3次元輻射流体計算で探る超大質量ブラックホールの起源
～浮遊する種ブラックホールへの超臨界降着過程～

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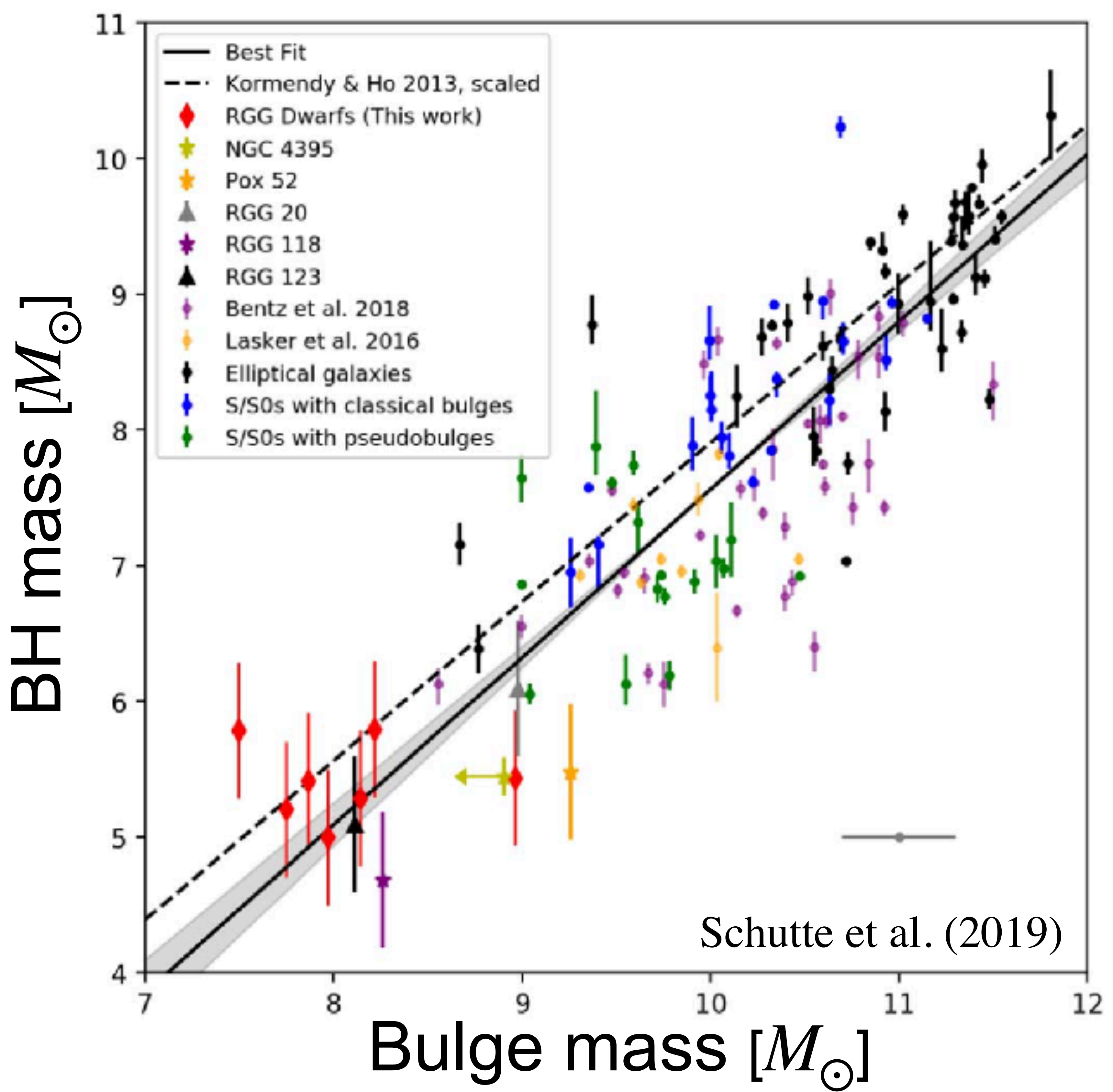
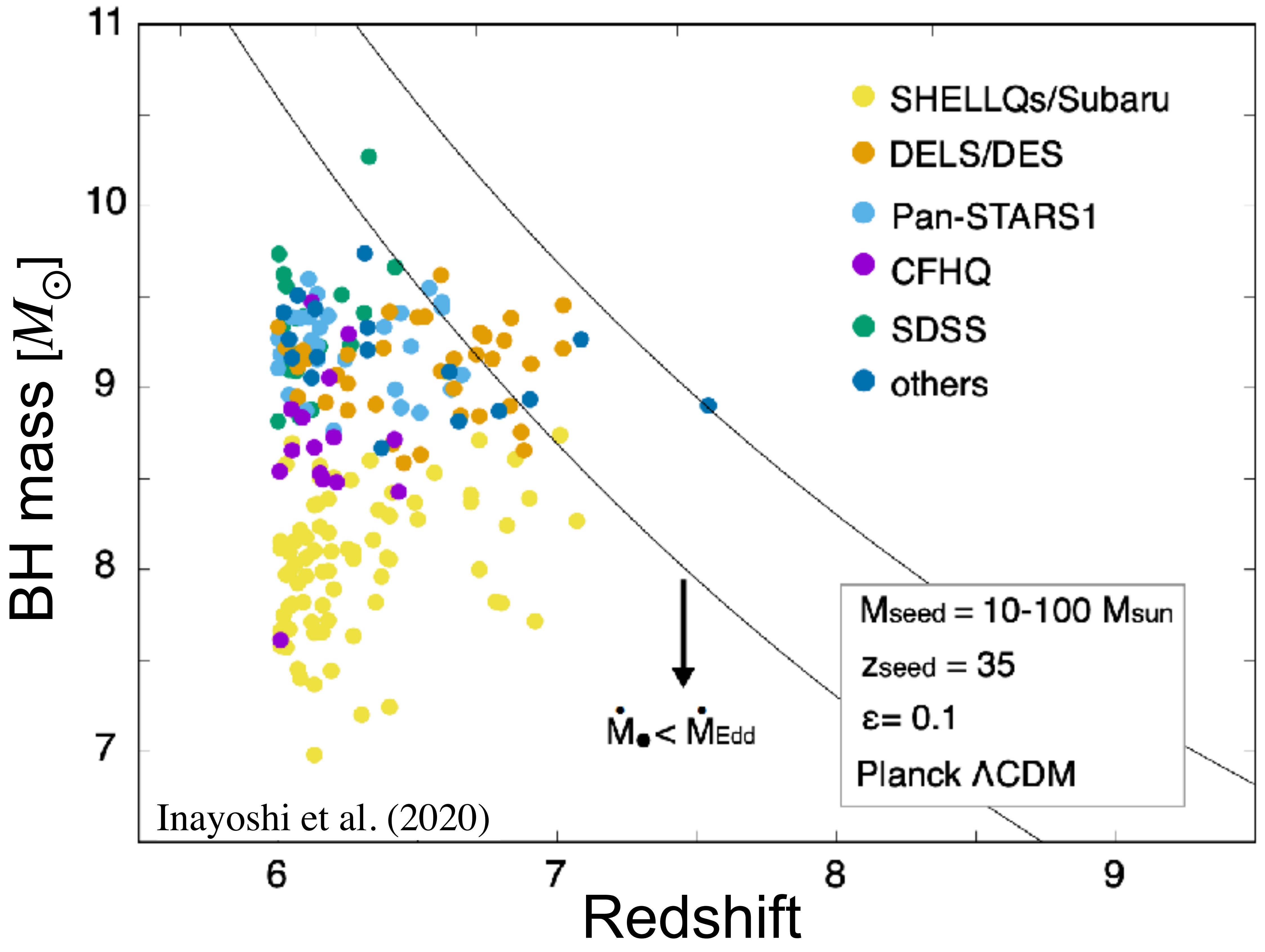
Supermassive Black Hole

- It exists universally at the center of the galaxies
- There is a strong relation with the bulge mass of the host galaxies (left Fig.)
- It already exists even in the early universe $z \gtrsim 7$ (right Fig.)

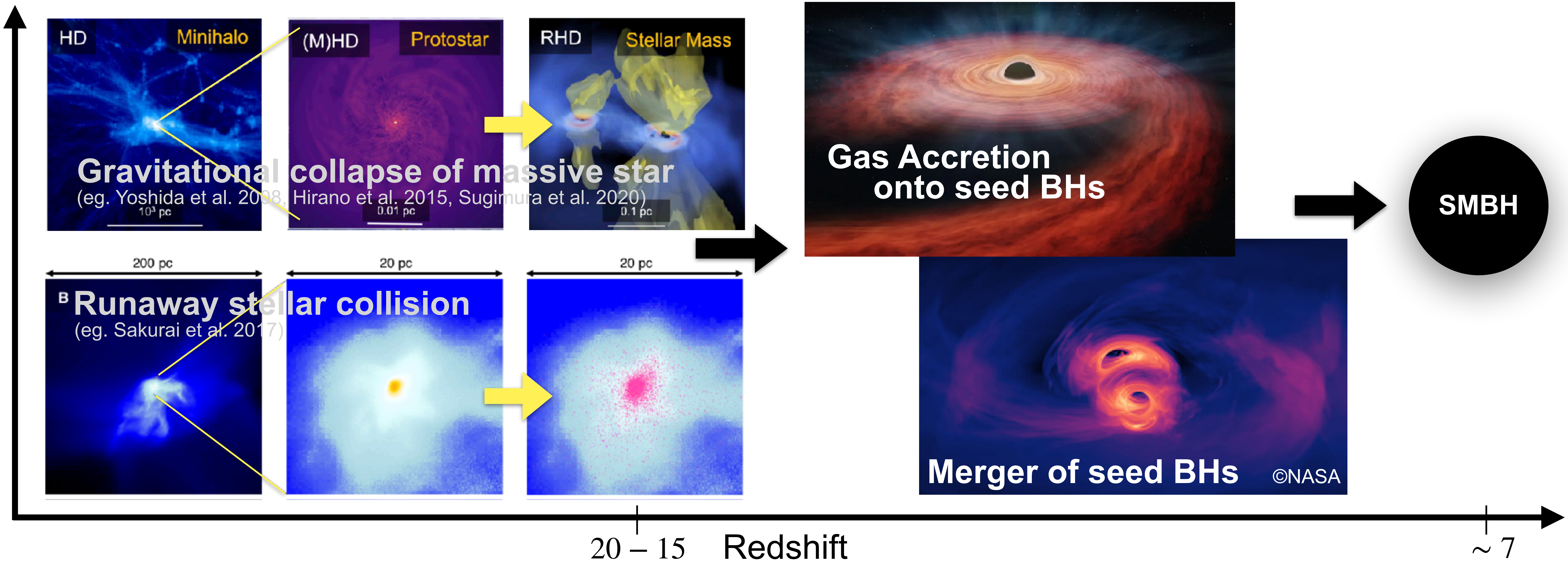
→**How is the supermassive BH born? (Open question in astronomy)**





Theoretical scenario of formation of SMBHs

- The formation process of supermassive black holes consists of 2 steps.
  ① Birth of seed BHs with a mass of $10^{2-5} M_\odot$
  ② Growth of the seed BHs to SMBHs (via Gas accretion, Merger with other BHs/stars)



