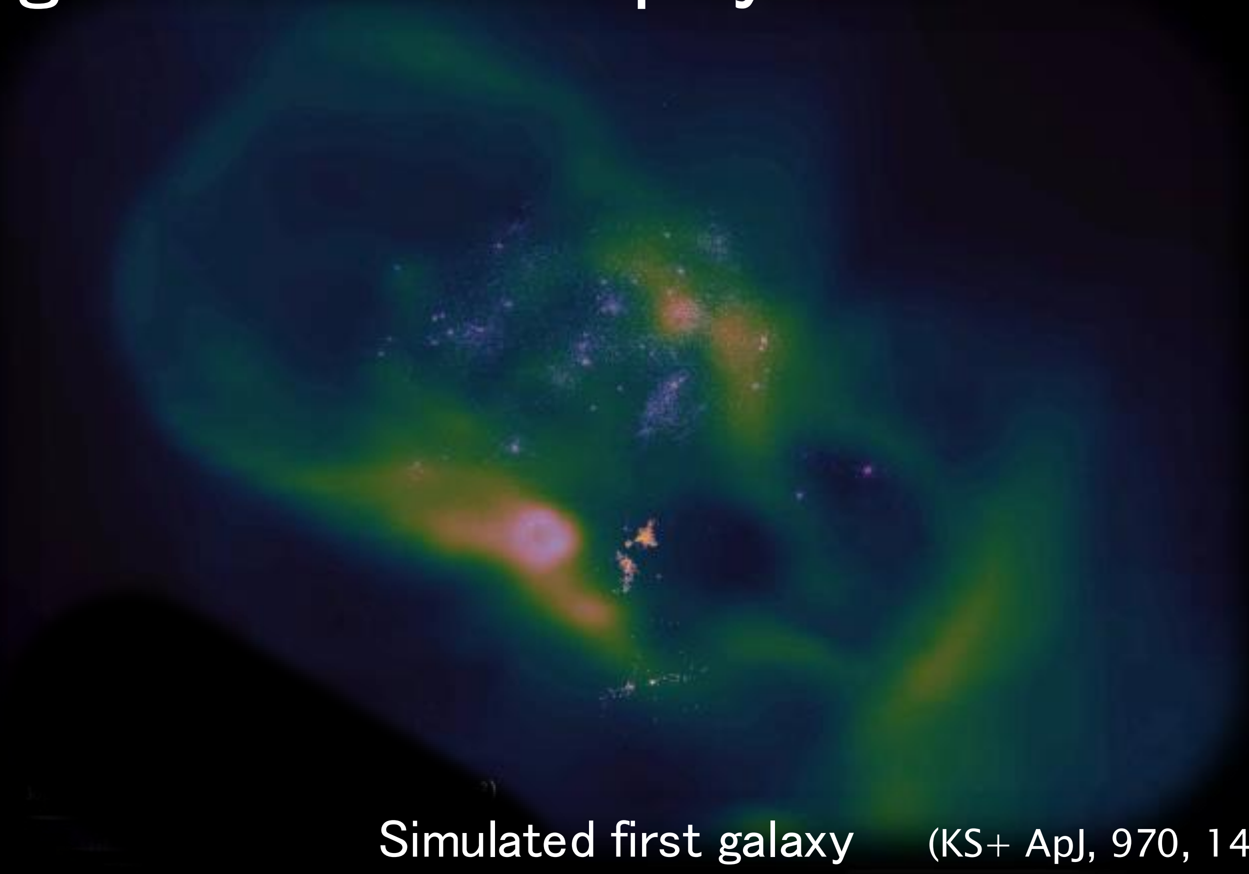
iTHEMS Cosmology Forum

Black hole formation and growth: insights from astrophysical simulations



Simulated first galaxy (KS+ ApJ, 970, 14, 2024)

Kazuyuki Sugimura (Hokkaido Univ.)

Contents

1. Introduction
   - current status of cosmological simulations
2. Seed formation
   - insights from Pop III formation simulations
3. BH growth
   - insights from first galaxy formation simulations
4. Conclusion

1. INTRODUCTION

Kormendy&Ho 13

BHs and galaxies co-evolve

(Super massive BHs)

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

- exist in almost all galaxies

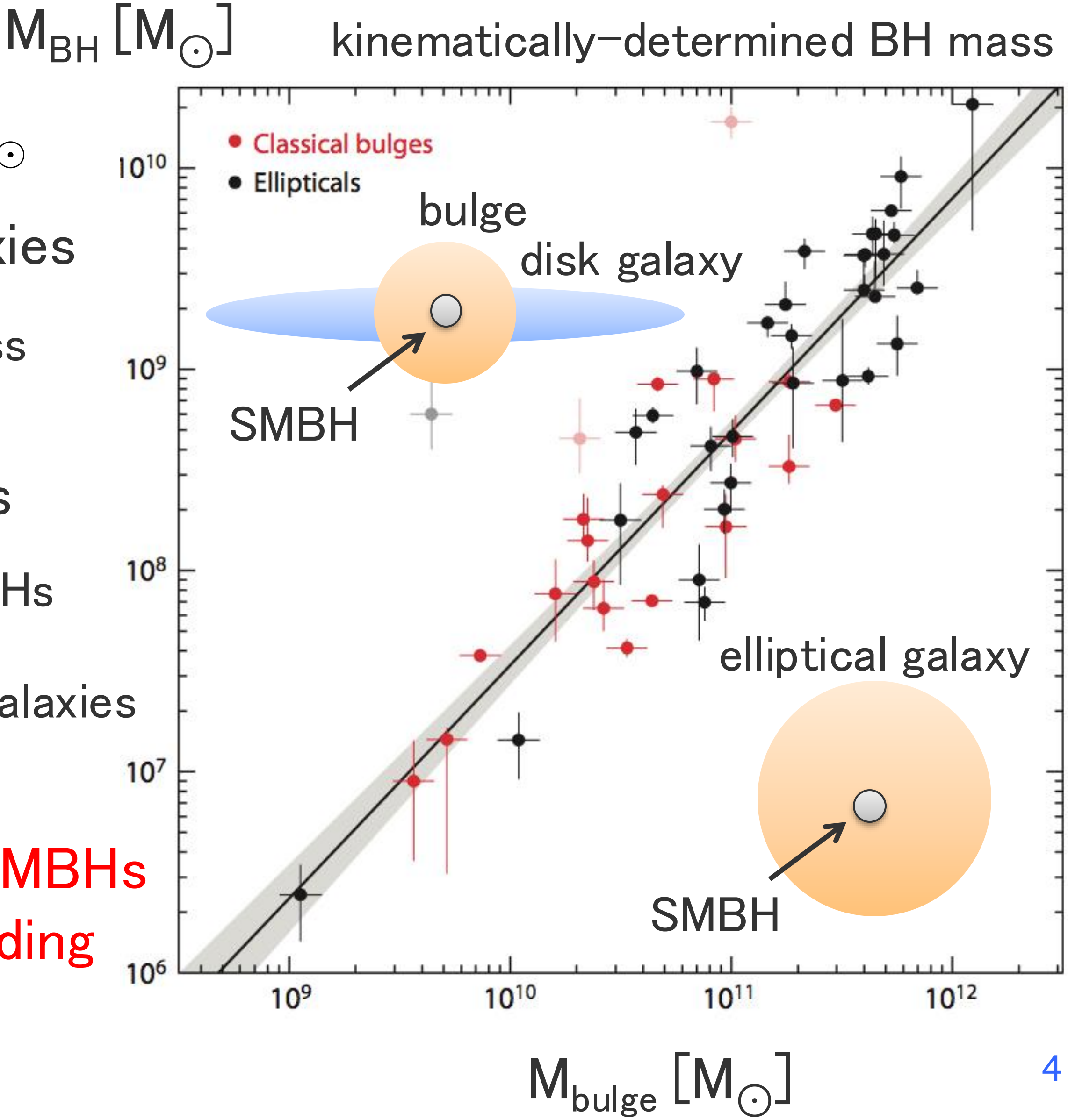
  $M_{BH} \sim 0.5\%$ of bulge mass

- co-evolve with galaxies

  gas supply: galaxies → SMBHs

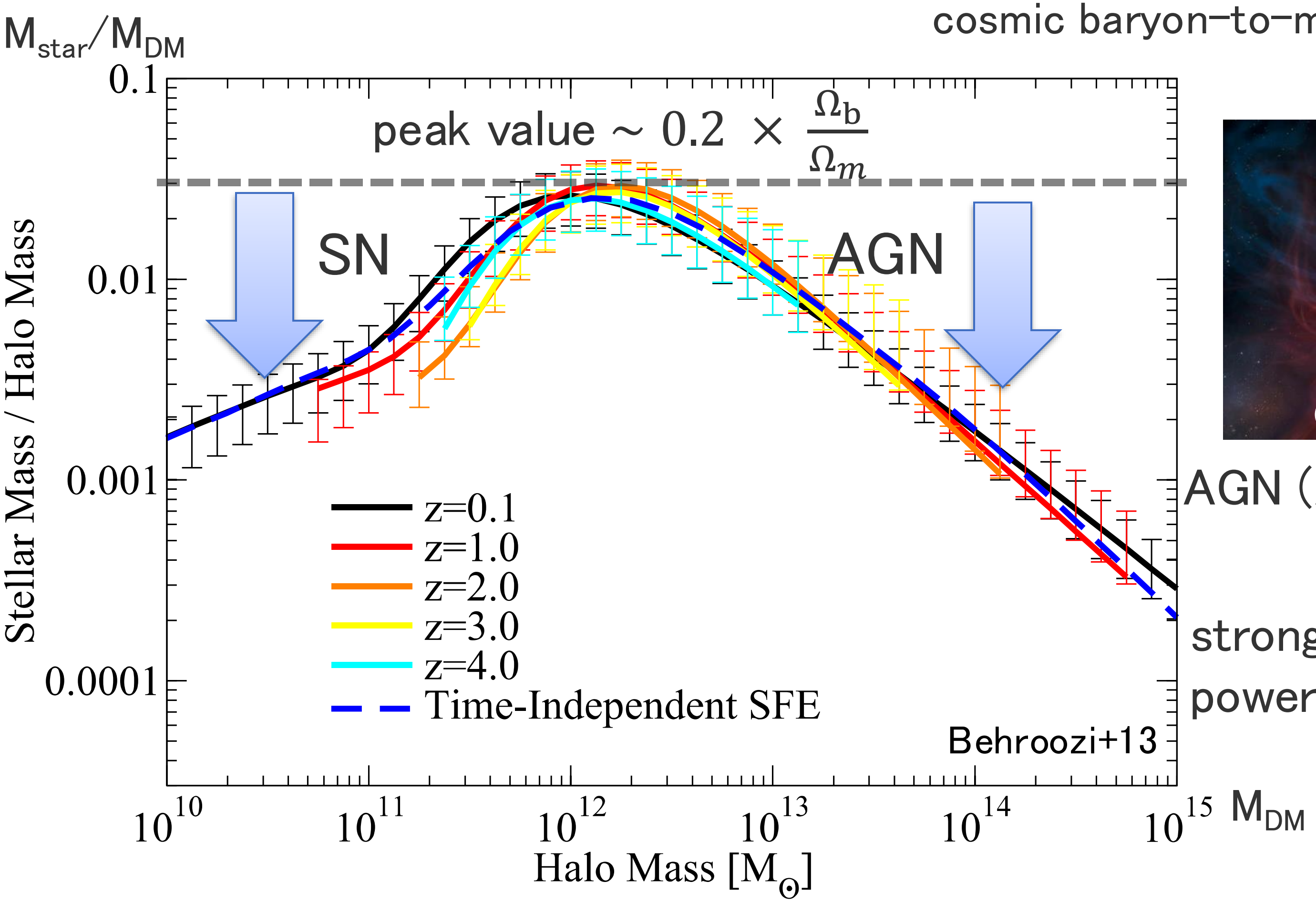
  AGN feedback: SMBHs → galaxies

The understanding of SMBHs is crucial for understanding the galaxy evolution



AGN feedback plays an important role in high-mass galaxies

cosmic baryon-to-matter ratio: $\frac{\Omega_b}{\Omega_m} \sim 0.17$



artistic illustration
(Credit: ESO/M. Kornmesser)

