First Galaxies, Globular Clusters and Ultra-faint Dwarfs with JWST

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JWST Meeting 10/15/2015

1. Globular Clusters (GCs) as Sources of Reionization

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

2. Reionization in a Bursty Universe

    (Hartley & Ricotti, work in preparation)

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

    (Ricotti, Parry & Gnedin, work in preparation)

GCs as Sources of Reionization: why?

- Hubble Deep field studies show that, to reionize with stars, small mass halos (close to 10^8 M_{sun}) must form stars rather efficiently and f_{esc}~0.2-1

- However, near-field studies show that the smallest mass halos in the Local Group are exceptionally faint or dark (ultra-faint dwarfs)

- But we also observe globular clusters in MW halo and dwarfs: old, low metallicity and dense clusters with high SF efficiency.

- Did they play a role in reionization?

GCs as Sources of Reionization: can they do it?

1. Dense clusters have high SF efficiency, instantaneous SF and found in the outer part of dark matter halos: these 3 elements suggest large f_{esc}.

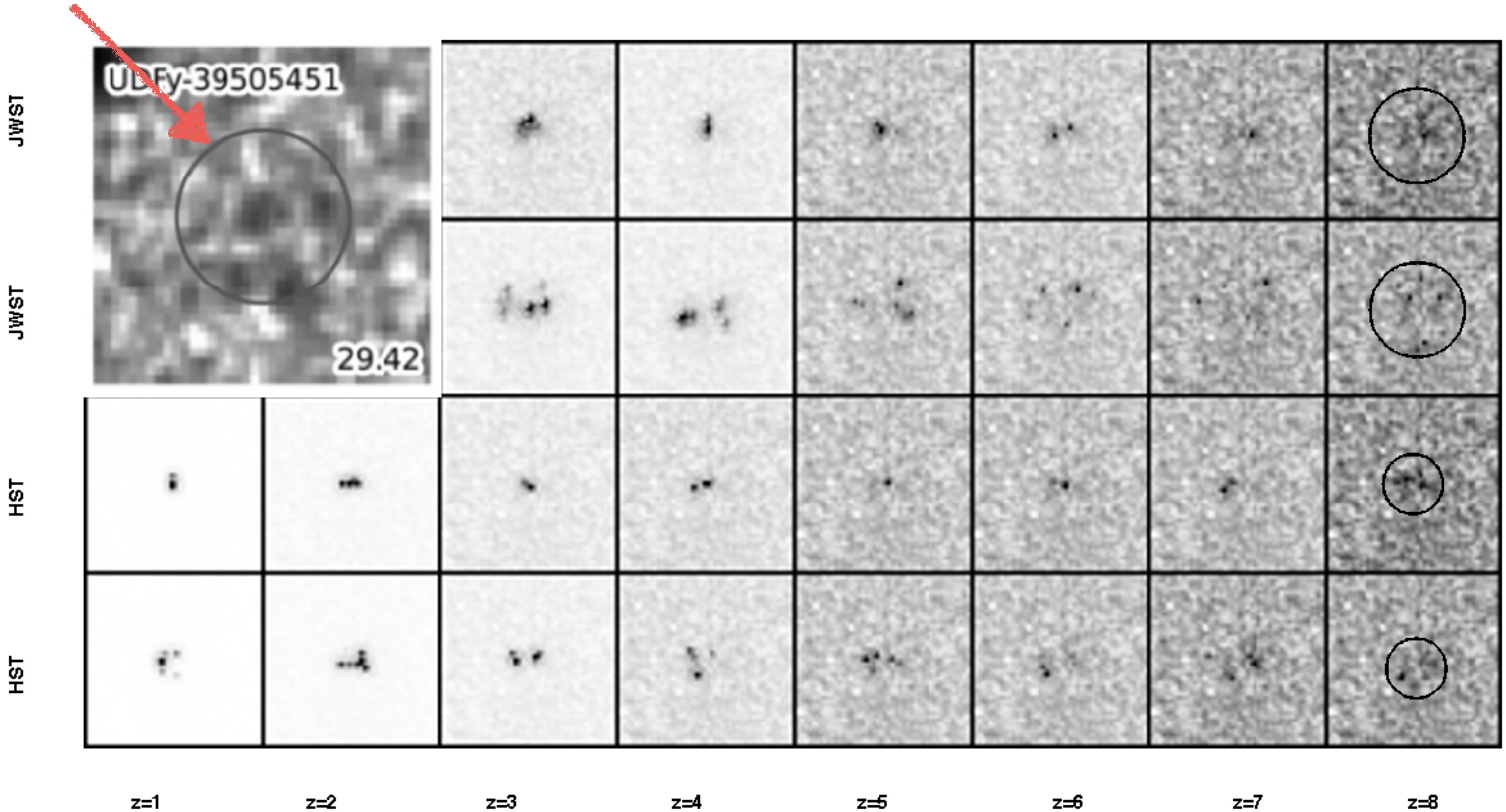
2. Tip of iceberg of a larger population of compact clusters that have been destroyed by dynamical effects and stellar evolution. So they might be tracers of a mode SF that was predominant at high redshift

- If a fraction of today's GCs (10%-50%) formed at $z>6$, emit enough UV to reionize the IGM (see Ricotti 2002)

- But when did they form?

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

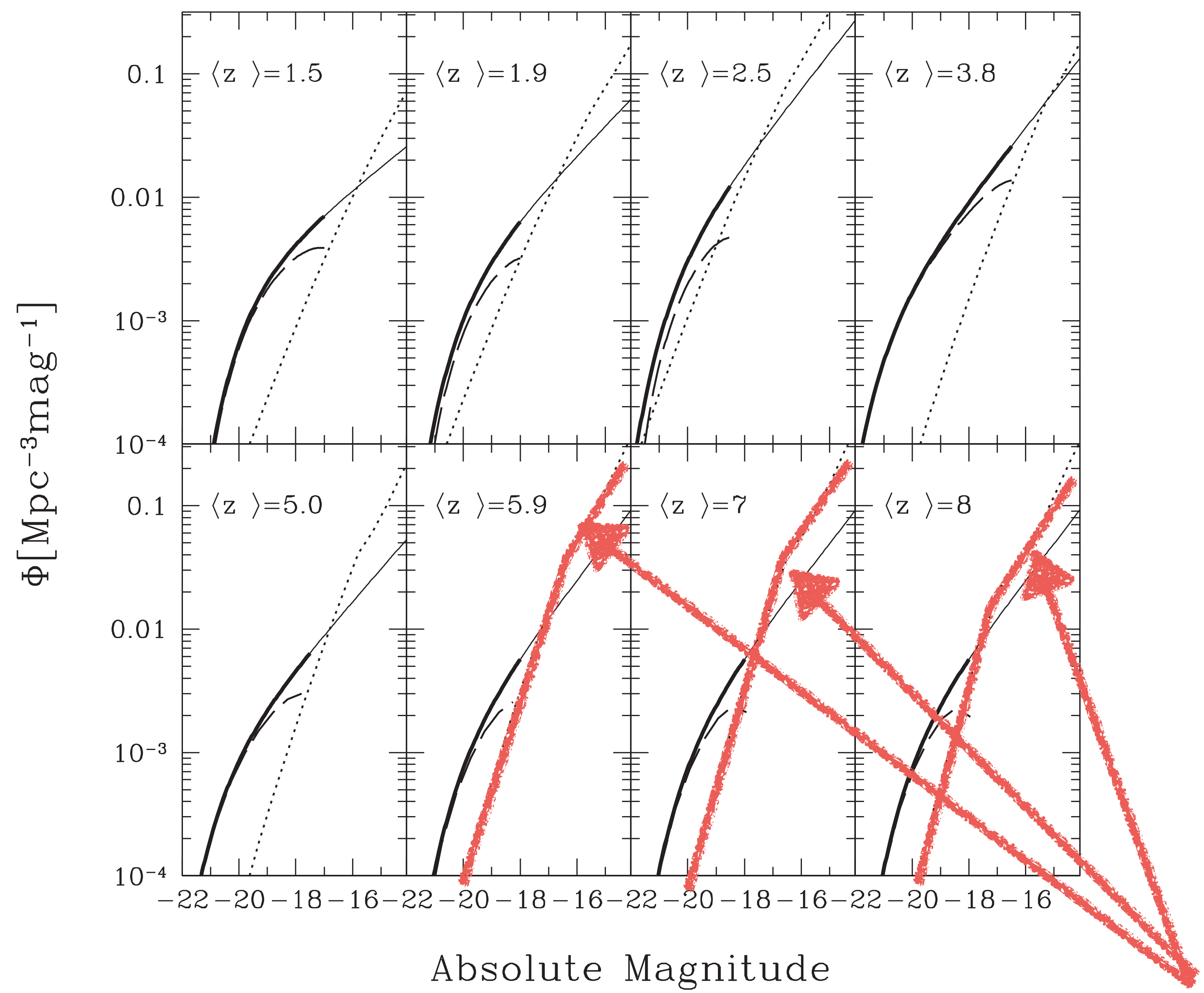
z=8 candidate for comparison (Bouwens et al. 2011)



NIRCam 1Ms

(Puzia & Sharin

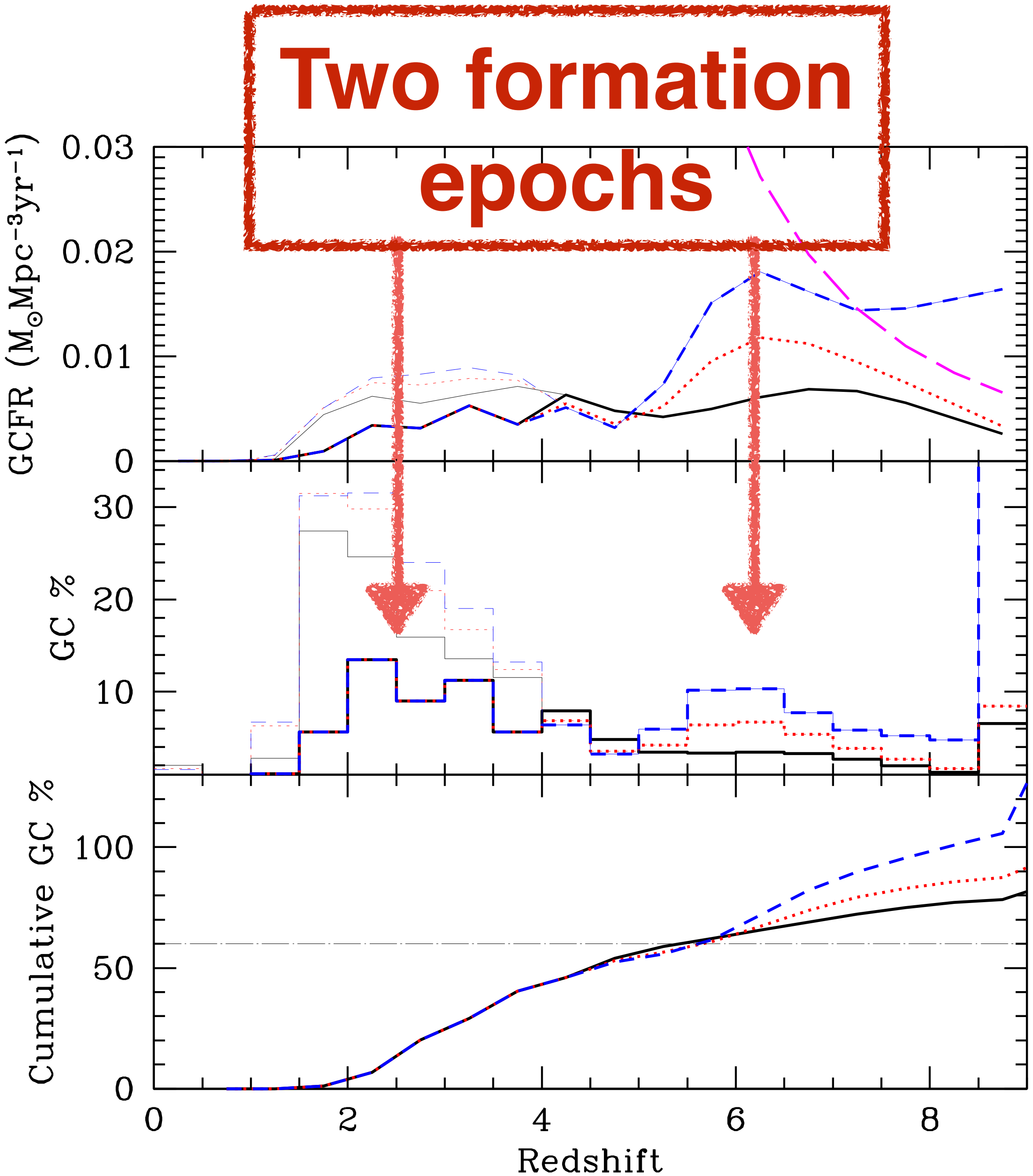
Constrain how many GCs can form at any given redshift using LF and colors in HDF

