

Britton Smith

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Sadegh Khochfar

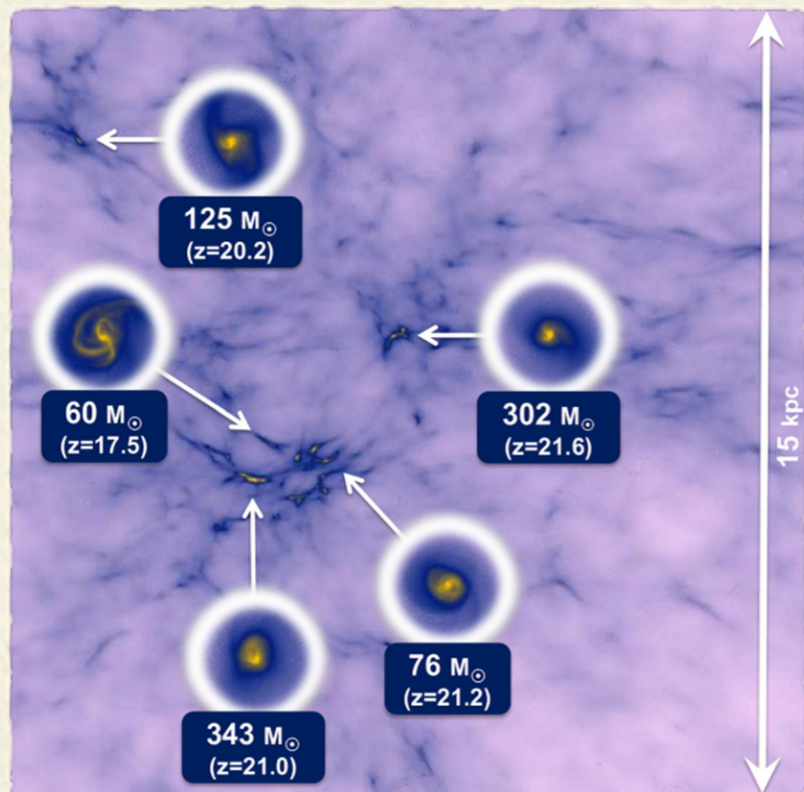
Mike Norman

Brian O'Shea

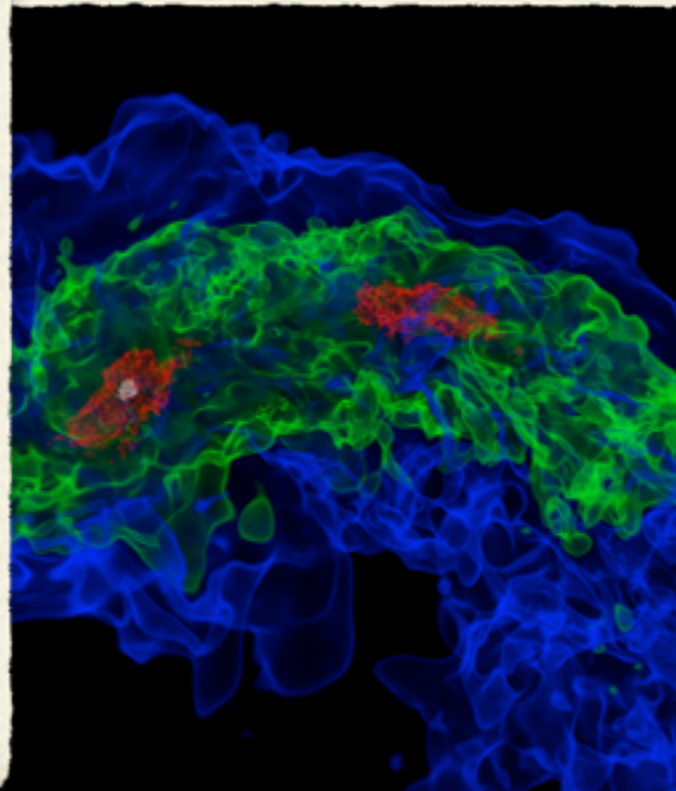
John Wise

Where did the first  
Pop II stars come from?

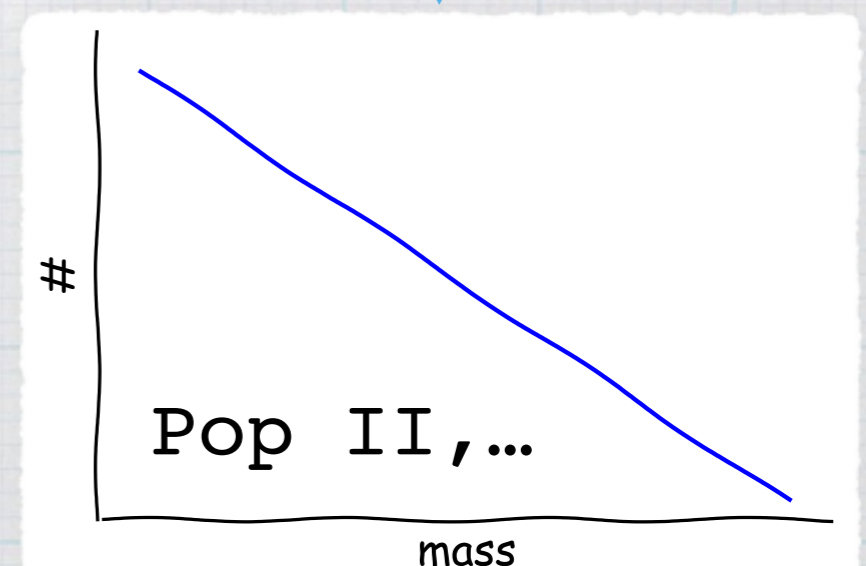
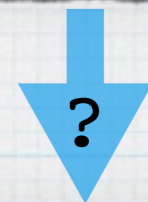
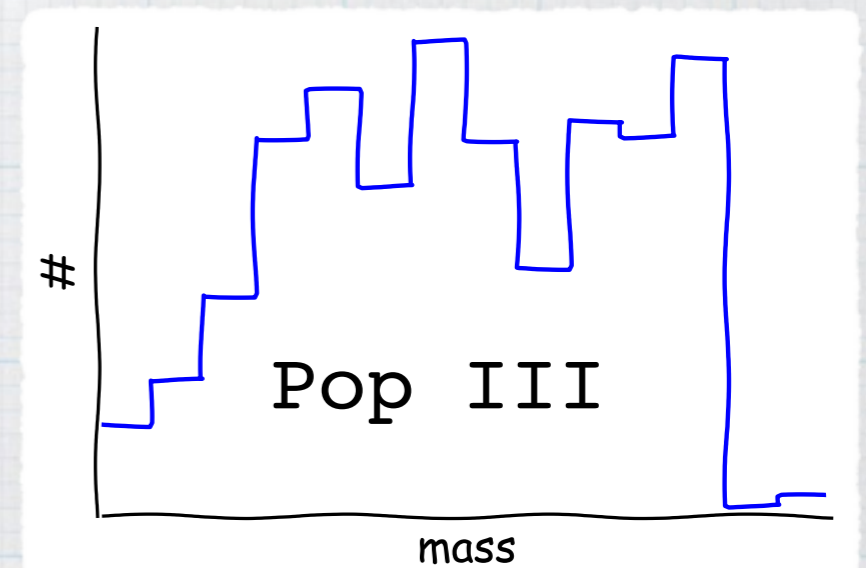
# Pop III to Pop II Transition



Hirano et al. (2014)

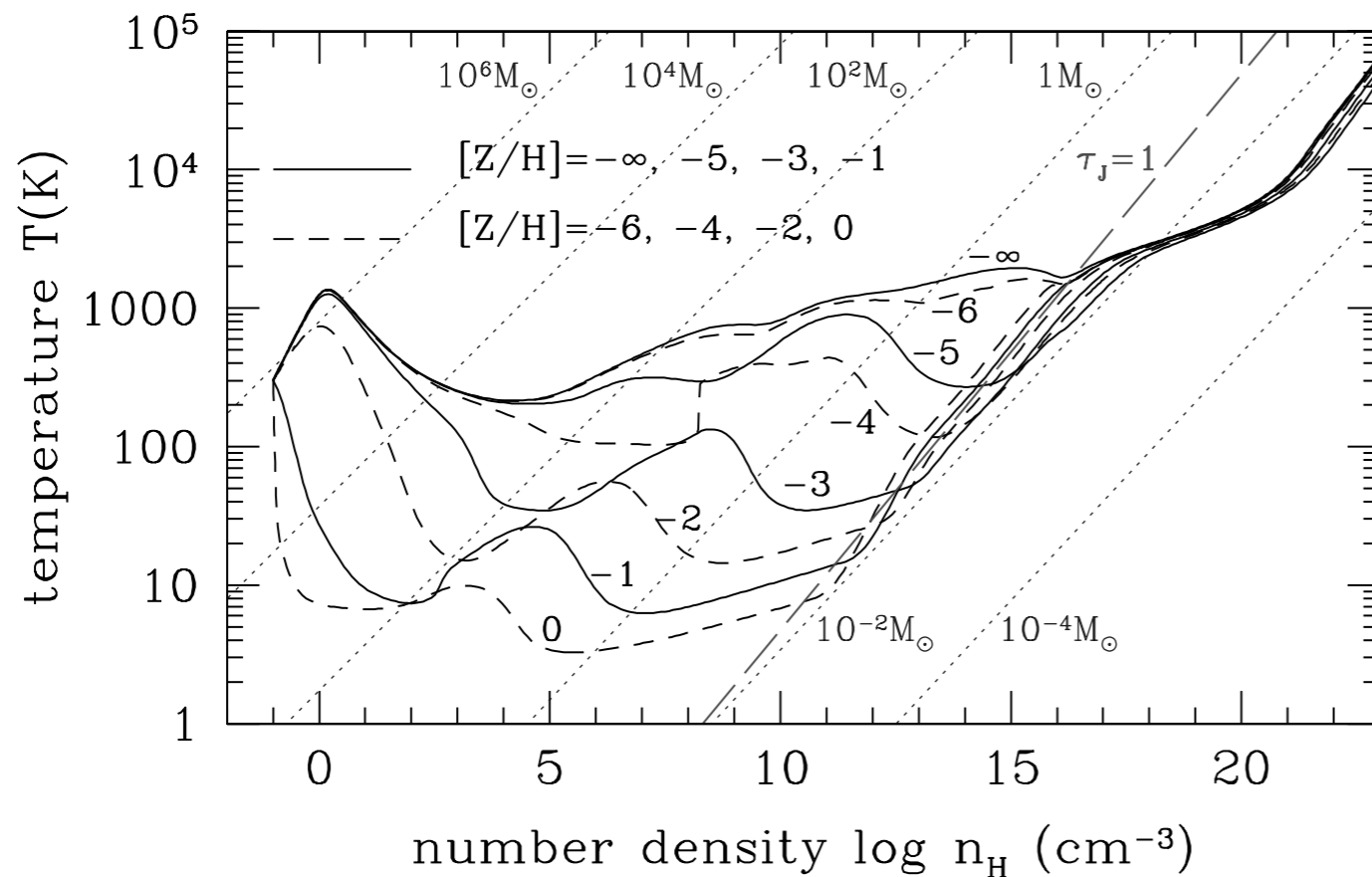


Matt Turk



- ▶ Pop III star formation seems fundamentally distinct.
- ▶ Pop III to Pop II transition informs the nature of stellar IMF.
- ▶ Metal-free stars have distinct spectral properties.
- ▶ Transition era ( $z \sim 10-20$ ) starting to be probed. What is the stellar content of these galaxies?

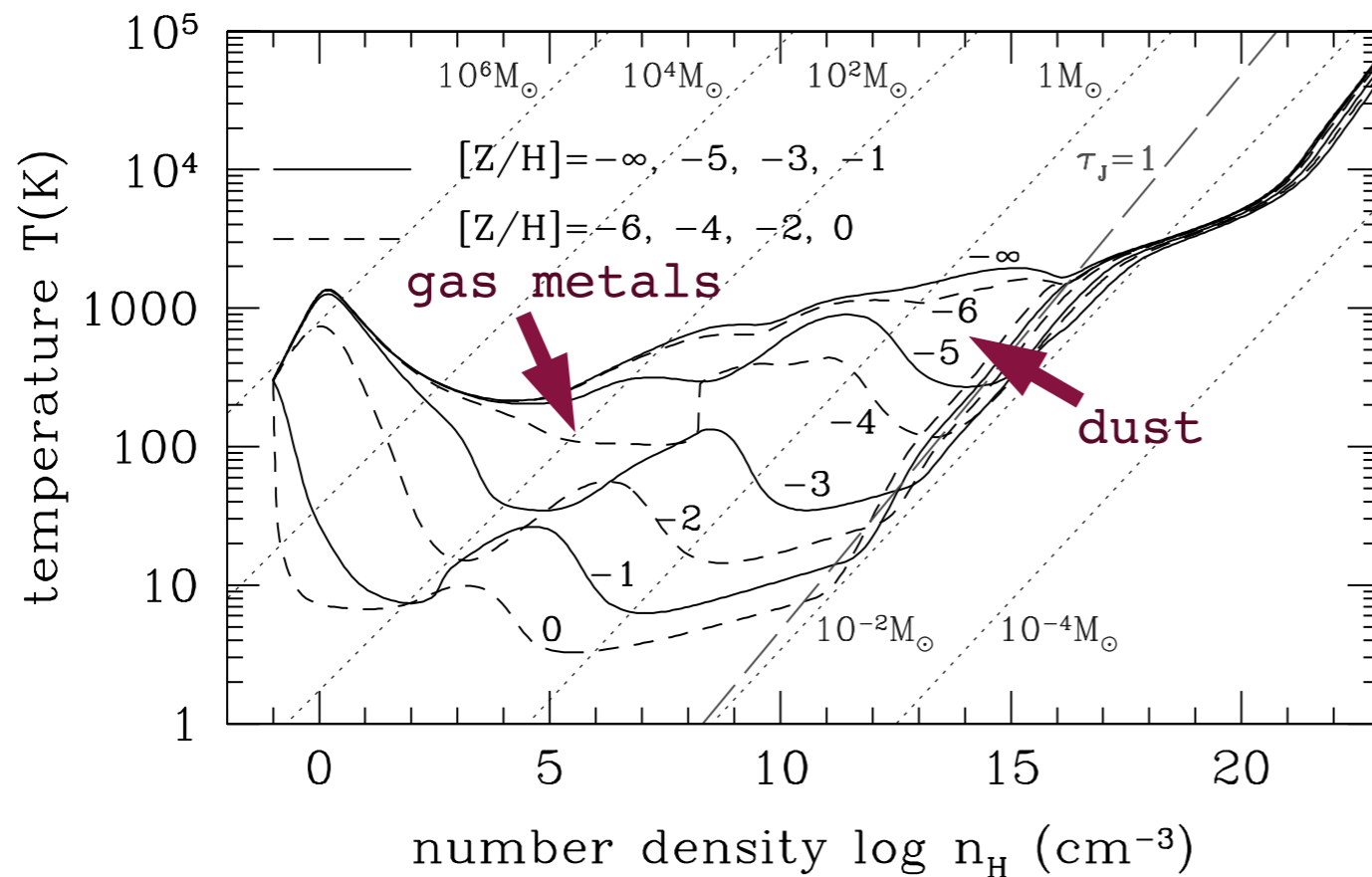
# The First Low-Mass Stars



Omukai et al. (2005)

- ▶ metals add cooling, decrease Jeans mass
- ▶ fragmentation is a 3D problem, AND highly dependent on initial conditions

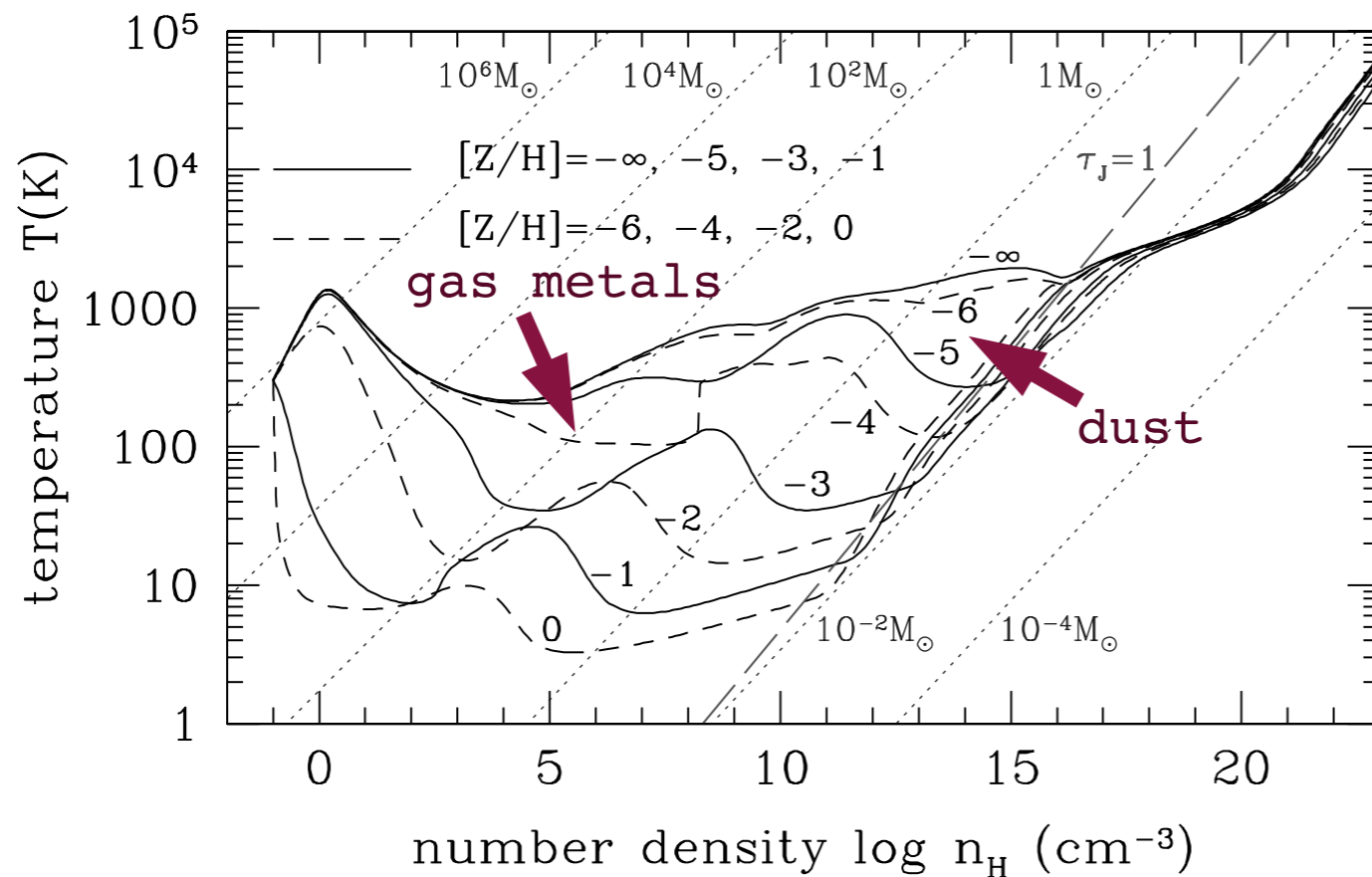
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# The First Low-Mass Stars



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- ▶ fragmentation is a 3D problem, AND highly dependent on initial conditions

We need to know the physical conditions of second generation star formation.

