Shocks power Tidal Disruption Events

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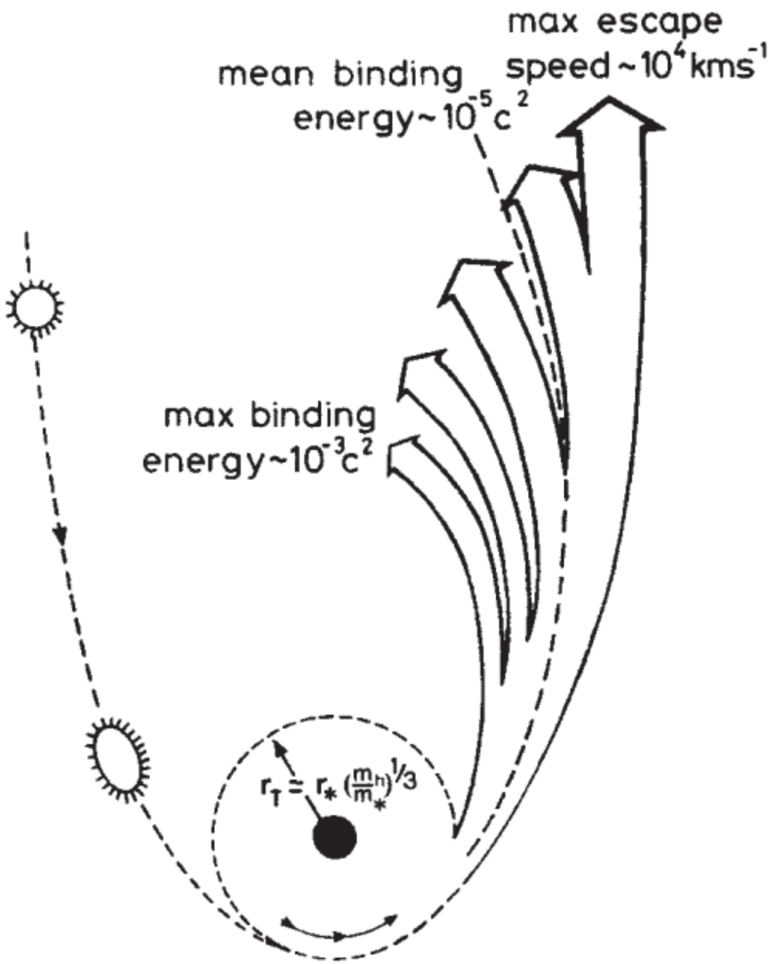
Introduction

- What is TDE?

A star approaching to an MBH is torn apart and accreted, producing a luminous flare that can last for months to years.

Classic picture (Rees 1988):

- half of the debris are bound to the SMBH
- the debris quickly circularize to an accretion disk
- Small accretion disk (size $\sim 2r_{\mathrm{p}}$)
- High temperature → soft X-ray, EUV
- Light curve closely follow the mass fall back rate → Super Eddington accretion



Rees (1988)

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Challenged by observation:

- Observed luminosity rarely exceed Eddington
- Many TDEs are discovered in UV/Optical surveys
- Effective temperature is low: few 10^4 K

Inverse Energy Crisis (Piran+2015): more energy than demand

Milestones in energy (see the Conclusion section of this paper)

