（初代星起源の）連星質量輸送に伴う輻射駆動円盤風の生成

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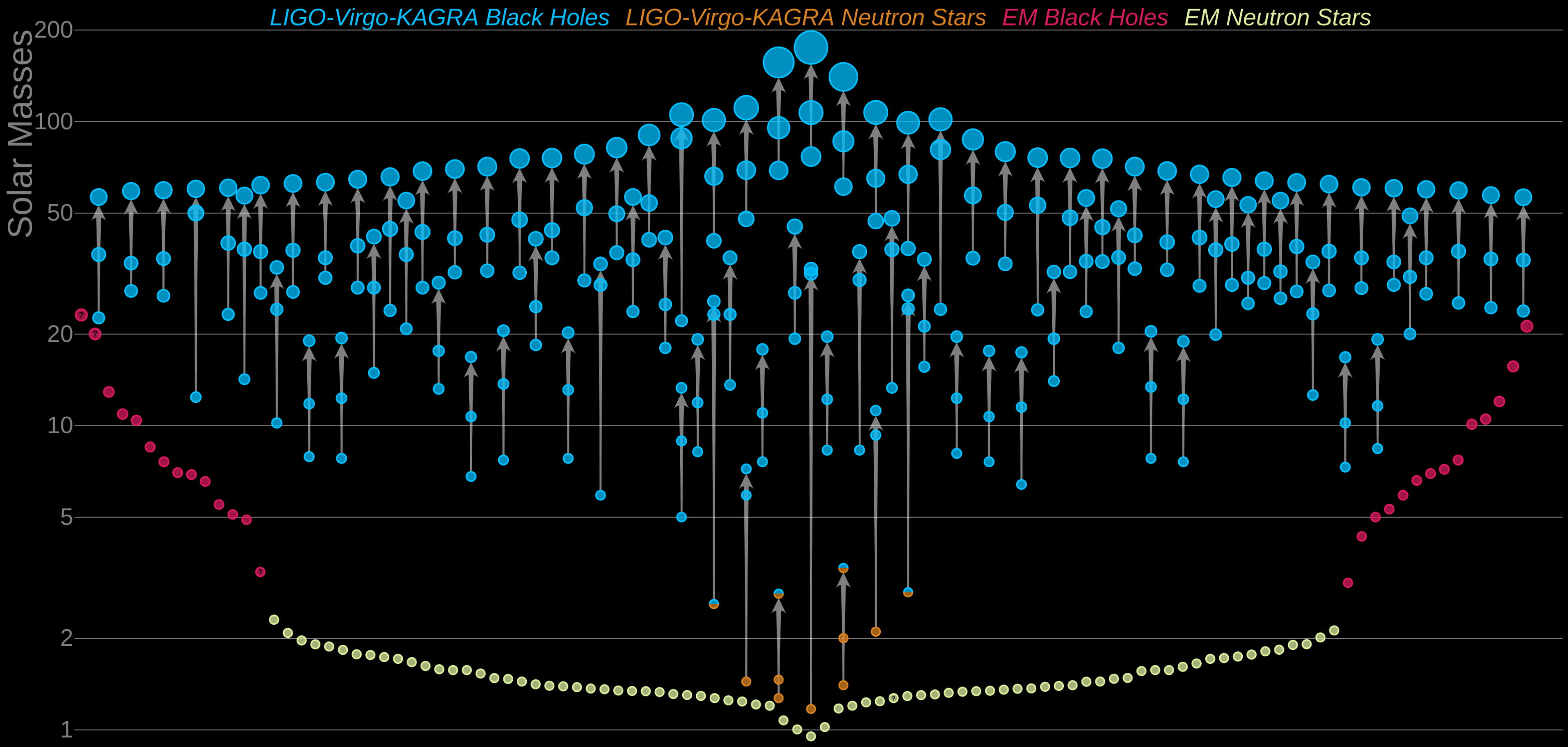
Masses in the Stellar Graveyard



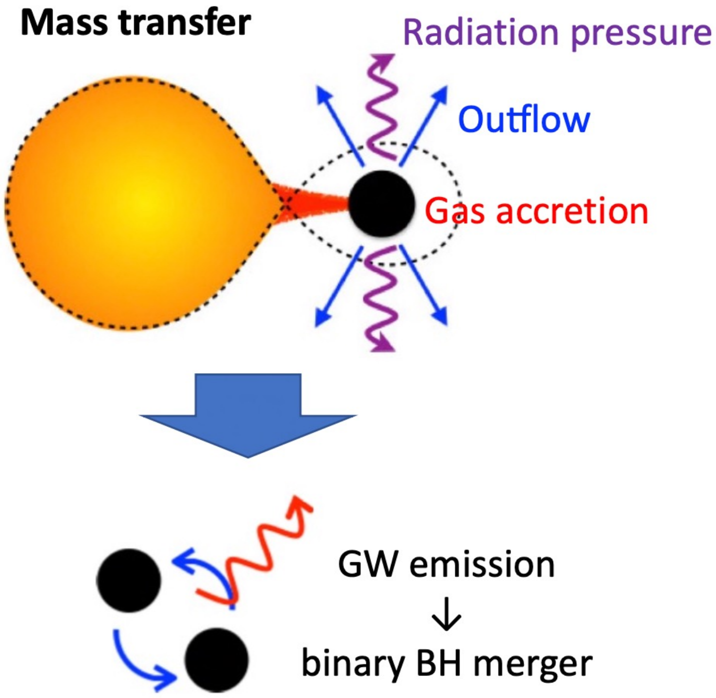
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Roche lobe overflows in PopIII binaries

- PopIII stars are promising origin of merging BBHs
    - ✓ massive (e.g., Hirano+14)
    - ✓ no significant mass loss (e.g., Spera+15)
    - ✓ binary formation (e.g., Sugimura+20)

- Outflows during RLO shrink the binary separation.
    - ✓ tight BBH formation

- Studying RLOs is also important to understand
    - ✓ X-ray binaries, especially HMXBs and ULXs
    - ✓ Thermal evolution of the early universe
    - ✓ Chemical enrichment in the early universe



Key question

Orbital evolution driven by mass transfer

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

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

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

Mass transfer rate

For $M_d \sim 10\ M_\odot$, $\tau_{KH} \sim 10^3$ yr

$$\dot{M}_\mathrm{d} \sim -\frac{M_\mathrm{d}}{\tau_\mathrm{KH}} \sim 10^{-2}\ \mathrm{M_\odot yr^{-1}} \sim \boldsymbol{10^4\ \dot{M}_{Edd}}$$

- Mass transfer rates are usually super-Eddington for stellar-mass BHs.
- How much mass and angular momentum is removed by radiation-driven winds?