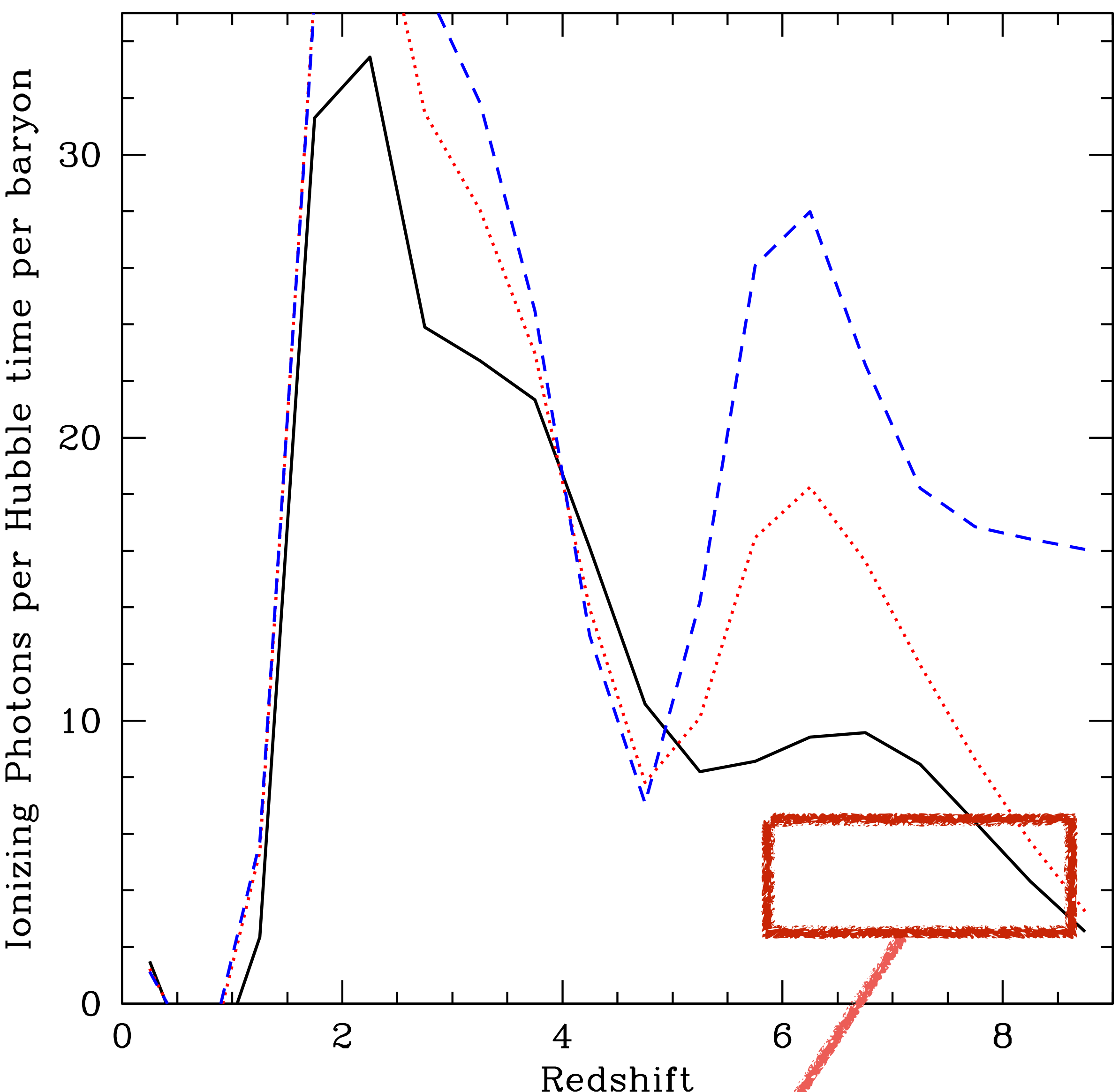


Fixed fraction of present day GCs forming at given z

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

Upper limits on ionizing photons from forming GCs

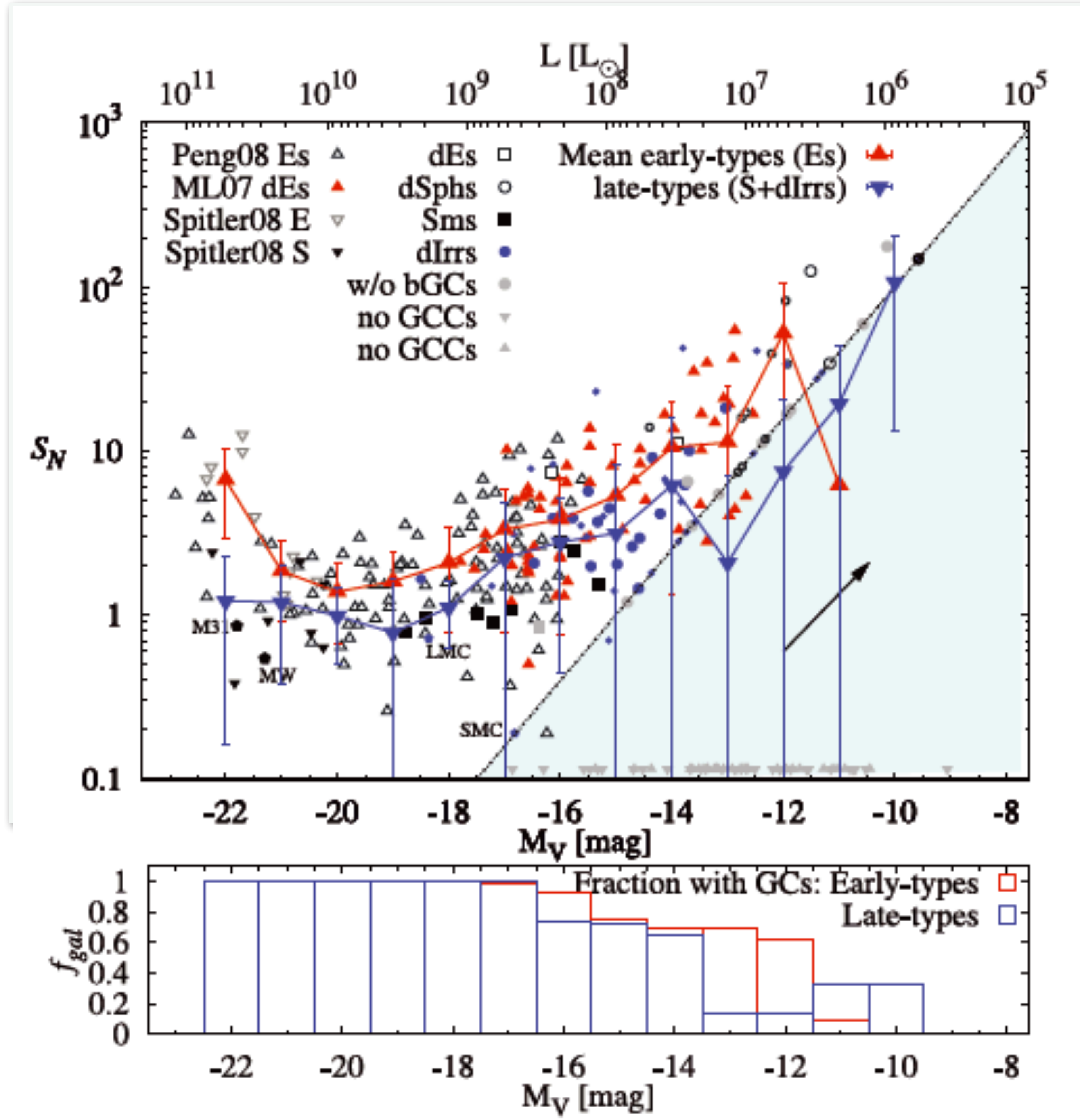




Needed to reionize (f_{esc}~1)

Joint Modeling of GC systems in Milky Way and nearby dwarfs

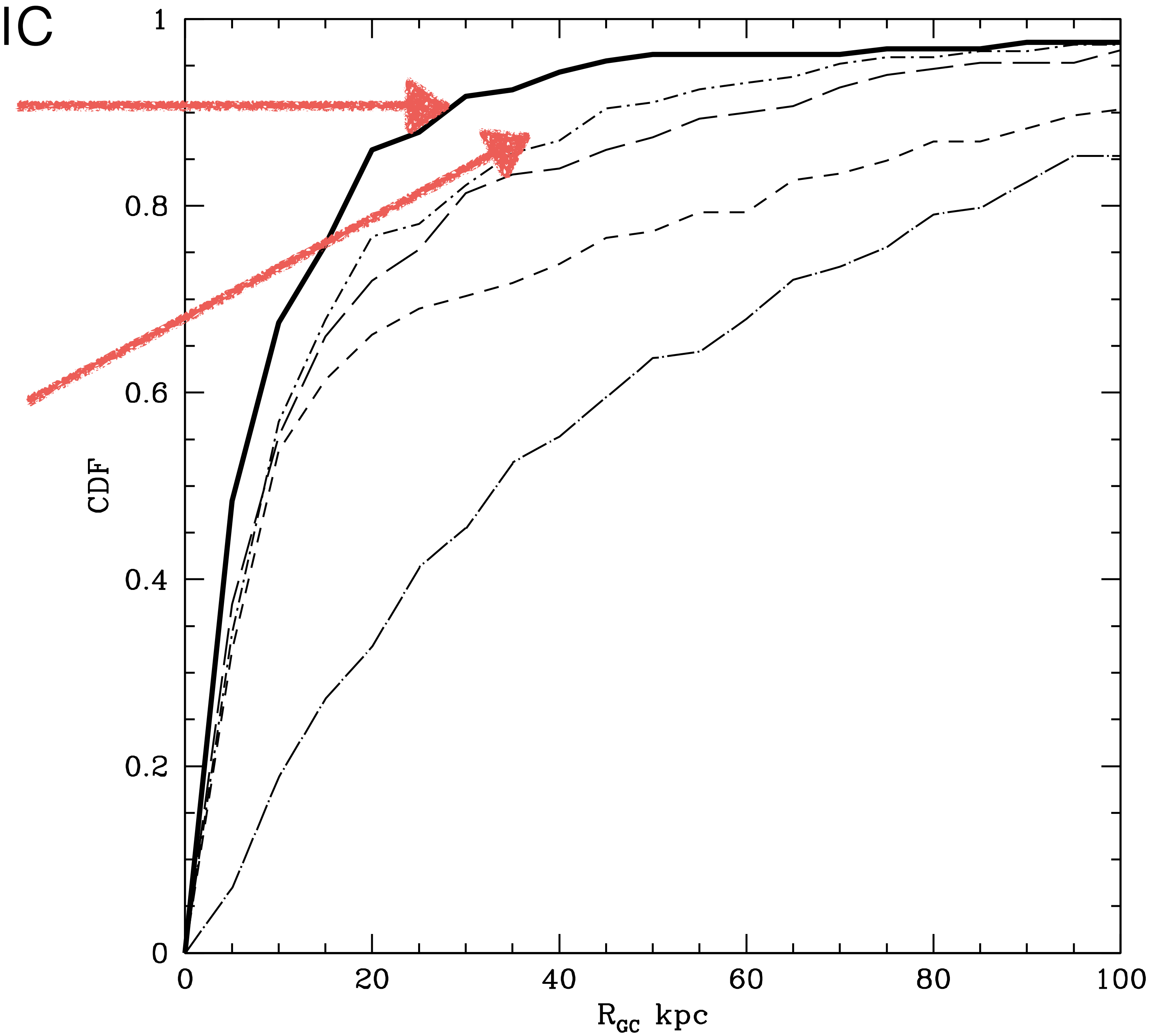
- Via Lactea II merger tree
- Populate dark matter halos with GCs to reproduce observations of nearby dwarfs (Georgiev et al 2010)
- Follow orbits of accreted GCs from satellites including dynamical processes
- In situ GCs formation of higher metallicity GCs



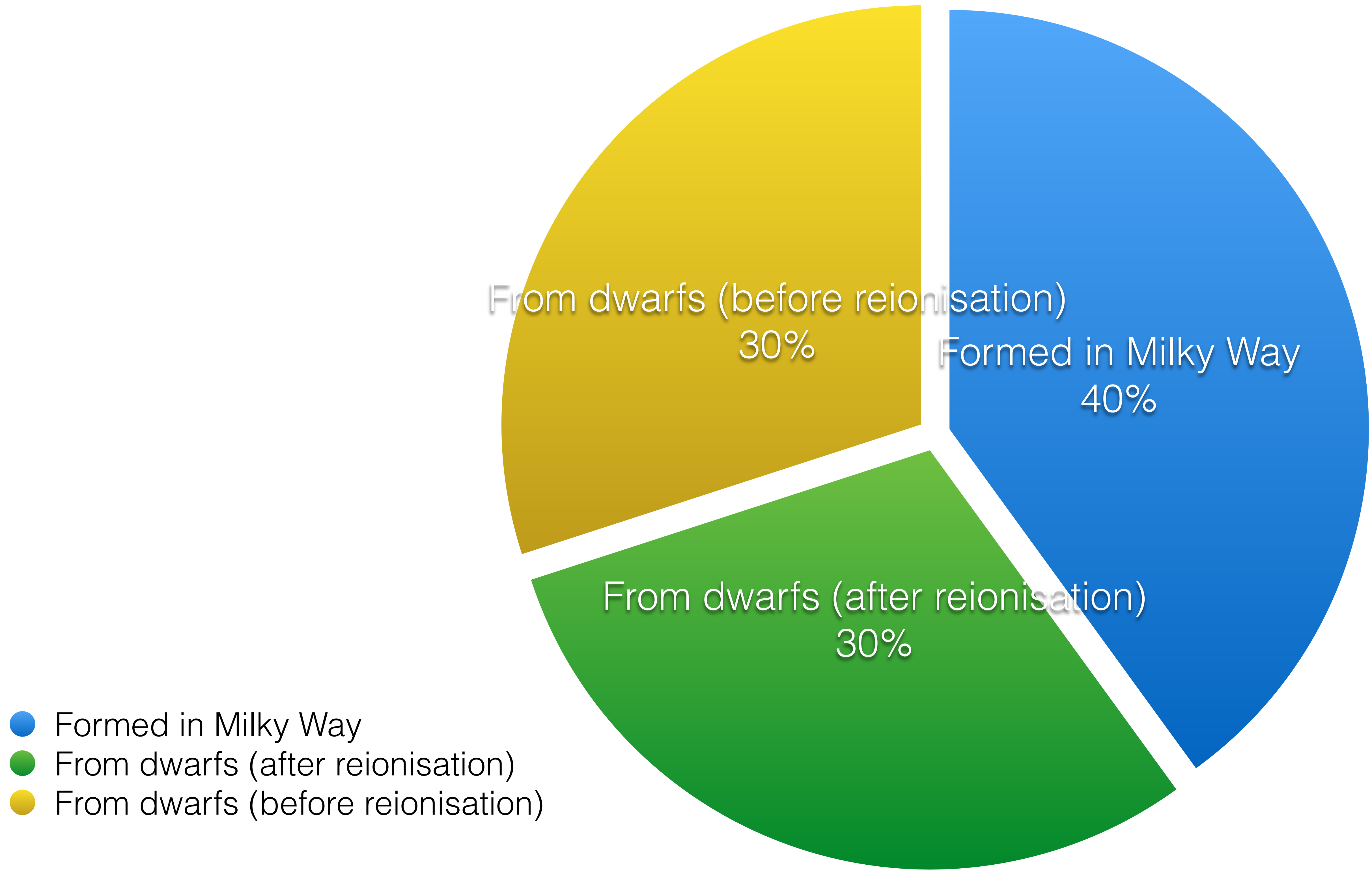
Joint Modeling of GC systems in Milky Way and nearby dwarfs

