Escape Fraction from Early Galaxies

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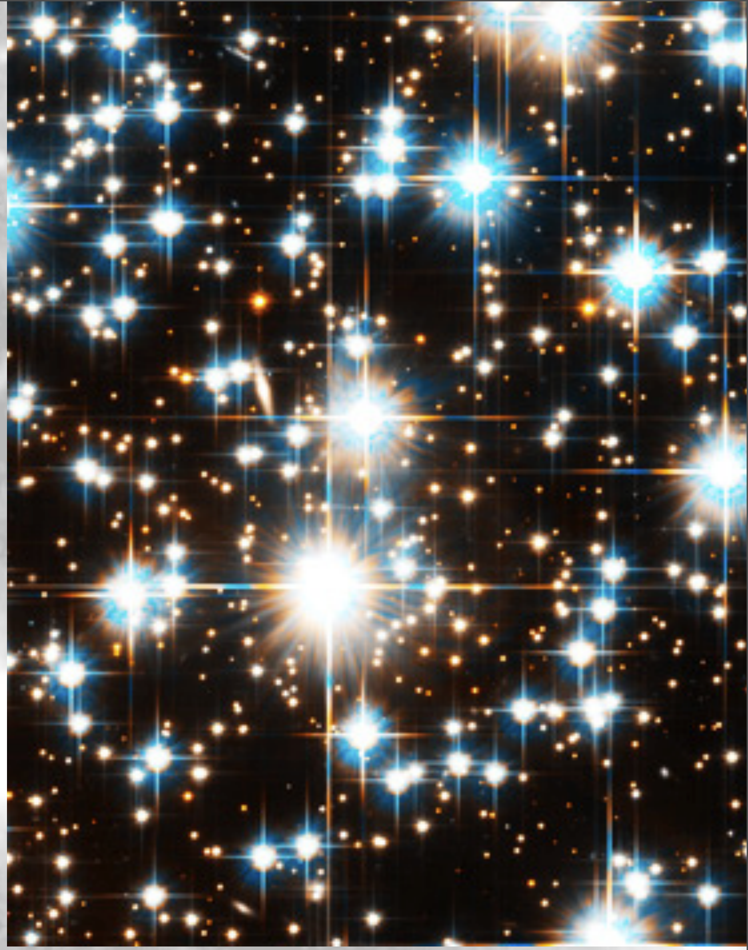
Reionization



- What reionized the universe?
- Understand the relationship of galaxies to reionization
    - Crucial to know how many photons are escaping from these galaxies

The Escape Fraction

- Fraction of ionizing photons that escape the galaxy
- Many studies as to what affects it:

The Escape Fraction

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Supernova

Dust Content

Redshift

Mass

Baryon Mass Fraction

Spin of Galaxy

Internal Structure

Morphology

Star Formation History

Shells

Star Formation Rate

Minimum Mass of Galaxy

The Escape Fraction

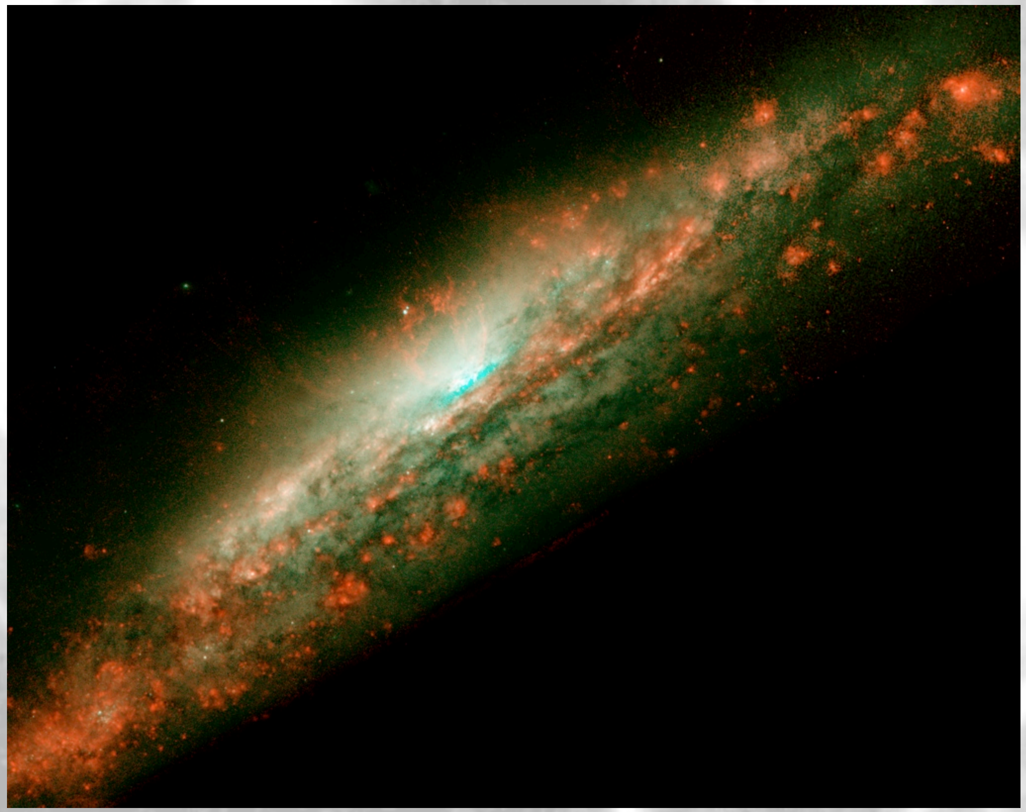
- Fraction of ionizing photons that escape the galaxy
- Many studies as to what affects it:
- Previous studies range from $0.01<f_{esc}<1$
- We want to simplify the physics and see how the internal structure affects the escape fraction - namely, clumping

Properties of the Disk

- Exponential hyperbolic secant profile:

$$n_H(Z) = n_0 e^{-r/r_h} \operatorname{sech}^2(\frac{\mathrm{Z}}{\mathrm{z}_0})$$

- Dependent on redshift (disks at higher redshift are denser and smaller)



Stars in the Disk

- Mass spectrum and metallicity of stars
  - Larson, Pop III
  - Salpeter, Pop II
- Compute number of ionizing photons from the entire stellar population

$$Q_{pop} = \frac{\int_{m_1}^{m_2} \overline{Q}_H(m) f(m) dm}{\int m f(m) dm} \times M_*$$

