External Enrichment as a Pathway to Metal-Poor Star Formation

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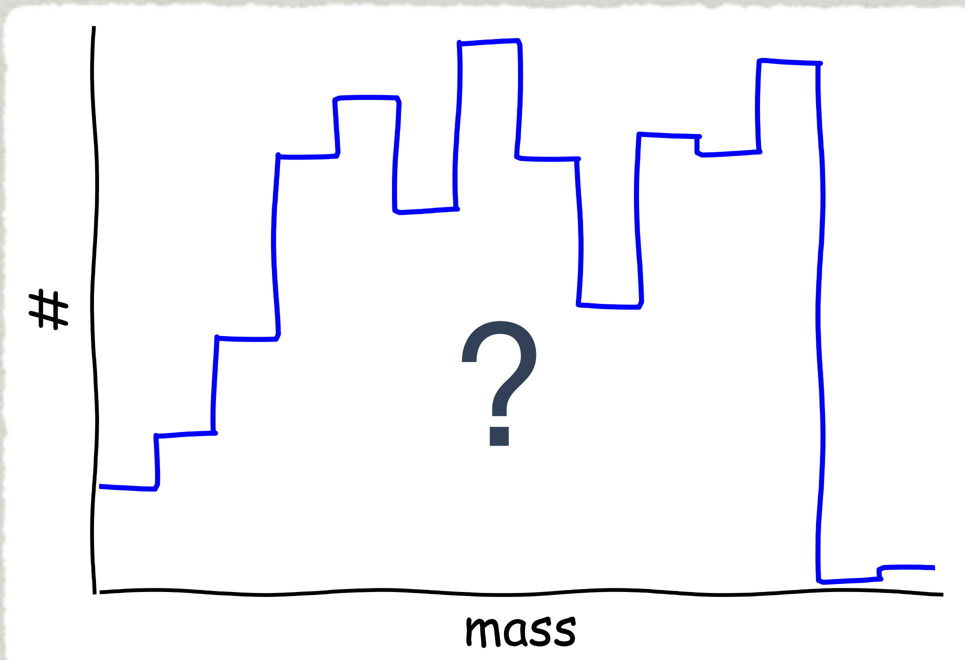
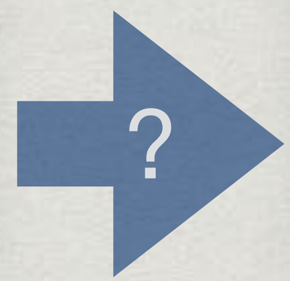
Purpose: understand the Pop III to Pop II transition

Pop III

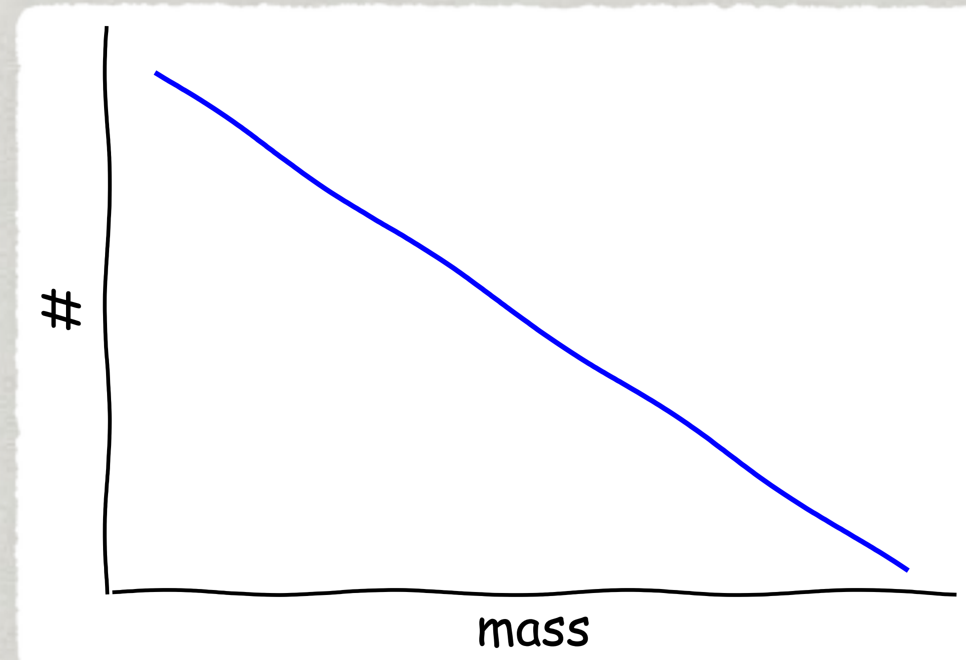


- [x] initial conditions
- [ ] IMF
- [ ] duration



how?
where?
when?

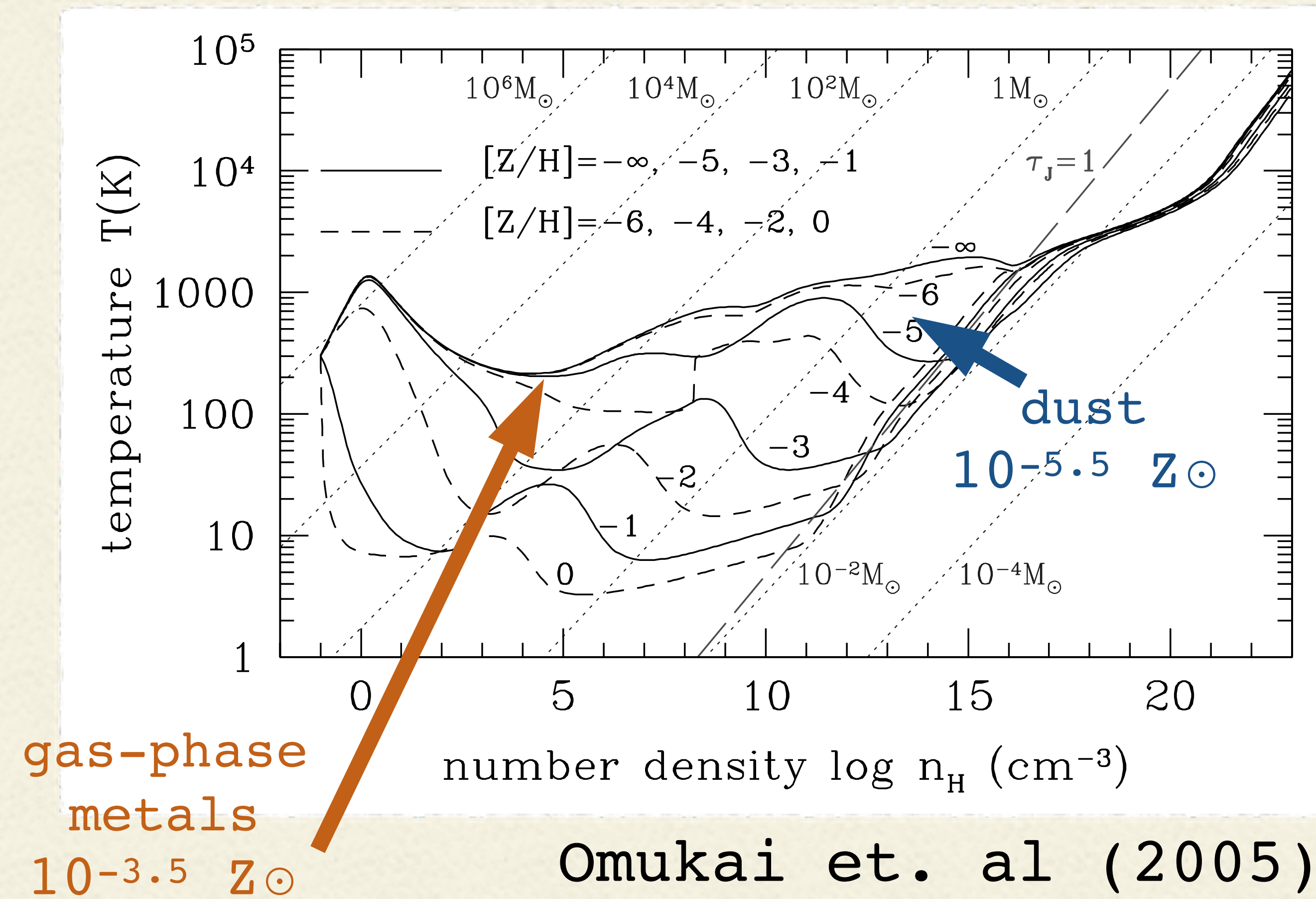
Pop II, I



- [ ] initial conditions
- [x] IMF
- [ ] physical origin

The First Pop II Stars: knowns and unknowns

- 2 critical metallicities - are they both relevant?
    - $10^{-5.5}$ Z⊙: physical minimum
    - $10^{-3.5}$ Z⊙: most MP stars in MW
- How/when do we reach these metallicities?
    - enrichment mechanisms
    - physical conditions of SF
- What is necessary for fragmentation?
    - metals
    - turbulence

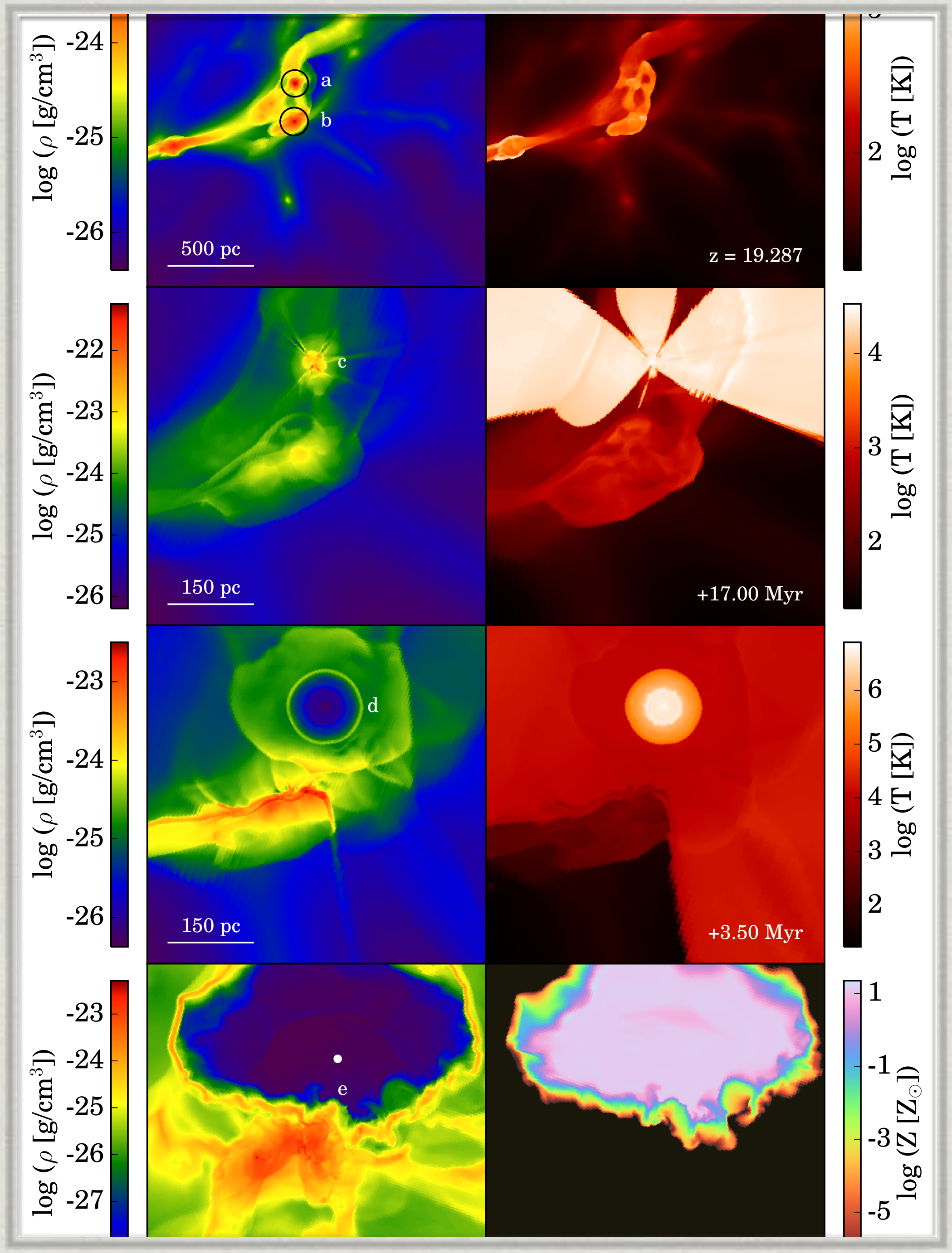


Omukai et. al (2005)

- Where do the most metal-poor stars come from?

