BRAHMA cosmological simulations: Unveiling the origins of supermassive black holes using LISA

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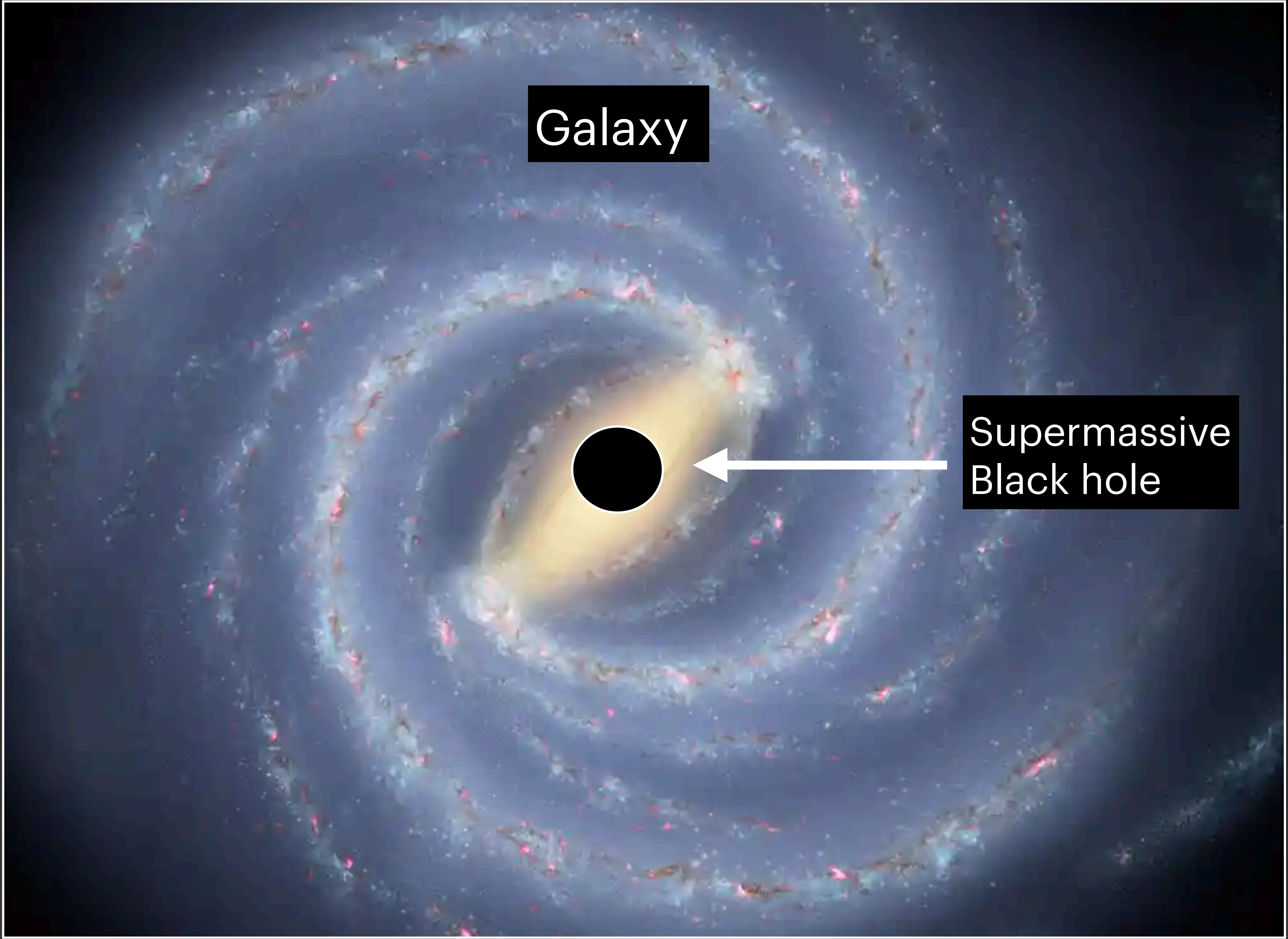
Origin of supermassive black holes: A big cosmic mystery!



Three most popular candidates for seeds of supermassive black holes

Pop III remnants

$\sim 10^2\ M_\odot$

Light

Pop III seeds

Daxal's talk!

Runaway collisions of stars in dense nuclear star clusters

$\sim 10^3 - 10^4\ M_\odot$

Medium weight

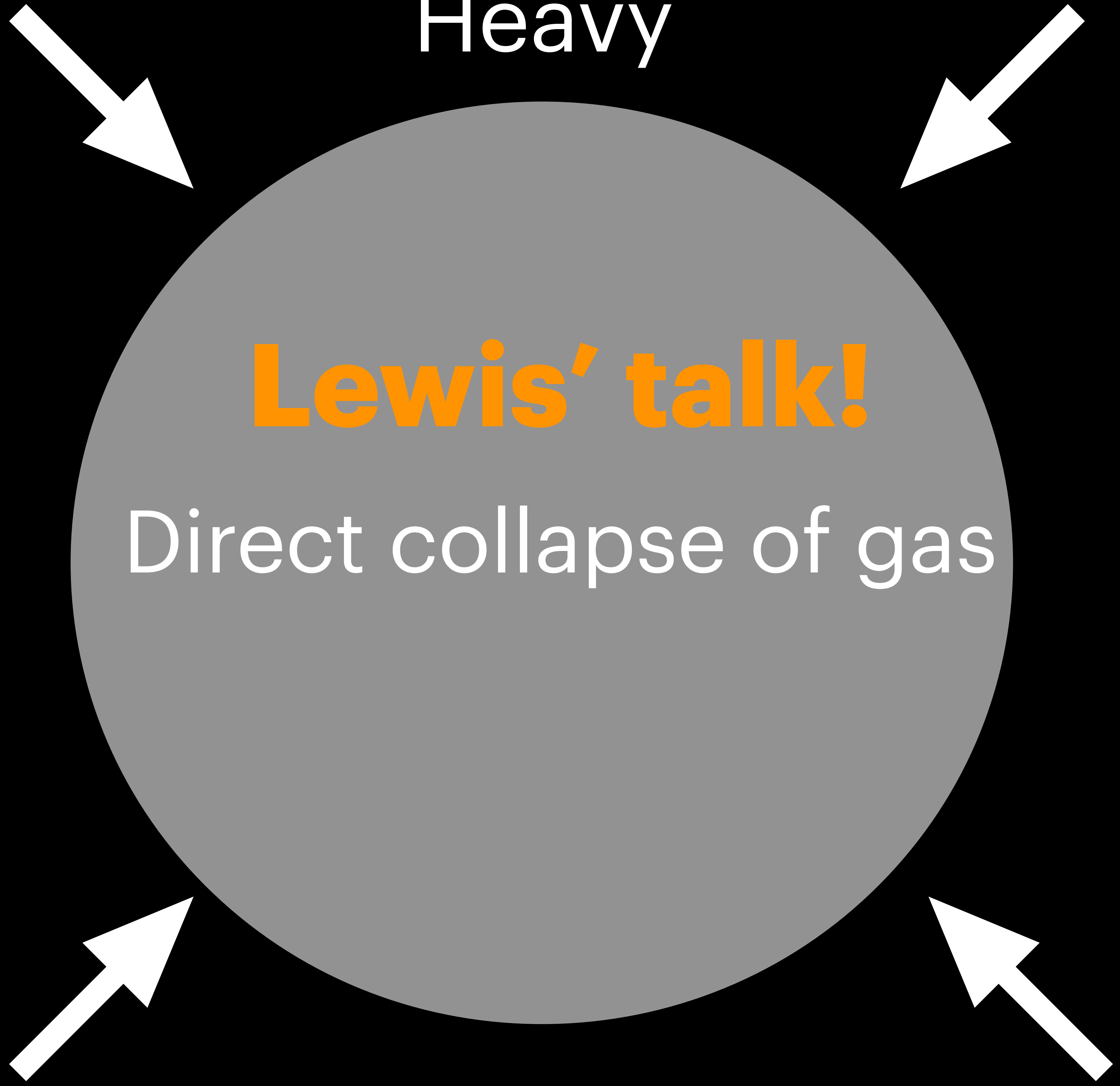
NSC seeds

Manuel's talk!
Bastian's talk!

Direct Collapse Black Holes

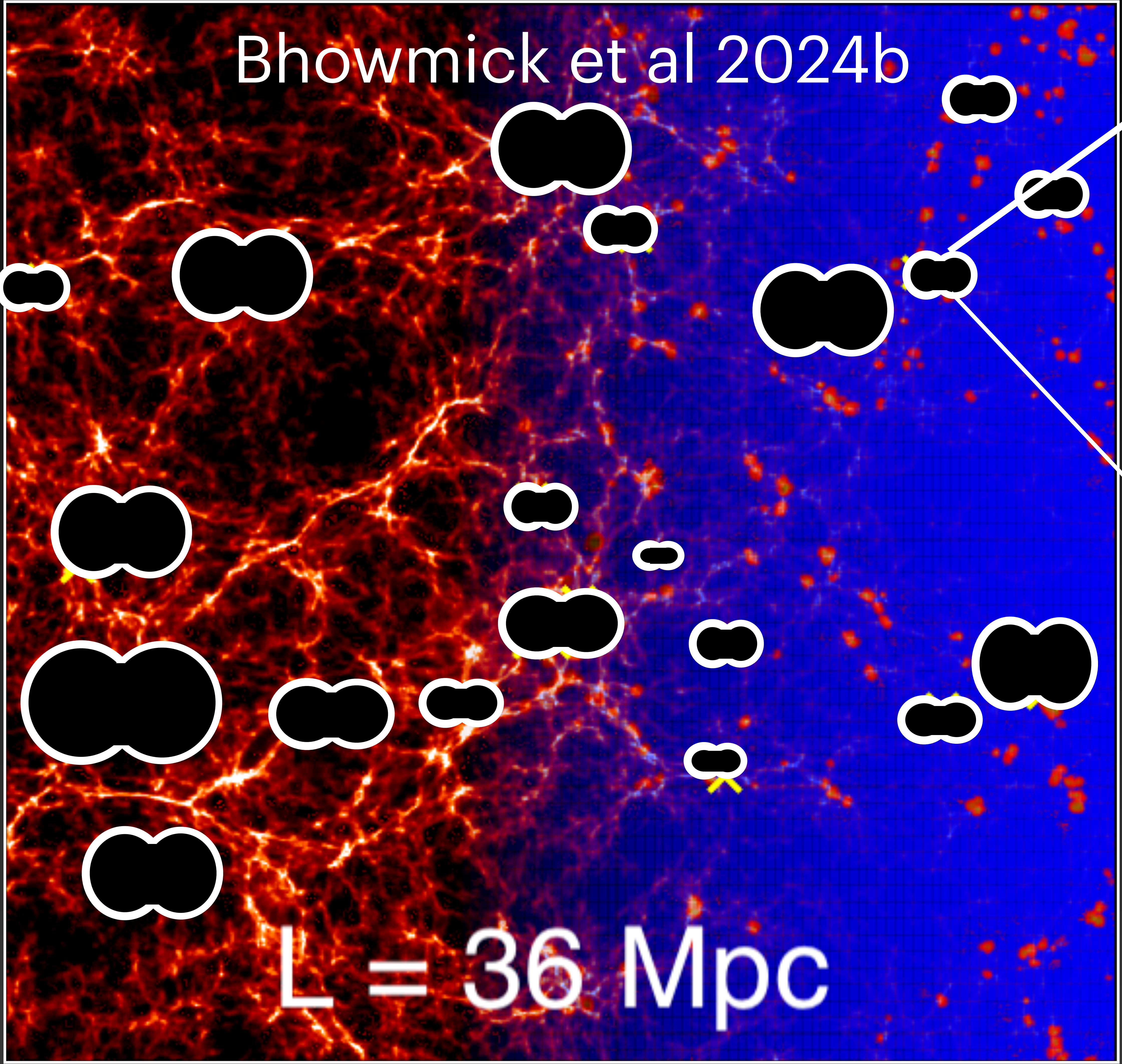
$\sim 10^4 - 10^5\ M_\odot$

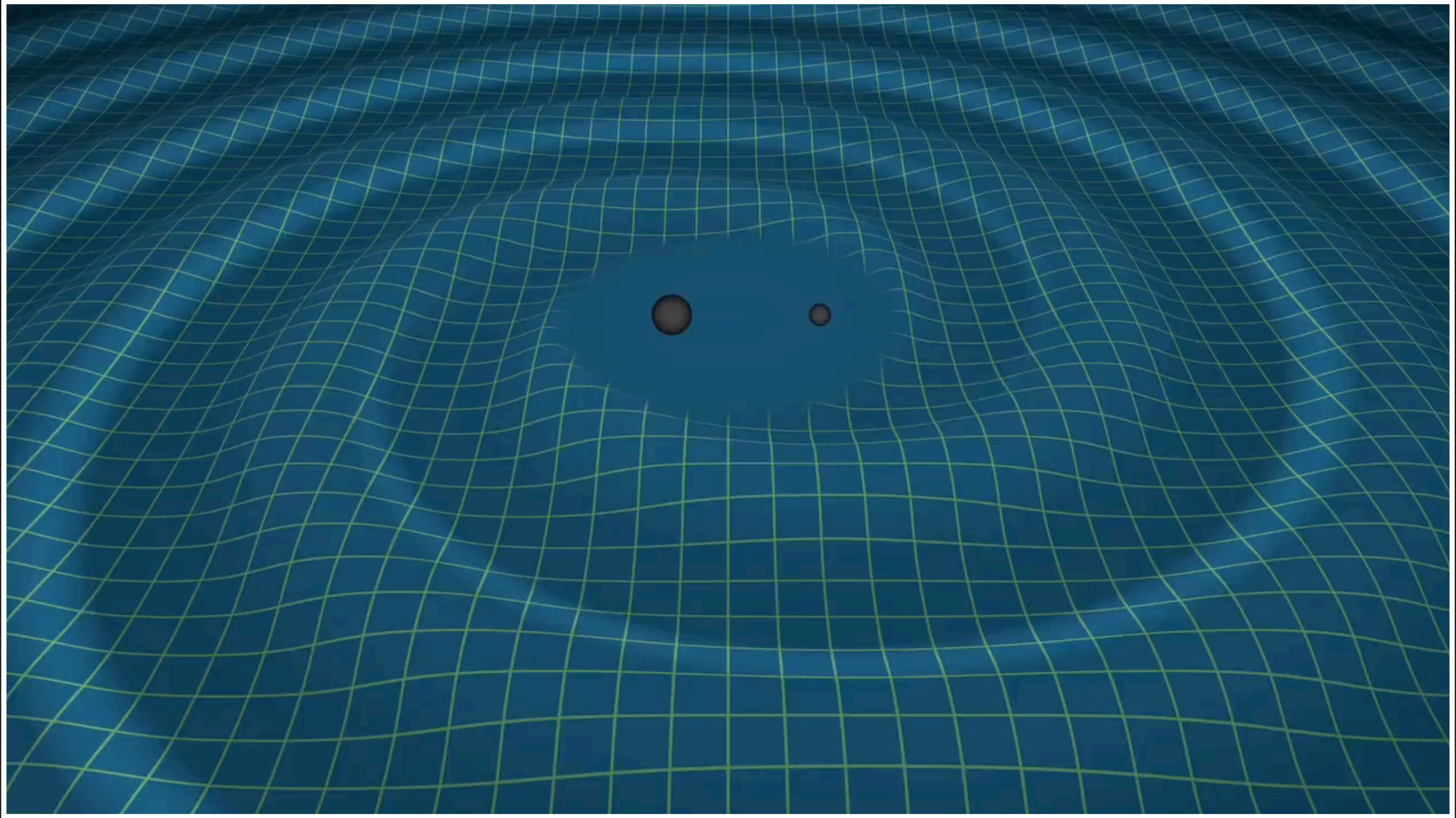
Heavy



DCBH seeds

Cosmological simulations can produce statistically large samples of merging BH binaries to compare with LISA

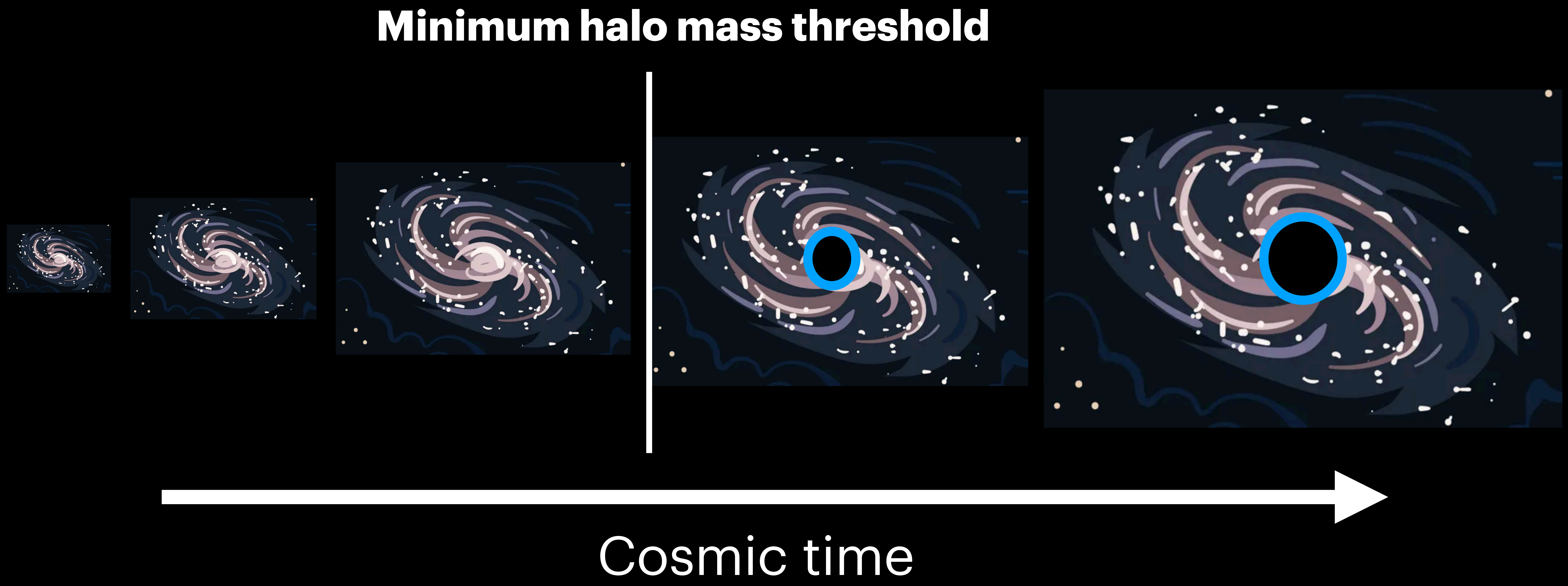




LISA
Laser Interferometer Space Antenna

A long standing challenge: Cosmological simulations often cannot resolve the seed masses

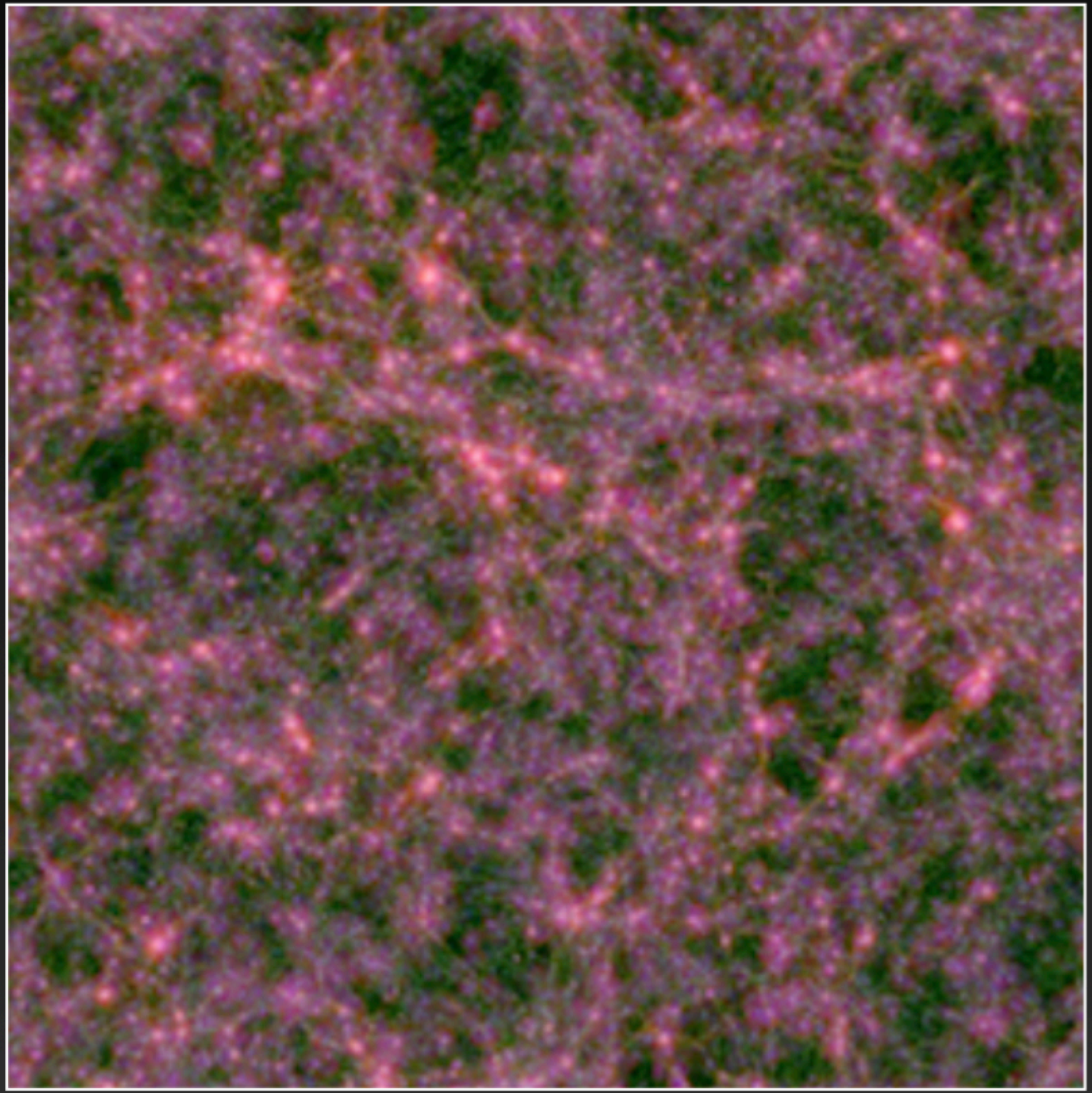
The vast majority of simulations use very simplistic sub-grid black hole seed models



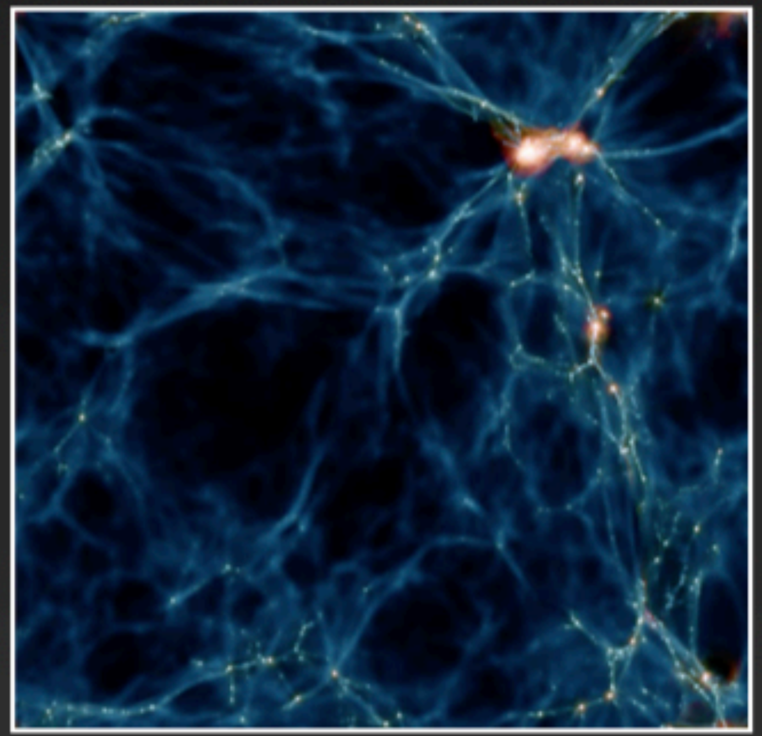
Many recent simulations use more physically motivated seed models

Seed based on local gas properties!

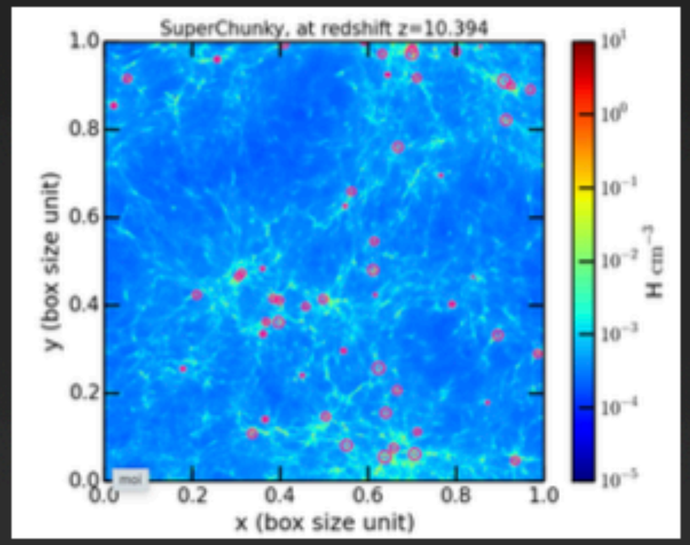
Horizon-AGN Kaviraj et al 2016



ROMULUS Tremmel+2017



SuperChunky Habouzit+2016



Due to uncertain seeding mechanisms, we need to *systematic exploration of seed model variations!

Semi-Analytic models

Barausse 2012

Ricarte and Natarajan 2018

Dayal et al 2018

Banik et al 2019

Degraf et al 2020

Sassano et al 2021

Spinoso et al 2022

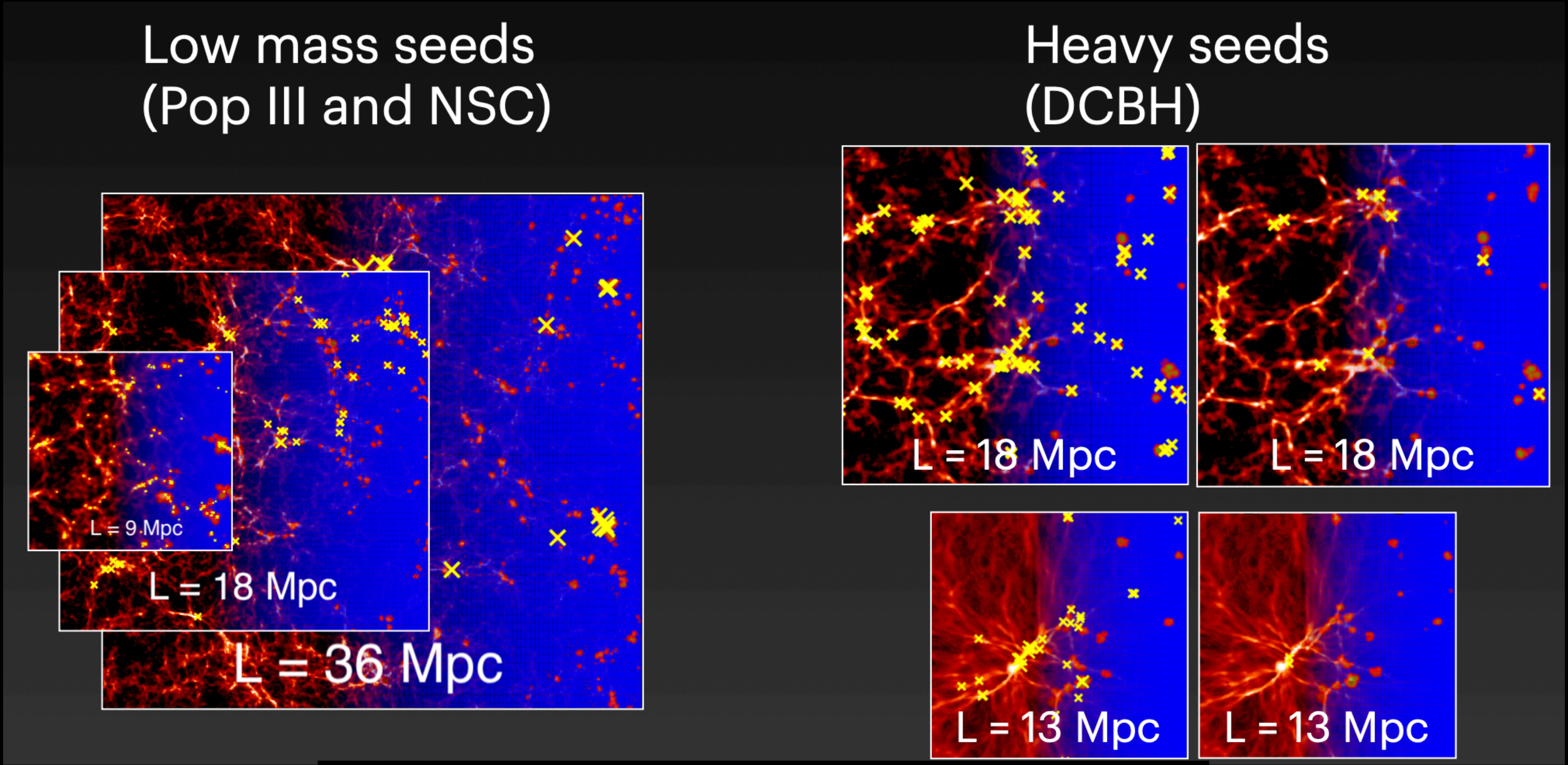
Trinca et al 2022, 23, 24

Evans et al 2023

BRAHMA simulations

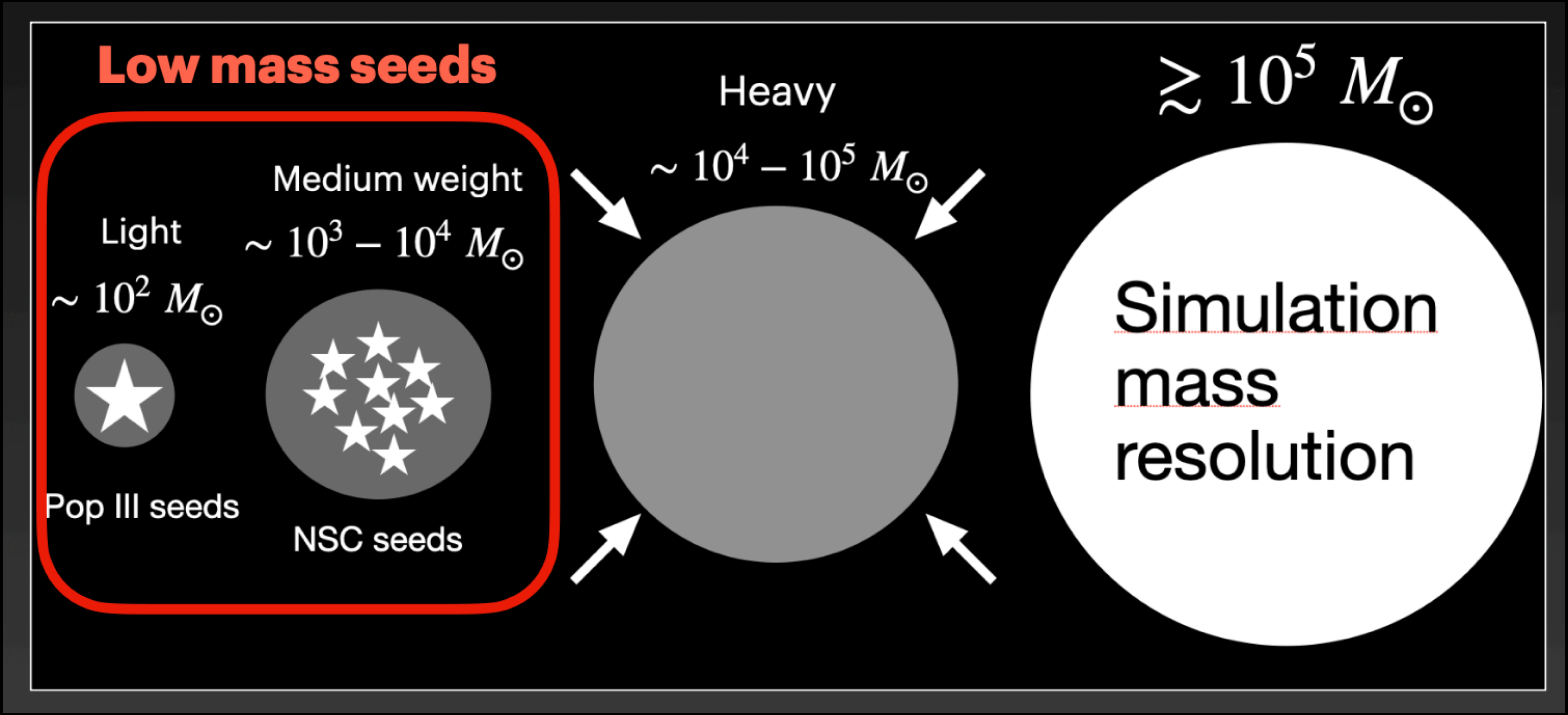
A large systematic exploration of seed model variations

IllustrisTNG + Seed model variations



How do we model low mass seeds in BRAHMA?

