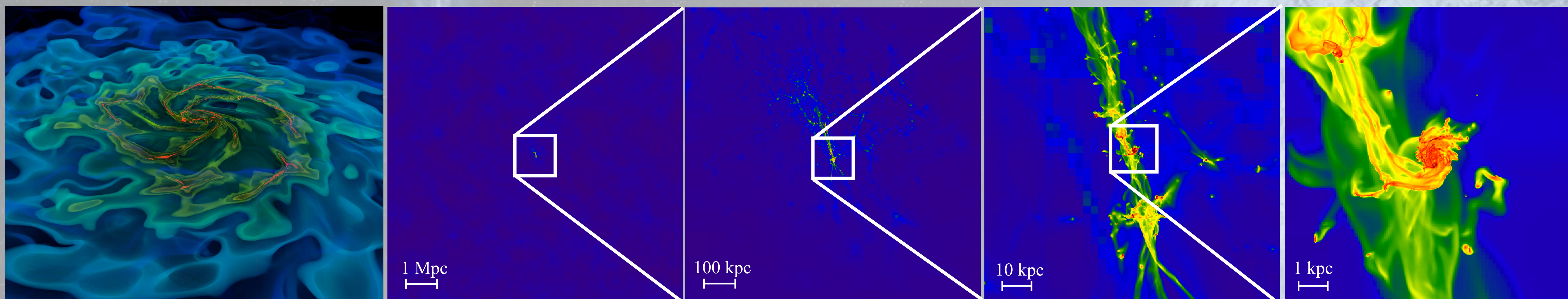
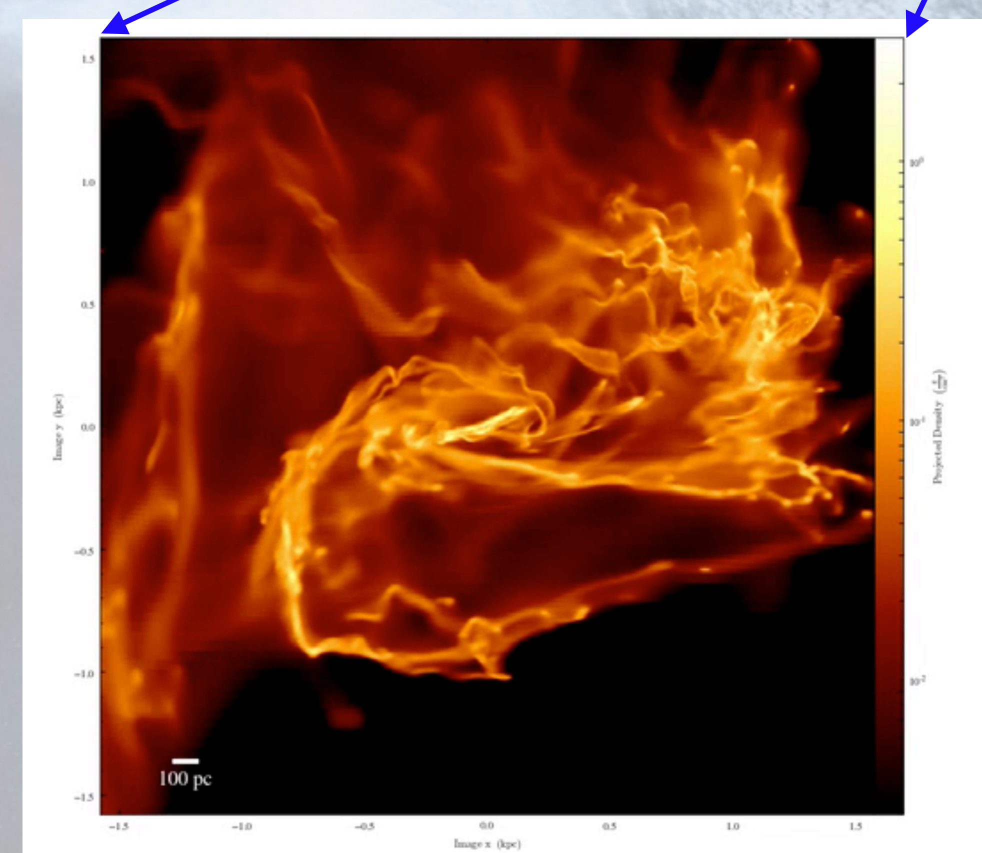
Solving the Mysteries of Supermassive Black Holes in the Era of High-resolution Simulations



Kim et al. 2019



Ji-hoon Kim (Seoul National Univ.)

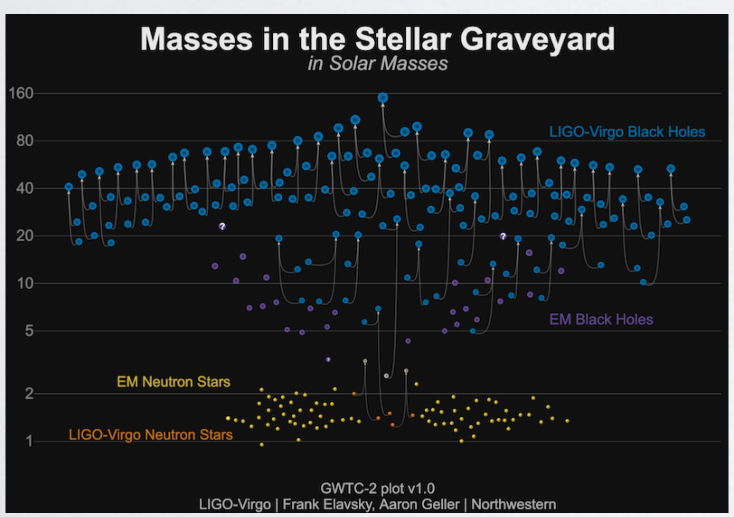
Collaborators: T. Abel (Stanford), P. Hopkins (Caltech), Y. Jo (SNU), J. Primack (UCSC), J. Wise (GATech), et al.

Known Black Hole Mass Distribution

- Two different types of black holes have been discovered.

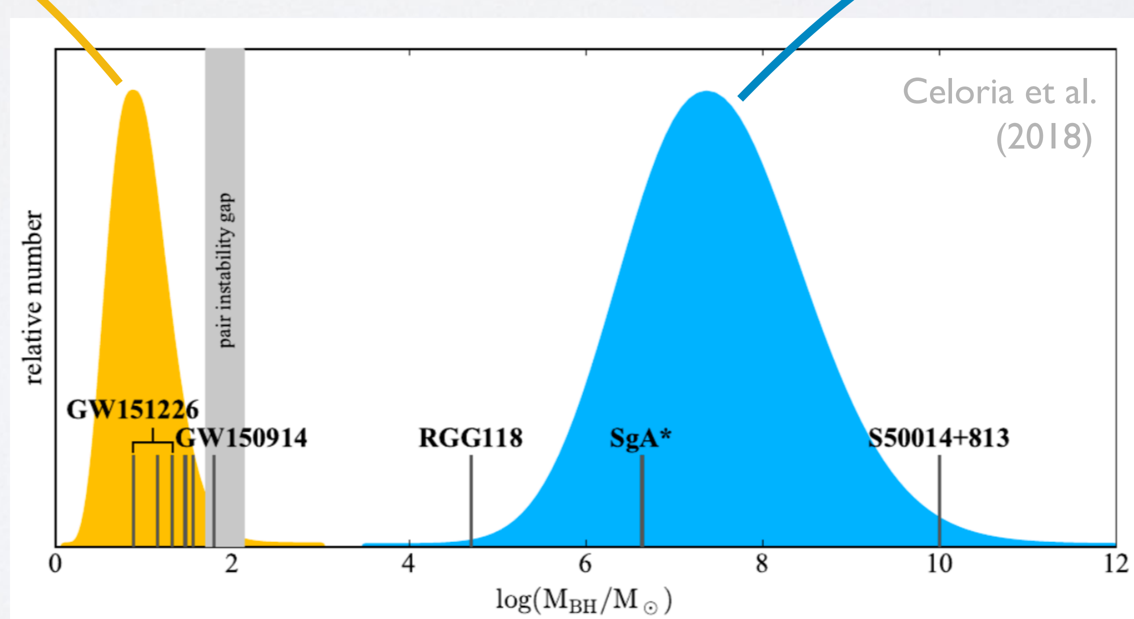
Stellar mass BHs
($M_{BH} < 10^3 M_{sun}$)

Supermassive BHs
($M_{BH} > 10^6 M_{sun}$, 1 per galaxy)

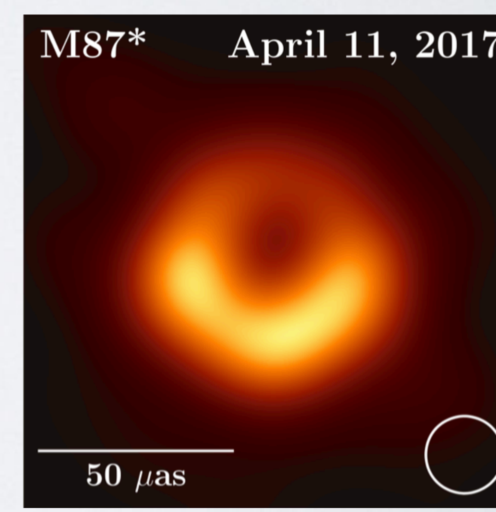


LIGO/VIRGO (2020)

