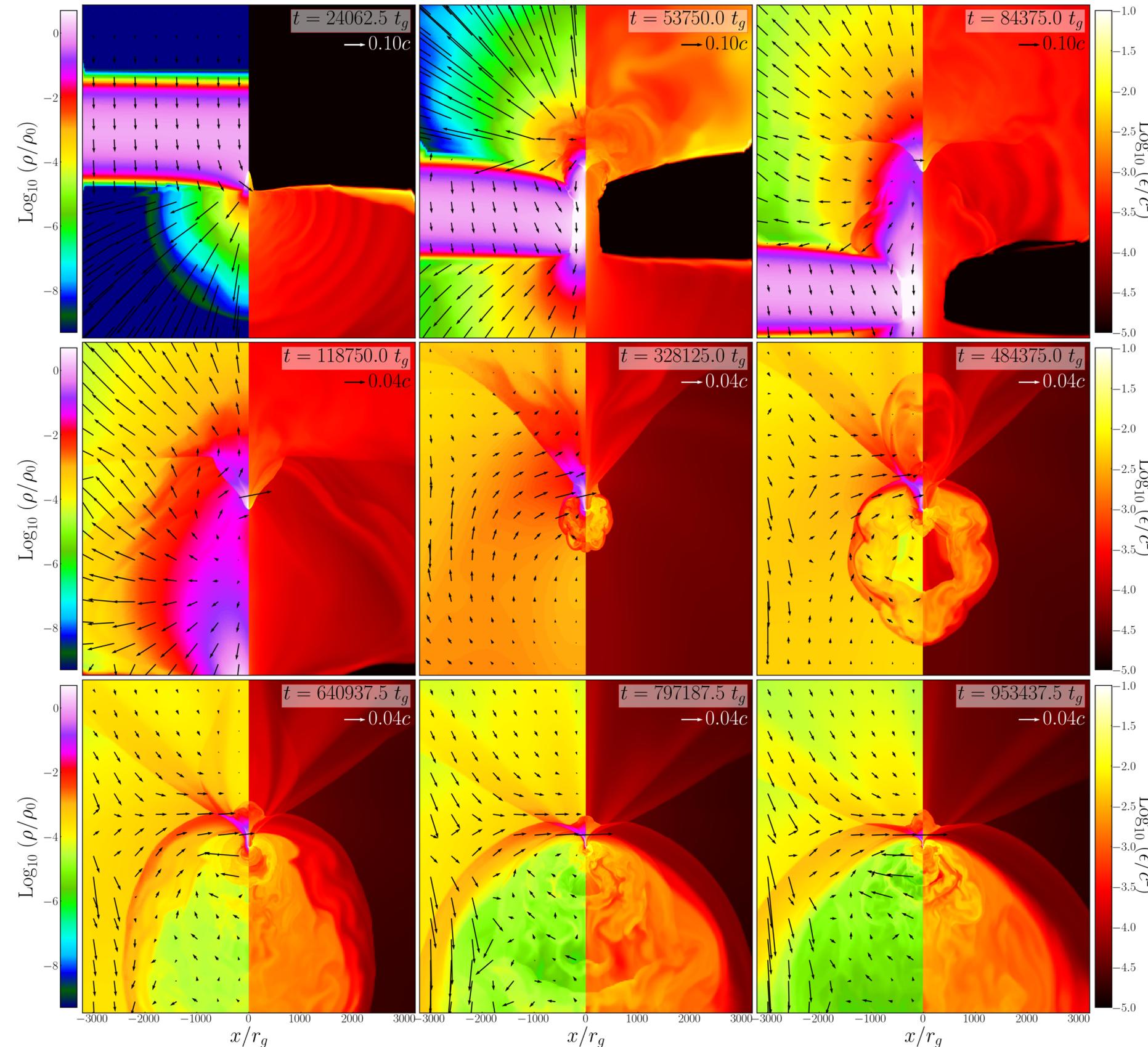
Lam...JP+2025



Hydrodynamics

- Spherically expanding outflows on each side (see also Ivanov+1998)
- Reverse **BHL-type shock**
- **Convective region** at late times
- **Hyper-Eddington** accretion onto the secondary

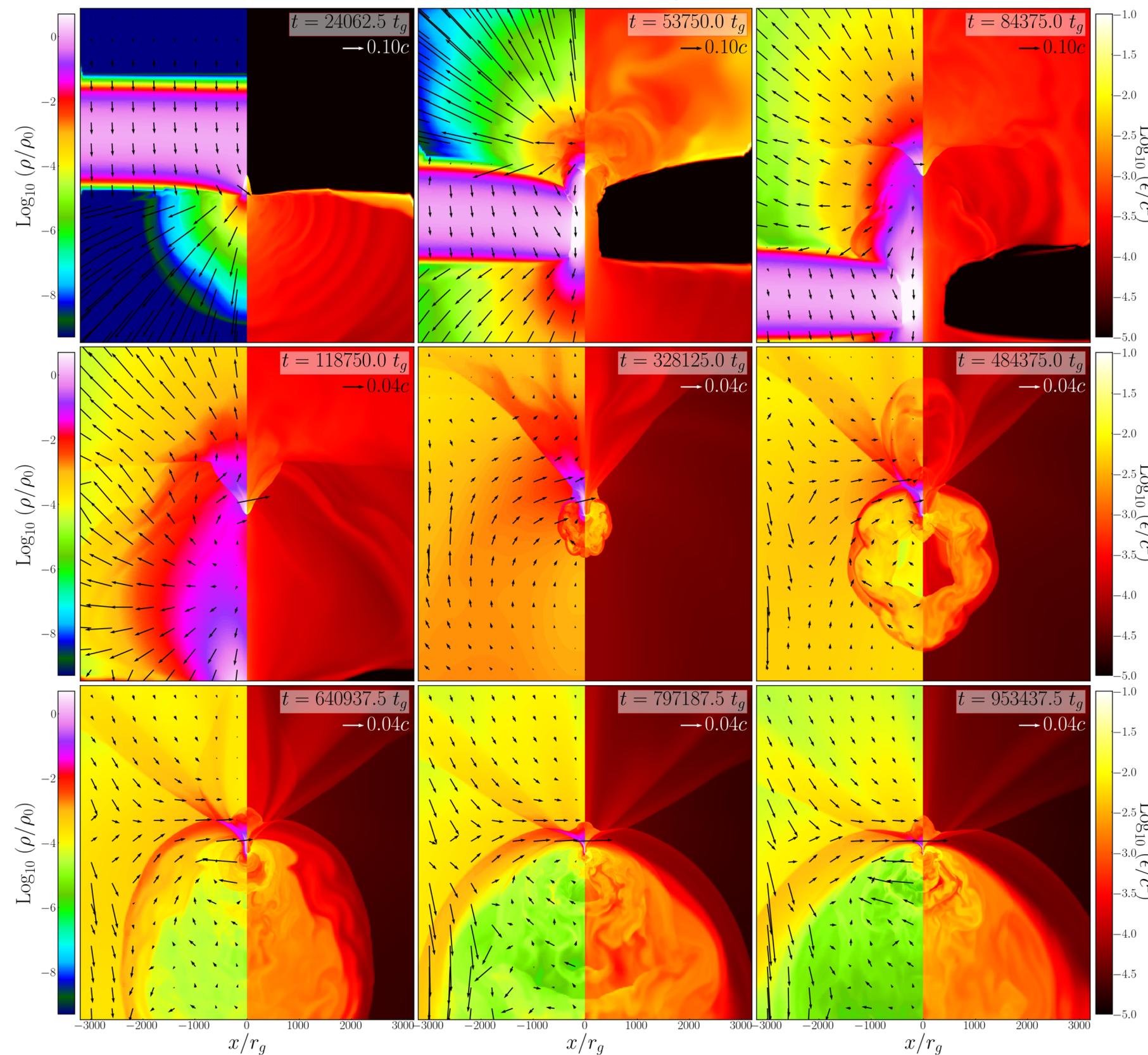
$$\dot{M} \gtrsim 10^3 \dot{M}_{\text{Edd,BH}} M_{c,6}^{-1/3} P_{\text{QPE,1d}}^{1/3} \Sigma_4$$