AGN (Active Galactic Nuclei)

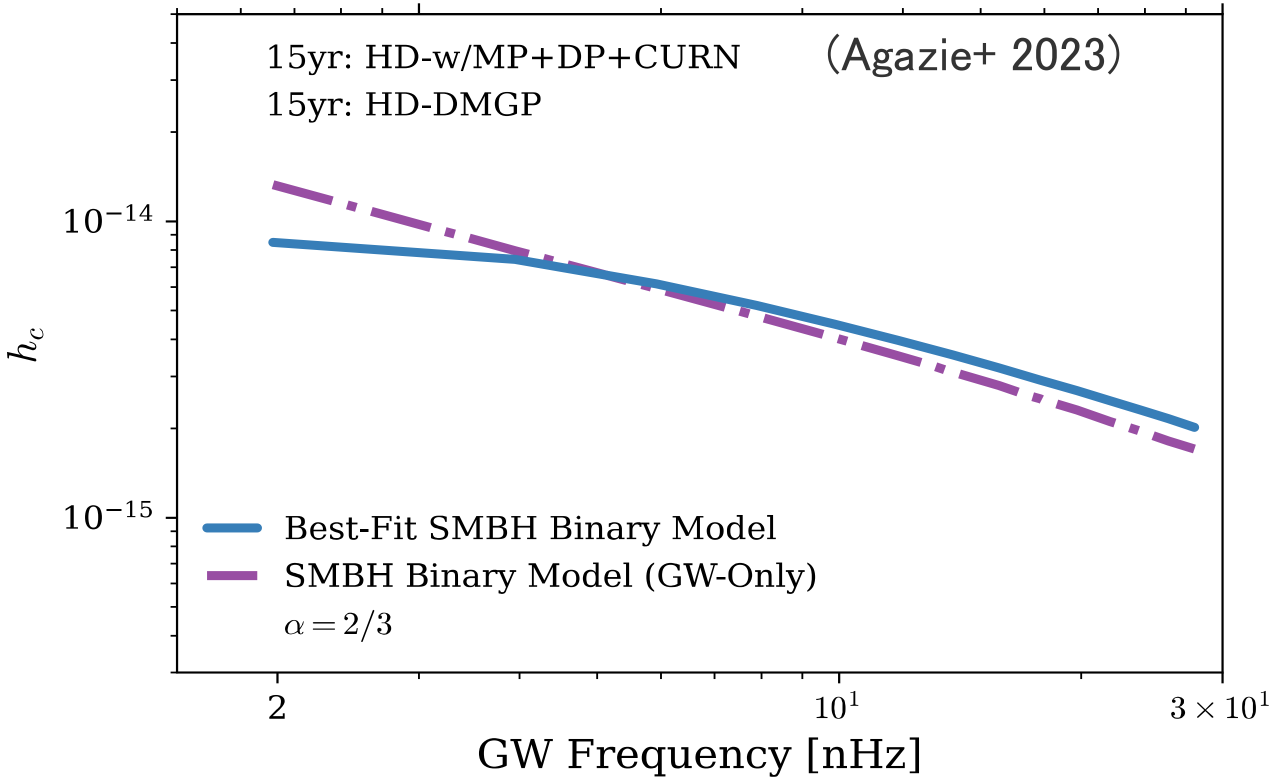
||

strong radiation/outflows
powered by accreting SMBH

cosmological simulations suggest AGN feedback suppresses star formation in high-mass galaxies (e.g. Okamoto+14)

GW from SMBH mergers seems consistent with NANOGrav 15yr

(see Takahashi-san's talk)



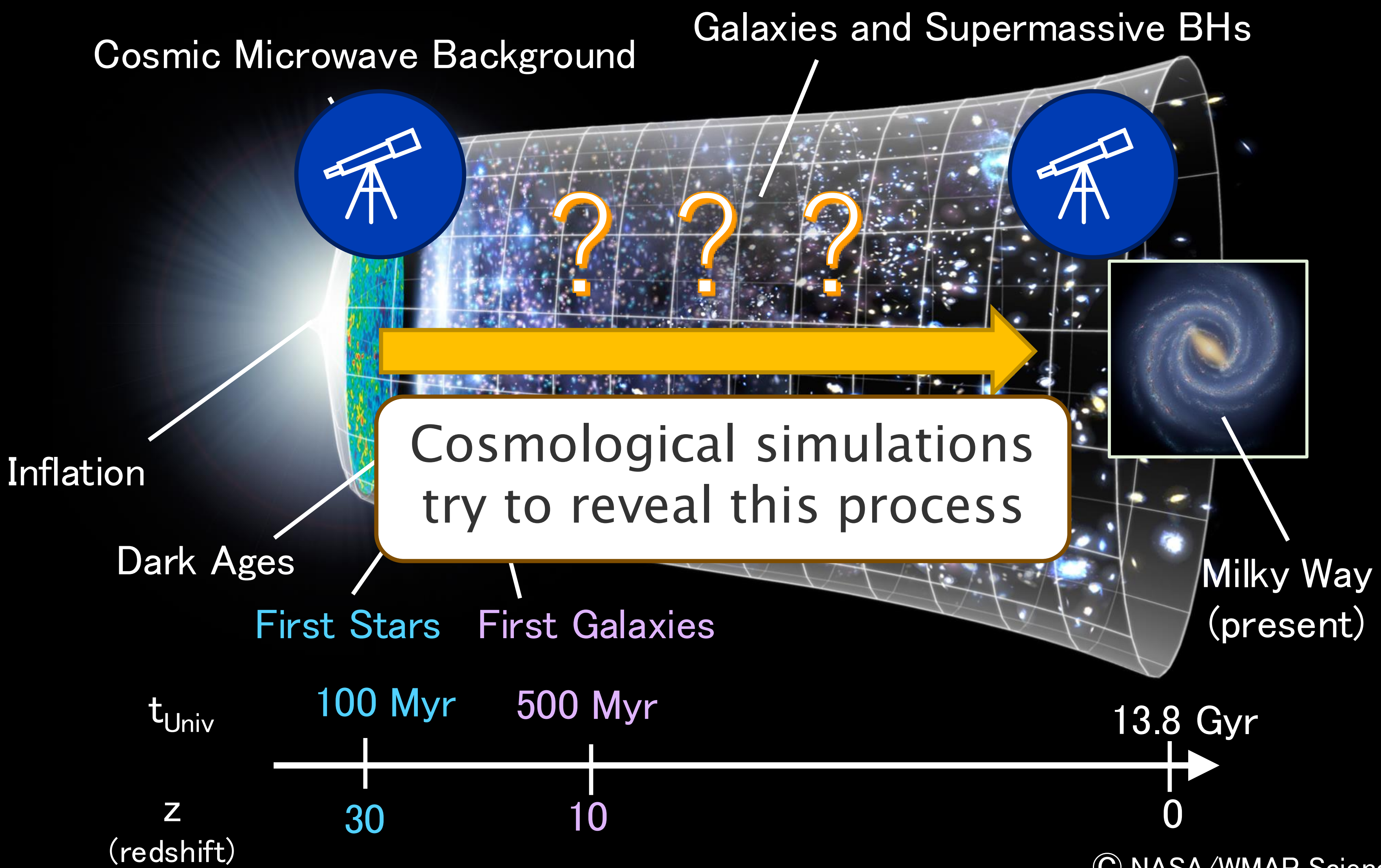
(Agazie+ 2023)

(see also Bi+23)

- A simple semi-analytical model of SMBH formation and evolution can reproduce the observational results with reasonable model parameter choice (but see also, e.g., Shannon+13,15; Sato-Polito+23, Sato-Polito &Zaldarriaga24)
- But, to what extent do we understand SMBH formation and evolution?

⇨ Let's see the current status of more elaborate cosmological simulations

Structure formation history in the universe



Cosmological simulations try to reveal this process

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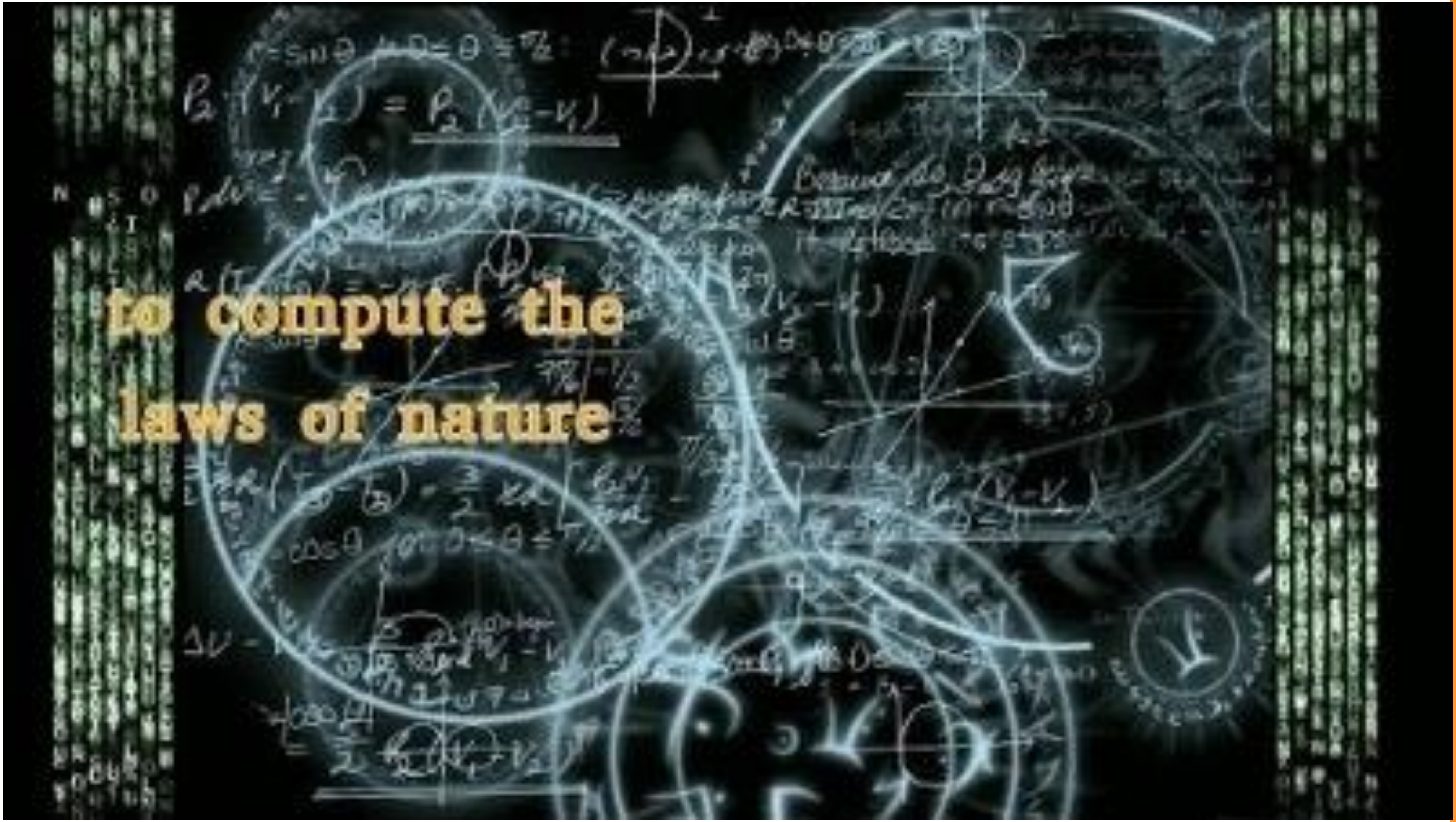
Ref: Vogelsberger et al. (2014) and following many papers

Illustris:

a state-of-art cosmological simulation

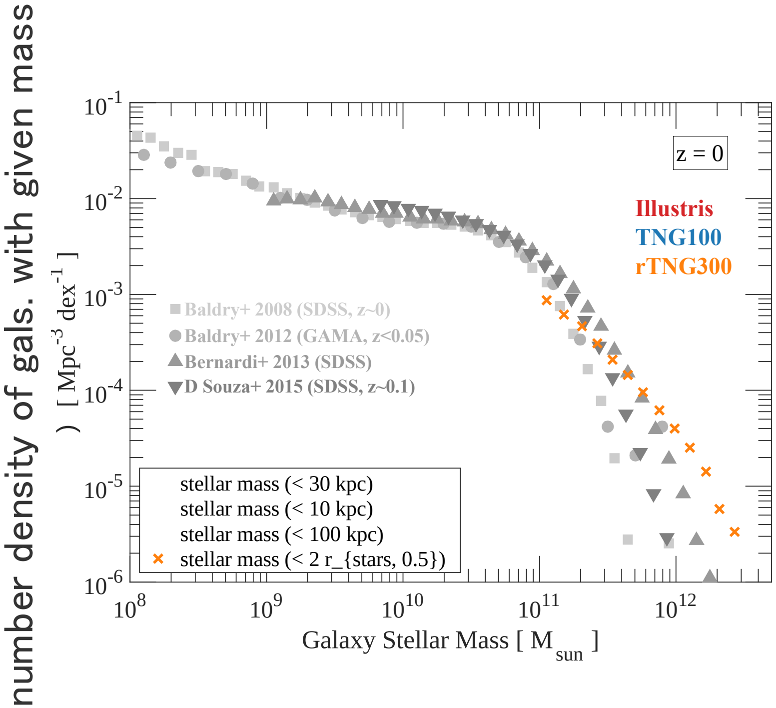


https://youtu.be/NjSFR40SY58

Structure formation has been reproduced in simulations???

