The life cycle of star clusters in low-metallicity dwarf galaxies

with GRIFFIN: Galaxy Realizations Including Feedback From INdividual massive stars

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MAX PLANCK INSTITUTE
FOR ASTROPHYSICS

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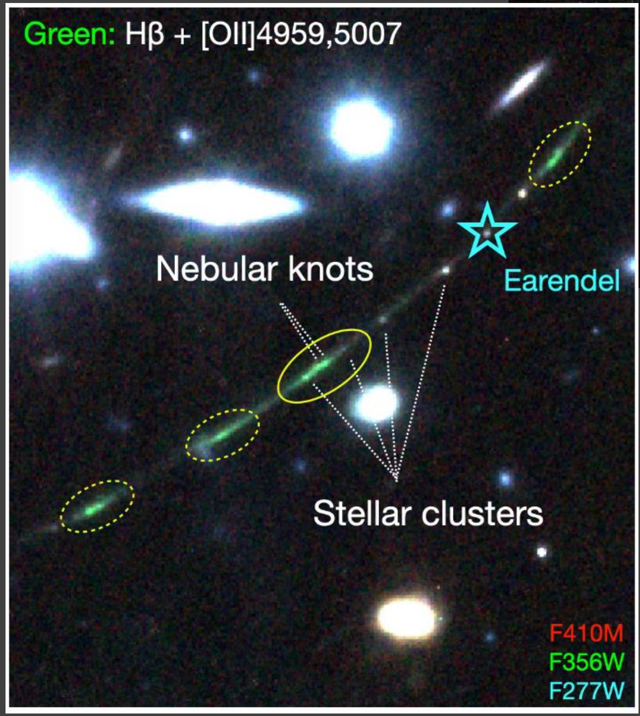
TOSCA - Topical Overview on Star Cluster Astrophysics

How did GCs form?

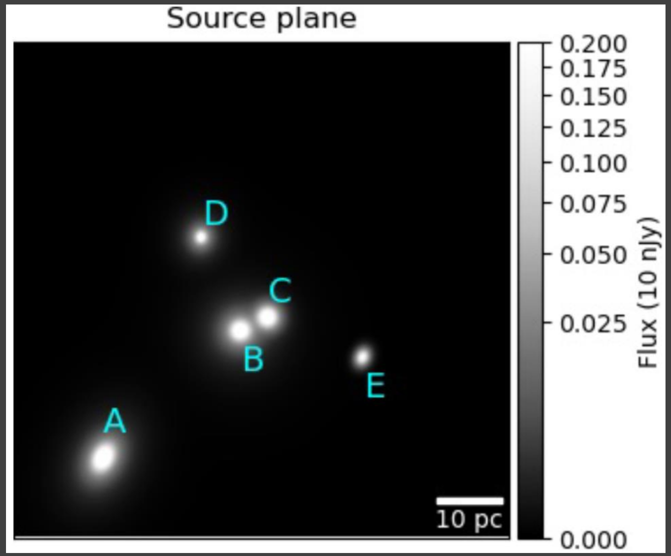
Simulations provide a view of clustered star formation beyond spatial and temporal scales accessible to state-of-the-art observations:

- How did GCs form in the clumpy structures of high-redshift galaxies?
    - Is their formation process simply an extreme example of normal star formation?
- How was the chemodynamical structure of GCs set? What role did massive stars play in chemical enrichment, ionisation and origin of massive black holes?
    - N-body and cloud-scale simulations at ~0.01 $Z_\odot$ indicate >few % of cluster mass can end up in one massive object (stellar collisions, gas accretion; Reinoso+2023, Fujii+2024, Rantala+2024, original works by Portegies Zwart et al.)
    - How is material released by short-lived massive stars recycled within star cluster forming regions?



Sunrise arc at $z \sim 6$ with JWST/NIRCam (Vanzella+2022)

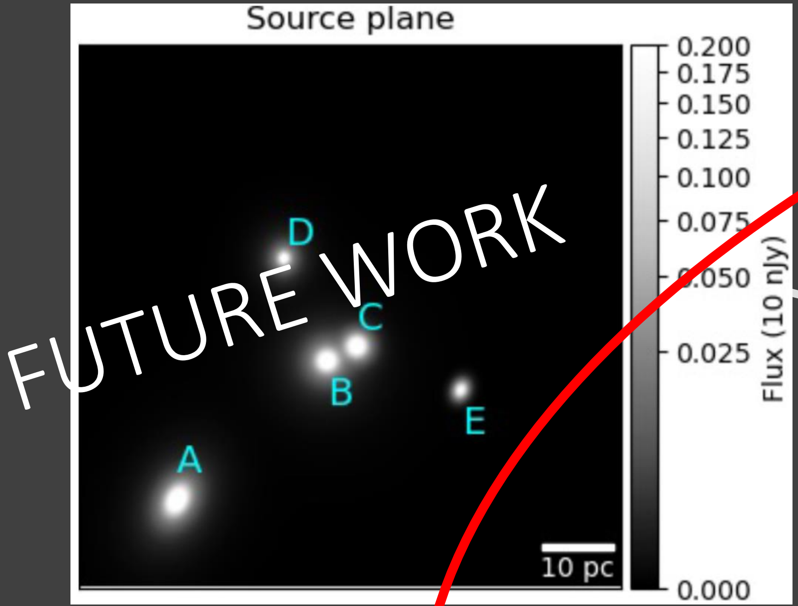
$z \sim 0$ NGC 1569 with young massive $>5\times10^5$ $M_\odot$ clusters (NASA,ESA / A. Aloisi STScI/ESA)



Compact star forming complexes at $z \sim 10.2$ (Adamo+24)

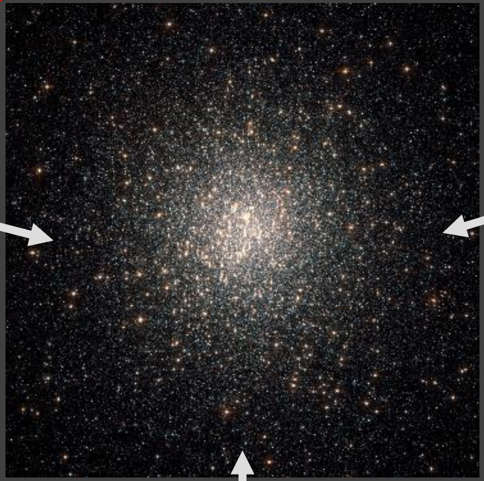
Modelling globular cluster formation in galactic environments

GCs formed within compact star forming complexes, first detections at $z \sim 10.2$



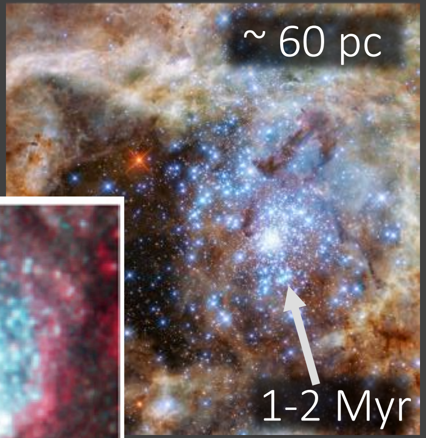
Adamo+24

NASA, ESA, A. Sarajedini, G. Piotto

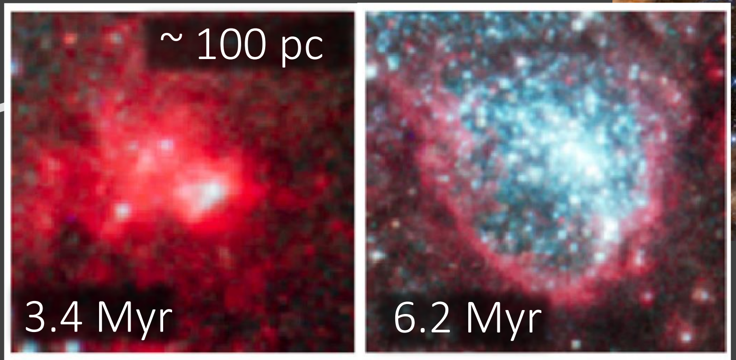


Star formation, stellar evolution & feedback

In nearby galaxies, exposed clusters typically emerge at <5 Myr timescale



R136 in LMC (NASA, ESA, and P. Crowther)



Whitmore+2011, HST 438W (blue), 550W (green), 814W + Hα (red)

NASA, ESA, the Hubble Heritage Team, A. Aloisi

Two and few-body interactions: collisional dynamics

- Mass segregation, core-collapse, dynamical mass-loss, evaporation
- Influenced by IMF, rotation

Star clusters form and evolve in a galactic tidal field

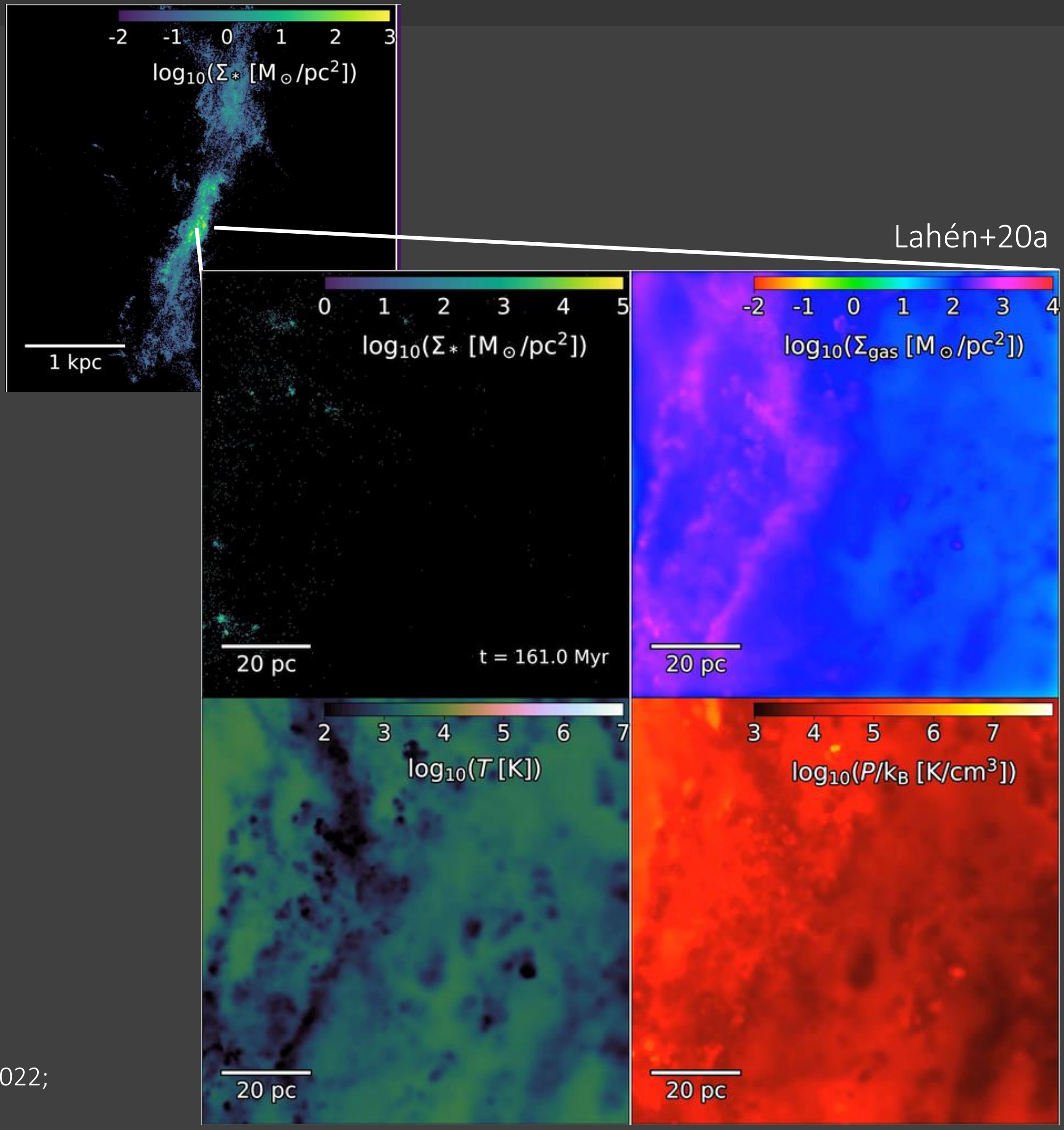
- Encounters with GMCs, other clusters, dark matter? …