Simulation code

- ✓ PLUTO 4.1 (Mignone et al. 2007)
  - We improved FLD module incorporated in Kolb et al. (2013)
- ✓ Basic equations

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho v_i) = 0,$$

$$\frac{\partial \rho v_i}{\partial t} + \frac{\partial}{\partial x_j}(\rho v_i v_j) = \rho g_i - \frac{\partial P_{ij}}{\partial x_j} ,$$

$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial x_i}(E v_i + v_j P_{ij} + F_i) = \rho v_i g_i + \rho\, \Gamma_{\mathrm{irr}},$$

$$\frac{\partial E_{\mathrm{rad}}}{\partial t} = -\frac{\partial}{\partial x_i}(E_{\mathrm{rad}} v_i) - \frac{\partial v_j}{\partial x_i} P_{r,ij} - \frac{\partial F_i}{\partial x_i} + \kappa \rho c \left(a T^4 - E_{\mathrm{rad}} \right),$$

Stress tensor

$$P_{ij} = p\delta_{ij} + P_{r,ij} - \sigma_{ij}$$

p : Gas pressure

$P_{r,ij}$: Radiation pressure tensor

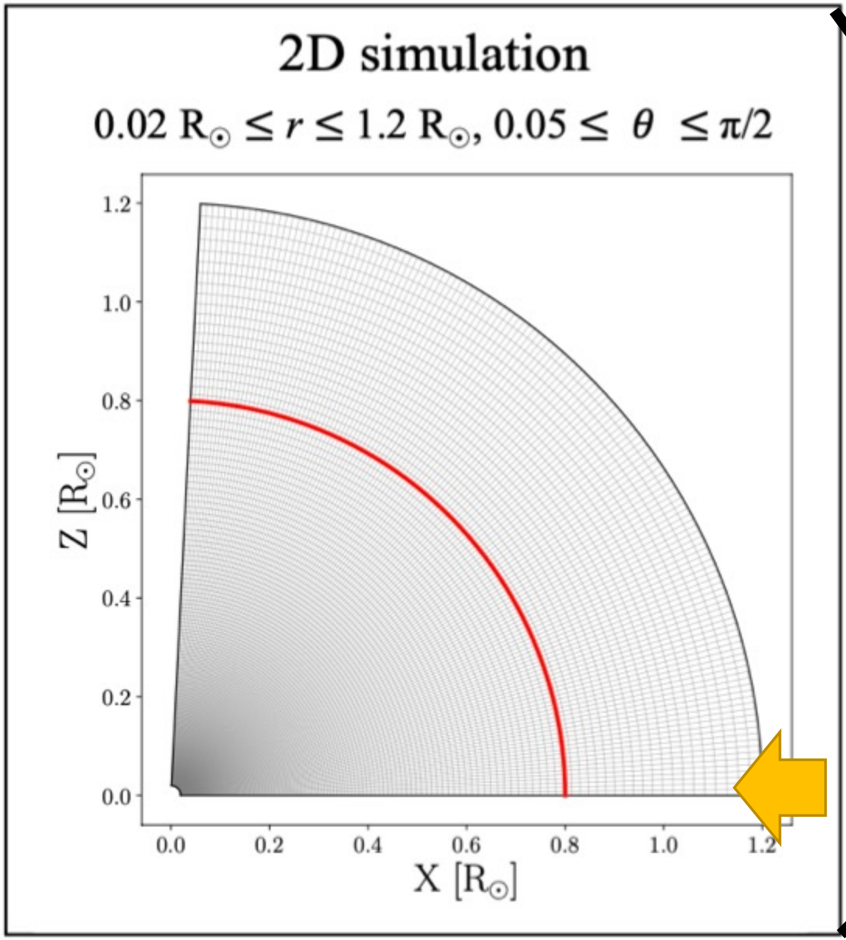
σ_{ij} : Viscous stress tensor

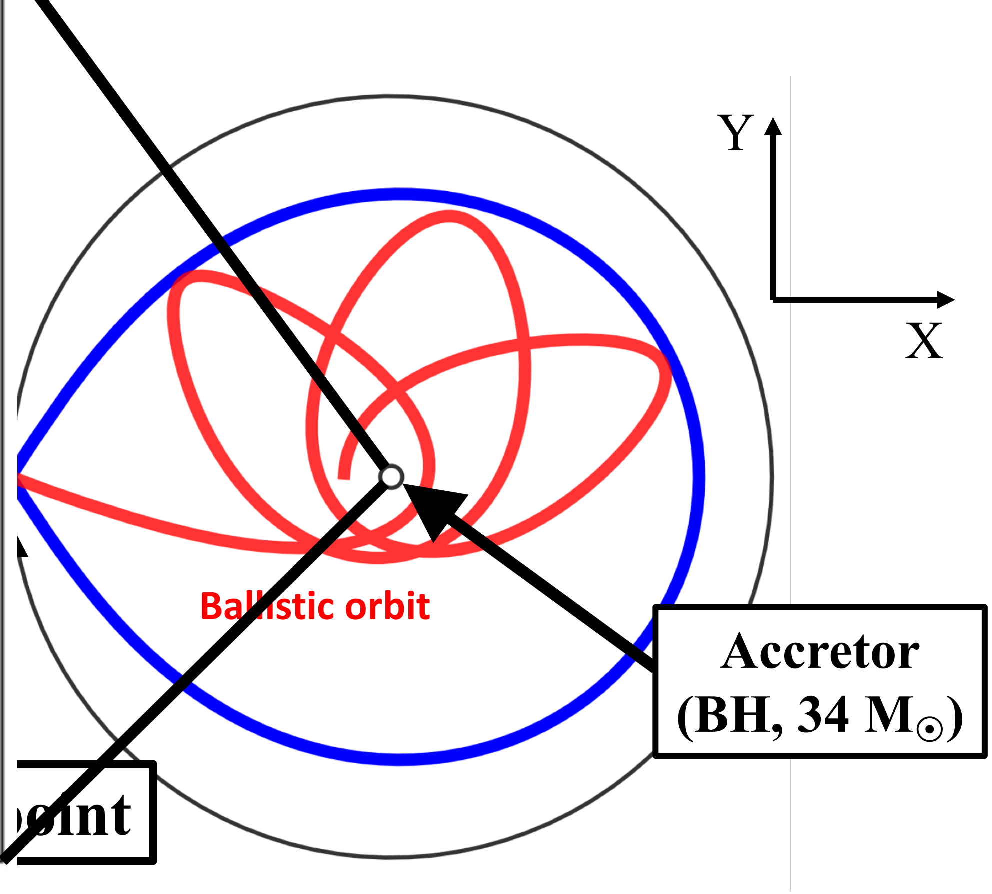
Up to *O(v/c)* terms are taken into account in the radiation energy equation.

