Formation of supermassive black holes at high-z

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Peking University

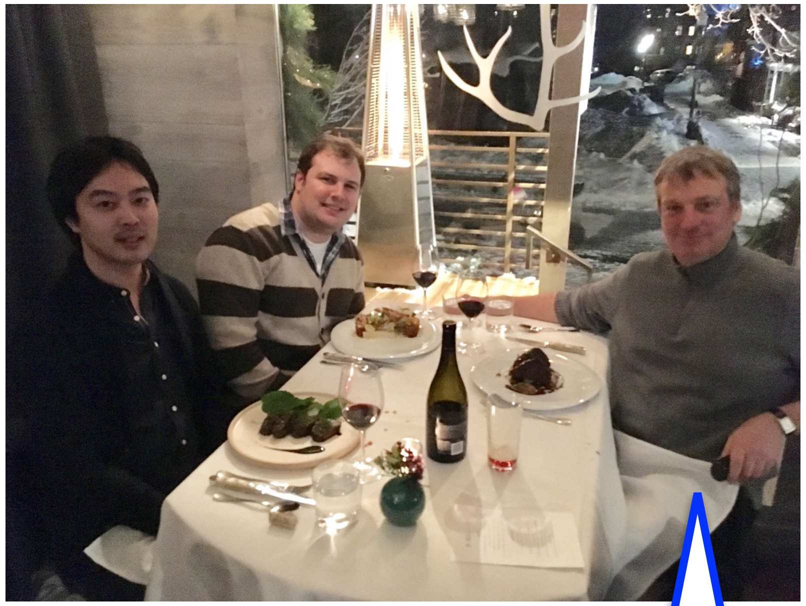
初代星・初代銀河研究会 @ 名大

初代星研究会と私

2010年3月（長崎大学）	M1	
2011年1月（愛媛大学）	M2	DCBH (UV/X-ray/CR)
2011年12月（九州大学）	D1	DCBH (cold acc shock)
2013年1月（北海道大学）	D2	DCBH (pulsation instability)
2014年1月（鹿児島大学）	D3	DCBH (3D simulation)
2015年1月（東北大学）	PD	**BH growth / DCBH**
2016年10月（金沢大学）	PD	**BH growth / binary BH / GW**
2018年2月（呉高専）	PD	BH growth
2019年11月（名古屋大学）	助教	**BH growth / DCBH**

※ review talk

Thanks to all of your supports



Published in 2020
(will be on arXiv soon…)

The Assembly of the First Massive Black Holes

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Keywords

black holes, cosmology, first galaxies, active galactic nuclei, quasars

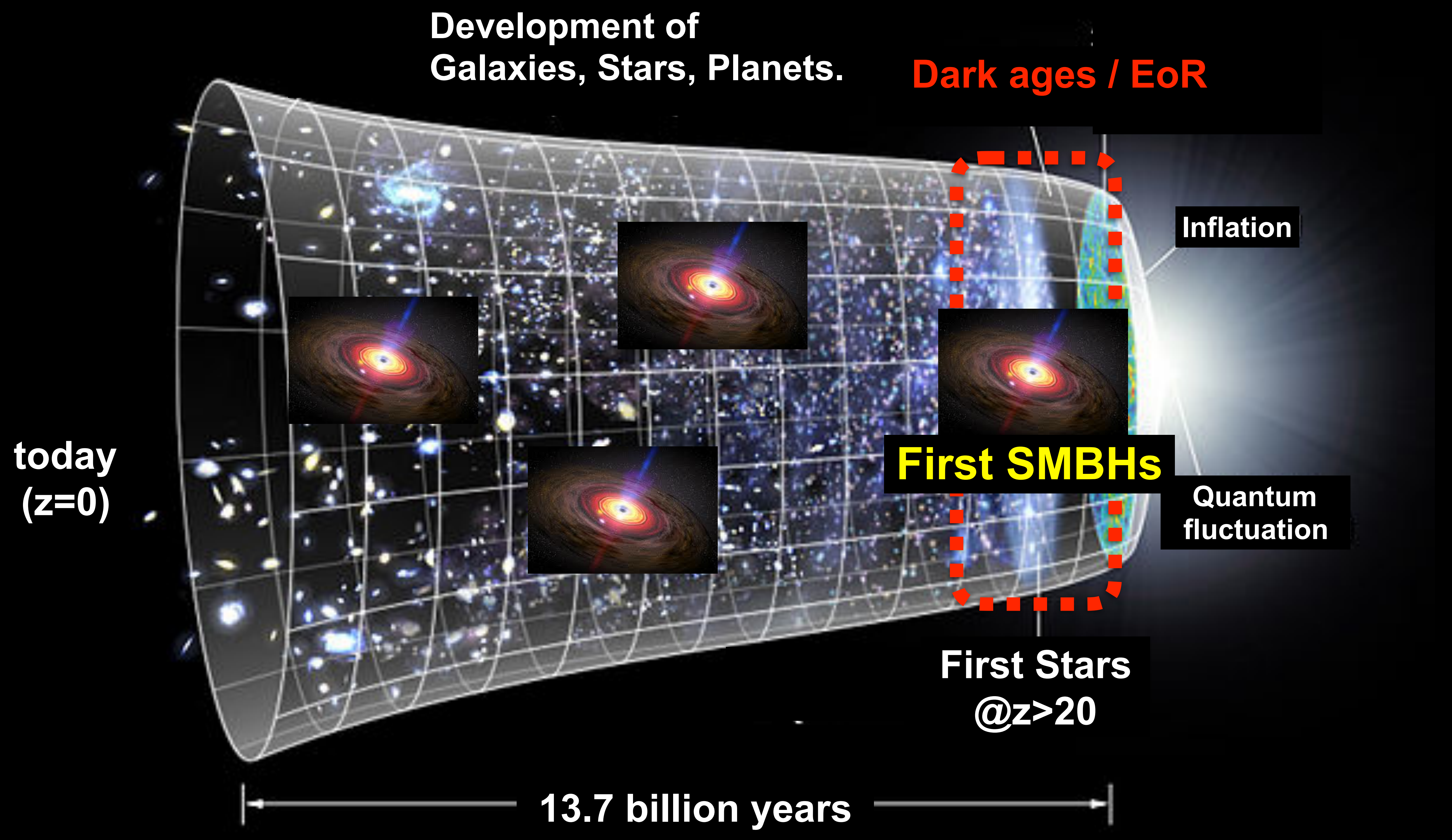
Abstract

The existence of $\sim 10^9$ $M_\odot$ supermassive black holes (SMBHs) within the first billion year of the universe has stimulated numerous ideas for the prompt formation and rapid growth of BHs in the early universe. Here we review ways in which the seeds of massive BHs may have first assembled, how they may have subsequently grown as massive as $\sim 10^9$ $M_\odot$, and how multi-messenger observations could distinguish between different SMBH assembly scenarios. We conclude the following:

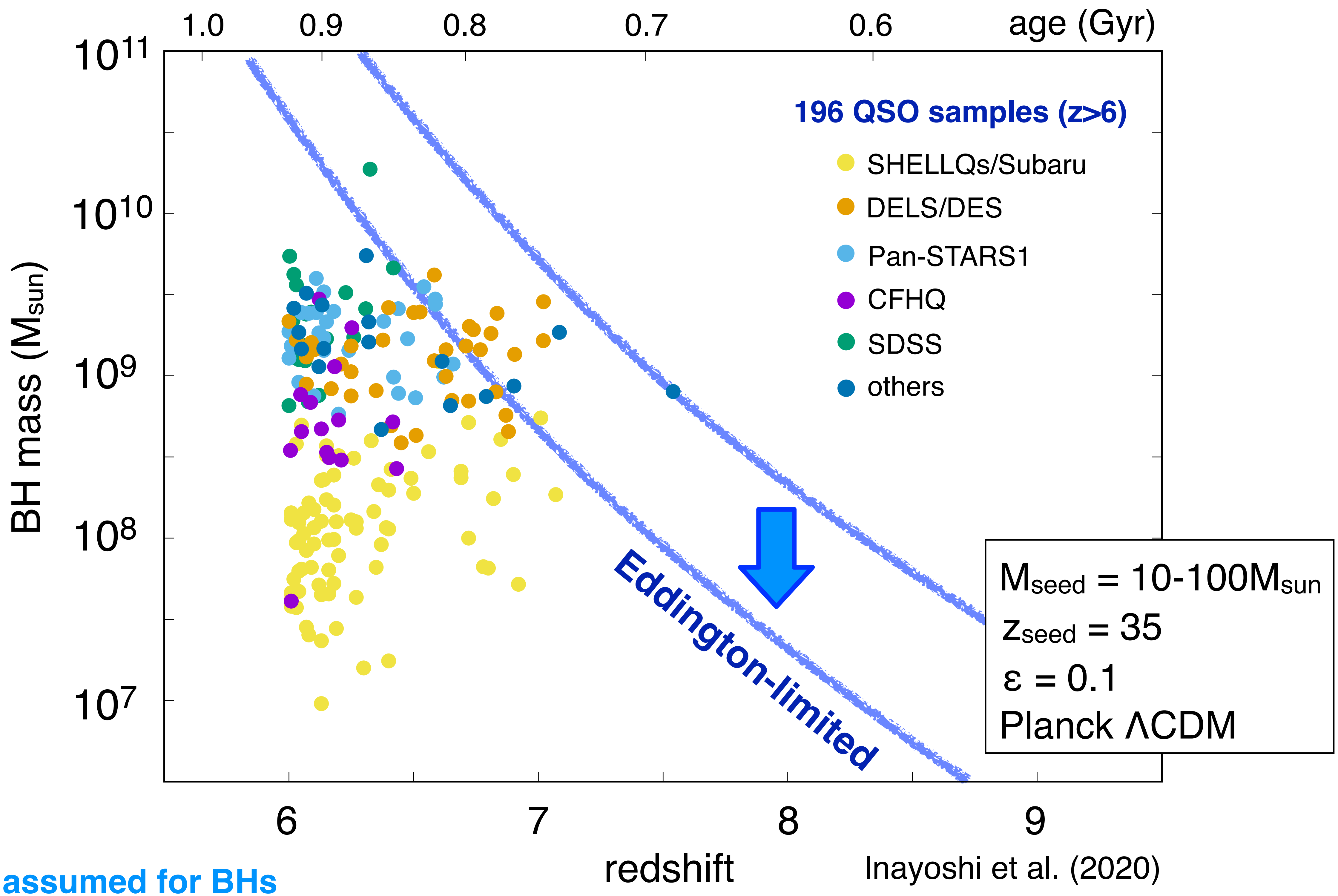
Thanks to all of your supports

OK, let’s start!

Cosmological QSO population



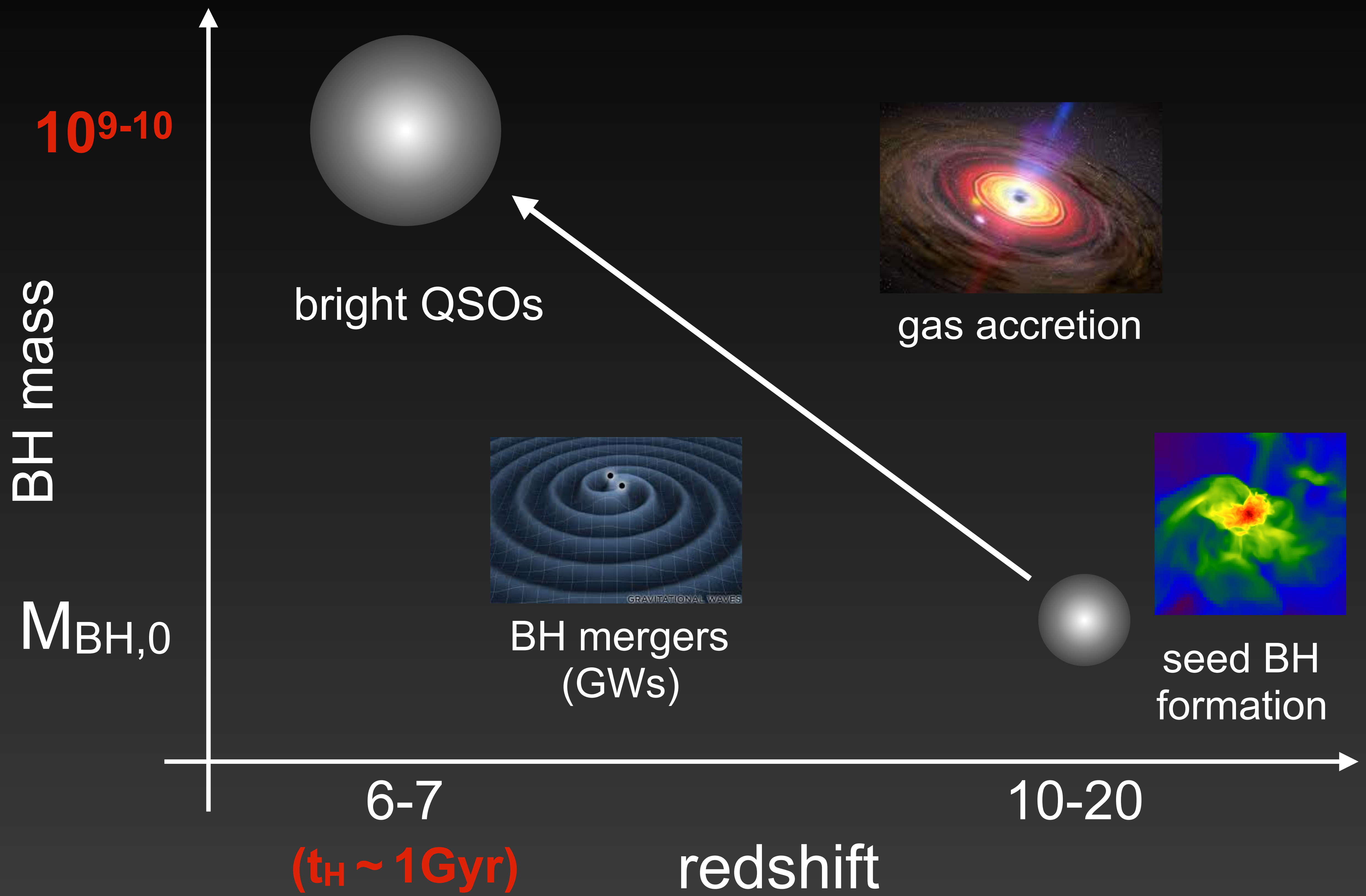
High-redshift monster BHs



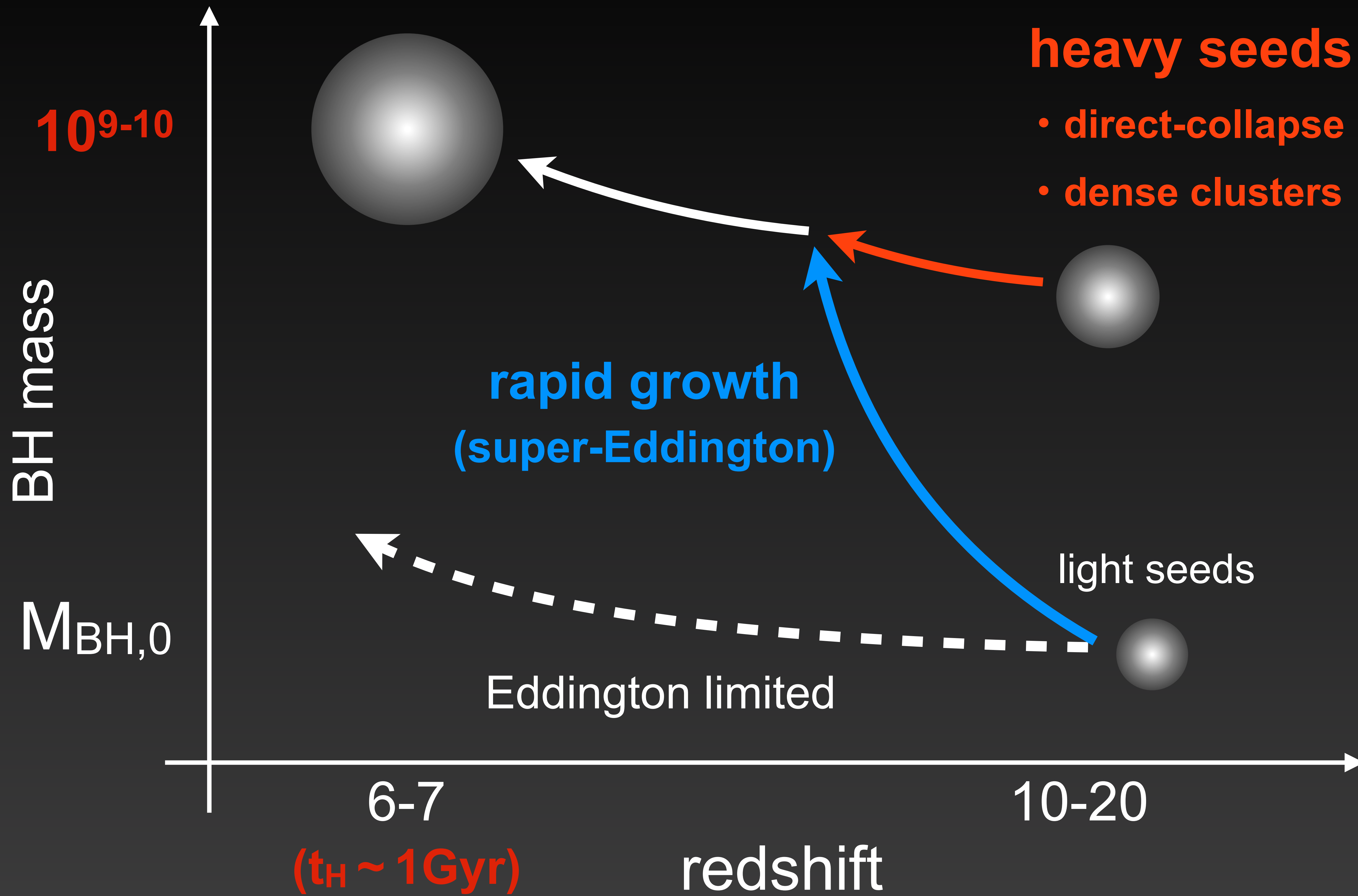
Inayoshi et al. (2020)

*λ_{Edd}=1 is assumed for BHs if not mass measurements

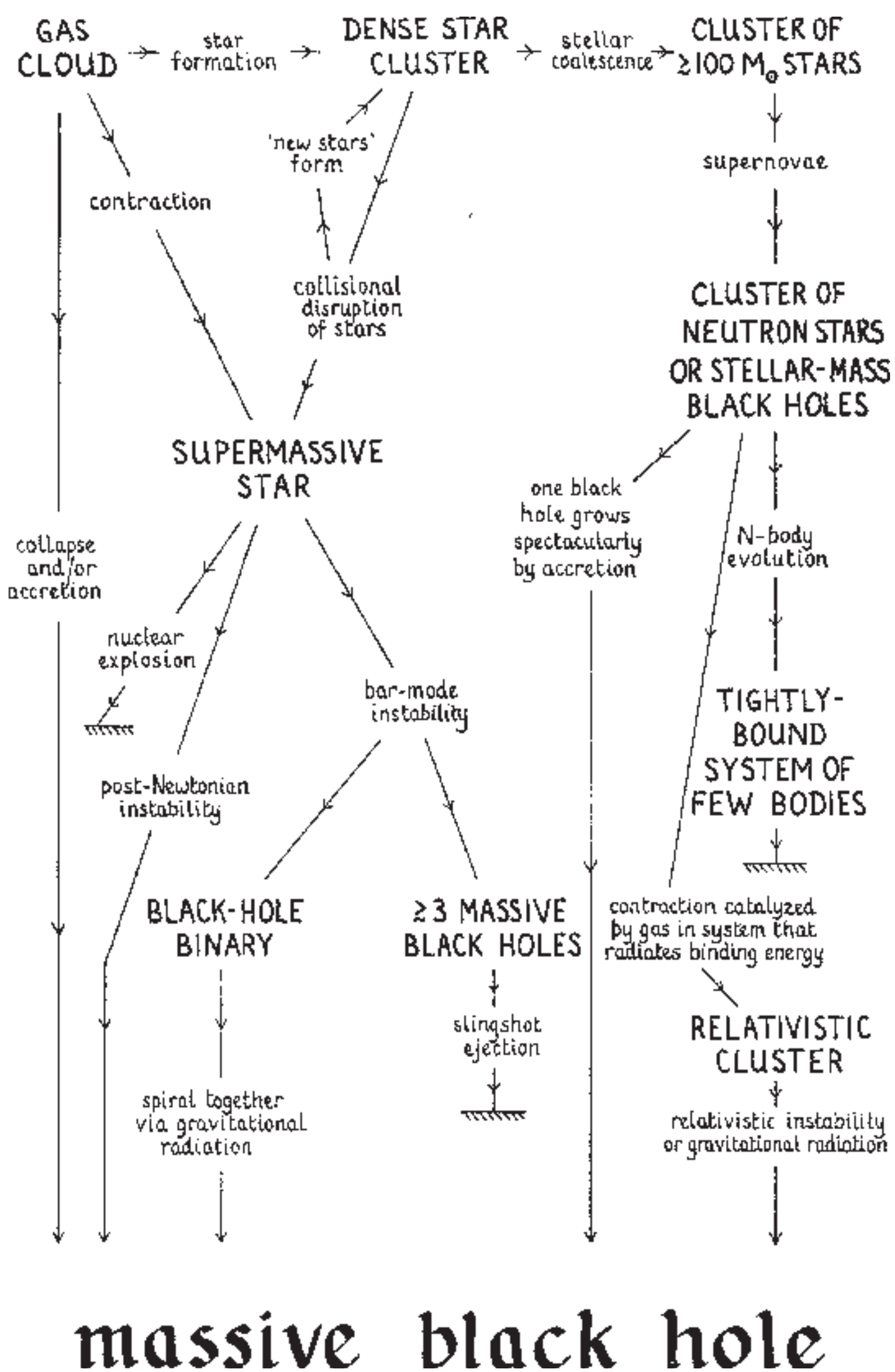
Rapid SMBH assembly



Rapid SMBH assembly



Theory of early BH formation

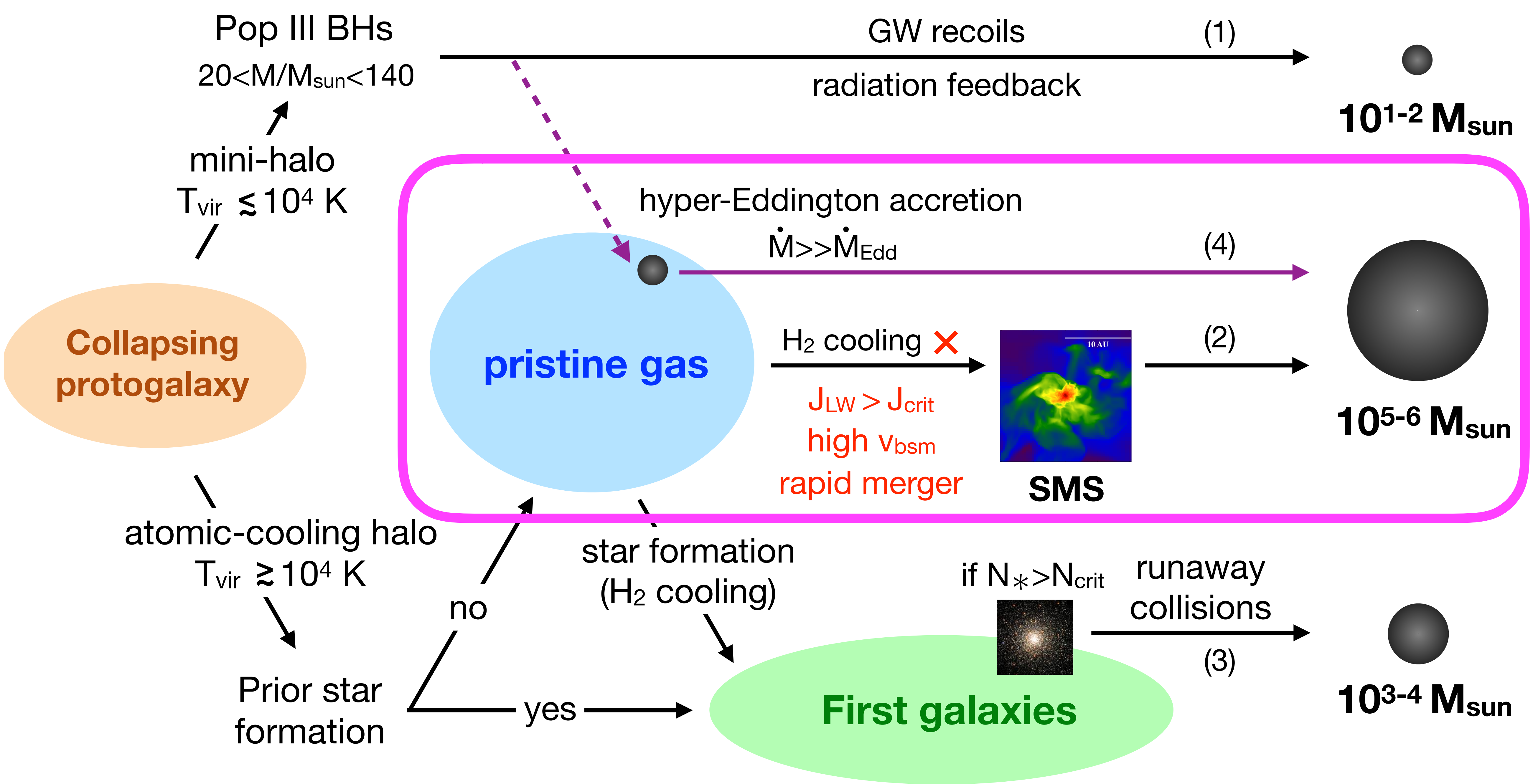


SMBH formation (not only high-z)

