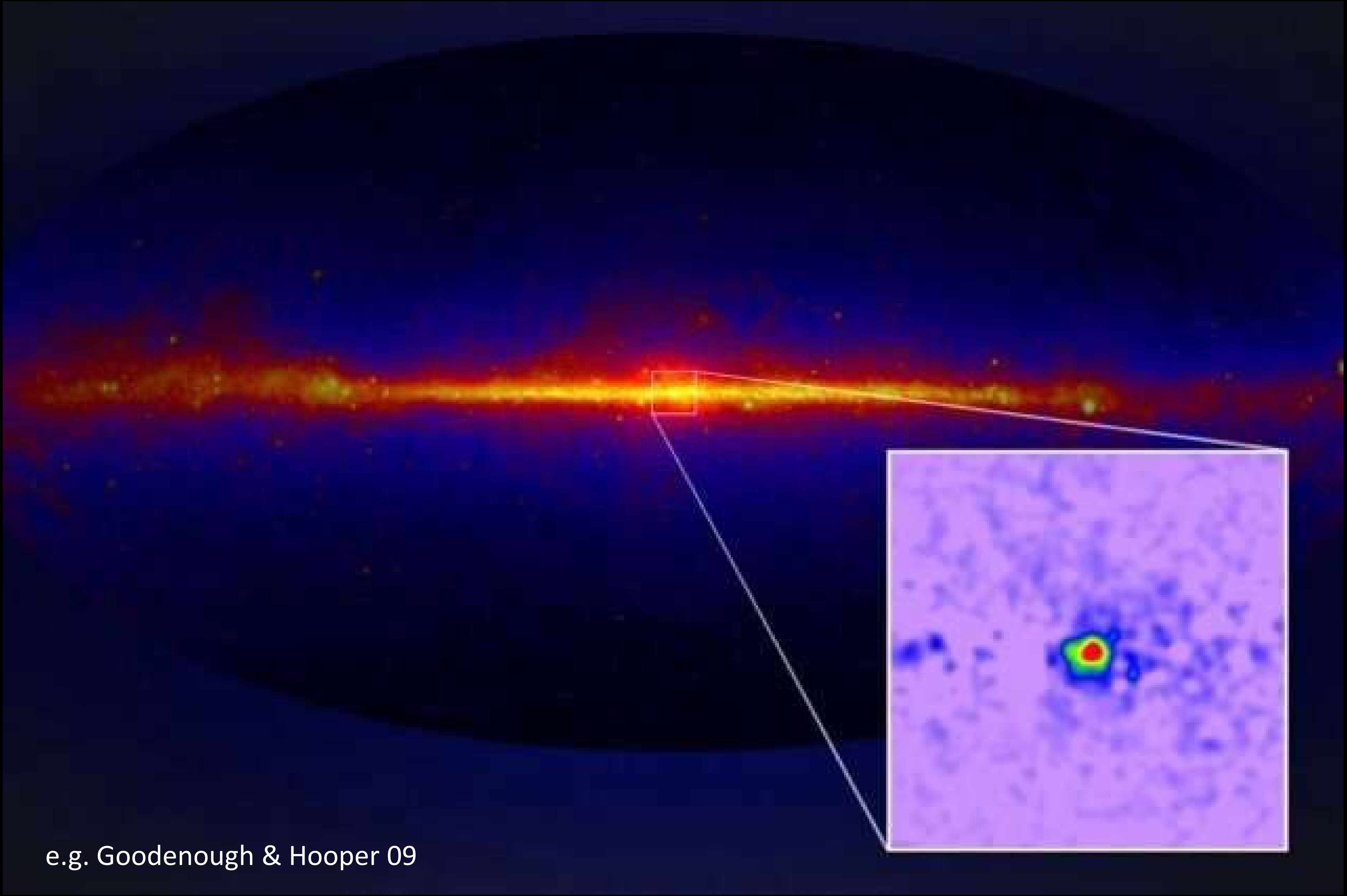
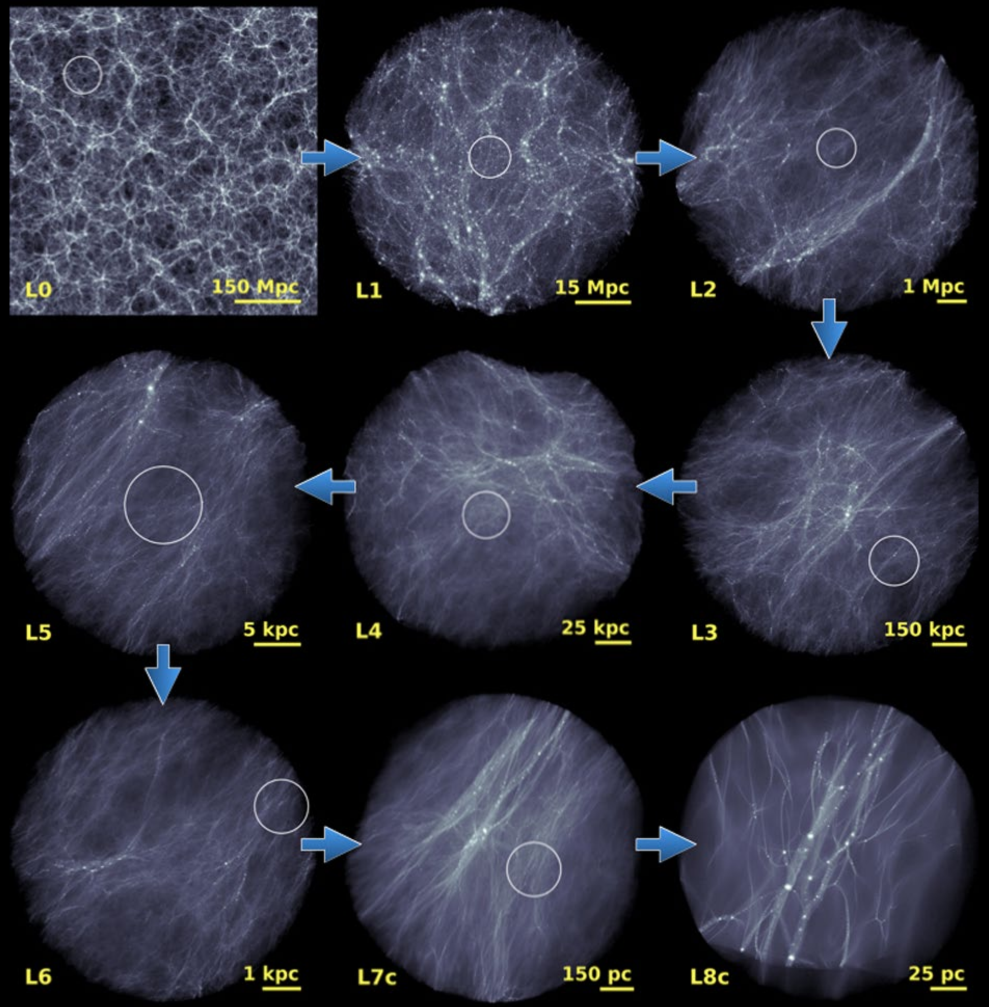
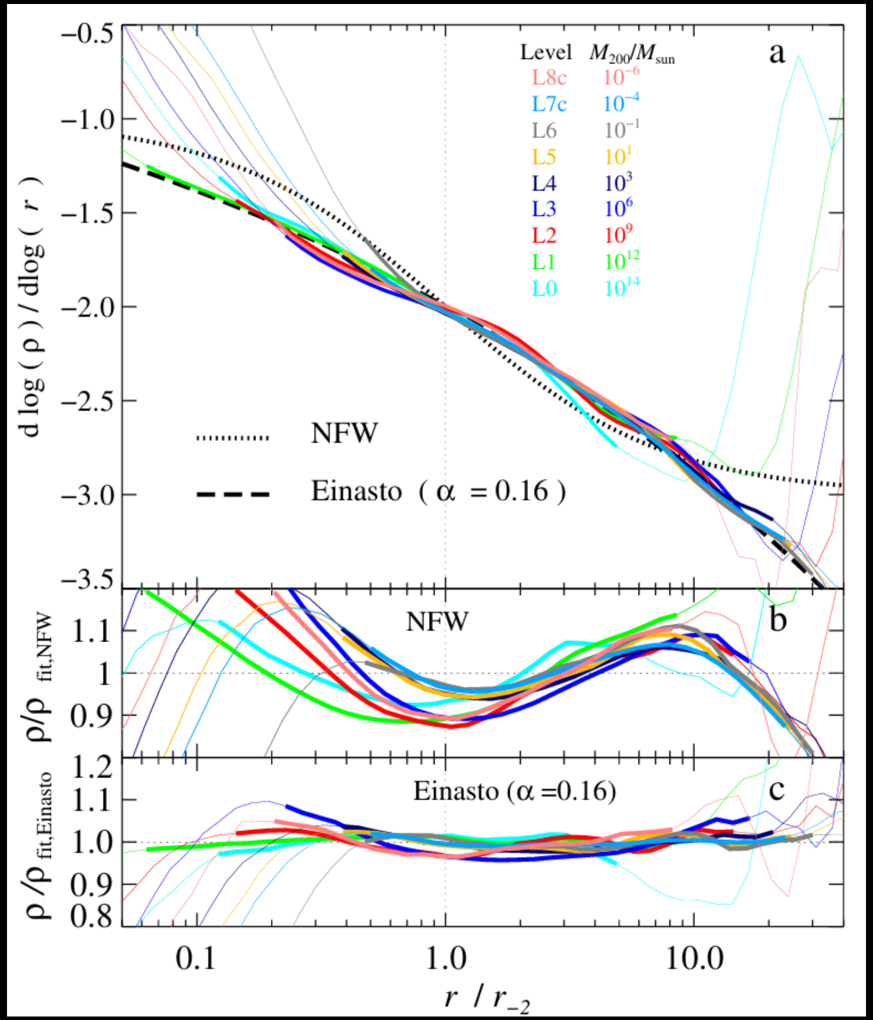


e.g. Goodenough & Hooper 09

Universal DM density profile: a consequence of collisionless self-gravitating system



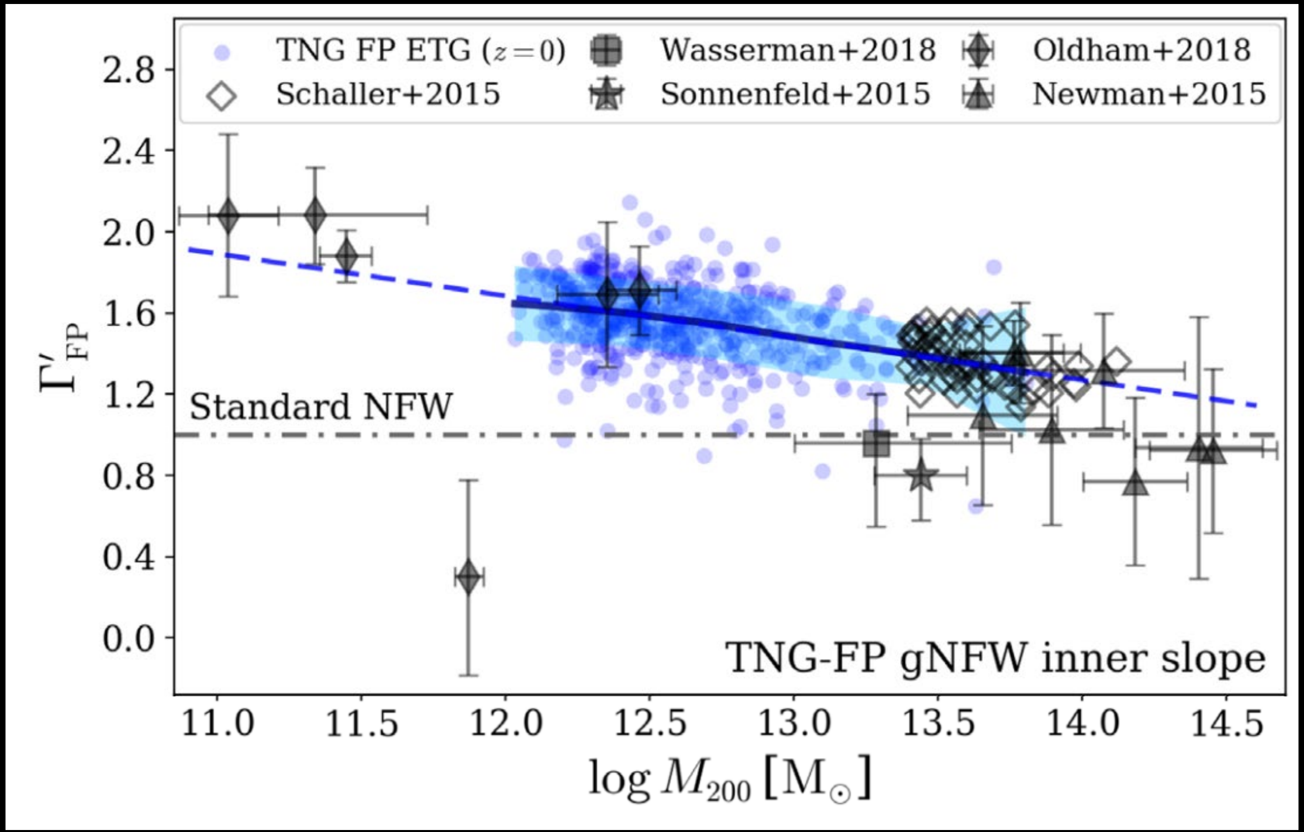


Wang et al. 2020

Not universal with baryonic physics: adiabatic contraction

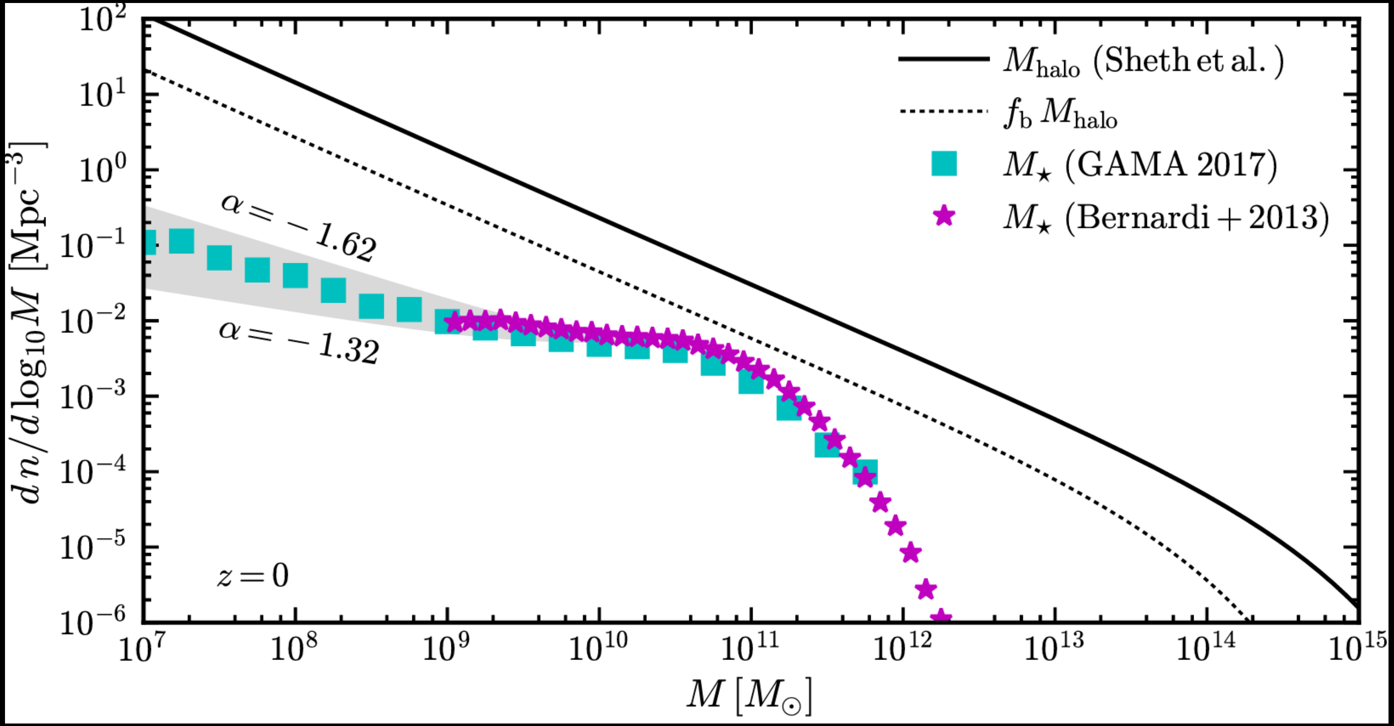
- In TNG simulations, the inner dark matter density profiles of the ETG are steeper in the full physics (FP) run than their counterparts in the dark matter-only (DMO) run.