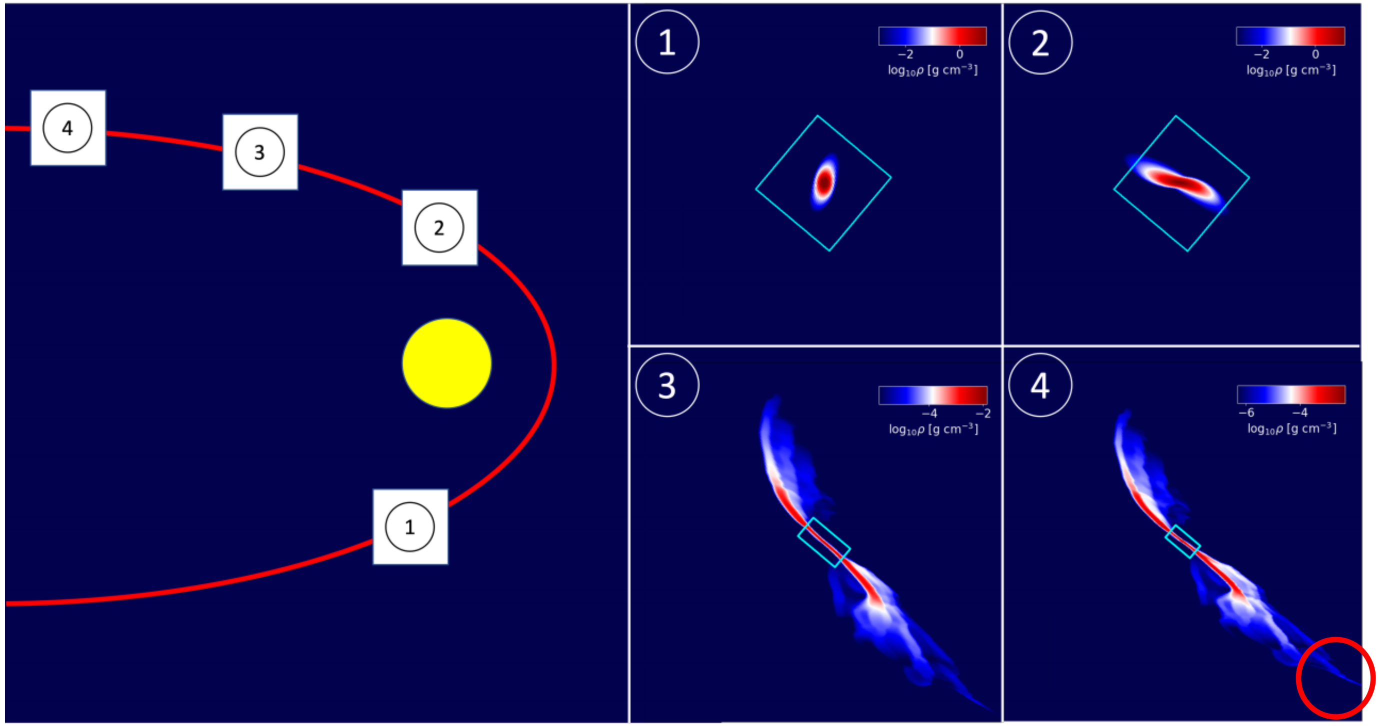
- Typical TDE flare radiates 3×10^{50} erg
- Circularizing bound debris into a disk (size $\sim 2r_{\mathrm{p}}$), shall release 7.5×10^{51} erg
- Accretion of all bound debris shall release 3×10^{53} erg

Proposed Solutions to Inverse Energy Crisis

- within the framework of classic picture (Piran+2015)
  - Photon trapping in the accretion flow
  - Outflow (kinetic energy)
  - Outflow (blow the debris away)
  - Outflow (reprocess higher energy photon)

- Alternative possibility (Shiokawa+2015; Piran+2015; Krolik+2016)
  - Circularization is slow
  - Radiation is powered by shocks at the pericenter and apocenter

Simulation setup



Most tightly bound debris

Time unit in the presentation

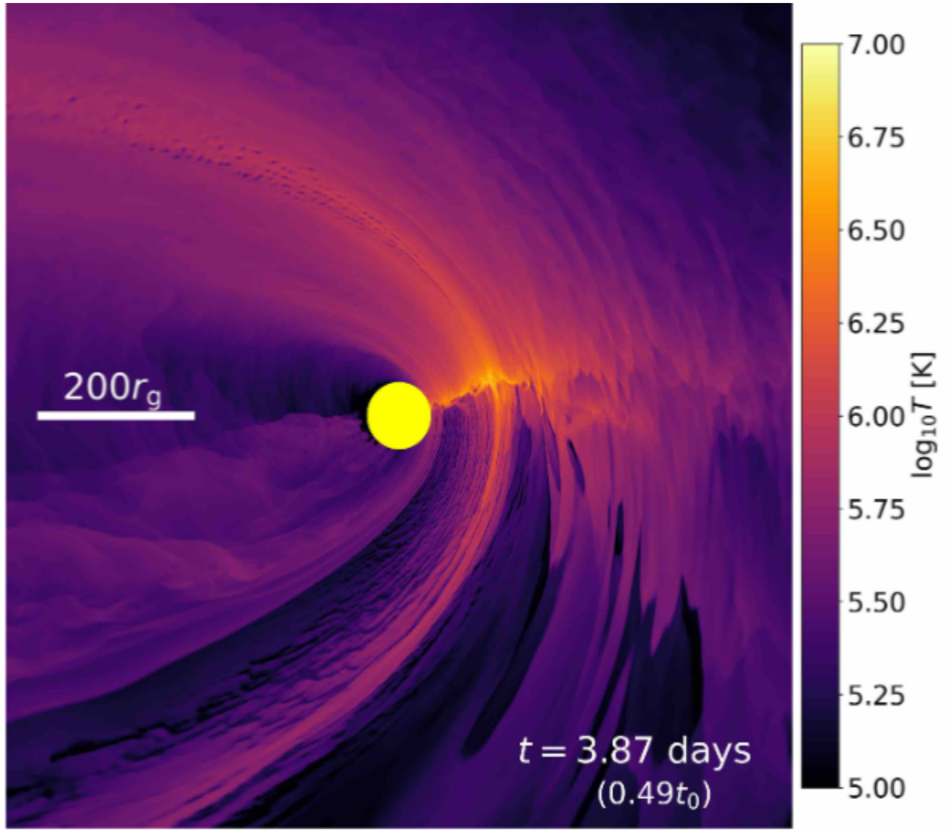
$$t_0 = \frac{\pi}{\sqrt{2}}\frac{GM_\bullet}{\Delta E^{3/2}} \simeq 7.6\ \mathrm{days}\left(\frac{\Xi}{1.64}\right)^{-3/2}\left(\frac{M_\bullet}{10^5\ M_\odot}\right)^{1/2}\left(\frac{M_\star}{3\ M_\odot}\right)^{-1}\left(\frac{R_\star}{2.4\ R_\odot}\right)^{3/2}.$$

