Radiation hydrodynamics simulations of super-Eddington mass transfer in close BH binaries

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in collaboration with

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Relativistic fluids around compact objects @ Warsaw, 2025/5/5-9

Binaries undergoing super-Edd. mass transfer

Ultra-luminous X-ray (ULX) binaries

- $L_X > 10^{39}$ erg/s （**Brighter than Ledd for stellar-mass BHs**）

- Massive donor with > 10 $M_\odot$ can cause super-Edd. mass transfer

$$\dot{M}_d \sim -\frac{M_d}{\tau_{KH}} \sim 10^{-2}\ M_\odot yr^{-1} \sim \mathbf{10^4}\ \dot{M}_{Edd} \quad \text{for } M_d \sim 10\ M_\odot,\ \tau_{KH} \sim 10^3\ \text{yr}$$

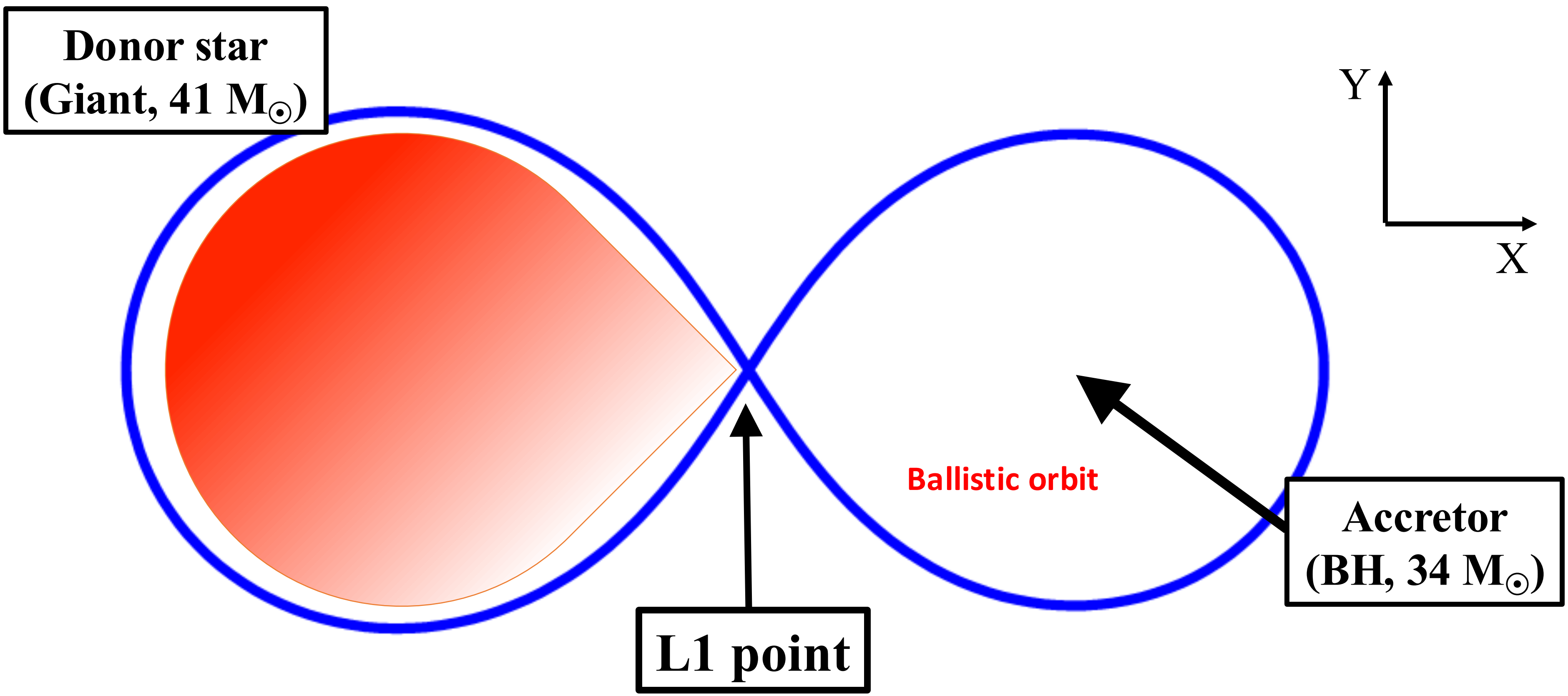
- Most ULXs have **fast outflows with ~ 0.1 c.**

Purpose of this study

1. Understand origin of outflows in ULXs（P_{rad}-driven? ）
2. Discuss the long-term evolution of ULXs

3D & 2D RHD simulations

- Suppose a BH+RGB star binary undergoing stable mass transfer (Inayoshi+2017)
- $M_1 = 34\ M_{sun}$, $M_2 = 41\ M_{sun}$, $a = 36\ R_{sun}$, $P = 2\pi/\Omega \sim 3$ day
- Mass transfer rate: $\dot{M}_T \sim 10^4\ \dot{M}_{Edd} \sim 7.5 \times 10^{-3}\ M_{sun}/yr$



