# The initial stage of supermassive black hole formation and evolution

(up to $\sim 10^5\ M_{sun}$)


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Image credit: ESO/M. Kornmesser

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Kohno-san's review

- Introduction
  - observational constraints on SMBHs
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    - ✓ light seeds ($\sim 10^2$–$10^3$ $M_{sun}$)
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- Current status of each scenario
- Discussion
- Summary

# INTRODUCTION

Kormendy&Ho 2013

# Supermassive BHs (SMBHs)

- SMBHs: $M_{\rm BH} > 10^6 M_\odot$

- exist in almost all galaxies

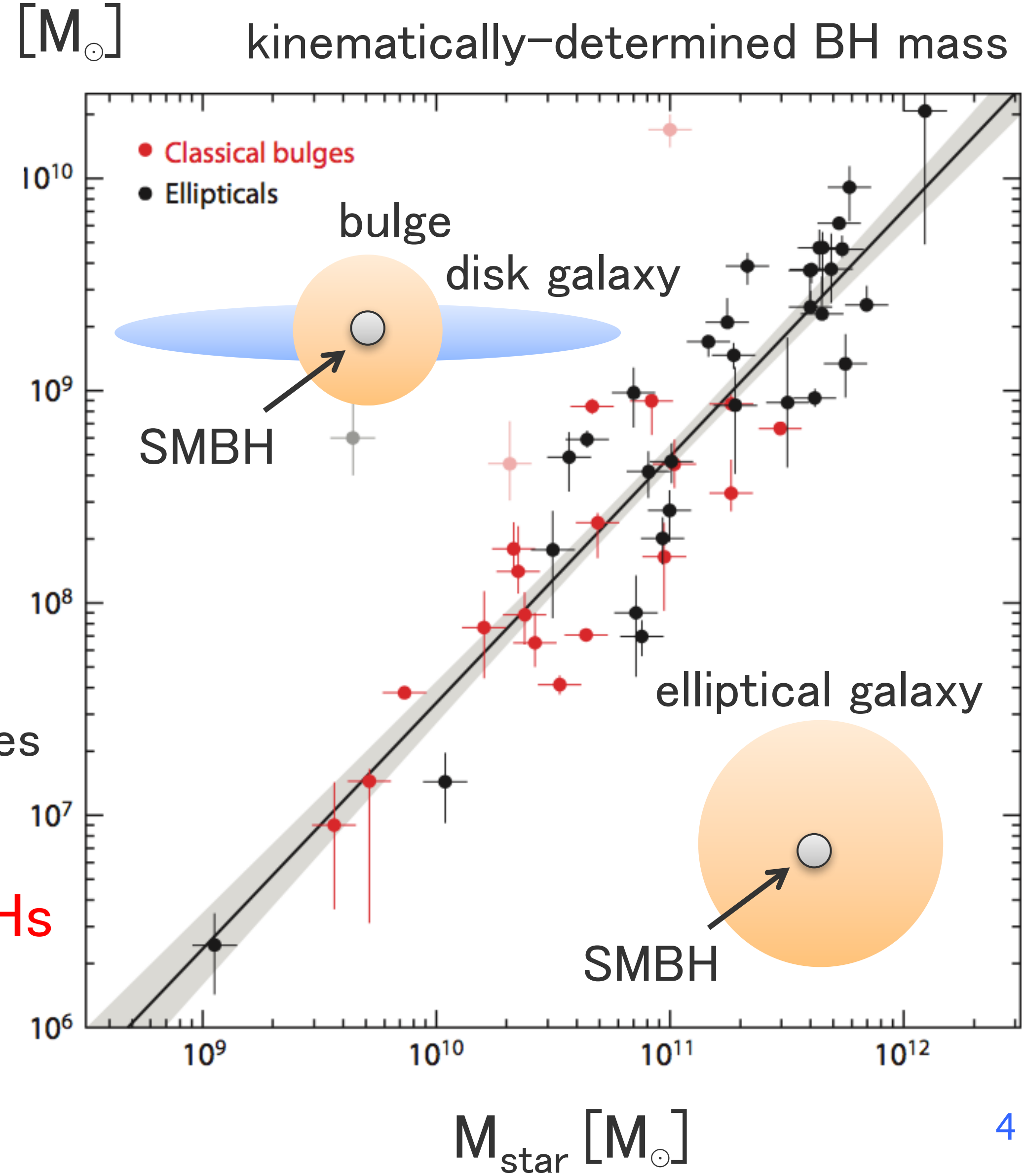
  $M_{BH} \sim$ 0.5% of bulge mass

- co-evolve with galaxies

  gas supply: galaxies → SMBHs

  AGN feedback: SMBHs → galaxies

The understanding of SMBHs is crucial for understanding the galaxy evolution



# Observational constraints from high-z quasars


- What is the origin of SMBHs?

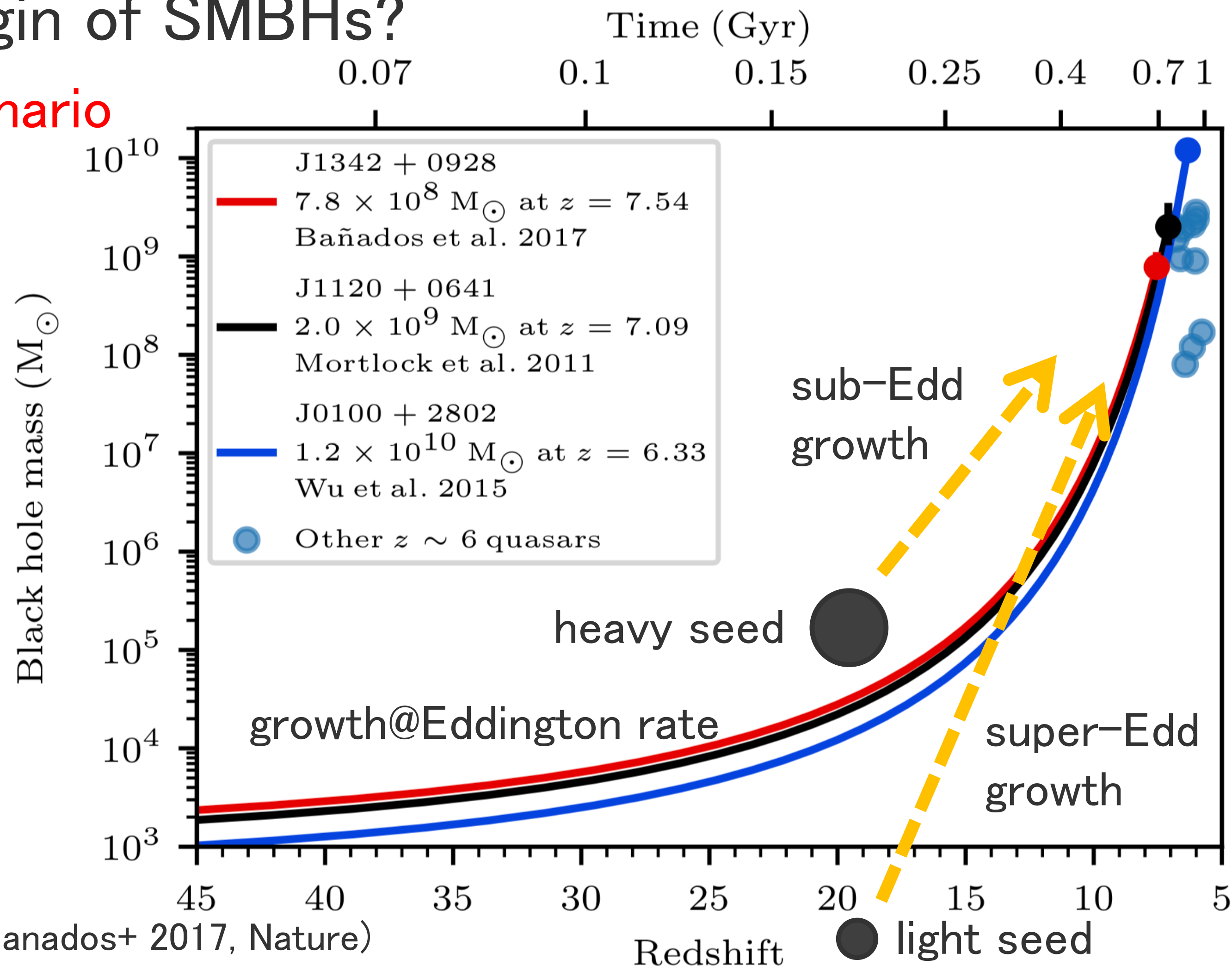
  NO standard scenario

- Existence of high-z quasars

  ✓ heavy seed

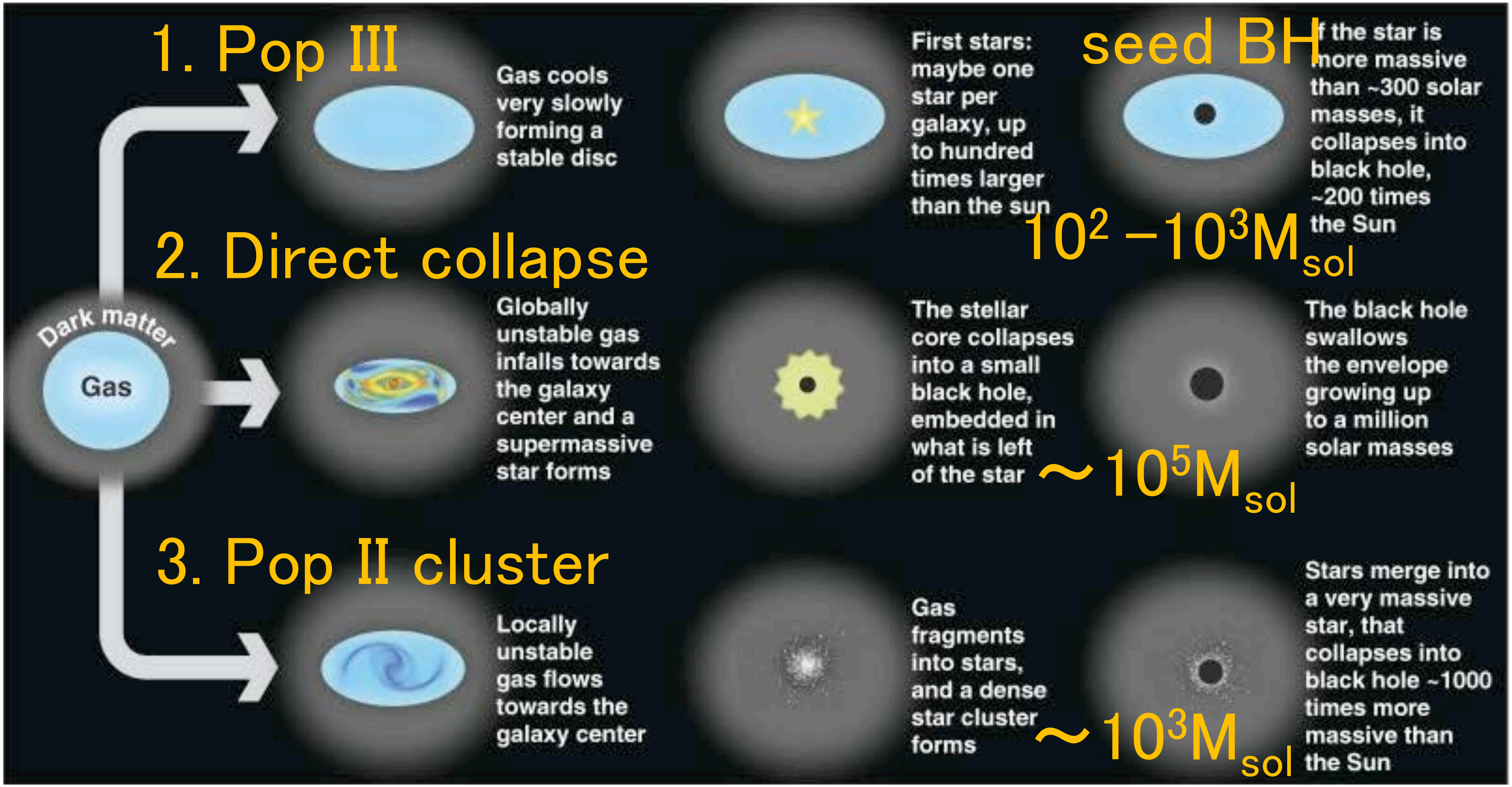
  and/or

  ✓ rapid growth (super-Eddington)