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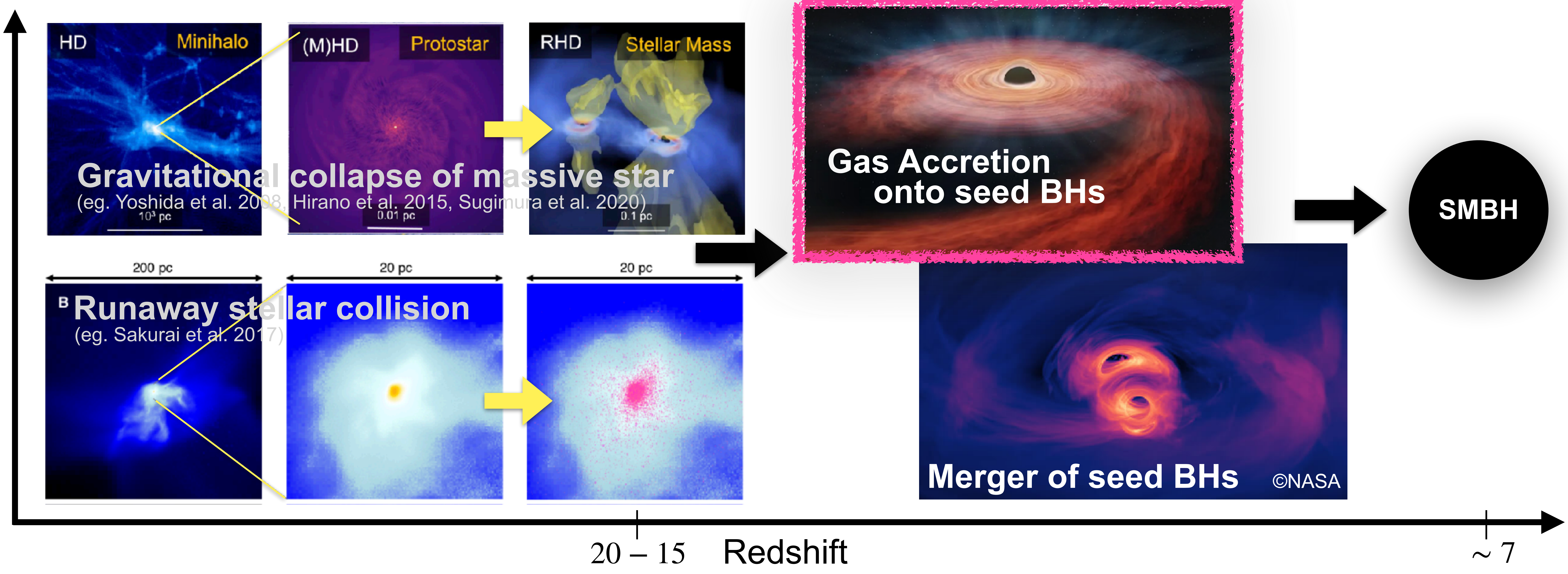
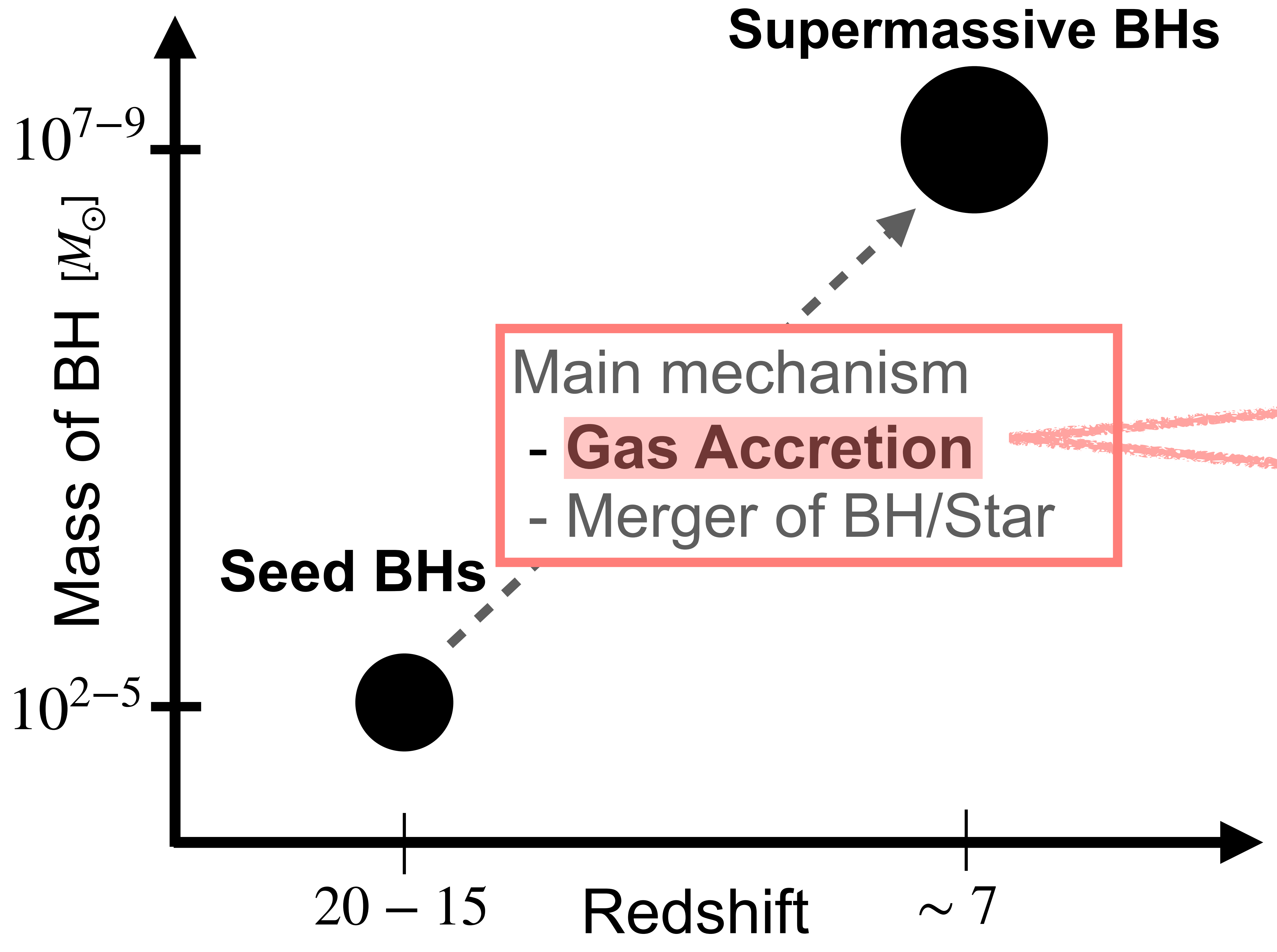
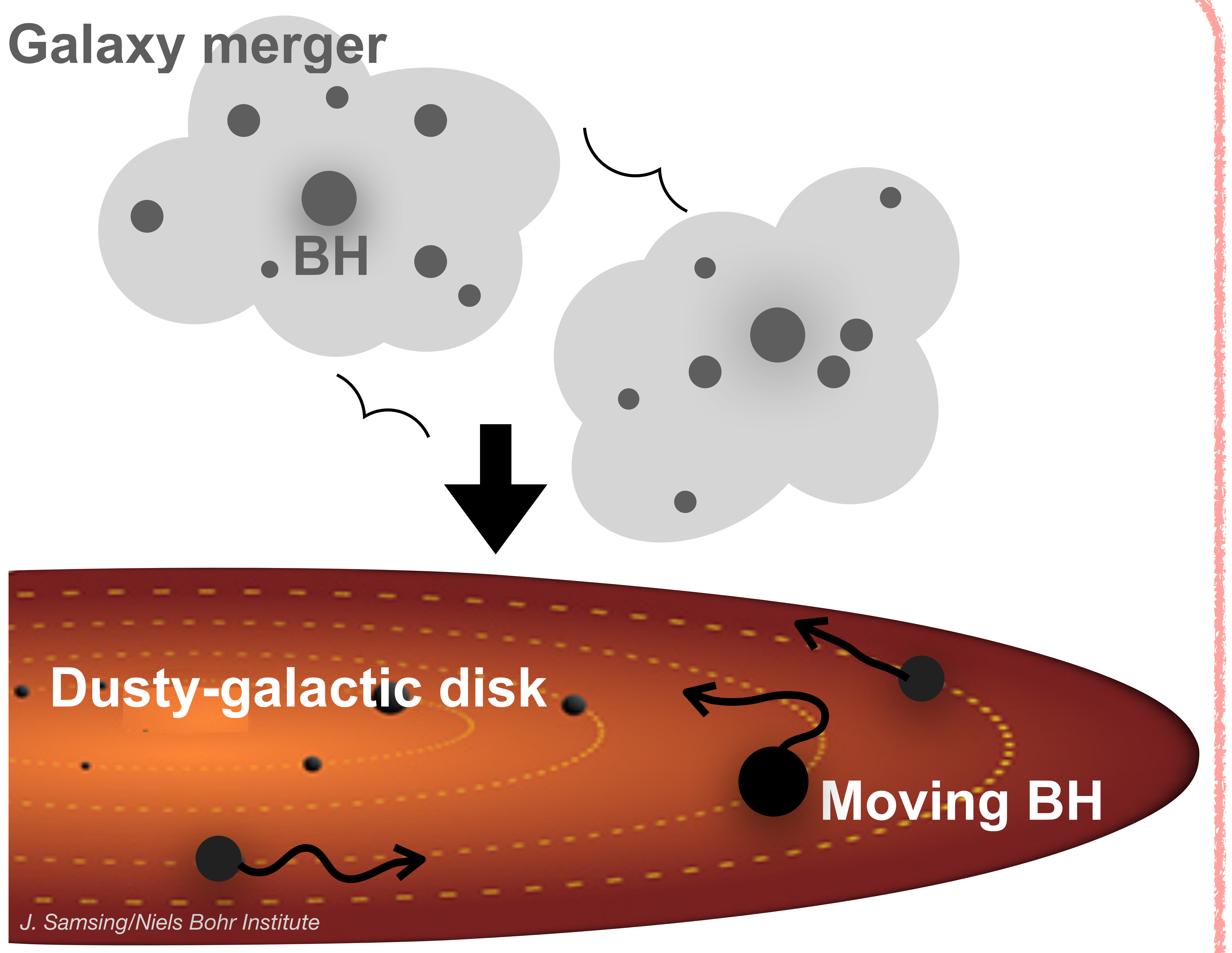
"We focus only this process" (~pc scale)



What do we do?

- To contribute to understanding of the formation process of SMBHs, we investigate gas **accretion mechanism of the seed BHs <u>floating in the dusty remnant galactic gas</u>**