Timing start point $t = 0$: when the most tightly bound debris return to the orbital pericenter

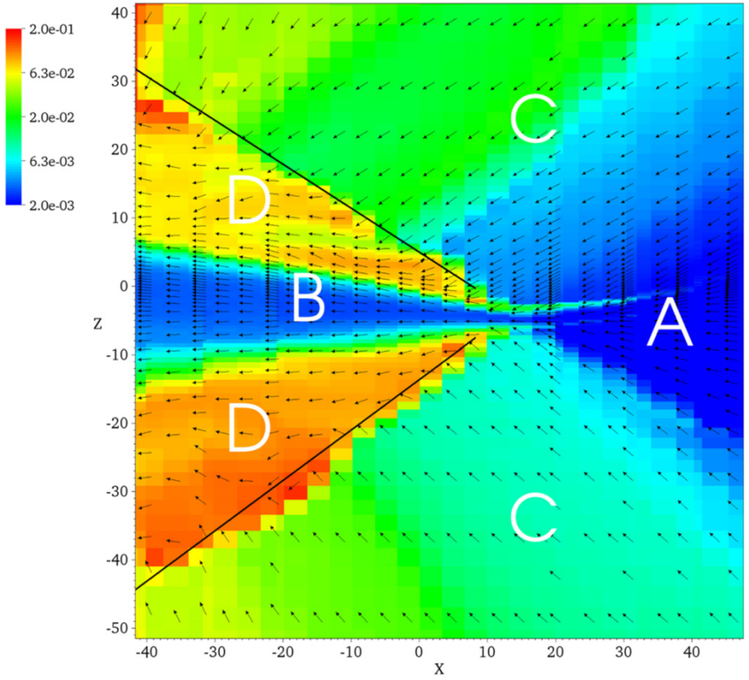
- fully relativistic hydrodynamic simulation
- 3 Msol star (MESA) + 10^5 Msol SMBH
- Long duration ~3 weeks.
- Energy dissipated only through shocks, no viscosity

The shock regions

Nozzle shock: debris stream converges to the equatorial plane



Temperature map in equatorial plane

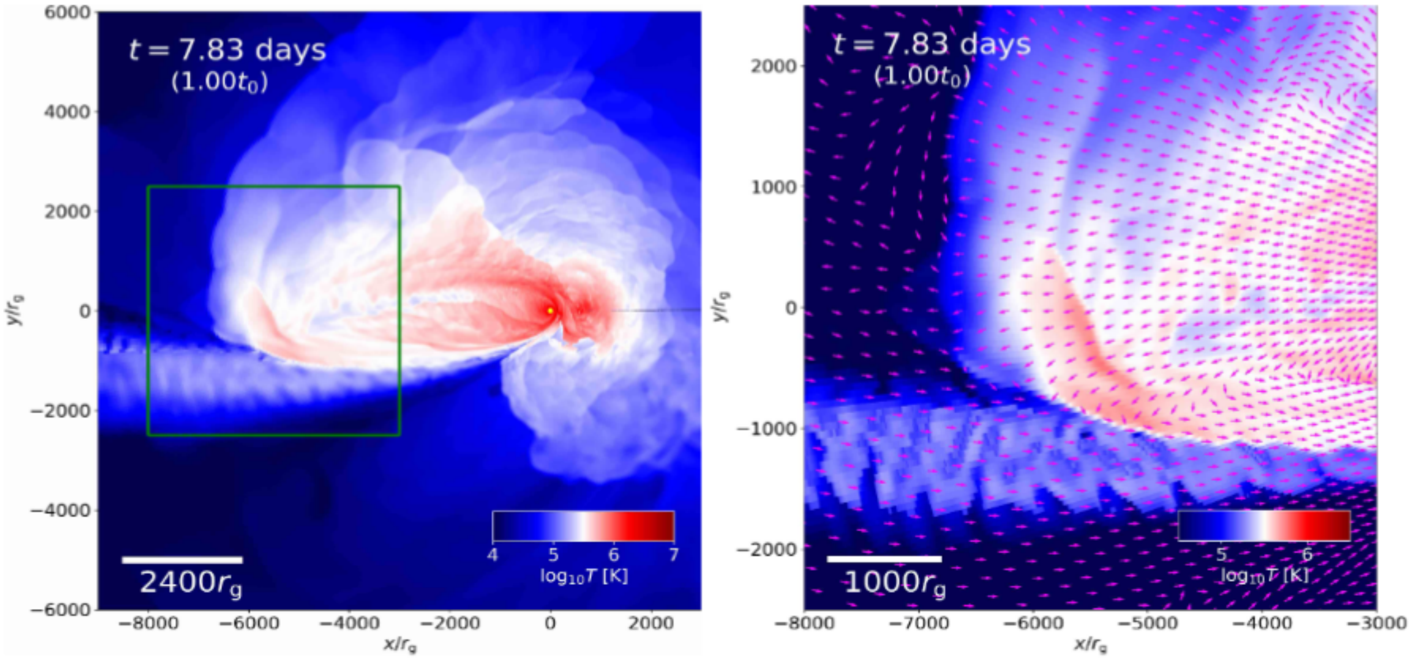


Entropy map in nozzle shock region (side view)