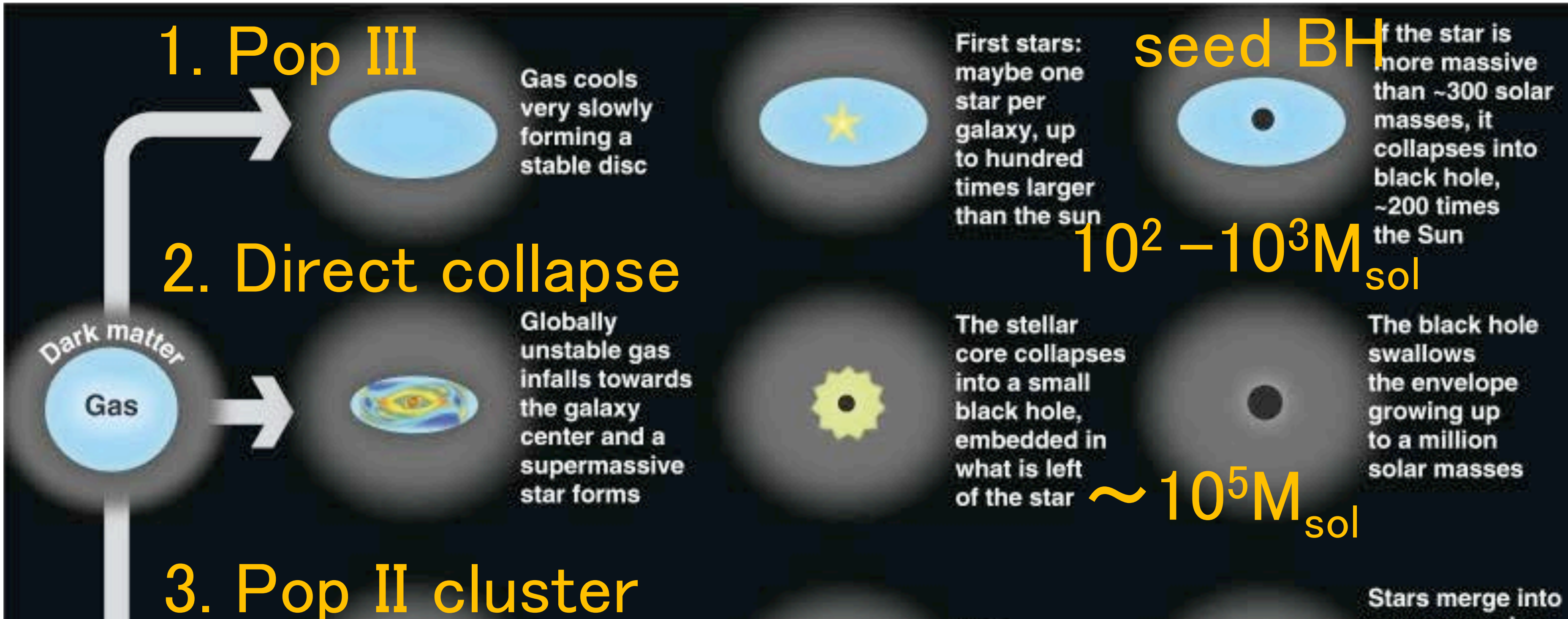

(Banados+ 2017, Nature)

# Three SMBH seed scenarios




(Volonteri 2012, Science, with modification)

# Three SMBH seed scenarios




Topic for group study:

Consider uncertainties and observational consequences of each scenario. Then, discuss a direction of theoretical and observational studies to pin down the true SMBH formation scenario.

# ~~Three~~ Two SMBH seed scenarios

1. Light seed scenario

- Pop III
- Pop II cluster

seed BH：

$\sim 10^2 - 10^3 M_{sol}$

2. Heavy seed scenario

- Direct collapse

seed BH：

$\sim 10^5 M_{sol}$

# pro&con of each scenario

| Scenario | Light seed ($\sim 10^2 - 10^3$ $M_{sun}$) | Heavy seed ($\sim 10^5$ $M_{sun}$) |
|---|---|---|
| | PopIII/Pop II cluster | Direct collapse |
| Seed formation | ○ massive Pop III stars have $>10^2$ $M_{sun}$ | △ uncertain but at least not easy |
| Early growth (up to $10^5$ $M_{sun}$) | △ uncertain but at least not easy | ◎ Direct collapse BHs have $\sim 10^5$ $M_{sun}$ |

In this review, I will focus on the formation of $10^5$ $M_{sun}$ BHs

# CURRENT STATUS OF EACH SCENARIO

# Light seed scenario

1. Light seed scenario

- Pop III
- Pop II cluster

seed BH:

$\sim 10^2 - 10^3 M_{sol}$

2. Heavy seed scenario

- Direct collapse

seed BH:

$\sim 10^5 M_{sol}$

Light seed scenario

# SEED FORMATION

- Pop III
- Pop II cluster

# Light seed formation: Pop III stars

**Fate of Pop III stars**

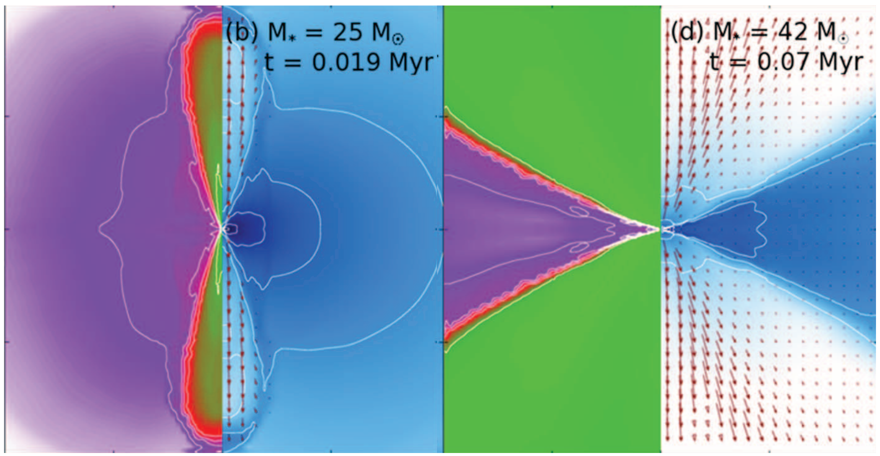
(cf. Heger & Woosley 2002)

$M_{PopIII}$ = 40–140 or > 260 $M_{sun}$

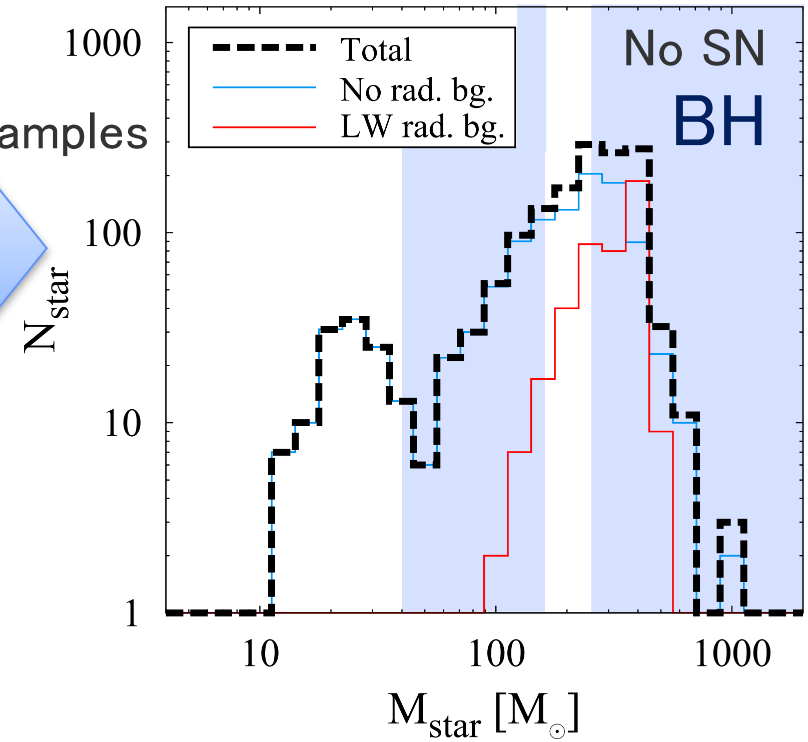
→ BHs w/o SN explosion

- From Big Bang to the first stars

Hosokawa, Omukai, Yoshida, Yorke (2011, Science)




many samples




- start from cosmological initial conditions and extract minihalos
- follow the Pop III star formation with all relevant chemical/thermal/radiative processes

**Pop III IMF**

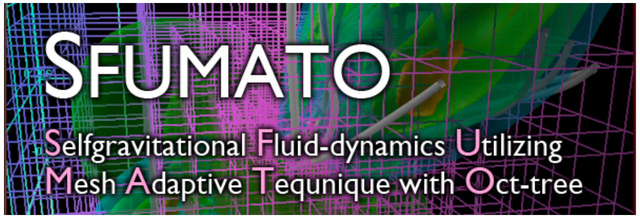
(Hirano+ 2015 w/ modification)

Pop III IMF was based on axisymmetric 2D simulations
-> effect of gas fragmentation/binary formation was not considered

(KS, Matsumoto, Hosokawa, Hirano, Omukai 2020)

# New AMR simulations with SFUMATO-RT

- ✓ self-gravitational (M)HD
- ✓ AMR
- ✓ sink particle




(Matsumoto 2007)

+

- ✓ Radiation transfer

**Adaptive Ray-Tracing**

(Abel&Wandelt 2002)

