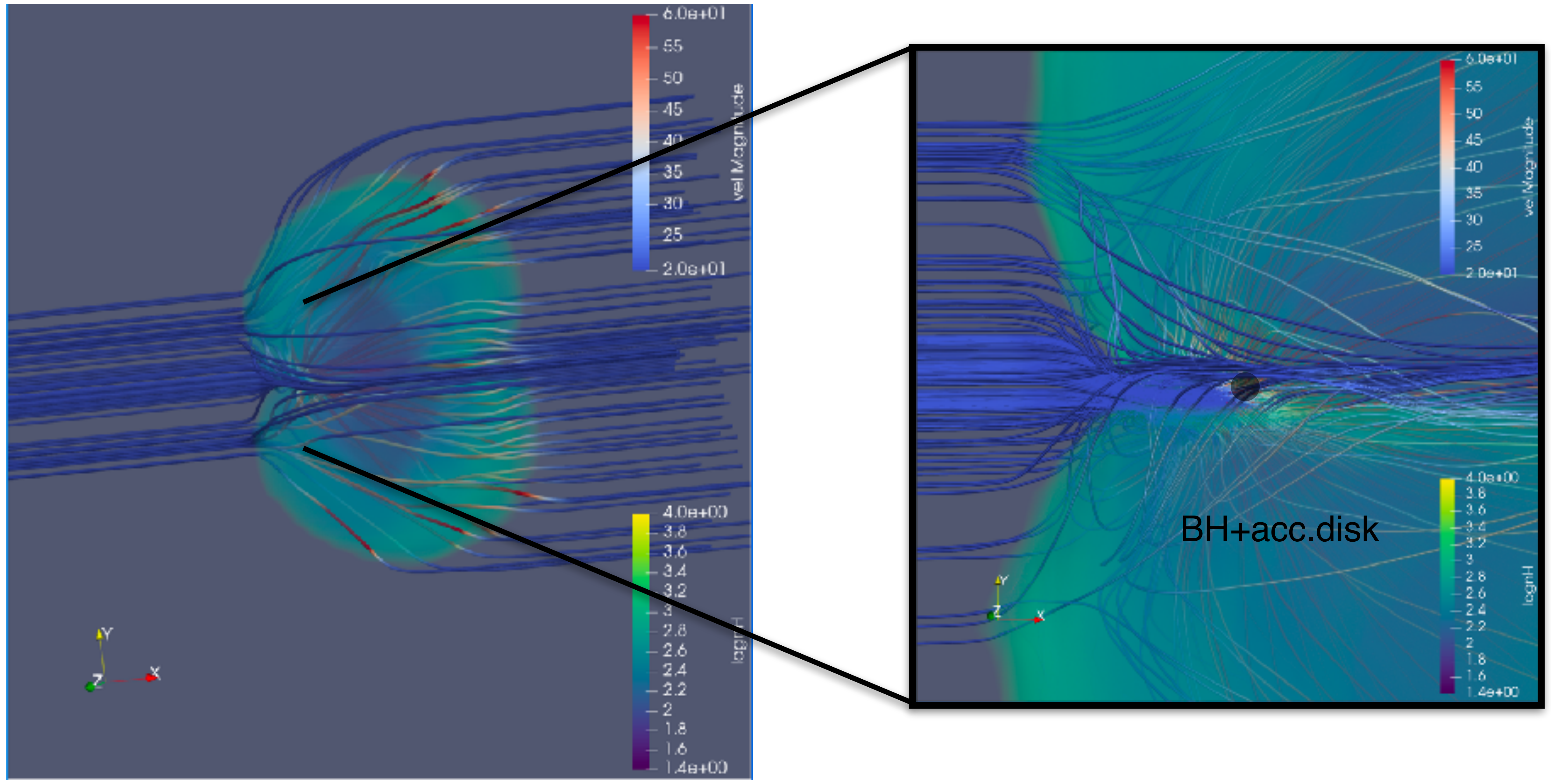
Evolution of wandering intermediate-mass black holes in high-z galaxies with 3D radiation hydrodynamics simulations

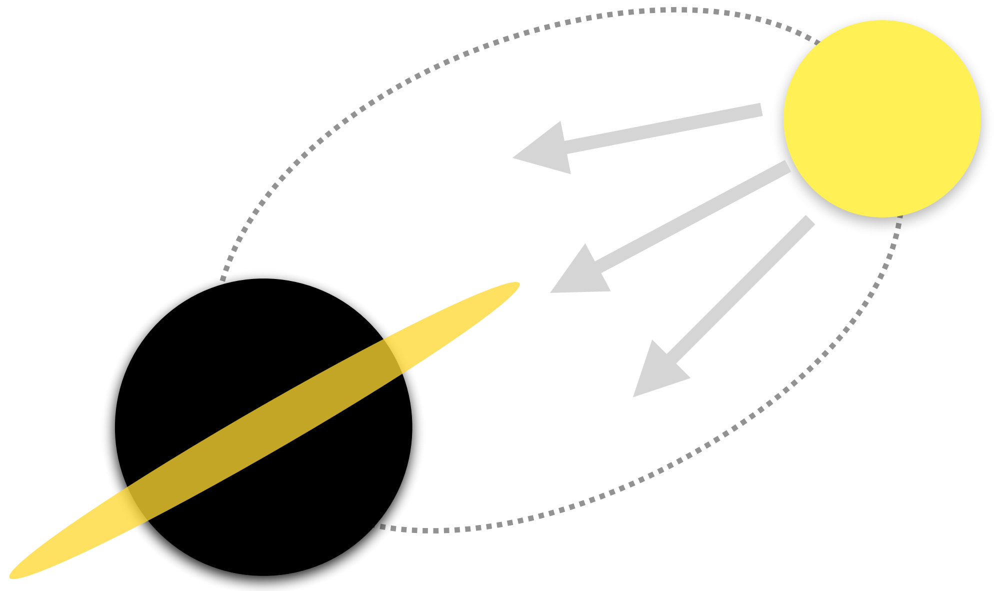
Erika OGATA (Univ. of Tsukuba)
Ken OHSUGA*
Hajime FUKUSHIMA*
Hidenobu YAJIMA*
(*Center for Computational Sciences, University of Tsukuba)



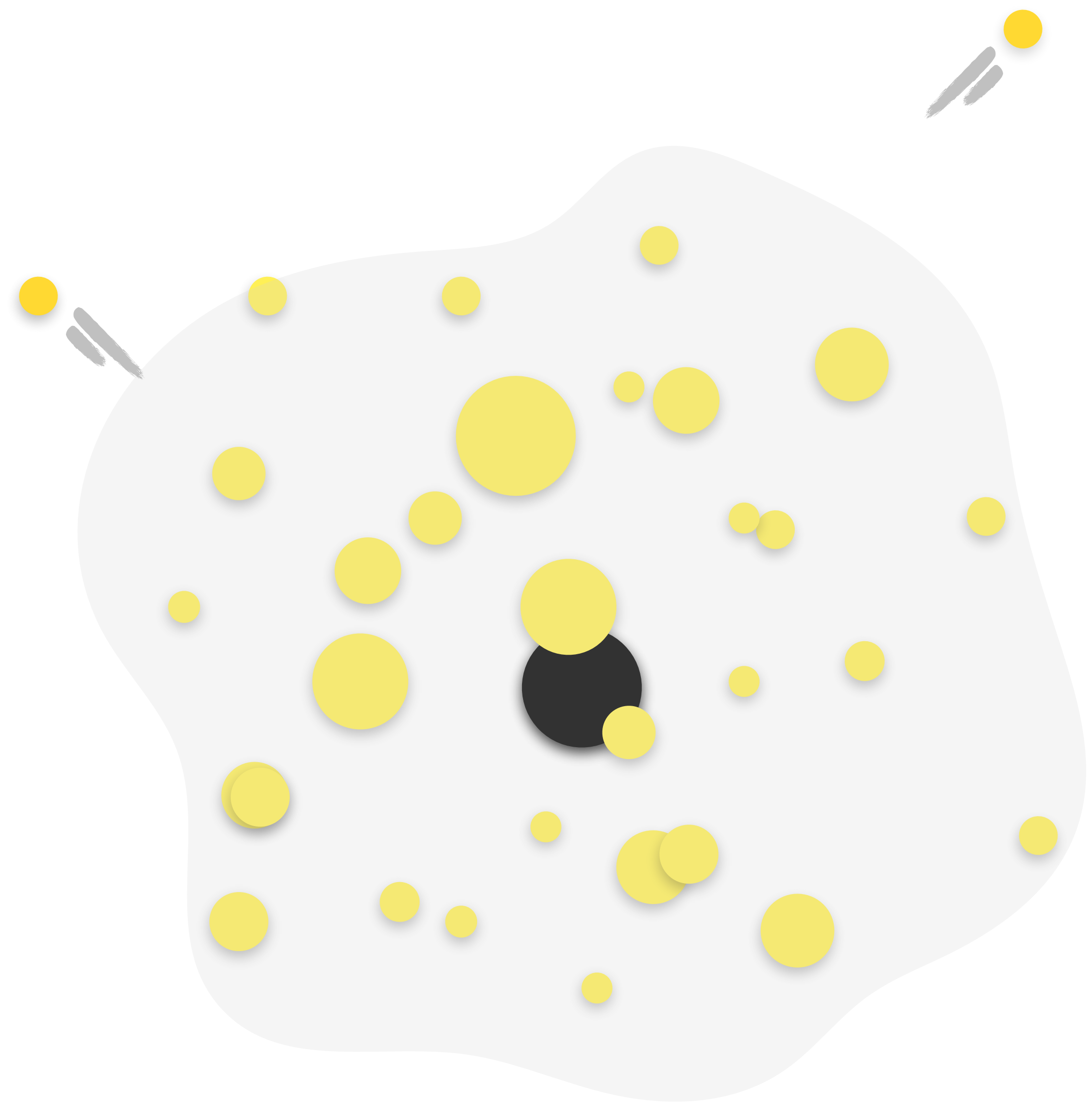
INTRODUCTION : What is Bondi-Hoyle-Lyttleton accr.?