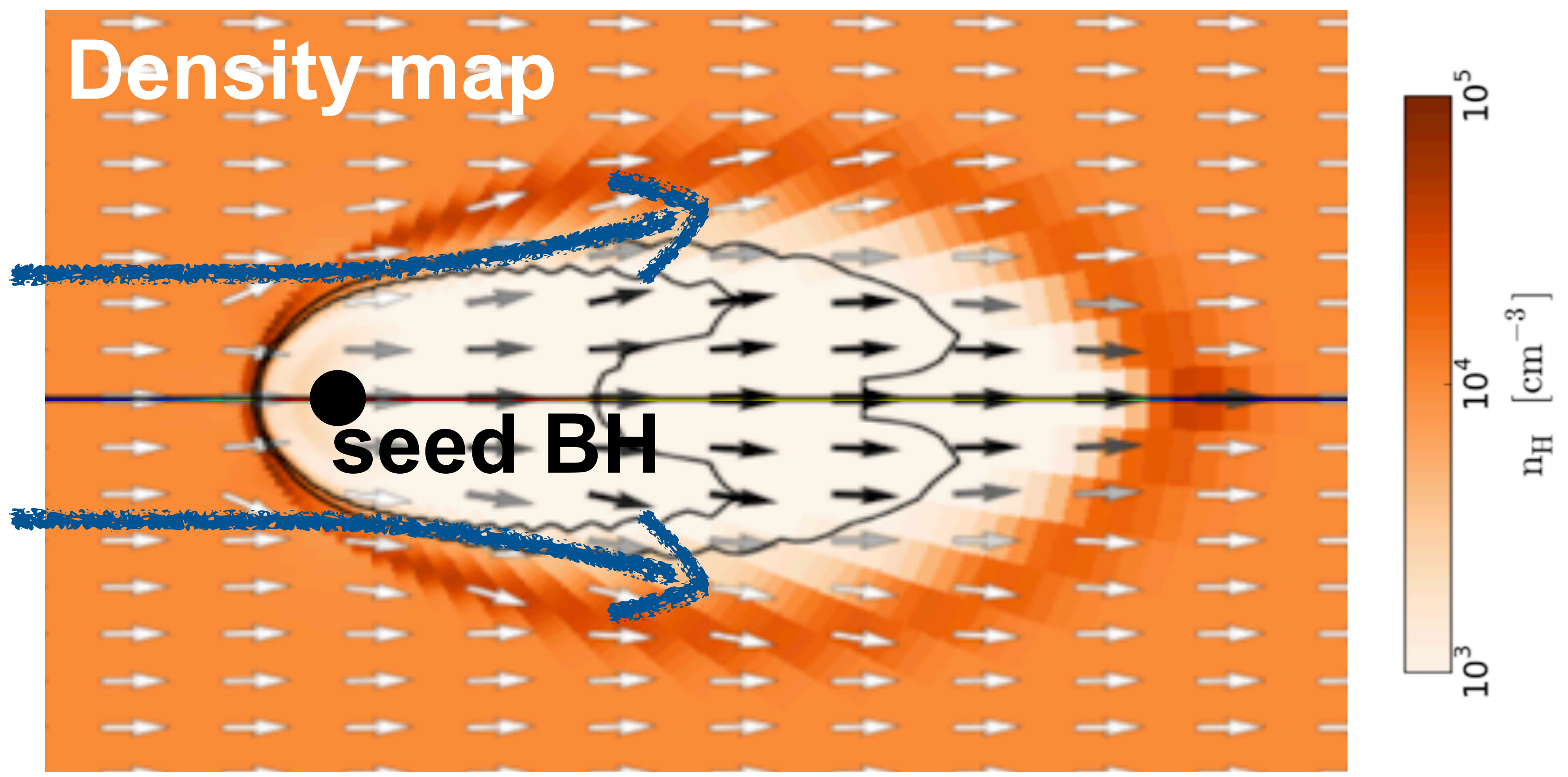


Q. <u>How much is the accretion rate?</u>

Previous studies of moving objects in dusty-gas

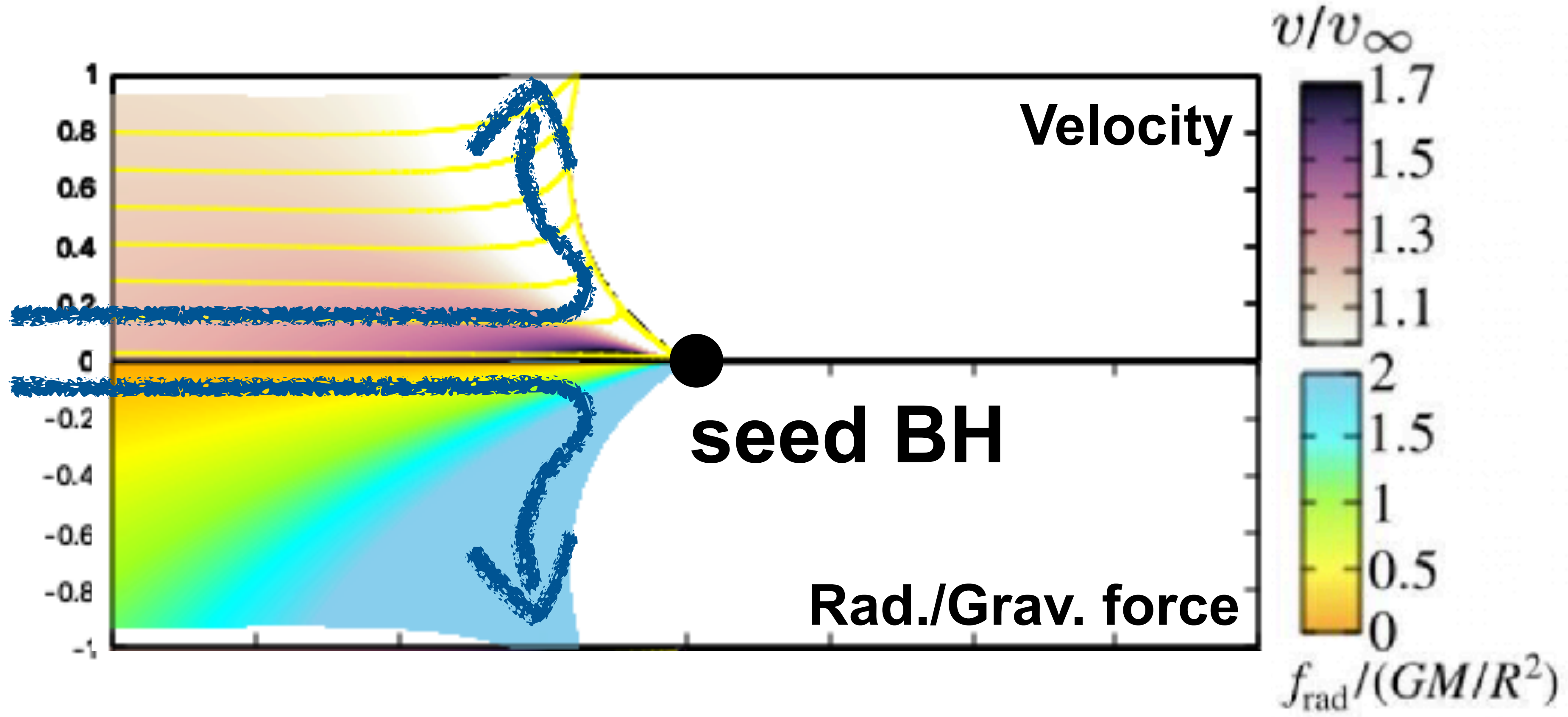
- Toyouchi et al. 2020

  3D-**radiation hydrodynamics** sim.
  assuming the **isotropic radiation**



- Ogata et al .2021

  Non-hydrodynamics calculation
  assuming the **anisotropic radiation**



These works indicate that

both the hydrodynamics and the anisotropy of the radiation are important factors for the growth rate of seed BHs in dusty-gas

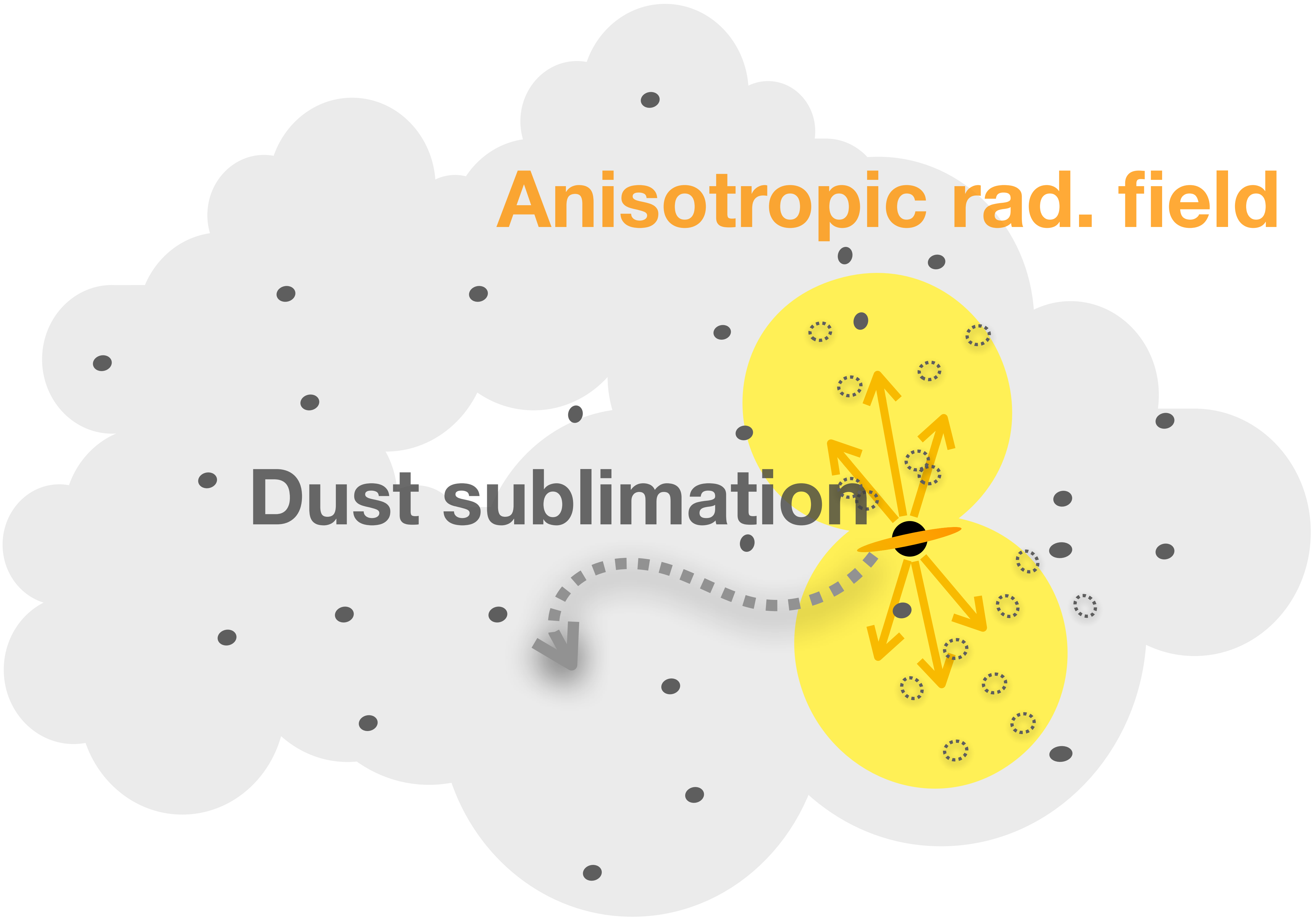
What are our strengths?

- In general, the BHs have accretion disks, and they produce anisotropic radiation field
- Such strong radiation heats and sublimates dust grains

- We perform **3D-Radiation Hydrodynamics simulations**

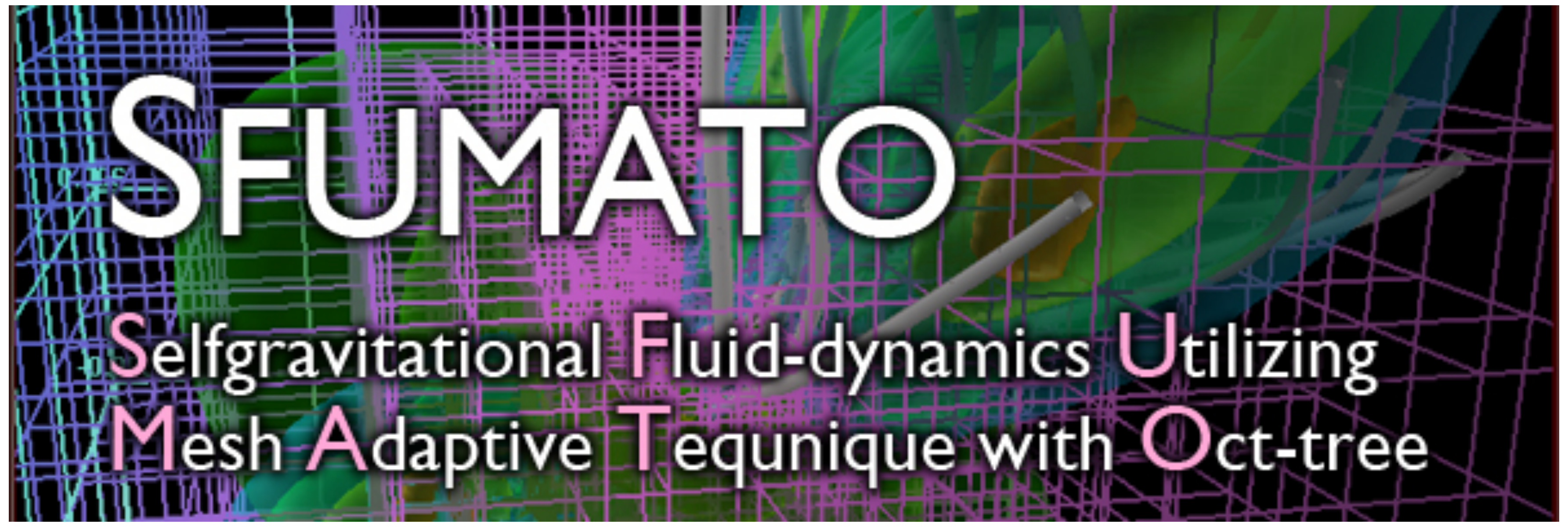
- considering the **Anisotropic radiation** and **Sublimation of the dust**

	Hydro-dynamics	Radiation	Dust sublimation
Toyouchi+2020	○	Isotropic	×
Ogata+2021	×	Anisotropic	×
This work	○	Anisotropic	○



Methods

- We use the 3D-radiation hydrodynamics sim. code **SFUMATO-M1** (Fukushima & Yajima 2021) with the adaptive mesh refinement, the modified ver. of **SFUMATO** (e.g.Matsumoto 2007) and **SFUMATO-RT** (Sugimura+2020).



Radiation hydrodynamics eq.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \nabla(\rho \boldsymbol{v} \otimes \boldsymbol{v}) + \nabla P = \rho(\boldsymbol{g} + \boldsymbol{f})$$

$$\frac{\partial (\rho E)}{\partial t} + \nabla[(\rho E + P)\boldsymbol{v}] = \rho(\boldsymbol{g} + \boldsymbol{f}) \cdot \boldsymbol{v} + \Gamma - \Lambda$$

$$E = \frac{|\boldsymbol{v}|^2}{2} + (\gamma - 1)^{-1}\frac{P}{\rho}$$

Moment eq. (M1 closure)

$$\frac{\partial E_{\rm rad}}{\partial t} + \nabla \cdot \boldsymbol{F}_{\rm rad} = S - \alpha_{\rm E}\tilde{c}E_{\rm rad}$$

$$\frac{1}{\tilde{c}}\frac{\partial \boldsymbol{F}_{\rm rad}}{\partial t} + \tilde{c}\nabla \cdot \boldsymbol{P} = -\alpha_{\rm F}\boldsymbol{F}_{\rm rad}$$

$$\boldsymbol{P}_{\rm rad} = E_{\rm rad}\boldsymbol{D}$$

$$\boldsymbol{D} = \frac{1-\chi}{2}\boldsymbol{I} + \frac{3\chi - 1}{2}\boldsymbol{n} \otimes \boldsymbol{n} \quad , \boldsymbol{n} = \frac{\boldsymbol{F}}{|\boldsymbol{F}|}$$

$$\chi = \frac{3 + 4f^2}{5 + 2\sqrt{4 - 3f^2}} \quad , f = \frac{|\boldsymbol{F}|}{\tilde{c}E}$$

Chemical networks

$$\frac{\partial (y_i n_{\rm H})}{\partial t} + \nabla \cdot (y_i n_{\rm H} \boldsymbol{v}) = n_{\rm H} R_i$$

