Formation of Proto-Globular Clusters in the First Galaxies:

Impact on Reionization, JWST Observations and Near-field Cosmology

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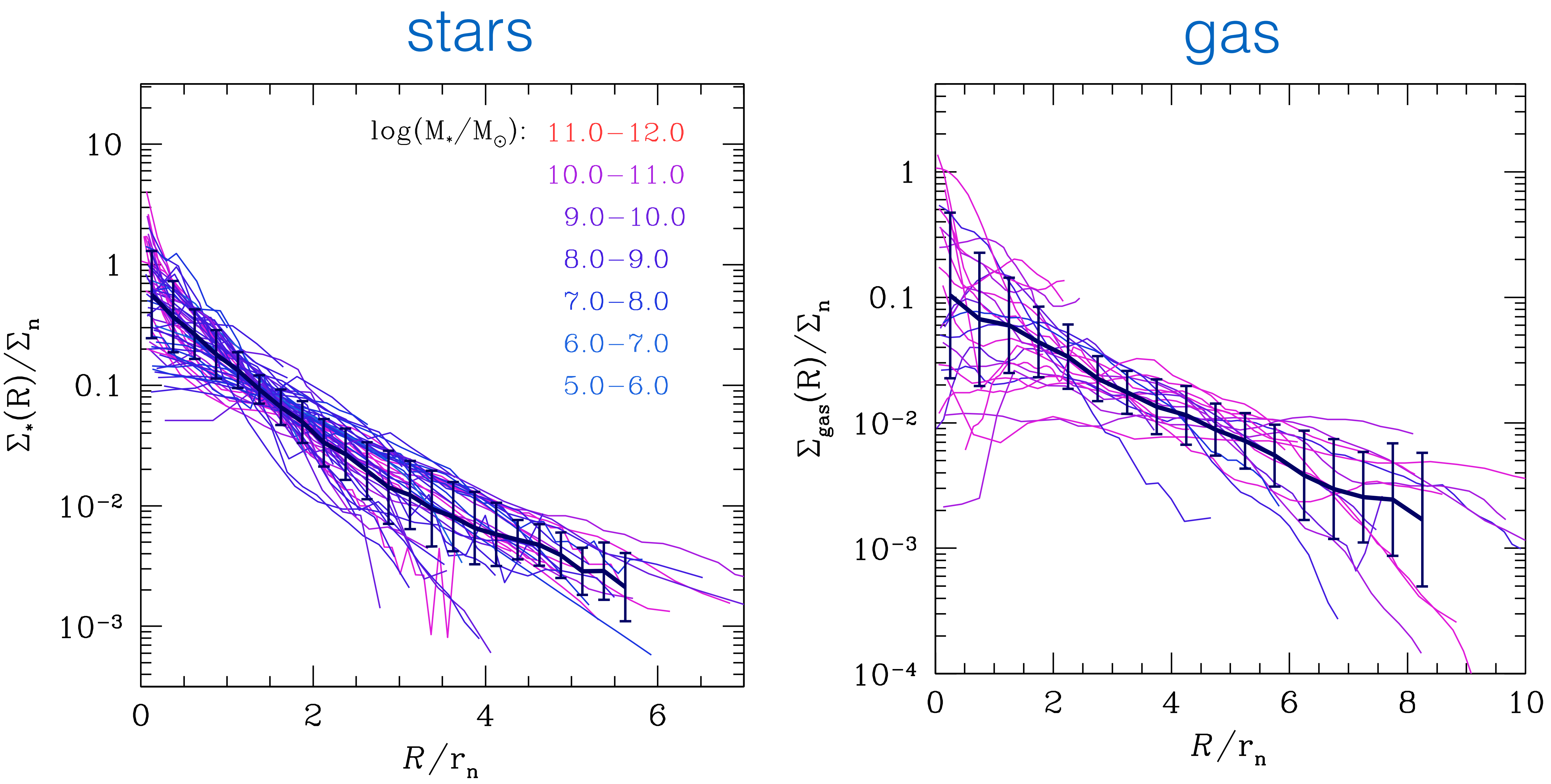
KITP Globular Clusters 2020 - 5/18/20

What sets the size and morphology of stars in the first galaxies?

Star formation in high-redshift galaxies takes place in especially compact molecular clouds, potentially leading to formation of GCs progenitors

In Galaxies Gas and stars roughly trace each other



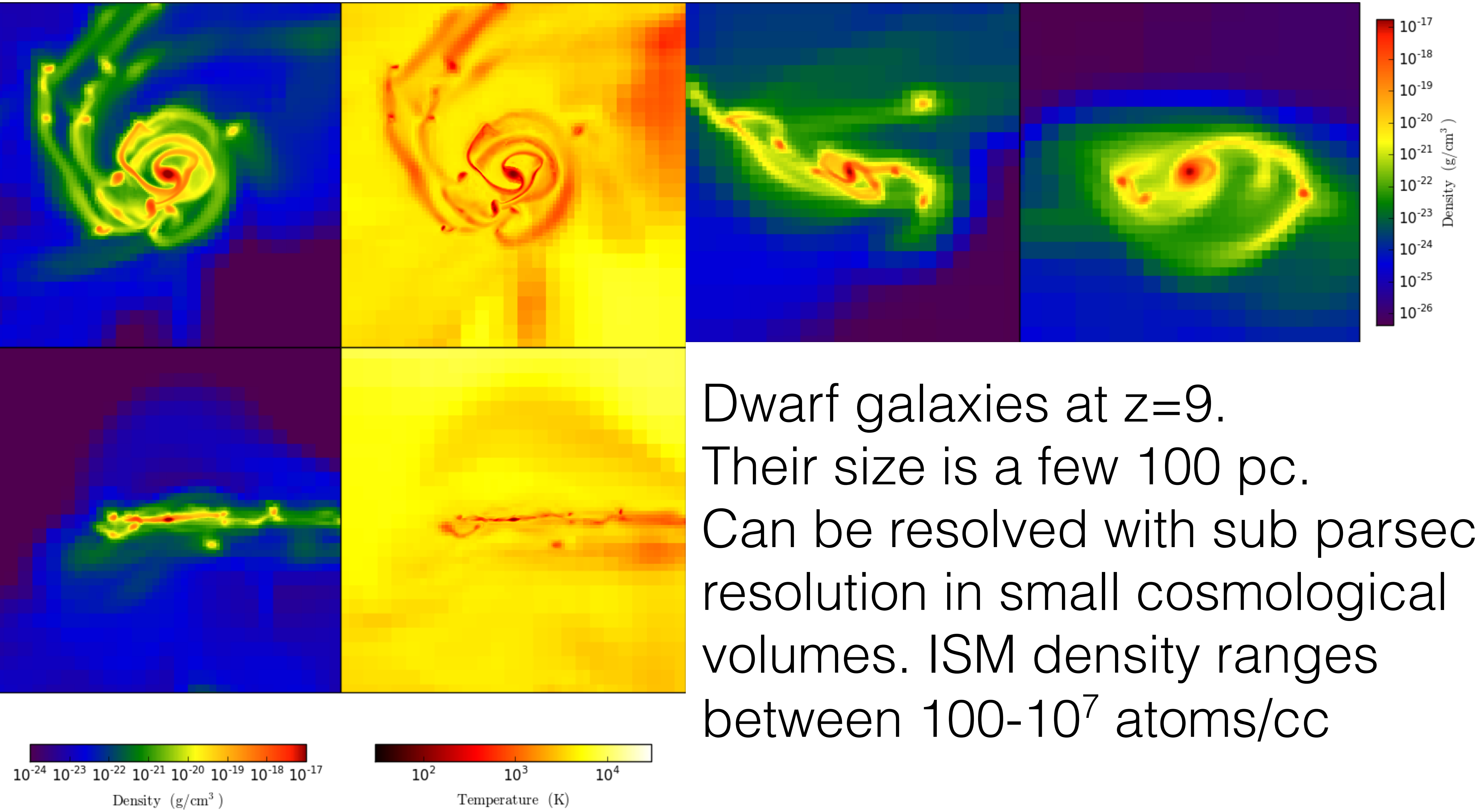
stars

gas

Kravtsov 2013

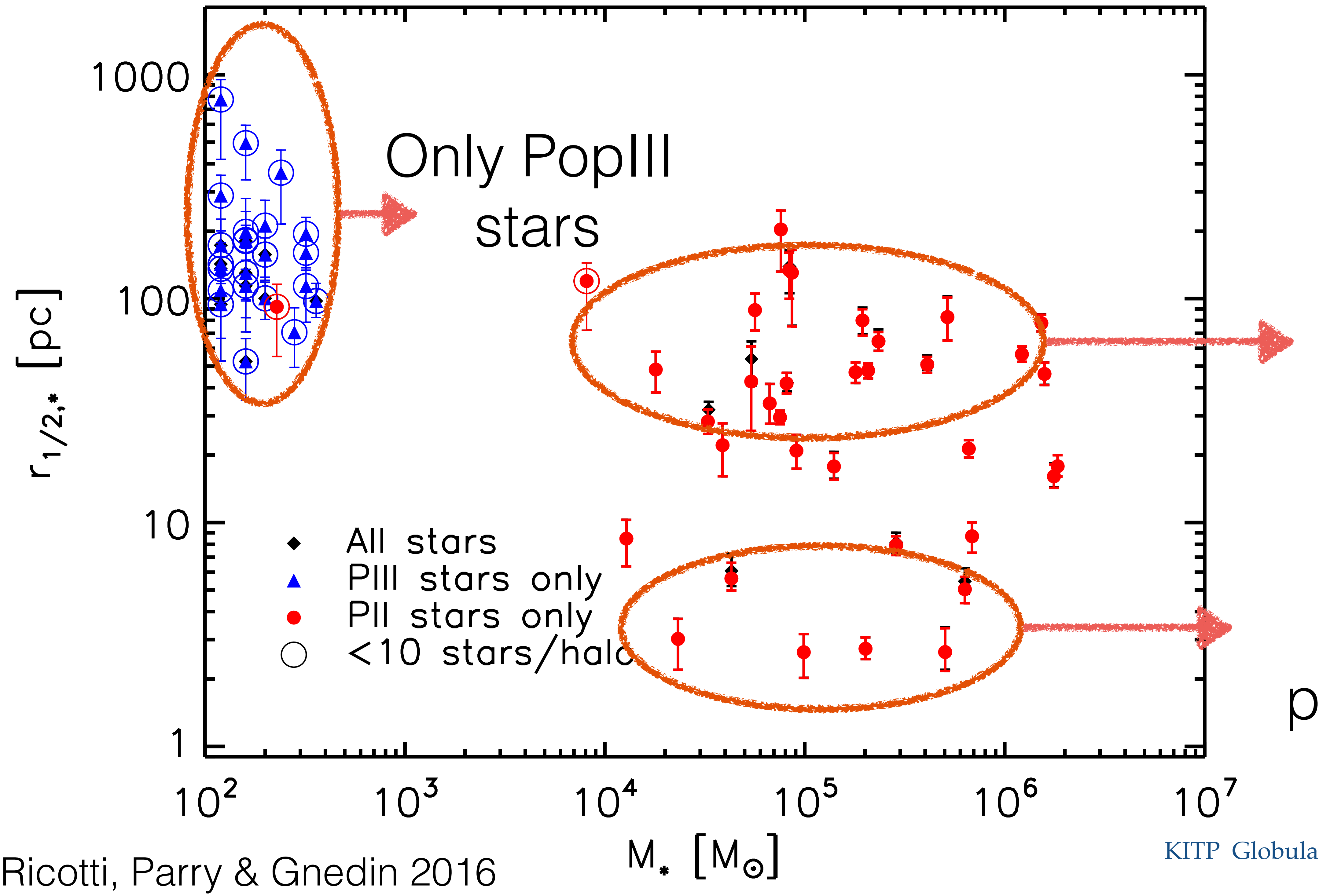
Simulations of the First Galaxies with ART:

(Ricotti, Parry & Gnedin 2016)



Dwarf galaxies at z=9.
Their size is a few 100 pc.
Can be resolved with sub parsec resolution in small cosmological volumes. ISM density ranges between 100-10^7 atoms/cc

Dense clusters and Ultra-faint dwarfs at redshift z~9



Only PopIII stars

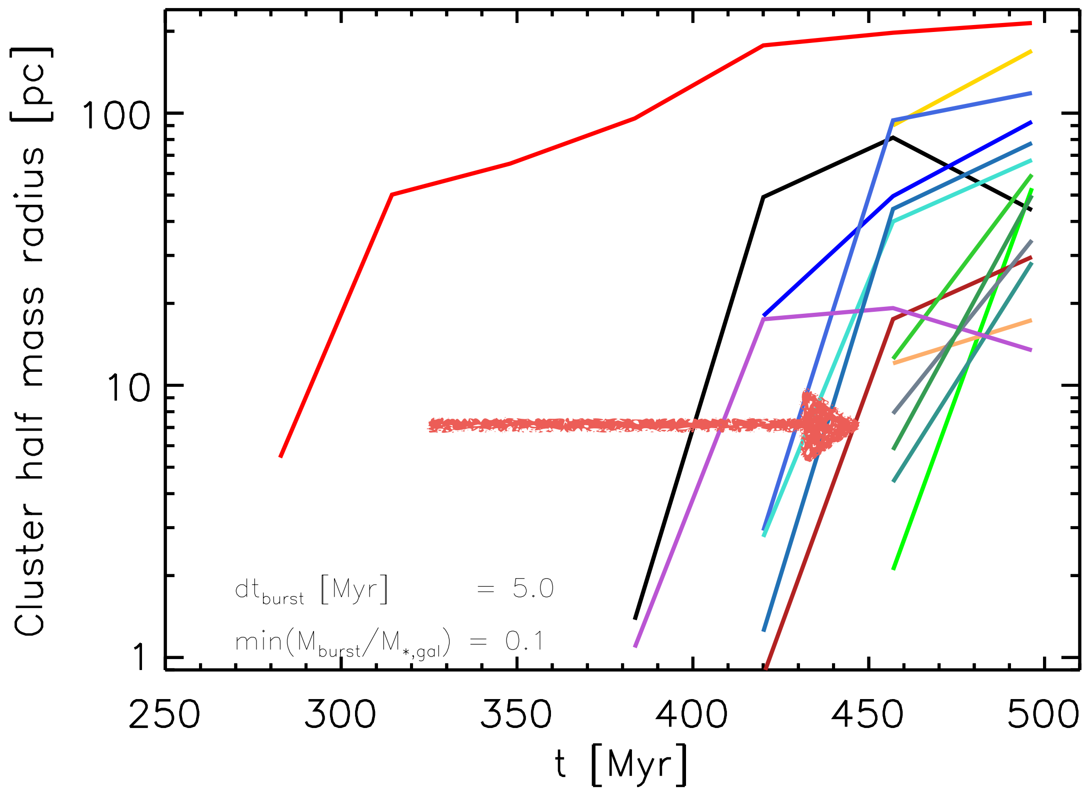
Ultra-faint dwarfs

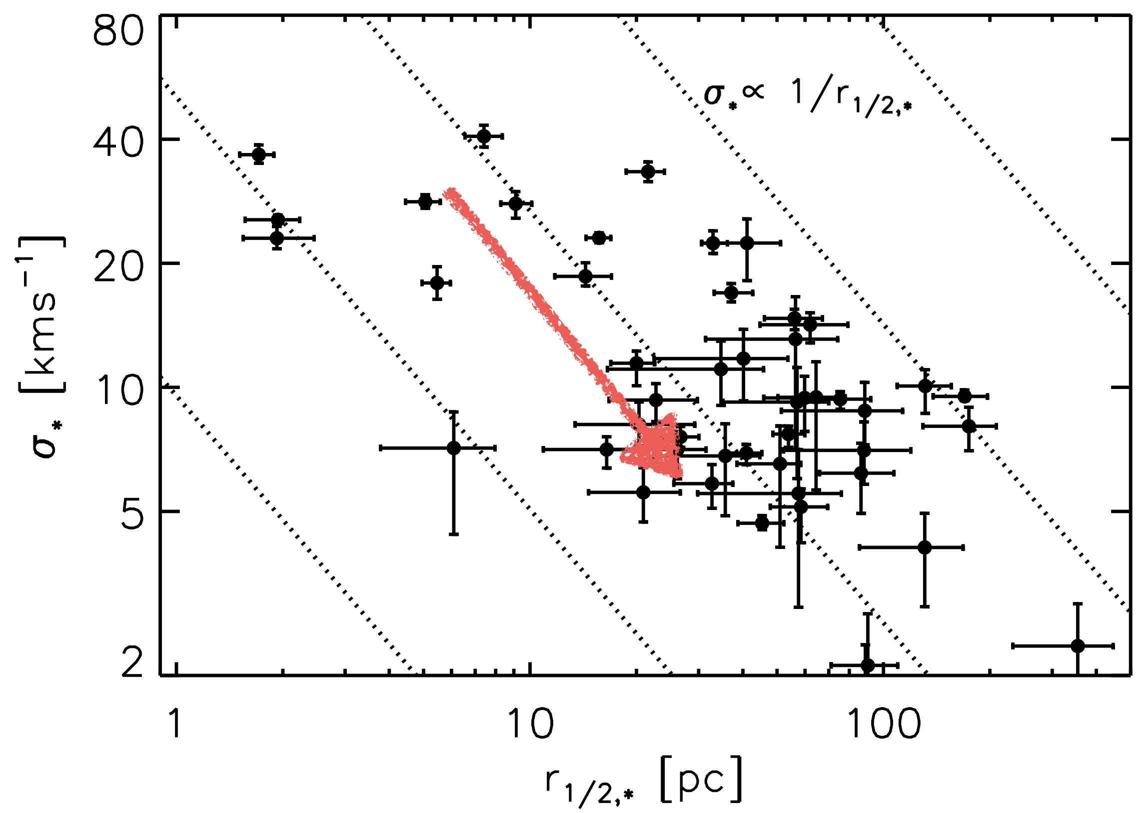
Globular clusters progenitors

Ricotti, Parry & Gnedin 2016

GCs and Ultra-faint dwarfs

Ricotti, Parry & Gnedin 2016





- Stars form in very compact dense clusters: 1 pc scale, velocity dispersion 20-40 km/s
- Probably due to gas loss, many become unbound and evolve as shown by the red lines
- Become bound again by dark matter halos with circular velocities: 5-10 km/s

Toy model following Hills 1980:

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

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

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

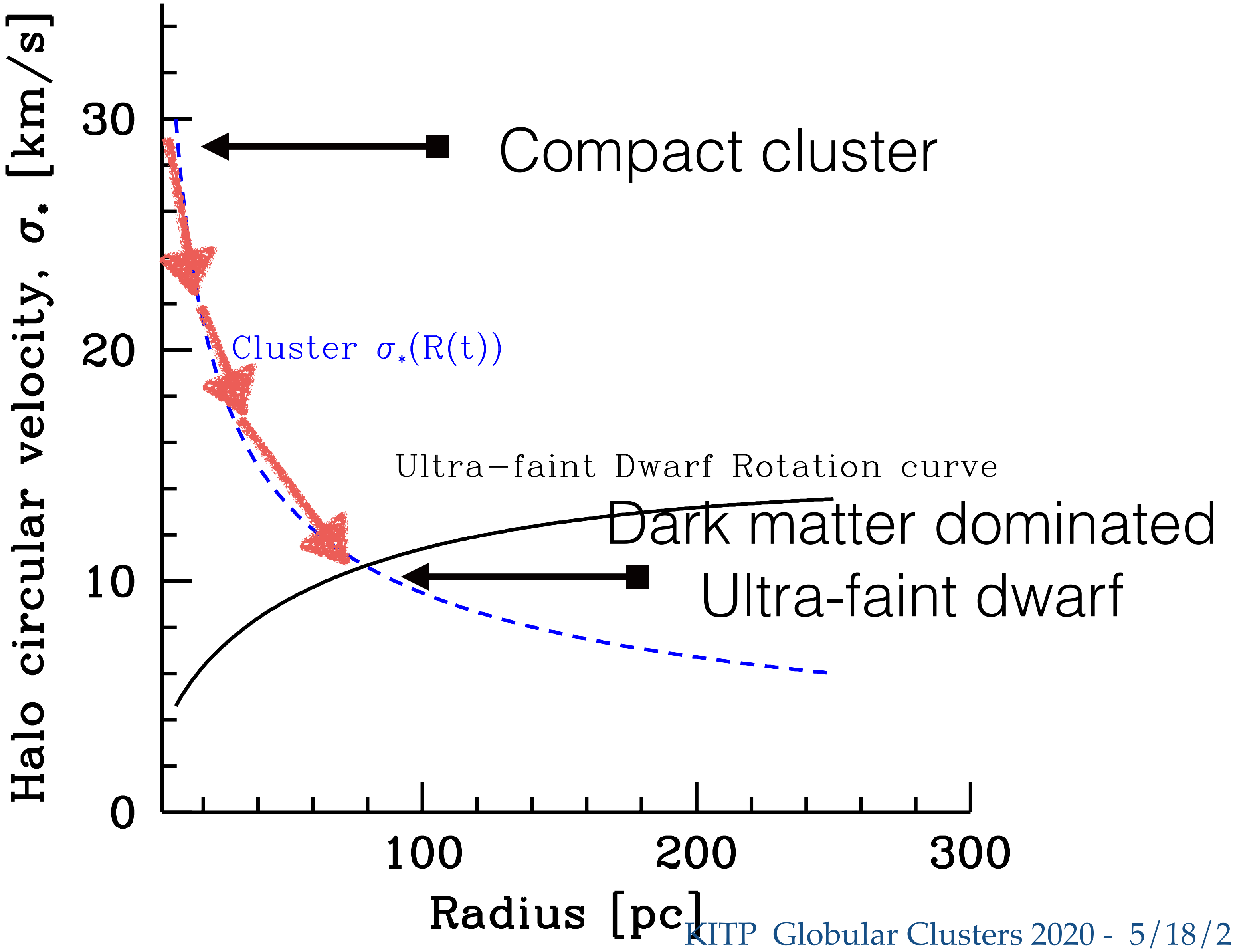
If $t_{\rm loss} \gg t_{\rm dyn}$ (quasi-adiabatic expansion):

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

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

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

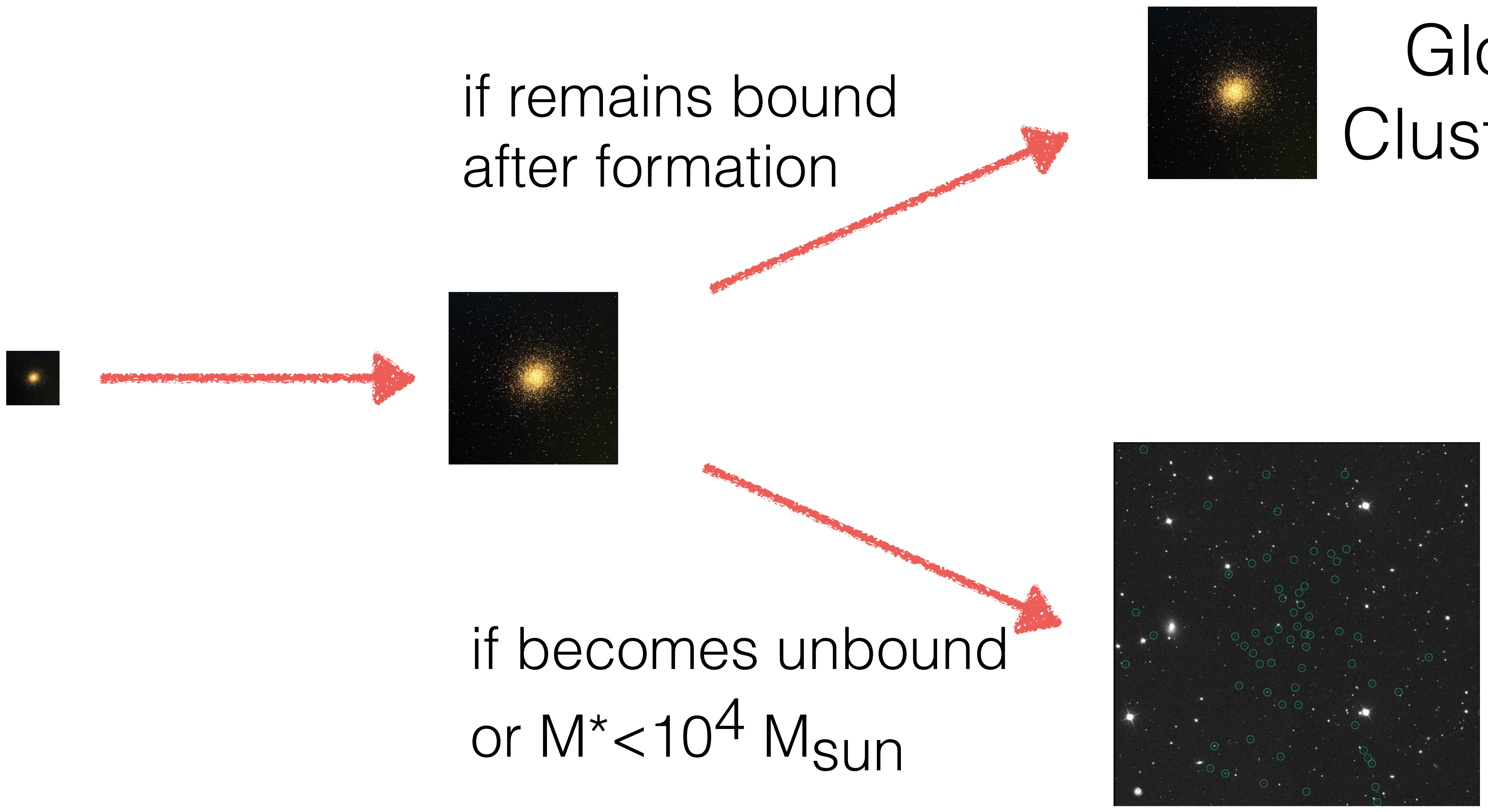
$$\sigma_*(r_h) = v_{\rm cir}(r_h).$$



Compact cluster

Dark matter dominated
Ultra-faint dwarf

Compact clusters and Ultra-faint dwarfs



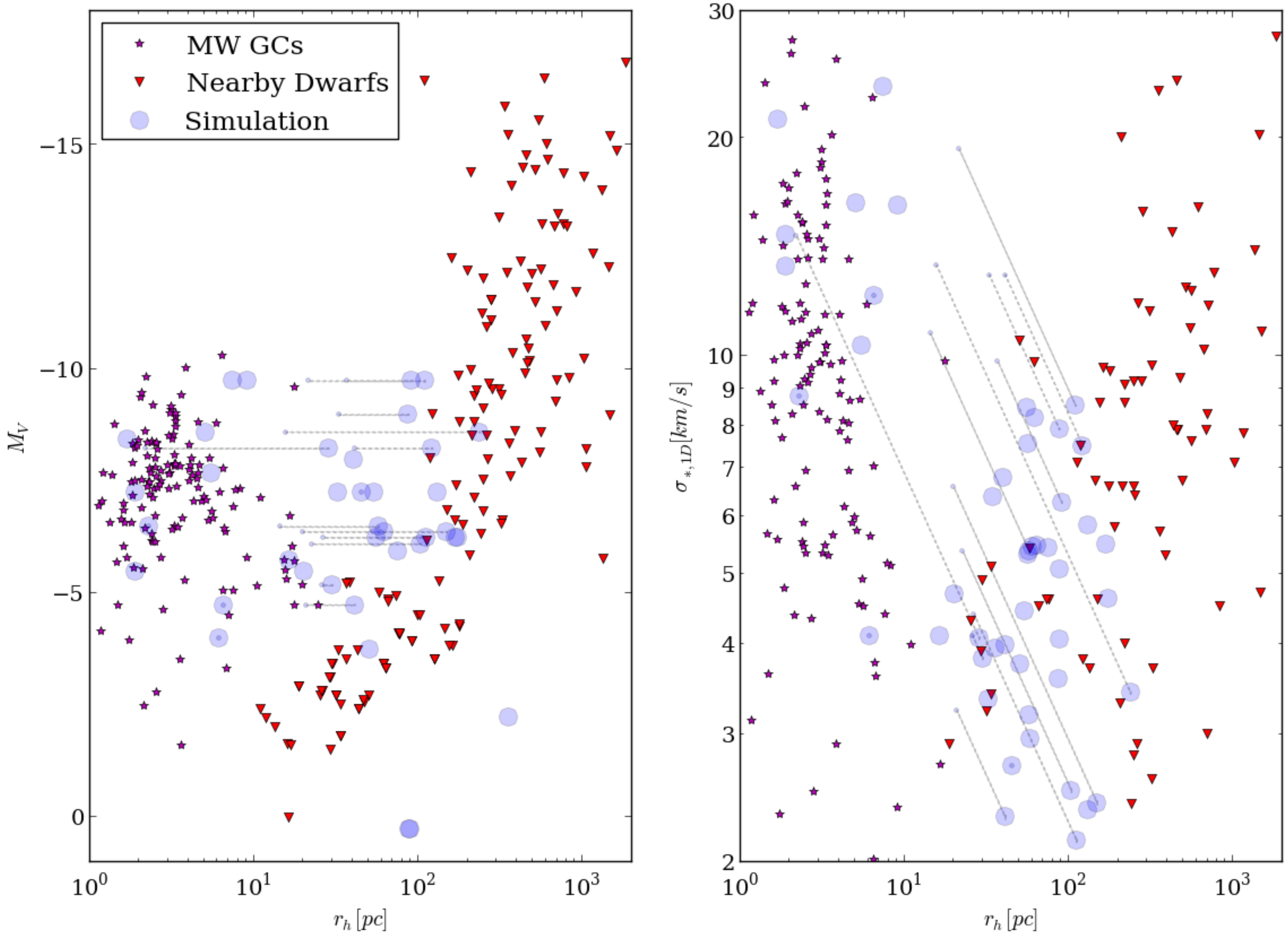
if remains bound
after formation

Globular
Cluster/UCD

if becomes unbound
or $M^* < 10^4\ M_{sun}$

Ultra-faint
dwarf
(dark matter dominated)

Comparison to Nearby Dwarfs and MW GCs



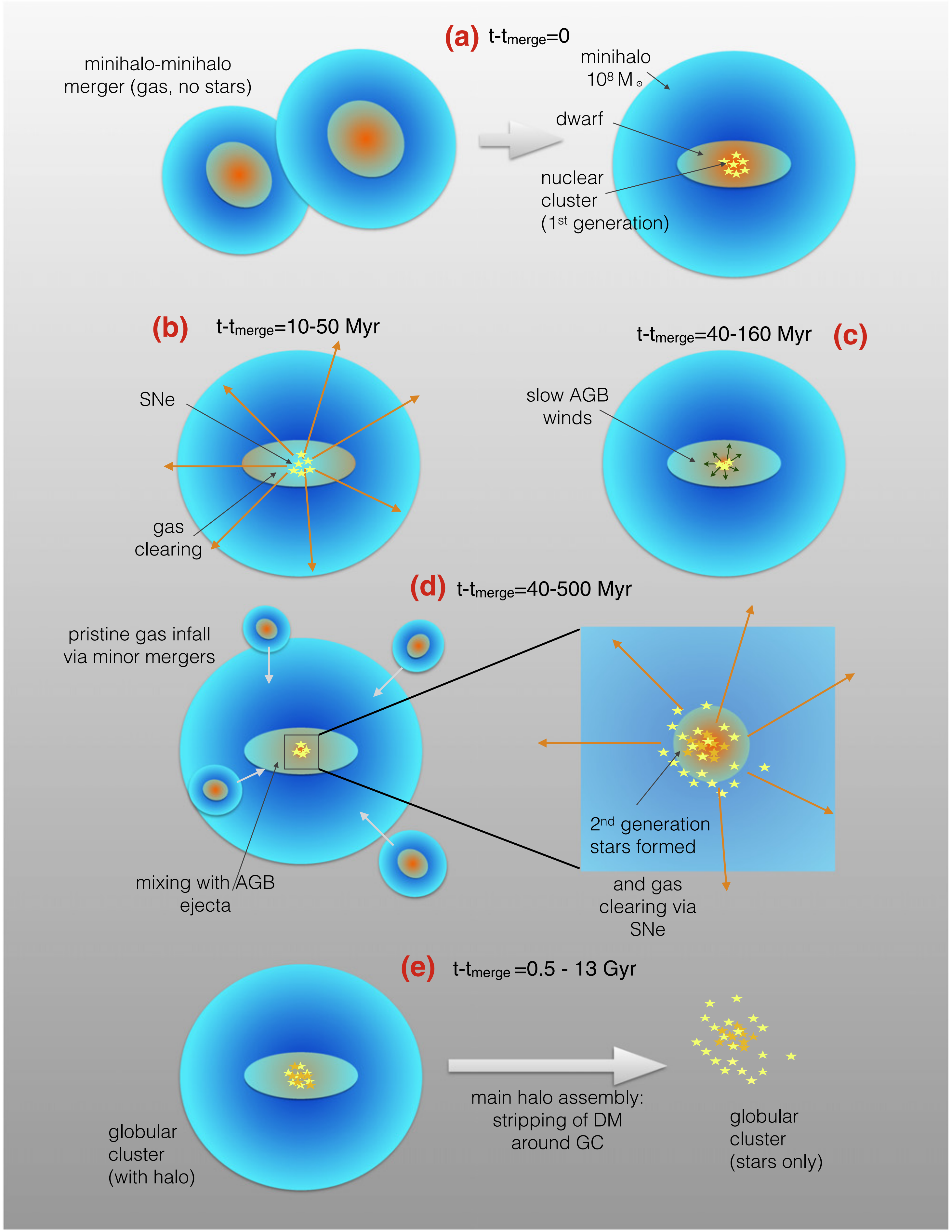
Proto-GCs as nuclear star clusters in atomic cooling halos

$$z_{form} = 9 \pm 2$$

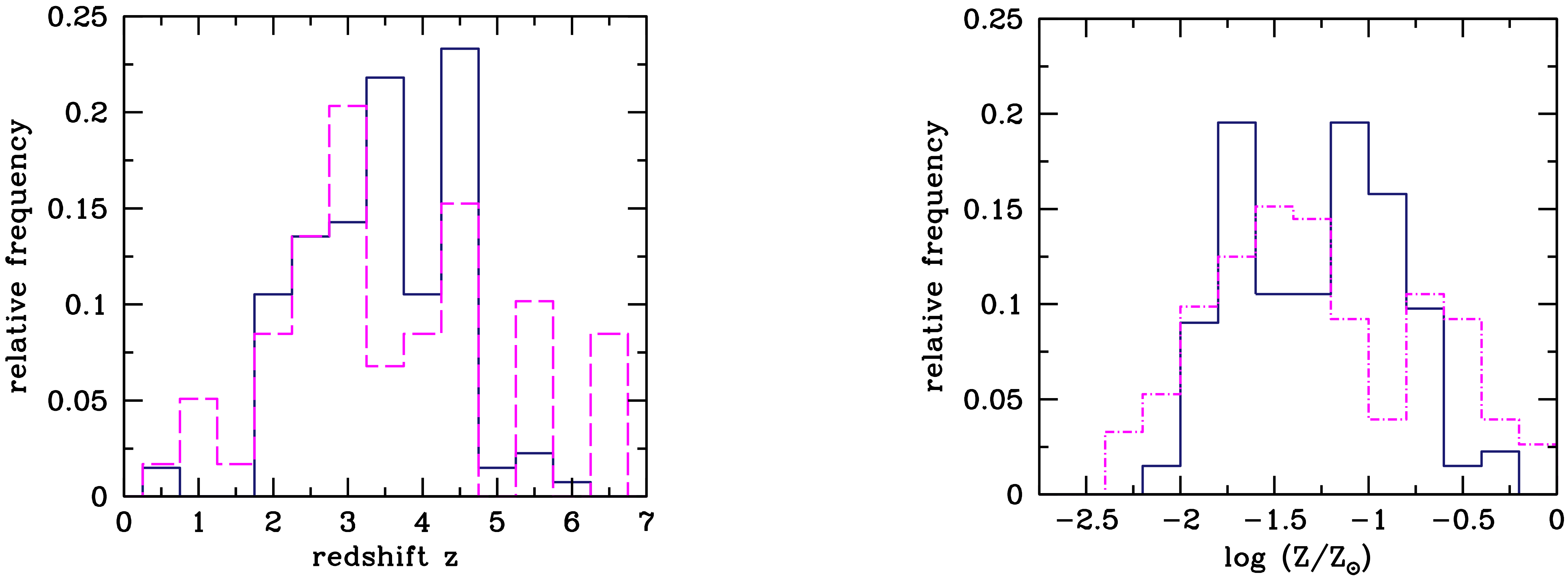
$$t_{form} = (13 \pm 0.2)\ Gyr$$

Michele Trenti , Paolo Padoan,

and Raul Jimenez 2015

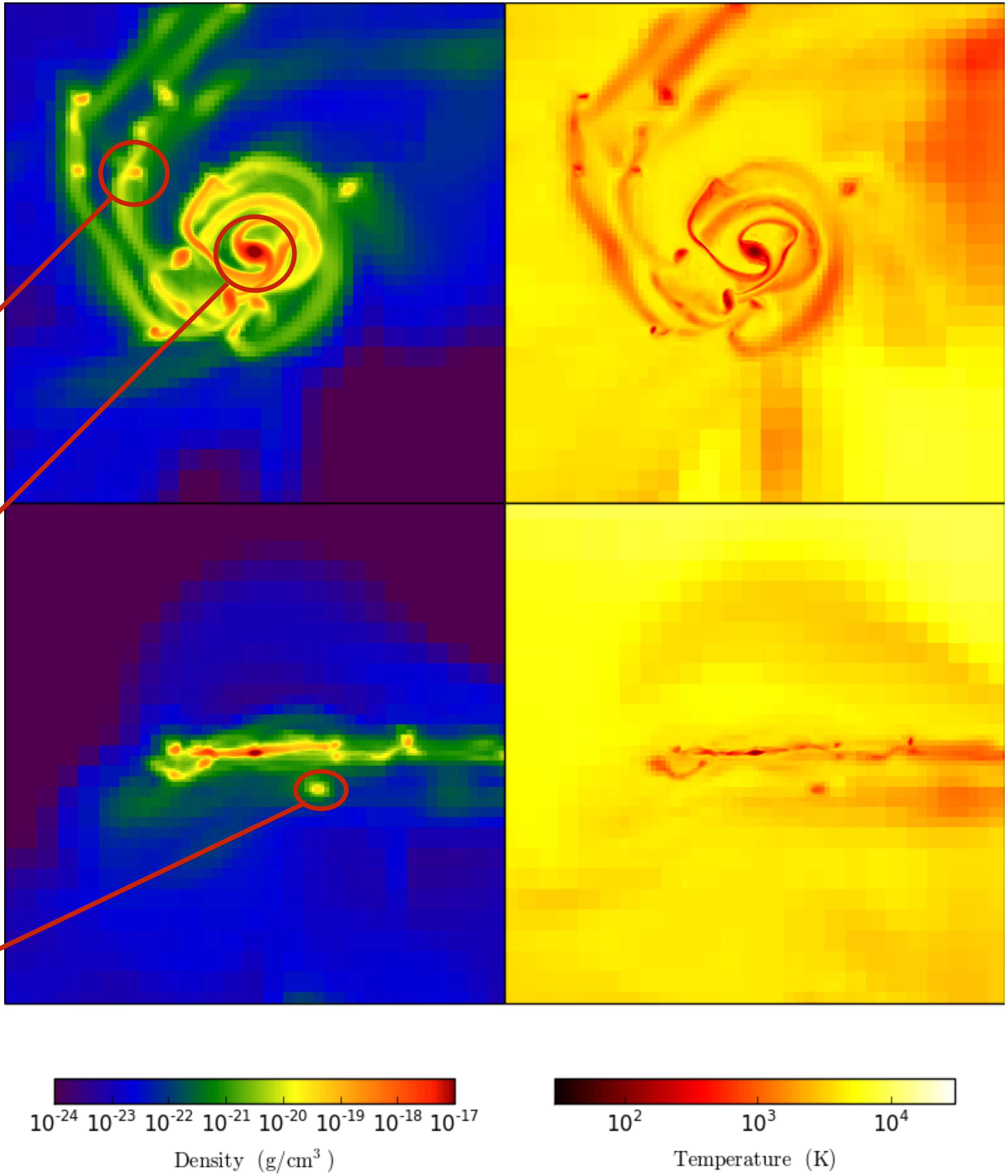


Proto-GCs from colliding substructures (satellites)