✓The phenomenon that the gravitational object attracts and swallows gas when **there is relative motion with the surrounding gas**

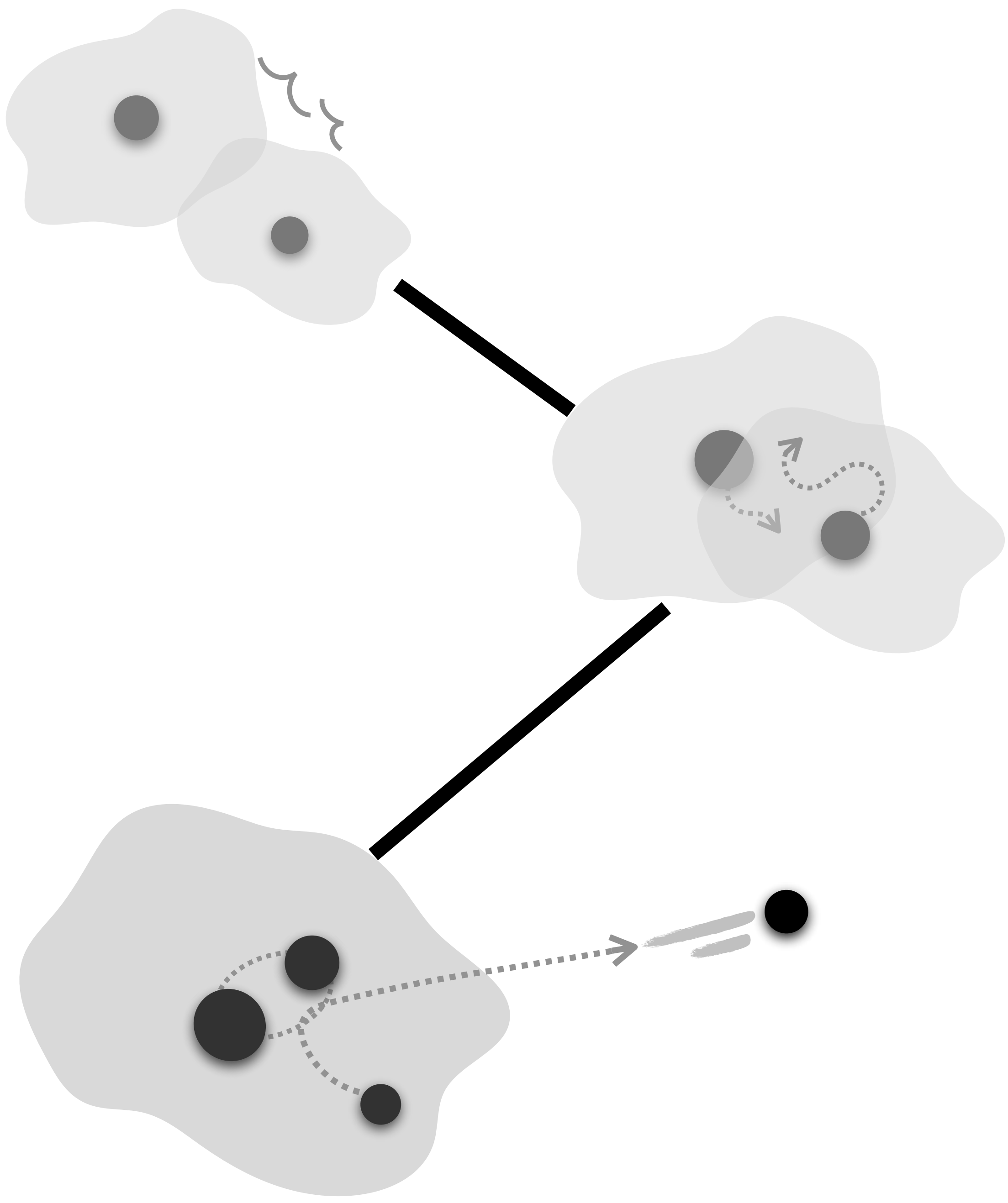
Stellar winds in binary systems



Runaway collision

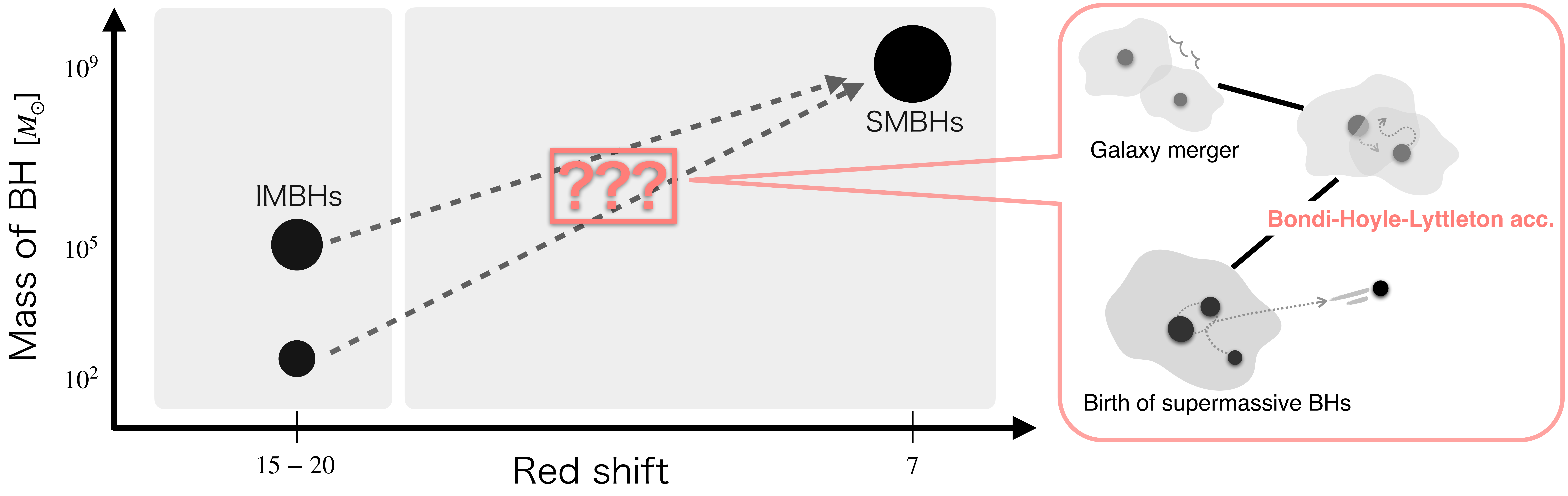


Galactic merger



INTRODUCTION：Our motivation

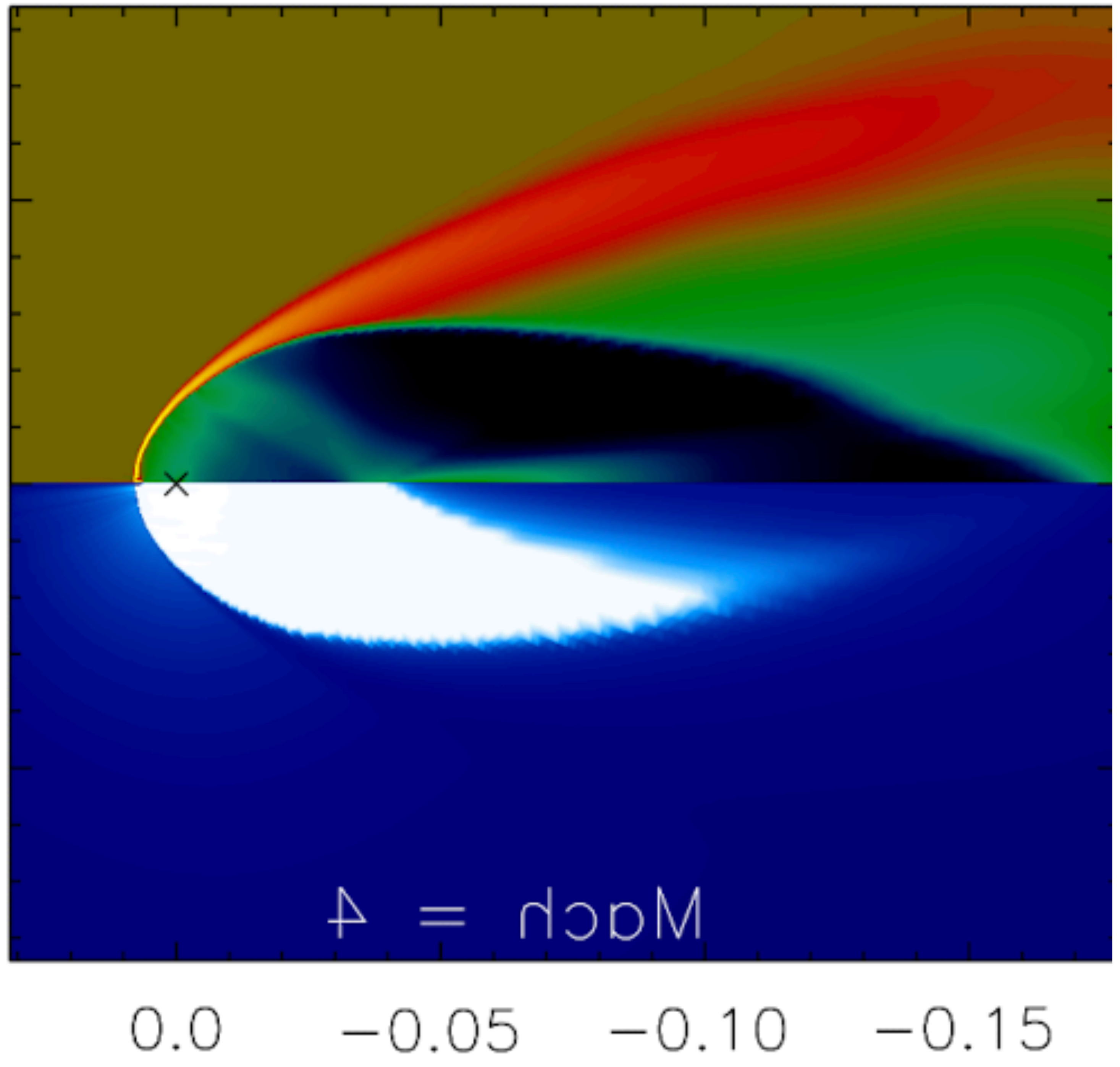
