Simulating Supernovae in the Early Universe

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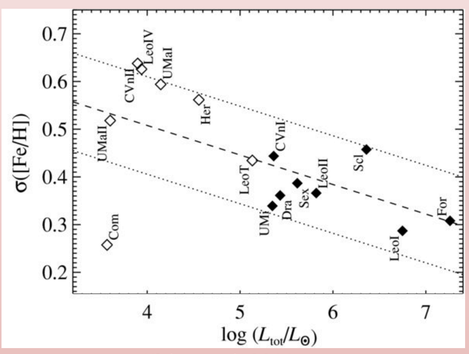
Metal-poor stars show scatter in abundances.

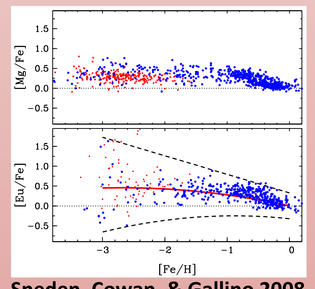
The spectra of the most metal-poor stars in the galactic halo and nearby ultra-faint dwarf satellites (UFDs) exhibit increasing scatter in elemental abundances with decreasing metallicity below [Fe/H] < −1. **Could the most metal-poor stars have been enriched by only one (or a few) Population III stars, thereby preserving the fossil record of the first stars? Assuming the individual yields of supernovae are determined by the stellar parameters (e.g. stellar masses) of the progenitors, what mechanism could produce such a large scatter in the observed abundances of these stars that have only been enriched by a few discrete sources?**



Kirby et al. 2011

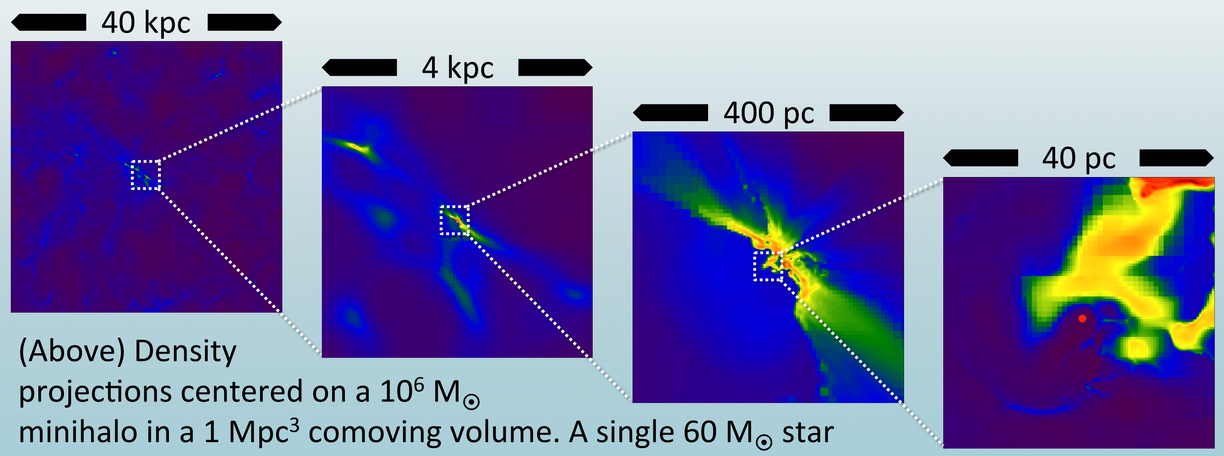
(Left) Spread in stellar metallicities observed in the stellar populations of nearby UFDs. The scatter increases as total galaxy stellar mass and average metallicity decrease. Successive episodes of enrichment raise the average metallicity.

(Right) Abundances of magnesium (α-element) and europium (R-process) in the galactic halo. The turnover in abundance and sudden decrease in scatter above [Fe/H] > −1 represents increased enrichment by sources other than core collapse supernovae (e.g. Type Ia, AGB stars, etc.). The abundance scatter is averaged out after many episodes of enrichment.



Sneden, Cowan, & Gallino 2008

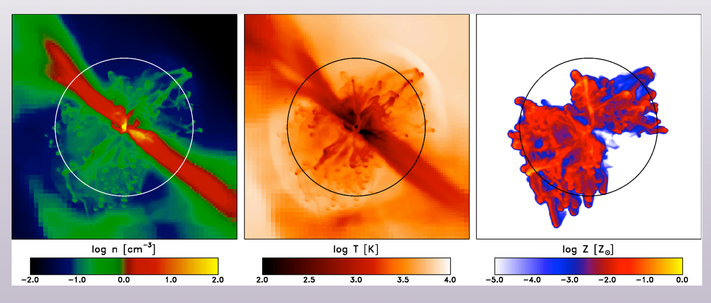
Setting up the cosmological context.



