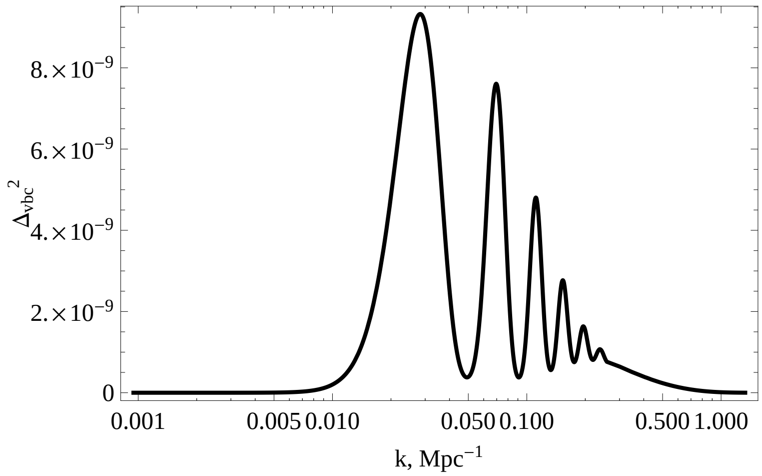

Figure 1 The variance of the velocity difference perturbations (in units of c) between baryons and dark matter per $\ln k$ as a function of comoving wavenumber k at $z = 10^3$. Figure credit: D. Tseliakhovic & C. Hirata, Phys. Rev. **D82**, 3520 (2010).

0.1 PRIMORDIAL STREAMING OF BARYONS RELATIVE TO DARK MATTER

Prior to cosmological recombination, the baryons and the cosmic background radiation were tightly coupled and behaved as a single fluid, separate from the dark matter. The primordial density fluctuations produced acoustic waves in the radiation-baryon fluid. When the gas decoupled from the radiation at $z \approx 10^3$, it was streaming relative to the dark matter with a root-mean-square (*rms*) speed of $v_{\rm bc} \approx 10^{-4}c = 30\ {\rm km\ s^{-1}}$. Figure 1 shows the variance of the velocity difference perturbations (in units of c) per $\ln k$ as a function of the mode wavenumber k at $z = 10^3$. The power extends to scales as large as the sound horizon at recombination, ~ 140 comoving Mpc, but declines rapidly at $k > 0.5\ {\rm Mpc^{-1}}$, indicating that the velocity of the baryons relative to the dark matter was coherent over the photon diffusion (Silk damping) scale of several comoving Mpc. This scale is larger by two orders of magnitude than the size of the regions out of which the first galaxies were assembled at later times. Therefore, in the rest-frame of those galaxies, the background intergalactic baryons appeared to be moving coherently as a wind. It is therefore interesting to examine whether this wind had a significant effect on the assembly of baryons onto the earliest galaxies.

Following recombination, the neutral gas was freed to fall into the gravitational potential wells of the dark matter and so its velocity difference from the dark matter declined as $\mathbf{v}_{\rm bc} \propto (1+z)$. This implies that by $z \sim 50$, the typical streaming velocity $\sim (50/10^3) \times 30 = 1.5\ {\rm km\ s^{-1}}$ corresponded to an equivalent gas temperature

$T_{\rm bc} \sim m_p v_{\rm bc}^2/k_B = 270\ {\rm K}[(1+z)/50]^2$, comparable to the virial temperature of the first gas clouds that cooled through molecular hydrogen (H_2) transitions. Therefore, in the frame of the dark matter the baryonic wind have increased by a factor of order unity the minimum halo mass in which the very first generation of stars could have formed. The effect was more dramatic for the filtering mass (the time-averaged Jeans mass, without the cooling constraint), which increased at $z \sim 20$–100 from $\sim 2 \times 10^4 M_\odot$ without streaming to $\sim 2 \times 10^5 M_\odot$ at the *rms* streaming speed. Figure 2 shows the increase in the minimum halo mass in which gas was able to assemble and cool at various redshifts, as a function of the initial streaming velocity, $v_{\rm stream} \equiv v_{\rm bc}(z = 100)$. The *rms* value of $v_{\rm stream} = 3\ {\rm km\ s^{-1}}$ at $z = 100$ is marked by the horizontal line. As expected, the infall of gas into halos more massive than $\sim 10^6 M_\odot$ for which the virial temperature $T_{\rm vir} \gg T_{\rm bc}$, was not affected significantly by the baryonic wind.

In linear perturbation theory (§**??**), each Fourier mode evolves independently. However, the streaming effect on the growth of structure[1] is manifestly non-linear and results from second-order terms, such as the convective derivative $(\mathbf{v_k} \cdot \mathbf{k})\mathbf{v_k}$ in the equation of motion, which couple small-scale (high-k) modes – as they become nonlinear, to large scale (low-k) modes. Effectively, the relative velocity acts as an increased sound speed (since it needs to be dissipated upon virialization of the gas) and prevents the baryons from settling into the shallowest potential wells. Figure 3 compares the fraction of baryons that collapsed into halos above the H_2 cooling threshold with and without streaming.