3D & 2D RHD simulations

- Suppose a BH+PopIII 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

$7.5\times10^{-3}\ M_{sun}/yr$



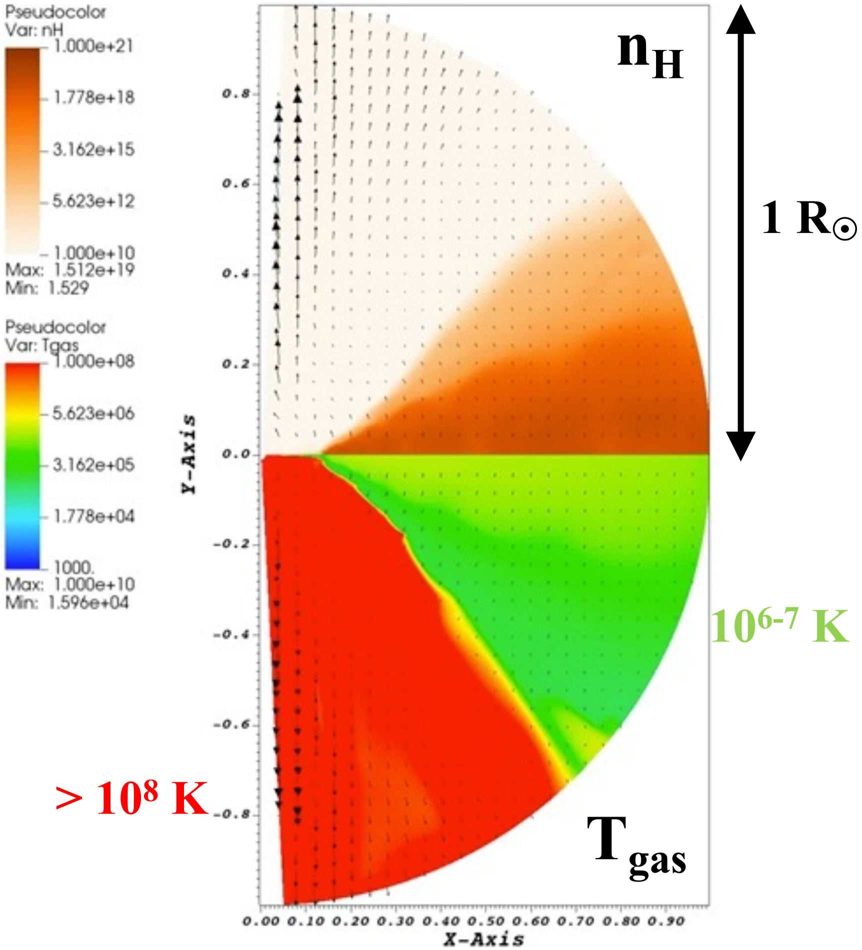


Accretor (BH, 34 M⊙)

Simulation results

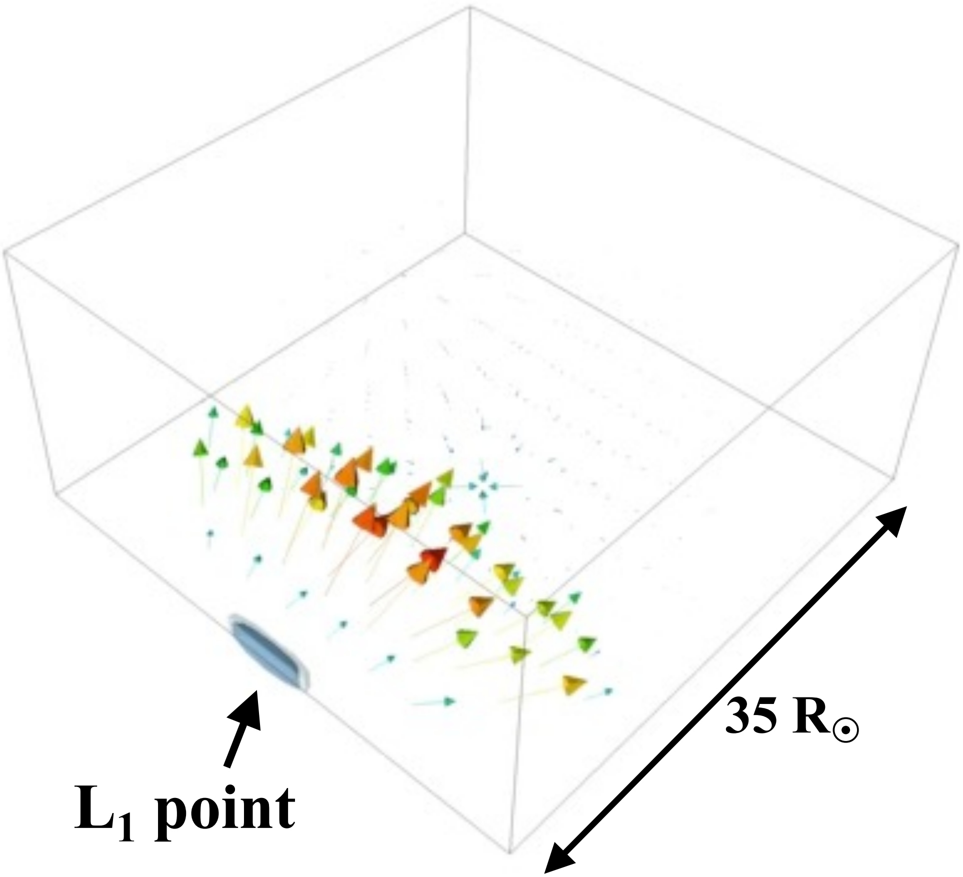
Inner region

r = 0.01-1 $R_\odot$ (~100-10^4 R_g)

