Formation and evolution of star clusters in galactic environments

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MAX PLANCK INSTITUTE
FOR ASTROPHYSICS

Toward self-consistent globular cluster formation in galactic environments

NASA, ESA, A. Sarajedini, G. Piotto

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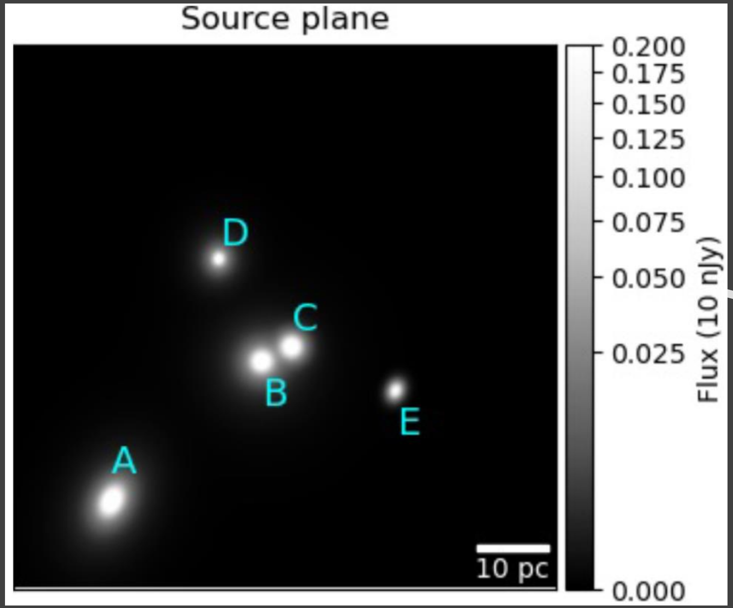
GCs formed within compact star forming complexes, already at z~10.2?



Adamo+24 arXiv

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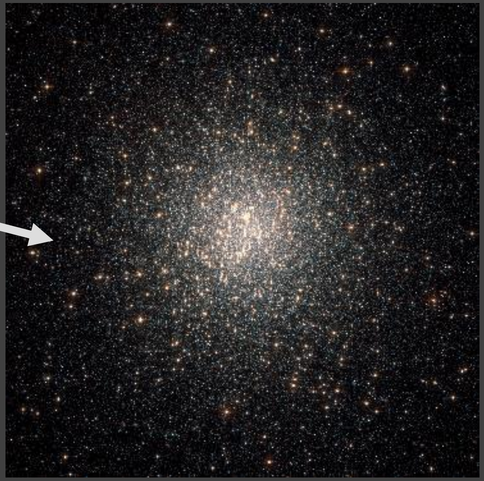

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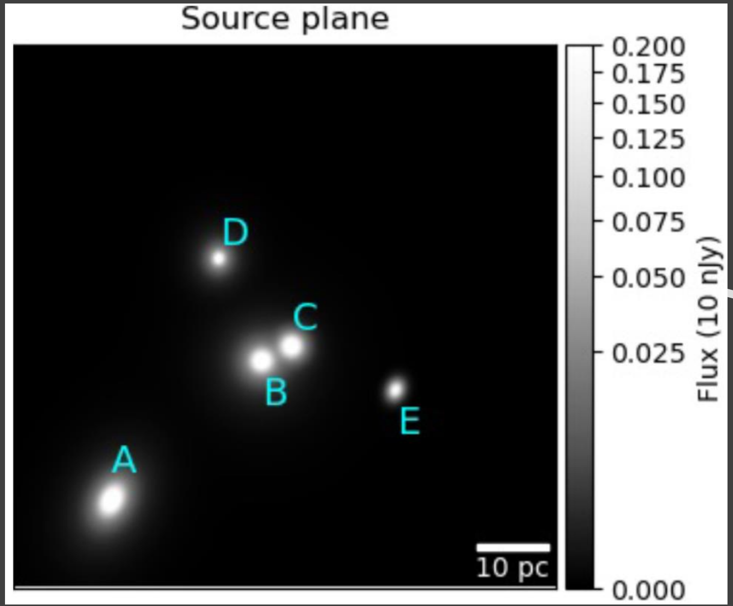

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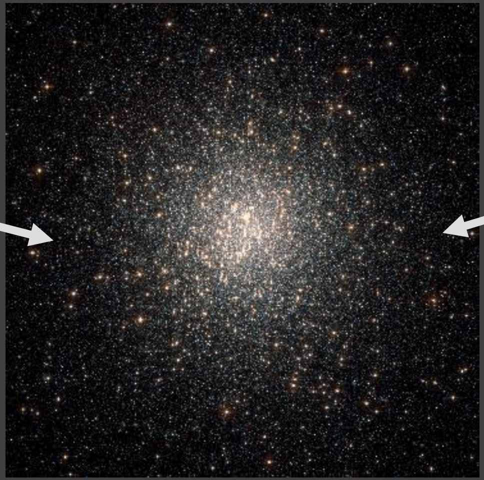
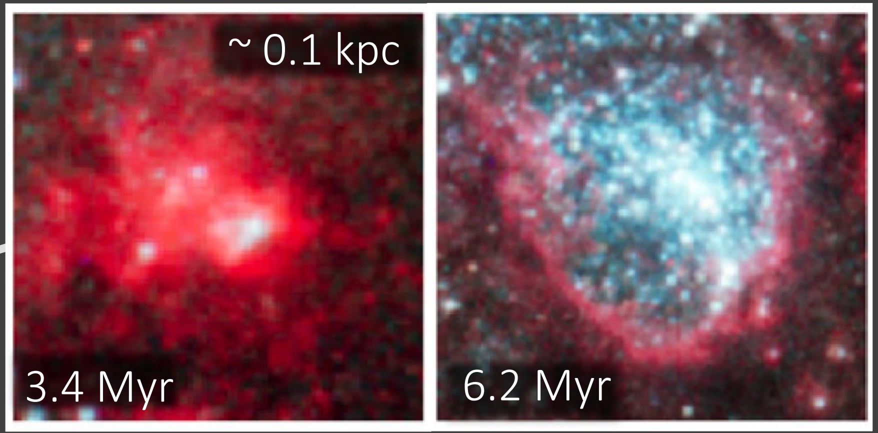


In nearby galaxies, exposed clusters typically emerge at <5 Myr timescale



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

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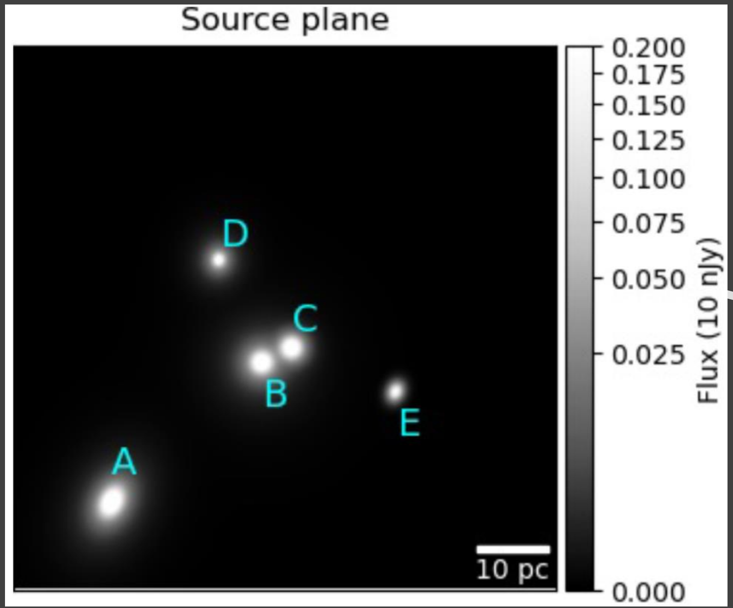

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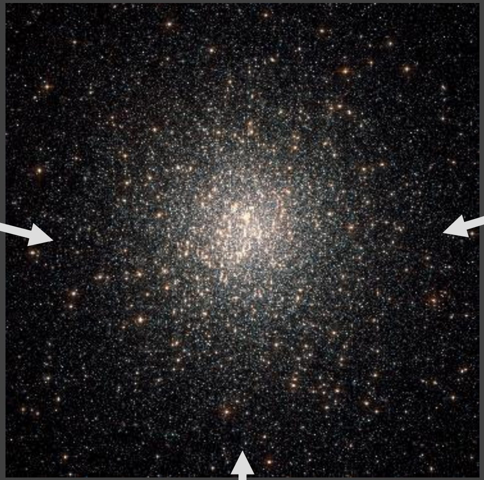

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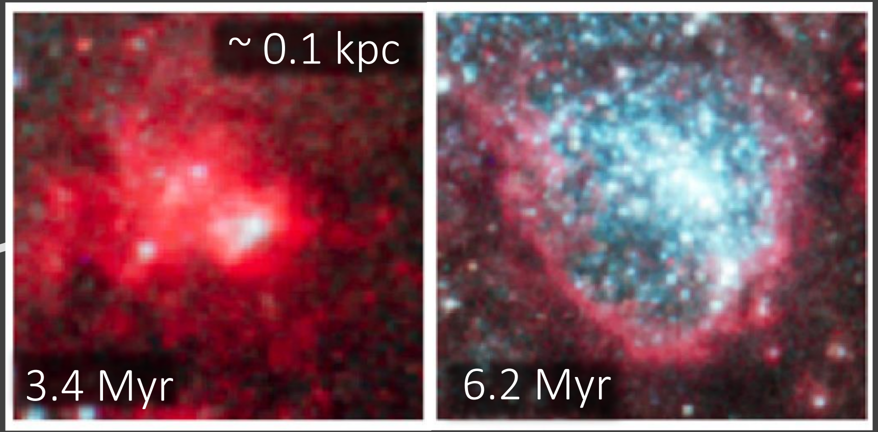

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NASA, ESA, the Hubble Heritage Team, and A. Aloisi

Star clusters form and evolve in a galactic tidal field

- Mass segregation, core-collapse, dynamical mass-loss, evaporation
- influenced by IMF, rotation, encounters with GMCs, other clusters, dark matter?

