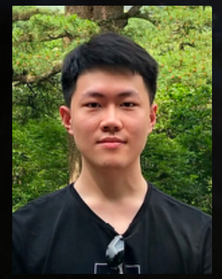
The assembly of first massive BHs and prospects of JWST observations

Kohei Inayoshi



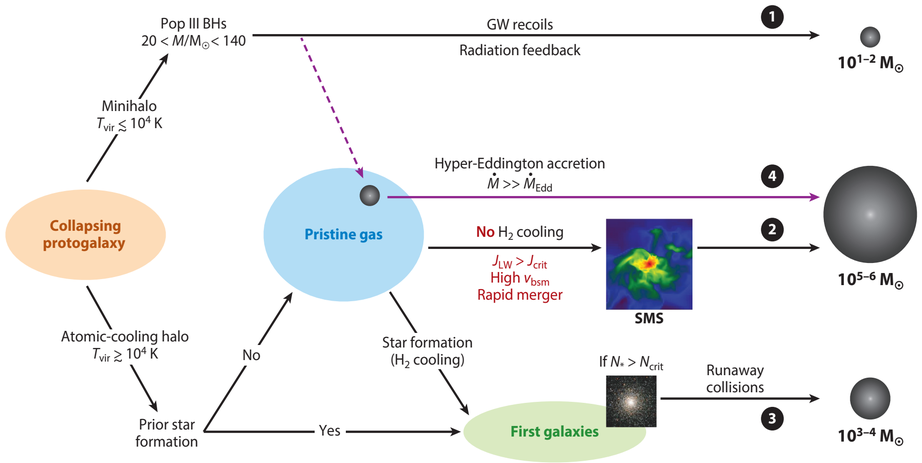
Peking University
Kavli Institute for Astronomy & Astrophysics

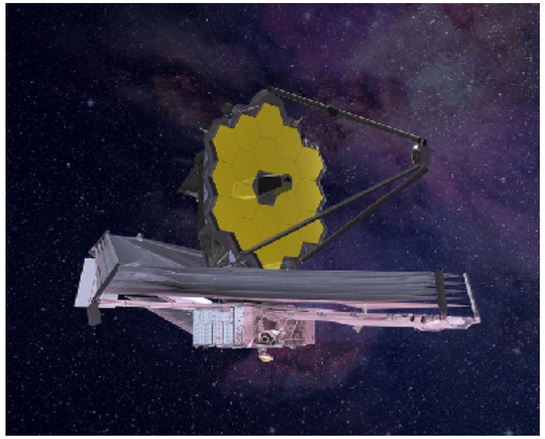
Collaborators: Masafusa Onoue, **Wenxiu Li**, **Haojie Hu**, Luis C. Ho, Akio Inoue, Yuichi Harikane, Yuma Sugahara, Zoltán Haiman, Eliot Quataert, Daisuke Toyouchi, Rolf Kuiper, Riouhei Nakatani, Takashi Hosokawa + CEERS team + Subaru HSC AGN team

初代星・初代銀河研究会2023@北海道大学

Talk's outline

1. Introduction & overview
2. Rapid growth of seed BHs
3. Excavating the first massive BHs

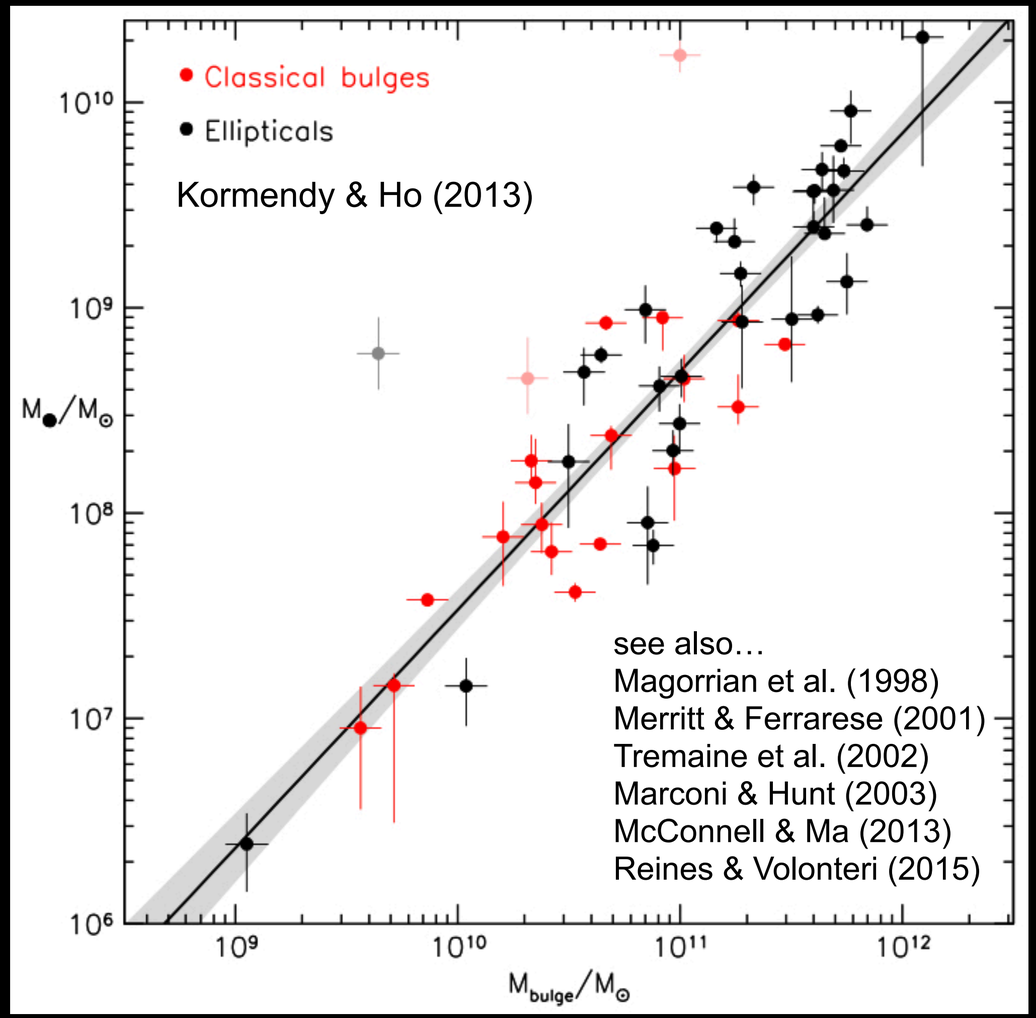




Supermassive Black Holes (SMBH)

https://en.wikipedia.org/wiki/Messier_87

artist's illustration [ESA/Hubble, L. Calçada (ESO)]



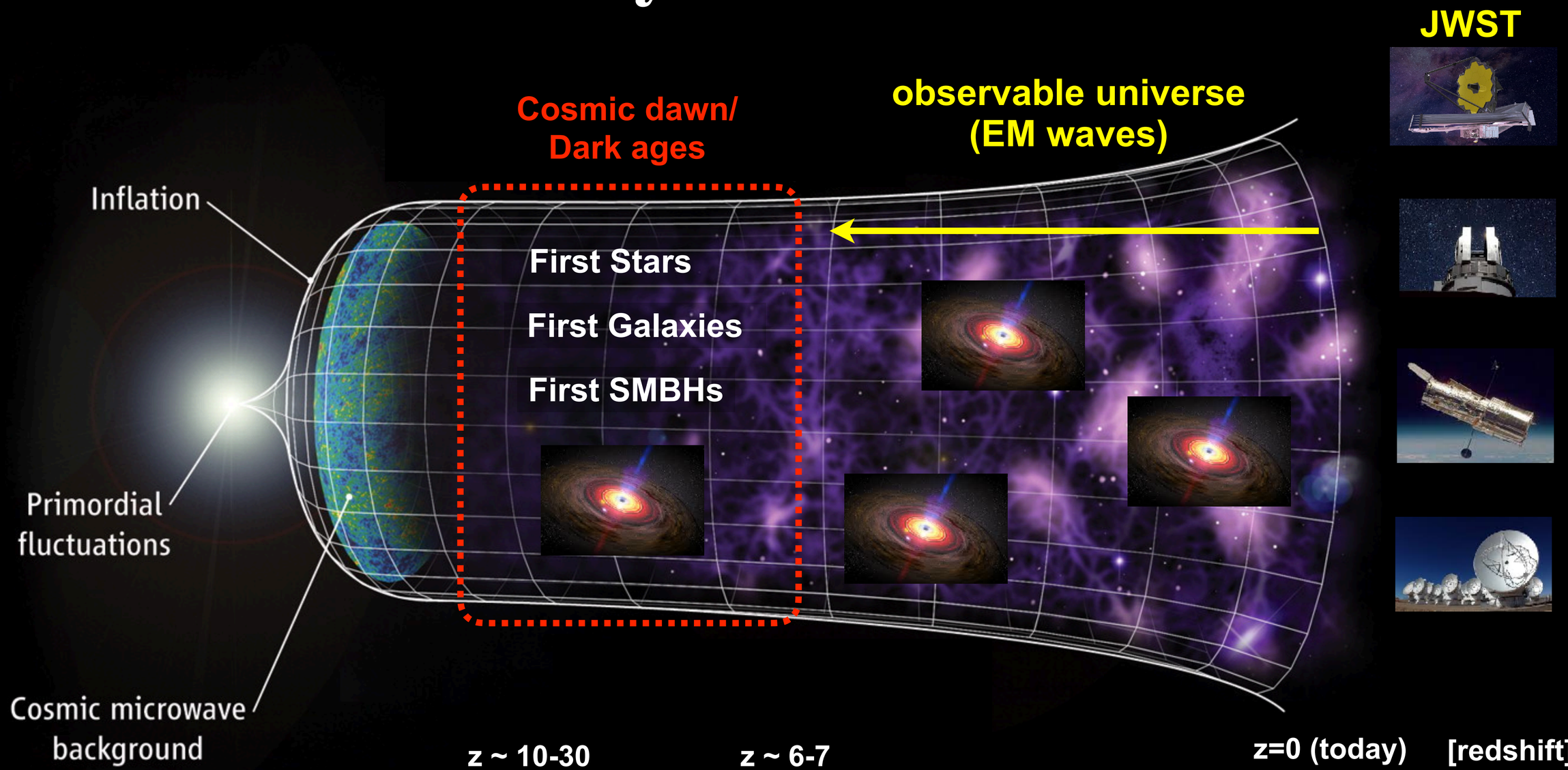
Black Hole mass

Galaxy mass

Key questions:

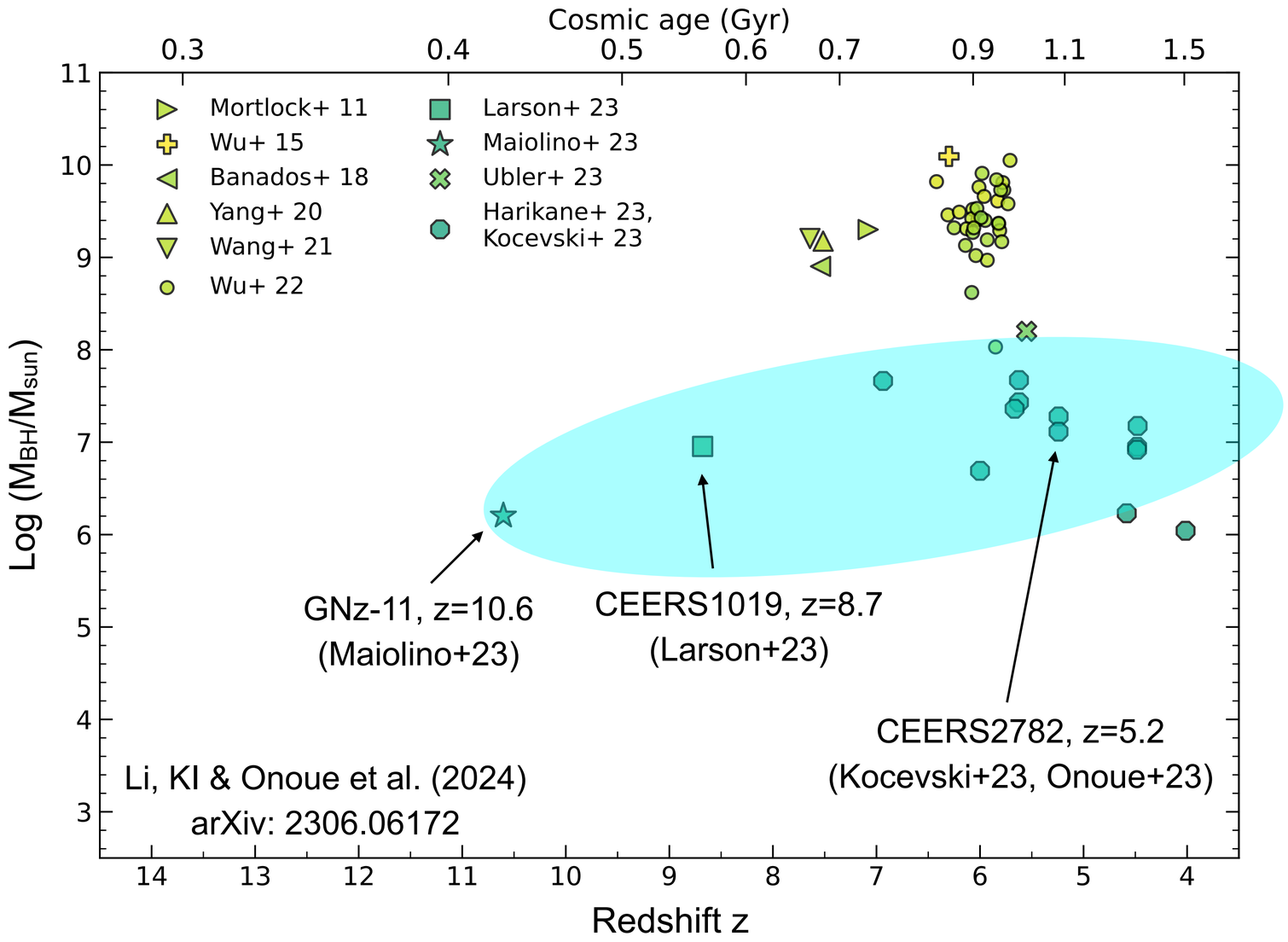
1) What is the origin of SMBHs?
2) How did BHs and galaxies interact?
3) Cosmological coevolution & high-z?