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



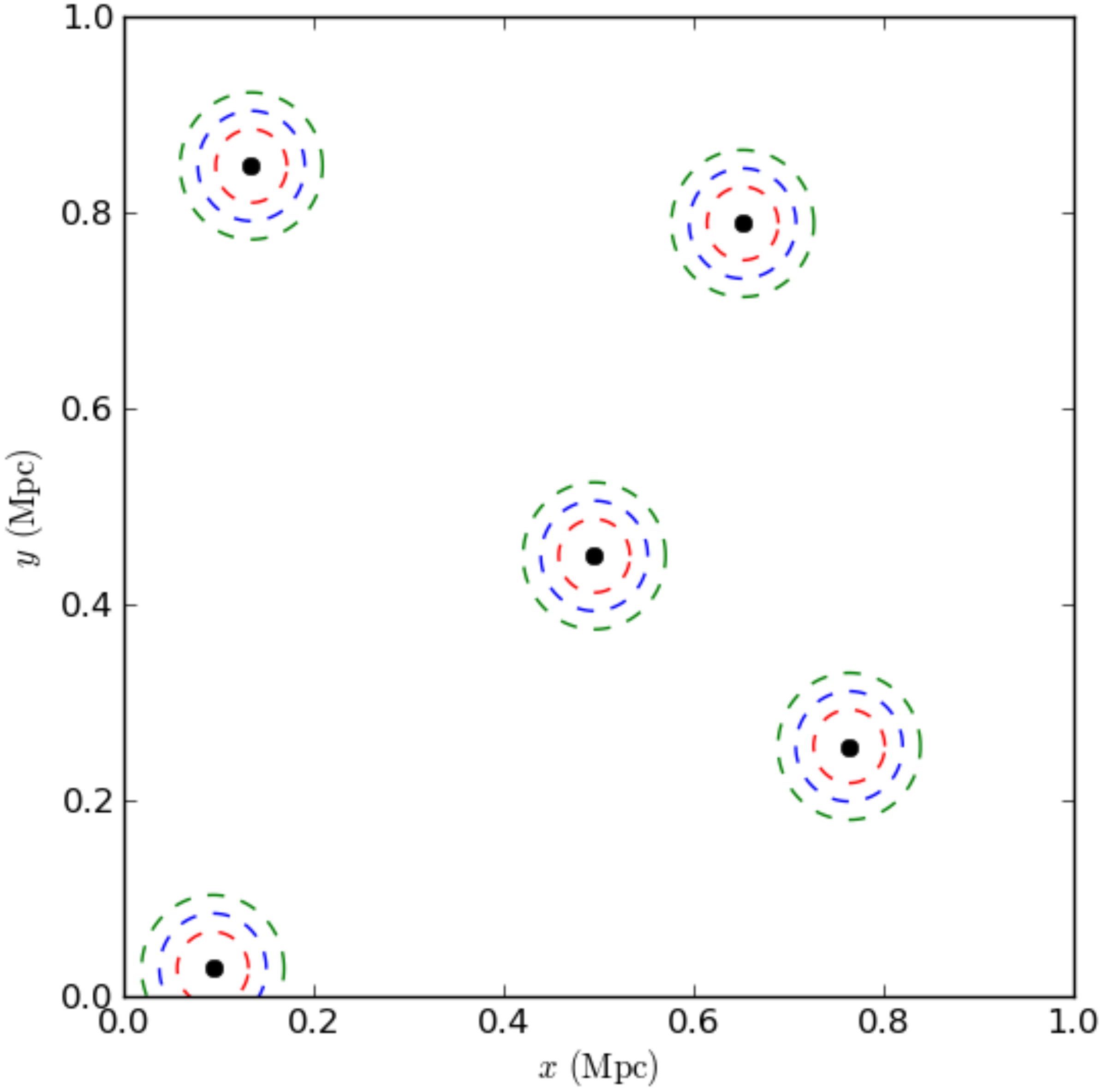
Origin of globular clusters in Milky Way
(best model)



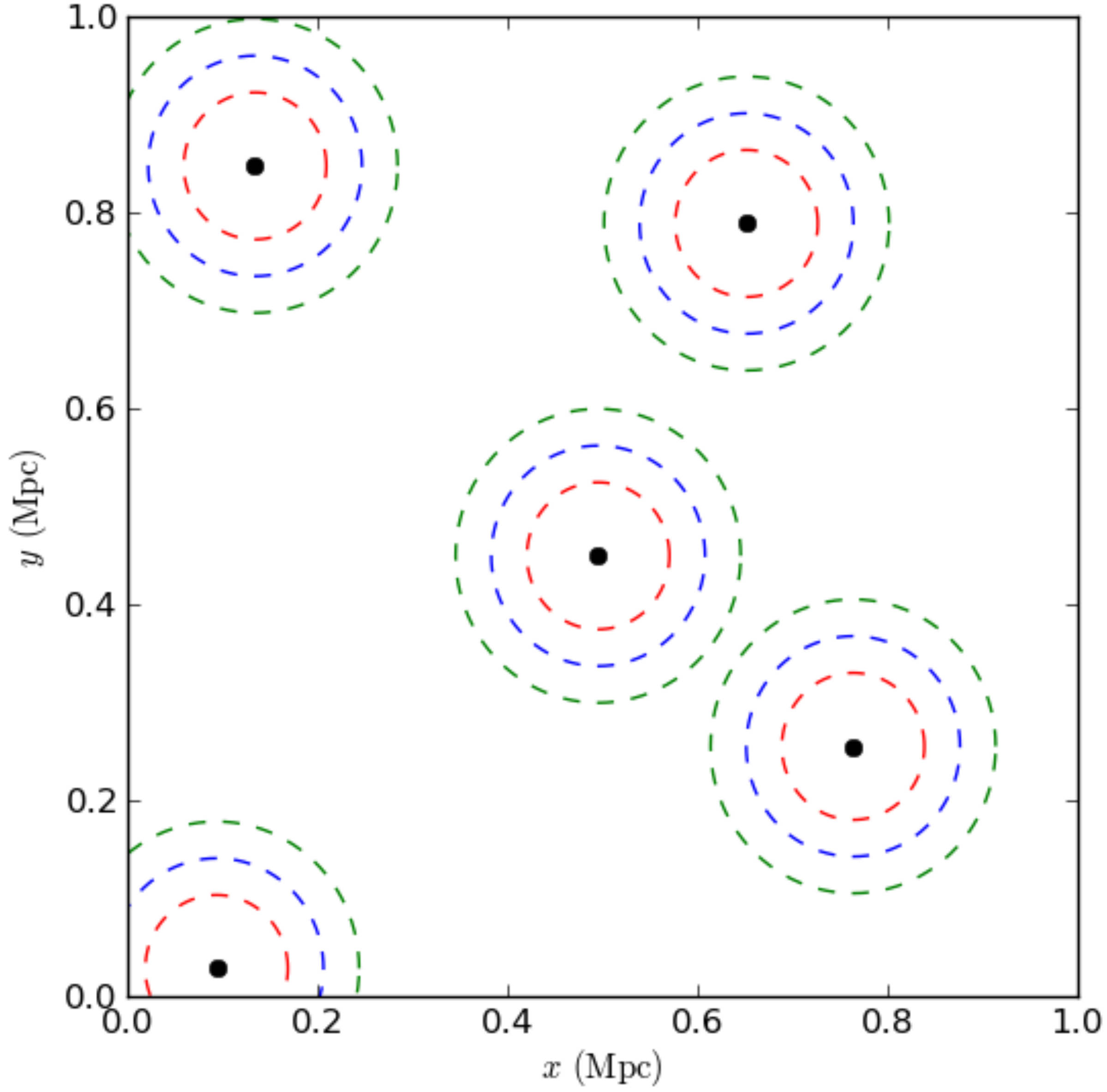
2. Reionization in a bursty universe

- Whether or not some GCs formed before reionization, simulations show that SF in early galaxies is quite bursty
- And UV from Population III stars definitely have to be modeled as short bursts