Black Hole Count →



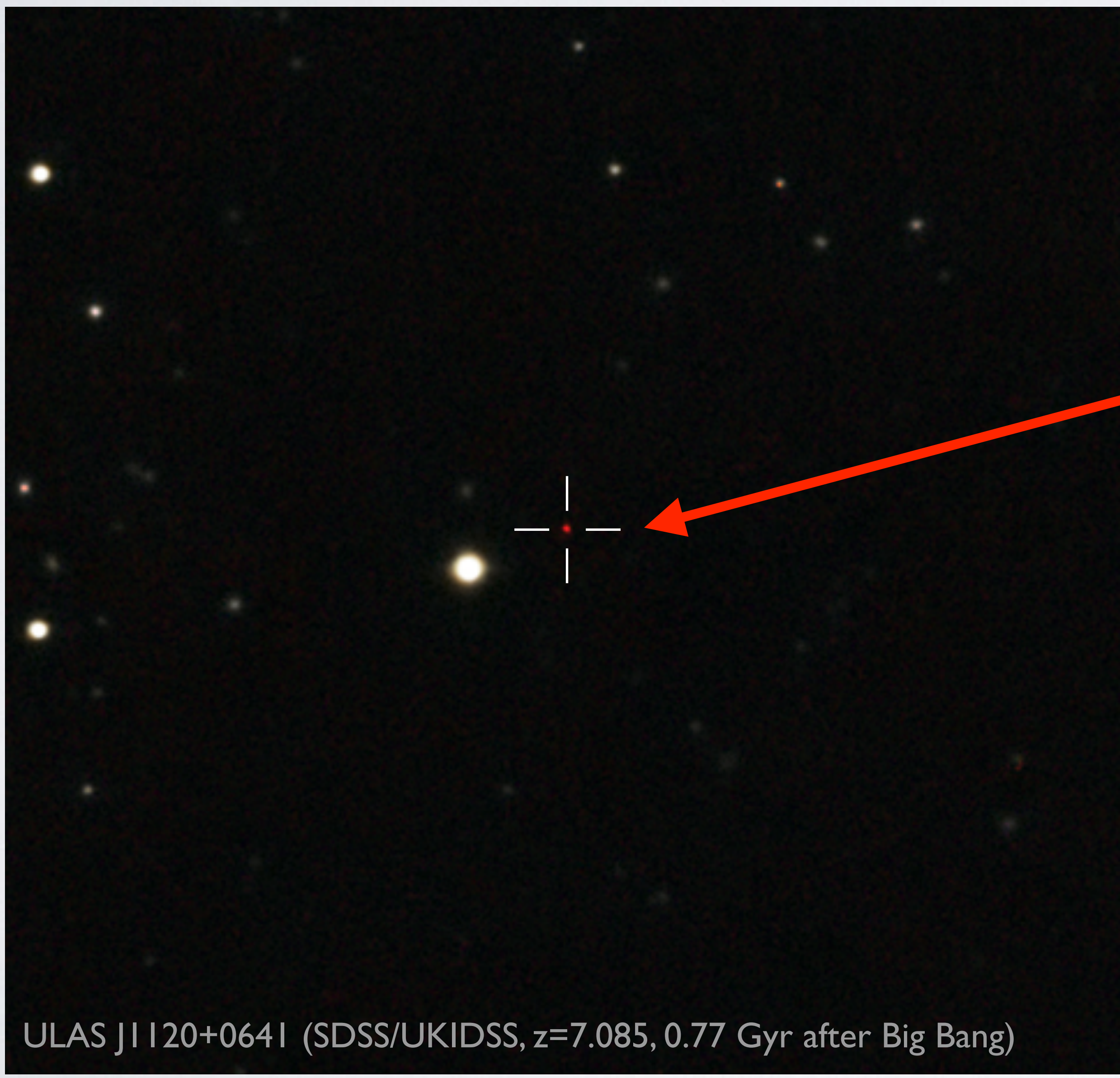
log (Black Hole Mass in M_{sun}) →



EHT (2019)

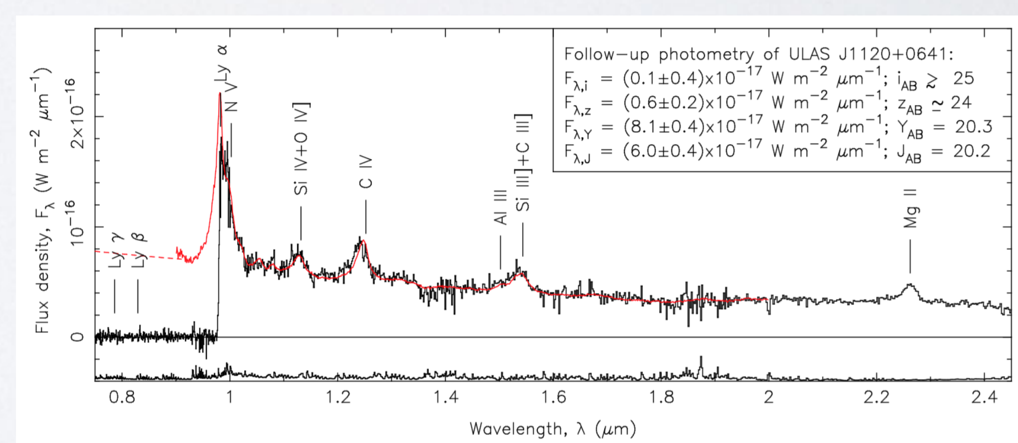
High-redshift Supermassive Black Holes

- Many SMBHs existed in the very early Universe ("high-z"; z>7), only a few hundreds of Myrs after the Big Bang.



ULAS J1120+0641 (SDSS/UKIDSS, z=7.085, 0.77 Gyr after Big Bang)

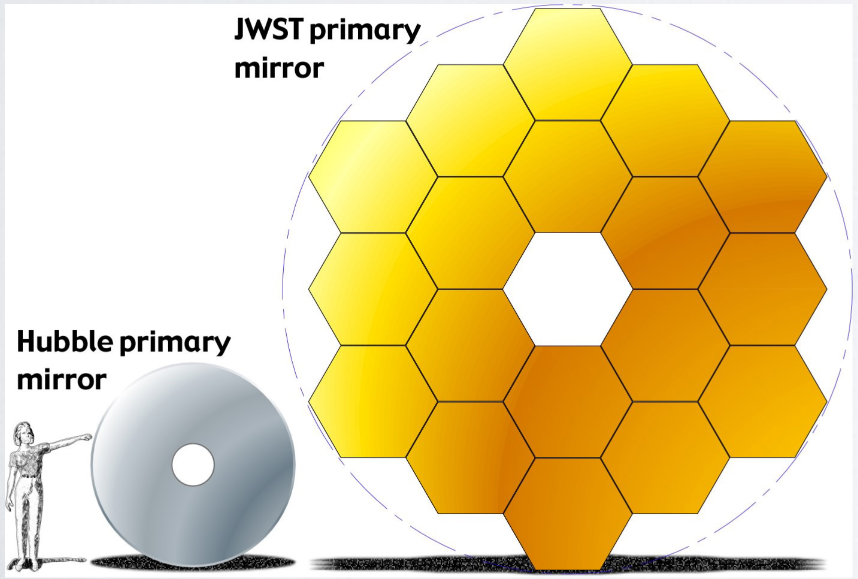
Artist's rendering of AGN disk (ESO)



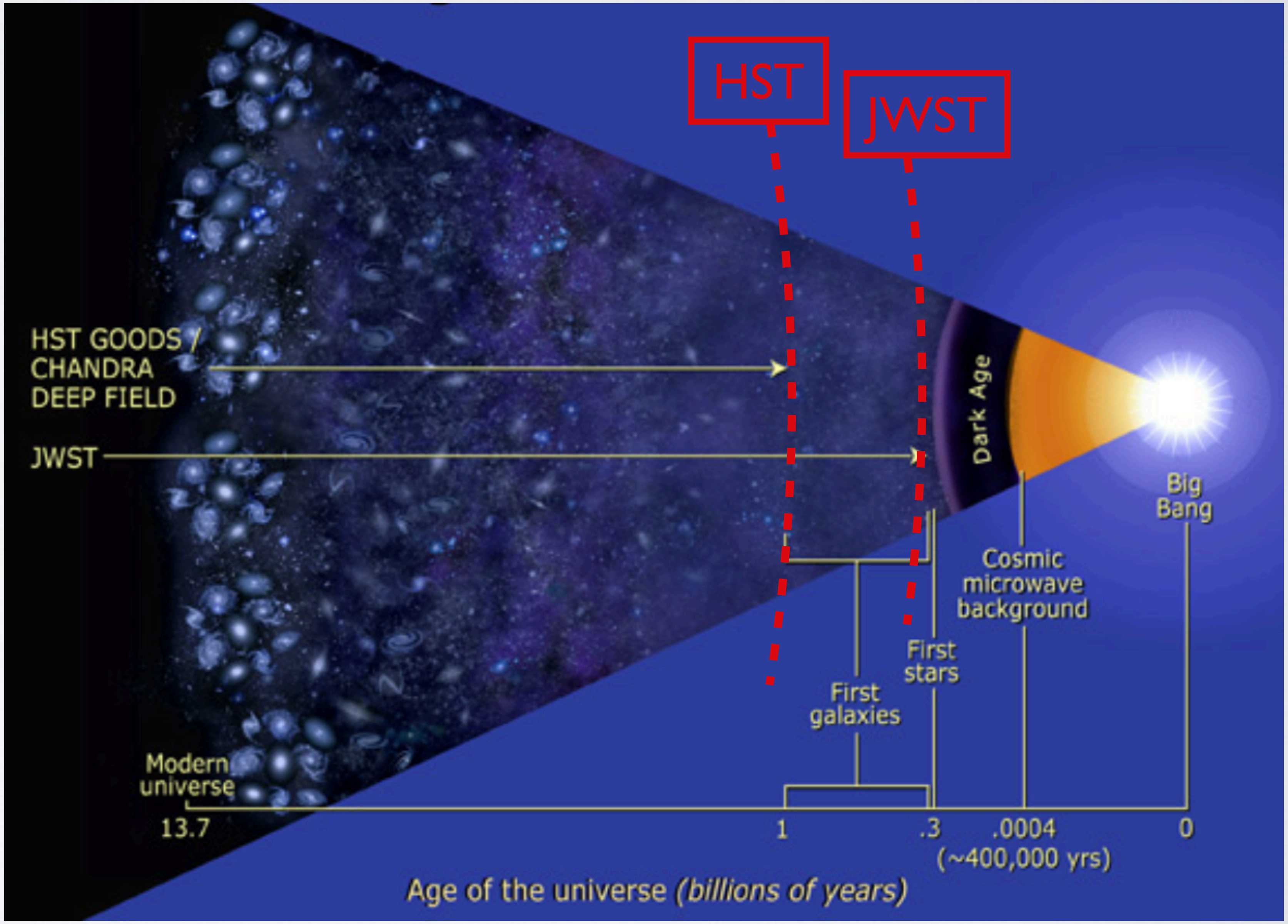
Mortlock et al. (2011)

James Webb Space Telescope (JWST)

• JWST will observe distant galaxies in the early universe, and see photons from very young stars that penetrate dusty shrouds.



