

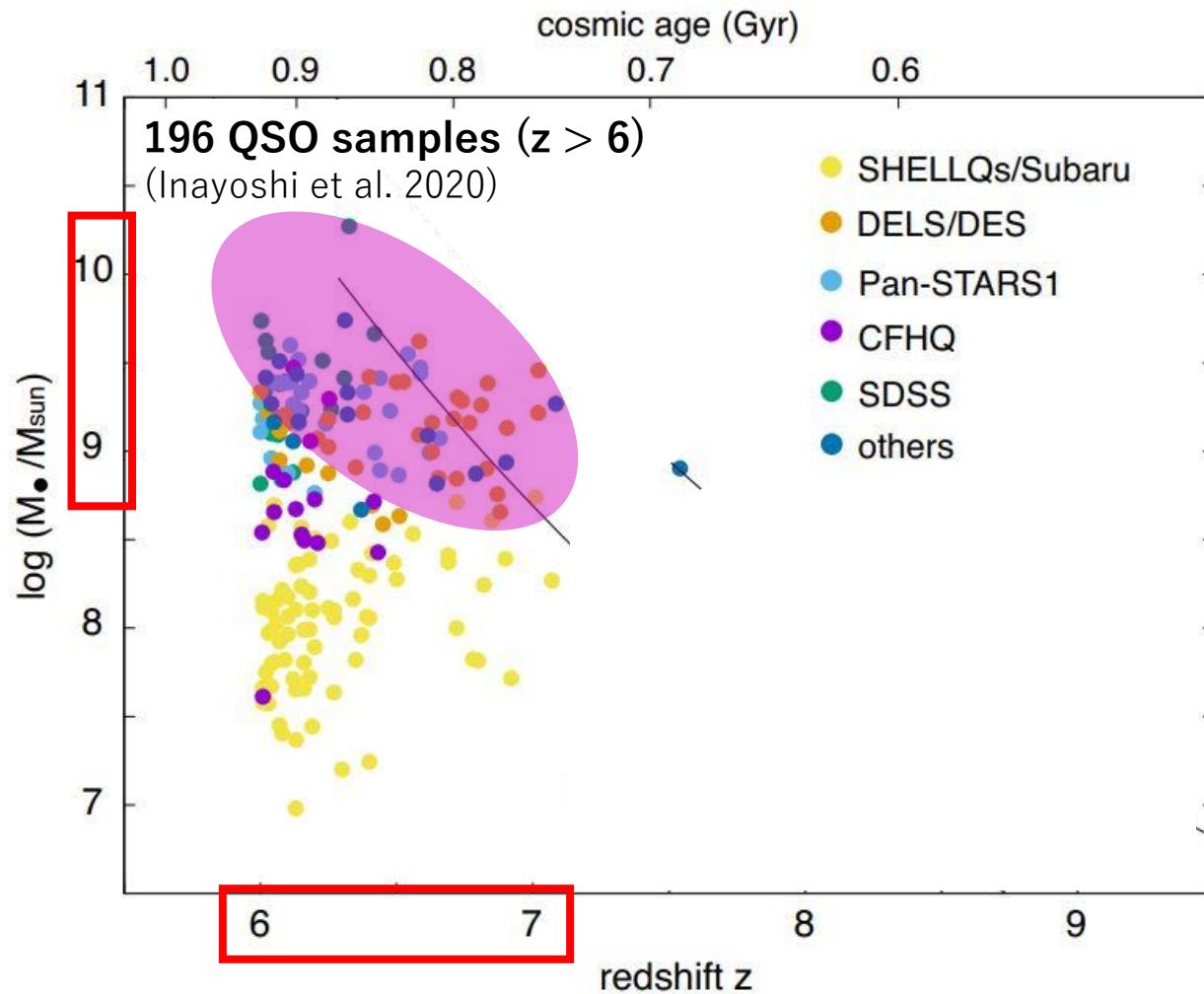
超臨界ブラックホール降着流における ライマンアルファ輝線の輻射力の計算

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High-z SuperMassive Black Holes(SMBHs)



Existence of High- z ($z > 6$) SMBHs ($M_{\text{BH}} > 10^9 M_{\odot}$)
⇒ Severe Constraints on Formation Scenarios

M_{\odot} :Solar Mass
 M_{BH} :BH mass

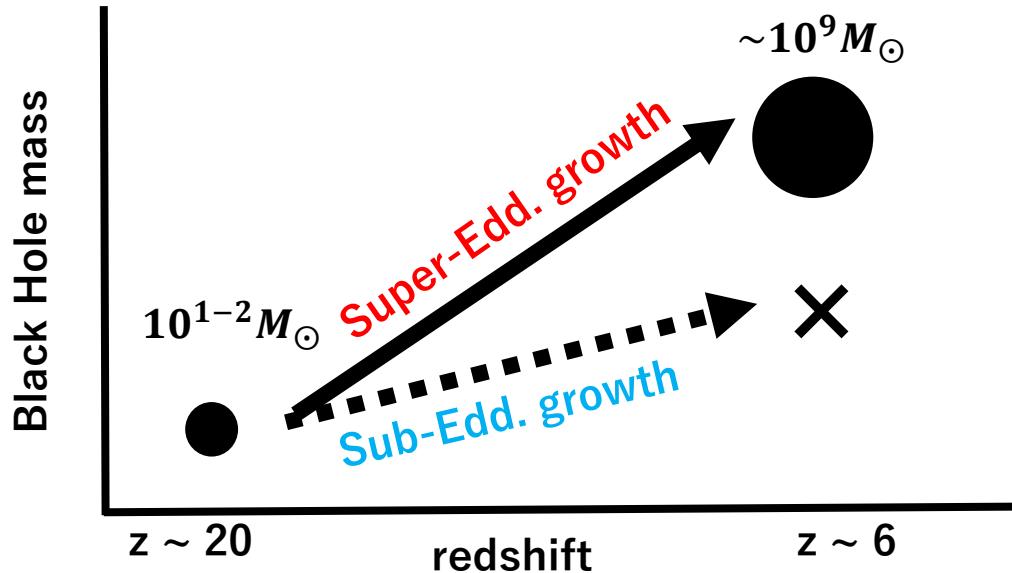
Growth Time Issues for High-z SMBHs

One possible pathway to high-z SMBHs : Rapid accretion

BH seeds ($M_{\text{BH}} \sim 10^{1-2} M_{\odot}$, $z \sim 20$; PopIII BHs)



Rapid growth via gas accretion



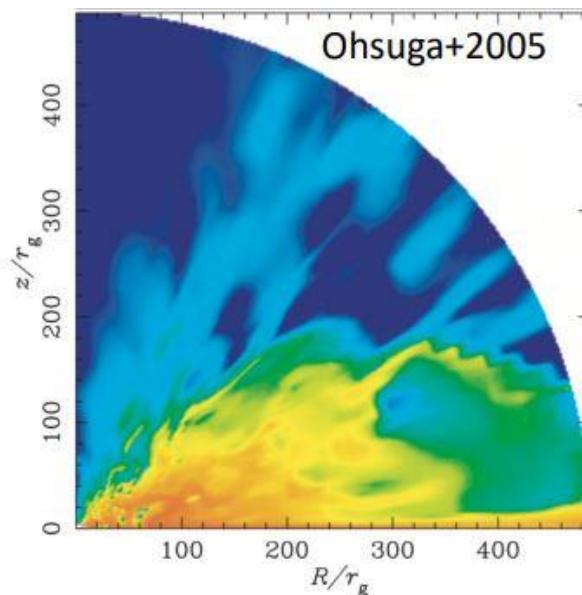
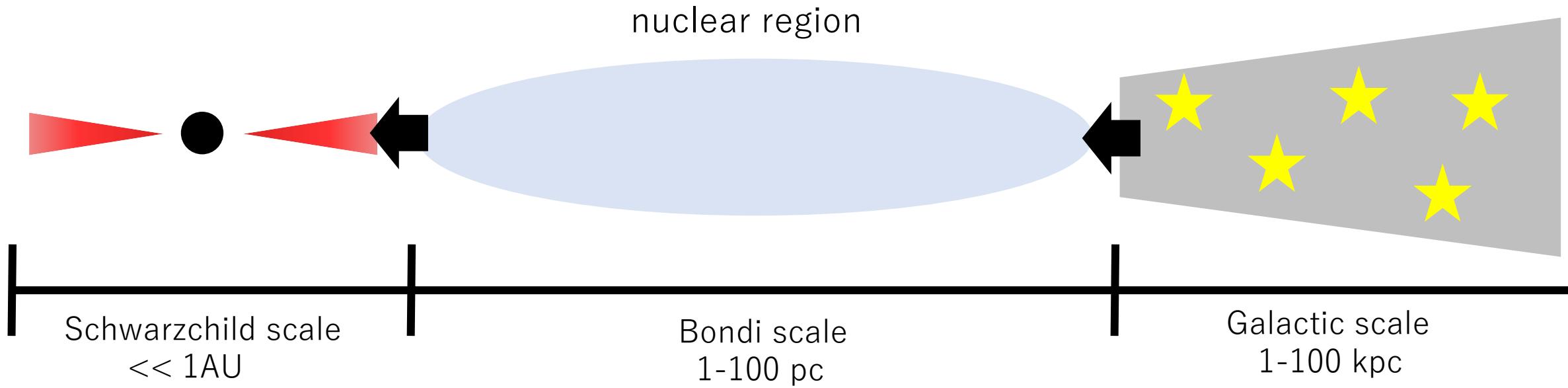
Sub-Eddington accretion

Growth time > Cosmic age of SMBHs.