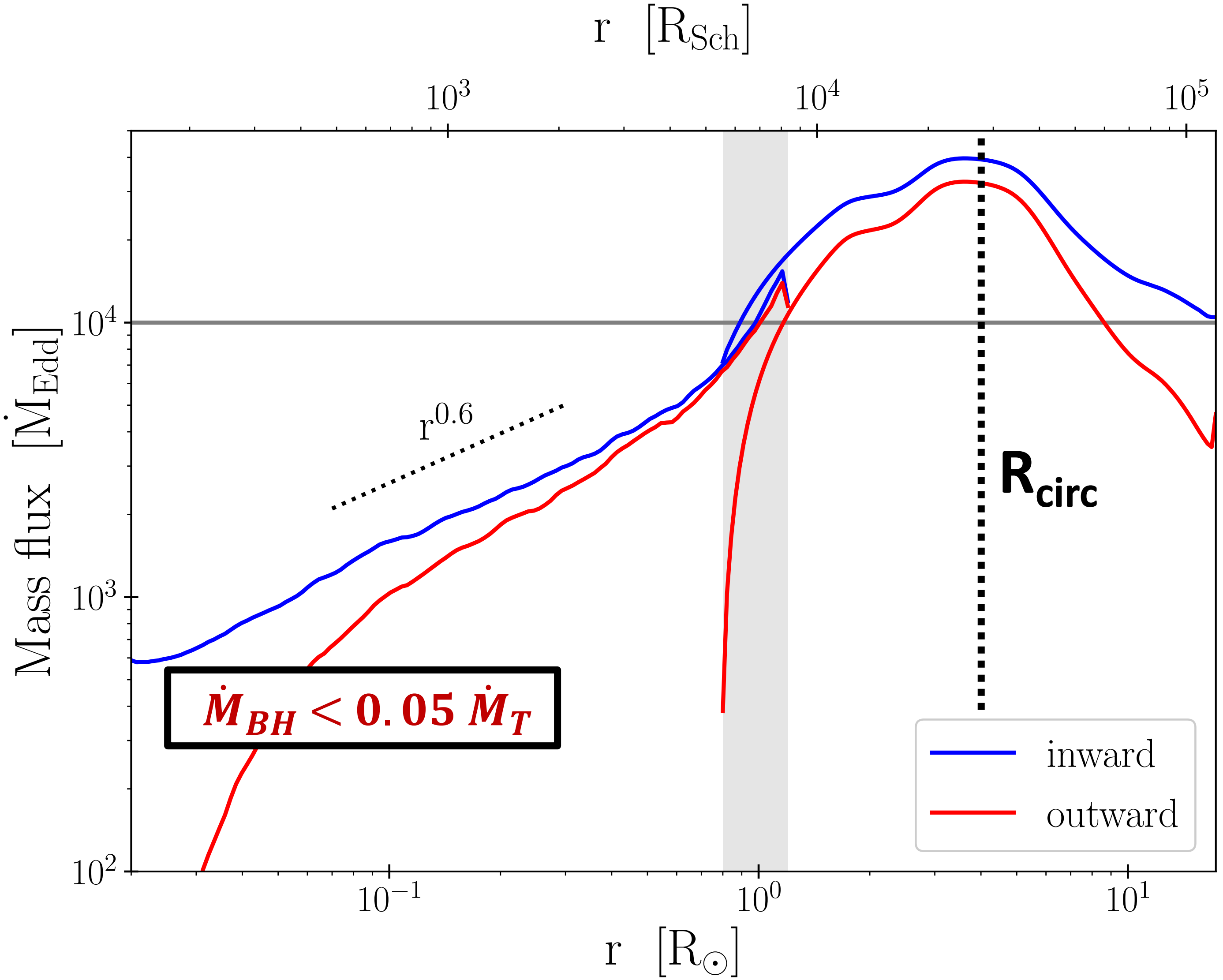


Outer region

r = 0.8-17.3 $R_\odot$ (~10^4-10^5 R_g)



Inward and Outward mass fluxes

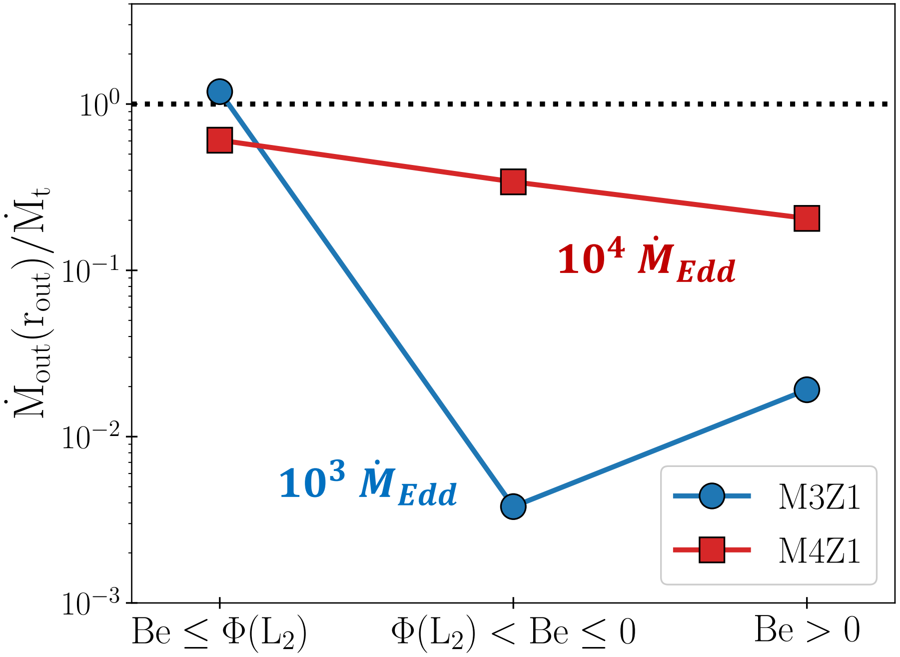


$\dot{M}_{BH} < 0.05\ \dot{M}_T$

Energetics of outflows

Bernoulli number

$$Be \equiv \frac{1}{2}v^2 + \Phi + h$$



$$\dot{M}_T = 10^4\ \dot{M}_{Edd}$$

20 %: Unbound outflows ($Be > 0$)

30 %: Marginally unbound ($0 > Be > \Phi_{L2}$)

- ✓ leak out from L2 point → circum-binary disk
- ✓ further accelerate by binary's torque
- ✓ possibly finally escape (Shu+79, Pejcha+17)

50 %: Bound outflows ($Be < \Phi_{L2}$)

- ✓ become failed winds (e.g., Kitaki+21)
- ✓ finally accrete on the BH? or become unbound outflows?