NASA

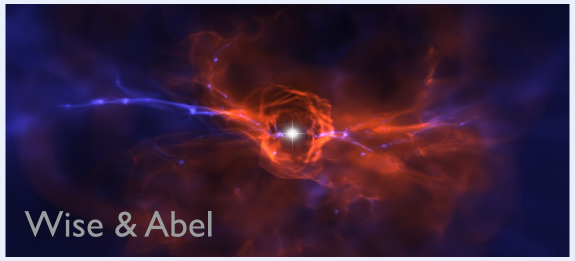


NASA

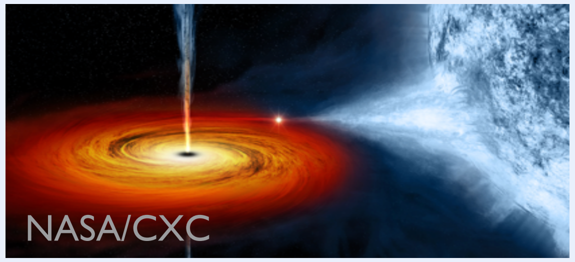
Supermassive Black Hole Mysteries

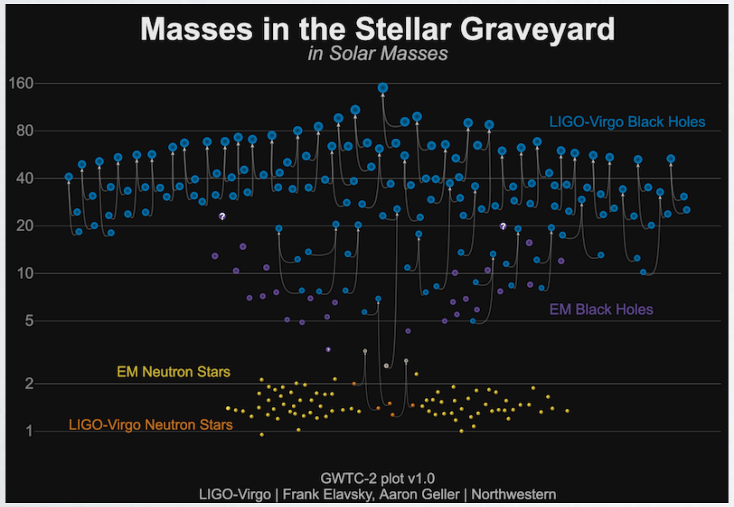
- SMBHs raise questions about our understandings of Universe.

Q1: What were the SMBH seeds?



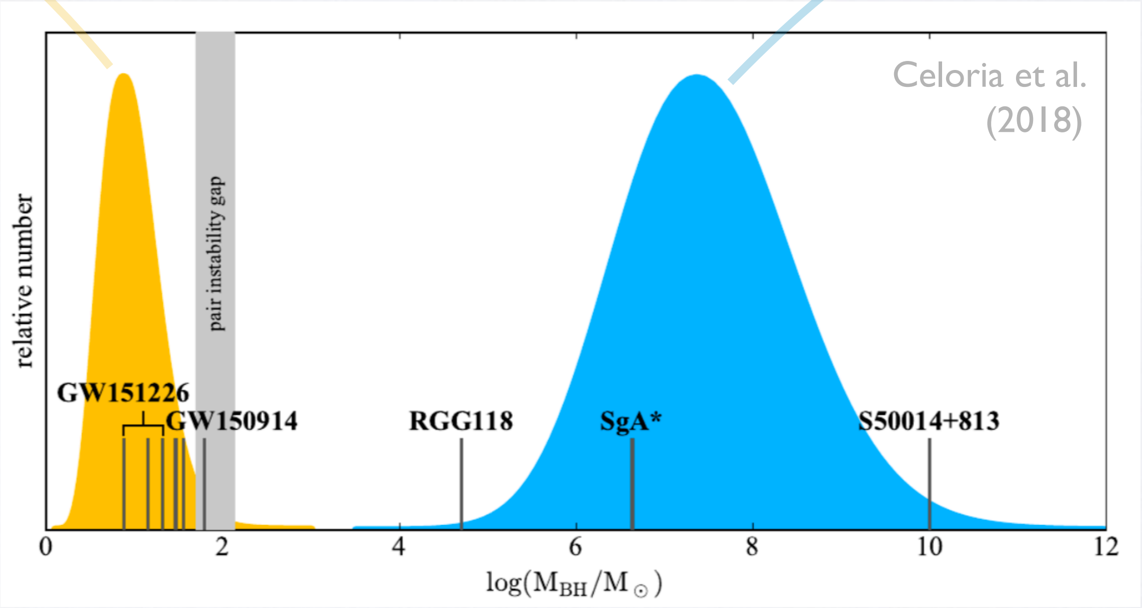
Q2: How did SMBHs grow so fast?



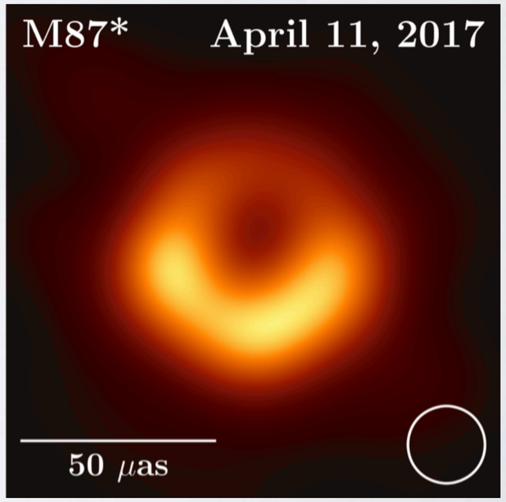


LIGO/VIRGO (2020)

Black Hole Count ↑



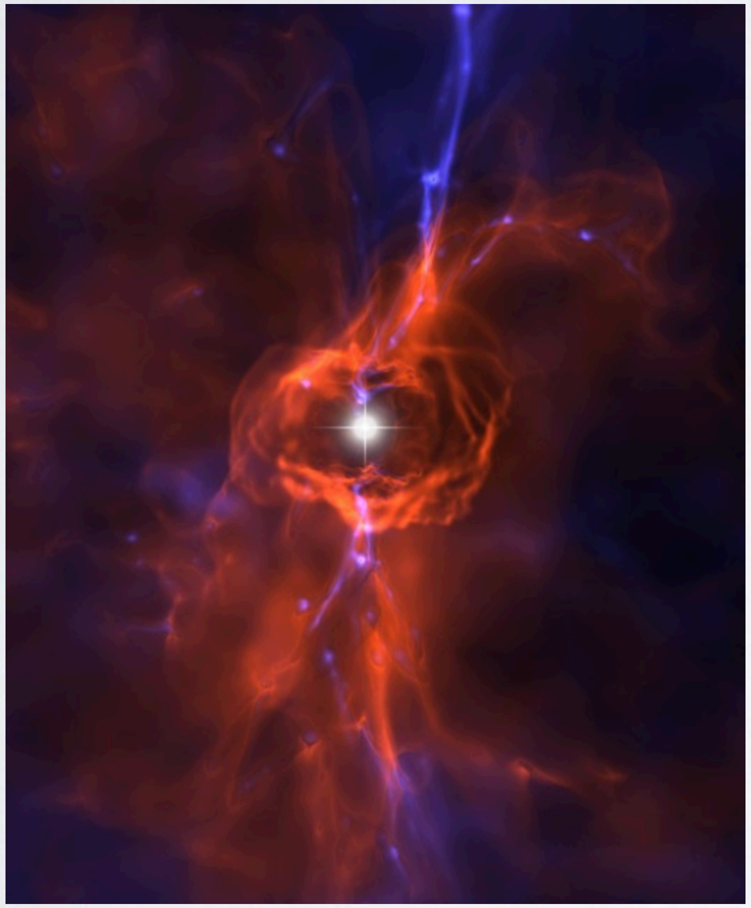
log (Black Hole Mass in M_{sun}) →



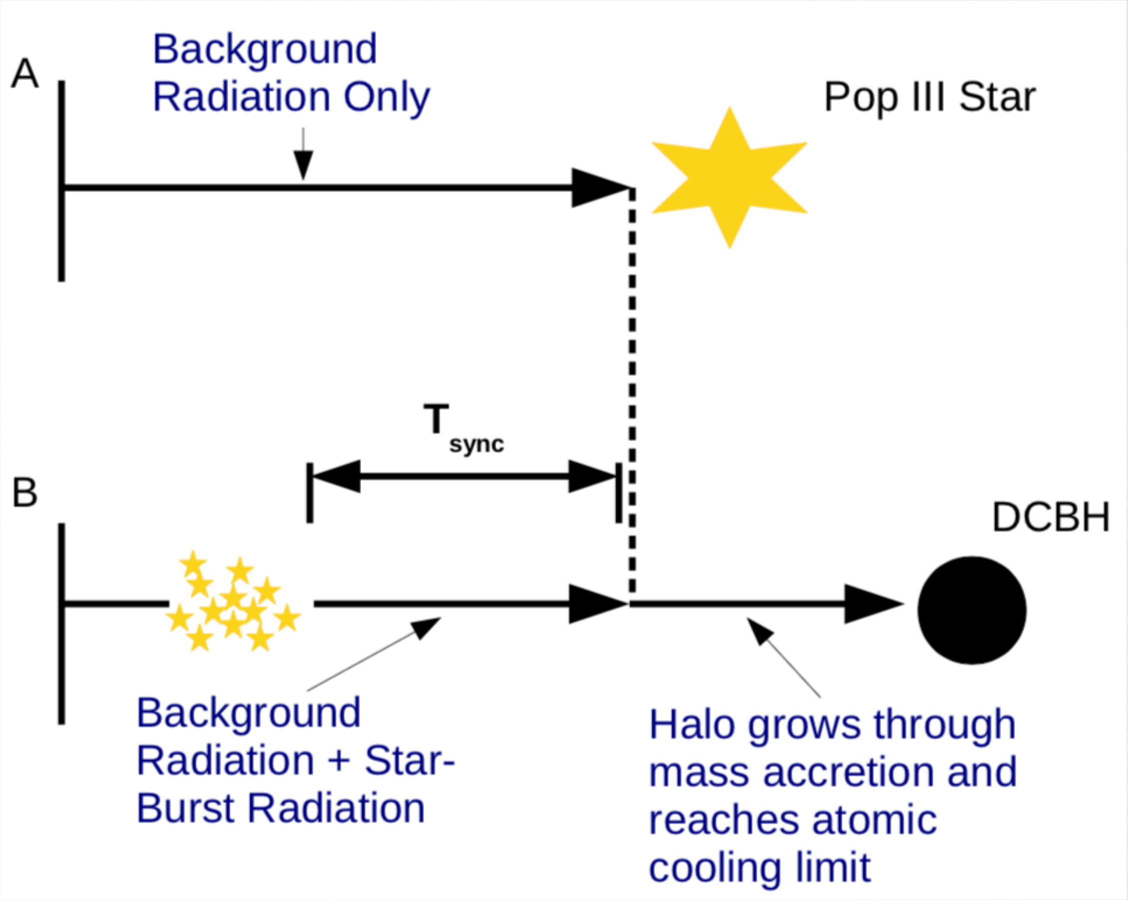
EHT (2019)

Q1: What Were The SMBH seeds?