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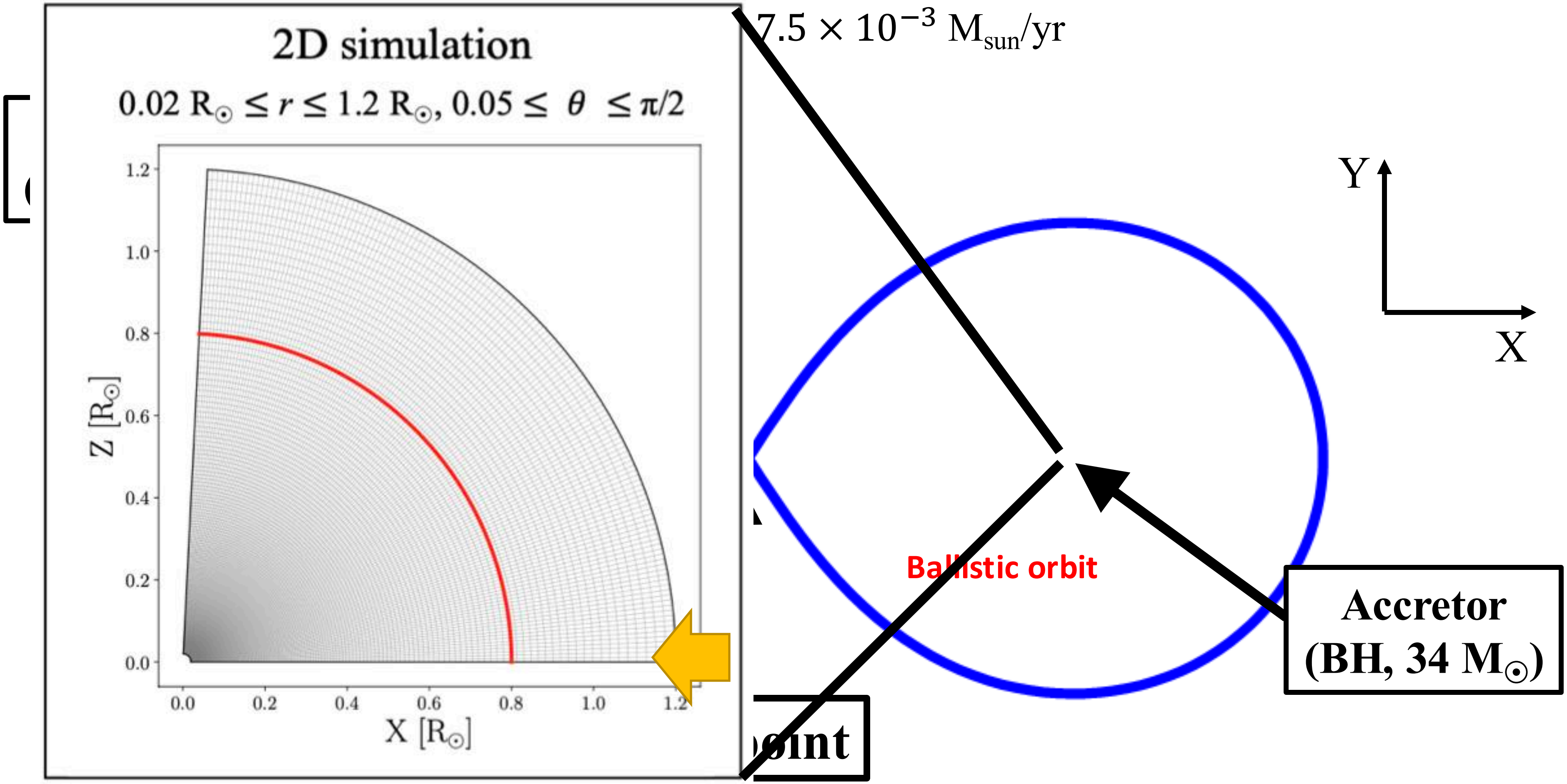