Piero Madau, A. Lupi J. Diemand, A. Burkert, and D. N. C. Lin 2020

Sites of clusters formation:



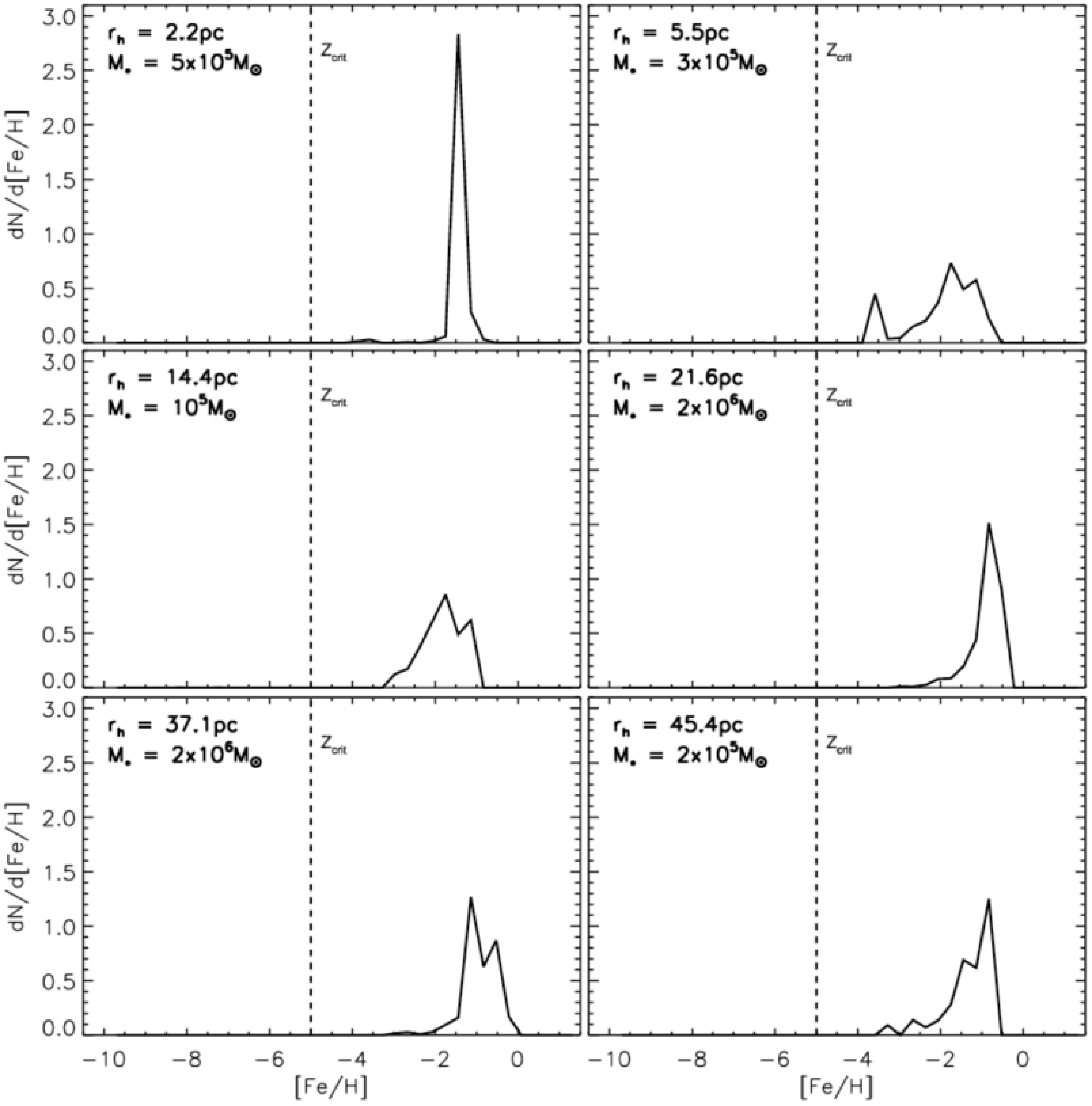
Globular clusters

UCD or nuclear star cluster

Satellite minihalos:
Globular clusters?

Ricotti, Parry & Gnedin 2016

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?

Emissivity of GCs at reionisation

see Ricotti 2002

$$\mathcal{N}_{ph}^{gc} = \eta \omega_{gc}^{f} \frac{t_H(z=6)}{\Delta t_{gc}} = (5.1^{+4.3}_{-3.2}) \frac{f_{di}}{\Delta t_{gc}\,(Gyr)},$$

where η is number of ionising photons emitted per H atom for a Salpeter IMF,

- $1 \leq f_{di} \lesssim 100$
- $0.5 \lesssim \Delta t_{gc} \lesssim 2$ Gyr

The IGM is reionised when

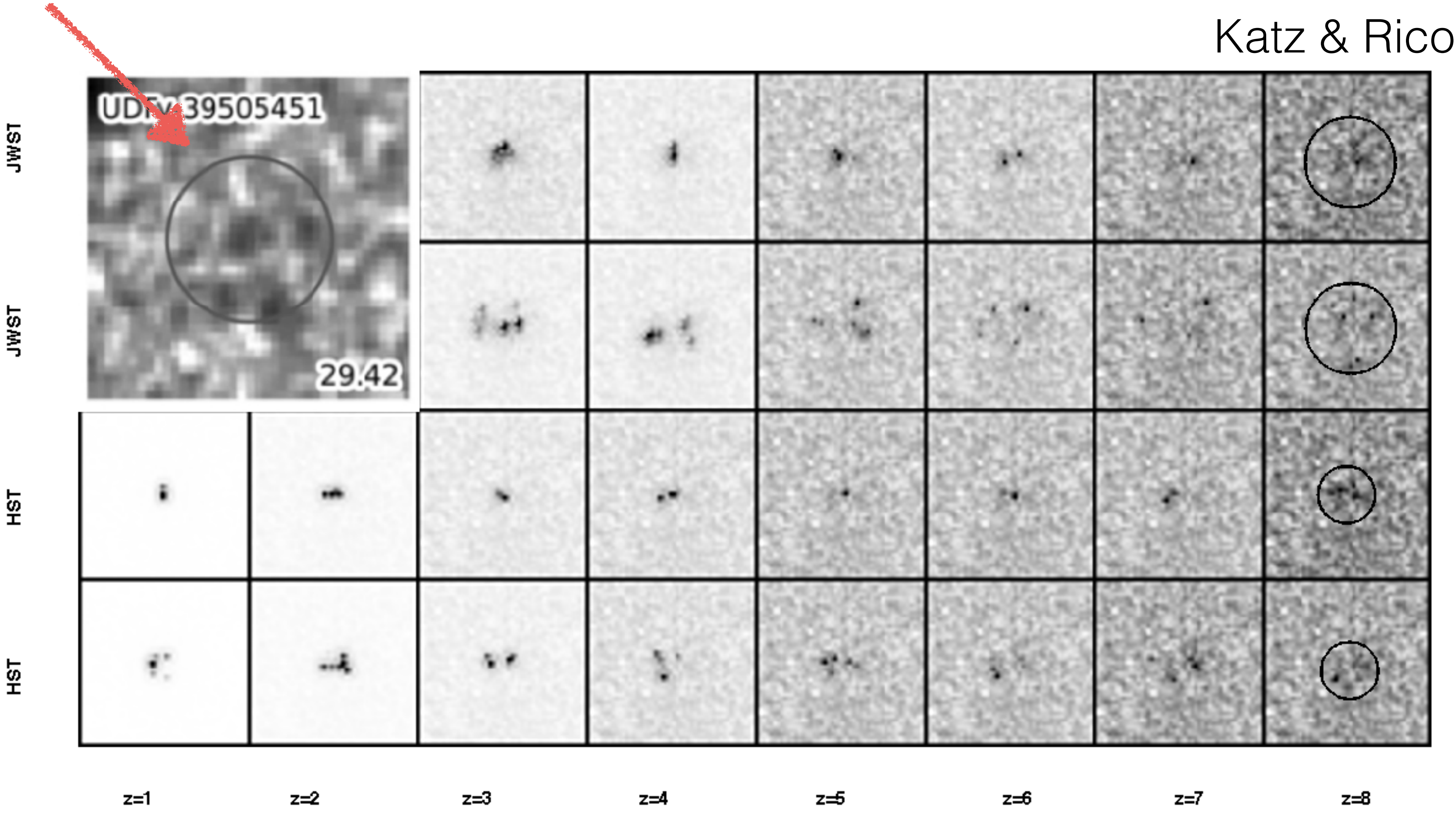
$$\mathcal{N}_{ph} \sim 1 - 10$$

depending on $C = \langle n_{HII}^2 \rangle / \langle n_{HII} \rangle^2$ = the clumping factor of ionised IGM

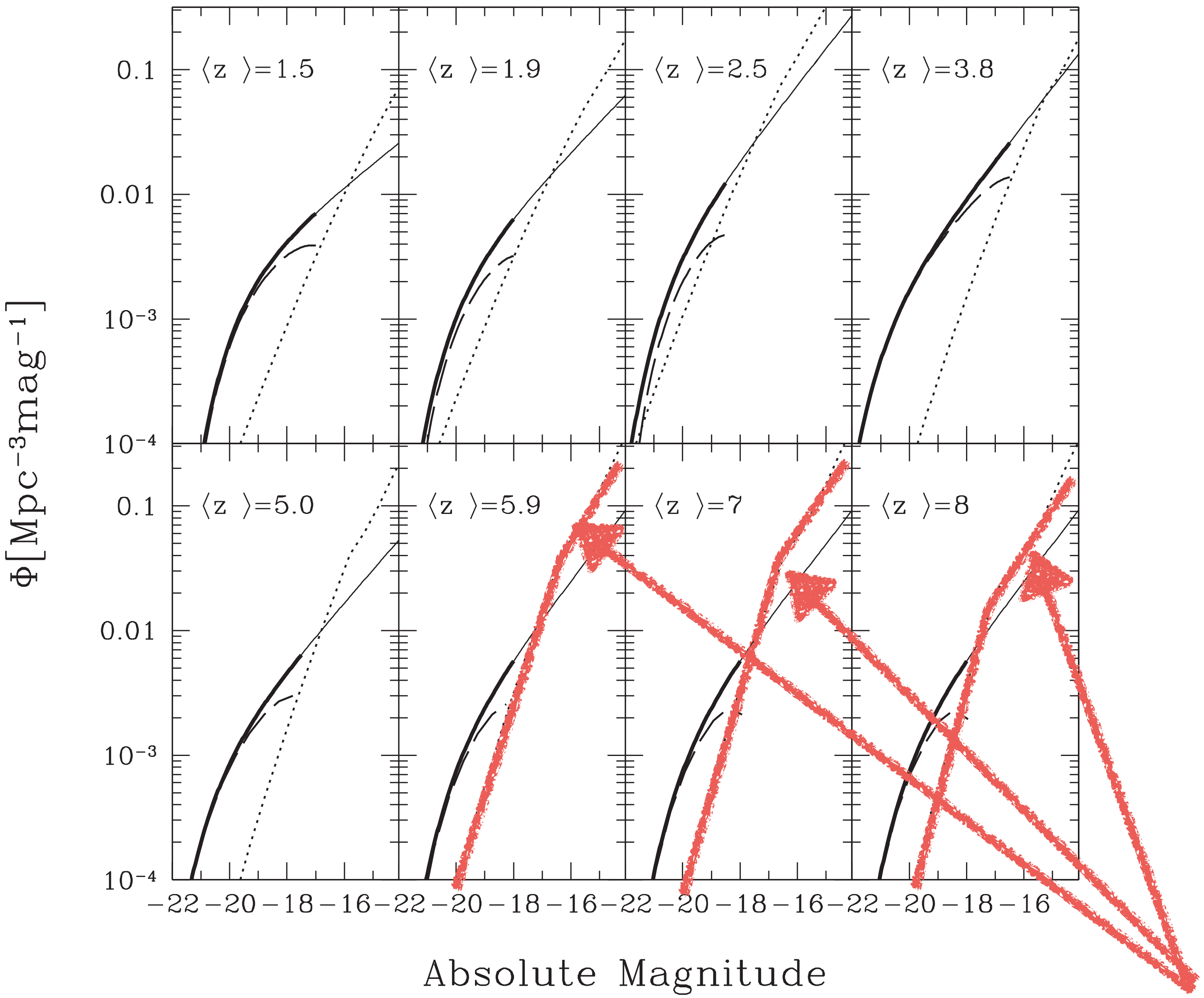
Nearby dwarfs with GC systems as seen by JWST and HST if their GCs formed at redshifts z=1 to 8

z=8 candidate for comparison (Bouwens et al. 2011)

Katz & Ricotti (2013)



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



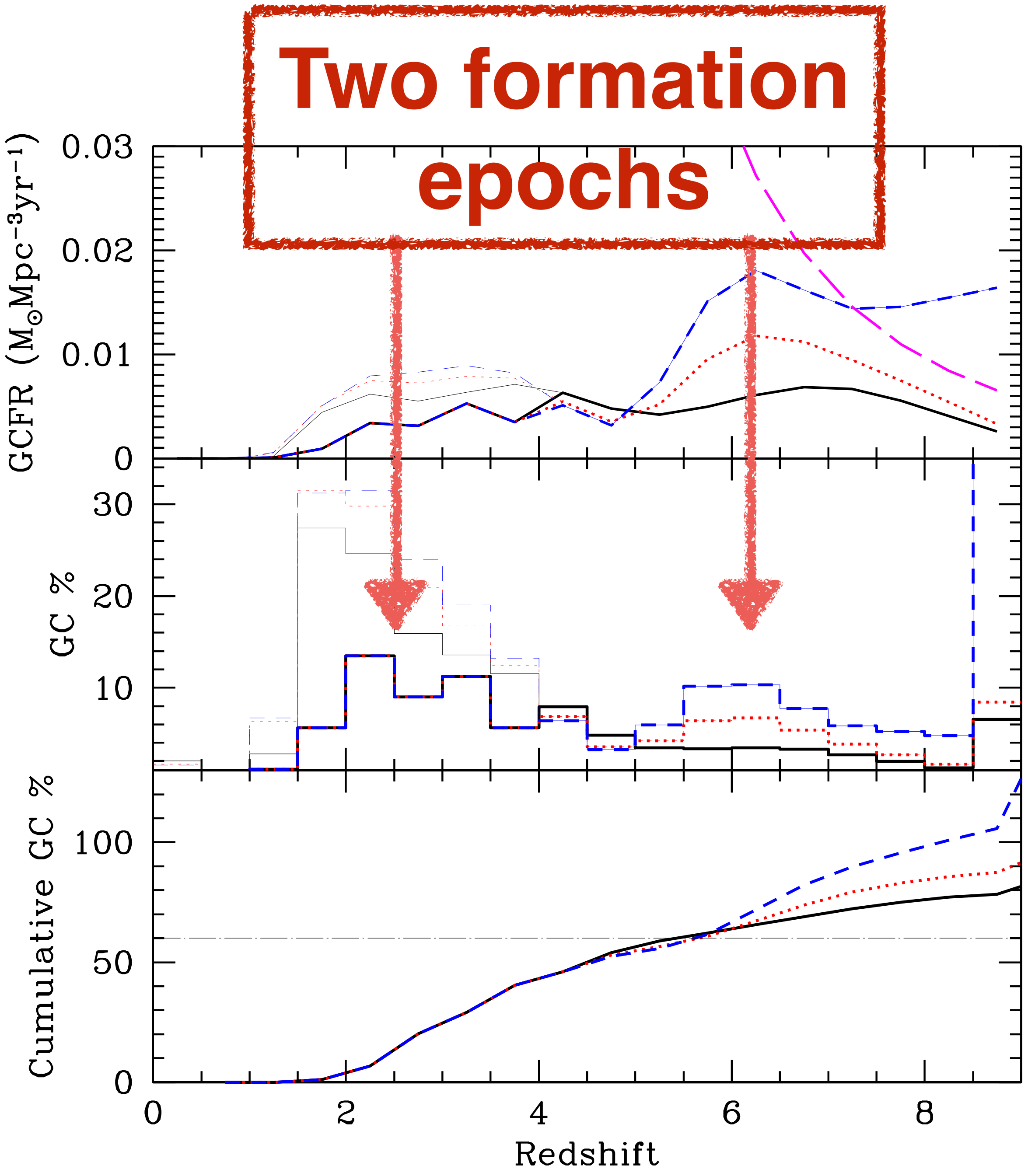
Katz & Ricotti (2013)