(Vogelsberger+ 2014)

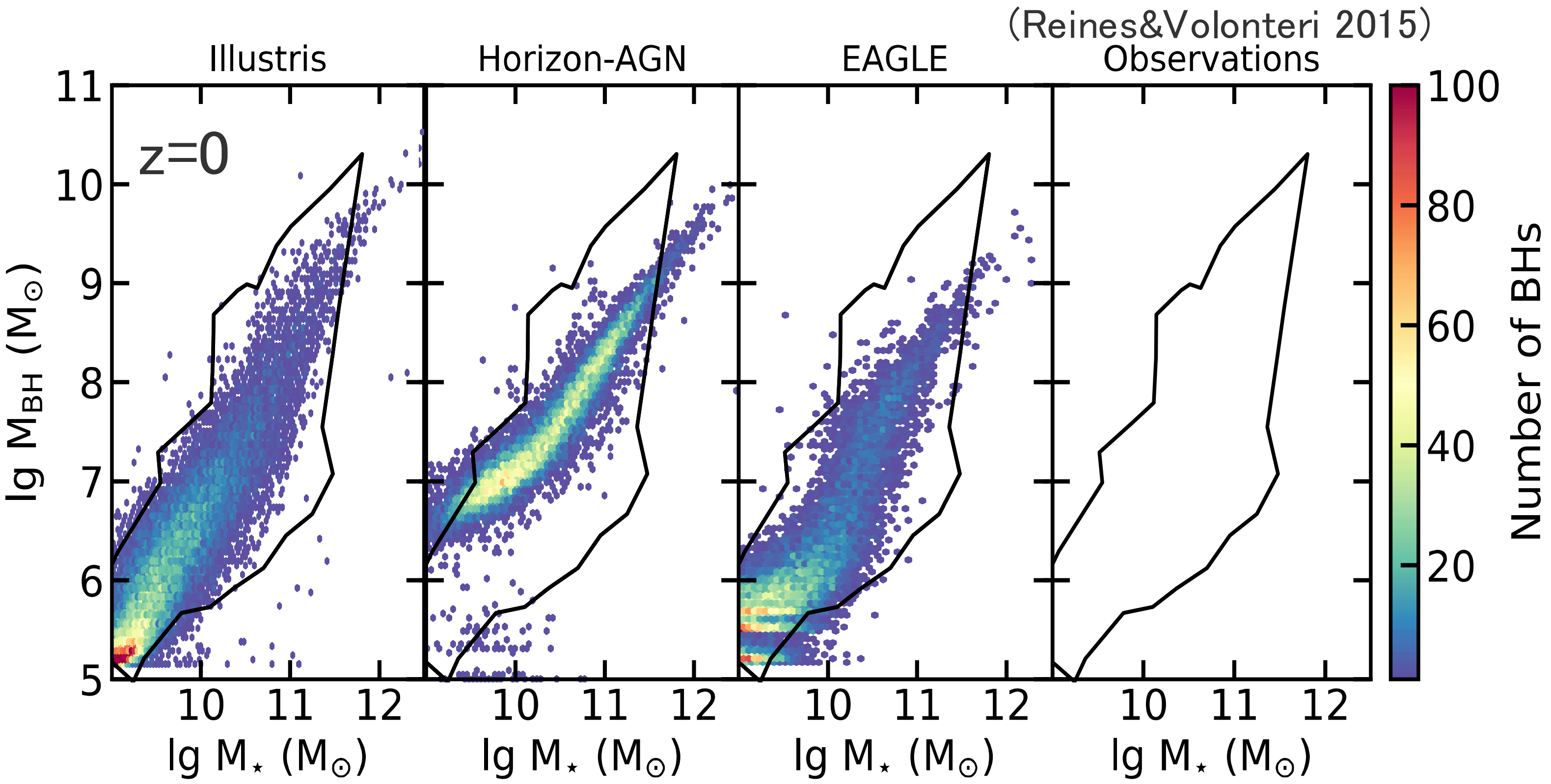
- galaxies in Illustris simulations
- looks almost same as the real observational images of galaxies



- cosmic number density of galaxies is consistent with observations

(Pillepich+ 2018a)

simulations also reproduce M_{BH}–M_{star} relation



(Habouzit+21, modified)

(see also Crain&van de Voort 23)

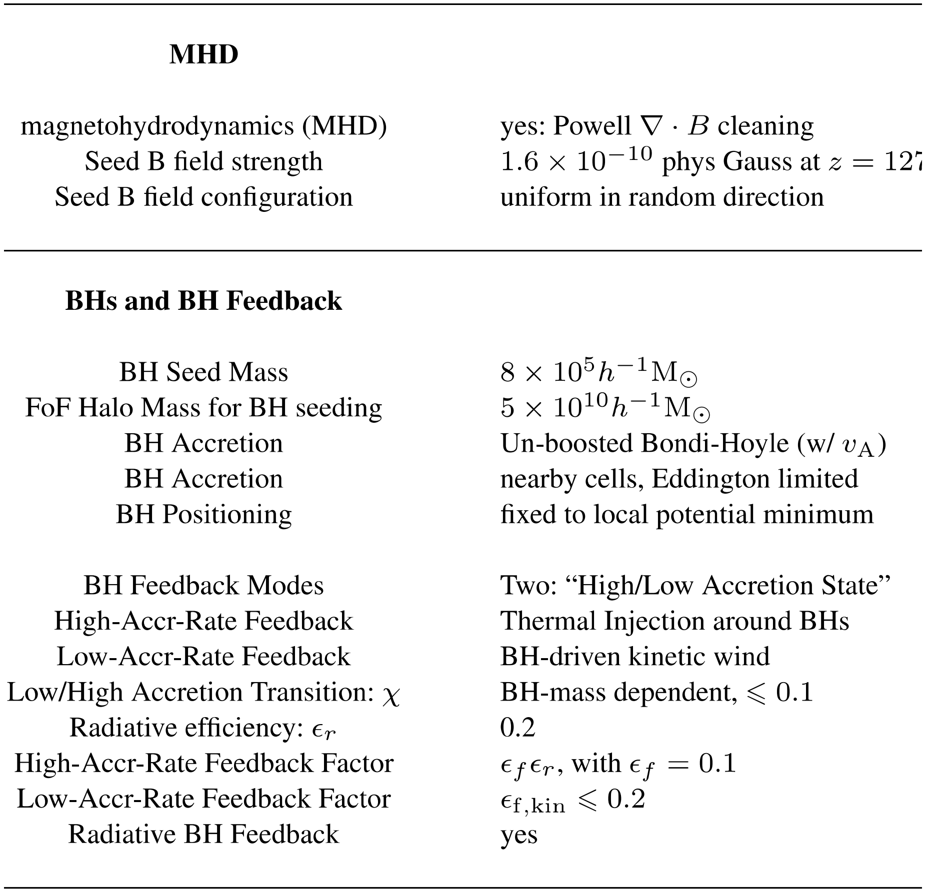
fairly good agreement with observations

SMBH formation has been reproduced in simulations???

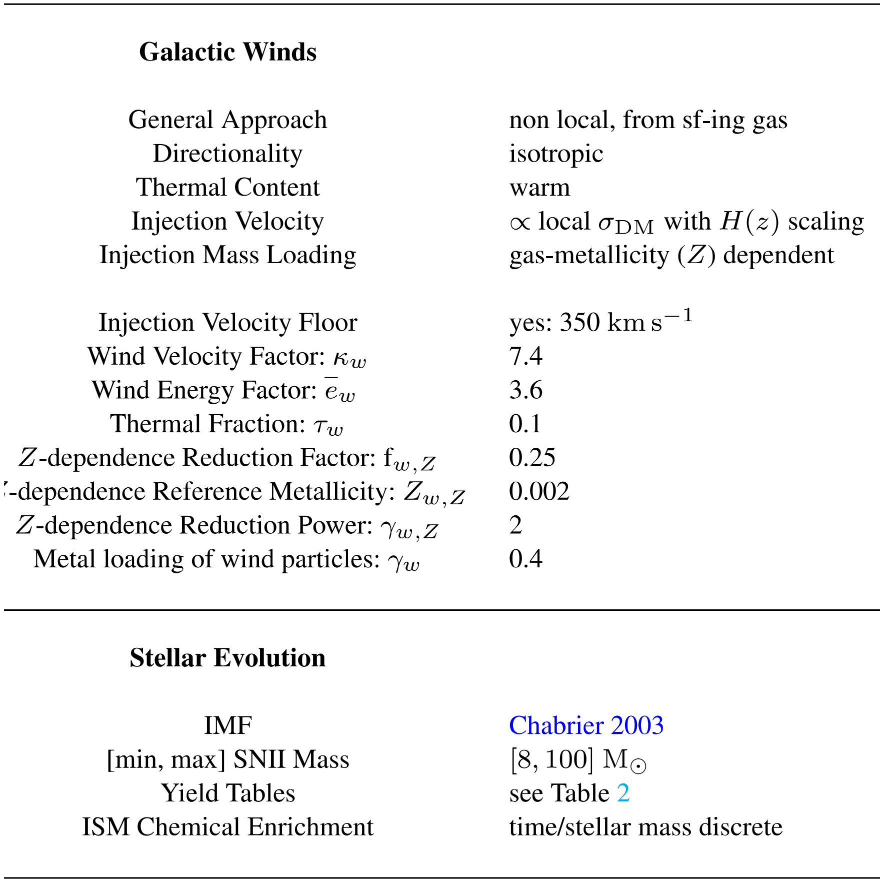
Be cautious. There are many (artificial) model parameters

(Pillepich+2018)

Model parameters for IllustrisTNG (The Next Generation), a newer version of Illustris



MHD	
magnetohydrodynamics (MHD)	yes: Powell $\nabla \cdot B$ cleaning
Seed B field strength	1.6×10^{-10} phys Gauss at $z = 127$
Seed B field configuration	uniform in random direction
BHs and BH Feedback	
BH Seed Mass	$8 \times 10^{5} h^{-1} \mathrm{M}_{\odot}$
FoF Halo Mass for BH seeding	$5 \times 10^{10} h^{-1} \mathrm{M}_{\odot}$
BH Accretion	Un-boosted Bondi-Hoyle (w/ v_{A})
BH Accretion	nearby cells, Eddington limited
BH Positioning	fixed to local potential minimum
BH Feedback Modes	Two: “High/Low Accretion State”
High-Accr-Rate Feedback	Thermal Injection around BHs
Low-Accr-Rate Feedback	BH-driven kinetic wind
Low/High Accretion Transition: χ	BH-mass dependent, $\leqslant 0.1$
Radiative efficiency: ϵ_r	0.2
High-Accr-Rate Feedback Factor	$\epsilon_f \epsilon_r$, with $\epsilon_f = 0.1$
Low-Accr-Rate Feedback Factor	$\epsilon_{\mathrm{f,kin}} \leqslant 0.2$
Radiative BH Feedback	yes



