Formation of Compact Star Clusters before the Epoch of Reionization

… preparing for JWST data

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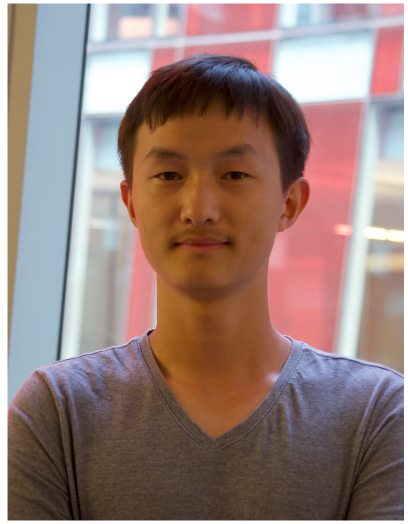
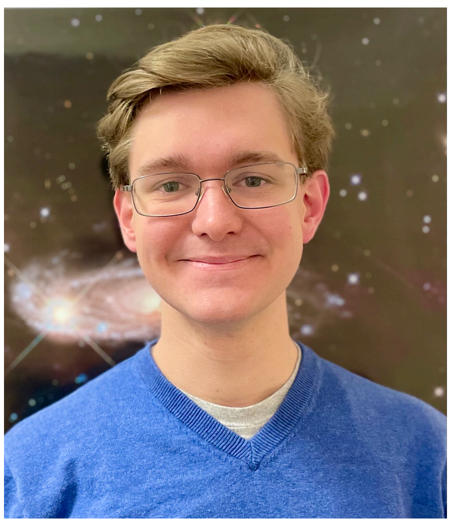


ChongChong
He
(Grad student)

Jongwon
Park
(Grad student)



Ronan
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Other collaborators on GC work:
Sam Geen
Nick Gnedin
Owen Parry
Blake Hartley
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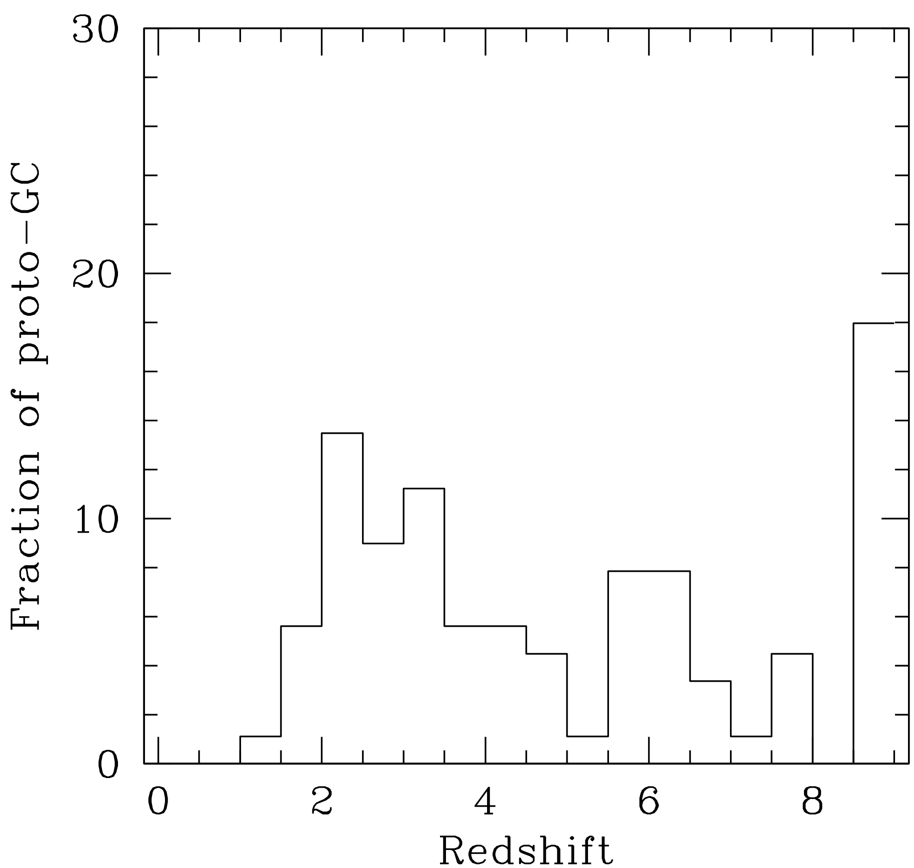
Some Big Questions

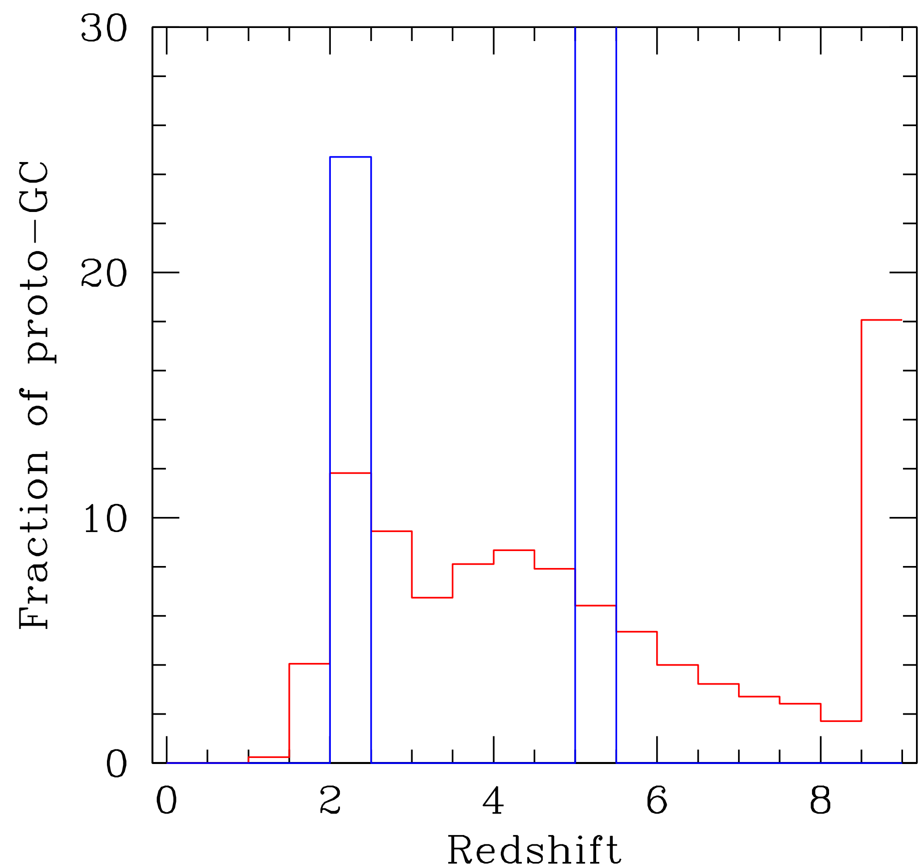
- **Is GC the main star formation mode in the first galaxies?**
    - **Can HST and JWST detect their formation at z>6?**
- What is the connection to ultra-faint dwarfs?
- Are GC drivers of reionization?

What are the ages of Milky Way's globular clusters?

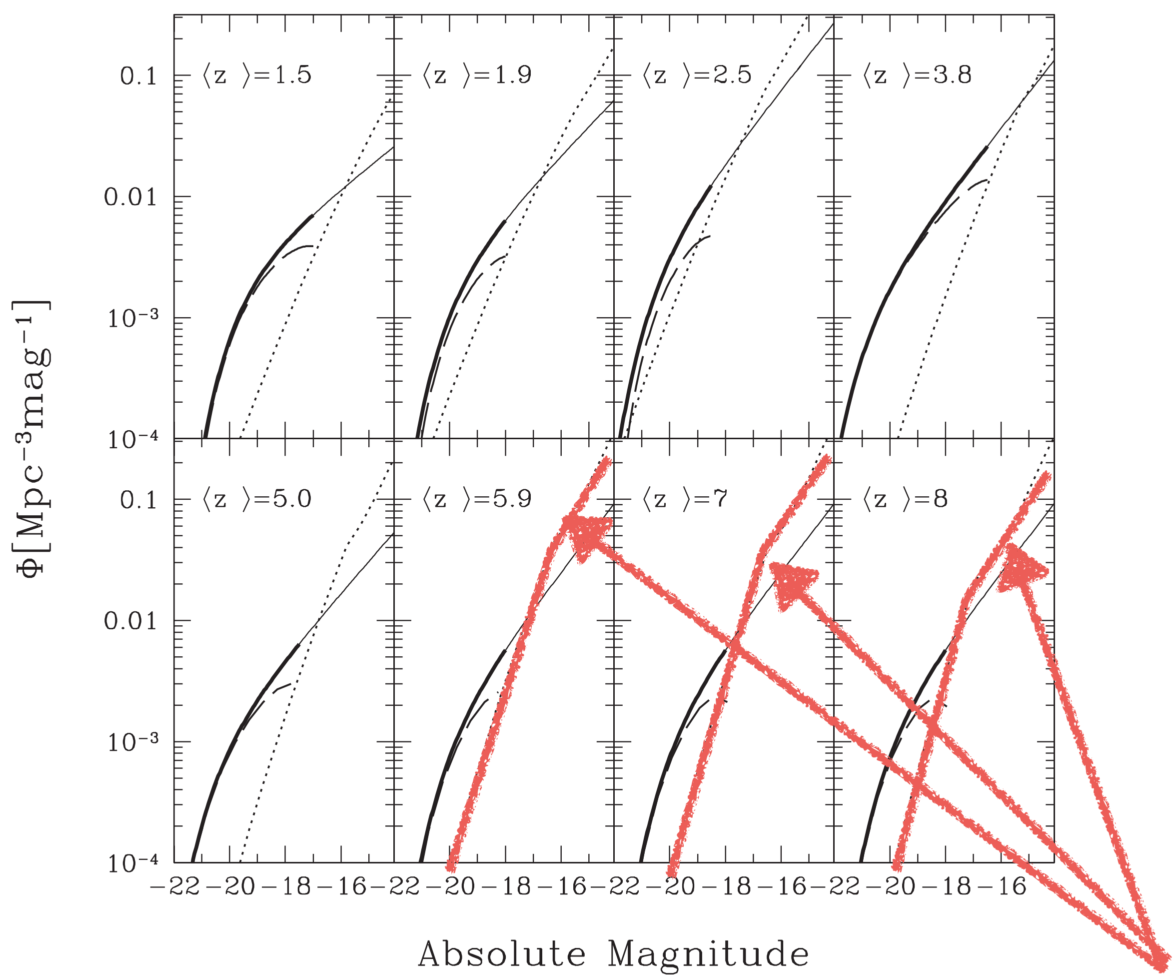
Ages of GCs
(Forbes & Bridges 2010)



Errors are about 1 Gyr
(MonteCarlo simulation)



Constrain how many GCs can form at any given redshift using LF and colors in HDF

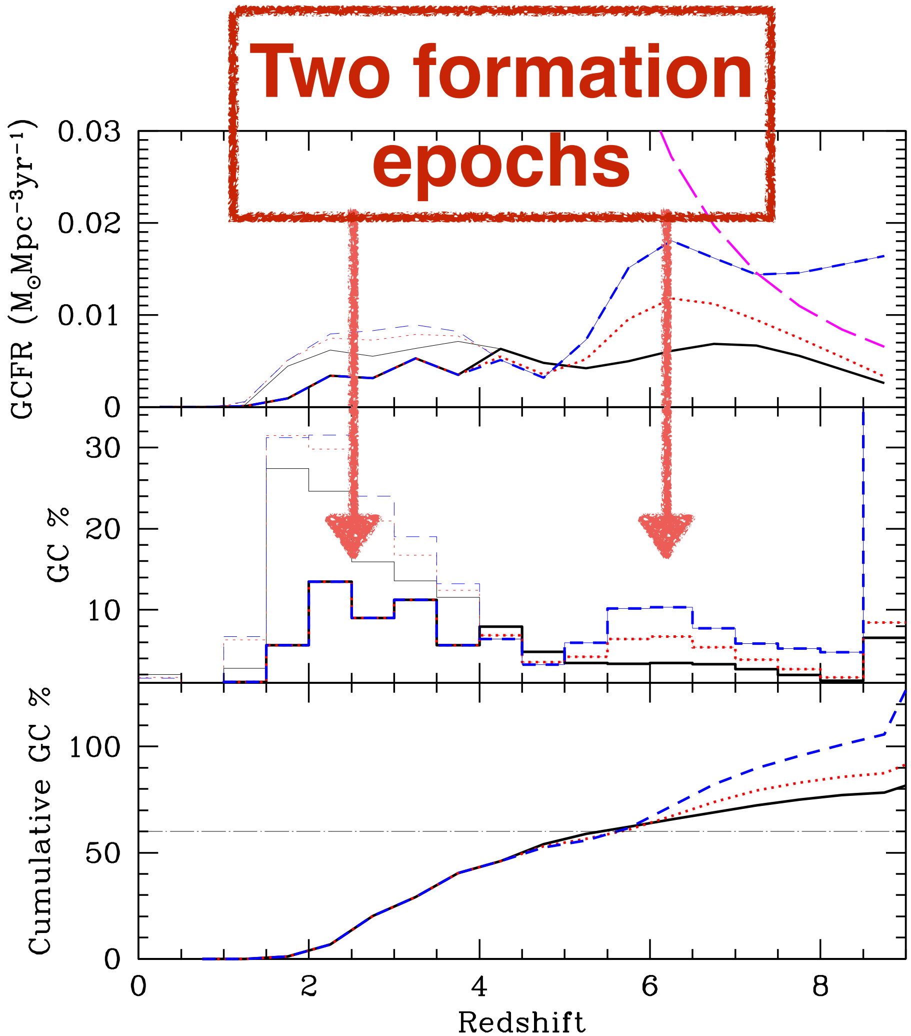


Katz & Ricotti (2013)

Fixed fraction of present day GCs forming at given z

Upper limits on GC formation rate and fraction of present day population

Katz & Ricotti (2013)