Fixed fraction of present day GCs forming at given z

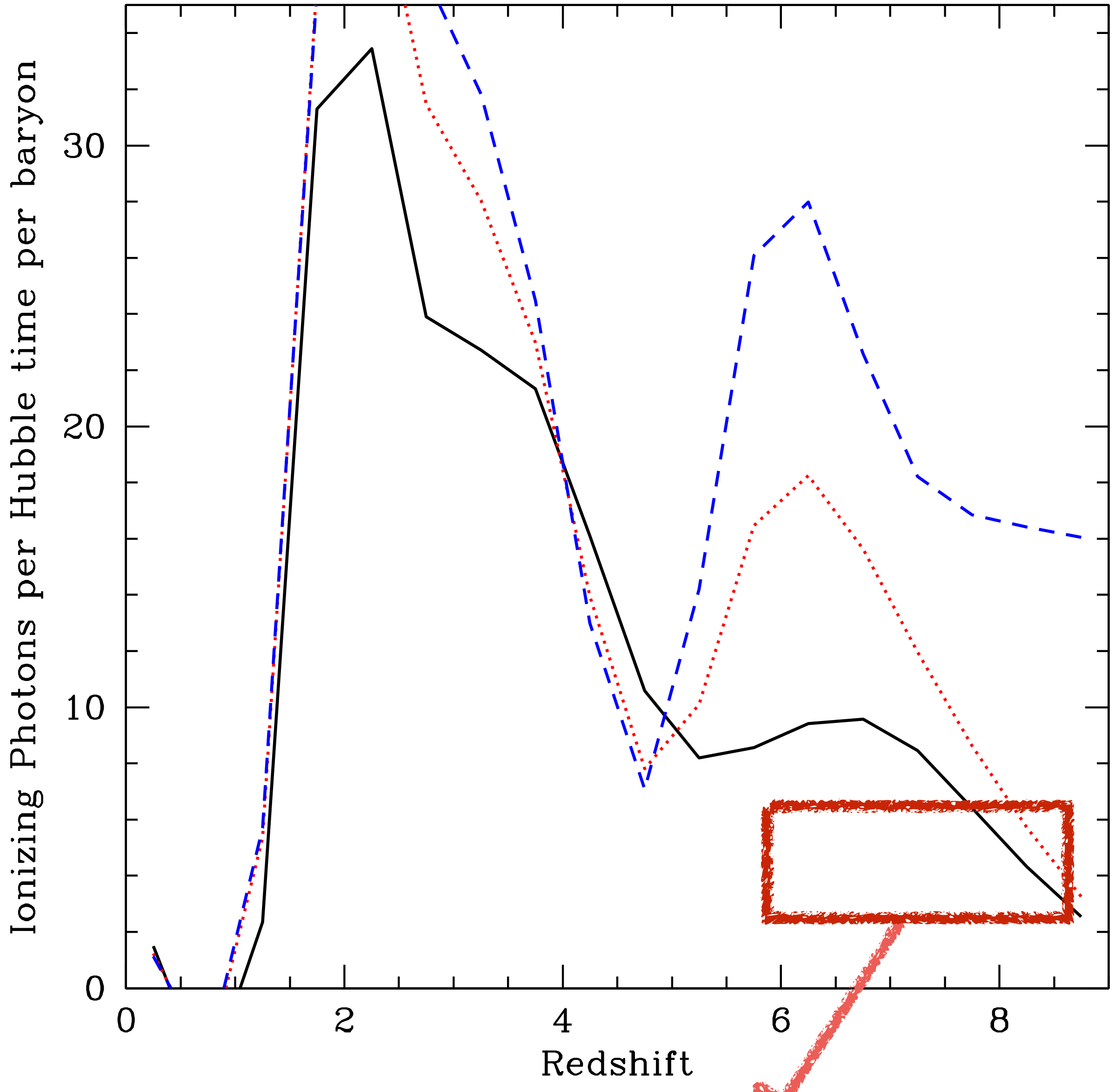
Upper limits on GC formation rate and fraction of present day population

Upper limits on ionizing photons from forming GCs

Katz & Ricotti (2013)

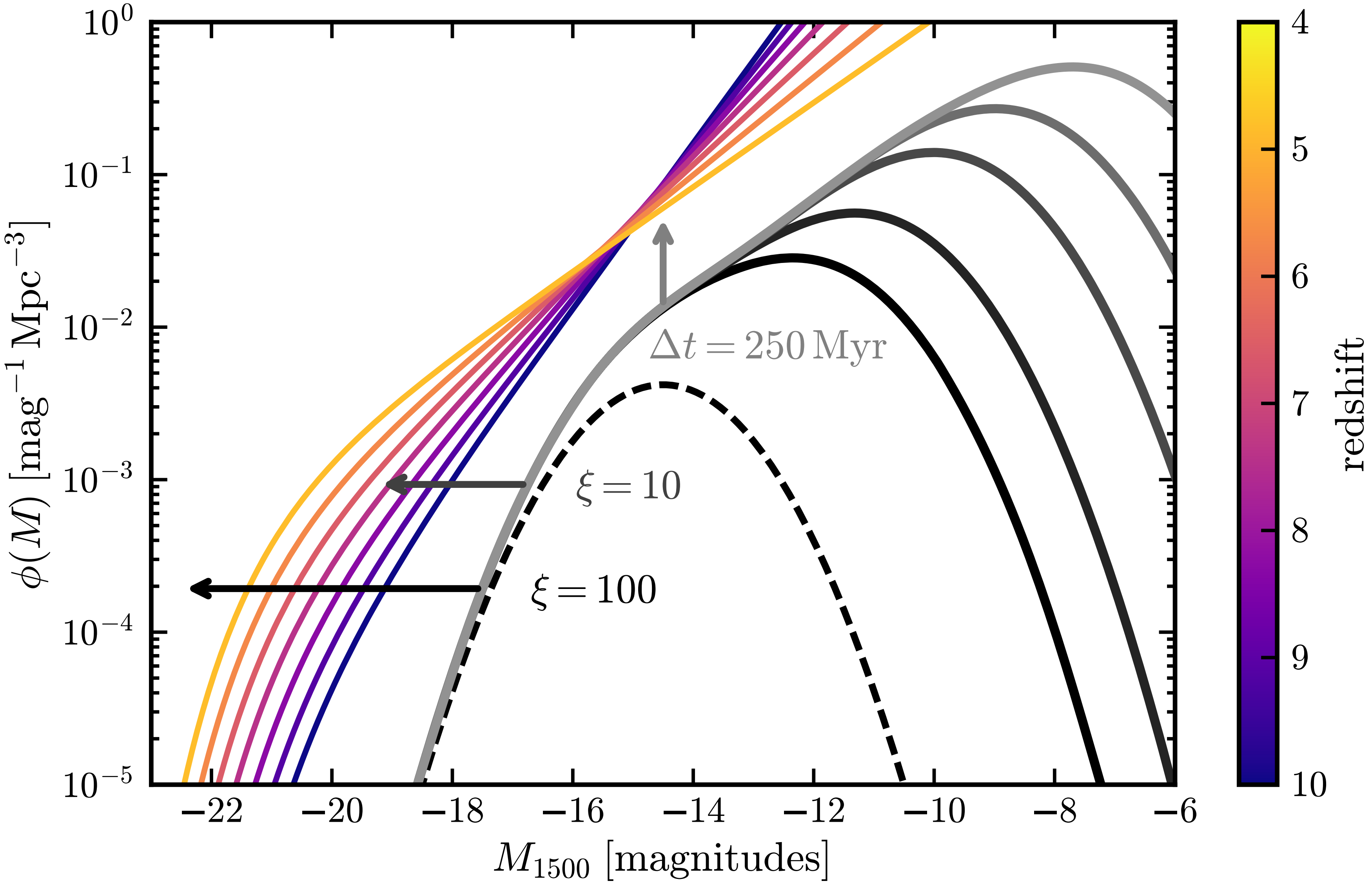


Two formation epochs



Needed to reionize (f_{esc}~1)

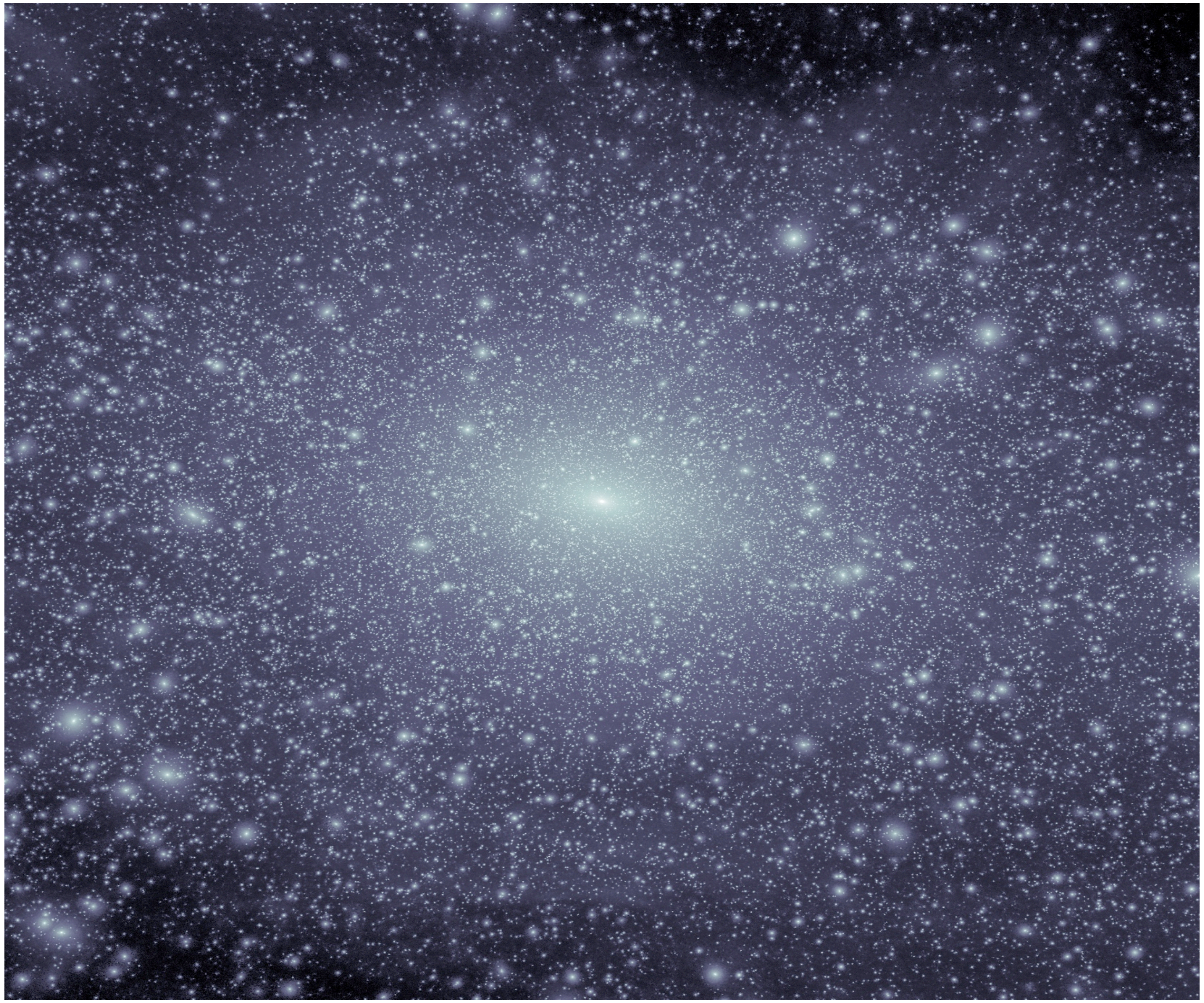
High-z luminosity functions



Michael Boylan-Kolchin 2018

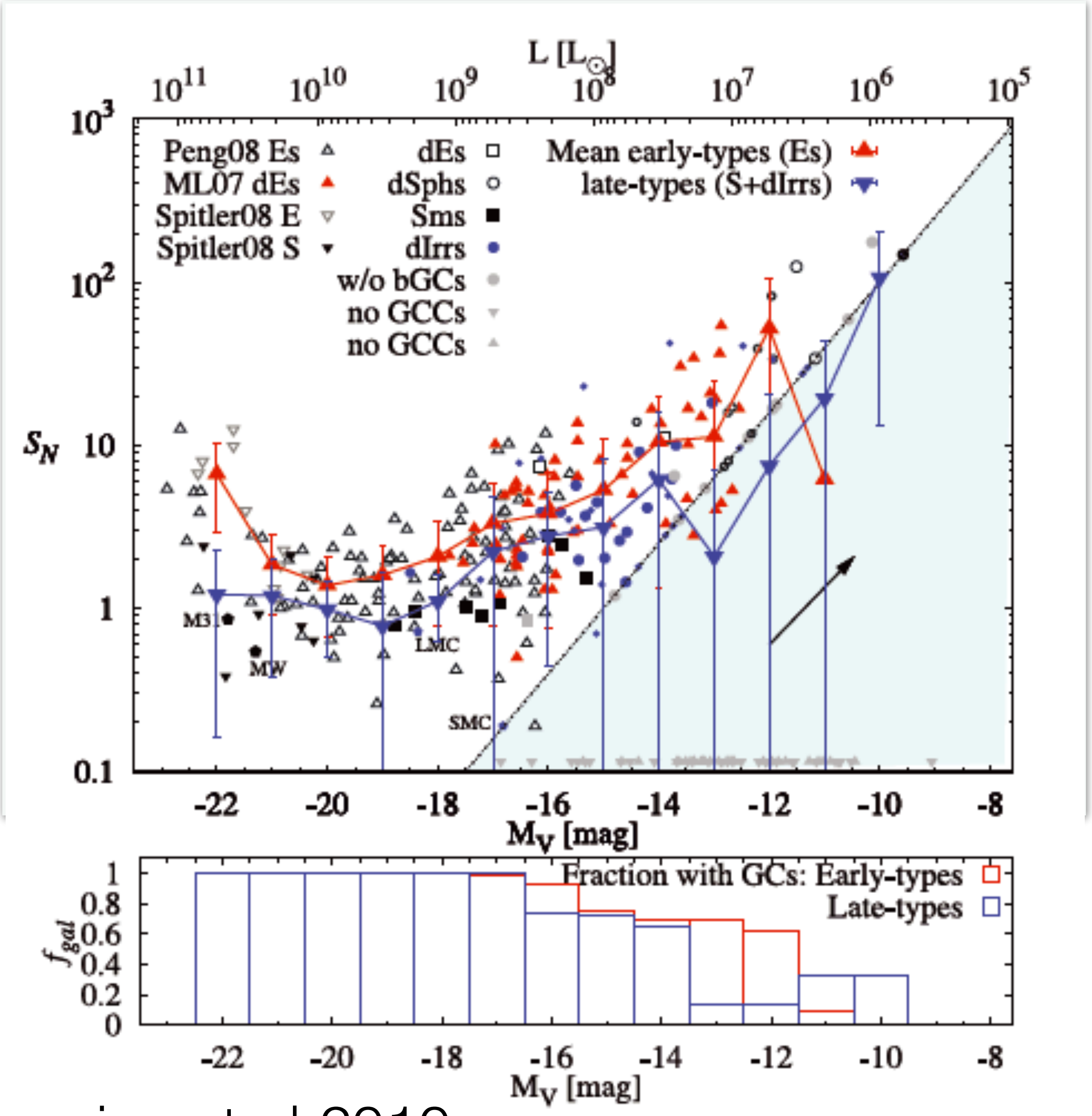
Joint Modeling of GC systems in Milky Way and nearby dwarfs

- We have developed a model which attempts to recreate the Milky Way's system of old GCs
- Utilizing the Via Lactea II simulation halo catalog, we distribute GCs to the dwarf halos and model the dynamical effects and stellar of evolution GCs as we numerically integrate their orbits.
- We determine when they are accreted, where they end up, if they are destroyed as well as many other interesting phenomena



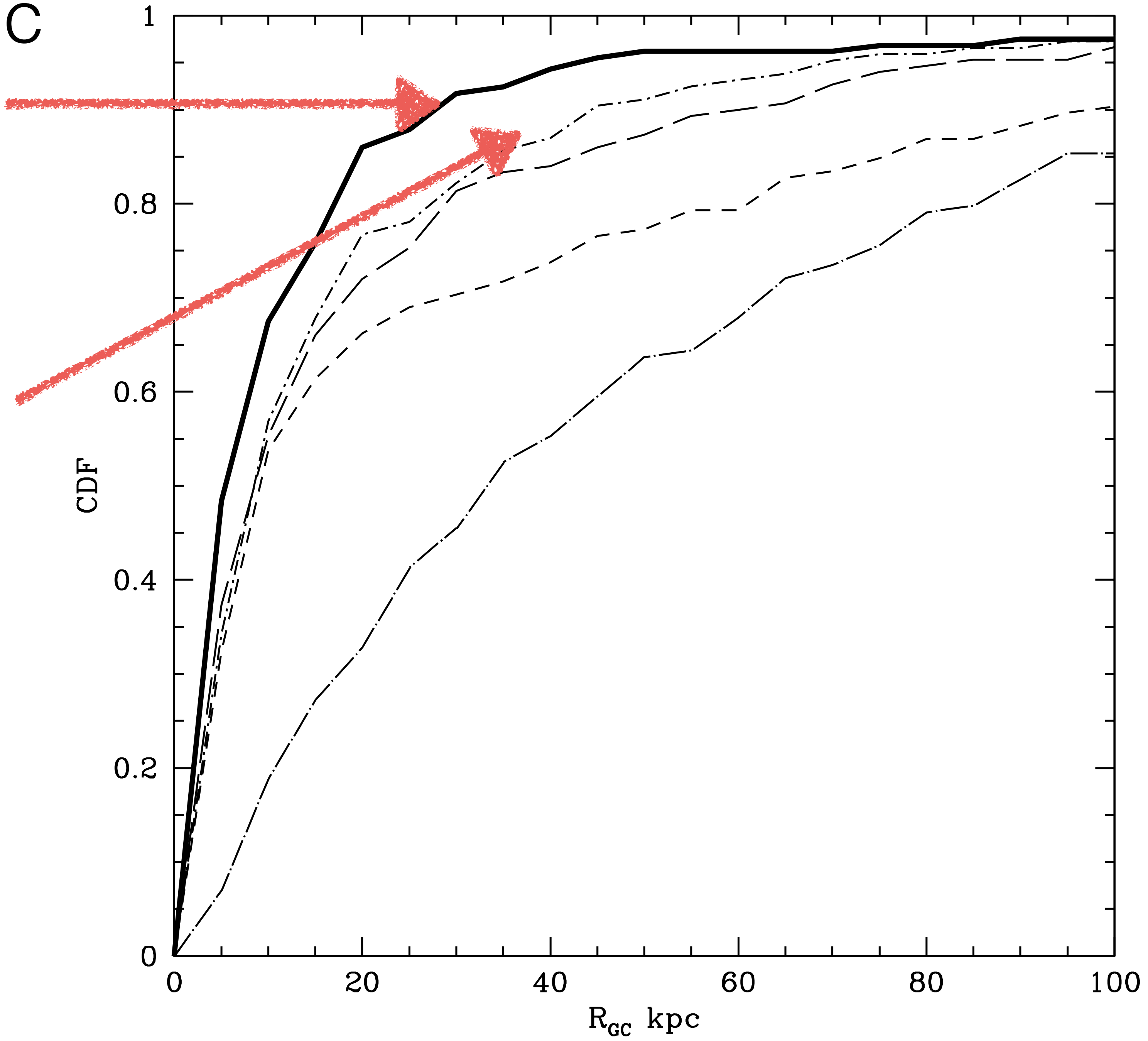
Joint Modeling of GC systems in Milky Way and nearby dwarfs

