Origin of supermassive black holes from dense star clusters: Implications for the Local Universe and for JWST

Prof. Dominik Schleicher
Sapienza University of Rome

Supermassive black holes are common in the Universe

- Supermassive black holes are in the centers of galaxies.

- More than 200 quasars are currently known at z>5.6 (Inayoshi et al. 2020).
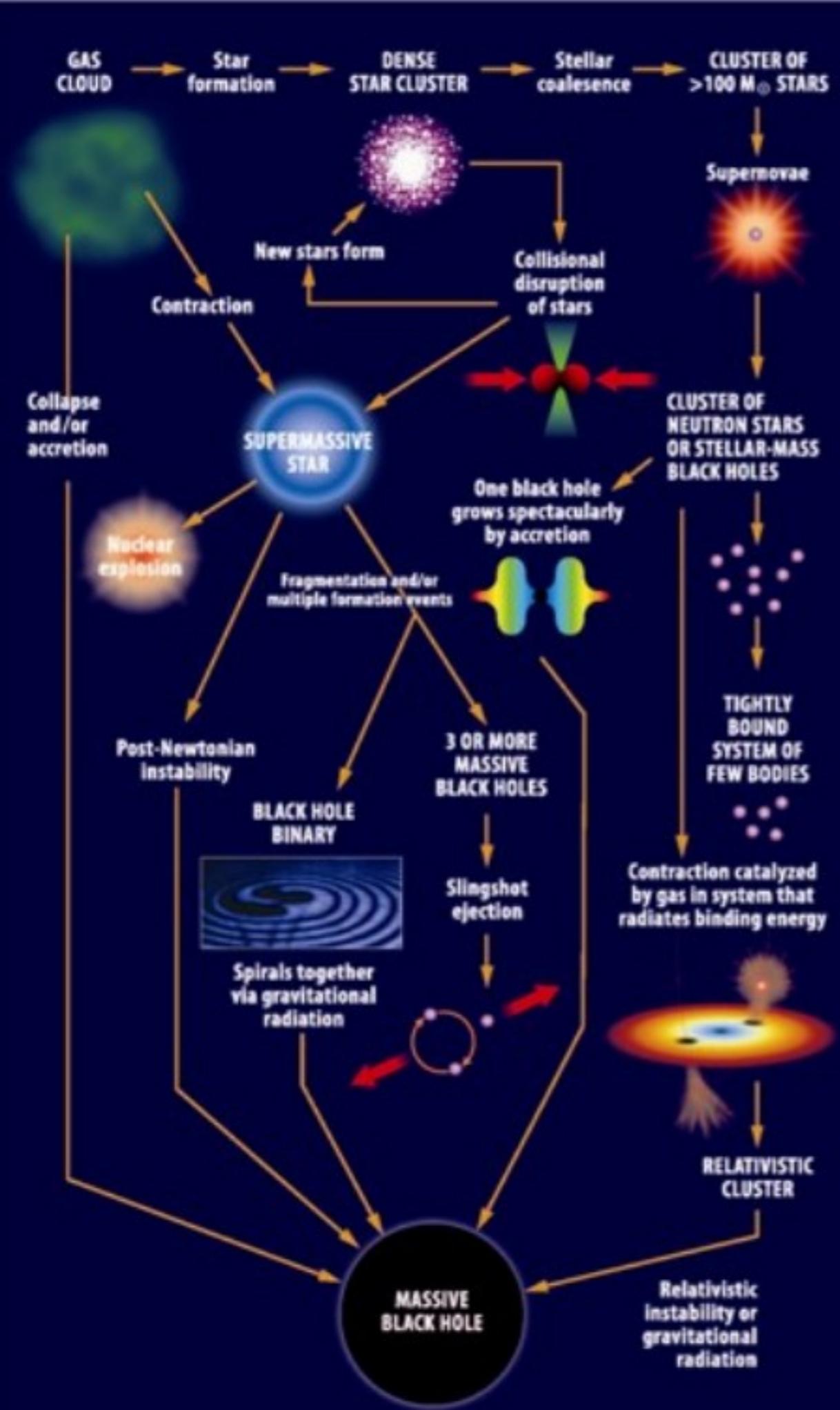
- Many potential candidates for high-redshift supermassive black holes were discovered by JWST as Little Red Dot galaxies (LRDs) and high-redshift AGN.
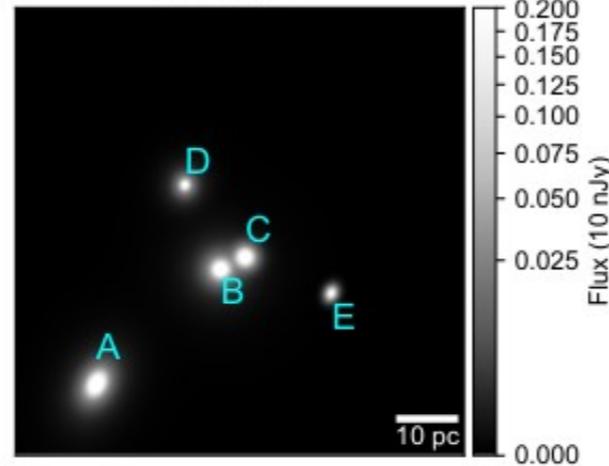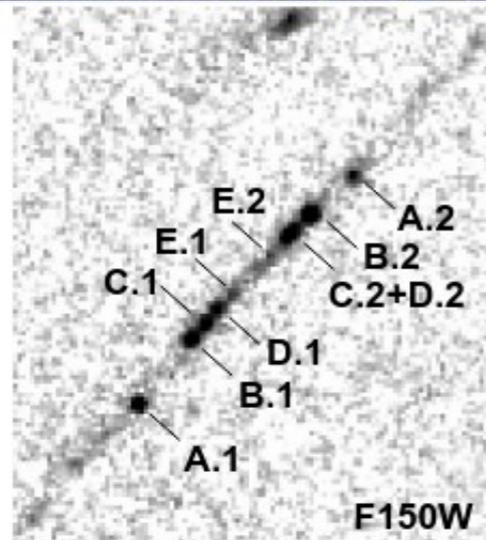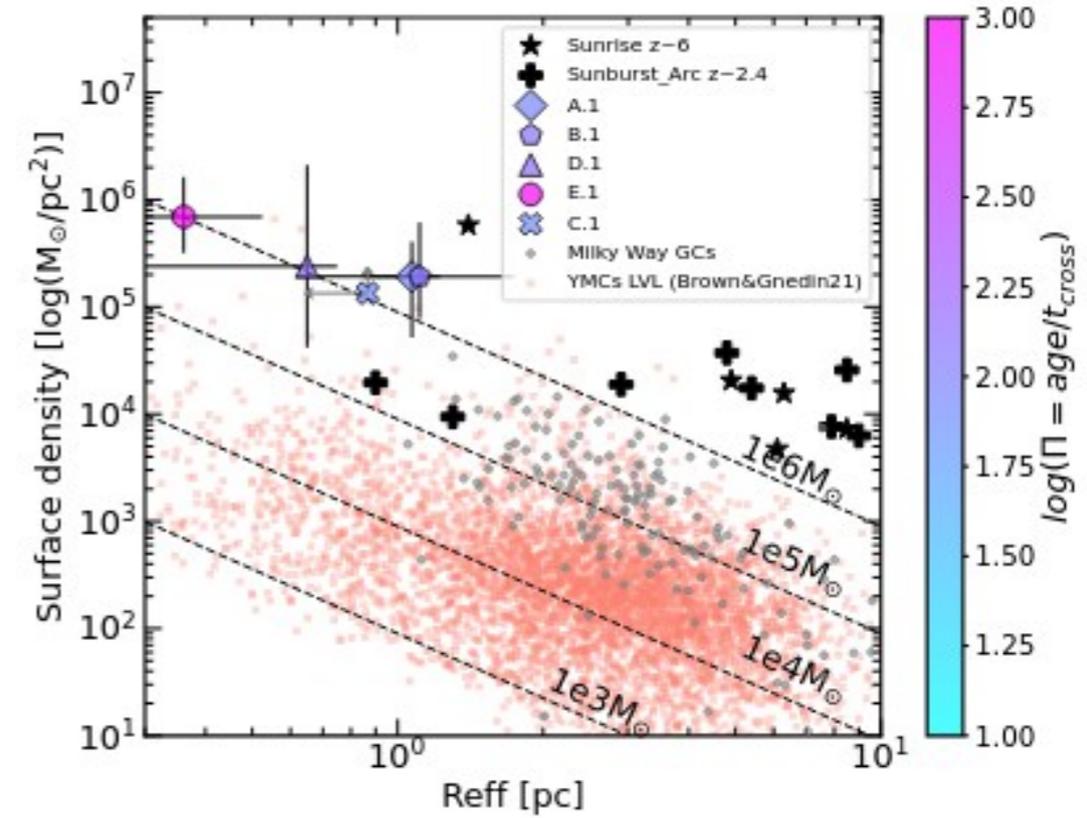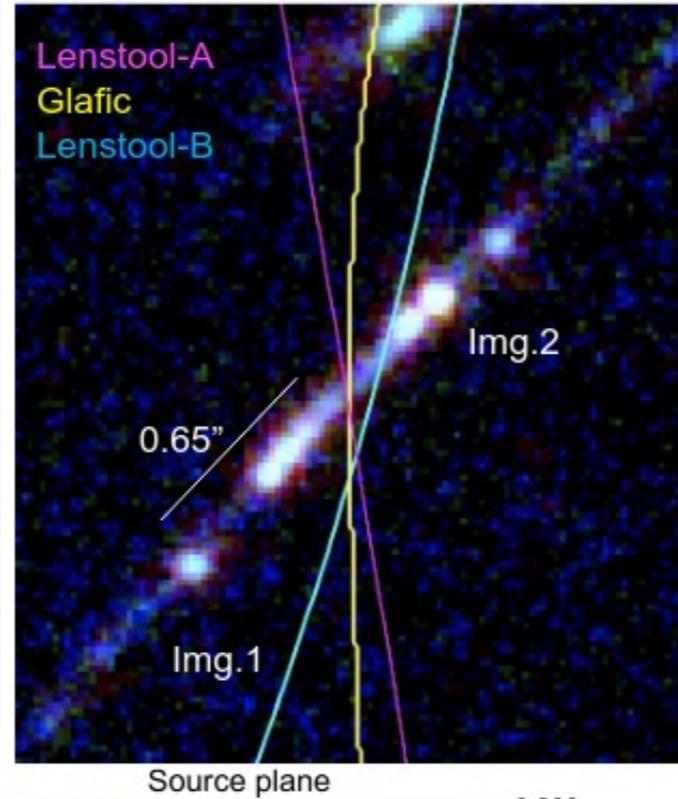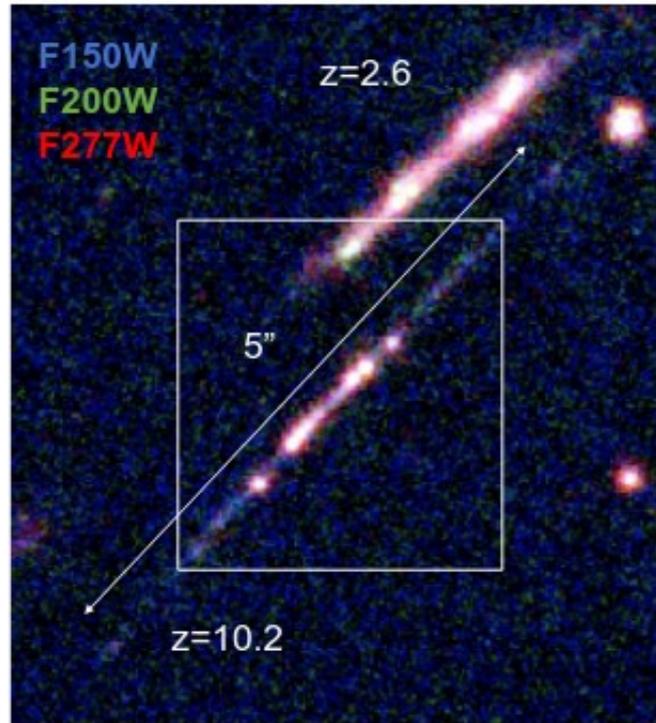
How did supermassive black holes form?

Direct collapse? Collisions in star clusters? Other mechanisms?
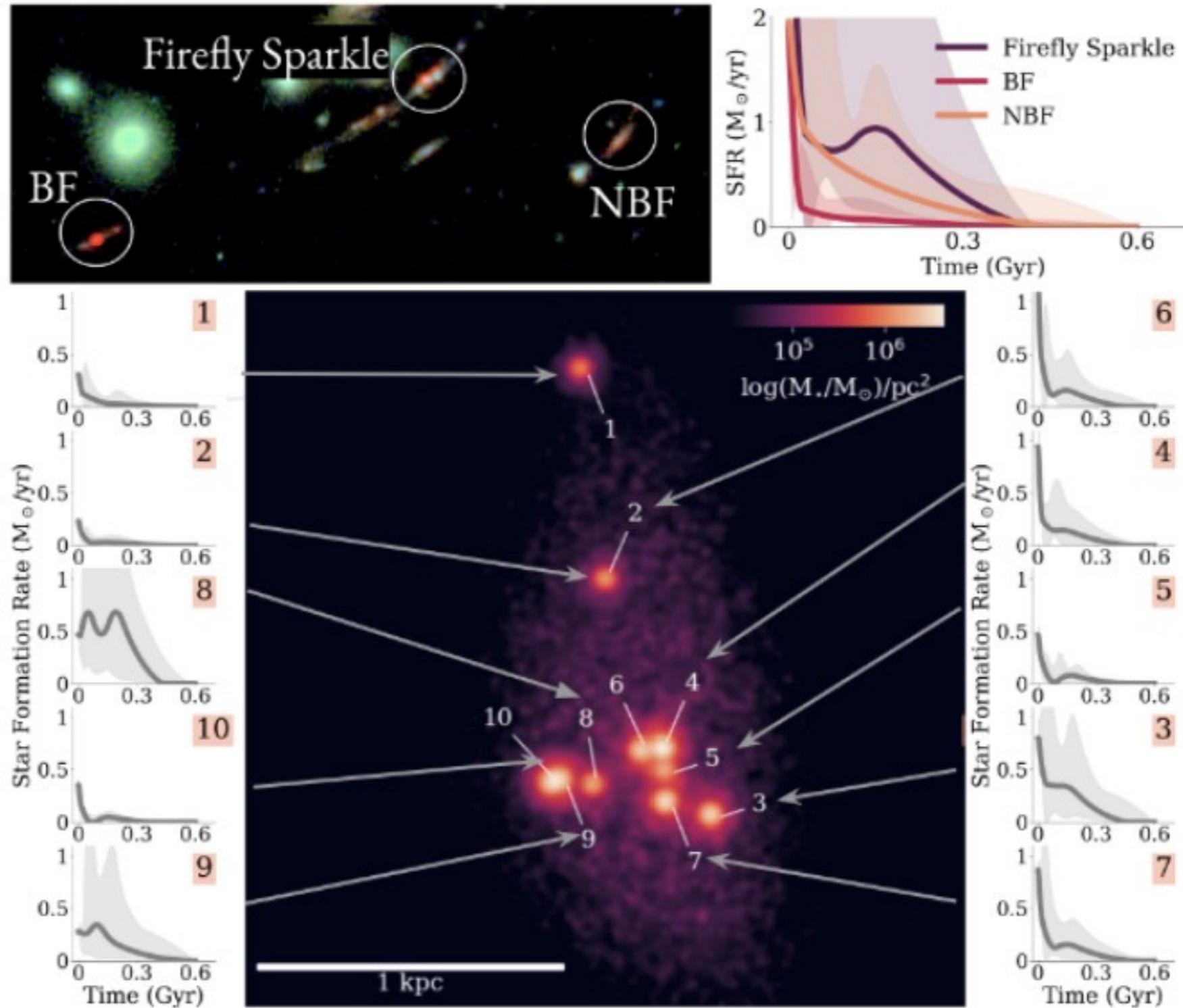
Begelman & Rees (2010); original sketch by Rees (1978)

Young Massive Star Clusters in the Cosmic Gems at z~10.2

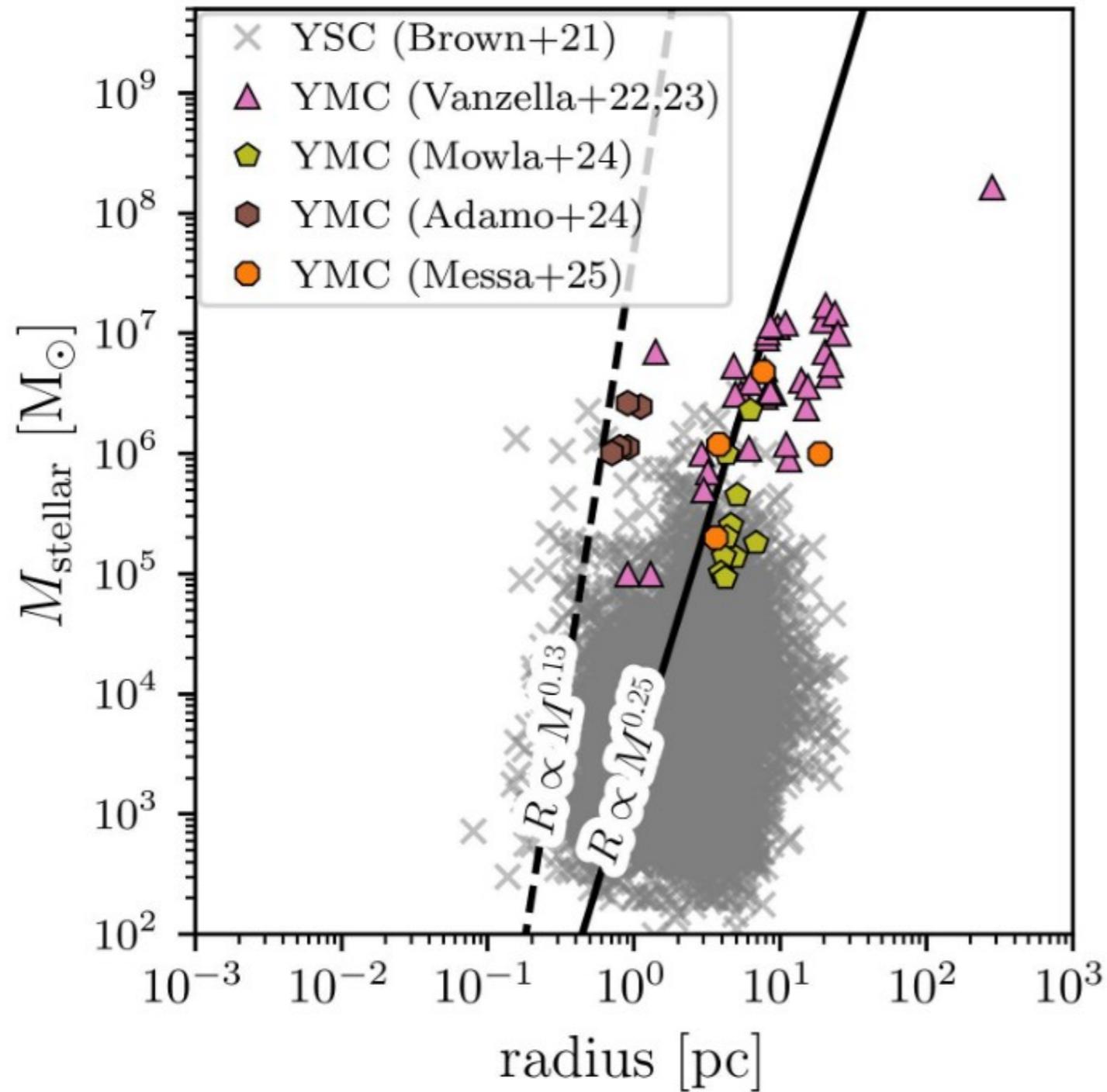Young Massive Clusters found by JWST through strong lensing.