Galactic Winds	
General Approach	non local, from sf-ing gas
Directionality	isotropic
Thermal Content	warm
Injection Velocity	$\propto$ local σ_{DM} with $H(z)$ scaling
Injection Mass Loading	gas-metallicity (Z) dependent
Injection Velocity Floor	yes: $350\ \mathrm{km\,s}^{-1}$
Wind Velocity Factor: κ_w	7.4
Wind Energy Factor: $\bar{e}_w$	3.6
Thermal Fraction: τ_w	0.1
Z-dependence Reduction Factor: $\mathrm{f}_{w,Z}$	0.25
-dependence Reference Metallicity: $Z_{w,Z}$	0.002
Z-dependence Reduction Power: $\gamma_{w,Z}$	2
Metal loading of wind particles: γ_w	0.4
Stellar Evolution	
IMF	Chabrier 2003
[min, max] SNII Mass	$[8, 100]\ \mathrm{M}_{\odot}$
Yield Tables	see Table 2
ISM Chemical Enrichment	time/stellar mass discrete

and more parameters not shown here

BH formation and evolution is controlled by model parameters

(Pillepich+2018)

BHs and BH Feedback

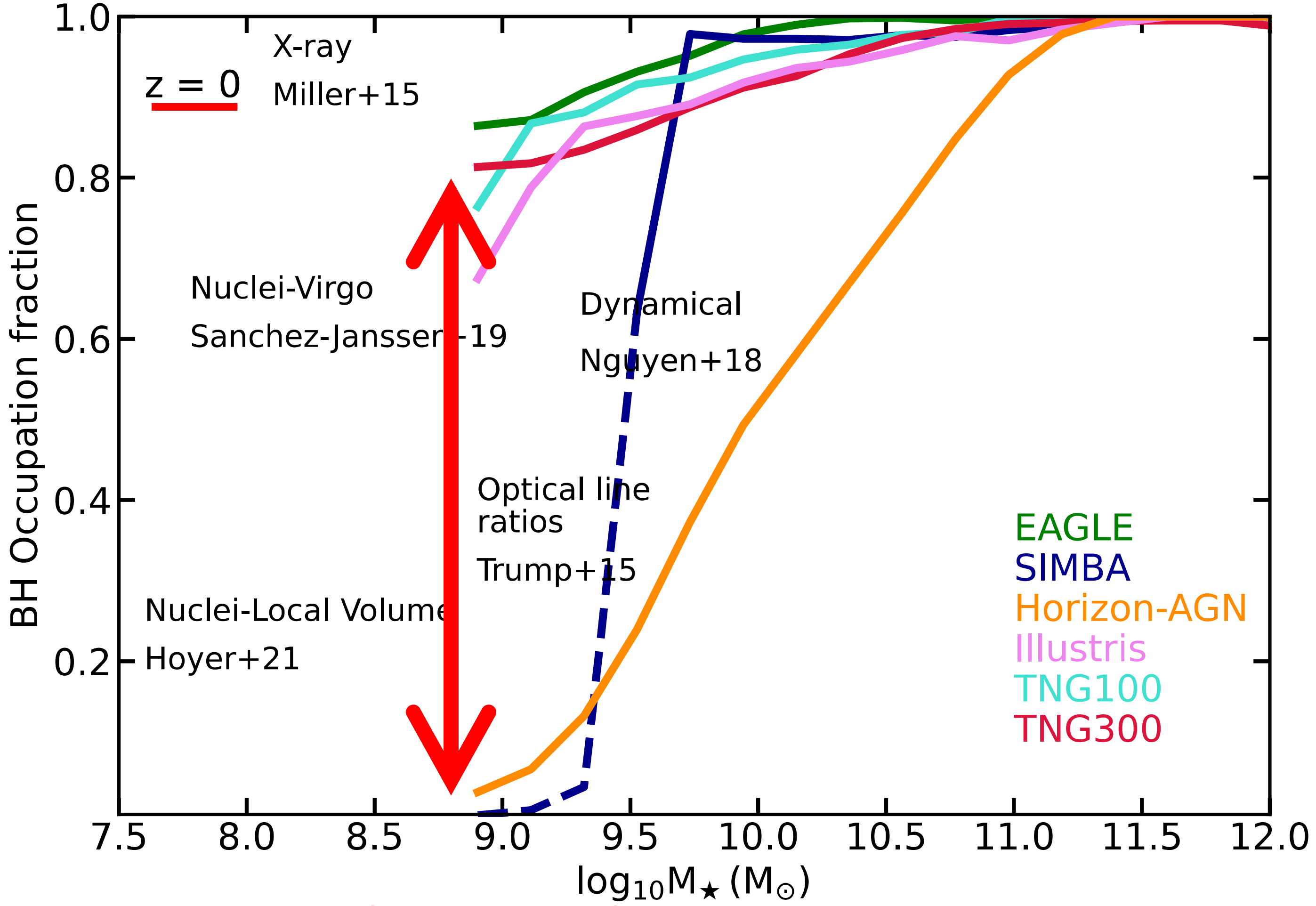
→	BH Seed Mass	$8 \times 10^{5} h^{-1} \mathrm{M}_\odot$
→	FoF Halo Mass for BH seeding	$5 \times 10^{10} h^{-1} \mathrm{M}_\odot$
→	BH Accretion	Un-boosted Bondi-Hoyle (w/ v_A)
	BH Accretion	nearby cells, Eddington limited
→	BH Positioning	fixed to local potential minimum
→	BH Feedback Modes	Two: “High/Low Accretion State”
	High-Accr-Rate Feedback	Thermal Injection around BHs
	Low-Accr-Rate Feedback	BH-driven kinetic wind

BH evolution depends directly on these (artificial) assumptions

and indirectly on other assumptions

The freedom of parameter choices has been used to reproduce observational results

Different results from different simulations I: BH occupation frac.



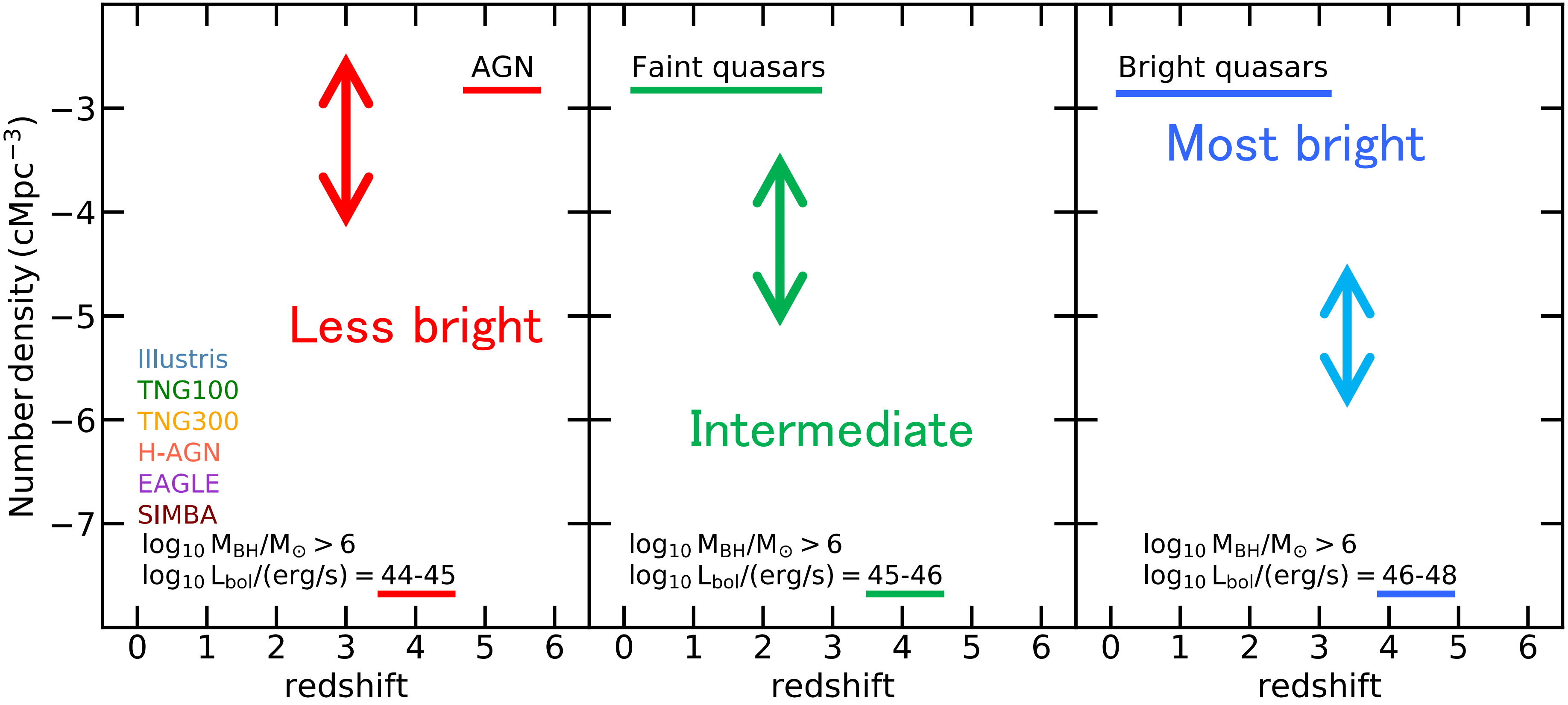
Haidar+22

BH occupation fraction of low−mass galaxies widely varies among simulations

Different results from different simulations II: AGN abundance

AGN (Active Galactic Nuclei) = accreting SMBH

Habouzit+22



Number density of accreting SMBHs also widely varies among simulations

What is theoretically uncertain about SMBHs?

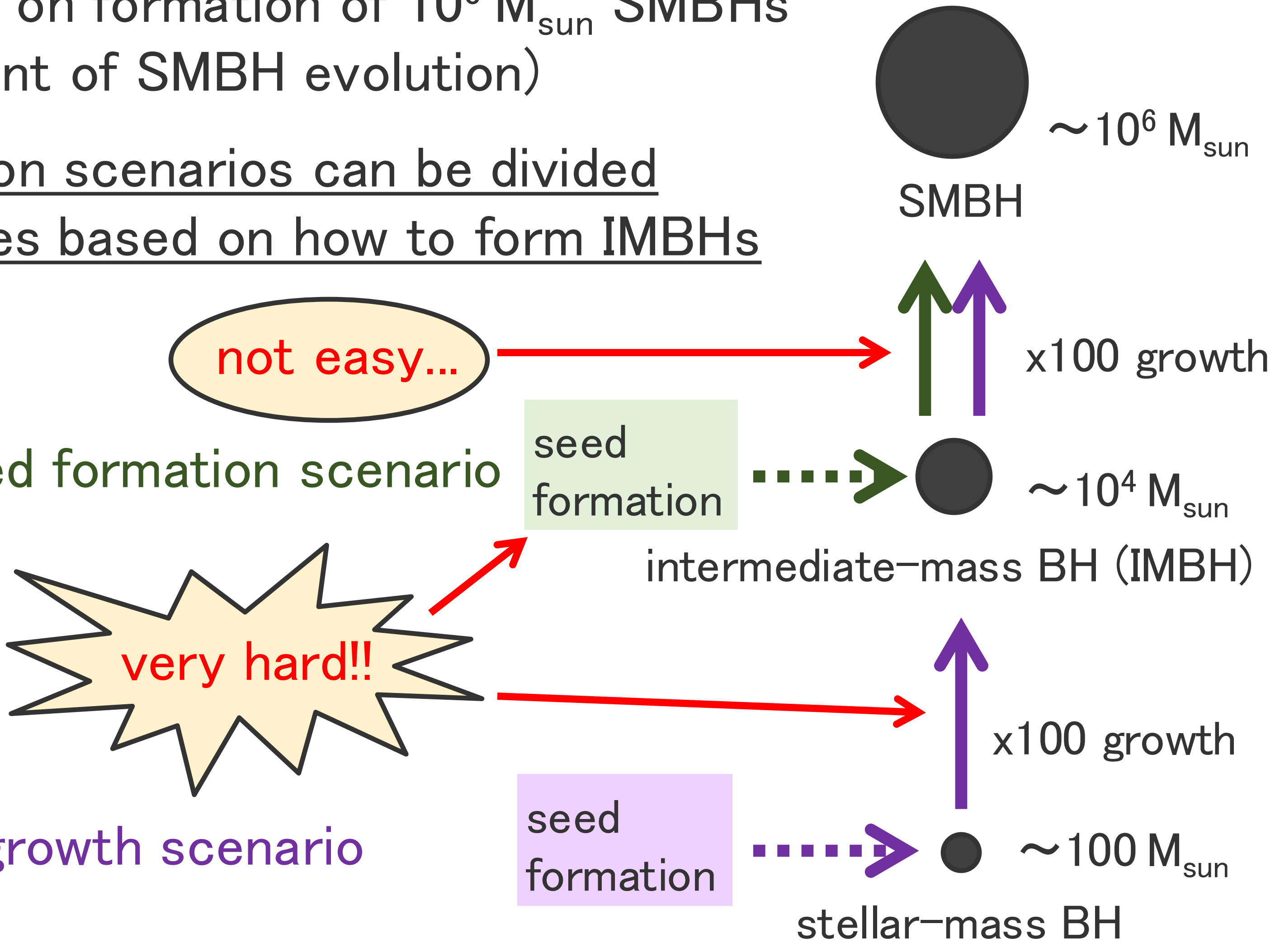
A. everything

Their formation, orbit, growth, and feedback are
not understood well (and often artificially assumed)