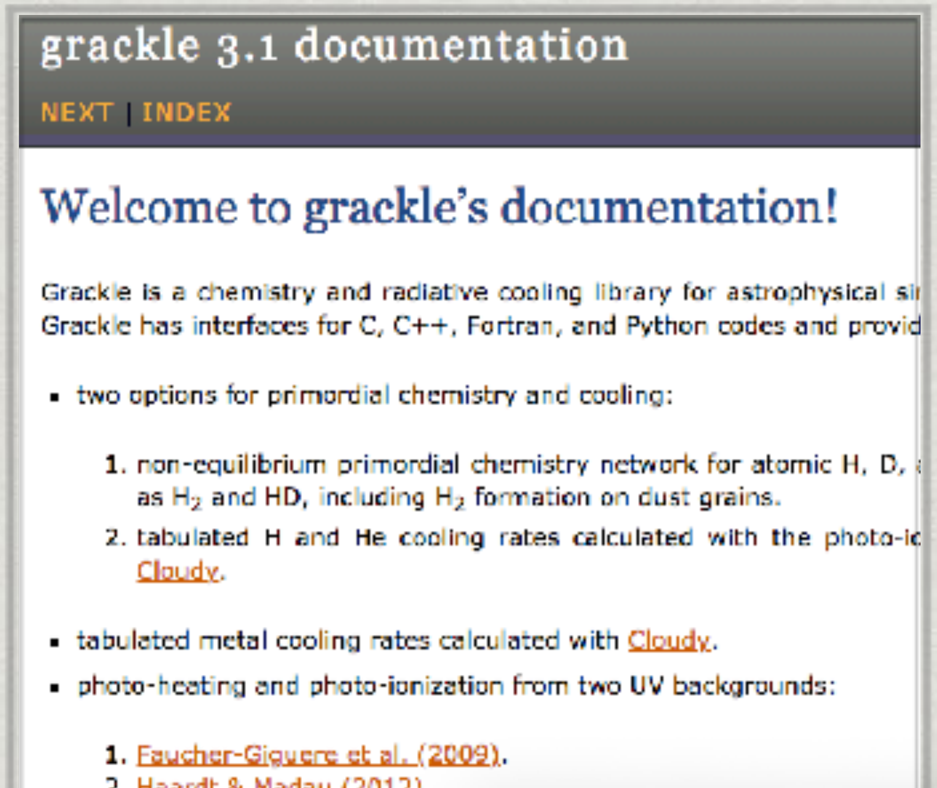
Pop2Prime: metal-enriched stars in a cosmological context

- Enzo: open-source AMR
- Cosmology: 0.5 Mpc/h box
  10^7 $M_\odot$ halo at $z = 10$.
- Resolution:
  - 1 $M_\odot$ dark matter particles.
  - AMR: spatial resolution ~ 1 AU.
- Physics and models:
  - Star particles: 40 $M_\odot$ Pop III star
    t_{ms} = 3.86 Myr, core-collapse SN (1 β).
  - Adaptive ray-tracing rad. hydro.
  - Non-eq. H/D/He chemistry, dust, metal cooling with Grackle.
- Run until collapse with $Z > 10^{-6}$ $Z_\odot$.



Grackle: chemistry and cooling as a resource

- Non-eq. H/D/He/dust chemistry, heavy element cooling, UV radiation backgrounds, self-shielding,…
- Library with **stable** APIs for C, C++, Fortran, Python: used in >14 codes.
- Optimized and OpenMP parallel.
- Community developed.
- Access to established models, updated rates.
- Disseminate your research, be credited for it.


grackle 3.1 documentation

NEXT | INDEX

Welcome to grackle's documentation!

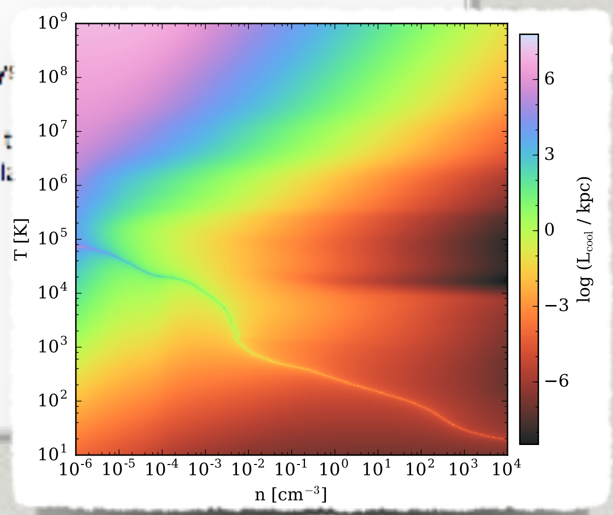
Grackle is a chemistry and radiative cooling library for astrophysical si
Grackle has interfaces for C, C++, Fortran, and Python codes and provid

- two options for primordial chemistry and cooling:
  1. non-equilibrium primordial chemistry network for atomic H, D, a as H_2 and HD, including H_2 formation on dust grains.
  2. tabulated H and He cooling rates calculated with the photo-io Cloudy.
- tabulated metal cooling rates calculated with Cloudy.
- photo-heating and photo-ionization from two UV backgrounds:
  1. Faucher-Giguere et al. (2009).
  2. Haardt & Madau (2012).
- support for user-provided arrays

The Grackle provides functions t update internal energy; and calcul heats (gamma).

Contents:

- Installation
  - Dependencies
  - Downloading



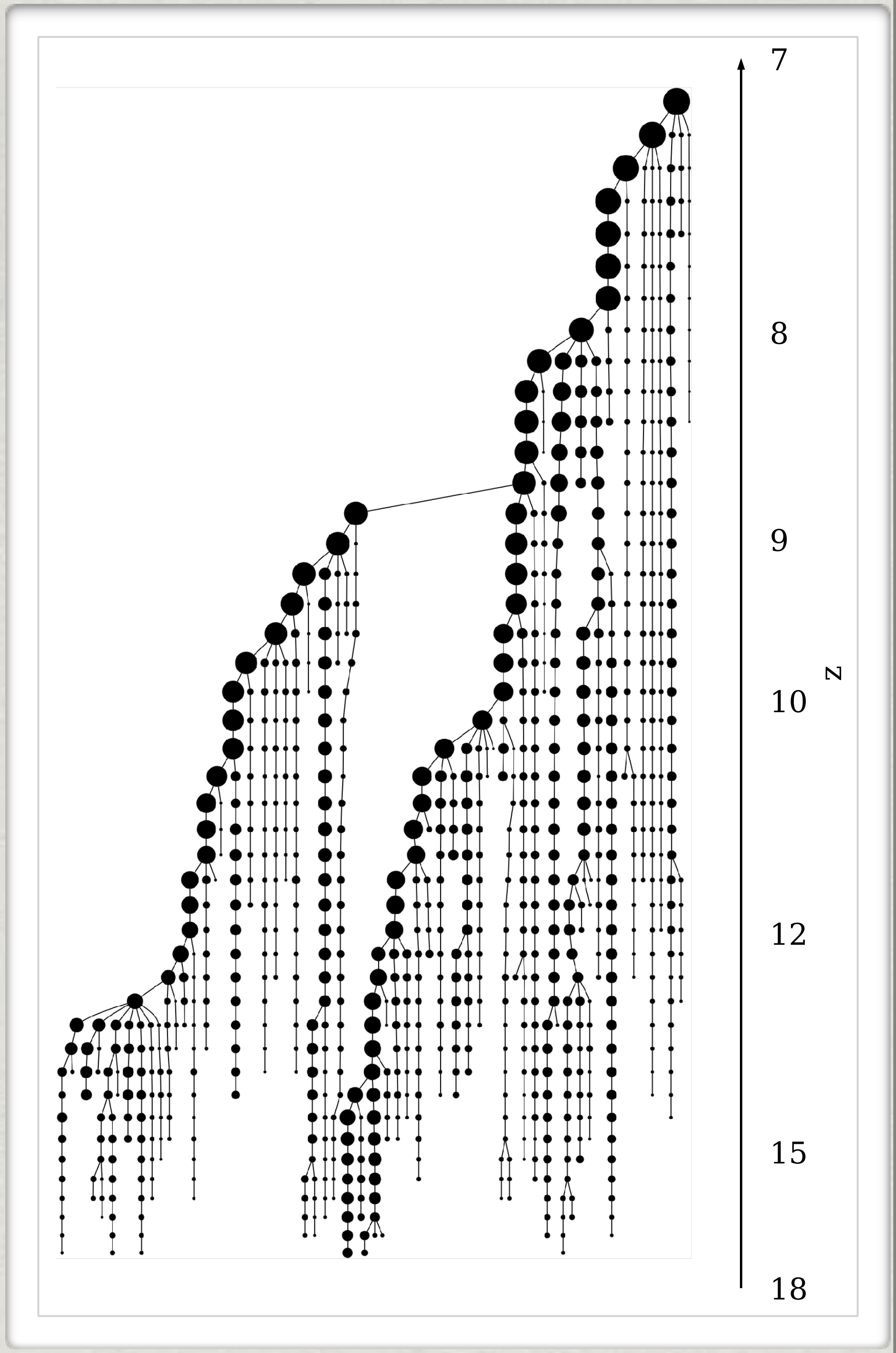
grackle.readthedocs.io

Smith et al. (2017)

ytree: yt for tree data

```
>>> import ytree
>>> a = ytree.load("tree_0_0_0.dat")
>>> print (a[0]["prog", "mass"])
YTArray([  6.57410072e+14,   6.57410072e+14, ...
           7.72949640e+13,   5.99280576e+13]) Msun
```

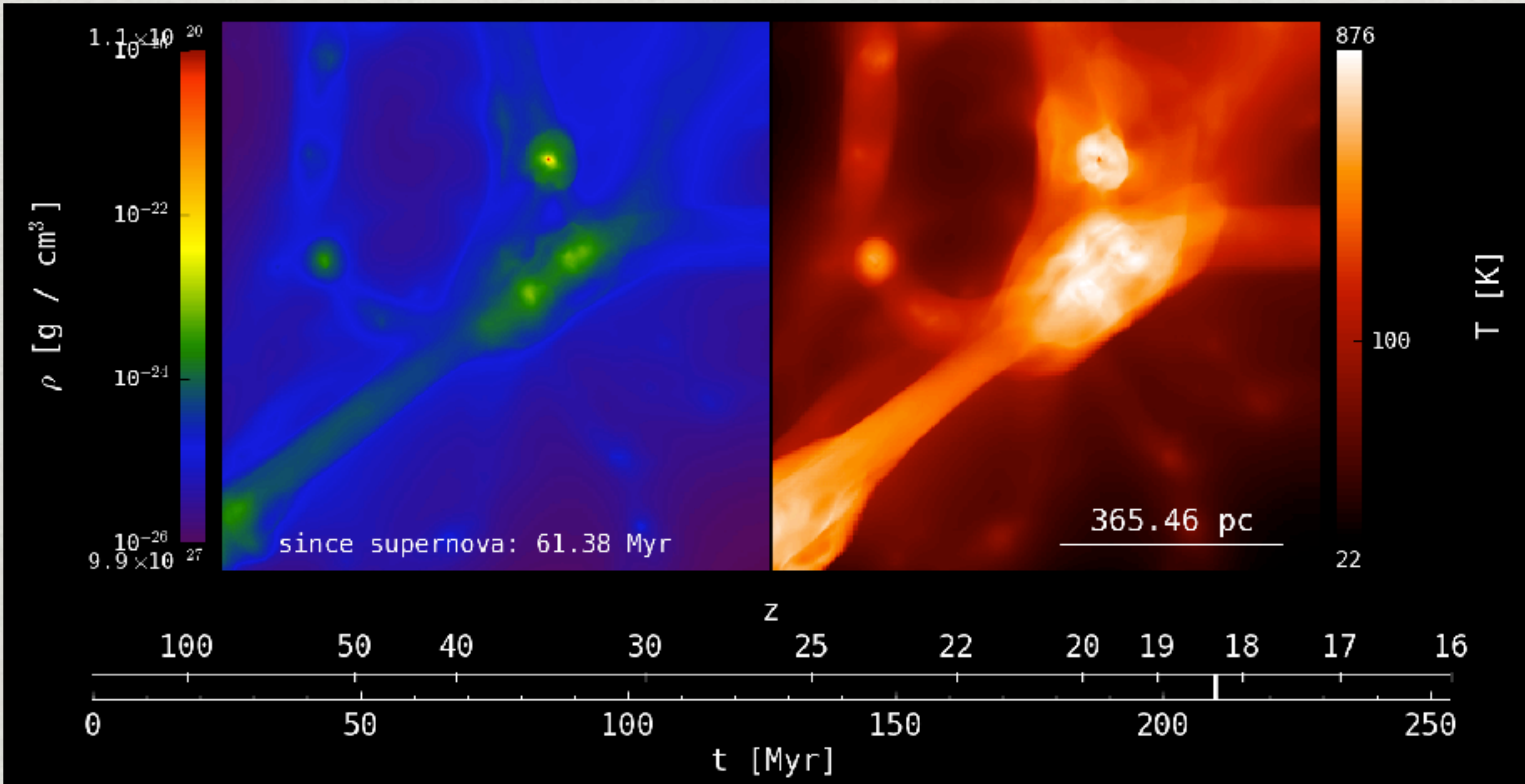
- merger-tree data from multiple formats
  - Amiga Halo Finder
  - Consistent-trees/Rockstar
  - LHaloTree
- Create merger trees for Gadget FoF/SUBFIND
- incremental tree building, on-demand field loading, derived fields, symbolic units
- re-save trees in optimized format