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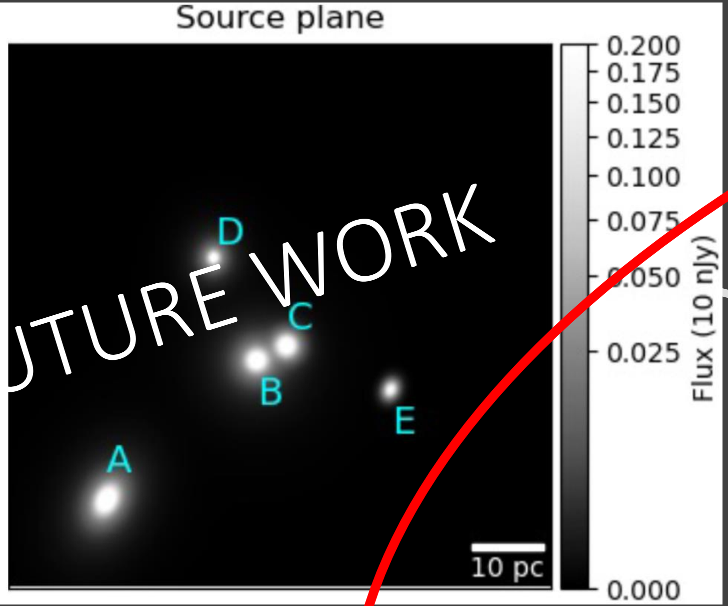

FUTURE WORK

Adamo+24 arXiv

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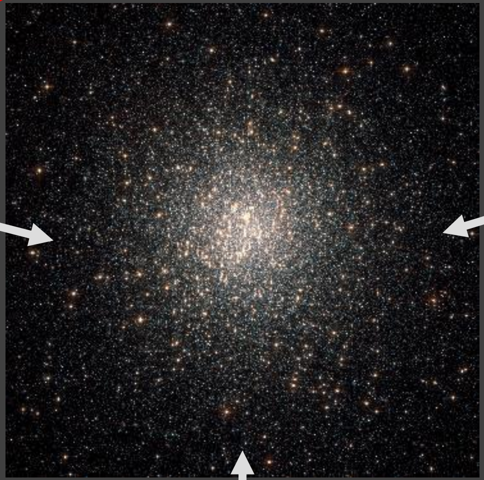

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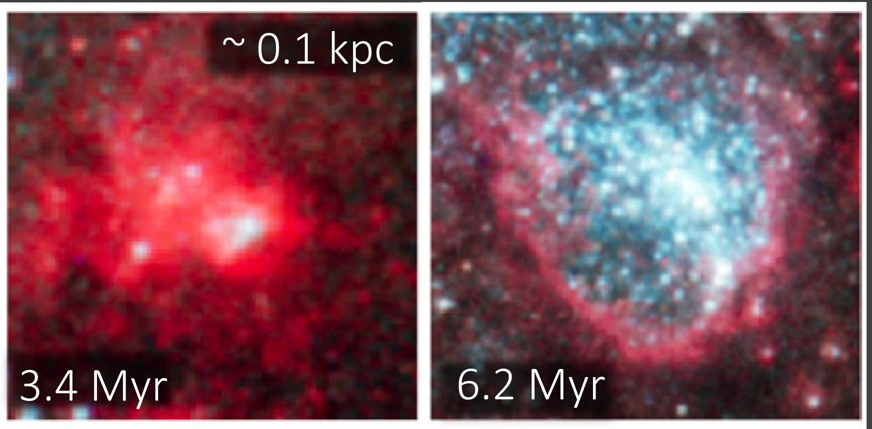

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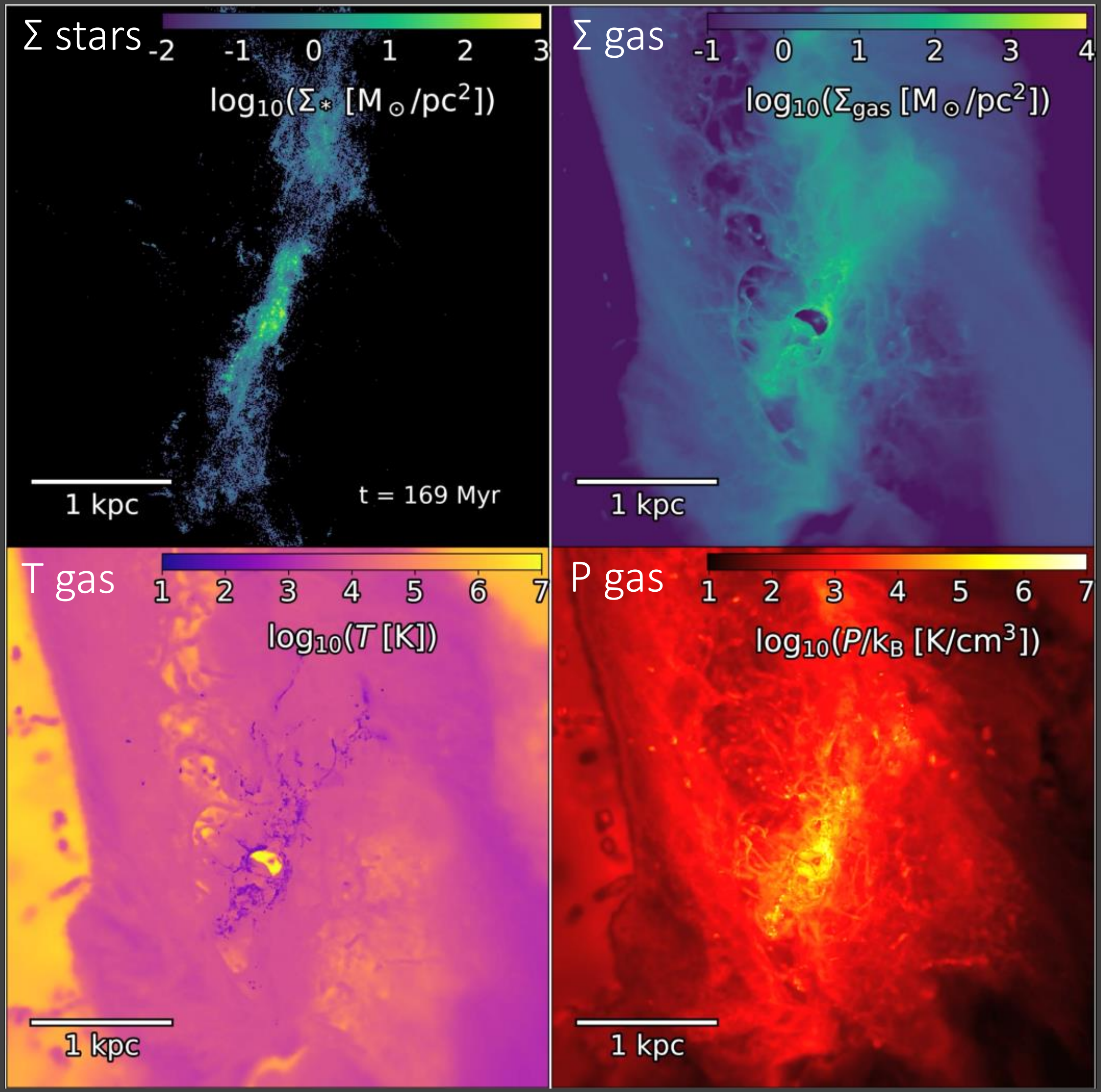
GRIFFIN Galaxy Realizations Including Feedback From INdividual massive star

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



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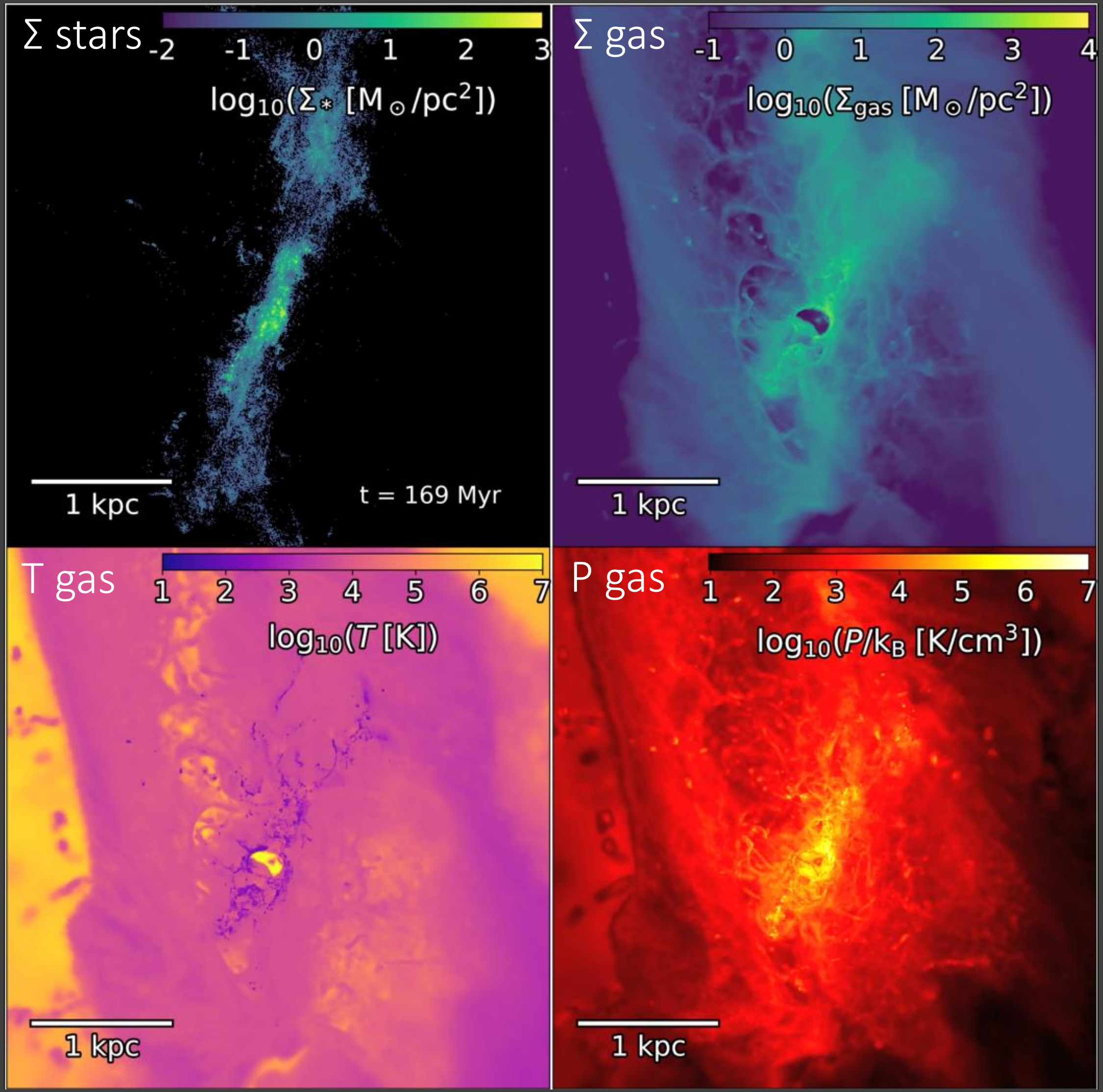
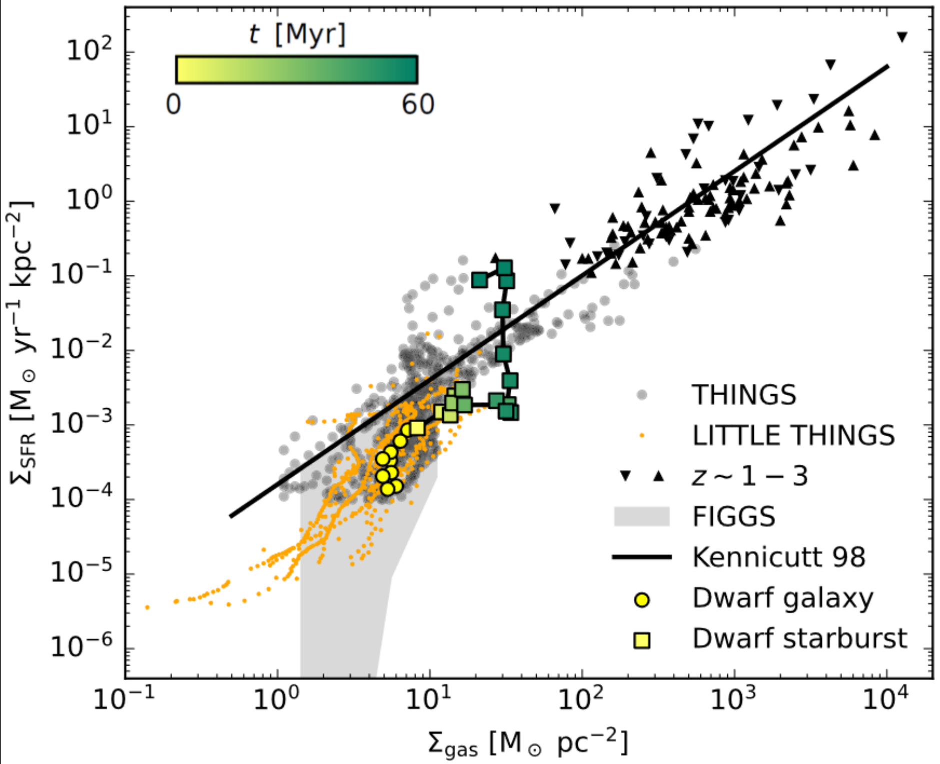
- Star formation: Jeans threshold, IMF sampled stars-by-star between 0.08-500 $M_\odot$ (Lahén+ 23)
- Feedback from individual stars (Geneva + BoOST models):
  - ➢ FUV interstellar radiation field with shielding by dust and gas (HEALPIX+TREECOL), photoionisation
  - ➢ Enrichment element-by-element & channel-by-channel: stellar winds, core-collapse SNe, pair-instability SNe, AGB winds