- Conventional ideas: Remnant BHs of massive stars (<~10^2 $M_\odot$), or direct collapse BHs (~10^4 $M_\odot$) if the radiation from a nearby galaxy prevented the formation of essential coolants, H_2.



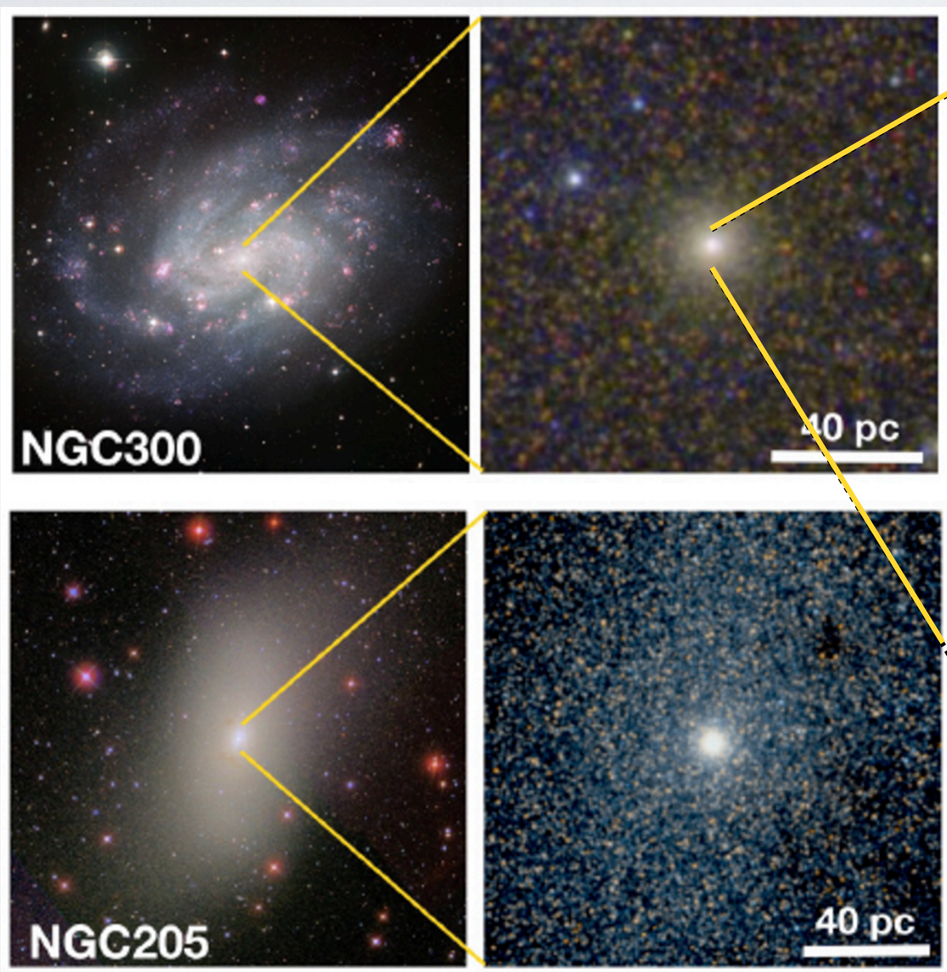
Wise et al.



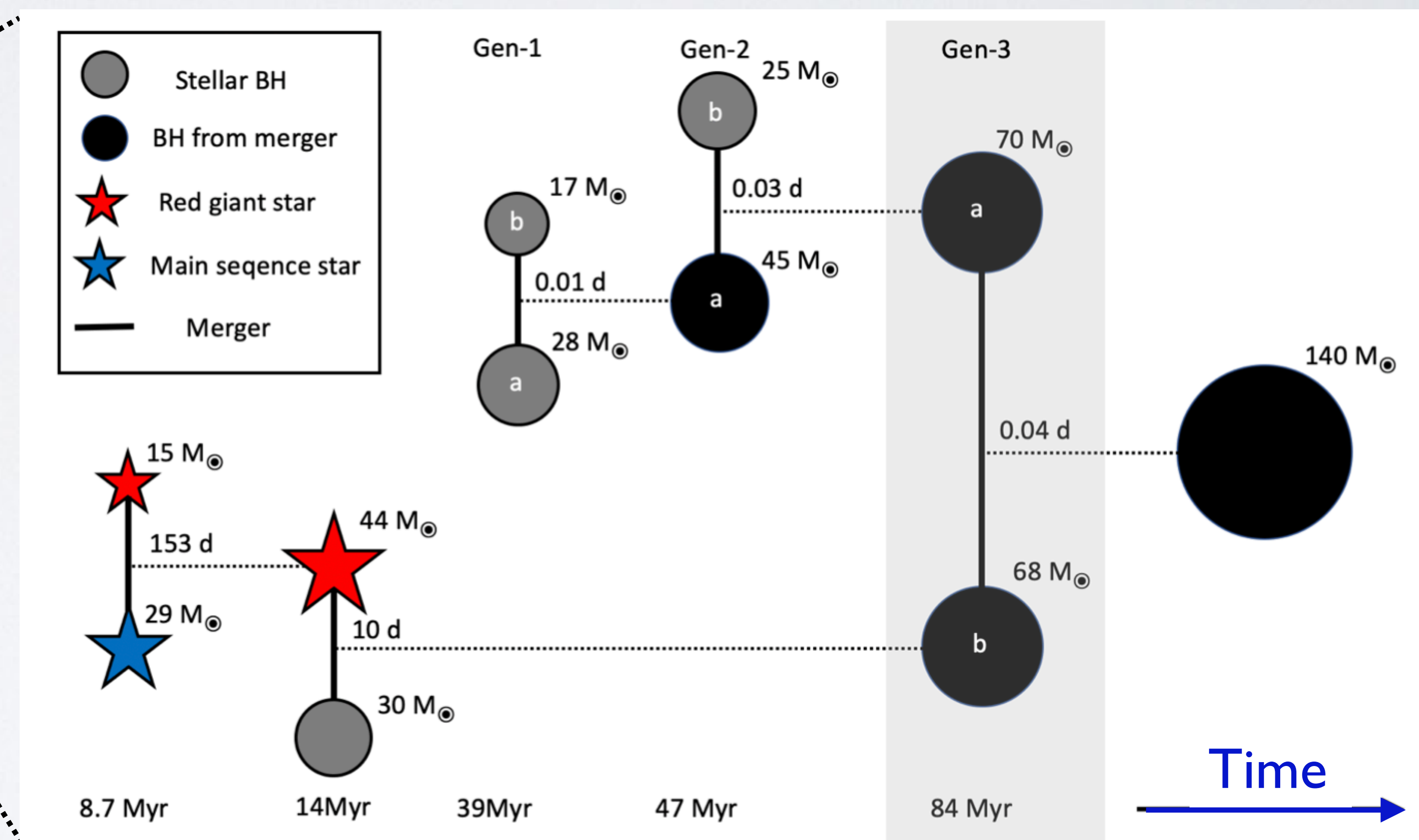
Regan et al. (2017)

Q1: What Were The SMBH seeds?

- Recent idea: A dense, nuclear star cluster (NSC) often found to coexist with a SMBH at a galactic nucleus might be where a massive BH seed (~>10^2 $M_\odot$) formed via successive BH mergers.



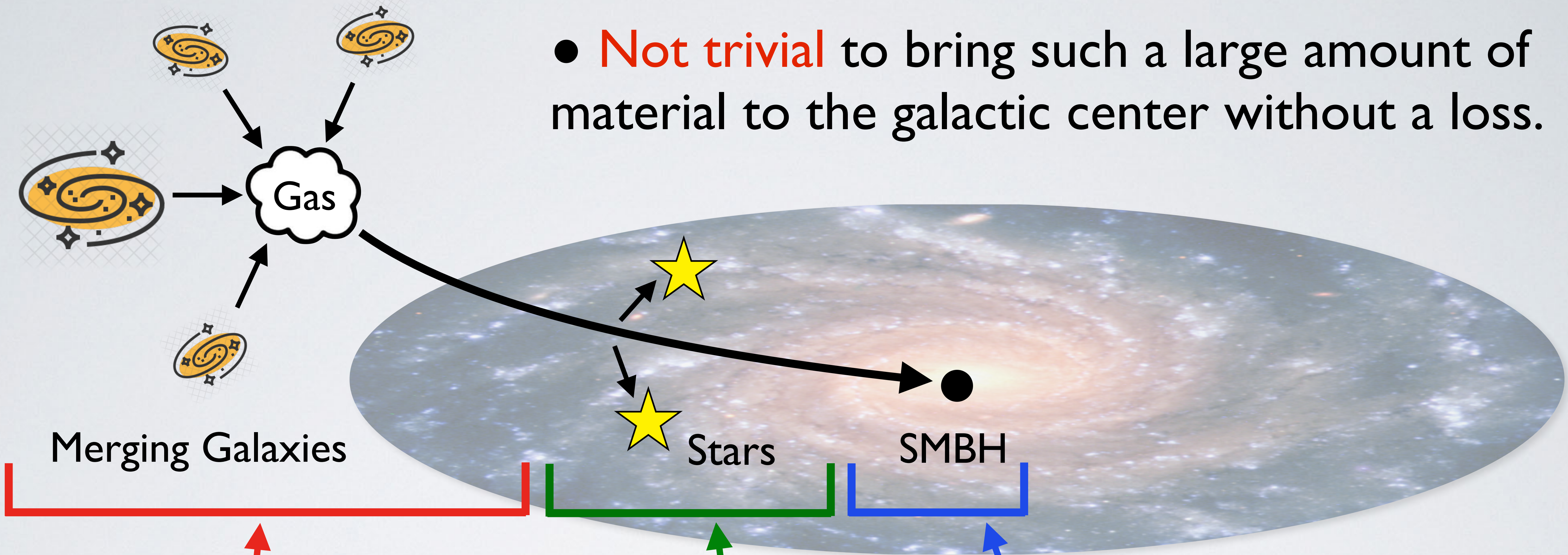
Carson et al. (2015)



Sedda et al. (2021), see also Miller & Davies (2012)

Q2: How Did SMBHs Grow So Fast?

