High-mass Star Cluster Formation in a Galactic Context

A simulator's view

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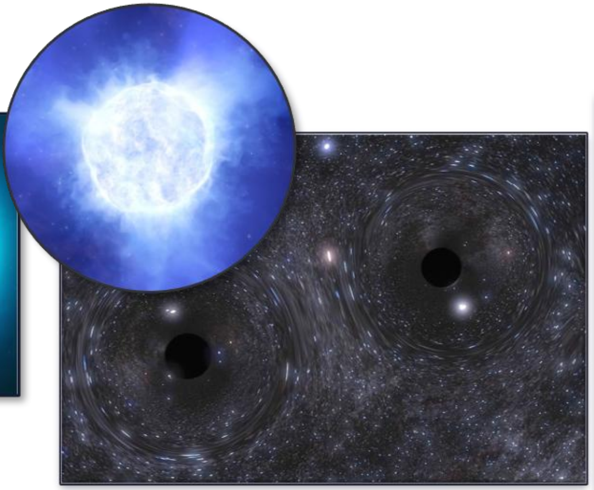
With Thorsten Naab, Guinevere Kauffmann

Christian Partmann, Antti Rantala, Dorottya Szécsi, Peter H. Johansson,
Bruce Elmegreen, Jessica May Hislop, Stefanie Walch, Chia-Yu Hu, Alexandra Kozyreva, …

Super star clusters: gravitationally bound? long-lived? ~~treasure~~ chest of exotic phenomena?

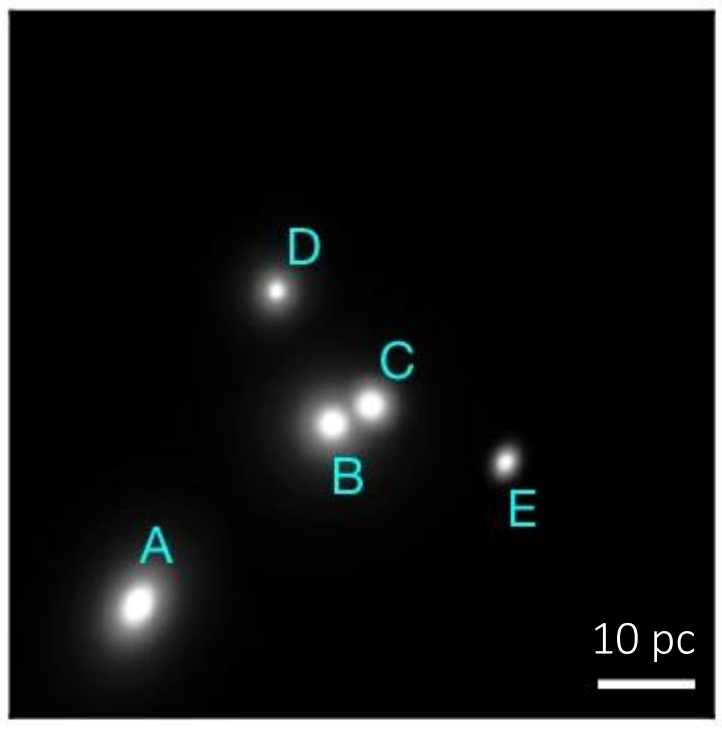
Pandora's box

NGC 2070 / R136 in LMC



SSCs in NGC 1569

Cosmic Gems @ z~10:
globular cluster progenitors?



NASA, ESA, F. Paresce, R. O'Connell
NASA / A. Aloisi; Adamo+ 2024
ESO/L. Calçada
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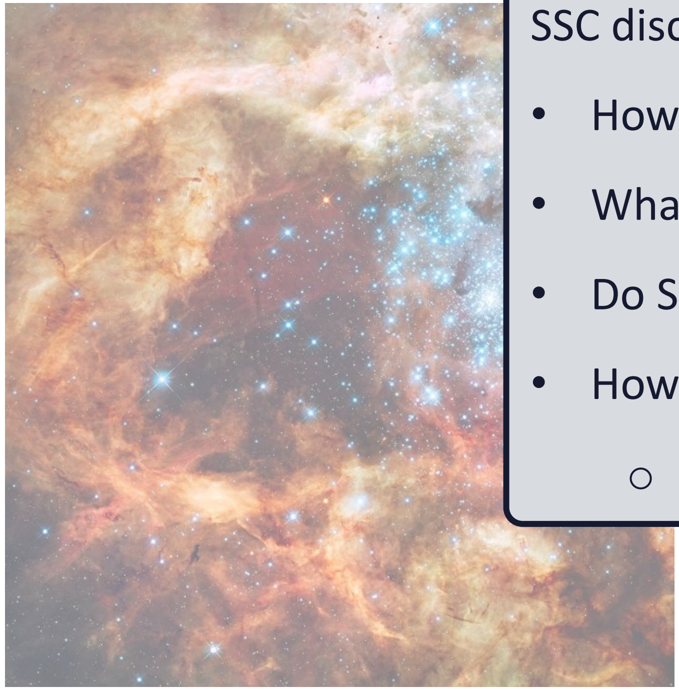
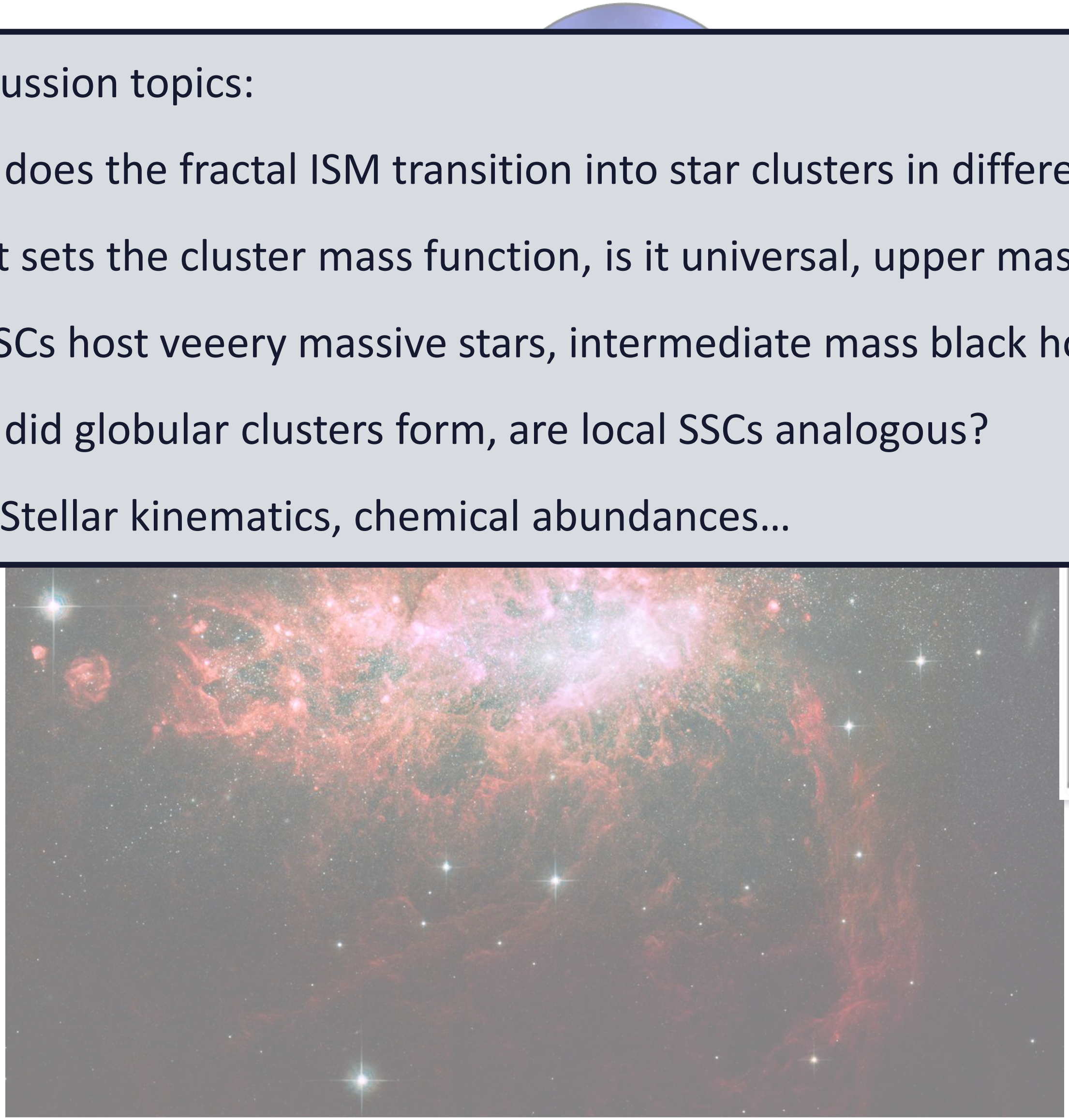
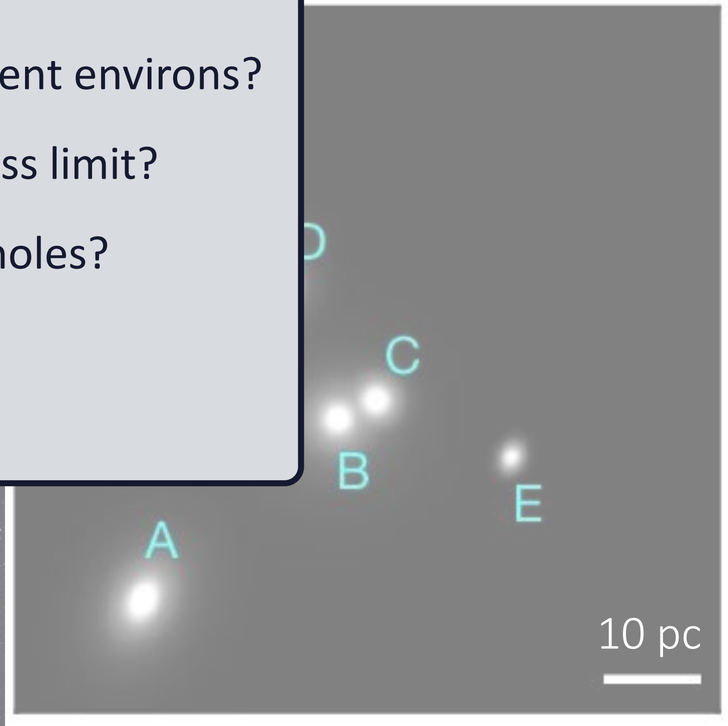




