Simulating Supernovae in the Early Universe

Jeremy Ritter

Alan Sluder, Chalence Safranek-Shrader (UCSC),
Miloš Milosavljević, Volker Bromm

The University of Texas at Austin

First Stars & Supernovae Team

Chalence Safranek-Shrader

Alan Sluder

Miloš Milosavljević

Volker Bromm

Open Questions

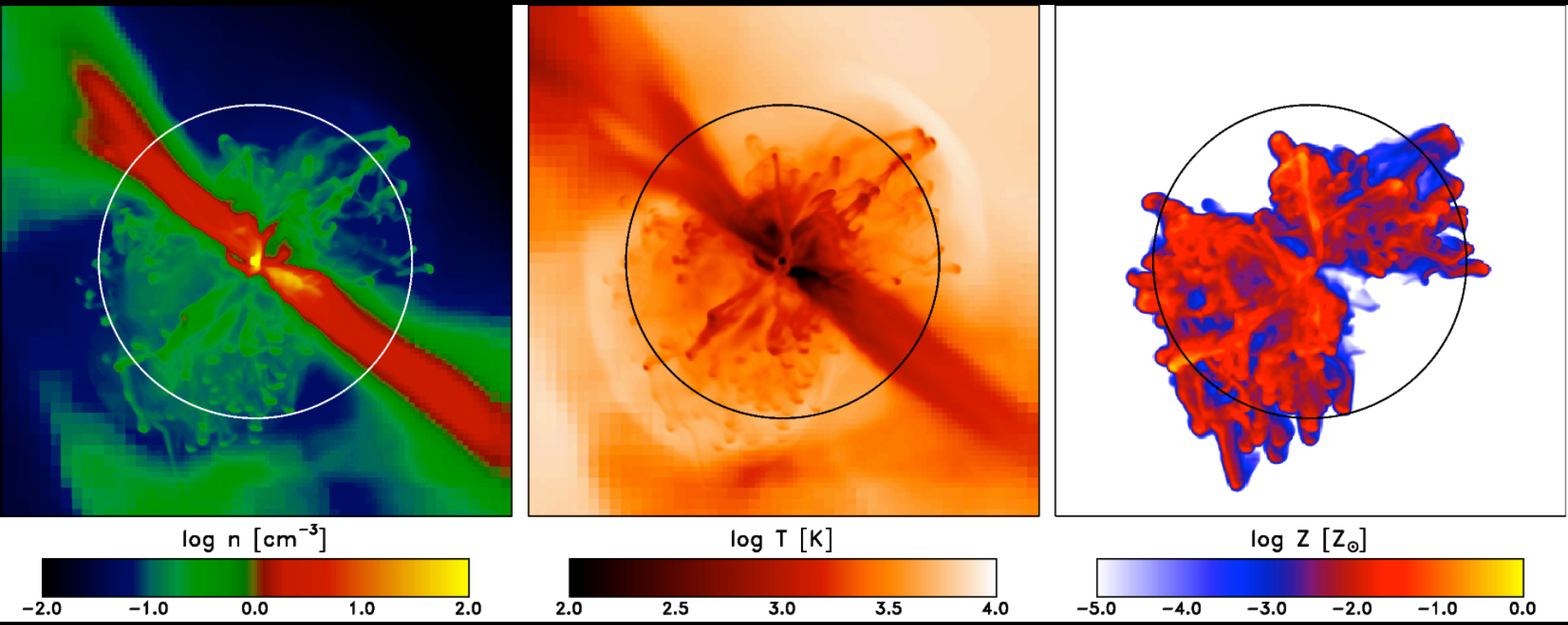
- Can moderate-mass Pop III supernovae explain abundance patterns in ancient, metal-poor stellar populations (e.g. UFDs)?
- Does the hydrodynamics of ejecta dispersal and fallback homogenize the abundances?
- How long does it take before metal-enriched gas is able to cool and recollapse ("recovery time")?
- What fraction of metals end up in the IGM, ISM, and the next generation of stars?

