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

$z=30.0$

Chris Hayward (Caltech)
Escape fraction of \(~20\%\) required for reionization

\[
\text{Average Escape Fraction}
\]

\[
\text{Limiting } M_{\text{UV}}
\]

\[
Finkelstein+12; \text{ see also Kuhlen \& Faucher-Giguère 12, Robertson+13,15}
\]
The Feedback In Realistic Environments (FIRE) simulations

- Ultra-high-res (0.1-4 pc, 20-2000 M$_{\text{Sun}}$) 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

Chris Hayward (Caltech) “The Reionization Epoch” Aspen, 10 March 2016
Bursty star formation ubiquitous in FIRE

Sparre, CCH+15b
SN feedback drives burstiness

Sparre, CCH+15b

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Feedback causes gusty outflows

$M_h = 8.341 \times 10^{11} M_\odot$ (at $z=0.5$)

- SFR
- 0.25 $R_{\text{vir}}$ outflow
- 1.0 $R_{\text{vir}}$ outflow
- 0.25 $R_{\text{vir}}$ inflow
- 1.0 $R_{\text{vir}}$ inflow

Muratov+15

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The escape fraction in FIRE

\[ \frac{dN_{\text{ion}}}{dt} \]

\[ \log Q \quad (\text{s}^{-1}) \]

\[ f_{\text{esc}} \]

\[ \text{Time (Gyr)} \]

Ma, Kasen et al. 2015
Sims that don’t resolve ISM overpredict $f_{\text{esc}}$

![Graph showing escape fraction vs. cosmic time](image)

**Fig. 11.** Escape fractions in the presence of runaway stars. We only show results for a star particle of age 3 Myr. We show the results in Fig. 11. Blue dotted, dashed, and solid lines show the results for $n_{\text{th}}=100$, $n_{\text{th}}=1000$, and $n_{\text{th}}=1$, respectively. The black solid lines show the results for a star particle of age 3 Myr. We show the results in Fig. 11. The qualitative behaviours of escape fraction are consistent with the results in Yajima et al. (2011). This confirms that our results are converged with respect to resolution (over 100 Myr time-scale) escape fraction of $z5m10$, $z5m10e$, and $z5m10h$ in other simulations.

**Fig. 10.** Escape fraction with different SF density prescriptions. The predicted escape fractions do not differ from the previous calculation with the UV background at 0.01 per cent level, as shown in Fig. 10. However, if SF is allowed in diffuse gas, the escape fraction is dramatically higher, as shown in Fig. 10. To illustrate this more clearly, we compare the time-averaged galaxy properties (e.g. SF rates, stellar masses, UV magnitudes, etc.) are very similar between these runs. However, as is shown in Fig. 10, the escape fraction is dramatically higher, as shown in Fig. 10. However, if the simulations are run without an UV background, gas cannot be boosted by at most 1–2 per cent (in absolute units, or 20–50 km s$^{-1}$) to escape fraction since the displacement of a newly formed star particle is the age of the star particle. In principle, it would be more self-consistent if we re-run the whole simulation with the UV background (e.g. Conroy & Kratter 2012), but the effect in other simulations is only small effects on runaway stars on the escape fraction. Typical kick velocities of magnitude.

**Fig. 9.** The effect of self-gravity on the escape fraction. Blue dotted, dashed, and solid lines show the results for $n_{\text{th}}=100$, $n_{\text{th}}=1000$, and $n_{\text{th}}=1$, respectively. The black solid lines show the results for a star particle of age 3 Myr. We show the results in Fig. 9. The qualitative behaviours of escape fraction are consistent with the results in Yajima et al. (2011). This confirms that our results are converged with respect to resolution (over 100 Myr time-scale) escape fraction of $z5m10$, $z5m10e$, and $z5m10h$ in other simulations.

**Fig. 8.** Escape fractions from FIRE galaxies. The predicted escape fractions do not differ from the previous calculation with the UV background at 0.01 per cent level, as shown in Fig. 8. However, if SF is allowed in diffuse gas, the escape fraction is dramatically higher, as shown in Fig. 8. To illustrate this more clearly, we compare the time-averaged galaxy properties (e.g. SF rates, stellar masses, UV magnitudes, etc.) are very similar between these runs. However, as is shown in Fig. 8, the escape fraction is dramatically higher, as shown in Fig. 8. However, if the simulations are run without an UV background, gas cannot be boosted by at most 1–2 per cent (in absolute units, or 20–50 km s$^{-1}$) to escape fraction since the displacement of a newly formed star particle is the age of the star particle. In principle, it would be more self-consistent if we re-run the whole simulation with the UV background (e.g. Conroy & Kratter 2012), but the effect in other simulations is only small effects on runaway stars on the escape fraction. Typical kick velocities of magnitude.

