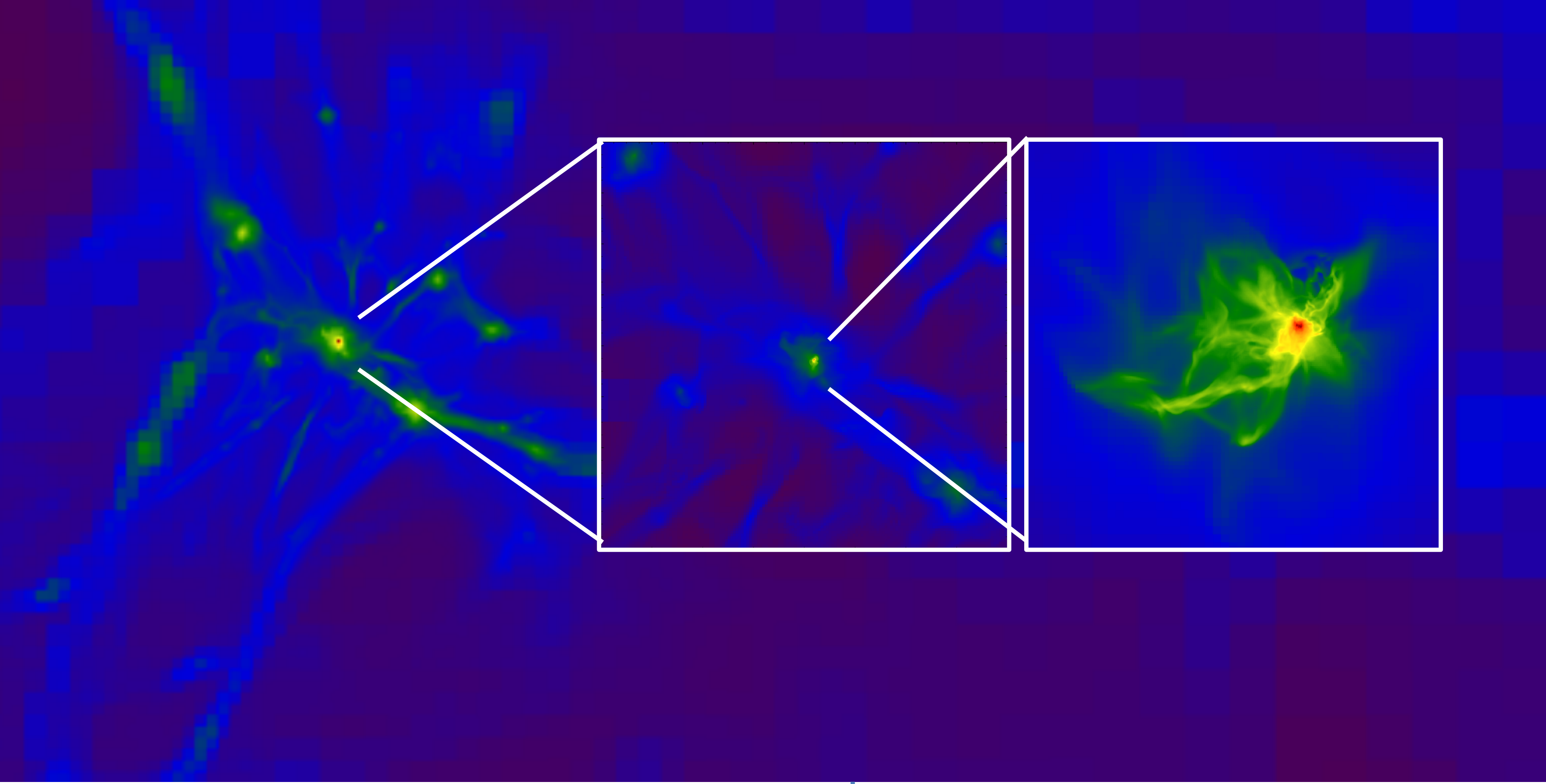


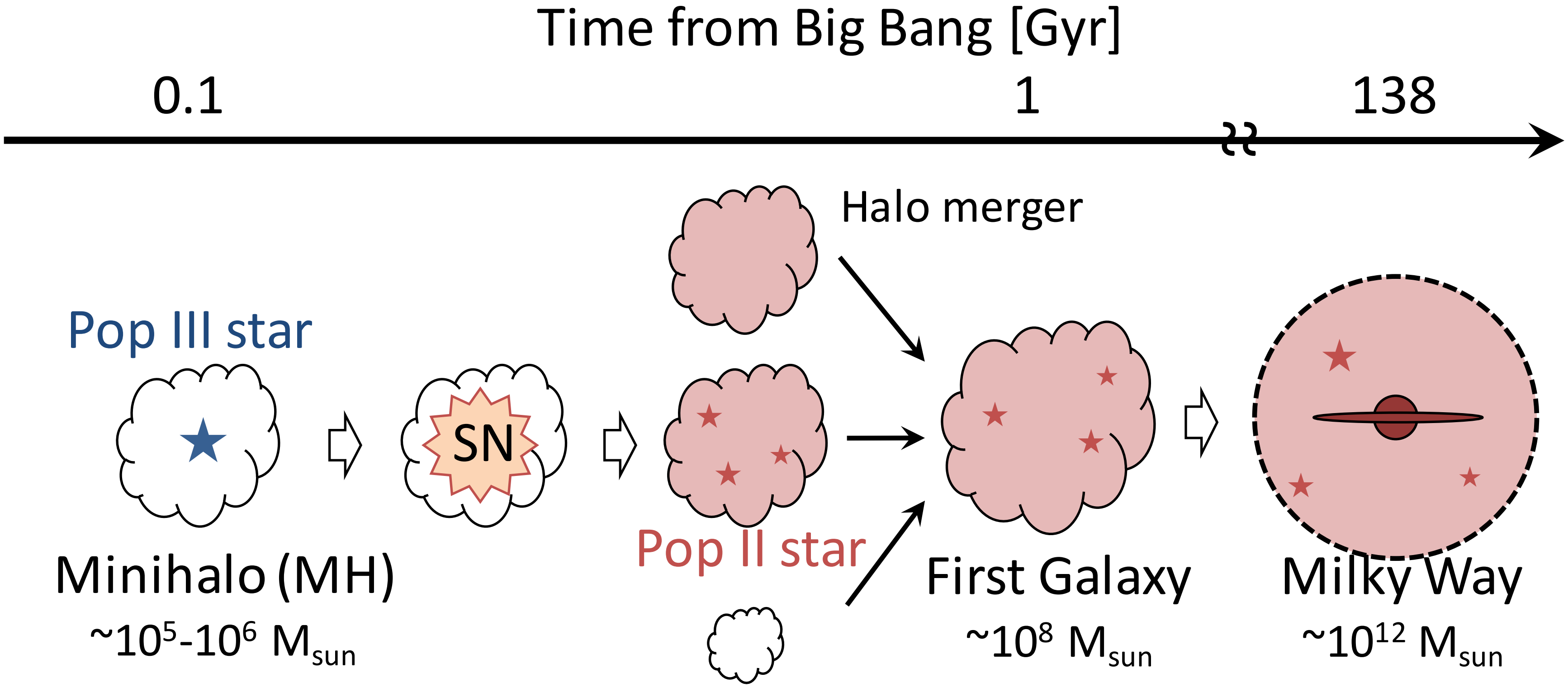
初代星超新星のフィードバックを考慮した金属欠乏星形成

MNRAS in printing (arXiv:1808.09515)

初代星・初代銀河研究会2018@茨城
2018年11月19日（月）15:30

Gen Chiaki
John Wise
(Konan-U, Georgia Tech)

Research interest: what is the mass scale of **metal-poor stars**?


Time from Big Bang [Gyr]

0.1

1

138

Halo merger

Pop III star

SN

Pop II star

Minihalo (MH)

$\sim 10^5\text{-}10^6\ M_{sun}$

First Galaxy

$\sim 10^8\ M_{sun}$

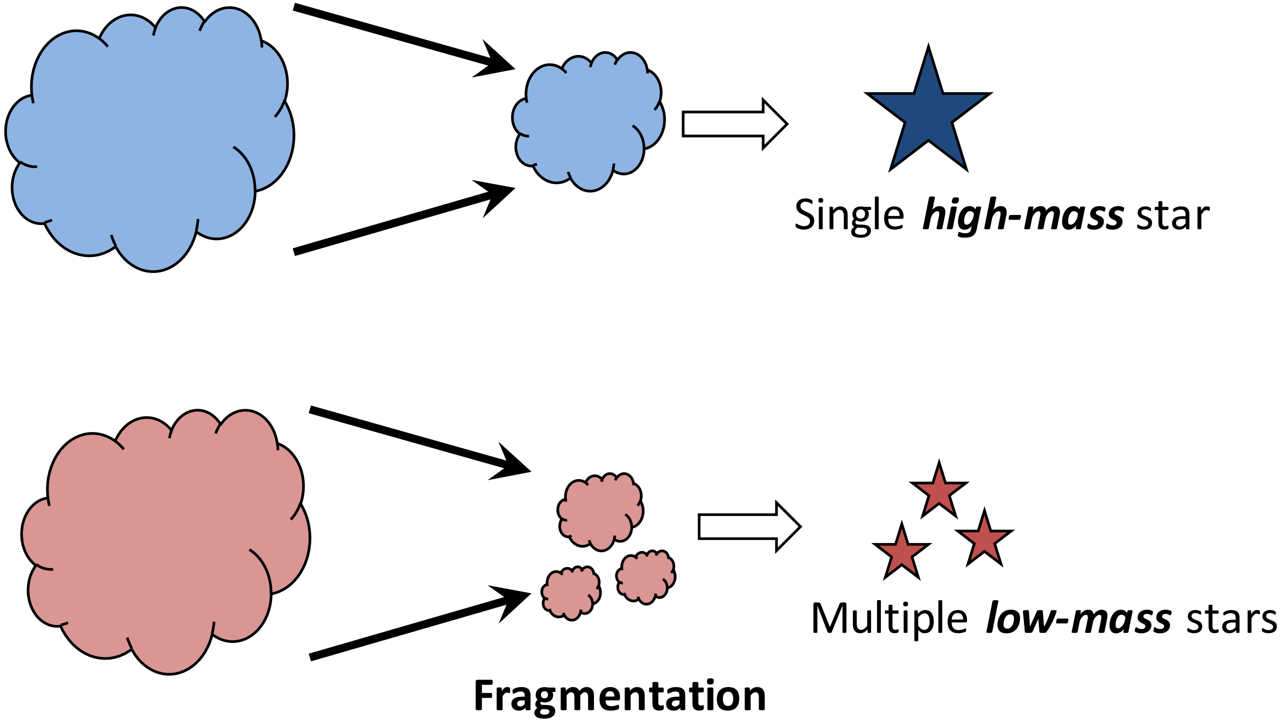
Milky Way

$\sim 10^{12}\ M_{sun}$

✓ **First metal-free stars (Pop III stars)** provide
  - first metal and dust
  - first light.