Simulated star cluster populations in starburst dwarf galaxies

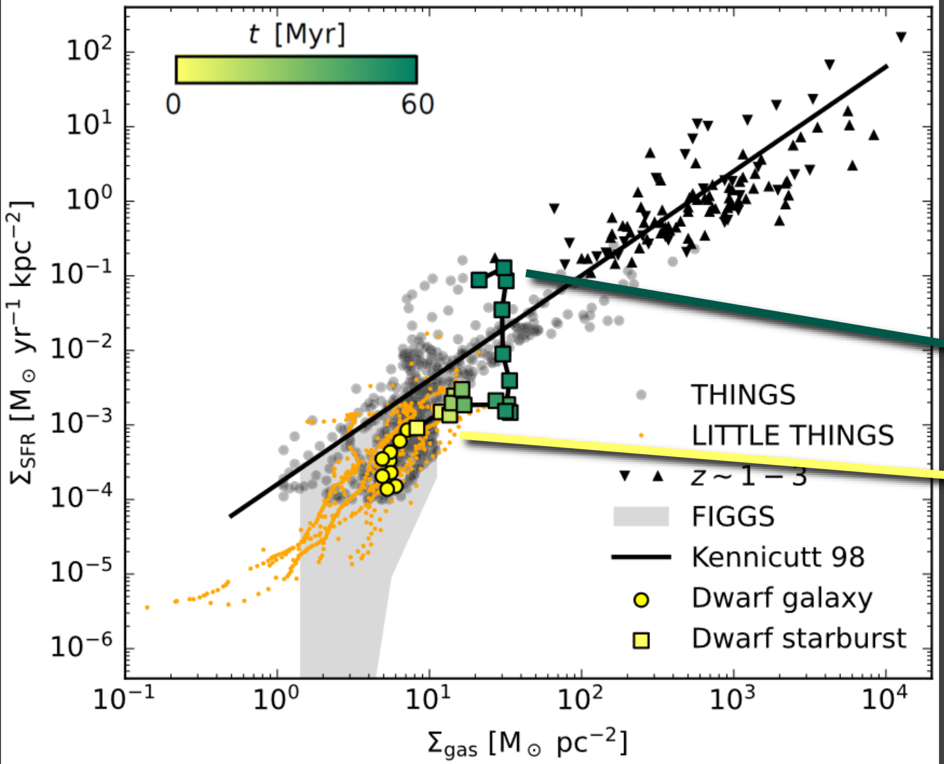


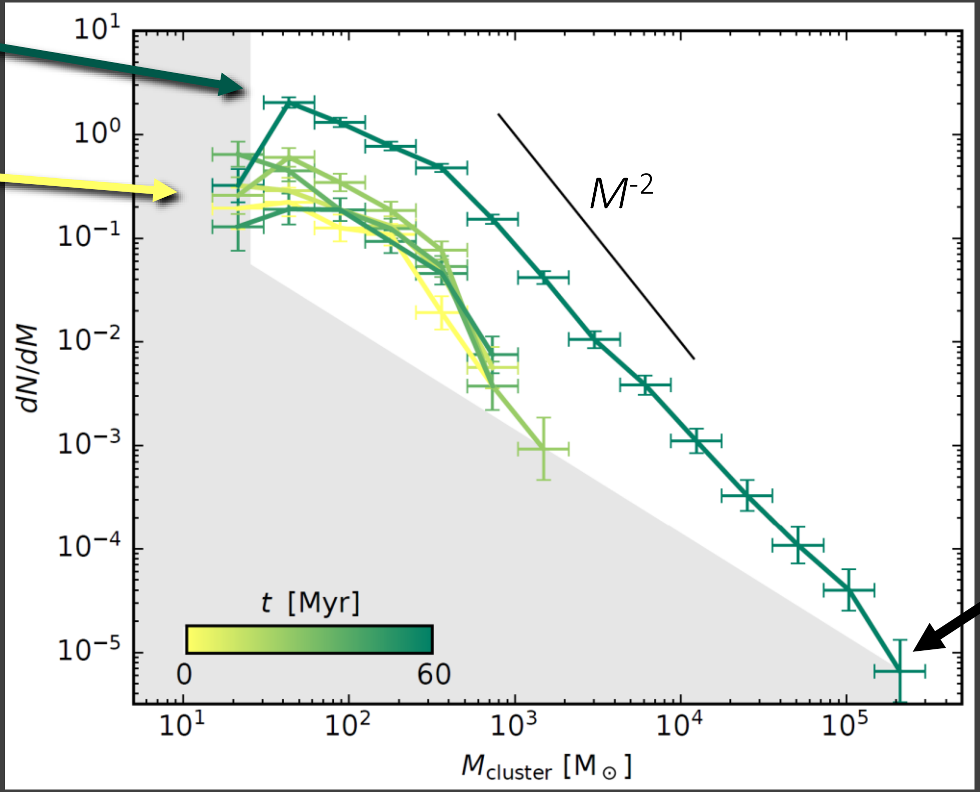
Lahén+ 2020a, 2024

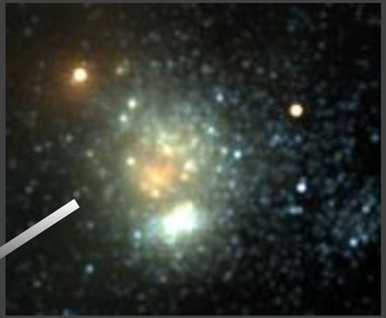
Simulated star cluster populations in starburst dwarf galaxies

Power-law slope in high-mass end of the cluster mass function regulated by pre-supernova stellar feedback (Ma+ 18, Lahén+ 20a/24, Garcia+ 23, Andersson+ 24)

GC-mass clusters form <u>hierarchically</u>, with <u>high central densities</u>, <u>rotating</u>, with <u>rapid self-enrichment</u> due to winds of massive stars
→ toward multiple populations in almost uniform age clusters formed in dwarf starbursts (Lahén+ 24)







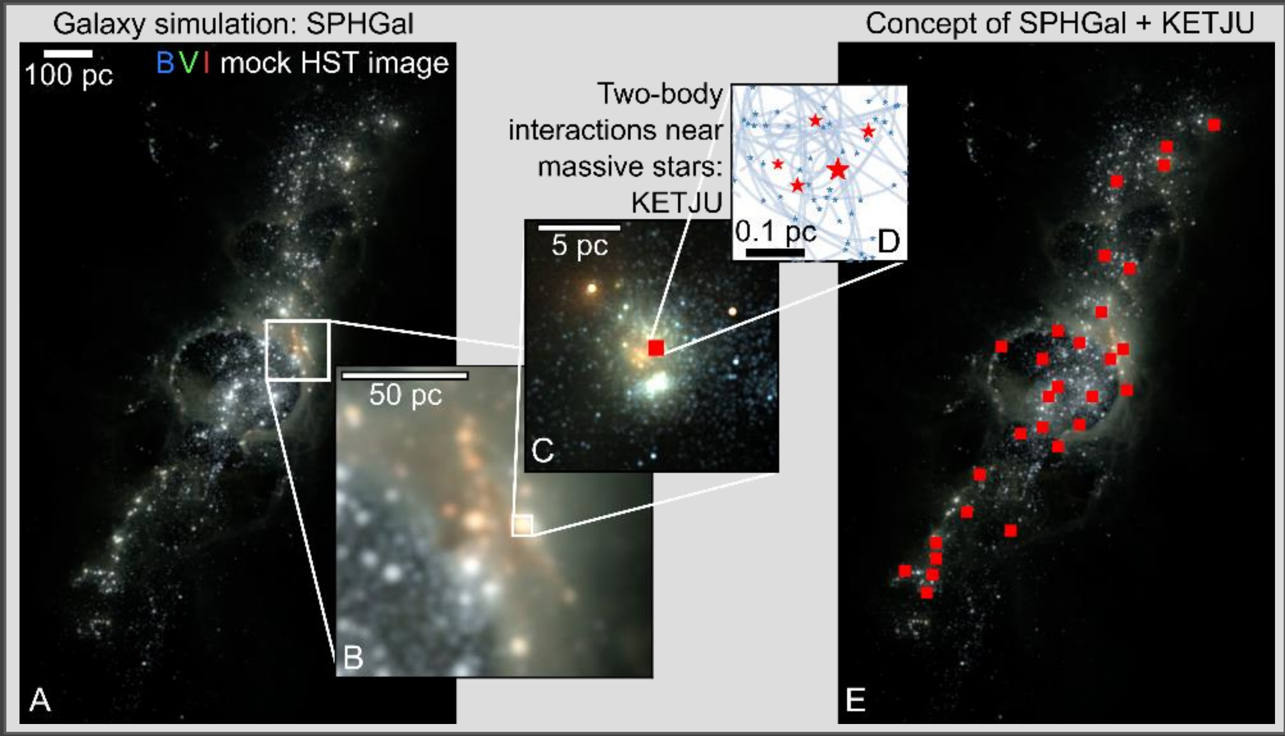
Lahén+ 2020a, 2024

Accurate collisional dynamics in star clusters with KETJU

How to get rid of gravitational softening:

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 × grav. softening length; here 0.03–0.3 pc