M.Rees (1984) ARA&A

- rapid gas accretion
- supermassive star formation
- dense clusters

Theory of early BH formation

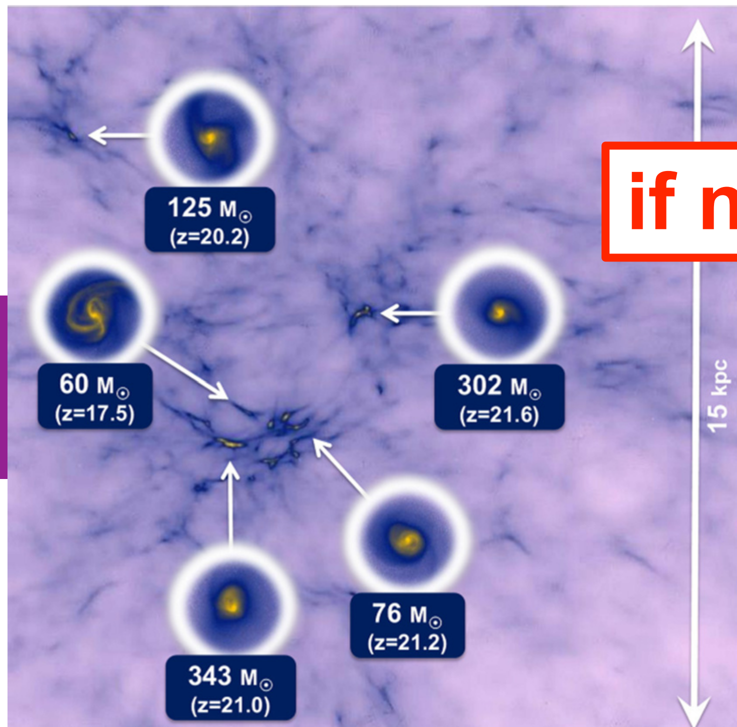


Inayoshi, Visbal & Haiman (2020) ARA&A

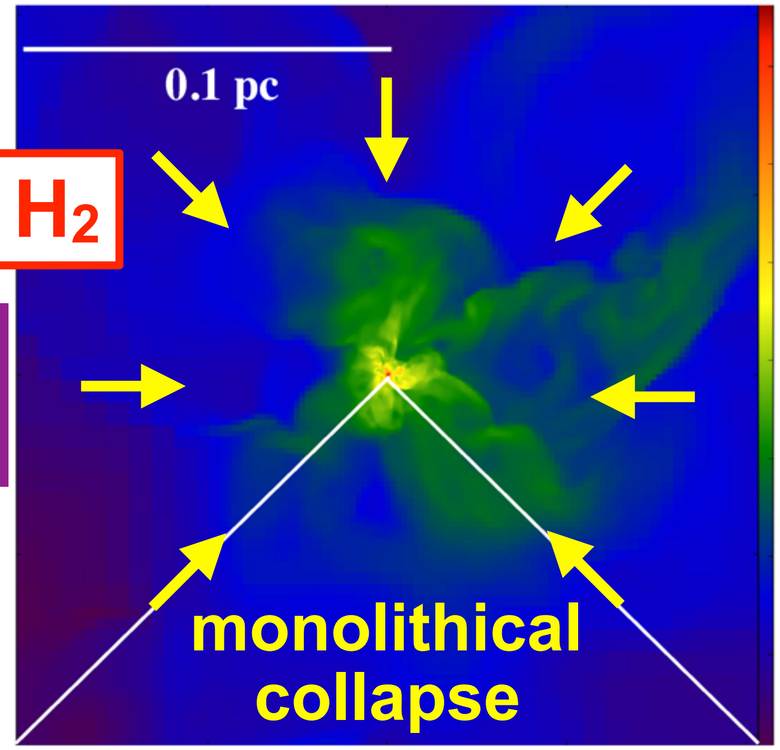
Heavy BH Seeds

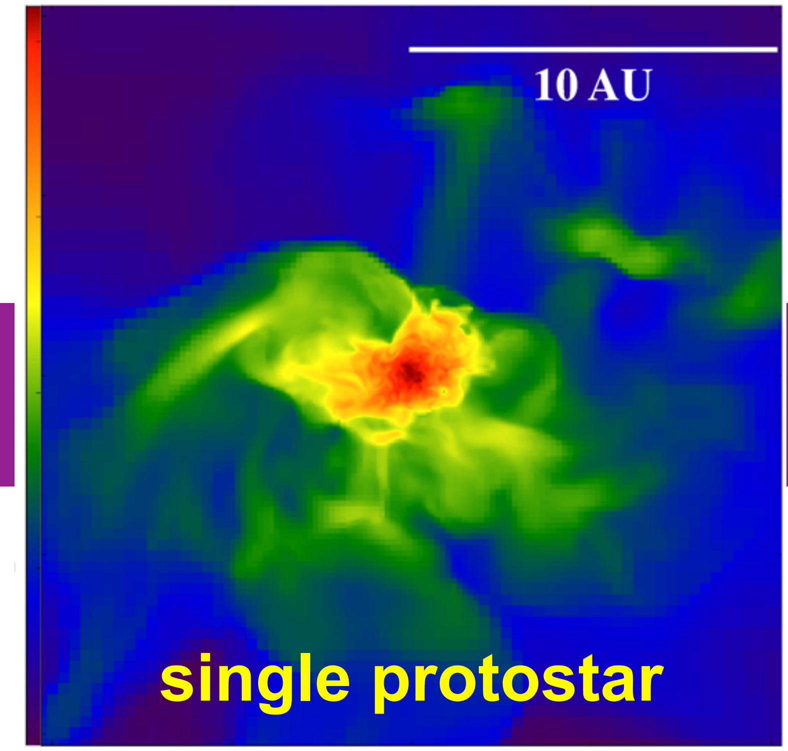
High-z star formation

cosmological scales



if no H_2





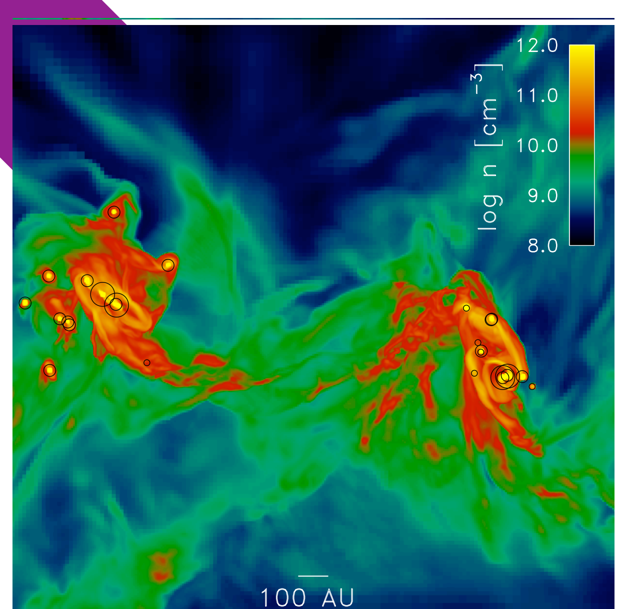
H cooling
~10^4K

no fragment

normally…

H_2 cooling
~$10^{2\text{-}3}$ K

fragment

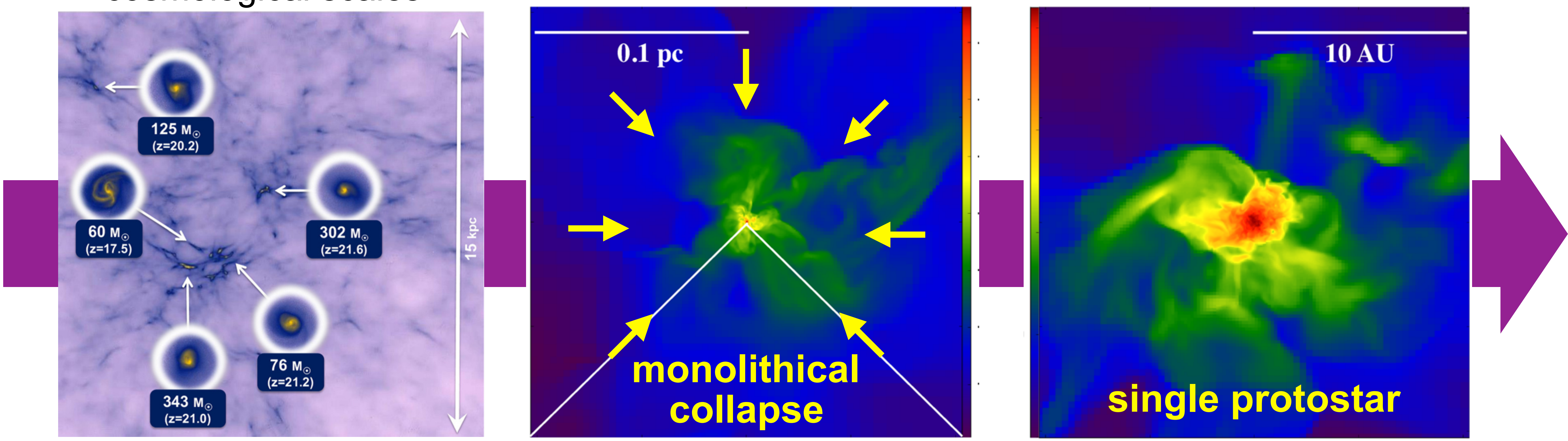


Safranek-Shrader et al. (2016)

Pop III stars

$$M_* \sim 100\ M_\odot$$

High-z star formation



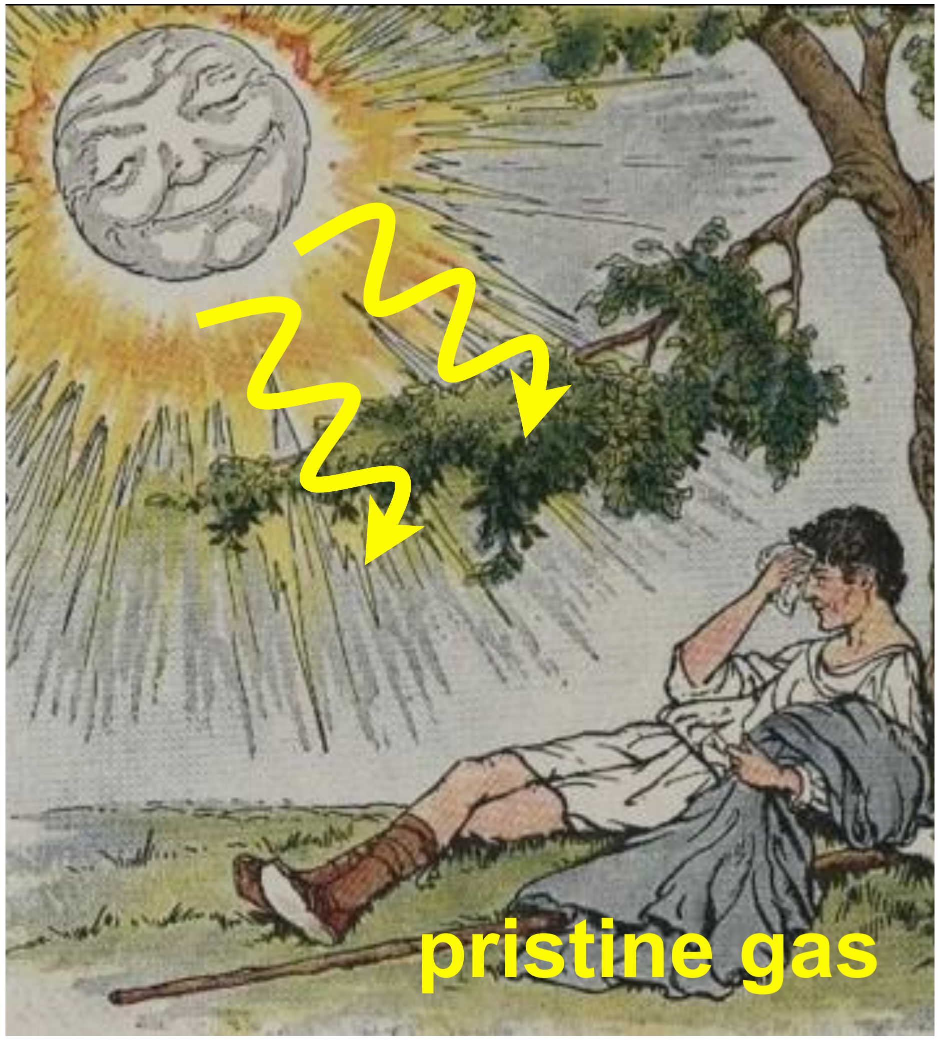
- high mass / no fragments: $M_\mathrm{J} \sim \rho \lambda_\mathrm{J}^3 \propto \frac{c_\mathrm{s}^3}{\sqrt{\rho}}$
- very high accretion rate: $\dot{M}_\mathrm{acc} \sim \frac{M_\mathrm{J}}{t_\mathrm{ff}} \sim \frac{c_\mathrm{s}^3}{G}$

$\propto T^{3/2}$

higher temperature is required

Ways to suppress H_2 formation

Lyman-Werner irradiation



$$H_2 + \gamma_{\rm LW} \rightarrow 2\ {\rm H}$$

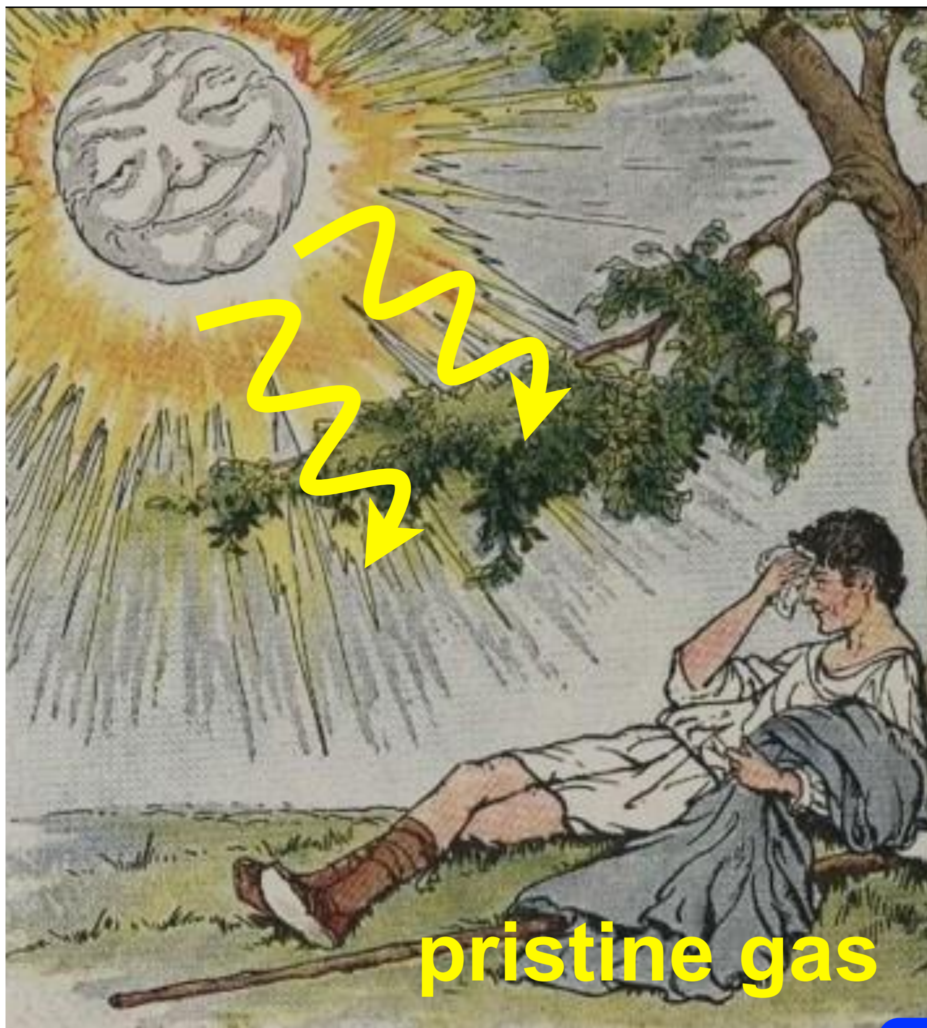
baryonic streaming motion

$$v_{\rm eff}^2 \equiv c_s^2 + v_{\rm bsm}^2$$

Bromm & Loeb 2003; Shang +2010; Latif +2013; Johnson +(2013); Regan +2014; Inayoshi +2014; Sugimura + 2014; Visbal +2015; Latif +2016; Chon+2016; Hirano+2018; Inayoshi+2018; Wise +2019; Luo+2019 etc…

Ways to suppress H_2 formation

Lyman-Werner irradiation



$$H_2 + \gamma_{\rm LW} \rightarrow 2\ {\rm H}$$

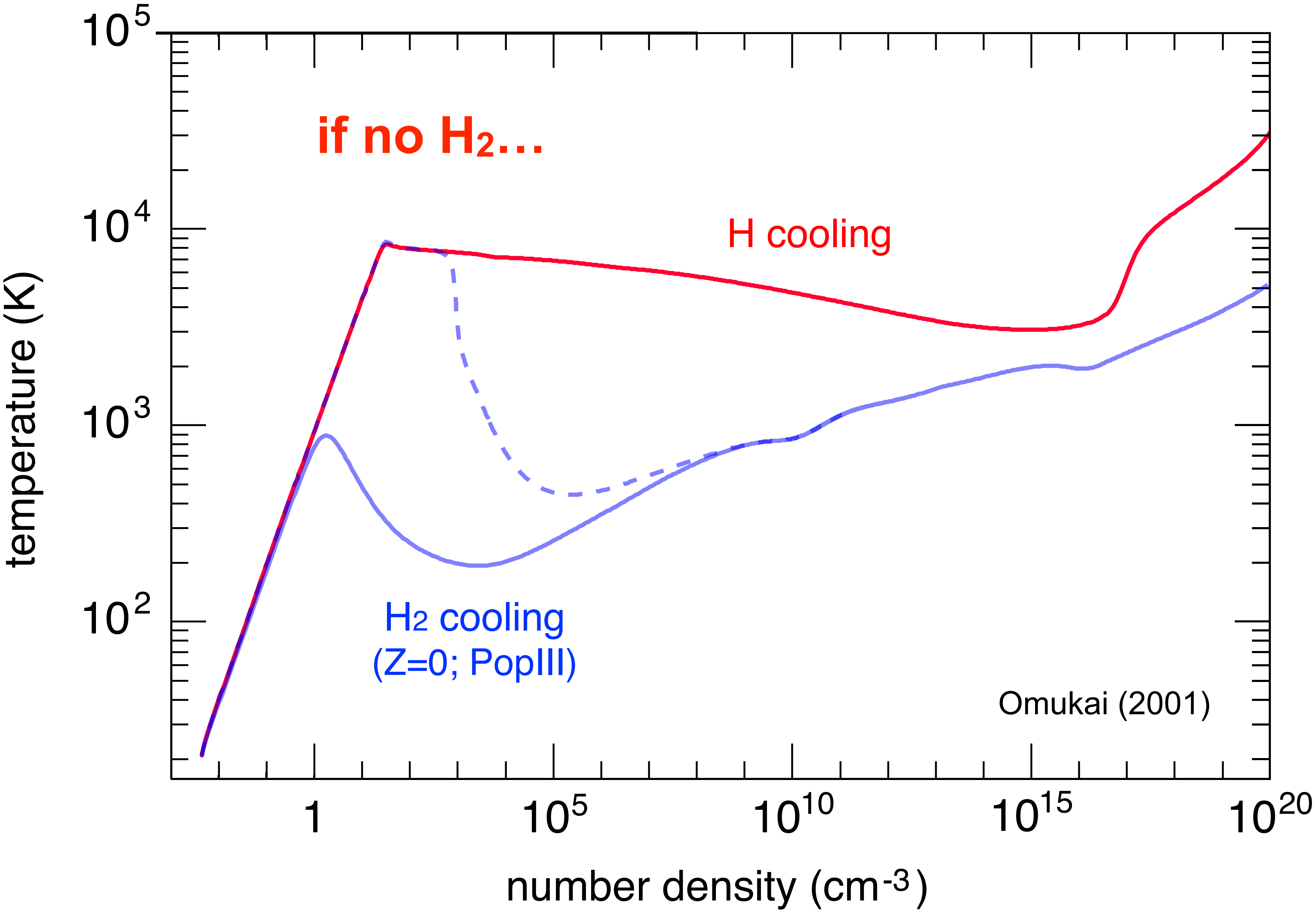
Bromm & Loeb 2003; Shang +2010; Latif +201
+ 2014; Visbal +2015; Latif +2016; Chon+2016

baryonic streaming motion

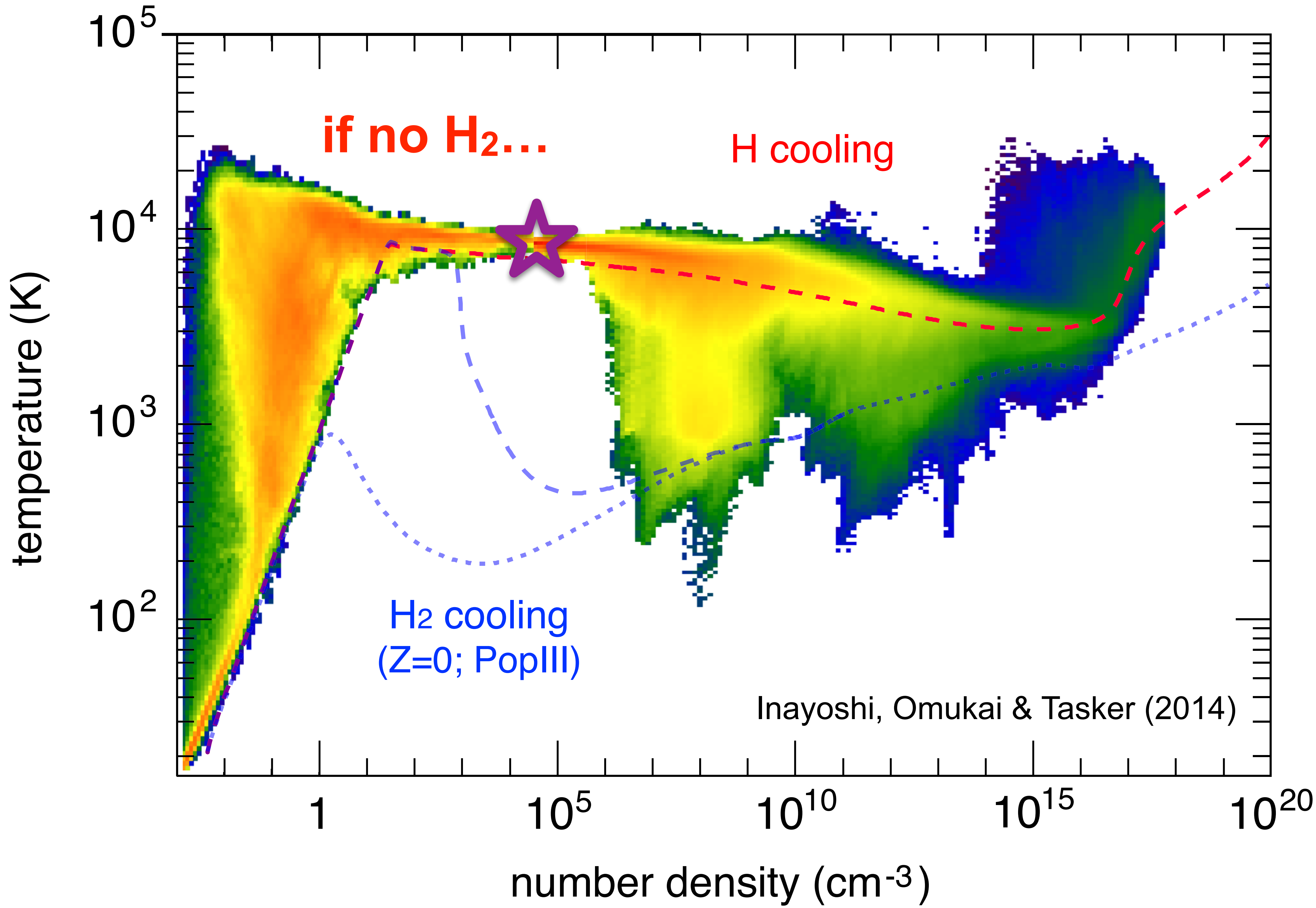
Combination of the two effects leads to H_2 suppression **further**…