2. Reionization in a bursty universe

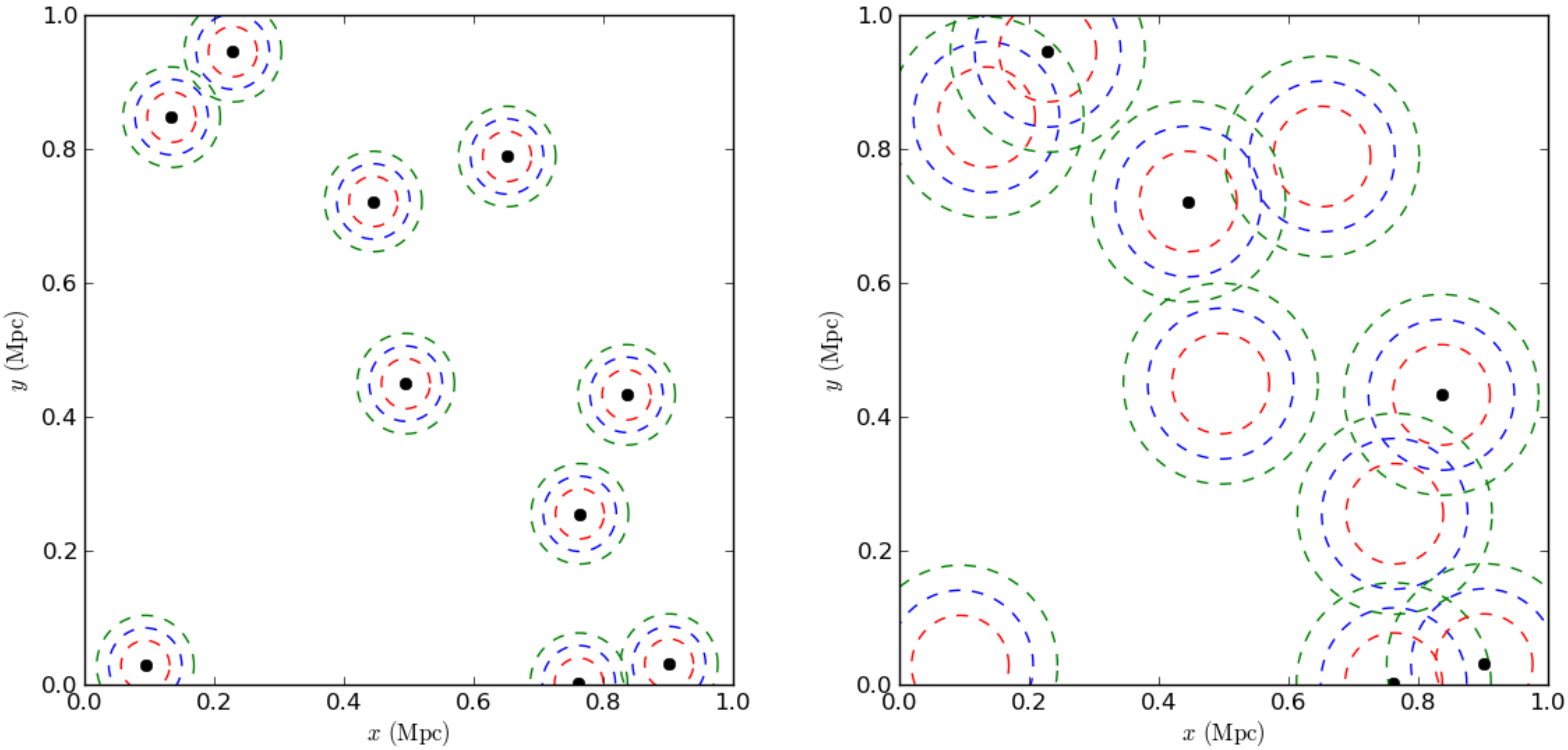


Continuous SF



Bursty SF

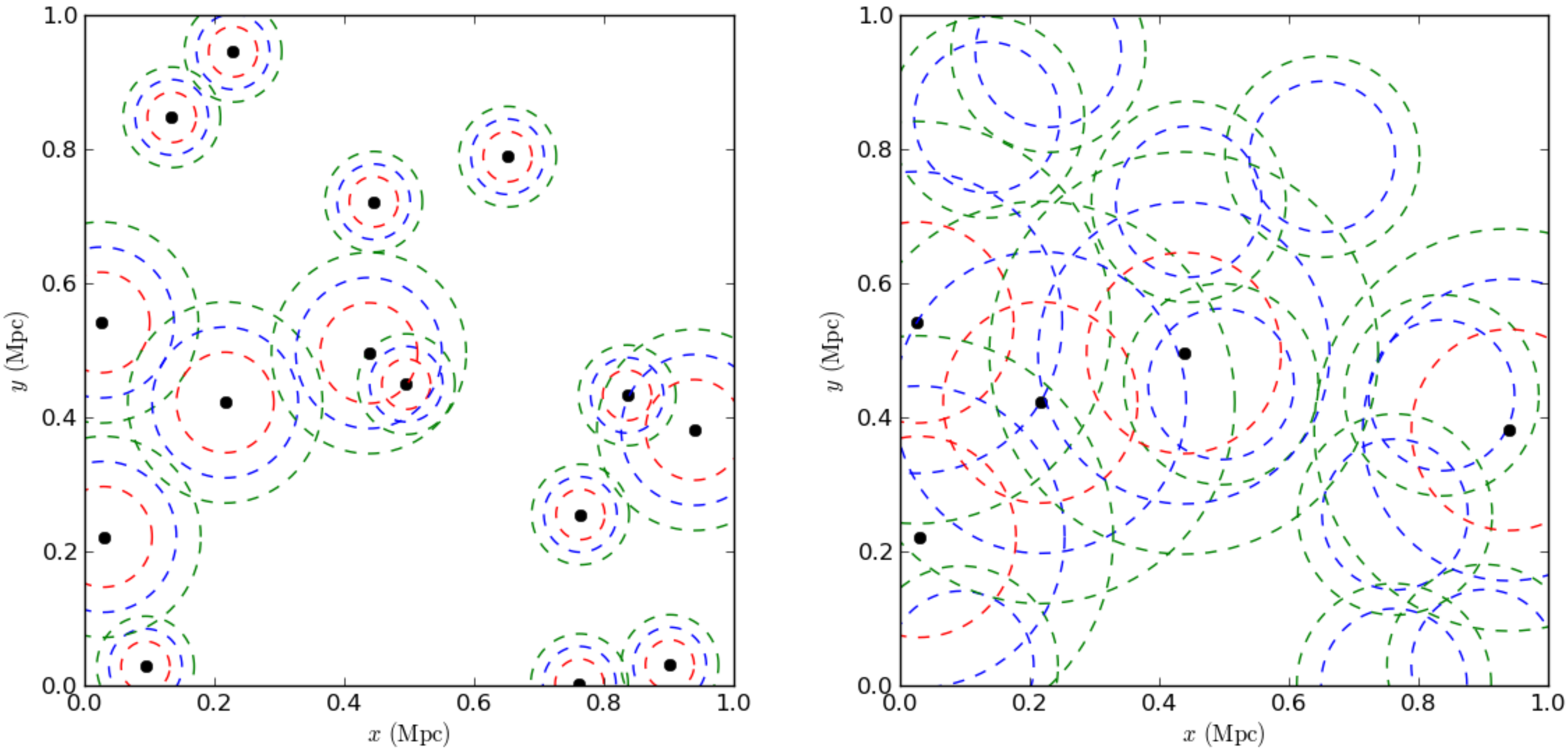
2. Reionization in a bursty universe



Continuous SF

Bursty SF

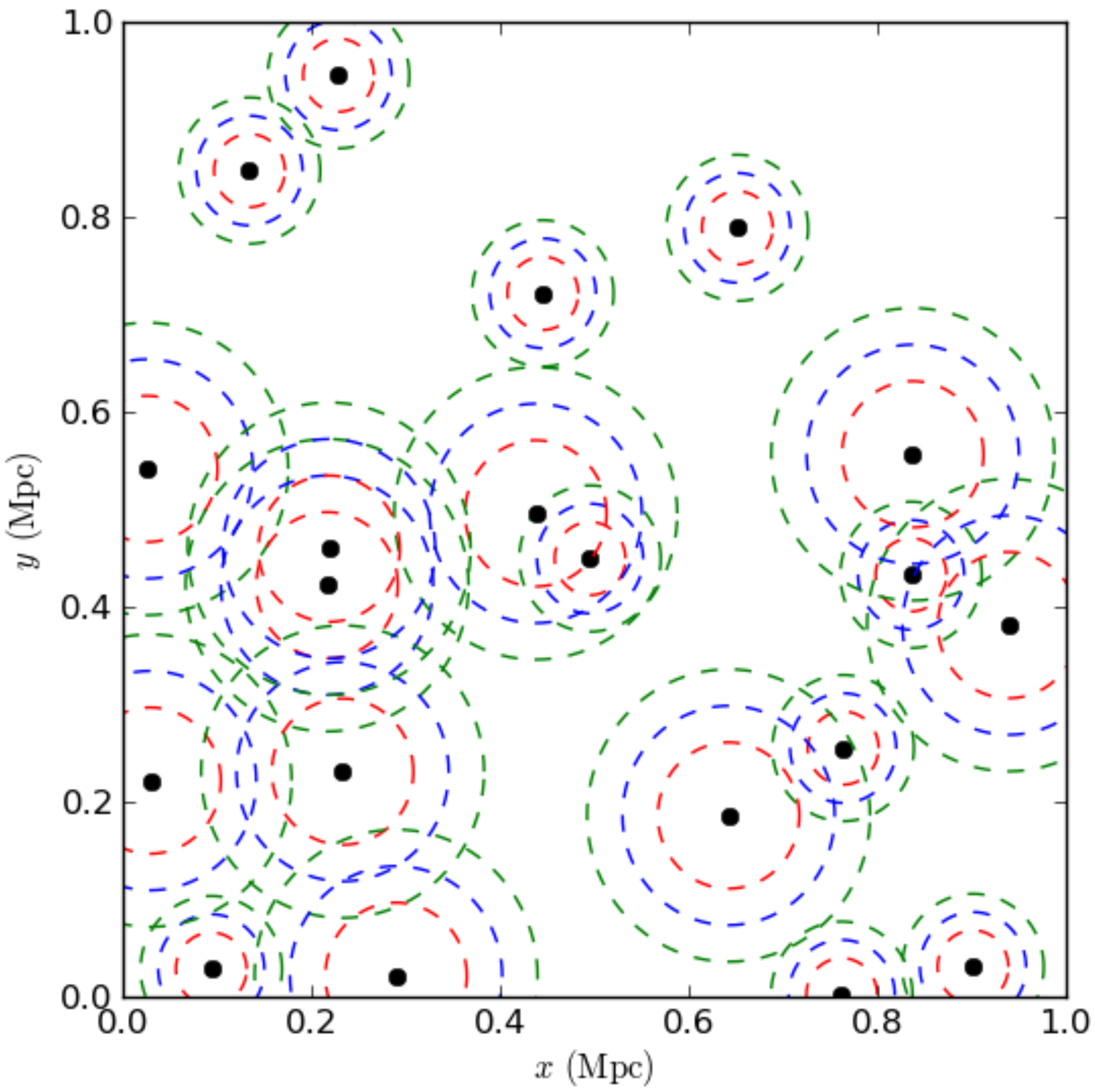
2. Reionization in a bursty universe



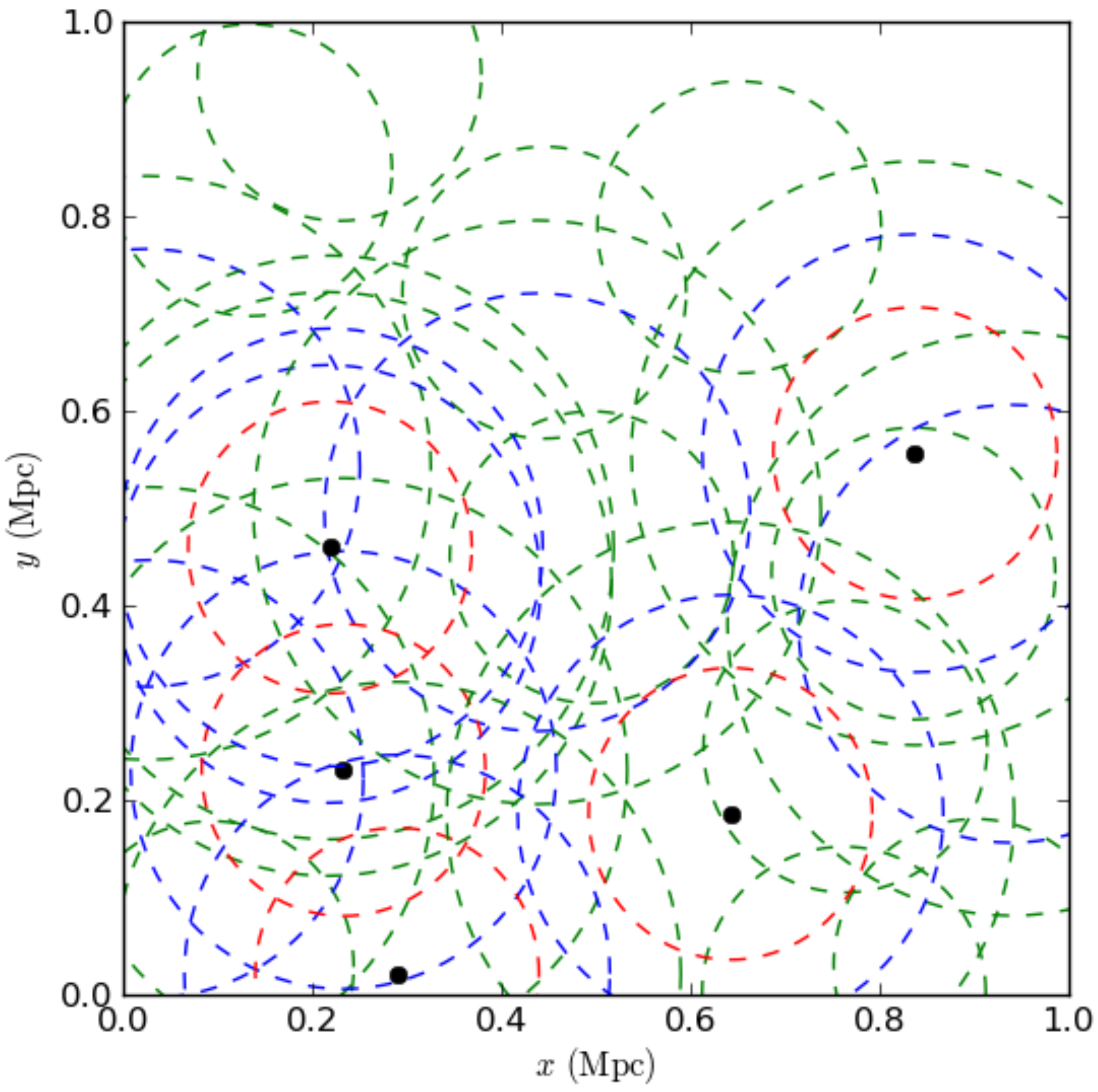