See work by Antti Rantala, Matias Mannerkoski and Christian Partmann

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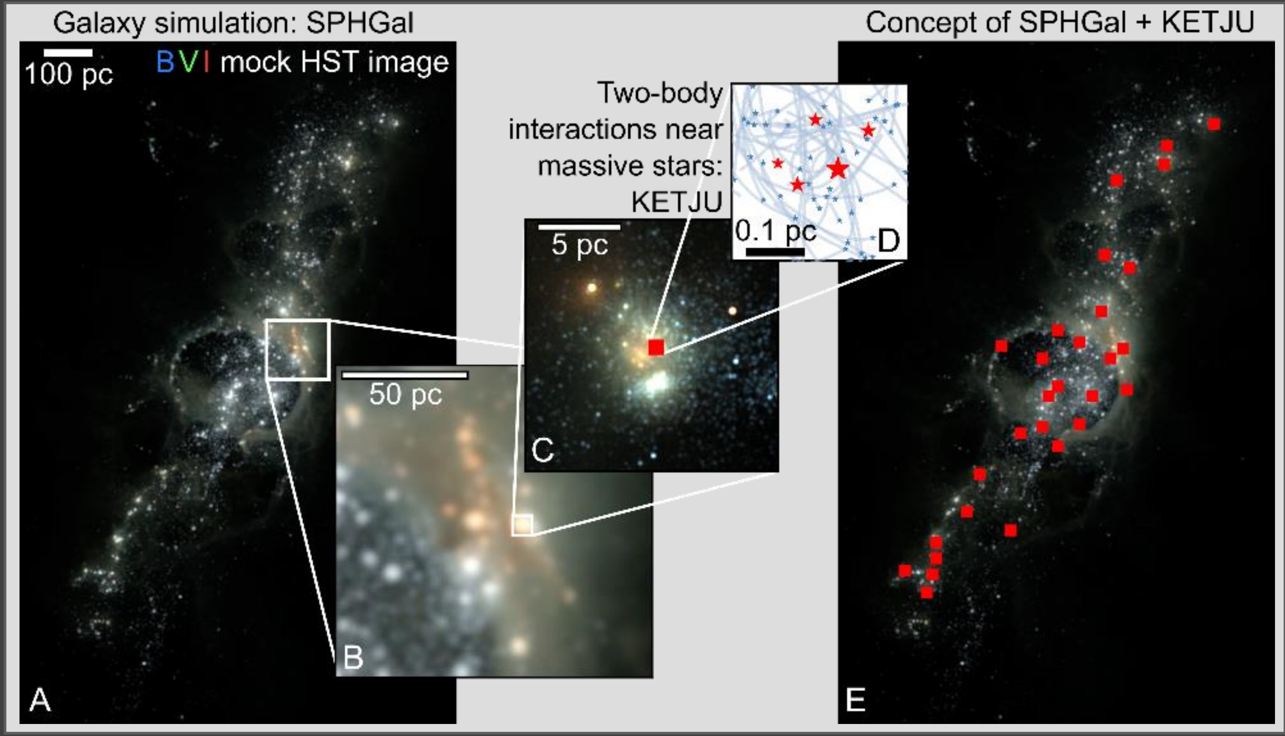
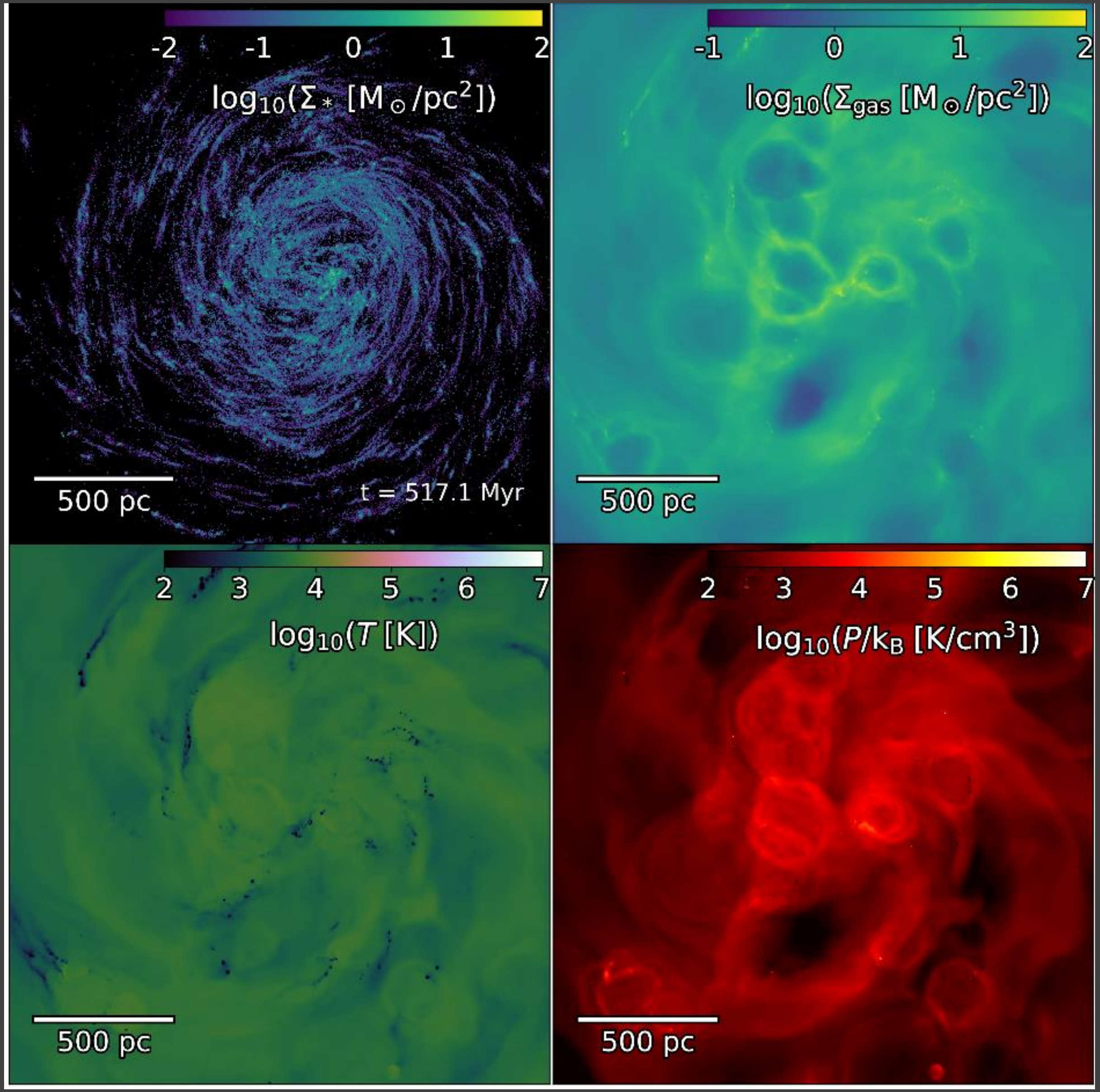
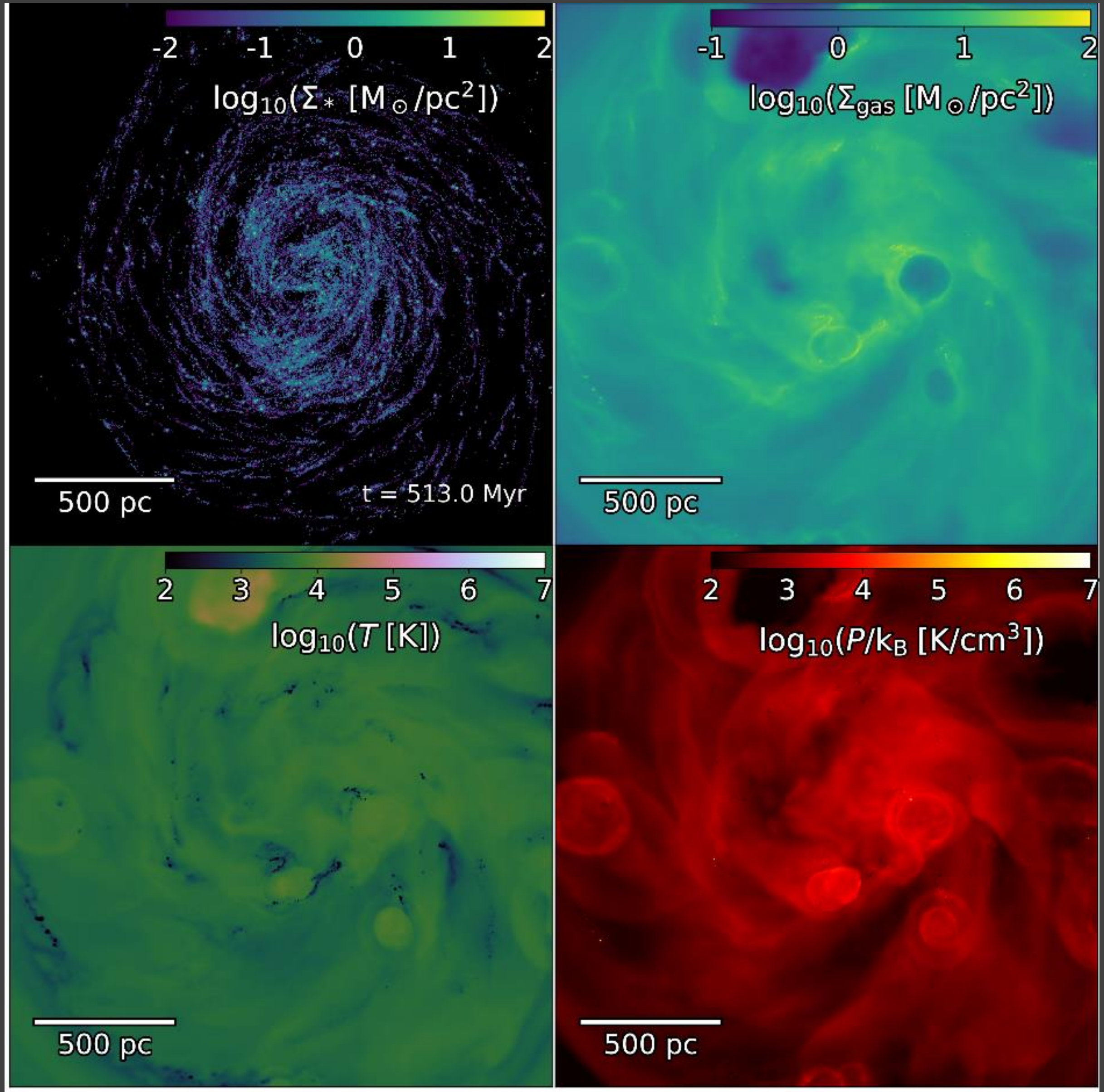


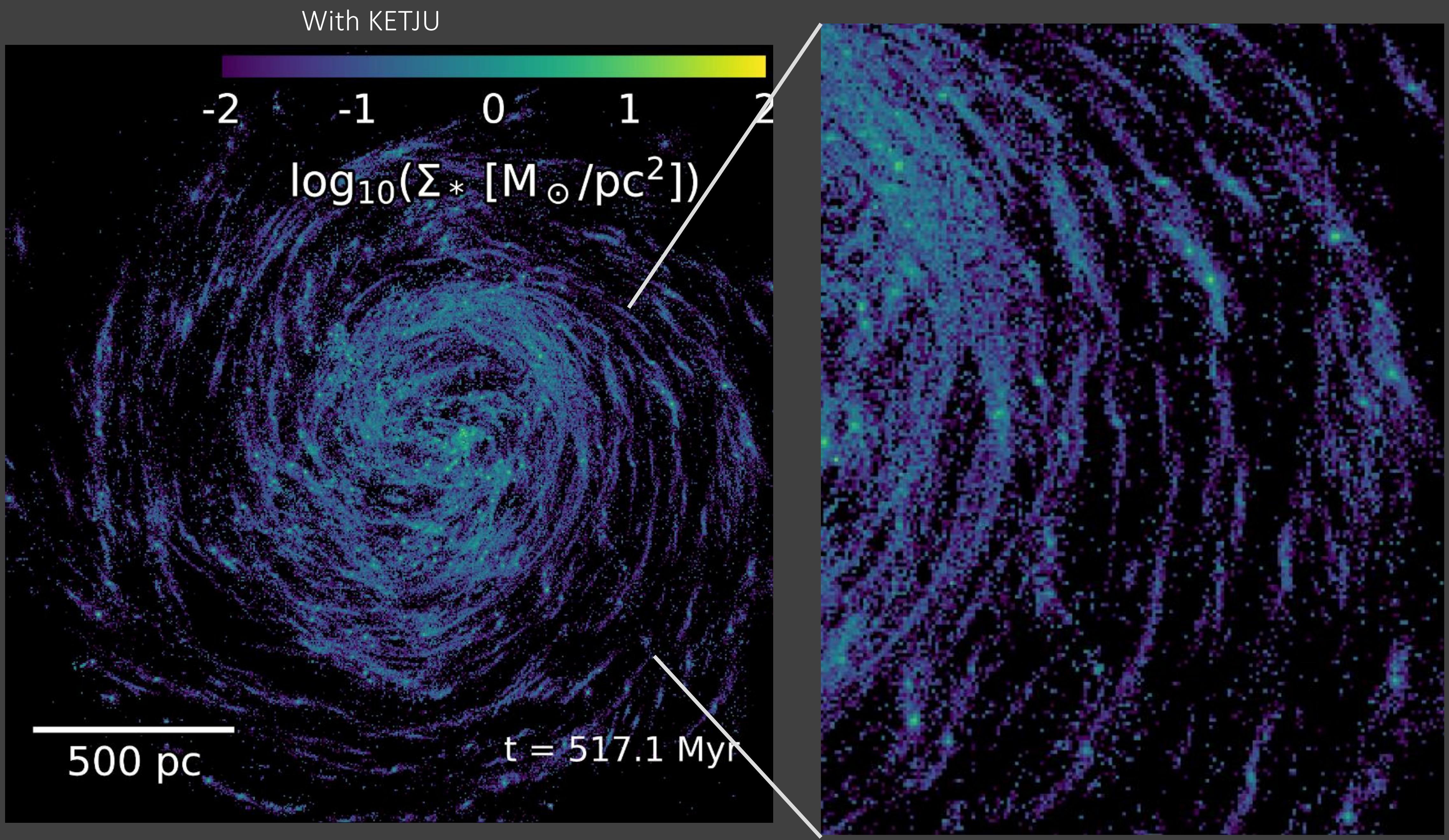
- KETJU uses three numerical recipes in the algorithmically regularized MSTAR library (Rantala+ 20) to guarantee user-specified accuracy without gravitational softening:
    - ➢ Time-transformed equations of motion (incl. optional post-Newtonian corrections)
    - ➢ Minimum spanning tree coordinate system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

