SUPERNOVAE AND CHEMICAL ENRICHMENT IN THE FIRST GALAXIES

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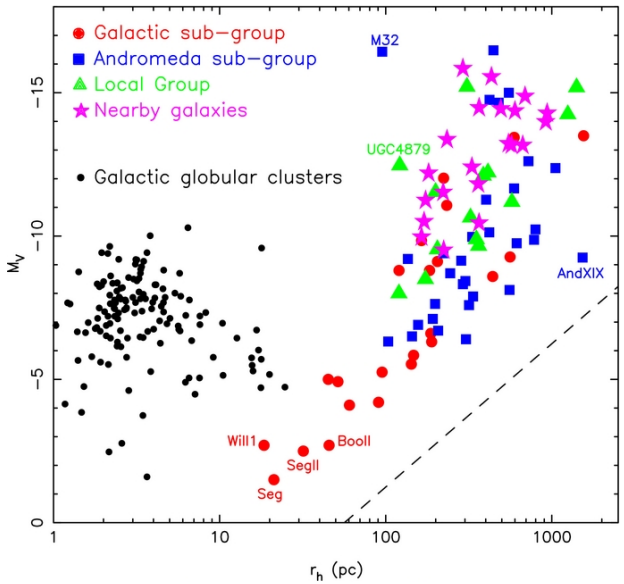
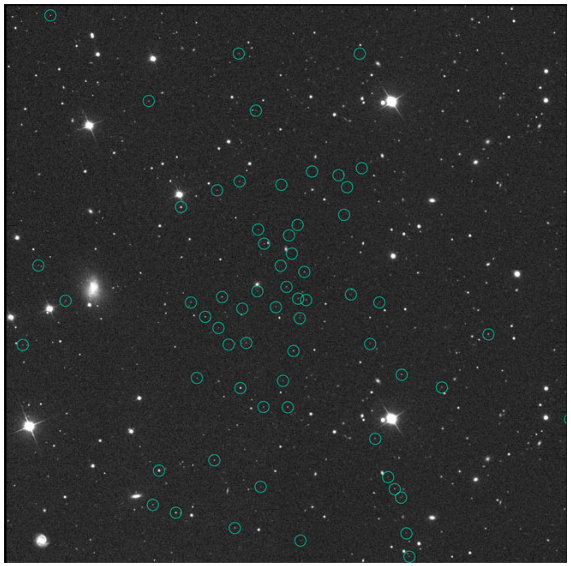
The First Galaxies

- Ancient stellar systems containing dark matter
- Primitive chemical evolution history: contributing nucleosynthetic sources not fully homogenized
- Not directly observable before James Webb Space Telescope
- Potential surviving relics in the local universe: Milky Way's satellites ("near-field cosmology")

Ultra Faint Dwarfs (UFDs)



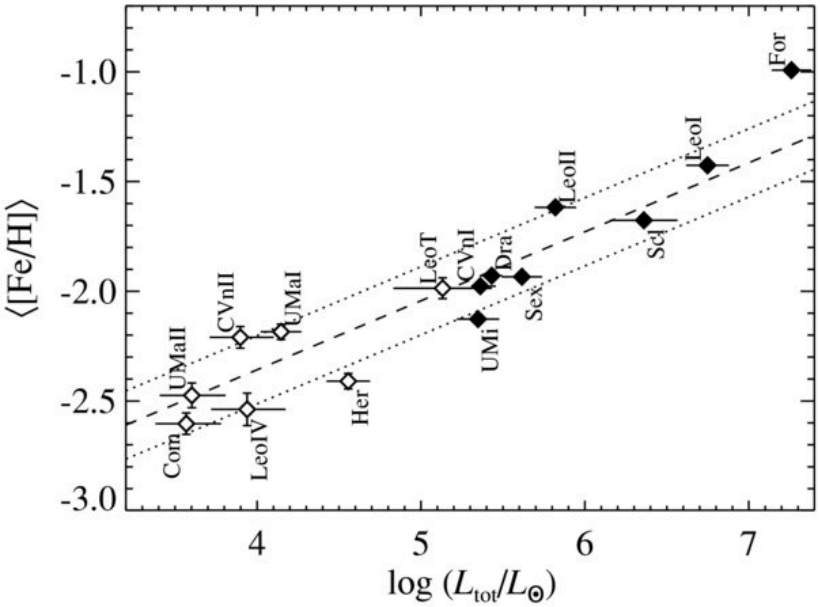
Alan W. McConnachie 2012, AJ 144, 4

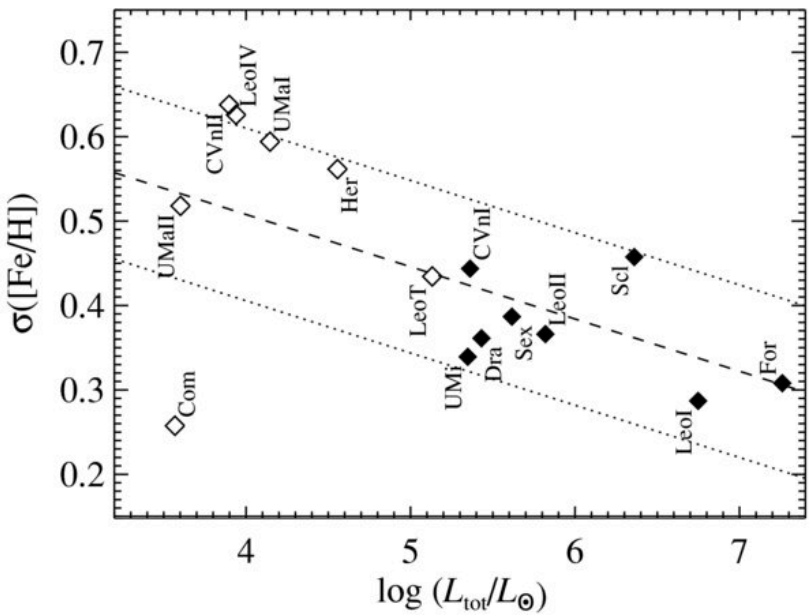


Segue 1: M. Geha (DEIMOS)

- Could they be examples of the first galaxies?
  - The lowest luminosity dark matter dominated stellar systems known
- Why are the mass to light ratios so large?
  - Dark matter-stellar mass ratio
    $M_{dm} / M_{stars} \sim 1000$
  - Compare to the cosmological ratio
    $\Omega_{dm}/\Omega_b \sim 5$
- How did they lose their baryons?
  - Ram pressure stripping?
  - HII regions and supernova explosions can unbind gas from dark matter minihalos

UFD Metallicity Trends

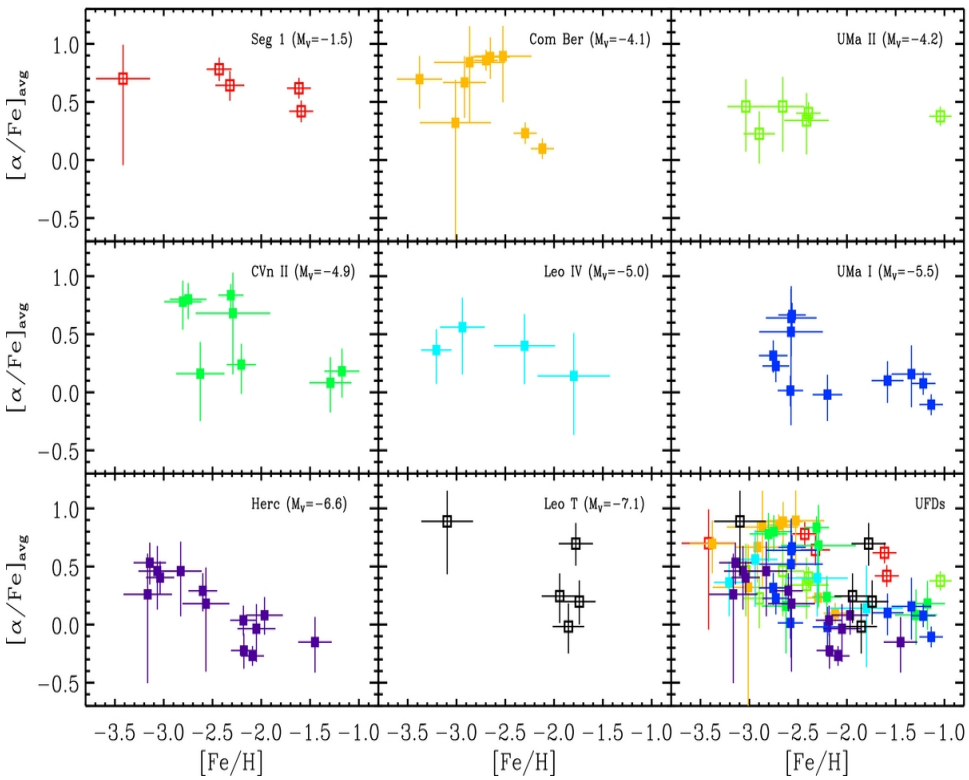




Evan N. Kirby et al. 2011, ApJ 727, 78

- Low average metallicities
  $$-2.5 < \langle[\mathrm{Fe/H}]\rangle < -1.0$$
- Significant metallicity spread
  $$0.25 < \sigma_{[\mathrm{Fe/H}]} < 0.65$$
  - Chemically distinct progenitors?
  - Inhomogeneous local enrichment?
- Metallicity increases with luminosity
  - Does metallicity remain an accurate cosmic clock at these low metallicities?
  - What are the astrophysical conditions for a specific abundance variation to survive or to be wiped out?