Adamo et al. (2024)

Young Massive Star Clusters in the Firefly Sparkle at z~8.3

Young Massive Clusters found by JWST through strong lensing.

Mowla et al. (2024)

Star clusters in the local Universe and at high redshift

- YSCs: Young Star Clusters from a sample of nearby galaxies (Brown et al. 2021).

- YMCs: Young Massive Clusters detected with JWST at high redshift via strong lensing.

- The more compact clusters follow the Marks & Kroupa (2012) relation.

- The more typical clusters follow the relation from Grudic et al. (2023).

Schleicher et al., in prep.

Star clusters: characteristic timescales
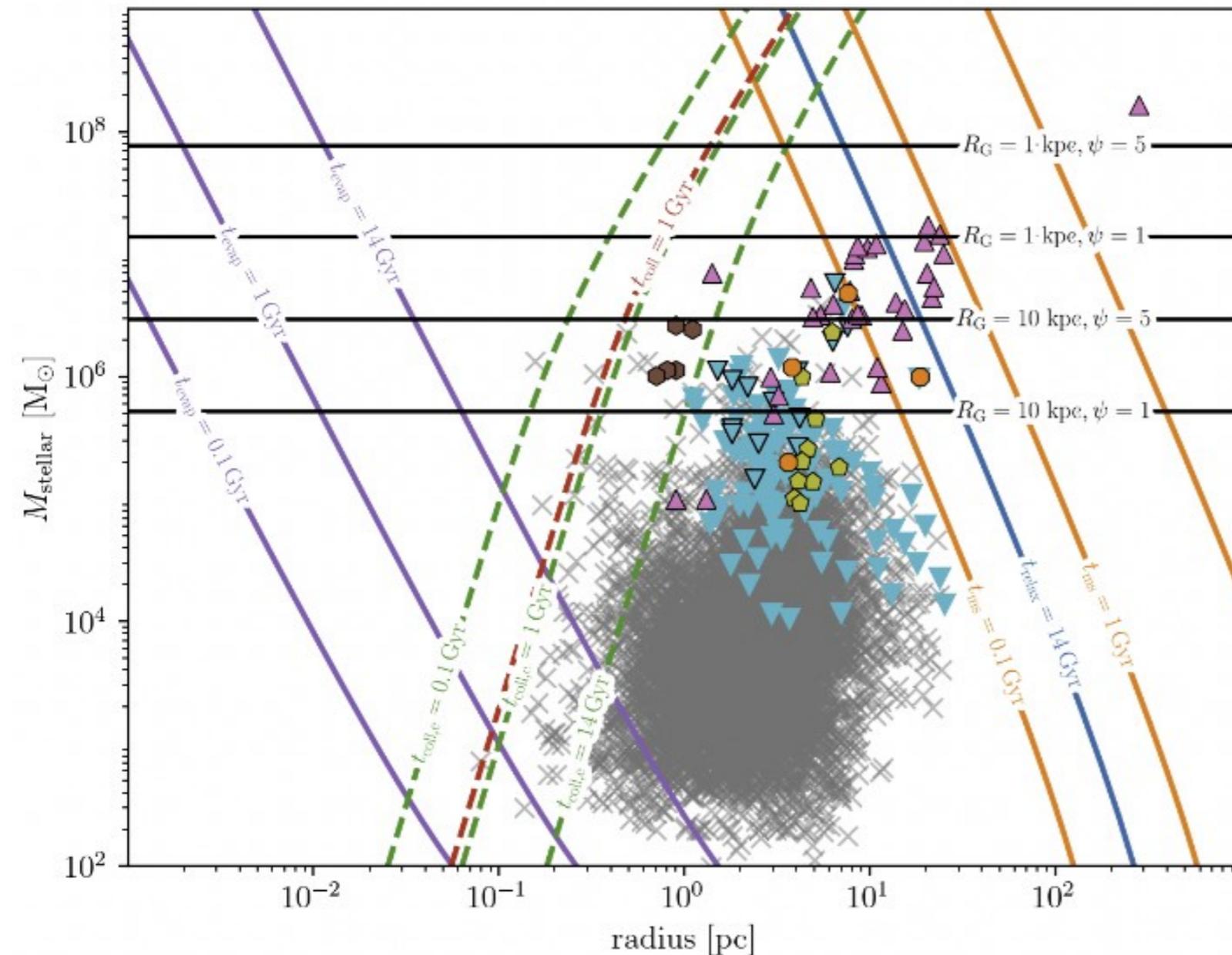
Blue line:
Relaxation time at 14 Gyr.

Orange lines:
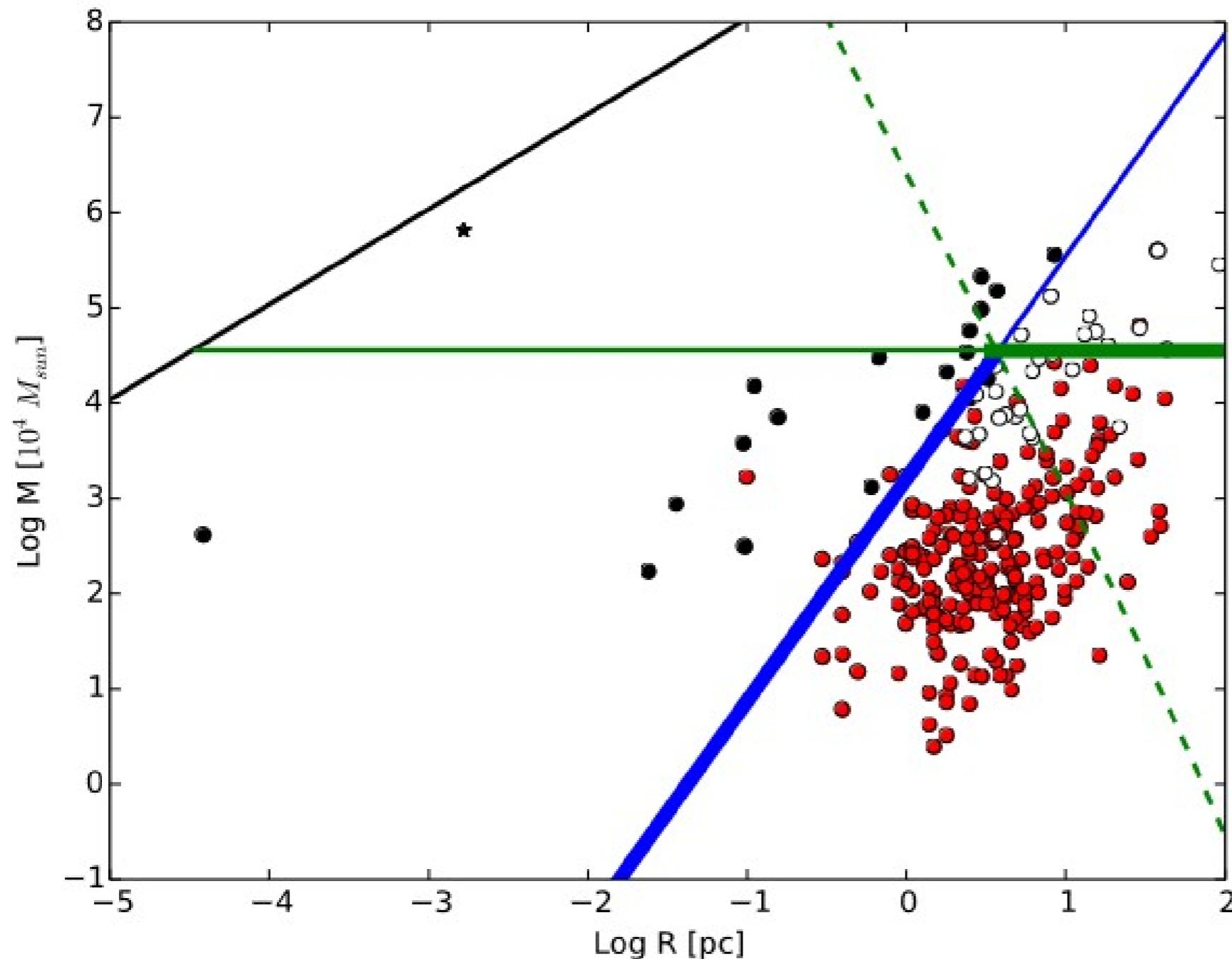Mass segregation time at 0.1, 1.0 and 14 Gyr.

Green lines:
Collision time in the cluster center at 0.1, 1.0 and 14 Gyr.

Purple line:
Evaporation time at 0.1, 1.0 and 14 Gyr.

Grey dots: Young star clusters
Blue dots: Globular Clusters
Other colours: JWST clusters

Schleicher et al., in prep.

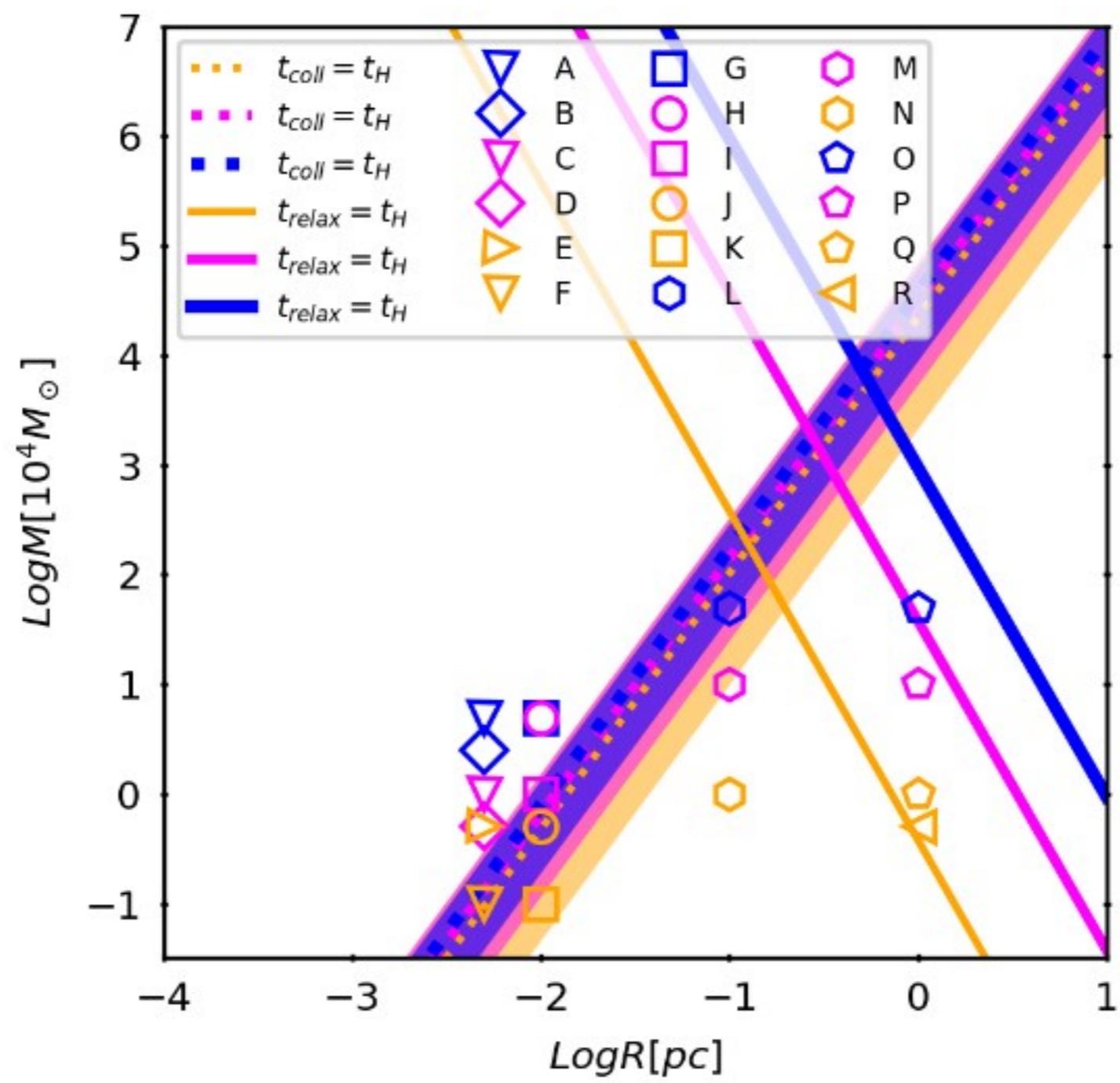# Relevance of the collision timescale from observed systems

- Solid blue: collision time equal to age of the system.

- Green dashed: relaxation time equal to age of system.

- Black circles: massive black holes.

- Red circles: Nuclear Star Clusters

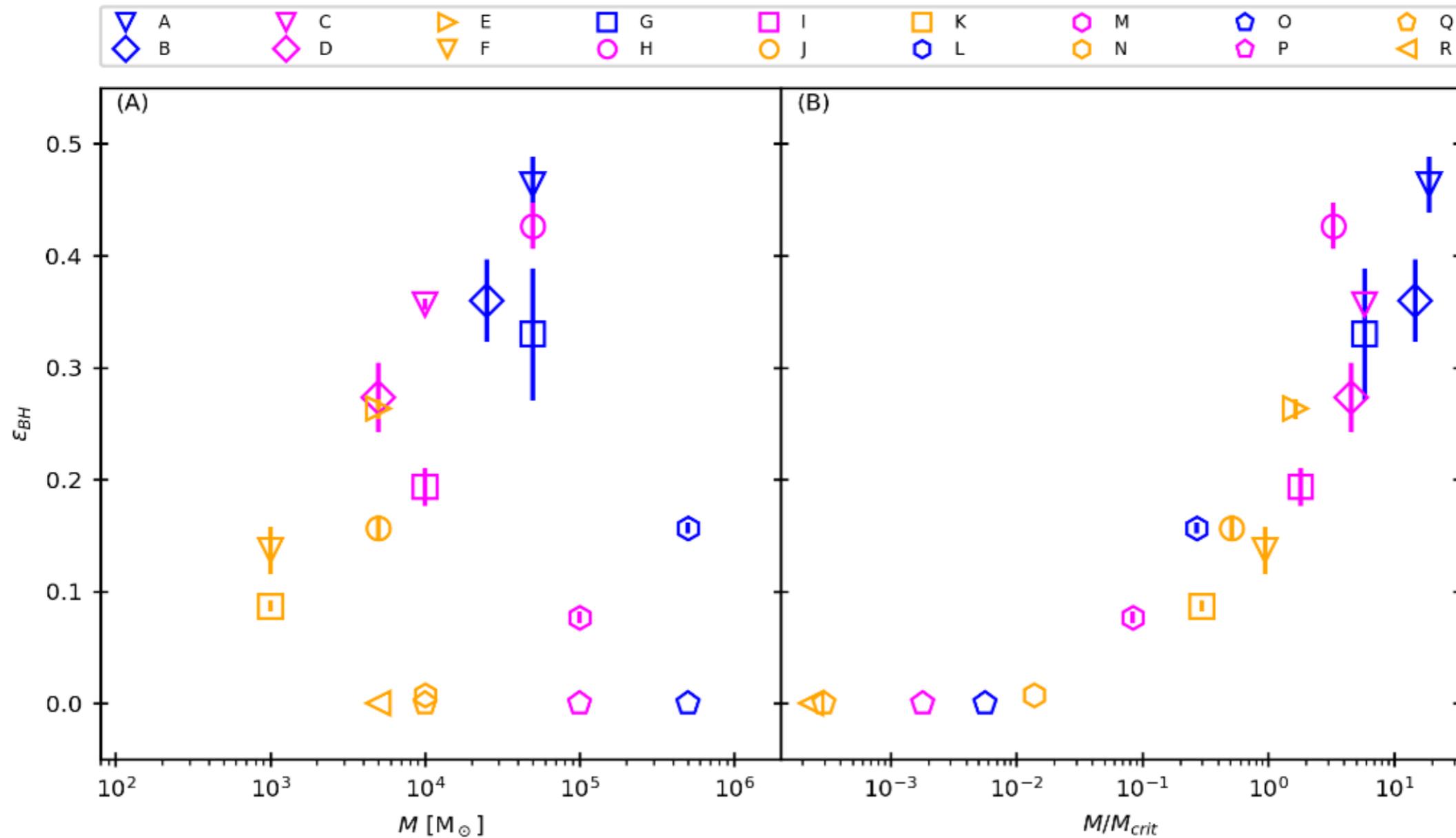Nuclear Star Cluster data from Georgiev et al. (2016)

Escala (2021)