SSC discussion topics:

- How does the fractal ISM transition into star clusters in different environs?
- What sets the cluster mass function, is it universal, upper mass limit?
- Do SSCs host veeery massive stars, intermediate mass black holes?
- How did globular clusters form, are local SSCs analogous?
  - Stellar kinematics, chemical abundances…

Cosmic Gems @ z~10: cluster progenitors?



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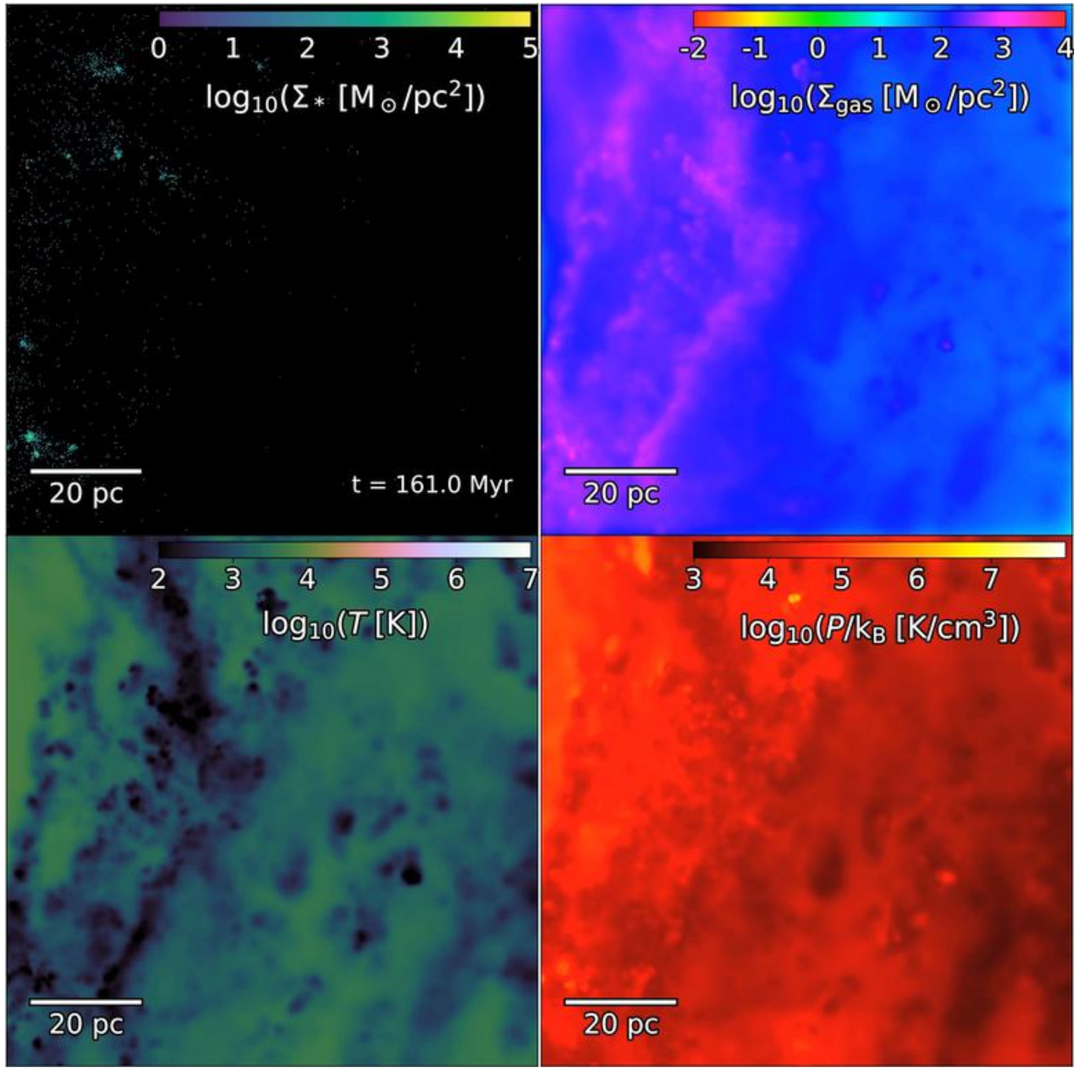
Zoom into a dwarf galaxy starburst (Lahén+ 2020a)

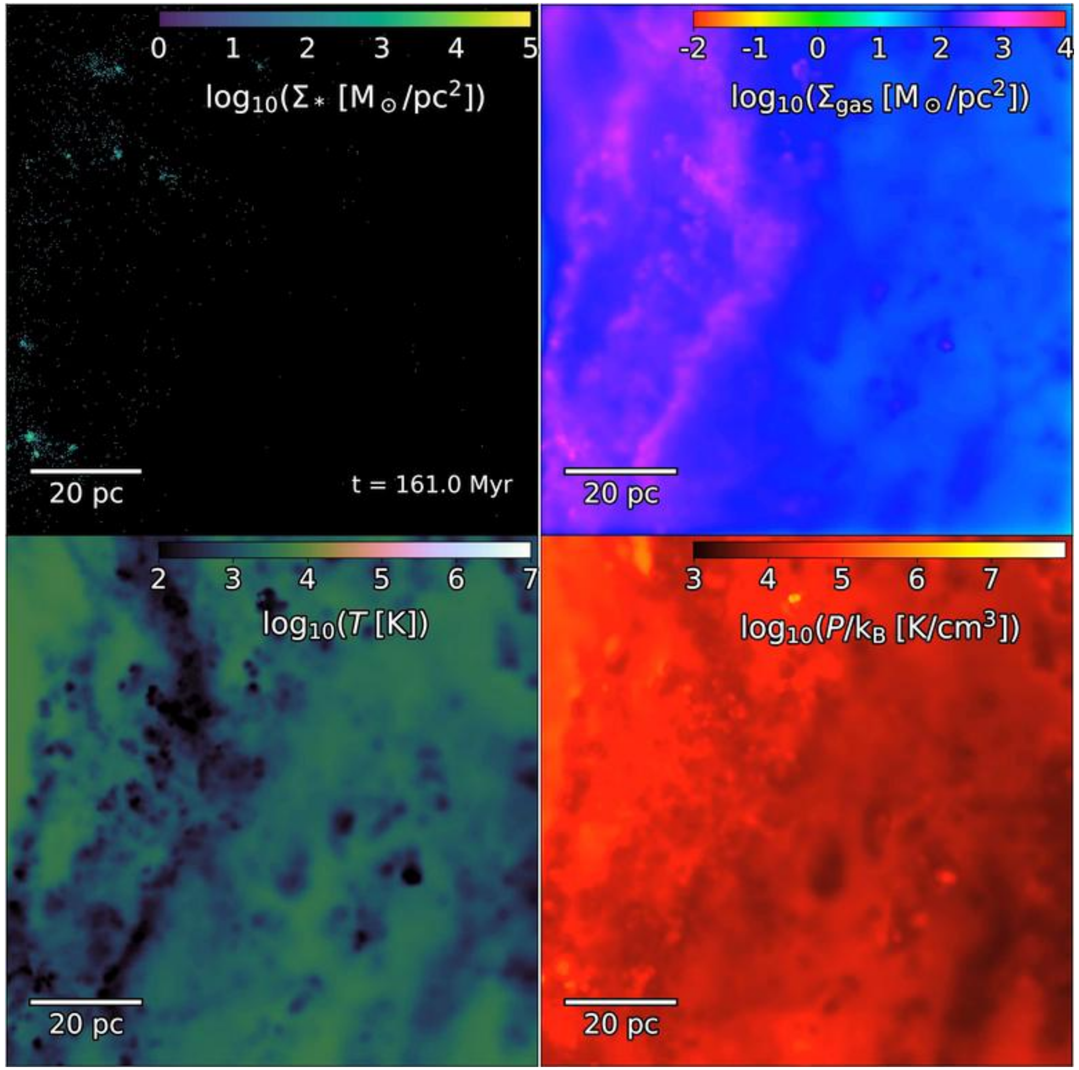


Critical ingredients

1. Multiphase gas
2. Individual stars and their gravitational interactions; feedback: chemical enrichment and energy
3. The galactic environment