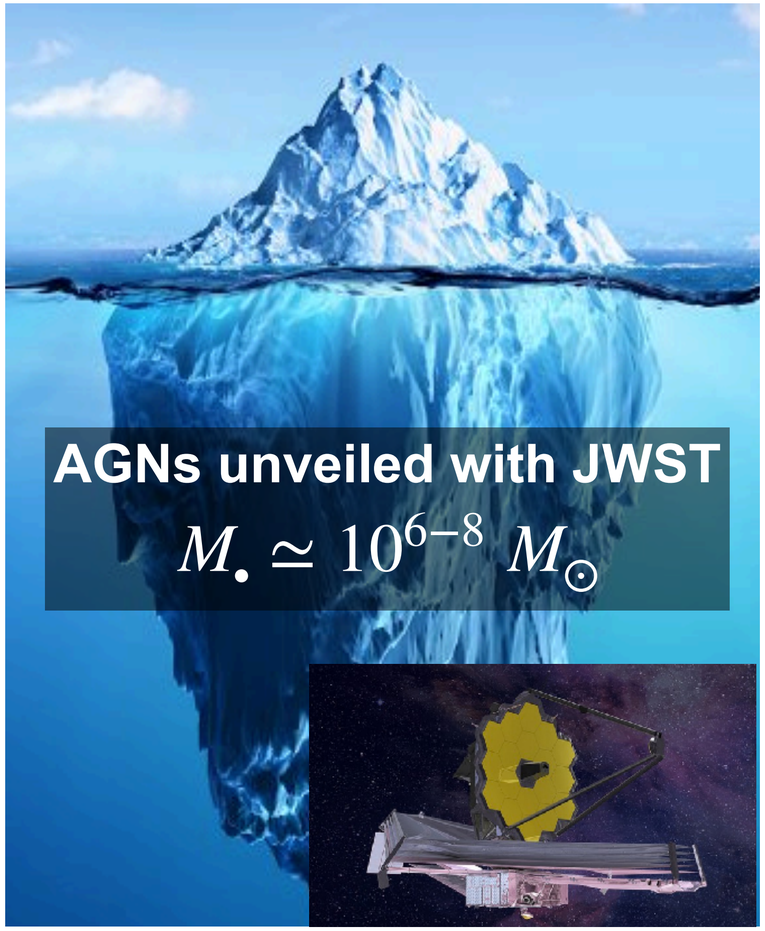
History of the universe



https://science.sciencemag.org/content/319/5859/52

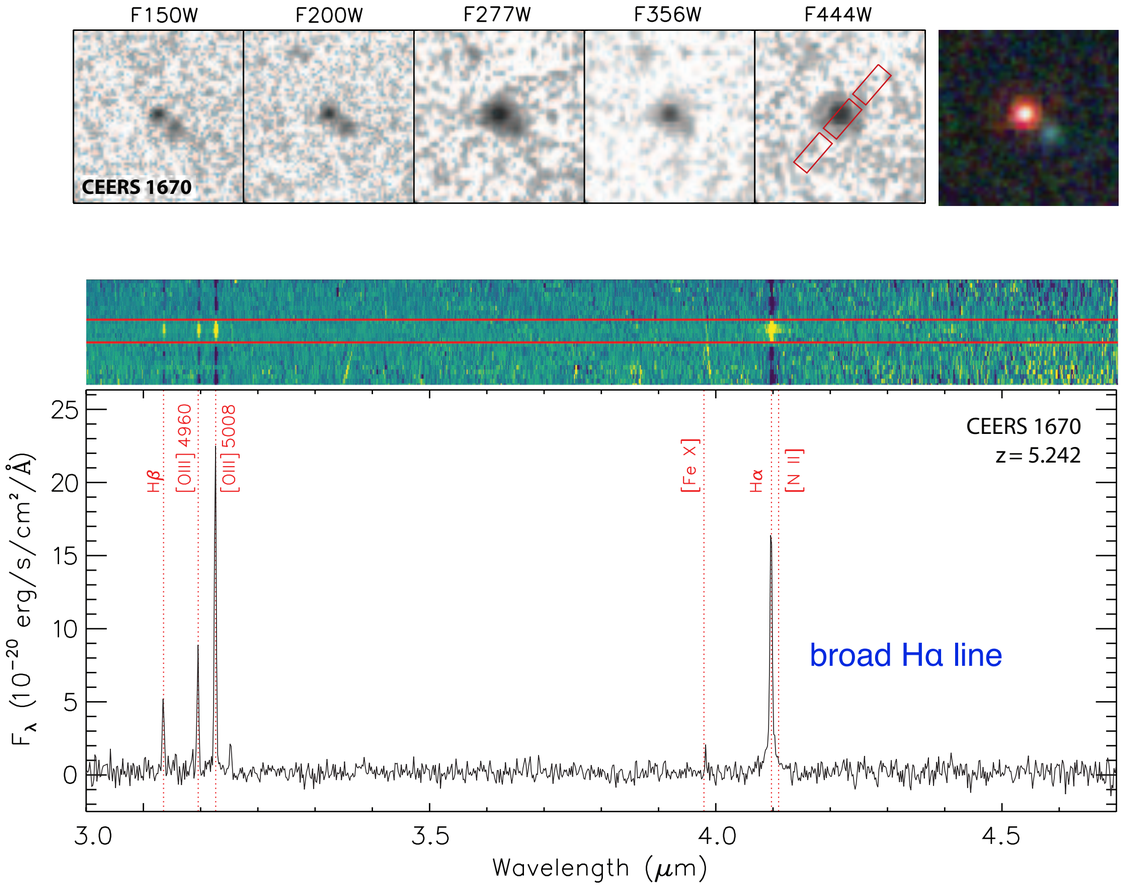
High-z SMBH population

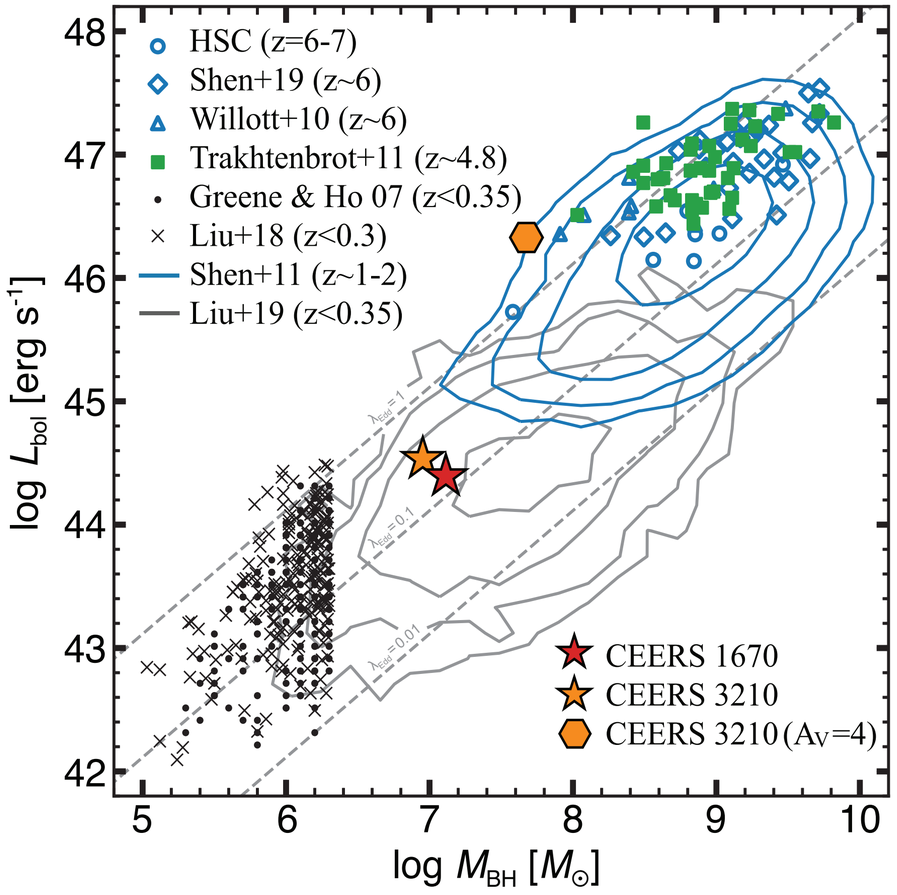




Hidden little monsters uncovered by JWST

Hidden Little Monsters: Spectroscopic Identification of Low-Mass, Broad-Line AGN at $z > 5$ with CEERS





Onoue, KI, Ding+ (2023), Kocevski, Onoue, KI+ (2023)

See also Harikane+ (2023), Übler+ (2023), Larson+ (2023)
Maiolino+ (2023), Matthee+ (2023), Bogdan+ (2023)

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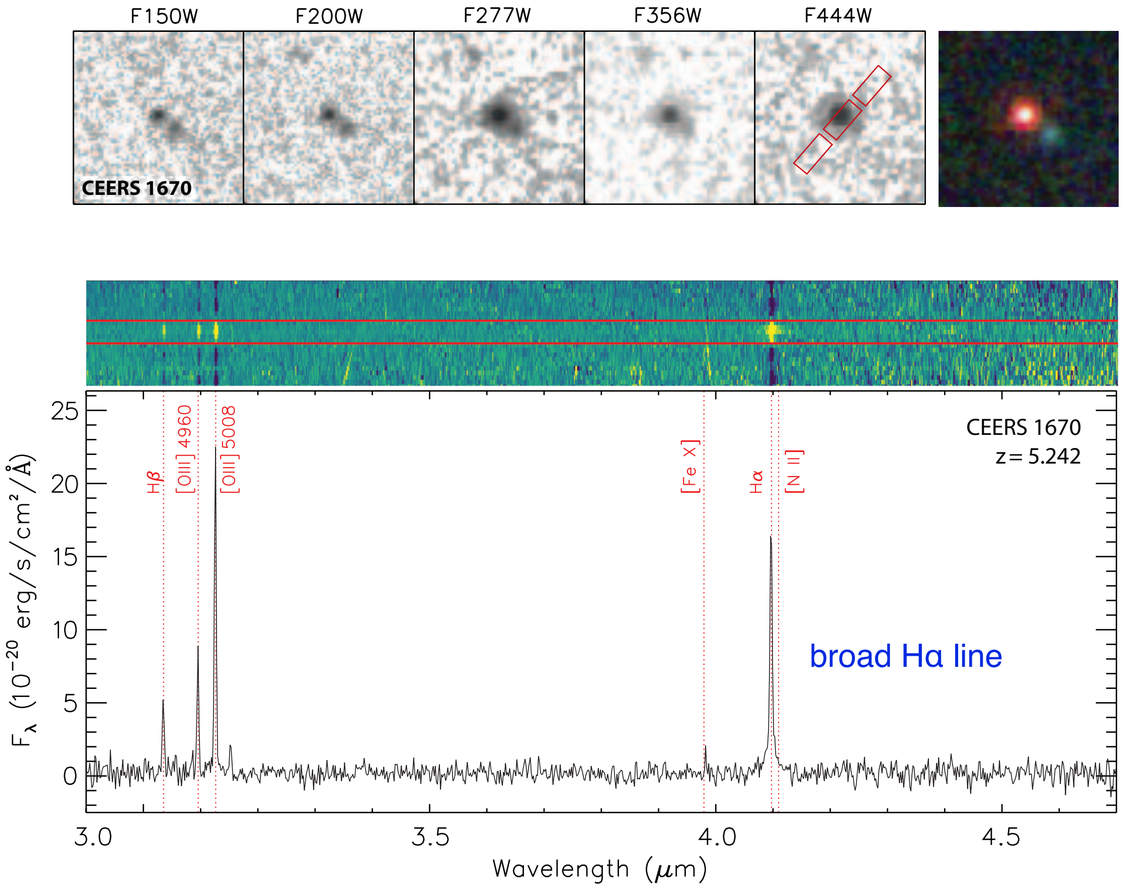

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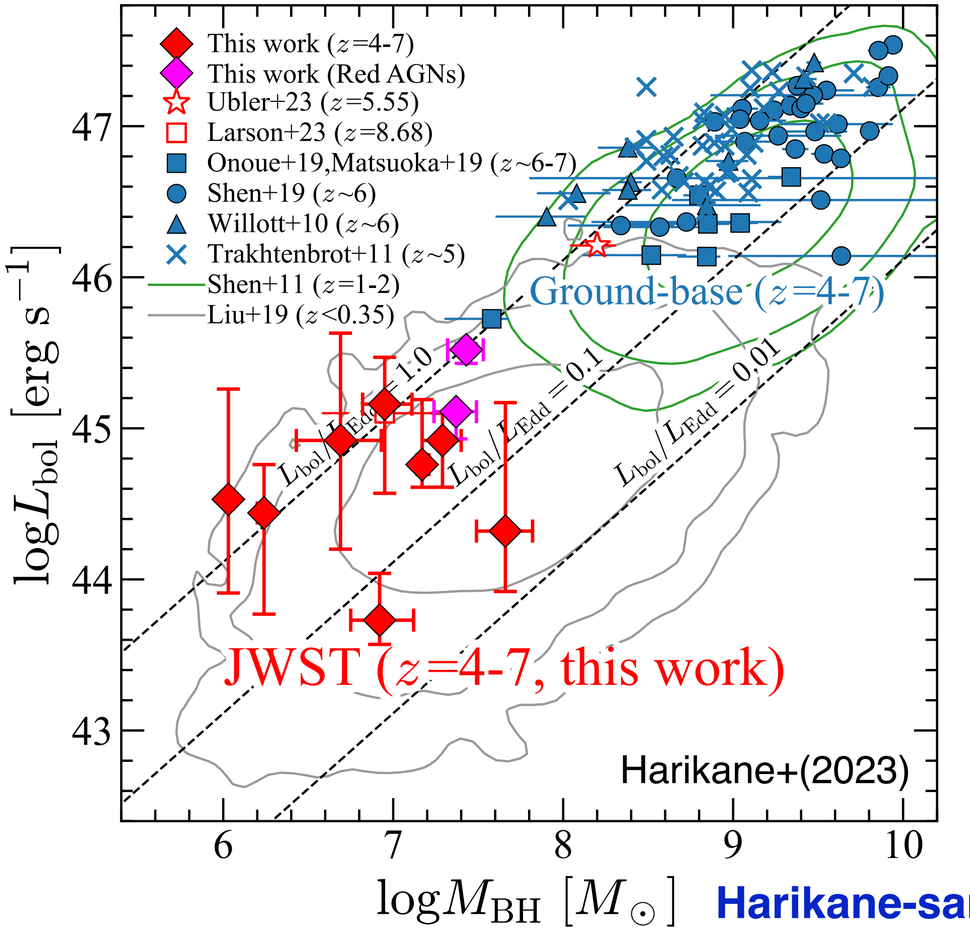
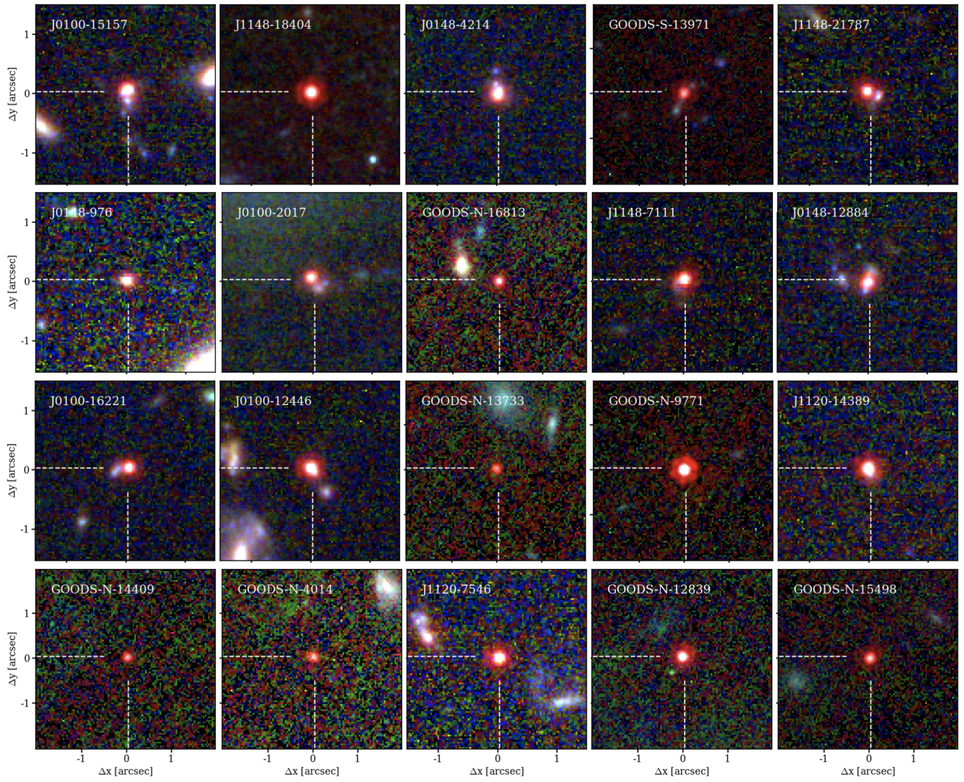


Harikane-san's talk!

