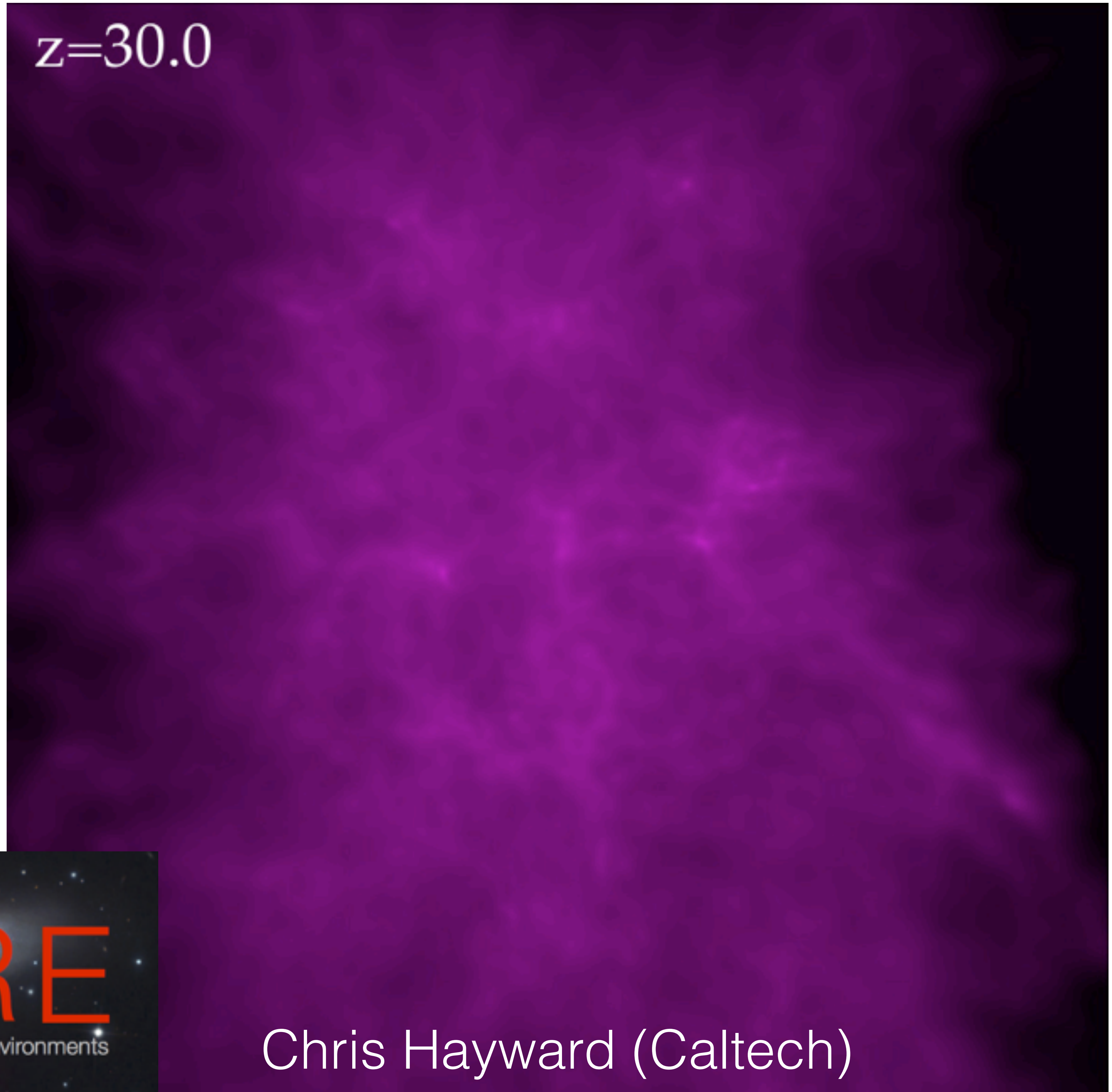
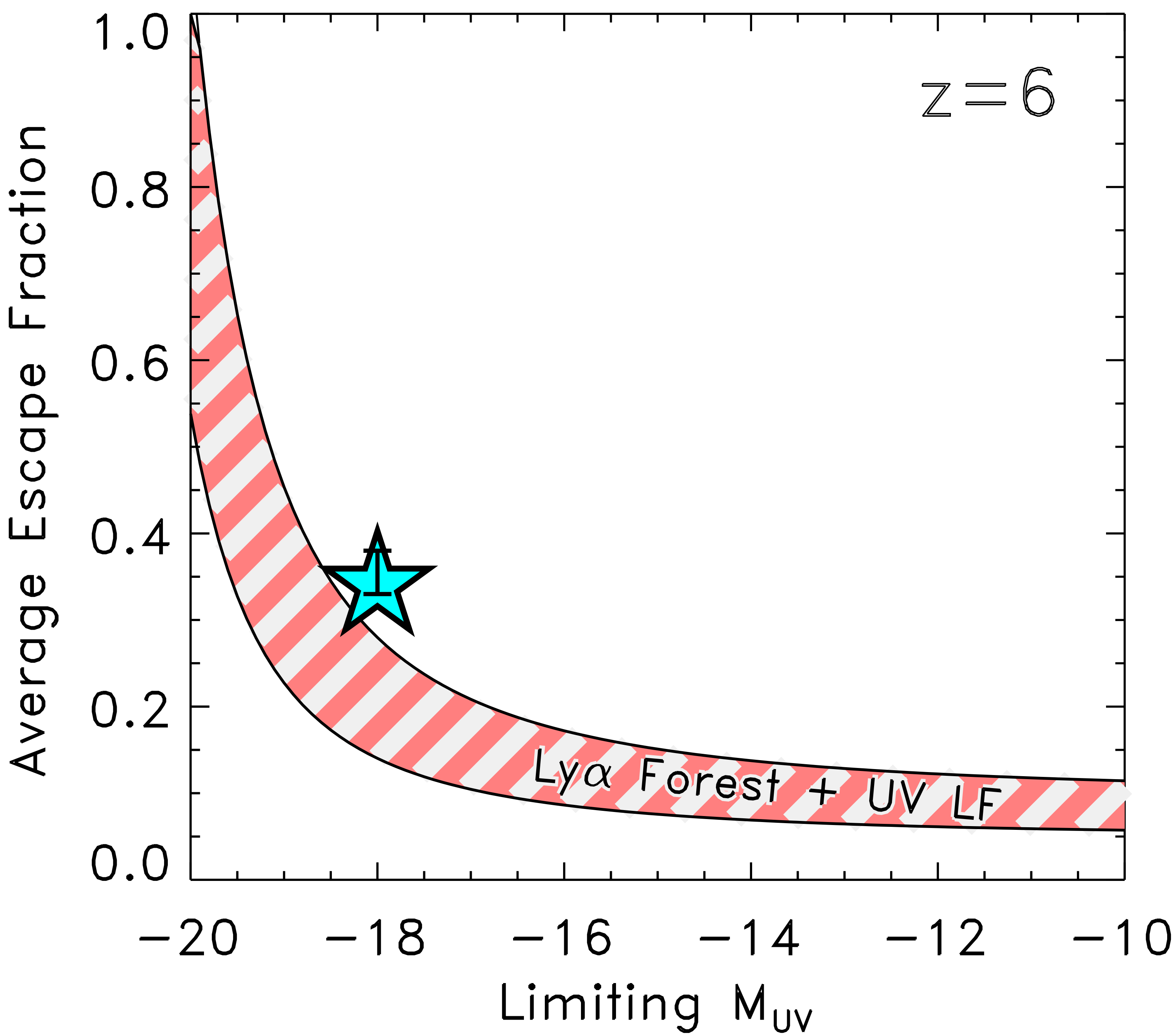
How to achieve the escape fraction necessary for galaxies to reionize the Universe



