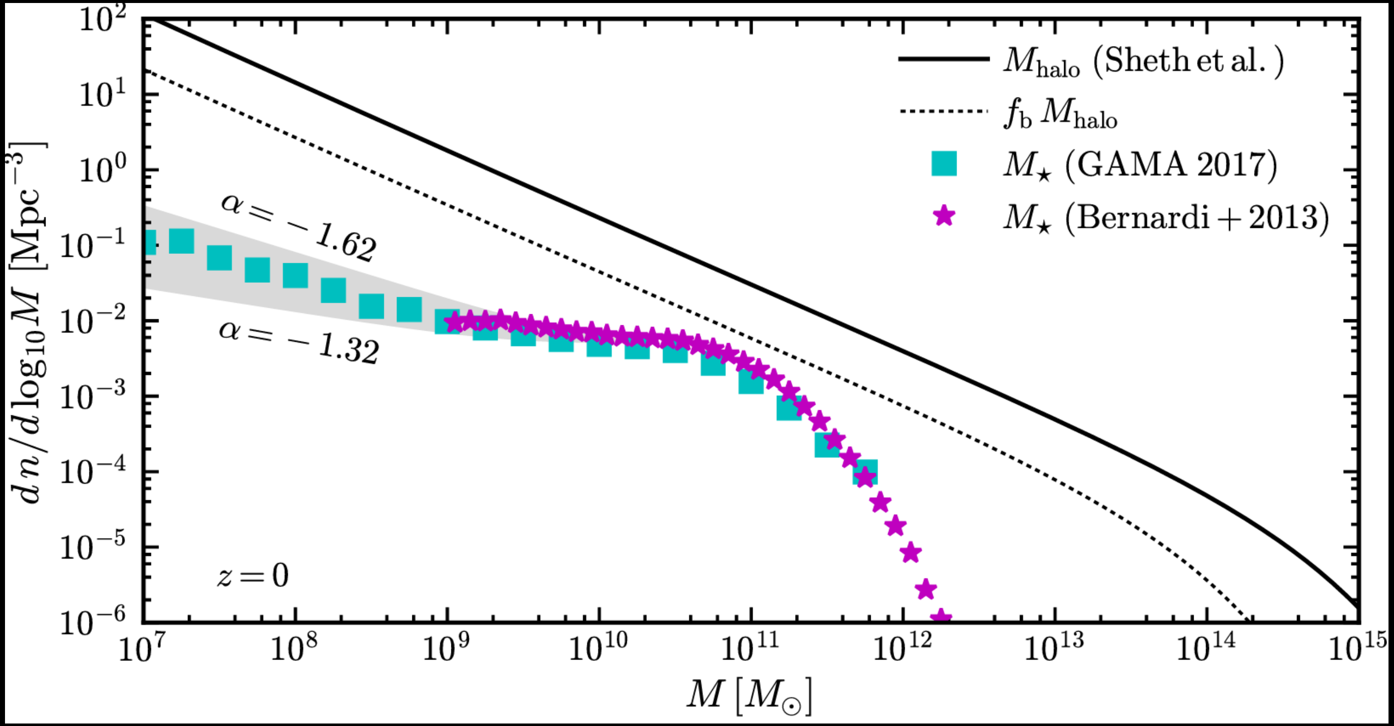
RIGEL: Simulating dwarf galaxies at solar mass resolution

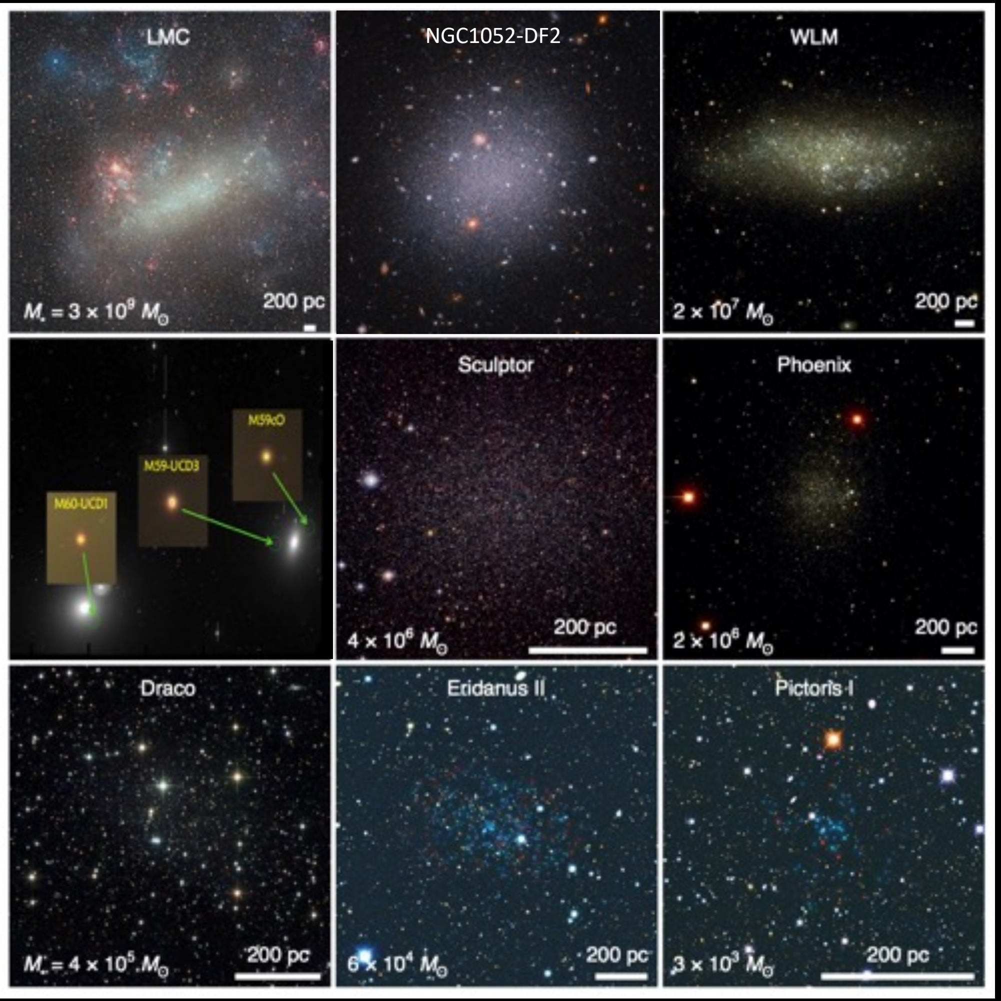
Hui Li

(Tsinghua University)

Key Collaborators: **Yunwei Deng, Chuizheng Kong, Alvaro Otero, Elizabeth Moreno, David Robinson**, Boyuan Liu, Greg Bryan, Mark Vogelsberger, Federico Marinacci, Laura Sales, Paul Torrey, Rahul Kannan, Aaron Smith

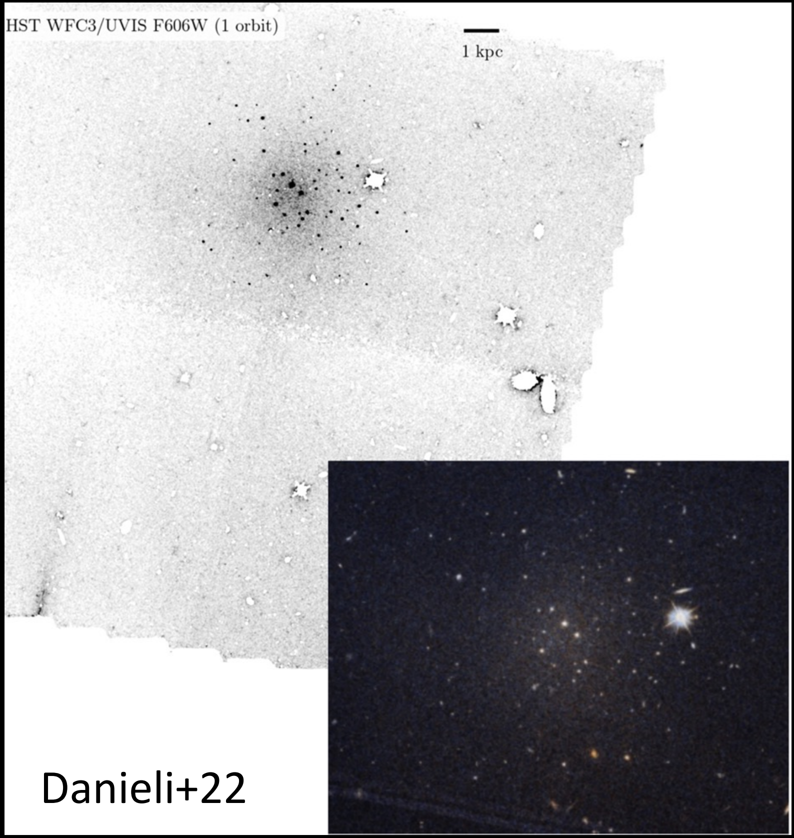
Dwarf galaxies are abundant and diverse!