- Via Lactea II merger tree
- Populate dark matter halos with GCs to reproduce observations of nearby dwarfs (Georgiev et al 2010)
- Follow orbits of accreted GCs from satellites including dynamical processes
- In situ GCs formation of higher metallicity GCs



- Georgiev et al 2010

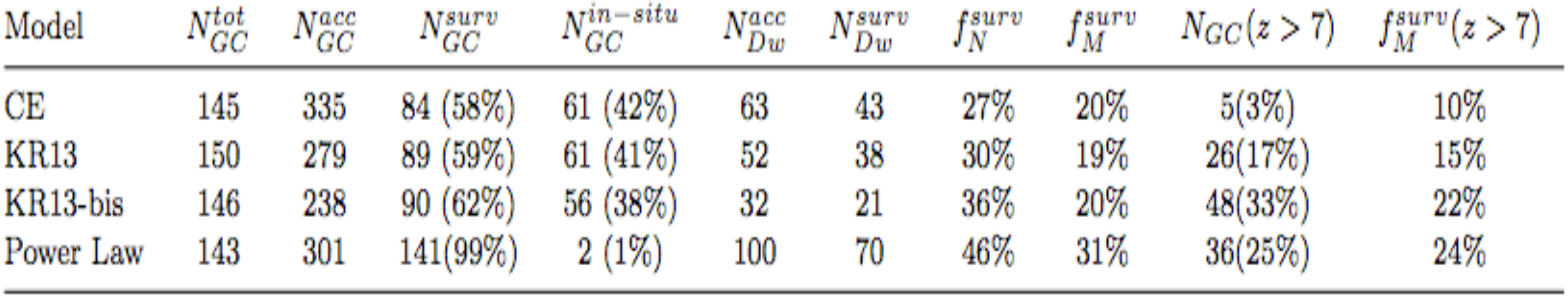
…results of modeling also favor the existence of a pre-reionization population formed in the first galaxies



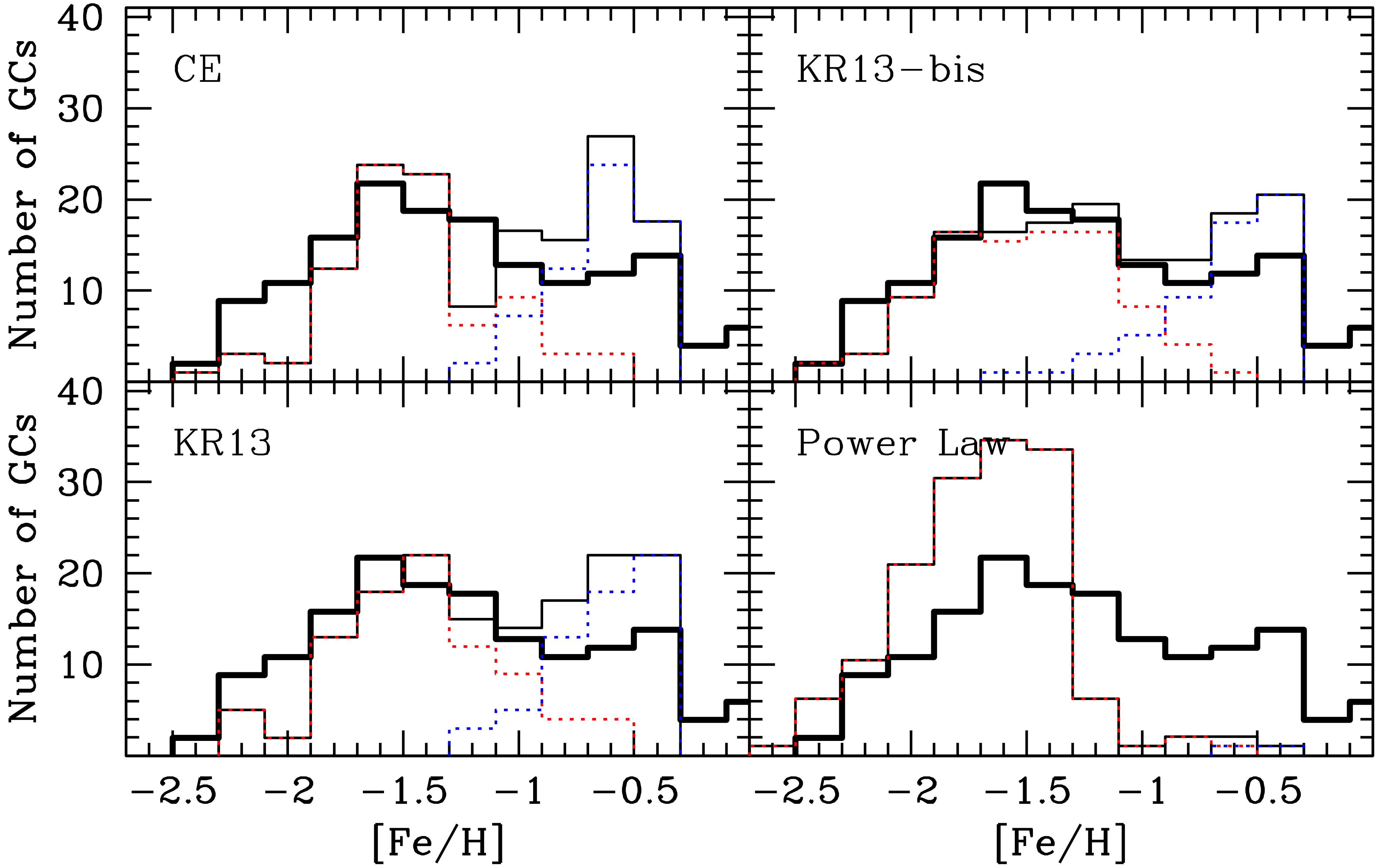
Observed Galactocentric distribution of GCs in Milky Way

Two epochs of formation as in Katz & Ricotti 2013 reproduce best radial distribution of GCs and metallicity distribution

Katz & Ricotti 2014

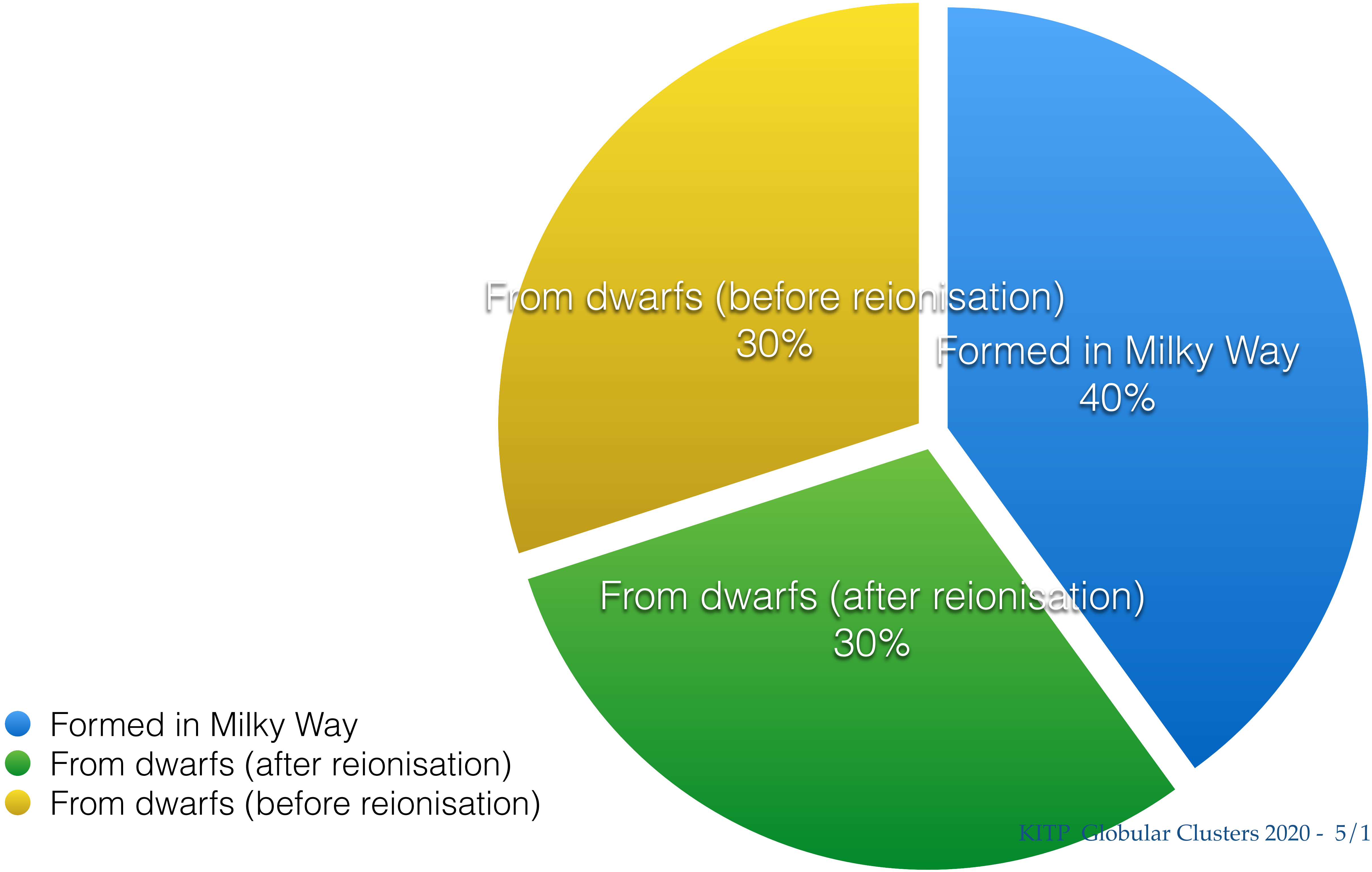


Model	N_{GC}^{tot}	N_{GC}^{acc}	N_{GC}^{surv}	$N_{GC}^{in-situ}$	N_{Dw}^{acc}	N_{Dw}^{surv}	f_N^{surv}	f_M^{surv}	$N_{GC}(z > 7)$	$f_M^{surv}(z > 7)$
CE	145	335	84 (58%)	61 (42%)	63	43	27%	20%	5(3%)	10%
KR13	150	279	89 (59%)	61 (41%)	52	38	30%	19%	26(17%)	15%
KR13-bis	146	238	90 (62%)	56 (38%)	32	21	36%	20%	48(33%)	22%
Power Law	143	301	141(99%)	2 (1%)	100	70	46%	31%	36(25%)	24%



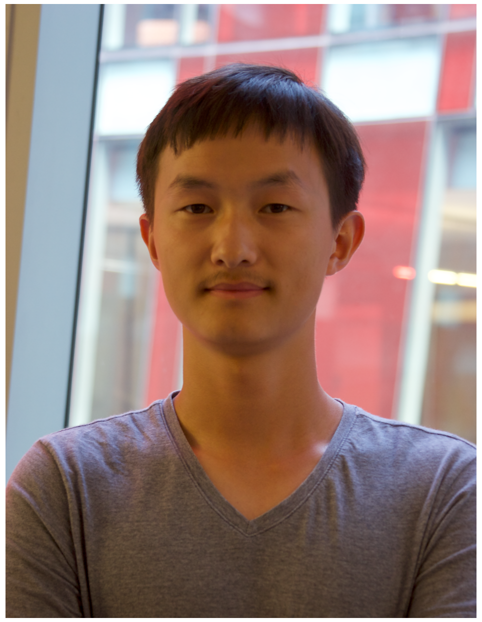
Katz & Ricotti 2014

Origin of globular clusters in Milky Way (best model)

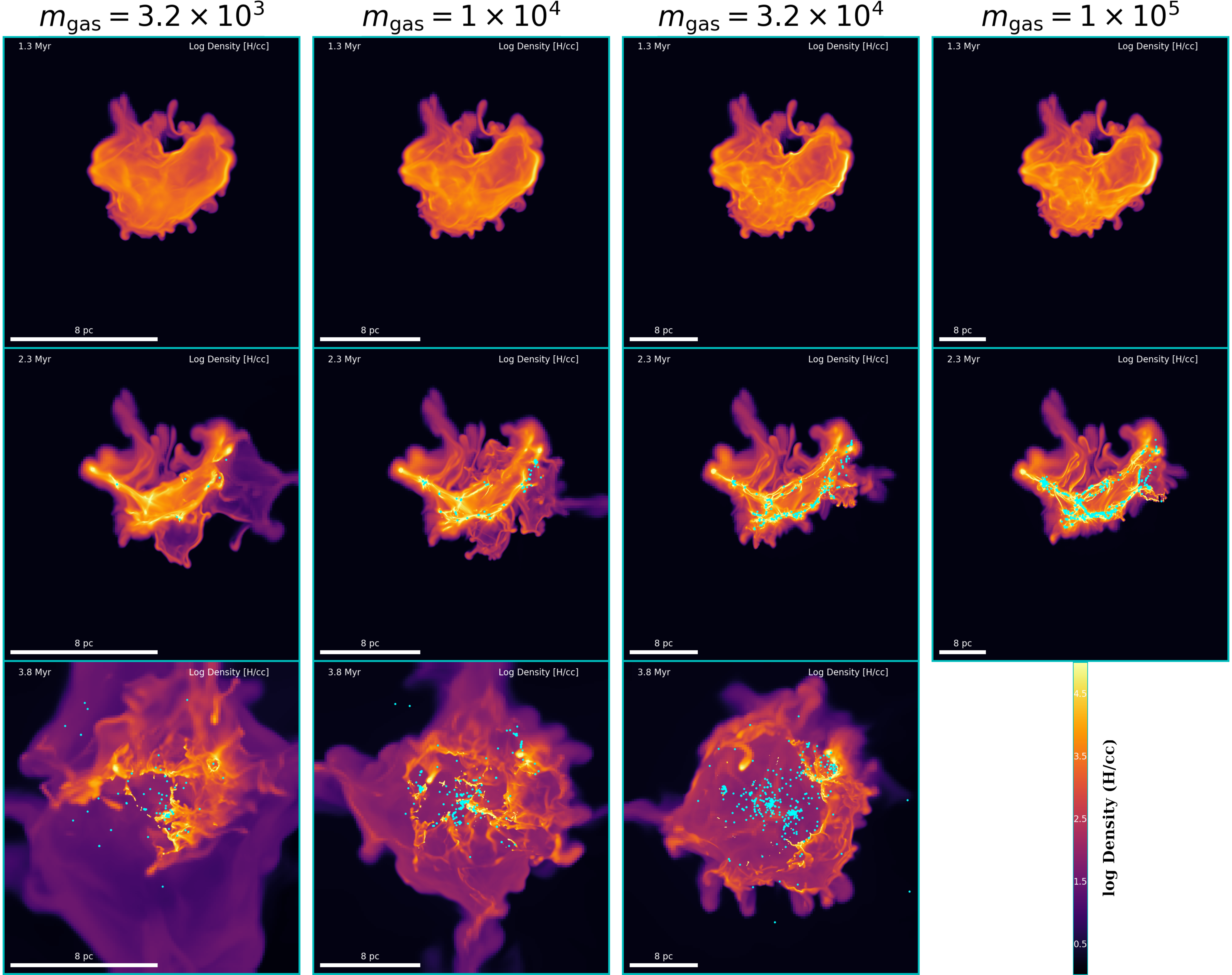


What is the ionizing escape fraction from proto-GCs?