see Wenxiu's talk

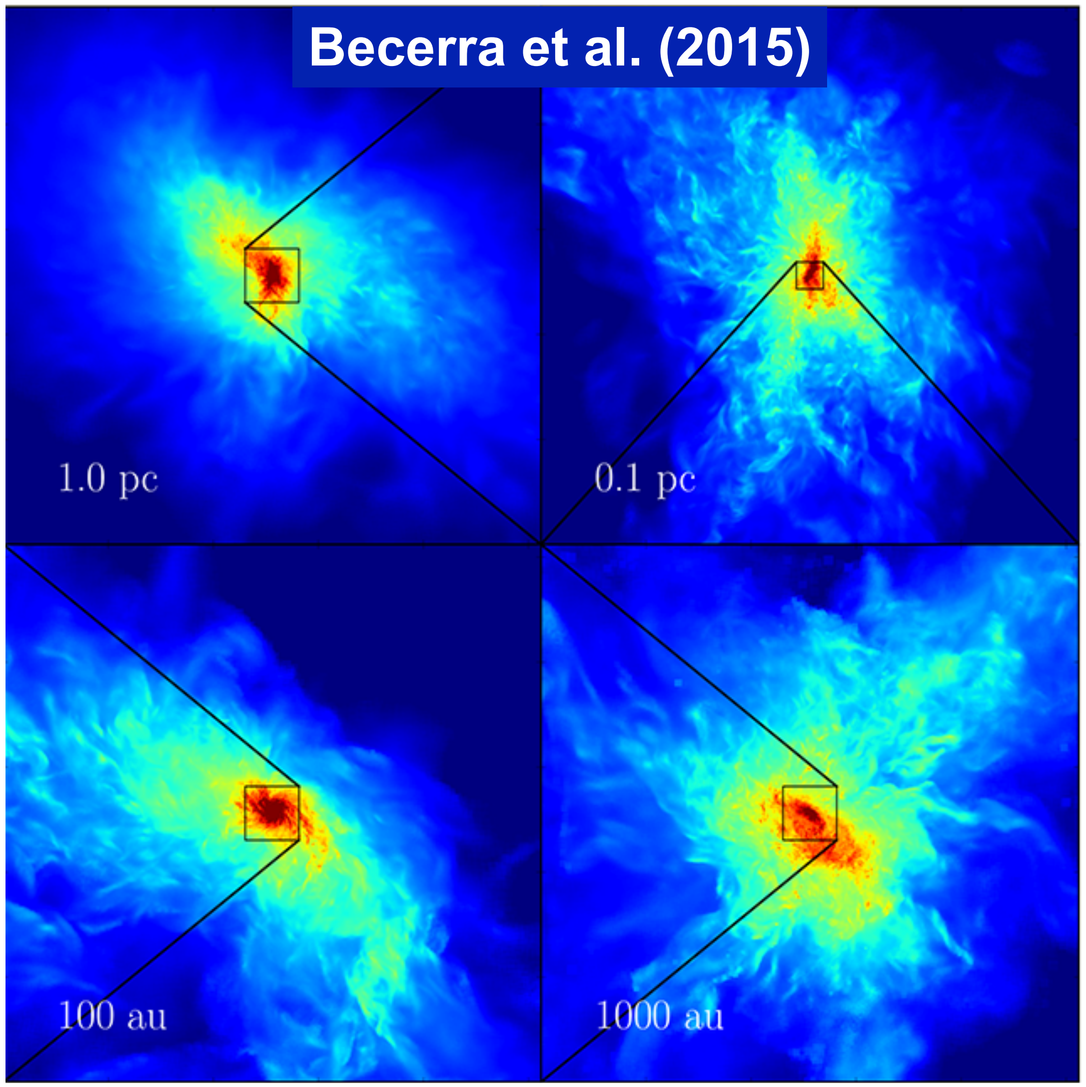
Metal-free gas collapse phase



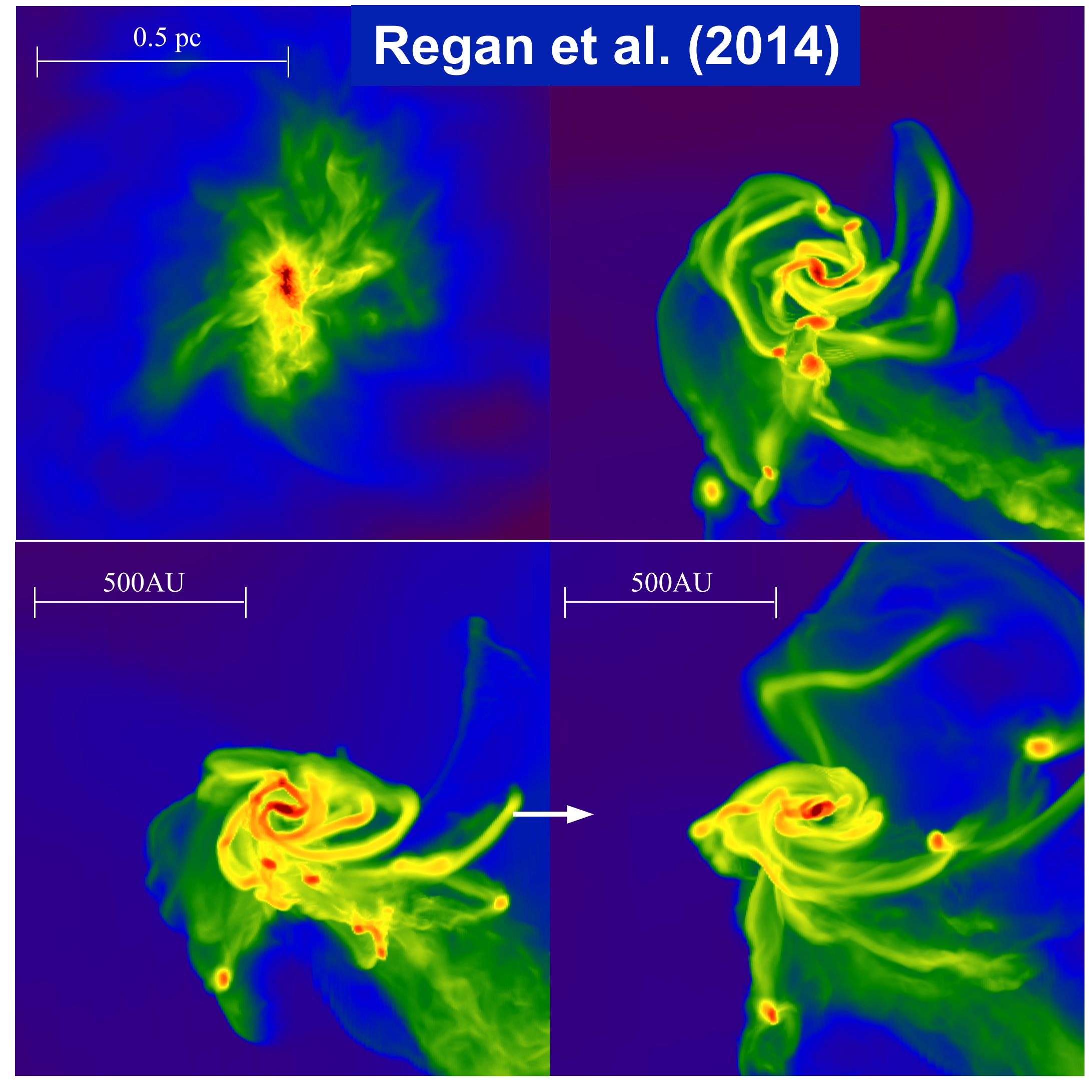
Metal-free gas collapse phase



No fragments / high Mdot!



gravitational collapse



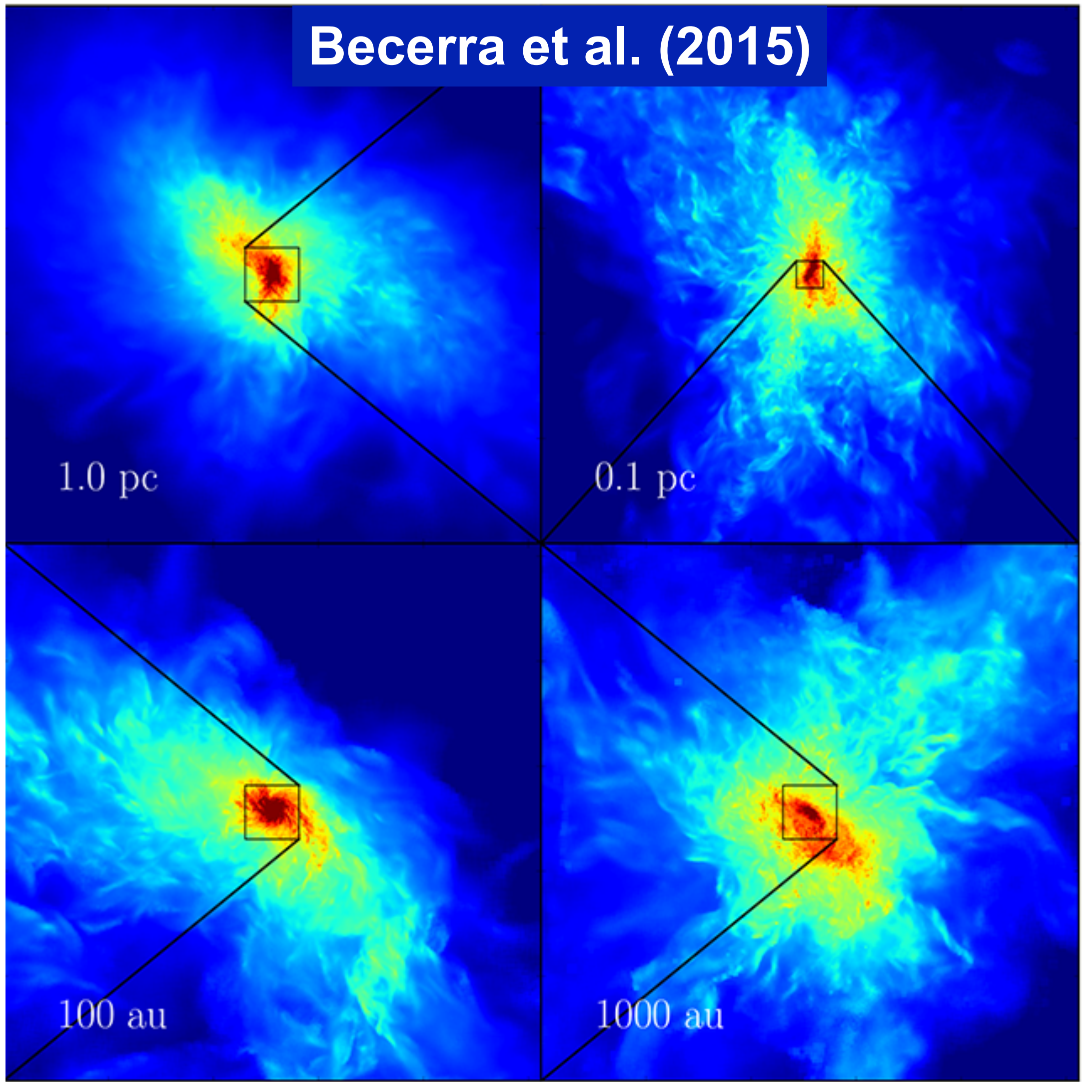
accretion disk

pristine & H_2 free gas ➡

- **no/weak fragmentation**
- **high accretion rate**

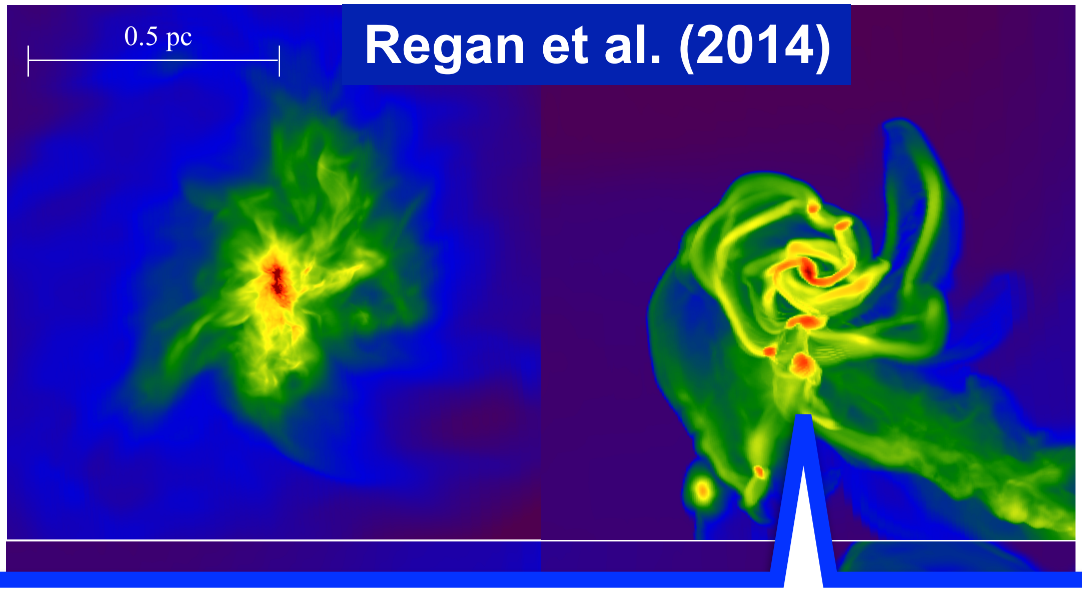
No fragments / high Mdot!

Becerra et al. (2015)



gravitational collapse

Regan et al. (2014)



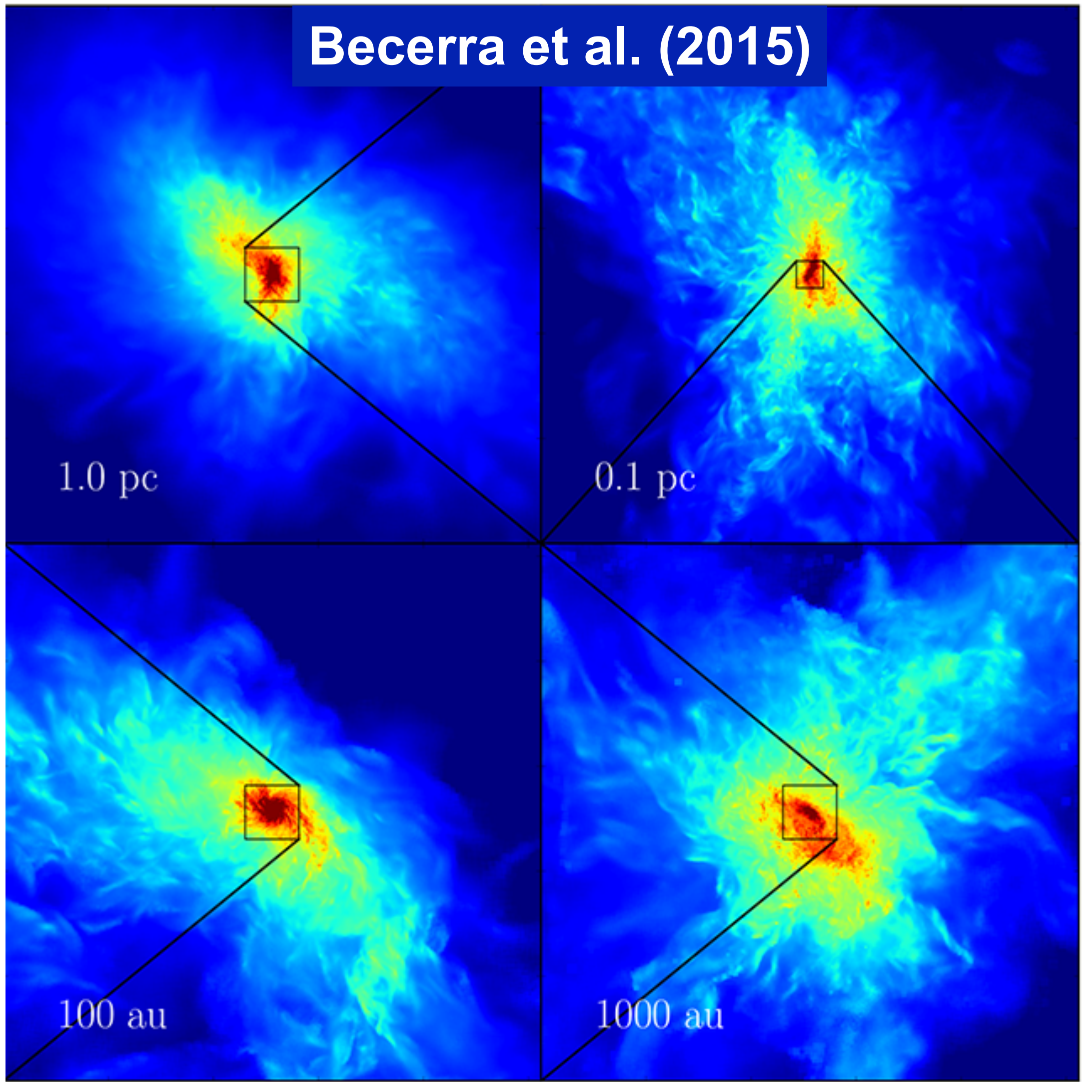
Clump migration is quick!
unlikely to affect the central star
(Inayoshi & Haiman 2014; Sakurai et al. 2015)

see Matsukoba-kun's talk

pristine & H_2 free gas ➡

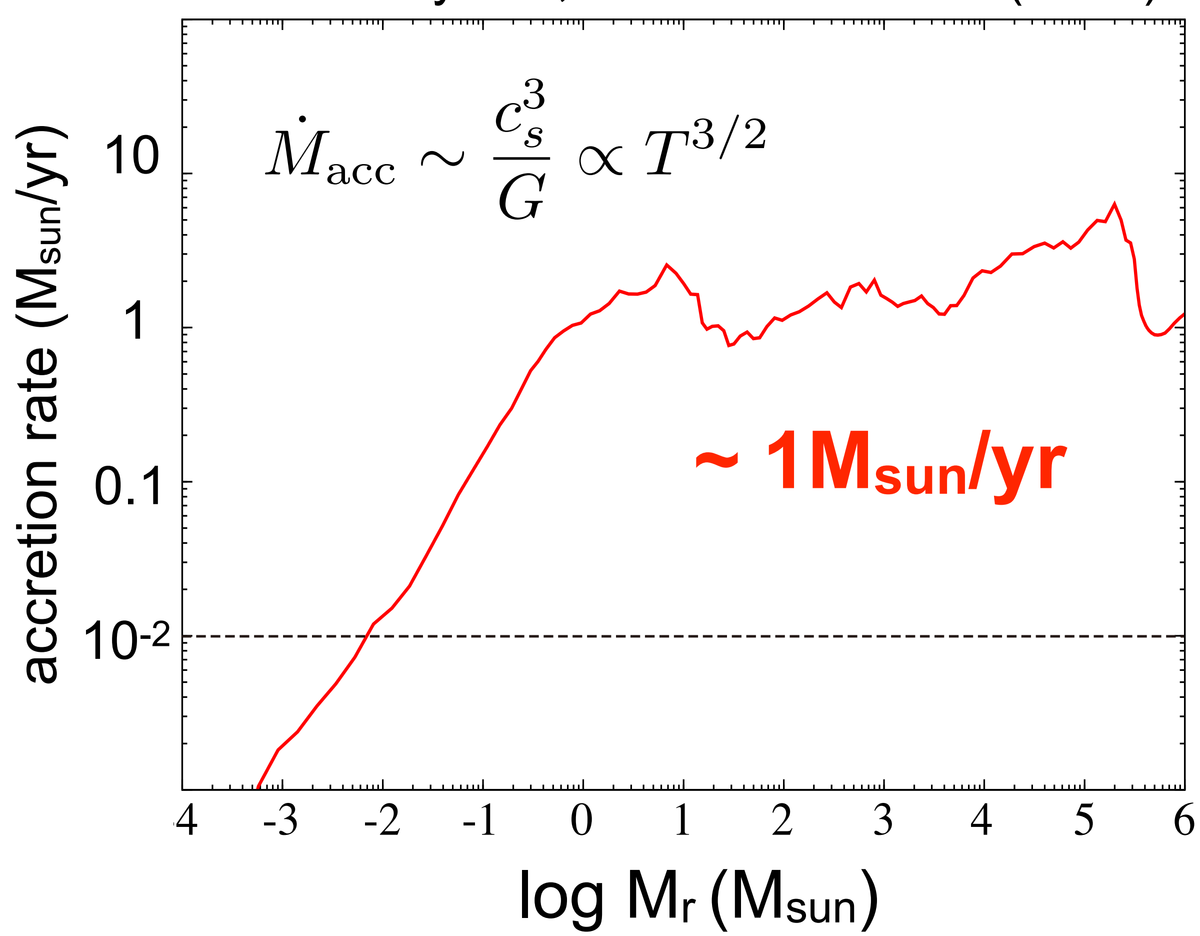
- **no/weak fragmentation**
- **high accretion rate**

No fragments / high Mdot!



gravitational collapse

Inayoshi, Omukai & Tasker (2014)