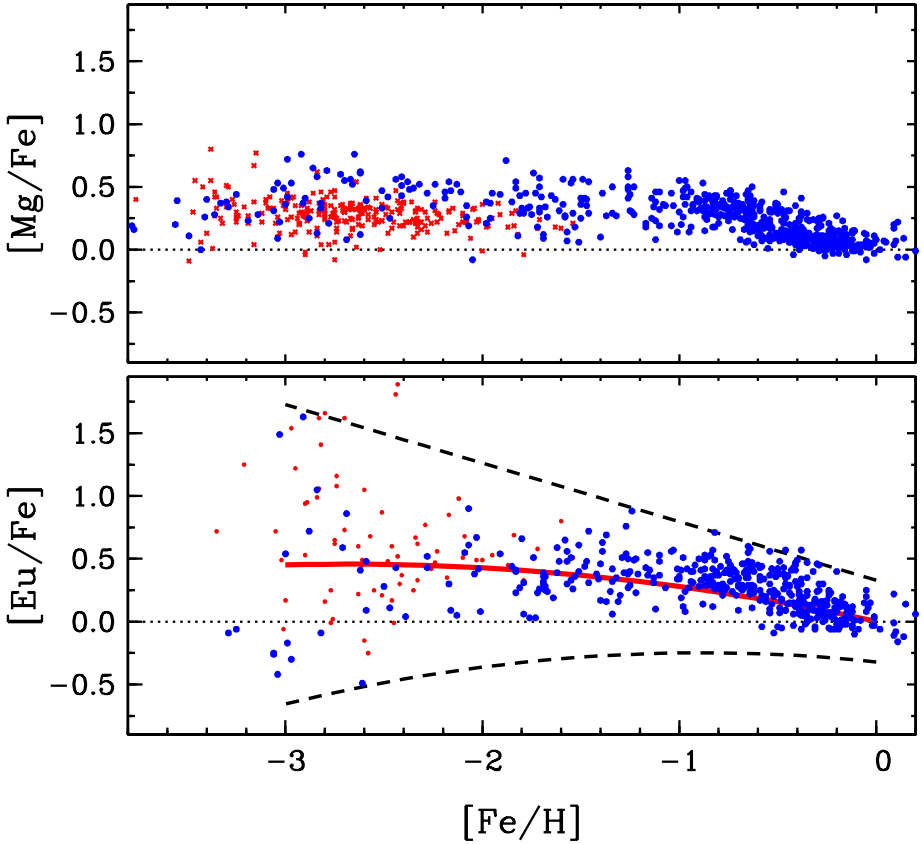
UFD Chemical Evolution Histories



Luis C. Vargas et al. 2013, ApJ 767, 134

- Enhanced α-element abundances [α/Fe] > 0
- α-enhancement declines above a critical [Fe/H]
  - Signature of SN Ia enrichment even at very low metallicities
- Segue 1
  - Extremely low luminosity and metallicity
  - Pure core collapse chemisty: no pair-instability SN (odd-even) or SN Ia signatures; no AGB (s-process) signatures

Cosmic Homogenization

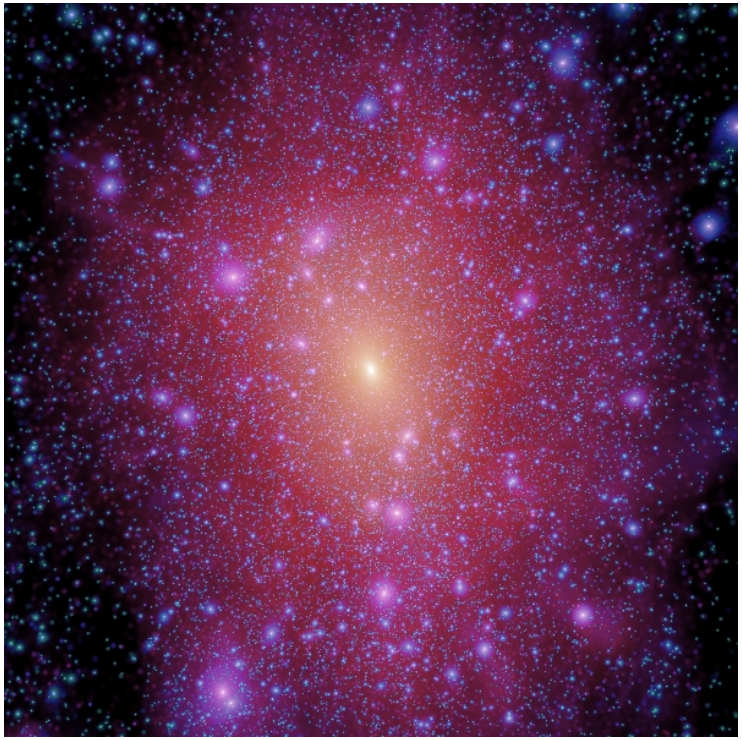


Sneden, Cowan, & Gallino 2008, ARA&A 46, 241

All core collapse supernovae produce α-elements, but…

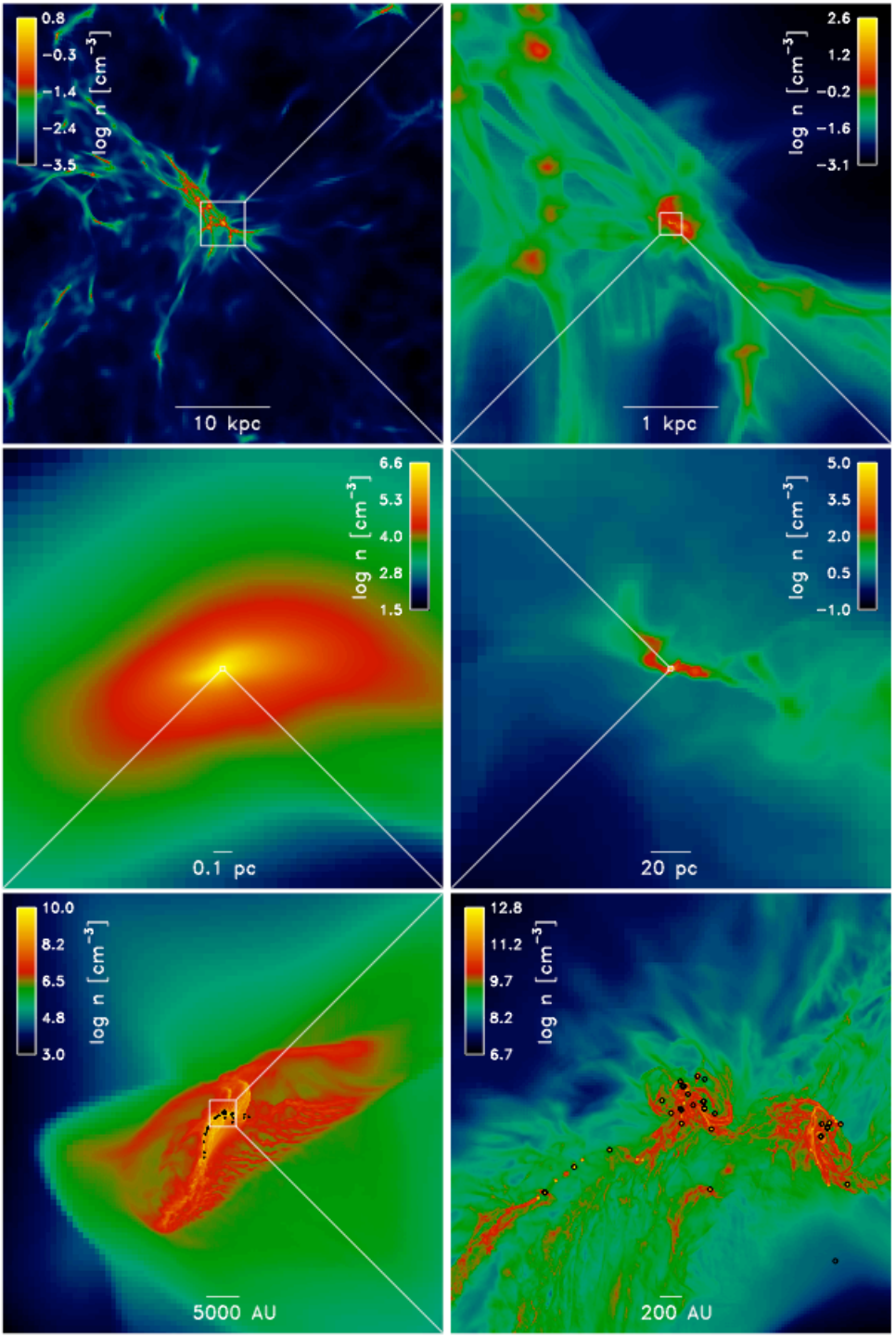
… only a small fraction of those (e.g., from progenitors in a narrow mass range) are sources of the r-process