Formation rate

Formation fraction

Cumulative fraction

Gravitationally lensed galaxy at z~6

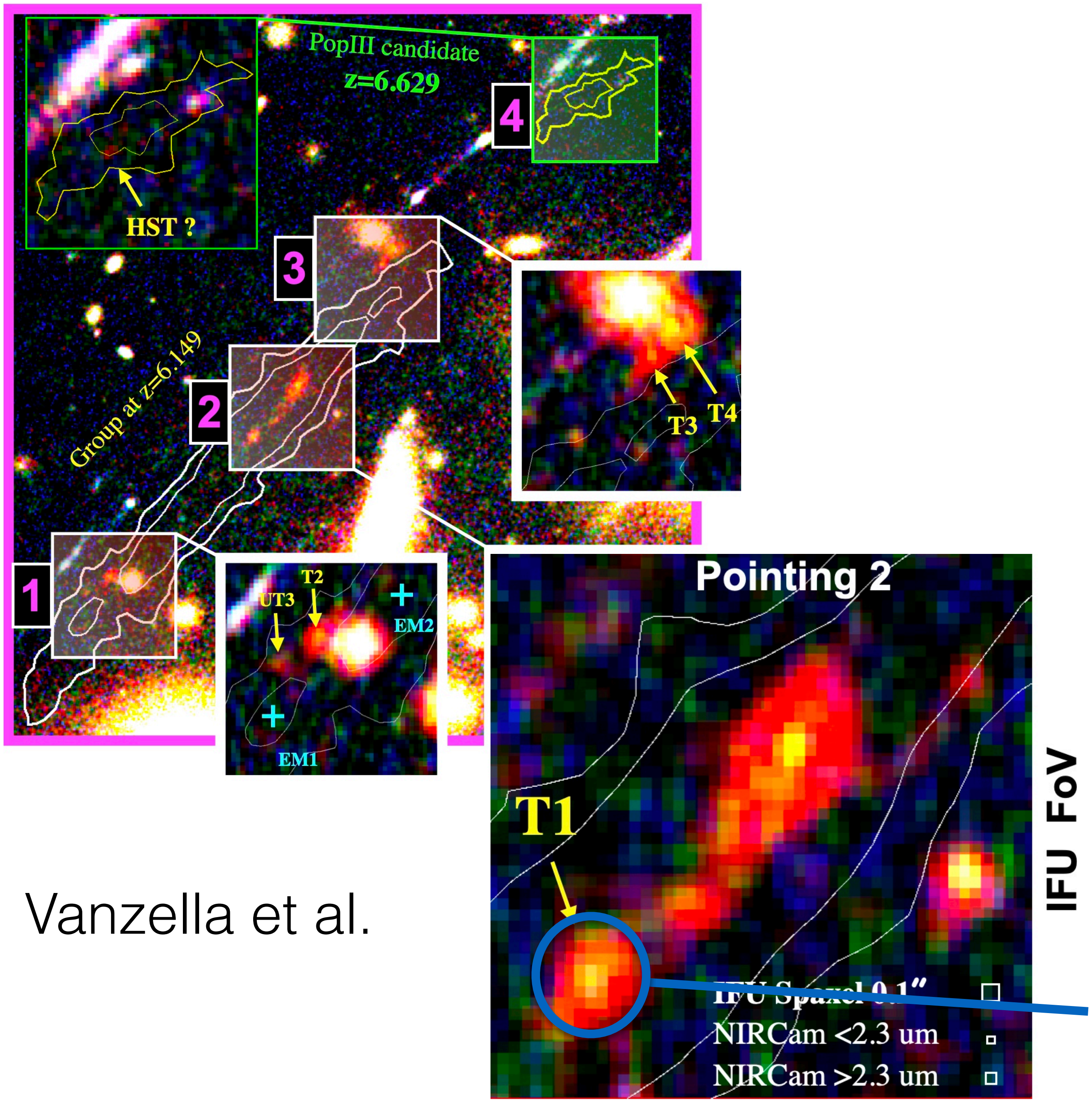


Table 1: list of tiny SF complexes

Obj/P	F105W Obs.	F105W Intr.	Mass Intr. ($\times 10^6 M_\odot$)	R_{eff} Intr. (pc)
D2/5	28.33	29.76	4.3	< 70
D1/2	26.49	29.66	21.8	150
D1/2 (core)	27.90	31.05	1.0	< 12
T1/2	27.88	31.34	2.8	16
T2/1	27.55	30.82	1.7	< 19
T3/3	28.15	30.98	2.1	< 15
T4/3	27.25	30.08	3.0	56
UT1/2	28.84	32.11	0.6	< 12
UT2/2	≈ 29	≈ 32.0	< 1	< 15
UT3/1	≈ 29	≈ 32.3	< 1	< 10
EM1/1	> 30.5	> 33.8	< 1	?
EM2/1	> 30.5	> 33.4	< 1	?
PopIII /4	> 31.0	> 35.0	?	?

Obj/P: object/Pointing; R_{eff}: effective radius
z=6.149 **Mass** : stellar mass
z=6.629 **F105W** : magnitude

Vanzella et al.

Diameter ~32 pc
Mass ~2.8x10^6 M$_{sun}$

PI: Eros Vanzella et al. …. including M.Ricotti

James Webb Space Telescope   Cycle 1 GO Proposal   **1908**

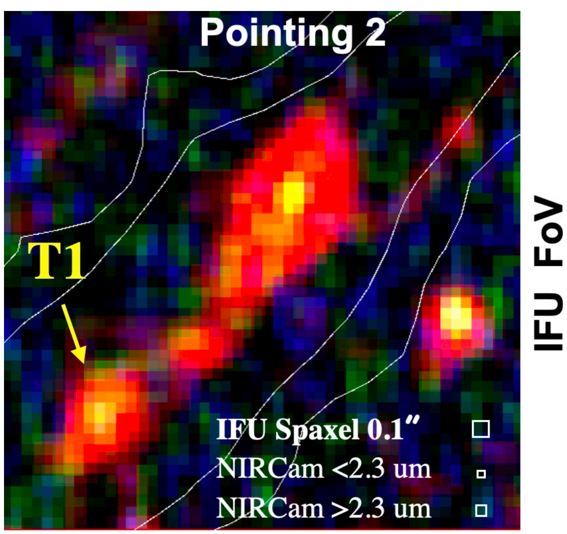
Constraining the nature of the first stellar complexes: globular cluster precursors and Population III stellar clusters at z~6-7

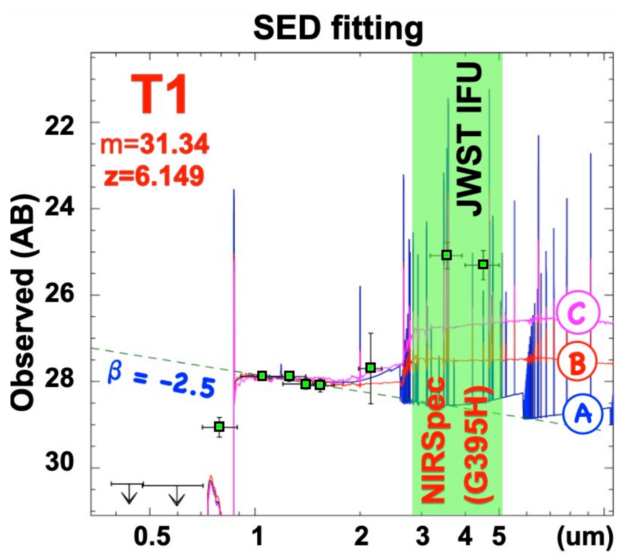
Scientific Category: Stellar Populations and the Interstellar Medium

Scientific Keywords: Dwarf Galaxies, Globular Star Clusters, Population III Stars, Star Clusters

Instruments: NIRSPEC

We are preparing for this data: see Chongchong He's talk on Tue





IFU data cube

30x30

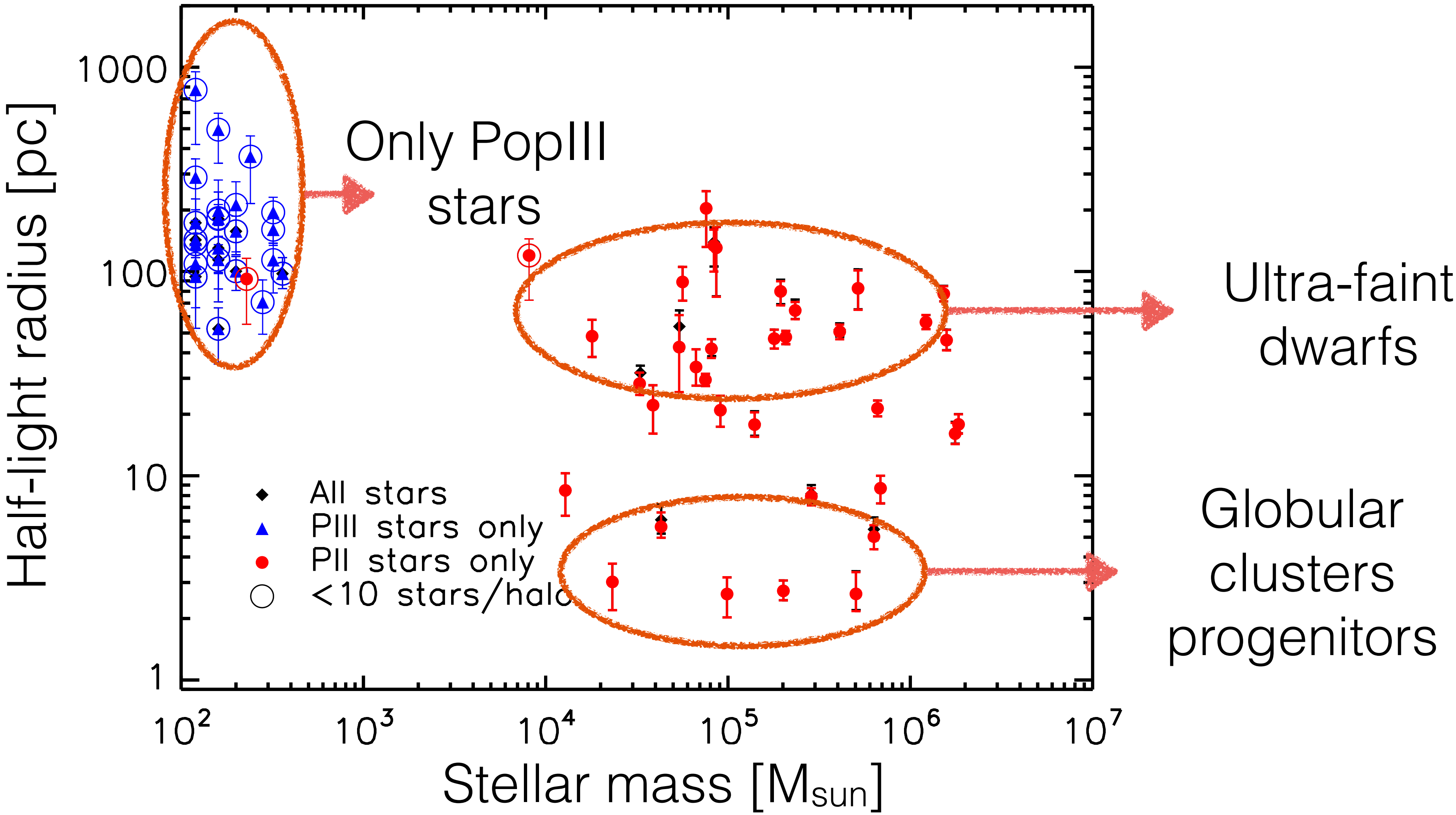
R~2700

Some Big Questions

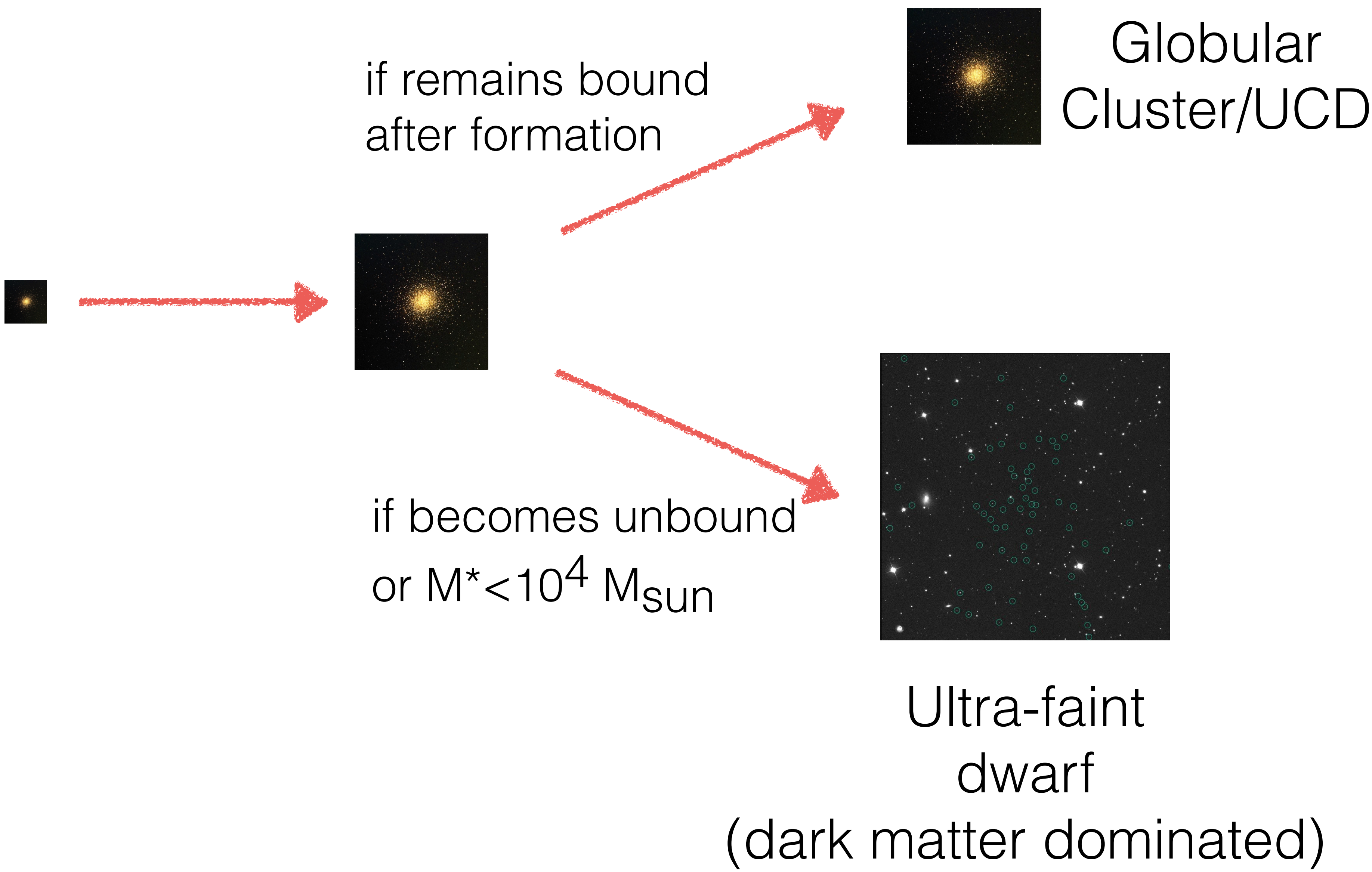
- Is GC the main star formation mode in the first galaxies?
    - Can HST and JWST detect their formation at z>6?
- **What is the connection to ultra-faint dwarfs?**
- Are GC drivers of reionization?

Dense clusters and Ultra-faint dwarfs at redshift z~9 in cosmological volume sims.

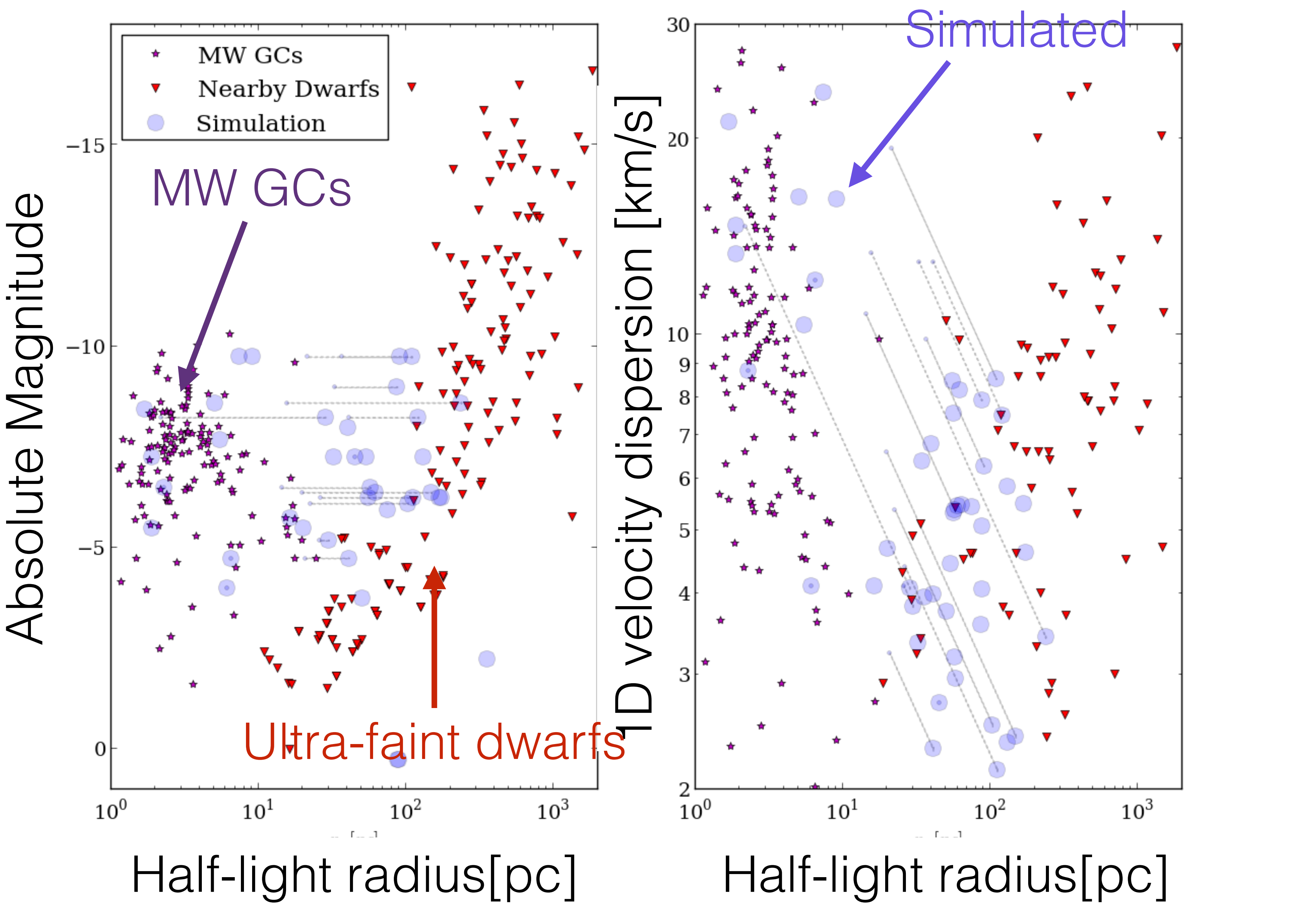
Ricotti, Parry & Gnedin 2016



Compact clusters and Ultra-faint dwarfs



Comparison to Nearby Dwarfs and MW GCs



We want to understand the physics in greater detail

Volume simulations have limited resolution (~1pc)