+

- ✓ chemical/thermal evolution
- ✓ protostellar evolution

**Pop III physics**

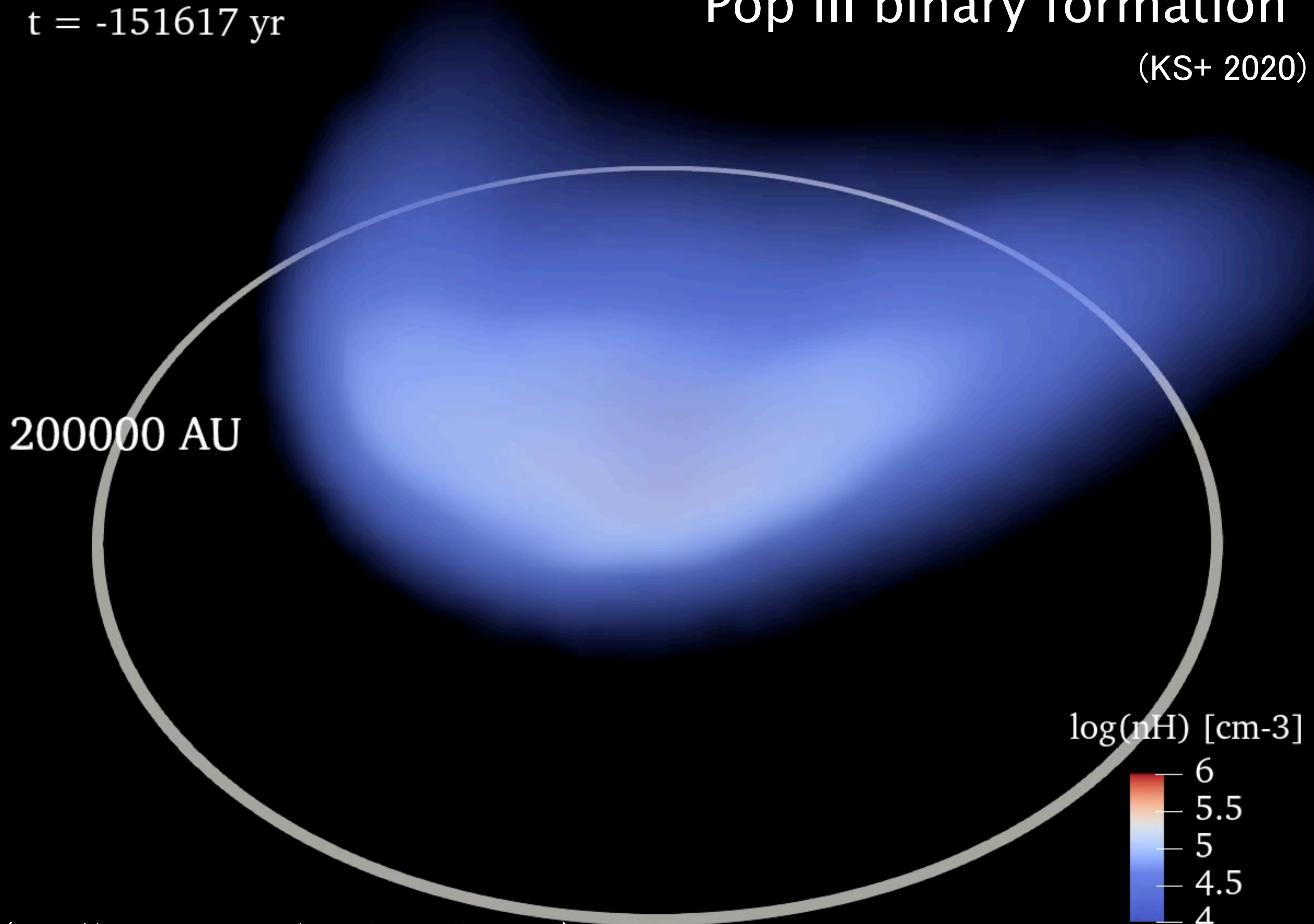
(Hosokawa+ 2016)

=

## SFUMATO-RT!!

# Pop III binary formation

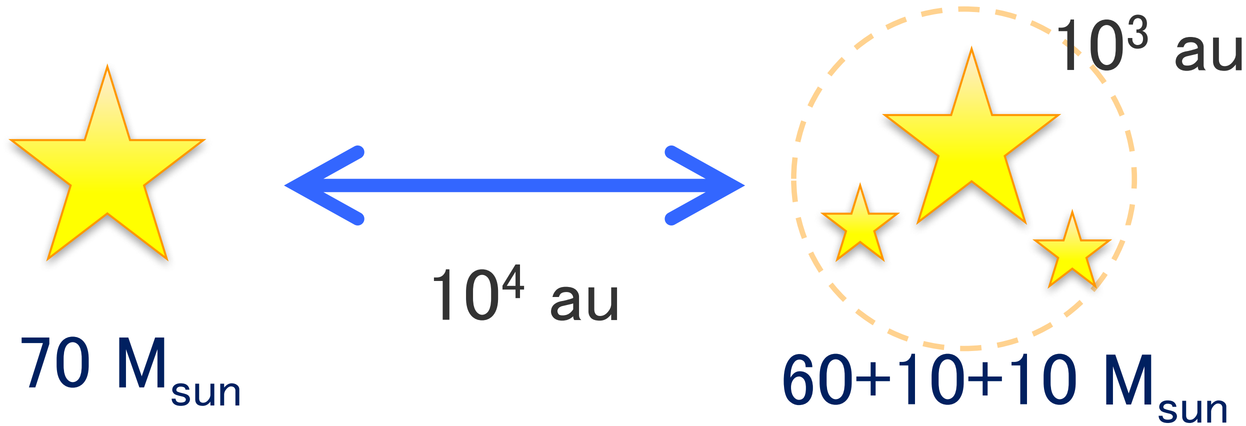
(KS+ 2020)




(https://www.youtube.com/watch?v=794O0yGWGp0)

(KS, Matsumoto, Hosokawa, Hirano, Omukai 2020)

# The resulting Pop III system




A wide binary of massive single and mini-triplet systems

(↔ single 300 $M_{sun}$ star in the previous simulation by Hosokawa+16)

## Implication for Pop III remnant BHs

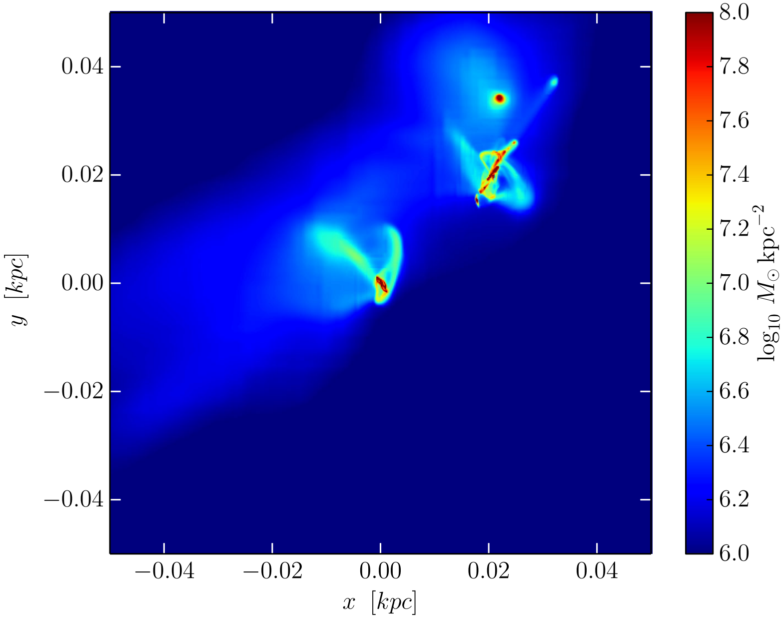
- Pop III IMF must be reconsidered
- The high-mass end of Pop III IMF may be smaller by a factor of a few, but it seems that Pop III remnant BHs with $M_{BH}$ >100 $M_{sun}$ still exist

The picture of Pop III star formation is drastically changing → stay tuned!

# Light seed formation: Pop II clusters

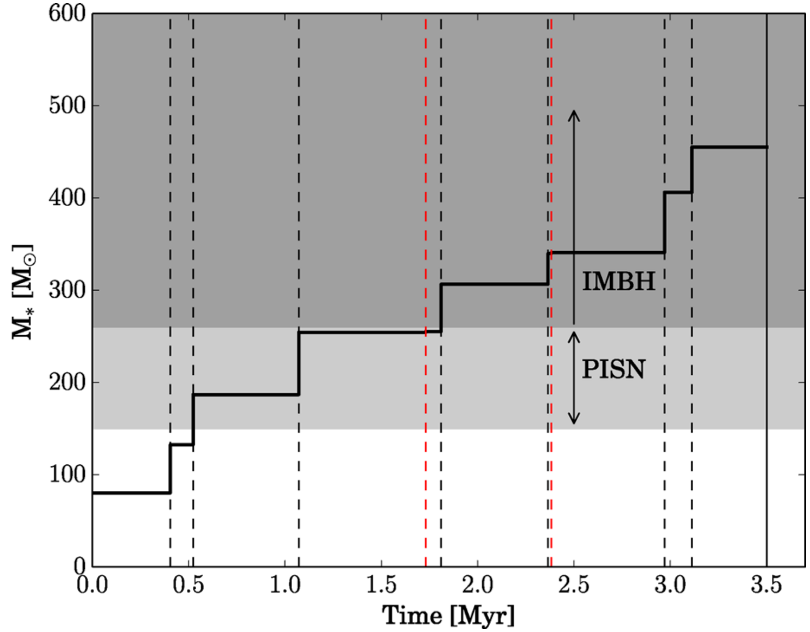
Katz+ 2015 (see also Sakurai+ 2017)

Cosmological hydro simulation




switch simulation

N-body simulation




formation of dense Pop II cluster

formation of very massive star by runaway collisions

Very massive stars with $M_* \sim 500\ M_{sun}$ → seed BHs

Light seed scenario

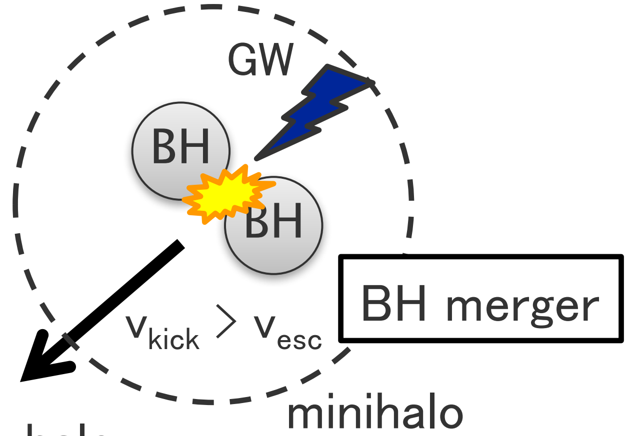
# EARLY GROWTH TO $10^5$ $M_{SUN}$

# Channels of early BH growth

## Growth by BH merger

- $v_{kick}$ ~100km/s due to GW recoil (e.g., Baker+ 2006, Koppitz+ 2007)
- $v_{esc}$~10km/s in small galaxies

BH will escape from the host halo

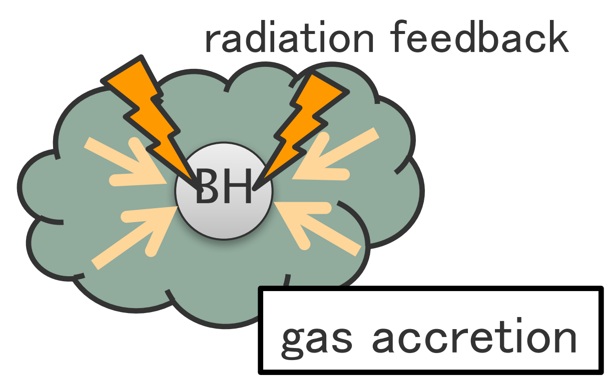



BH merger cannot be the main channel of early BH growth

## Growth by gas accretion

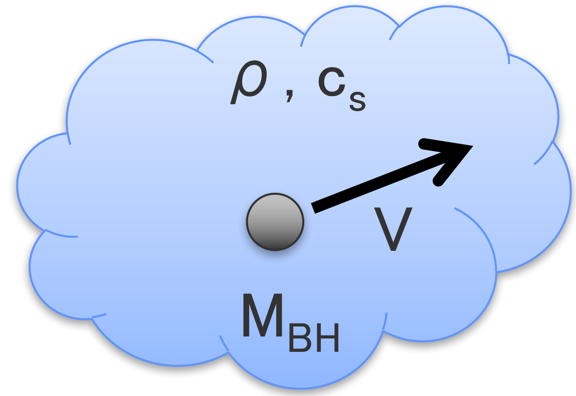
Uncertain due to two reasons:

1. Environment around BHs depends on how galaxies form and where BHs are located
2. Even if the environment is known (or given), accretion rate depends on the detail of feedback effects



# Basics of gas accretion I: accretion without feedback

- Bondi(–Hoyle–Lyttleton) accretion




$$\dot{M}_{\rm B} = \frac{4\pi G^2 M_{\rm BH}^2 \rho}{(c_{\rm s}^2 + V^2)^{3/2}}$$

