ブラックホールへの超臨界降着

〜 X線連星 から 活動銀河核 まで 〜

豊内大輔 (大阪大学)

YITP workshop @ 京都大学 ２０２４年8月5日

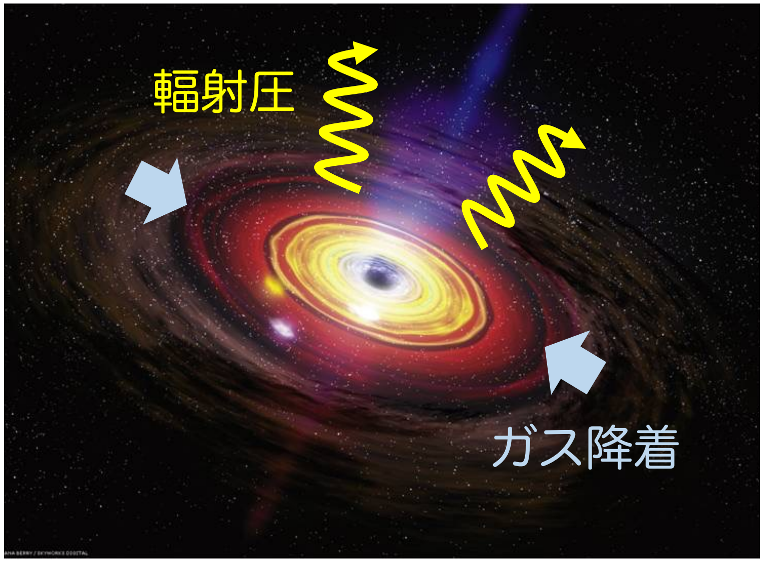
Eddington限界降着率

BHの重力 vs. 電子散乱輻射圧

$$\frac{GM_{\rm BH}}{r^2} \geq \frac{\kappa L}{4\pi c r^2}$$

κ :電子散乱断面積

$$\Rightarrow \quad L \leq L_{\rm Edd} \equiv \frac{4\pi c G M_{\rm BH}}{\kappa}$$



Credit: NASA

光度は降着率に対して

$$L = \frac{GM_{\rm BH}\dot{M}}{r_{\rm in}} = 0.1\dot{M}c^2 \quad (r_{\rm in} = 10\ GM_{\rm BH}/c^2)$$

このとき、輻射圧が重力を上回る限界降着率は

$$\dot{M}_{\rm Edd} = \frac{L_{\rm Edd}}{0.1c^2} = 2\times 10^{-8}\left(\frac{M_{\rm BH}}{M_\odot}\right)\mathrm{M}_\odot/\mathrm{yr}$$

Super-Eddington X-ray binaries

- **SS433**
  - A Galactic X-ray binary composed of a stellar mass BH + A-type giant
  - accreting gas at 10^{-5} M_{sun}/yr ~ 100 times the Edd. rate (King+2000).
  - Strong disk winds with 1000 km/s (Fabrika 2004).

- **Ultraluminous X-ray (ULX) binaries**
  - Extragalactic X-ray sources with $L_X > 10^{39}$ erg/s (~ L_{edd} for 10 M_{sun} BH)
  - 1800 ULXs have been detected and some have $L_X > 10^{42}$ erg/s (Walton+2022).

Super-Eddington mass transfer

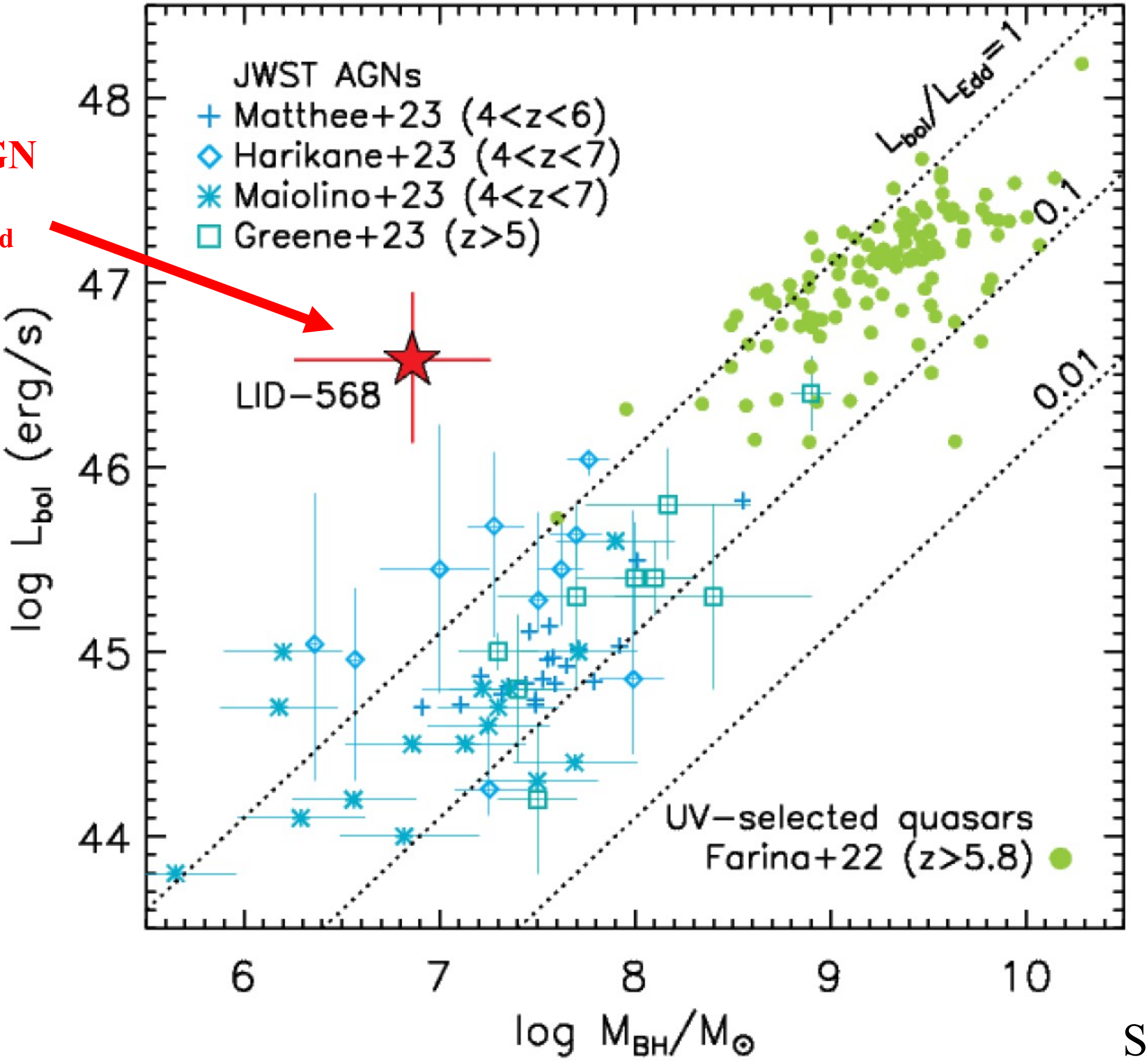
for $M_d \sim 10\ M_\odot$, $\tau_{KH} \sim 10^3$ yr

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

Super-Edd. accreting SMBHs at z > 4

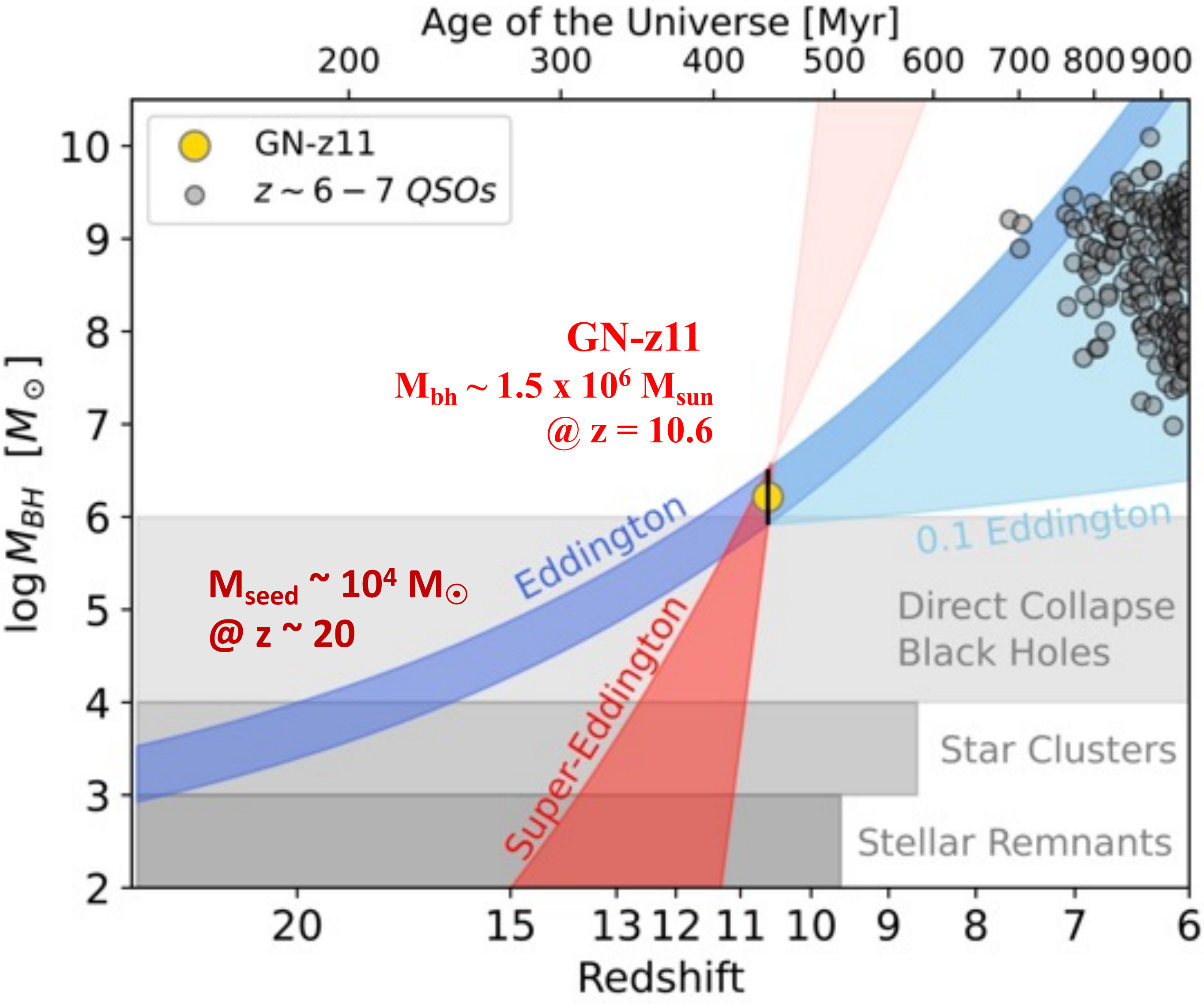
X-ray bright AGN

$L_{bol} \sim 4000\ L_{Edd}$



Suh et al. (2024)

Mass growth history of SMBHs



GN-z11

$M_{bh} \sim 1.5 \times 10^6 M_{sun}$

@ $z = 10.6$

$M_{seed} \sim 10^4 M_\odot$

@ $z \sim 20$

Photon trapping radius

- Photon diffusion timescale H τ / c > viscous timescale R / v_r

$$R_{\rm trapp} = \frac{H\tau v_r}{c} = \frac{H\kappa\Sigma}{c}\frac{\dot{M}}{2\pi R\Sigma} = 20\frac{H}{R}\dot{m}R_g, \qquad \text{where } \dot{m} \equiv \dot{M}/\dot{M}_{Edd}$$

- At trapping radius, the viscous flux exceeds the Eddington flux.

$$\boxed{F_{\rm visc} = \frac{3}{8\pi}\frac{R_g}{R^3}\dot{M}c^2\left[1-\left(\frac{R_{\rm in}}{R}\right)^{1/2}\right],} \quad = \quad \boxed{F_{\rm Edd} = \frac{L_{\rm Edd}}{4\pi R^2}.}$$

⇨ $R_{\rm sph} = 15\dot{m}\,R_g, \sim R_{\rm trapp}$

- **Radiation-pressure driven outflows can arise from r < $R_{\rm trapp}$.**

Bondi radius

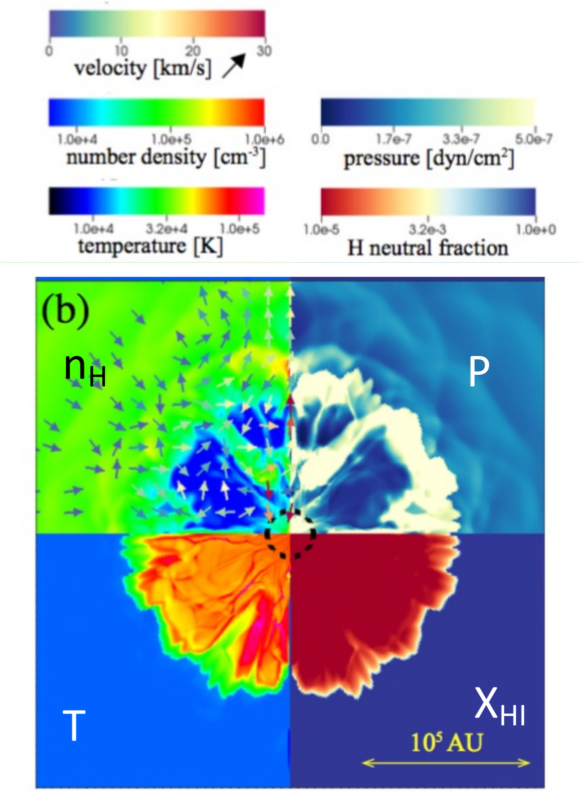
$$R_{\rm B} = \frac{G M_{\rm BH}}{c_{\rm s,\infty}^2}$$
$$= 1.4 \times 10^4 \ {\rm au} \left(\frac{M_{\rm BH}}{10^3 \ {\rm M_\odot}}\right) \left(\frac{T_\infty}{10^4 \ {\rm K}}\right)^{-1},$$