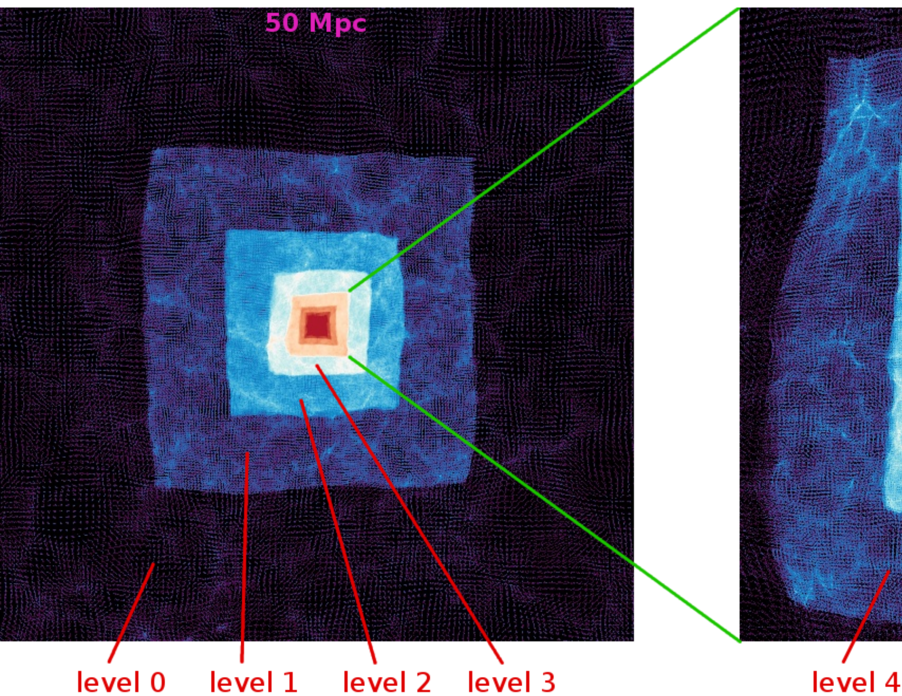
There are many open questions:

- What is the fraction of bound star clusters at formation (or what is the star formation efficiency in MC)?
- What is the star clusters dynamical evolution?
- Is the galaxy luminosity dominated by stars in proto-GCs or field stars (open clusters)
- Is the escaping ionizing radiation dominated by proto-GCs or field stars?

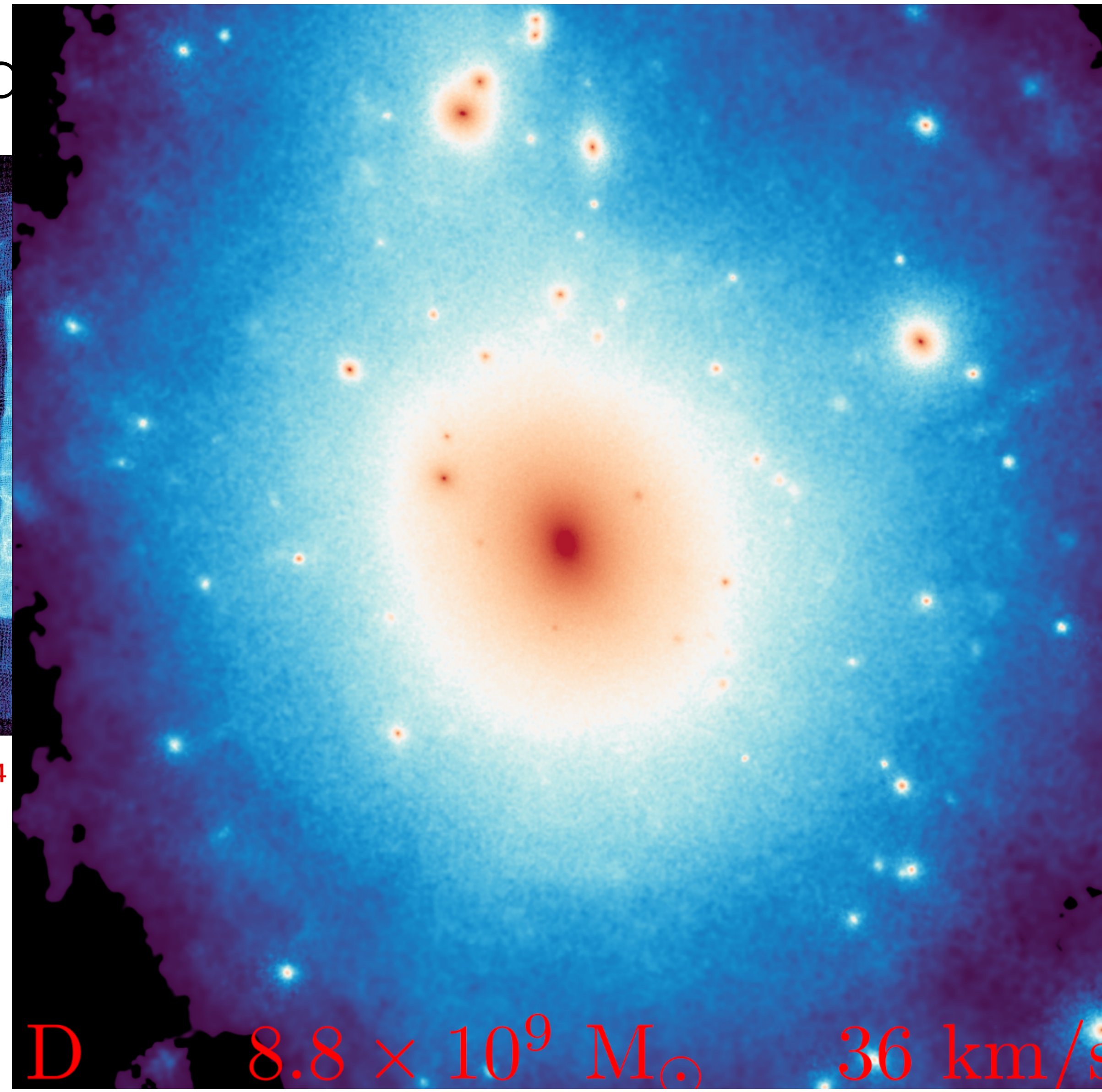
Zoom simulations of a single galaxy

(Work in progress by Fred Garcia et al.)

Dark matter structure and



Halo D at z=0



	value	note
Simulation code	RAMSES-RT (Teyssier 2002, Rosdahl&Teyssier 2015)	Cosmological AMR (M)HD, Moment method RT (M1 closure) , DM particle, sink (BH) particle, stellar radiation, SN feedback, non-equilibrium chemistry/cooling/heating
IC code	MUSIC (Hahn&Abel 2011)	Generate initial condition at z = 127 w/ zoom technique
Box size	0.3 h^{-1} cMpc (zoom-region)	35 h^{-1}cMpc (base-box)
DM mass	800 M_{sun} (zoom-region)	10^{11} M_{sun} (base-box)
Stars mass	10 M_{sun}	Constant (no IMF sampling)
Refinement	N_J = 8 (Δx >1pc), 4 (Δx <1pc)	at least N_J cells per Jeans length
Cell size	Δx_{min} = 0.15 pc * ((1+z)/10)	AMR level = 25
Star formation	$n_{SF} = 5\times10^4$ cm^{-3} * $((1+z)/10)^2$ * (T/100 K)	Same as refinement condition to create AMR level = 26 (not existing)

Implementation of sub-grid physics

low-metal (Pop II) stellar clusters

- **formation criteria**: $n_H > n_{SF}$ and $Z > Z_{cr}$

  $$n_{SF} = 5\times10^4\,\mathrm{cm}^{-3} * ((1+z)/10)^2 * (T/100\ \mathrm{K}), \qquad Z_{cr} = 10^{-5}\,Z_{sun}$$

- **size** of star forming cloud (stellar cluster) : R_{cl}

  $$n_{1D}(R_{cl}) = 1/10 * n_{SF}$$

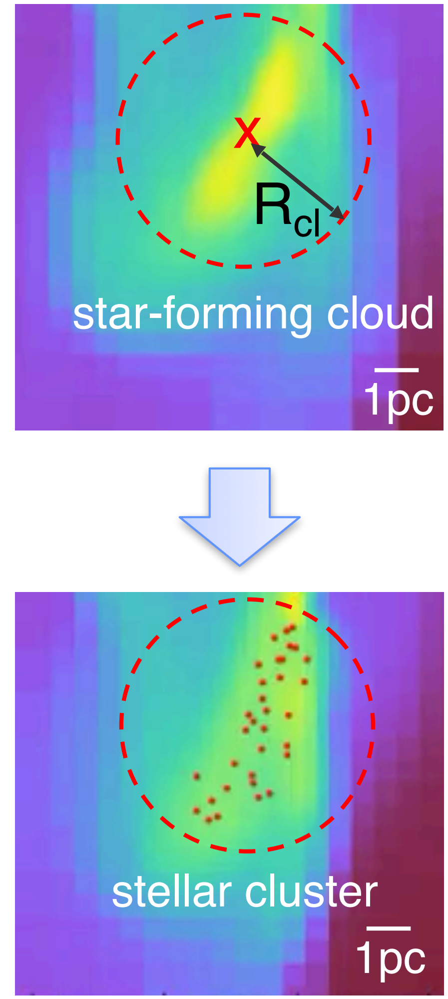
- **gas-to-star** conversion efficiency:

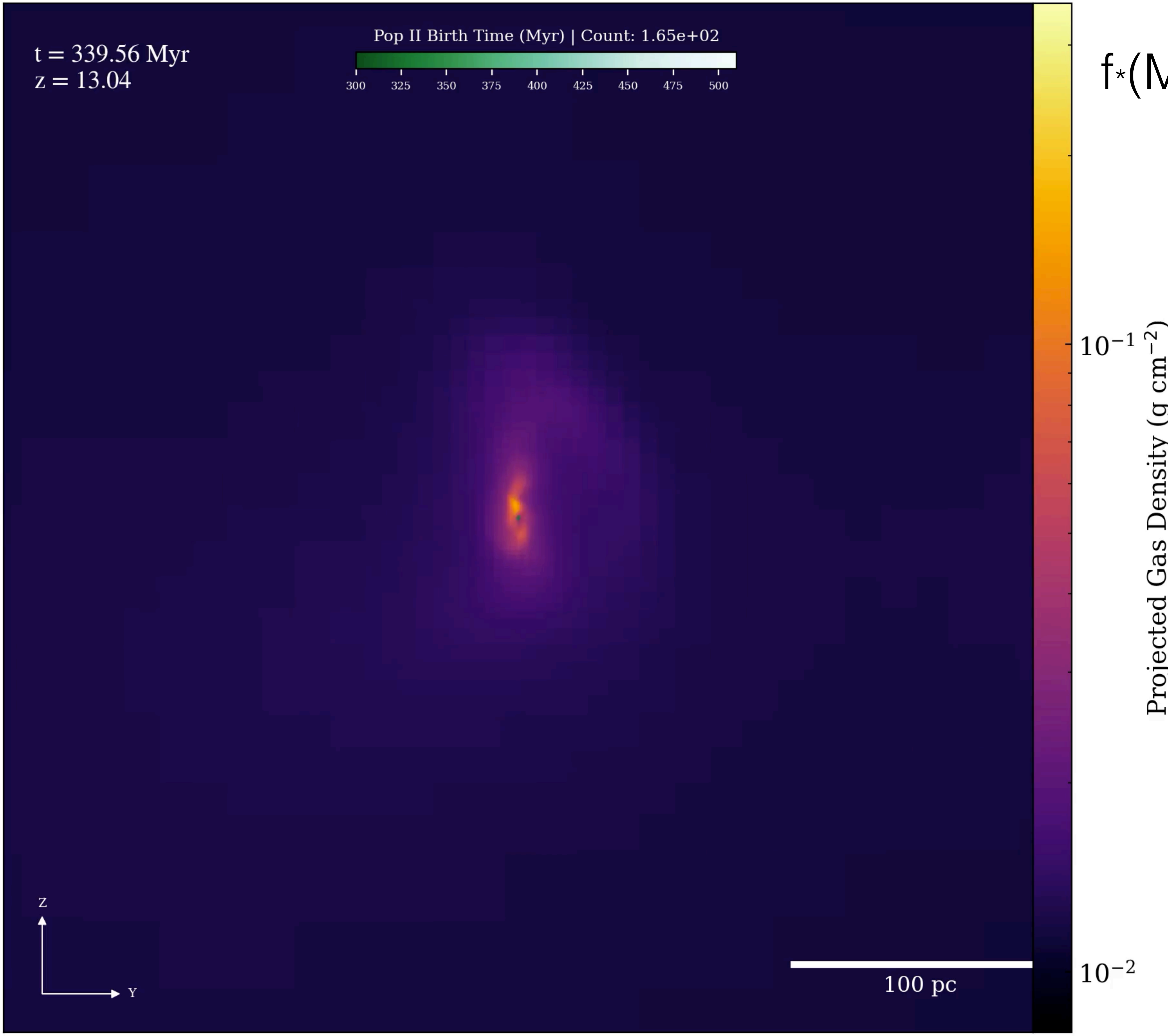
  A) f_{star} = constant (70% and 35%)
  B) $f_{star}(M_{cl}, R_{cl}, Z_{cl})$ based on cloud-scale simulations (He, Ricotti, Geen 2019)

  (see also Starforge project, Gavagnin +, Fukushima +, Lee +, Kim +)