✓ **Metal-poor stars (Pop II stars)**
  - "living fossils" of early metal enrichment if low-mass (< 1 $M_\odot$; long-lived)
  - gravitational wave sources (binary neutron stars or black holes) if massive

Fragmentation: precursor of low-mass star formation

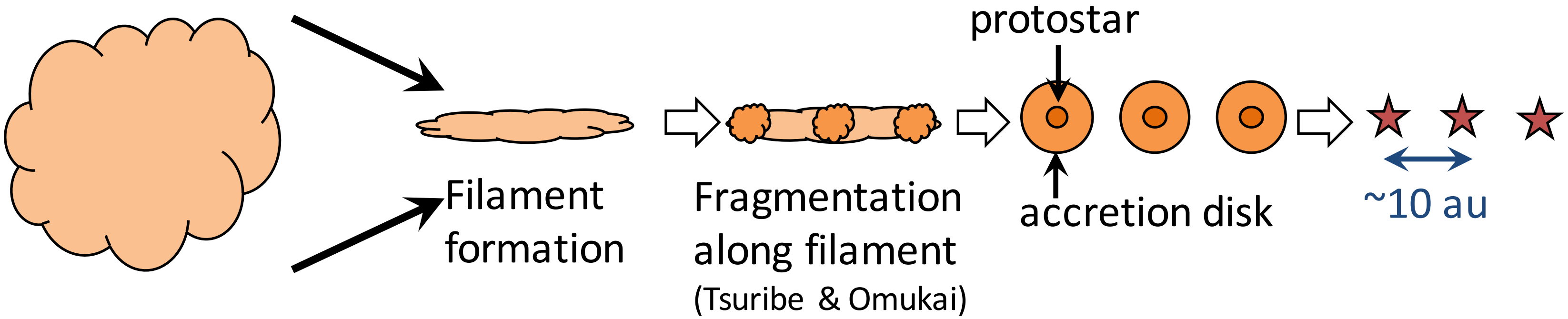


Two Fragmentation modes: disk fragmentation/filament fragmentation

see Chiaki et al. (2016); Yoshida-san’s talk

Filament fragmentation (FF): fragmentation in **collapsing phase**

Induced by **radiative cooling** in the collapsing phase



protostar

Filament formation

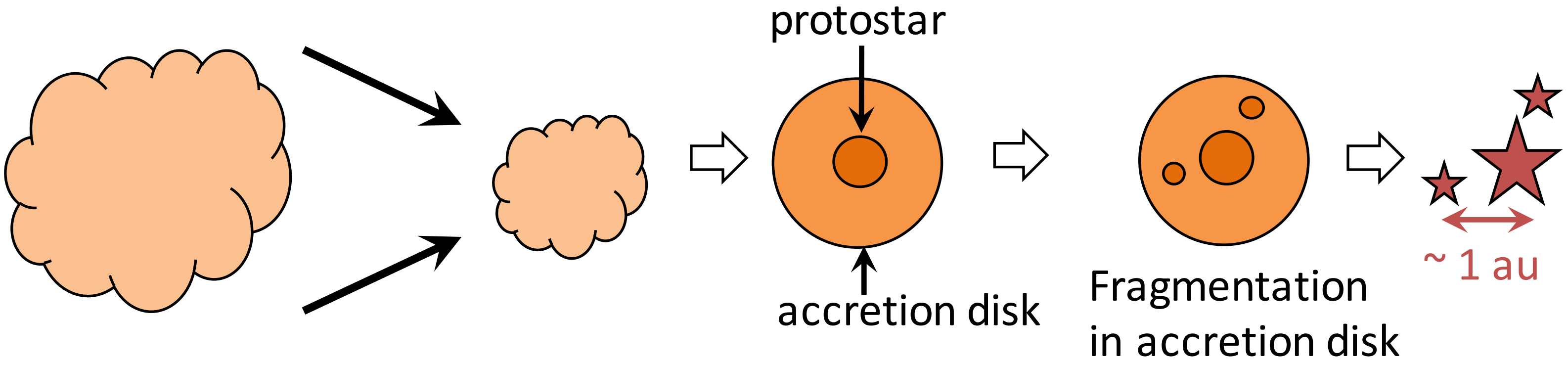
Fragmentation along filament (Tsuribe & Omukai)