The Simulation Setup

- 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

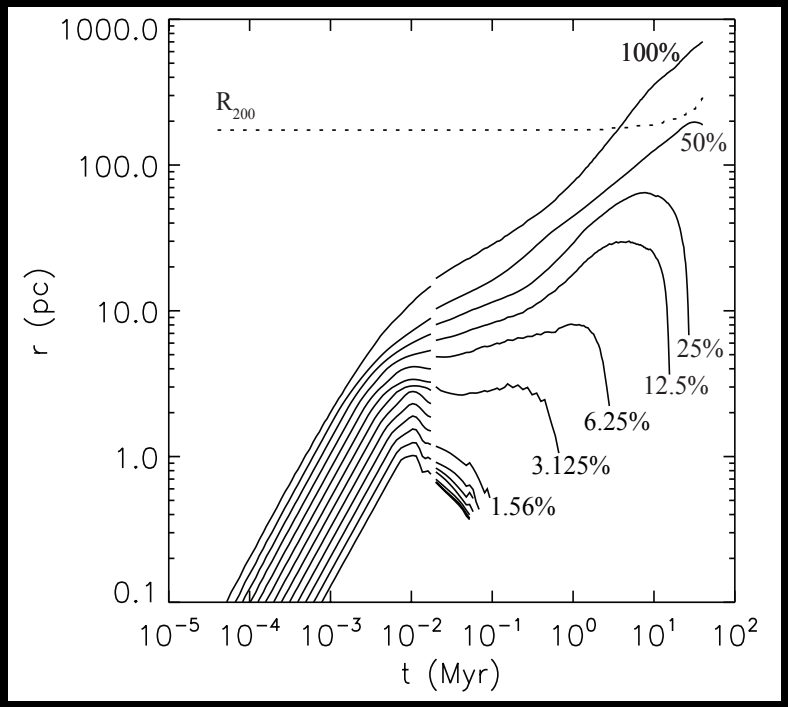
Single Core Collapse Supernova

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

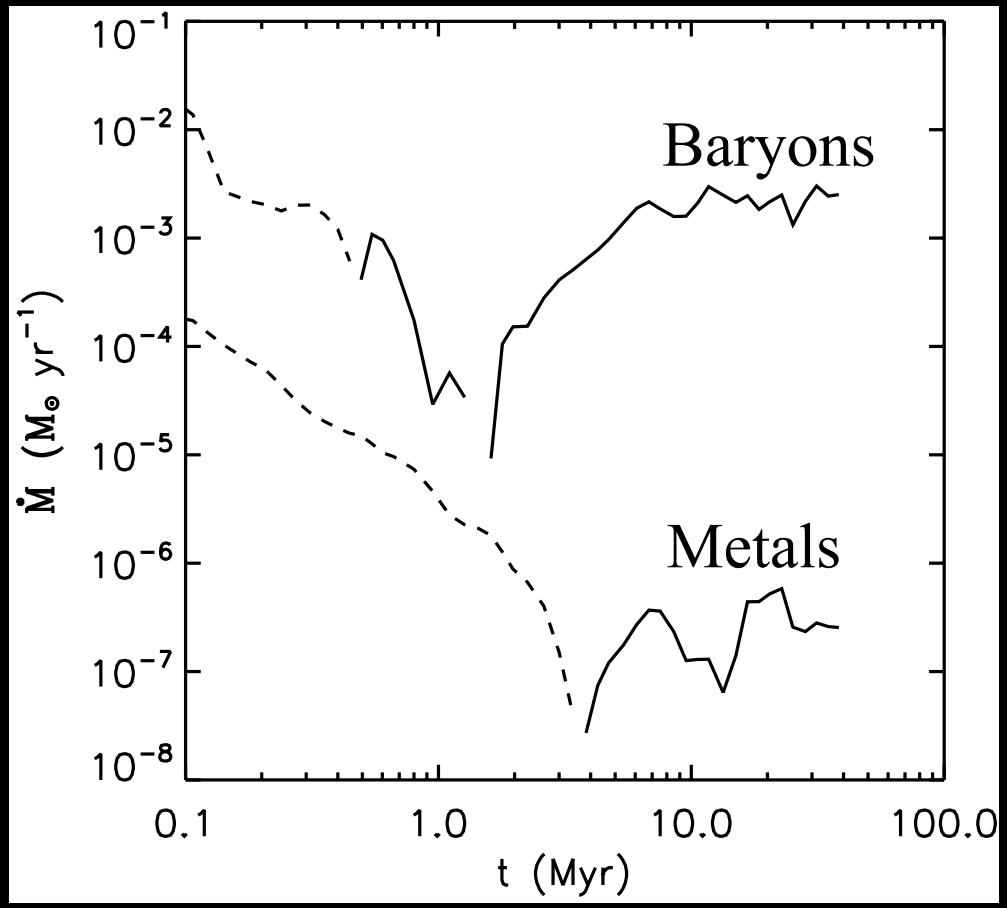