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depends on f_*

The Ionizing Front

- An ionized HII region develops around the stars

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The Escape of a Ray Over a Path

- So, the amount of photons that escape depend on the path that the photons follow, which depends on θ

$$f_{esc}(\theta) = 1 - \frac{4\pi\alpha_B}{Q_{pop}} \int_0^\infty n_H^2(Z) r^2 dr$$

Integrate over θ →

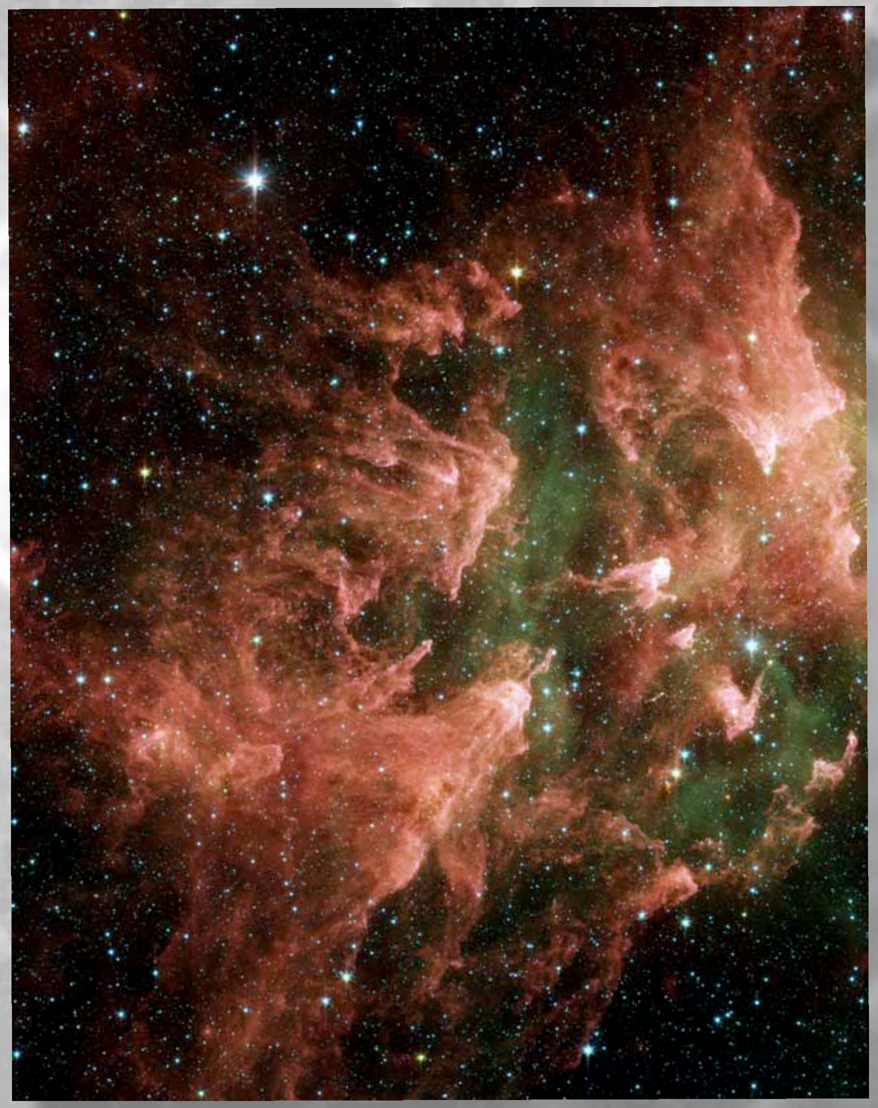
$$\begin{aligned} \eta_{esc}(Q_{pop}) &= \int\int \frac{f_{esc}}{4\pi} d\theta d\Omega \\ &= \int \frac{1}{2} f_{esc} \sin(\theta)\, d\theta \end{aligned}$$

Density Contrasts

- We add clumps to describe density contrasts
  - $C = n_c / n_{ic}$
  - f_v = volume in clumps / total volume

$$n_c = \frac{n_{mean}}{f_V + (1 - f_V)/C}$$

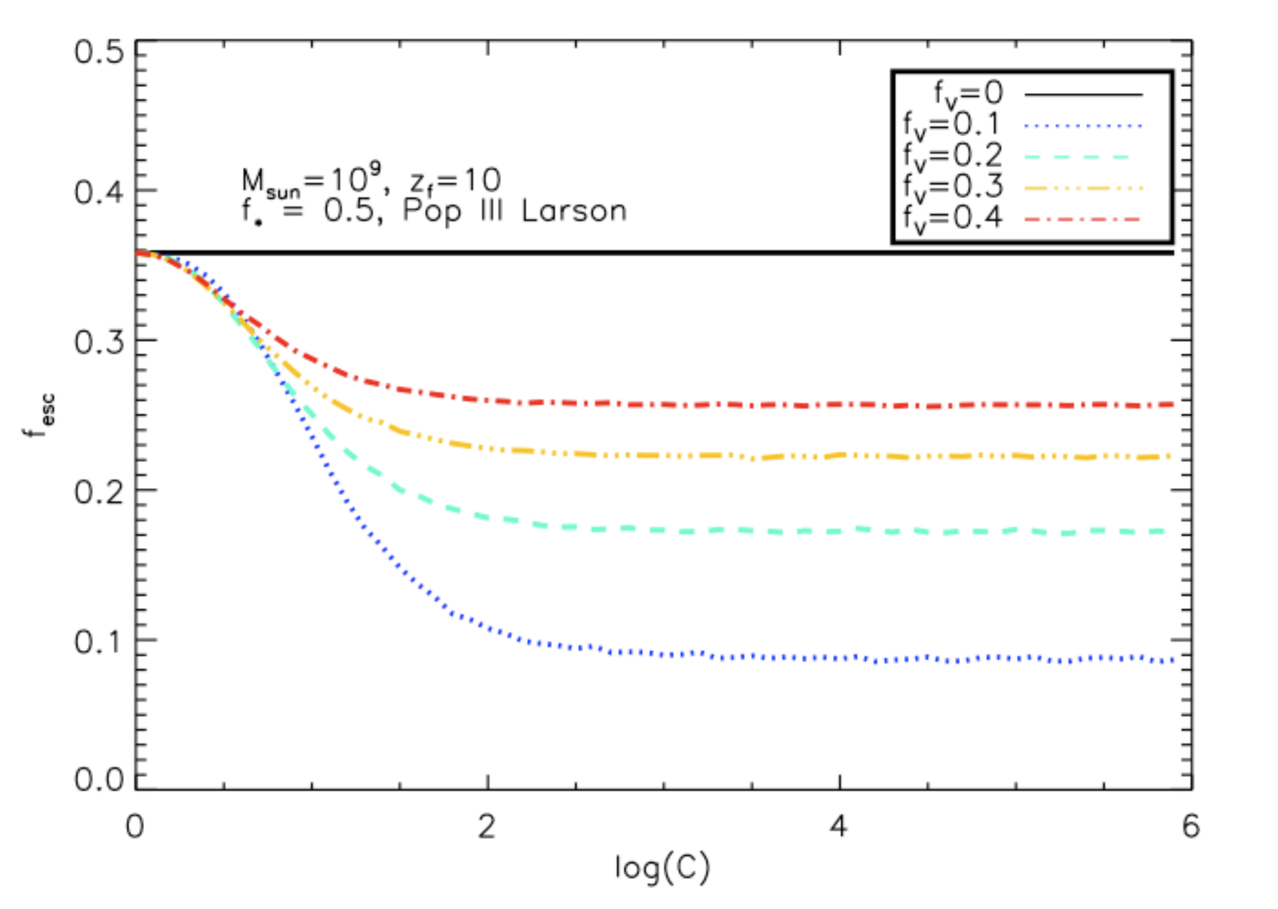
$$n_{ic} = \frac{n_{mean}}{f_V(C-1)+1}$$