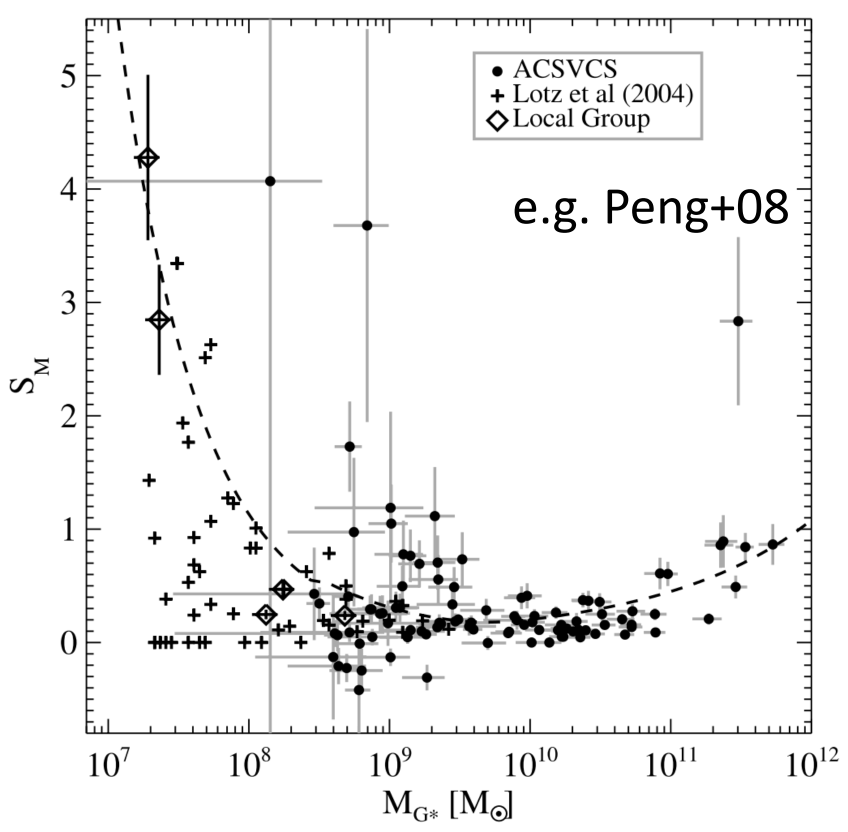


Bullock & Boylan-Kolchin 2019

Dwarf galaxies have a special star/cluster formation behavior



Globular clusters dominate the stellar component in NGC 5846-UDG1



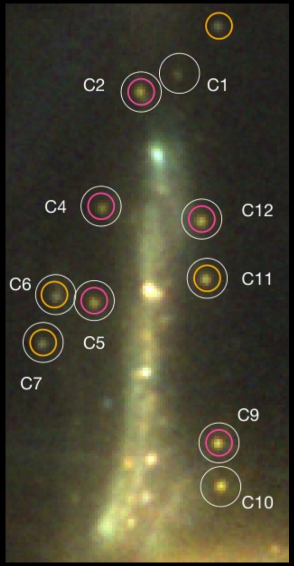
Many dwarf galaxies are rich in globular clusters