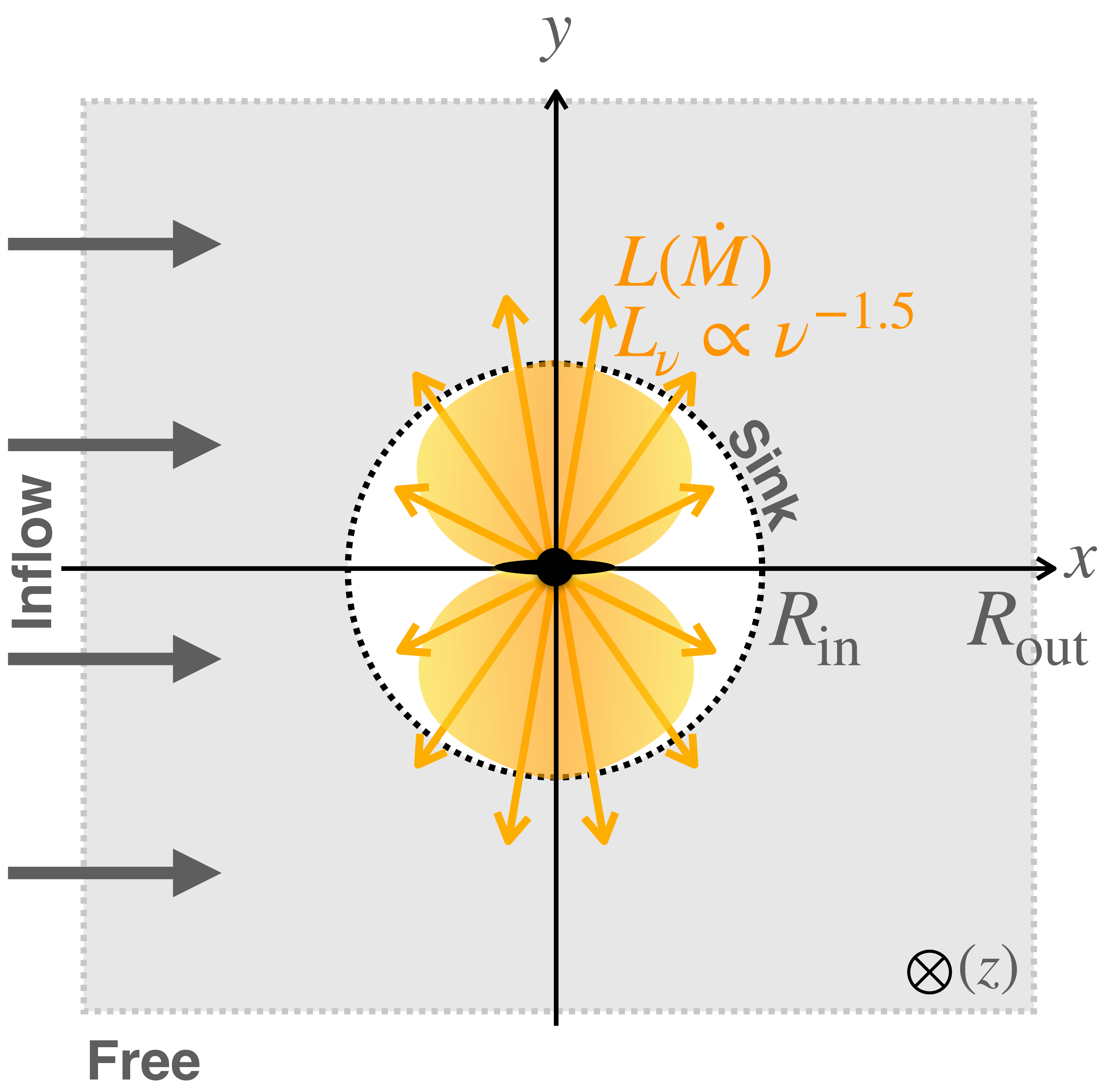
H, H_2, H^+, H^-, H_2^+

$CO, C^+, O, O^+, O^{2+}, e$

ρ : density
$\boldsymbol{v}$: velocity
P : pressure
E : total energy
$\boldsymbol{g}$: gravity
$\boldsymbol{f}$: radiation force
Γ : heating rate
Λ : cooling rate
$E_{\rm rad}$: radiative energy density
$\boldsymbol{F}_{\rm rad}$: radiative flux
$\boldsymbol{P}_{\rm rad}$: radiative pressure tensor
$\alpha_{\rm E}$: absorption coefficient
$\alpha_{\rm F}$: absorption coefficient
$\tilde{c}$: reduce light speed
y_i : $n_i/n_{\rm H}$
R_i : chemical reaction rate

Simulation Settings

- **We mask the BH accretion disk by the sink region and inject ionizing photons at the inner boundary with anisotropy ($\propto \cos\theta$)**



- **Sink radius** $R_{\rm in} = 2 \times 10^{-3}{\rm pc}$

  <Dust sublimation radi.

- **Simulation box size** $R_{\rm out} = 2 \times 10^{1}{\rm pc}$

  ≫Ionized region & Bondi-Hoyle-Lyttleton radi.

- **Luminosity** $L = \begin{cases} 2L_{\rm E}\left[1 + \ln\left(\frac{\dot{M}}{2\dot{M}_{\rm E}}\right)\right] & (\dot{M}/\dot{M}_{\rm E} > 2) \\ L_{\rm E}\frac{\dot{M}}{\dot{M}_{\rm E}} & ({\rm otherwise}) \end{cases}$