Hydrodynamics \longrightarrow Radiation

- Highly super-Eddington flow
- Highly optically thick
- Radiation is regulated by **diffusion** and **advection**

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Radiation framework

$$L(t) \approx \int \dot{e}(\mathbf{x}, t) f_{\text{esc}}(\mathbf{x}, t) dV$$

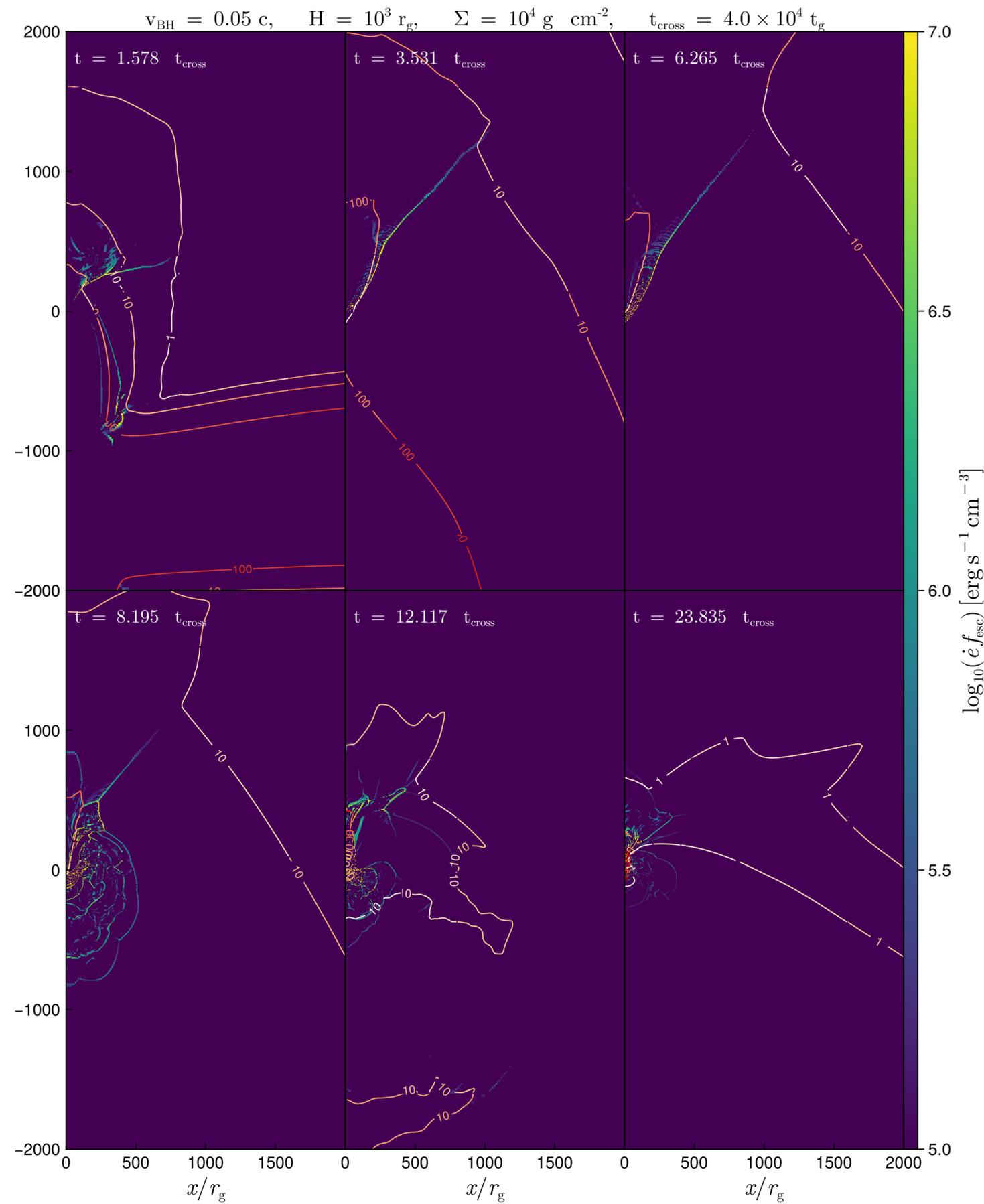
- Energy generation rate (shock heating):

$$\dot{e} \propto \rho_u (v_u - v_{\text{sh}}) (\varepsilon_d - \varepsilon_u)$$

- Optical depth: we solve eikonal equation

$$|\nabla \tau| = \kappa \rho, \quad \tau|_{\partial\Omega} = 0$$

$$\kappa = 0.34 \text{ cm}^2 \text{ g}^{-1}$$



Radiation framework

$$L_{\text{bol}}(t) \approx \int \dot{e}(\mathbf{x}, t) f_{\text{esc}}(\mathbf{x}, t) dV$$