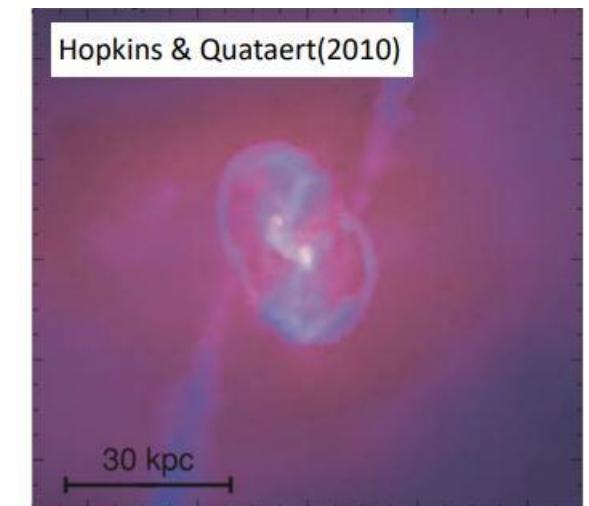
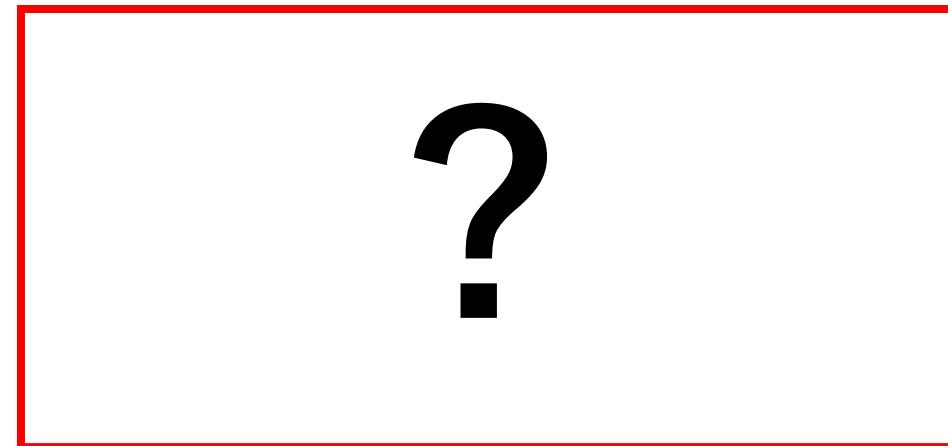
**Super-Eddington accretion
is required.**

※ $M_{\text{BH}} \sim 10^{3-4} M_{\odot}$ の超大質量星由来のBHを種とする説もある

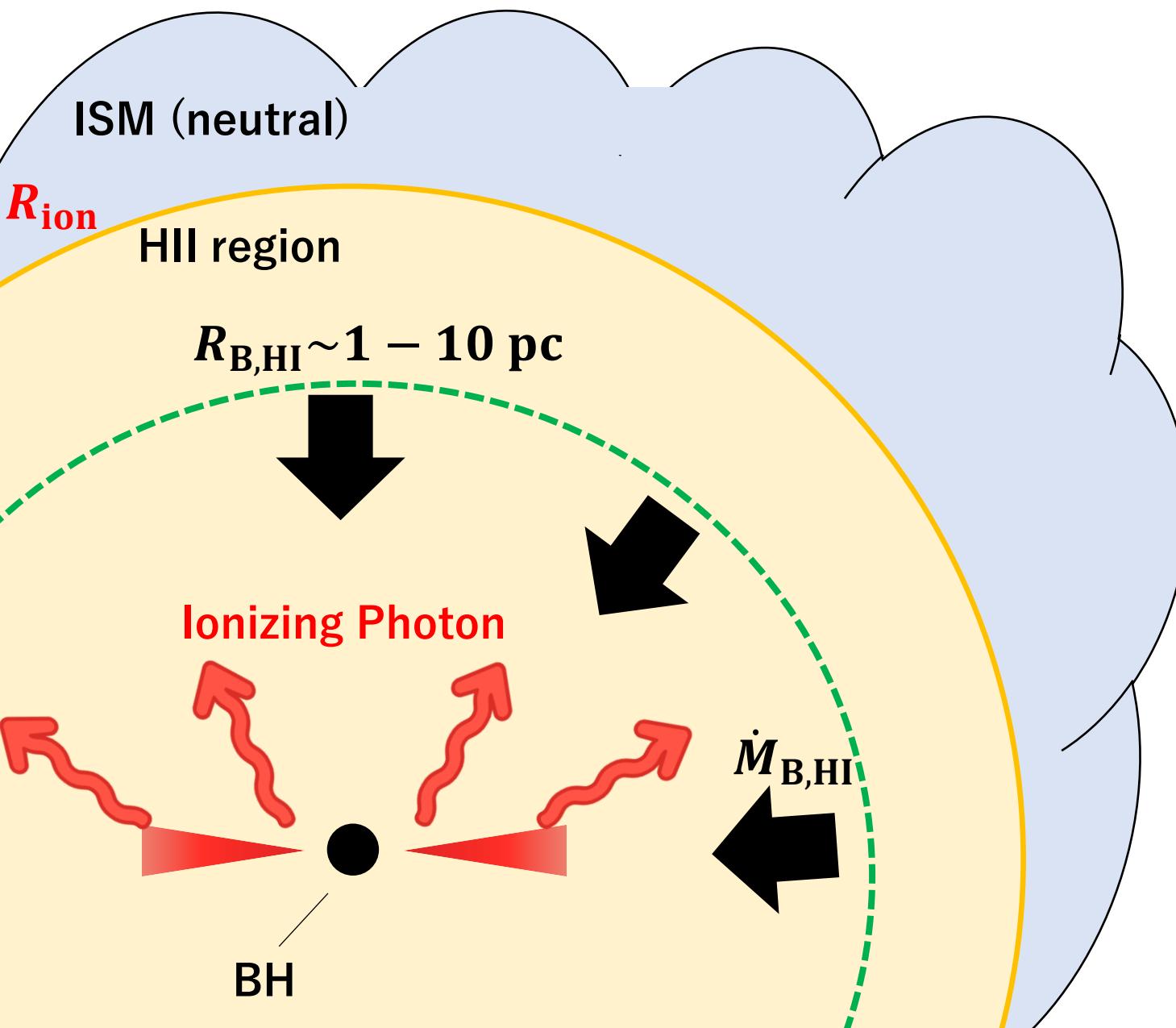
BHs Growth via Mass Accretion



Is continuous gas supply
from Bondi scale possible?



Suppression of Gas Accretion by Photoionization Heating

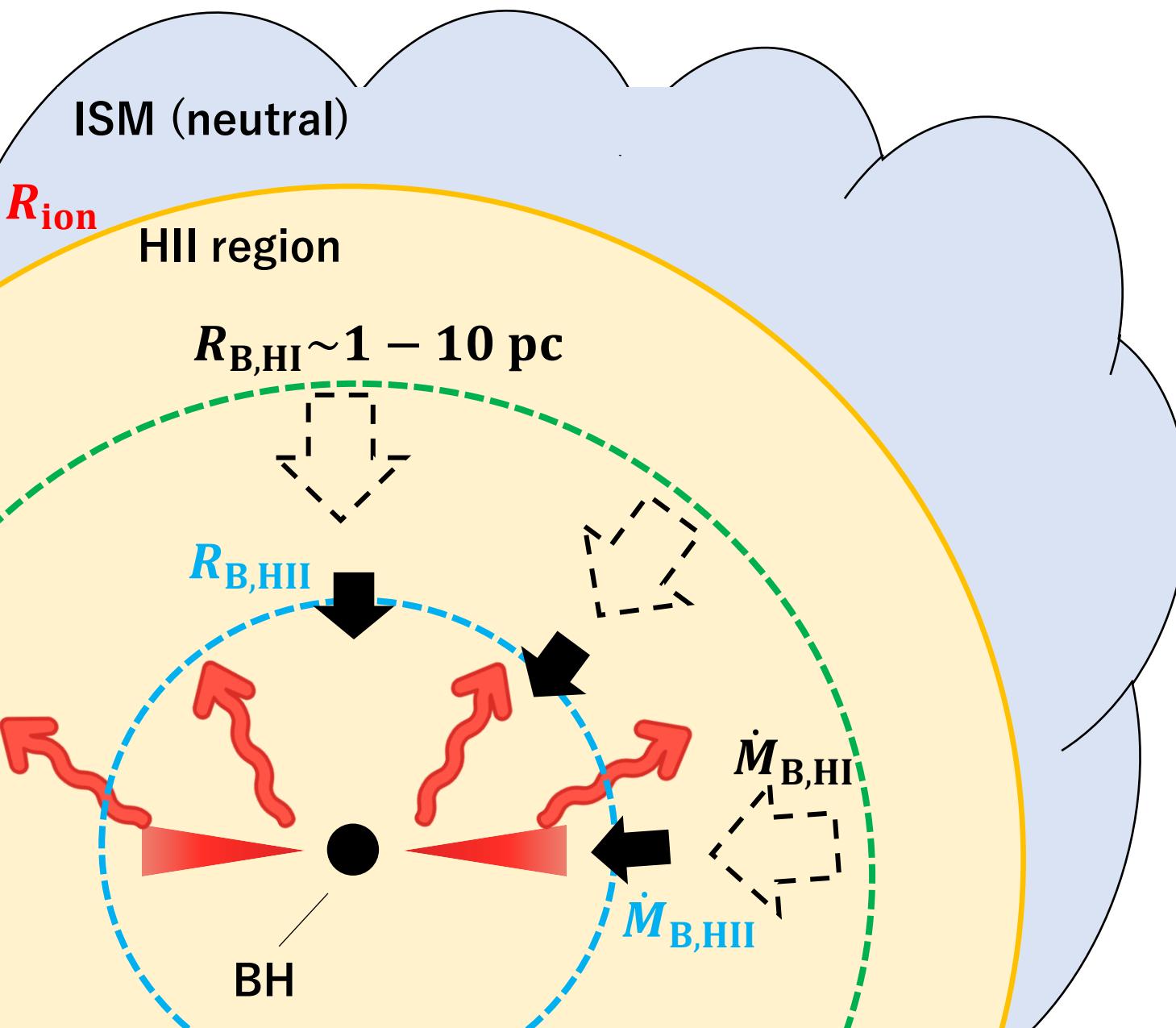


ISM falls to BH from Bondi radius
 \Rightarrow Accretion disk formation
 \Rightarrow Ionizing photon emission from accretion disk
 \Rightarrow Formation of HII region ;
temperature rise

Milosavljevic et al. 2009

R_B : Bondi radius, \dot{M}_B : Bondi accretion rate
 R_{ion} : radius of HII region
 n_∞ : number density of ISM, T_∞ : temperature of ISM