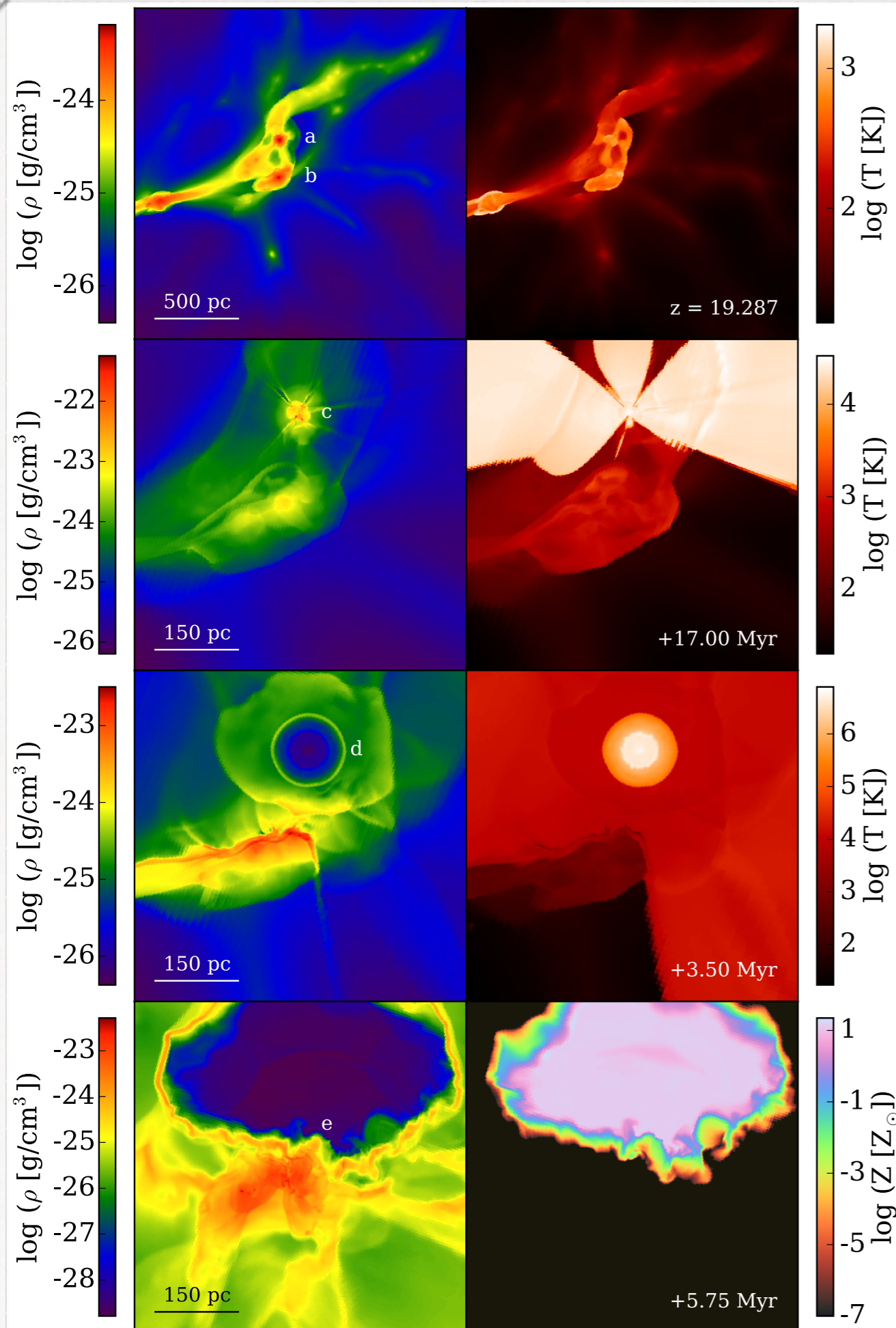
# Simulations

- ▶ Enzo: open-source AMR, rad-hydro
- ▶  $L = 500/h$  kpc,  $m_{\text{dm}} = 1.5 M_{\odot}$
- ▶ Target halo:  $10^7 M_{\odot}$  at  $z=10$  with max Pop III star halos
- ▶ non-equilibrium H/D/He chemistry, metal cooling, dust
- ▶ Single Pop III star particles:
  - ▶  $M = 40 M_{\odot}$ ,  $t_{\text{MS}} \sim 4$  Myr
  - ▶ H/He ion., H<sub>2</sub> photo-diss rad.
  - ▶ core-collapse SN ( $10^{51}$  erg)
- ▶ stop when dense, metal-enriched gas ( $Z > 10^{-6} Z_{\odot}$ ) collapses to  $n \sim 10^{13} \text{ cm}^{-3}$
- ▶ ensure collapse is well-resolved ( $dx < L_J/64$ )

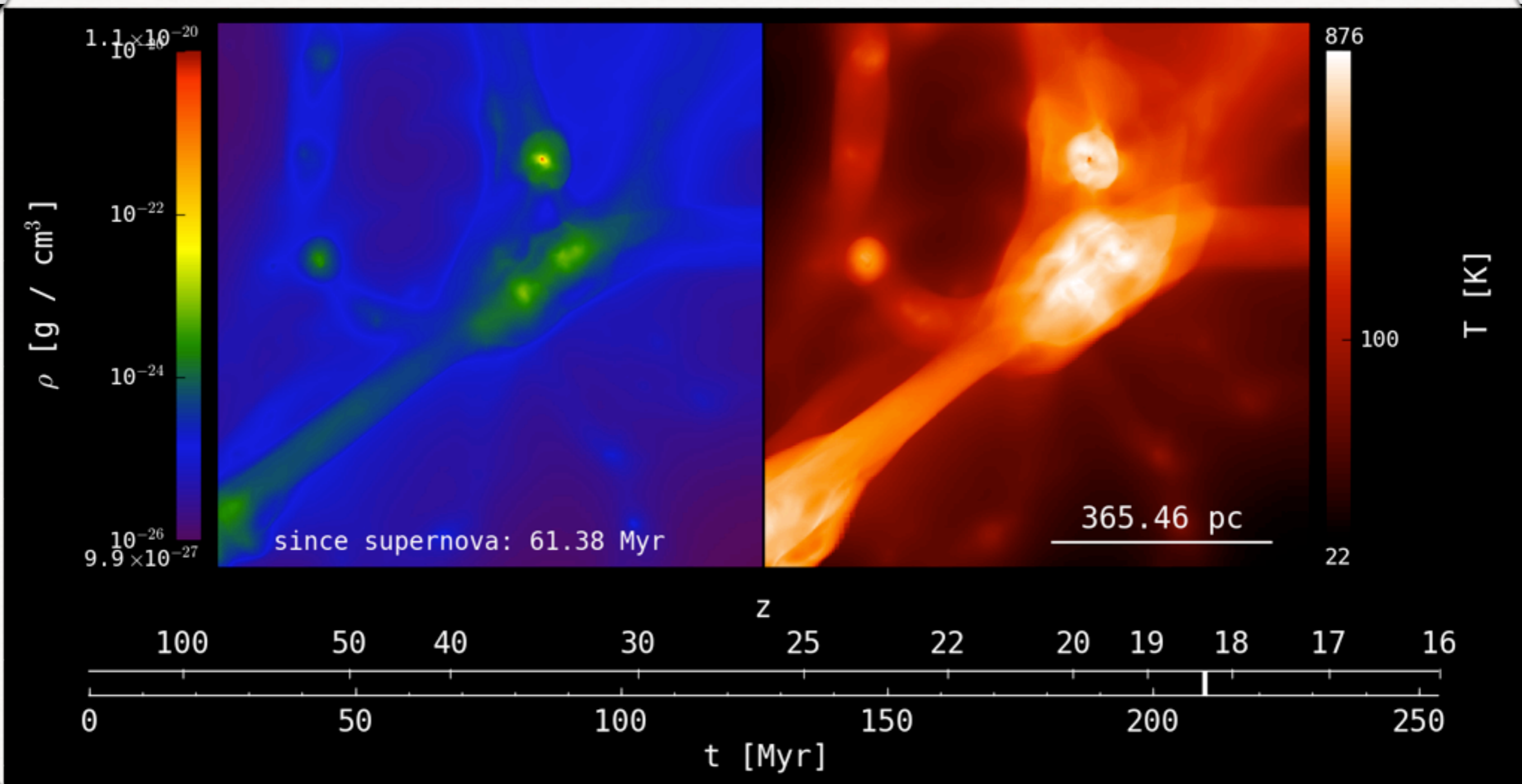
# Evolution

- ▶ 2 Pop III events ( $z \sim 23.7, 18.2$ )
- ▶ Pop III stars destroy host mini-halos
- ▶ metal-enriched collapse at  $z \sim 16.6$  in separate halo ( $M \sim 3 \times 10^5 M_{\odot}$ )

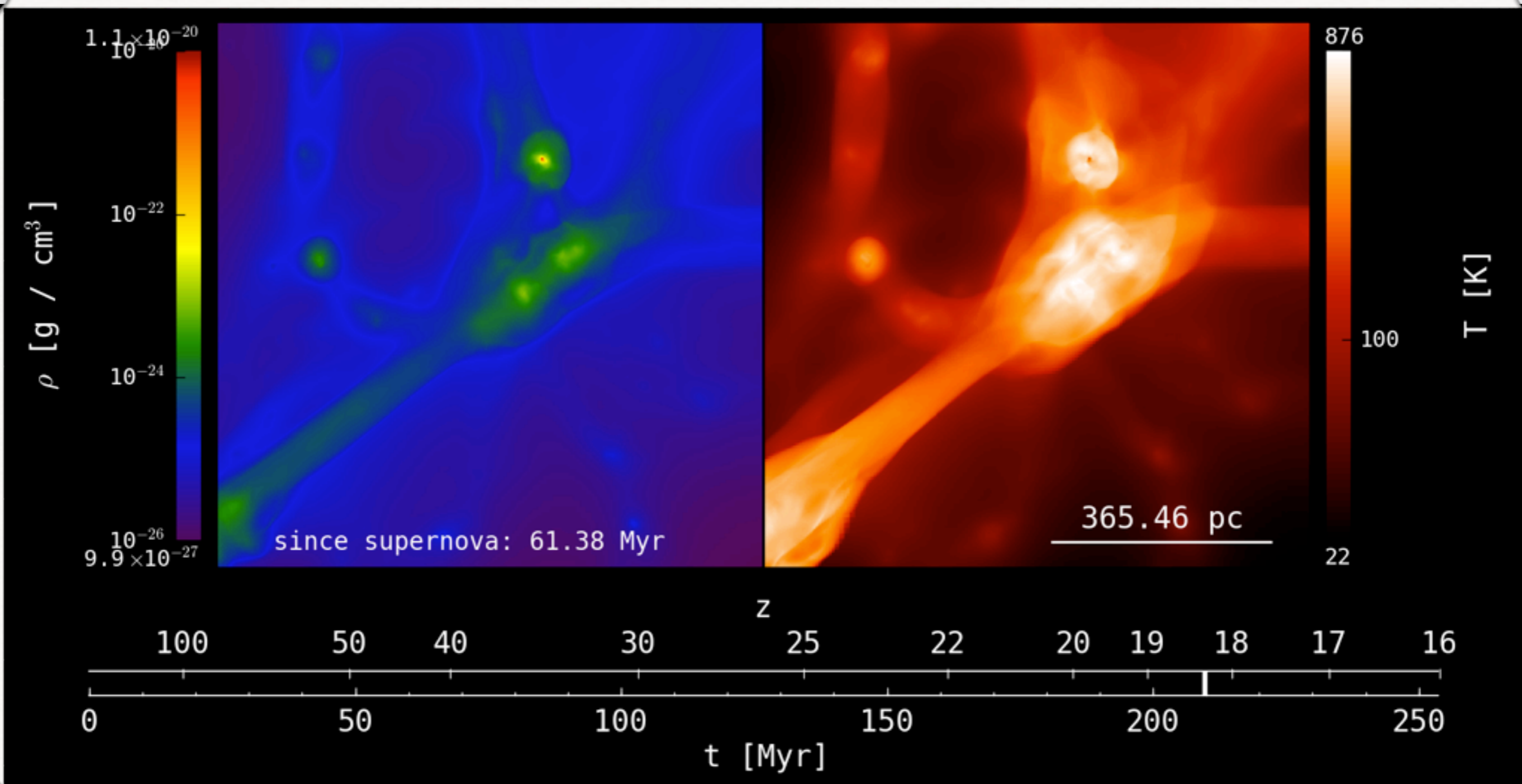
Smith ea. (2015)



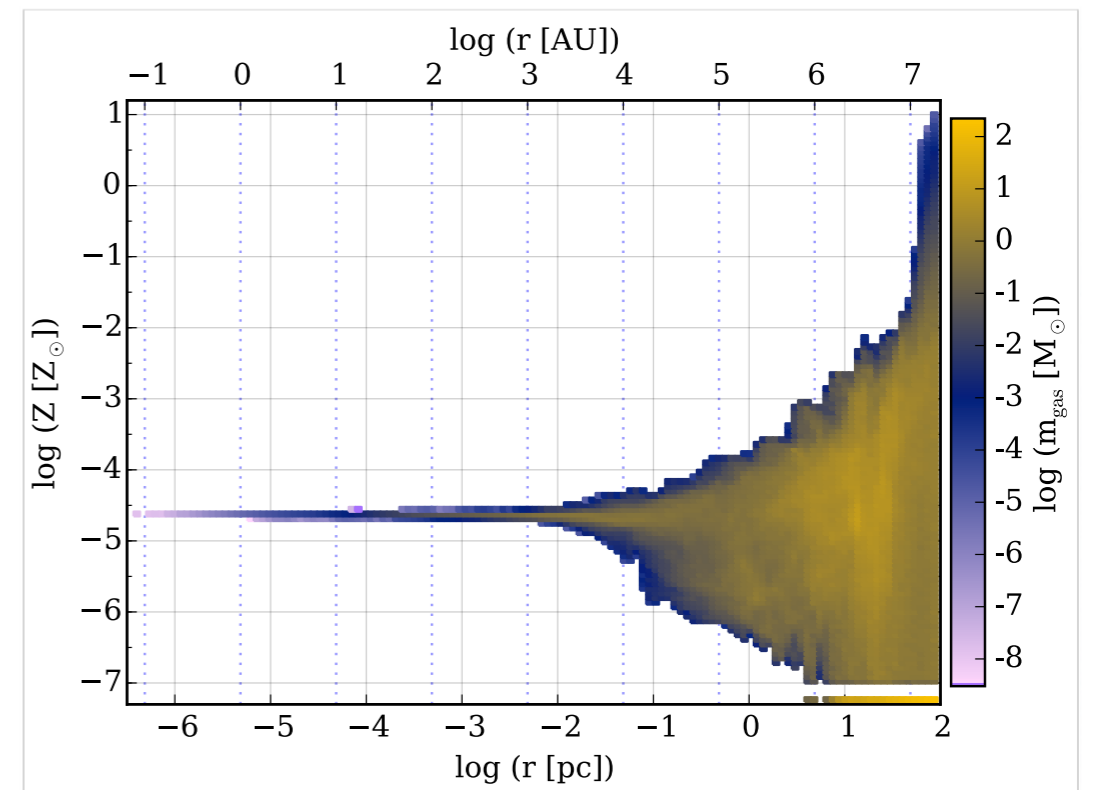
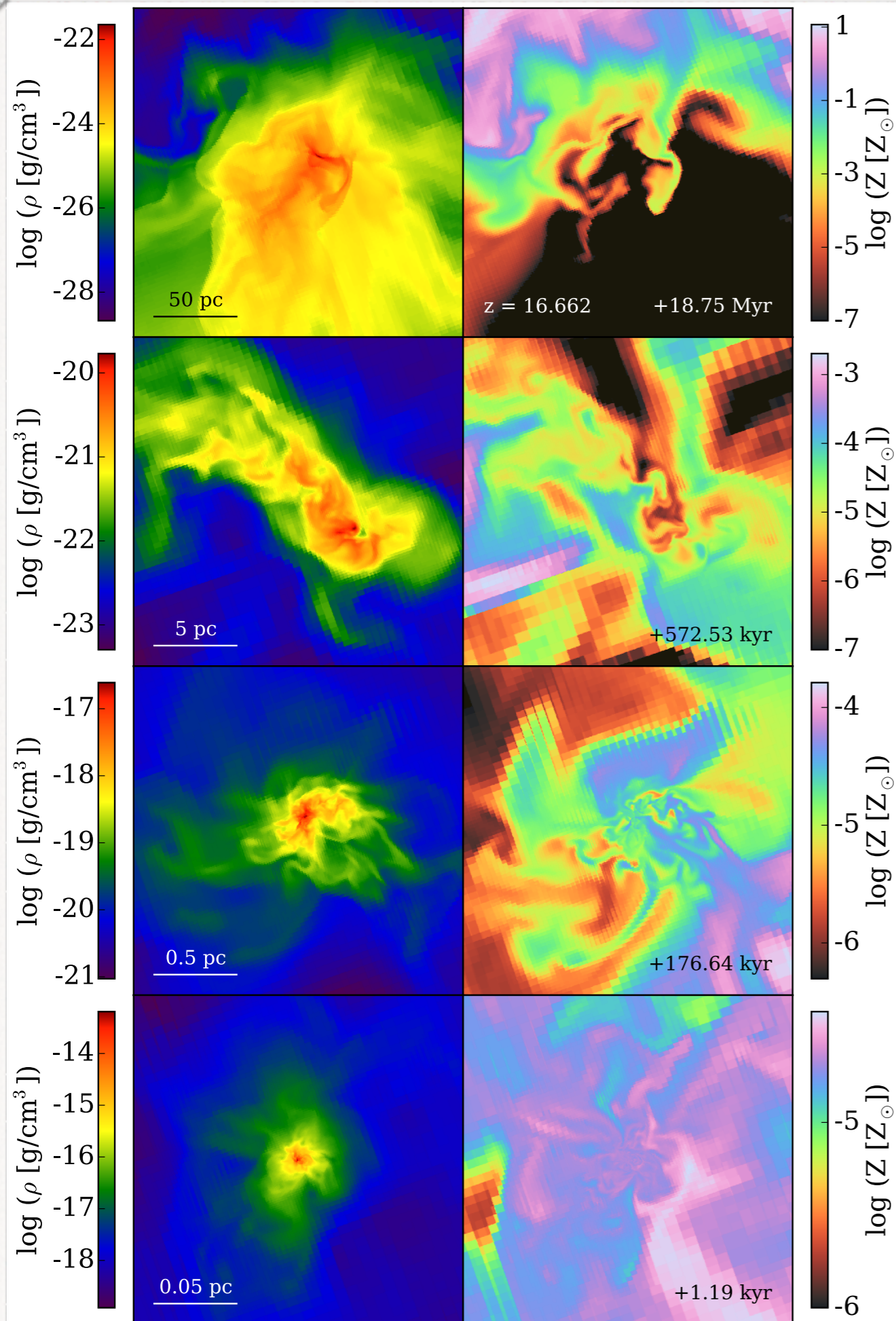
# Metal Enrichment



