銀河・超巨大ブラックホール共進化過程の理解に向けて

豊内大輔 (大阪大学)

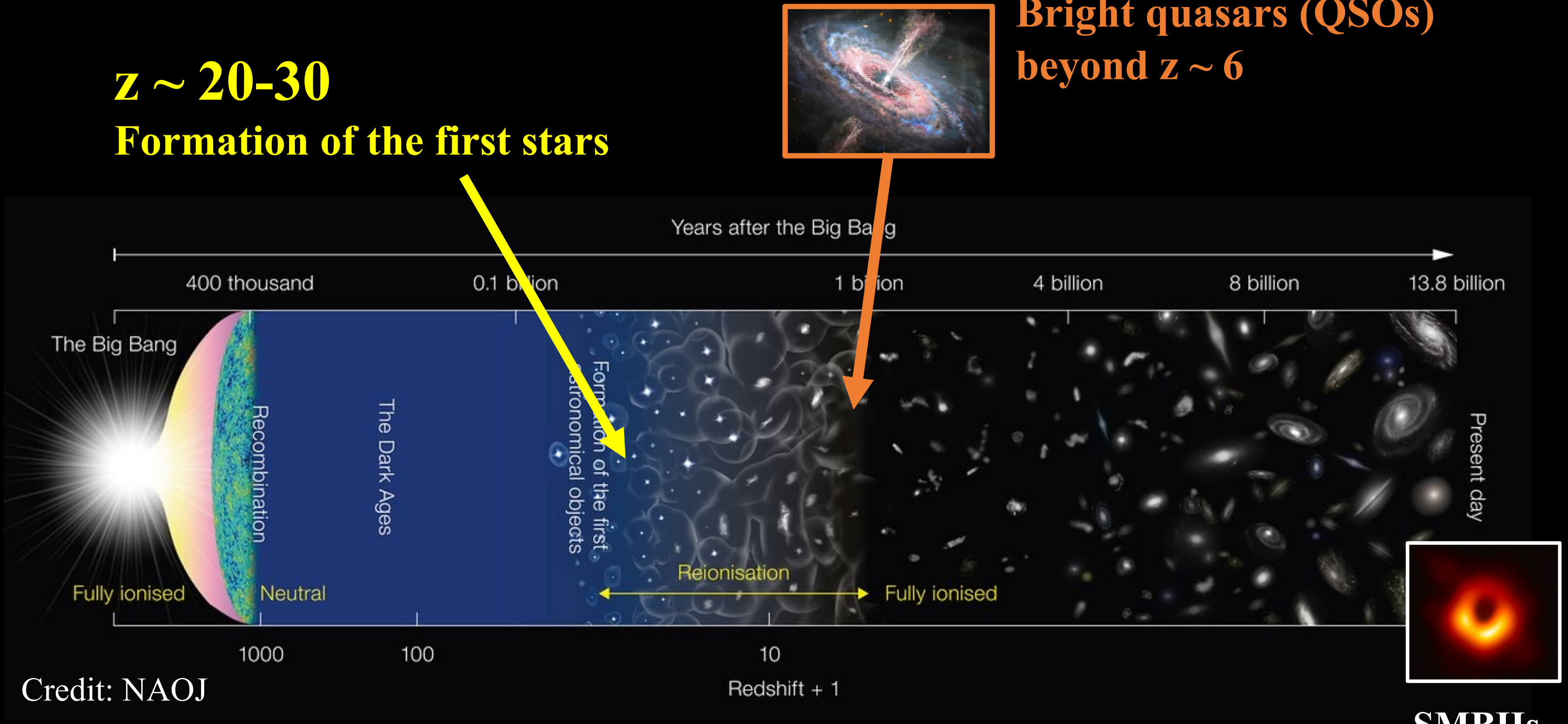
BH大研究会 @ 御殿場高原ホテル ２０２４年2月29日

Super massive black holes in the universe

$z \sim 20\text{-}30$

Formation of the first stars

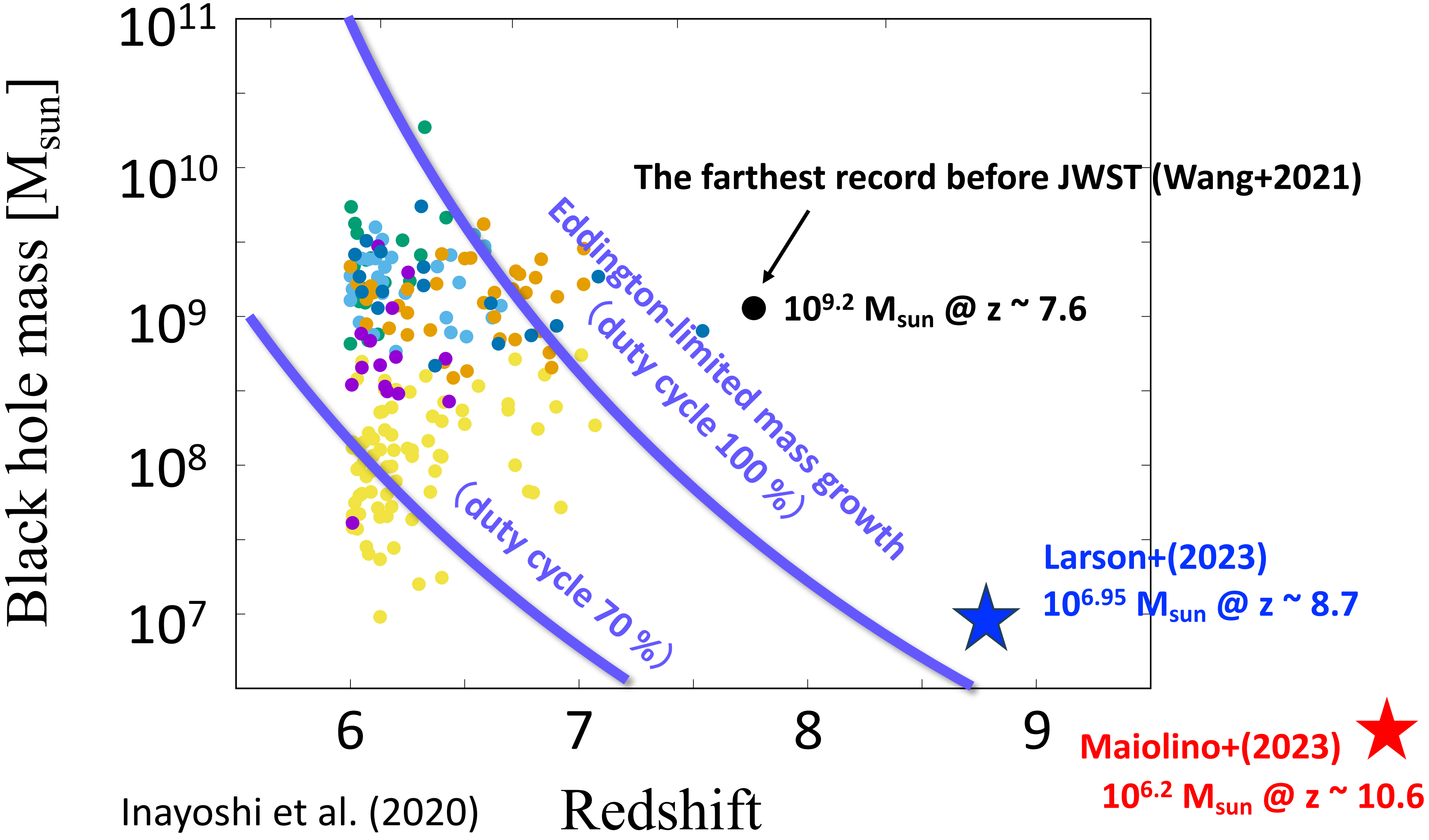
Bright quasars (QSOs) beyond $z \sim 6$



Credit: NAOJ

SMBHs

($> 10^6\ M_\odot$)



The farthest record before JWST (Wang+2021)

$10^{9.2}$ M_{sun} @ z ~ 7.6

Larson+(2023)
$10^{6.95}$ M_{sun} @ z ~ 8.7

Maiolino+(2023)
$10^{6.2}$ M_{sun} @ z ~ 10.6

Inayoshi et al. (2020)

Two possible solutions

(1) $M_{BH,seed} > 10^4$ M_{sun} or (2) Super-Eddington accretion

1. Supermassive star (SMS) formation

(DT et al. 2023; Li et al. 2021, 2023)

Basic idea of SMS formation

Mass accretion rates

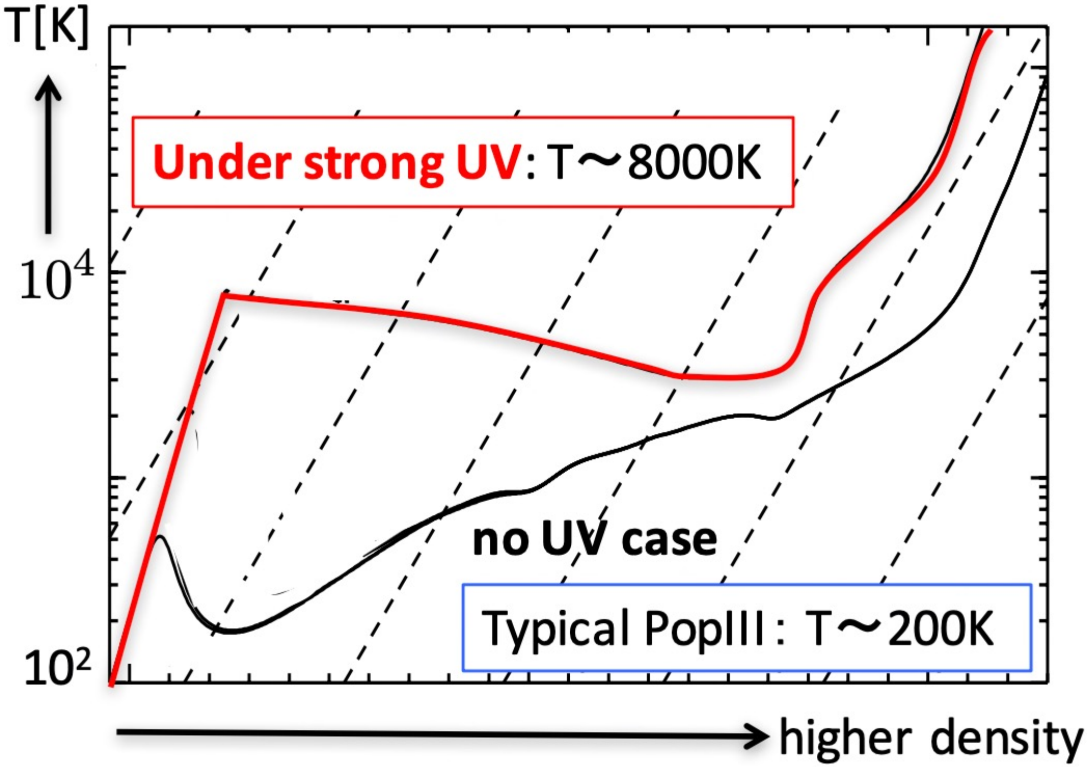
$$\dot{M}_{acc} \sim \frac{M_{Jeans}}{t_{freefall}} \sim 4 \times 10^{-4}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1} \left(\frac{T}{200\,K}\right)^{1.5}$$

$$\sim 0.1\ \mathrm{M}_\odot\ \mathrm{yr}^{-1} \left(\frac{T}{8000\,K}\right)^{1.5}$$

Final mass (lifetime ~ 1 Myr)

$$\mathrm{M}_* \sim 400\ \mathrm{M}_\odot$$

$$\sim 10^5\ \mathrm{M}_\odot$$

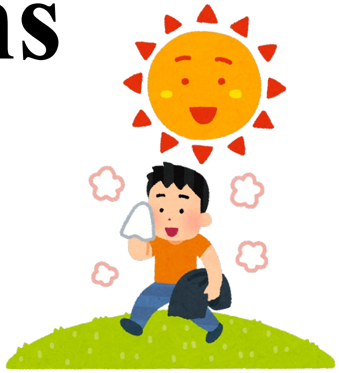


Omukai(2001)

Various formation paths

- **H_2 photodissociation by LW backgrounds**
  - ✓ Onset of star formation at T ~ 8000K

  (e.g., Omukai 2001; Oh & Haiman 2002; Visbal+2014; Chon+2016)



- **Cosmological baryonic streaming motion**
  - ✓ delays the baryonic mass assembly

  (e.g., Tanaka & Li 2014; Hirano+2017, Schauer+2017)

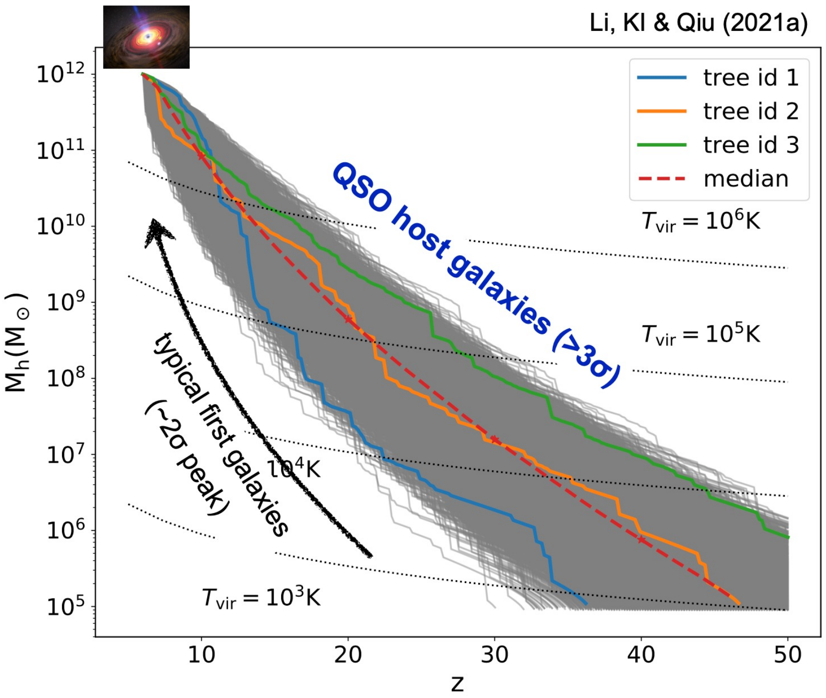
- **Dynamical heating via DM halo mergers**
  - ✓ drives turbulence and prevents gravitational gas collapse