- conversion from star-forming cloud to stellar cluster

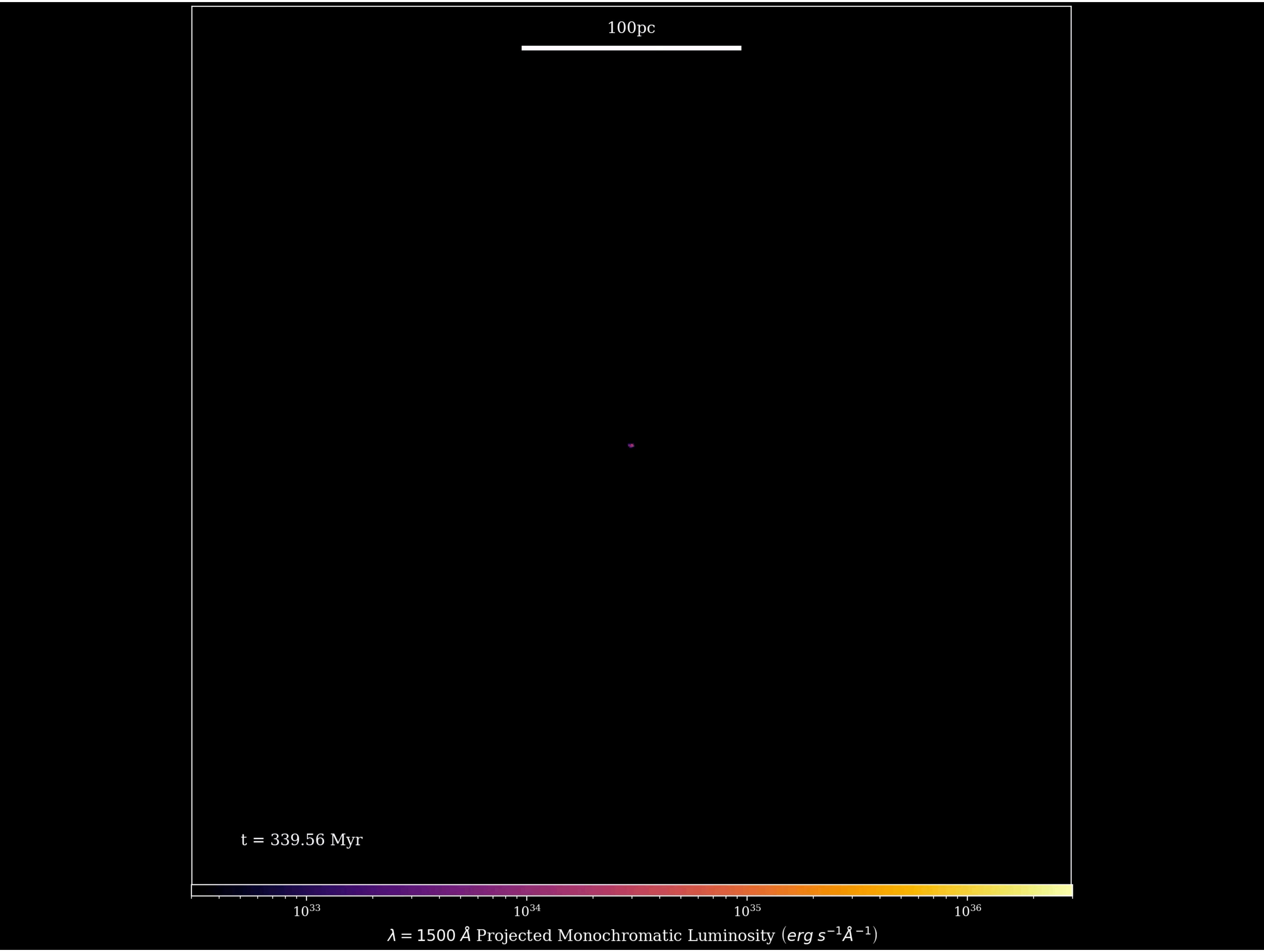
  mass-weighted scattering of PopII particles within $r < R_{cl}$

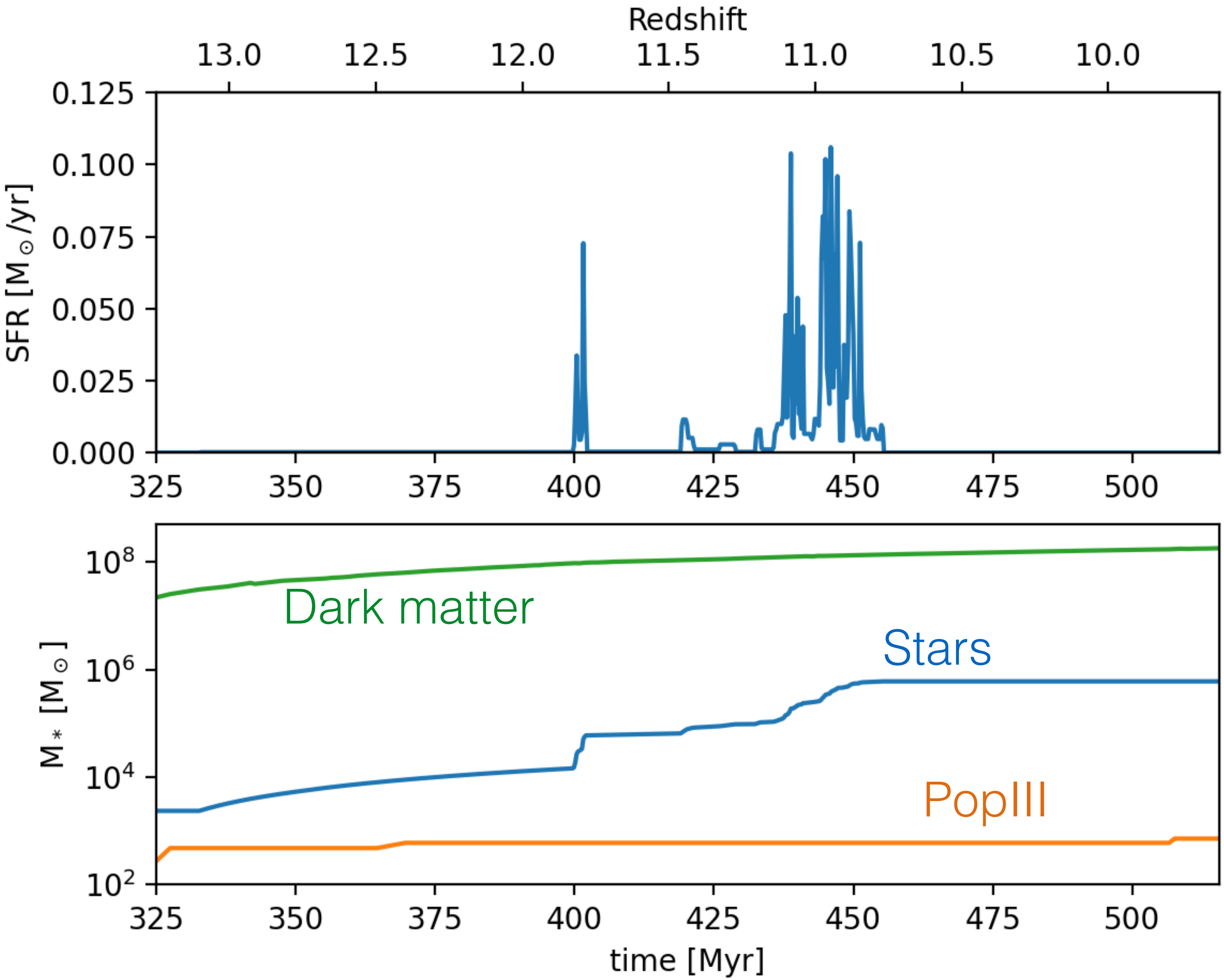




t = 339.56 Myr
z = 13.04
Pop II Birth Time (Myr) | Count: 1.65e+02
300
325
350
375
400
425
450
475
500
Z
Y
100 pc
10^{-1}
10^{-2}
Projected Gas Density (g cm^{-2})

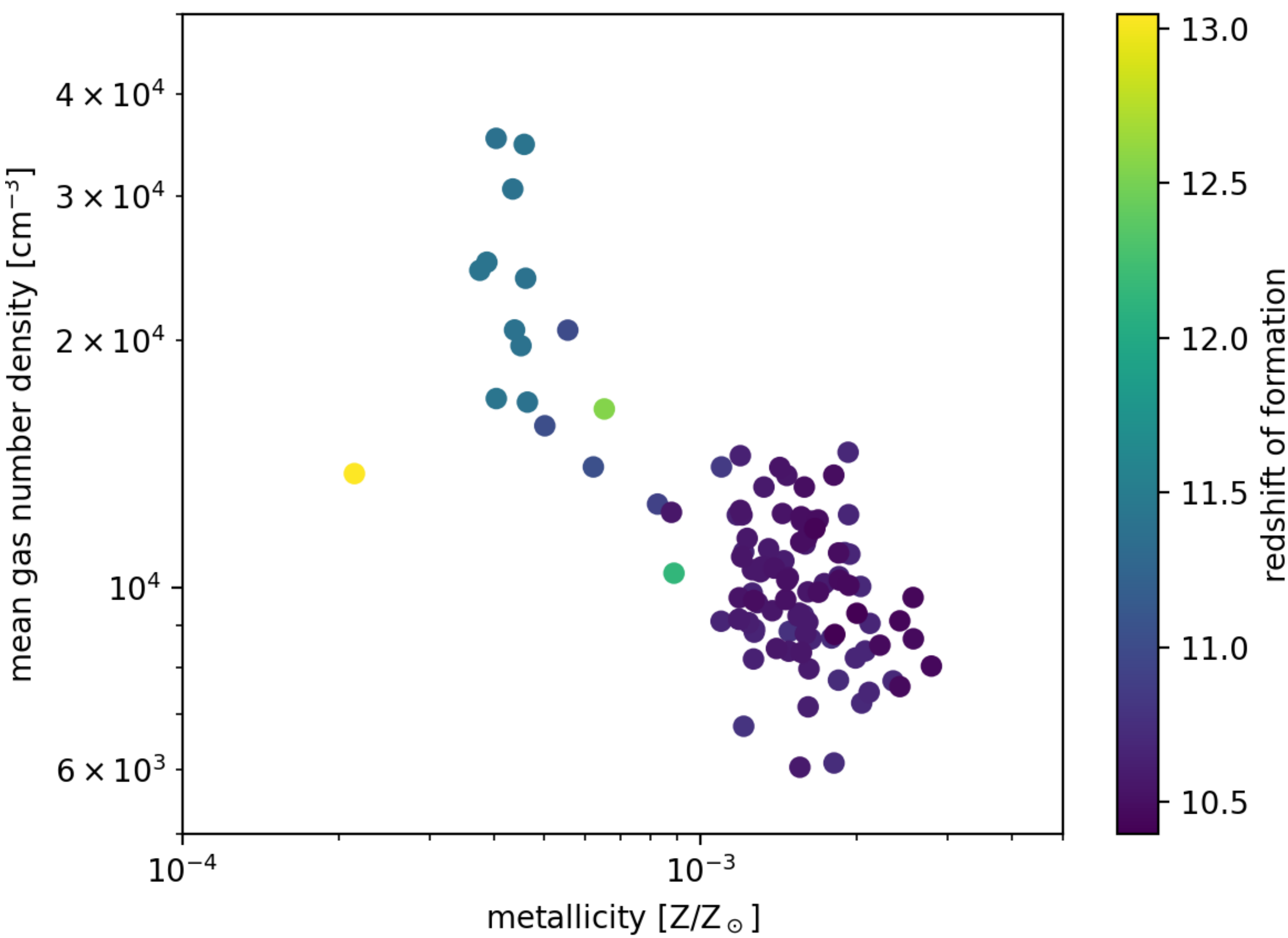
f*(MC)=70%


100pc
t = 339.56 Myr
10^{33}
10^{34}
10^{35}
10^{36}
$\lambda = 1500$ Å Projected Monochromatic Luminosity $(erg\ s^{-1}Å^{-1})$



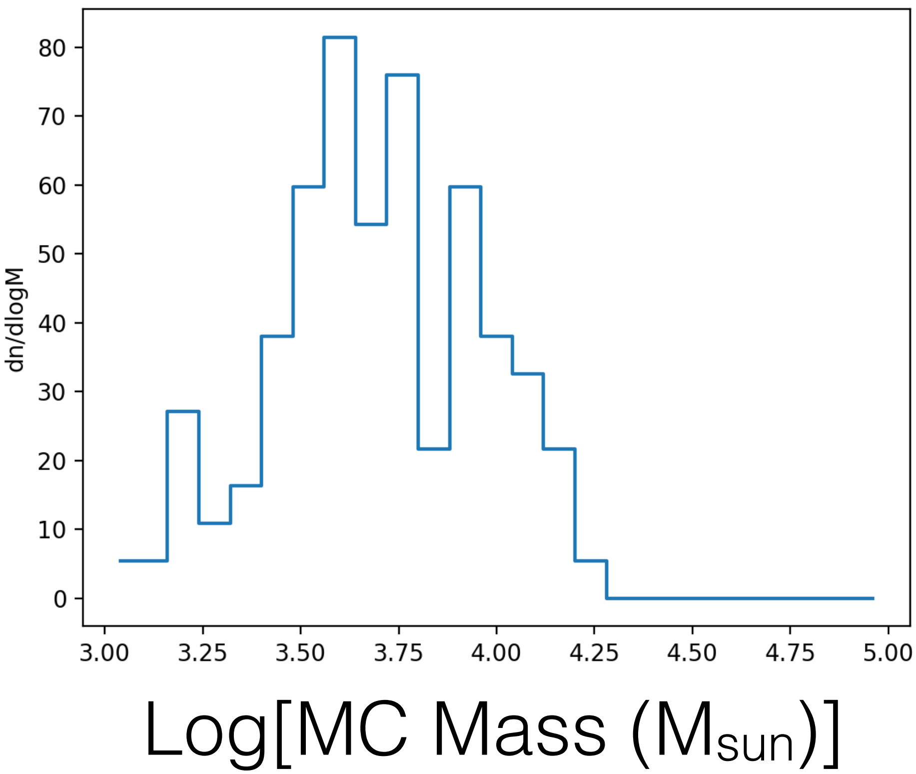
Redshift
13.0
12.5
12.0
11.5
11.0
10.5
10.0
SFR [M$_\odot$/yr]
0.125
0.100
0.075
0.050
0.025
0.000
325
350
375
400
425
450
475
500
Dark matter
Stars
PopIII
M$_*$ [M$_\odot$]
10^8
10^6
10^4
10^2
time [Myr]