Suppression of Gas Accretion by Photoionization Heating



ISM falls to BH from Bondi radius
 \Rightarrow Accretion disk formation
 \Rightarrow Ionizing photon emission from accretion disk
 \Rightarrow Formation of HII region ;
temperature rise
 \Rightarrow **Reduction of accretion rate**

$$\dot{M}_B \propto M_{\text{BH}}^2 n_\infty T_\infty^{-3/2}$$

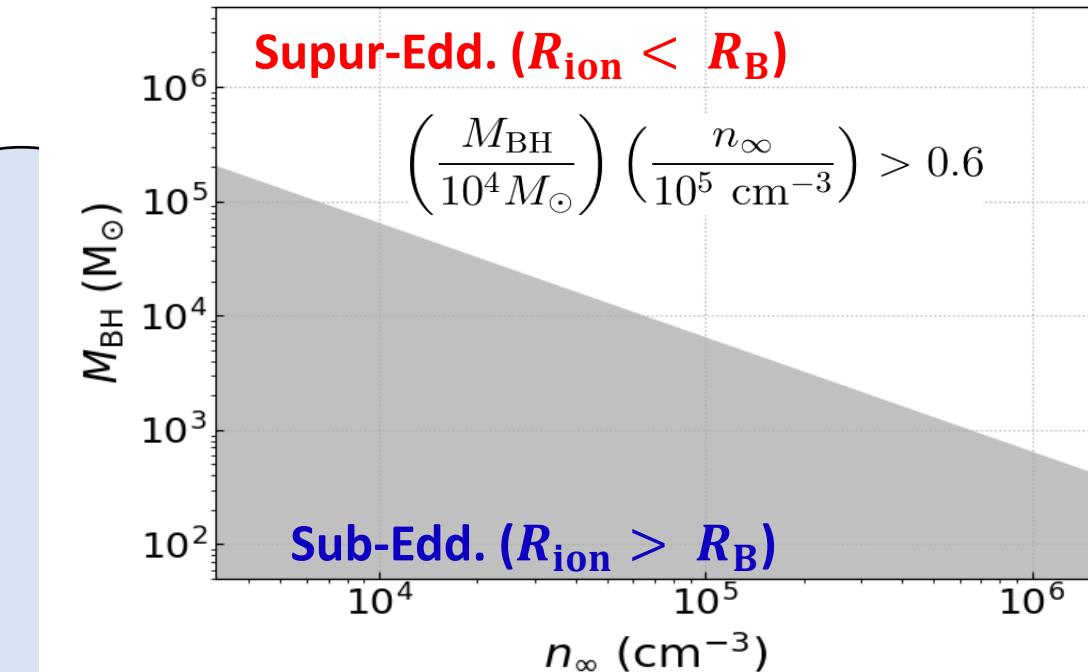
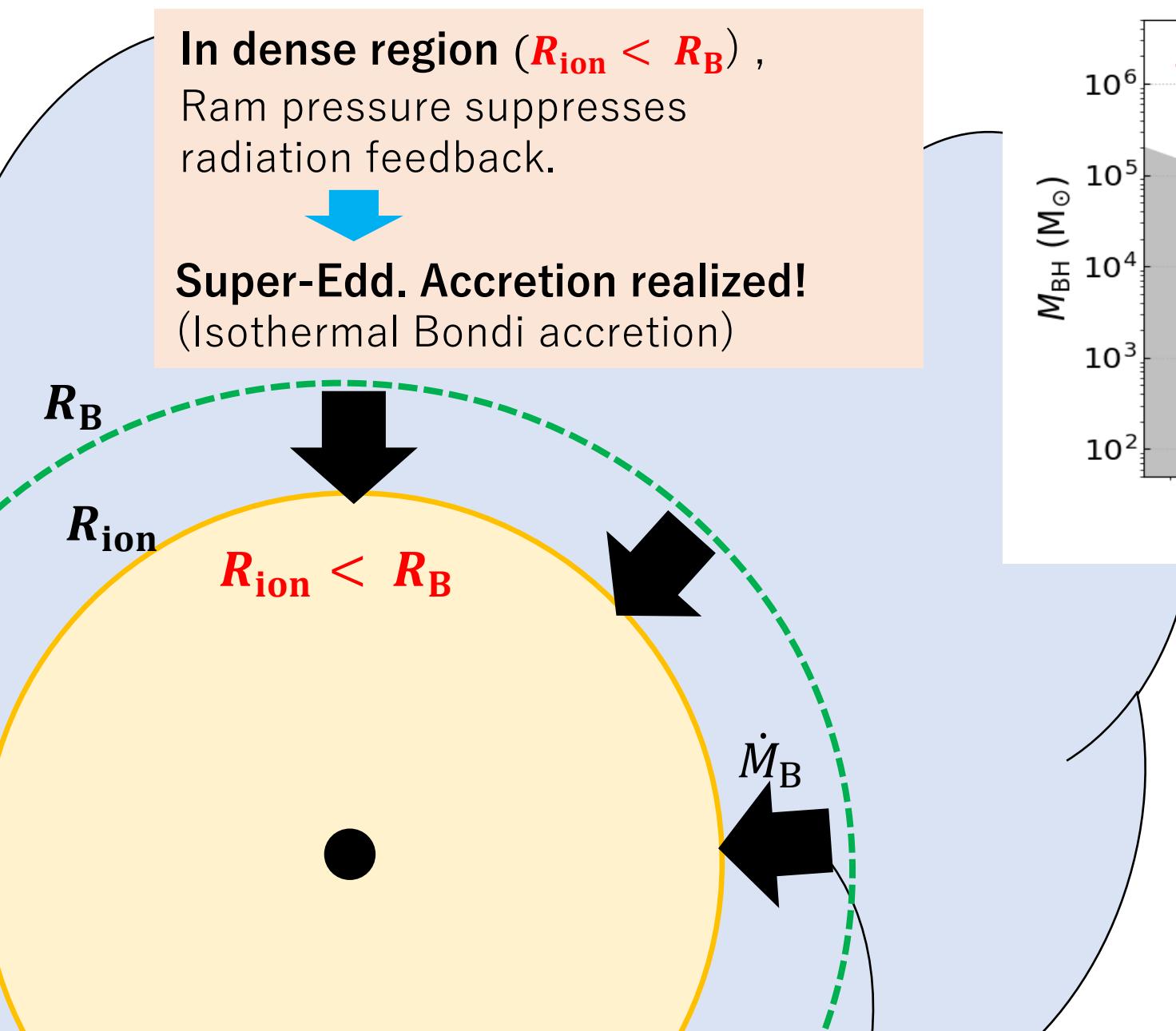
Milosavljevic et al. 2009

R_B : Bondi radius, \dot{M}_B : Bondi accretion rate
 R_{ion} : radius of HII region
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Possibility of Super-Eddington Accretion

(Inayoshi, et. al. 2016, Sakurai, et al. 2016)

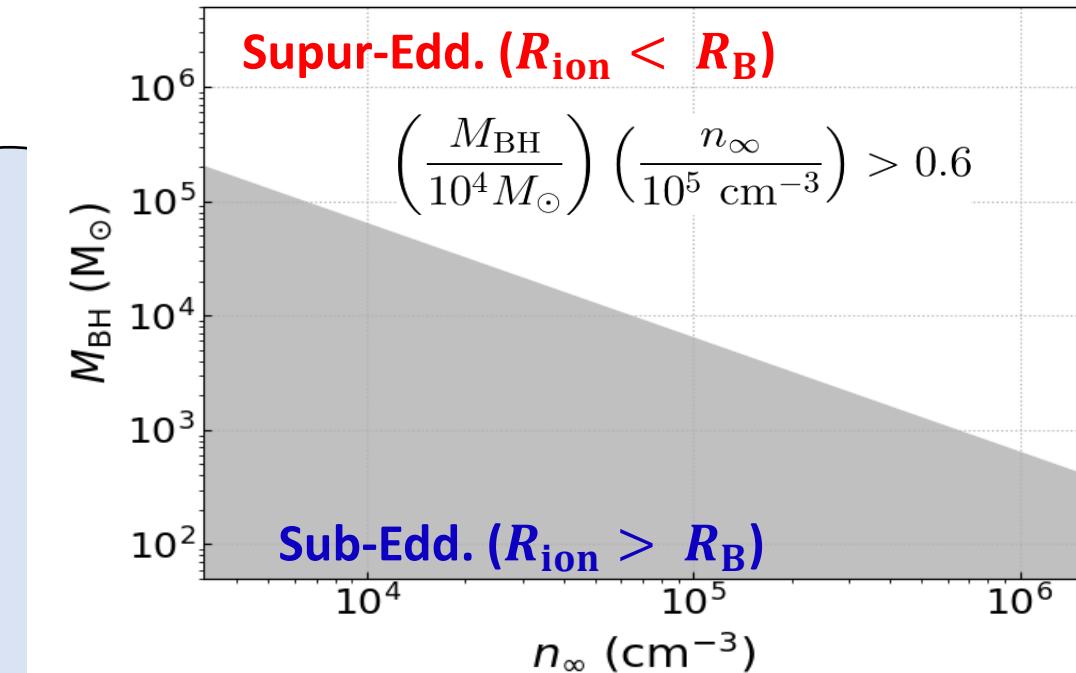
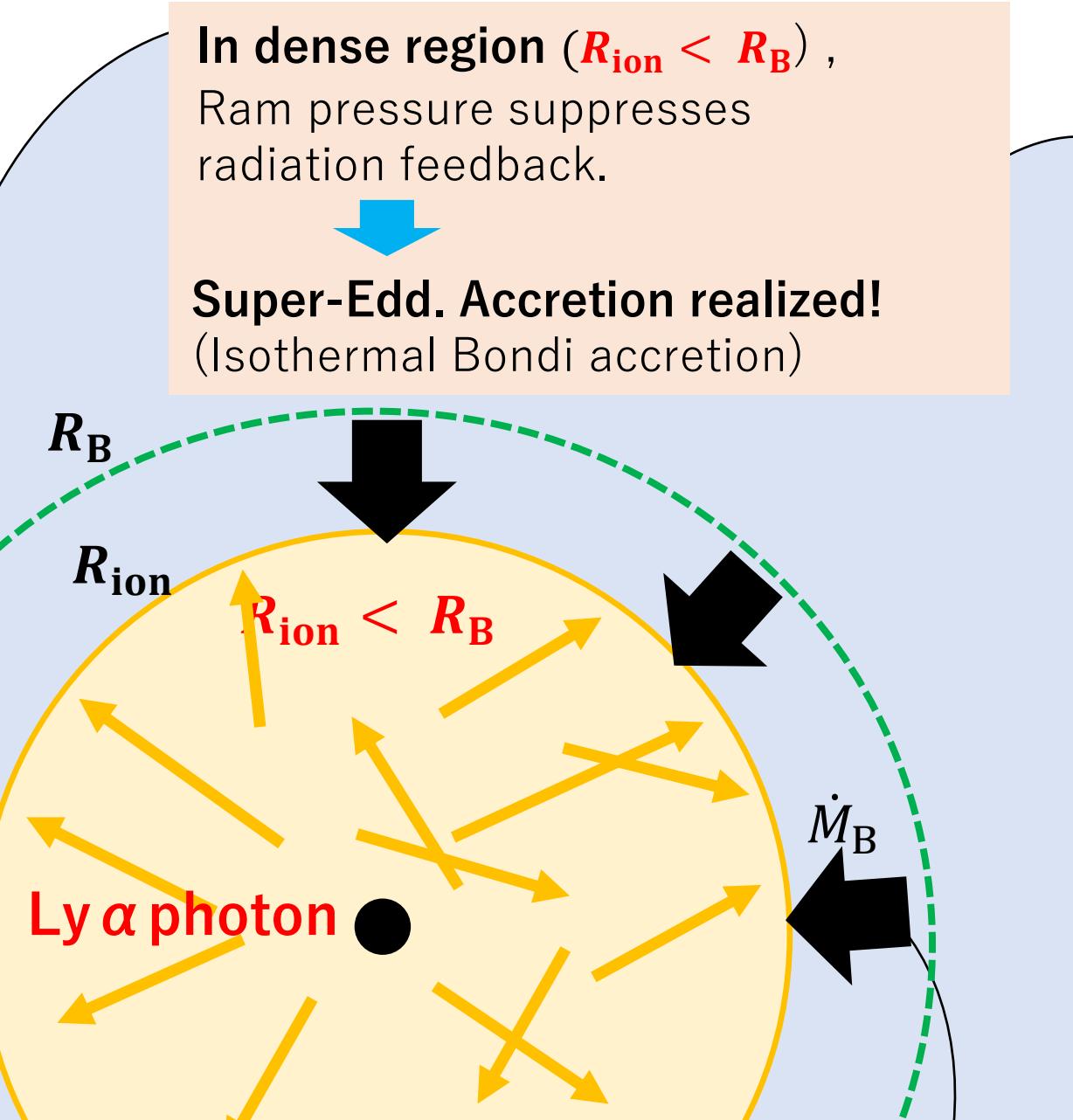
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Possibility of Super-Eddington Accretion