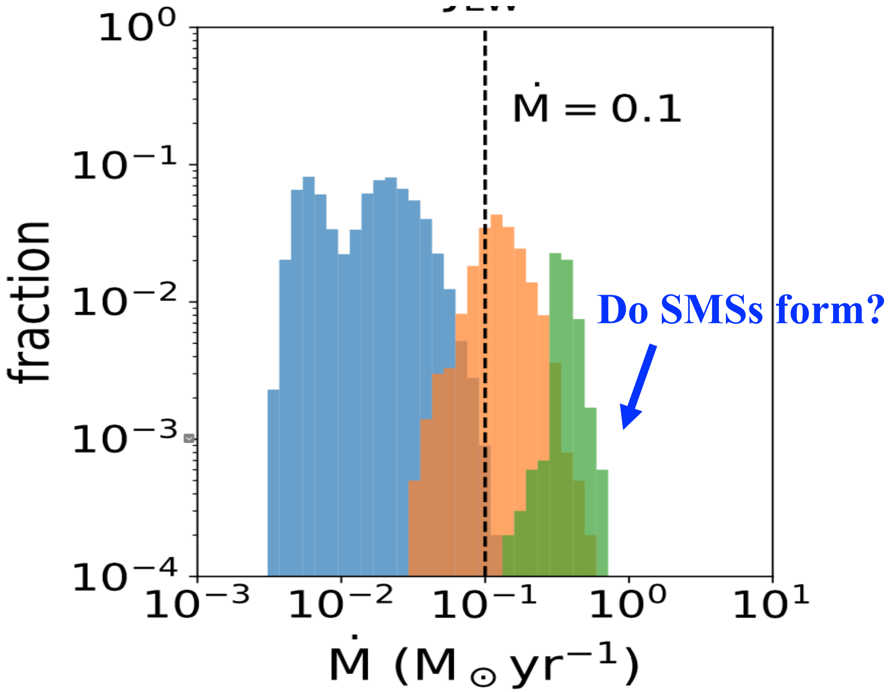
  (e.g., Wise+2019; Regan+2020)

- Others: Runaway stellar collision, Cold accretion shock etc.

Semi-analytic calculations (Li+2021)

- ΛCDM cosmology + galaxy formation model
  - ✓ Generate 10^4 merger trees of z ~ 7 QSO progenitors
  - ✓ Calculate temperature evolution of gas clouds considering thermal and dynamical heating
  - ✓ Derive PDF of mass supply rates onto the central protostars



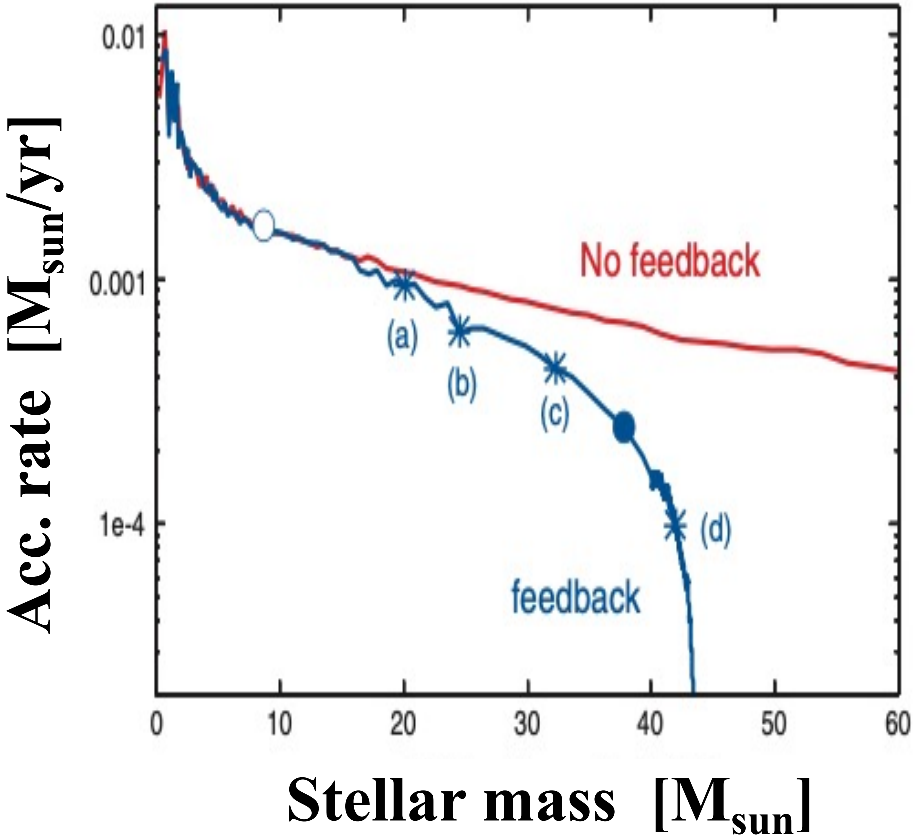


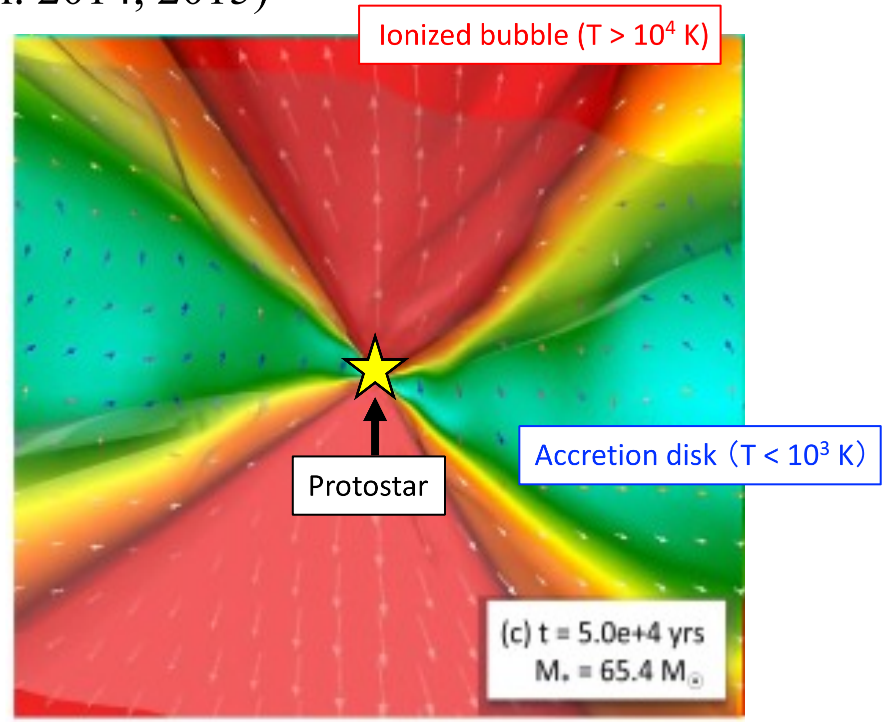
Radiative feedback

Radiation hydrodynamics (RHD) simulations of PopIII star formation:

- **Radiative transfer + Non-equilibrium chemistry + Stellar mass growth**

(e.g., Hosokawa et al. 2011, 2016; Hirano et al. 2014, 2015)



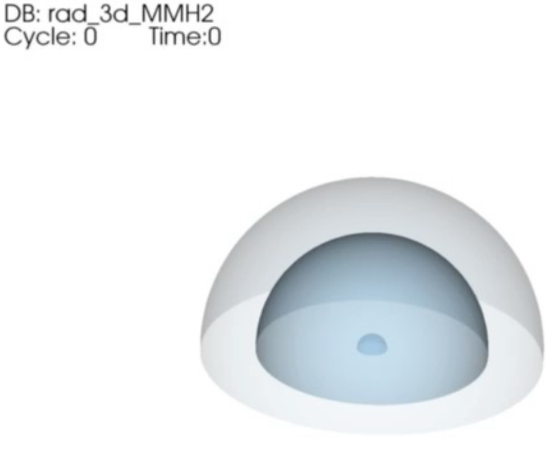


Disk photoevaporation due to UV radiation

→ **Self-regulation of the mass growth**

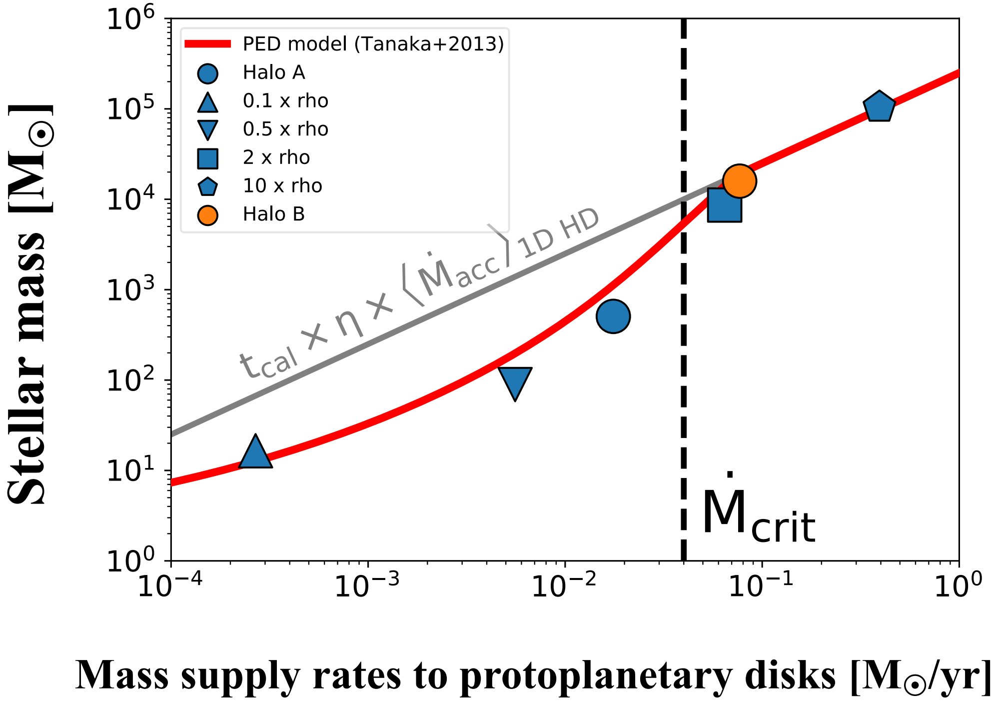
3D RHD sims. of SMS formation (DT+2023)

- ✓ Targeted several PopIII star forming regions extracted from a cosmological protogalaxy formation simulation (Wise+2019).
- ✓ **Succeeded to form SMSs with > 10^4 M_{sun} in some haloes.**
- ✓ **Diversity in the stellar mass, 10^2-10^5 M_{sun}**, depending on mass supply rates to protoplanetary disks ($\propto T^{1.5}$).



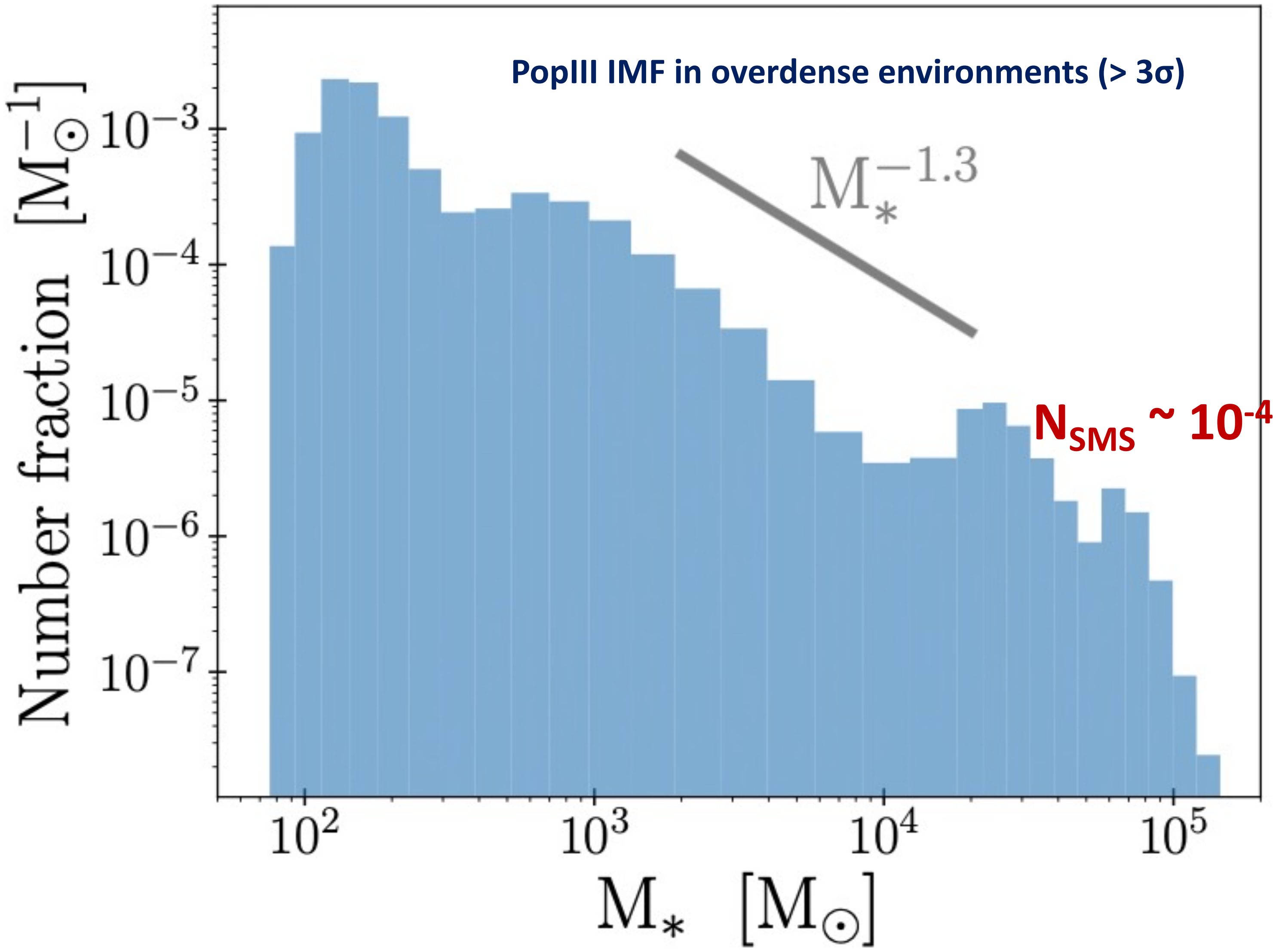
HI + H_2 ($T < 10^3$ K)