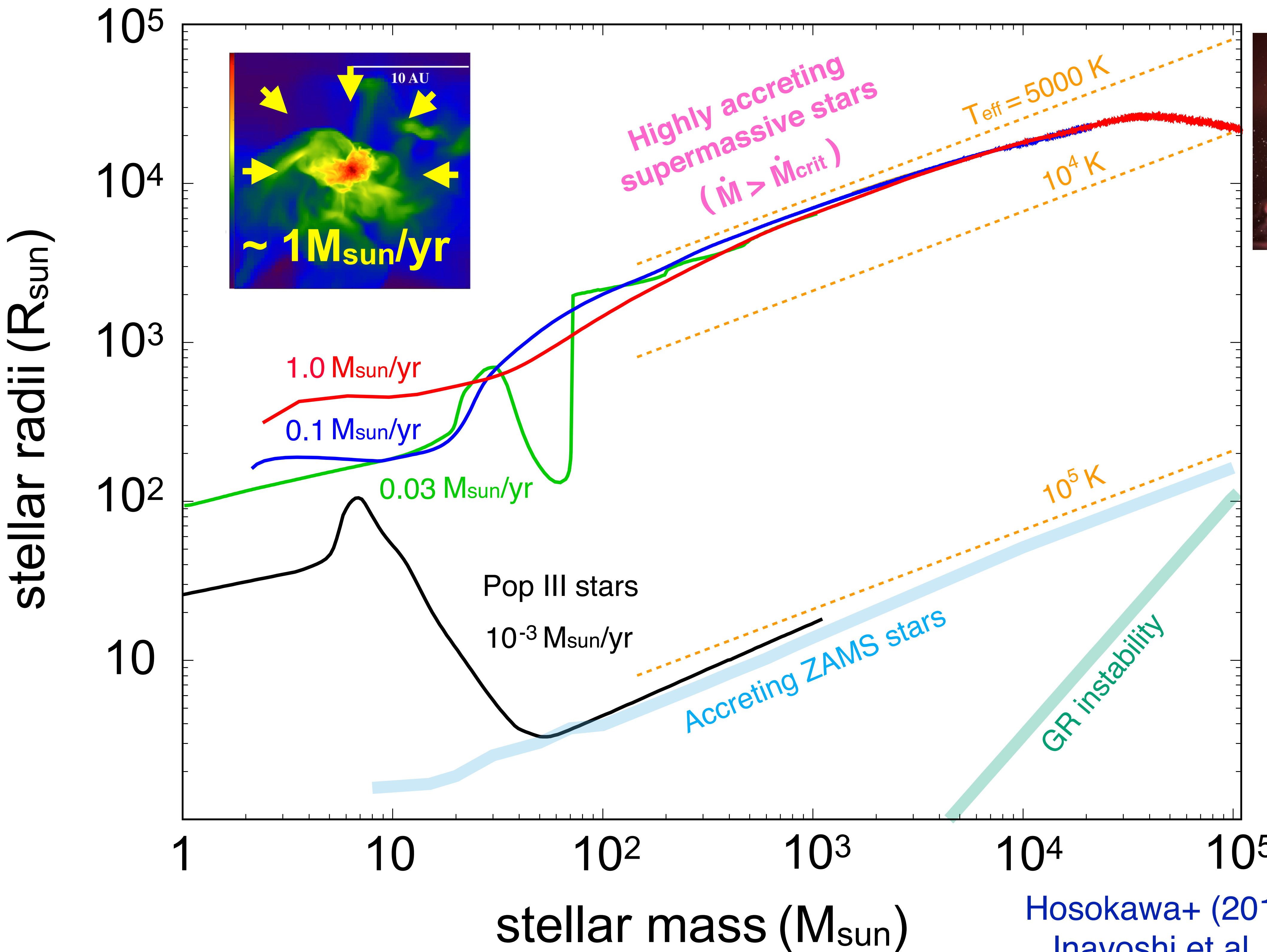


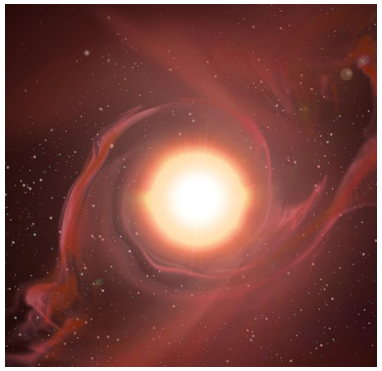
$$M_\star \approx \dot{M}_{\rm acc} \times t_{\rm life} \sim O(10^5)\ M_\odot$$

pristine & H_2 free gas ➡

- **no/weak fragmentation**
- **high accretion rate**

Rapidly accreting protostar





growth to

~10^5Msun

Hosokawa+ (2012,2013)
Inayoshi et al. (2020)

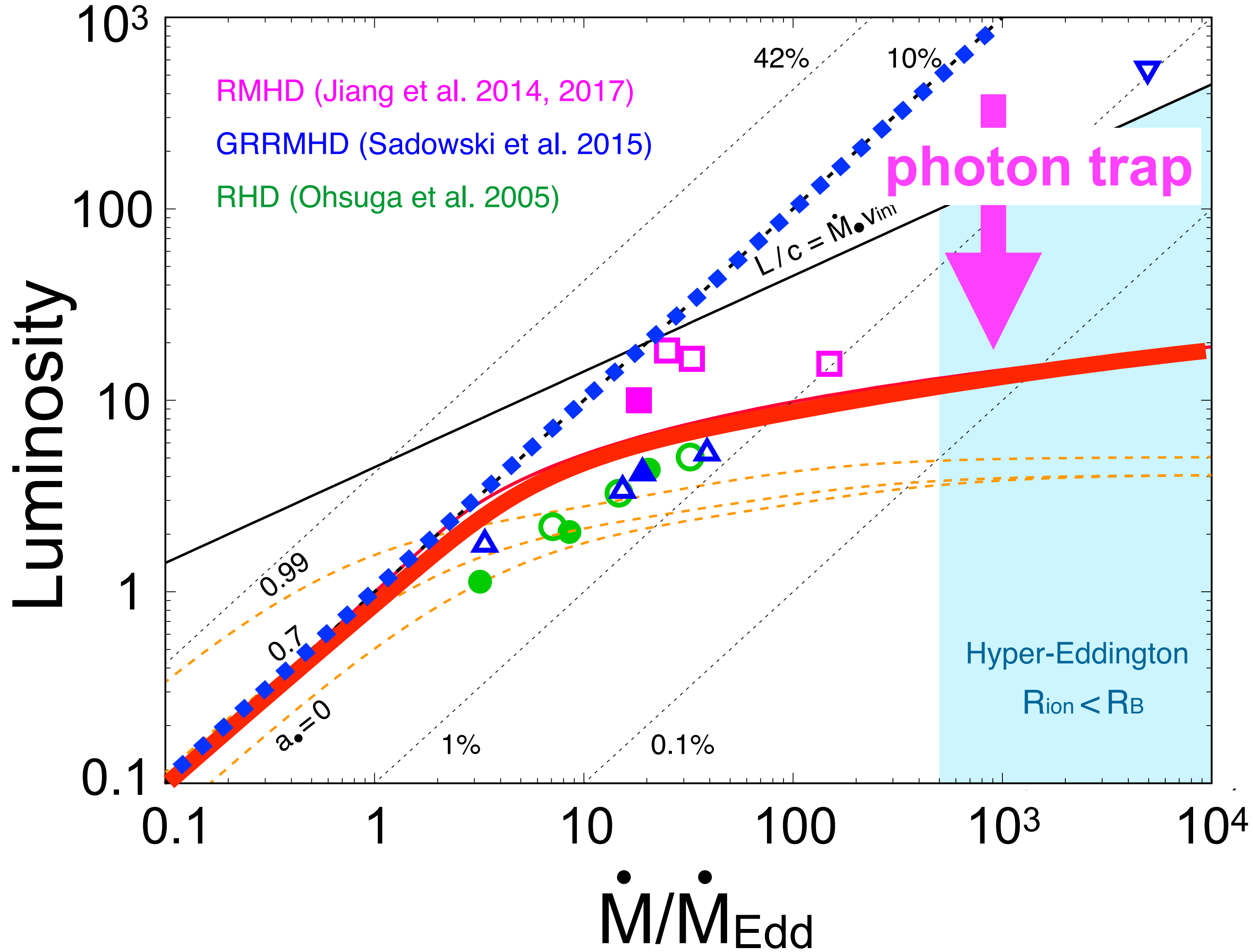
Rapid BH accretion

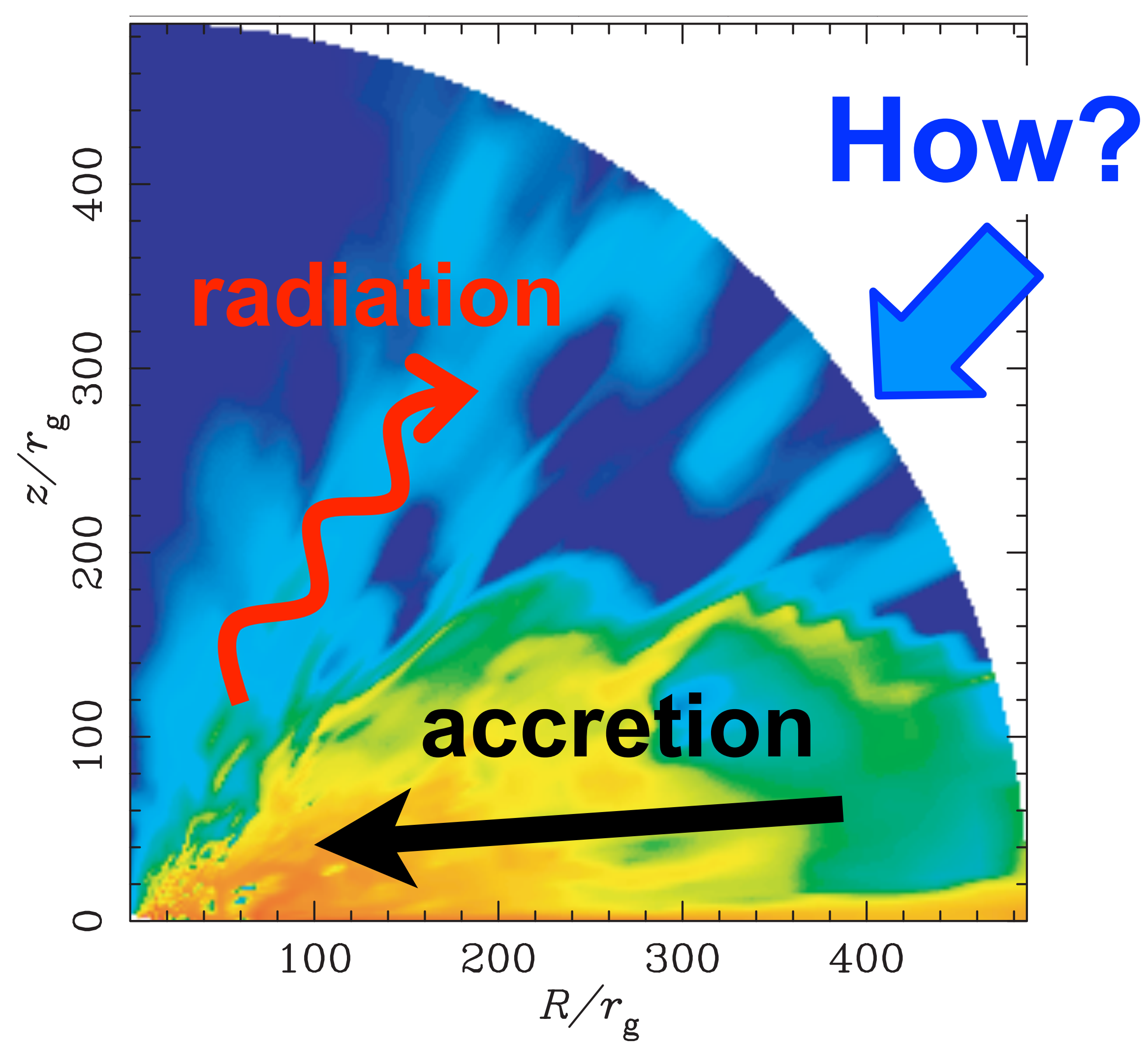
Super-Eddington accretion

- GR/Radiation/MHD simulations (Ohsuga+ 2009; Jiang+ 2014; Sadowski+ 2015)
  - **photon trapping** in a disk
  - radiative flux to the poles

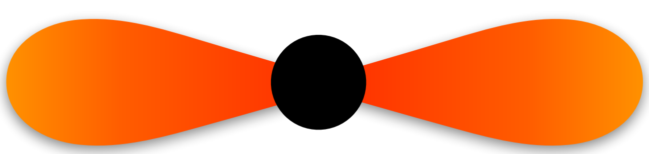
$\dot{M} \gg \dot{M}_{\rm Edd}$ is possible!

at small scales





Bondi accretion limit

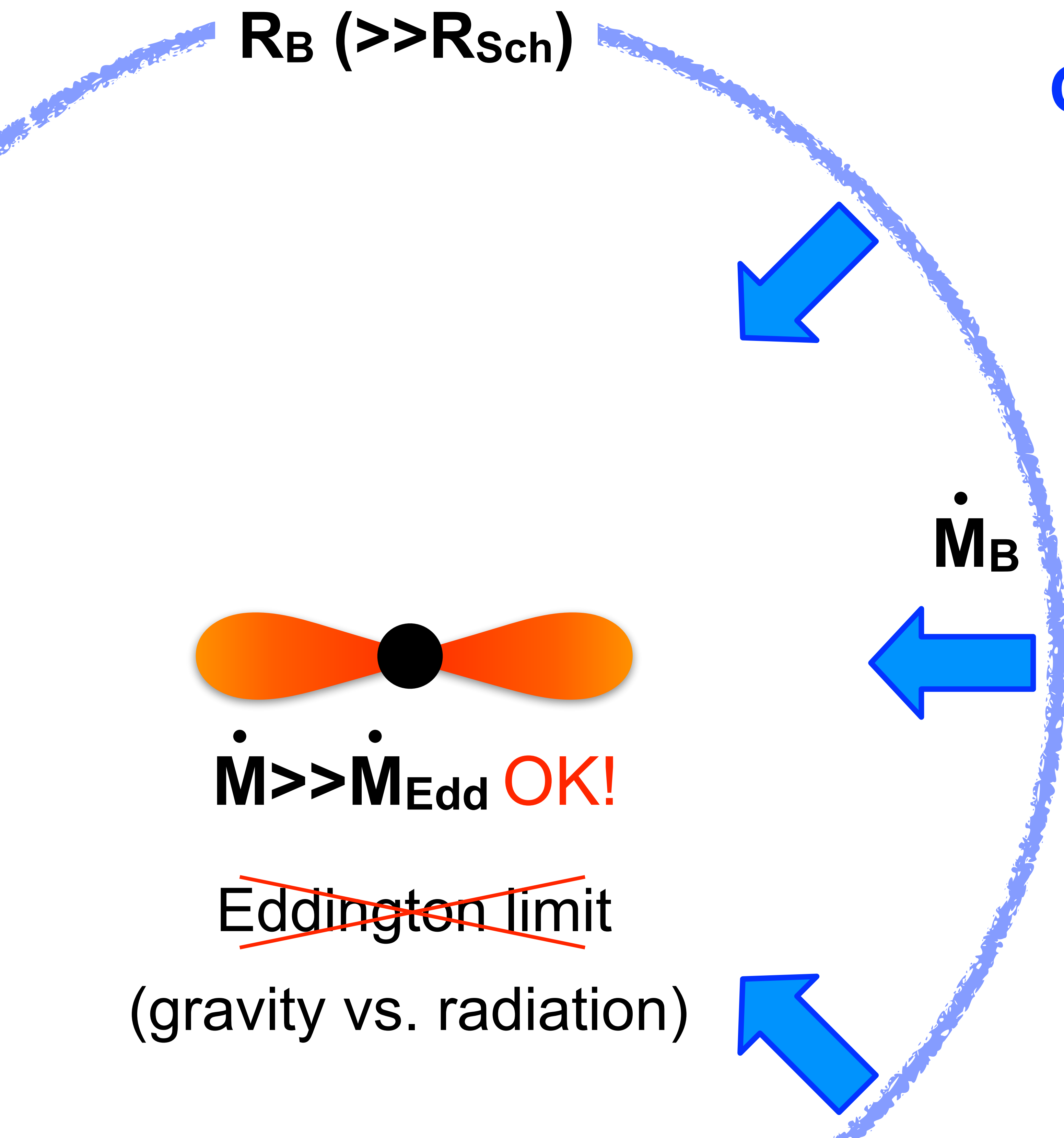


$\dot{M} \gg \dot{M}_{Edd}$ OK!

~~Eddington limit~~

(gravity vs. radiation)

Bondi accretion limit



Gas accretion within R_B

(gravity vs. gas pressure)

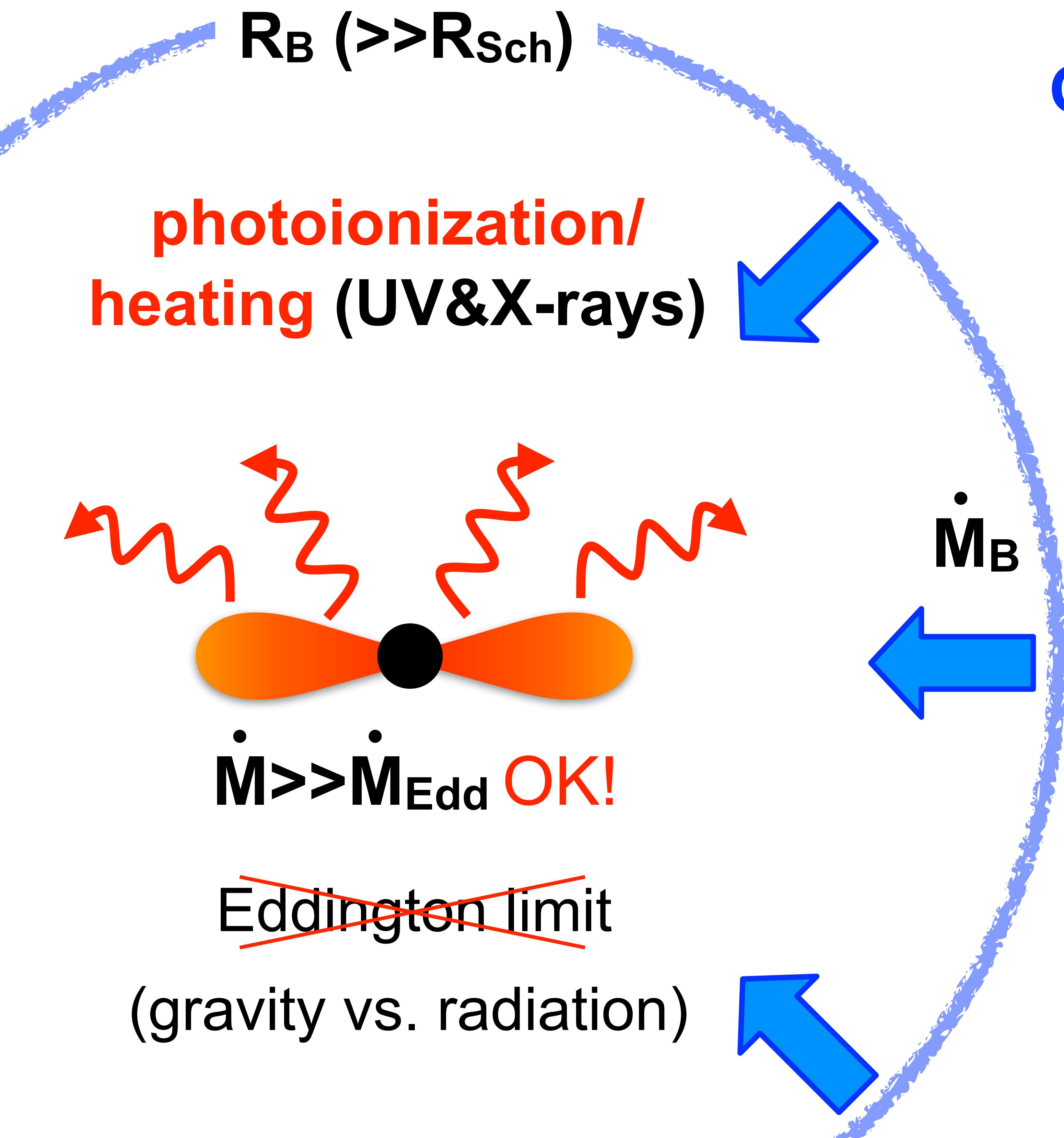
$$R_{\rm B} = \frac{GM_\bullet}{c_\infty^2} \propto \frac{M_\bullet}{T_\infty}$$

mass inflow from R_B

$$\dot{M}_{\rm B} \simeq 4\pi\rho_\infty R_{\rm B}^2 c_\infty$$

$$\propto \rho_\infty M_\bullet^2 T_\infty^{-3/2}$$

Bondi accretion limit



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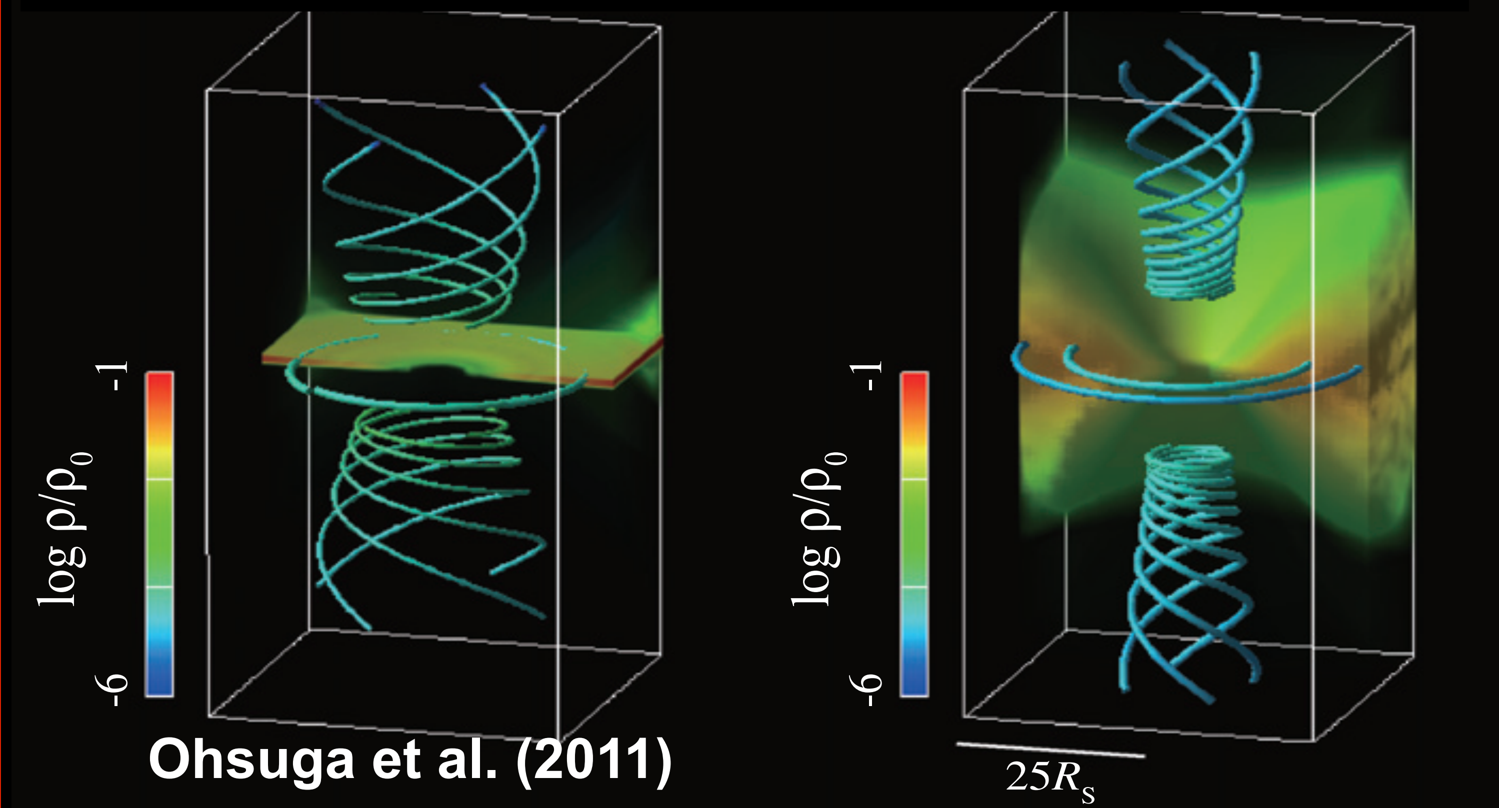
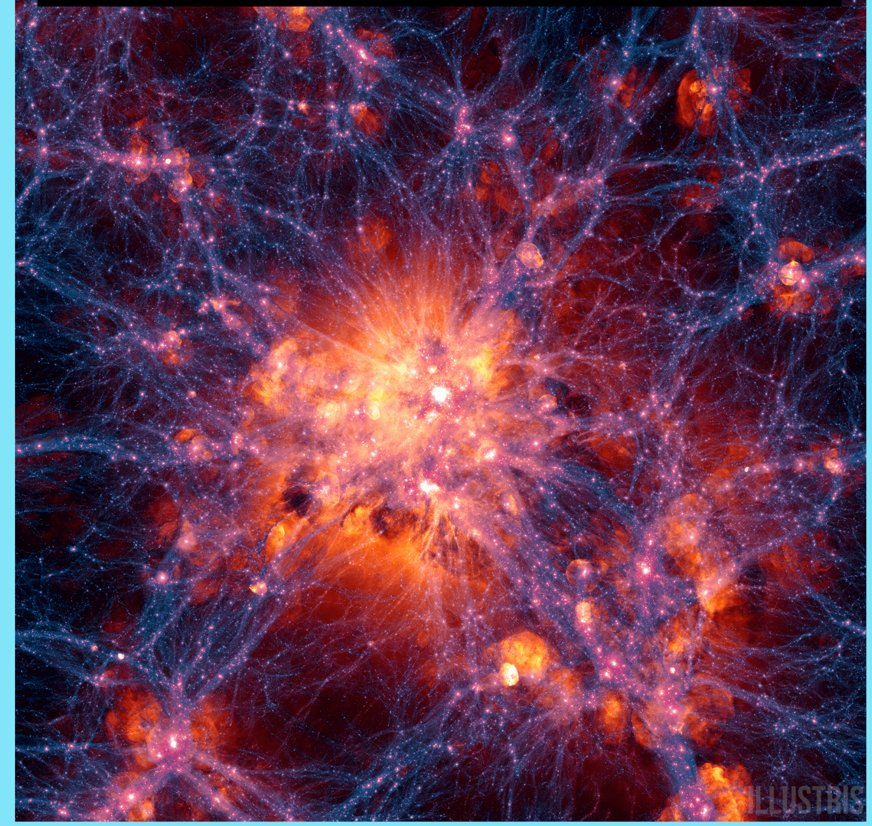
BH accretion in multi-scales

smaller scales: ~*O*(100)*R_{Sch} ~ 0.1-1 mpc



larger scales: < *O*(kpc)