See work by Antti Rantala, Matias Mannerkoski and Christian Partmann

$Z=0.01\ Z_\odot$ $M_{vir}=4\times10^{10}\ M_\odot$ $M_{cluster}$ up to ~1000 $M_\odot$







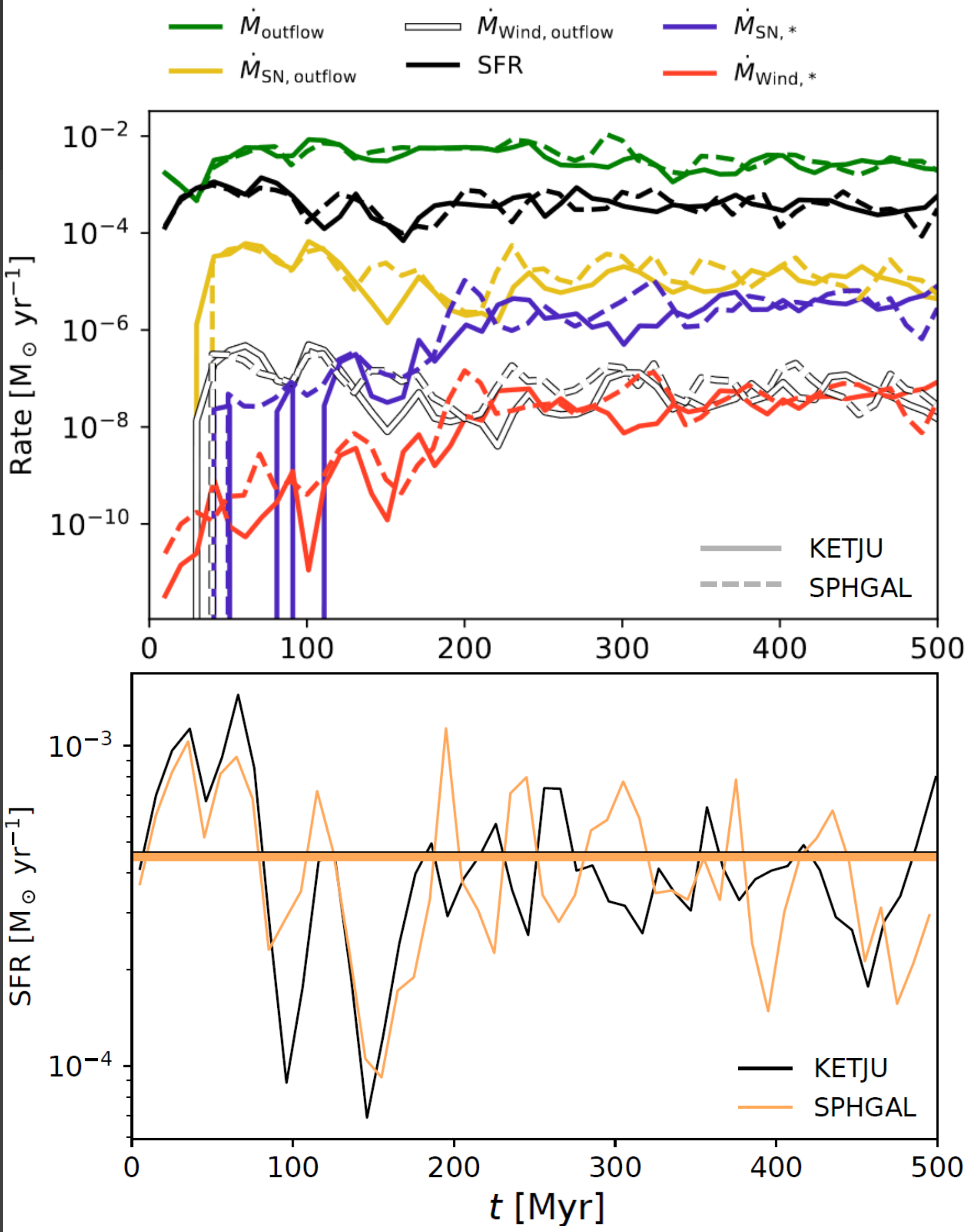
With KETJU
-2 -1 0 1 2
$\log_{10}(\Sigma_* \, [M_\odot/pc^2])$
500 pc
t = 517.1 Myr

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

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

~65% of clusters disrupt by 100 Myr → SNae in clusters reduced by a factor of 2.6

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



Lahén+ in prep.

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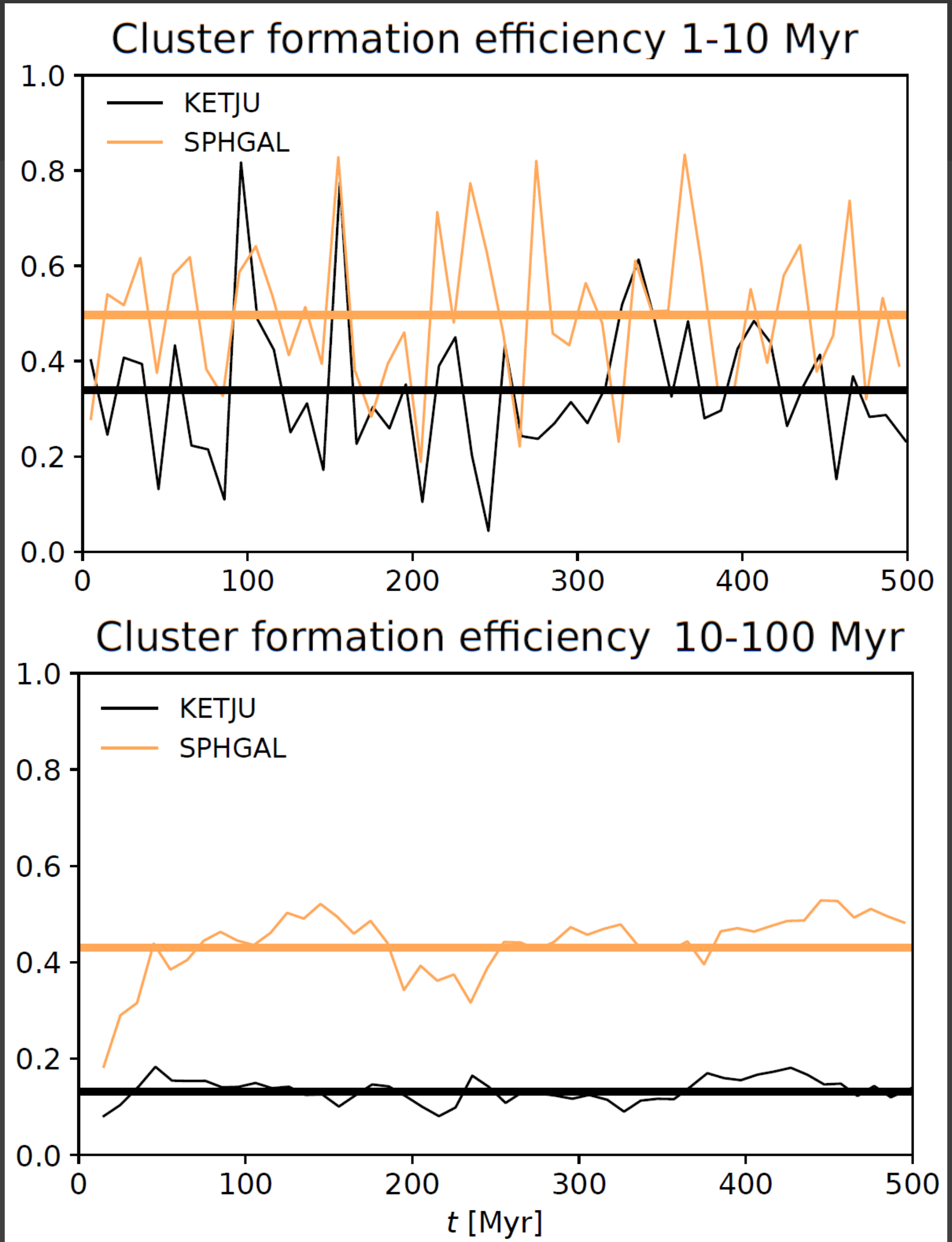
Rapid cluster evolution seen as reduction of measured „cluster formation efficiency" (cluster formation rate/SFR)

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



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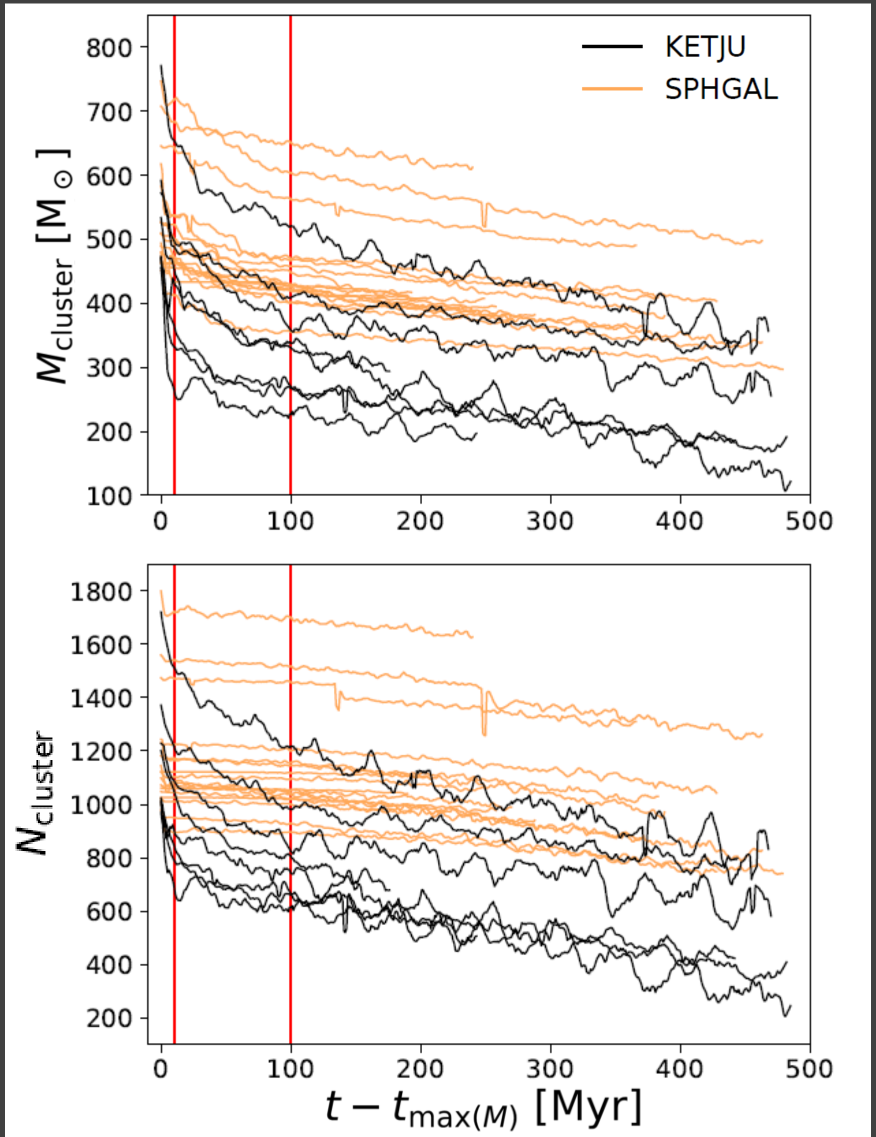
KETJU+SPHGal: star cluster mass-loss and size-growth in a galactic environment