✓To understand the formation of SMBHs, **we focus on the growth process of intermediate-mass BHs (IMBHs) by Bondi-Hoyle-Lyttleton accr.**



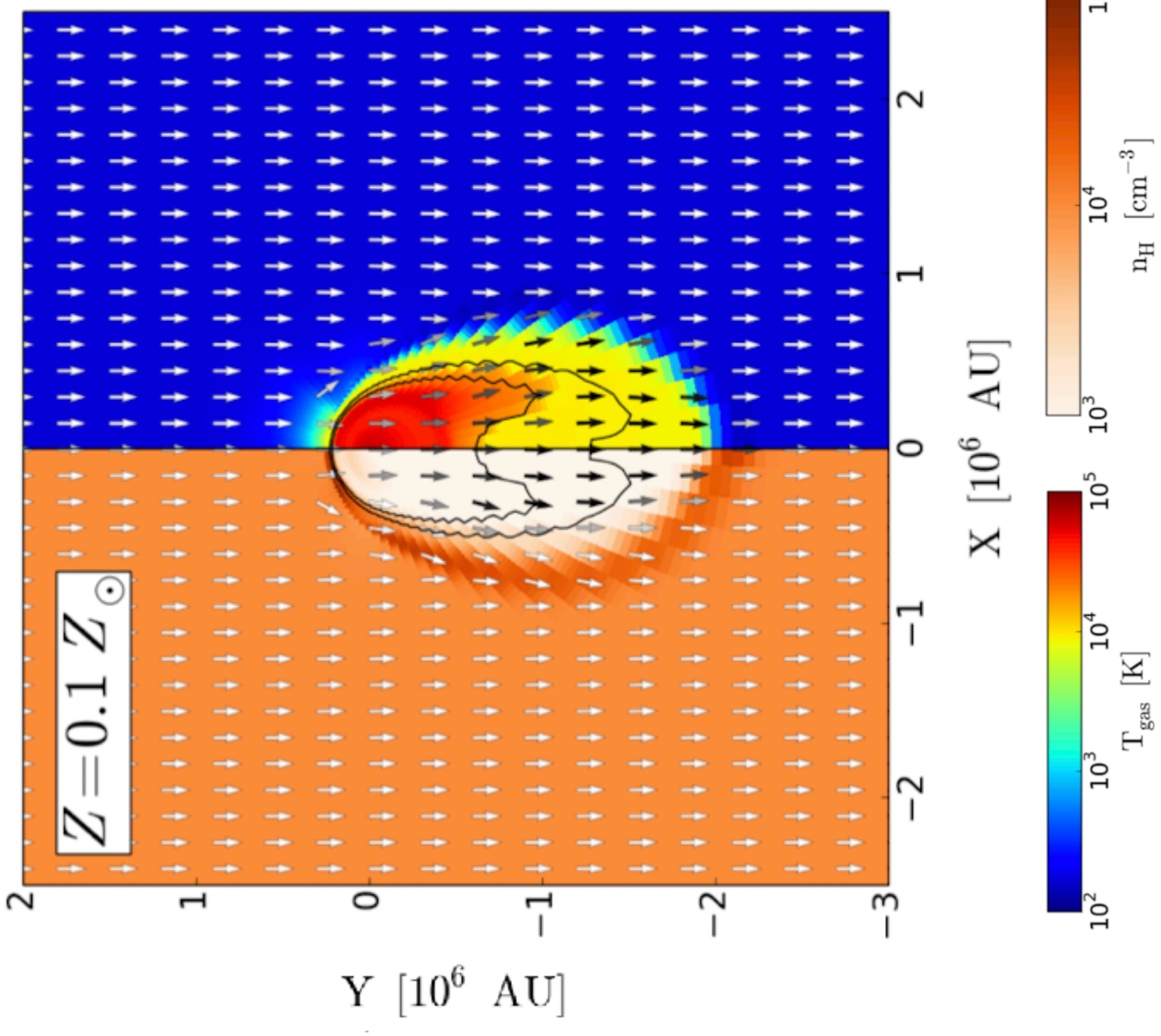
INTRODUCTION：Previous works

✔Most of radiation hydrodynamics simulations of Bondi-Hoyle-Lyttleton accr. have **assumed isotropic radiation**

2D RHD (Park & Ricotti 2013)



3D RHD (Toyouchi et al. 2020)