GRIFFIN Galaxy Realizations Including Feedback From INdividual massive stars

Low-metallicity (0.1 – 0.01 $Z_\odot$), gas-rich dwarf galaxy models with 10^7 – 10^8 particles, 4 $M_\odot$ gas mass resolution

GADGET-3 based tree/SPH code SPHGal (Hu+ 14,16,17):

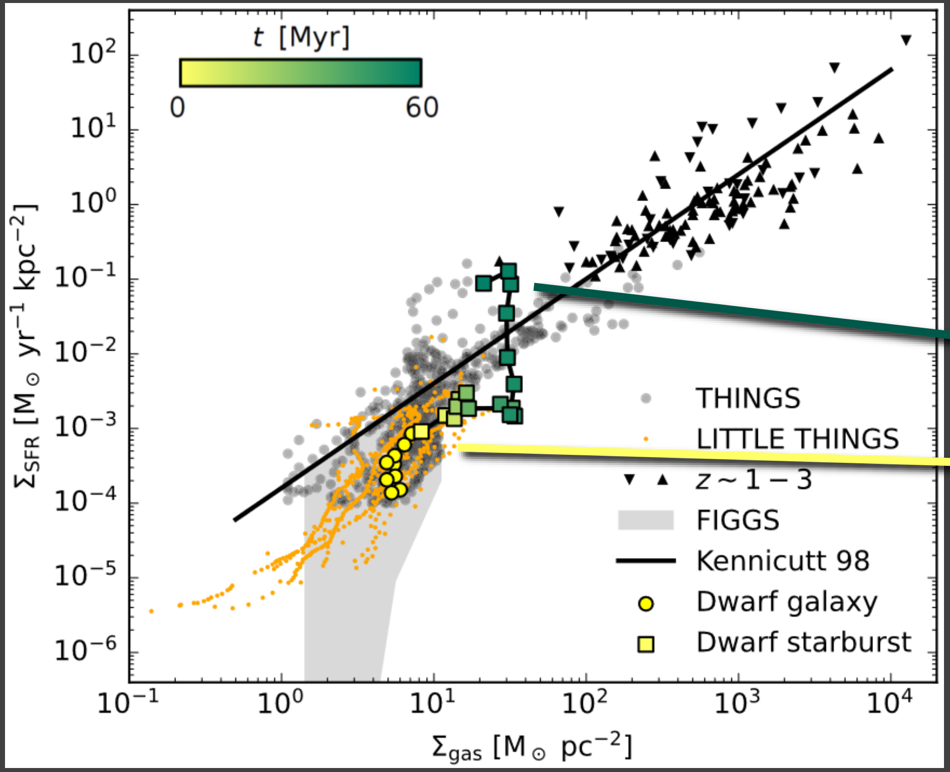
- Multiphase ISM: non-equilibrium cooling with a chemical network down to 10 K (H, H^+, H_2, C^+, CO, O) + metallicity-dependent cooling at high temperatures
- Star formation: Jeans threshold, IMF sampled stars-by-star between 0.08-500 $M_\odot$ (Lahén+23)
- Feedback from individual stars (Geneva + BoOST models):
    - ➢ FUV interstellar radiation field with shielding by dust and gas (HEALPIX+TREECOL), photoionisation
    - ➢ Enrichment element-by-element & channel-by-channel: stellar winds, core-collapse SNe, pair-instability SNe, AGB winds



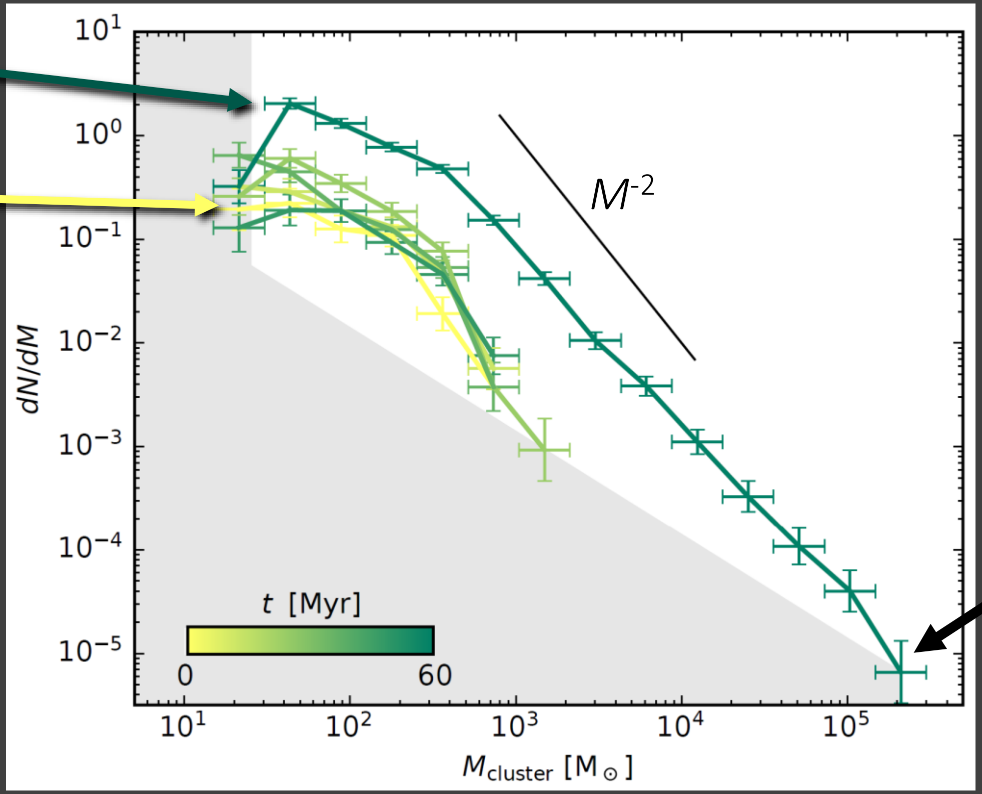
Hu+2014,2016,2017; Lahén+2019,2020ab,2022,2023,2024ab; Steinwandel+2020; Hislop+2022; Szakacs+2022; Bisbas+2022; Sarbadhicary+2024; Elmegreen & Lahén 2024; Fotopoulou+2024; Partmann+2024

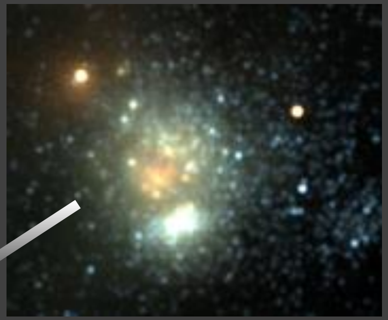
Simulated star cluster populations in starburst dwarf galaxies

Kennicutt-Schmidt relation without assumptions for SF-efficiency



Power-law slope of the cluster mass function regulated by pre-supernova stellar feedback (Ma+18, Lahén+20a,24, Garcia+23, Andersson+24; for cold clouds see Fotopoulou+2024)





Lahén+2020a, 2024a

Simulated star cluster populations in starburst dwarf galaxies

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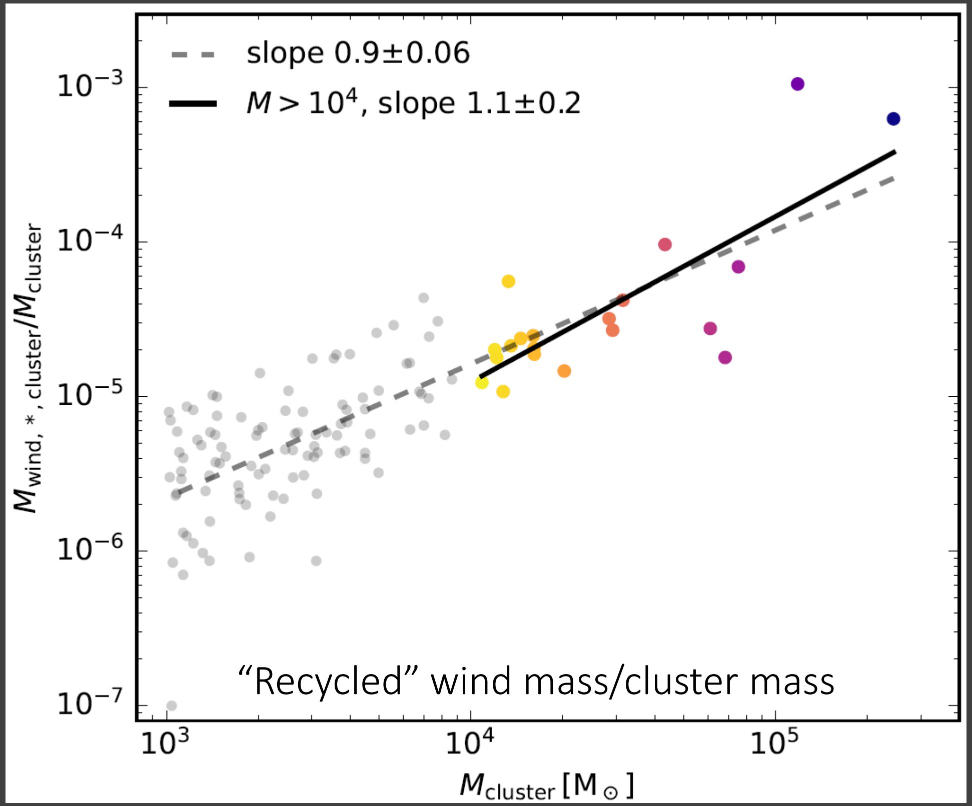
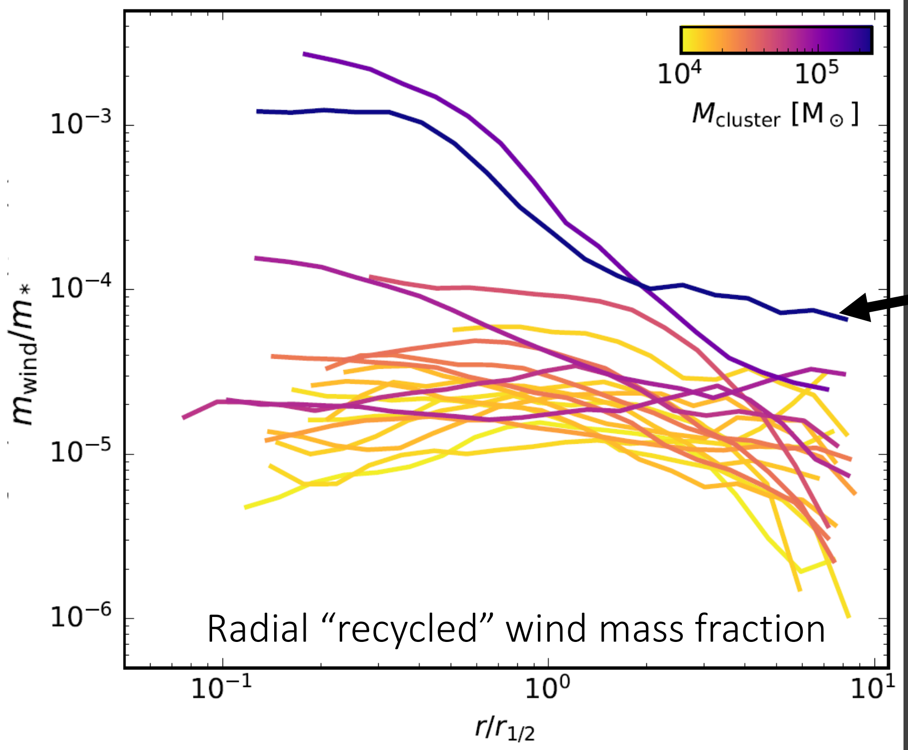
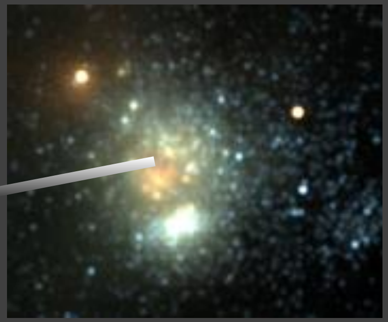
GC-mass clusters form hierarchically, with high central densities, rotating, with rapid centrally concentrated self-enrichment due to winds of massive stars (Lahén+20ab,24)