Cloud density-metallicity relation

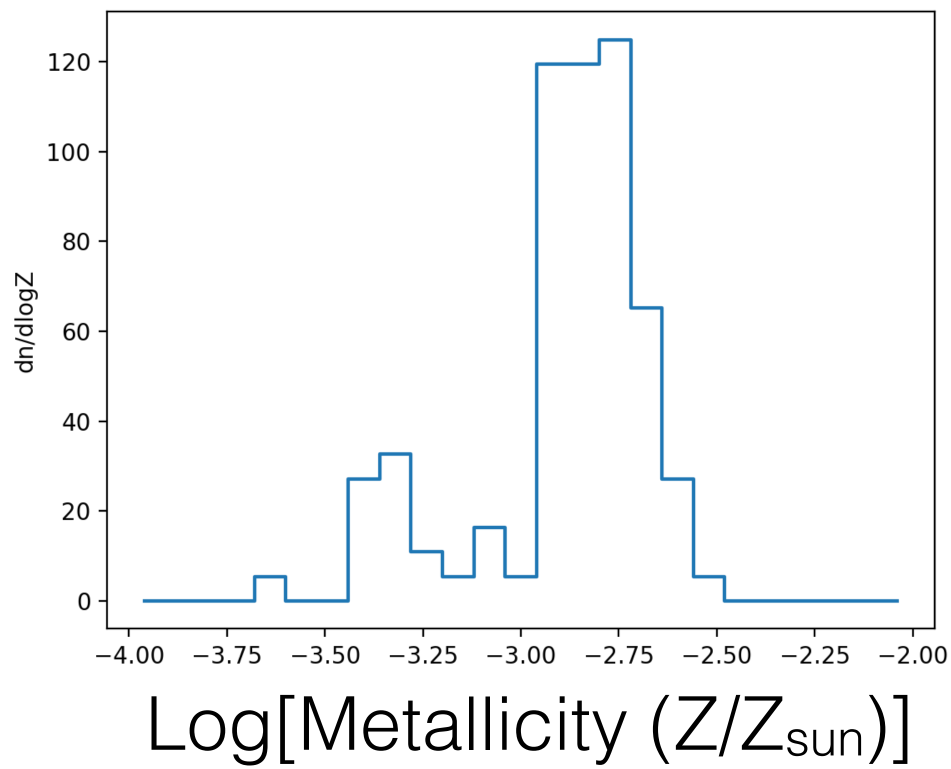


Molecular Clouds Mass function and metallicity distribution

Molecular clouds mass function

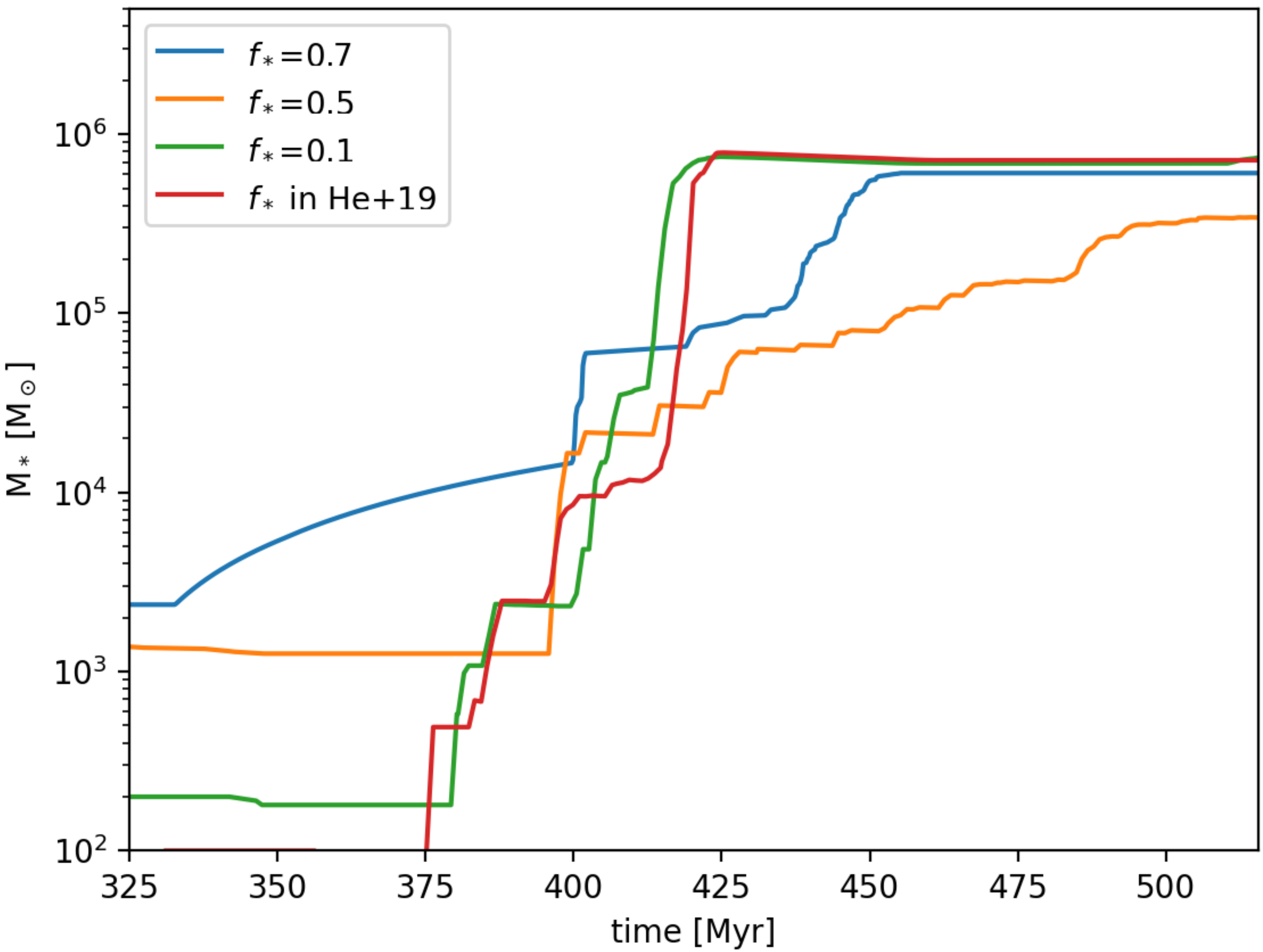


Clouds metallicity distribution



What is the SFE in star forming molecular clouds?

- Star formation in the galaxy is self-regulated by feedback: changing the sub-grid SFE does not affect much the overall mass in stars in the galaxy.



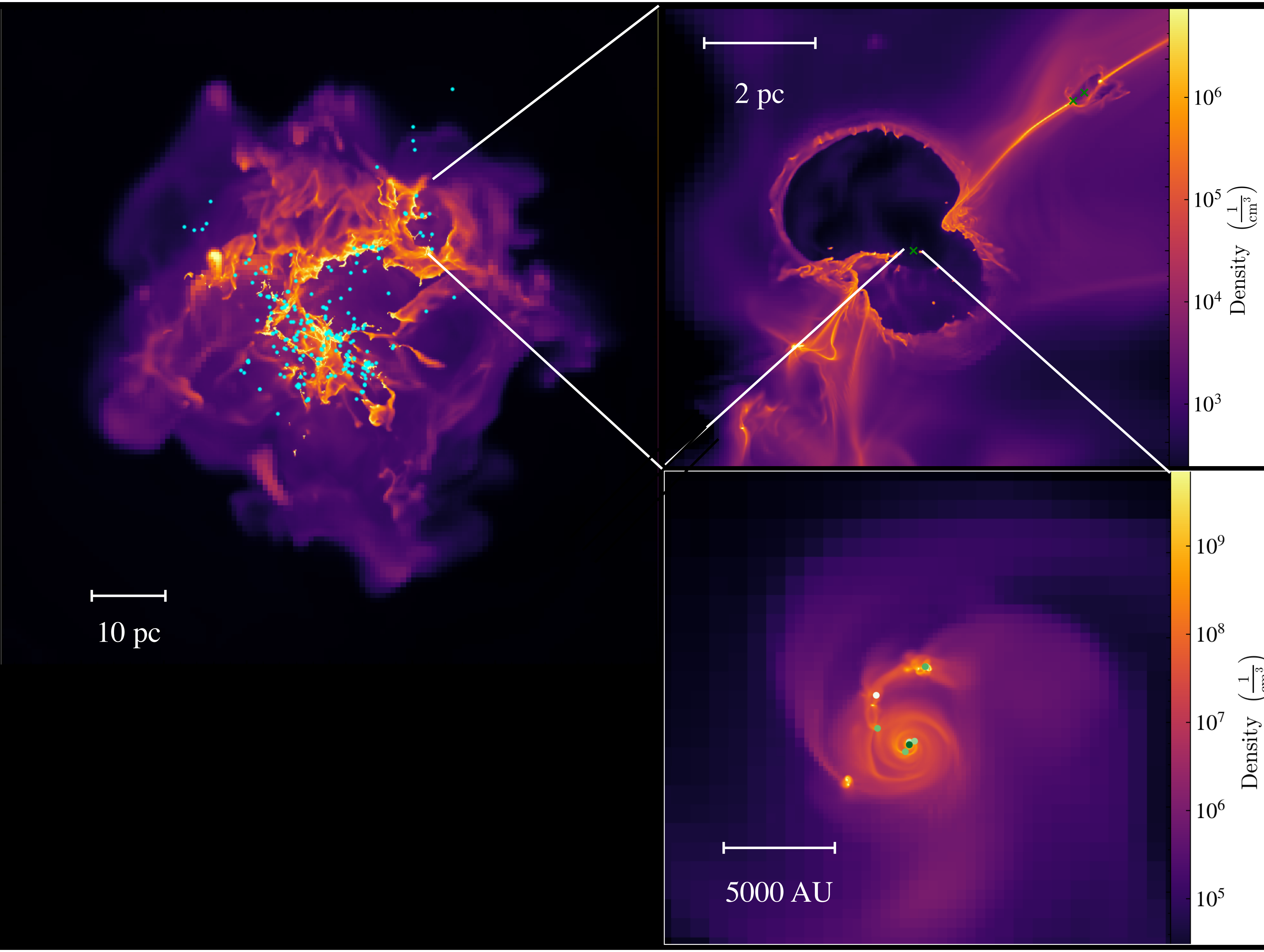
f_*=0.7
f_*=0.5
f_*=0.1
f_* in He+19
M_* [$M_\odot$]
10^2
10^3
10^4
10^5
10^6
325
350
375
400
425
450
475
500
time [Myr]

What is the SFE in star forming molecular clouds?

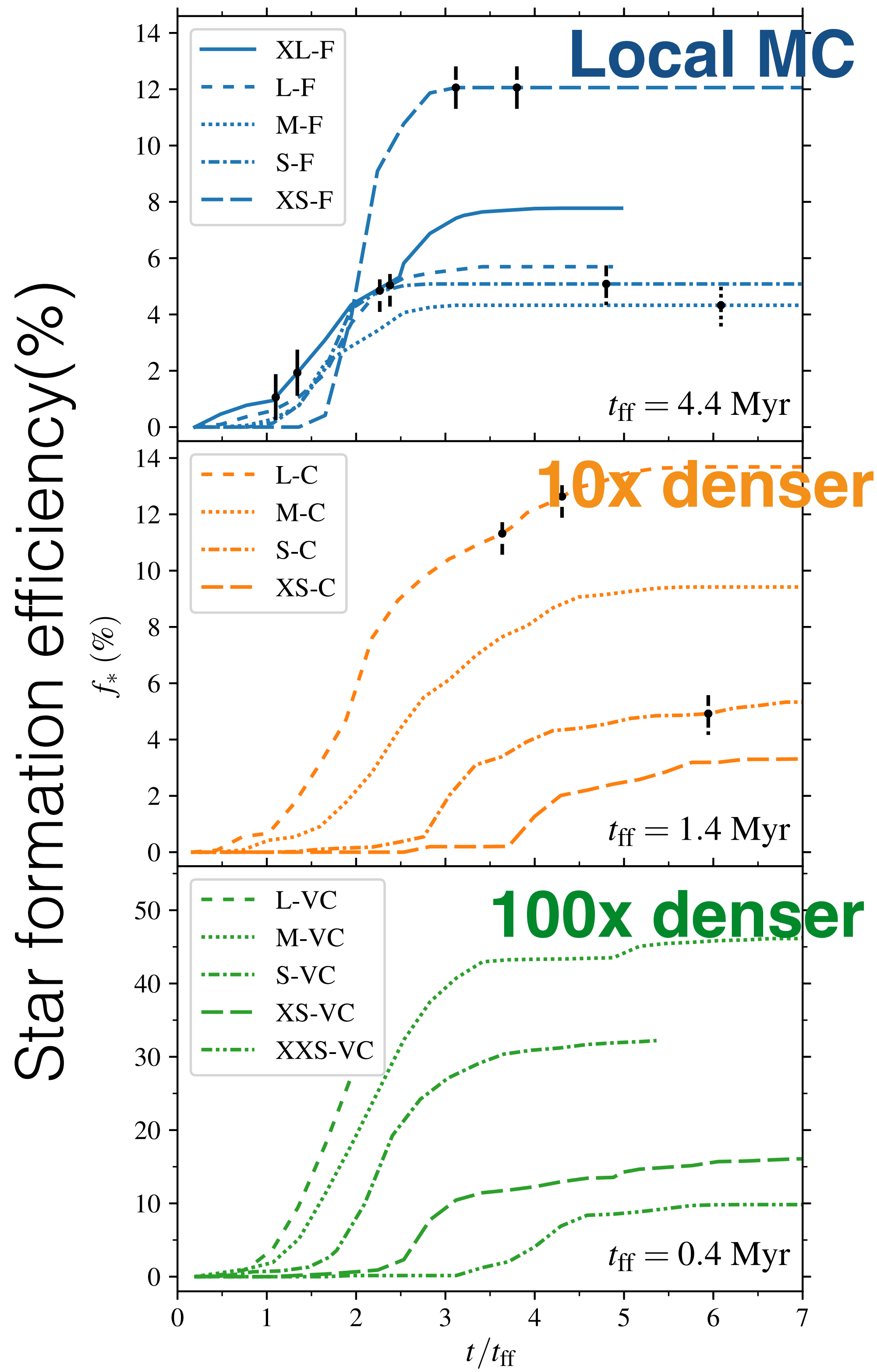
- Star formation in the galaxy is self-regulated by feedback: changing the sub-grid SFE does not affect much the overall mass in stars in the galaxy.

- However, the SFE determines the fraction star clusters that are bound/unbound (proto-GC/open clusters)

- **We rely on results of (idealized IC) molecular cloud scale simulations (see He, Ricotti & Geen 2019)**

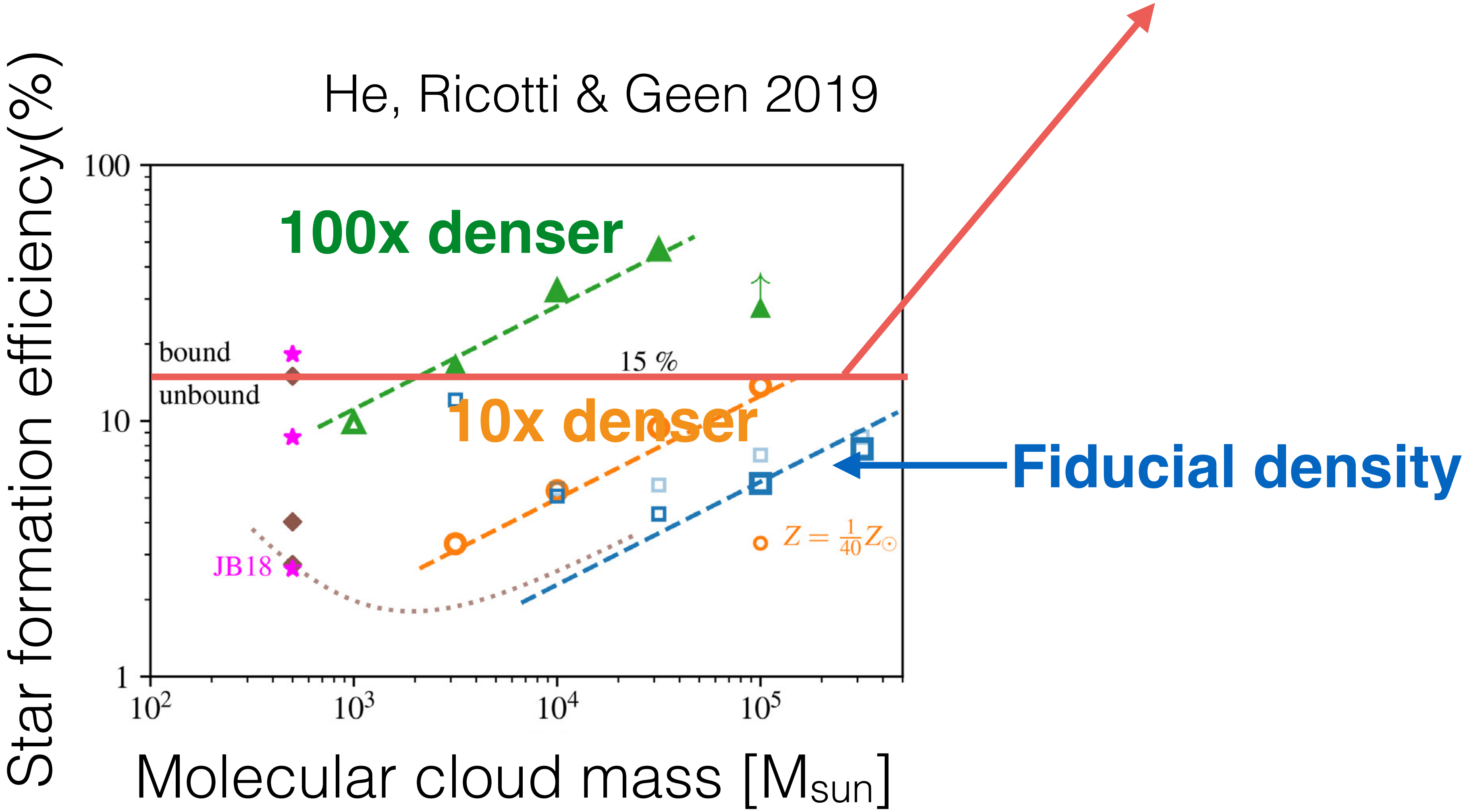

10 pc
2 pc
5000 AU
Density $\left(\frac{1}{cm^3}\right)$
10^3
10^4
10^5
10^6
Density $\left(\frac{1}{cm^3}\right)$
10^5
10^6
10^7
10^8
10^9

Methods and Grid of Simulations



- MHD+RT simulations with ~100 to 1000 AU resolution
- Turbulent MCs with range of cloud masses and densities (virial ratio 0.4)
- Resolve formation of massive stars and self-consistently include UV radiation feedback (no SN explosions)
- Empirical prescription: mass of massive stars ~1/3 of sink particles mass