HII ($T > 10^4$ K)



($\propto T^{1.5}$)

Semi-analytic modeling (Li+2021, DT+2023)



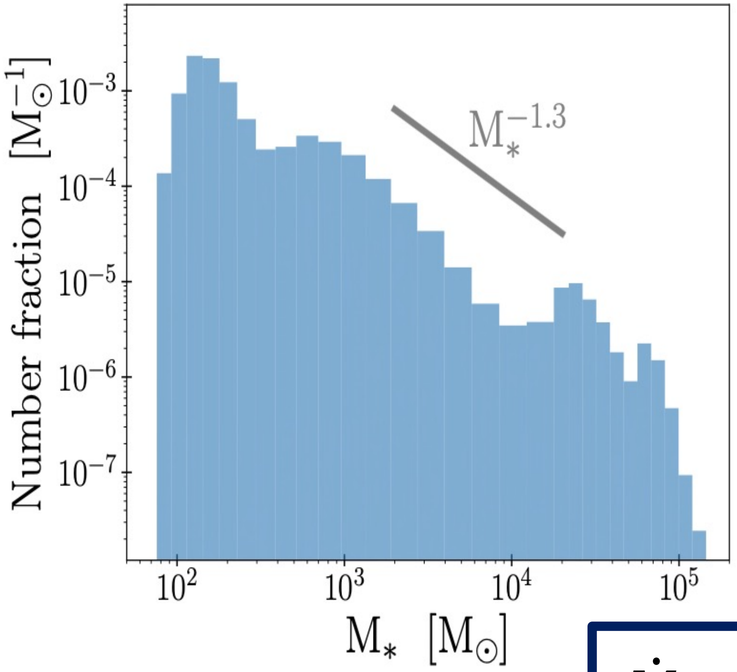
$N_{SMS} \sim 10^{-4}$ Mpc^{-3}

Toward formation of high-z QSOs

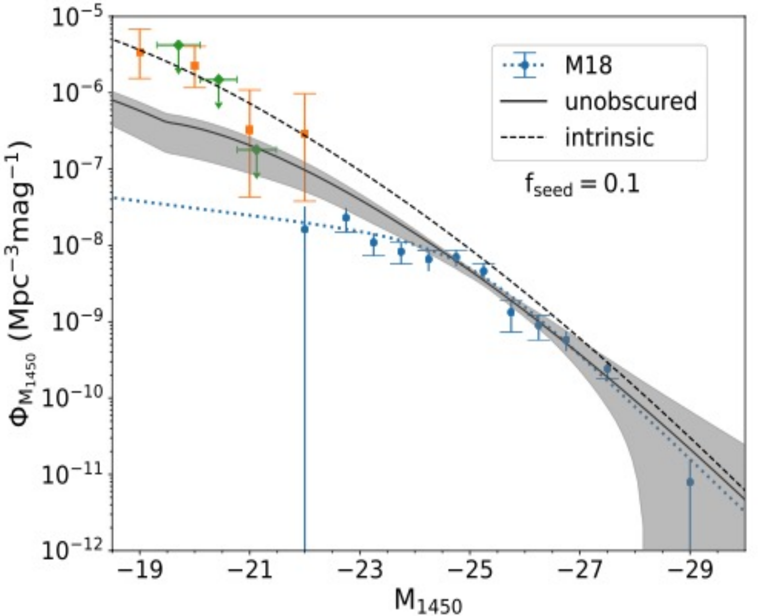
Li, Inayoshi, DT, et al. (2022)

- ✓ **Several episodes of super-Edd. accretion with a duty cycle of ~ 20 Myr** are needed to explain the bright end of the QSO LF.

PopIII IMF at z ~ 20



QSO luminosity function at z = 6

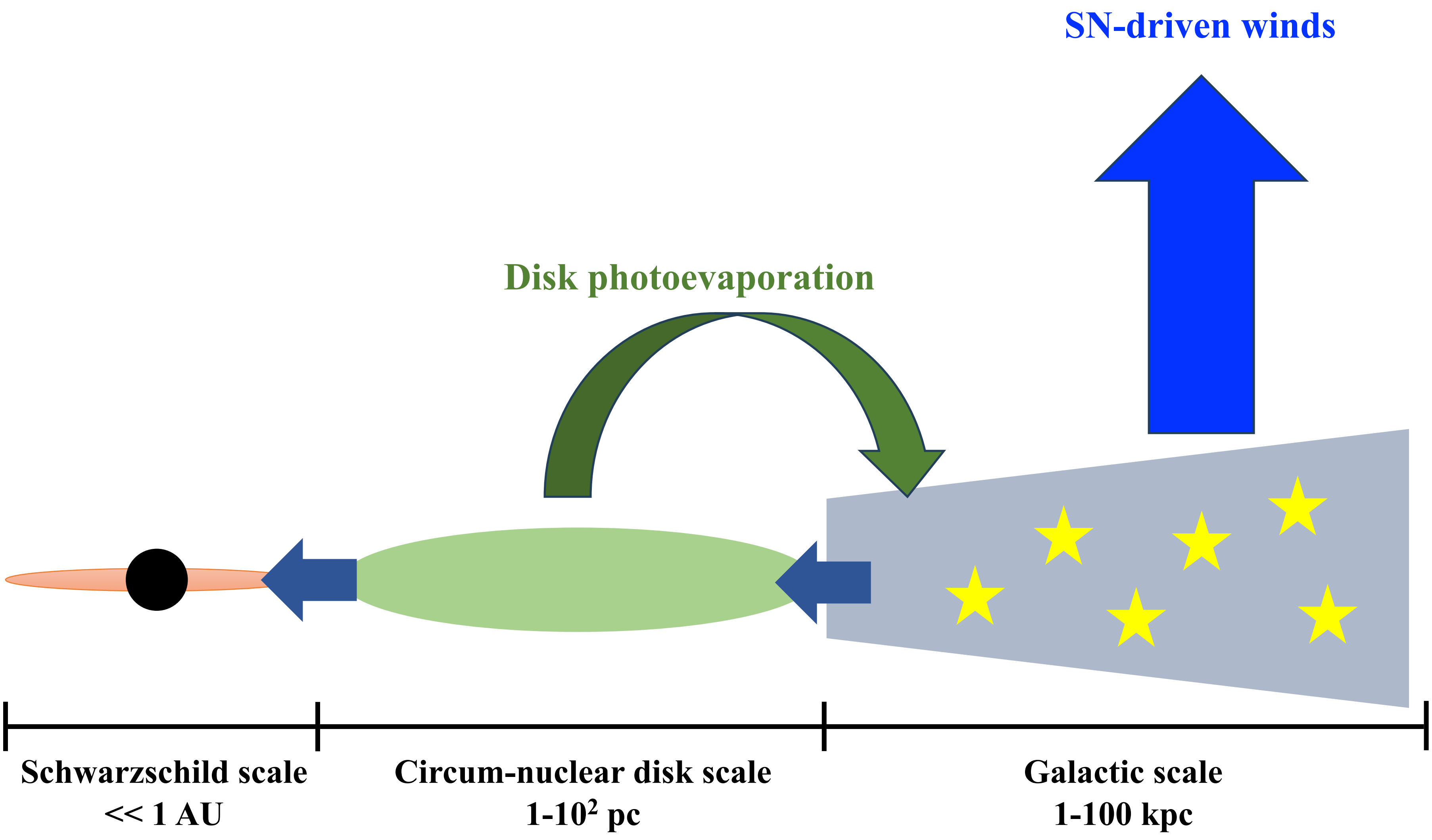


$$\dot{M}_{BH} \leftarrow P(\varepsilon_{Edd}, \tau_{duty})$$

2. Super-Edd. accretion onto IMBHs

(DT et al. 2019, 2020, 2021; Inayoshi, DT, et al. 2022)

Gas accretion onto the galactic center BHs



SN-driven winds

Disk photoevaporation

Schwarzschild scale
<< 1 AU

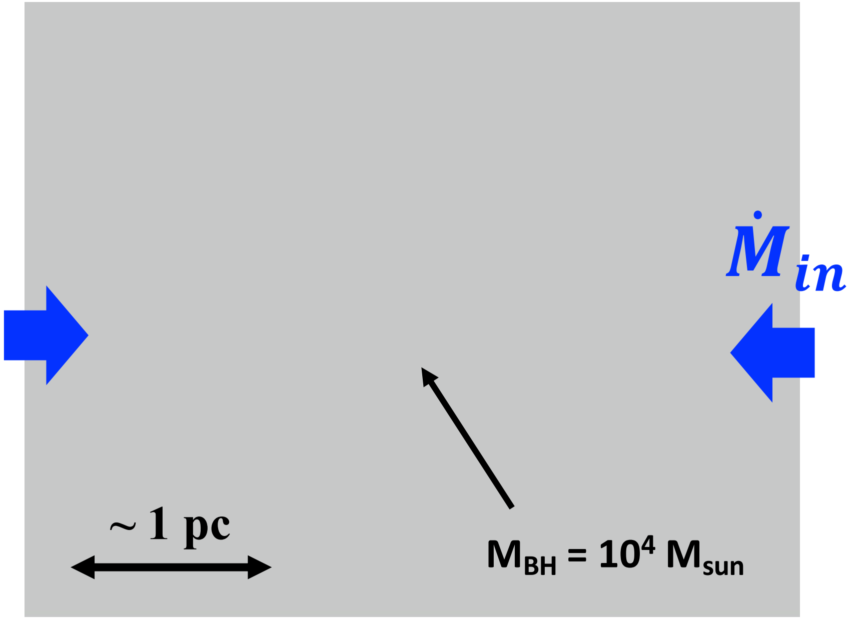
Circum-nuclear disk scale
1-10^2 pc

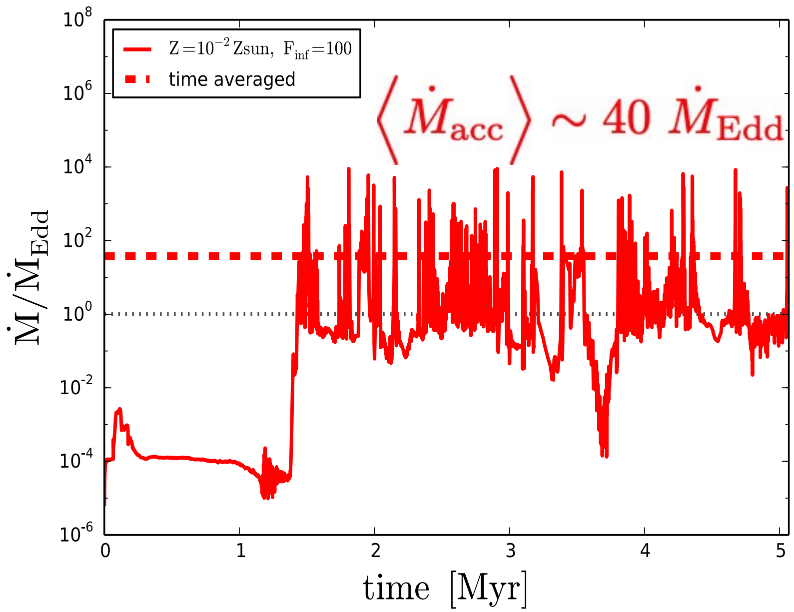
Galactic scale
1-100 kpc

3D RHD simulations in CND scale

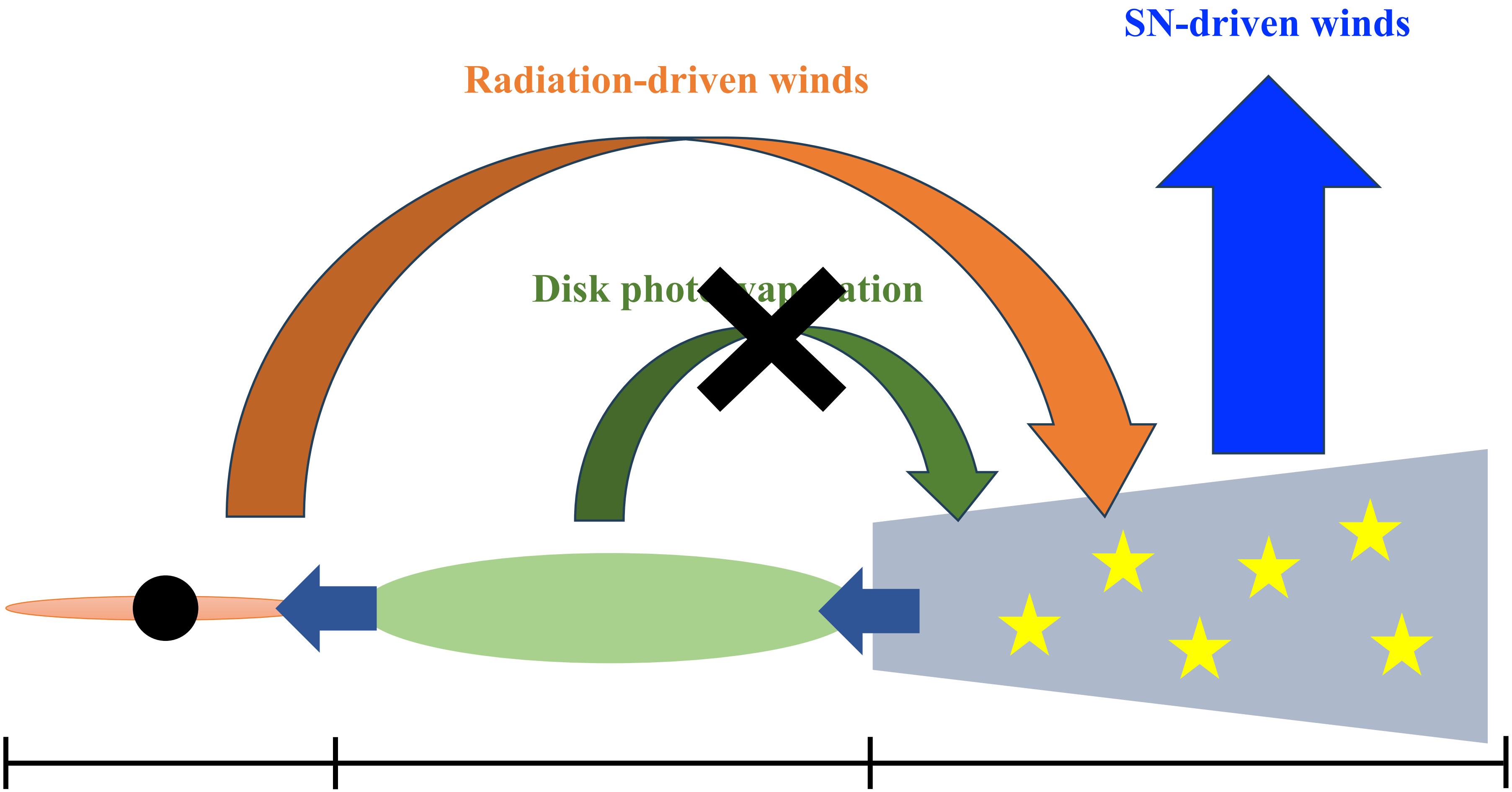
- **Disk photoevaporation is avoidable (e.g., Inayoshi+16, 22, DT+19, 21).**
- The accretion disk becomes optically thick to UV irradiation, when satisfying

$$\boxed{\dot{M}_{\rm acc} \gtrsim 0.01\ {\rm M_\odot\ yr^{-1}} \left(\frac{c_{\rm s}}{1\ {\rm km\ s^{-1}}}\right) \left(1+\frac{Z}{0.01\ Z_\odot}\right)^{-1}}$$