→ toward chemically discernible multiple populations in almost uniform age clusters







See e.g.
L. Lancaster´s work

Lahén+2020a, 2024a

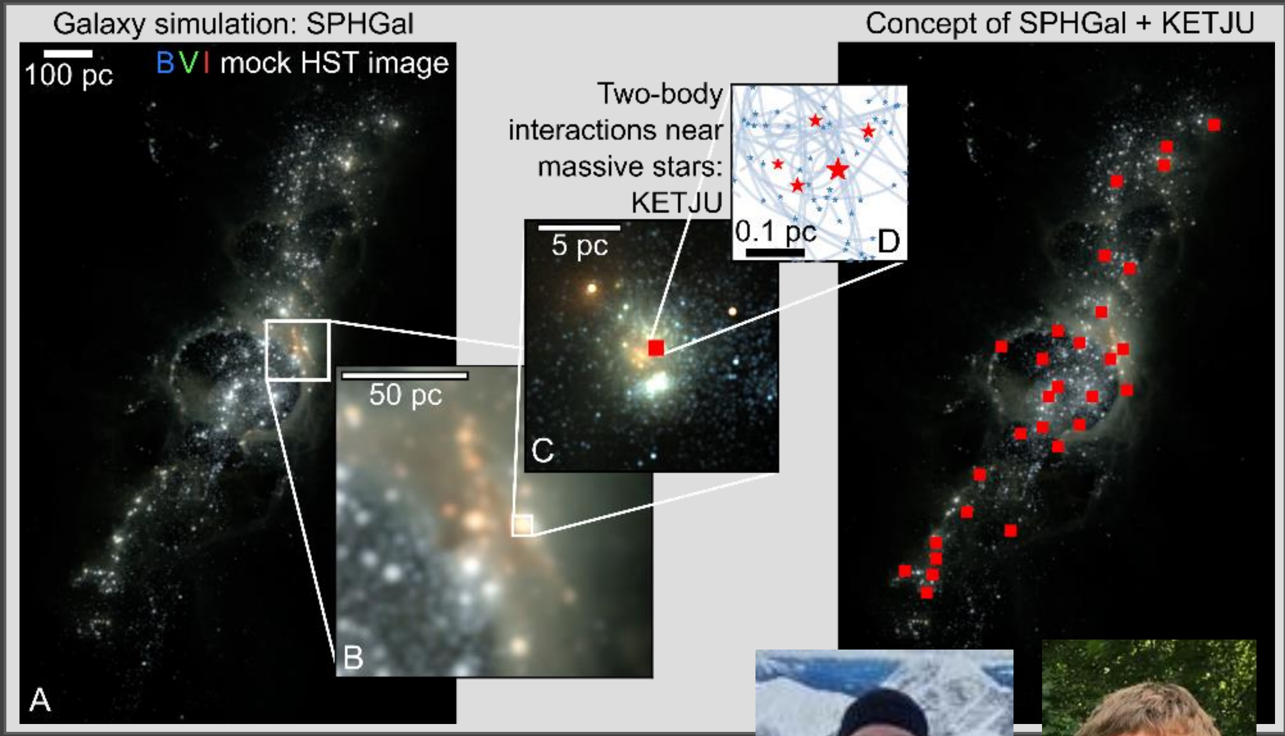
Accurate collisional dynamics in star clusters with KETJU

How to account for two and few-body dynamics:

Publicly available KETJU-module (Rantala+17, Mannerkoski+23) in a nutshell:

- Select region(s) of space where you need higher accuracy in gravitational interactions:
    - center at every $m_* > m_i$; here m_i = 3 $M_\odot$
    - radius: $n \times$ grav. softening length; here 0.03–0.3 pc

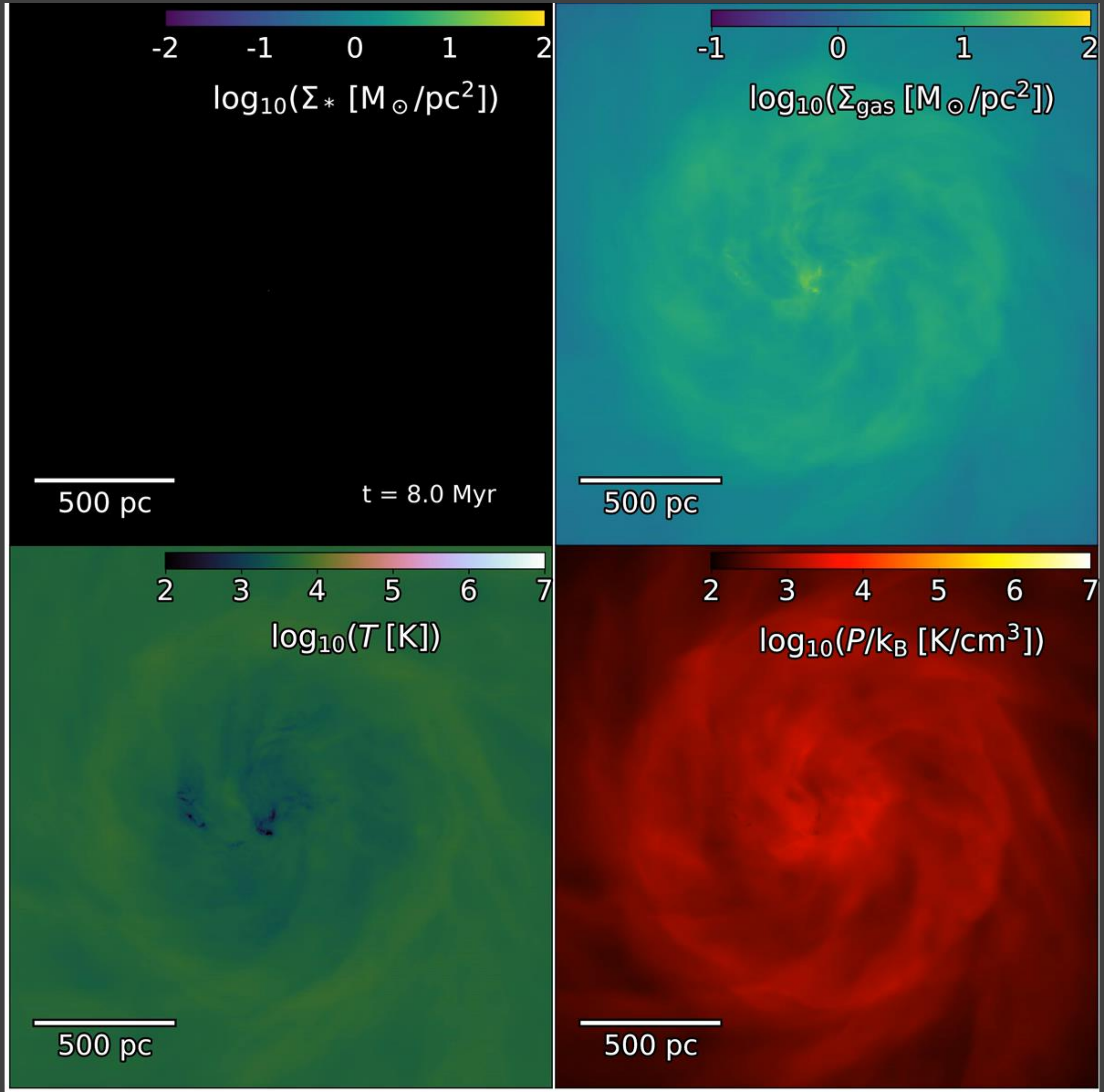
- KETJU uses three numerical recipes in the algorithmically regularized MSTAR library (Rantala+20) to guarantee user-specified accuracy without gravitational softening:
    - ➢ Time-transformed equations of motion (incl. optional post-Newtonian corrections)
    - ➢ Minimum spanning tree coordinate system
    - ➢ Gragg-Bulirsch-Stoer extrapolation technique combined with leap-frog integrator



Antti Rantala, Christian Partmann

Lahén+2024b, arXiv:2410.01891
Partmann+2024, arXiv:2409.18096

First results: quiescent dwarf galaxies, $Z=0.01\ Z_\odot$, $M_{vir}=4\times10^{10}\ M_\odot$, $M_{cluster}$ up to ~1000 $M_\odot$



