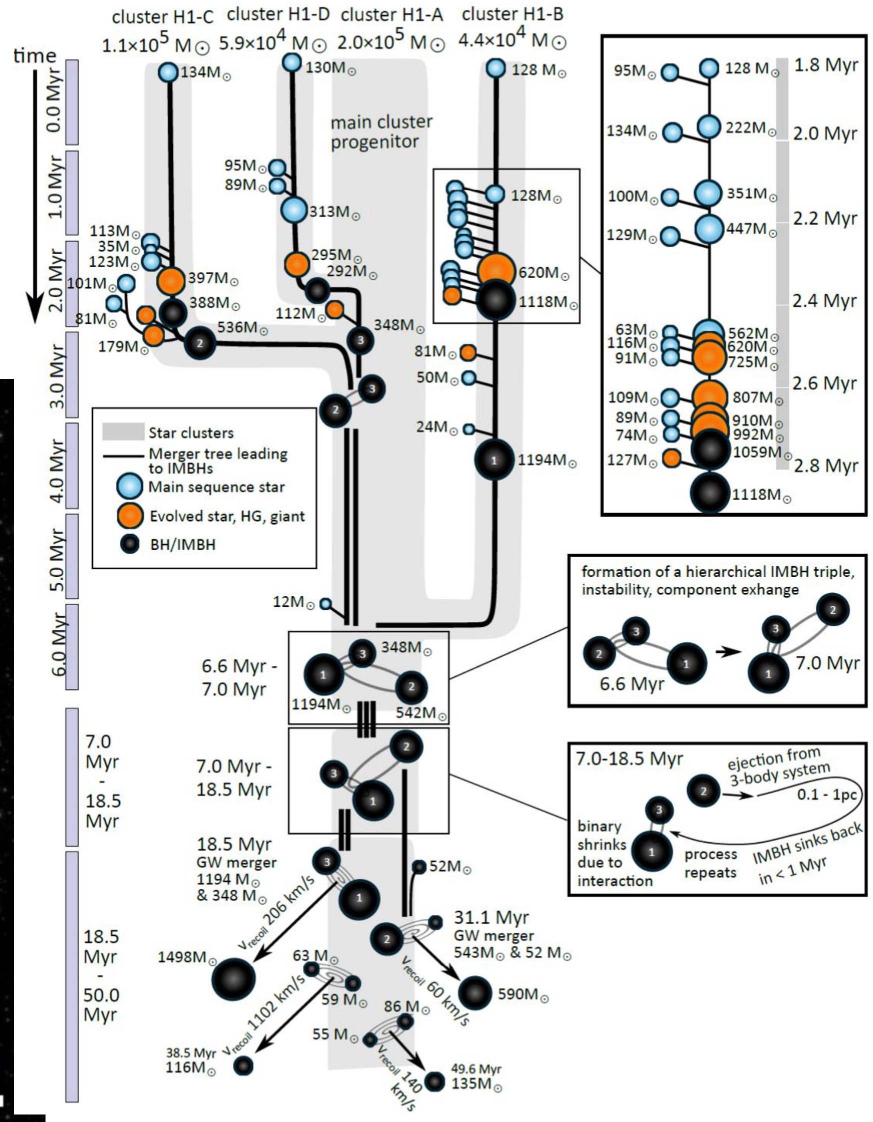
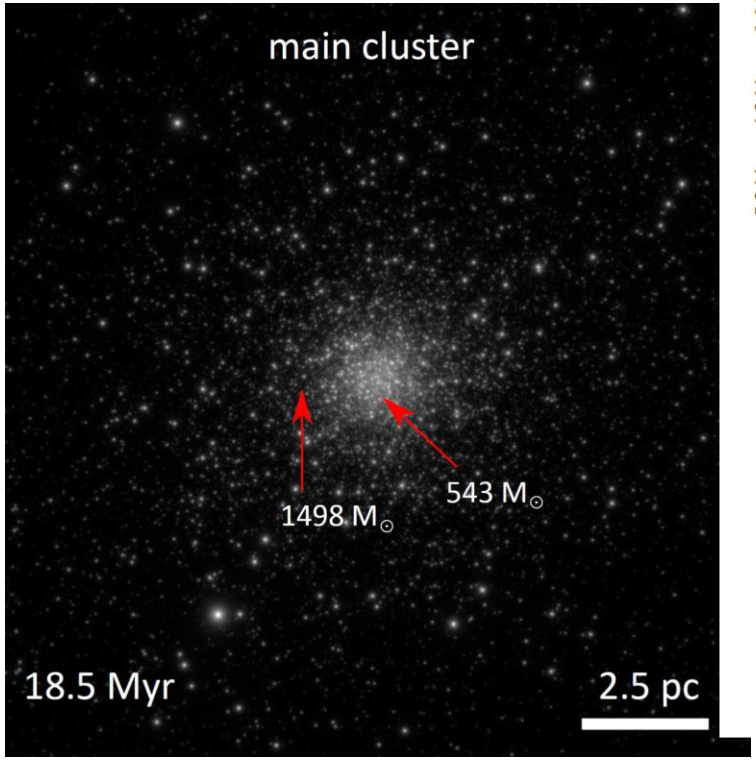
SMBH seeds and GWs from dense, low-metallicity star formation





$$\mathbf{e}^{\epsilon \mathbf{H}} = e^{\frac{1}{6}\epsilon \mathbf{U}_{\mathrm{SF}}} e^{\frac{1}{2}\epsilon \mathbf{H}_{\mathrm{S}}} e^{\frac{1}{2}\epsilon \mathbf{H}_{\mathrm{F}}} e^{\frac{2}{3}\epsilon \tilde{\mathbf{U}}_{\mathrm{SF}}} e^{\frac{1}{2}\epsilon \mathbf{H}_{\mathrm{F}}} e^{\frac{1}{2}\epsilon \mathbf{H}_{\mathrm{S}}} e^{\frac{1}{6}\epsilon \mathbf{U}_{\mathrm{SF}}}$$

Antti Rantala

MPA Postdoctoral Fellow

Thorsten Naab, Natalia Lahén

MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK

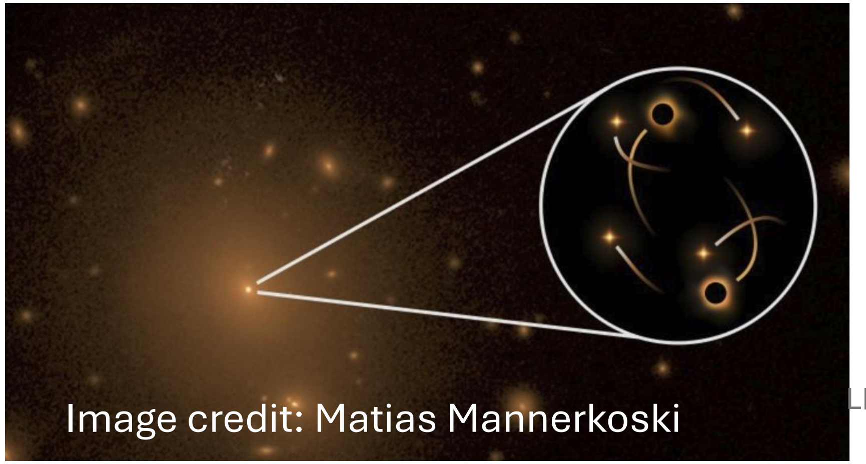
My work

KETJU

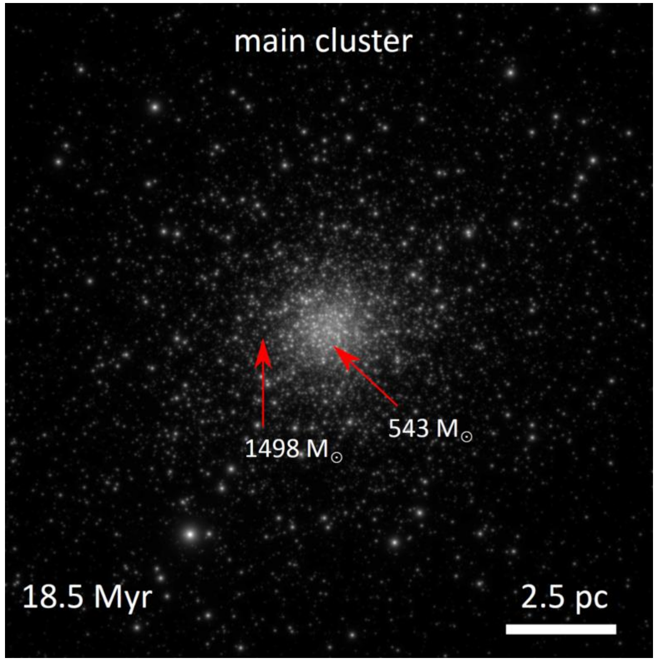
- Modelling BHs of all masses in their stellar-dynamical environments...
- ... with novel integrators and HPC codes I have developed

BIFROST

- Galaxies and their supermassive black holes (SMBHs)
- public dynamics library → Peter Johansson‘s group homepage
- talks by Alex Rawlings and Atte Keitaanranta, Nianyi Chen



- Massive star clusters including collisional SMBH seed formation



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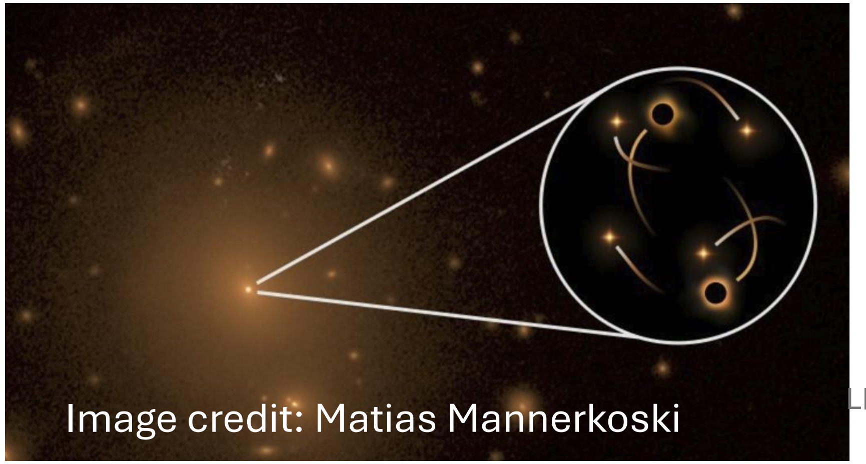
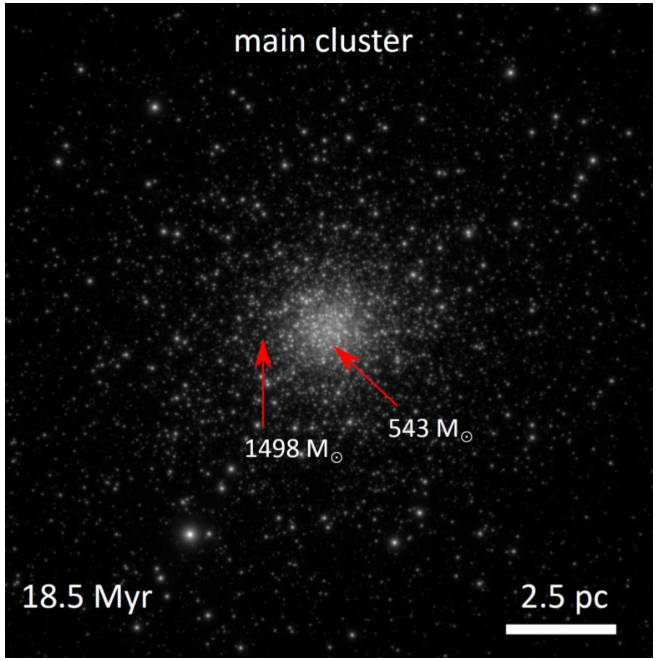


An one-slide first look after the main talk: *the new faster KETJU*



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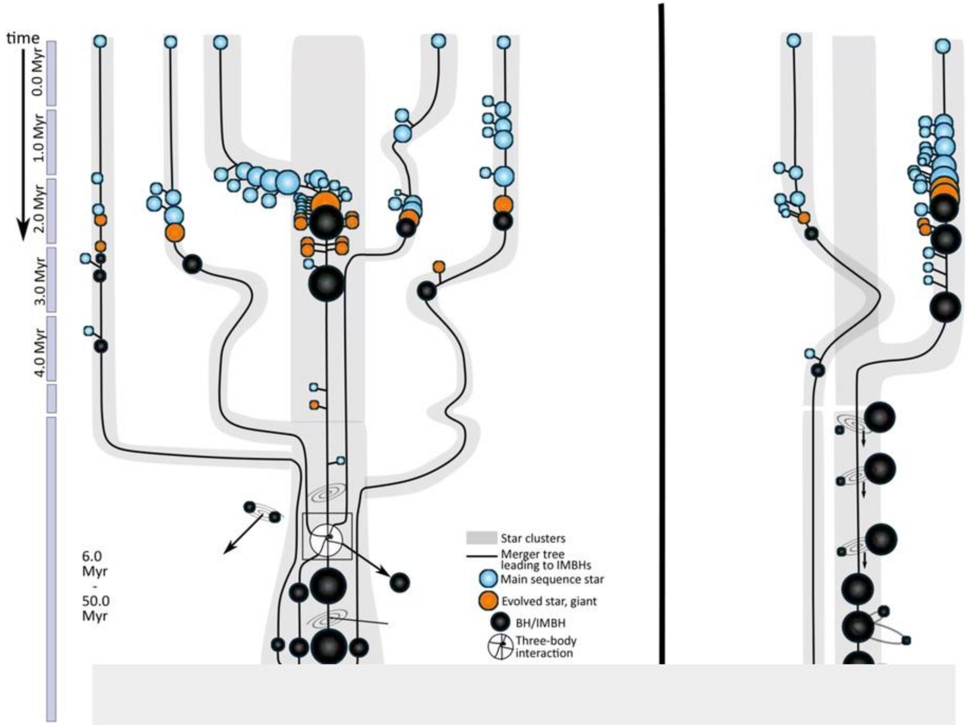
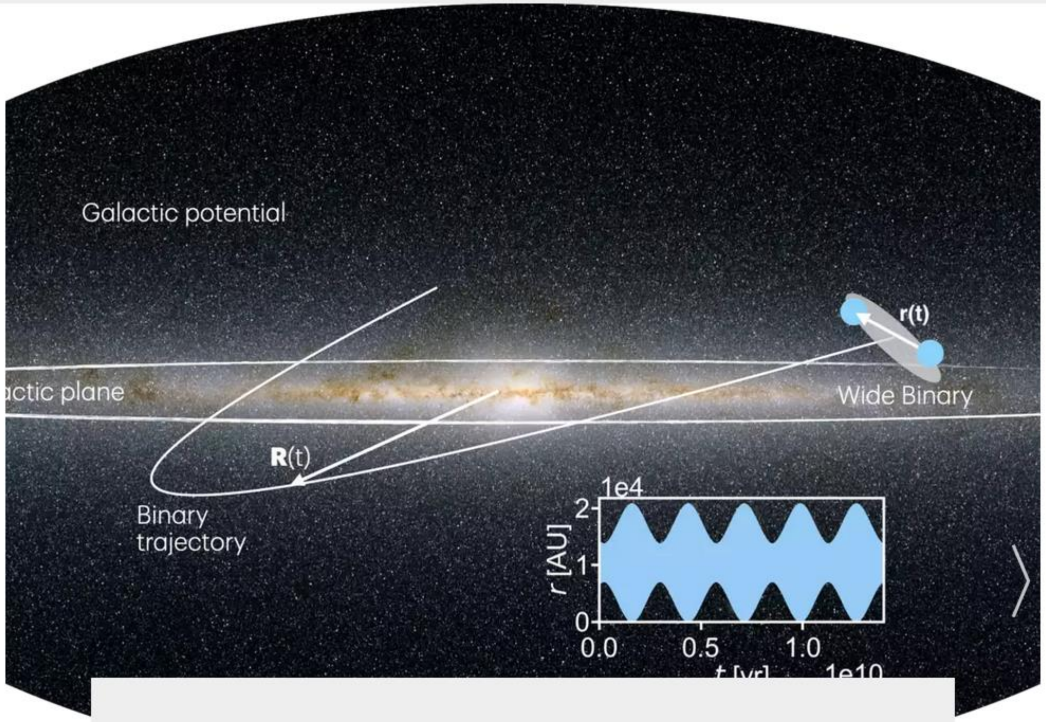