Cote et al. (2018)

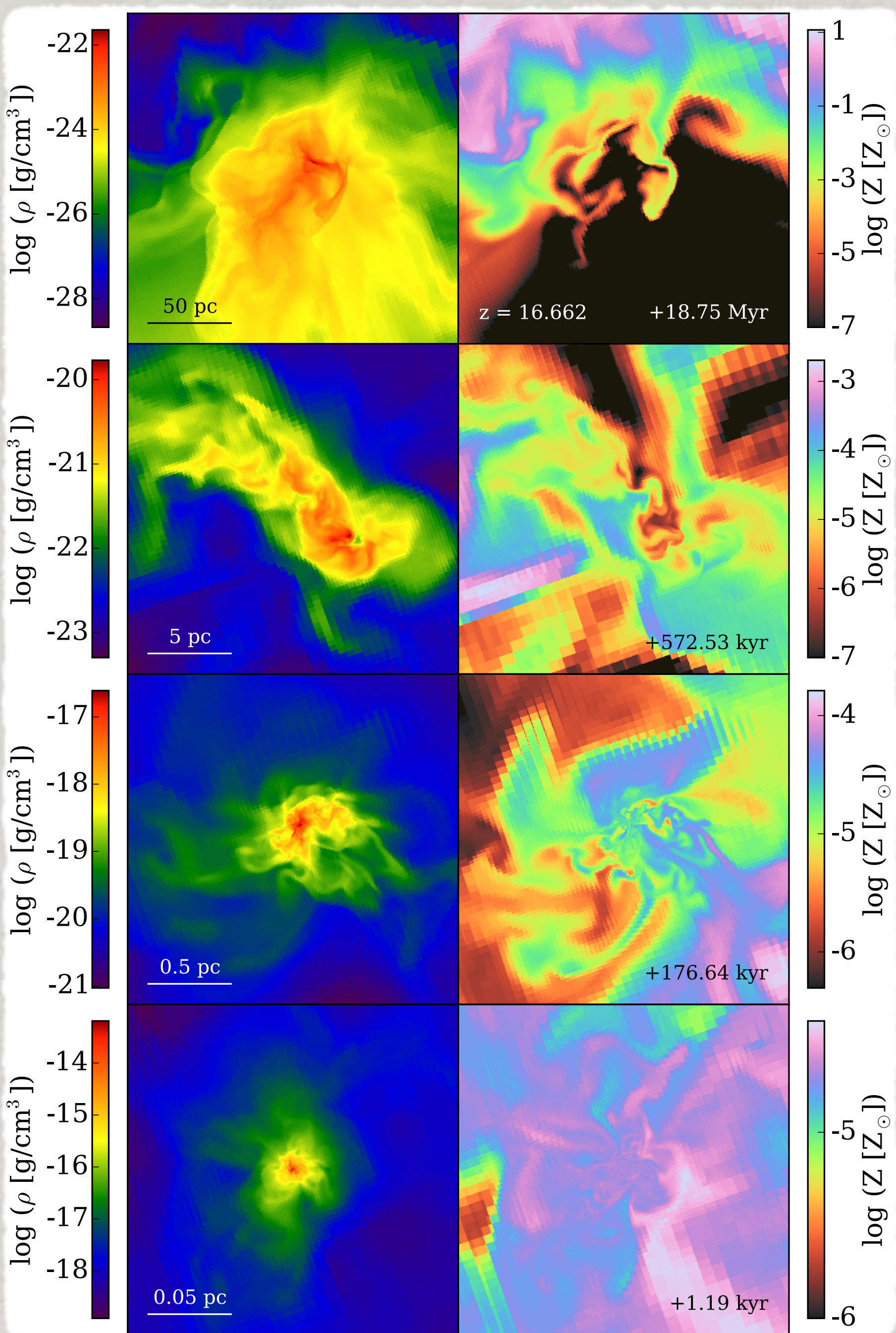
ytree.readthedocs.io (Smith and Lang, 2018)

External Enrichment

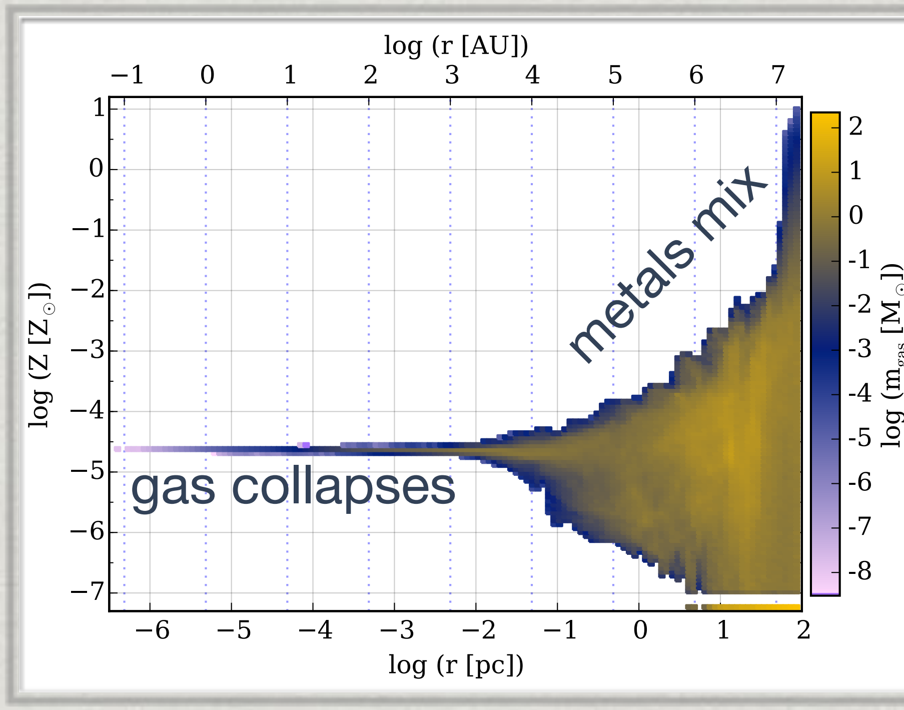


Smith et al. (2015)

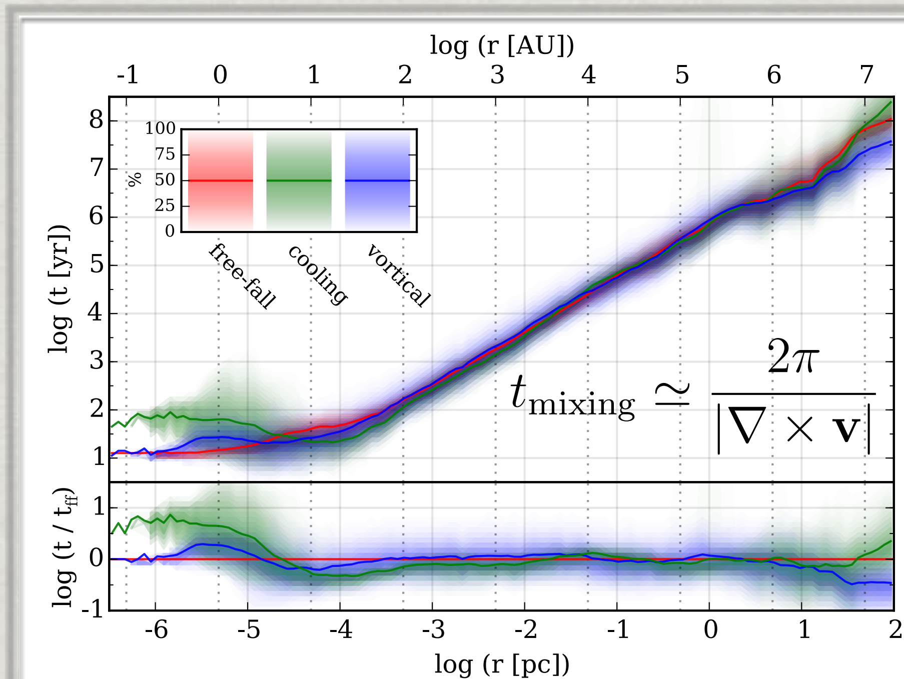
External Enrichment



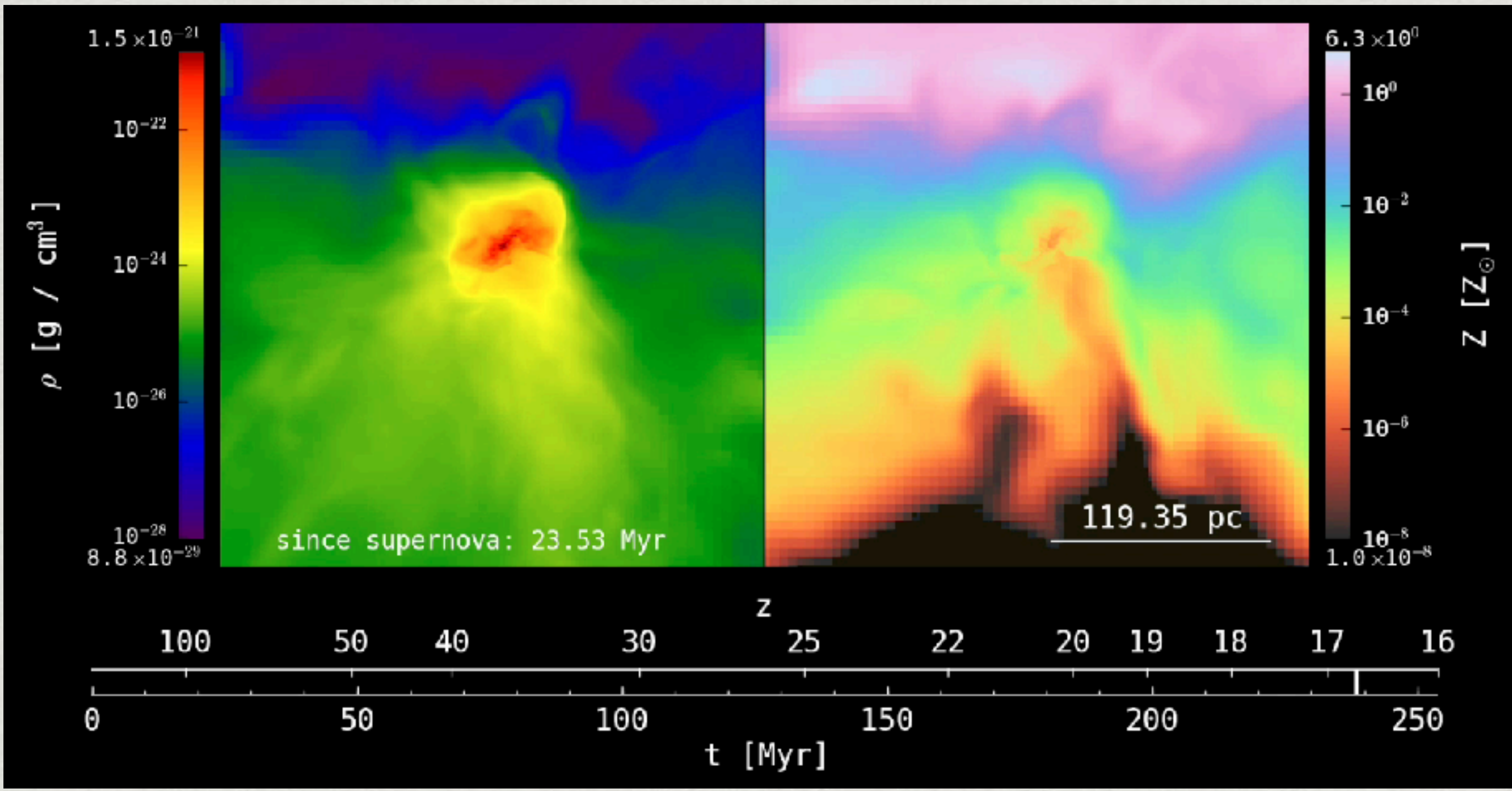
Smith et al. (2015)