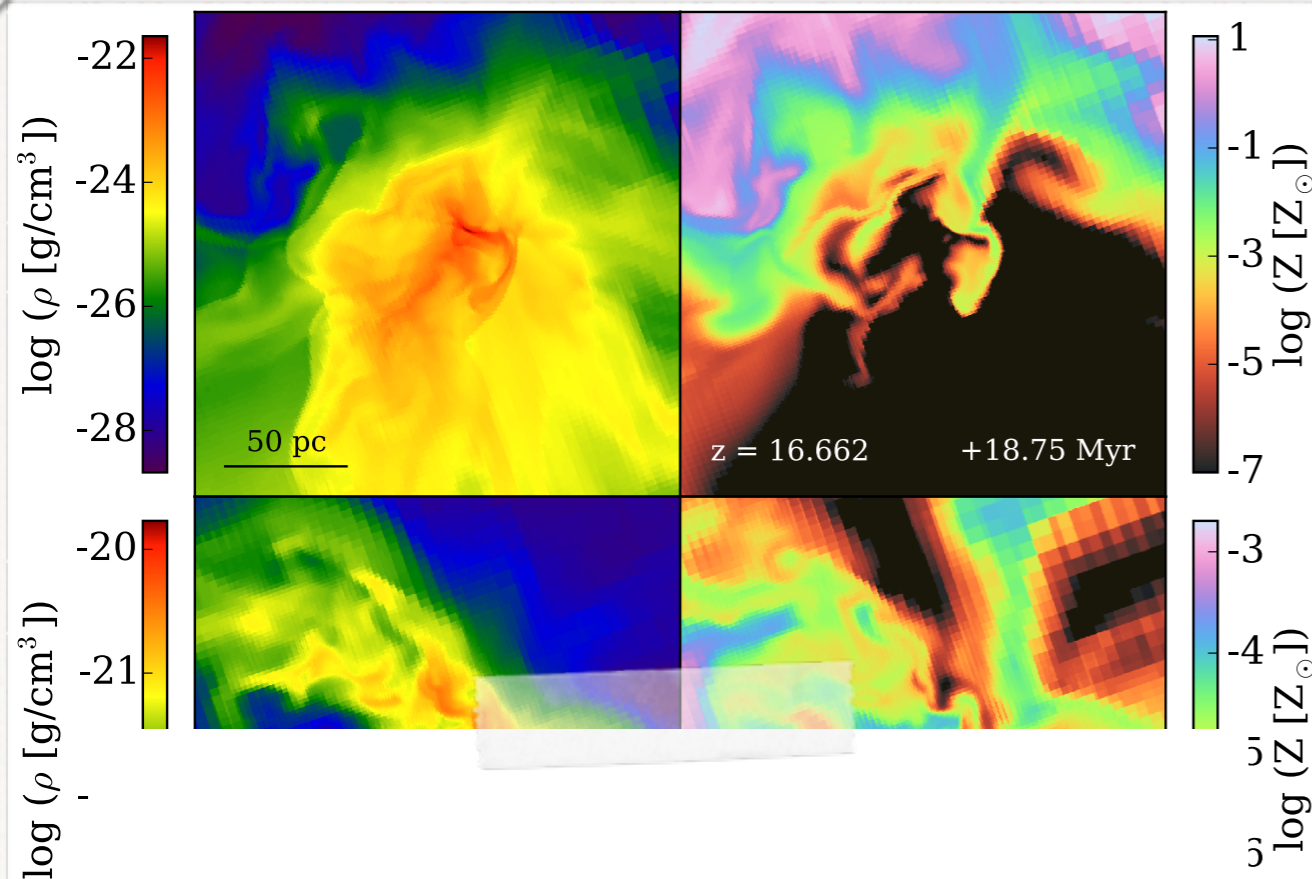
# Metal Enrichment



# Metal Mixing



# Metal Mixing

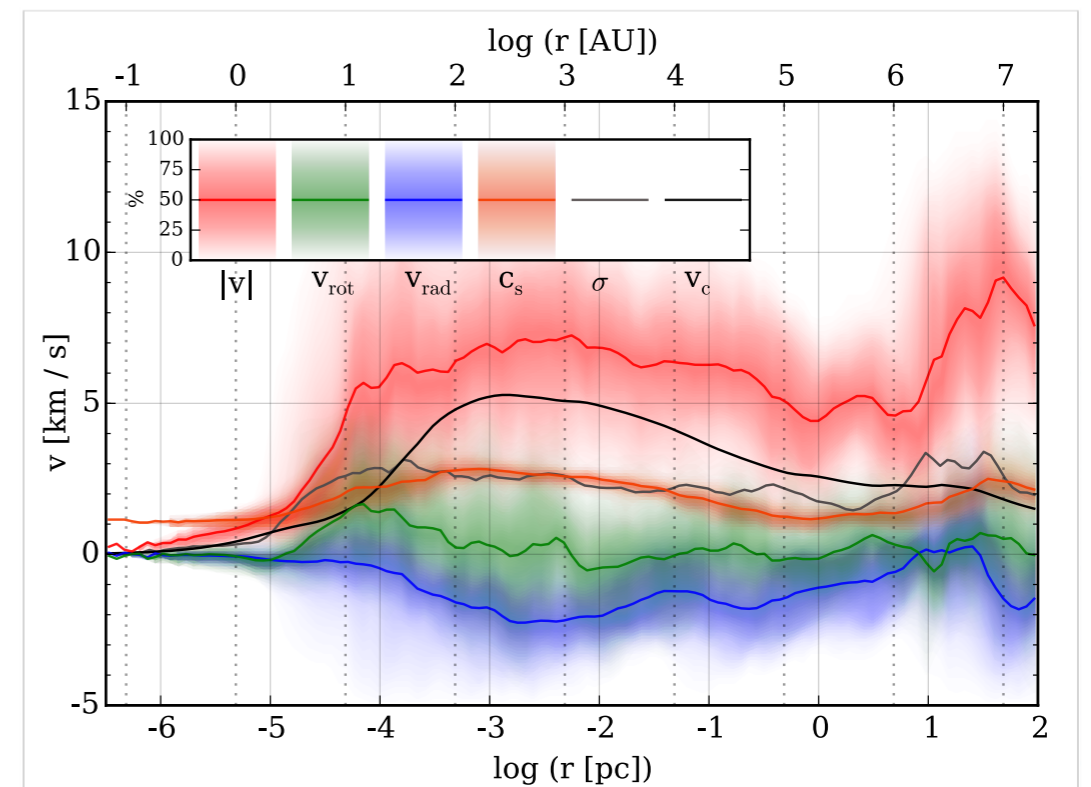
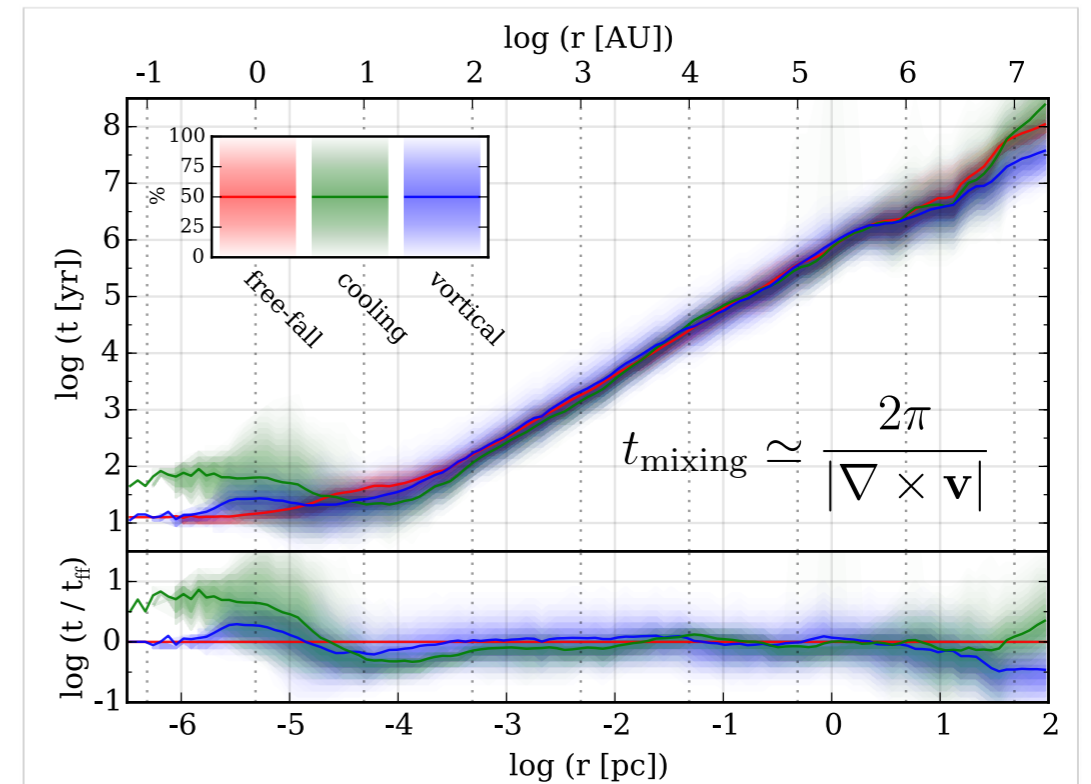
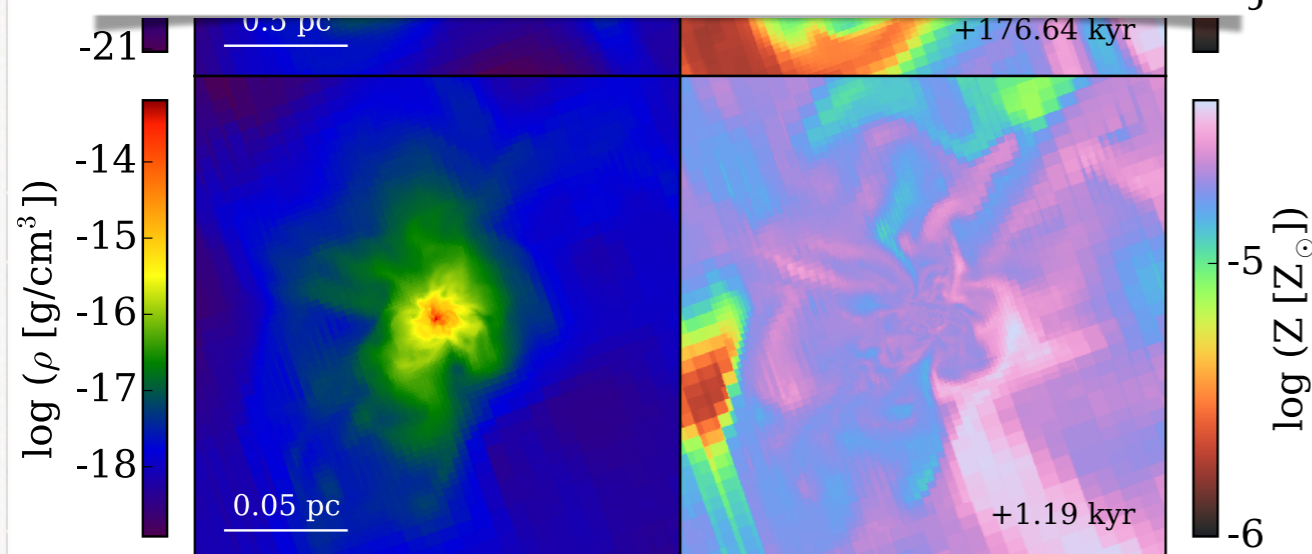


►  $t_{\text{mixing}} < t_{\text{cool}}, t_{\text{ff}}$  at large radii where mixing occurs

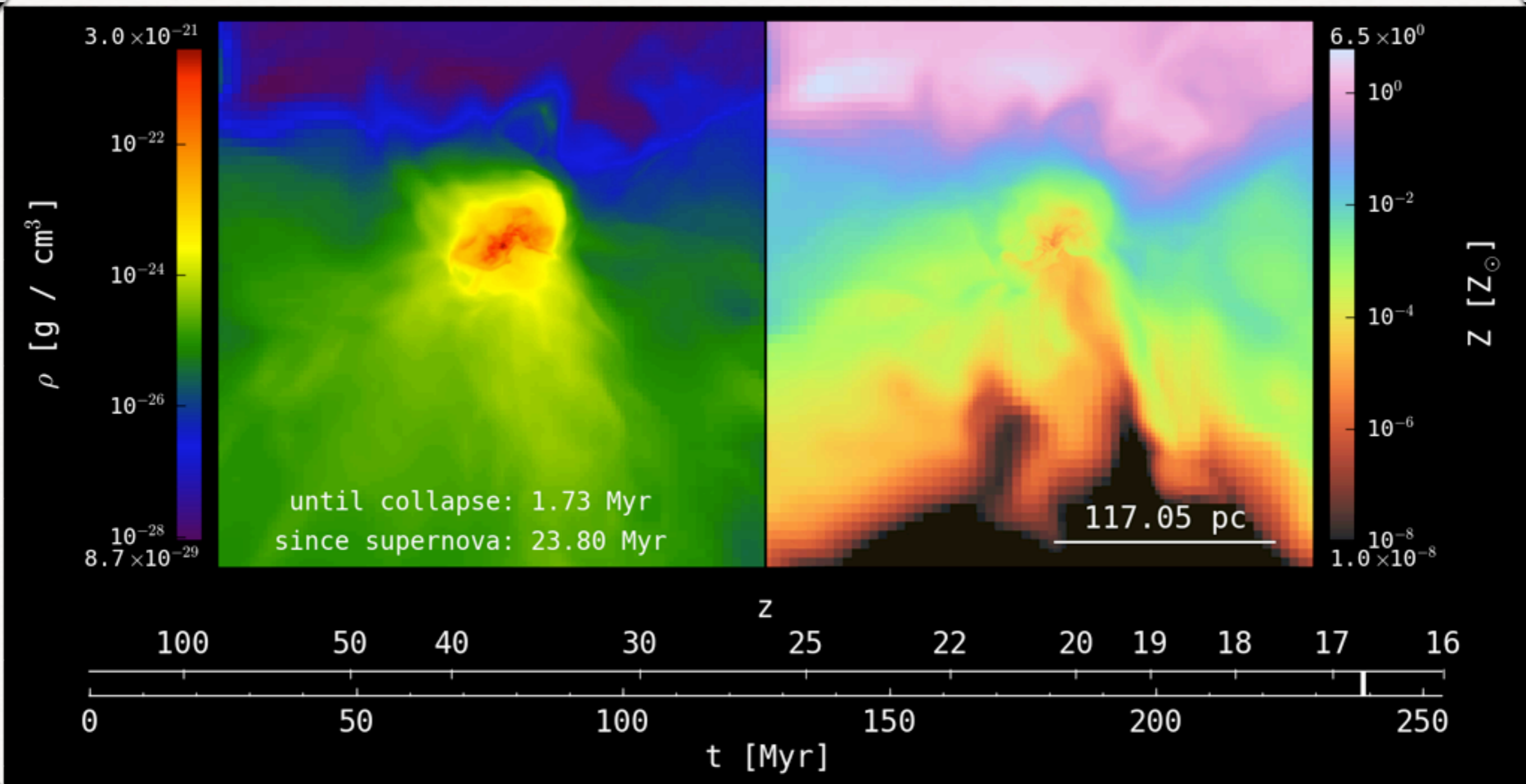
► velocity structure dominated by turbulent-like motions and infall