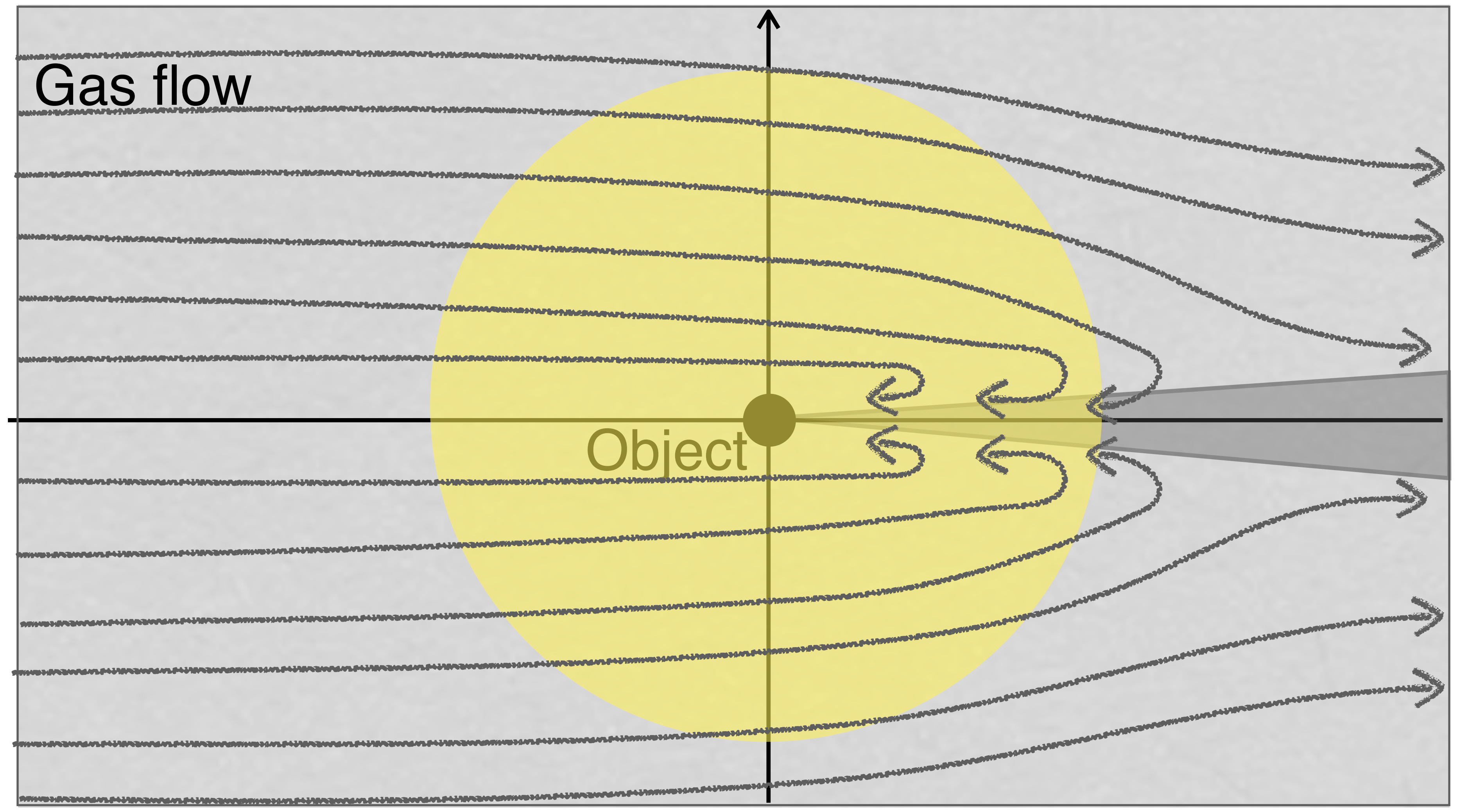


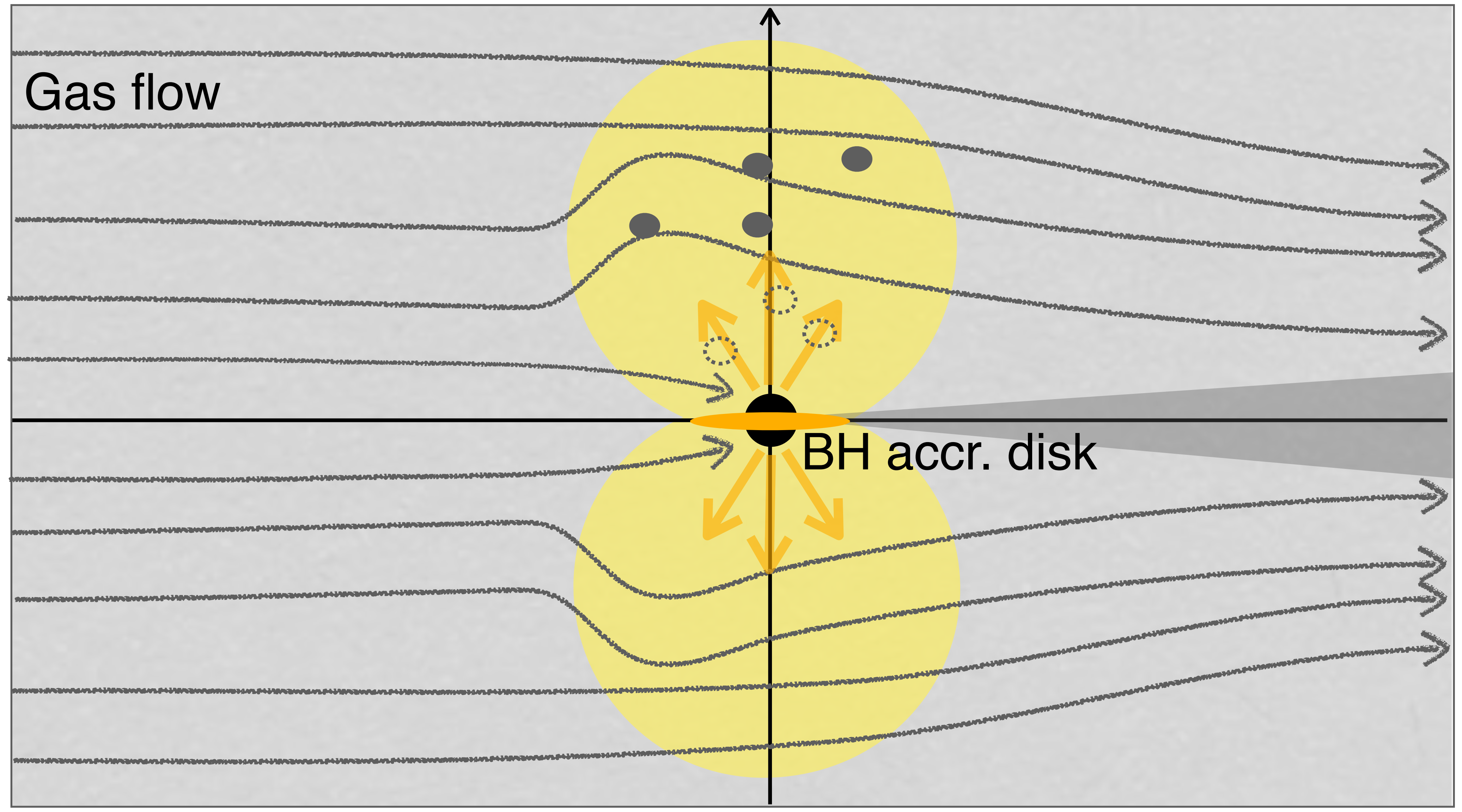
INTRODUCTION : This work

✔If the gravitational source is a compact object,

- The accretion disk is formed around BHs and **radiation field could be anisotropic**
- **The dust sublimates** due to the strong radiation from the accretion disk

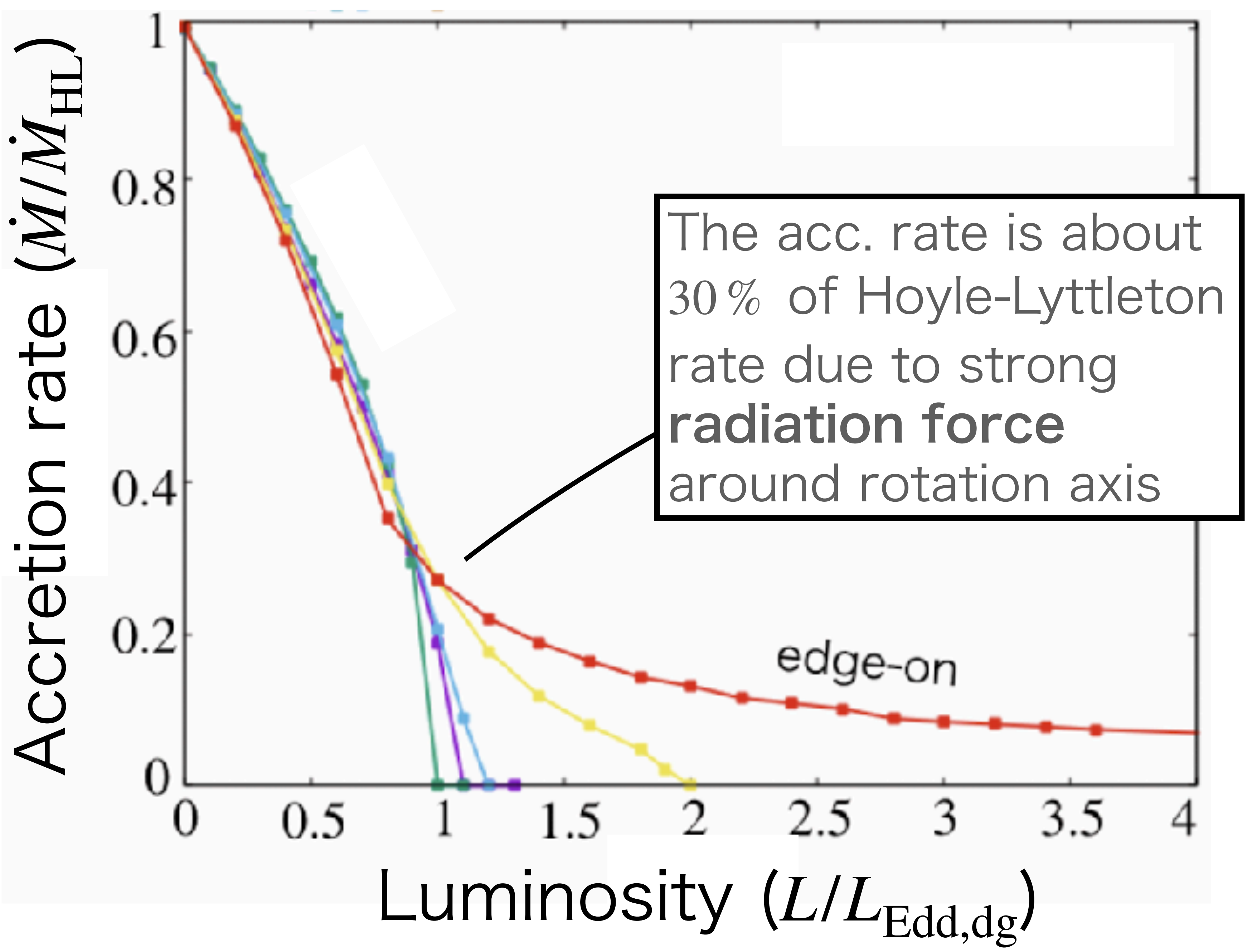
Previous works (e.g. Park & Ricotti 2013, Toyouchi et al. 2020)





INTRODUCTION：This work

✔We have successfully performed numerical calculation considering anisotropic radiation field **(Ogata et al. 2021)**

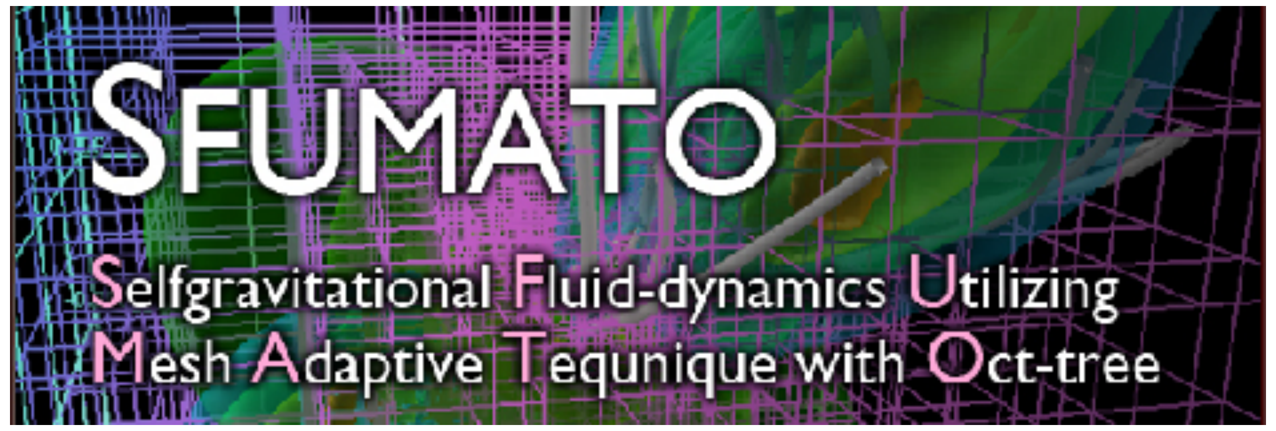


However, **the fluid effects were not considered**

(thermal pressure, shock at the ionization front etc..)