FIRE
Feedback In Realistic Environments

Chris Hayward (Caltech)

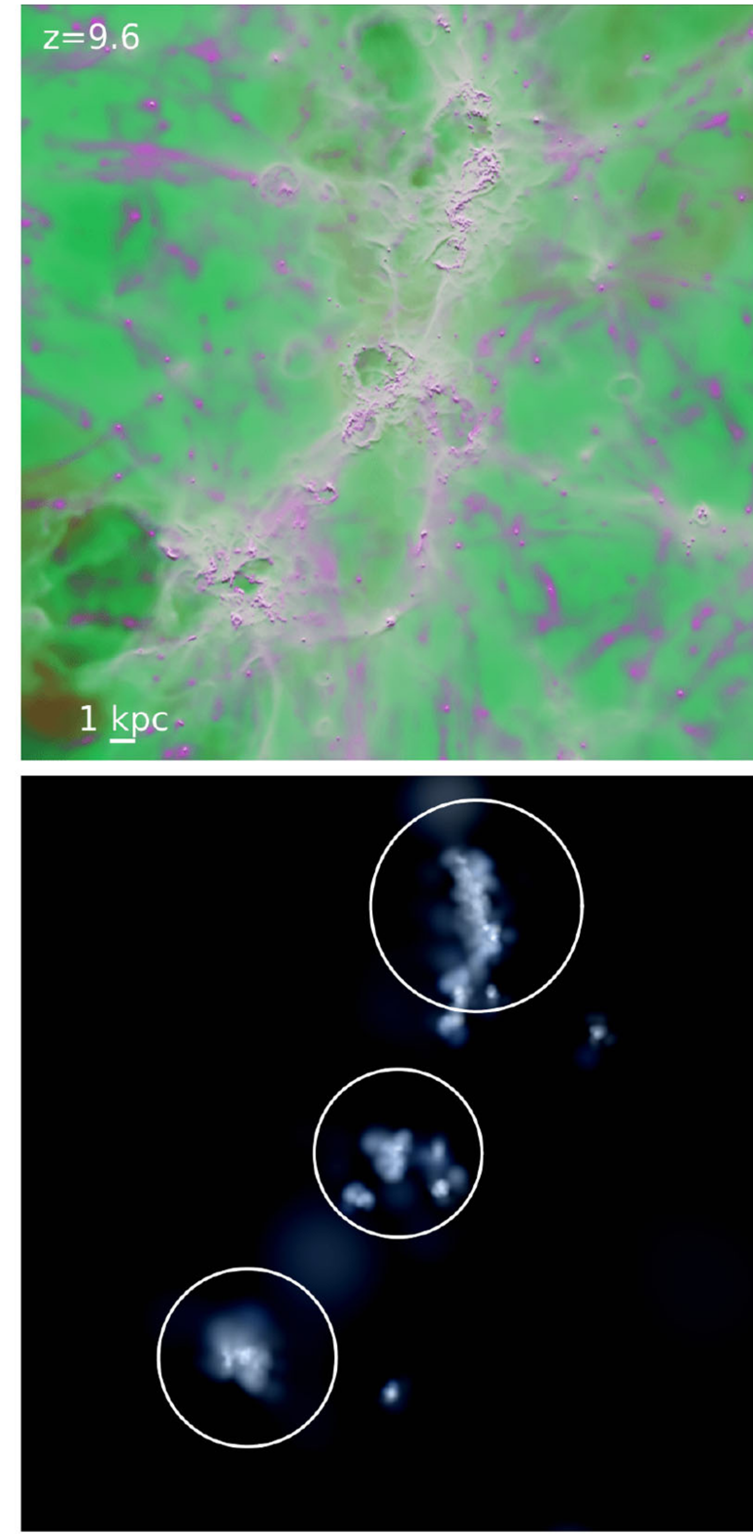
Escape fraction of ~20% required for reionization