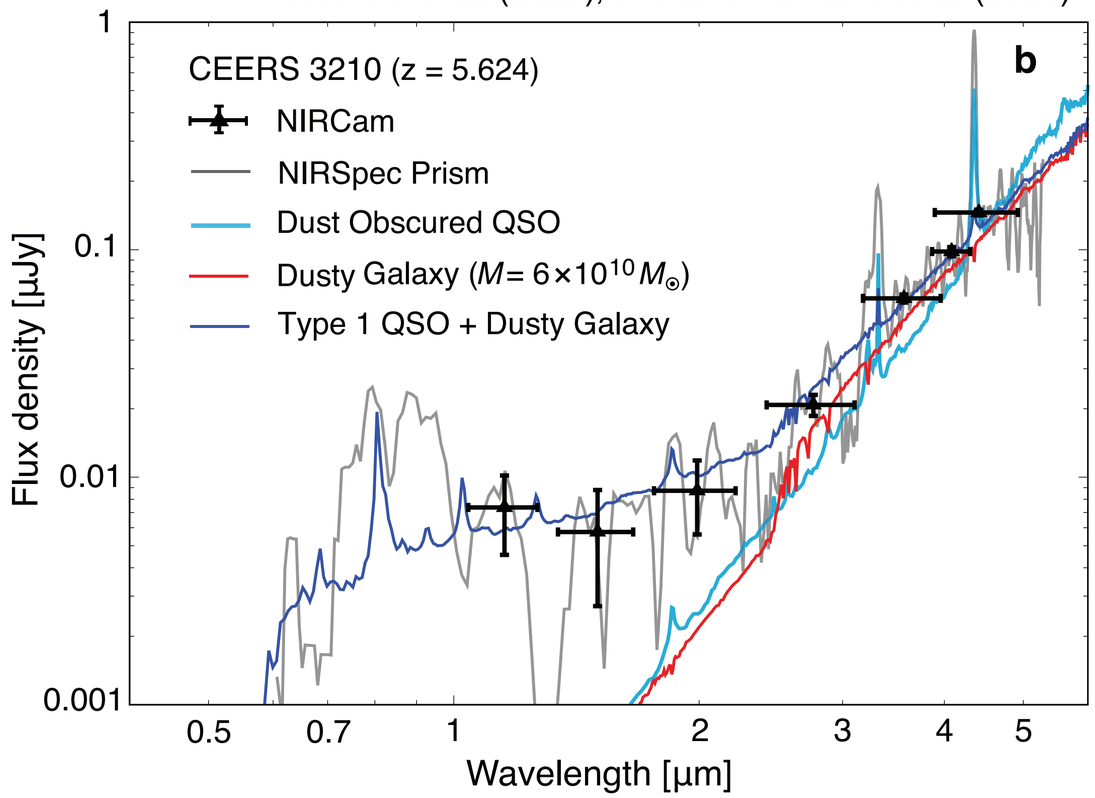
See also Harikane+ (2023), Übler+ (2023), Larson+ (2023)
Maiolino+ (2023), Matthee+ (2023), Bogdan+ (2023)

Dust-reddened AGNs at z>4

Matthee et al. (2023), Labbe et al. (2023), Greene et al. (2023)



Kocevski et al. (2023), see also Harikane et al. (2023)

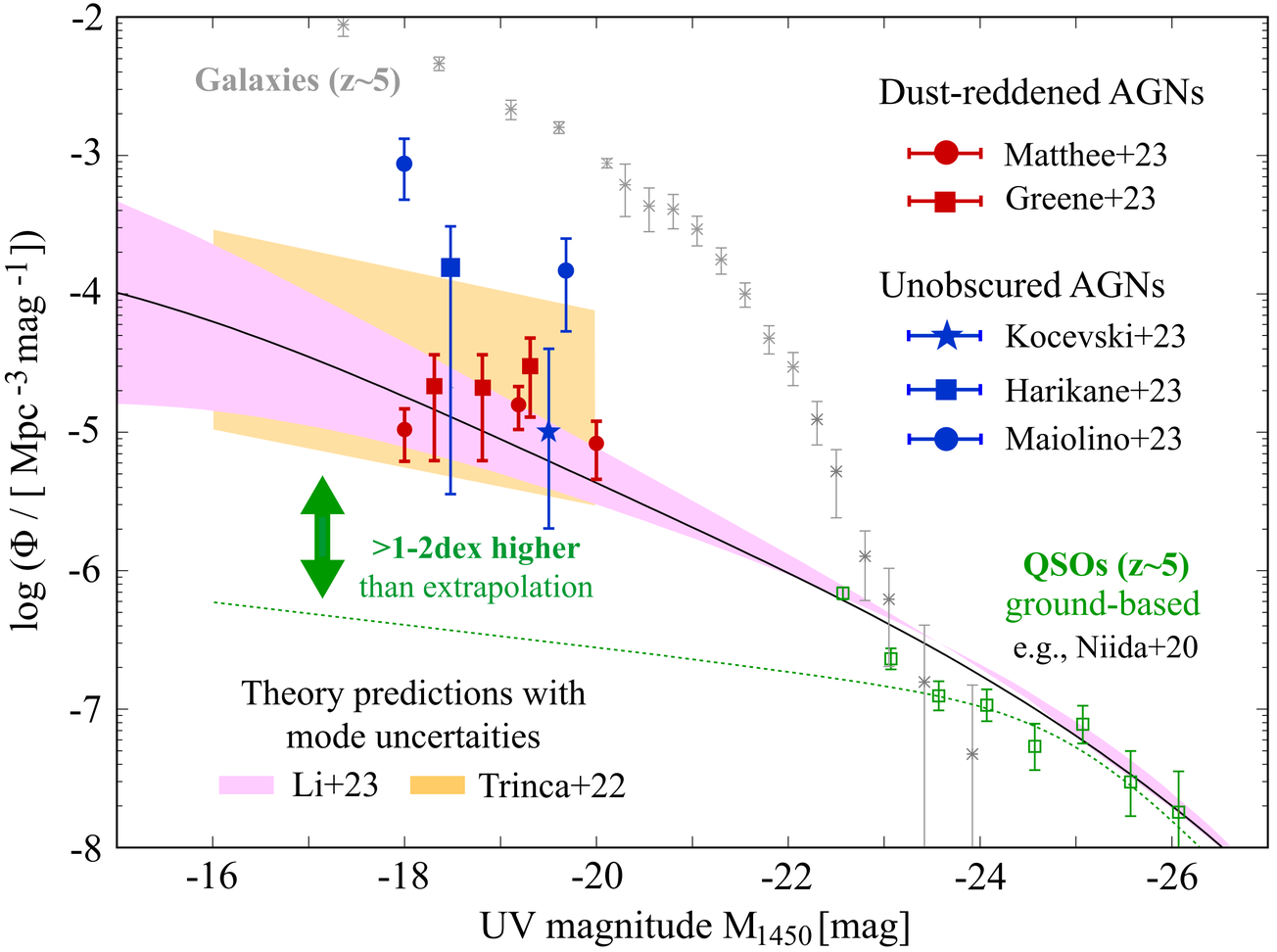


See Noboriguchi-san's talk!

✓ Very compact and red sources with broad Hα lines, "**little red dots**"

✓ Early stages of quasar activity? (mergers→dust production→quasars)

Many AGNs with JWST…

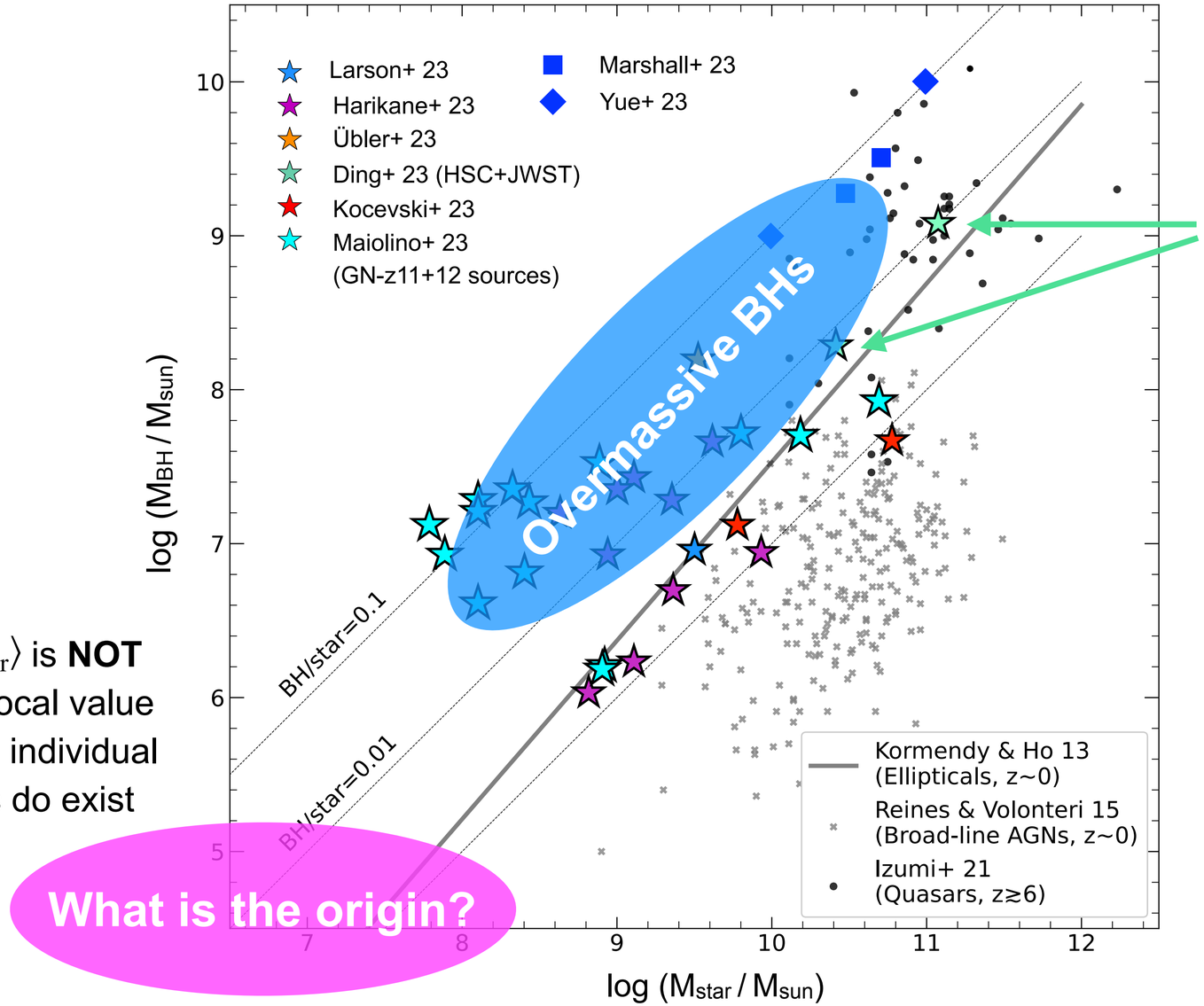


z~5 quasar luminosity function
(**JWST**+HSC+SDSS+others)

Li, KI & Onoue et al. (2024)
arXiv: 2306.06172

Low-luminosity AGNs detected with JWST are **>10 times abundant**
more than extrapolation of the QLFs based on SDSS/HSC/others

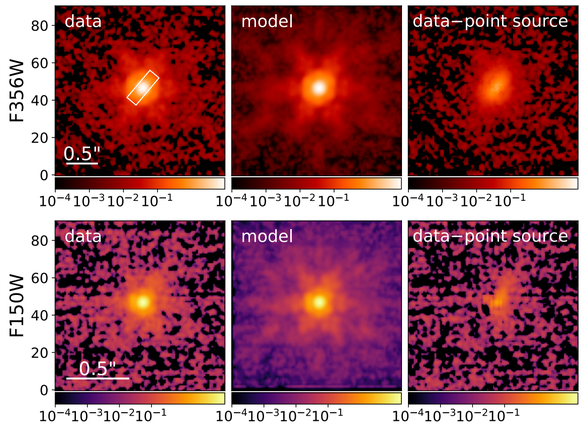
Early BH-galaxy coevolution



What is the origin?

Note: the average $\langle M_{\rm BH}/M_{\rm star}\rangle$ is **NOT** necessarily higher than the local value due to biased sampling. But, individual overmassive BH populations do exist (see also J.Li et al. 2022)

Detection of stellar light from QSO hosts



Ding, Onoue & Silverman et al.+KI (2023); HSC+JWST (PI: Onoue), Nature, 621,51

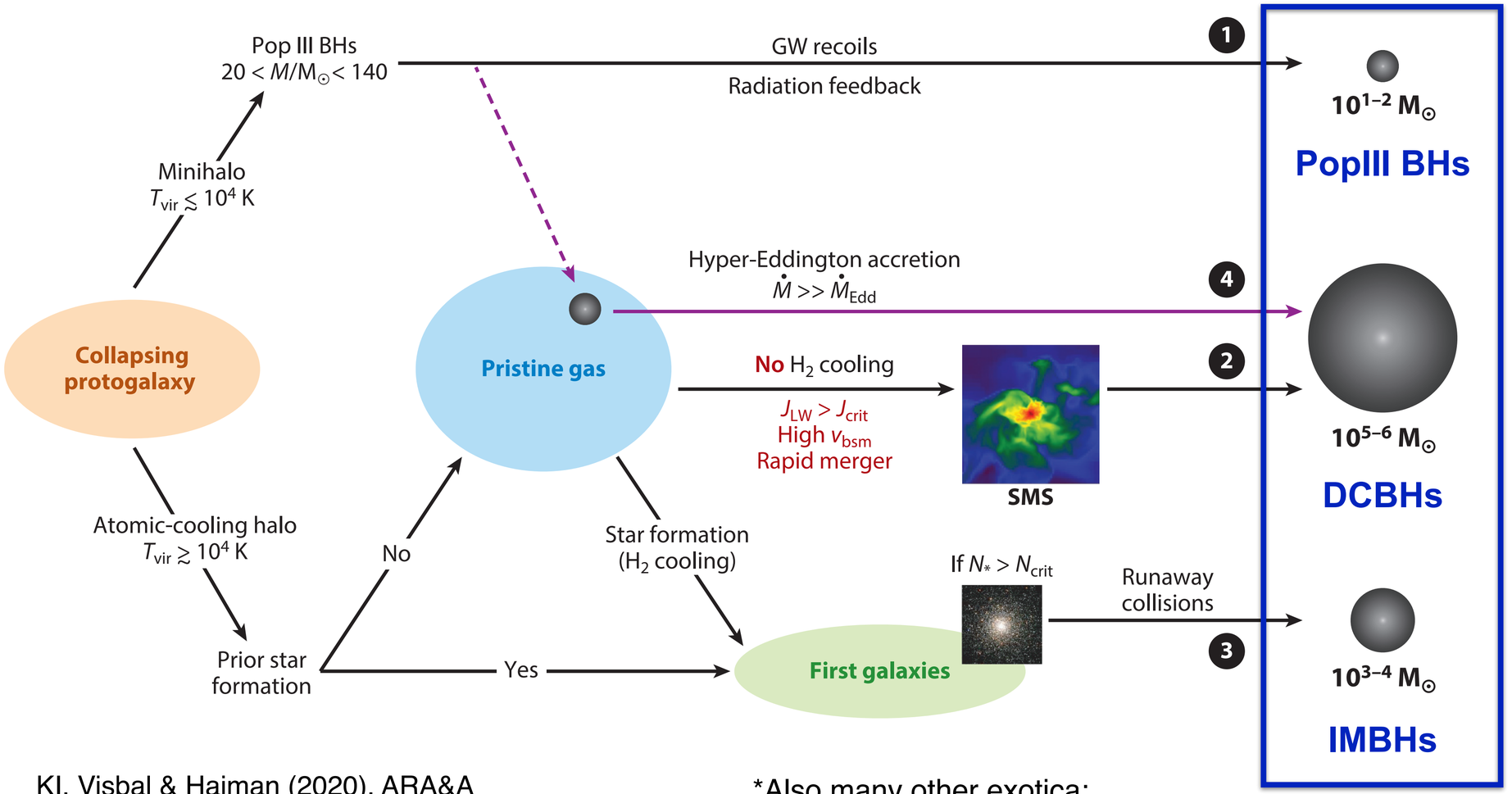
BH mass (single-epoch method)
Stellar mass (SED fitting)

Li, KI & Onoue et al. (2024)
arXiv: 2306.06172

Rapid growth of seed BHs

Formation channels of early BHs

Various masses of seed BHs depending on SF environments (the “up-to-date” Rees diagram)



KI, Visbal & Haiman (2020), ARA&A

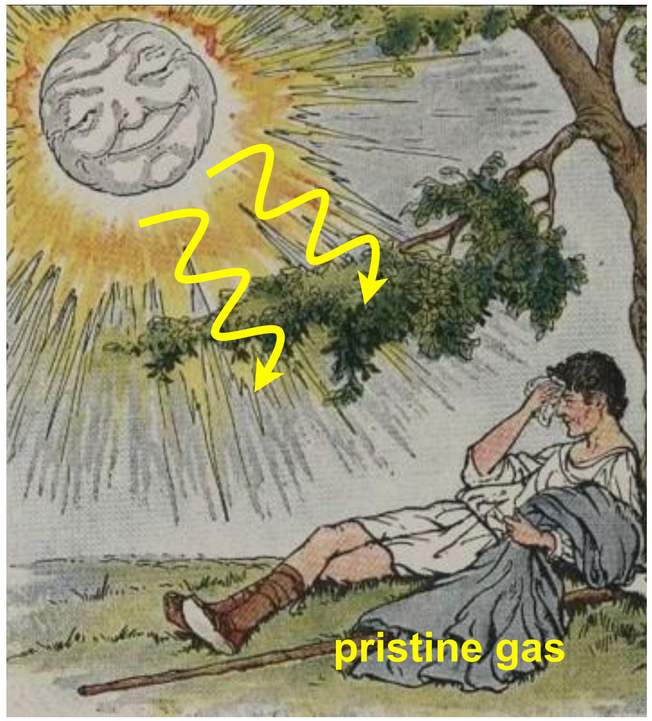
See also Volonteri, Habouzit & Colpi (2021)

*Also many other exotica:
PBHs, collisional DM, dark stars…

See Omukai-san’s talk!