accretion disk

~10 au

← Collapsing phase → ← Accretion phase →

Disk fragmentation (DF): fragmentation in **accretion phase**



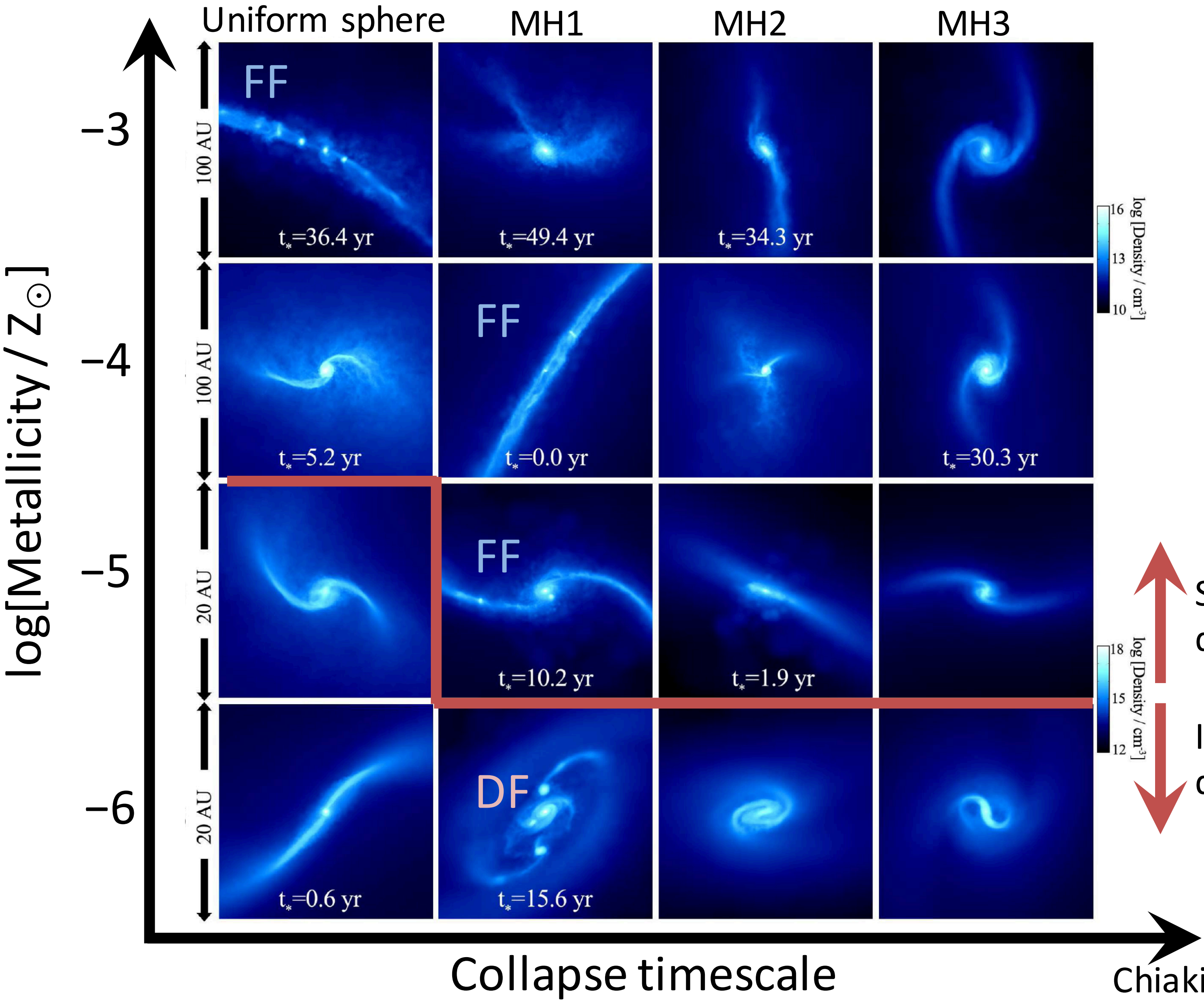
protostar

accretion disk

Fragmentation in accretion disk

~ 1 au

Various frag. modes in low-Z clouds

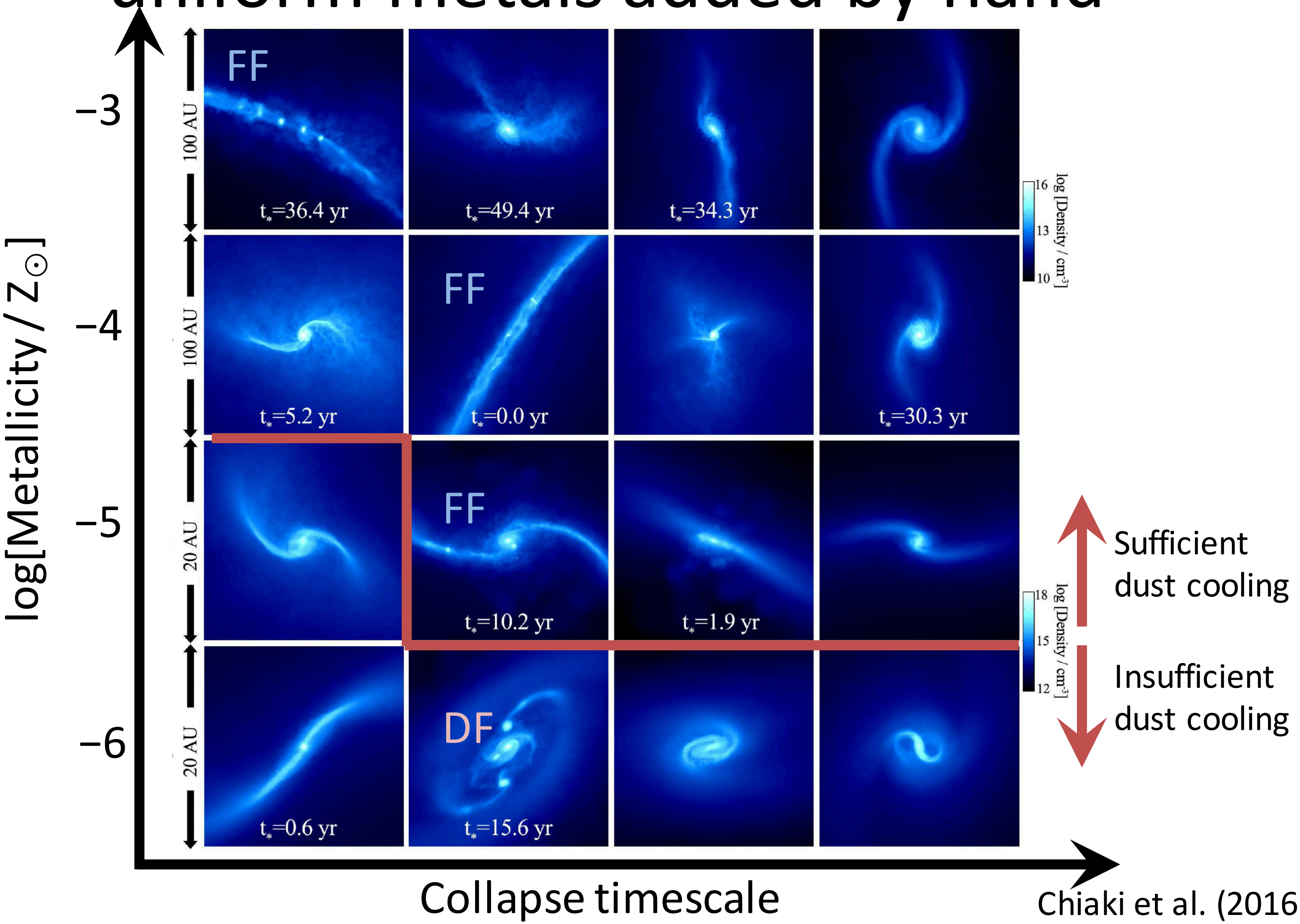


Sufficient
dust cooling

Insufficient
dust cooling

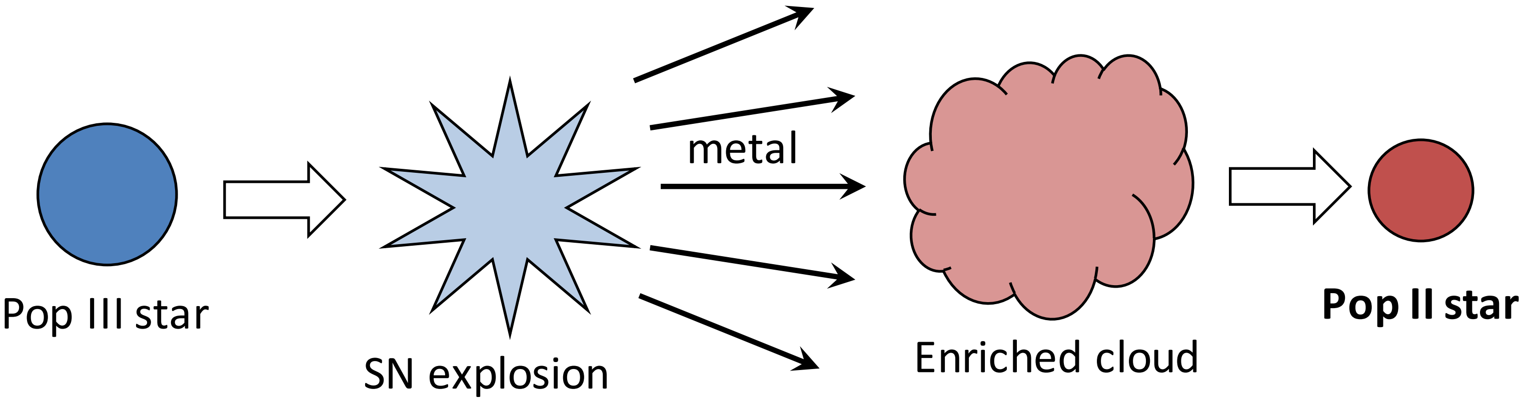
Chiaki et al. (2016)

Ideal initial condition: clouds with uniform metals added by hand



Chiaki et al. (2016)

In this work, we run simulation with more realistic initial condition



Pop III star

SN explosion

metal

Enriched cloud

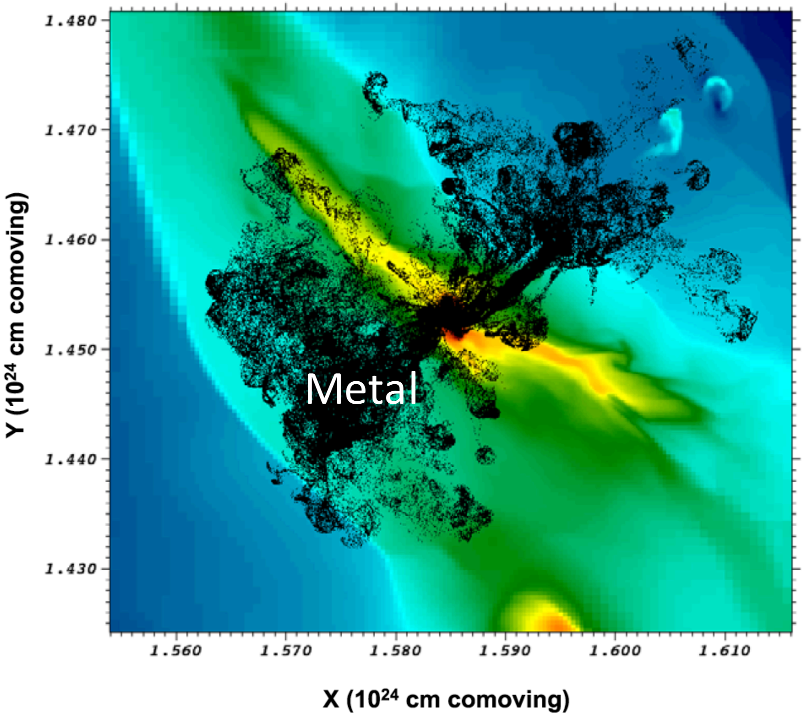
Pop II star

- ✓ Non-uniform distribution of metals
  - ➢ This affects cooling rate
- ✓ Turbulence induced by SN
  - ➢ Enhanced initial density perturbation

Earlier works

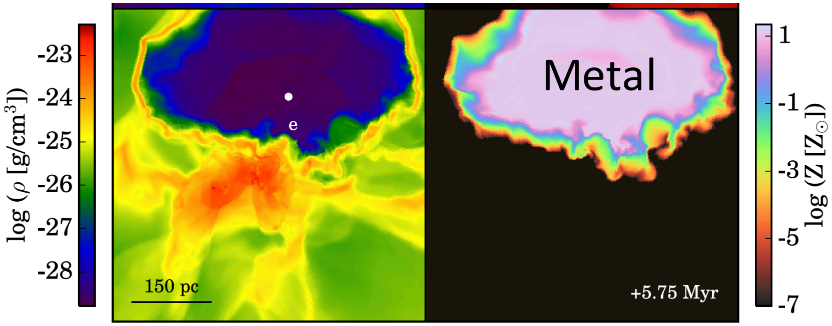
Ritter et al. (2012, 2015, 2016)
Sluder et al. (2015)

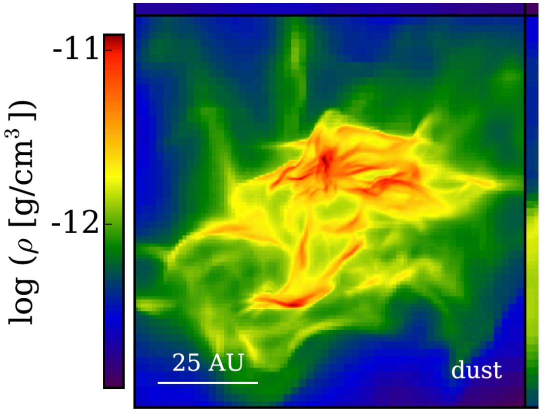
- ✓Cosmological initial condition
- ✓Self-enrichment of a Pop III cloud
- ✓$Z = 0.001\text{-}0.01\, Z_\odot$



Smith et al. (2015)

- ✓Cosmological initial condition
- ✓Enrichment of a neighboring halo
- ✓$Z = 2 \times 10^{-5}\, Z_\odot$





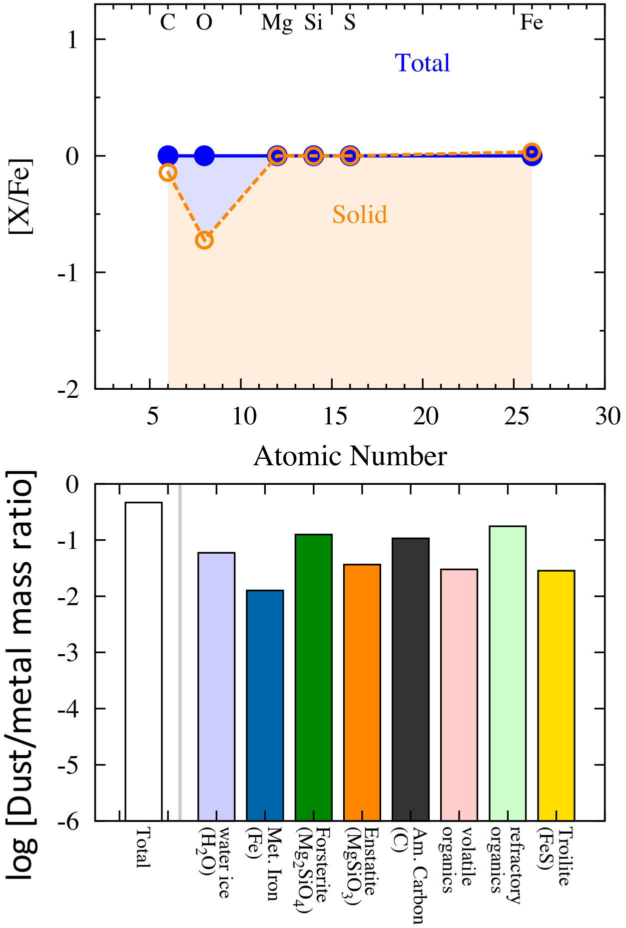
Cloud fragmentation by dust cooling

However, they employ present-day dust model.

