Gravitational Wave Physics and Astronomy Genesis

Gaseous dynamical friction on intermediate-mass BHs

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in collaboration with

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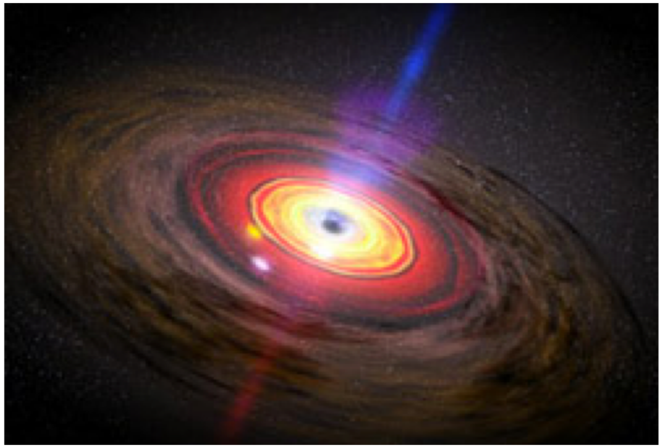
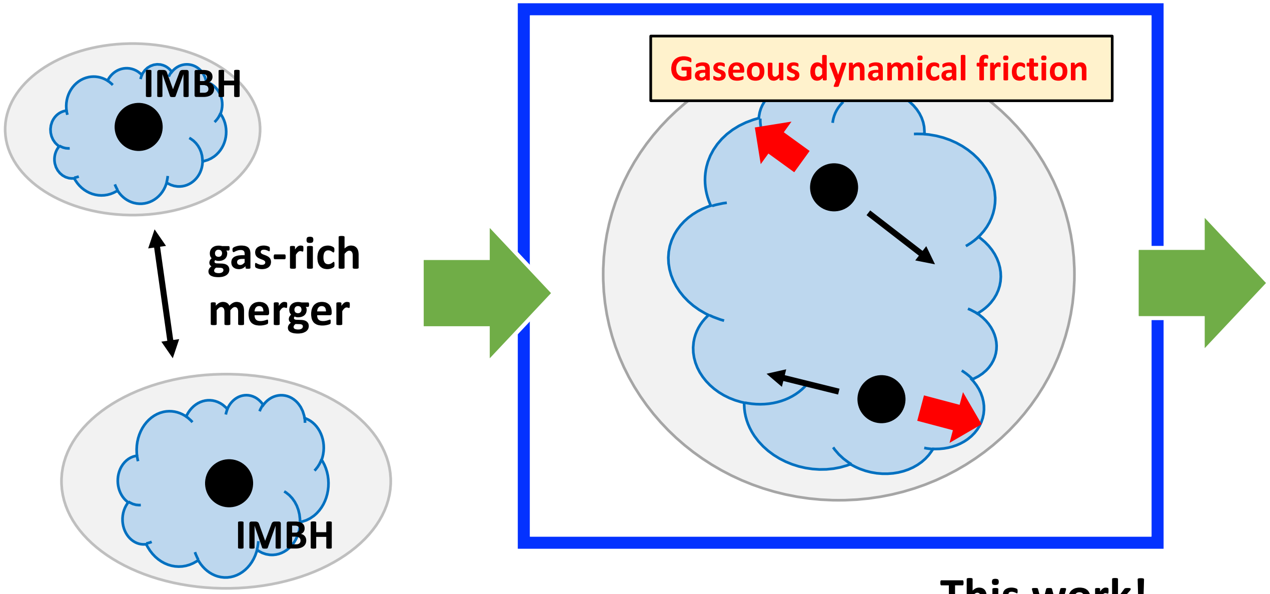
Introduction

Binary of Intermediate-mass black holes (IMBH)

- ✓ IMBHs with $10^{3\text{-}5}$ Msun are seeds of more massive BHs
- ✓ One of the targets of the space-based GW detector LISA
- ✓ IMBH binaries form via galaxy-galaxy-merger





IMBH

IMBH

gas-rich merger

Gaseous dynamical friction

Final pc problem?

This work!

Gaseous dynamical friction

Gaseous dynamical friction in BHL accretion

(Ostriker 1999)

$$F_{\mathrm{DF,gas}} = -\frac{4\pi (G M_{\mathrm{BH}})^2 \rho_{\mathrm{gas}}}{v_{\mathrm{BH}}^2} \ln \left[\Lambda \left(1 - \frac{1}{\mathcal{M}^2} \right)^{0.5} \right]$$

$(\mathcal{M} > 1)$

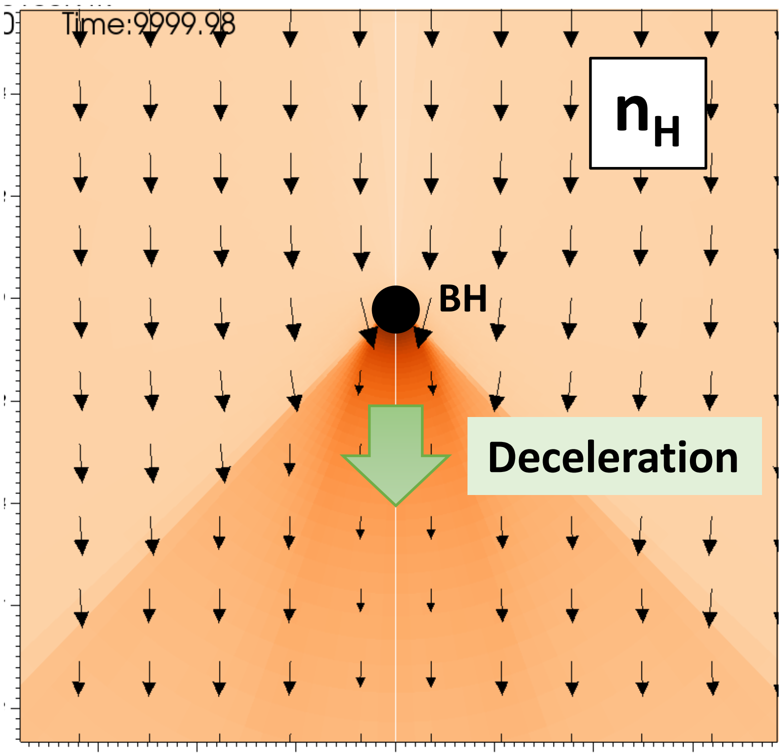
(Chandrasekhar 1943)

$$F_{\mathrm{DF,star}} = -\frac{4\pi (G M_{\mathrm{BH}})^2 \rho_{\mathrm{star}}}{v_{\mathrm{BH}}^2} \ln\Lambda \left[\mathrm{erf}(X) - \frac{2X}{\sqrt{\pi}} e^{-X^2} \right]$$

if $v_{\mathrm{BH}} >> c_s$ and $v_{\mathrm{BH}} >> \sigma_{\mathrm{star}}$

$$\frac{F_{\mathrm{DF,gas}}}{F_{\mathrm{DF,star}}} \sim \frac{\rho_{\mathrm{gas}}}{\rho_{\mathrm{star}}}$$

✓ **if $\rho_{\mathrm{gas}} > \rho_{\mathrm{star}}$, gaseous dynamical friction is a dominant mechanism for BH orbital evolution**



Gas aggregates at the downstream side.