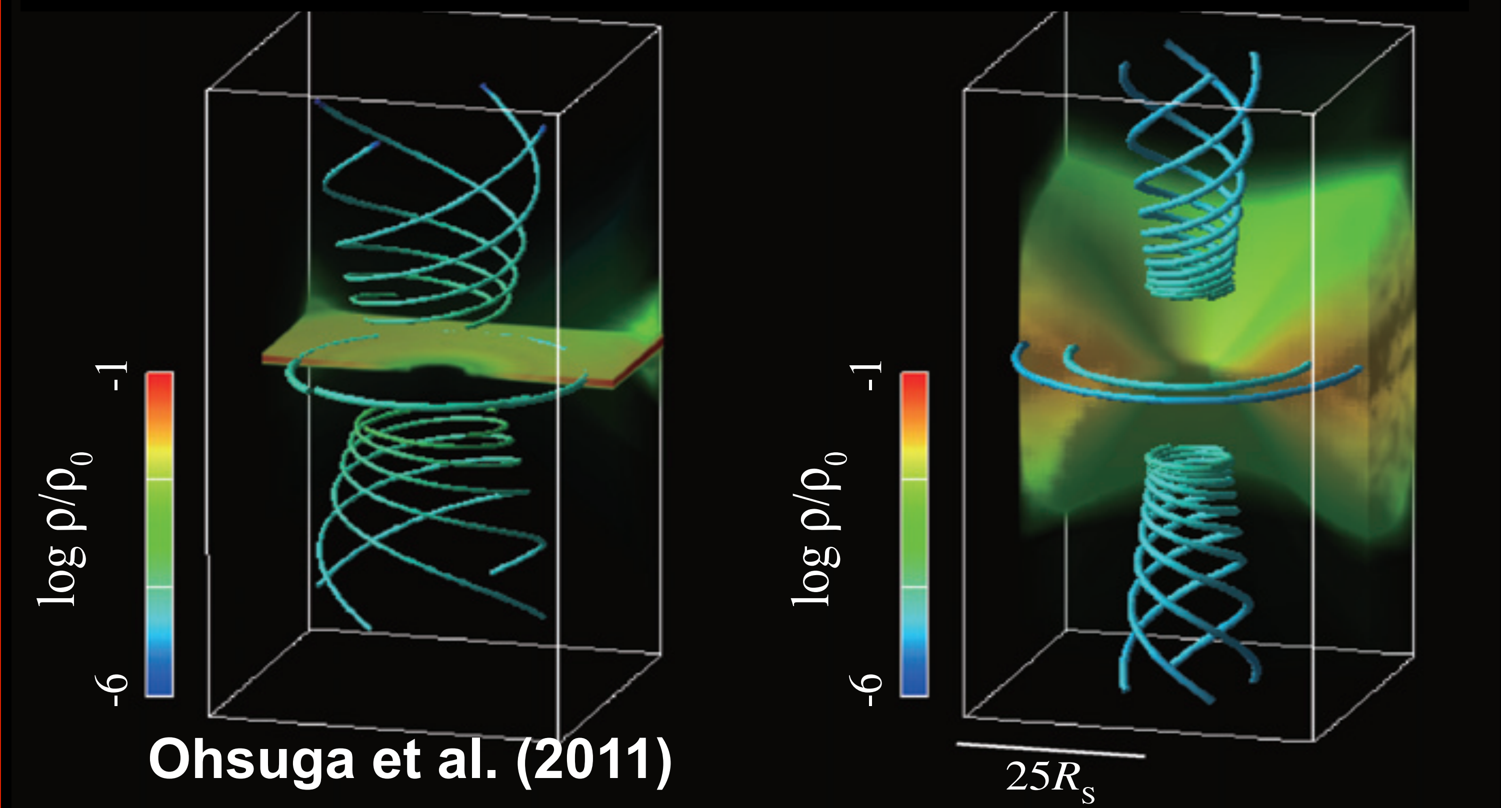
standard disks
Shakura & Sunyaev (1973)

Slim disk
Abramowicz et al. (1988)

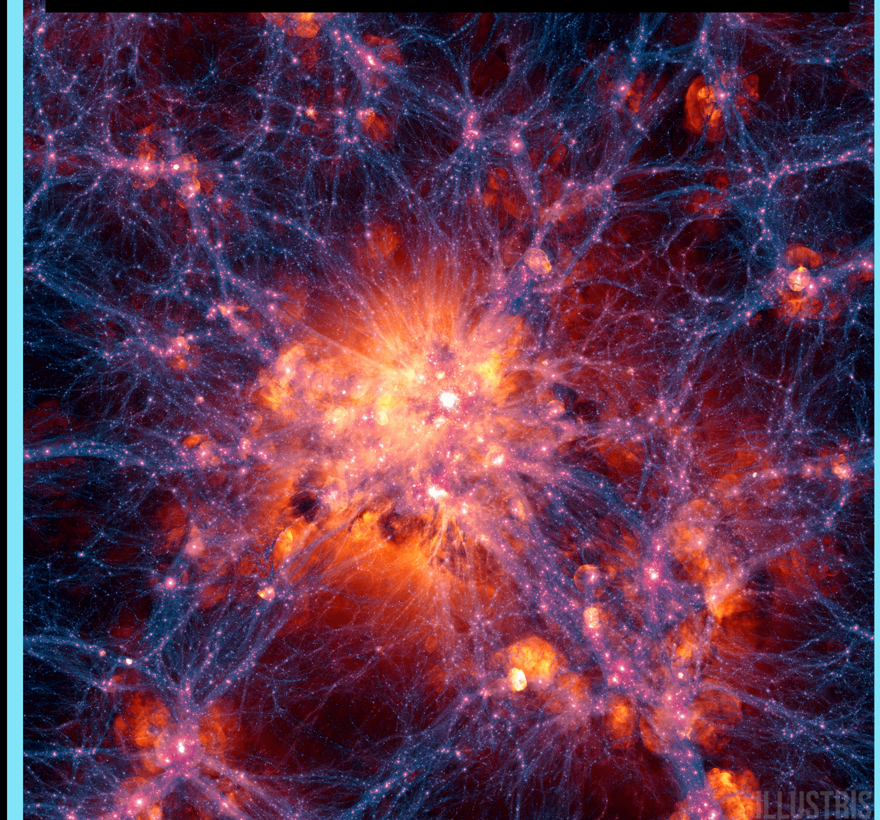
cosmological simulations
(e.g., Illustris, EAGLE, FIRE)

BH accretion in multi-scales

smaller scales: ~$O(100)$*R_{Sch} ~ 0.1-1 mpc



larger scales: < O(kpc)



standard disks

Shakura & Sunyaev (1973)

Slim disk

Abramowicz et al. (1988)

cosmological simulations

(e.g., Illustris, EAGLE, FIRE)

$\dot{M} \gg \dot{M}_{\rm Edd}$ is possible !

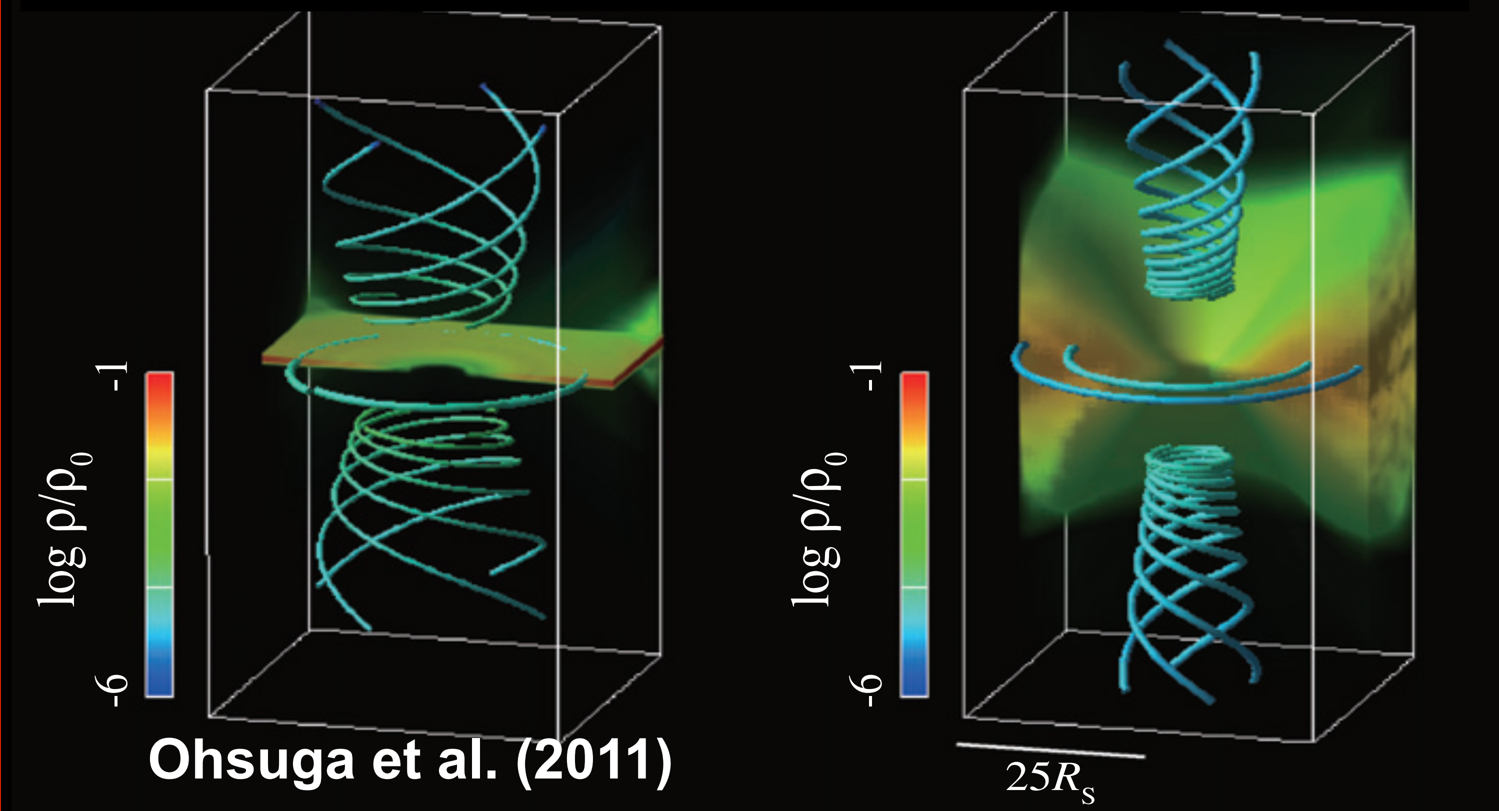
at small scales

$\dot{M} \simeq \min(\dot{M}_{\rm Edd}, \dot{M}_{\rm Bondi})$

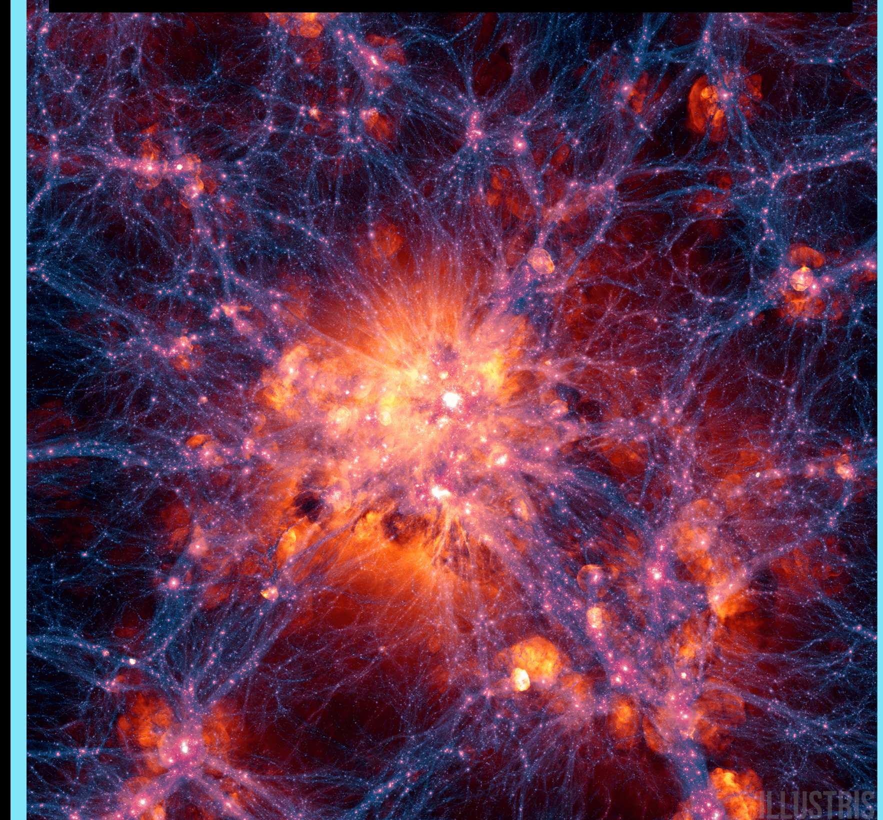
without resolving R_B

BH accretion in multi-scales

smaller scales: ~$O(100)*R_{Sch}$ ~ 0.1-1 mpc



larger scales: < O(kpc)



standard disks

Shakura & Sunyaev (1973)

Slim disk

Abramowicz et al. (1988)

cosmological simulations

(e.g., Illustris, EAGLE, FIRE)

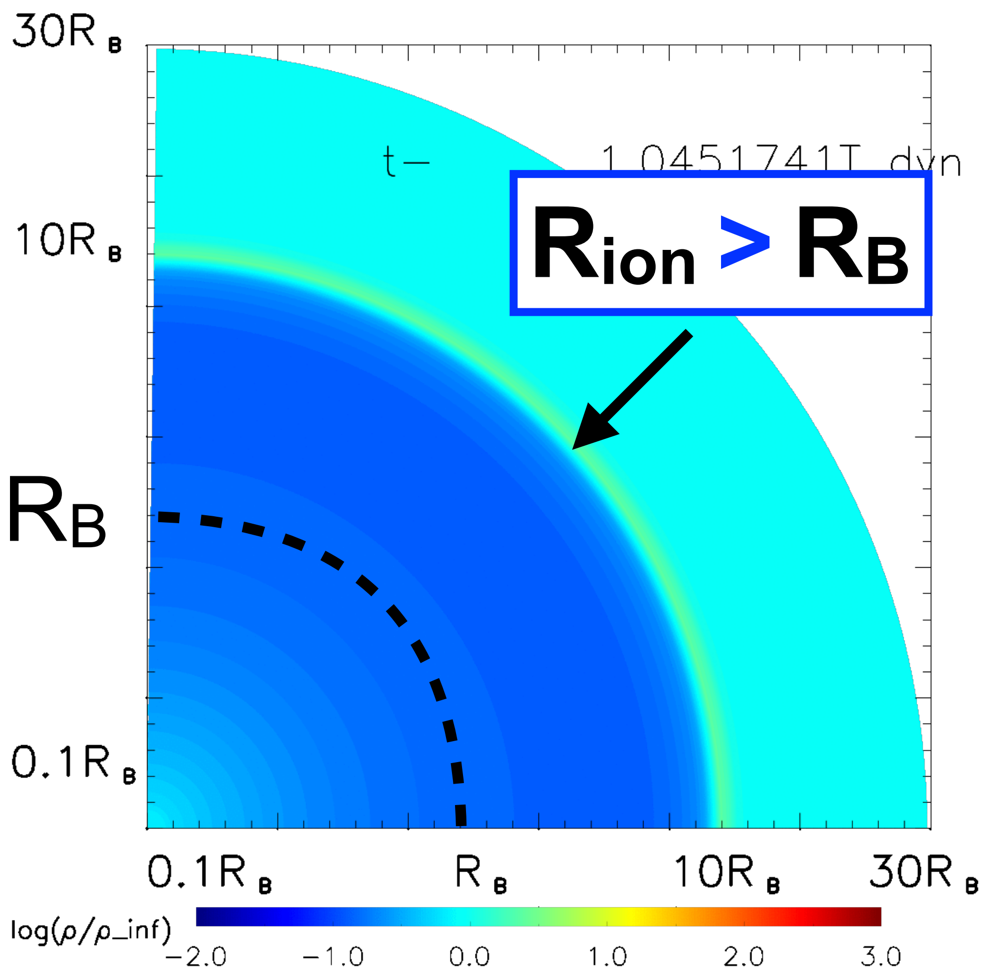
How can we connect the two different scales?

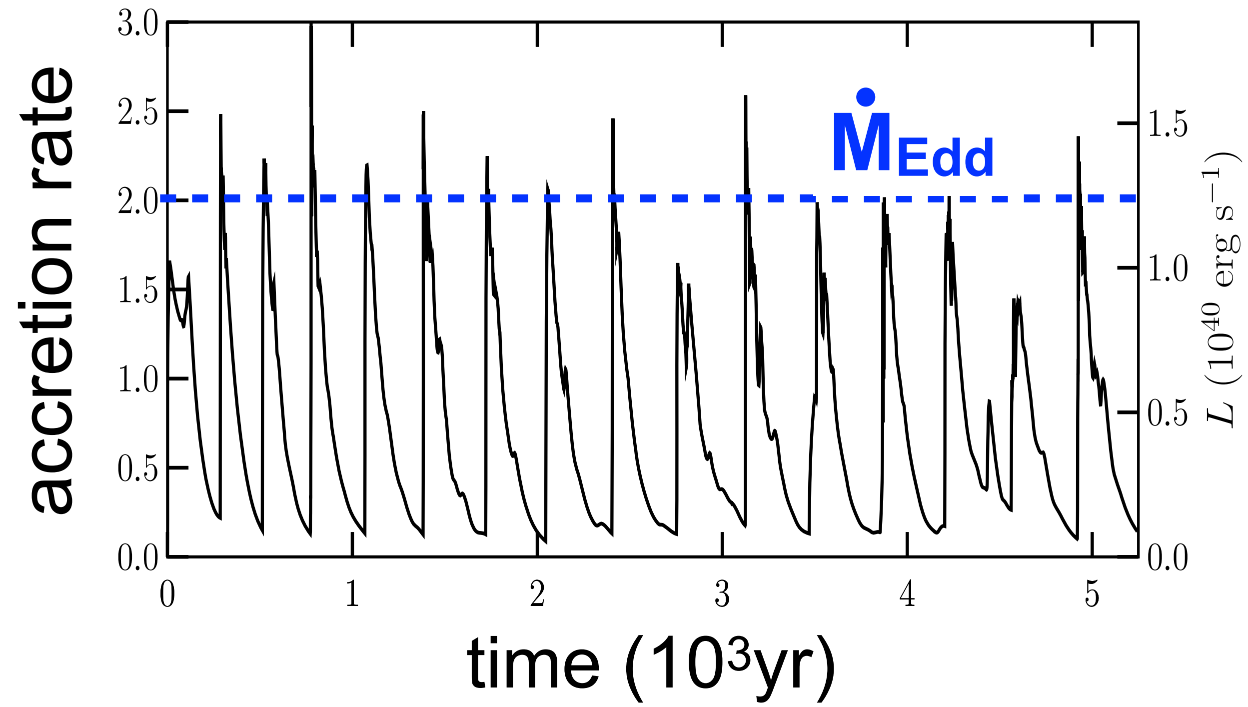
➡ ***Construct the global solution including R_B !***

Gas supply from large scales

- **low density** case ($\dot{M}_{\rm B,ini} \sim 10\dot{M}_{\rm Edd}$)

Ciotti & Ostriker (2001)
Milosavljevic+ (2009)
Park & Ricotti (2011, 2012)





$$\dot{M}_{\rm B} \propto \rho_\infty M_\bullet^2 T_\infty^{-3/2}$$

burst accretion
(radiation heating)

$\langle \dot{M} \rangle \ll \dot{M}_{\rm Edd}$

Gas supply from large scales

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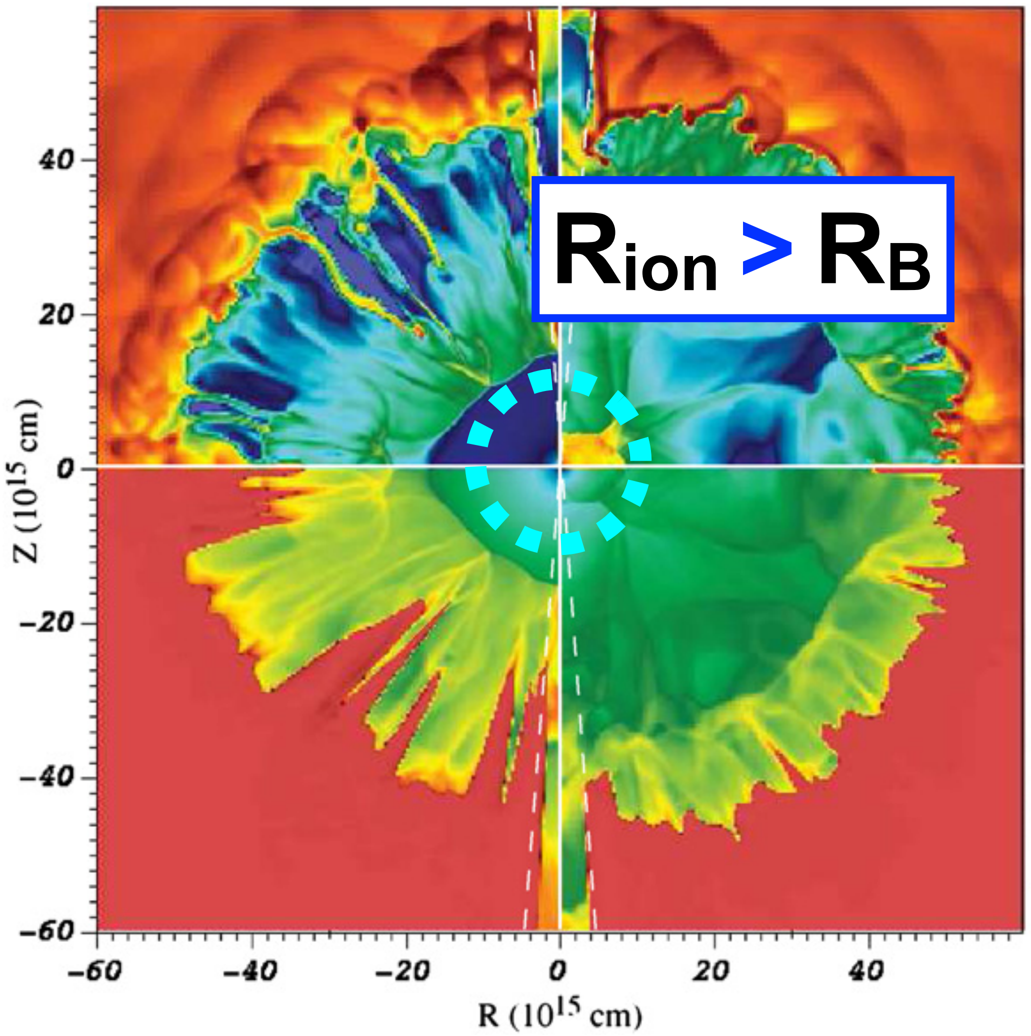
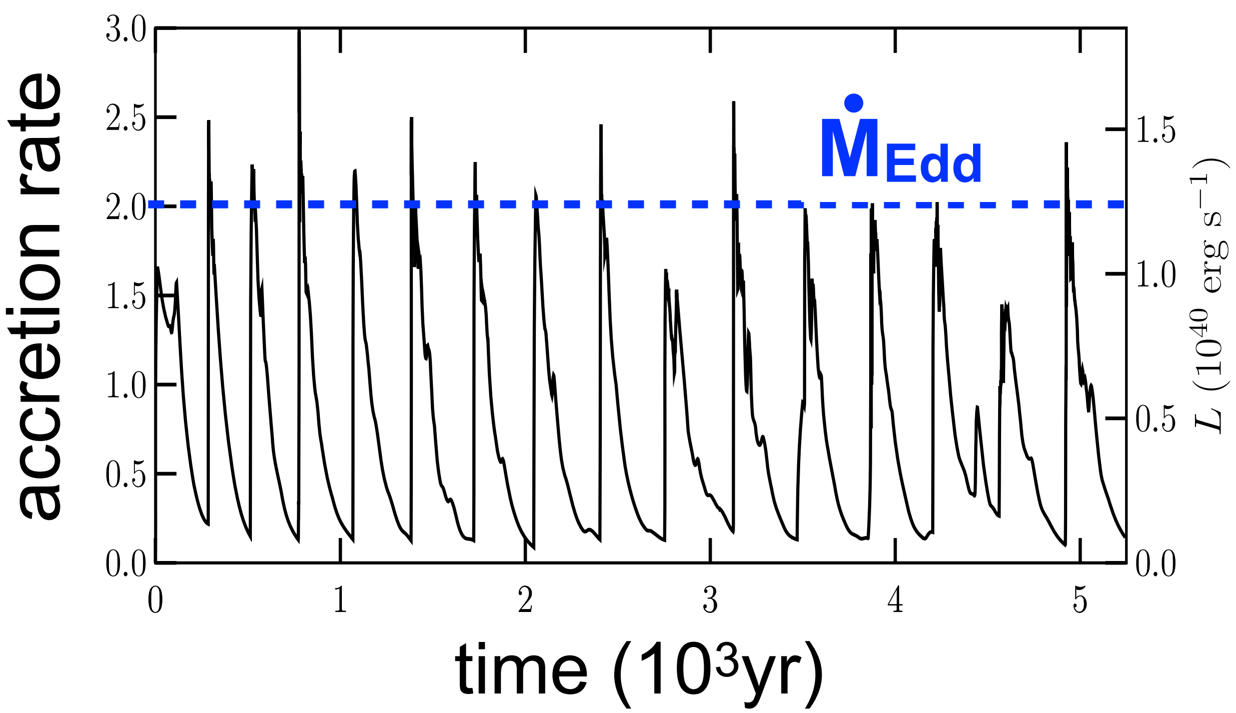




