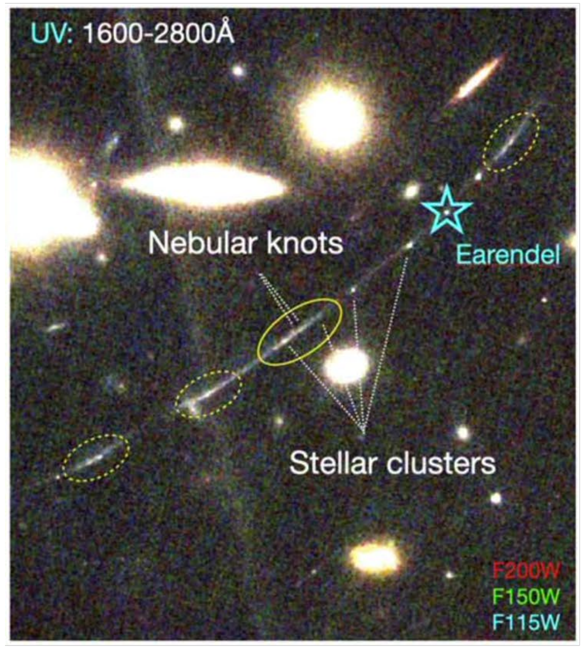
Modeling of star clusters in galaxy formation simulations

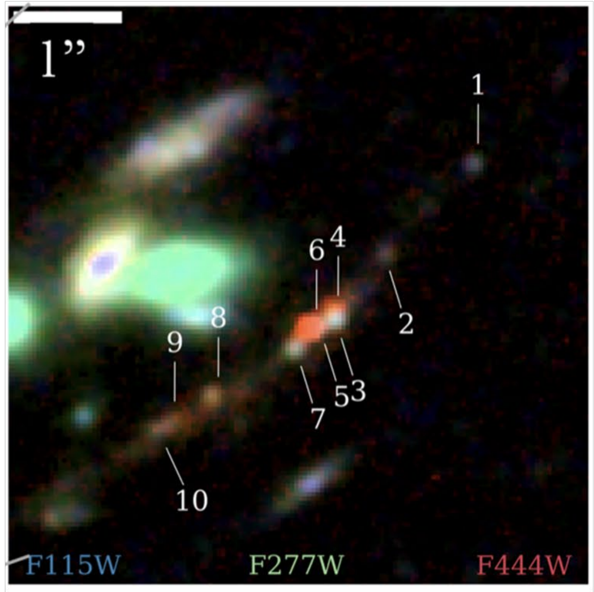
Oleg Gnedin

University of Michigan, USA



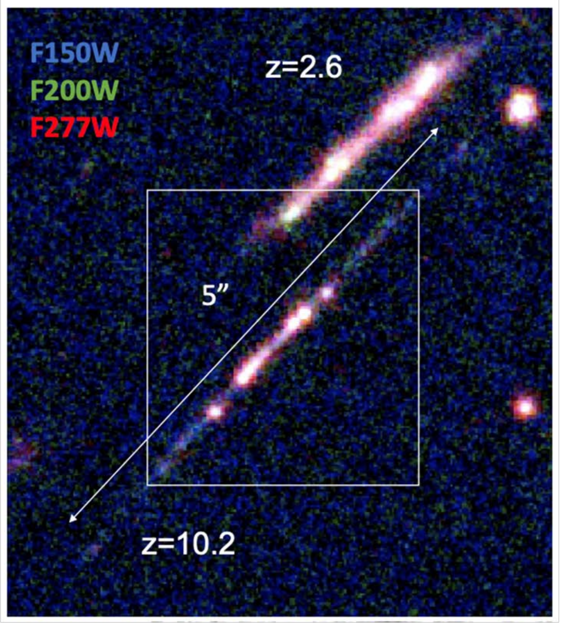
Vanzella+ (2023)

Sunrise arc
(z~6) from JWST



Mowla+ (2024)

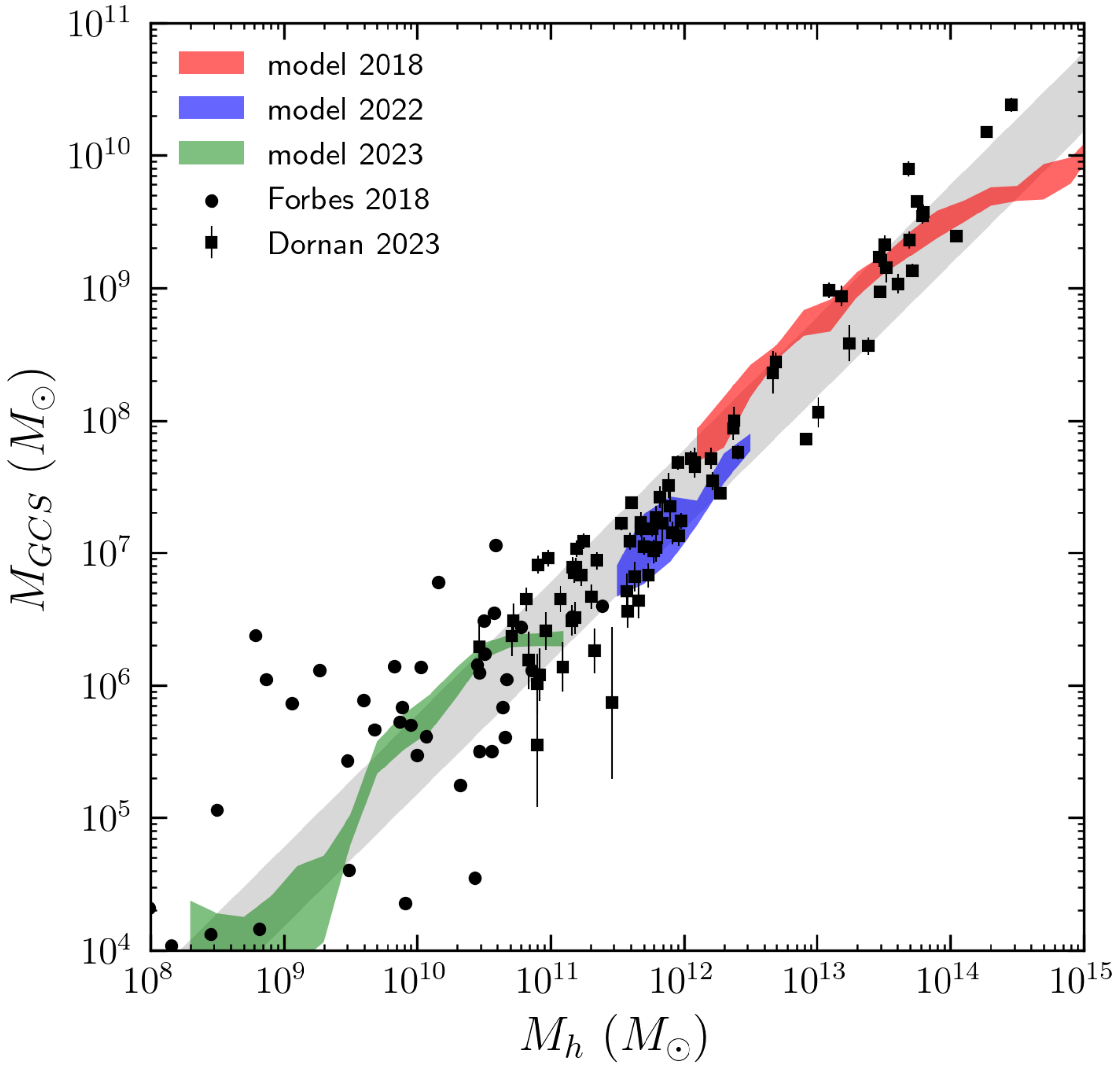
Firefly Sparkle
(z~8.3) from JWST



Adamo+ (2024)

Cosmic Gems arc
(z~10.2) from JWST

Globular clusters are massive ($M > 10^4\ M_\odot$) bound star clusters.
GC System mass is linearly proportional to the total halo mass of the host galaxy