A systematic test on the role of the collision timescale
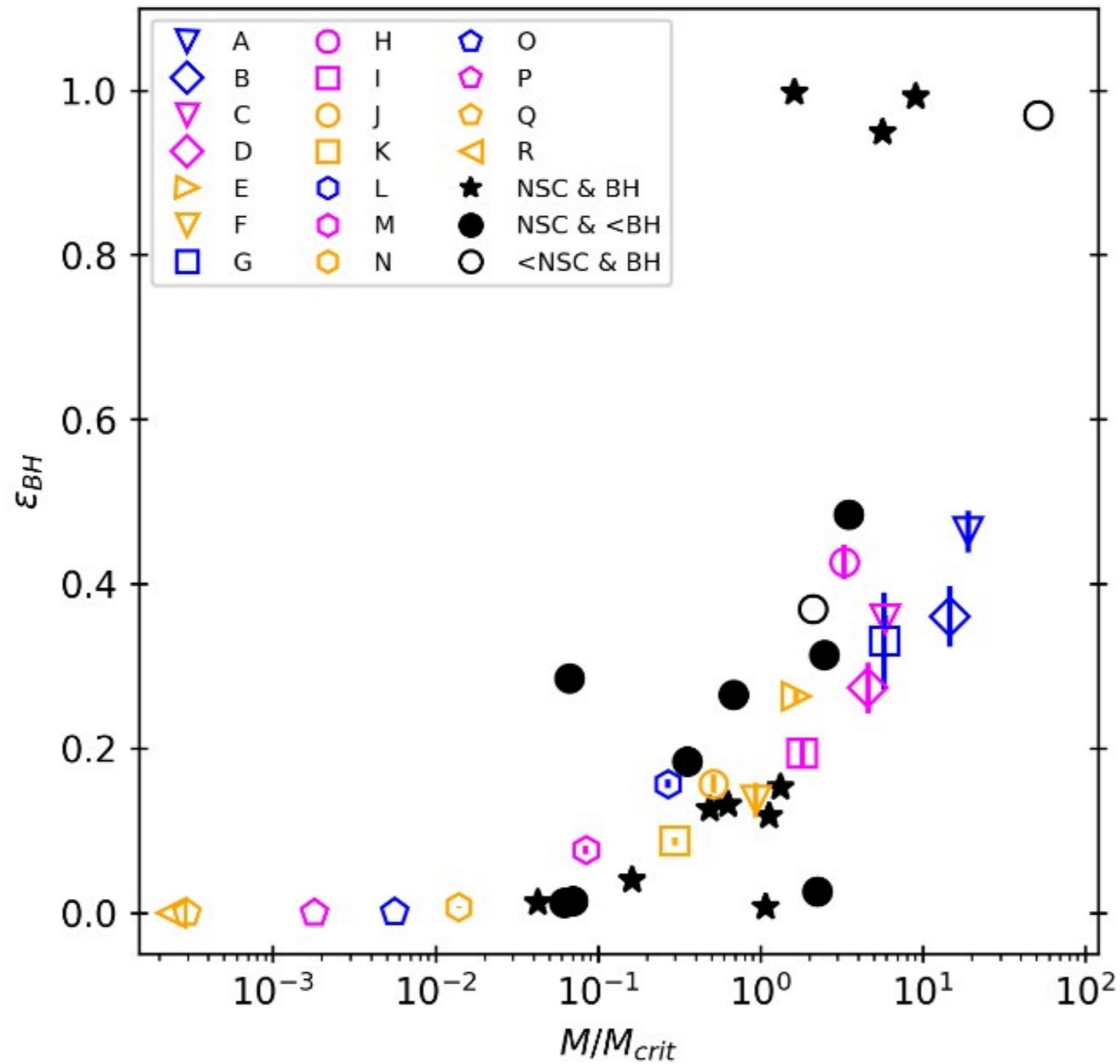

Vergara et al. (2023)

A critical mass scale for black hole formation

$$M_{crit} = R^{7/3} \left(\frac{4\pi M_*}{3\Sigma_0\, t_H\, G^{1/2}} \right)^{2/3}$$
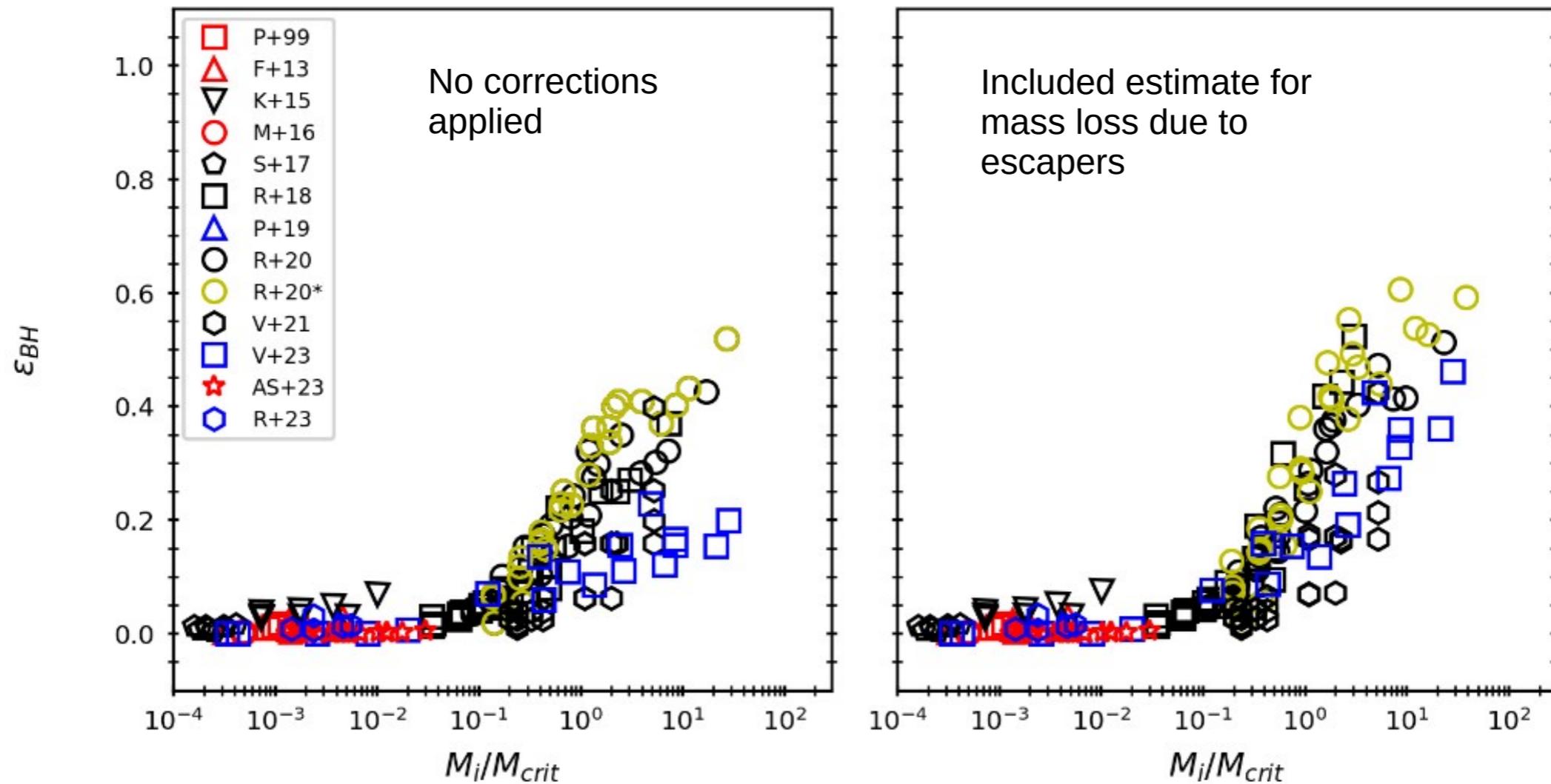
Vergara et al. (2023)

Comparison of trends in simulations and observations
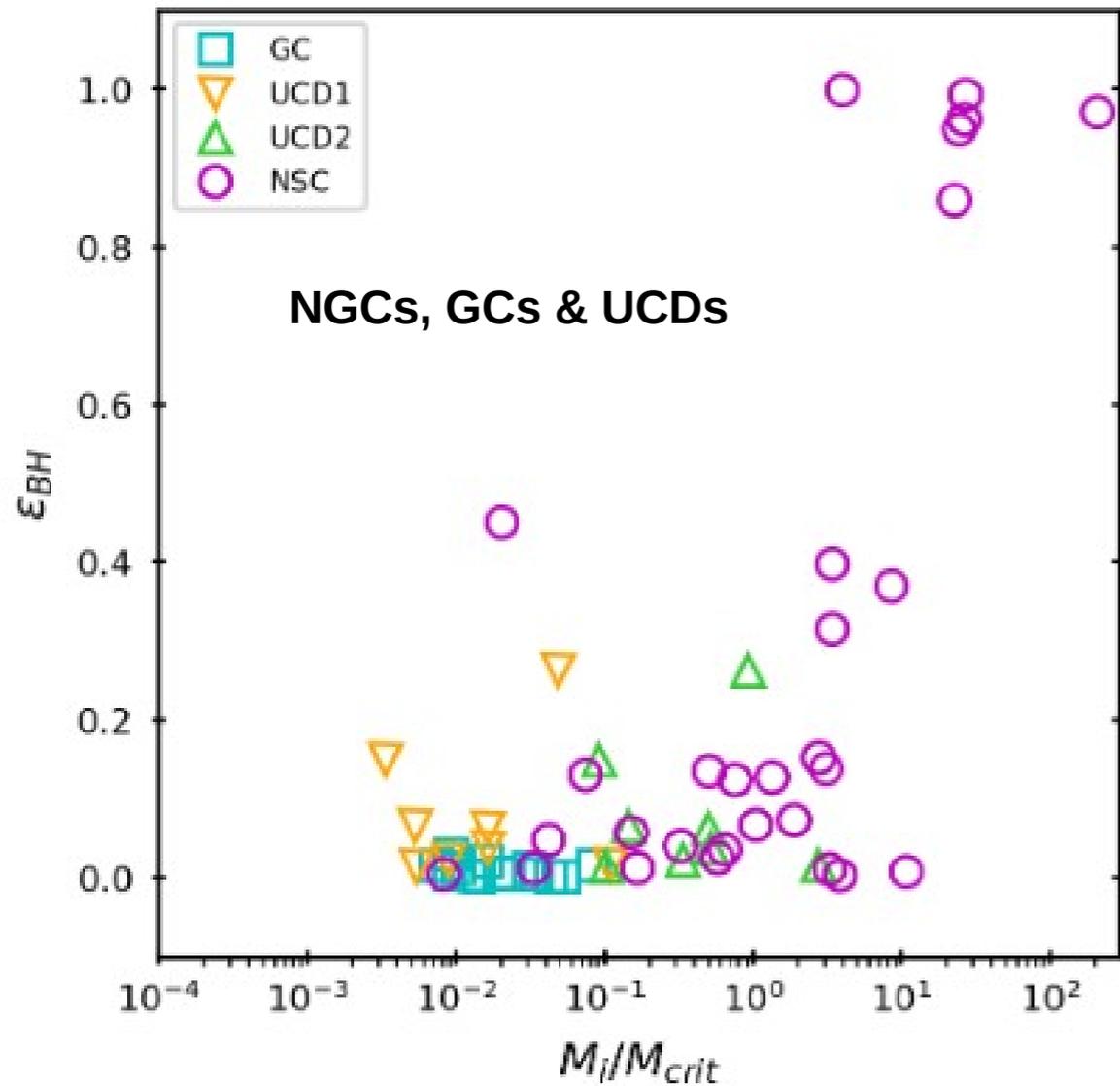

Vergara et al. (2023)

Suite of numerical simulations from the literature

Large set of simulations from different groups using different initial conditions, initial mass functions and details in the physics.
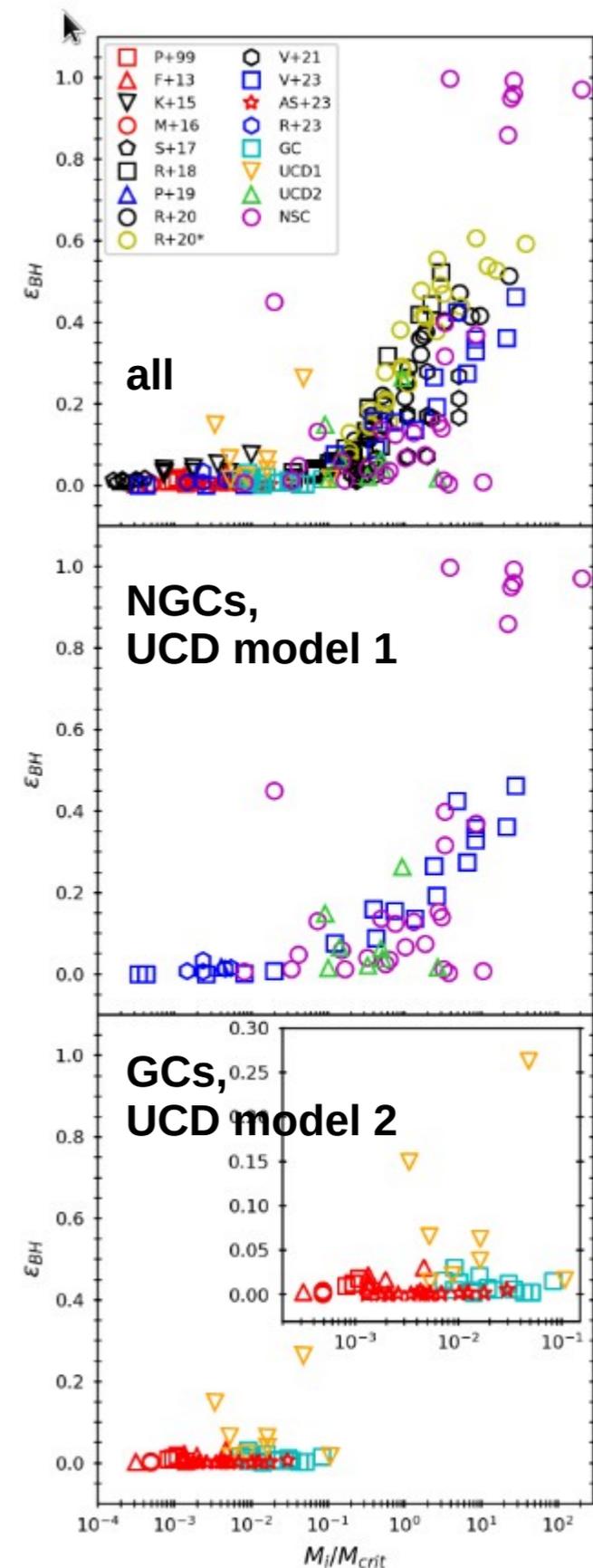
Vergara et al. (2024)

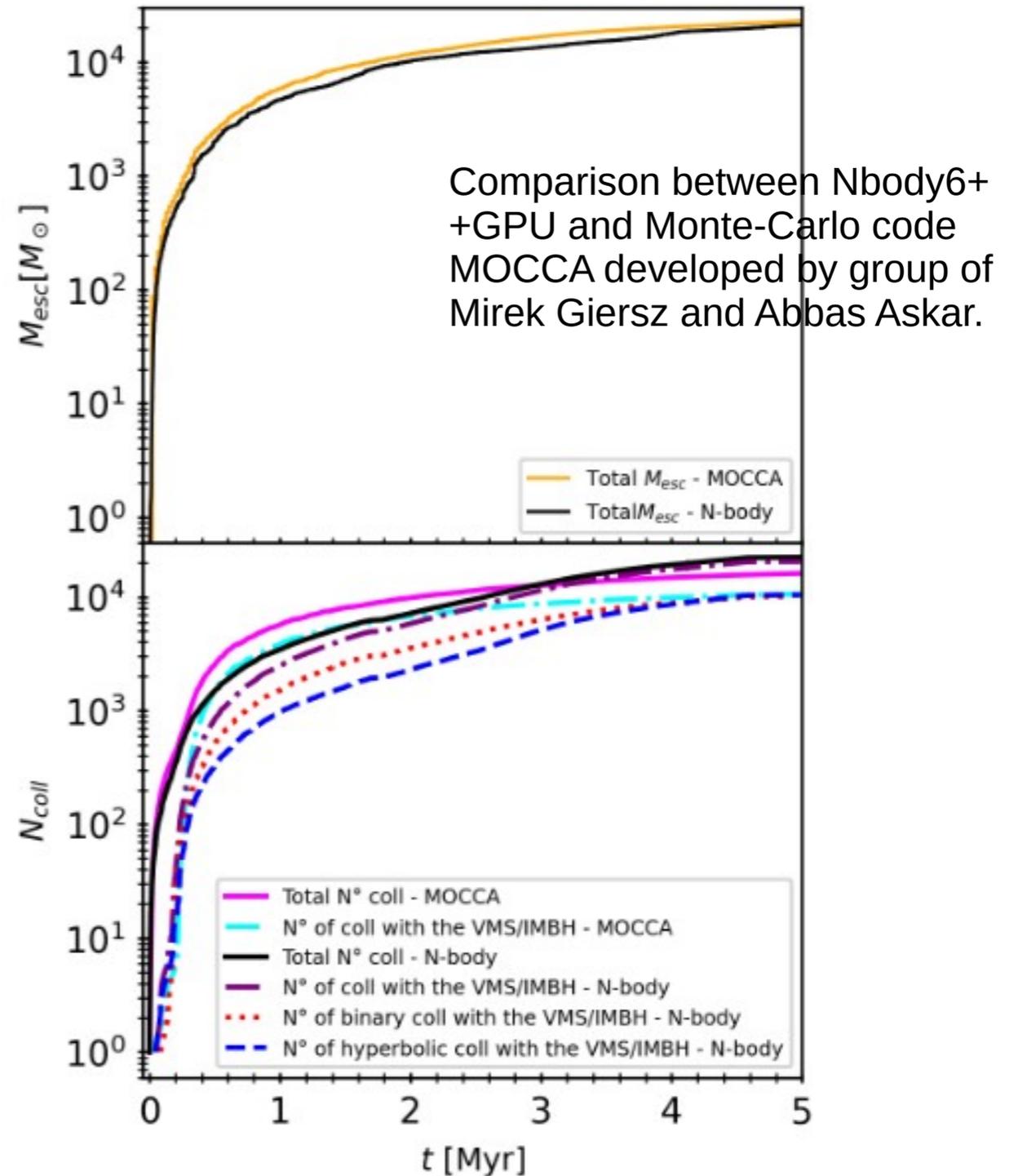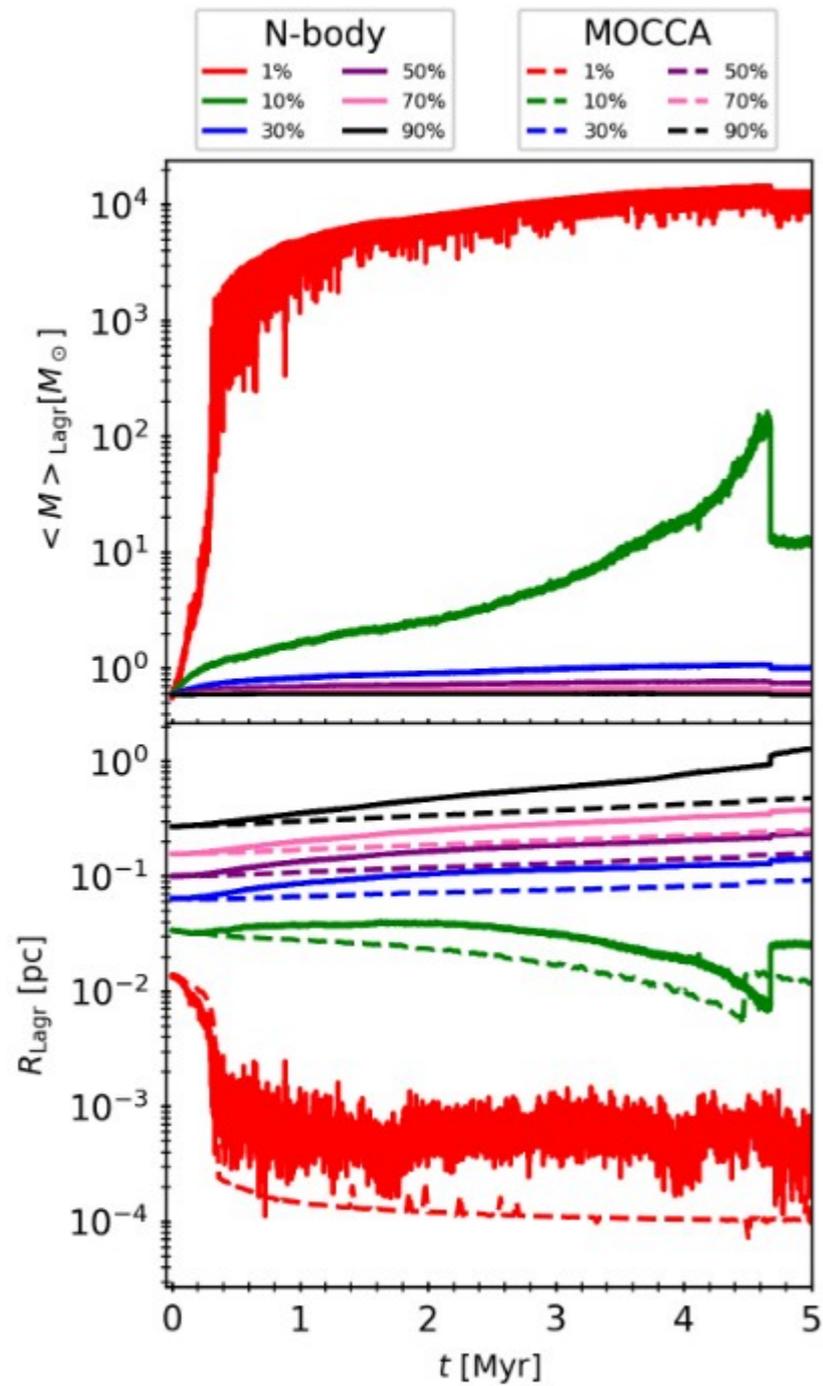# Comparison with observed NSCs, Gcs and UCDs

