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Population III Supernovae and Prompt Star Formation in Cosmological Minihalos

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Numerical simulations suggest that as single primordial stars consecutively formed in small dark matter halos at high redshift, gravitational mergers congregated the halos into the first primitive galaxies. In this picture, protogalaxies were assembled a few stars at a time and were only gradually contaminated by the first heavy elements because primordial supernovae preferentially expelled them into low density voids, away from the sites of mergers. However, the large computational boxes required to form the halos from cosmological initial conditions in these models prevent them from resolving the true fate of the supernova remnants. We present one-dimensional calculations of Population III supernovae in both neutral halos and primordial H II regions that resolve the flows over all relevant spatial scales. Our models indicate that the cycle of stellar birth, H II region formation, and second star formation within a halo may have been punctuated by prompt star formation in the supernova remnant. If so, low-mass stars may have been swept up into the first galaxies at earlier times and in much greater numbers than are now supposed. The chemical signatures and luminosity functions of such galaxies would be very different from those in the current paradigm, and observations by *JWST* and *ALMA* may soon discriminate between these two formation pathways. We also find that differential mixing of metals in primordial explosions may account for the skewed C and O to Fe ratios observed in extremely metal poor (EMP) and ultra metal poor (UMP) stars in the galactic halo, which may be remnants of the first few generations of stars in the universe.

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1. Introduction

Numerical models suggest that the first stars in the universe formed in small dark matter halos $\gtrsim 10^6\ M_\odot$ at $z \sim 20$ - 30 [1, 2, 3]. These stars formed in isolation, one per halo, and had masses of 100 - 500 $M_\odot$ and surface temperatures and ionizing photon emissivites in excess of 10^5 K and 10^{50} s^{-1}, respectively. They profoundly transformed the halos that gave birth to them, creating H II regions 2 - 5 kpc in radius and sweeping half of the baryons in the halos into dense shells 100 - 200 pc in radius by the end of the life of the star [4, 5]. One-dimensional non-rotating stellar evolution models predict a variety of fates for these stars depending on their zero-age main sequence (ZAMS) masses [6]. Stars from 10 - 30 $M_\odot$ die in Type II supernova (SN) explosions while 140 - 260 $M_\odot$ stars explode in much more energetic pair-instability supernovae (PISN) that completely disperse the star, leaving no compact remnant. Stars from 30 - 50 $M_\odot$ may instead explode as hypernovae, with energies intermediate to those of Type II SN and PISN [7].

Calculations of Population III SN in lone cosmological minihalos and in large scale structure formation calculations have been performed but are approximate [8, 9]. Usually, the progenitor is assumed to completely photoevaporate the halo and the explosions are initialized either with thermal energy or Sedov-Taylor blast profiles rather than the free expansion that actually erupts through the envelope of the star. The simulations find that supernovae in H II regions completely unbind the baryons from the halo. Some of the gas can later return to the halo by accretion inflows and mergers, but only on timescales of 50 - 100 Myr. In contrast, if the supernova occurs in a neutral halo, Kitayama & Yoshida find that it 'fizzles' because the ejecta encounters large circumstellar densities that radiate away the energy of the blast as bremsstrahlung x-rays before gas can be driven outward.

O'Shea et al. and Yoshida et al. have discovered that a halo can host consecutive episodes of single star formation if the stars do not explode [11, 12]. When the progenitor dies its H II region cools more quickly than it recombines, reaching relatively low temperatures at substantial ionized fractions that are ideal conditions for the rapid formation of H_2 and HD through the H^- channel. HD can cool the relic H II region down to the cosmic microwave background (CMB), reducing the characteristic mass scales on which it fragments. As accretion and mergers return the gas to the halo it can collapse into a single, smaller star on timescales of 50 - 100 Myr. The cycle continues as the new star ionizes the halo, leading to later generations of stars that are smaller than the first.

As single stars formed in succession within a halo, gravitational mergers assembled them into the first small galaxies as illustrated in Figure 1. Numerical attempts to model this process find that metals expelled by supernovae are taken up relatively slowly into protogalaxies because they are blown out into low-density voids where star formation does not occur [10, Wise & Abel(2008)]. Since they return to the halos on timescales of 100 Myr and are diluted by their expulsion into the IGM, these heavy elements are incorporated into later generations of stars relatively slowly. In this scenario, new stars form gradually, are contaminated by metals slowly, and populate the first galaxies in small numbers.