Simulations of star (cluster) formation with attention to massive stars

Zoom into a dwarf galaxy starburst (Lahén+ 2020a)



- Cloud-scale simulation projects

  TORCH (Wall+ 2020), STARFORGE (protostellar jets! Grudić+ 2021)
  SIRIUS (Hirai+ 2021)

- (Cosmological) galaxy evolution projects

  GRIFFIN (Lahén+ 2020a), LYRA (Gutcke+ 2020), SIEGE (Calura+ 2022), INFERNO (Andersson+ 2023), Garcia+ 23, RIGEL (Deng+ 2024)

Massive star clusters

- In single clouds

  Fujii+ 2024, Polak+ 2024, Cournoyer-Cloutier+ 2024 (binary stars!)

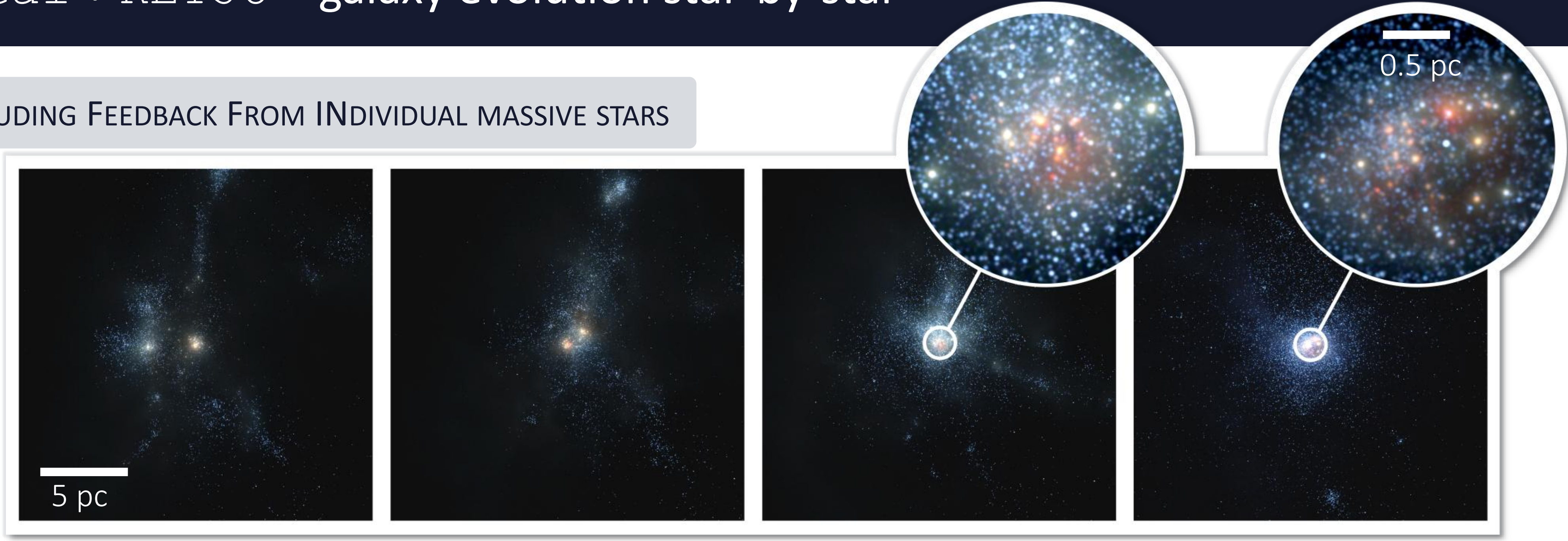
- In galaxies

  Lahén+ 2020a/2024/2025b; Calura+ 2024; Gutcke 2024; Garcia+ 2025

More simulations of cluster formation in galaxies:
Bekki+ 01; Kravtsov & Gnedin 02; Bournaud+ 08; Boley+ 09; Kruijssen+ 11; Renaud+ 15; Ricotti+ 16; Kimm+ 16; Li+ 17; Maji+ 17; Dobbs+ 17/20; Ma+ 18; Pfeffer+ 18; Rieder+ 22; Reina-Campos+ 22; Sameie+ 23; Lake+ 23; van Donkelaar+ 23; Grudić+ 23; Andersson+ 24; Mayer+ 24; Reina-Campos+ 25; Williams+ 25; Matsui+ 25; Gray+ 25 …

GRIFFIN: SPHGal + KETJU = galaxy evolution star-by-star

GALAXY REALIZATIONS INCLUDING FEEDBACK FROM INDIVIDUAL MASSIVE STARS



- The SPHGal galaxy evolution code: multiphase ISM with 4 $M_\odot$ hydro resolution & 1—10% solar metallicity

Bold incl NL:
SPHGal/GADGET-3 & KETJU by Springel 2005; Hu+ 2014,2016,2017; **Rantala+ 2017**; Mannerkoski+ 2021; **Lahén+ 2023,2025a,b**; **Partmann+ 2024**

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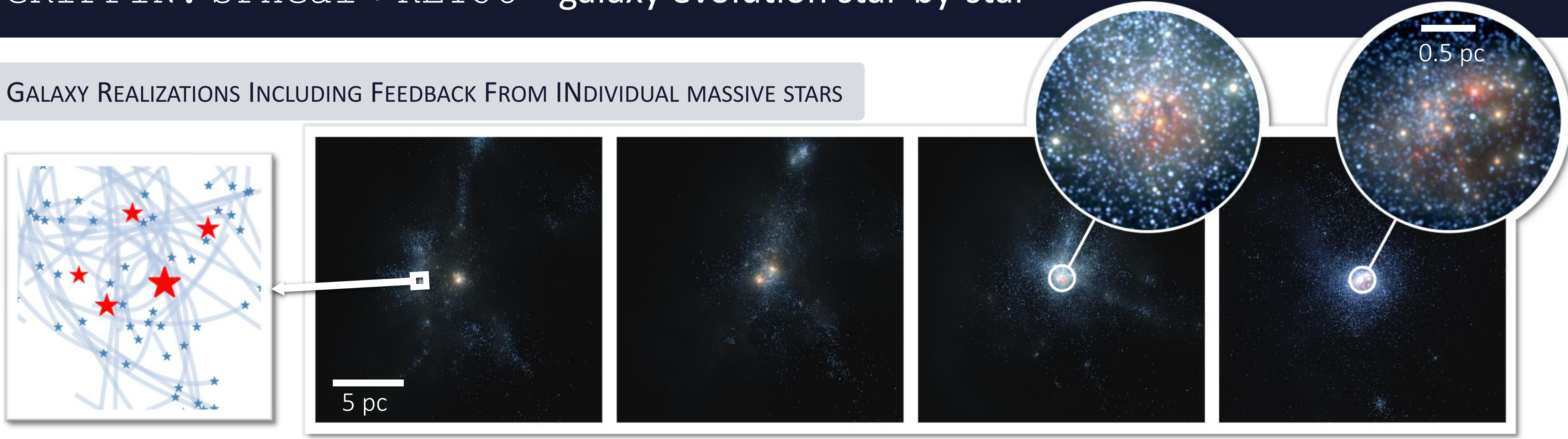