Finkelstein+12; see also Kuhlen & Faucher-Giguère 12, Robertson+13,15

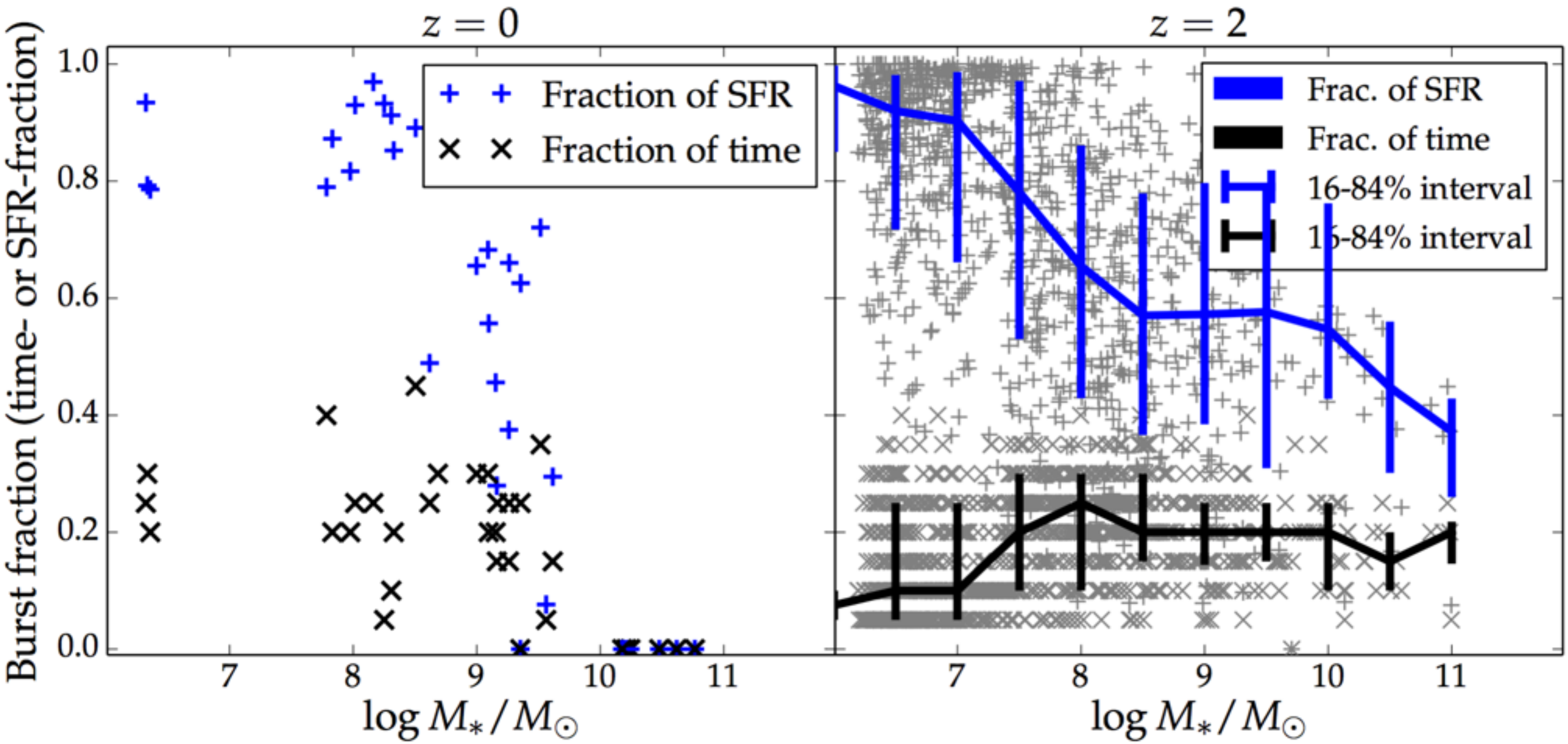
The Feedback In Realistic Environments (FIRE) simulations

- Ultra-high-res (0.1-4 pc, 20-2000 M_{sun}) zooms
- SF threshold: $n = 100\ cm^{-3}$
- Multiple stellar feedback channels:
  1. Supernovae
  2. Radiation pressure
  3. Stellar winds
  4. Photoheating
- See Hopkins+14 for details