- **Bondi accretion rate**

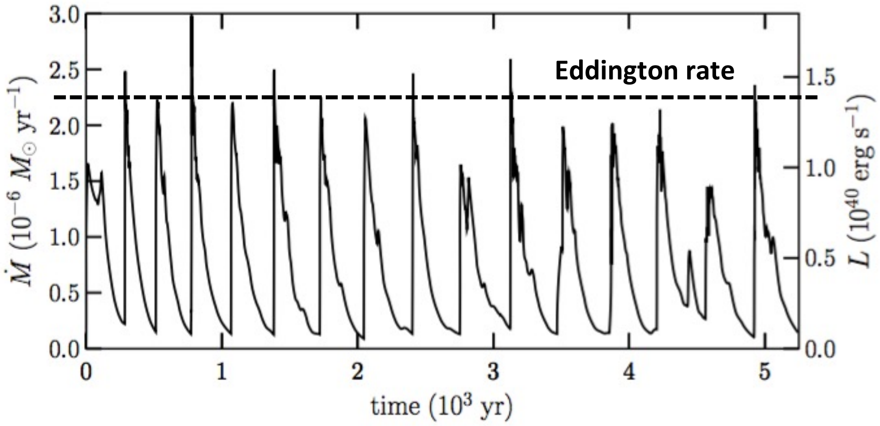
$$\begin{aligned} \dot{M}_{\rm acc} &\simeq 4\pi \rho_\infty R_{\rm B}^2 c_{\rm s} \\ &\propto \rho_\infty T_\infty^{-3/2} M_{\rm BH}^2 \end{aligned}$$

- **Photoionization heating**
  - ✓ **T** ↑↑
  - ✓ $\dot{M}_{\rm acc}$ ↓↓

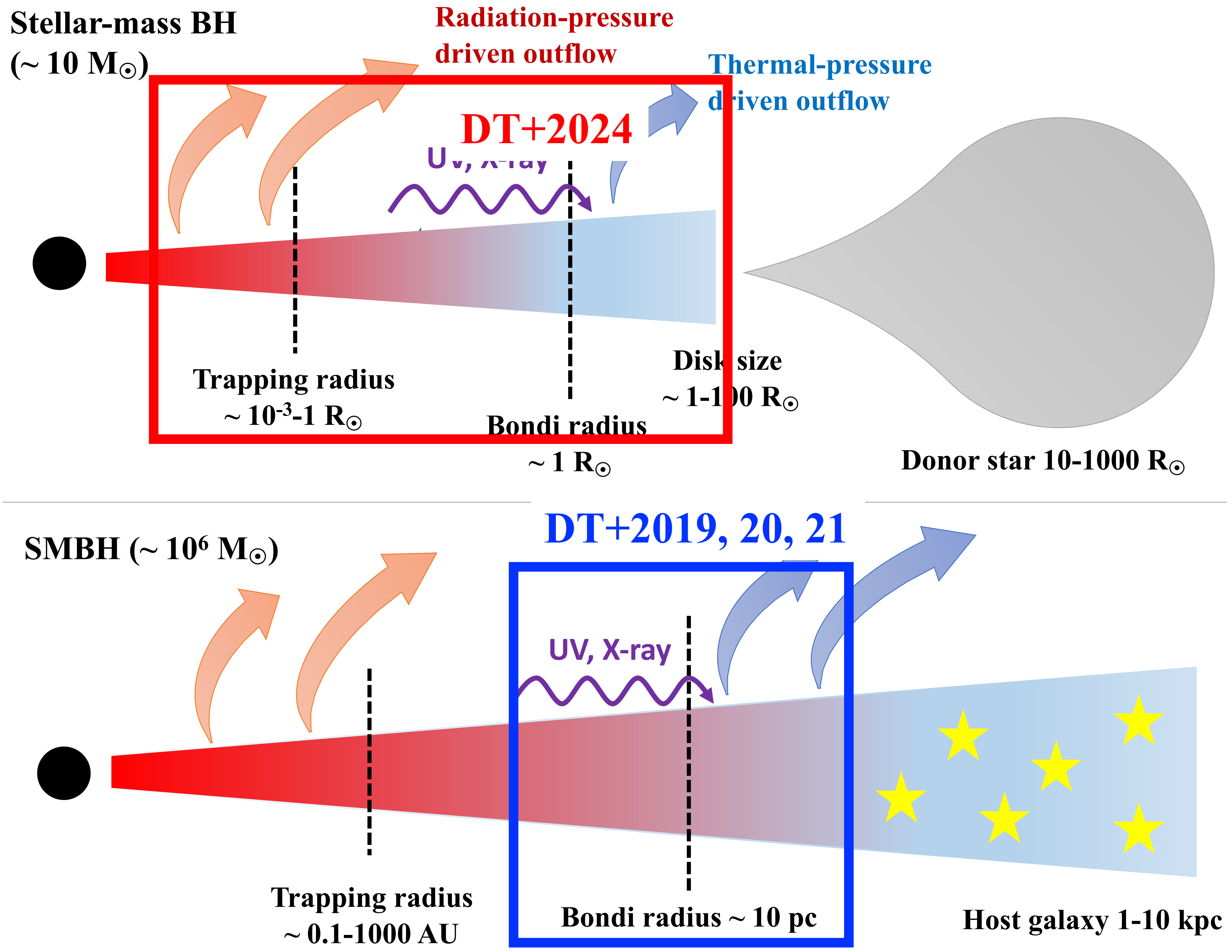
⇨ $\left\langle \dot{M}_{\rm acc} \right\rangle << \dot{M}_{\rm Edd}$



Sugimura et al. (2017)



Milosavljec et al. (2009)


Stellar-mass BH
(~ 10 M☉)
Radiation-pressure driven outflow
Thermal-pressure driven outflow
DT+2024
UV, X-ray
Trapping radius
~ 10^{-3}-1 R☉
Bondi radius
~ 1 R☉
Disk size
~ 1-100 R☉
Donor star 10-1000 R☉
DT+2019, 20, 21
SMBH (~ 10^{6} M☉)
UV, X-ray
Trapping radius
~ 0.1-1000 AU
Bondi radius ~ 10 pc
Host galaxy 1-10 kpc

RHD simulations of super-Eddington mass transfer (DT+24, MNRAS accepted)

RHD simulations of slim disks

Outer boundary ↓

Disk size ↓

Acc. rate

OF rate

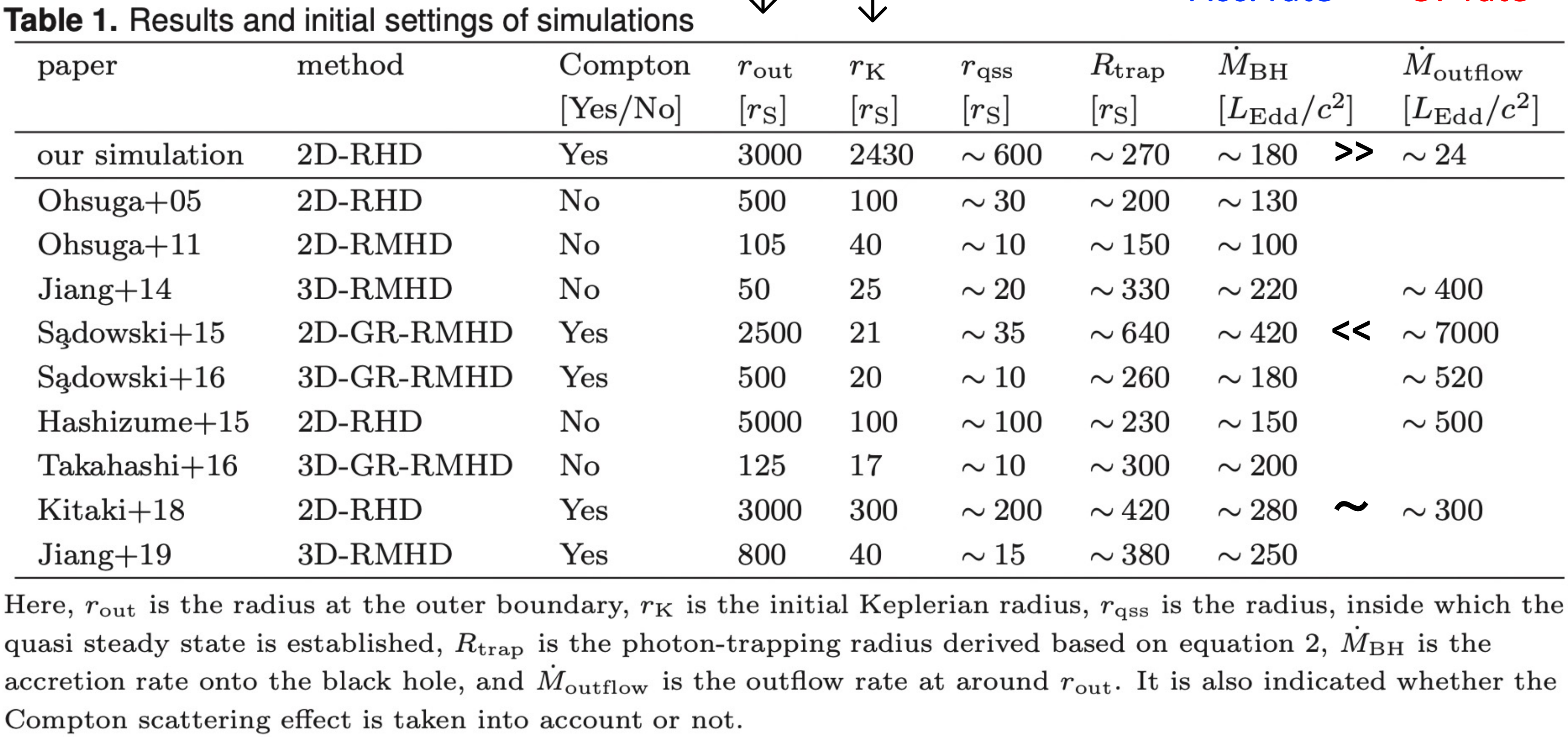


Table 1. Results and initial settings of simulations

paper	method	Compton [Yes/No]	$r_{\rm out}$ $[r_{\rm S}]$	$r_{\rm K}$ $[r_{\rm S}]$	$r_{\rm qss}$ $[r_{\rm S}]$	$R_{\rm trap}$ $[r_{\rm S}]$	$\dot{M}_{\rm BH}$ $[L_{\rm Edd}/c^2]$		$\dot{M}_{\rm outflow}$ $[L_{\rm Edd}/c^2]$
our simulation	2D-RHD	Yes	3000	2430	~ 600	~ 270	~ 180	>>	~ 24
Ohsuga+05	2D-RHD	No	500	100	~ 30	~ 200	~ 130		
Ohsuga+11	2D-RMHD	No	105	40	~ 10	~ 150	~ 100		
Jiang+14	3D-RMHD	No	50	25	~ 20	~ 330	~ 220		~ 400
Sądowski+15	2D-GR-RMHD	Yes	2500	21	~ 35	~ 640	~ 420	<<	~ 7000
Sądowski+16	3D-GR-RMHD	Yes	500	20	~ 10	~ 260	~ 180		~ 520
Hashizume+15	2D-RHD	No	5000	100	~ 100	~ 230	~ 150		~ 500
Takahashi+16	3D-GR-RMHD	No	125	17	~ 10	~ 300	~ 200		
Kitaki+18	2D-RHD	Yes	3000	300	~ 200	~ 420	~ 280	~	~ 300
Jiang+19	3D-RMHD	Yes	800	40	~ 15	~ 380	~ 250		

Here, $r_{\rm out}$ is the radius at the outer boundary, $r_{\rm K}$ is the initial Keplerian radius, $r_{\rm qss}$ is the radius, inside which the quasi steady state is established, $R_{\rm trap}$ is the photon-trapping radius derived based on equation 2, $\dot{M}_{\rm BH}$ is the accretion rate onto the black hole, and $\dot{M}_{\rm outflow}$ is the outflow rate at around $r_{\rm out}$. It is also indicated whether the Compton scattering effect is taken into account or not.

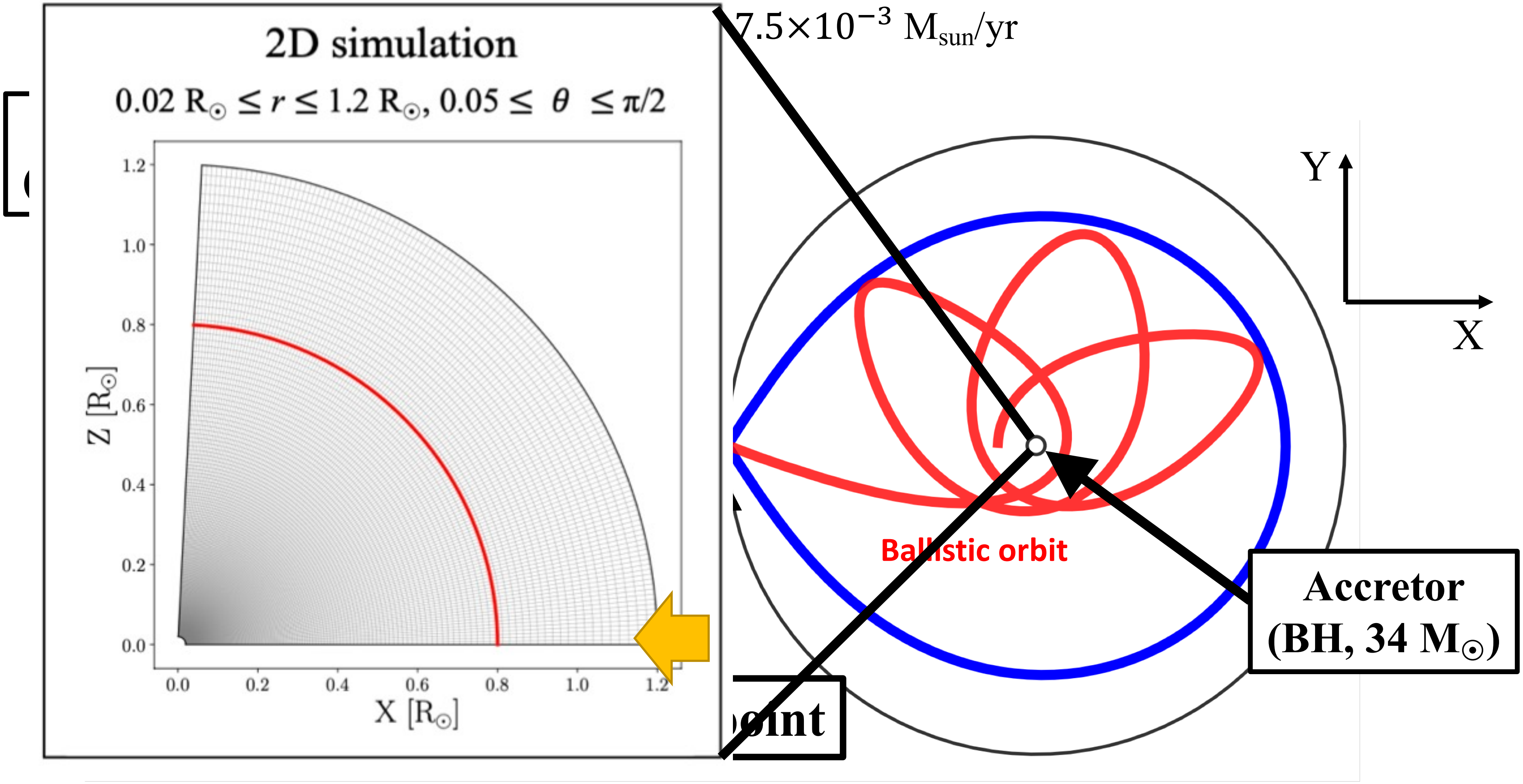
Kitaki+2021

Do outer boundary conditions affect the results?