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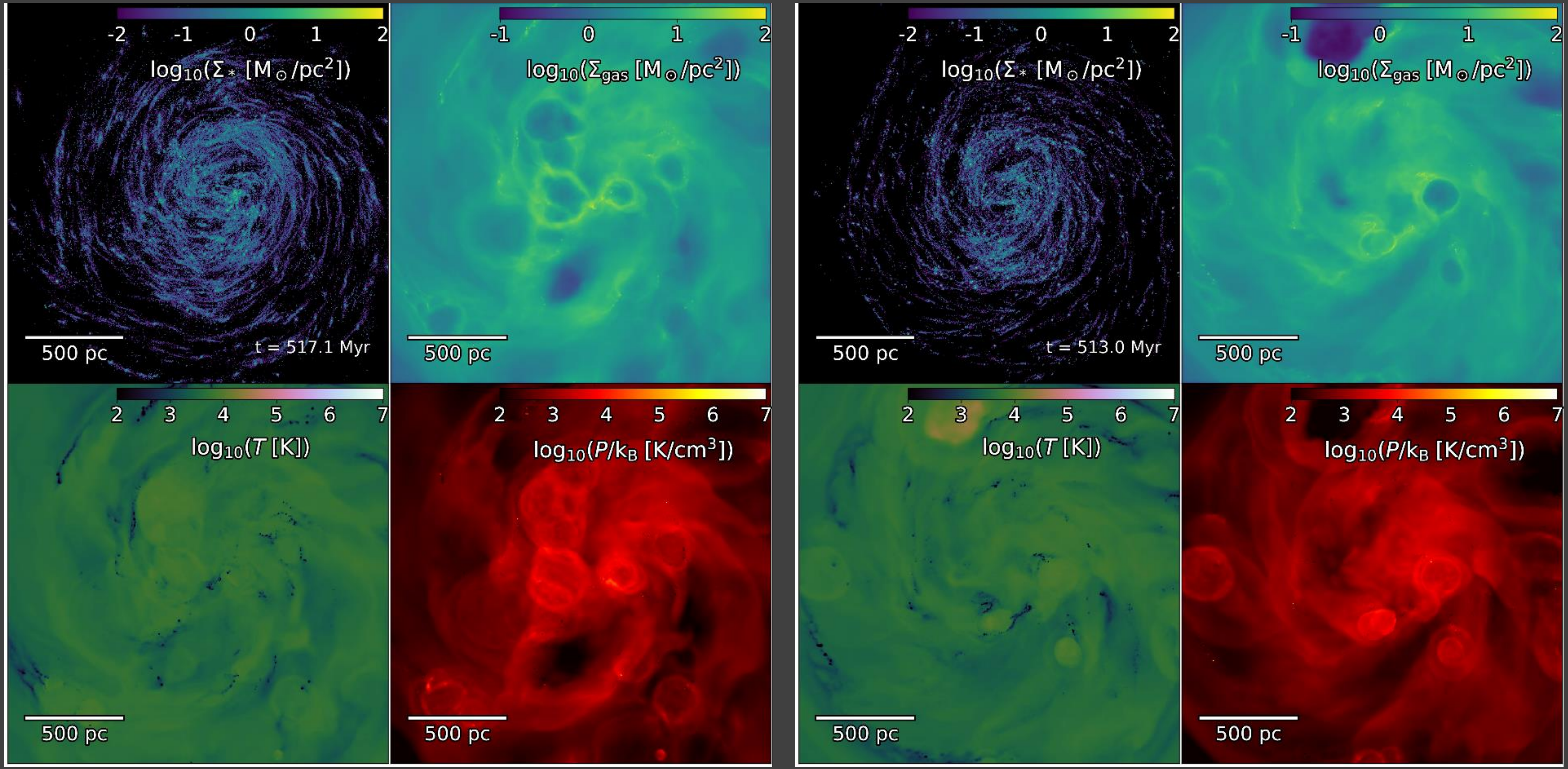
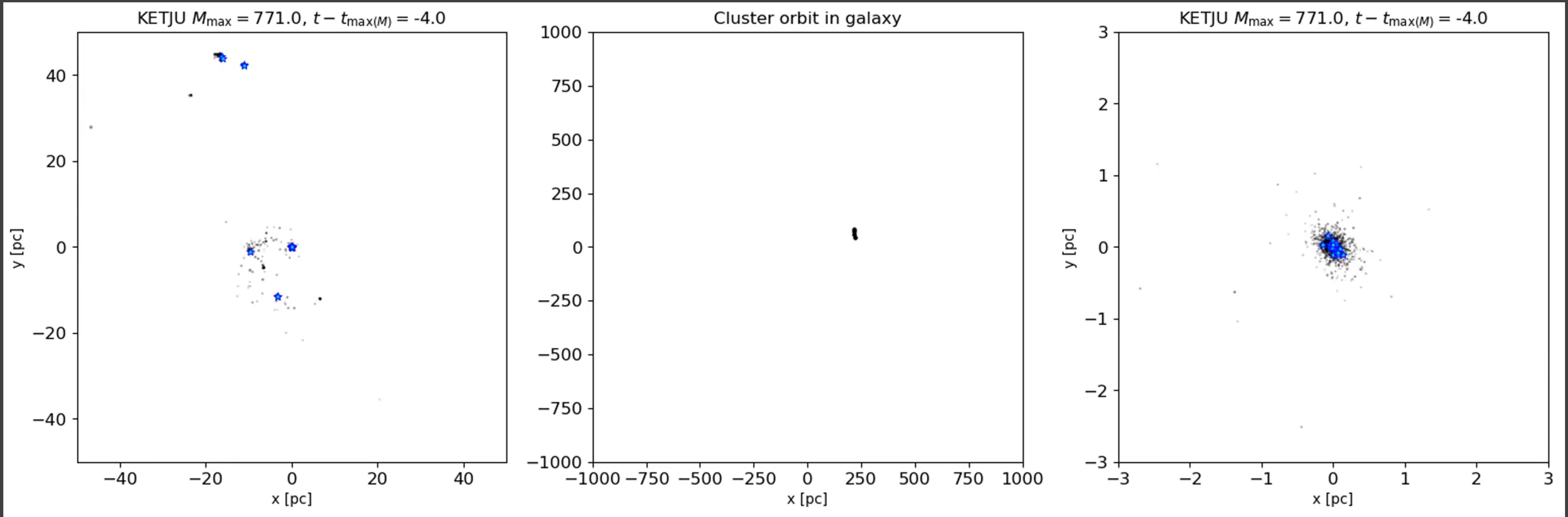


First results: quiescent dwarf galaxies, $Z=0.01\ Z_{\odot}$, $M_{vir}=4\times10^{10}\ M_{\odot}$, $M_{cluster}$ up to ~$1000\ M_{\odot}$

~65% of clusters disrupt by age of 100 Myr

→ SNae in clusters reduced by a factor of >2 compared to softened simulation

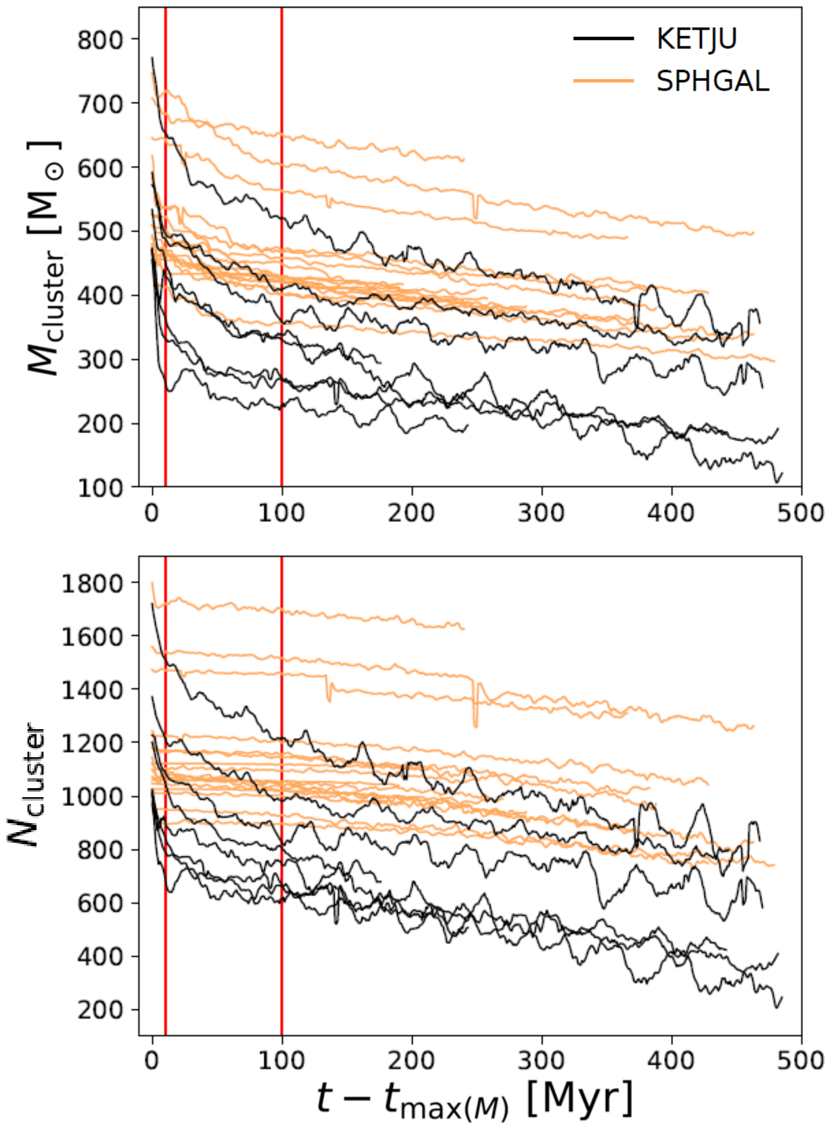


Lahén+2024b, arXiv:2410.01891

KETJU+SPHGal: star cluster mass-loss and size-growth in a galactic environment

Examples: 500 – 1000 $M_\odot$ clusters in a dwarf galaxy

Size-evolution and mass-loss rapid but not necessarily destructive

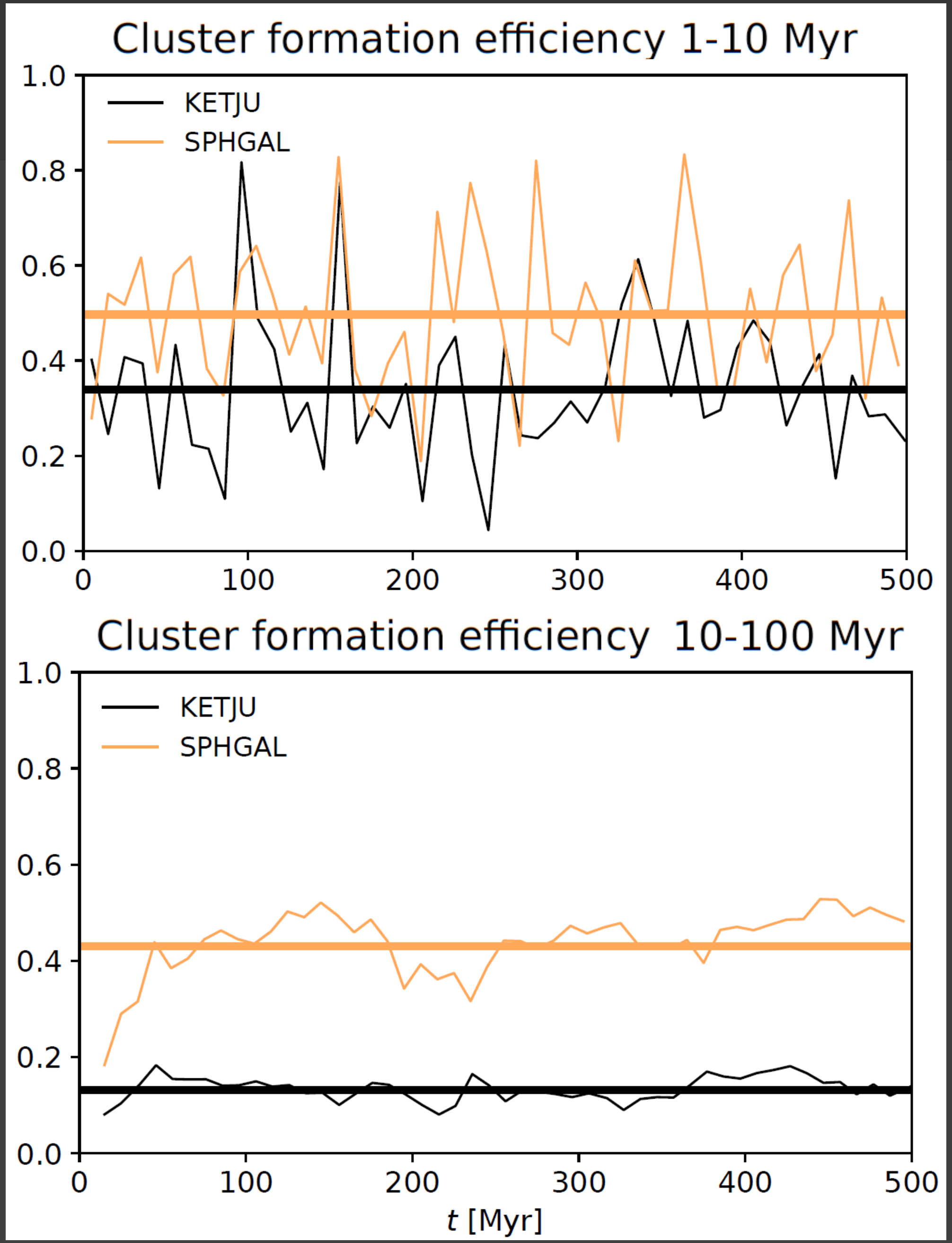


Lahén+2024b, arXiv:2410.01891

KETJU+SPHGal: (low-mass) star cluster population in a low-metallicity dwarf galaxy

Rapid cluster evolution seen as reduction in the measured "cluster formation efficiency" = "clustered fraction at certain age" = cluster formation rate/SFR

- After 10—100 Myr of evolution, ~10% of all stars reside in bound >100 $M_\odot$ star clusters



Lahén+2024b, arXiv:2410.01891

KETJU+SPHGal: (low-mass) star cluster population in a low-metallicity dwarf galaxy