$M_{GCS} \approx 3 \times 10^{-5}\ M_h$

obs scatter 0.28 dex

intrinsic scatter ≈ 0

Spitler & Forbes 2009

Hudson et al. 2014

Harris et al. 2017

models:

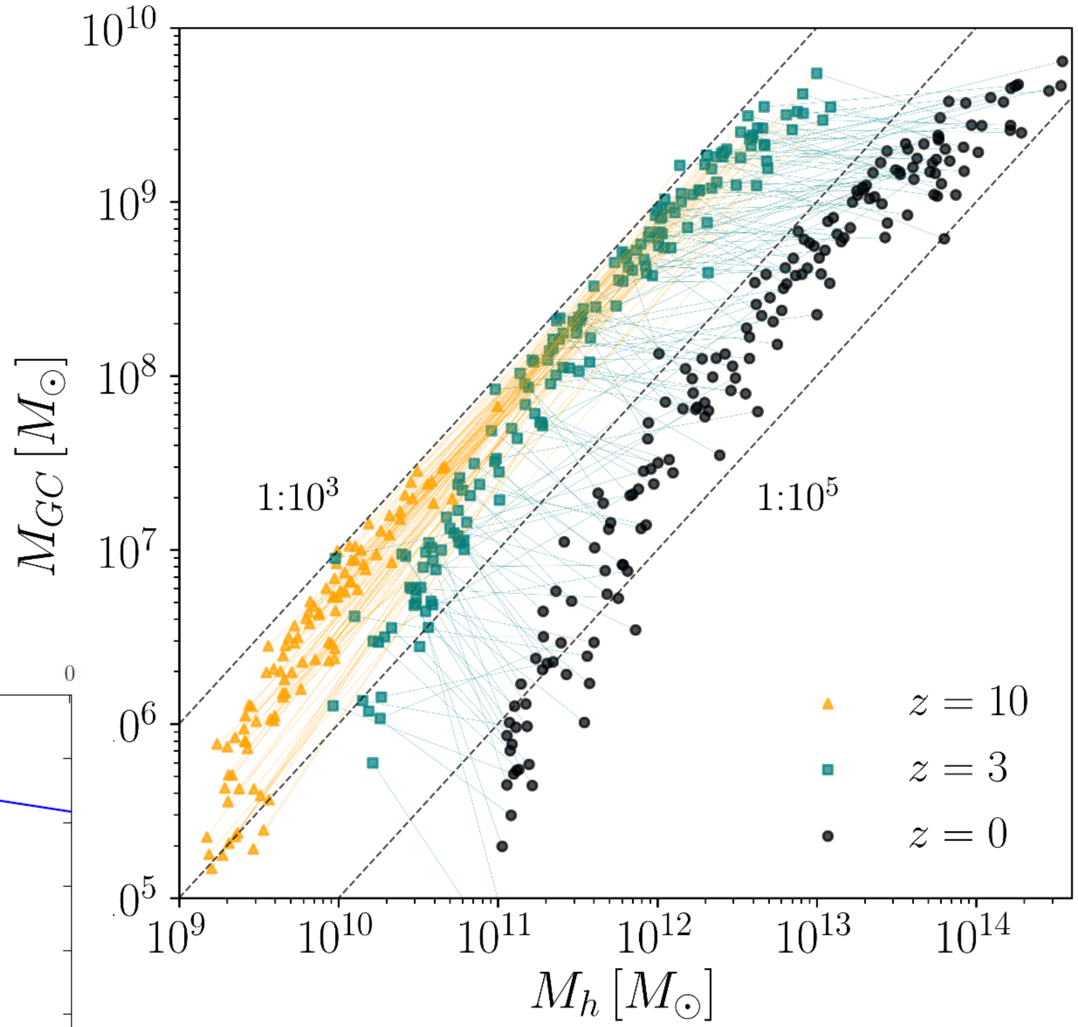
Choksi et al. 2018

Choksi & OG 2019

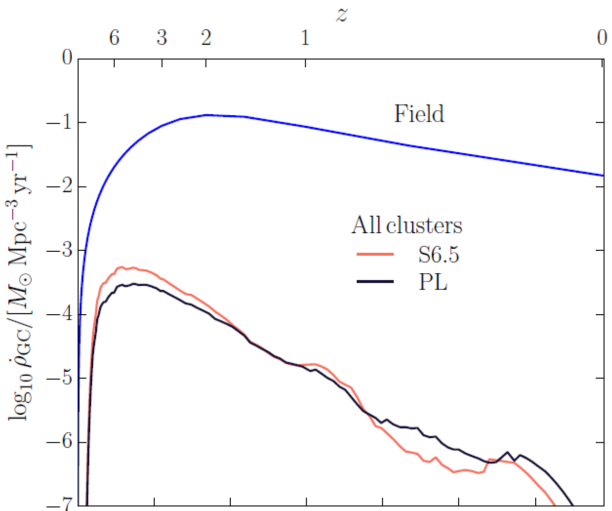
Chen & OG 2022

Chen & OG 2023

Models predict that at z > 3 massive star clusters constitute a much higher fraction of galactic star formation than now



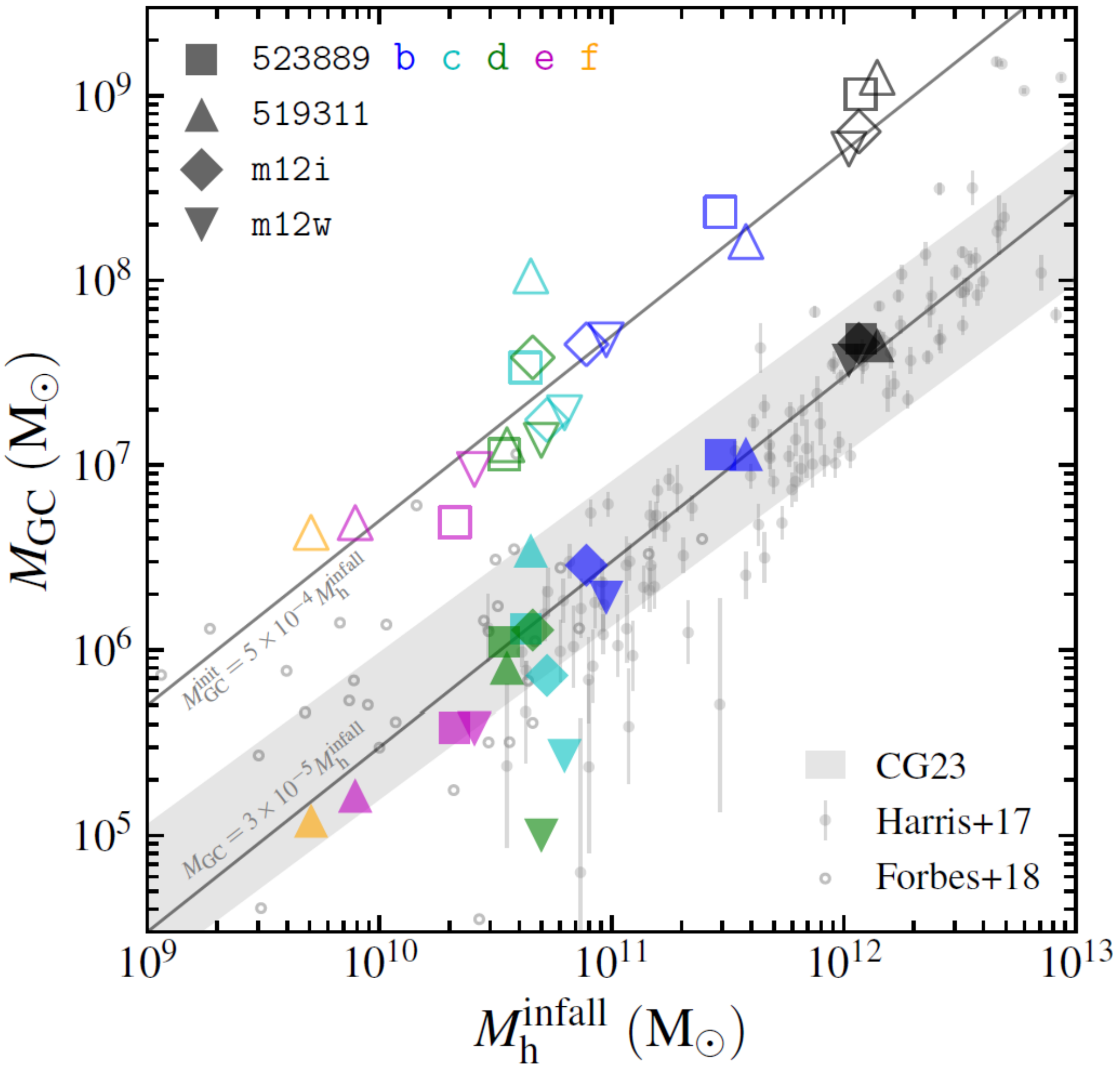
Model is based on halo mass assembly from simulations.
All baryon physics is from empirical galaxy scaling relations.
Massive cluster formation is triggered/enhanced by gas-rich galaxy mergers.
Follows cluster disruption until the present.