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

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

Cluster mass-loss with KETJU:

- Early evolution both through dynamical mass-loss and stellar evolution
- Evaporation of low-mass stars (median m_* increases)
- Total life-times ~0.5-2.2 Gyr, fit with mass-loss rate of $\dot{M} \propto M^{1-\gamma}$ using γ~0.7 (Lamers+ 05)



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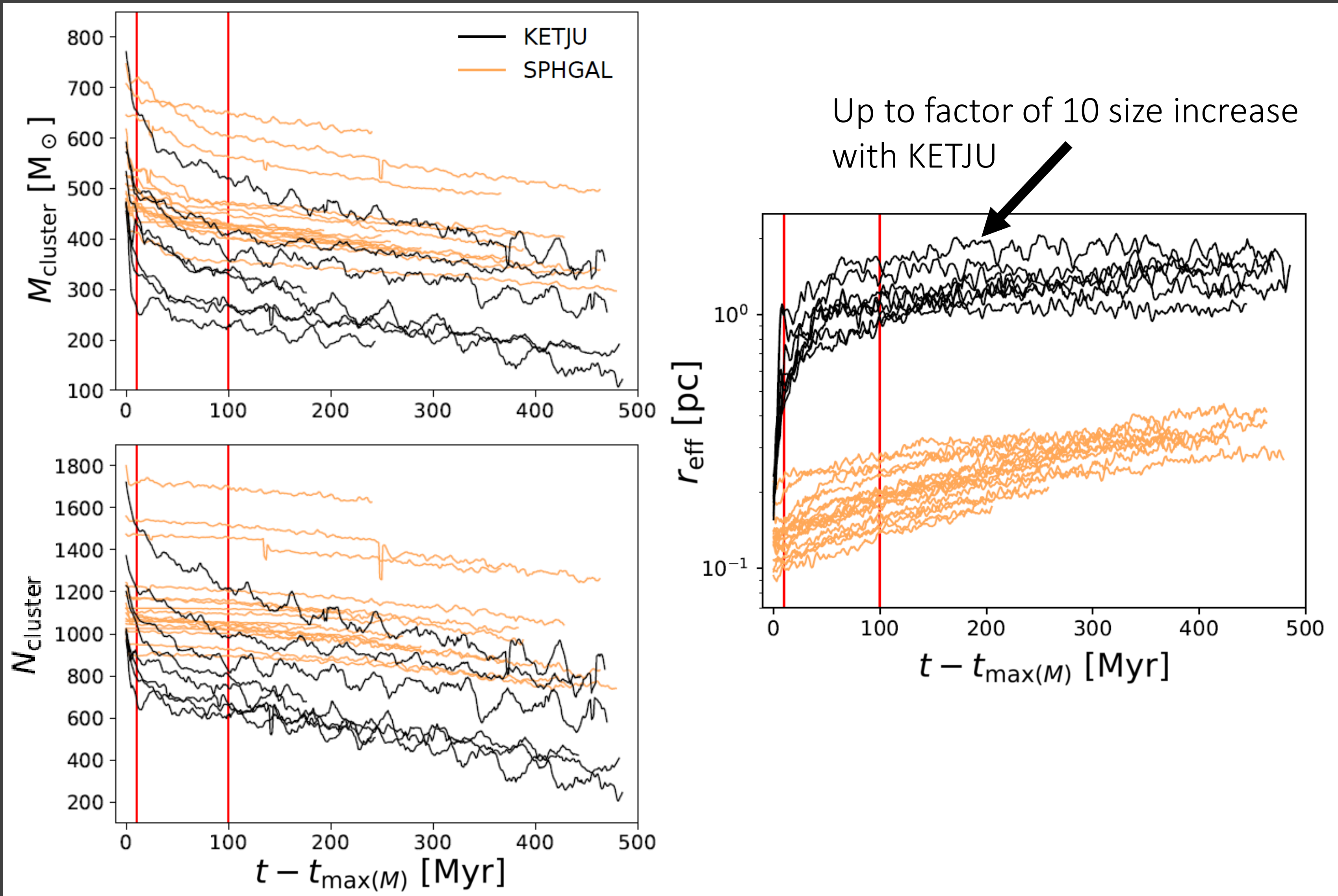

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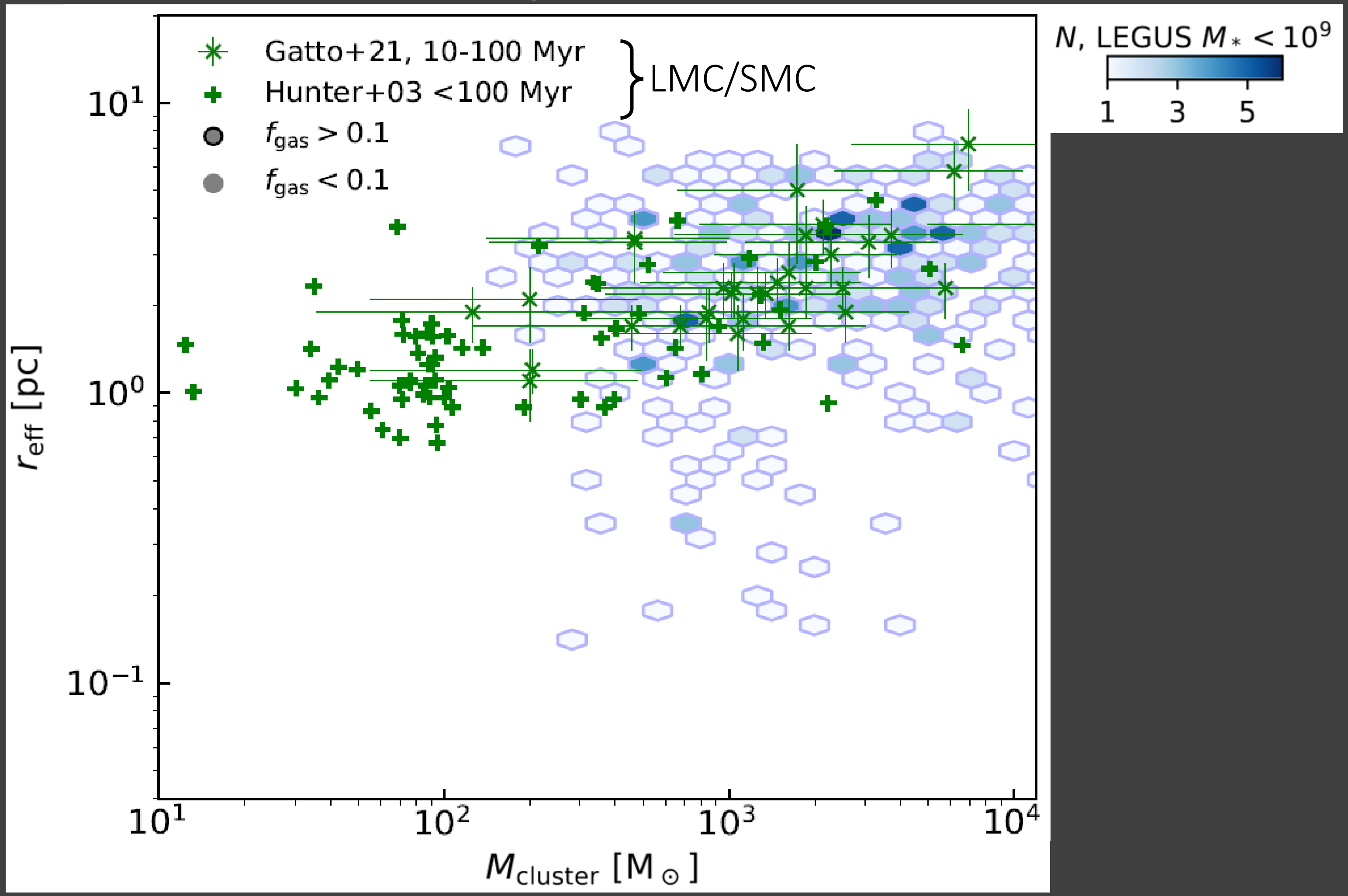
KETJU+SPHGal: Mass-size evolution

Around m_i>3 $M_\odot$ not softened



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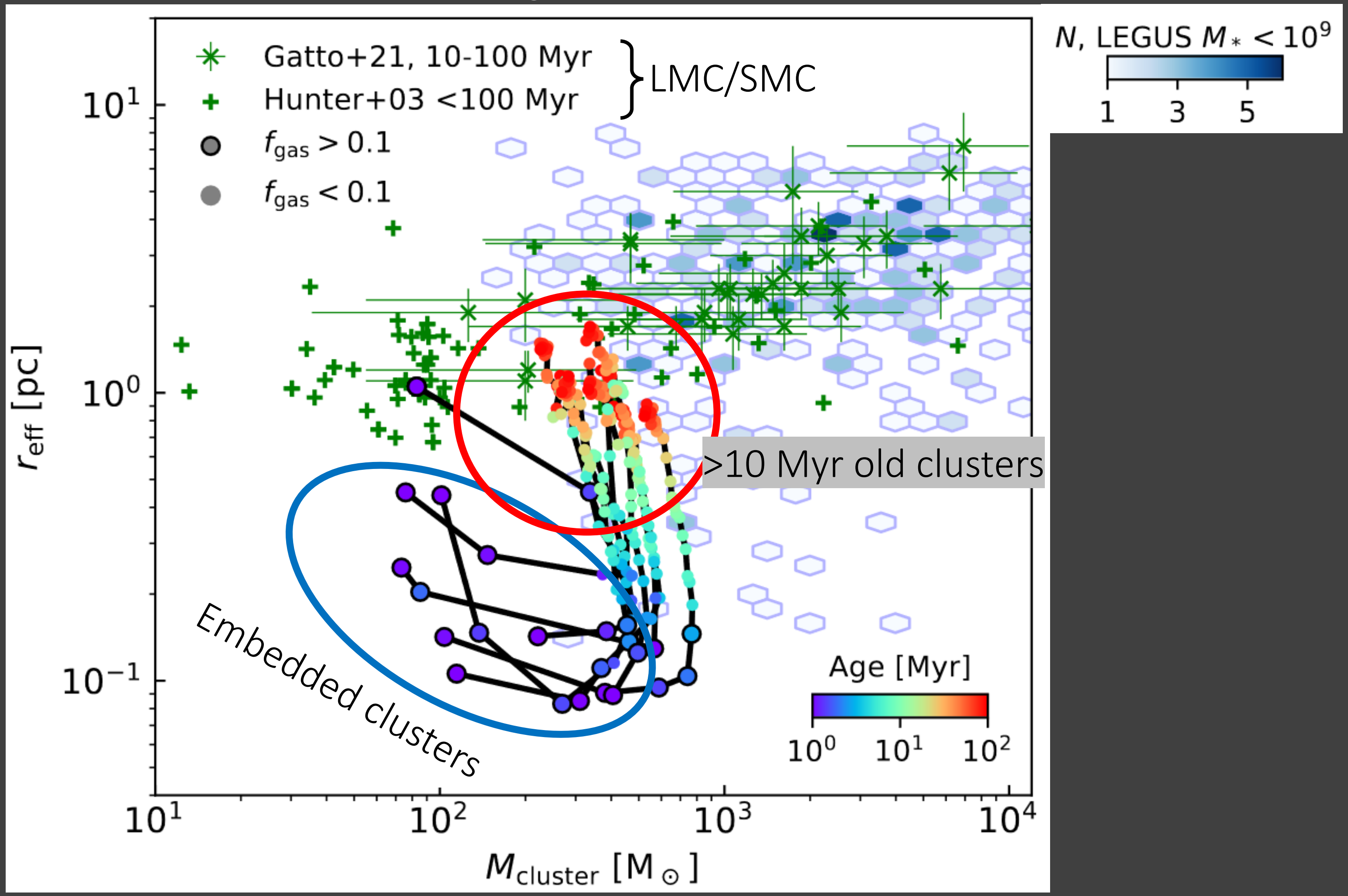