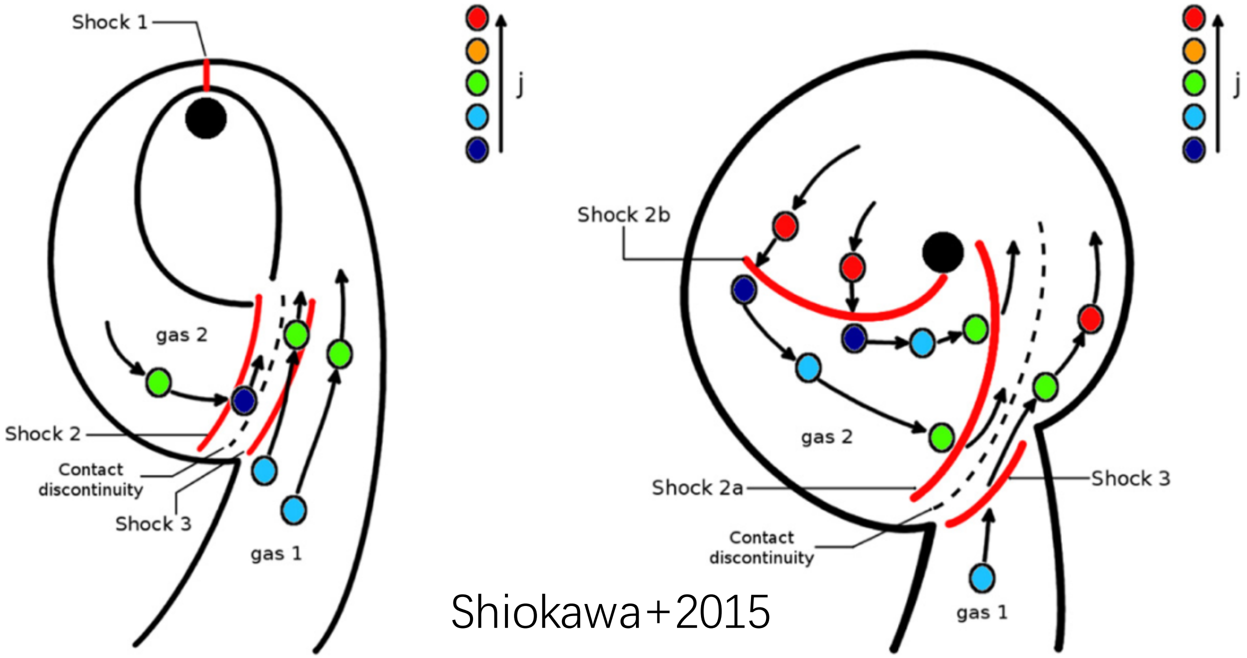
Shiokawa+2015

The shock regions:

Self-intersecting shock at apocenter



Note the shocks also redistribute the angular momentum of the fluid element, making the gas flow rounder and rounder.



Shiokawa+2015

Circularized or not?