Rapidly merging stars and black holes



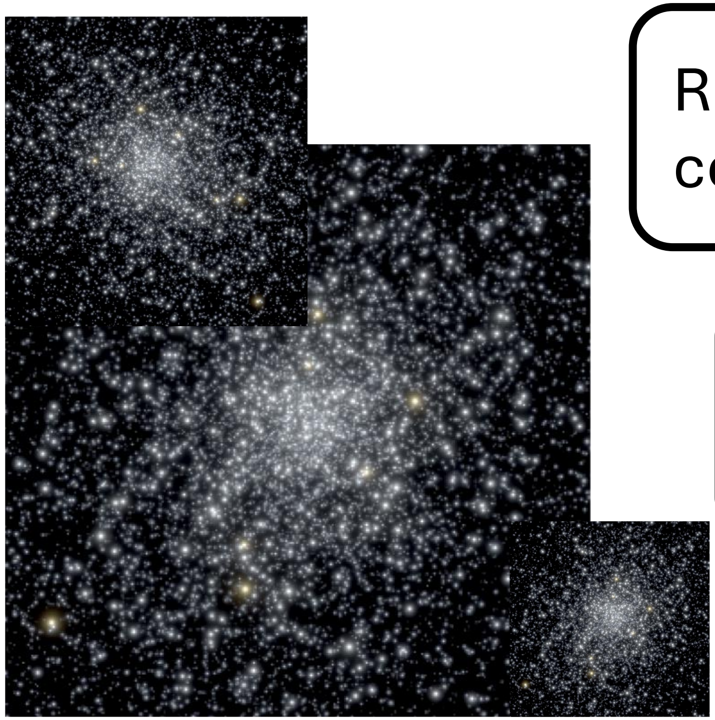
How galaxies make black holes collide

Jakob‘s galactic binaries

MPA homepage highlight this month

The SMBH seed origin puzzle

Proposed SMBH seeding mechanisms



Directly collapsing gas clouds

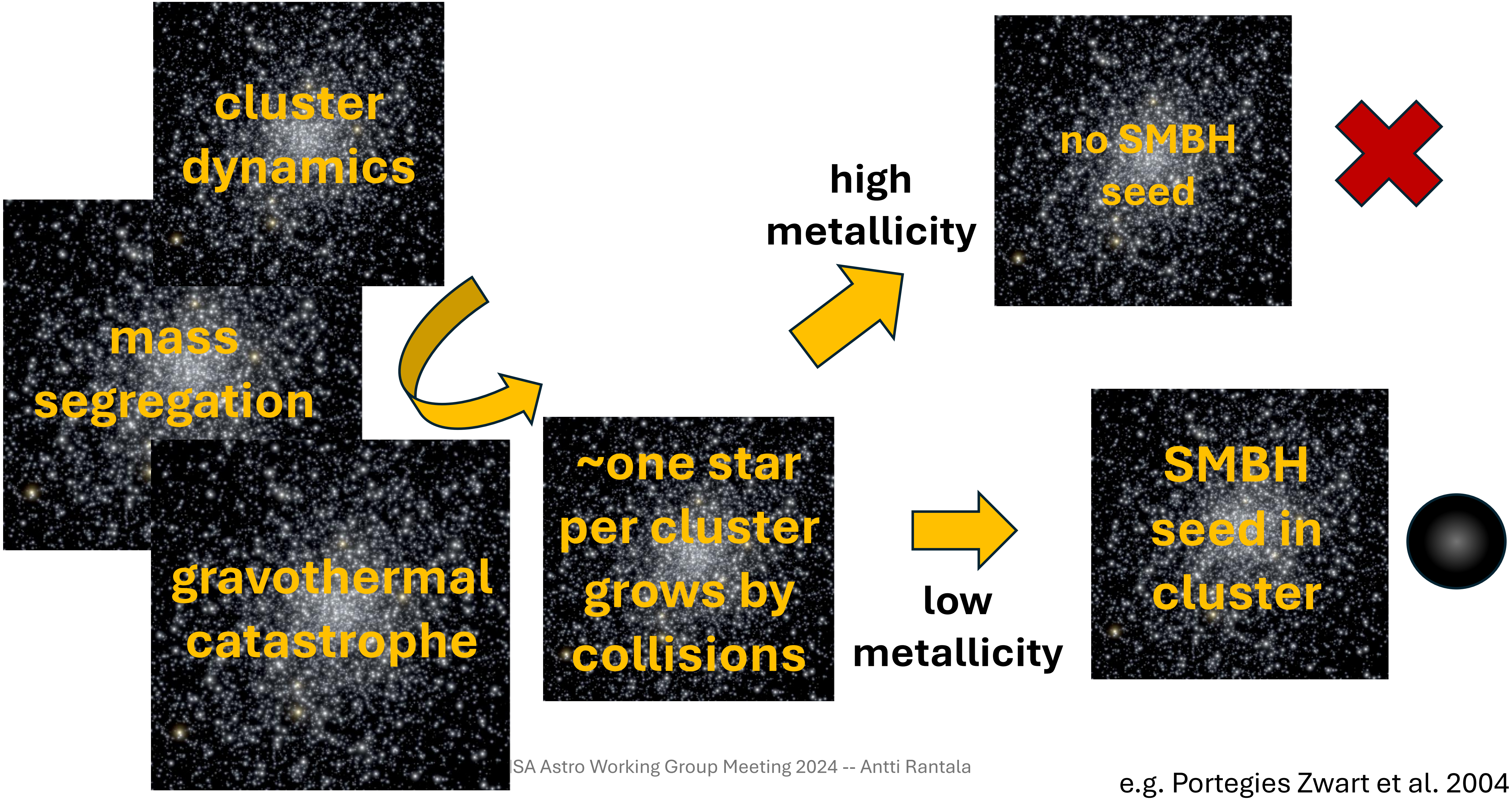
Runaway stellar collisions

Stellar remnants

Exotic “new” physics

Natural consequence of clustered, dense, low-metallicity star formation in the early Universe?

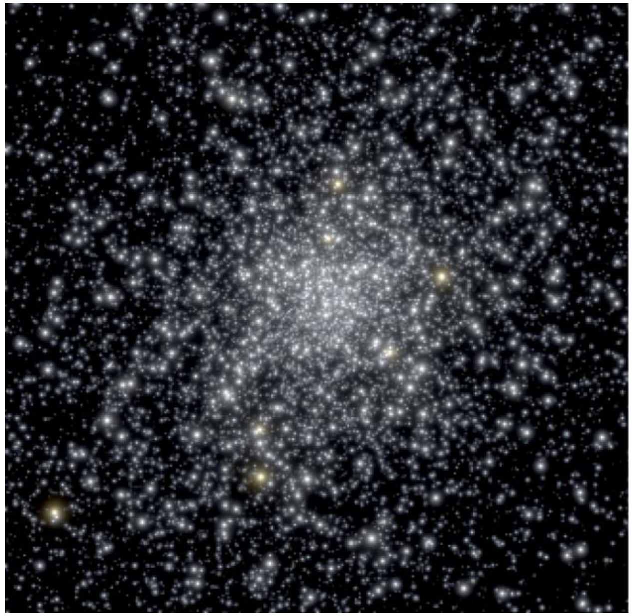
SMBH seeds from runaway stellar collisions



e.g. Portegies Zwart et al. 2004

Simulating the runaway channel – isolated clusters

Portegies Zwart et al. 1999;
Portegies Zwart & McMillan 2002;
Gürkan et al. 2004;
Portegies Zwart et al. 2004;
Freitag et al. 2006a,b;
Baumgardt & Klessen 2011;
Mapelli 2016;
Rodriguez+19;
Rizzuto et al. 2021, 2022;
Vergara et al. 2023, 2024 ;
Arca Sedda et al. 2023a,c,b;
Prieto et al. 2024;

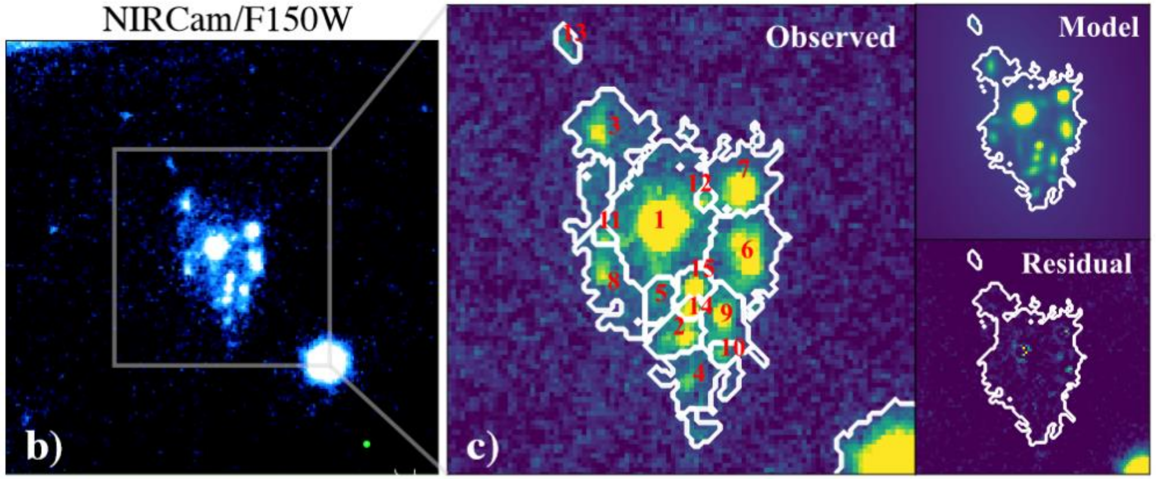


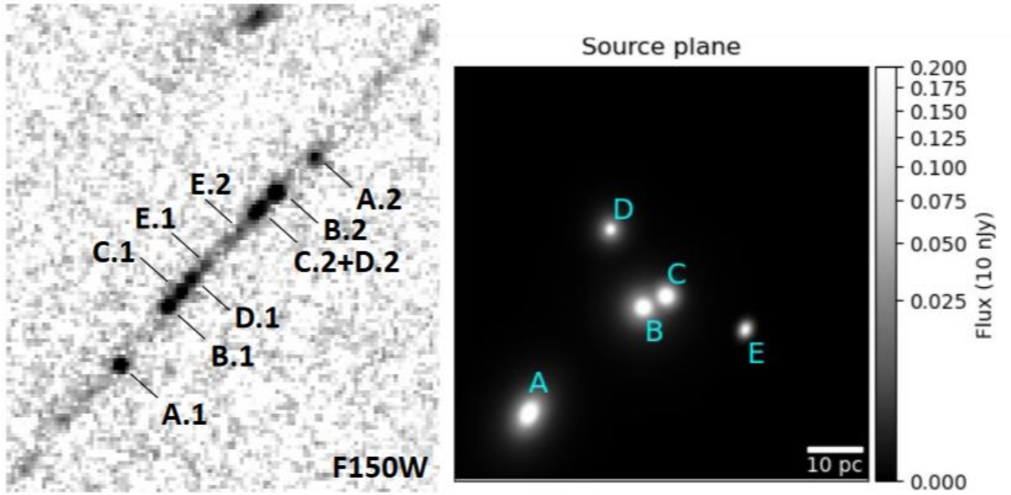
but do young, dense, low-metallicity star clusters look like this?

Massive star cluster formation regions at high z

Fujimoto+24

- recent JWST observations reveal clumpy, clustered star formation at high z
- the Cosmic Grapes at z=6 (Fujimoto+24)
- the Cosmic Gems arc: *five close parsec-size young star clusters at z=10.2 with masses of* $M \sim 10^6\ M_\odot$ in (Adamo+24)
- early MW history was clumpy (Belokurov & Kravtsov 2023)
- hydrodynamical simulations of massive star cluster formation in low-metallicity dwarf starbursts support this view (Lahén+20,24)





Adamo+24

What are the consequences of
the hierarchical star cluster assembly
for the collisional runaway scenario?

The modern direct N-body simulation code *BIFROST*

Rantala, Naab, Springel (2021)
Rantala et al. (2023)
Rizzuto, Naab, Rantala et al. (2023)
Rantala & Naab 2024a
Rantala, Naab & Lahén 2024b
Rantala 2024d in prep.
Souvaitzis, Rantala, Naab in prep.