Choksi & OG 2019, MNRAS, 488, 5409

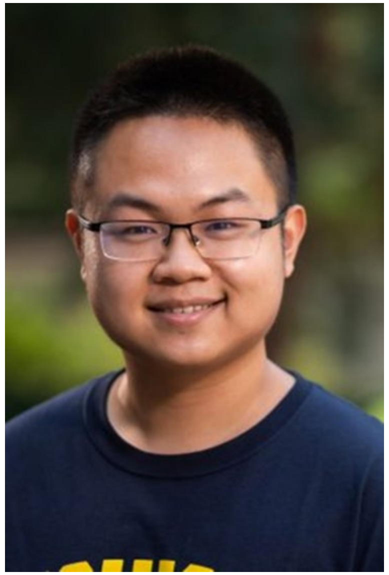
Nick Choksi

The linear GC system – halo mass relation holds for both to central and satellite galaxies



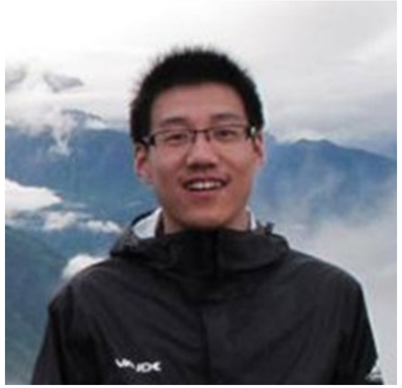
Chen & OG 2023, MNRAS, 522, 5638

Milky Way and dwarf satellites



Yingtian Chen

New algorithm for the formation of star cluster particles in simulations



Hui Li

Seed — local density peak

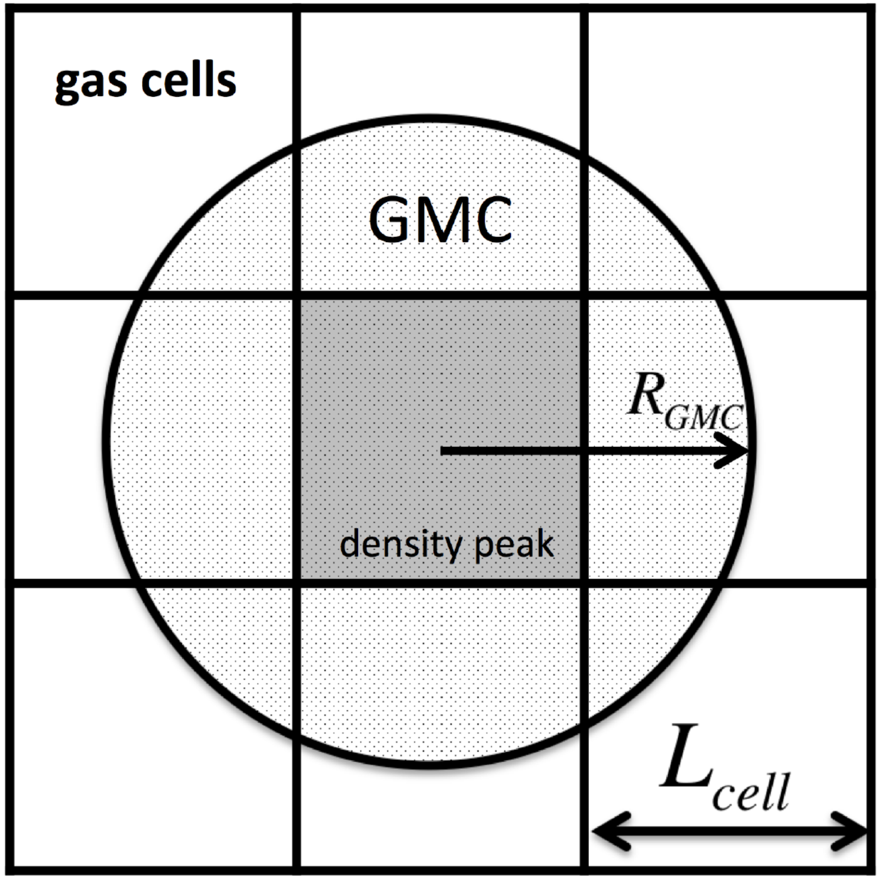
↓

Grow — $$\rho_{\rm SFR} = \epsilon_{\rm ff} \frac{f_{\rm H_2}\rho_{\rm gas}}{\tau_{\rm ff}}$$

↓

Terminate — feedback of own stars

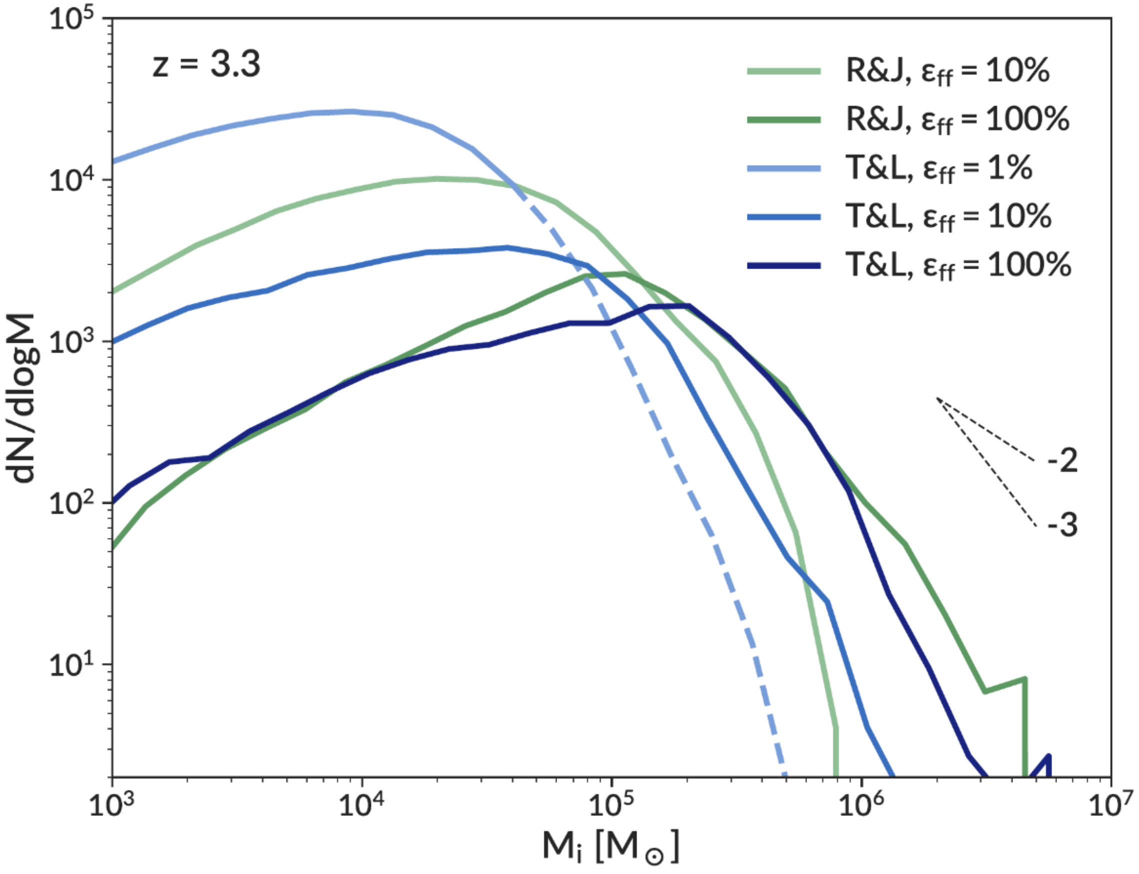
(Li, OG et al. 2018, ApJ, 861:107)



R_{GMC} = 5 pc (not comoving) L_{cell} = 3-6 pc

- Growth of individual star clusters is resolved in time, with local time steps ~ 100 years. *Thousands of time steps per cluster formation*. Track formation of individual massive stars.
- Mass growth of a given cluster is terminated by *its own radiative, energy, and momentum feedback*.
- Final mass is thus obtained *self-consistently* and represents the actual mass of a newly formed star cluster within the GMC.