NGCs, GCs & UCDs

For NSC and GC models assume cluster expansion during evolution (Banerjee & Kroupa 2017).

NSC data from Neumayer et al. (2020).
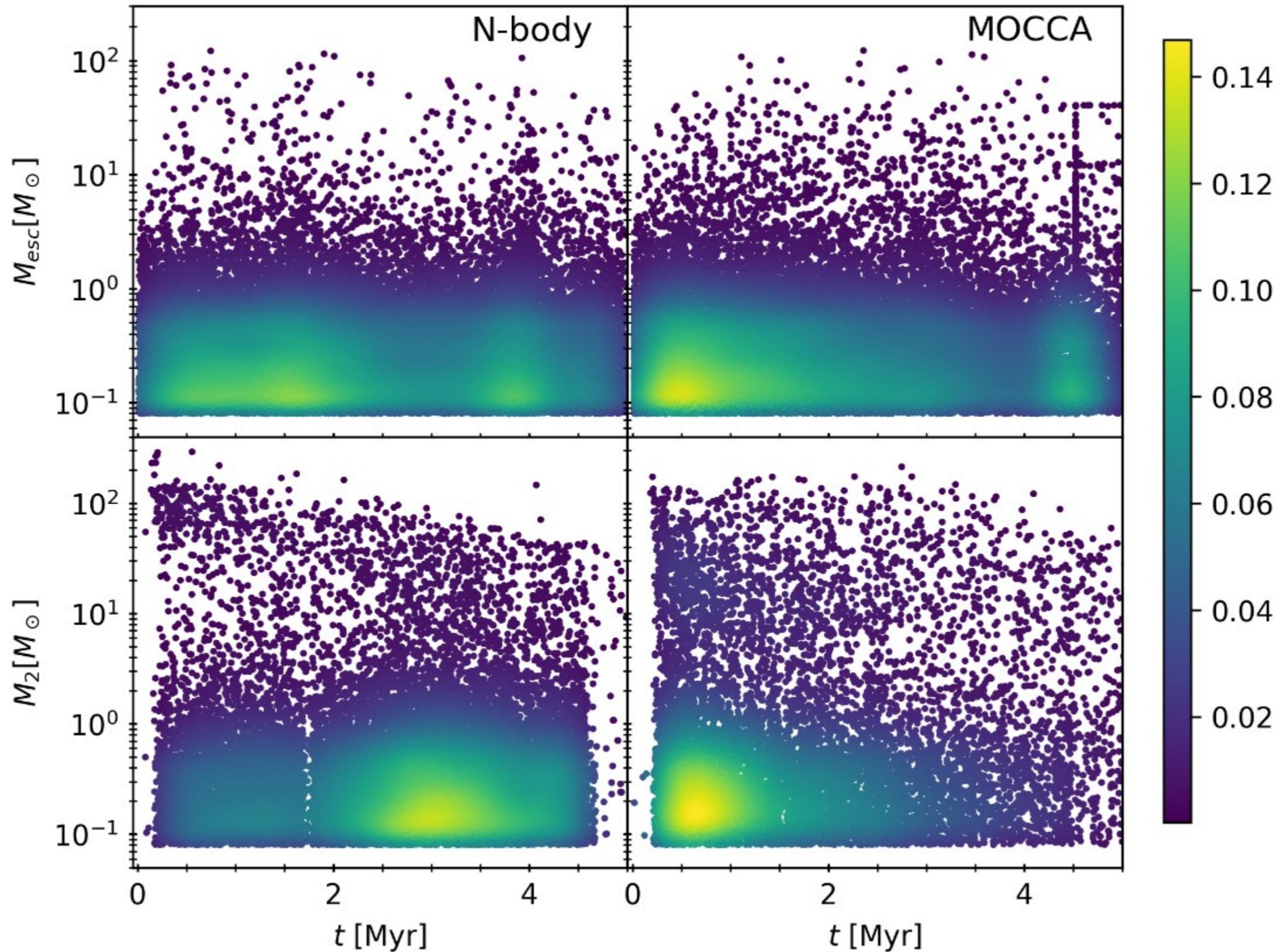
Vergara et al. (2024)

First N-body simulation showing the formation of a 20.000 solar mass stars

Comparison between Nbody6+ +GPU and Monte-Carlo code MOCCA developed by group of Mirek Giersz and Abbas Askar.

Dense cluster with ~3x10⁵ solar masses in ~ 0.1 pc, one million stars
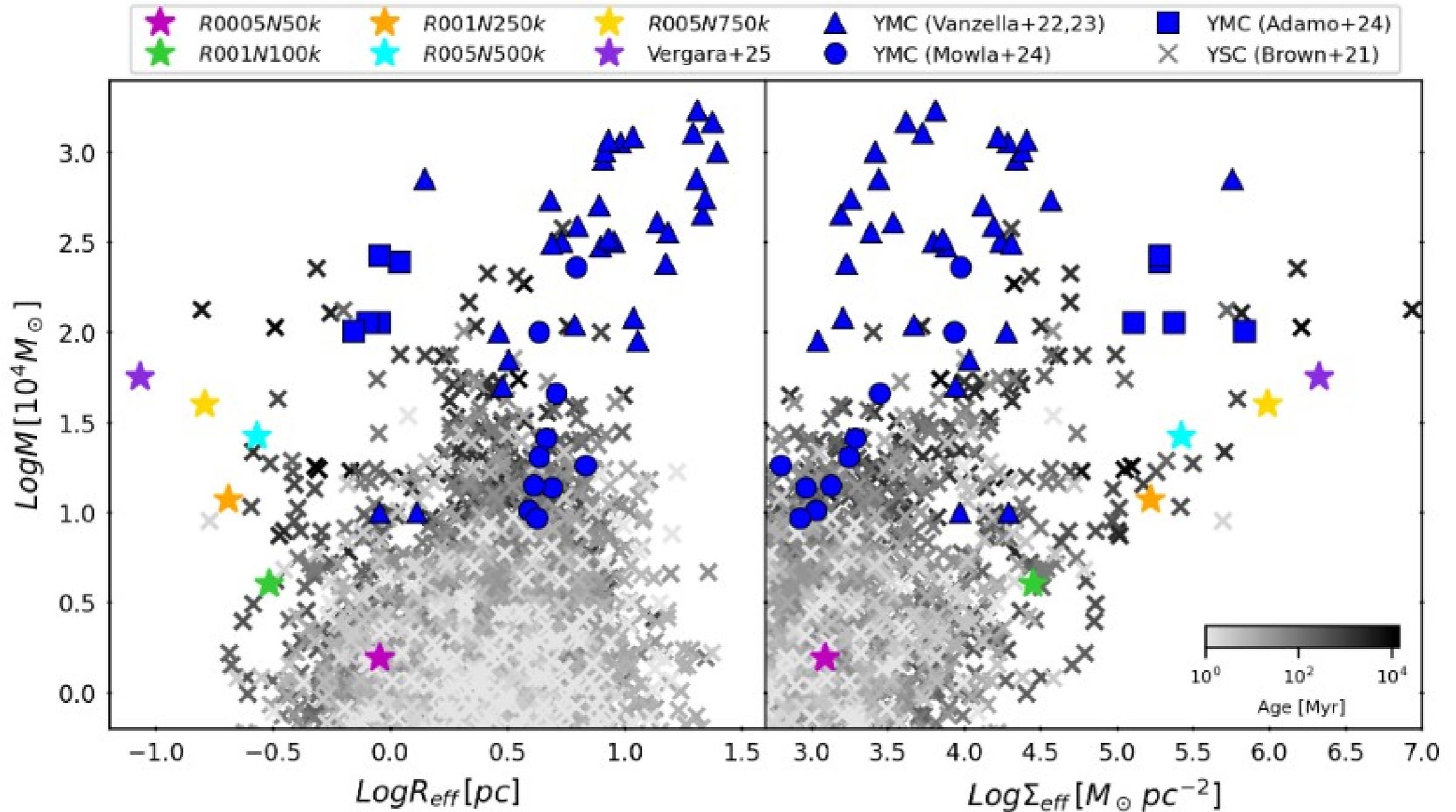
Vergara et al. (2025)

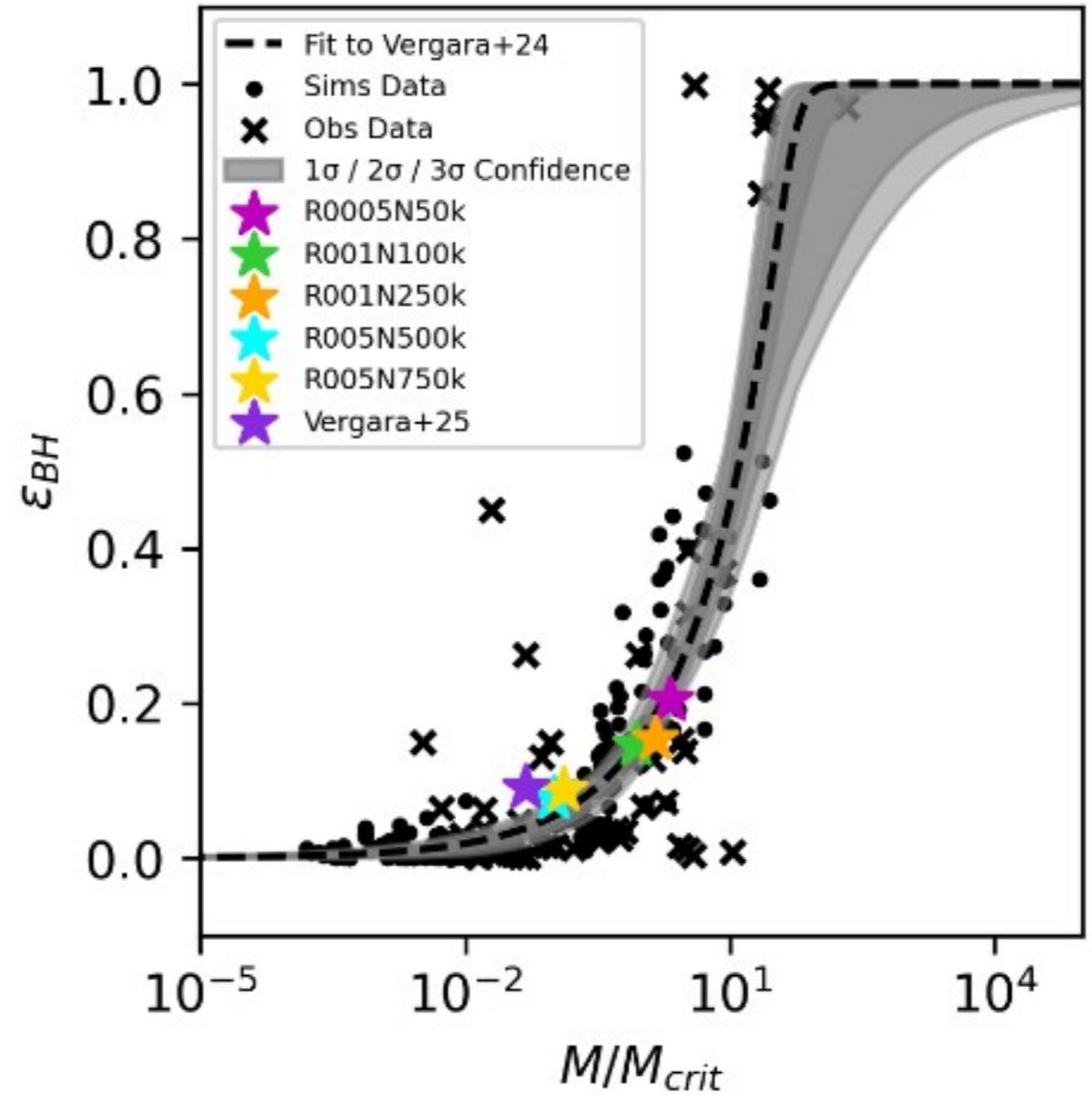# Mass of escapers and mass of secondaries in mergers