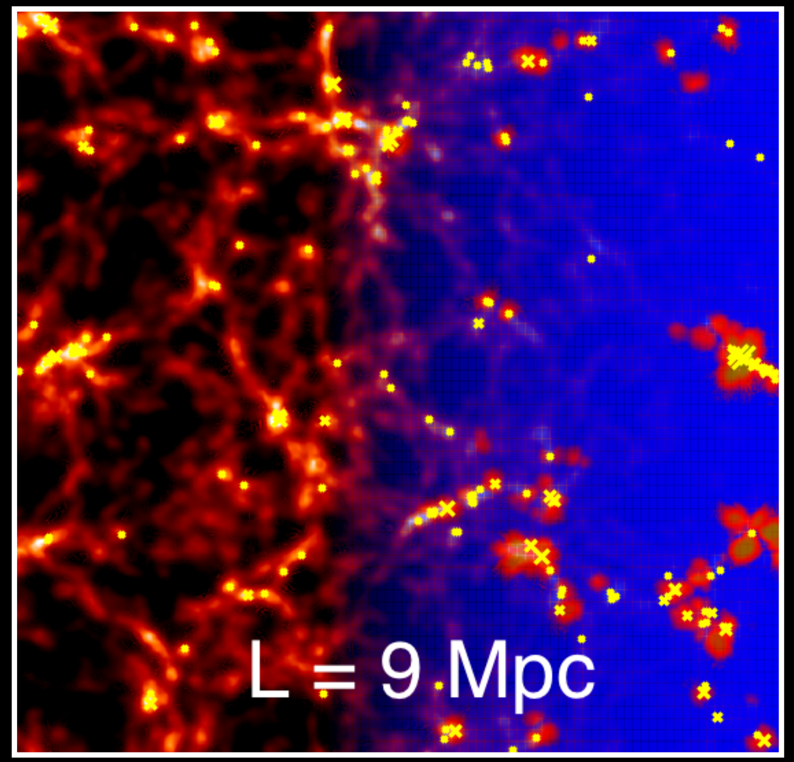
Surpassing the resolution limitation

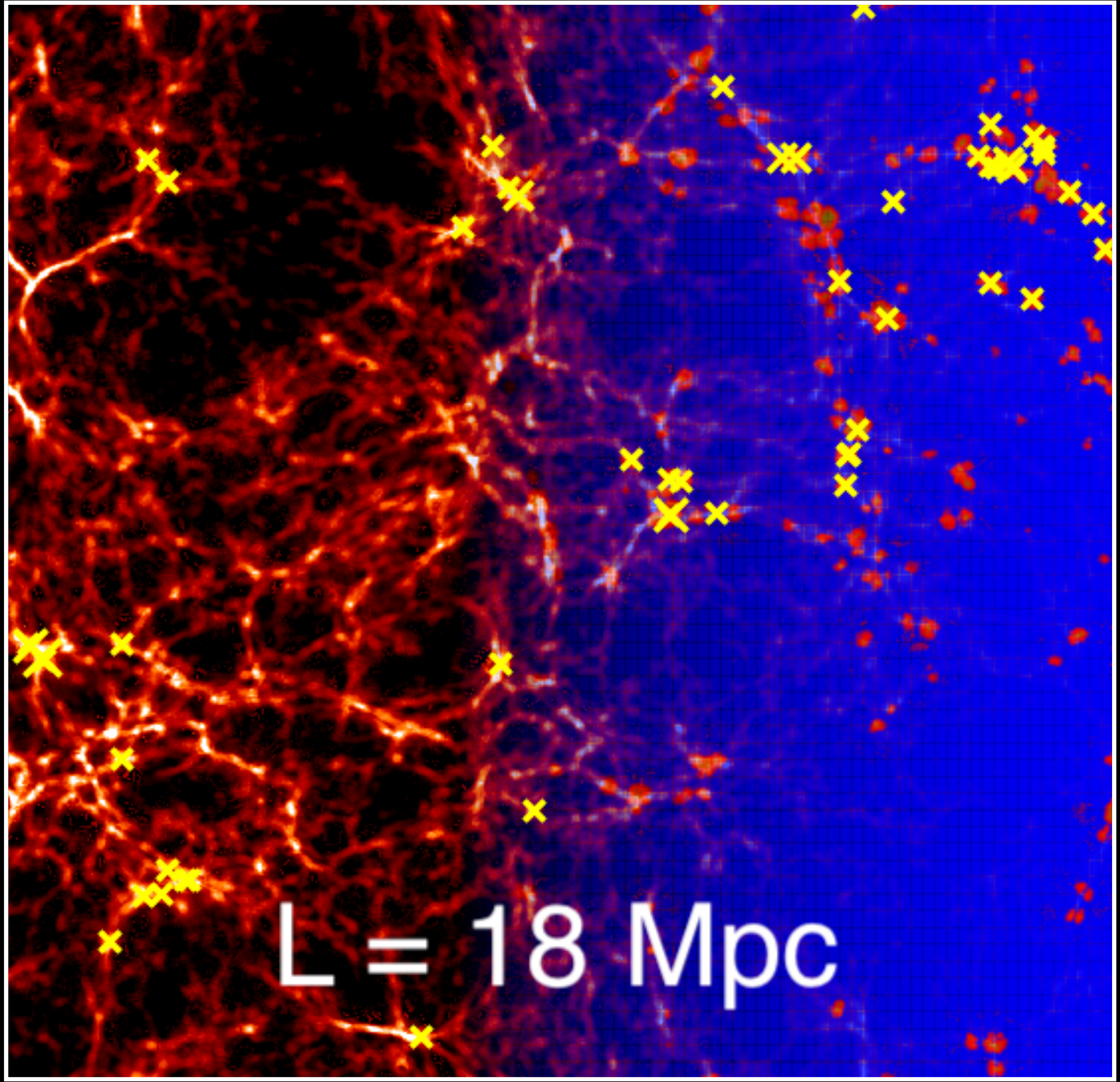


Surpassing the resolution limit in BRAHMA

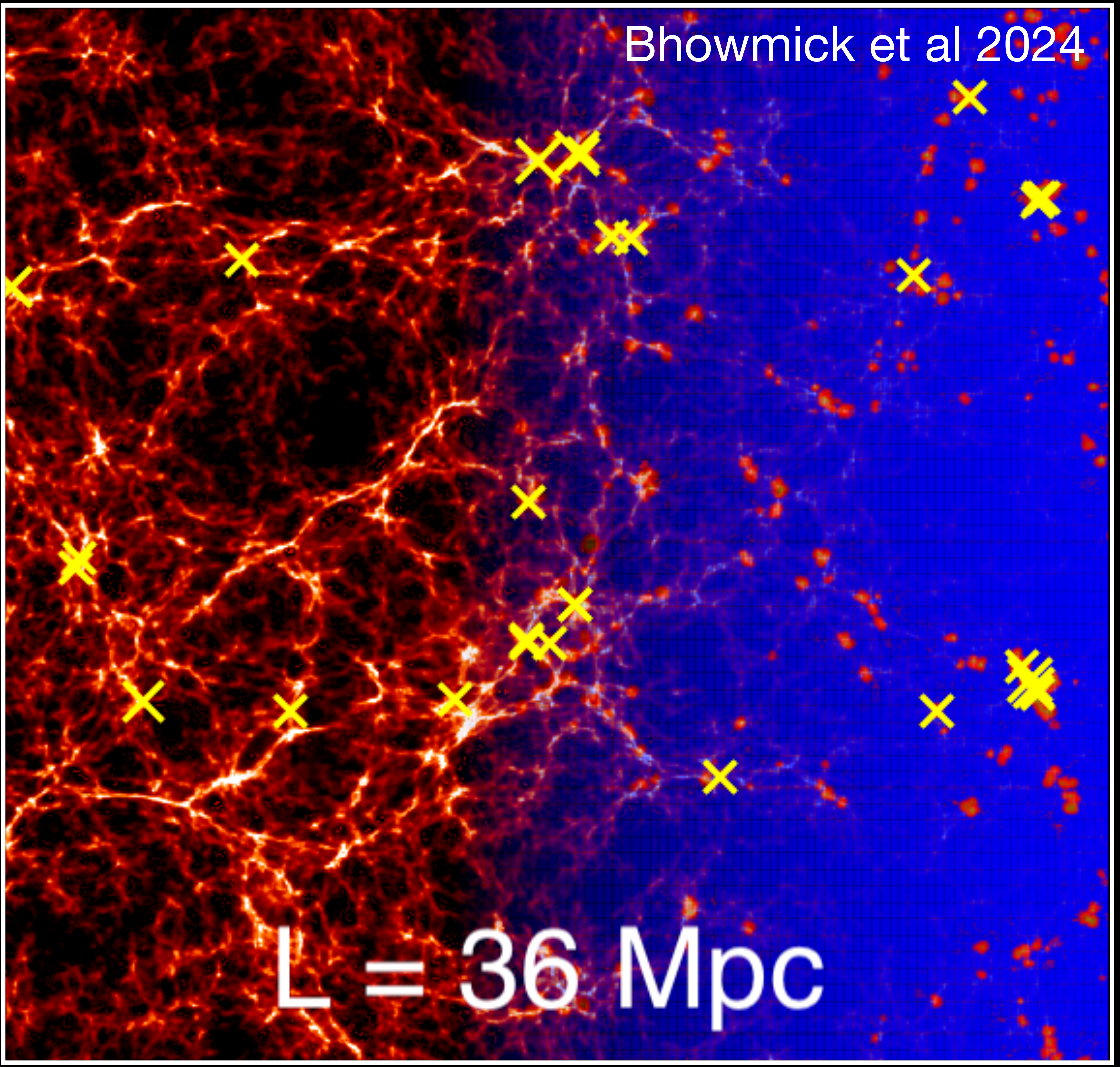
Multiple simulation boxes with increasing volumes and decreasing resolution

Smallest volume, highest resolution





Largest volume, lowest resolution

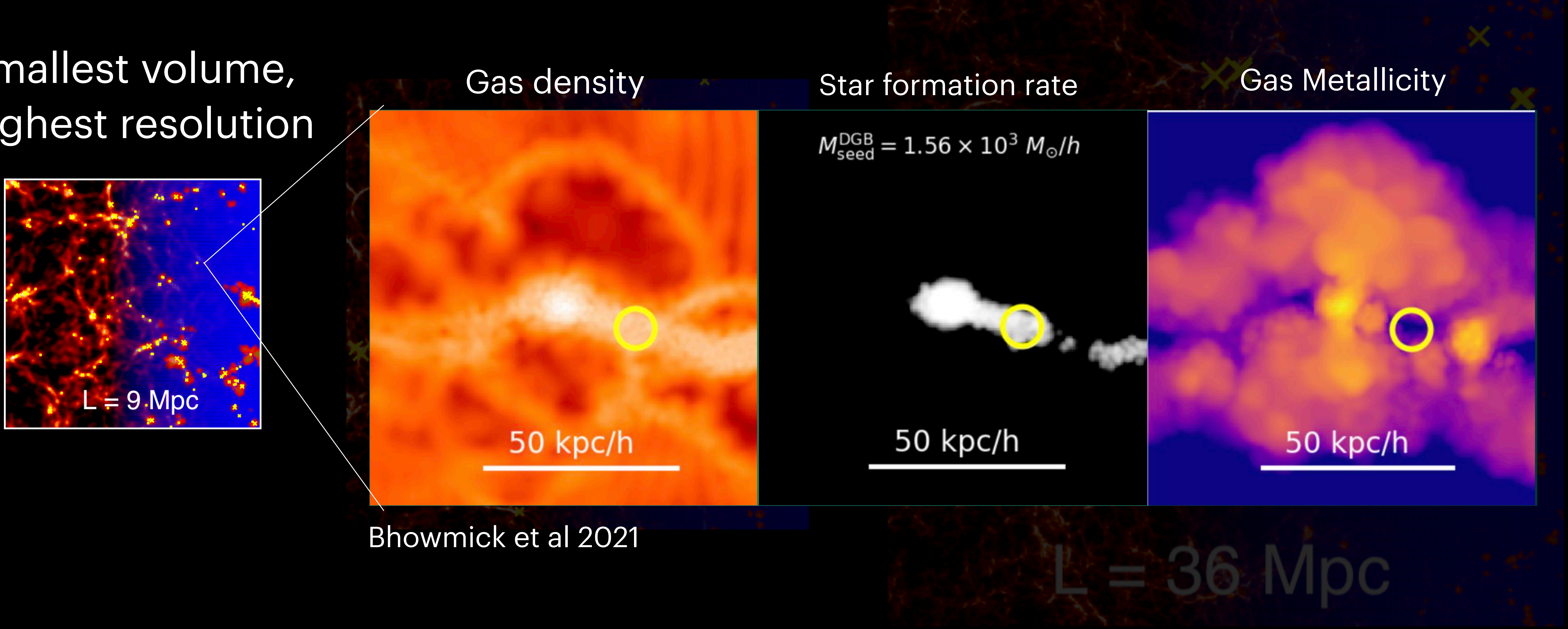


Bhowmick et al 2024b

Explicitly resolve low mass ($\sim 10^3\ M_\odot$) seeds only in the smallest volume box

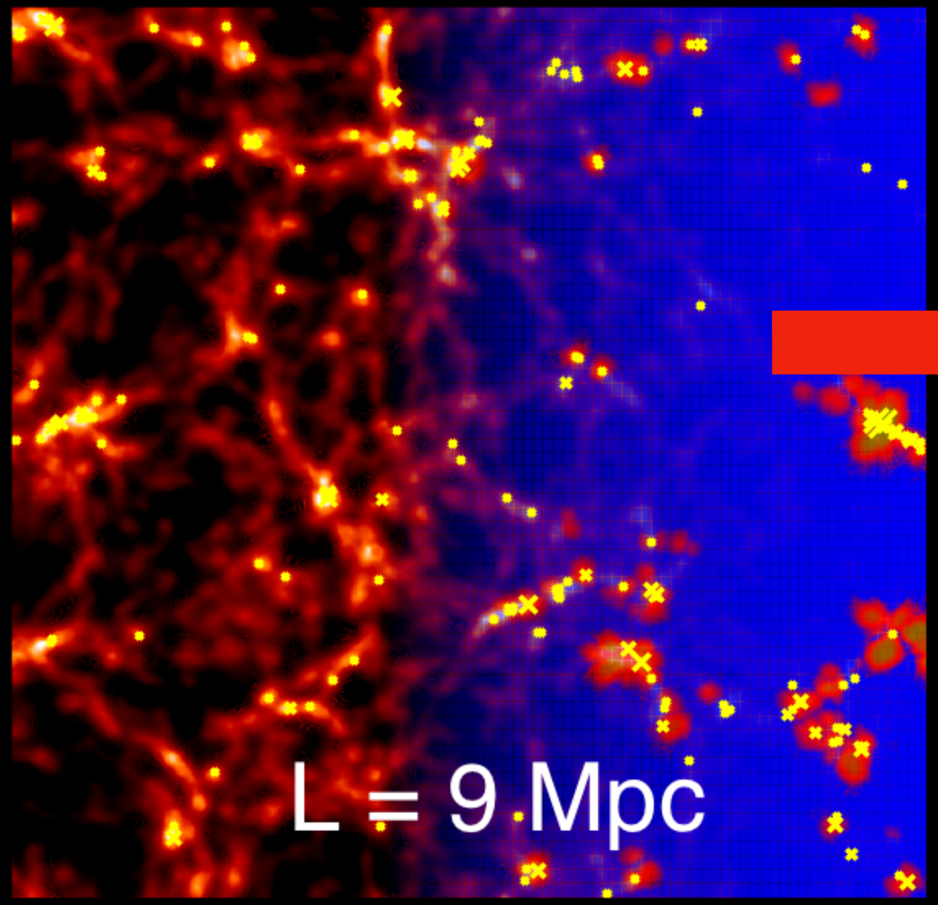
Seeding in halos with sufficient dense and metal poor gas

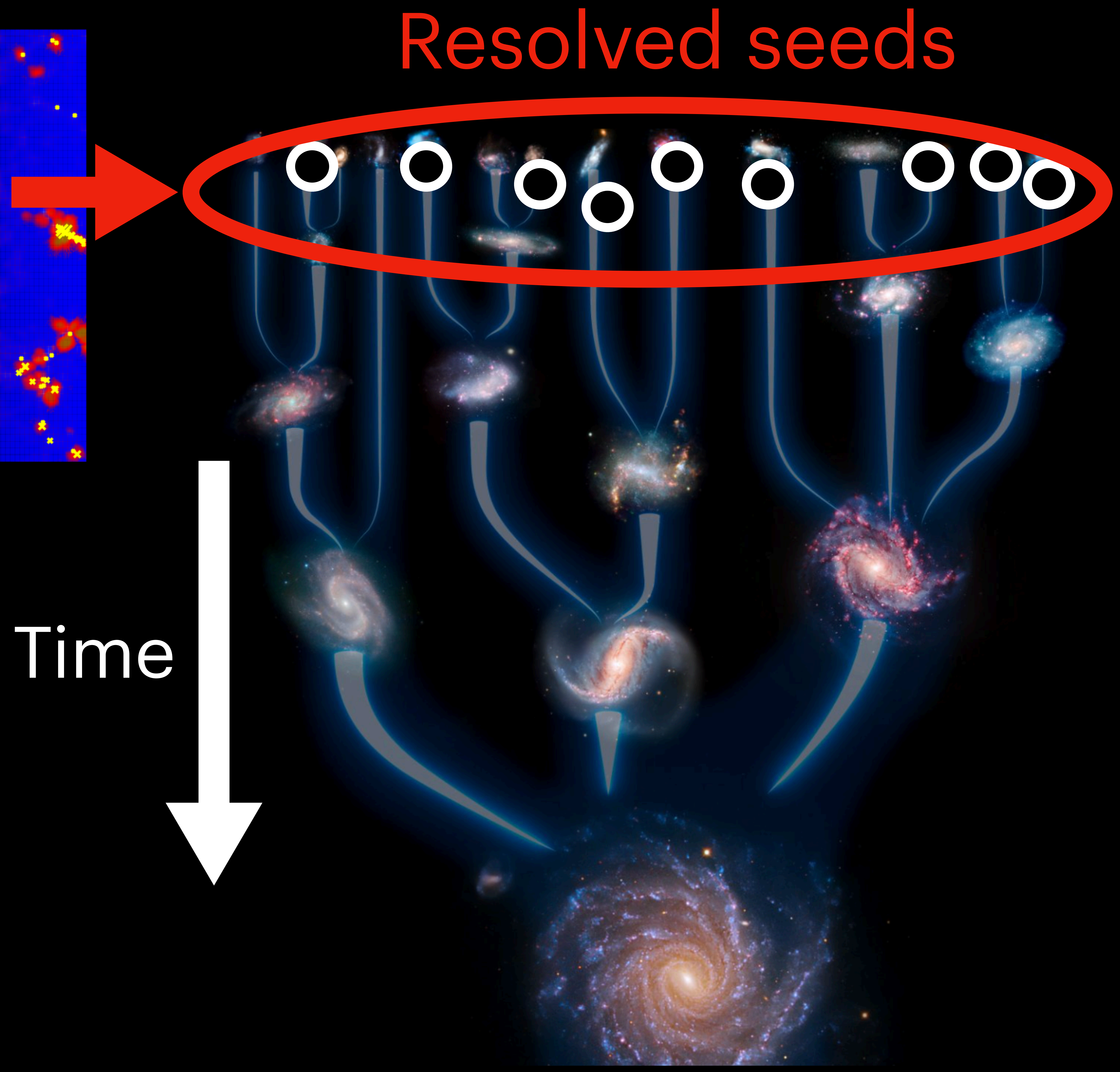
Smallest volume, highest resolution

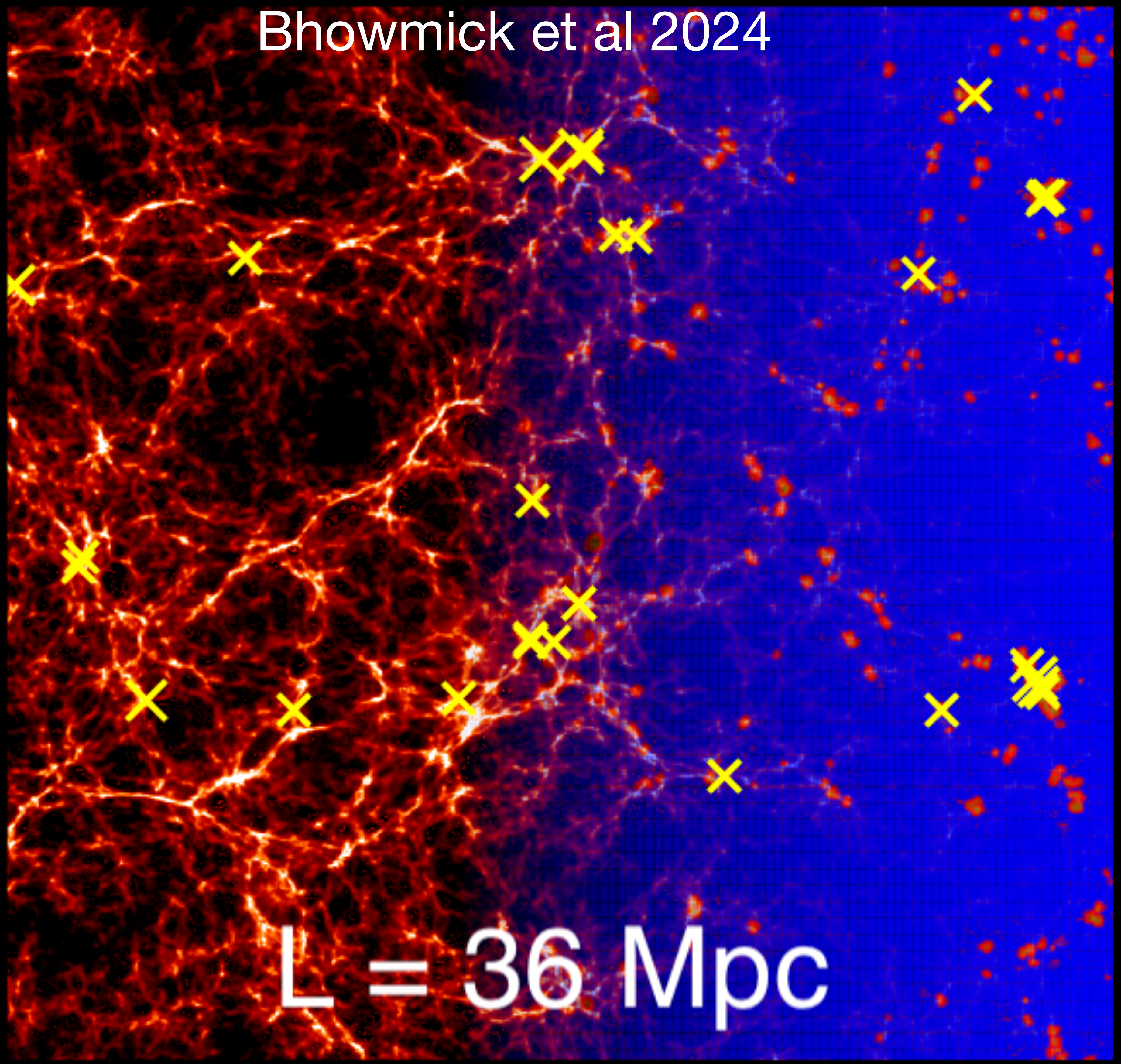


Bhowmick et al 2021

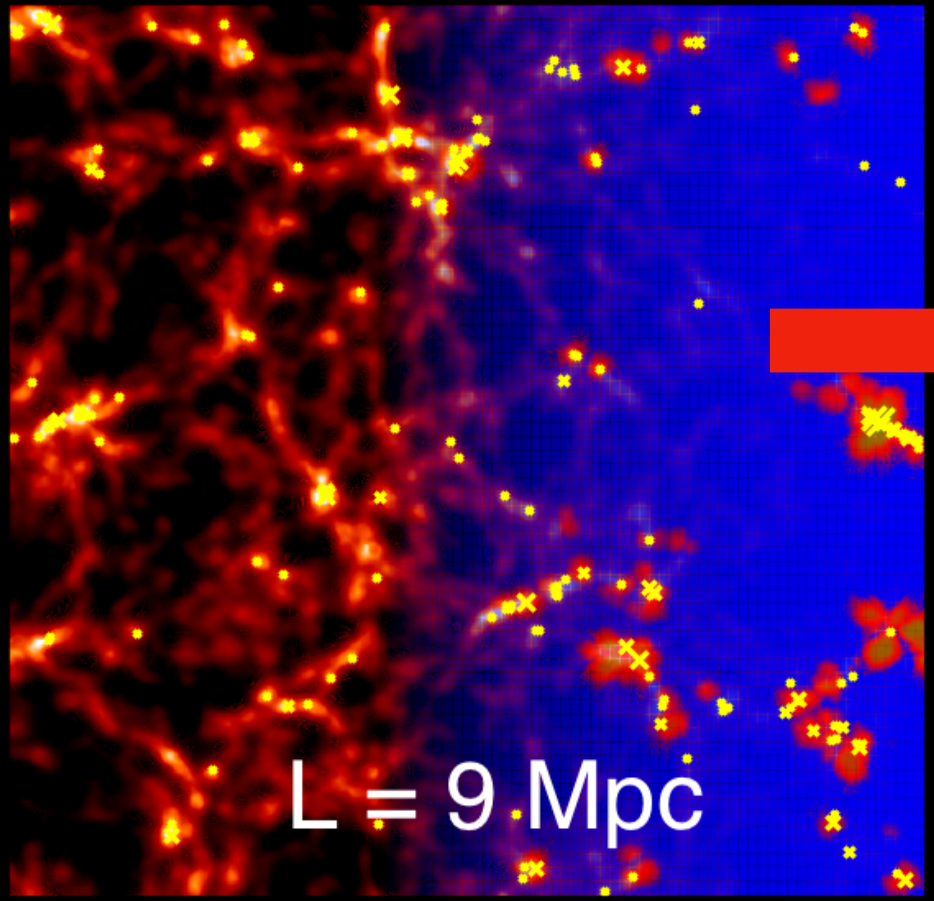
Following the growth of these low mass ($\sim 10^3\ M_\odot$) seeds along the galaxy merger tree

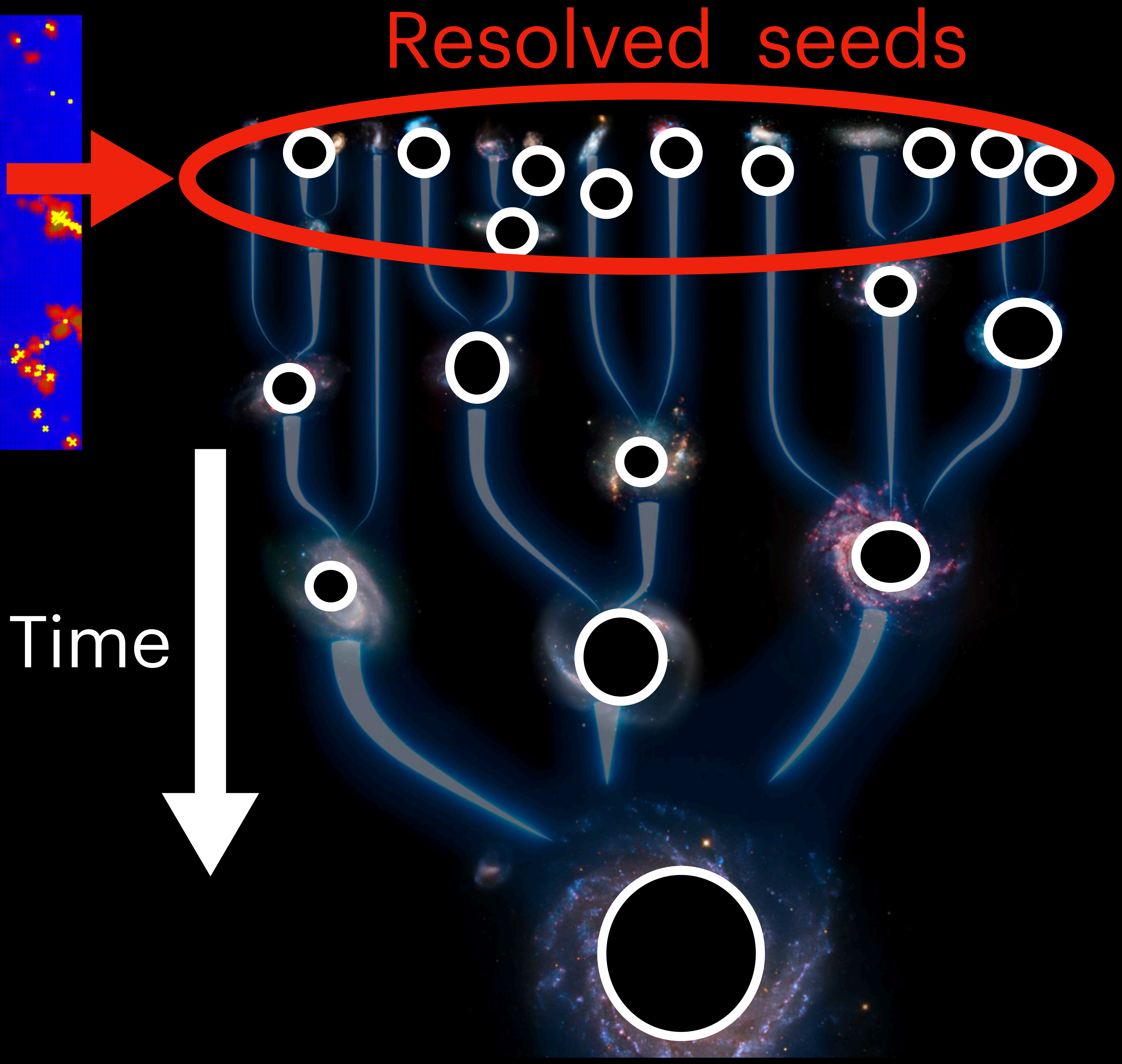


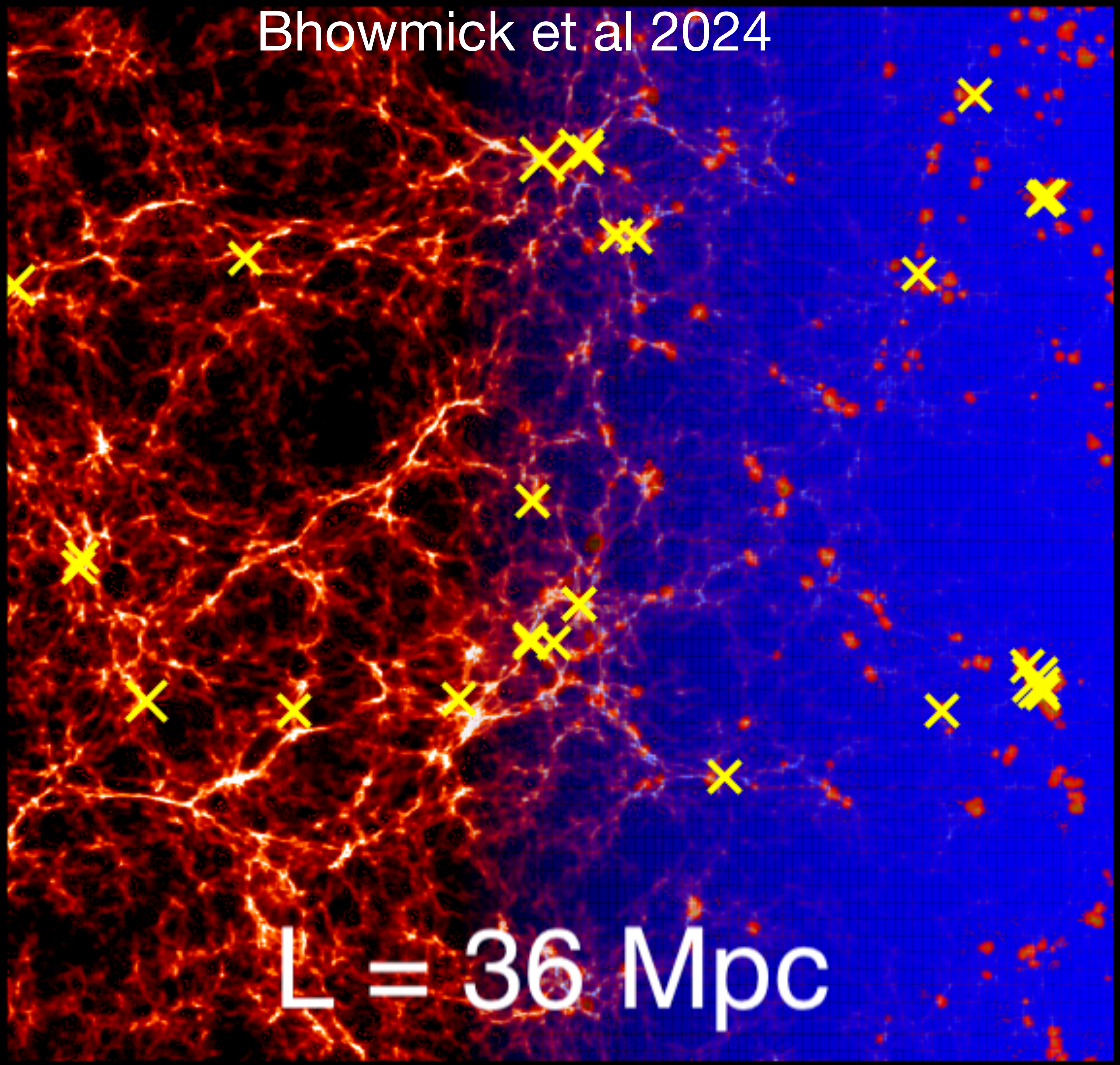




Tracing the galaxies wherein these seeds assembled higher mass descendants





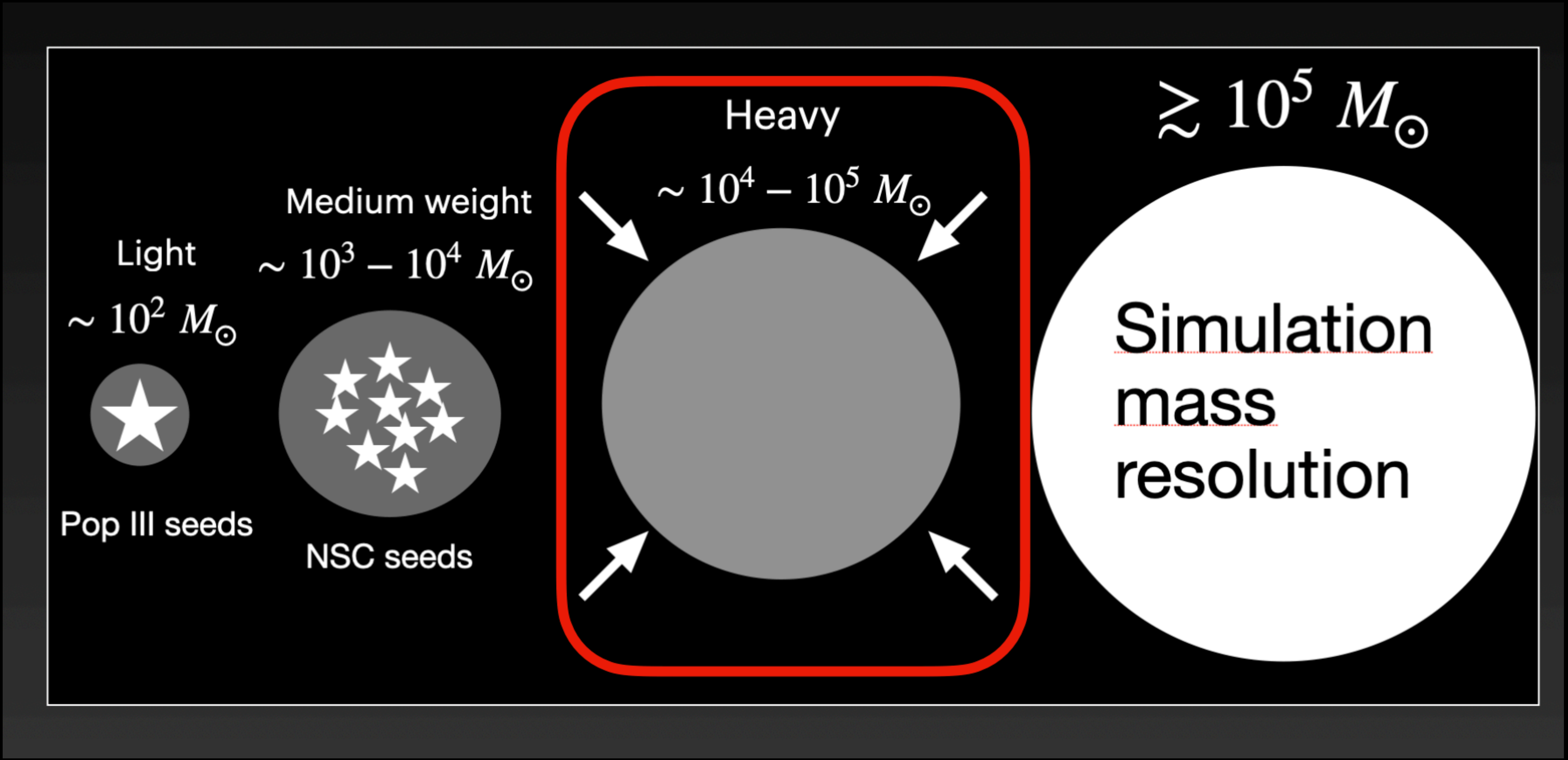


Seeding these descendants in the larger volume simulations

A new subgrid "stochastic seed model" to represent low mass seeds in larger cosmological volumes without the need to resolve them