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

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



2D simulation

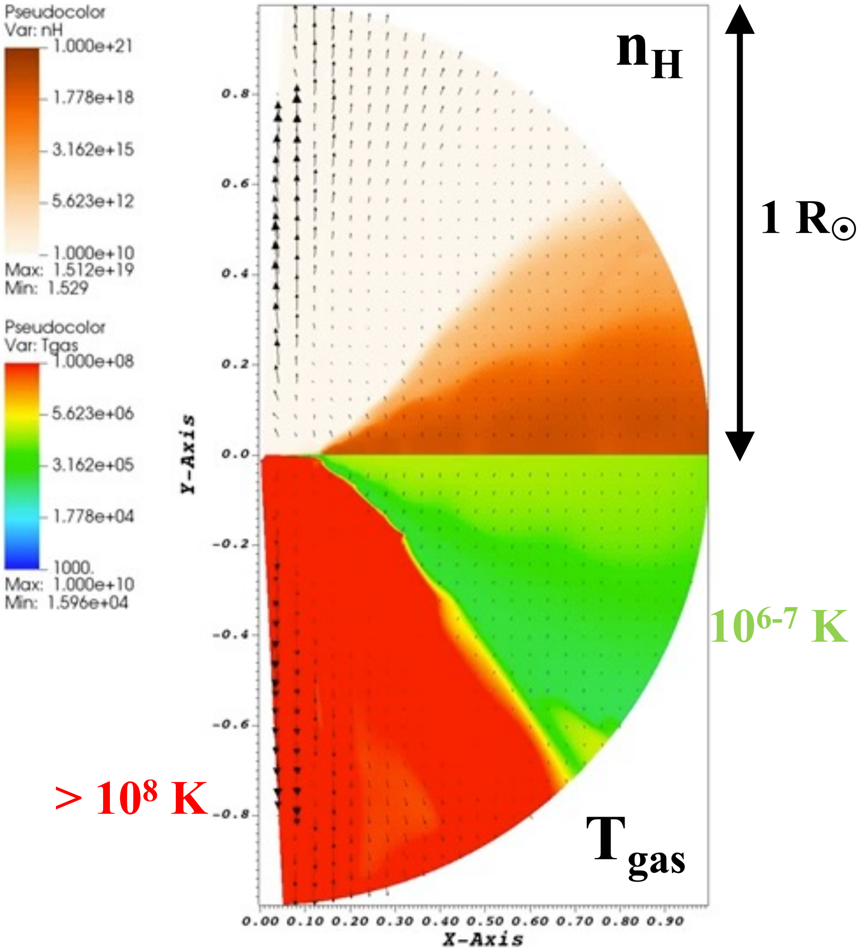
$0.02\ R_\odot \leq r \leq 1.2\ R_\odot,\ 0.05 \leq \theta \leq \pi/2$

Accretor (BH, 34 M⊙)