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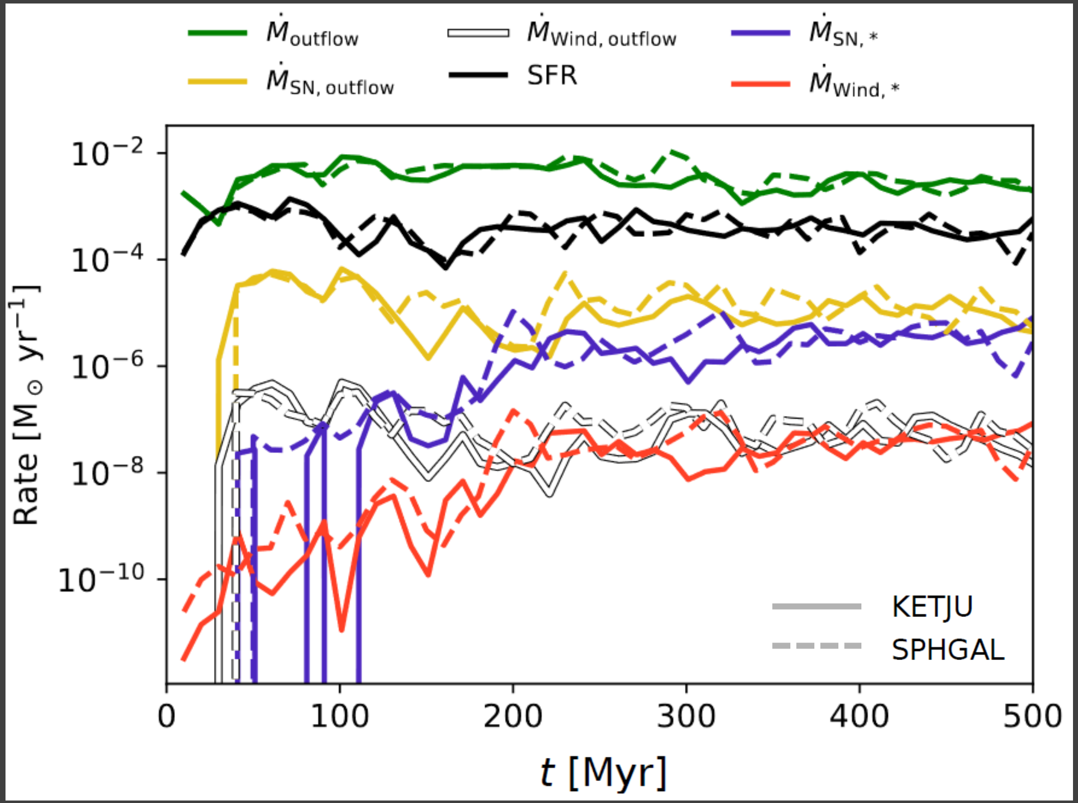
- After 10—100 Myr of evolution, ~10% of all stars reside in bound >100 $M_\odot$ star clusters

SN clustering is reduced compared to softened simulation

- ➢ Still, cluster evolution has only a minor impact on galactic scales in an isolated, quiescent dwarf galaxy

Early stellar feedback clears the clusters of gas (photoionization, stellar winds, can be external!)

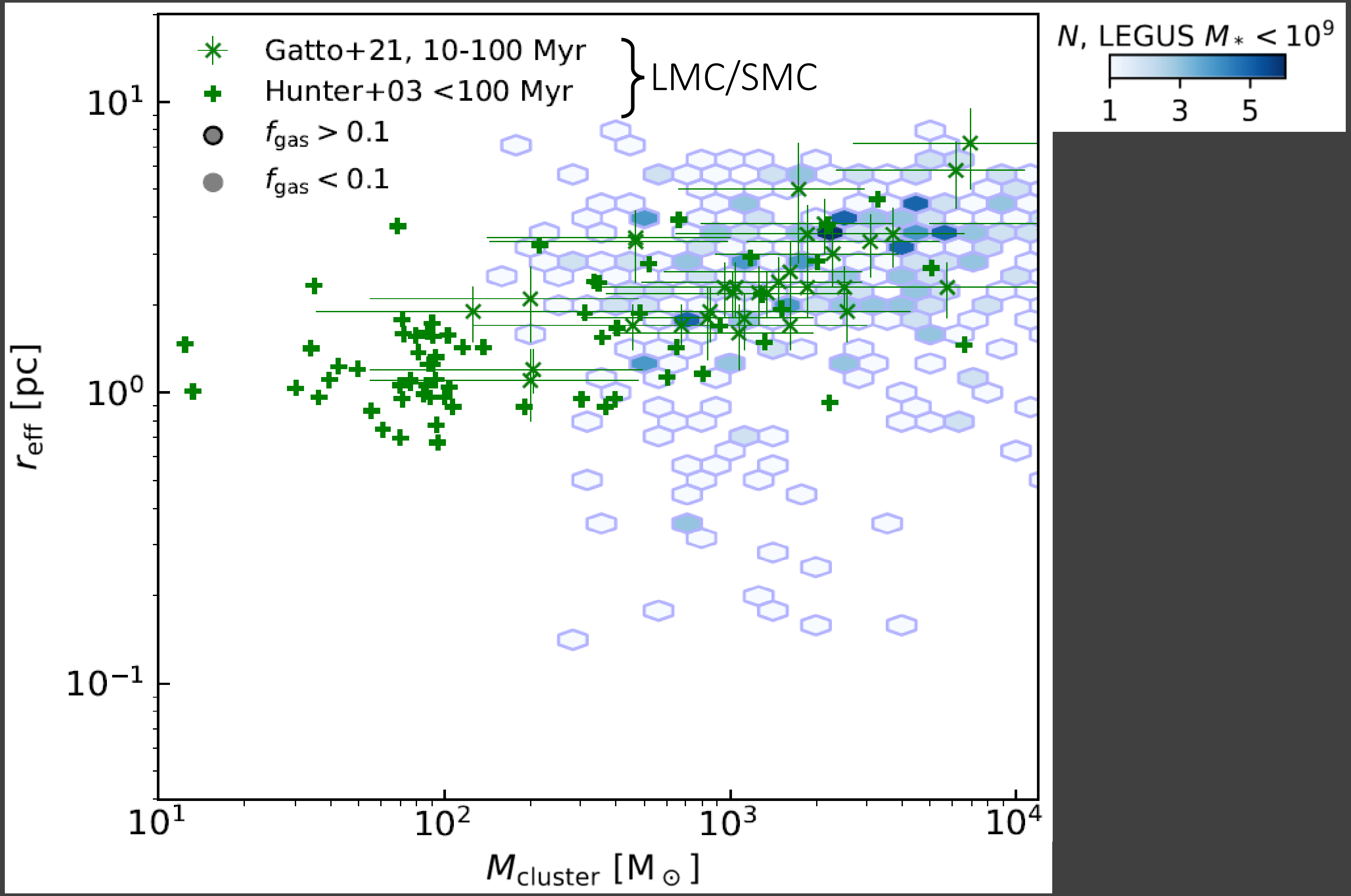
SFR, gas outflow rate, SN and wind mass outflow rate…



Lahén+2024b, arXiv:2410.01891

KETJU+SPHGal: Mass-size evolution

Around m_i>3 $M_\odot$ not softened



Lahén+2024b, arXiv:2410.01891

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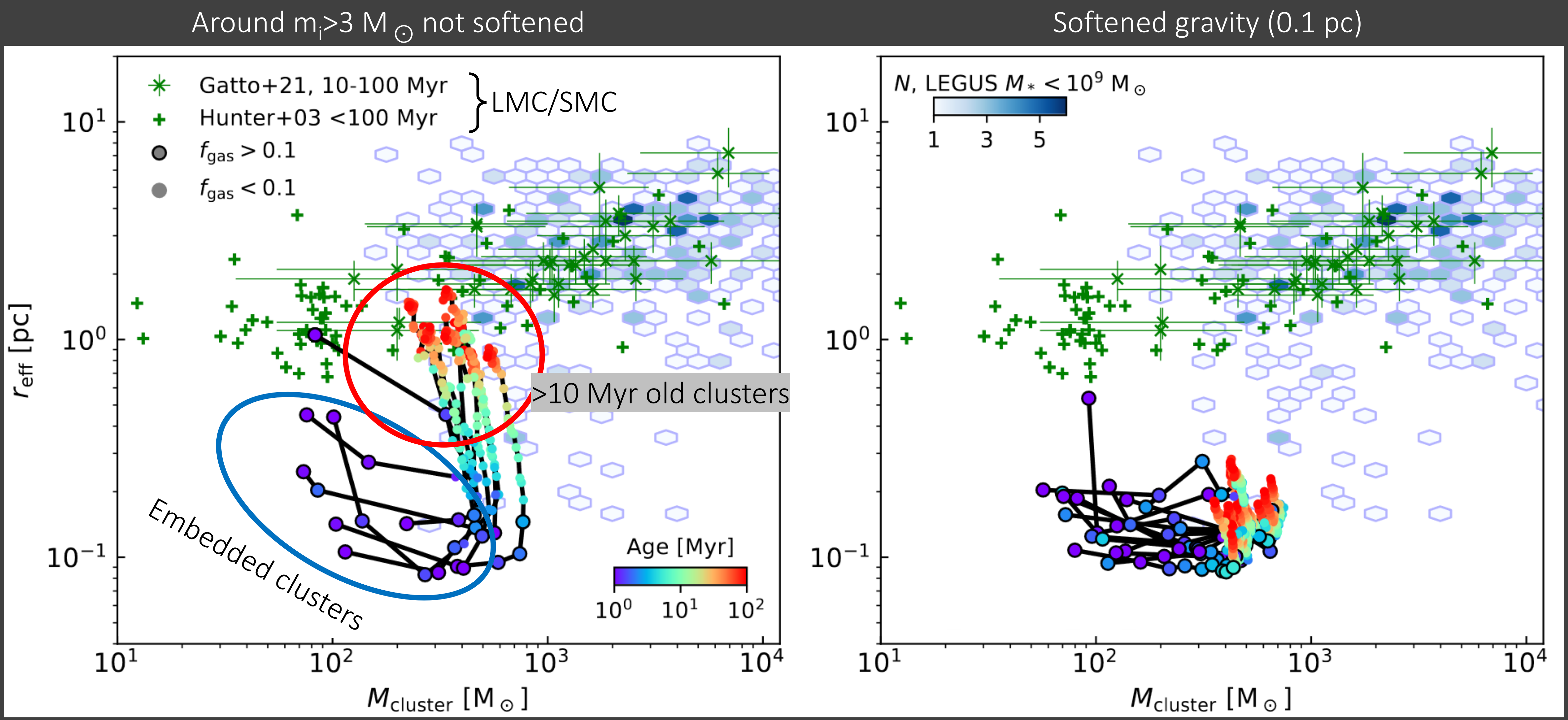


Lahén+2024b, arXiv:2410.01891

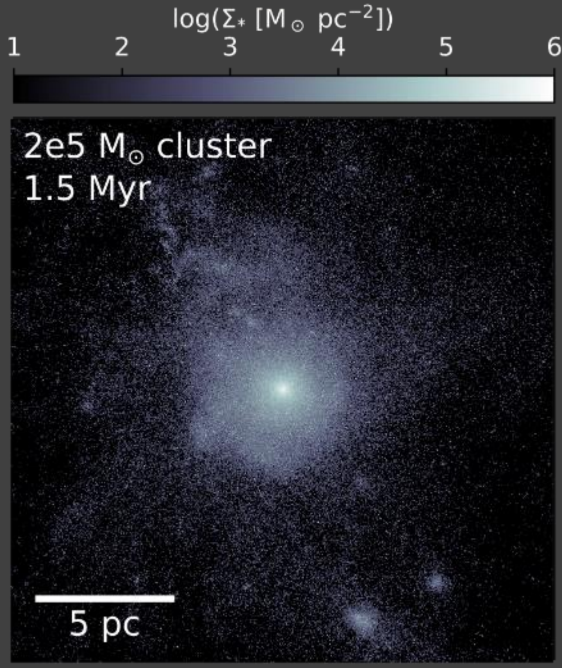
Massive star cluster formation with KETJU: R136 in Tarantula to scale