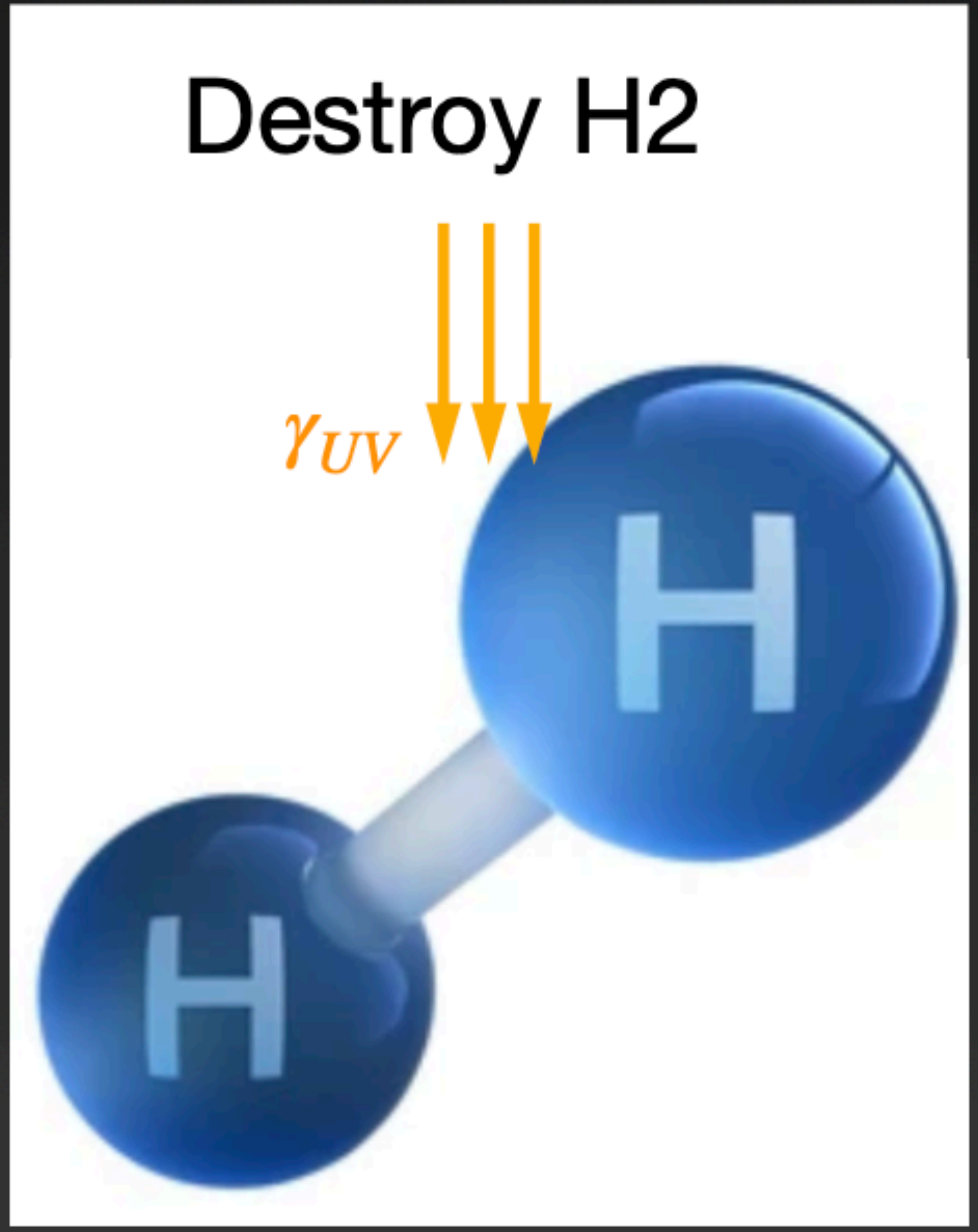
Bhowmick et al 2024a

How do we model heavy seeds in BRAHMA?



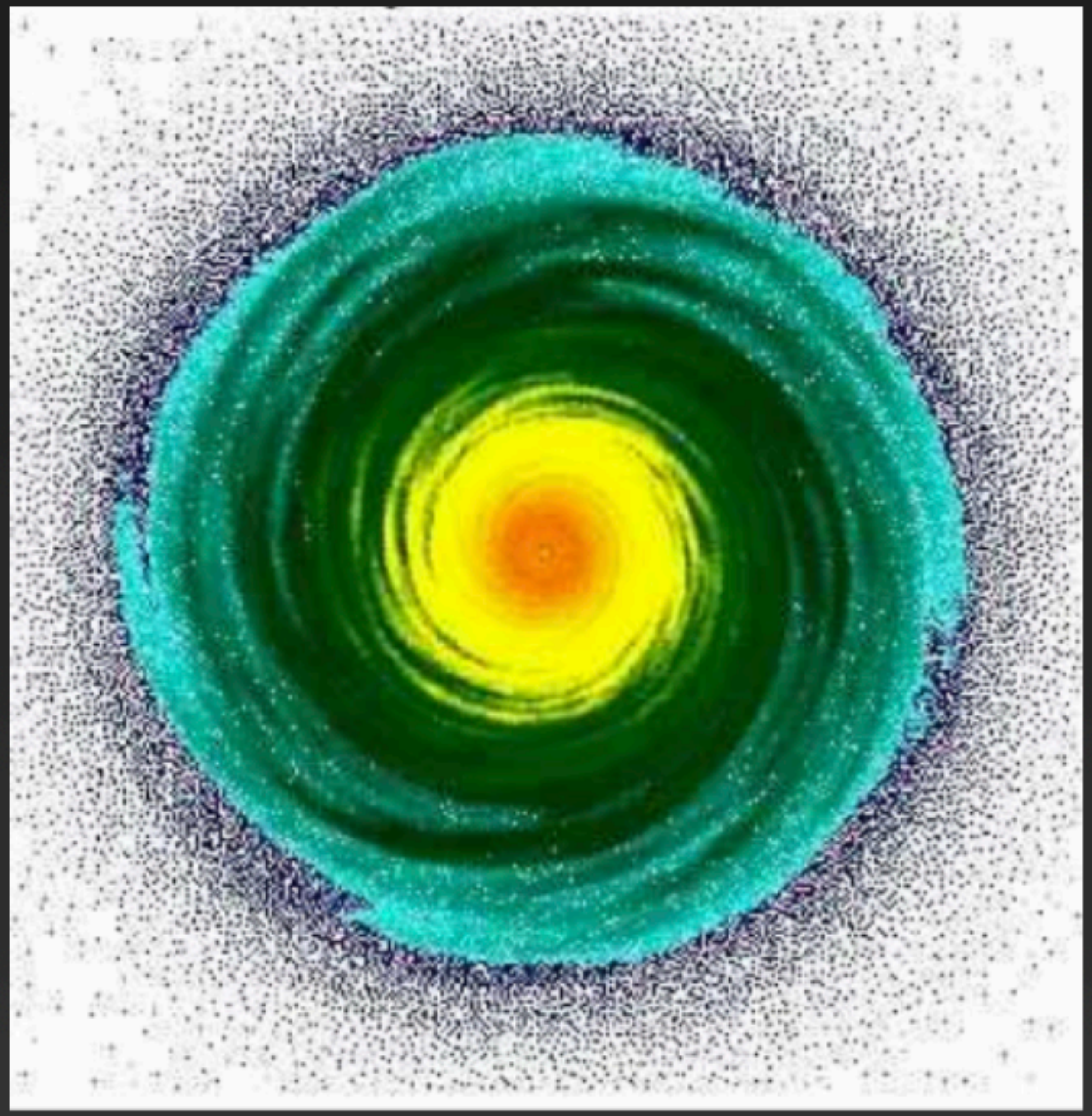
Additional criteria beyond high density and low metallicity gas

Minimum Lyman Werner flux



Maximum gas spin

Toomre instability threshold



Rich environment

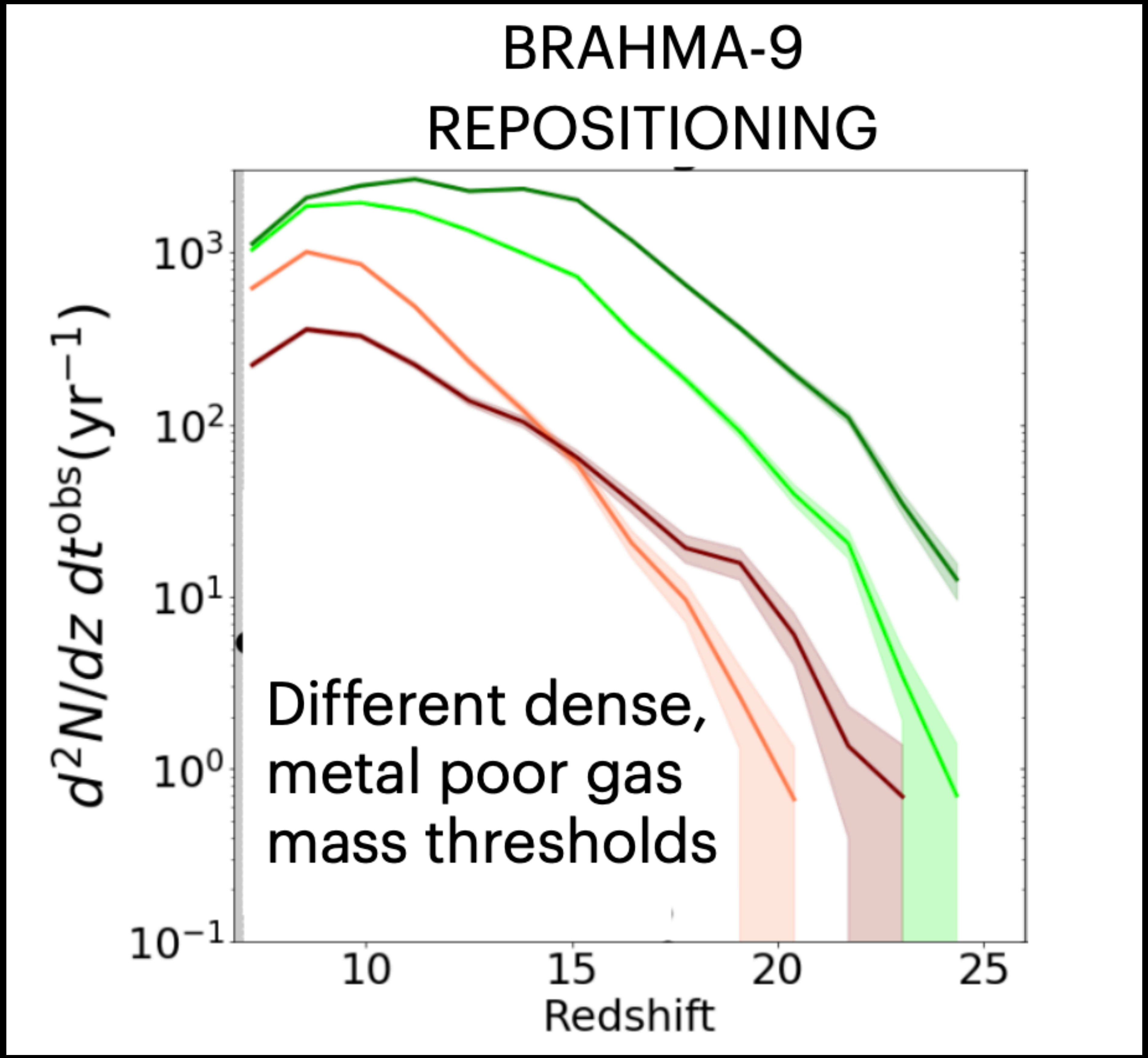
At least one neighboring galaxy

Lewis' talk

Bhowmick et al 2022a

Implications for LISA!

Merger rates (upper limits) of $\geq 10^3\ M_\odot$ BHs

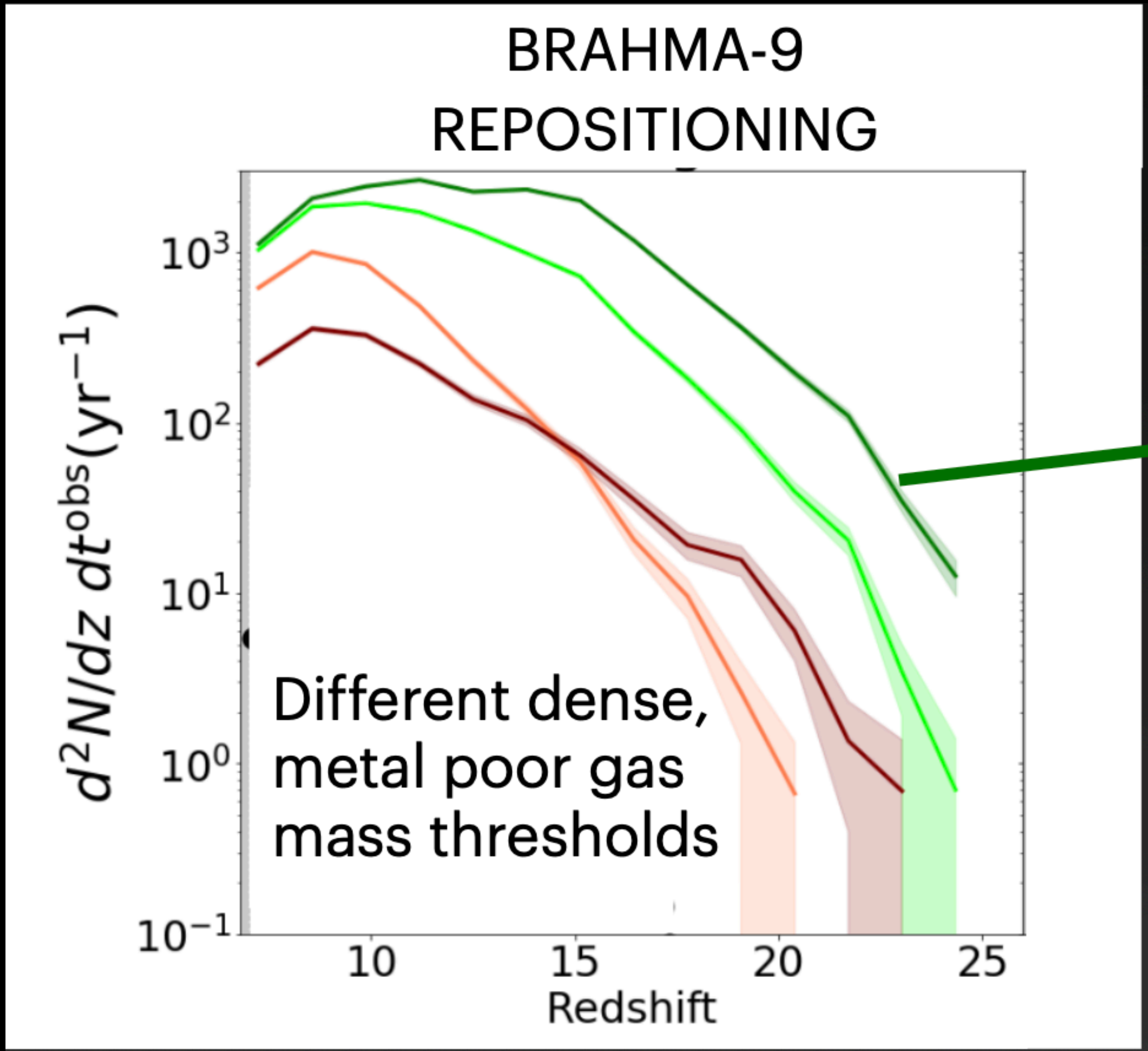


Bhowmick et al 2024b

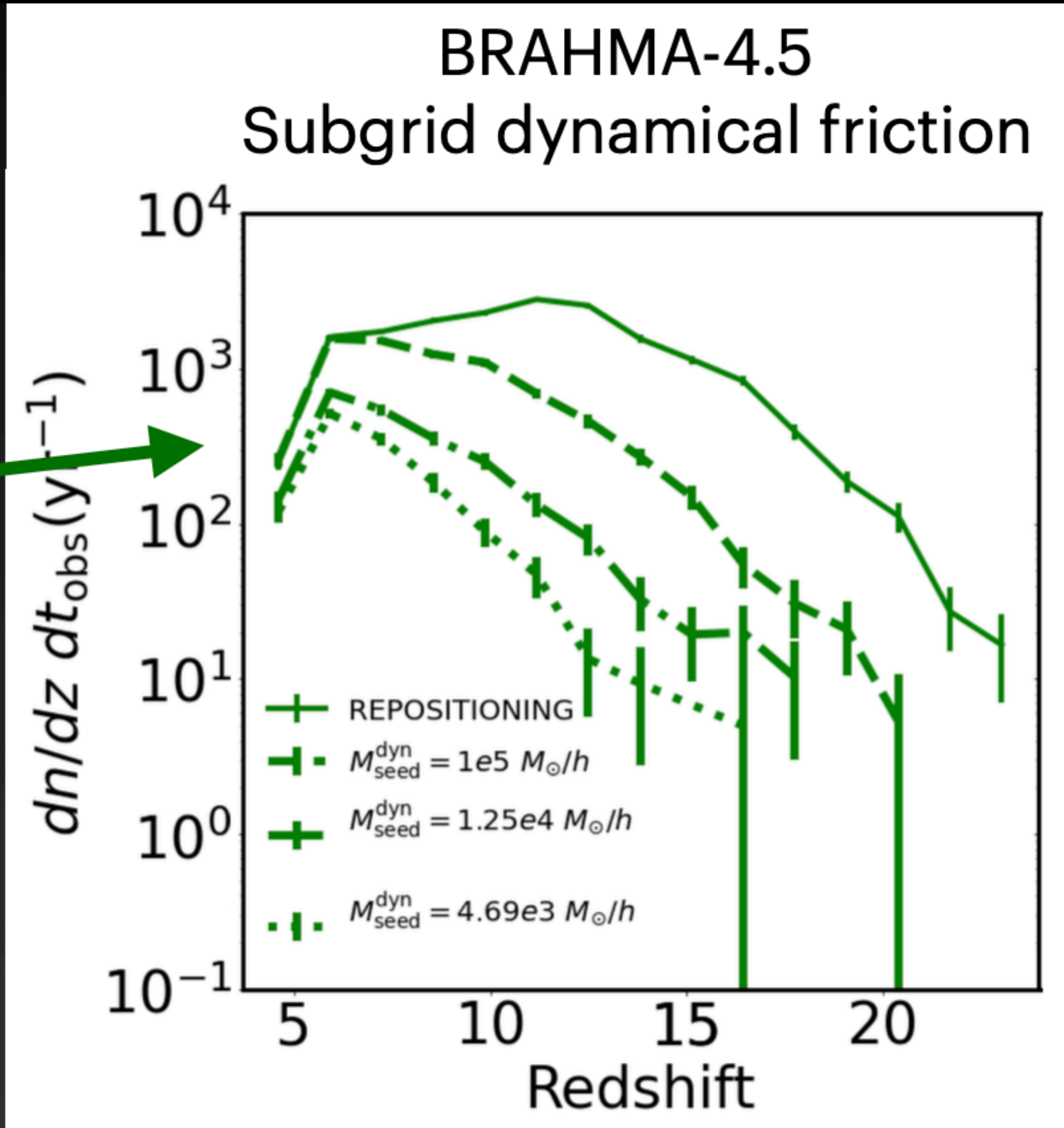
Strong sensitivity to the seeding environment!

Up to ~200-2000 potential mergers per year

Merger rates (upper limits) of $\geq 10^3\ M_\odot$ Bus

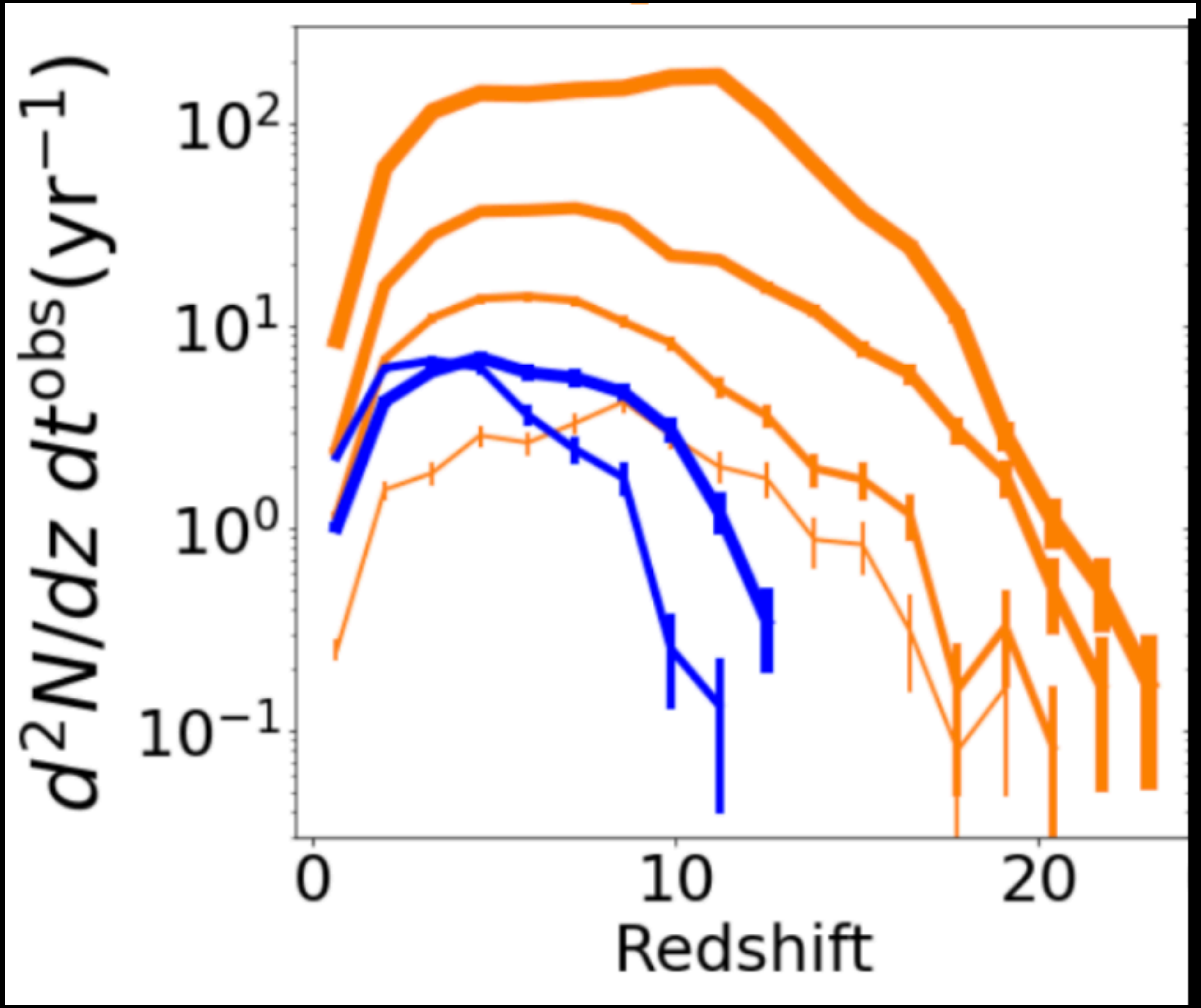


Bhowmick et al 2024b



Bhowmick et al in prep

Merger rates (upper limits) of $\geq 10^5\ M_{\odot}$ BHs



Bhowmick et al in prep

Formed as heavy seeds

vs

Descendants of low mass seeds

Conclusions

1) We present BRAHMA, a new cosmological simulation suite that systematically explores the impact of black hole seeding on high-z supermassive BH populations.

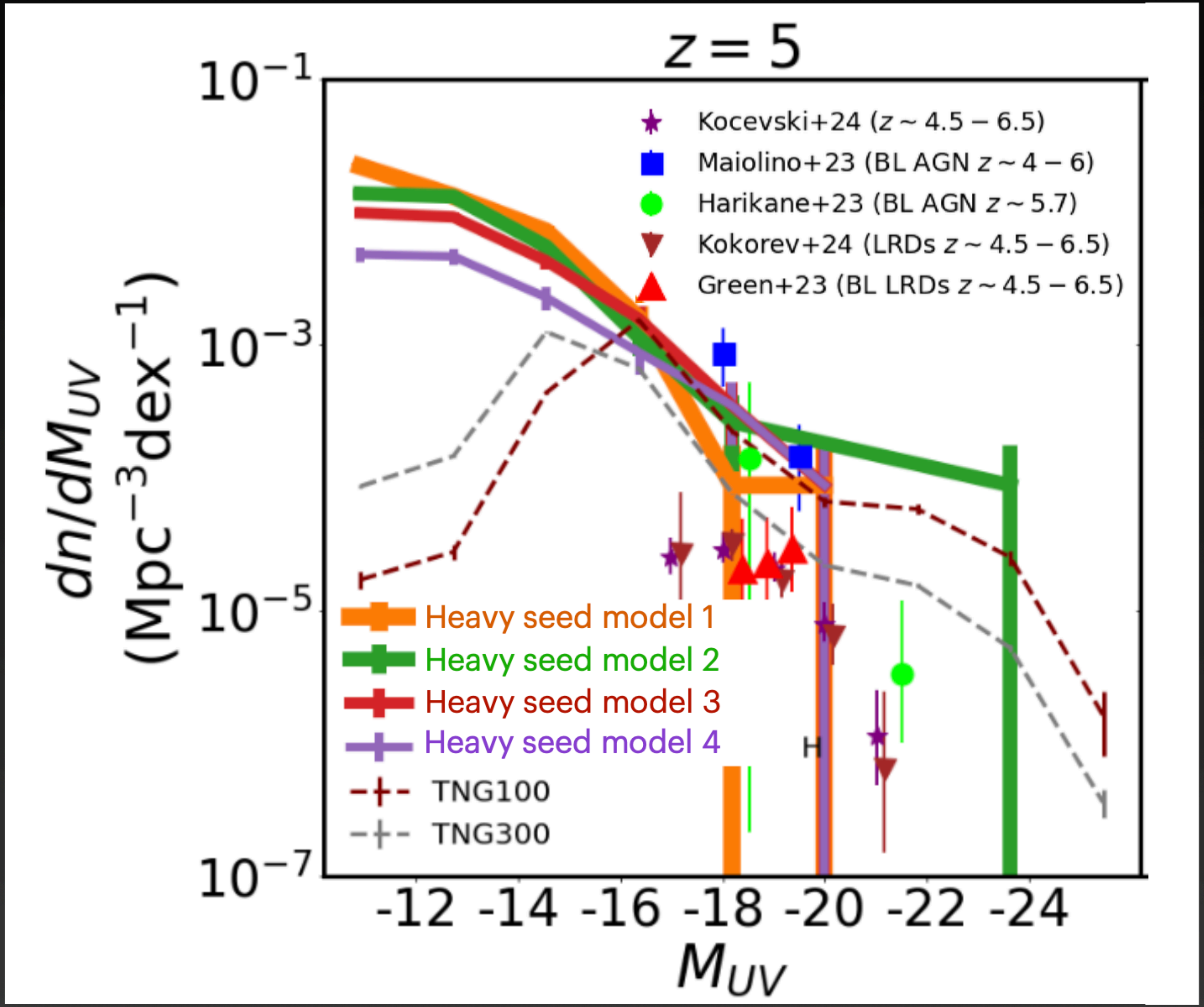
2) BRAHMA implements novel seed models, including an approach to model seeds ~10-100 times below the simulation resolution.

3) Simulations provide upper limits of 200-2000 mergers per year for LISA. The merger rates are strongly sensitive to the seeding environment and seed mass.

LISA will revolutionize our understanding of supermassive black hole origins

Cosmological simulations like BRAHMA will play a key role in making this happen!

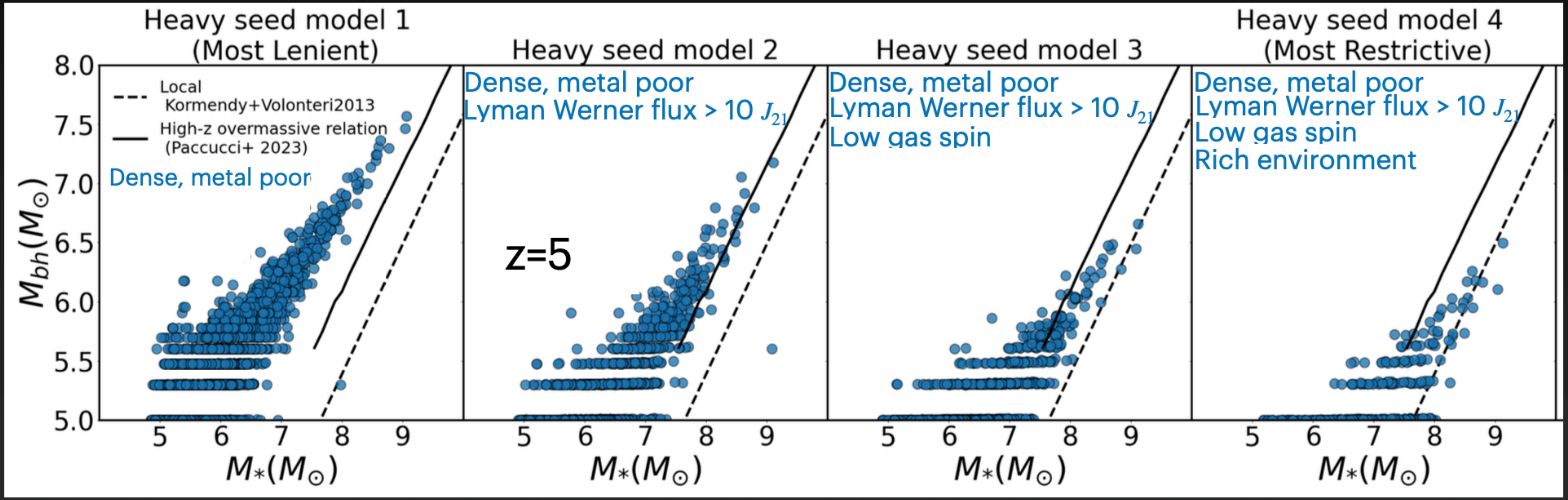
AGN luminosity functions: Seed models have no consequence at the bright (observable) end



Broad agreement with JWST

But the BH mass - stellar mass relations have substantial seed model variations

Bhowmick et al 2024c



If heavy seed formation is efficient enough, one could produce overmassive BHs via BH-BH mergers

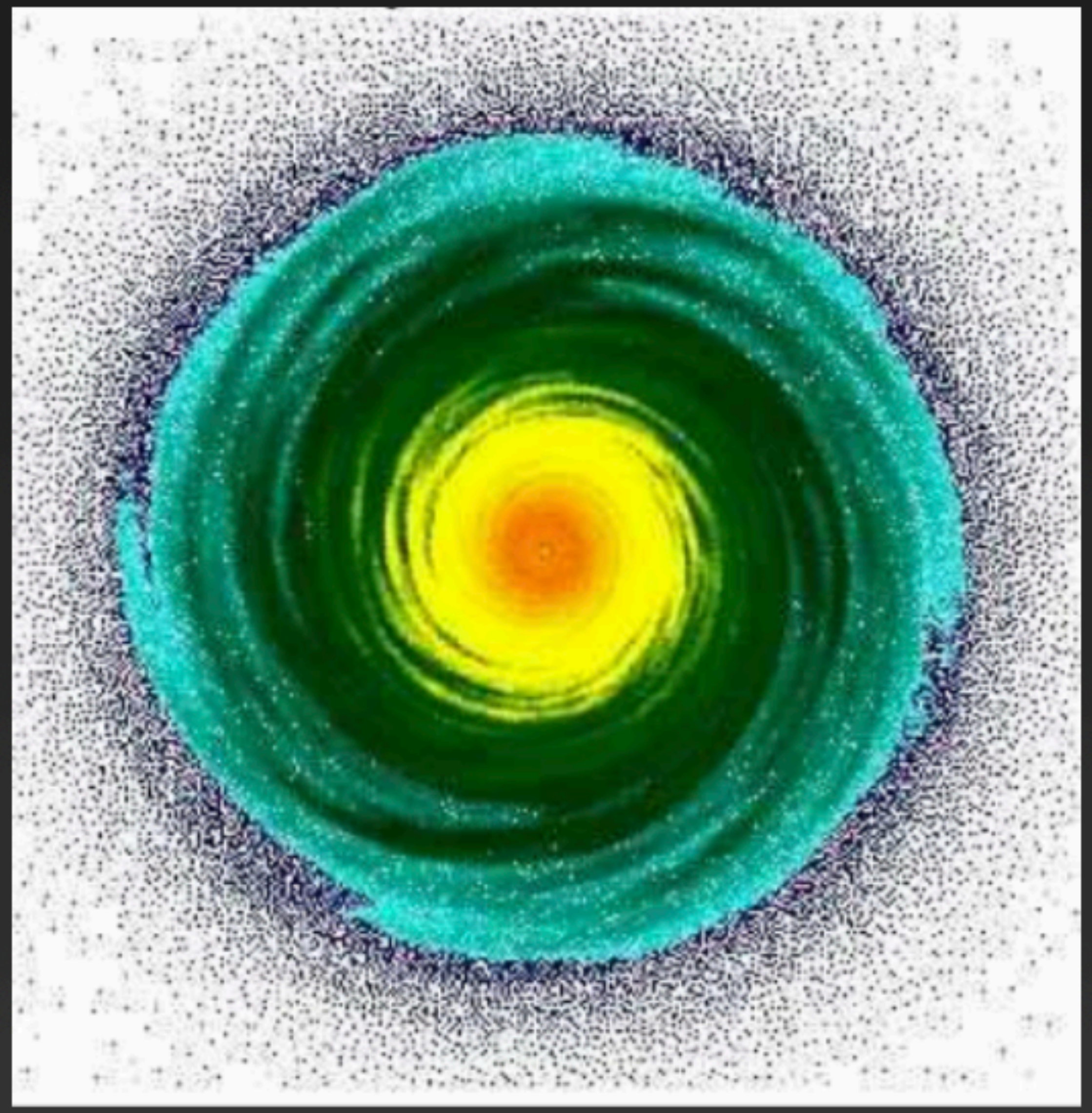
Modeling heavy seeds in large cosmological simulations?