Seed formation ≈ H_2 suppression

H_2 dissociating radiation



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

Dynamical heating

$$c_{\rm eff}^2 = c_{\rm s}^2 + v_{\rm tur}^2$$

Bromm & Loeb 2003, Shang+2010, Latif+2013, Johnson+(2013), Regan+2014, KI+2014, Visbal+2015, Latif+2016, Chon+2016, Hirano+2018, KI+2018, Wise+2019, Regan+2020, Lupi +2021, Li +2021, Latif+2022, etc…

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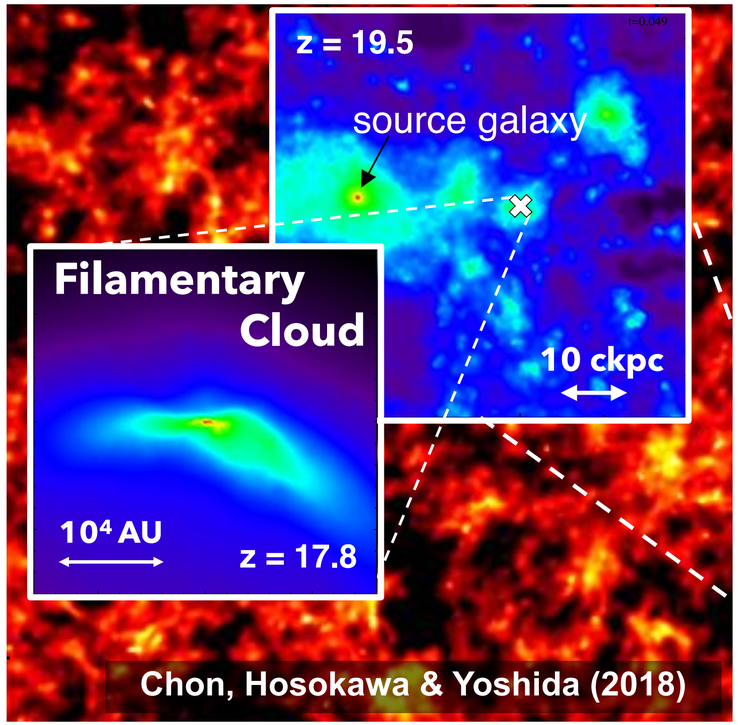

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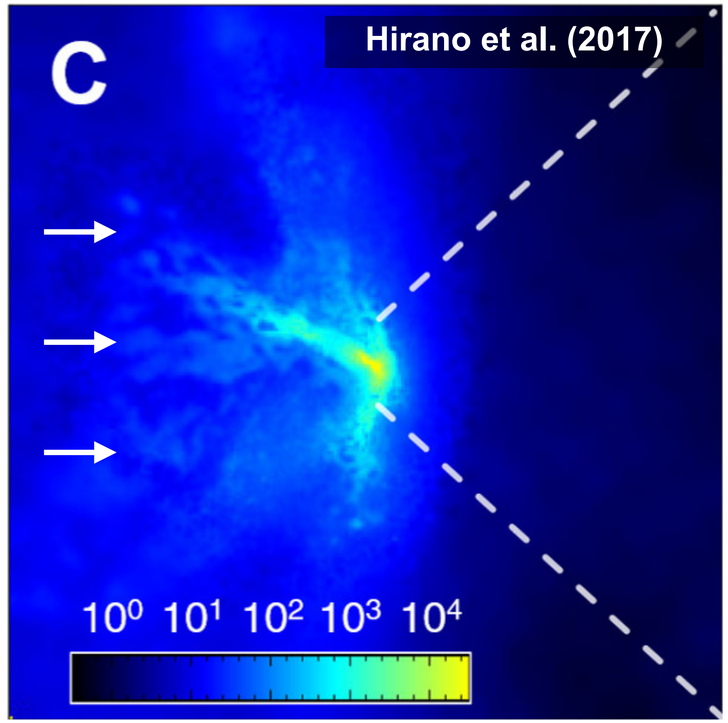

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Seed BH mass function @high-z

Progenitors of quasar hosts

overdense (>4σ) rare regions

stronger UV & more mergers

(Li et al. 2021, Lupi et al. 2021)

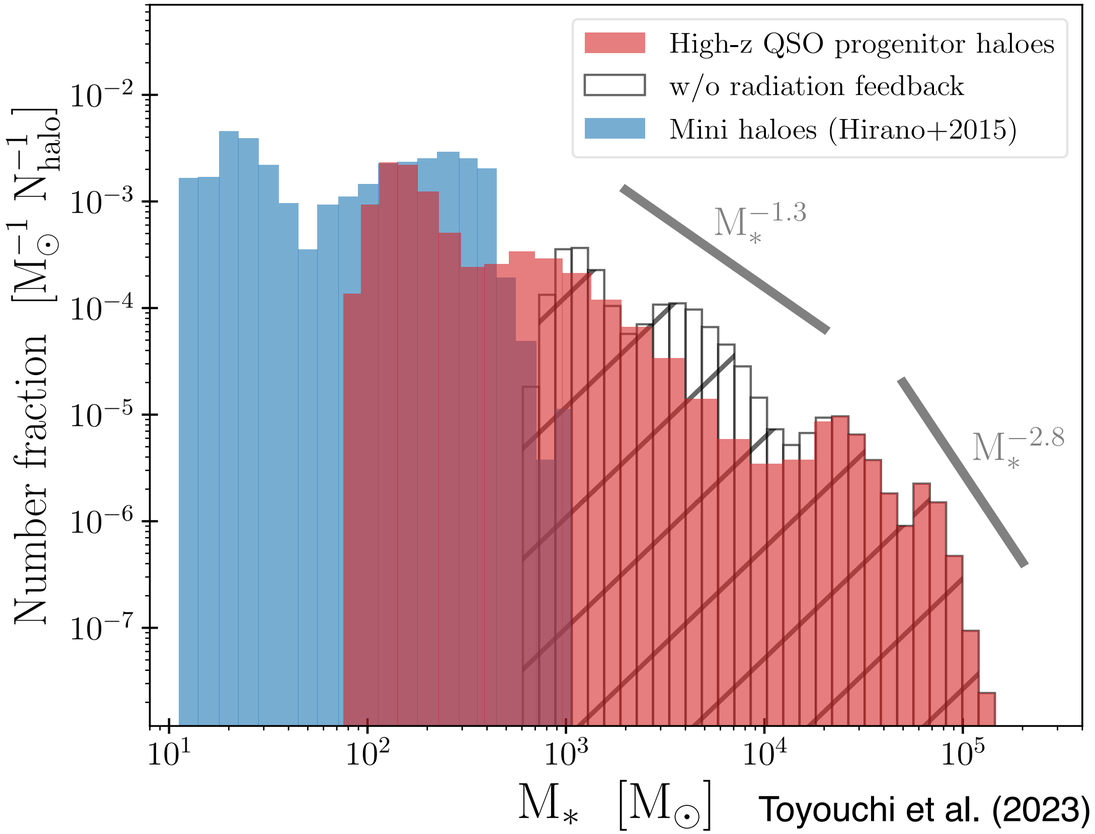
Typical protogalaxies

common (~2σ) regions

(Ahn et al. 2009, Dijkstra et al. 2008, 2014)

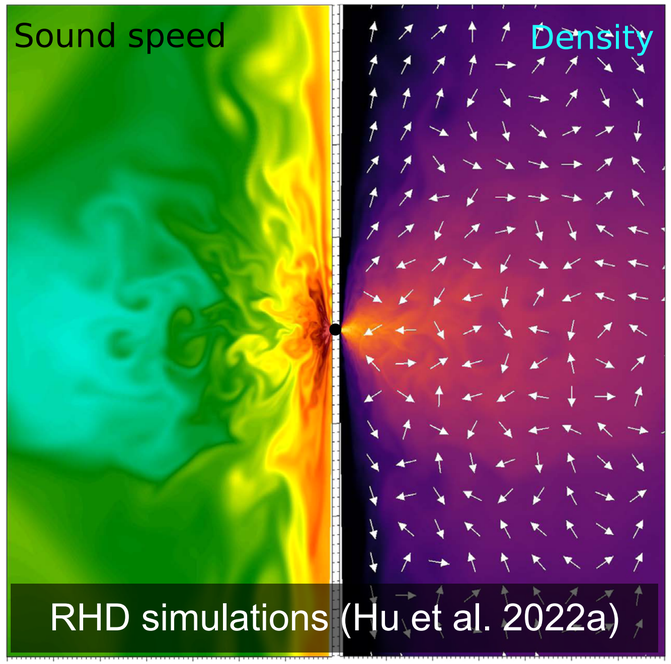
ILLUSTRIS

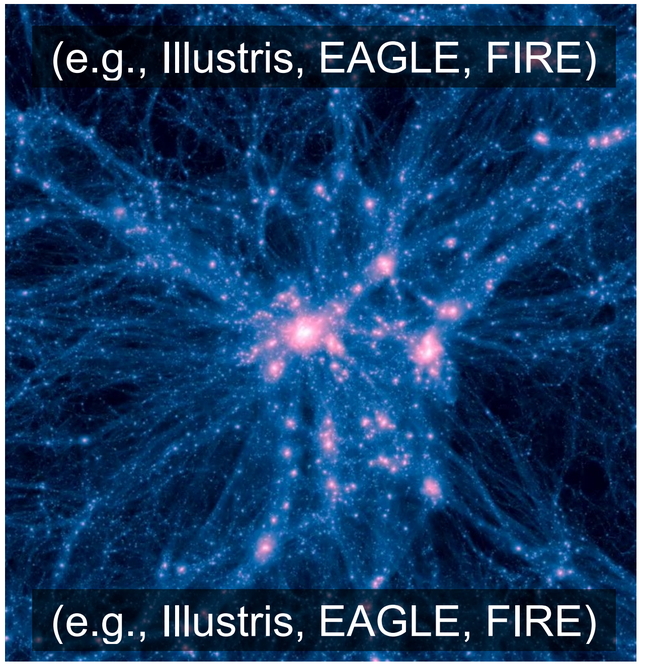
RHD simulations + semi-analytical seeding model (Li et al. 2021)



Toyouchi et al. (2023)

BH accretion in multi-scales





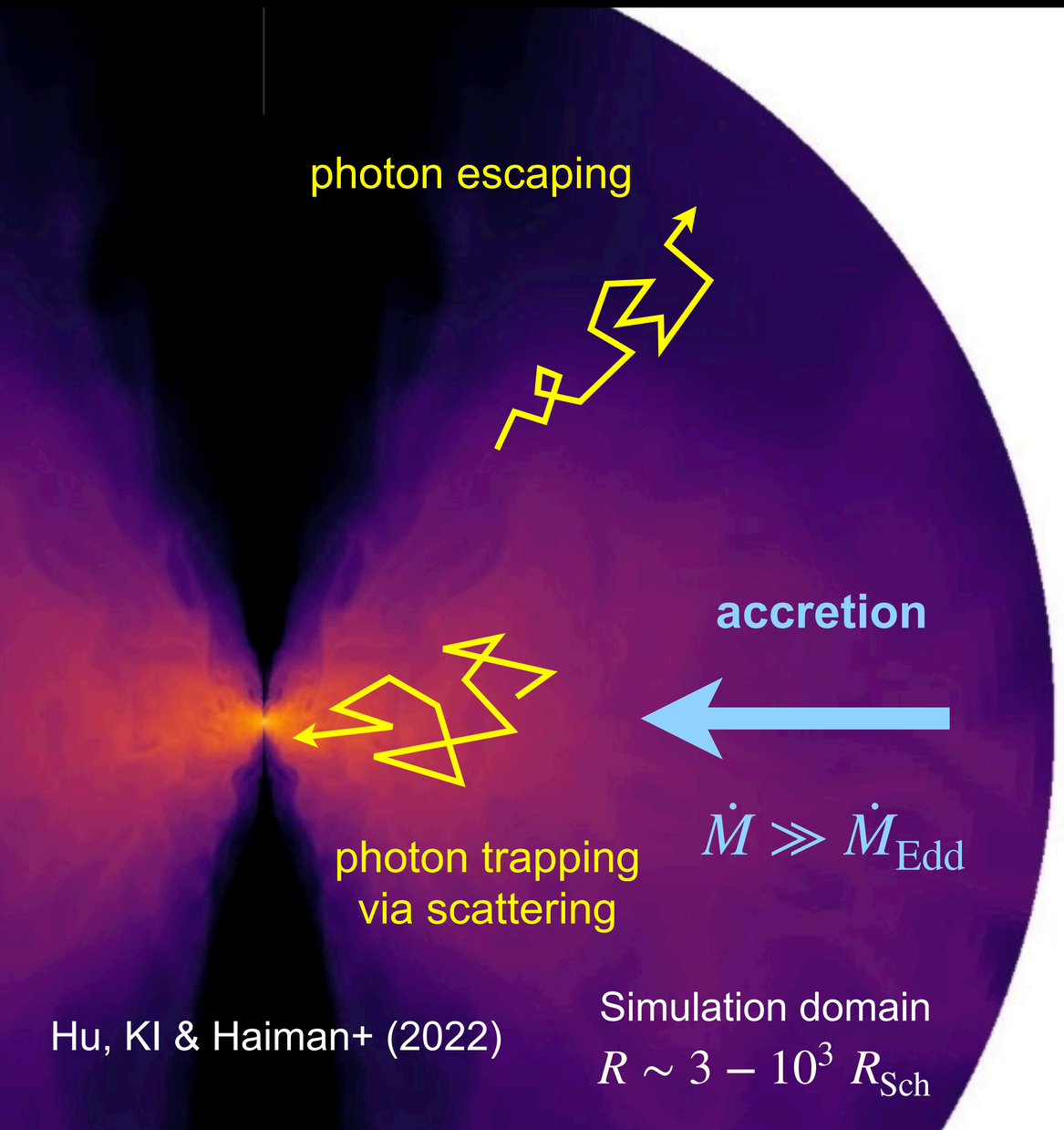
BH horizon scales

$r \sim \mu\mathrm{pc} \sim O(R_{\mathrm{Sch}})$

galactic scales

$r \sim \mathrm{kpc}$

Is super-Eddington accretion possible?



Hu, KI & Haiman+ (2022)

Super-Eddington accretion (disk-like) flows

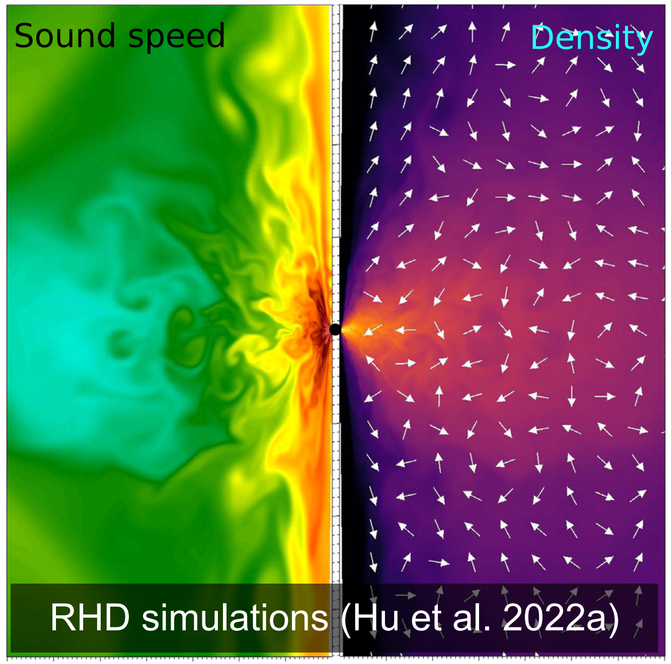
Begelman (1979), Abramowicz et al. (1988), Watarai et al. (2001), Ohsuga et al. (2005, 2009), Jiang et al. (2014), Sadowski et al. (2015)

- photon trapping in dense & rapid inflows
- radiative fluxes toward the polar directions

$$L \simeq \frac{GM_\bullet}{R_{\rm trap}}\dot{M} \sim O(L_{\rm Edd})$$

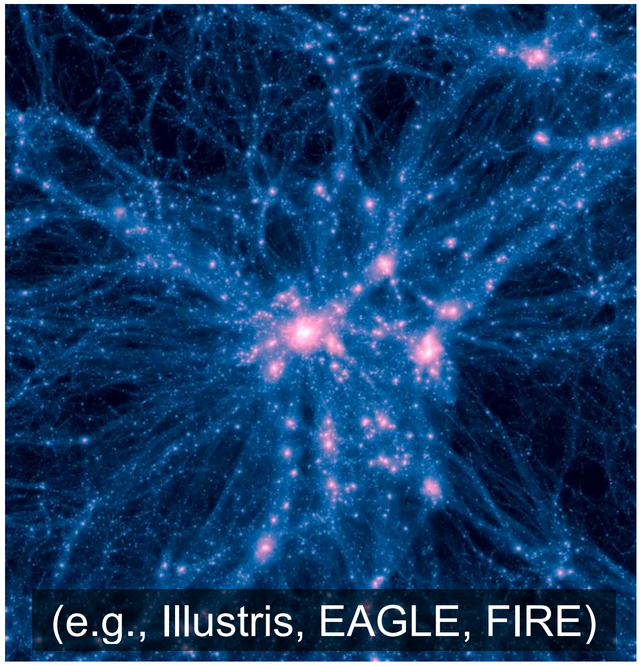
Breaking the Eddington limit **at small scales**
if a high rate is sustained from larger scales

BH accretion in multi-scales



?