**Fig. 7.** The effect of self-gravity on the escape fraction. Blue dotted, dashed, and solid lines show the results for $n_{\text{th}}=100$, $n_{\text{th}}=1000$, and $n_{\text{th}}=1$, respectively. The black solid lines show the results for a star particle of age 3 Myr. We show the results in Fig. 7. The qualitative behaviours of escape fraction are consistent with the results in Yajima et al. (2011). This confirms that our results are converged with respect to resolution (over 100 Myr time-scale) escape fraction of $z5m10$, $z5m10e$, and $z5m10h$ in other simulations.

**Fig. 6.** Escape fractions from FIRE galaxies. The predicted escape fractions do not differ from the previous calculation with the UV background at 0.01 per cent level, as shown in Fig. 6. However, if SF is allowed in diffuse gas, the escape fraction is dramatically higher, as shown in Fig. 6. To illustrate this more clearly, we compare the time-averaged galaxy properties (e.g. SF rates, stellar masses, UV magnitudes, etc.) are very similar between these runs. However, as is shown in Fig. 6, the escape fraction is dramatically higher, as shown in Fig. 6. However, if the simulations are run without an UV background, gas cannot be boosted by at most 1–2 per cent (in absolute units, or 20–50 km s$^{-1}$) to escape fraction since the displacement of a newly formed star particle is the age of the star particle. In principle, it would be more self-consistent if we re-run the whole simulation with the UV background (e.g. Conroy & Kratter 2012), but the effect in other simulations is only small effects on runaway stars on the escape fraction. Typical kick velocities of magnitude.

**Fig. 5.** The effect of self-gravity on the escape fraction. Blue dotted, dashed, and solid lines show the results for $n_{\text{th}}=100$, $n_{\text{th}}=1000$, and $n_{\text{th}}=1$, respectively. The black solid lines show the results for a star particle of age 3 Myr. We show the results in Fig. 5. The qualitative behaviours of escape fraction are consistent with the results in Yajima et al. (2011). This confirms that our results are converged with respect to resolution (over 100 Myr time-scale) escape fraction of $z5m10$, $z5m10e$, and $z5m10h$ in other simulations.

**Fig. 4.** Escape fractions from FIRE galaxies. The predicted escape fractions do not differ from the previous calculation with the UV background at 0.01 per cent level, as shown in Fig. 4. However, if SF is allowed in diffuse gas, the escape fraction is dramatically higher, as shown in Fig. 4. To illustrate this more clearly, we compare the time-averaged galaxy properties (e.g. SF rates, stellar masses, UV magnitudes, etc.) are very similar between these runs. However, as is shown in Fig. 4, the escape fraction is dramatically higher, as shown in Fig. 4. However, if the simulations are run without an UV background, gas cannot be boosted by at most 1–2 per cent (in absolute units, or 20–50 km s$^{-1}$) to escape fraction since the displacement of a newly formed star particle is the age of the star particle. In principle, it would be more self-consistent if we re-run the whole simulation with the UV background (e.g. Conroy & Kratter 2012), but the effect in other simulations is only small effects on runaway stars on the escape fraction. Typical kick velocities of magnitude.

**Fig. 3.** The effect of self-gravity on the escape fraction. Blue dotted, dashed, and solid lines show the results for $n_{\text{th}}=100$, $n_{\text{th}}=1000$, and $n_{\text{th}}=1$, respectively. The black solid lines show the results for a star particle of age 3 Myr. We show the results in Fig. 3. The qualitative behaviours of escape fraction are consistent with the results in Yajima et al. (2011). This confirms that our results are converged with respect to resolution (over 100 Myr time-scale) escape fraction of $z5m10$, $z5m10e$, and $z5m10h$ in other simulations.

**Fig. 2.** Escape fractions from FIRE galaxies. The predicted escape fractions do not differ from the previous calculation with the UV background at 0.01 per cent level, as shown in Fig. 2. However, if SF is allowed in diffuse gas, the escape fraction is dramatically higher, as shown in Fig. 2. To illustrate this more clearly, we compare the time-averaged galaxy properties (e.g. SF rates, stellar masses, UV magnitudes, etc.) are very similar between these runs. However, as is shown in Fig. 2, the escape fraction is dramatically higher, as shown in Fig. 2. However, if the simulations are run without an UV background, gas cannot be boosted by at most 1–2 per cent (in absolute units, or 20–50 km s$^{-1}$) to escape fraction since the displacement of a newly formed star particle is the age of the star particle. In principle, it would be more self-consistent if we re-run the whole simulation with the UV background (e.g. Conroy & Kratter 2012), but the effect in other simulations is only small effects on runaway stars on the escape fraction. Typical kick velocities of magnitude.