Additional criteria beyond high density and low metallicity gas

Minimum Lyman Werner flux

Maximum gas spin

Toomre instability threshold

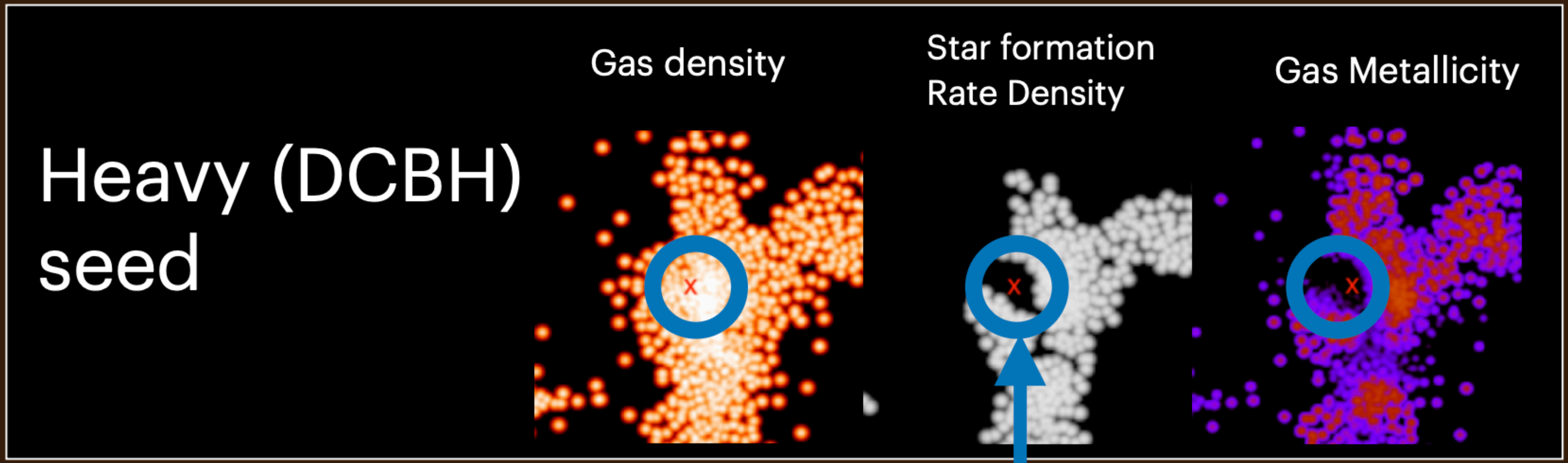


Rich environment

At least one neighboring galaxy

See Lewis Prole's talk

Typical sites for DCBH formation



No star formation at the seeding site

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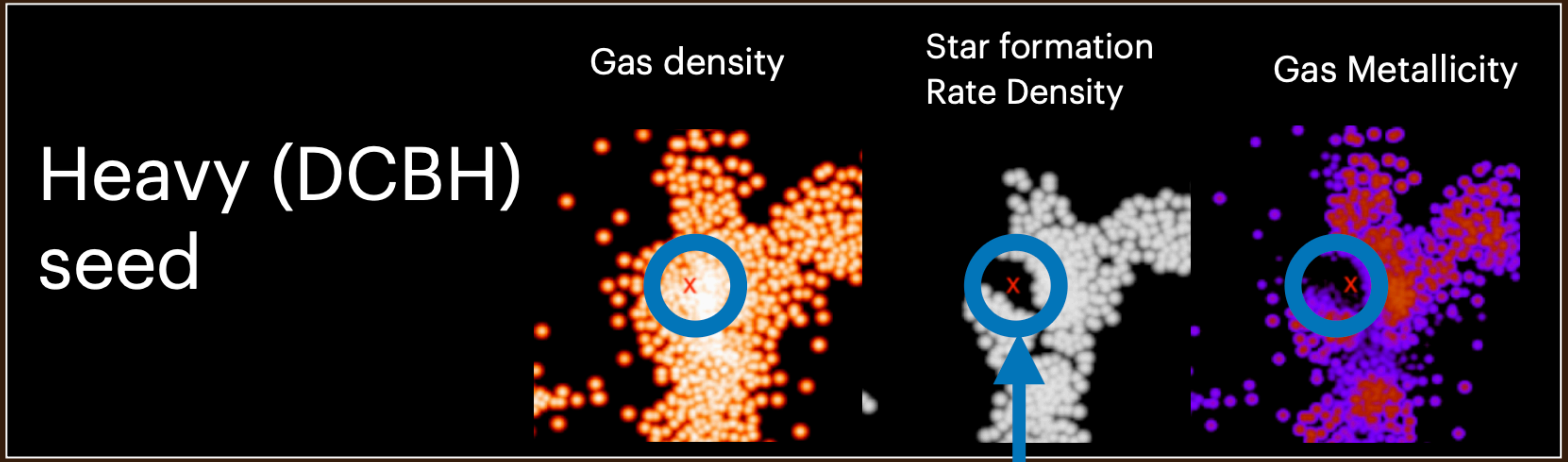

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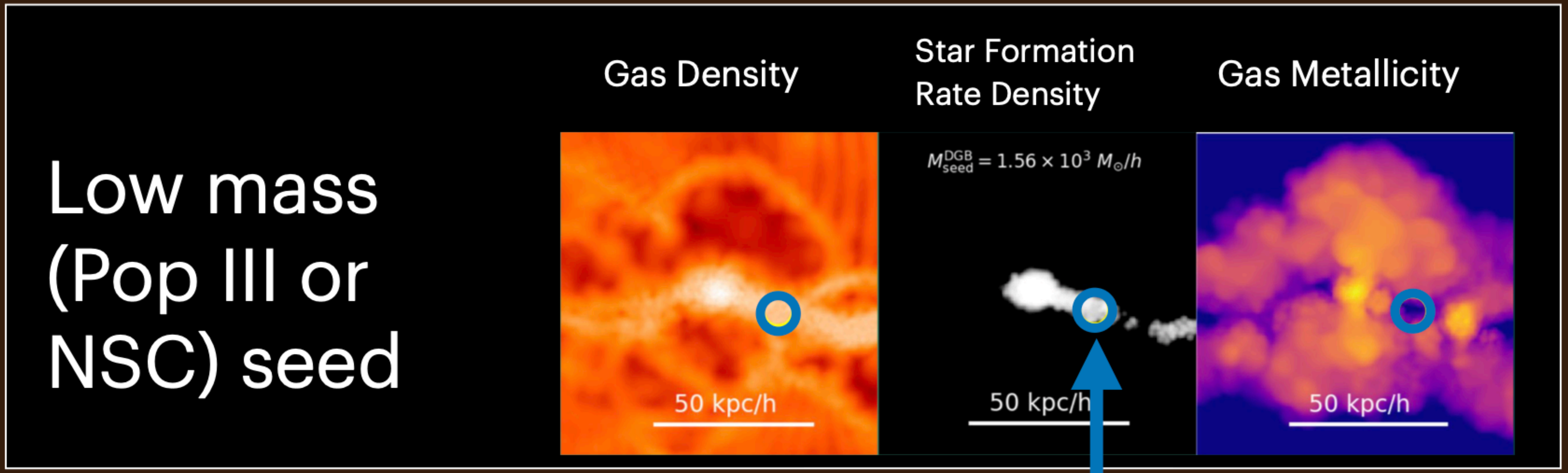
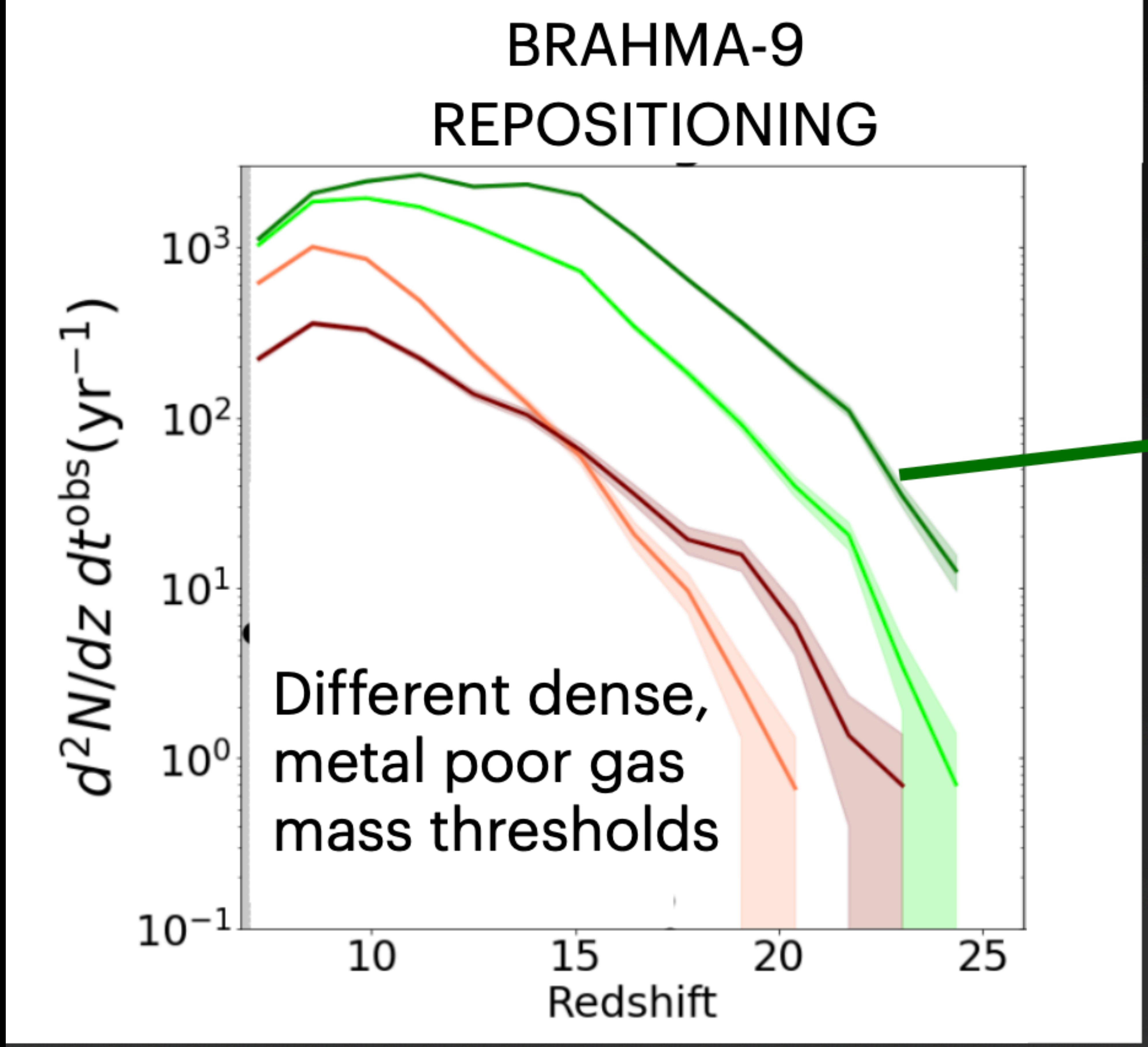
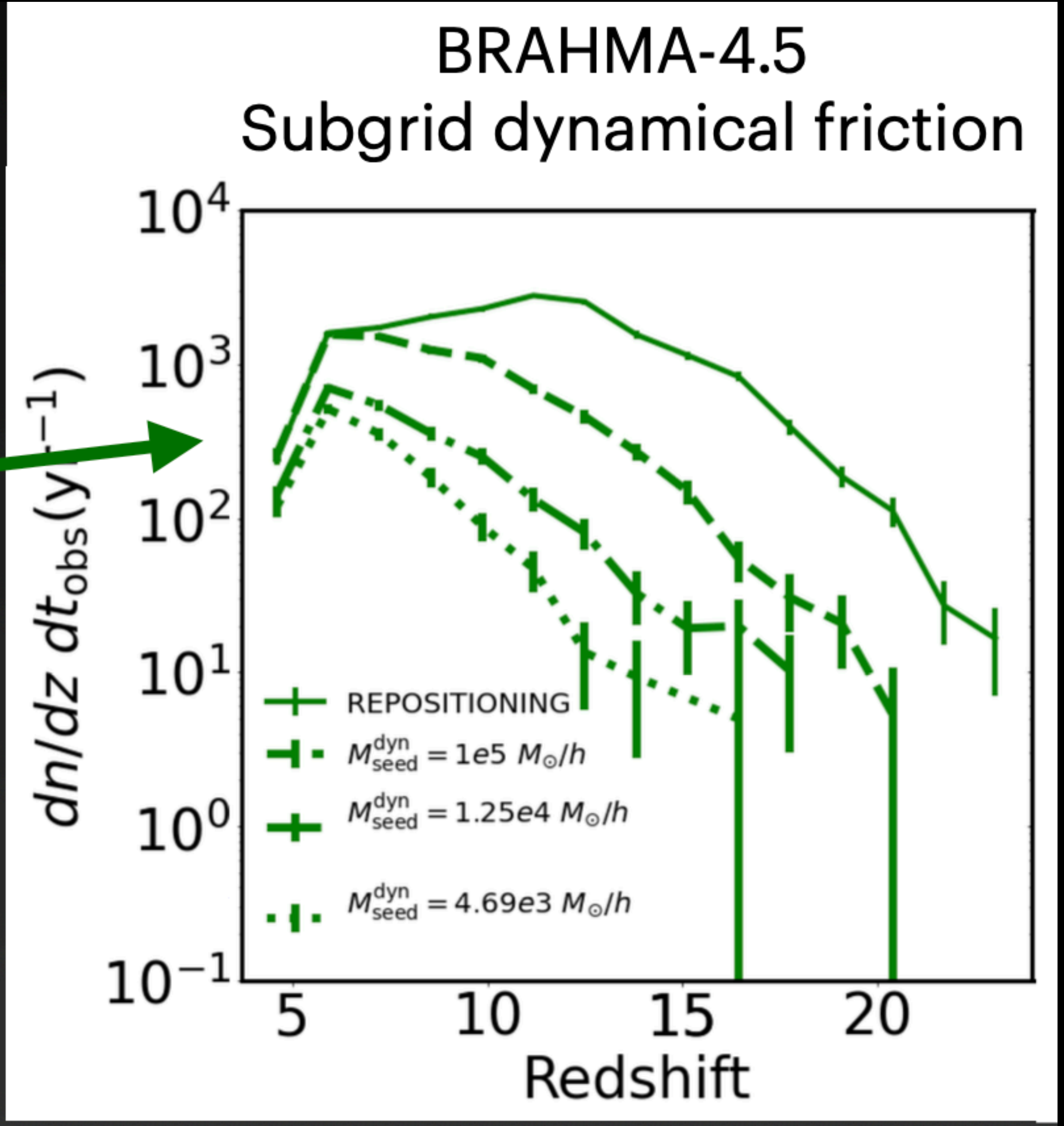


Active star formation at the seeding site

Merger rates (upper limits) of $\geq 10^3\ M_\odot$ Bus



Bhowmick et al 2024b

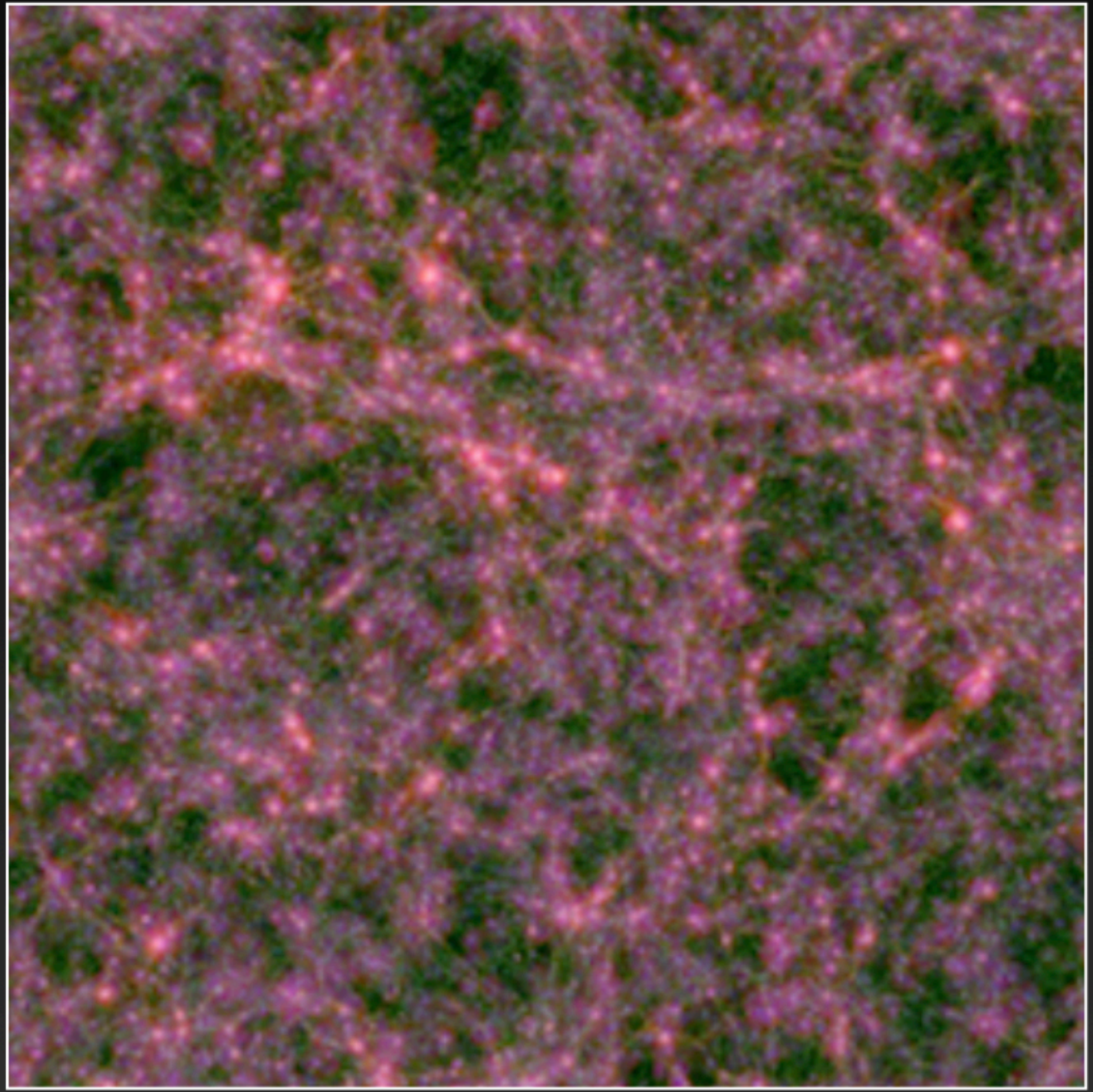


Bhowmick et al in pr

Simulations have started adopting more physically motivated seeding prescriptions

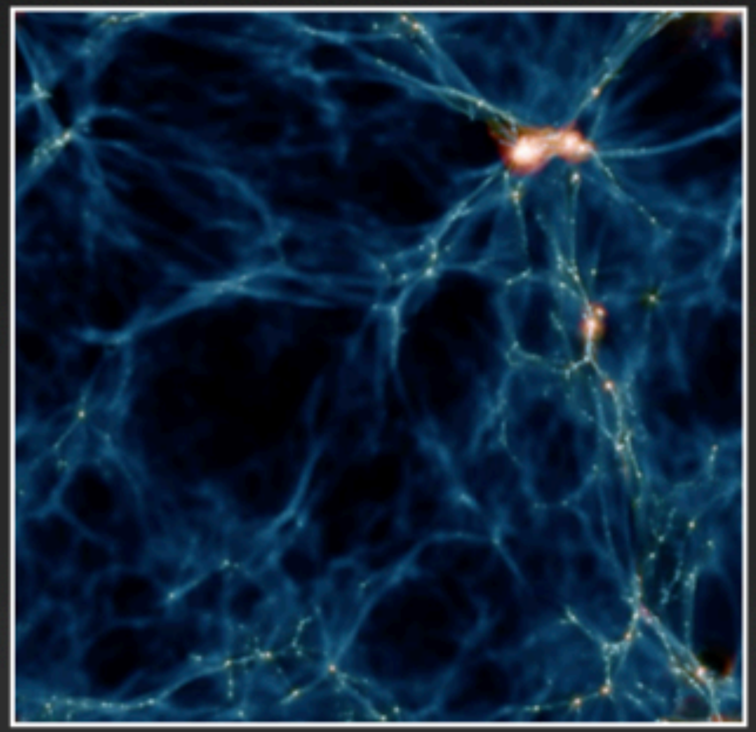
Seeding based on local gas properties

Horizon-AGN Kaviraj et al 2016



Taylor and Kobayashi+ 2014
Wang+ 2019
Bellovary+ 2019

ROMULUS Tremmel+2017



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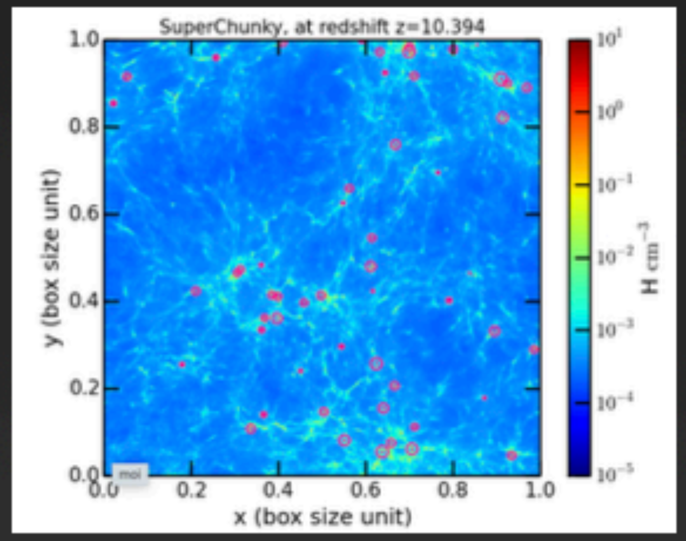

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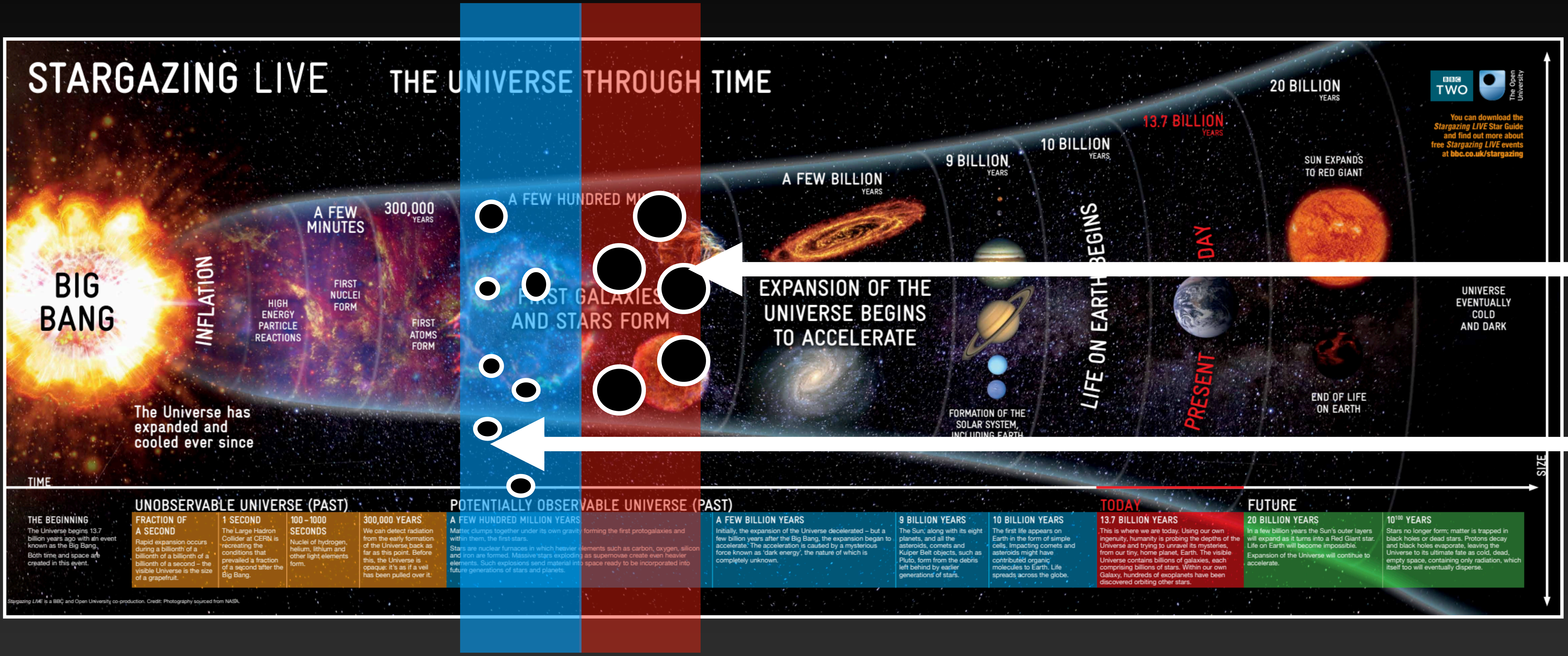
Trinca et al 2022, 23, 24

Evans et al 2023

We are pushing new observational frontiers for high-z black holes, and will continue to do so!



WEBB SPACE TELESCOPE

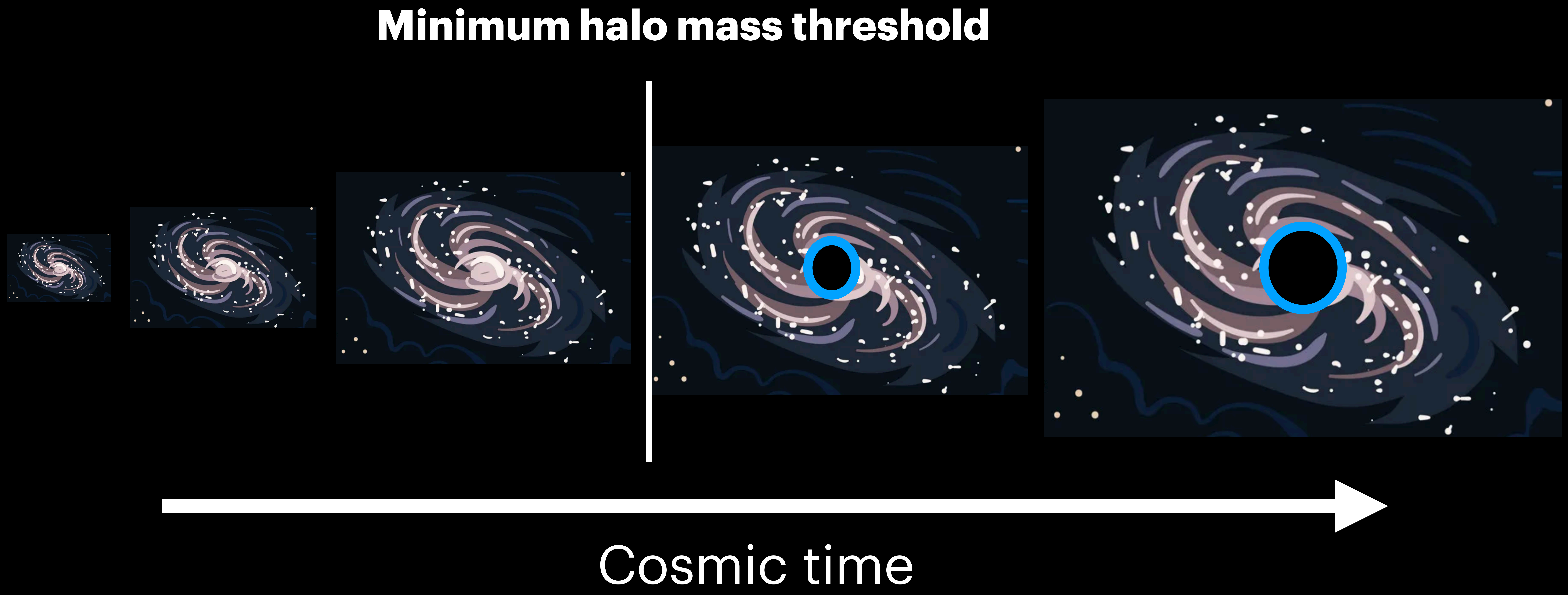
LISA
Laser Interferometer Space Antenna

Current JWST observations $\sim 10^6 - 10^8 \, M_\odot$ BHs at z ~ 4 - 11

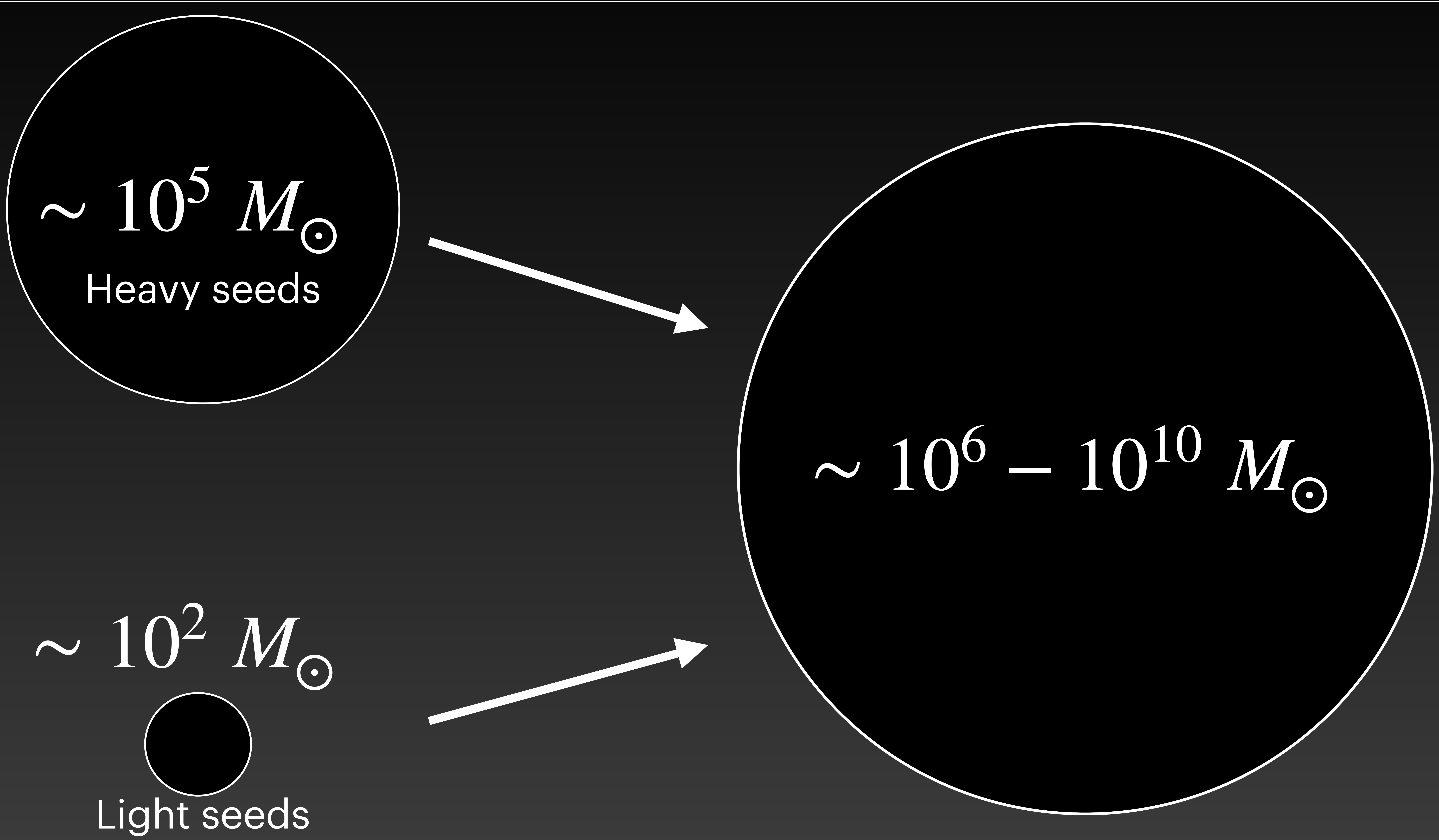
Future LISA observations $\sim 10^3 - 10^7 \, M_\odot$ up to z ~ 15

Crucial time to make theoretical predictions!!