Continuous SF

Bursty SF

3. Reionization in a bursty universe

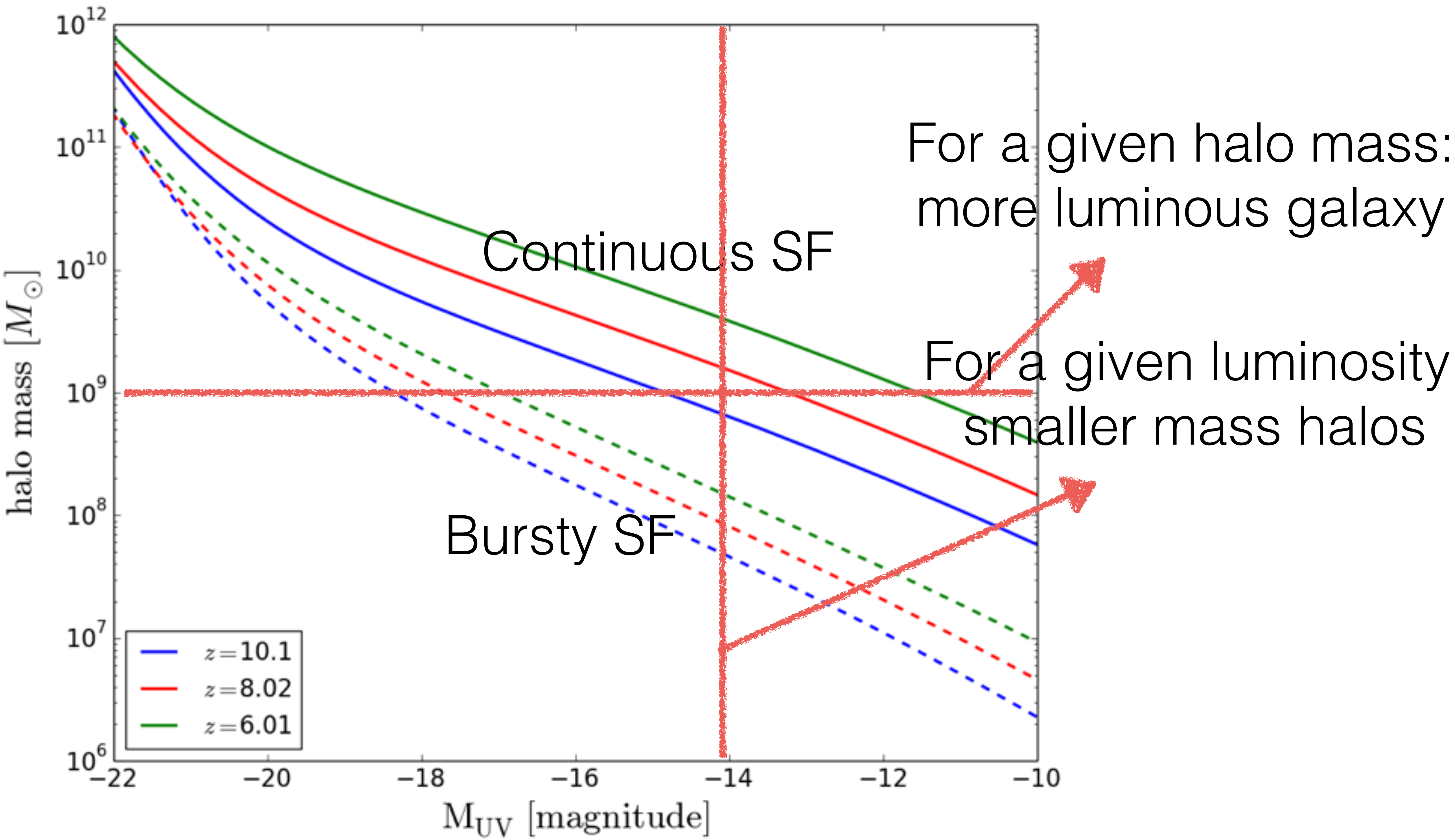


Continuous SF

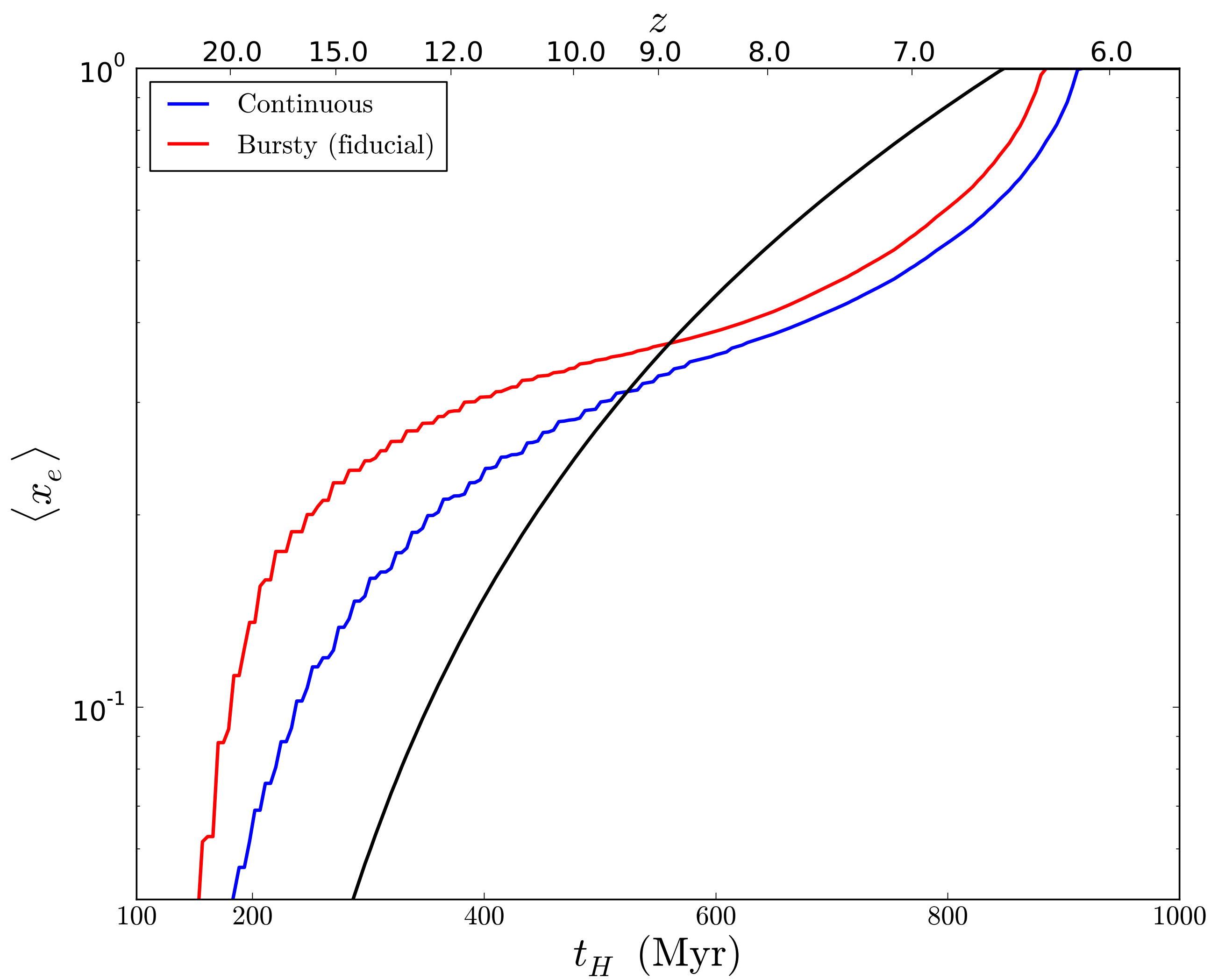


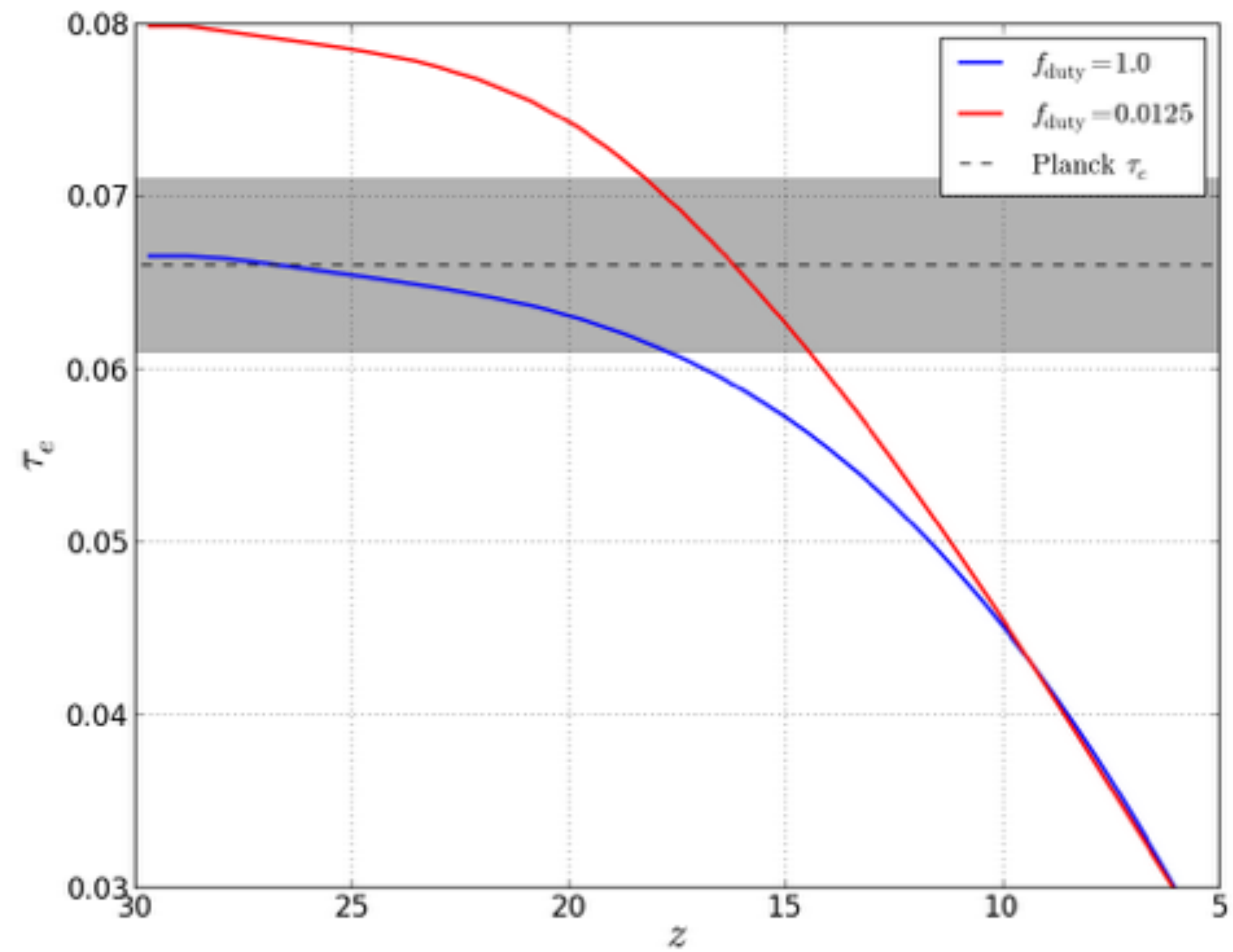
Bursty SF

Halo matching with duty cycle:



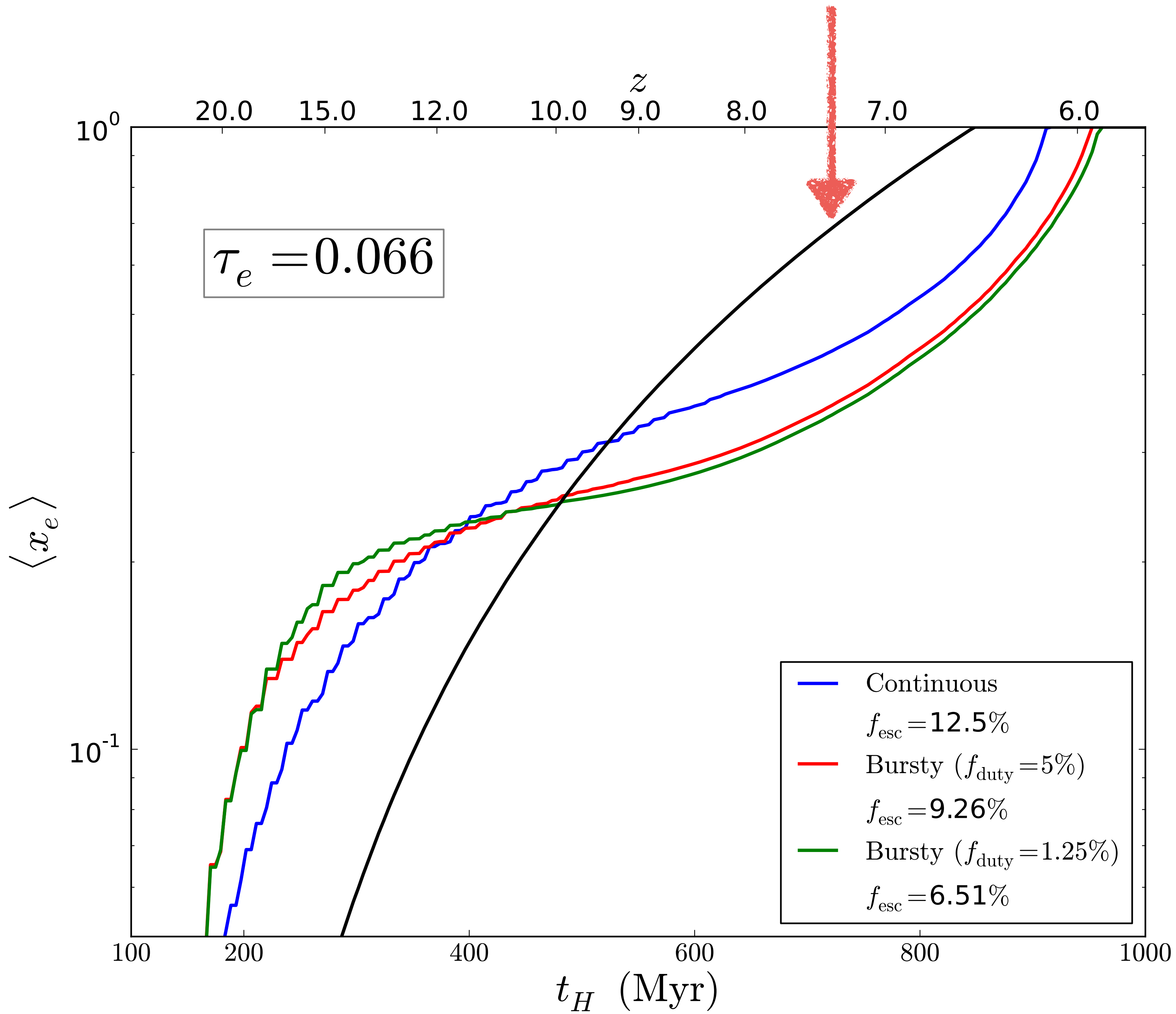
Similar to X-ray ionization: due to relic HII regions