UFDs in Cosmic Context



Springel et al. 2008, MNRAS 391, 1685

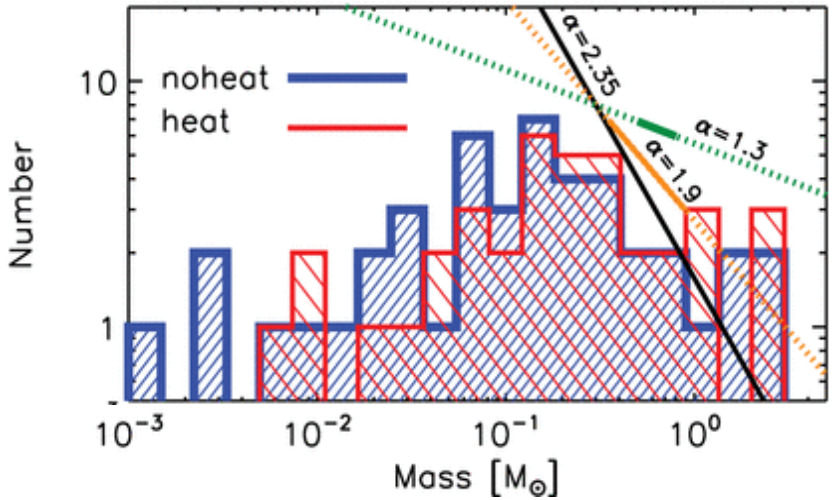
- High dark matter densities within the effective radius
- Survival as satellites of the Milky Way implies low mass
- Number abundance of UFDs similar to low mass satellites in ΛCDM simulations,
- Suggests UFDs formed in H_2 and/or Lyα cooled halos ($10^6 - 10^8$ $M_\odot$) at high redshift ($z \sim 10$).
- Amenable to *direct numerical simulations*!



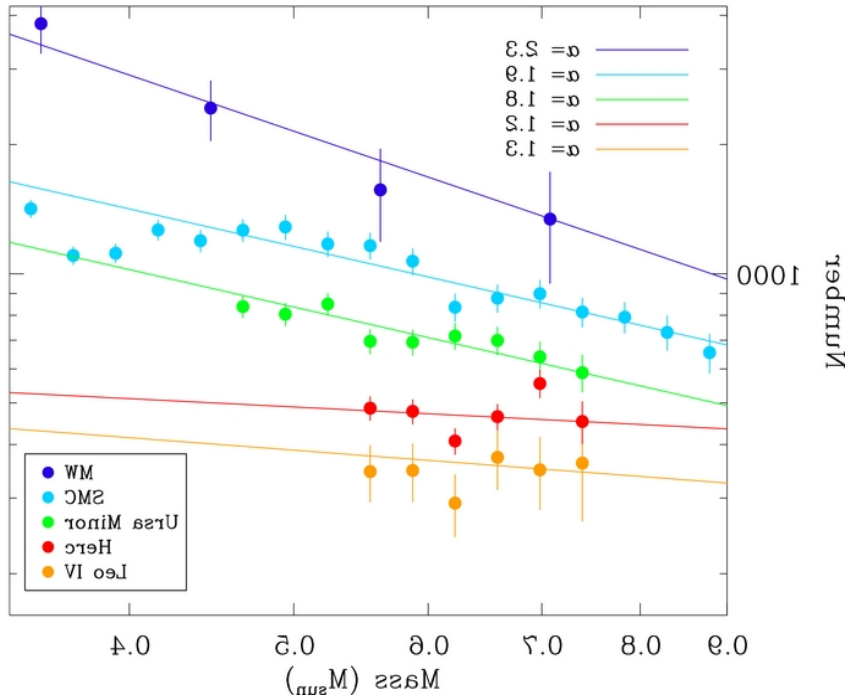
Star Formation from Cosmological Initial Conditions

Chalence Safranek-Shrader, Milosavljevic, & Bromm 2014, MNRAS 440L, 76

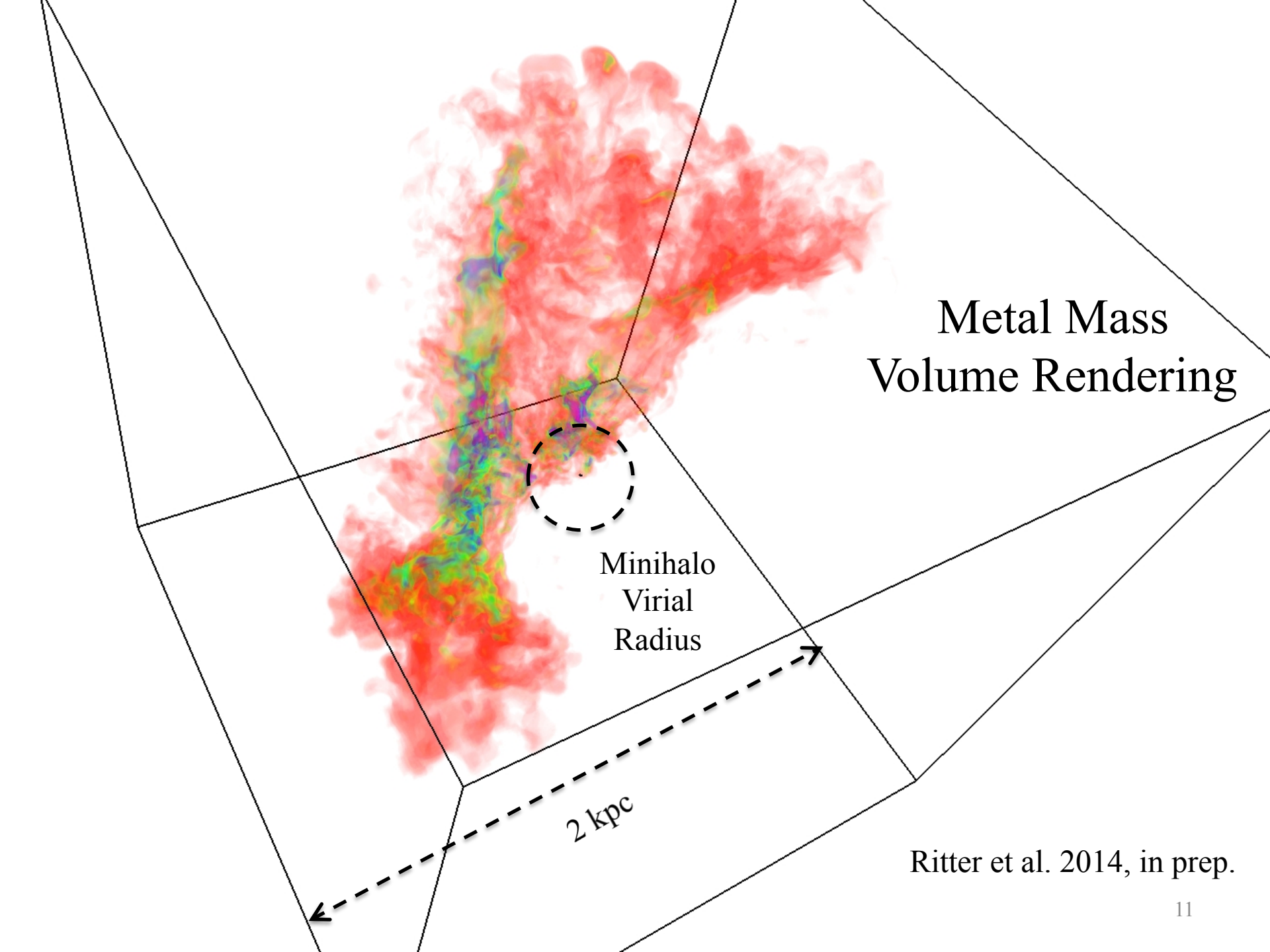
- Set up cosmological density perturbations in dark matter and baryons
- Evolve in time while adaptively refining the computational mesh on the first galaxies and star-forming clouds (dynamic range > 10^8)
- Study the star-forming process



Safranek-Shrader et al. 2014 MNRAS 440L, 76
(assuming $Z = 10^{-2}\ Z_\odot$)



Marla Geha et al. 2013, ApJ 771, 29



Ritter et al. 2014, in prep.