$c_s$=8km/s @T=$10^4$K

$$= 2\times10^{-8}\left(\frac{M_{\rm BH}}{10^2\,M_\odot}\right)^2\left(\frac{n_{\rm H}}{10^2\,{\rm cm^{-3}}}\right)\left(\frac{(c_{\rm s}^2+V^2)^{\frac{1}{2}}}{8\,{\rm km/s}}\right)^{-3} M_\odot/{\rm yr}$$

$$M_{\rm BH}(t) = \frac{M_{\rm BH,0}}{1 - t/t_{\rm grow,0}}$$

- Growth time scale ($M_{BH}$ doubles in 0.5 $t_{grow}$, becomes infinite in $t_{grow}$)

$$t_{\rm grow} \equiv \frac{M_{\rm BH}}{\dot{M}_{\rm B}} = 5\times10^9\,{\rm yr}\left(\frac{M_{\rm BH}}{10^2\,M_\odot}\right)^{-1}\left(\frac{n_{\rm H}}{10^2\,{\rm cm^{-3}}}\right)^{-1}\left(\frac{(c_{\rm s}^2+V^2)^{\frac{1}{2}}}{8\,{\rm km/s}}\right)^{3}$$

- Accretion growth is usually inefficient unless the density is very high (situation is worse if seed mass is smaller)
- But, in principle, BHs can also attain an arbitrary amount of mass in a short time in extremely dense gas (cf. Volonteri&Rees 2005)

# Basics of gas accretion II: radiation feedback (Eddington limit)

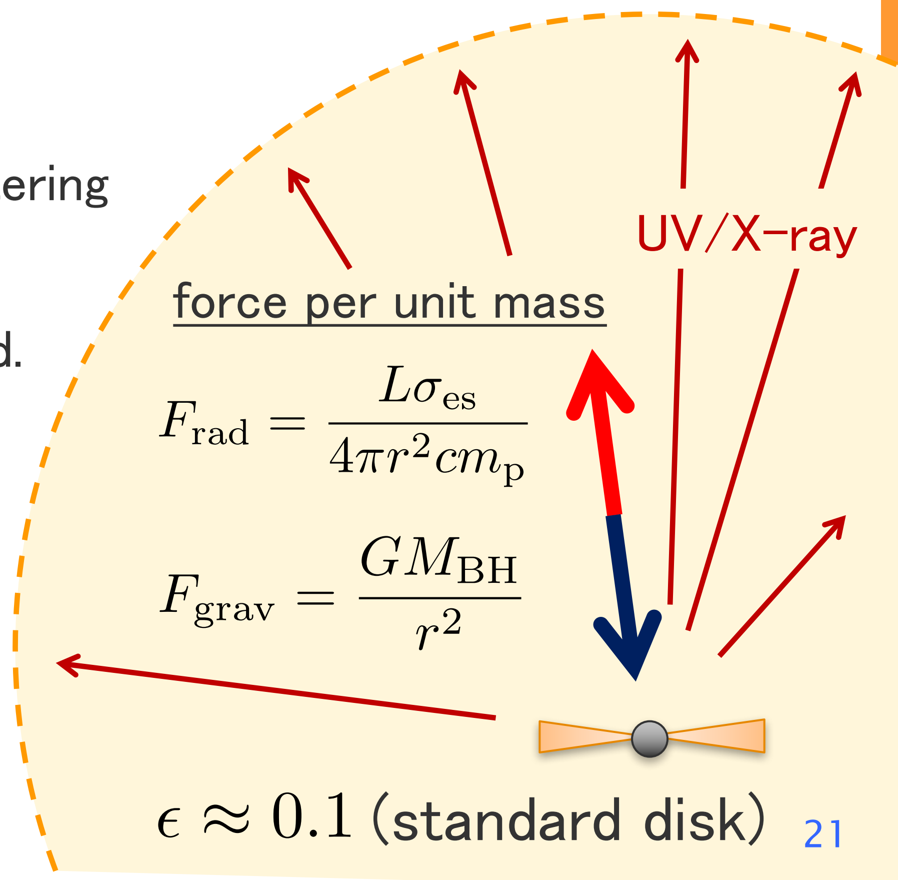
- Eddington-limited Bondi accretion rate: $\dot{M} = \min(\dot{M}_{\rm B},\, \dot{M}_{\rm E})$
  - often assumed in large-scale simulations for simplicity but not very realistic

- Eddington limit
  - Radiation force due to Thomson scattering should not exceed BH gravity
  - Assumptions: ionized gas, isotropic rad.

$$L_{\rm E} = \frac{4\pi G M_{\rm BH} c m_{\rm p}}{\sigma_{\rm es}}$$

$$L = \epsilon \dot{M} c^2$$

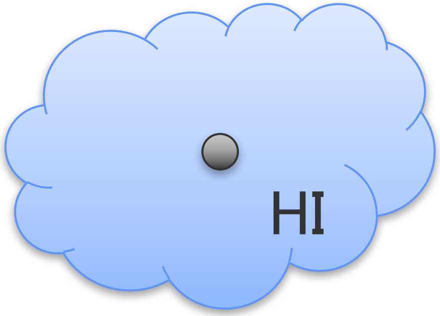
$$\dot{M}_{\rm E} = \frac{4\pi G M_{\rm BH} m_{\rm p}}{\epsilon\, c\, \sigma_{\rm es}}$$



# Basics of gas accretion III:
## radiation feedback (photoionization heating)

- Acc. from cold HI cloud

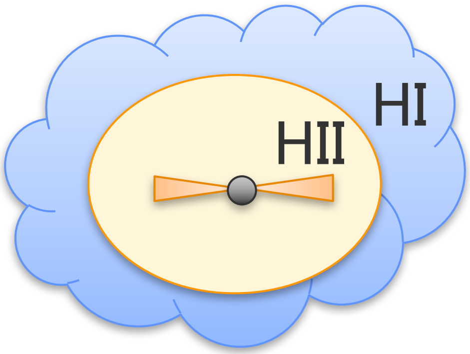
$$\dot{M}_{\mathrm{B,HI}} = \frac{4\pi G^2 M_{\mathrm{BH}}^2 \boxed{\rho_{\mathrm{HI}}}}{\boxed{c_{\mathrm{s,HI}}^3}}$$




- Acc. from hot HII bubble

$$\begin{cases} \underline{\rho_{\mathrm{HII}} < \rho_{\mathrm{HI}}} \\ \underline{c_{\mathrm{s,HII}} > c_{\mathrm{s,HI}}} \end{cases}$$

$$\dot{M}_{\mathrm{B,HII}} = \left(\frac{\rho_{\mathrm{HII}}}{\rho_{\mathrm{HI}}}\right)\left(\frac{c_{\mathrm{s,HII}}}{c_{\mathrm{s,HI}}}\right)^{-3} \dot{M}_{\mathrm{B,HI}}$$




TII = $7\times10^4$K
TI = $1\times10^4$K

$\dot{M}_{\mathrm{B,HII}}$ is typically 1/1000 of $\dot{M}_{\mathrm{B,HI}}$

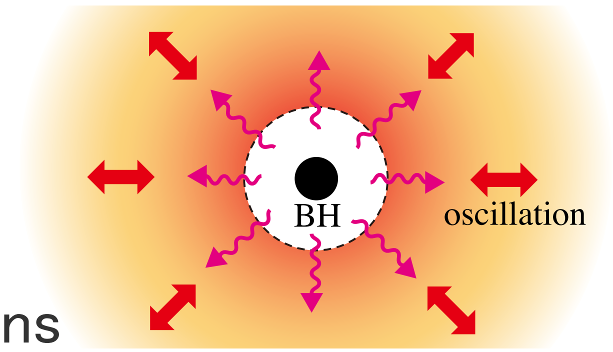
Often ignored in large-scale simulations, this mechanism easily causes significant reduction of accretion rate

# Multi-dimensional effects change the story

## Isotropic radiation

(Park&Ricotti 11, Milosavljevic+ 09)

Acc. rate is significantly reduced by radiation feedback working in all directions



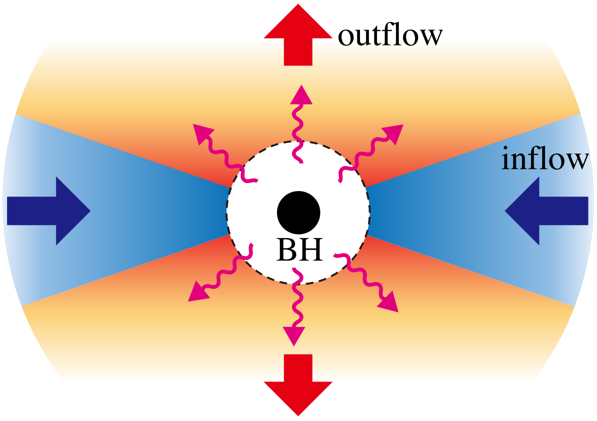

Note: the reduction becomes ineffective if gas density is so high that the HII region cannot expand (n > $10^7$ cm$^{-3}$ for $10^3$ $M_{sun}$ BHs)

(Inayoshi+16, Sakurai+17, Takeo+18)

## Anisotropic radiation

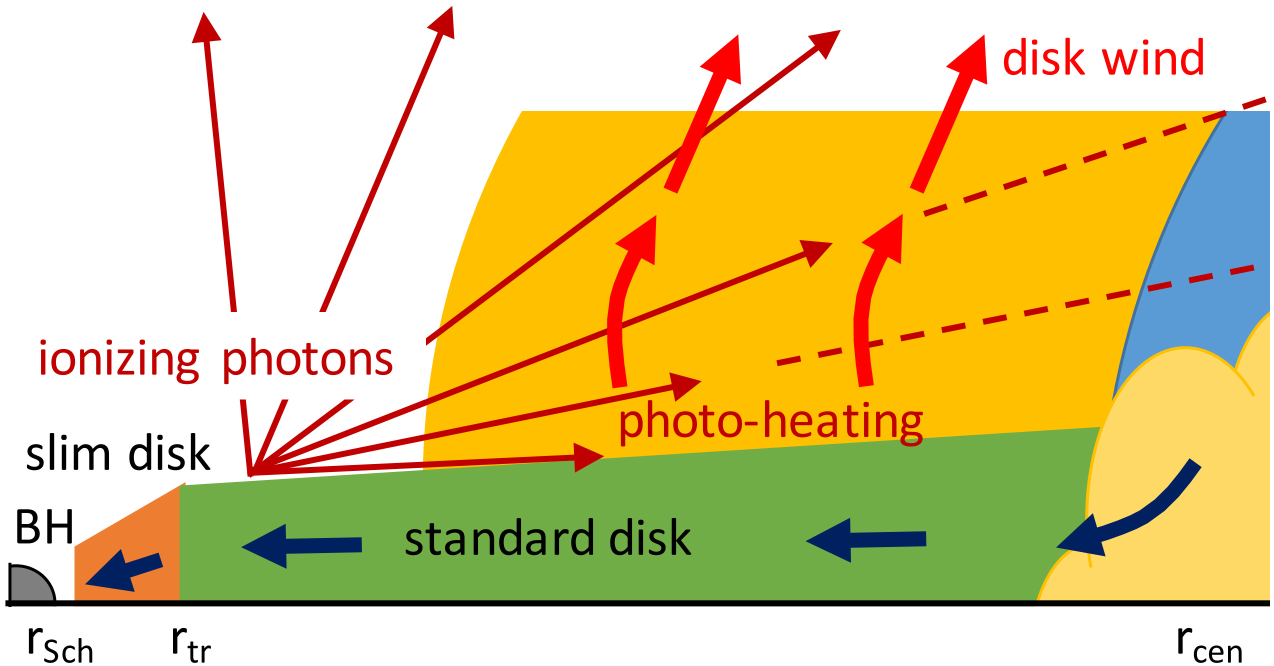
(KS, Hosokawa, Yajima, Omukai 2017)