Crowther+2016, 2024, Shenar+2023

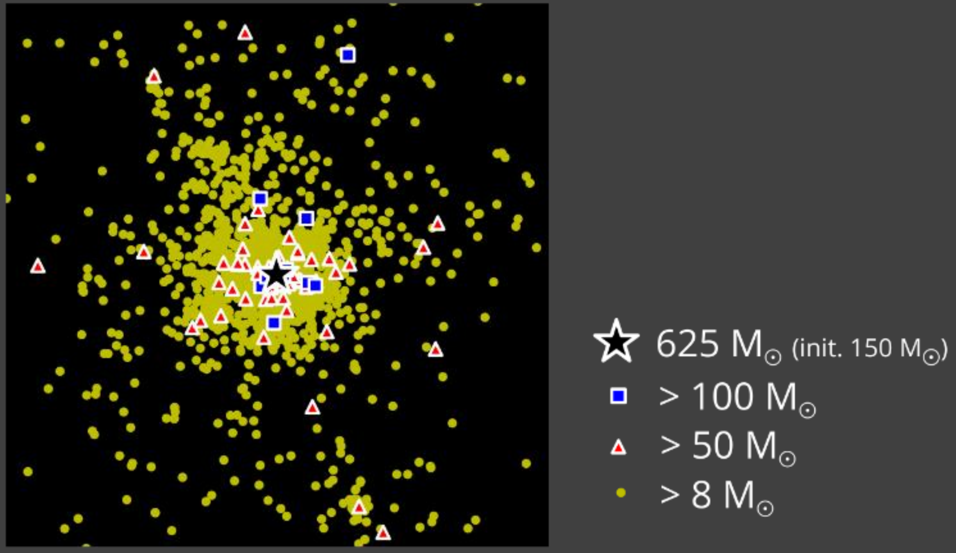
HII region NGC 2070:
2-4 Myr
$M_* \lesssim$ 1e5 $M_\odot$

R136: 1-2 Myr

(Higher metallicity)



20 pc



20 pc

Lahén+ in prep;
see also Rantala+2024b & Fujii+2024

Massive star cluster formation with KETJU: R136 in Tarantula to scale

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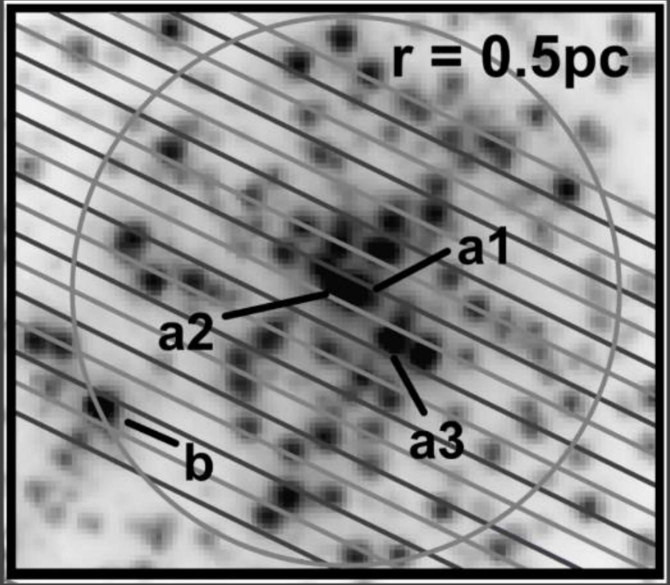
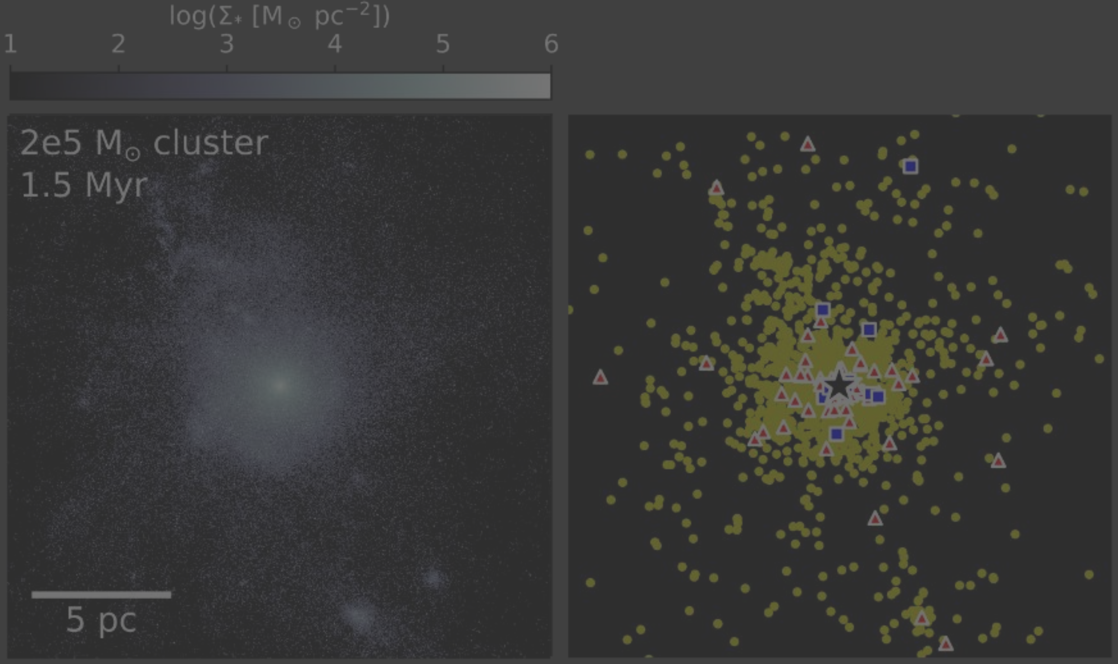


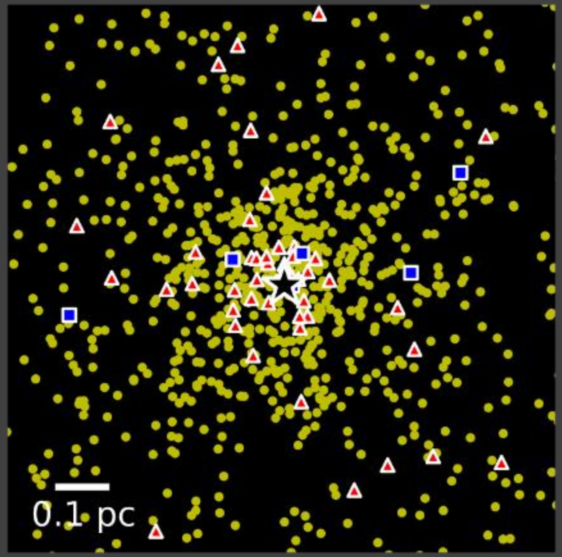
R136 a1, a2, a3 > 150 $M_\odot$
(not binaries?)



20 pc

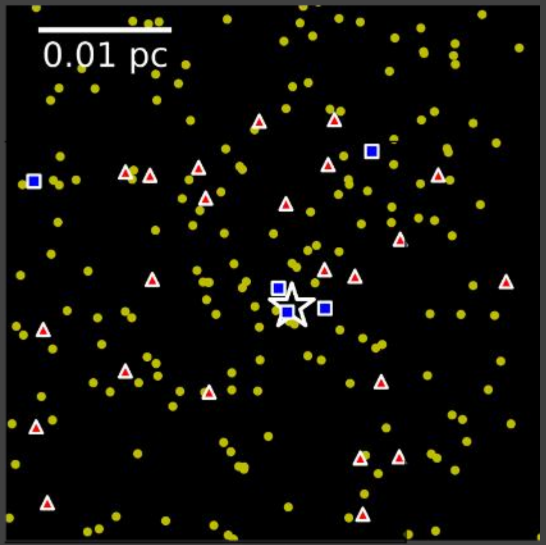
20 pc

zoom



1 pc

zoooom



0.04 pc

☆ 625 $M_\odot$ (init. 150 $M_\odot$)
■ > 100 $M_\odot$
▲ > 50 $M_\odot$
• > 8 $M_\odot$

Lahén+ in prep;
see also Rantala+2024b & Fujii+2024

Conclusions & outlook

Formation of star clusters up to > $10^5\,M_\odot$ can be modelled in galactic environments while sampling the entire IMF (0.08 - 500 $M_\odot$)

- Star clusters don't need to be point masses or simple stellar populations
- Pre-SN feedback is efficient: often disperses dense gas before SNe start (see also observations in Sarbadhicary,…,NL+24 subm.)

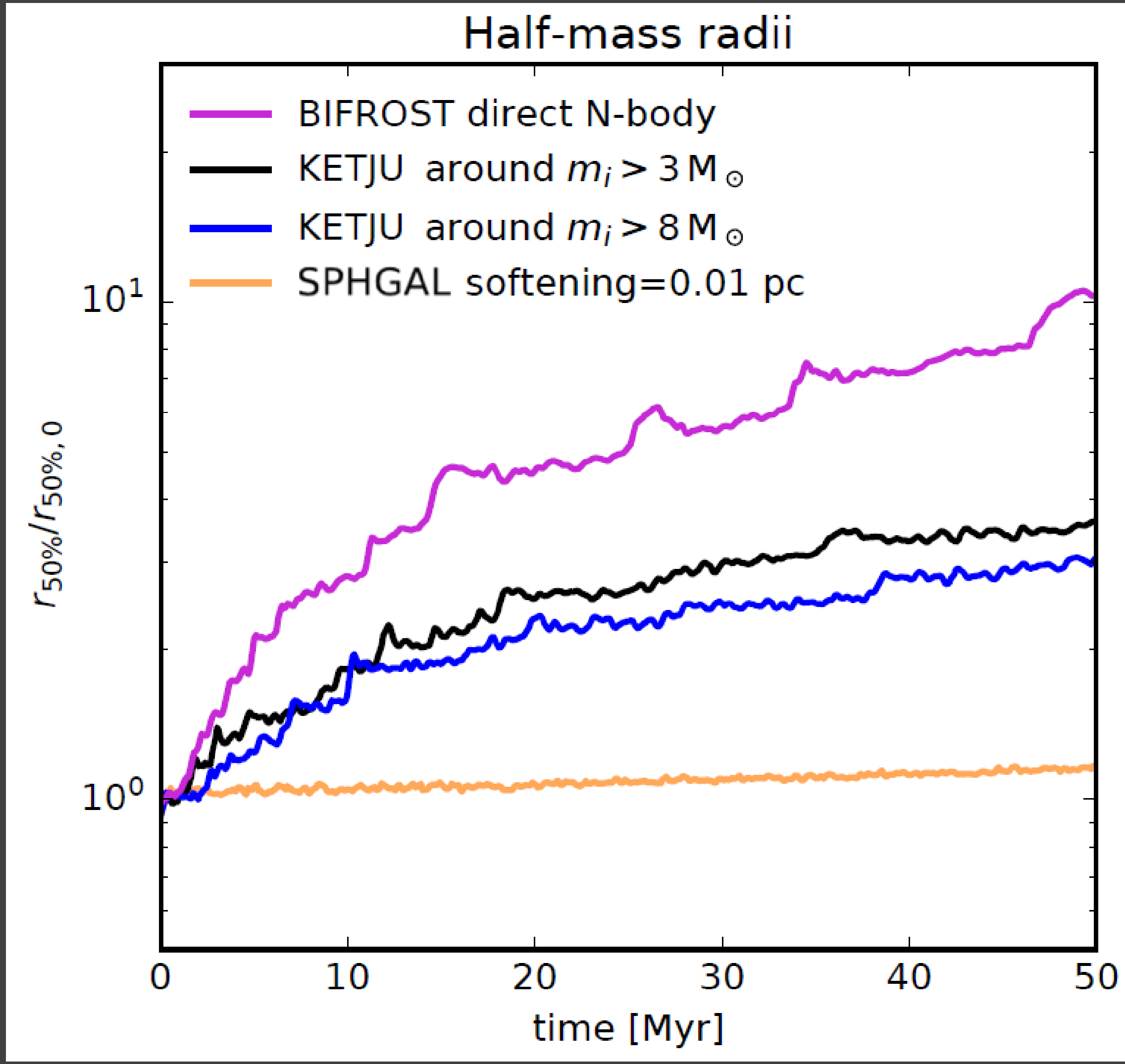
Avenues toward chemically and dynamically realistic simulated globular clusters:

- Various enrichment sources (to be done: binaries, more massive / supermassive stars)
- Collisional dynamics+hydro+feedback: stellar interactions (binaries, mergers, runaways, SMBH seeds?), long-term evolution, cluster disruption in a galactic and/or cosmological context

Thank you!