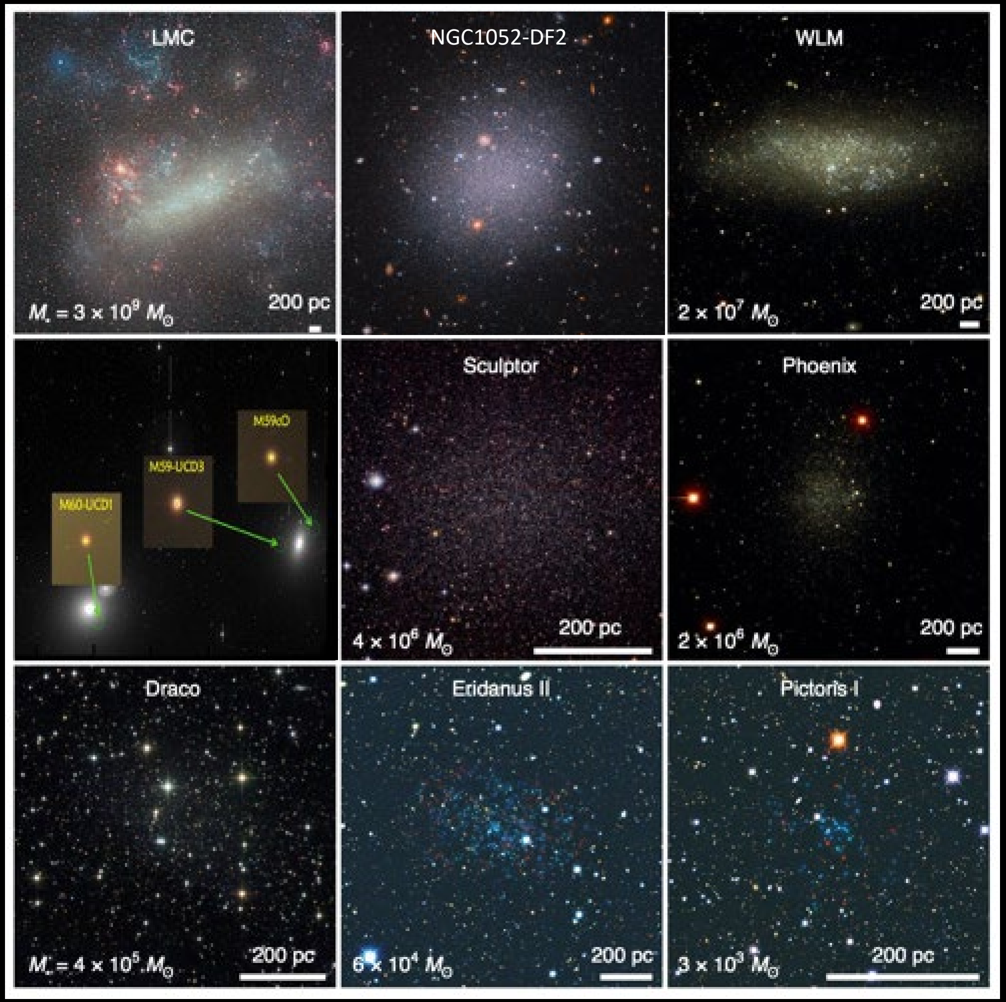
- Their inner density slopes anticorrelate (remain constant) with the halo mass in the FP (DMO) run, and anticorrelate with the halo concentration parameter c200 in both the types of runs.



Wang et al. 2020

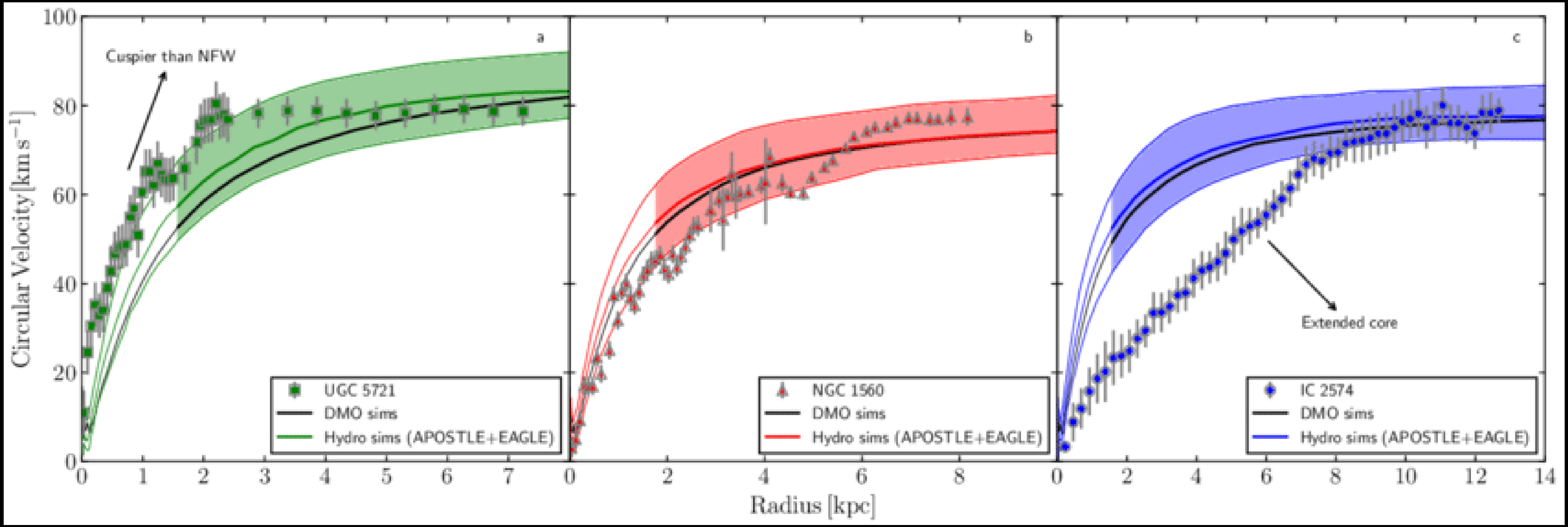
Dwarf galaxies are abundant and diverse!





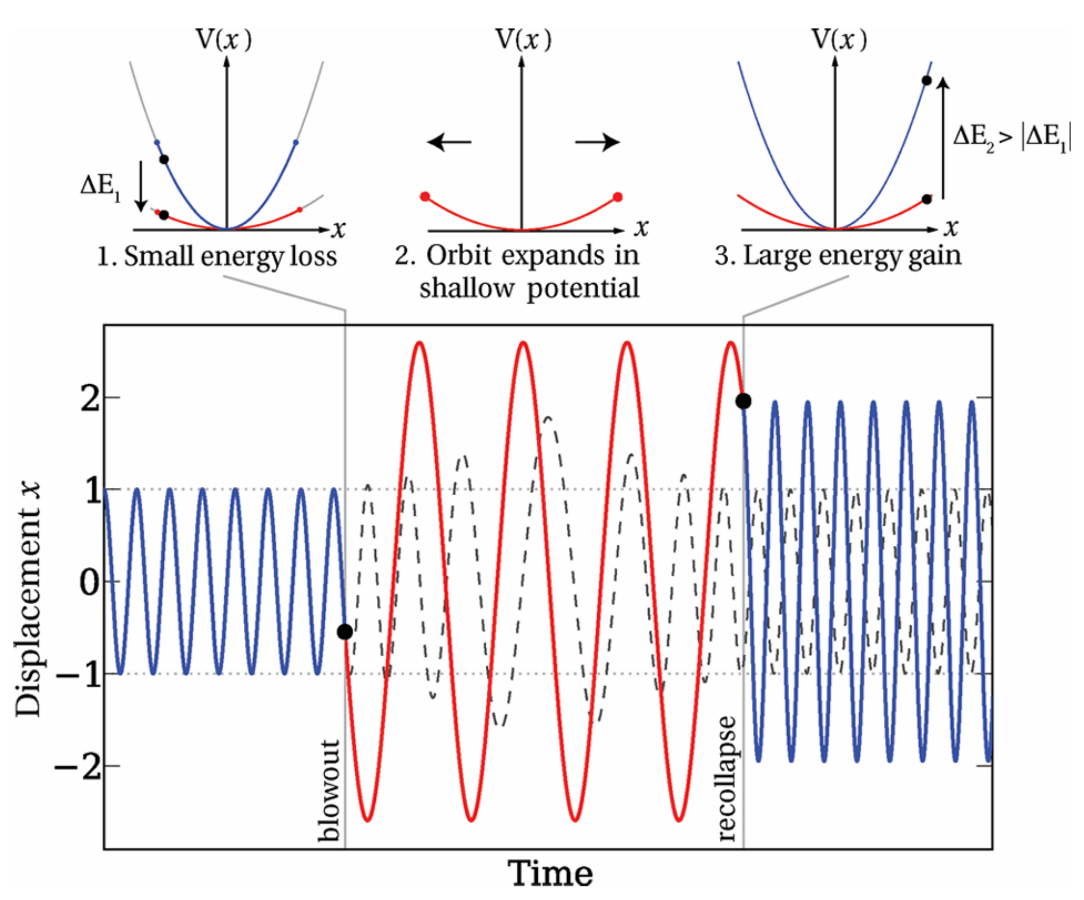
Bullock & Boylan-Kolchin 2019

Diverse rotation curves in dwarf galaxies

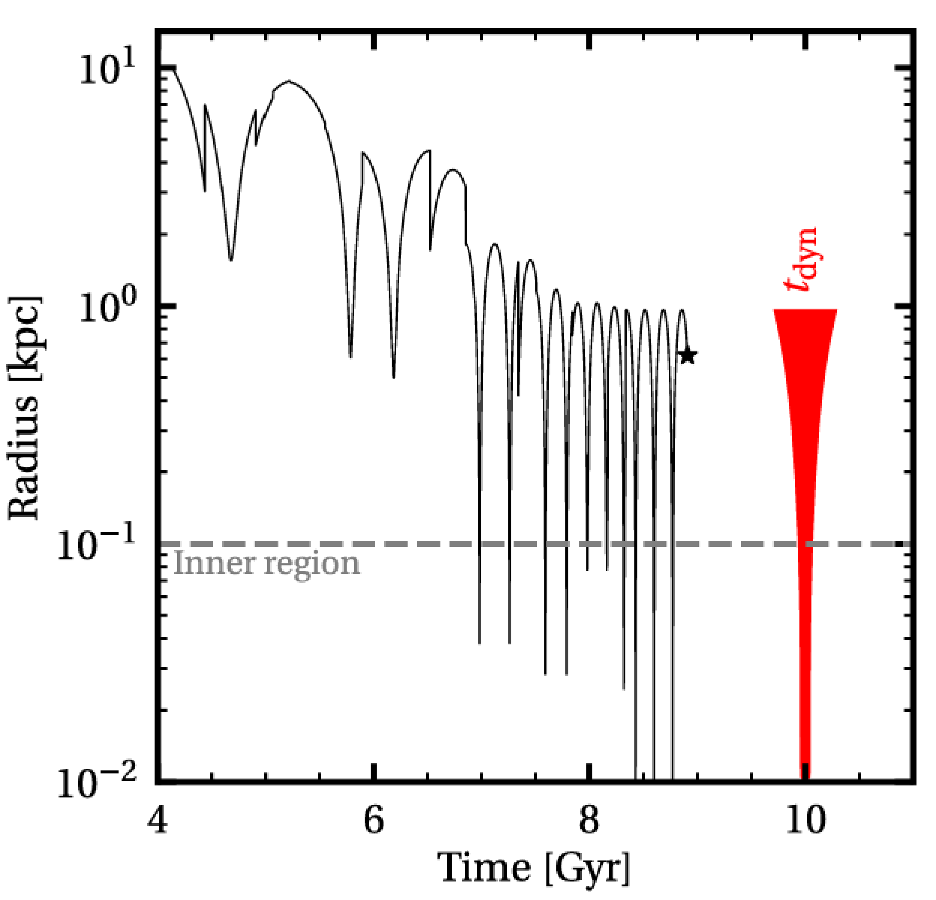


Sales et al. 2022

Not universal with baryonic physics: dynamical heating

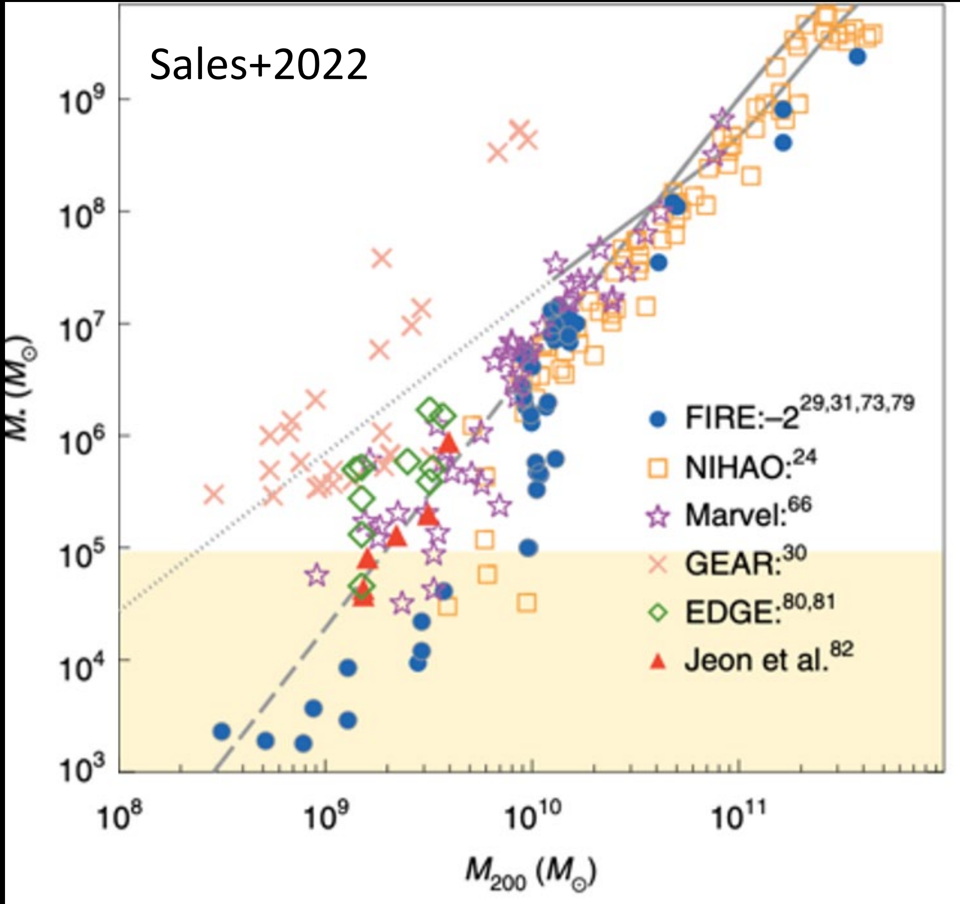


Stellar feedback from bursty star formation (Pontzen+12)



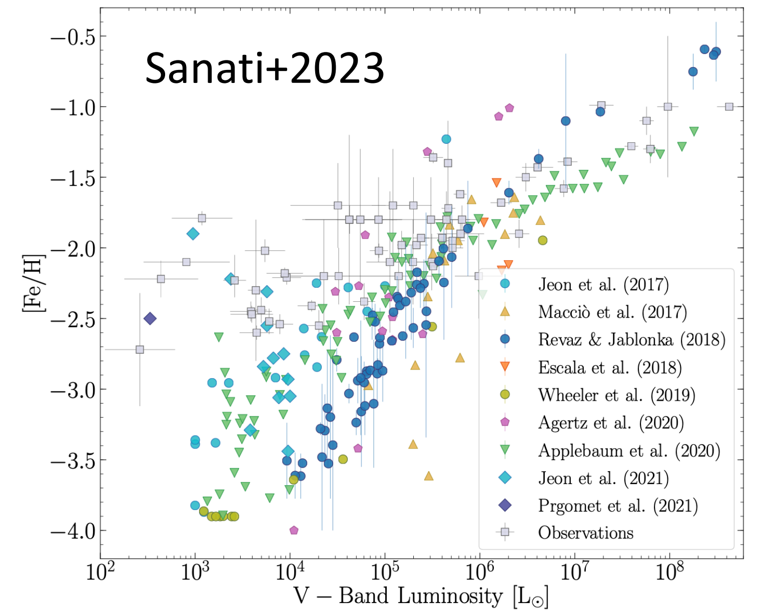
Minor mergers with radial orbit (Orkney+21)

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. **Ideal testbed of baryonic physics!**

RIGEL: Realistic Ism modeling in Galaxy Evolution and Lifecycles

Physical ingredients:

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

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

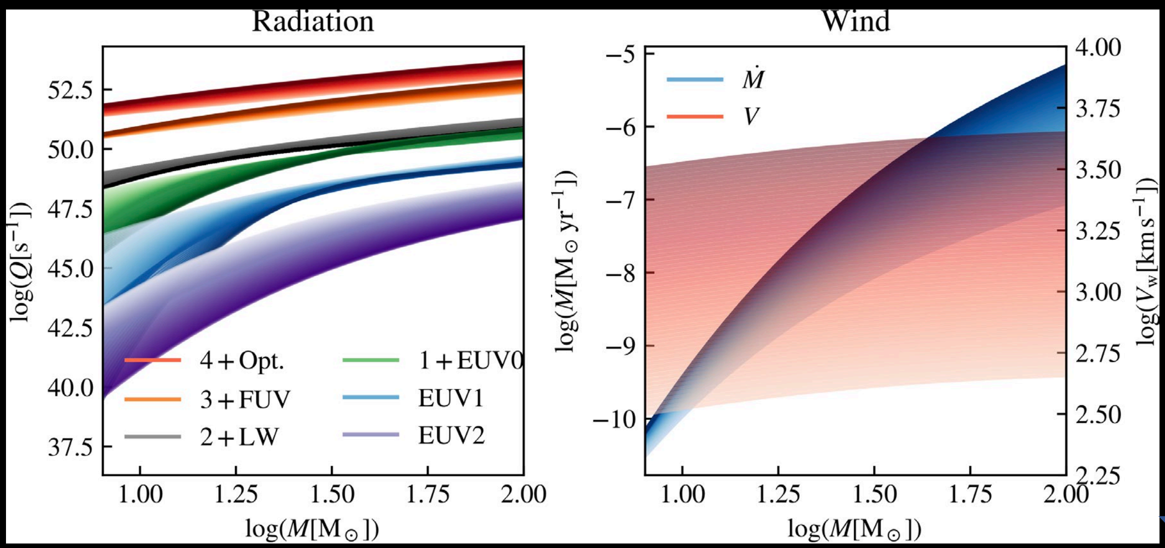
Non-equilibrium cooling, H & He chemistry (Kannan+19)

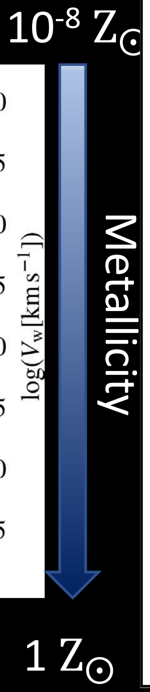
Equilibrium C/O chemistry and Cooling (**Deng, LH+24a**)

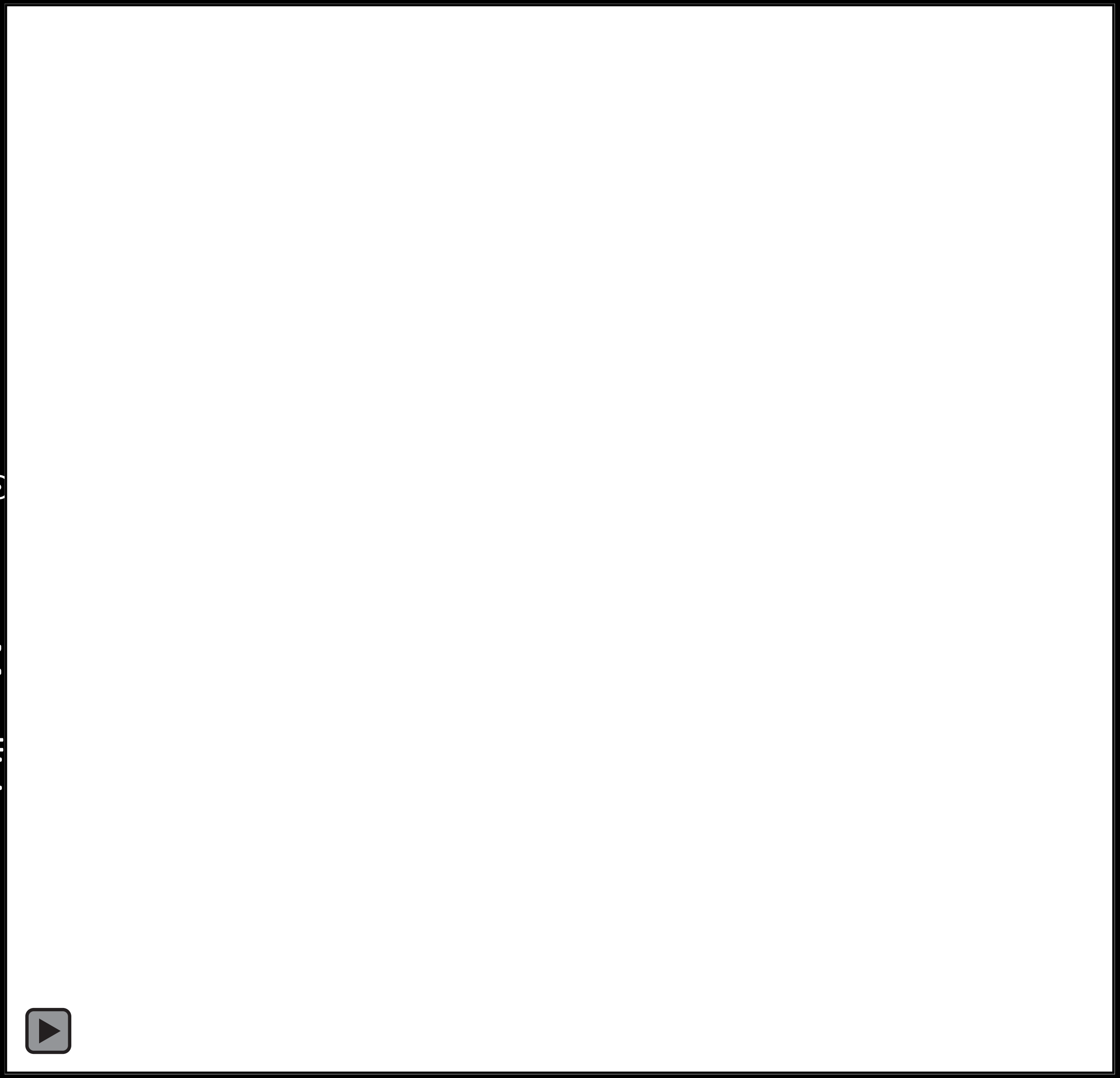
Star formation: resolving individual massive stars

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

Resolution: 1 Msun resolution in galaxy simulations.



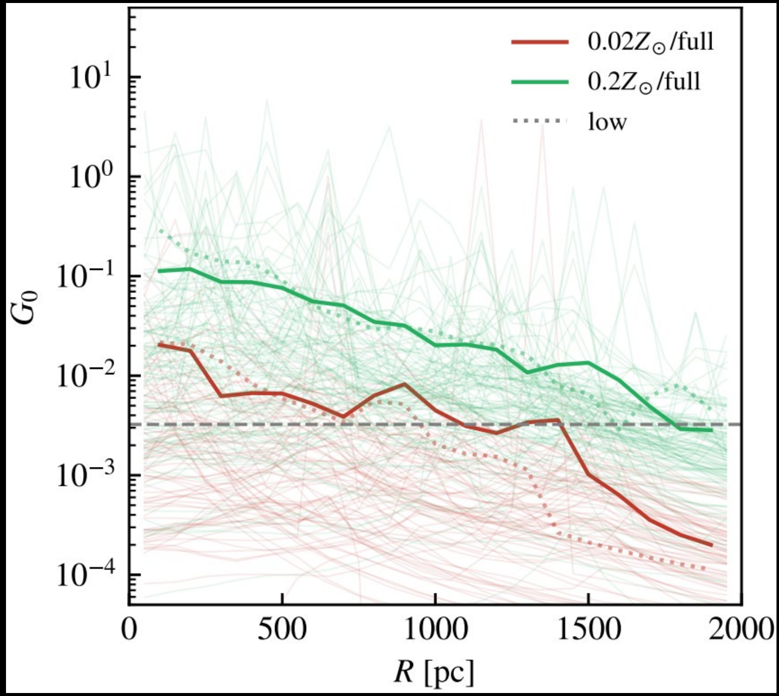




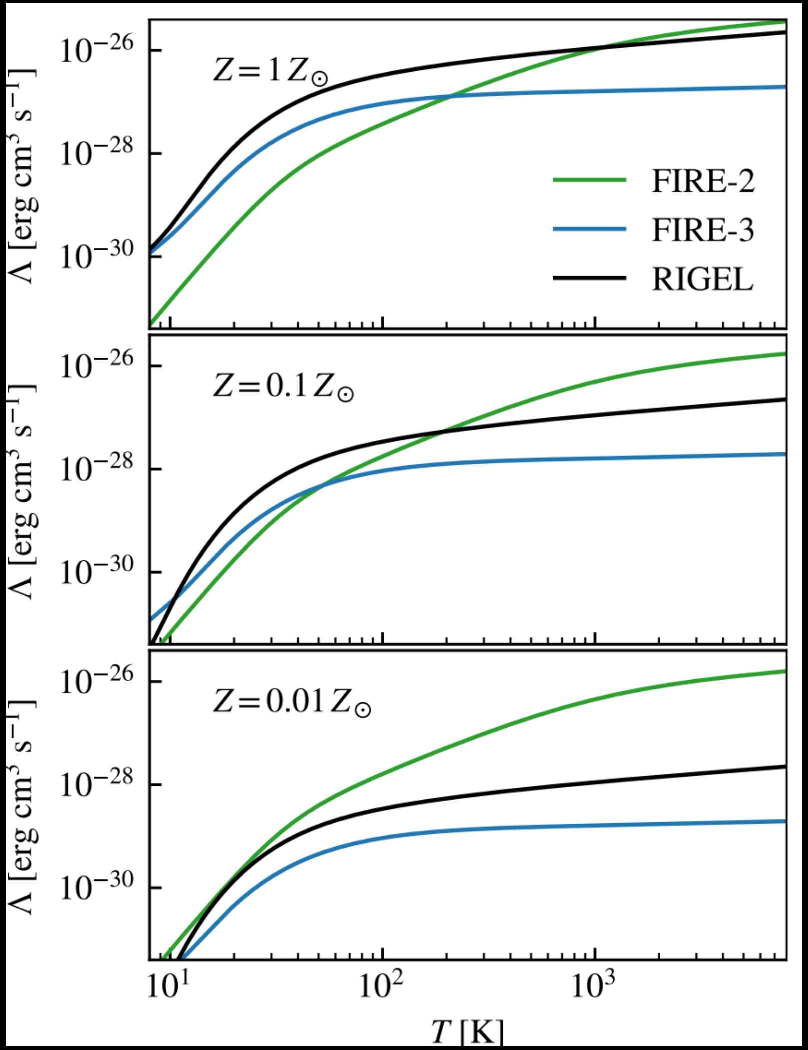
Deng, LH+24a,b

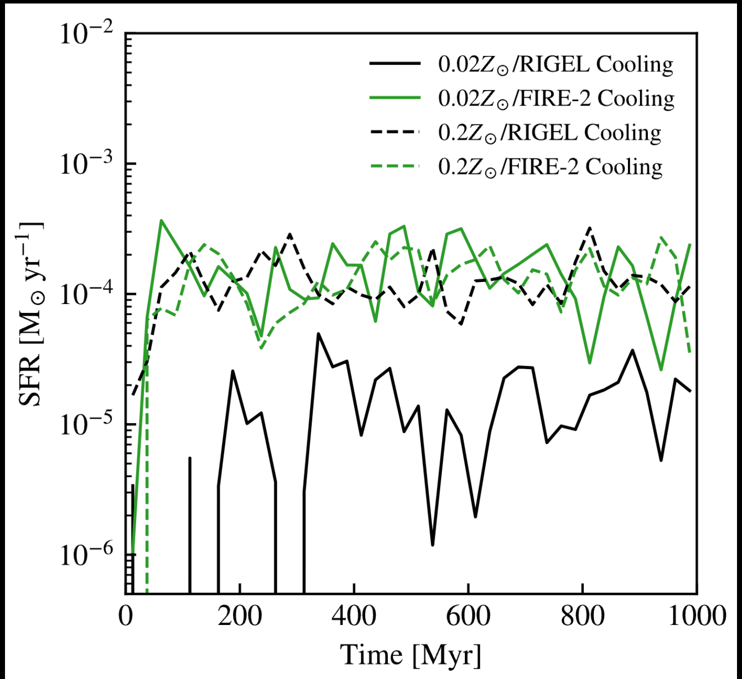

Wolf–Lundmark–Melotte (WLM)
a lonely galaxy in the local Universe

Radiation feedback matters on thermal-chemistry of the ISM



Radiation fields vary strongly at different location and different time, depend on massive star formation activities!

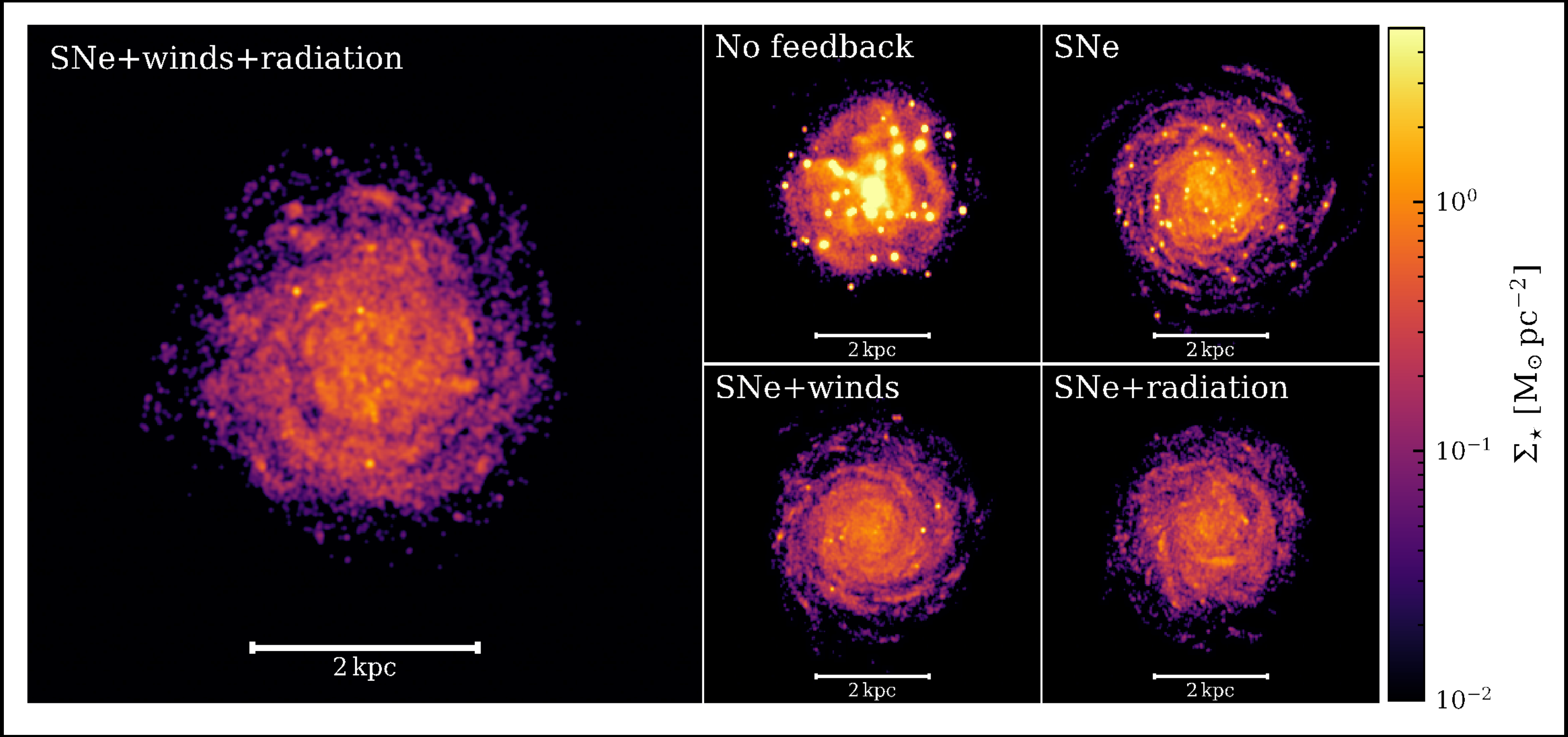




Variable radiation fields and detail treatments of low-temperature cooling leads to different cooling curve and star formation history, compared to the traditional, simplified cooling treatment.