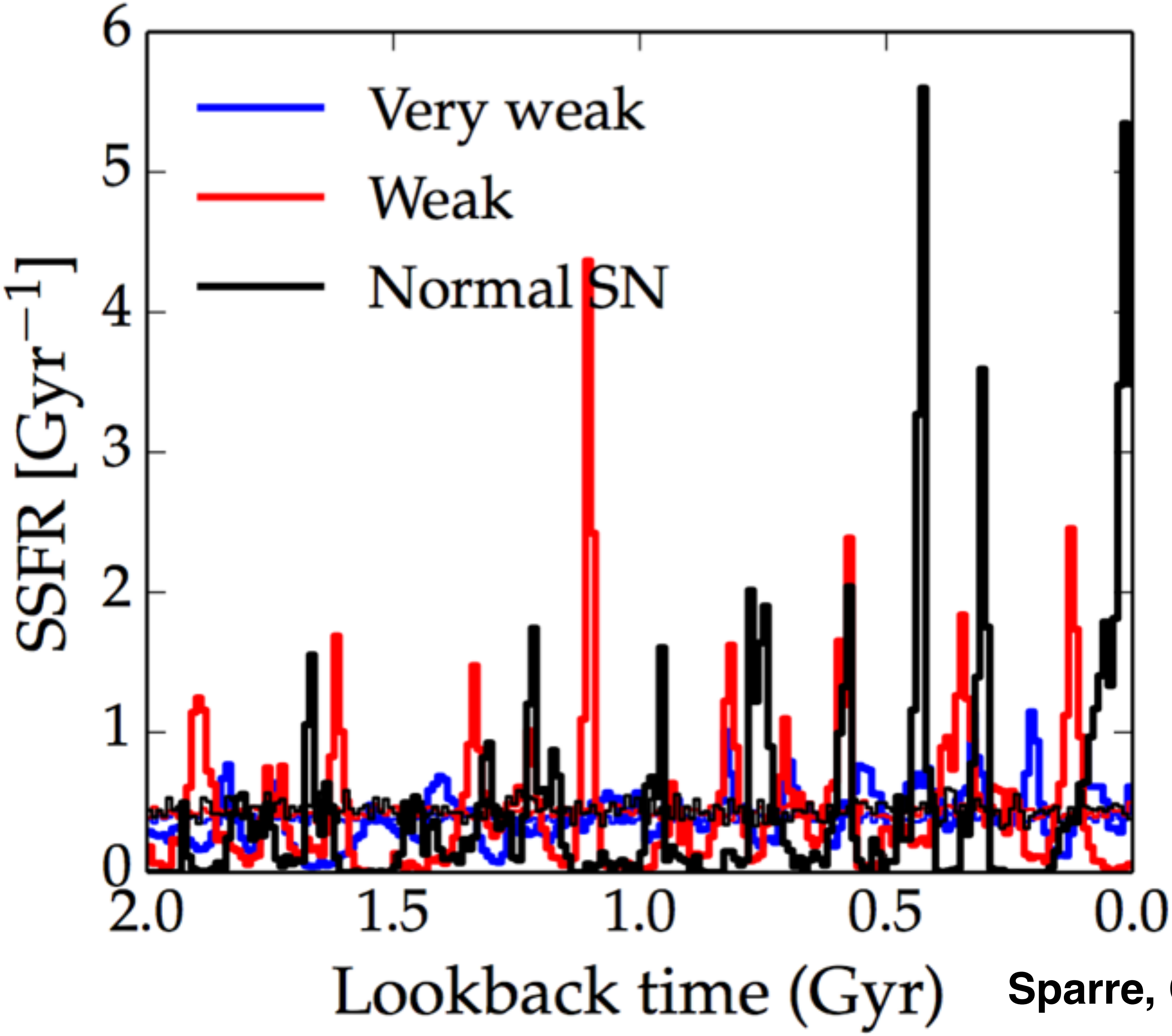
Ma, Kasen+15

Bursty star formation ubiquitous in FIRE



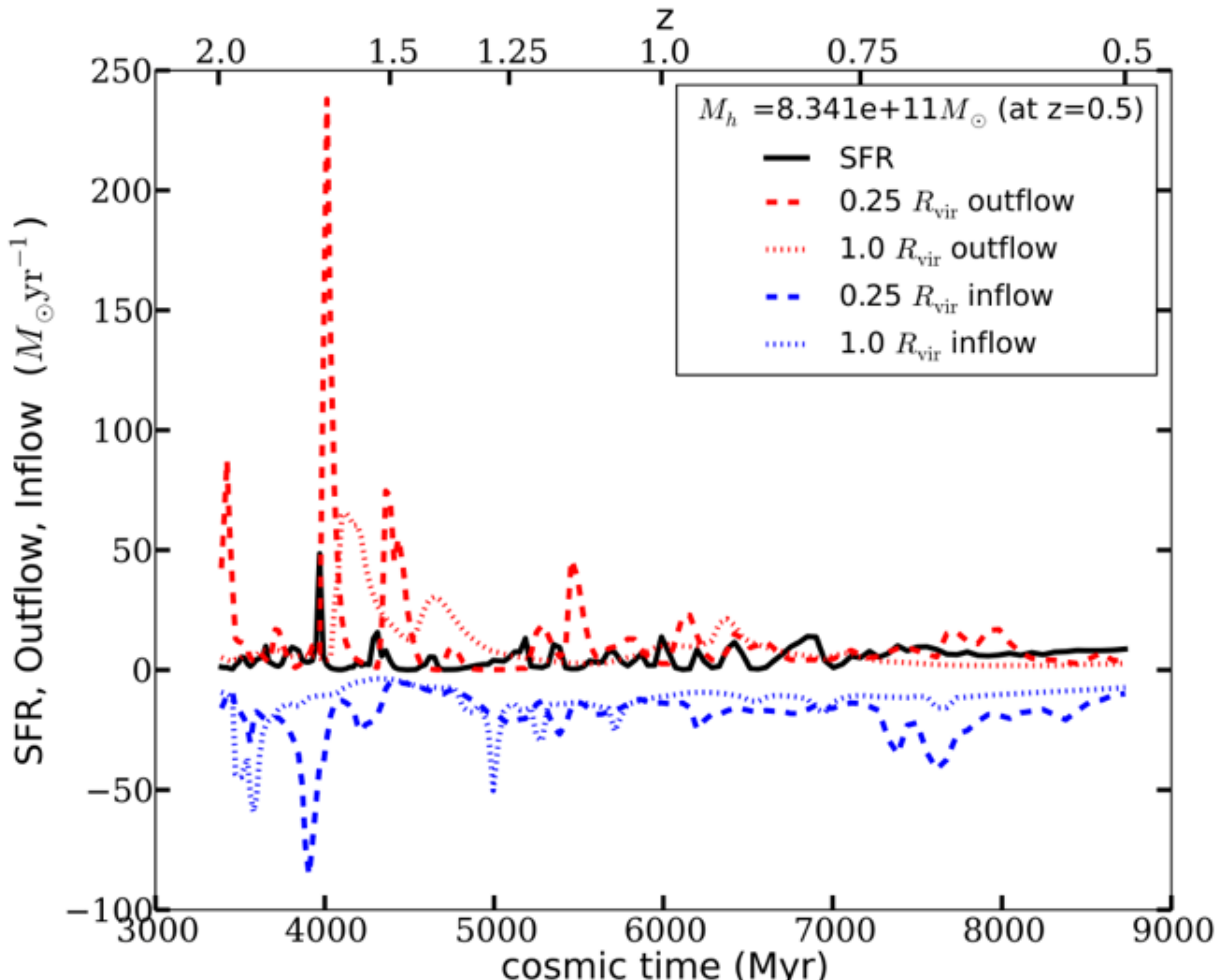
Sparre, CCH+15b

SN feedback drives burstiness