Star clusters with KETJU+SPHGal: code comparison

Star cluster, 10k stars, dense Plummer profile with initial $r_{50\%}$=0.3 pc



3 pc

0.3 pc

Star clusters with KETJU+SPHGal: code comparison

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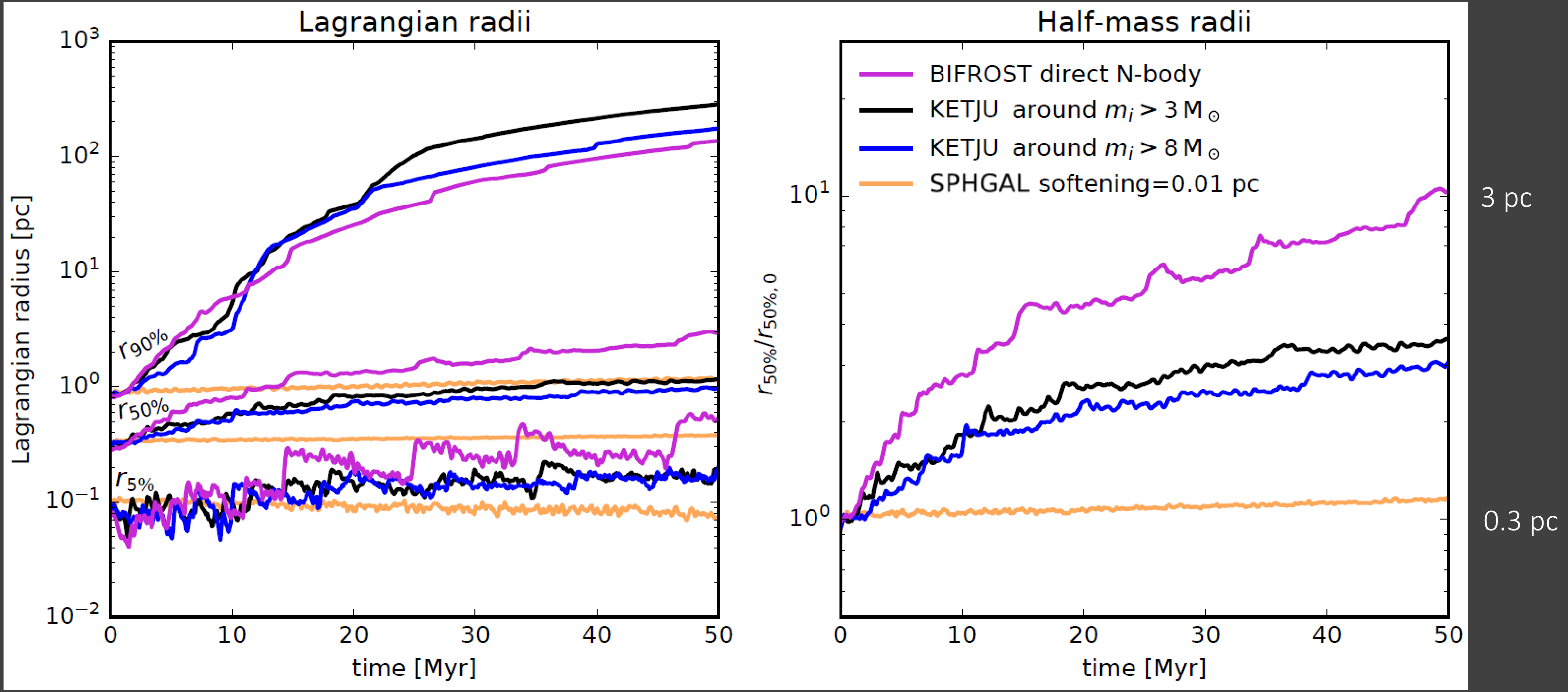
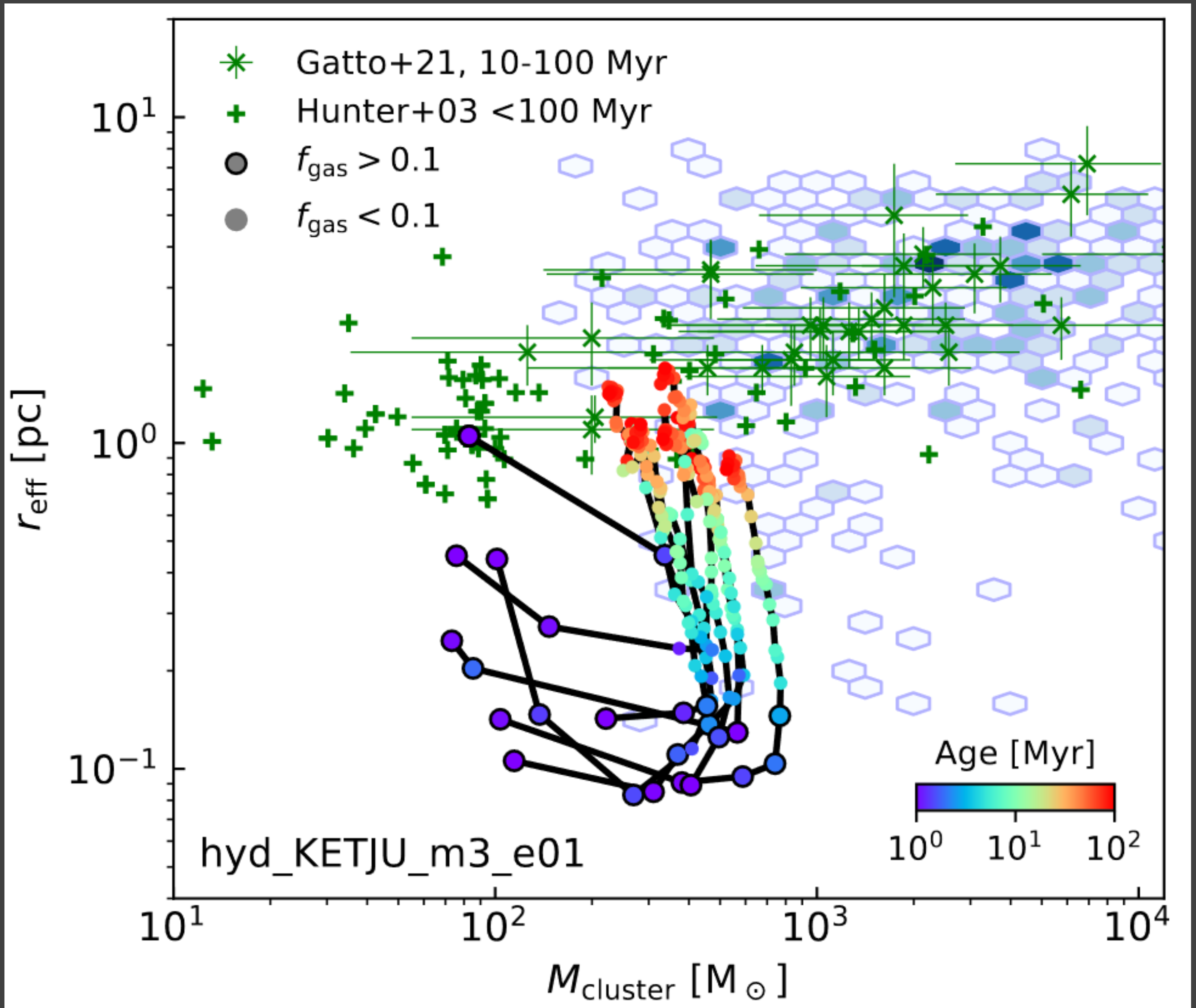
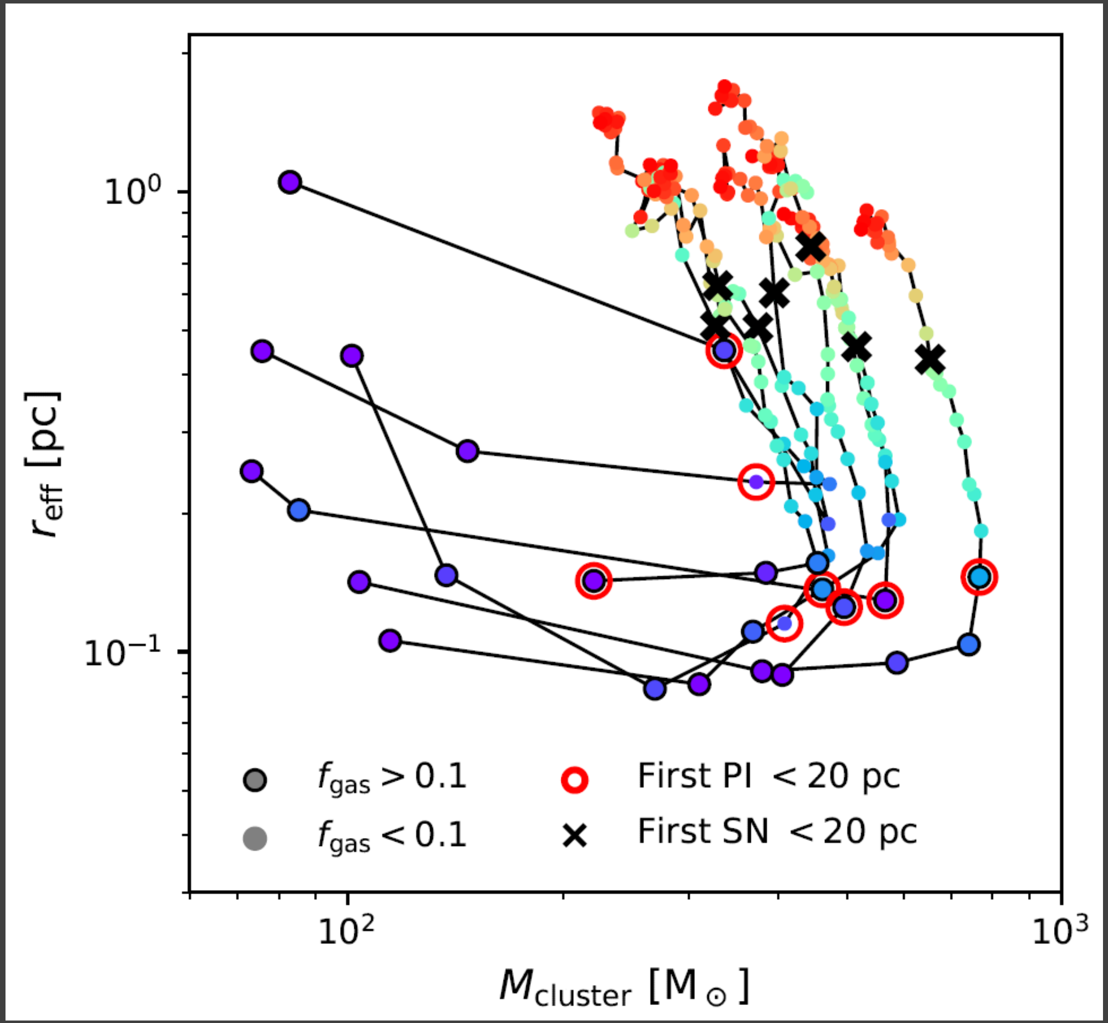
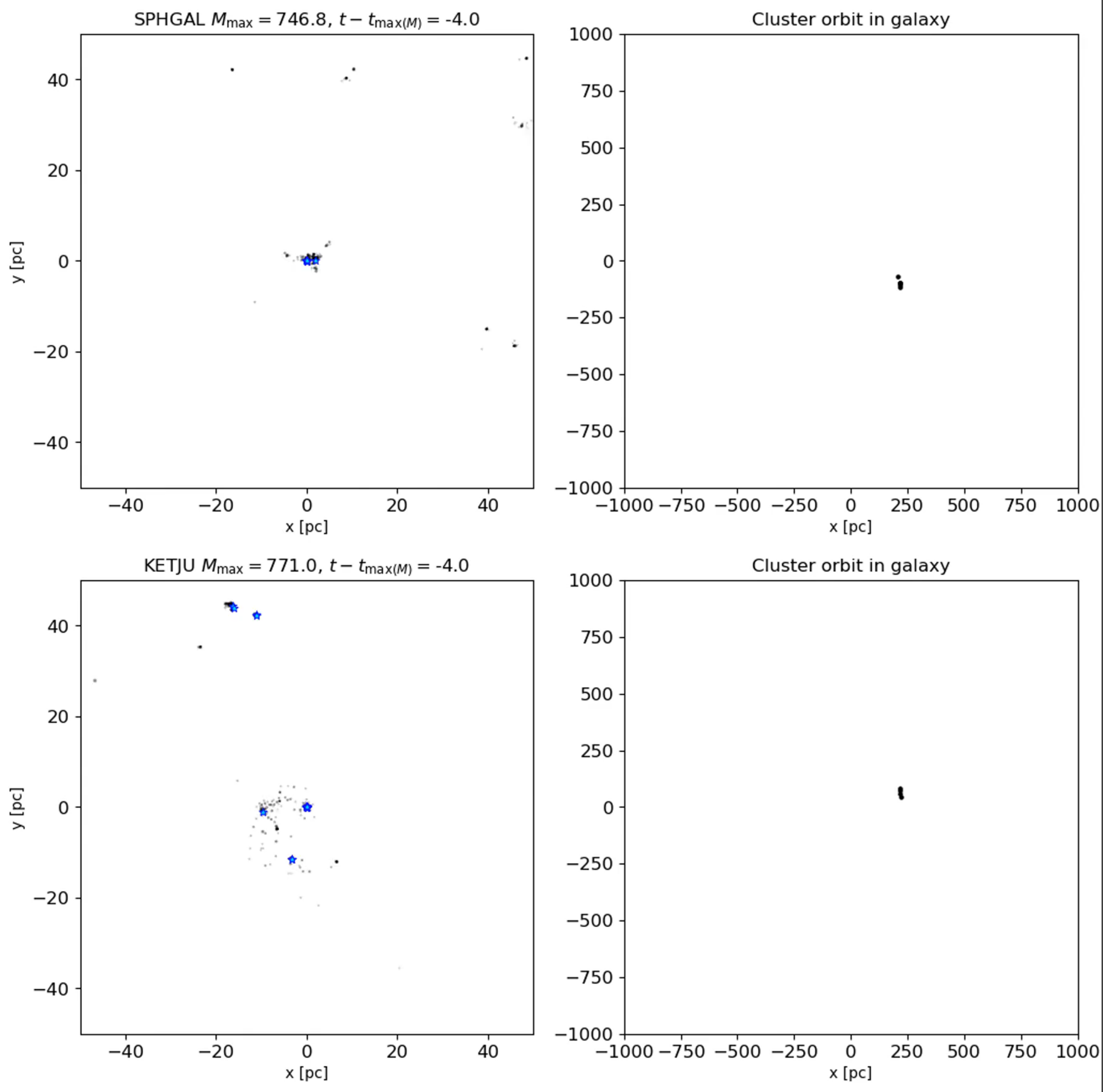