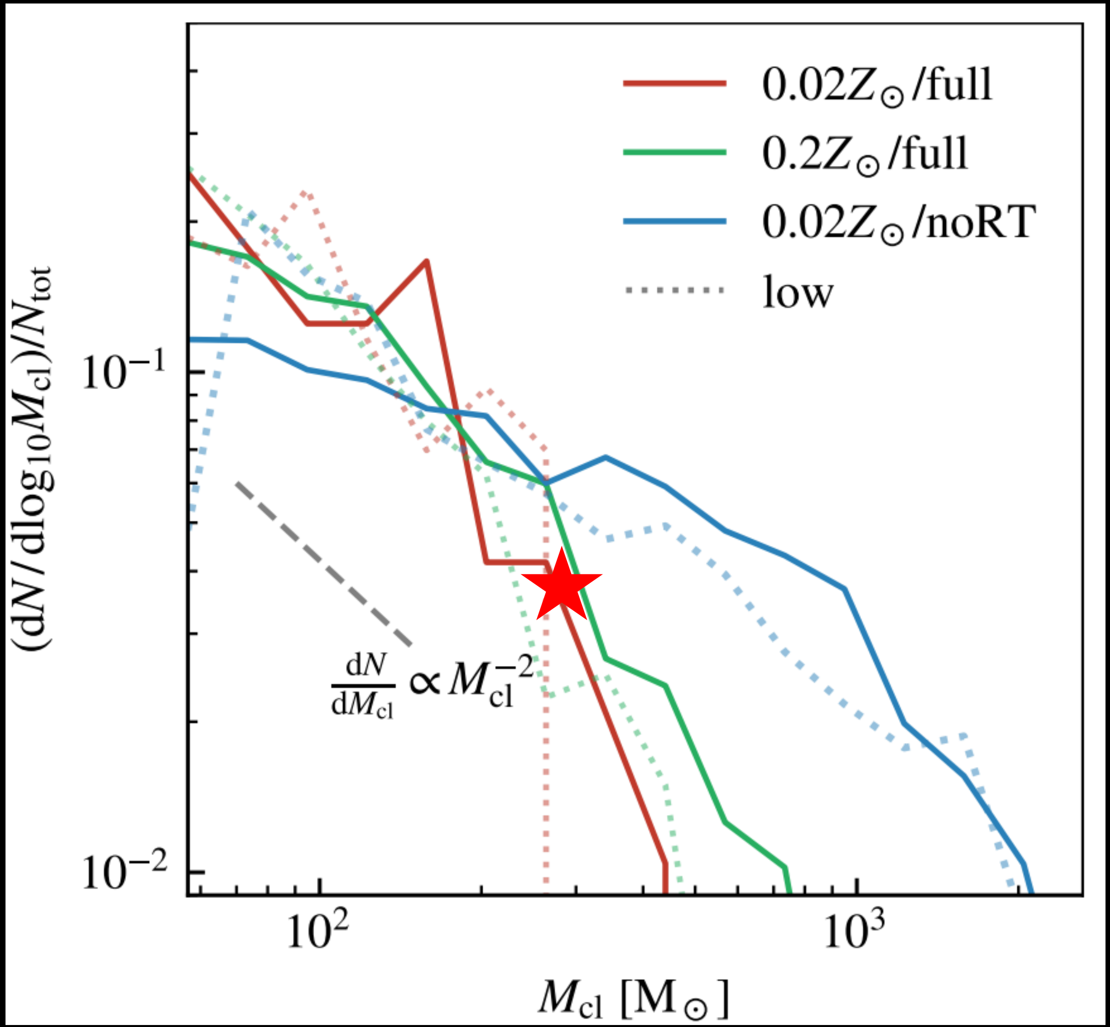
Deng, LH+24b

Cluster formation efficiency is significantly reduced with radiation feedback



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

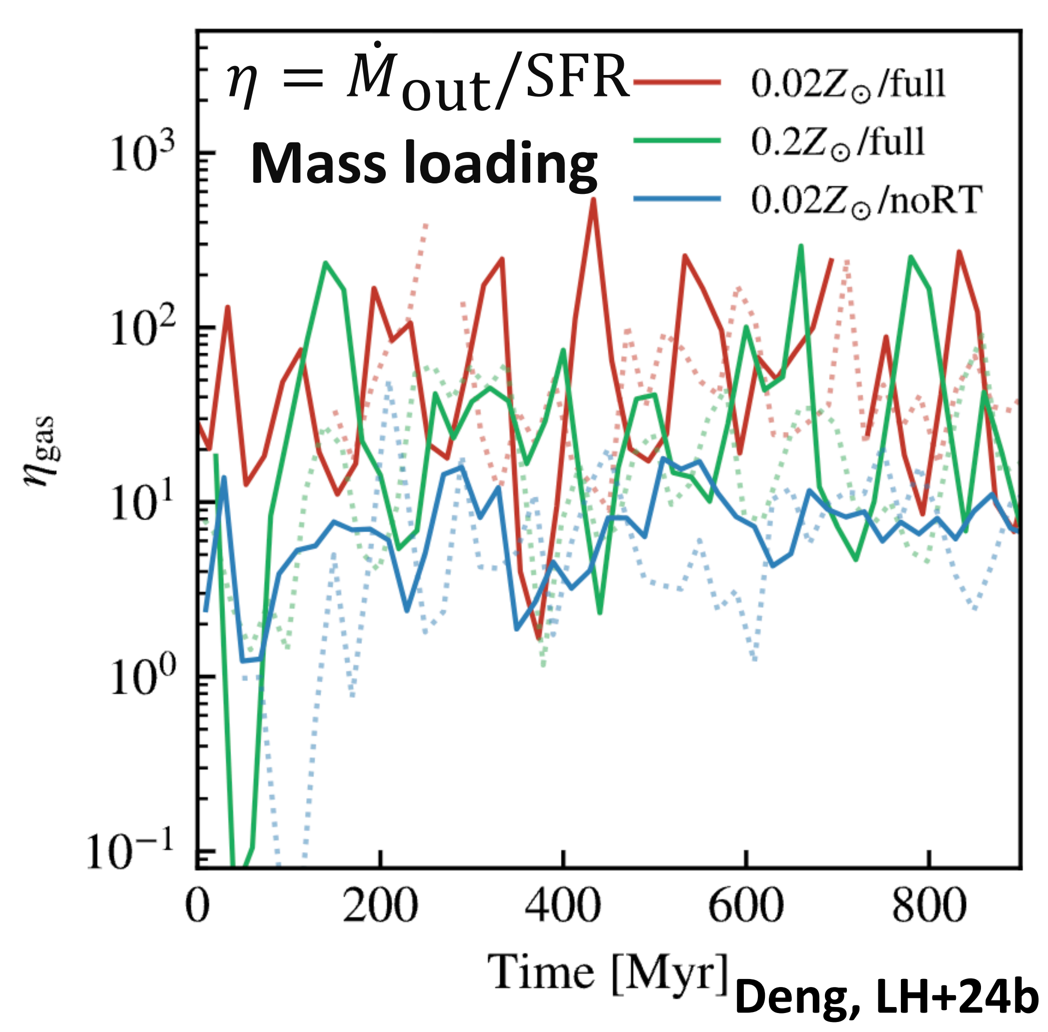
Radiation feedback matters on small-scale cluster formation



- 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



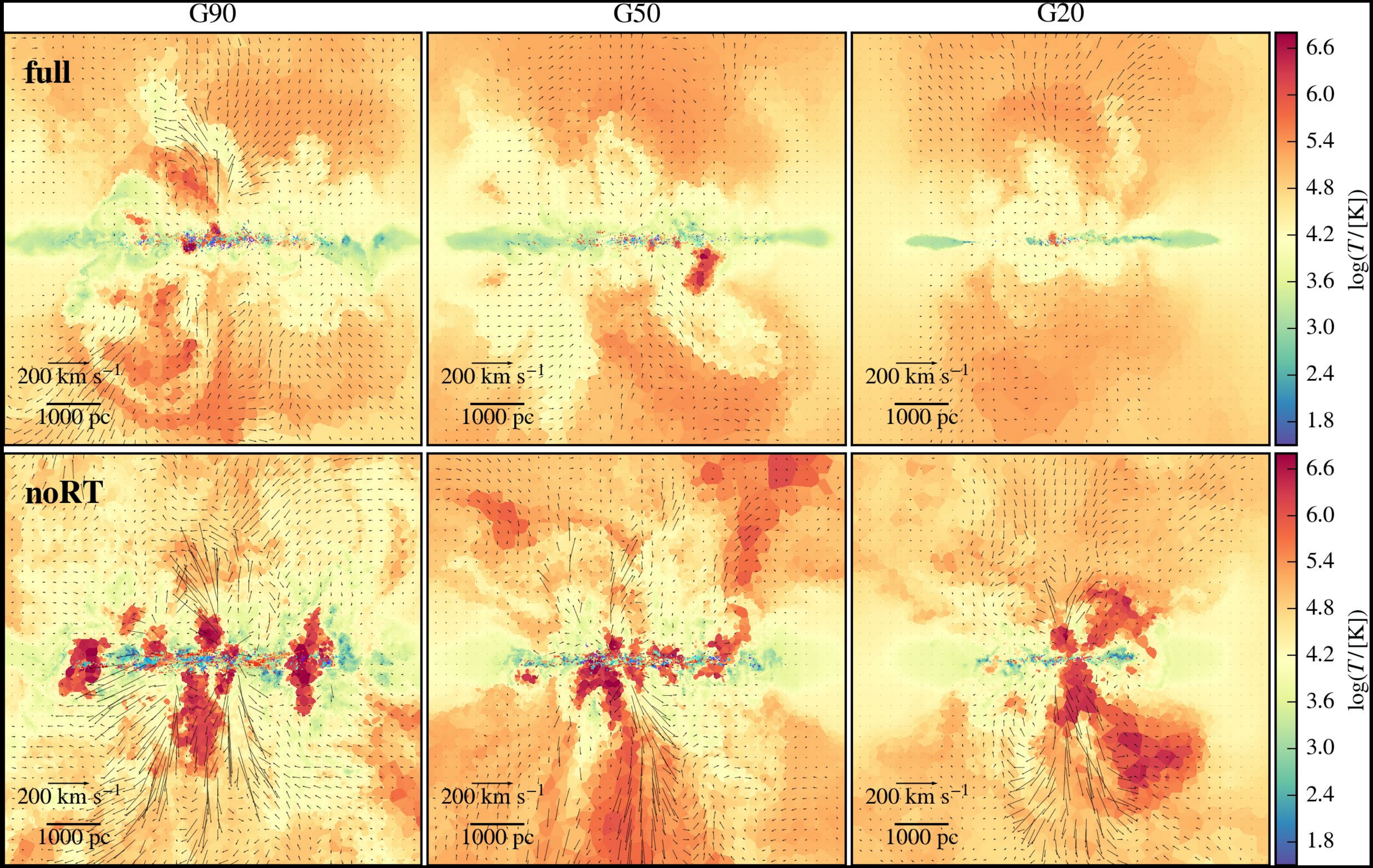
Radiation feedback enhances the mass/energy loading of the galactic winds: 1) higher feedback energy output due to photo-ionization and radiative pressure; 2) reduce the SN explosion density by pre-processing the ambient medium.

Radiation feedback matters on large-scale galactic winds

Fixed baryon & DM mass
Gas : Star

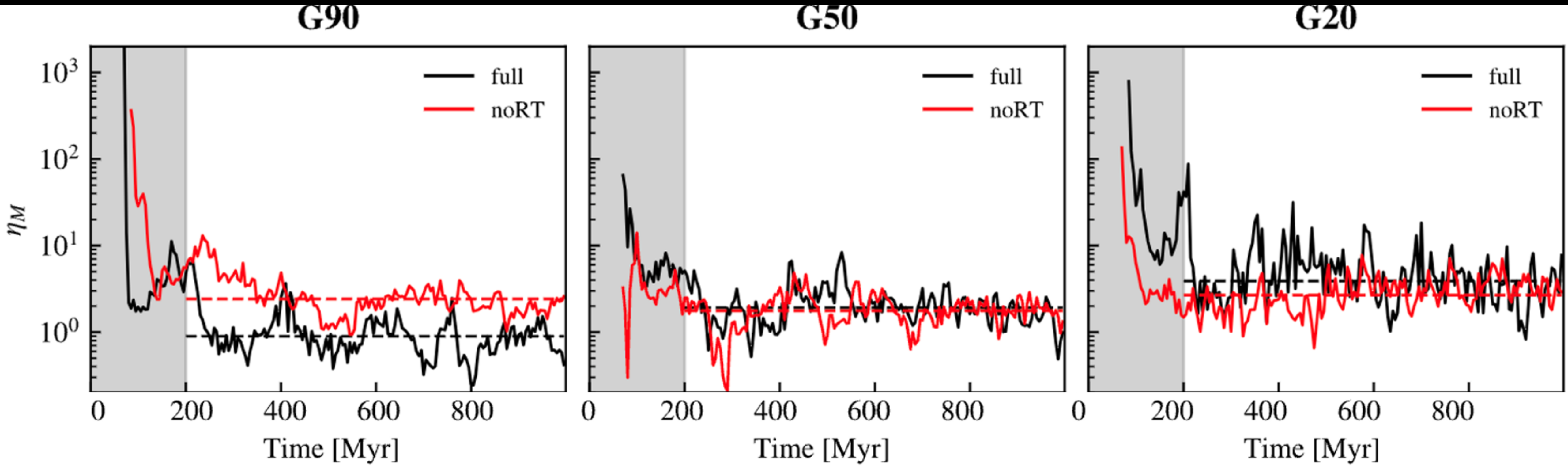
G90 9 : 1
G50 1 : 1
G20 1 : 4

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

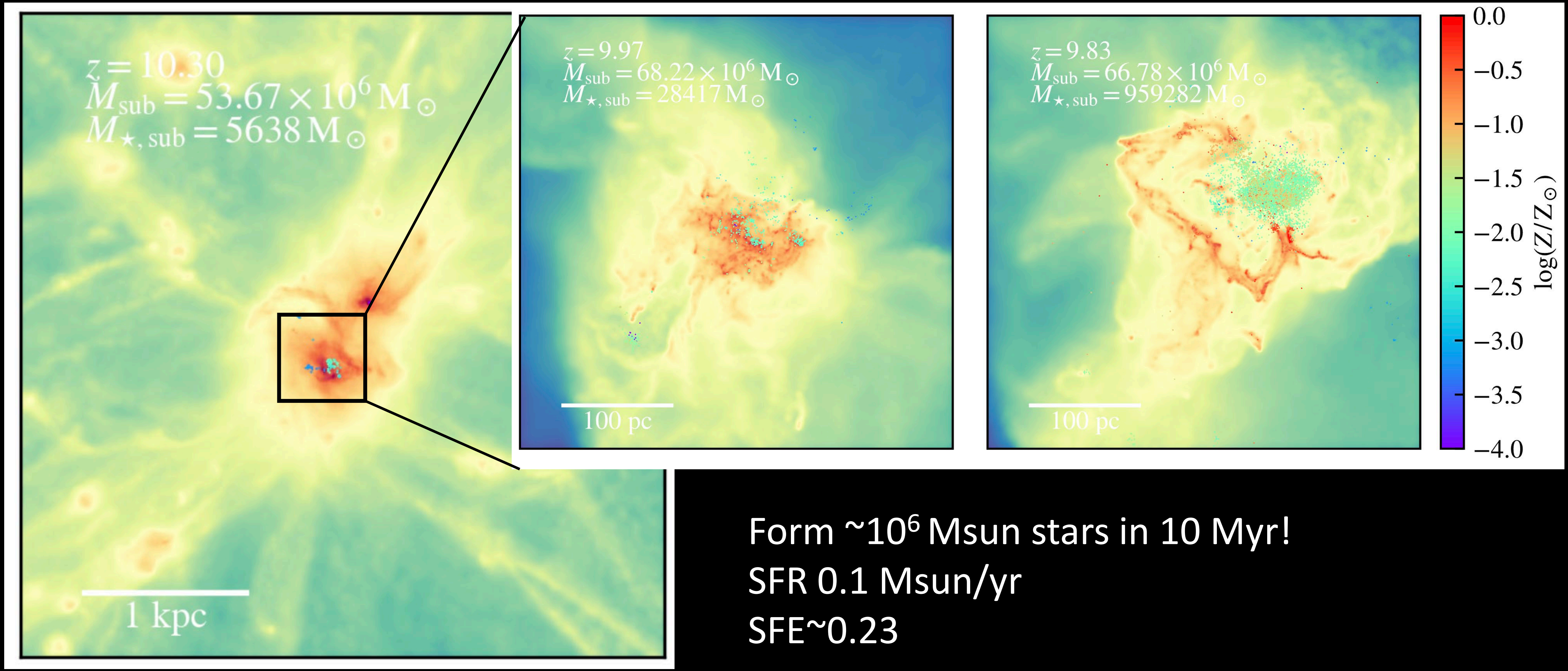


Although stellar feedback affects strongly the gas motion and galactic winds, it does not change the inner dark matter density profiles at all from present-day star formation activities. This is because the baryonic fraction is too low. This suggests that the cusp-core transformation can happen only in high-z, gas-rich phase.