Unfortunately, these models exclude two key effects that could completely alter their outcomes. First, their large computational boxes, which are necessary to form dark matter halos from cosmological initial conditions, prevent them from properly resolving the early evolution of SN remnants. Second, they neglect fine structure cooling due to metals which can destabilize the

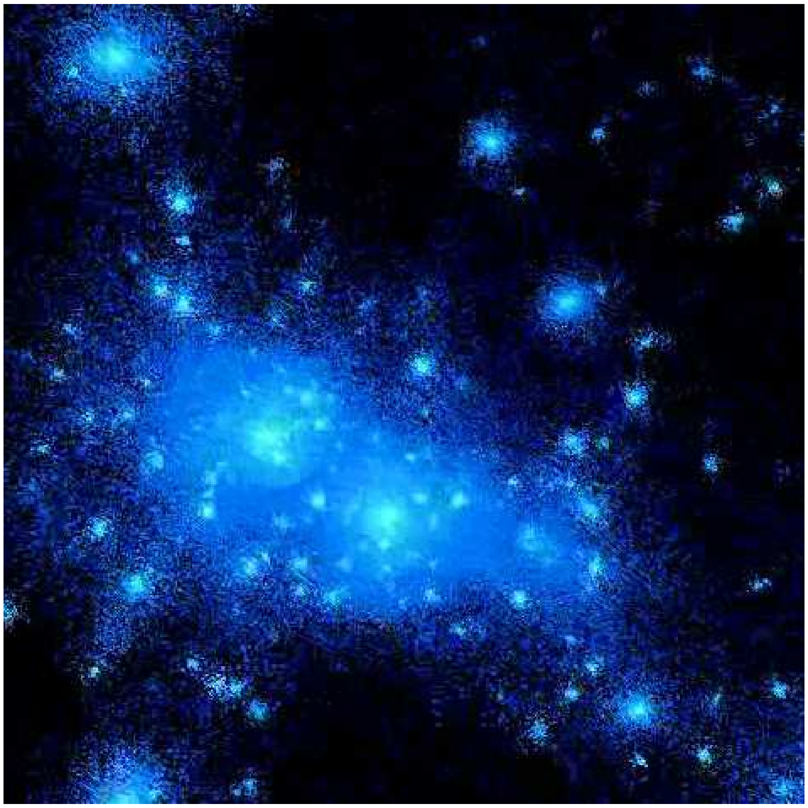

Figure 1: The morphology of dark matter halo mergers. Image courtesy of Andrey Kravtsov and the ART code, KICP, University of Chicago.

shock and fracture it into dense clumps that could later become gravitationally unstable to collapse into new stars. These stars would be less massive than those that preceded them because metals, like HD, also efficiently cool the gas and lower its mass scales of breakup. Furthermore, they would be more heavily enriched by metals than those in present models due to the direct deposition of SN ejecta onto clumps. If prompt generations of stars formed in primordial supernova remnants, low-mass stars would have been swept up into the first galaxies in far greater numbers and at earlier times than currently thought. These galaxies would have very different chemical signatures and luminosity functions than in current models, raising the possibility that upcoming measurements by *JWST* and *ALMA* may distinguish between the two formation paradigms. Furthermore, if metals are not well mixed in the initial free expansion, heavier elements at the center of the blast will have lower velocities and may never reach the dynamical instabilities at larger radii that later lead to direct star formation. This might explain the low ratios of Fe to C and O found in EMP and UMP stars now being surveyed in the galactic halo, which may be remnants of the first chemically enriched stars in the universe [14].