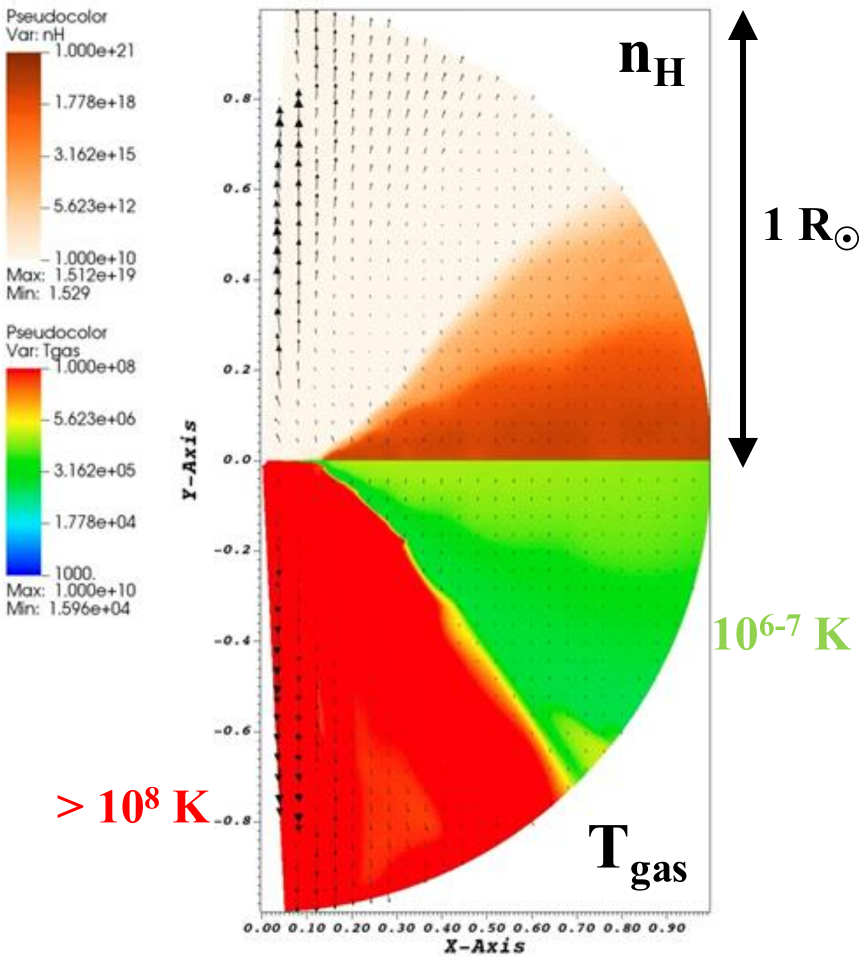
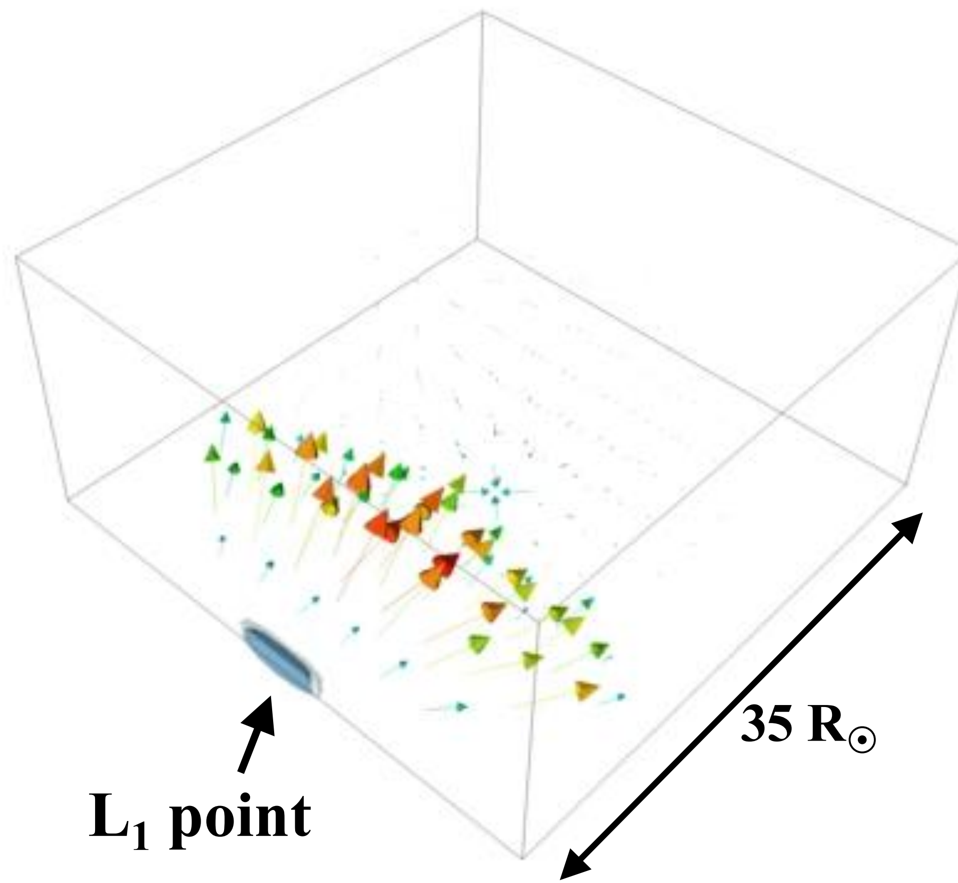