Bound Stellar Clusters
Globular Clusters Progenitors

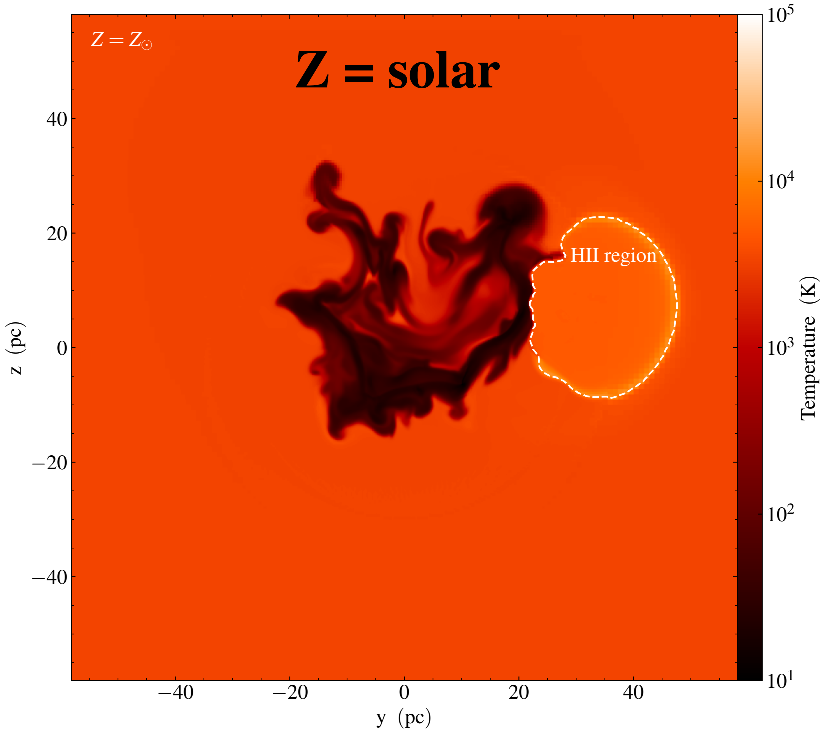


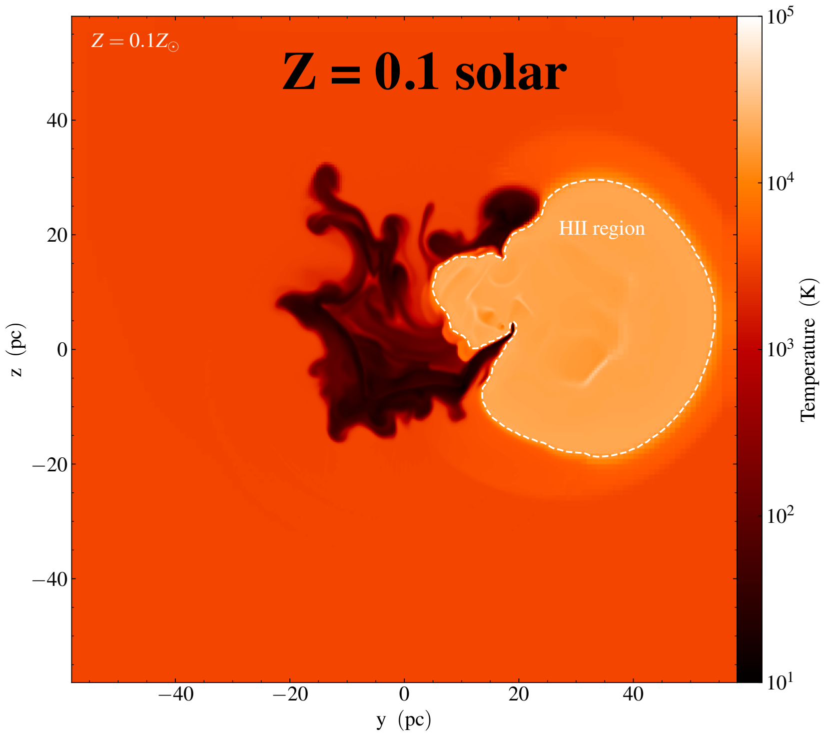
Fitting function

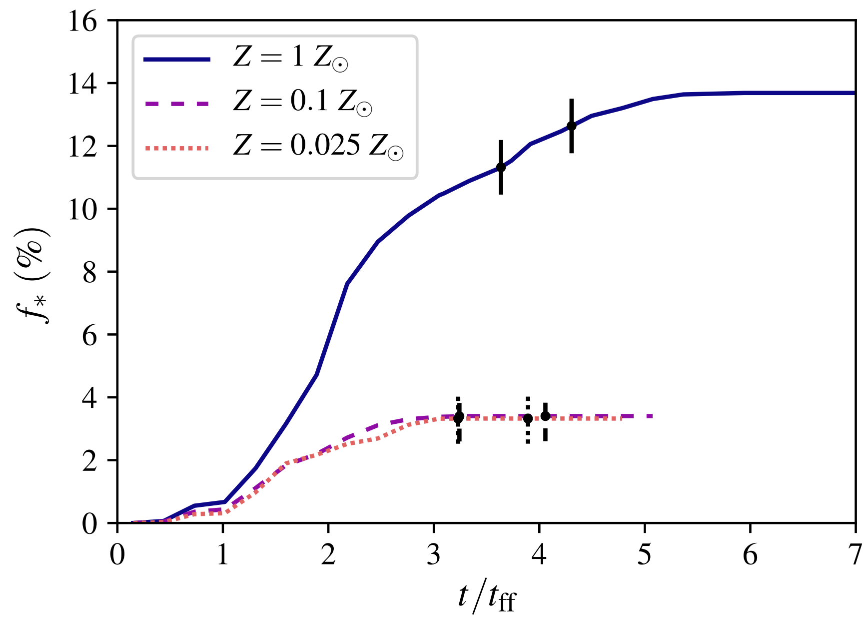
$$f_{*,\mathrm{tot}} = 2.0 \text{ per cent} \left(\frac{m_{\mathrm{gas}}}{10^4 \ \mathrm{M_\odot}} \right)^{0.4} \left(1 + \frac{\overline{n}_{\mathrm{gas}}}{n_{\mathrm{cri}}} \right)^{0.91} .$$

$$n_{\mathrm{cri}} \approx 10^3 \quad \mathrm{cm}^{-3}$$

Reducing gas Metallicity







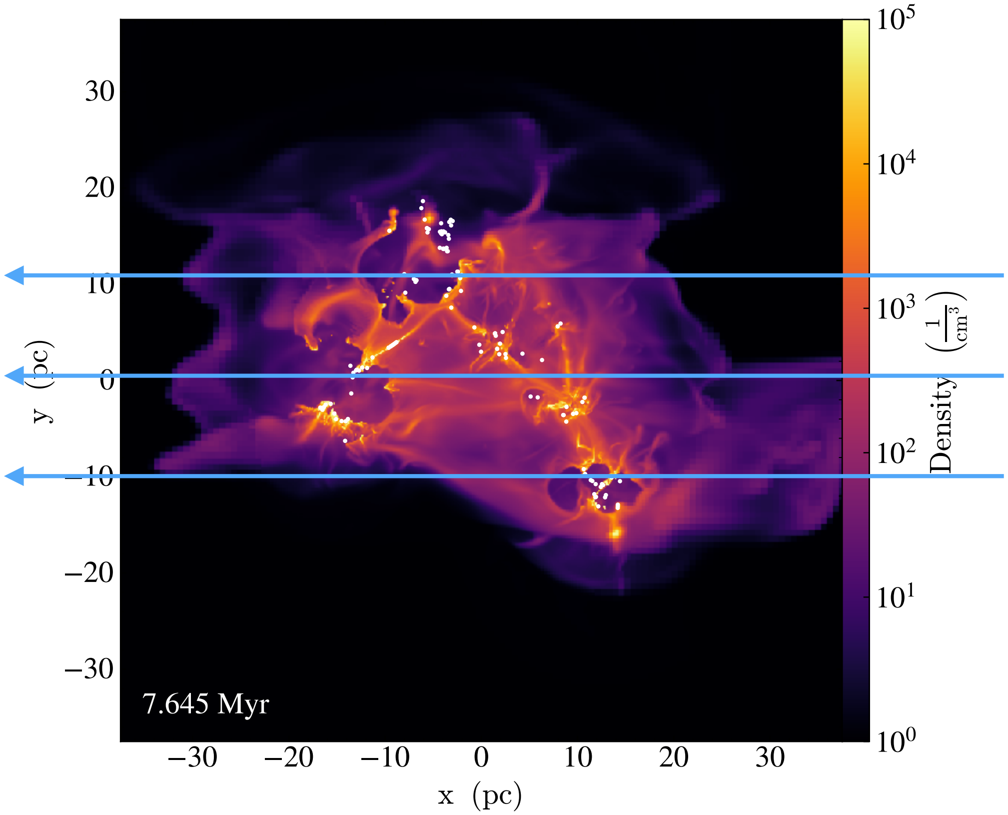
f_* reduced by factor of 5

stronger feedback at low metallicity (due to hotter HII regions)

Increasing magnetic field strength

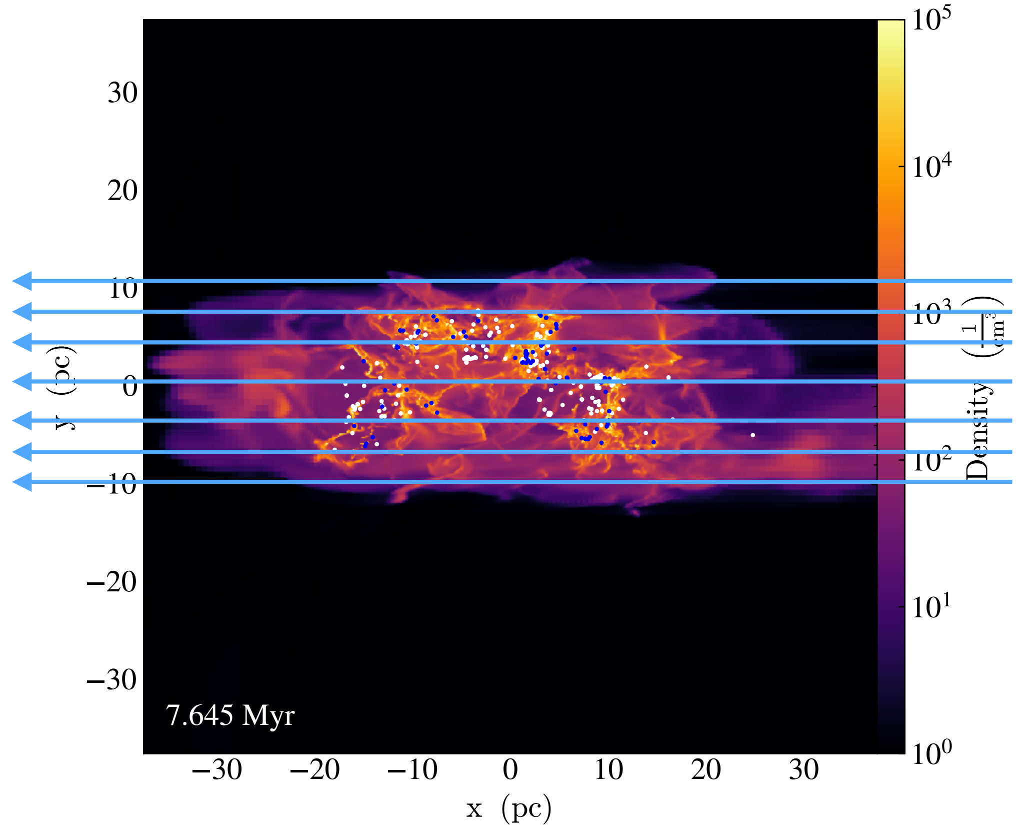
(Work in progress by Ronan Hix)