Gas accretion onto the galactic center BHs



SN-driven winds

Radiation-driven winds

Disk photoevaporation

Schwarzschild scale
<< 1 AU

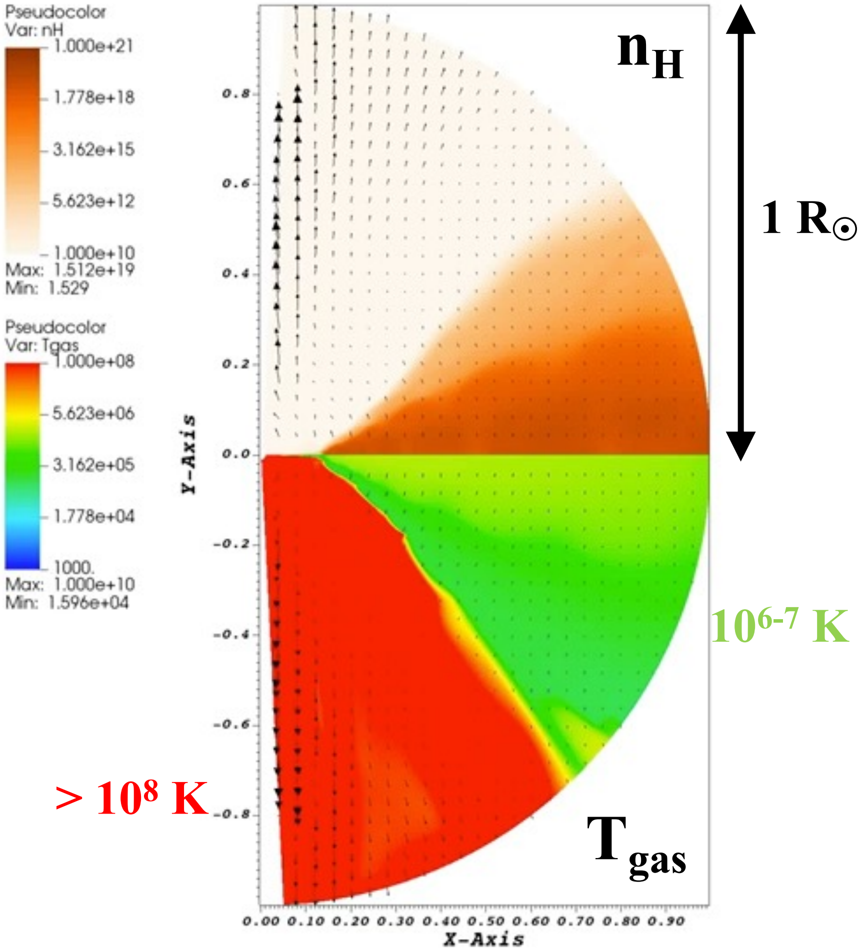
Bondi scale
1-10^2 pc

Galactic scale
1-100 kpc

3D+2D RHD simulations of super-Edd. mass transfer in BH binaries

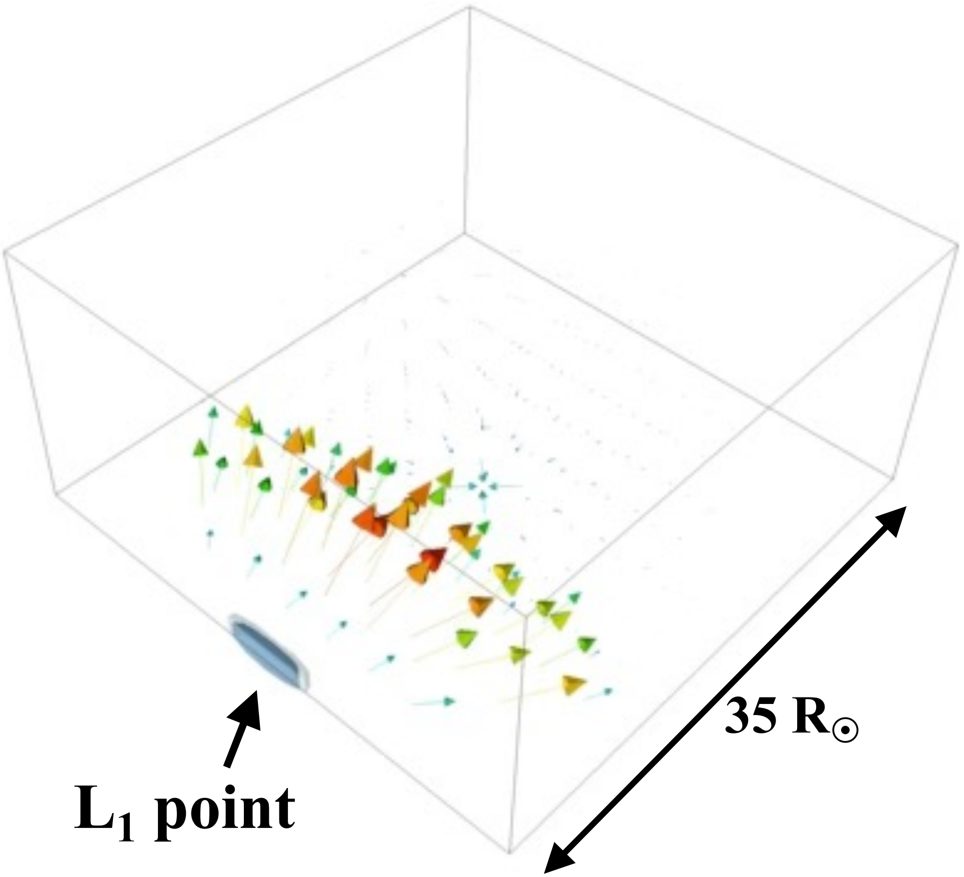
Inner region

$r = 0.01\text{-}1\ R_\odot$ ($\sim 100\text{-}10^4\ R_g$)

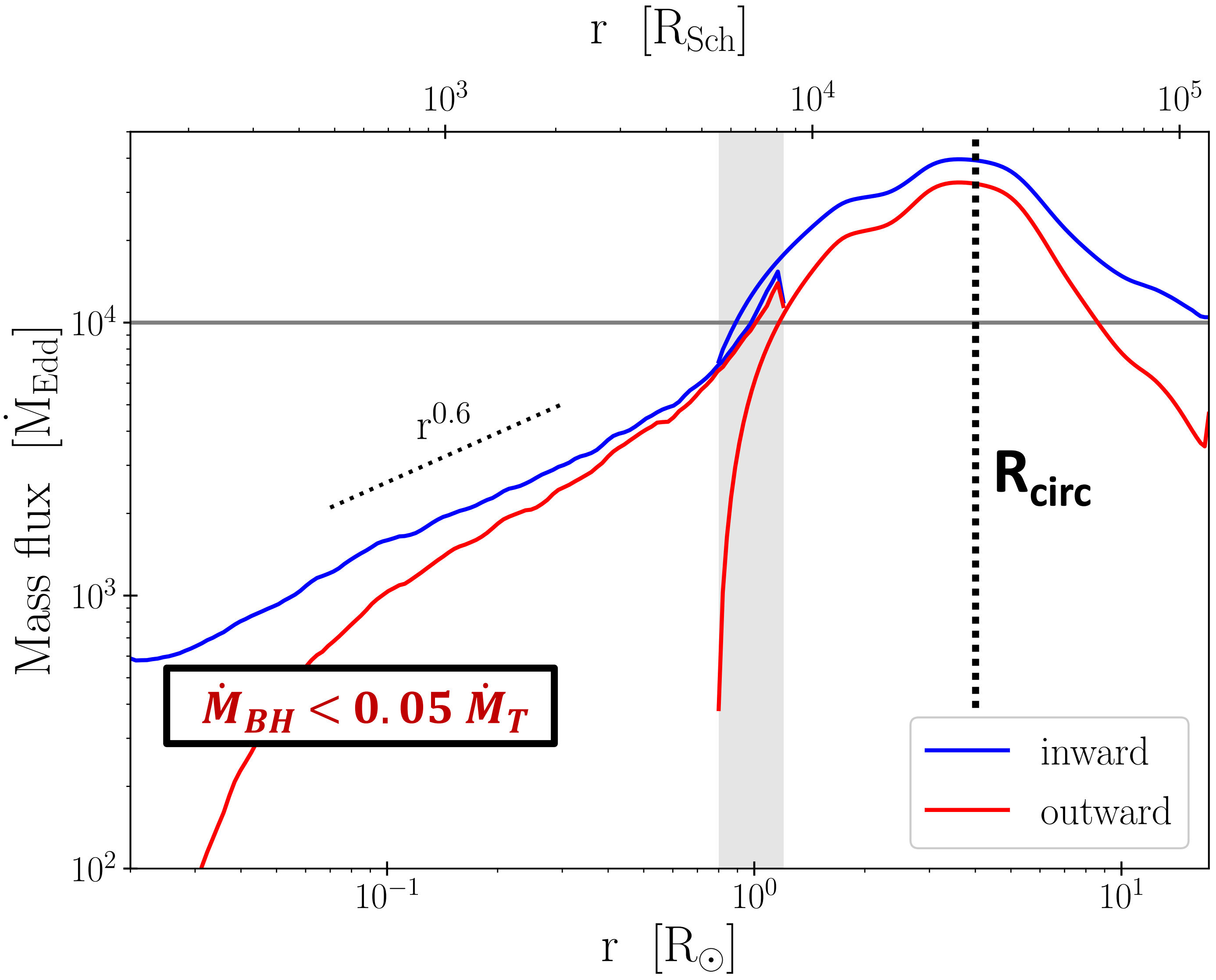


Outer region

$r = 0.8\text{-}17.3\ R_\odot$ ($\sim 10^4\text{-}10^5\ R_g$)