Circle encloses R_{vir} = 200 pc of a 10^6 $M_\odot$ minihalo

Ejecta Fallback

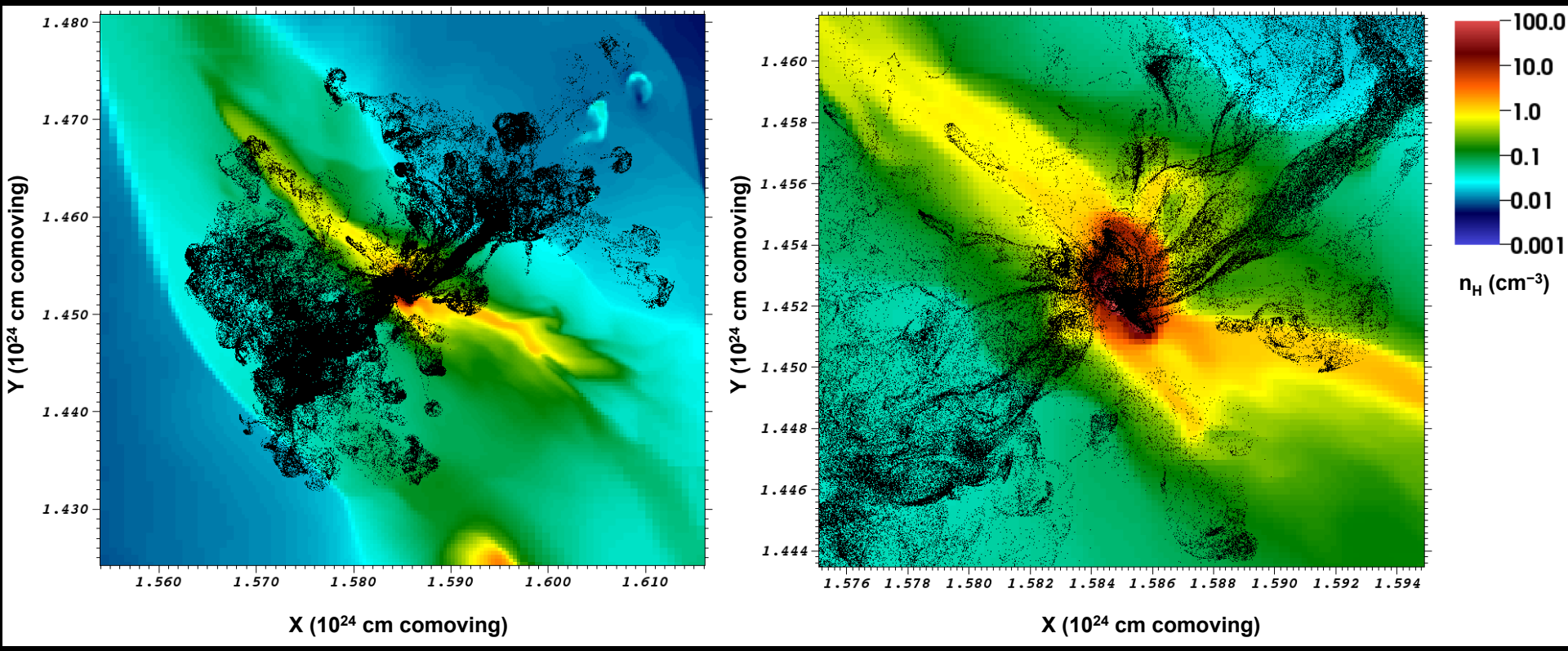


- Fragments of the snowplow shell turn around at different times
- A significant fraction of metal ejecta may be retained within the virial radius