$$R_{\rm B} \simeq \frac{GM_\bullet}{c_{\rm s}^2}$$



BH horizon scales

$r \sim \mu\mathrm{pc} \sim O(R_{\rm Sch})$

circum-nuclear scales

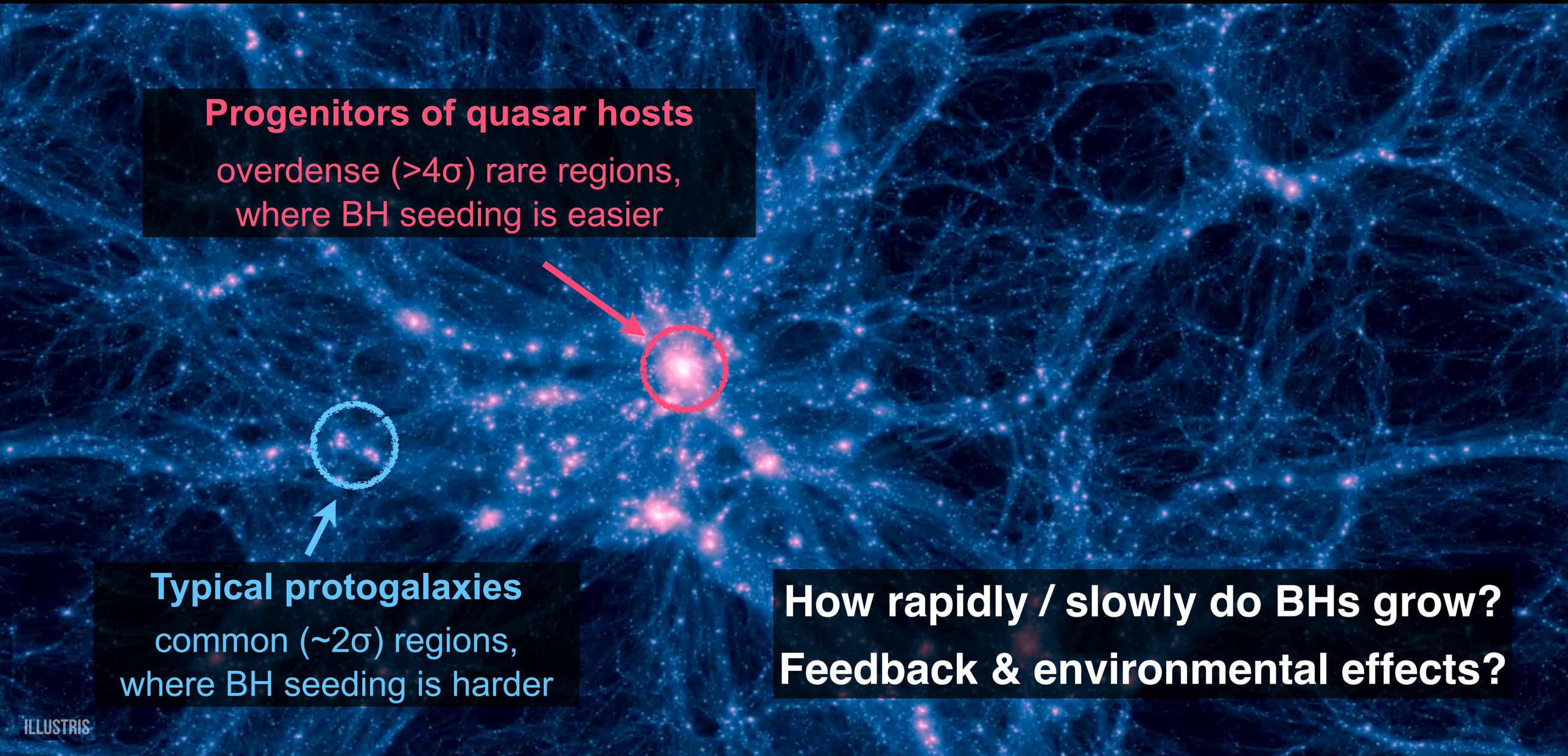
$1\ \mathrm{pc} \lesssim r \lesssim 100\ \mathrm{pc}$

galactic scales

$r \sim \mathrm{kpc}$

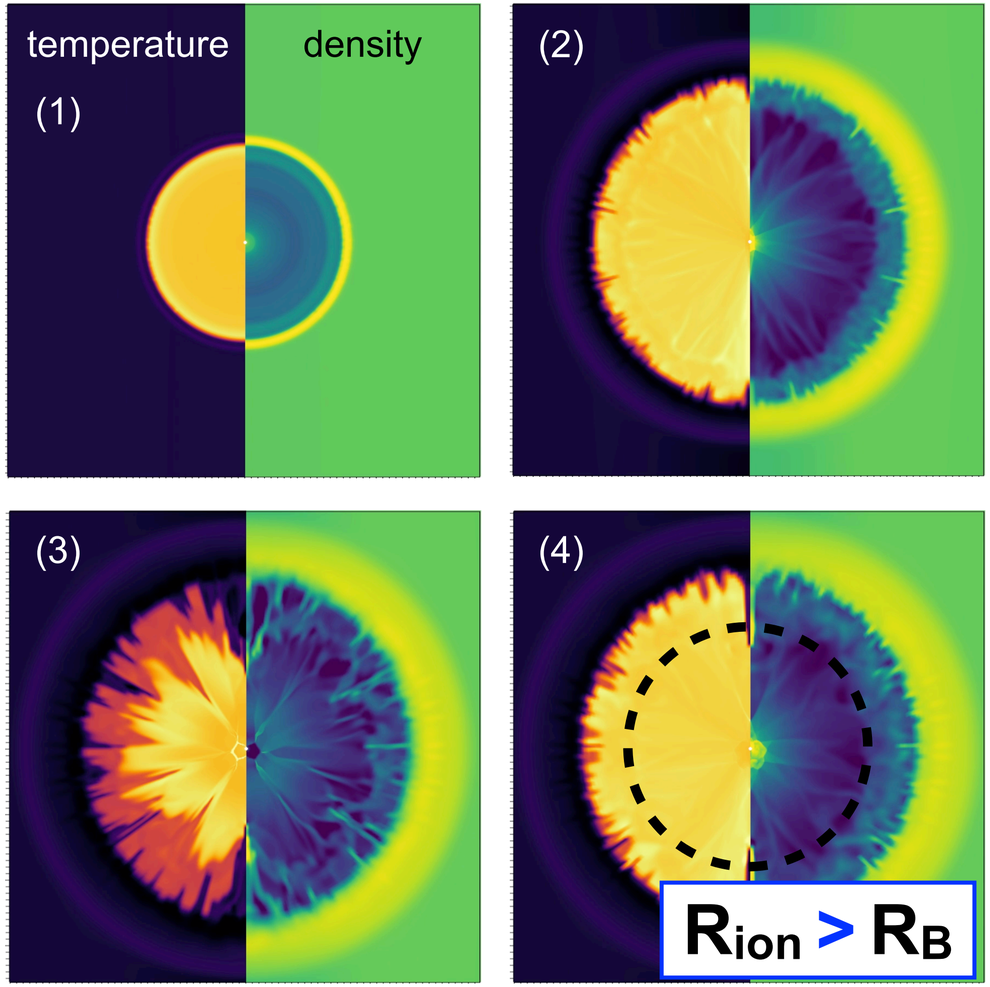
Bridging two distinct physical scales by resolving
the intermediate missing scale (BH gravity dominates)

BH accretion in various environments

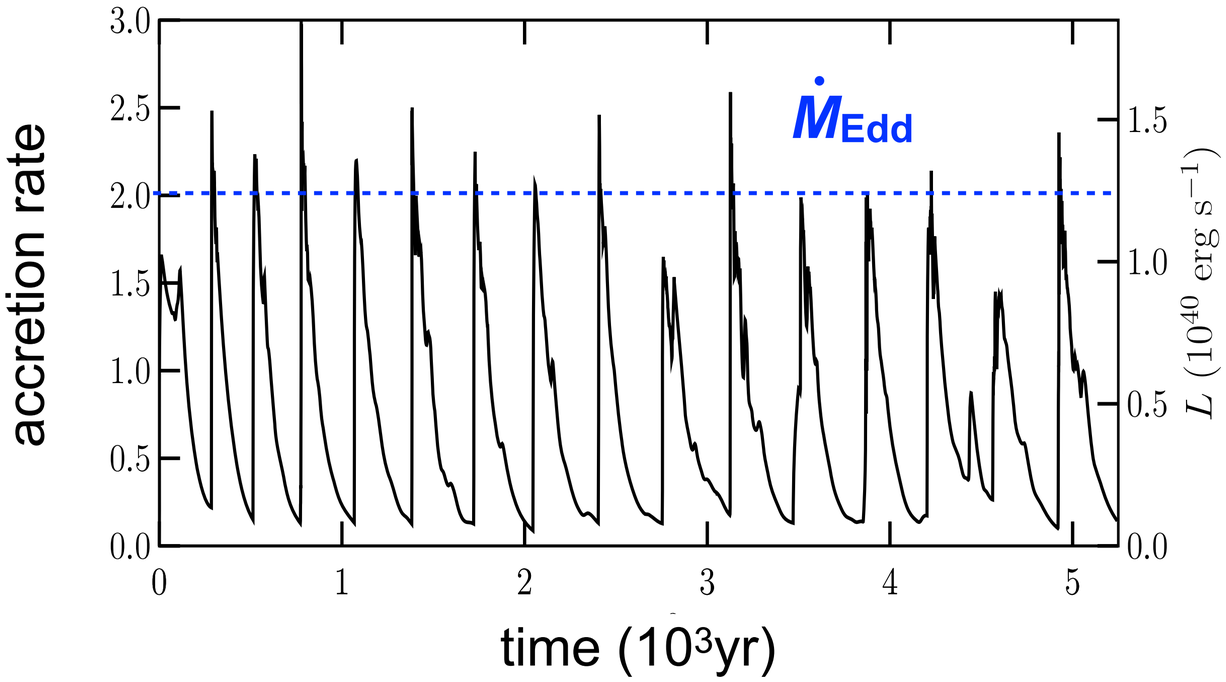


BH accretion in typical protogalaxies

- Feedback regulated case ($M_{halo} = 10^7\ M_{sun}$; z=10; 2σ)



Ciotti & Ostriker (2001), Cowie et al. (1978), Milosavljevic et al. (2009), Alvarez et al. (2009), Park & Ricotti (2011, 2012), Jeon et al. (2012)



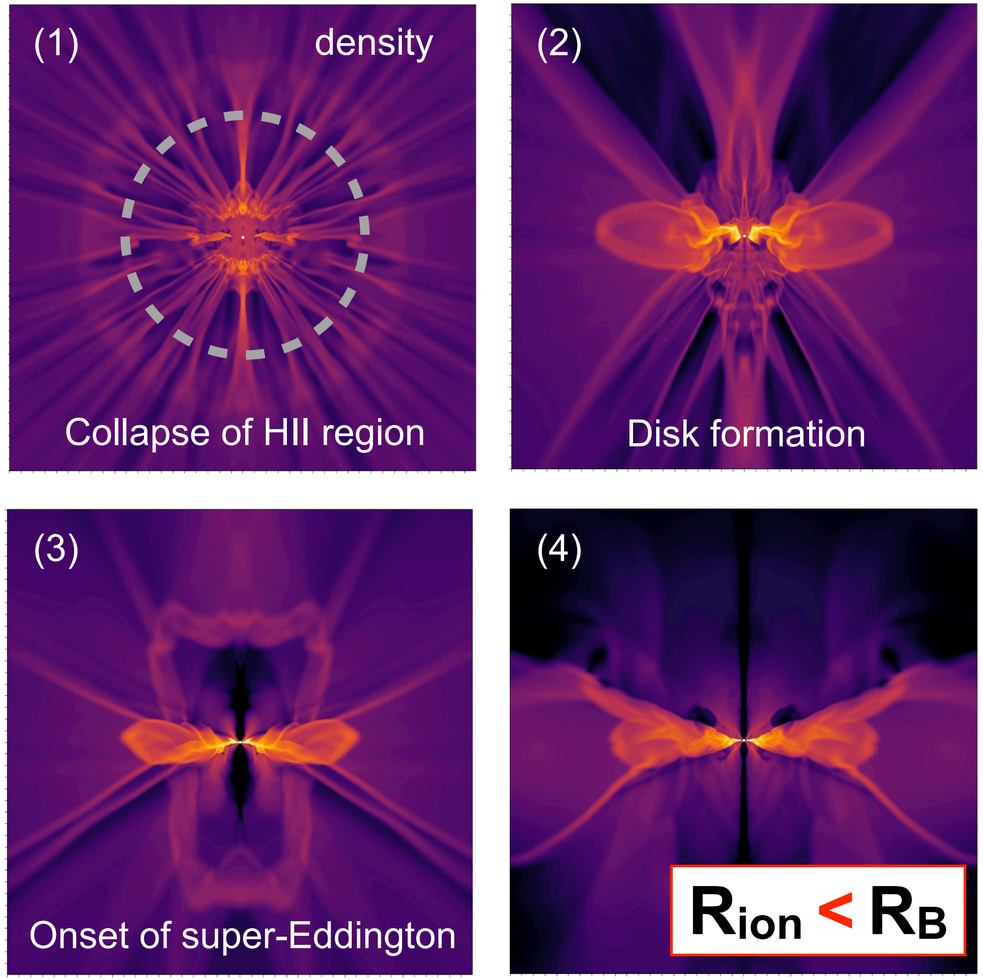
episodic accretion (radiation heating)

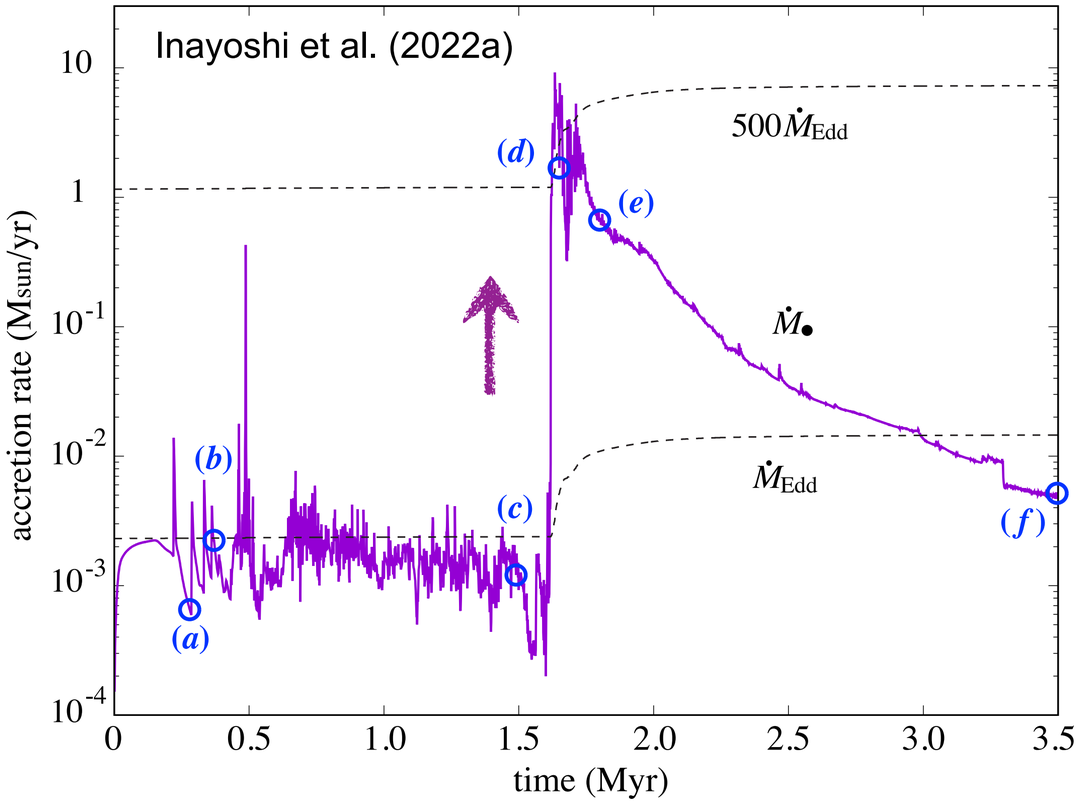
$$\langle \dot{M} \rangle \ll \dot{M}_{\rm Edd}$$

BH accretion in massive quasar-host galaxies

- Rapid growing case ($M_{halo} = 10^9\,M_{sun}$; z=15; 4σ)

KI, Haiman & Ostriker (2016), Pacucci et al. (2016), Park et al. (2016, 2020), Takeo et al. (2018, 2020)





collapsing HII regions
(dense disk forms)