To capture the evolution of primordial supernova remnants over all relevant spatial scales, we have performed one-dimensional calculations of explosions in dark matter minihalos that have been preprocessed by the ionizing UV radiation of the progenitor star [13]. We follow the blast from its earliest stage as a free expansion deep within the halo out to radii of 1 - 2 kpc. Our models do

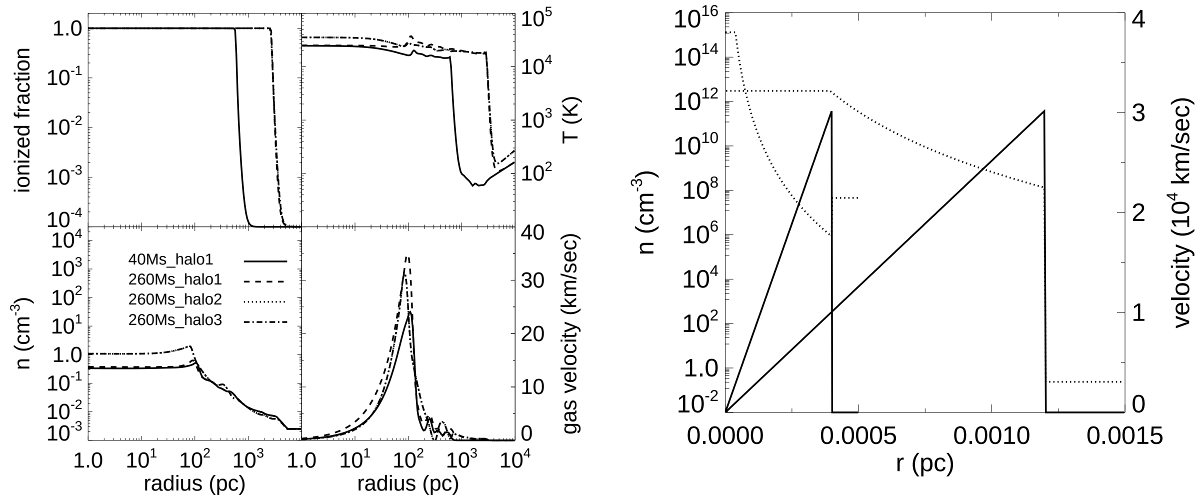

Figure 2: Left panel: H II region profiles of stars that fully ionize their halos. Right panel: Truelove & McKee free-expansion density and velocity (triangular) profiles.

not include the transport of metals or fine-structure cooling but they do solve non-equilibrium H and He gas chemistry together with hydrodynamics to monitor where gas swept up by the ejecta is collisionally excited and strongly radiating. Since it is this luminosity that governs the advance of the flow, our calculations reproduce the basic energetics of the remnants. Our aim is to determine the final fates of the halos and to identify stages in the flow at which hydrodynamical instabilities are likely to incite metal mixing and breakup in three dimensions.

2. Code Algorithm/Models

We examined the supernovae of 15, 40, and 260 $M_\odot$ stars (Type II SN, hypernovae, and PISN) in dark matter halos of 5.9 $\times$ 10^5, 2.1 $\times$ 10^6, and 1.2 $\times$ 10^7 $M_\odot$, which sample the mass range in which stars are expected to form by H_2 cooling. Each model was implemented in two stages: first, spherically-averaged halo baryon profiles computed from cosmological initial conditions in the Enzo AMR code were imported into the ZEUS-MP code [15] and photoionized by the star, which is located at the center of the halo. We then initialized the blast in the H II region of the star using the Truelove & McKee free expansion solutions [16]. The initial radius of the free expansion was less than 0.0012 pc to guarantee that the profile enclosed less ambient gas than ejecta mass. The explosion was then evolved with primordial gas chemistry and hydrodynamics to follow the energy losses from the remnant due to line, bremsstrahlung, and inverse Compton scattering in gas swept up by the ejecta. We employed expanding Eulerian grids in ZEUS-MP to model the flow, recomputing the grid each time the profile approaches the outer boundary. This crucial feature ensures that the explosion is always resolved by the same number of mesh points regardless of the scale of the flow, allowing us to bypass much more expensive adaptive mesh refinement (AMR)