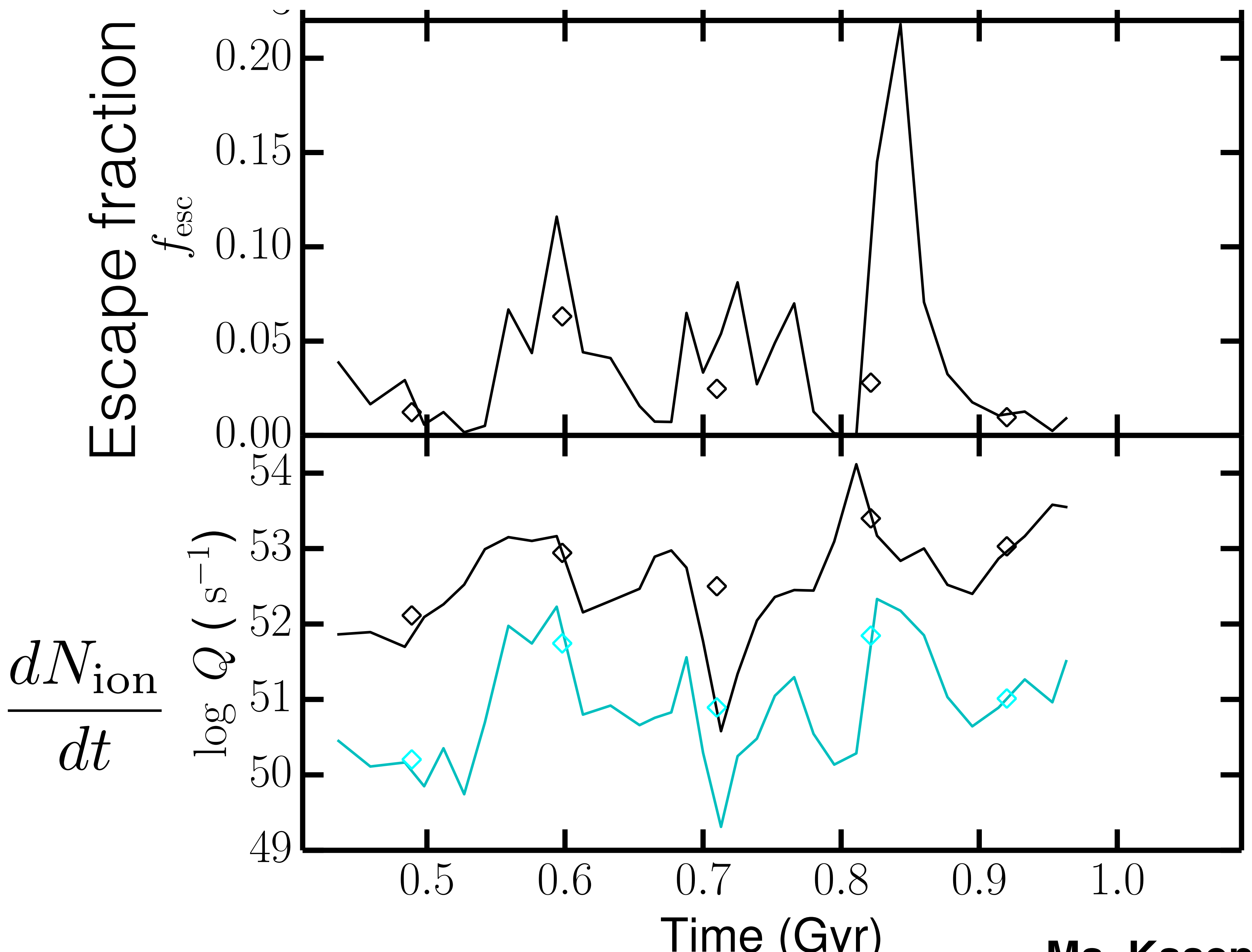
Sparre, CCH+15b

Feedback causes gusty outflows



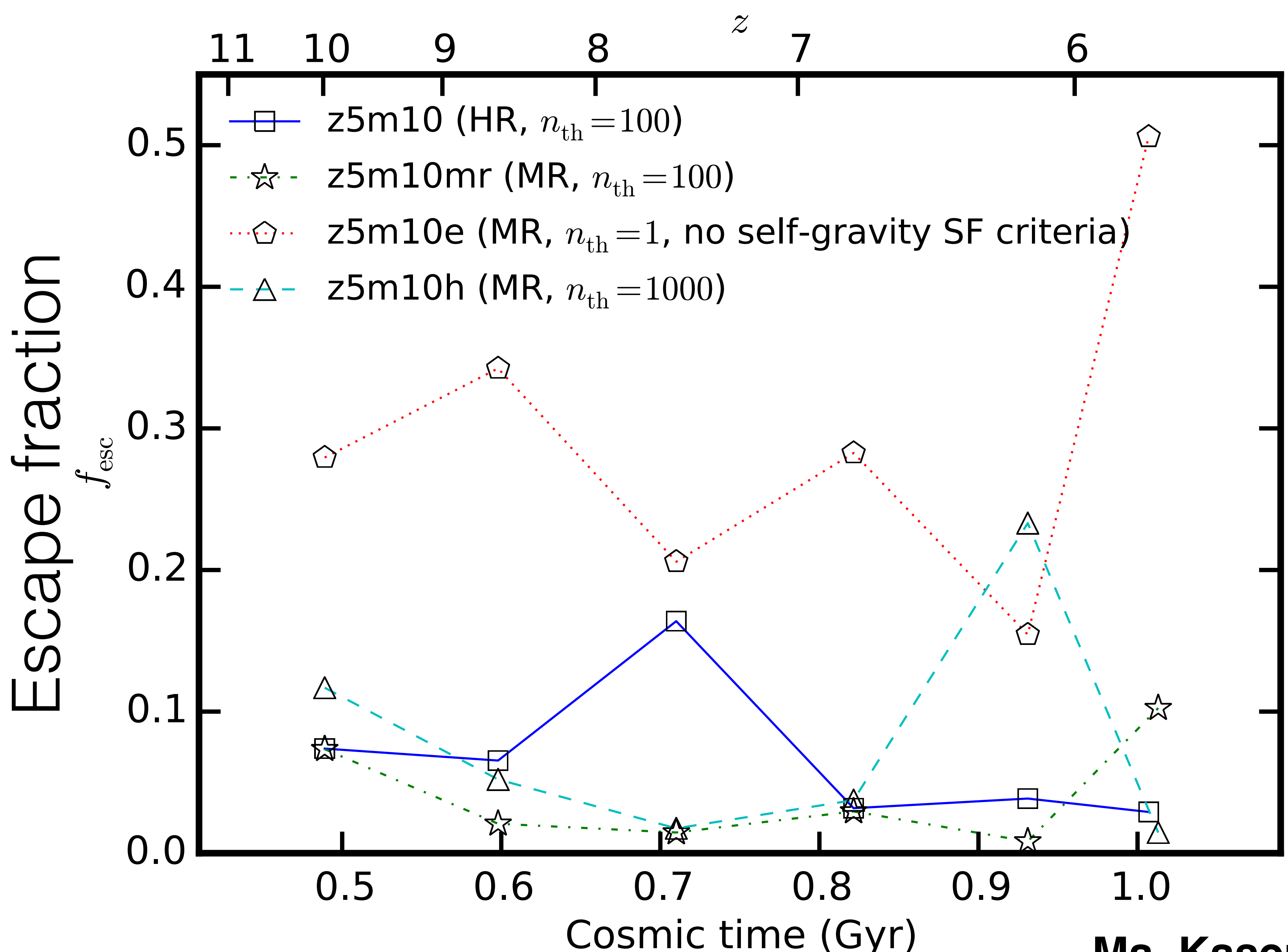
Muratov+15

The escape fraction in FIRE