Witnessing the on-site YMC formation at high-z with JWST

(Proto-) globular clusters

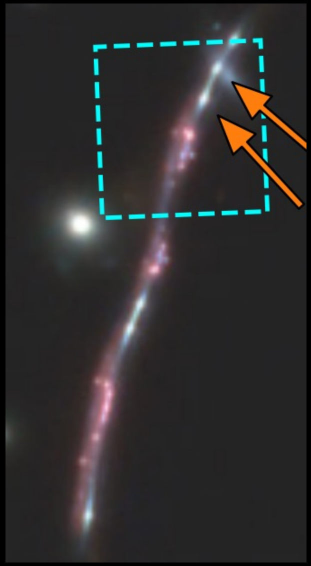
Young Massive Clusters at high-z

Mowla+22
Adamo+23
Sparkler



z=1.37

Rivera-Thorsen+24
Sunburst

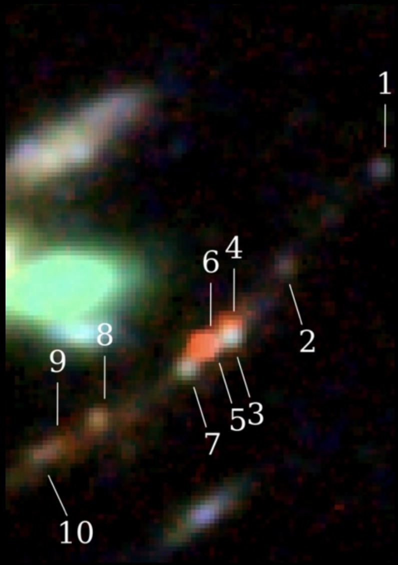


z=2.37

Vanzella+23
Sunrise

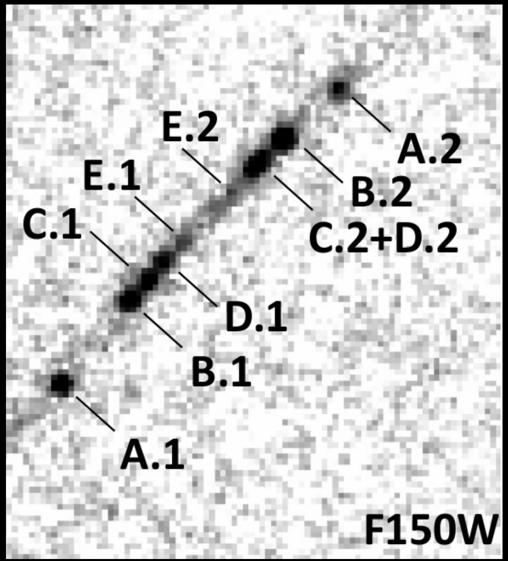
z=6.0

Mowla+24
Firefly



z=8.3

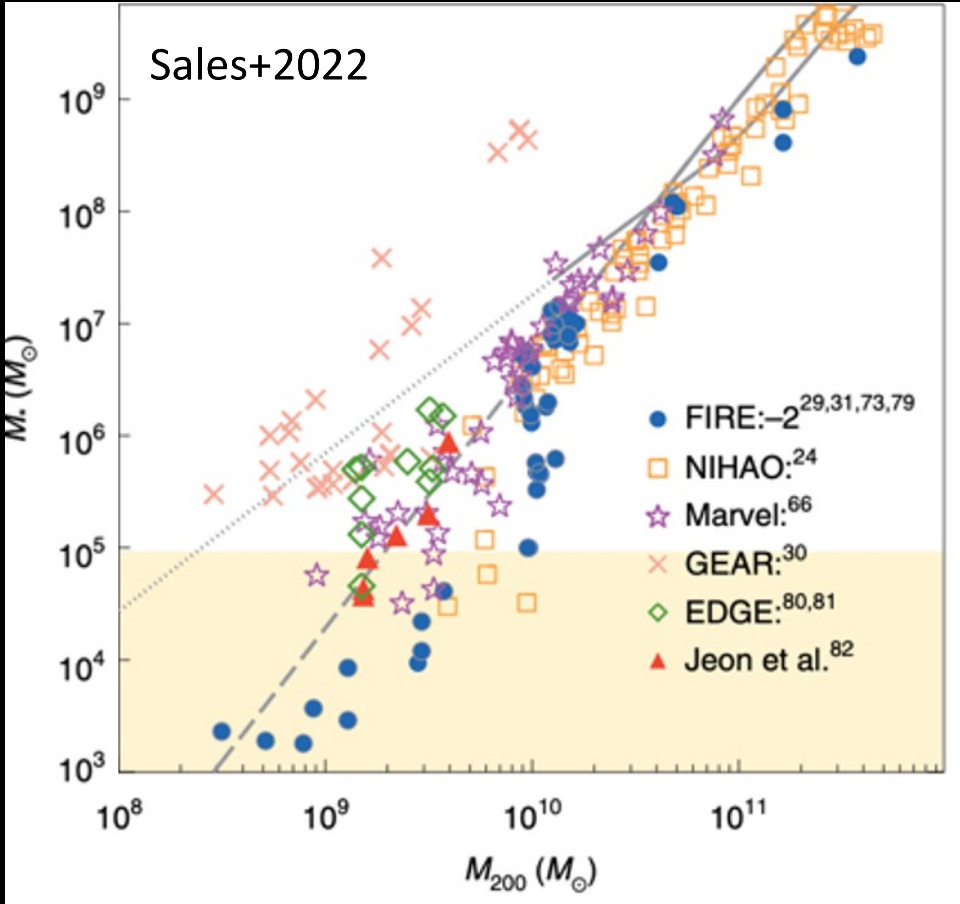
Adamo+24
Cosmic Gems



z=10.0

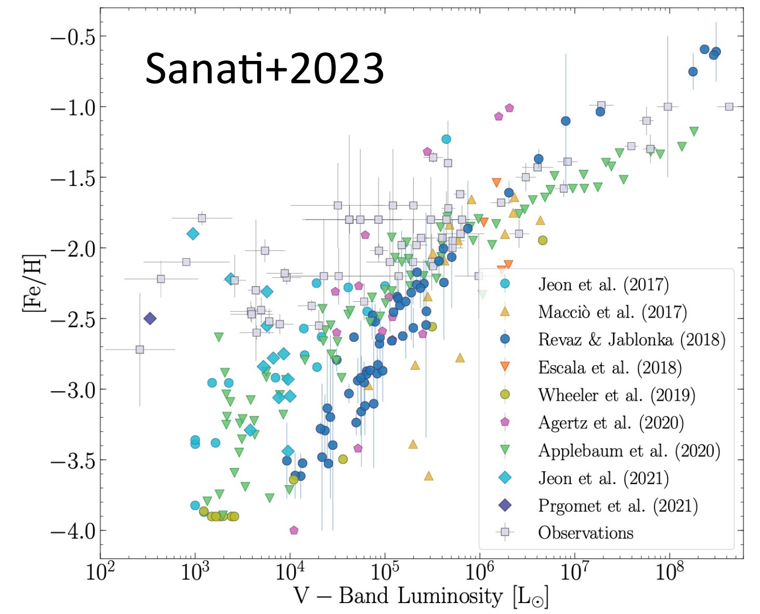
Redshift

Evolution of dwarf galaxies challenges galaxy formation simulations



Current dwarf galaxy simulations show drastic variation on scaling relations, e.g. stellar mass-halo mass relation and mass-metallicity relations.

1. **External**: histories; halo assembly histories) Consider different environments (e.g. inhomogenous reionization



Patchy reionization simulations have make promising progress (Kim+23)

2. **Internal**: Dwarf galaxies are sensitive to the choice of baryonic physics, such as cooling/heating, star formation, feedback models.

RIGEL: Realistic Ism modeling in Galaxy Evolution and Lifecycles

Physical ingredients:

Gravity: BH tree, Hydrodynamics: Arepo (Springel 10)

Radiative transfer: M1 method (Kannan+19, **Deng, LH+24a**)

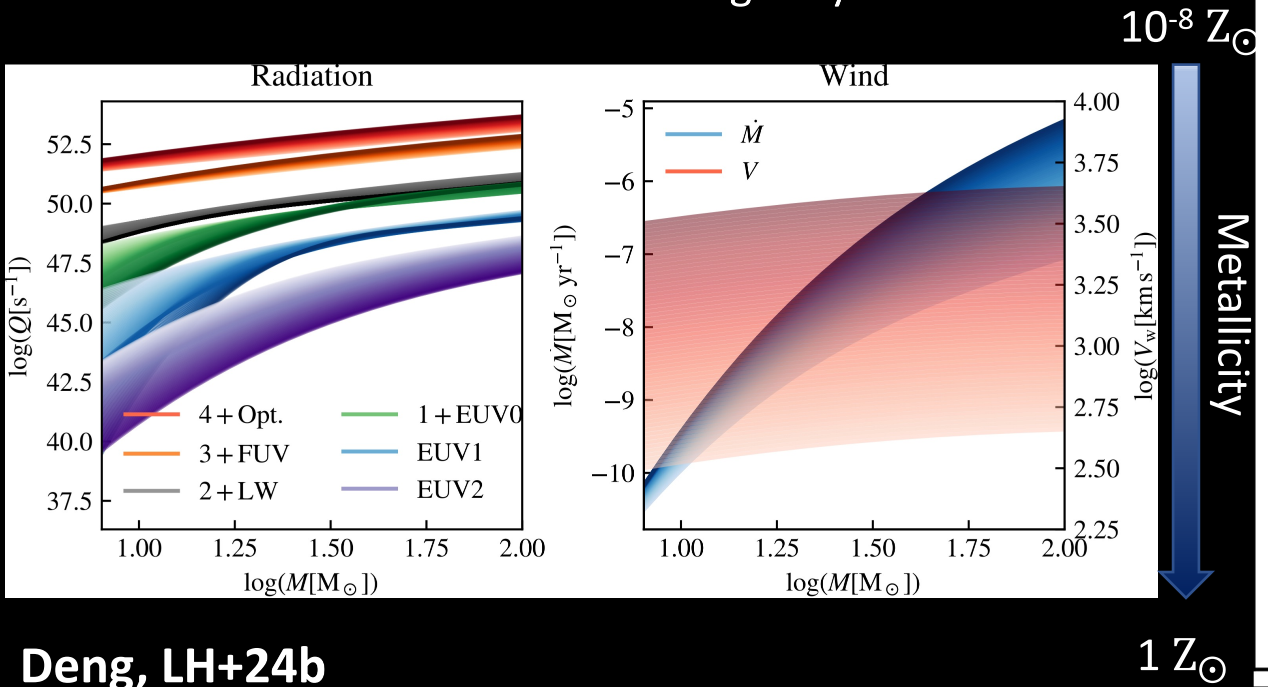
Non-equilibrium H, He chemistry (Kannan+19)

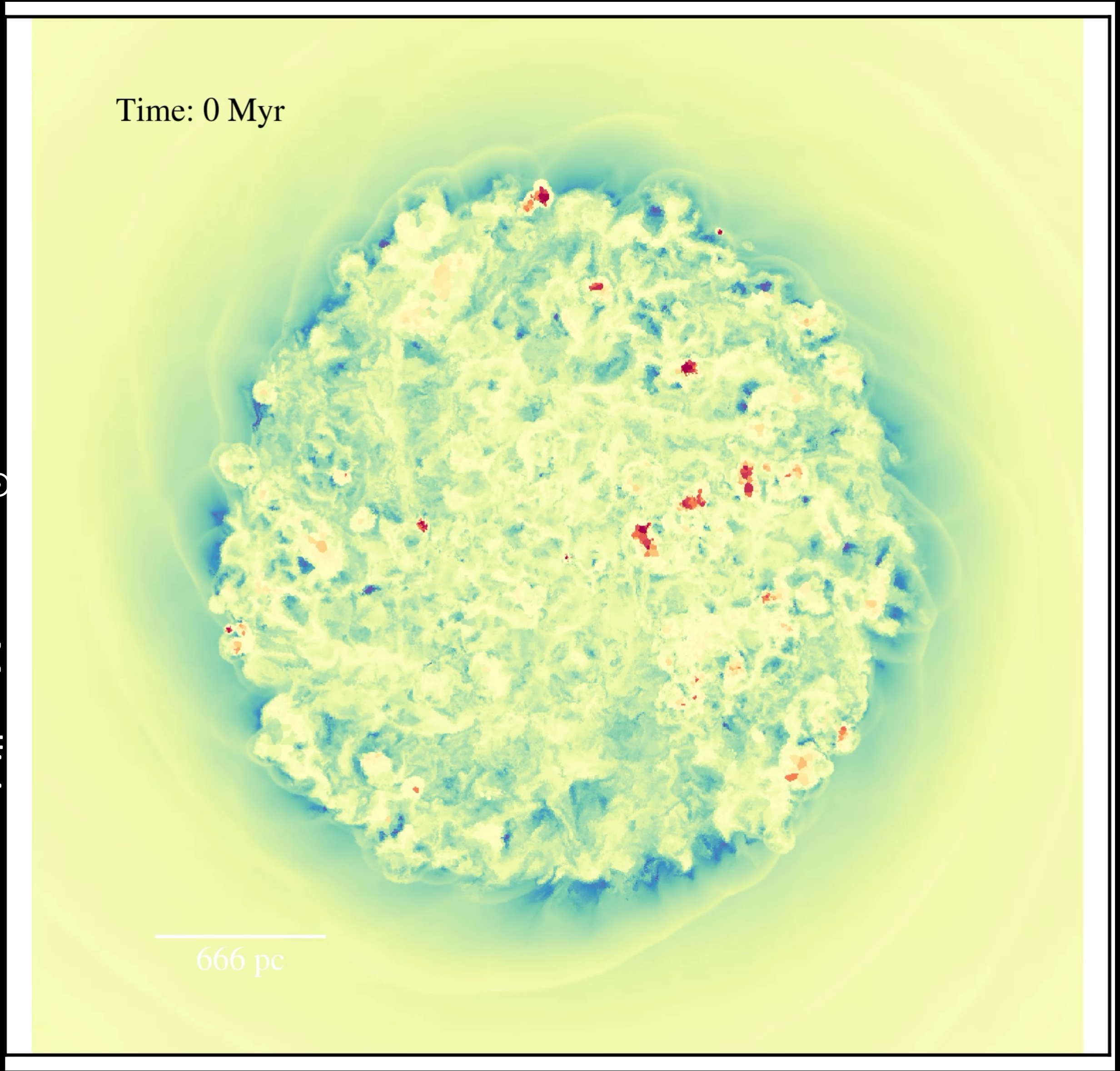
Equilibrium C/O chemistry and Cooling (**Deng, LH+24a**)

Star formation: resolving individual massive stars

Stellar feedback model: from individual massive stars based on their masses and metallicity.