Pollack et al. (1994)

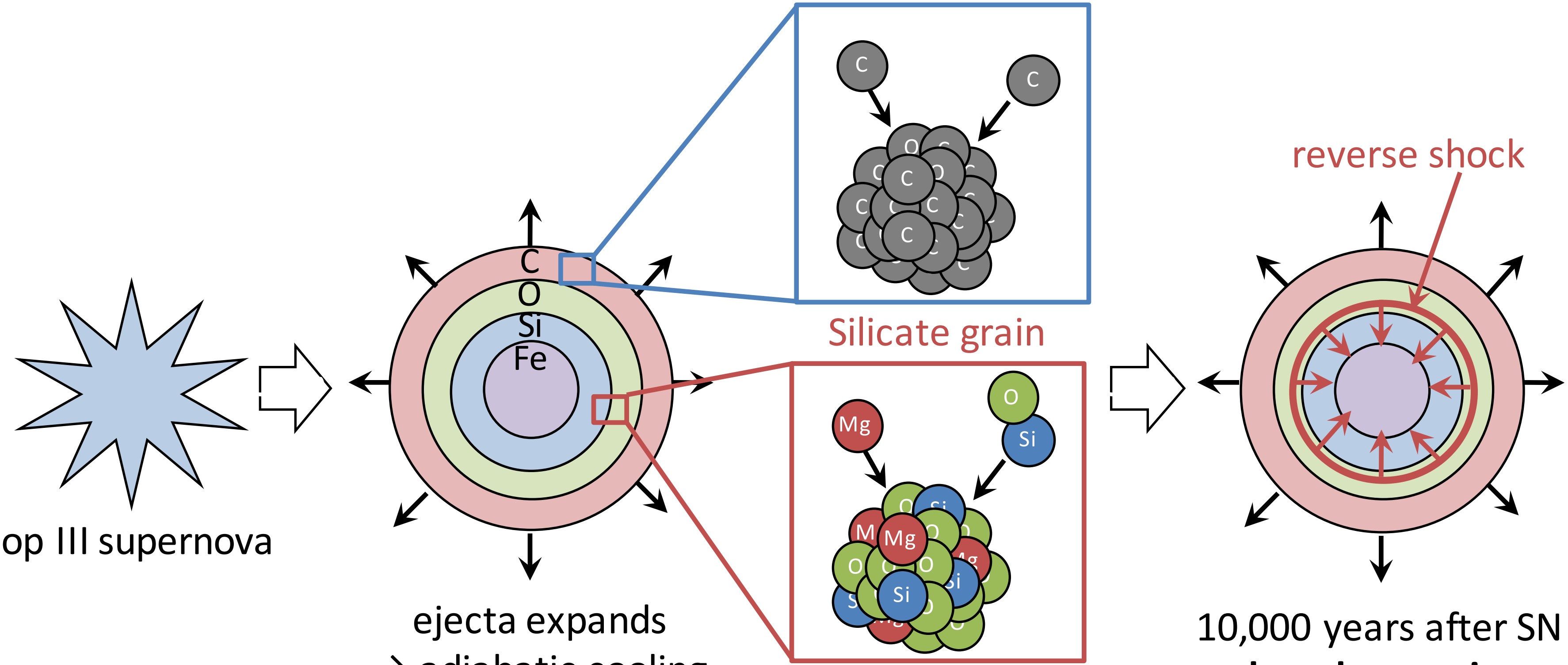
Dust model in the early Universe

Dust model in the present-day



Dust is supplied only by Pop III SNe and partly destroyed by reverse shocks

(Todini & Ferrara 2001; Nozawa et al. 2007; Bianchi & Schneider 2007)



Carbon grain

Silicate grain

reverse shock

Pop III supernova

ejecta expands
→ adiabatic cooling

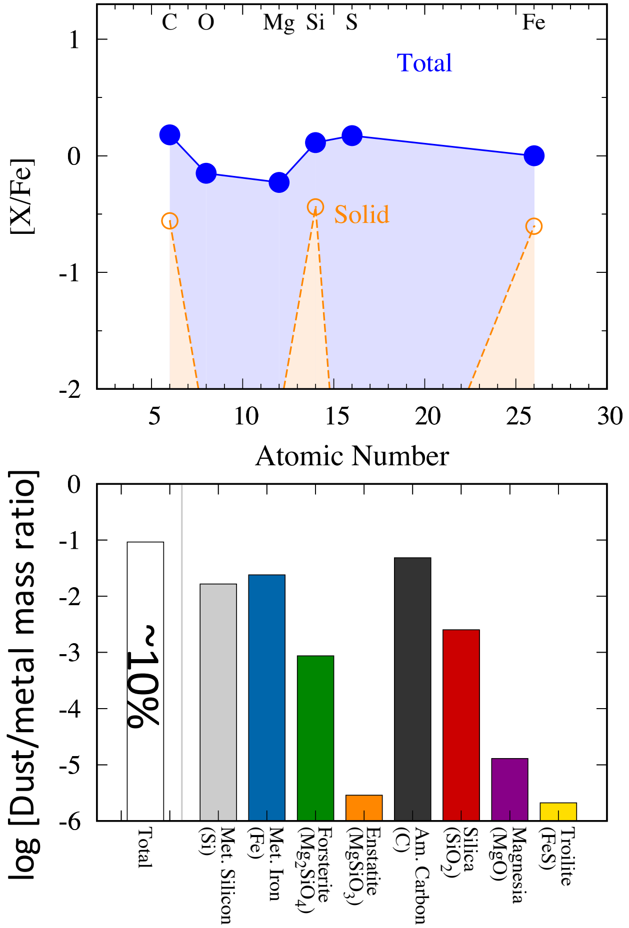
300 days after SN
T < 1,000 K
dust formation (nucleation)

10,000 years after SN
dust destruction

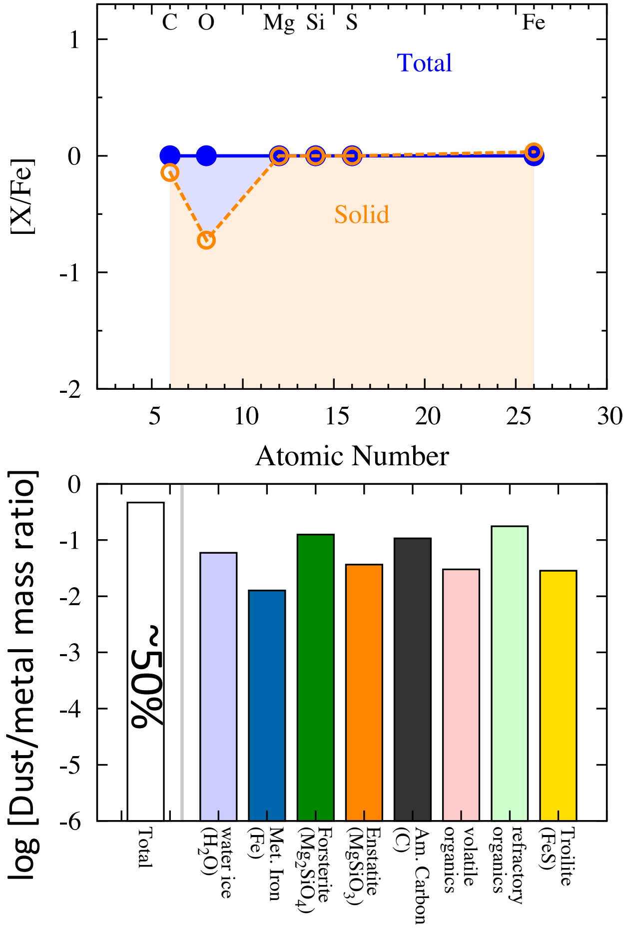
In the early Universe, dust amount is smaller than in the present-day.

(Umeda & Nomoto 2002; Nozawa et al. 2003, 2007)

Dust model in the early Universe

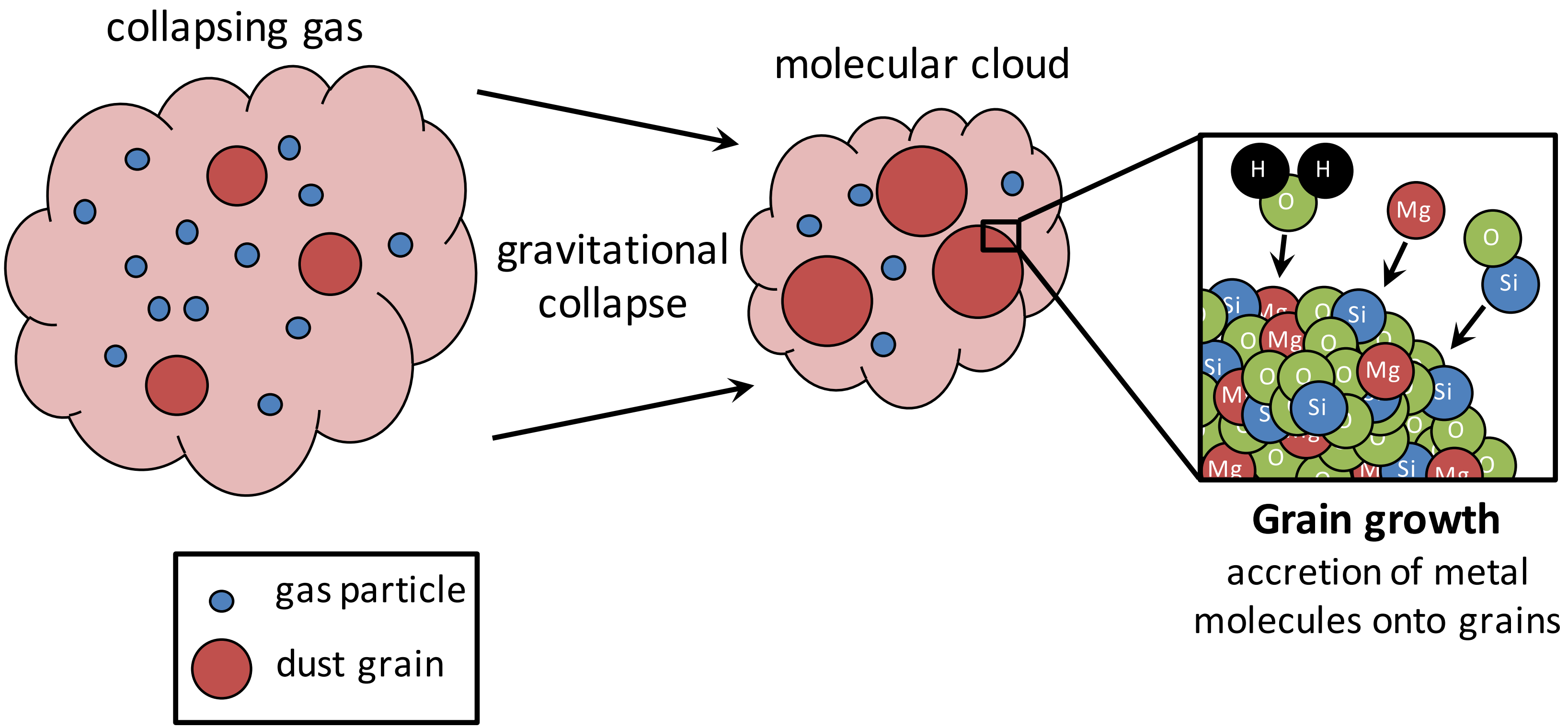


Dust model in the present-day



Also, **grain growth** is important to enhance dust cooling rate.