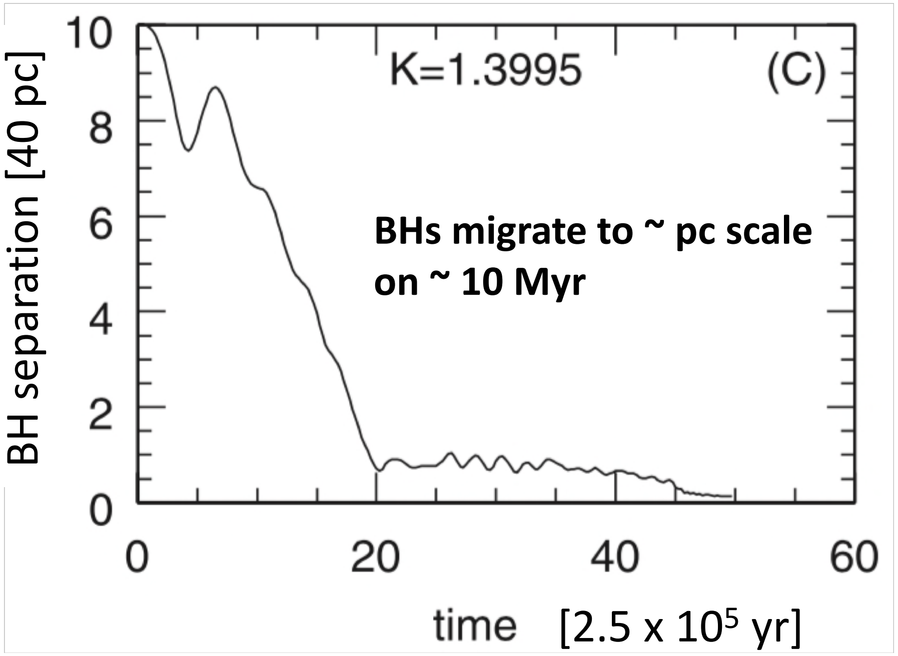
→ BH is decelerated by the downstream gas.

BH orbital evolution

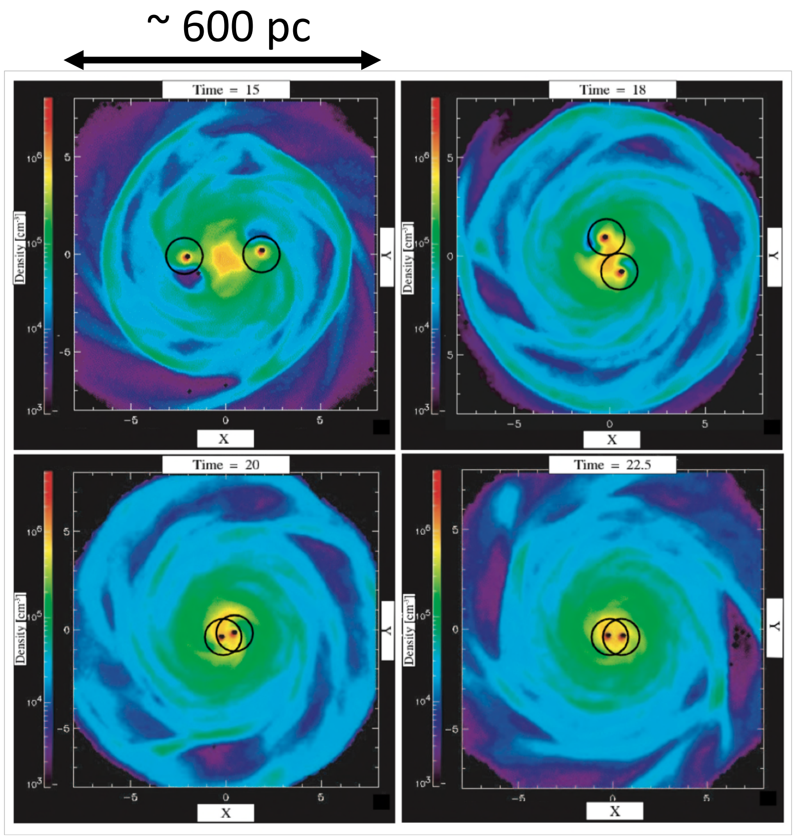
Escala et al. (2005)

- ✓ 3D simulation (SPH: GADGET), adiabatic
- ✓ BH pair : $M_{bh} = 5 \times 10^7 M_{sun}$, D_{bh} = 400 pc
- ✓ disk : $M_{disk} = 5 \times 10^9 M_{sun}$, R_{disk} = 400 pc

→ remnant of a gas-rich galaxy-galaxy merger



BHs migrate to ~ pc scale on ~ 10 Myr



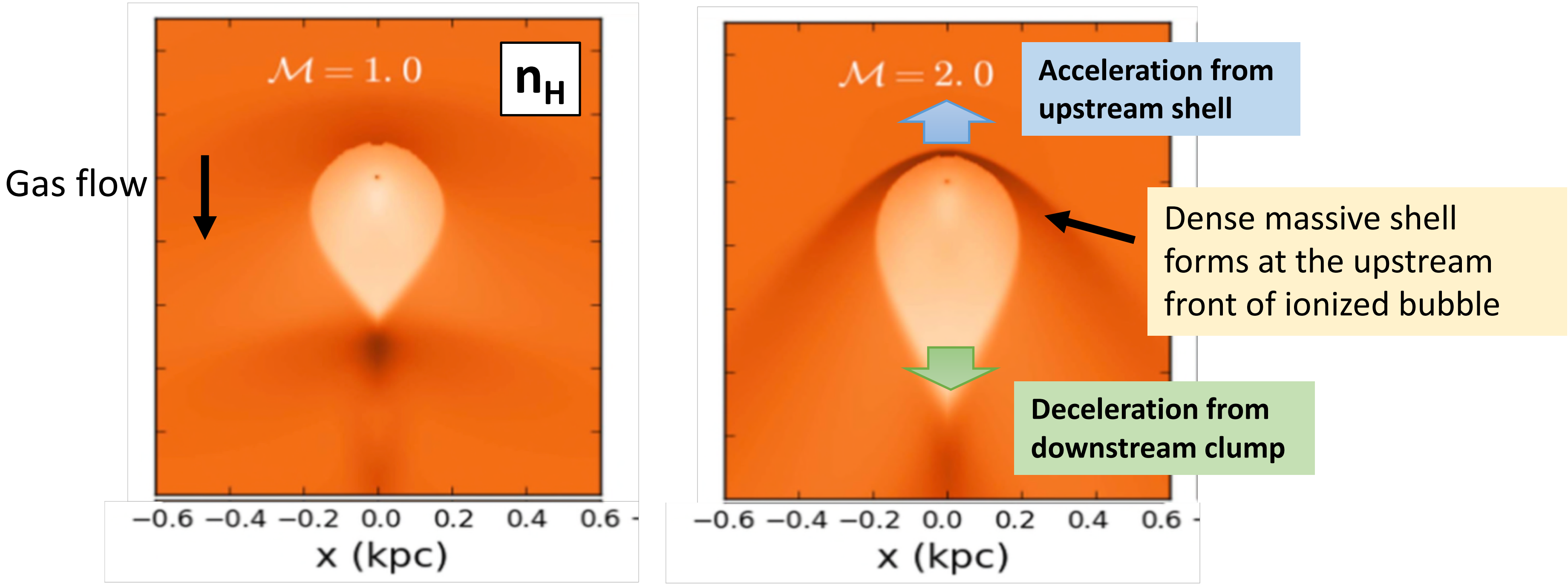
~ 600 pc

However, most of simulations don't consider the radiative feedback from moving BHs...