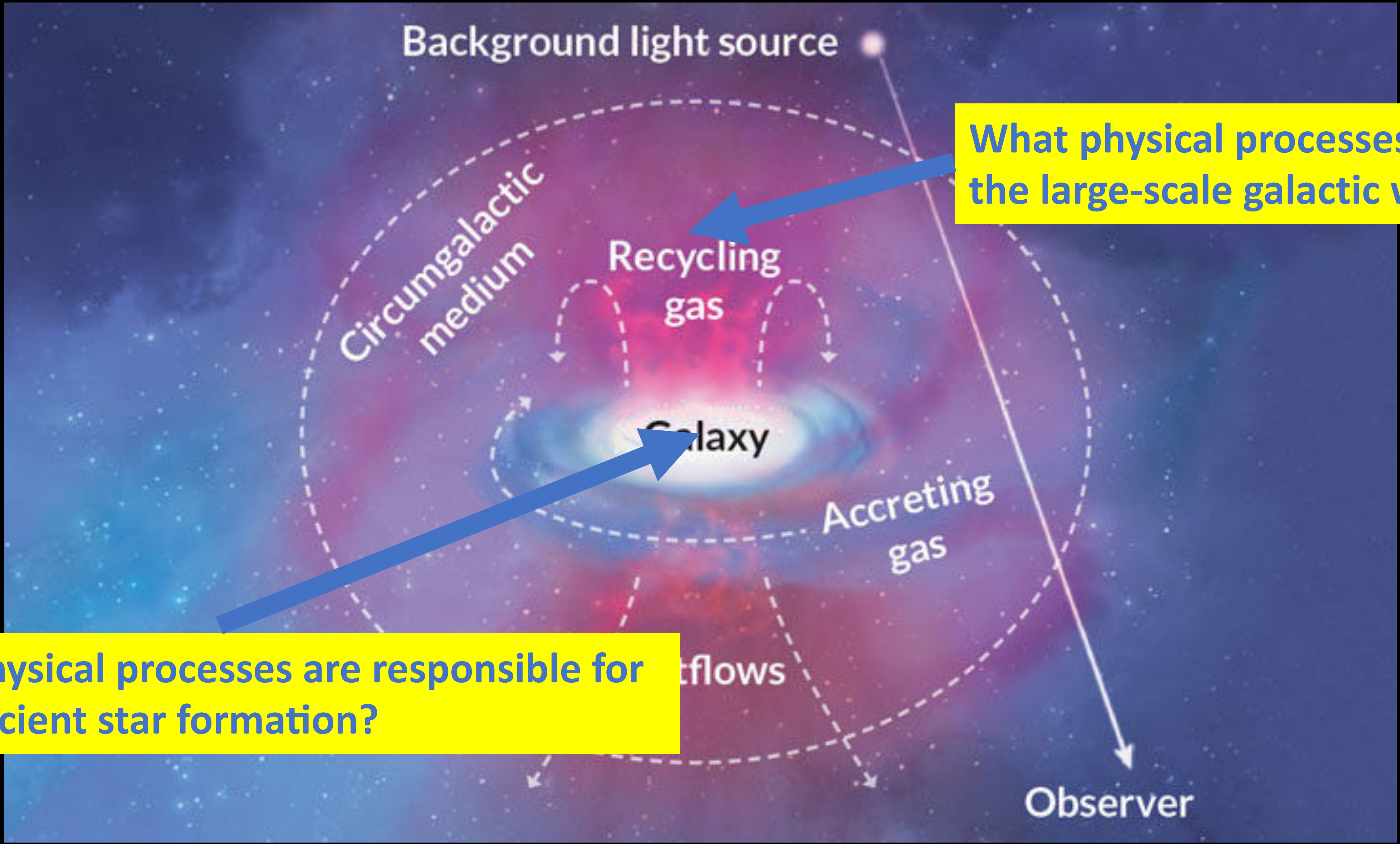
Resolution: 1 Msun resolution in galaxy simulations.





Deng, LH+24b

Baryonic cycle in and around dwarf galaxies



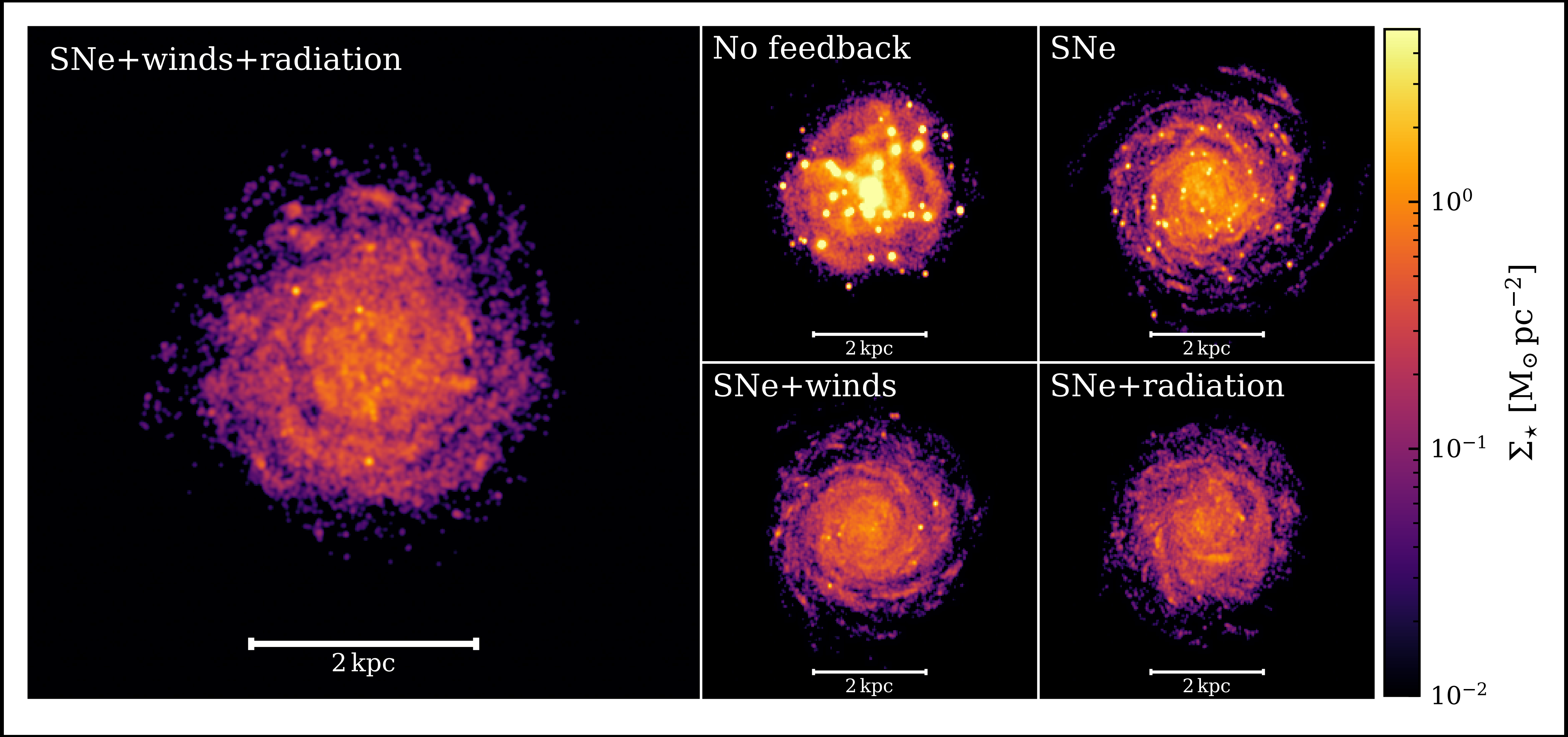
What physical processes drive the large-scale galactic winds?

Which physical processes are responsible for the inefficient star formation?

