Escape Fraction from Early Galaxies

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Abstract: Understanding the escape fraction from early galaxies gives an important constraint on the sources that reionize the universe. Previous studies to measure the escape fraction have found a wide range of values, varying from less than 0.01 to 1. Rather than try to find an exact value of the escape fraction, we seek to understand how internal properties of the galaxy affect the escape fraction. Two major galactic properties affect the escape fraction: 1) the density and distribution of neutral hydrogen within the galaxy and 2) the number of ionizing photons produced. How the neutral medium is clumped significantly affects the escape fraction. If there are some paths that photons follow out of the galaxy do not intercept a clump, the escape fraction is greater than the case with no clumps, with clumps of higher density cause a greater escape fraction. If all paths intersect at least one clump, the escape fraction will drop below the no-clump case, and increasing the density of the clump will decrease the escape fraction. Populations of stars that increase the number of ionizing photons produced (such as metal free or more massive stars or disks with a high star formation efficiency) increase the escape fraction because the angle out of the disk that photons can escape is increased, allowing more photons to escape. The escape fraction also decreases for halos formed at higher redshifts, since halos are more dense, assuming no change in stellar population over redshift. We also find mass of the galaxy does not affect the escape fraction, as long as the star formation efficiency is constant.

Modeling a Galaxy:

1. Density of the hydrogen within the galaxy.

We assume that a galaxy has an exponential hyperbolic secant profile:

$$n_H(Z) = n_0 e^{-r/r_h}\,\mathrm{sech}^2\left(\frac{Z}{z_0}\right)$$

Clumps are added to a galaxy, parameterized by the clumping factor, which is the ratio of the density of the clumped medium to the interclump medium, $C = n_c/n_{ic}$. The fraction of volume taken up by the clumps is described by the filling factor, f_V. Clumps are randomly distributed in the galaxy. The density of the clumped and interclump medium is:

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

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

2. Adding stars to the galaxy.

We assume either Pop III or Pop II stars with either a heavy (Larson) IMF or light (Salpeter) IMF. The number of ionizing photons emitted from a stellar population is:

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

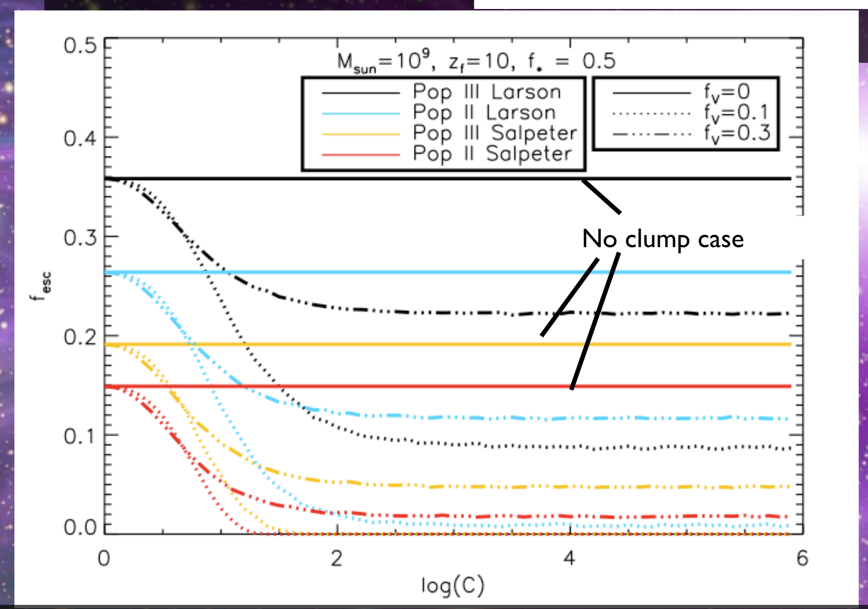
3. Calculating the escape fraction.

We follow photon rays as they leave the galaxy. The escape fraction of each ray is:

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

Integrating over angle gives the total escape fraction:

$$f_{esc}(Q_{pop}) = \int\int \frac{f'_{esc}(\theta)}{4\pi} d\theta d\Omega = \int \frac{1}{2} f'_{esc}(\theta)\,\sin(\theta)\,d\theta$$



Stellar Population

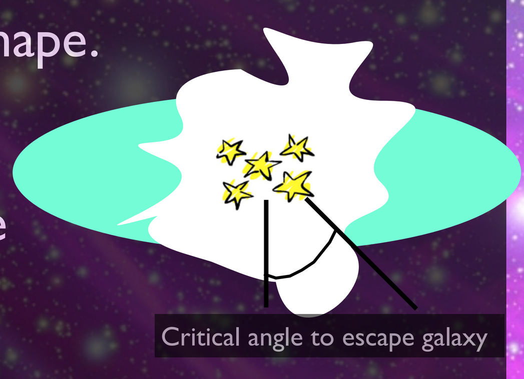
★ Stars that produce more ionizing photons (metal free, heavier stars, or with a larger star formation efficiency (f_*)) lead to a higher f_{esc}.