The vast majority of simulations use very simplistic black hole seed models

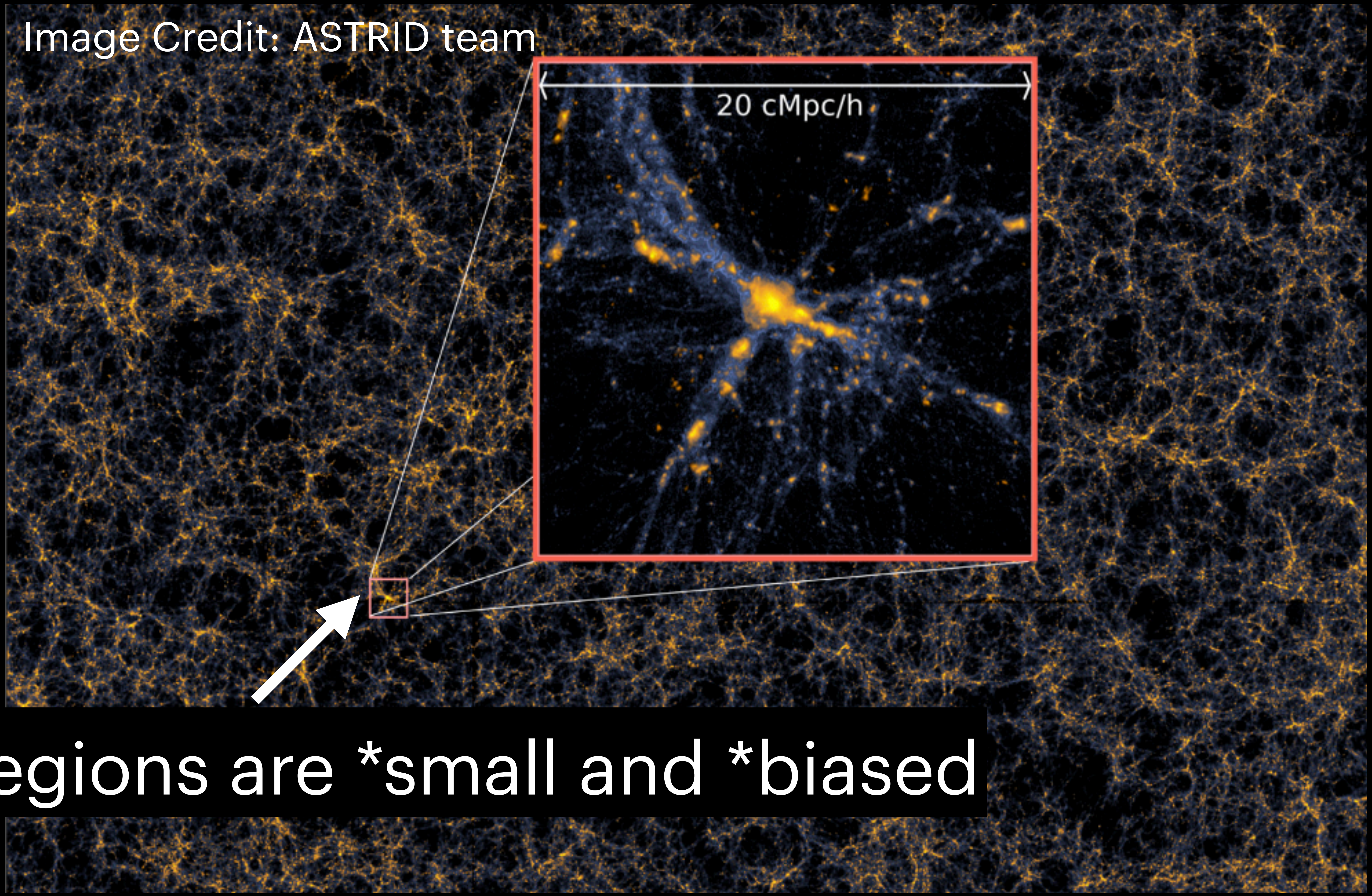


What were the first "seed" black holes that grew into supermassive black holes?



Zoom simulations predictions are difficult to compare with observations

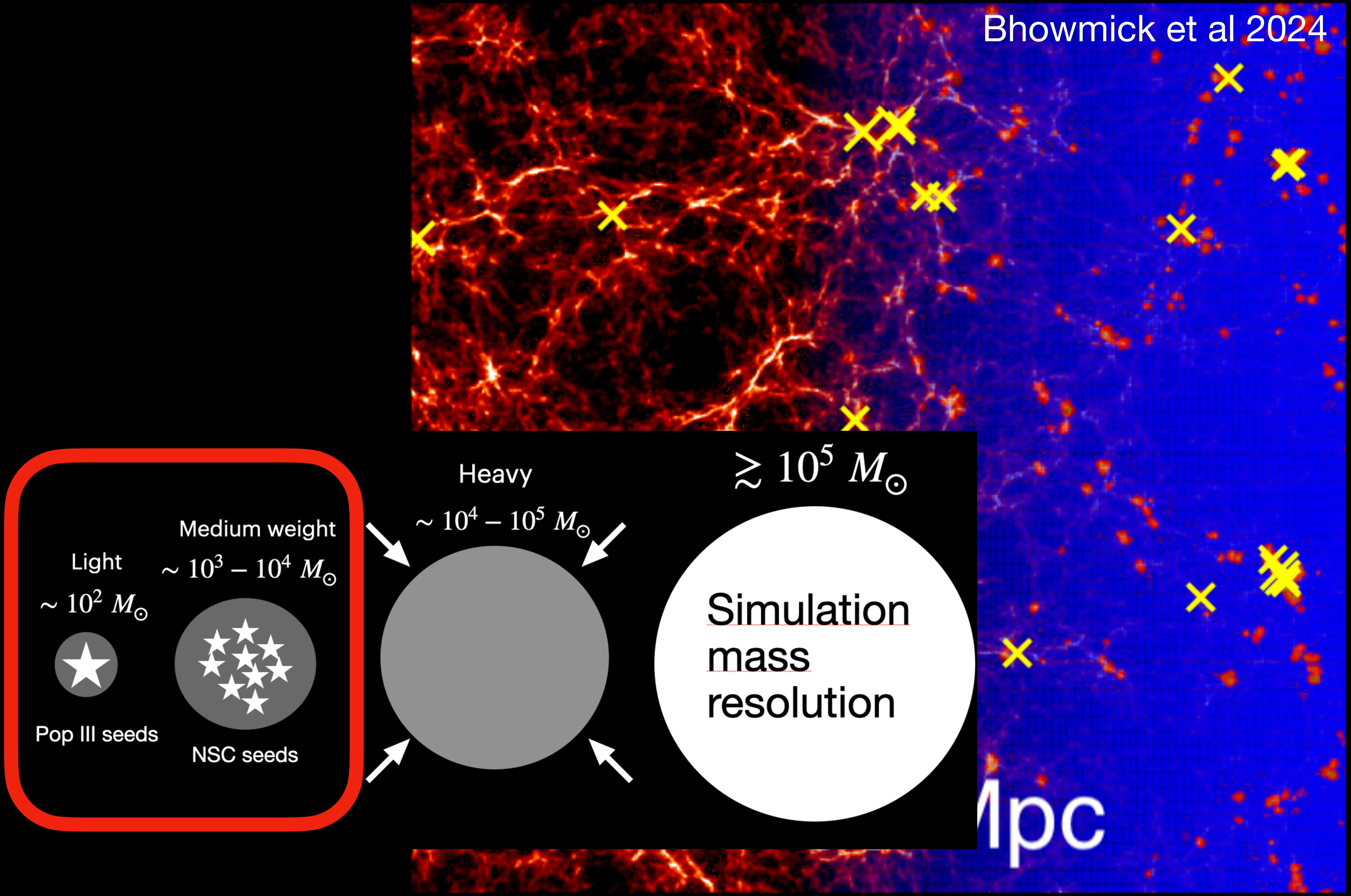
Bhowmick et al 2021, 2022, 2023



Zoom regions are *small and *biased

How do we model these low mass seeds in large cosmological simulations?

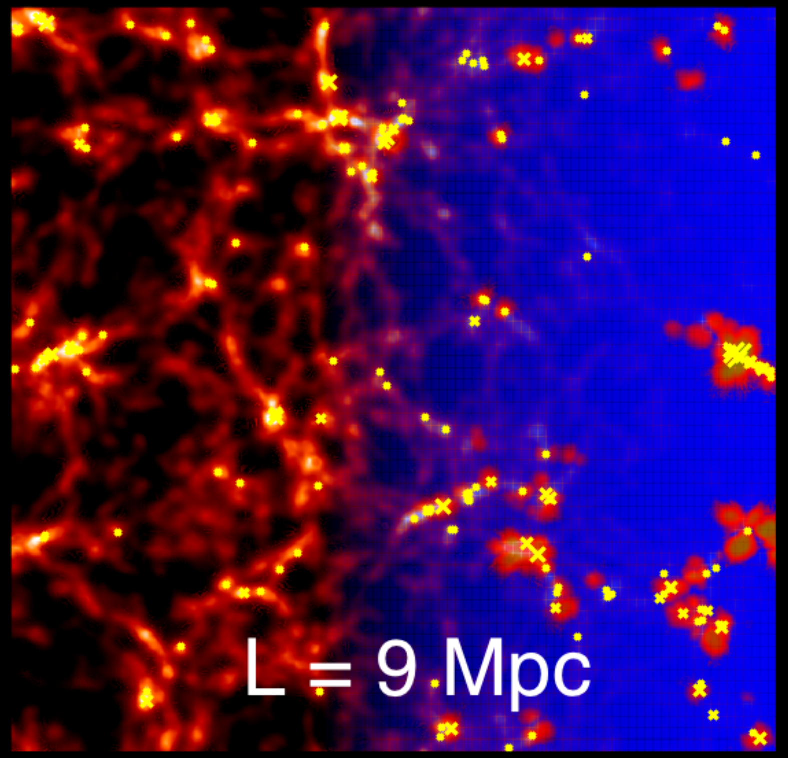
Surpassing the resolution limitation

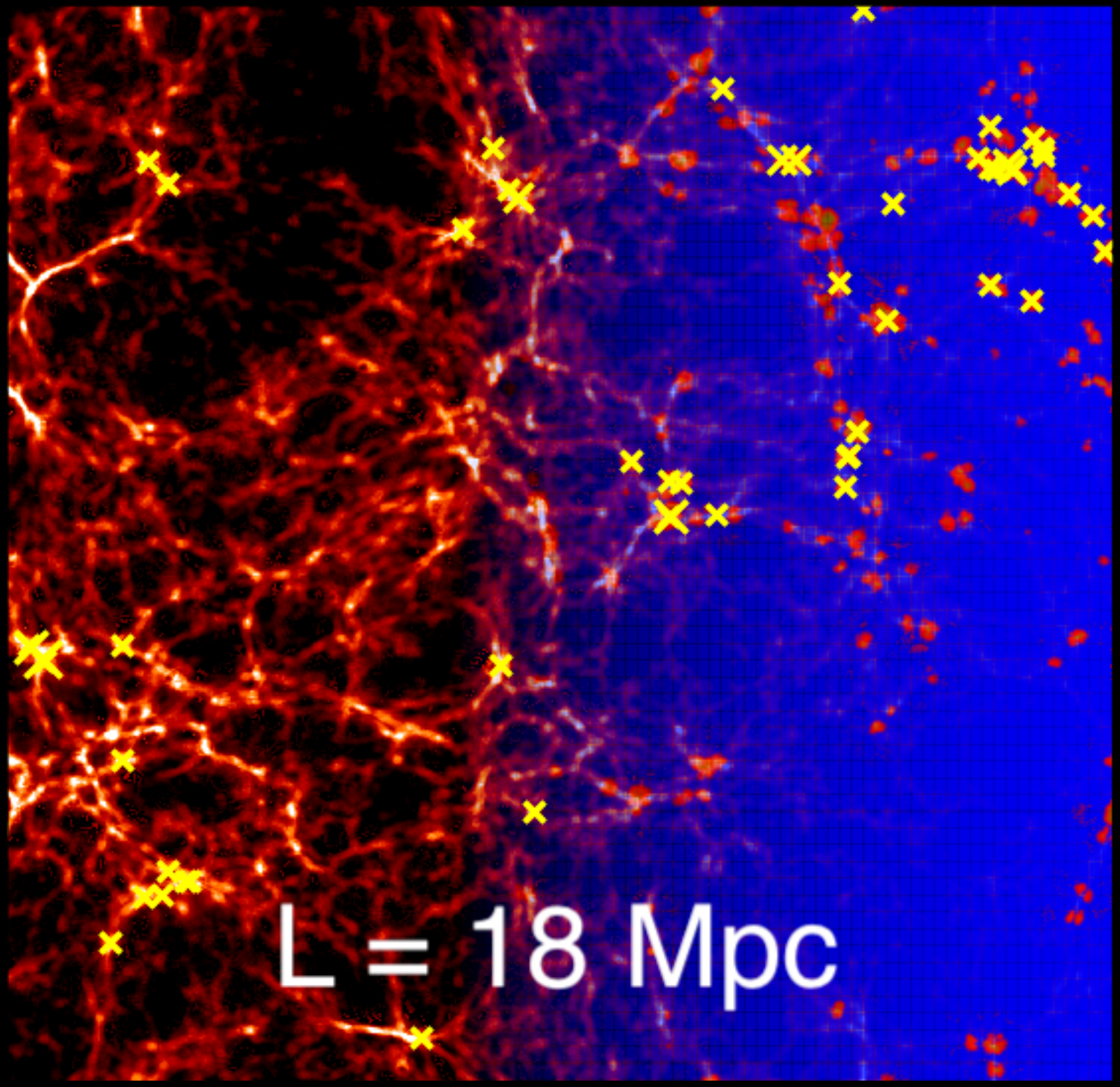


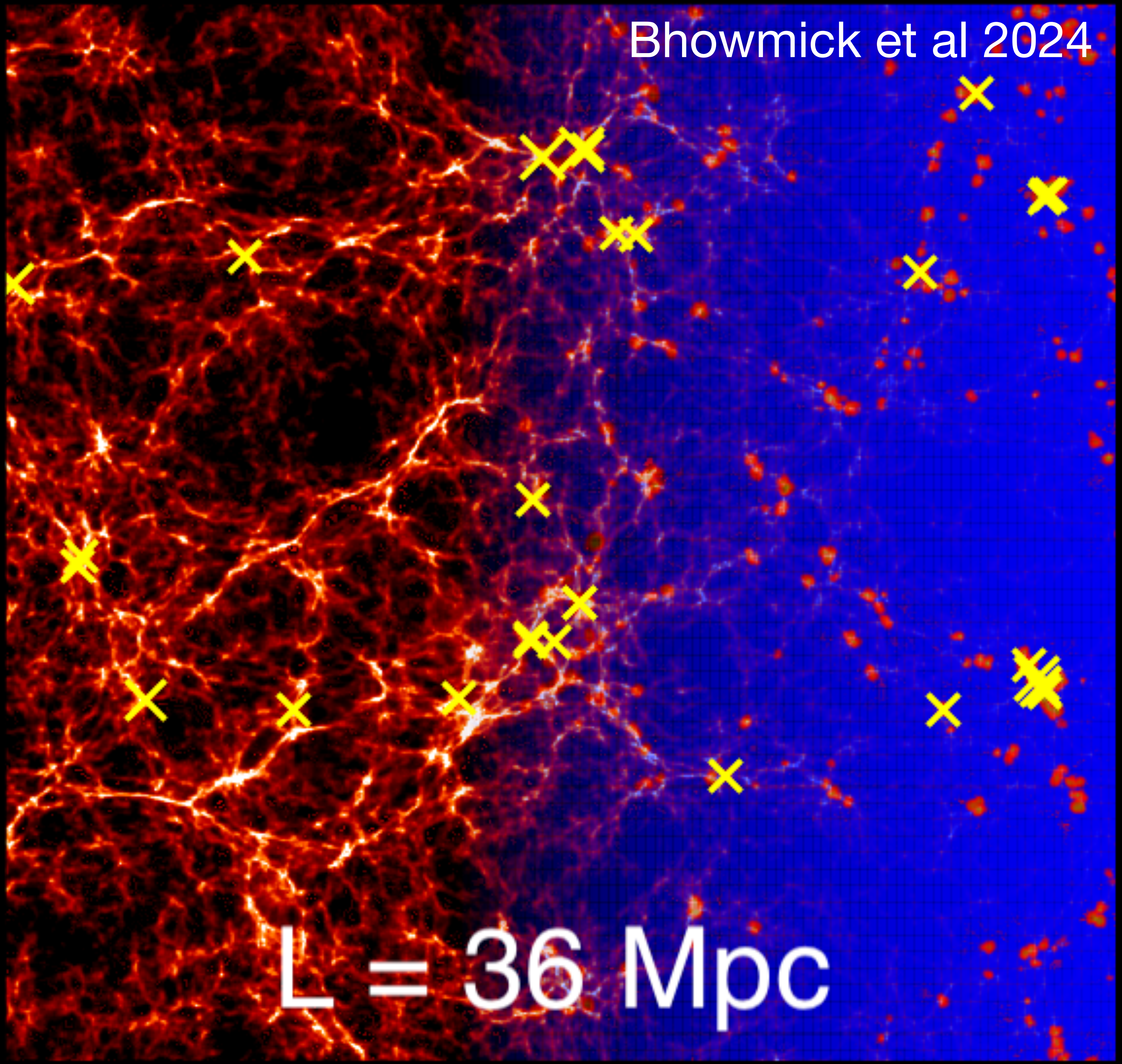
Having multiple simulation boxes with increasing volumes and decreasing resolution

Largest volume, lowest resolution

Smallest volume, highest resolution



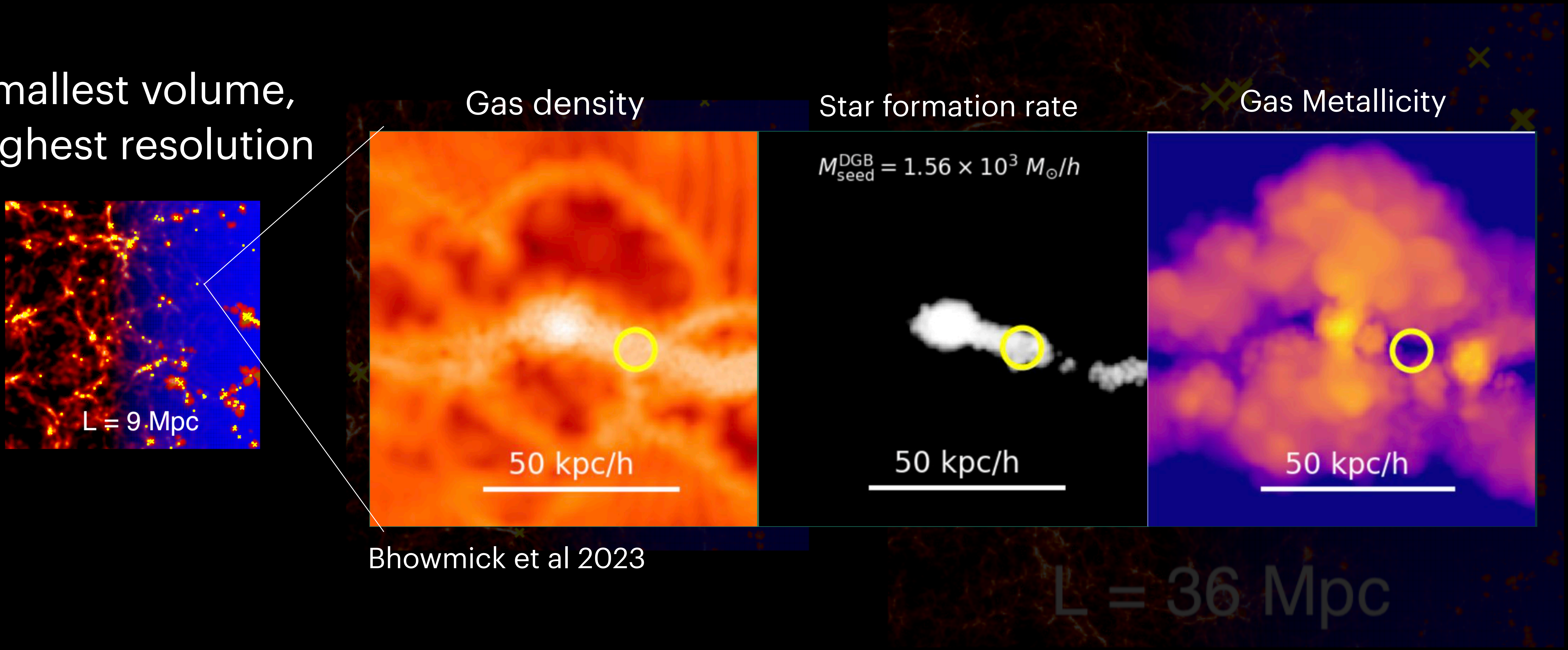




Bhowmick et al 2024

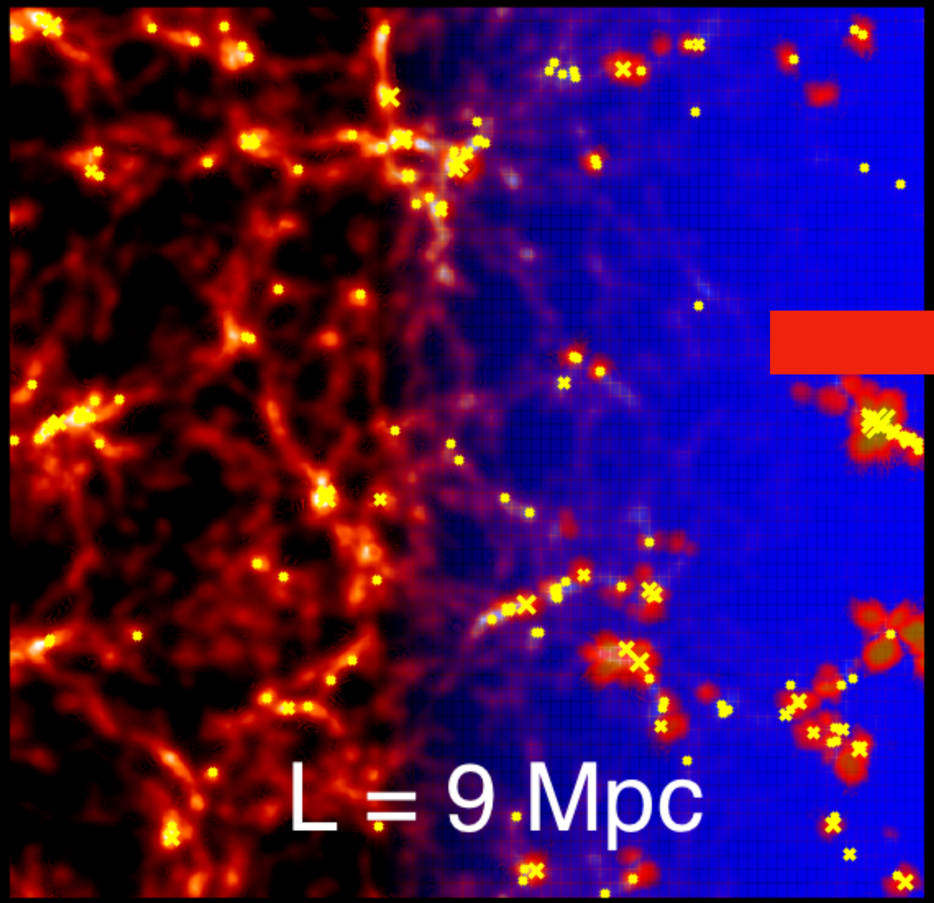
Placing seeds in the smallest volume box

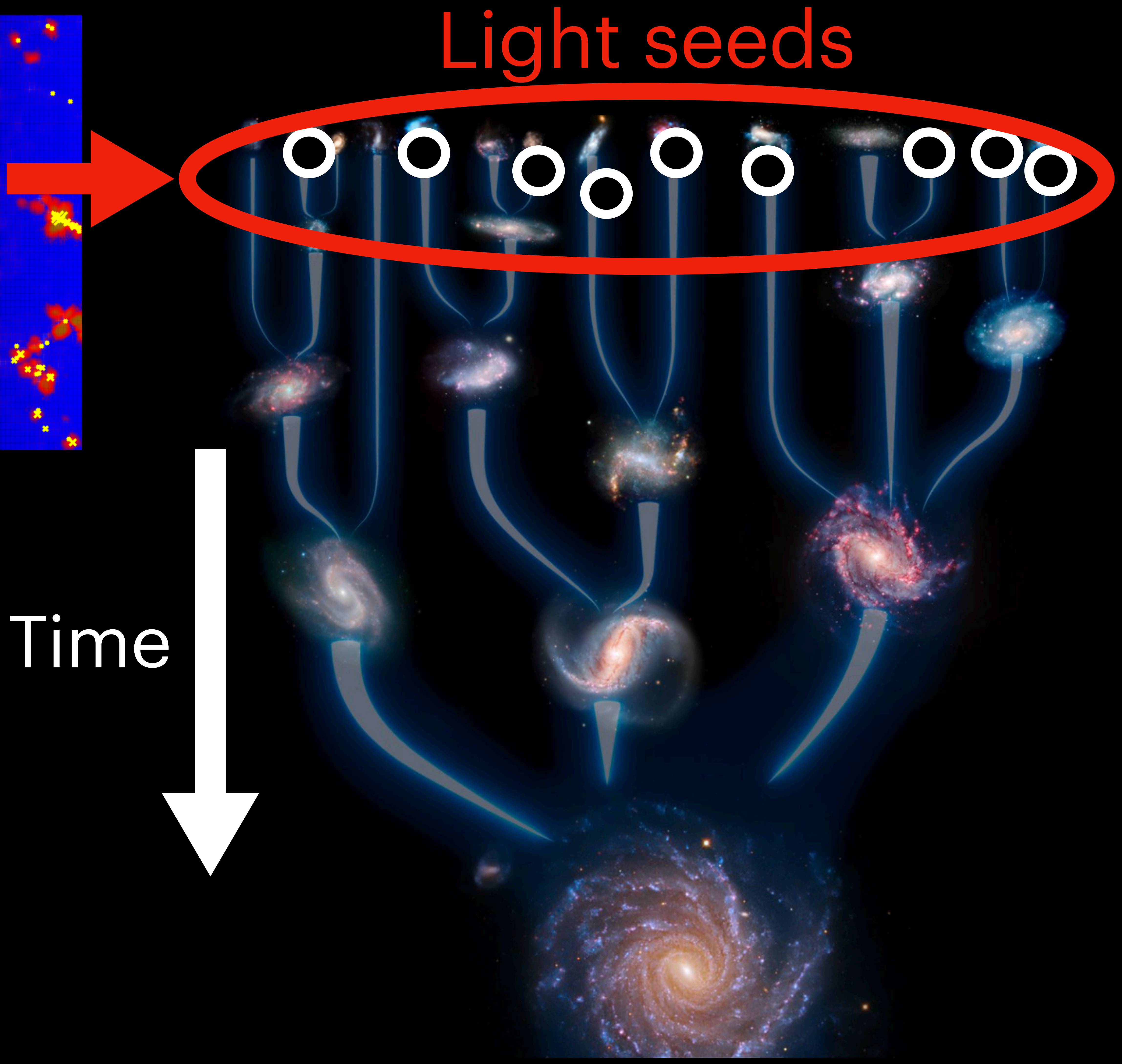
Smallest volume,
highest resolution

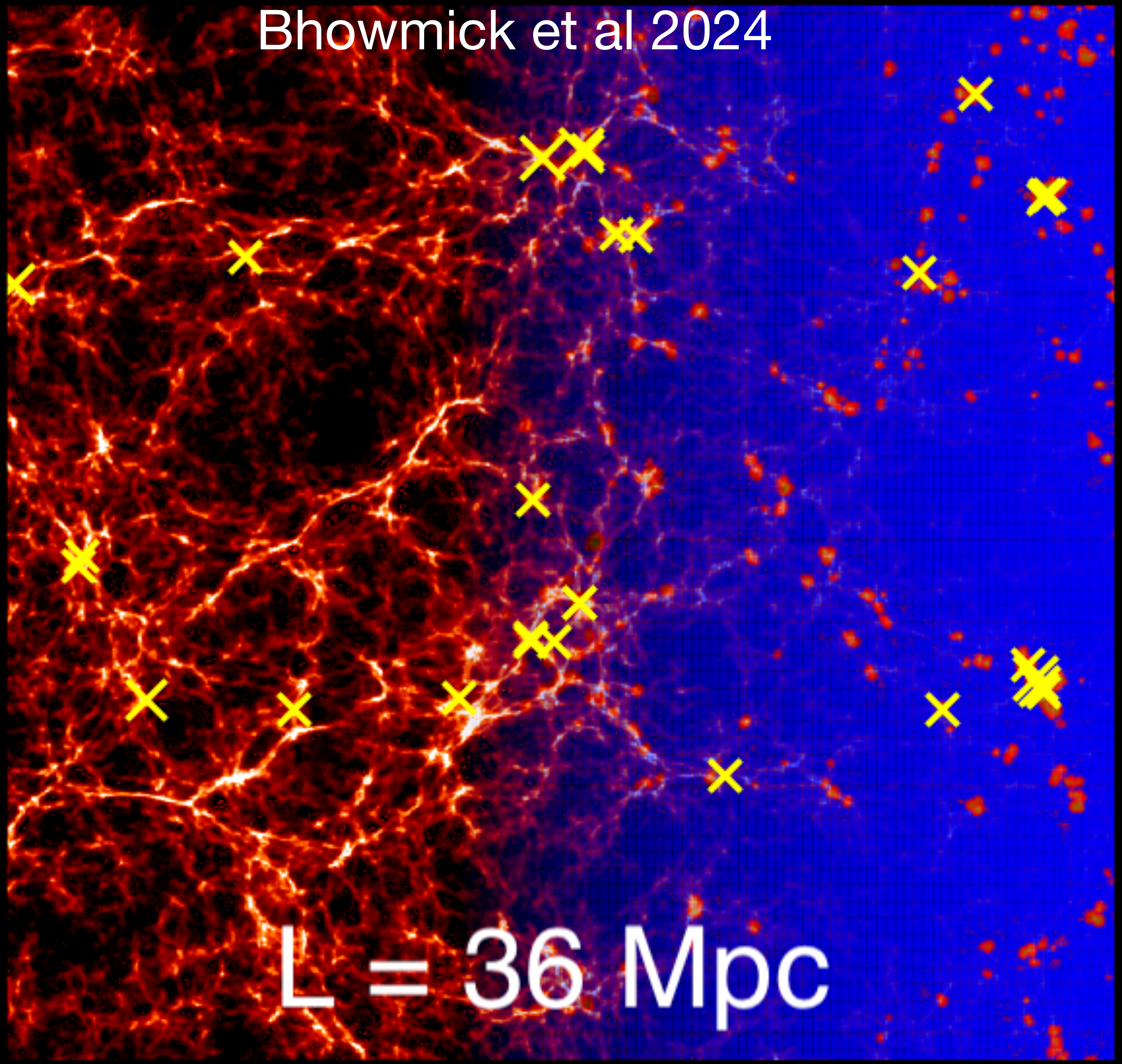


Bhowmick et al 2023

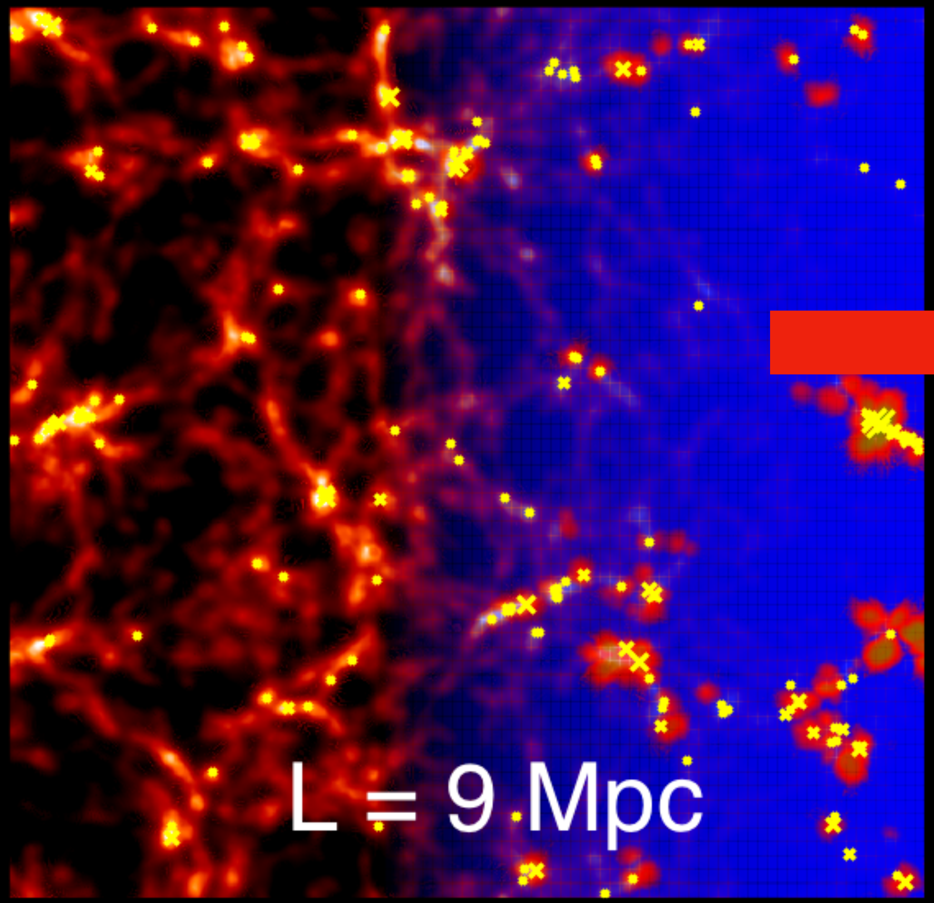
Following the growth of these low mass seeds along the 'evolution tree' of their host galaxies