Let's proceed step by step

Let's focus on formation of 10^6 M_{sun} SMBHs (starting point of SMBH evolution)

SMBH formation scenarios can be divided into two classes based on how to form IMBHs



SMBH

~10^6 M_{sun}

not easy...

x100 growth

1. Massive seed formation scenario

seed formation

~10^4 M_{sun}

intermediate-mass BH (IMBH)

very hard!!

x100 growth

2. Light seed growth scenario

seed formation

~100 M_{sun}

stellar-mass BH

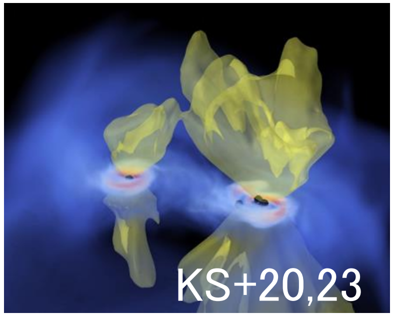
We need to understand seed formation and seed growth

2. SEED FORMATION

Seed formation

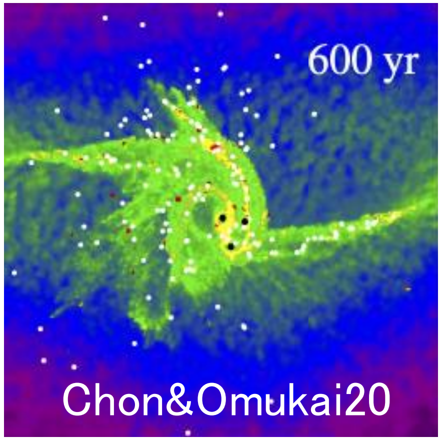
Pop III stars = zero−metal stars
= first−generation stars = first stars

I will present later

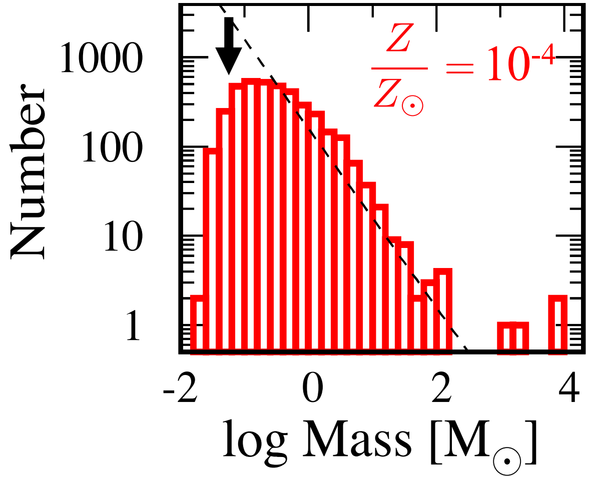

KS+20,23

- Light seed: Pop III remnant BH （$\sim$100−1000 M_{sun}）
- Heavy seed: direct collapse BH（$\sim 10^{4-5}$ M_{sun}）
  - ✓ pristine gas + strong FUV field（J_{21}>1000） (e.g., Omukai01, Bromm&Loeb03, KS+14)
  - ✓ dynamical heating reduces the condition for FUV（J_{21}>1） (Wise+19, Toyouchi+23)
  - ✓ small amount of metal（$Z<10^{-3}$ Z_{sun}）is allowed (Chon&Omukai20)

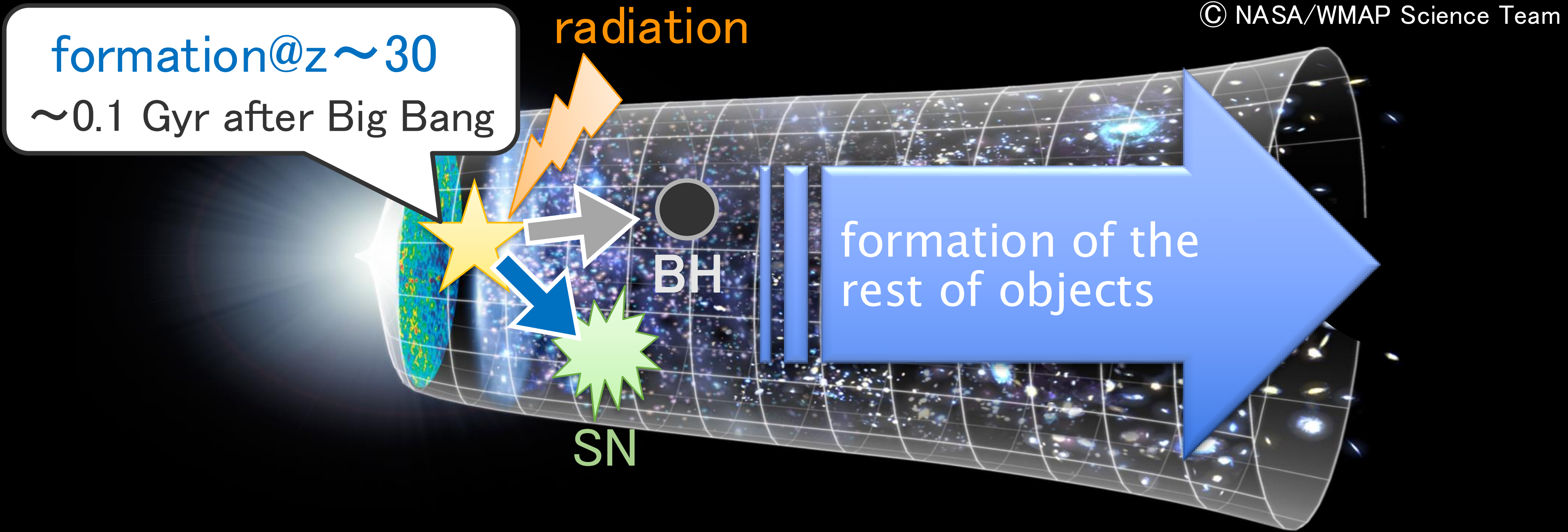
Super−massive stars can form in dense clusters via mergers and gas accretion



Chon&Omukai20



How did the first stars form in the universe?



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formation@z～30
～0.1 Gyr after Big Bang

radiation

BH

SN

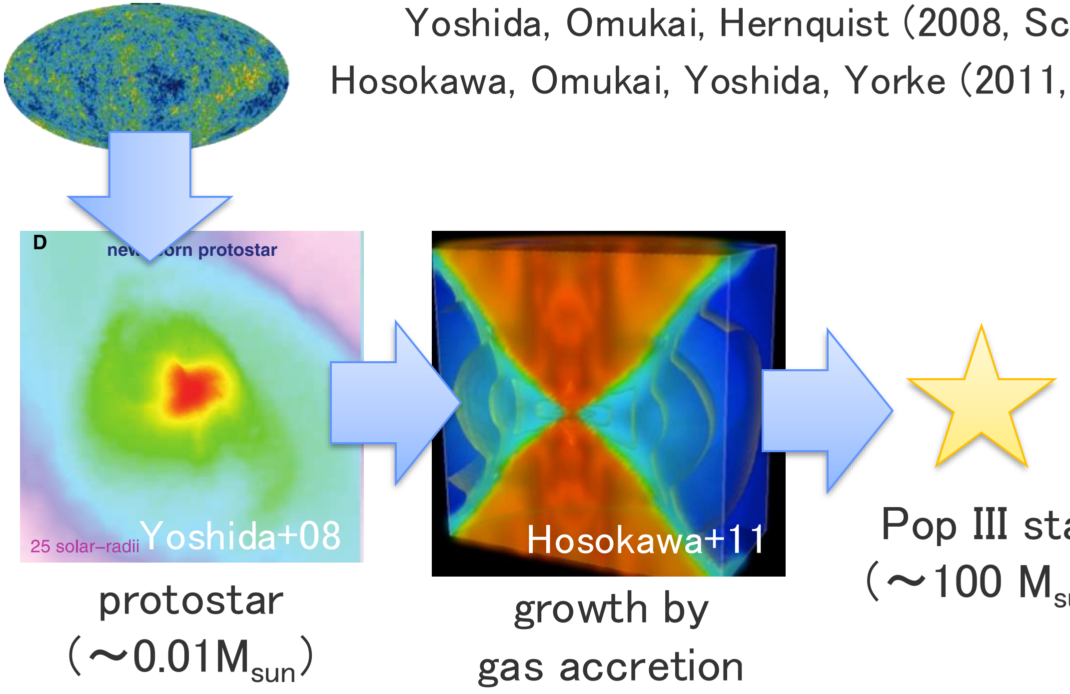
formation of the rest of objects

- ✓ the first stars determine the following evolution through SNe, radiation, and seeding BHs
- ✓ key question: what is the mass (distribution) of the first stars
- ✓ We performed 3D Adaptive-Mesh-Refinement simulations considering gas fragmentation and binary formation (KS+20, 23)

Simulating Pop III star formation

- From Big Bang to the first stars

Yoshida, Omukai, Hernquist (2008, Science)
Hosokawa, Omukai, Yoshida, Yorke (2011, Science)



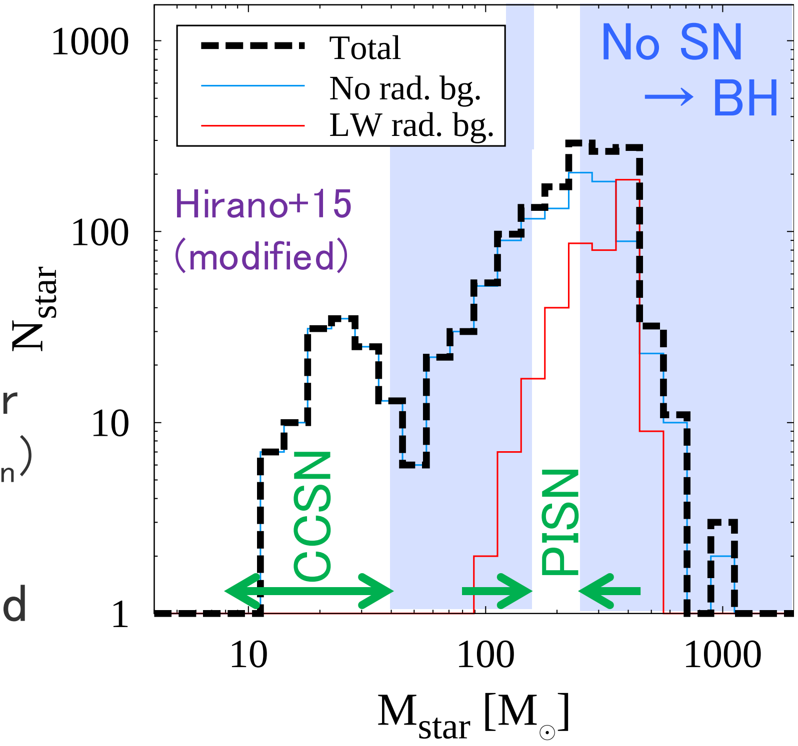
protostar (~0.01M_{sun})

growth by gas accretion

Pop III star (~100 M_{sun})