Tumlinson et al. 2017

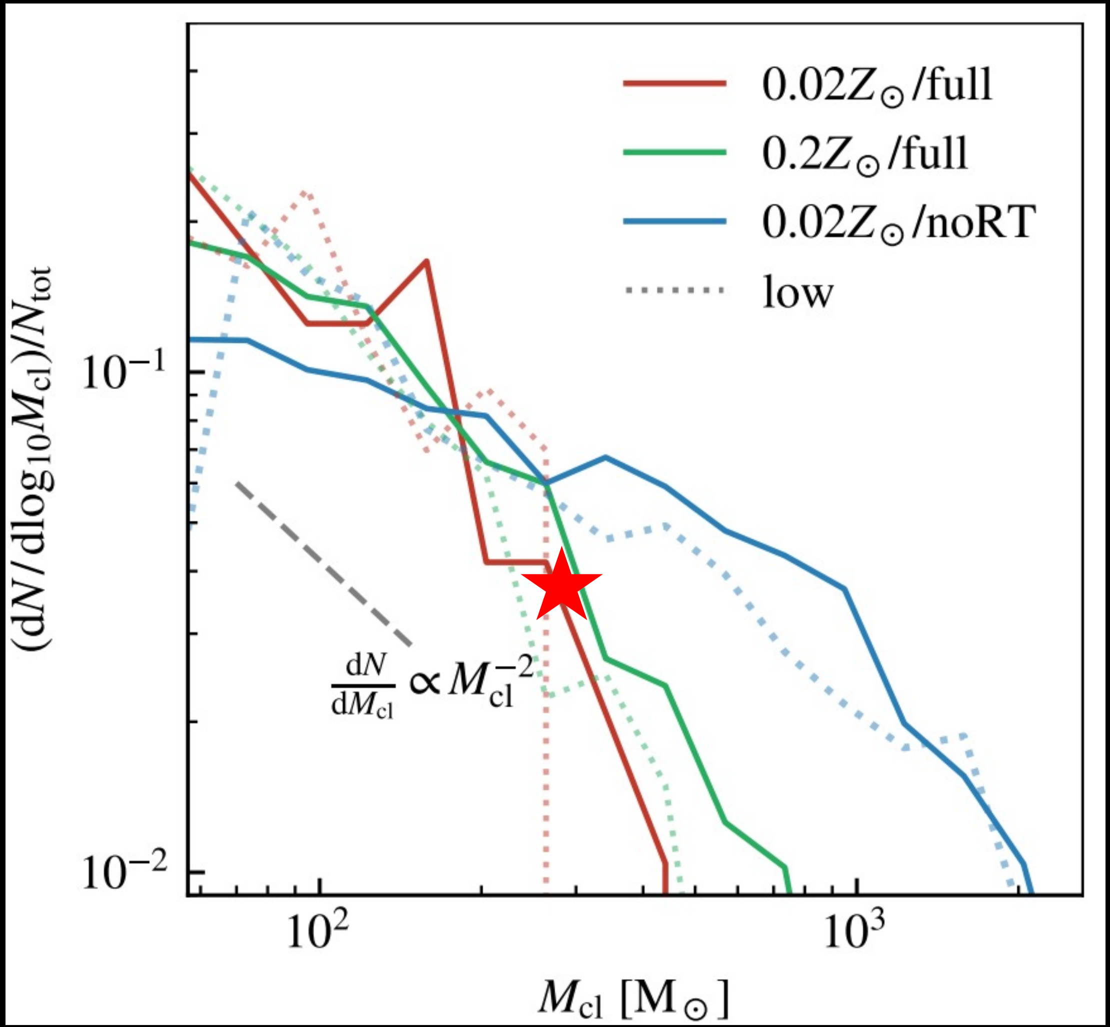

Wolf–Lundmark–Melotte (WLM)
a lonely galaxy in the local Universe

Cluster formation efficiency is significantly reduced with radiation feedback



Andersson, **w/LH+23, Deng, LH+24b**

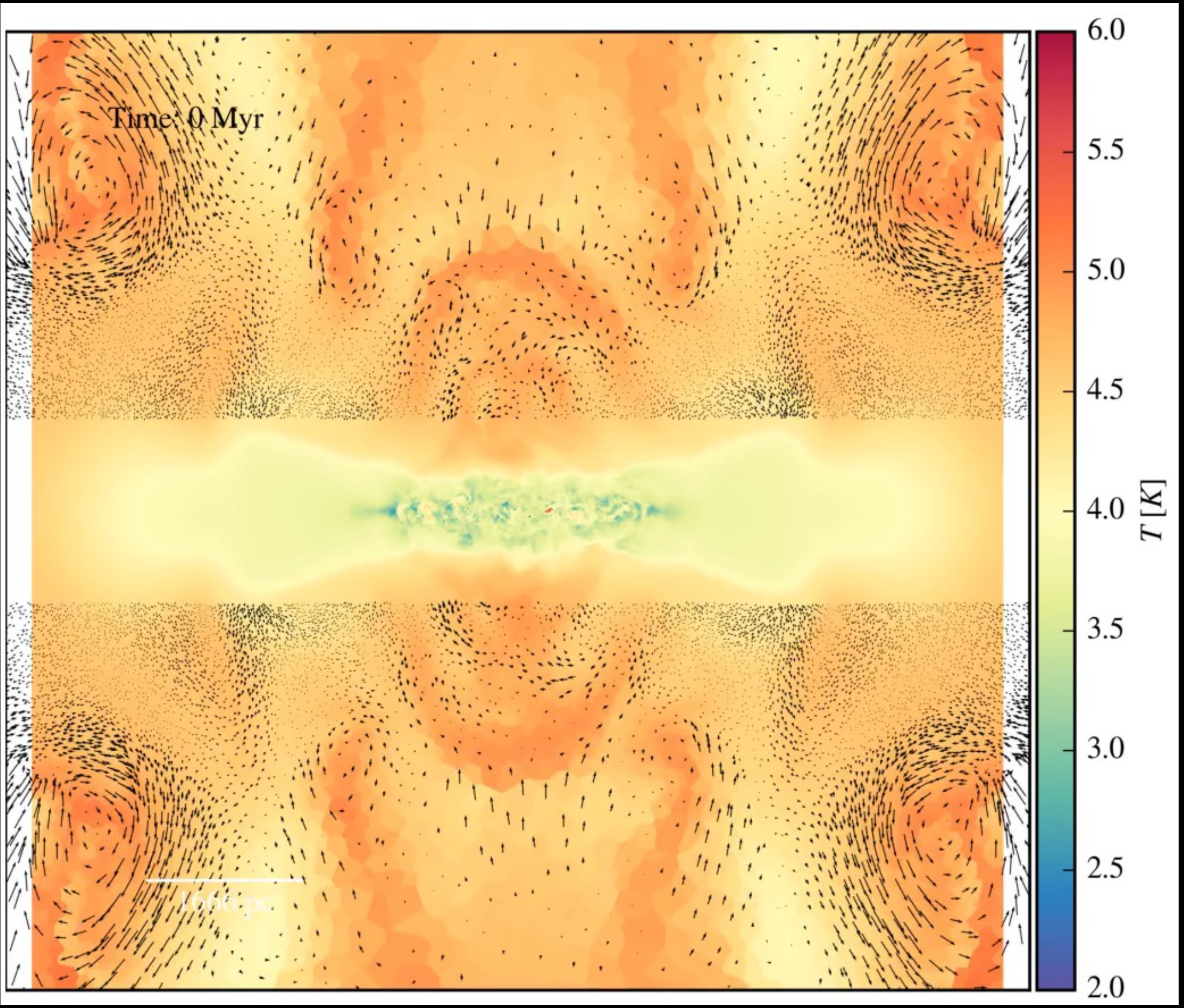
Radiation feedback matters on small-scale cluster formation

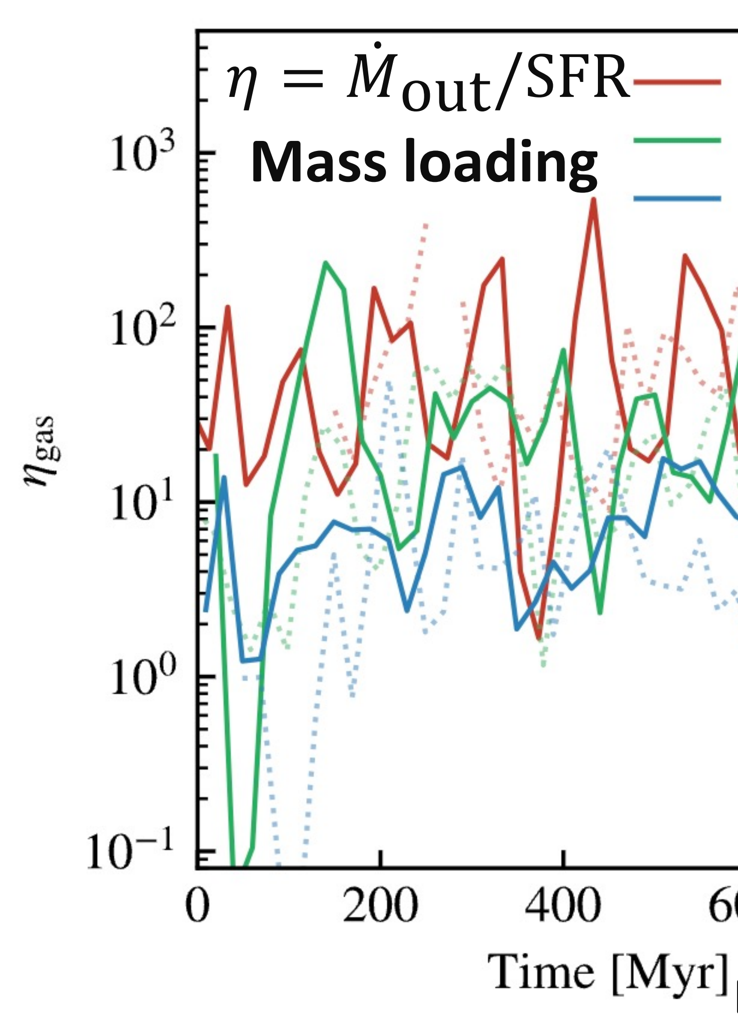


- SN-only feedback cannot destroy GMCs because it has to wait until the first massive star to explodes.
- Radiation feedback, especially photo-ionization, destroys GMCs early, reduces the mass of the star clusters emerged from GMCs.
- Radiation feedback also helps to reproduce the observed slope of the cluster initial mass function.