► turbulence close to sound speed

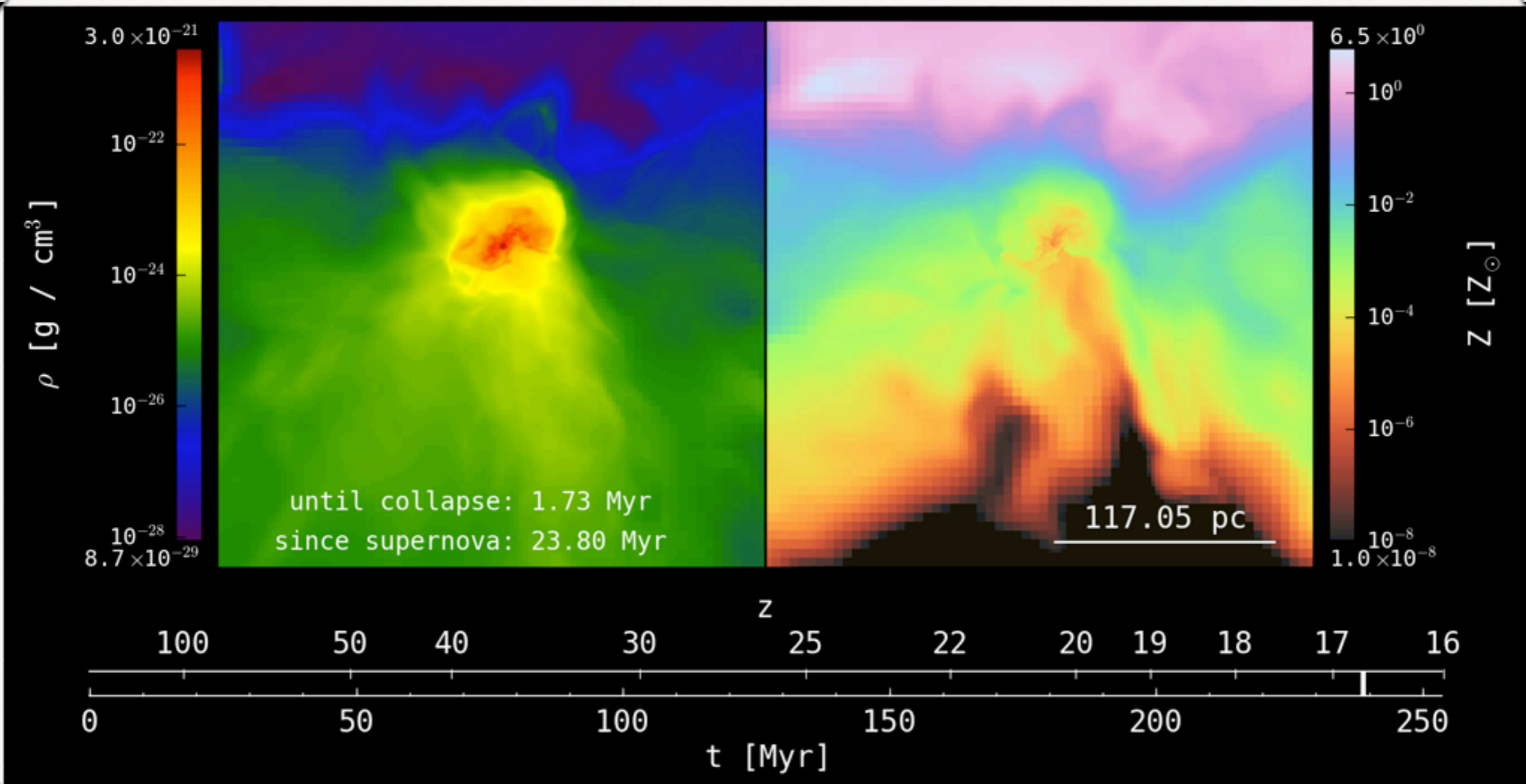
► no coherent rotation



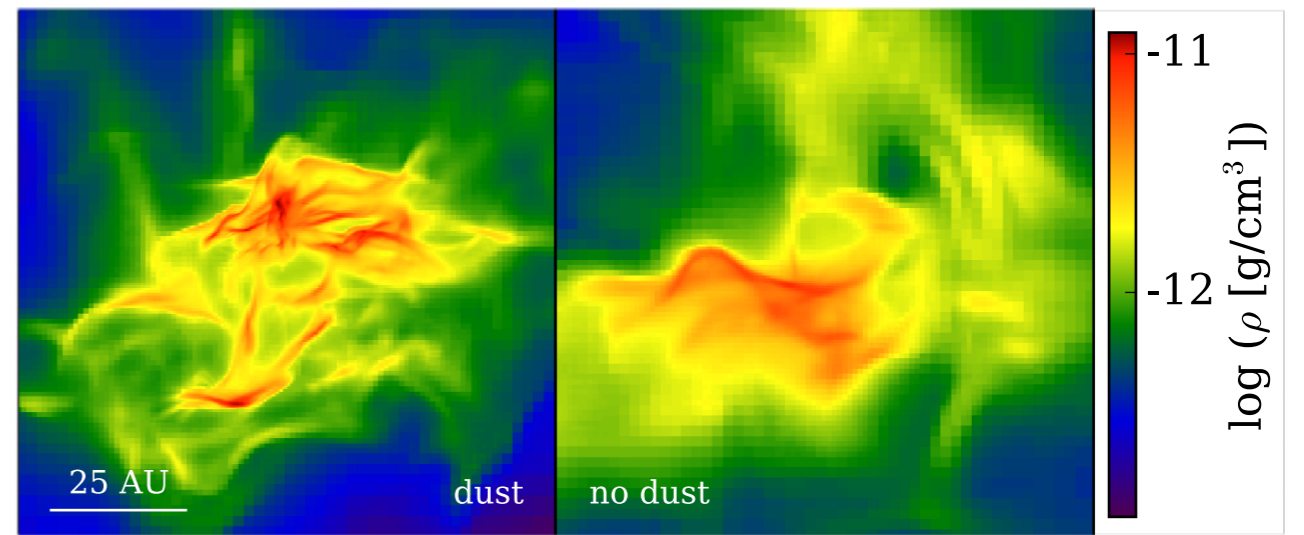
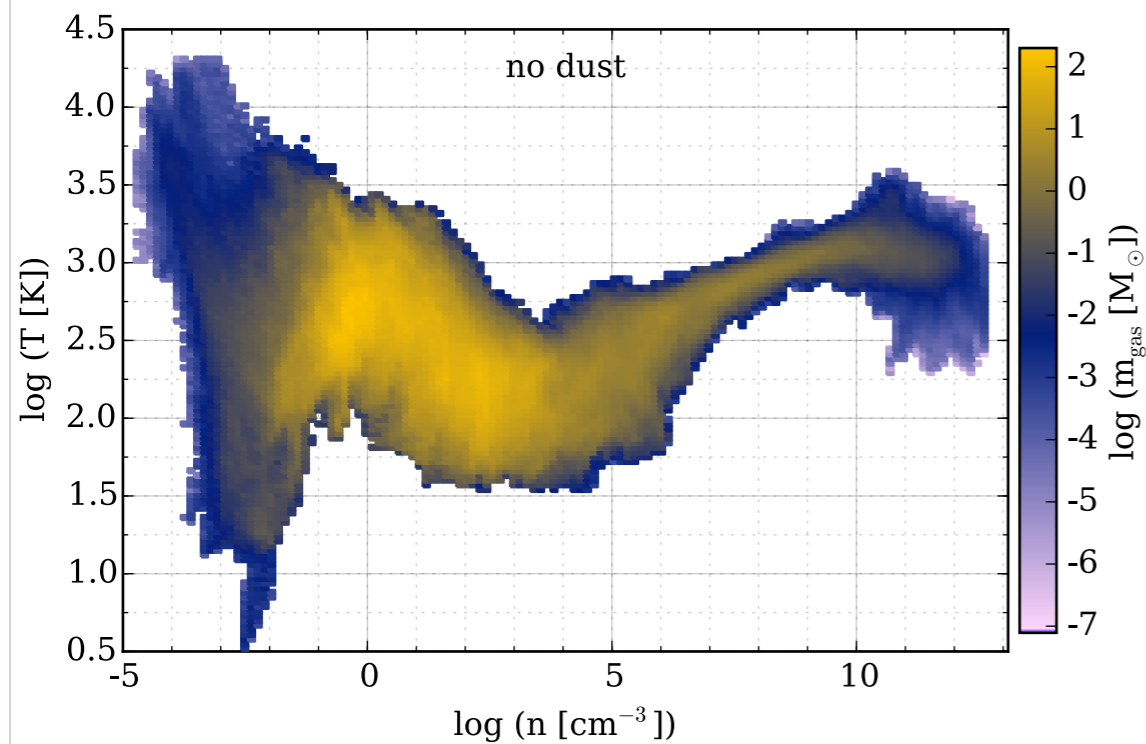
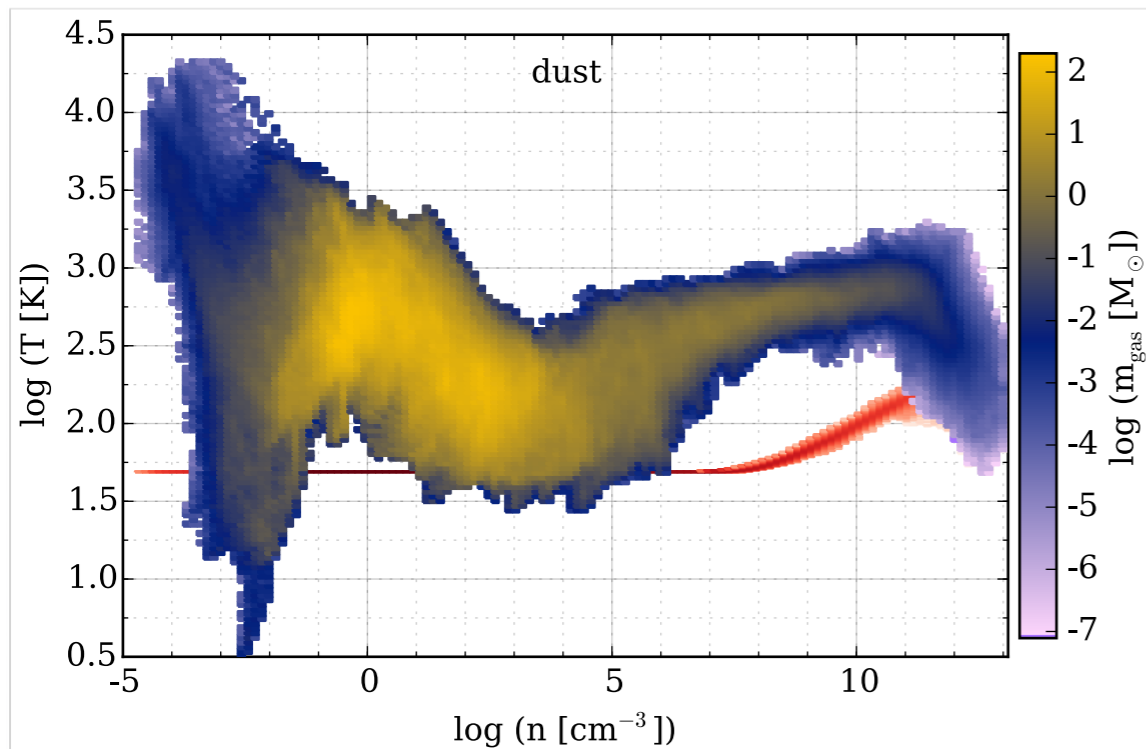
# Collapse



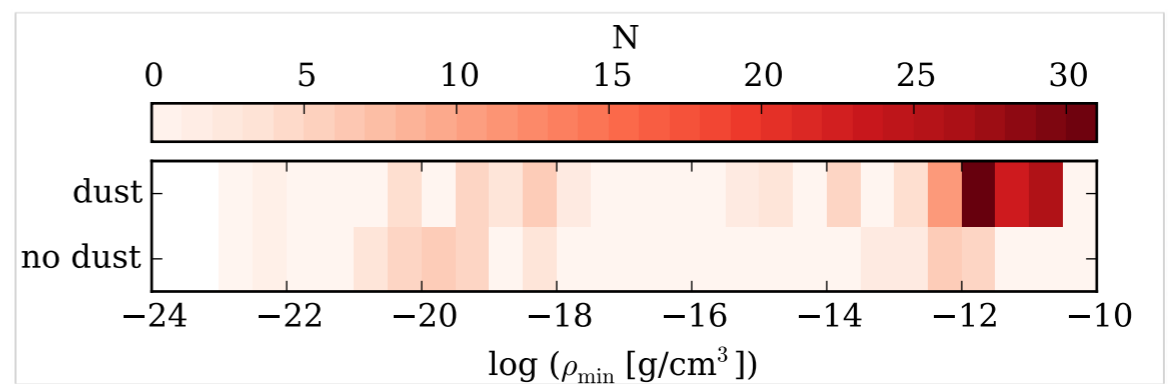
# Collapse



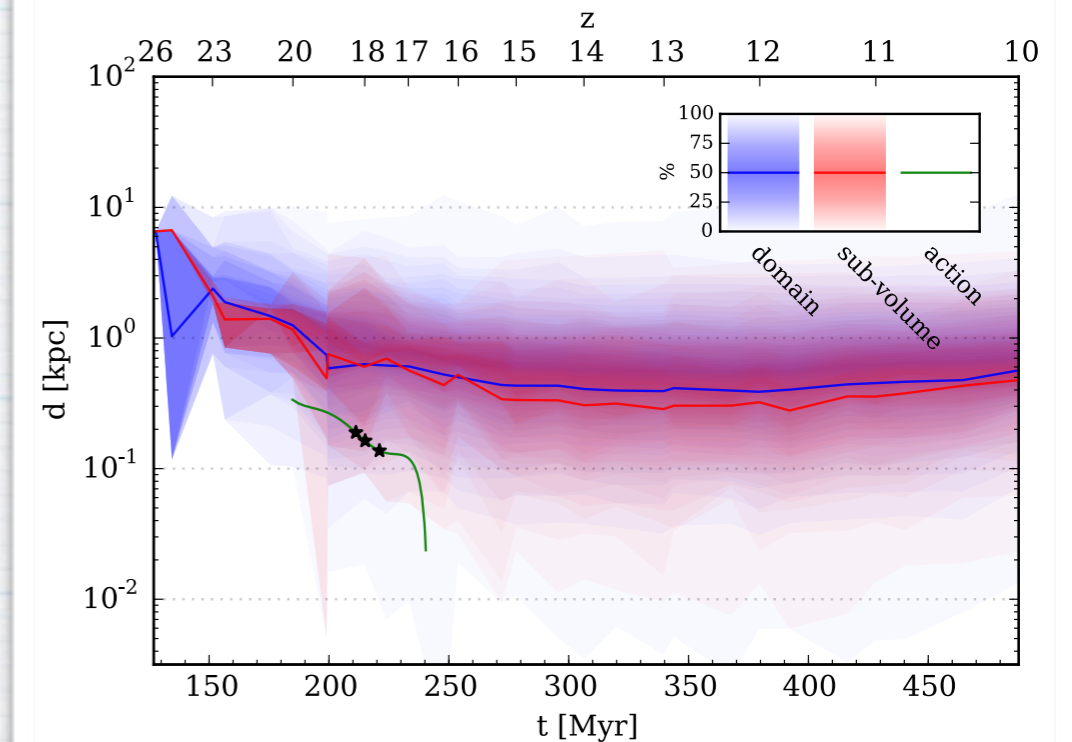
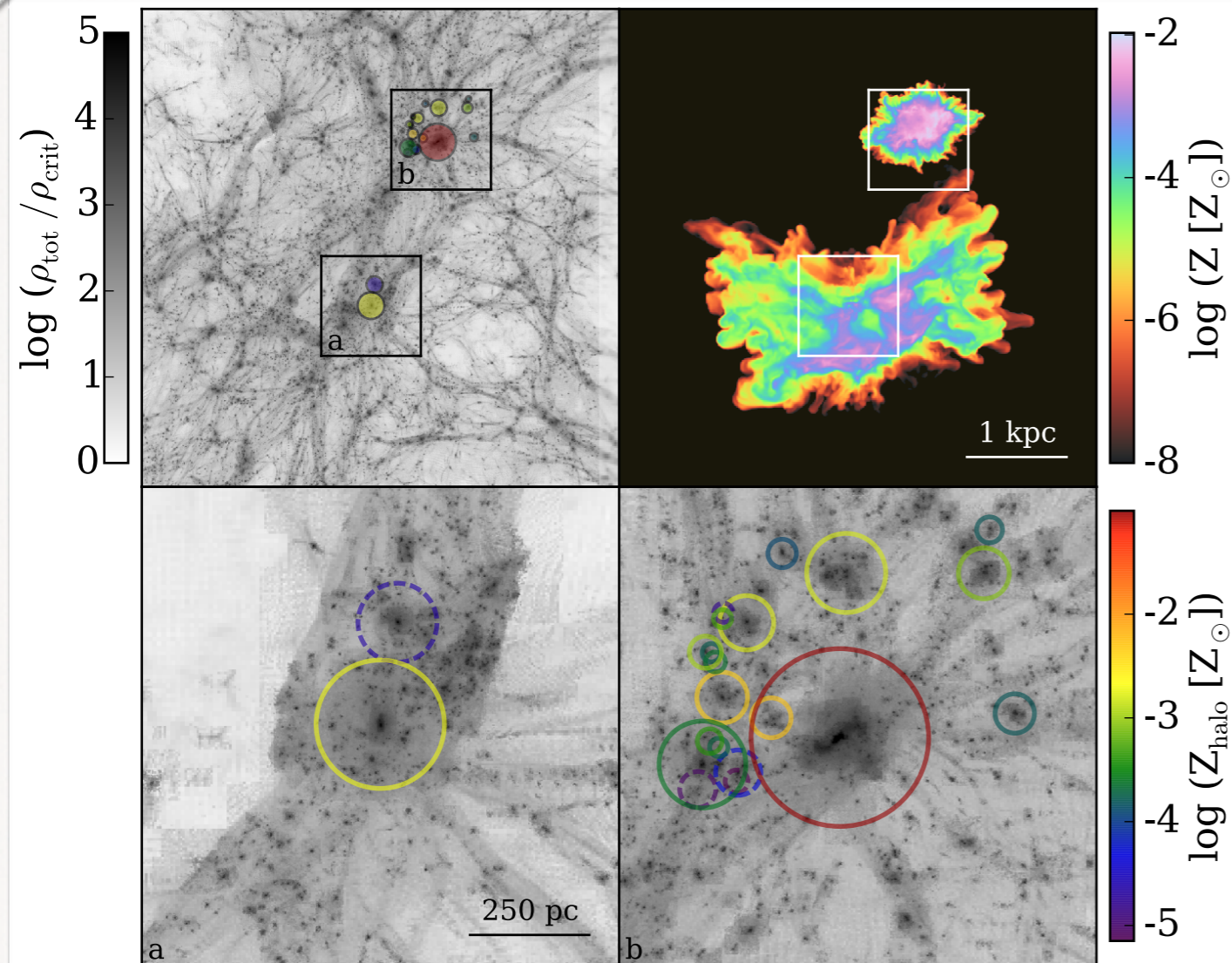
# Fragmentation