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



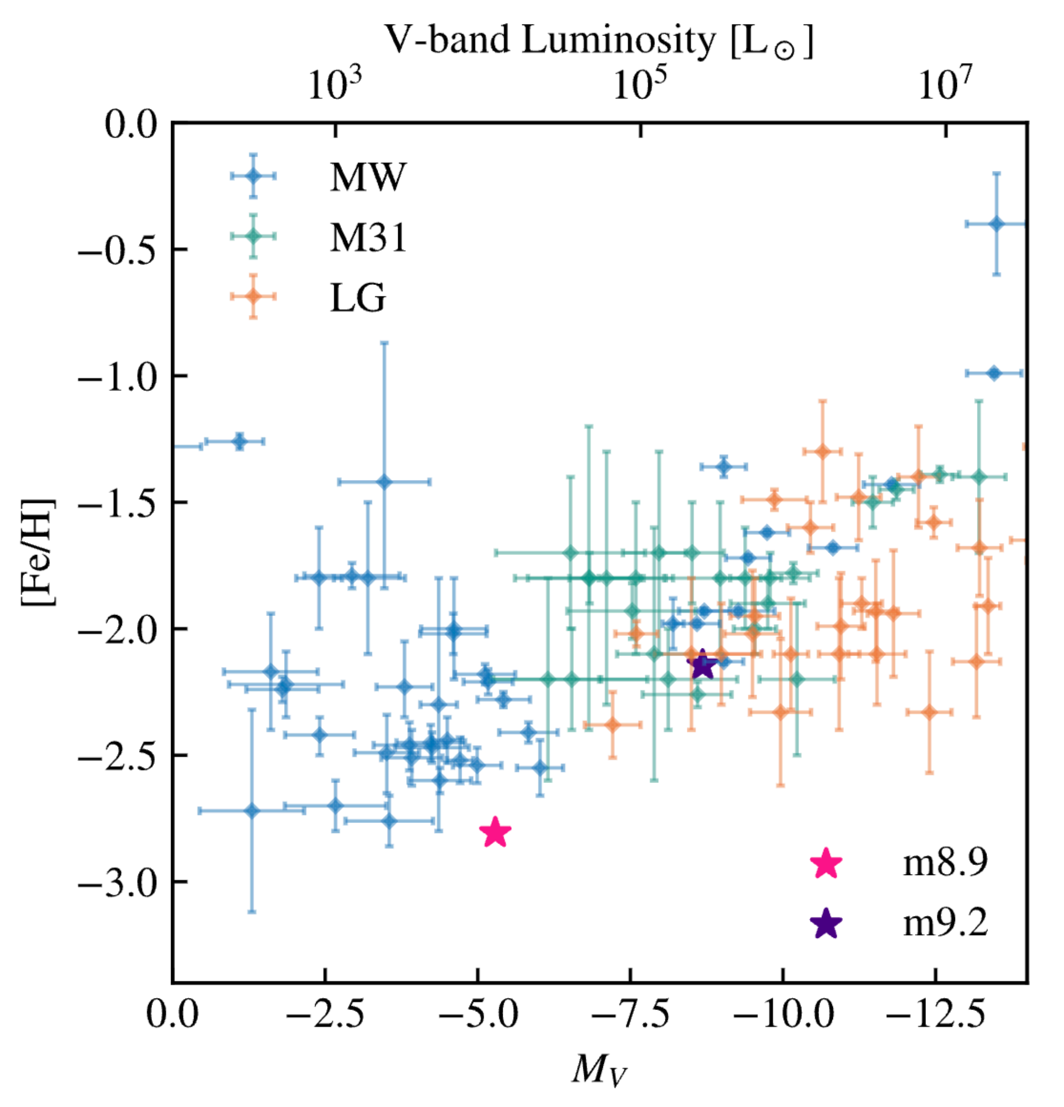
Form ~10^6 Msun stars in 10 Myr!

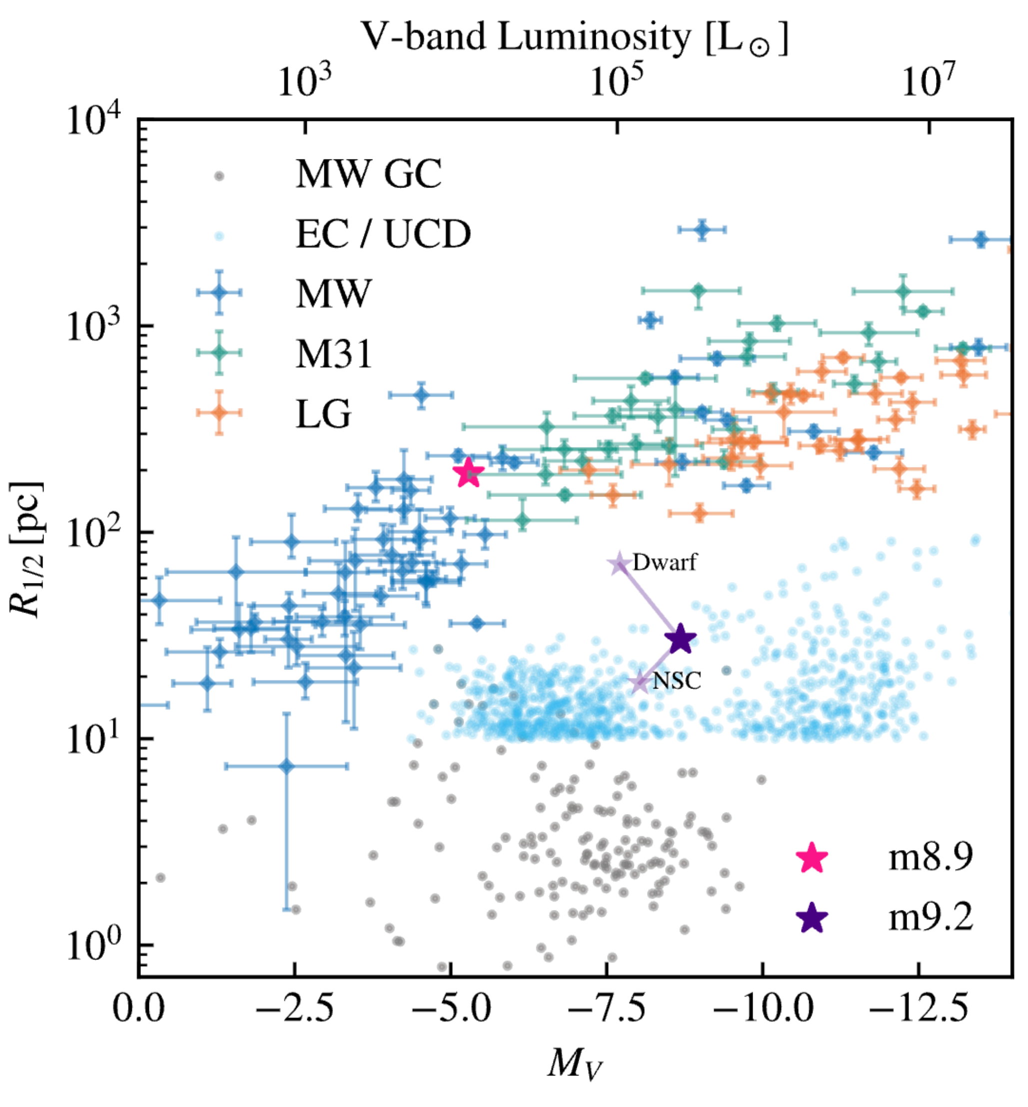
SFR 0.1 Msun/yr

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.

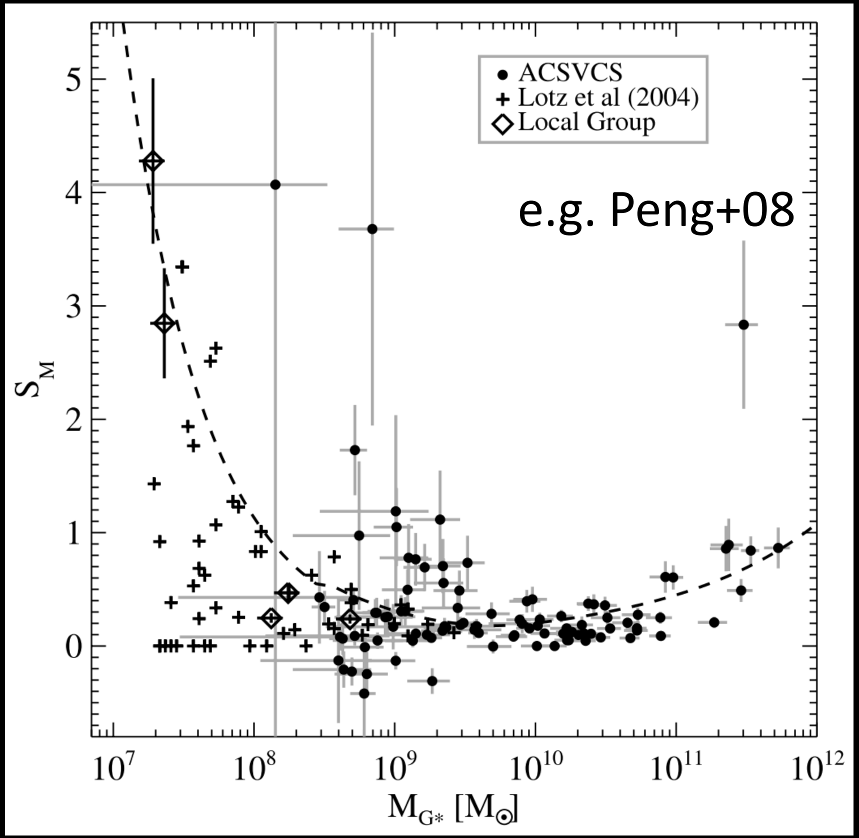
Simulated ultra compact dwarf in isolation at z=0



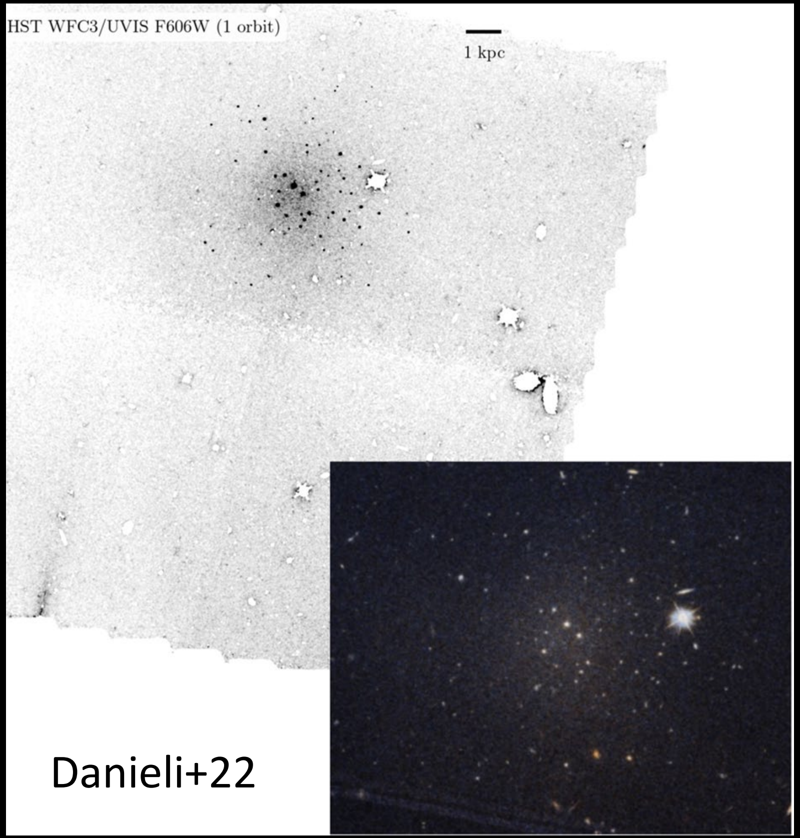


Deng et al. in prep.

Dwarf galaxies have a special star/cluster formation behavior



Many dwarf galaxies are rich in globular clusters



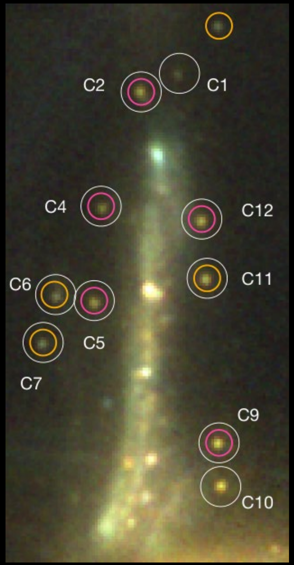
Globular clusters dominate the stellar component in NGC 5846-UDG1

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

(Proto-) globular clusters

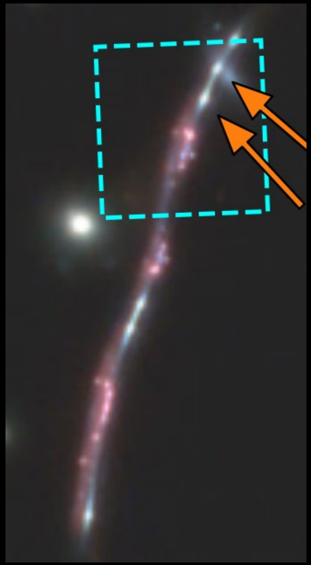
Young Massive Clusters at high-z: **promising sites to host IMBH!**