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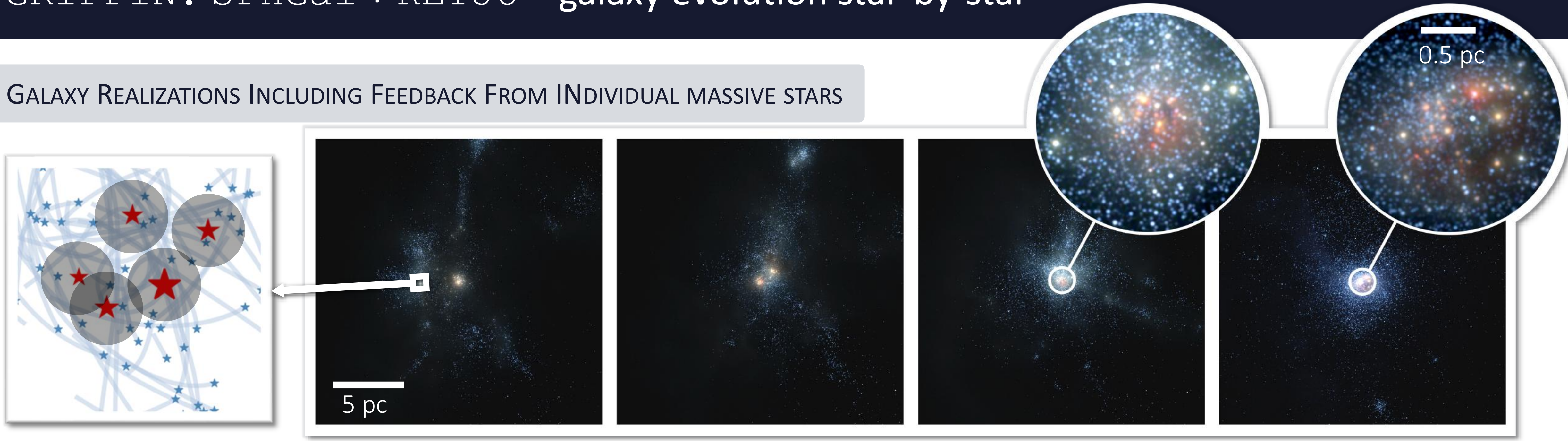
Galaxy Realizations Including Feedback From INdividual massive stars



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- The KETJU gravity solver: small-scale stellar dynamics

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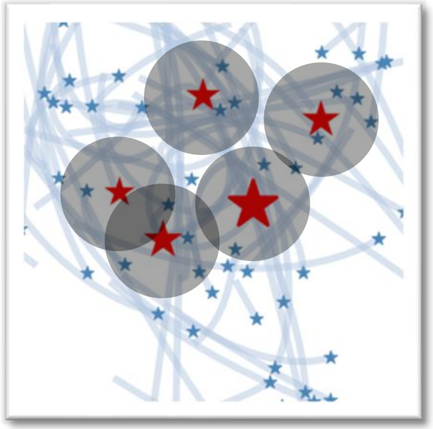
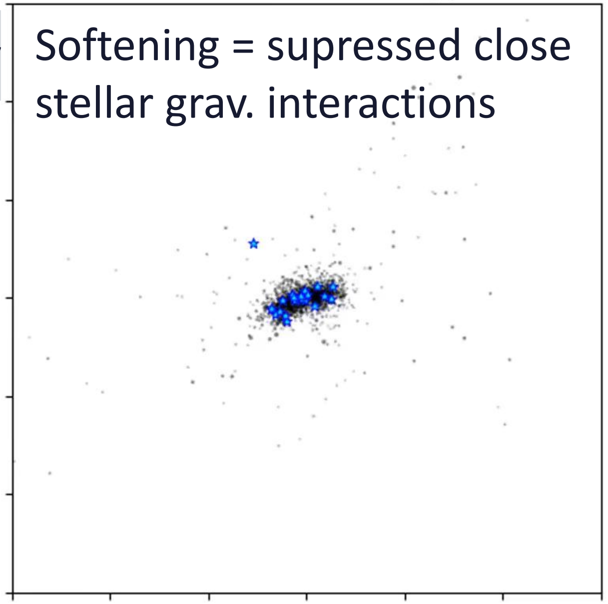
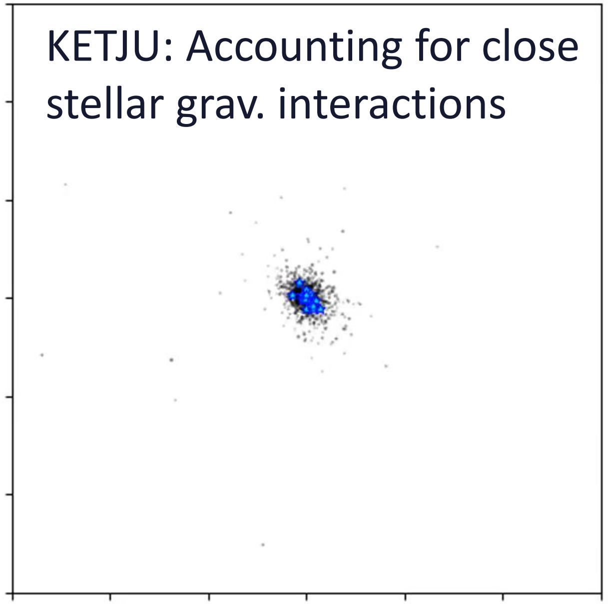


800 $M_\odot$
6 pc accross





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First approximate galaxy-scale treatment for

- Stellar collisions
- Tidal disruption events

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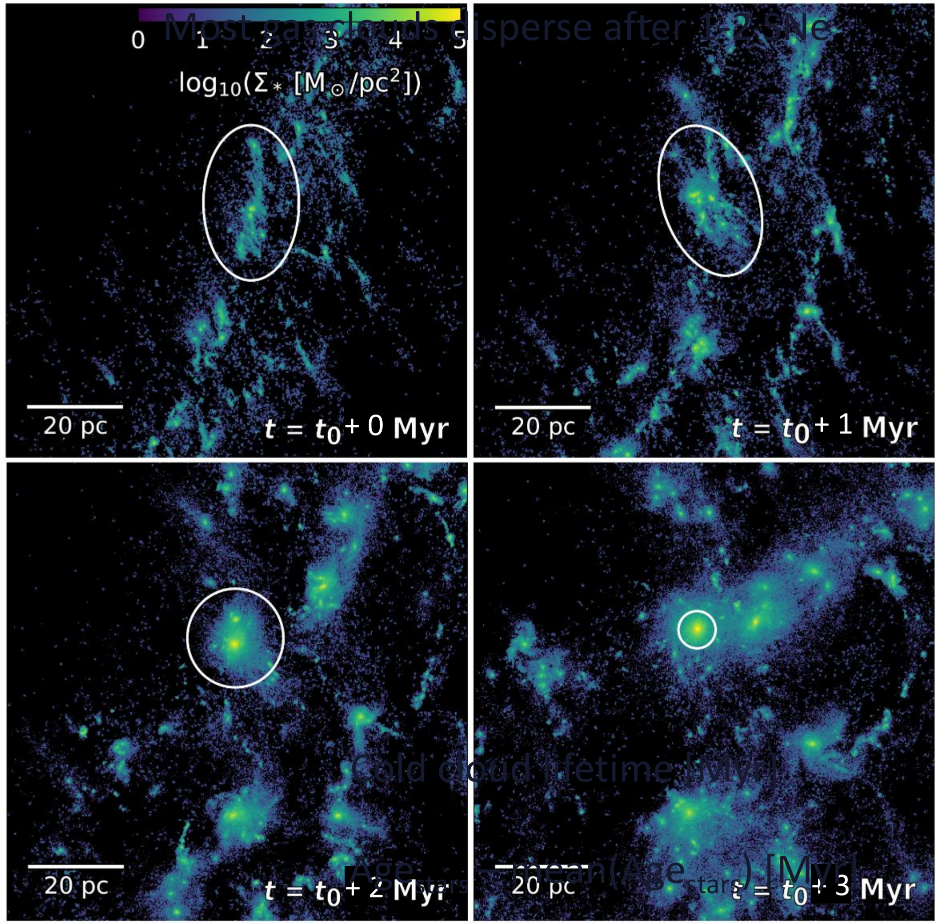
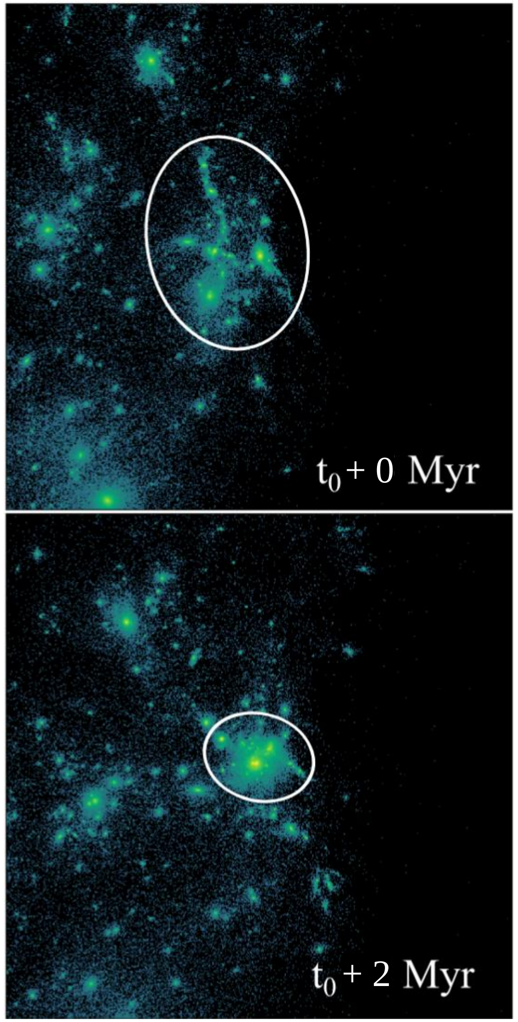
Massive star cluster formation