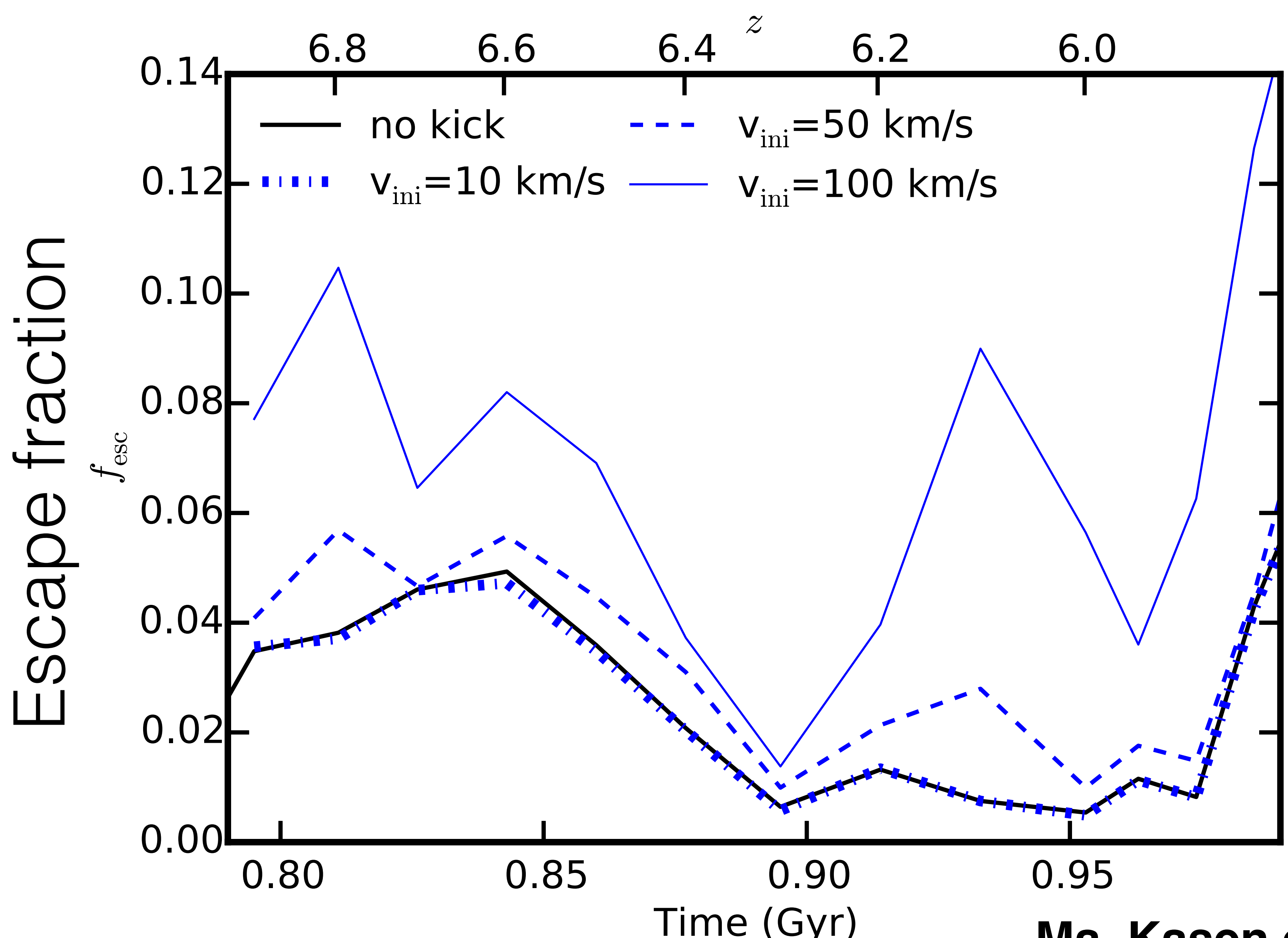
Ma, Kasen et al. 2015

Sims that don't resolve ISM overpredict f_{esc}



Ma, Kasen et al. 2015

Runaway stars insufficient

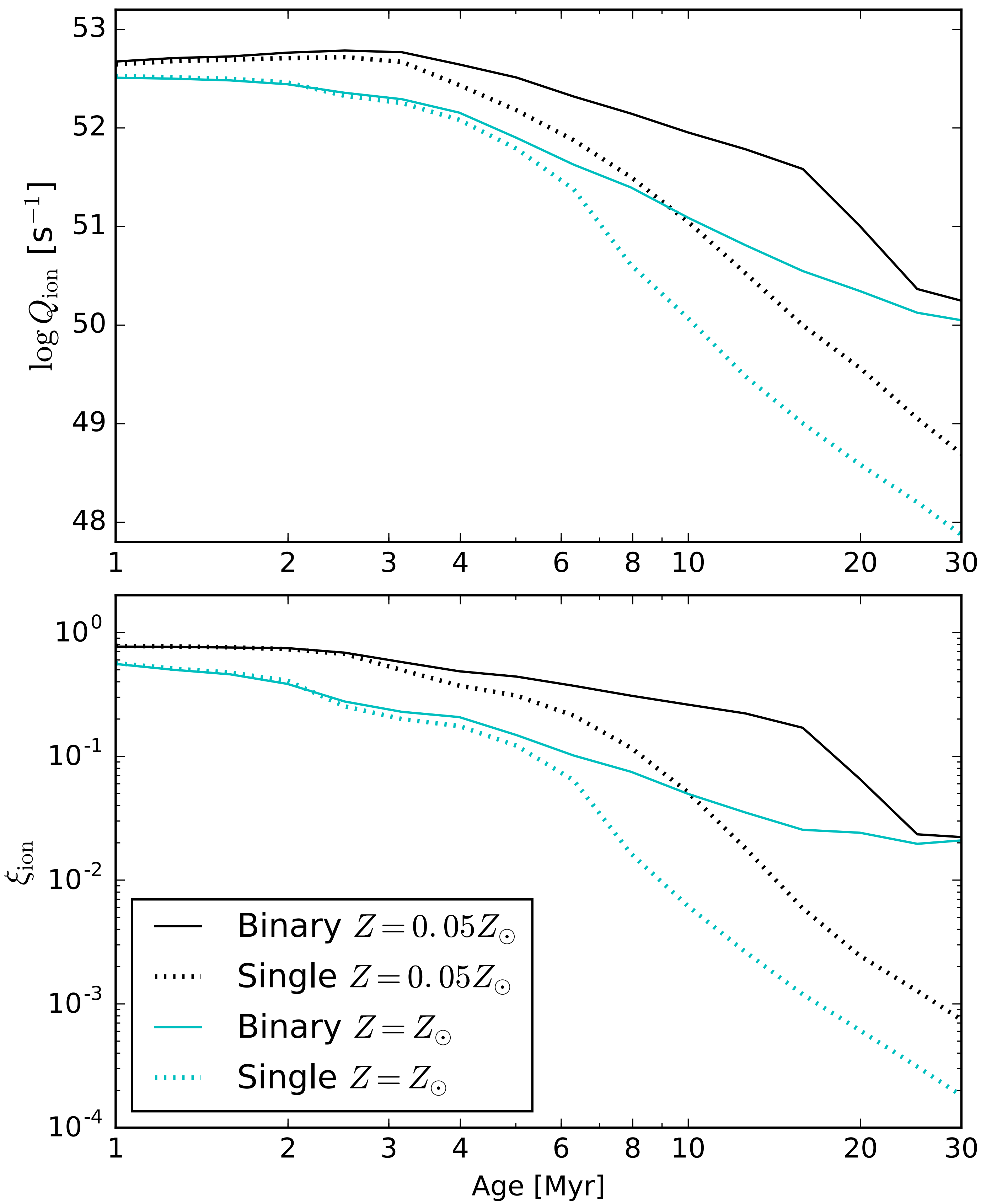


Ma, Kasen et al. 2015

Binaries —> more ionizing photons at ‘late’ times

$$\frac{dN_{\rm ion}}{dt}$$

$$\frac{L_{\rm ion}}{L_{1500}}$$



BPASS models (Eldridge et al.)