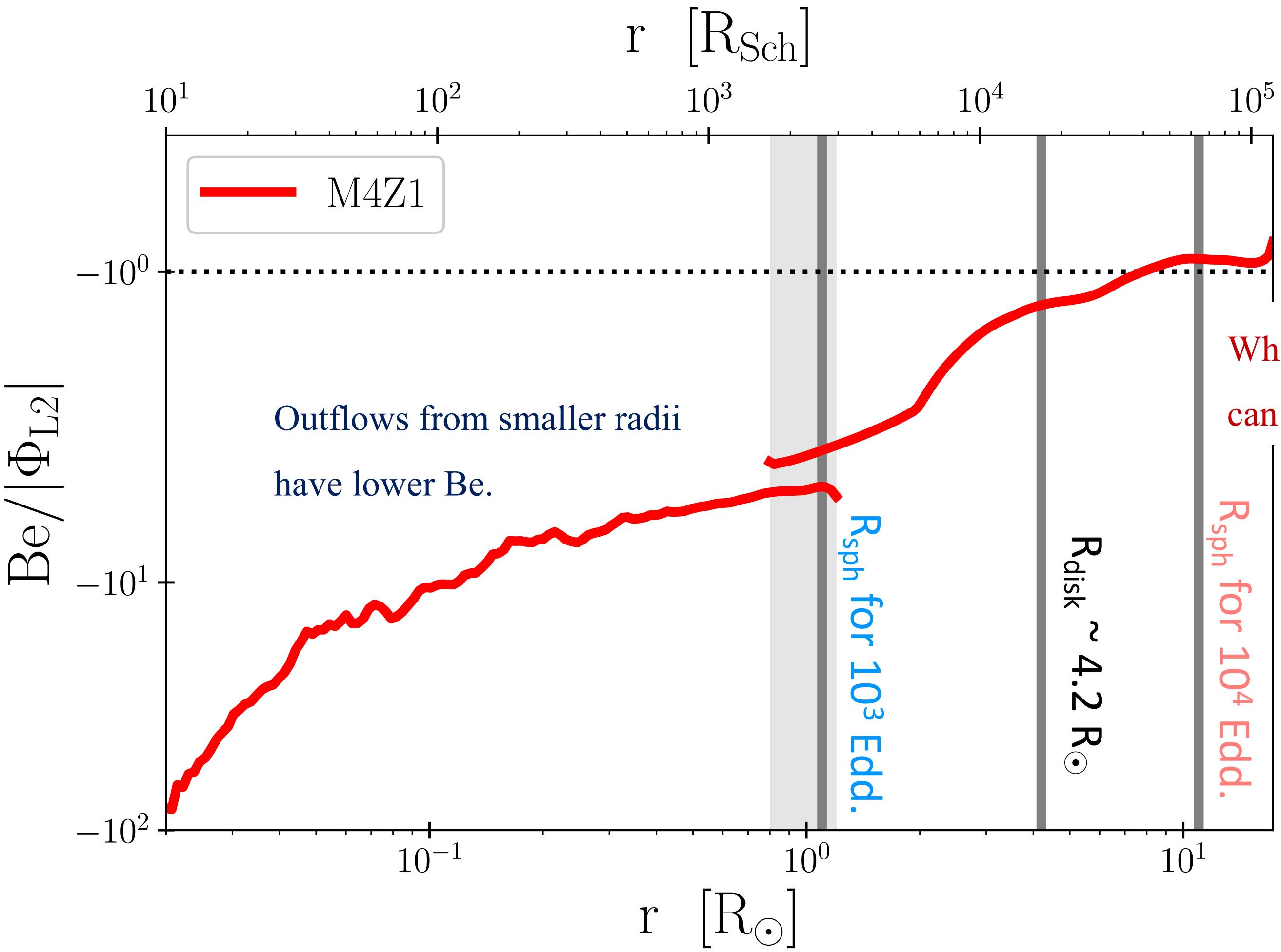
$$\dot{M}_T = 10^3\ \dot{M}_{Edd}$$

~ 100 %: Bound outflows

- ✓ Outflows cannot escape from the binary?

Spherization radius ($F_{vis} = F_{Edd}$)

$$R_{\rm sph} \;=\; \frac{3}{4}\,\frac{\dot{M}c^2}{L_{\rm Edd}}\,r_{\rm Sch} \;\sim\; 1.1\ {\rm R}_\odot \left(\frac{\dot{M}/\dot{M}_{\rm Edd}}{10^3}\right)\left(\frac{M_\bullet}{34\ {\rm M}_\odot}\right)^{-1}$$