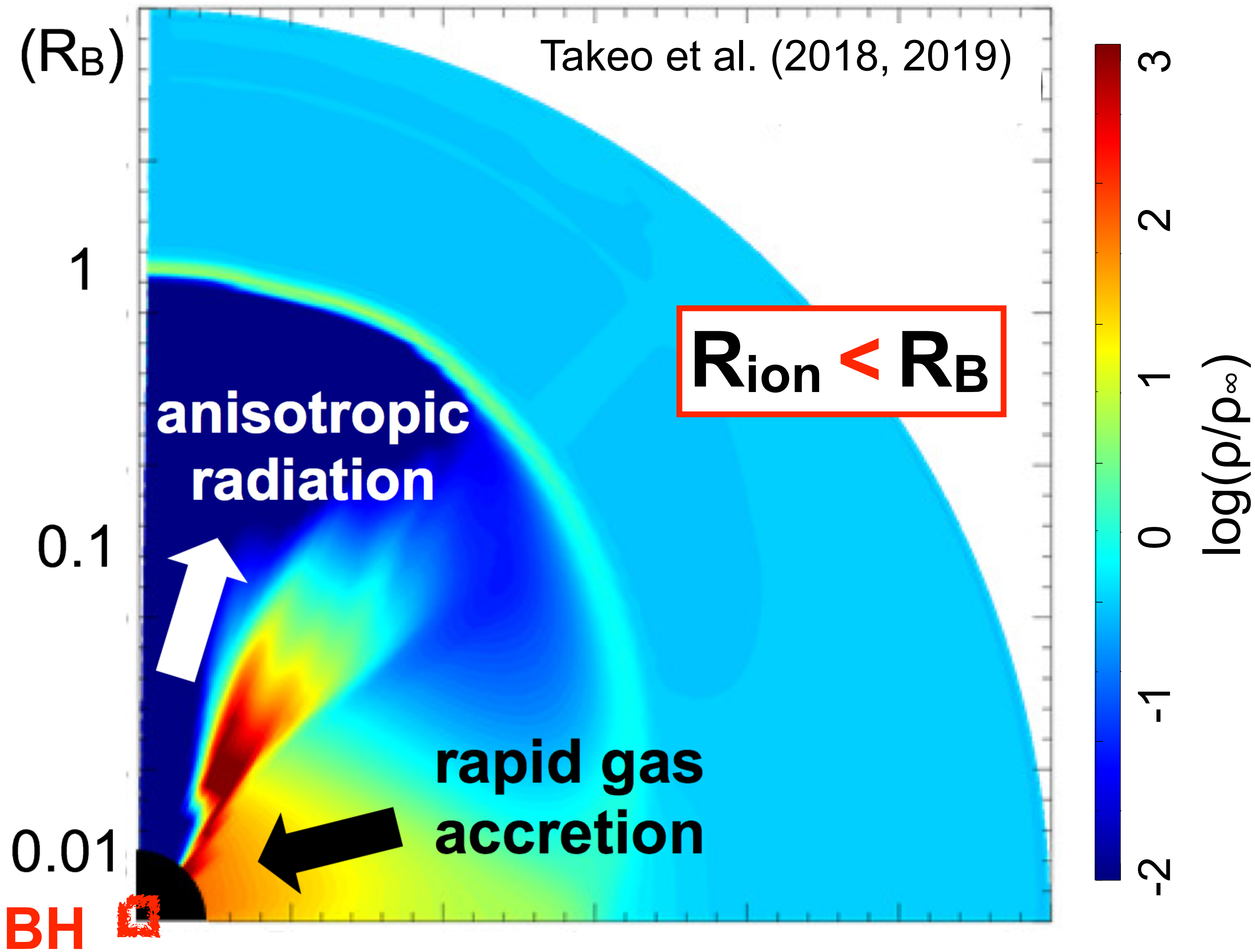
$$\dot{M}_{\rm B} \propto \rho_\infty M_\bullet^2 T_\infty^{-3/2}$$

burst accretion
(radiation heating)

→ $\langle \dot{M} \rangle \ll \dot{M}_{\rm Edd}$

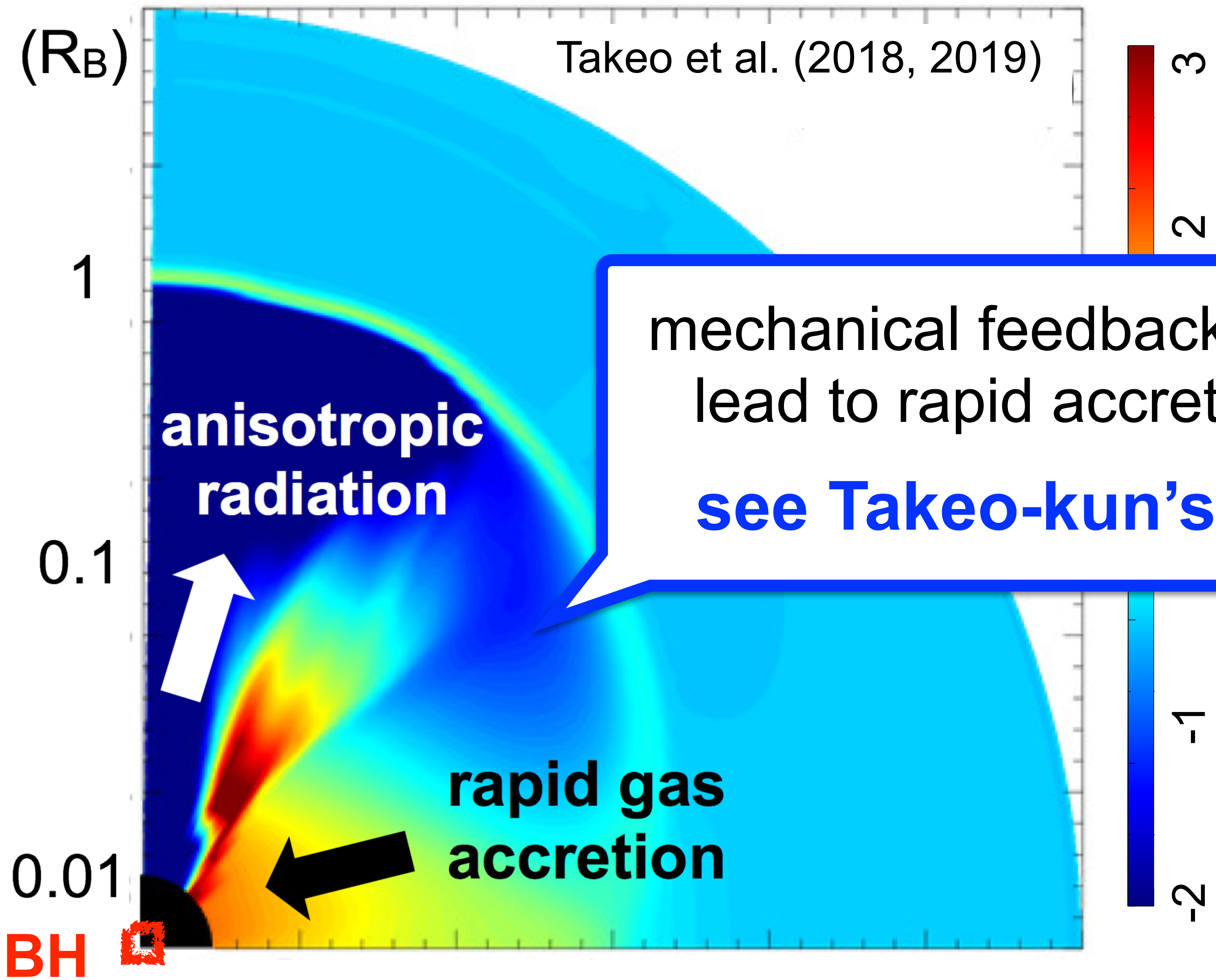
Rapid BH accretion in first galaxies

- **high density** case ($\dot{M}_{\mathrm{B,ini}} \sim 500\ \dot{M}_{\mathrm{Edd}}$)



Rapid BH accretion in first galaxies

- **high density** case ($\dot{M}_{\rm B,ini} \sim 500\ \dot{M}_{\rm Edd}$)

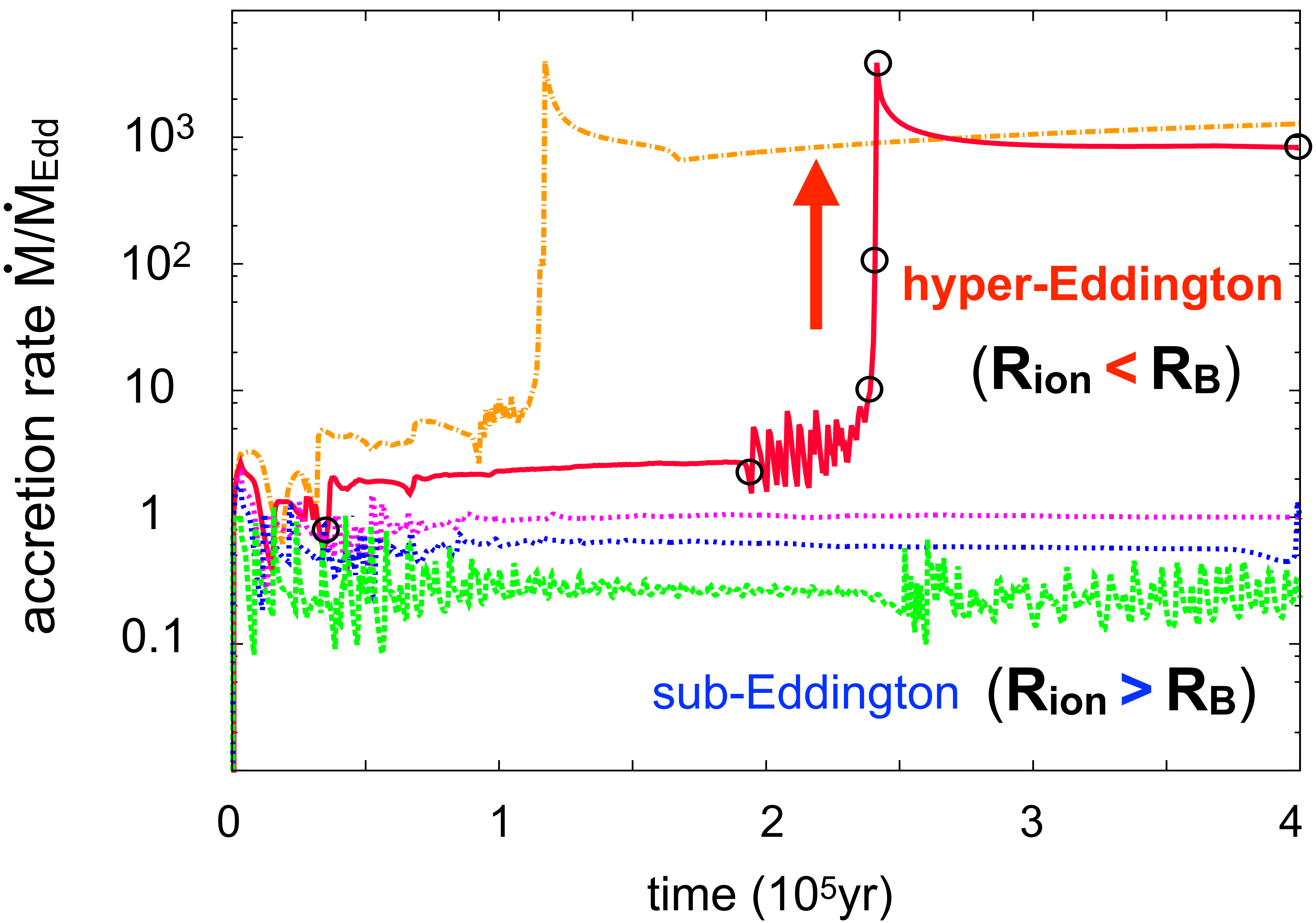


mechanical feedback would lead to rapid accretion…

see Takeo-kun's talk

Global hyper-Eddington accretion

Inayoshi, Haiman & Ostriker (2016); Sakurai, **Inayoshi** & Haiman (2016)



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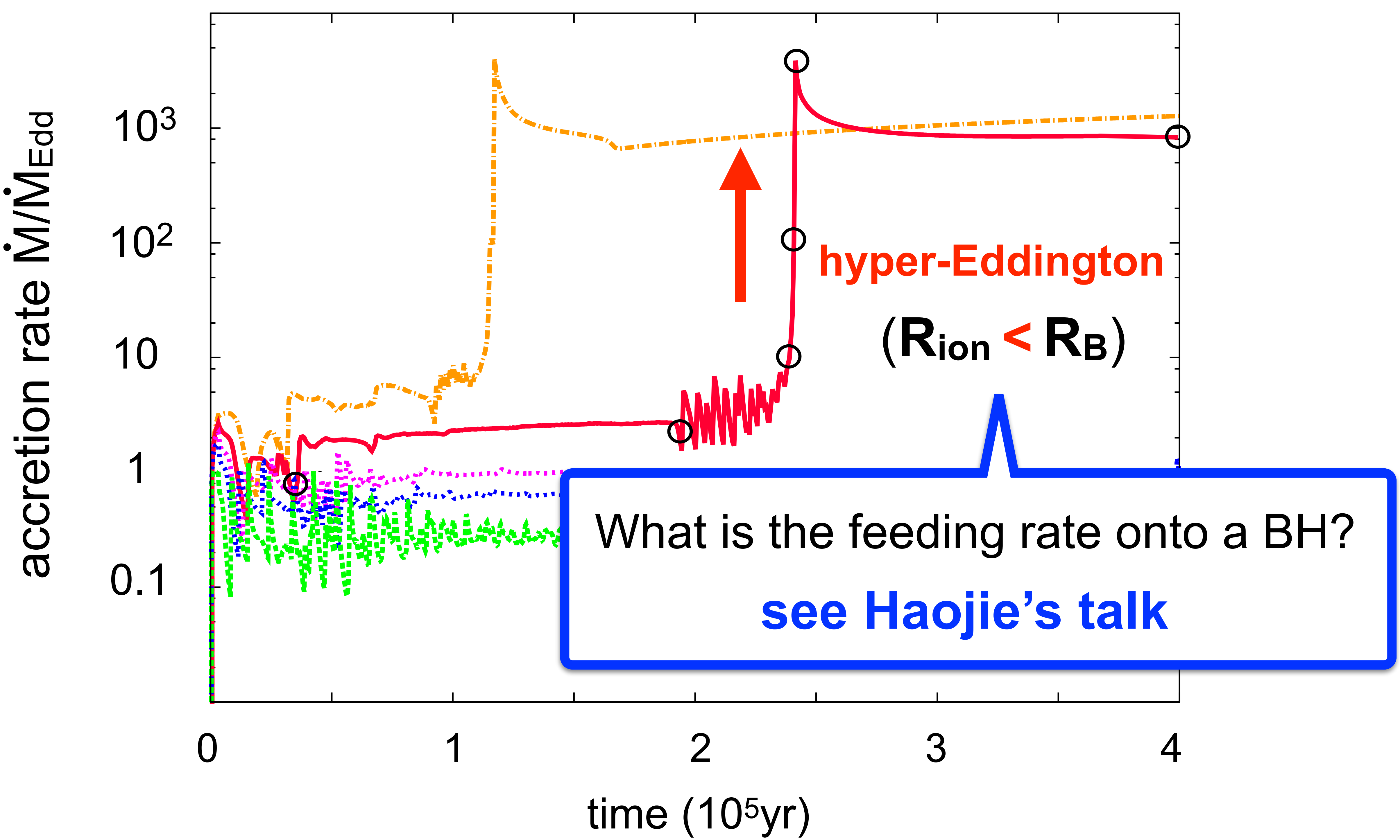
Inayoshi, Haiman & Ostriker (2016); Sakurai, **Inayoshi** & Haiman (2016)



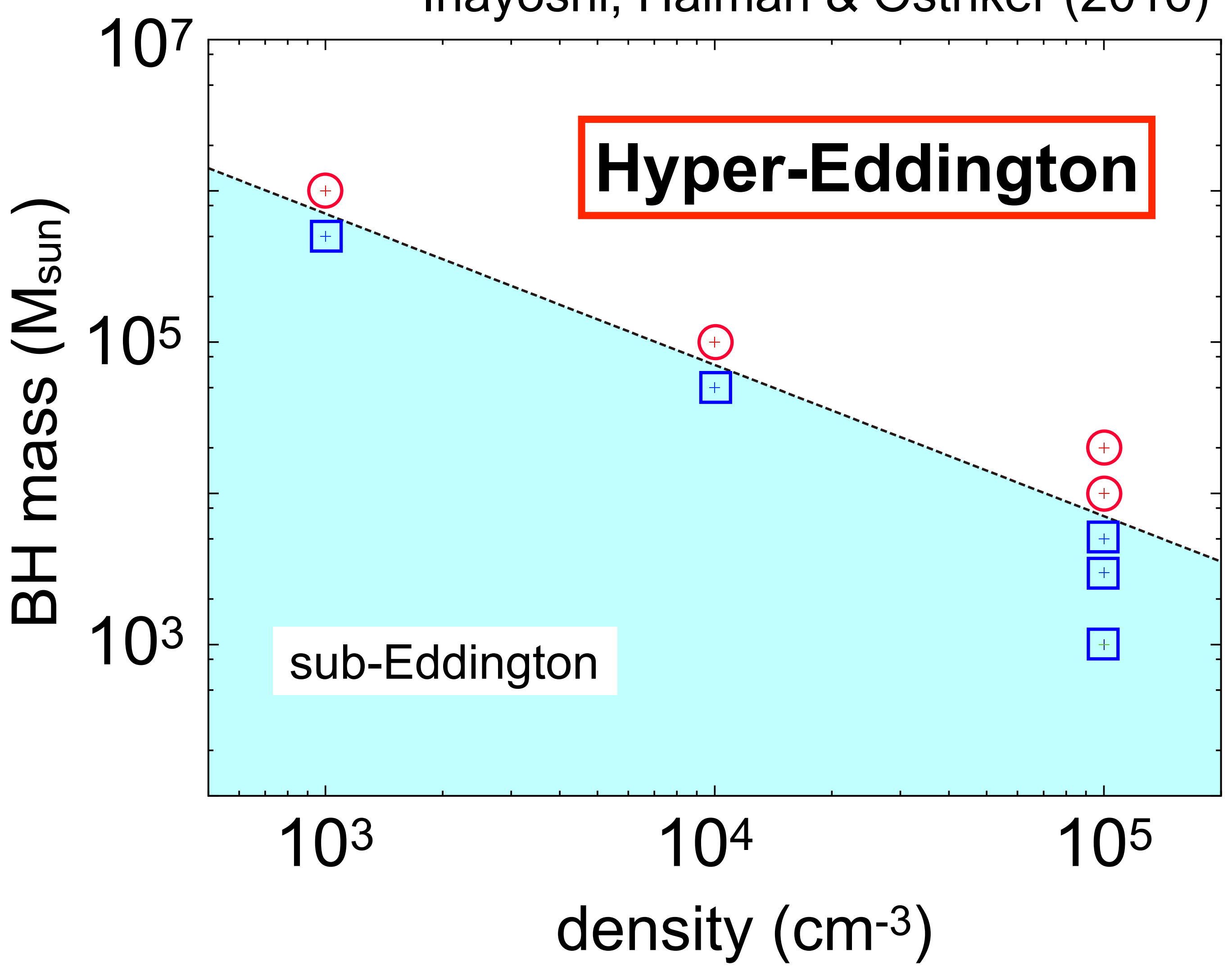
Conditions for rapid accretion

- analytical argument

$$R_{\rm ion} = \left(\frac{3Q_{\rm ion}}{4\pi \alpha_{\rm rec,B} n_\infty^2} \right)^{1/3}$$

$$\propto L^{1/3} n_\infty^{-2/3} \propto M_\bullet^{1/3} n_\infty^{-2/3}$$

$$R_{\rm B} = \frac{GM_\bullet}{c_\infty^2} \propto M_\bullet T_\infty^{-1}$$

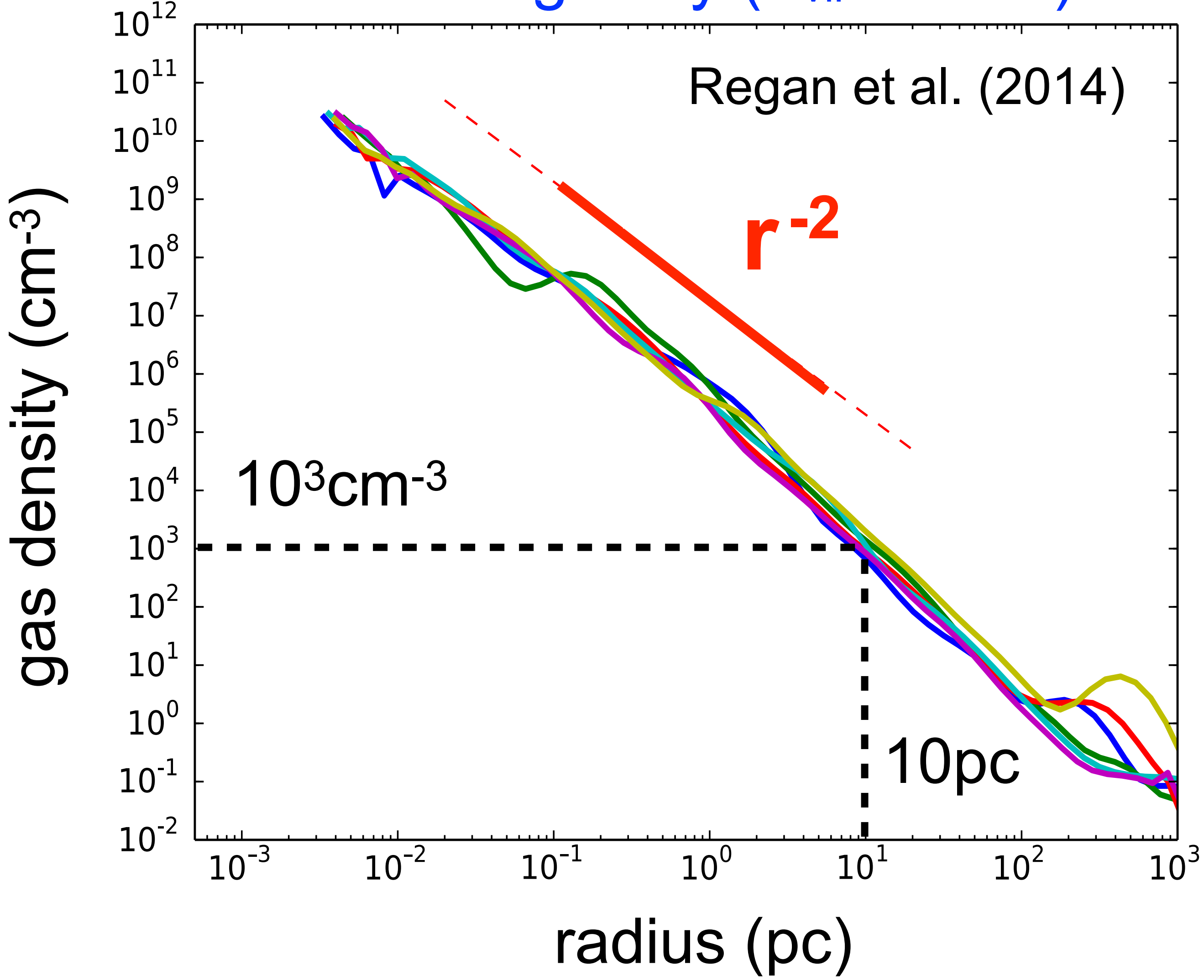


Hyper-Eddington conditions ($R_{\rm ion}$ < $R_{\rm B}$)