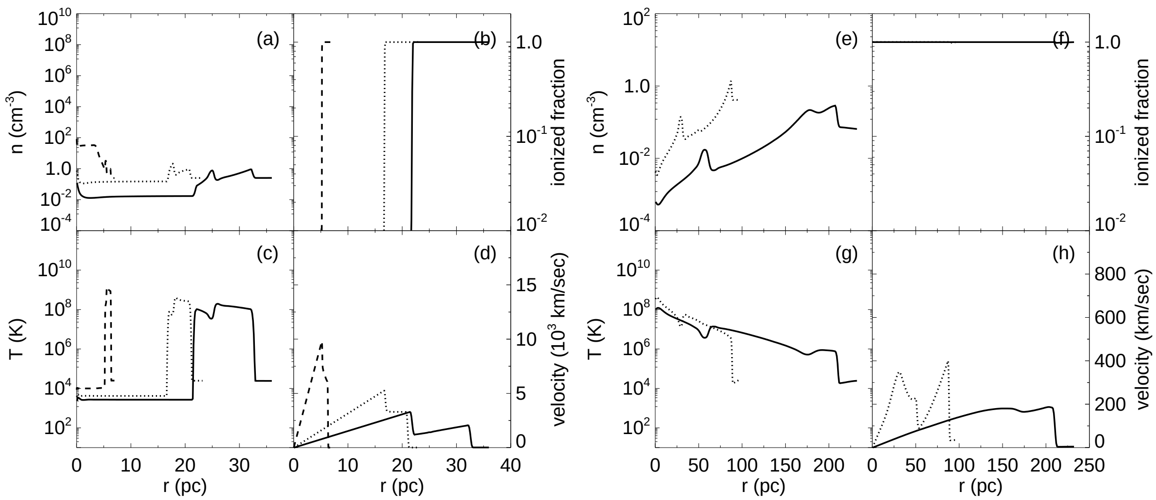

Figure 3: Panels a - d: formation of a reverse shock in a 260 $M_\odot$ PISN. Dashed: 31.7 yr; dotted: 587 yr; solid: 2380 yr. Panels e - h: collision of the remnant with the H II region shell. Dotted: 19.8 kyr; solid: 420 kyr.

methods and use spherical polar coordinates that are less prone to introducing artifacts in the blast front. We show the H II region and initial blast profiles in Figure 2. The 260 $M_\odot$ star fully ionizes the first two halos and partially ionizes the most massive; the 15 and 40 $M_\odot$ stars fail to ionize the third halo, but either fully or partially ionize the two less massive halos. We find that the explosions evolve along two distinct pathways according to whether they occur in H II regions or in neutral halos.

3. Explosions in H II Regions

We show profiles of density, temperature, ionization fraction, and velocity for a 260 $M_\odot$ PISN in the 5.9 $\times$ 10^5 halo at 31.7, 587, and 2380 yr, respectively, in Figure 3 a-d. At 31.7 yr a homologous free expansion is still apparent in the density profile, which retains a flat central core and power-law dropoff. By 2380 yr the remnant has swept up more than its own mass in ambient material, forming a reverse shock that is separated from the forward shock by a contact discontinuity. In three dimensions it is at this stage that the contact discontinuity will break down into Rayleigh-Taylor instabilities, mixing the surrounding pristine gas with metals at radii of less than 15 pc. Mixing will therefore occur well before the remnant collides with the shell, which we show in Figure 2 e-h at 19.8 and 420 kyr. The 400 km s^{-1} shock overtakes the 25 km s^{-1} H II region shell at r = 85 pc at 61.1 kyr. Its impact is so powerful that a second reverse shock forms and separates from the forward shock at 420 kyr. Both are visible in the density and velocity profiles of Figure 3 at 175 and 210 pc. The interaction of the remnant with the shell in reality is more gradual: the remnant encounters the tail of the shell at 60 pc at 19.8 kyr, at which time the greatest radiative losses begin, tapering off by 7 Myr with the formation of another reverse shock. More than 80% of