- **Spectrum** $L_\nu \propto \nu^{-1.5}$

Simulation Models

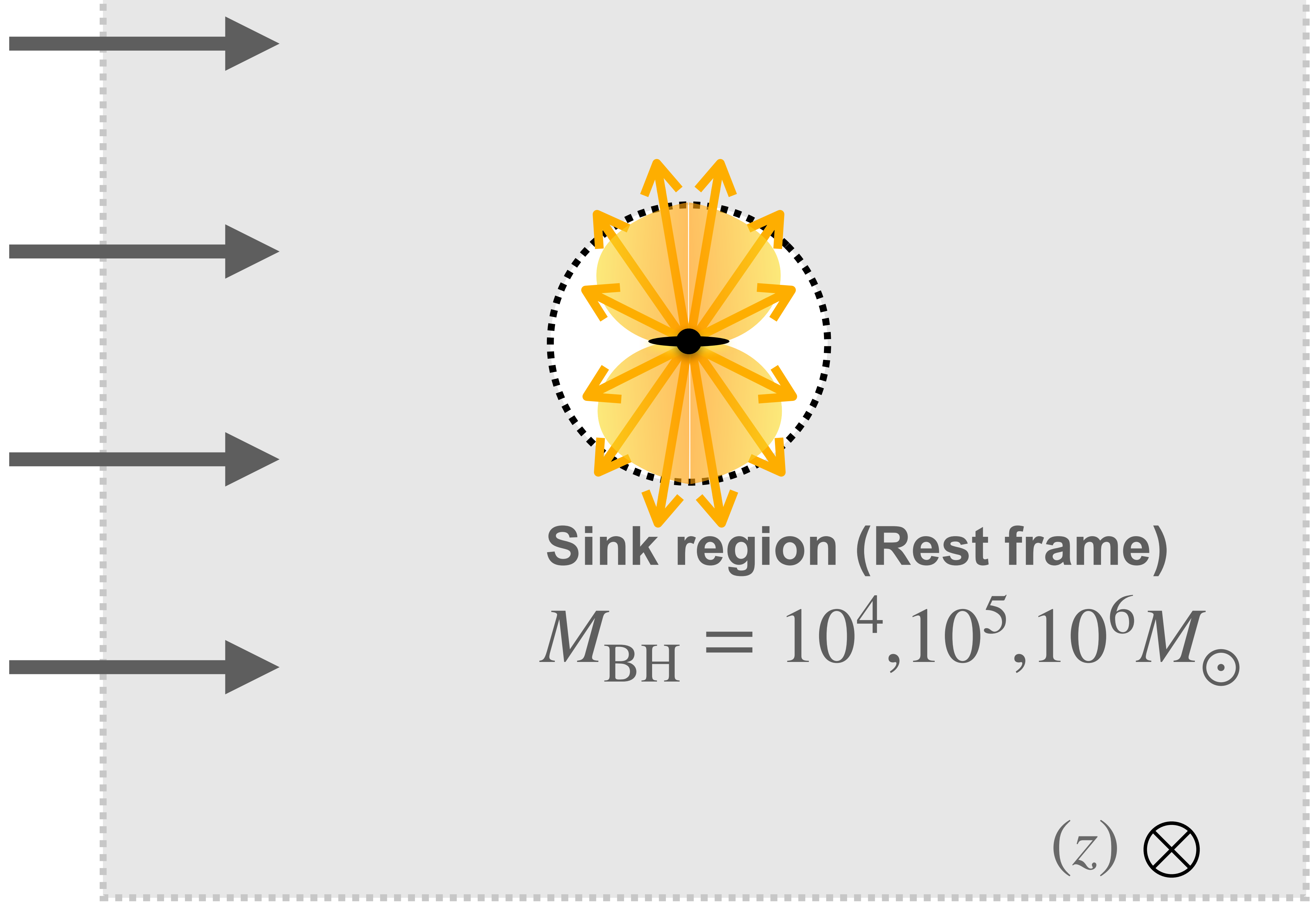
Parameters

$Z = 0.1 Z_\odot$

$T_\infty = 180$ K

$v_\infty = 10, 20, 40, 80, 100$ km/s

$n_\infty = 10^3, 10^4, 10^5, 10^6$ /cm^3



Fiducial model

BH mass : $M_{BH} = 10^4 M_\odot$

Gas velocity : $v_\infty = 20$ km/s

Gas number density : $n_\infty = 10^4$ cm^{-3}

Gas temperature : $T_\infty = 180$ K

Metallicity : $Z = 0.1 Z_\odot$

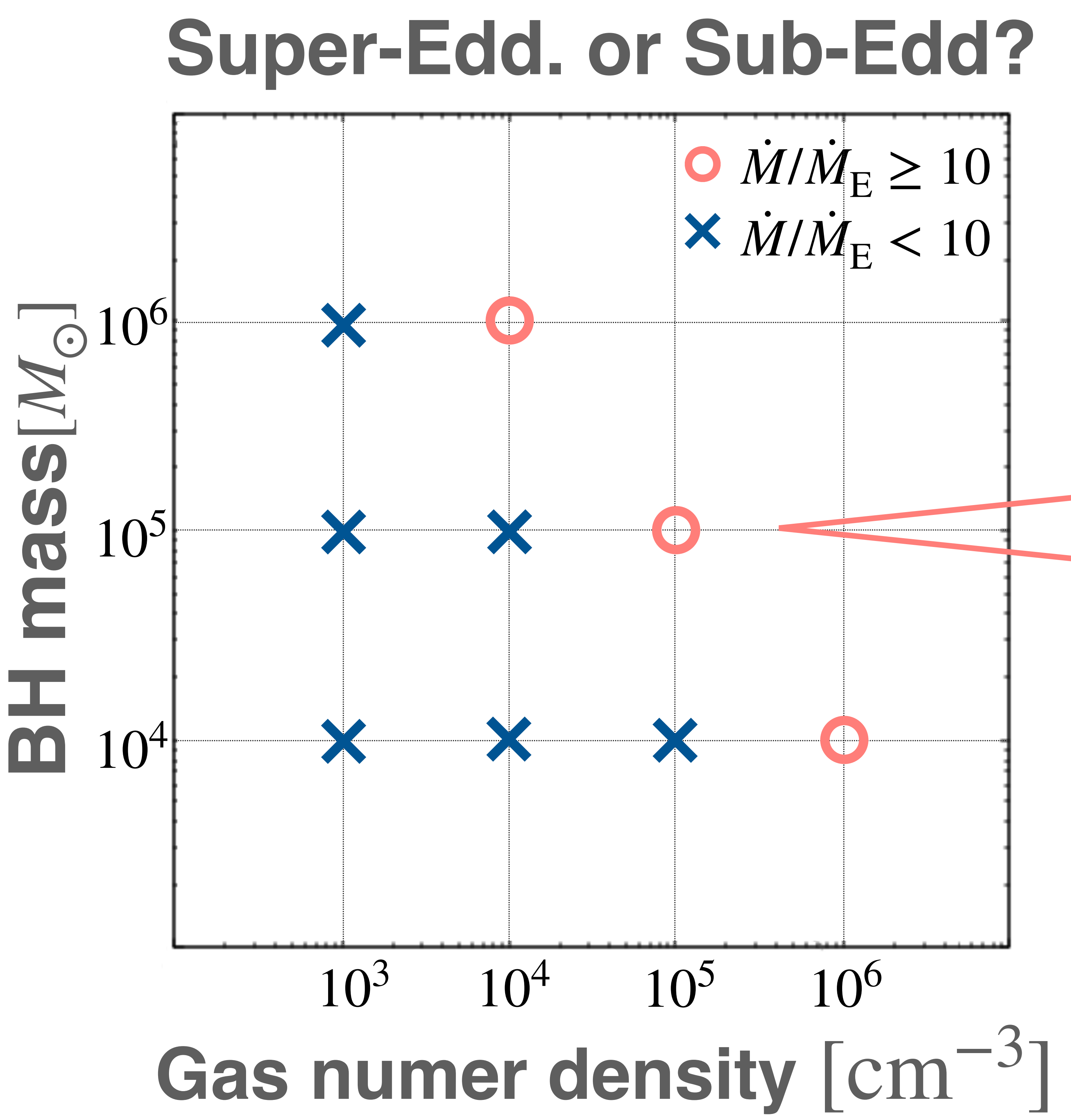
Disk inclination : edge-on

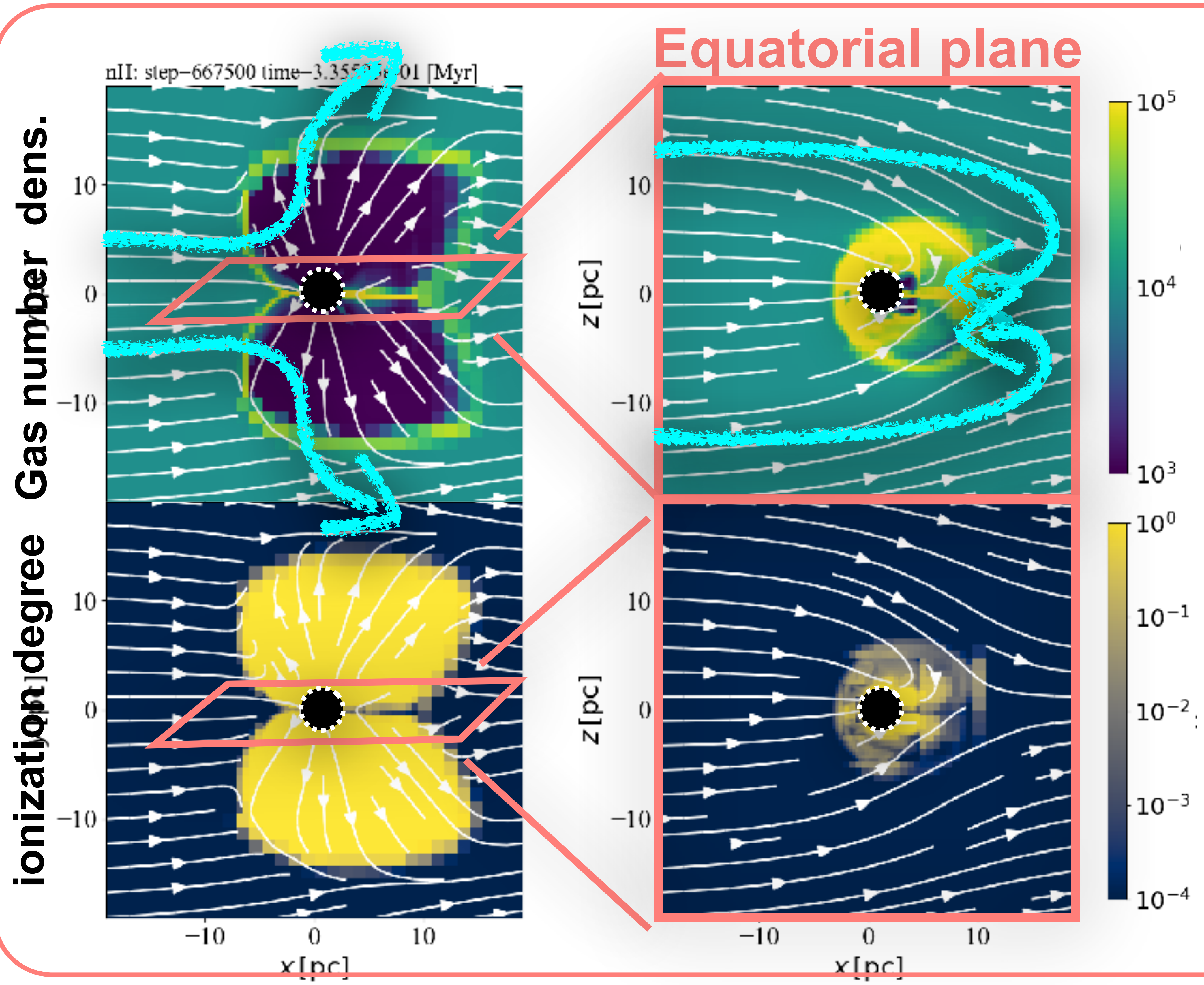
※Why do we choose these values as a fiducial model?

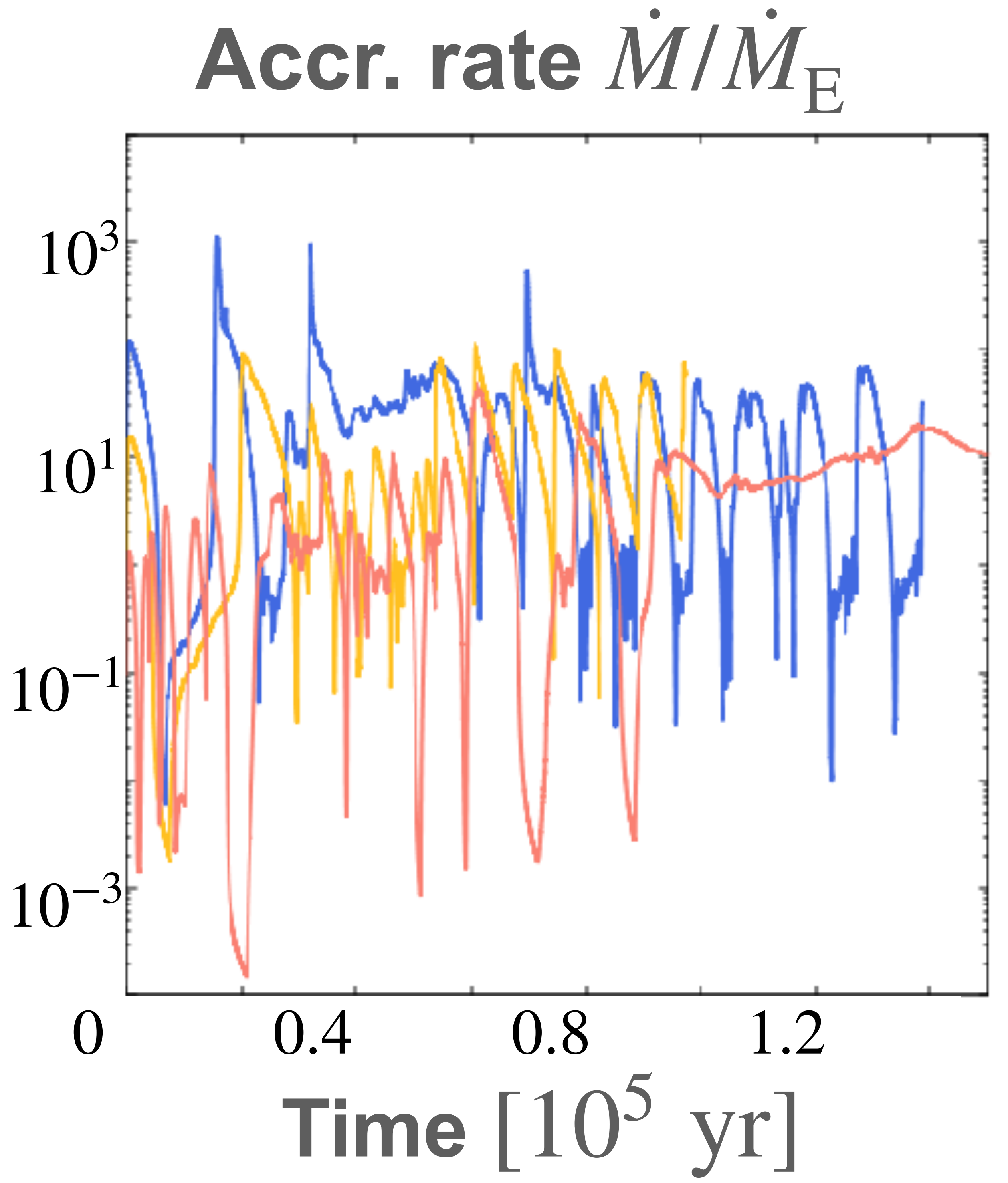
- Cosmological sim. show the flow structure with these values (in the remnant galaxies)

Mass accretion rate onto seed BHs

- **Time-averaged accr. rate could be Super-Eddington rate** ($\dot{M}/\dot{M}_{\rm E} \geq 10$, $\dot{M}_{\rm E} \equiv L_{\rm E}/c^2$) **if** $M_{\rm BH} n_\infty \gtrsim 10^{10}\ [M_\odot {\rm cm}^{-3}]$ (left Fig.)
- **Super-Eddington accr. occurs only by gas accr. near the equatorial plane** (middle Fig.) (Collapse of the ionization region (e.g. Inayoshi+2016) is not a necessary condition)
- The accretion occurs intermittent (right Fig.)