- Prompt star formation after enrichment: ~25 Myr
- Star formation from a single Pop III progenitor: Z ~ 2x10^{-5} Z$_\odot$

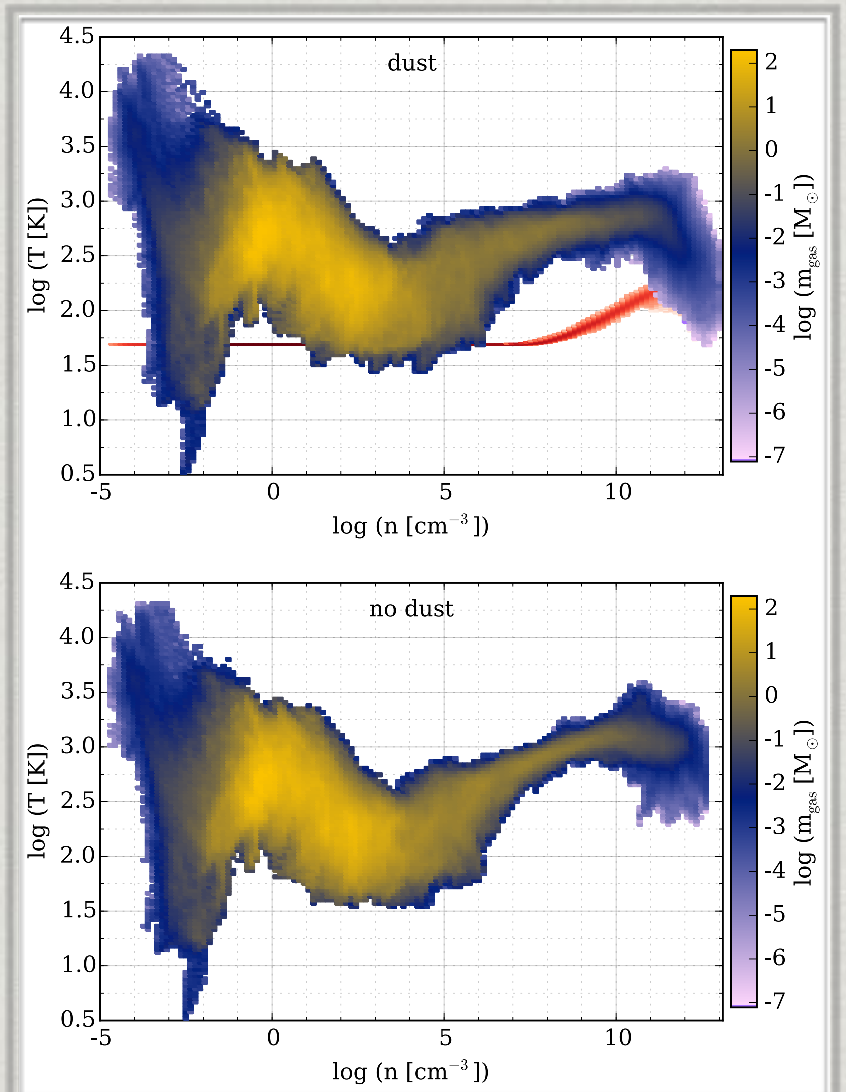


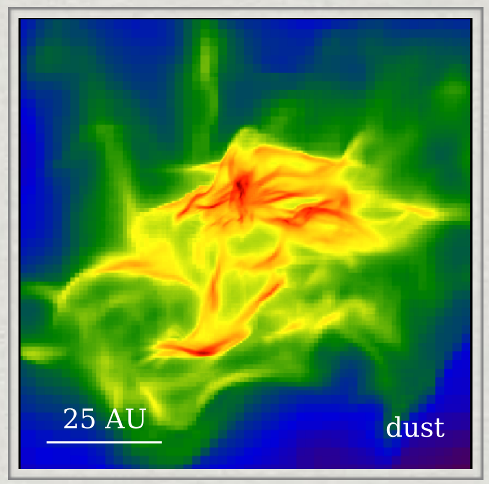
Collapse and Fragmentation

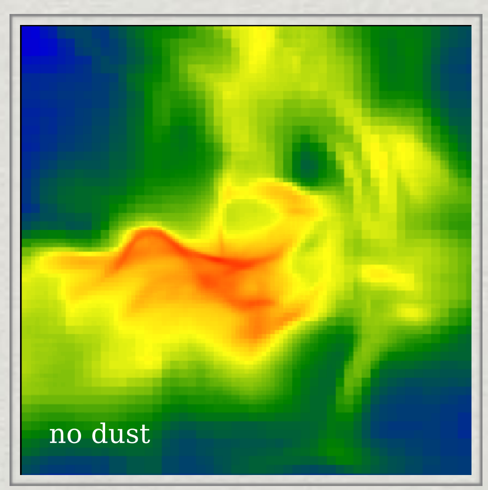


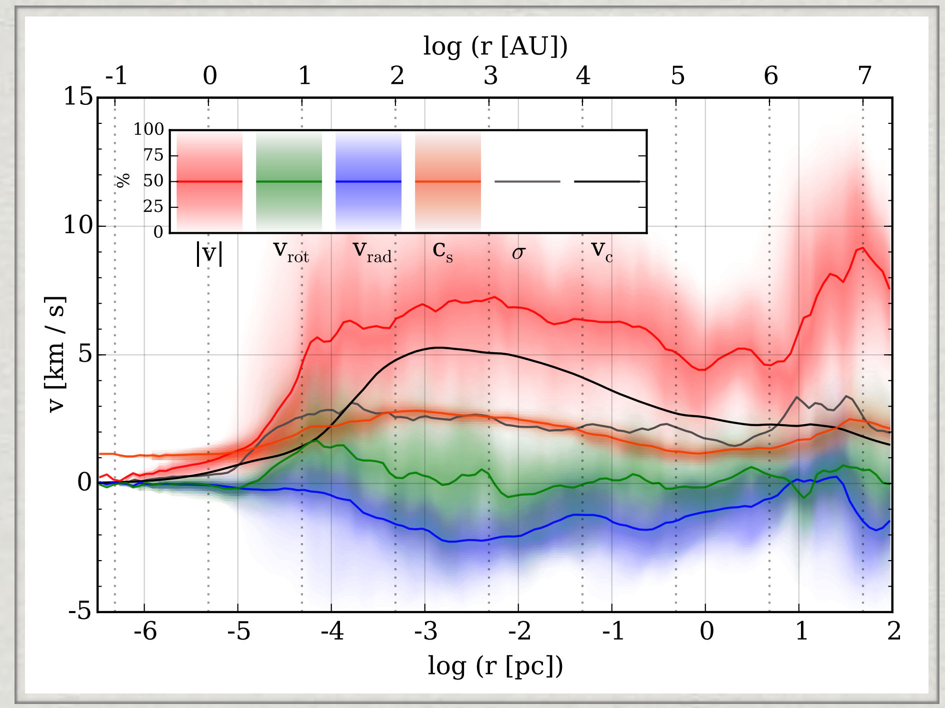
Smith et al. (2015)

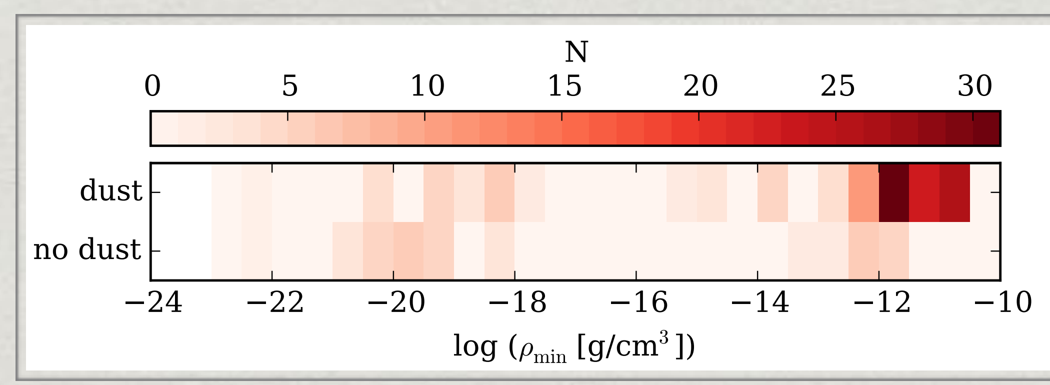
Fragmentation and Physical Conditions ($10^{-5} Z_{\odot}$)