He, Ricotti & Geen 2019
He, Ricotti & Geen 2020



Chongchong He
grad student at UMD


$m_{\rm gas} = 3.2 \times 10^3$
$m_{\rm gas} = 1 \times 10^4$
$m_{\rm gas} = 3.2 \times 10^4$
$m_{\rm gas} = 1 \times 10^5$
1.3 Myr
2.3 Myr
3.8 Myr
Log Density [H/cc]
8 pc
log Density (H/cc)
4.5
3.5
2.5
1.5
0.5

Increasing mass of MCs

Local MC

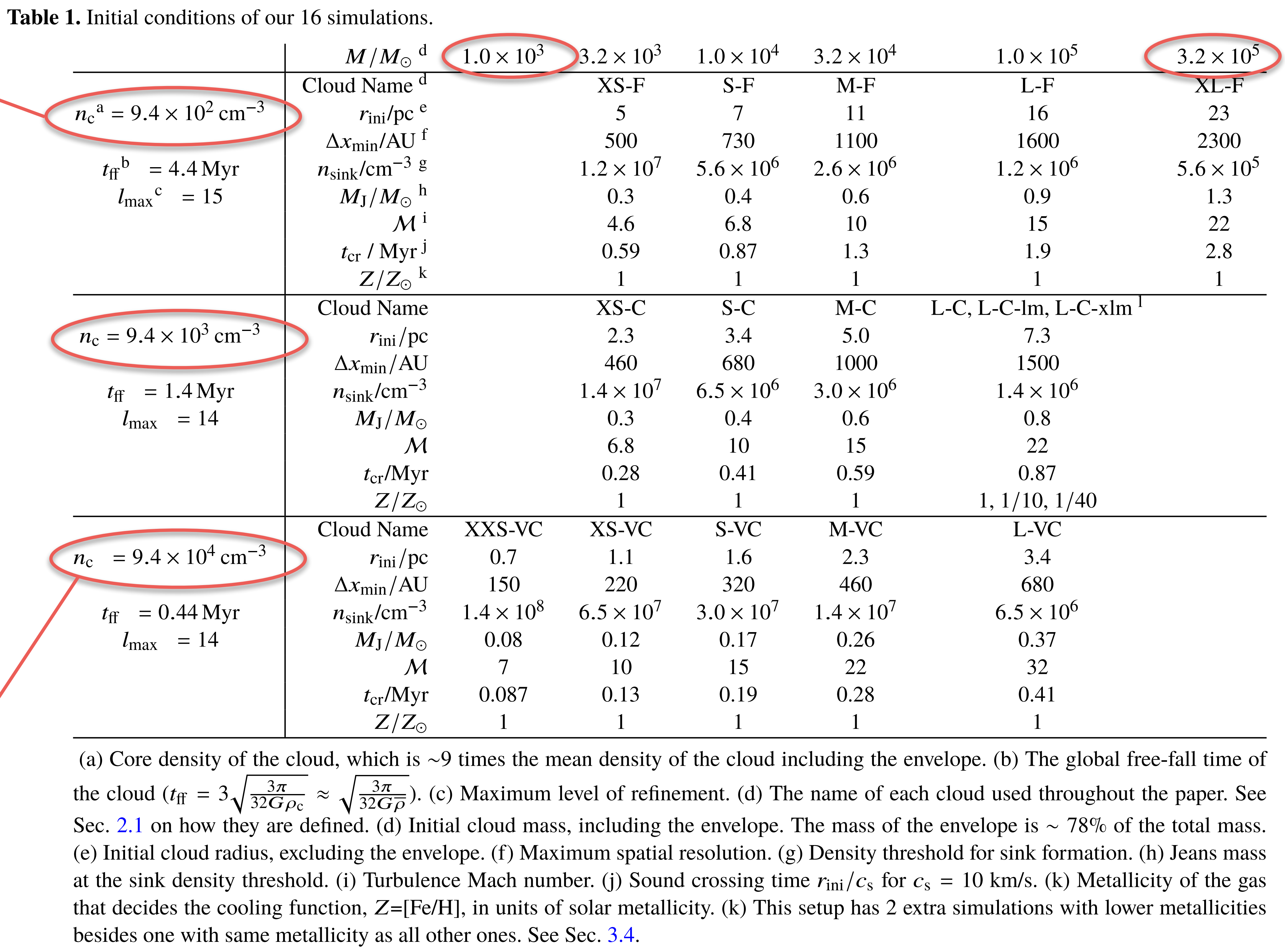


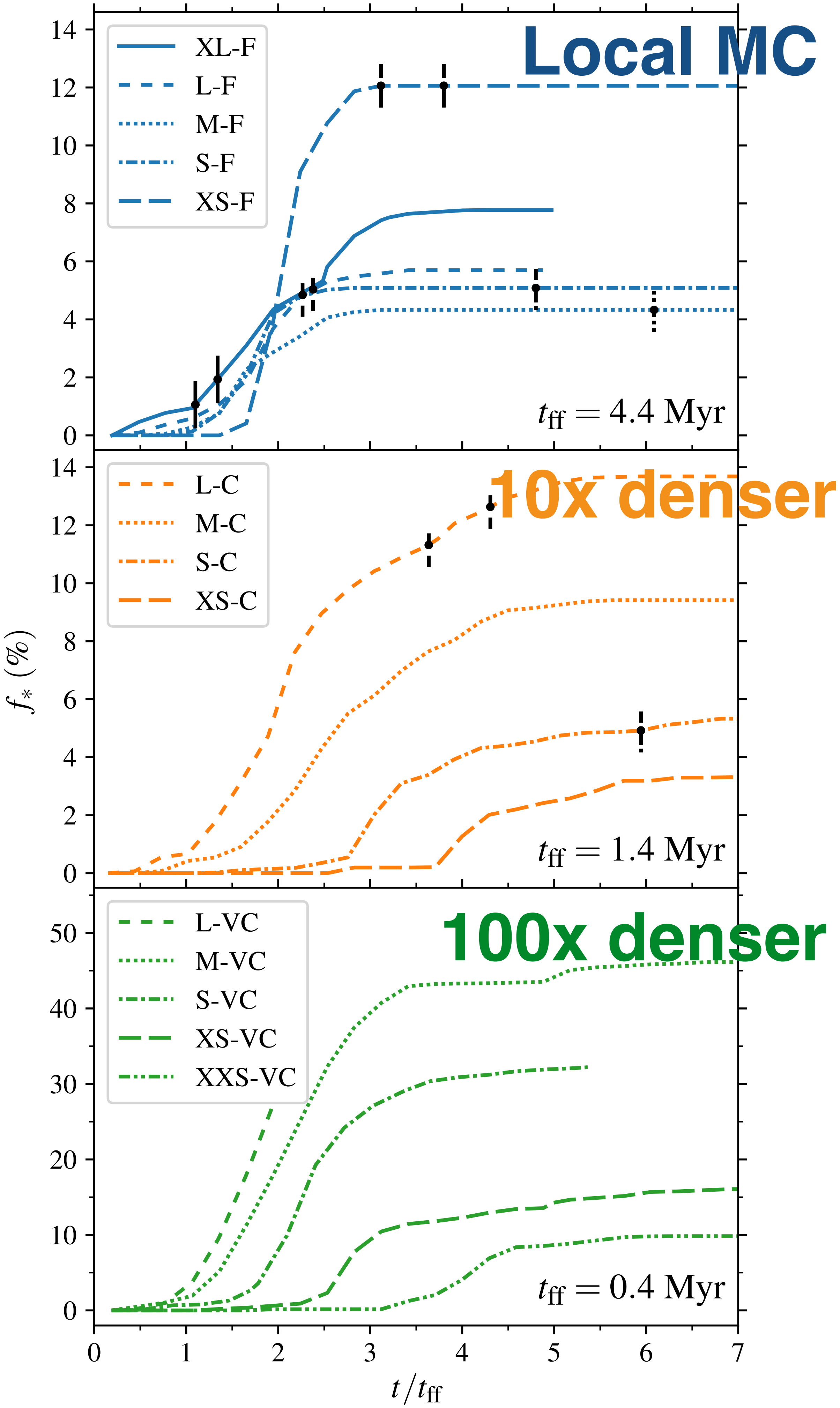
Table 1. Initial conditions of our 16 simulations.

	$M/M_\odot$ [d]	1.0×10^3	3.2×10^3	1.0×10^4	3.2×10^4	1.0×10^5	3.2×10^5
	Cloud Name [d]		XS-F	S-F	M-F	L-F	XL-F
n_c [a] $= 9.4\times10^2\ \mathrm{cm}^{-3}$	$r_{\rm ini}/\mathrm{pc}$ [e]		5	7	11	16	23
	$\Delta x_{\rm min}/\mathrm{AU}$ [f]		500	730	1100	1600	2300
$t_{\rm ff}$ [b] $= 4.4\,\mathrm{Myr}$	$n_{\rm sink}/\mathrm{cm}^{-3}$ [g]		1.2×10^7	5.6×10^6	2.6×10^6	1.2×10^6	5.6×10^5
$l_{\rm max}$ [c] $= 15$	$M_J/M_\odot$ [h]		0.3	0.4	0.6	0.9	1.3
	$\mathcal{M}$ [i]		4.6	6.8	10	15	22
	$t_{\rm cr}$ / Myr [j]		0.59	0.87	1.3	1.9	2.8
	$Z/Z_\odot$ [k]		1	1	1	1	1
	Cloud Name		XS-C	S-C	M-C	L-C, L-C-lm, L-C-xlm [l]	
$n_c = 9.4\times10^3\ \mathrm{cm}^{-3}$	$r_{\rm ini}/\mathrm{pc}$		2.3	3.4	5.0	7.3	
	$\Delta x_{\rm min}/\mathrm{AU}$		460	680	1000	1500	
$t_{\rm ff} = 1.4\,\mathrm{Myr}$	$n_{\rm sink}/\mathrm{cm}^{-3}$		1.4×10^7	6.5×10^6	3.0×10^6	1.4×10^6	
$l_{\rm max} = 14$	$M_J/M_\odot$		0.3	0.4	0.6	0.8	
	$\mathcal{M}$		6.8	10	15	22	
	$t_{\rm cr}$/Myr		0.28	0.41	0.59	0.87	
	$Z/Z_\odot$		1	1	1	1, 1/10, 1/40	
	Cloud Name	XXS-VC	XS-VC	S-VC	M-VC	L-VC	
$n_c = 9.4\times10^4\ \mathrm{cm}^{-3}$	$r_{\rm ini}/\mathrm{pc}$	0.7	1.1	1.6	2.3	3.4	
	$\Delta x_{\rm min}/\mathrm{AU}$	150	220	320	460	680	
$t_{\rm ff} = 0.44\,\mathrm{Myr}$	$n_{\rm sink}/\mathrm{cm}^{-3}$	1.4×10^8	6.5×10^7	3.0×10^7	1.4×10^7	6.5×10^6	
$l_{\rm max} = 14$	$M_J/M_\odot$	0.08	0.12	0.17	0.26	0.37	
	$\mathcal{M}$	7	10	15	22	32	
	$t_{\rm cr}$/Myr	0.087	0.13	0.19	0.28	0.41	
	$Z/Z_\odot$	1	1	1	1	1	

(a) Core density of the cloud, which is ~9 times the mean density of the cloud including the envelope. (b) The global free-fall time of the cloud ($t_{\rm ff} = 3\sqrt{\frac{3\pi}{32G\rho_c}} \approx \sqrt{\frac{3\pi}{32G\bar{\rho}}}$). (c) Maximum level of refinement. (d) The name of each cloud used throughout the paper. See Sec. 2.1 on how they are defined. (d) Initial cloud mass, including the envelope. The mass of the envelope is ~ 78% of the total mass. (e) Initial cloud radius, excluding the envelope. (f) Maximum spatial resolution. (g) Density threshold for sink formation. (h) Jeans mass at the sink density threshold. (i) Turbulence Mach number. (j) Sound crossing time $r_{\rm ini}/c_s$ for c_s = 10 km/s. (k) Metallicity of the gas that decides the cooling function, Z=[Fe/H], in units of solar metallicity. (k) This setup has 2 extra simulations with lower metallicities besides one with same metallicity as all other ones. See Sec. 3.4.

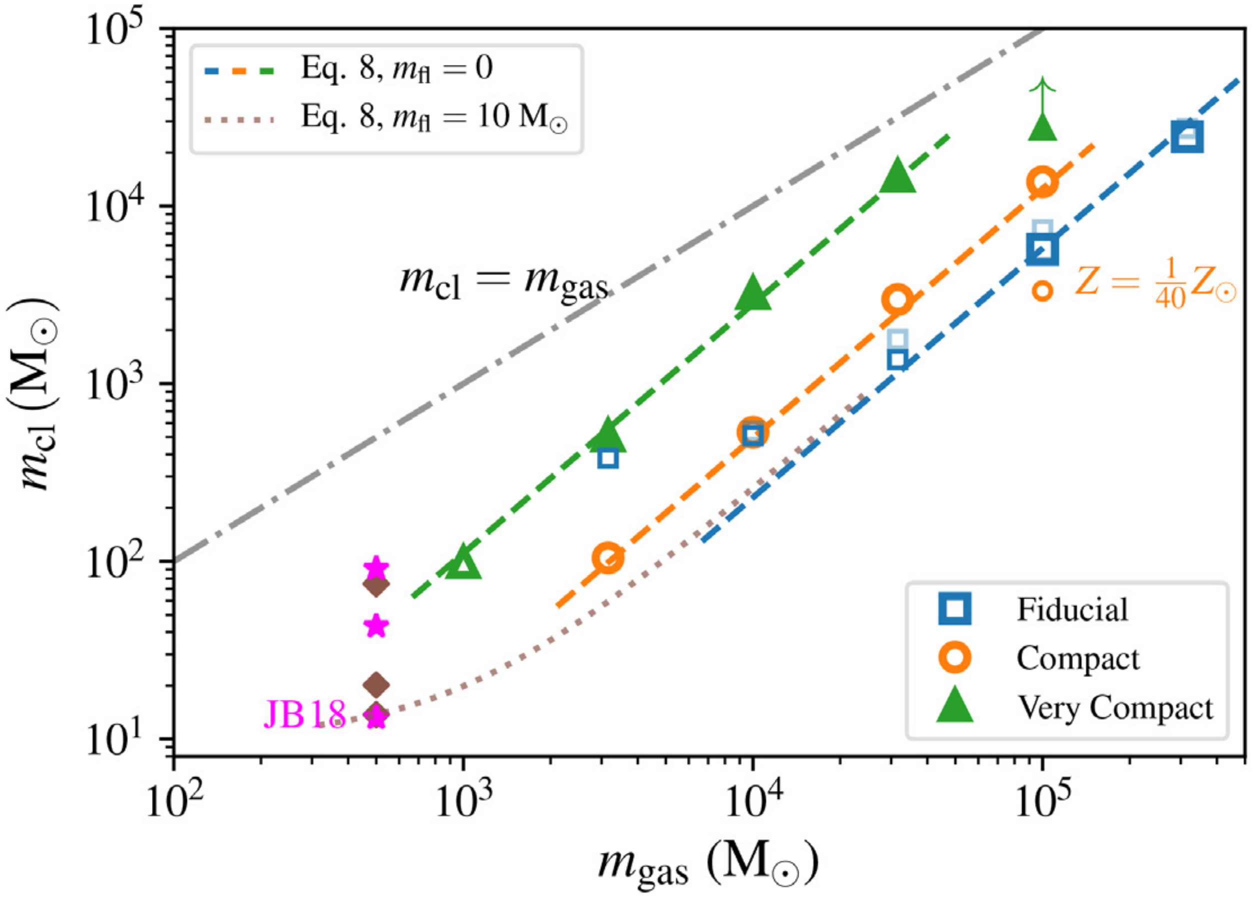
Increasing density

High-z MC



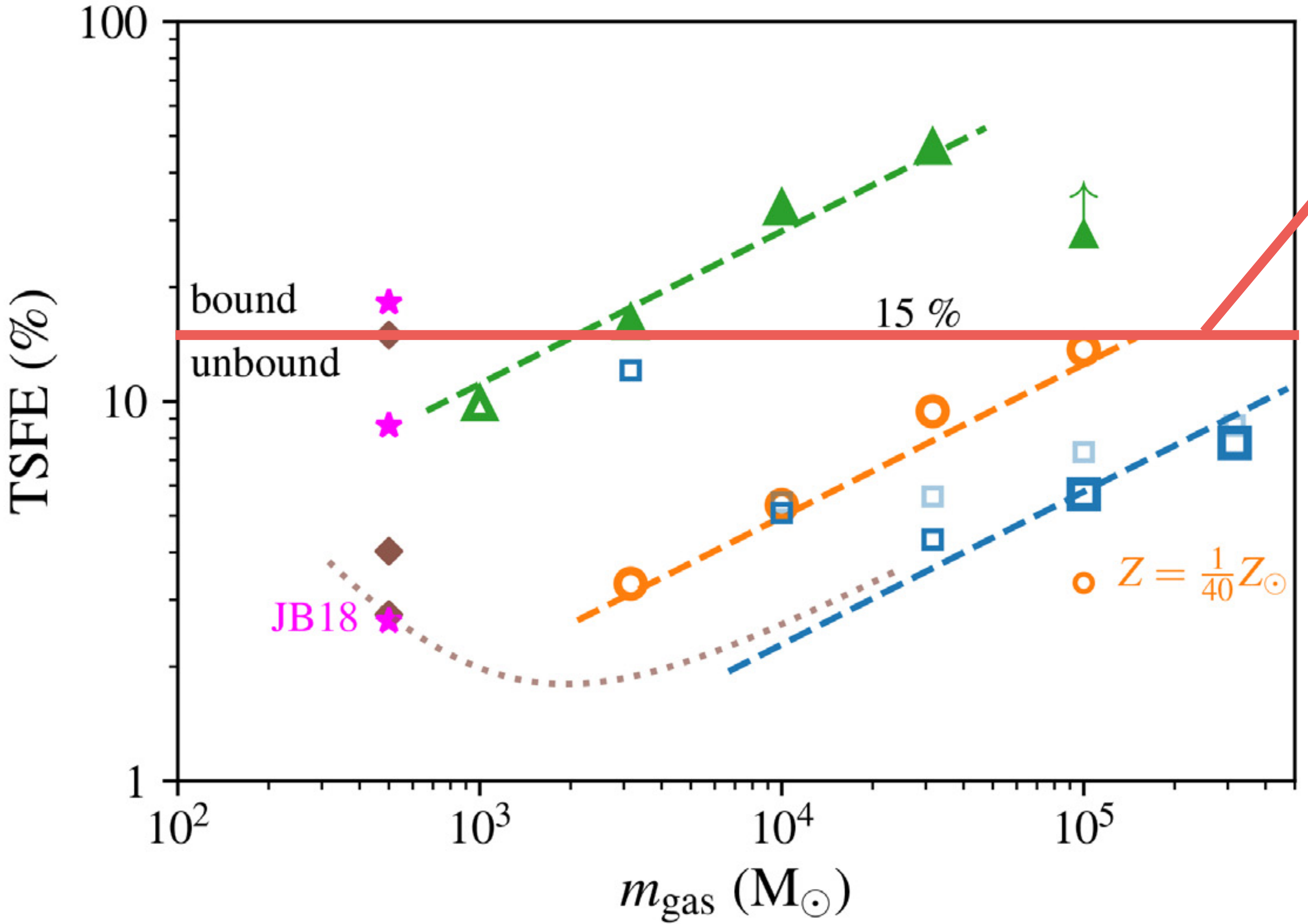
Methods and Grid of Simulations

- 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 presecription: mass of massive stars ~1/3 of sink particles mass