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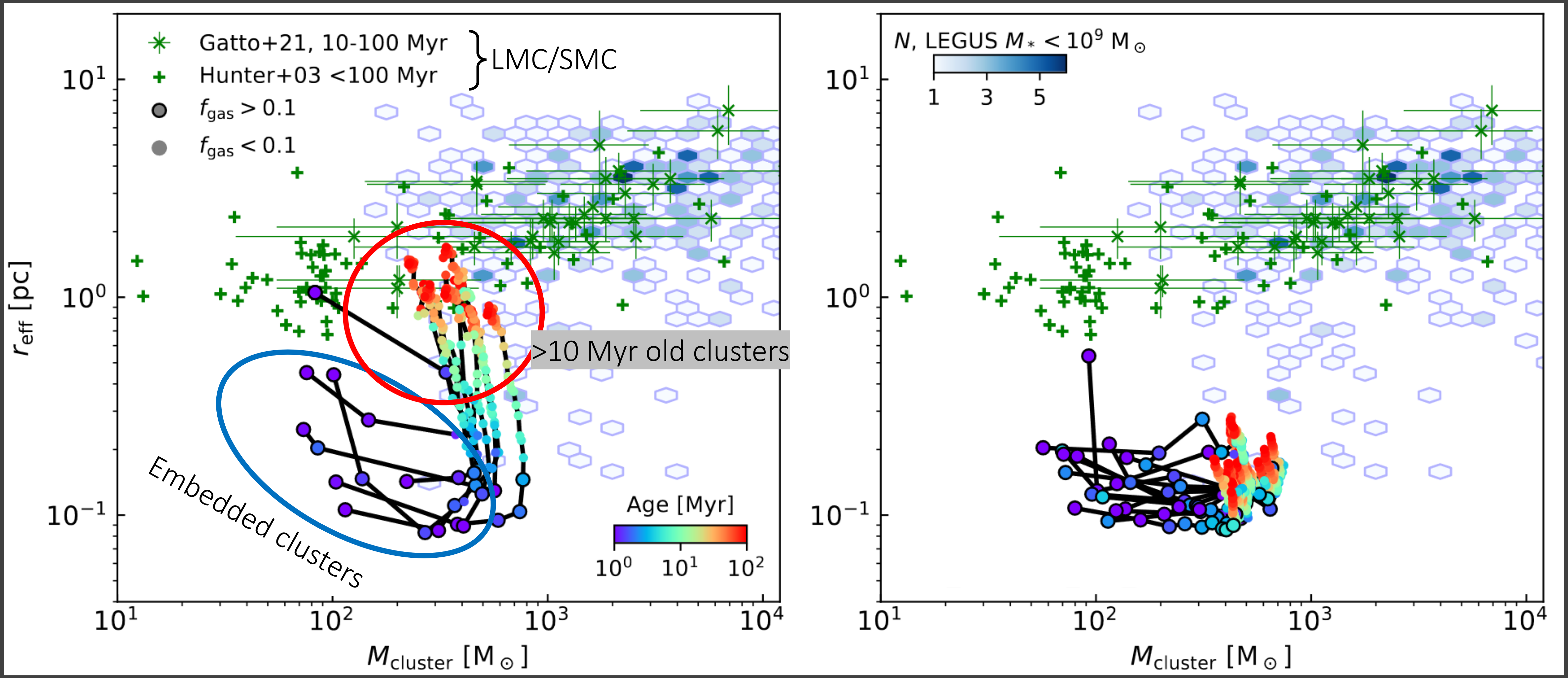
Softened gravity (0.1 pc)



Lahén+ in prep.

Conclusions & outlook

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

- Simulated star clusters are not anymore 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.)

The power of high-resolution galaxy simulations lies in the simultaneous modelling of resolved populations of star clusters

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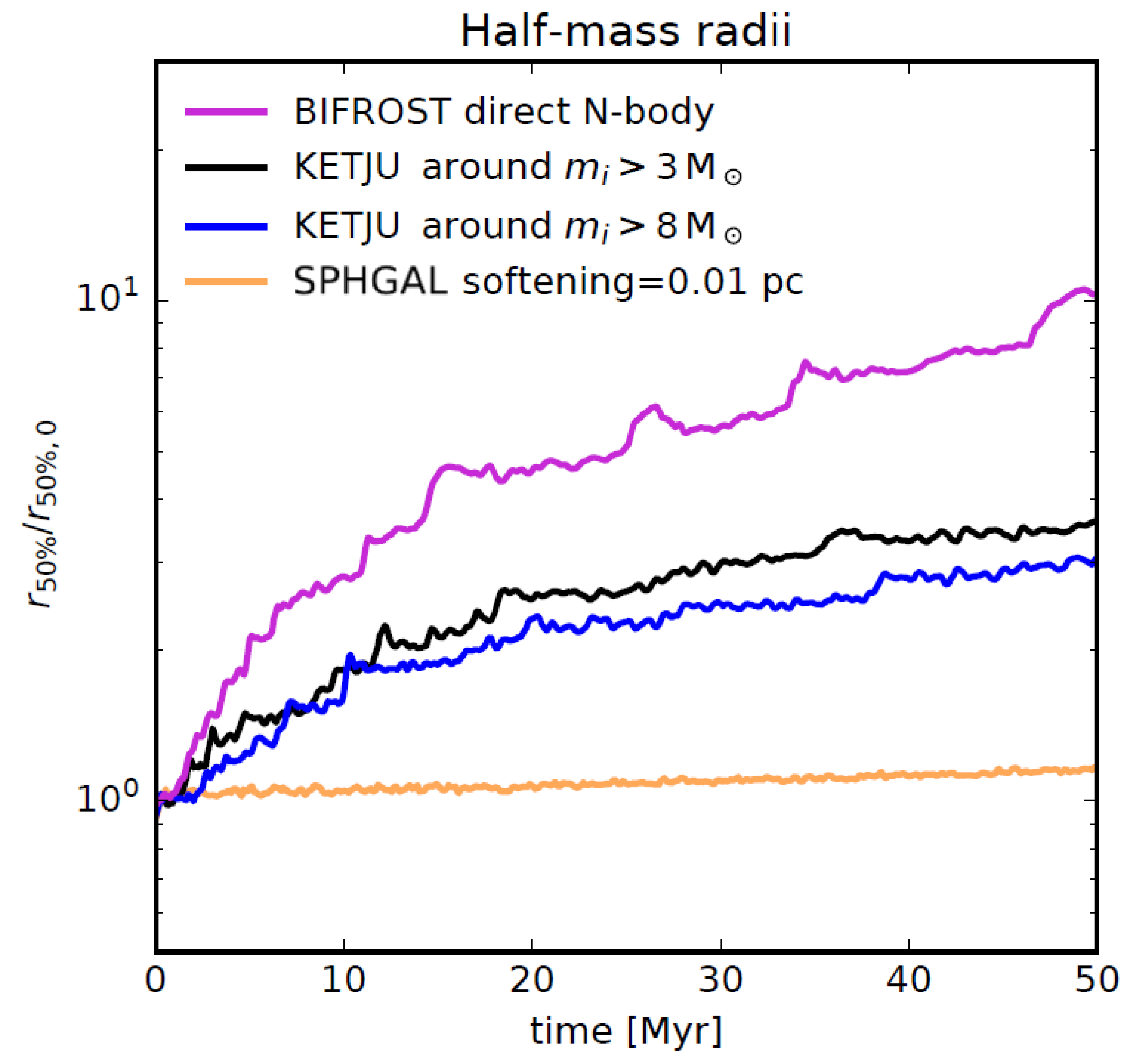
Avenues toward chemically and dynamically realistic simulated globular clusters:

- Various enrichment sources (to be done: binaries, more massive / supermassive stars)
- Collisional dynamics+hydro+feedback: stellar interactions (binaries, mergers, IMBH 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