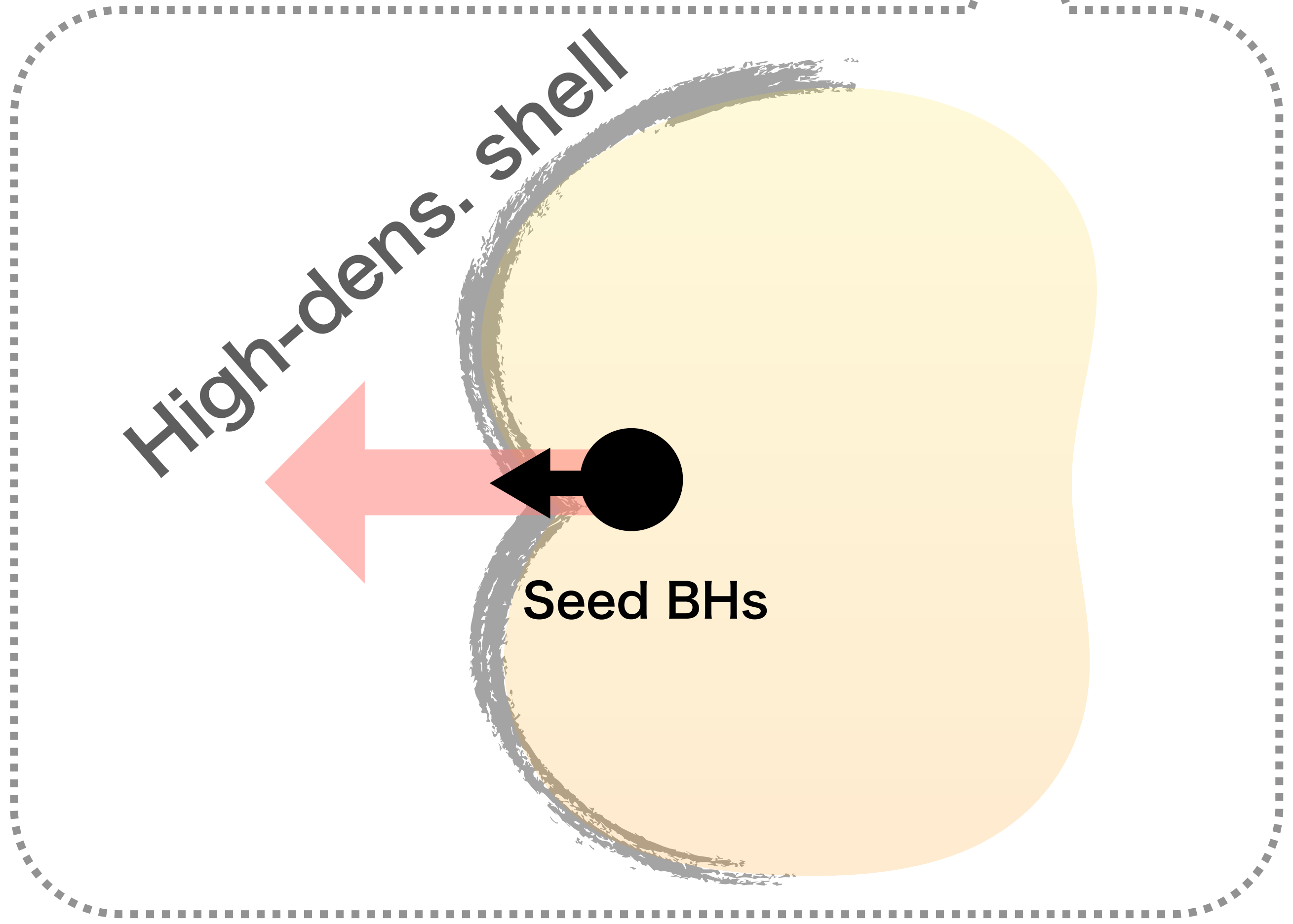


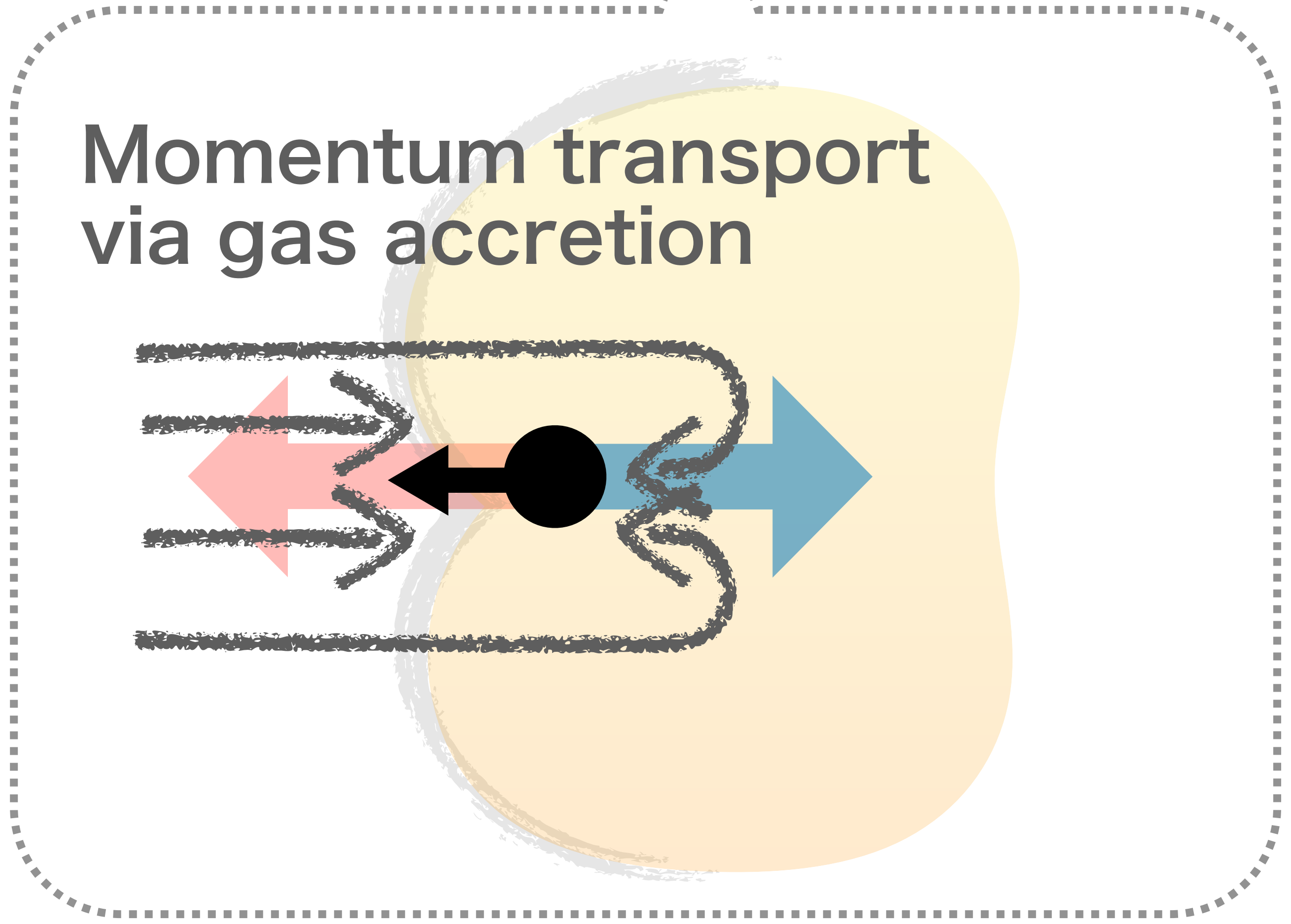
Acceleration of seed BHs

- We calculate the acceleration of seed BHs using the density and velocity distribution obtained from our simulations (below eq.)
- **In the dusty-gas for $n_\infty \lesssim 10^5\ [\mathrm{cm}^{-3}]$, seed BHs moving at $\gtrsim \mathrm{several} \times 10 \mathrm{km/s}$ could accelerate in the direction of its motion**
- **The main factor of acceleration is gravity caused by the high-density shell near the upstream ionization front**

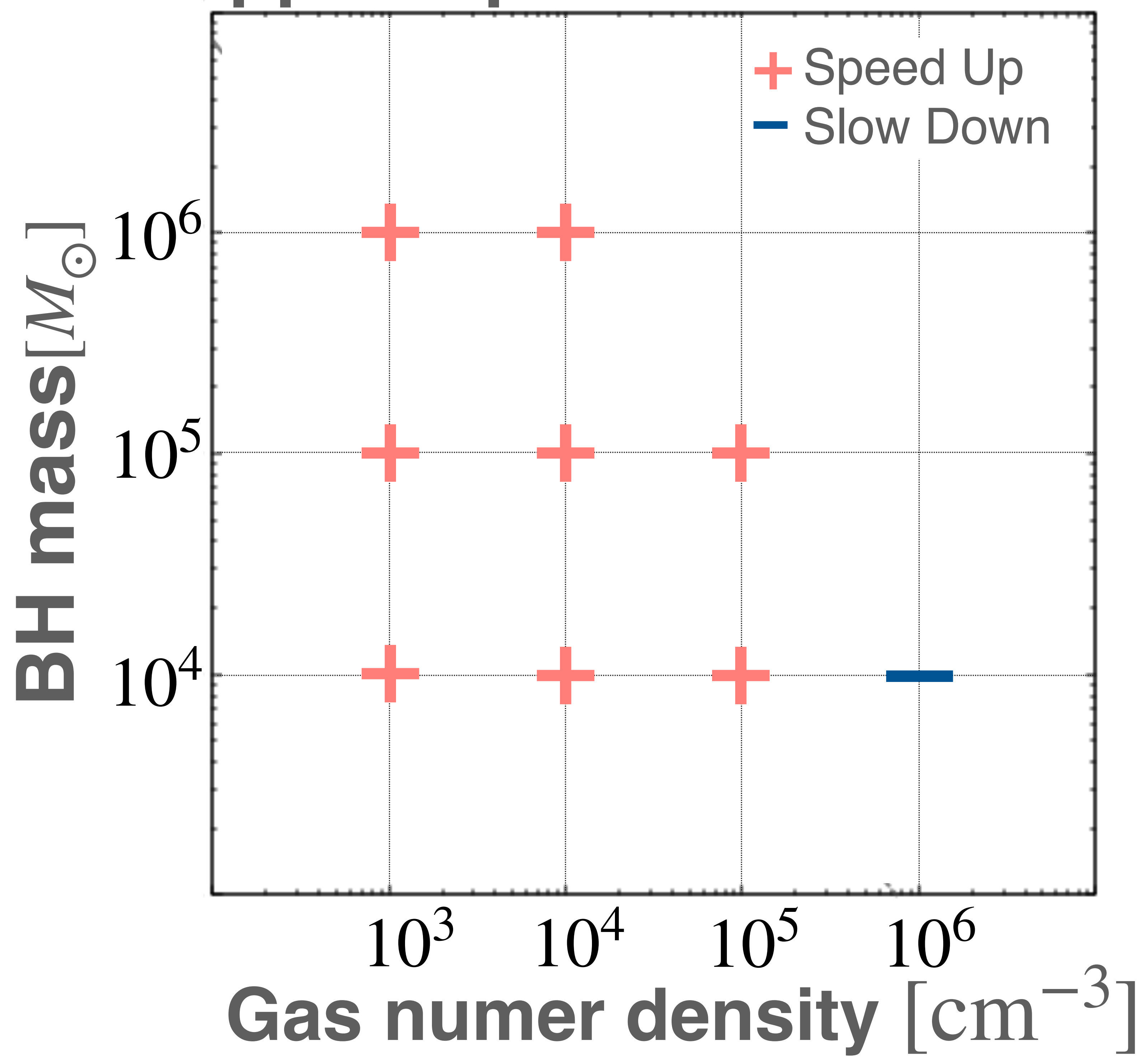
(e.g. Toyouchi+20, Ogata et al. Submitted)

Acceleration $= \int_0^{4\pi} \int_R^{R_\mathrm{out}} \frac{\rho G x}{R'^3} dR' d\Omega + \int_{S_\mathrm{sink}} \rho v_x \boldsymbol{v} \cdot d\boldsymbol{S}_\mathrm{sink}$





Spped-up. or Slow-down?



DISCUSSION：Evolution of seed BHs

Accretion rate, acceleration → → Timescales of mass growth (t_M) and velocity change (t_v)

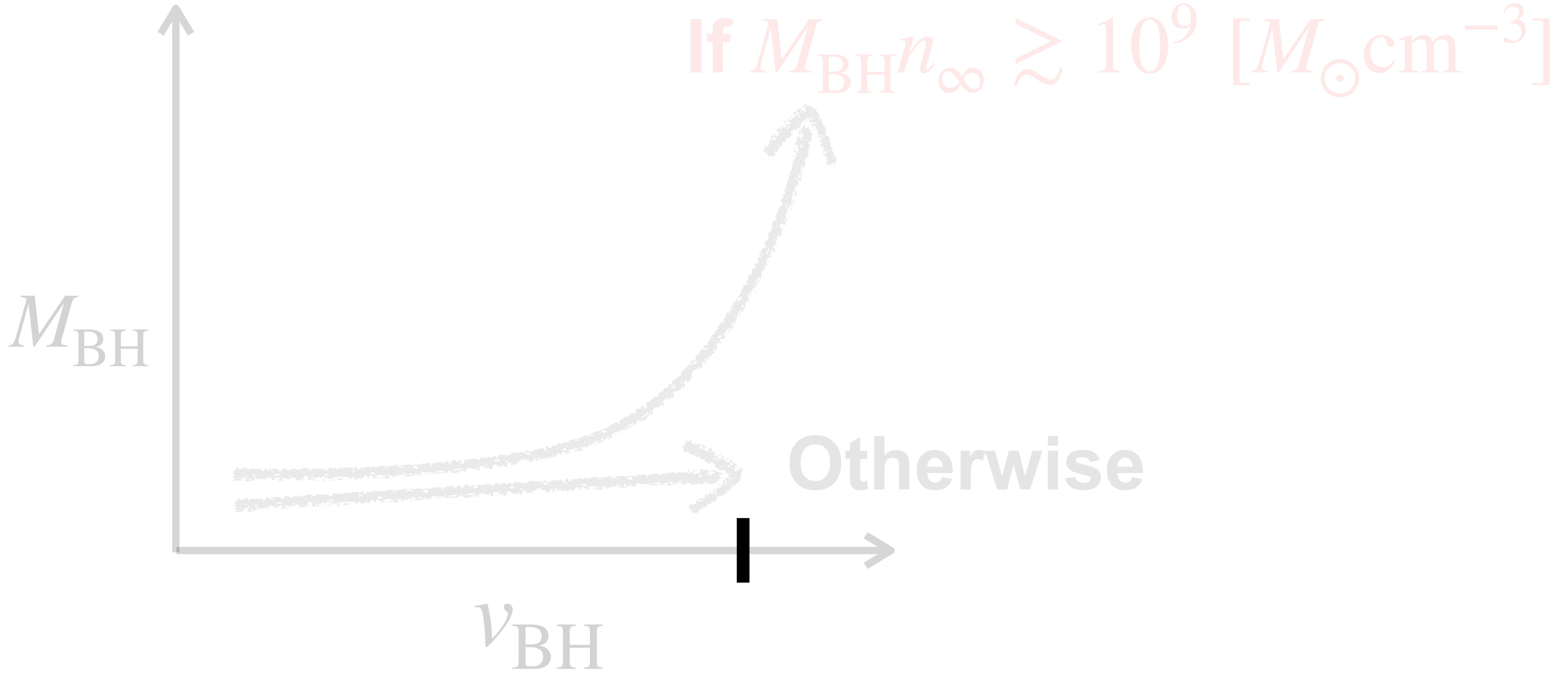
- **In any situation,** t_v **(velocity change)** $\ll t_{z=6}$ **(age of the universe at** $z = 6$**)**

  t_v **(velocity change)** $\ll t_M$ **(mass growth)**

  → Any seed BHs change velocity first and grow in mass later

- **Only if** $M_{\rm BH} n_\infty \gtrsim 10^9\ [M_\odot {\rm cm}^{-3}]$, t_M **(mass growth)** $\ll t_{z=6}$ **(age of the universe at** $z = 6$**)**