(Inayoshi, et. al. 2016, Sakurai, et al. 2016)

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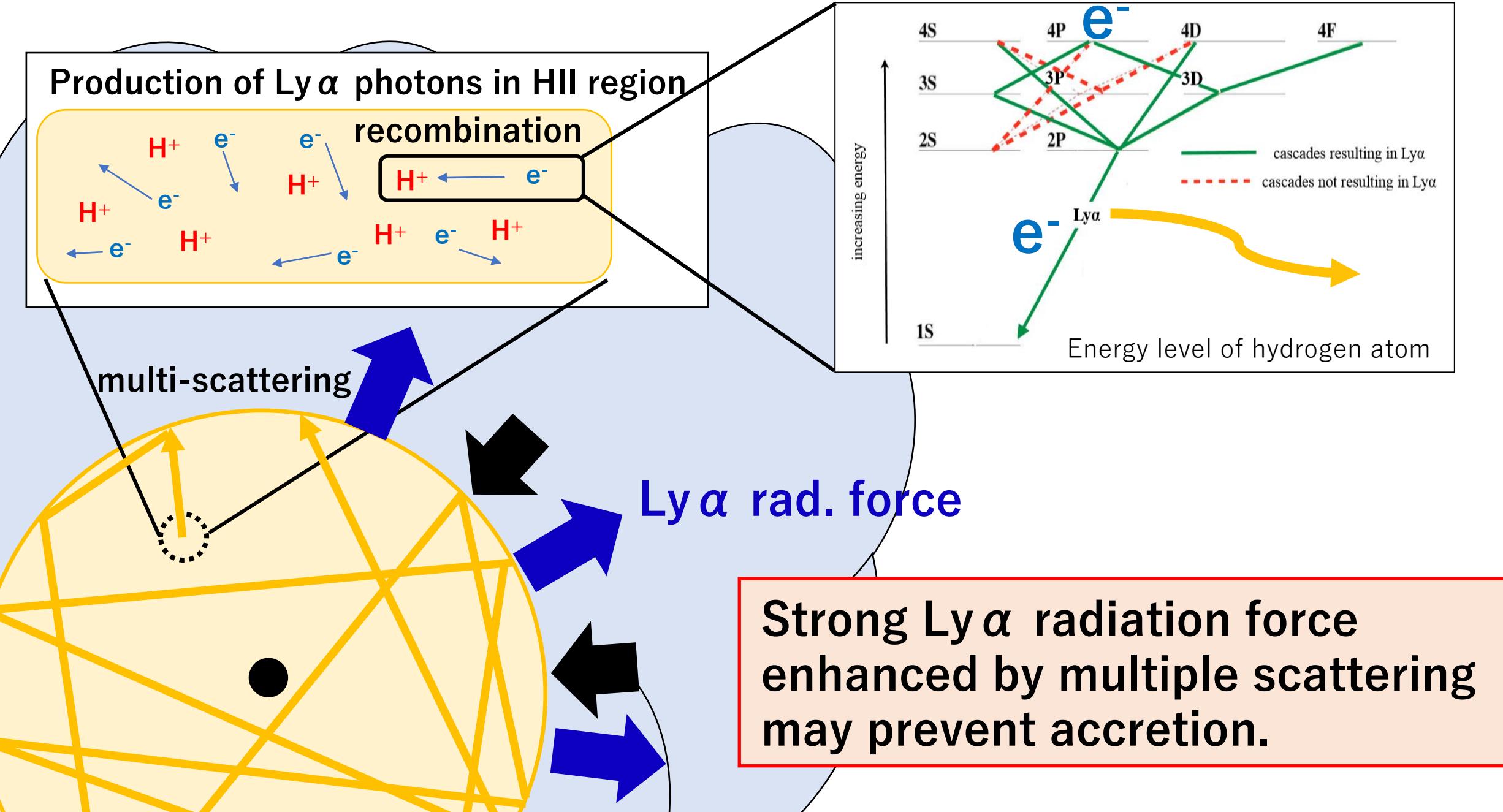


Problem?
Strong radiation force of
Ly α photons produced in
HII region is not considered.

Strong Ly α Radiation Force Impedes Accretion?

Dijkstrra (2017)

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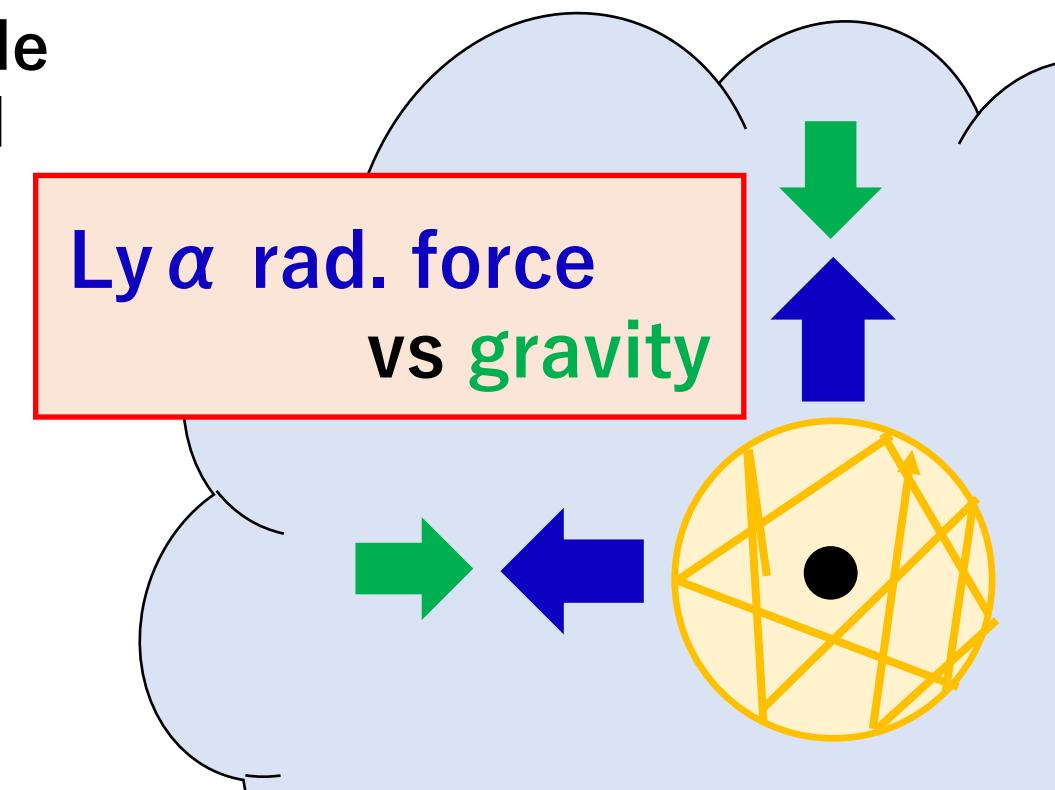


Previous Works

- Super-accretion is feasible?
→ **Unclear:** because $\text{Ly}\alpha$ radiation force is not considered.
- There is no $\text{Ly}\alpha$ radiation transfer code suitable for coupling with hydrodynamic calculations of BH accretion flows.

This work

- Development of $\text{Ly}\alpha$ radiation transfer code that considers the velocity field of the fluid and two photon decay.
(as a first step for $\text{Ly}\alpha$ RHD simulations)
- Evaluate the $\text{Ly}\alpha$ radiation force :
Comparing $\text{Ly}\alpha$ radiation force and gravity
by solving $\text{Ly}\alpha$ radiation transfer in a steady Super-accretion flow.



Basic Equaion

Fokker-Planck equation **extended** from the **static case** to the **dynamic gas** case.

$$\frac{\partial E_{x_0}}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(\frac{c}{3\kappa_{x_0}} \frac{\partial E_{x_0}}{\partial r} \right) + \frac{1}{2} \frac{\partial}{\partial x_0} \left(c\kappa_{x_0}^s \frac{\partial E_{x_0}}{\partial x_0} \right) - \kappa_{x_0}^a c E_{x_0} + 4\pi \eta_{x_0}^r$$

same as static case
(Dijkstra+ 2006)

$$- \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 v E_{x_0}) - \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 v) \frac{1}{3} E_{x_0} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 v) \frac{\partial}{\partial x_0} \left[\left(\frac{c}{v_{\text{th}}} + x_0 \right) \frac{1}{3} E_{x_0} \right]$$

Subscript with 0: Quantity in

About absorption term...

effect of dynamic gas

※ Steady-state radiation field is used when evaluating Ly α radiation power.

Approximations included in this formulation:

- Eddington approx. in fluid rest frame. ($P_{x_0} = E_{x_0}/3$)
- Fokker-Planck approx.
- Sub-relativistic approx. : ignoring the term of $O(\beta^2)$
- Ignoring the term of $O(\beta/\tau_{x_0})$

We numerically solved the above equation by ADI method.