- start from cosmological initial conditions and follow the evolution considering all relevant chemical/thermal/radiative processes

Fate of Pop III stars
(cf. Heger & Woosley 2002)
M_{PopIII} = 40–140 or > 260 M_{sun}
→ BHs w/o SN explosion



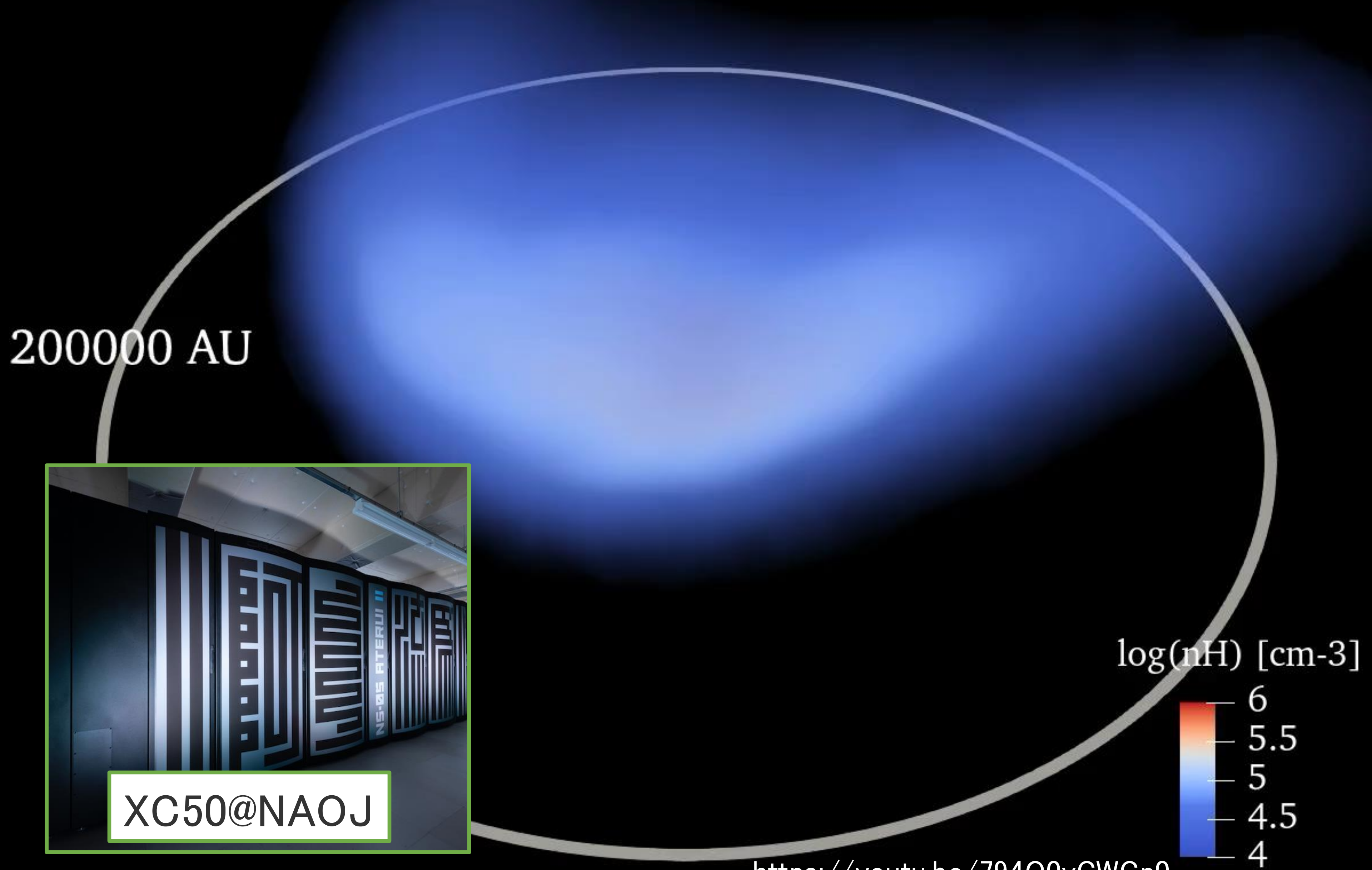
Pop III mass

Pop III IMF was obtained using axisymmetric 2D simulations (Hirano+14, 15)
→ We performed 3D Adaptive-Mesh-Refinement simulations (KS+ 20, 23)

t = -151617 yr

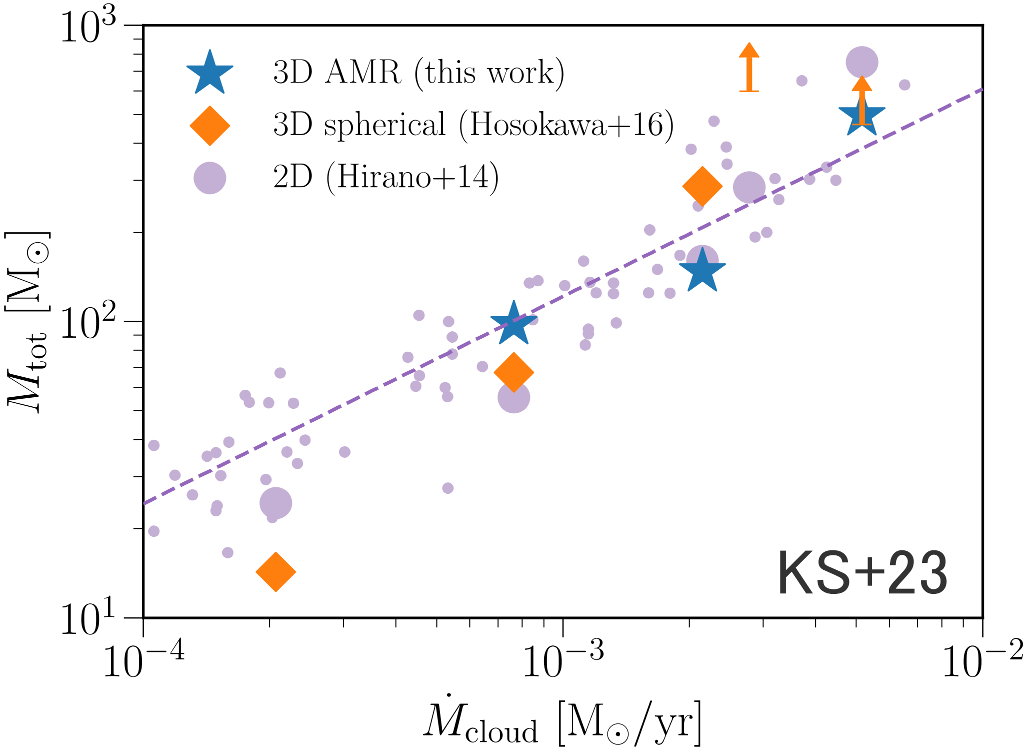
First stars form as massive multiples

KS, Matsumoto, Hosokawa, Hirano, Omukai (2020, 2023)



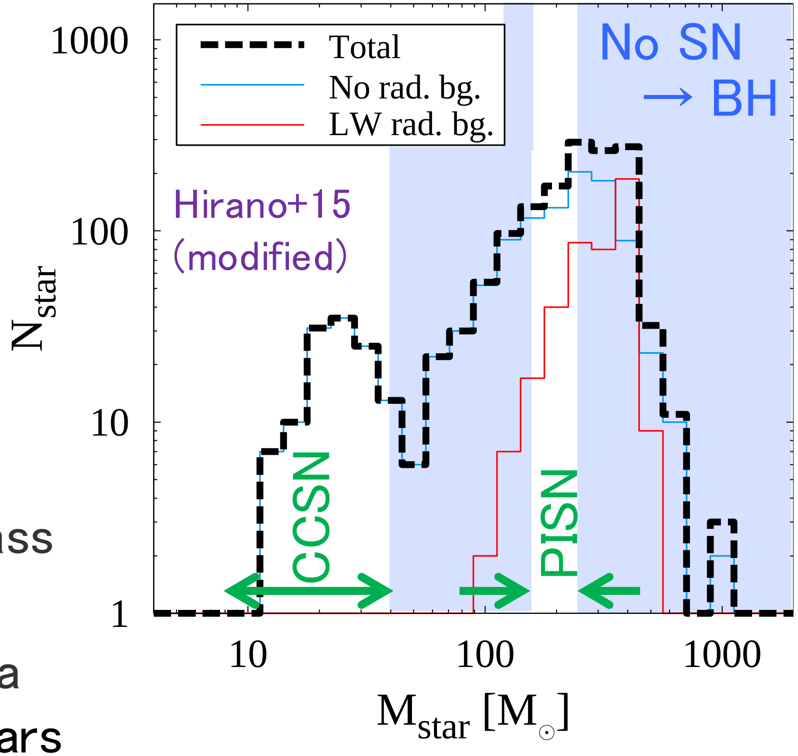
https://youtu.be/794O0yGWGp0

But, total mass is unchanged



Fitting formula from 2D simulations (Hirano+15)

$$M_{\rm tot} = 250\,M_\odot \left(\frac{\dot M_{\rm cloud}}{2.8\times10^{-3}\,M_\odot\,{\rm yr}^{-1}}\right)^{0.7}$$



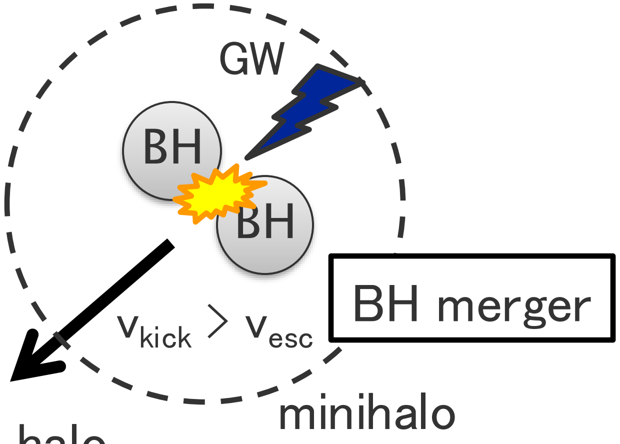
Pop III total mass

- Total mass is related to the large-scale mass inflow rate (same as former 2D works)
- While the mass of each star is reduced by a factor of a few due to mass sharing, Pop III stars still likely leave 100–1000 $M_{\rm sun}$ BHs

3. SEED GROWTH

Channels of seed BH growth

☐ Growth by BH merger



- v_{kick} ～100km/s due to GW recoil

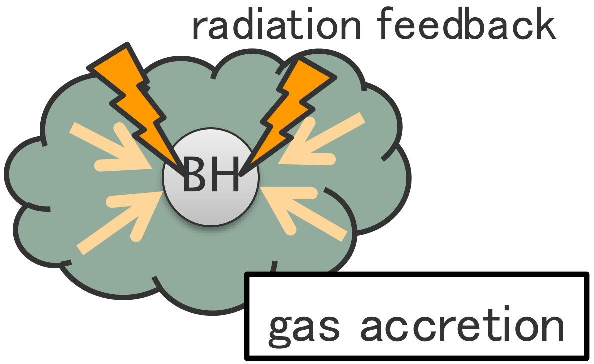
  (e.g., Baker+ 2006, Koppitz+ 2007)