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

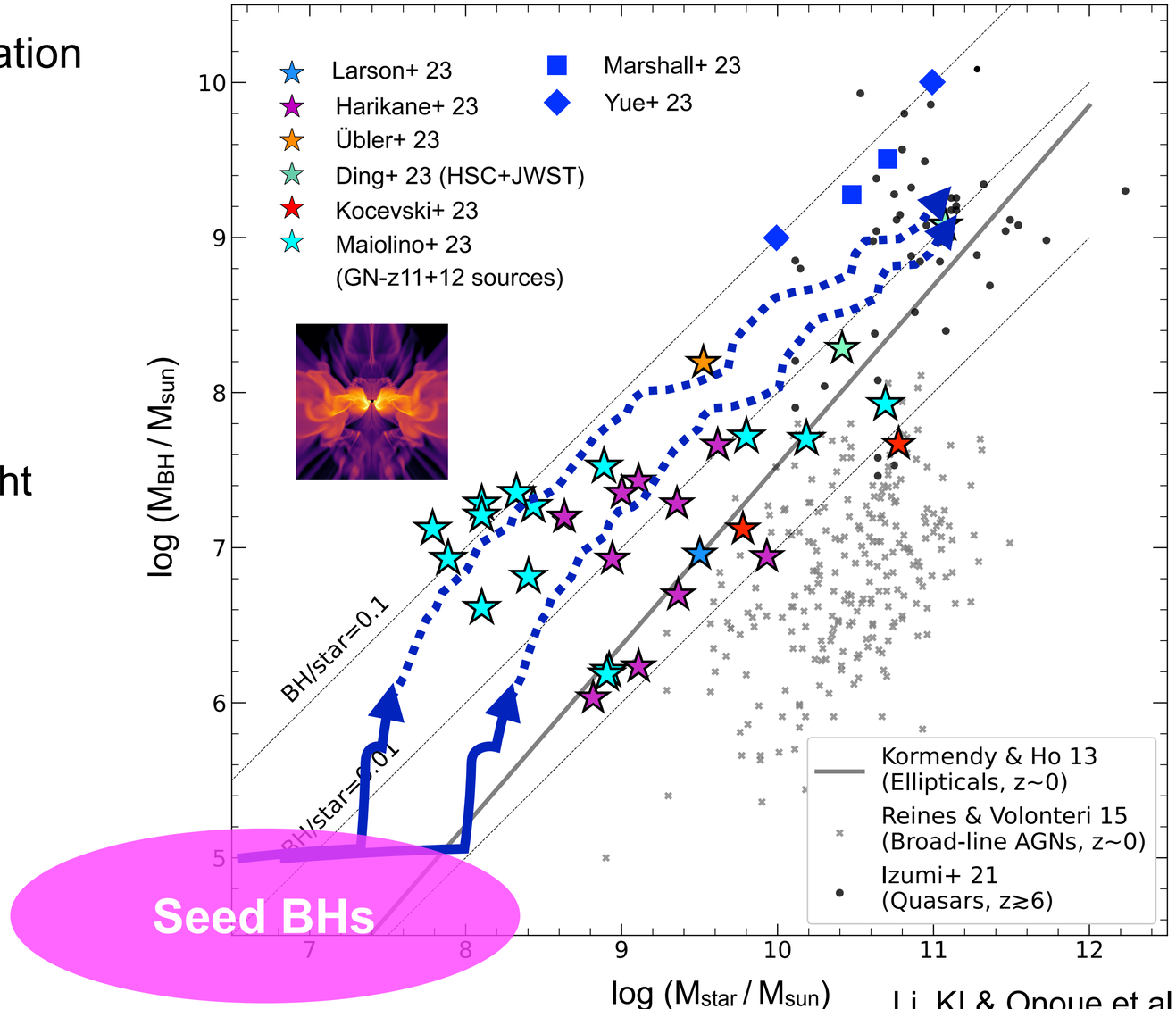
Early BH-galaxy coevolution

✦ **Overmassive BHs** relative to the local relation

RHD simulations (KI et al. 2022a,b; Hu et al. 2022a,b)
see also Visbal & Haiman (2018), Scoggins et al. (2023)

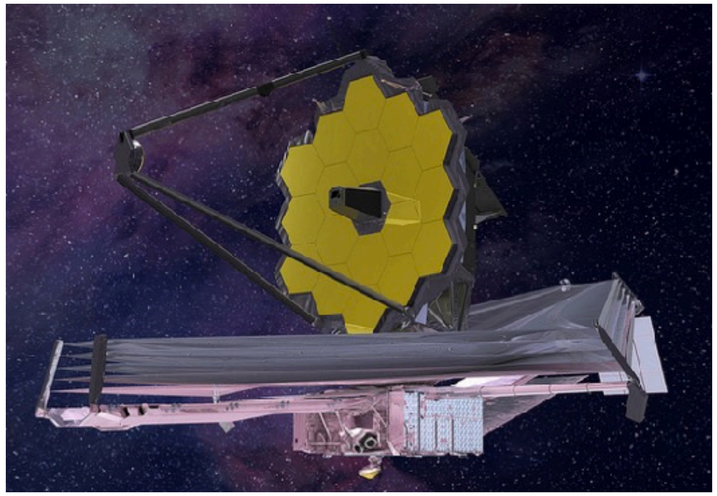
- Transient super-Eddington accretion brings seed BHs to $M_{\rm BH}/M_{\rm star} \gtrsim 0.01$

- Those active and young BHs becomes bright enough to be detected/selected with JWST



Li, KI & Onoue et al. (2023)

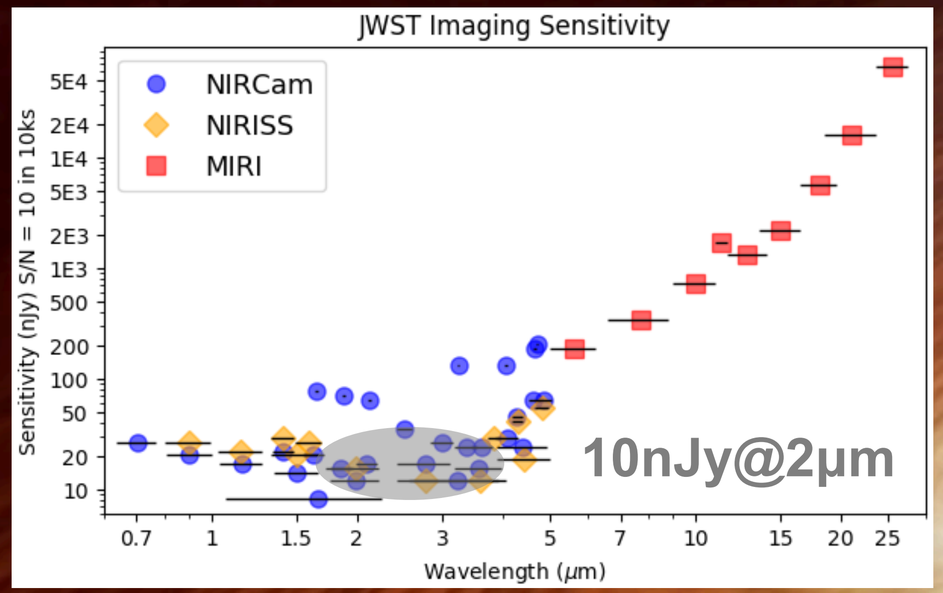
Excavating the First Massive BHs



JWST for hunting seed BHs

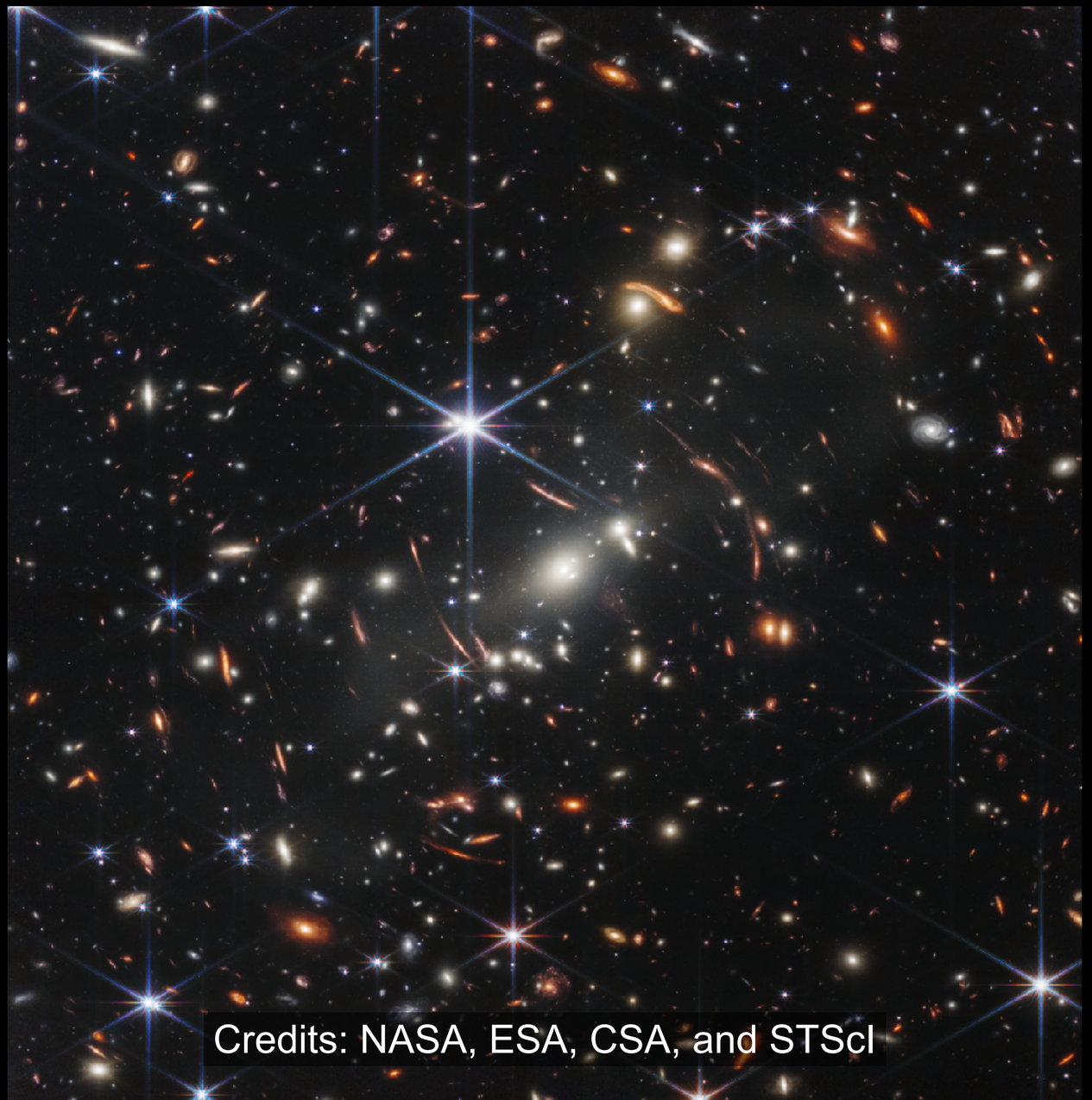
Observed wavelength **1.98μm** [(1+z)/16]

Rest-frame ~ 10eV (0.124μm)

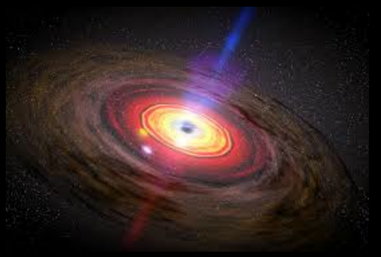


How to find seed BHs from images?