Chiaki et al. (2015; 2016)



collapsing gas

gravitational collapse

molecular cloud

Grain growth

accretion of metal molecules onto grains

- ● gas particle
- ● dust grain

In this work, we elaborate **dust models**

- ✓Supernova dust model
- ✓Grain growth

Initial condition

AMR/N-body Code: ENZO
Chemistry: GRACKLE (modified)
Box size: 300 ckpc (periodic)
Top grid: 64^3 ($m_{\rm DM}=2.86\times10^3\ M_\odot$)
Initial redshift: 140
Level: 2 → **37**

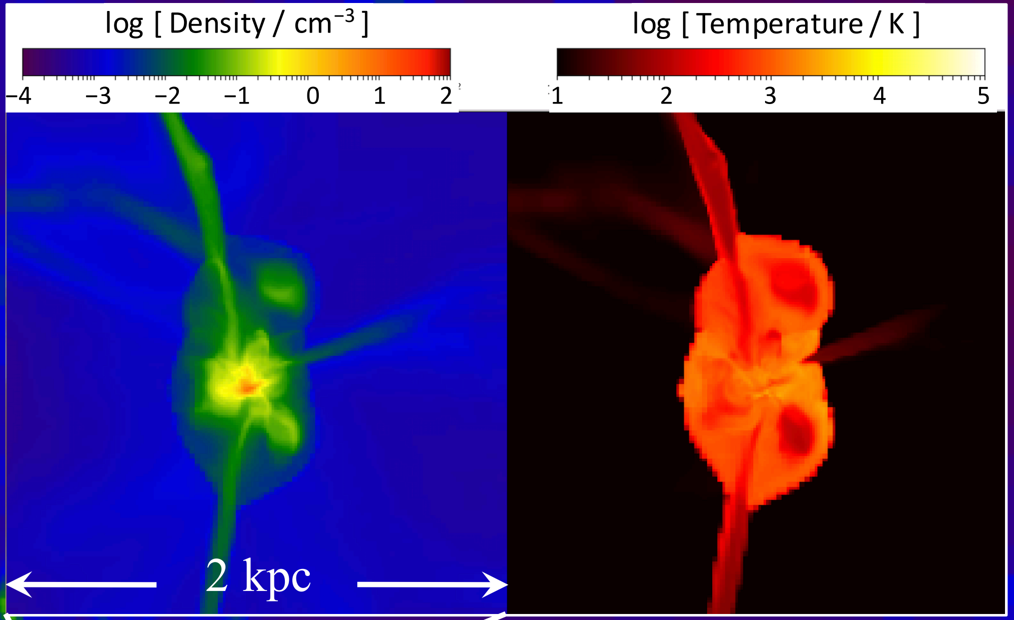
Refinement criterion:
(i) gas mass in a cell $M_{\rm g} > 3\times2^{-0.2L}\ M_{\rm ref,\ g}$
(ii) DM mass in a cell $M_{\rm d} > 3\ M_{\rm ref,\ d}$
(iii) Jeans length $\lambda_{\rm J} < 64\ \Delta x$

Pop III star formation criterion:
(i) gas density $n_{\rm H} > 10^6\ {\rm cm}^{-3}$
(ii) convergent flow $\nabla\ .\ v < 0$
(iii) $t_{\rm cool} < t_{\rm dyn}$
(iv) metallicity $Z < 5\times10^{-5}\ Z_\odot$
(v) H_2 fraction $f_{\rm H2} > 10^{-3}$

Pop III star sampling mass function

$$f(\log M_{\rm PopIII}) = M^{-1}\exp\left[-\left(\frac{M_{\rm char}}{M_{\rm PopIII}}\right)^{1.6}\right]$$

$M_{\rm char} = 20\ M_\odot$



Minihalo

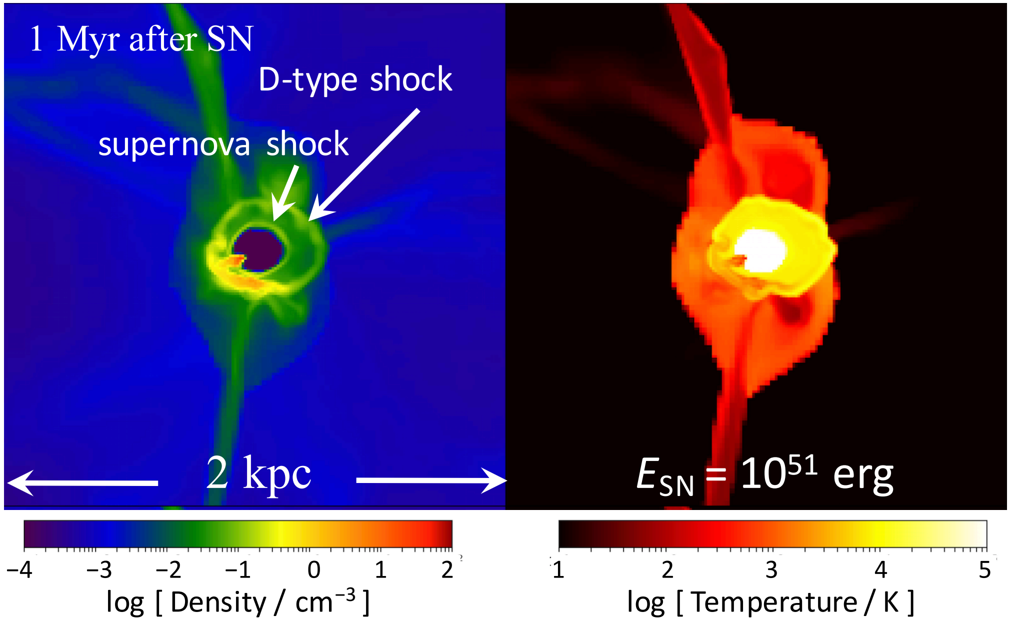
✓$z_{\rm form} = 12.1$
✓$R_{\rm halo} = 478$ kpc
✓$M_{\rm halo} = 1.46\times10^6\ M_\odot$

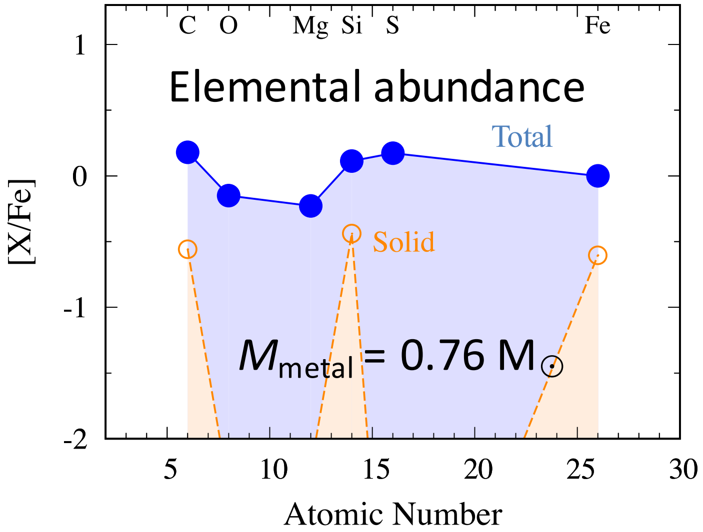
→ Pop III star particle with 13 $M_\odot$ is created.

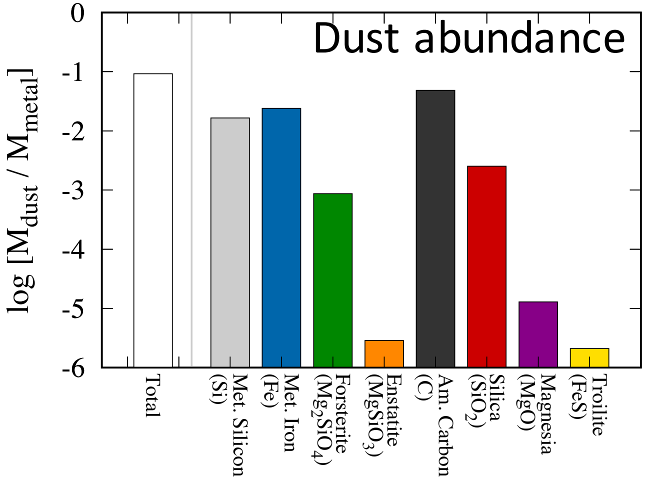
Box size
300 comoving kpc

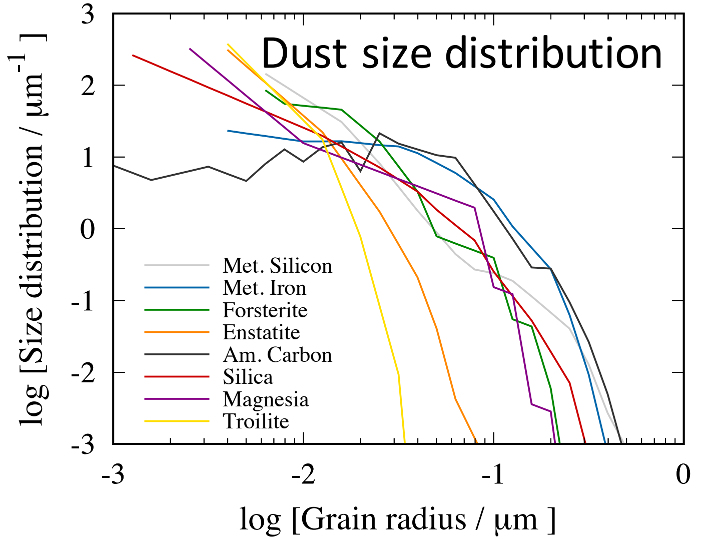
Supernova and metal/dust dispersion

Dust model for 13 $M_\odot$ Pop III SN

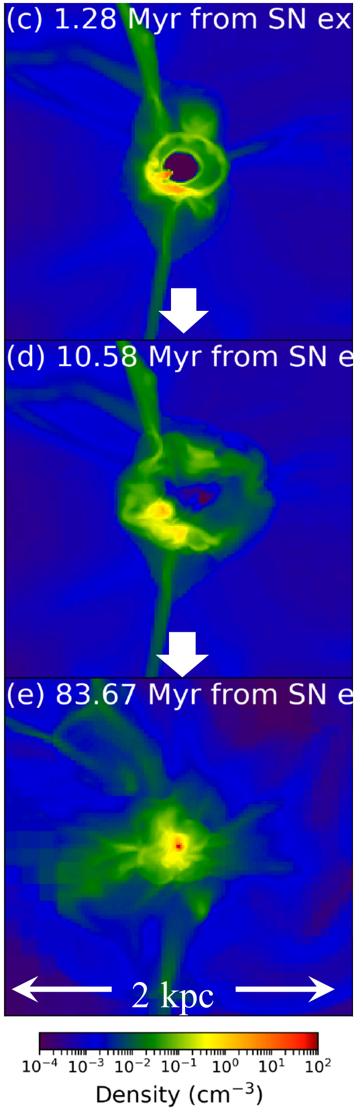








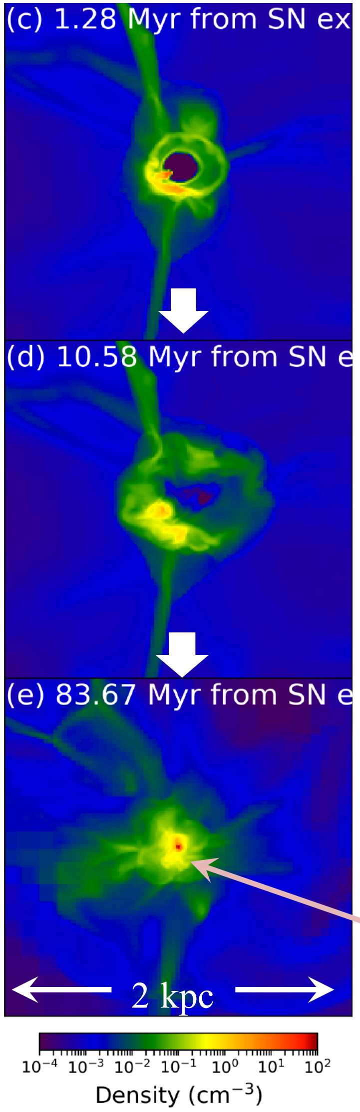
Shocked gas falls back and enriched cloud collapses