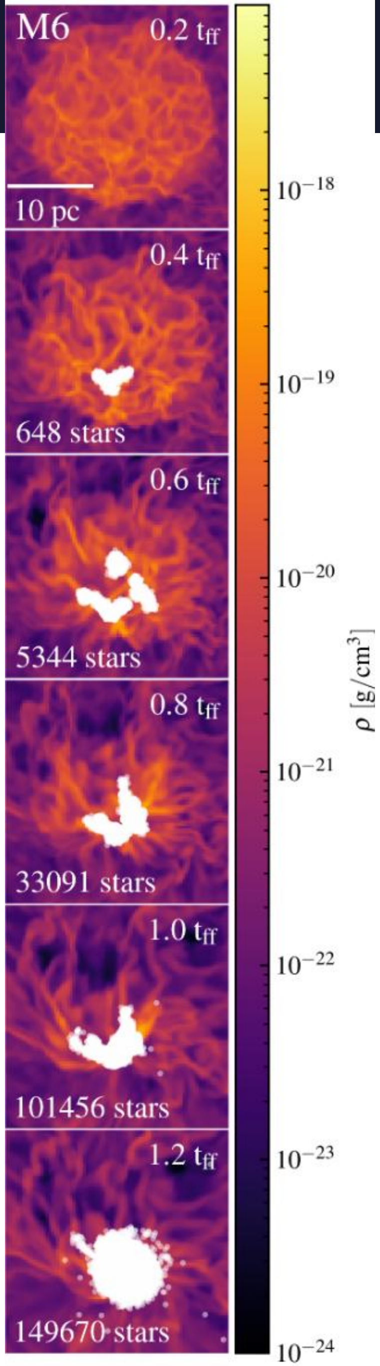
2×10^5 M$_\odot$ cluster, 1% solar metallicity (Lahén+ 2024)



7×10^5 M$_\odot$ cluster, 10% solar metallicity (Lahén+ 2020a)



8×10^5 M$_\odot$ cluster, solar metallicity
(Polak+ 2024)



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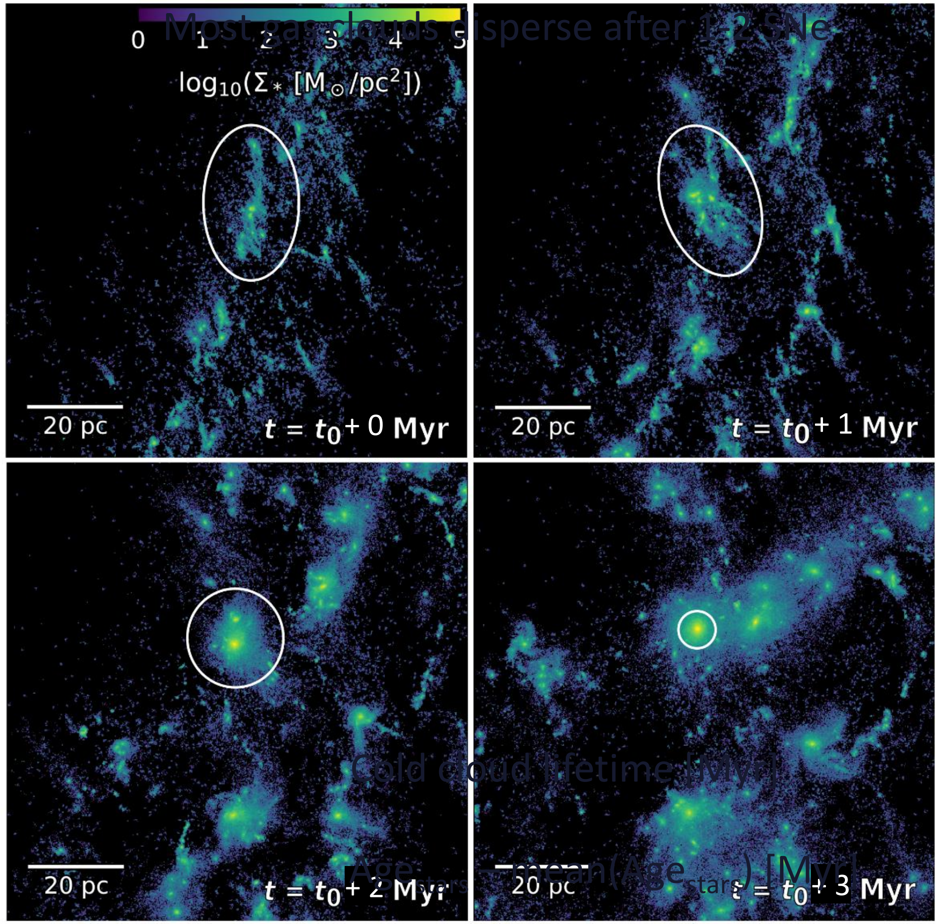
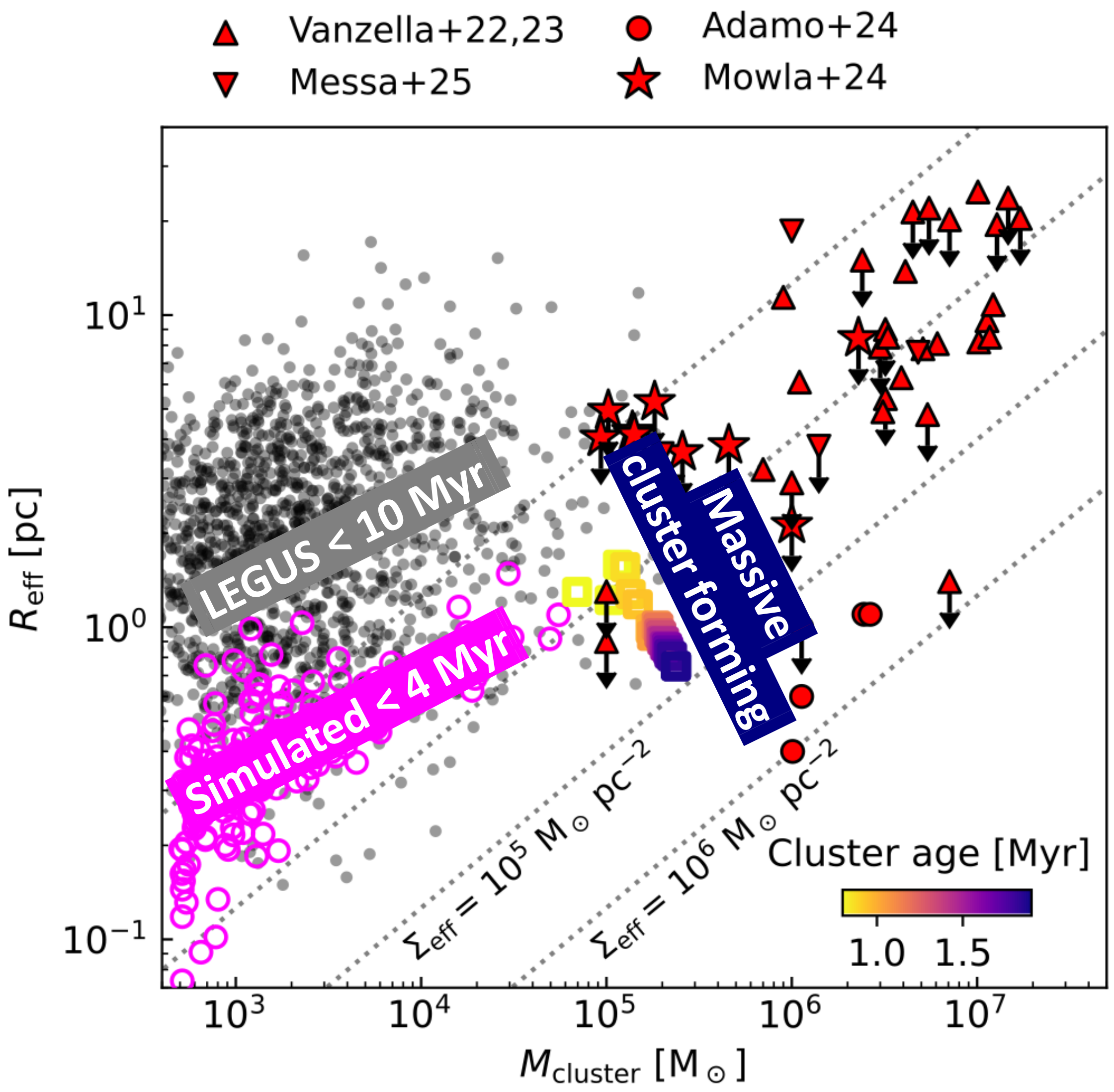