Effect of Radiative Feedback

Park & Bagdanovic (2017)

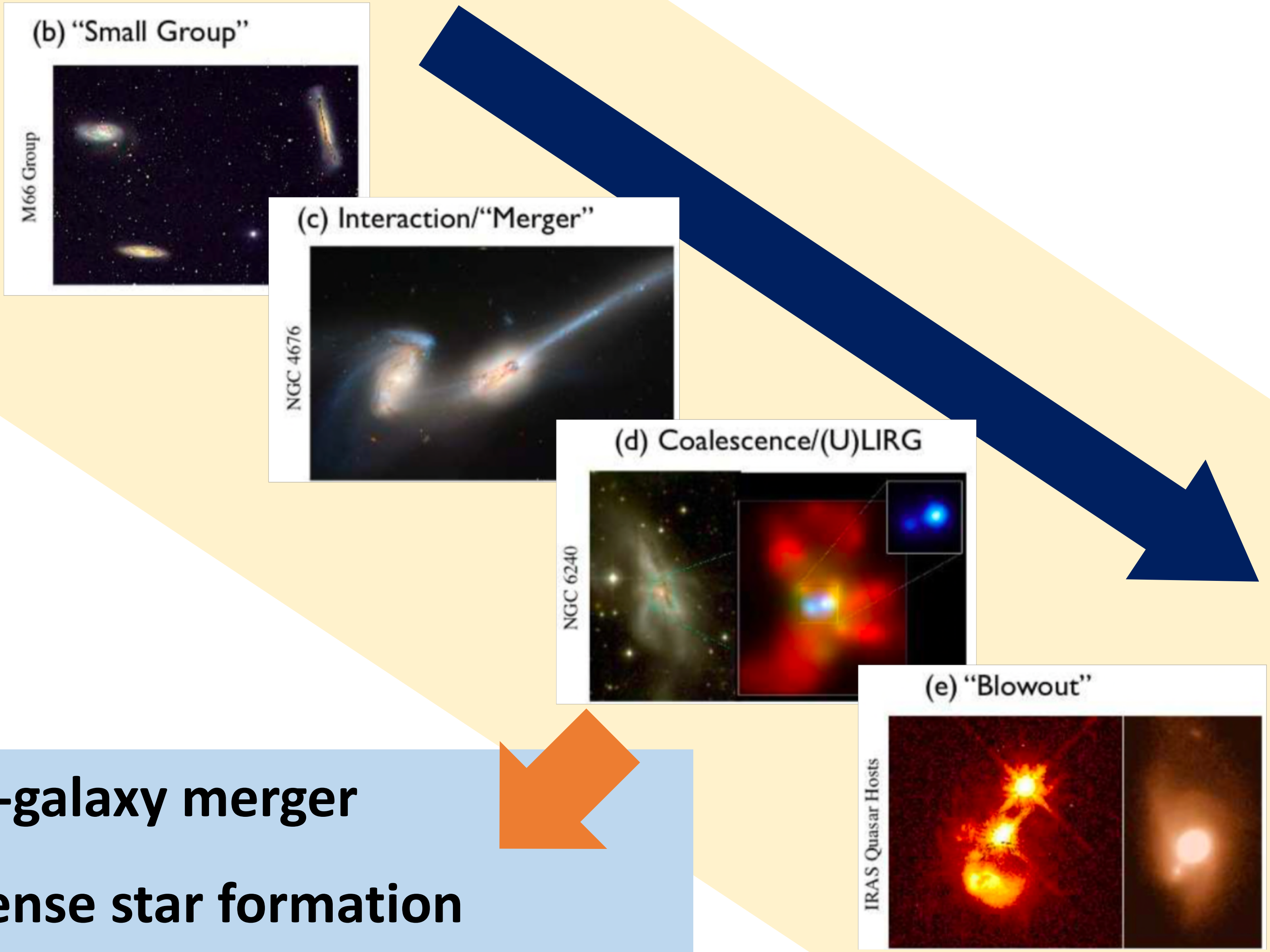
- ✓ **high-resolution 2D-RHD simulations**
- ✓ **Gas accretion onto a moving MBH**
- ✓ **assuming primordial gas**
- ✓ **Upstream dense shell can accelerate the moving BH forward.**



Acceleration from upstream shell

Dense massive shell forms at the upstream front of ionized bubble

Deceleration from downstream clump



Hopkins et al. (2008)

Galaxy-galaxy merger

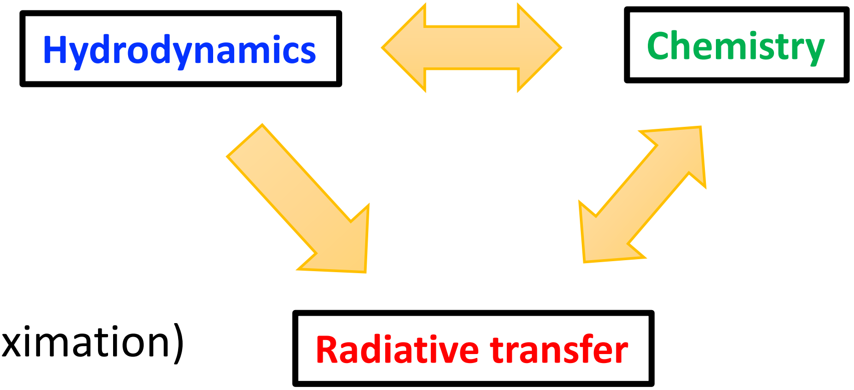
→ Intense star formation

→ Dusty and Dense environment

Method :

3D-RHD simulation

Simulation code



- **HD simulation (public code “PLUTO”)**
- **Radiative transfer**
  - ✓ photoionization (EUV)
  - ✓ dust attenuation (FUV, EUV)
  - ✓ dust thermal emission (IR; FLD approximation)
  - ✓ radiation pressure (Thomson scattering, photoionization, dust UV & IR radiative force)
- **Non-equilibrium Chemistry**
  - ✓ six species: HI, HII, HeI, HeII, HeIII, e-, (some heavy elements, molecules)
  - ✓ photoionization, recombination, collisional excitation & ionization, free-free emission, metal line cooling, dust-gas collisional cooling etc.