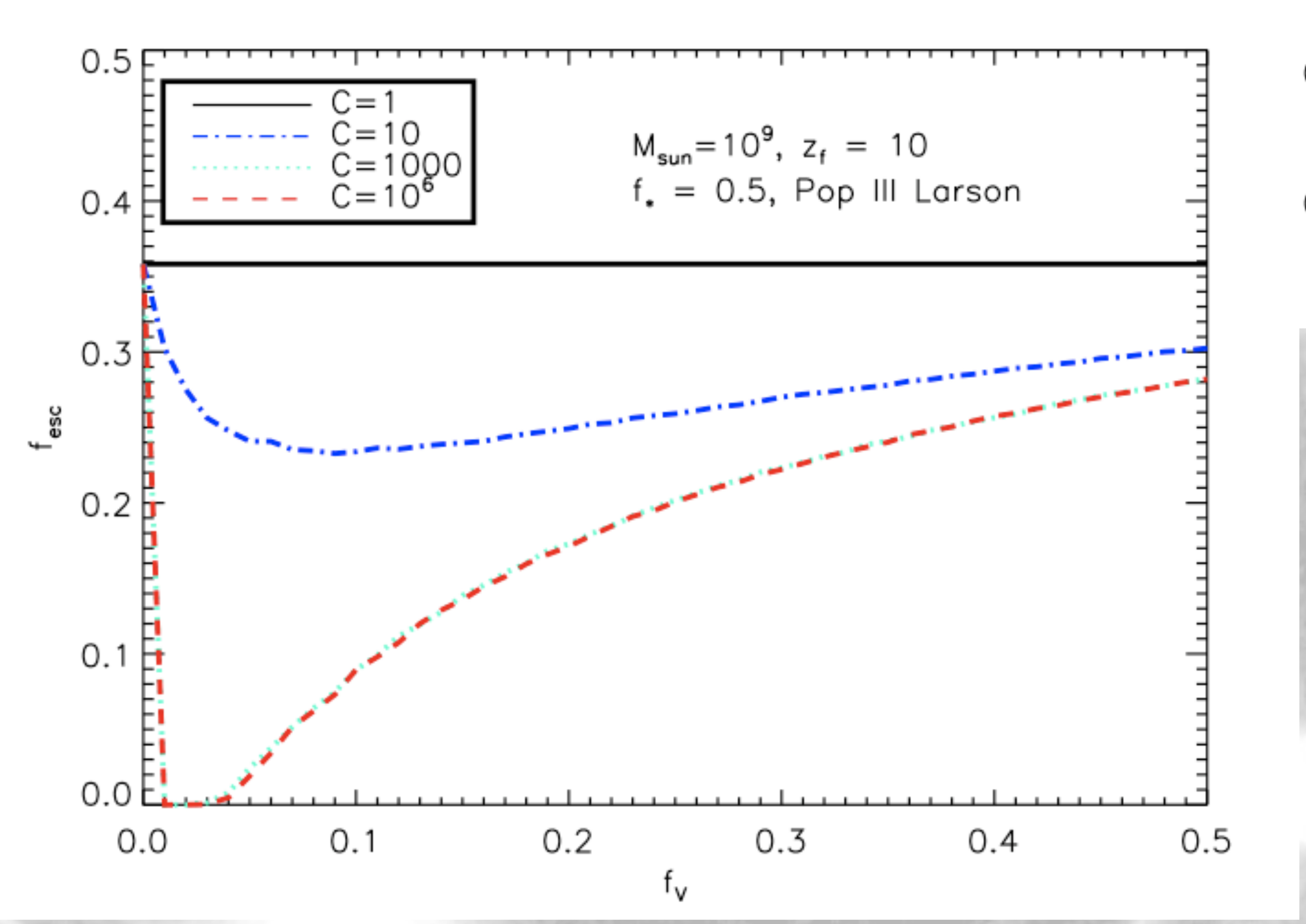


Clumps are randomly distributed in galaxy

The Effect of Clumps

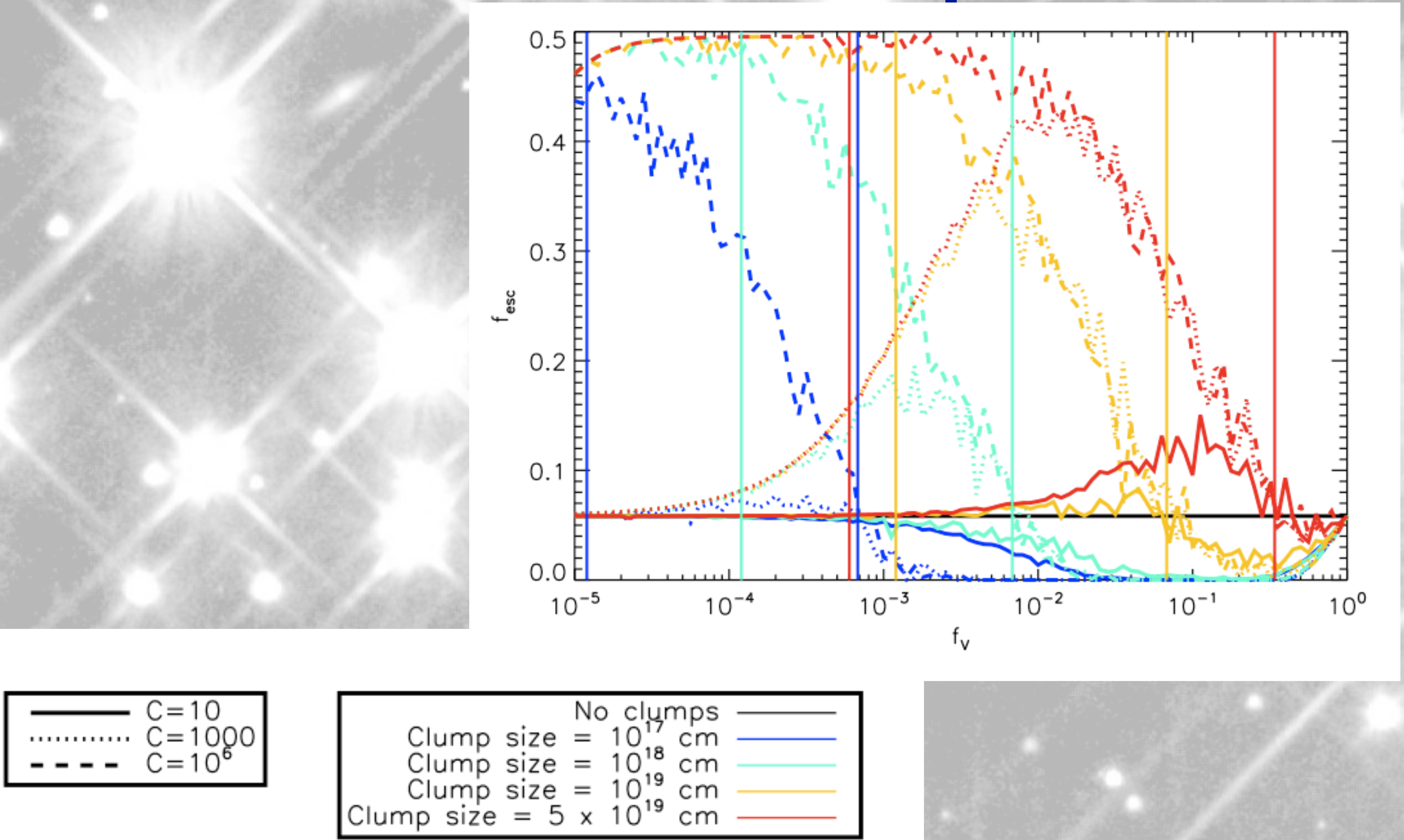
f_{esc} smallest when density contrast largest