- Not trivial to bring such a large amount of material to the galactic center without a loss.



STAGE 1

A SMBH requires gas from the outside to grow.

STAGE 2

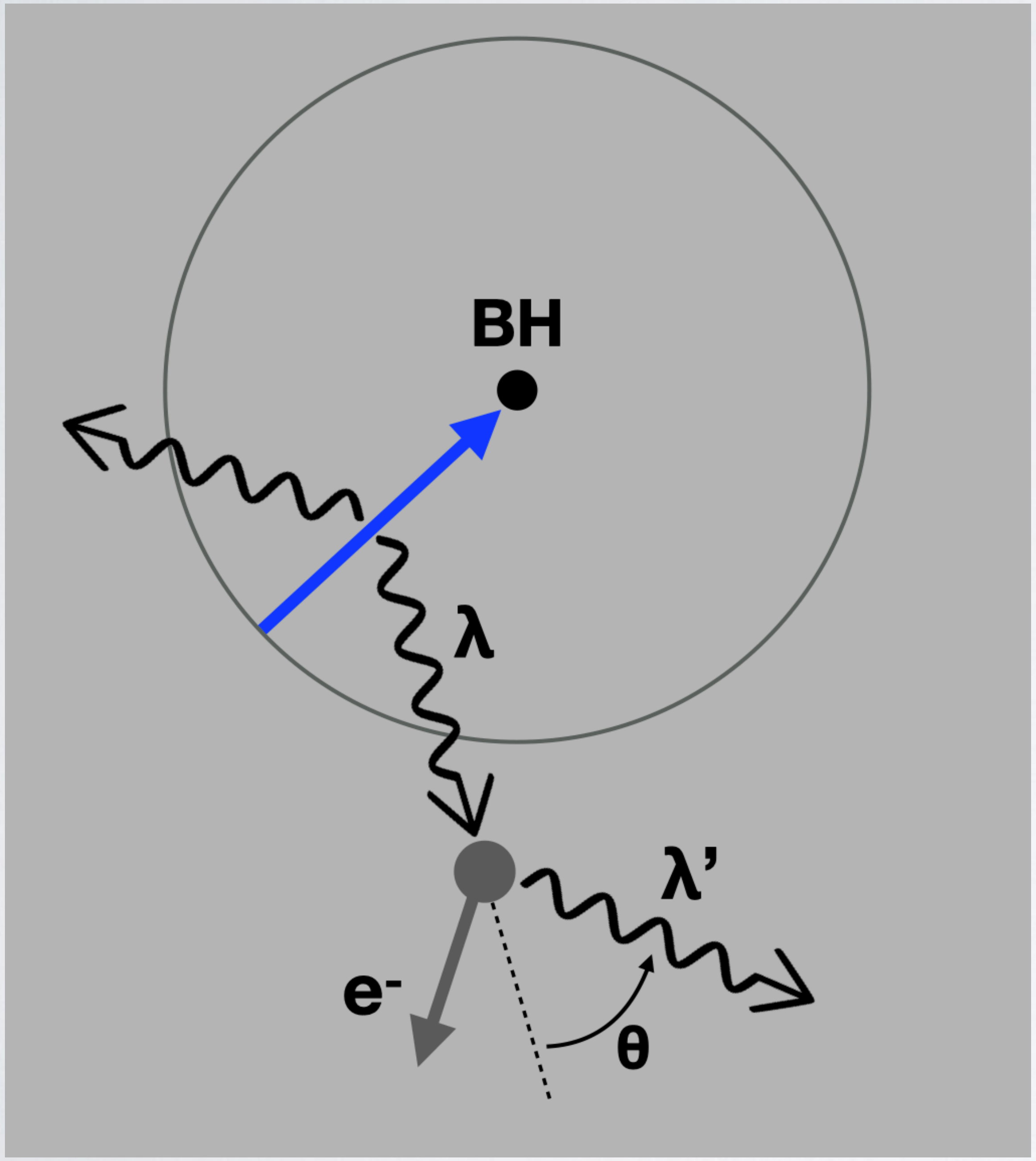
Gas may turn into stars, or be ejected by supernova.

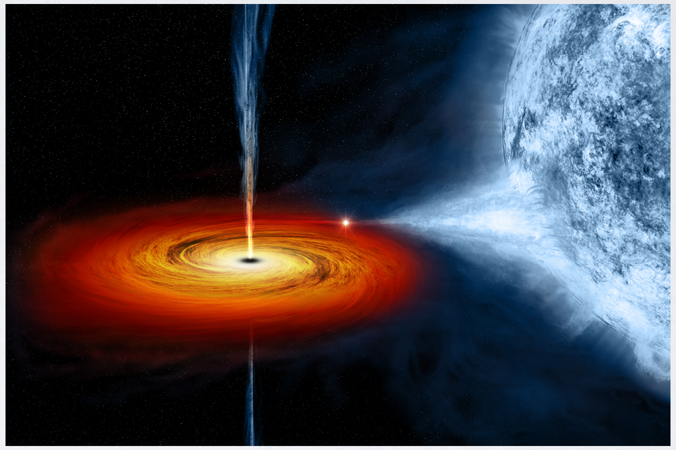
STAGE 3

We need ways to bypass BH's Eddington limit.

Eddington Accretion Limit

- BHs are thought not to grow faster than the Eddington limit.





$$F_{\rm rad} = \frac{L_{\rm rad}}{4\pi R^2}\frac{\sigma_{\rm T}}{c} = F_{\rm grav} = \frac{GM_{\rm BH}m_p}{R^2}$$

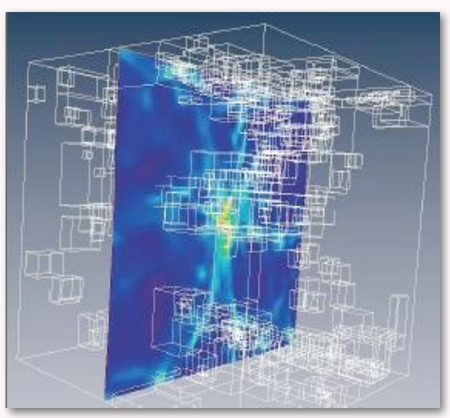
$$L_{\rm Edd} = \frac{4\pi G M_{\rm BH} m_p c}{\sigma_{\rm T}} \simeq 0.1\dot{M}_{\rm Edd}c^2$$

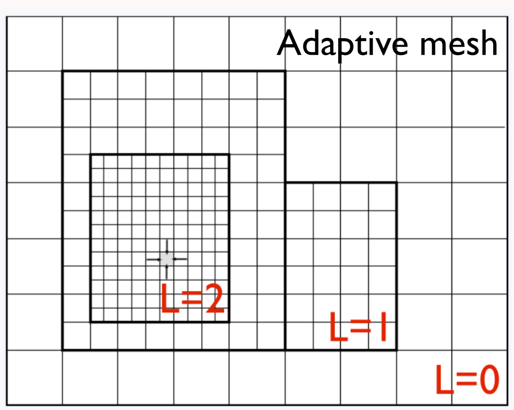
Self-consistent Simulation Framework

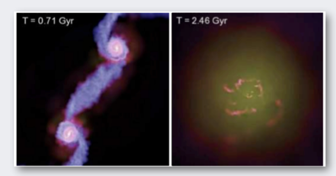
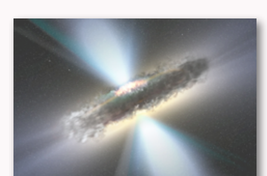
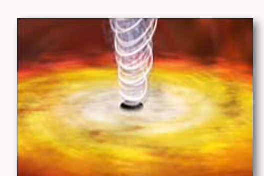
- Self-consistent galaxy-SMBH co-evolution from first principles
  - computing techniques like adaptive refinement help include more physics

Multi-scale Hydrodynamics Simulation Code

Adaptive Mesh Refinement Enzo (Bryan et al. 2019)

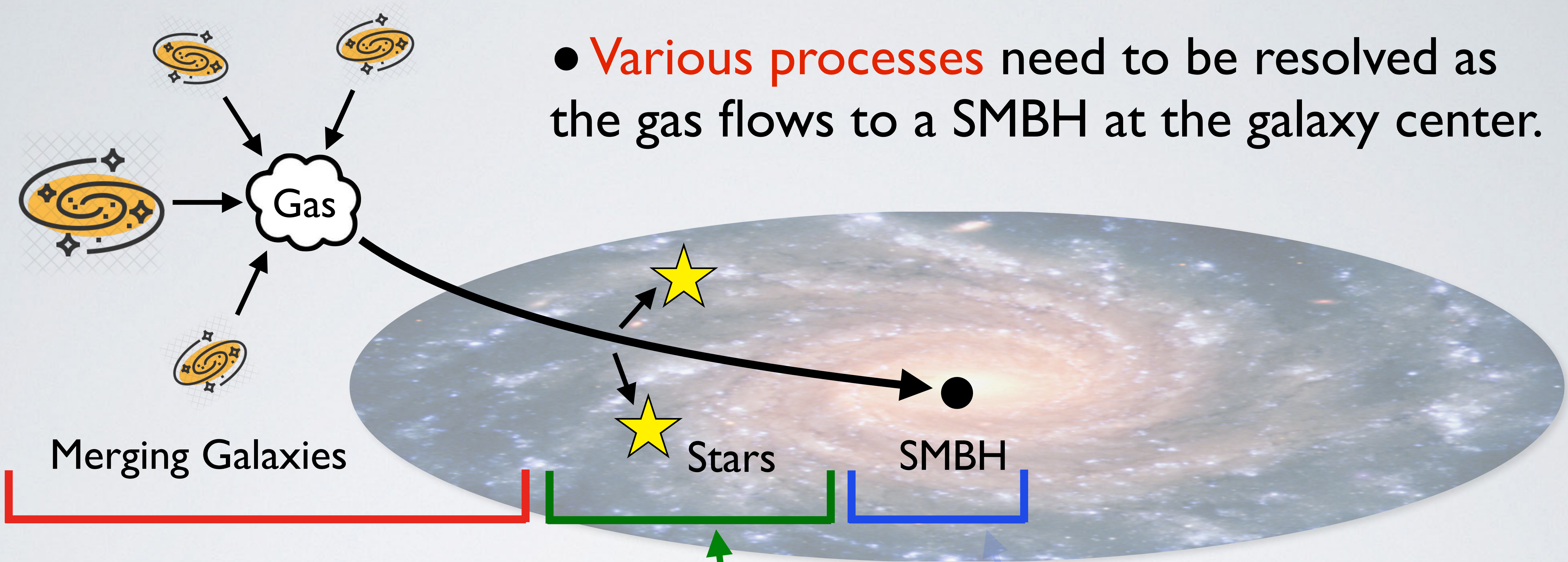




	Massive Black Hole Accretion & Feedback	Star-forming Clumps Formation & Feedback
Previous Work	Artificially boosted Bondi accretion	Insert a star simply by Schmidt law ($\rho_{SFR} \sim \rho_{gas}^{1.5}$)
	Thermal energy 	Turn off gas cooling or thermal energy
New Approach	Bondi accretion without any boost factor	Insert a star when a cell of ~10^3 $M_\odot$ turns Jeans unstable
	UV/X-ray photons + Winds  	UV photons radiative transfer (photoheating & ionization) + Supernova thermal energy

Inflow of Fuel: Trip To The SMBH

- Various processes need to be resolved as the gas flows to a SMBH at the galaxy center.