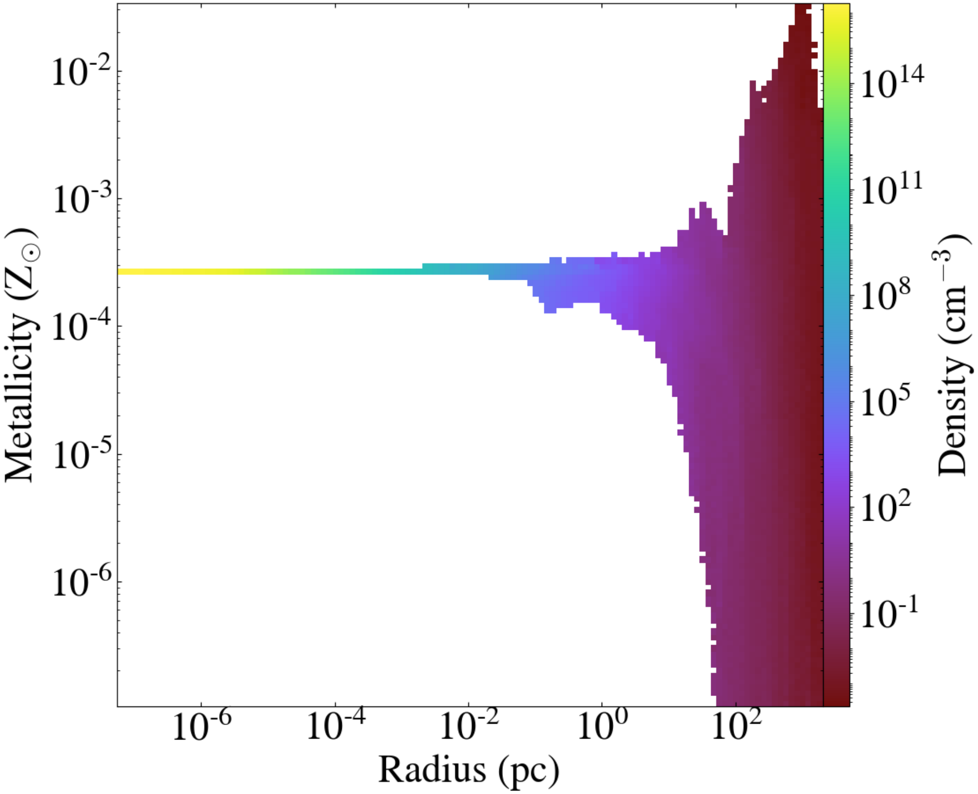
Consistent with the results of

- Ritter et al. (2012, 2015, 2016);
- Sluder et al. (2015);
- Chiaki et al. (2018) for CCSNe!

Metallicity is uniform within 0.1 pc in the recollapsing region.

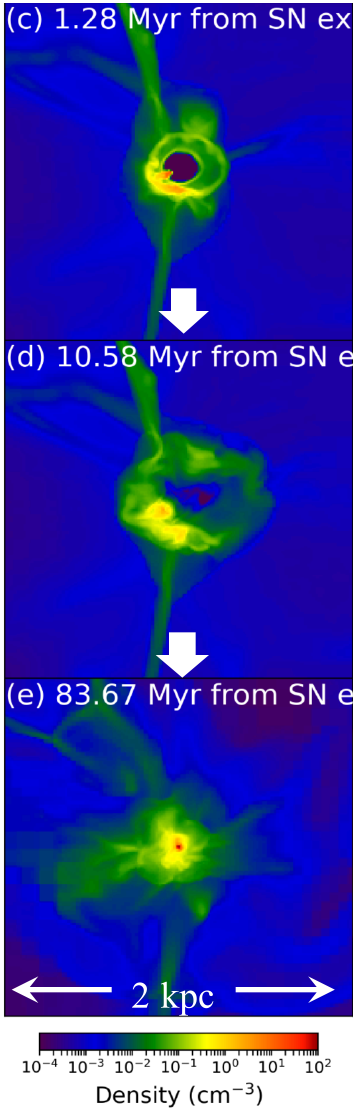


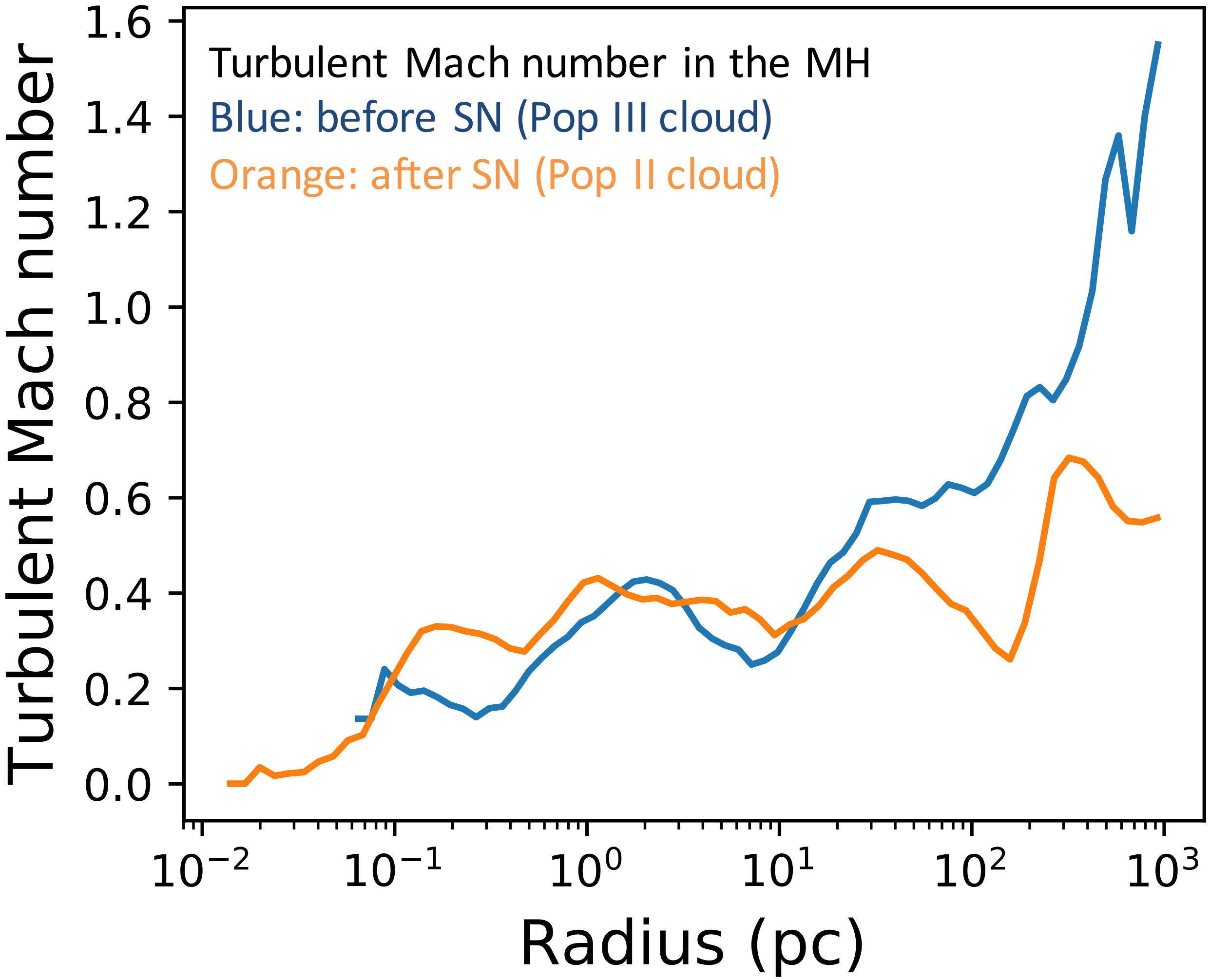
The same result as Smith et al. (2015)



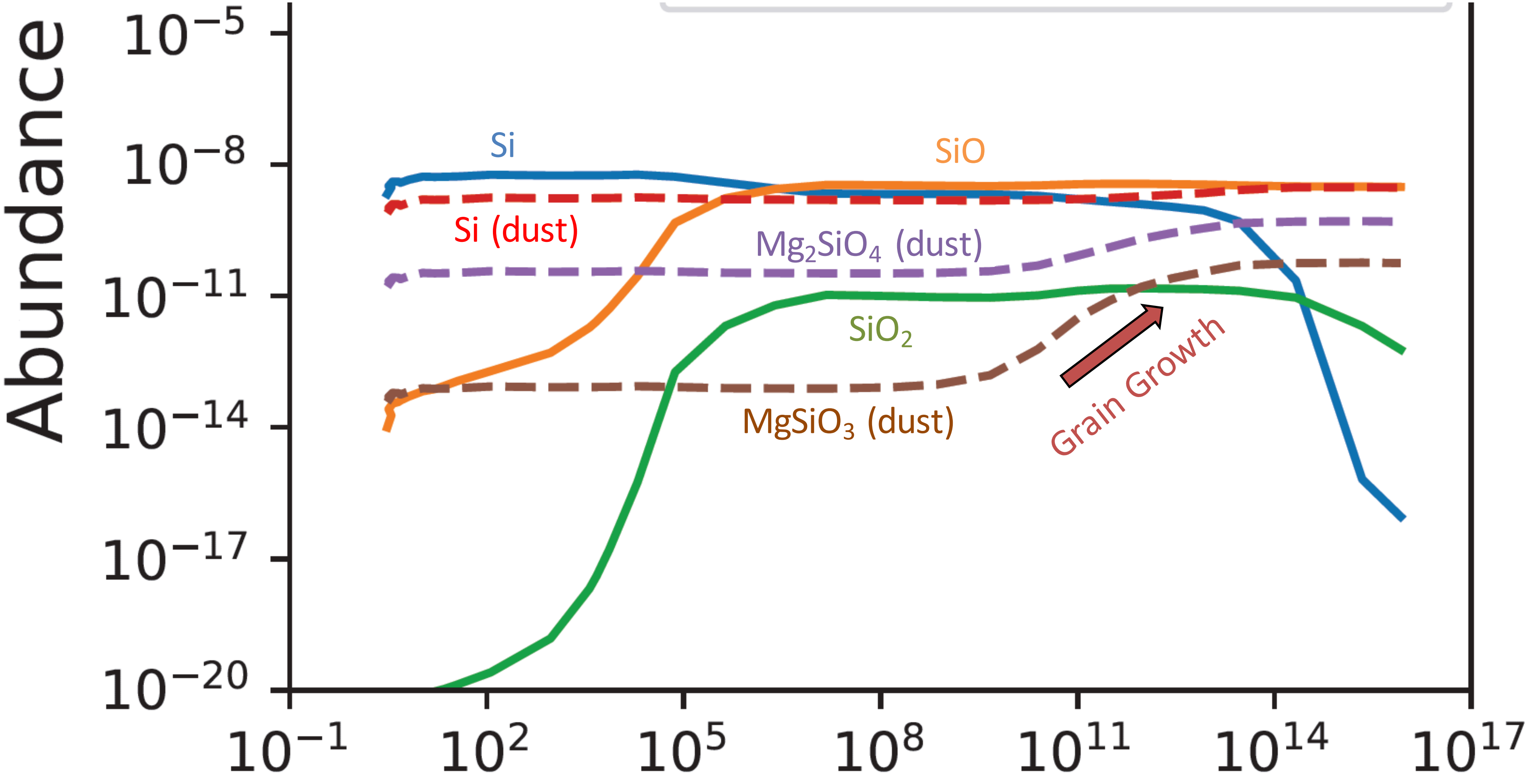
In the recollapsing region, the metallicity is uniformly **$2.6 \times 10^{-4}\ Z_\odot$**