4^{th} order forward direct summation code *BIFROST*

Hierarchical 4^{th} order forward symplectic integrator

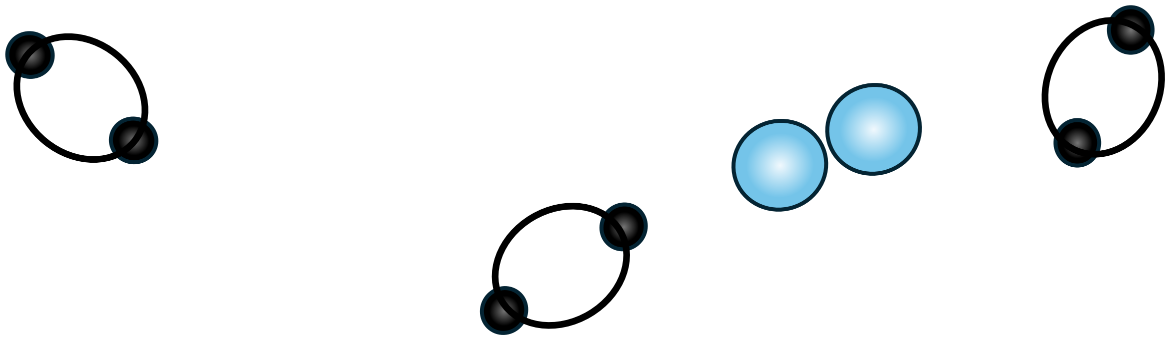
Direct summation, GPU acceleration

$$e^{\epsilon \mathbf{H}} = e^{\frac{1}{6}\epsilon \mathbf{U}_{\mathrm{SF}}} e^{\frac{1}{2}\epsilon \mathbf{H}_{\mathrm{S}}} e^{\frac{1}{2}\epsilon \mathbf{H}_{\mathrm{F}}} e^{\frac{2}{3}\epsilon \tilde{\mathbf{U}}_{\mathrm{SF}}} e^{\frac{1}{2}\epsilon \mathbf{H}_{\mathrm{F}}} e^{\frac{1}{2}\epsilon \mathbf{H}_{\mathrm{S}}} e^{\frac{1}{6}\epsilon \mathbf{U}_{\mathrm{SF}}}$$

Rantala+21,23,24b

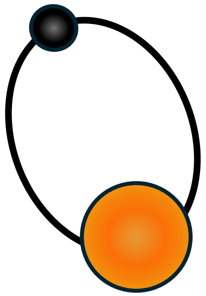
4^{th} order forward direct summation code *BIFROST*

Hierarchical 4^{th} order forward symplectic integrator

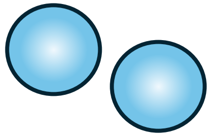


Secular and regularized integration of few-body systems incl. post-Newtonian terms

Roughly similar approach as in KETJU: MSTAR-like integrator (Rantala+20)
+ slow-down algorithm (Mikkola+96, Wang+20)



Efficient parallelization (MPI shared memory): arbitrary binary fractions up to 100% supported



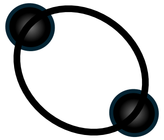
Rantala+21,23,24b

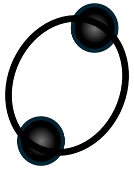
4^{th} order forward direct summation code *BIFROST*

Hierarchical 4^{th} order forward symplectic integrator

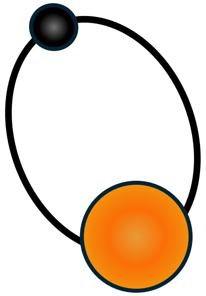
Secular and regularized integration of few-body systems incl. post-Newtonian terms

Rapid single & binary stellar population synthesis code SEVN (Iorio+23)

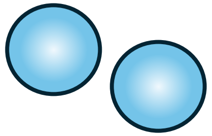




BH-BH mergers using fitting formulas to numerical relativity



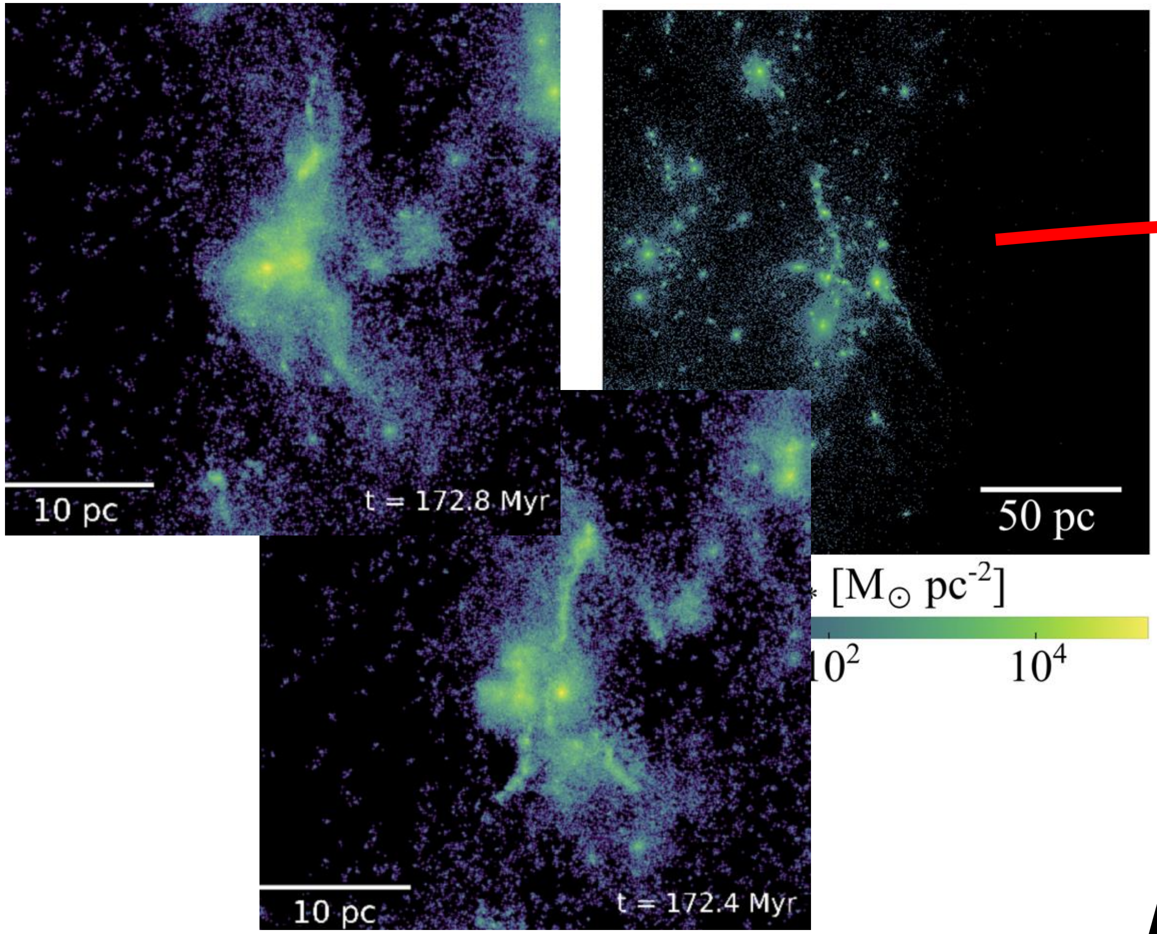
Prescriptions for tidal disruption events and stellar mergers

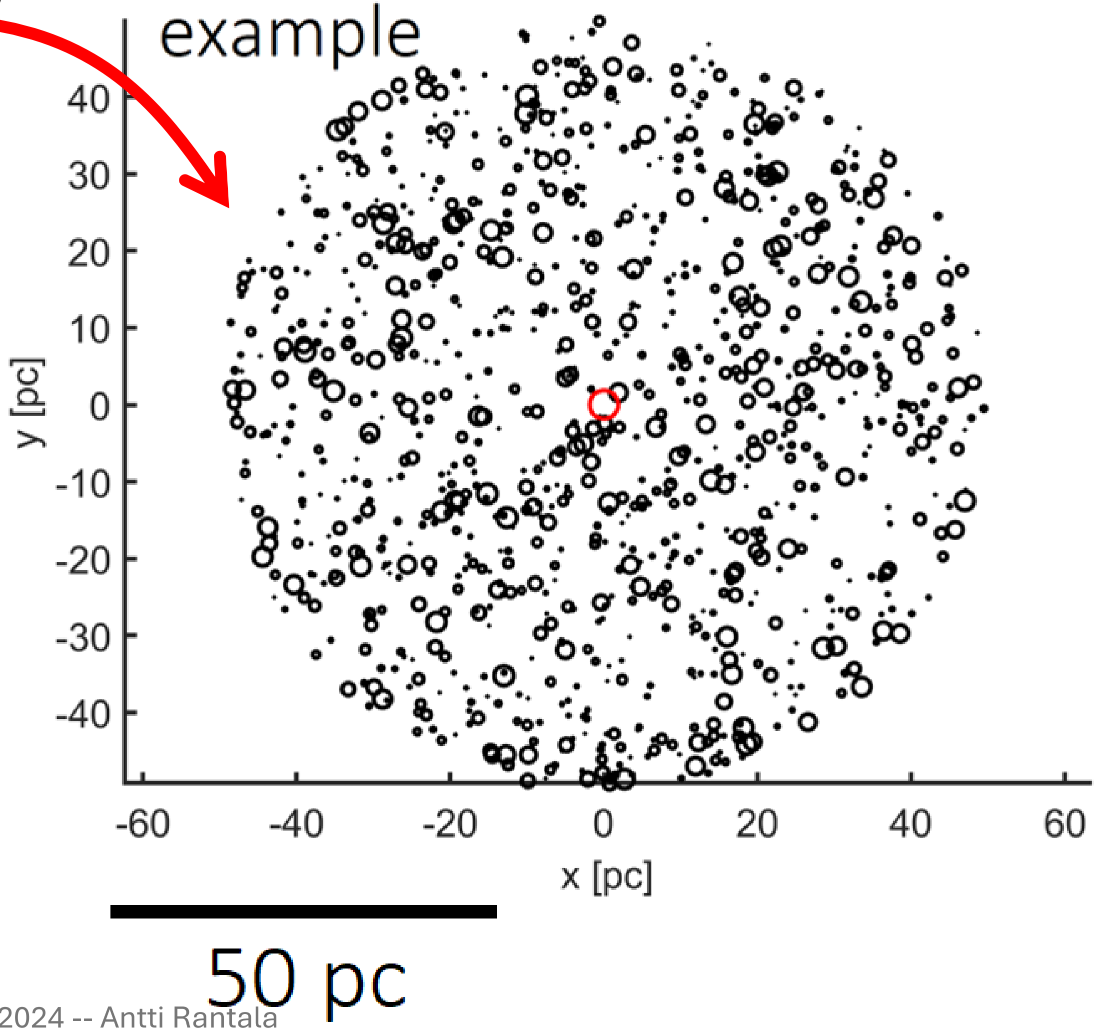


Rantala+21,23,24b

Lahén+2020, 2024 the GRIFFIN project

Initial conditions for the N-body FROST-CLUSTERS project (Rantala+24b)



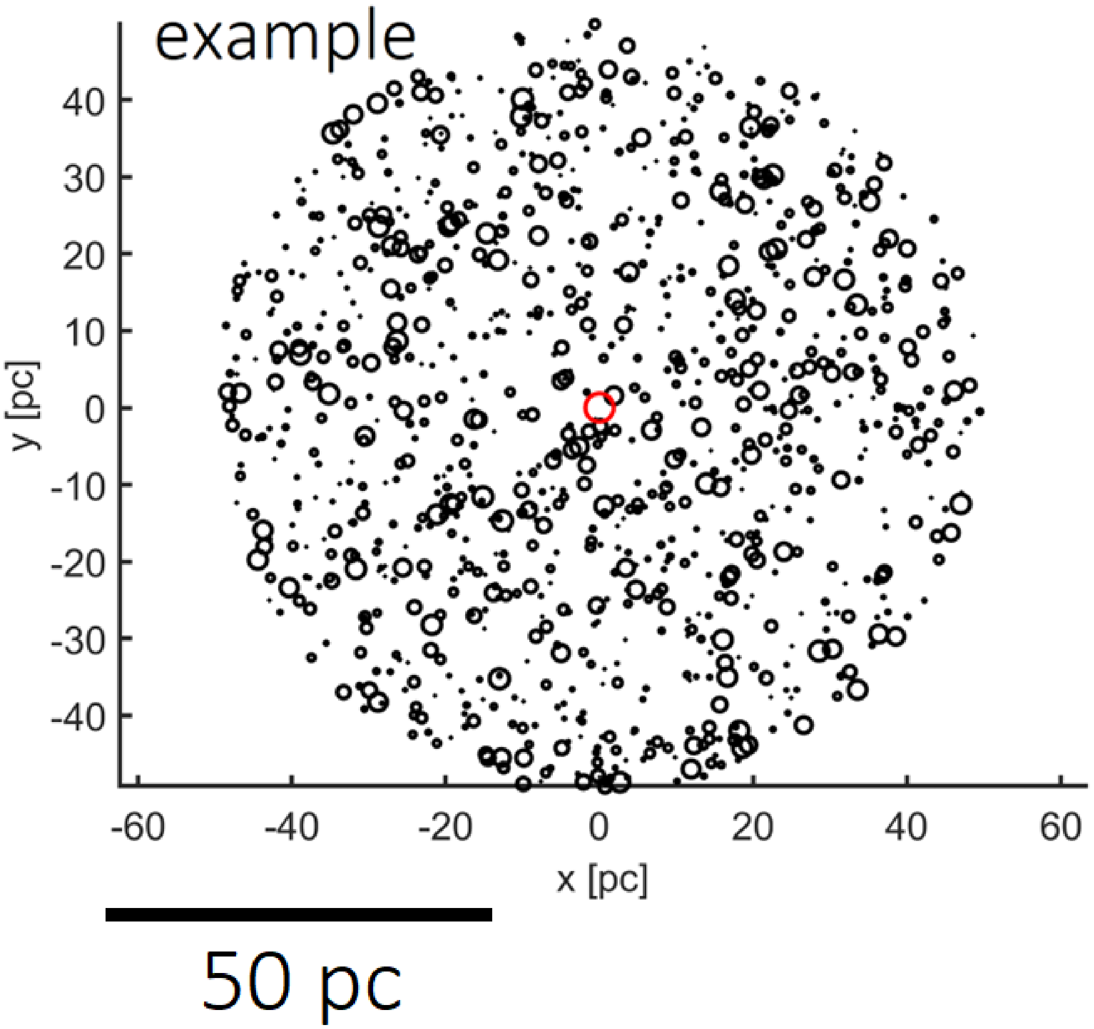


star-by-star star cluster formation simulations in a full hydrodynamical dwarf galaxy setting

Simulation setup

Key model ingredients:

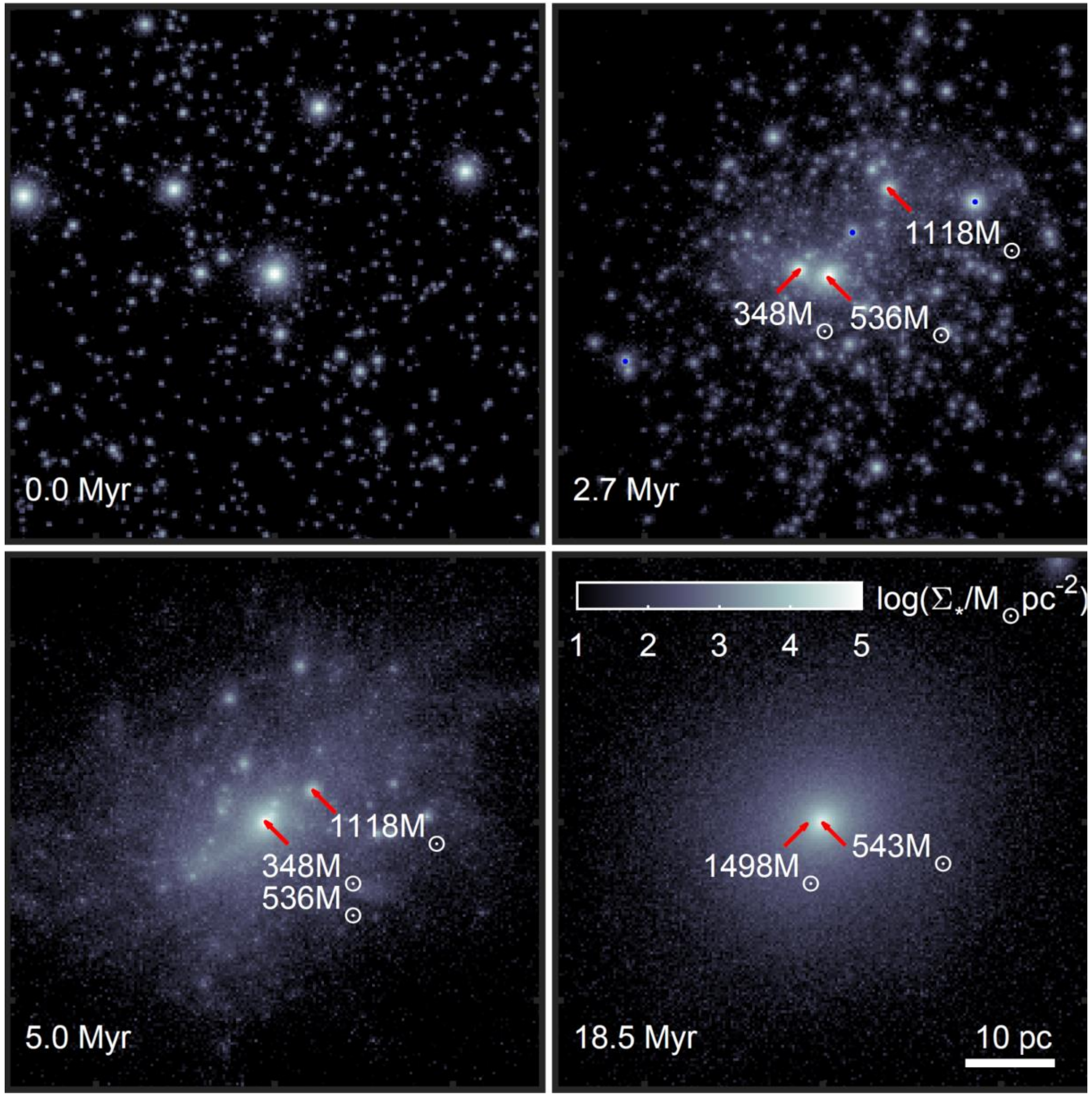
- Universal cluster mass function (slope -2)
- Shallow star cluster mass-size relation with small birth radii
- metallicity Z = 0.01 of solar



Simulation setup

Key model ingredients:

- Universal cluster mass function (slope -2)
- Shallow star cluster mass-size relation with small birth radii
- metallicity Z = 0.01 of solar
- N~2.4 million stars in ~1000 star clusters between ~100 $M_\odot$ and 2.5×10^5 $M_\odot$
- converging radial flow of -3.5 km/s and similar random component
- central cluster densities ~$10^6 M_\odot\ pc^{-3}$
- single-star Kroupa IMF up to 150$M_\odot$ with Yan&Kroupa (2023) mmax limit for low-mass star clusters



Simulation setup

Key model ingredients:

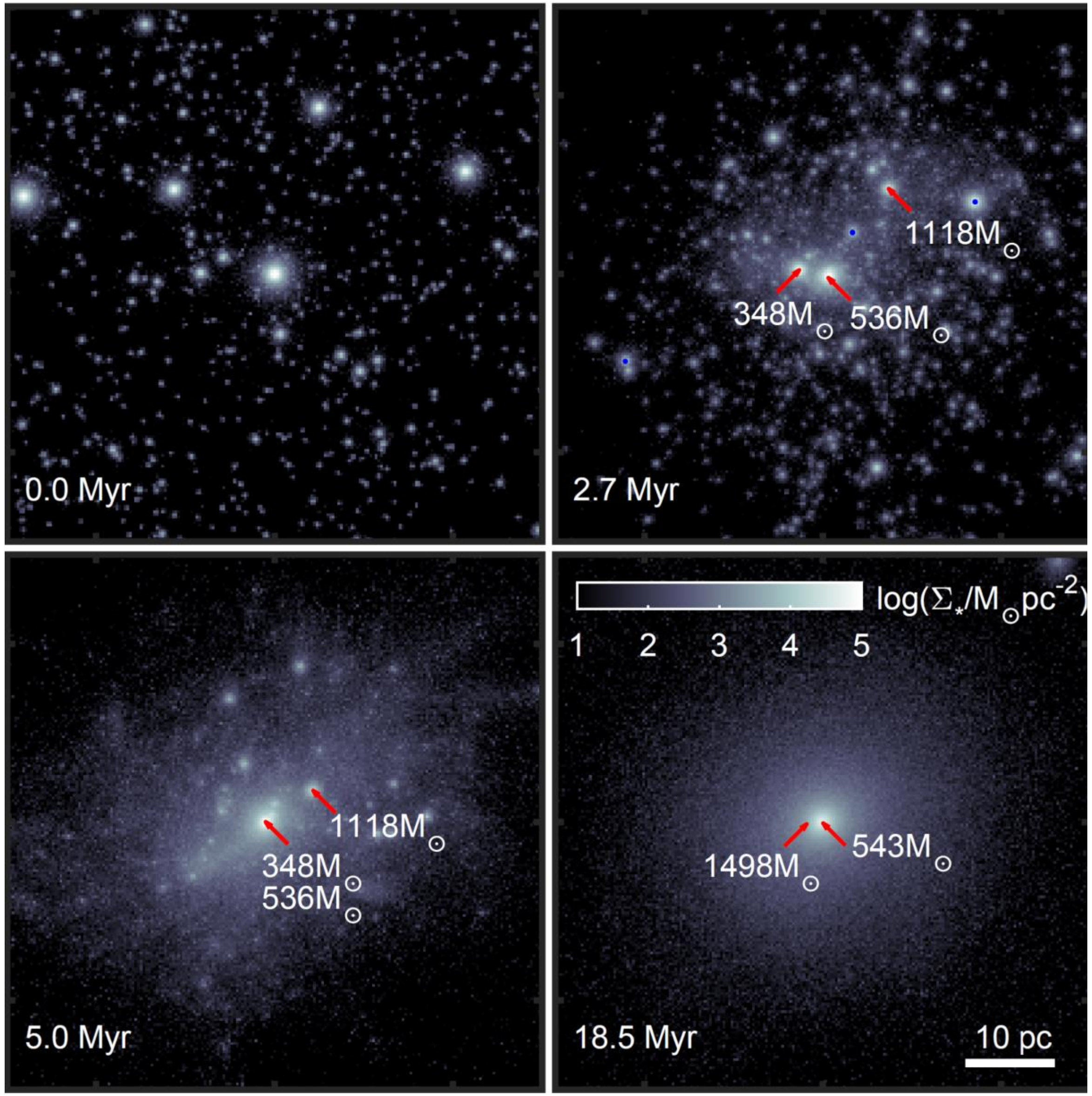
Simulations so far:

~1/3 runs with single stars (mmax = 150 Msun or 450 Msun)

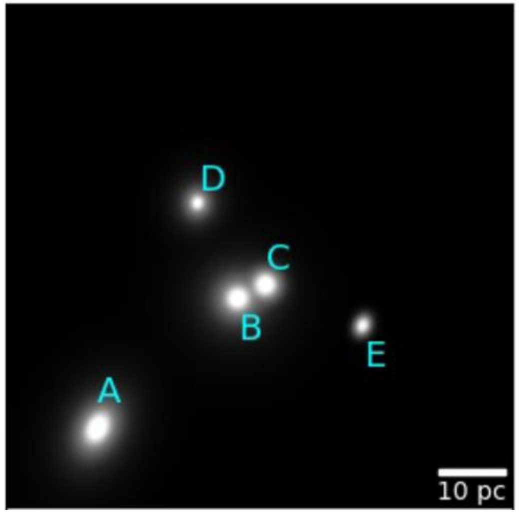
~ 1/3 of runs with primordial **binaries**

~ 1/3 runs with primordial **triples**

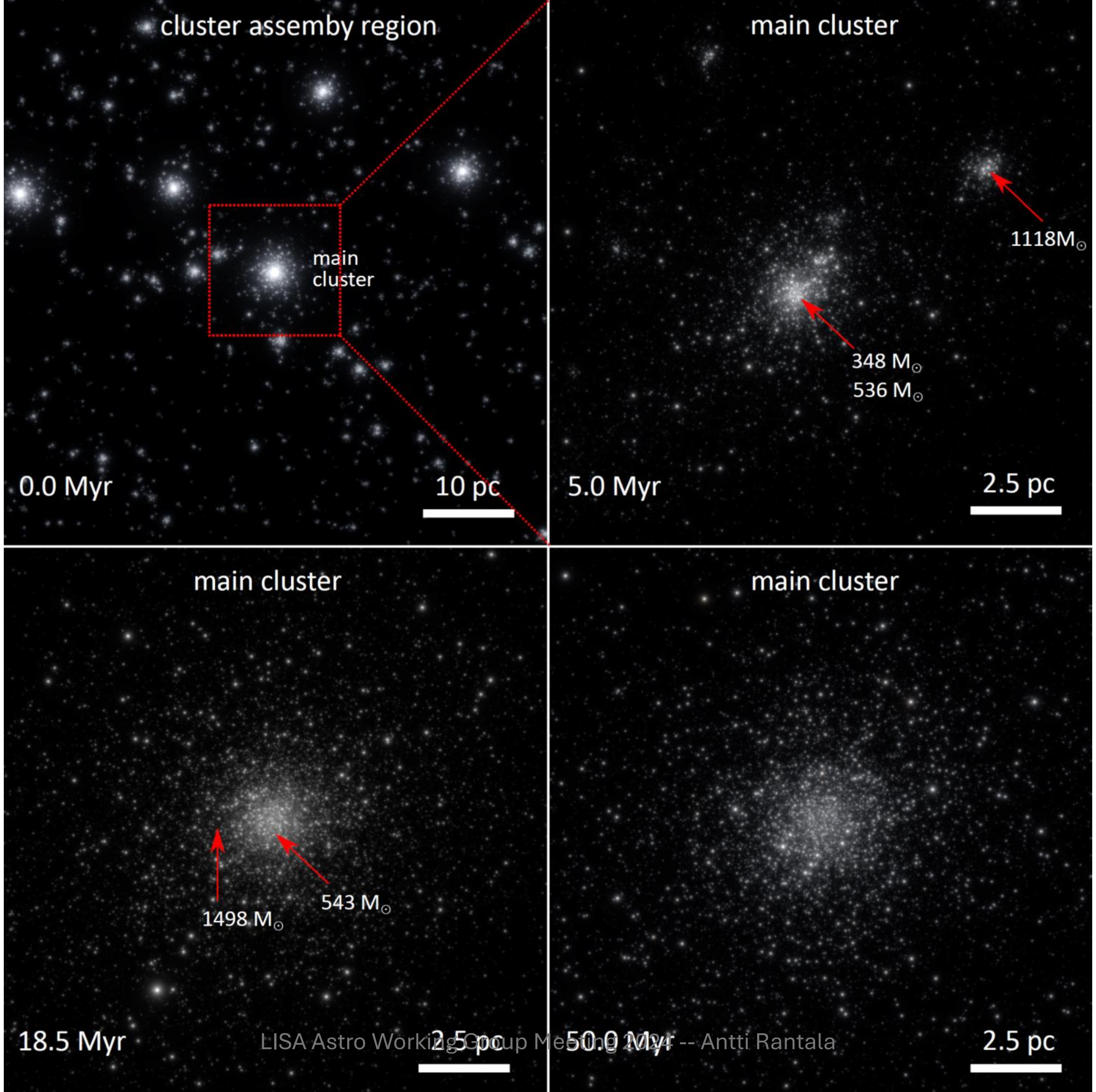
→ up to 800k stars in binaries and triples in the simulations