Separation of inflow and outflow regions increases the efficiency of accretion



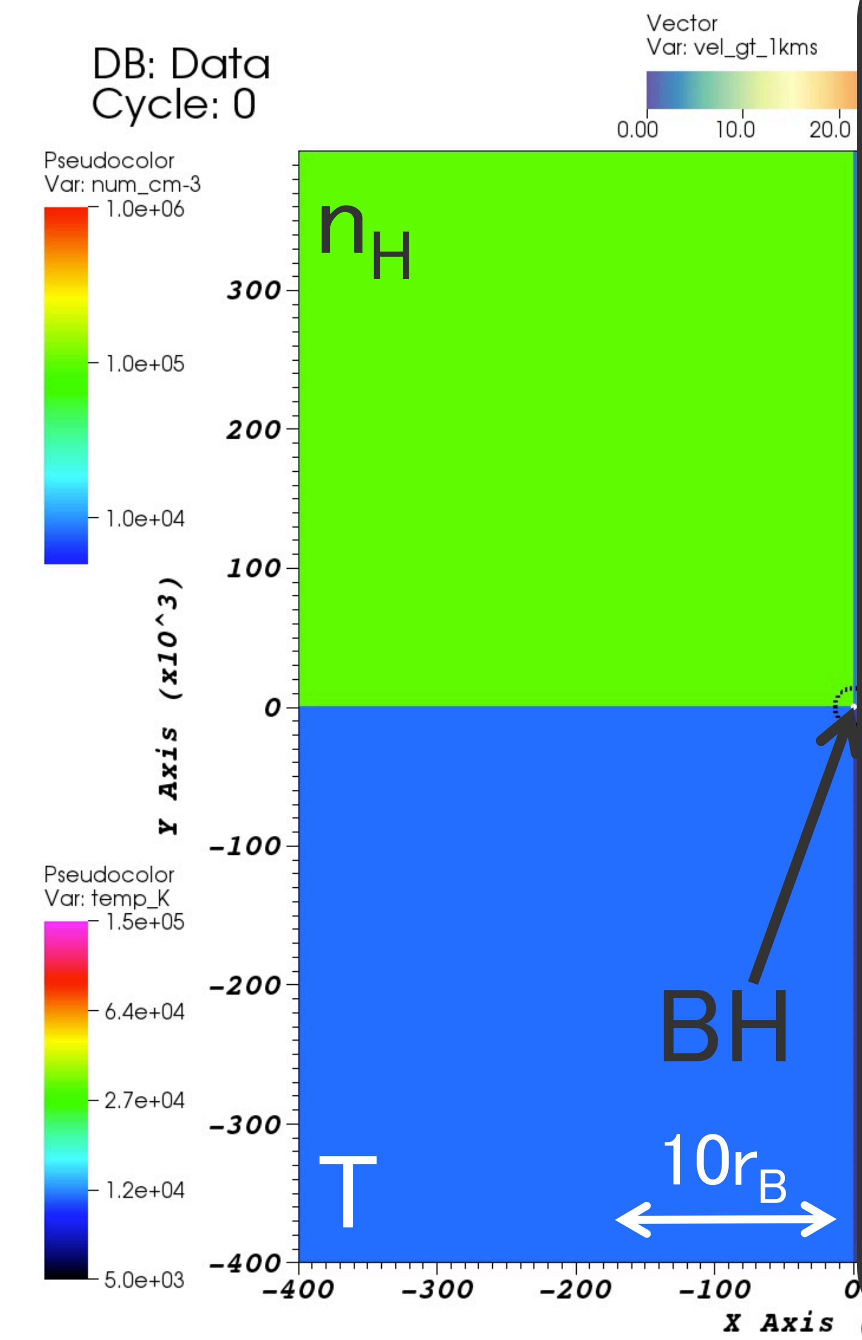
# Possible mechanism to generate large anisotropy

(KS, Hosokawa, Yajima, Omukai 2017)




- Any kind of disk winds can generate large anisotropy of radiation
- The degree of anisotropy is not well known yet

Let's see how anisotropy works using a simple model




# Accretion under anisotropic radiation

KS+ 2017

- Simulation parameters

$$n_\infty = 10^5\,\mathrm{cm}^{-3}$$
$$T_\infty = 10^4\,\mathrm{K}$$
$$M_{\mathrm{BH}} = 10^3 M_\odot$$

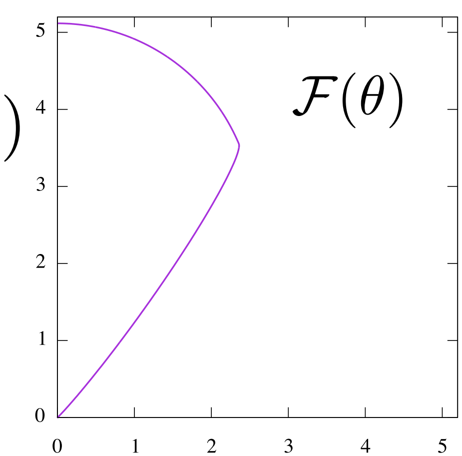
- Computational domain

$$0.1\,r_{\mathrm{B}} < r < 200\,r_{\mathrm{B}}$$

$$(r_{\mathrm{B}} = GM_{\mathrm{BH}}/c_s^2 \sim 10^4\,\mathrm{au})$$

- Radiation model

$$L(\theta) = \epsilon \dot{M} c^2 \mathcal{F}(\theta)$$



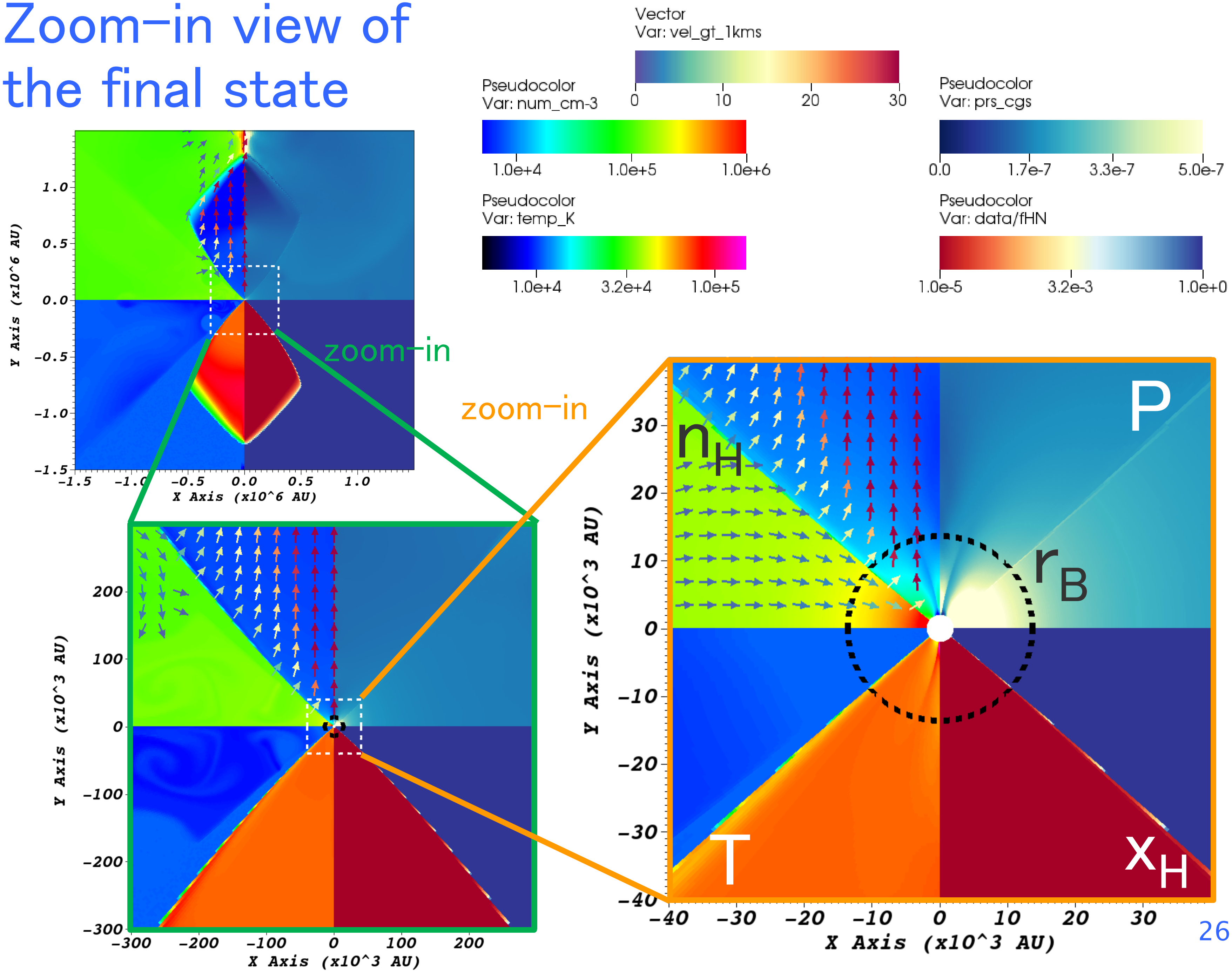

efficiency of slim disk:

$\varepsilon = 0.1$ $(\dot{M} < 2\dot{M}_E)$

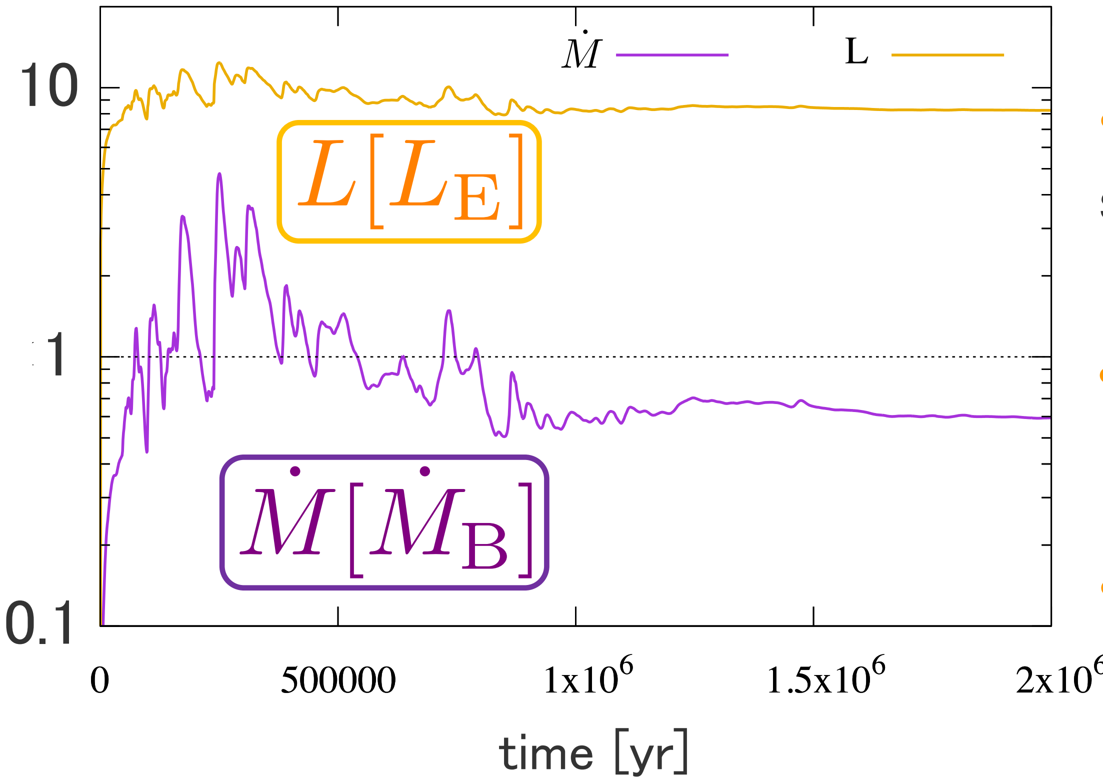
$< 0.1$ $(\dot{M} > 2\dot{M}_E)$

(Watarai+00)