Turbulent is enhanced by a factor of three but still Mach number < 1.



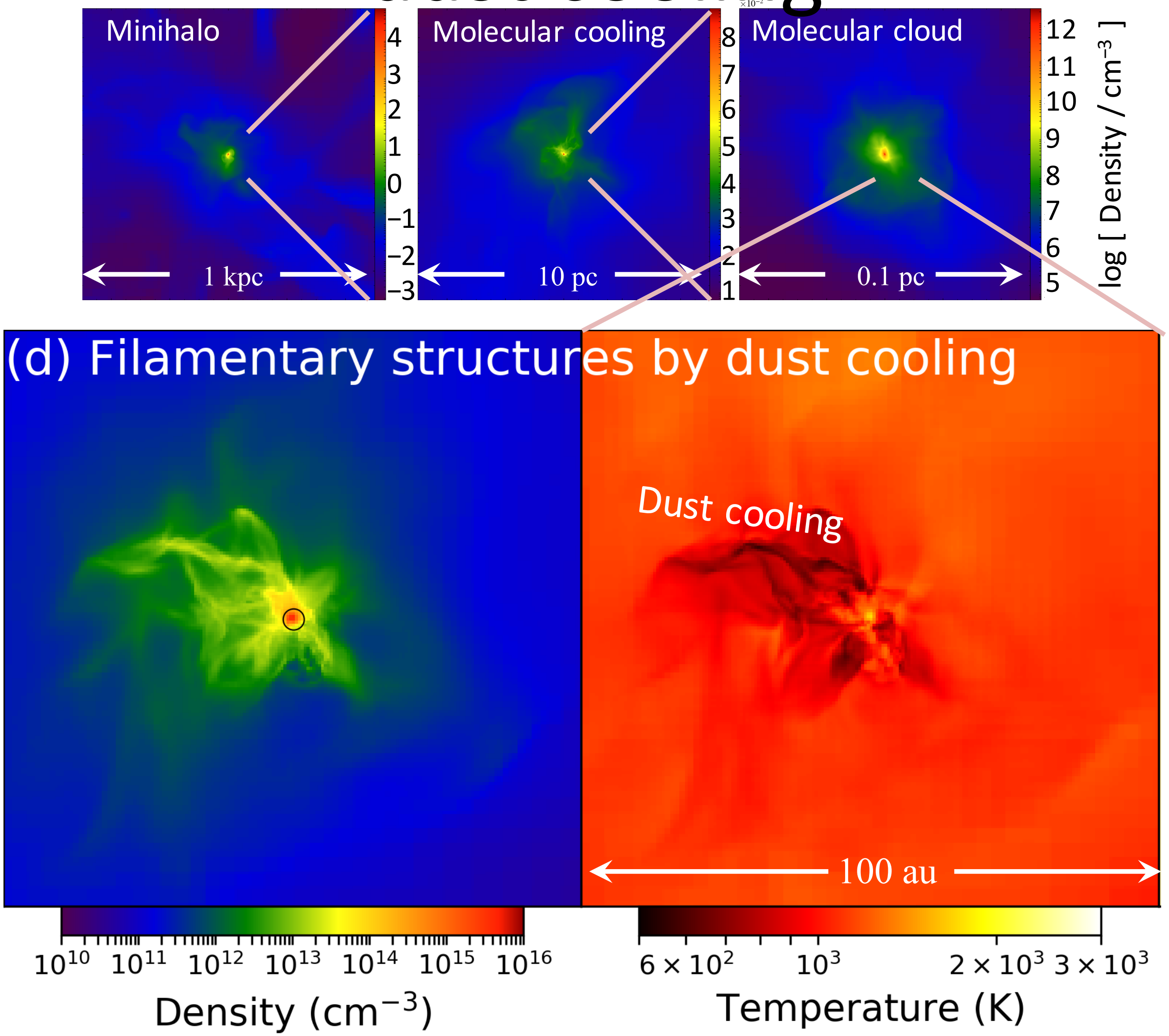


Grain growth is properly solved!



Time sequence

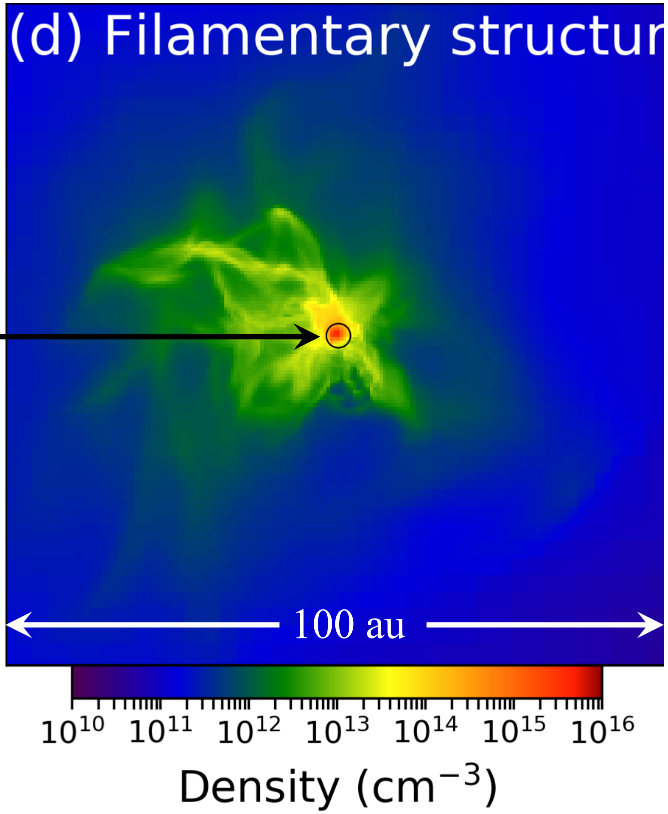
Filamentary structure induced by dust cooling



Filamentary structure induced by dust cooling

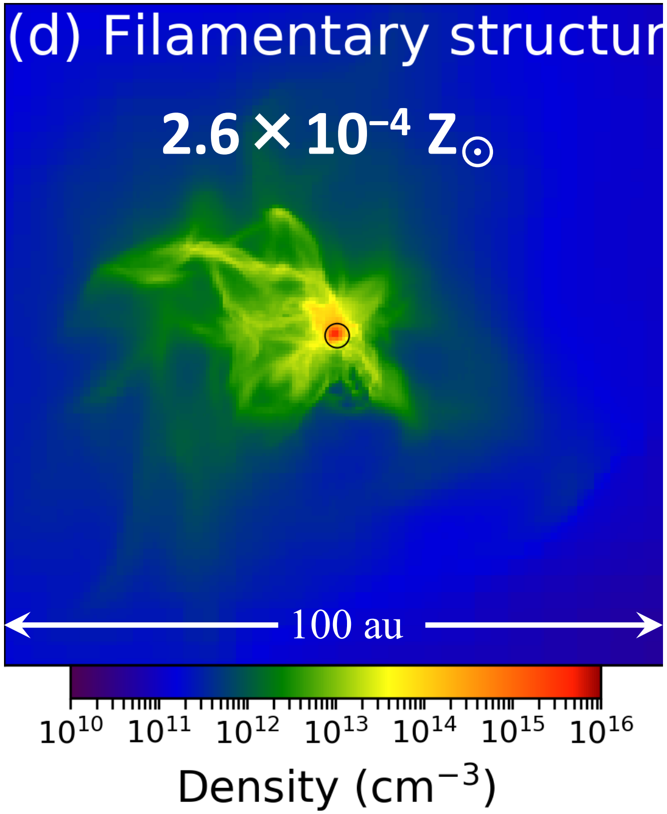
Protostellar core
- spherical reagion
- thermal > gravitational energy
- **mass: 0.06 $M_\odot$**
- **radius: 1.8 au**
- consistent with Jeans mass/radius for 10^{15} cm^{-3}, 500 K

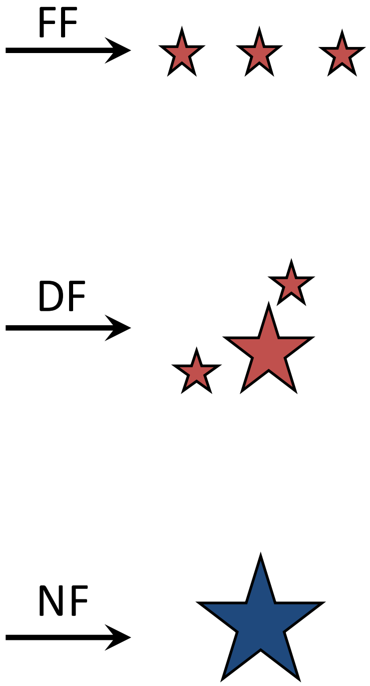
when we terminate the simulation ($n_\mathrm{H} = 10^{16}$ cm^{-3}).



Current work: what is final fate of this protostar and filaments?

with a sink particle technique (Regan et al.)





FF →
- ✓ Stellar cluster
- ✓ Wide binary

DF →
- ✓ Close binary

recently observed by Hansen et al. (2016)

NF →
- ✓ Metal-poor massive star

FF: Filament Fragmentation
DF: Disk Fragmentation
NF: No Fragmentation

Summary

We follow the whole story from Pop III to Pop II star formation.