E_x : radiation energy density

$x = (v - v_\alpha)/\Delta v_\alpha$

$v_\alpha = 2.47 \times 10^{15}$ Hz (Ly α frequency)

$\Delta v_\alpha = v_\alpha (v_{\text{th}}/c)$

c : light speed

v_{th} : thermal velocity of fluid

v : bulk velocity of fluid

$\kappa_x = \sigma_0 \phi(x) n(r)$: scattering coefficient

κ_a : absorption coefficient

ϕ : Voight profile

σ_0 : cross section for Ly α line center

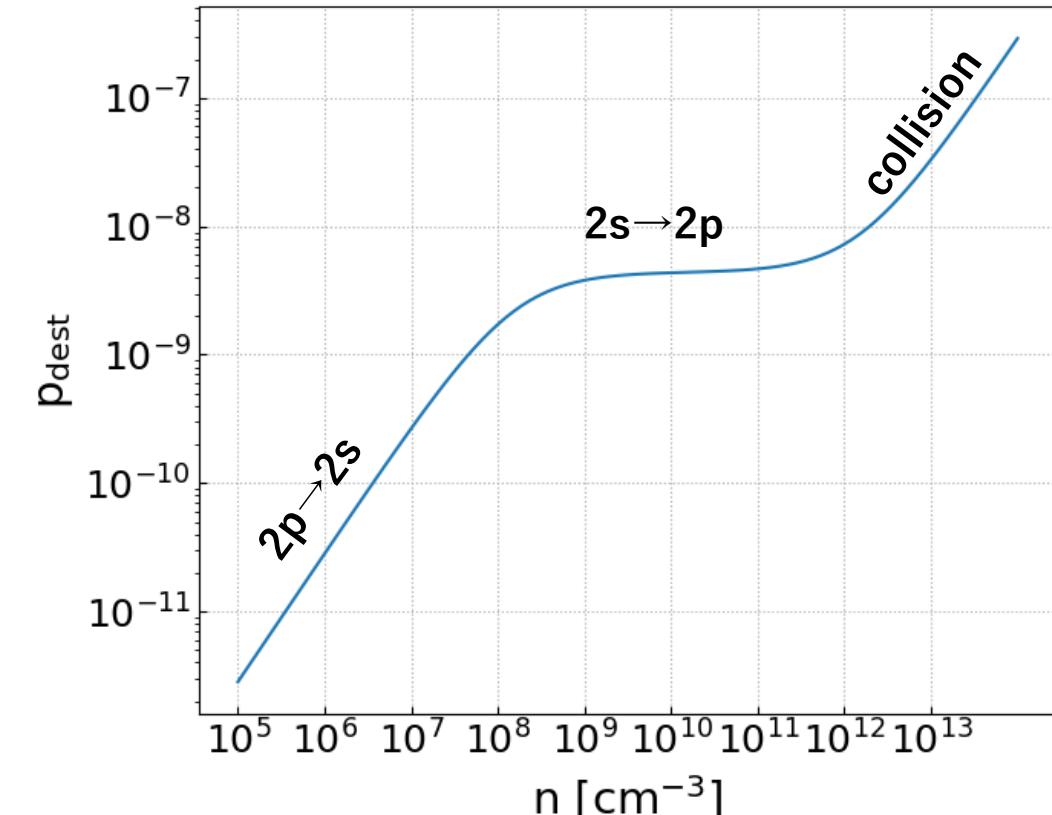
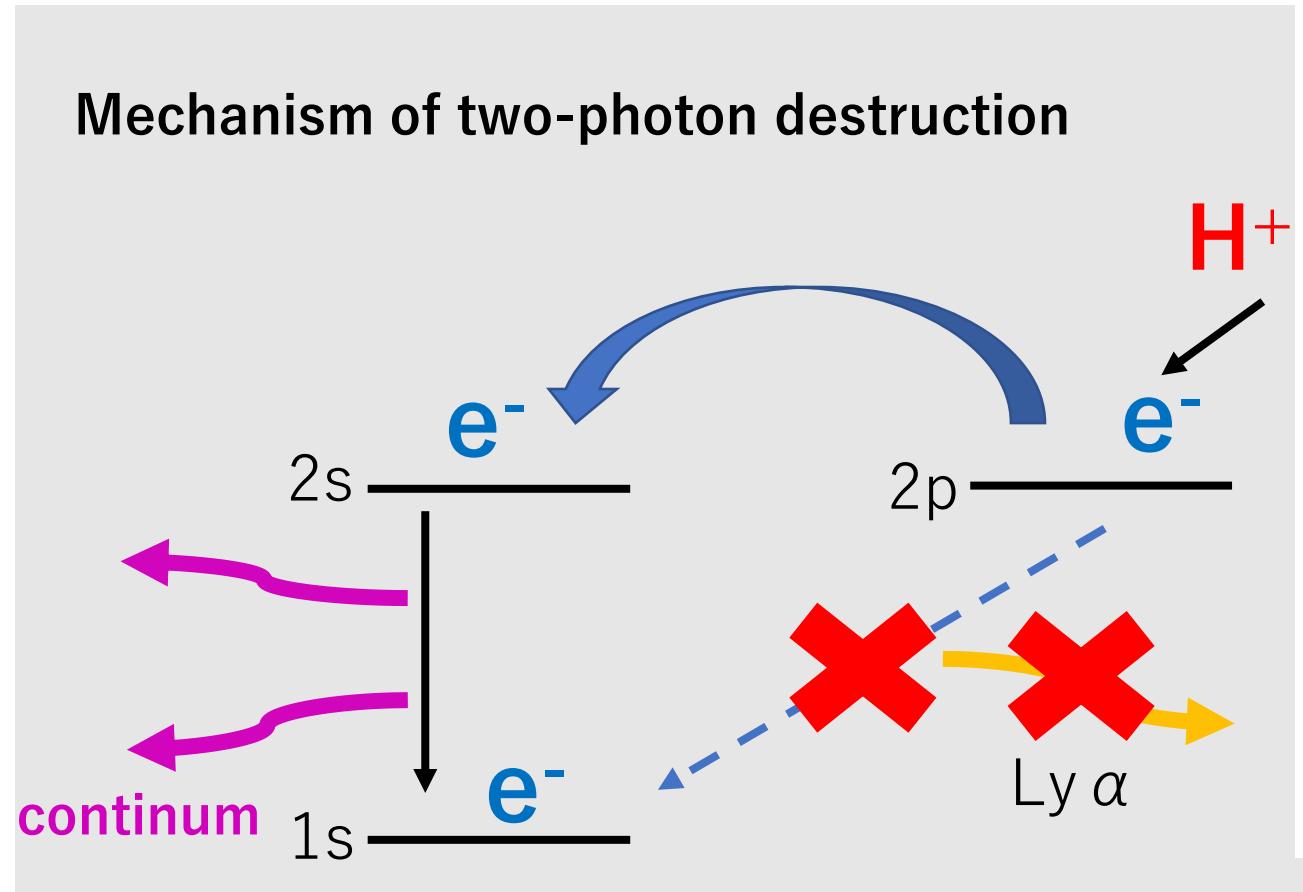
n : number density of hydrogen atom.

η : emissivity

Absorption term: Ly α Destructive Effects of Two-Photon Emission¹² and Collisional Deexcitation.

$$\kappa_a = p_{\text{dest}} \kappa_x$$

p_{dest} : probability of destroying Ly α photon per scattering.

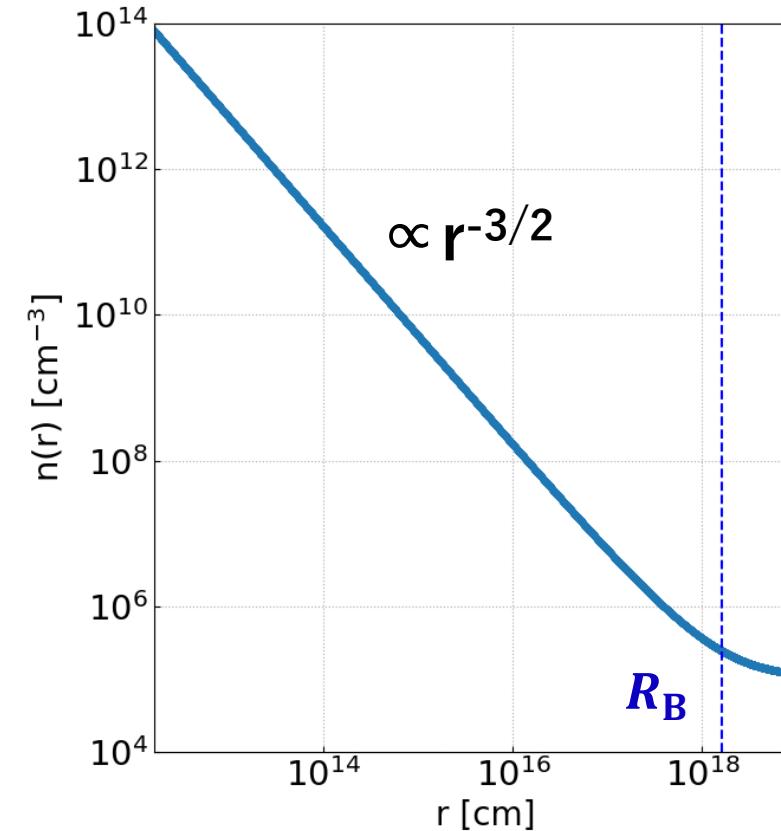
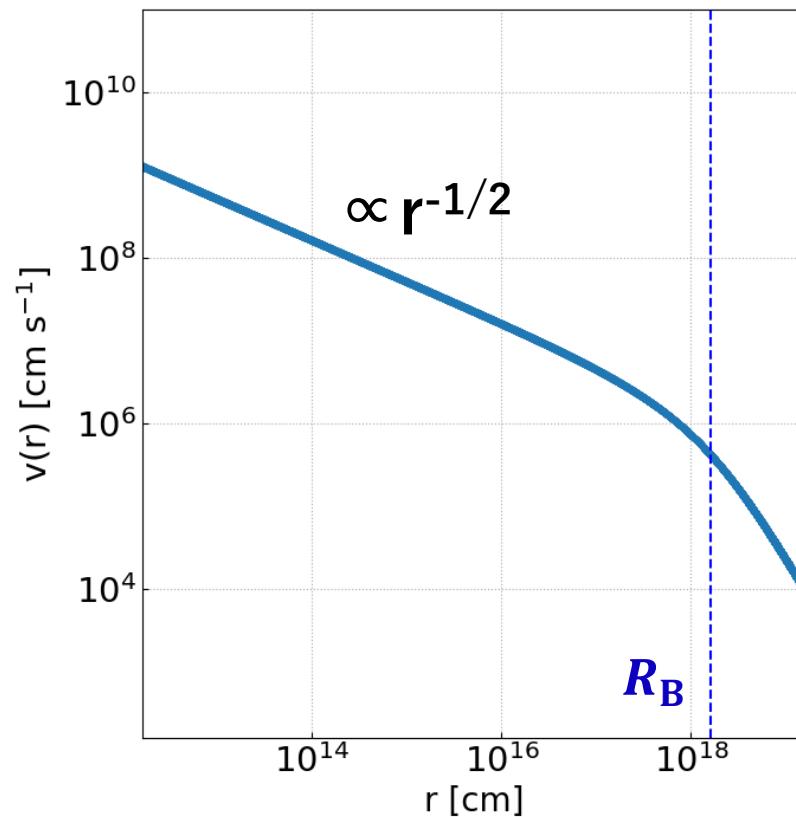