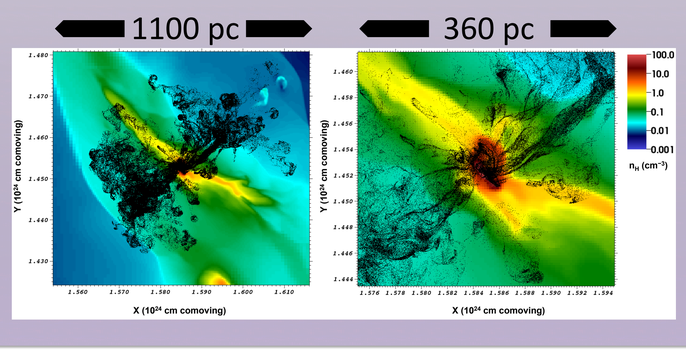
(Above) Density projections centered on a 10^6 $M_\odot$ minihalo in a 1 Mpc^3 comoving volume. A single 60 $M_\odot$ star has partially ionized the surrounding gas, leaving behind a few dense neutral clouds.

(Far Right) We zoom in to high resolution (Δx ≈ 0.05 pc) and insert a supernova blastwave with 10^{51} ergs of kinetic energy. The ejecta is tracked using 10^7 particles, enabling us to map ejecta from collapsing clouds back to their progenitor supernova.

Capturing inflows and outflows in 3D.

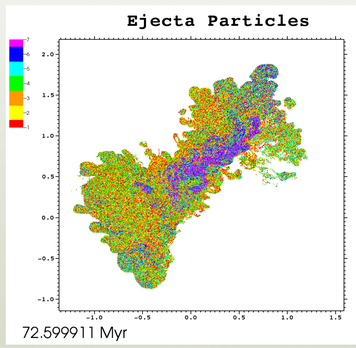


(Left to right) Density, temperature and metallicity projections 8.5 Myr after a single supernova. The blastwave has been completely fragmented. Some ejecta escapes the virial radius (180 pc) while the filaments of the cosmic web resume flowing back into the central gas cloud.



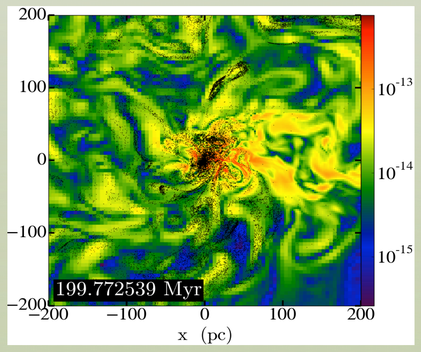
Density slices with ejecta tracer particles 40 Myr after the explosion. Ejecta-rich fragments are falling back in streams that intersect with the inflowing pristine hydrogen from the cosmic web filaments.

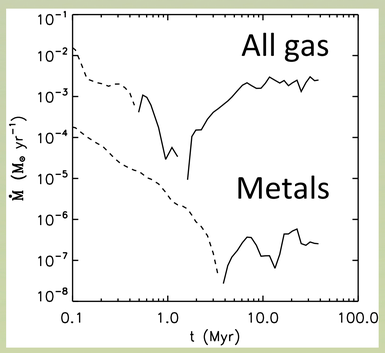
Ejecta and fallback are inhomogeneous.



Cross-section of the ejecta particles through the middle of a super-bubble, 72 Myr after the sequential explosions of 7 supernovae. The ejecta tracer particles are colored according to their progenitor supernova. Large inhomogeneities remain between the ejecta from different supernovae.

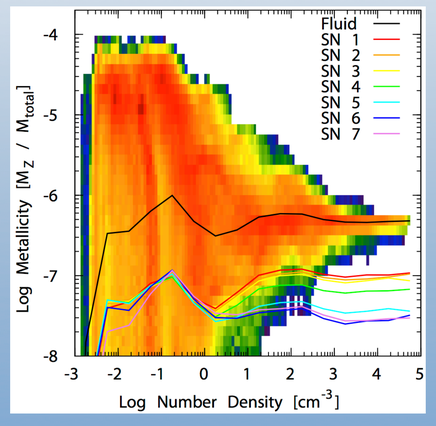
Slice through the recollapsing remnant showing the vorticity magnitude, 200 Myr after the 7 supernovae. A larger vorticity implies a shorter mixing timescale if a turbulent cascade is present. The inhomogeneous metal-rich fluid is traced by the black particles. The ejecta fragments remain mostly unmixed with one another down to the resolution limit of our simulations, however the vorticity rises as the gas falls onto the dense central cloud and there we do expect efficient mixing.





Average rate of gas inflow (solid) and outflow (dashed) through the central 10 pc of a minihalo following a single supernova. Inflow from the cosmic web resumes relatively quickly after 1 Myr while the accretion of metal fragments is bursty and takes a longer time.

Enrichment is biased!



Density-metallicity phase diagram of the gas in a recollapsing dark matter halo 200 Myr after the explosion of 7 supernovae. The cell color reflects the total gas mass at given density and metallicity. The solid lines show the average metallicity contribution from each supernova (color) and total (black). Fragments from the first few supernovae contribute more to the collapsing gas than the ejecta from the final few supernovae that were raised to the highest entropies.

These simulations show that hydrodynamically induced biases must be accounted for when attempting to reverse engineer the properties of the first stars and their supernovae from the stellar archaeology of metal-poor populations. <u>Measured abundances in the spectra of metal-poor stars do not necessarily reflect the cumulative yields of contributing supernovae.</u>

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