- Hierarchical
- Radial power-law density profiles, even within sub-pc scales
- High mean surface densities
- High star formation efficiencies
- High star cluster formation efficiencies
- Short (σ_{age} < 10 Myr) formation (and clearing?) timescales
- ➢ Pre-supernova feedback has a critical role

Massive star cluster formation



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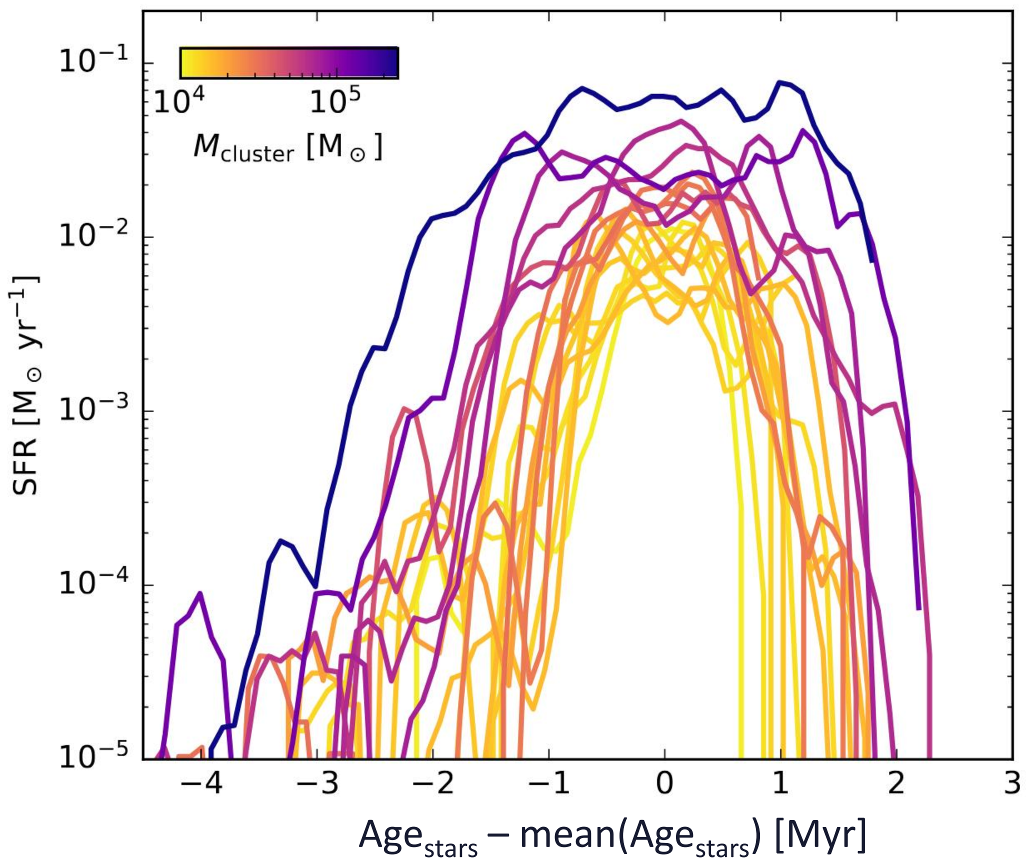
Massive star cluster formation

Lahén+ 2020a, 2024



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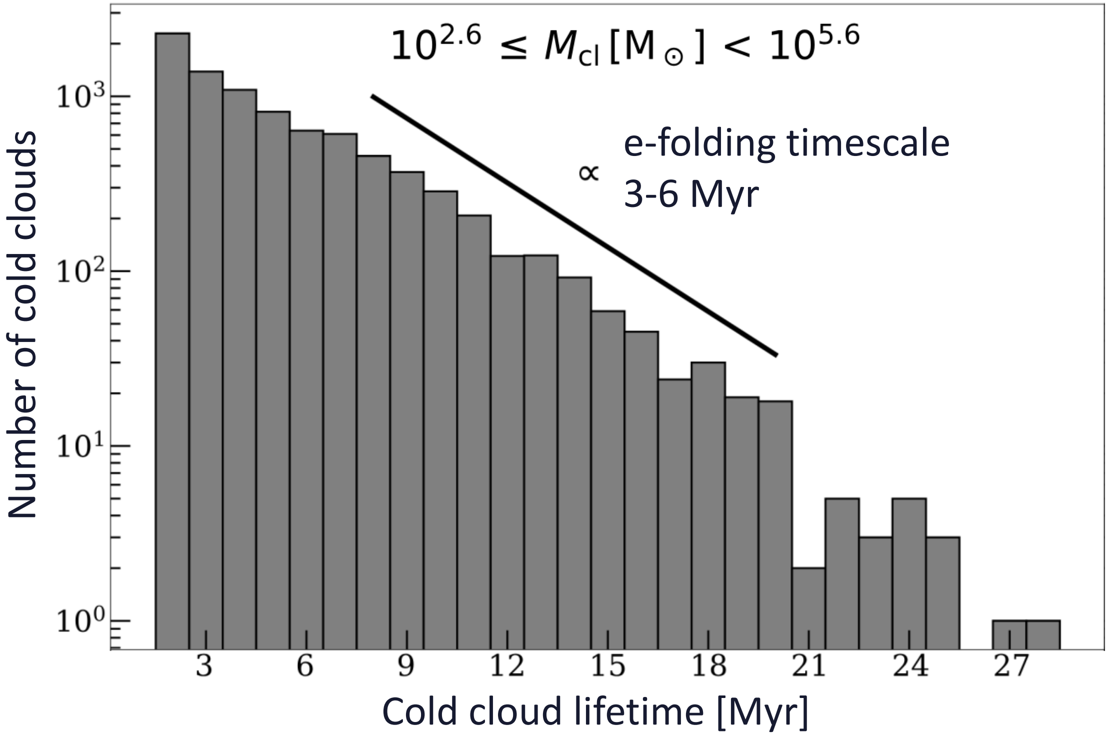
Massive star cluster formation

Fotopoulou+ 2024 (GRIFFIN):
Most clouds disrupt after 1-2 SNe



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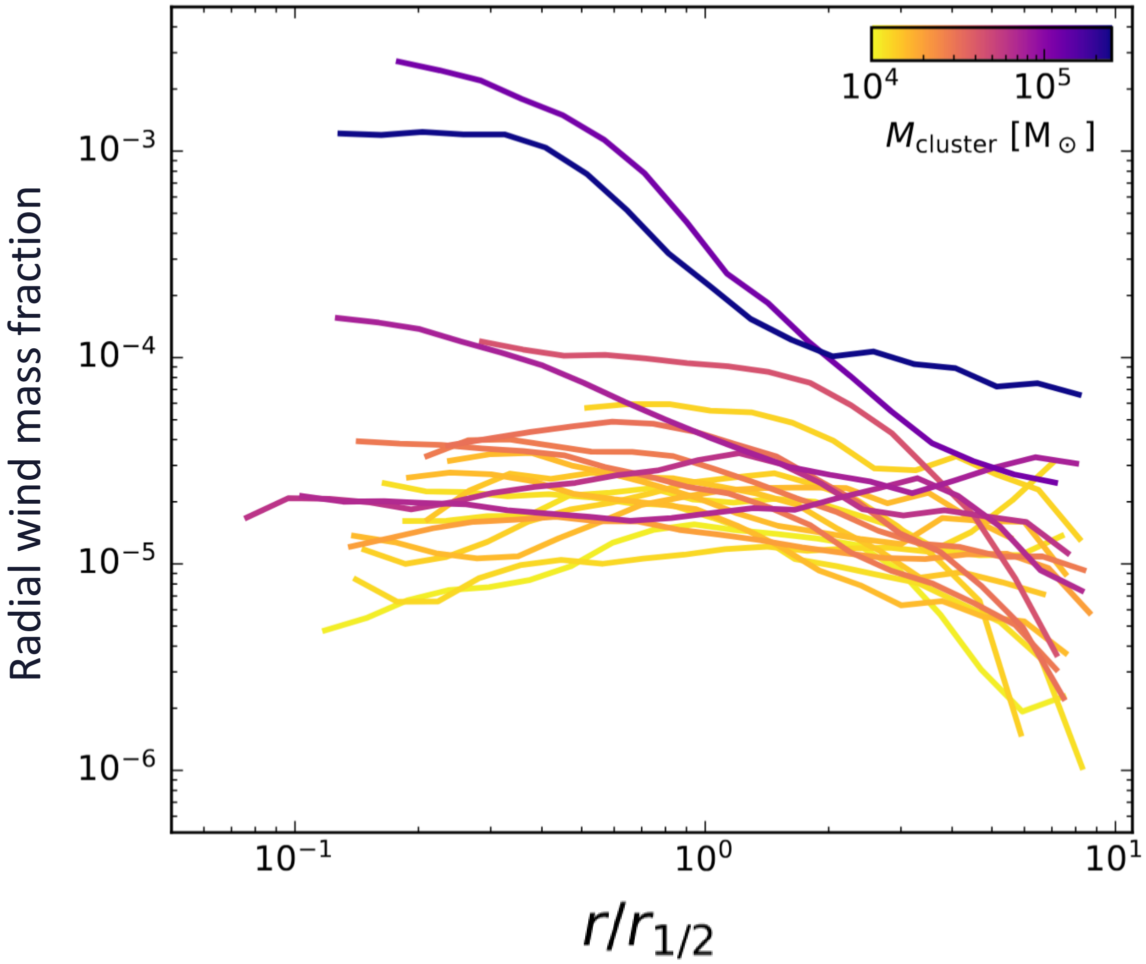
Rapid chemical enrichment in massive clusters