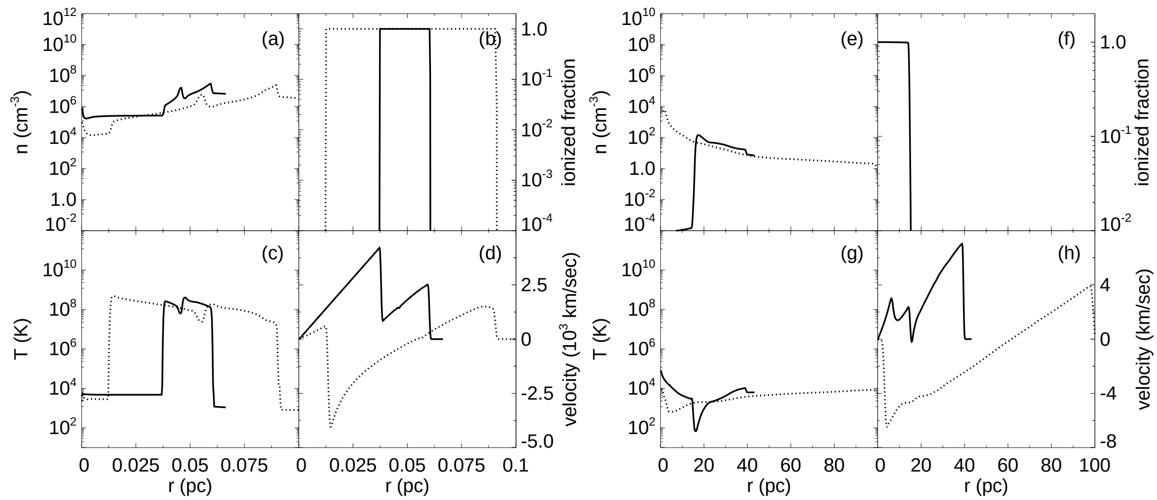

Figure 4: Panels a - d: early flow profiles of a 40 $M_\odot$ hypernova in a neutral halo. Solid: 7.45 yr; dotted: 17.4 yr. Panels e - h: collapse of the remnant. Dotted: 2.14 Myr; solid: 6.82 Myr.

the energy of the blast is radiated away upon collision of the remnant with the shell formed in the H II region. Hydrogen Ly-α radiation losses dominate, followed by inverse Compton scattering, collisional excitation of He^+ and bremsstrahlung, but the remnant also collisionally ionizes H and He in the dense shell.

Although dynamical instabilities will already have mixed ejecta with the relic H II region, the impact of the remnant with the shell will lead to a second episode of violent metal mixing. Prior to impact, the shell itself may already have broken up into clumps due to instabilities in the ionization front (I-front). What remains to be investigated is if in three dimensions the clumps become enriched with metals, cool, and condense into gravitationally-untable cores. If so, the mixed shell will break up into low mass stars. Because the shell expands at 20 - 30 km s^{-1}, or $\sim$ 10 times the escape velocity from the halo, the stars would not be gravitationally bound to the halo, but inflows and mergers would still collect them into primitive galaxies.

4. Supernovae in Neutral Halos

In Figure 4 we show hydrodynamical profiles for a 40 $M_\odot$ hypernova remnant in the 1.2 $\times$ 10^7 $M_\odot$ halo, which has not been significantly ionized by the progenitor star. In panels (a) - (d) the formation of the reverse shock between 7.45 and 17.4 yr is evident. This Chevalier phase, in which a reverse shock backsteps from the forward shock with an intervening contact discontinuity, occurs at much earlier times when the halo is neutral because of its large central densities. Heavy element mixing consequently begins at much smaller radii. The remnant expands, halts, and then falls back into the dark matter potential of the halo, as shown in panels (e) - (f) in which profiles are taken at 2.14 and 6.82 Myr. The hot bubble reaches a final radius of $\sim$ 40 pc before recollapsing toward the center of the halo. Several cycles of expansion, cotraction, and bounce can occur, resulting in the multiple episodes of large central accretion rates shown in the left panel of Figure 5. As the remnant expands and falls back, dynamical mixing will enrich several tens of thousands of solar masses of baryons with metals to levels above the threshold for low-mass star formation. The likely result will be a swarm of stars that are gravitationally confined to the the halo.

Three-dimensional cosmological halos exhibit density variations along lines of sight that might permit some blowout of ejecta from the halo or result in less coordinated fallback than that described here. Also, UV radiation might break out of the halo through these channels and enable the escape of metals even though most of the halo remains neutral. However, minihalos are mostly spheroidal so it is reasonable to conclude that most of the radiation of the star will be contained and that the growth of the remnant will still mostly be halted and then reversed. Since recent ensemble calculations extend the lower mass limit of primordial stars down to 15 - 30 $M_{\odot}$ [17], we must consider that some supernovae may have occured in neutral halos. In addition, other studies indicate that primordial star formation was delayed by the rise of Lyman-Werner UV backgrounds in the early universe, in effect forcing halos to grow to larger masses before they could host the formation of a star [18, 19, 20]. Consequently, at somewhat lower redshifts, explosions of lower-mass stars in large halos that they could not ionize may have been common.