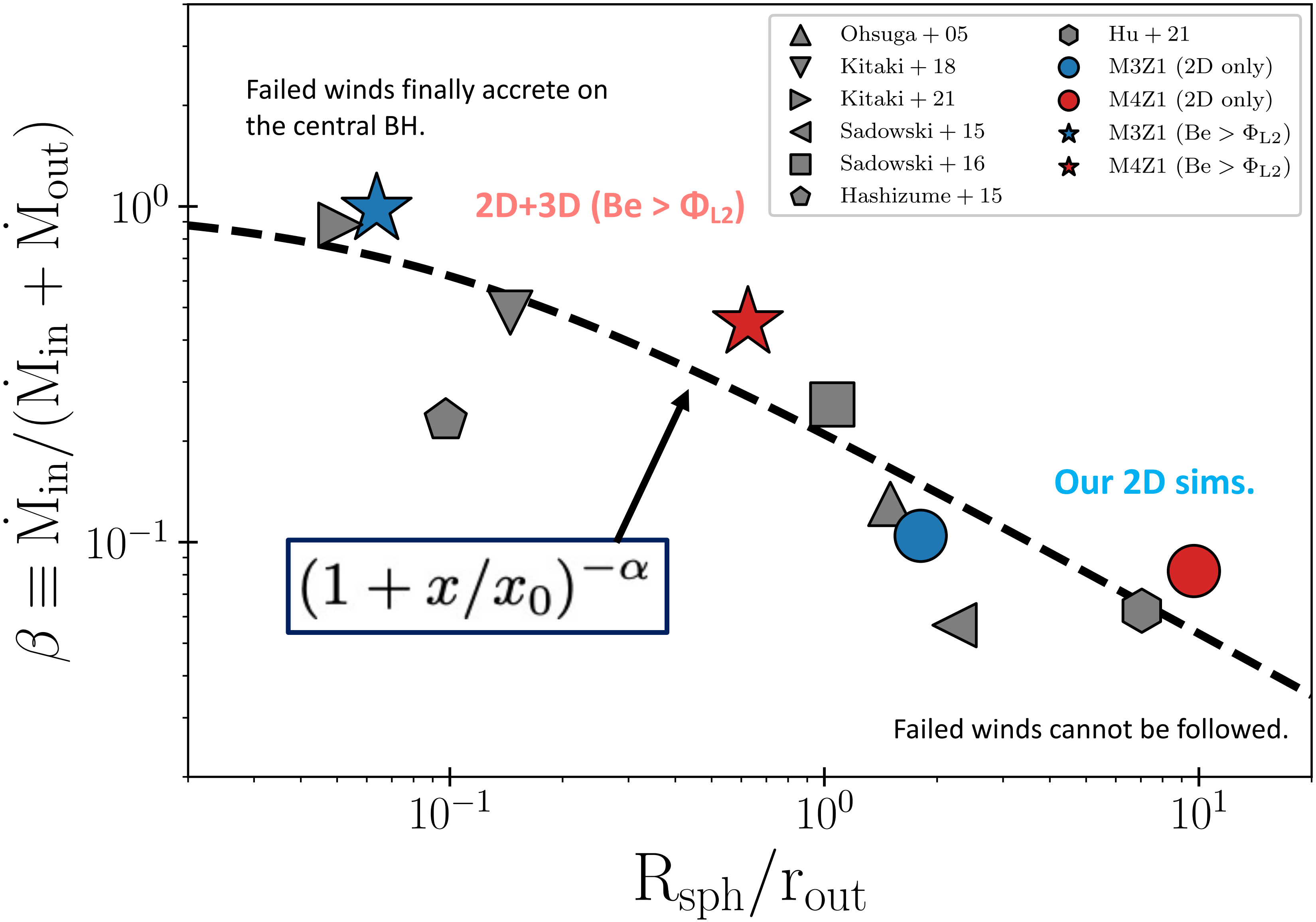
Outflows from smaller radii

have lower Be.

When $R_{\rm sph} > R_{\rm disk}$, outflows

can escape from L2 point.

Destination of Failed winds


Failed winds finally accrete on the central BH.

2D+3D (Be > Φ_{L2})

Our 2D sims.

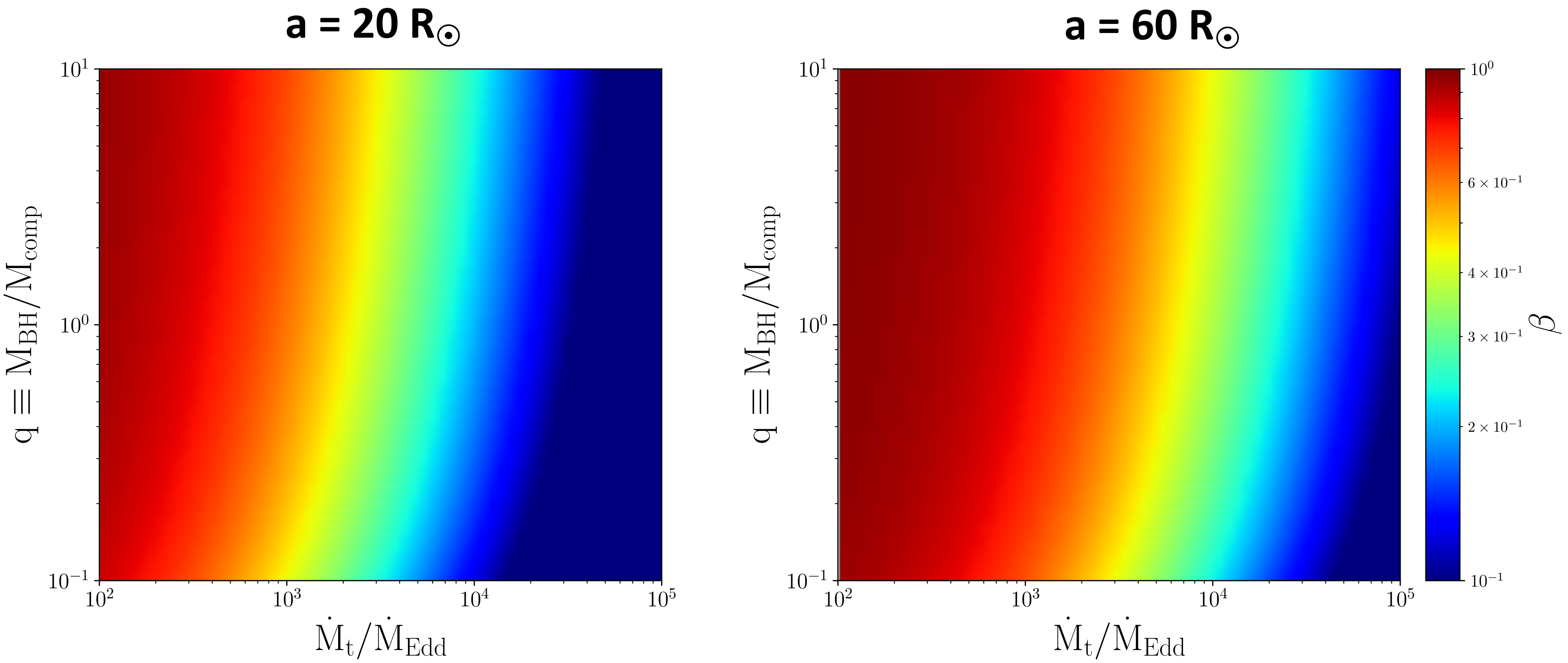
$(1+x/x_0)^{-\alpha}$

Failed winds cannot be followed.

β in various binary conditions

$$\beta = (1 + x/x_0)^{-\alpha}$$ $x \equiv R_{sph}/R_{L1}$, $x_0 = 0.085$, $\alpha = 0.61$