* Electron fraction $x_e = 10^{-4}$ is assumed

Calculation of Super-Eddington Flows

Calculation Conditions: Fluid Fields

Example of $M_{\text{BH}} = 10^4 M_{\odot}$, $n_{\infty} = 10^5 \text{ cm}^{-3}$

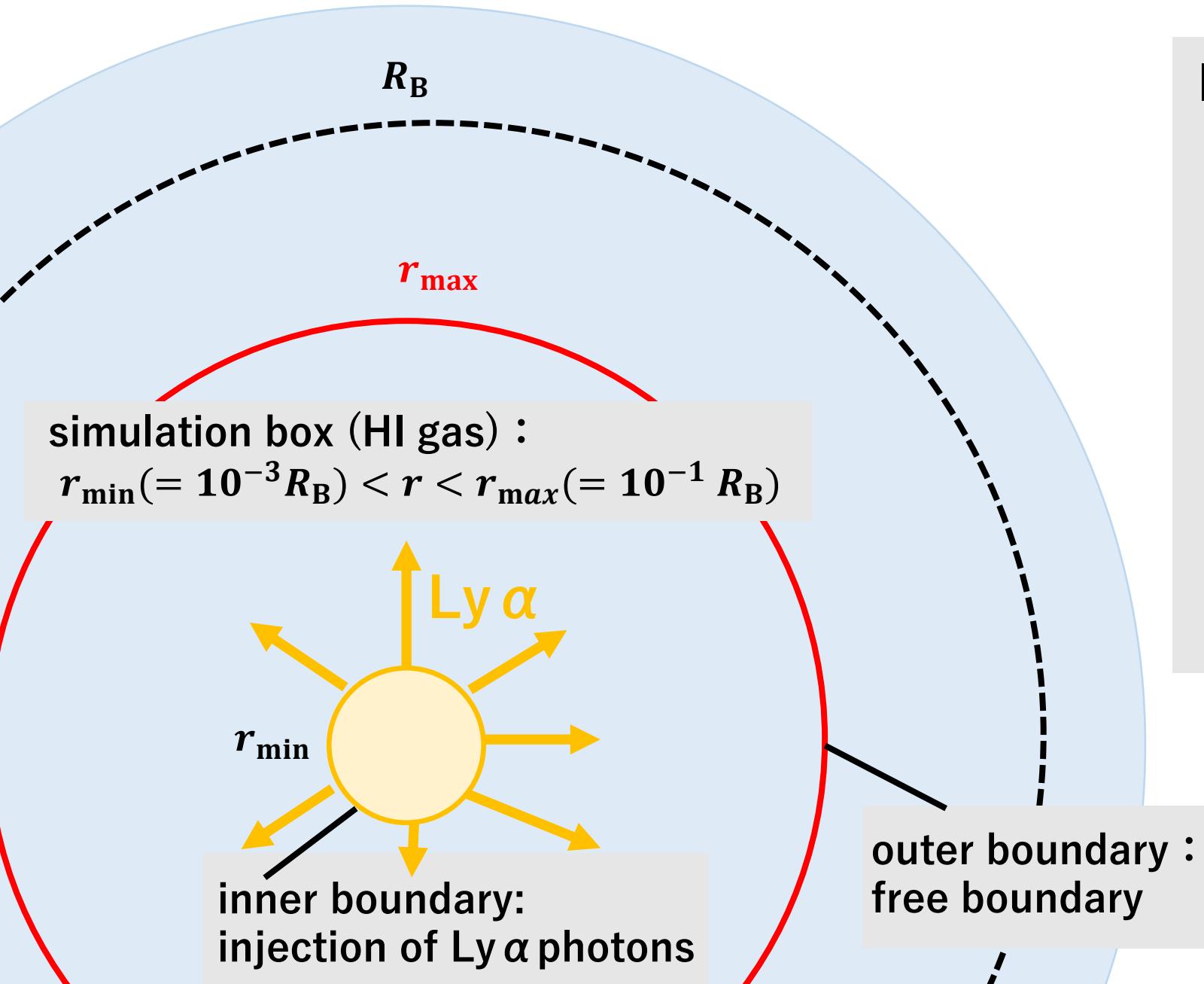


- Super-Edd. accretion flow (isothermal Bondi flow of $T=10^4 \text{ K}$)
- 10 models for parameters ($M_{\text{BH}}, n_{\infty}$).

* Electron fraction $x_e = 10^{-4}$ is assumed

Calculation Conditions: Simulation Box & Boundary

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Injected Ly α luminosity $L_{Ly\alpha}$

$$L_{Ly\alpha} = L_{\text{Edd}} \frac{L_{\text{bol}}}{L_{\text{Edd}}} \frac{L_{Ly\alpha}}{L_{\text{bol}}} = L_{\text{Edd}} l_E f_{Ly\alpha}$$

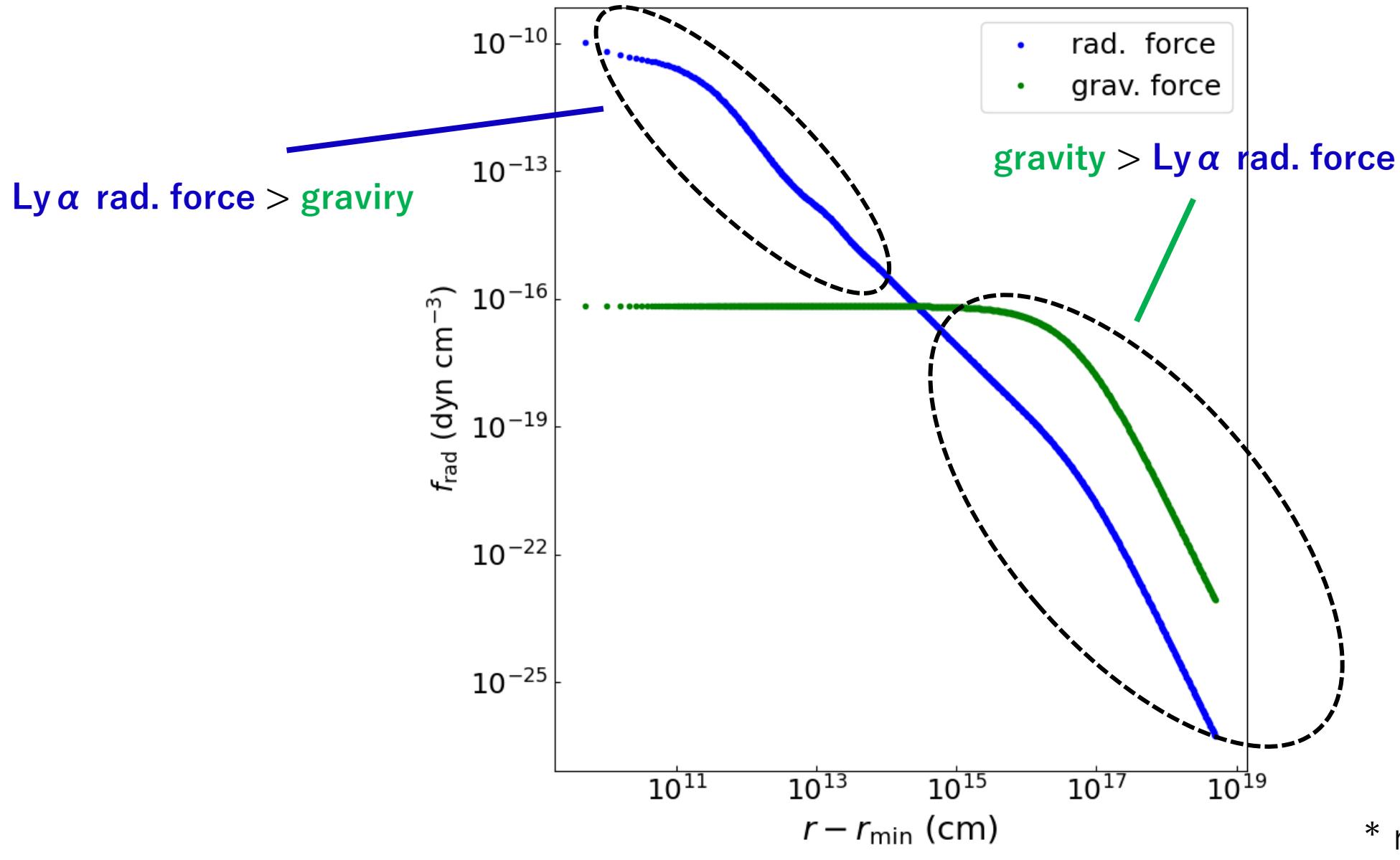
- Eddington ratio l_E
slimdisks model (Watarai+ 2000)

$$l_E = \begin{cases} 0.1\dot{m} & (\dot{m} < 20) \\ 2\left[1 + \ln\left(\frac{\dot{m}}{20}\right)\right] & (\dot{m} \geq 20) \end{cases}$$

- Ly α fraction $f_{Ly\alpha} = 0.1$ (fixed)