Since less massive progenitors that fail to ionize their halos die in Type II SN, they form black holes whose growth might be rapidly fed by repeated bouts of massive fallback. This process will strongly depend on angular momentum transfer out of the accreting gas and radiation hydrodynamical transport of energy away from the black hole and requires further investigation. Nevertheless, fallback in neutral halos may provide a mechanism for the early formation of intermediate mass black holes (IMBH), which are needed at high redshifts to seed the growth of the supermassive black holes residing in most large galaxies today. Furthermore, IMBH in the first galaxies would have strongly influenced their evolution and has never been considered in primeval galaxy formation models.

We note that our explosion models in neutral halos differ from the quenched SN in Kitayama & Yoshida's work because they were initialized as free expansions rather than thermal pulses. Like Kitayama & Yoshida, we find that over 90% of the energy of the blast is promptly lost as x-rays in the high central densities of the halo. However, unlike a thermal 'bomb', the free expansion has momentum that cannot be radiated away, and even though most of the energy is immediately lost, enough remains for the blast to seriously disrupt the interior of the halo and disseminate heavy elements.

5. Conclusions and Future Work

In the right panel of Figure 5 we show the final outcome of each explosion model. In summary, any progenitor star greater than 15 $M_{\odot}$ will destroy (completely unbind the gas from) any halo below 10^7 $M_{\odot}$ because it first ionizes the halo. Only partial ionization is necessary to ensure that the supernova expels all the baryons from the halo, as in the case of the 260 $M_{\odot}$ star in the 1.2 $\times$ $10^7 M_{\odot}$ halo. Stars below 50 $M_{\odot}$ cannot destroy halos greater than $10^7 M_{\odot}$ but do mix a large fraction of their gas with heavy elements, with probable star formation on timescales of less than 10 Myr that are much shorter than those in current protogalaxy formation calculations.

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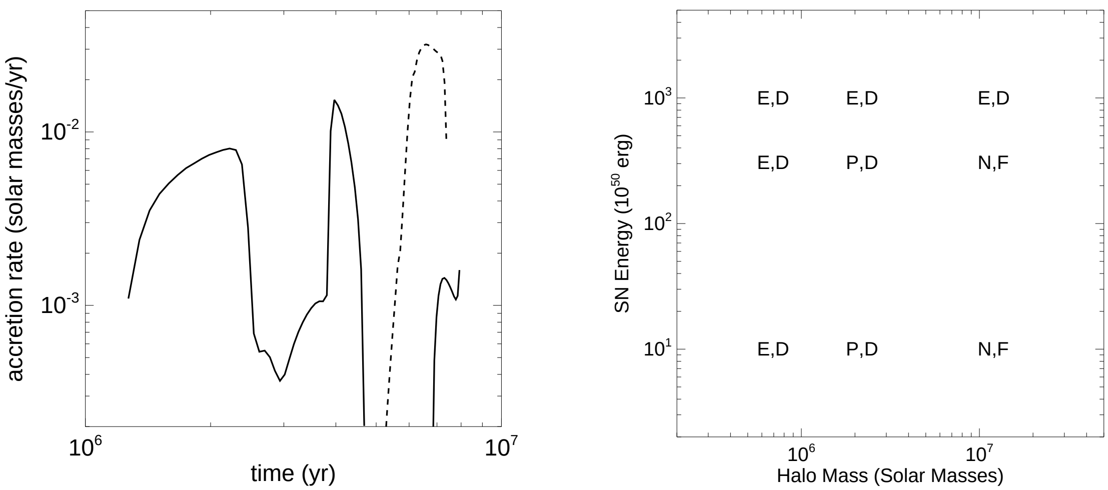

Figure 5: Left panel: Infall rates associated with fallback of the 15 (solid) and 40 (dashed) $M_\odot$ remnants in the most massive of the three halos. Right panel: eventual fate of a halo given the indicated explosion energy. The first letter refers to the final state of the halo prior to the explosion; E: photoevaporated; P: partly ionized, defined as the I-front not reaching the virial radius; N: neutral, or a failed H II region. The second letter indicates outcome of the explosion; D: destroyed, or F: fallback.