- fragmentation induced by dust cooling
- almost no fragmentation without dust
- clump finding agrees



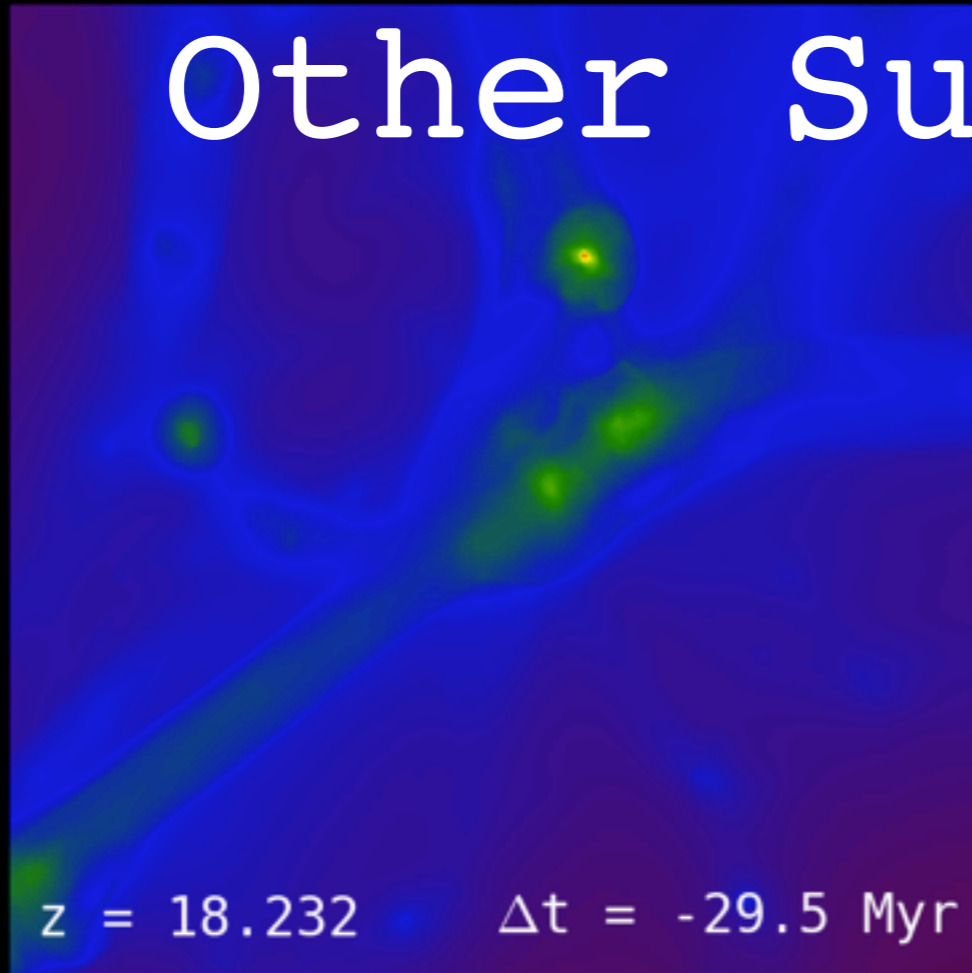
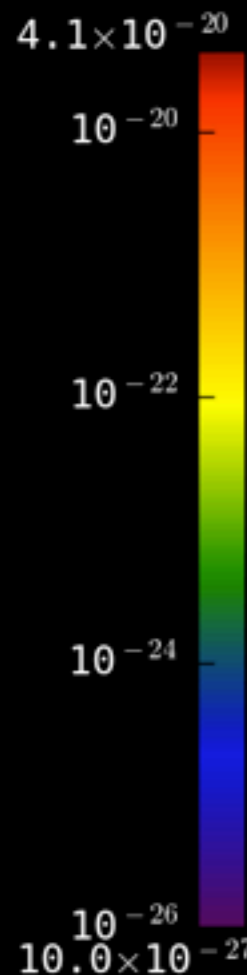
# External Enrichment Mechanism



- ▶ external enrichment is region dependent
- ▶ wide range of metallicities from a single supernova
- ▶ requires below average mini-halo separation ( $\sim 1\sigma$ )

# Other Supernovae

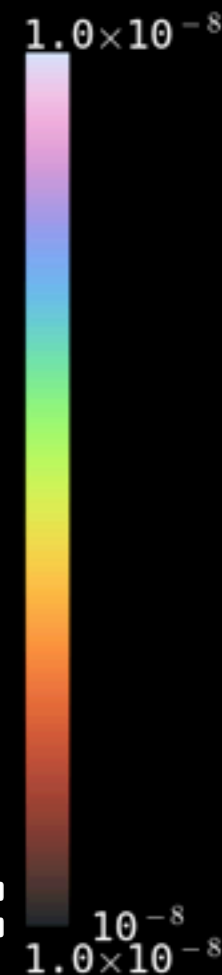
$\rho$  [g / cm<sup>3</sup>]



$z = 18.232$

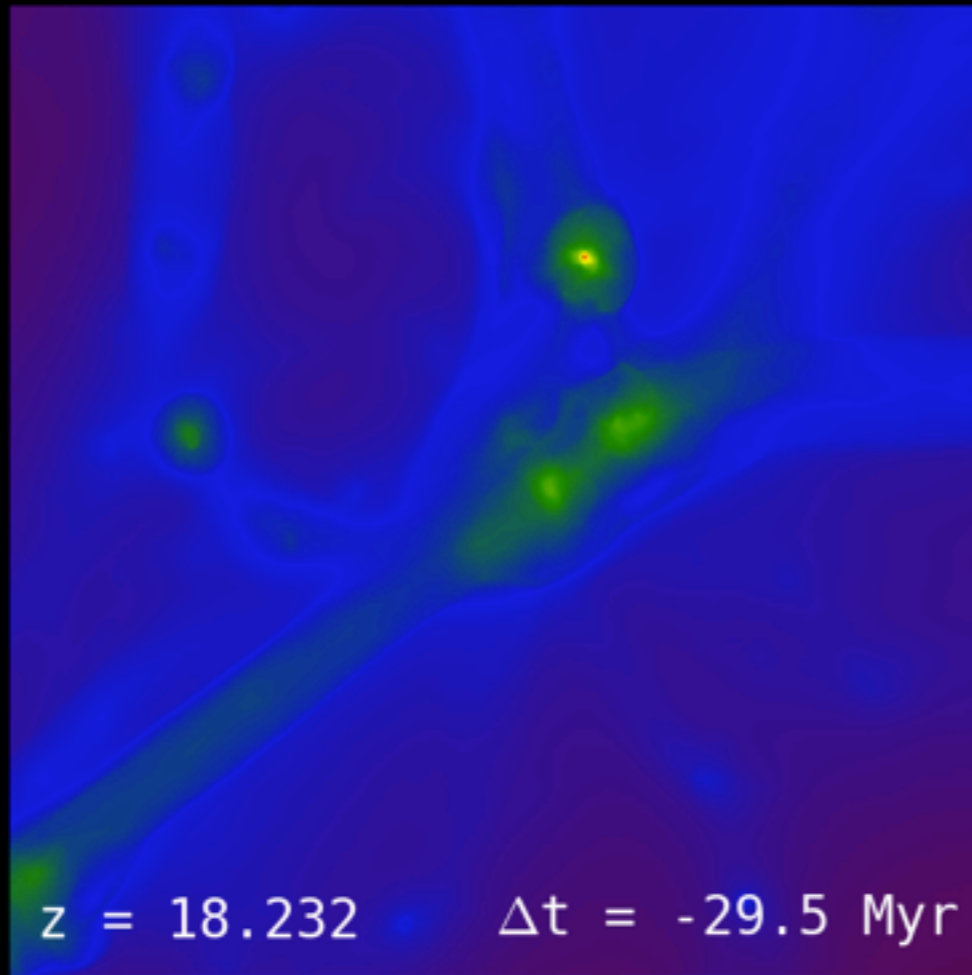
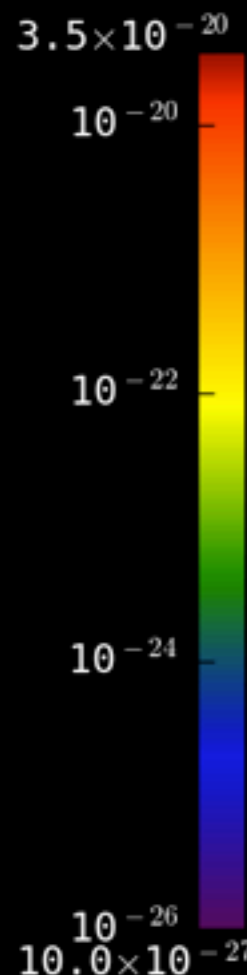
$\Delta t = -29.5$  Myr

Hypernova: 30 FOE



$Z$  [ $Z_{\odot}$ ]

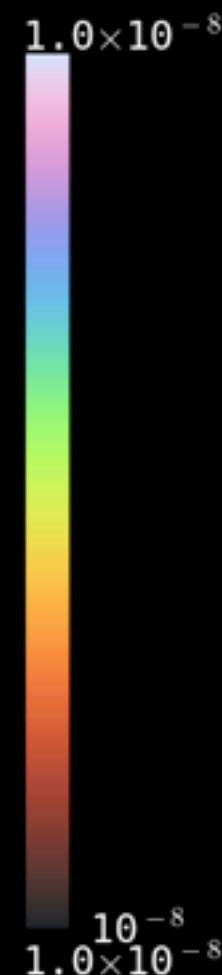
$\rho$  [g / cm<sup>3</sup>]



$z = 18.232$

$\Delta t = -29.5$  Myr

PISN: 100 FOE

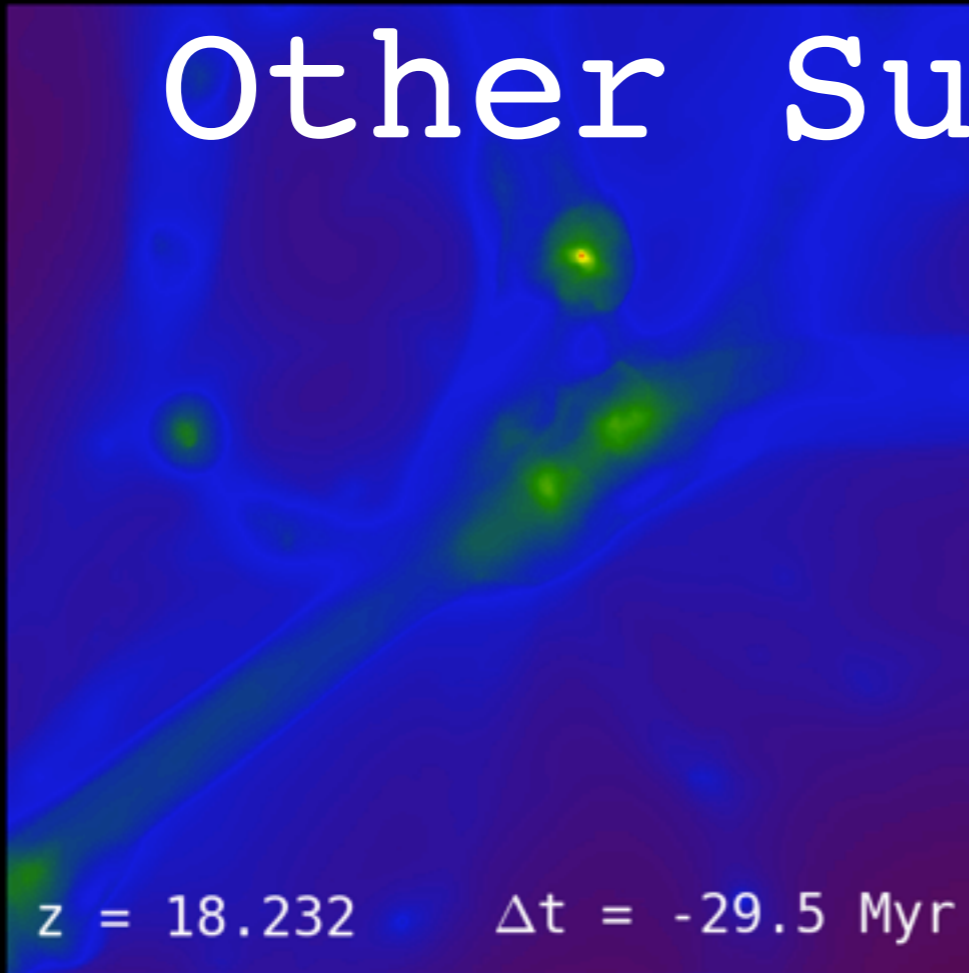
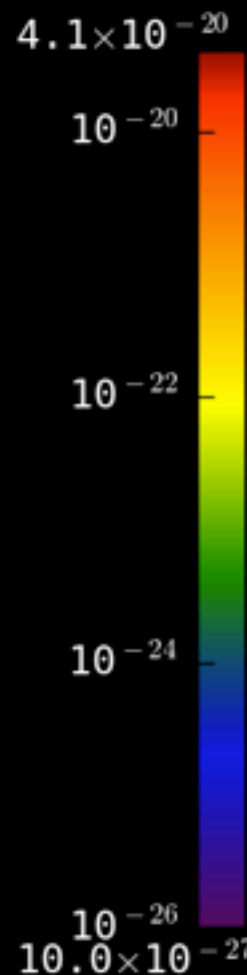


$Z$  [ $Z_{\odot}$ ]

Smith ea. (2016, ip)

# Other Supernovae

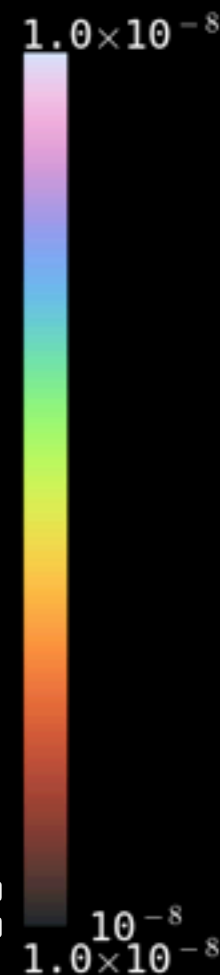
$\rho$  [g / cm<sup>3</sup>]



$z = 18.232$

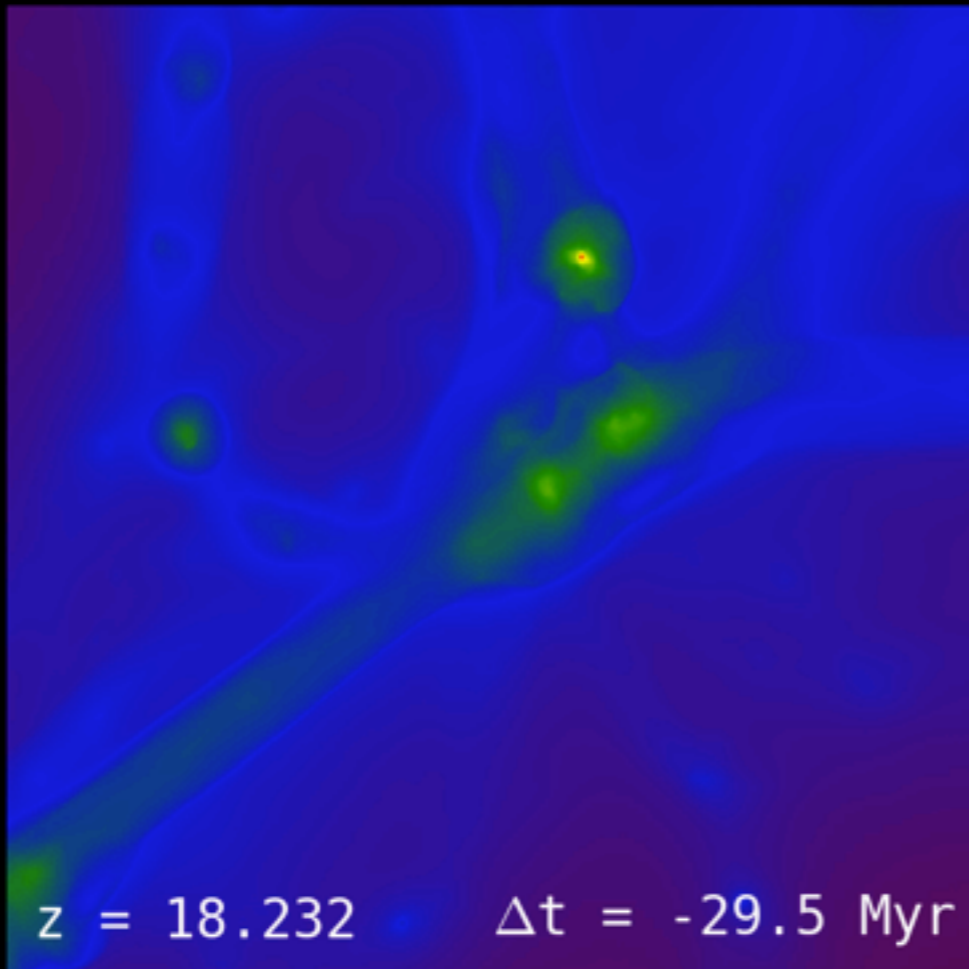
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$Z$  [ $Z_{\odot}$ ]