Simulation results

Inner region
$r = 0.01\text{-}1\ R_\odot$ ($\sim 100\text{-}10^4\ R_g$)

Outer region
$r = 0.8\text{-}17.3\ R_\odot$ ($\sim 10^4\text{-}10^5\ R_g$)





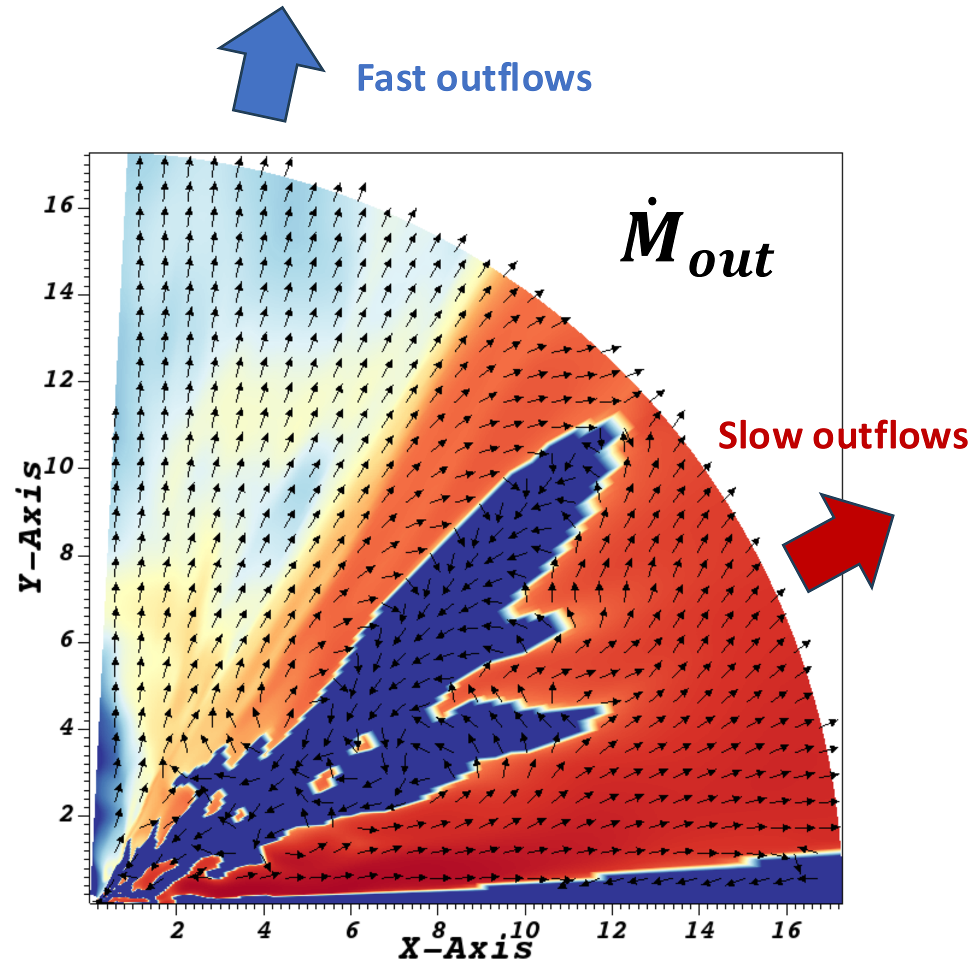
Properties of outflows

Fast outflows (~ 0.1 c)