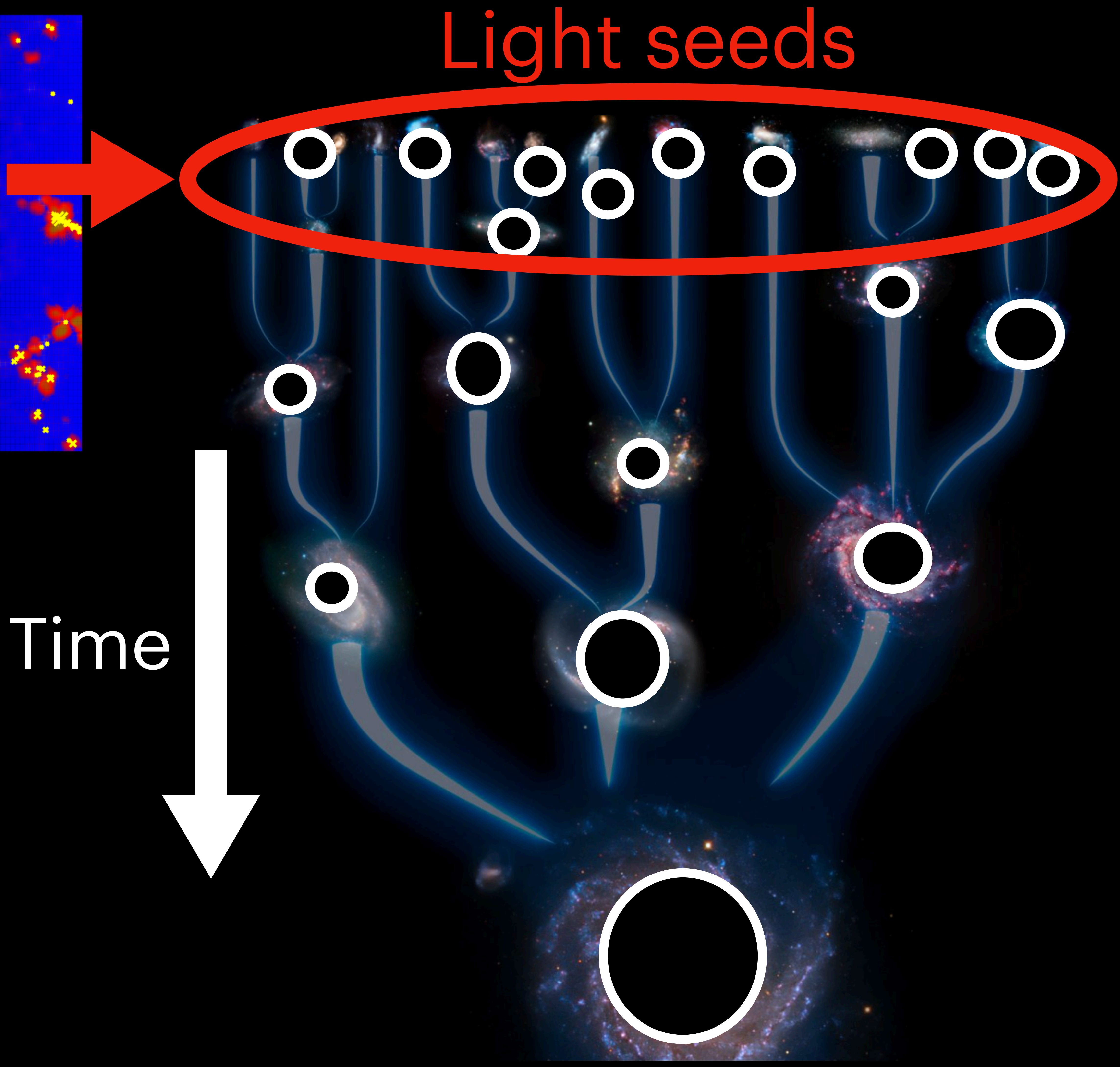


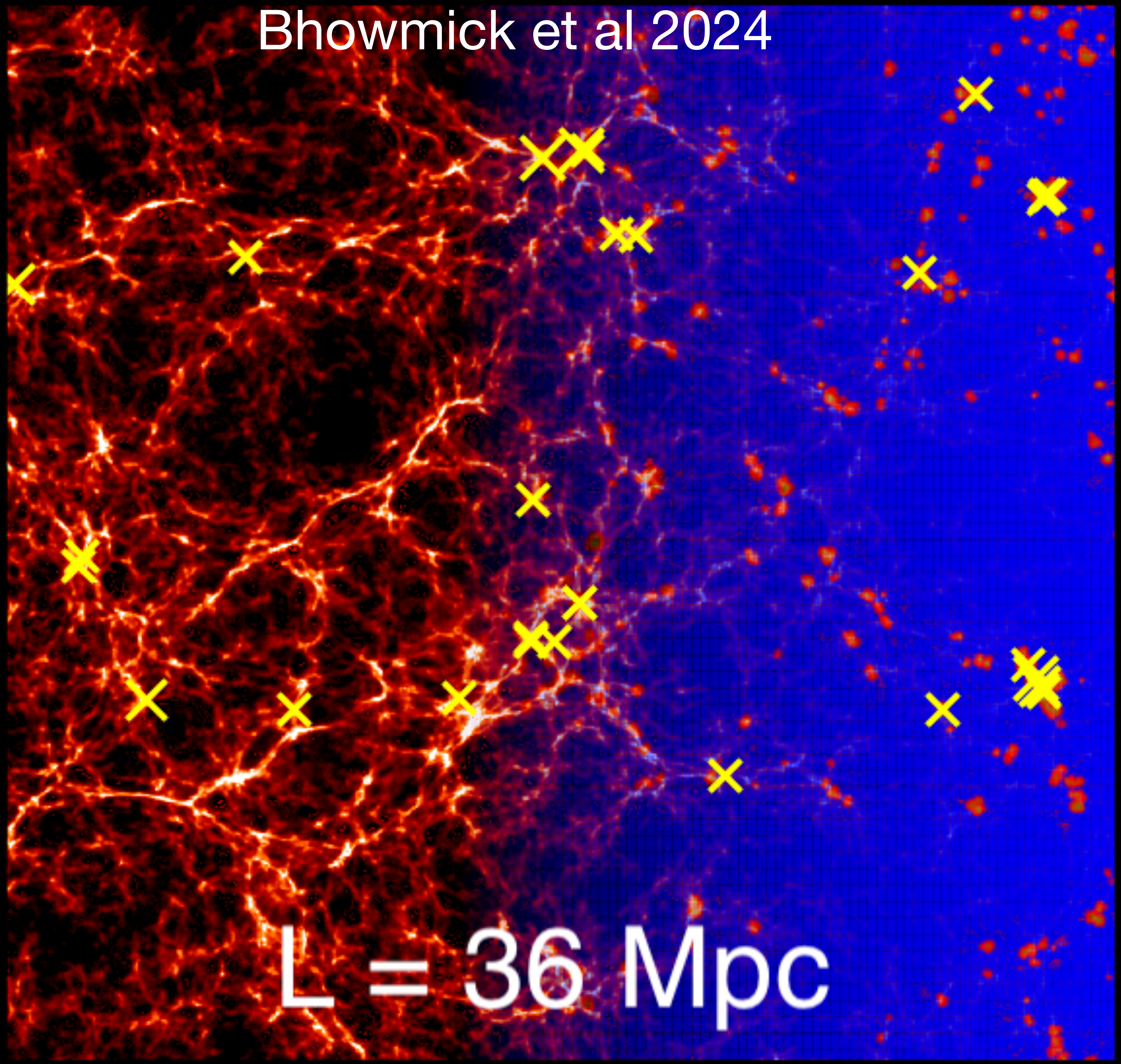




Tracing the galaxies wherein these low mass seeds assembled higher mass descendants





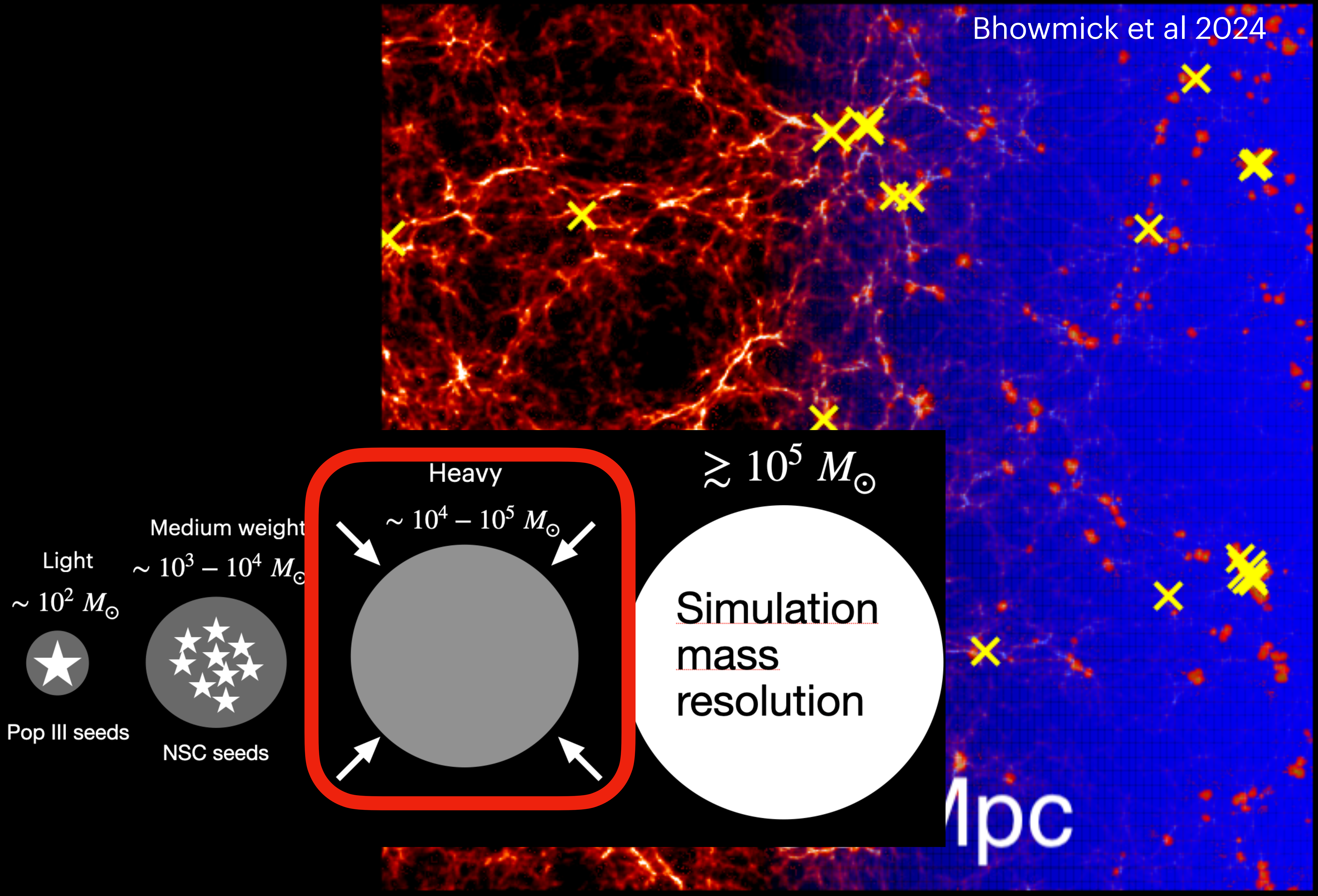


Seeding these descendants in the larger volume simulations

A new “stochastic seed model” to represent low mass seeds in larger cosmological volumes without the need to resolve them

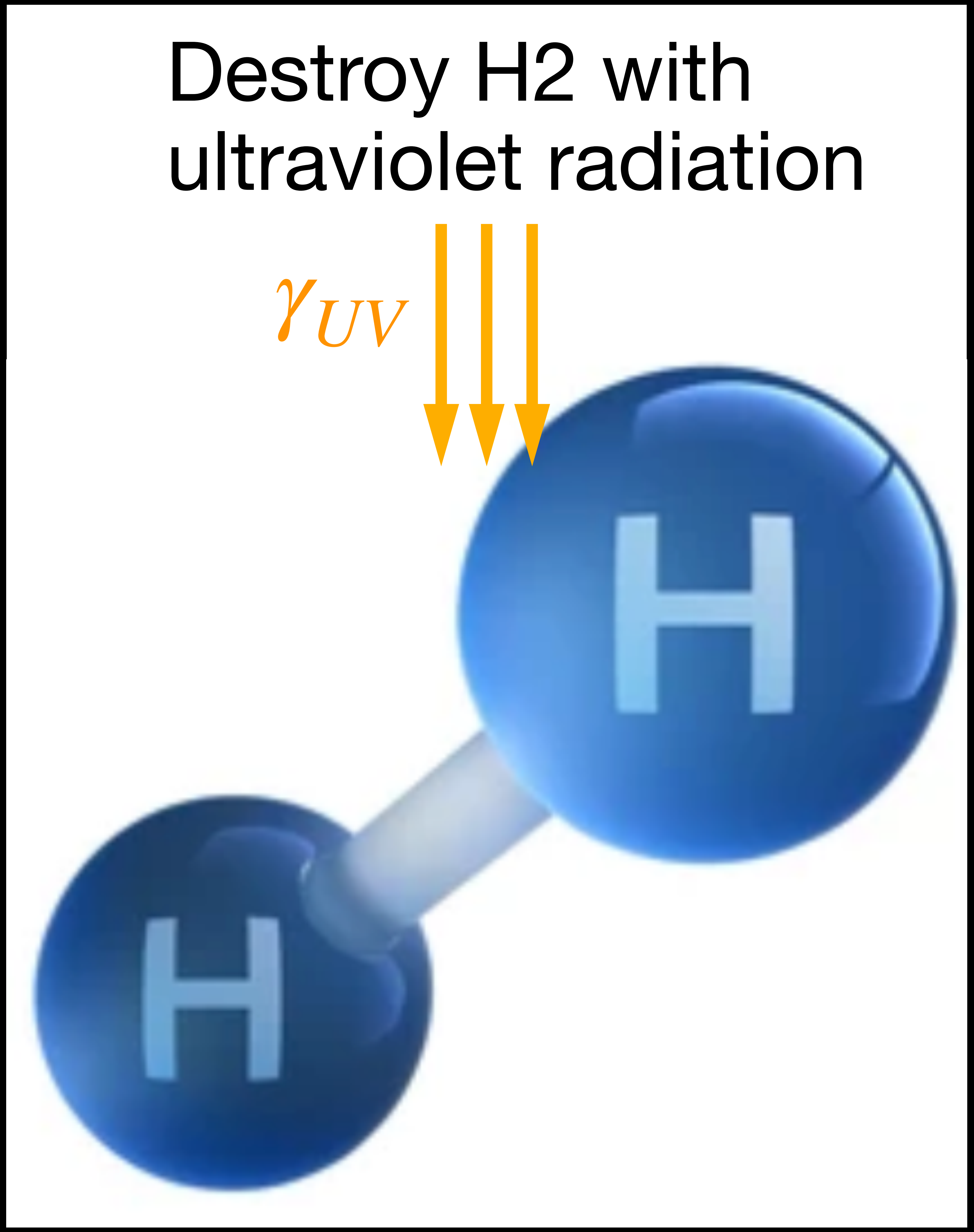
Bhowmick et al 2024a

How do we model heavy DCBH seeds in large cosmological simulations?



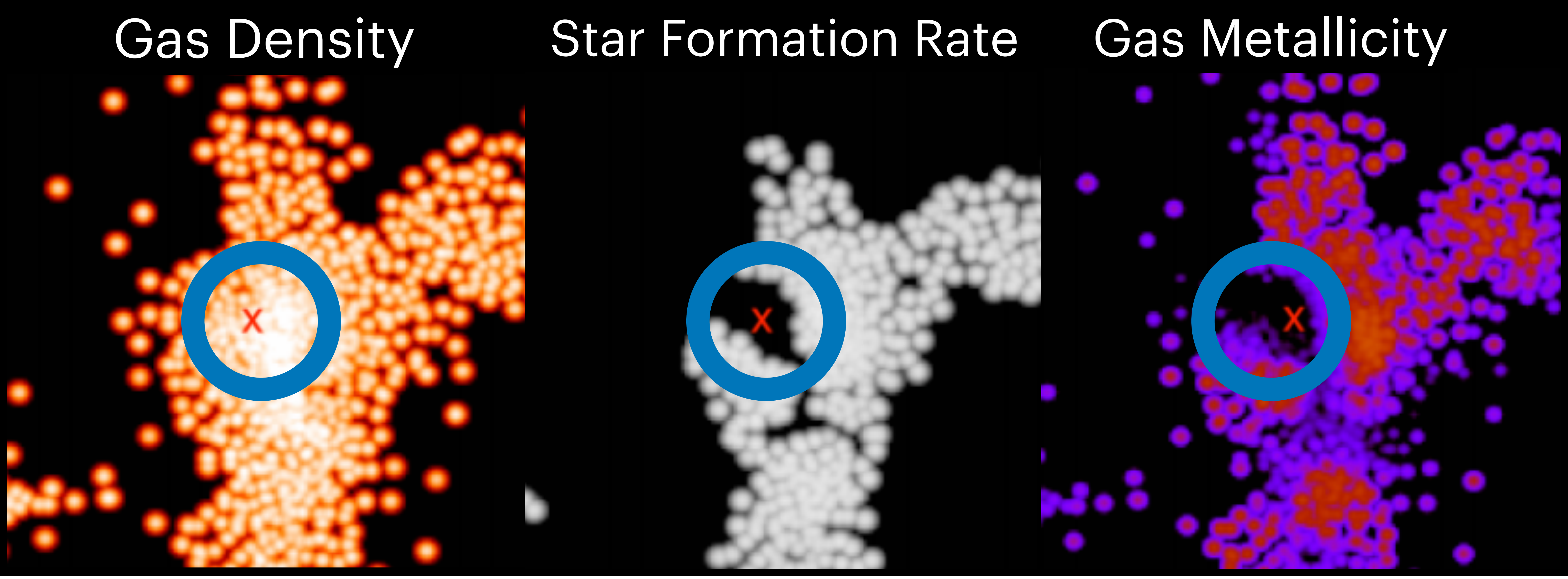
To model direct collapse black hole formation conditions

How to suppress molecular hydrogen cooling in pristine dense gas



I ensure that seeds are only forming in dense and metal poor gas pockets with sufficient UV radiation

DCBH heavy seed formation site



Bhowmick et al 2022a

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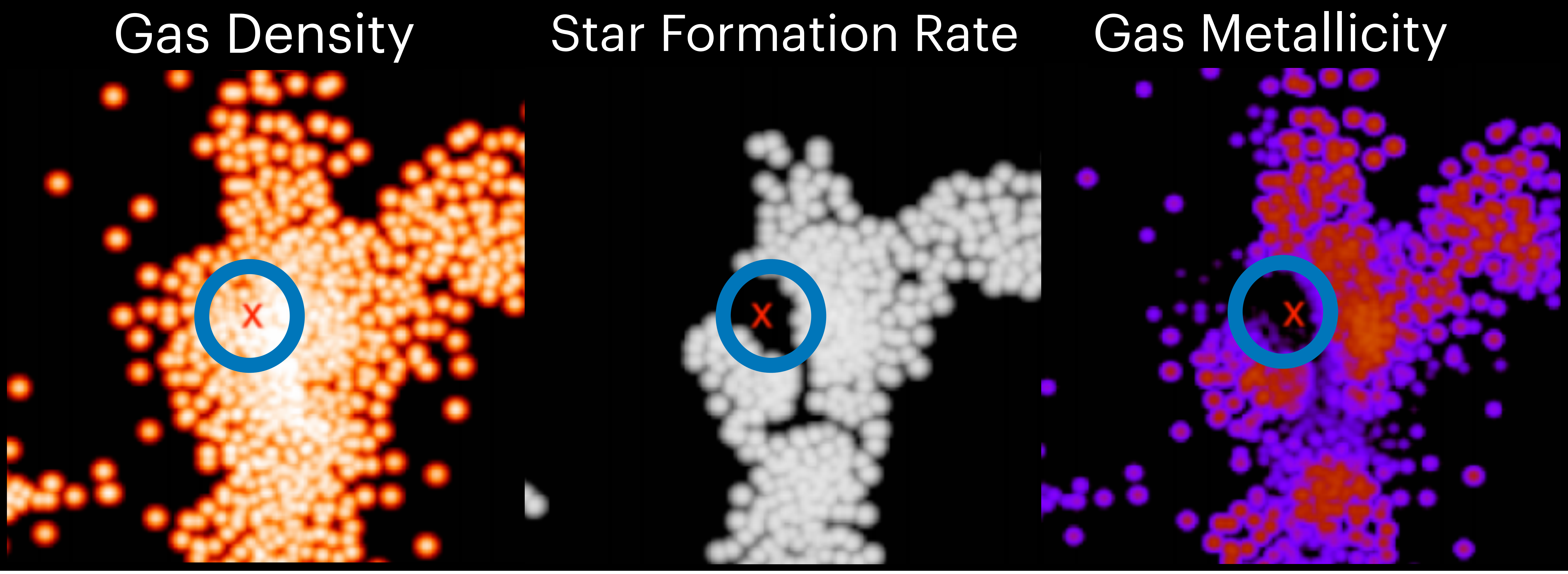
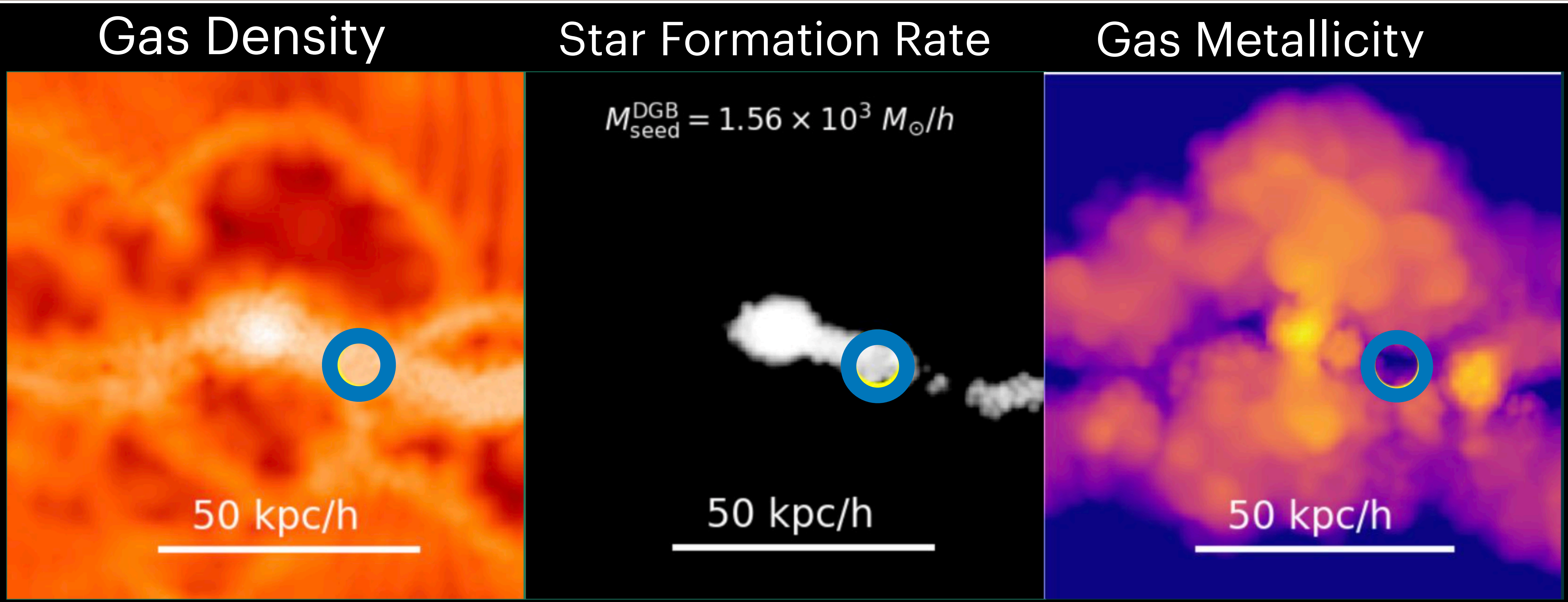
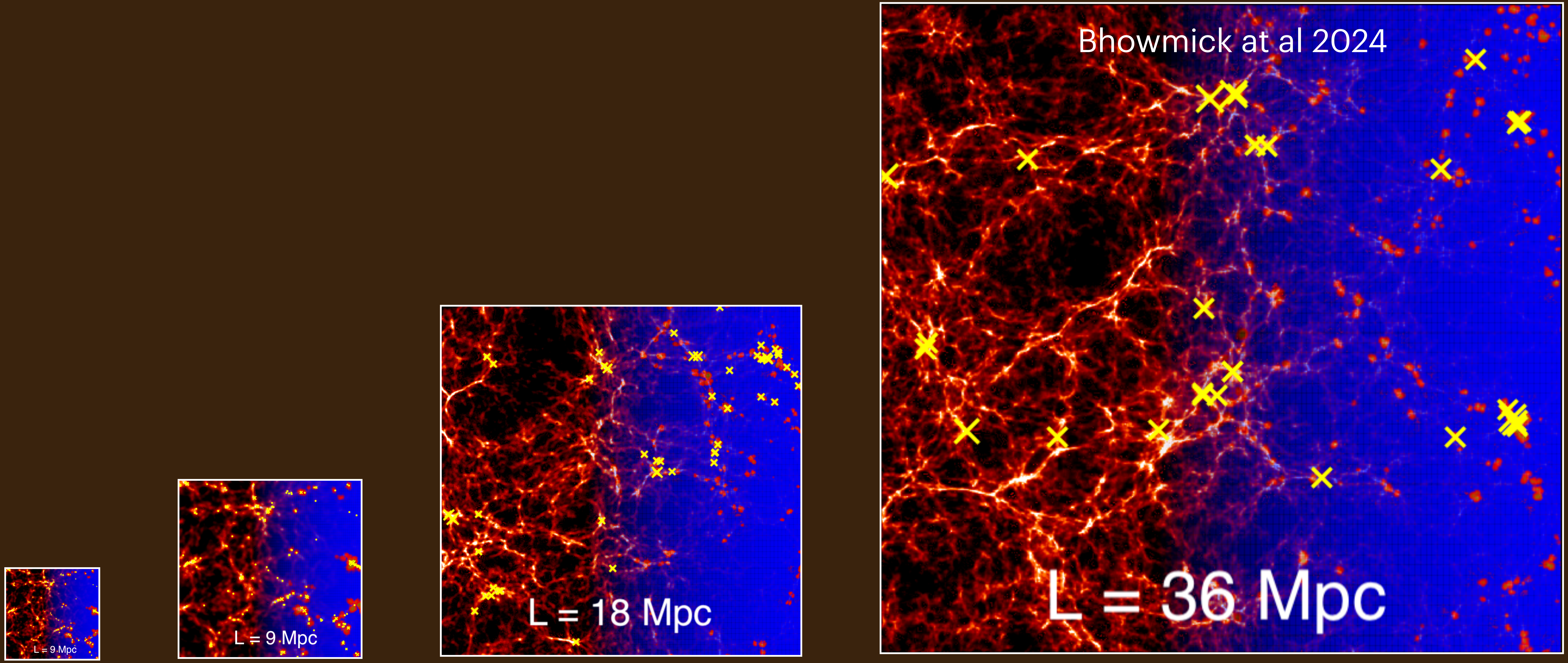


Bhowmick et al 2022a

Pop III or NSC seed formation site



BRAHMA simulations: Exploring the impact of black hole seeding in earliest supermassive black hole populations



Data to be made public soon!

Predictions from BRAHMA simulations

LISA
Laser Interferometer Space Antenna

WEBB
SPACE TELESCOPE

Intermediate-mass black hole populations with LISA

$\sim 10^3\ M_\odot$ BHs mergers rates: Light seed model predictions

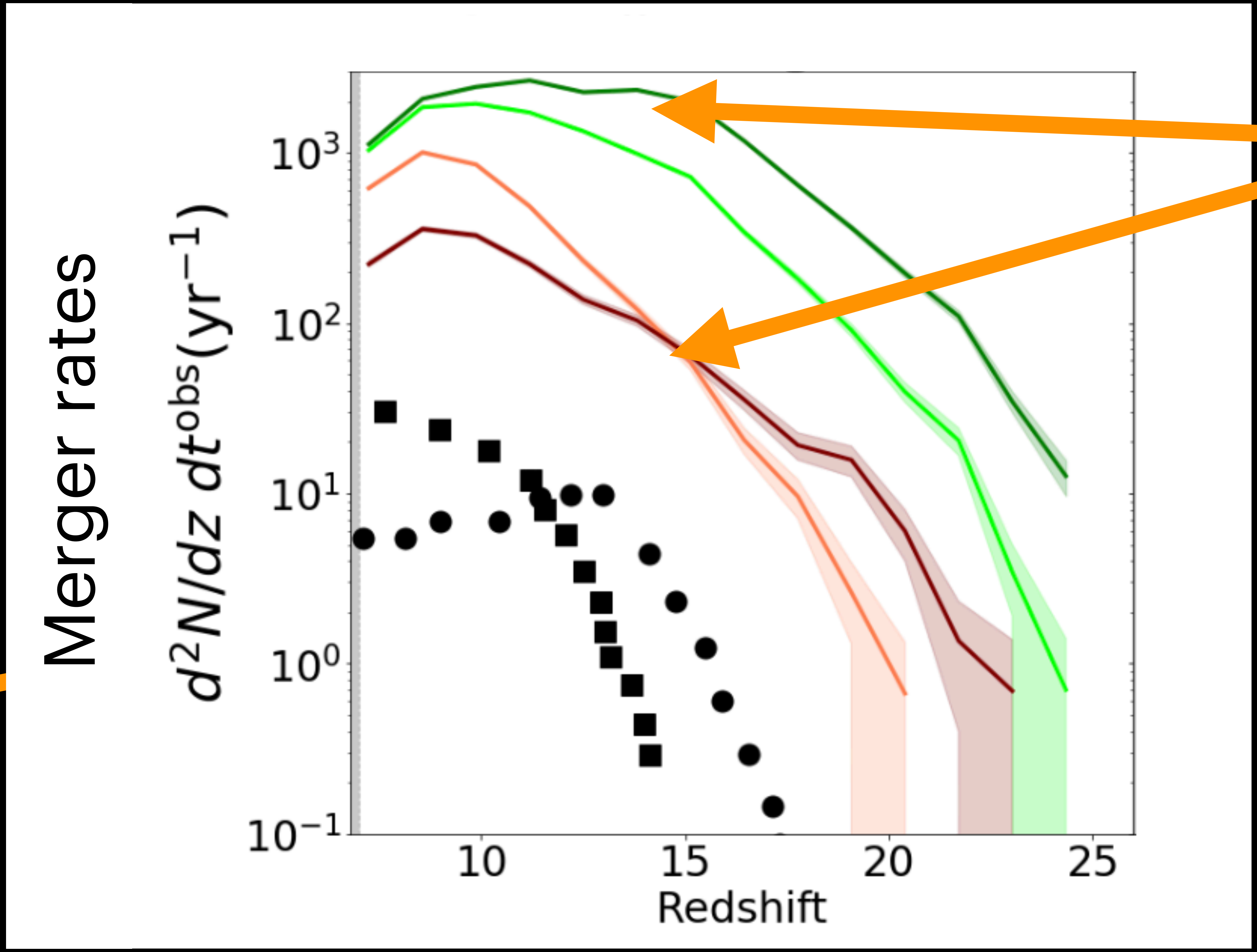
Caveat assumption: For every galaxy merger, there is a black hole merger

My predictions

~200—2000 events per year

Upper limits for LISA event rates

Previous literature

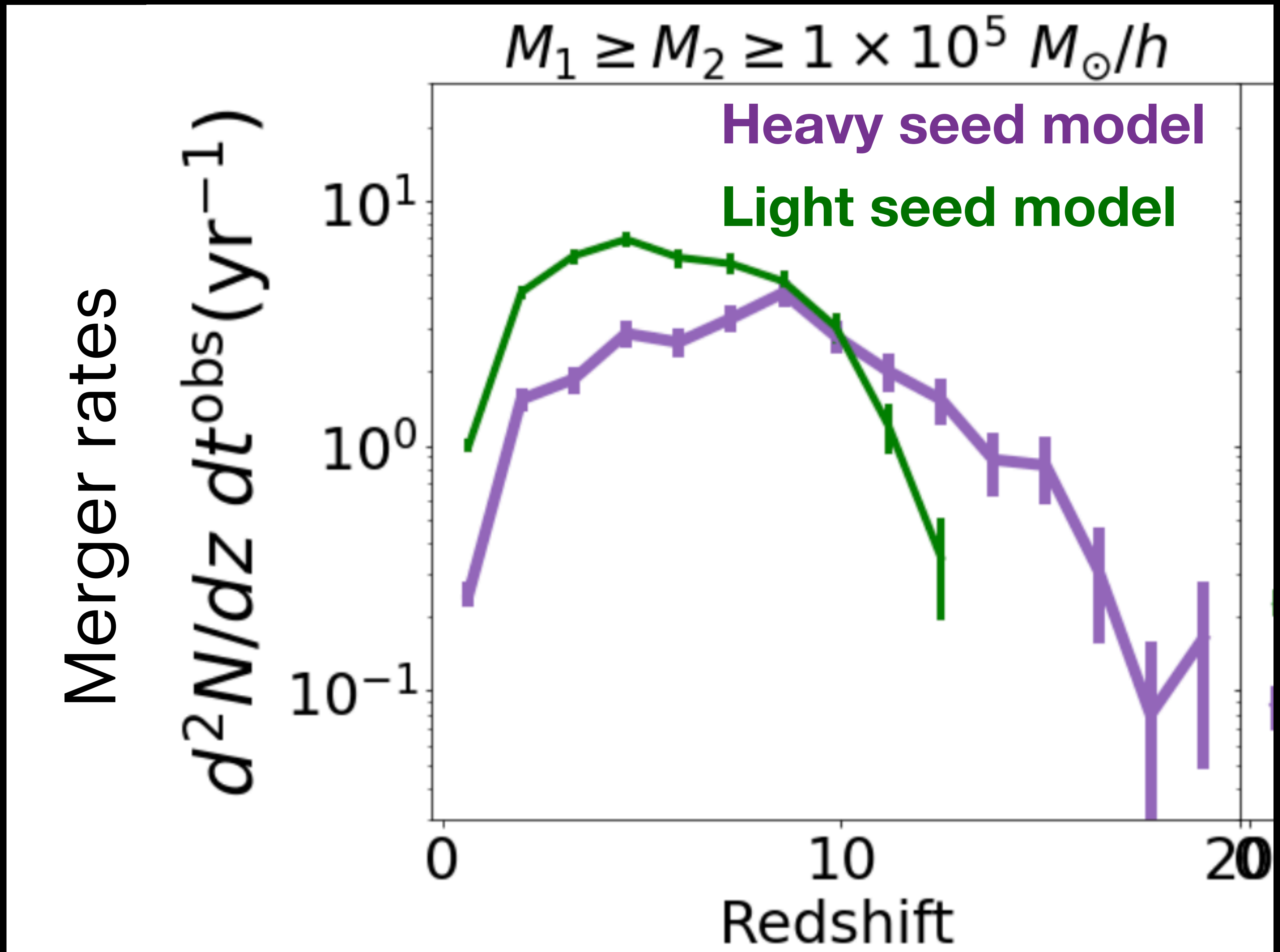


Bhowmick et al 2024

Intermediate-mass black hole populations with LISA

$\sim 10^5\ M_\odot$ BH mergers rates : Light vs heavy seed model predictions

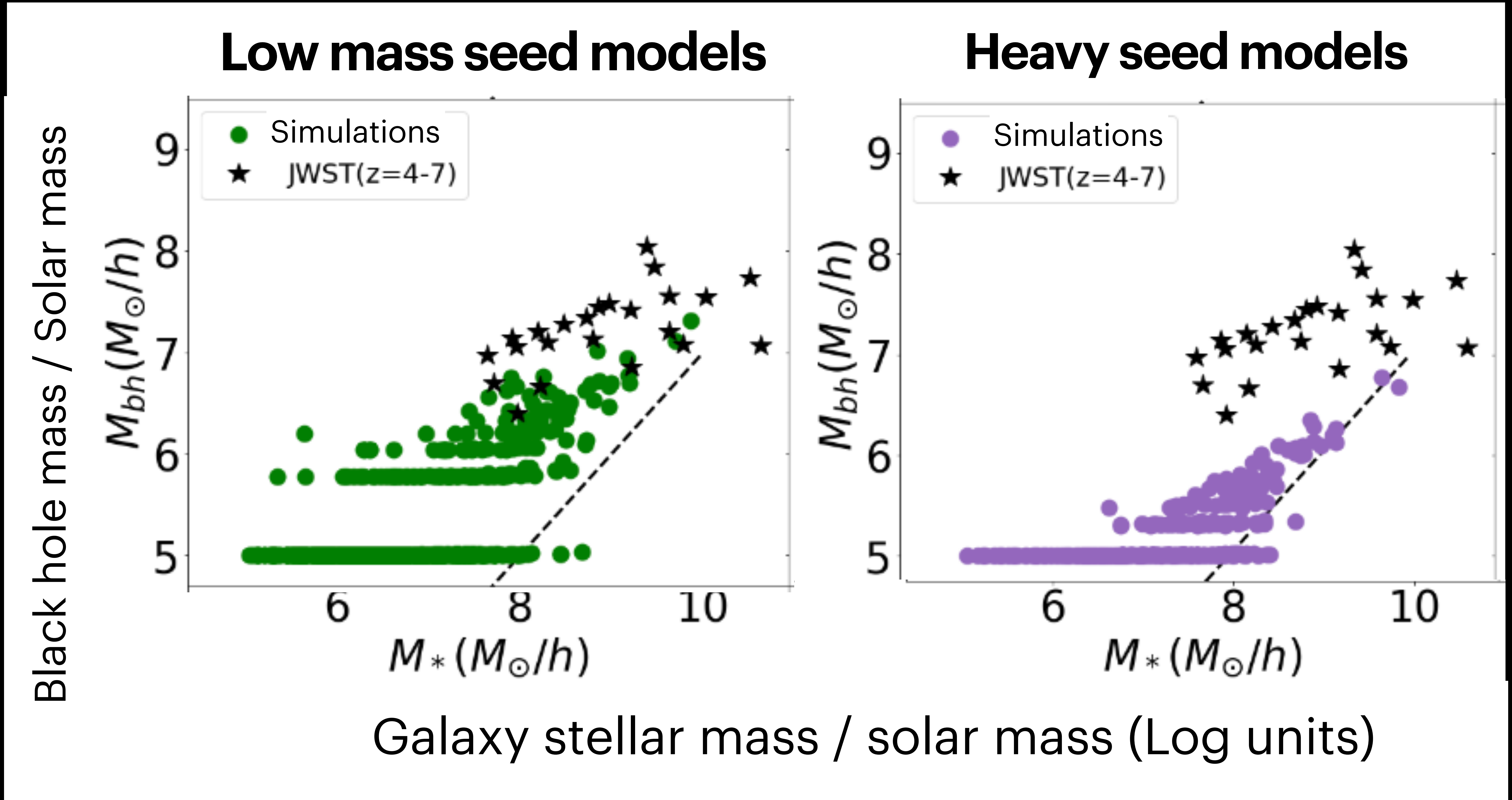
Descendant of a low mass seed	**VS**	**Formed as a heavy seed**



Bhowmick et al 2024

Distinct imprints of light vs heavy seeds in the LISA event rates

Supermassive black hole populations with JWST



Low mass seed models can reproduce the JWST observations

Heavy seed models cannot reproduce the JWST observations

Bhowmick et al 2024

Main takeaways from past research

1) Transforms our ability to model the formation of black holes in cosmological simulations.