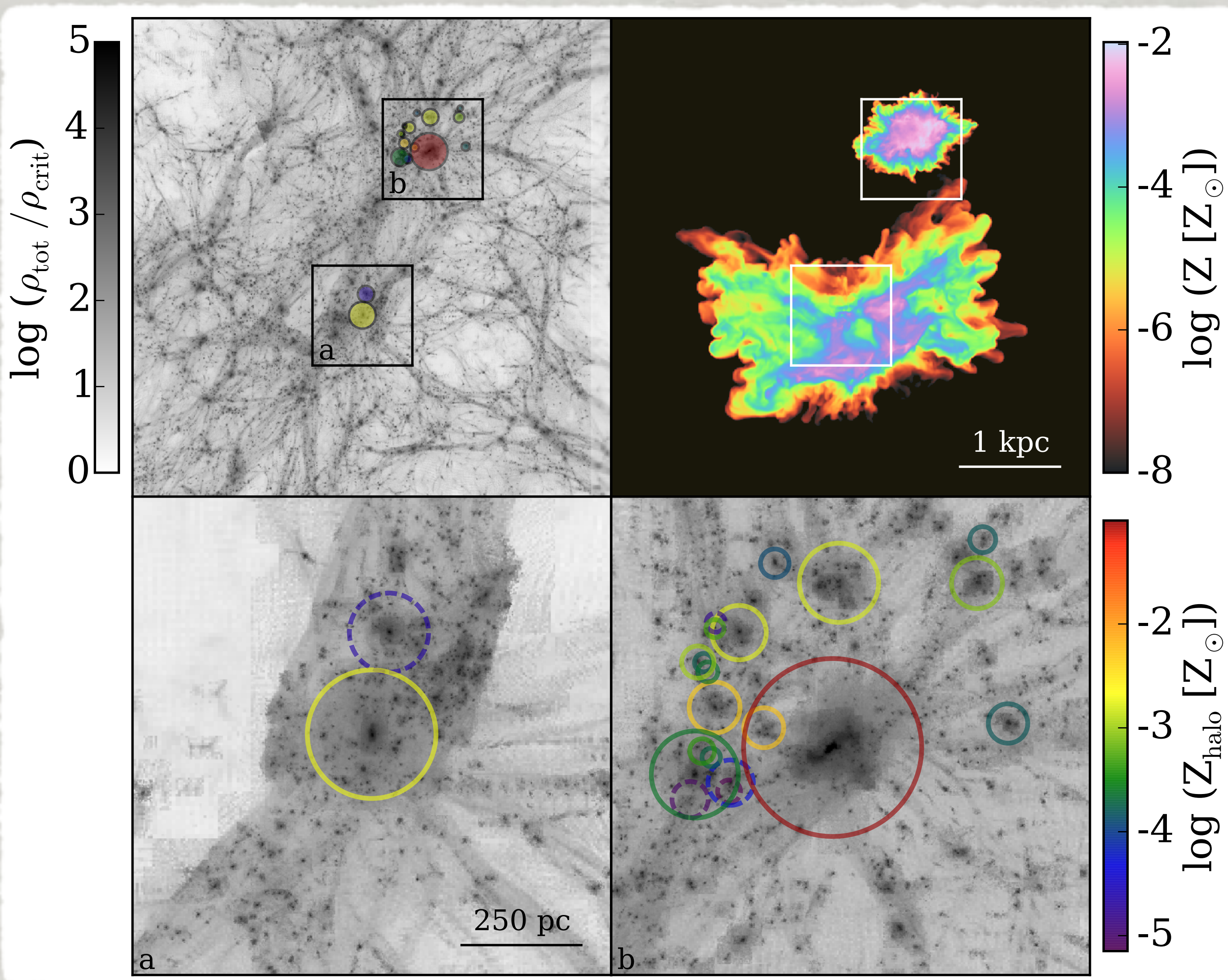




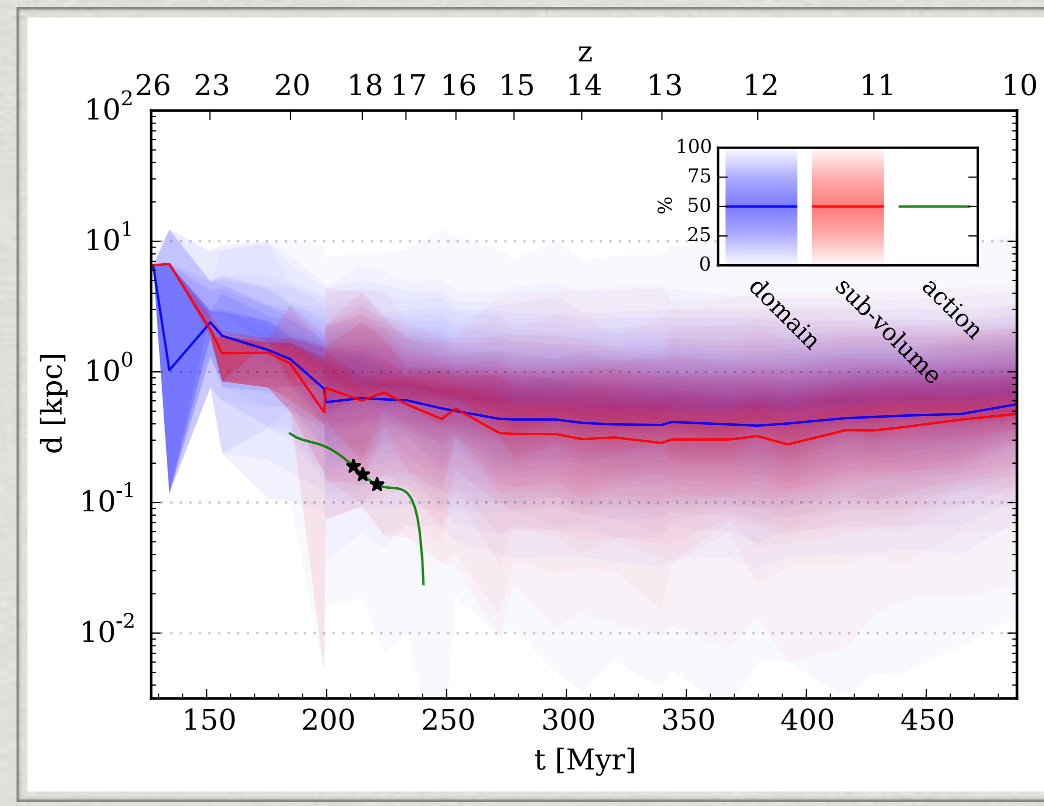


Smith et al. (2015)

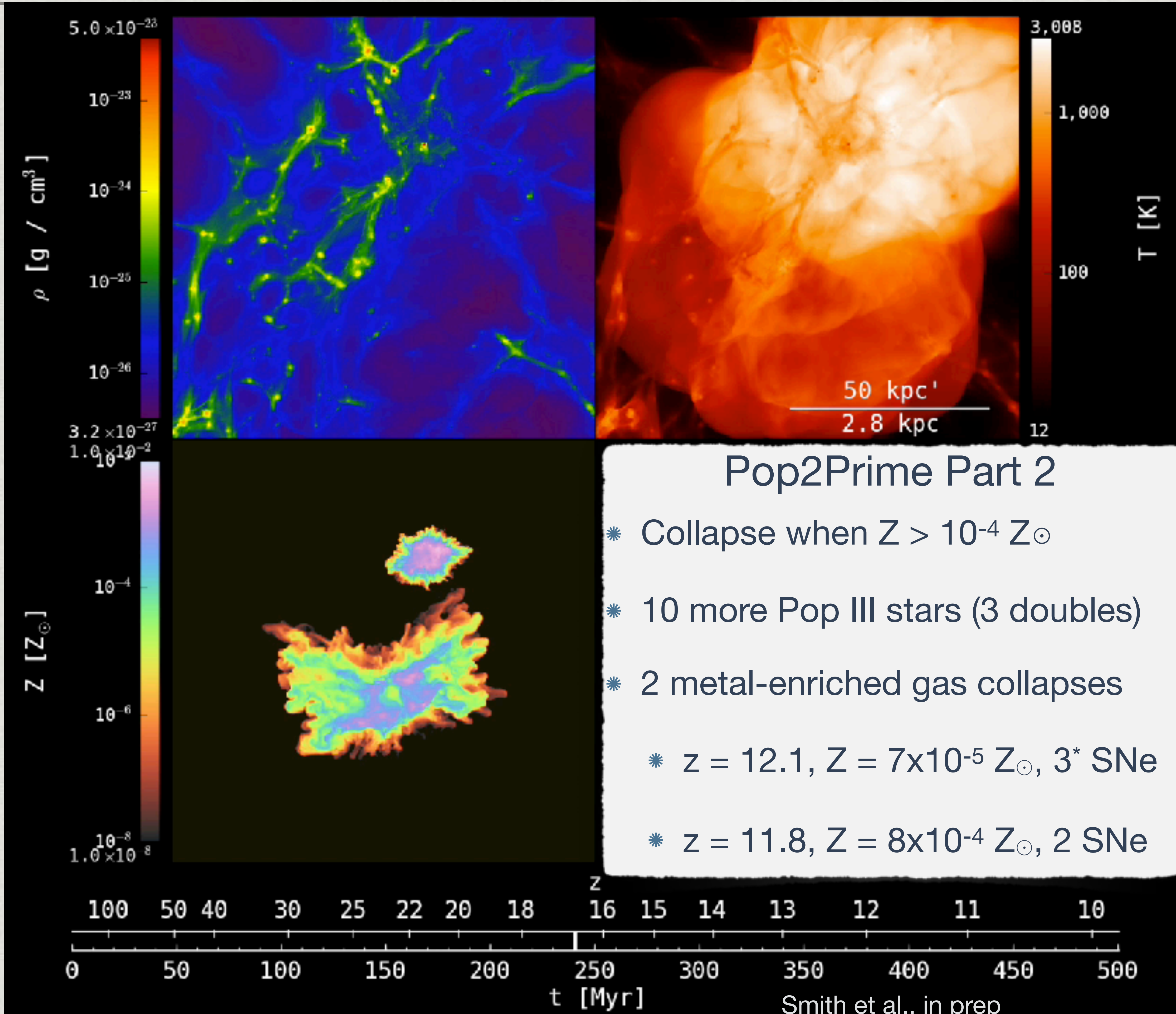
External Enrichment: slightly bigger picture



Smith et al. (2015)



- mini-halo separation ~1σ below average
- single progenitor, wide range of halo metallicities