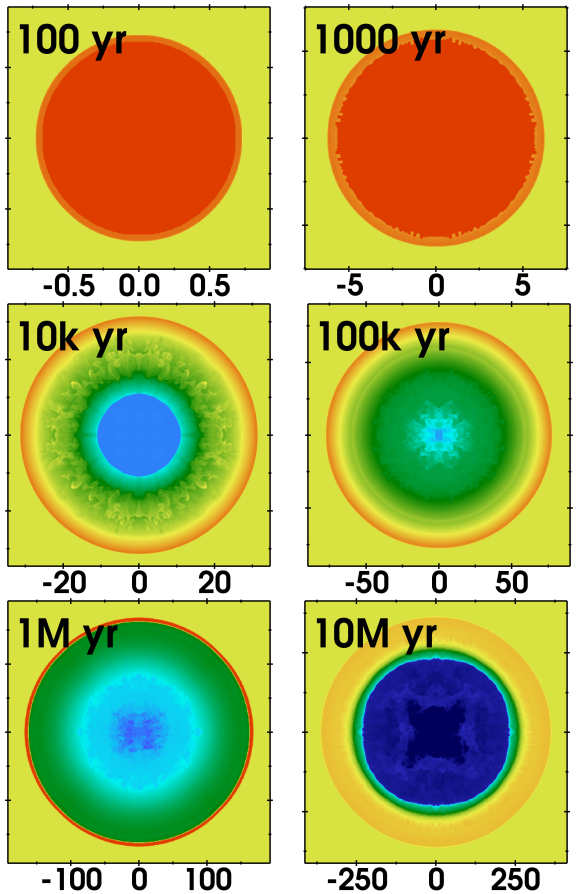
Open Questions

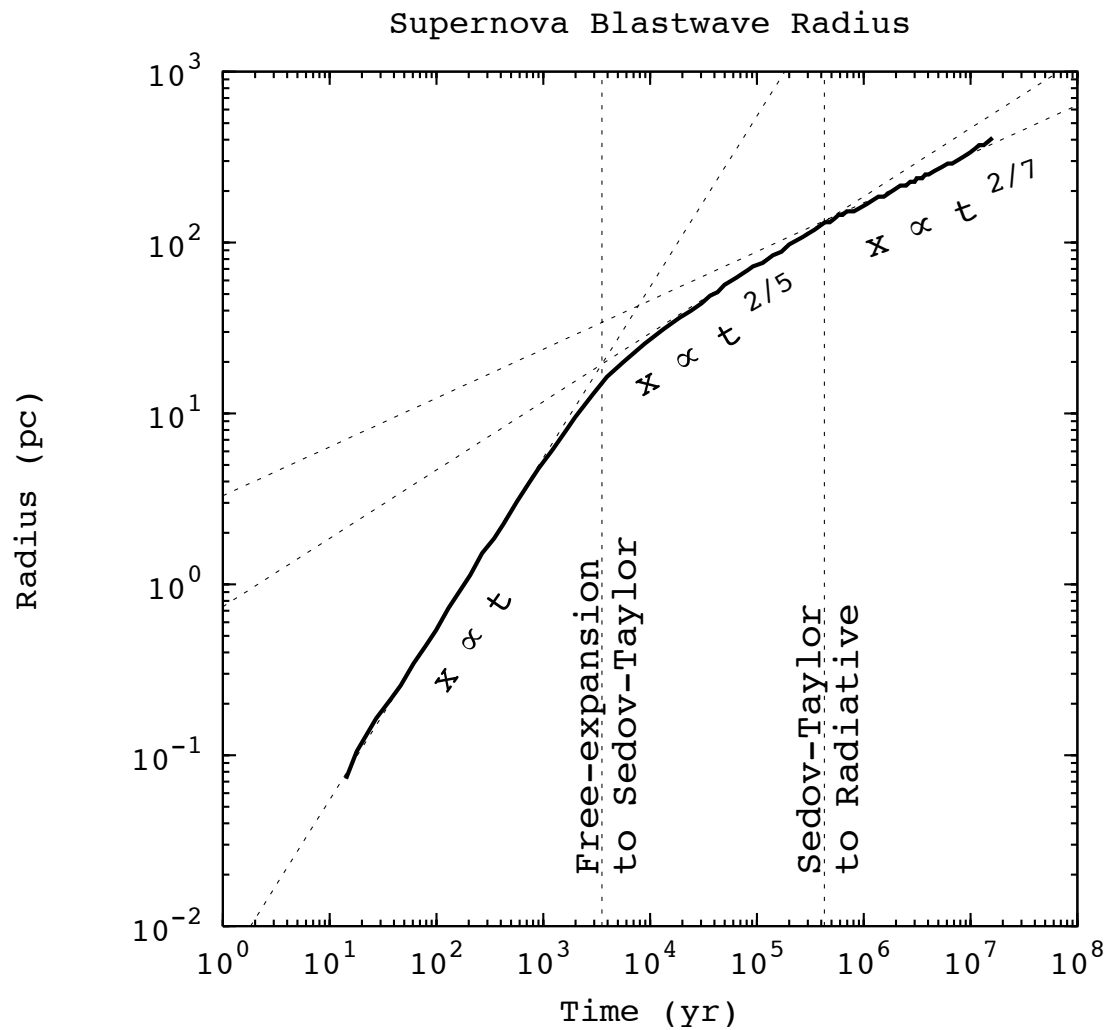
1) Can moderate-mass Pop III stars, which are expected to explode as core-collapse supernovae, explain UFD abundance patterns?
2) How far from a minihalo is supernova ejecta dispersed?
3) How long does it take for the ejecta to fall back and enrich gas that can cool, collapse, and form new stars?
4) Does the hydrodynamics of the supernova remnant expansion and the fallback homogenize the abundances?

Methodology

- Cosmological simulations with dark matter and baryons
  - Simulate a Pop III star forming halo at high redshift
  - FLASH AMR hydro code embedded with N-body dark matter particle integration and multi-grid gravity solver
  - Non-equilibrium atomic and molecular chemistry leading to Pop III stars, and photoionization and cooling tables tabulated from CLOUDY after Pop III stars have been inserted
- Track the aspherical H II region
- Insert supernovae in the kinetic-energy-dominated, free-expansion phase, and follow the gas and ejecta hydrodynamics for several tens of Myr

Test of Supernova Remnant Hydrodynamics

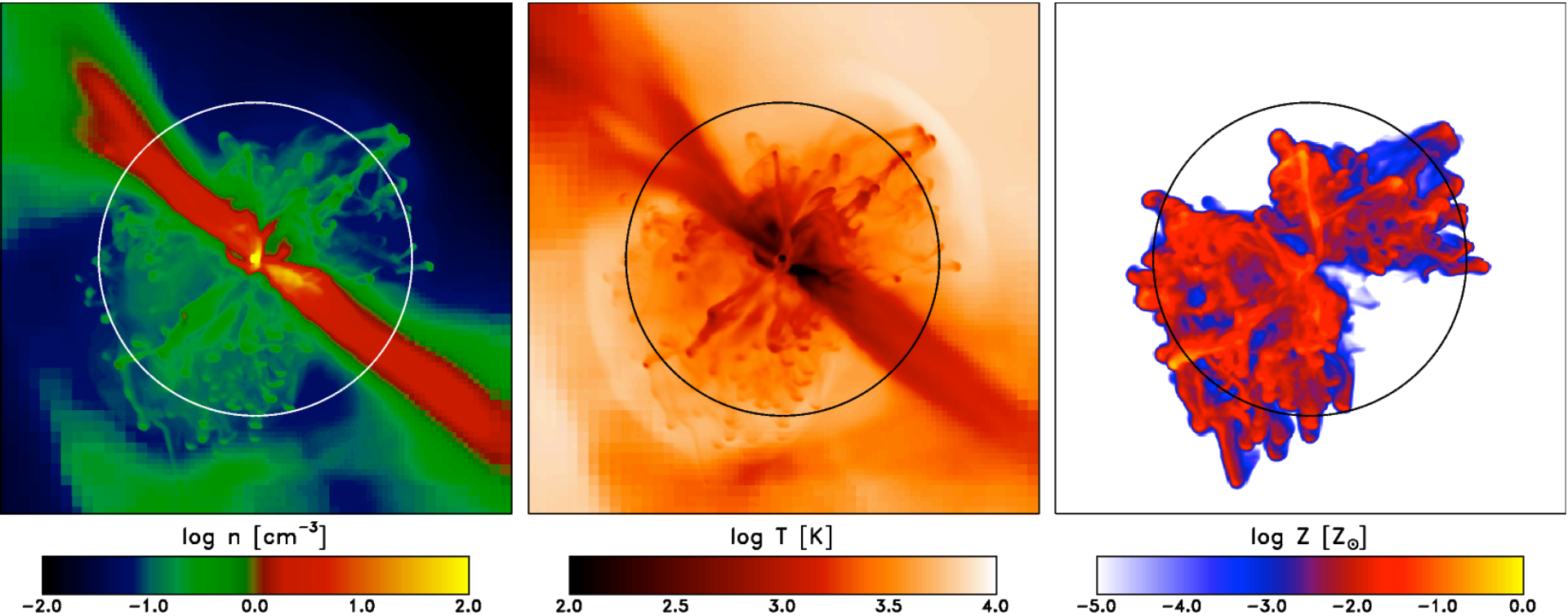




- $M_{ejecta} = 40\ M_{\odot}$
- $E_{kinetic} = 6\times10^{51}$ ergs
- $M_Z\ /\ M_{ejecta} = 0.3$ (α-enhanced composition)