As f_V increases, more clumps exist, so each individual clump is less dense

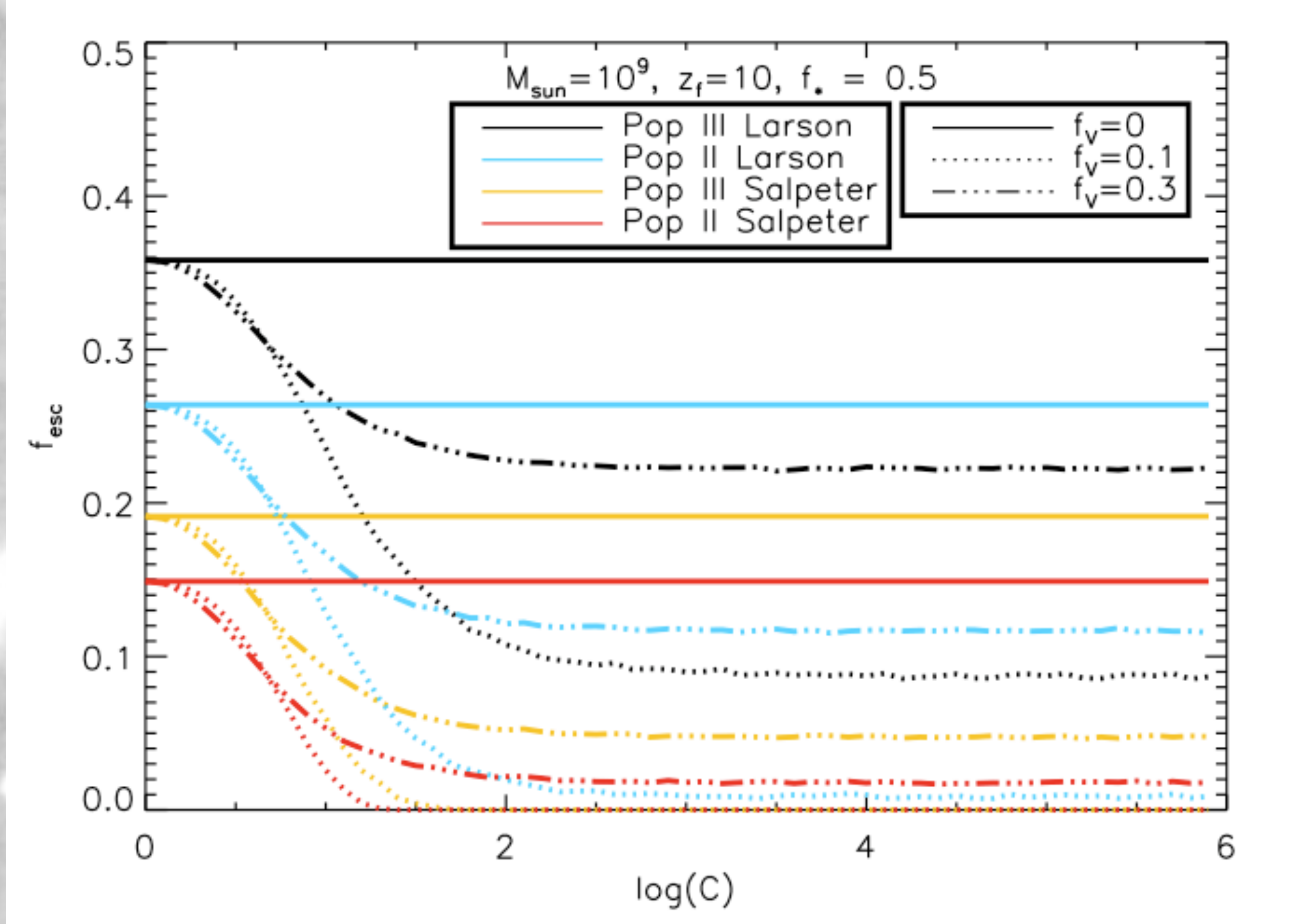
Affect of Clump Size



z_f = 10, f_* = 0.1, Pop III Larson

What Factors Affect f_{esc}?