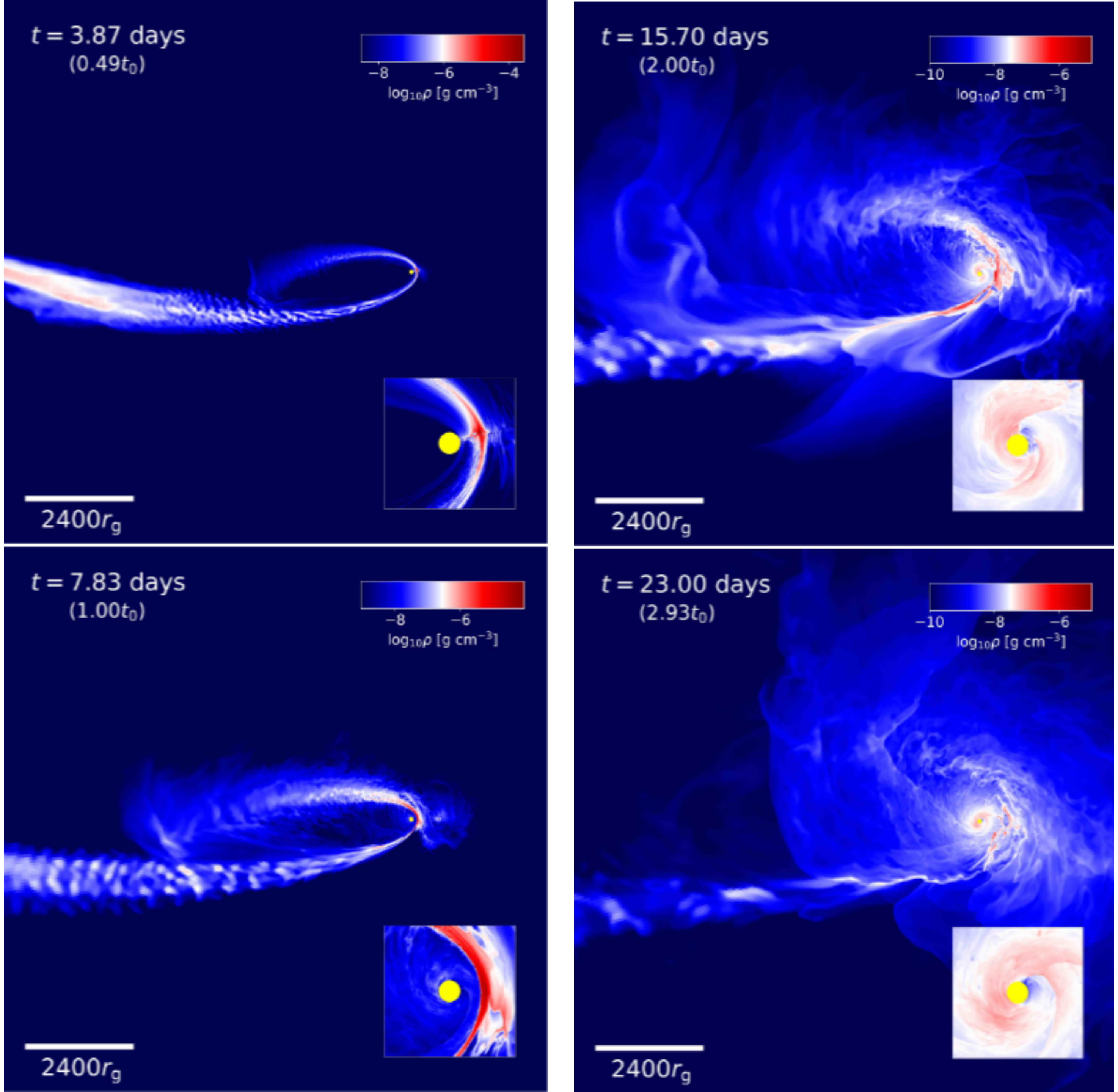
At the end of simulation ($t \approx 3t_0$), the dissipated specific orbital energy is only 10% of $E_{\rm circ}$

$$E_{\rm circ} = \frac{GM_{\rm BH}}{4r_{\rm p}}$$

Just enough to power the radiation during the simulated period.

The debris forms an extended eccentric accretion flow with eccentricity $\approx 0.4 - 0.5$

To fully circularize, $> 30t_0$



Outflow?

The shocked gas expand outwards quasi-symmetrically, **marginally bound, and eventually falls back**

- Radiation pressure gradient built by shock heating
- Deflection caused by stream-stream collision