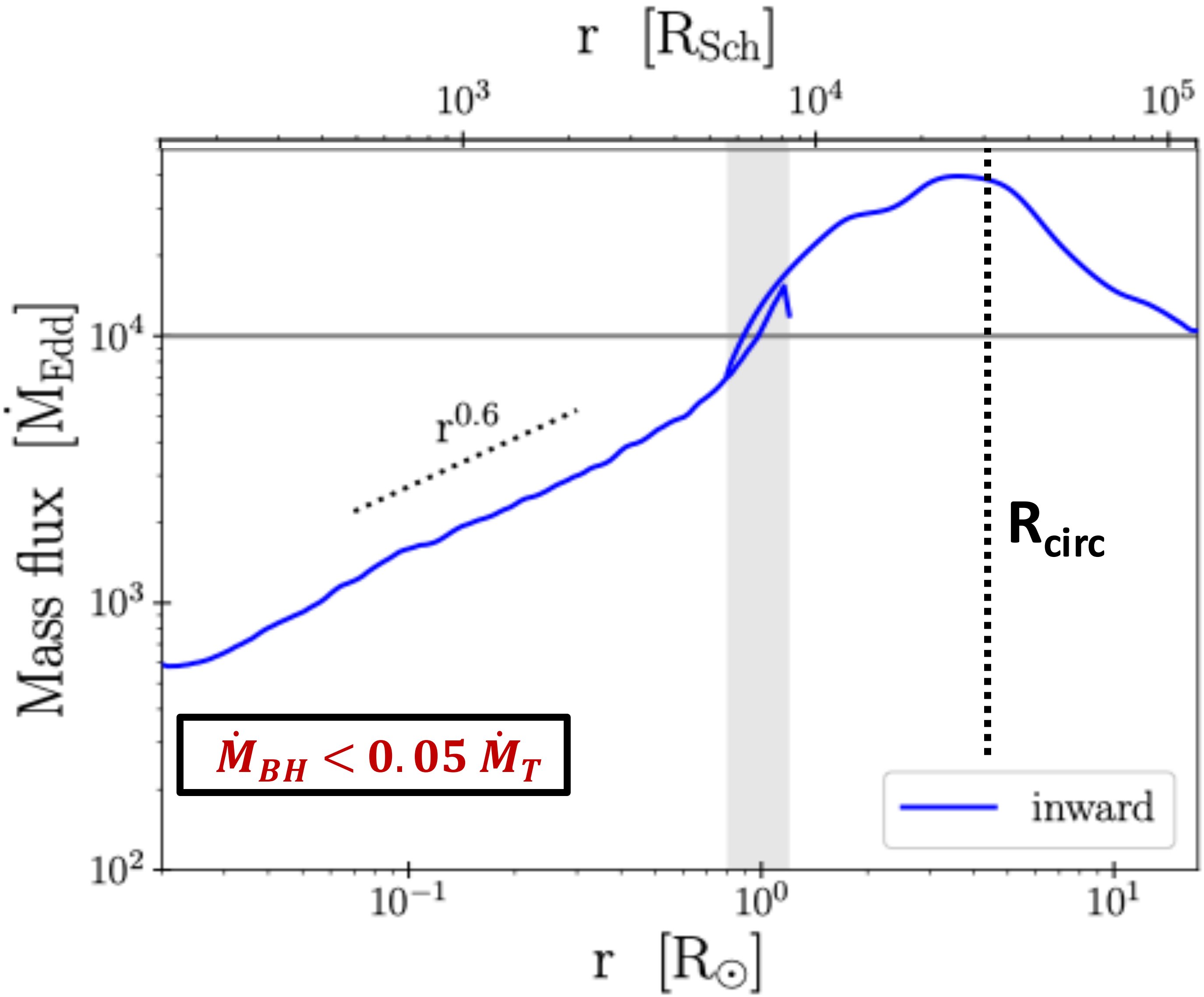
- Toward polar regions
- Large energy, and **small mass fluxes**
- similar to fast outflows observed in ULXs.

Slow outflows (< 1000 km/s)

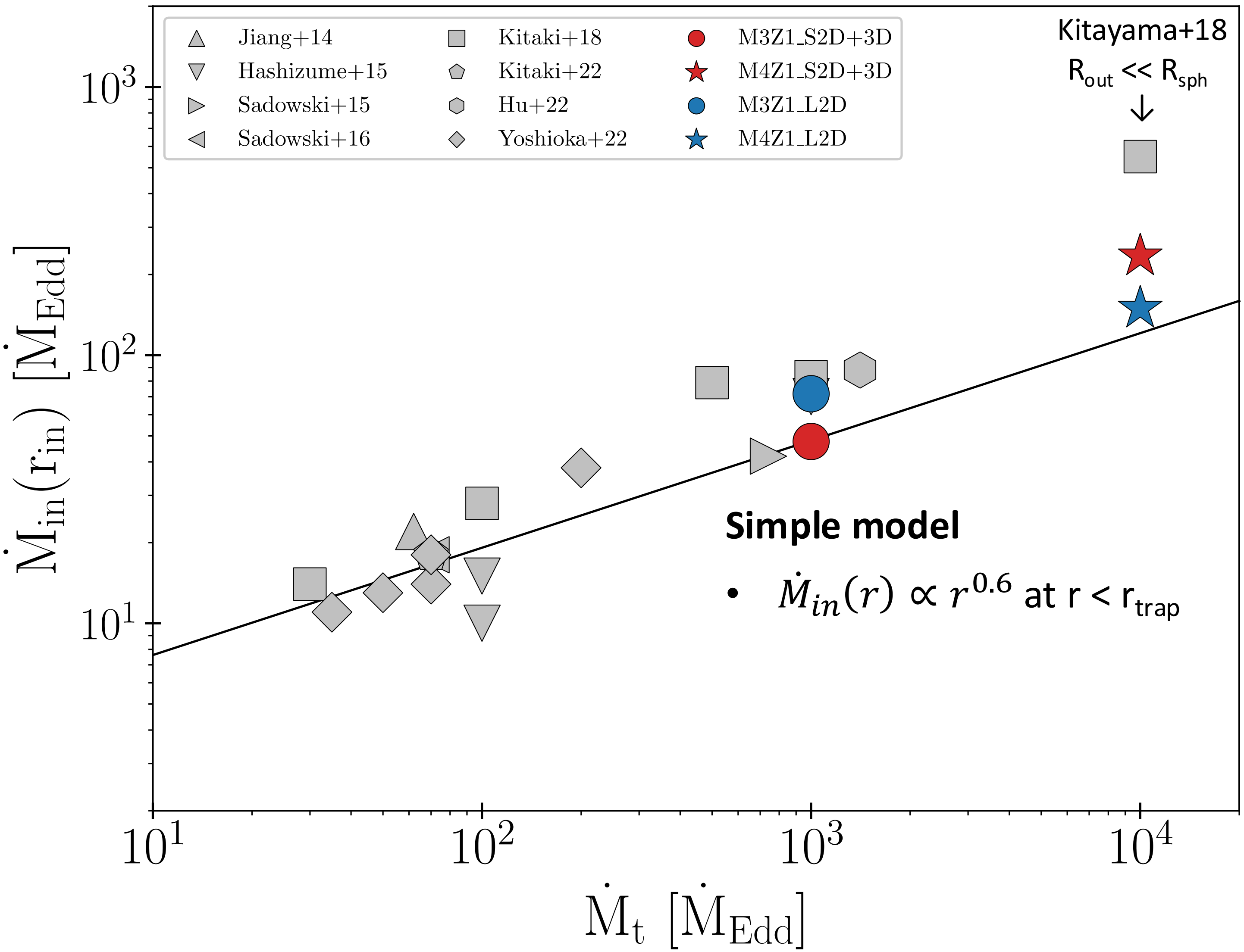
- Near equatorial plane
- Small energy, and **large mass fluxes**
- Convection in disk transports mass and energy outward, driving slow outflows.
- **Convection-Dominated Accretion Flow (CDAF; cf., Quataert & Gruzinov 2000)**