Population - stars that produce more ionizing photons increase f_{esc}



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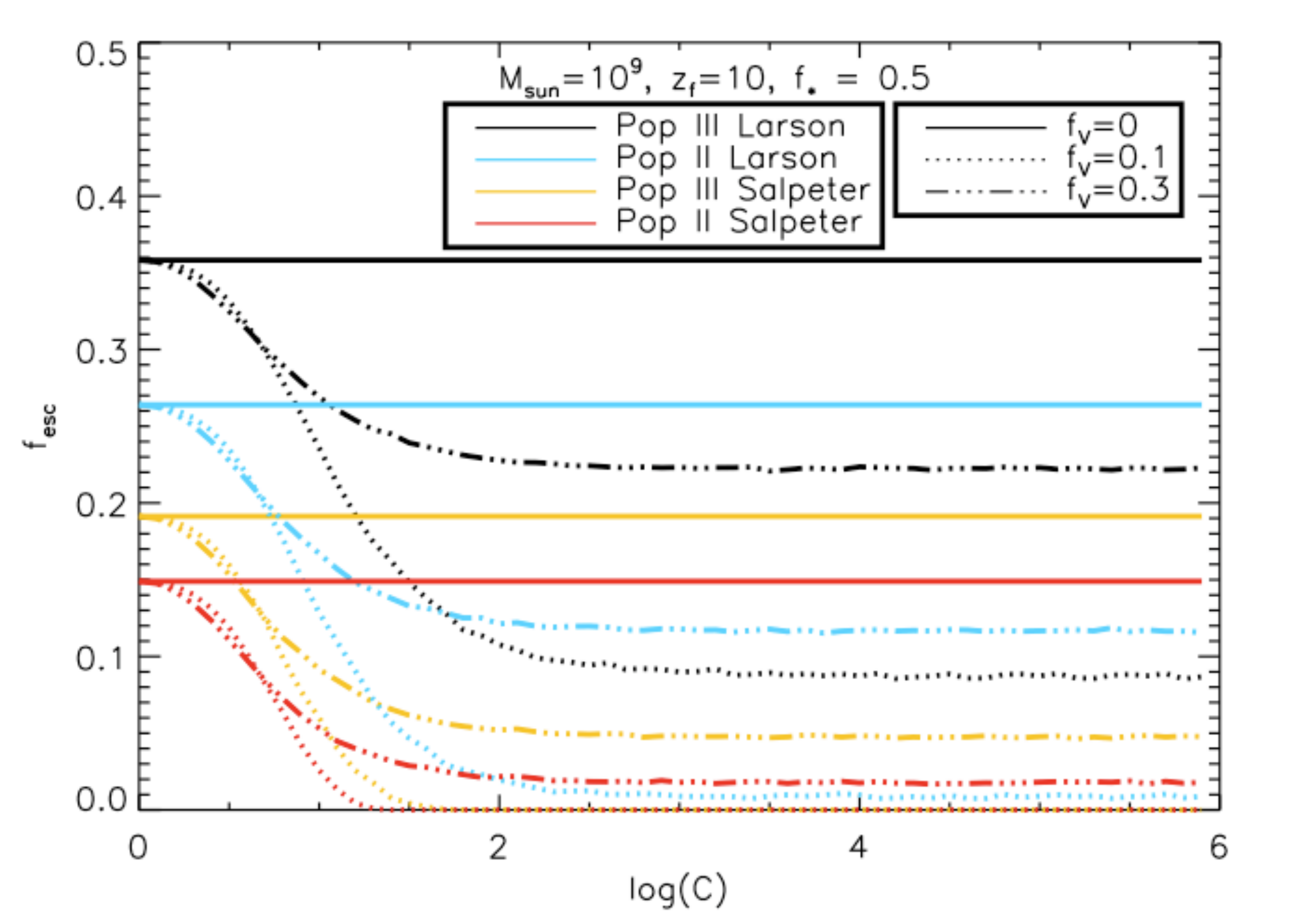