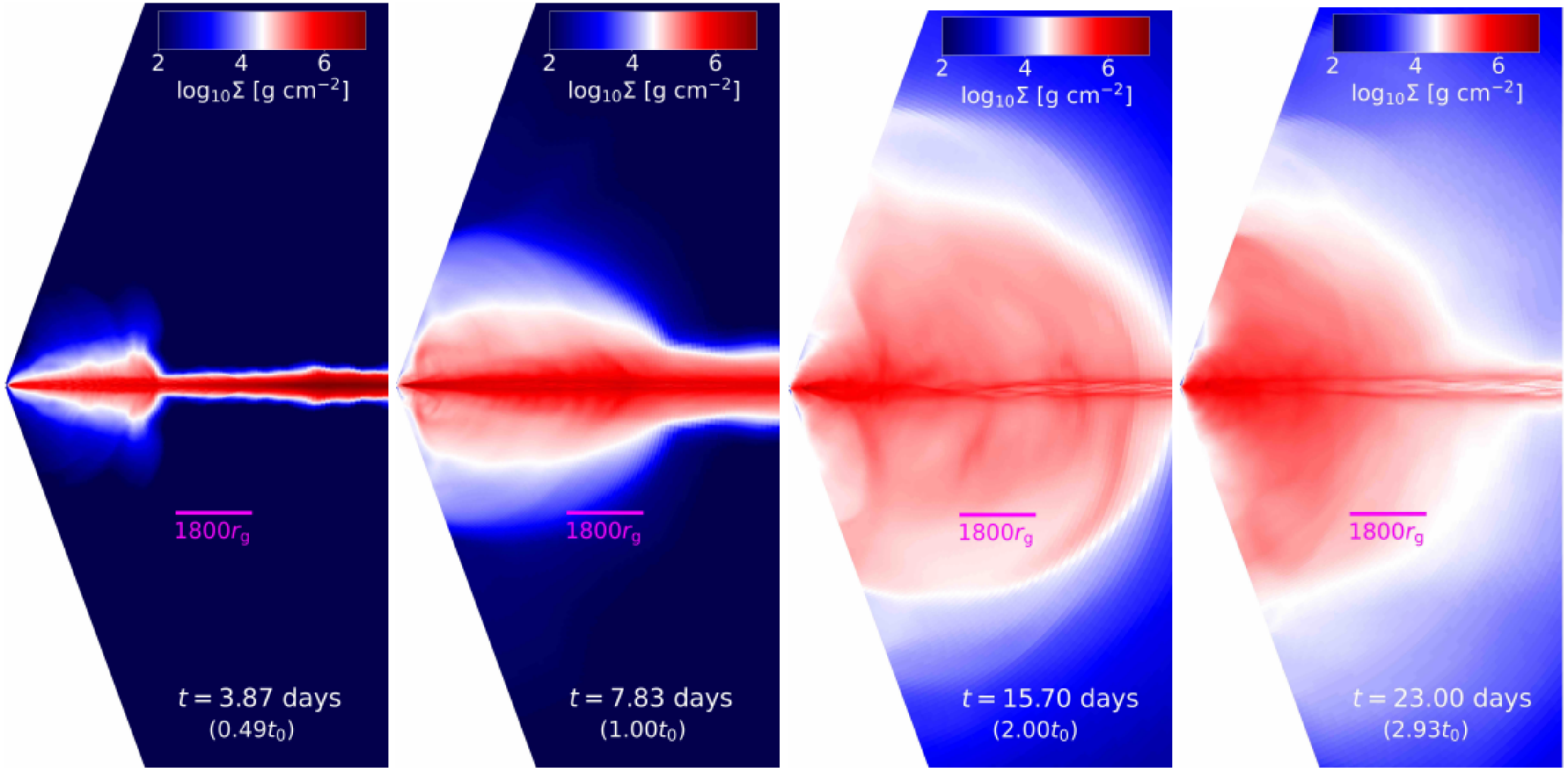


Figure 6. The azimuthally integrated density distribution at $t/t_0 = 0.5$, 1, 2, and 3.

Photosphere radius

Thermalization photosphere

$$\sqrt{\tau_{\rm T}\tau_{\rm ff}} \simeq 1$$

Generally quasi-spherical in shape, but also depend on the azimuthal angle Φ

$$\text{At } t = t_0, \qquad r \simeq 4000 - 5000 r_{\rm g}.$$

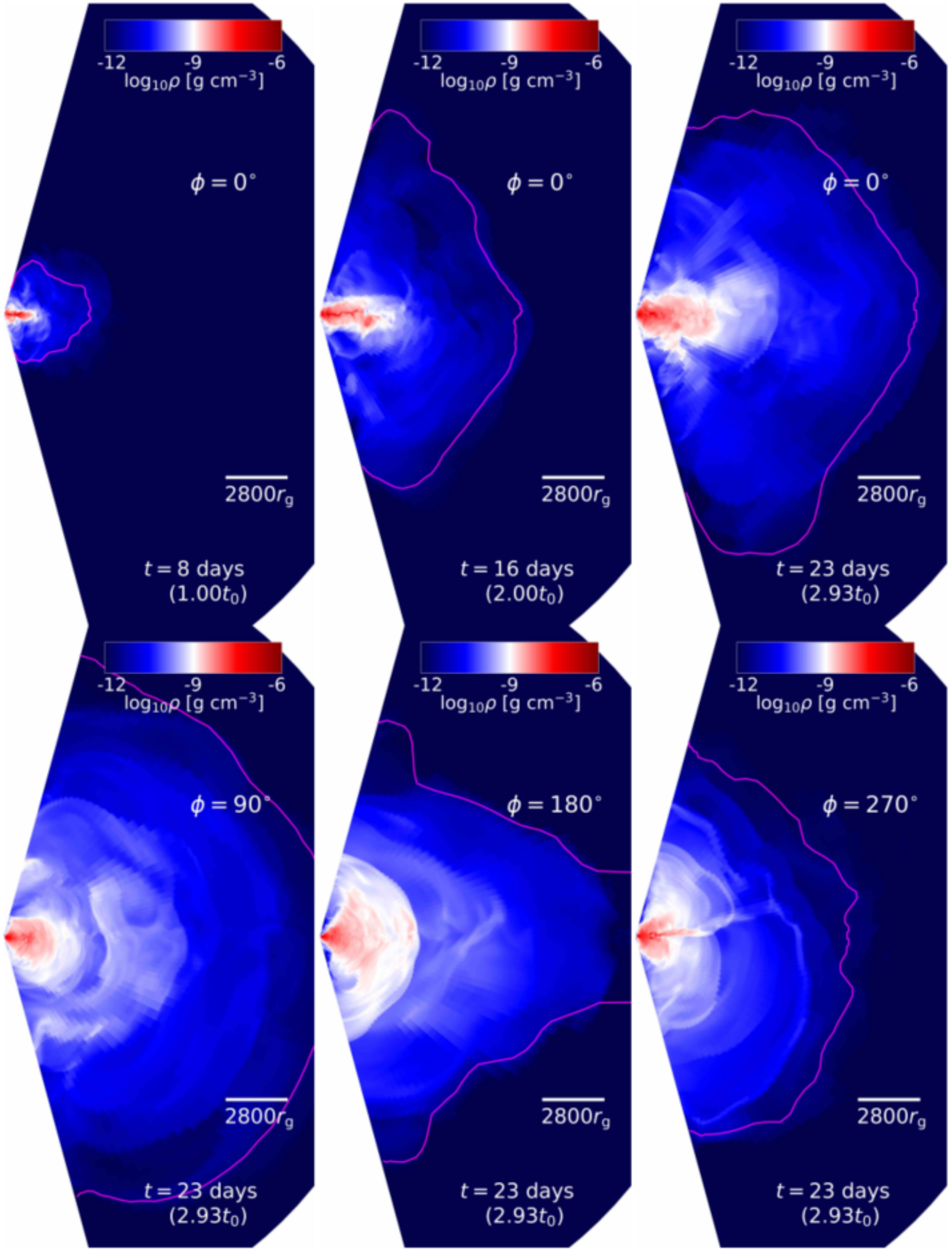
$$t = 2t_0 \qquad 9000 - 10000 r_{\rm g}$$