Radial profile of Inflow Rate



Comparison with previous RHD simulations

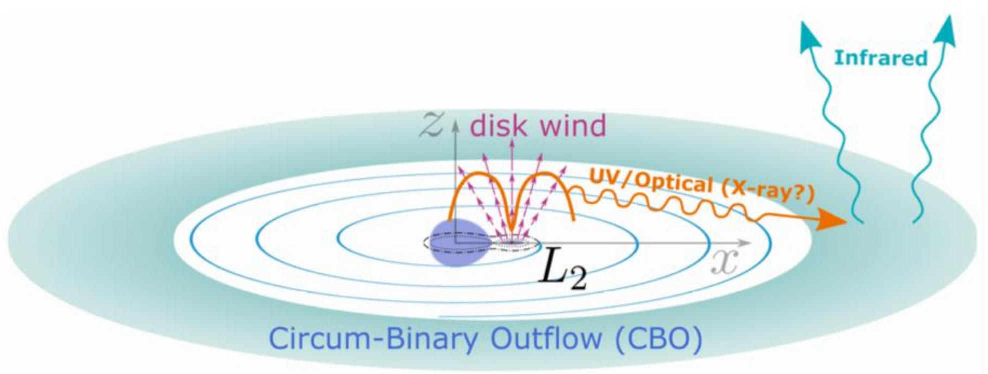


Simple model

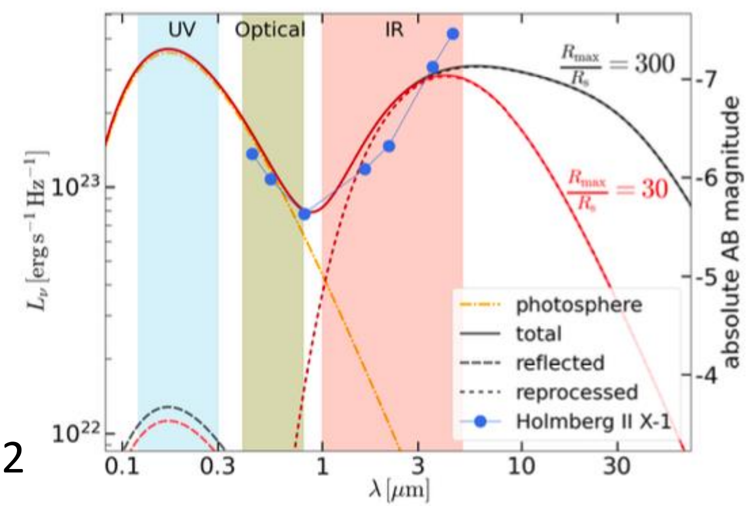
- $\dot{M}_{in}(r) \propto r^{0.6}$ at r < r_{trap}

Circum-binary disk (CBD) formation

- ✓ Over 90 % of slow outflows in our simulations are still gravitationally bound.
  - ➢ **Slow outflows will cool down and form a circum-binary disk.**
- ✓ Over 30 % of ULX binaries exhibit IR excess, indicating the presence of CBD (e.g., Heida+2014, Lopez+2017, Lau+2019, Lu+2022).
  - ➢ **Indirect evidence of radiation pressure-driven outflows in ULXs?**