Fiducial

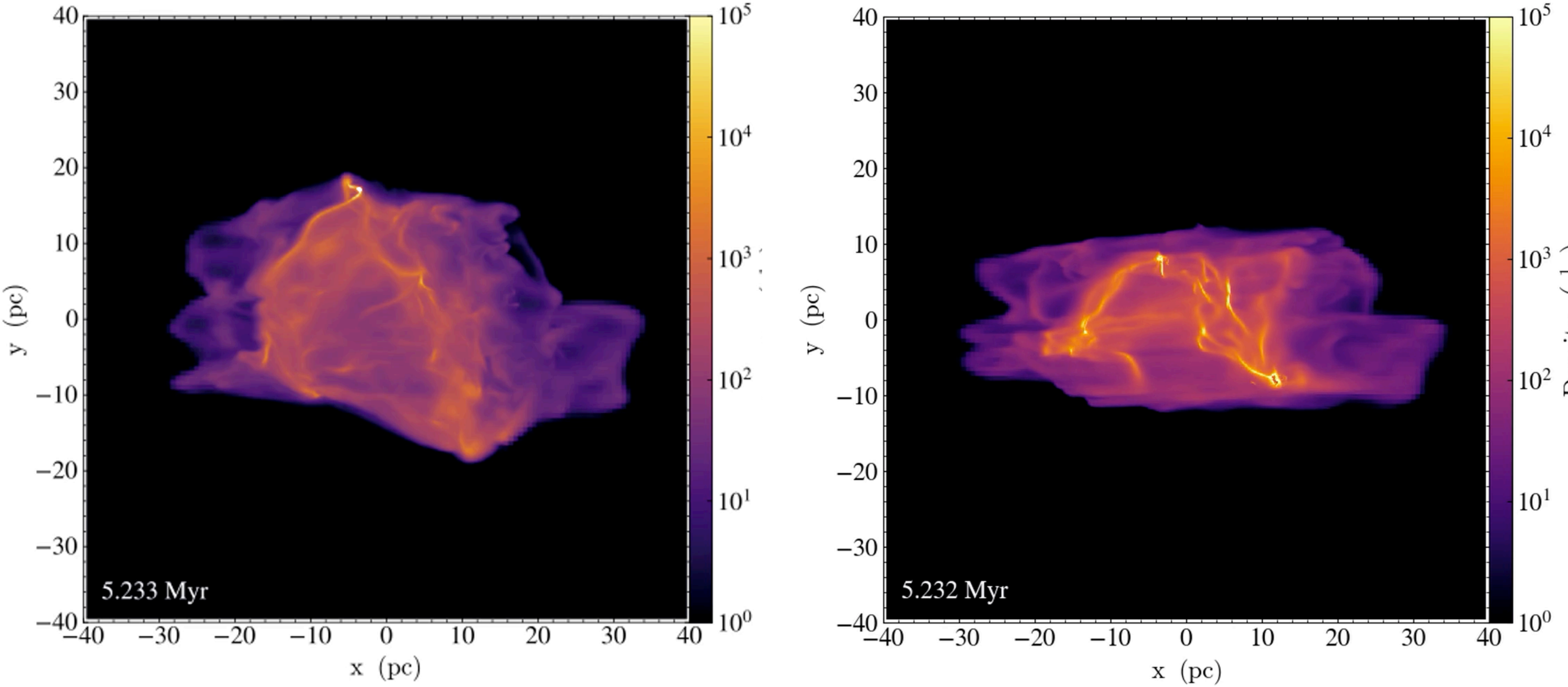


$3\mu G$ at $n \sim 200cm^{-3}$

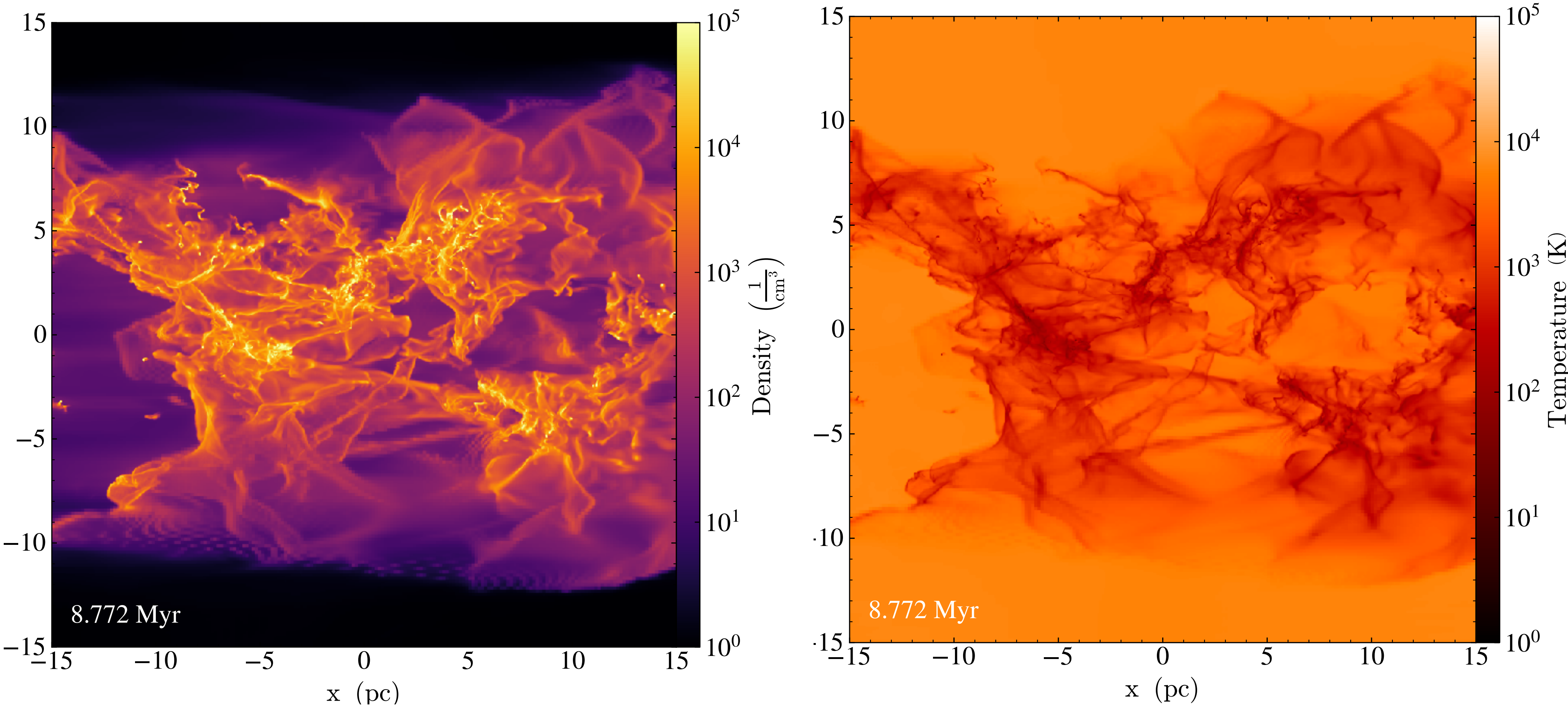
5x B-field



$15\mu G$ at $n \sim 200cm^{-3}$

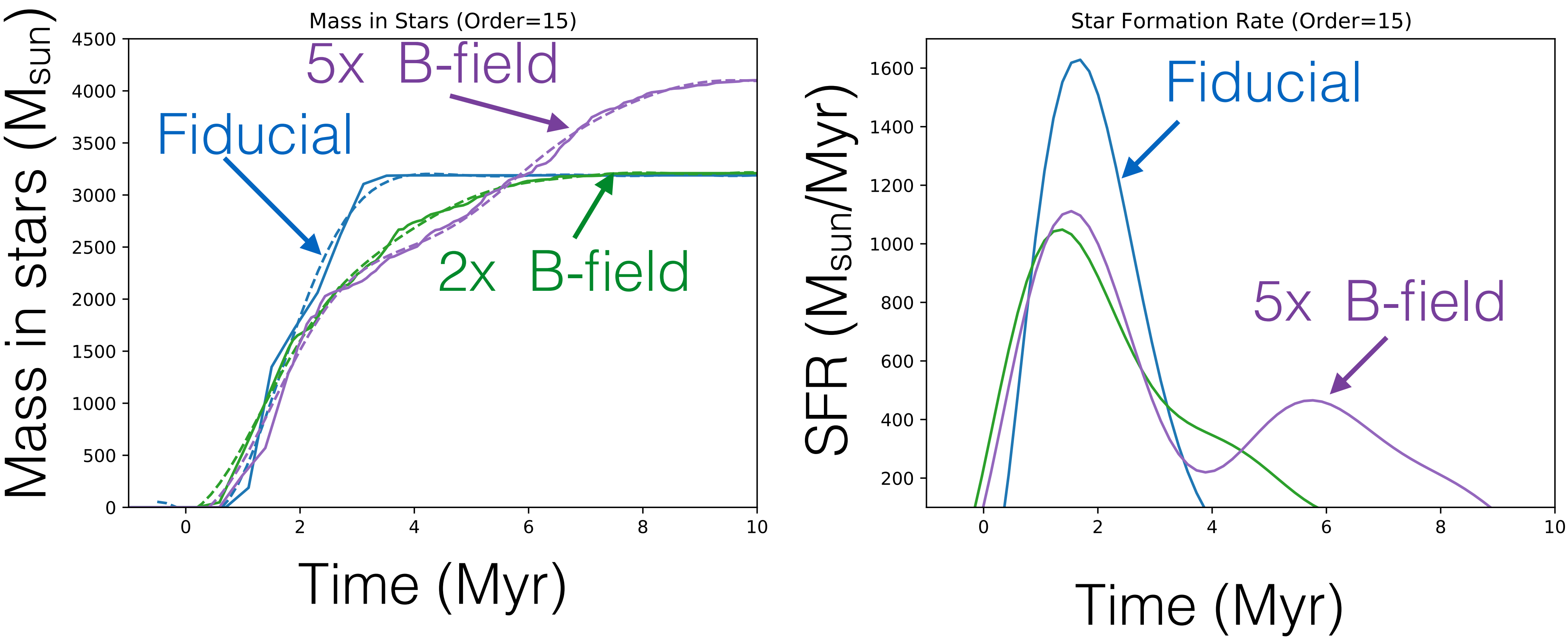


5.233 Myr
5.232 Myr
x (pc)
y (pc)

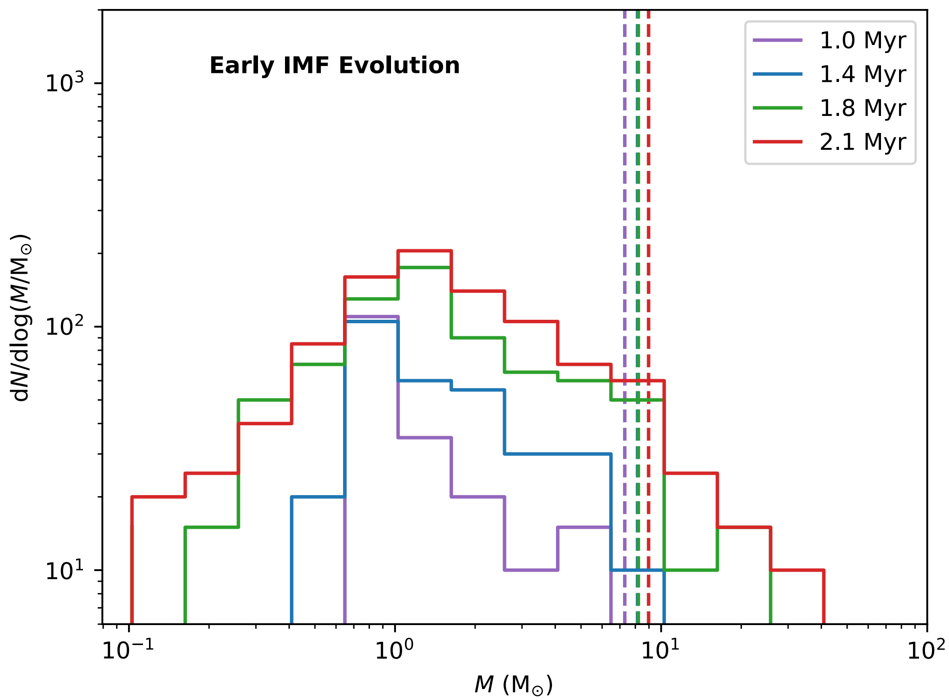

8.772 Myr
x (pc)
Density $\left(\frac{1}{cm^3}\right)$
8.772 Myr
x (pc)
Temperature (K)

Effects on the SFE and SFR

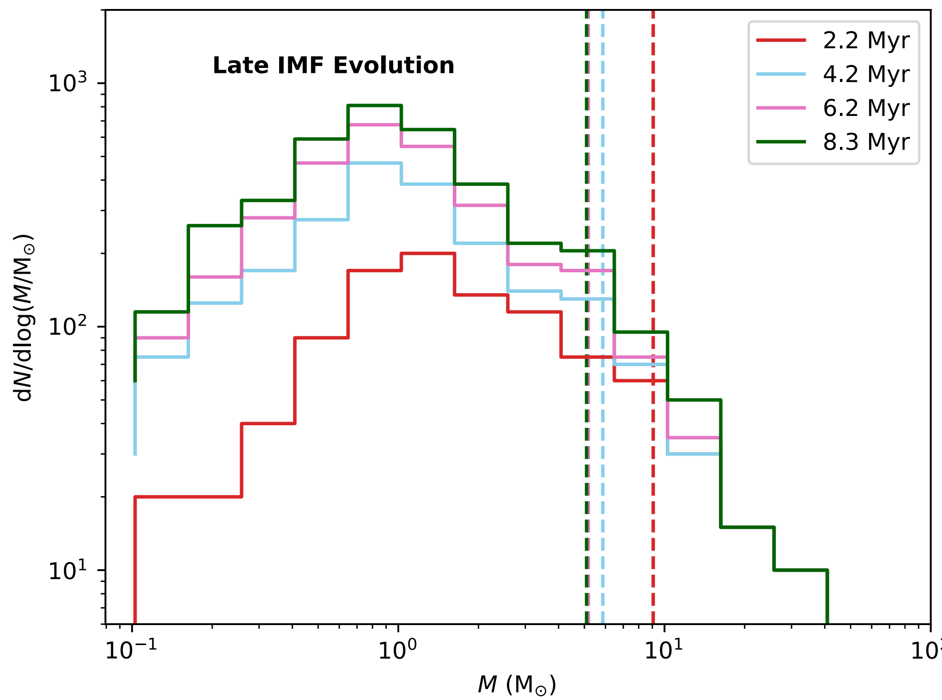
SFR: bimodal!



Effects on IMF in stronger B-field



Phase I:
Self-similar stars formation

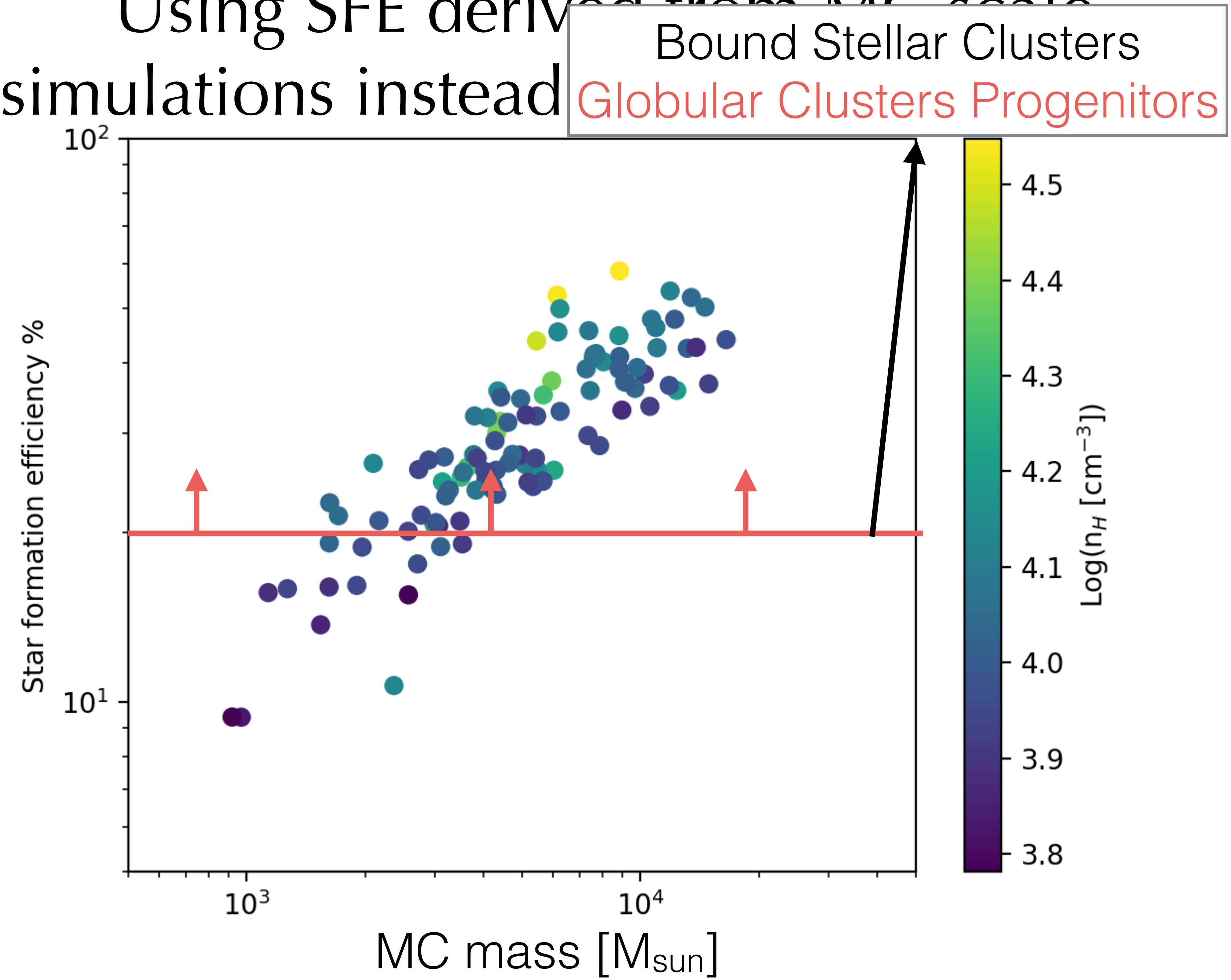


Phase II:
Low mass stars formation

Getting back to cosmological zoom simulations

If we use SFE from He, Ricotti and Geen 2019

Using SFE derived from MC scale simulations instead



Summary

- Preliminary results suggest proto-GC formation was the dominant mode of star formation in the first galaxies. But too small mass to survive for a Hubble time?