- v_{esc}～10km/s in small galaxies

⇨ BH will escape from the host halo

BH merger cannot be the main channel of seed BH growth

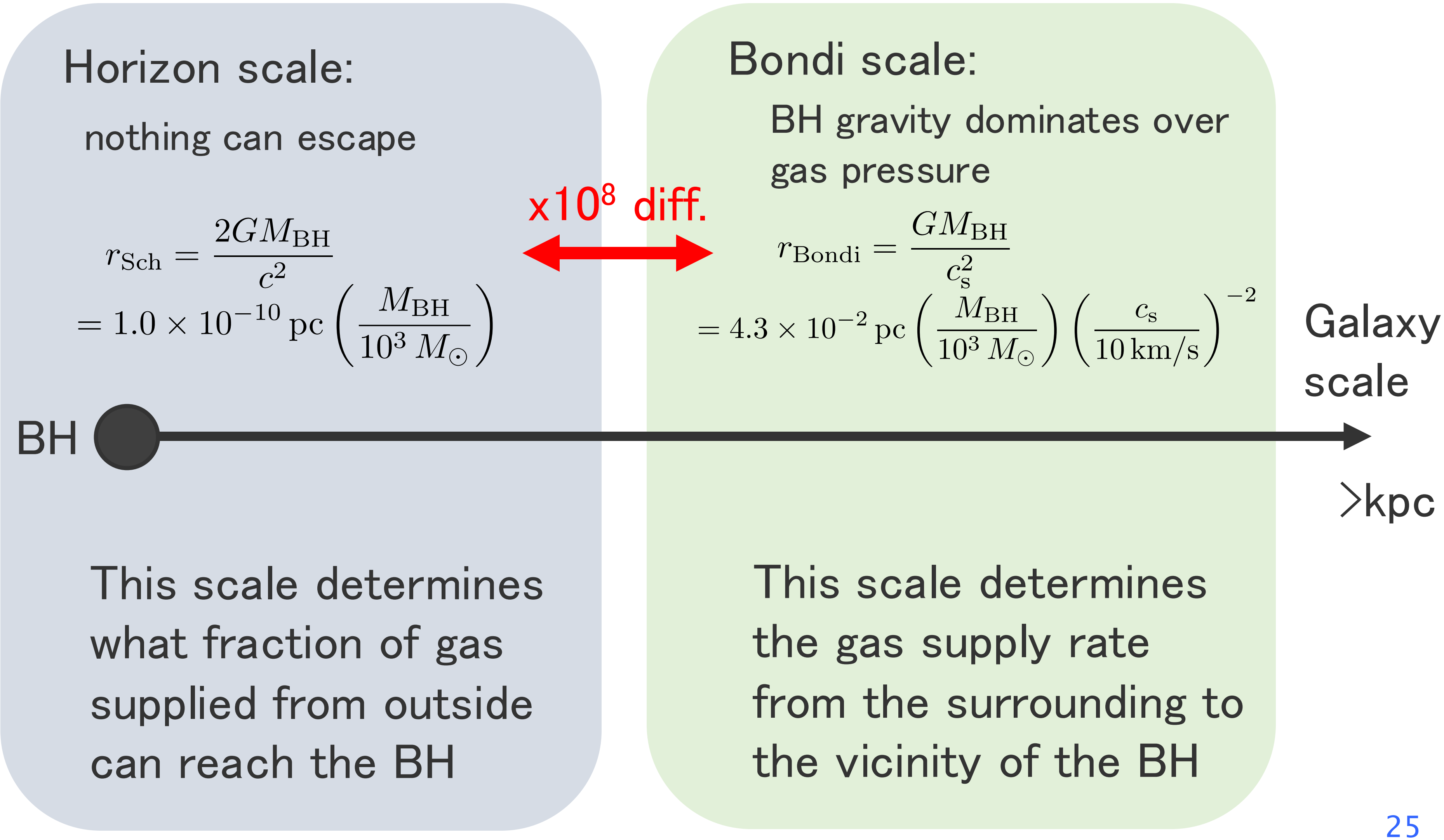
☐ Growth by gas accretion



- likely the main growth mechanism of seed BHs
- however, radiative feedback from BH disk may be an obstacle for the gas accretion

Let’s see the recent understanding in following slides

BH accretion is a multi-scale process



Horizon scale:

nothing can escape

$$r_{\rm Sch} = \frac{2GM_{\rm BH}}{c^2}$$
$$= 1.0 \times 10^{-10}\,{\rm pc}\left(\frac{M_{\rm BH}}{10^3\,M_\odot}\right)$$

x10^8 diff.

Bondi scale:

BH gravity dominates over gas pressure

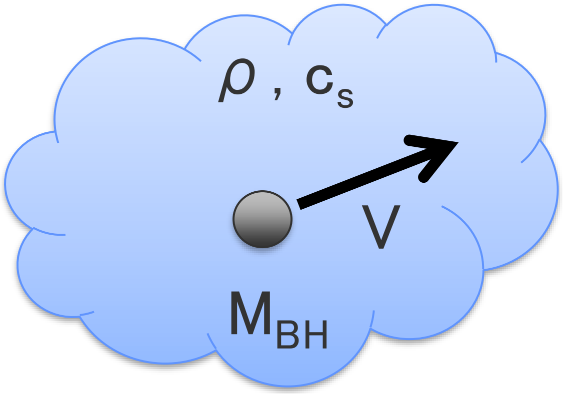
$$r_{\rm Bondi} = \frac{GM_{\rm BH}}{c_{\rm s}^2}$$
$$= 4.3 \times 10^{-2}\,{\rm pc}\left(\frac{M_{\rm BH}}{10^3\,M_\odot}\right)\left(\frac{c_{\rm s}}{10\,{\rm km/s}}\right)^{-2}$$

This scale determines what fraction of gas supplied from outside can reach the BH

This scale determines the gas supply rate from the surrounding to the vicinity of the BH

Basics of gas accretion I: accretion without feedback

- Bondi(−Hoyle−Lyttleton) accretion



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

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

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

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

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

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

  - 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 limit

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

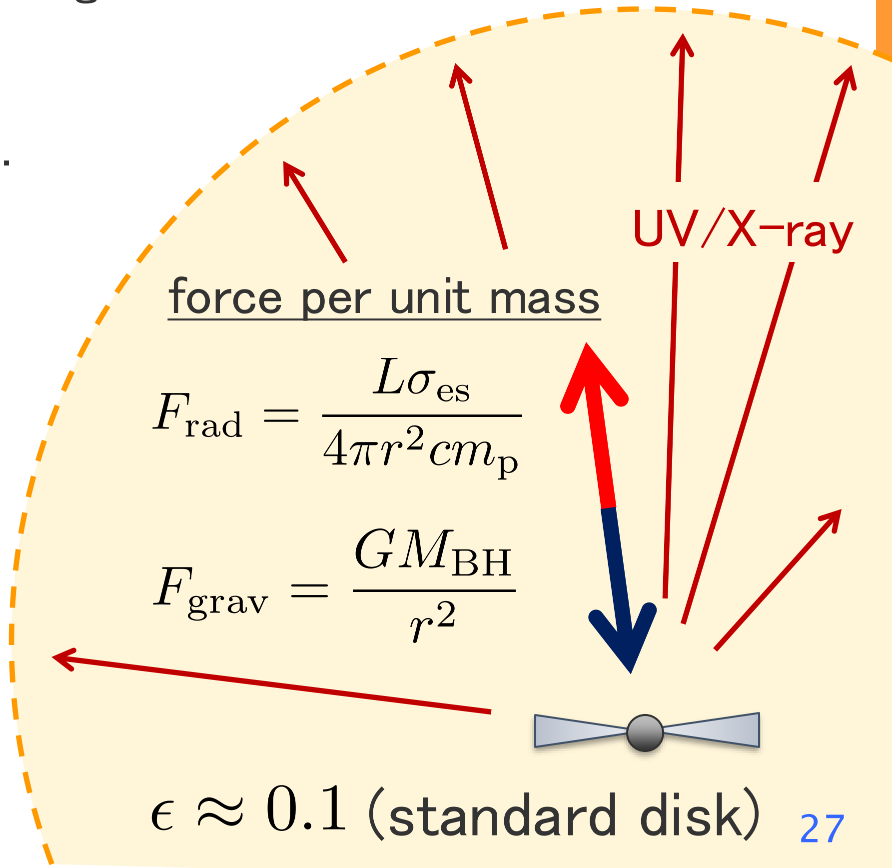
Eddington luminosity

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

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

Eddington accretion rate

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



force per unit mass

$$F_{\rm rad} = \frac{L\sigma_{\rm es}}{4\pi r^2 c m_{\rm p}}$$

$$F_{\rm grav} = \frac{G M_{\rm BH}}{r^2}$$

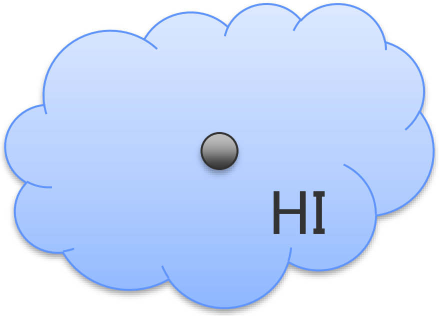
$\epsilon \approx 0.1$ (standard disk)

Milosavljevic+ 09, Park&Ricotti 11

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

- Acc. from cold HI cloud

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



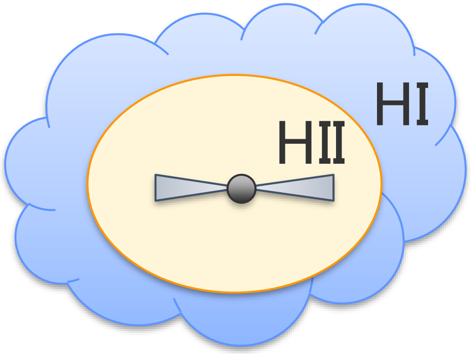
HI: neutral hydrogen H^0

HII: ionized hydrogen H^+

- Acc. from hot HII bubble

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

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



$T_{\rm II} = 7\text{x}10^4$K
$T_{\rm I} = 1\text{x}10^4$K

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

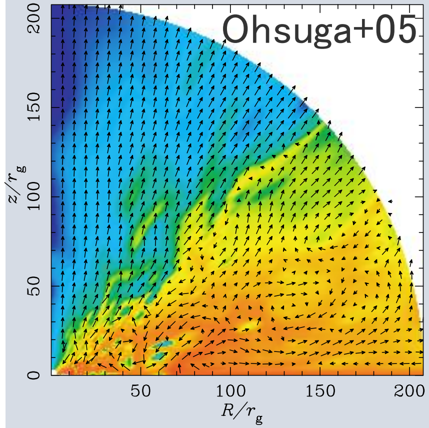
Often ignored in large-scale simulations, this mechanism easily causes significant reduction of accretion rate

BH can grow efficiently (at a super-Eddington rate) in a dense region

Horizon scale: what fraction of gas can reach BH?

Bondi scale: how much gas is supplied to BH's vicinity?

BH



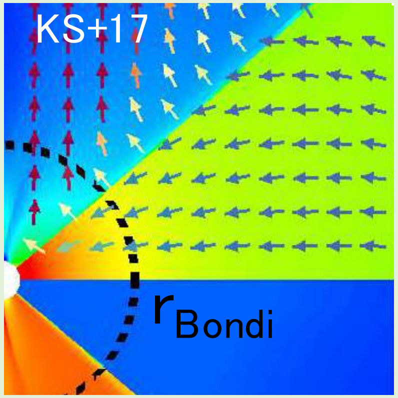
Super-Eddington accretion can be sustained though large mass is lost by outflow

(Ohsuga+05,Sadowski+15)

- BH accretion rate at horizon for a given large-scale mass supply rate

(Hu+22)

$$\dot{M}_{\rm BH} \approx 17\dot{M}_{\rm Edd}\left(\frac{\dot{M}_{\rm suply}}{300\dot{M}_{\rm Edd}}\right)^{0.5}$$



Gas can be supplied at a super-Edd. rate due to inflow/outflow separation with anisotropic radiation

(e.g., KS+17, Takeo+18)

- HII bubble trapping in extremely dense gas also leads to rapid accretion

(Inayoshi+16, Toyouchi+19)

$$n_{\rm H} \gtrsim 10^7\,{\rm cm}^{-3}\left(\frac{M_{\rm BH}}{10^3\,M_\odot}\right)^{-1}$$

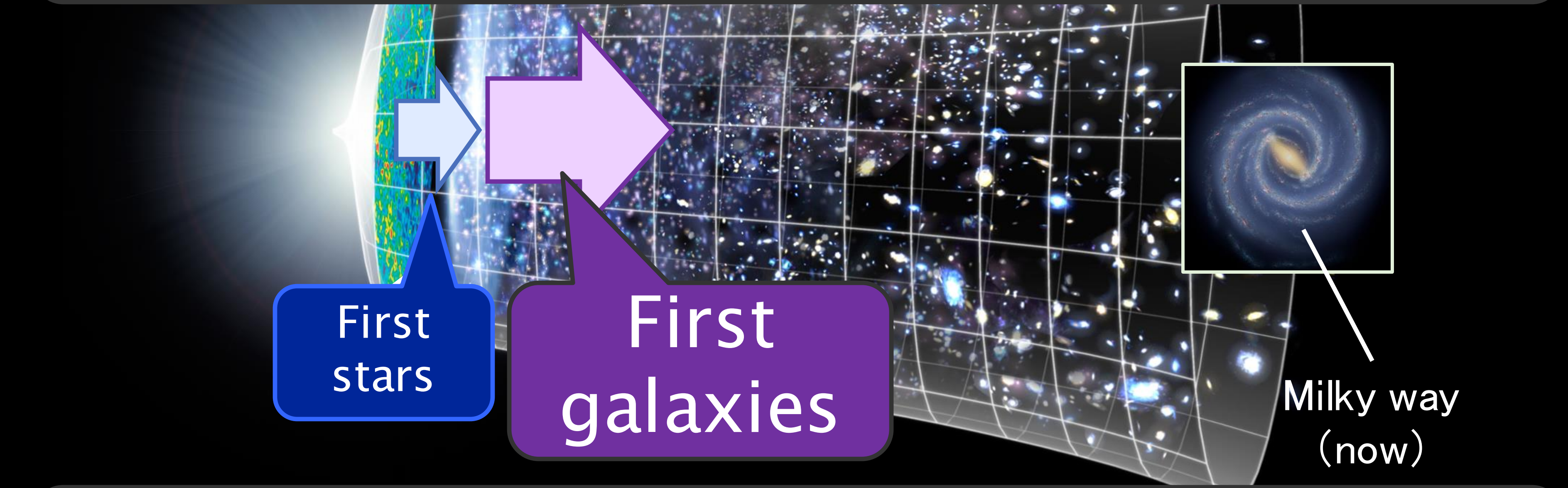
BHs grow efficiently (at super-Eddington rate) in a dense region

→ what is BHs' environment during first galaxy formation?