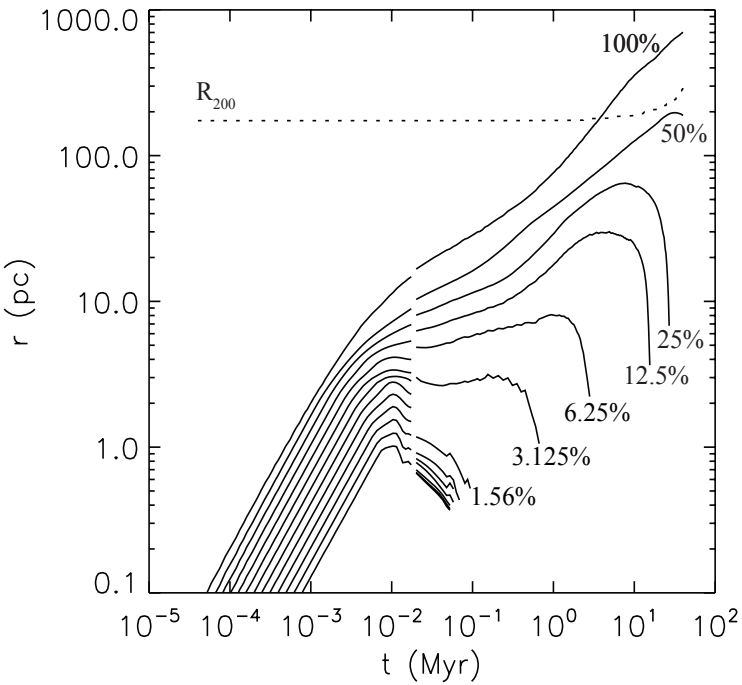
Single Core Collapse Supernova

8.5 Myr after a 10^{51} erg supernova with 40 $M_\odot$ of ejecta

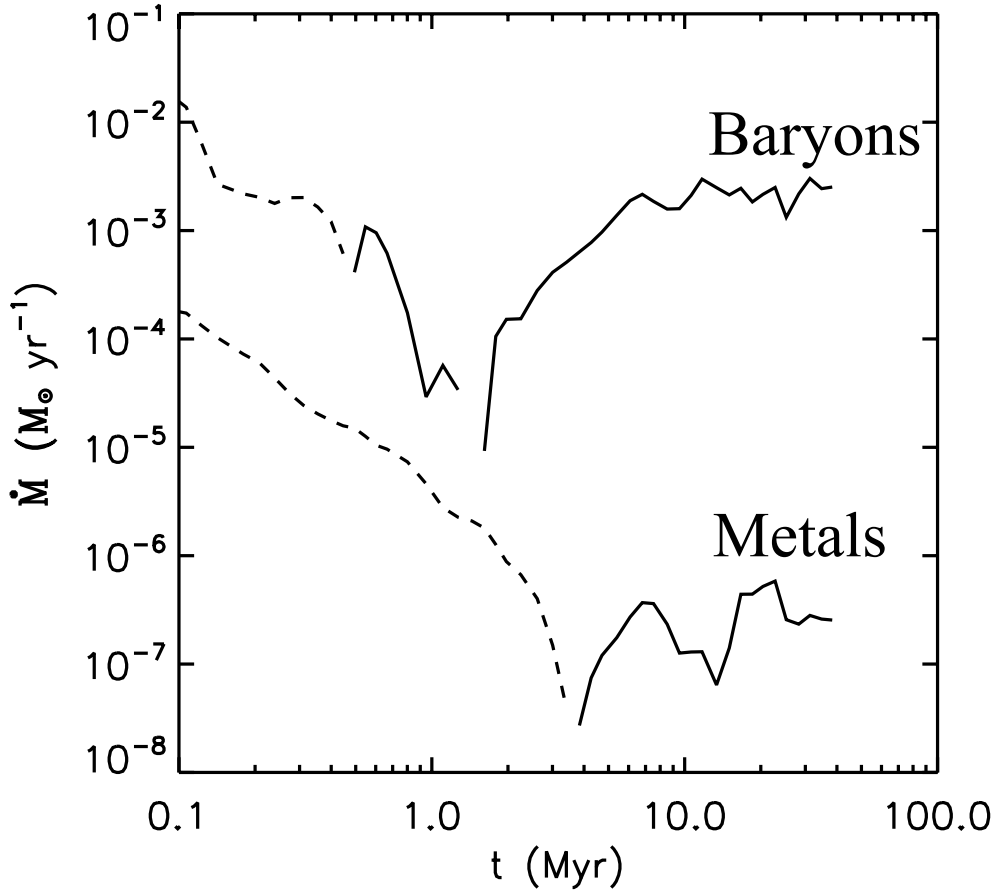


Circle encloses R_{vir} = 200 pc of a 10^6 $M_\odot$ minihalo

Ejecta Fallback

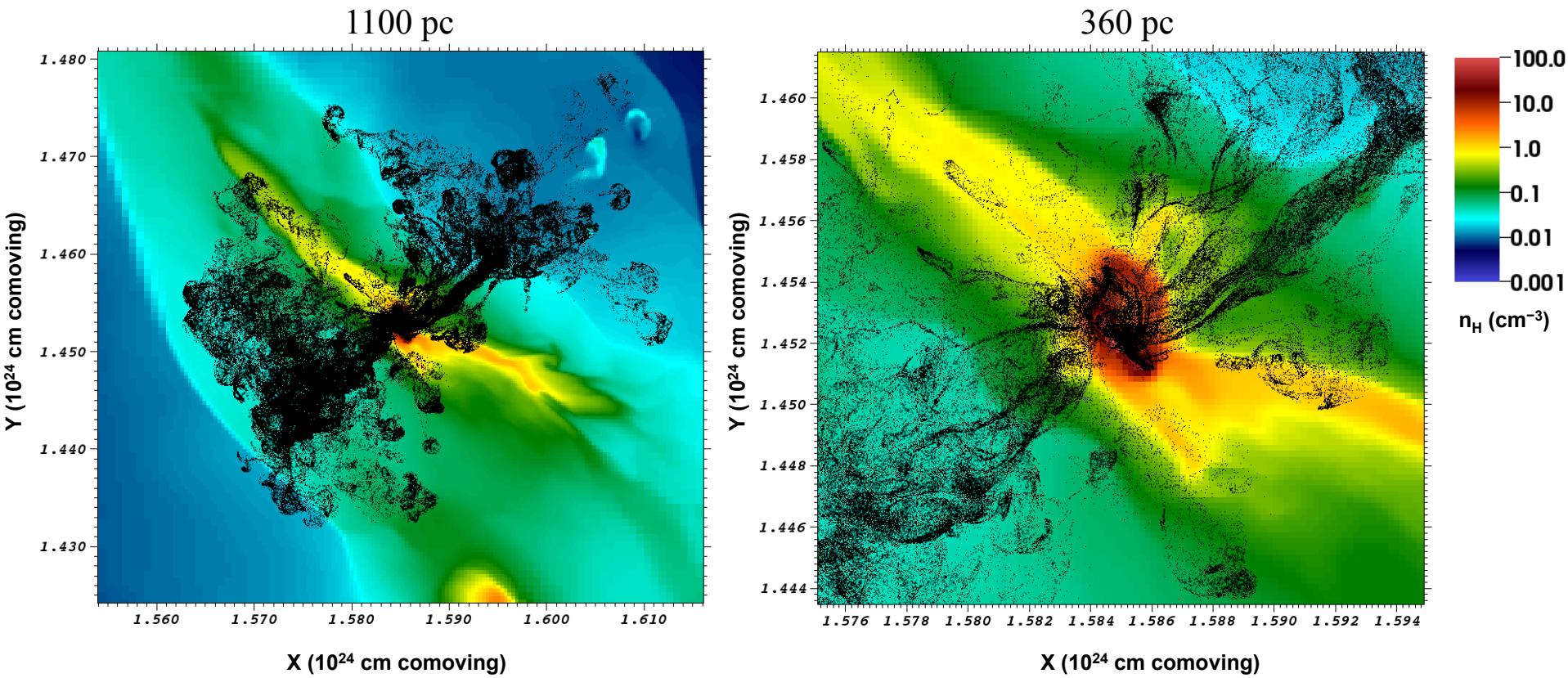


- Fragments of the snowplow shell turn around at different times
- A significant fraction of metal ejecta may be retained within the virial radius



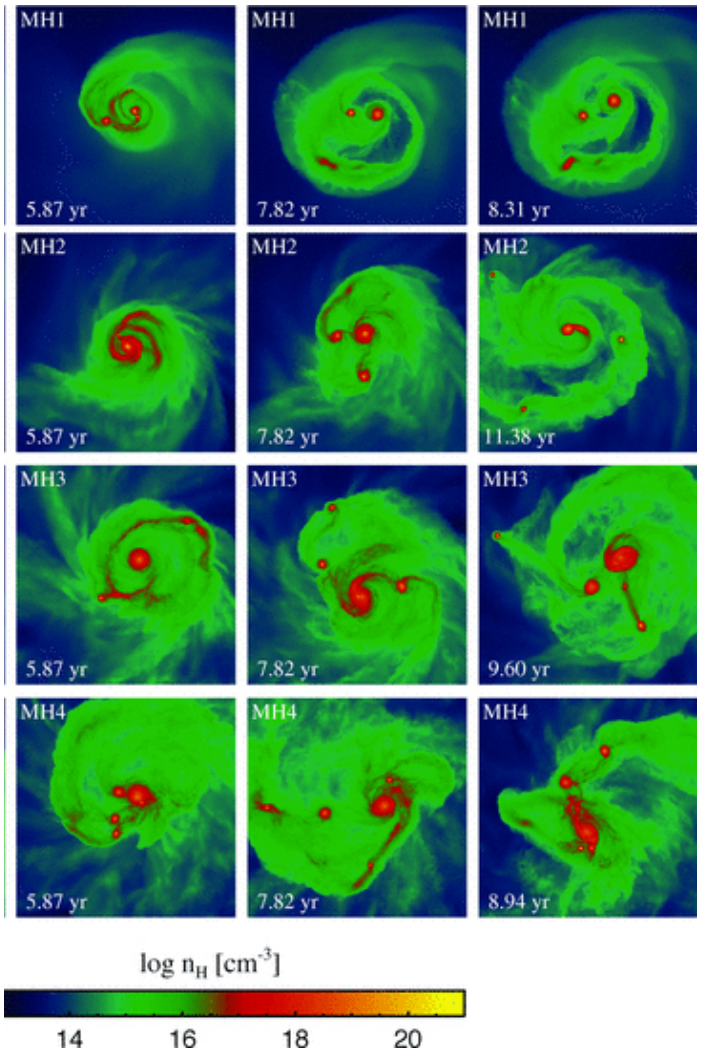
- Sustained inflow of mass after ~ 1 Myr
  - Metals return after ~ 5 Myr
  - Total mass inflow rate ~ 2×10^{-3} $M_\odot$ yr^{-1}
  - Average metallicity ~ 10^{-2} $Z_\odot$
  - Metals highly inhomogeneous in returning gas