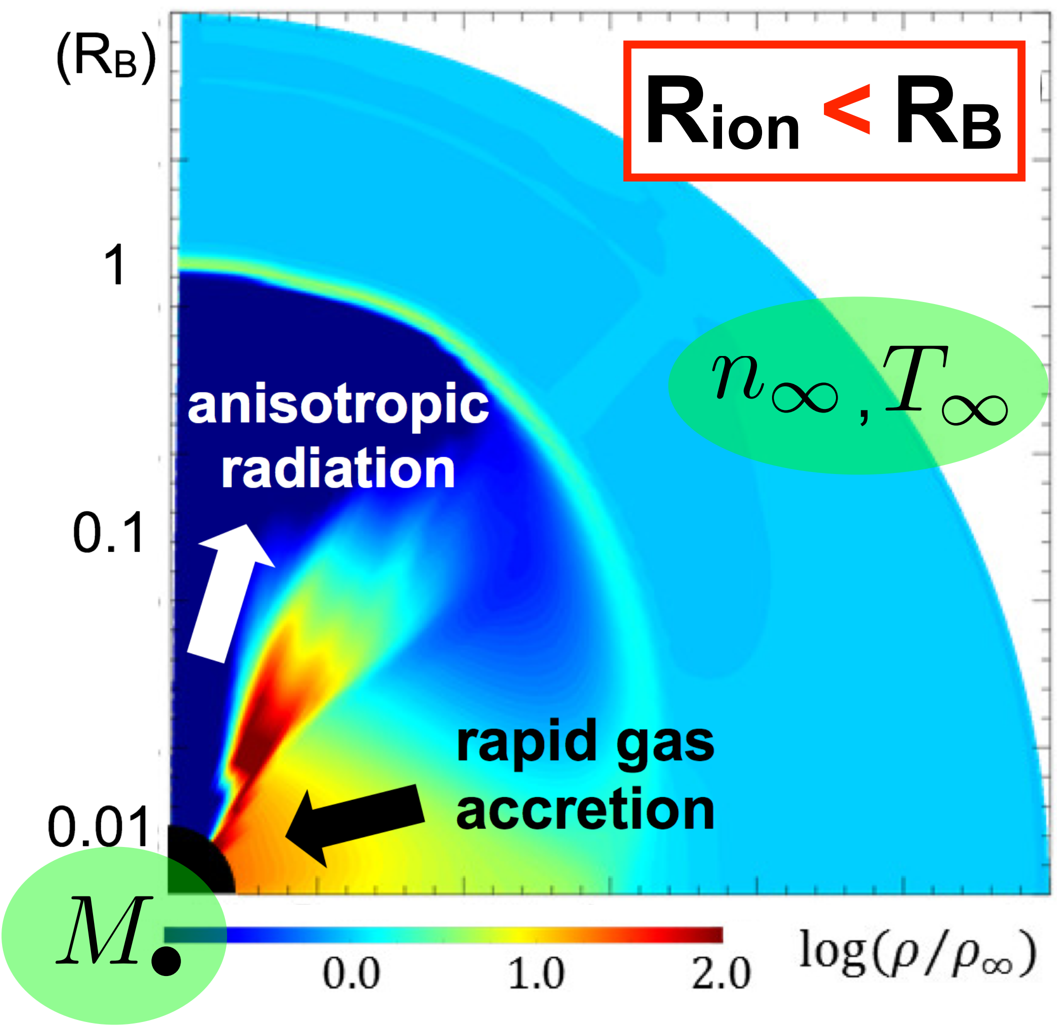
$$\left(\frac{n_\infty}{10^5 \ {\rm cm}^{-3}} \right) \left(\frac{M_\bullet}{10^4 \ M_\odot} \right) \gtrsim \left(\frac{T_\infty}{10^4 \ {\rm K}} \right)^{3/2} \Leftrightarrow \quad \dot{m} = \frac{\dot{M}}{\dot{M}_{\rm Edd}} \geq \ 500$$

Rapid growth of seed BHs

in a first galaxy ($T_{vir} = 10^4$K)



Takeo, Inayoshi +(2018, 2019)