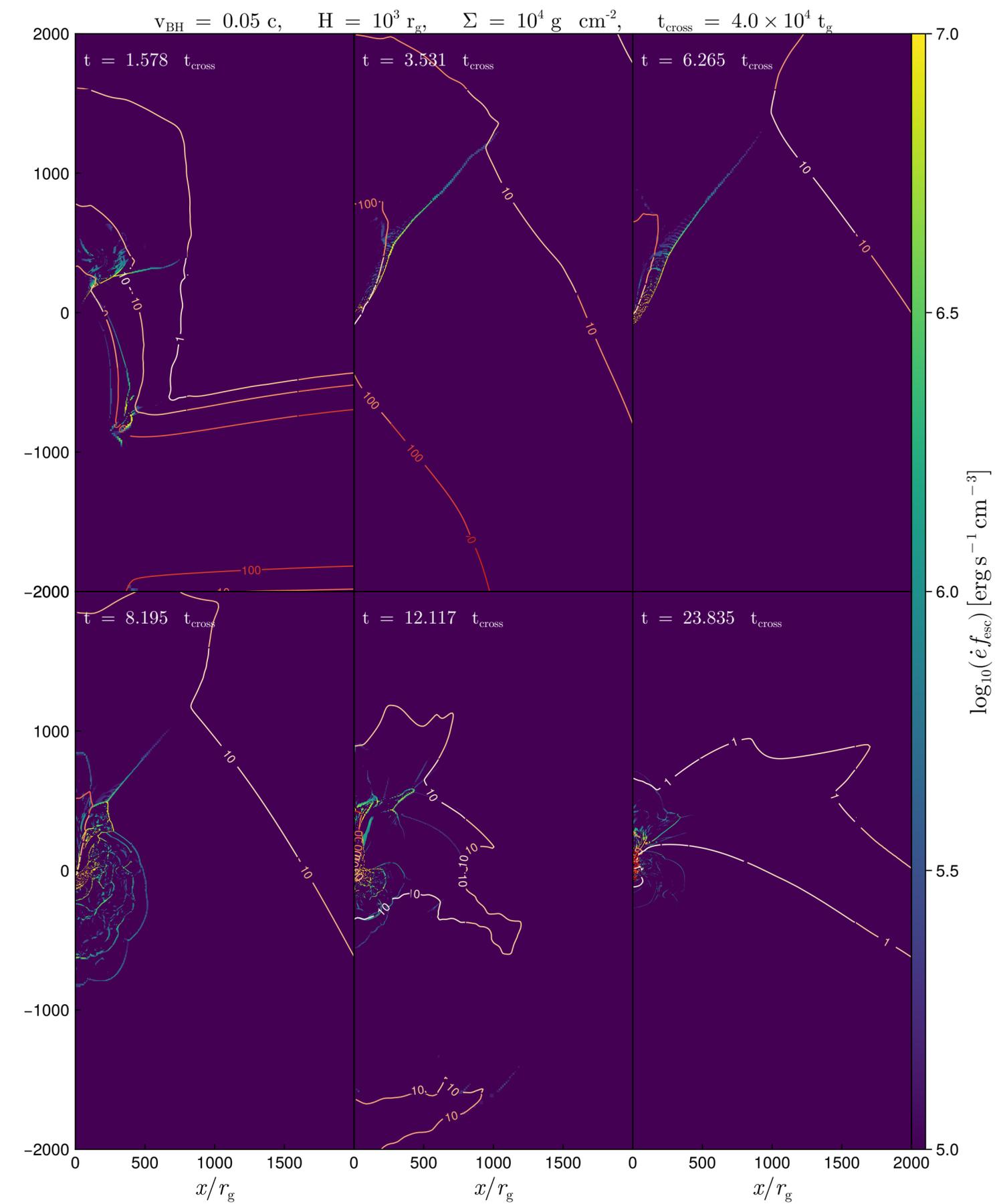
- Escape fraction: $f_{\text{esc}} := f_{\text{adv}} f_{\text{diff}}$

- Advection factor:

$$f_{\text{adv}} := \exp \left[-\frac{4}{c} \int_{\gamma_{\text{esc}}} \min(v_r, 0) d\tau \right]$$

- Diffusion factor:

$$f_{\text{diff}} := \exp \left[-\frac{t_{\text{diff}}}{t - t_{\text{coll}}} \right] \quad t_{\text{diff}}(\mathbf{x}, t) := \tau(\mathbf{x}, t) \ell_{\text{esc}}(\mathbf{x}, t)/c$$



Radiation framework

- Free-free emission and Comptonization (Nakar & Sari 2010)

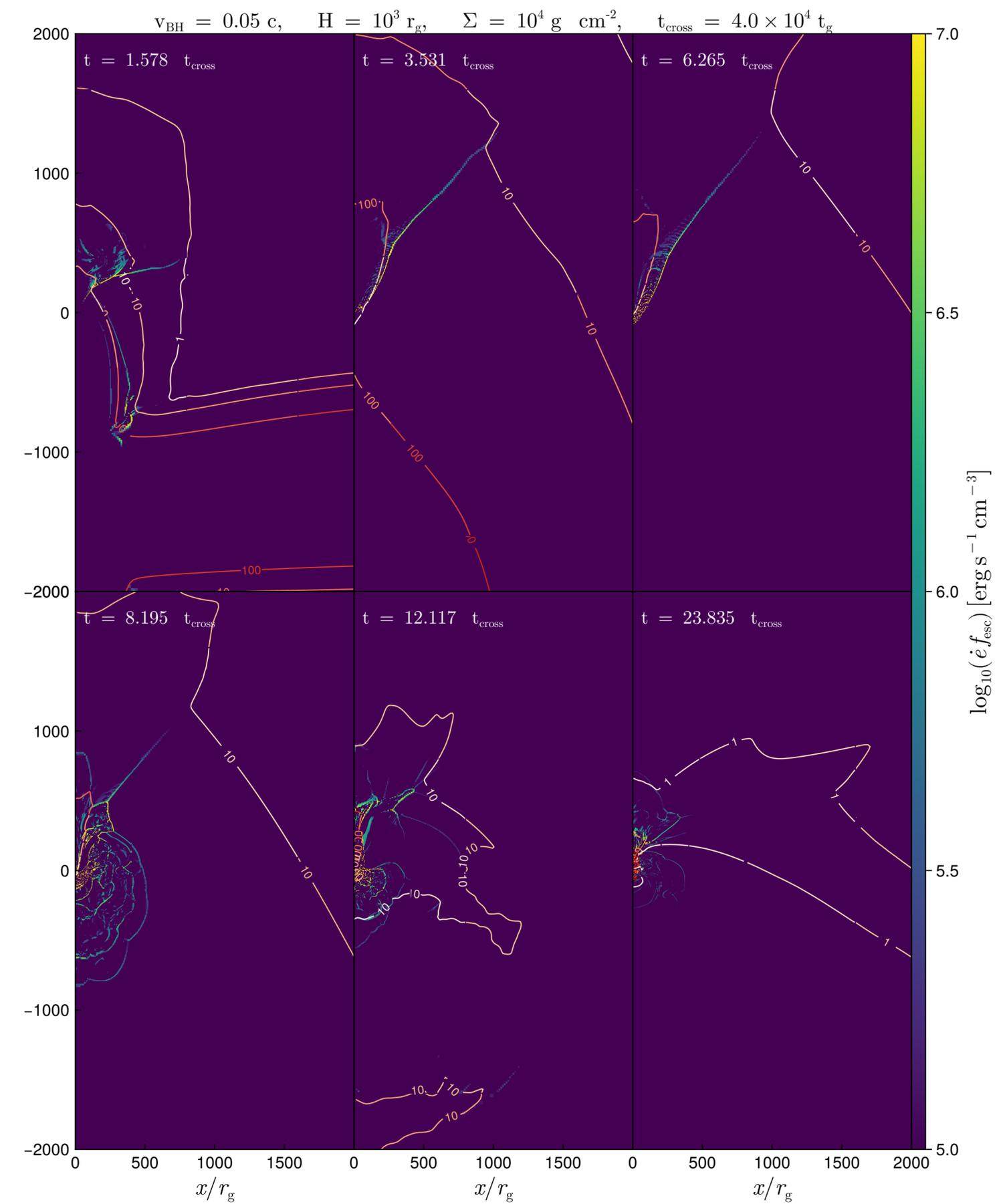
$$\frac{u_{\text{rad}}}{3k_B T} = t_{\text{diff}} \dot{n}_{\text{ff}}(\rho, T) \xi(T)$$

- Capped by blackbody and pair-production saturation temperatures (Weaver 1976)