Part I

By Fixing Stellar Feedback,

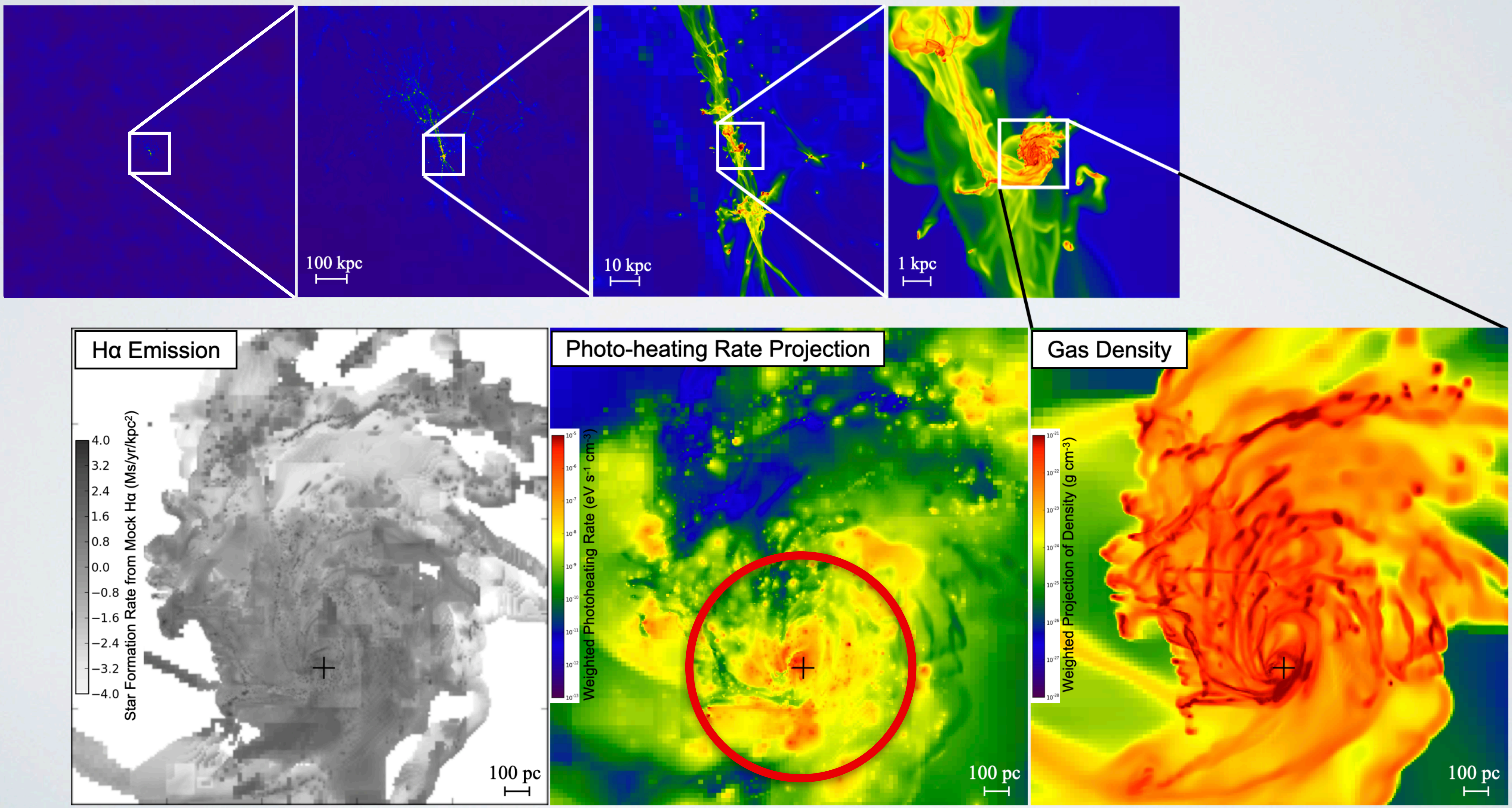
Can we not lose the gas on the way?

With Accretion of Stars, (not just gas)

Can we bypass BH's Eddington limit?

Designing High-z Universe in A Computer

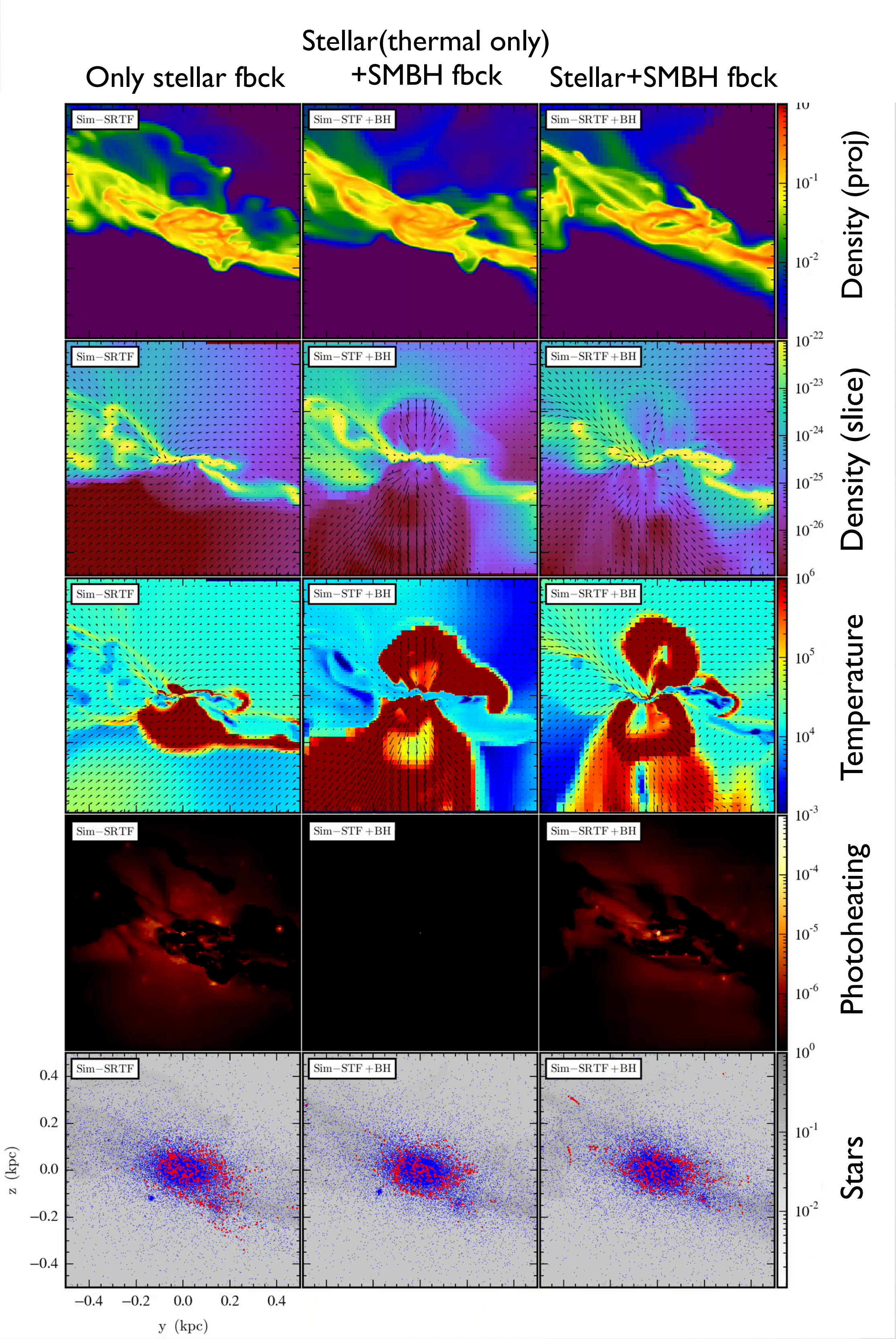
- 10^{11} $M_\odot$ galaxy at z~7.5 and a ~10^6 $M_\odot$ BH seed simulated with sophisticated SMBH and stellar physics such as radiative feedback.