Bound Stellar Clusters

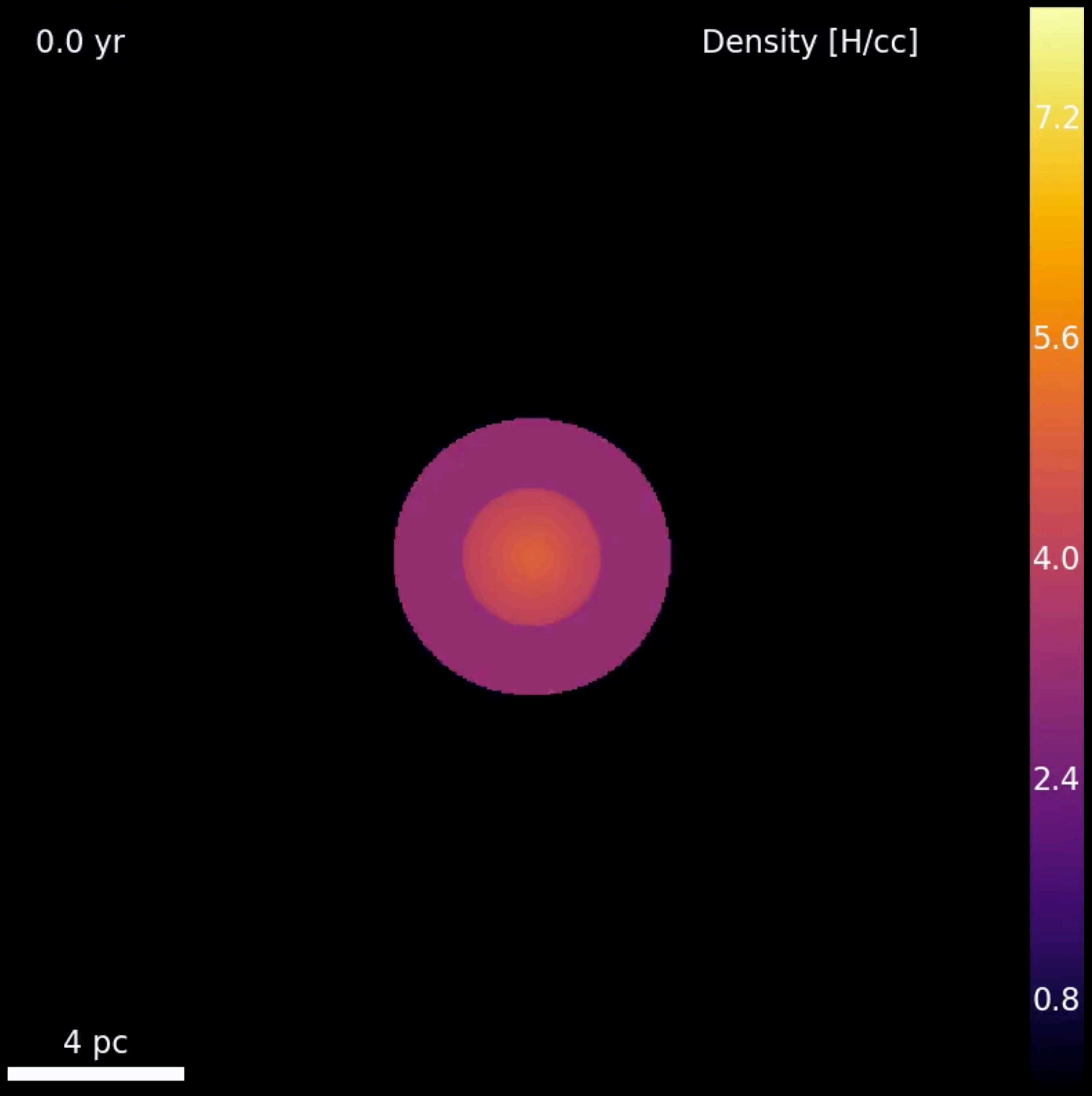
Globular Clusters Progenitors

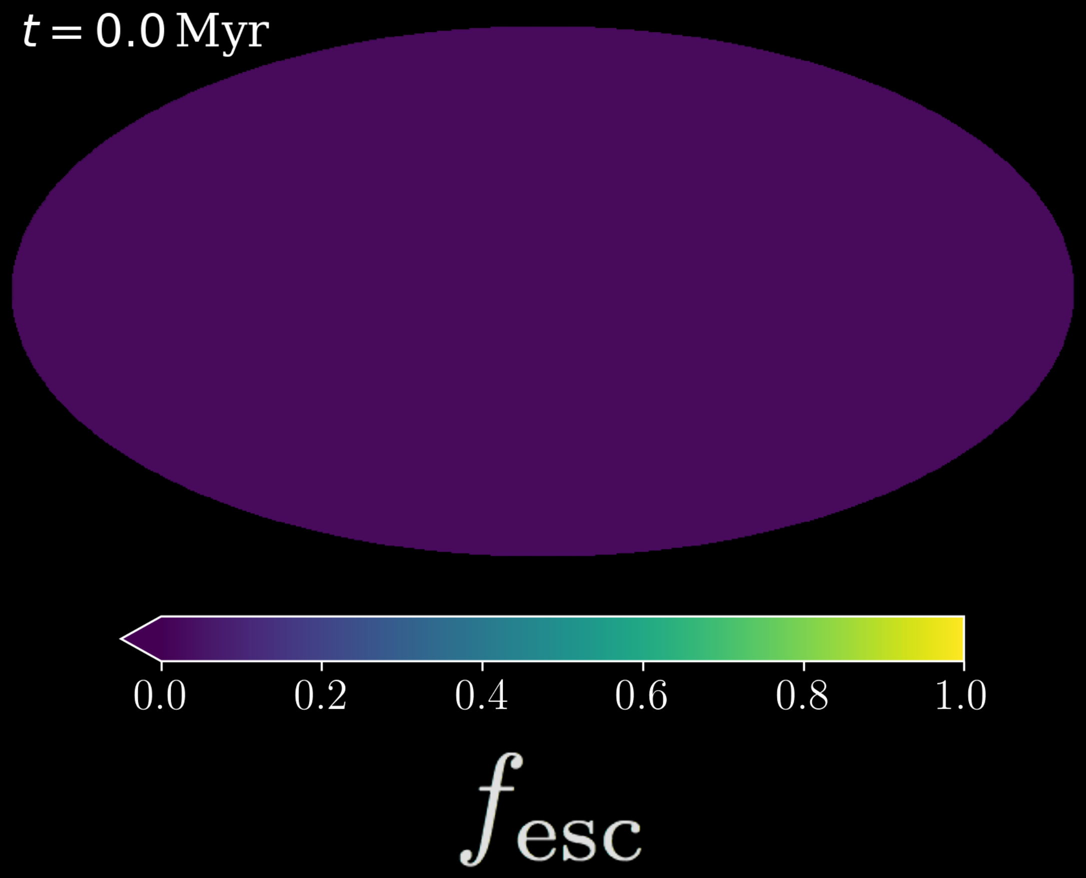


$$f_{*,\rm tot} = 2.0\ \text{per cent} \left(\frac{m_{\rm gas}}{10^4\ \mathrm{M_\odot}} \right)^{0.4} \left(1 + \frac{\overline{n}_{\rm gas}}{n_{\rm cri}} \right)^{0.91} .$$

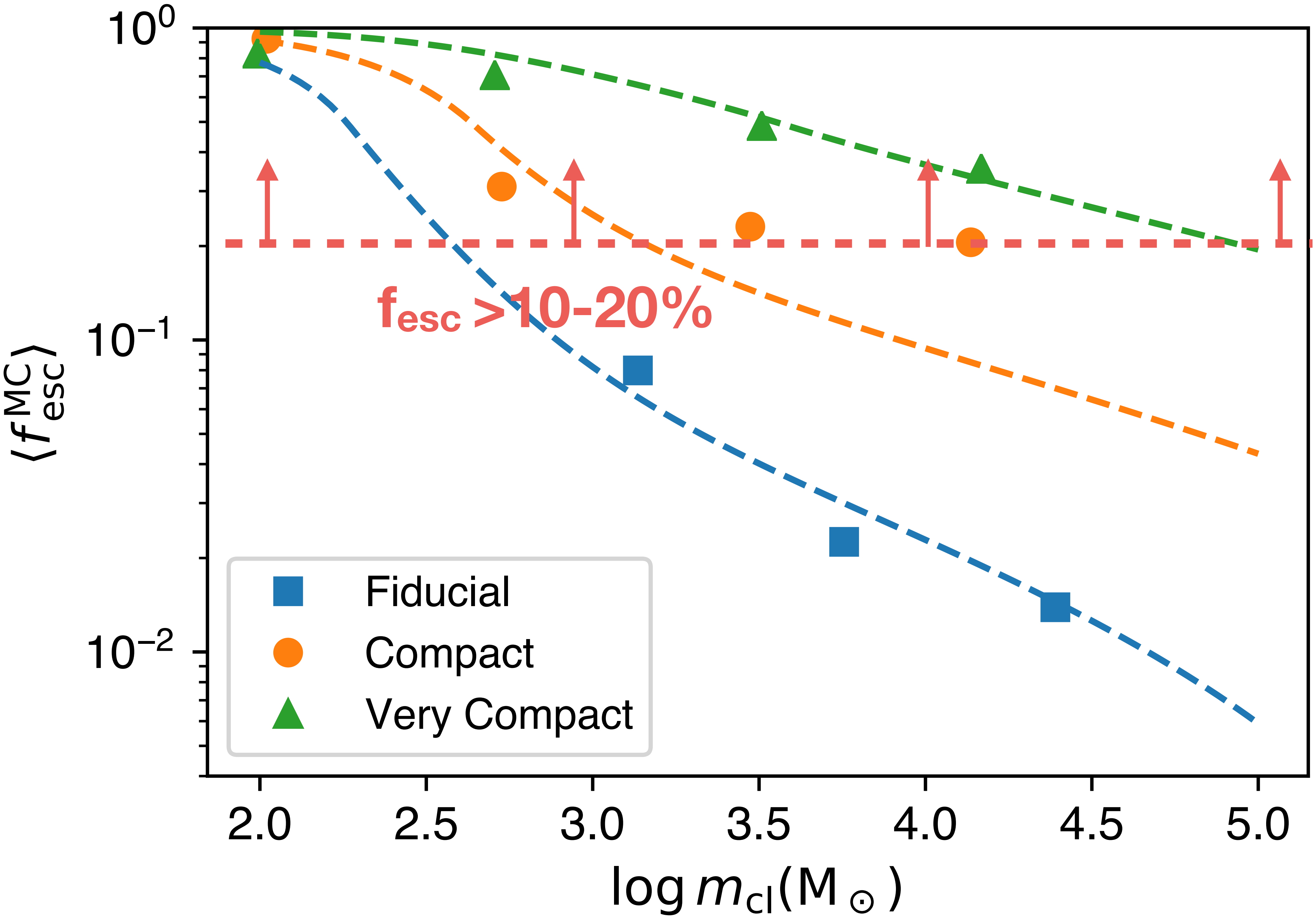
$$n_{\rm cri} \approx 10^3\ \ \mathrm{cm^{-3}}$$

Escape fraction of ionizing photons





Photon Escape Fraction



Summary

- Formation of compact star cluster is dominant mode of star formation in high-redshift dwarf galaxies.

- It’s important for a number of reasons:

  1. Can be dominant sources of reionization. May be necessary to have escape fractions from MC >10%.

  2. Channel to produce seed SMBHs.

  3. Useful constraints from Near Field Cosmology (# of ultra-faint dwarfs and globular clusters) and nearby dwarfs.

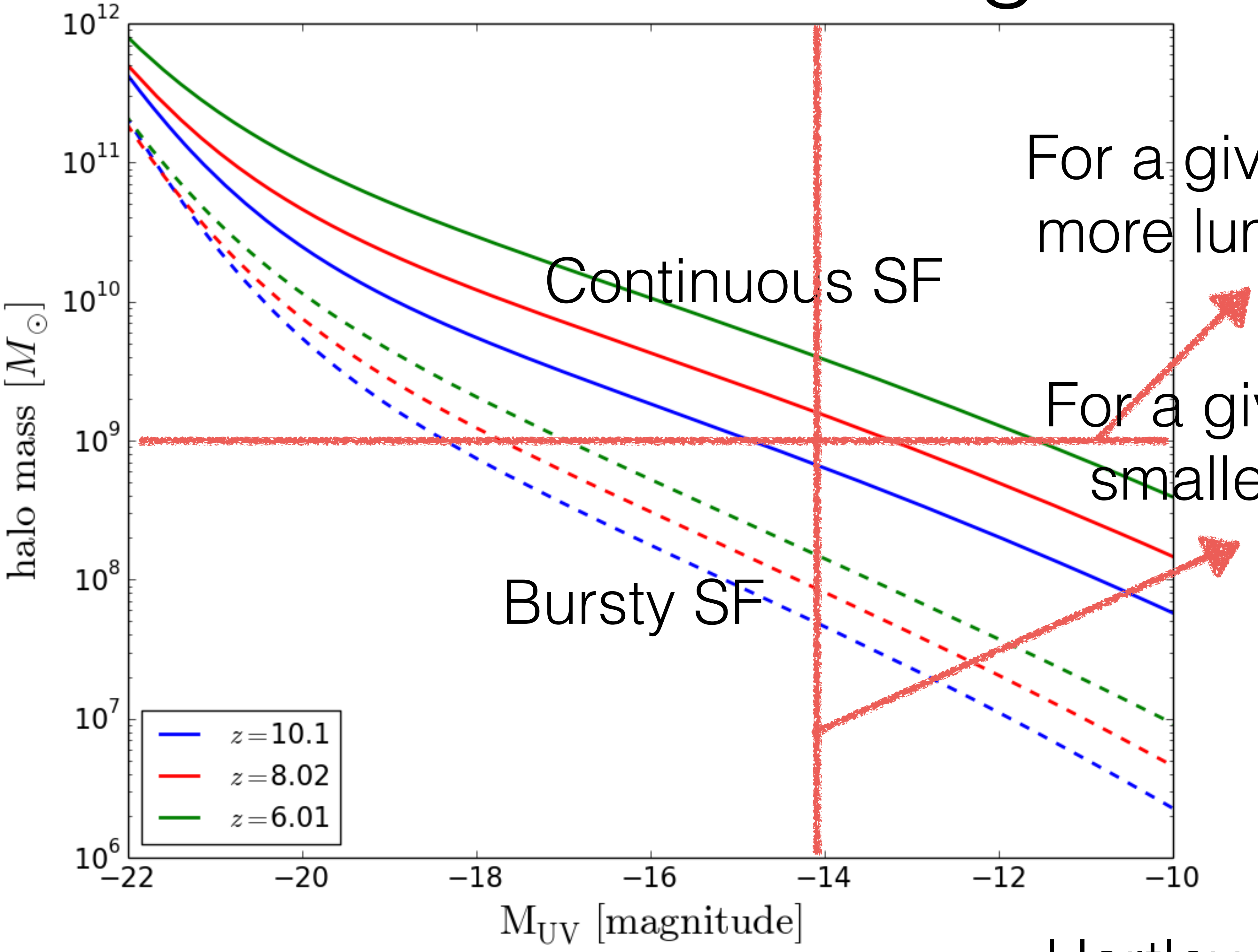
“Extra Slides”

If the **“formation of compact star clusters”** was indeed the dominant mode star formation in the first galaxies:

- Interesting implications for the origin of GCs and UFDs observed around the Milky Way and Andromeda
- Reionization of the IGM can be achieved with fesc~4%

Can this idea be tested observationally?

Other implications: HST and JWST observations at high redshift



Continuous SF

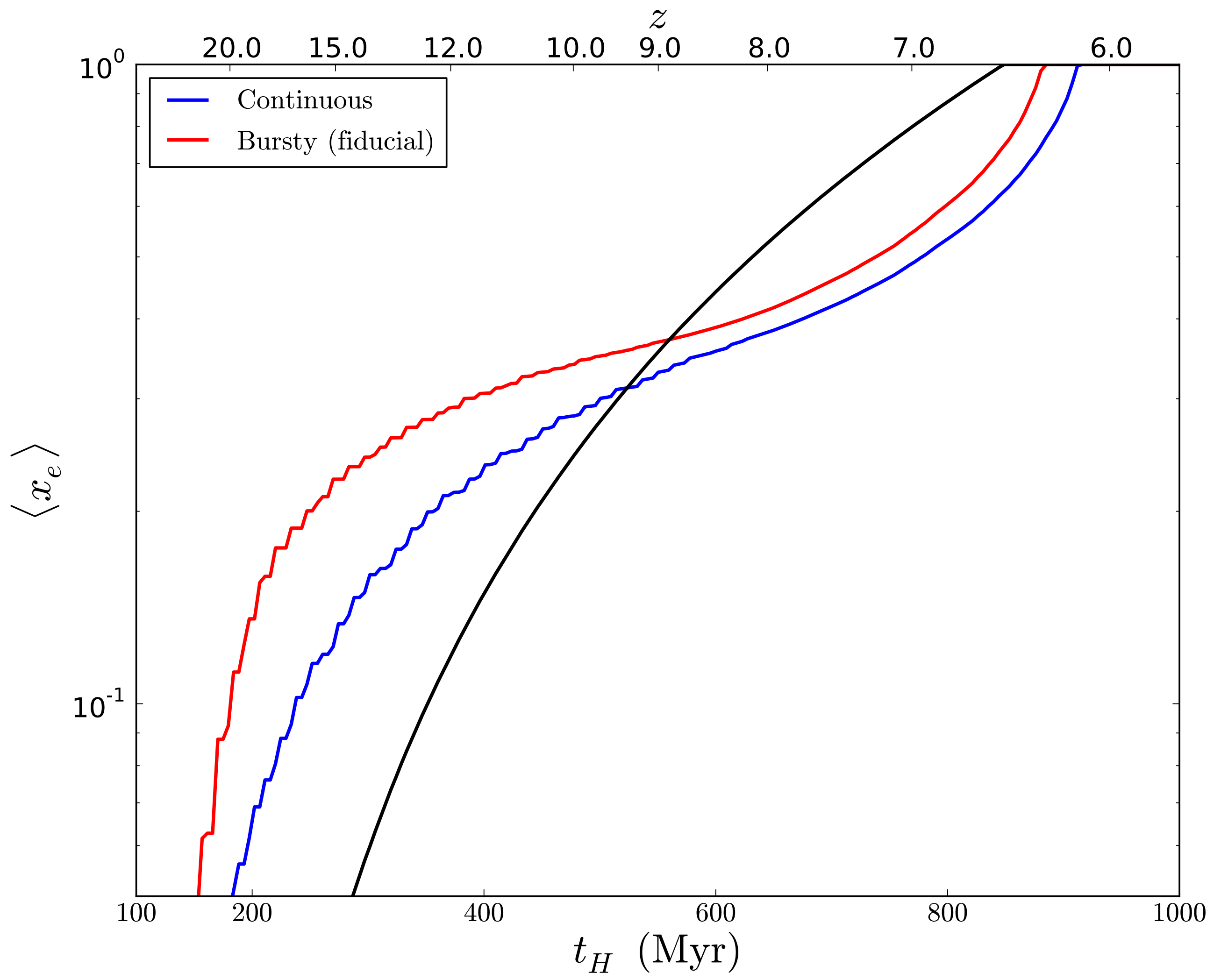
Bursty SF

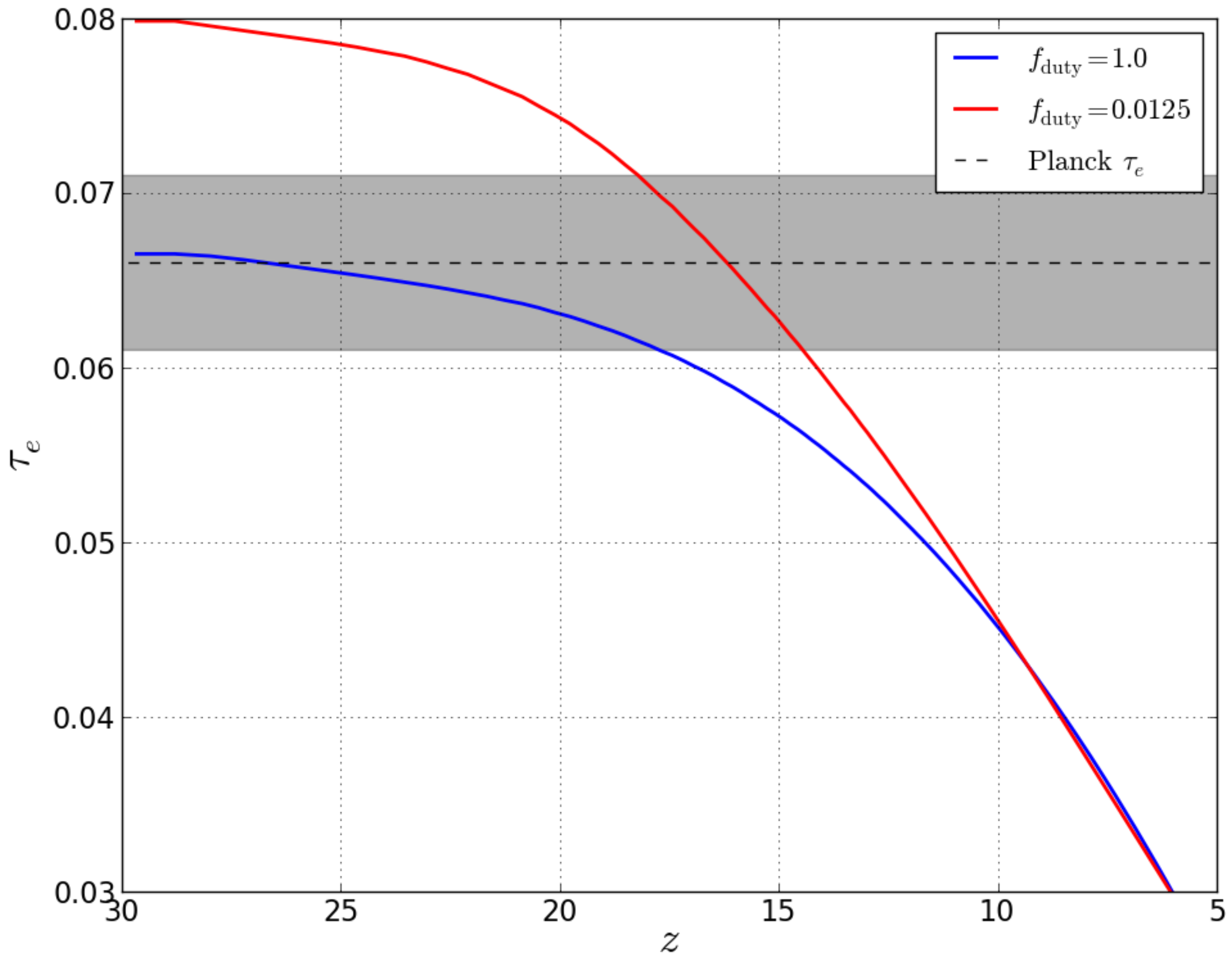
For a given halo mass:
more luminous galaxy