Hierarchical assembly on a 10 Myr time-scale

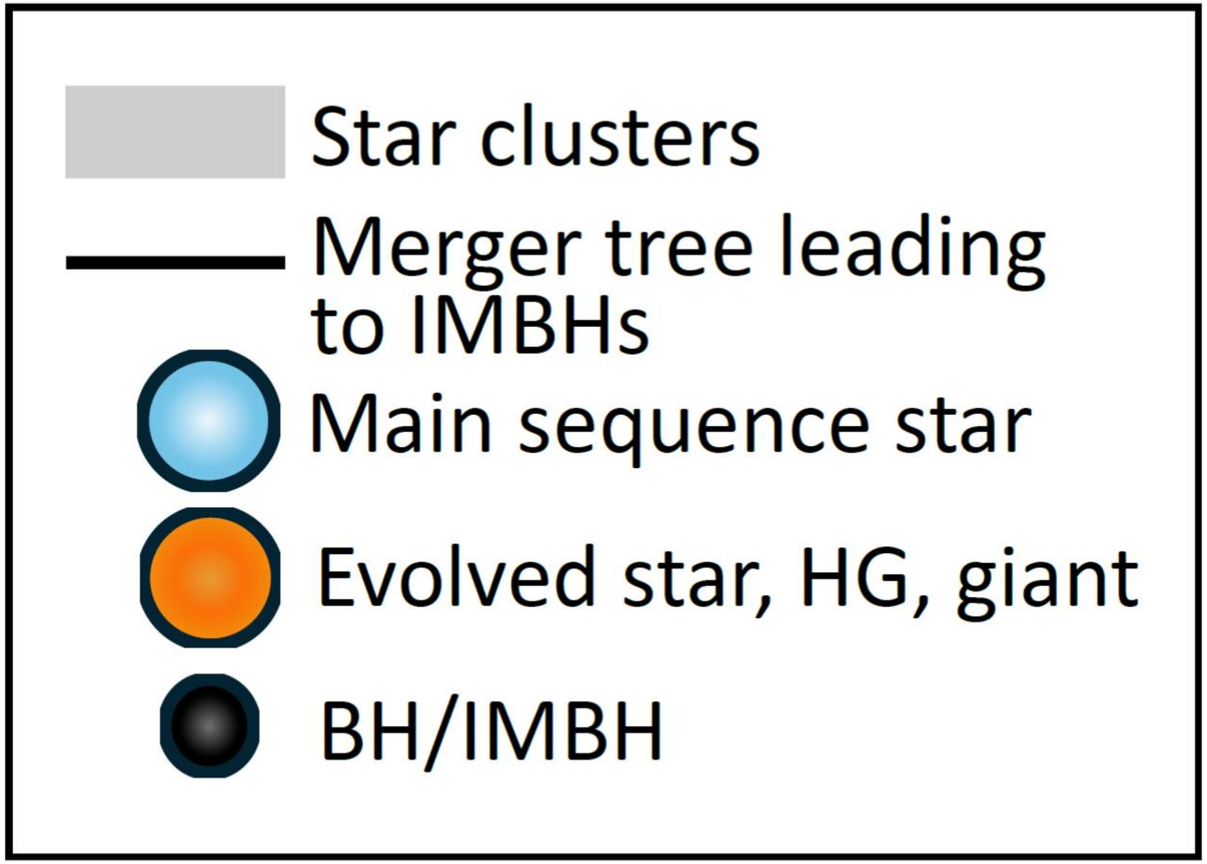


observations of Adamo+24 at z=10.2



FROST-CLUSTERS I mock BVR view MYOSOTIS code by Khorrami+19

Star cluster and SMBH seed progenitor star merger trees



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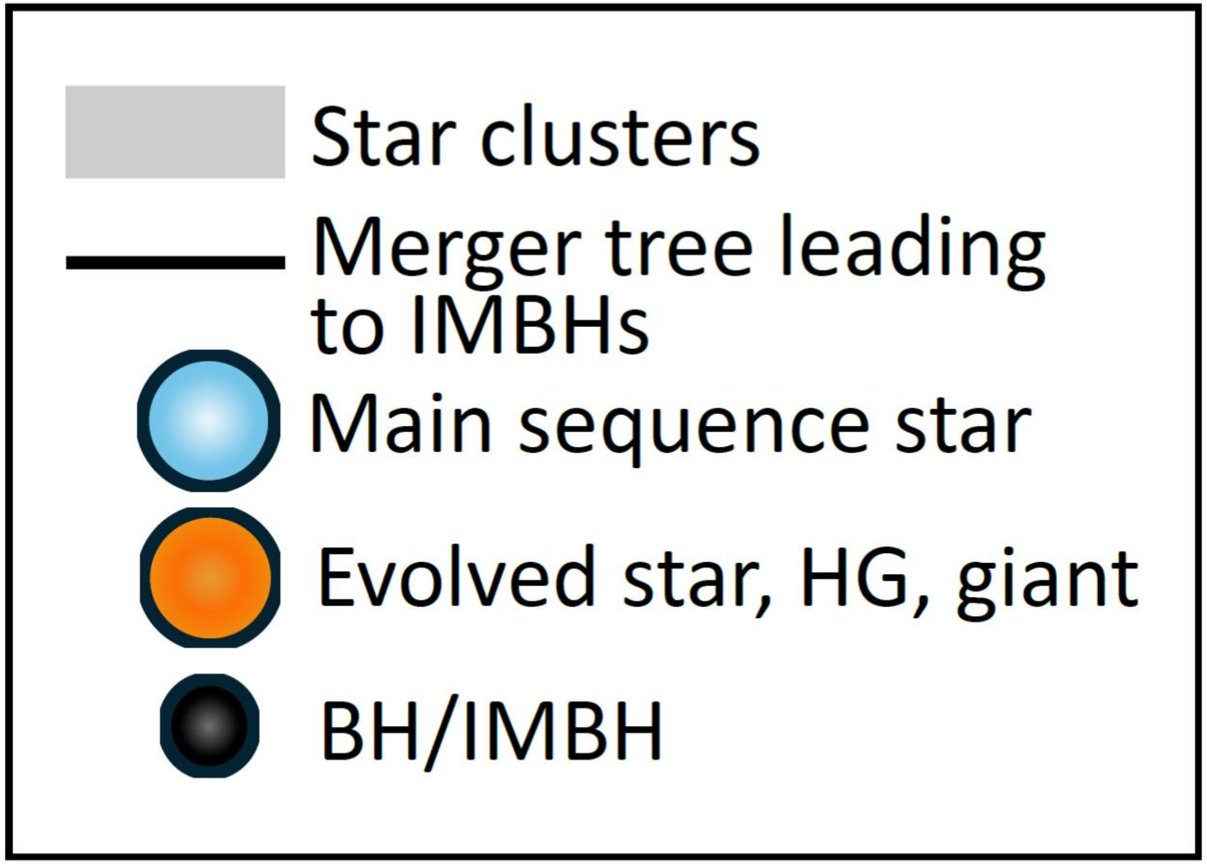

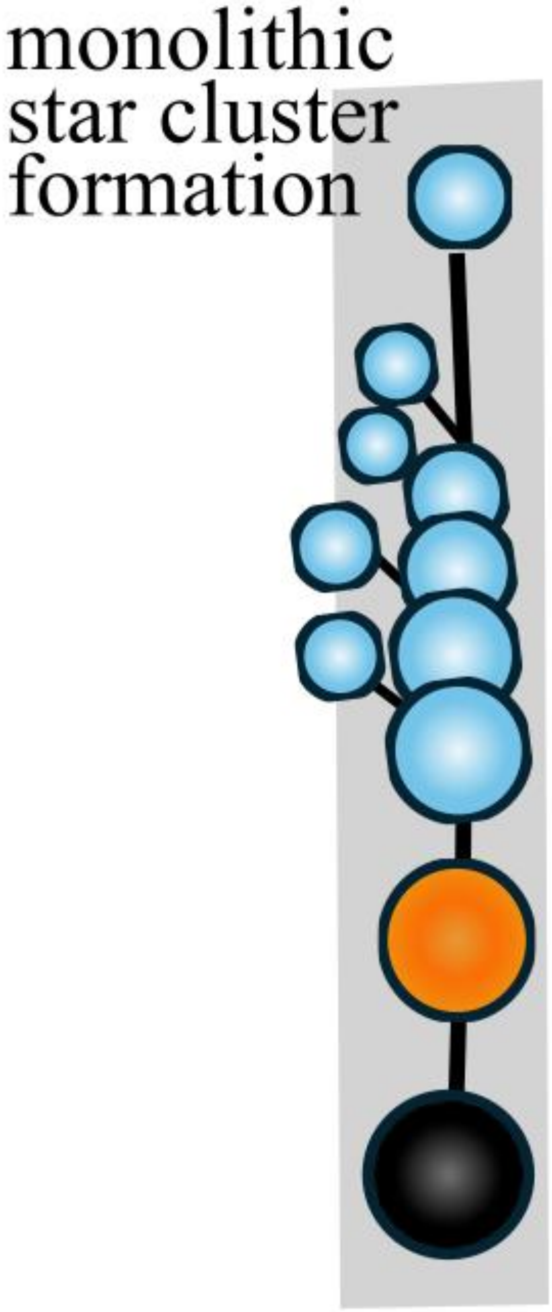

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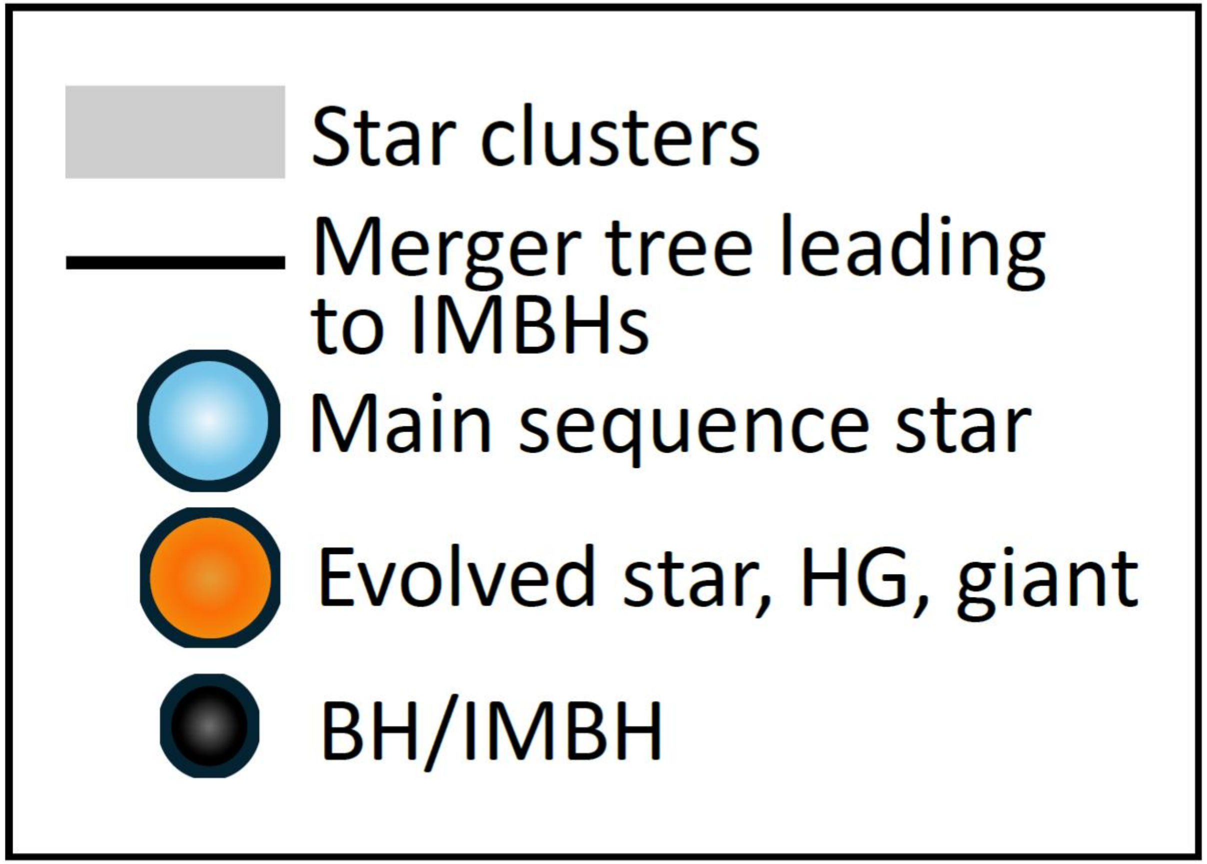
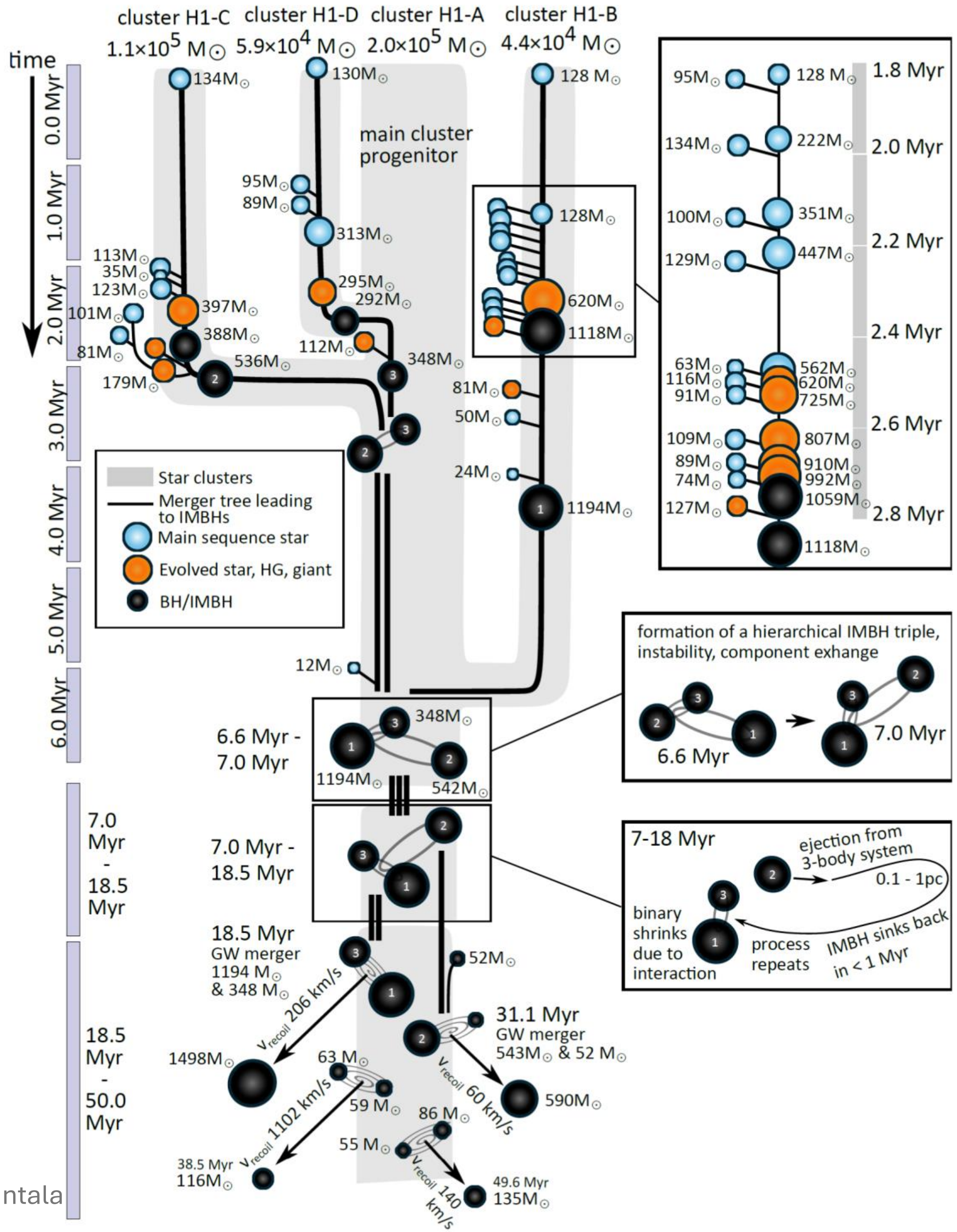
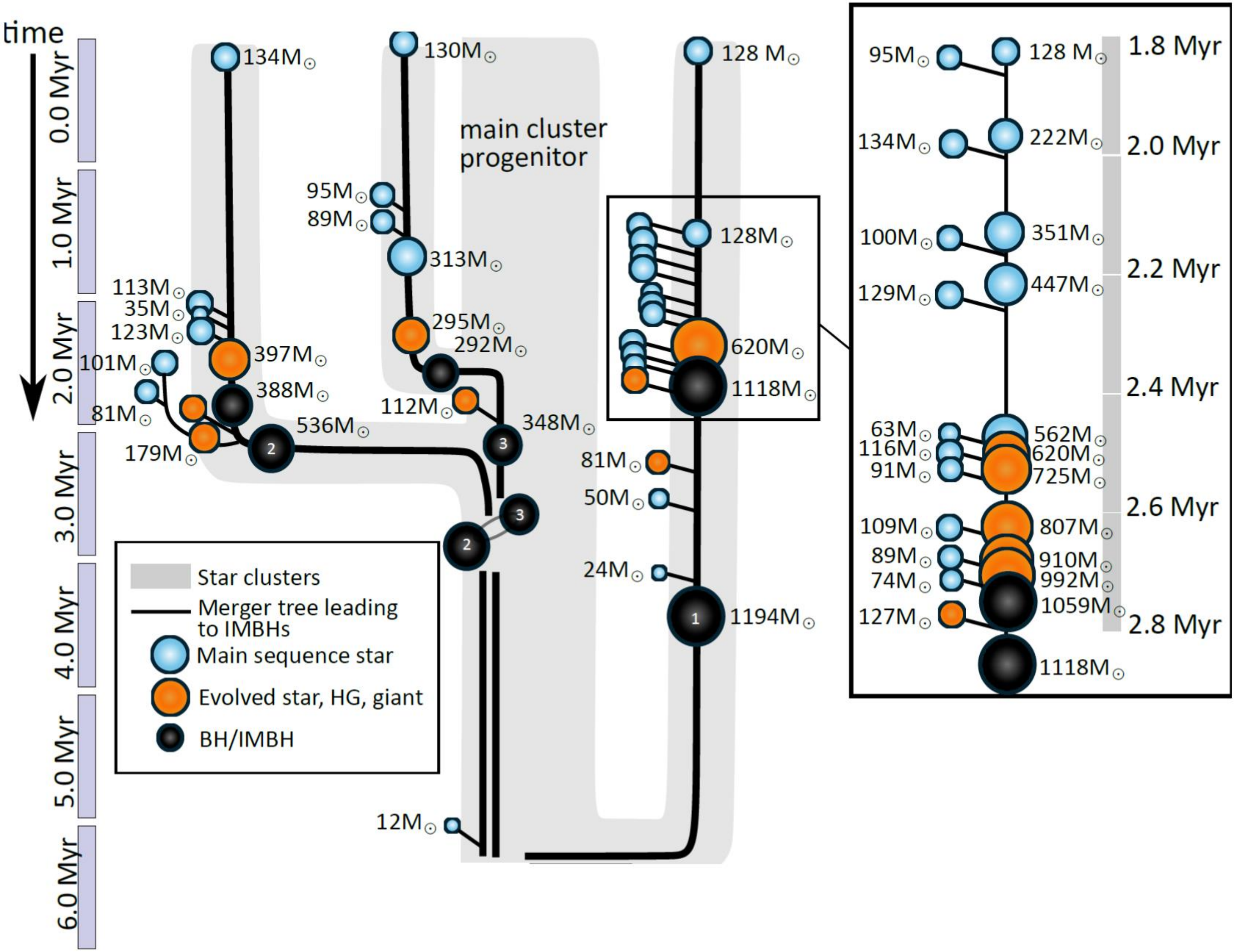