Result : Radial profiles of Ly α Radiation Force

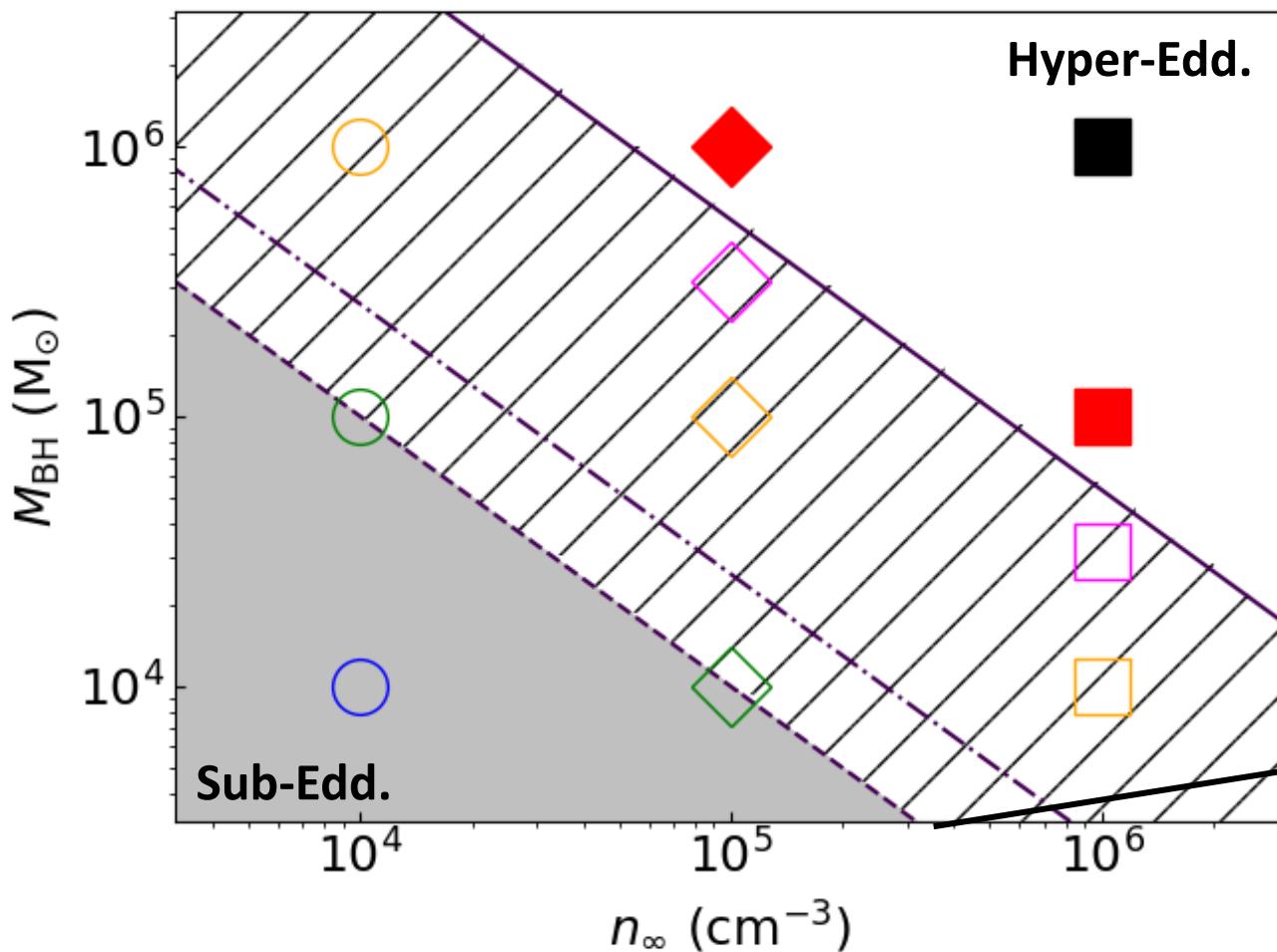
($M_{\text{BH}} = 10^{5.5} M_{\odot}$, $n_{\infty} = 10^5 \text{ cm}^{-3}$)



$\text{Ly}\alpha$ Radiation Force v.s. Gravity Exerted on The Entire System.

Open circle : $\text{Ly}\alpha$ rad. force > gravity

Filled circle : gravity > $\text{Ly}\alpha$ rad. force



Previous work : Super-Edd. acc. ok
This work : $\text{Ly}\alpha$ rad. force > gravity



$\text{Ly}\alpha$ suppresses the accretion?



Further studies of full $\text{Ly}\alpha$ RHD simulation are needed in the future.

Interpretation of Results : Force Multiplier M_F

y-axis : force multiplier M_F

$$\frac{L_{\text{Ly}\alpha}}{c} M_F := \int f_{\text{rad}}(r) dV$$

f_{rad} : Ly α rad. force density

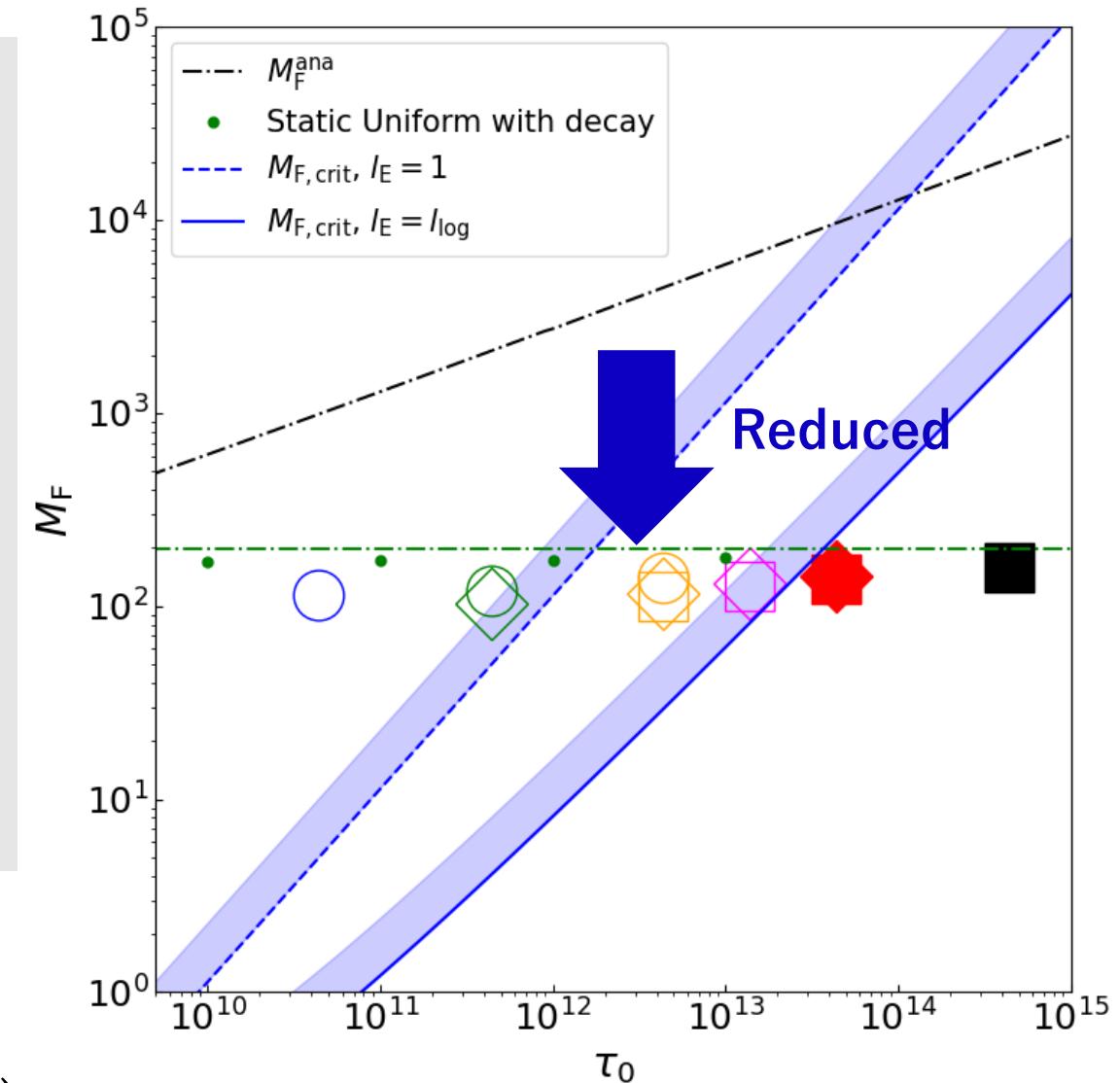
x-axis : Optical depth of the entire system

$$\tau_0 \approx 7 \times 10^{11} \left(\frac{M_{\text{BH}}}{10^4 M_\odot} \right) \left(\frac{n_\infty}{10^5 \text{ cm}^{-3}} \right)$$

M_F^{ana} : M_F for the case of the static uniform without decay effect.

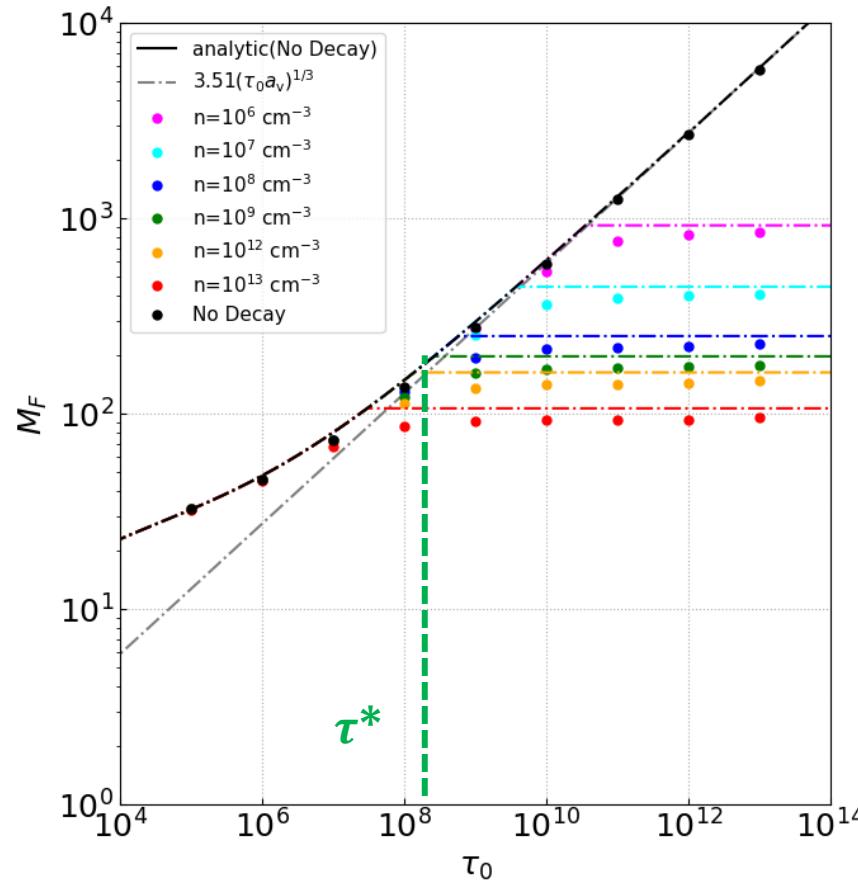
$M_{F,\text{crit}}$: M_F when gravity and radi. force are balanced

- $M_F \sim 100$ (constant)
- Reduction from analytical solution M_F^{ana} (for the case of the static uniform without decay) is due to two photon decays.