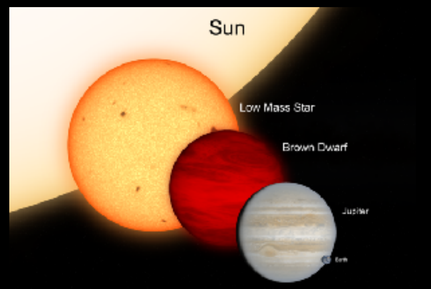
galaxies



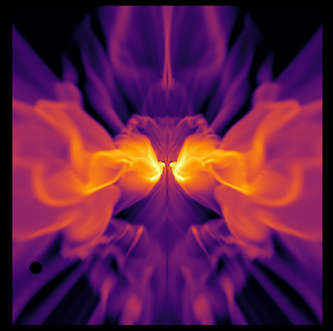
Credits: NASA, ESA, CSA, and STScI



quasars

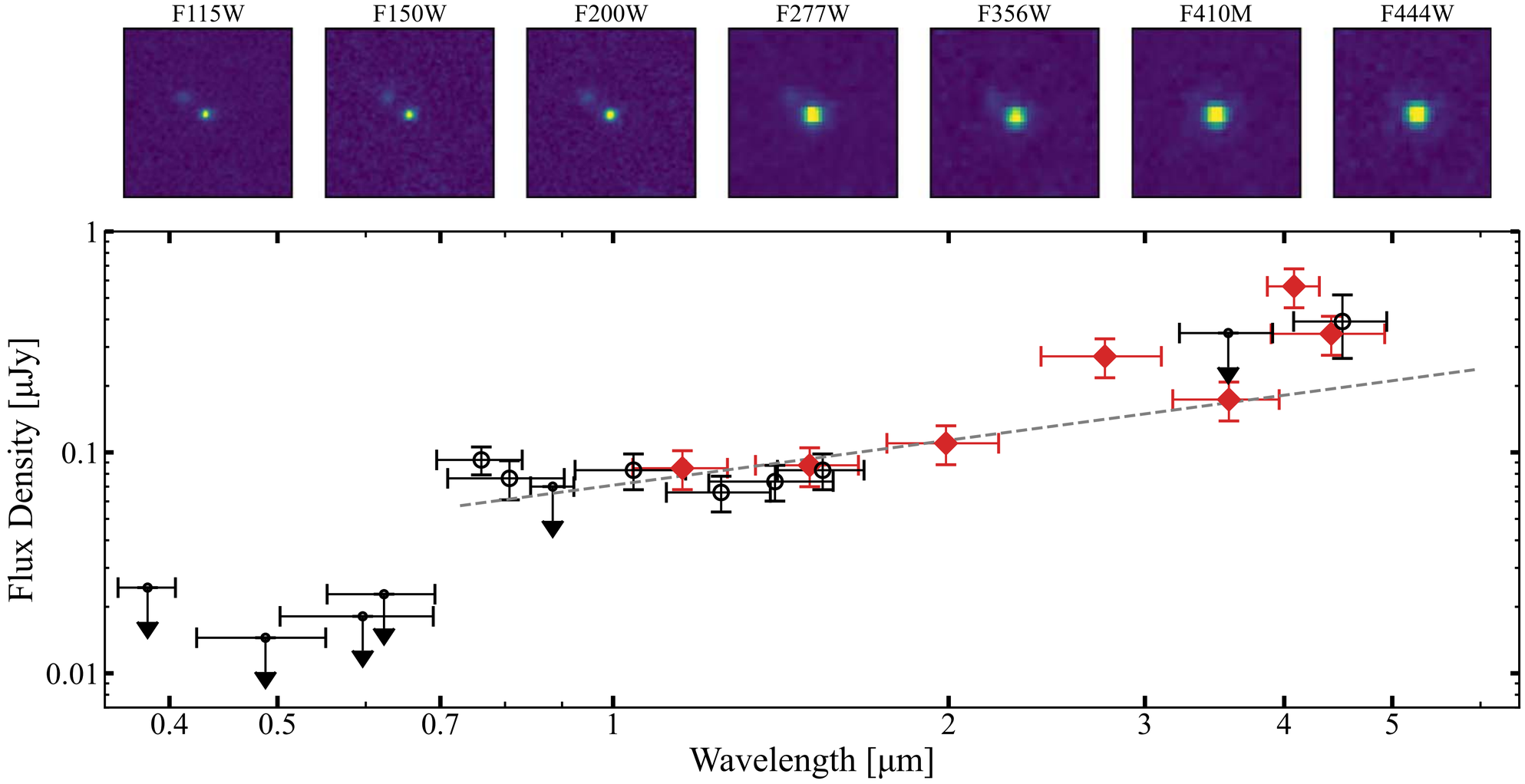


brown dwarfs



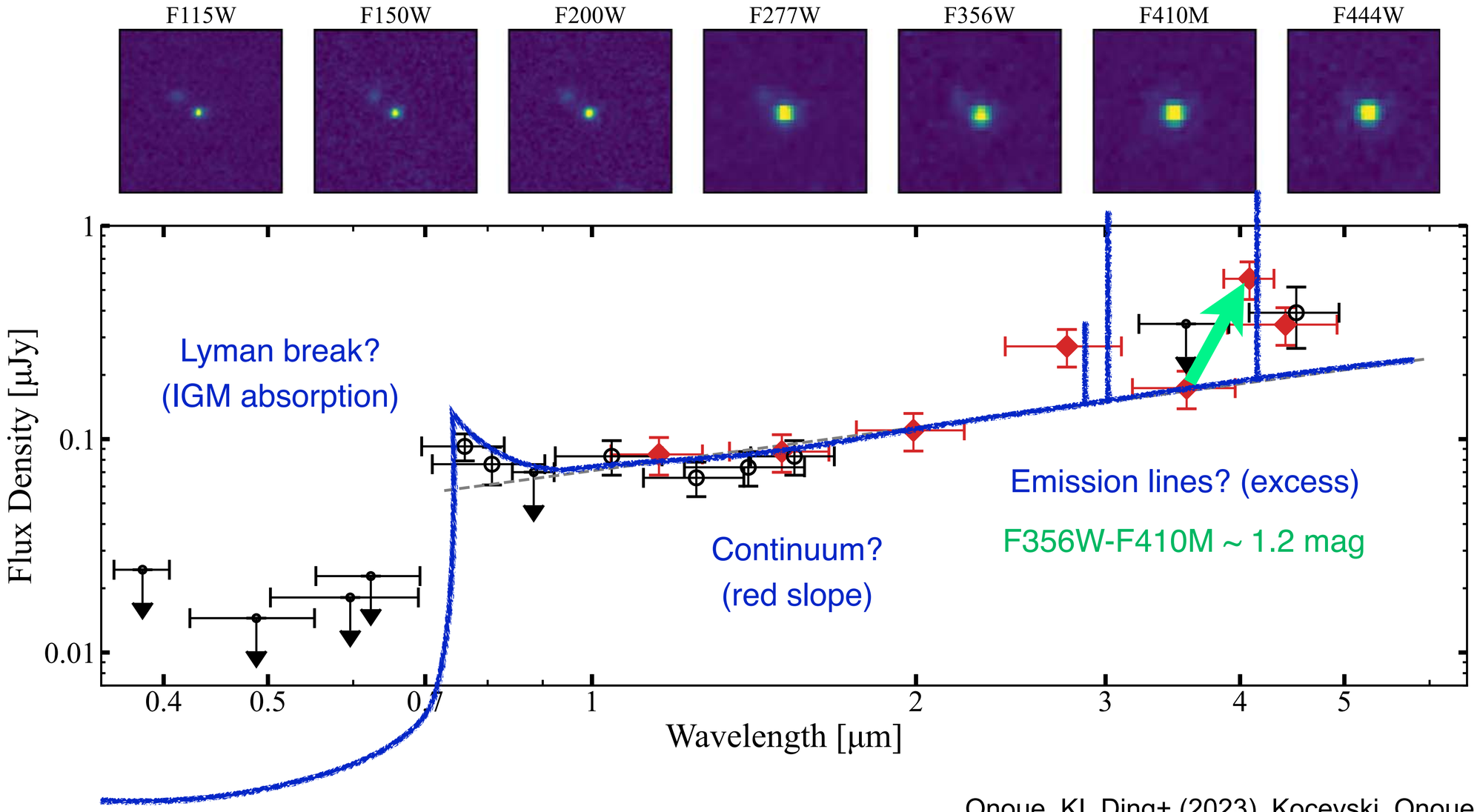
seed BHs

Exercises of QSO hunting



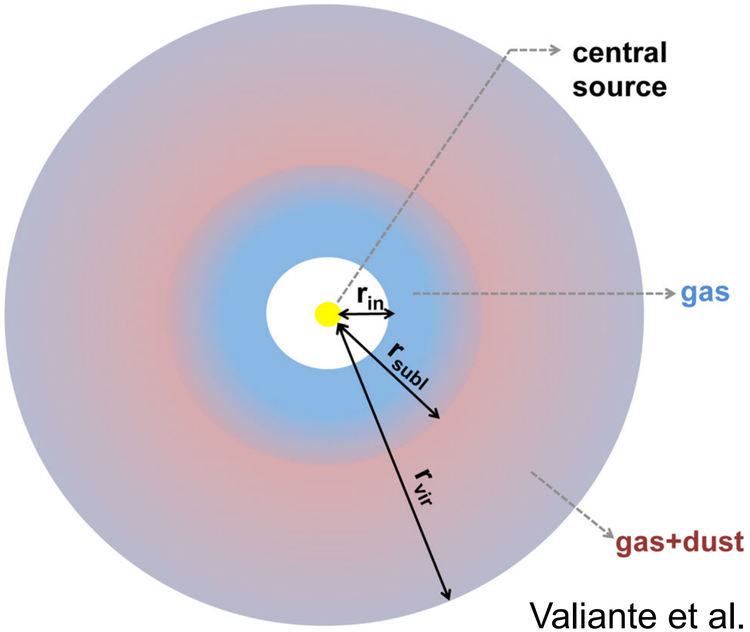
Onoue, KI, Ding+ (2023), Kocevski, Onoue, KI+ (2023)

Exercises of QSO hunting



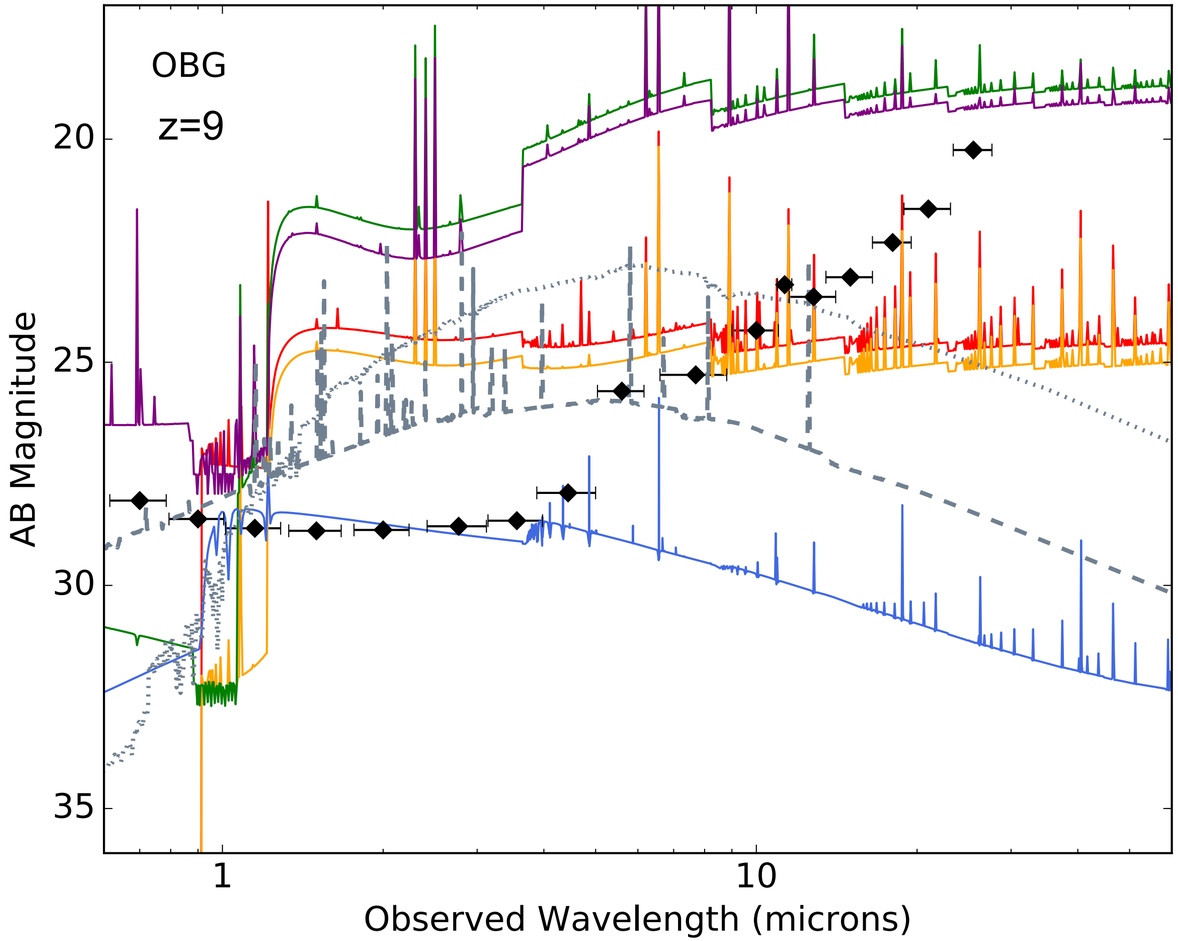
Onoue, KI, Ding+ (2023), Kocevski, Onoue, KI+ (2023)

Spectra for fast growing seed BHs (1D)



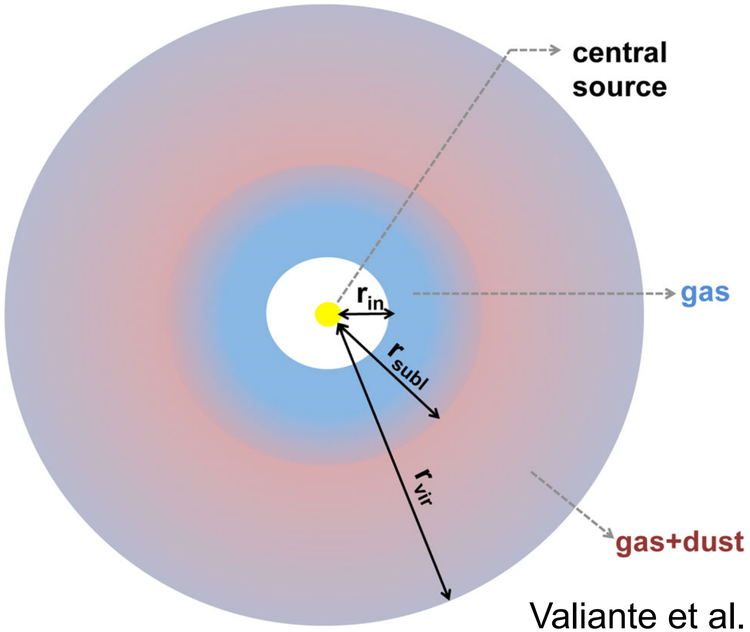
Valiante et al. (2018)

Natarajan et al. (2017)



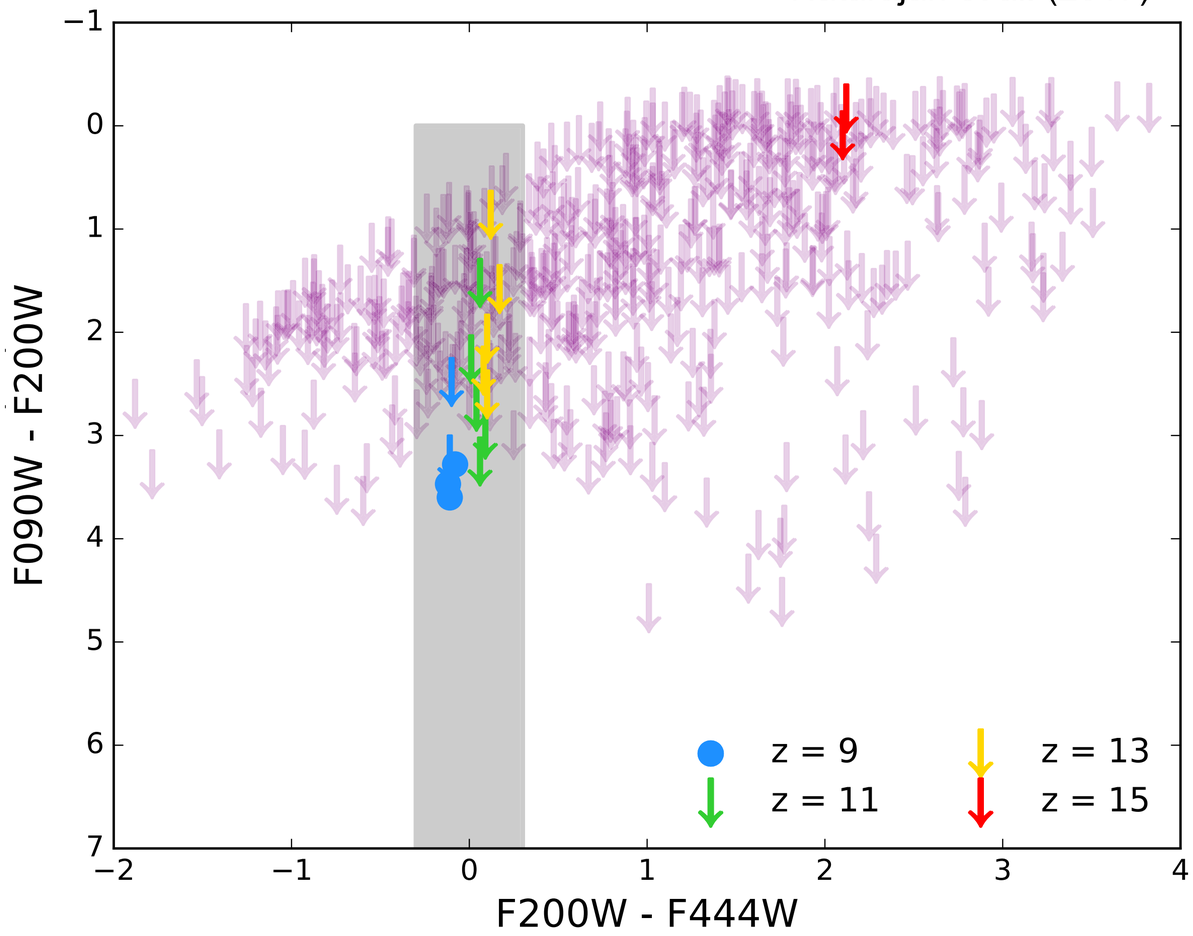
- Flat continuum spectra (color~0)
- AGN radiation is reprocessed into lines due to spherically symmetric geometry
- The color-selection conditions are heavily contaminated by galaxies and brown dwarfs

Spectra for fast growing seed BHs (1D)



Valiante et al. (2018)

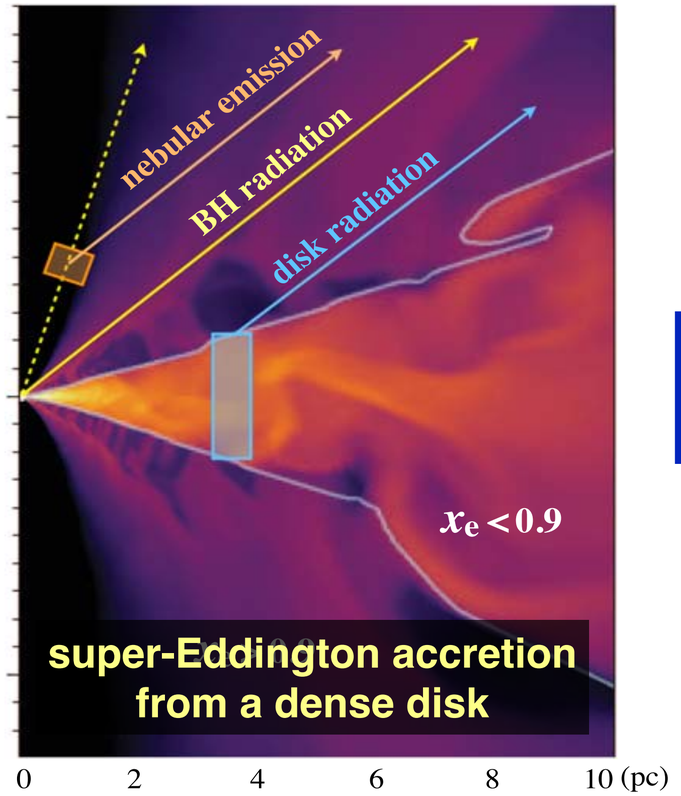
Natarajan et al. (2017)



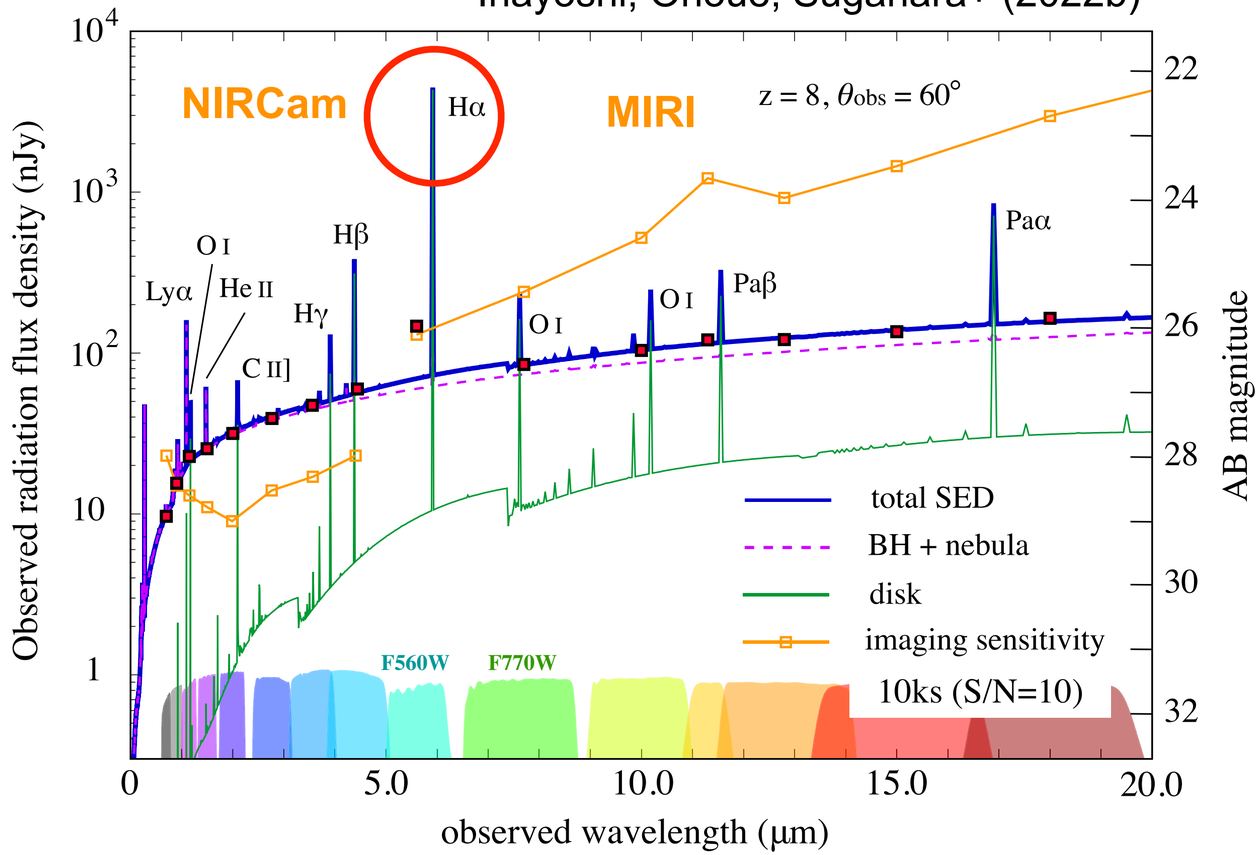
- Flat continuum spectra (color~0)
- AGN radiation is reprocessed into lines due to spherically symmetric geometry
- The color-selection conditions are heavily contaminated by galaxies and brown dwarfs