✔In this work, we perform **3D radiation hydrodynamics simulations** of Bondi-Hoyle-Lyttleton acc. under the anisotropic radiation **(Ogata et al. submitted)**

METHODS



e.g. Matsumoto (2007), Sugimura et al. (2020)
Fukushima & Yajima (2021)

Code : SFUMATO-M1

Settings :

Sink radius $R_{\rm in} = 2 \times 10^{-3}{\rm pc}$ (< dust sublimation radius)

Simulation box $R_{\rm out} = 2 \times 10^{1}{\rm pc}$ (≫ionization radius, Bondi-Hoyle-Lyttleton radius)

Dust sublimation temperature $T_{\rm subl} = 10^3\ {\rm K}$, Luminosity $L \propto \dot{M}$, Spectrum $L_\nu \propto \nu^{-1.5}$

Basic Eq. :

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

$\rm H, H_2, H^+, H^-,$
$\rm H_2^+, CO, C^+, O,$
$\rm O^+, O^{2+}, e$

ρ : density
E : total energy
Γ : heating rate
$E_{\rm rad}$: radiative energy density
$\alpha_{\rm E}$: absorption coefficient

$\boldsymbol{v}$: velocity
$\boldsymbol{g}$: gravity
Λ : cooling rate
$\boldsymbol{F}_{\rm rad}$: radiative flux
$\alpha_{\rm F}$: absorption coefficient

P : pressure
$\boldsymbol{f}$: radiation force
$\boldsymbol{P}_{\rm rad}$: radiative pressure tensor
$\tilde{c}$: reduce light speed

MODELS

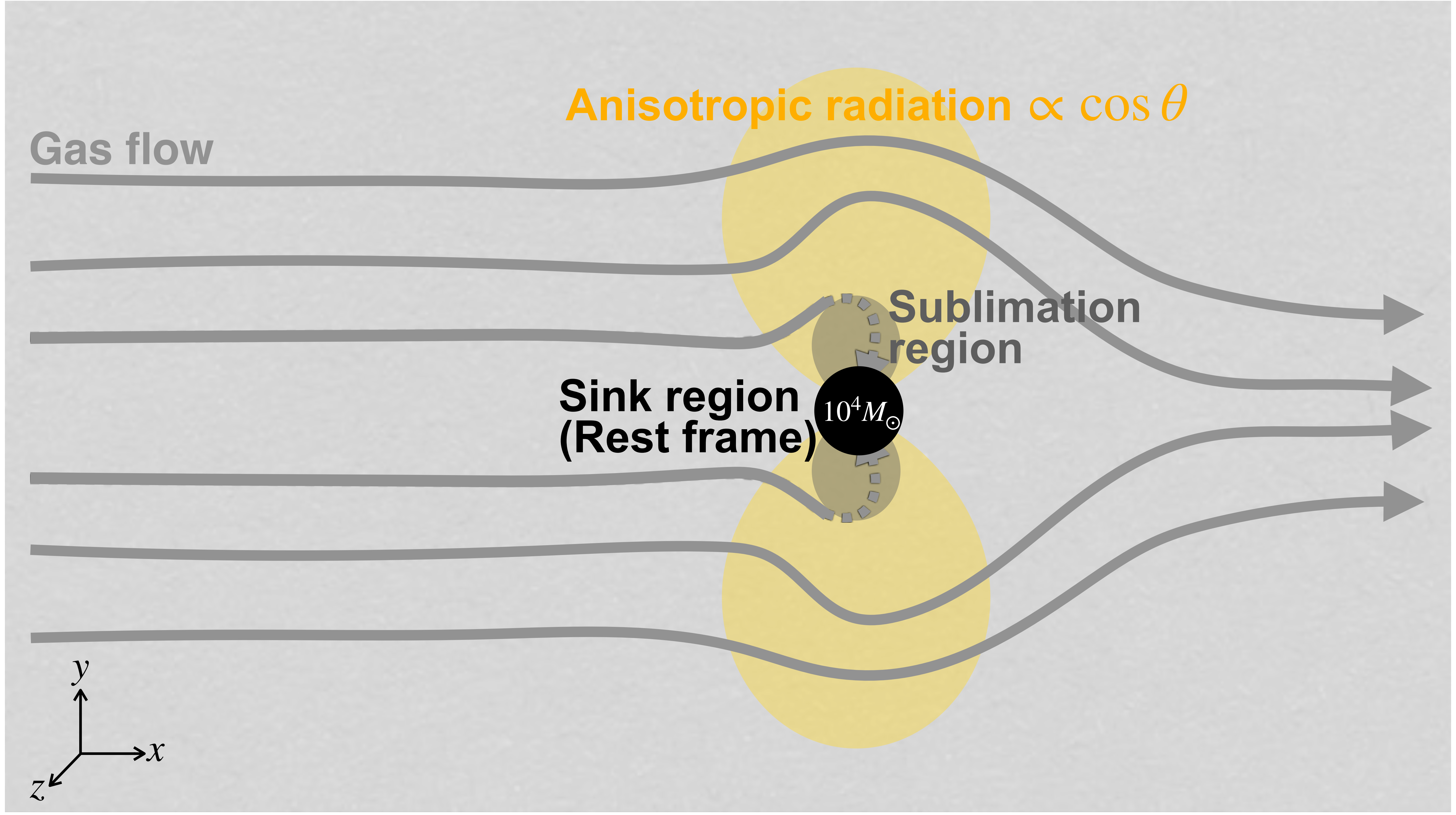
Fixed values

- ✔BH mass：$M_{\rm BH} = 10^4 M_\odot$
- ✔Metallicity ：$Z = 0.1 Z_\odot$
- ✔Temperature：$T = 180$ K
- ✔Disk inclination：edge-on

Parmeters

- ✔Gas velocity：
  $v_\infty = 20,\ 100$ km/s
- ✔Gas density：
  $n_\infty = 10^4,\ 10^6\ {\rm cm}^{-3}$