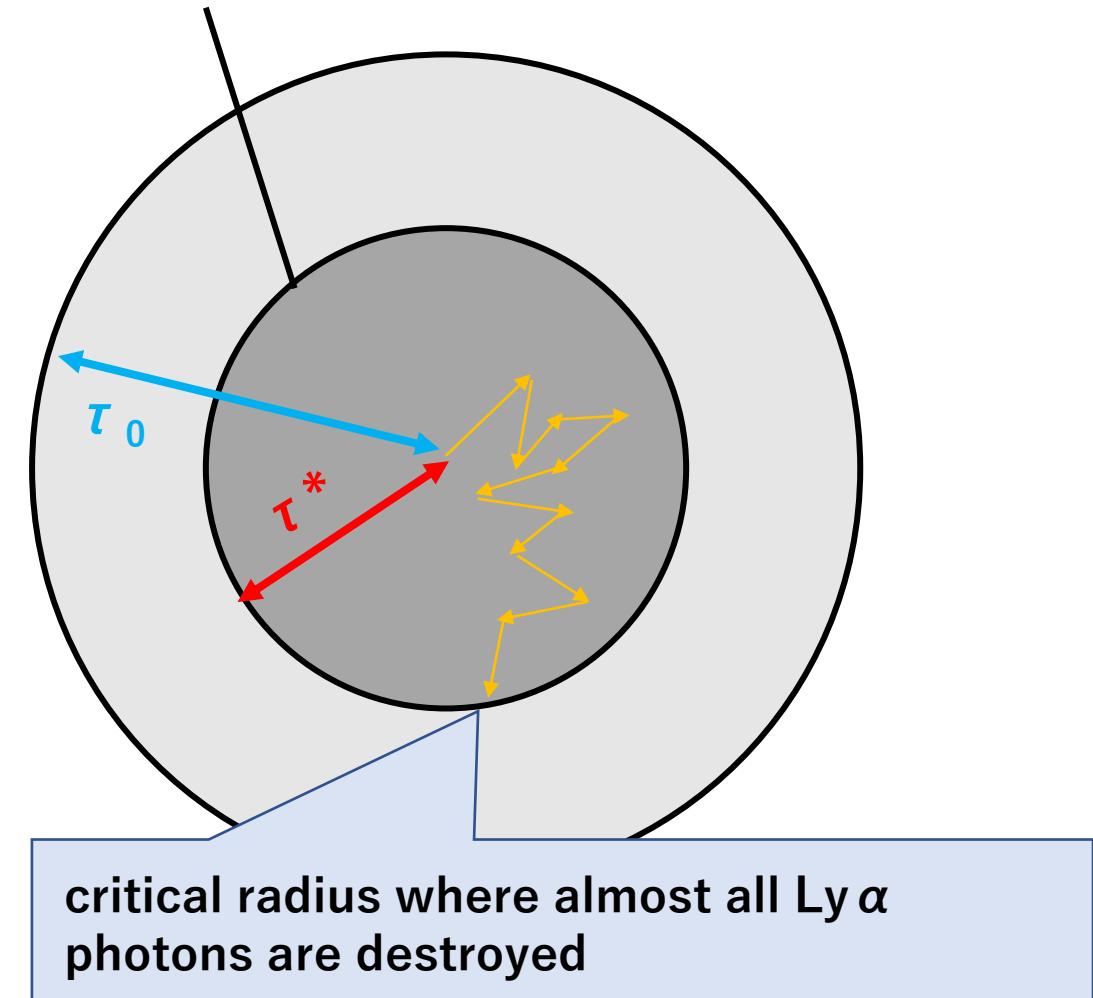


Effects of Ly α Photon Destruction Effects

M_F for static uniform with decay



Almost all photons are destroyed up to a certain τ^* .
 $= M_F$ is determined where $\tau_0 < \tau^*$.
 \Rightarrow Rad. force amplification stops at $\tau_0 = \tau^*$.



* Electron fraction $x_e = 10^{-4}$ is assumed

Summary

① Code Development:

To evaluate the effect of Ly α radiation on super-Eddington accretion flows of seed BHs in the early universe, we developed a Ly α radiation transfer code that considers the effects of velocity fields and Ly α destructive effects.

② Evaluation of Ly α radiation force on to hyper-Eddington accretion flows:

Even though previous studies have shown that super-Eddington accretion is feasible, there are conditions under which the Ly α radiation force exceeds the gravity force.

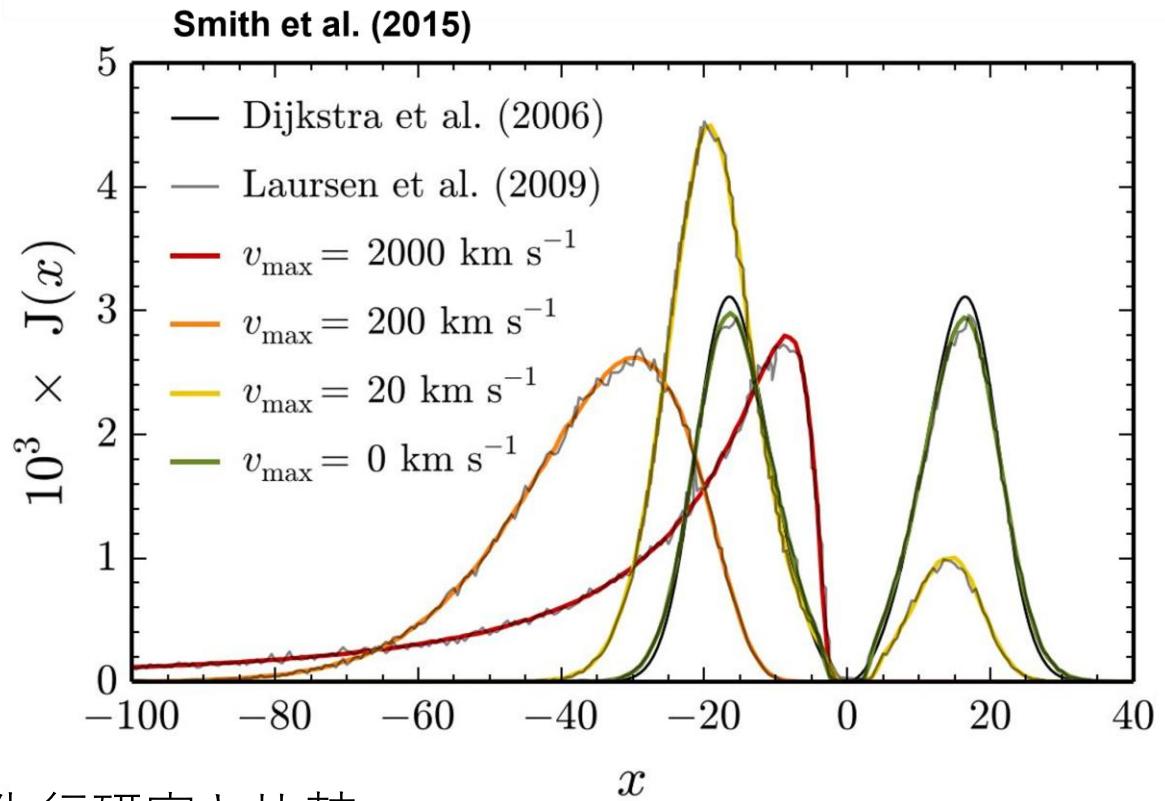
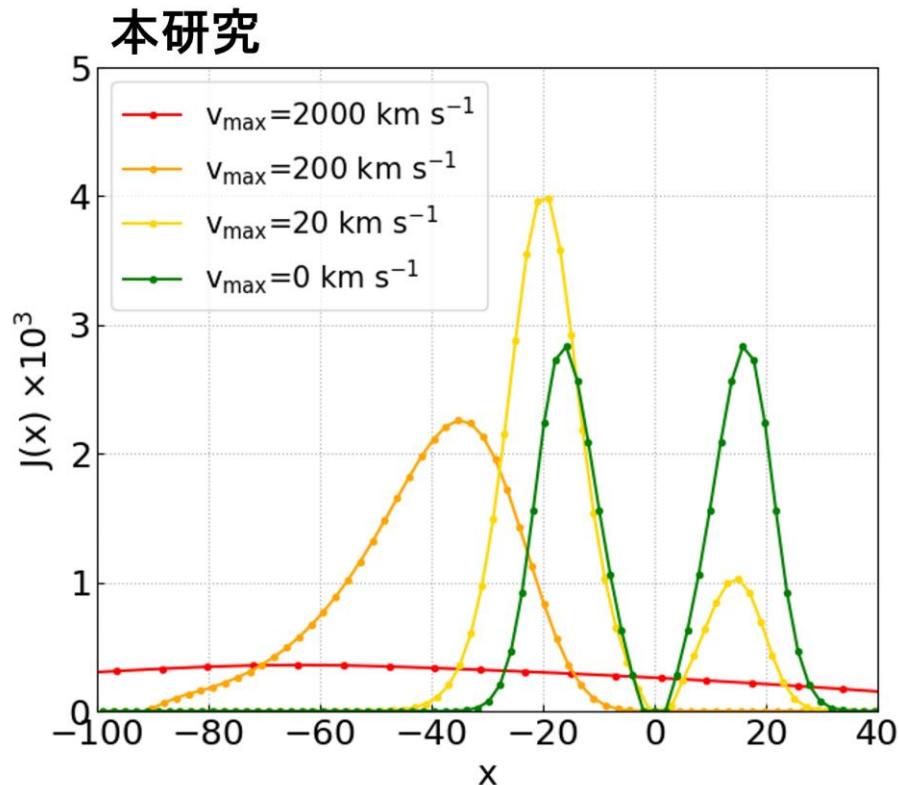
③ M_F reduction is mainly determined by the Ly α destructive effects.

future work

- Fully coupled Ly α RHD simulations.
- Extend the Ly α radiation transport code to multiple dimensions.

動的ガスのテスト計算：Hubble-like flow からの脱出光子スペクトル

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- Hubble-like flow からの脱出光子スペクトルを先行研究と比較
- 先行研究と一致 ($v_{\max} = 2000 \text{ km/s}$ 以外)
⇒ ライン拡散方程式は動的ガスにおける Ly α の輻射輸送を正しく記述
- $v_{\max} = 2000 \text{ km/s}$ では不一致だが、今回は問題ない
(詳細はバックアップスライド)

計算条件

- $v_{\text{bulk}}(r) = v_{\max}(r/R)$
- 等温一樣ガス ($T=10^4 \text{ K}$)
- $\tau_0 = 1.2 \times 10^7$