- 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

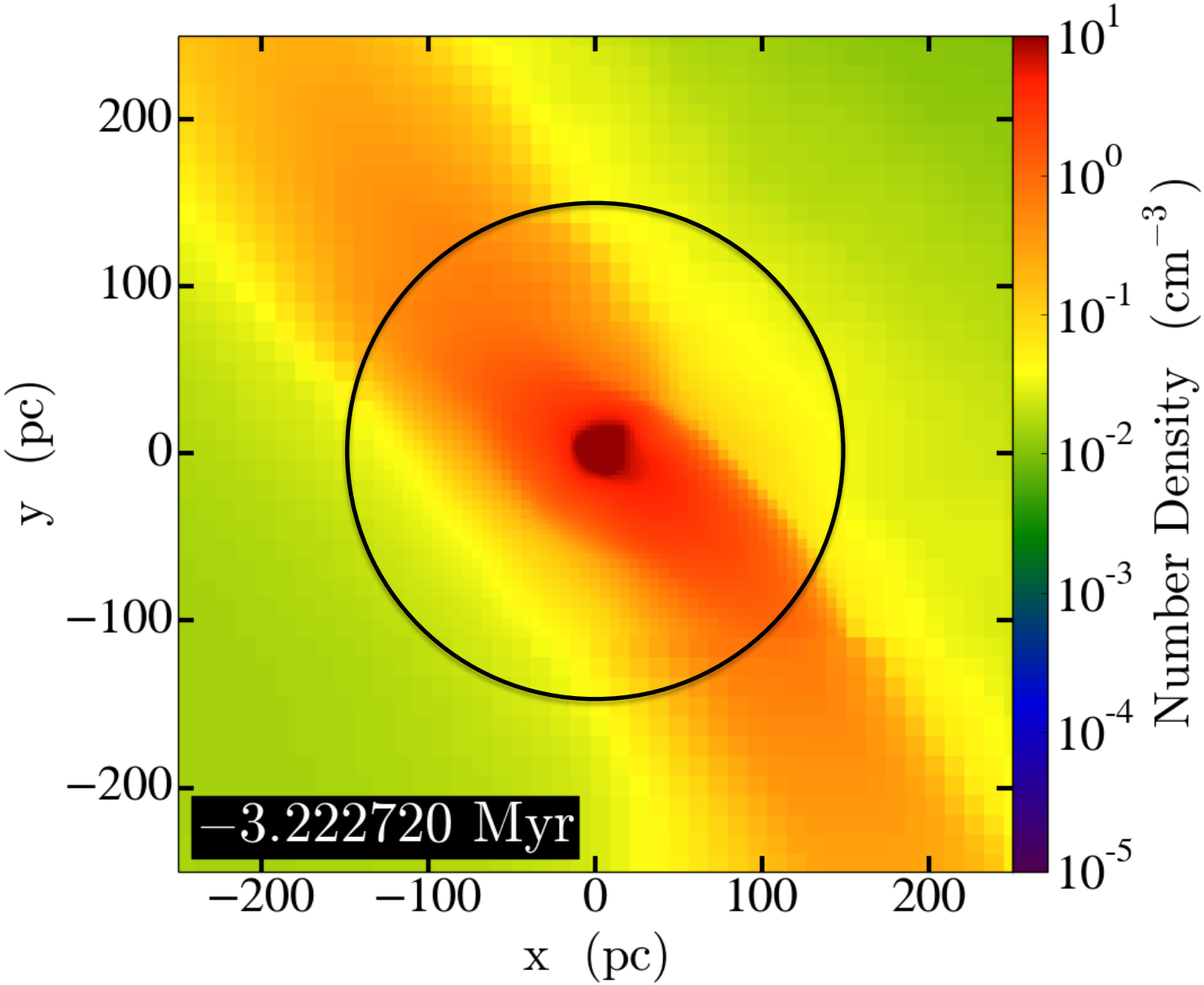
Inhomogeneous Fallback



baryon density slice + ejecta particles in projection

Multiple Supernovae

- 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