# Zoom-in view of the final state



# Super-Eddington accretion under anisotropic radiation (KS, Hosokawa, Yajima, Omukai 2017)




- Accretion reaches a steady state
- super-Eddington lum.

$$L > L_{\rm E}$$

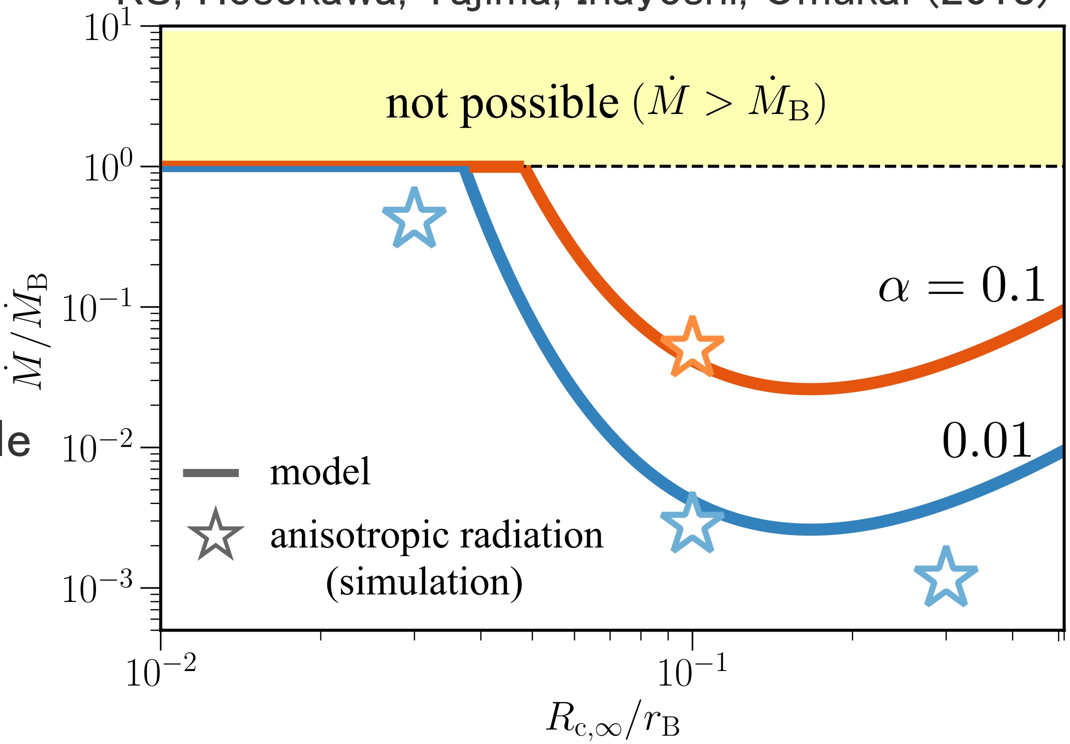
- very high acc. rate

$$\dot{M} \sim \dot{M}_{\rm B} \left(\sim 400\,\dot{M}_{\rm E}\right)$$

Super-Eddington accretion is possible
if the anisotropy of radiation is sufficiently large!!

# But Mdot can be suppressed by…

KS, Hosokawa, Yajima, Inayoshi, Omukai (2018)




## Angular momentum

In reality, $\dot{M}$ can be reduced due to finite ang. mom of gas

<u>$\dot{M}$ is significantly reduced if:</u>

- centrifugal radius is comparable to the Bondi radius
- viscosity parameter $\alpha$ in the disc is small

## Dust

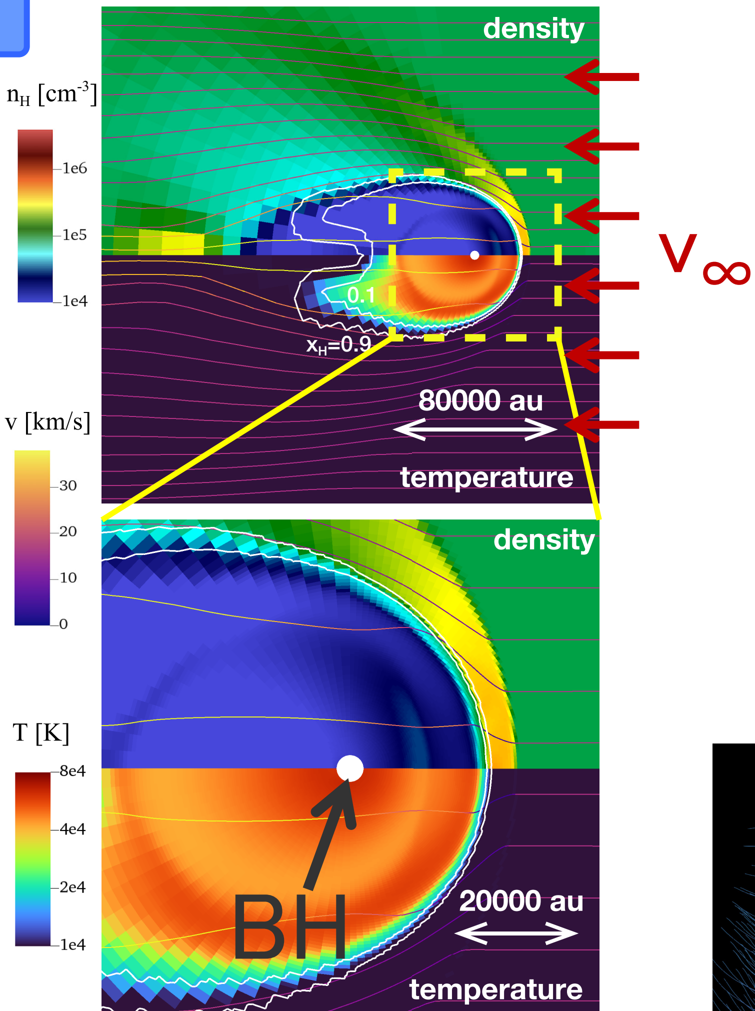
For accretion of non-primordial gas, radiation force on dust grains must be considered

⇒ significant reduction of $\dot{M}$ occurs if $Z > 0.02\ Z_{\rm sun}$

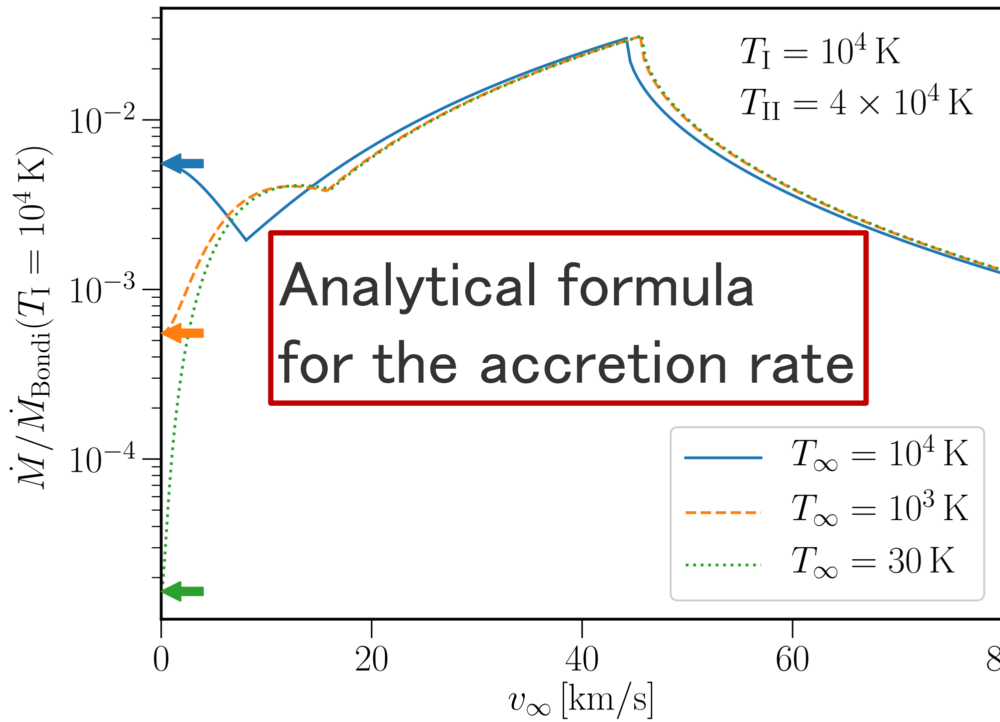
Yajima, Ricotti, Park, KS (2017), Toyouchi, Hosokawa, KS+ (2019)

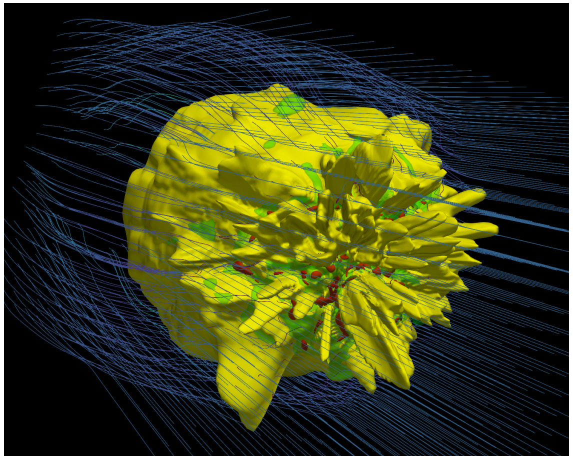
# And BHs move with respect to ISM

KS&Ricotti 2020 (see also Park&Ricotti 2013, Toyouchi,Hosokawa,KS,Kuiper 2020)




Headwind flowing into the comp. region in the rest frame of BH



Instability of the dense shell in front of the BH may lead to accretion/radiation bursts

# Seed BH growth in cosmological simulations

❑ Cosmological simulations

give realistic environments for seed BH growth (density, temperature, relative velocity)

- A Pop III BH during first galaxy assembly

⇨ feedback is crucial for the BH growth (Jeon+ 12)

↕ not consistent??

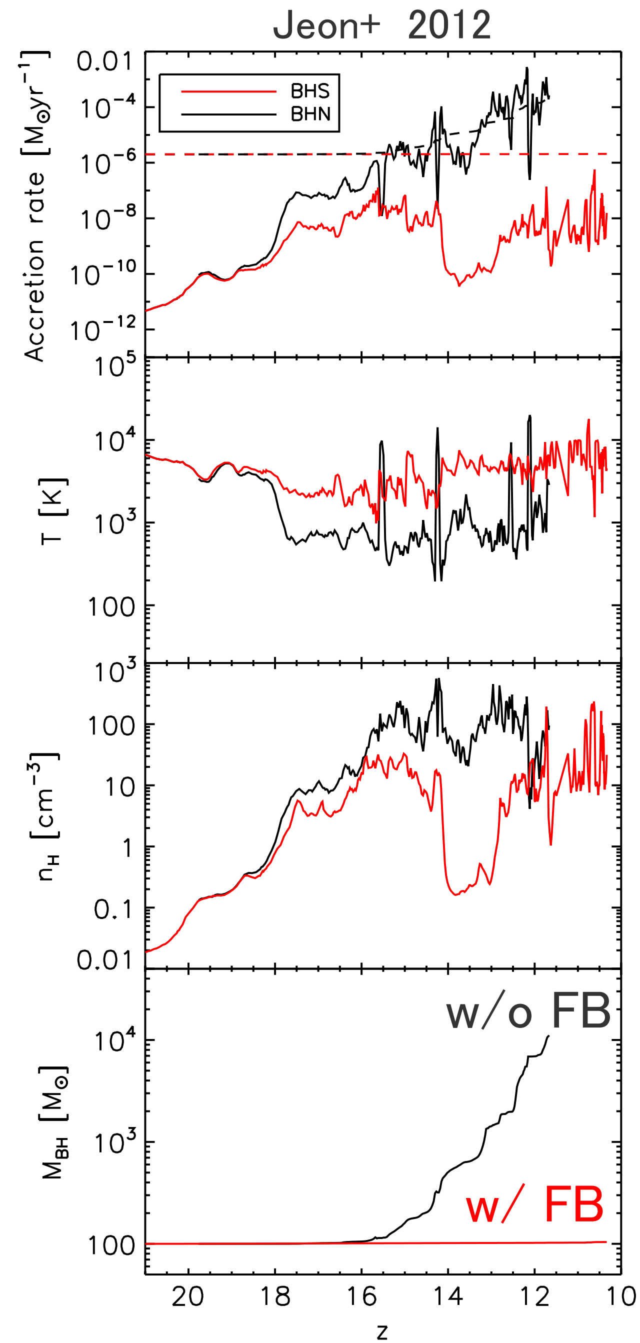
- post-processed 15000 Pop III BHs at z > 10

⇨ the largest mass increase is only 10% (Smith+ 18)

- Simplified accretion models are widely used

**Large room for improvement**

Realistic accretion rate, more samples w/ feedback, to lower-z...