  → Seed BHs could grow into supermassive BHs until $z \sim 6$



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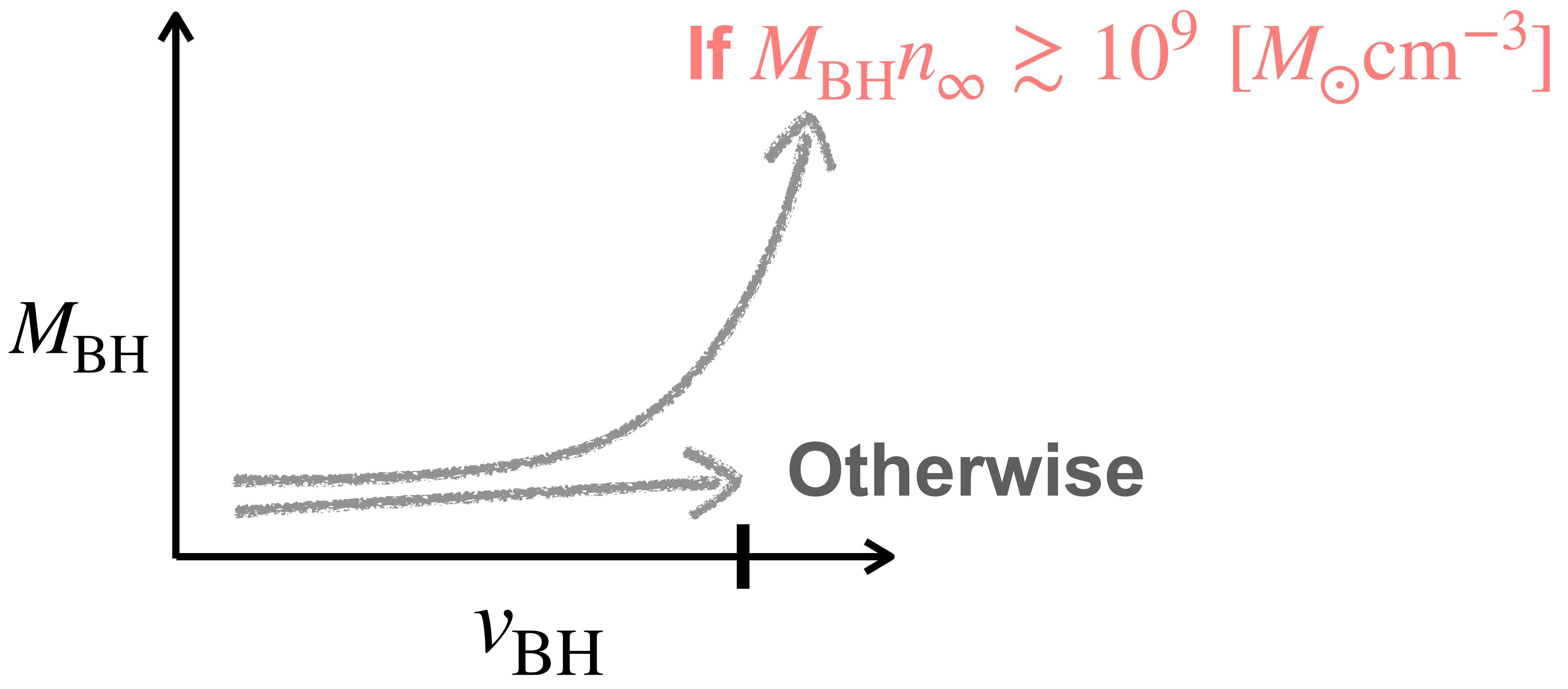
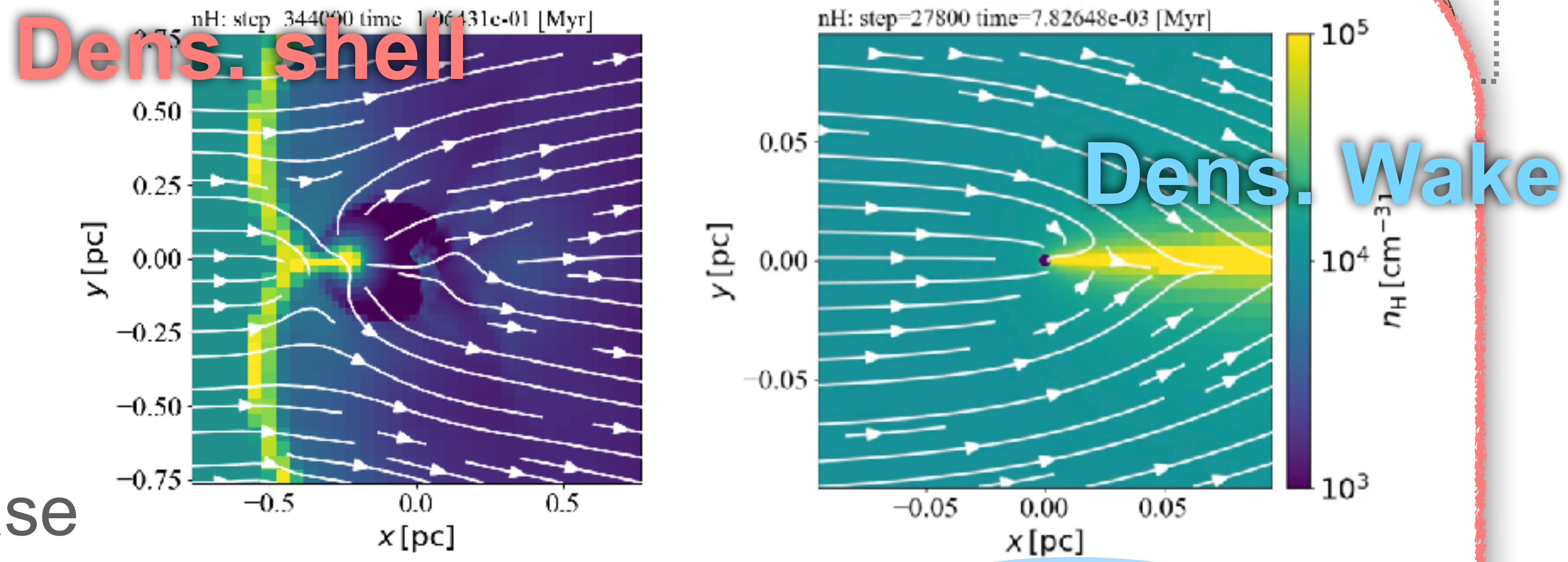
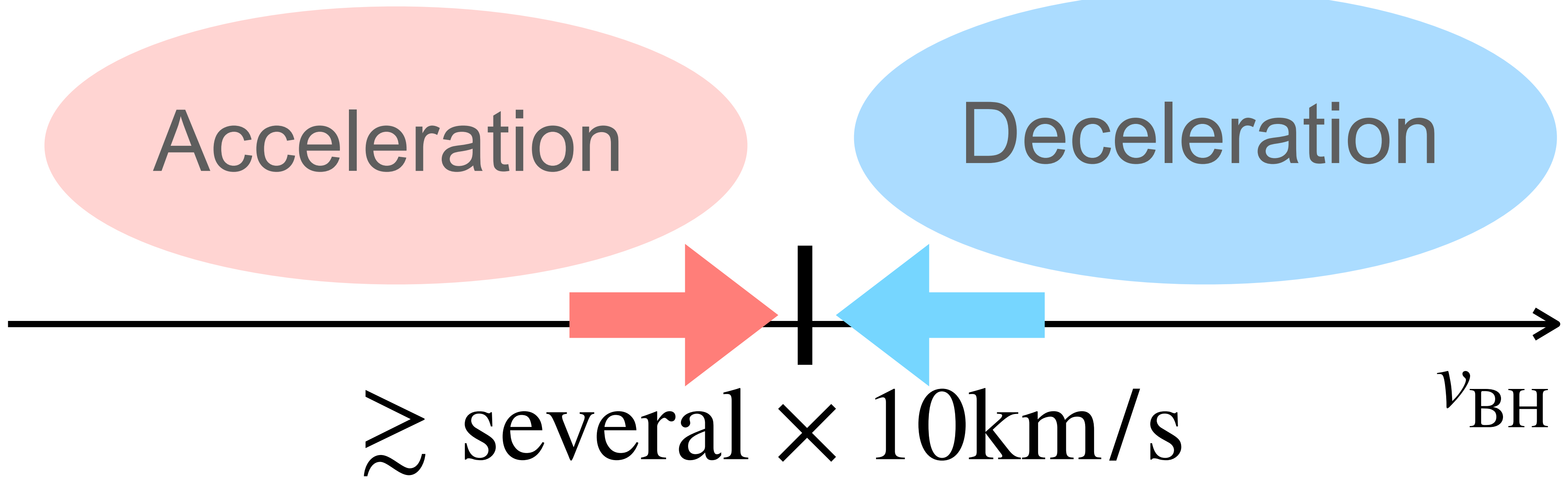


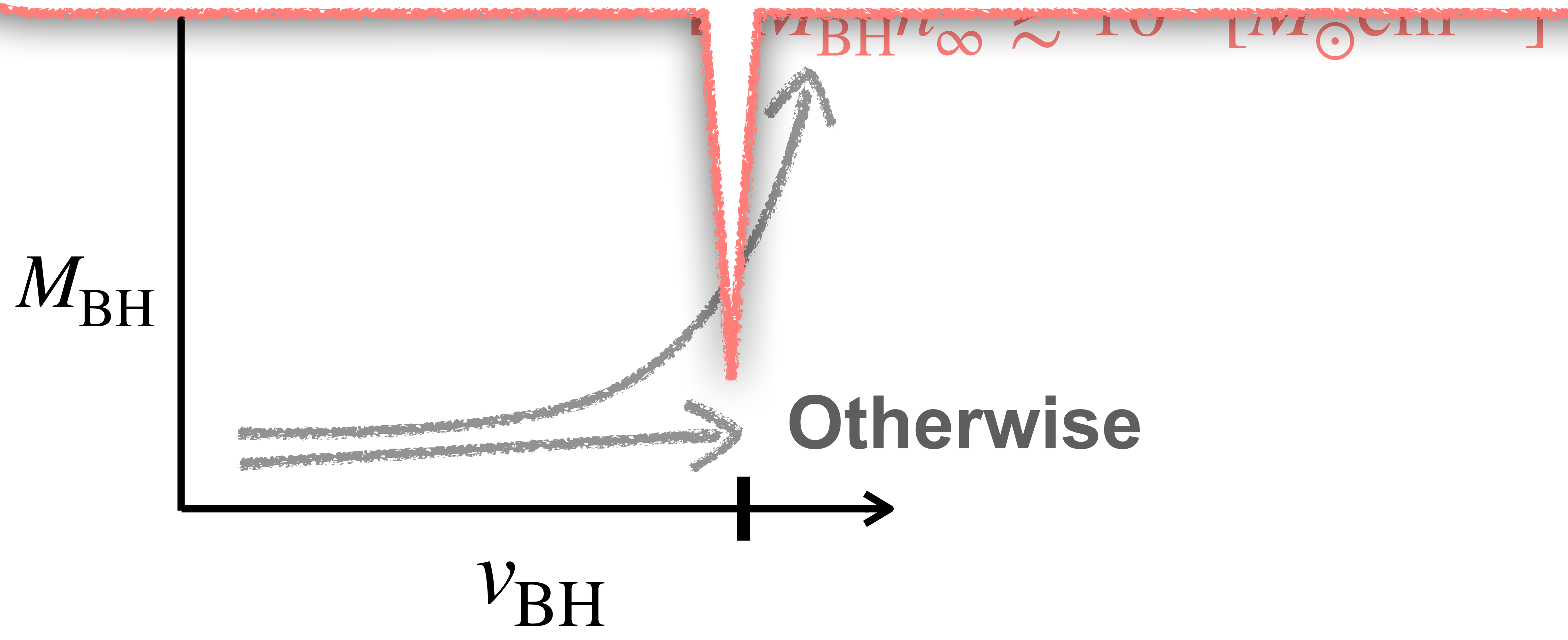
DISCUSSION：Evolution of seed BHs

Note that,

- When the seed BHs accelerate to the velocity of about $\sim 100\ \mathrm{km/s}$, the flow structure becomes similar to the classical Bondi-Hoyle-Lyttleton accretion
- That is, seed BHs are in the deceleration phase (It doesn't keep accelerating all the time)
- Therefore, **the velocity distribution of seed BH could be biased** $\gtrsim \mathrm{several} \times 10\mathrm{km/s}$

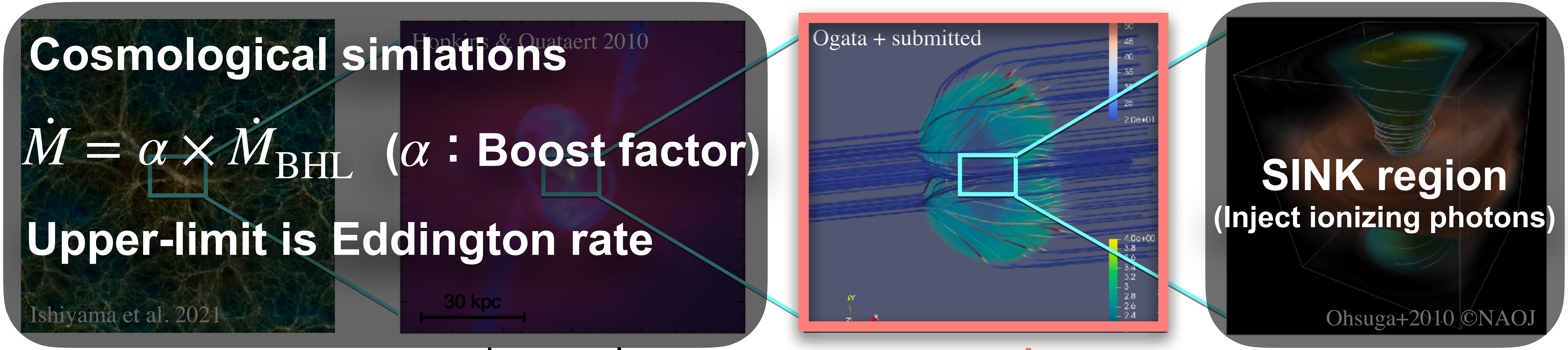






FUTURE WORK

- Because of the huge simulation costs, this study aims to understand the gas accretion mechanism at the sub-pc scale



Mpc scale | kpc scale | **pc scale** | $\ll$ pc scale

- Our redults suggest that

$M_{\rm BH} n_\infty \gtrsim 10^{10}\ [M_\odot {\rm cm}^{-3}]$: $\dot{M} \gg \dot{M}_{\rm Edd}$ (This presentation, Ogata et al. in prep.)