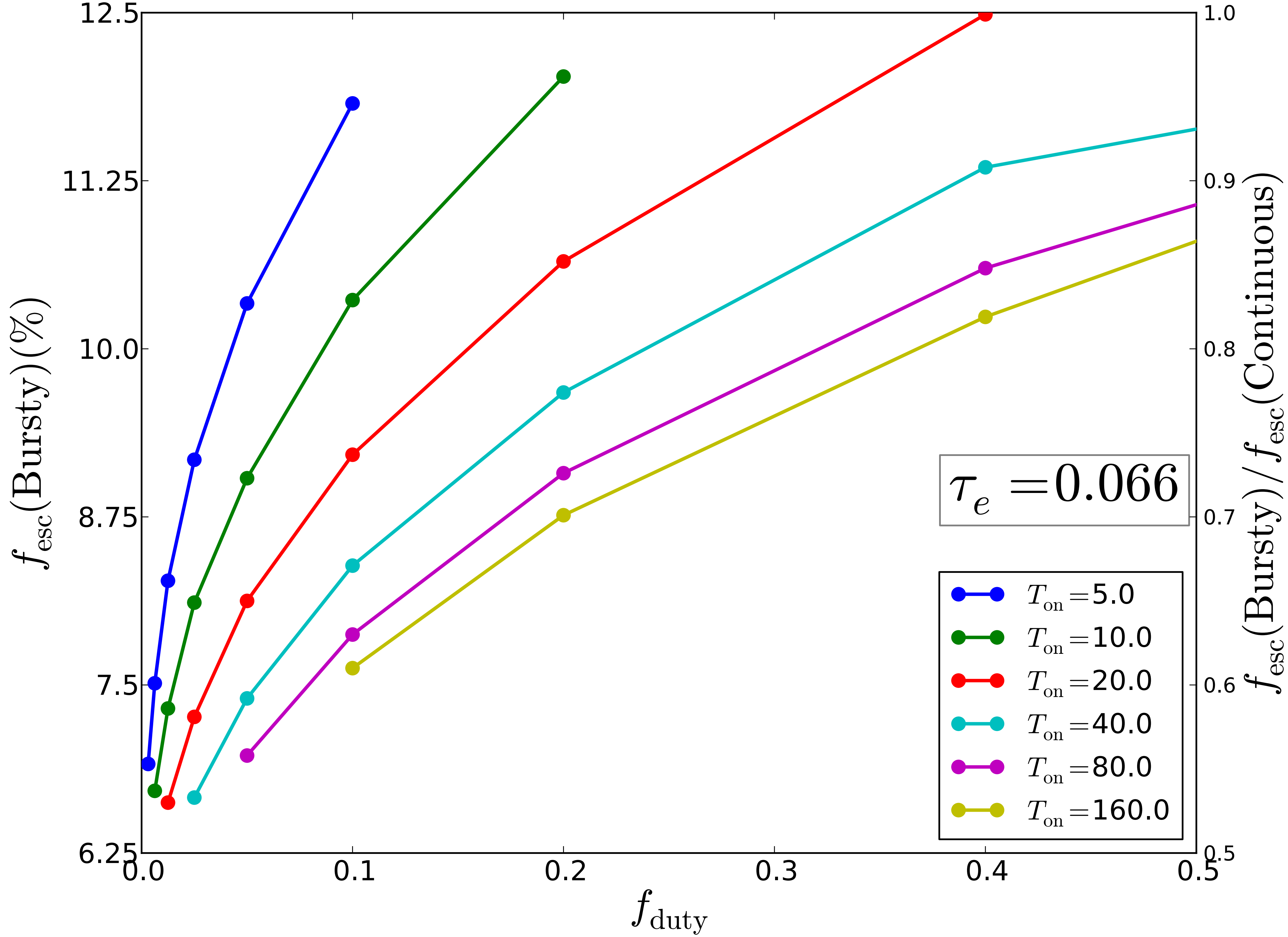




fixed f_{esc}=12.5%

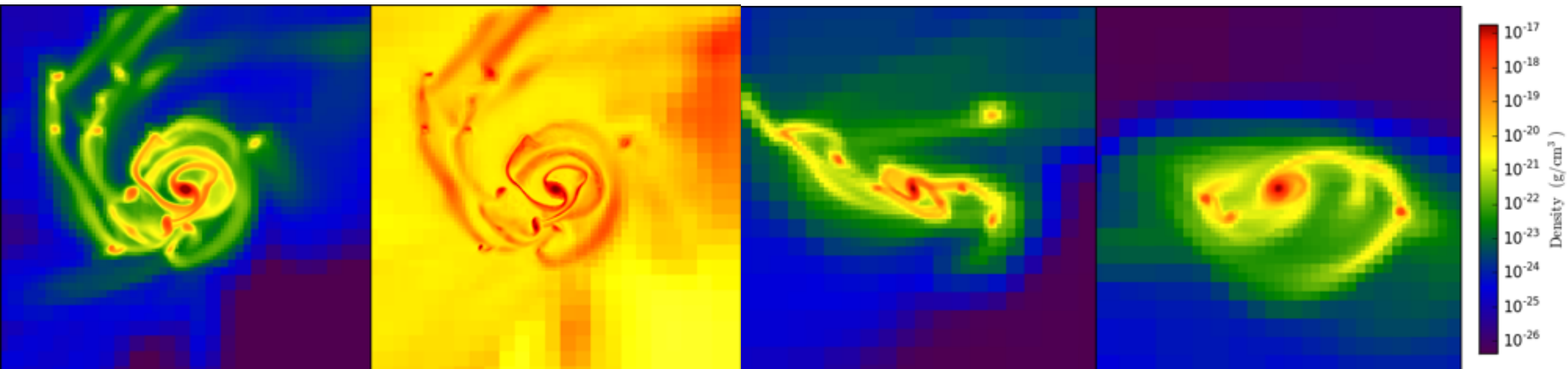
Q_{HII} as in Madau et al 1999

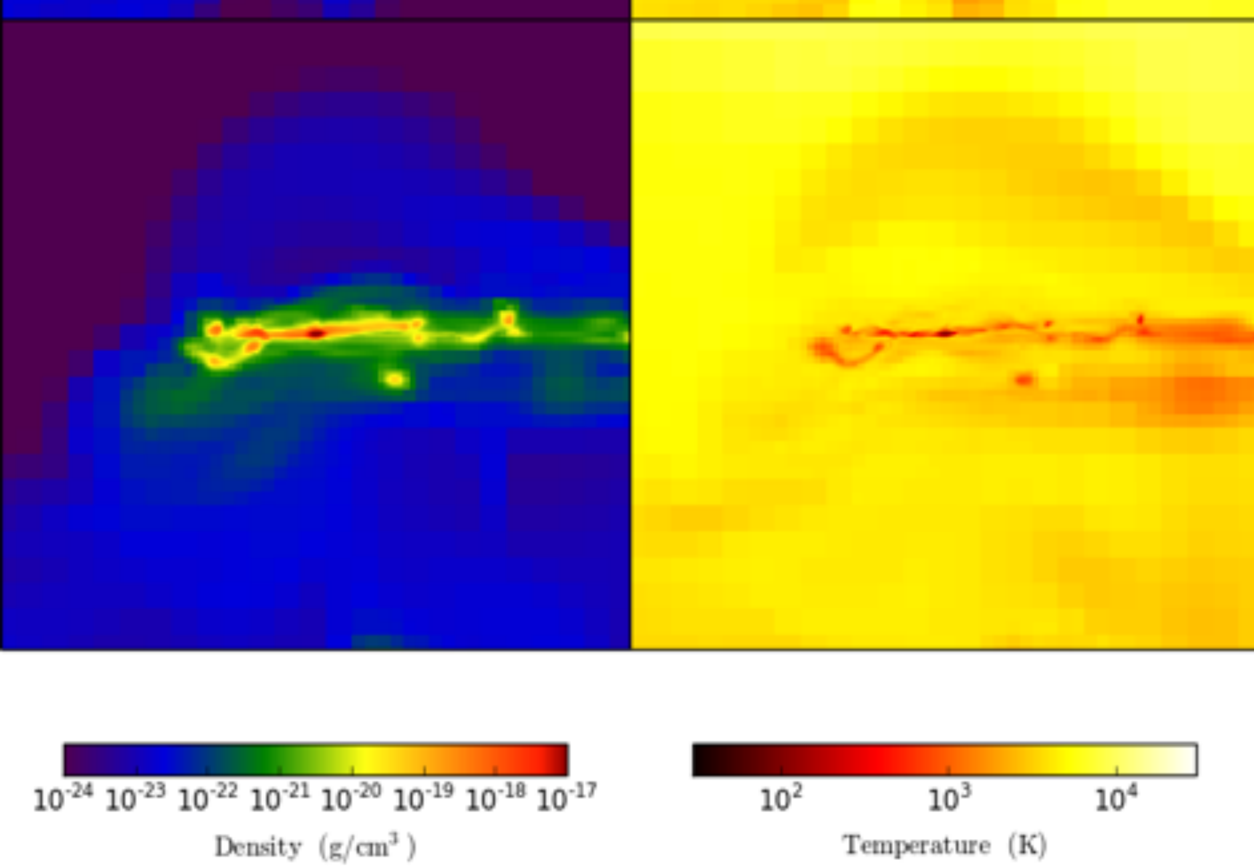




12.5
11.25
10.0
8.75
7.5
6.25
0.0
0.1
0.2
0.3
0.4
0.5
1.0
0.9
0.8
0.7
0.6
0.5
$f_{\rm esc}({\rm Bursty})(\%)$
$f_{\rm duty}$
$f_{\rm esc}({\rm Bursty})/f_{\rm esc}({\rm Continuous})$
$\tau_e = 0.066$
$T_{\rm on} = 5.0$
$T_{\rm on} = 10.0$
$T_{\rm on} = 20.0$
$T_{\rm on} = 40.0$
$T_{\rm on} = 80.0$
$T_{\rm on} = 160.0$

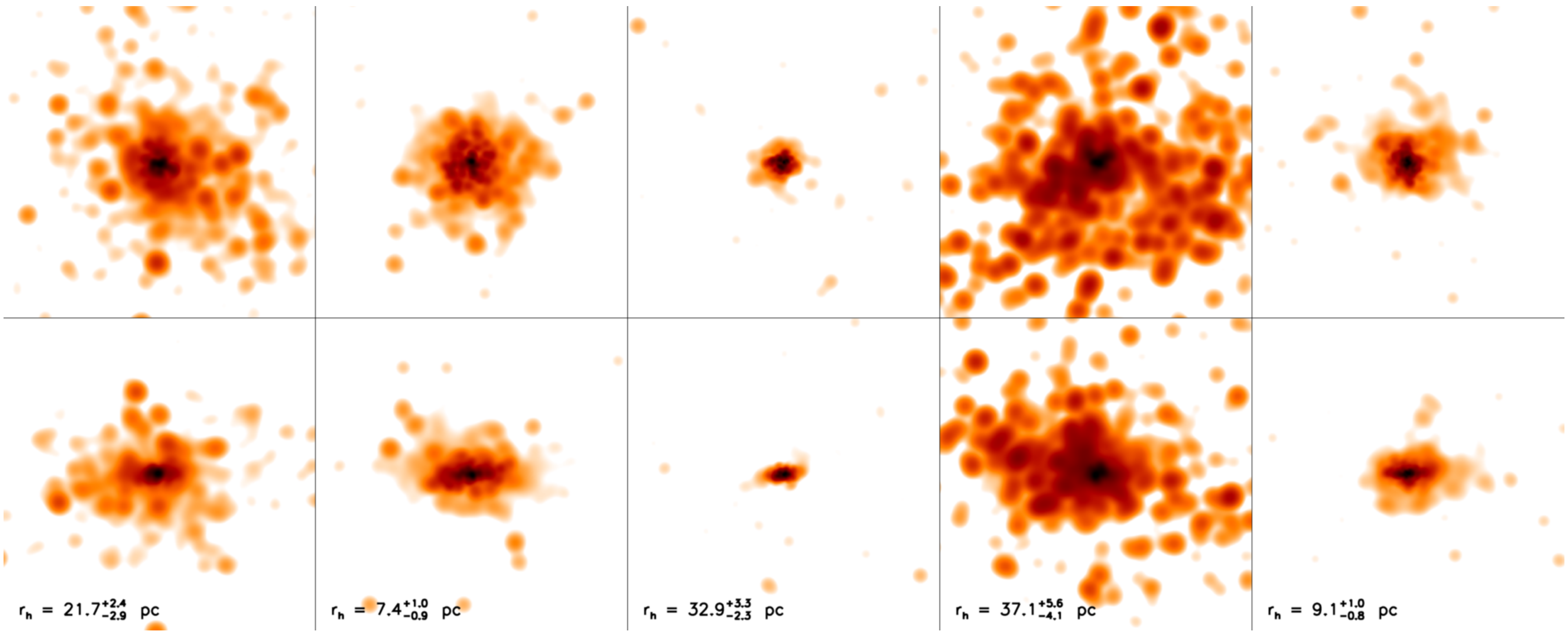
3. Simulations of the First Stars and Galaxies with ART





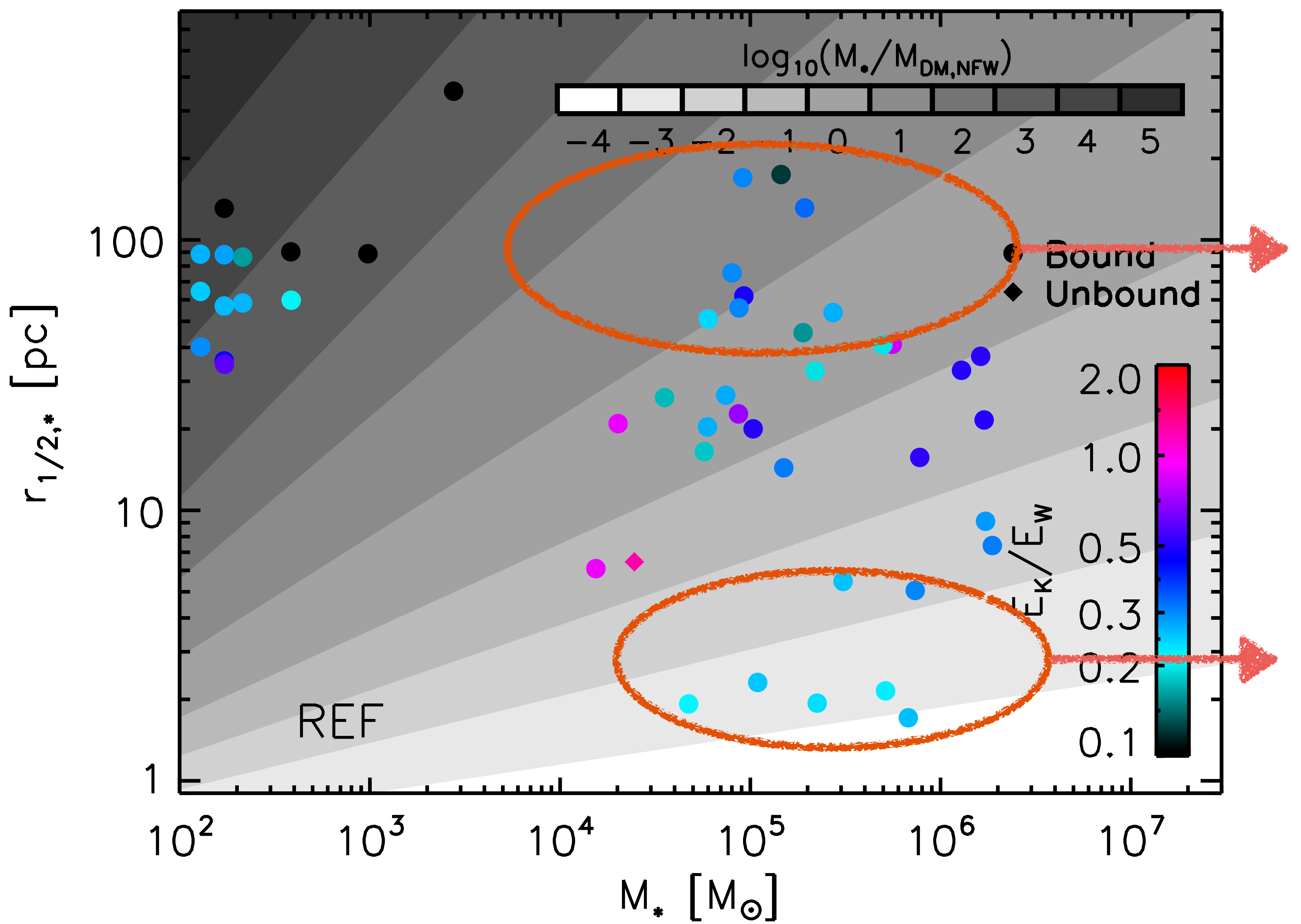
Dwarf galaxies at z=10
with sub parsec resolution in
small cosmological Volume
Dense Gas settles in
disky structures .. but

3. Simulations of the First Stars and Galaxies with ART



Stars are in spheroids larger than disks thickness

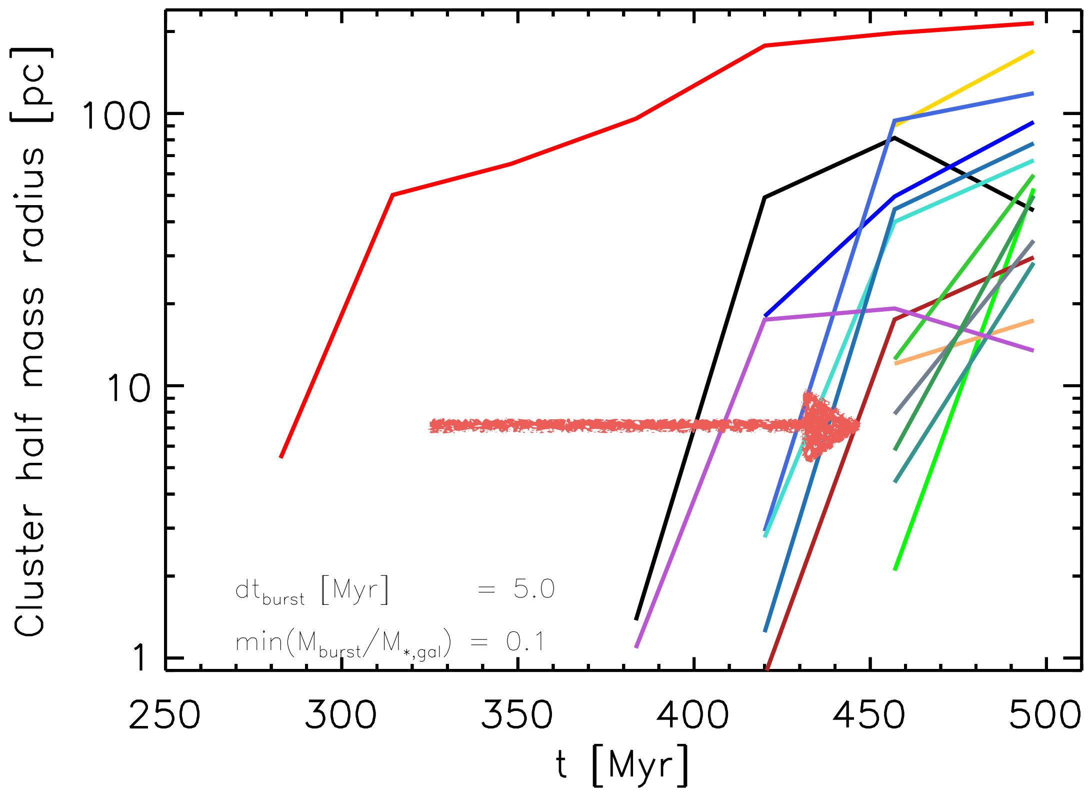
Dense clusters and Ultra-faint dwarfs at z=10