Since the streaming velocity varied spatially, the formation of the earliest Population III stars was modulated on large spatial scales of up to ~ 140 cMpc. The effects of baryonic streaming were most pronounced in the lowest mass halos ($< 10^6 M_\odot$) and at the highest redshifts ($z > 20$) – when the global collapse fraction of baryons and the corresponding radiative effects of stars were small.

The baryonic streaming alters the growth of structure, causing a small ($\sim 15\%$) suppression in the matter power spectrum around the Jeans wavenumber $k_J \sim 200 {\rm Mpc}^{-1}$, and a strong scale-dependent bias for the earliest gas clouds on scales of up to ~ 140 cMpc. As long as H_2 was not quickly dissociated by the UV background produced by the first stars, the streaming effects might have left observable signatures on the 21-cm signal at redshifts $z > 20$. However, at the reionization redshifts during which the global star formation rate was dominated by halos with a virial temperature above the cooling threshold of atomic hydrogen $T_{\rm vir} > 10^4$ K and a corresponding mass $> 10^8 M_\odot[(1+z)/10]^{-3/2}$ (equation **??**), the radiative signatures of the primordial baryonic streaming were likely negligible.

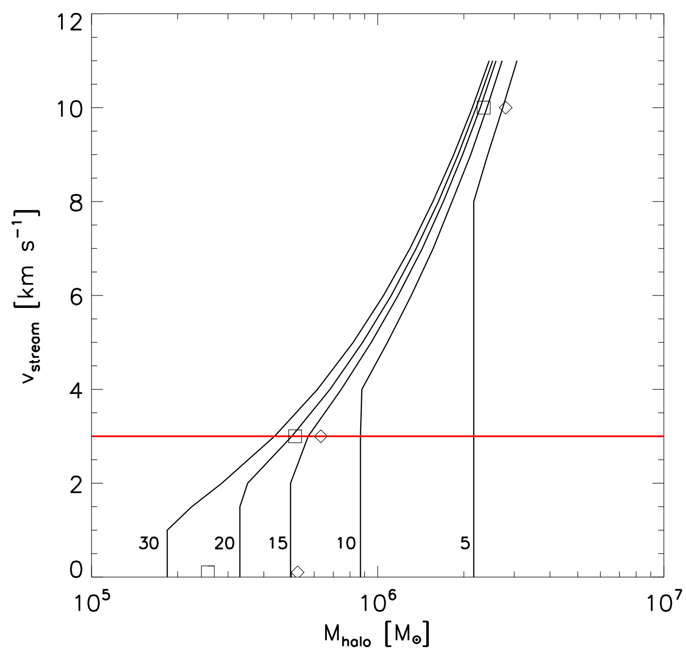

Figure 2 Effect of initial streaming speed $v_{\rm stream}$ at $z = 100$ on the minimum halo mass into which gas can assemble later and form stars (with the horizontal bar at $3\ {\rm km\,s^{-1}}$ marking the expected *rms* value). Each line represents the necessary halo mass for baryon collapse at the labeled redshift. Diamonds represent the final halo masses found in standard collapse simulations ($z = 14$ with no streaming), squares represent masses from accelerated collapse simulations ($z = 24$ with no streaming), and the lines delineate the prediction of a simple analytic model. The halo masses do not increase significantly at low streaming velocities. Halos collapsing at high redshift are more affected by relative streaming, as the physical streaming velocities are higher at these early times. Figure credit: A. Stacy, V. Bromm, & A. Loeb, MNRAS, in press (2010); arXiv:1011.4512.

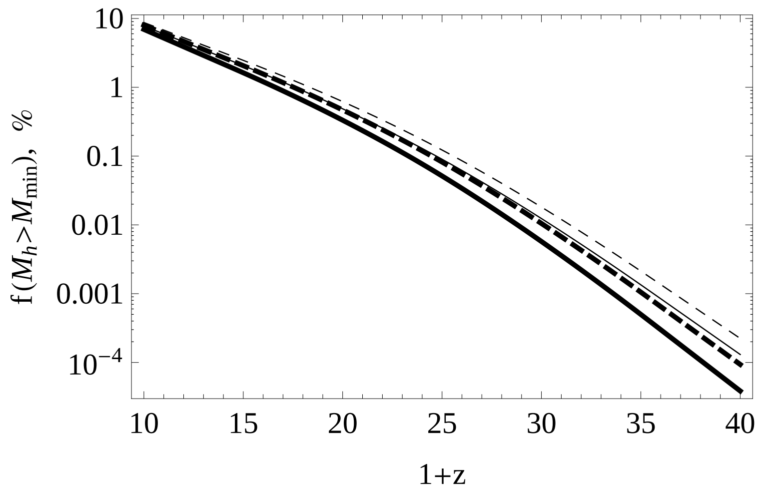

Figure 3 The total mass fraction (in percent) in halos above the filtering mass (dashed lines) and above the H_2 cooling mass (solid lines). Thin lines ignore baryon streaming and thick lines include it. Figure credit: D. Tseliakhovic, R. Barkana, & C. Hirata, MNRAS, submitted (2010); arXiv:1012.2574.