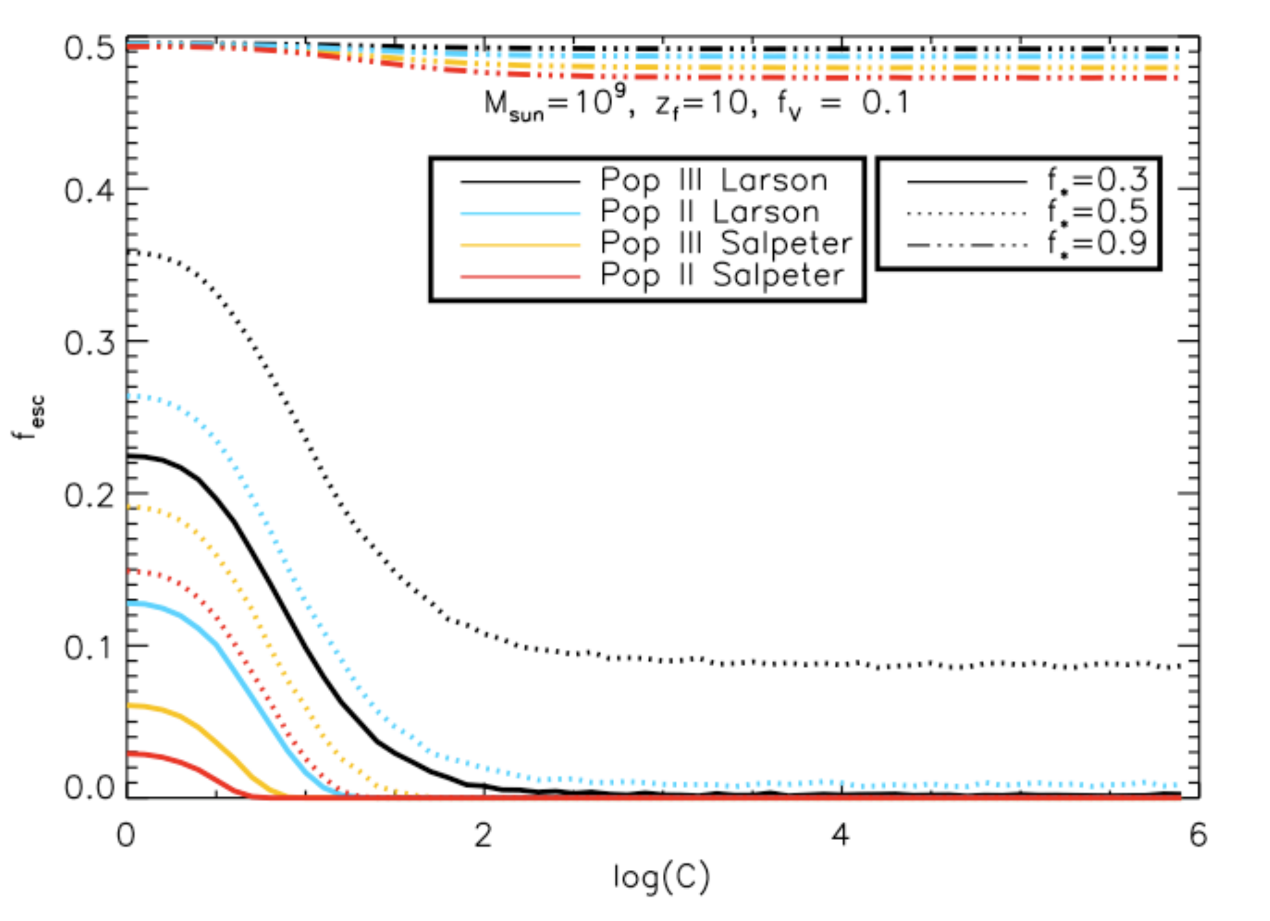
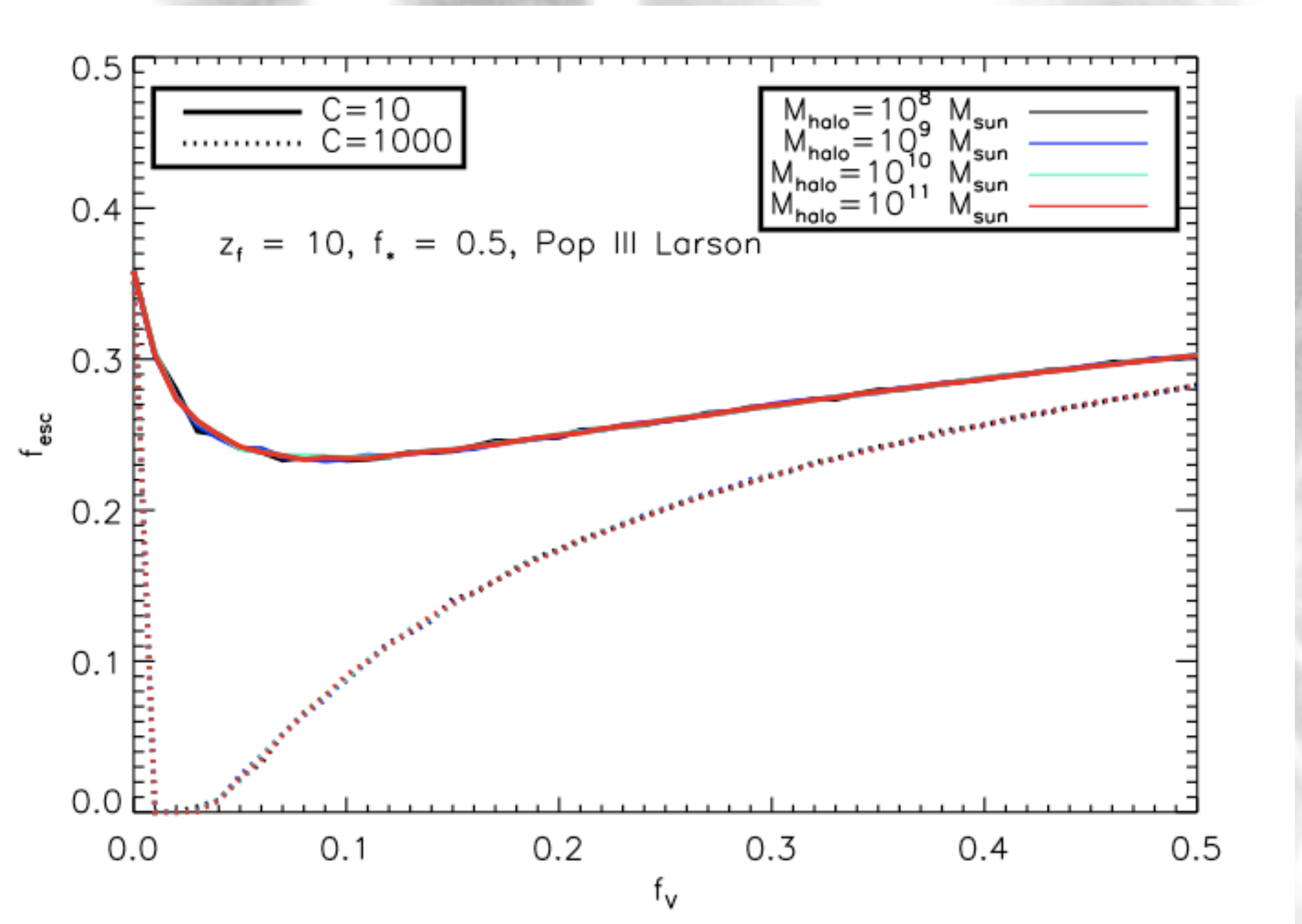
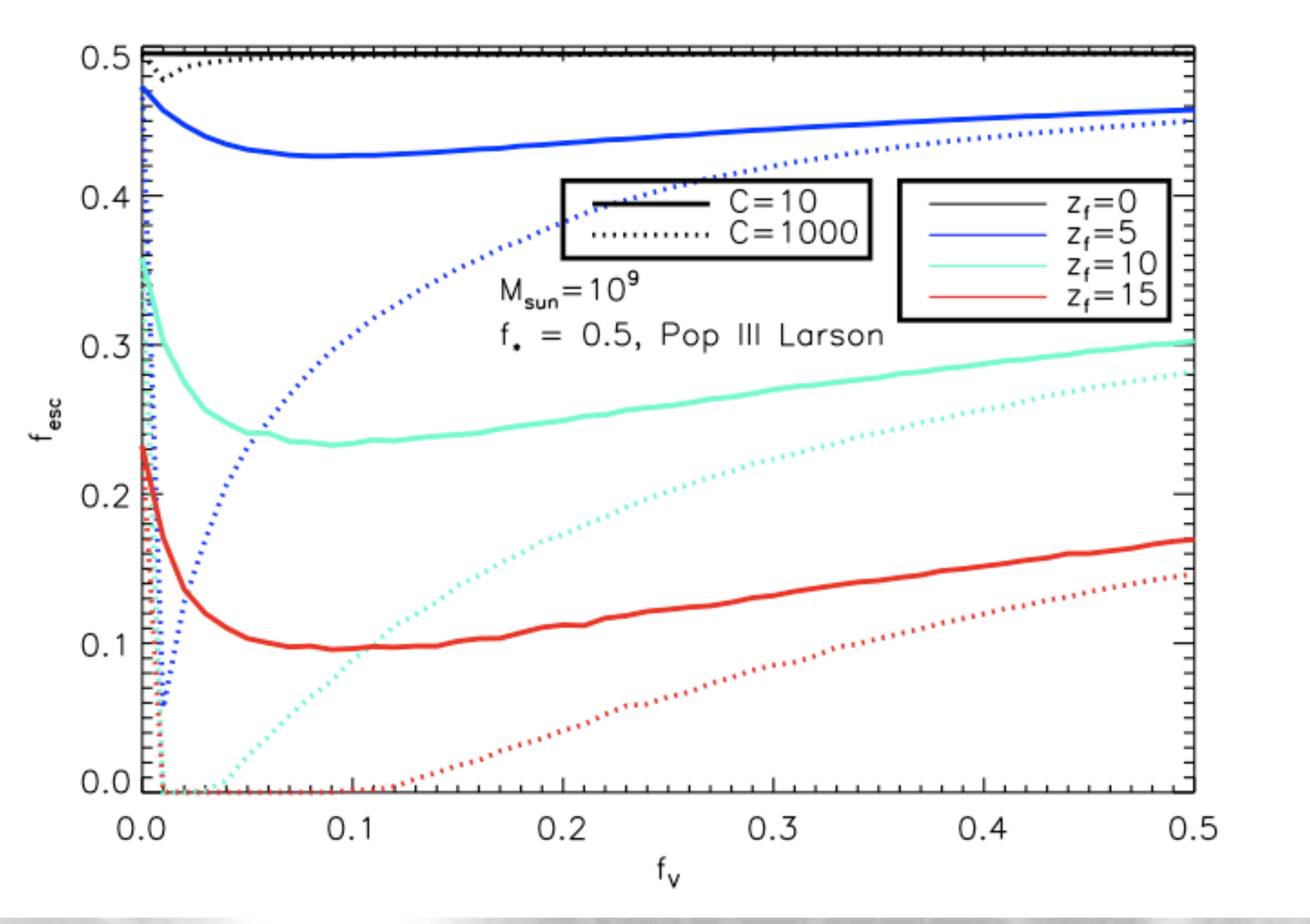