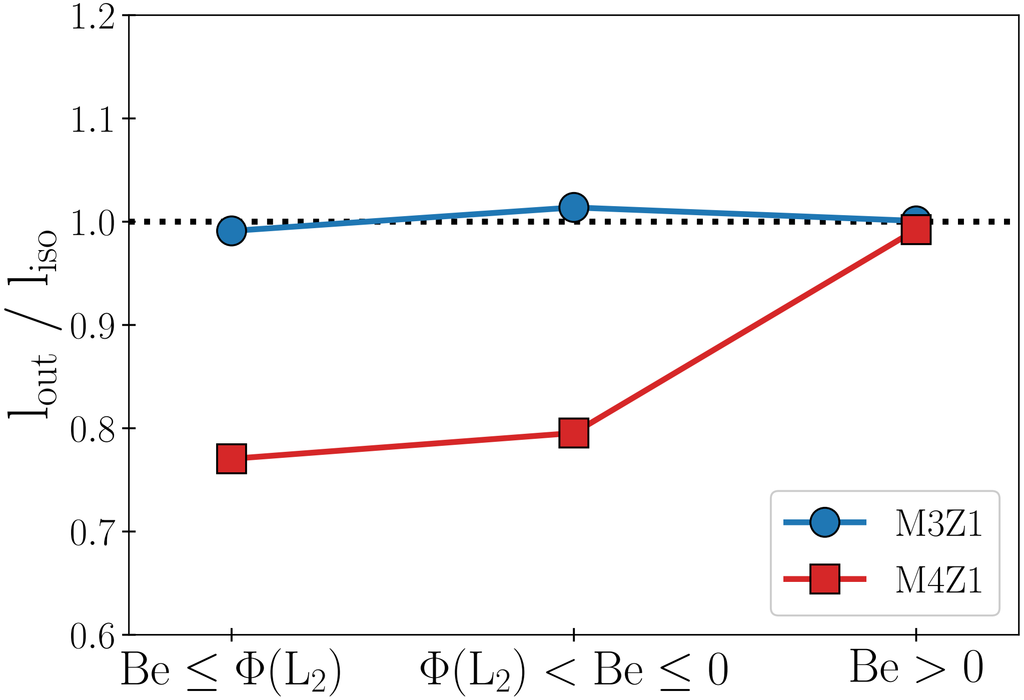
ex) $M_1 = 34\ M_{sun}$, $M_2 = 41\ M_{sun}$, $a = 36\ R_{sun}$ → $\beta \sim \begin{cases} 0.3 \text{ for } 10^4 \text{ Edd. rate} \\ 0.7 \text{ for } 10^3 \text{ Edd. rate} \end{cases}$


a = 20 R⊙ **a = 60 R⊙**

Specific angular momentum (SAM) of outflows

✓ SAM of outflowing gas is slightly lower than that in the isotropic emission case.

✓ This would be a lower-limit because outflows can further accelerate by binary's torque.

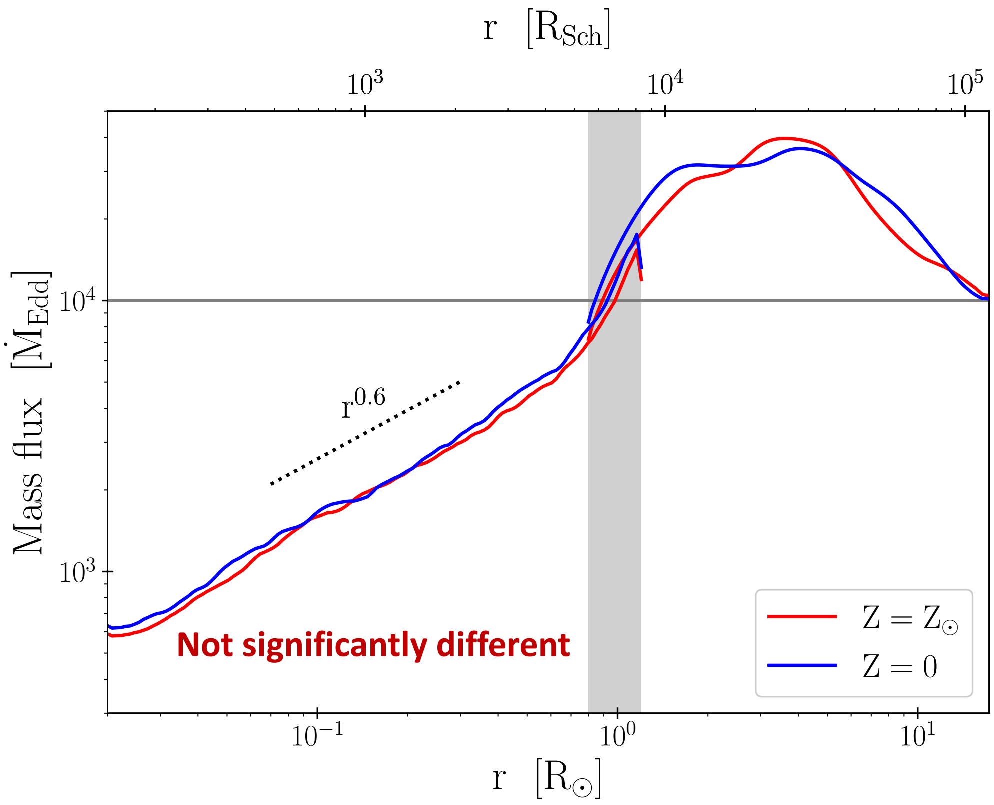


SAM of isotropic outflows

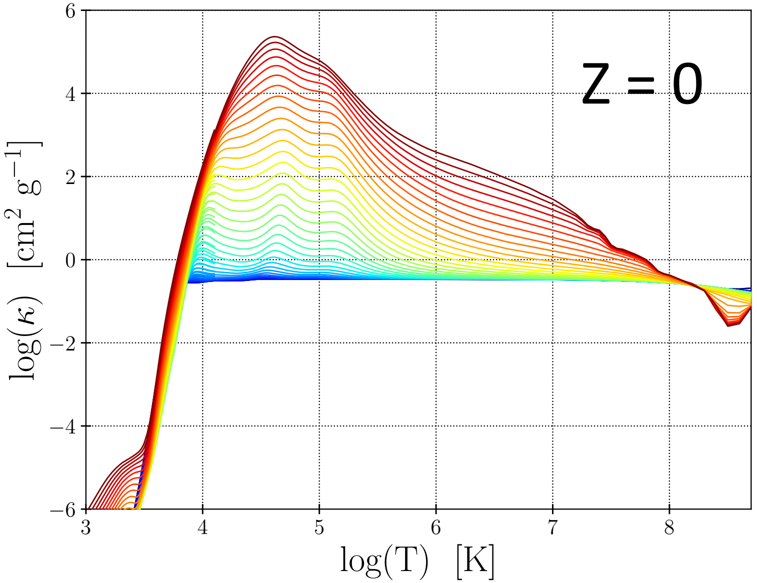
$$l_{z,\mathrm{iso}} = \frac{M_*^2}{M_{\mathrm{tot}}^2}\sqrt{GM_{\mathrm{tot}}a}$$