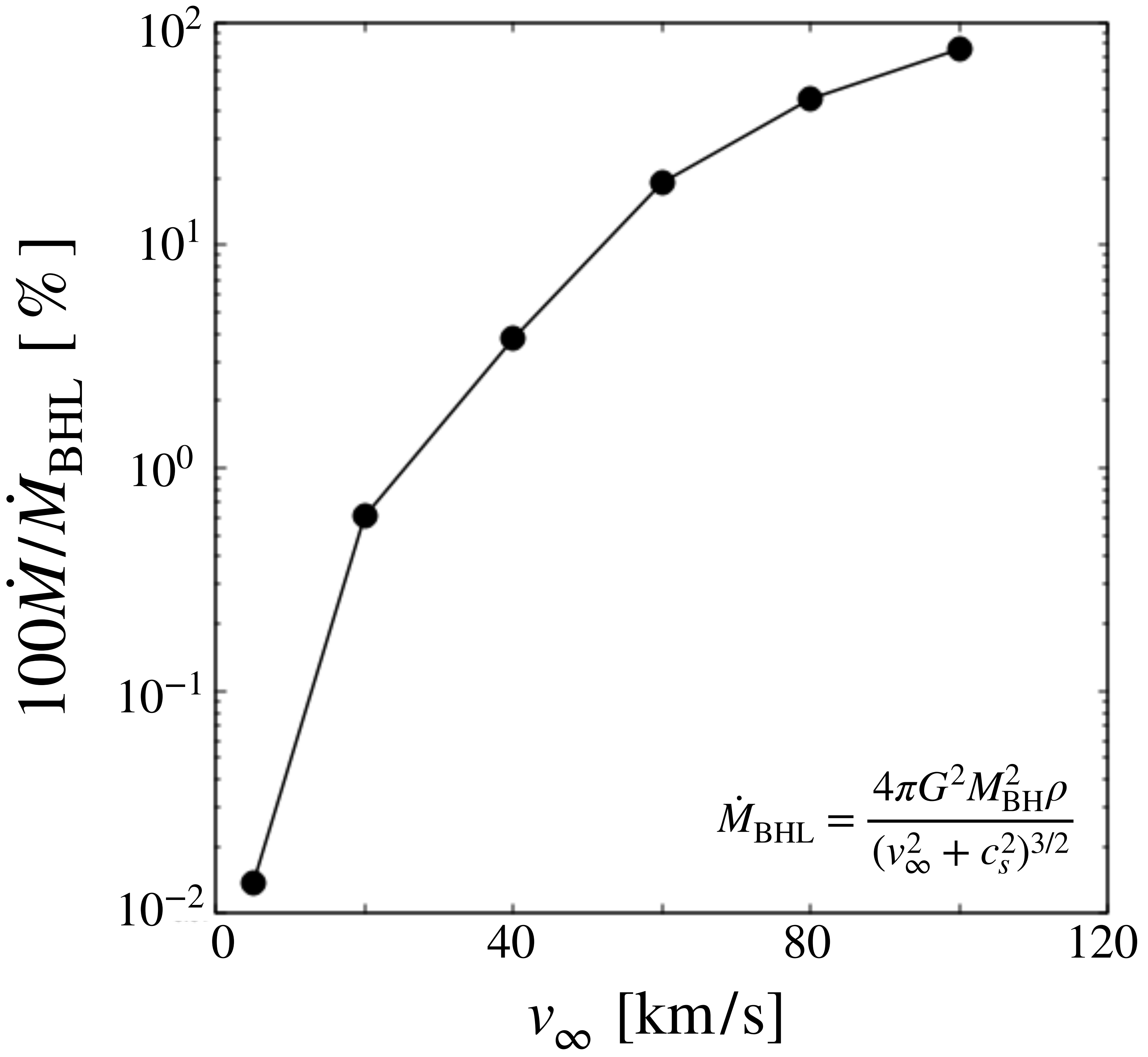
Schematic view



RESULTS : Accretion rate

✔ When the relative velocity is high ($\gtrsim 100\ \mathrm{km/s}$), the accr. rate is nearly consistent with classical Bondi-Hoyle-Lyttleton rate $\dot{M}_{\rm BHL}$

✔ **When the relative velocity is low, the accr. rate is $< \mathrm{several} \times 10\,\%$ of $\dot{M}_{\rm BHL}$**

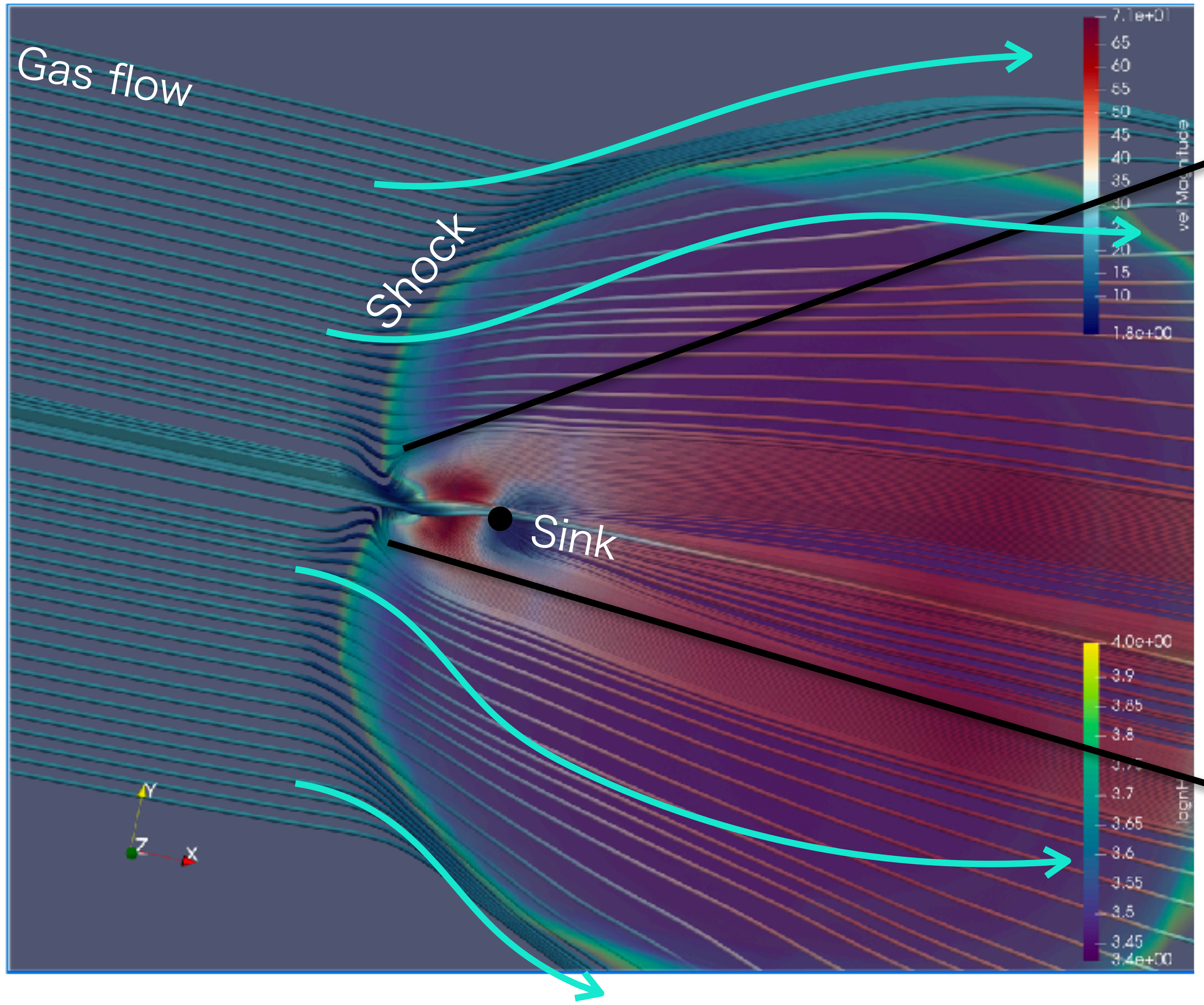


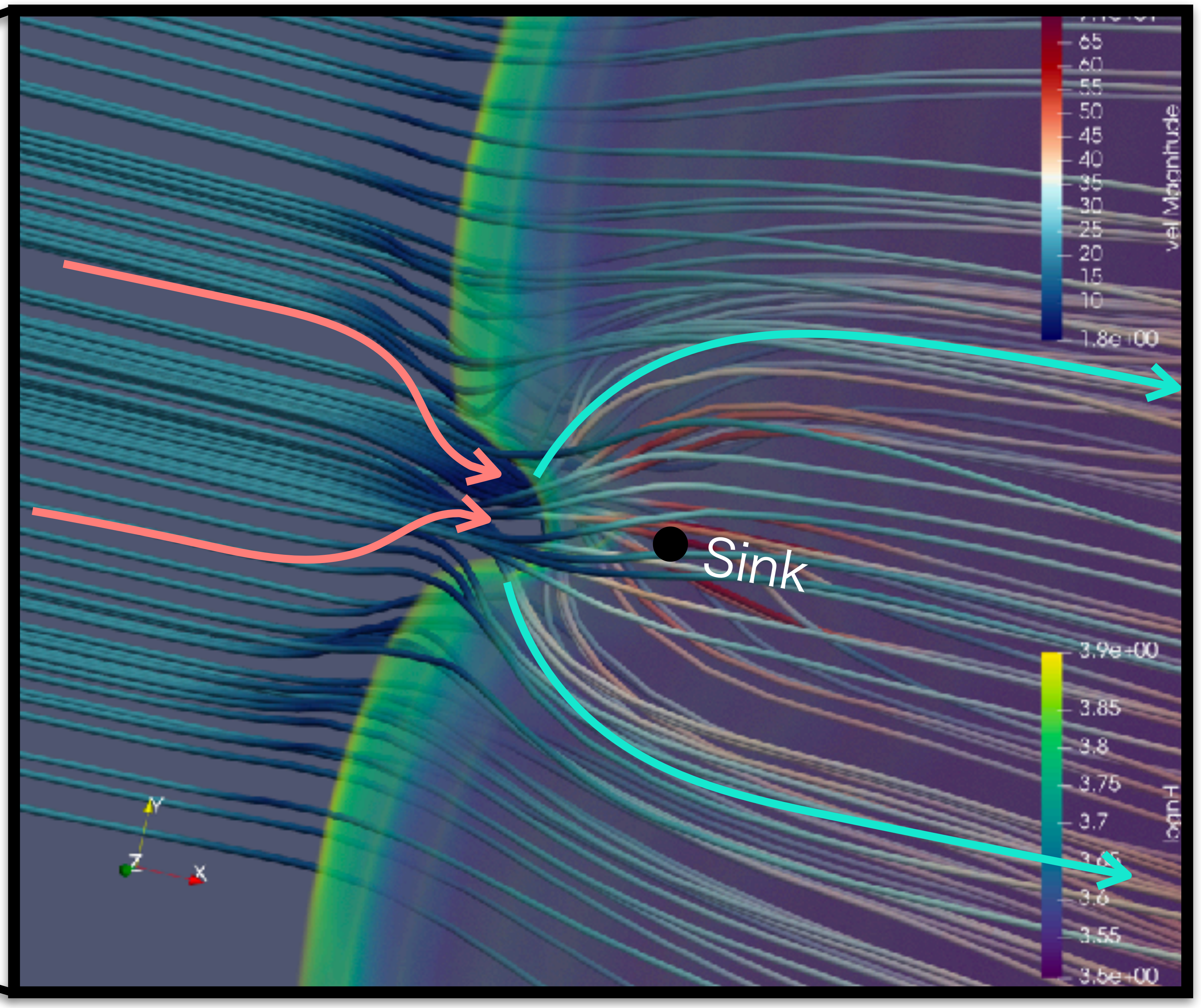
What's happening in the low velocity?
(Next page)