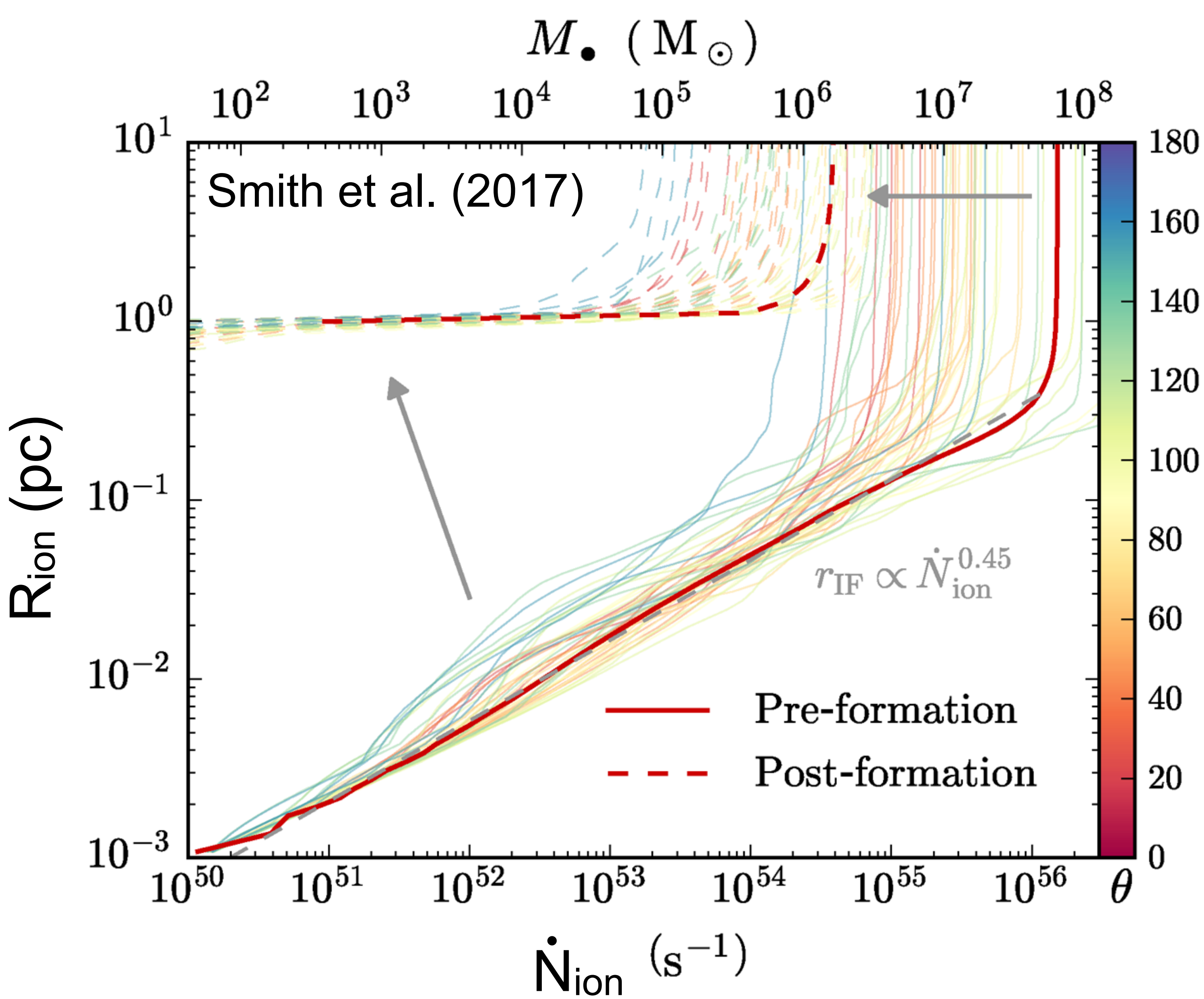


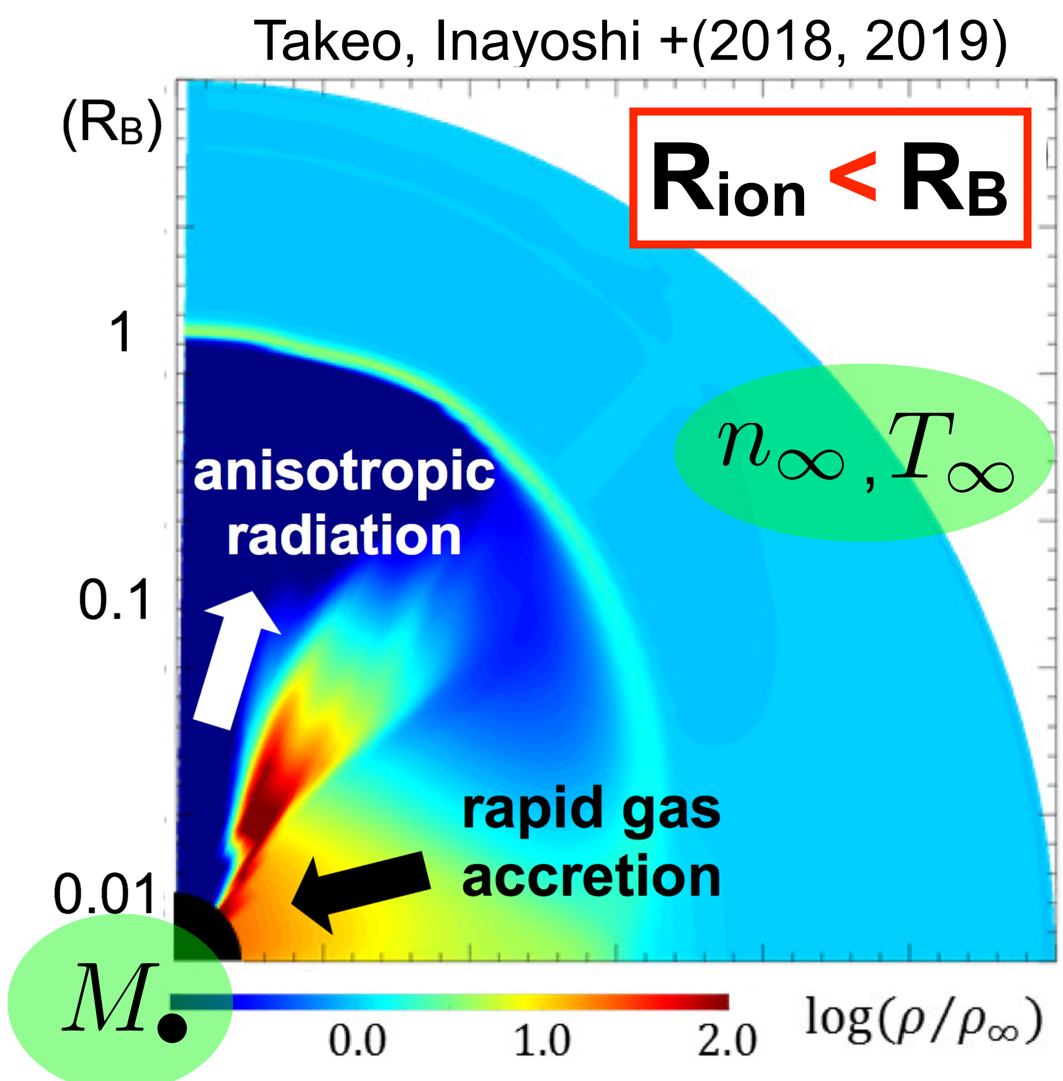
Rapid gas accretion is possible for BHs

halo virial temp

$$M_{\rm BH} \lesssim 2 \times 10^5 \; T_{\rm vir,4} \; M_\odot$$

Rapid growth of seed BHs



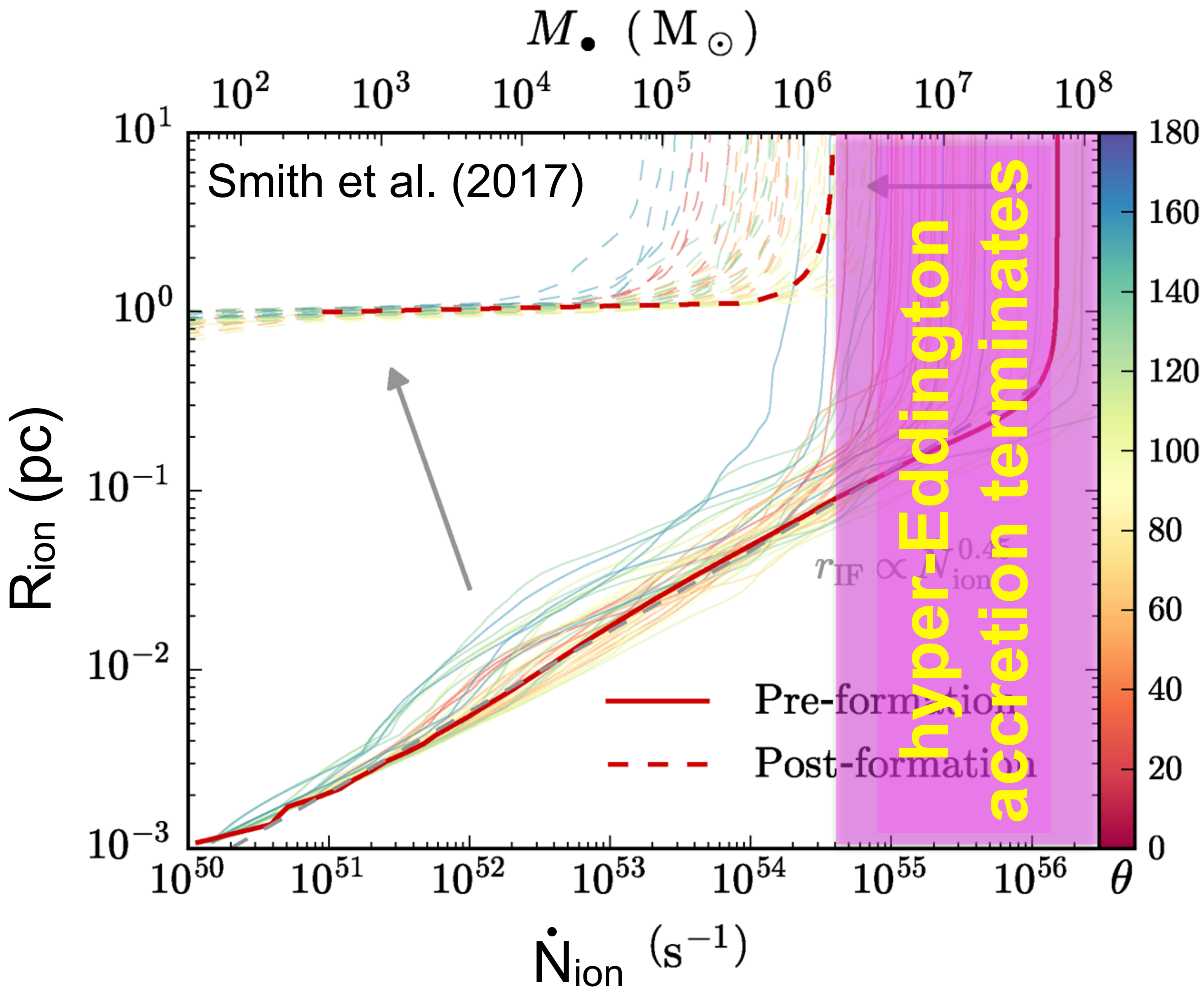


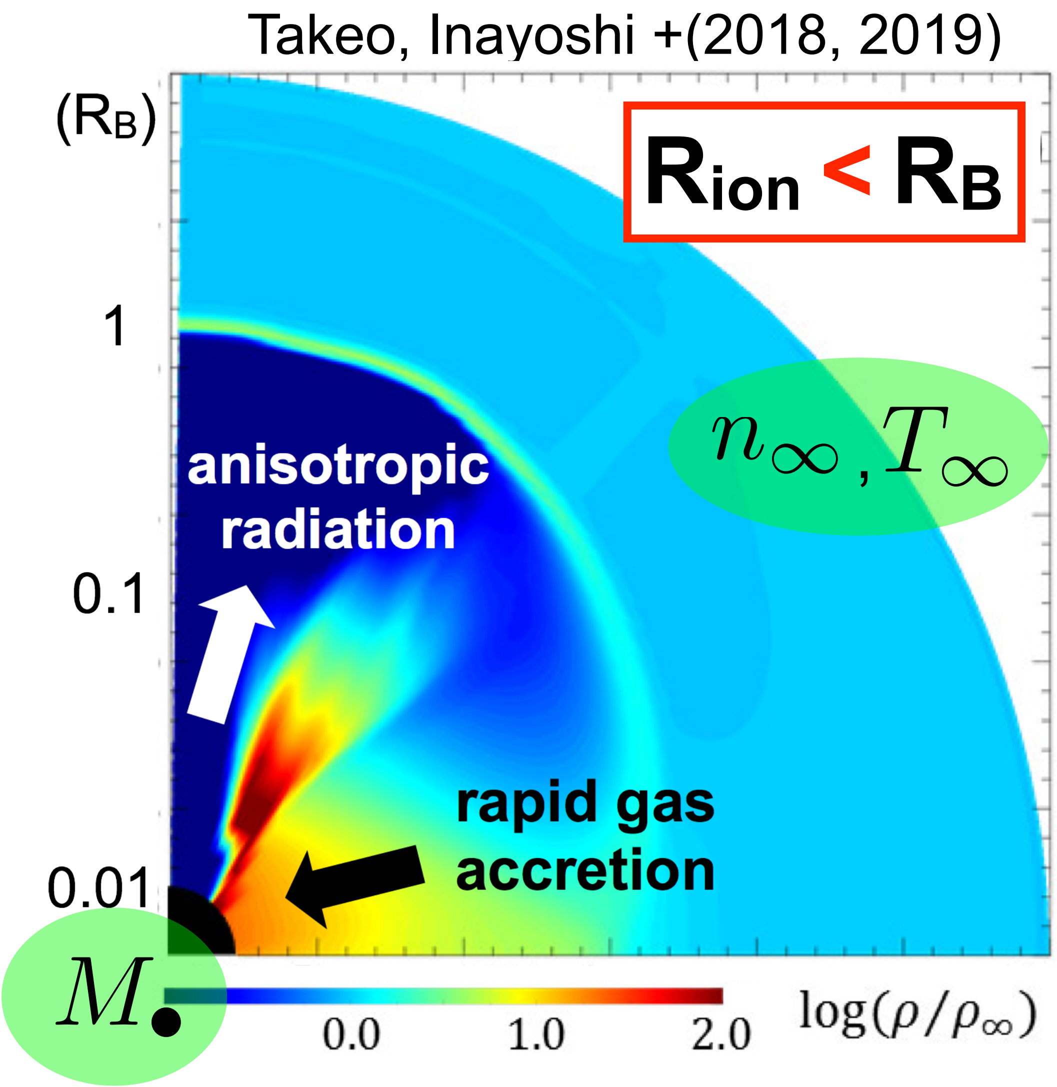
Rapid gas accretion is possible for BHs

halo virial temp

$$M_{\rm BH} \lesssim 2 \times 10^5 \; T_{\rm vir,4} \; M_\odot$$

Rapid growth of seed BHs



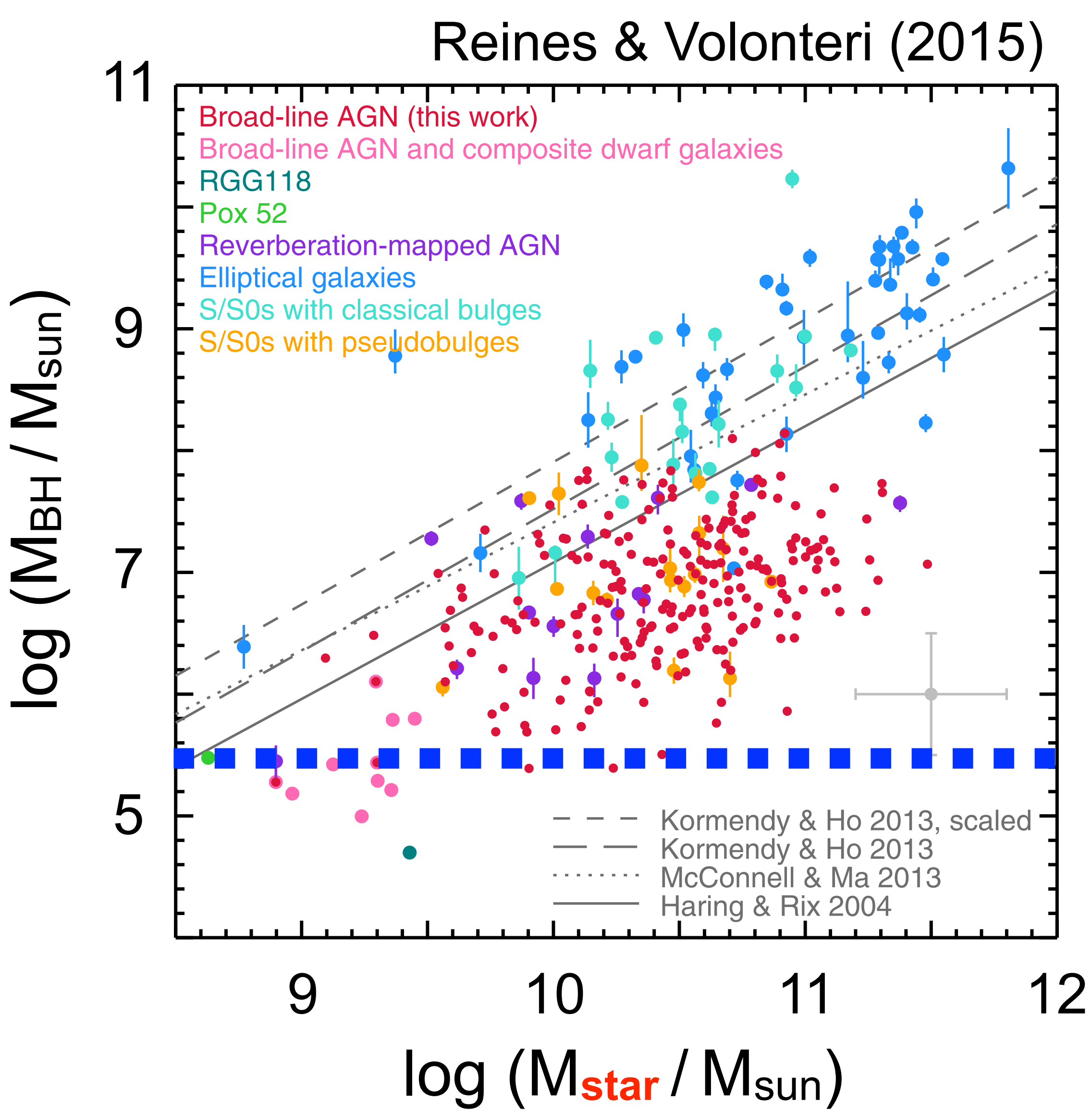


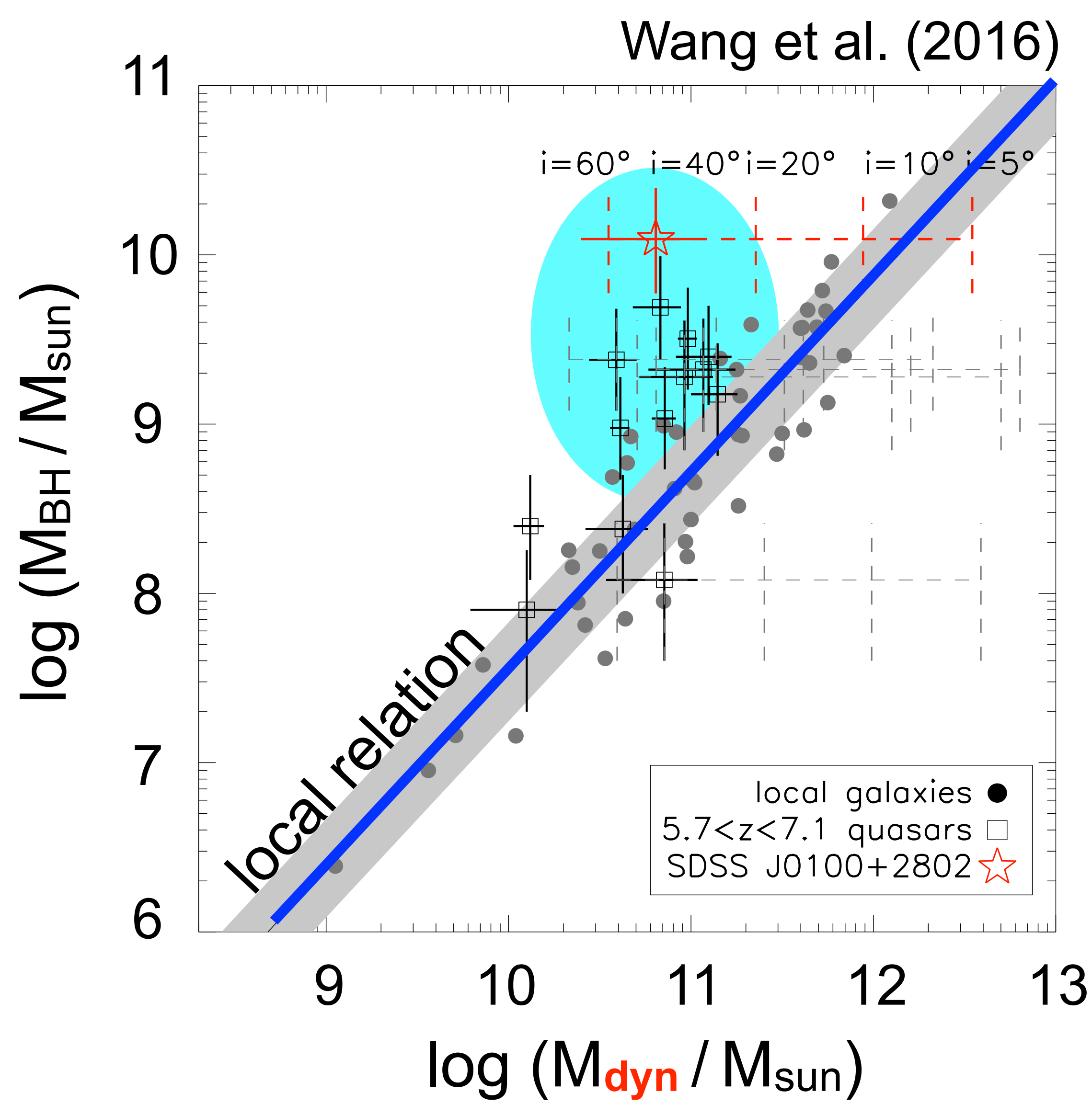
Rapid gas accretion is possible for BHs

halo virial temp

$$M_{BH} \lesssim 2 \times 10^5 \; T_{vir,4} \; M_\odot$$

Implications to observations

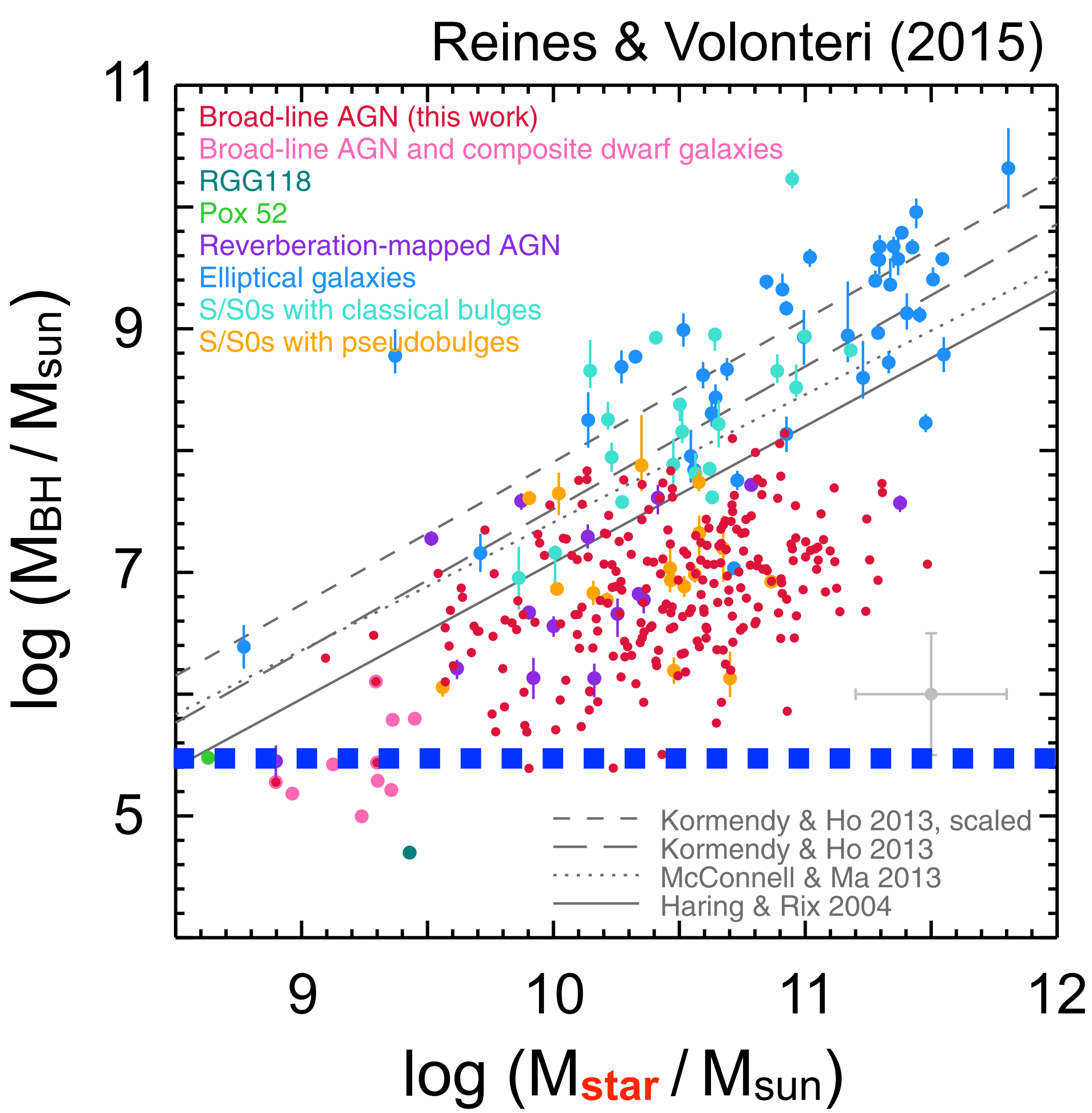


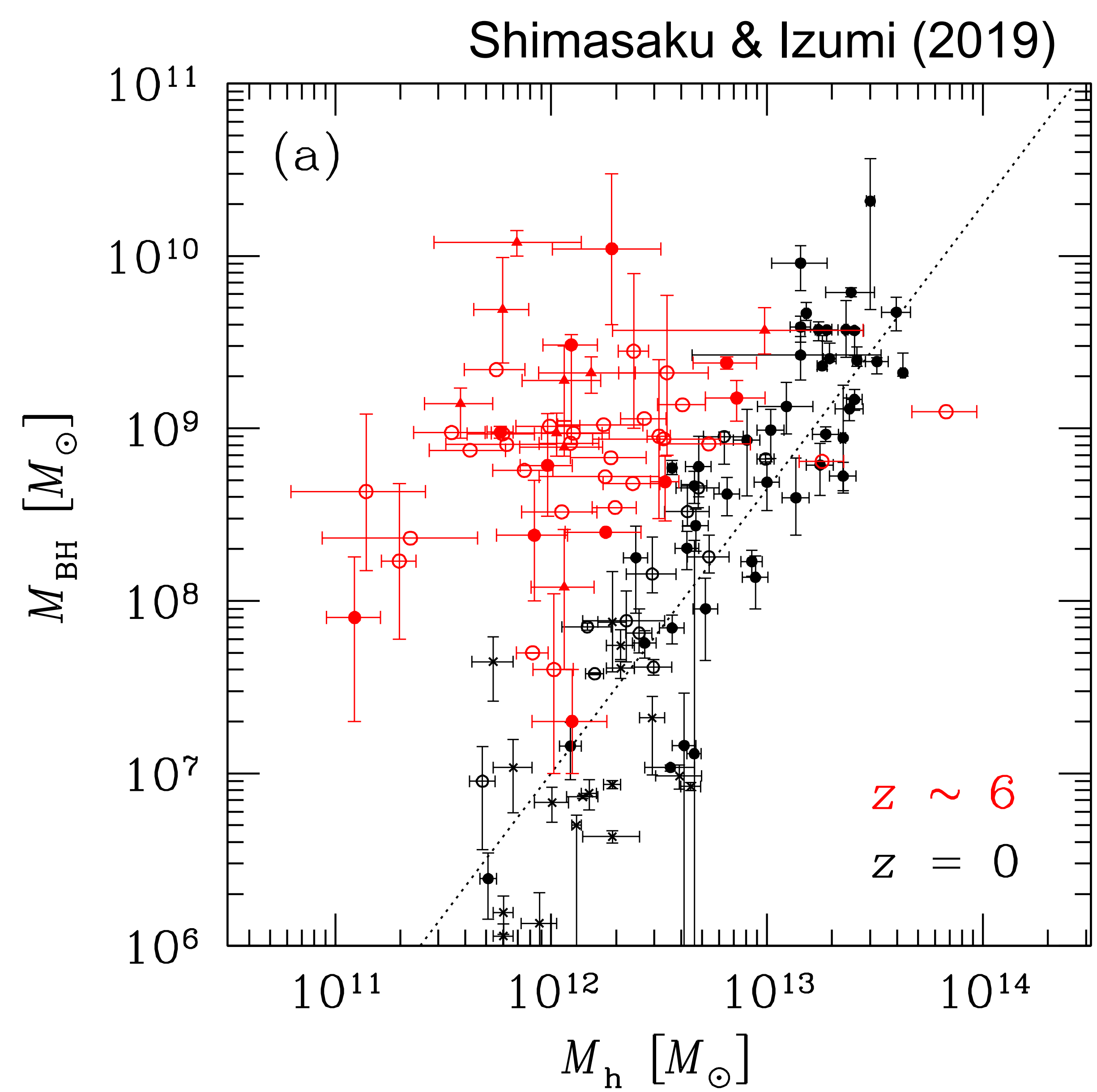


Rarity of IMBHs with $M_{BH} < 10^5 M_{sun}$

Overmassive BHs in high-z QSOs

Implications to observations

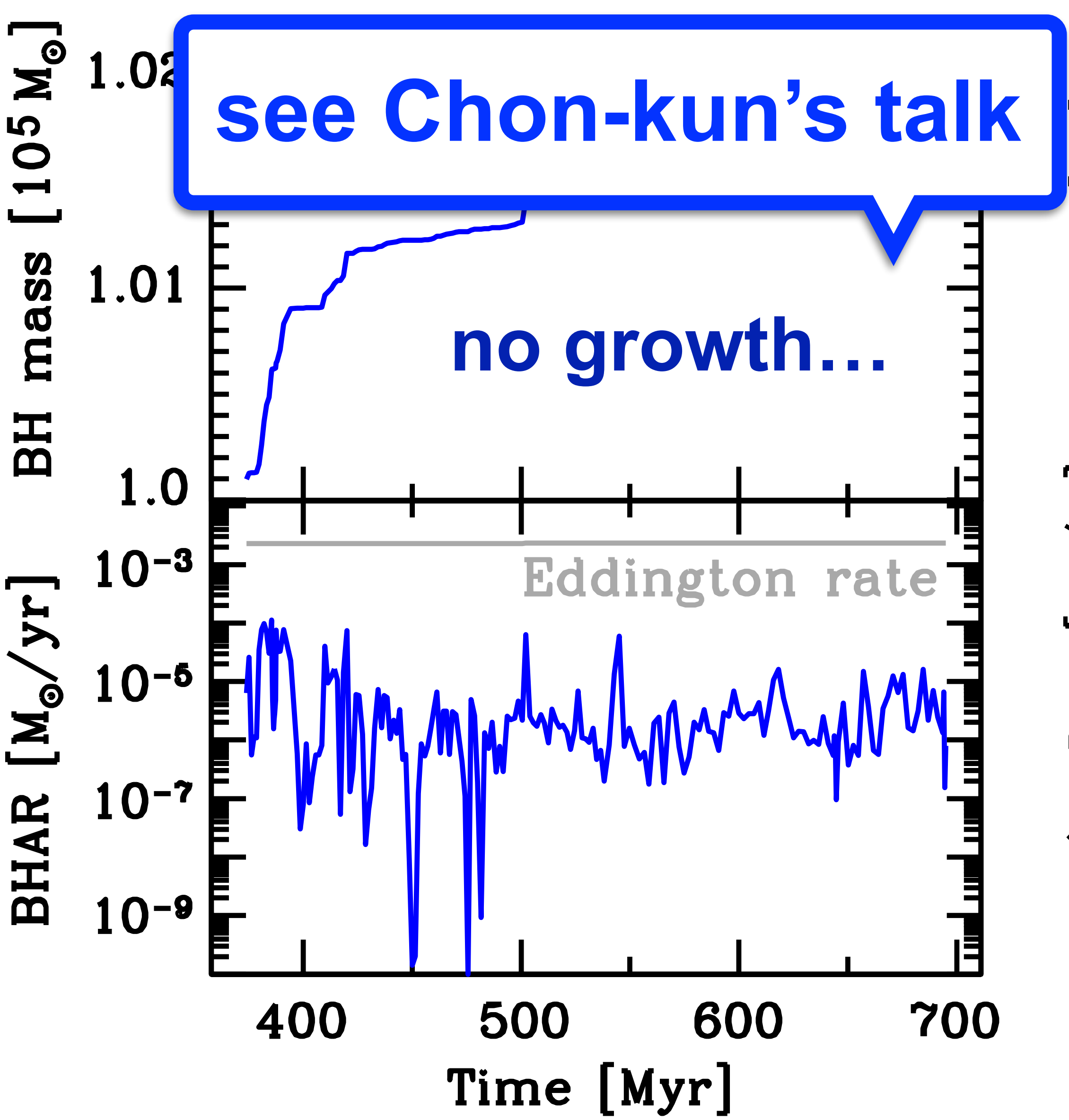


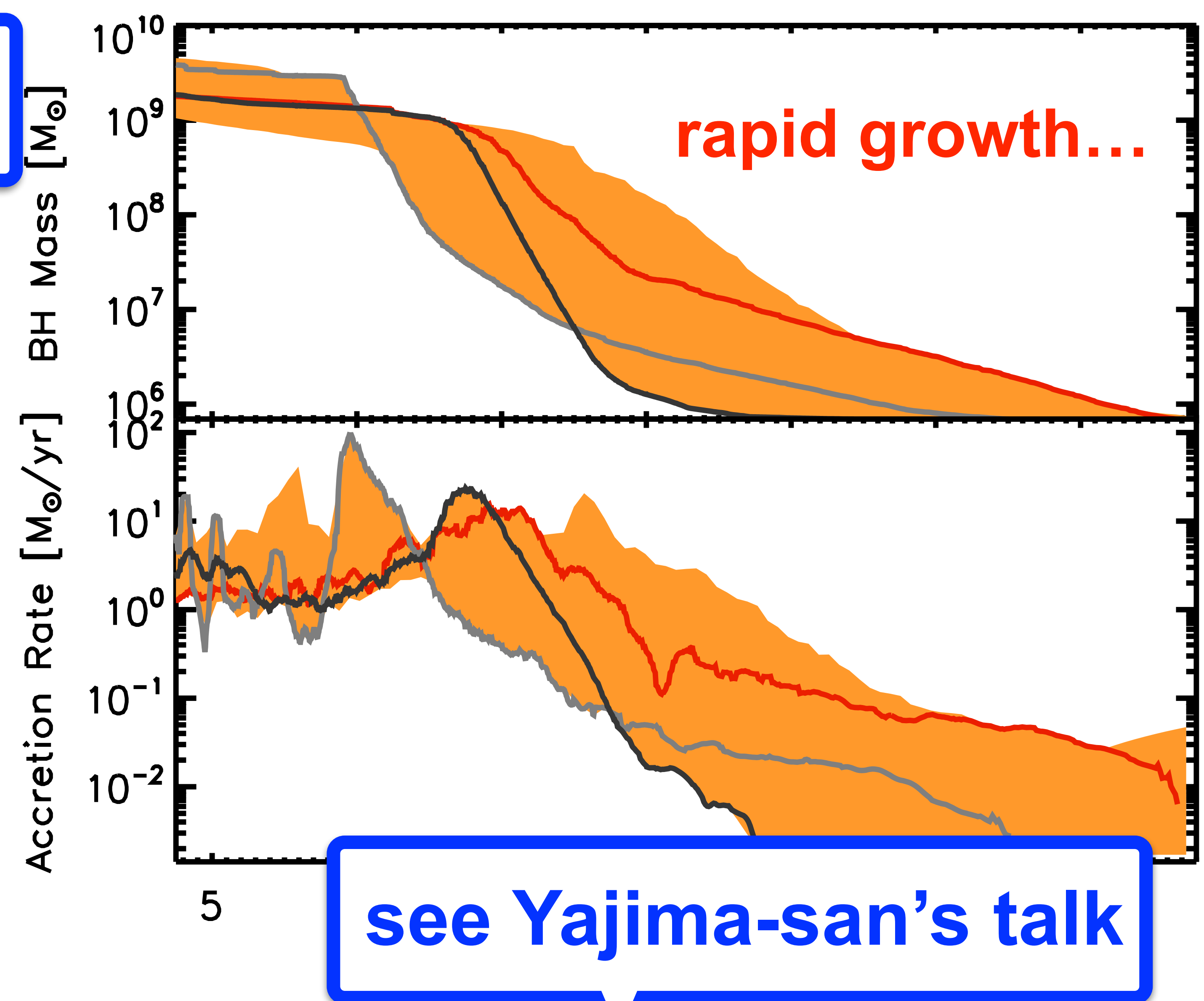


Rarity of IMBHs with $M_{BH} < 10^5 M_{sun}$

Overmassive BHs in high-z QSOs

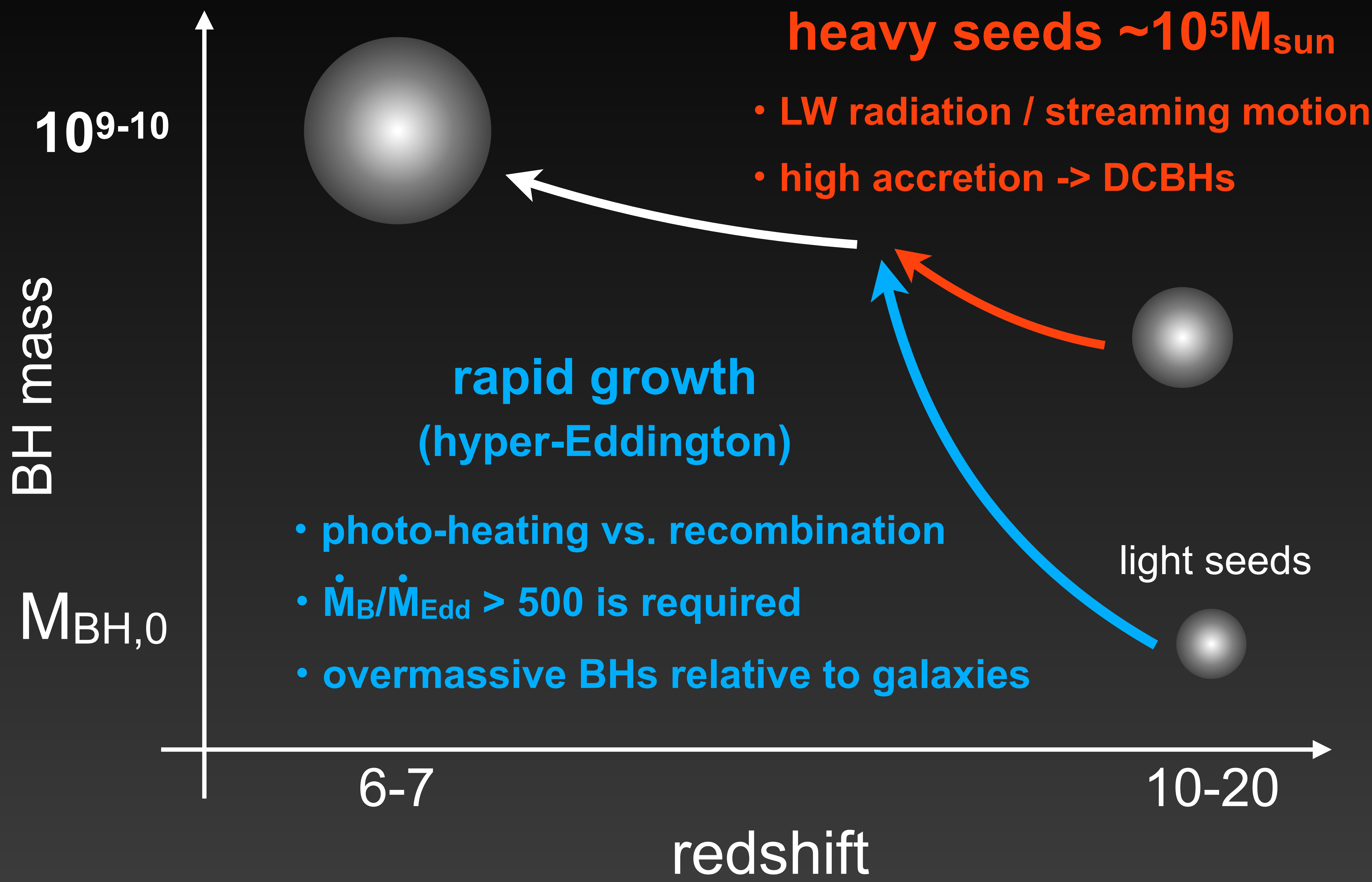
Subsequent growth of BHs…





Efficient BH growth in rare regions? (>3σ)

Summary


heavy seeds ~$10^5 M_{sun}$
• LW radiation / streaming motion
• high accretion -> DCBHs
10^{9-10}
BH mass
$M_{BH,0}$
rapid growth
(hyper-Eddington)
• photo-heating vs. recombination
• $\dot{M}_B/\dot{M}_{Edd}$ > 500 is required
• overmassive BHs relative to galaxies
light seeds
6-7
10-20
redshift

KIAA / PKU


Welcome!
Kohei
Wenxiu Li
Haojie Hu
Yu Qiu
+ 2 undergrads
25 faculties
22 postdocs
80 PhD students

KIAA / PKU

The Kavli Institute for Astronomy and Astrophysics at Peking University
北京大学科维理天文与天体物理研究所

- **KIAA fellowships** (all fields)
  https://jobregister.aas.org/ad/de436c12

BHOLE
Black hole–Host Lifecycle Evolution

- **BHOLE** postdoc researchers
  (SMBH, galaxies and coevolution, high-z)
  https://jobregister.aas.org/ad/930735dc

PKING

- **PKING** postdoc researchers
  (**Gravitational Astrophysics**, Interstellar Medium, Sky-Survey Science)
  https://jobregister.aas.org/ad/0bb38802

- Kavli Astrophysics Postdoctoral Fellowship (KIAA-IMPU)
  https://jobregister.aas.org/ad/3cbd55c3

Thank you!