Vergara et al. (2025)
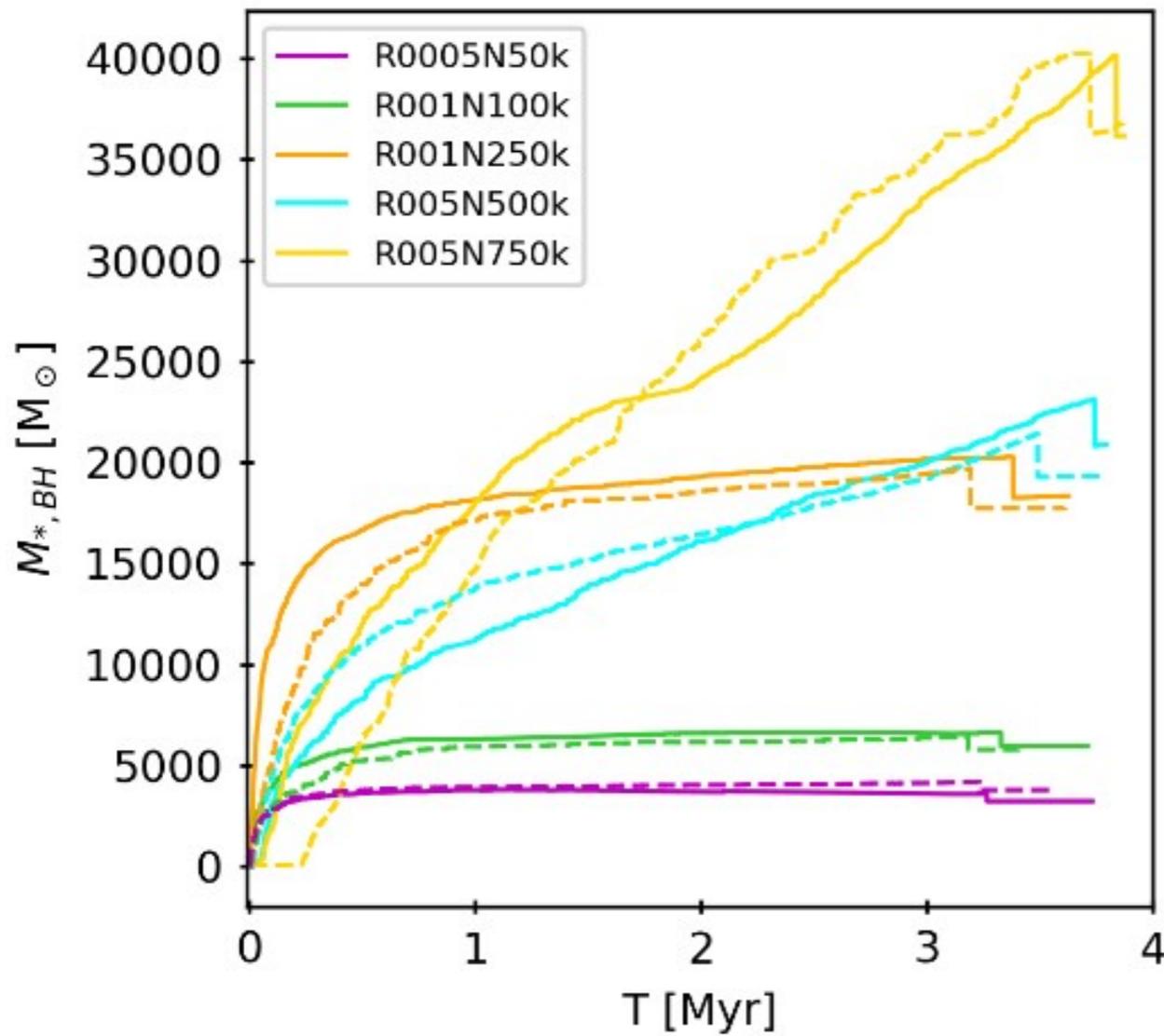
Direct N-body simulations of Young Massive Star Clusters including stellar evolution (YMCs)
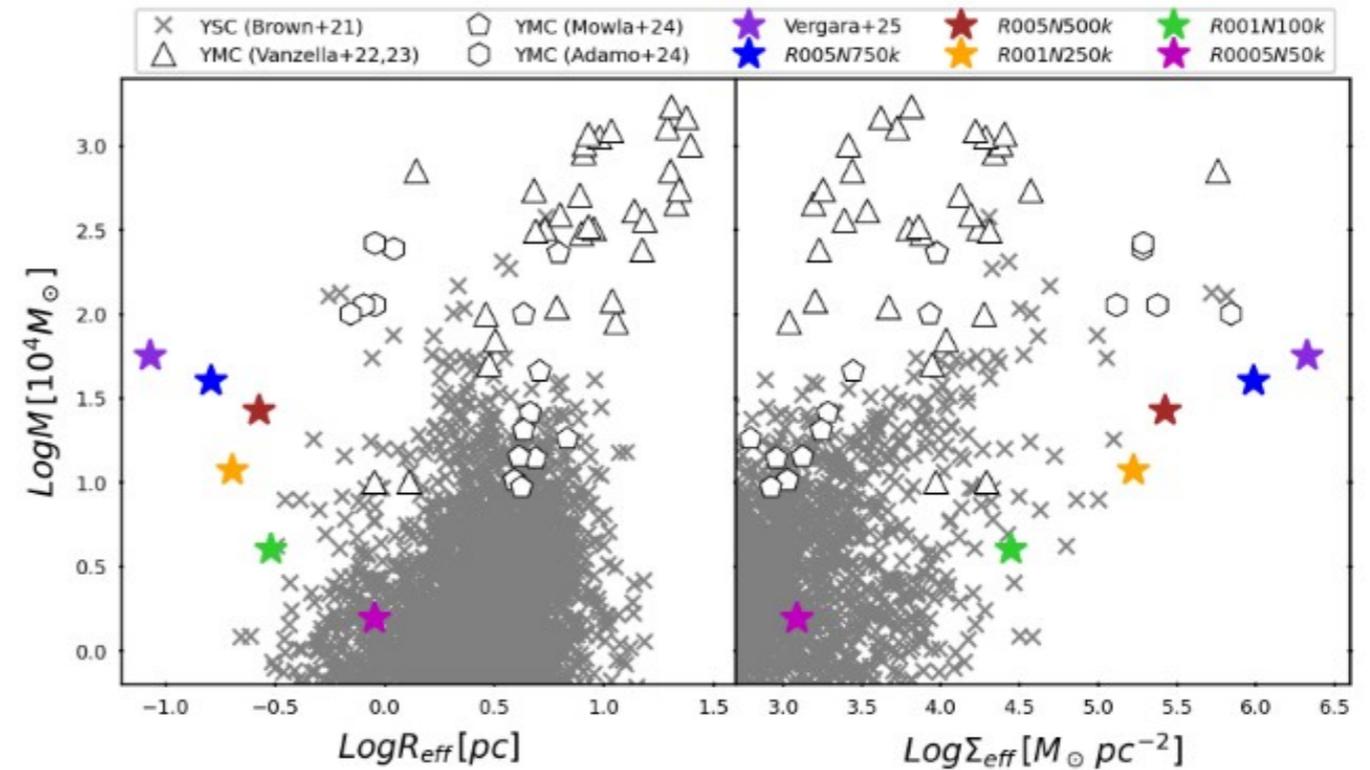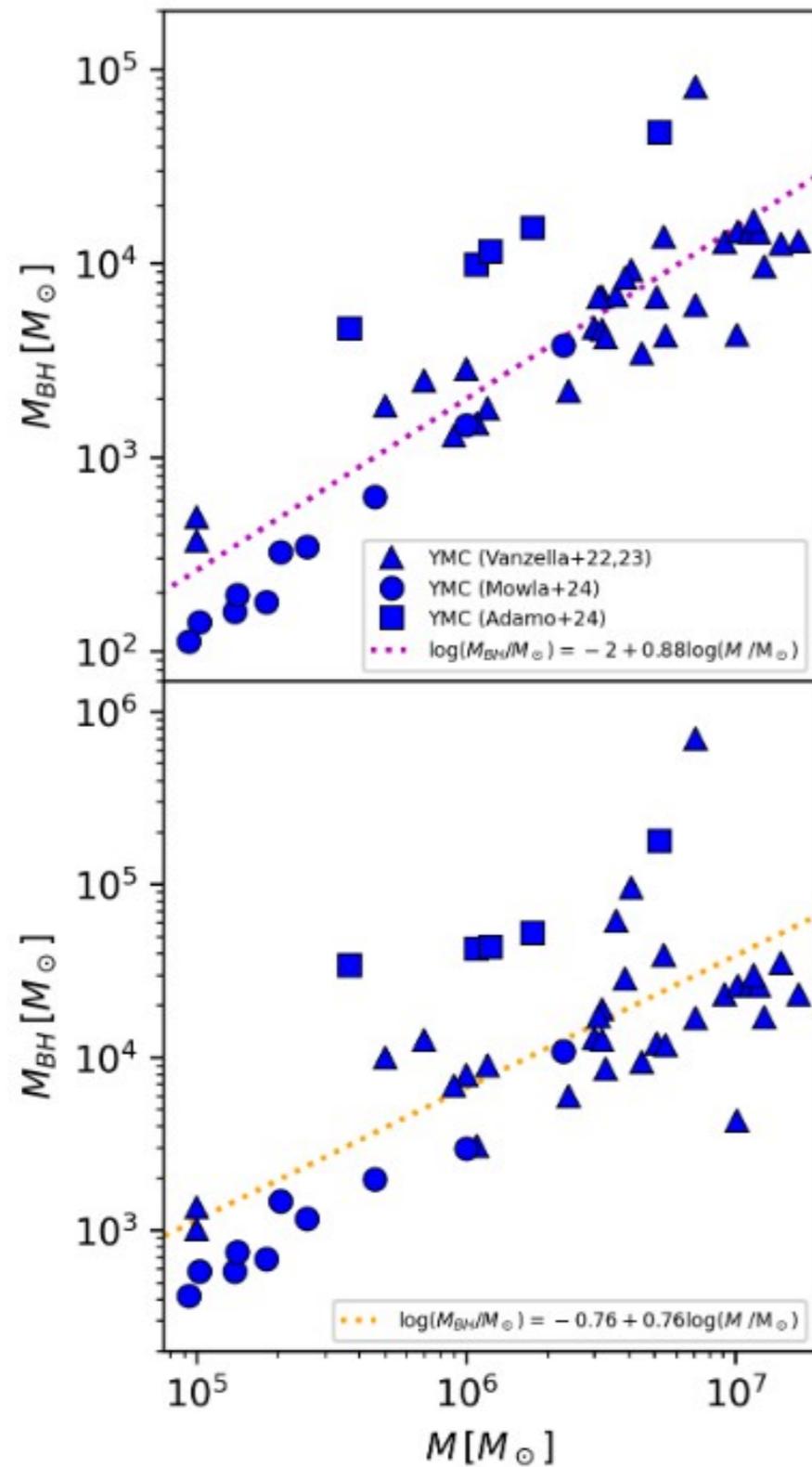

Vergara et al. 2025, submitted

Formation of massive objects in Young Massive Clusters

Efficient formation of massive black holes in Young Massive Clusters via collisions.

Vergara et al. 2025, submitted

Expected black hole masses in Young Massive Clusters

Comparison of our models with YMCs and young star clusters.
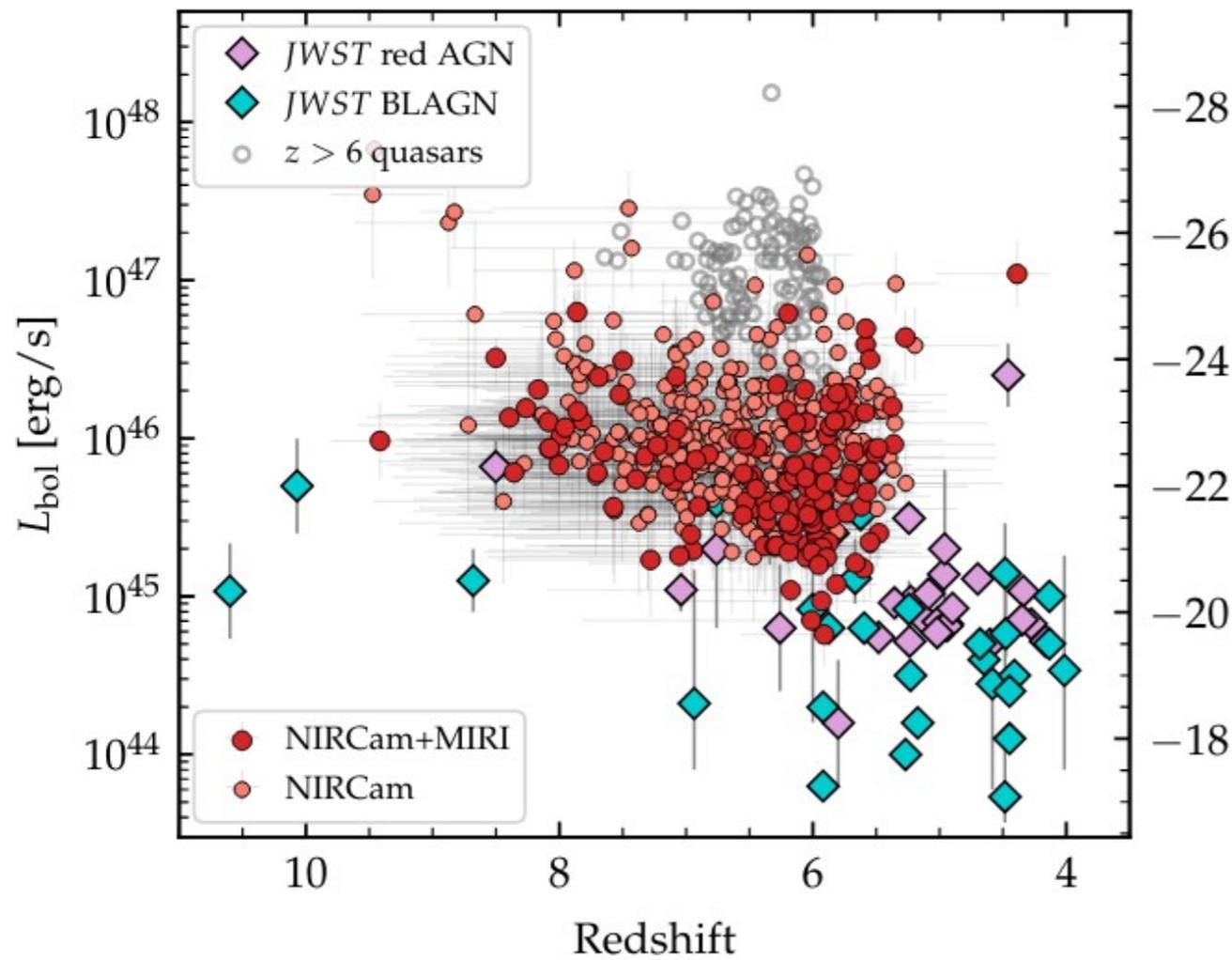
Vergara et al. 2025, submitted

Little Red Dot galaxies: Possible hosts of high-redshift black holes?
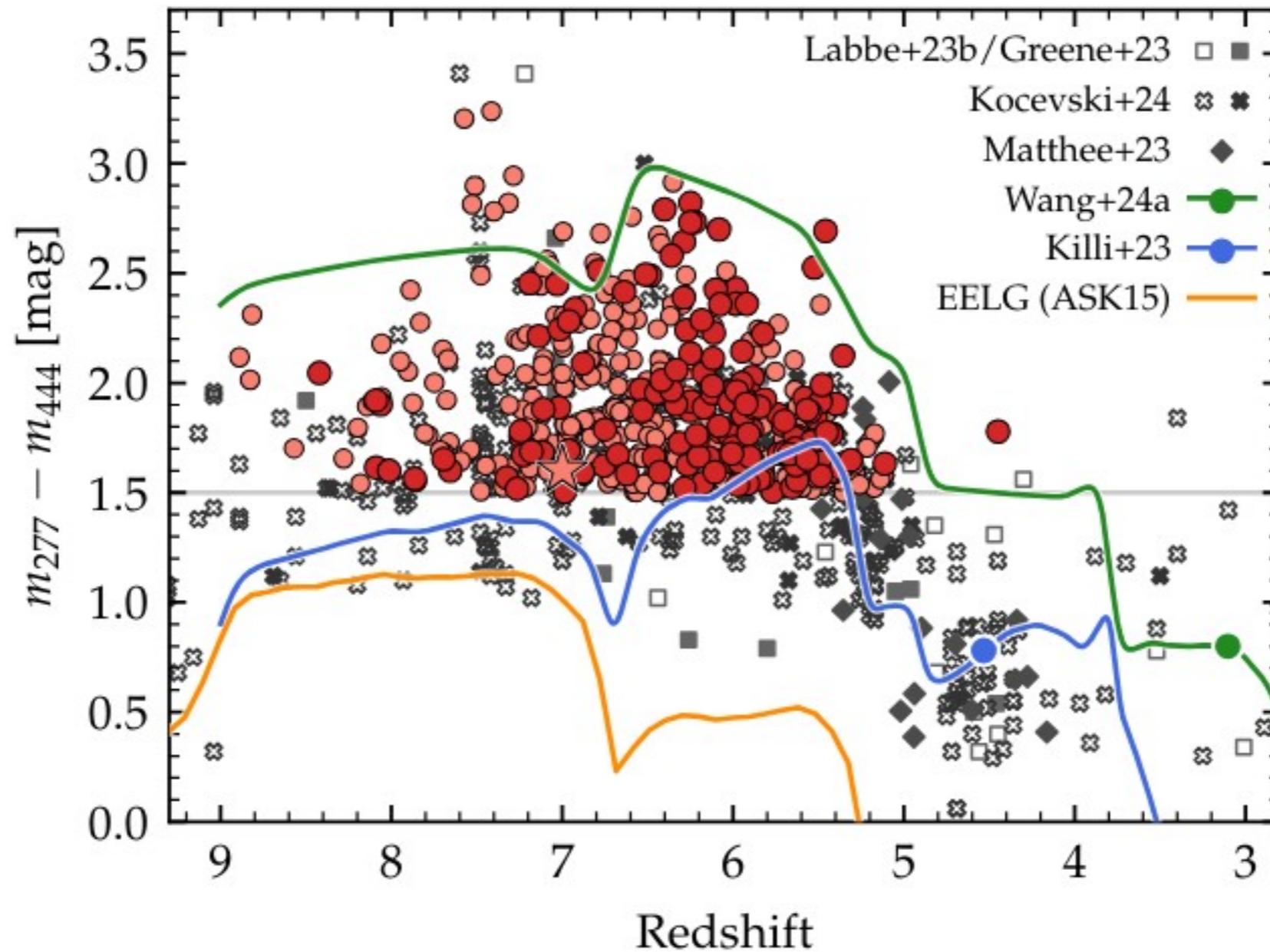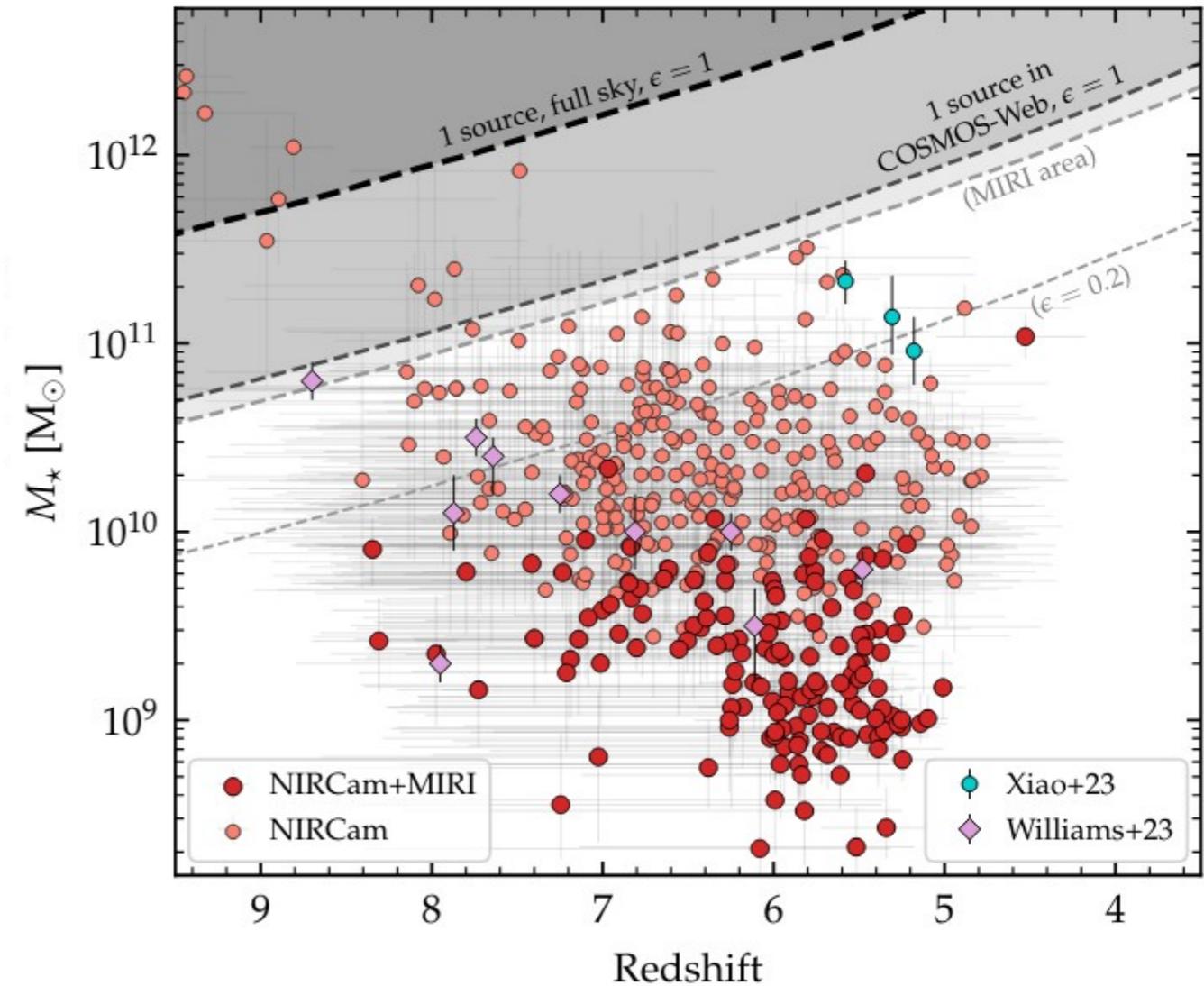

Population of compact (<300 pc), massive red galaxies discovered with JWST.