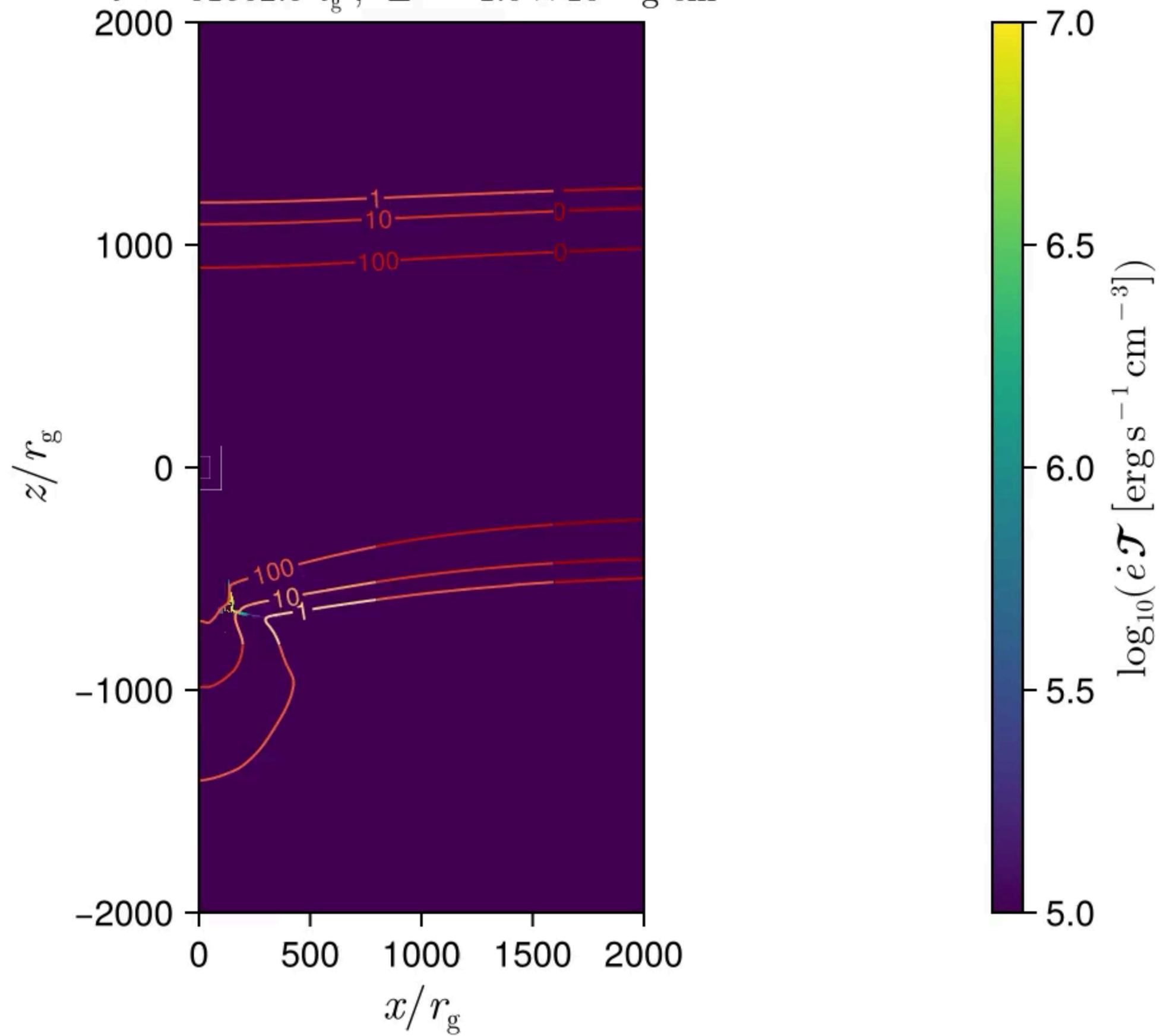
$$T_{\text{BB}} \leq T \leq T_{\gamma\gamma} (\sim 200 \text{ keV})$$

- We construct rough specific luminosity estimates

$$\nu L_\nu \approx \nu \int \dot{e} f_{\text{esc}} \frac{\pi B_\nu(T)}{\sigma T^4} dV,$$

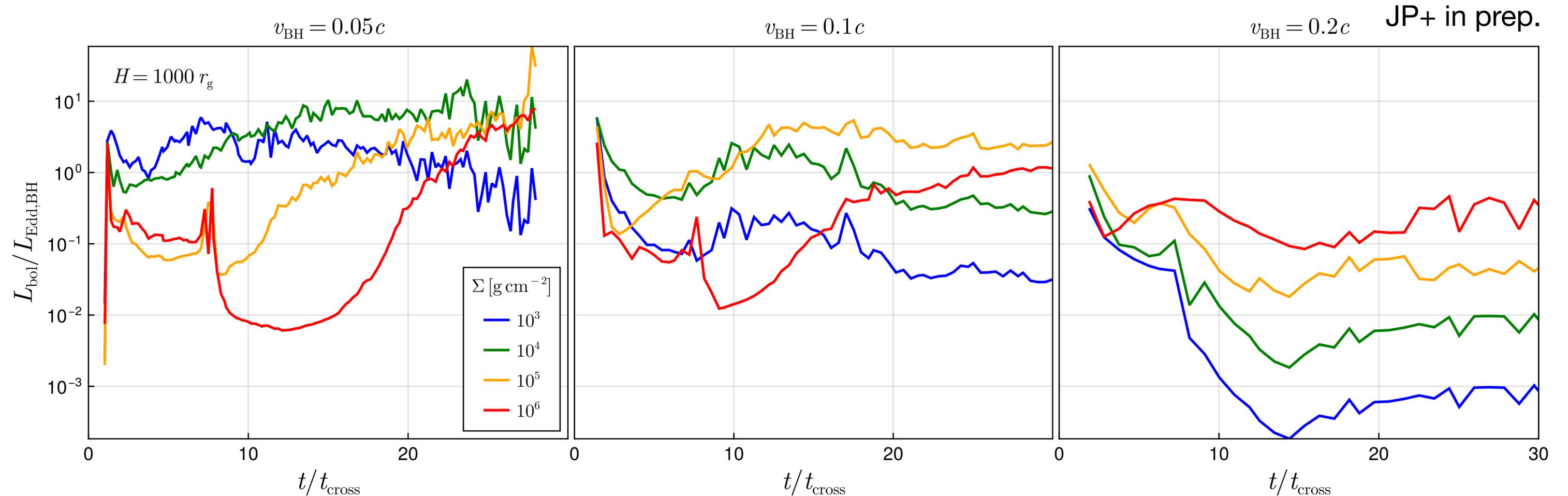


$t = 31562.5 t_g$, $\Sigma = 1.0 \times 10^4 \text{ g cm}^{-2}$ JP+ in prep.



$$r_a := \frac{2Gm_{\text{BH}}}{v_{\text{BH}}^2} \approx 400 r_g M_{c,6}^{-2/3} P_{\text{QPE},1\text{d}}^{2/3}$$