# Heavy seed scenario

1. Light seed scenario

- Pop III
- Pop II cluster

seed BH :

$\sim 10^2 - 10^3 M_{sol}$

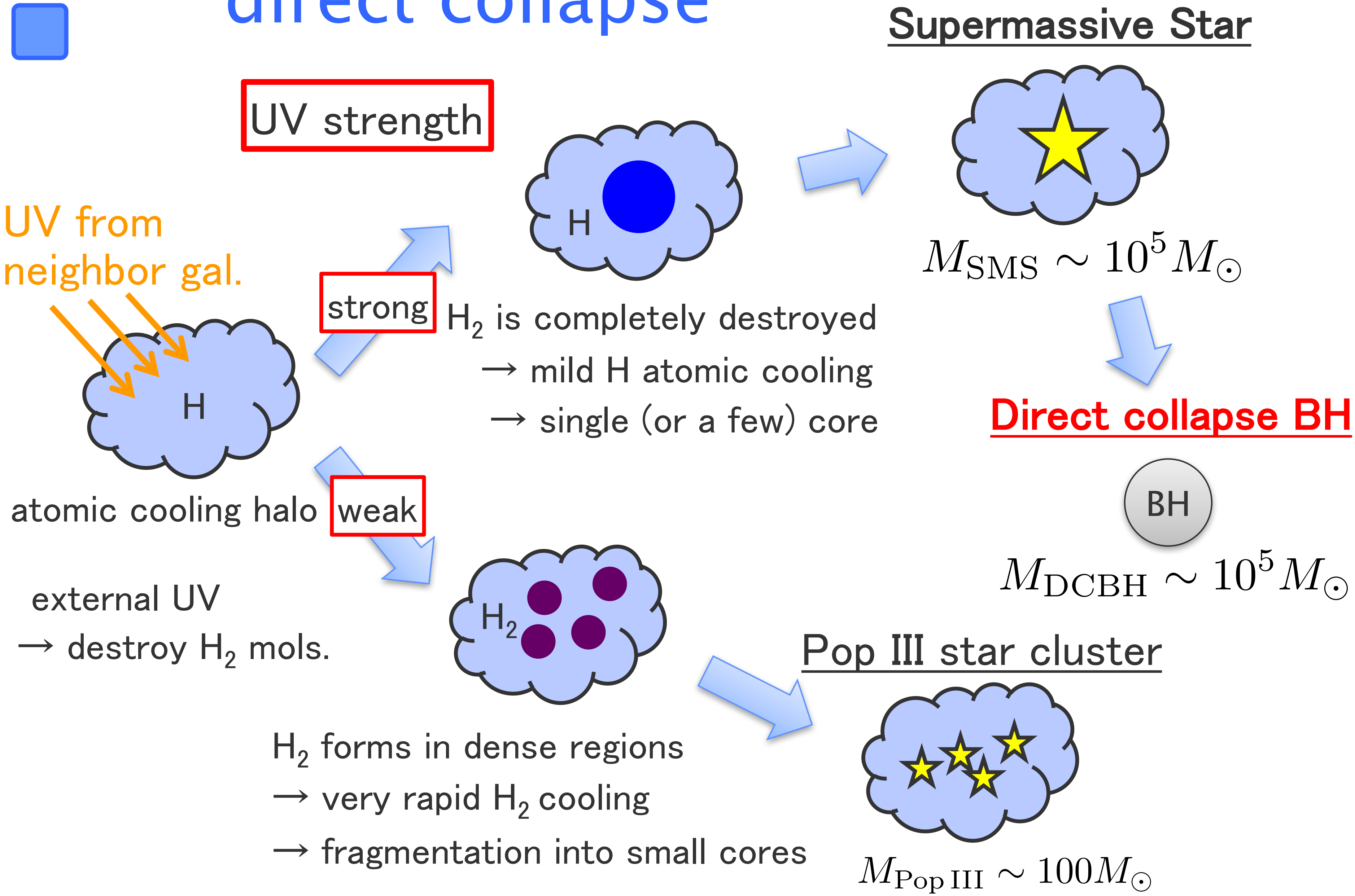
2. Heavy seed scenario

- Direct collapse

seed BH :

$\sim 10^5 M_{sol}$

# Heavy seed formation via direct collapse

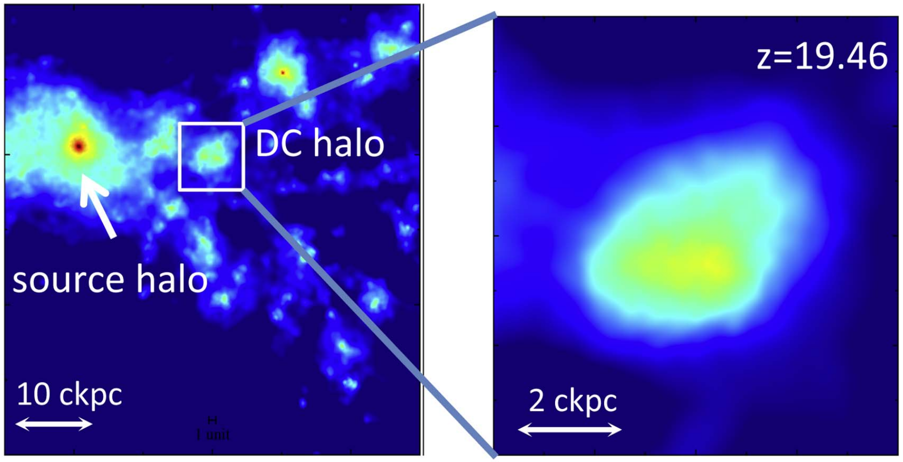


(Chon+ 2016, 2018)

# Direct collapse (DC) in simulations

## DC halos in cosmological simulations (Chon+ 2016)

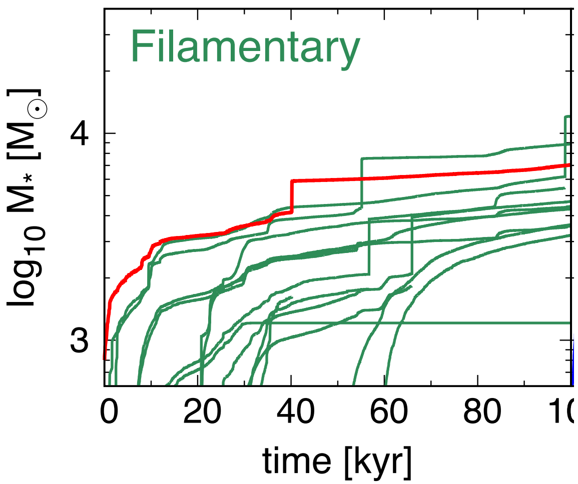
- identify 2 DC halos where $H_2$ formation is fully suppressed by UV irradiation
- strong UV field realized in close pair of host + satellite system

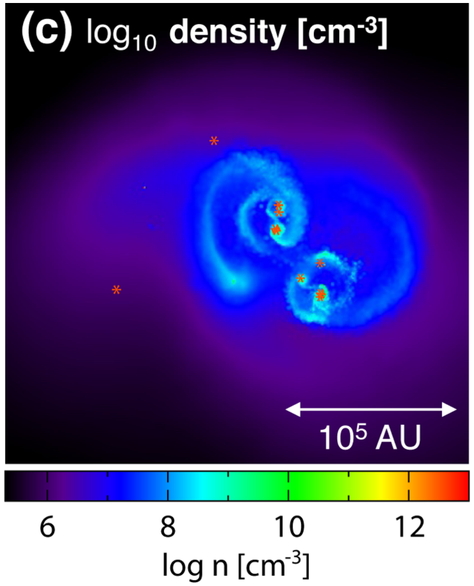



## Supermassive star formation in DC halos

(Chon+ 2018)

- switch to RHD simulations to follow the subsequent star formation process
- confirm the formation of supermassive stars
- weak gas fragmentation into ～10 stars is also observed



# Number of sites where $H_2$ is fully destroyed by strong UV field

$J_{21} = J_{12.4\mathrm{eV}}\ [10^{-21}\ \mathrm{erg\ cm^{-2}\ s^{-1}\ Hz^{-1}\ sr^{-1}}]$

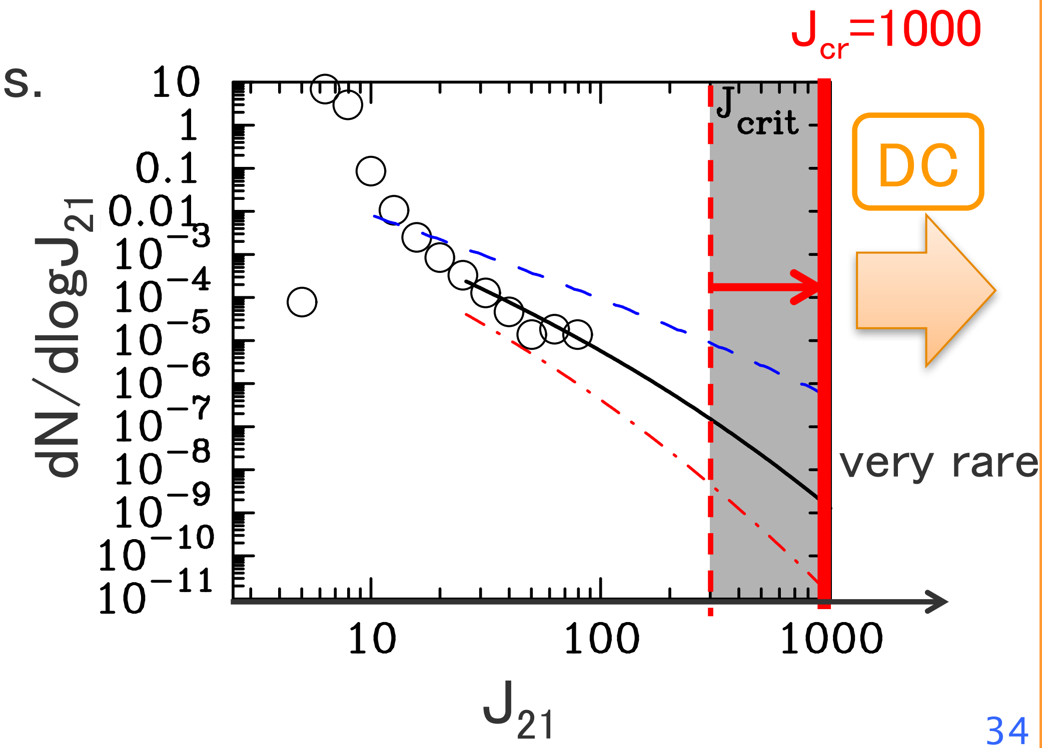
- Critical UV intensity $J_{cr}$
  - is the minimum value of $J_{21}$ needed for direct collapse
  - =1000 for realistic spectra of Pop II galaxies (KS, Omukai, Inoue 2014)
  - may be even larger in 3D simulations (Shang+2010, Luo+2020)