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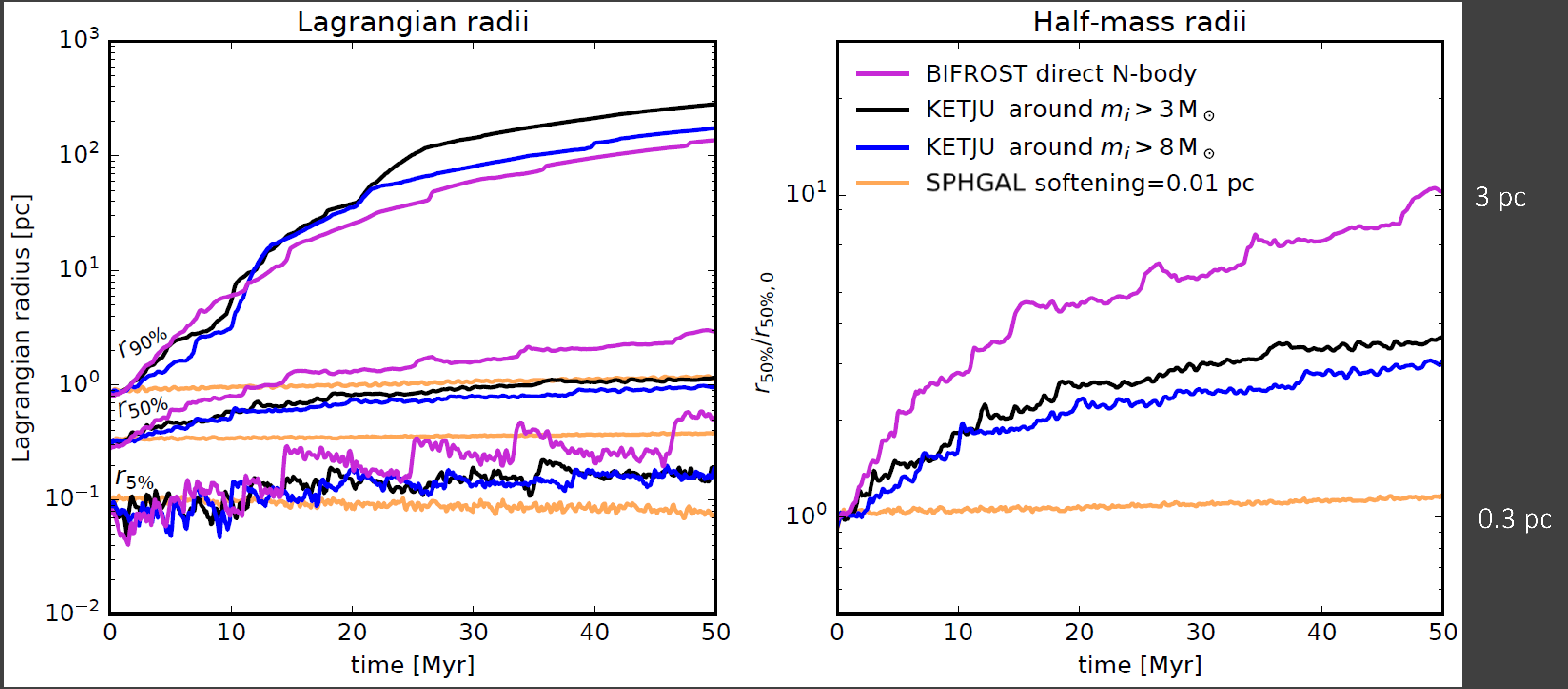
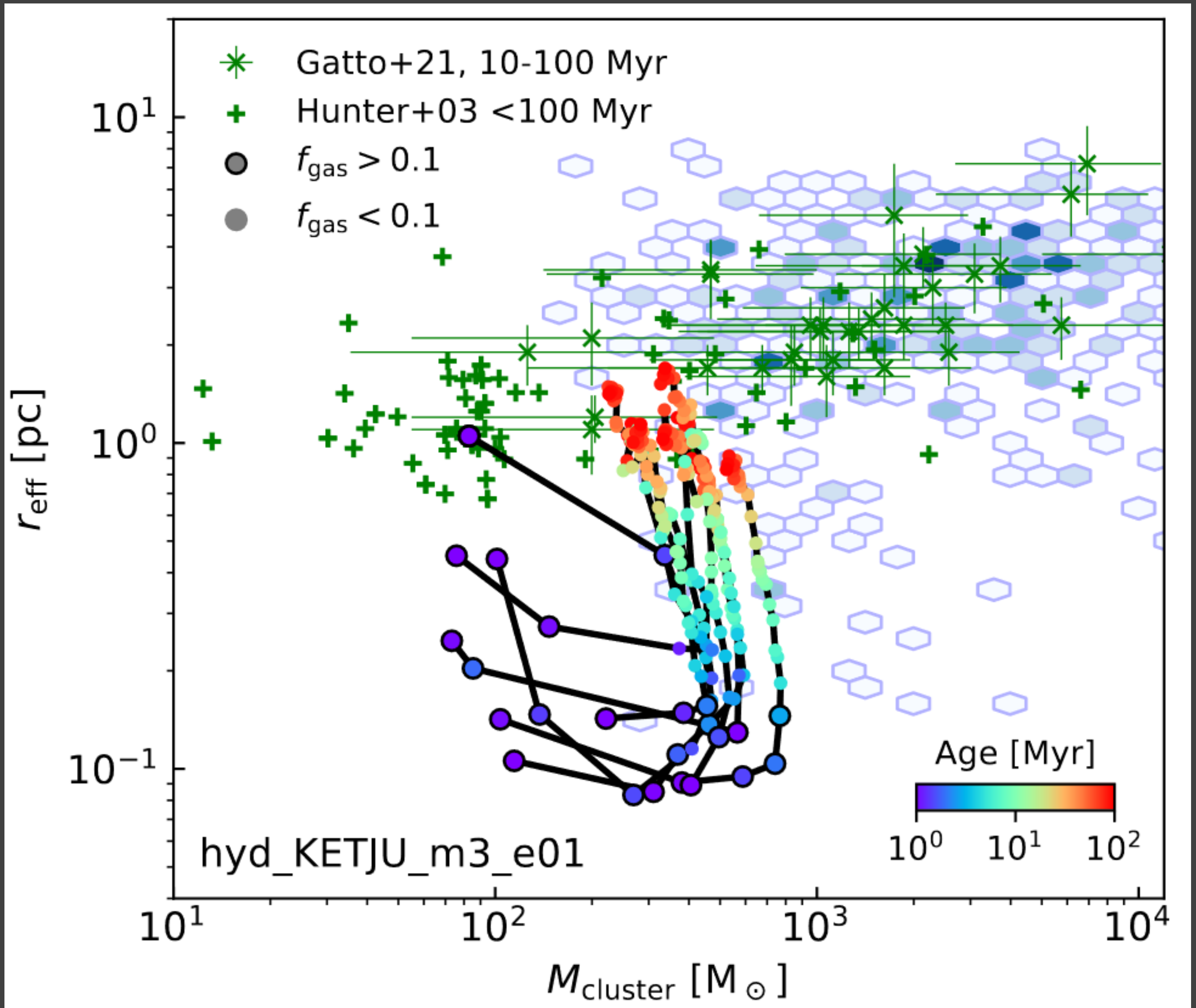
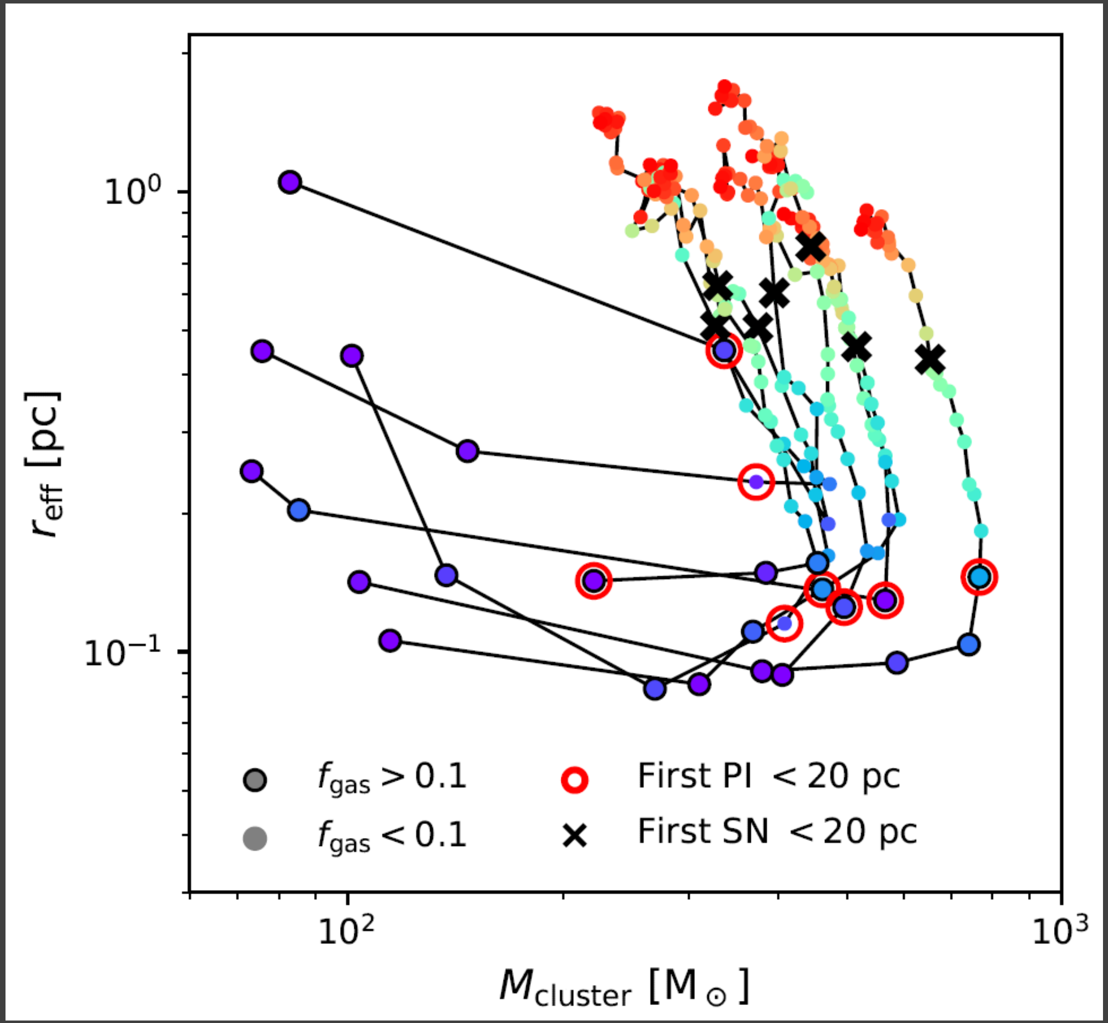


Photoionization (PI) evacuates gas before SNe



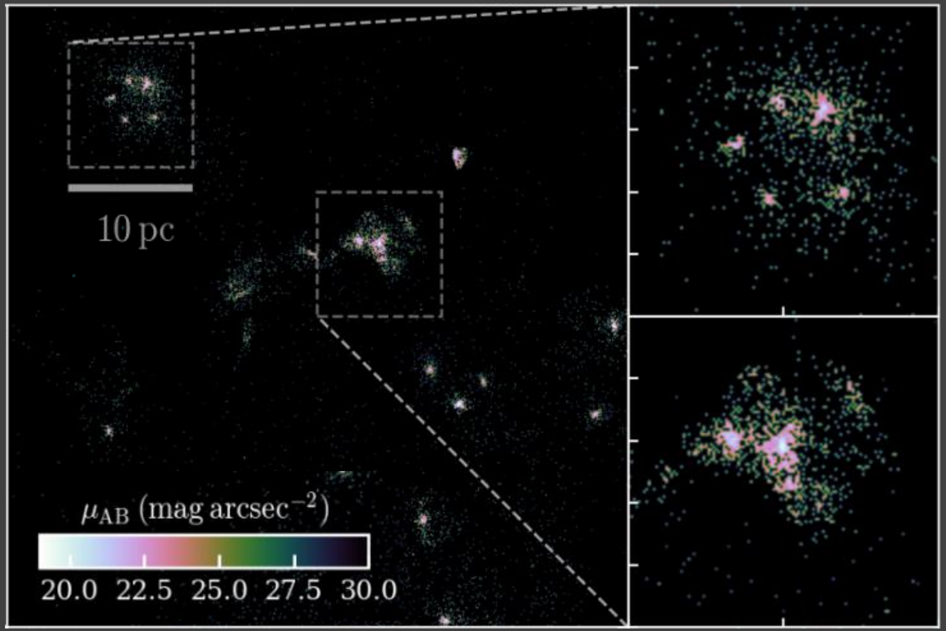


Galaxy scale simulations of star cluster formation

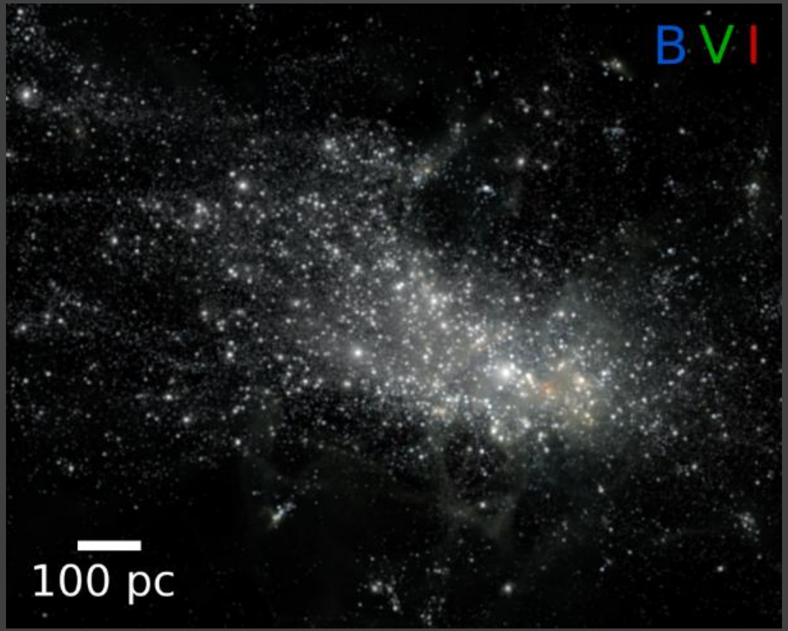
Non-exhaustive list of simulations of cluster/clump formation including non-equilibrium chemistry and varying detail of stellar feedback including early stellar feedback (pre-SN):

- 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