Simulation code

- HD simulation (public code “PLUTO”)
- Radiative transfer
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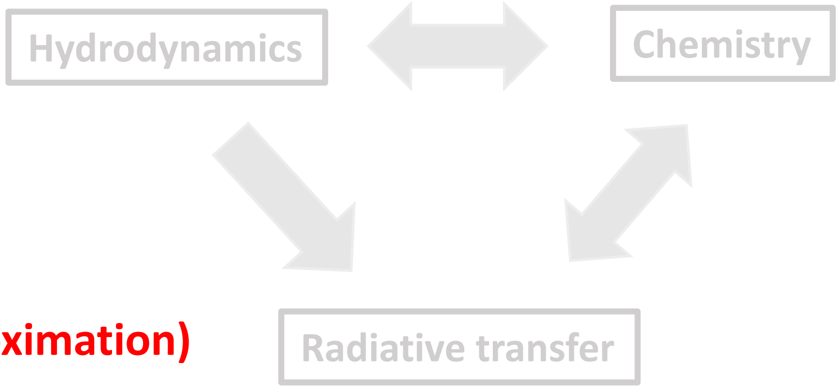
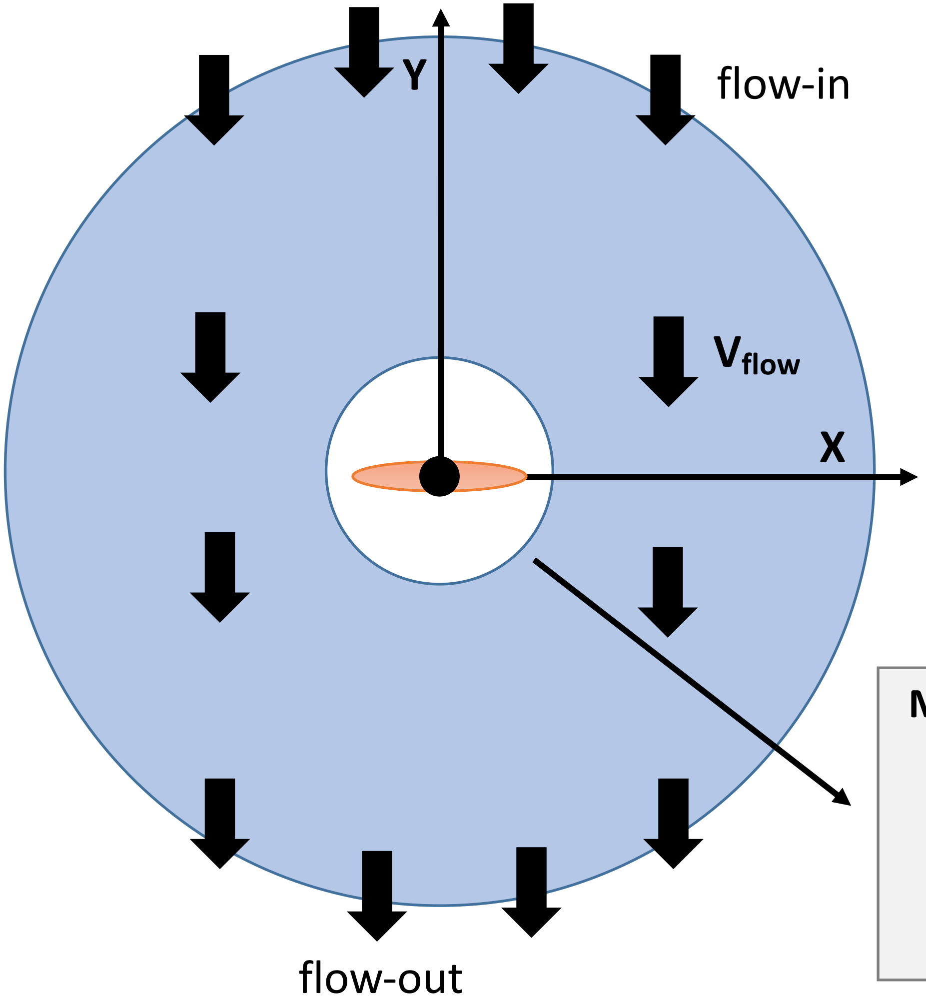


Originality !!

- Non-equilibrium Chemistry
  - ✓ six species: HI, HII, HeI, HeII, HeIII, e-, (some heavy elements, molecules)
  - ✓ photoionization, recombination, collisional excitation & ionization, free-free emission, **metal line cooling, dust-gas collisional cooling** etc.

Initial condition

3D-simulation : $(N_r, N_\theta, N_\phi) = (256, 36, 72)$,
$0.01\ r_{bondi} < r < 10\ r_{bondi}$



Fiducial setup

- ✓ $M_{BH} = 10^4$ Msun
- ✓ $n_{gas} = 10^4\ cm^{-3}$
- ✓ $v_{flow} = 20$ km/s
- ✓ $T_{gas} = T_{eq}$ (<-- heating rate = cooling rate)
- ✓ $Z = 0.01\ Z_{sun}$
- ✓ dust-to-gas mass ratio, D = 0.01 (Z/Zsun)

Mass flux at inner boundary → BH luminosity

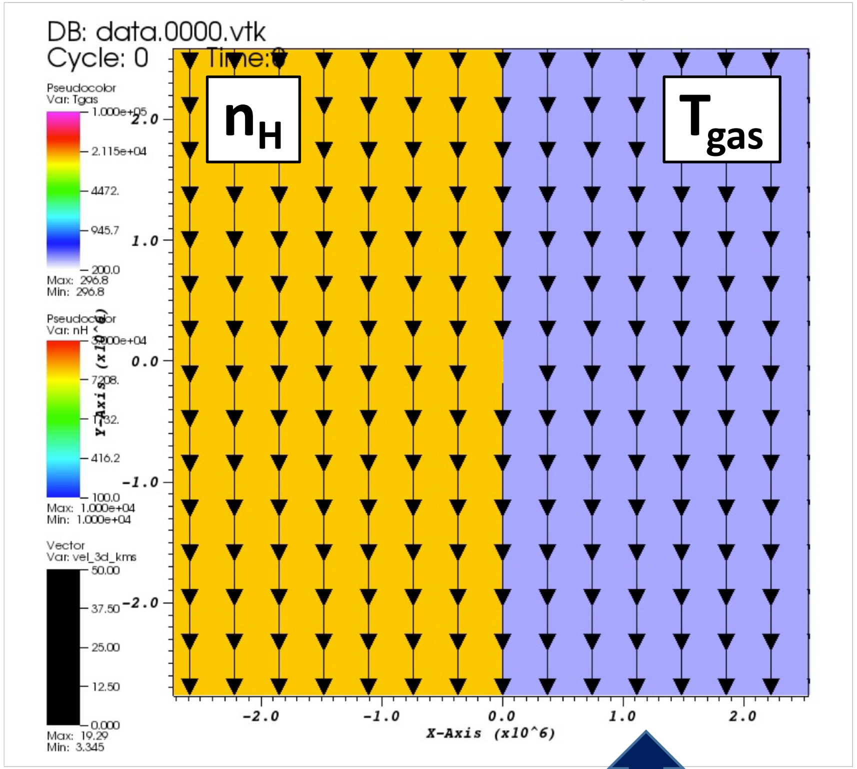
$$L = \begin{cases} 2L_{\rm Edd}\left[1+\ln\left(\frac{\dot{M}}{2\dot{M}_{\rm Edd}}\right)\right] & (\dot{M} > 2\dot{M}_{\rm Edd}) \\ L_{\rm Edd}\left(\frac{\dot{M}}{\dot{M}_{\rm Edd}}\right) & (\dot{M} < 2\dot{M}_{\rm Edd}) \end{cases}$$

slim disk (Watarai+2000)