Dynamical instabilities and metal mixing in the first supernova remnants, although relatively small scale phenomena, could completely alter the course of early structure formation on much larger scales by triggering prompt star formation in minihalos. Three-dimensional multiscale explosion models that include the transport of metals and fine structure cooling are needed to discover if populations of stars formed in the remnants of Population III SN. The calculations must be implemented in realistic profiles of the H II region of the progenitor to ensure that the explosion occurs in its true circumstellar evironment. The H II region models mandate multifrequency UV transport fully coupled to primordial chemistry and hydrodynamics in three dimensional halo baryon profiles that are computed from cosmological initial conditions. Multifrequency photon transport is key to capturing the formation of H_2 in the outer layers of the I-front that can lead to its complete destabilization and breakup into clumps, as shown in Figure 6 [21]. Such models are now being constructed, and will determine if primordial stars exploded in clumpy environments.

In addition to recovering the true morphologies, chemical signatures, and luminosity functions of the first galaxies, the next generation of 3D primordial explosion calculations might account for the unusual elemental abundance patterns observed in EMP and UMP stars in the galactic halo. These dim stars, suspected to be long-lived remnants from the first stellar populations, exhibit large C and O ratios to Fe in their atmospheres. If layers of elements within the star do not efficiently mix as the shock breaks through its outer envelope, heavier metals like Fe near the core will have much lower velocities than lighter elements like C and O at higher altitudes, as can be seen in the velocity profile of the free expansion. Consequently, very little iron may ever reach the outer regions of the

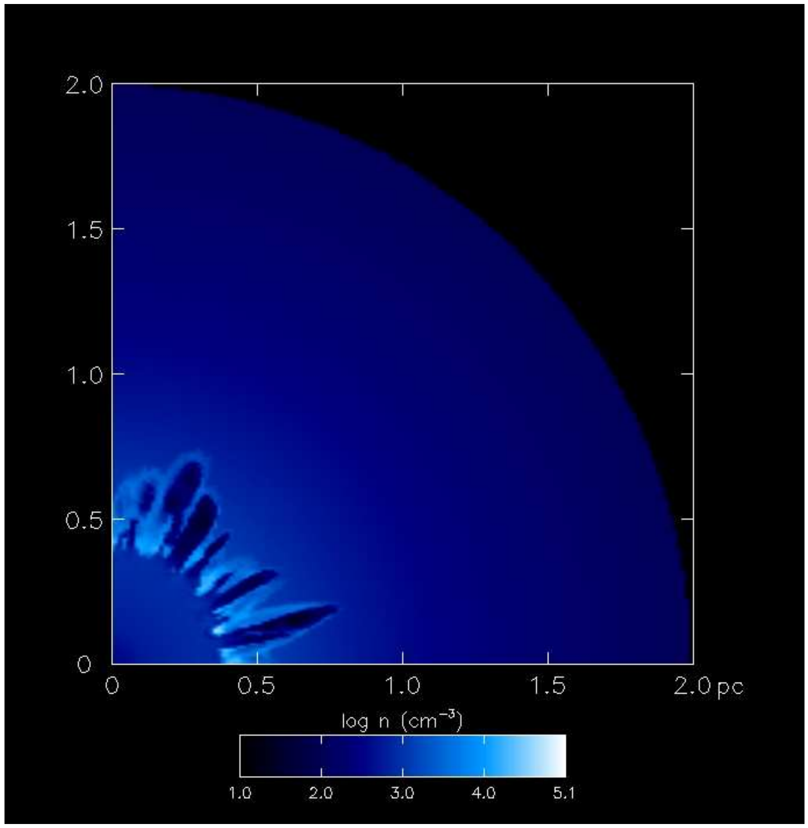

Figure 6: Dynamical instability caused by H_2 formation in a D-type primordial ionization front in an idealized density profile similar to that of a cosmological minihalo.

remnant where instabilities and clumps develop, or be taken up into stars that result. Calculations of early mixing during shock breakout from the star are now underway to constrain the distribution of elements within the initial free expansion in future primordial supernova simulations.

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