Simulation results

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

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



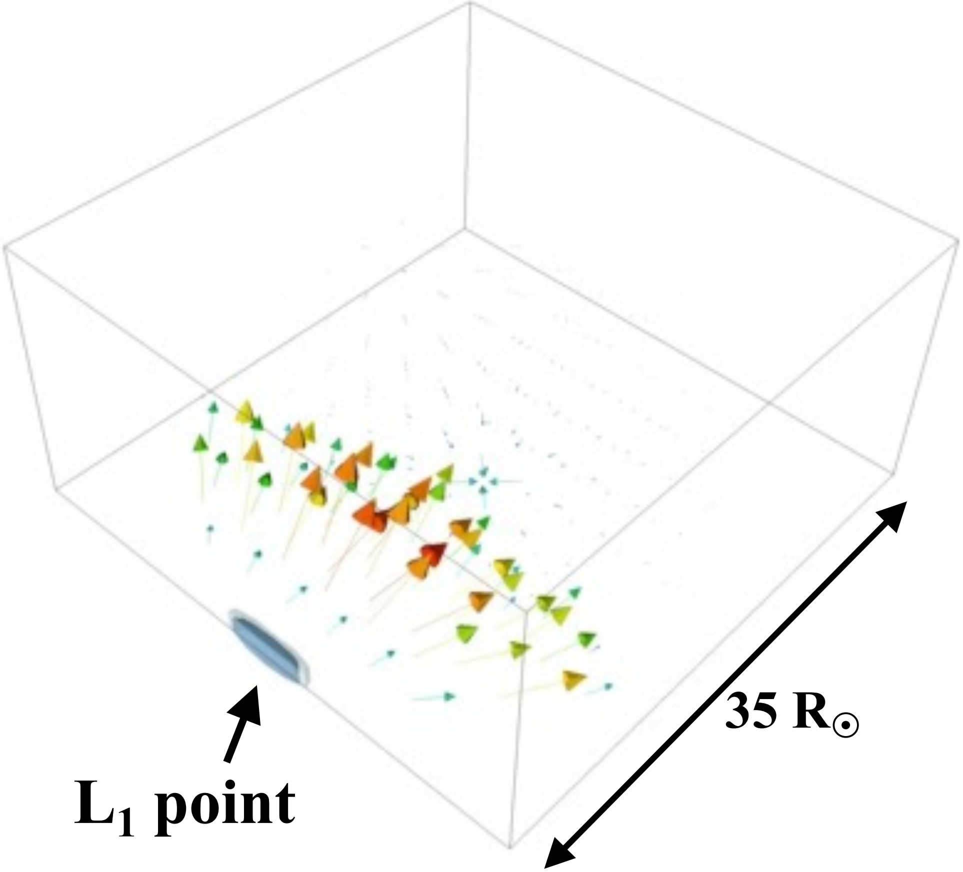
n_H

$1\ R_\odot$

$10^{6\text{-}7}$ K

$> 10^8$ K

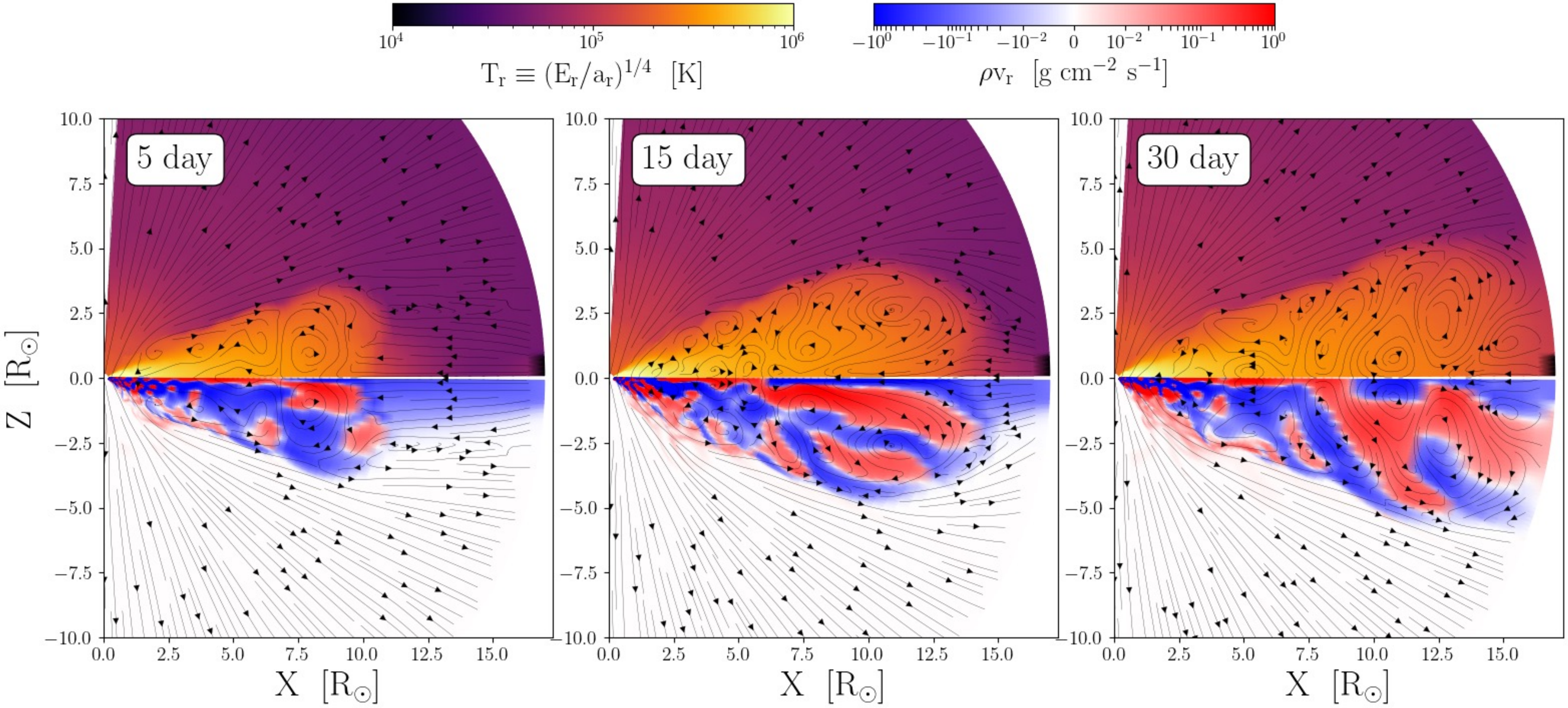
T_{gas}



L_1 point

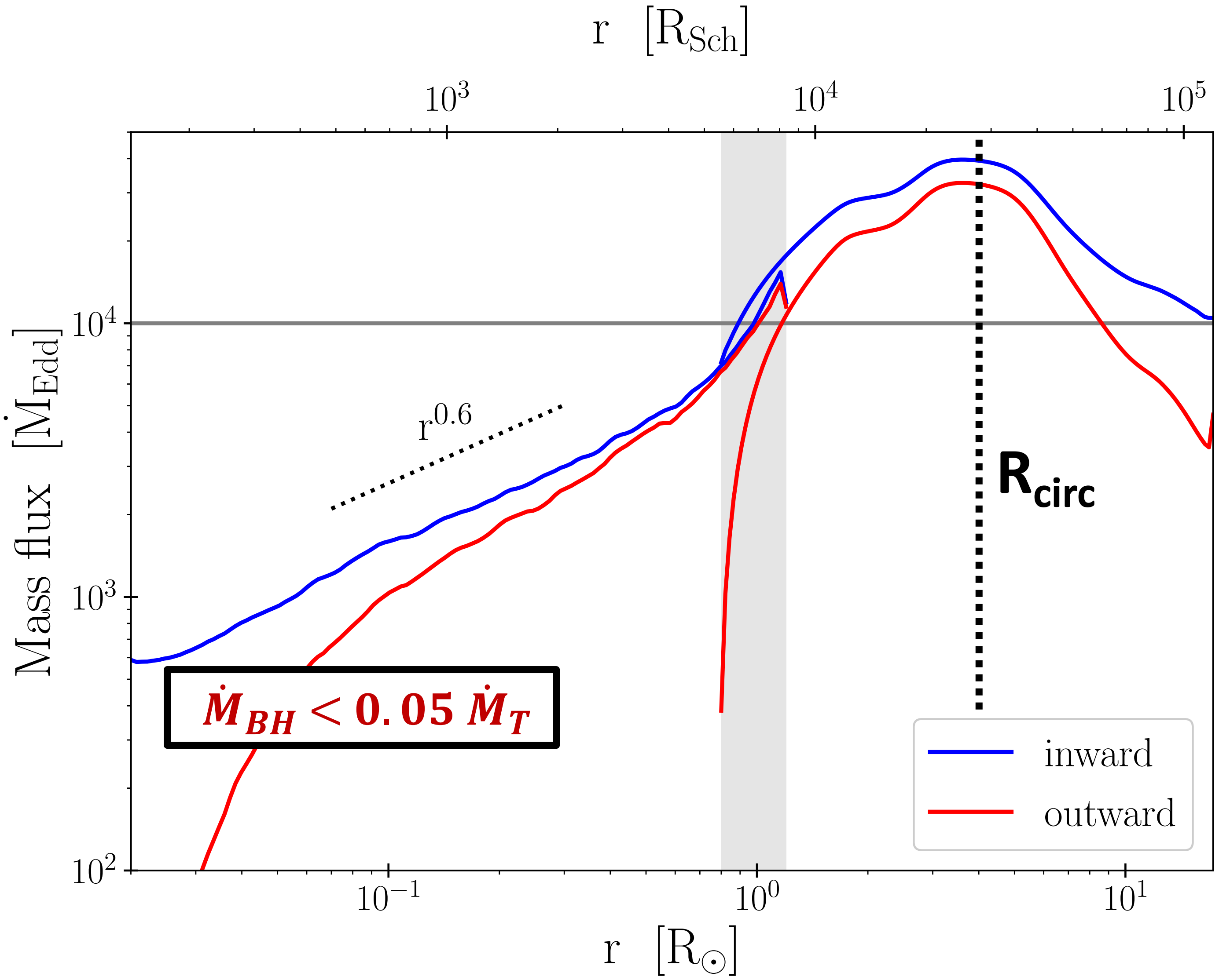
$35\ R_\odot$

Generation of outflows



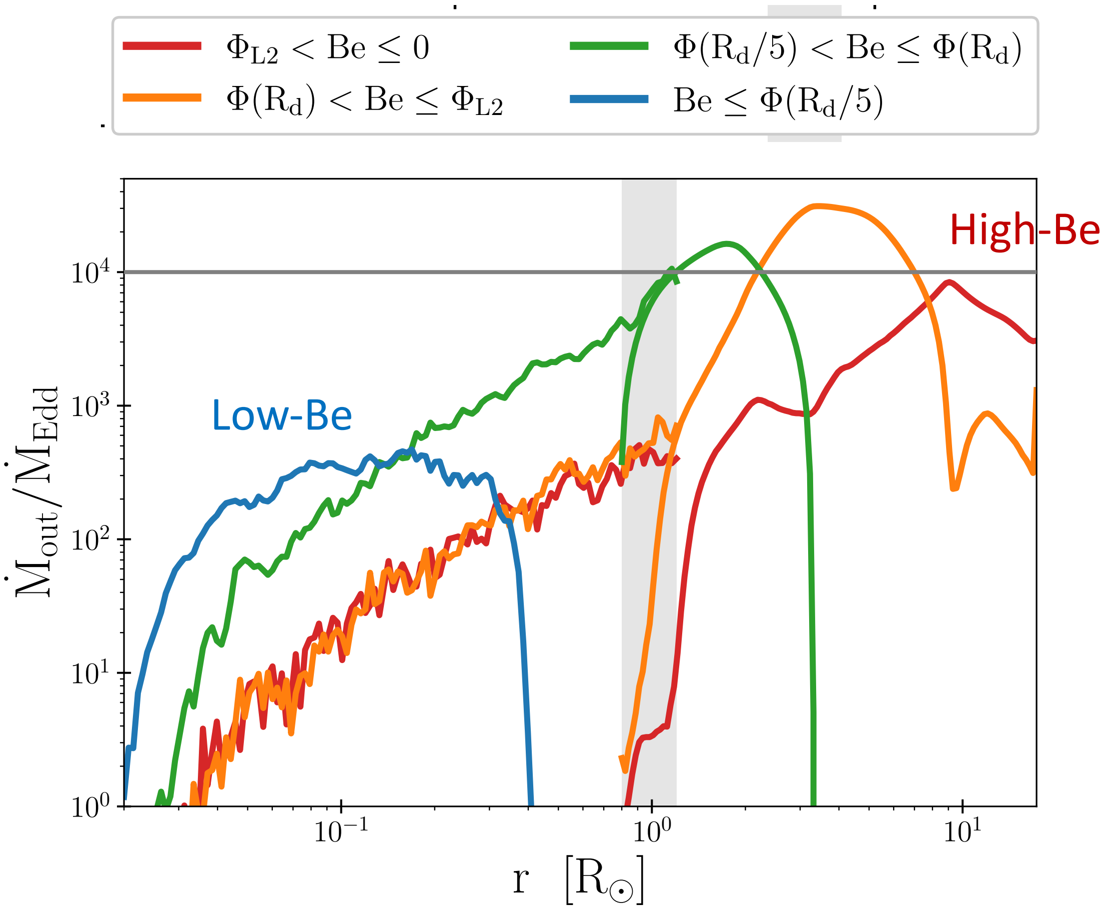
- Hot convective region is established at the outskirts of the disk, gradually extending outward.
- Finally, outflows arise from the hot convective region with sufficient energy to escape from the Roche lobe.

Inward and Outward mass fluxes



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

Propagation of outflows

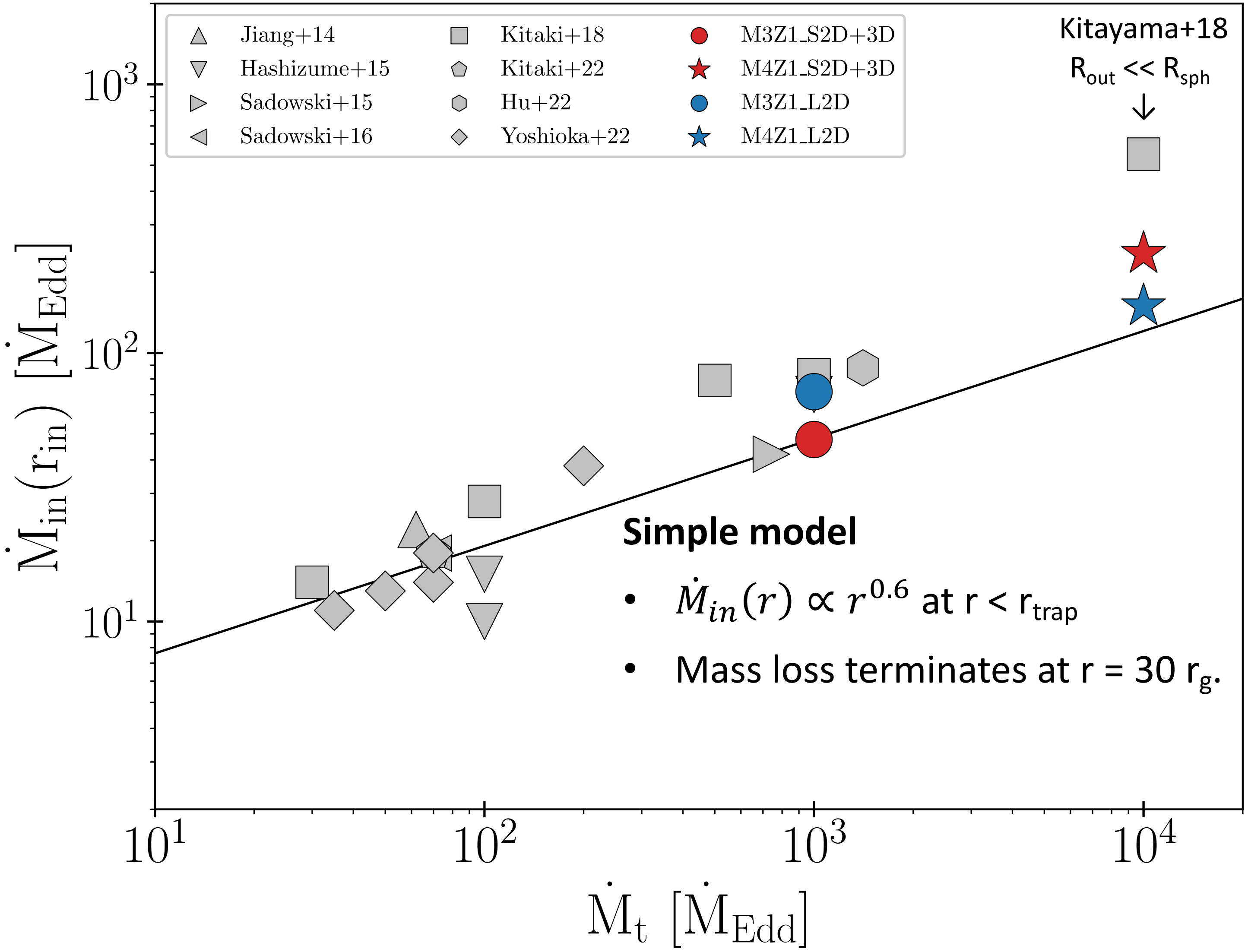


Bernoulli number

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

- 内側からはエネルギー的に弱いアウトフローが出る。
- 少し外側に落ちたアウトフローがそこで加速され、伝播していく。
- 遠心力半径付近から吹くアウトフローは連星脱出に十分なエネルギーを持つ。

Comparison with previous RHD simulations

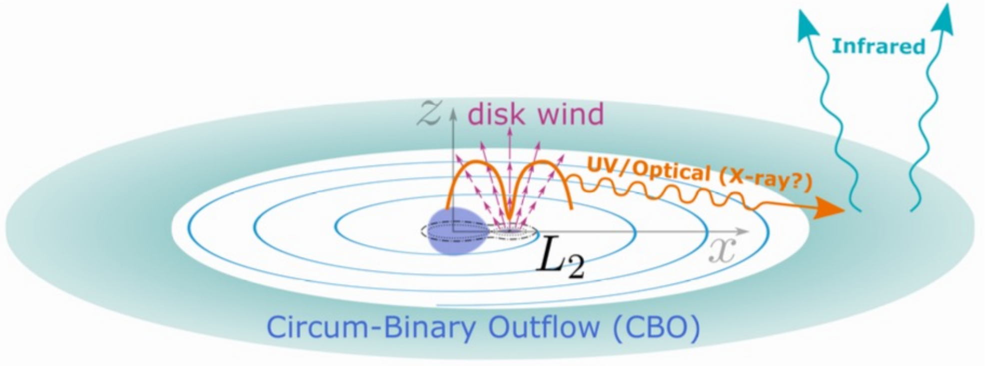


Simple model

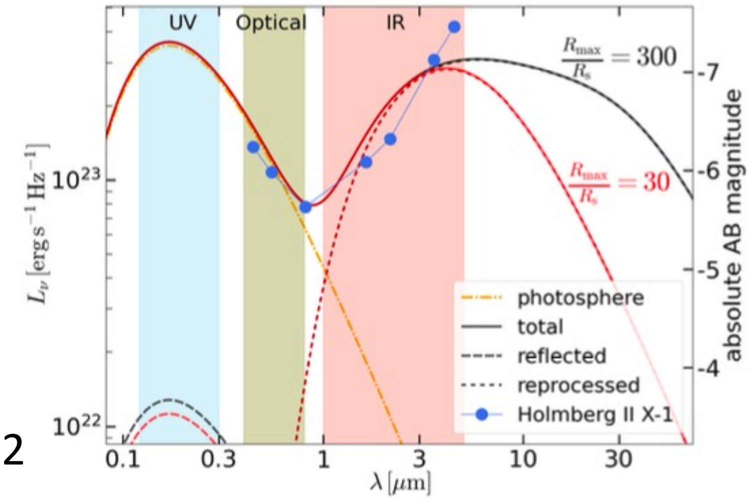
- $\dot{M}_{in}(r) \propto r^{0.6}$ at $r < r_{trap}$
- Mass loss terminates at $r = 30\ r_g$.

Circum-binary disk (CBD) formation

- ✓ Over 90 % of outflows in our simulations have $\Phi_{L2} < Be < 0$.
  - ➢ **Outflows will form a circum-binary disk.**
- ✓ A large fraction of ULX binaries exhibit IR excess, indicating the presence of CBD (e.g., Heida+2014, Lopez+2017).
- ✓ CBD scenario can successfully explain the observed SED of some ULX binaries (e.g., Lau+2019, Lu+2022)
- ✓ When the donor star causes a CCSN, the light curve would be affected by CBD.



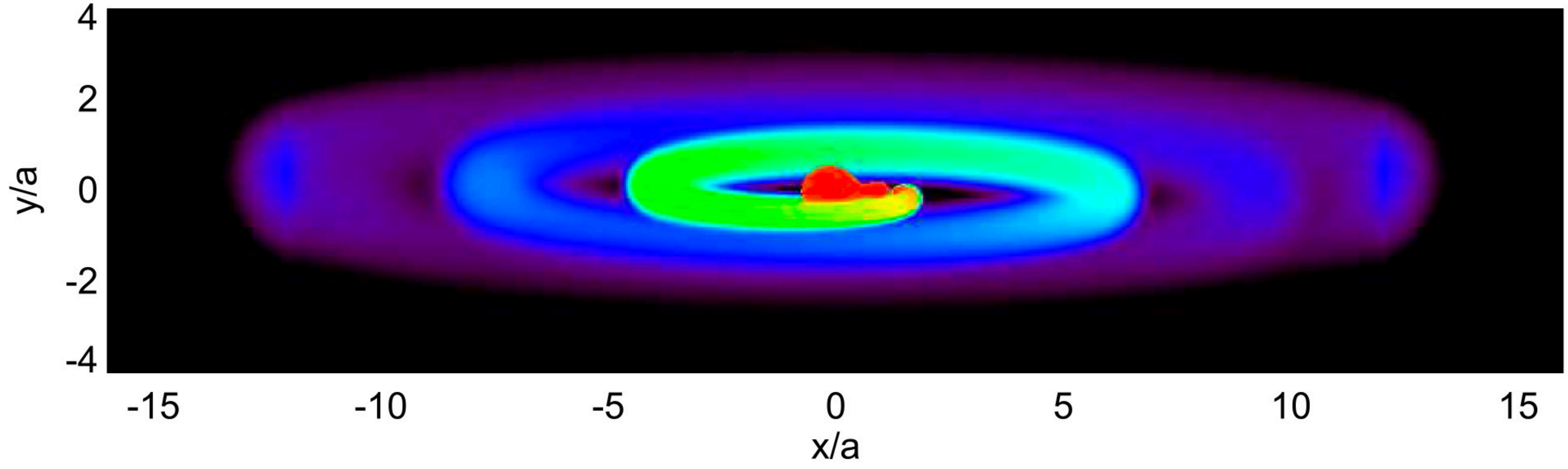
Lu+2022



Evolution of Circum-binary disk

- ✓ CBD gradually expands due to the tidal torque from the binary.
- ✓ **SAM of CBD mass loss is about five times higher than that of isotropic outflows.**