Higher star formation efficiencies increase ionizing photons produced and hence f_{esc}

Mass - no affect!

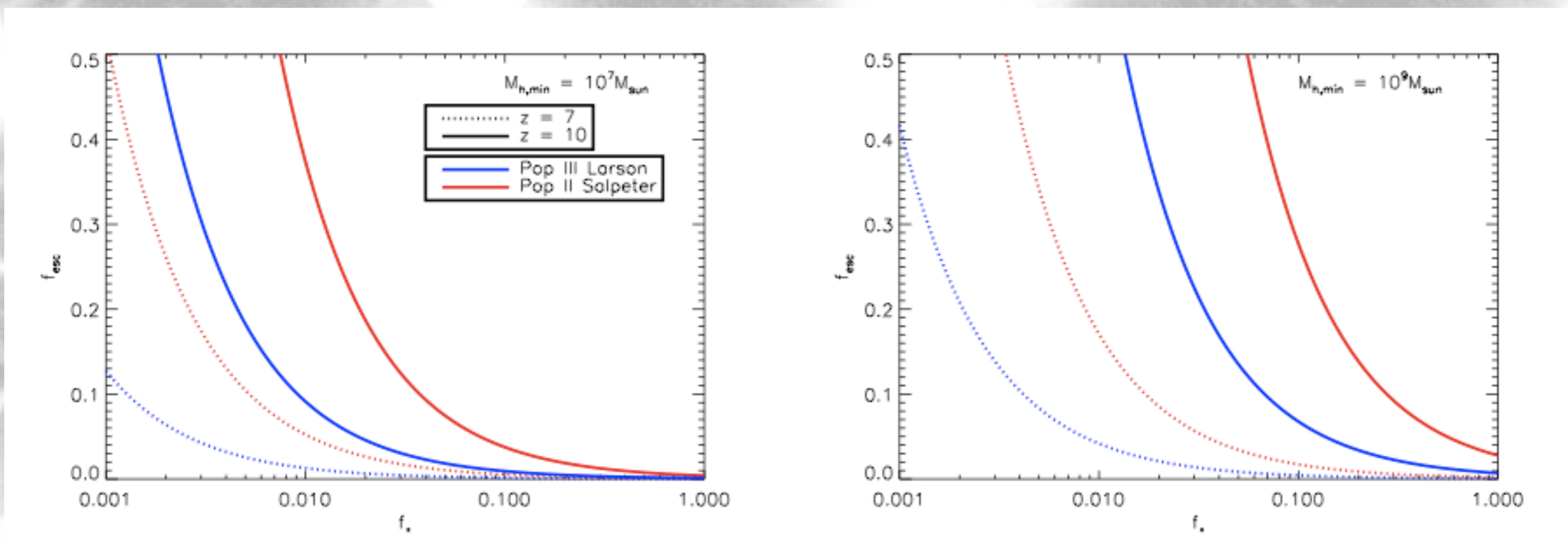




At higher redshifts, halos are denser. f_{esc} is lower.