$M_{\rm BH} n_\infty \ll 10^{10}\ [M_\odot {\rm cm}^{-3}]$: $\dot{M} \ll \dot{M}_{\rm BHL}$ & $\dot{M}_{\rm Edd}$ (Ogata et al. submitted)

➡ **Boost factor and the condition of upper-limit should be modified**

FUTURE WORK

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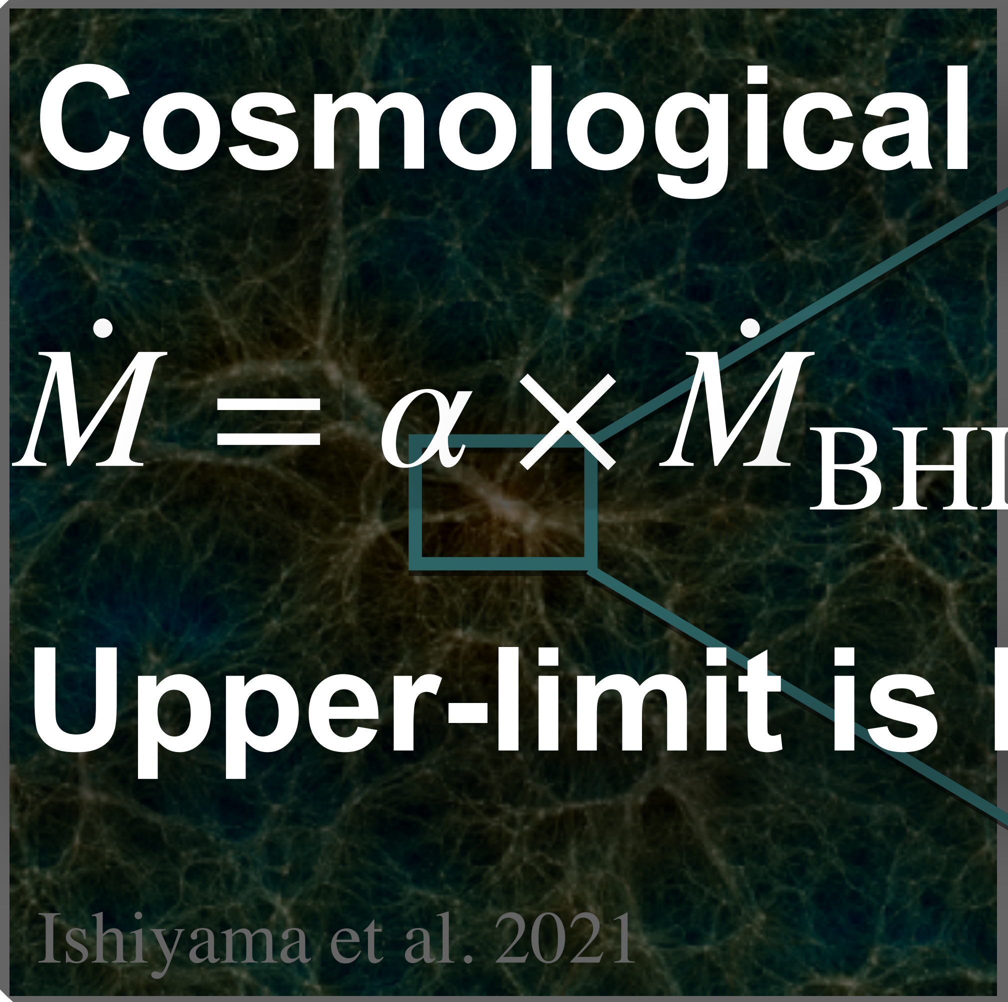
Cosmological simlations

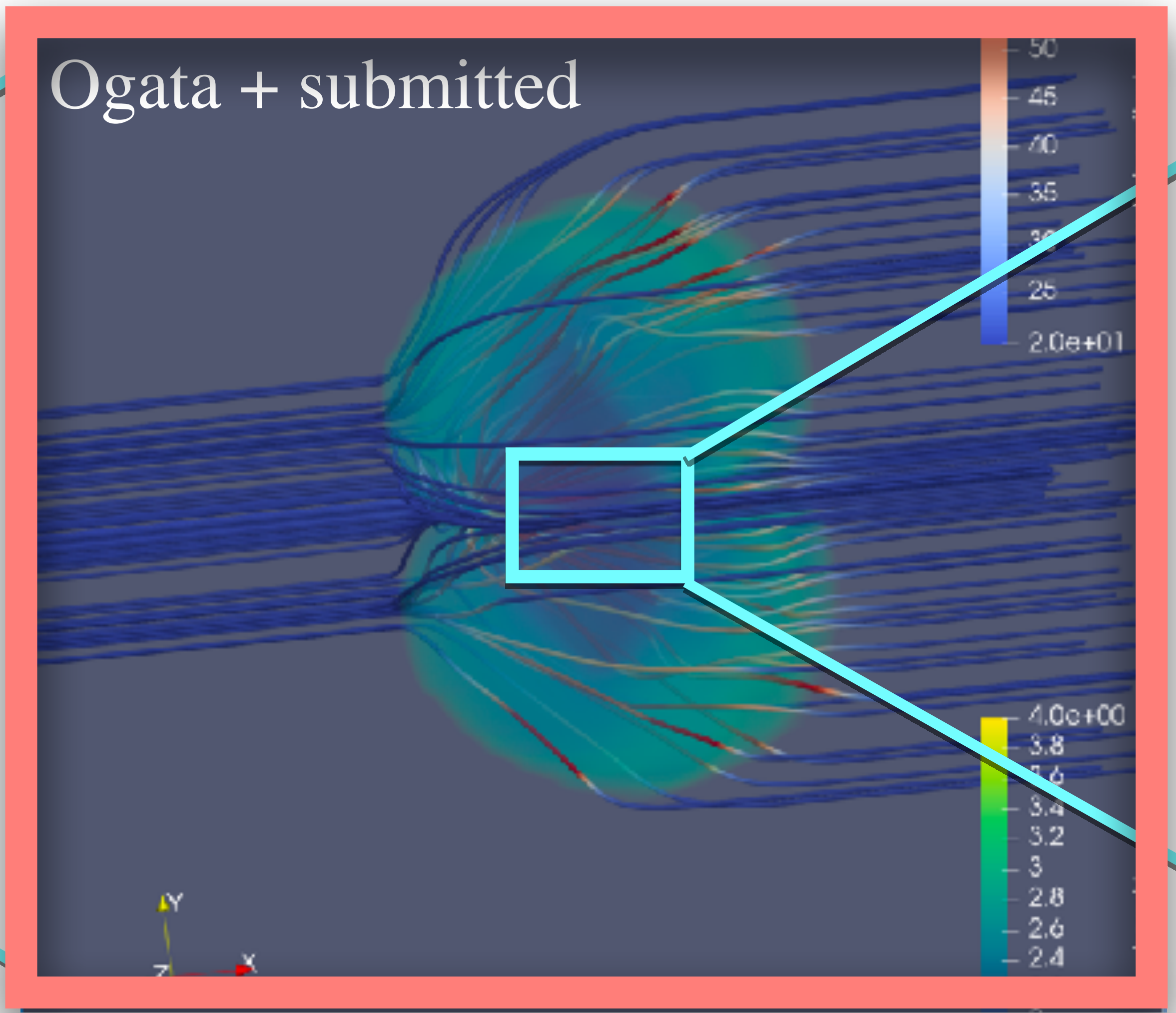
$$\dot{M} = \alpha \times \dot{M}_{\rm BHL} \quad (\alpha : \text{Boost factor})$$

Upper-limit is Eddington rate

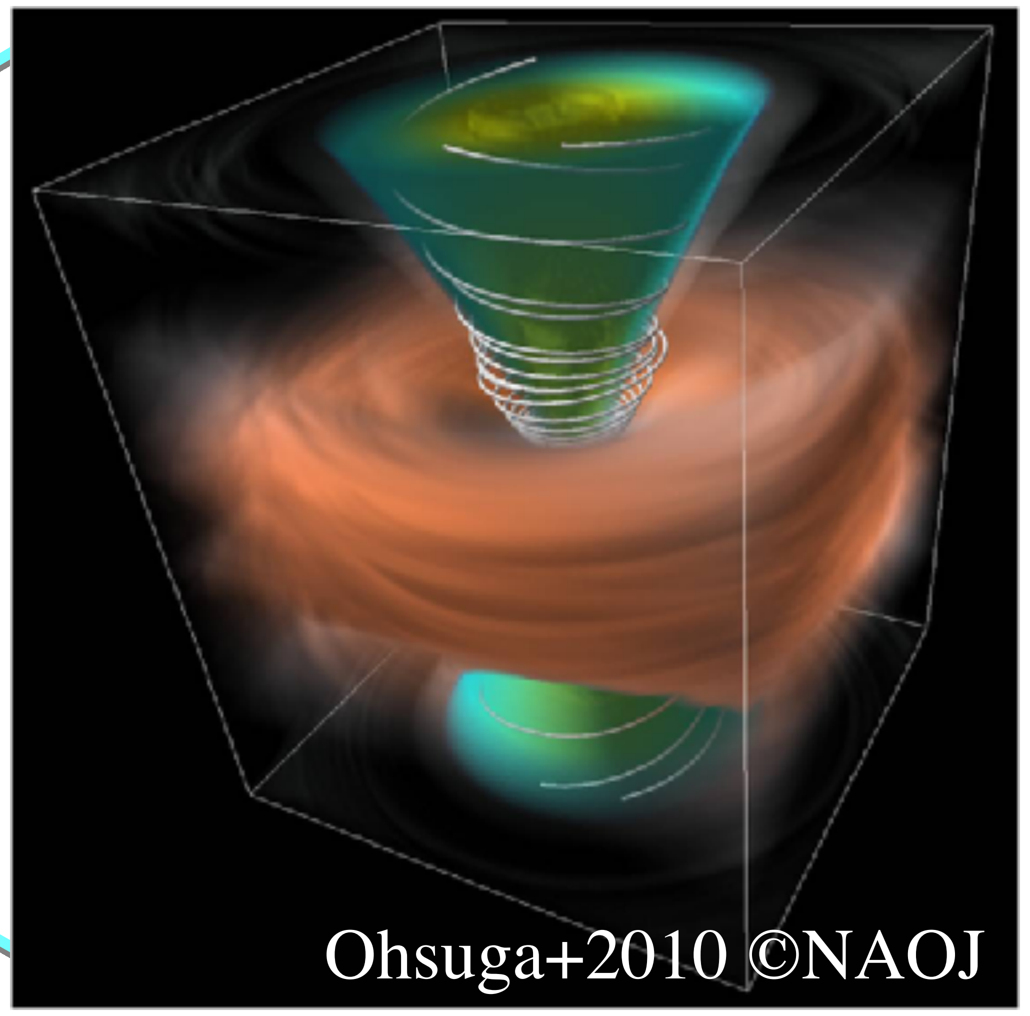


Mpc scale

kpc scale



pc scale



≪ pc scale

① We will simulate iteratively between the PC and << PC scales to make new Bondi-Hoyle-Lyttleton formula

② Adopting the new boost factor and upper-limit condition???

CONCLUSIONS

We study the growth rate of seed BH floating in dusty galaxies in the early universe with 3D-radiation hydrodynamics simulations

FEATURES

- **Considering anisotropy of radiation and dust sublimation**

RESULTS

Regarding seed BHs moving in the dusty gas,

- **Super-Eddington accretion $(\dot{M} \gtrsim 10\dot{M}_{\rm E})$ could occur due to gas supply from near the equatorial plane on the Bondi-Hoyle-Lyttleton scale**

- **If $M_{\rm BH} n_\infty \gtrsim 10^9\ [M_\odot {\rm cm}^{-3}]$, seed BHs could grow into supermassive BHs at high-z, while the others could float with velocity changing and constant mass**