Mowla+22 Adamo+23 Sparkler



z=1.37

Rivera-Thorsen+24 Sunburst

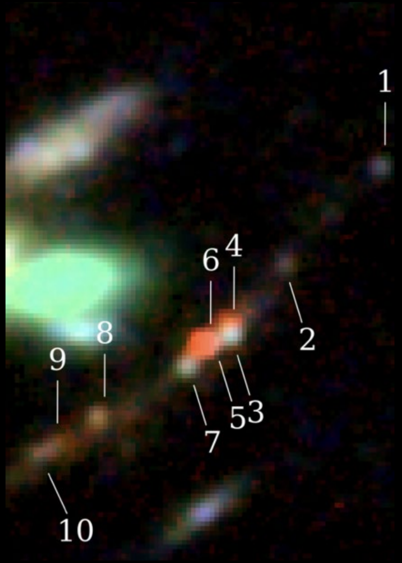


z=2.37

Vanzella+23 Sunrise

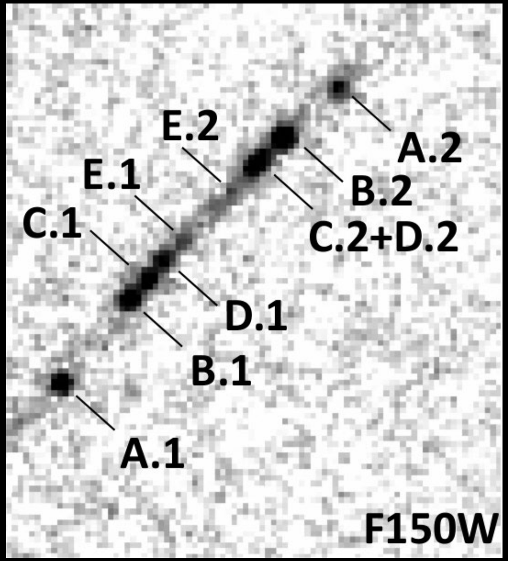
z=6.0

Mowla+24 Firefly



z=8.3

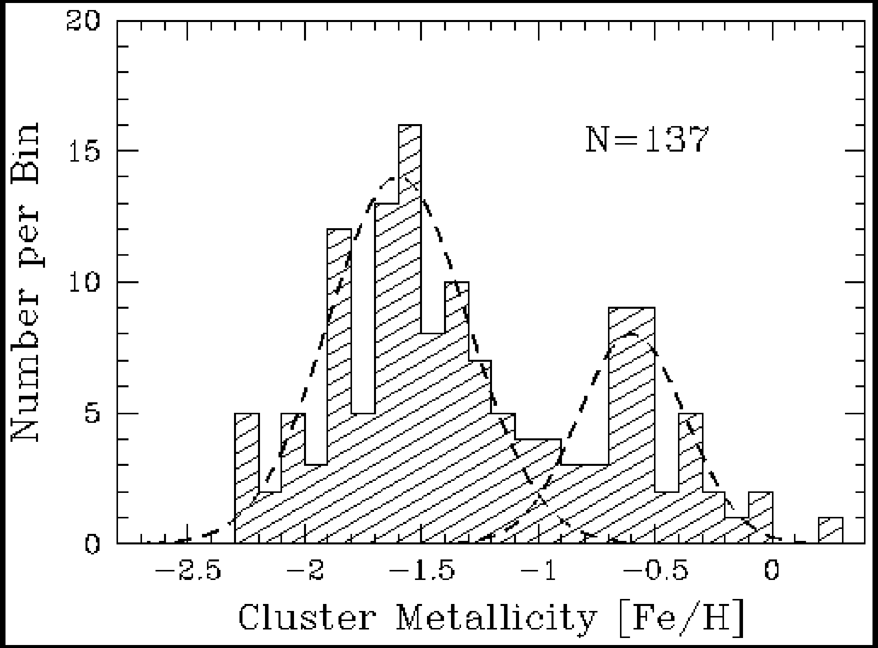
Adamo+24 Cosmic Gems



z=10.0

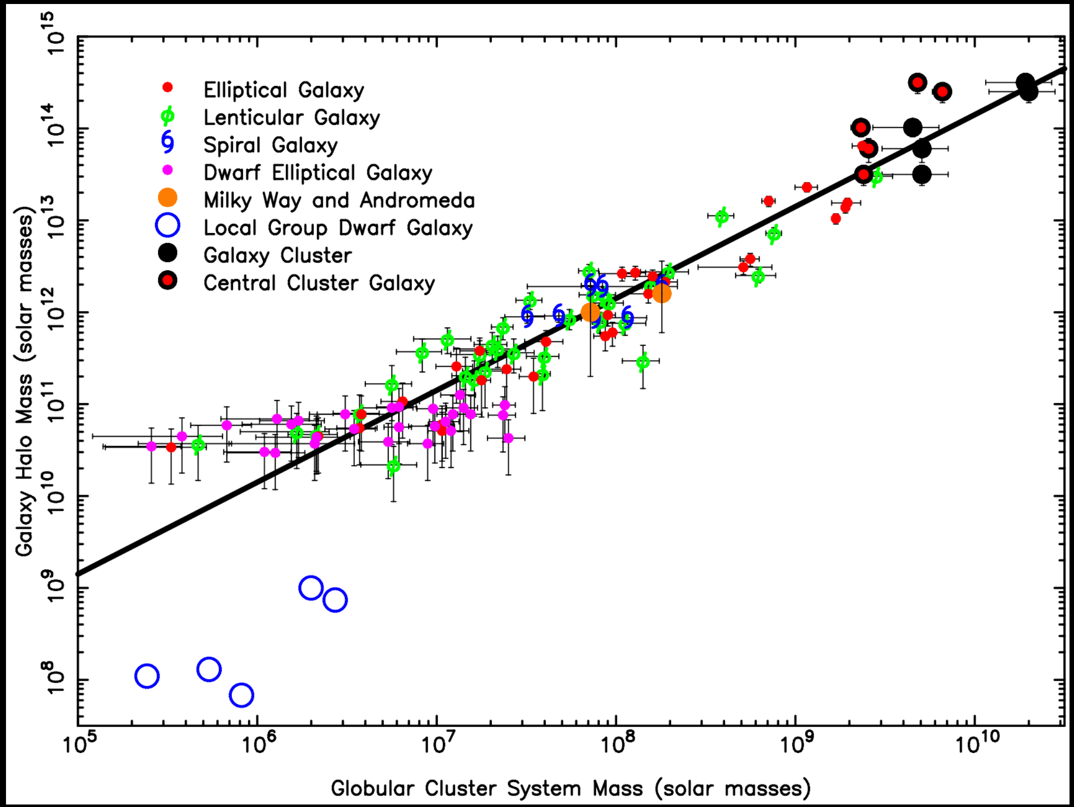
Redshift

Co-evolution of galaxies and globular cluster systems



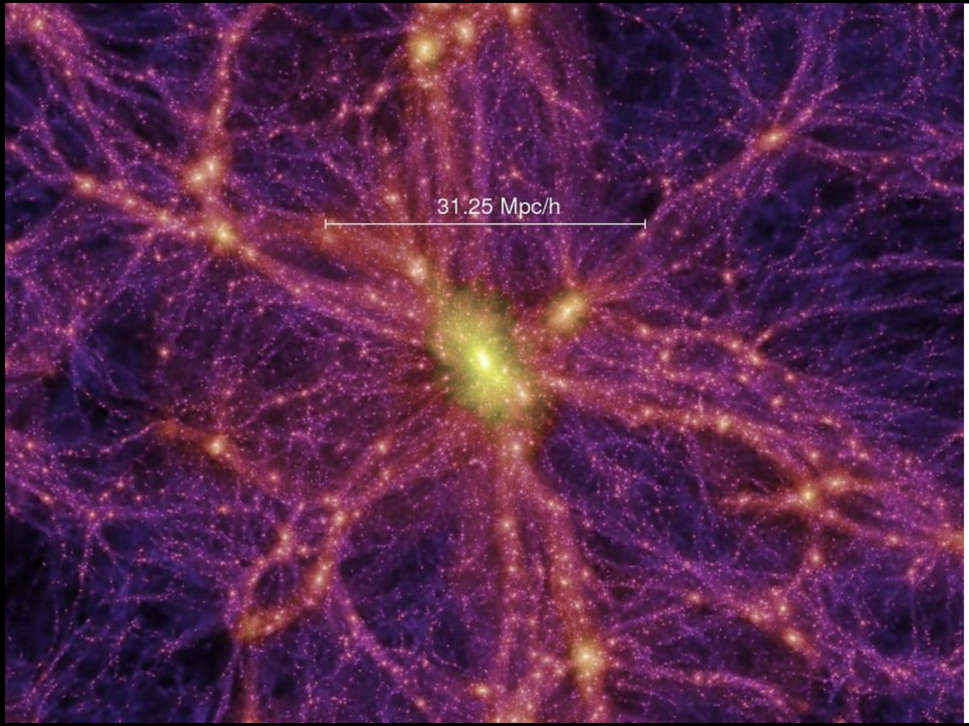
GCs in general have low metallicity, but they are not absent of metals. Instead, GCs show a broad range of metallicity. Metal-rich subpopulation has metallicity similar to their host galaxies at low-z.

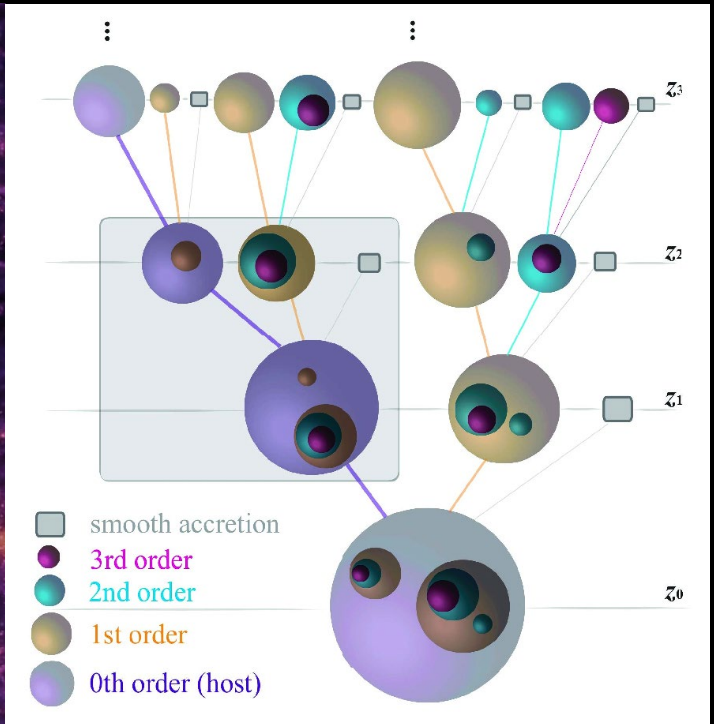
e.g. Harris+99



A tight, linear correlation between the total GC mass and the halo mass of their host galaxy suggests the formation of GCs follows the halo assembly history.

e.g. Spitler&Forbes+09; Harris+15





A lazy man's approach: semi-analytical model on halo merger trees with only two model parameters

$$M_{\rm GC} = 1.8 \times 10^{-4} p_2 M_g$$

GCS rate scales with cold gas mass

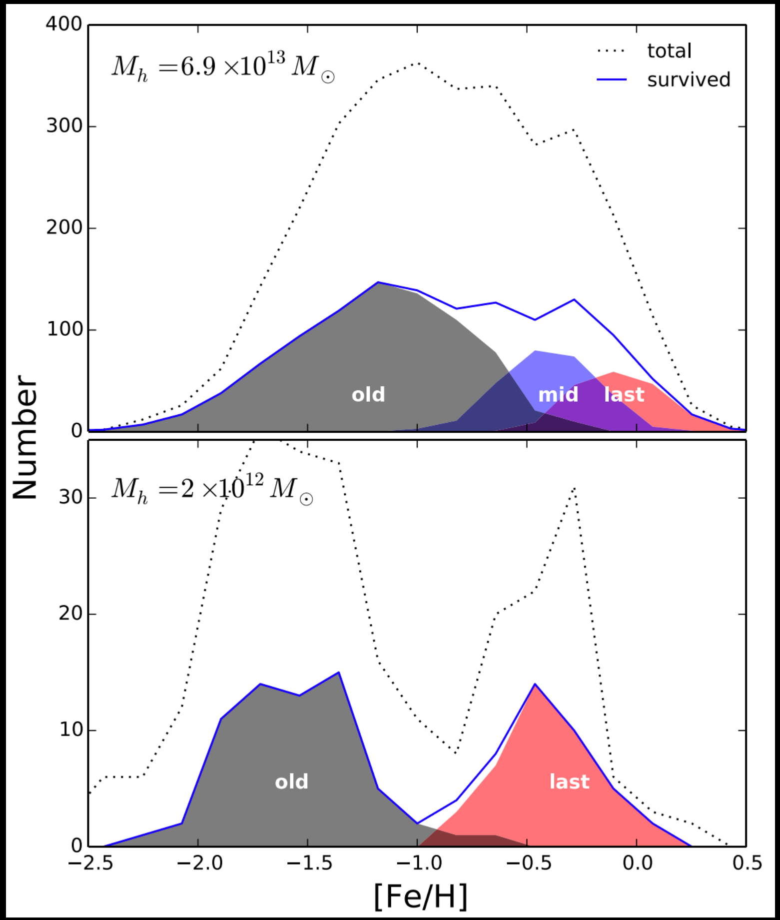
$$R_m \equiv \frac{M_{h,2} - M_{h,1}}{t_2 - t_1} \frac{1}{M_{h,1}}.$$

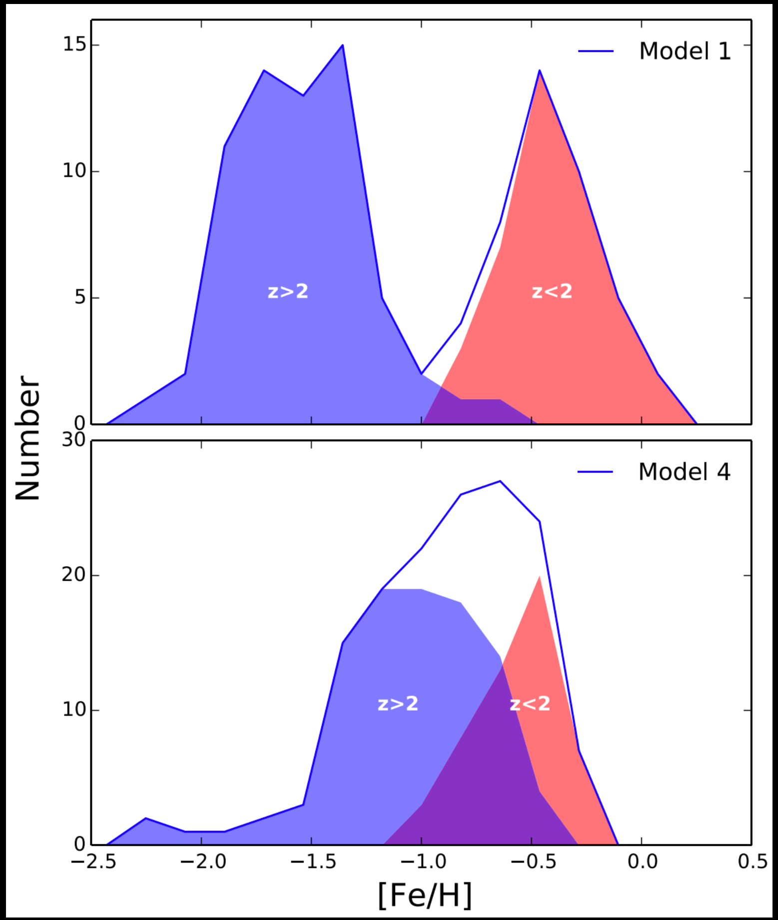
GC form when halo is actively growing (often due to mergers)

Cluster formation is triggered if $R_m > p_3$

Li&Gnedin14, Choksi,Gnedin&Li18, Choksi+19, Chen+22

Metallicity bimodality of GCs in the MW



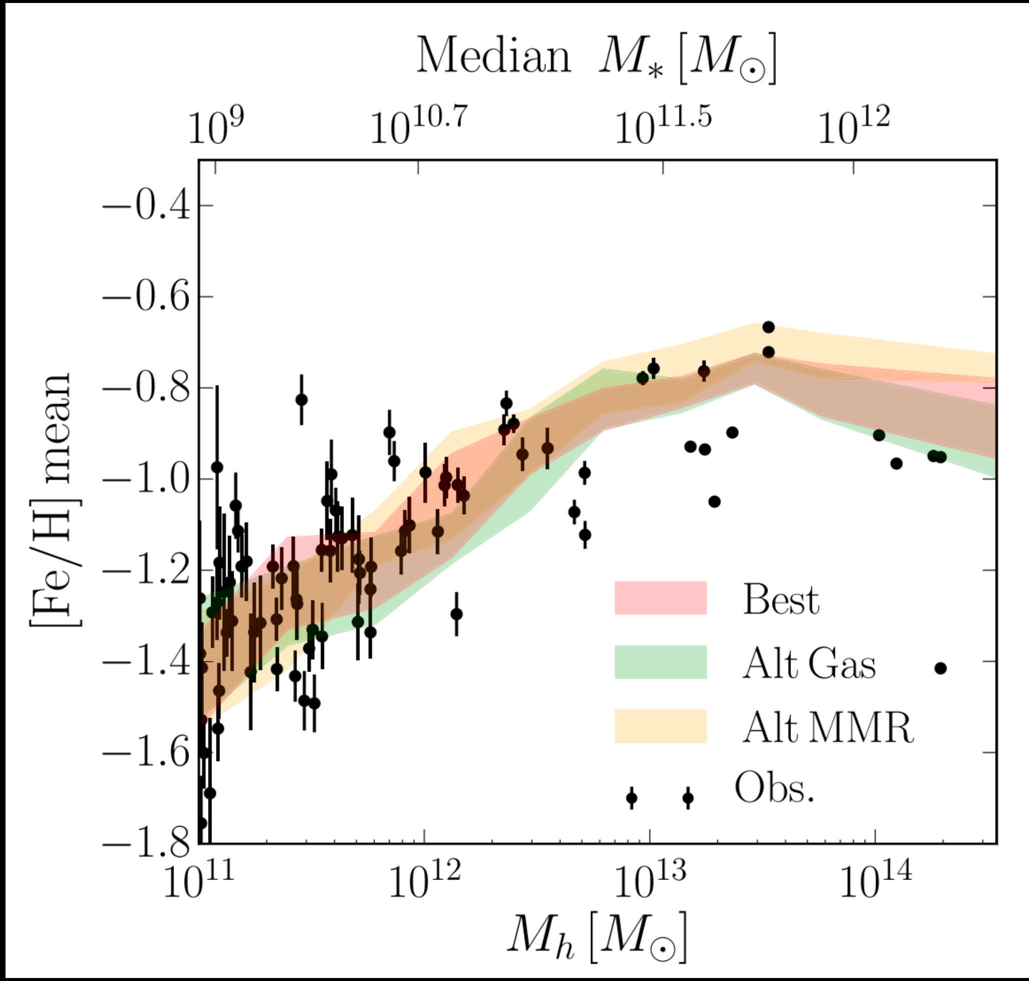


Blue clusters are formed from a collective of major merger events at high-z; while red clusters are formed from rare low-z merger events depends strongly on the halo assembly history.