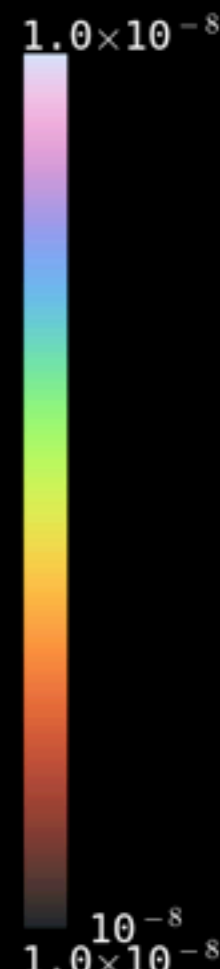
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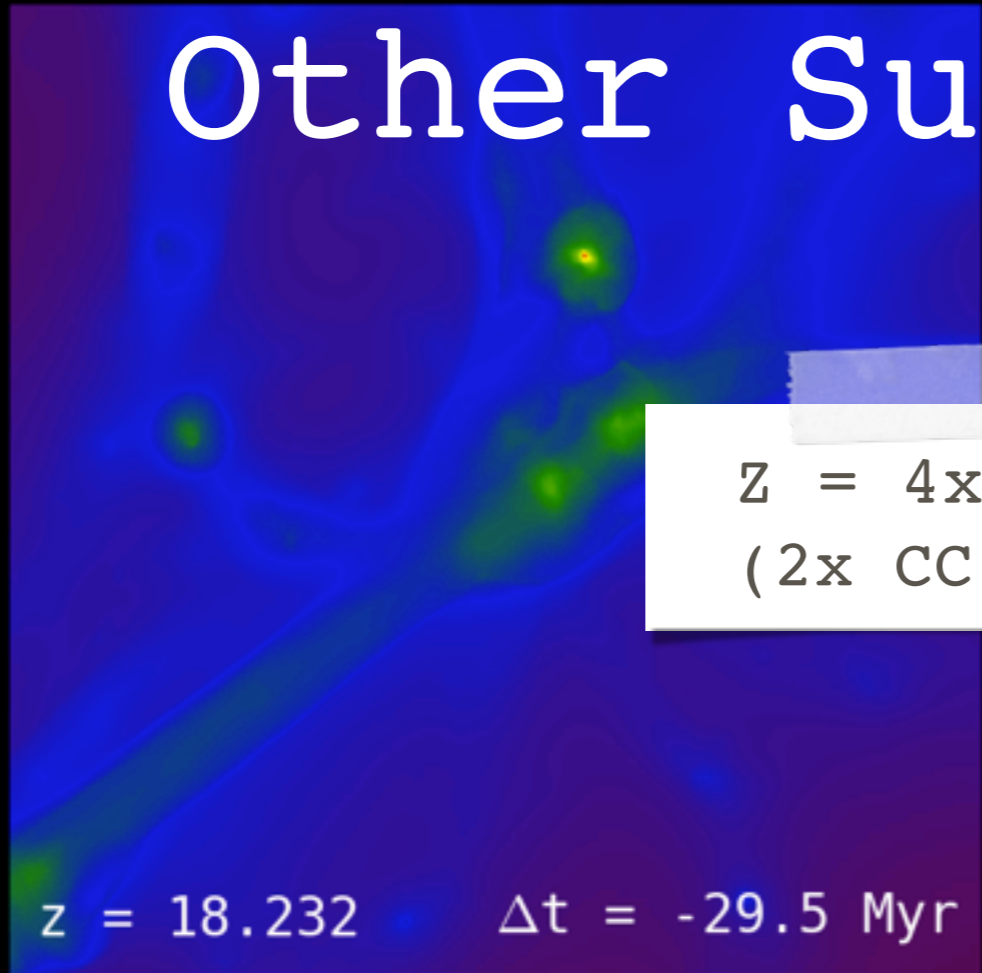
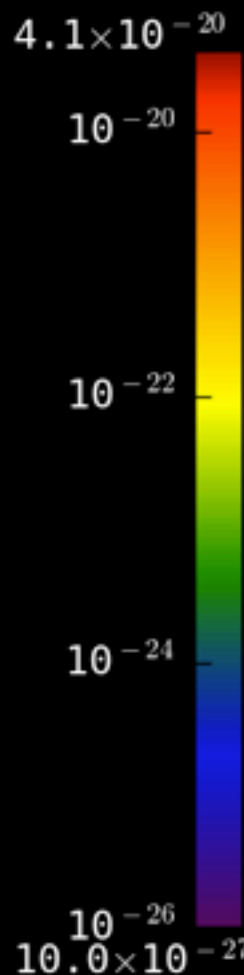


$Z$  [ $Z_{\odot}$ ]

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# Other Supernovae

$\rho$  [g / cm<sup>3</sup>]

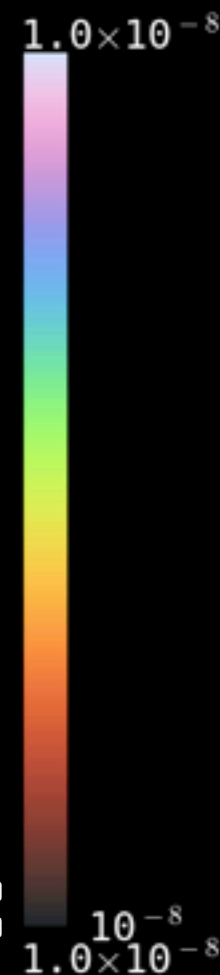


$Z = 4 \times 10^{-5} Z_{\odot}$   
(2x CC case)

$z = 18.232$

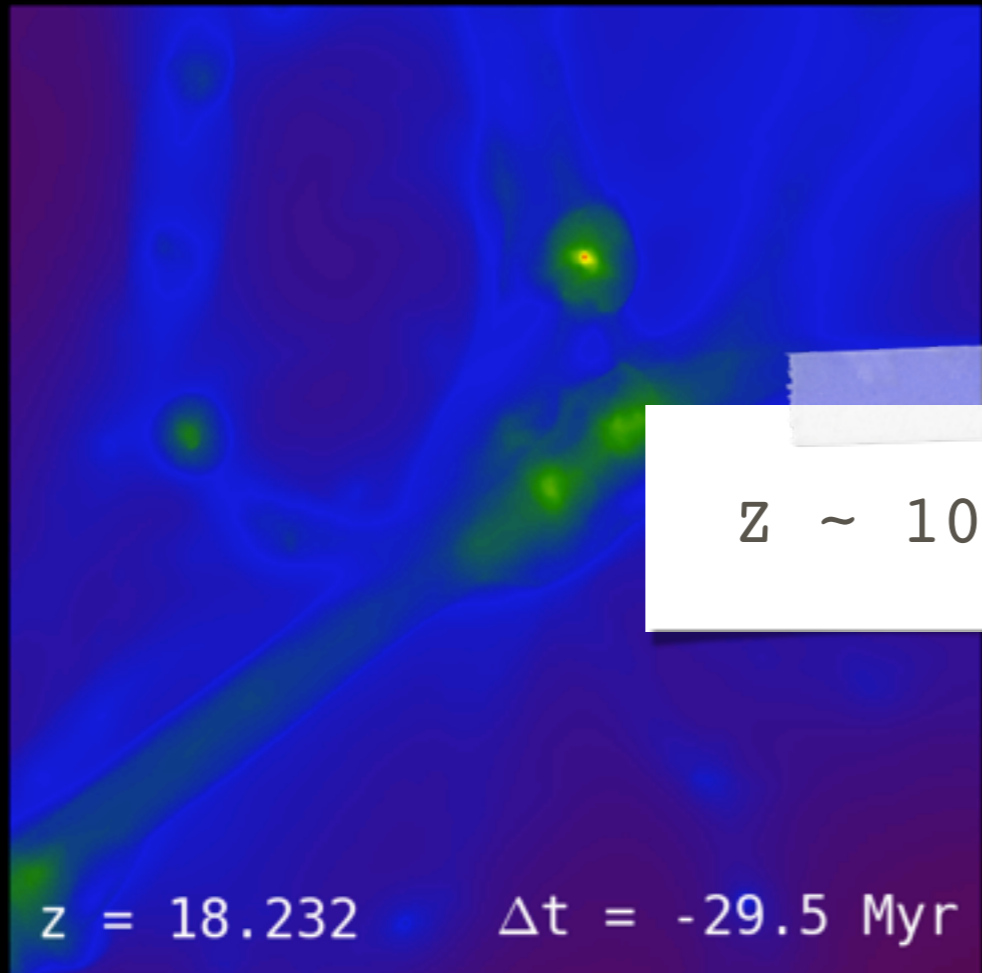
$\Delta t = -29.5$  Myr

Hypernova: 30 FOE



$Z [Z_{\odot}]$

$\rho$  [g / cm<sup>3</sup>]