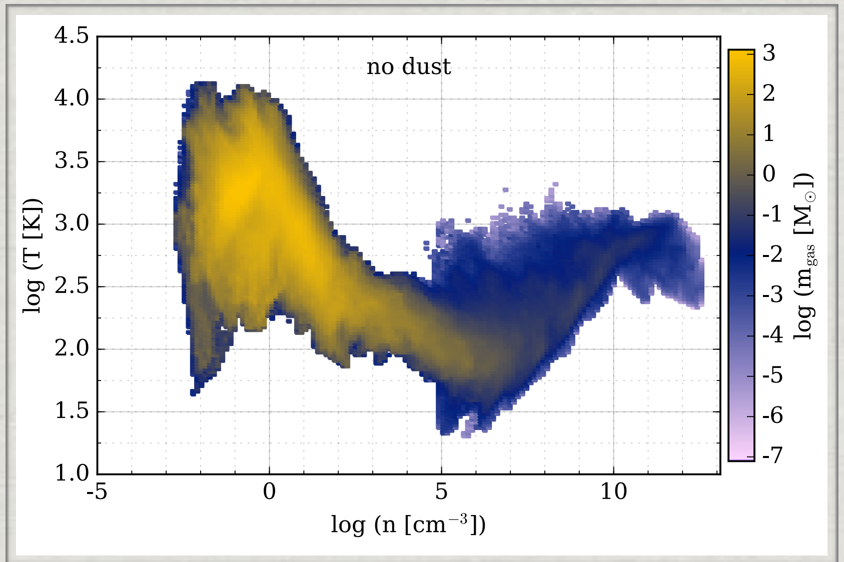


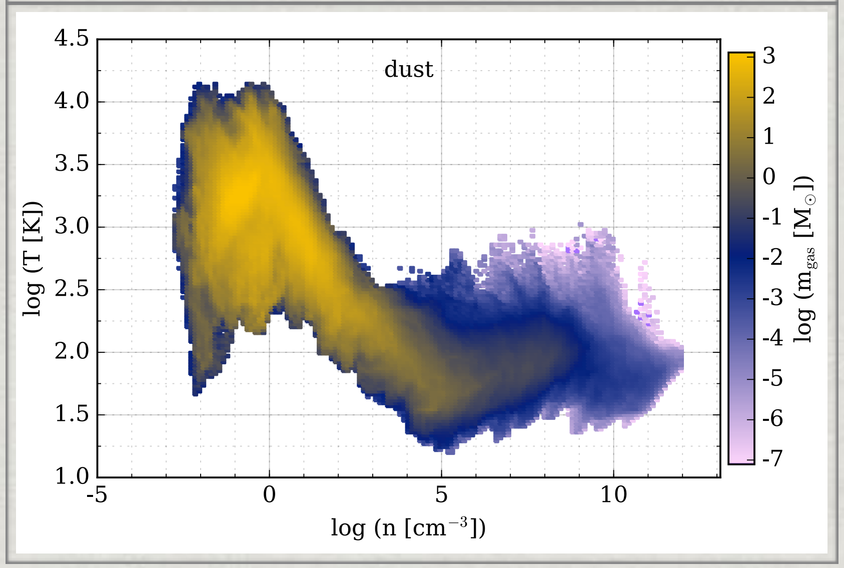
Pop2Prime Part 2

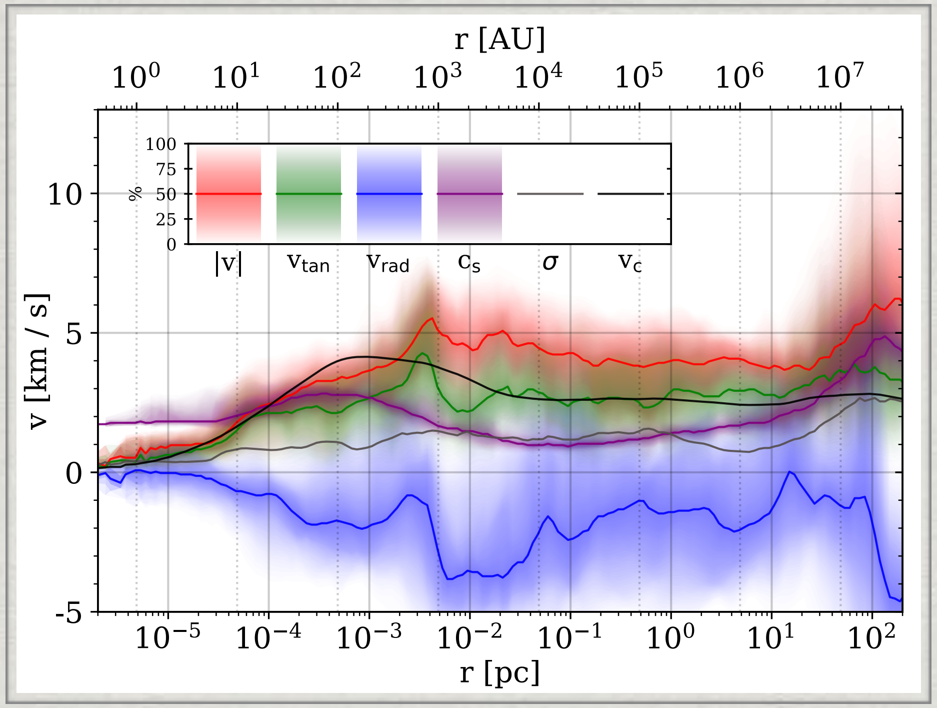
- Collapse when $Z > 10^{-4}\ Z_{\odot}$
- 10 more Pop III stars (3 doubles)
- 2 metal-enriched gas collapses
  - $z = 12.1$, $Z = 7\times10^{-5}\ Z_{\odot}$, 3* SNe
  - $z = 11.8$, $Z = 8\times10^{-4}\ Z_{\odot}$, 2 SNe

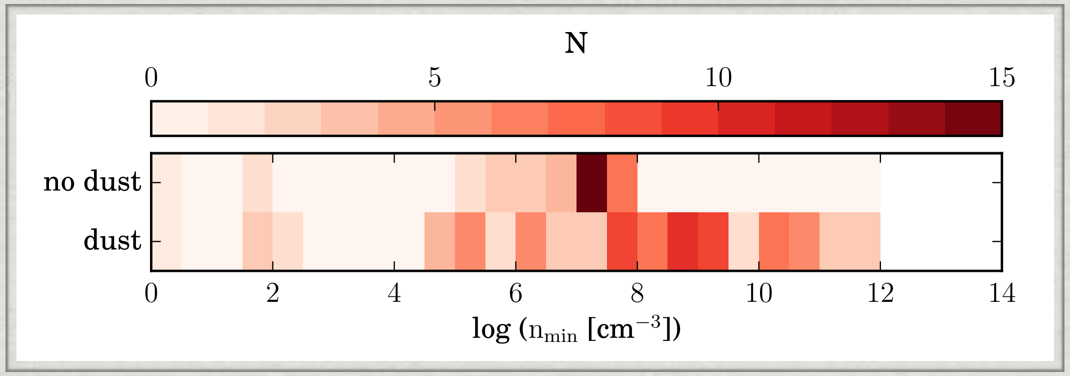
Smith et al., in prep

Fragmentation and Physical Conditions (10^{-3} $Z_\odot$)