- Proto-GCs at z~6 may be the dominant sources of reionization

- We are preparing for JWST data on proto-GCs in z~6 lensed galaxies:

  - Galaxy scale simulations

  - Molecular cloud scale simulations

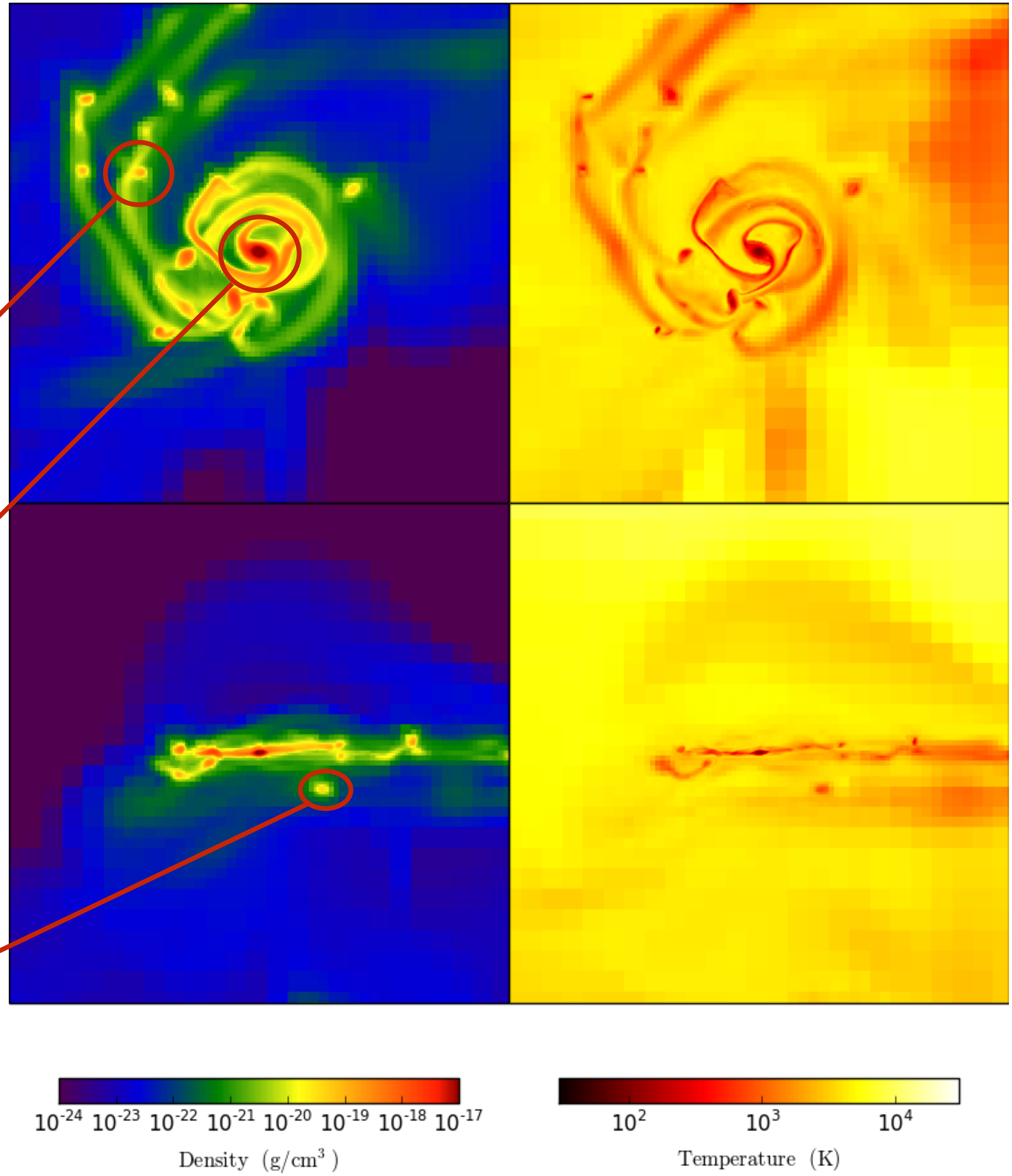
“Extra Slides”

Sites of clusters formation:

Globular clusters

UCD or nuclear star cluster

Satellite minihalos: Globular clusters?



Ricotti, Parry & Gnedin 2016

Toy model following Hills 1980:

If $t_{\rm loss} \ll t_{\rm dyn}$ (impulsive gas loss):

$$\frac{r_h}{r_h^{ic}} = \frac{\epsilon_{cl}}{2\epsilon_{cl} - 1} \quad \text{with } 0.5 < \epsilon_{cl} < 1,$$

$$\frac{\sigma_*}{\sigma_*^{ic}} \approx \left(\epsilon_{cl}\frac{r_h^{ic}}{r_h}\right)^{1/2}.$$

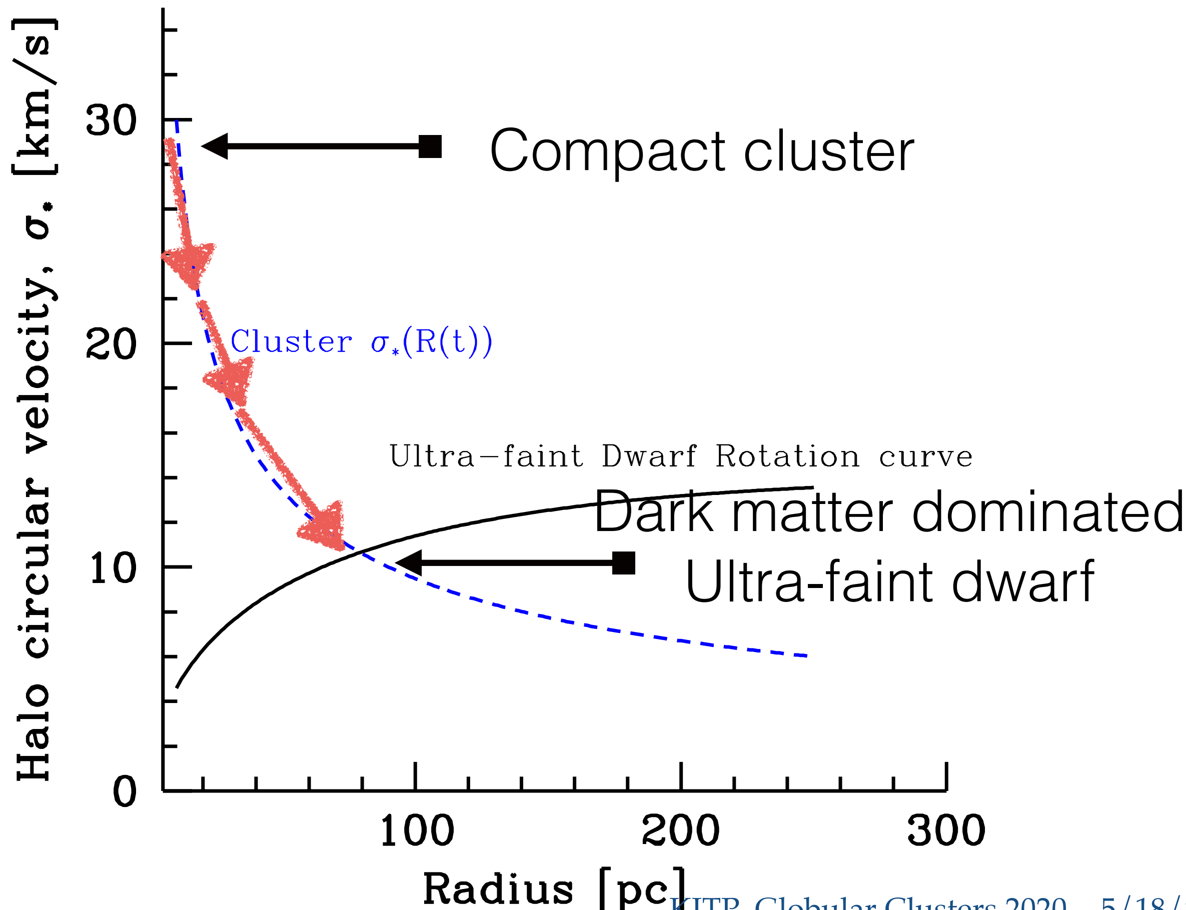
If $t_{\rm loss} \gg t_{\rm dyn}$ (quasi-adiabatic expansion):

$$\frac{r_h}{r_h^{ic}} = \frac{1}{\epsilon_{gc}} \quad \text{with } 0 < \epsilon_{cl} < 1,$$

$$\frac{\sigma_*}{\sigma_*^{ic}} \approx \frac{r_h^{ic}}{r_h}.$$

Expansion stops when grav. potential is dominated by the dark matter halo:

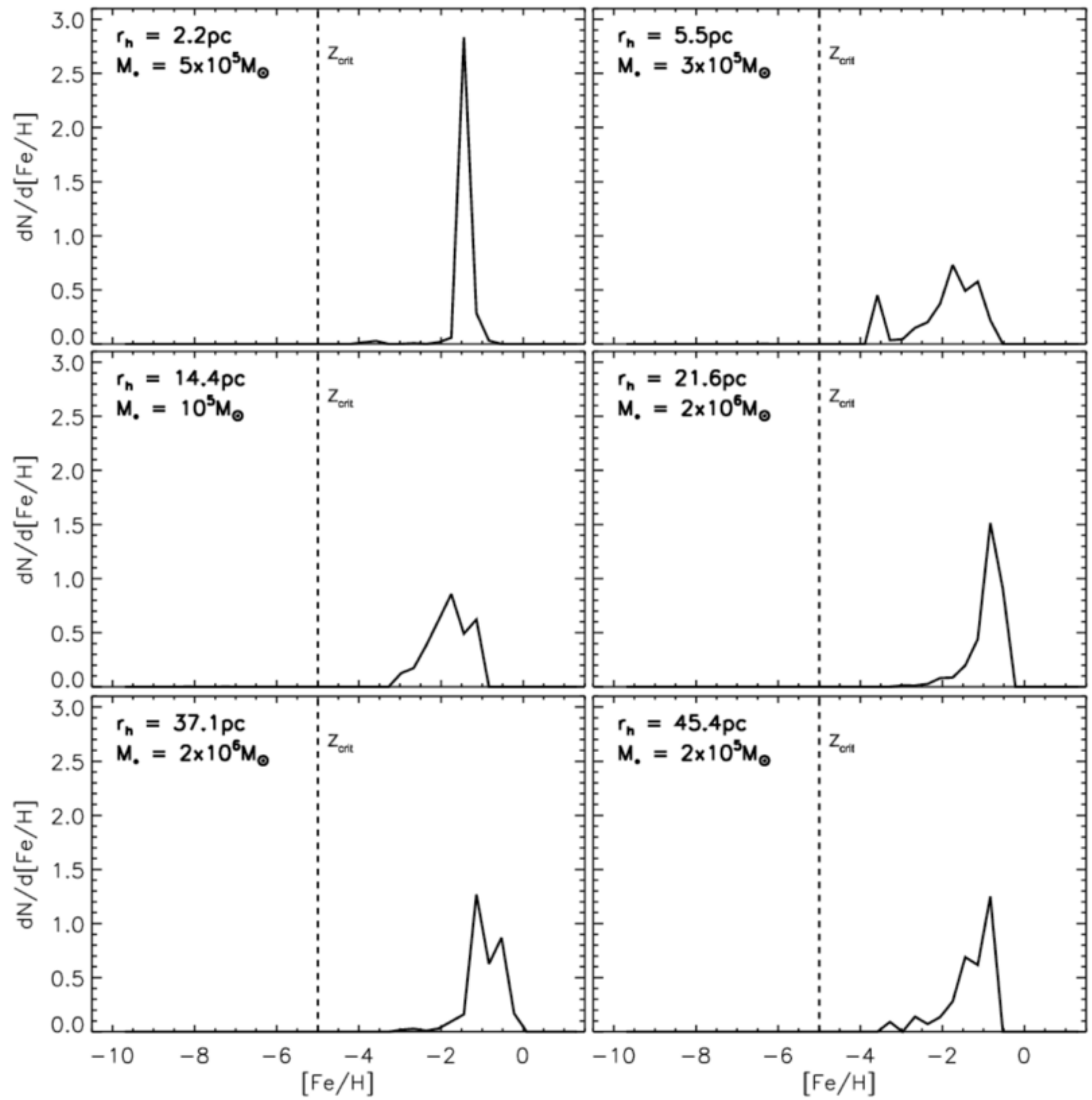
$$\sigma_*(r_h) = v_{\rm cir}(r_h).$$



Ultra-faint dwarfs and GCs today clearly look very different, but the origin (of a fraction of them) may have been similar:

1. Stars in ultra-faint dwarfs traced back to few dense clusters?

2. Hard to distinguish between UCDs nuclei and GCs based on morphology without detailed metallicity DFs.

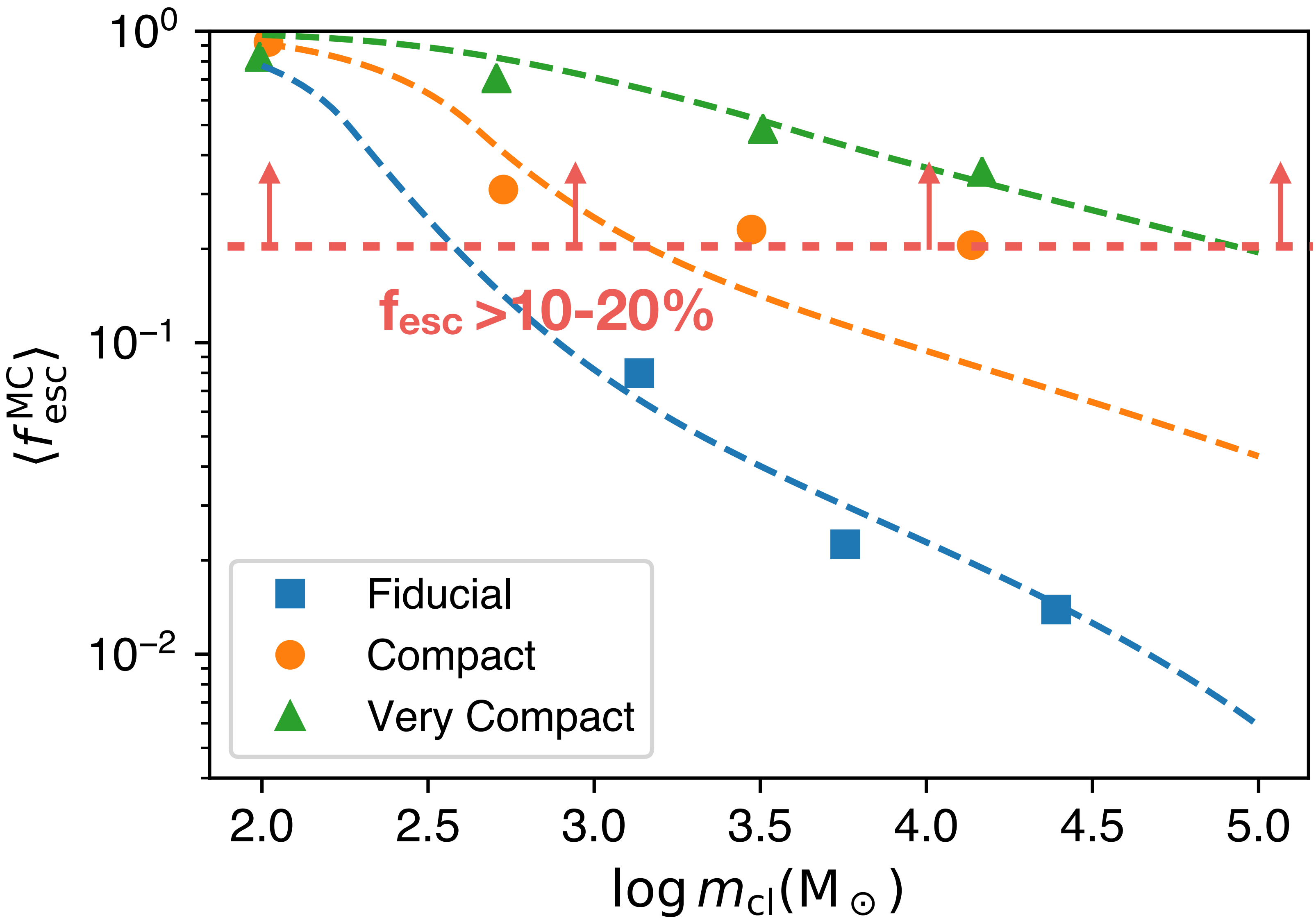


Ricotti, Parry & Gnedin 2016

- GC progenitors can be dominant sources for reionization (see Ricotti 2002, Schraerer & Charbonnel 2011, Katz & Ricotti 2013,2014, Hartley & Ricotti 2016, Boylan-Kolchin 2018)

What are the implications of star formation in compact star clusters on reionization?

Photon Escape Fraction



References

1. Globular Clusters (GCs) as Sources of Reionization

    (Ricotti 2002, Katz & Ricotti 2013, Katz & Ricotti 2014)

    https://ui.adsabs.harvard.edu/abs/2002MNRAS.336L..33R/abstract

    https://ui.adsabs.harvard.edu/abs/2013MNRAS.432.3250K/abstract

    https://ui.adsabs.harvard.edu/abs/2014MNRAS.444.2377K/abstract

    A. Simulations of Reionization by GCs (bursty star formation)

        (Hartley & Ricotti 2016, 2018 + work in preparation)

        https://ui.adsabs.harvard.edu/abs/2016MNRAS.462.1164H/abstract

    B. Simulations of Star Clusters and Escape Fraction

        (He, Ricotti & Geen 2019, He, Ricotti & Geen 2020 + work in preparation)

        https://ui.adsabs.harvard.edu/abs/2020MNRAS.492.4858H/abstract

        https://ui.adsabs.harvard.edu/abs/2019MNRAS.489.1880H/abstract

2. Formation of GCs and Ultra-faint Dwarfs in Simulations of the First Galaxies

    (Ricotti, Parry & Gnedin 2016)

    https://ui.adsabs.harvard.edu/abs/2016ApJ...831..204R/abstract