- $J_{21}$ distribution & num. dens.
  - distribution of $J_{21}$ in halos from galaxy correlation function

    (Dijkstra, Ferrara & Mesinger 2014)

  - $J_{cr}$=1000 suggests the number density of DC halos is very low

n(DC halo) ∼1 $\mathrm{cGpc^{-3}}$

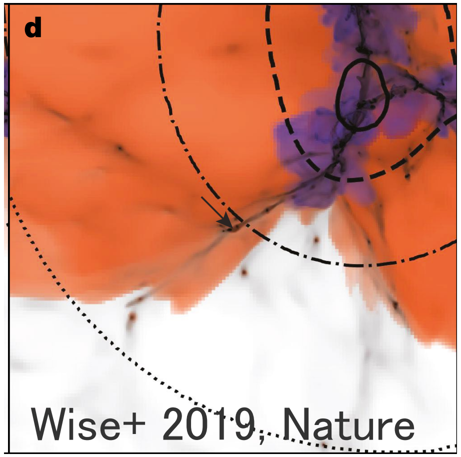


# But the condition for the direct-collapse (DC) maybe more flexible

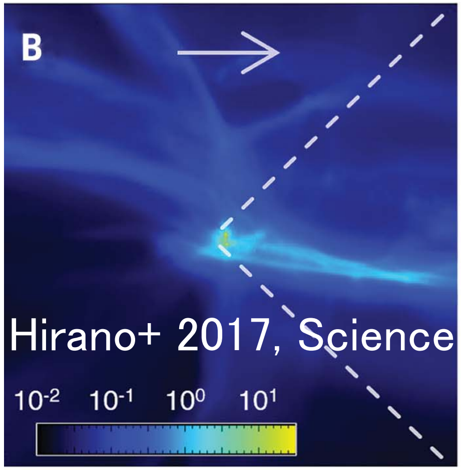
## ❑ $H_2$ dissociation

- Just the delay of star formation by some mechanism may be sufficient
- Full dissociation of $H_2$ during collapse may not be necessary

weak UV + dynamical heating

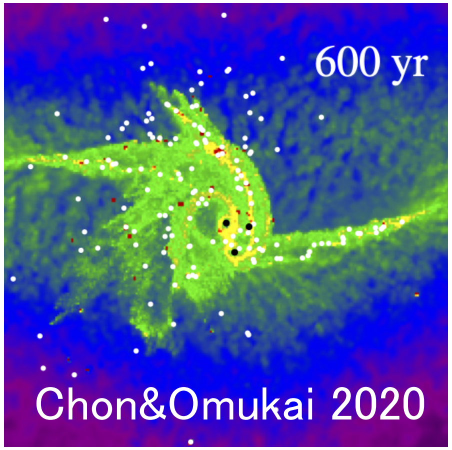


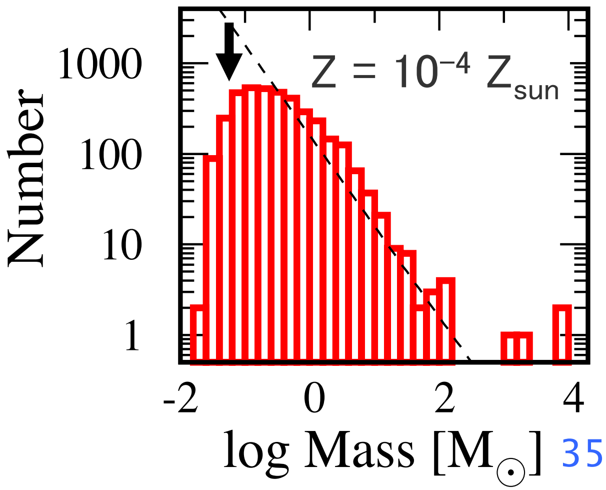

DM–baryon relative velocity




## ❑ Metallicity

- Gas fragmentation induced by dust cooling lead to formation of N>1000 stars
- Nevertheless, massive stars preferentially grow to $M > 10^4\ M_{sun}$ if $Z < 10^{-4}\ Z_{sun}$

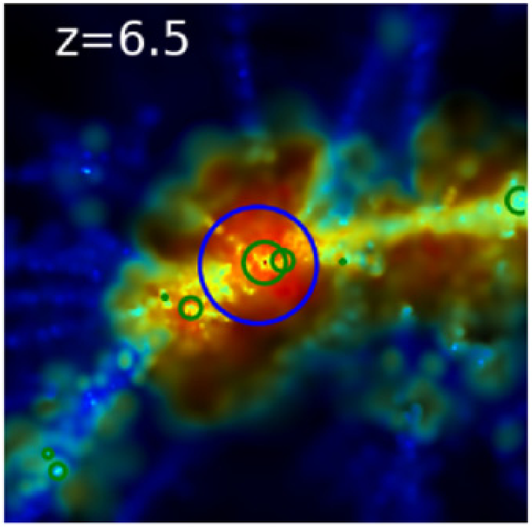


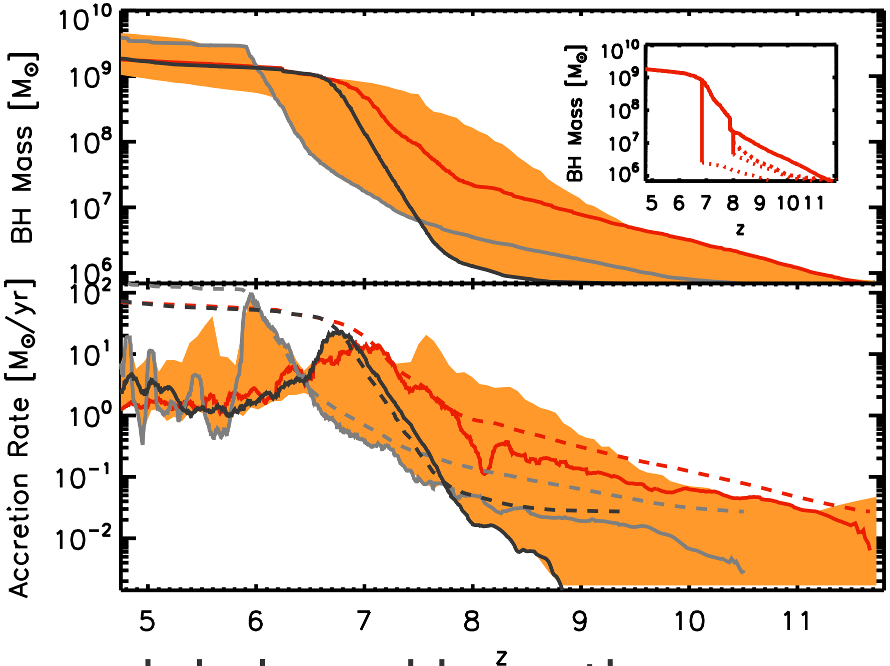



# DISCUSSION

# After the initial stage: BH growth from $10^5 M_{sun}$ to $10^9 M_{sun}$

- Quasar formation in cosmological simulations (Di Matteo+ 2012)




- introduce $10^5 M_{sun}$ seed BHs to each halo and keep them at the bottom of halo's gravitational potential
- seed BHs grow to quasars before z=6 by roughly continuous Eddington accretion due to cold gas inflows to the center

# Where are BHs located in galaxies

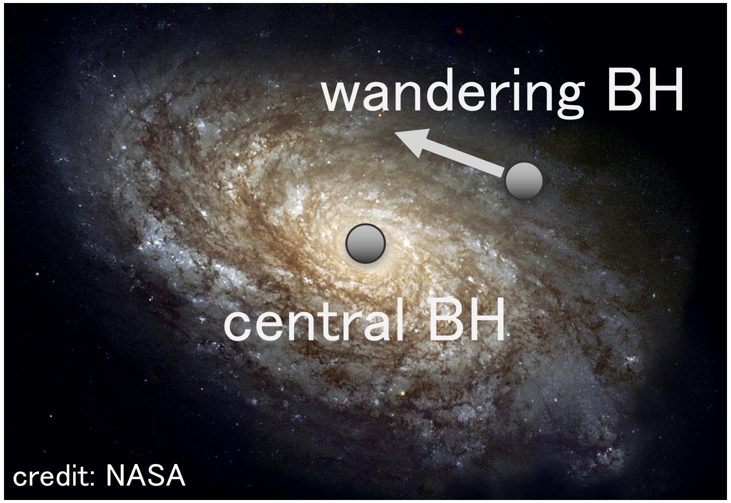
(cf. discussion in KS+ 18)

## ❑ wandering BH vs. central BH

- wandering BH accretes gas in ISM while it moves around the galaxy (active)

↕ largely different processes!

- central BH accretes gas supplied to the center by galactic-scale processes (passive)




## ❑ Dynamical friction timescale

(Binney&Tremain 1987)

$$t_{\rm DF} \simeq \frac{1.17}{\ln[M_*/M_{\rm BH}]}\frac{M_*}{M_{\rm BH}}t_{\rm cross}$$

$$\simeq 120\,{\rm Myr}\left(\frac{M_{\rm BH}}{10^5\,M_\odot}\right)^{-1}\left(\frac{M_*}{10^7\,M_\odot}\right)^{\frac{1}{2}}\left(\frac{R_{\rm BH}}{100\,{\rm pc}}\right)^{\frac{3}{2}}$$

$R_{BH}$: dist. from the gal. cen.

$M_*$: stellar mass at $R < R_{BH}$

$t_{cross}$: crossing time at $R = R_{BH}$

$$\left(t_{\rm cross} = R_{\rm BH}^{\frac{3}{2}}G^{-\frac{1}{2}}M_*^{-\frac{1}{2}}\right)$$

- wondering BHs sink to the galactic center on this timescale
- higher-mass BHs tend to be central BHs due to shorter $t_{DF}$ (transition at $M_{BH}$〜$10^5 M_{sun}$?)

# Implications for SMBHs in the low-z Universe

- Much more time is available for low-z SMBHs to grow to their observed masses compared with high-z SMBHs at $z > 6$

- However, most of light seed BHs are likely not to grow at all even for the cosmic age of 13.8 Gyr
  - growth time scale by Bondi accretion with normal ISM density of $1\,\mathrm{cm}^{-3}$

$$t_{\rm grow} \equiv \frac{M_{\rm BH}}{\dot{M}_{\rm B}} = 500\,{\rm Gyr} \left(\frac{M_{\rm BH}}{10^2\,M_\odot}\right)^{-1} \left(\frac{n_{\rm H}}{1\,{\rm cm}^{-3}}\right)^{-1} \left(\frac{\left(c_{\rm s}^2 + V^2\right)^{\frac{1}{2}}}{8\,{\rm km/s}}\right)^3$$

- Therefore, the formation of $10^5\,M_{sun}$ BHs is a problem not only for high-z SMBHs but also for low-z SMBHs

# SUMMARY

# Summary

| Scenario | Light seed ($\sim 10^2 - 10^3\ M_{sun}$) | Heavy seed ($\sim 10^5\ M_{sun}$) |
|---|---|---|
| | Pop III/Pop II cluster | Direct collapse |
| Seed formation | ○<br>on-going<br>but seems OK | ?<br>on-going |
| Early growth<br>(up to $10^5\ M_{sun}$) | ?<br>on-going | ◎<br>OK by definition |

- Both scenarios survive:
  - no strong reason to deny super-Eddington growth
  - cosmological simulations suggest formation of DCBHs
- Forming $10^5\ M_{sun}$ BHs is the first but difficult milestone toward SMBHs