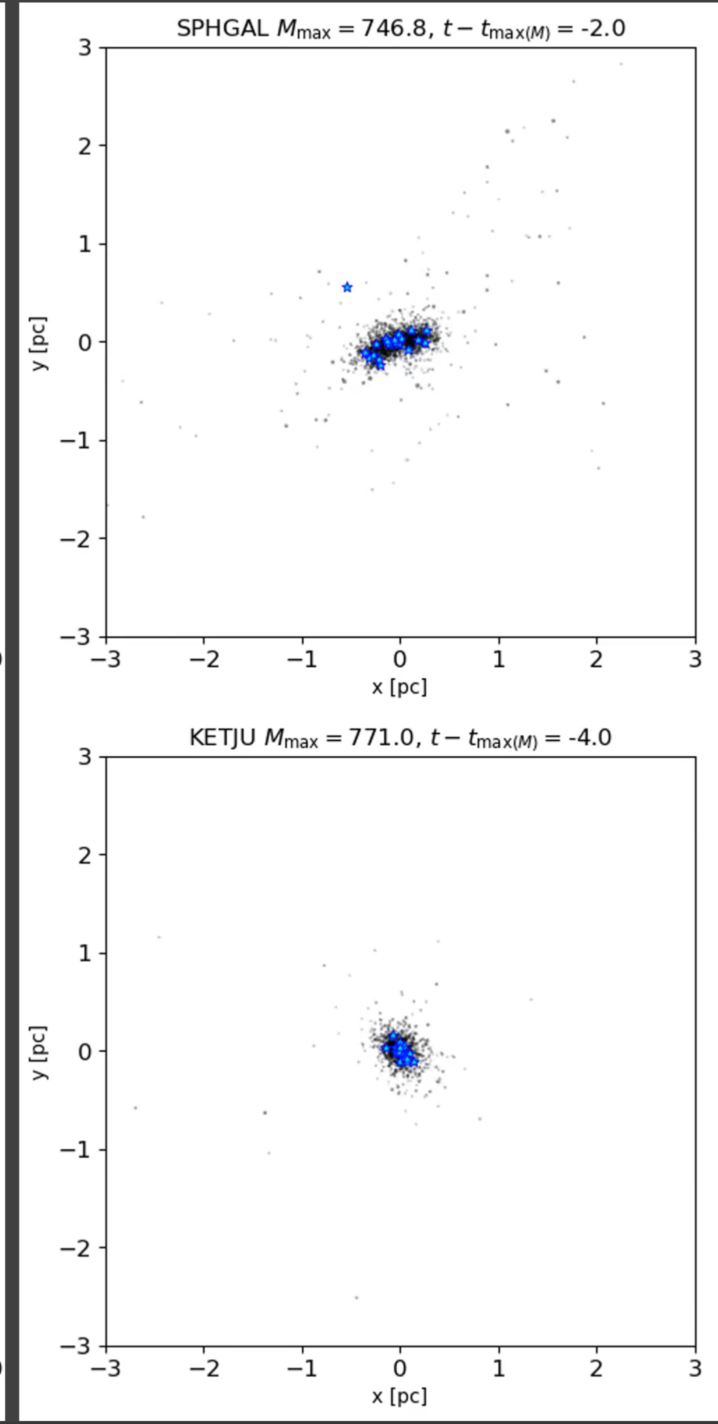
Photoionization (PI) evacuates gas before SNe







SPHGAL $M_{\rm max} = 746.8$, $t - t_{{\rm max}(M)}$ = -4.0
Cluster orbit in galaxy
KETJU $M_{\rm max} = 771.0$, $t - t_{{\rm max}(M)}$ = -4.0
Cluster orbit in galaxy
x [pc]
y [pc]



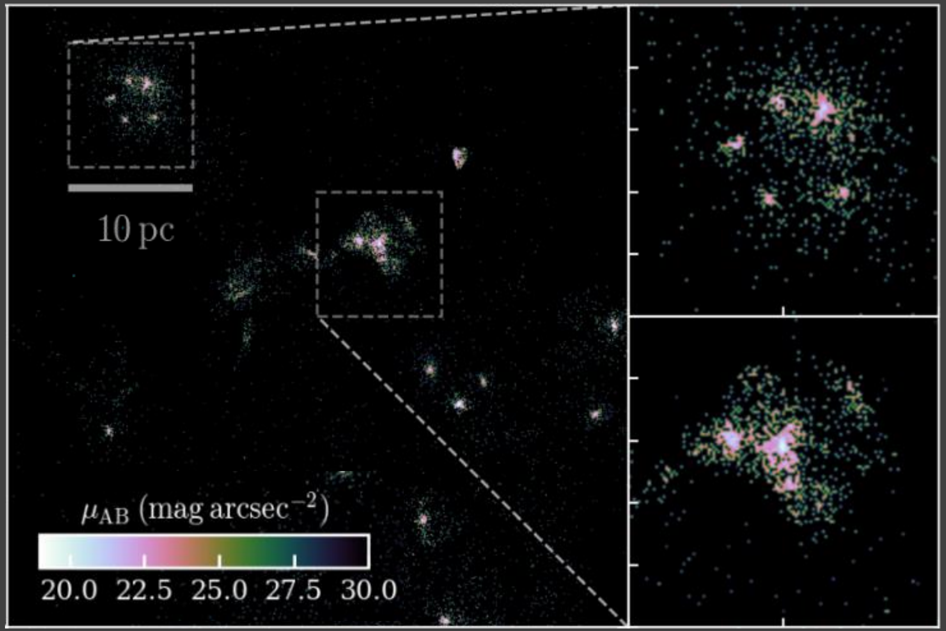
SPHGAL $M_{\rm max} = 746.8$, $t - t_{{\rm max}(M)}$ = -2.0
KETJU $M_{\rm max} = 771.0$, $t - t_{{\rm max}(M)}$ = -4.0
x [pc]
y [pc]

Galaxy scale simulations of star cluster formation

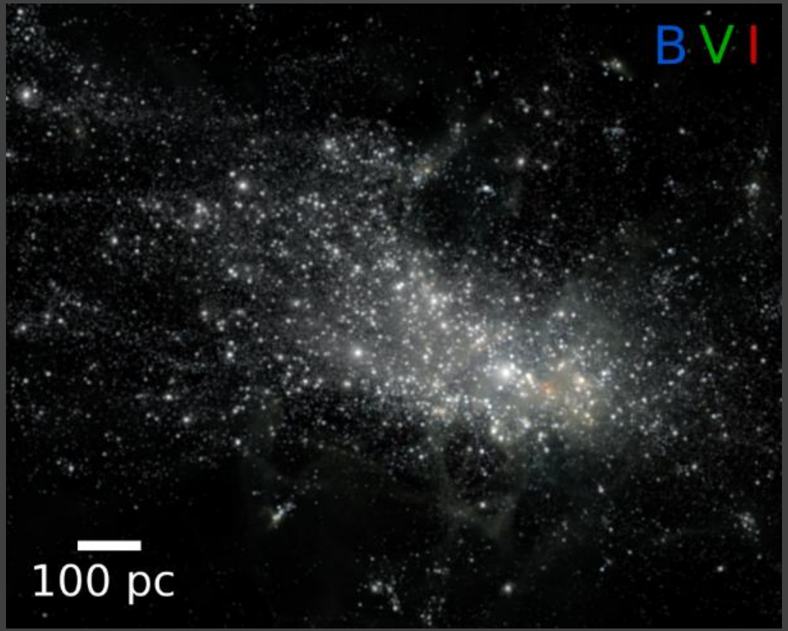
Non-exhaustive list of simulations of cluster/clump formation including non-equilibrium chemistry and varying detail of stellar feedback including early stellar feedback (pre-SN):

- Cosmological conditions: Boley+ 09; Ricotti+ 16; Kimm+ 16; Ma+ 18; Phipps+ 20; Calura+ 22; Garcia+ 23; Sameie+ 23
- Idealized spiral arm / dwarf galaxy / dwarf galaxy starburst simulations: Dobbs+ 17/20; Lahén+ 20a/24; Li+ 22; Hislop+ 22; Andersson+ 24

Garcia+ 23



Lahén+ 22



Resolution to model feedback of individual (massive) stars increasingly common

More simulations of cluster formation in galaxies:

Bekki+ 01; Kravtsov & Gnedin 02; Bournaud+ 08; Kruijssen+ 11; Renaud+ 15; Li+ 17; Maji+ 17; Pfeffer+ 18; Hirai+ 21; Rieder+ 22; Reina-Campos+ 22; Lake+ 23; van Donkelaar+ 23; Gutcke 24