Bolometric luminosity



- $L_{\text{peak}} \sim 1-10 L_{\text{Edd}}$
- Different morphologies

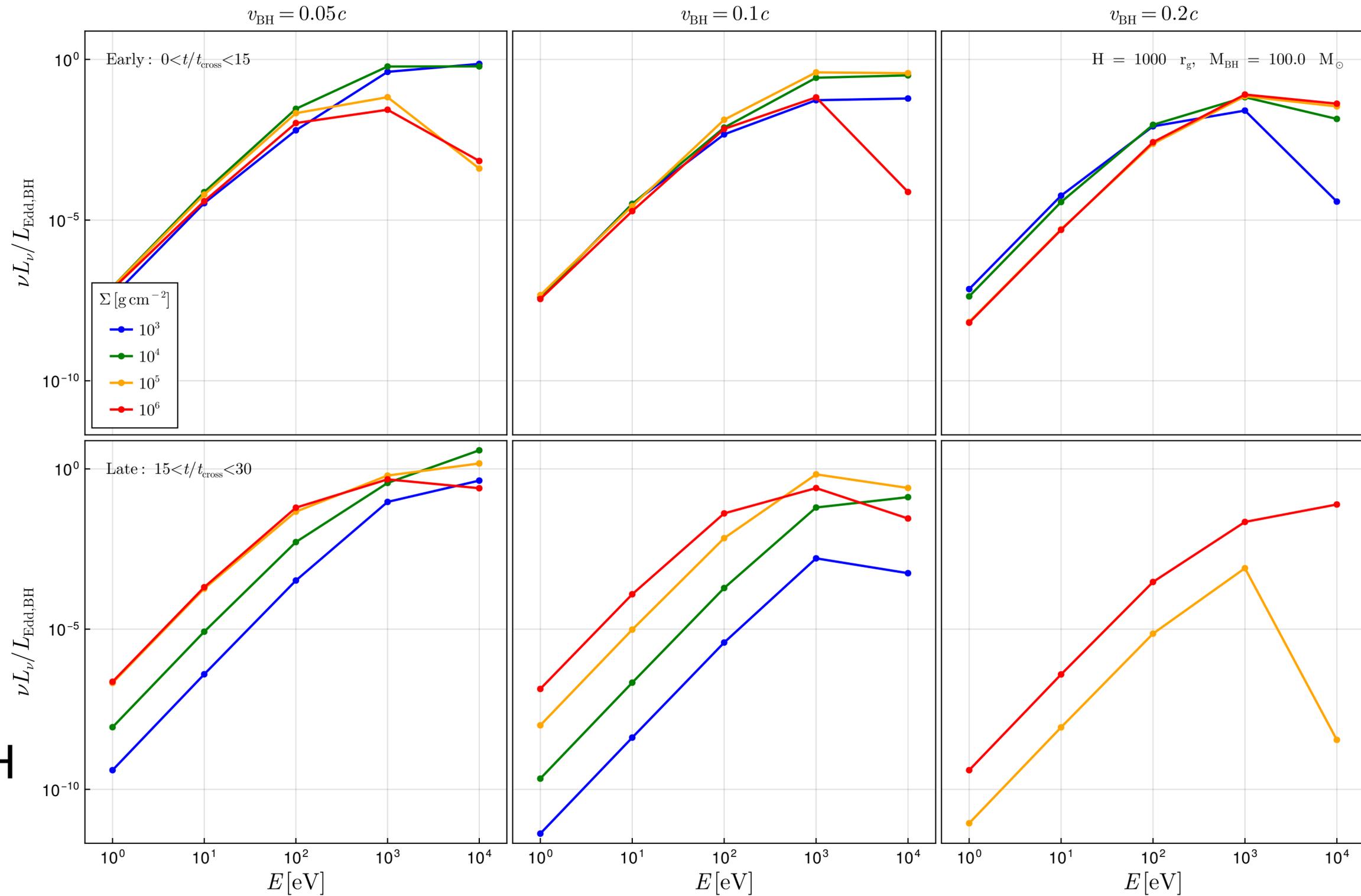
- Higher v_{BH} implies smaller interaction time and lengthscale

- Higher Σ favors dip-and-rebrightening

SEDs

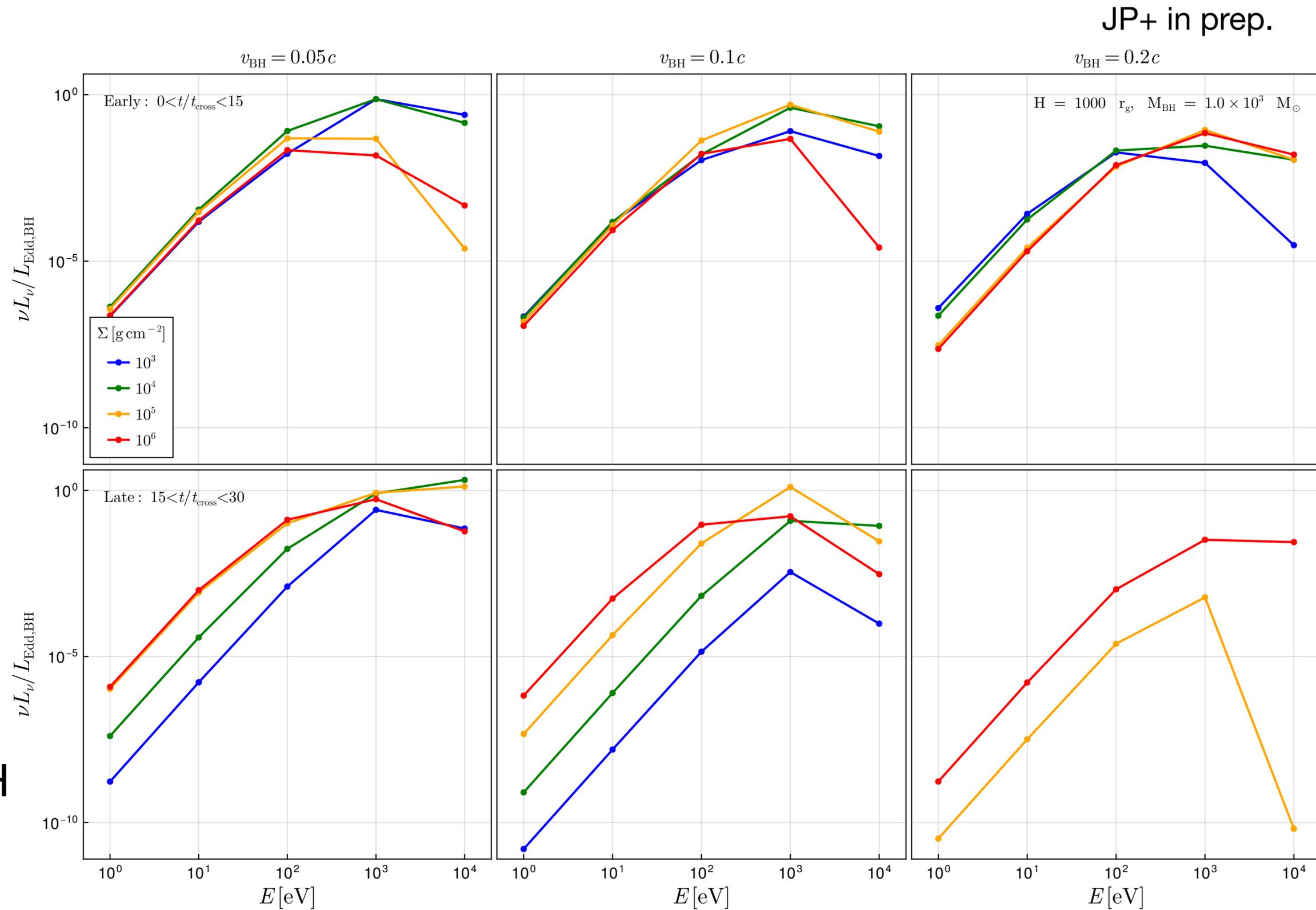
- Soft X-rays \sim keV
- Mild hardening for
 - Higher v_{BH}
 - Lower Σ
 - Late times
- Softening for higher BH mass

JP+ in prep.