$$t = 3t_0 \qquad \simeq 12000 r_{\rm g}$$

$$r_g = 1.48 \times 10^{10}\,\mathrm{cm}$$

$$L = \int_0^{2\pi}\int_{\theta_c}^{\pi-\theta_c}\int_{r=r(t_{\rm cool}<t)}^{r=r(\tau=1)} \frac{aT^4}{t_{\rm cool}} r^2 \sin\theta dr d\theta d\phi,$$

We estimate that the peak luminosity is $\simeq 10^{44}$ erg/s $\simeq 10 L_{\rm Edd}$, which occurs at $t \simeq t_0$. This is roughly the mean rate of thermal energy creation during the simulation. The photospheric temperature distribution at

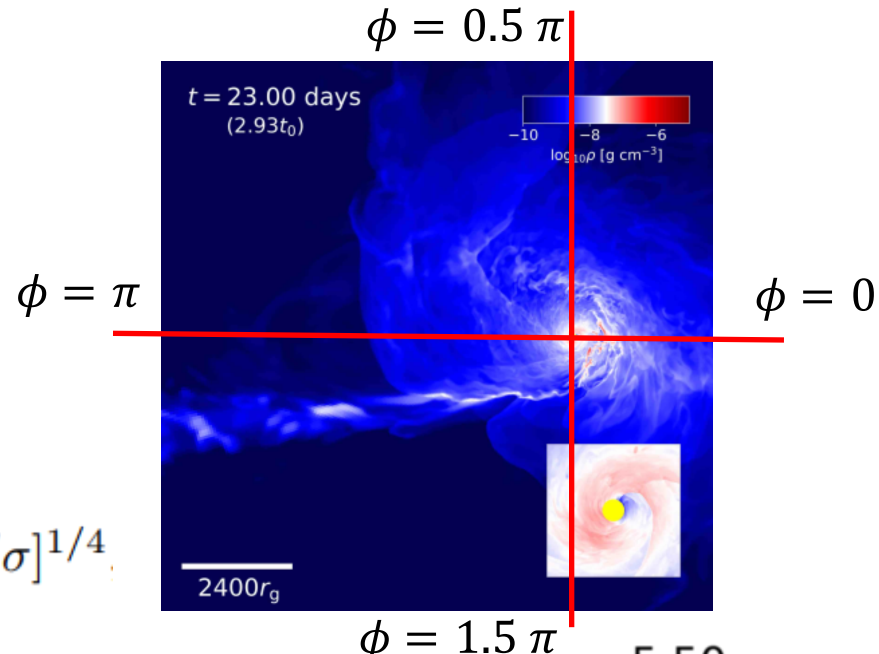