How did the first galaxies form?

Let’s advance the understanding of cosmic evolution step by step

We are working on first galaxy formation simulations incorporating physically-motivated small-scale models (Garcia+23, KS+24)



Small mass and short duration of first galaxy formation
= small computational cost and/or high resolution ($\Delta x \sim 0.1$pc)

(redshift)

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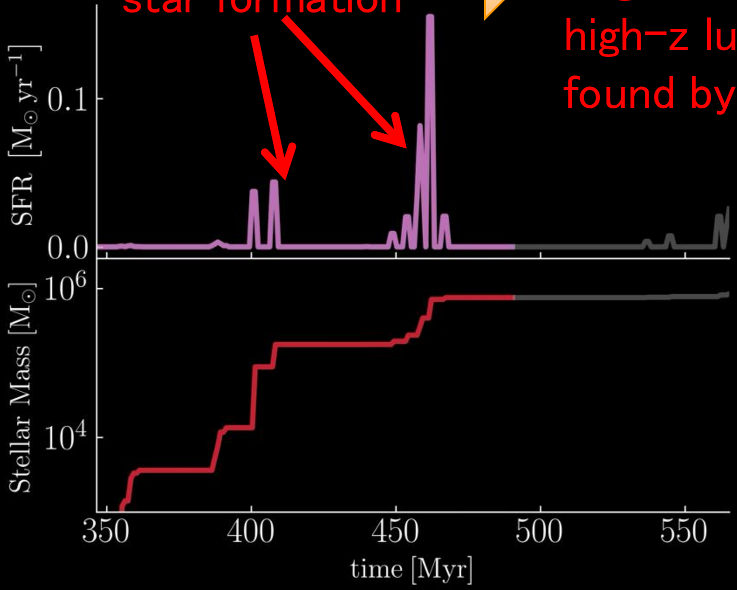
Zoom-in simulations of a single galaxy ($M_{halo} = 10^8 M_{sun}$ at $z = 10$)

Code	RAMSES-RT (Teyssier 2002, Rosdahl & Teyssier 2015)	Cosmological AMR (M)HD, Moment method RT (M1 closure), DM particle, sink (BH) particle, stellar radiation, SN feedback, non-equil. chemistry/cooling/heating
Initial Cond.	MUSIC (Hahn & Abel 2011)	Zoom-in initial condition at $z = 127$
Final Time	500 Myr after Big Bang	same as $z \sim 10$
Box Size	0.3 h^{-1} cMpc (zoom-region)	35 h^{-1}cMpc (base-box)
DM Mass	800 $M_\odot$ resolution (zoom-region)	10^{11} $M_\odot$ (base-box)
Star Mass	100 $M_\odot$ resolution	Internal Salpeter-like IMF
Refinement	$N_J = 8$ ($\Delta x > 1$ pc), 4 ($\Delta x < 1$ pc)	at least N_J cells per Jeans length
Resolution	$\Delta x_{min} = 0.15$ pc * [(1 + z) / 10]	AMR level = 25
Star Formation	$n_{SF,th} = 5 \times 10^4$ cm^{-3} $[(1+z)/10]^2$ (T/100 K)	Resolving gravitational collapse of clouds

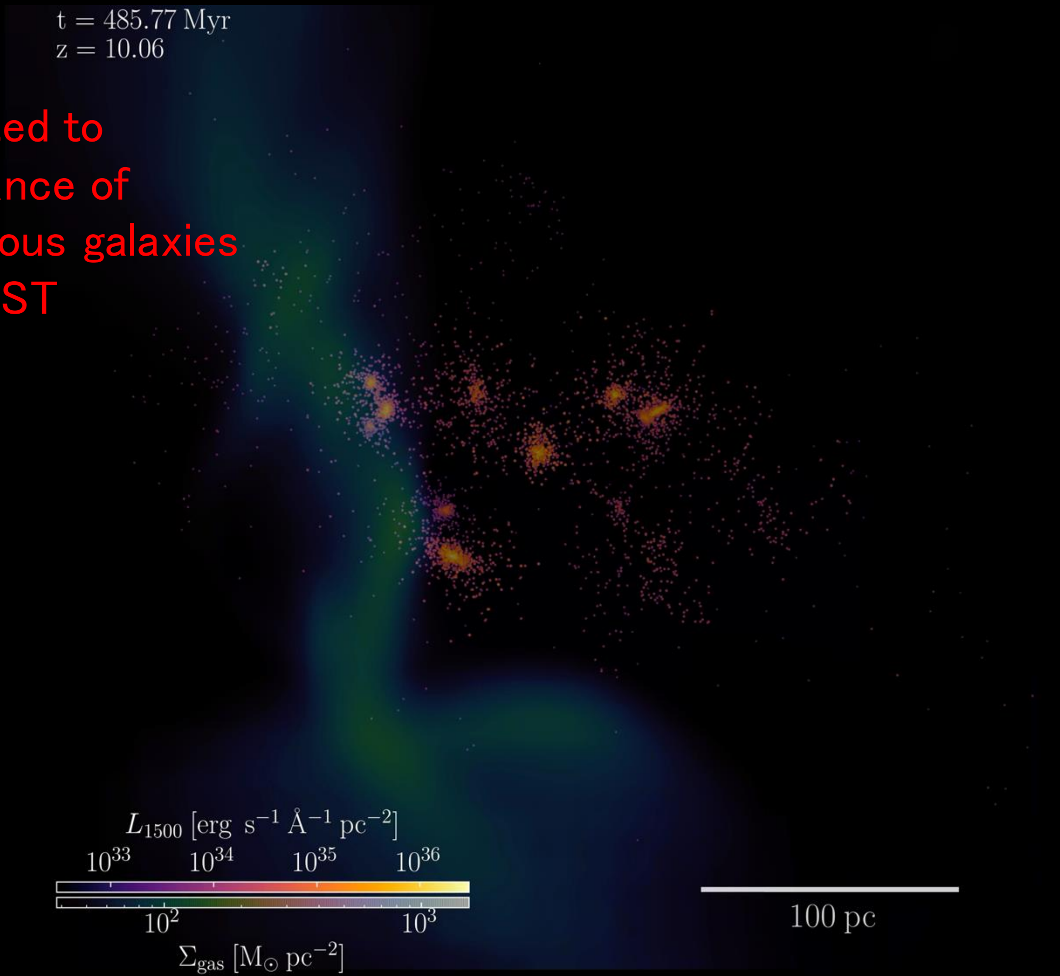
Star formation proceeds in a bursty way

(KS+24)



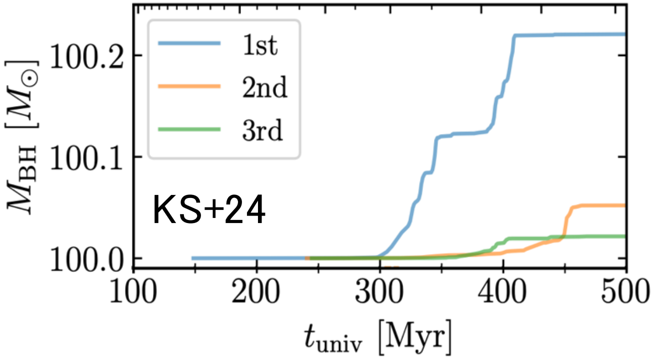
Burst Pop II
star formation

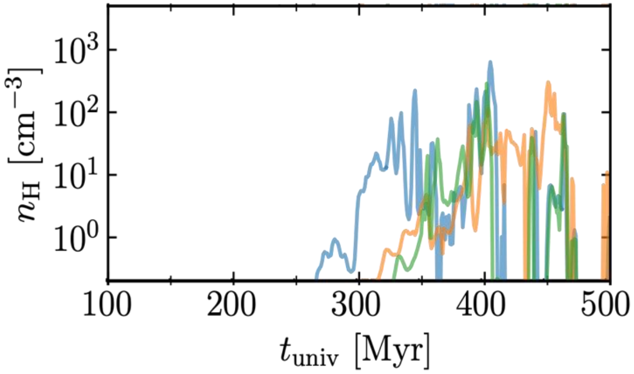
may be related to
large abundance of
high-z luminous galaxies
found by JWST



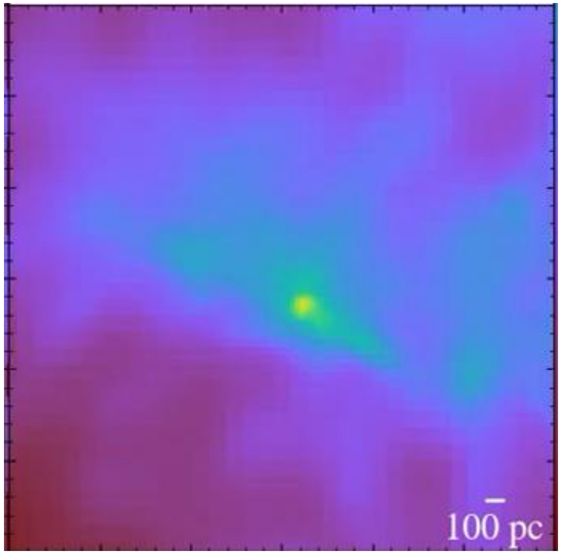
Pop III-remnant BHs hardly grow during the first galaxy formation

- We follow the formation of Pop III remnant BHs and their growth via Bondi-Hoyle-Lyttleton accretion
- The first galaxy hosts a few BHs at z～10
- However, their accretion growth is extremely inefficient





color: density
X: Pop III-remnant BH
•: Pop II star



<u>Stellar-mass seed BHs hardly grow because the surrounding density cannot be very high</u> (see also Alvarez+09, Smith+18)

⇨ massive seeds or positive BH feedback?

Other simulations also suggest IMBHs still hardly grow (e.g., Ma+21, Bahe+22)

4. CONCLUSION

Conclusion

- NANOGrav 15yr seems not to contradict with GW background from SMBH mergers based on the current astrophysical understanding
- Cosmological simulations reproduces observational results, such as M_{BH}–M_{star} relation, but with many tuning parameters
- There are a lot of uncertainties in theoretical modeling of SMBH formation and evolution
- Even the formation of $10^6 M_{sun}$ SMBHs (starting point of SMBH evolution) is a theoretical challenge (an unsolved astrophysical problem)

and some thoughts…

- astrophysics is so poorly understood that astrophysical origin of GW background observations cannot be excluded
- At the same time, cosmological origin cannot be excluded (though not strongly motivated)
- In my opinion, better astrophysical understanding is a key to maximize the power of GW background observations in constraining cosmology