Deng, LH+24b

Isolate dwarf galaxy: Outflow and mass loading





Deng, LH+24b

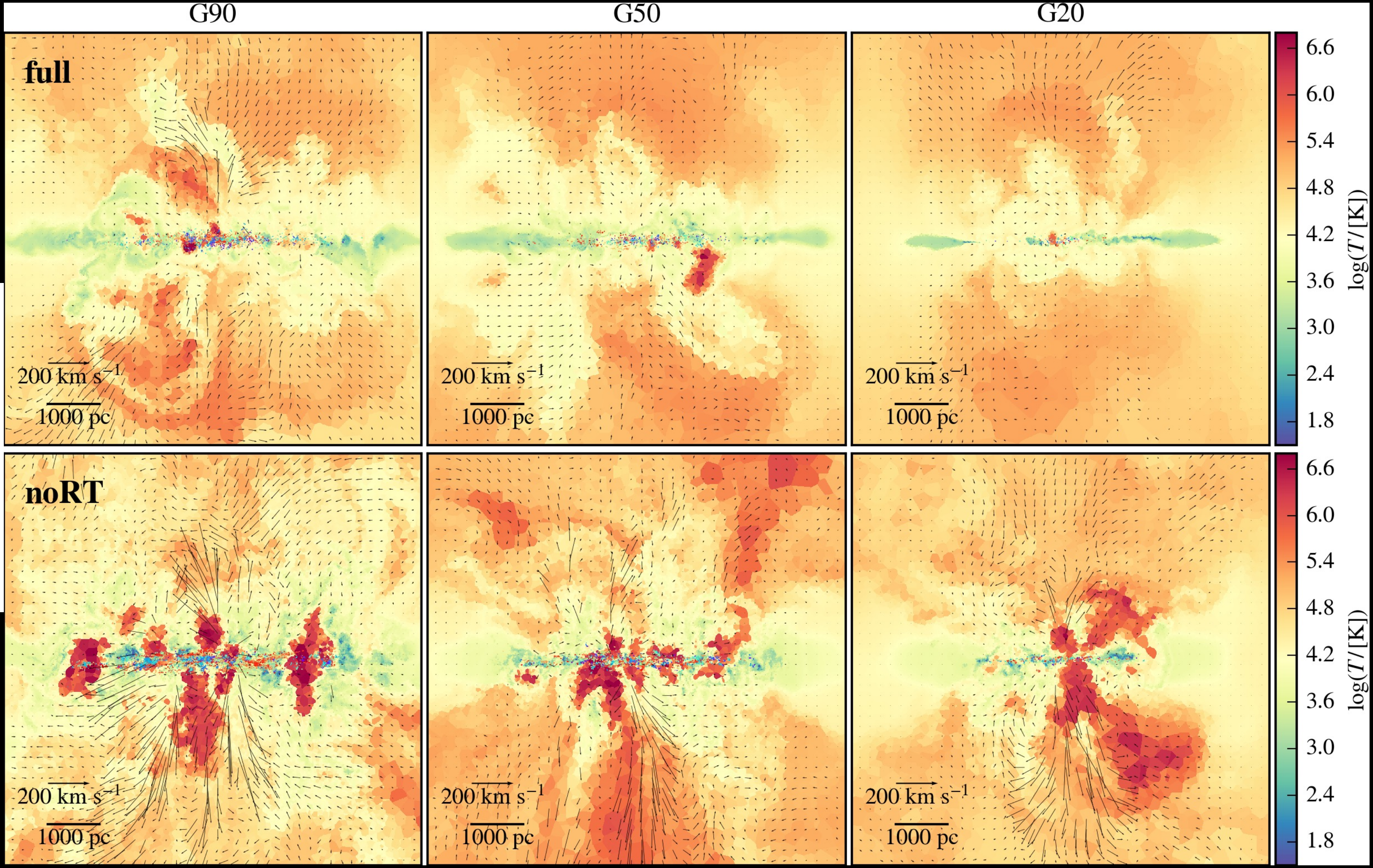
Radiation feedback enhances the mass/energy loading of the galactic winds: 1) higher feedback energy output due to photo-ionization and radiative pressure; 2) reduce the SN explosion density by pre-processing the ambient medium.

Outflow vs gas fraction: New simulation suite

Fixed baryon & DM mass
Gas : Star

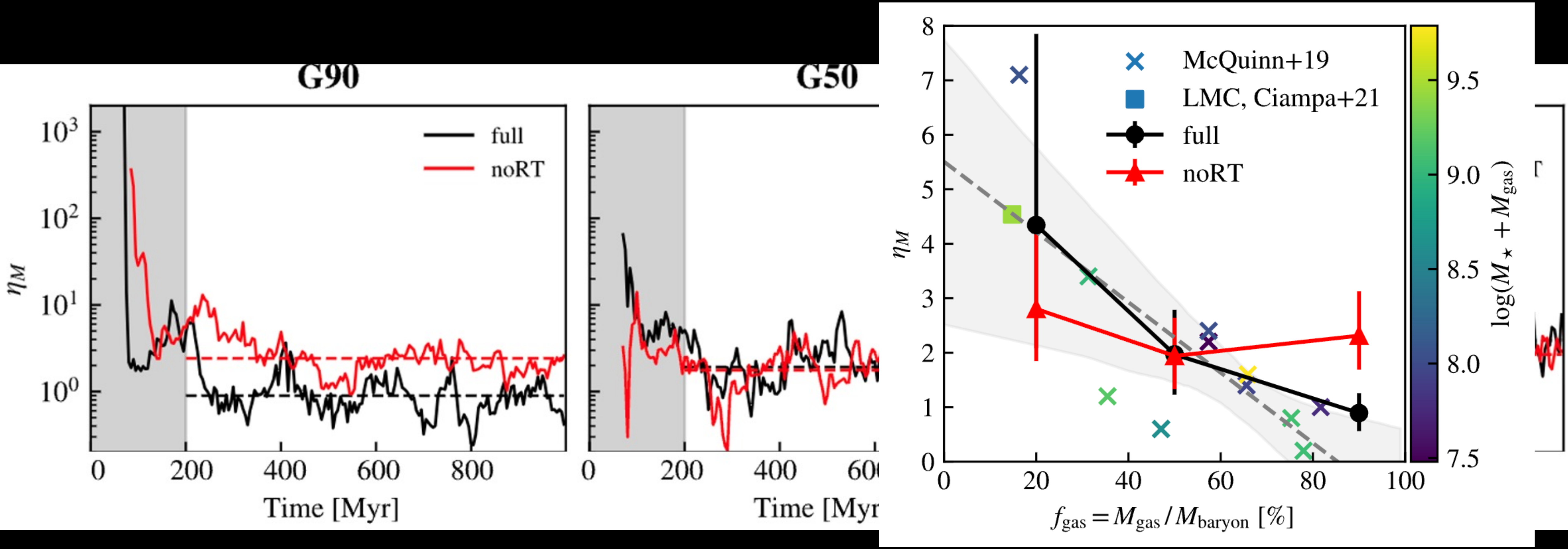
G90 9 : 1
G50 1 : 1
G20 1 : 4

Properties	Value (G20/G50/G90)
Virial mass ($M_{\rm vir}$)	1×10^{10} M$_\odot$
Concentration factor (c)	15
Spin parameter (λ)	0.04
Gas mass ($M_{\rm g,init}$)	$\{1.6, 4.0, 7.2\} \times 10^7$ M$_\odot$
Disc mass ($M_{\star,\rm init}$)	$\{6.4, 4.0, 0.8\} \times 10^7$ M$_\odot$
Gas scalelength	1100 pc
Disc scalelength	1100 pc
Scaleheight	700 pc
DM mass resolution ($m_{\rm DM}$)	1×10^3 M$_\odot$
gas mass resolution ($m_{\rm gas}$)	10 M$_\odot$
DM softening length	29 pc
Max. baryon softening length	0.3 pc
Min. baryon softening length	0.004 pc



Li et al. to be submitted.