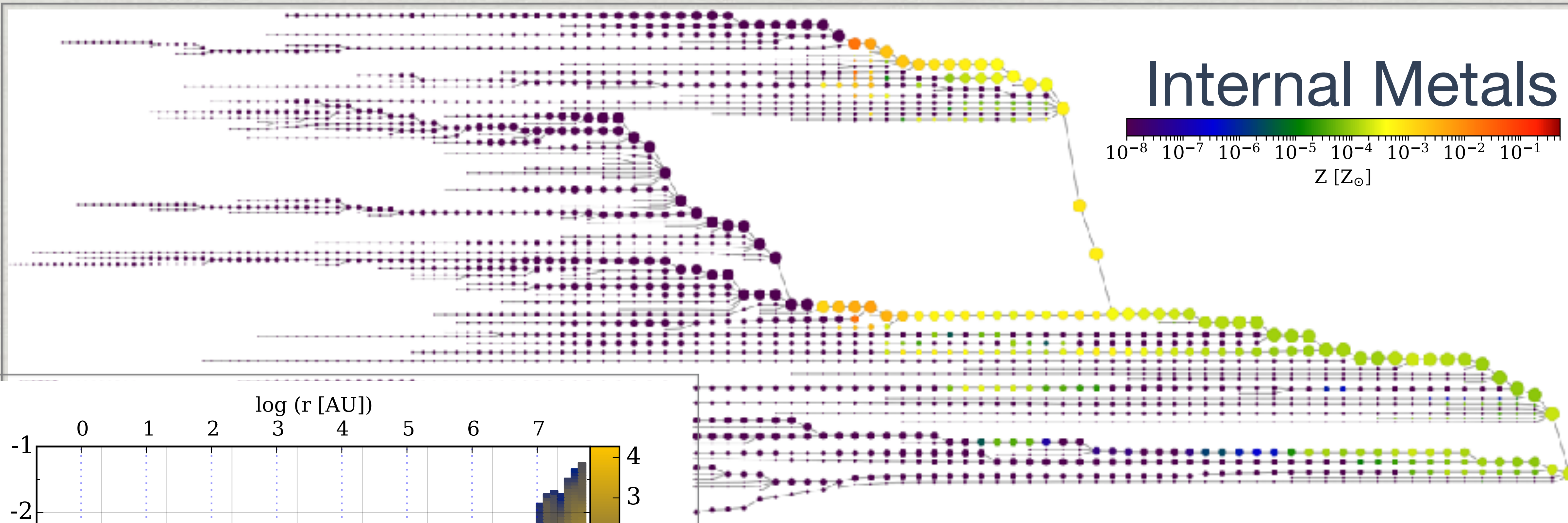


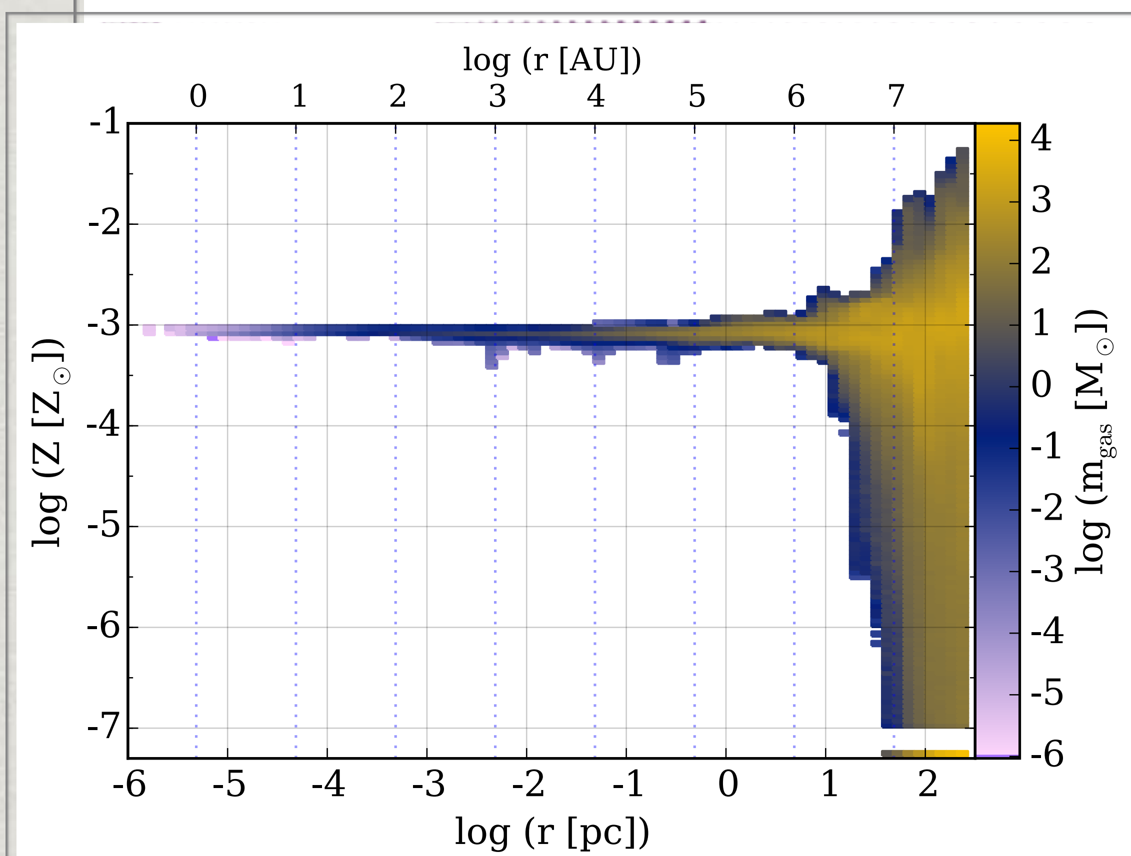






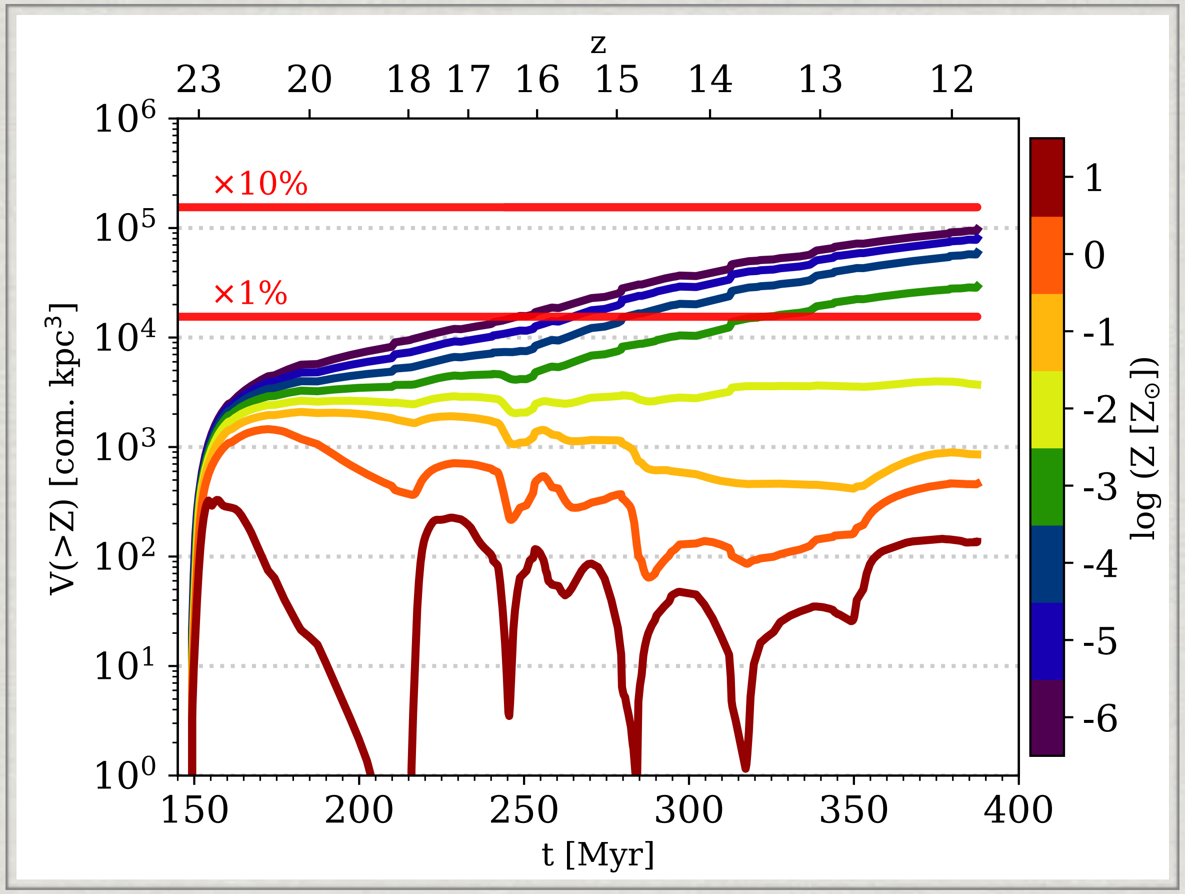
Prompt Enrichment
Delayed Collapse



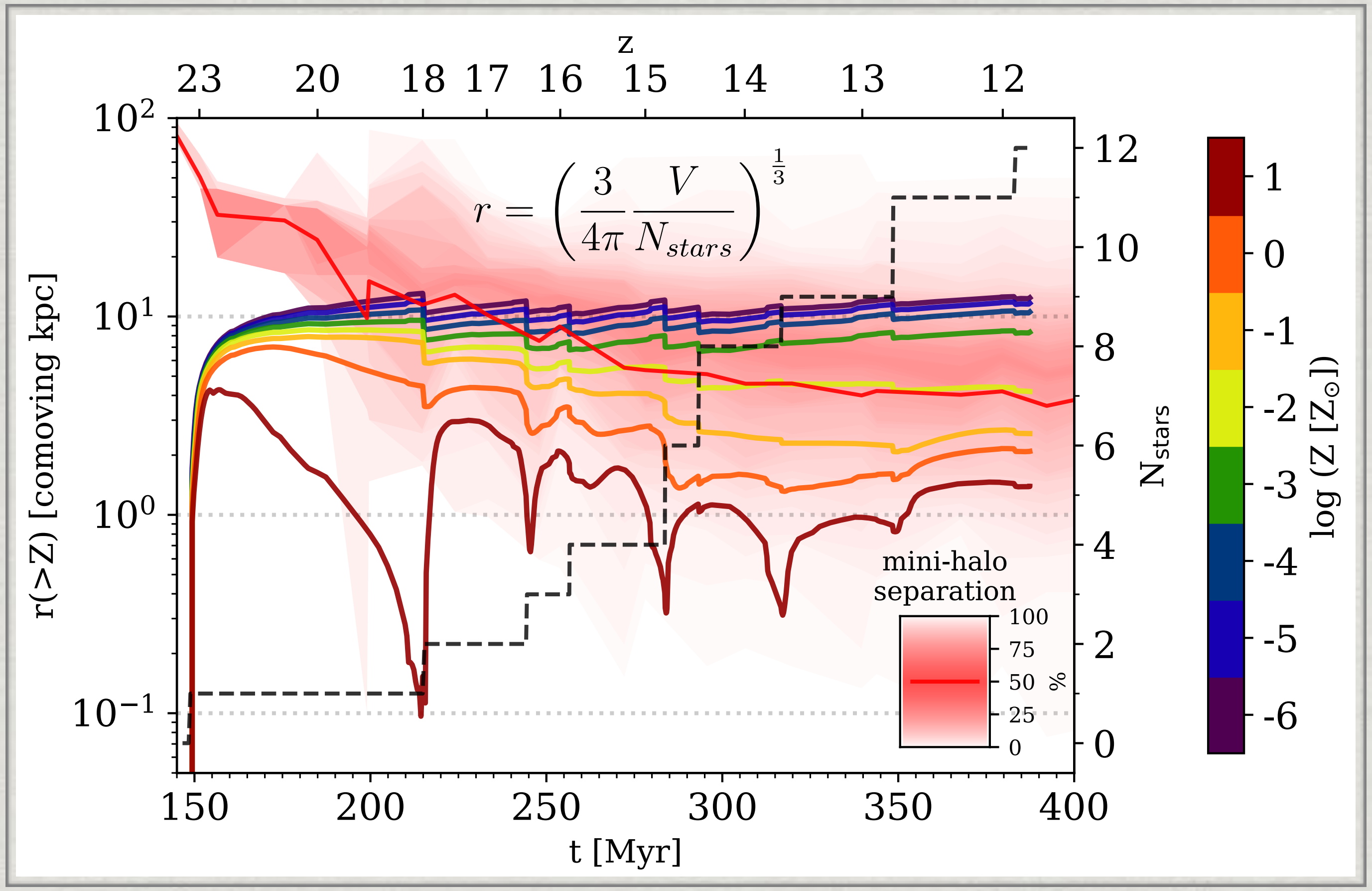


- collapse with Z = 8×10^{-4} $Z_\odot$ at z = 11.8
- 2 blast-waves:
  - SN distances: 740 pc, 757 pc
  - cross-over times: 79 Myr, 105 Myr