HD simulation of CBD by Pejcha+2017



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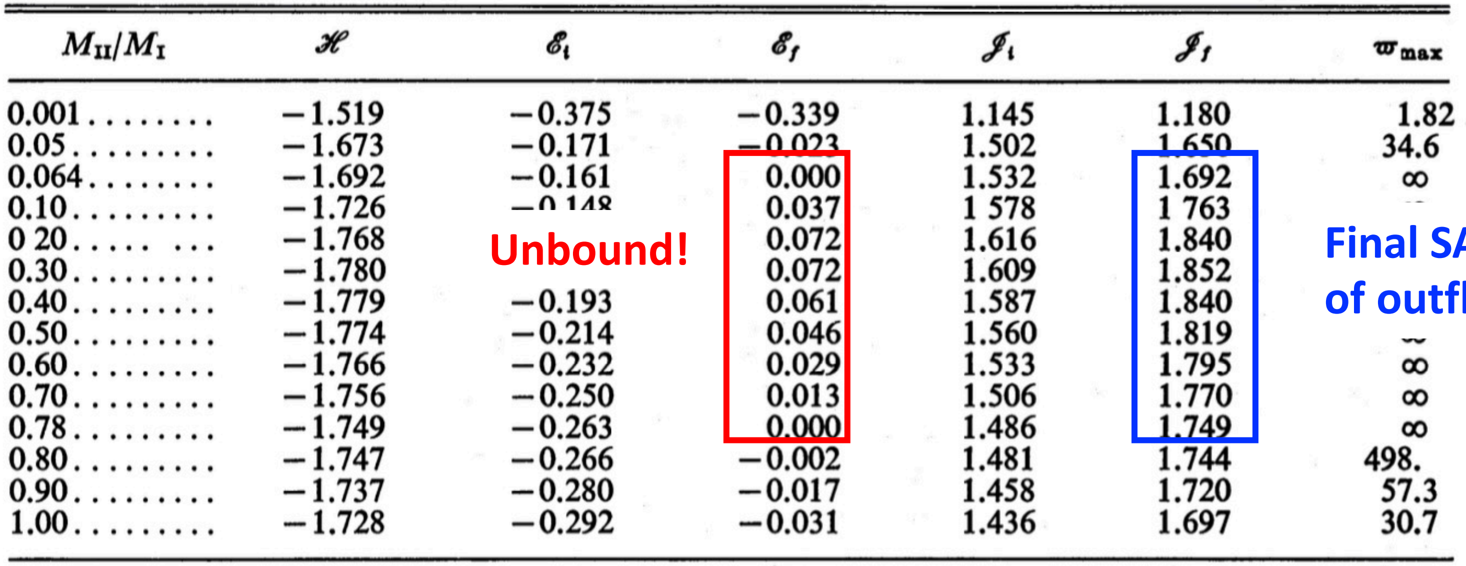
Numerical calculation by Shu+1979



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	
0.20	−1.768		0.072	1.616	1.840	
0.30	−1.780		0.072	1.609	1.852	
0.40	−1.779	−0.193	0.061	1.587	1.840	
0.50	−1.774	−0.214	0.046	1.560	1.819	
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

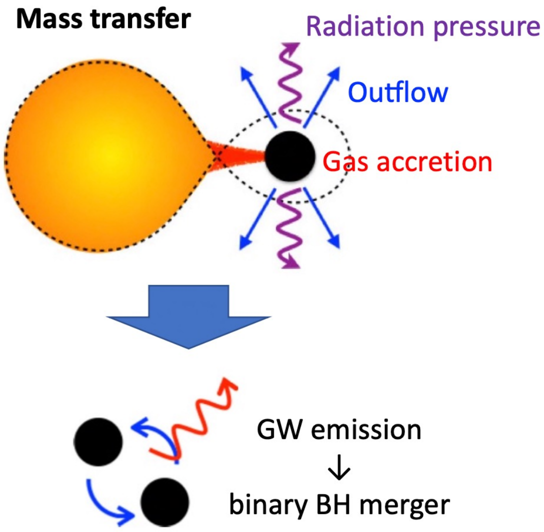
Implication for orbital evolution of binaries

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: $\gamma_{loss} \sim 1.44 \times M^2/(M_dM_a)$

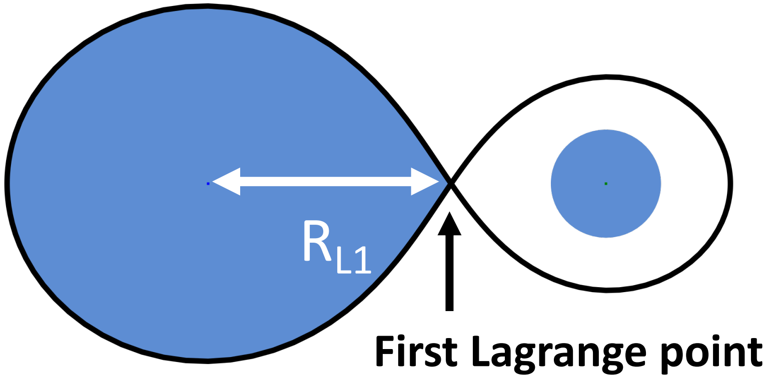
(Shu+1979, Pejcha+2017)

Stability of mass-transferring binaries

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

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

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

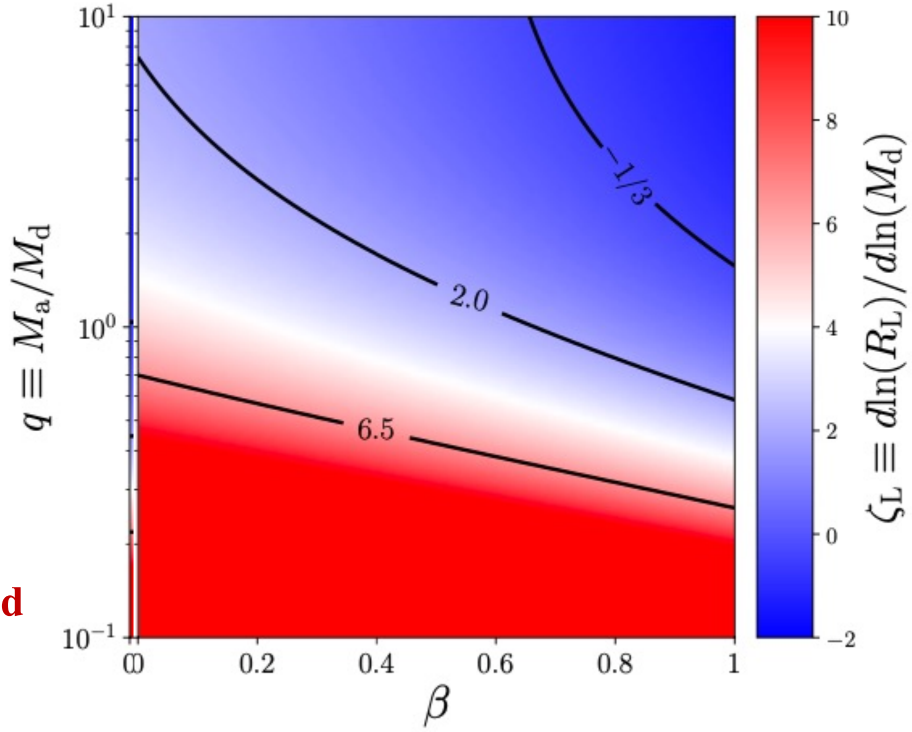


Convective donor: $\zeta_{ad} \sim -0.3$

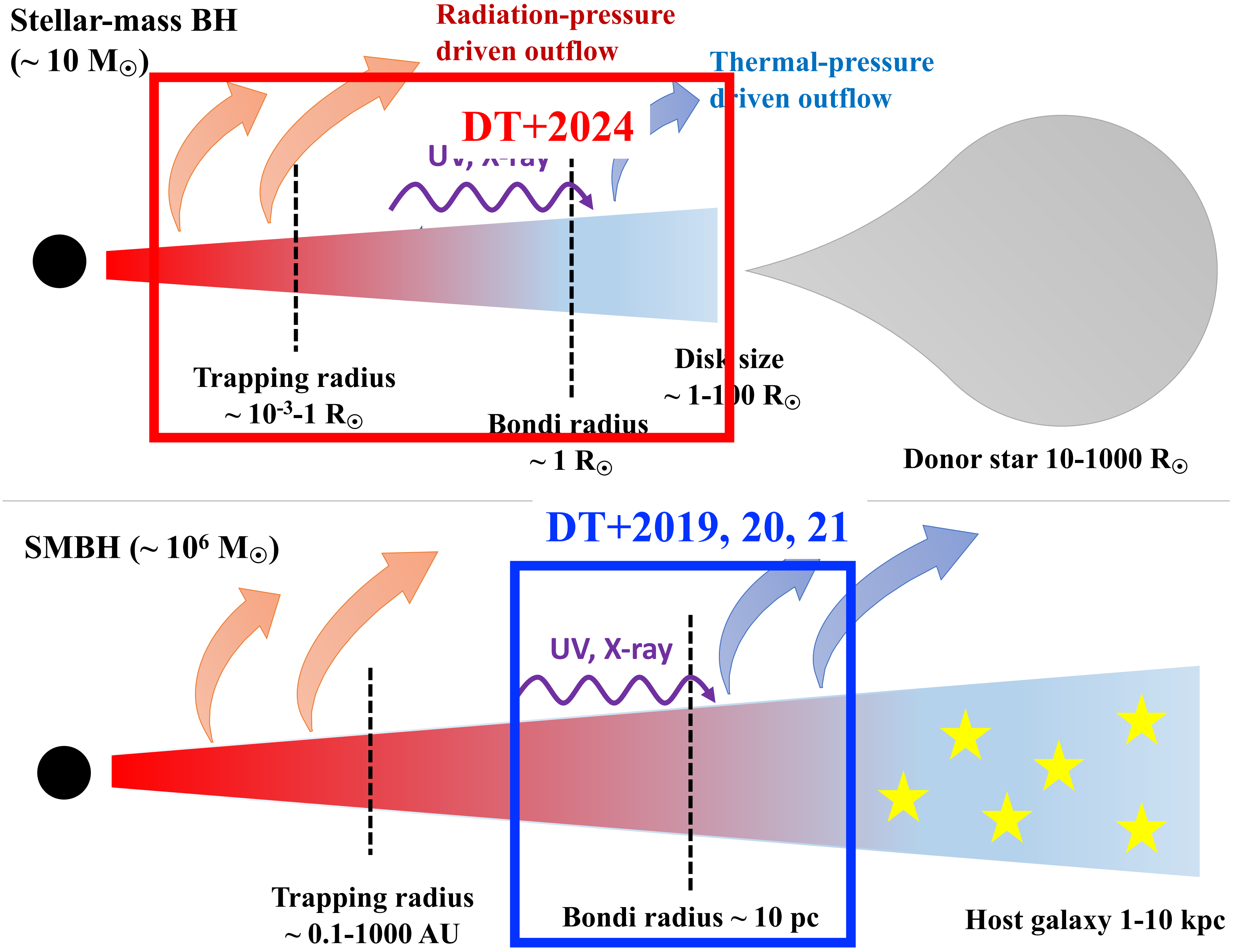
$q_{crit} \sim 2$ $(\beta = 1)$
$>> 10$ $(\beta = 0)$

Radiative donor: $\zeta_{ad} \sim 6.5$

$q_{crit} \sim 0.3$ $(\beta = 1)$
~ 0.7 $(\beta = 0)$



Super-Eddington mass transferring binaries would undergo common envelope evolution.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Bondi radius ~ 1 $R_\odot$
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SMBH (~ 10^6 $M_\odot$)
DT+2019, 20, 21
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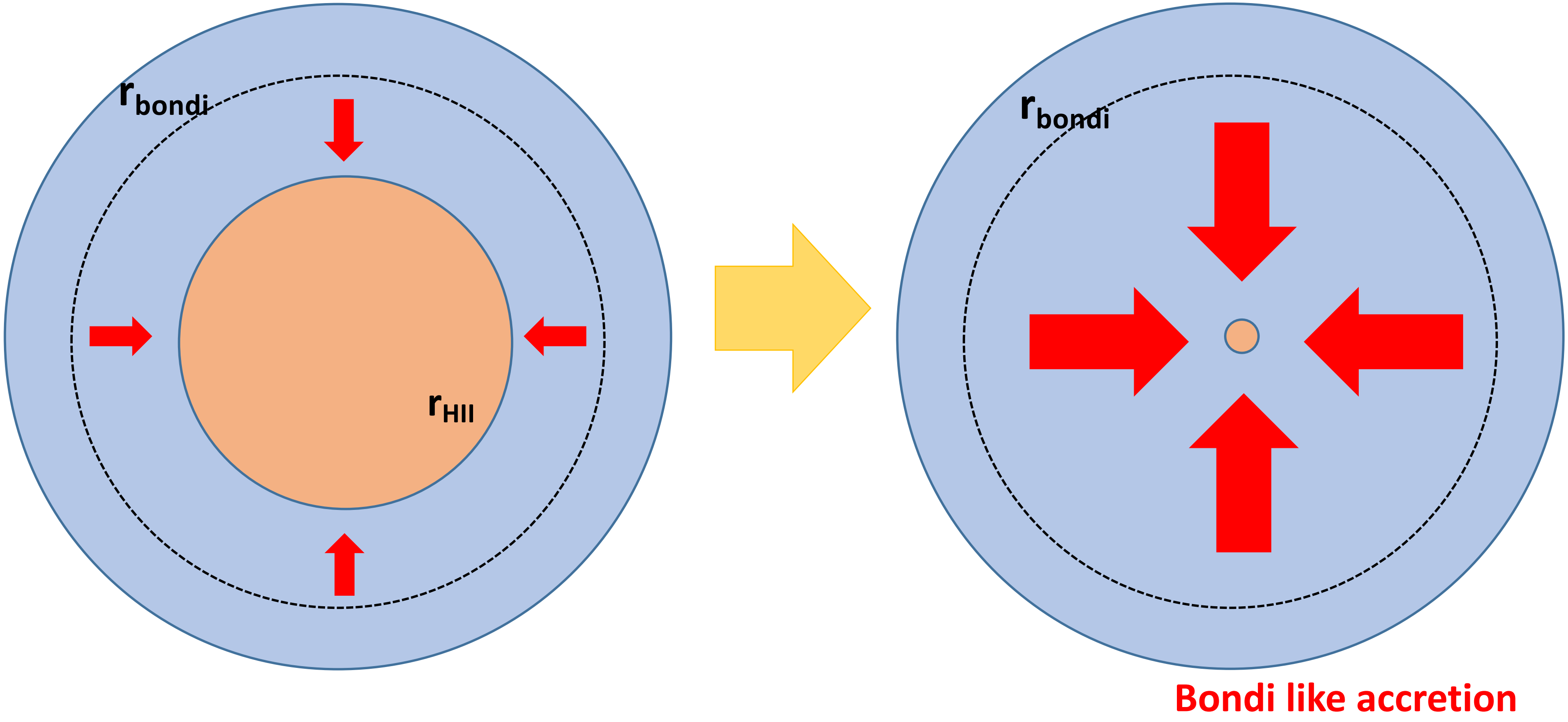
Trapping radius ~ 0.1-1000 AU
Bondi radius ~ 10 pc
Host galaxy 1-10 kpc