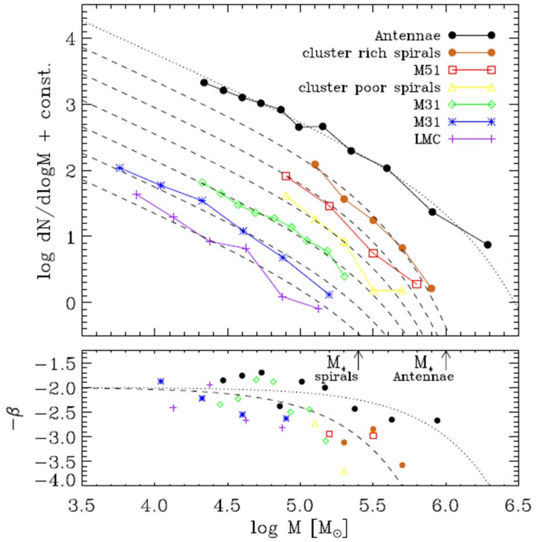
Modeling the formation of star clusters in cosmological simulations allows additional powerful tests of the implementation of star formation and stellar feedback on parsec scales



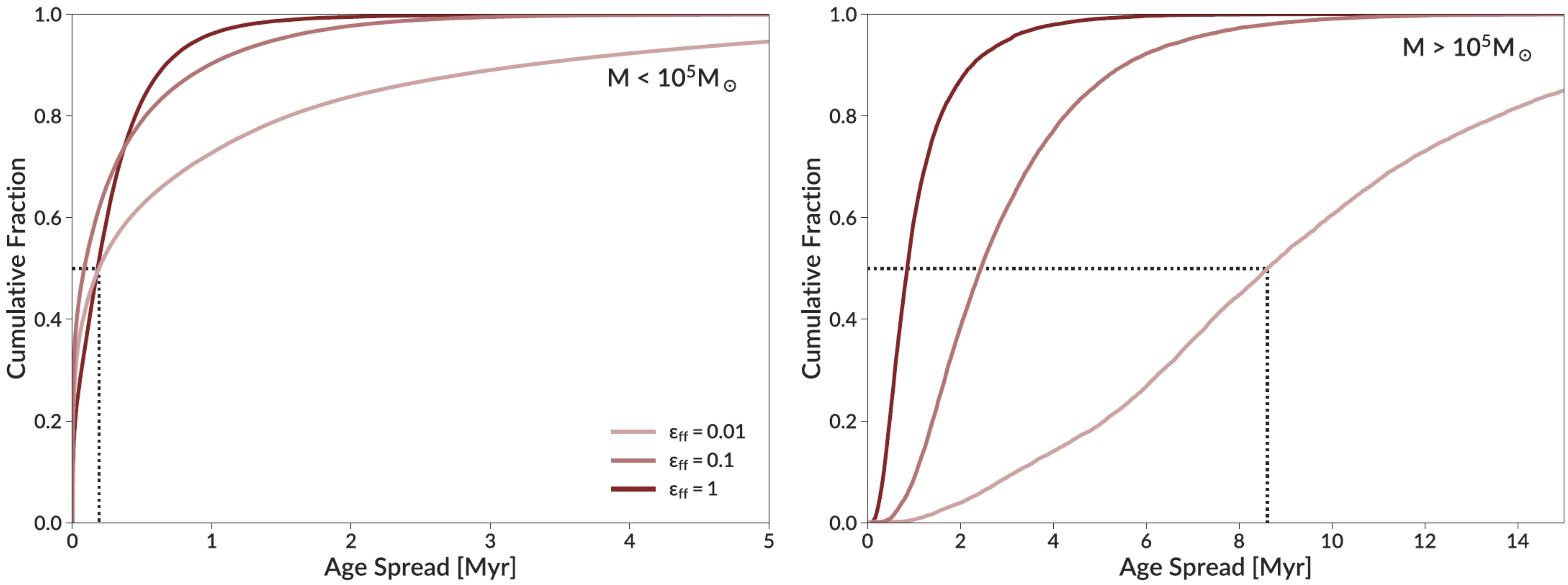
Li et al. 2017, 2018 · Li & OG 2019 · Brown & OG 2022 · Meng & OG 2022

Star cluster growth is implemented in adaptive-mesh-refinement code ART.
Non-equilibrium cooling and heating of ISM; formation and dissociation of H_2; radiative transfer; radiative, thermal, and momentum feedback.
Cluster particle mass is set self-consistently by its own feedback on infalling gas (analogs of sink particles).

Cluster mass function can be directly compared with observations of young star clusters in local universe:

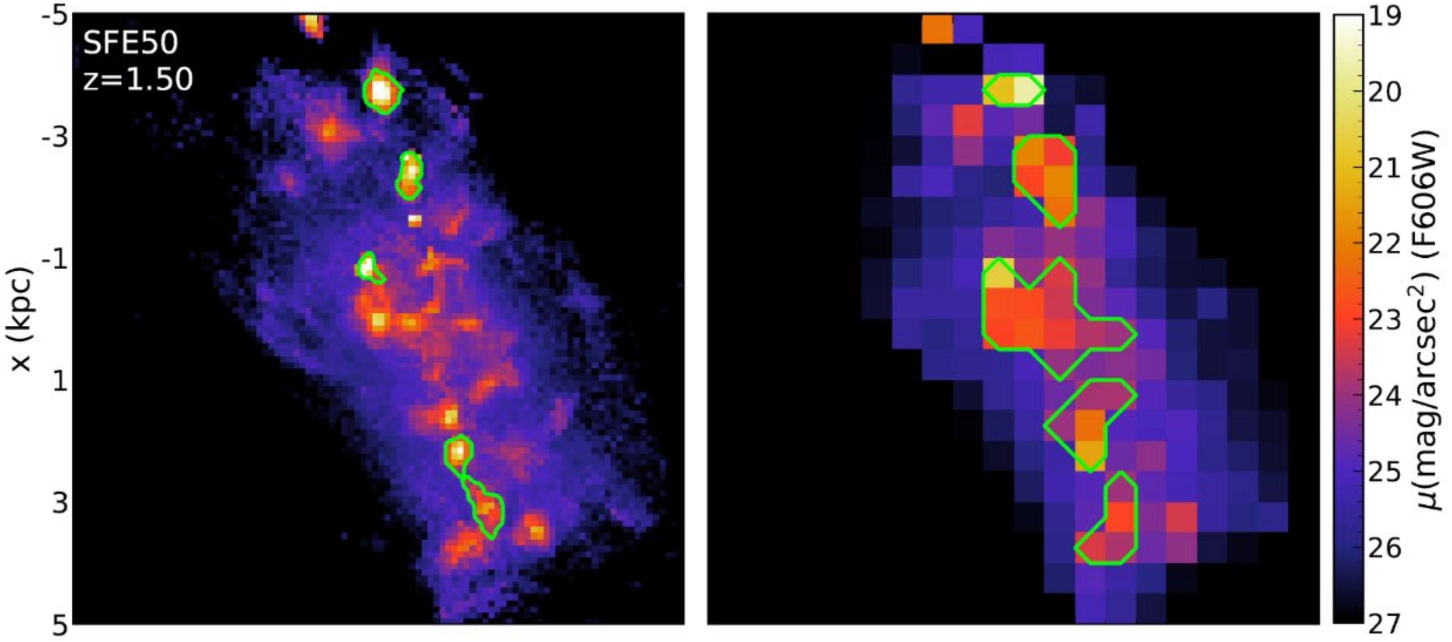


Very powerful test: spread of ages of stars within simulated clusters vs. observations of local clusters