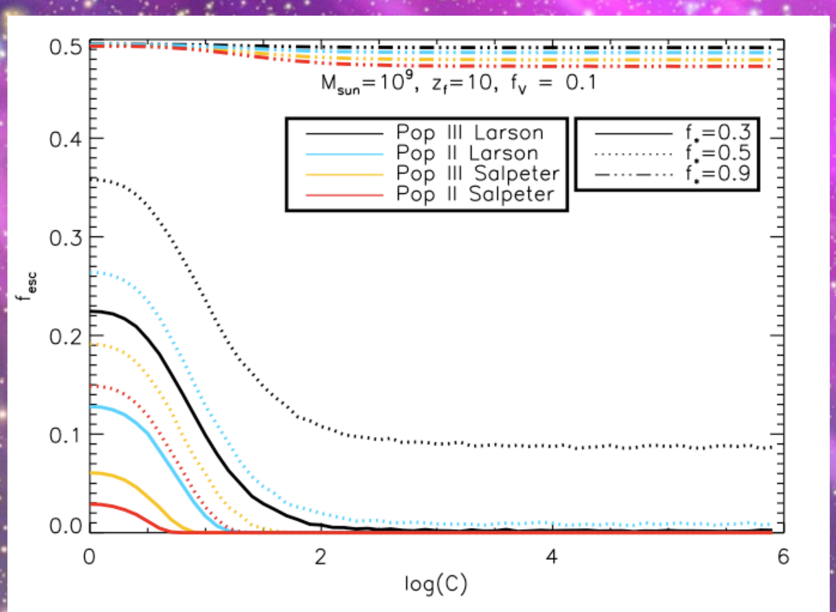
★ These all increase the critical angle that photons can escape out of the disk.

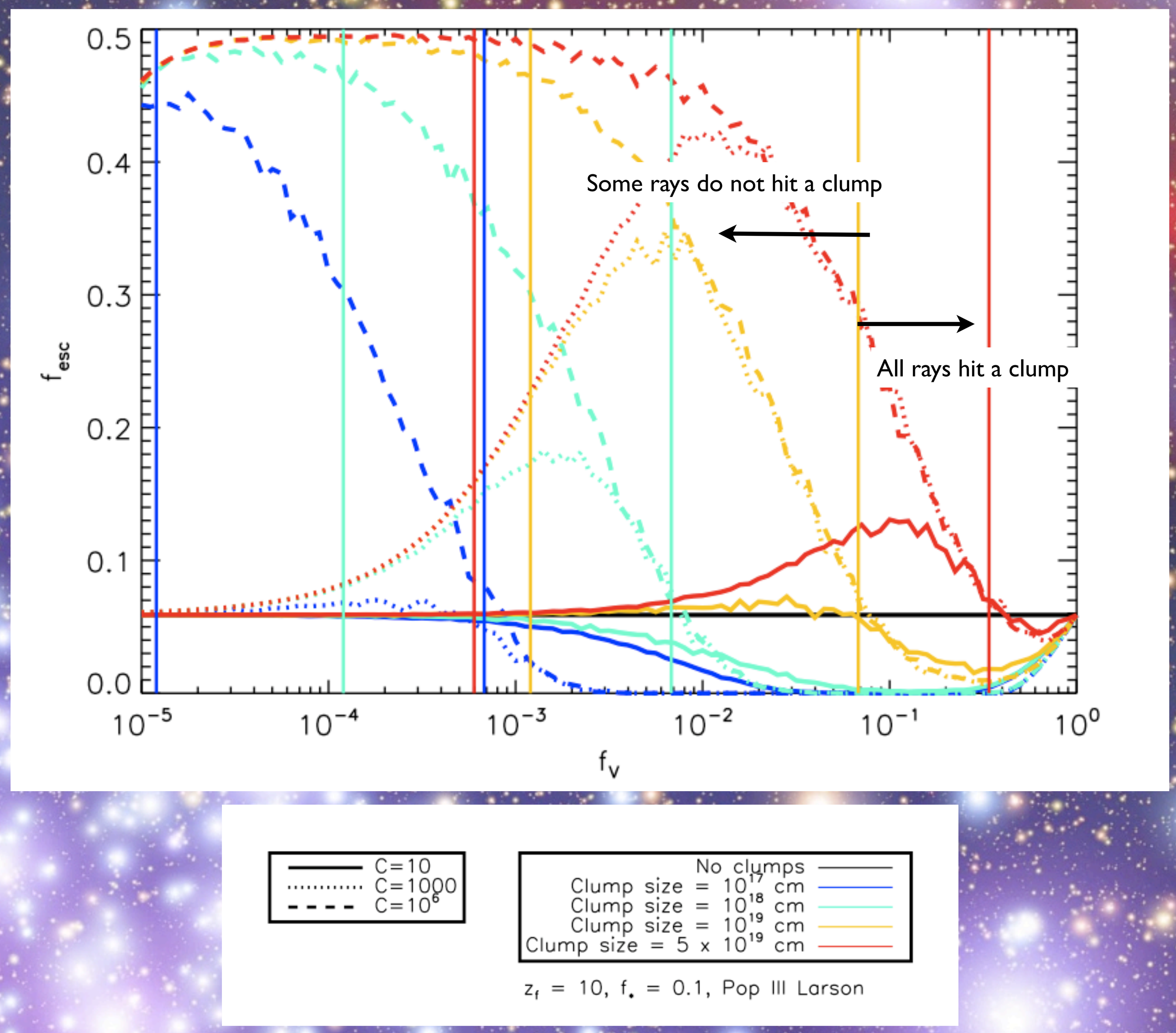
★ Escape fractions shown are out of half the disk.