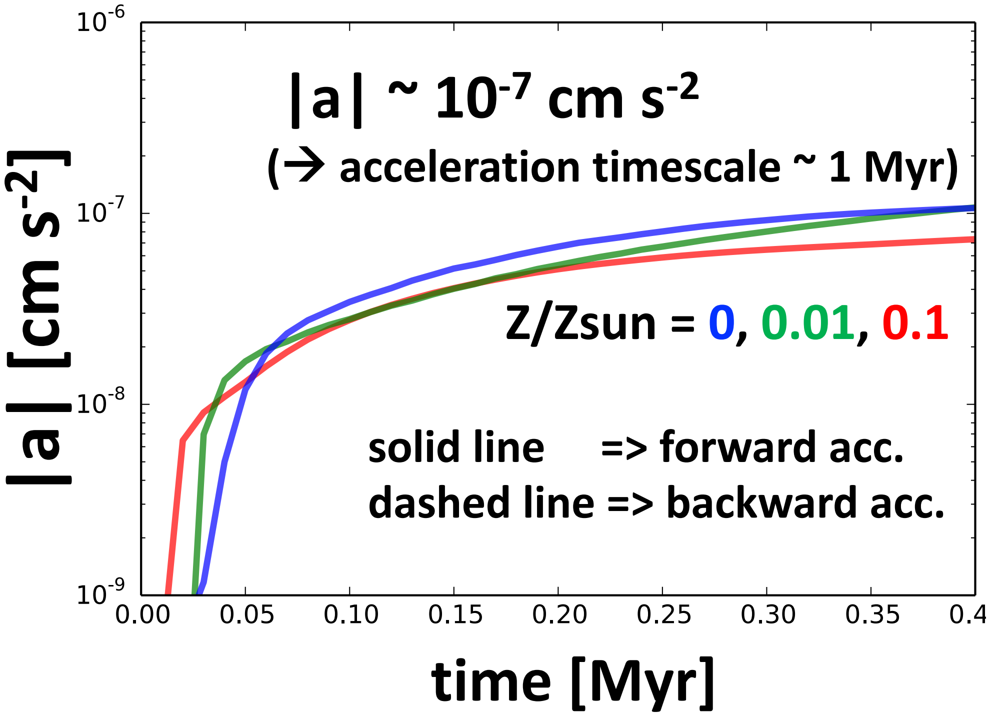
Results

Gas accretion onto a moving BH

Z = 0.01 Z_{sun}



T ∼ 10^2 K (cold ambient)
10^4 K (partially ionized)
10^5 K (ionized gas)



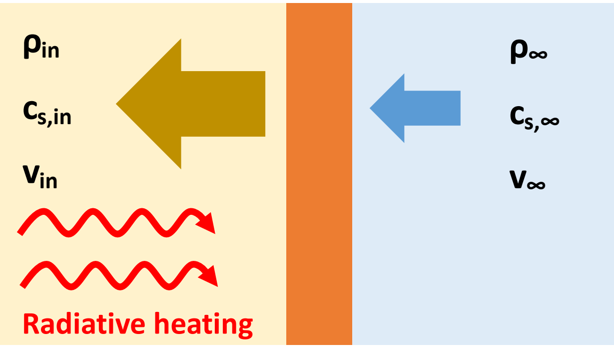
$|a| \sim 10^{-7}$ cm s^{-2}
(→ acceleration timescale ~ 1 Myr)

Z/Zsun = 0, 0.01, 0.1

solid line => forward acc.
dashed line => backward acc.

- ✓ Dense massive shell forms at the upstream front of ionized bubble.
- ✓ moving IMBHs can speed up even in dusty environments.

Can BH accelerate unlimitedly?


ρ_{in}

$c_{s,in}$

v_{in}

Radiative heating

ρ_∞

$c_{s,\infty}$

v_∞

mass conservation

$$\rho_{\rm in} v_{\rm in} = \rho_\infty v_\infty$$

momentum conservation

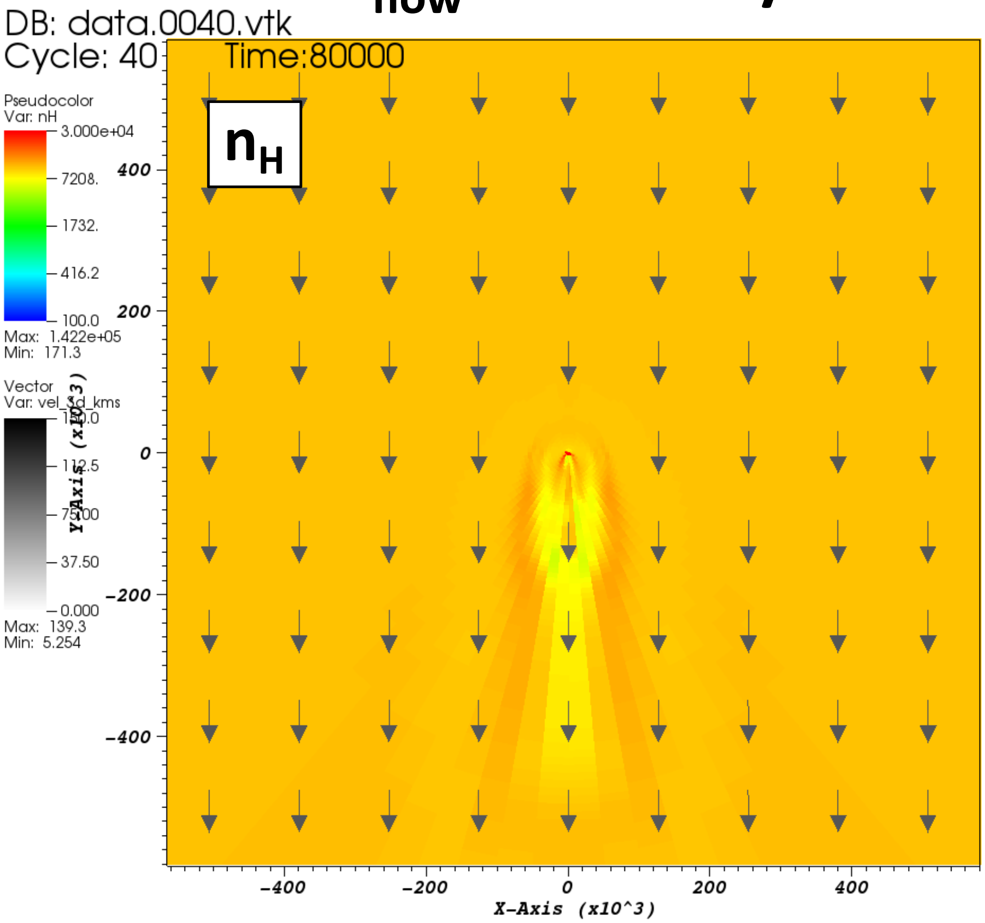
$$\rho_{\rm in} v_{\rm in}^2 + \rho_{\rm in} c_{\rm s,in}^2 = \rho_\infty v_\infty^2 + \rho_\infty c_{\rm s,\infty}^2$$

weak R-type I-front ($v_\infty > 2\, c_{s,in}$)