Super-Edd. accretion in dense environments

Inayoshi+2016, DT+2019, 20

- **Condition for the bondi like accretion ($r_{\rm Bondi} > r_{\rm HII}$)**

$$\boxed{\frac{\dot{M}_{\rm Bondi}}{\dot{M}_{\rm Edd}} \gtrsim 10^4}$$



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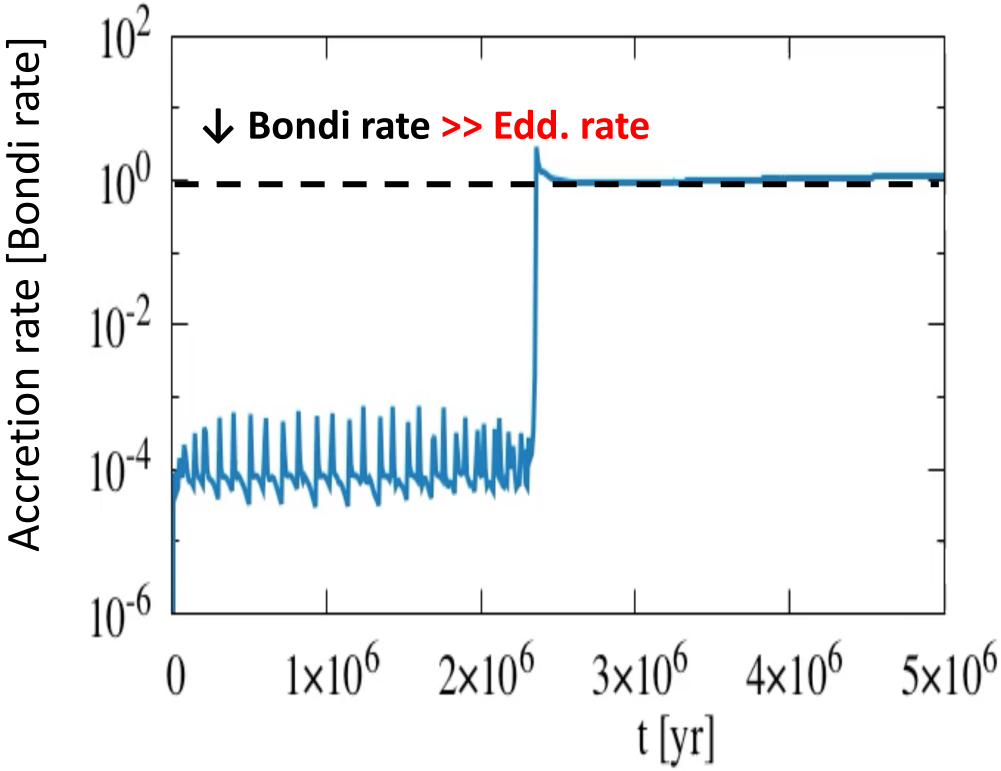
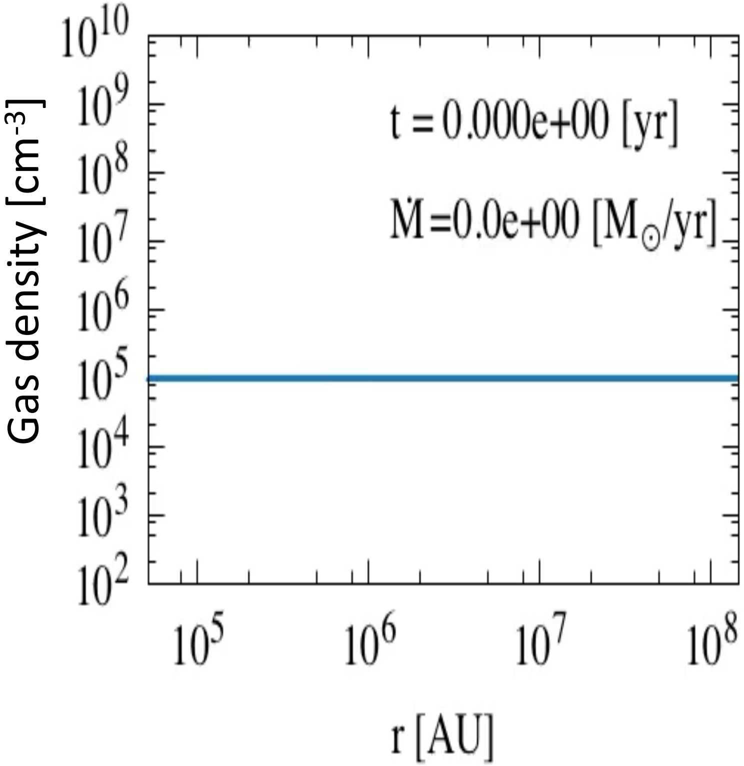
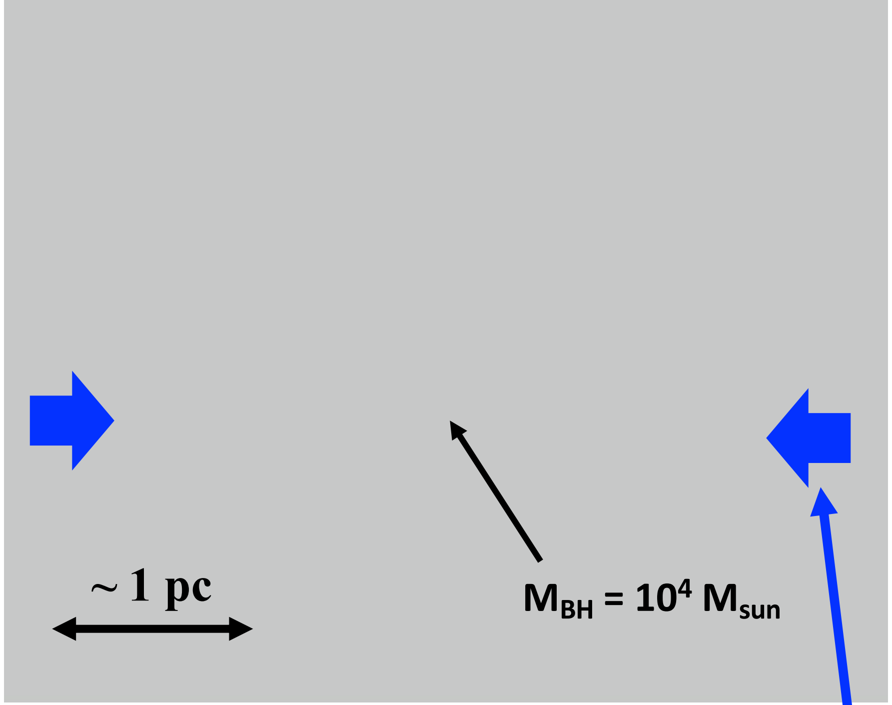




Toyouchi et al. (2021)

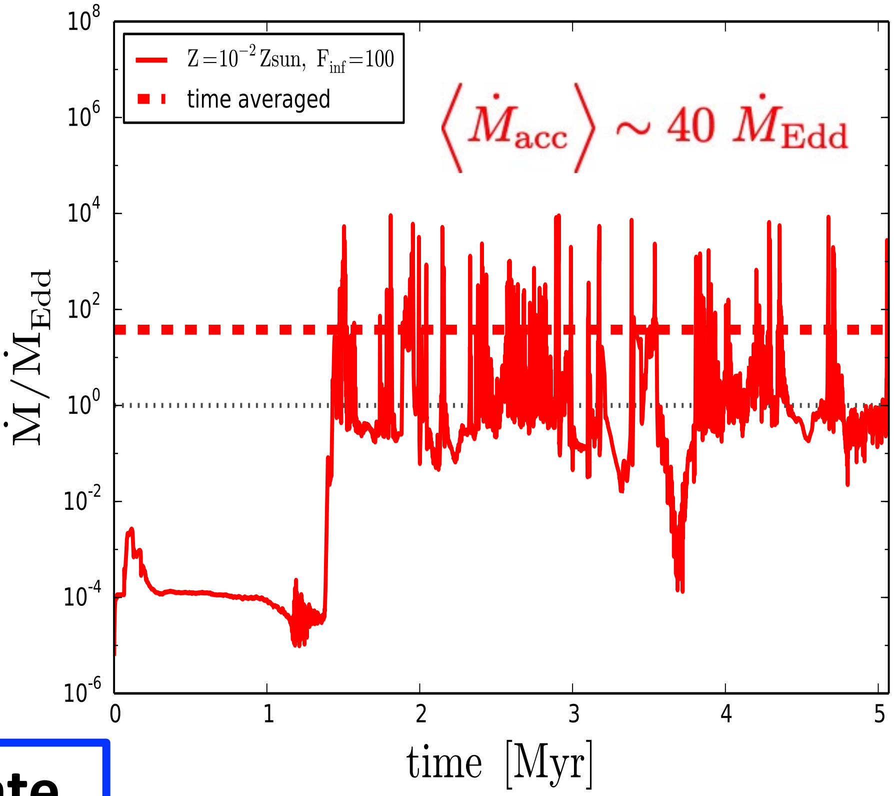
- 3D RHD simulations of dusty accretion disks
- **Super-Edd. accretion is possible!!**