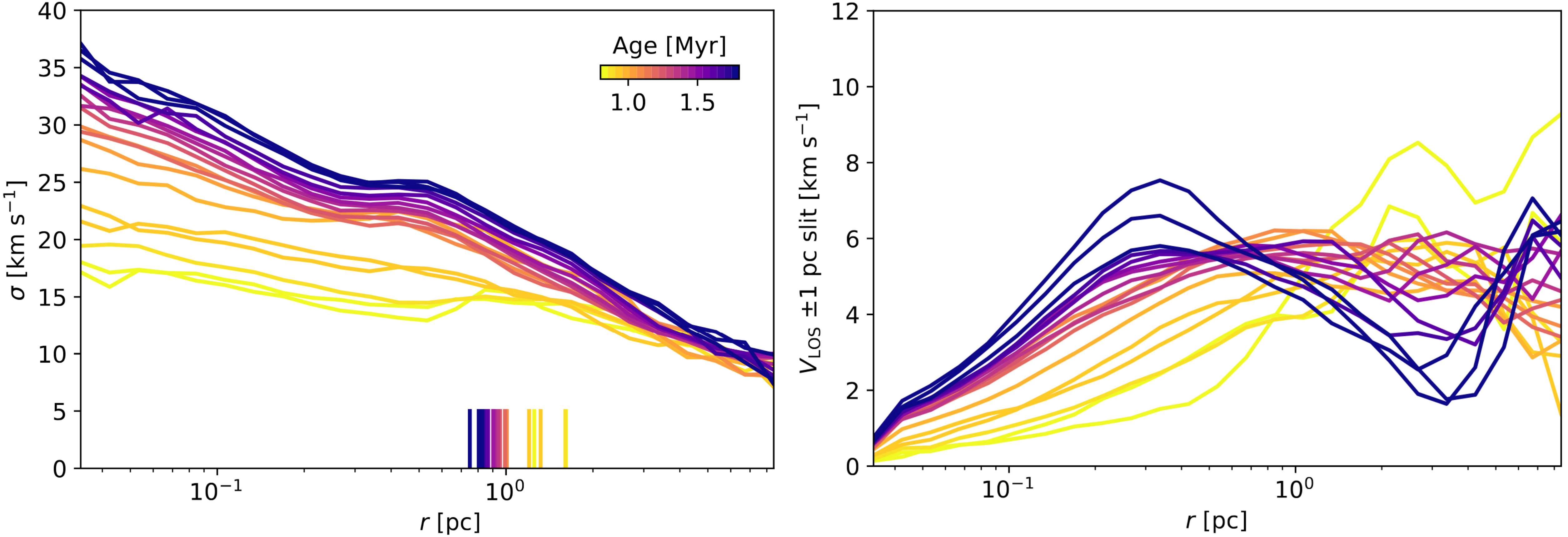
At low-metallicity/in low-mass galaxies:

- Chemical enrichment within massive clusters is dominated by pre-SN ejecta (SN ejecta escape)
  - ➢ Majority of wind recycling happens in the cores of massive clusters (light element enhancement)
- Still, only small amount (~10%) of total ejecta (SN, winds) end up recycled in new stars per starburst

Lahén+ 2023, 2024, 2025a,b; see also Lancaster+ 2021a,b,c

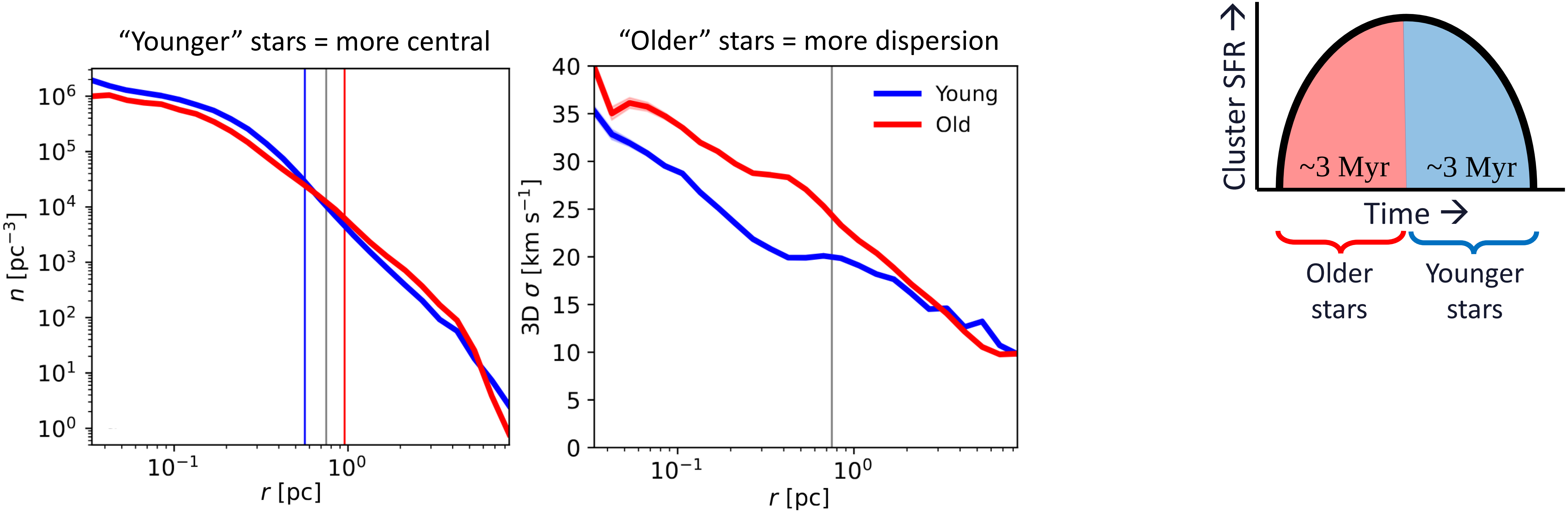
Folding in kinematics: bulk rotation in hierarchical assembly

Cluster assembly: development of bulk rotation in a ~2 × 10^5 $M_\odot$ cluster



Lahén+ 2025b; see also Mapelli 2017, Lahén 2020b, McKenzie & Bekki 2021, Lacchin+ 2022, …