Akins et al. 2024

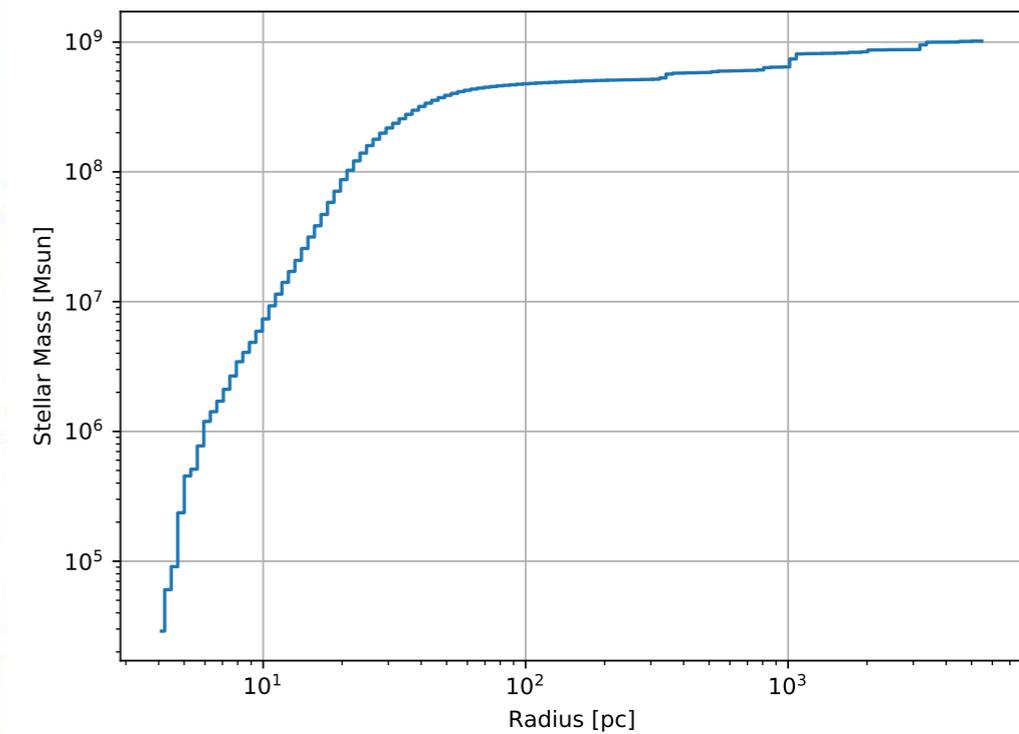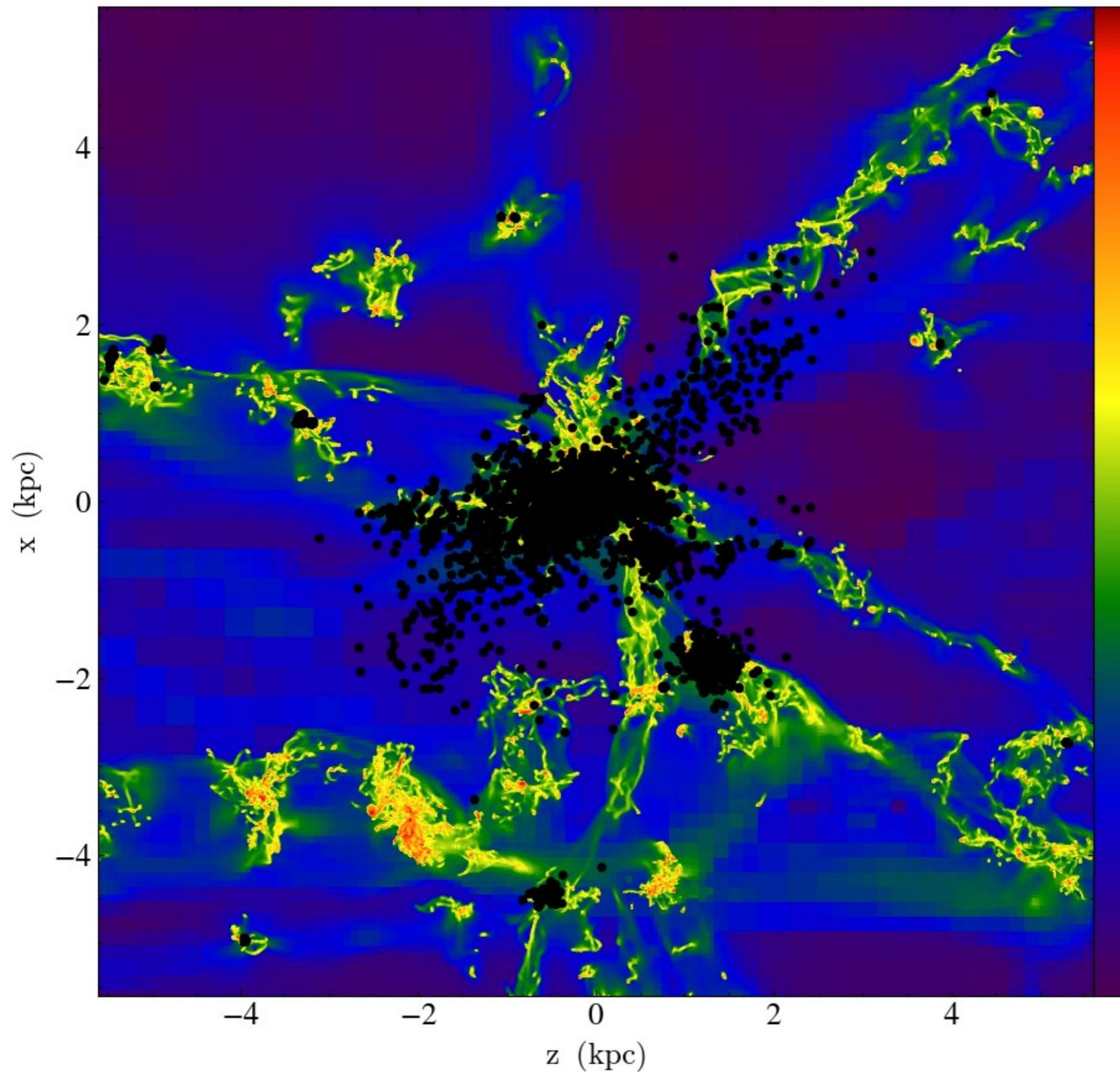# Little Red Dots: Interpretation as AGN or star-forming galaxies

Comparison to AGN identified with JWST and UV-bright quasars
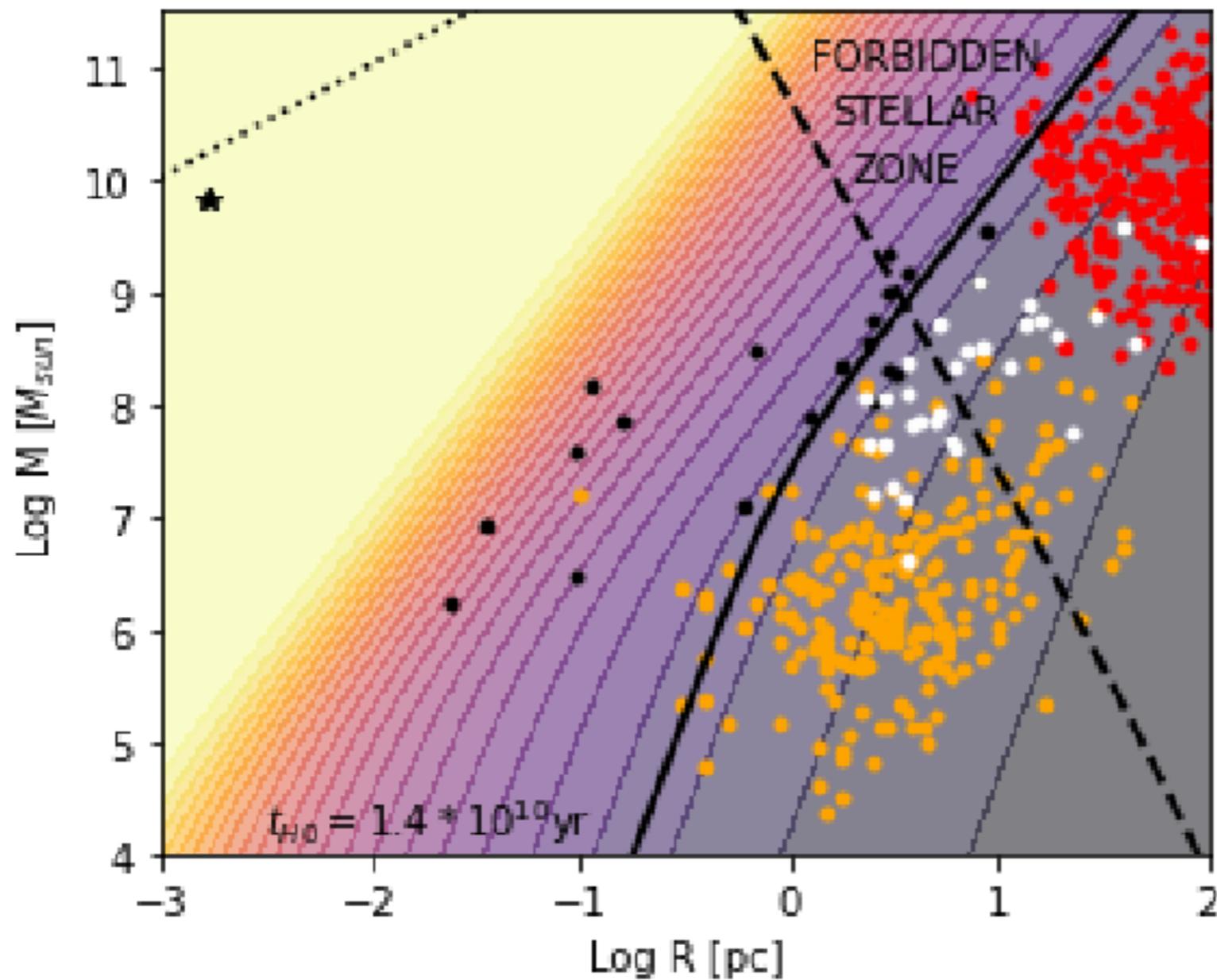
Interpretation as compact star-forming galaxies

Akins et al. 2024

Formation of Little Red Dot galaxies in cosmological simulations
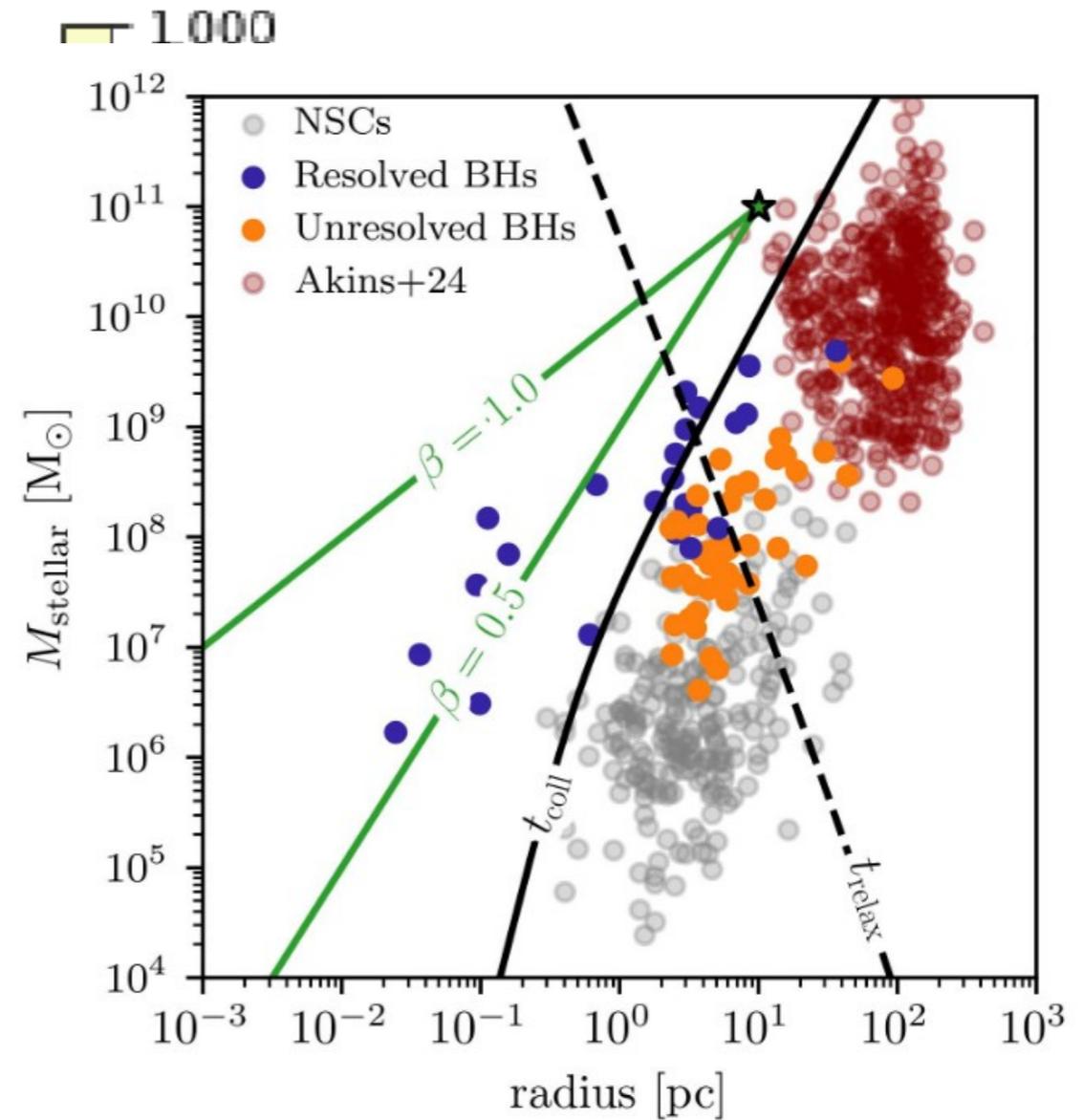

Formation of a compact galaxy with ~10^9 M_{sun} in stars and ~1.2×10^{10} M_{sun} in dark matter at redshift 12.5.

Latif et al., in prep.