RESULTS：Structure of flow

✔When the relative velocity is low ($\lesssim$ several $\times$ 10km/s), the shock appears near the ionization front

✔**Not only the radiation force near the disk rotation axis, but also the gas pressure gradient force near the shock front bends the streamlines away from the IMBHs**

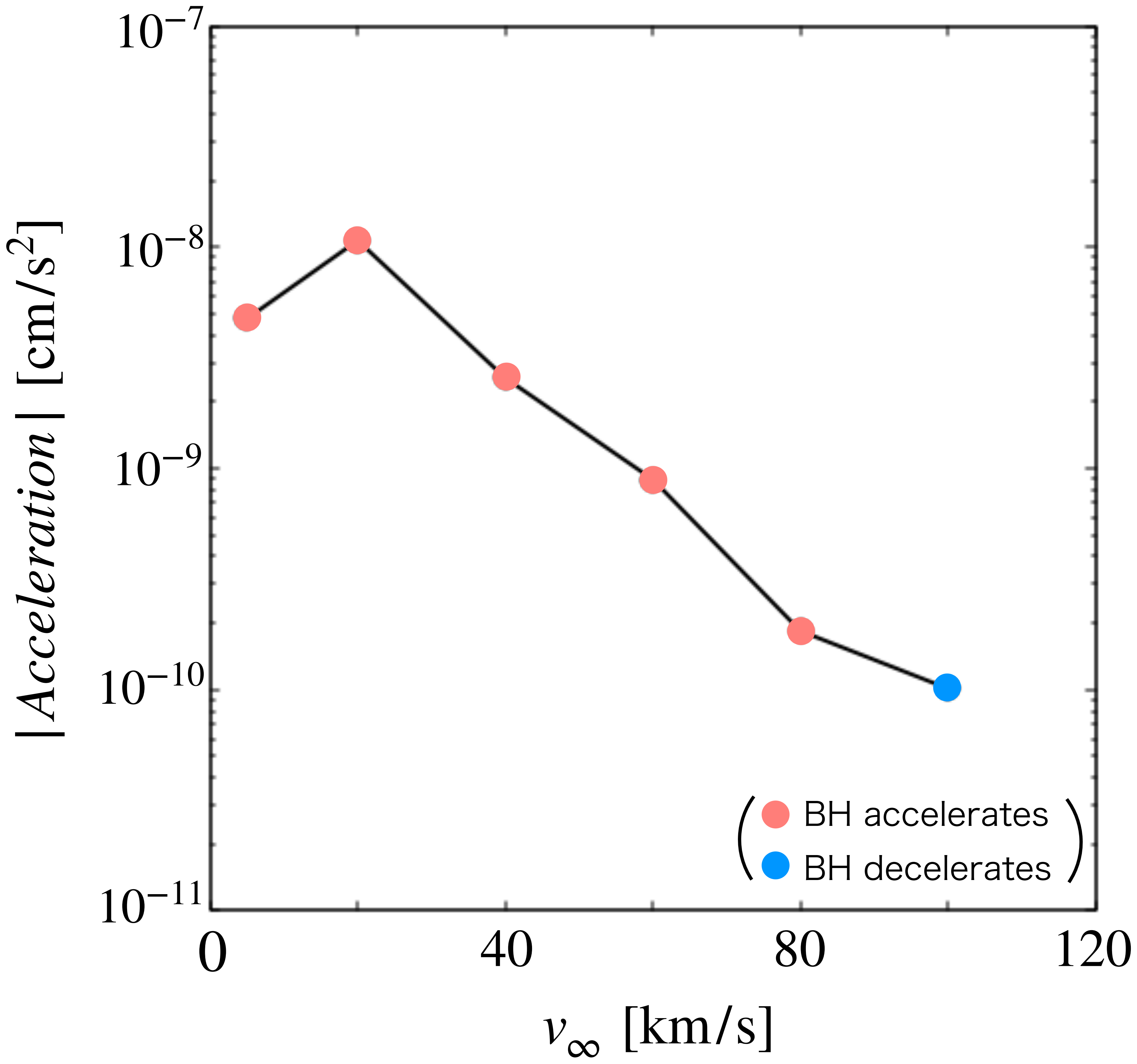




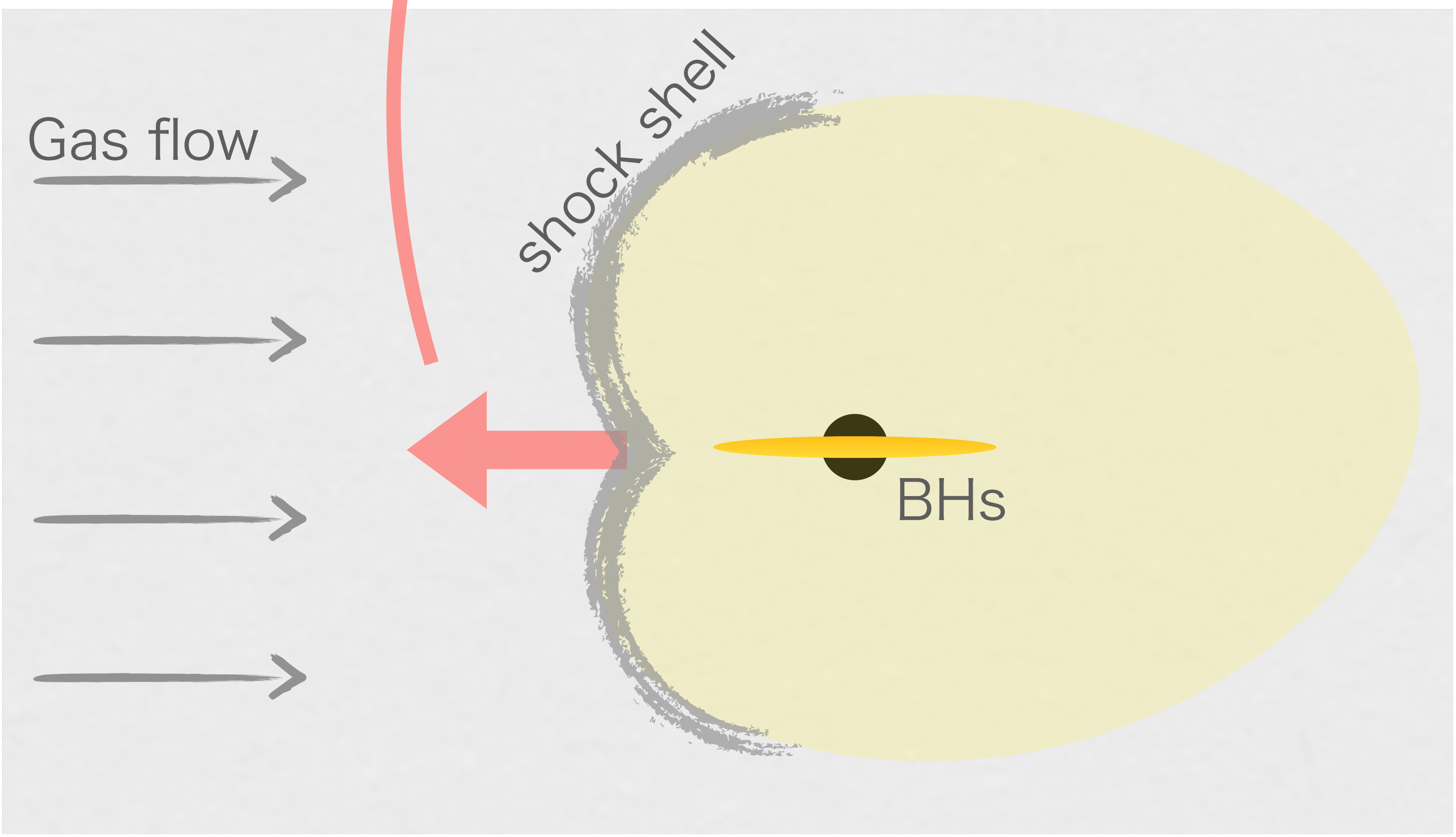
Near the shock front

RESULTS : Acceleration of IMBHs

✔The **IMBHs could accelerate** due to gravity caused by the high-density shell associated with the shock wave.