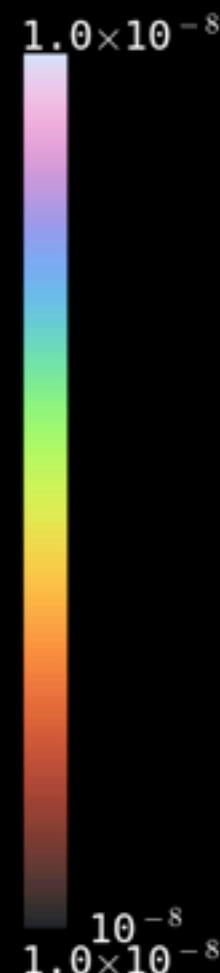


$Z \sim 10^{-3} Z_{\odot}$

$z = 18.232$

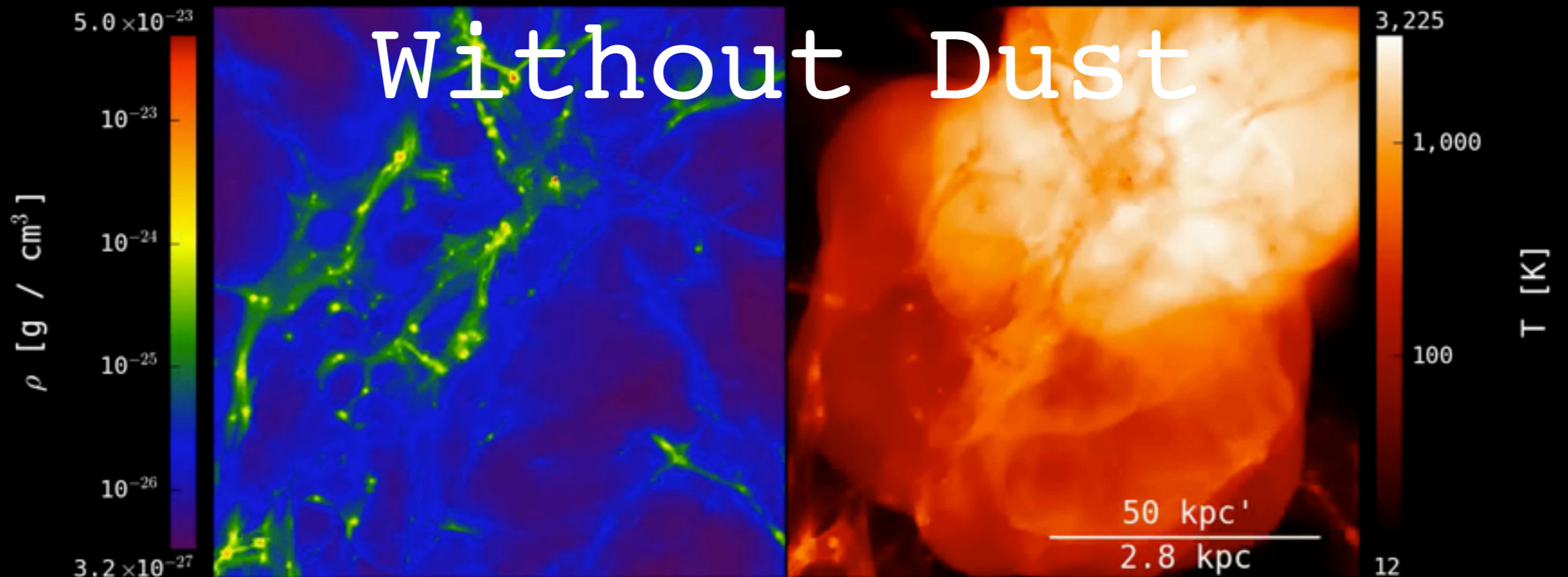
$\Delta t = -29.5$  Myr

PISN: 100 FOE



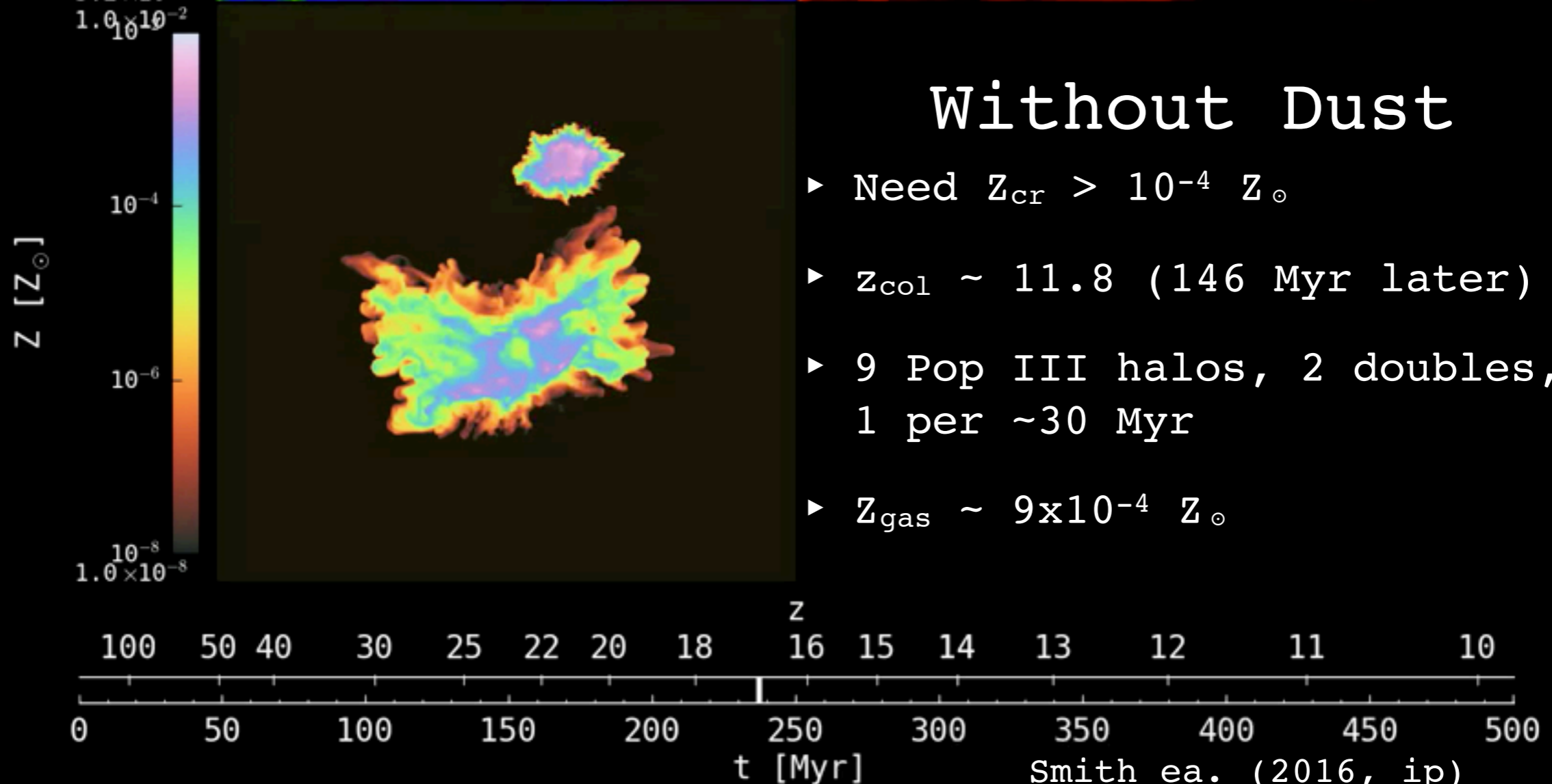
$Z [Z_{\odot}]$

# Without Dust

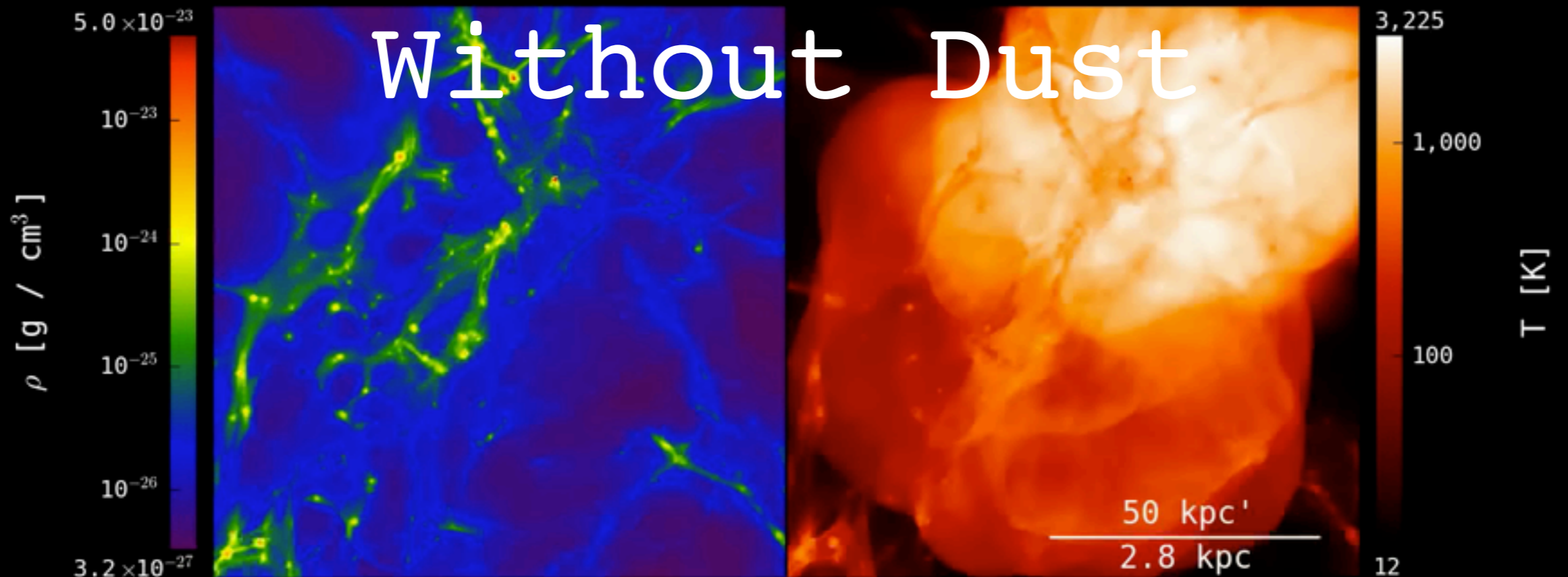


## Without Dust

- ▶ Need  $Z_{\text{cr}} > 10^{-4} Z_{\odot}$
- ▶  $Z_{\text{col}} \sim 11.8$  (146 Myr later)
- ▶ 9 Pop III halos, 2 doubles, 1 per  $\sim 30$  Myr
- ▶  $Z_{\text{gas}} \sim 9 \times 10^{-4} Z_{\odot}$

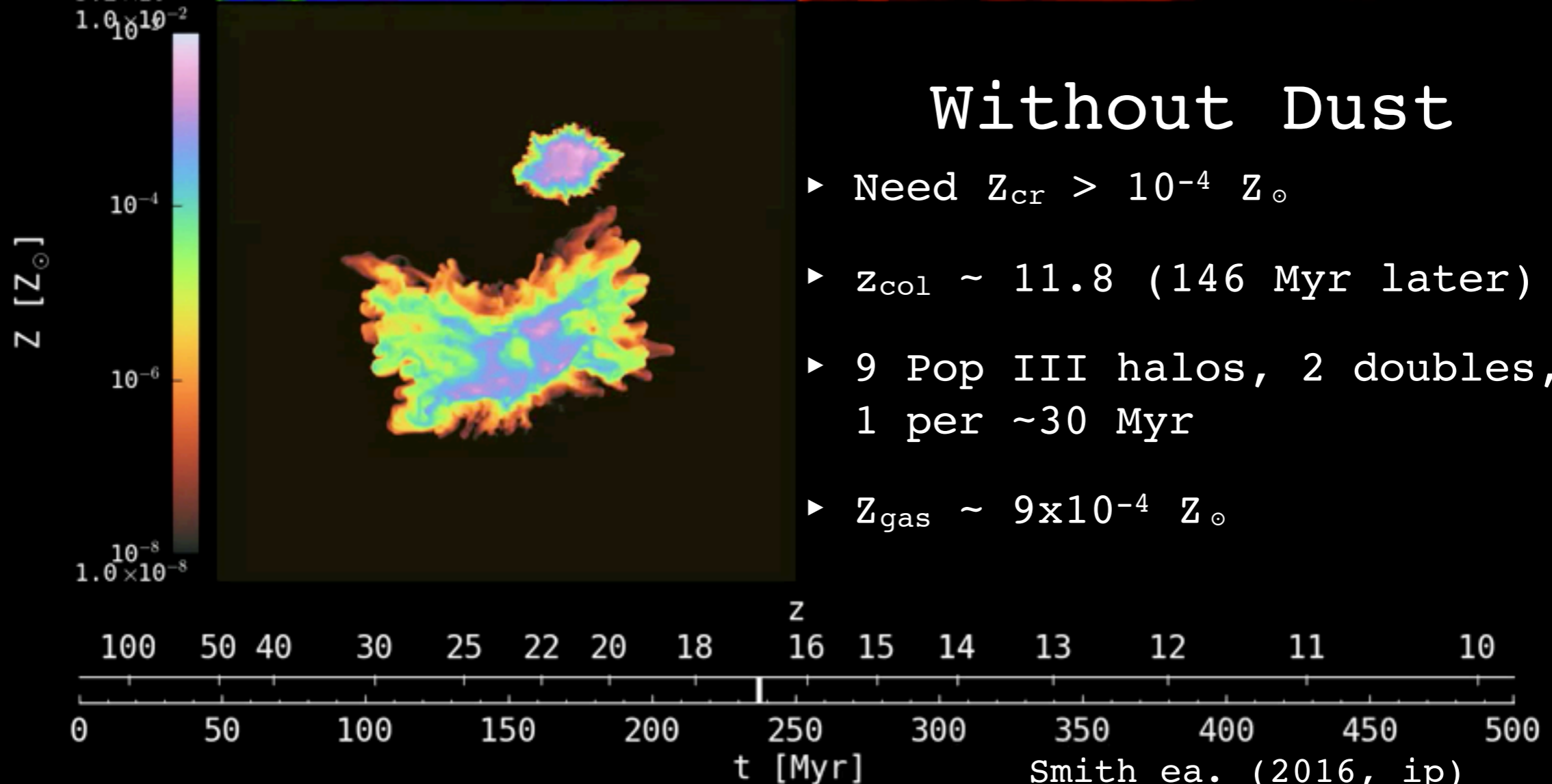


# Without Dust



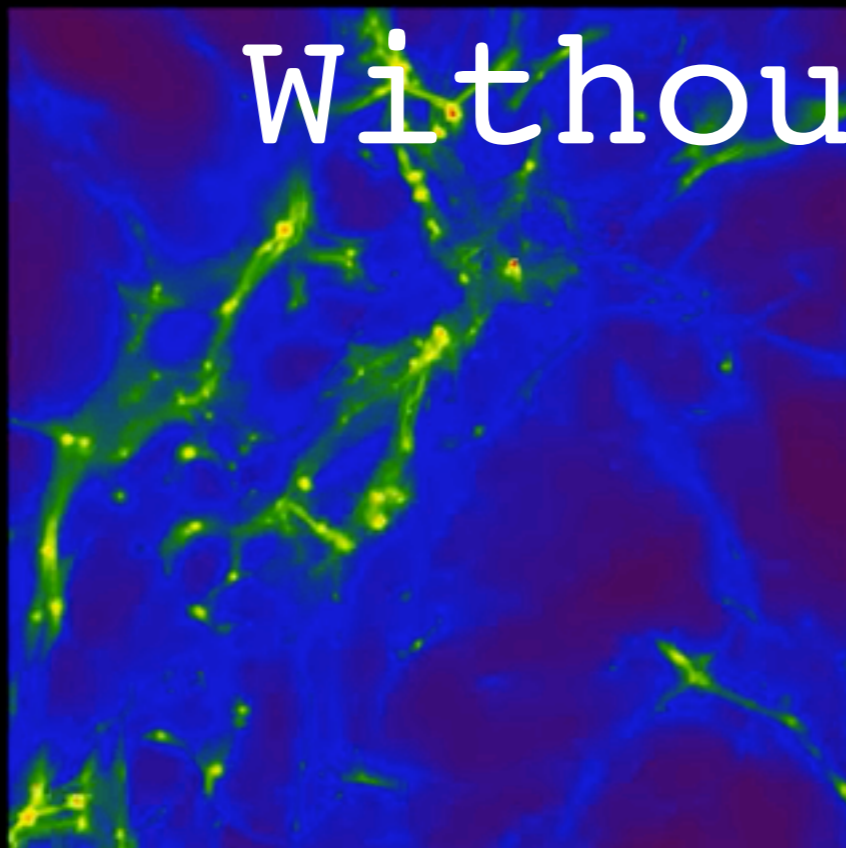
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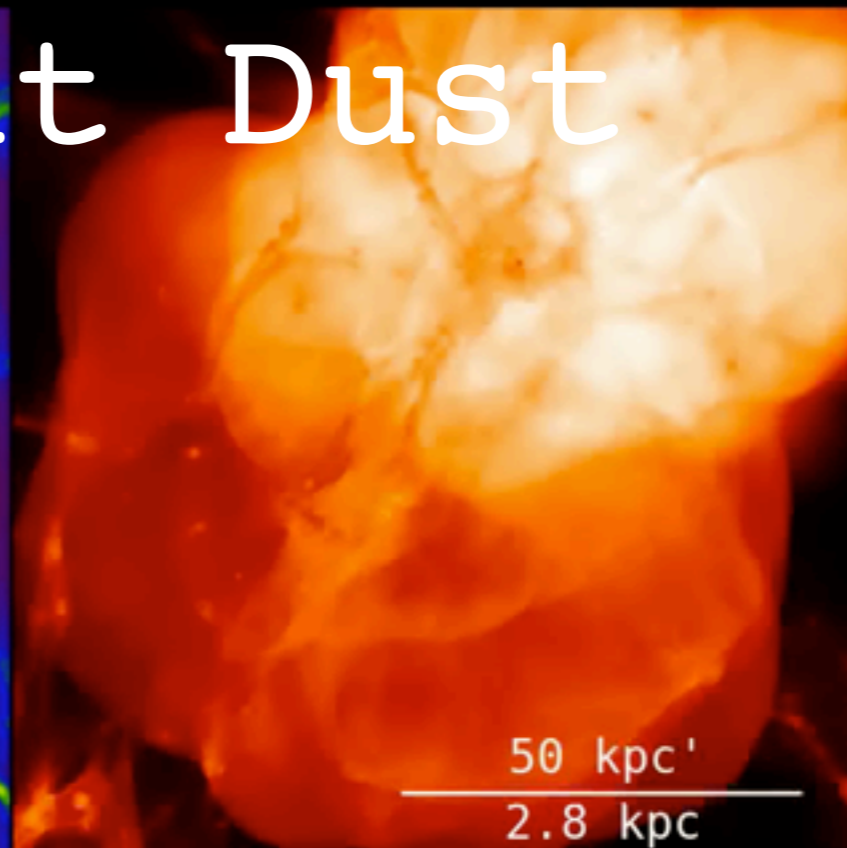


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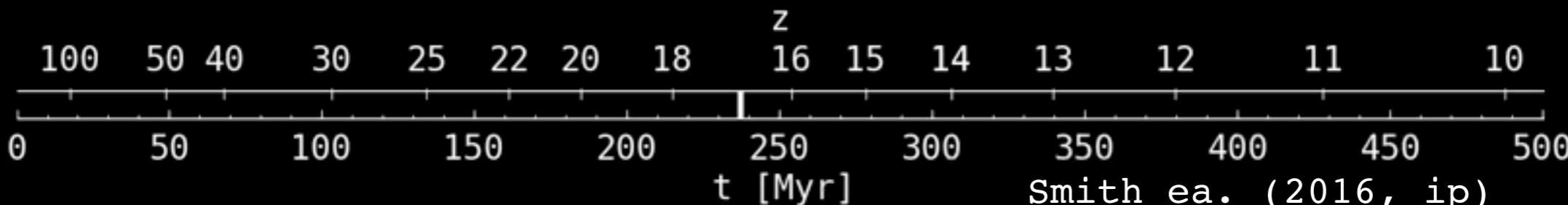
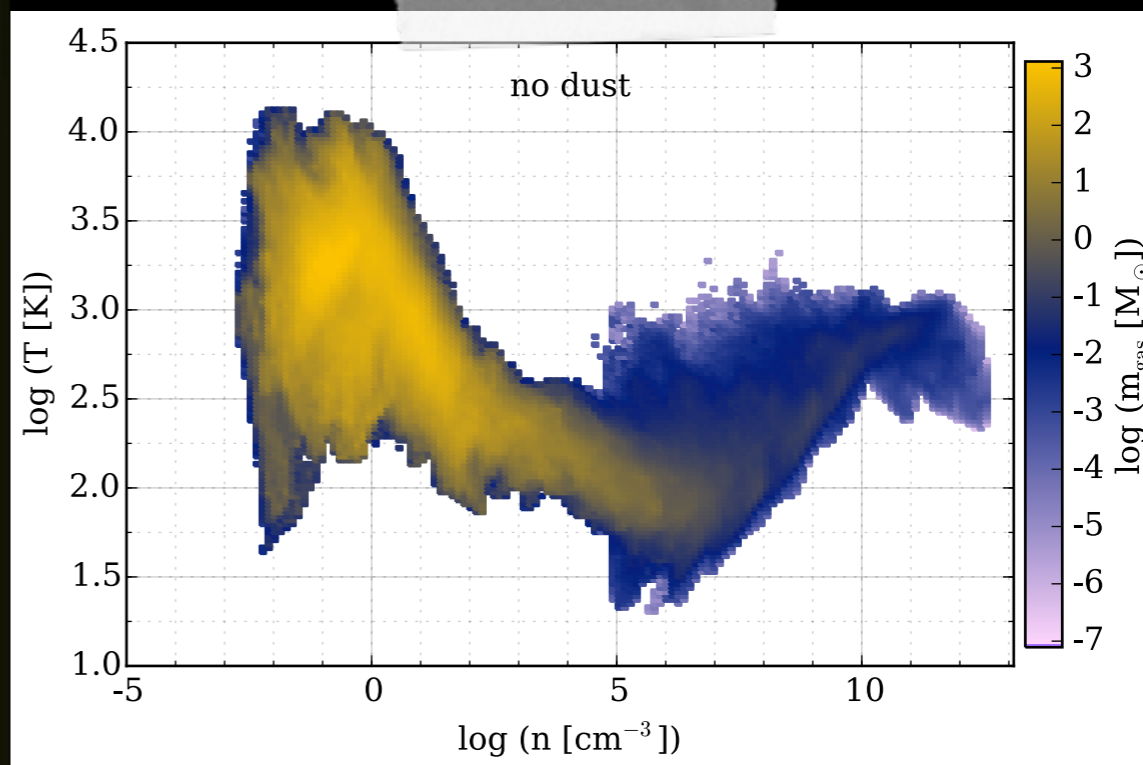
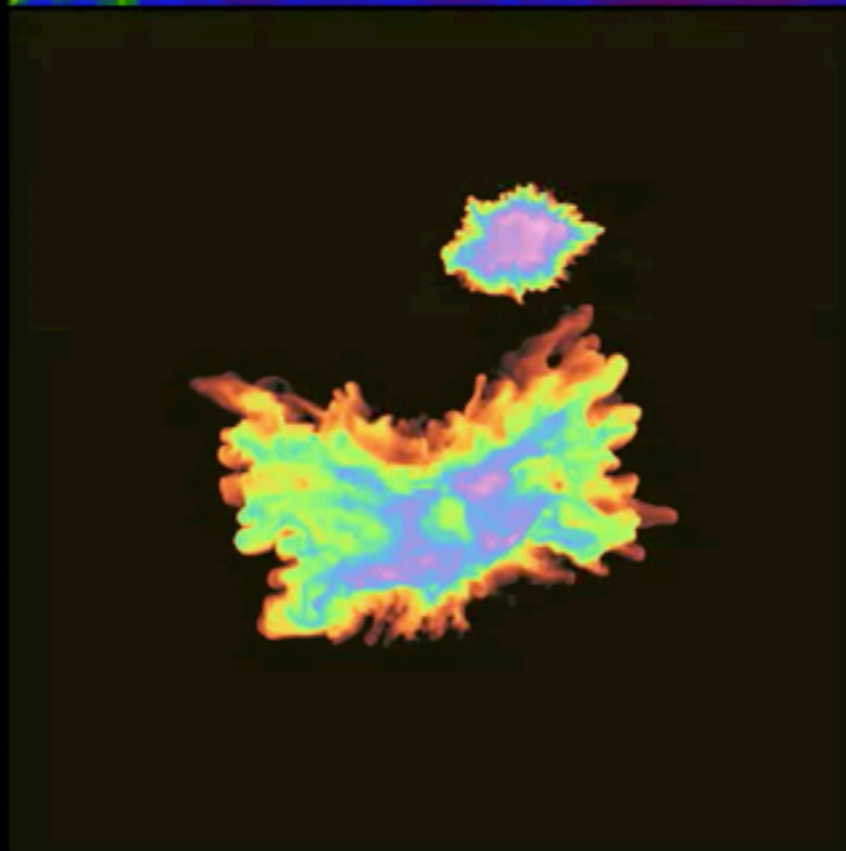
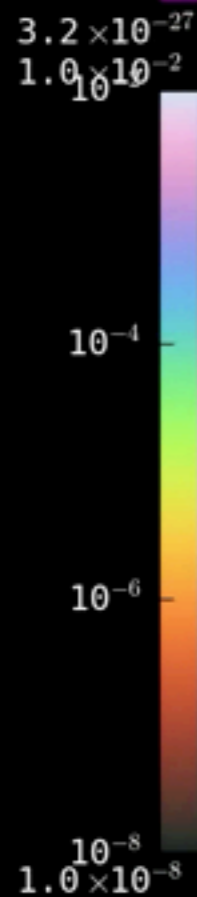
$\rho$  [ $\text{g} / \text{cm}^3$ ]