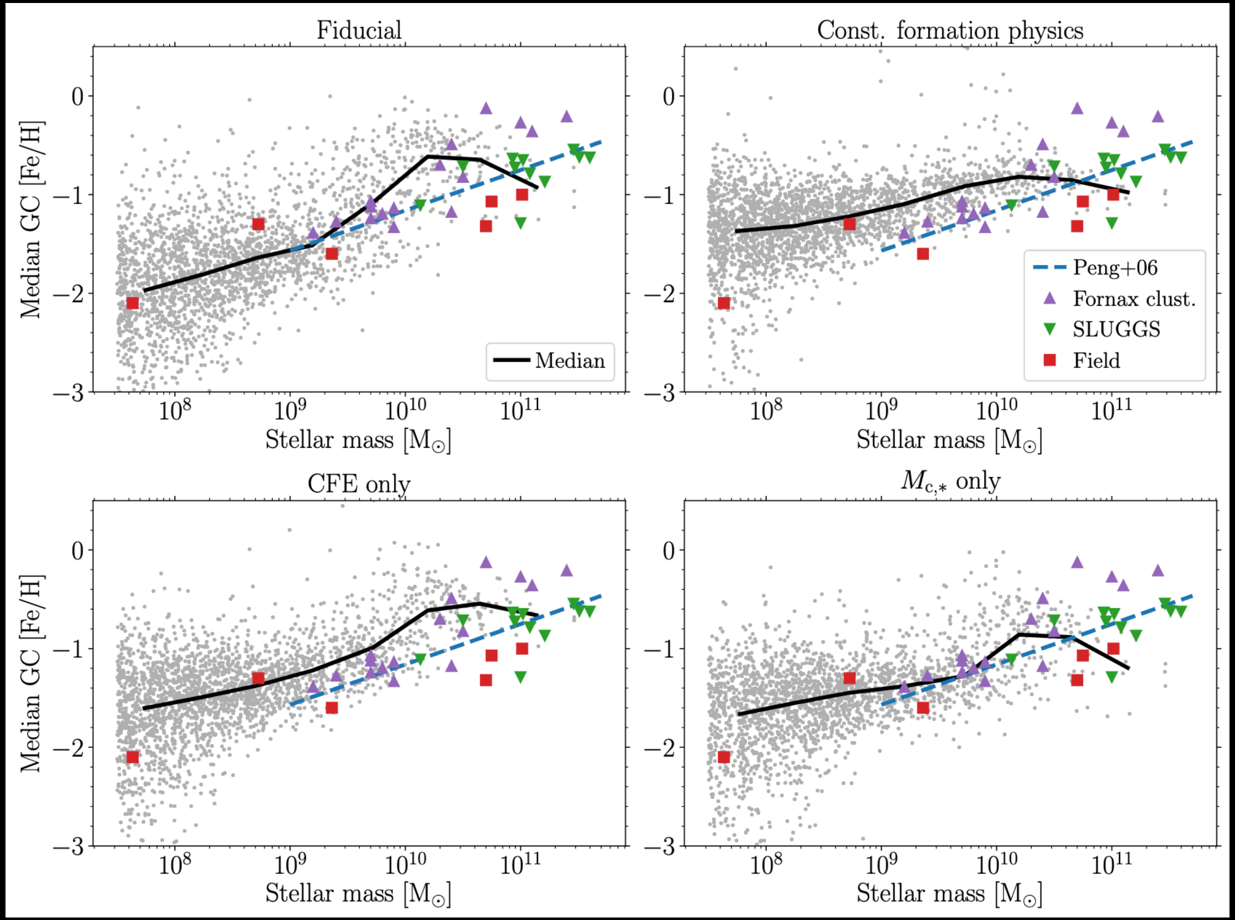
To reproduce observed metallicity distribution, GC formation cannot simply follow star formation history, but requires special conditions.

Li&Gnedin14

Halo mass – GC metallicity relations

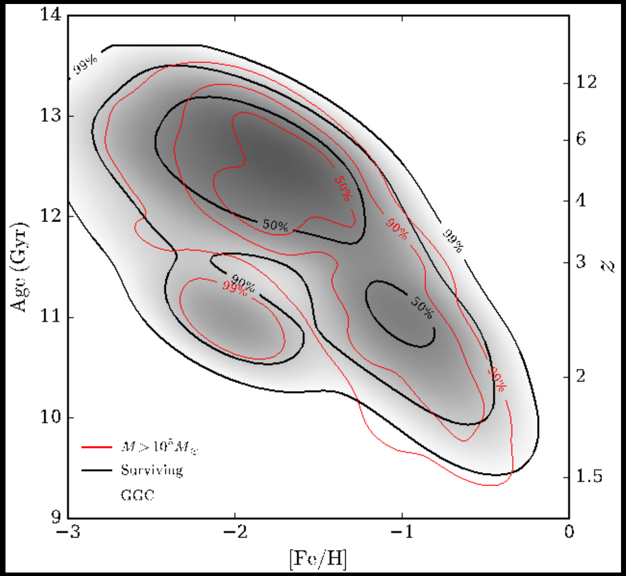


Choksi, Gnedin & Li 18

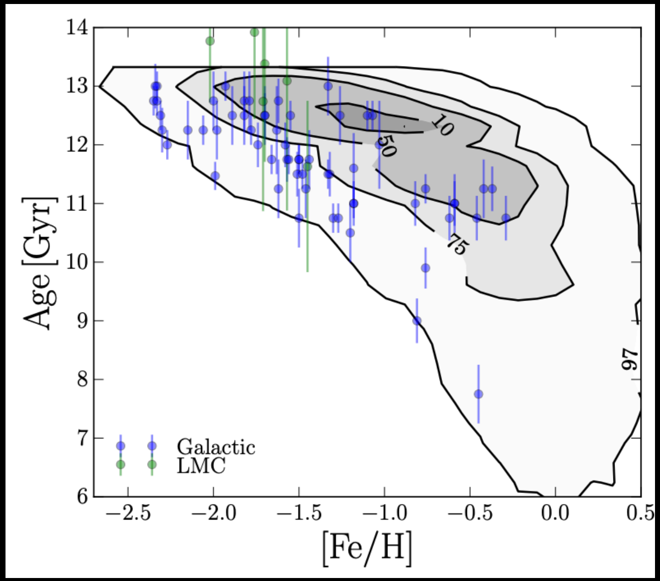


Pfeffer+22

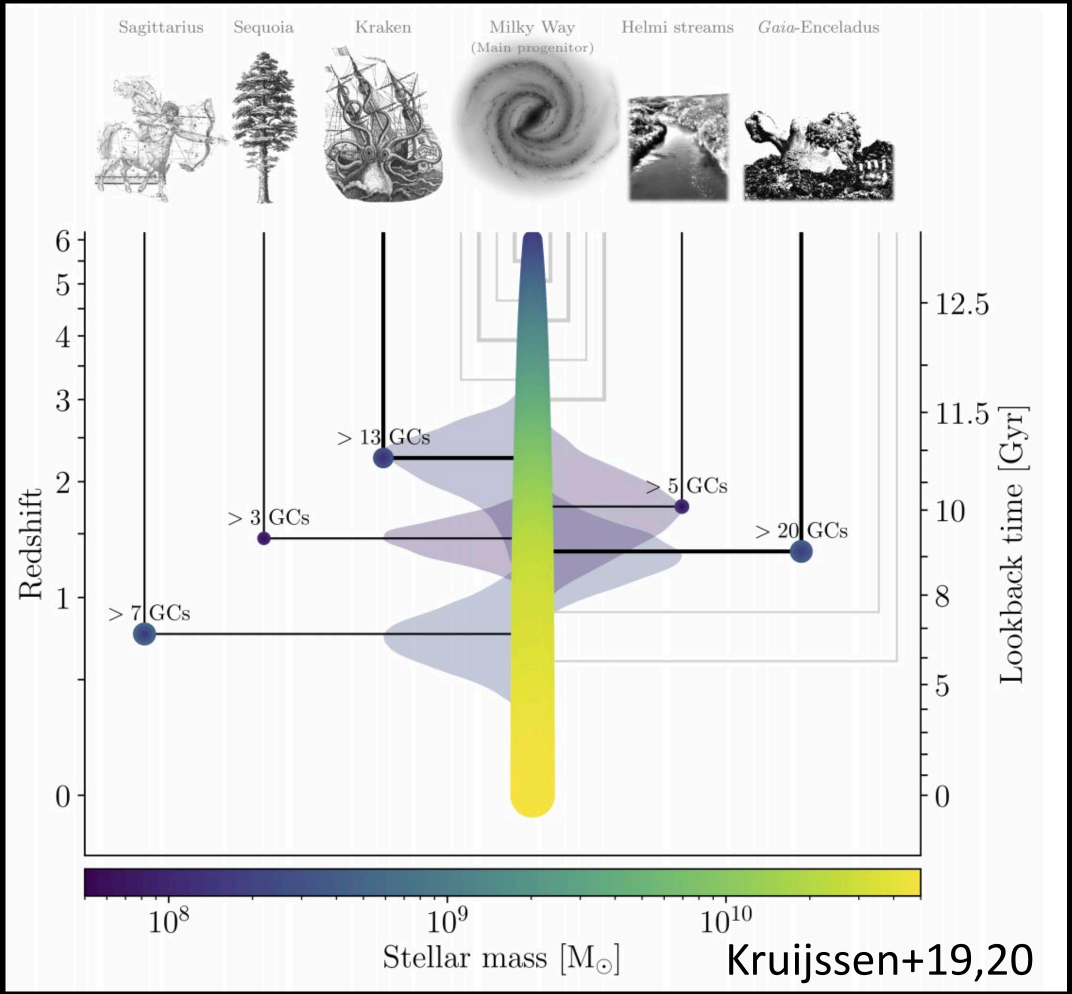
Age-metallicity distribution of GCs



Li+14, 19



Choksi+19



Kruijssen+19,20

Our model successfully reproduced the age-metallicity distribution of the MW GCs.
GCs are largely formed at z>3 but can still form around z~1 depending on the halo assembly history of the host galaxies.

Age-metallicity distribution of GC system becomes a powerful tool to infer the assembly history of host galaxies.

Nuclear Star Clusters

The formation of the nuclei of galaxies. I. M31.

Show affiliations

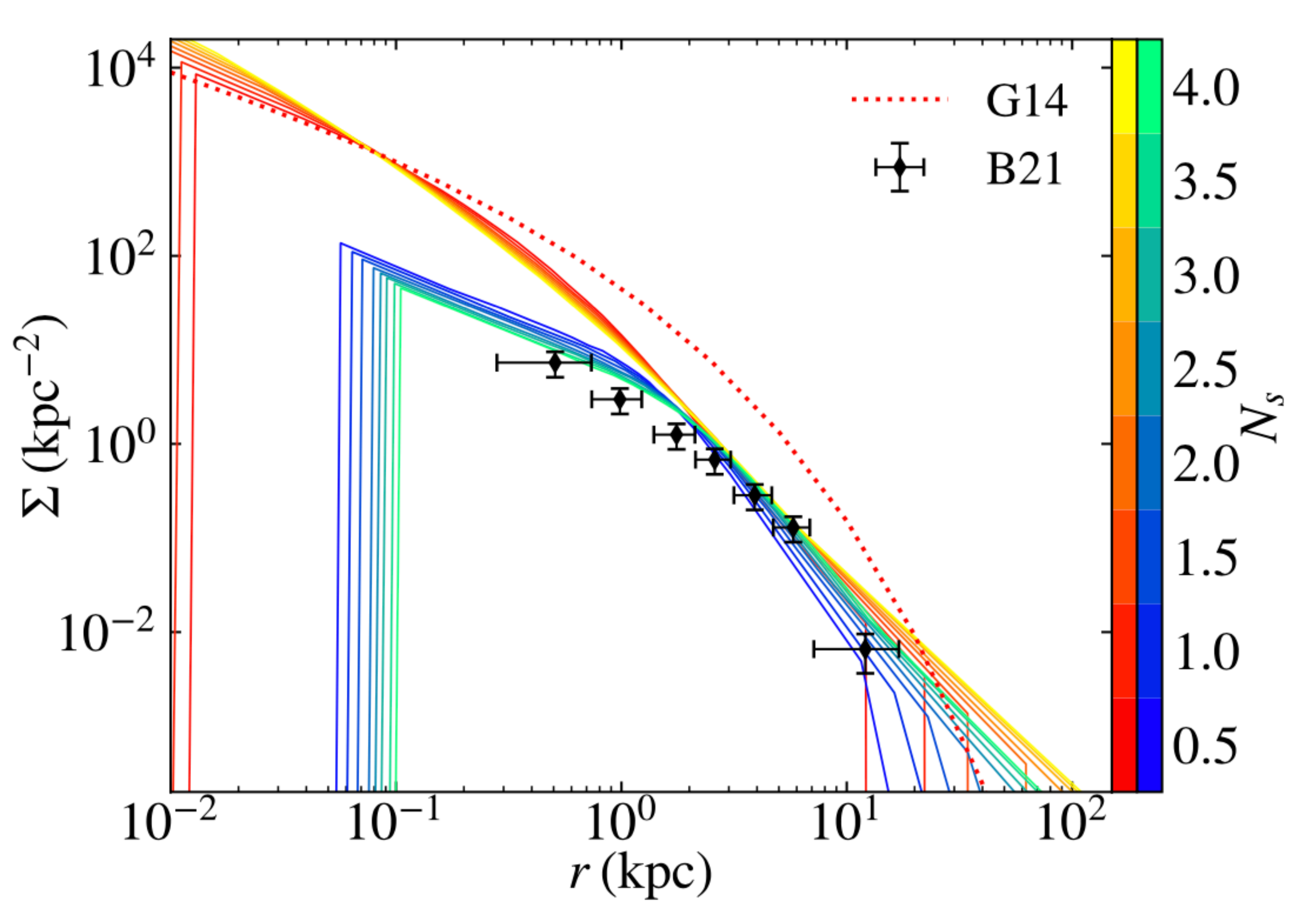
Tremaine, S. D.; Ostriker, J. P.; Spitzer, L., Jr.

Globular clusters passing near the center of M31 interact with the background stars through dynamical friction and spiral toward the center of the galaxy where they are tidally disrupted by interactions with the growing nucleus. This process will result in the formation of a high-density central nucleus of a mass roughly 50 million times the solar mass in 100 billion years. The mechanism outlined accounts for the development of massive nuclei within which stellar collisions and other exotic phenomena might possibly occur. The data derived from numerical calculations are consistent with Stratoscope balloon observations of the M31 nucleus.

Publication:	Astrophysical Journal, Vol. 196, p. 407-411 (1975)
Pub Date:	March 1975
DOI:	10.1086/153422
Bibcode:	1975ApJ...196..407T
Keywords:	Andromeda Galaxy; Astronomical Models; Galactic Evolution; Galactic Nuclei; Globular Clusters; Stellar Motions; Balloon Sounding; Galactic Structure; Luminous Intensity; Monte Carlo Method; Numerical Analysis; Spiral Galaxies; Star Distribution; Astrophysics

Neumayer et al. 2020 A&ARv

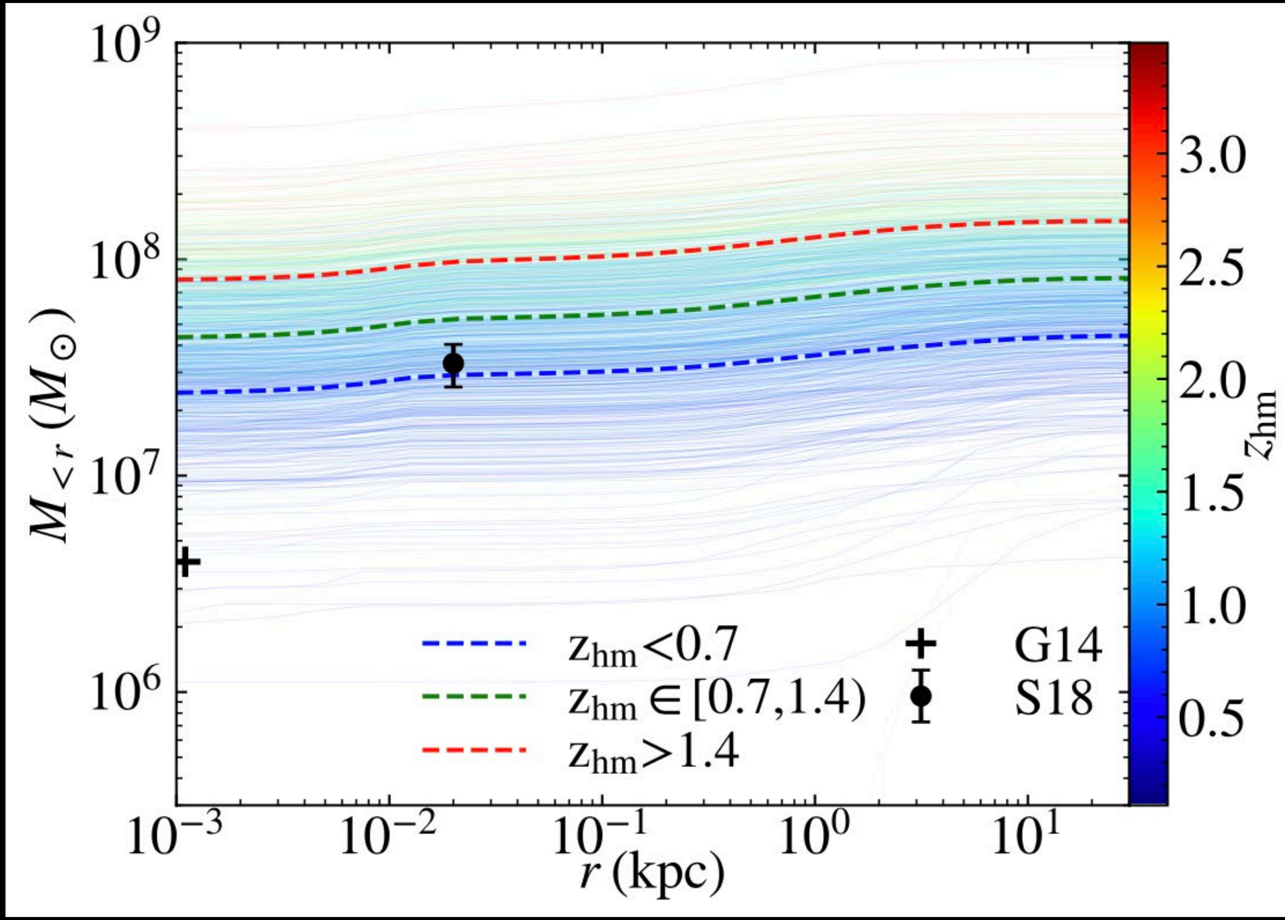
Spatial distribution of GCs under dynamical friction