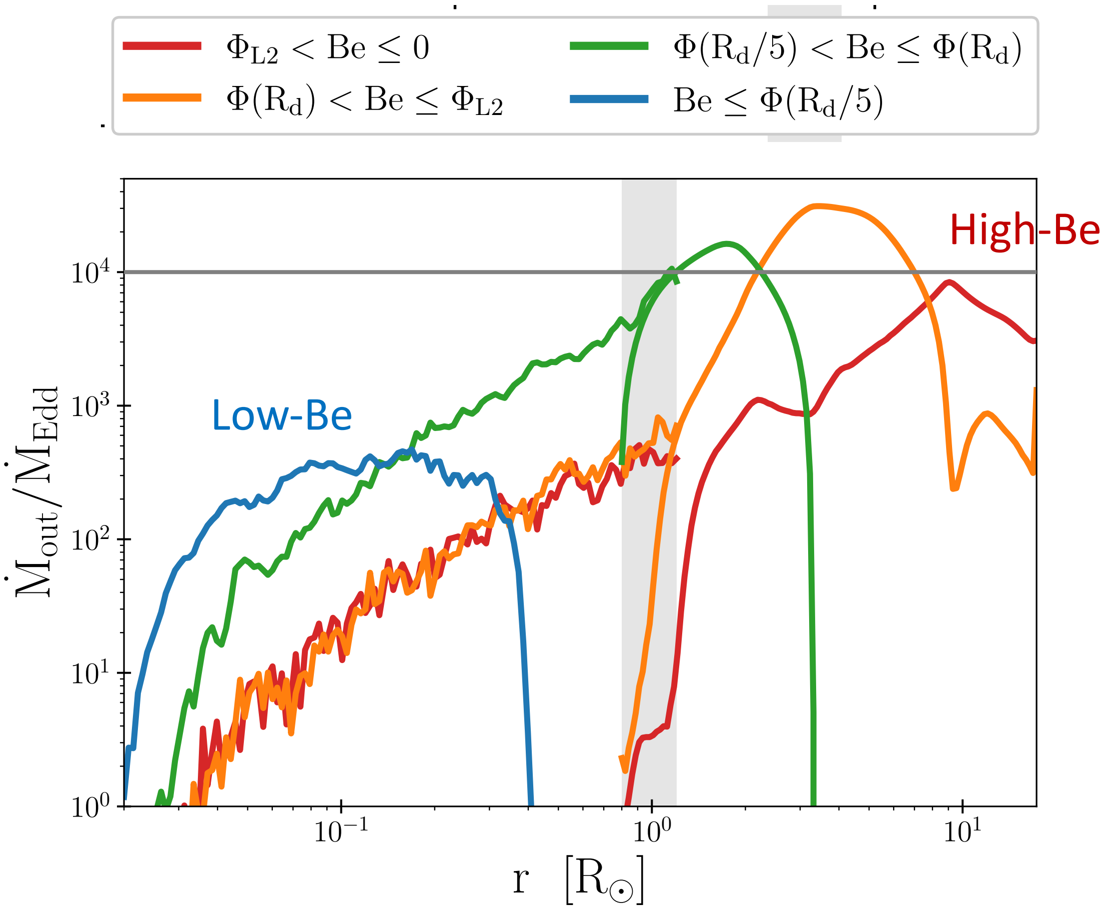


Inward and Outward mass fluxes



$\dot{M}_{BH} < 0.05\ \dot{M}_T$

Propagation of outflows

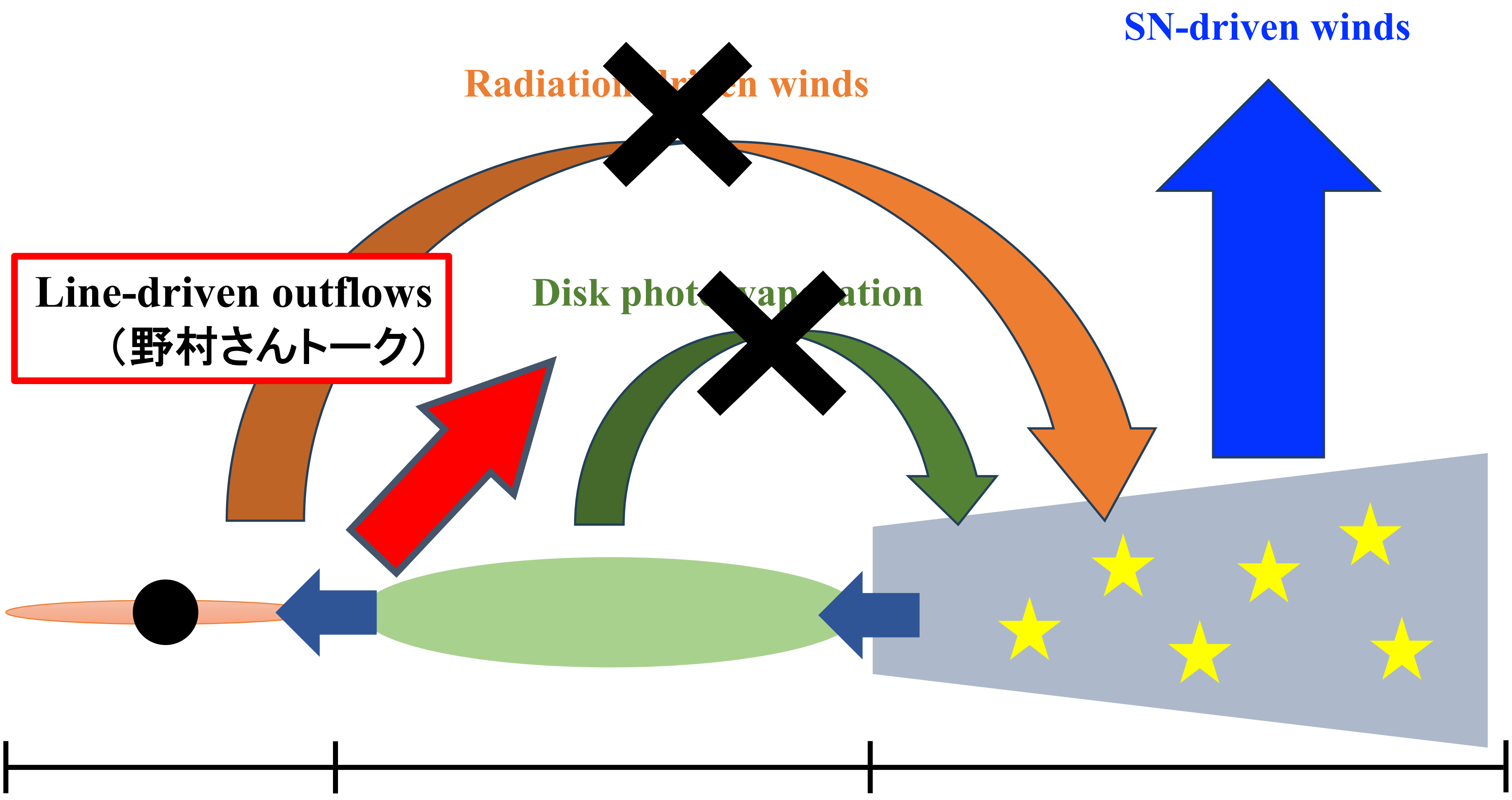


Bernoulli number

$$Be \equiv \frac{1}{2}v^2 + \Phi + h$$

- 内側からはエネルギー的に弱いアウトフローが出る。
- 少し外側に落ちたアウトフローがそこで加速され、伝播していく。
- 遠心力半径付近から吹くアウトフローは連星脱出に十分なエネルギーを持つ。

Gas accretion onto the galactic center BHs



SN-driven winds

Radiation-driven winds

Line-driven outflows
（野村さんトーク）

Disk photoevaporation

Schwarzschild scale
<< 1 AU

Bondi scale
1-10^2 pc

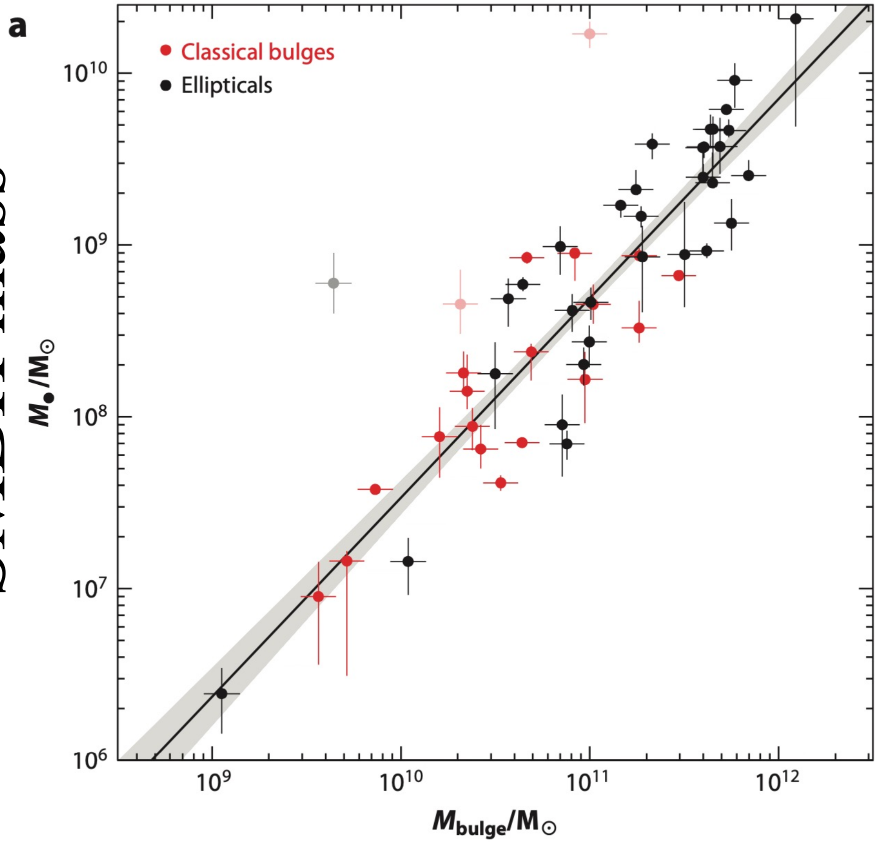
Galactic scale
1-100 kpc

3. Coevolution of galaxies and SMBHs

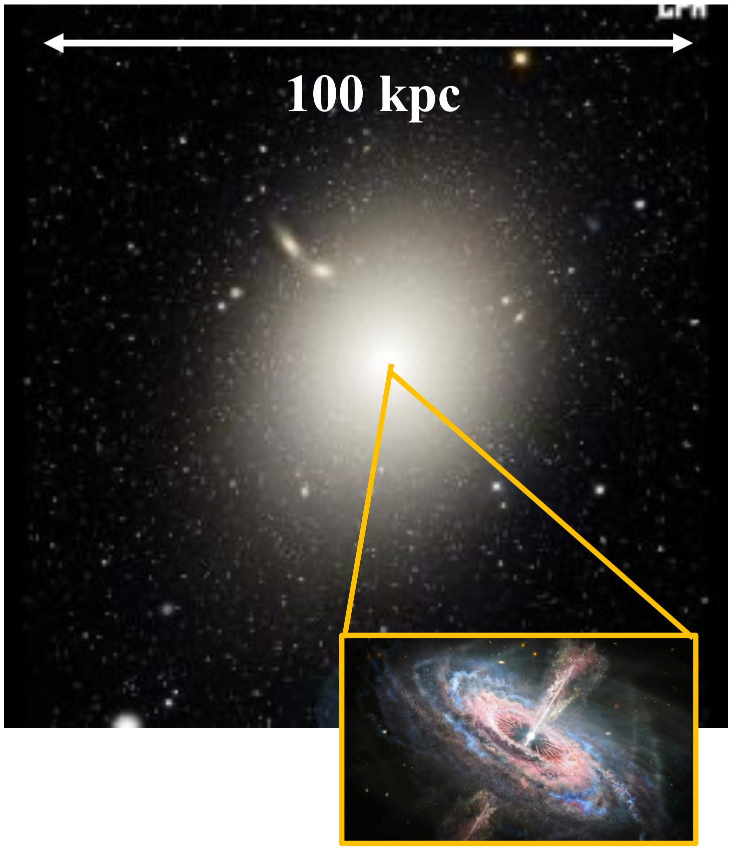
(DT, Kimura, and Hosokawa, in prep.)