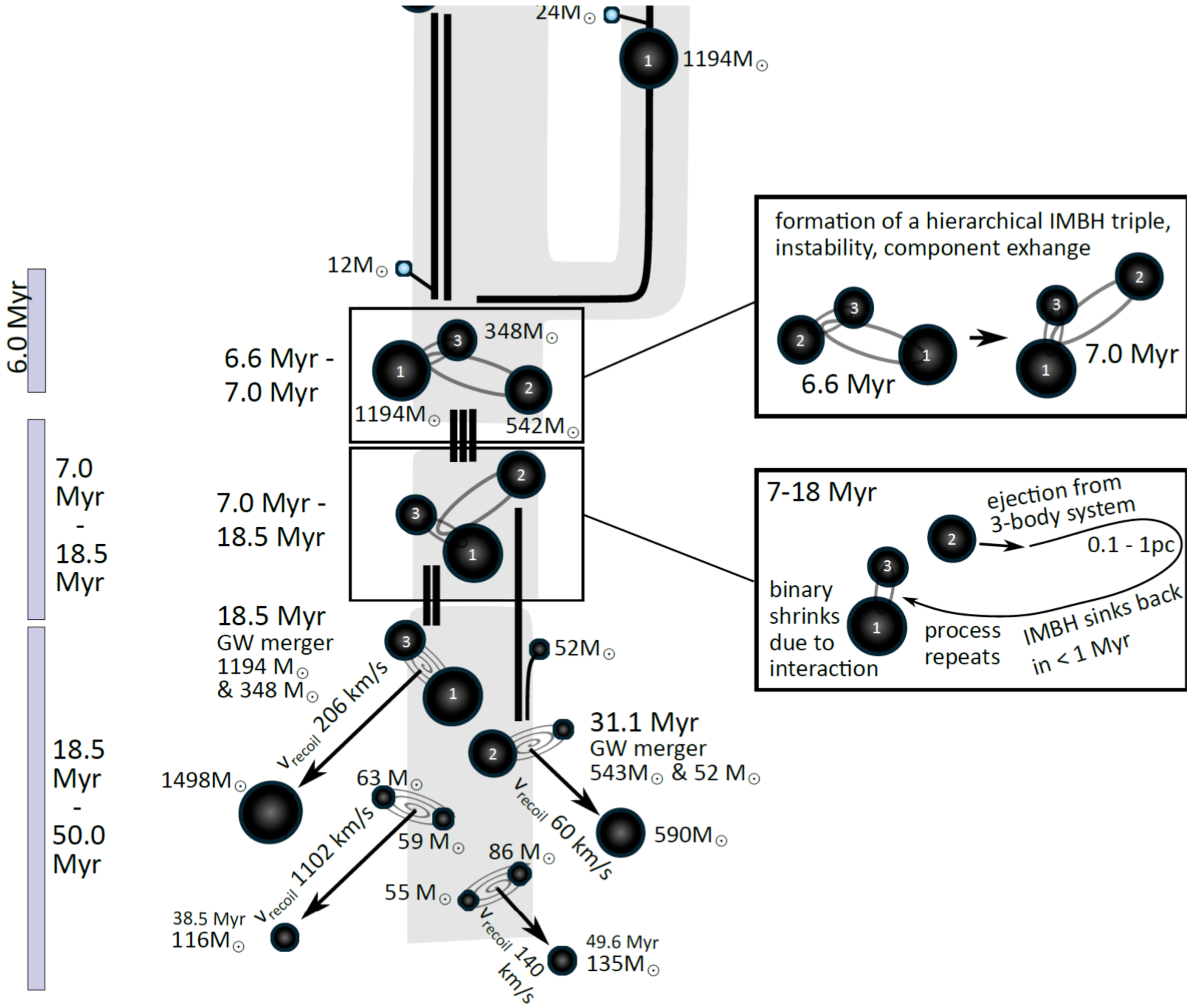


- The collision cascades begin from >80 Msun stars
- No more than one star per cluster significantly grows by mergers
- Most SMBH seed mass from the stellar collisions, up to ~30% by TDEs and BH-SMBH seed mergers

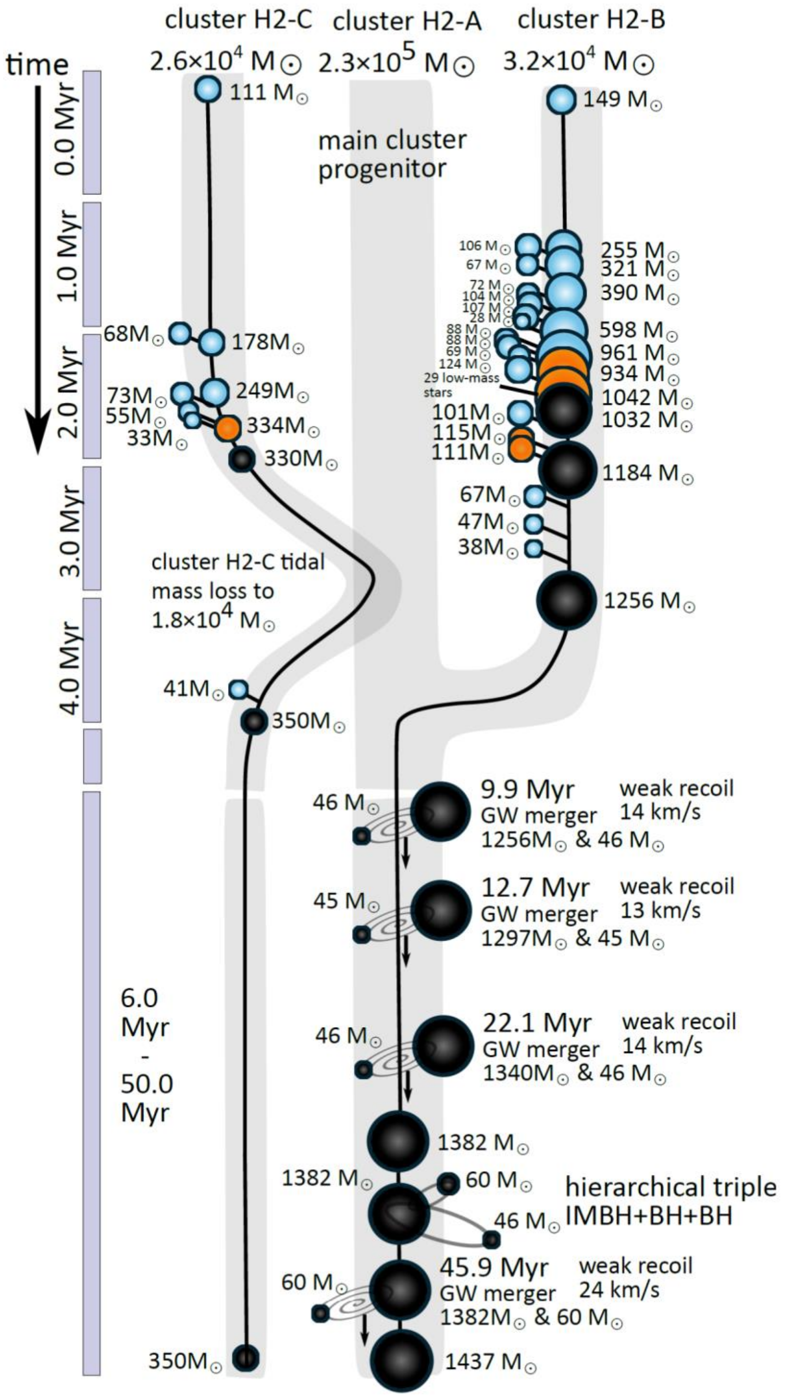


- Complex interaction histories of BHs and SMBH seeds

- seed mergers and GW recoil kicks may eject all seeds from the cluster in this simulation

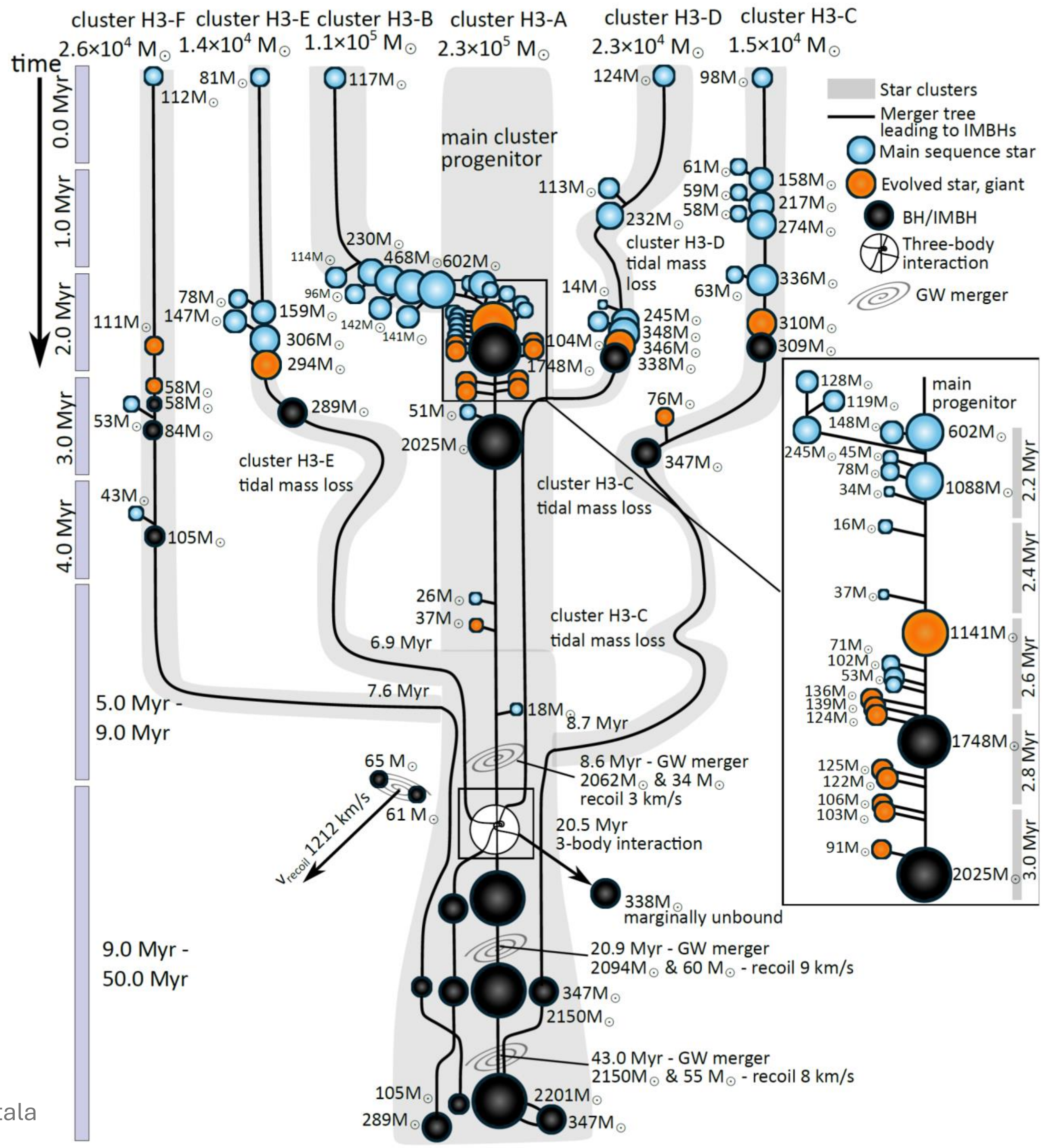


two SMBH seeds, but not in the same star cluster

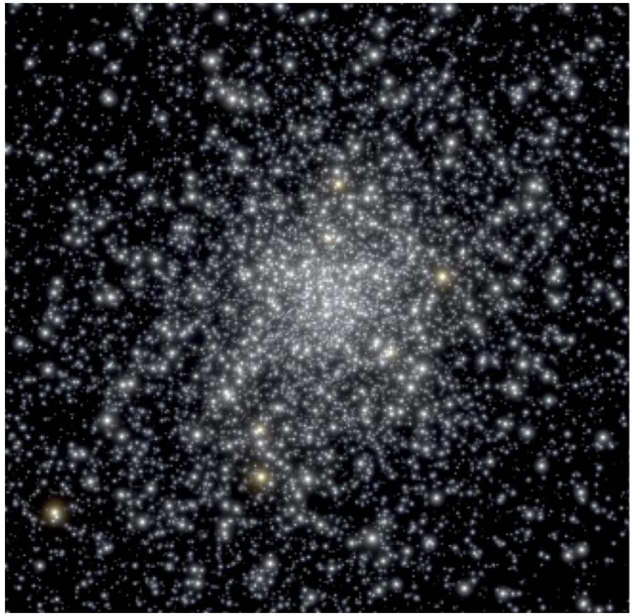


up to five seeds in the same cluster

a number of SMBHs seeds removed by three-body interactions and GW recoil kicks, others remain

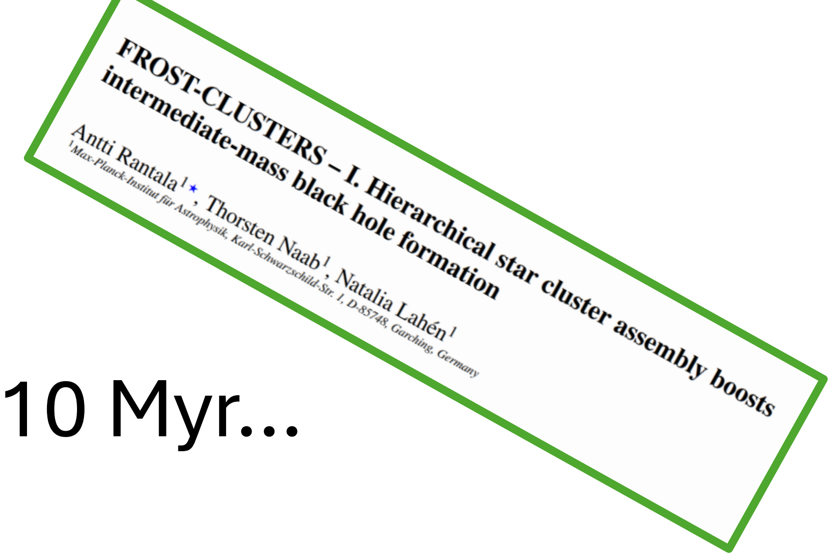


Answering the earlier question…



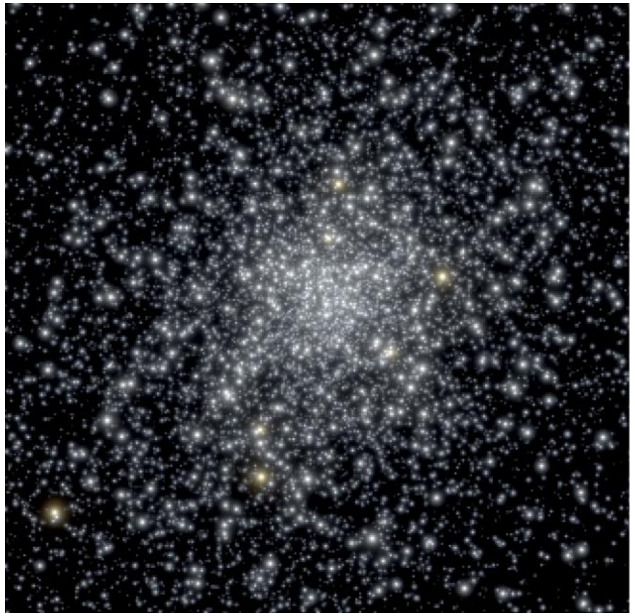
but do young, dense, low-metallicity star clusters look like this?