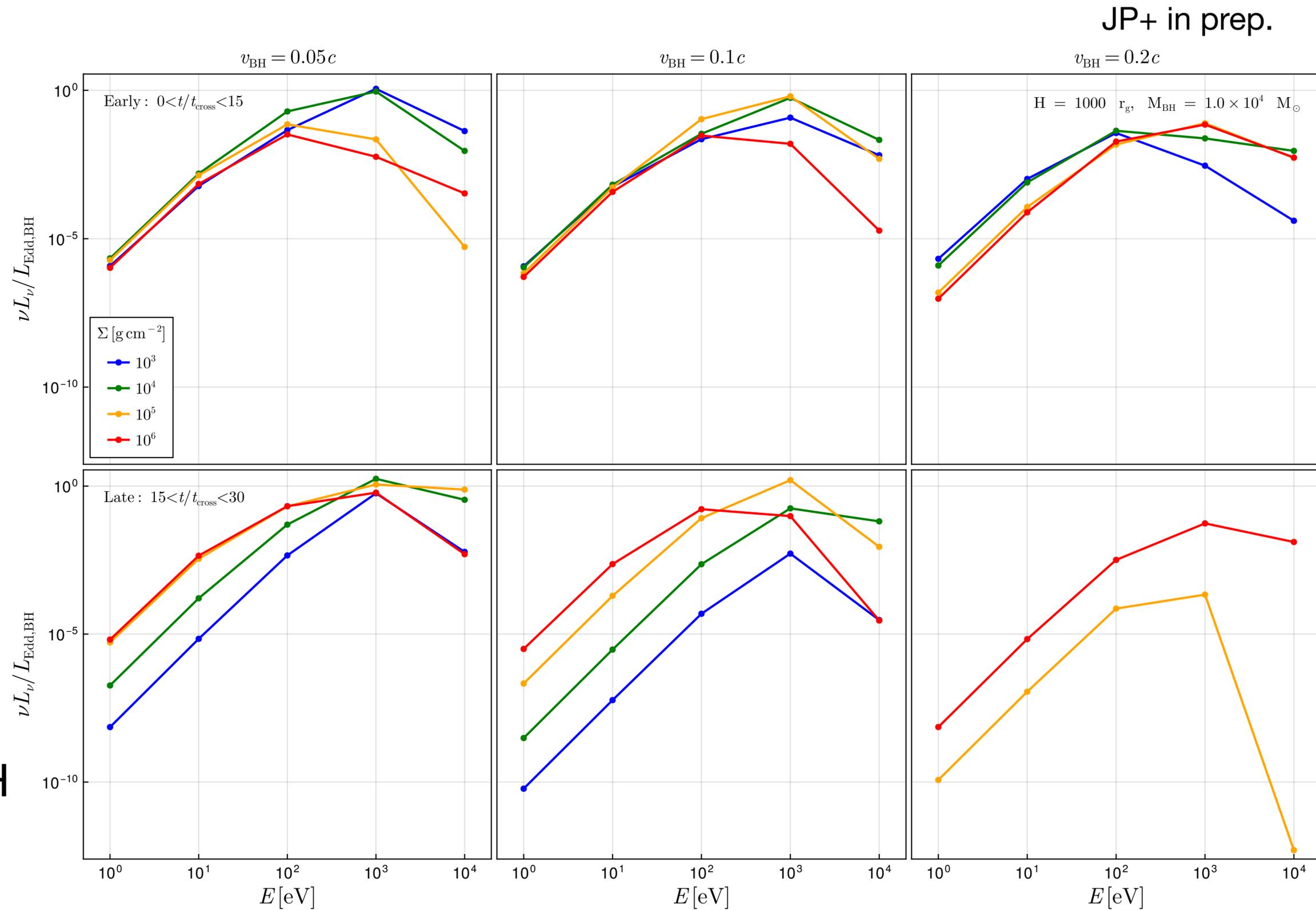
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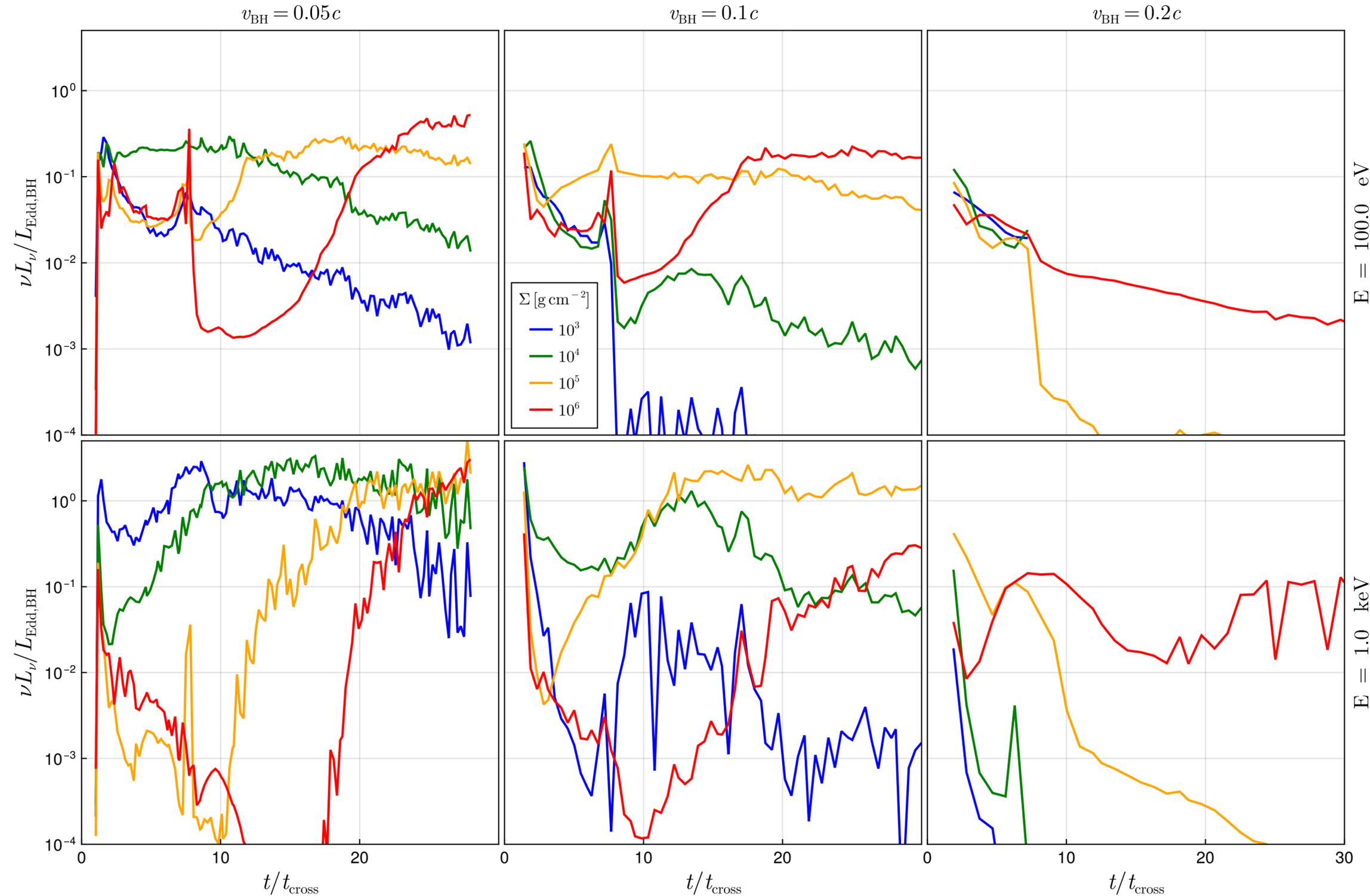


Specific luminosities

$$M_{\text{BH}} = 10^4 M_{\odot}$$

JP+ in prep.