2) Predicts unique observable signatures of different black hole formation theories within gravitational-wave and electromagnetic observations from LISA and JWST

3) Lays the foundation for my future research on early black hole evolution

Future Research (5 yr horizon): Confront every aspect of the earliest black hole evolution

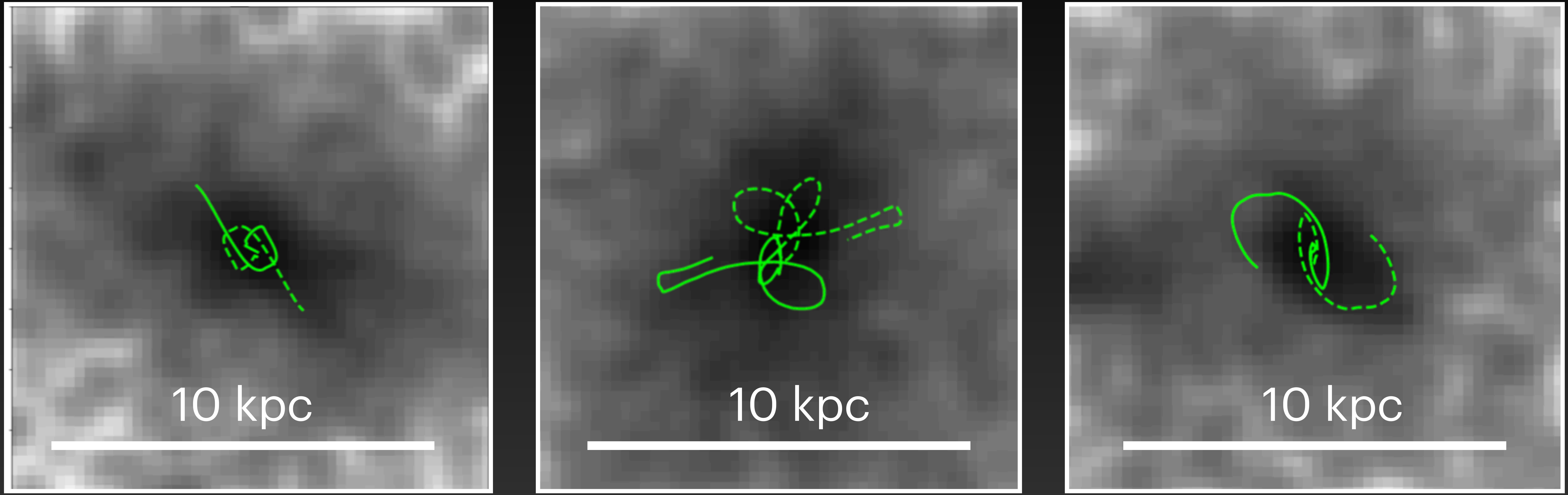
Black hole seeding

Black hole dynamics

Black hole accretion

Black hole feedback

Step 1: Dynamics of merging black hole seeds

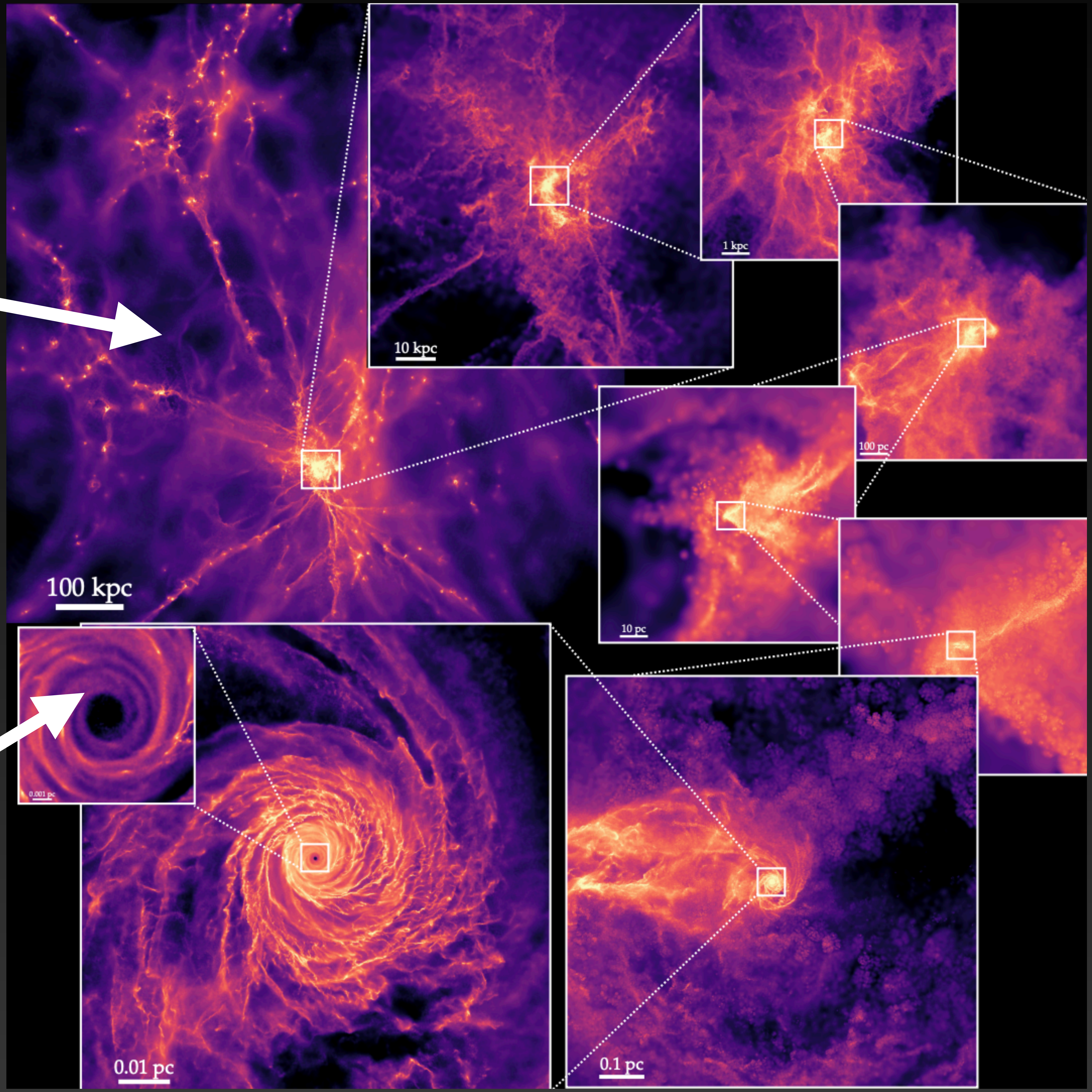


Bhowmick et al (ongoing)

What fraction of seeds can effectively merge and contribute to LISA events?

Step 2: Gas accretion onto black hole seeds

~1000 kpc scales
Galaxy cluster



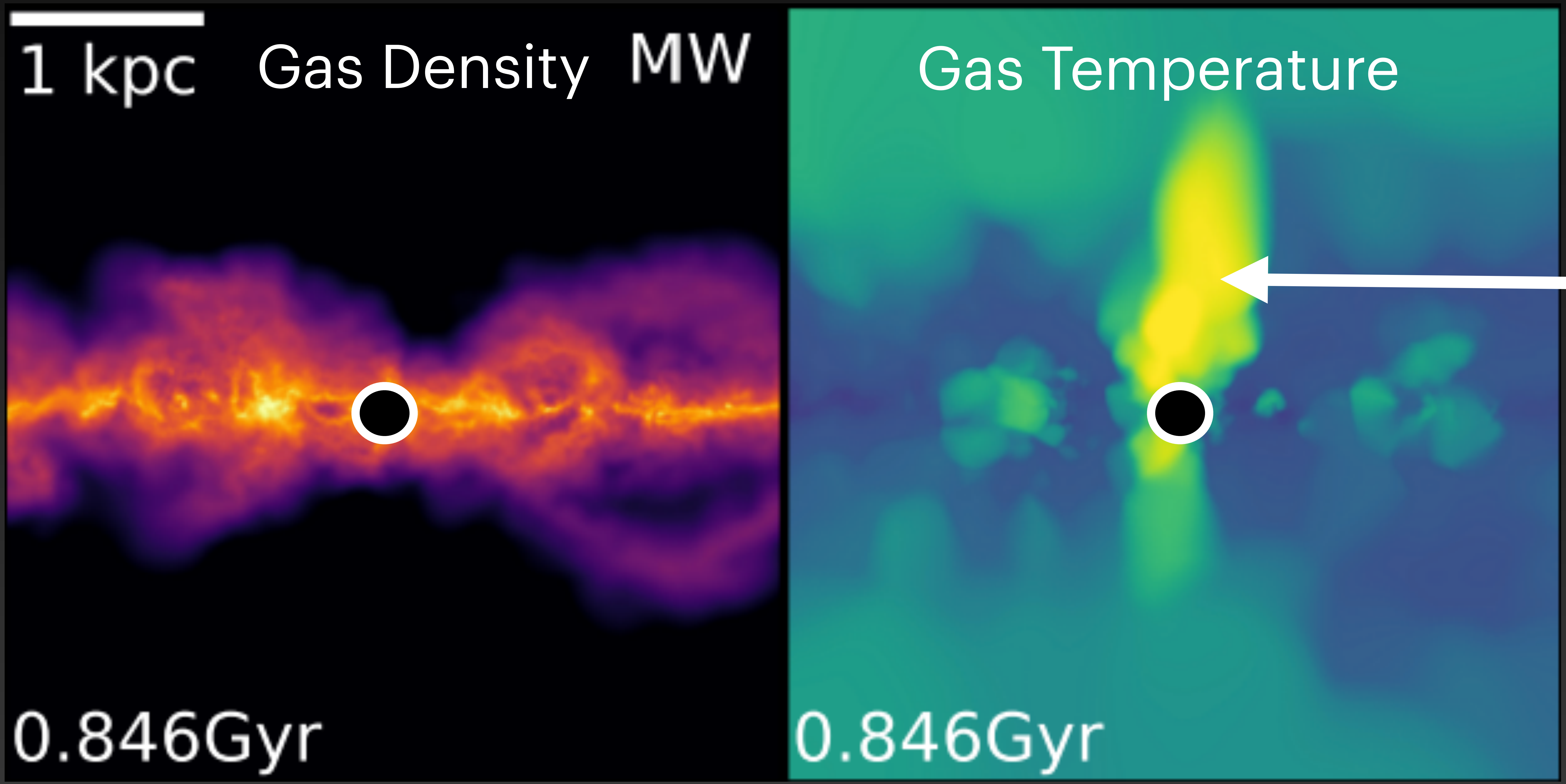
~0.01 pc scales
Accretion disk of a supermassive black hole

Hopkins et al 2023

Step 3: Black hole feedback

How do black hole seeds interact with earliest galaxies?

Milky-way galaxy simulation



Sivasankaran et al 2024

Black hole injecting energy and heating the gas

Future Outlook (5 yr horizon): Confront every aspect of supermassive black hole physics

Future Outlook (10 yr horizon)

Physics of dark energy and dark matter

Physics of the baryons

Physics of the black holes

Observed black hole and galaxy populations

Conclusions

- The missing origins of supermassive black holes is a crucial component for understanding our Universe?
- Using cosmological simulations, I have built the necessary foundation to reveal the missing supermassive blackhole origins from current and future observations?
- My research propels me towards future initiatives and broader questions about black hole evolution, and about the fundamental components of Universe in the longer run.

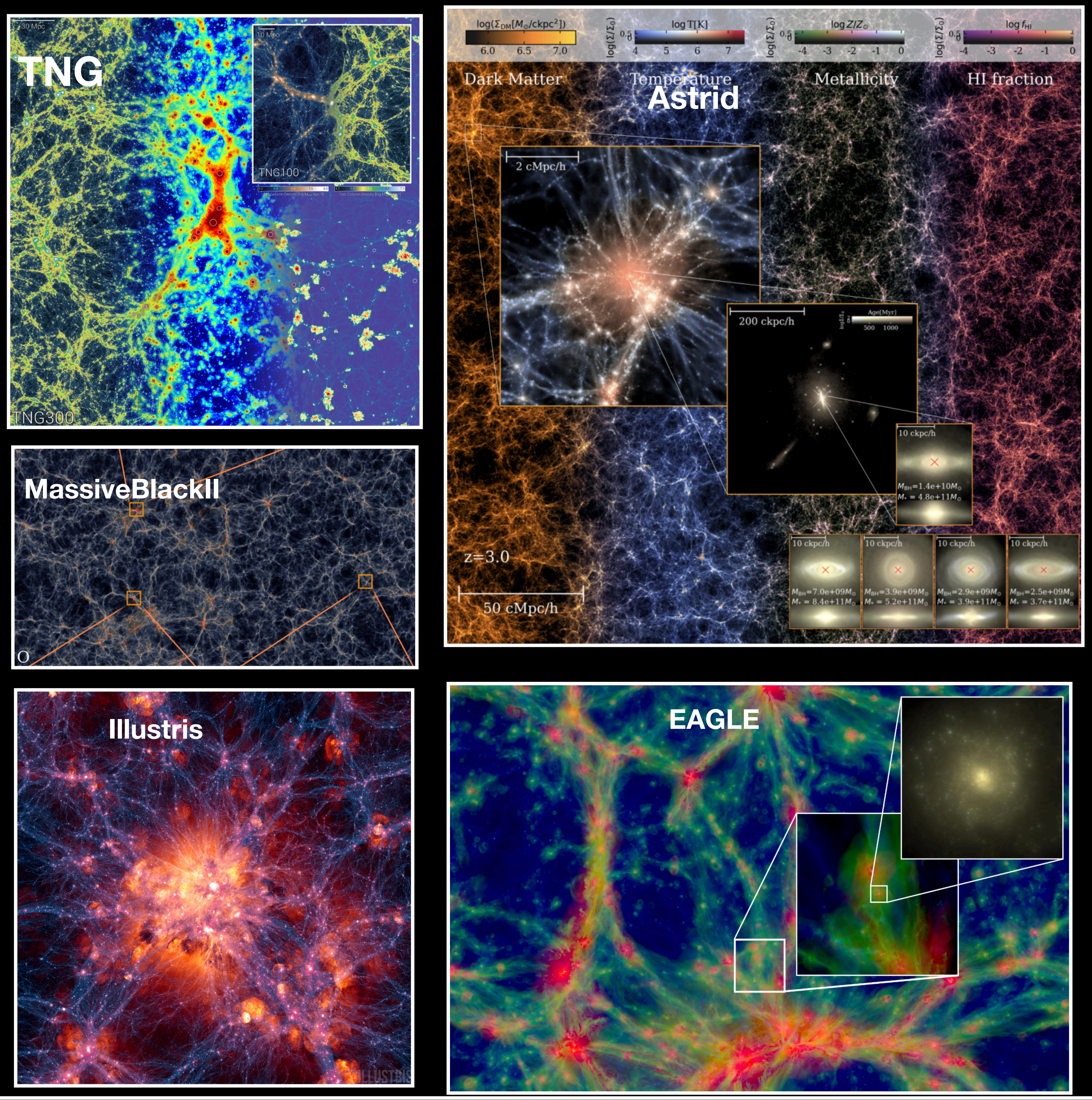
BACK UP SLIDES

Leveraging the golden age of AI and machine learning

I will confront our entire structure formation paradigm with all available observations

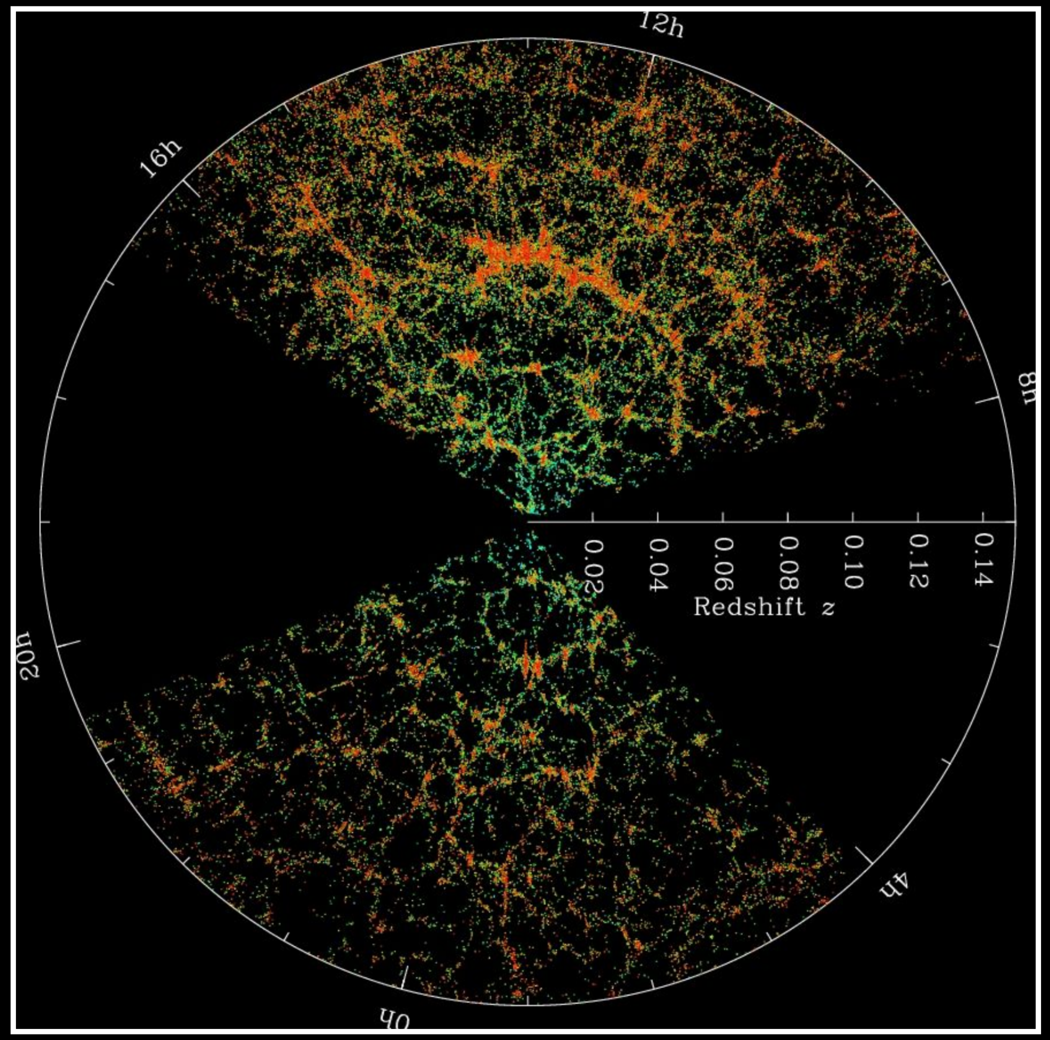
Training and testing data

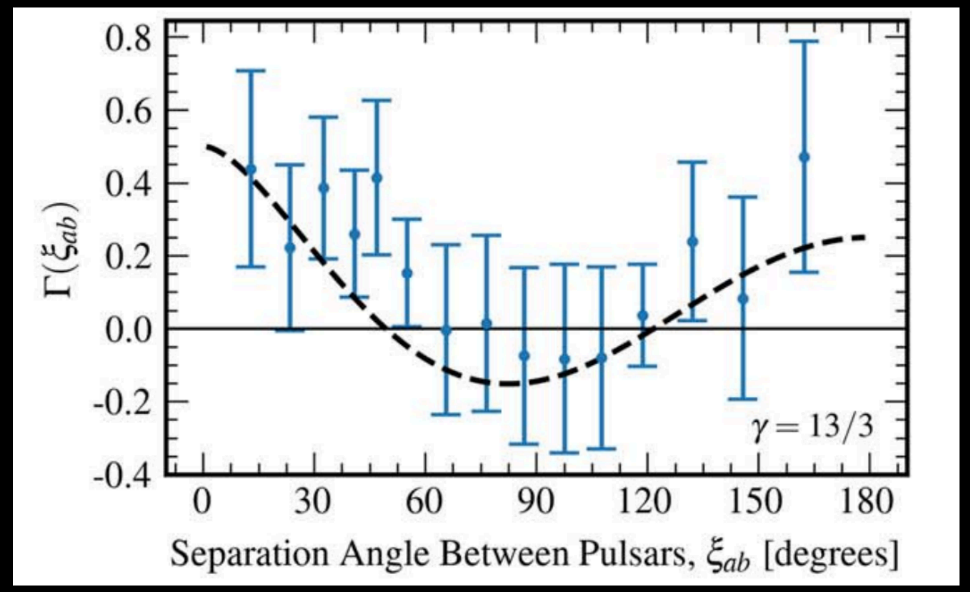
Large suite of cosmological simulations with systematic variations in unknown physics parameters

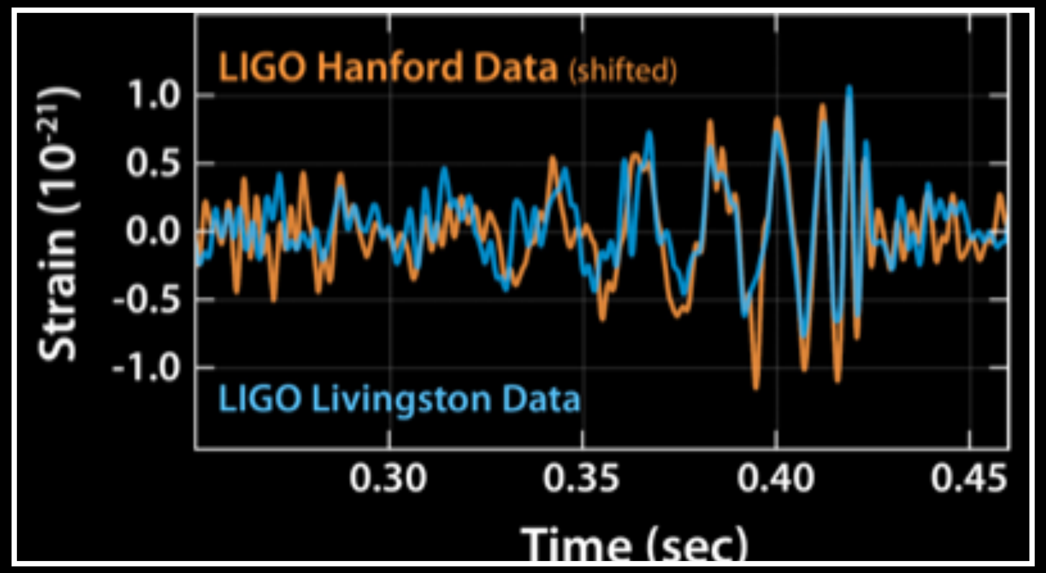


Deployment data

Multi-messenger, multi-epoch and multi-wavelength observations of galaxy and black hole populations

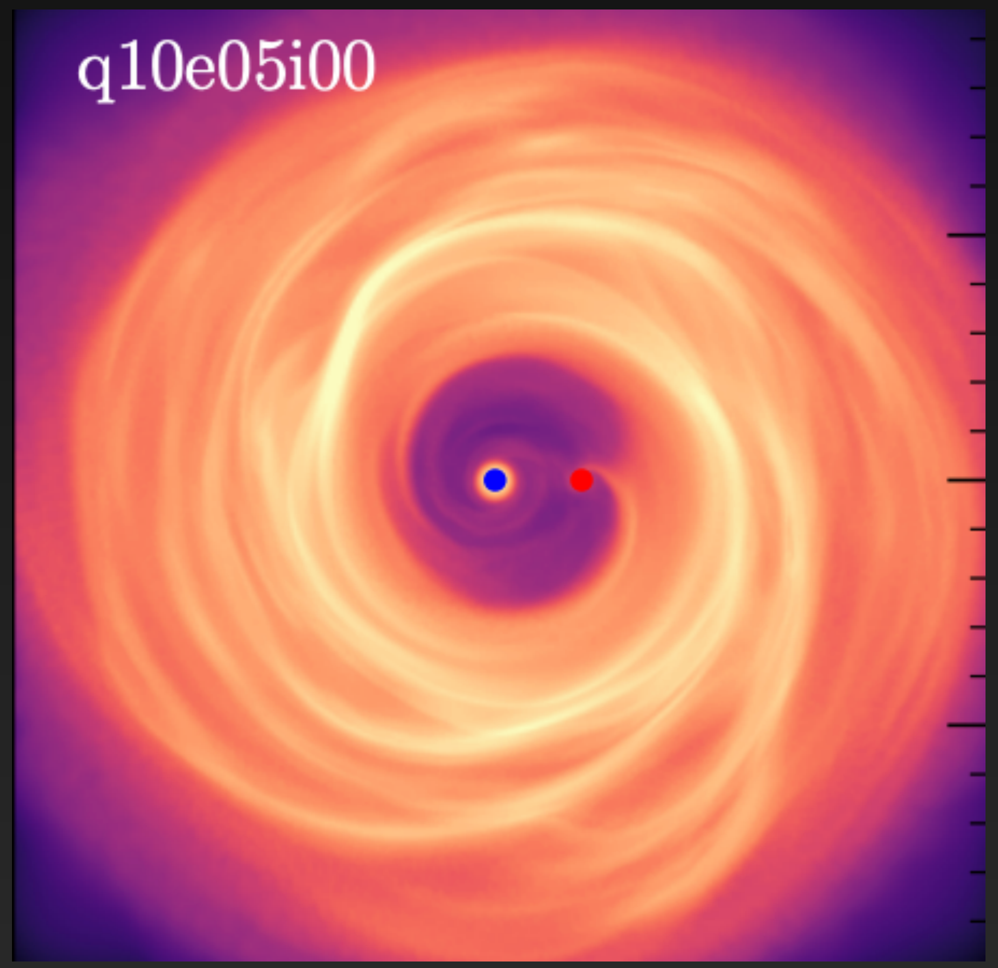






Future Outlook (5 yr horizon): Confront every aspect of supermassive black hole physics

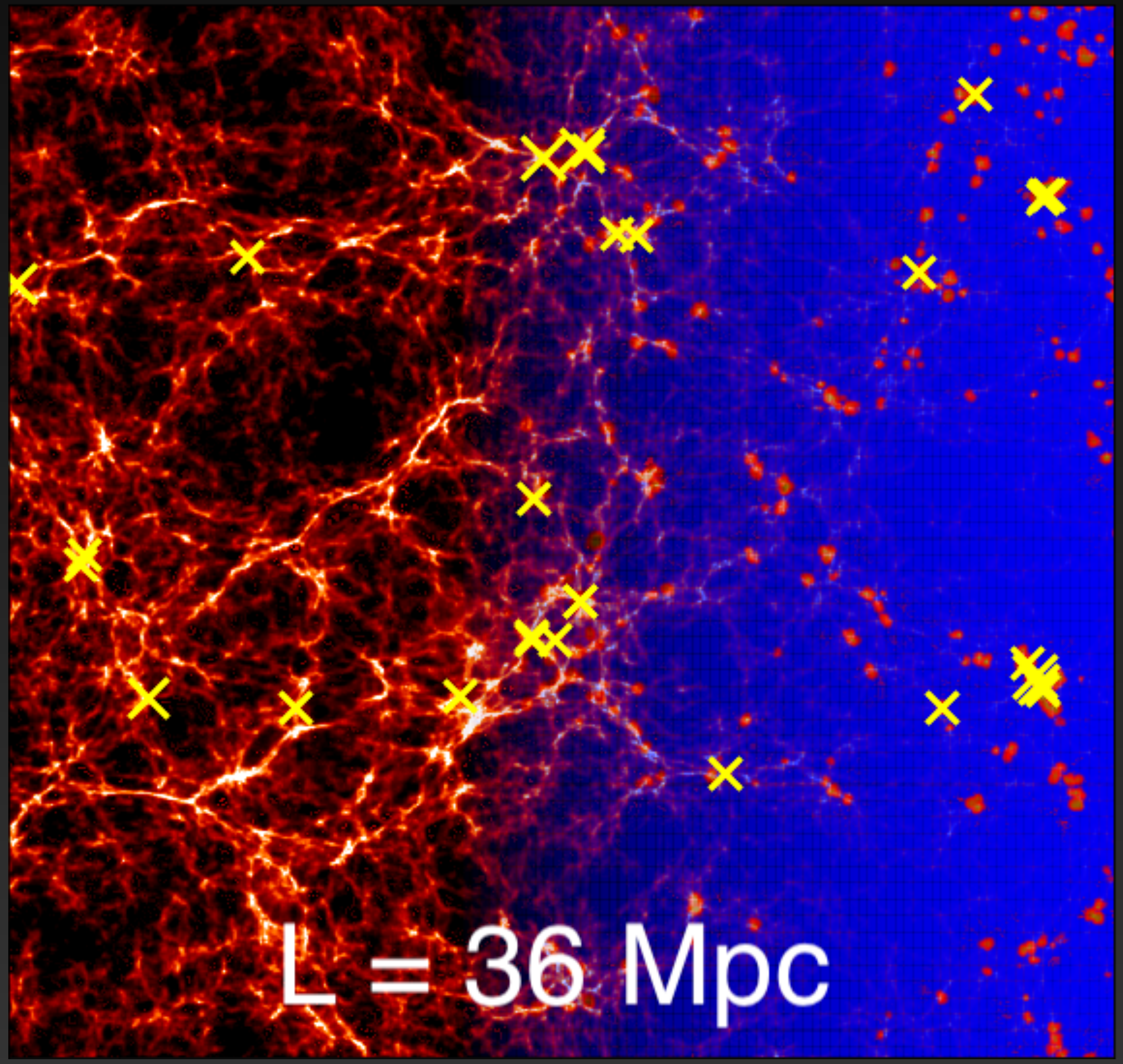
Bourne et. al. 2023



20 Pc

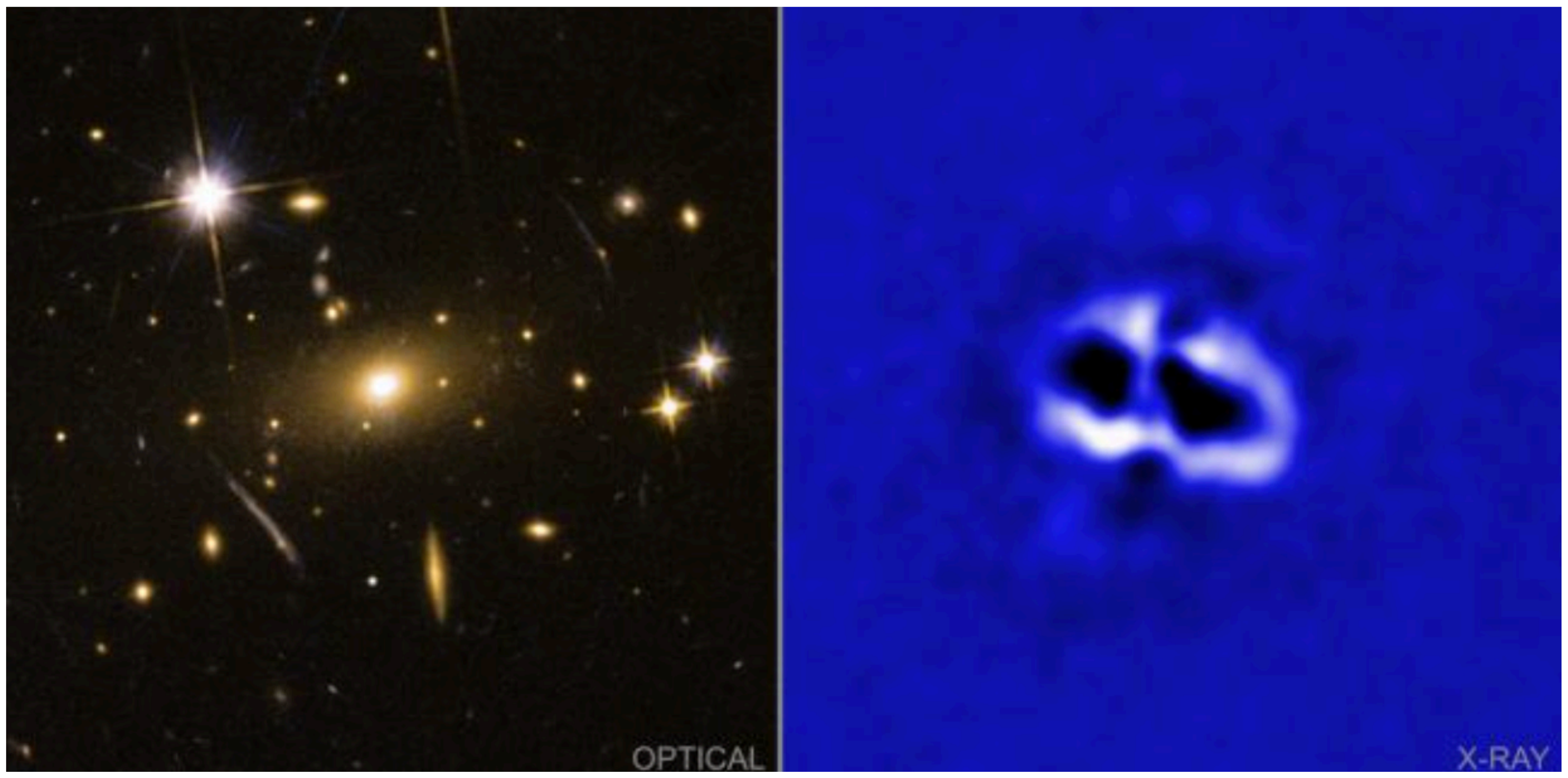
Imprint the impact of small scale physics in the modeling of large scale simulations