Face-on view of a target galaxy at z~7.5 (Kim et al. 2019)

Previously Undiscussed Physics Important

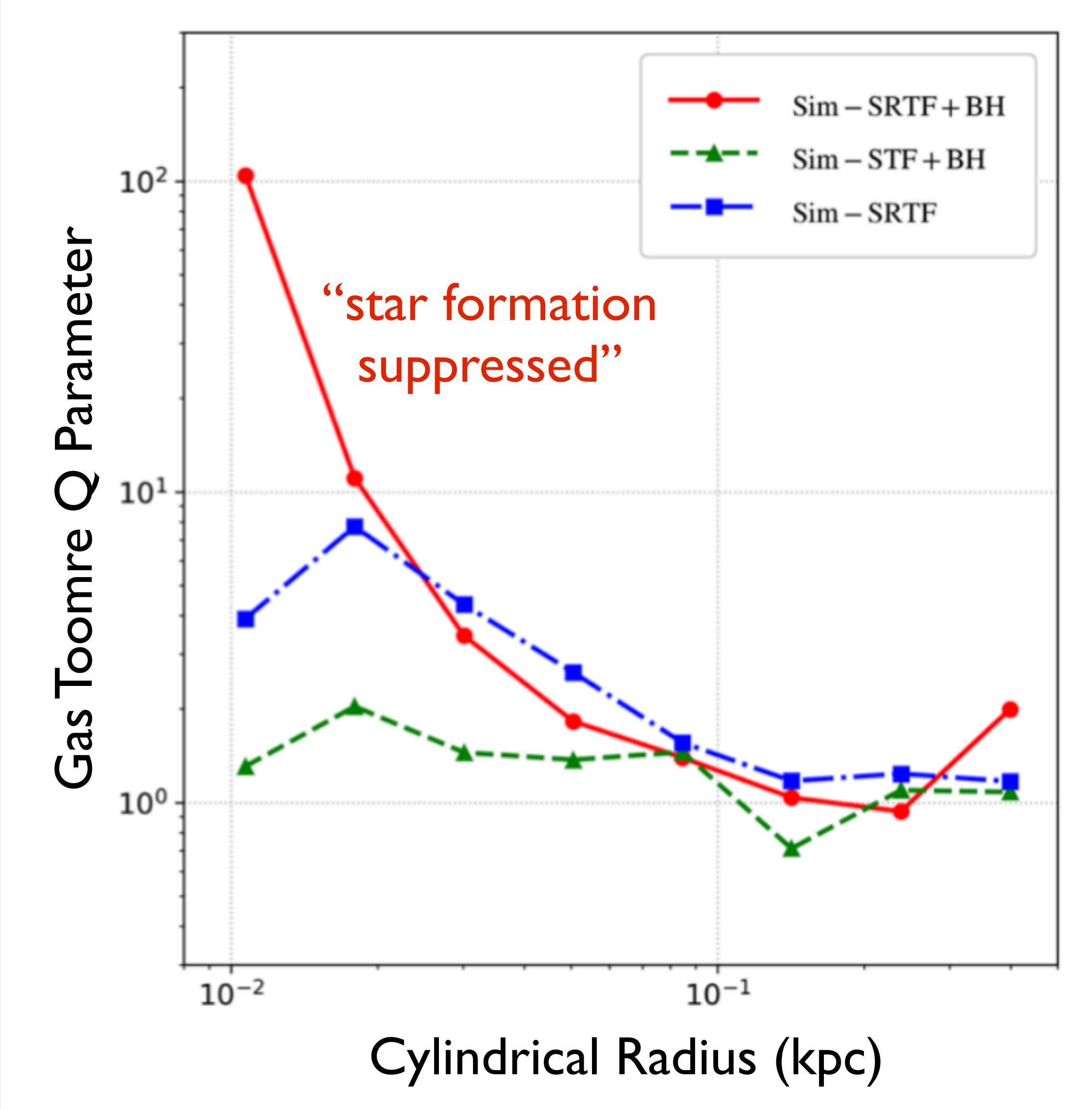
- We find that sophisticated feedback helps the SMBH to grow faster by retaining the gas that eventually falls in to the SMBH.

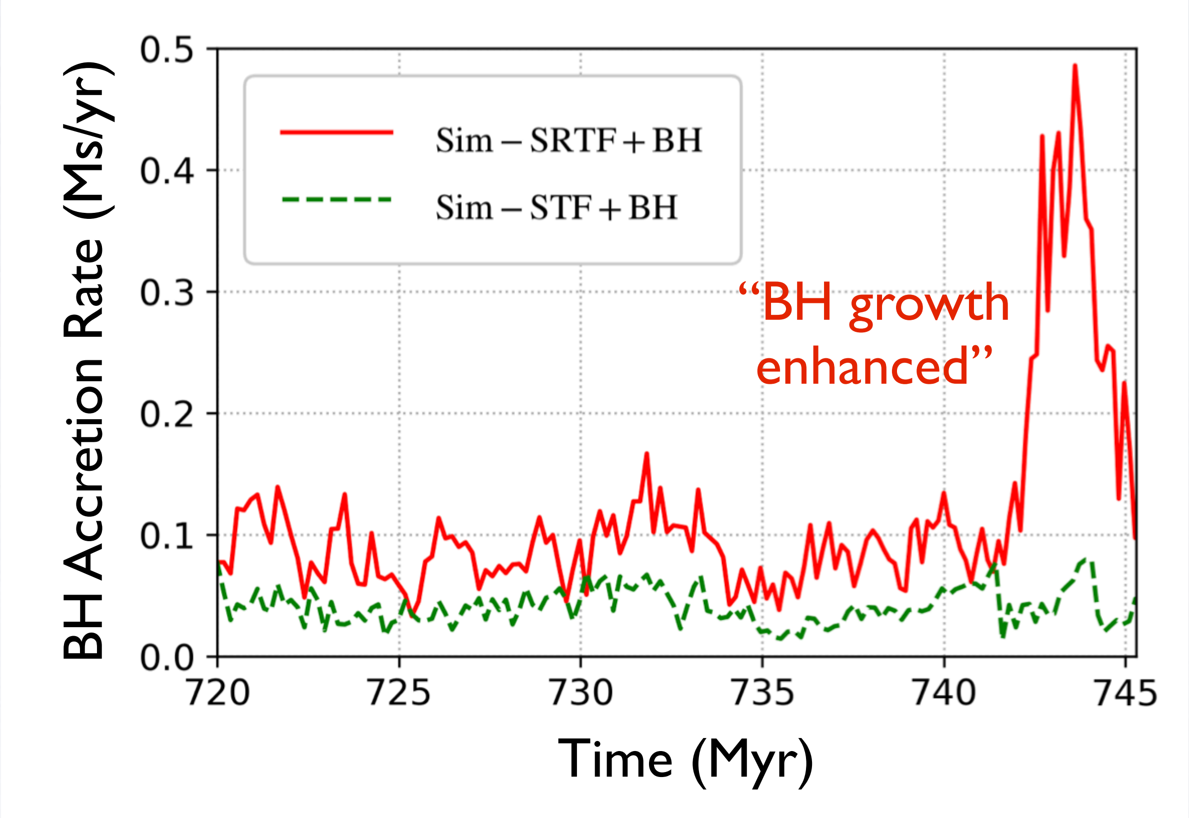


Edge-on view of a target galaxy disk
(Kim et al. 2019)

Previously Undiscussed Physics Important

- We find that sophisticated feedback helps the SMBH to grow faster by retaining the gas that eventually falls in to the SMBH. Previously never discussed physics near a SMBH seems critical.