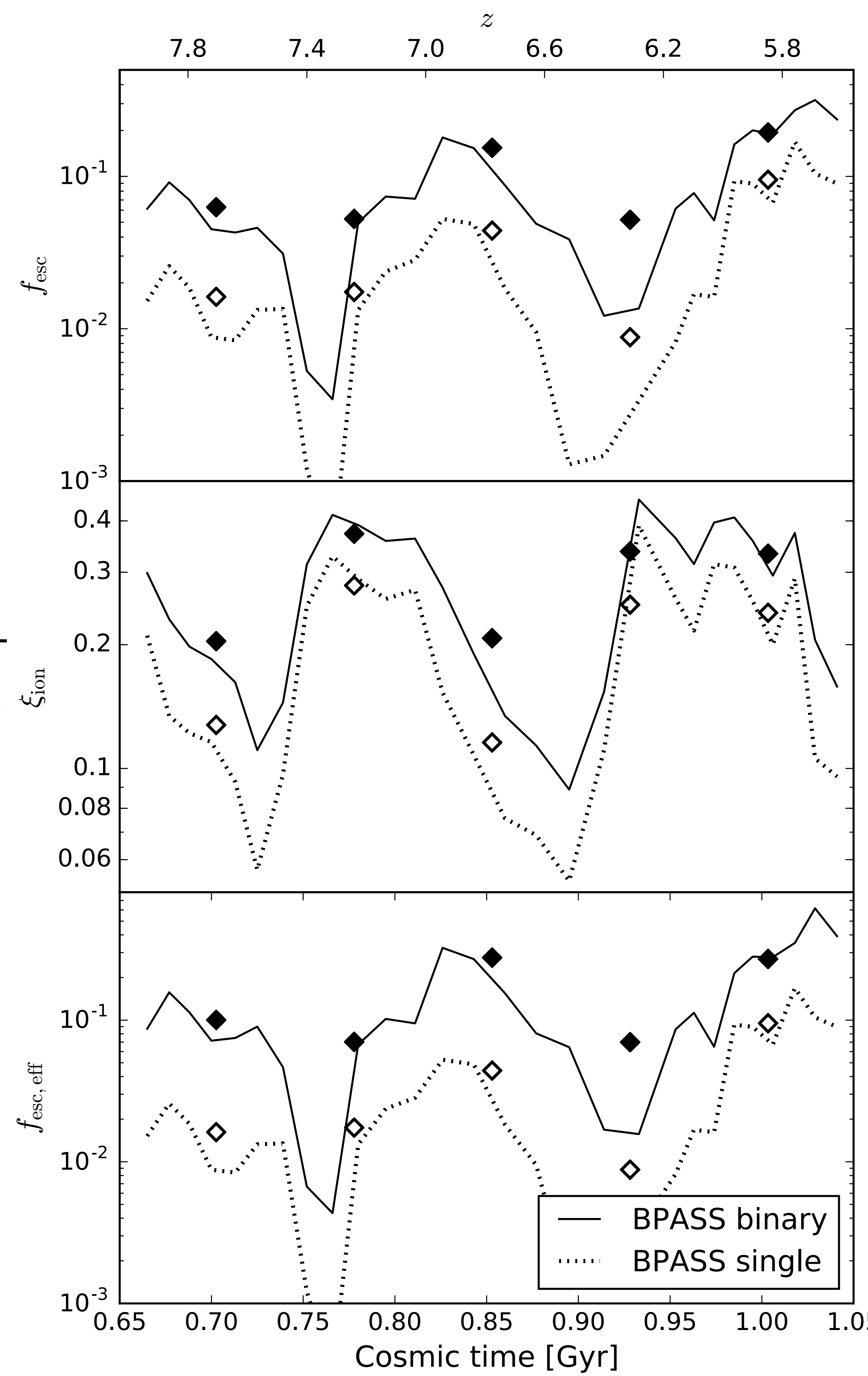
Ma, Hopkins et al. 2016

Effective escape fraction increased by 4-10x

Escape fraction

$$\frac{L_{\rm ion}}{L_{1500}}$$

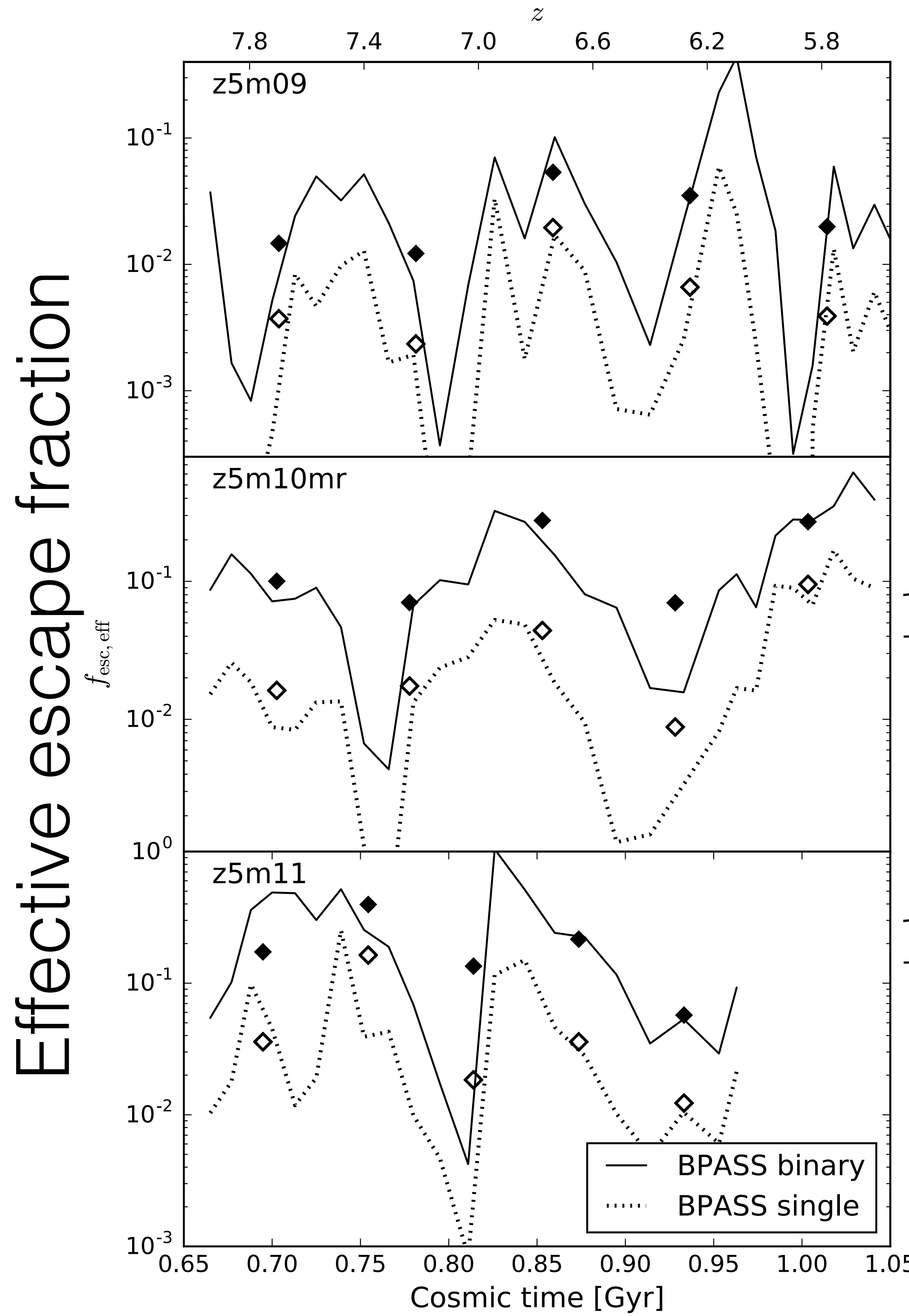
$$f_{\rm esc,eff} = f_{\rm esc}\frac{\xi_{\rm ion}}{\langle\xi_{\rm ion}\rangle_{\rm single}}$$



Ma, Hopkins et al. 2016

Effective escape fraction can reach 20%

$$f_{\mathrm{esc,\,eff}} = f_{\mathrm{esc}} \frac{\xi_{\mathrm{ion}}}{\langle \xi_{\mathrm{ion}} \rangle_{\mathrm{single}}}$$



$M_{\mathrm{h},z=6} = 10^{8.9}\mathrm{M}_\odot$

$10^{10.2}\mathrm{M}_\odot$

$10^{10.7}\mathrm{M}_\odot$

Ma, Hopkins et al. 2016

Summary

- FIRE sims (multi-channel stellar feedback, resolved ISM) exhibit ubiquitous starbursts and outflows at high z
- With single-star stellar evolution models, time-averaged escape fractions much too low (~5%)
- Runaway stars insufficient to boost escape fraction
- Sims without resolved ISM overpredict f_{esc}
- Binaries extend the lives of some massive stars and thus ionizing photon production rates at late times
- With binaries, can achieve f_{esc} ~ 20% because feedback ‘punches holes’ in ISM around 10-30-Myr-old stars, for which ionizing photon rate is still high when binaries are included

Simulation details

Name	m_b ($M_\odot$)	ϵ_b (pc)	$m_{\rm dm}$ ($M_\odot$)	$\epsilon_{\rm dm}$ (pc)	$M_{\rm vir}$ ($M_\odot$)	M_* ($M_\odot$)	$M_{\rm UV}$ (AB mag)
z5m09	16.8	0.14	81.9	5.6	7.6e8	3.1e5	-10.1
z5m10mr	1.1e3	1.9	5.2e3	14	1.5e10	5.0e7	-17.5
z5m11	2.1e3	4.2	1.0e4	14	5.6e10	2.0e8	-18.5

Notes. Initial conditions and galaxy properties at $z = 6$.
(1) Name: Simulation designation.
(2) m_b: Initial baryonic particle mass.
(3) ϵ_b: Minimum baryonic force softening. Force softening is adaptive.
(4) $m_{\rm dm}$: Dark matter particle mass in the high-resolution regions.
(5) $\epsilon_{\rm dm}$: Minimum dark matter force softening.
(6) $M_{\rm vir}$: Halo mass of the primary galaxy at $z = 6$.
(7) M_*: Stellar mass of the primary galaxy at $z = 6$.
(8) $M_{\rm UV}$: Galaxy UV magnitude (absolute AB magnitude at 1500 Å).