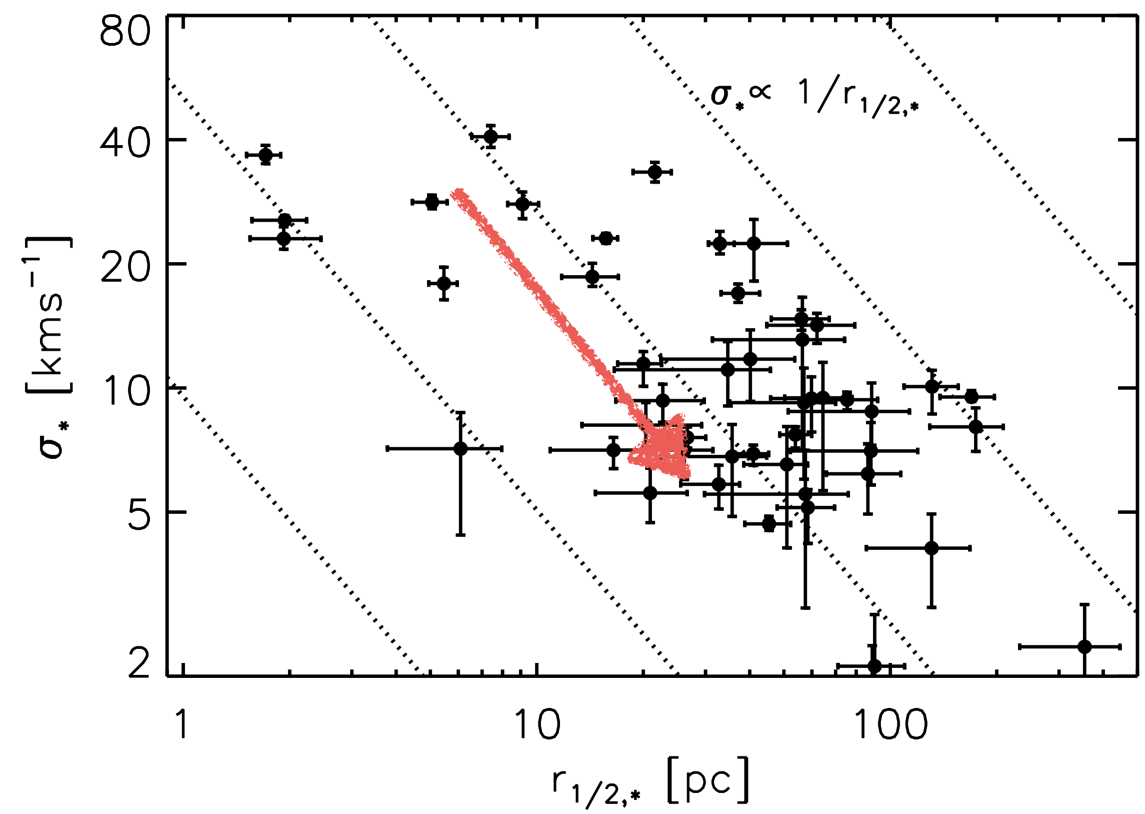


Ultra-faint dwarfs

Globular cluster?

GCs and Ultra-faint dwarfs





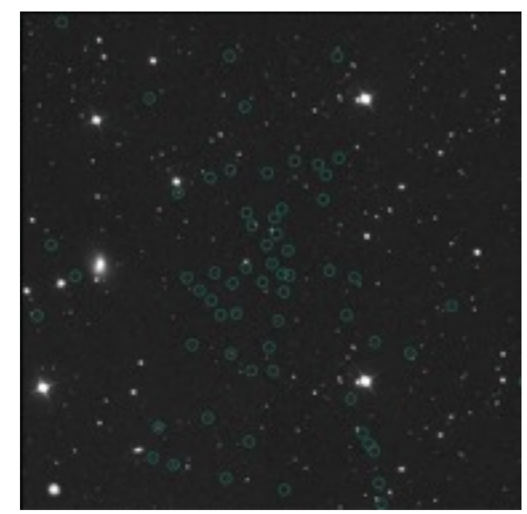
- Stars form in very compact dense clusters: 1 pc scale, velocity dispersion 20-40 km/s
- Due to gas loss, many become unbound and evolve as shown by the red lines
- Become bound again by dark matter halos with circular velocities: 5-10 km/s

GCs and Ultra-faint dwarfs

SF efficiency
>50%

Globular
Cluster

SF efficiency
<50%
or $M^{*}<10^{4}\ M_{sun}$

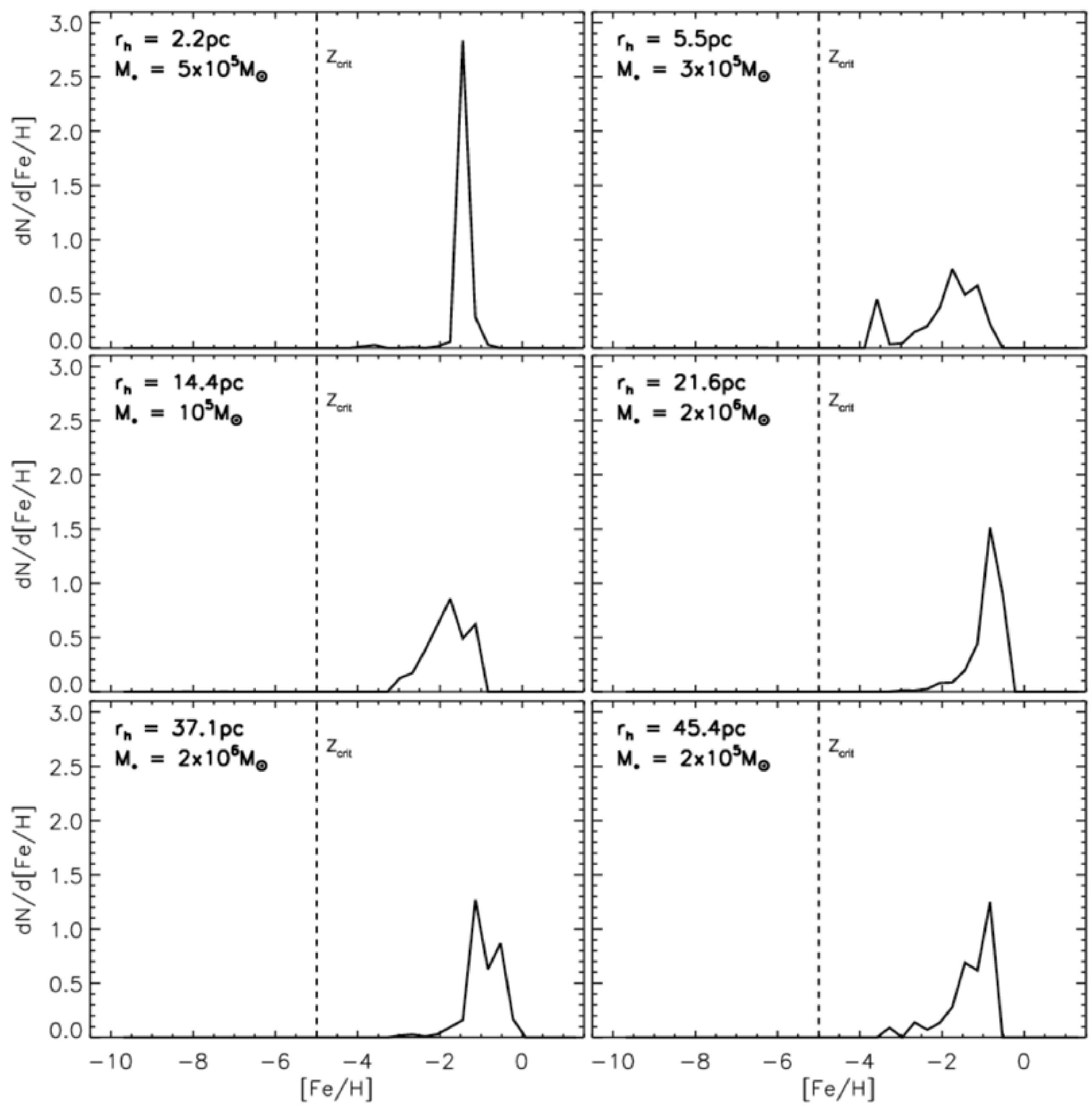


Ultra-faint
dwarf
(dark matter dominated)

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. Dark matter in some GCs?

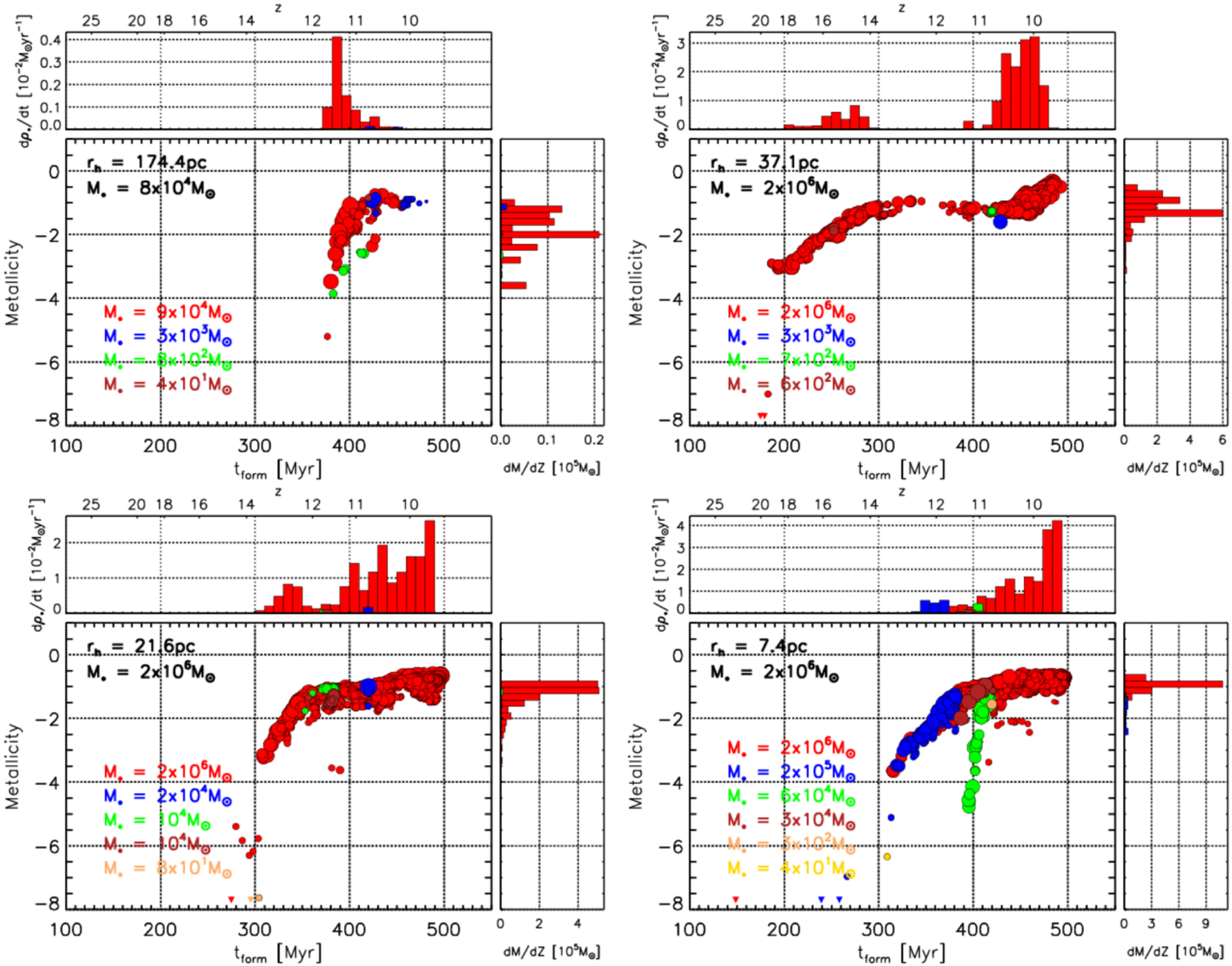


Summary

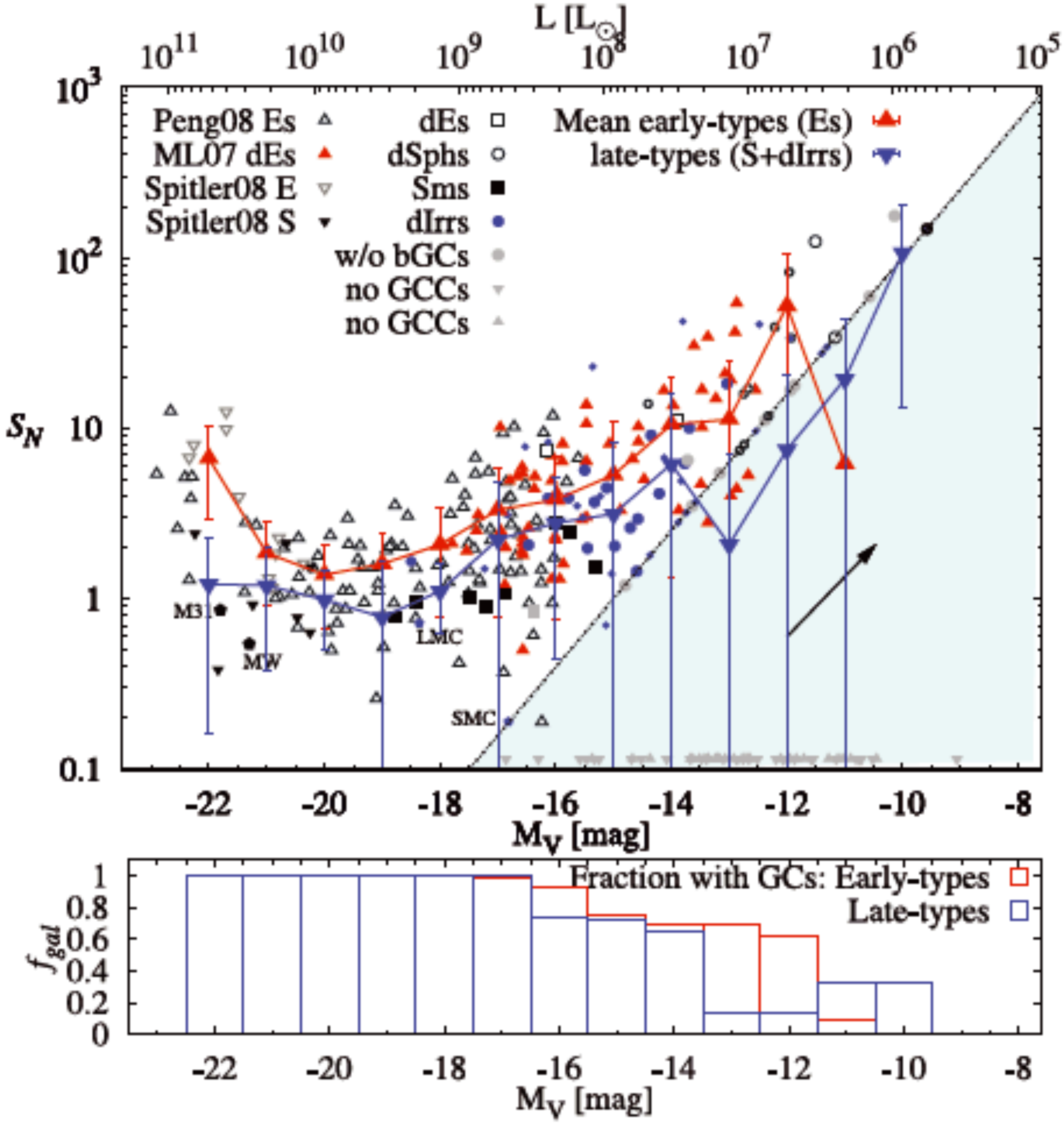
1. From Hubble deep fields and modeling of Milky Way, evidence of two epochs of GC formation: at z~2 and z>6. The z>6 population suggest that SF in dense clusters was a dominant mode of SF in the early universe, contributing to reionization

2. Bursty SF has similar effect on IGM as ionization by X-rays: escaping ionizing radiation needed to produce a given optical depth to Thompson scattering is about half the value assuming continuous SF.