Li et al. 2017, 2018 · Li & OG 2019 · Brown & OG 2022 · Meng & OG 2022

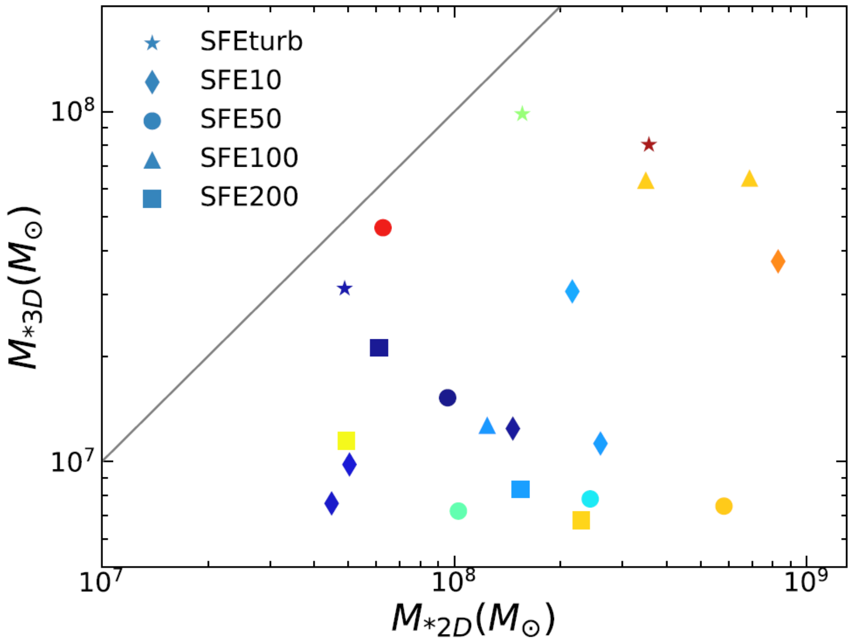
Without strong gravitational lensing, giant clumps in galaxies at $z>1$ may blend many independent clusters. Realistic physical modeling of SF and ISM is necessary to recover the properties of massive star clusters.

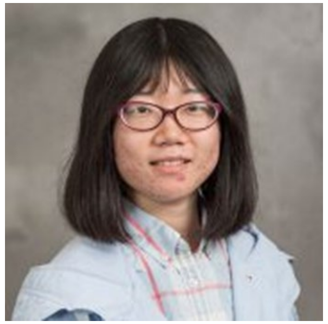


Galaxy formation simulation processed for HST/WFC3 photometry

Meng & OG 2020, MNRAS, 494, 1263

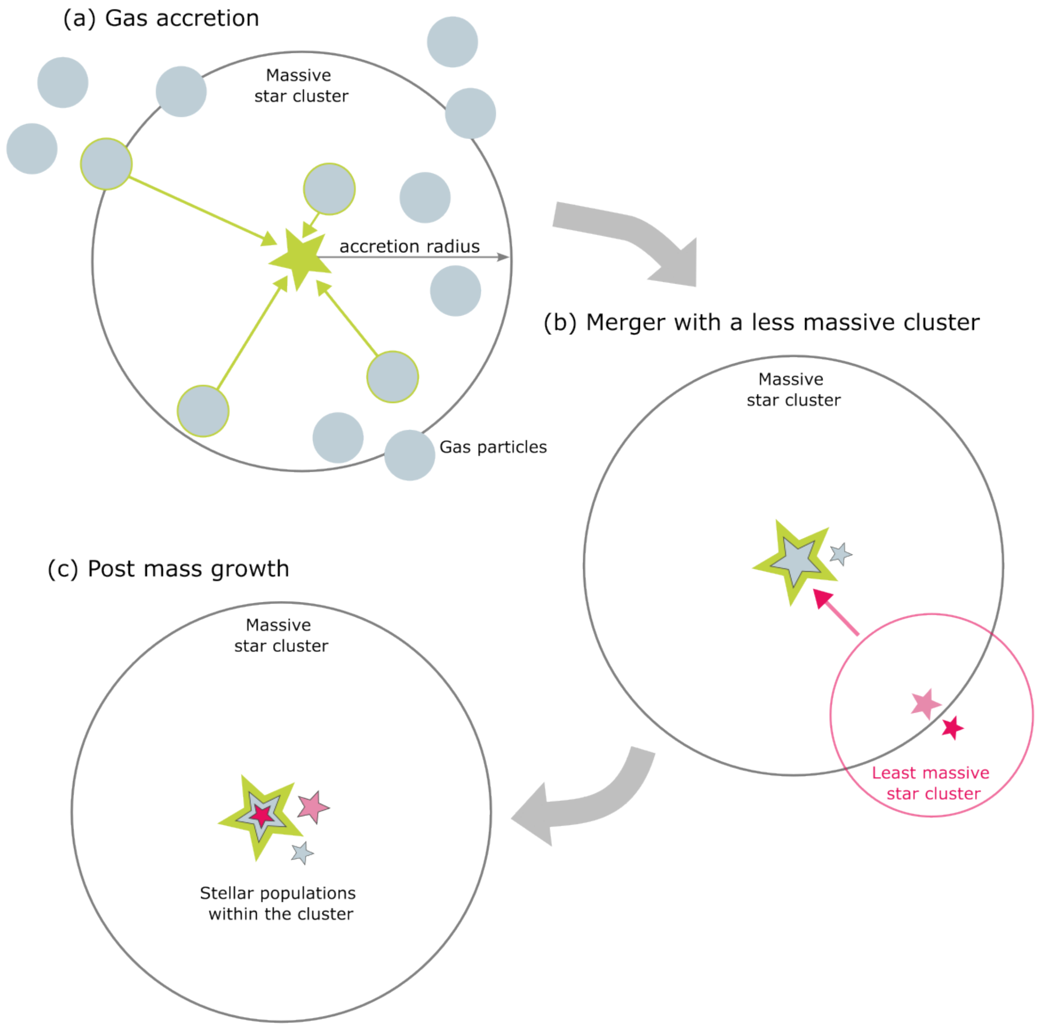
Projection along the galaxy:
Mass (and size) of the main proto-GC may be overestimated by an order of magnitude