For a given luminosity:
smaller mass halos

Hartley & Ricotti 2016

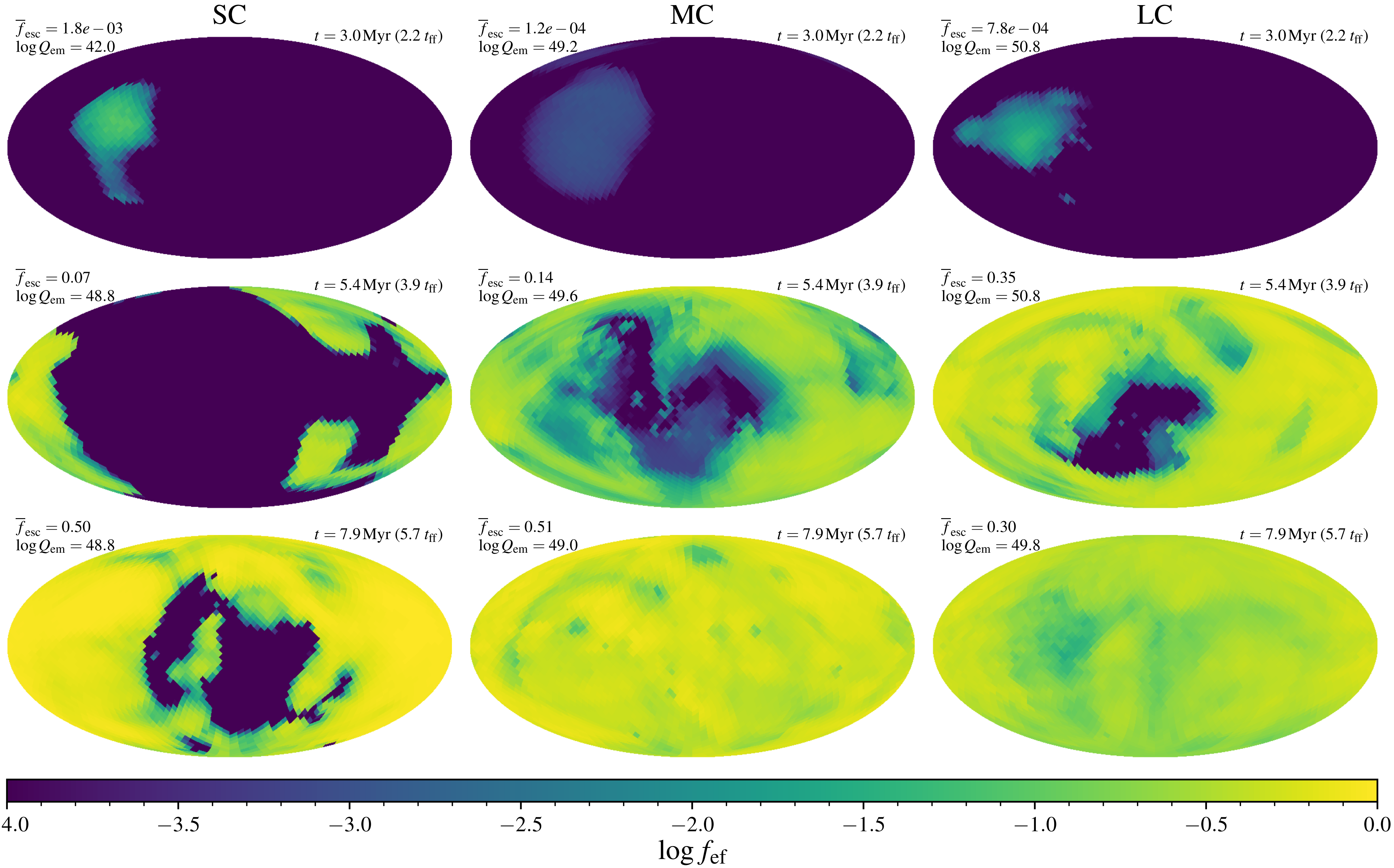
Similar to X-ray ionization: due to relic HII regions



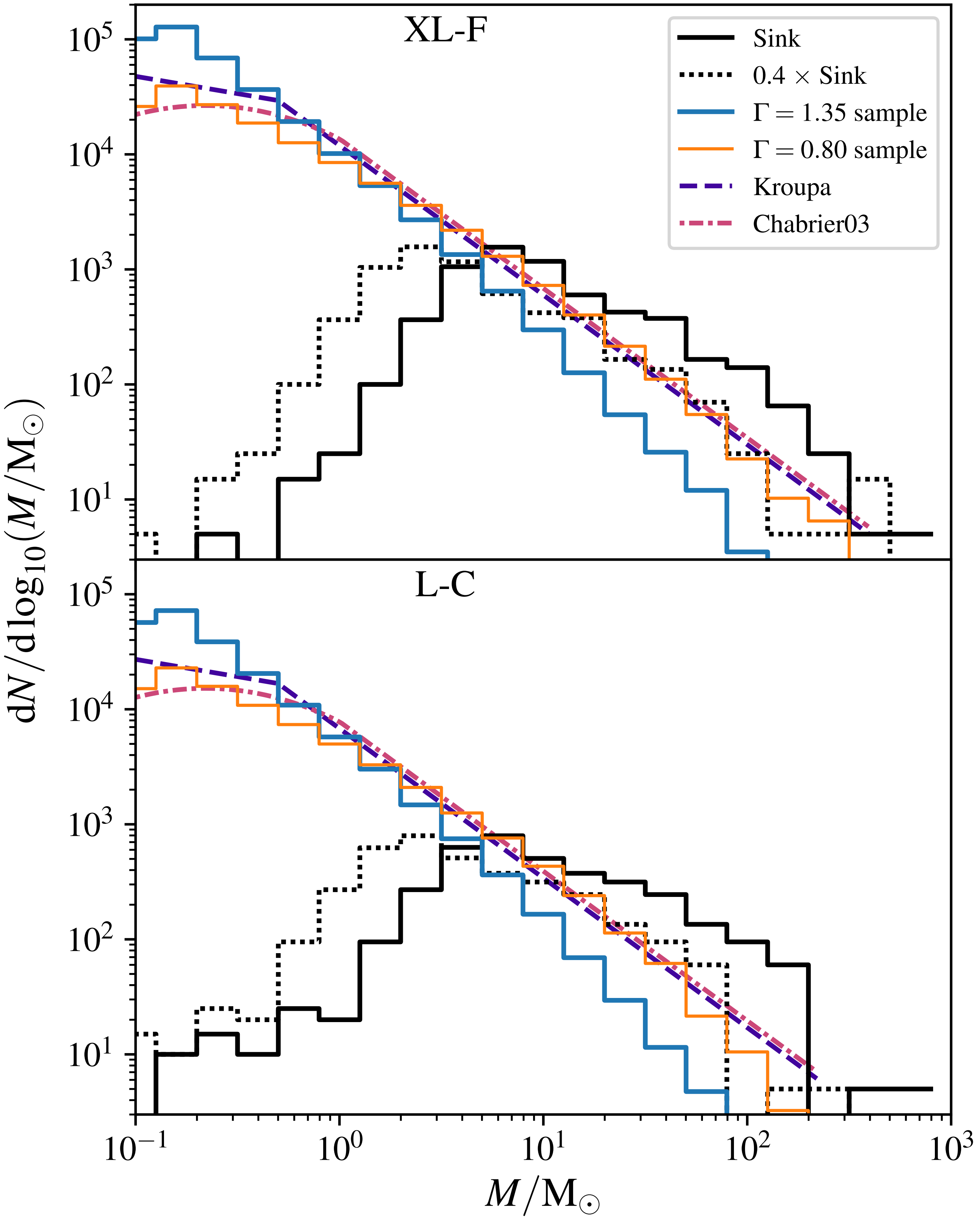


fixed f_{esc}=12.5%

Escape fraction of ionizing photons



Fragmentation of Sink Particles

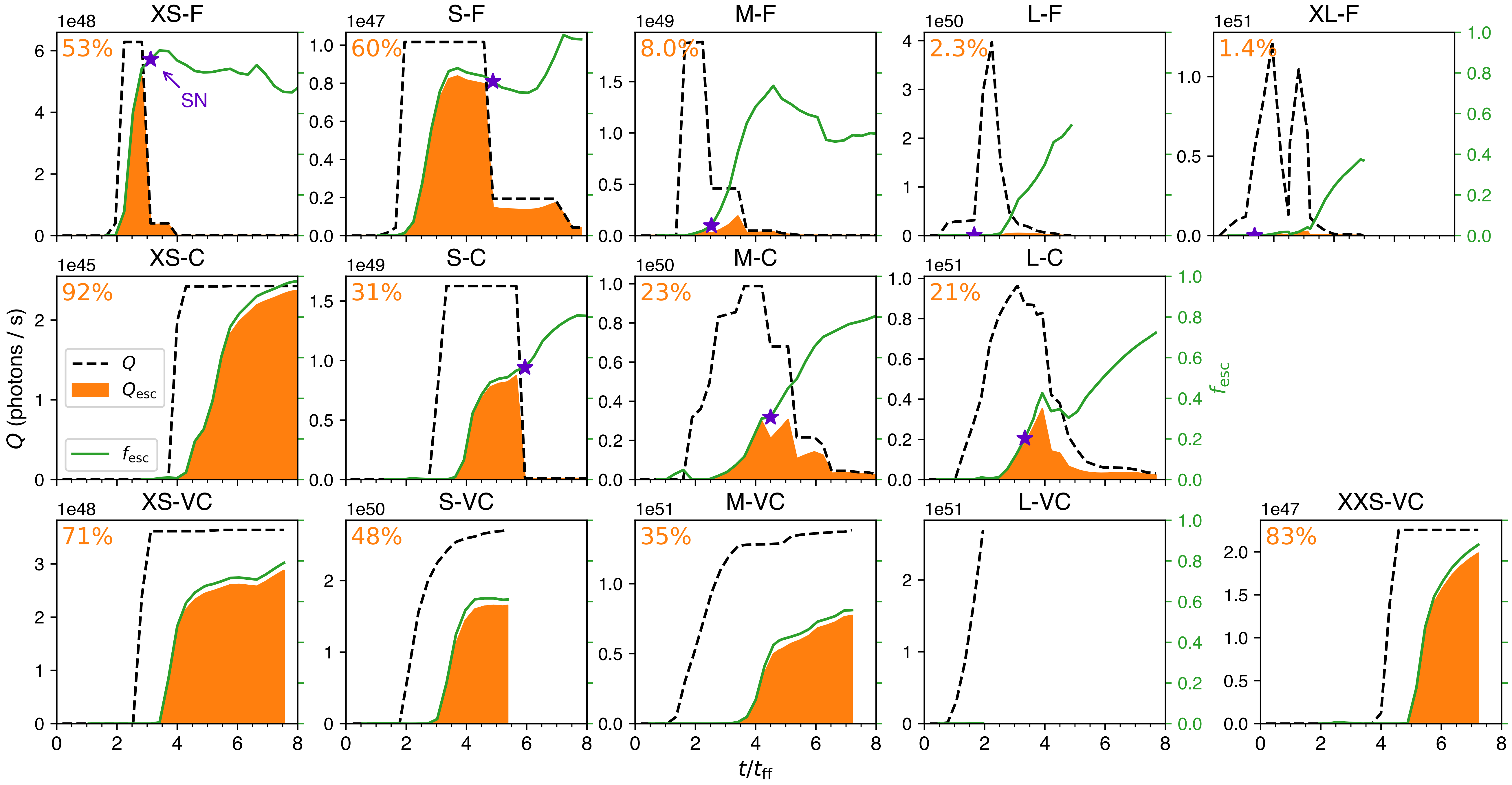


- Each sink particle fragments with a power-law slope **0.8** (flatter than Salpeter ~1.35) in mass range **M_{sink} - 0.01 M_{sun}** —>reproduces shape and normalization of Chabrier IMF

- Turbulence (lognormal PDF) makes Saltpeter-like mass function of sinks

- Self-gravity (power-law PDF) produces flatter slope of sink fragments (see Lee & Hennebelle 2018)

Escape fraction of ionizing photons



M14 - Globular cluster

Newly discovered Milky Way satellite Horologium-1. Image via V. Belokurov, S. Koposov (IoA, Cambridge).

An infrared map of our Milky Way galaxy, showing 9 new objects – dwarf galaxies and/or globular clusters – marked in red. Image via S. Koposov, V. Belokurov (IoA, Cambridge) and 2MASS survey.

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

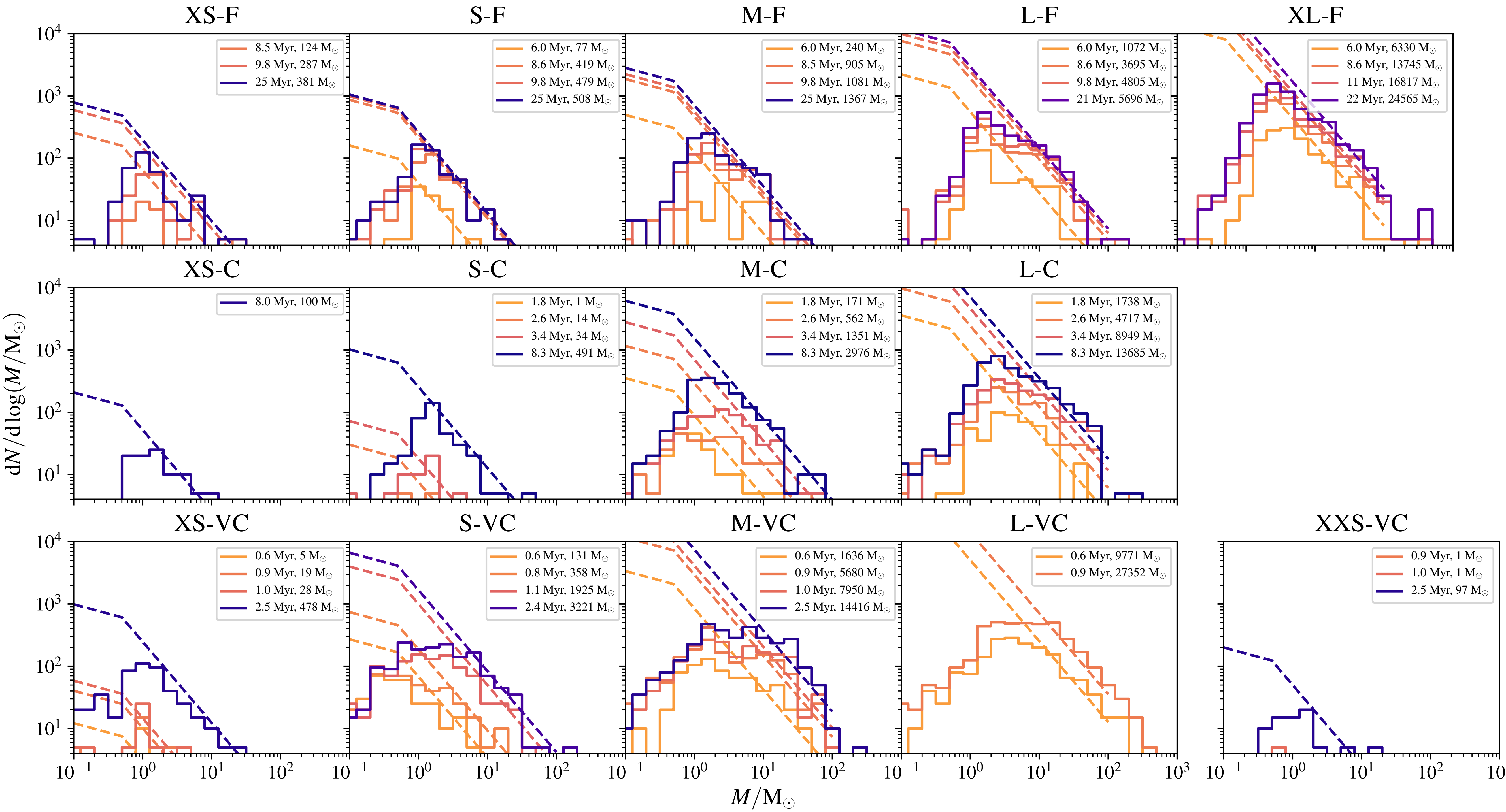
      https://ui.adsabs.harvard.edu/abs/2019MNRAS.489.1880H/abstract

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

Evolution of the IMF



Summary

1. Perhaps we captured the formation of the first GCs/UCDs in cosmological simulations of the dwarf galaxies at z=9.

2. Low surface brightness spheroidal galaxies similar to the ultra-faint dwarfs are produced by a few “failed” or “dissolved” compact star clusters.

3. HST deep field observations of galaxies and modeling of the Milky Way GCs suggest that ~20%-30% of MW’s GCs formed in the first galaxies. Depending on their fesc they may dominate the reionization process.

4. Bursts of star formation from compact star clusters have similar effect on IGM as ionization by X-rays.

5. Escaping ionizing radiation needed to produce observed optical depth to Thompson scattering is about 4%. Agrees better with limits from observations.