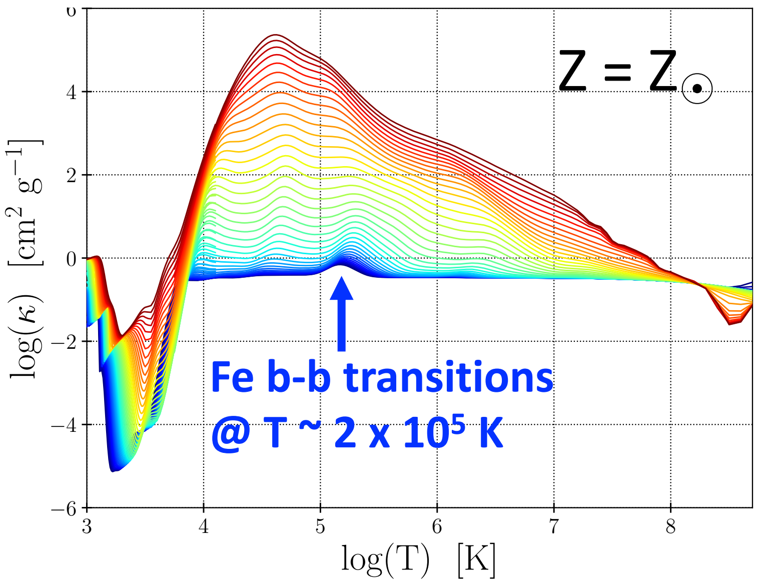
Metallicity dependence

- Properties of gas accretion is not significantly different between Z = 0 and Z = Z$_\odot$ cases.
- Because the accretion disk is hotter than 2 x 10^5 K.



Not significantly different

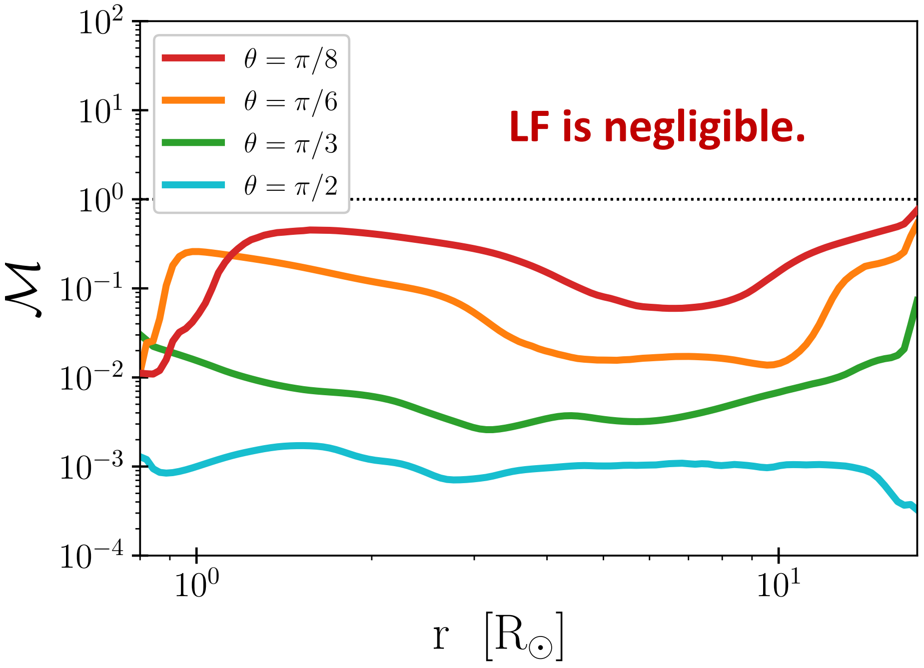




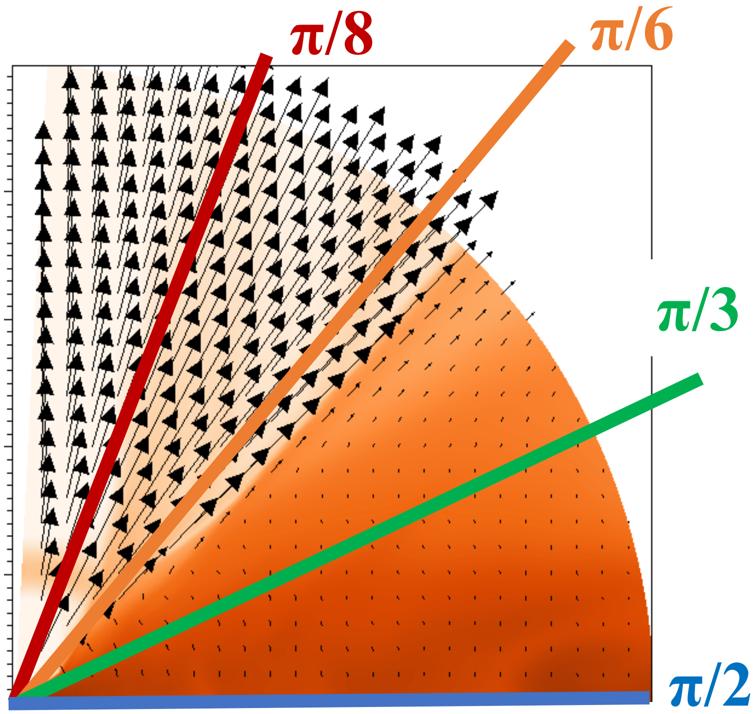
Fe b-b transitions @ T ~ 2 x 10^5 K

Line-force-driven winds

$$a_{\rm rad} = \{1 + \underset{\textbf{Force multiplier}}{\underline{M(\xi, t)}}\}\frac{\sigma_{\rm e} F_{\rm X}}{c}\ , \quad \xi \equiv \frac{4\pi F_{\rm X}}{n_{\rm e}}\ , \quad t \equiv \sigma_e n_{\rm e} c_{\rm s} \left|\frac{dv_r}{dr}\right|^{-1}\ ,$$



LF is negligible.



Summary

✓ We have performed 3D & 2D RHD simulations to study mass transfer in a close BH binary.

✓ Our simulations have revealed gas accretion and outflow structure from the L_1 point ($r \sim 10^5\ R_g$) to the vicinity of the BH ($r \sim 100\ R_g$).

✓ Outflows launched from the inner disk region ($r < 10^4\ R_\odot$) are too slow to leave the Roche lobe and would fall back to the disk.

✓ When Rsph > Rdisk, strong outflows leaking from the L2 point can occur.

✓ Based on previous RHD sims. and ours, β can be approximated with

$$\boxed{\beta = (1 + x/x_0)^{-\alpha} \quad x \equiv R_{sph}/R_{L1},\ \ x_0 = 0.085,\ \ \alpha = 0.61}$$

✓ γ is comparable to that expected in the isotropic emission case.