200
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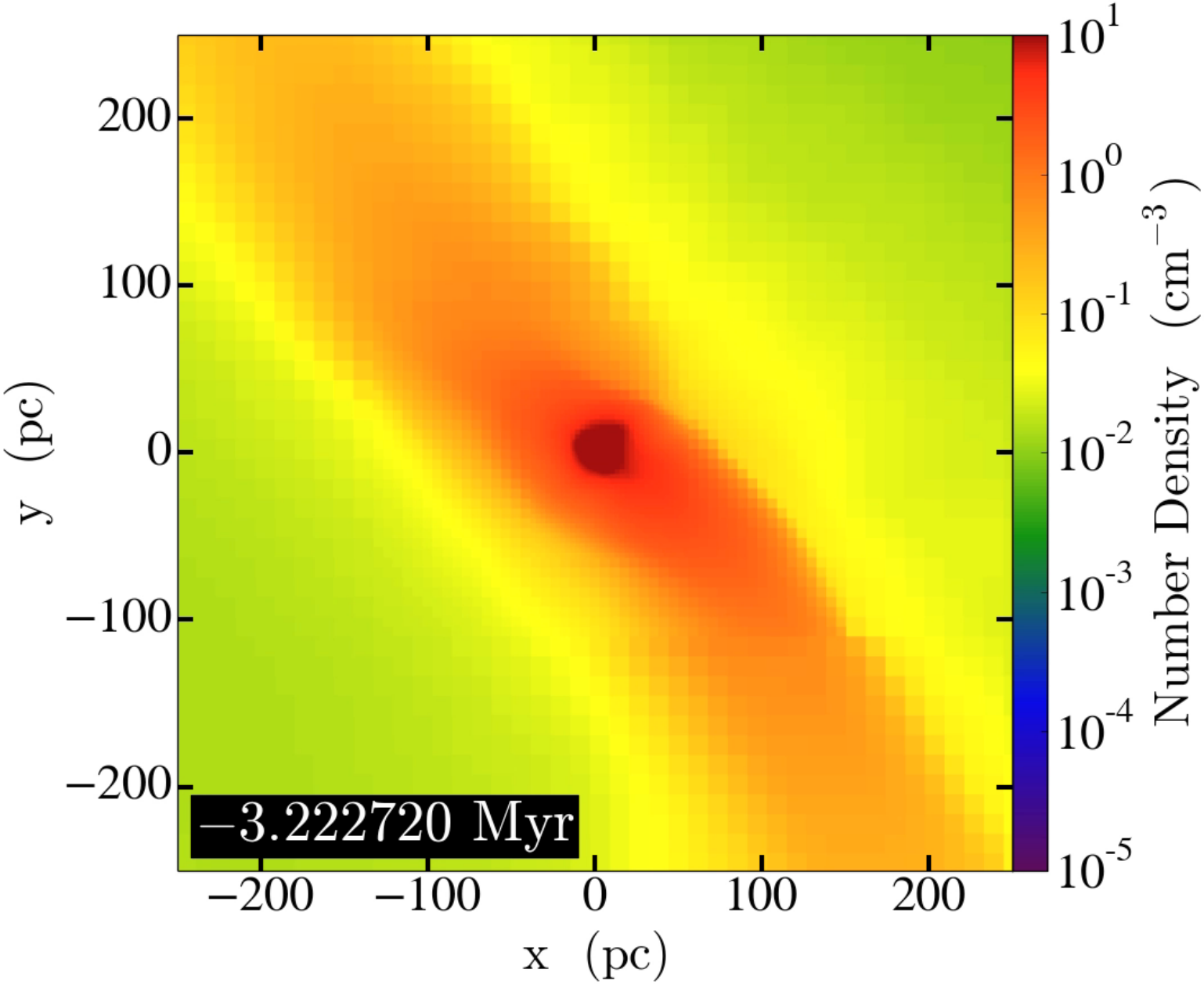
0
−100
−200
y (pc)
−200
−100
0
100
200
x (pc)
−3.222720 Myr
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Number Density (cm^{-3})