Answering the earlier question...


FROST-CLUSTERS – I. Hierarchical star cluster assembly boosts intermediate-mass black hole formation

Antti Rantala [1]★, Thorsten Naab [1], Natalia Lahén [1]

[1] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85748, Garching, Germany



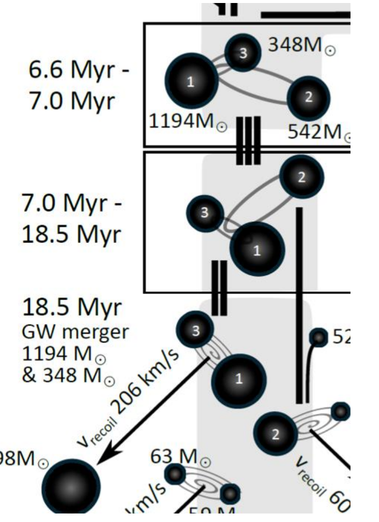
but do young, dense, low-metallicity star clusters look like this?

Yes, after ~10 Myr...

BUT

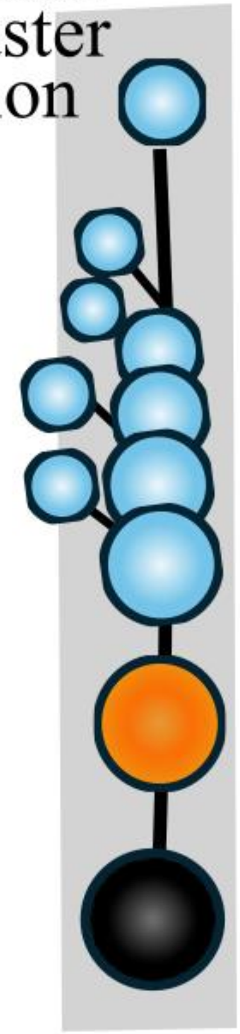
... the SMBH seed formation has already occurred!

... and the BH content of the cluster is very different to the isolated case!

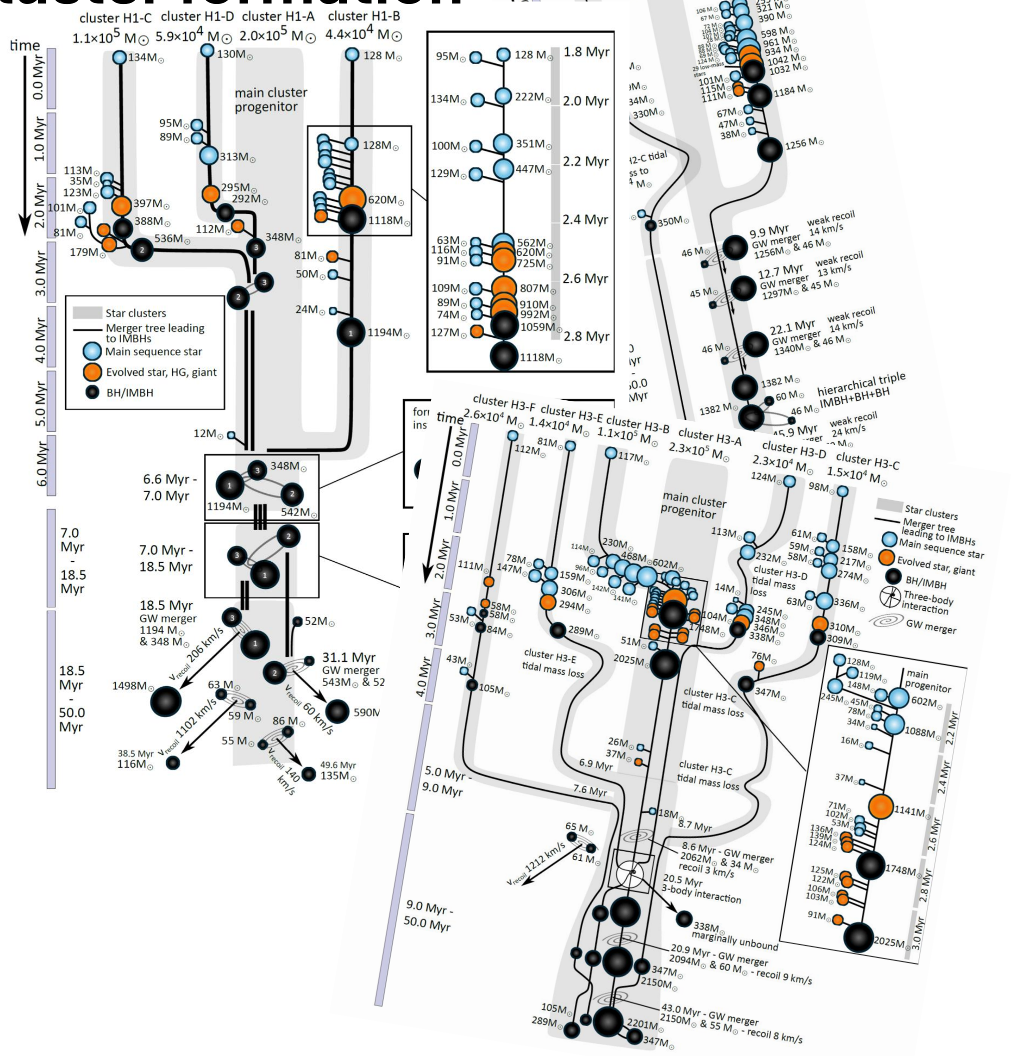


Gravitational waves

monolithic star cluster formation



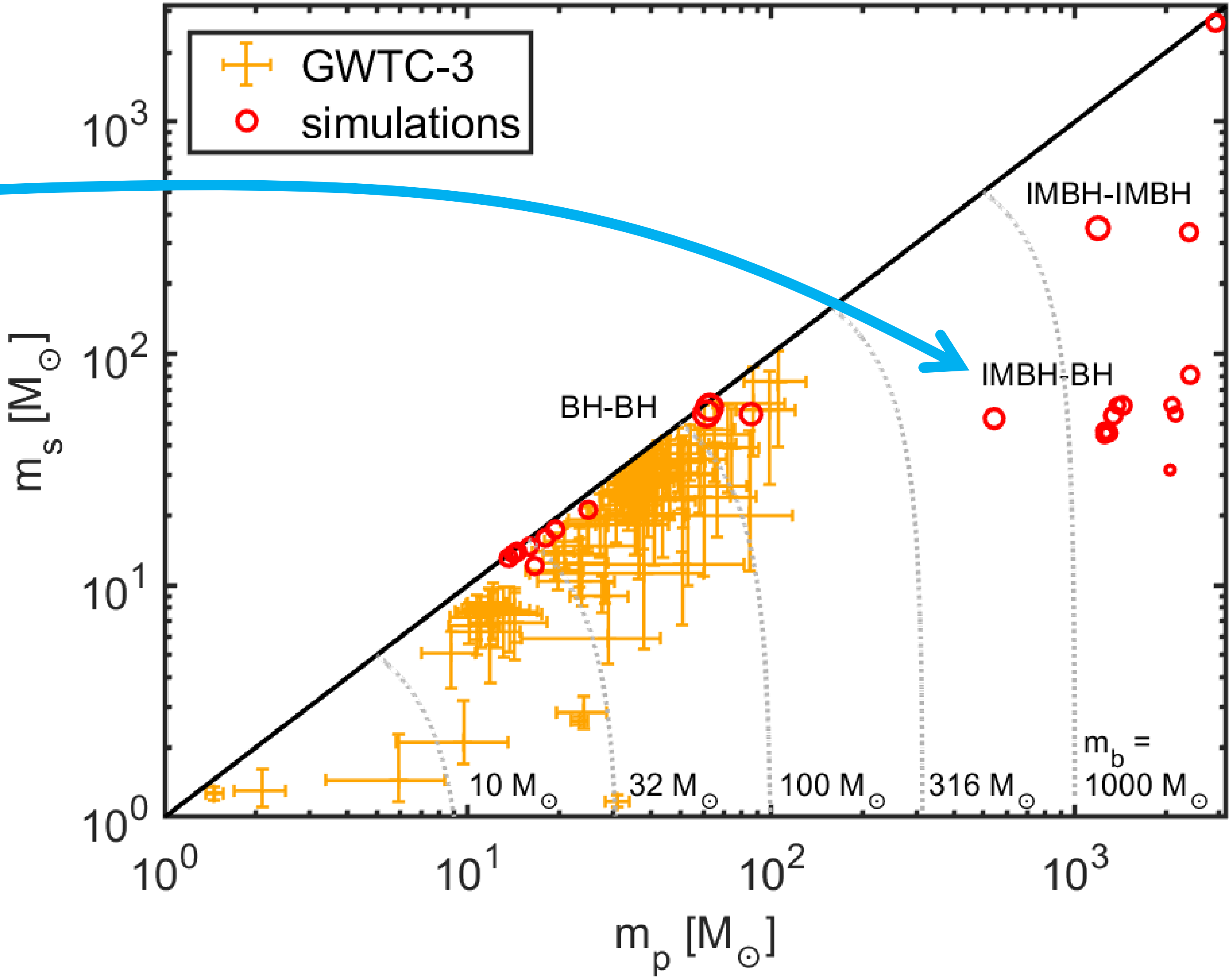
hierarchical star cluster formation



- Isolated monolithic and hierarchical assembly setups predict a very different GW fingerprint

Gravitational waves

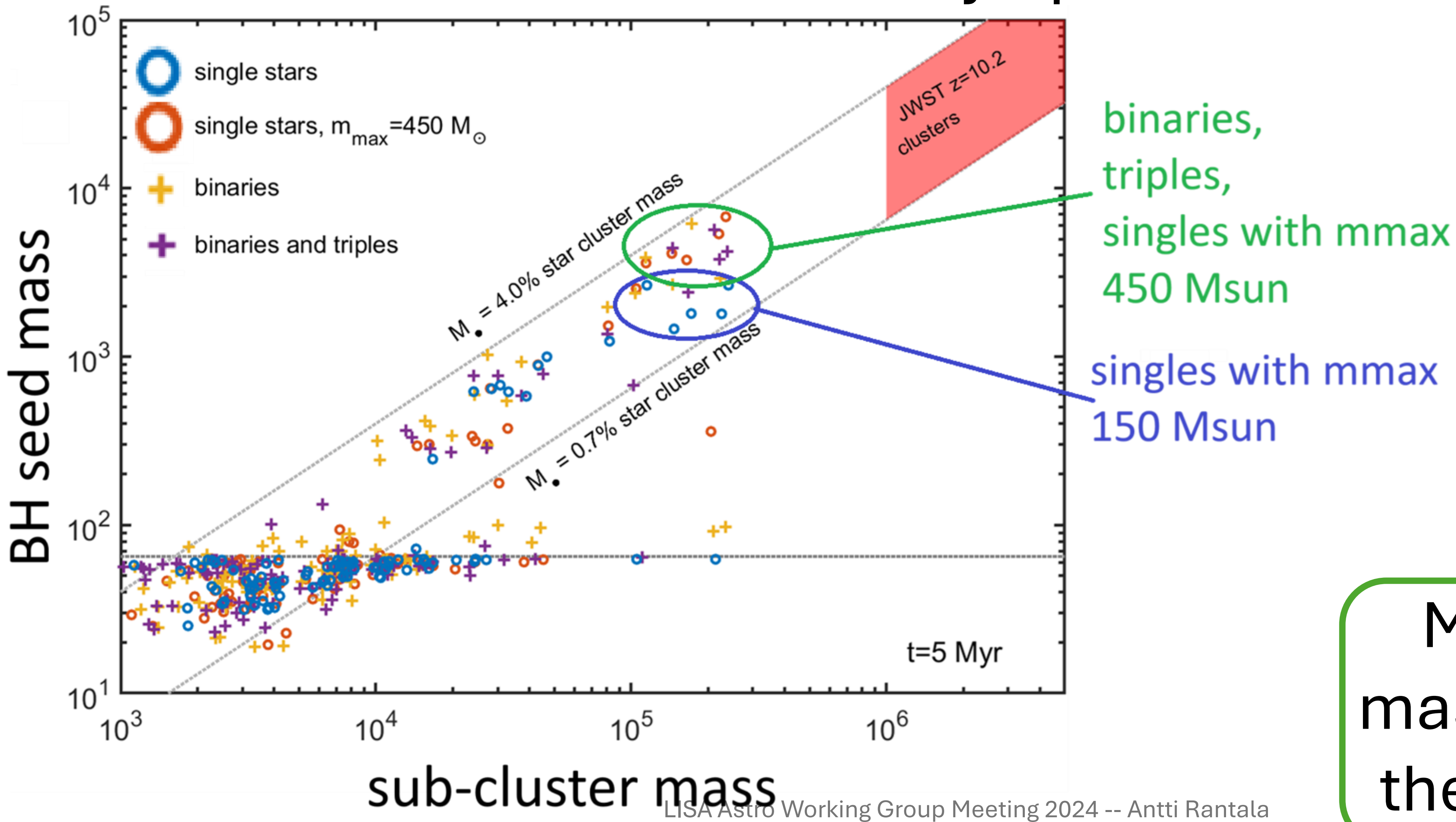
- Simulations predict IMBH GW merger population with q ~ 1/10
- Current LIGO/Virgo/KAGRA searches typically up to ~500 $M_\odot$, cannot observe higher-mass (low-frequency) mergers very well
- LISA, the Einstein Telescope, the Cosmic Explorer



How about binaries… and triples?