Metal Enrichment by Pop III

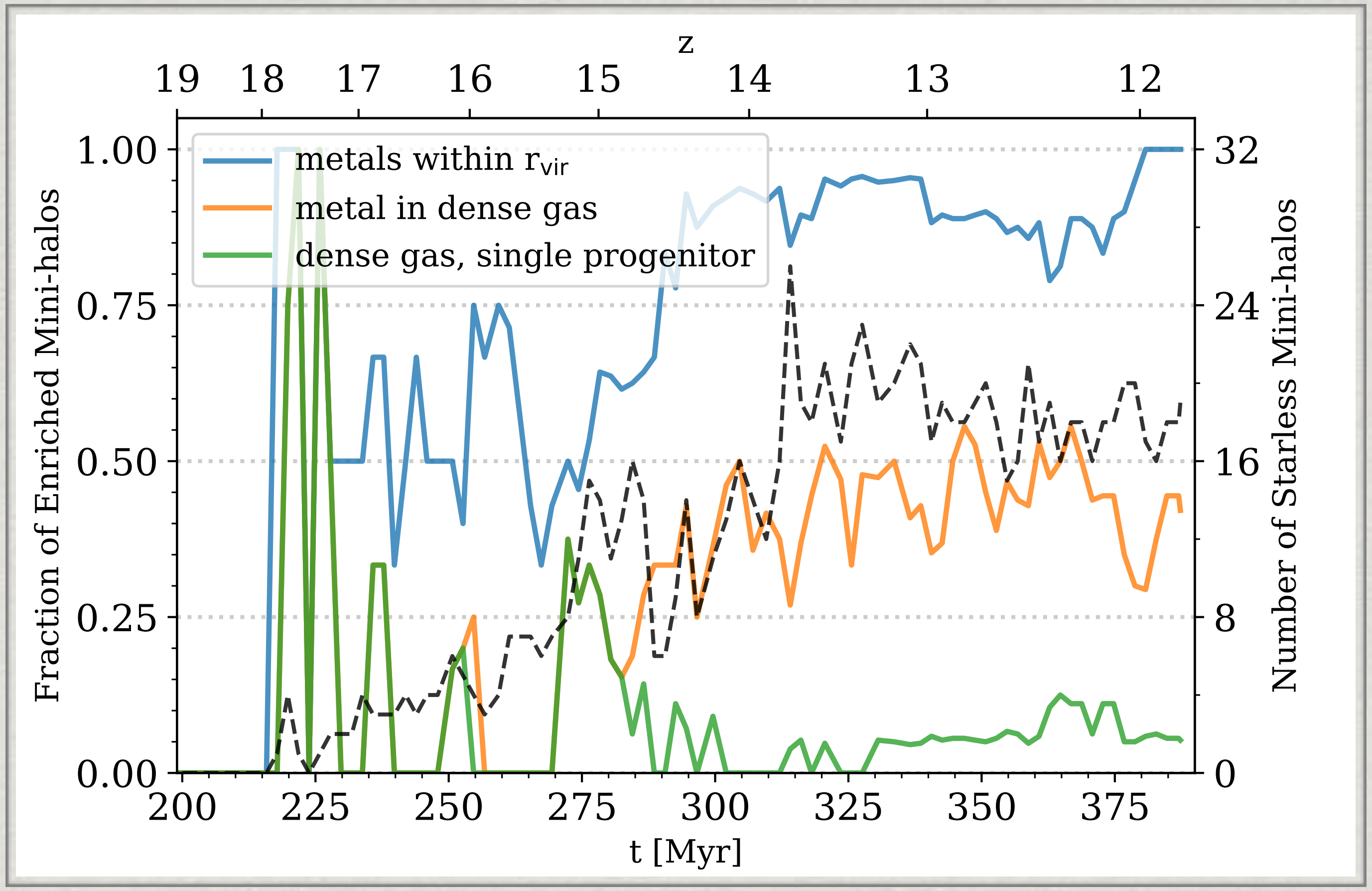


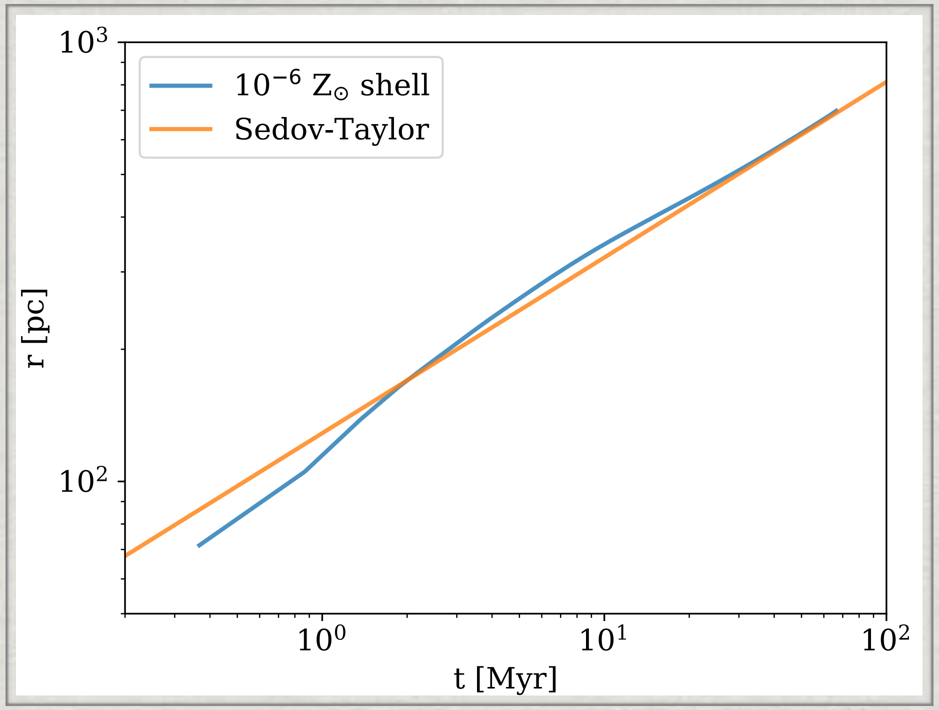
by volume



by spherical radius per star

Enrichment of Starless Mini-halos



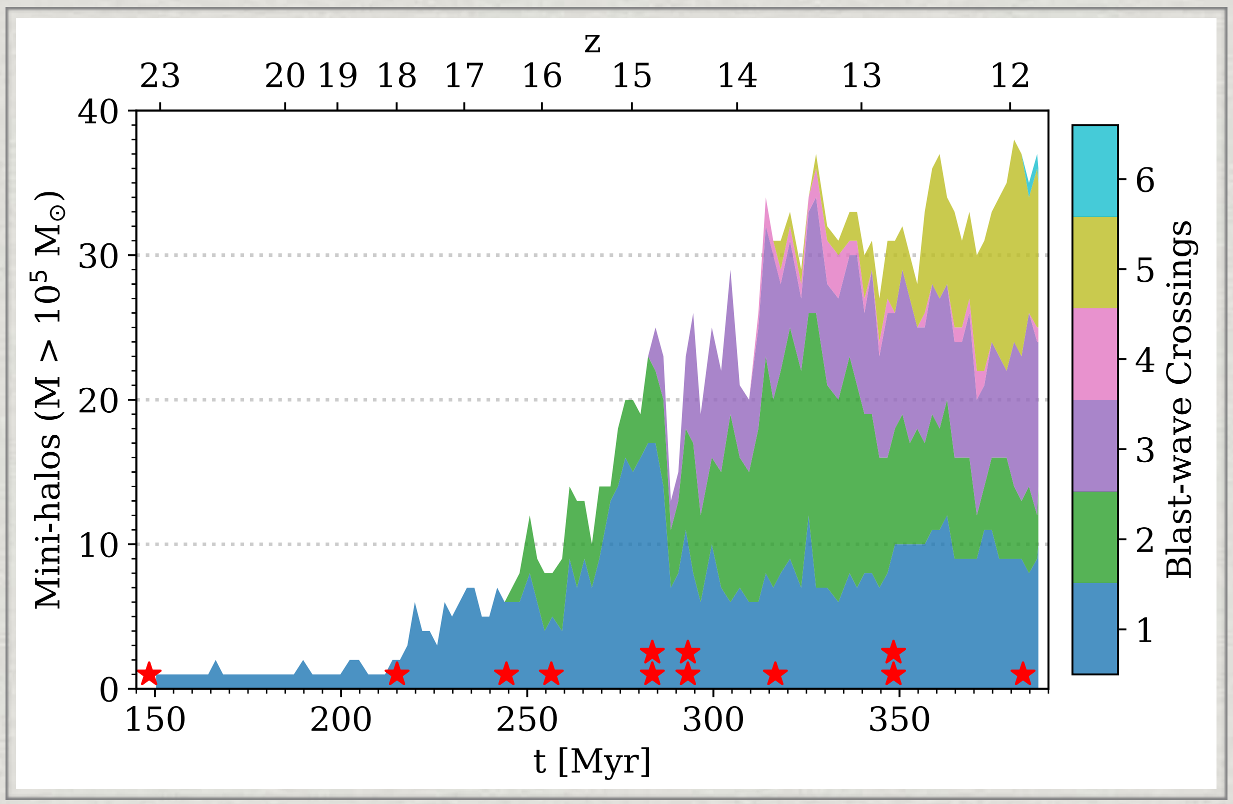


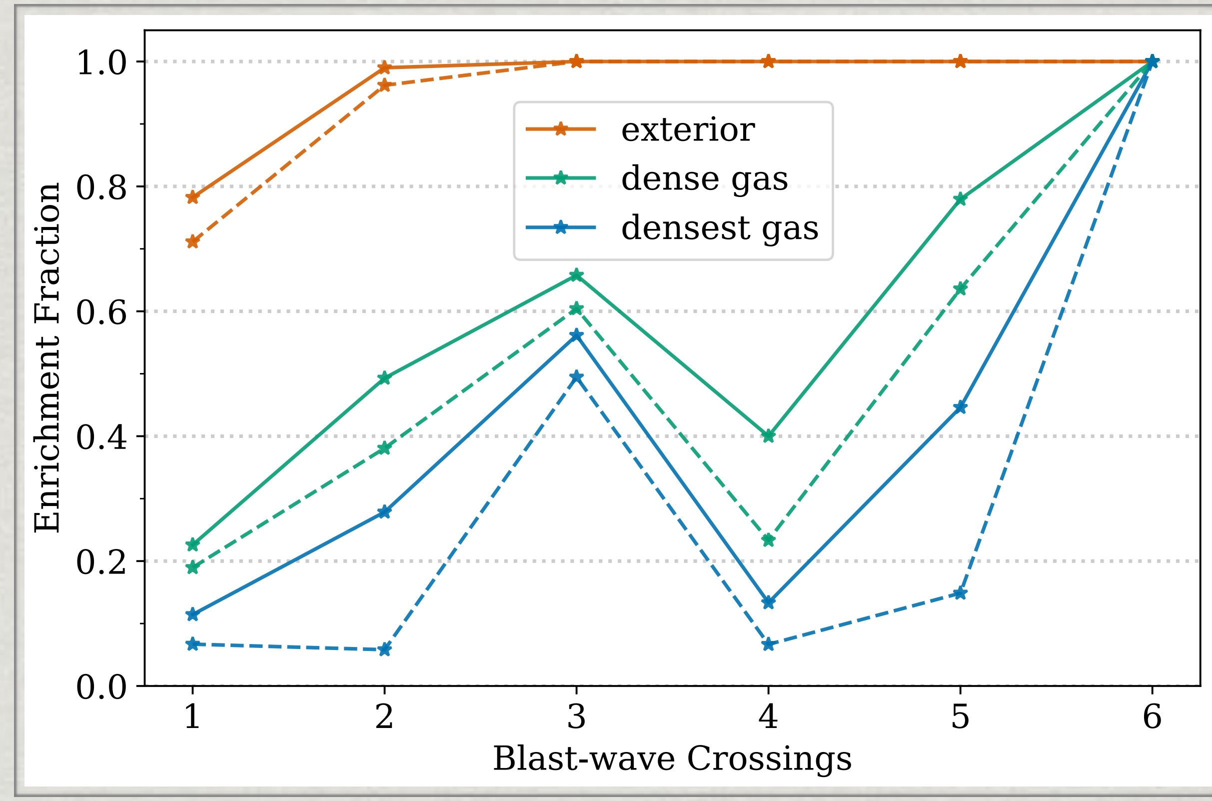
approximate metal bubble size

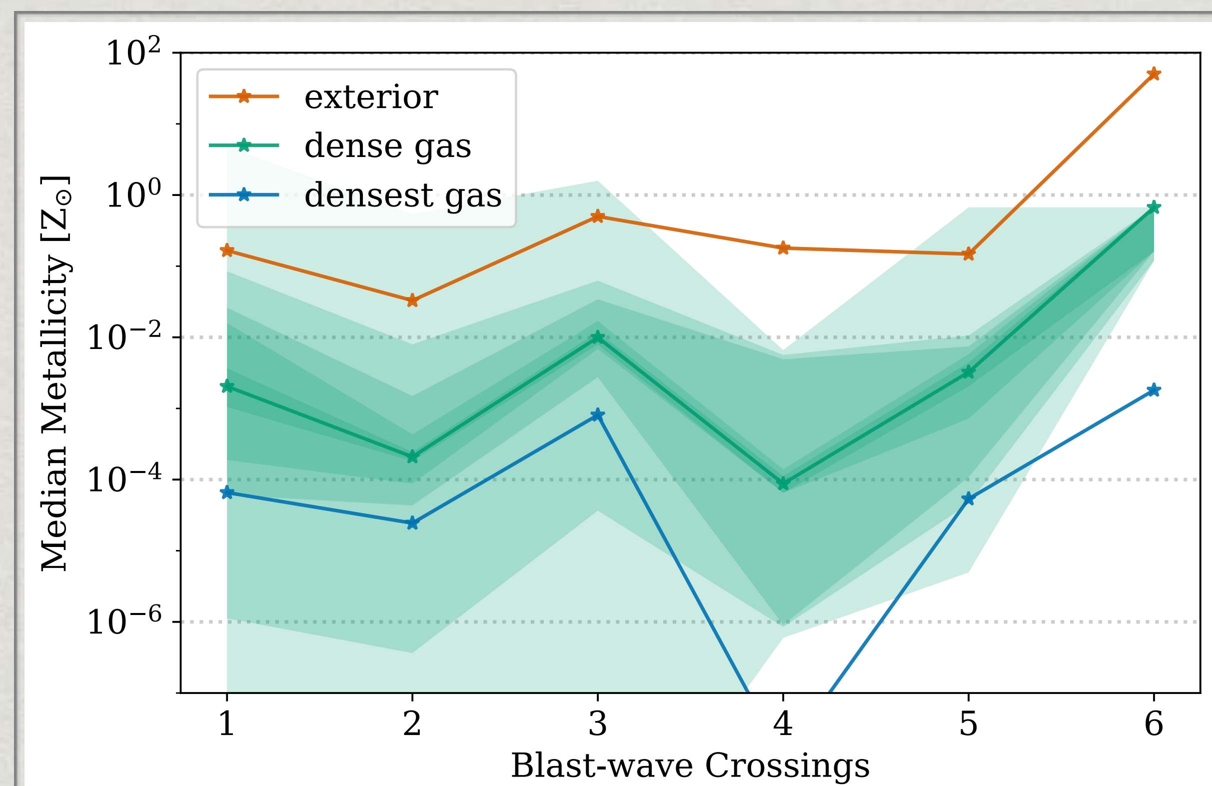
Blast-wave Crossings

$Z > 10^{-6} Z_\odot$

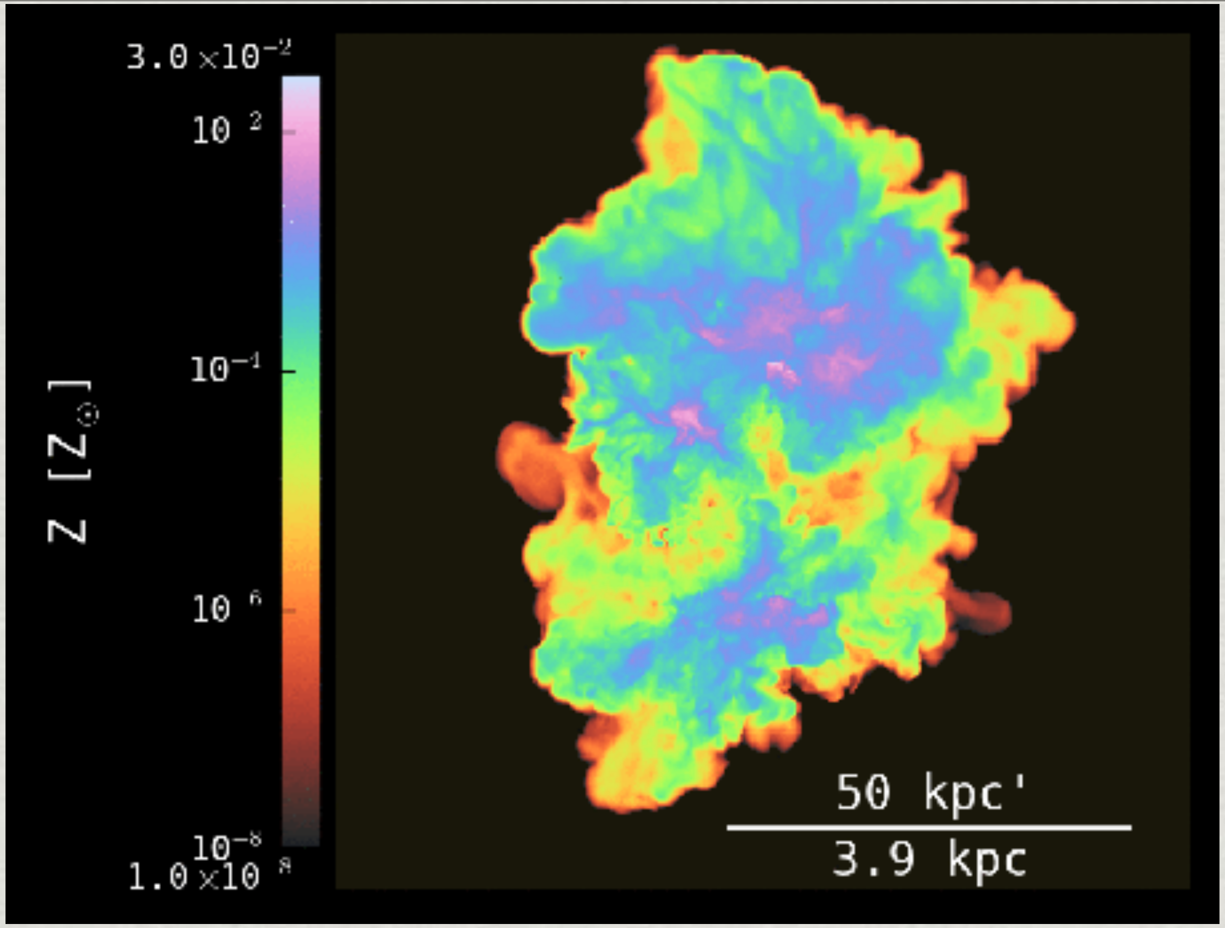
$Z > 10^{-4} Z_\odot$







Summary



- Check these out/get involved:
  - grackle.readthedocs.io
  - ytree.readthedocs.io
- Prompt metal-enriched star formation after a single Pop III SN is possible, but it might be rare.
- Low mass fragmentation needs dust even at gas-phase Z_{cr}.
- Singly enriched halos may form stars with a range of metallicities. Not all single-progenitor stars are low-Z.
- Halos impacted by multiple blast-waves have a range of metallicities. Not all low-Z stars have a single progenitor.