Coevolution of galaxies and SMBHs

SMBH mass

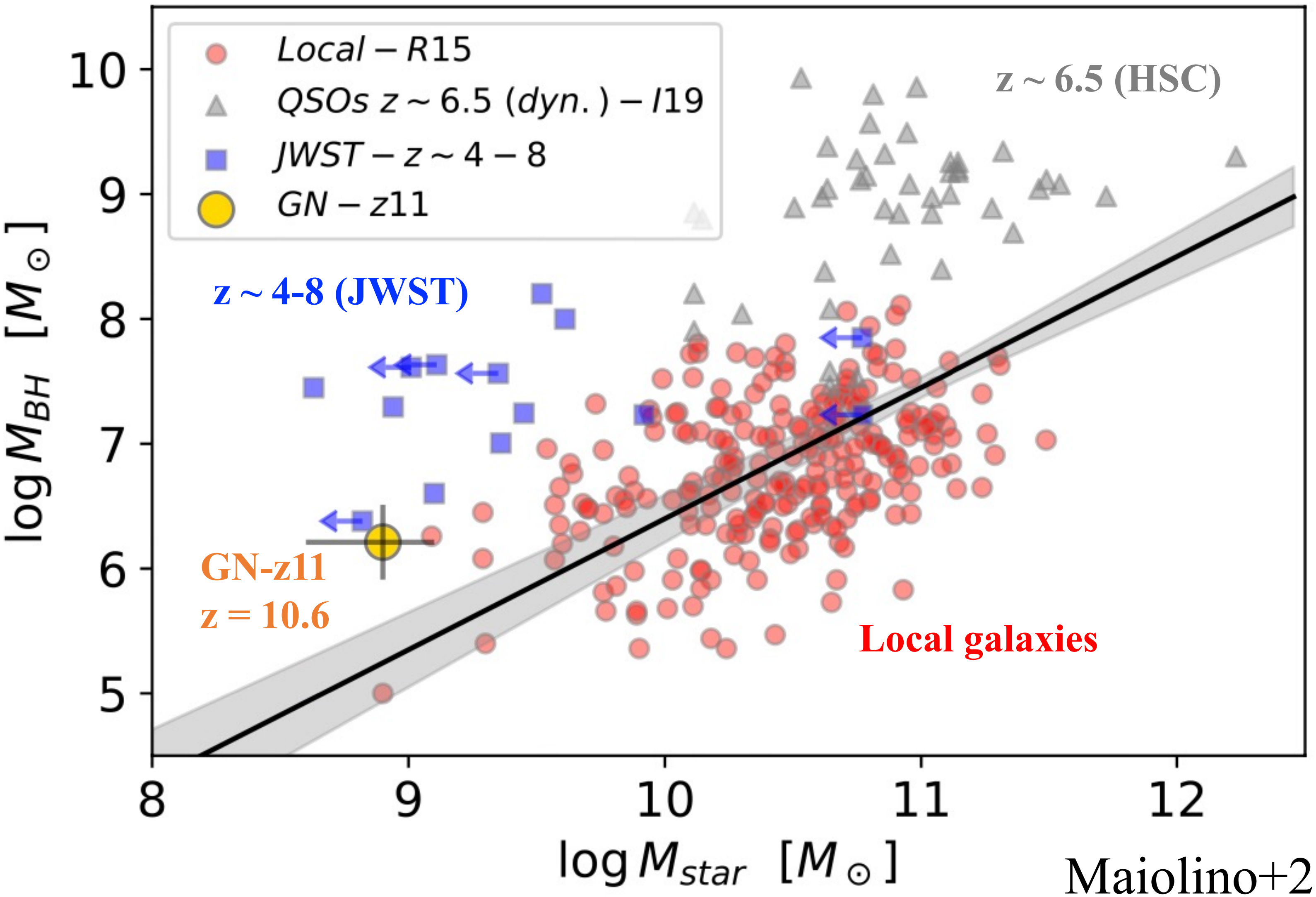


Bulge mass



< 1 pc

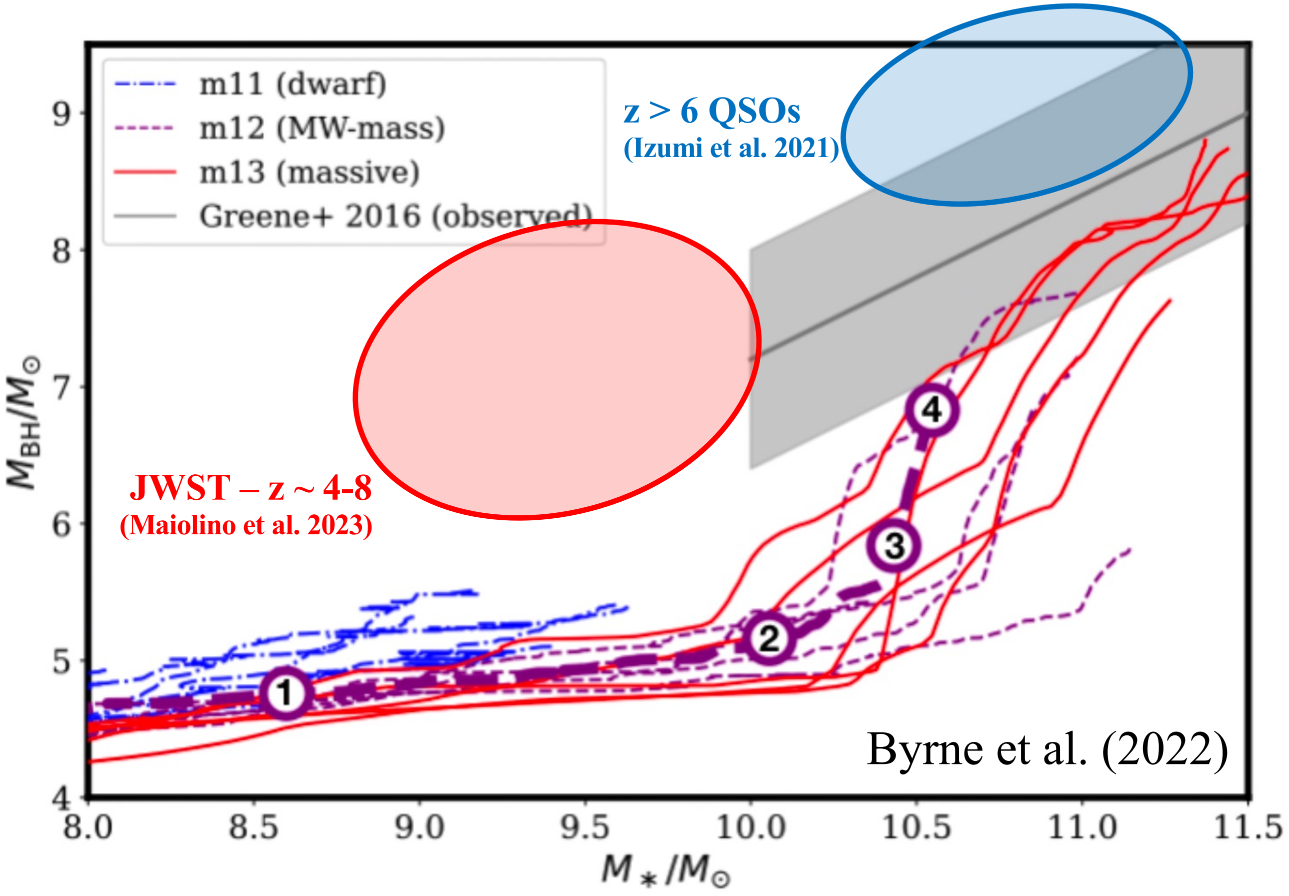
Overmassive BHs in the early universe



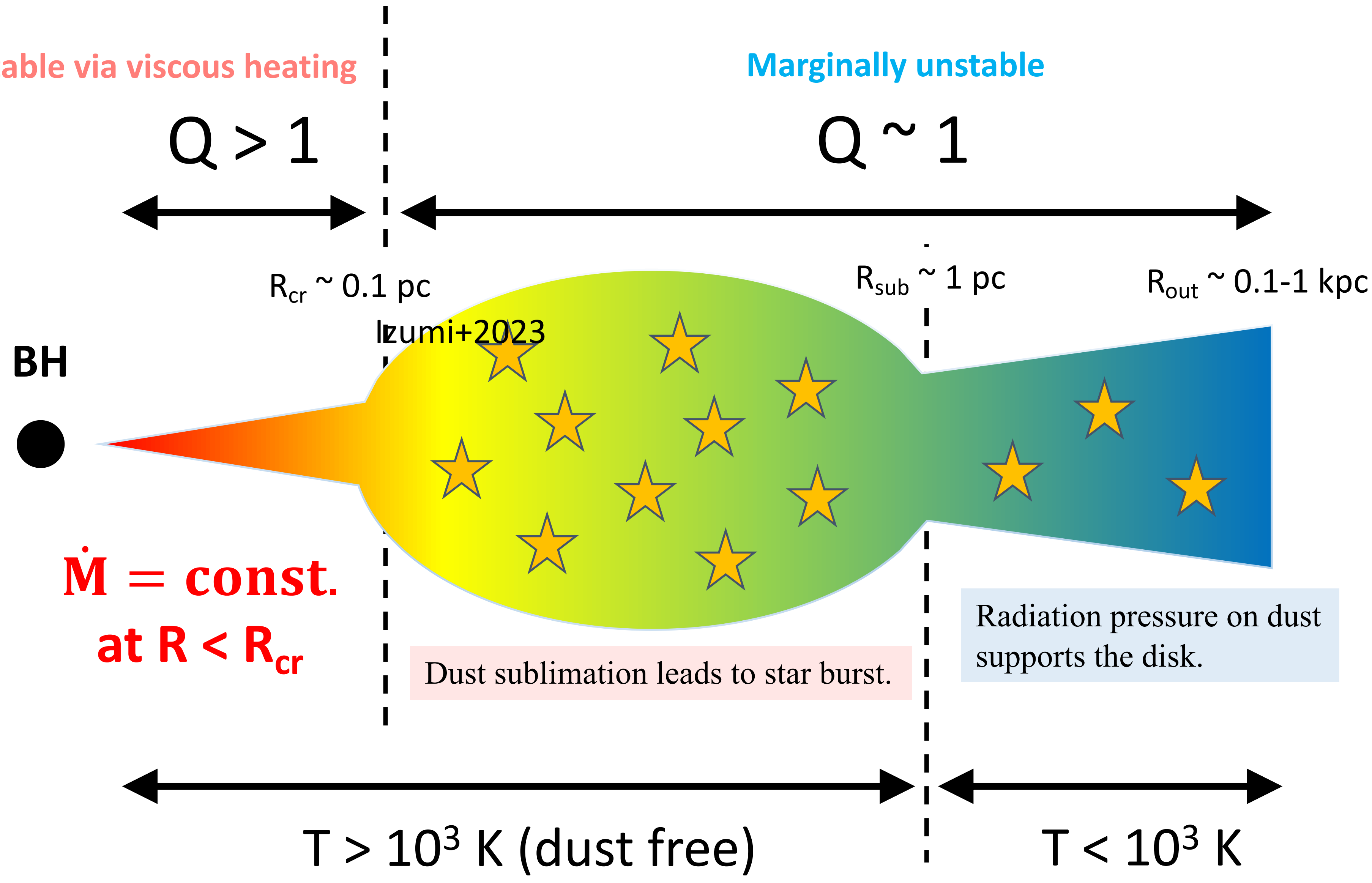
Maiolino+2023

SMBH formation in cosmological simulations

- M_{bh}-M_* relation has not been explained yet.
- e.g., Byrne+2022: suppose no AGN feedback



Star formation around the central BH



Stable via viscous heating

$Q > 1$

Marginally unstable

$Q \sim 1$

$R_{cr} \sim 0.1$ pc

Izumi+2023

$R_{sub} \sim 1$ pc

$R_{out} \sim 0.1\text{-}1$ kpc

BH

$\dot{M} = \text{const.}$

at $R < R_{cr}$

Dust sublimation leads to star burst.

Radiation pressure on dust supports the disk.

$T > 10^3$ K (dust free)

$T < 10^3$ K

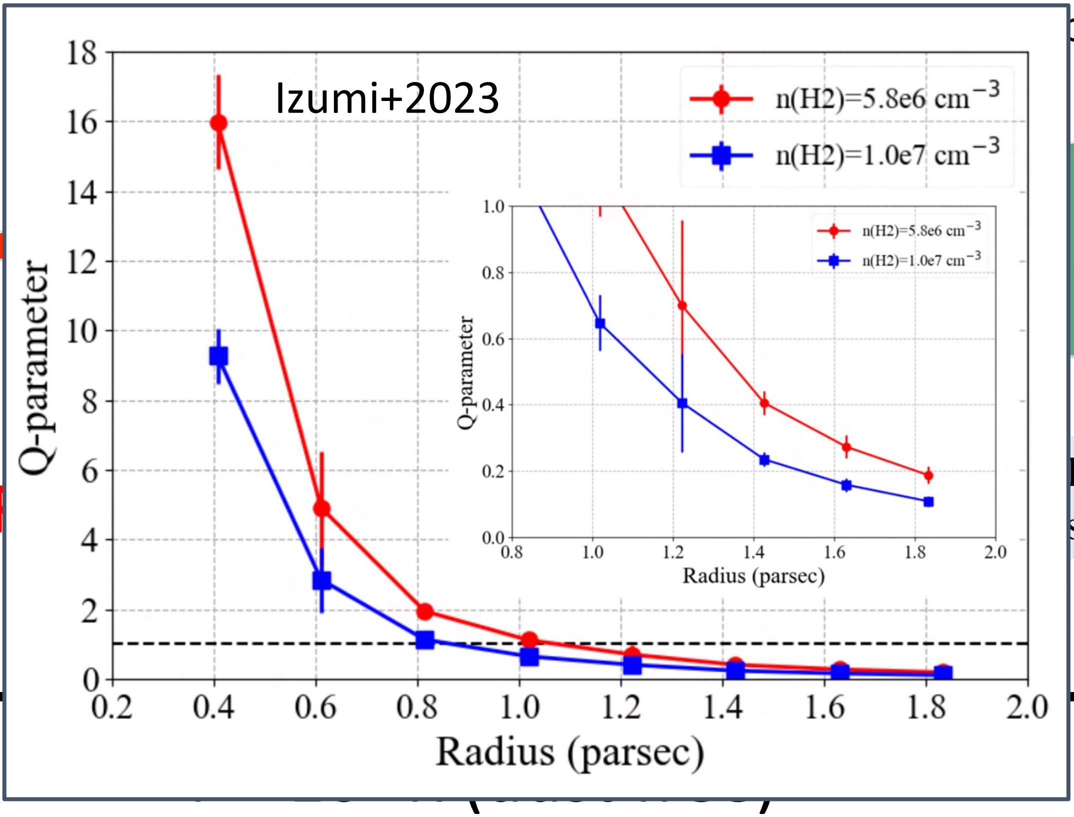
Star formation around the central BH

Stable via viscous heating

$Q > 1$

Marginally unstable

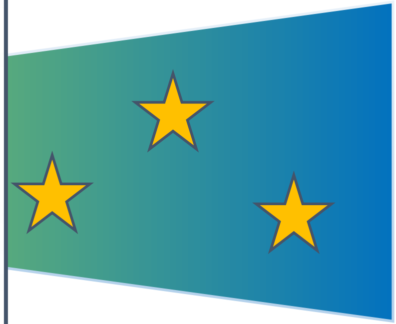
$Q \sim 1$



pc

$R_{out} \sim 0.1\text{-}1$ kpc

BH



$\dot{M} =$

at

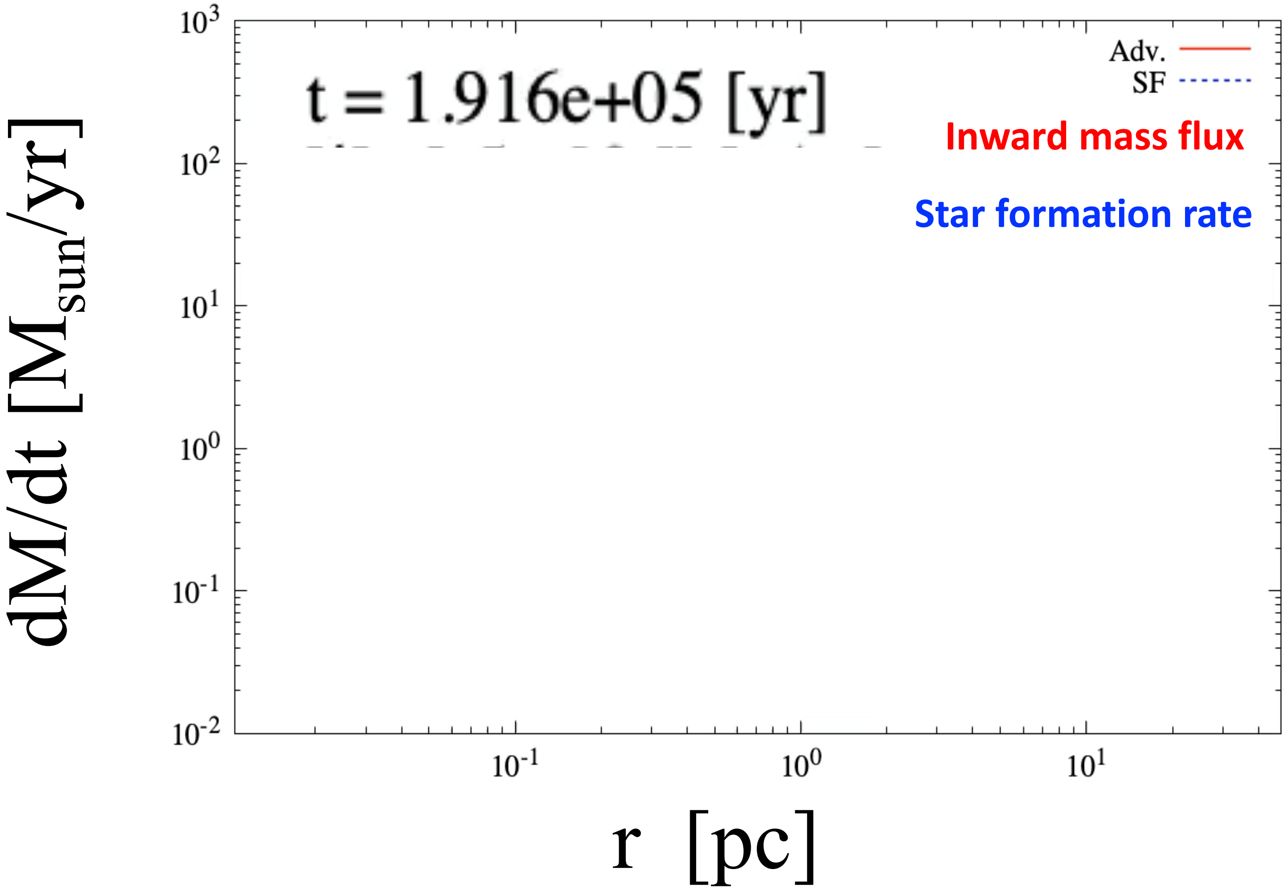
Radiation pressure on dust supports the disk.