Rantala 2024d in prep.

- Binaries, triples and massive singles increase the SMBH formed seed masses by up to ~ x3

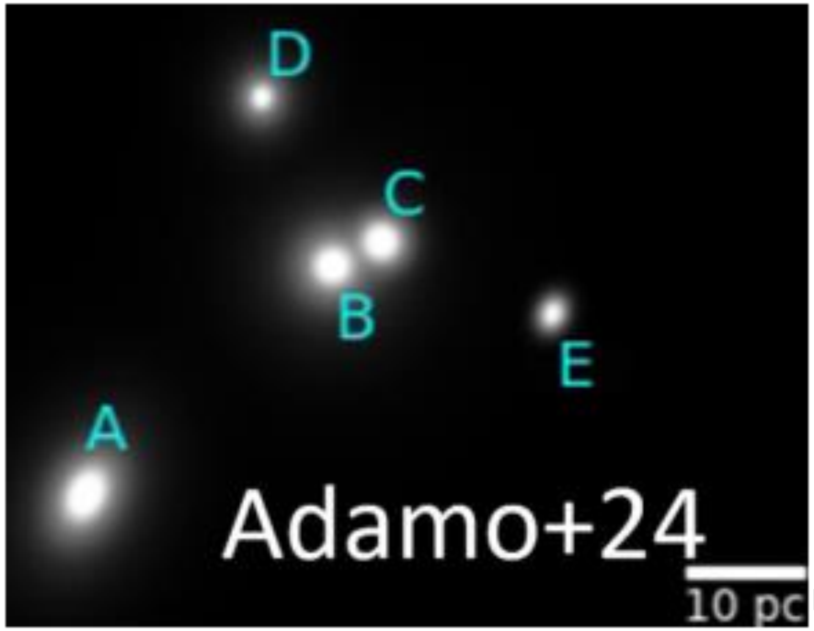


Max SMBH seed mass ~7000 Msun in the current sample

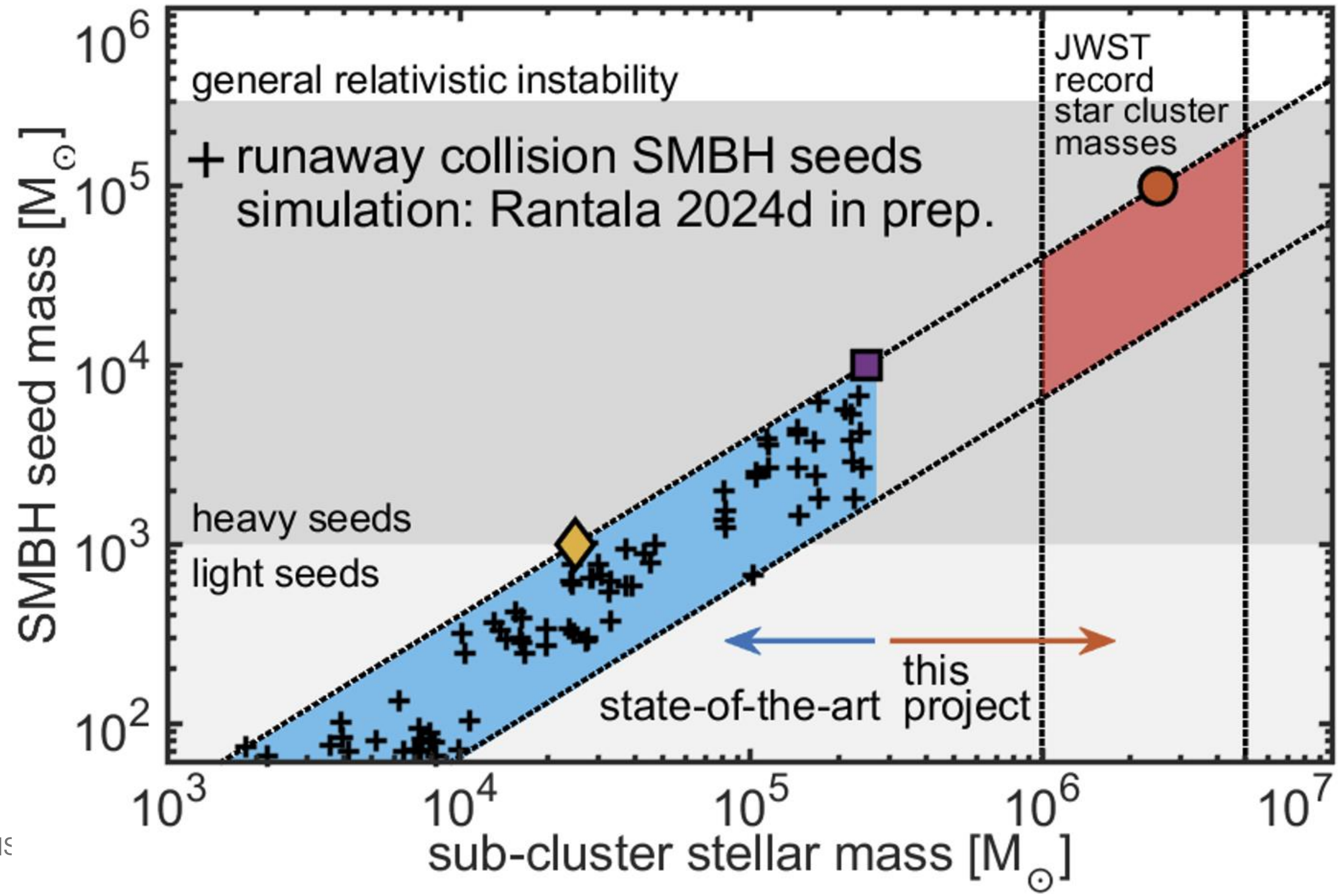
Maximum collisional SMBH seed mass?

similar %: Gieles+18, Fujii+24

- A few % SMBH seed formation efficiency + JWST z>10 star clusters = ???



LIS



Summary and outlook

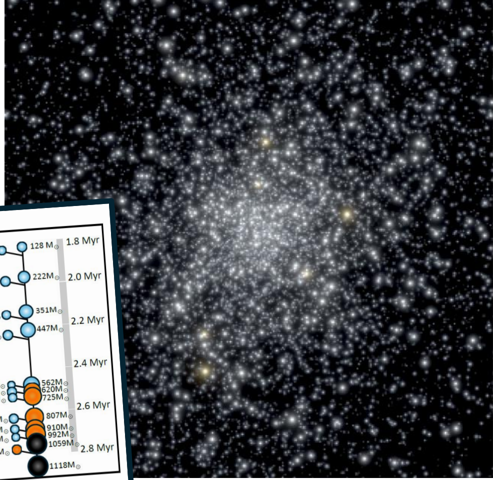
- Hierarchical star cluster assembly boosts SMBH seed formation…

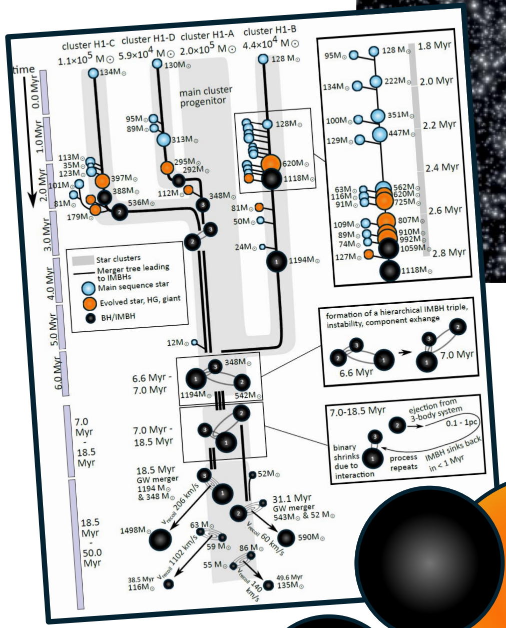
  … as do binaries, triples and massive singles.

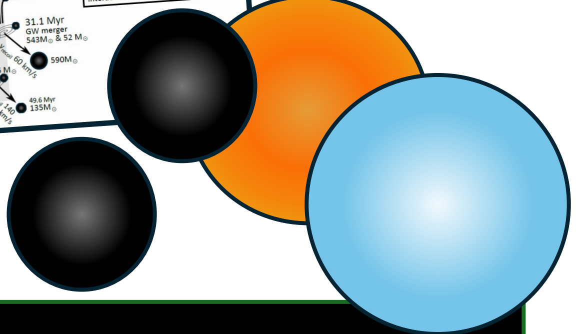
- Indications that the runaway channel might be able to form heavy 1e5 Msun seeds, and this can be tested soon.

- The scenario predicts an unique GW signature due to the BH content of the formed clusters

- Next-gen gravitational wave observatories will be a definite test for the scenario.







FROST-CLUSTERS

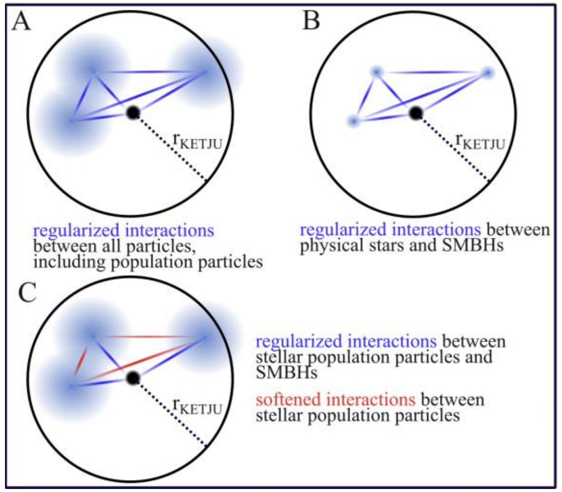
I: arXiv:2403.10602

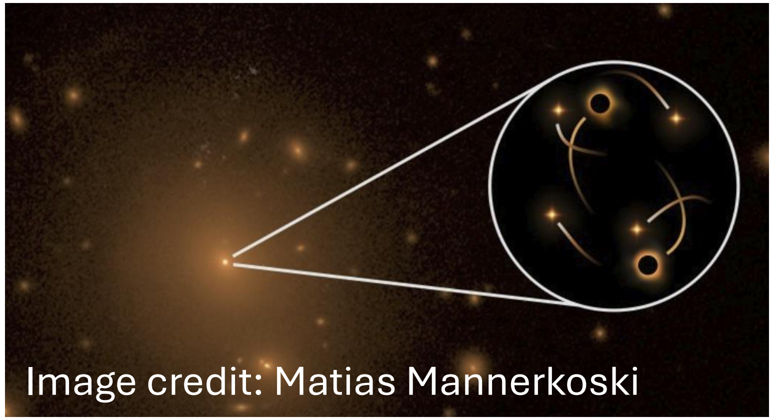
II: by the end of 2024

III: 2025

The KETJU scaling and speed update

The KETJU scaling and speed update





MSTAR integrator improvements

Regularized integrator scaling improves from $O(N^2)$ to O(N)

Results remain unchanged at 1% level

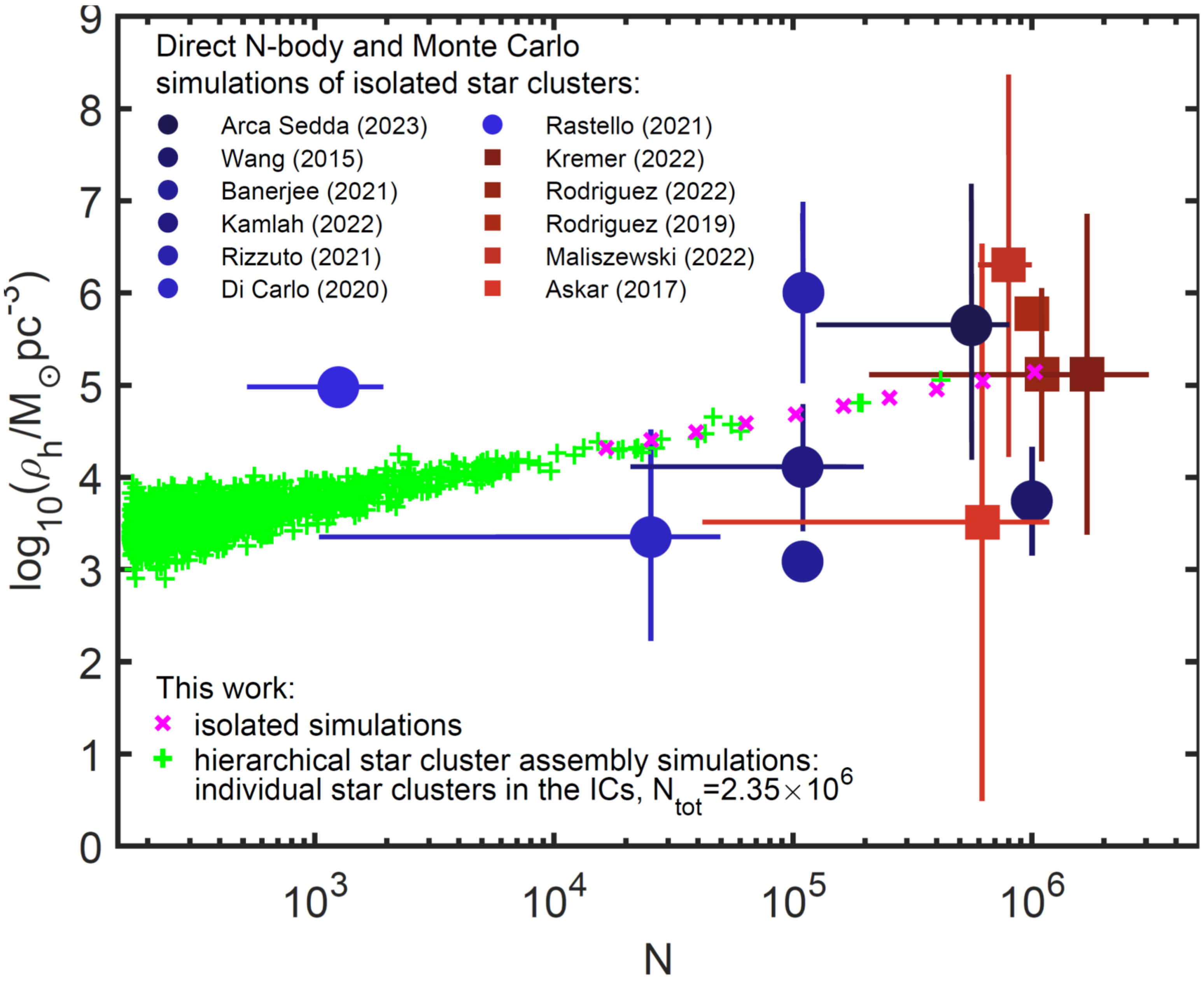
Removes the speed bottleneck of KETJU simulations

The new fast KETJU will be made publicly available on the job market this year

anttiran@mpa-garching.mpg.de

Extra slides

Extra slides



Runaway collisions?

- Only the most massive growing objects in each simulation show periods of runaway growth behaviour