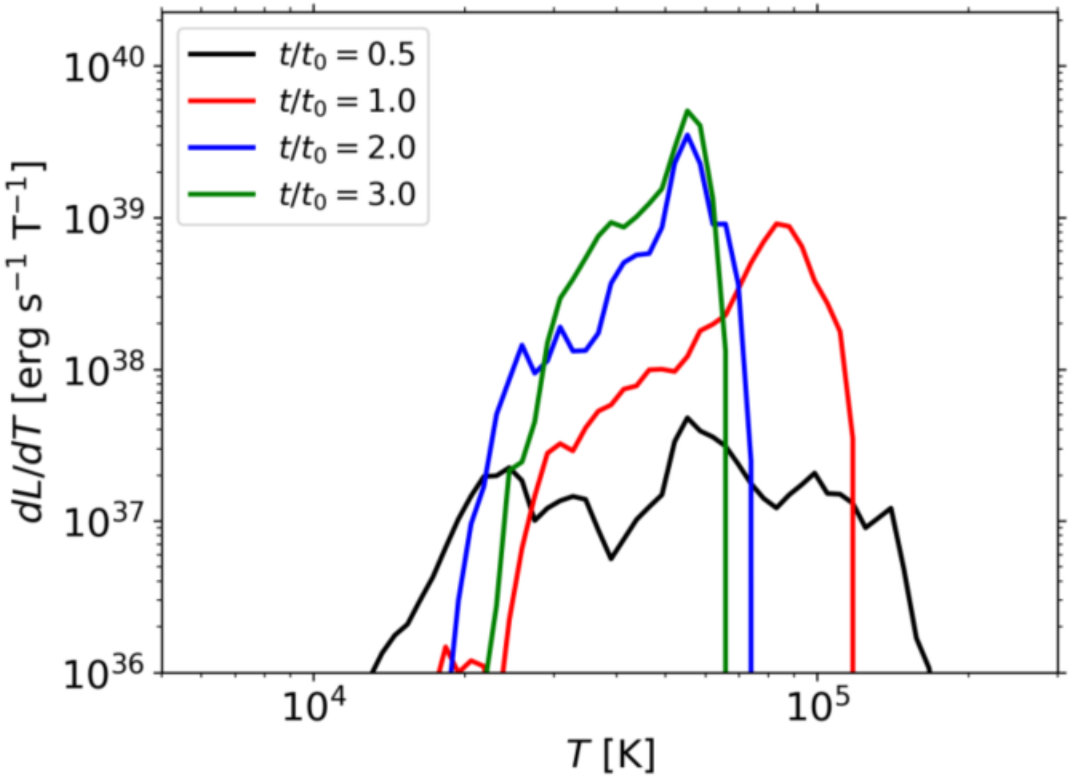
Temperature

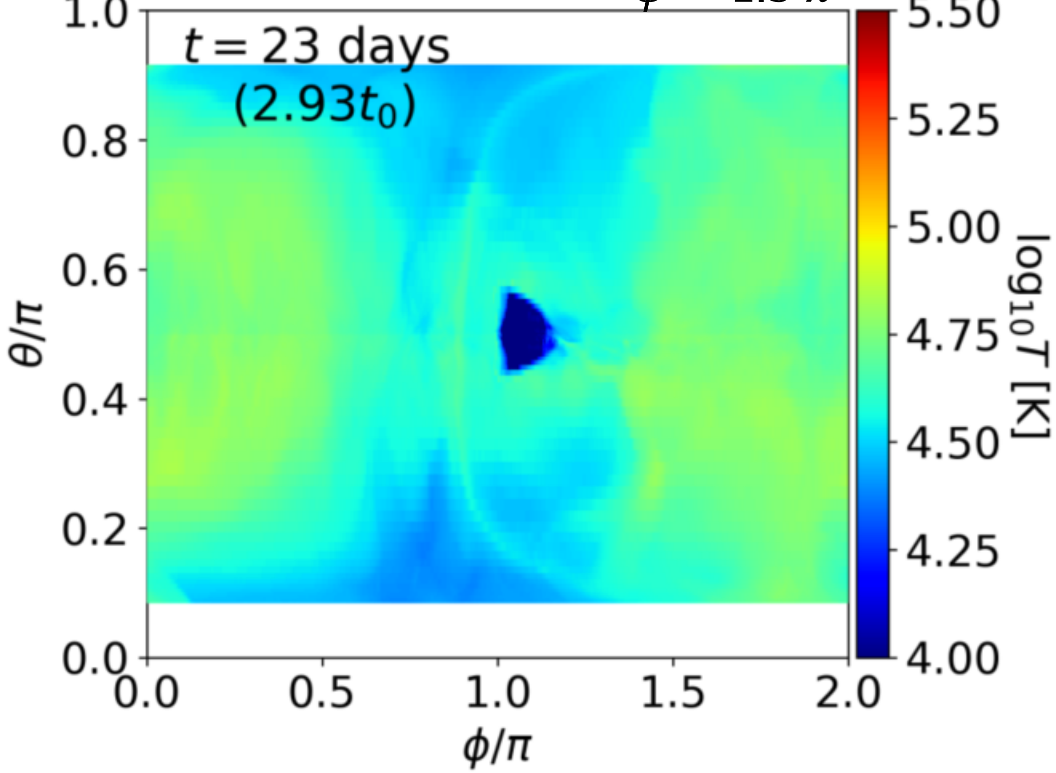
Interesting points:

- Multi-temperature photosphere
- Observed temperature depends on view angle?

$$T_{\rm ph} = [(dL/dA)/\sigma]^{1/4}$$







Conclusions

1. Shocks power the TDE radiation (at least in the simulated period)
2. Swift “circularization” does not happen, (need at least $30t_0$)
3. Radiatively efficient accretion of most of the debris mass onto the black hole certainly did not happen.
4. The initially bound debris does not become unbound.