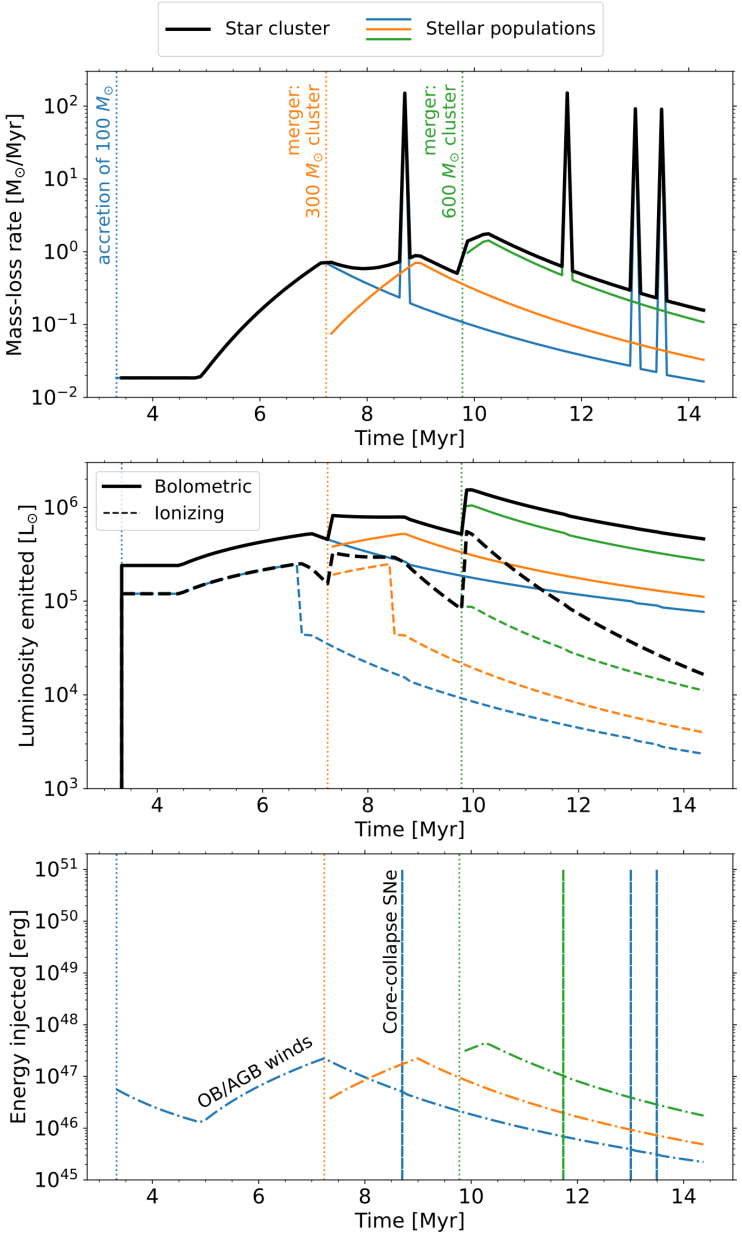


Xi Meng

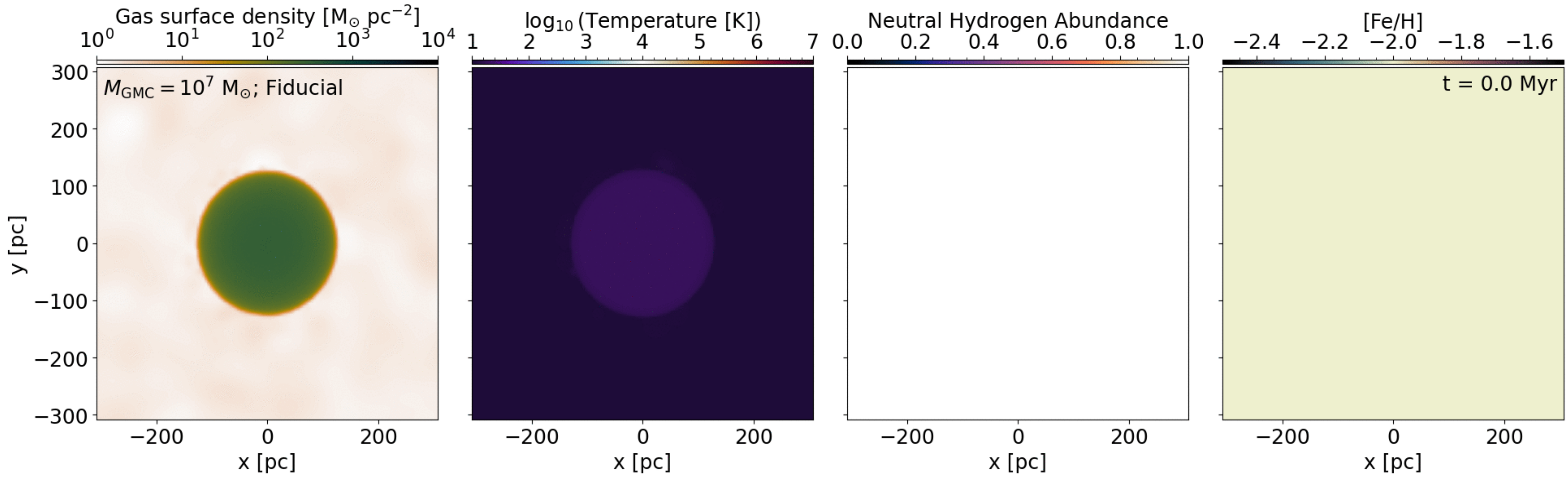
Modeling of sink particle accretion and mergers



Marta Reina-Campos



Time evolution of the feedback output from a single star cluster with three stellar populations star clusters are shown with red markers proportional to their mass



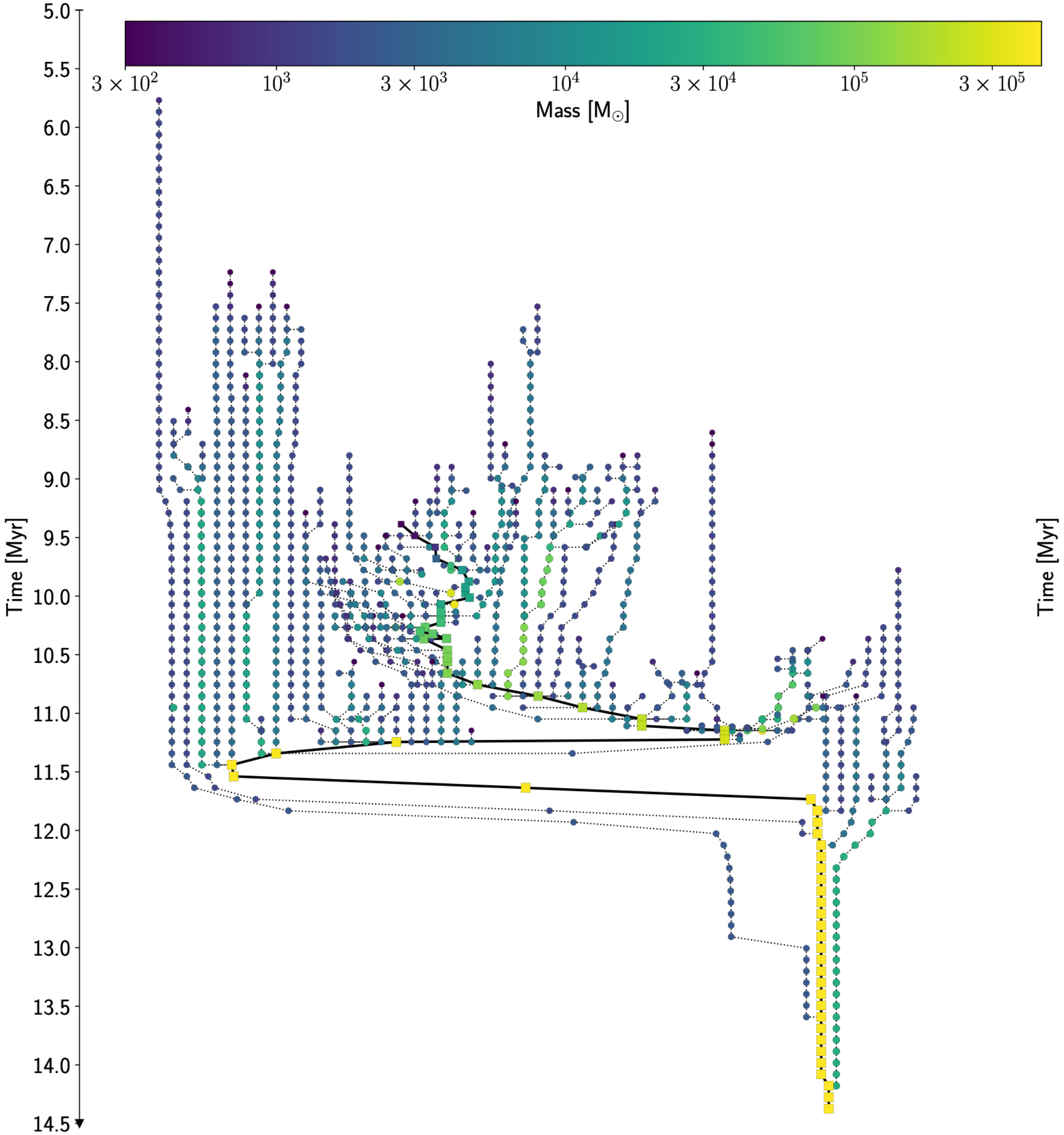
Isolated spherical cloud of 10^7 $M_\odot$ and surface density of 210 $M_\odot/pc^2$