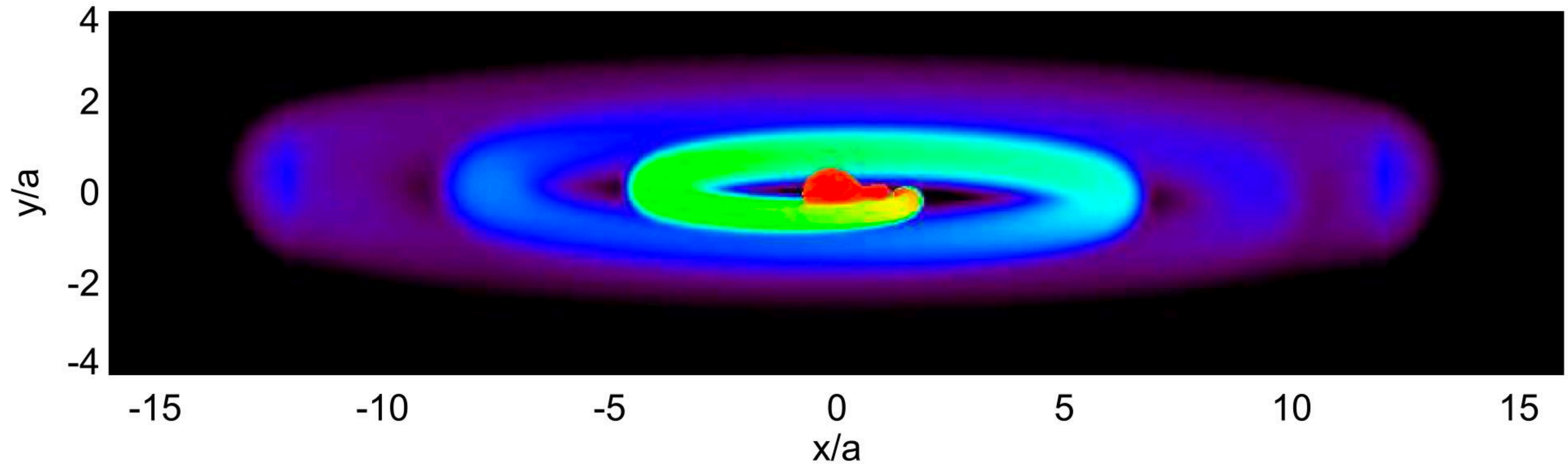
Lu+2022



Evolution of Circum-binary disk

- ✓ CBD gradually expands due to the tidal torque from the binary.
- ✓ **The binary loses its angular momentum via interaction with CBD efficiently.**

HD simulation of CBD by Pejcha+2017



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Numerical calculation by Shu+1979

M_{II}/M_I	$\mathscr{H}$	$\mathscr{E}_i$	$\mathscr{E}_f$	$\mathscr{J}_i$	$\mathscr{J}_f$	ϖ_{max}
0.001	−1.519	−0.375	−0.339	1.145	1.180	1.82
0.05	−1.673	−0.171	−0.023	1.502	1.650	34.6
0.064	−1.692	−0.161	0.000	1.532	1.692	∞
0.10	−1.726	−0.148	0.037	1 578	1 763	[illegible]
0 20	−1.768	[illegible]	0.072	1.616	1.840	[illegible]
0.30	−1.780	[illegible]	0.072	1.609	1.852	[illegible]
0.40	−1.779	−0.193	0.061	1.587	1.840	[illegible]
0.50	−1.774	−0.214	0.046	1.560	1.819	[illegible]
0.60	−1.766	−0.232	0.029	1.533	1.795	∞
0.70	−1.756	−0.250	0.013	1.506	1.770	∞
0.78	−1.749	−0.263	0.000	1.486	1.749	∞
0.80	−1.747	−0.266	−0.002	1.481	1.744	498.
0.90	−1.737	−0.280	−0.017	1.458	1.720	57.3
1.00	−1.728	−0.292	−0.031	1.436	1.697	30.7

Unbound!

Final SAM of outflow

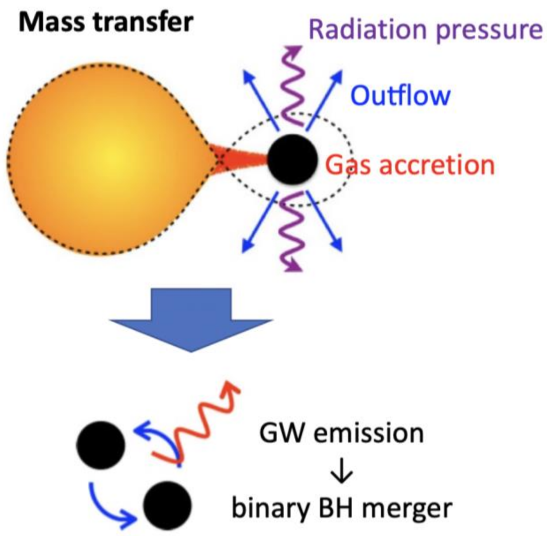
Implication for orbital evolution of binaries