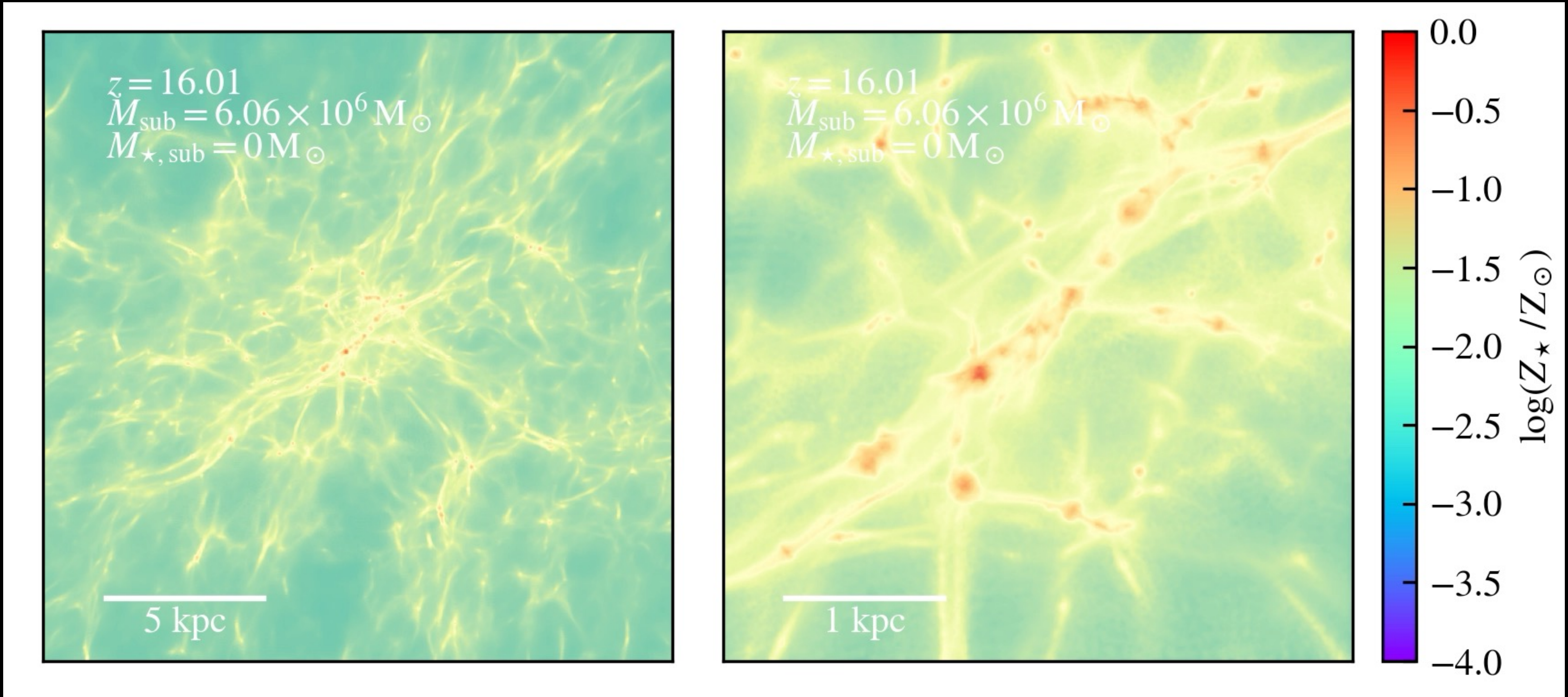
Loading factors of galactic winds are determined by the non-linear combination of early and SNe feedback from clustered star formation



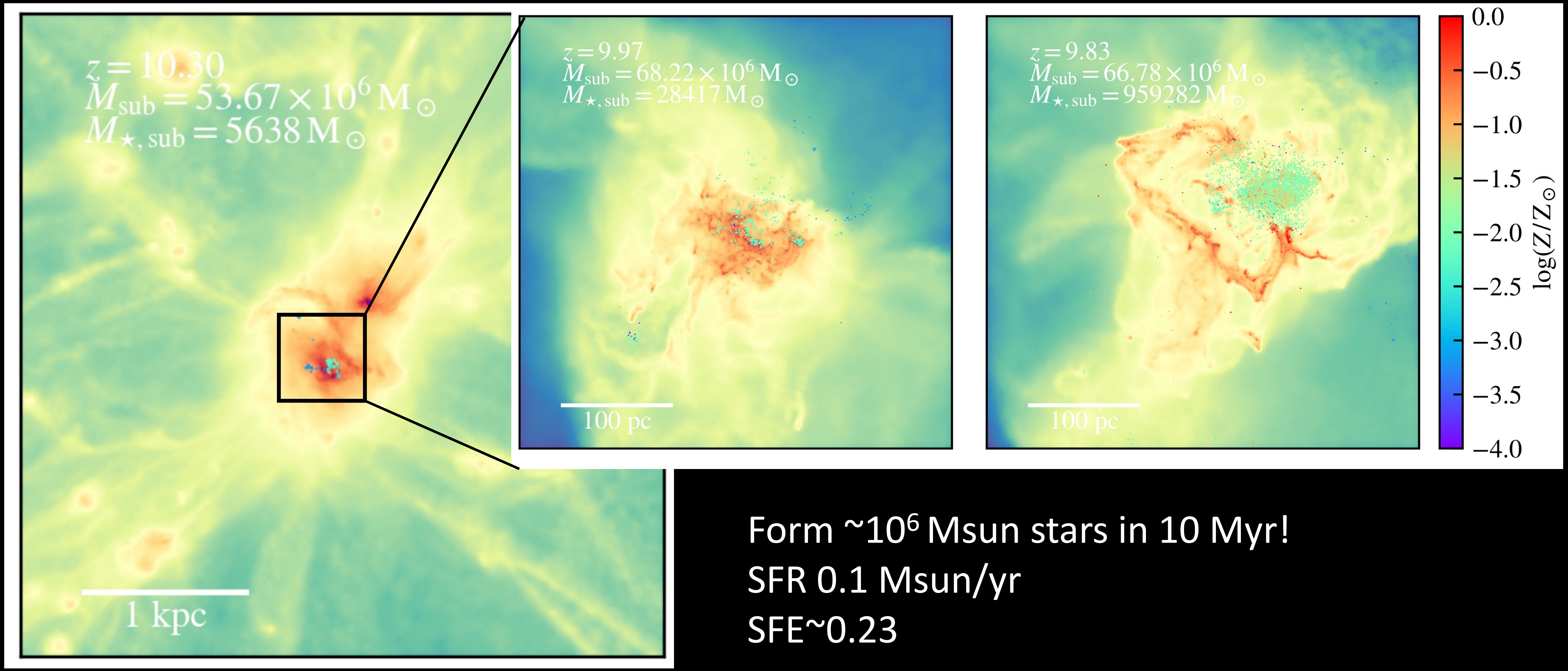
Simulations and observations:
Loading factor decrease with gas fraction

Li et al. to be submitted; Otero, LH+in prep.