★ Clumps and the density distribution can cause an ionization front with a non-spherical shape.

★ Photons are more likely to escape from the top and bottom of the disk.







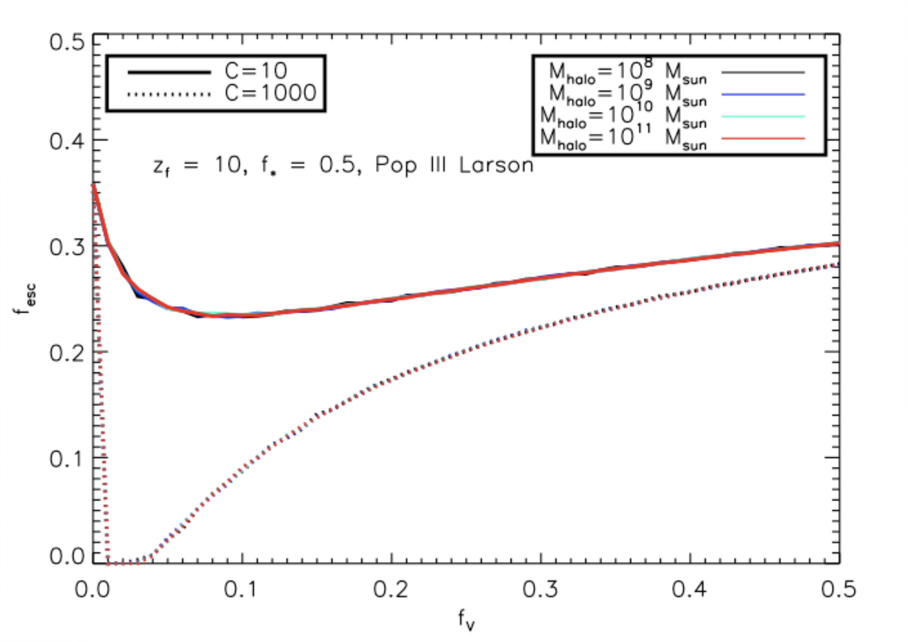
Clumps

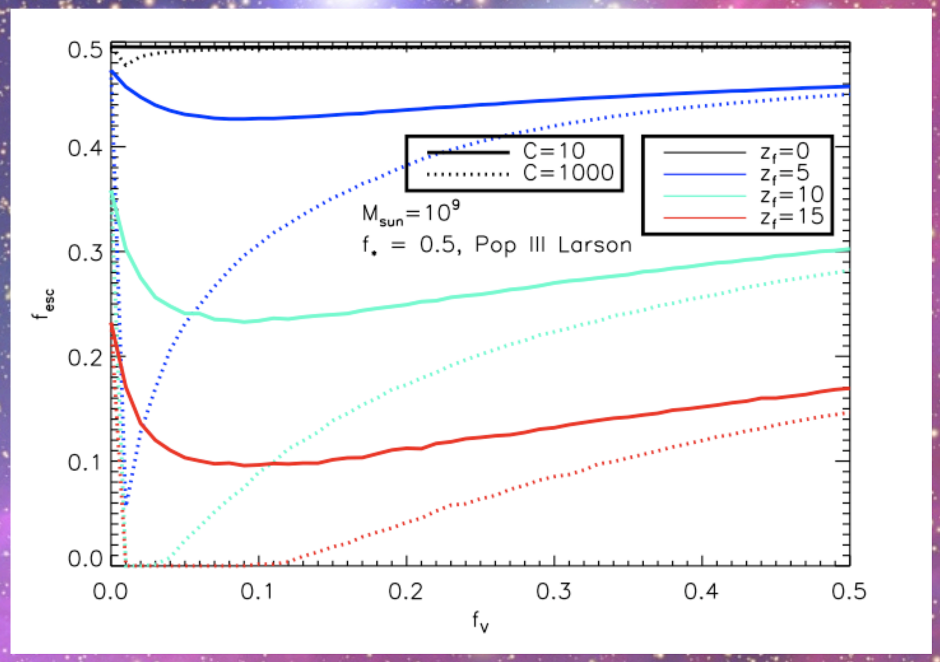
★ For low f_V:
- ★ Rays encounter less than one clump on average
- ★ f_{esc} greater than no-clump case
- ★ increasing C increases f_{esc}

★ For high f_V:
- ★ All rays encounter at least one clump
- ★ f_{esc} less than no-clump case
- ★ increasing C decreases f_{esc}

★ Mass
- ★ Has no affect on f_{esc}
- ★ Assuming f_* constant

★ Redshift
- ★ f_{esc} larger at lower redshifts - halos are less dense
- ★ Stars may be larger with less metals at higher redshift. This will increase ionizing photons produced and hence, f_{esc}.





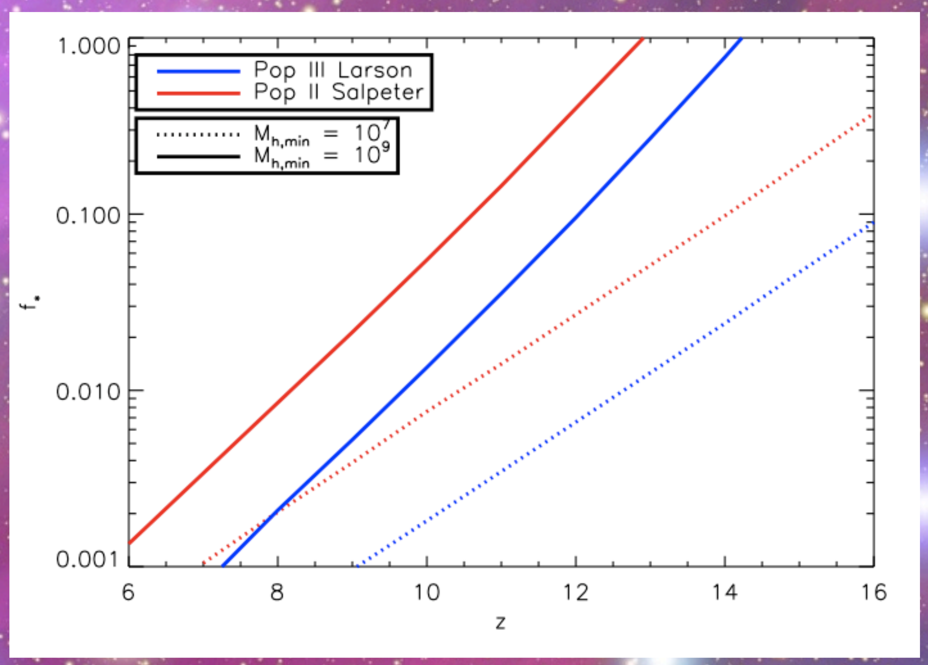
Constraints from Reionization

★ Assuming f_{esc} = 0.5, f_* needed to keep universe reionized is shown.

★ Easier to keep universe reionized using metal free, massive stars.

★ If low mass halos are suppressed, it is much harder to keep the universe reionized.

★ If $f_* > 1$, the universe cannot be kept reionized by these sources.



Conclusions

The escape fraction depends sensitively on the distribution of hydrogen. If there are clump-free paths out of the galaxy, the escape fraction is greater than a no-clump case. If all paths intersect a clump, then the escape fraction is less than the no-clump case. The number of ionizing photons produced also increases f_{esc}, for the angle from which photons can escape is larger. Escape fraction decreases with redshift, assuming the stellar population is the same, and is unchanged by galaxy mass.