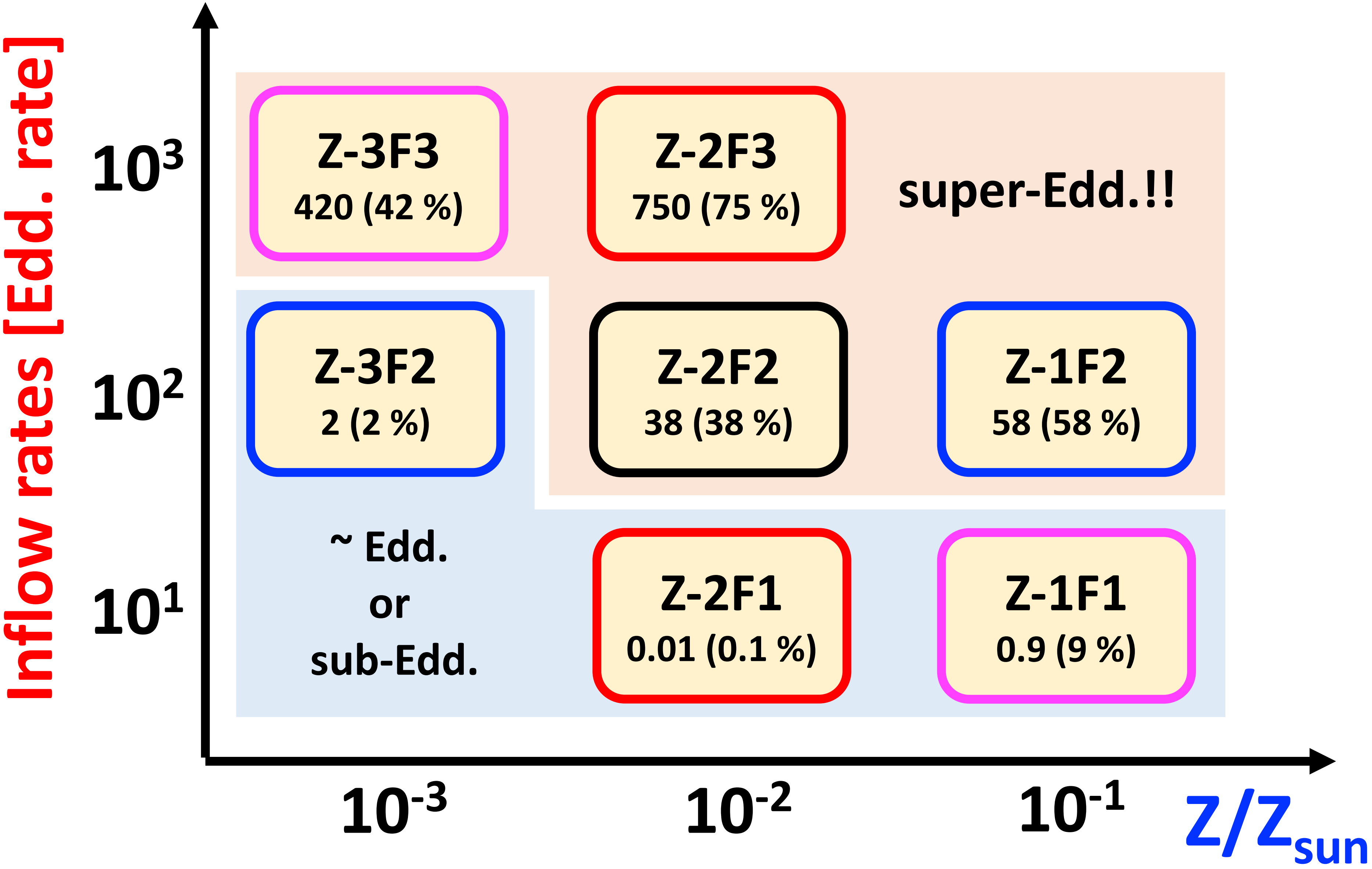
~ 1 pc

$M_{BH} = 10^4 M_{sun}$

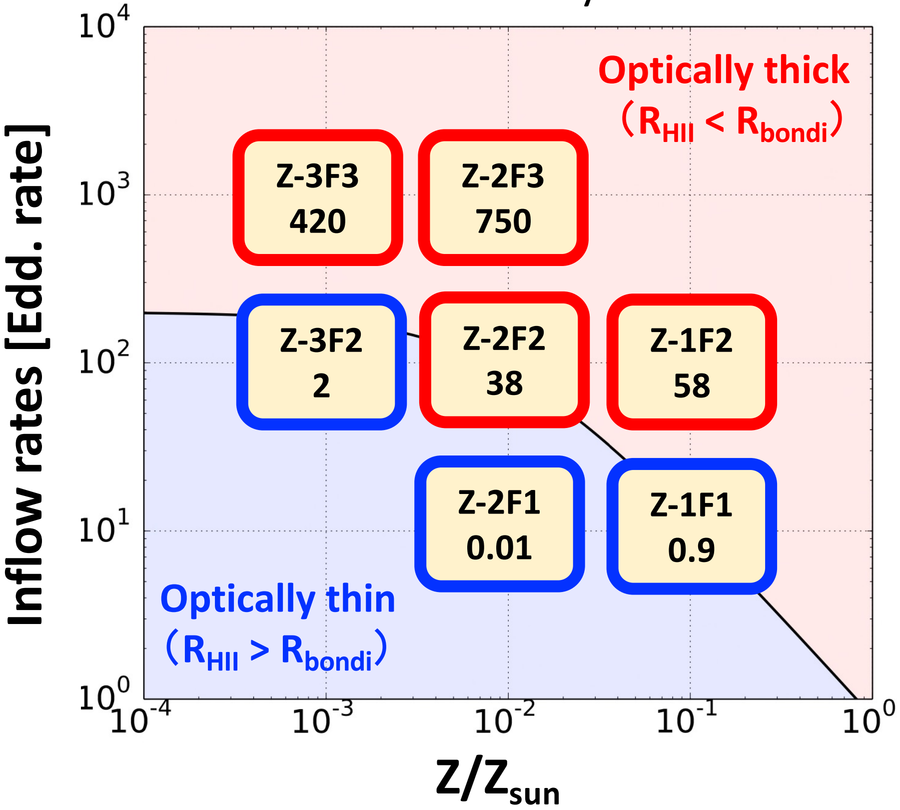
dM_{in}/dt = 100 Edd. rate



Time-averaged acc. rate

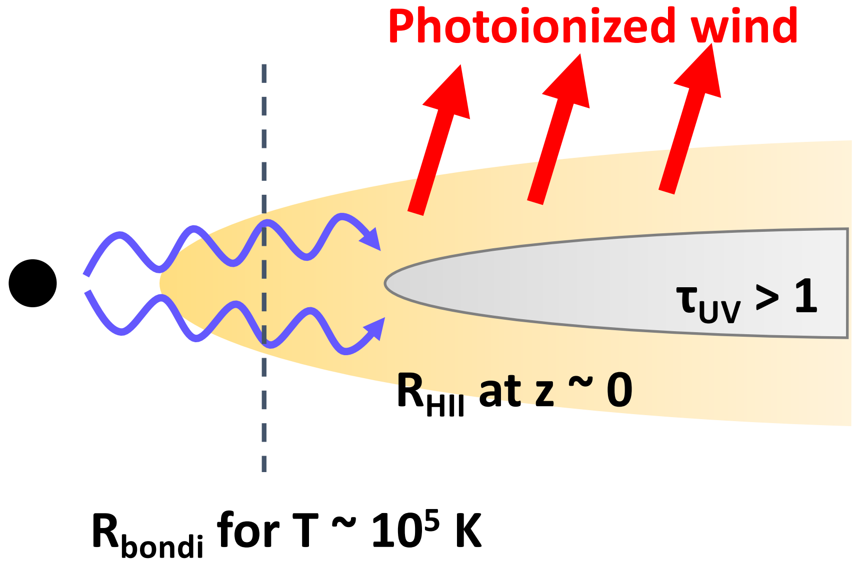


Inflow rates [Edd. rate] \ Z/Z_{sun}	10^{-3}	10^{-2}	10^{-1}
10^3	Z-3F3 420 (42 %)	Z-2F3 750 (75 %)	super-Edd.!!
10^2	Z-3F2 2 (2 %)	Z-2F2 38 (38 %)	Z-1F2 58 (58 %)
10^1	~ Edd. or sub-Edd.	Z-2F1 0.01 (0.1 %)	Z-1F1 0.9 (9 %)



1D disk analysis

low Z & low inflow rates

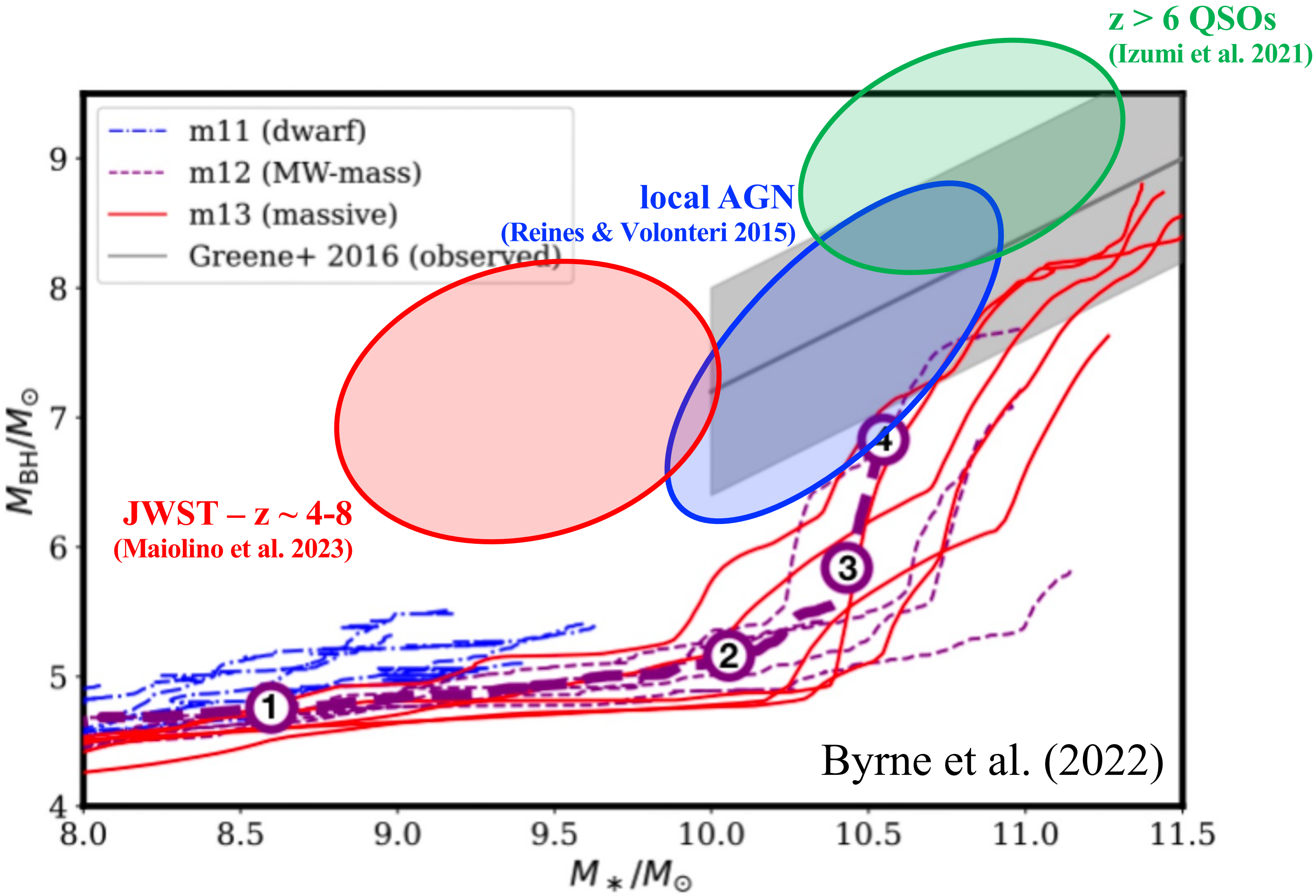


- Strong disk evaporation occurs when $R_{\rm HII} > R_{\rm bondi}$.
- **Condition for super-Eddington accretion**

$$\frac{\dot{M}_{\rm in}}{\dot{M}_{\rm Edd}} \gtrsim 10^2 \left\{1+\left(\frac{Z}{10^{-2}\ Z_\odot}\right)\right\}^{-1} \left(\frac{c_s}{1\ {\rm km\ s^{-1}}}\right)$$

Implications from cosmological simulations

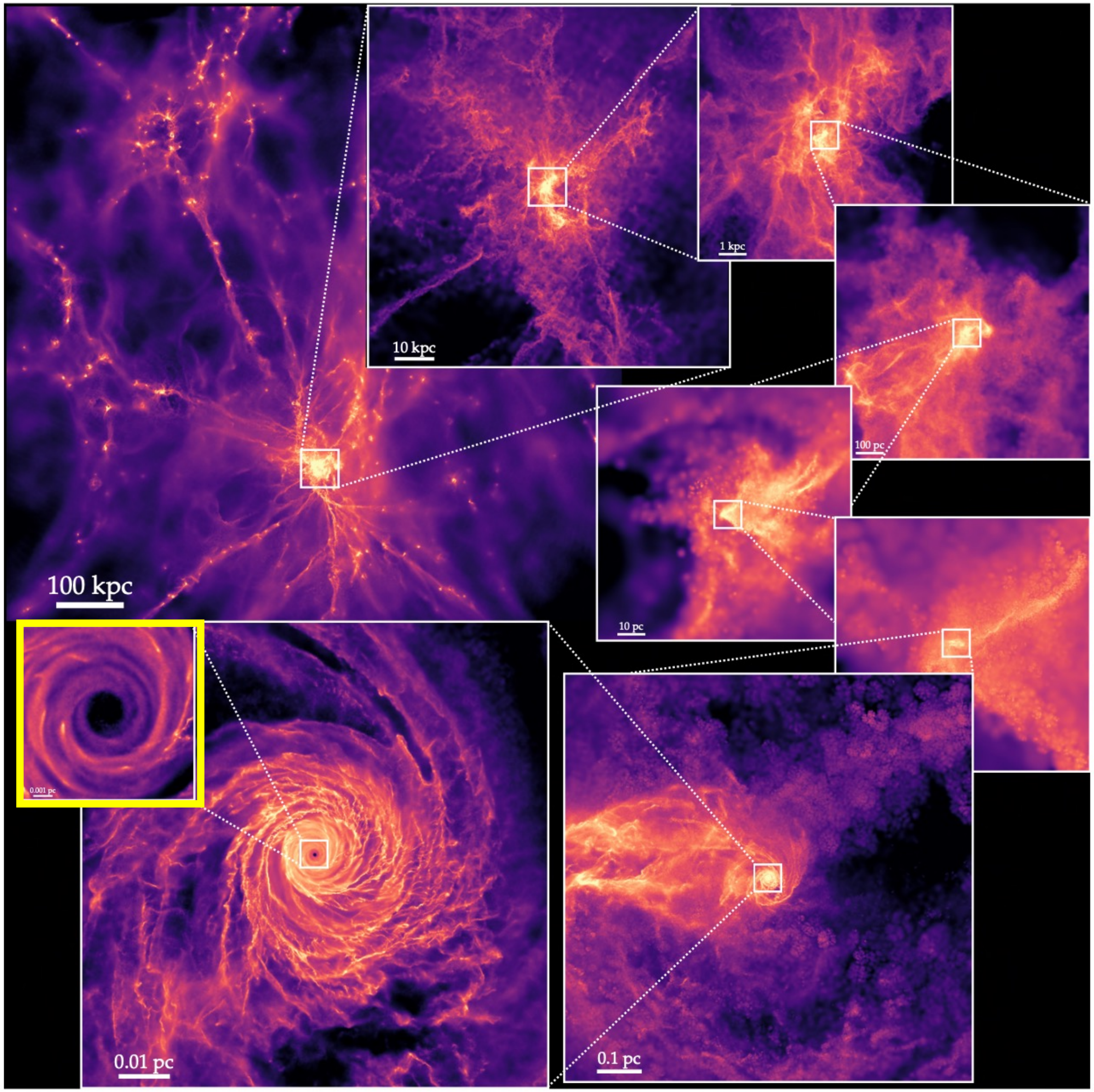
- **BH mass growth is strongly suppressed by stellar feedback!**
- We probably need higher spatial resolution to explore nuclear regions.



Byrne et al. (2022)

Hopkins et al. (2023)

- First RMHD simulation resolving AGN accretion disks from cosmological initial condition.