$$\rho_{\rm in} \sim \rho_\infty \ \& \ v_{\rm in} \sim v_\infty$$

✓ **No upstream dense shell!**

v_{flow} = 100 km/s



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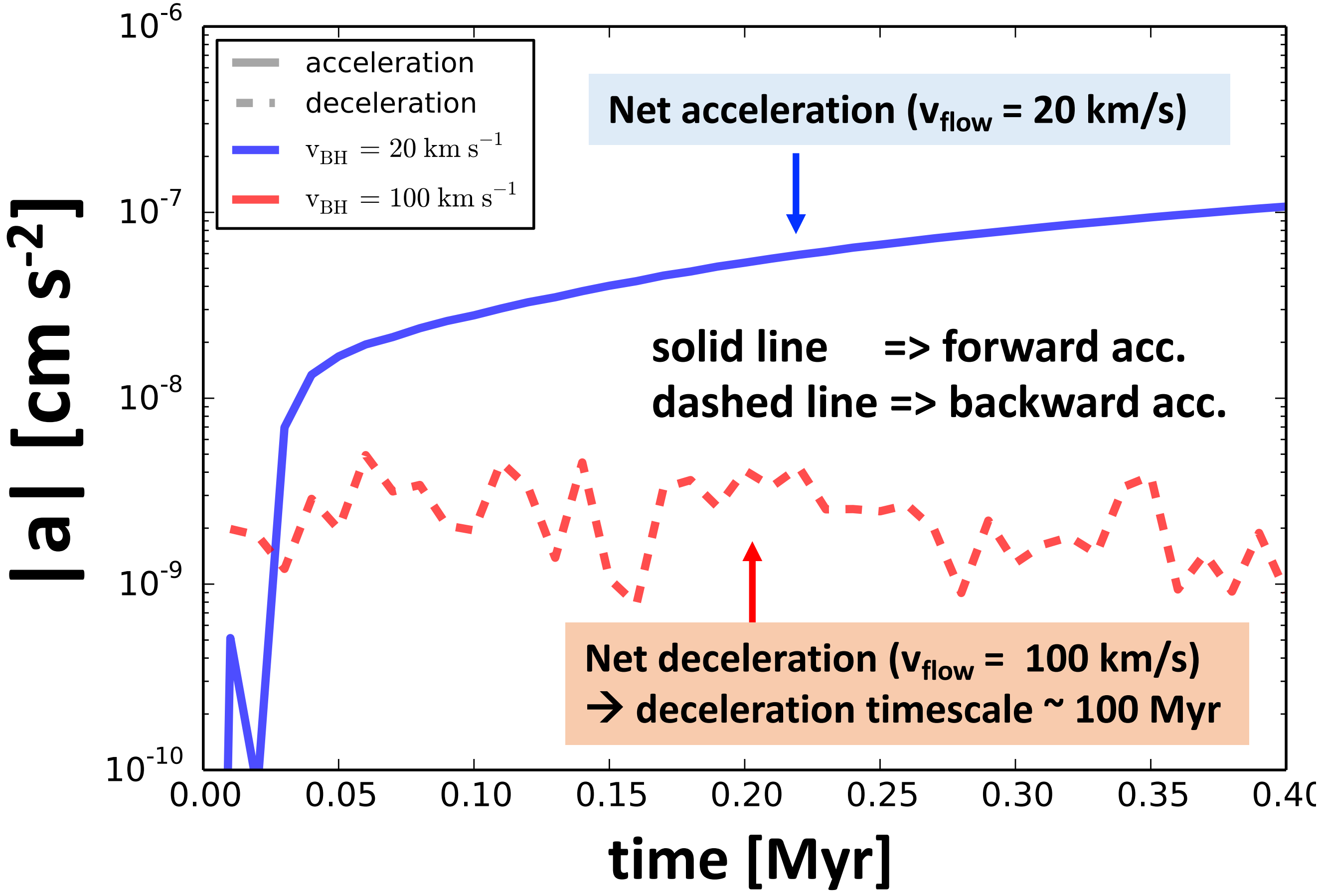


Net acceleration (v_{flow} = 20 km/s)

solid line => forward acc.
dashed line => backward acc.

Net deceleration (v_{flow} = 100 km/s)
→ deceleration timescale ~ 100 Myr

✓ **Once the velocity of moving BH becomes fast enough to realize R-type I-front ($v_{flow} >> c_{s,HII}$), the BH isn't accelerated anymore.**

Is it impossible for BHs to migrate to galactic centers?

Gas accretion in dense environment

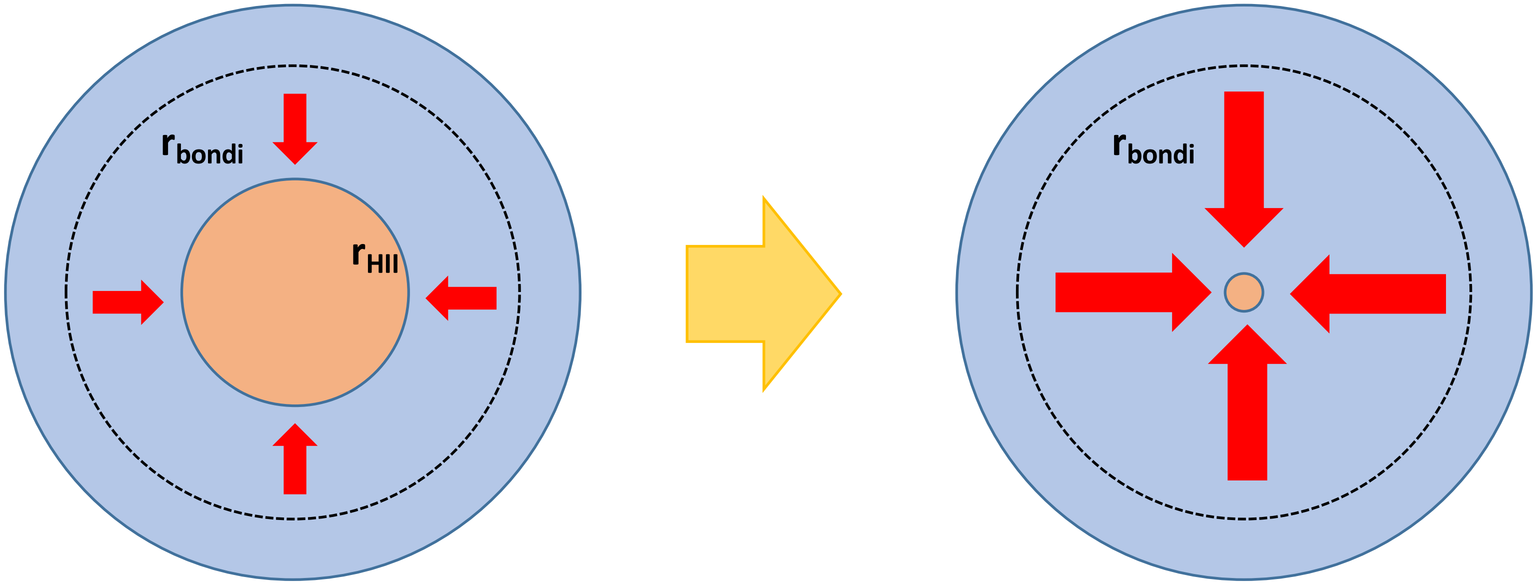
Inayoshi et al. (2016)

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

$$\left(\frac{M_{\rm BH}}{10^4\ {\rm M}_\odot}\right)\left(\frac{n_\infty}{10^6\ {\rm cm}^{-3}}\right) \gtrsim \left(\frac{c_{s,\infty}}{10\ {\rm km\ s}^{-1}}\right)\underline{\left\{1+7.1\left(\frac{Z}{10^{-2}\ {\rm Z}_\odot}\right)\right\}}^{-1/2}$$

Toyouchi et al. (2019)

Effects of dust radiative force



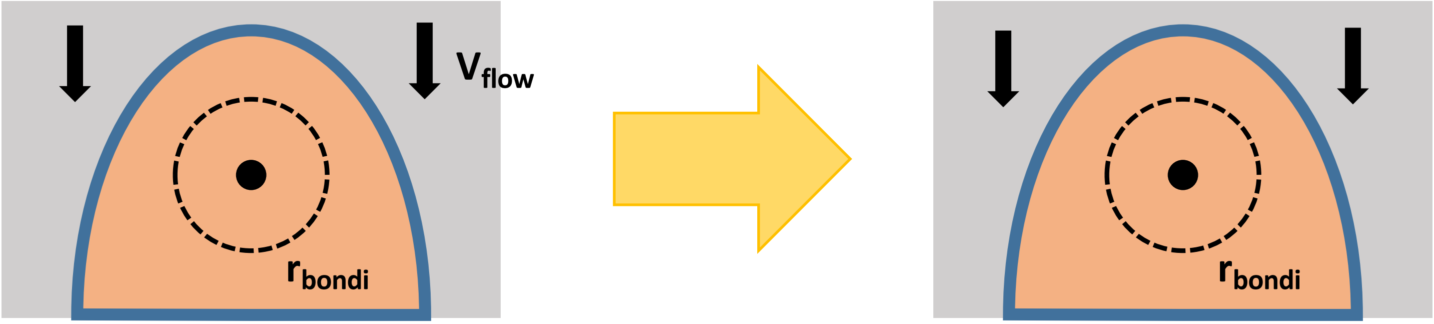
Gas within $r_{\rm bondi}$ can accrete onto the surface of ionized bubble