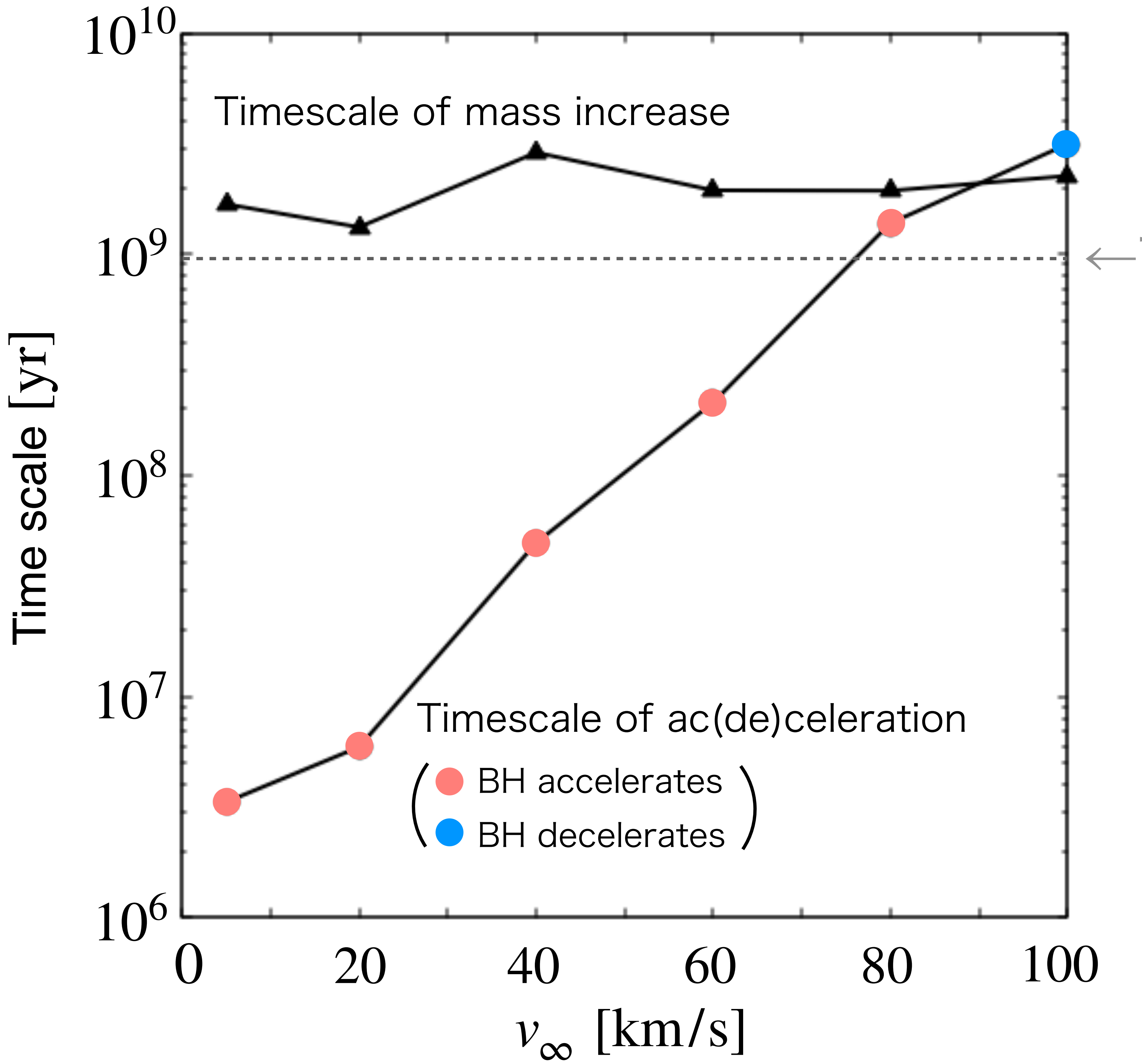
$$Acceleration = \underbrace{\int_0^{4\pi}\int_R^{R_{\rm out}} \frac{\rho G x}{R'^3} dR' d\Omega}_{} + \int_{S_{\rm sink}} \rho v_x \boldsymbol{v} \cdot d\boldsymbol{S}$$



RESULTS : Evolution of IMBHs ($\sim 10^4 \mathrm{cm}^{-3}$)

✔(Timescale of acceleration) << (Timescale of mass increase)

→The IMBHs in the early universe ($z \gtrsim 6,\ 0.1Z_{\odot}$) **float with relative velocity $\gtrsim$ several $\times\, 10\mathrm{km/s}$ without mass increase** when the gas density is $\sim 10^4 \mathrm{cm}^{-3}$

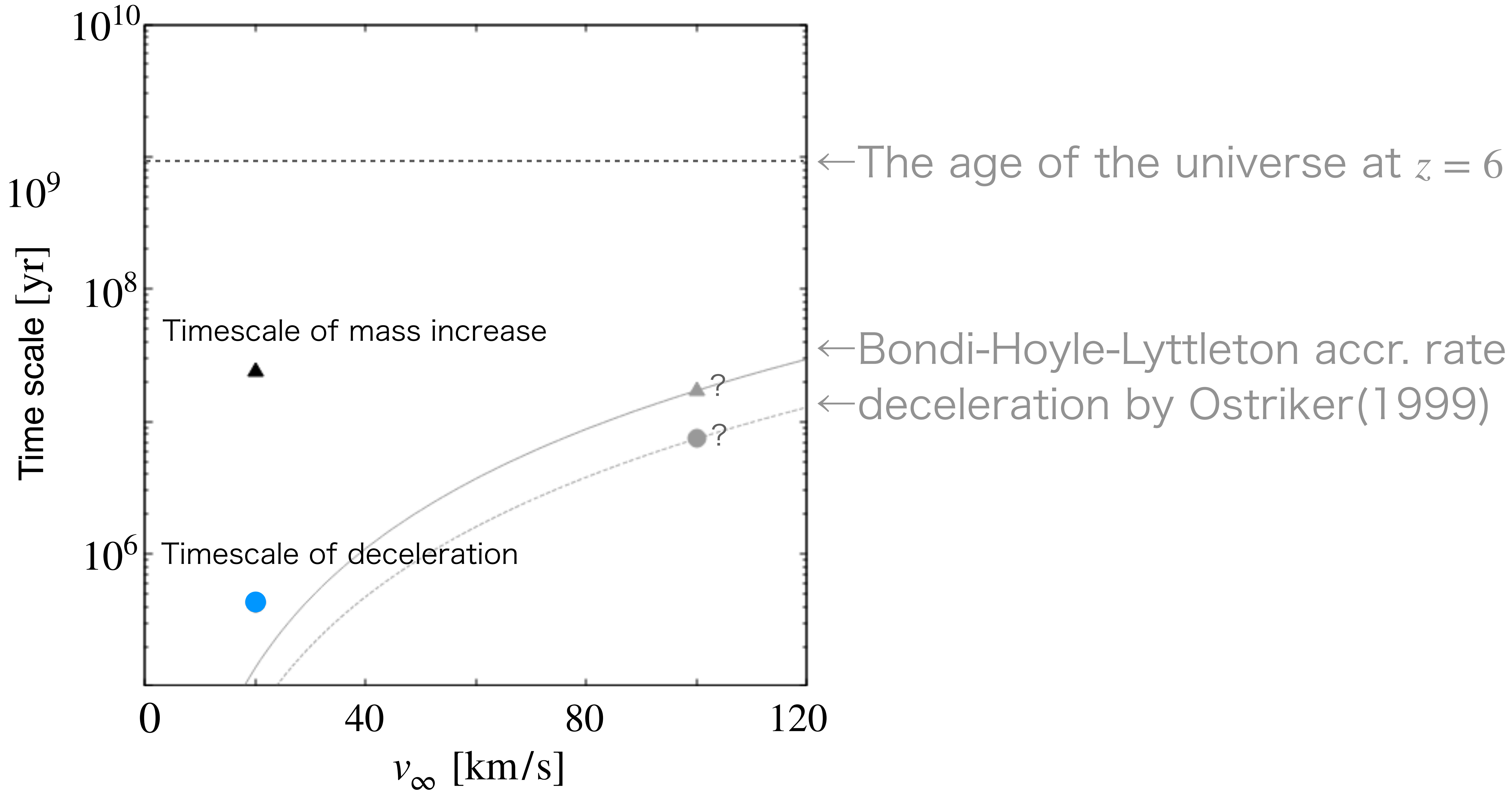


←The age of the universe at $z = 6$

RESULTS : Evolution of IMBHs ($\sim 10^6\mathrm{cm}^{-3}$)

✔ (Timescale of acceleration) << (Timescale of mass increase)

→ The IMBHs in the early universe ($z \gtrsim 6,\ 0.1Z_\odot$) **shift Bondi accr. in a few Myr, and then mass could increase significantly** when gas density is $\sim 10^6\mathrm{cm}^{-3}$



CONCLUSIONS

✔ We study the Bondi-Hoyle-Lyttleton accr. mechanism **onto IMBHs with accr. disks** wandering in dusty-gas by **3D radiation hydrodynamics simulations**

(Ogata et al. submitted)

✔ When the relative velocity is low ($\lesssim \mathrm{several} \times 10\mathrm{km/s}$), not only the radiation force near the disk rotation axis, but also **the gas pressure gradient force near the shock front bends the streamlines away from the IMBHs**

✔ Our simulations imply that the IMBHs in the early universe ($z \gtrsim 6$)

- **float with relative velocity** $\gtrsim \mathrm{several} \times 10\mathrm{km/s}$ when gas density is $\sim 10^4\mathrm{cm}^{-3}$
- **shift Bondi accr. in** $\mathrm{a\ few\ Myr}$ **, and then its mass increases significantly** when the gas density is $\sim 10^6\mathrm{cm}^{-3}$