Inhomogeneous Enrichment



baryon density slice + ejecta particles in projection

Multiple Supernovae in a Minihalo



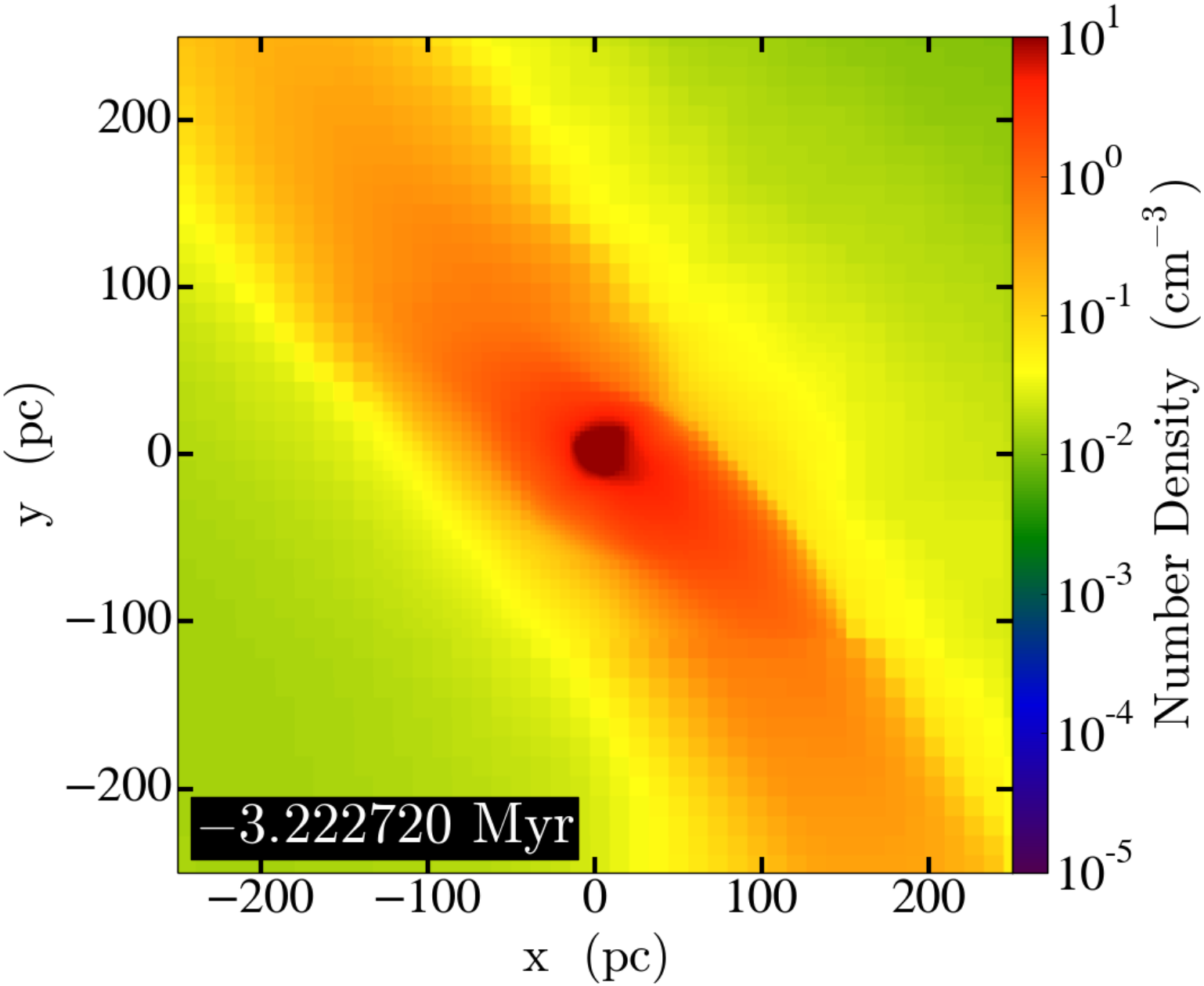
Greif et al. 2012, MNRAS 424, 399-415

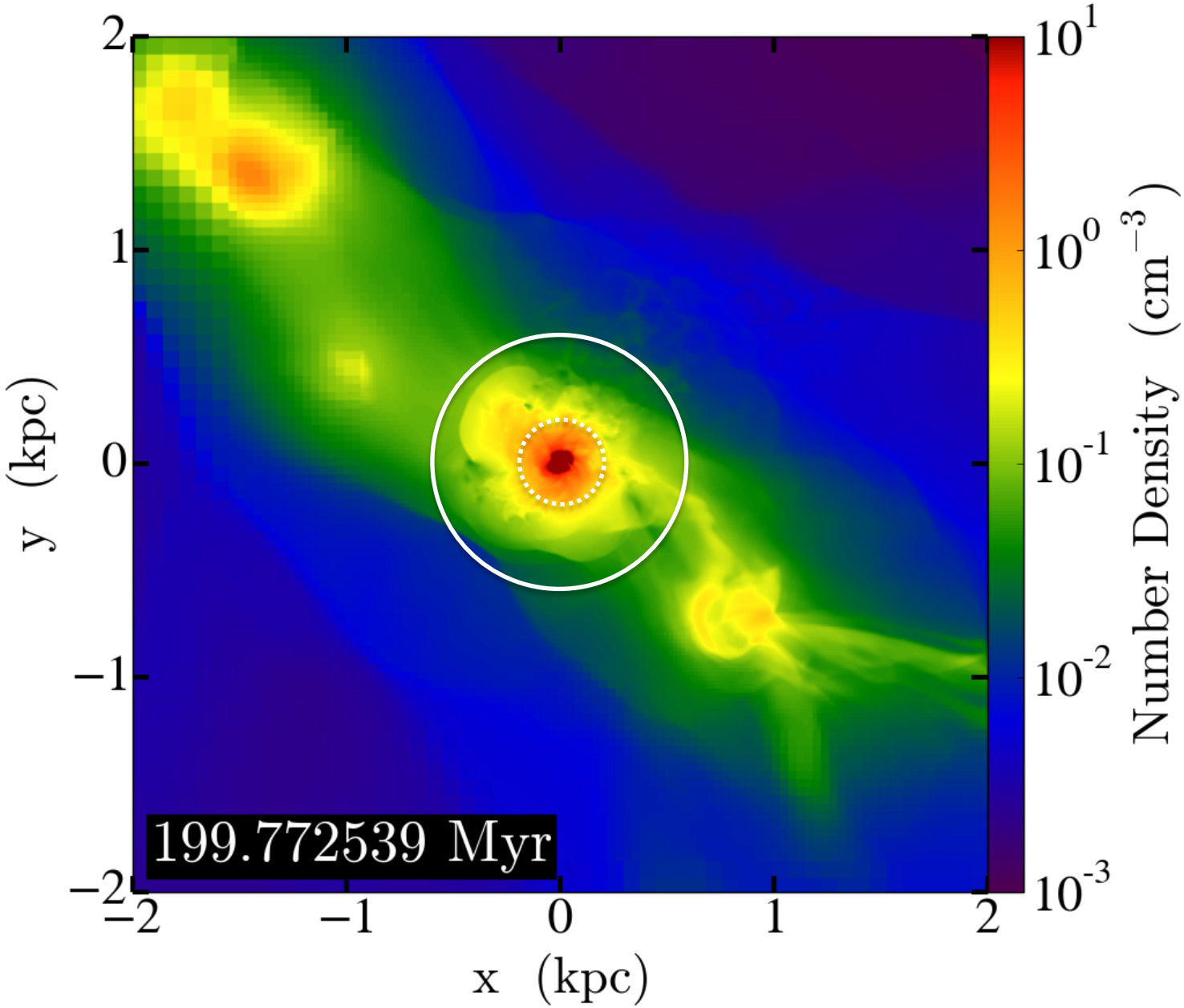
- Protostellar disk fragmentation produces Pop III stars in small, compact clusters
- We sample a Pop III initial mass function to compute delay times of consecutive supernovae
- Pop III stars of different masses should have distinct nucleosynthetic signatures (though the detailed yields are not currently known)
- Time separation of supernova events adds complexity to the dispersal of metal ejecta