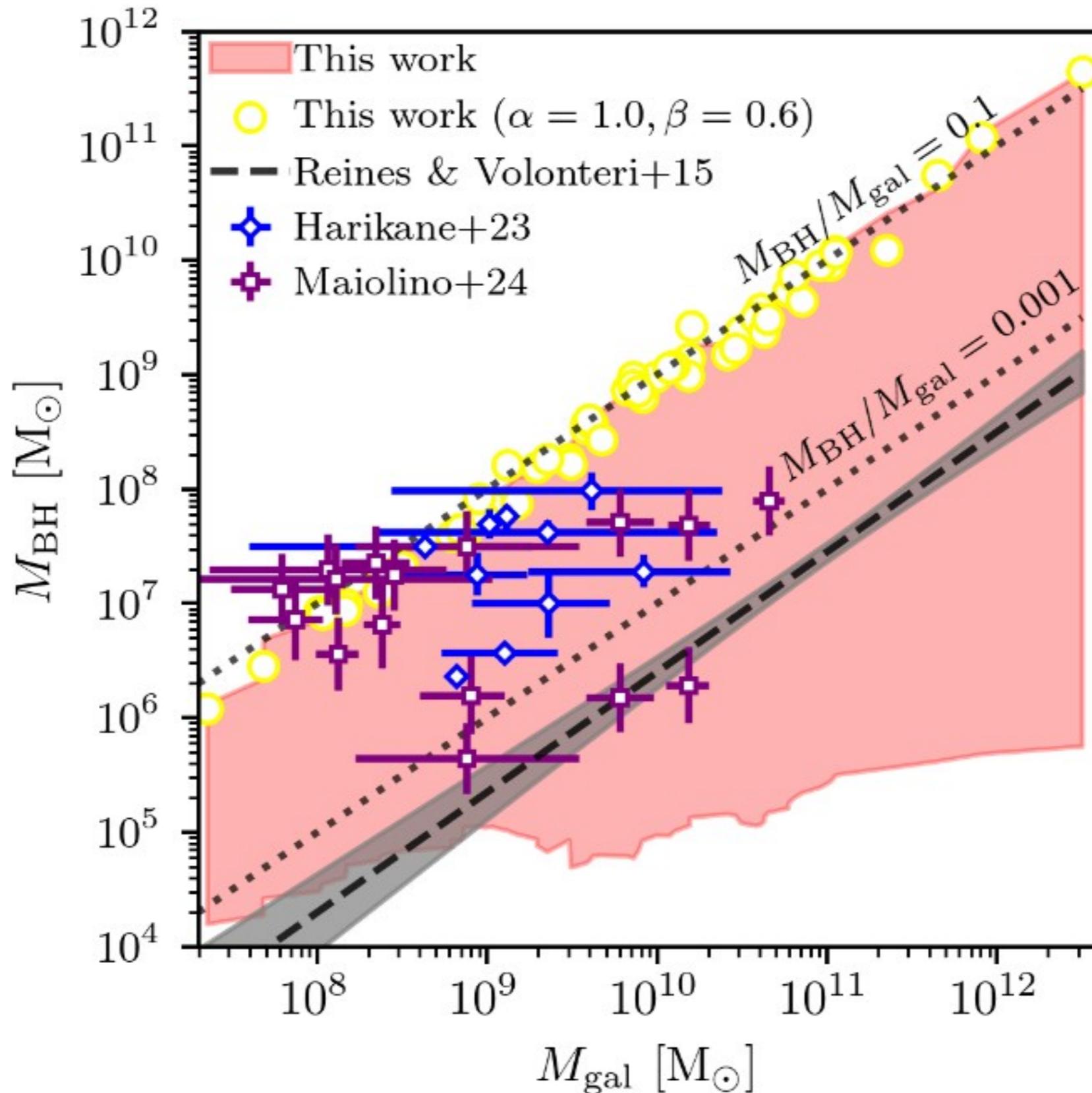# Timescales in Little Red Dot galaxies

Orange: Nuclear Star Clusters;
Red: Little Red Dots;
Black: resolved supermassive black holes;
White: unresolved supermassive black holes.
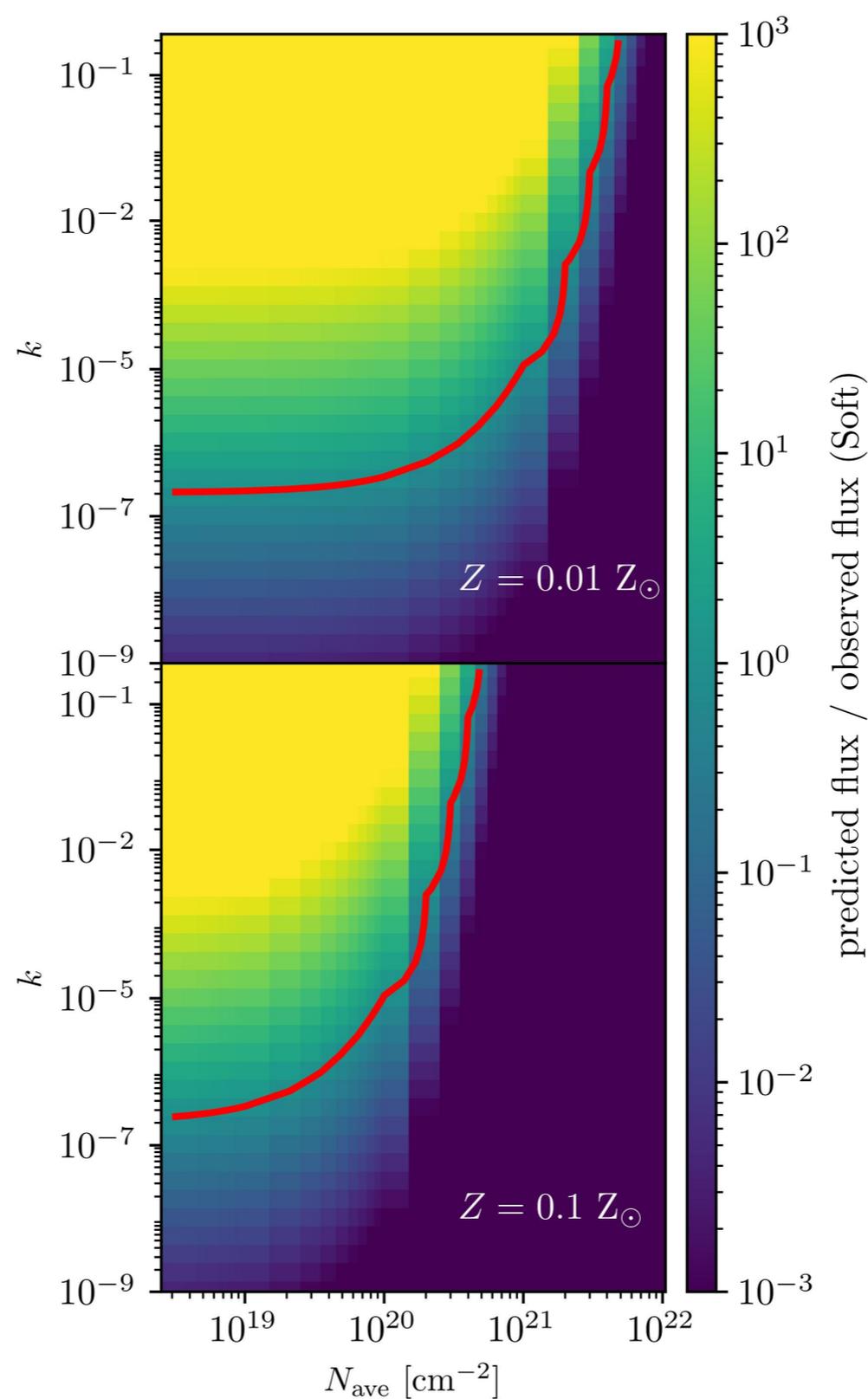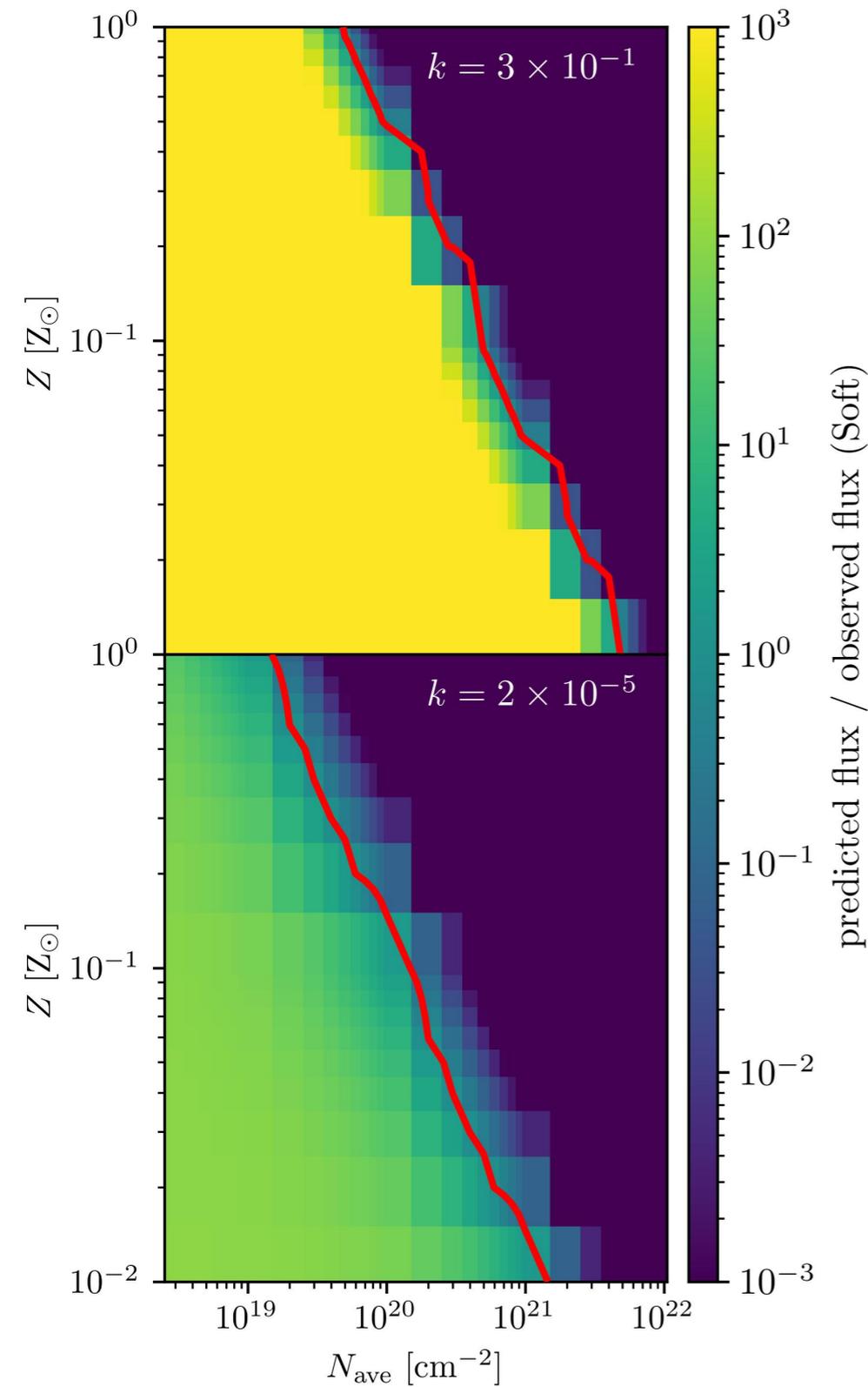
Escala et al. 2025

Liempi et al., in prep.

Expected black hole mass in LRDs from collision-based channel
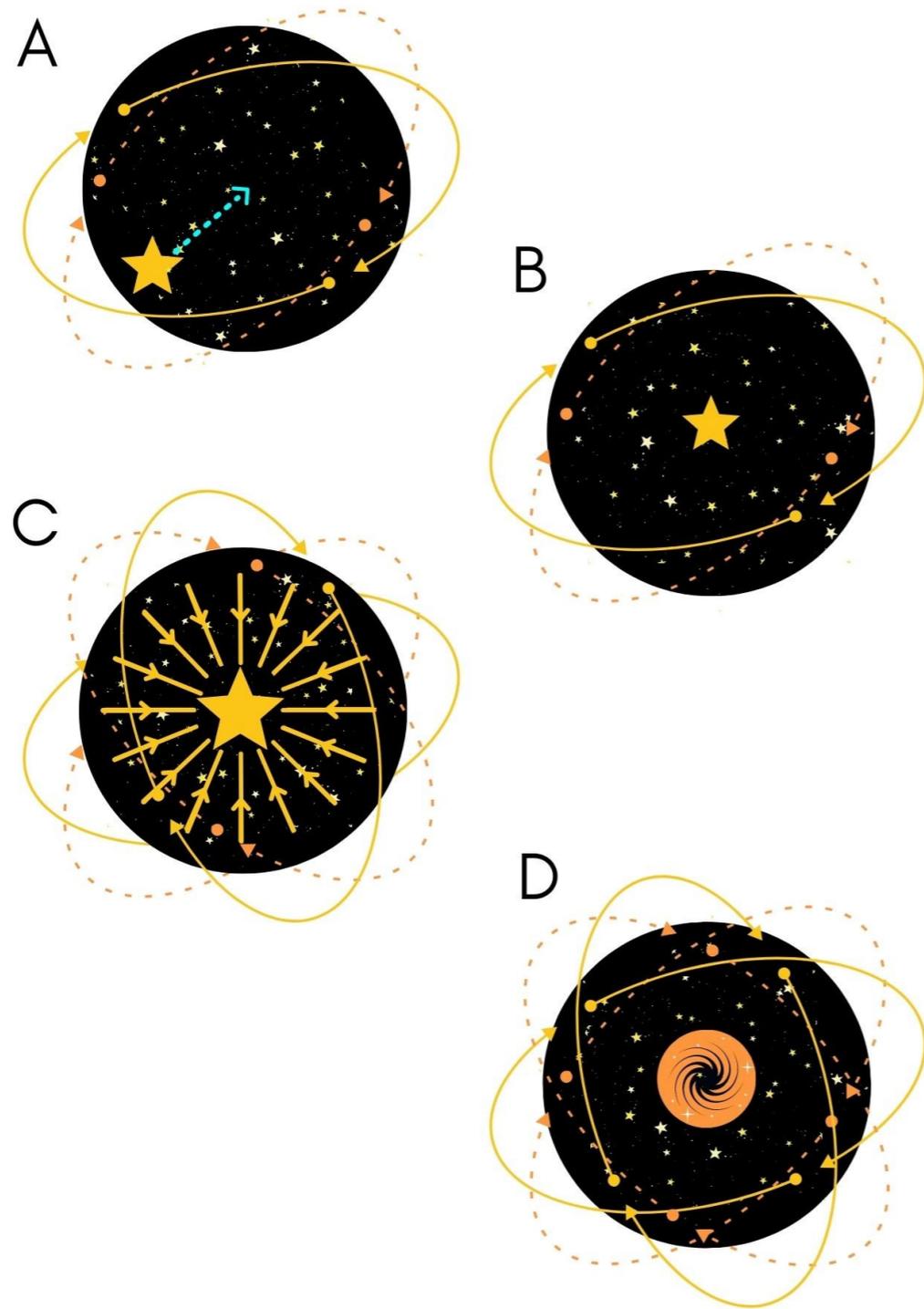

Liempi et al., in prep.

Comparison with Chandra X-ray constraints

Predicted X-ray flux versus upper limits from stacking of LRDs in the Chandra Deep Field South (CDF-S) by Sacchi & Bogdan (2025).

Liempi et al., in prep.

$$L_X = \underbrace{f_{\text{occupation}}^{\text{BH}} U_{\text{duty}} \epsilon_{\text{Edd}} \epsilon_X}_{k} L_{\text{Edd}},$$
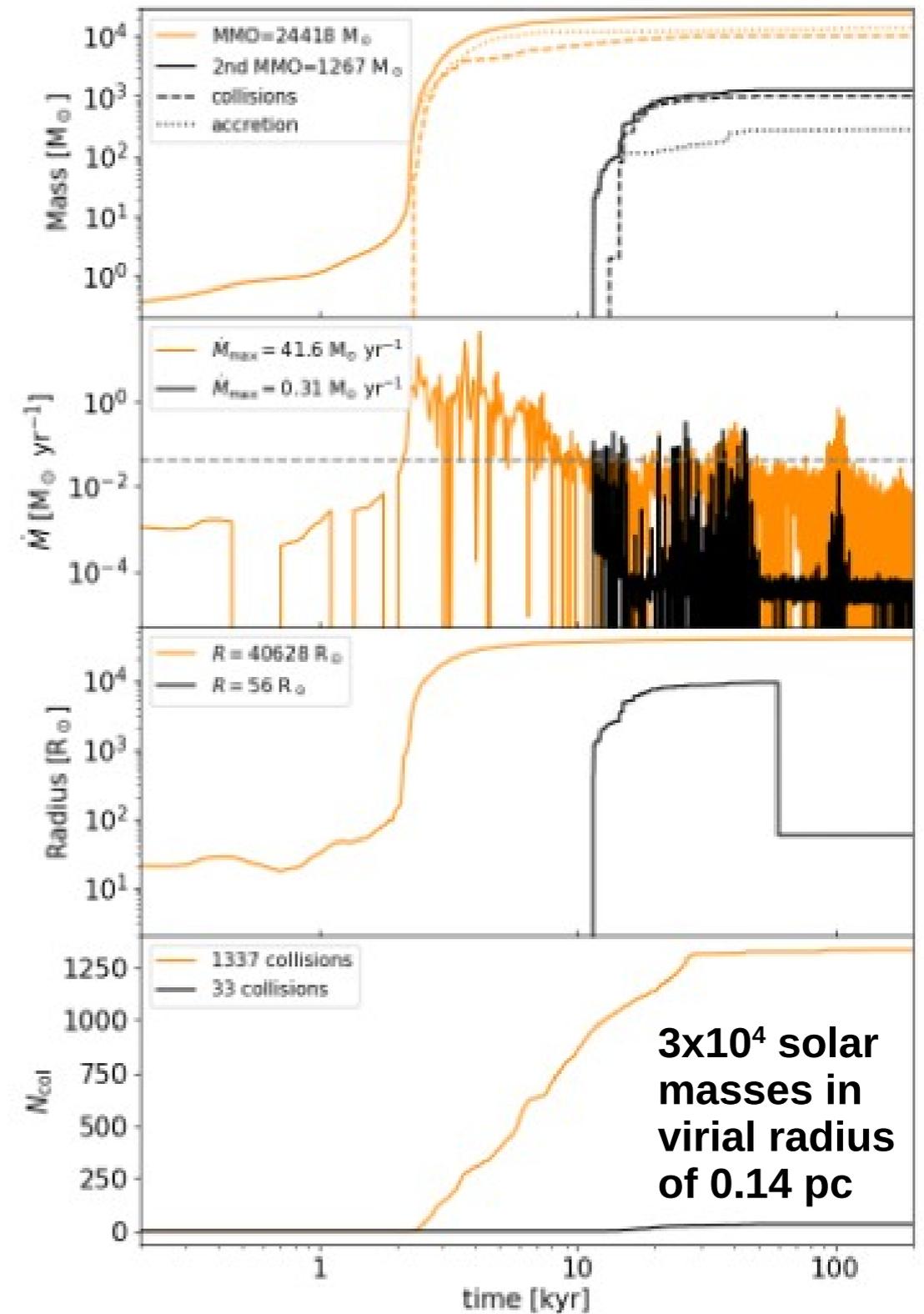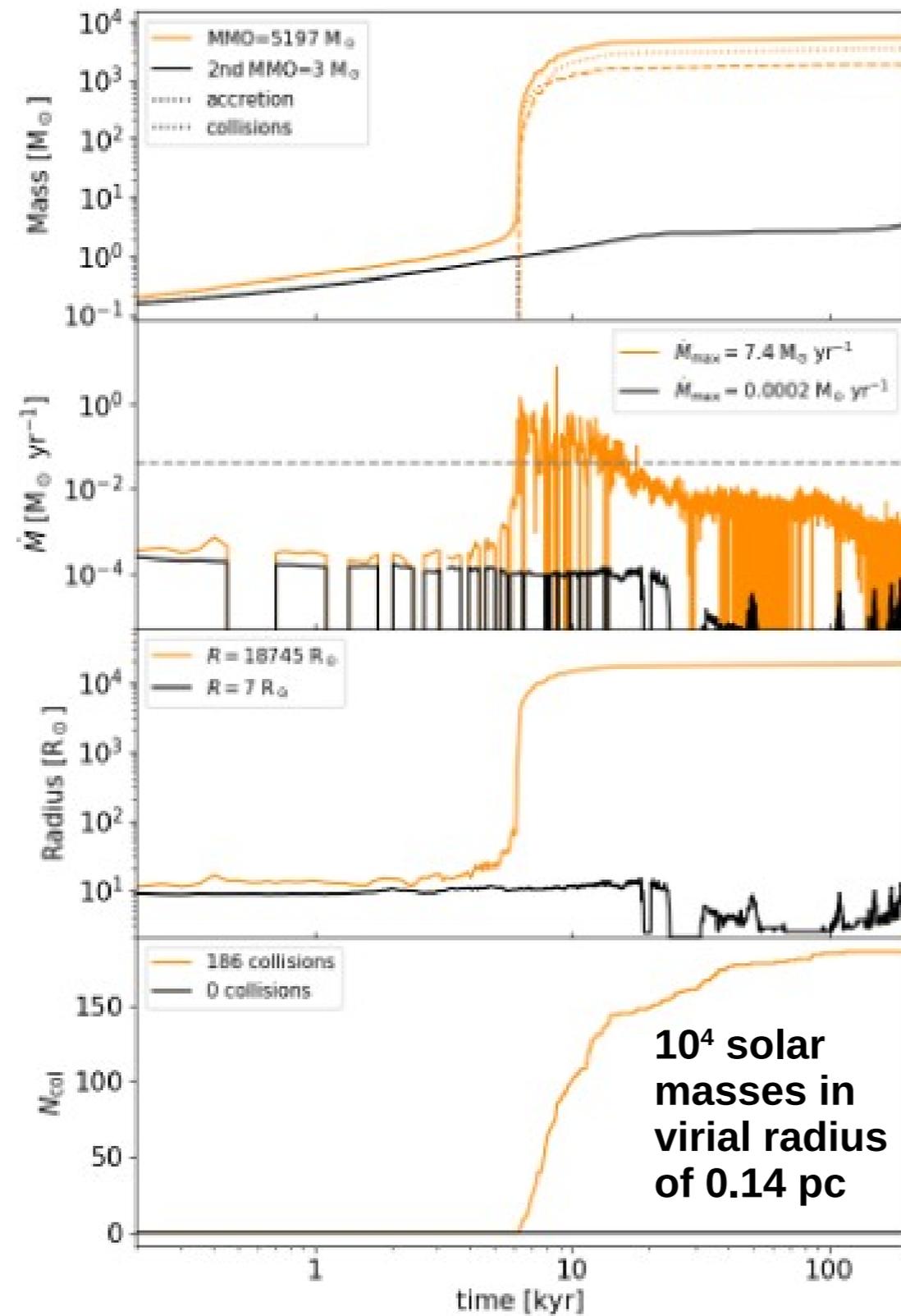
Black hole formation via collisions and accretion