a: Orbital separation M_a, M_d: Masses of the accretor and donor

l_{bin}, l_{loss}: Specific angular momentum of binary and removed by outflows

$$\frac{\dot{a}}{a} = -2\frac{\dot{M}_{\rm d}}{M_{\rm d}}\left[1-\beta\frac{M_{\rm d}}{M_{\rm a}}-(1-\beta)\left(\gamma_{\rm loss}+\frac{1}{2}\right)\frac{M_{\rm d}}{M}\right].$$

where $\boldsymbol{\beta \equiv \dot{M}_a/\dot{M}_d}$ and $\boldsymbol{\gamma_{loss} \equiv l_{loss}/l_{bin}}$



Mass accretion rate (DT+24)

$$\dot{M}_{\rm in} \approx \begin{cases} \dot{M}'_{\rm t} & (r > R'_{\rm sph}) \\ \dot{M}'_{\rm t}(r/R'_{\rm sph})^{0.6} & (r_{\rm t} \le r < R'_{\rm sph}) \\ \dot{M}_{\rm in}(r_{\rm t}) & (r < r_{\rm t}) \end{cases},$$

CBD mass loss scenario: $\gamma_{loss} \sim 1.44 \times M^2/(M_d M_a)$

(Shu+1979, Pejcha+2017)

New channel for common envelope evolution

Slow outflows under super-Edd. MT removes angular momentum efficiently.

→ Orbital separation becomes so small that the binary undergoes common envelope (CE) evolution.

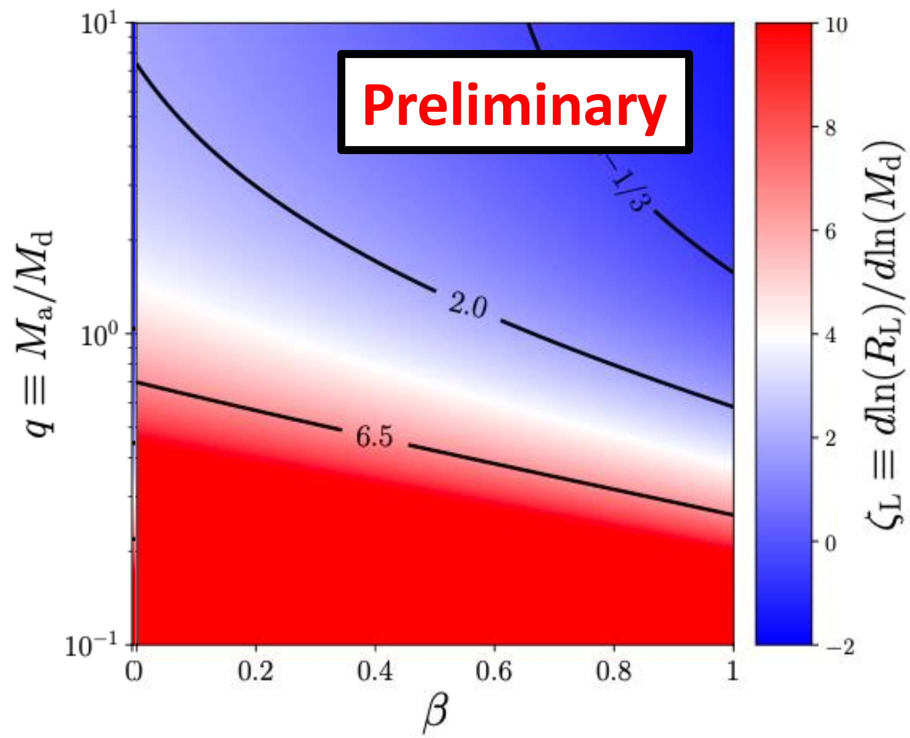
→ **ULX binaries are more likely to enter CE phases than previous expectation.**

Stability condition of mass transfer

$$\zeta_{\rm ad} \equiv \left(\frac{\partial \log R}{\partial \log M}\right)_{\rm ad} \qquad \zeta_{\rm L} = \frac{d\log R_{\rm L,1}}{d\log M_1},$$

$\zeta_{\rm ad} < \zeta_{\rm L}$ => dynamically unstable

=> $q \equiv M_a/M_d < q_{crit}$



Summary

- ✓ We have conducted 3D and 2D RHD simulations of super-Edd. mass transfer in binaries.
- ✓ We have explored global inflow/outflow structure covering from the L1 point to $r \sim 100\ r_g$ from the central BH.
- ✓ Convective motions in the disk transport mass and energy outward and generate slow outflows, which dominate the mass loss from the binary.
- ✓ Over 90 % of outflows are still gravitationally bound, such that they would cool down and form circum-binary disk, which is in good agreement with the observational fact in ULXs.
- ✓ Our simulation results are useful to describe long-term orbital evolution of binaries and formation mechanisms of close BBHs.