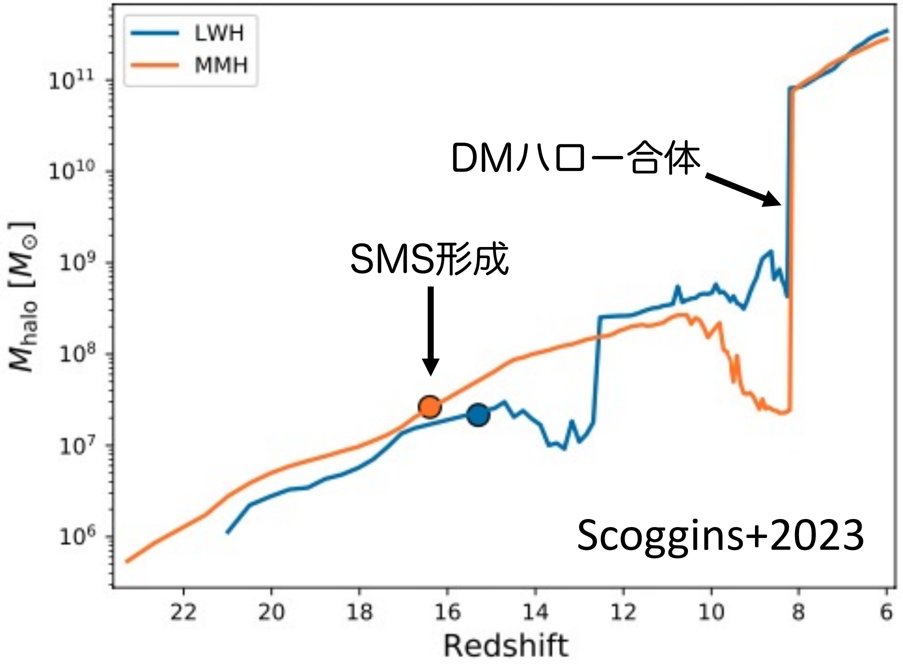


~ 10 Edd. rate

@ 300 r_S

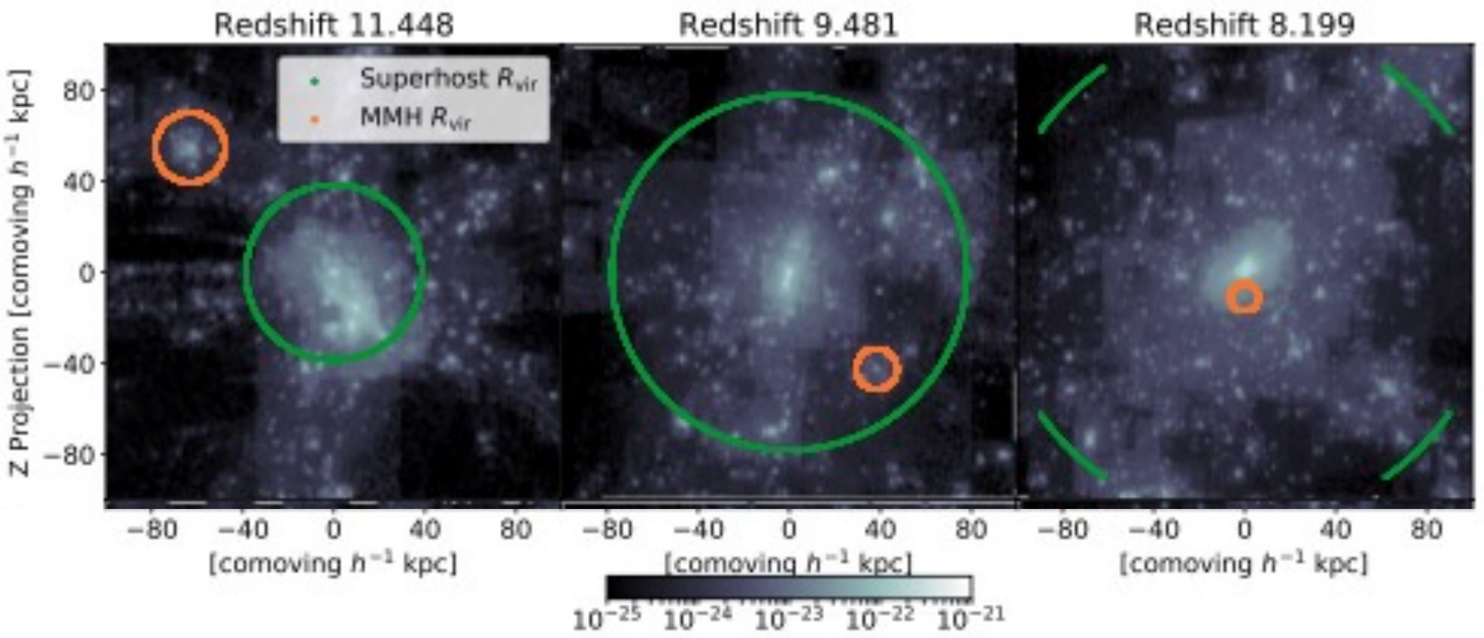
DMハロー合体の影響

- SMSを形成するハローの多くは、いつかより大きなハローに取り込まれる。
- ハロー外縁ではBHの成長率低いため、密度の高い中心に移動する必要がある (e.g., Chon+21)


DMハロー合体

SMS形成

Scoggins+2023

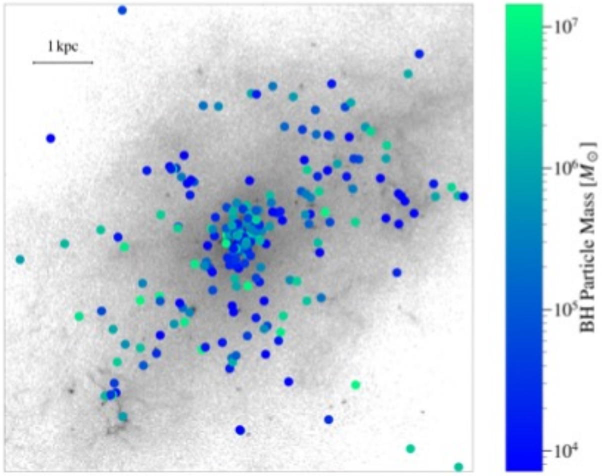

Redshift 11.448

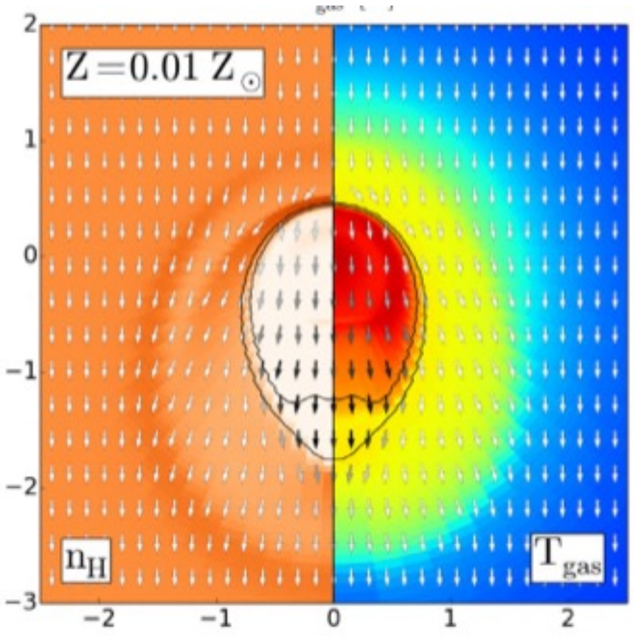
Redshift 9.481

Redshift 8.199

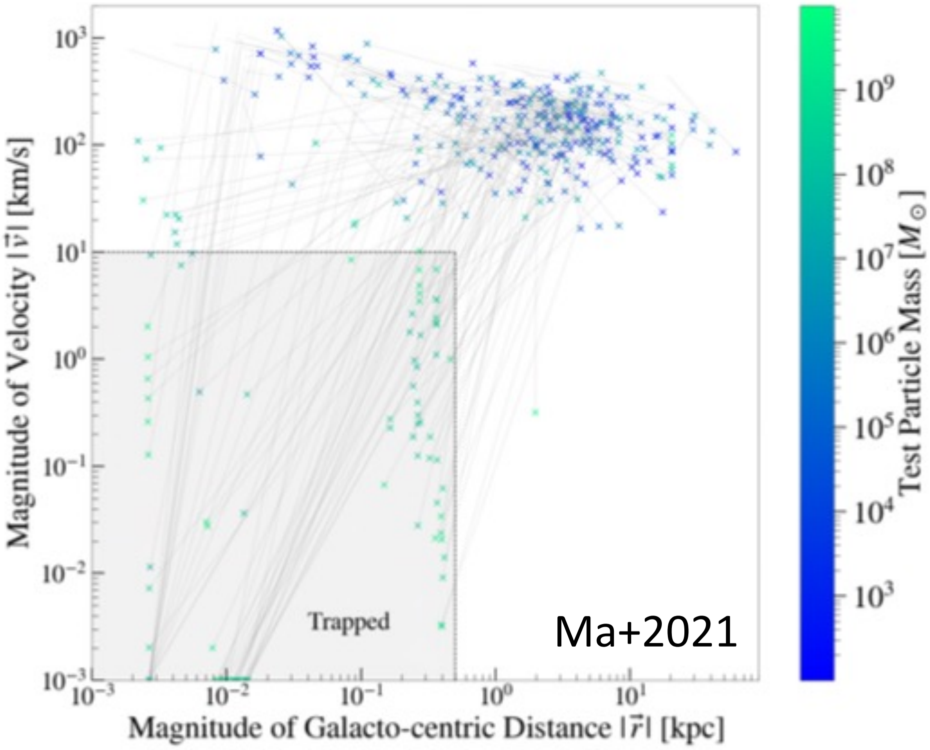
BHの銀河中心への移動

- 10^8 $M_\odot$より重いBHだけ力学摩擦によって銀河中心に落ちる (Ma+21)
- BHからの輻射を考慮すると力学摩擦はさらに弱まるはず(Park+17; DT+20)





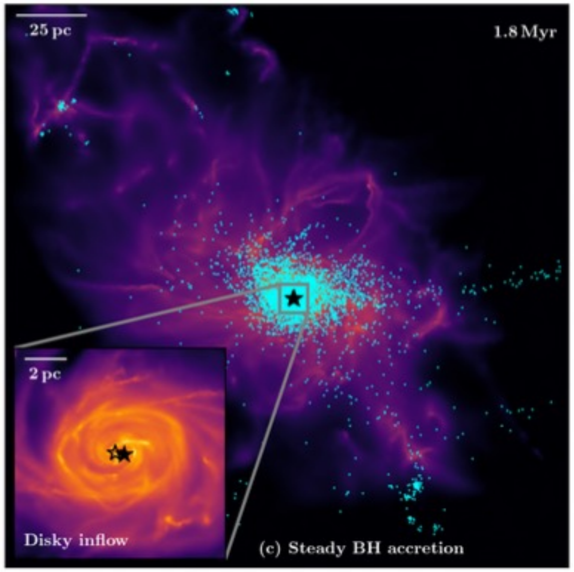
DT+2020



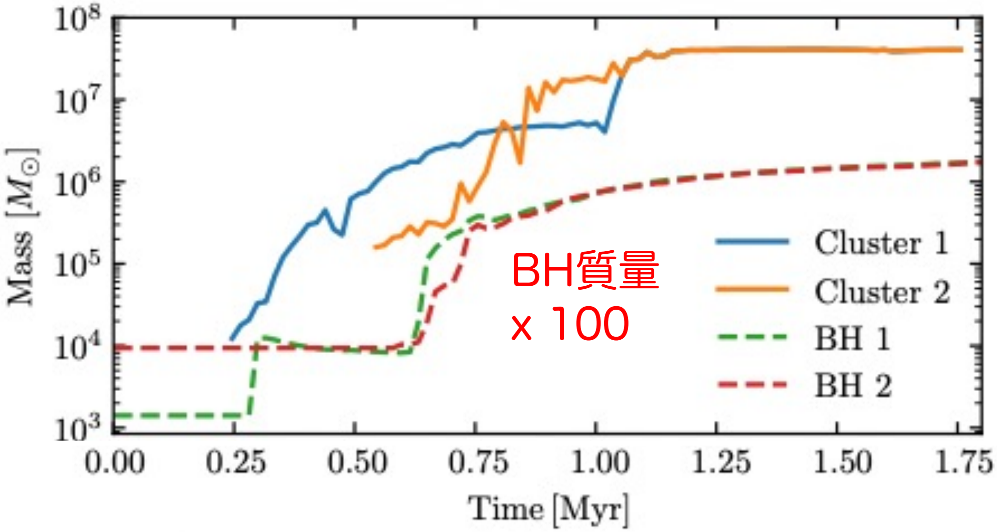
Ma+2021

Shi et al. (2023, 24a,b)

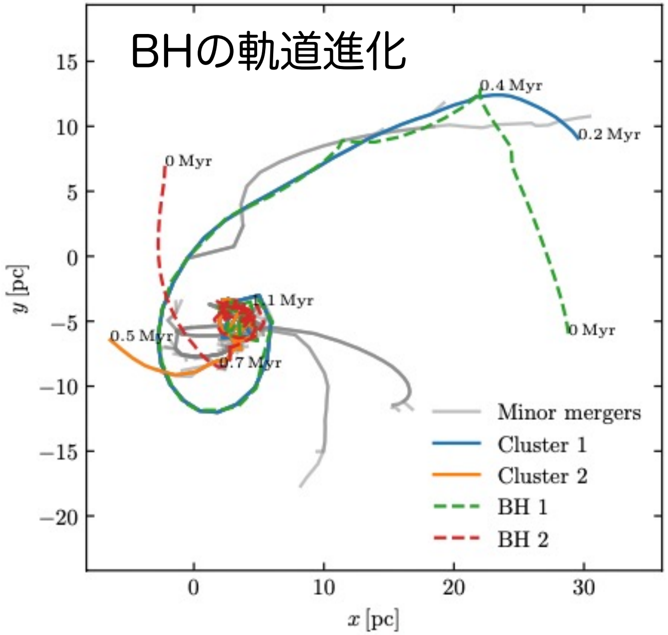
- 星形成 ＋ BH質量成長 の孤立系計算
- 初期に１０００個のBHを分子雲内にばら撒く
- 基本的にはBHへのガス降着率は低い。
- ごく一部（1% 以下）のBHは分子雲コアに遭遇。
  - 超臨界降着を経験。
  - 分子雲コアとともに星団中心に落ちる。
- 銀河進化の文脈で起こりうるか？



星団とBHの質量成長



BH質量
x 100


BHの軌道進化

まとめ

- 輻射流体シミュレーションを用いたBHへのガス降着過程の研究でULXや高赤方偏移AGNについて理解を深めたい。
- 円盤が十分光学的に厚いときはBHからボンディ半径のスケールからBHへ流れ込む超臨界降着が実現する。
- 一方で、円盤内縁の光子捕獲半径付近から大規模なアウトフローが吹くため、BHへ降着するガスは全体の1~10%程度になる。
- BHとホスト銀河の長期的共進化が課題。現状の銀河形成シミュレーションはBH成長を過小評価する。銀河スケールからBH重力圏にガスを供給するメカニズムについて理解する必要がある。
- ホストハローの合体によりBHは必ずしも銀河中心にいるとは限らない。銀河中のBHの質量成長と力学進化を整合的に扱う必要がある。