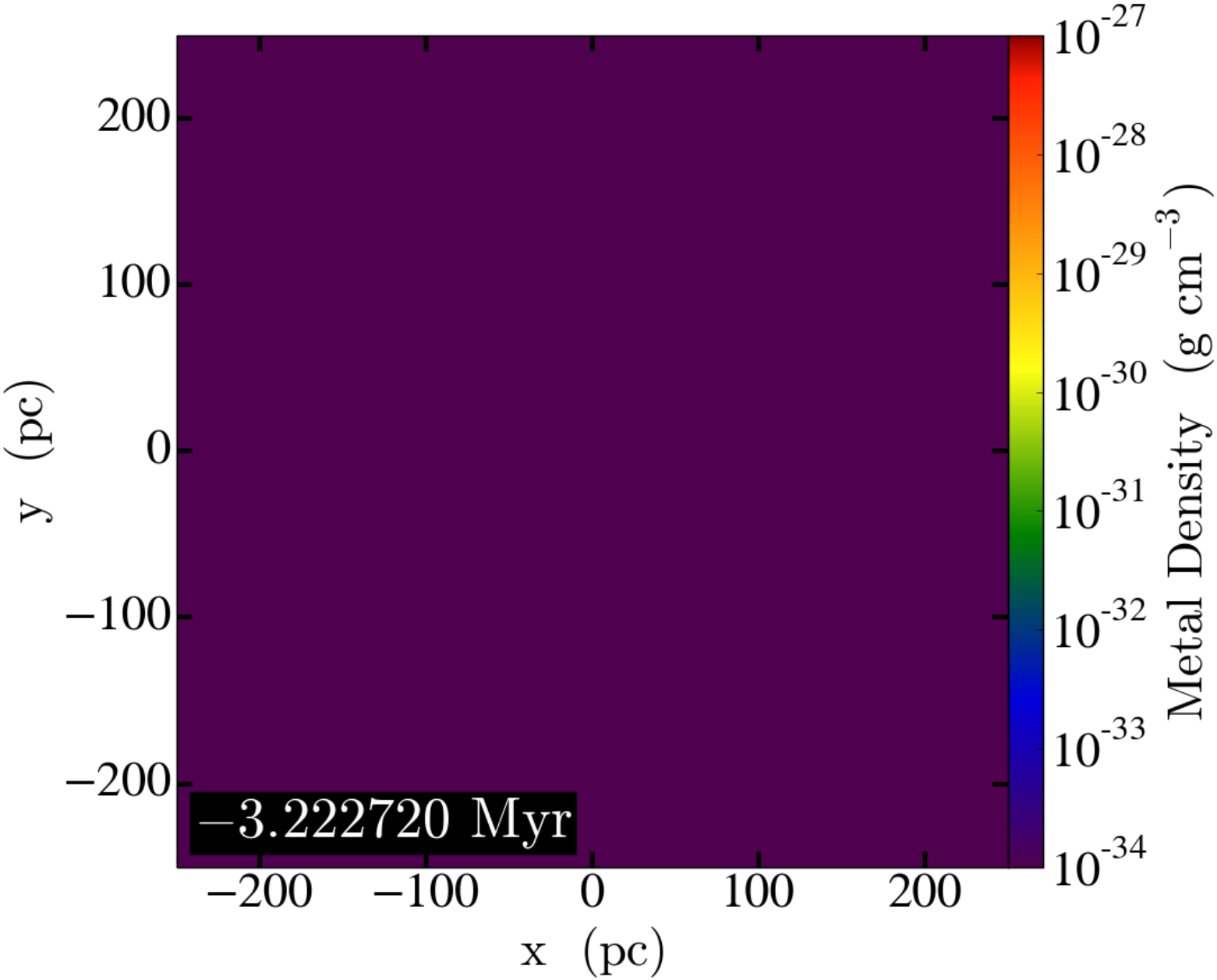
Multiple Supernovae: Methodology

- Pop III star cluster sampled from a flat IMF
  - Masses: 80, 63, 50, 40, 32, 25, and 20 $M_\odot$
  - Lifetimes: 3.1, 3.25, 3.6, 4.1, 4.9, 6.1, and 7.7 Myr
  - Combined ionizing luminosity: 2.2×10^{50} photon/s
- Kinetic blastwaves all inserted with 10^{51} ergs
  - Initial radius at high density 0.6 pc (cell size 0.02 pc) and at low density 2.9 pc (cell size 0.09 pc) much less than the radius of equivalent mass
- Track the ejecta from each supernova separately using individually tagged passive tracer particles

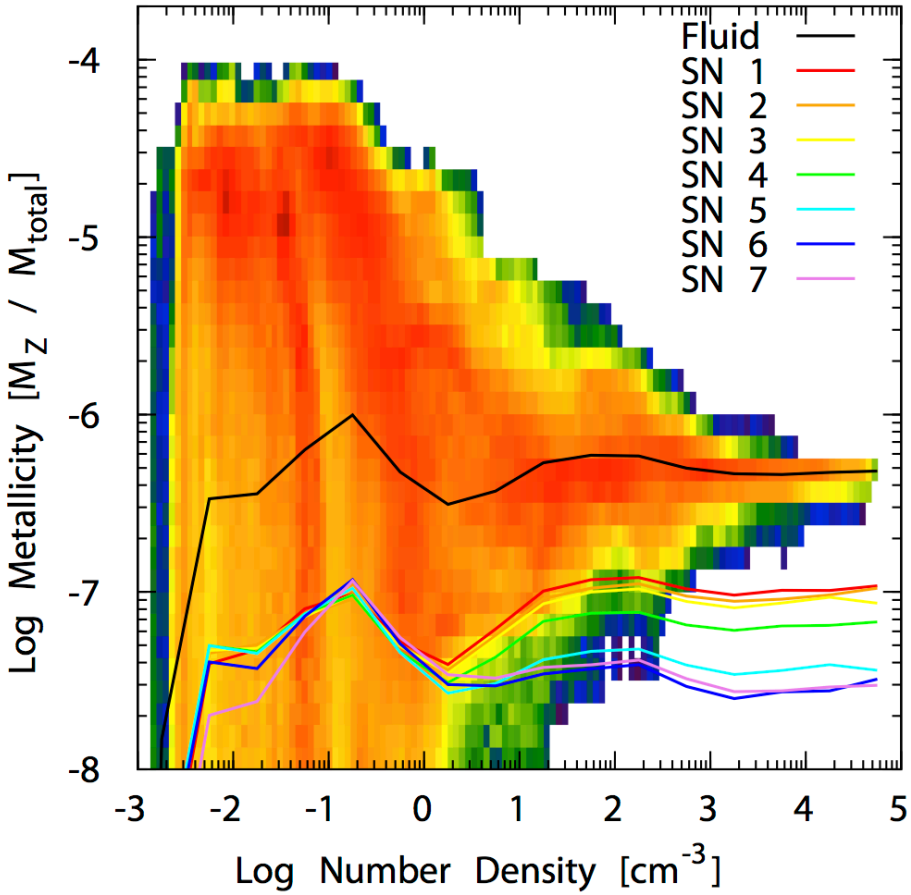
Download movies from http://grapenut.org/code/yt/paper/movies/