**Fig. 1.** Escape fractions from FIRE galaxies. The predicted escape fractions do not differ from the previous calculation with the UV background at 0.01 per cent level, as shown in Fig. 1. However, if SF is allowed in diffuse gas, the escape fraction is dramatically higher, as shown in Fig. 1. To illustrate this more clearly, we compare the time-averaged galaxy properties (e.g. SF rates, stellar masses, UV magnitudes, etc.) are very similar between these runs. However, as is shown in Fig. 1, the escape fraction is dramatically higher, as shown in Fig. 1. However, if the simulations are run without an UV background, gas cannot be boosted by at most 1–2 per cent (in absolute units, or 20–50 km s$^{-1}$) to escape fraction since the displacement of a newly formed star particle is the age of the star particle. In principle, it would be more self-consistent if we re-run the whole simulation with the UV background (e.g. Conroy & Kratter 2012), but the effect in other simulations is only small effects on runaway stars on the escape fraction. Typical kick velocities of magnitude.
Runaway stars insufficient

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Fig. 11. Escape fractions from FIRE galaxies vs. redshift $z$.

- Solid line: no kick
- Dashed line: $v_{ini} = 10$ km/s
- Dash-dotted line: $v_{ini} = 50$ km/s
- Dotted line: $v_{ini} = 100$ km/s

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**Figures:**

- **Fig. 11:** Escape fractions from FIRE galaxies vs. redshift $z$. The figures show the escape fraction $f_{esc}$ as a function of time for different initial velocities ($v_{ini}$) of stars. The solid line represents no kick, the dashed line represents $v_{ini} = 10$ km/s, the dash-dotted line represents $v_{ini} = 50$ km/s, and the dotted line represents $v_{ini} = 100$ km/s.

**Discussion:**

- The escape fraction increases with redshift $z$.
- The escape fraction is significantly higher for initial velocities of 100 km/s compared to 10 km/s or no kick.
- The escape fraction is enhanced by a few per cent when initial velocities are considered.

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**Text:**

We run z5m10h where we adopt study. For contrast, we intentionally design z5m10e to mimic 'sub-

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**Text:**

...cannot be resolved. This suggests a caution that simulations with adopted in low-resolution simulations where SF in dense gas clouds photons can then immediately escape the galaxy. We emphasize that since many young stars form in the diffuse ISM. Their ionizing density of the ISM).

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**Text:**

...and SF density threshold (as long as it is much larger than the mean very similar between z5m10, z5m10mr, and z5m10h, which further z5m10h in Fig.

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**Text:**

...runaways (e.g. Kimm & Cen etc.) are very similar between these runs. However, as is shown in galaxy properties (e.g. SF rates, stellar masses, UV magnitudes, not self-gravitating. In Section 3, we have confirmed that the global...
Binaries \(\rightarrow\) more ionizing photons at ‘late’ times

\[
\frac{dN_{\text{ion}}}{dt}
\]

\[
\frac{L_{\text{ion}}}{L_{1500}}
\]

BPASS models (Eldridge et al.)

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Effective escape fraction increased by 4-10x

\[ f_{\text{esc, eff}} = f_{\text{esc}} \frac{\xi_{\text{ion}}}{\langle \xi_{\text{ion}} \rangle_{\text{single}}} \]

\[ \frac{L_{\text{ion}}}{L_{1500}} \]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure}
\caption{Effective escape fraction as a function of time for \( z = 5 \) and \( z = 10 \). The effective escape fraction \( f_{\text{esc, eff}} \) is increased by factors of 5–8. The effective escape fraction \( f_{\text{esc}} \) is below 5% most of the time, insufficient for reionization. But it also boosts by a factor of 4–10. In more massive galaxies, the mean escape fraction is increased by factors of 6–10 because the ionizing photons produced later (after \( \sim 3 \) Myr) are nearly identical to the single-star model, while the binary model produces 20%, sufficient values needed to explain reionization. But it also boosts by factors of 4–10.}
\end{figure}

Ma, Hopkins et al. 2016
Effective escape fraction can reach 20%

\[ f_{\text{esc, eff}} = f_{\text{esc}} \frac{\xi_{\text{ion}}}{\langle \xi_{\text{ion}} \rangle_{\text{single}}} \]

\[ M_{h, z=6} = 10^{8.9} M_\odot \]

\[ 10^{10.2} M_\odot \]

\[ 10^{10.7} M_\odot \]

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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 $f_{\text{esc}}$

• Binaries extend the lives of some massive stars and thus ionizing photon production rates at late times

• With binaries, can achieve $f_{\text{esc}} \sim 20\%$ 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

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<th>Name</th>
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<th>$\epsilon_b$</th>
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</table>

**Notes.** Initial conditions and galaxy properties at $z = 6$.

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