$T < 10^3$ K

1D non-steady accretion disk model

Suppose BH mass growth in the early universe

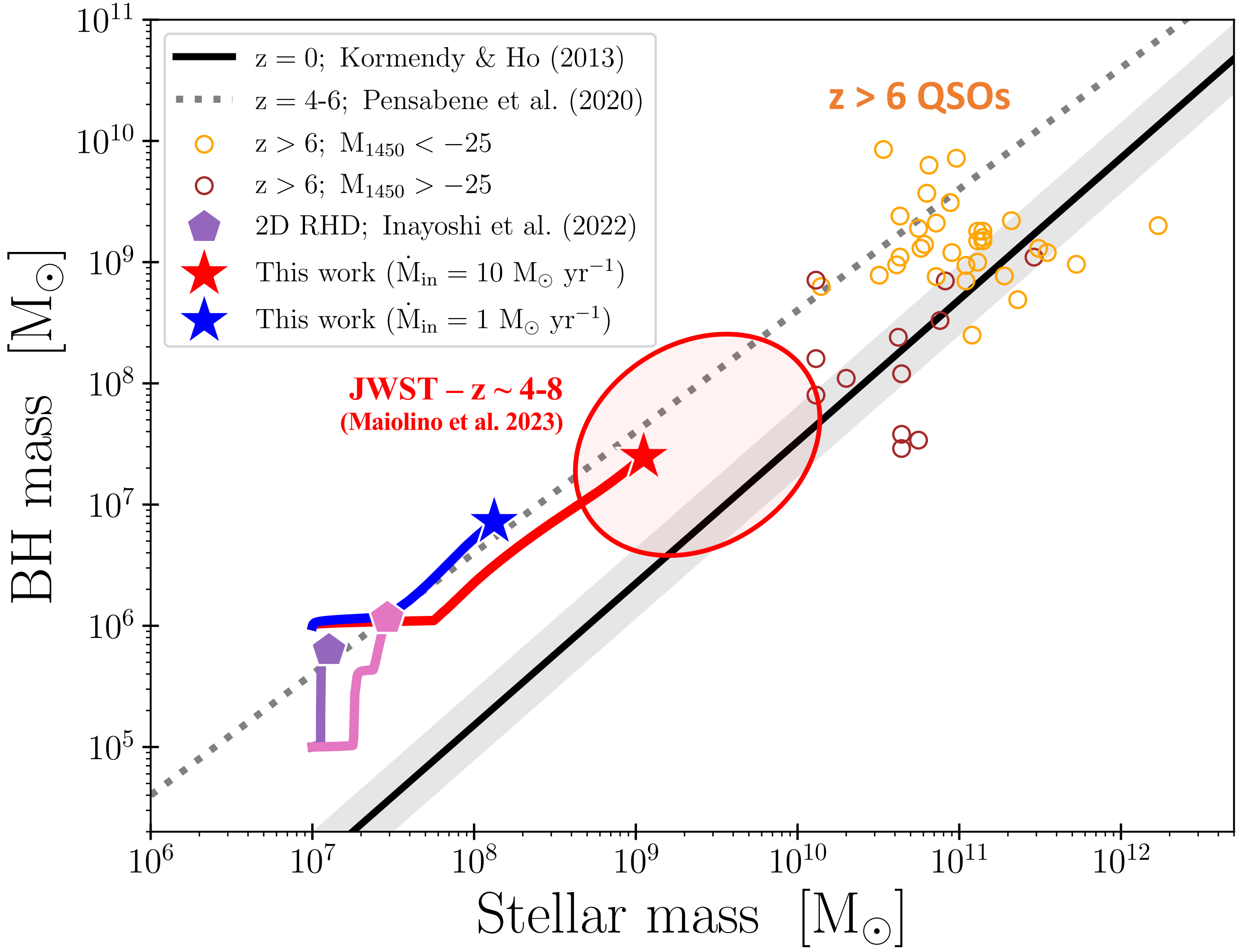
- **$M_{BH} = 10^6\ M_{sun}$, $M_{star} = 10^7\ M_{sun}$** (cf. 2D RHD sims. by Inayoshi+2022)
- **$\dot{M} = 10^{-2}\ M_{sun}$/yr @ t = 0 → $\dot{M} = 10\ M_{sun}$/yr @ t = 100 Myr**



Inward mass flux

Star formation rate

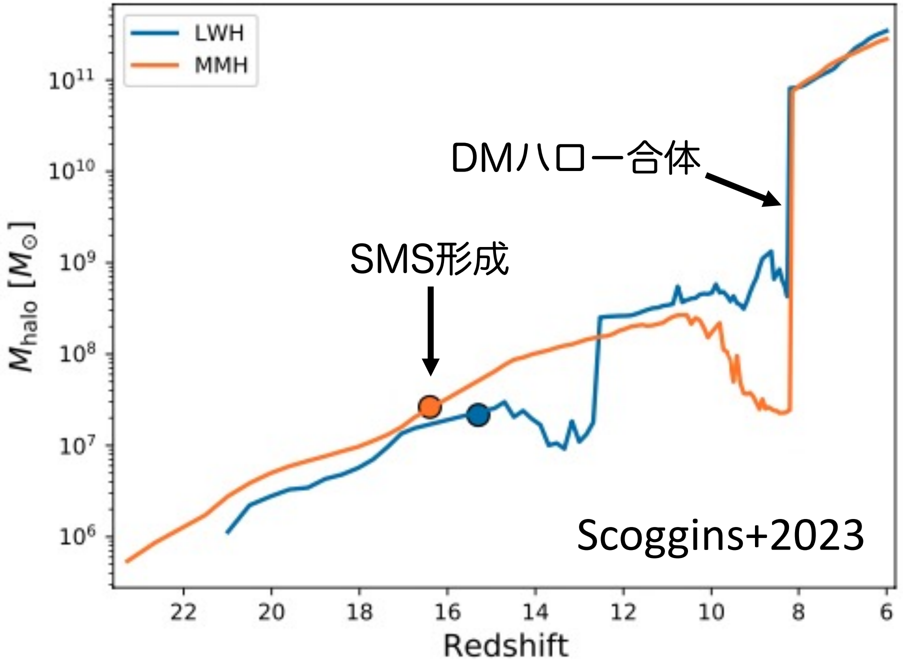
Coevolution of galaxies and SMBHs



4. 高赤方偏移SMBH形成の課題

DMハロー合体の影響

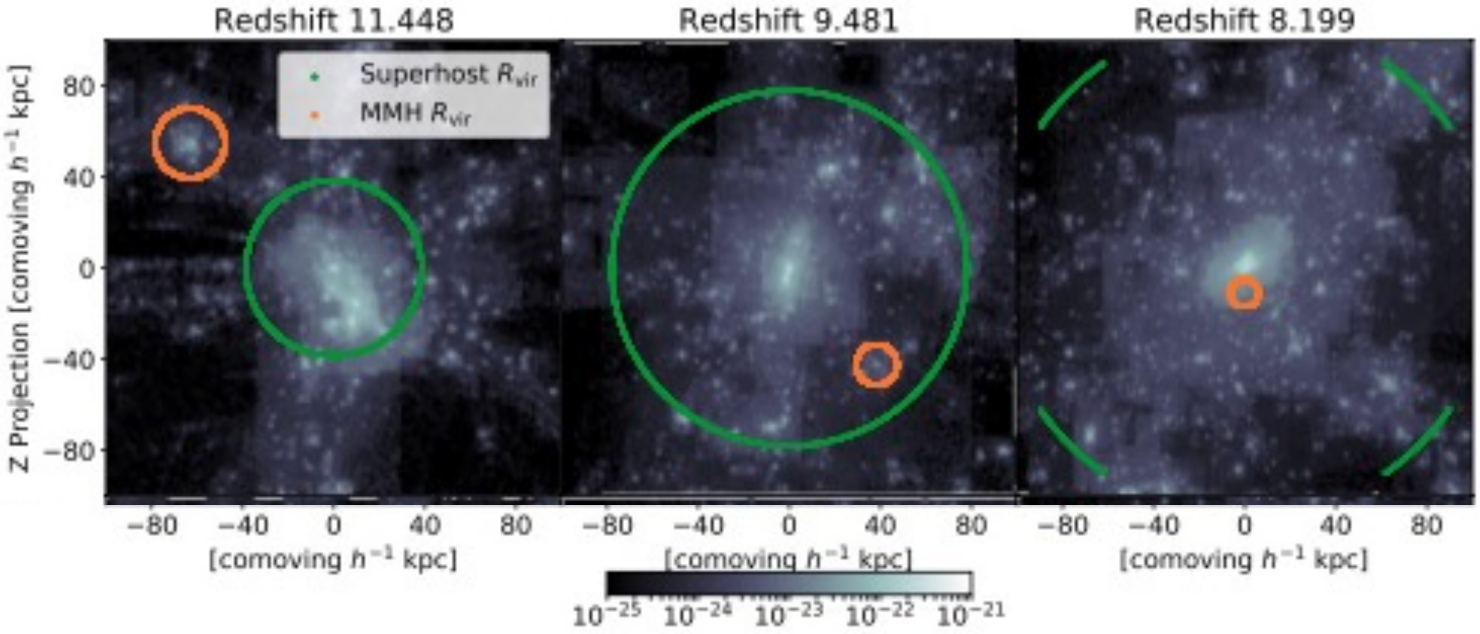
- SMSを形成するハローの多くは、いつかより大きなハローに取り込まれる。
- ハロー外縁ではBHの成長率低いため、密度の高い中心に移動する必要がある (e.g., Chon+21)



DMハロー合体

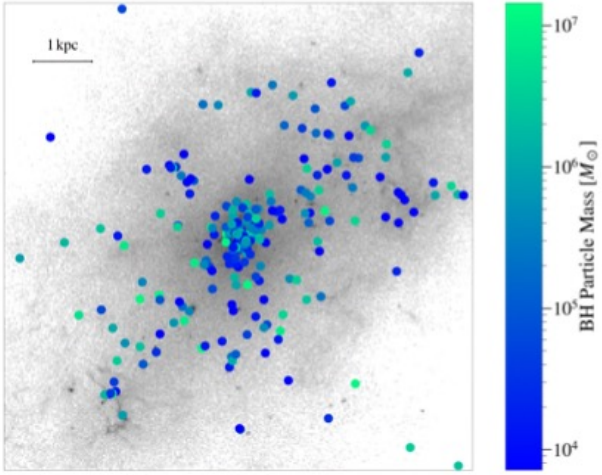
SMS形成

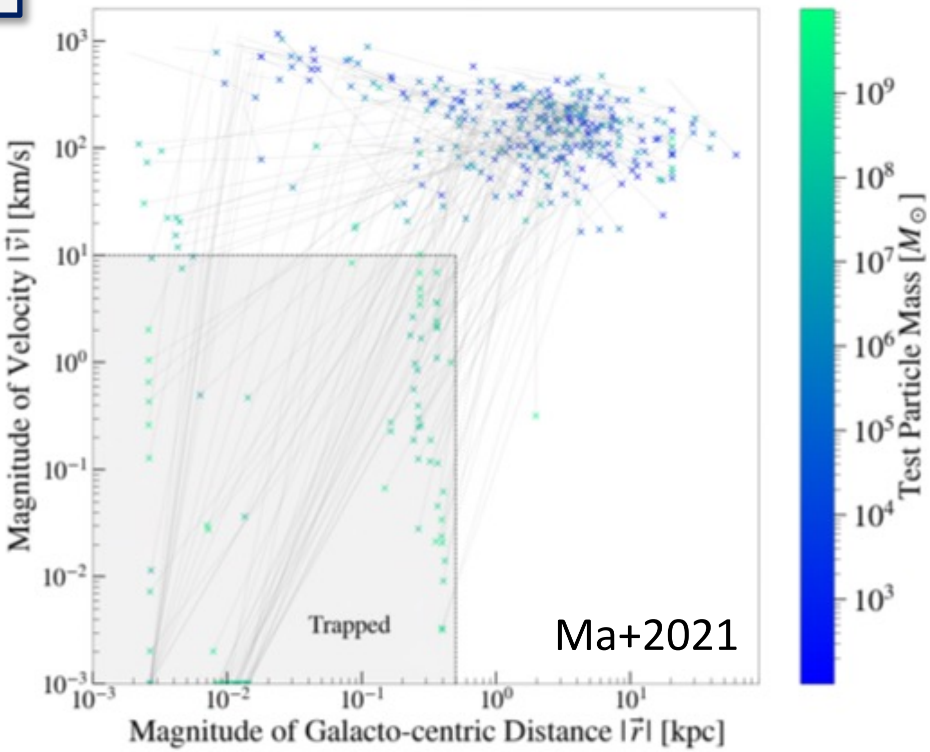
Scoggins+2023



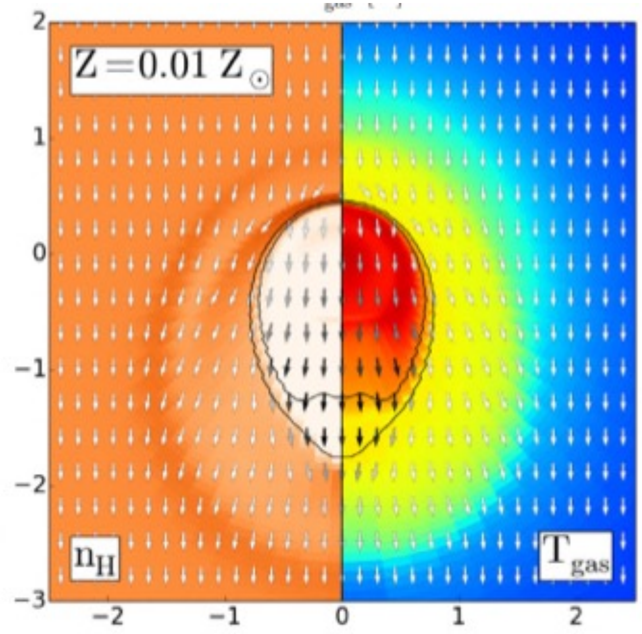
種BHの銀河中心への移動

- $10^8\ M_\odot$より重いBHだけ力学摩擦によって銀河中心に落ちる (Ma+21)
- BHからの輻射FBを考慮するとガス降着率、力学摩擦はさらに落ちる (Park+17; DT+20, 尾形さんトーク)