- L_X up to several $\times L_{\text{Edd,BH}}$
- Optical/UV $\lesssim 10^{-1} L_{\text{Edd,BH}}$
likely hidden by quiescent disk
- Highest velocities (shortest periods) are too dim



Flares from the expanding ejecta

- Approximately spherically expanding ejecta (Arnett 1980)
- Typically **shorter timescale** than accretion-powered emission

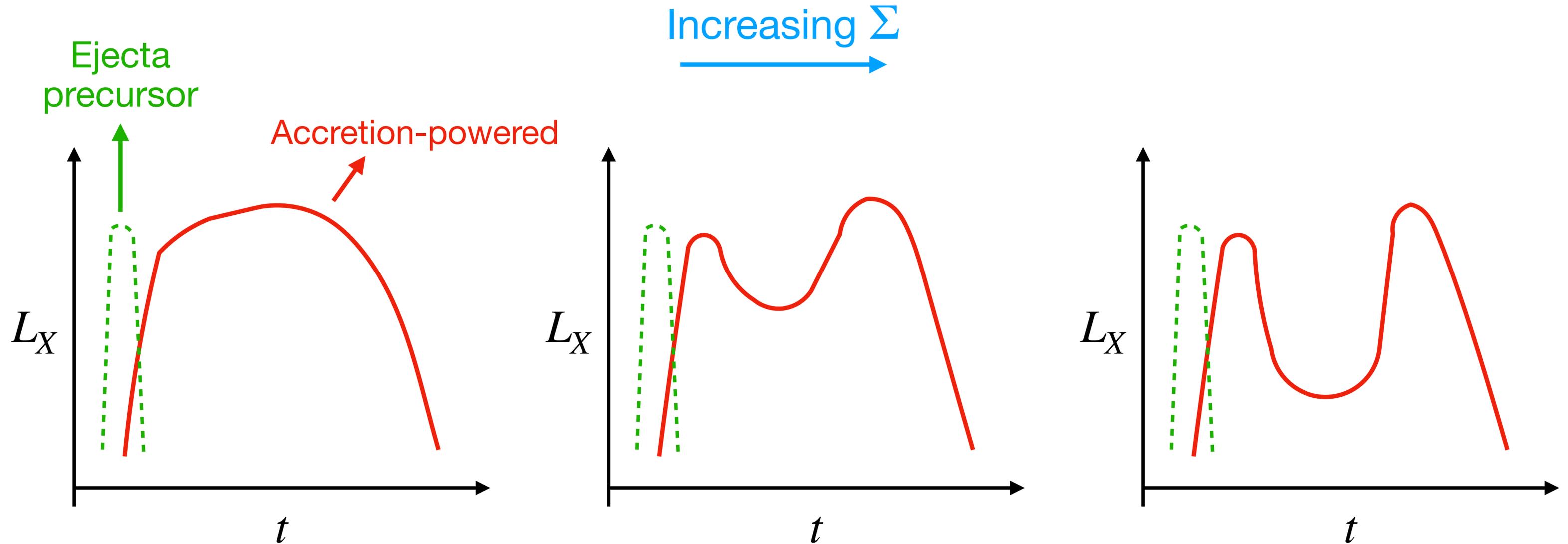
$$t_{\text{peak}} \approx \sqrt{\frac{3\kappa M_{\text{ej}}}{4\pi c v_{\text{ej}}}} \approx 6 \times 10^4 t_g \Sigma_4^{1/2} \left(\frac{v_{\text{BH}}}{0.05c}\right)^{-5/2} \left(\frac{v_{\text{ej}}}{v_{\text{BH}}}\right)^{-1/2} \left(\frac{M_{\text{ej}}}{0.1m_a}\right)^{1/2}$$

- **Around Eddington**, independent of parameters, similar to accretion-powered luminosity

$$L_{\text{peak}} \approx \frac{2}{3} L_{\text{Edd,BH}} \left(\frac{E_{\text{ej}}}{M_{\text{ej}} v_{\text{BH}}^2}\right)$$

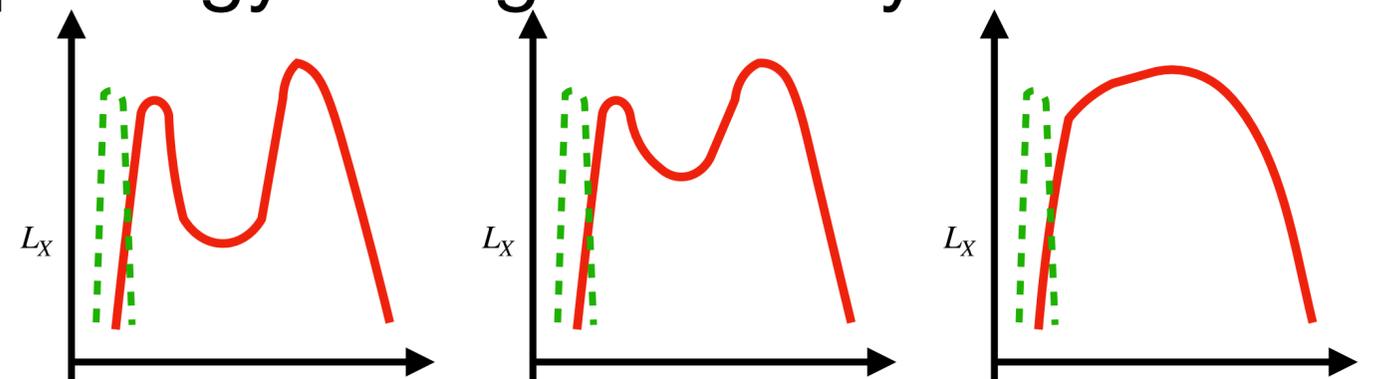
- Potentially contribute an **early component**, but unlikely to dominate for most parameters

Multi component flare “model”



Observational diagnostics

- Repeating soft-X ray flares (for IMBH regime)
- P_{QPE} determines possible ν_{BH}
- L_{QPE} determines the range of M_{BH} . t_{dur} should be consistent.
- Longer P_{QPE} are preferred (at fixed Σ) \rightarrow stronger interaction \rightarrow higher luminosity
- But require longer observational baseline
- In density decreases with time \rightarrow flare morphology change across years



Crested QPEs from J2344

- QPEs 5 years after TDE-like flare J2344 (Baldini+26; Homan+23, Goodwin+24)