Spectra for fast growing seed BHs (2D)

RHD simulations + CLOUDY

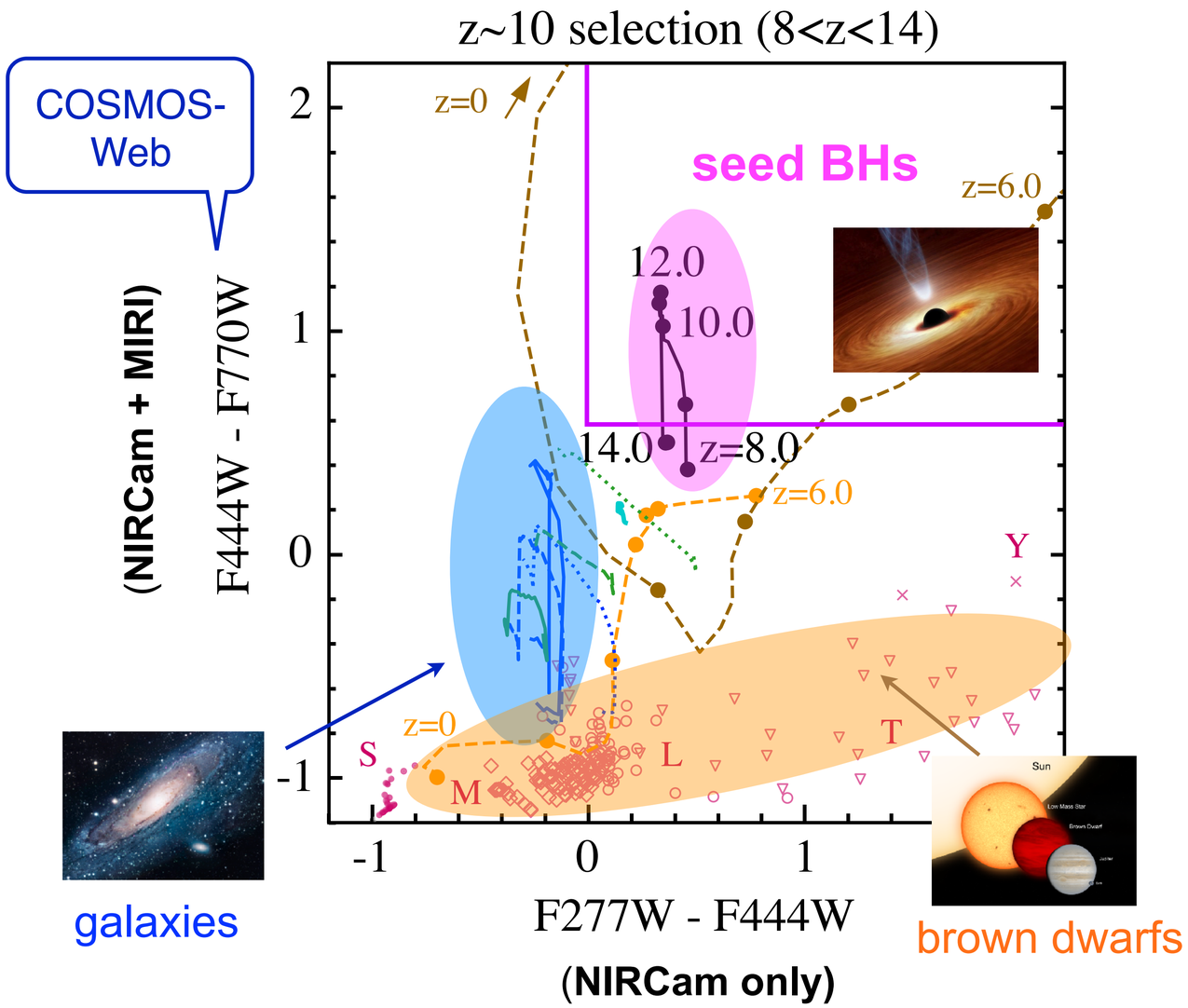


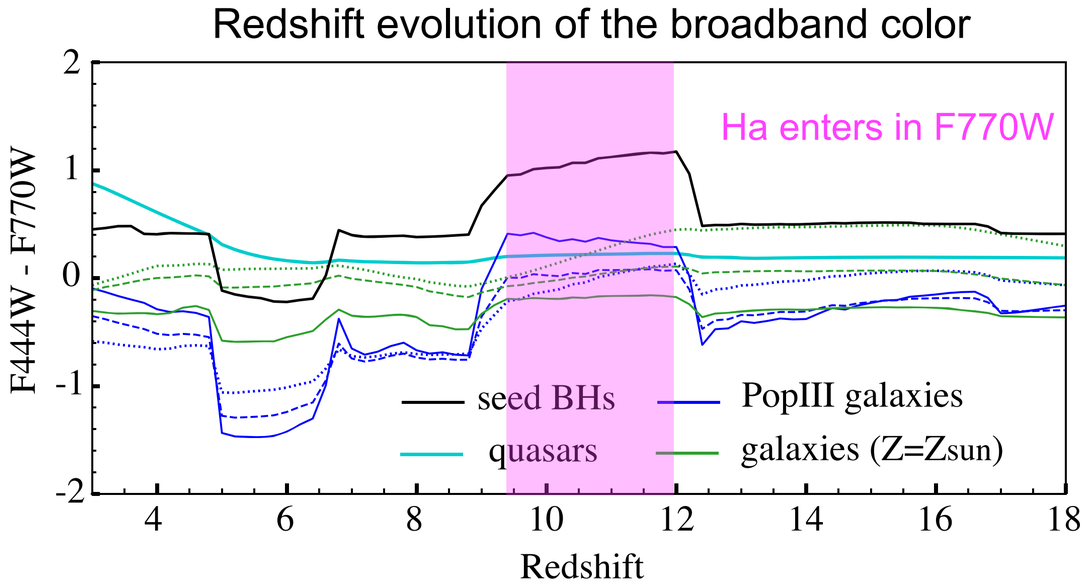
Inayoshi, Onoue, Sugahara+ (2022b)



- **Strong Balmer lines** (e.g., $EW_{H\alpha}$ = 1300 Å, $EW_{H\beta}$ = 100 Å)
- Emission lines of neutral oxygen due to Lyβ fluorescence

Color-cut conditions to hunt for seed BHs





- A unique color due to **strong Hα lines**

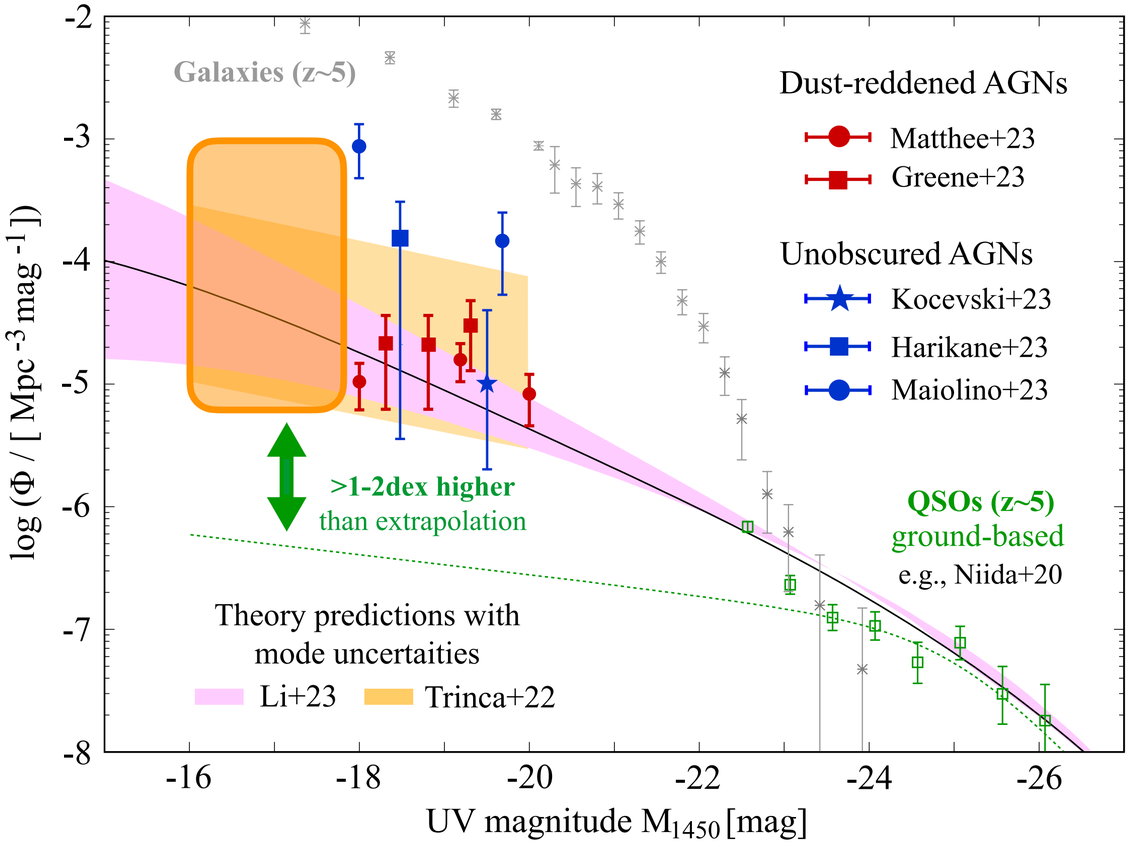
  F356W - F560W >1 at z~8

  F444W - F770W >1 at z~12

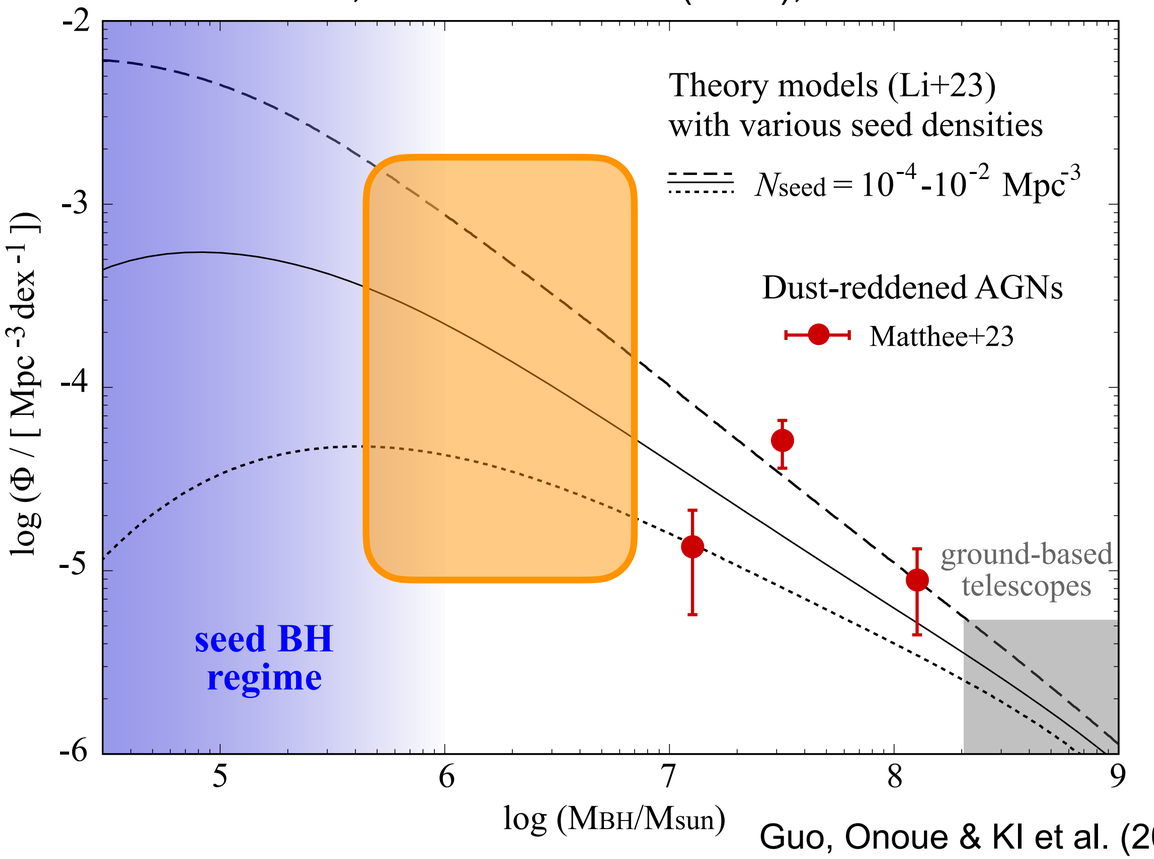
KI, Onoue, Sugahara+(2022b)

See also 1D RHD: Natarajan+(2017), Valiante+(2018)
Empirical SED: Goulding & Greene (2022)
NLR: Nakajima & Maiolino (2022)

Toward seed regimes…



Li, KI & Onoue et al. (2023), with modifications



Guo, Onoue & KI et al. (2024)

Observations of **fainter AGNs & lower-mass BHs** are crucial to constrain the the number density of seed BHs and their BHMF shape

Upcoming conferences!

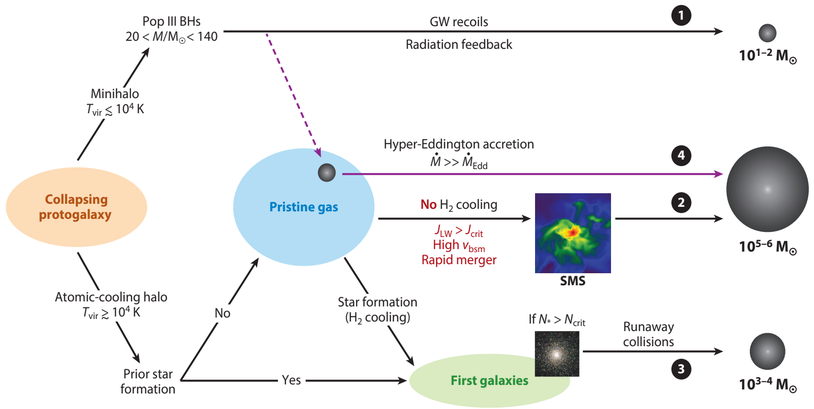
May 20-23, 2024 (abstract due **Nov 27**)

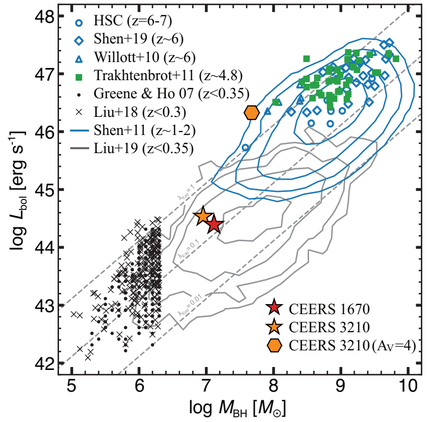
July 13-21, 2024 (abstract due **Feb 9**)

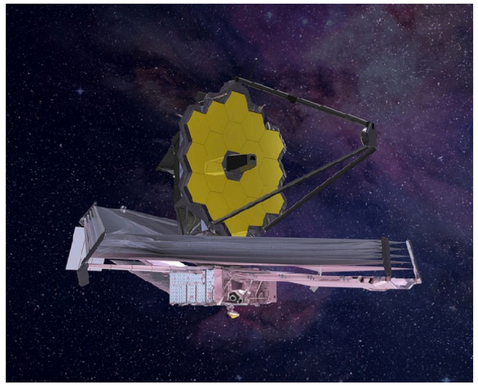
See you at NYC & Busan

Summary

- The existence of high-z SMBHs requires their quick assembly mechanisms (massive seed formation & rapid accretion)
- Transient super-Eddington accretion onto seed BHs in massive DM halos naturally produce“overmassive” BHs with unique radiative signatures
- JWST capabilities allow us to hunt for low-mass & low-luminosity AGNs at z>4, revealing the population hidden in pre-JWST era (so far, ~30 AGNs per year)








Thank you!