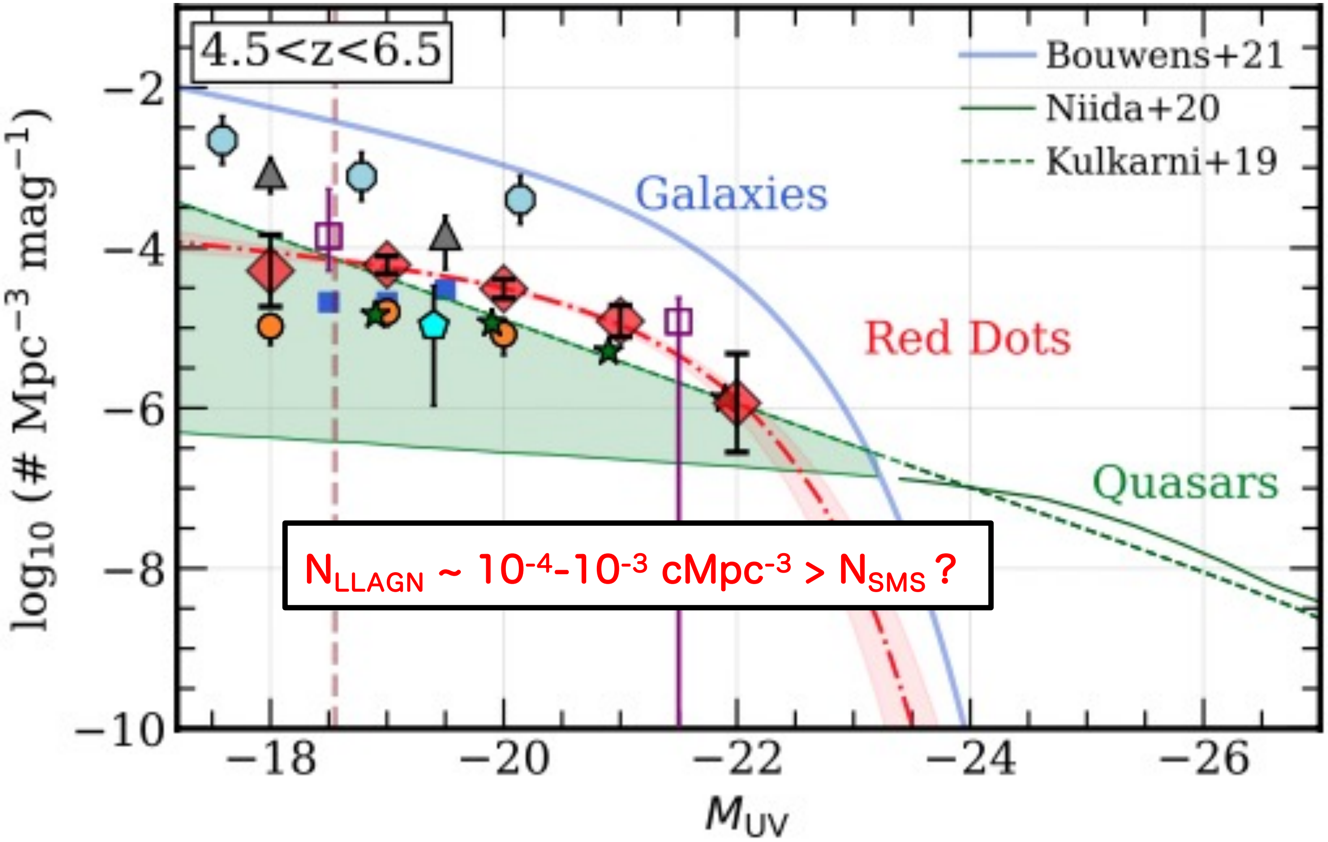
Ma+2021



DT+2020

高赤方偏移低光度AGN（$M_{bh} \sim 10^{6\text{-}7}\ M_{\odot}$）が多すぎる？

1. 恒星質量BHから急速成長？
2. より多くのSMSが必要？
   - 低金属量環境(Regan+20; Chon+20)、 星団中の恒星合体(e.g., Schleicher+22)



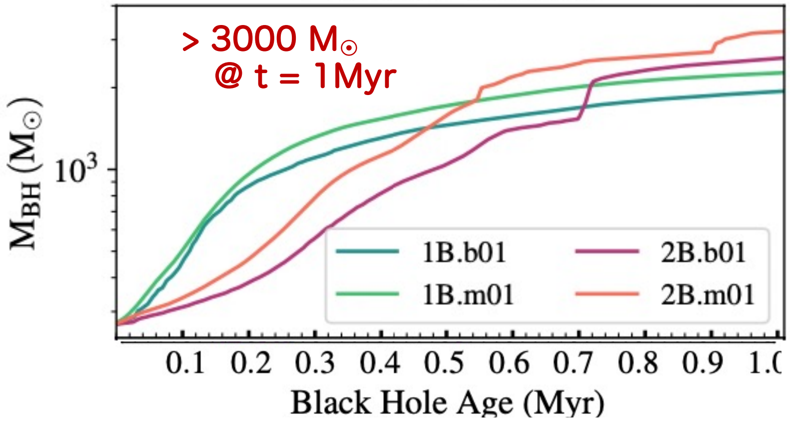
$N_{LLAGN} \sim 10^{-4}\text{-}10^{-3}\ \mathrm{cMpc}^{-3} > N_{SMS}$？

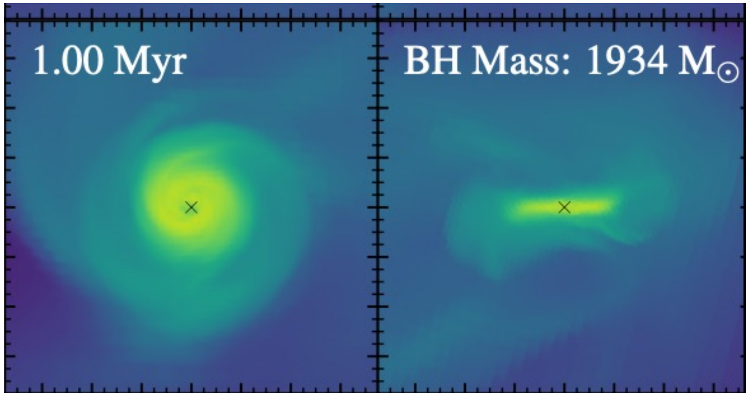
Kokorev+2024

恒星質量BHへのガス降着 (Gordon+24; cf. Beckmann+19)

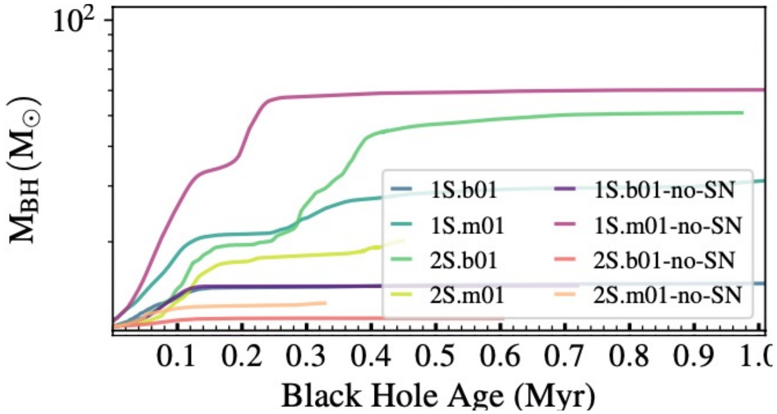
- ミニハロー（$M_h \sim 10^6\ M_\odot$）、$R_{BHL}/\Delta x_{min} > 1$、星形成・BH成長からのFBなし
- $M_{BH,0} = 270\ M_\odot$の場合、BHはハロー中心に滞在し、断続的に成長する。
- $M_{BH,0} = 10\ M_\odot$の場合、BHはガス円盤から離れて成長止まる。分裂雲による力学散乱？

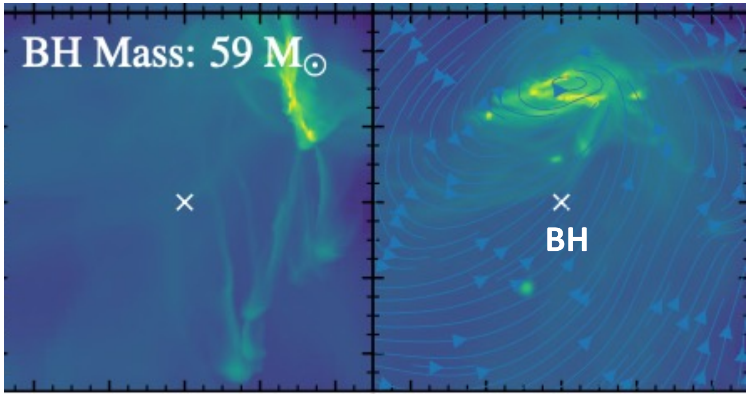
$M_{BH,0} = 270\ M_\odot$





$M_{BH,0} = 10\ M_\odot$





Runaway stellar collisionによるSMS形成

発生条件： $\rho_c \sim 10^6\ M_\odot/\mathrm{pc}^3$ → 緩和時間 << 1Myr

宇宙論的銀河形成シミュレーション (Garcia+23)

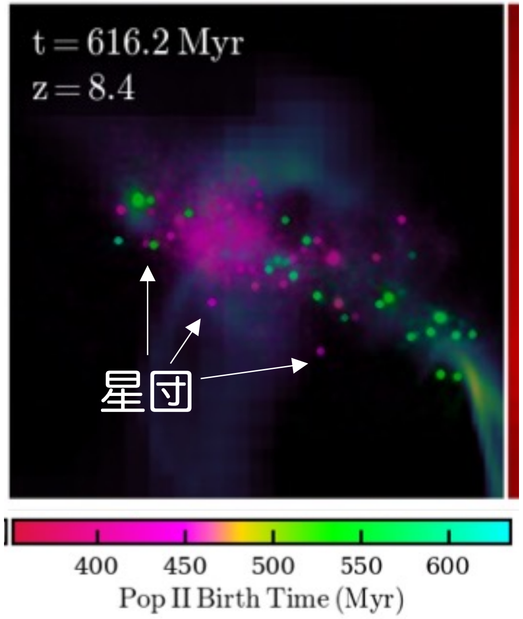
・矮小銀河（$M_h \sim 10^8\ M_\odot$）内の星団形成

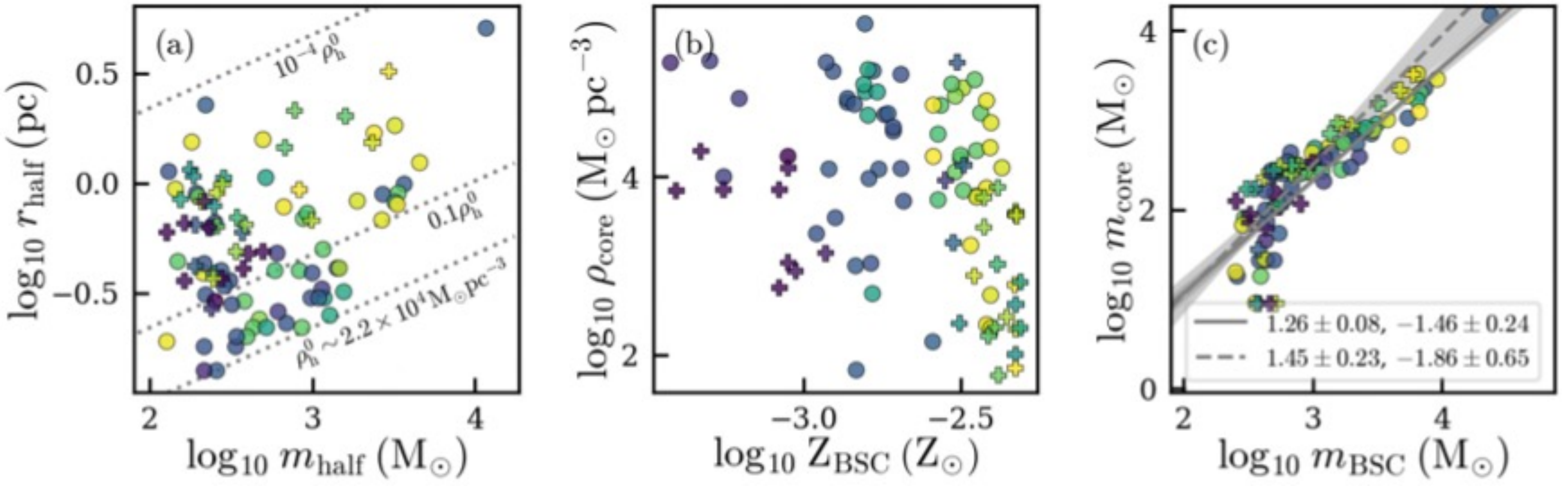
・$m_* = 10\ M_\odot$, $\Delta x_{min} = 0.1$ pc

・低金属量のためガスが高温

→ 通常より高い密度で分子雲収縮

→ 高密度星団（$\rho_c \sim 10^5\ M_\odot/\mathrm{pc}^3$）





まとめ

- 数値シミュレーションと準解析的モデルを組み合わせて初代星の統計的性質が議論されている。我々の研究ではSMSの形成頻度は $N_{SMS} \sim 10^{-4}$ cMpc^{-3}。

- 種BHへの超臨界降着は円盤が十分光学的に厚いときに実現する。円盤内縁の光子捕獲が起こる領域からアウトフロー吹くが、円盤サイズが十分大きい時はほぼ無視できる。

- BHとホスト銀河の長期的共進化が課題。現状の銀河形成シミュレーションはBH成長を過小評価する。BHが常に銀河中心にいるなら１次元非定常のモデルで質量成長を議論できる。

- 一方で、ホストハローの合体によりBHは必ずしも銀河中心にいるとは限らない。銀河中のBHの質量成長と力学進化を整合的に扱う必要がある。

- JWSTで期待より多くの低光度AGNが $z > 5$ で見つかっている。恒星質量BHの急速成長やSMSの新たな形成チャンネルを検討する必要がある。