Bondi like accretion

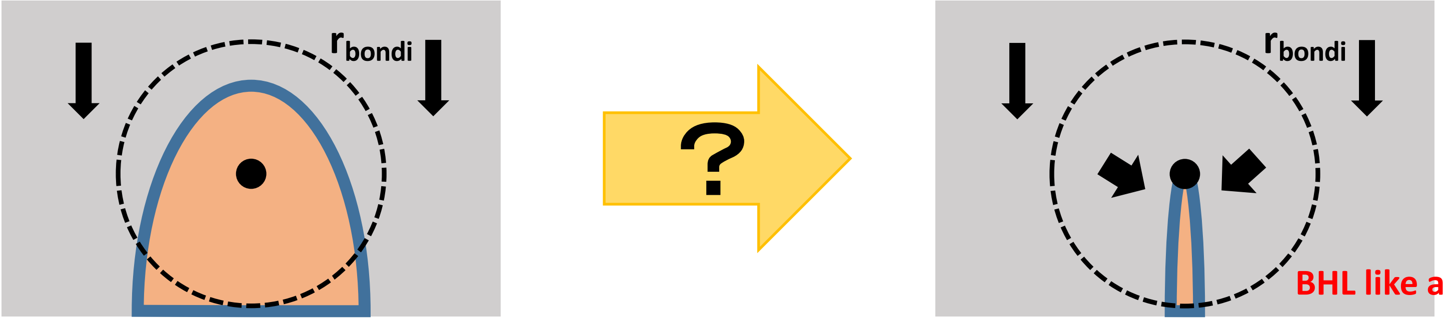
Gas accretion in dense environment

$$\left(\frac{M_{\rm BH}}{10^4\ {\rm M}_\odot}\right)\left(\frac{n_{\rm H}}{10^6\ {\rm cm}^{-3}}\right) \gtrsim \left(\frac{\sqrt{c_{\rm s,\infty}^2+v_{\rm flow}^2}}{10\ {\rm km\ s^{-1}}}\right)\left\{1+7.1\left(\frac{Z}{10^{-2}\ {\rm Z}_\odot}\right)\right\}^{-1/2}$$

$M_{\rm BH,4}\, n_{\rm H,6} < 1$



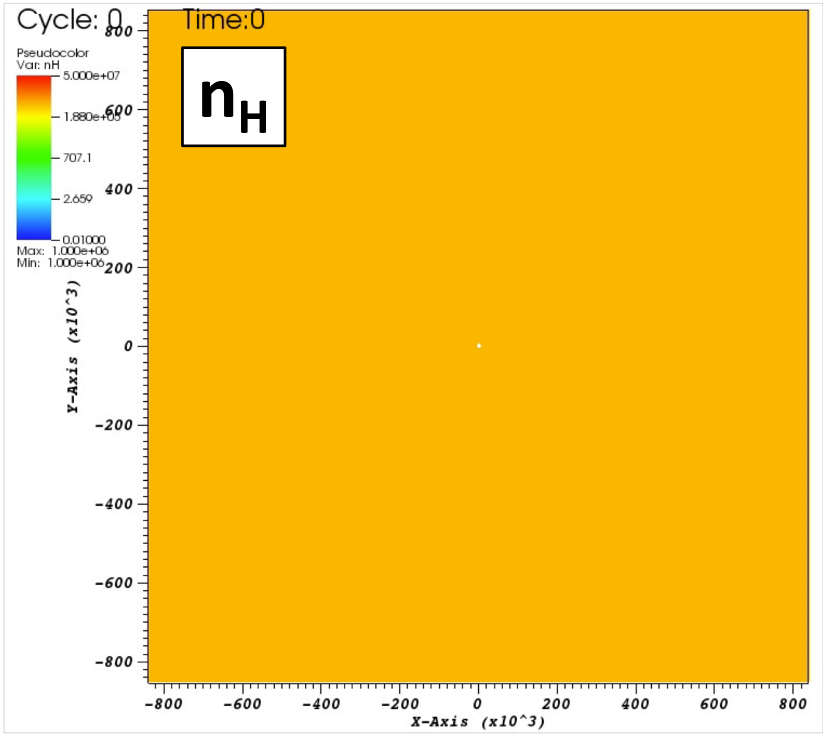
$M_{\rm BH,4}\, n_{\rm H,6} > 1$

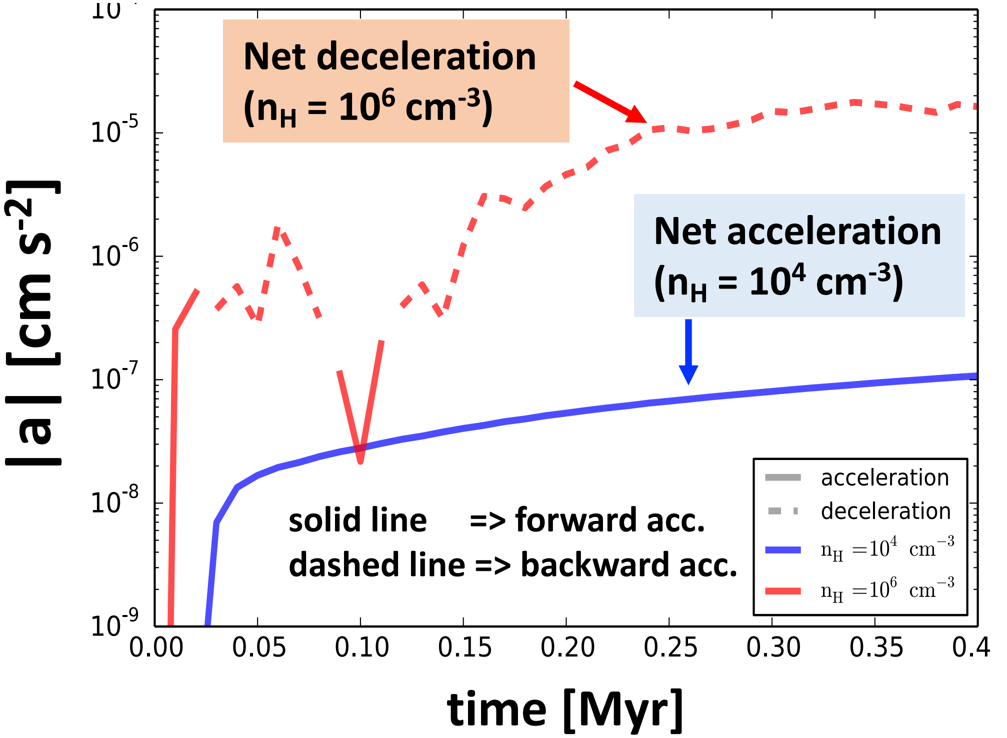


BHL like accretion？

$$\left(\frac{M_{\rm BH}}{10^4\ {\rm M}_\odot}\right)\left(\frac{n_{\rm H}}{10^6\ {\rm cm}^{-3}}\right) \gtrsim \left(\frac{\sqrt{c_{{\rm s},\infty}^2 + v_{\rm flow}^2}}{10\ {\rm km\ s}^{-1}}\right)\left\{1 + 7.1\left(\frac{Z}{10^{-2}\ {\rm Z}_\odot}\right)\right\}^{-1/2}$$