Toward full cosmological simulations of dwarf galaxies with RIGEL



Starburst produced by a major merger at z=10



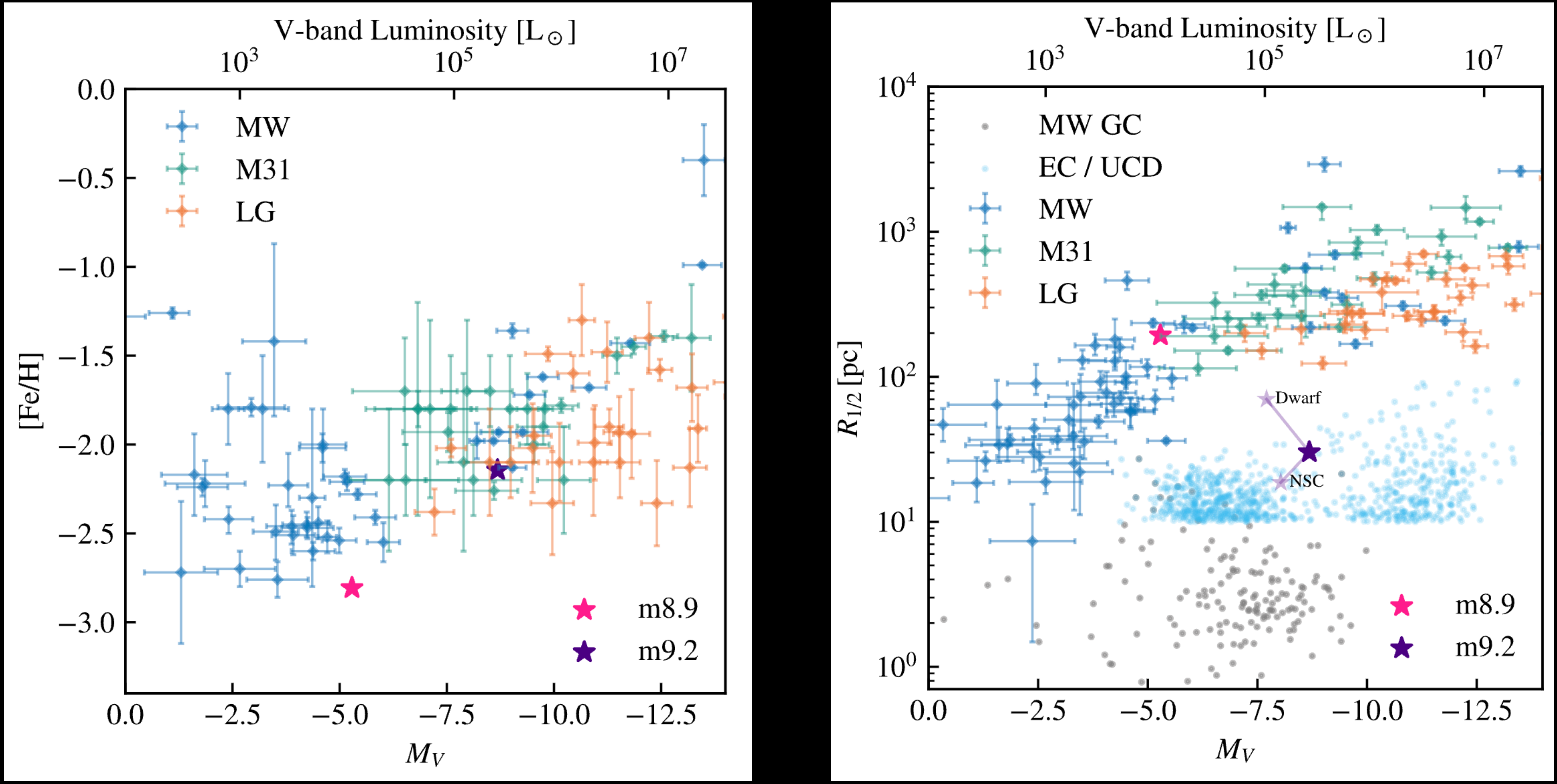
Form ~10^6 Msun stars in 10 Myr!

SFR 0.1 Msun/yr

SFE~0.23

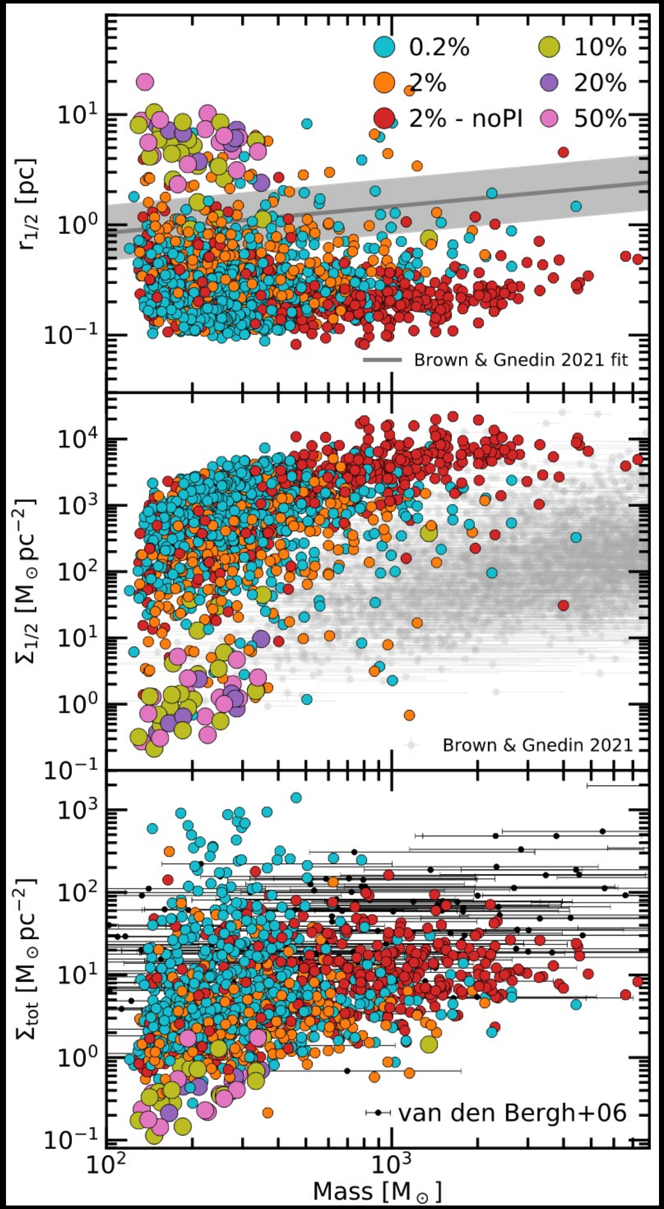
Consistent with observations of Cosmic Gems (Messa+25, Vanzella+25): 1) enter poststarburst phase after cluster formation 2) a possible existence of low-mass cutoff of the CIMF.

Simulated ultra compact dwarf in isolation at z=0

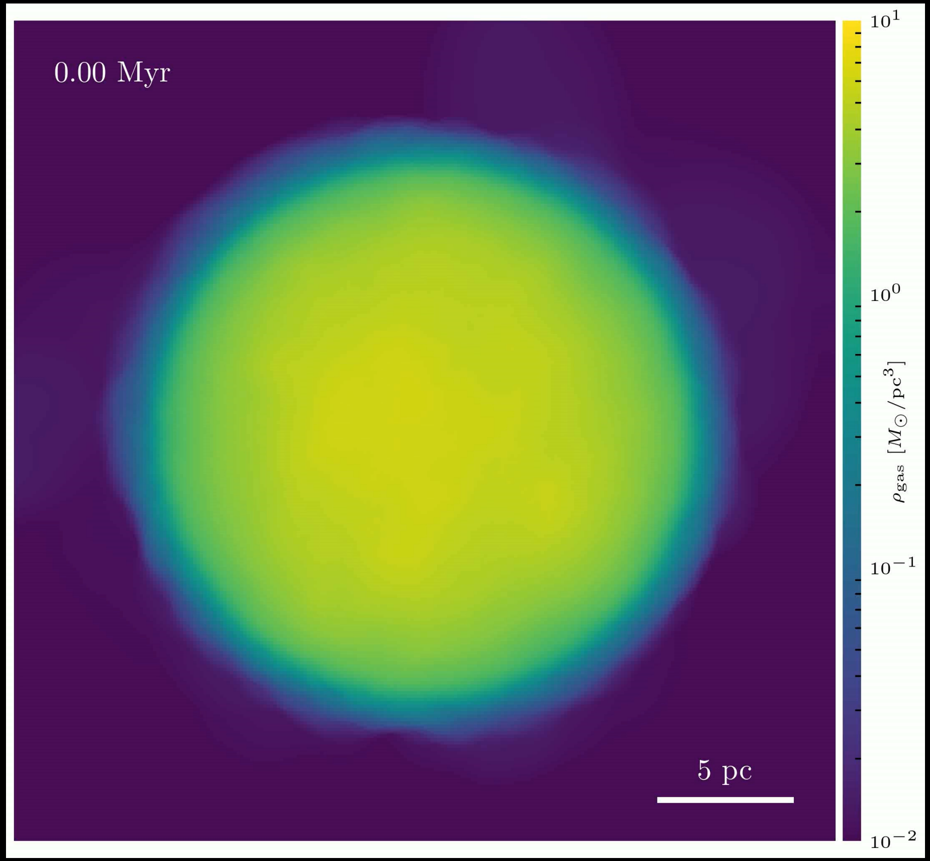


Deng et al. in prep.

Challenge: do simulations have any predictive power on the cluster mass-size relation?



Hislop+22



Bridging scales: connecting galaxy formation and N-body dynamics!

Arepo+Petar+RIGEL
Kong et al. in prep.

Summary

- Radiative feedback affects the properties of small-scale star-forming regions. Without radiative feedback, more massive star clusters are formed, and the lifetime of giant molecular clouds are longer than observational constraint.
- Galactic winds are triggered by breakout of supperbubbles produced by not only supernovae (SNe) but also early feedback such as radiation. The mass loading of the winds per stellar mass is a time and spatial variable. The loading factor depends strongly on the non-linear combination of early and SNe feedback.
- Simulations can get large-scale loading factor right only if they are able to resolve the local clustering of star formation activities.
- Gas-rich major mergers of dwarf galaxies at high-z can trigger starbursts and the formation of young massive clusters.