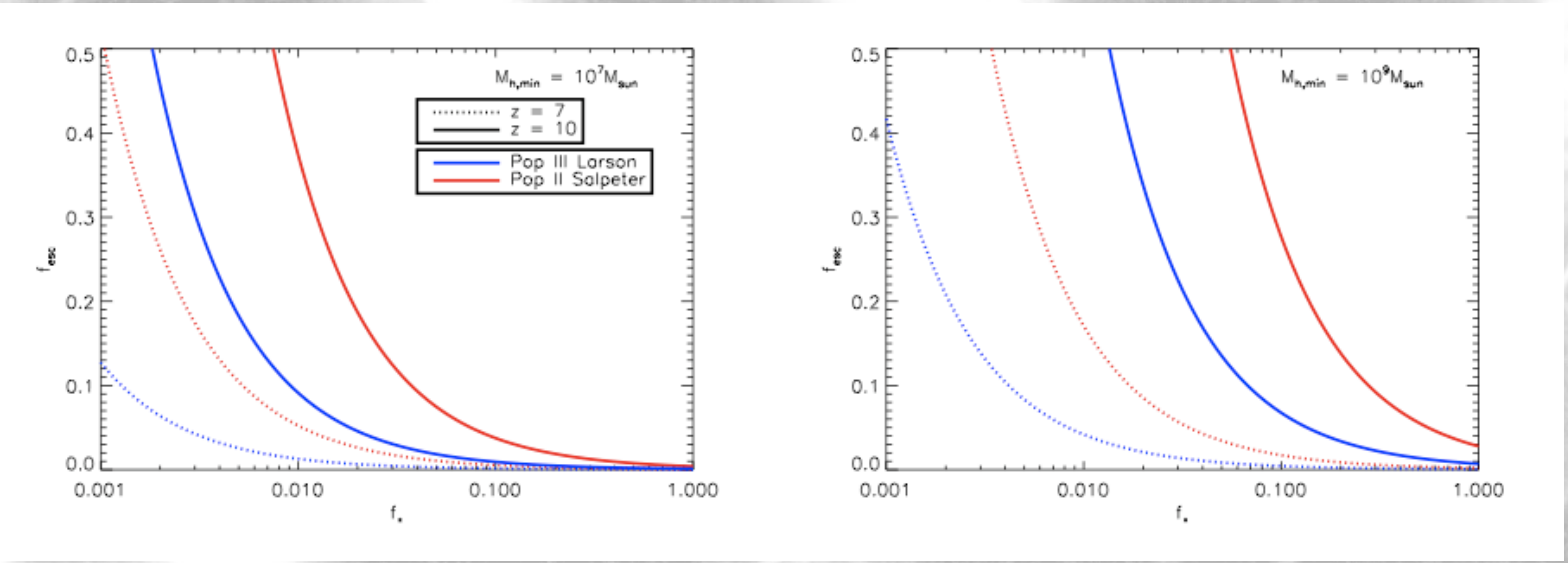
Galaxies Reionizing the Universe

- f_{esc} needed to keep universe reionized
- if above 0.5, universe cannot be reionized by these sources



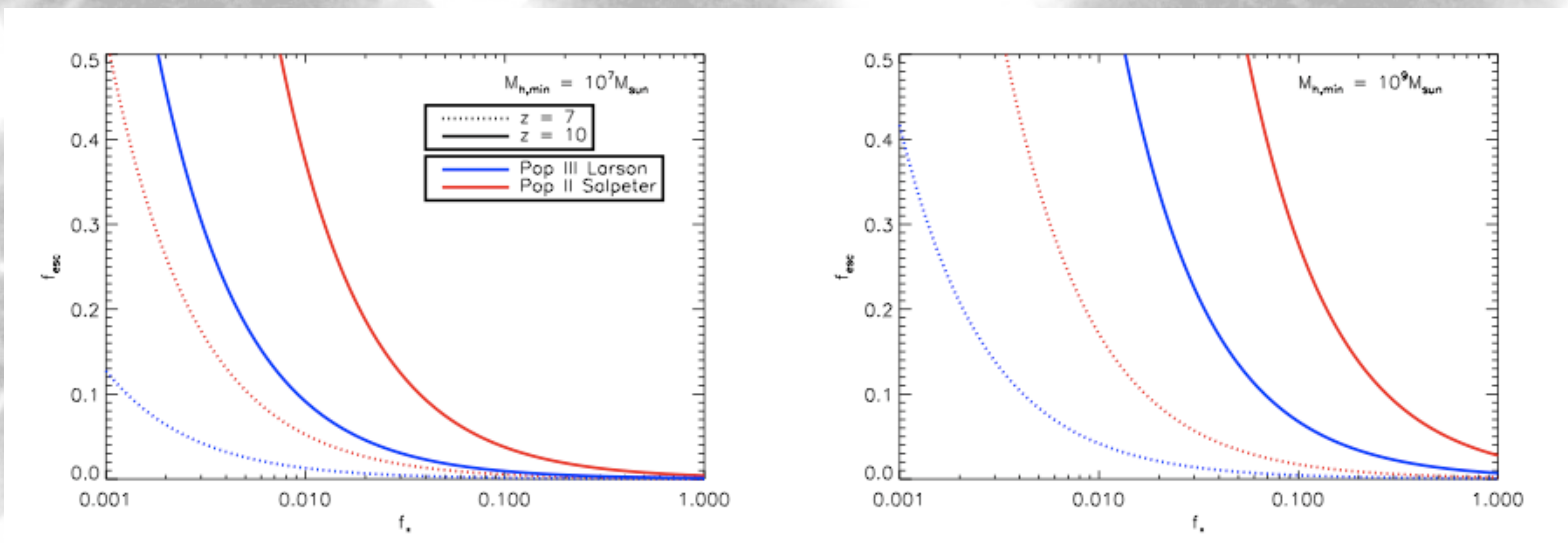
Galaxies Reionizing the Universe

- Harder to keep universe reionized:
  - at larger z
  - with stars that produce less ionizing photons



Galaxies Reionizing the Universe

- If low mass sources suppressed, much harder to keep universe reionized needed to keep universe reionized



Conclusions - What Affects f_{esc}?

- f_{esc} increases as number of ionizing photons (Q) produced increases
  - Q larger for metal free massive stars
  - Q increases as star formation efficiency increases
- Clump properties
  - Density of clump, parameterized by C - denser clumps decrease f_{esc}
  - Amount of clumps, parameterized by f_V - higher f_V increases f_{esc} (more clumps so therefore, clumps are less dense
  - Number of clumps along path length - if path lengths cross less than one clump, f_{esc} will increase above no-clump case (depends on clump size and f_V)