−3.222720 Myr
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y (pc)
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x (pc)
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10^{-1}
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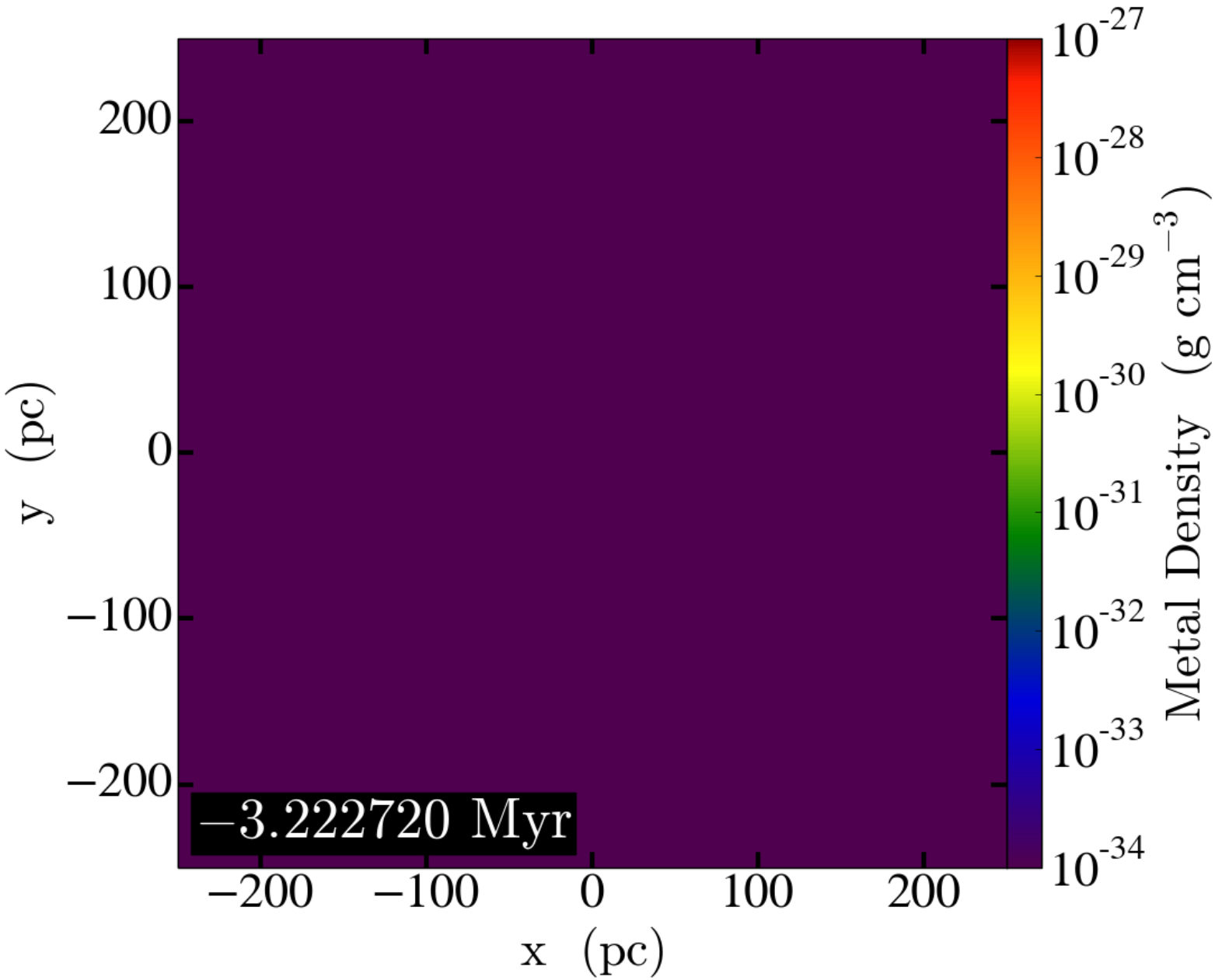
10^{-3}
10^{-4}
10^{-5}
Number Density (cm^{-3})