Kinematics of stellar populations carry information of the hierarchical assembly



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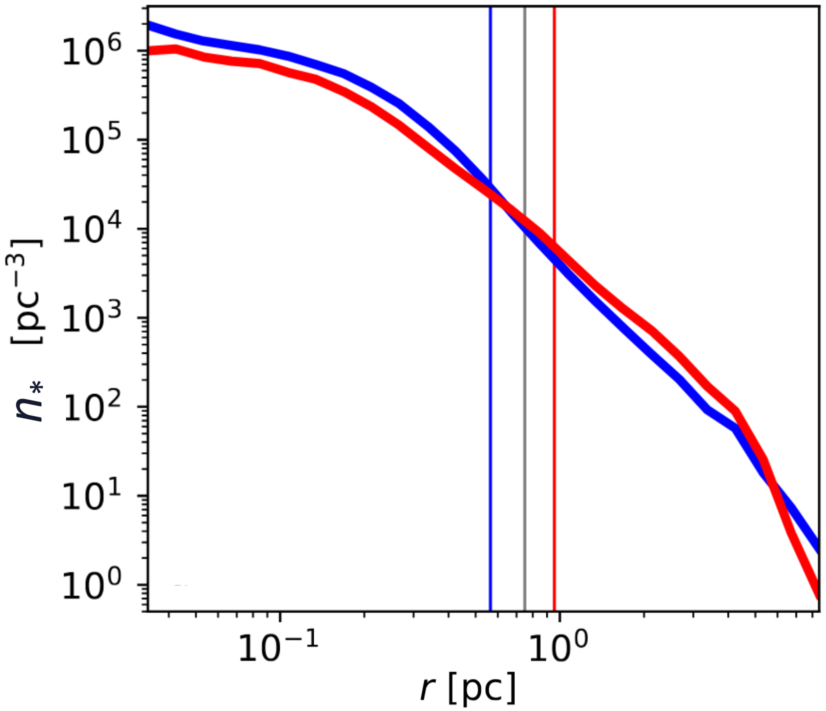
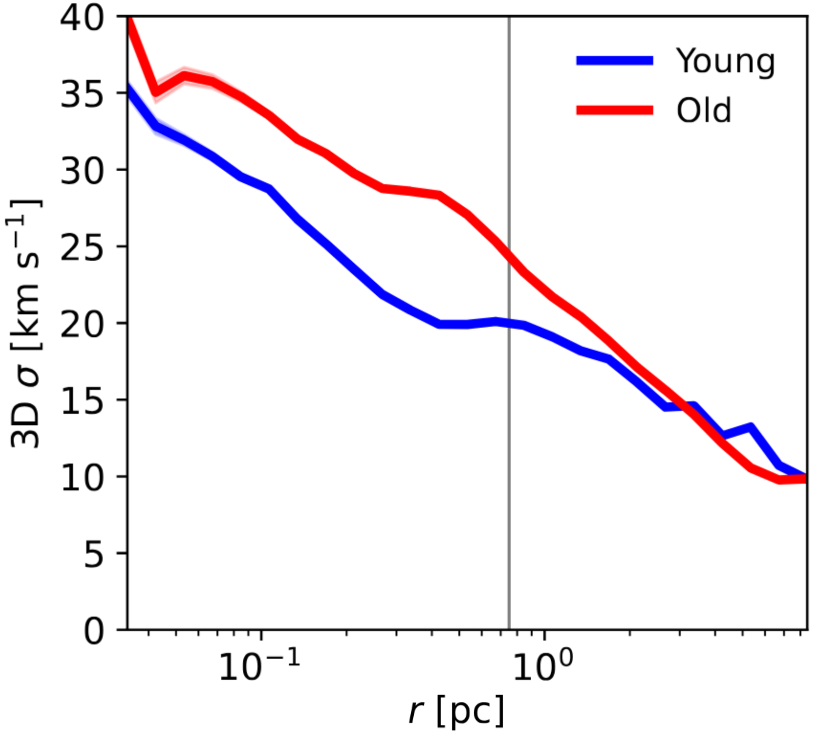
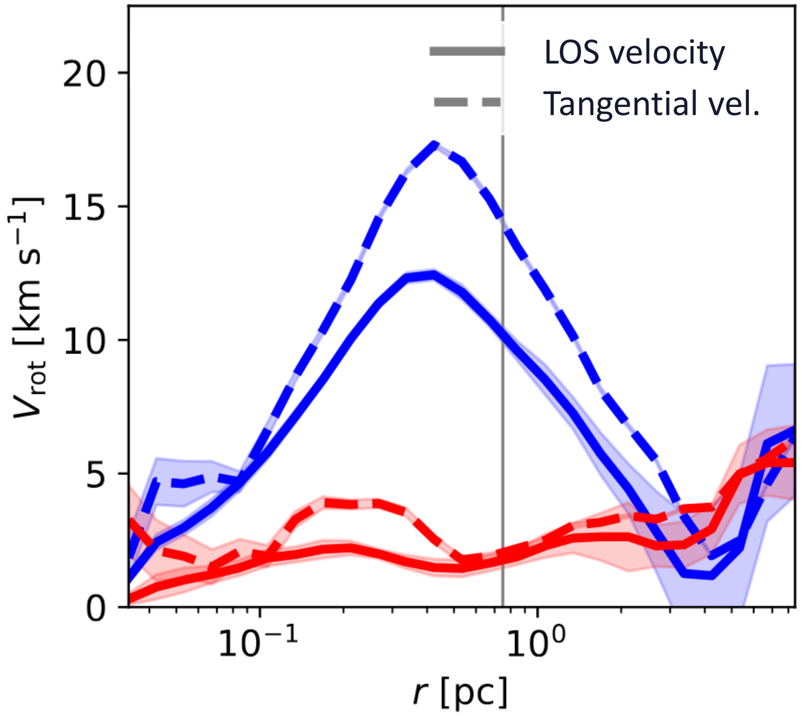






The "older" stars already relaxed through the hierarchical assembly

NGC 104/47 Tuc shows these features in its chemically identified "multiple populations", even at an age of >12 Gyr

Lahén+ 2025b; see also Mapelli 2017, Lahén 2020b, McKenzie & Bekki 2021, Lacchin+ 2022, …

Conclusions & outlook

Massive star clusters form…

- rapidly, yet over several Myr
  - ➢ Retain gas for several Myr, self-enrichment by stellar winds
- dense
  - ➢ Pre-processing by pre-SN feedback regulates the mass function of clouds and clusters?
  - ➢ Stellar collisions → veeery massive stars, intermediate mass black holes?
- hierarchically
  - ➢ Leaves an imprint in the kinematics of the stellar populations

We are probing the conditions of globular cluster formation

➢ Next steps: binary stars, cosmic environment, improved models for feedback of increasingly massive stars

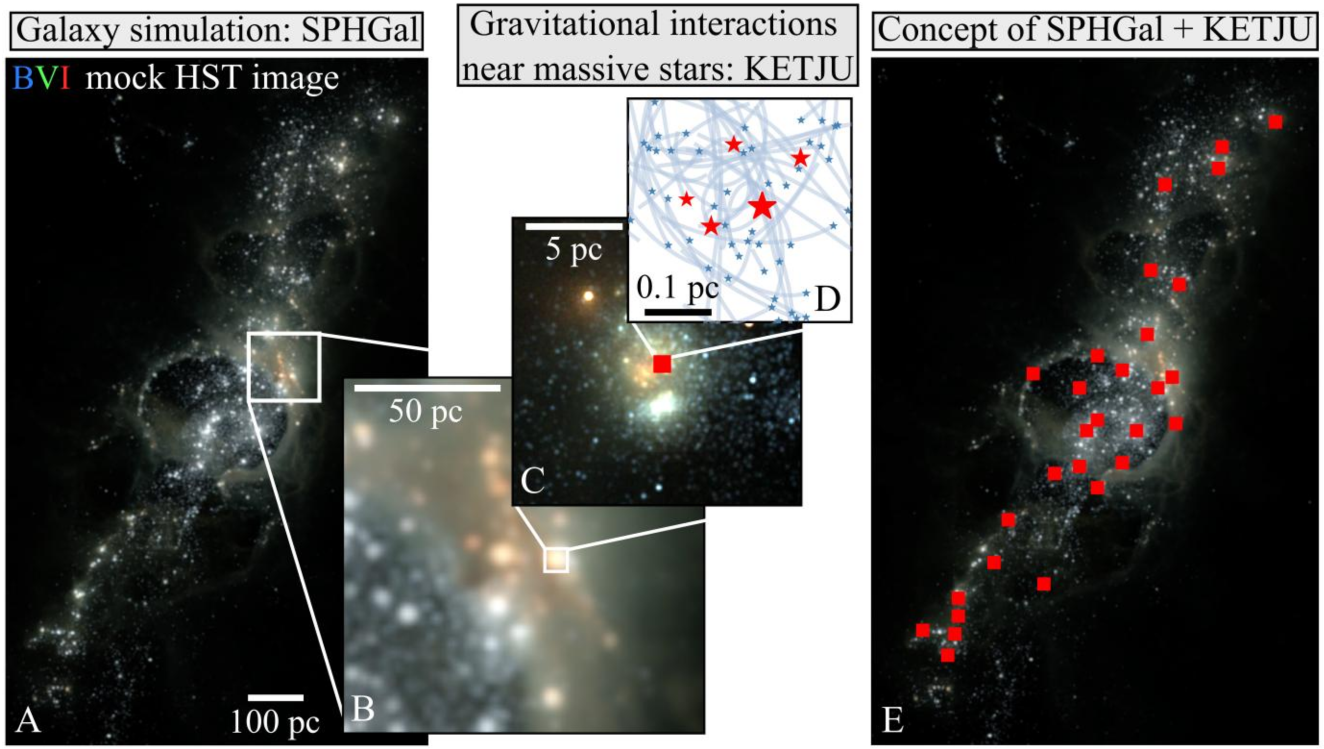
Extra slides

Accurate small-scale dynamics in star clusters with KETJU

KETJU integration module (Rantala+ 2017, Mannerkoski+ 2023) in a nutshell:

Select region(s) of space where you need higher accuracy in gravitational interactions

- center at every star with init. mass $> m_i$ (here a few $M_\odot$)
- radius: $n \times$ grav. softening length (here 0.01–0.1 pc)



KETJU: three numerical recipes in the algorithmically regularized MSTAR library (Rantala+ 2020) guarantee user-specified accuracy without gravitational softening

1. Time-transformed equations of motion (including optional post-Newtonian corrections)
2. Minimum spanning tree coordinate system
3. Gragg-Bulirsch-Stoer extrapolation technique combined with a leap-frog integrator