- $L_{\text{QPE}} \sim 10^{43} \text{ erg s}^{-1}$

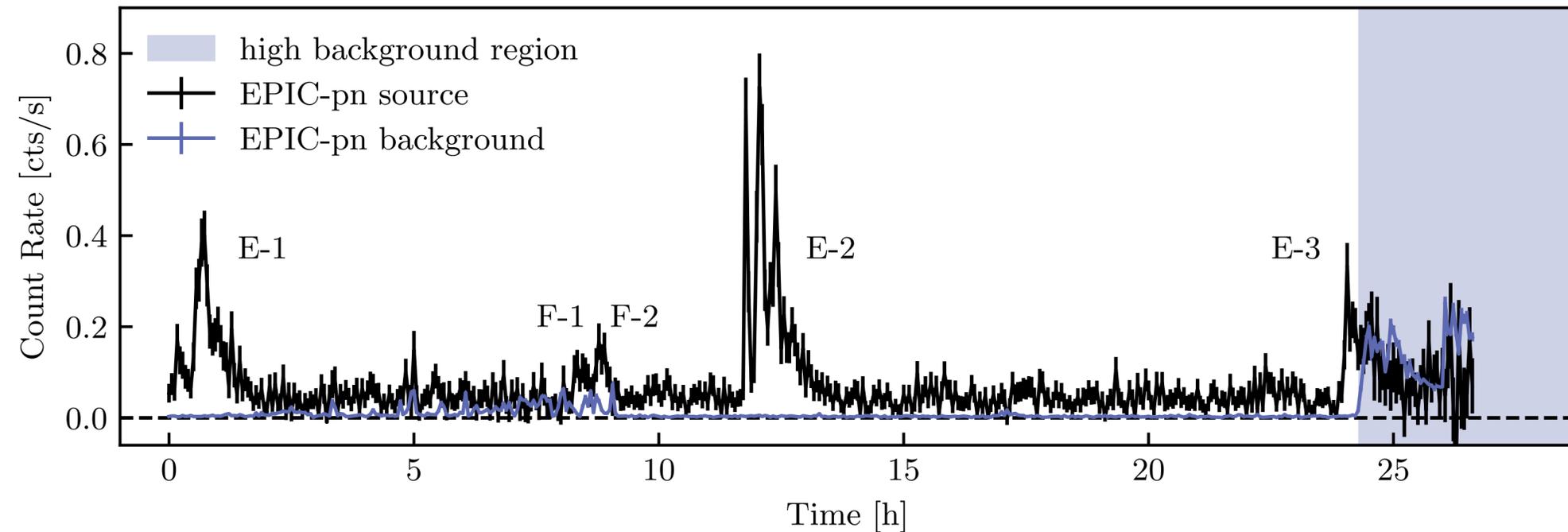
- $t_{\text{rec}} \sim 12 \text{ hrs}, t_{\text{dur}} \sim 2 \text{ hrs}$

- $M_c \sim 10^7 M_{\odot}$

- Narrow flares separated by 5-30 mins

XMM-Newton 2025-06-17

Baldini+2026

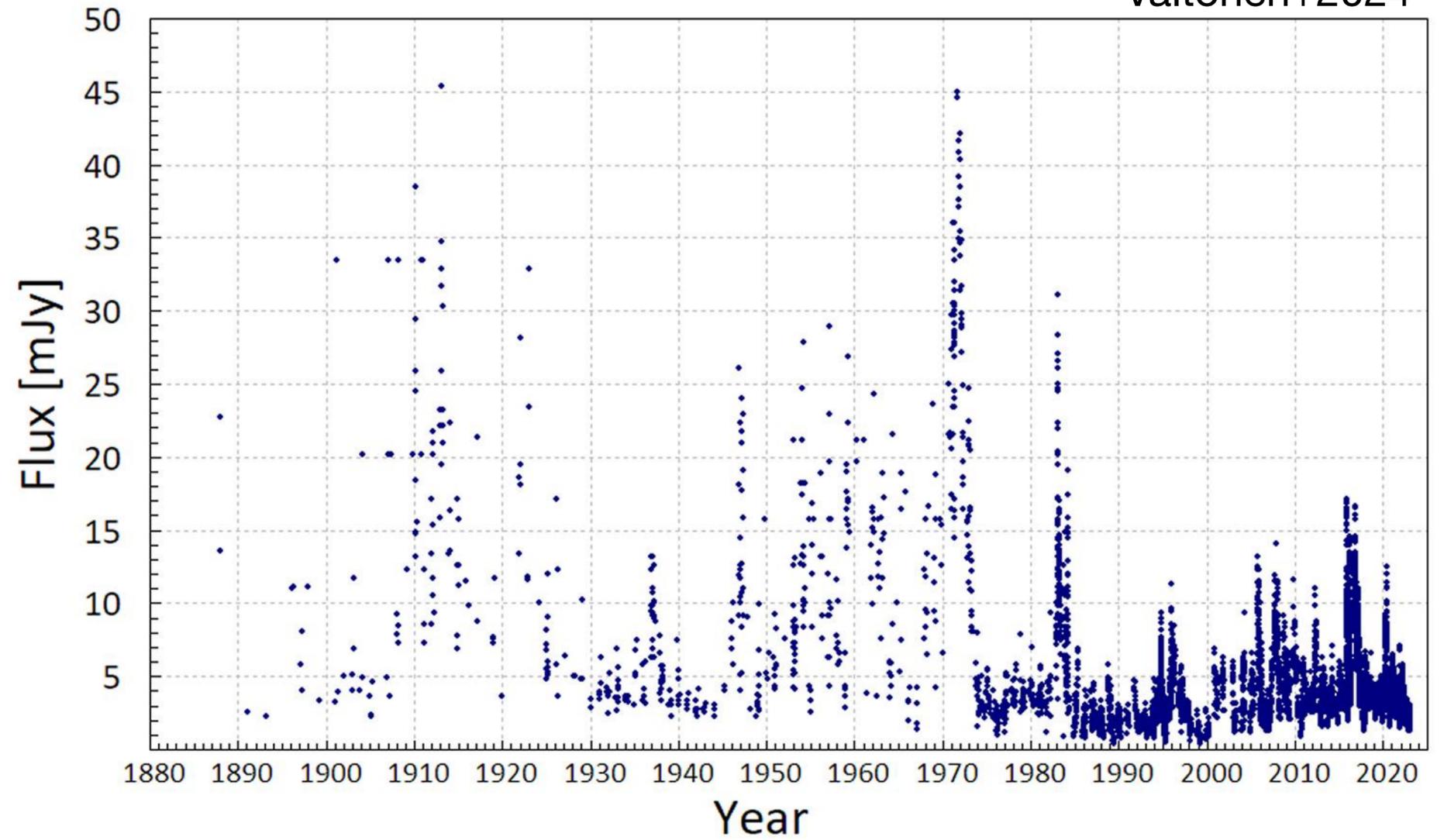


- BH-disk collisions?

- For $M_{\text{BH}} \sim 10^4 - 10^5 M_{\odot}, M_c \sim 10^7 M_{\odot}$
 $t_{\text{GW}} \sim 10 - 90 \text{ yrs}$

OJ 287

- One of the best-known SMBH binary candidates (Lehto & Valtonen 1996)
- ~ 9 yr rest-frame period, multiwavelength flares
- $L_V \sim 10^{46}$ erg s $^{-1}$
- Weeks-to-months flare durations
- Canonical model (Valtonen 2008):
 $10^{10}M_{\odot}$ - 10^8M_{\odot} binary
- $e \sim 0.6$, precessing orbit



- Our results imply $M_{\text{BH}} \sim 10^8 M_{\odot}$, but then timescale 10^5 - $10^6 t_g \sim$ yrs is too long (see also Linial & Metzger 2023)
- However, further work to remove local approximation is warranted

Summary

- BH-disk collisions may naturally produce **multi-component EM flares**
- Emission is typically **soft X-ray dominated** (IMBH regime)
- Peak luminosities may reach $\sim 1-10 L_{\text{Edd,BH}}$
- A short **ejecta precursor** may accompany the accretion flare
- Optical/UV emission is likely hidden by the quiescent disk
- We need fully-coupled radiation-hydrodynamics for more consistent picture