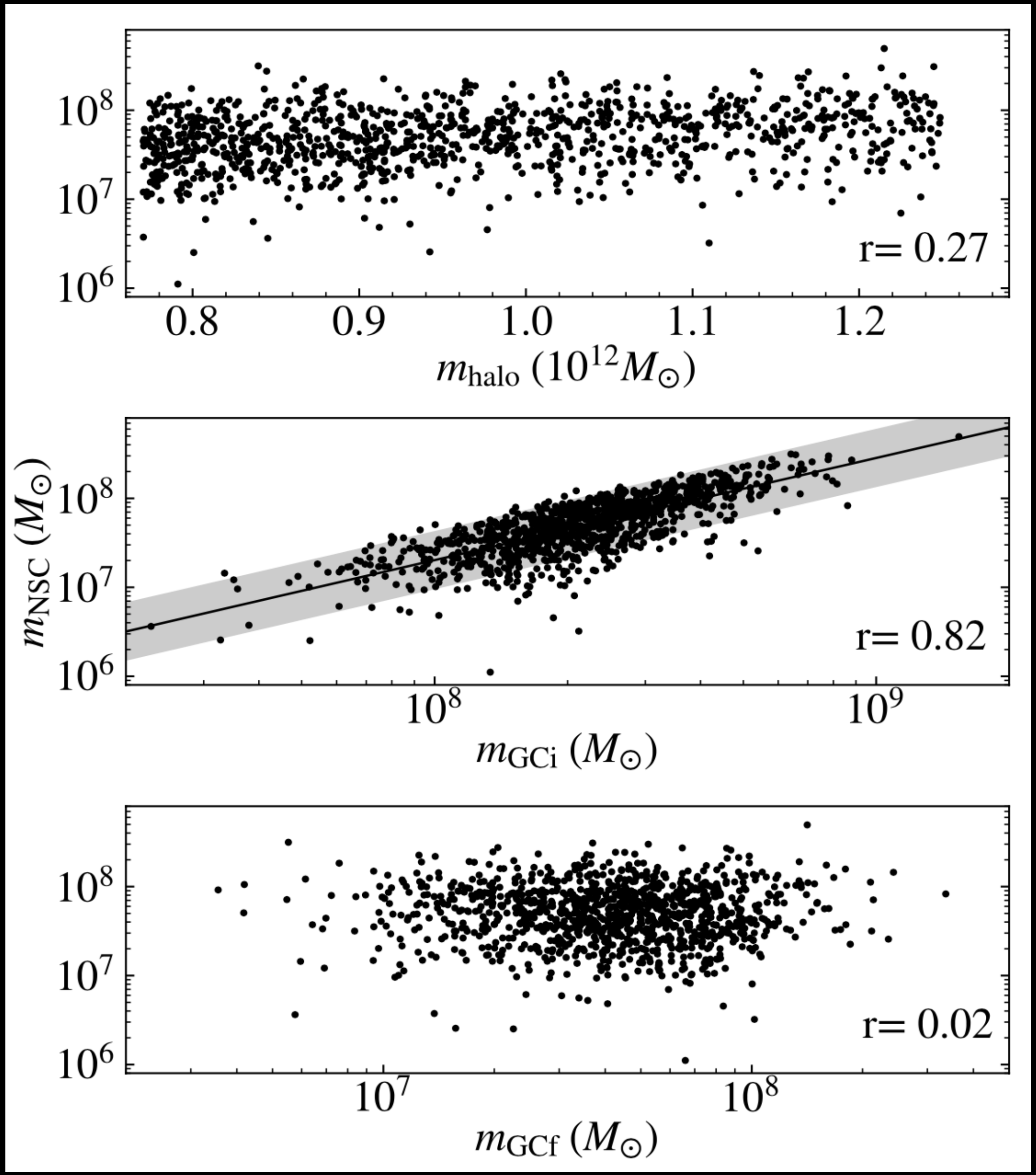


- Spatial distribution of surviving GCs at z=0 matches the observed MW shape.
- GCs formed within 2-3 kpc are strongly affected by dynamical friction and therefore a large fraction of GCs are sink into the central regions and disrupted along the way.
- The results are not sensitive to the choice of the initial Sersic index used for sampling the initial GC position.

Gao et al. 2024

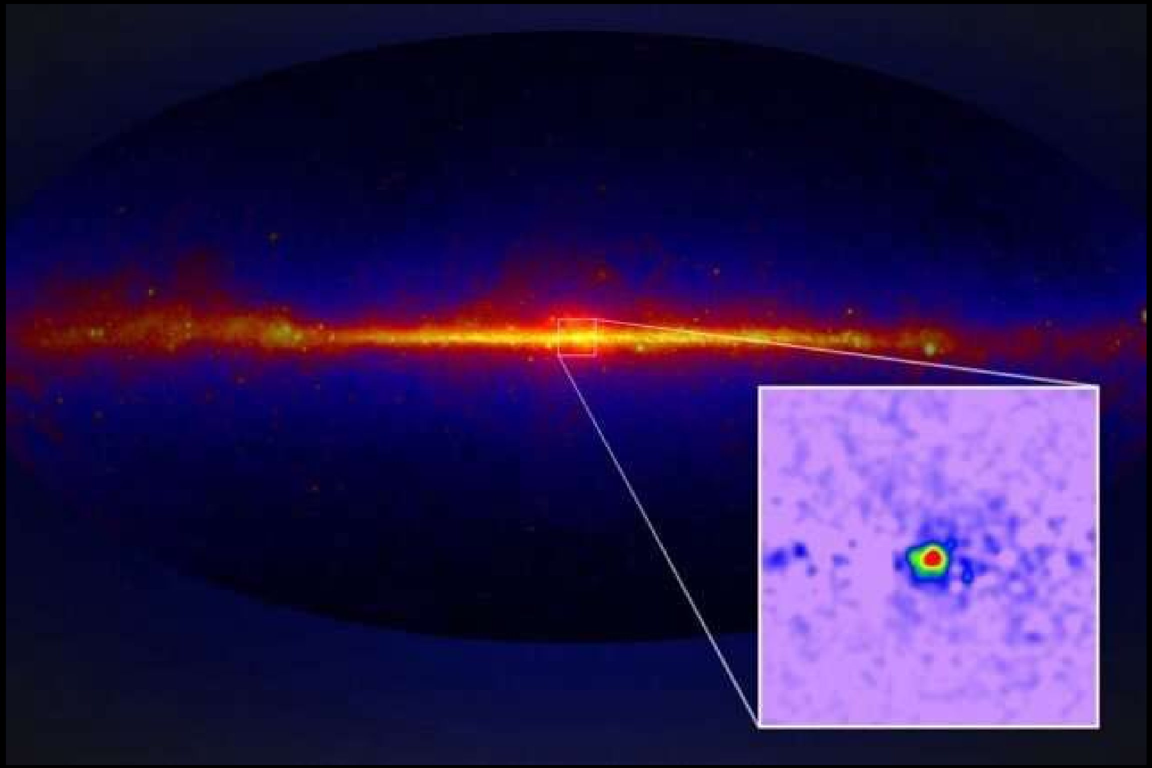
Assembly of NSCs depends strongly on the halo assembly history

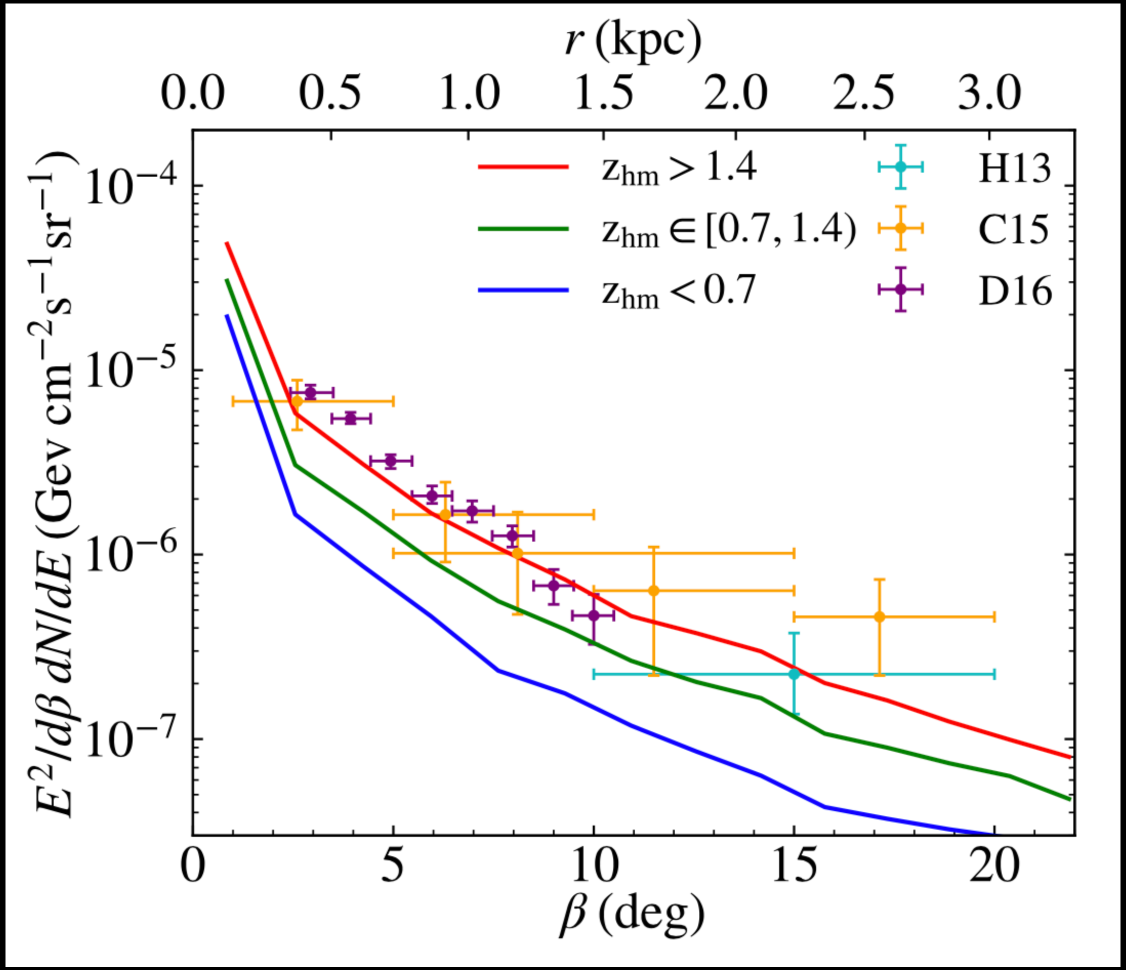




Gao et al. 2024

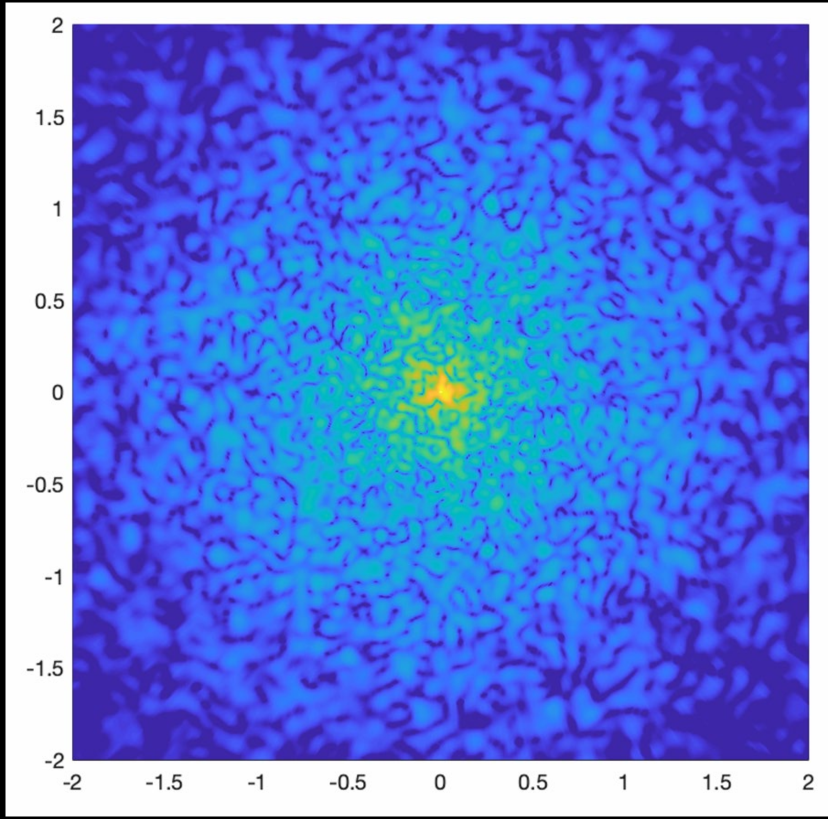
Millisecond pulsars in the NSC is enough to explain the observed gamma-ray excess at Galactic center!

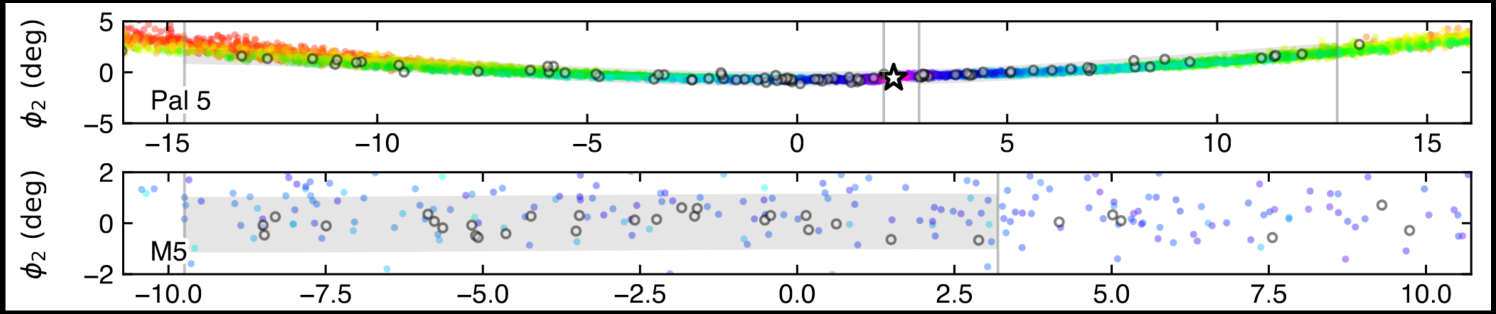




Gao et al. 2024

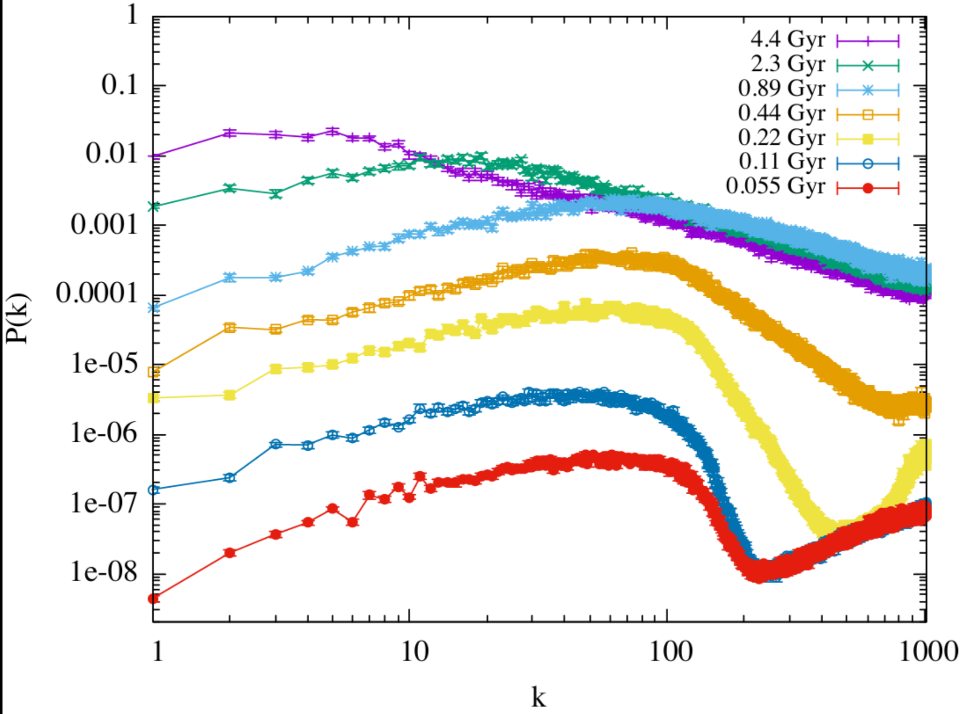
Stellar stream of GCs as a probe of fuzzy dark matter





Chen, Gnedin, Li 2025

The small-scale density fluctuation arises from the wave nature (de Broglie wavelength) of the fuzzy dark matter.



Moreno et al in prep.