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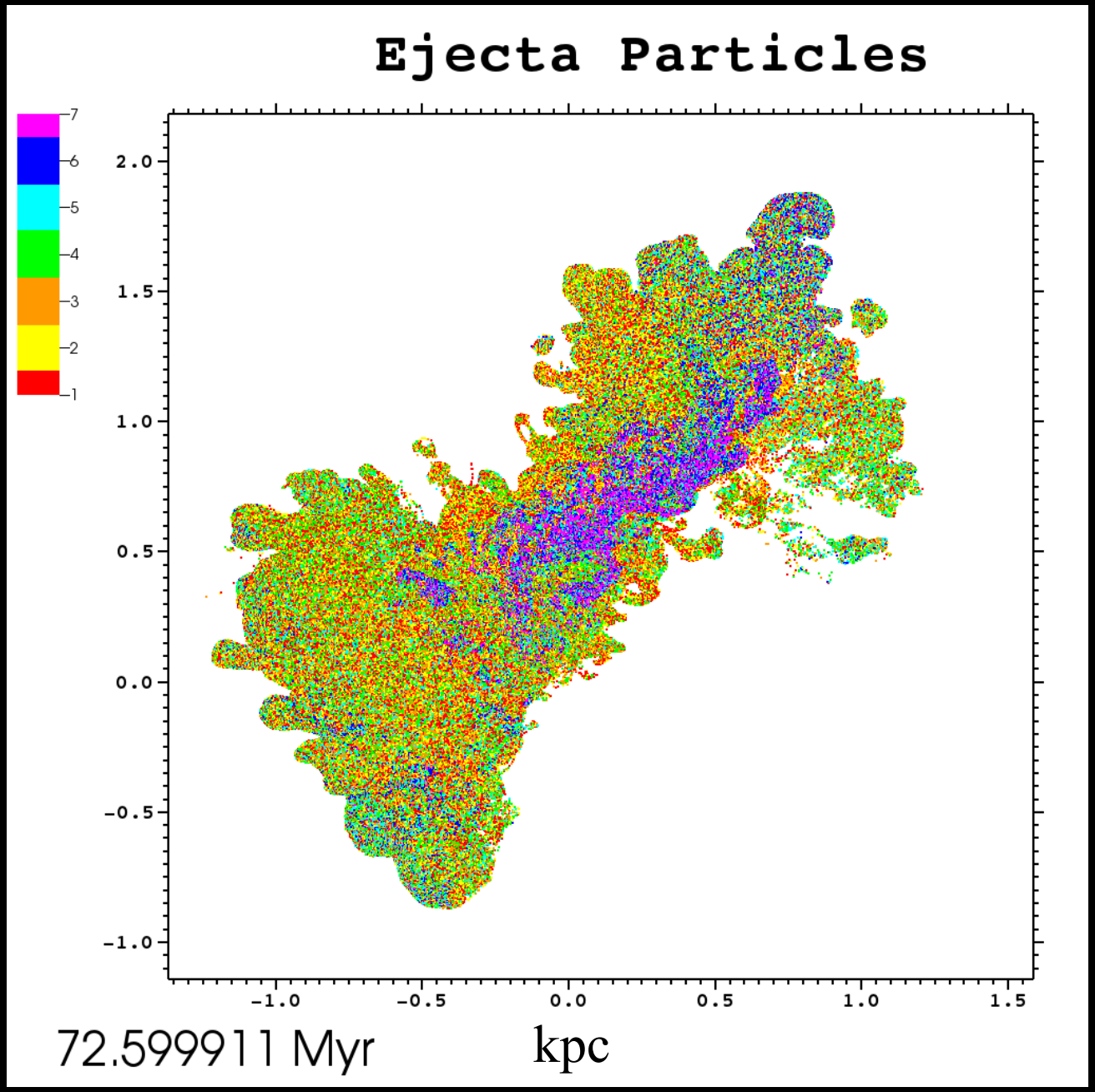
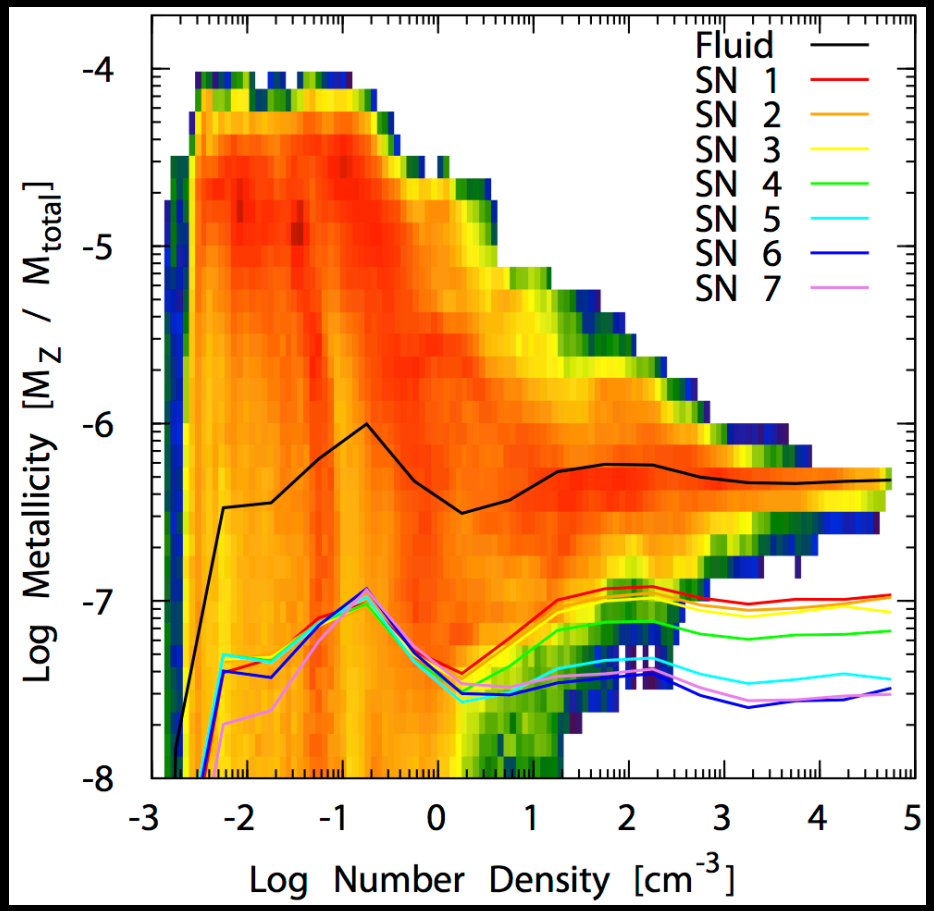
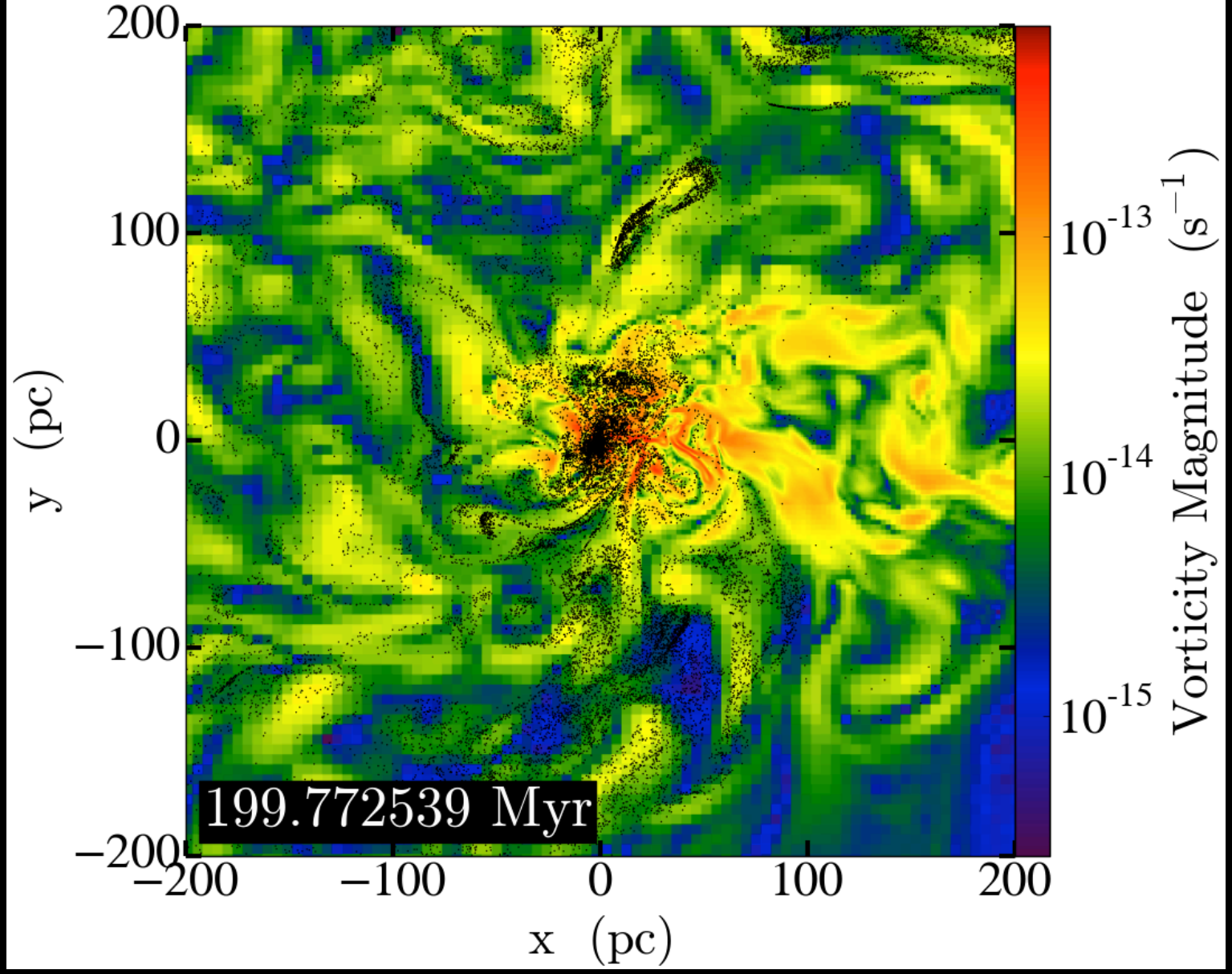
x (pc)
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
Metal Density (g cm^{-3})


Ejecta Particles
7
6
5
4
3
2
1
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.0
-0.5
0.0
0.5
1.0
1.5
72.599911 Myr
kpc

Enrichment Bias



- 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.

Conclusions

- Pop III supernova ejecta remain highly inhomogeneous for ~ 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 ~ 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 (~ 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!

That's all Folks!