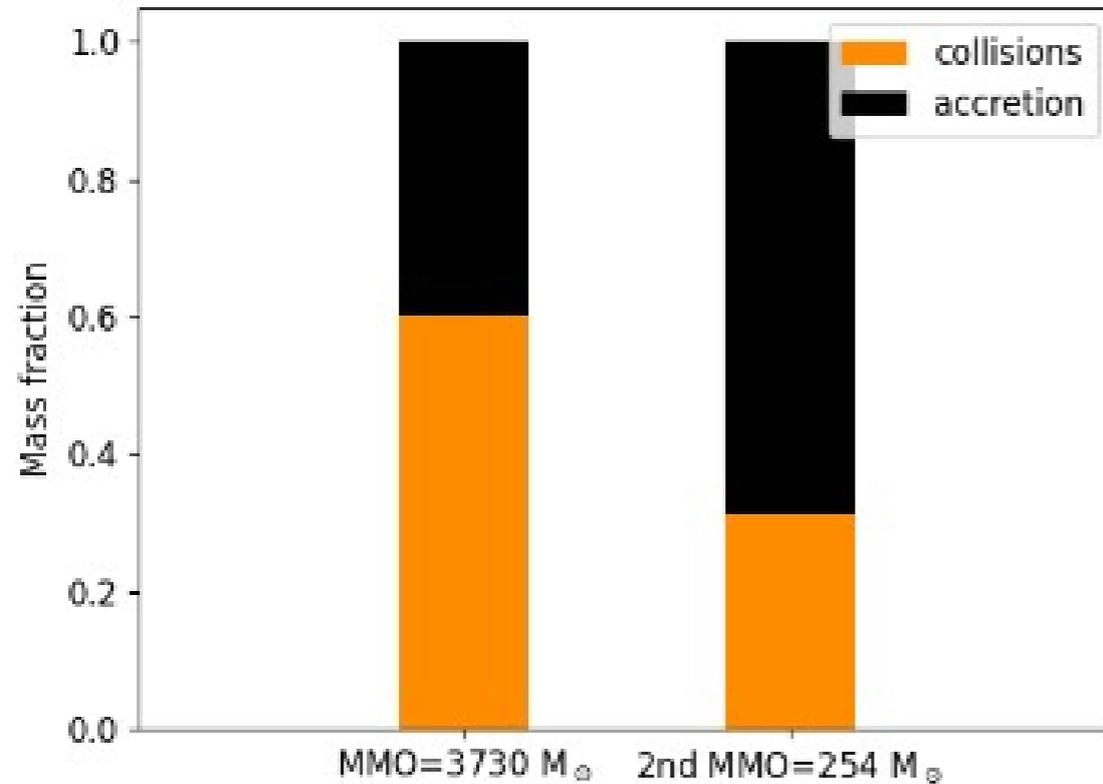- Potential to form very massive objects in dense compact clusters embedded in gas.

- Presence of gas enhances dynamical friction and contributes to growth via accretion.

Schleicher et al. (2022)
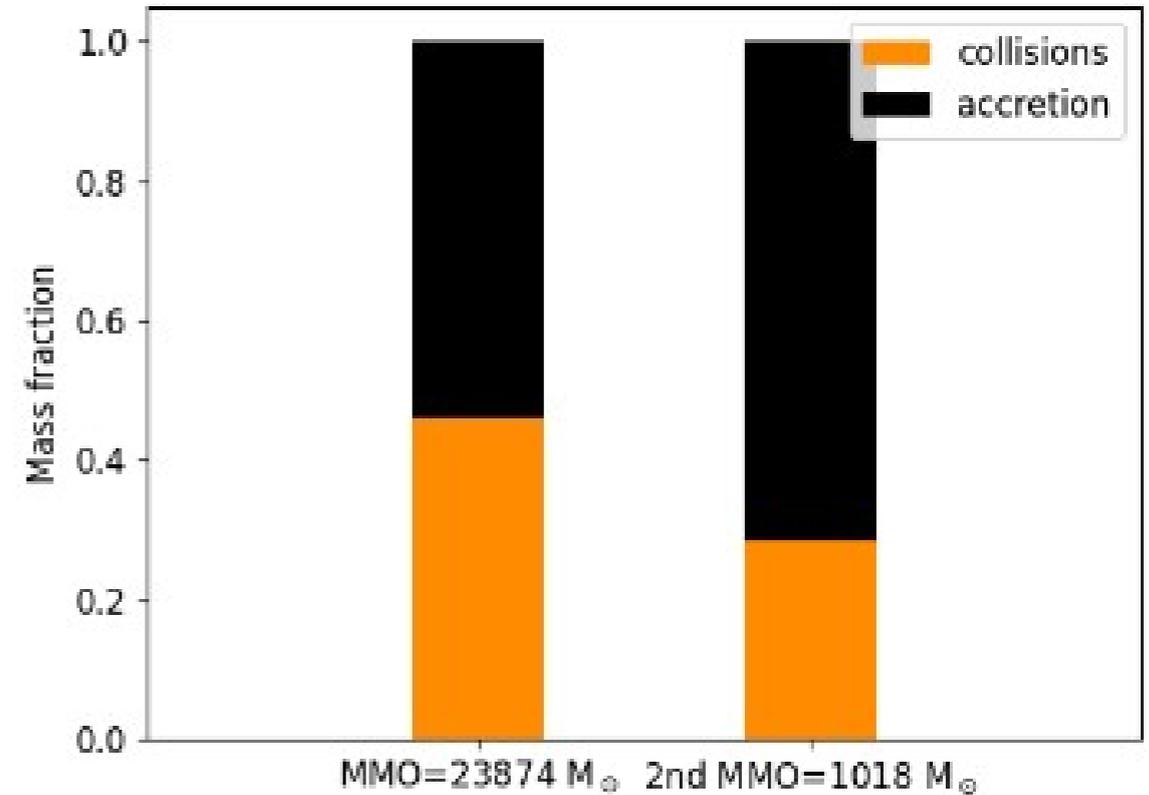
Simulations following gas- and stellar dynamics with AMUSE

Reinoso et al. (2023)

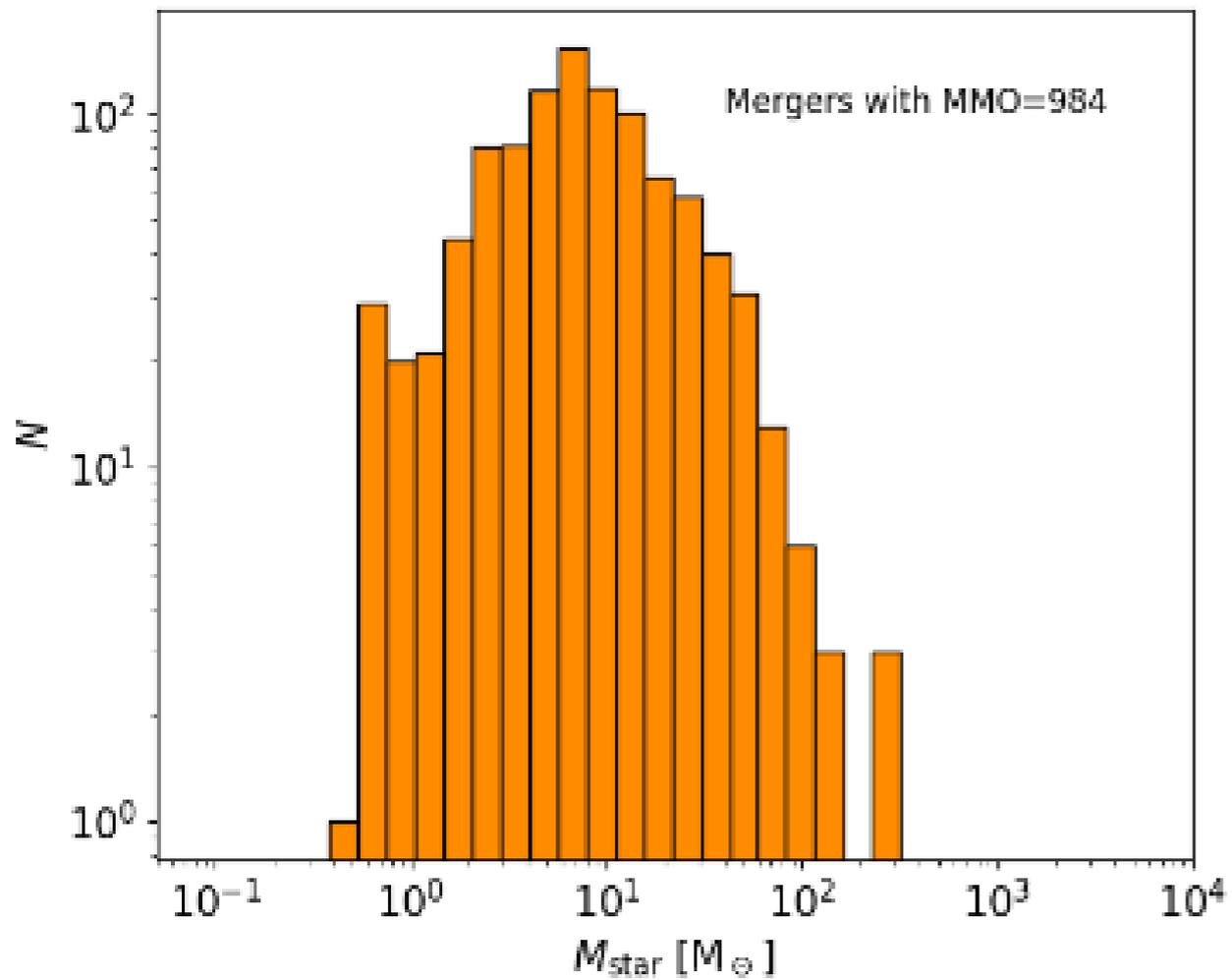# Growth via collisions vs accretion

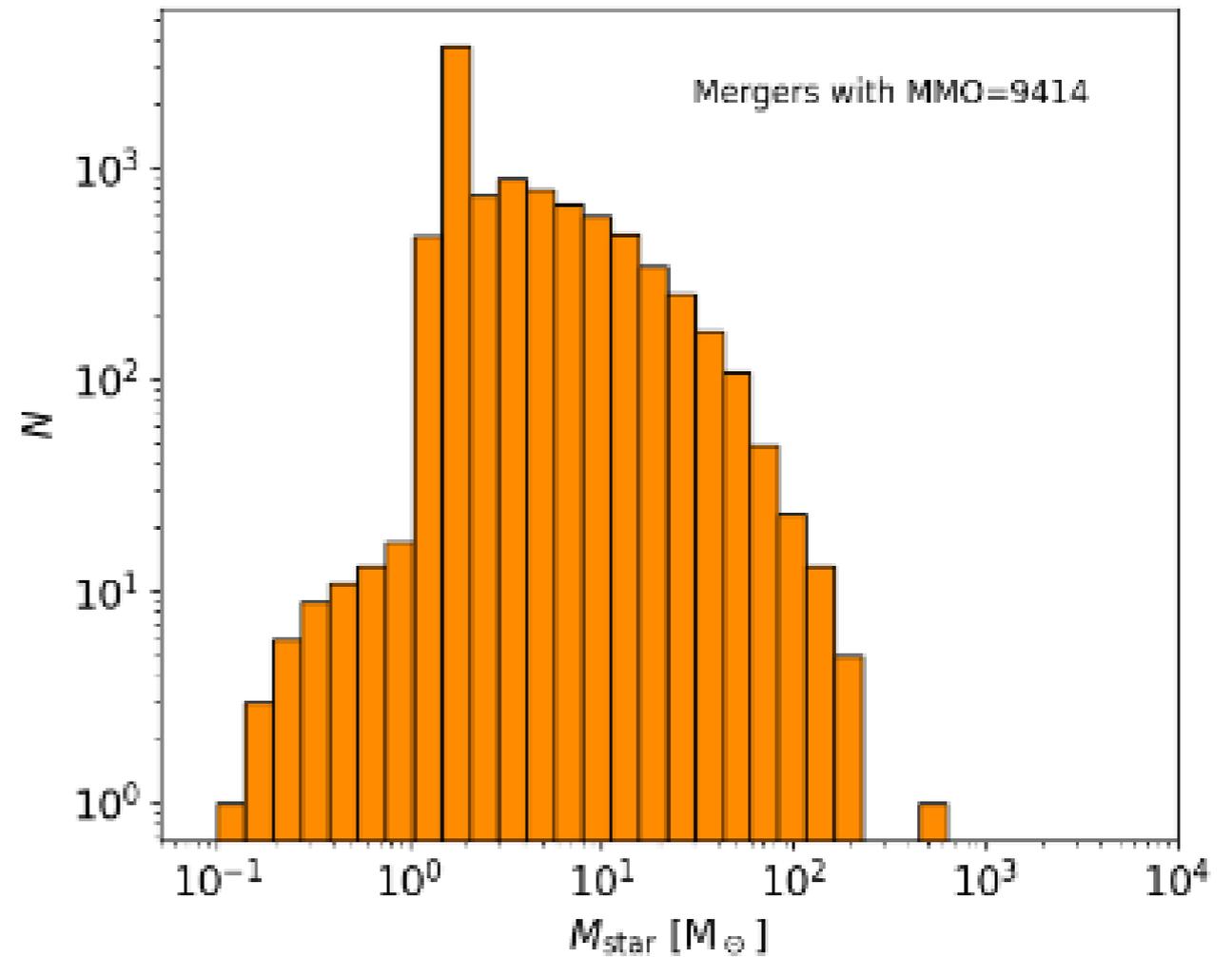
10⁴ solar mass cloud

3x10⁴ solar mass cloud

Significant contributions to growth via accretion and collisions.

Reinoso et al. (2023)

Mass distribution of stars merging with central object
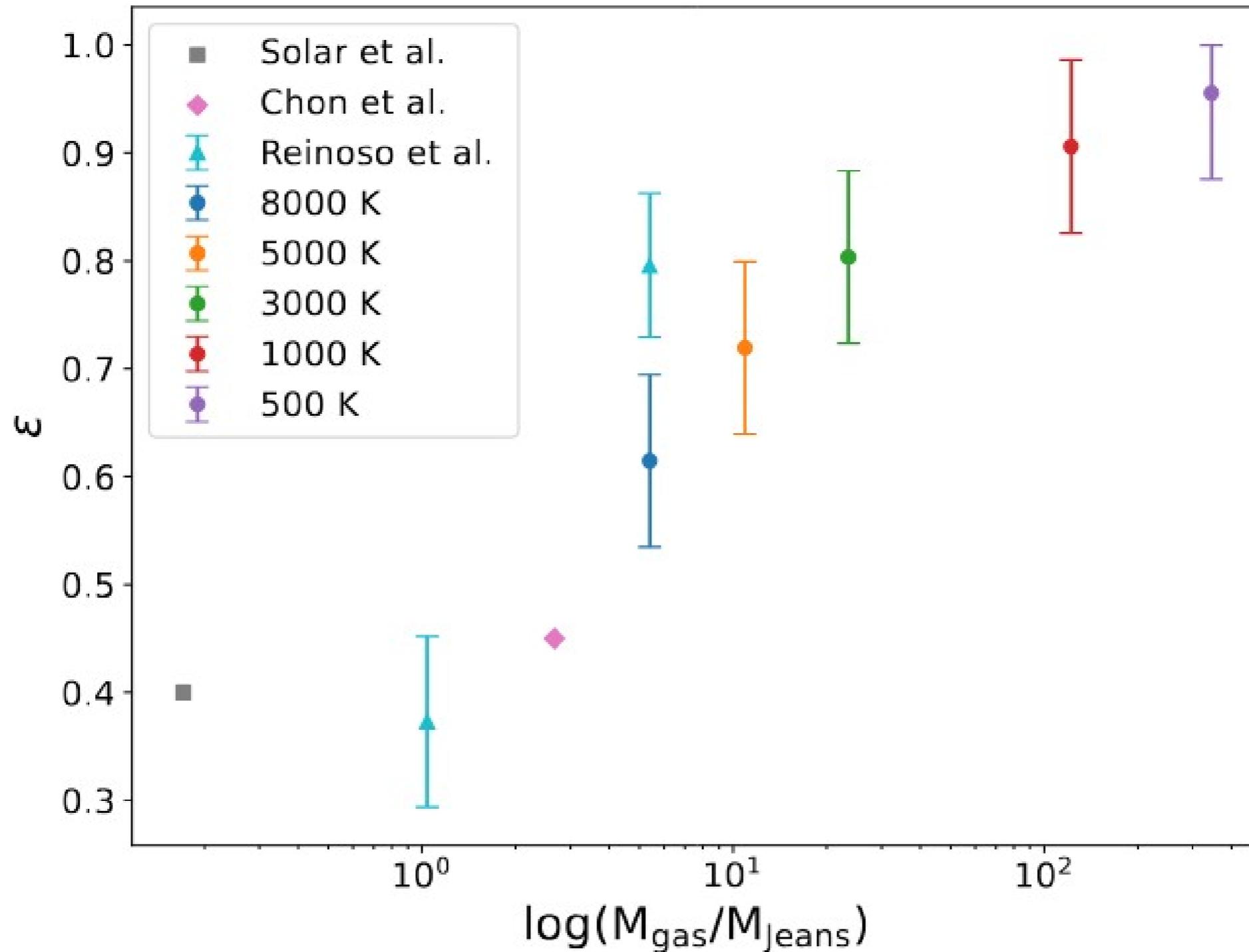

10⁴ solar mass cloud

3x10⁴ solar mass cloud

Mass growth per collision in the range of ~1 to 100 M$_{sun}$

Reinoso et al. (2023)

Efficiency to form massive object versus instability of the gas cloud

Solar et al. (2023)

Summary and conclusions

- Formation of central massive objects via collisions in dense massive clusters strongly supported by numerical simulations and observations from the Local Universe.

- Young Massive Star Clusters detected by JWST are ideal formation sites for intermediate-mass black holes.

- Efficient black hole formation via collision-based and gas-based channels.

- Little Red Dot galaxies suspected to harbor supermassive black holes at high redshift.

- Supermassive black hole formation in Little Red Dots compatible with Chandra constraints.