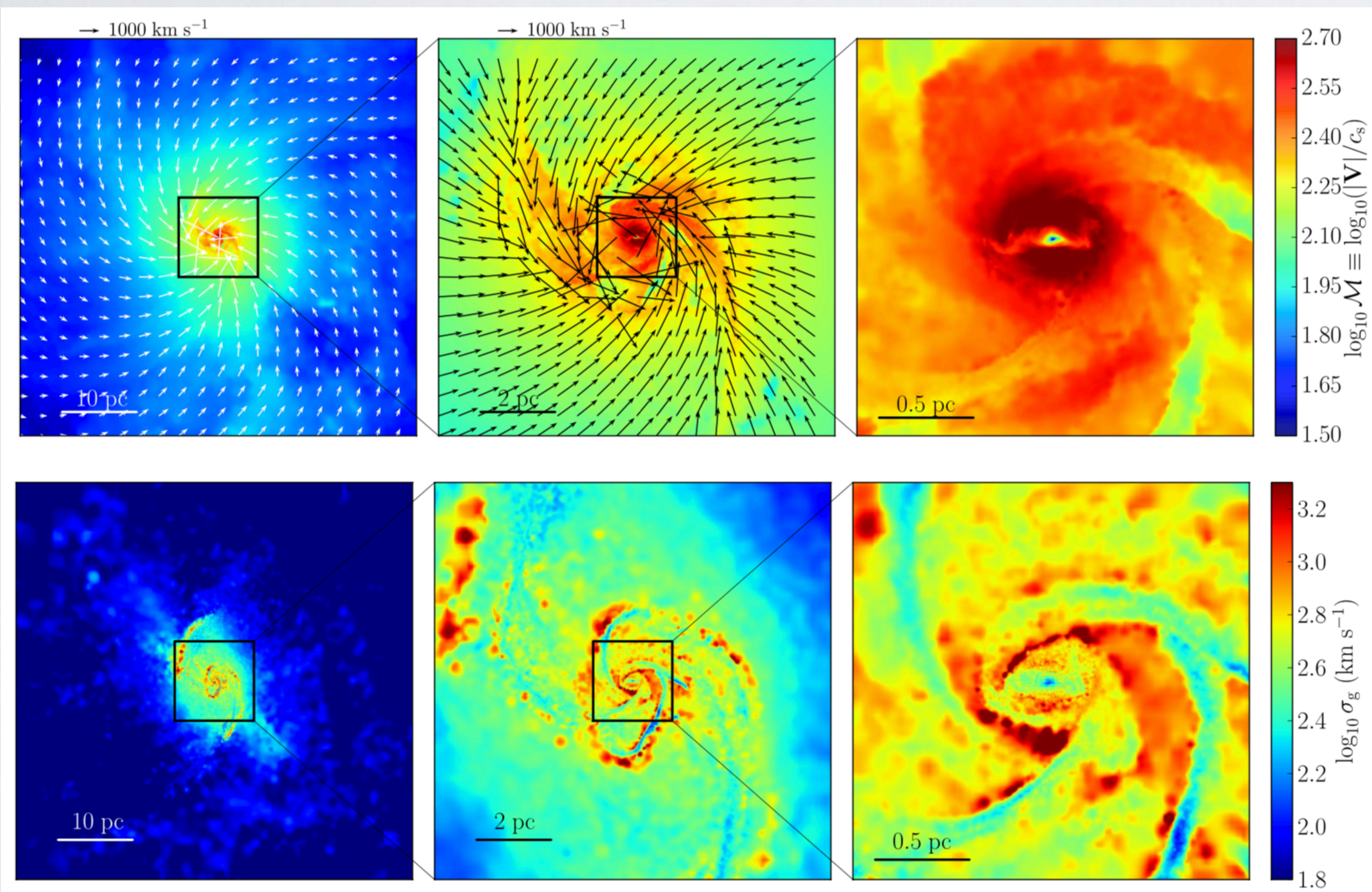




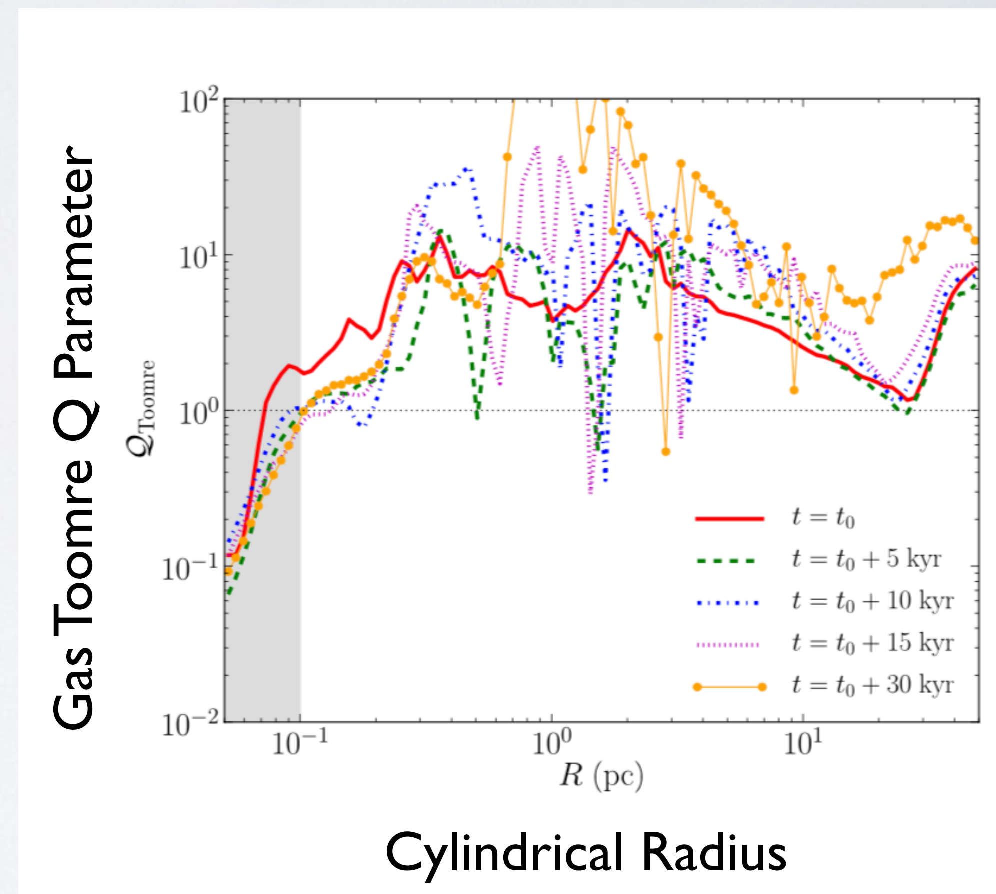
Kim et al. (2019)

Attempts To Enhance Gas Accretion

- Our study is largely in line with other attempts to search for a route to a direct gas collapse that quickly grows the SMBH.

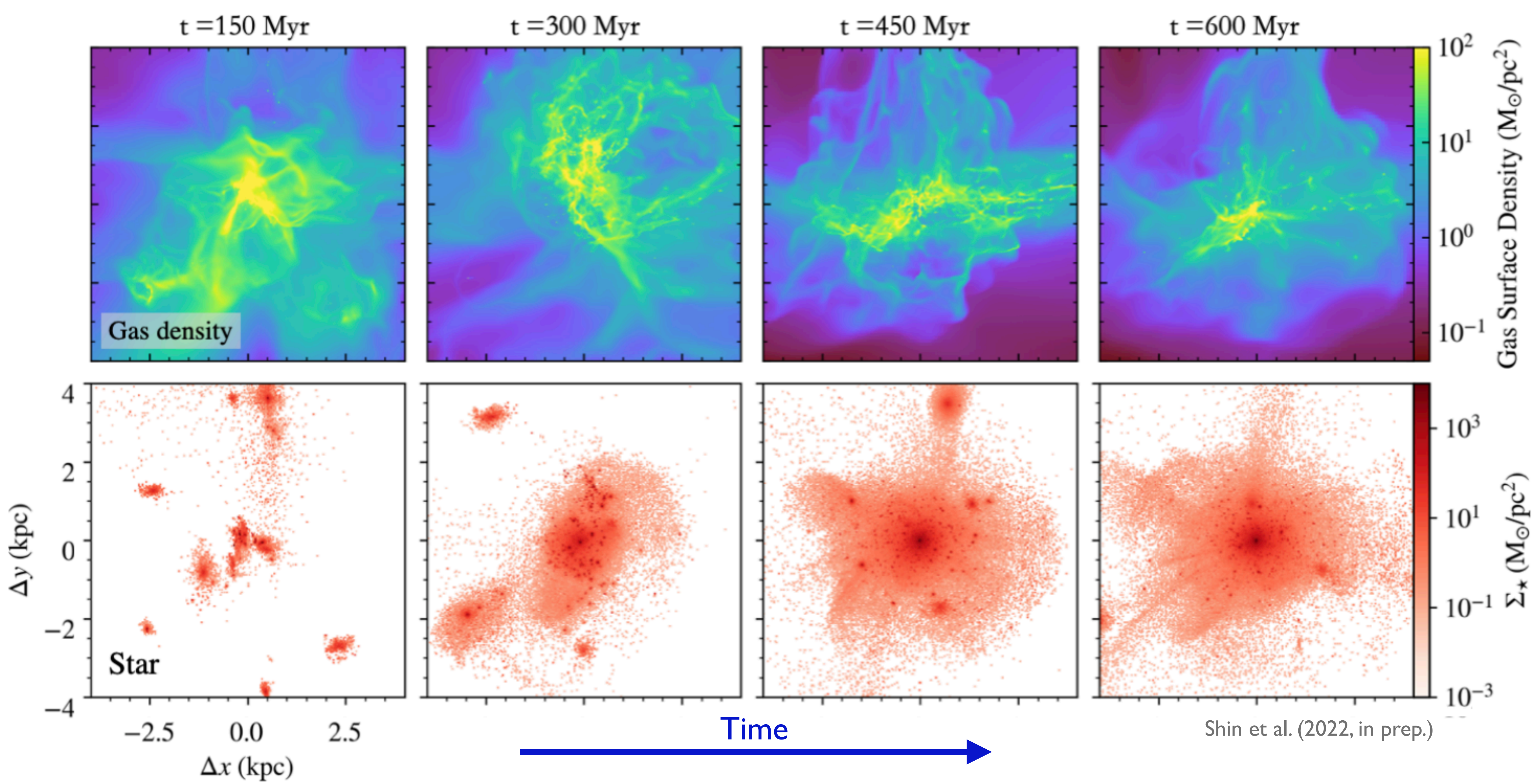


Mayer et al. (2015), Mayer & Bonoli (2018)



Galaxies Grow By Frequent Merging

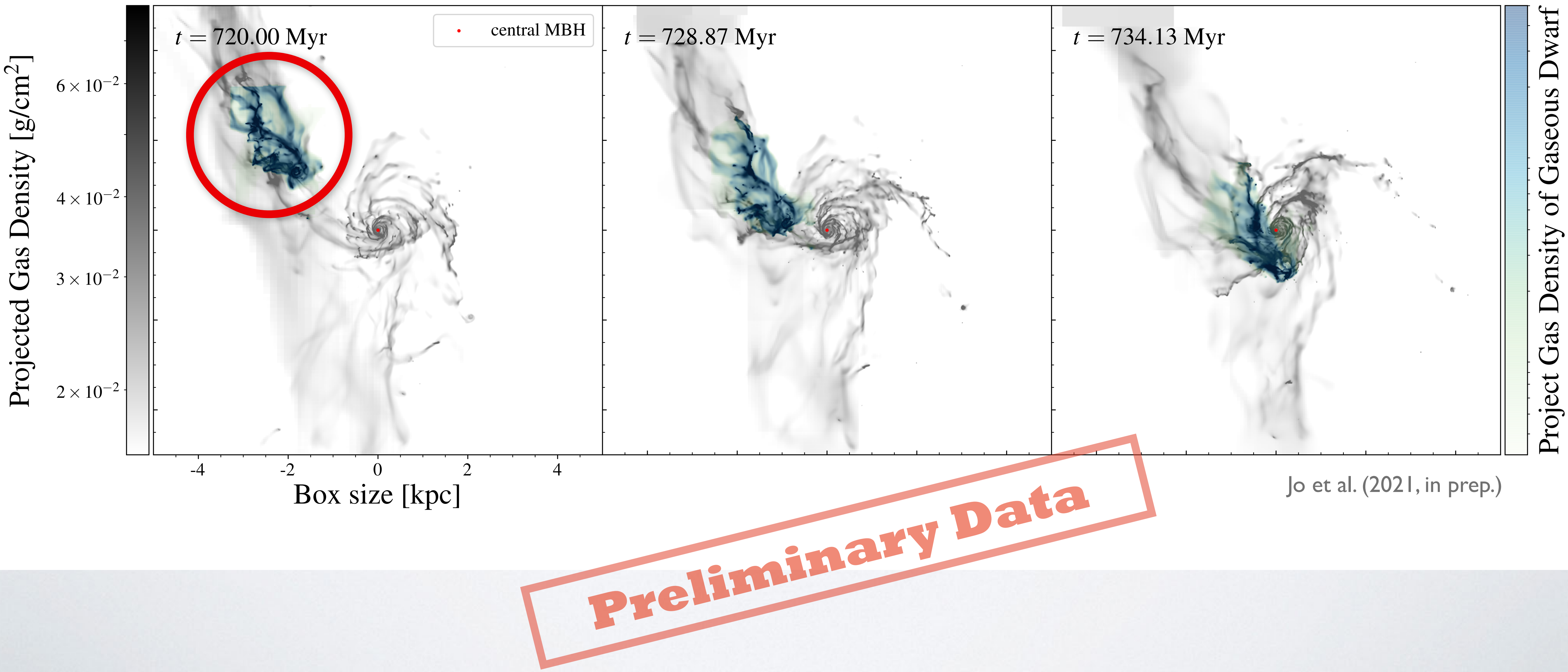
- SMBHs in the early Universe were born when proto-galaxies experience very frequent, high-speed mergers.



Shin et al. (2022, in prep.)

Merging Galaxies Bring Additional Fuel

- We can "dye" the incoming merging galaxy and trace its gas and stars as they travel deep into the primary galaxy's center.



Jo et al. (2021, in prep.)

Towards the Unabridged Understandings of the Growth of Supermassive Black Holes

- Self-consistent numerical experiment will help us to unlock the secret of how SMBHs formed and evolved in the early Universe.

I. Challenges and Opportunities:

- Mystery of Supermassive BHs That Grew Quickly

II. Ongoing and Future Research:

- Sophisticated Multi-scale Numerical Experiments To Study How SMBHs Have Evolved