Bhowmick et al 2024



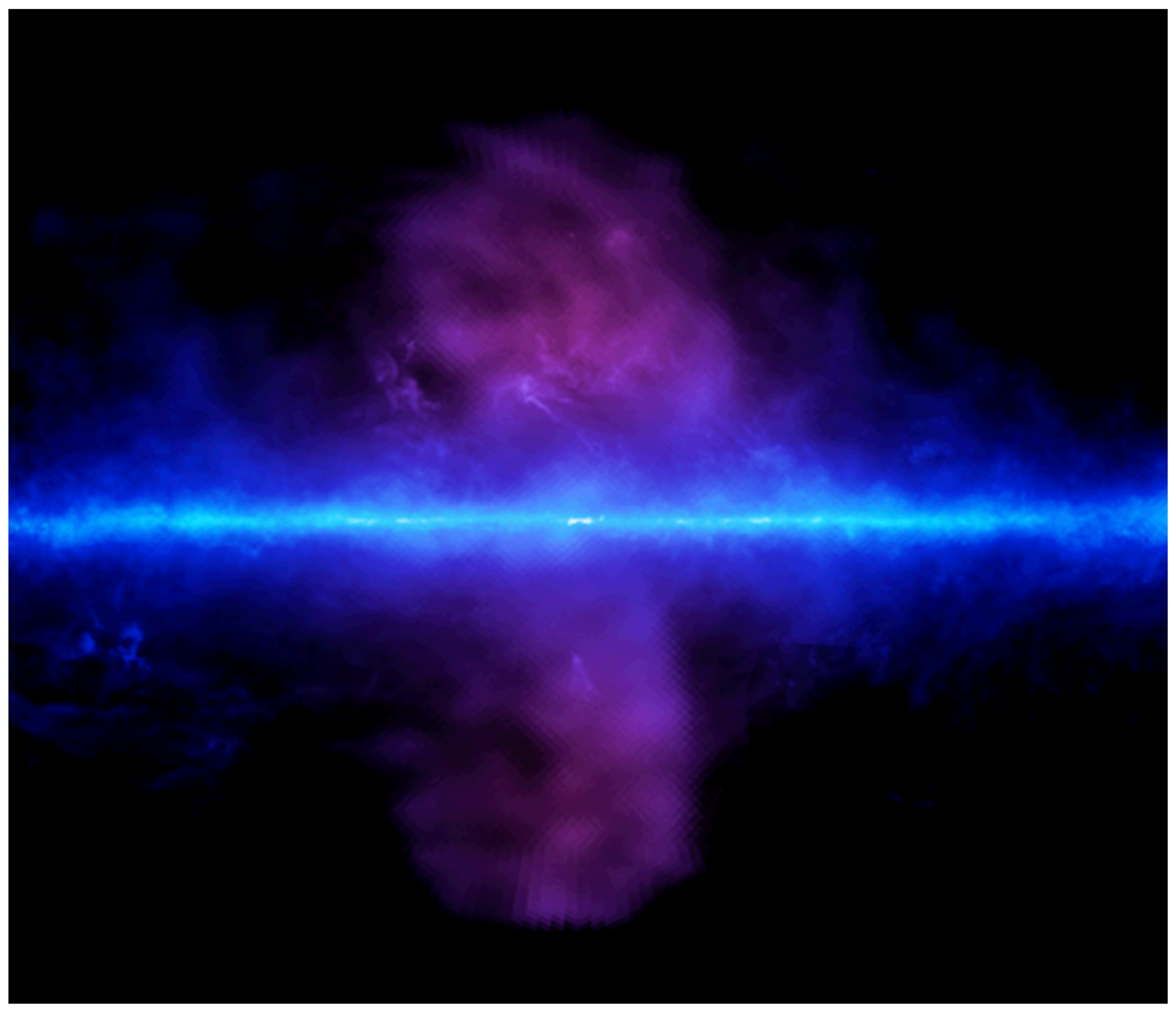
Observational support for the impact of supermassive black holes in their surrounding larger scale environment

X ray cavities in clusters



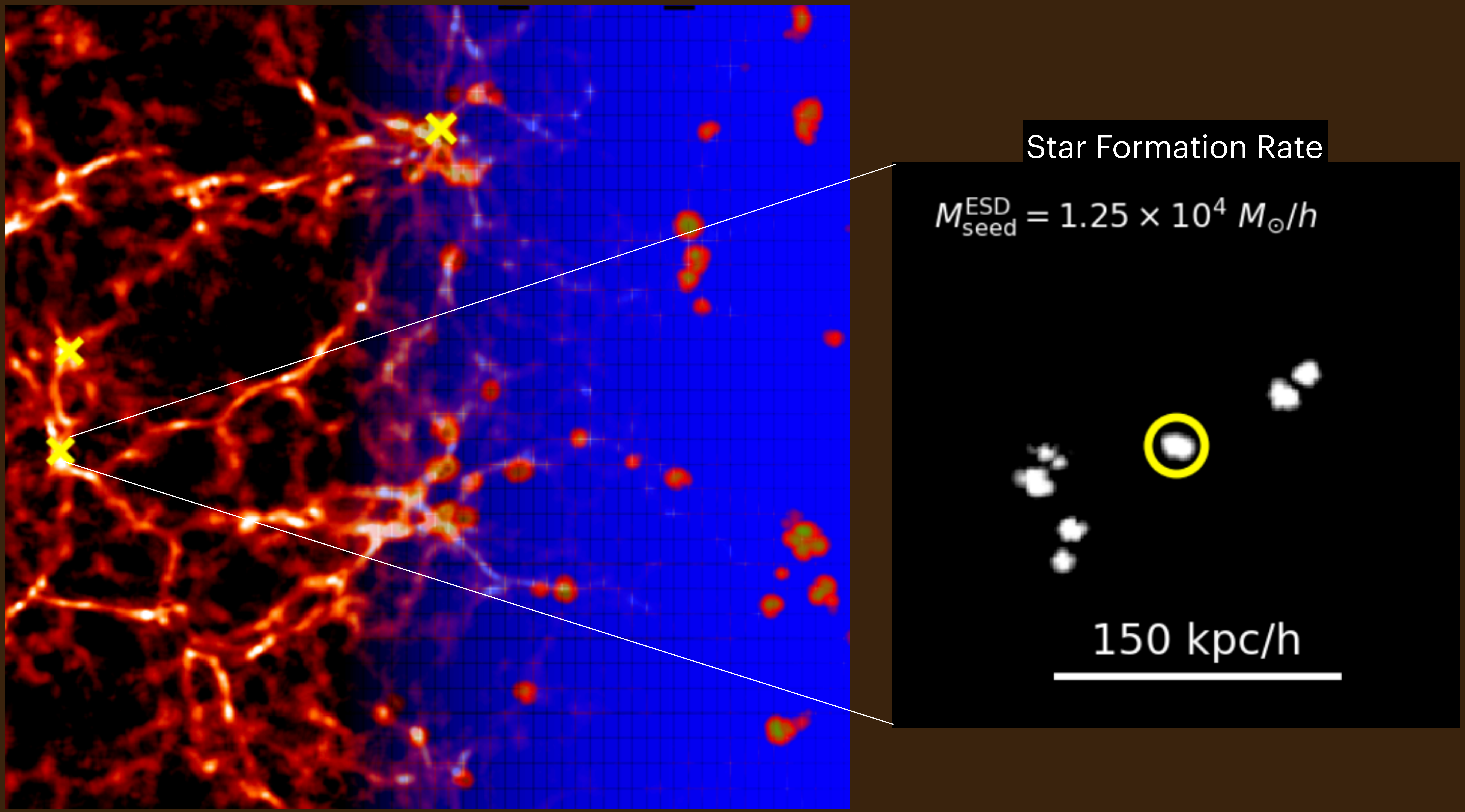
NASA / CXC / University of Bologna / F. Ubertosi / STScl / M. Calzadilla / NSF / NRAO / ALMA

Fermi bubbles in the Milky Way



Supermassive black holes may be major players in the evolution of the Universe

To model the impact of dynamical heating, DCBHs are seeded in rich environments with multiple neighboring galaxies



Theories of seed black hole formation

Theories of seed black hole formation

Jeans' instability: Gravity vs Thermal pressure

Segments of the cloud will collapse if it exceeds the Jeans' Mass $M_J \propto T^{3/2}$

Higher gas temperatures

↓

Higher Jeans' masses

↓

Higher mass seeds

How do the seed black holes form?

Jeans' instability criterion of a segment of gas cloud of mass M and temperature T.

The cloud will collapse if it exceeds the Jeans' Mass $$M_J \propto T^{3/2}$$

Typical gas cloud

Low Temperature, 10-30 K

Ordinary star formation,
stellar mass black holes

Theories of seed black hole formation

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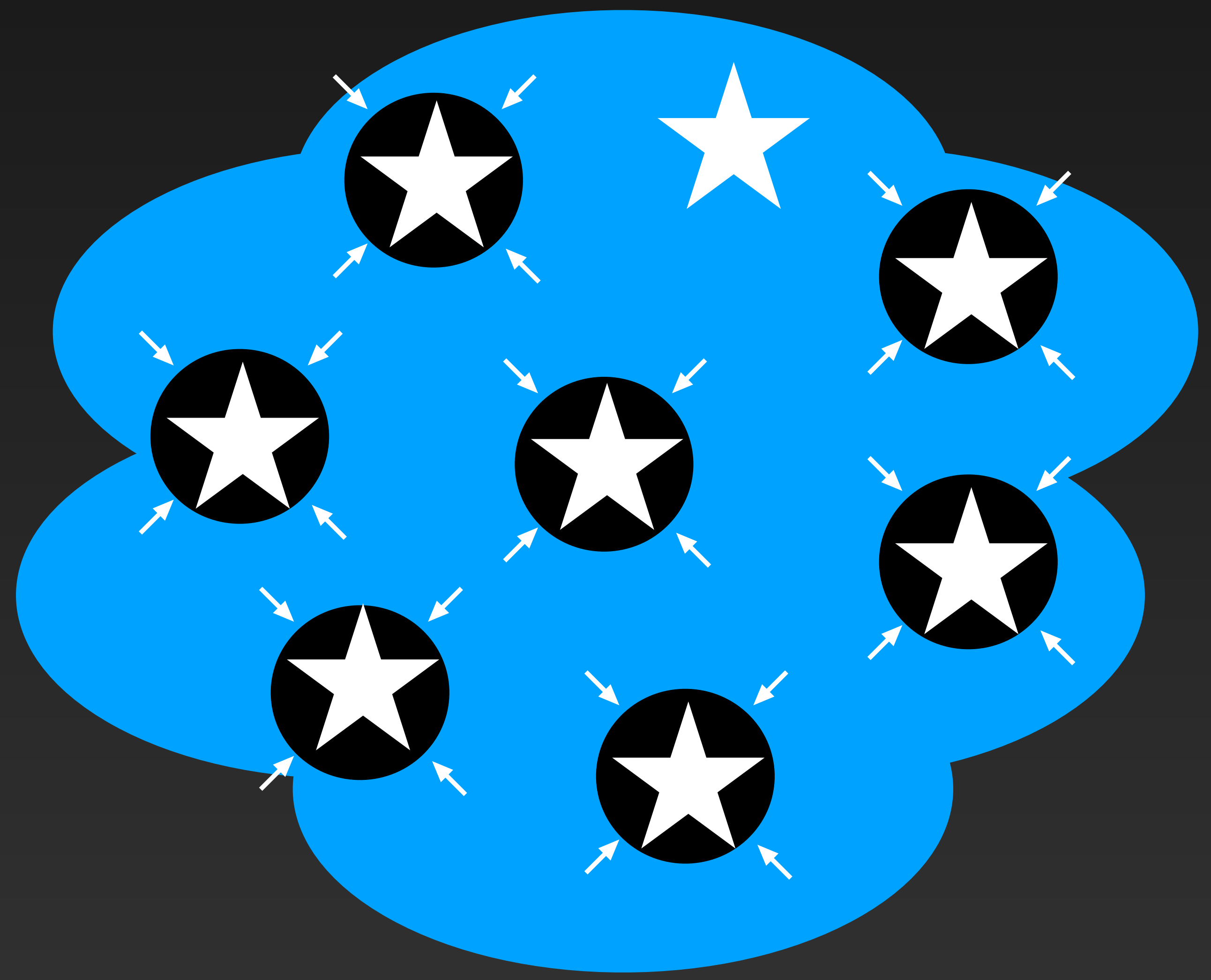
Typical gas cloud

Low Temperature, 10-30 K

Ordinary star formation leading to Stellar mass black holes

Pristine gas cloud (no metals)

Higher temperatures ~100-1000K



Pop III star formation, producing more massive remnants

Theories of seed black hole formation

Jeans' instability criterion of a segment of gas cloud of mass M and temperature T.

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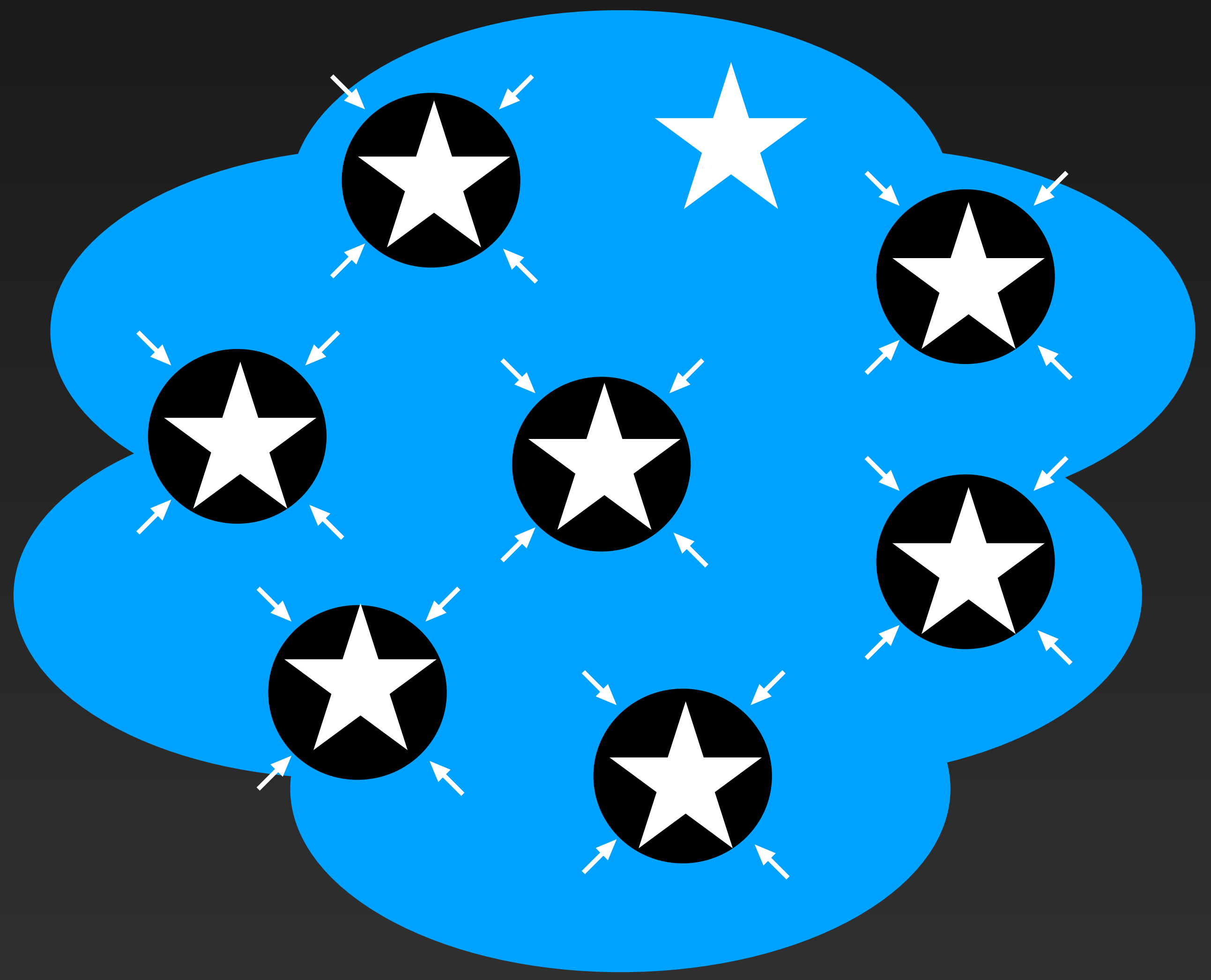
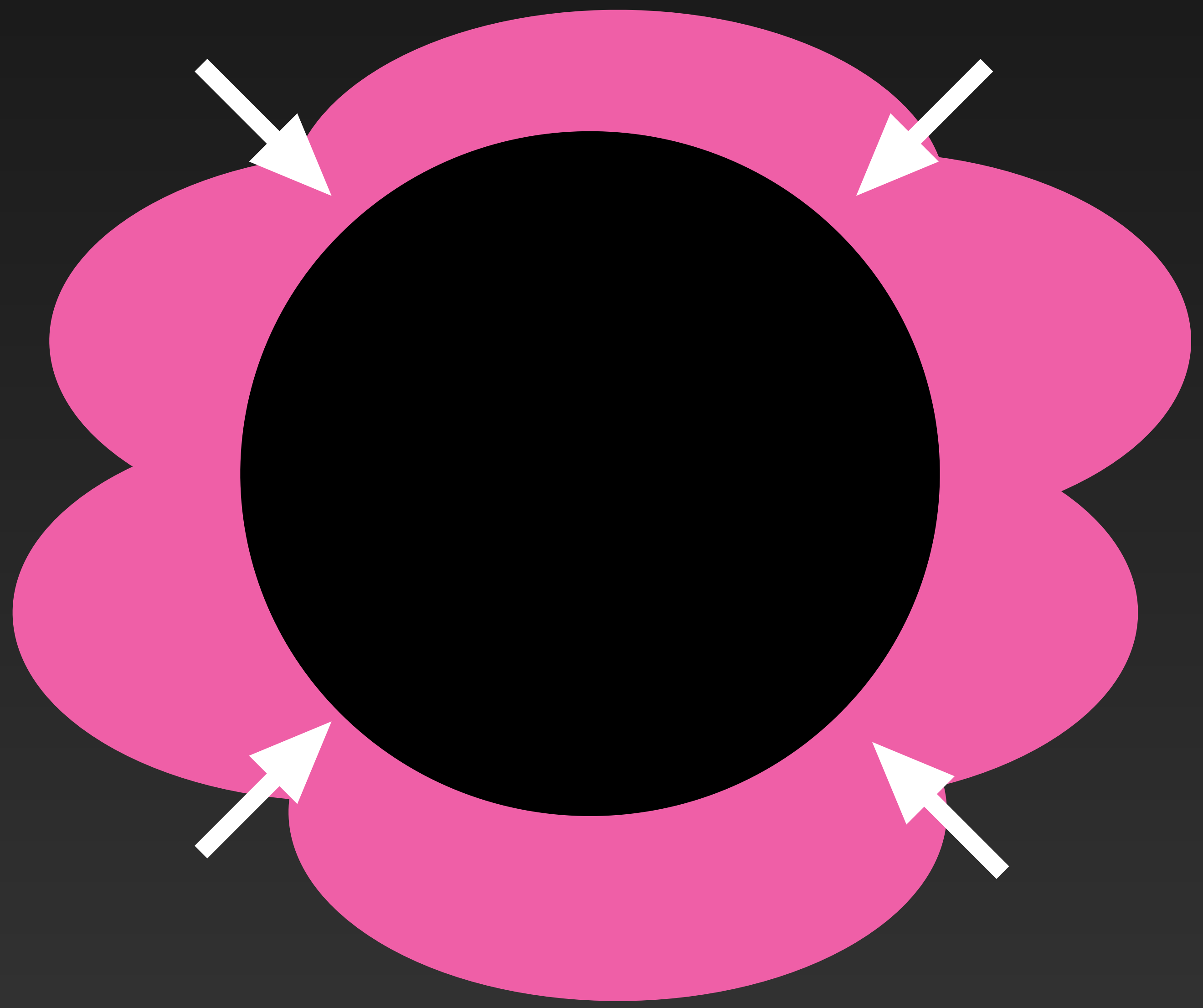


Pop III star formation, producing more massive remnants

Pristine gas cloud (no metals)

No molecular hydrogen

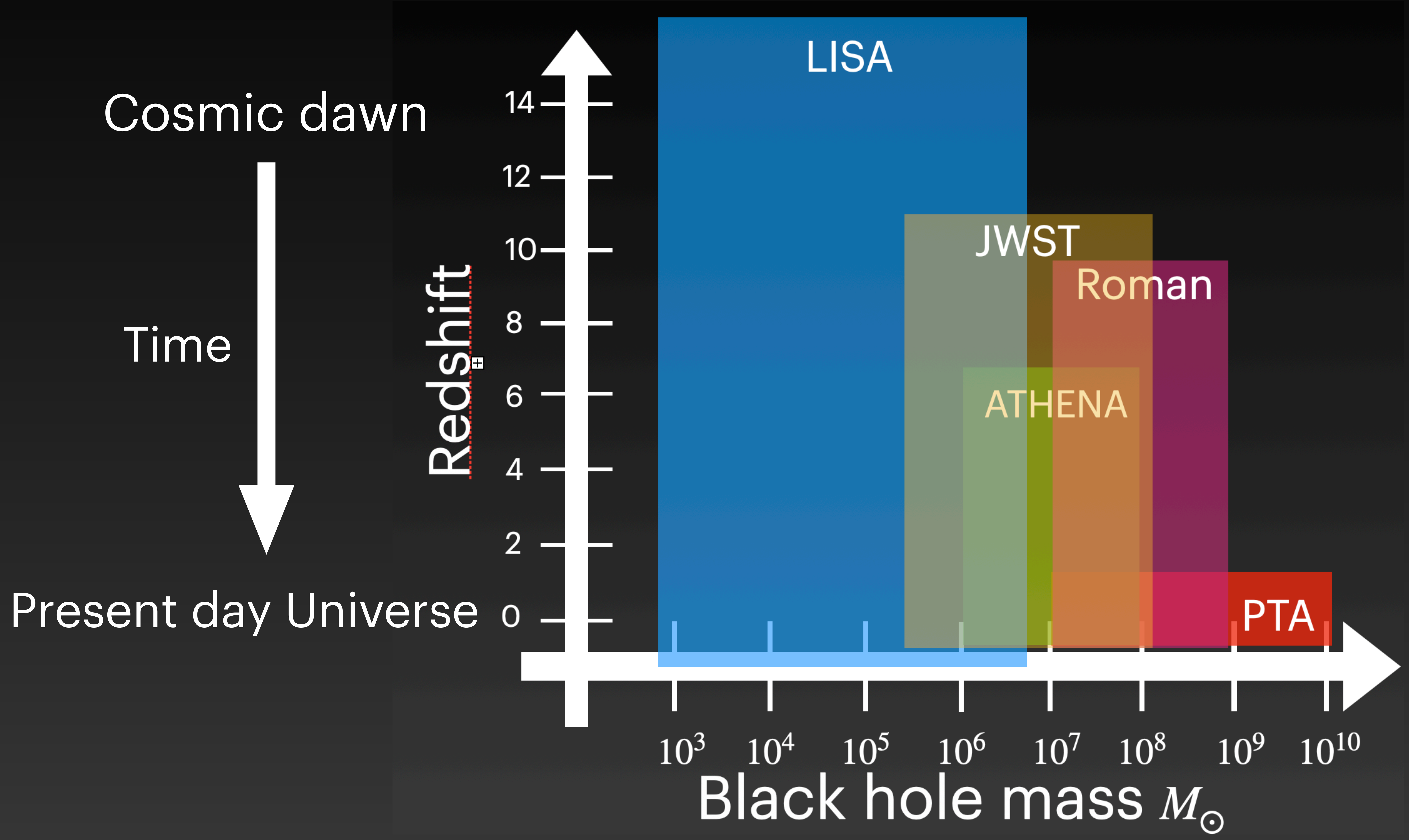
Highest temperatures > 10000 K



No Pop III star formation

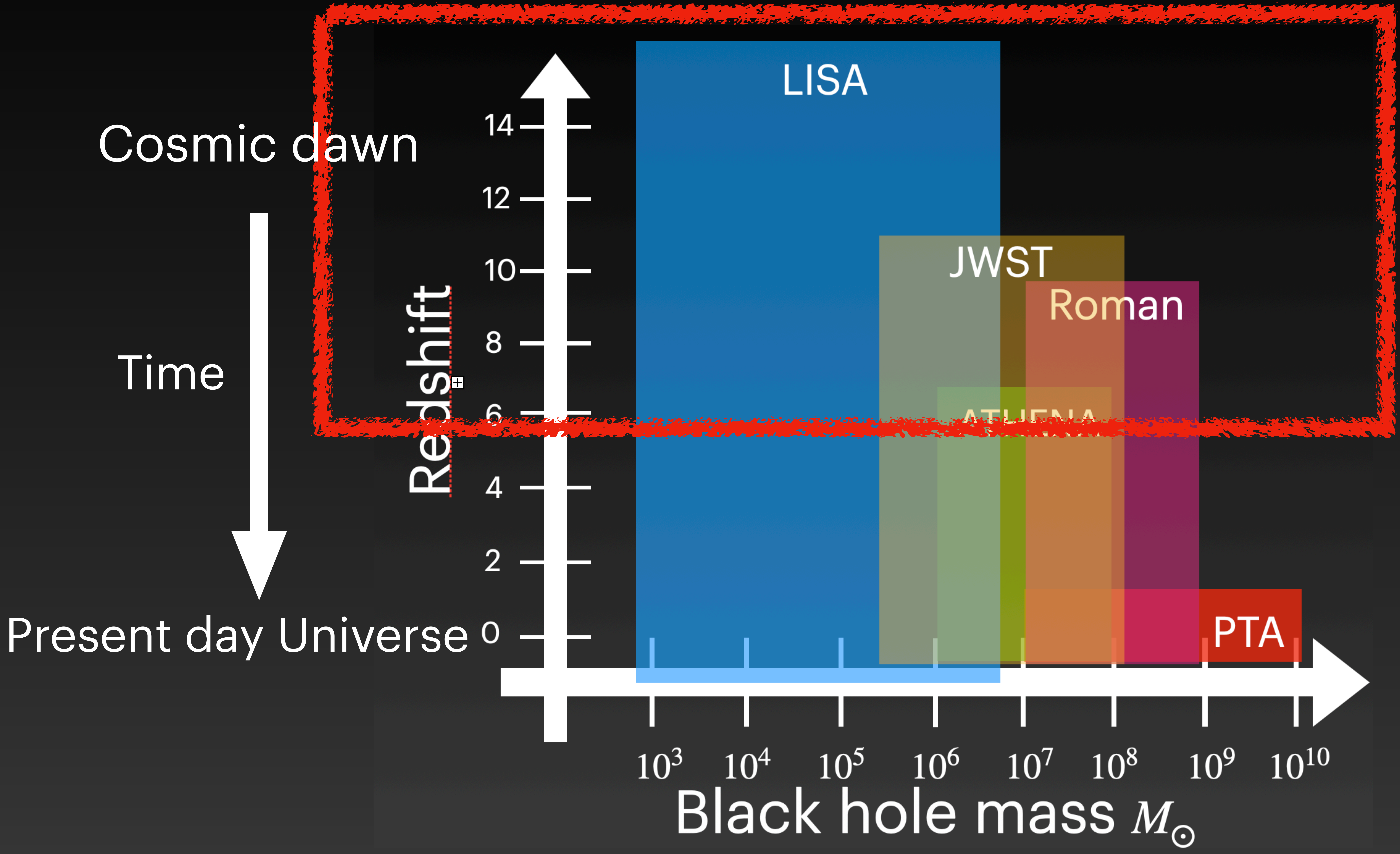
Gas directly collapses to most massive remnants

Huge amount of investment to reveal black hole populations across the entire cosmic timeline by the ~2040s



Need for a robust theoretical framework to make predictions!

Huge amount of investment to reveal black hole populations across the entire cosmic timeline by the ~2040s

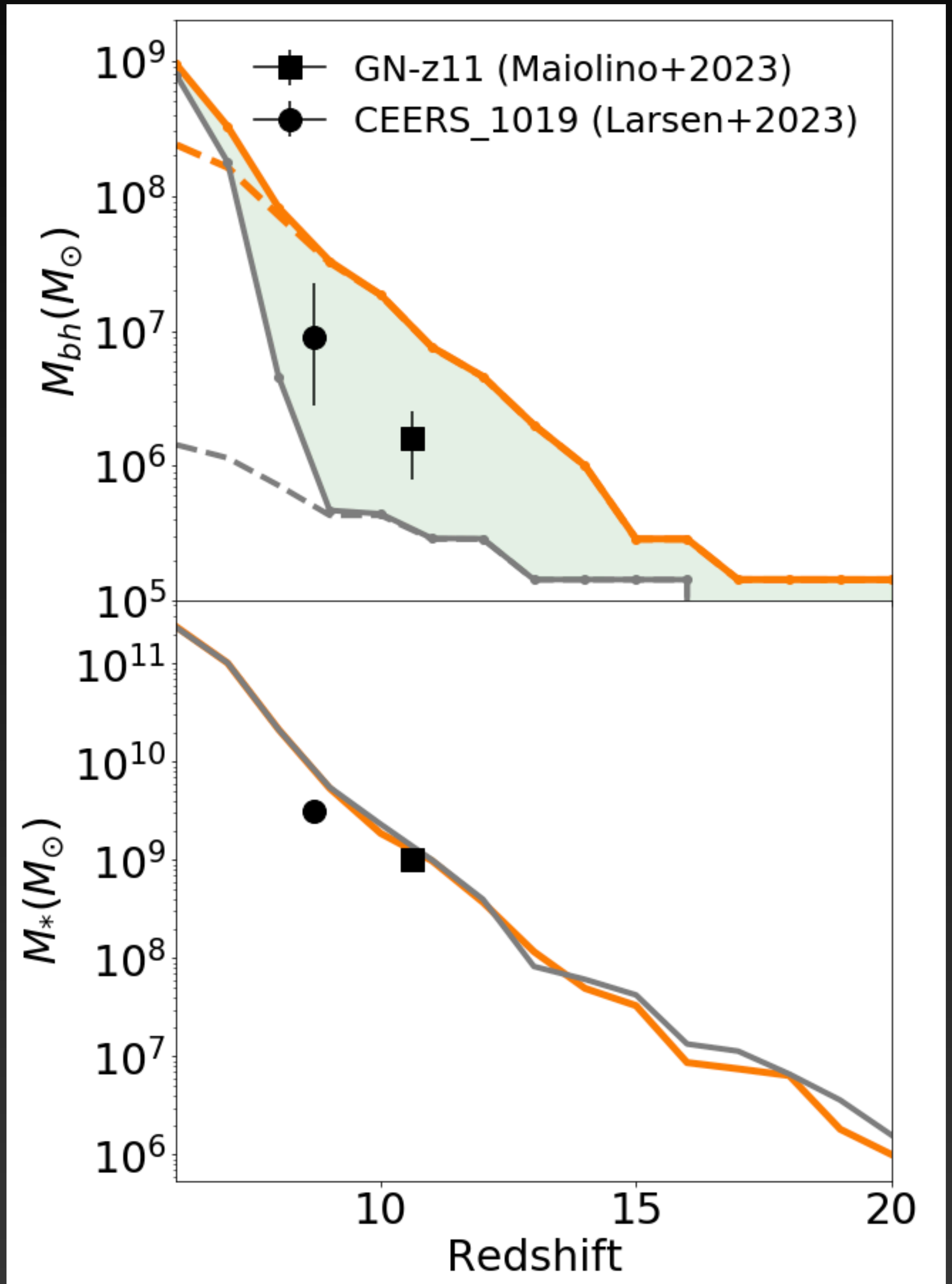


Earliest black hole populations

LISA
Laser Interferometer Space Antenna

WEBB
SPACE TELESCOPE

Two possible avenues for assembling the z~6 quasars:



Avenue 1: If we form higher number of seeds, early growth can be boosted by BH-BH mergers

Avenue 2: Allowing for Super-Eddington accretion