T [K]



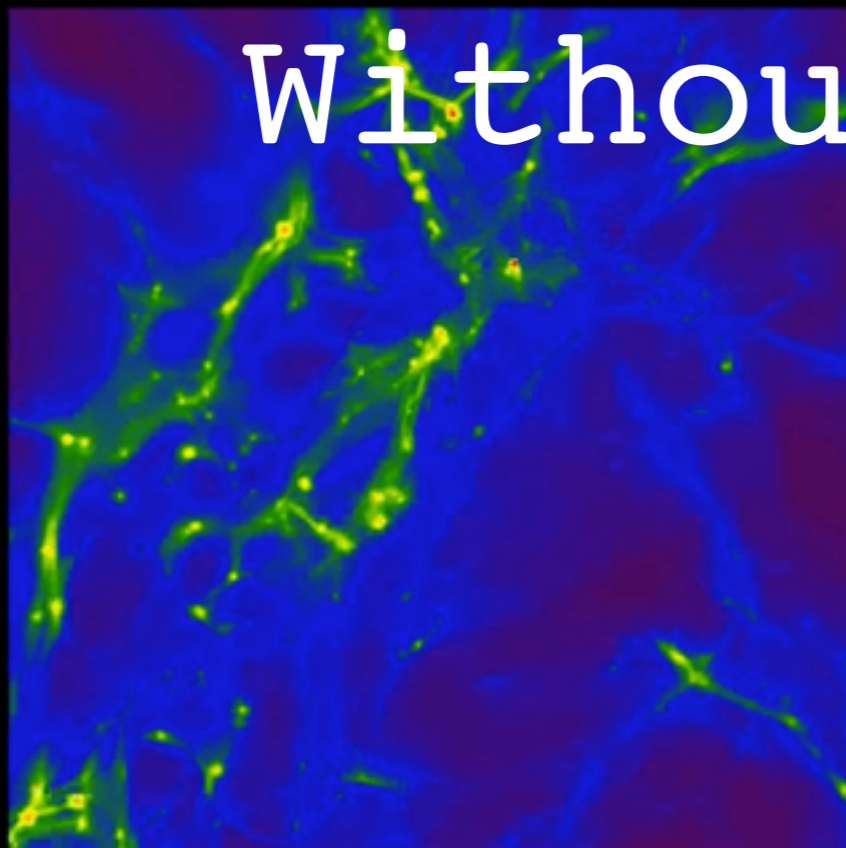
Z [ $Z_\odot$ ]



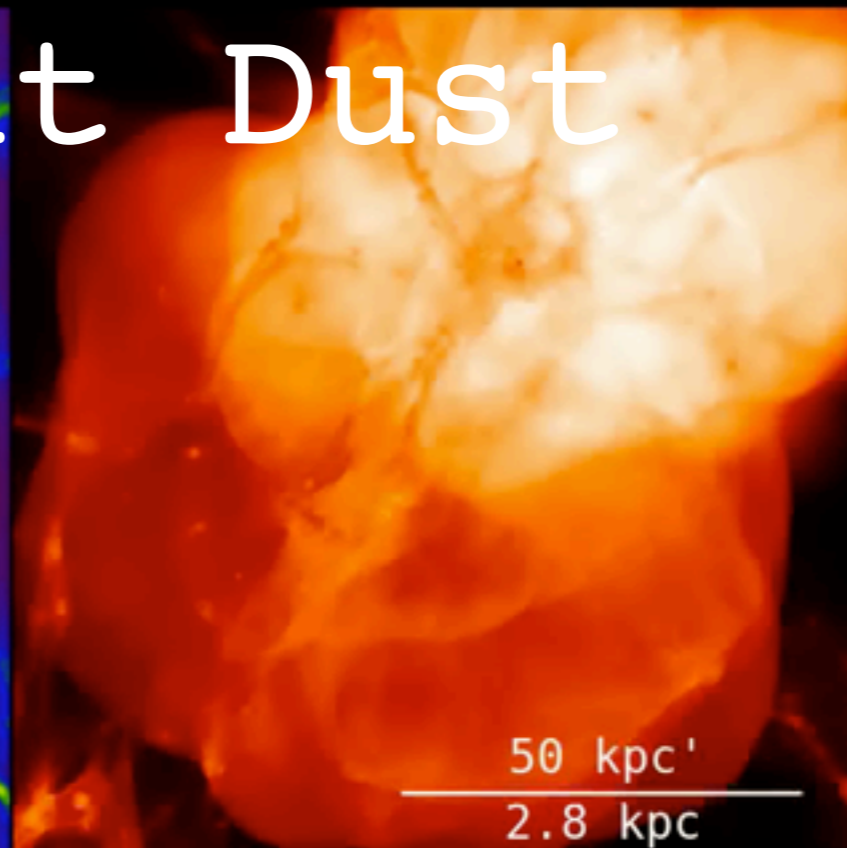
Smith ea. (2016, ip)

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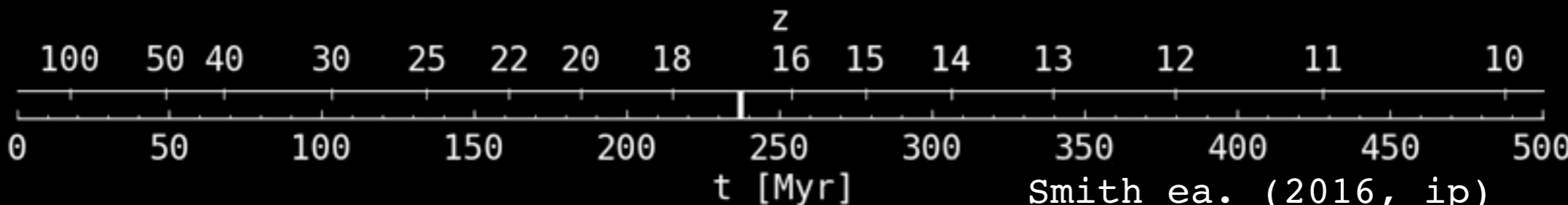
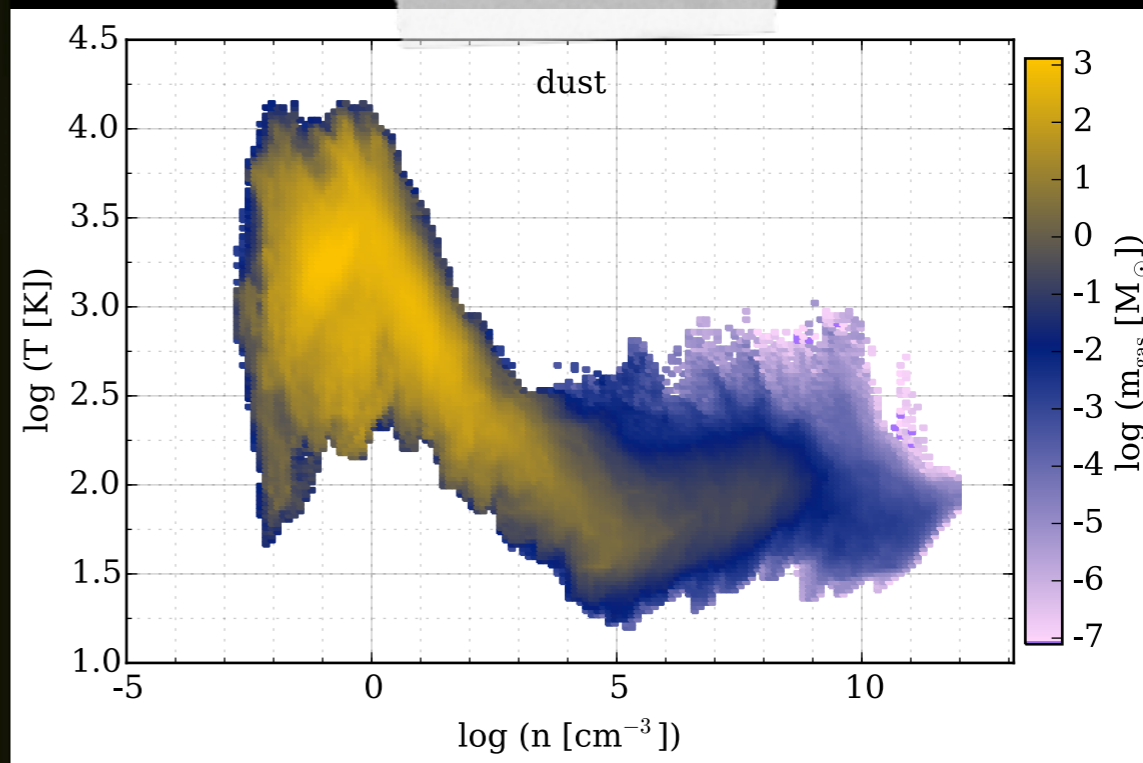
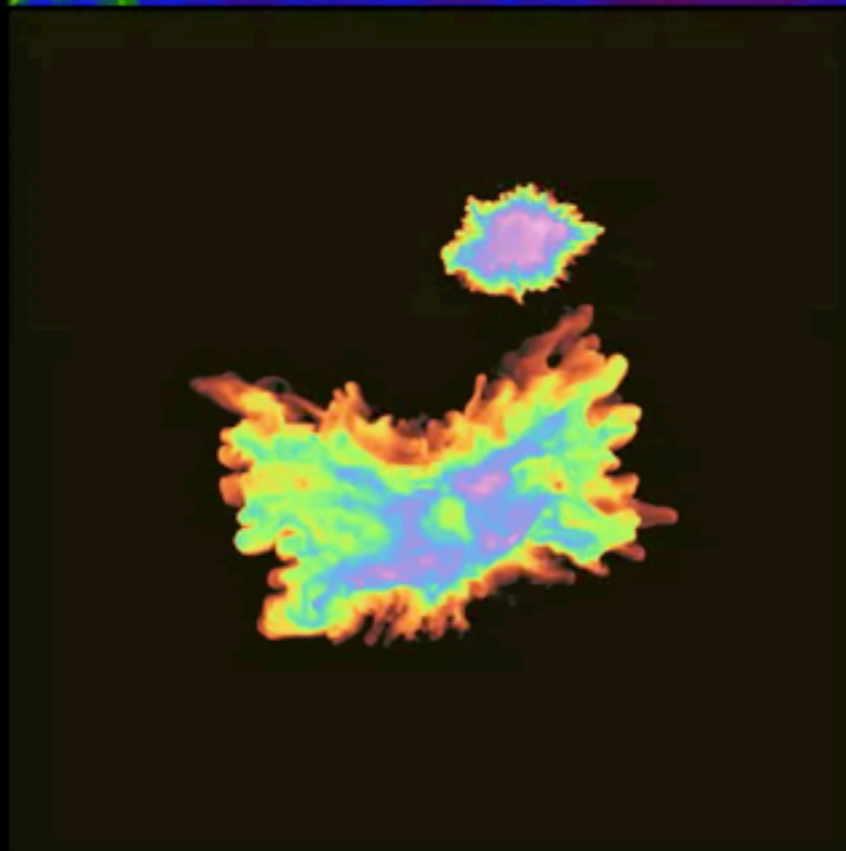
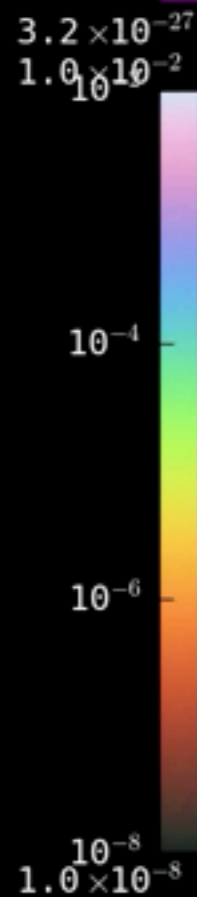
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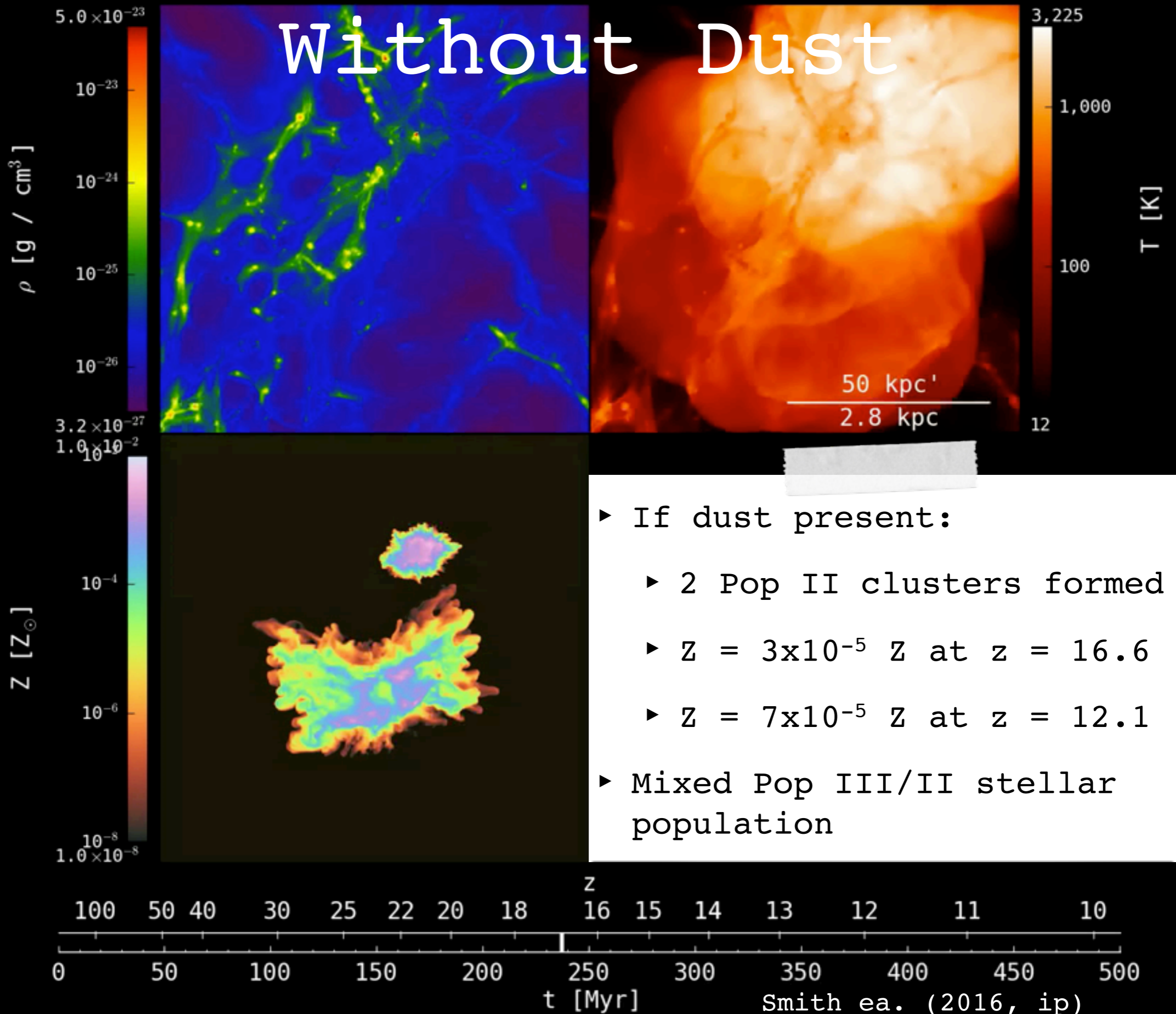
T [K]



Z [ $Z_\odot$ ]



# Without Dust



► If dust present:

► 2 Pop II clusters formed

►  $Z = 3 \times 10^{-5} Z$  at  $z = 16.6$

►  $Z = 7 \times 10^{-5} Z$  at  $z = 12.1$

► Mixed Pop III/II stellar population

# Summary

- ▶ External Enrichment Mechanism:
  - ▶ forms metal-enriched stars from a single SN.
  - ▶ forms metal-enriched stars before self-enrichment.
  - ▶ could be reasonably common.
- ▶ Stars enriched by single SN can exist at multiple metallicities: a new window for stellar archaeology?
- ▶ Two keys to low-mass star formation: turbulence and dust.
- ▶ Galaxies at  $z > 10$  are in the midst of the Pop III/II transition and may host multiple populations.
- ▶ It does not take a lot of metal to make normal stars.  
 $Z = 10$
- ▶ Galaxies are made of mini-halos.

"I was a PR image for the low- $Z$  ILS discovered by Crighton et al. (2016)."  
- this image

# Summary



"I was a PR image for the low- $z$  ILS  
discovered by Crighton ea. (2016)."  
- this image

# Community Tools: The Grackle

grackle 2.1 documentation

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[grackle.readthedocs.org](http://grackle.readthedocs.org)

## Welcome to grackle's documentation!

Grackle is a chemistry and radiative cooling library for astrophysical simulations with interfaces for C, C++, and Fortran codes. It is a generalized and trimmed down version of the chemistry network of the [Enzo](#) simulation code. Grackle provides:

- two options for primordial chemistry and cooling:
  1. non-equilibrium primordial chemistry network for atomic H, D, and He as well as H<sub>2</sub> and HD, including H<sub>2</sub> formation on dust grains.
  2. tabulated H and He cooling rates calculated with the photo-ionization code, [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 \(2012\)](#).

The Grackle provides functions to update chemistry species; solve radiative cooling and update internal energy; and calculate cooling time, temperature, pressure, and ratio of specific heats (gamma).

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