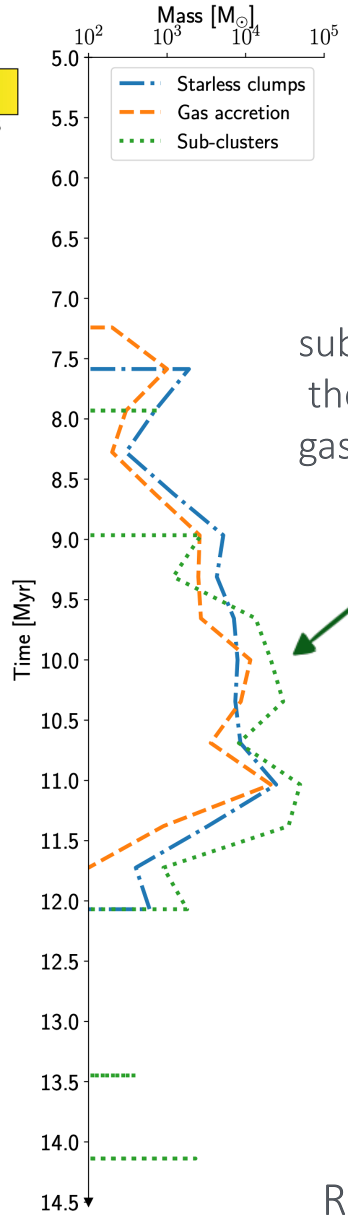
Initially low metallicity (1% solar) at 20 K in thermal equilibrium with the dust

Fiducial cloud at 100 $M_\odot$ mass resolution

Reina-Campos, OG et al. 2024

Merger tree of the most massive cluster in the fiducial cloud





sub-cluster mergers dominate
the mass growth over
gas accretion and starless sinks

Reina-Campos, OG et al. 2024

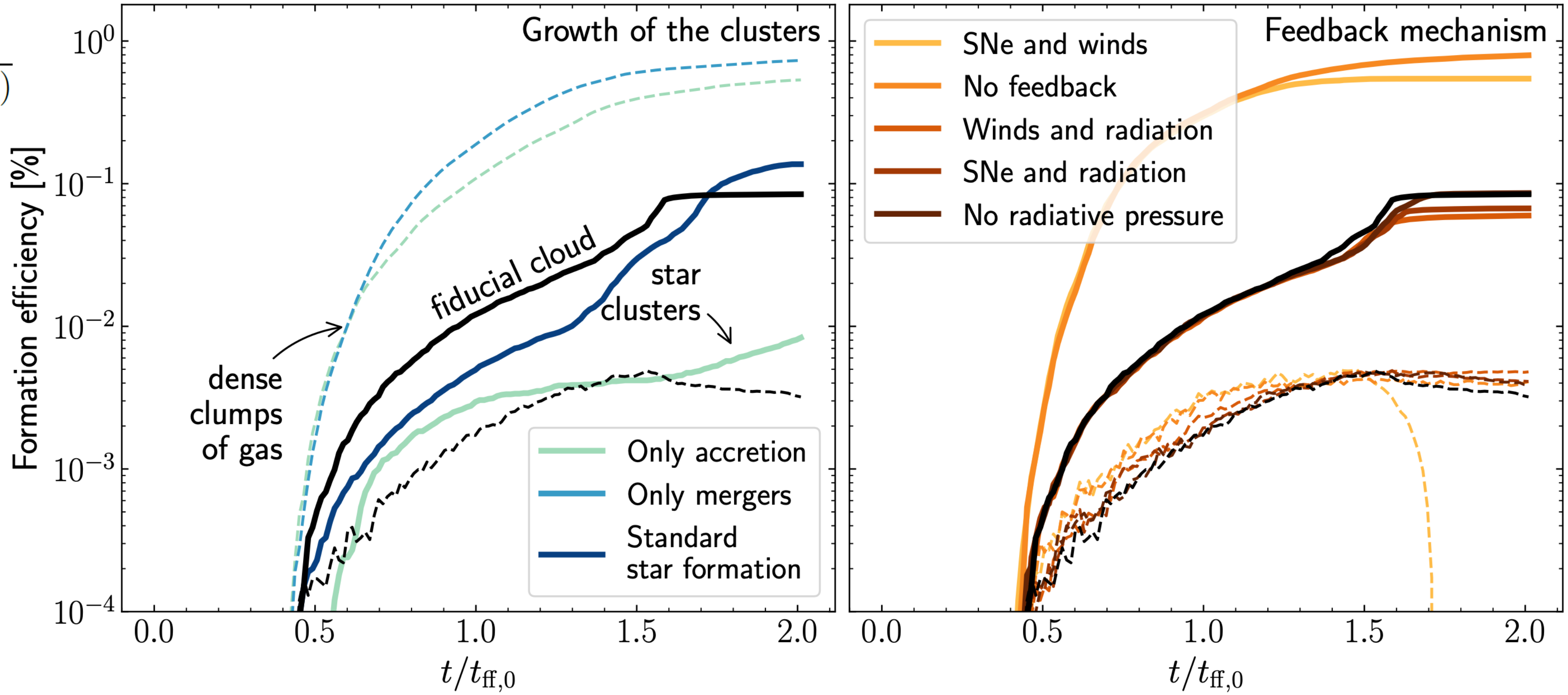
Marta Reina-Campos

Ionising radiation regulates formation efficiency

Hierarchical merging or gas accretion on their own can't form star clusters; both are required

Ionizing radiation regulates the formation efficiency by decreasing the accretion rate

$$\epsilon_* = \frac{M_*(t = 2t_{\rm ff})}{M_{\rm GMC}(t = 0)}$$



Time evolution of the formation efficiency of star clusters / stars in a subset of our tests