$n_H = 10^6\ cm^{-3}$





Net deceleration ($n_H = 10^6\ cm^{-3}$)

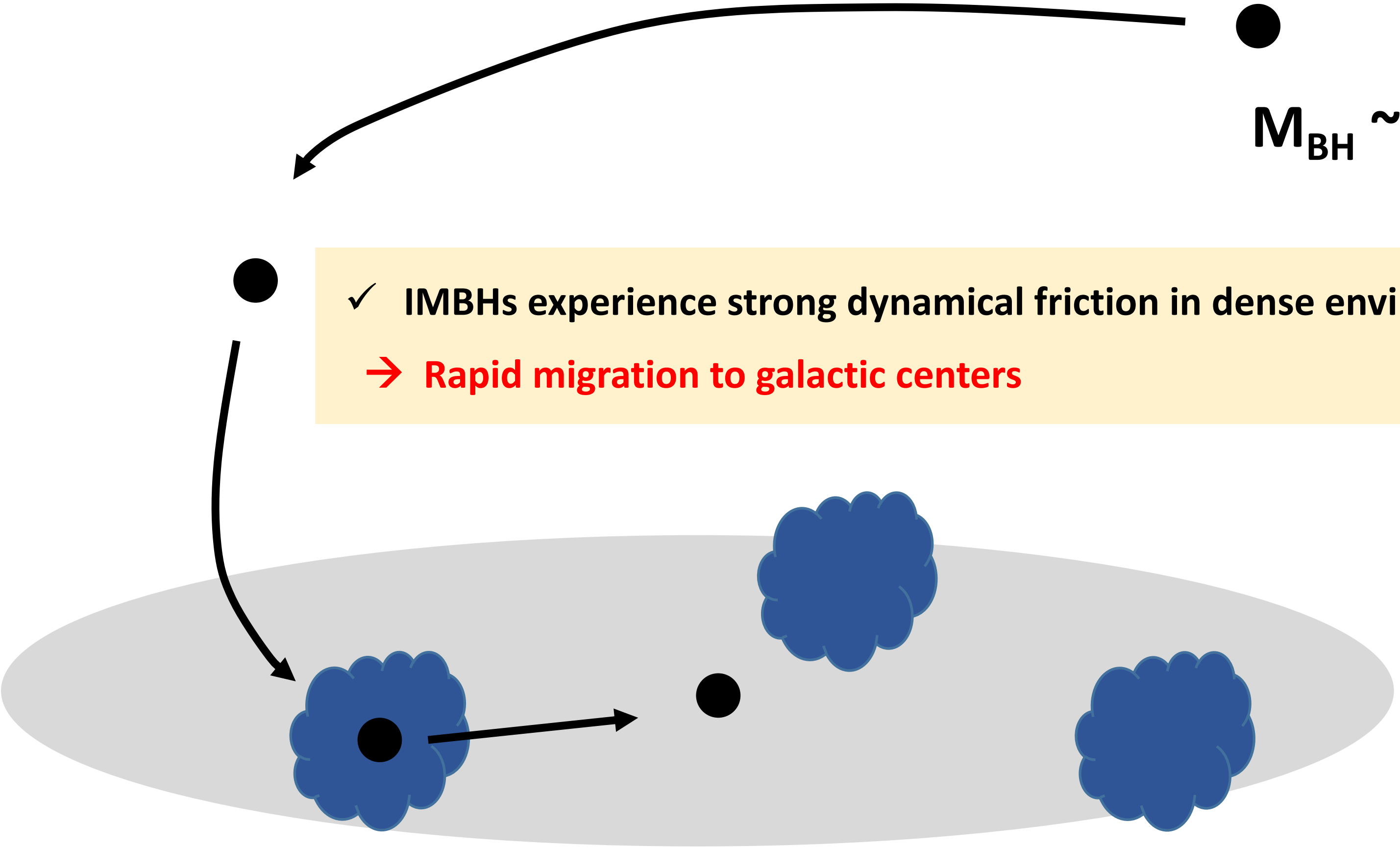
Net acceleration ($n_H = 10^4\ cm^{-3}$)

solid line => forward acc.
dashed line => backward acc.

- ✓ **No static upstream shell**
- ✓ **Gas aggregates at the downstream side.**

- ✓ **IMBHs can be dragged backward similar to the BHL accretion.**

Discussion and Summary



Sparse environment
($M_{BH,4}\, n_{H,6} < 1$)

- ✓ At first, IMBHs are moving in sparse environments.

  → Forward acceleration up to $v \sim 60$ km/s

$M_{BH} \sim 10^{4\text{-}6}\, M_{sun}$

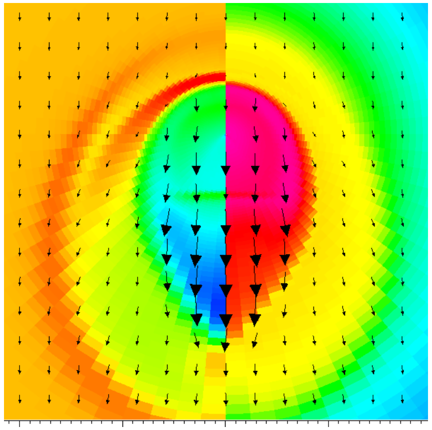
- ✓ IMBHs experience strong dynamical friction in dense environments.

  → Rapid migration to galactic centers

$n_H \sim 10^{4\text{-}6}\ \mathrm{cm}^{-3}$

Dense environment
($M_{BH,4}\, n_{H,6} > 1$)

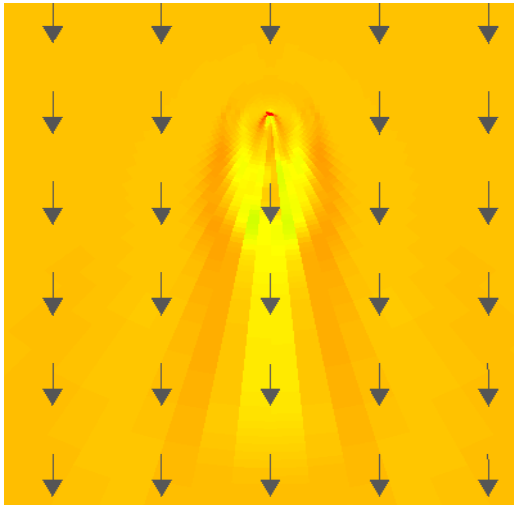
Sparse environment ($M_{BH,4}\, n_{H,6} < 1$)



- ✓ The upstream dense shells can gravitationally accelerate MBHs forward.
- ✓ No significant dependence on gas metallicity

BH speeds up, but…

No upstream dense shell!



Once the velocity of moving BH becomes fast enough to realize R-type I-front ($v_{flow} >> c_{s,HII}$), the BH isn't accelerated anymore.

Dense environment ($M_{BH,4}\, n_{H,6} > 1$)

- ✓ No static upstream shell
- ✓ Gas aggregates at the downstream side.
- ✓ MBHs can be dragged backward in a similar manner to BHL accretion.
- ✓ MBHs could migrate to galactic centers on very short timescale of ~ < 10 Myr.