3. Simulations of the first galaxies: perhaps we captured the formation of the first GCs. Low surface brightness spheroidal galaxies similar to the ultra-faint dwarfs produced by a few “failed” or “evaporated” compact star clusters.

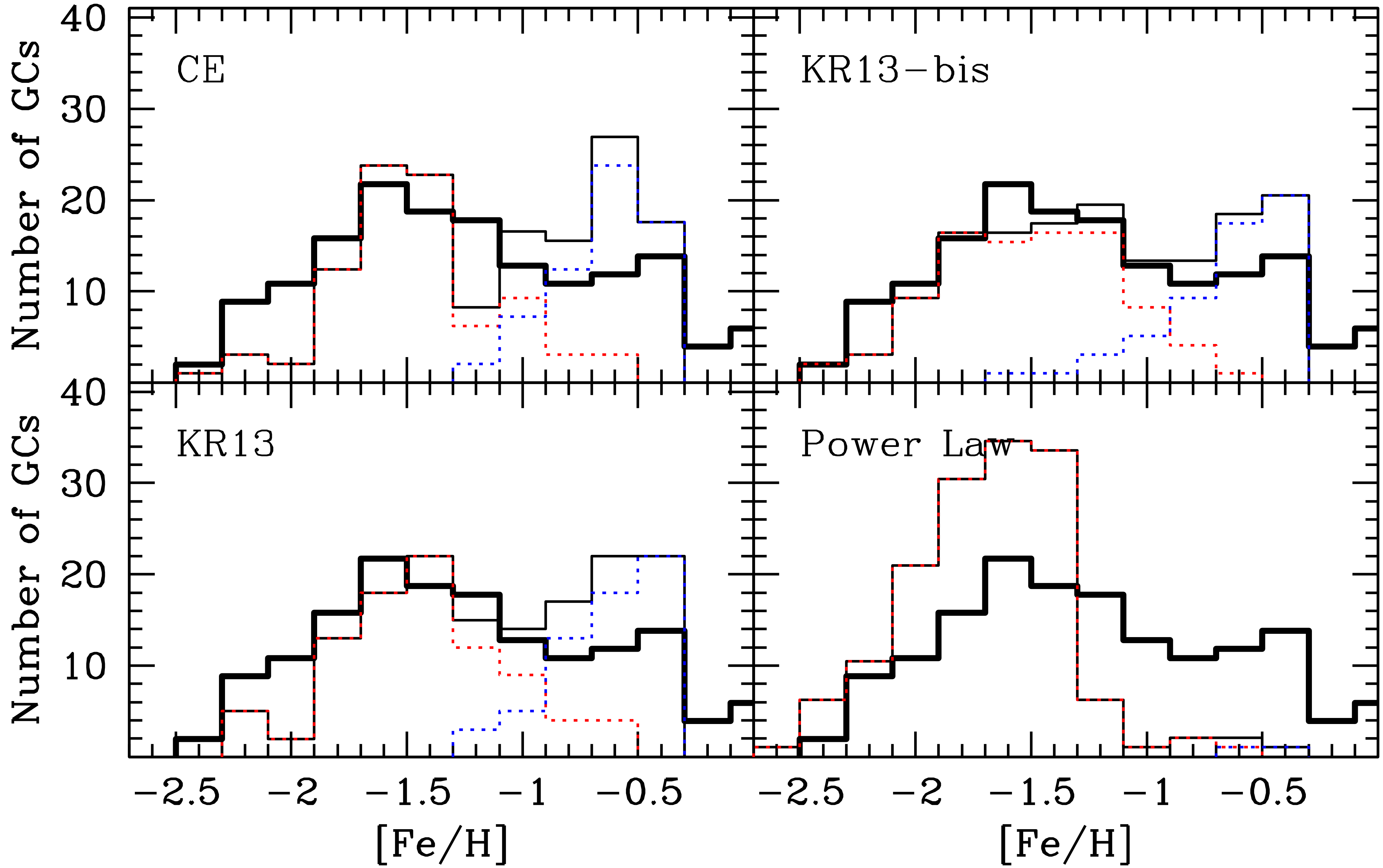


z
25 20 18 16 14 12 11 10
dρ•/dt [10^-2 M⊙yr^-1]
Metallicity
t_form [Myr]
dM/dZ [10^5 M⊙]
r_h = 174.4pc
M• = 8x10^4 M⊙
M• = 9x10^4 M⊙
M• = 3x10^3 M⊙
M• = 8x10^2 M⊙
M• = 4x10^1 M⊙
r_h = 37.1pc
M• = 2x10^6 M⊙
M• = 2x10^6 M⊙
M• = 3x10^3 M⊙
M• = 7x10^2 M⊙
M• = 6x10^2 M⊙
r_h = 21.6pc
M• = 2x10^6 M⊙
M• = 2x10^6 M⊙
M• = 2x10^4 M⊙
M• = 10^4 M⊙
M• = 10^4 M⊙
M• = 8x10^1 M⊙
r_h = 7.4pc
M• = 2x10^6 M⊙
M• = 2x10^6 M⊙
M• = 2x10^5 M⊙
M• = 6x10^4 M⊙
M• = 3x10^4 M⊙
M• = 3x10^2 M⊙
M• = 4x10^1 M⊙

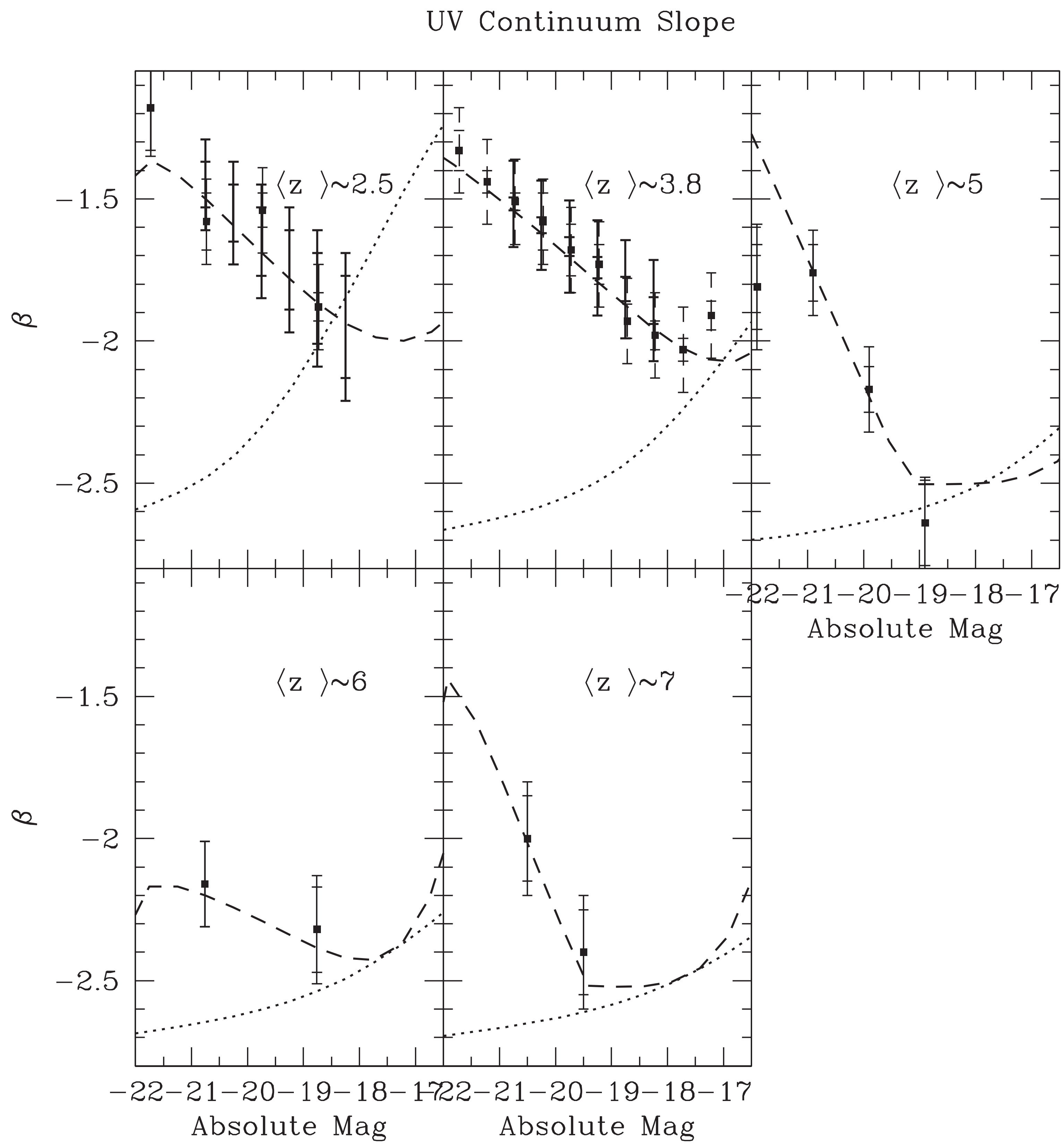


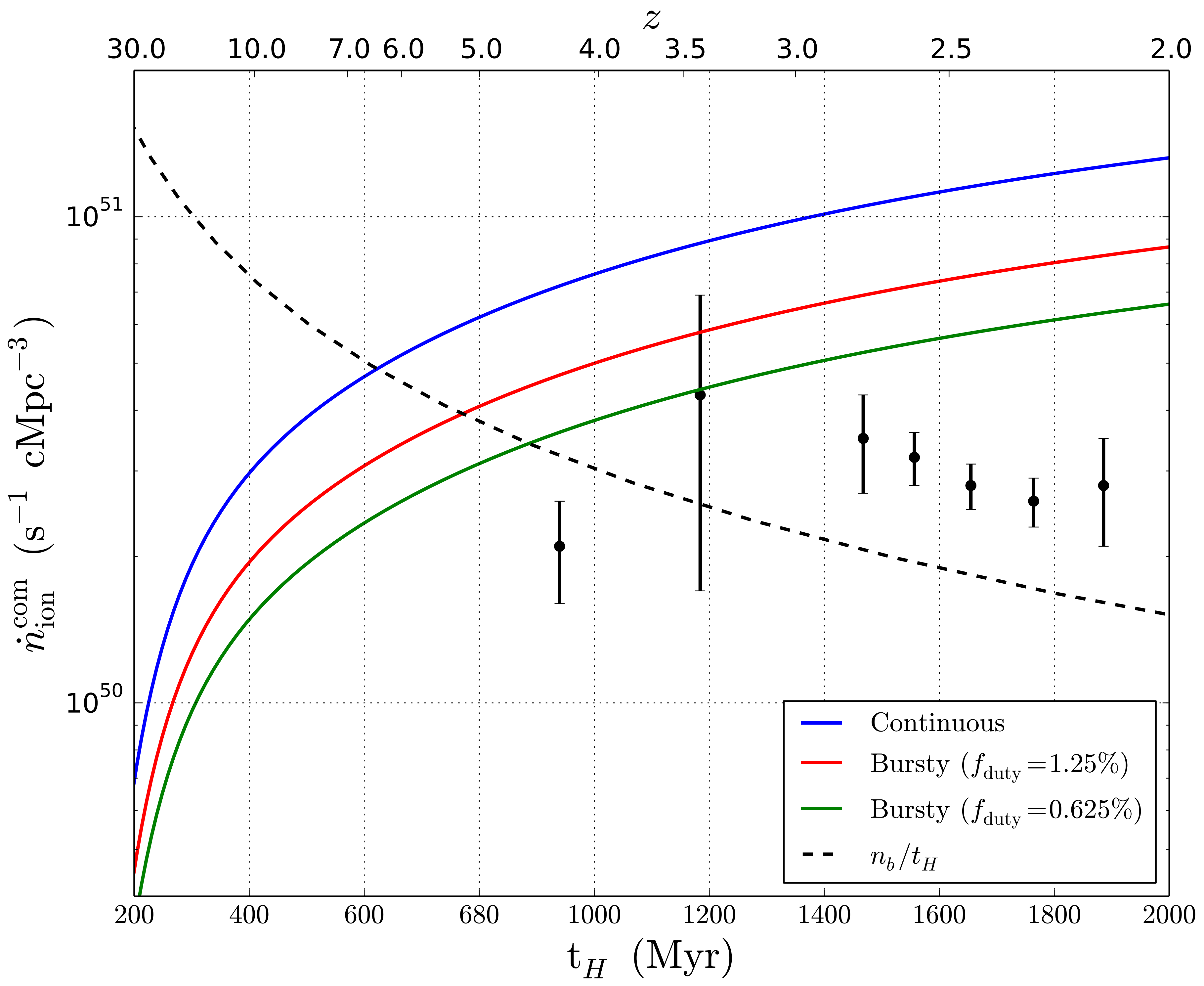
From Georgiev et al 2010

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%



CE
KR13-bis
KR13
Power Law
Number of GCs
Number of GCs
[Fe/H]
[Fe/H]


UV Continuum Slope
⟨z⟩~2.5
⟨z⟩~3.8
⟨z⟩~5
⟨z⟩~6
⟨z⟩~7
β
−1.5
−2
−2.5
−22 −21 −20 −19 −18 −17
Absolute Mag



z
30.0
10.0
7.0
6.0
5.0
4.0
3.5
3.0
2.5
2.0
10^{51}
10^{50}
$\dot{n}_{\rm ion}^{\rm com}$ $(\rm s^{-1}\ cMpc^{-3})$
Continuous
Bursty ($f_{\rm duty}$=1.25%)
Bursty ($f_{\rm duty}$=0.625%)
n_b/t_H
200
400
600
680
1000
1200
1400
1600
1800
2000
$\rm t_H$ (Myr)