Reina-Campos, OG et al. 2024

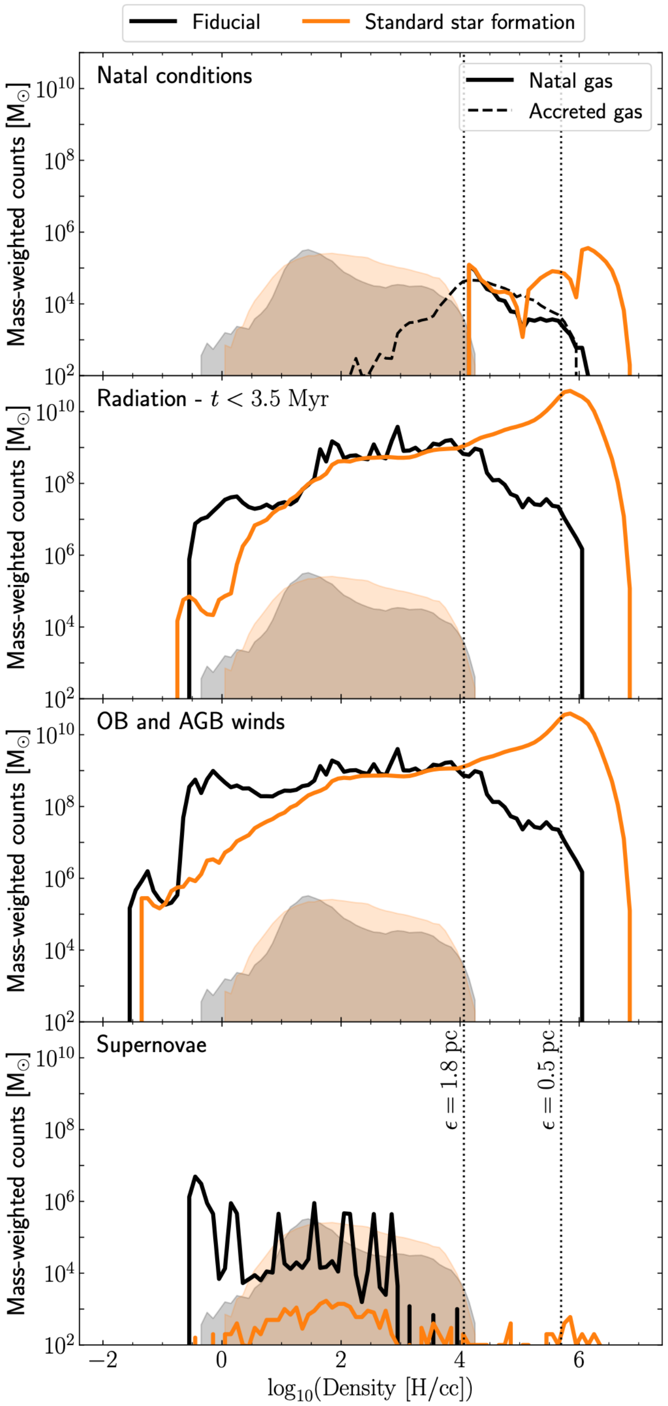
Marta Reina-Campos

Gas densities from which
star clusters form and accrete

Gas densities in which
ionising radiation is injected

Gas densities in which
OB and AGB winds are injected

Gas densities in which
SNe are injected

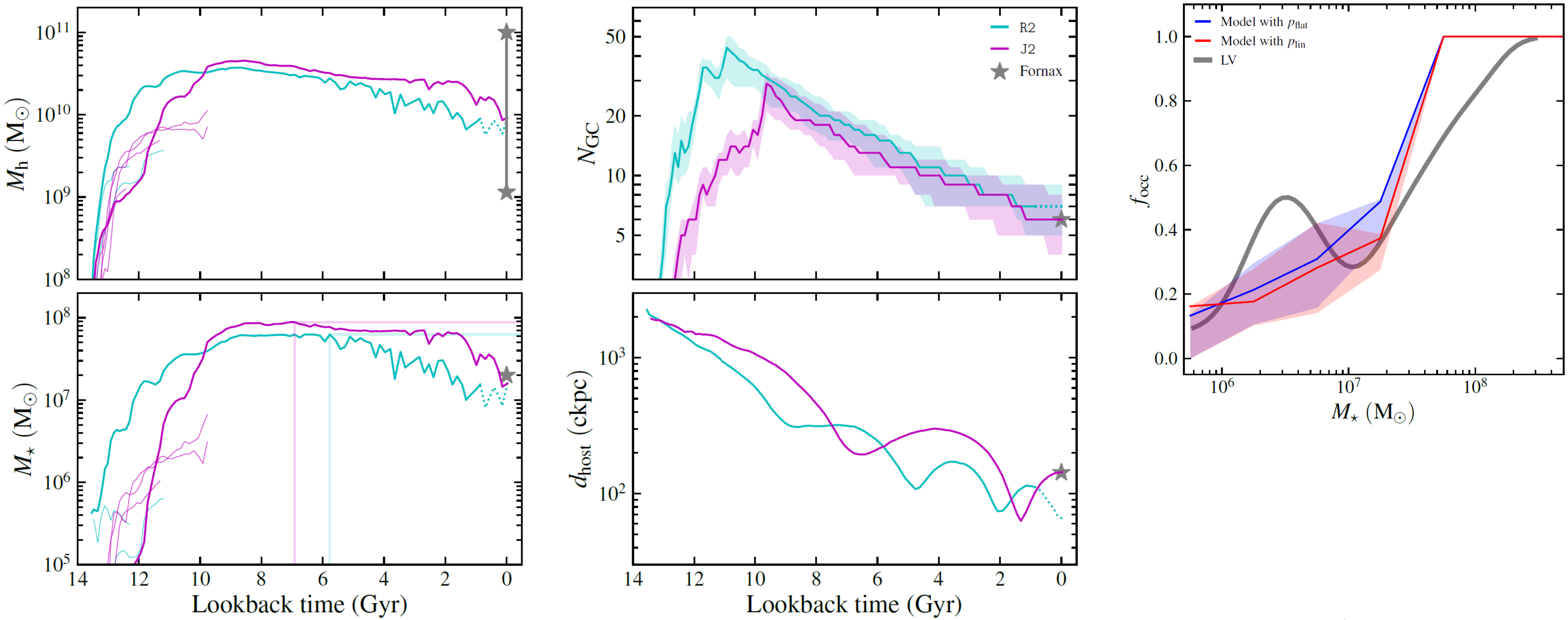


Gas accretion onto star clusters
reduces pockets of high density gas

Clustered feedback is injected in
lower gas density environments,
being more efficient at driving their evolution

Reina-Campos, OG et al. 2024

GCs in dwarf galaxies such as Fornax dSph: observed GCs are remnants of an even more numerous system



Chen & OG 2023

Catalogs of model GC properties (Chen & OG 2024)

specifically tuned to the Milky Way and M31 systems

https://github.com/ognedin/gc_model_mw

Catalog of model globular clusters in the Milky Way and M31 galaxies

This is a mock catalog of globular clusters calculated with a model for the formation and evolution of globular cluster systems. Current version of the model published in Chen & Gnedin (2022). It is based on the earlier versions developed in Muratov & Gnedin (2010), Li & Gnedin (2014), Choksi et al. 2018, Choksi & Gnedin 2019a, Choksi & Gnedin 2019b.

The model matches the observed mass function and age-metallicity distribution of the globular cluster systems. Current version of the model adds information on the spatial and kinematic distributions of the globular cluster system, based on tagging particles from the Illustris TNG50 simulation. It matches the observed surface number density profile and the velocity dispersion profile of the Galactic globular clusters.

The catalog of clusters survived to redshift z=0 provides information on cluster age, mass at formation and at z=0, Cartesian coordinates and velocities at z=0, orbital actions in the best-fitting halo+disk galaxy potential, apocenter and pericenter radii, value of the potential, cluster iron metallicity, total and stellar mass of host galaxy at formation, and total and stellar mass of host galaxy at z=0. The catalog also contains a tag `origin` to mark clusters formed in the central halo (in-situ) and in satellite galaxies (ex-situ), and gives the time of accretion for ex-situ clusters.

The catalog of disrupted clusters contains also the time of disruption. The coordinates and other orbital information is for the center of mass of the resulting stellar stream. By construction the model generates clusters with a minimum initial mass around 10^5 $M_\odot$. We plan to include clusters in the mass range $10^4 - 10^5$ $M_\odot$ soon; most of these are expected to be disrupted by the present time.

The MW catalogs contain GC systems of 3 halos most resembling the Milky Way in their growth of dark matter and stellar mass, and in the metallicity distribution of the GC system. Each halo provides an alternative possible history of the assembly of the MW system of globular clusters. GC systems can be analyzed combined for all 3 halos, or for each halo separately. The adjustable model parameters are tuned to match the MW system and are slightly different from the version published in Chen & Gnedin (2022): $p_2 = 4$, $\kappa_\lambda = 3$.

The M31 catalogs similarly contain GC systems of 3 halos most resembling the Andromeda galaxy in their growth of dark matter halo and merger history, and in the metallicity distribution of the GC system. Each halo provides an alternative possible history of the assembly of the MW system of globular clusters. The adjustable model parameters are the same as for the MW catalogs.

This notebook provides examples of reading the cluster catalog and making plots.

Summary

- Linear M_{GC} - M_h relation is matched by models of GC formation and evolution (Choksi & OG 2019, Chen & OG 2023)
- Proto-GCs are expected to contribute significantly higher fraction of host galaxy stellar mass at $z > 3$ (10-30 times)
- Modeling star clusters with sink particles allows additional tests of galaxy formation simulations: cluster mass function and age spread (Brown & OG 2022)
- Without strong lensing, masses and sizes of proto-GCs may be overestimated by up to an order of magnitude (Meng & OG 2020)
- New implementation of sink particle accretion and mergers allows tracking of multiple stellar populations in GCs (Reina-Campos, OG et al. 2024)