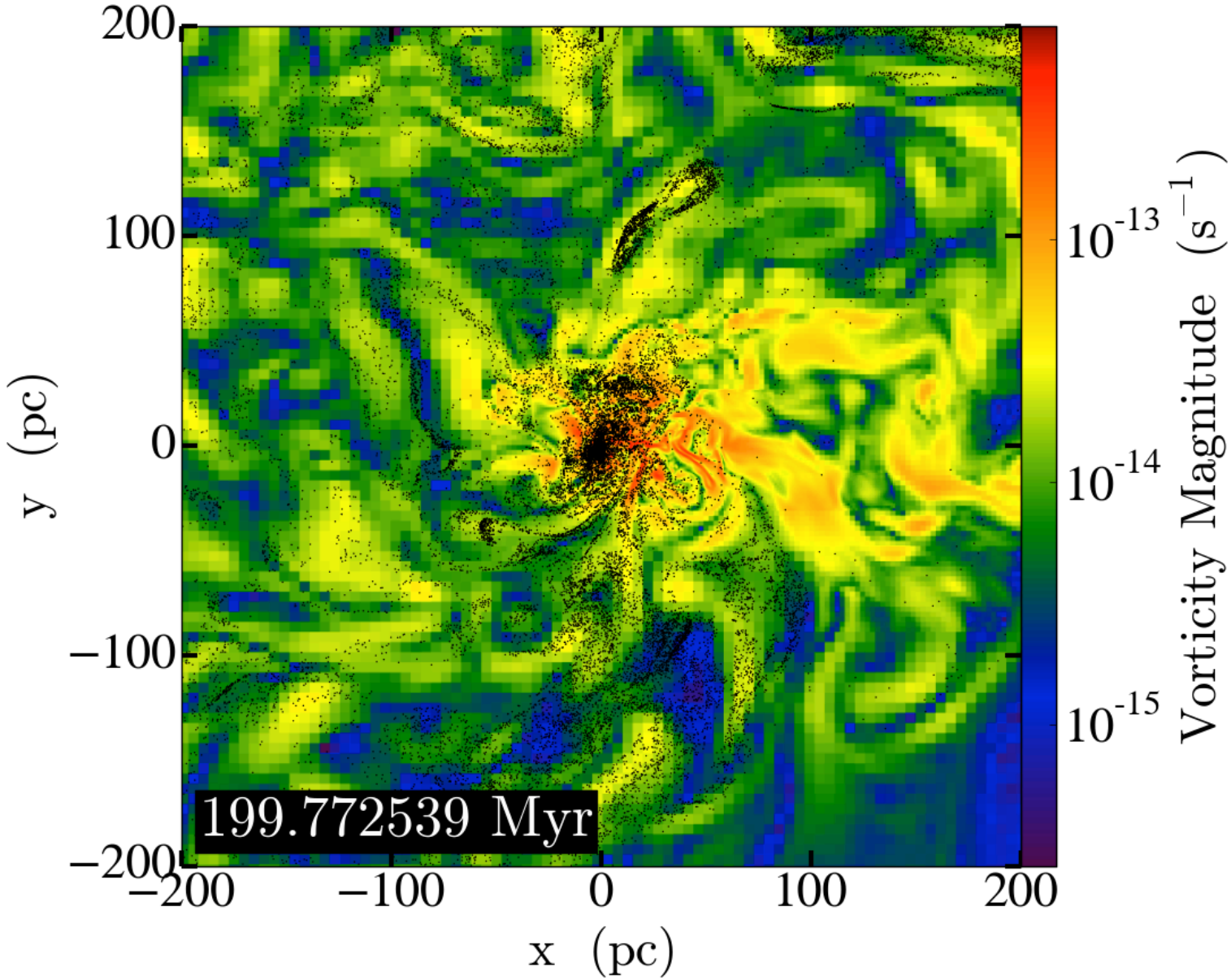

199.772539 Myr
y (kpc)
x (kpc)
Number Density (cm^{-3})
2
1
0
−1
−2
−2
−1
0
1
2
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}


−3.222720 Myr
200
100
0
−100
−200
y (pc)
−200
−100
0
100
200
x (pc)
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
Metal Density (g cm^{-3})

Inhomogeneous Enrichment

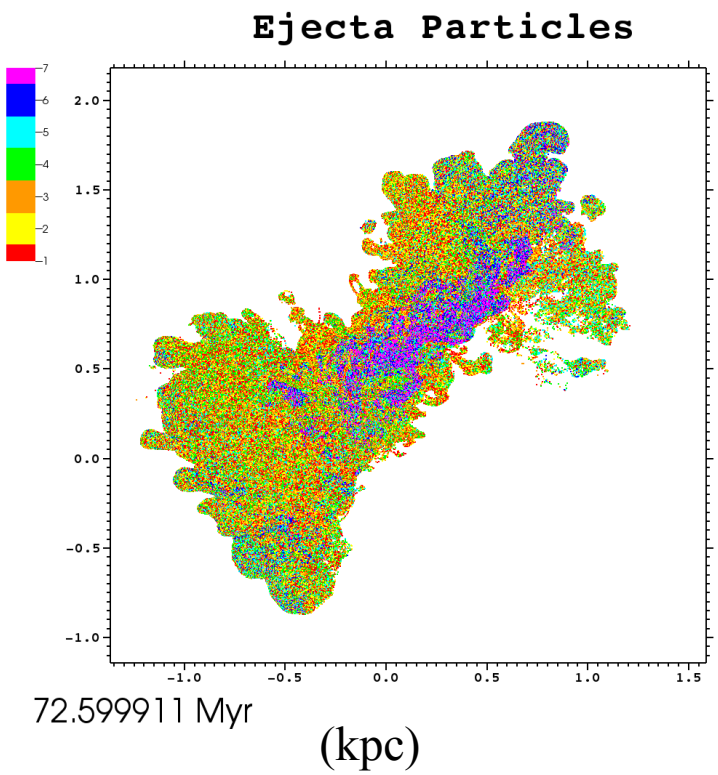


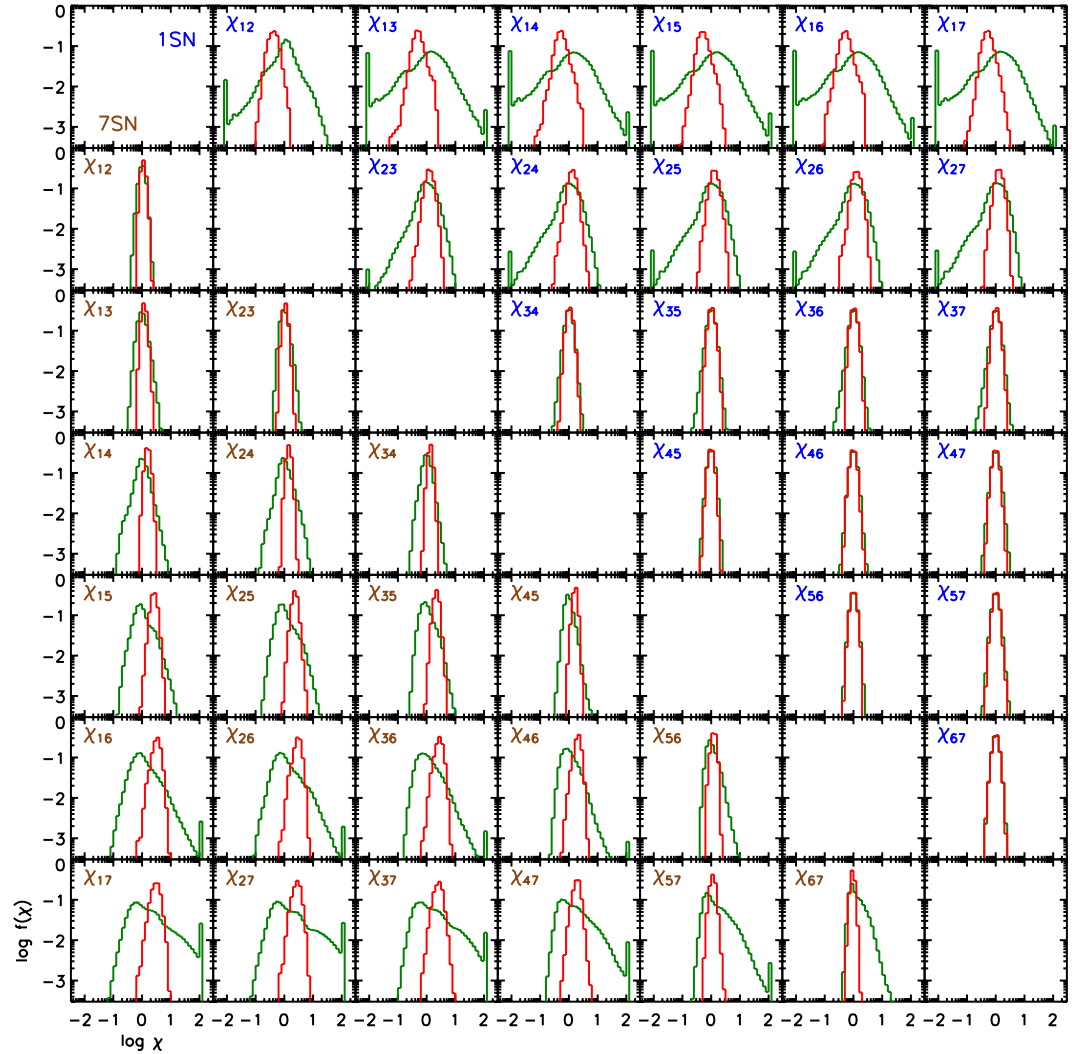
- Recollapse of metal-enriched gas after 200 Myr, when maximum density climbs up to n ~ 10^4 cm^{-3}
- Average metallicity of recollapsed gas is very low due to dilution with continued infall from the cosmic web
- Mixing of ejecta and dense primordial gas delayed at least until fallback
- The enrichment of metal-enriched star forming clouds is biased toward the earlier supernovae (material injected by later supernovae remains at high entropy)
- Infall-driven turbulence in the recollapsed gas has short vortical time scales, conducive to mixing
- Final dark matter-baryon ratio ~ 13
- Metal mass retained ~ 70%



Ejecta are sheet-like and highly inhomogeneous in the infalling gas. The vortical time scales $t_{vort} \sim |\nabla \times \mathbf{v}|^{-1}$ in the central turbulent core (10s of parsecs) are short enough to imply mixing down to microscopic scales.

Inhomogeneous Enrichment





χ_{ij} = ratio of local densities ρ_i/ρ_j

Conclusions

- Pop III supernova ejecta remain highly inhomogeneous for $\sim 10 - 100$ Myr.
- Pop III supernova bubble eventually collapses. A dense metal-enriched cloud, fed by fallback from the remnant and streaming of metal-free gas from the cosmic web, grows in the center.
- Gravitational infall excites turbulence in the the cloud. Vortical time scales are short enough to ensure chemical homogenization on subgrid scales.
- The abundances in metal-enriched stars forming in this cloud will be biased toward the earliest supernovae because ejecta of the later supernovae remain at relatively high entropy.
- Cosmic mini-halos in which Pop III stars have exploded can begin to form metal-enriched stars while the halo masses are still $\sim 10^7\ M_\odot$.
- The metallicity of second-generation stars can be low and may not positively correlate with the total Pop III nucleosynthetic return in the halo.
- Upcoming Stellar Archaeological surveys will greatly increase sample sizes, e.g., Gaia ($\sim 10^9$ stars)
- To fully harness the power of Stellar Archaeology to constrain properties of the first stars, need to understand the physics of early inhomogeneous mixing. Simulations are key!