Including **SN dust model** and **grain growth**.

We find a star-forming cloud is formed through internal enrichment.

Metallicity of the recollapsing region is $\mathbf{2.6 \times 10^{-4}\ Z_{\odot}}$.

consistent with that of observed metal-poor stars.

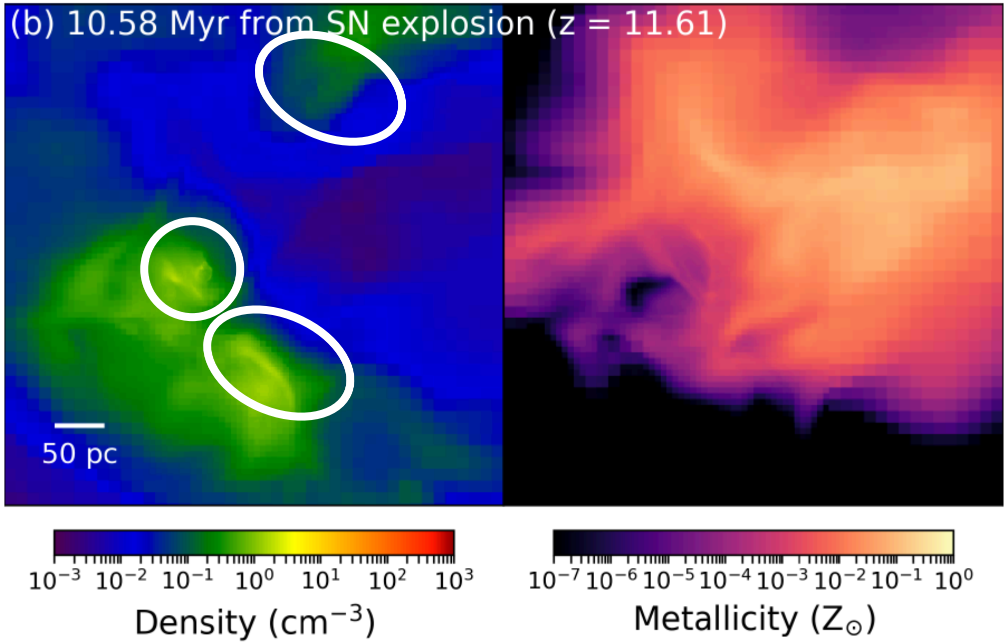
Current/Future works

To see the further evolution of the protostars.

To simulate for **C-enhanced** abundance ratio.

To extend simulation box size and time to see the formation of **multiple enrichment events**.

Why $2.6 \times 10^{-4}\ Z_\odot$?



Simple prediction of metallicity:

$$Z_{\rm pred} = \frac{M_{\rm met}}{M_{\rm cloud}} = 4 \times 10^{-2}\ {\rm Z}_\odot.$$

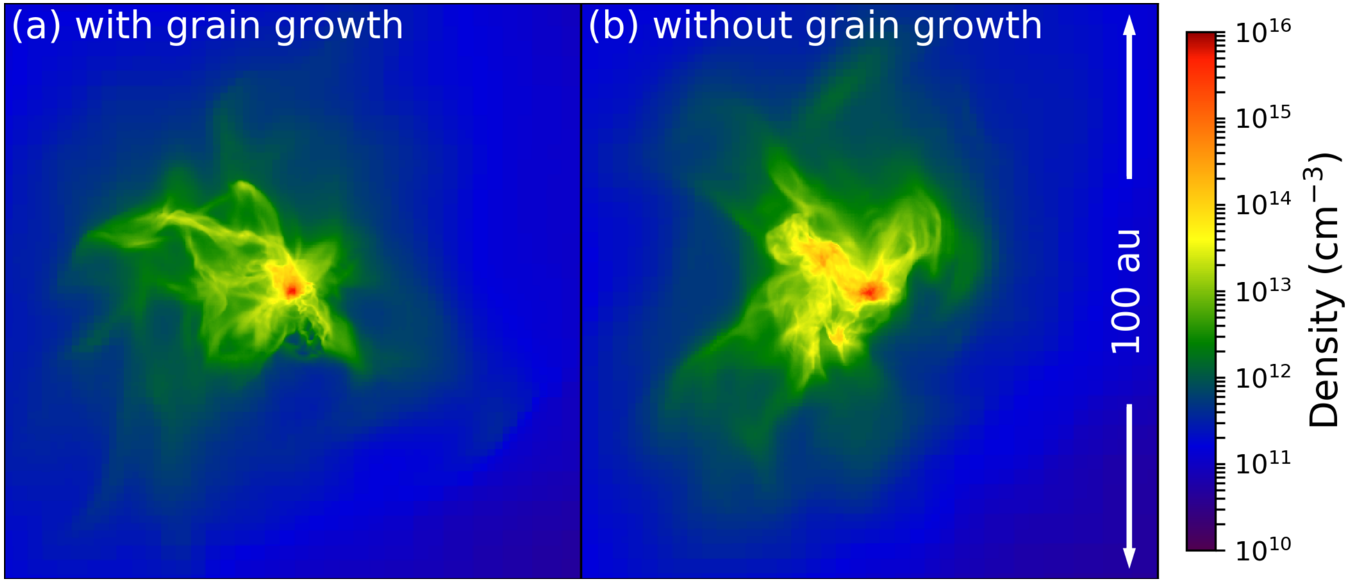
$M_{\rm met}$: ejected metal mass (1 $M_\odot$)
$M_{\rm cloud}$: cloud mass (2000 $M_\odot$)

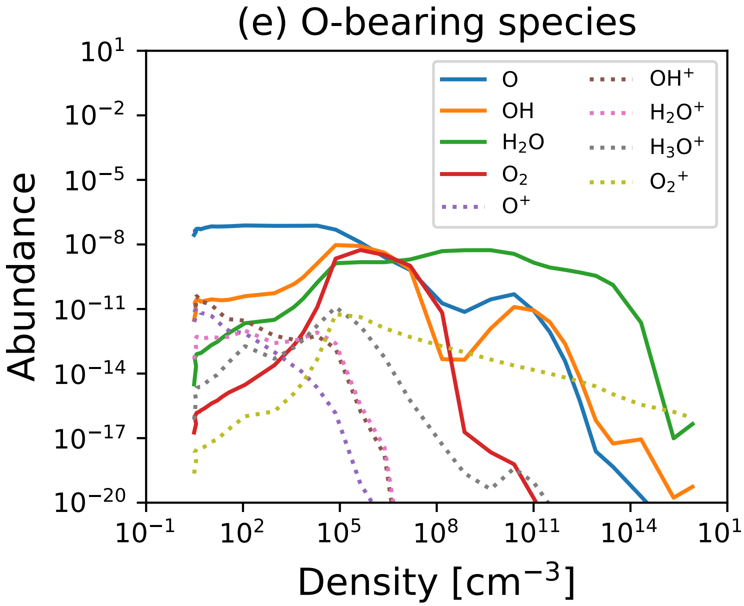
Enrichment model in this simulation

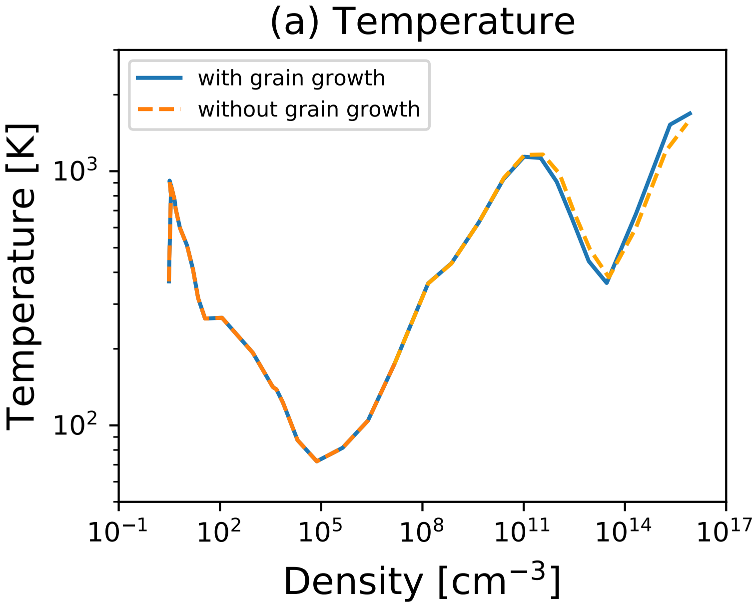
$$Z_{\rm recol} = \frac{f_{\rm fb} M_{\rm met}}{M_{\rm cloud}} = N_{\rm clump} \frac{\pi r^2}{4\pi R^2} \frac{M_{\rm met}}{M_{\rm cloud}} = 3 \times 10^{-4}\ {\rm Z}_\odot,$$

$N_{\rm clump}$: number of clumps which interrupt metal dispersion (3)
r: clump radius (~5 pc)
R: distance of clump from SN (~50 pc)

Effect of grain growth

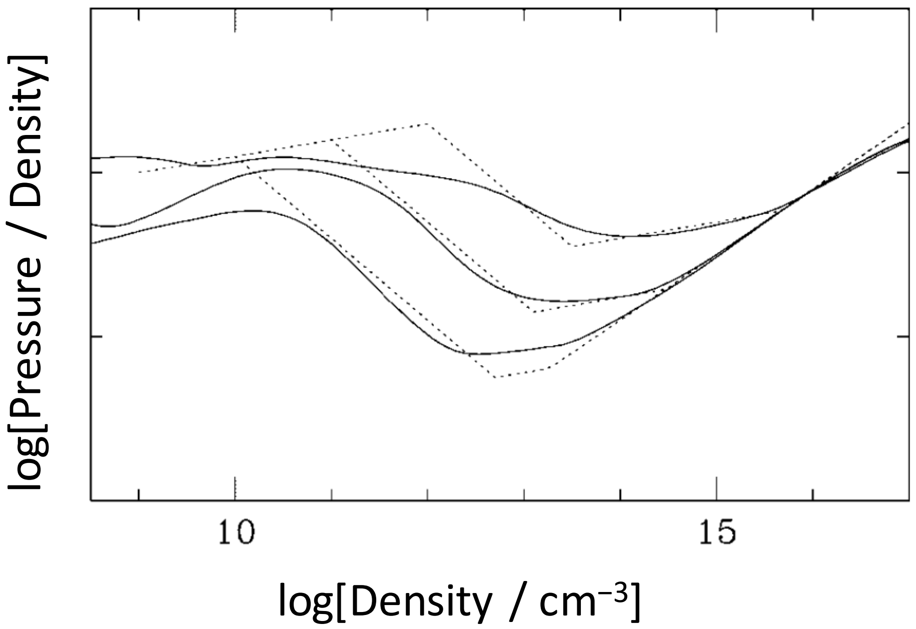


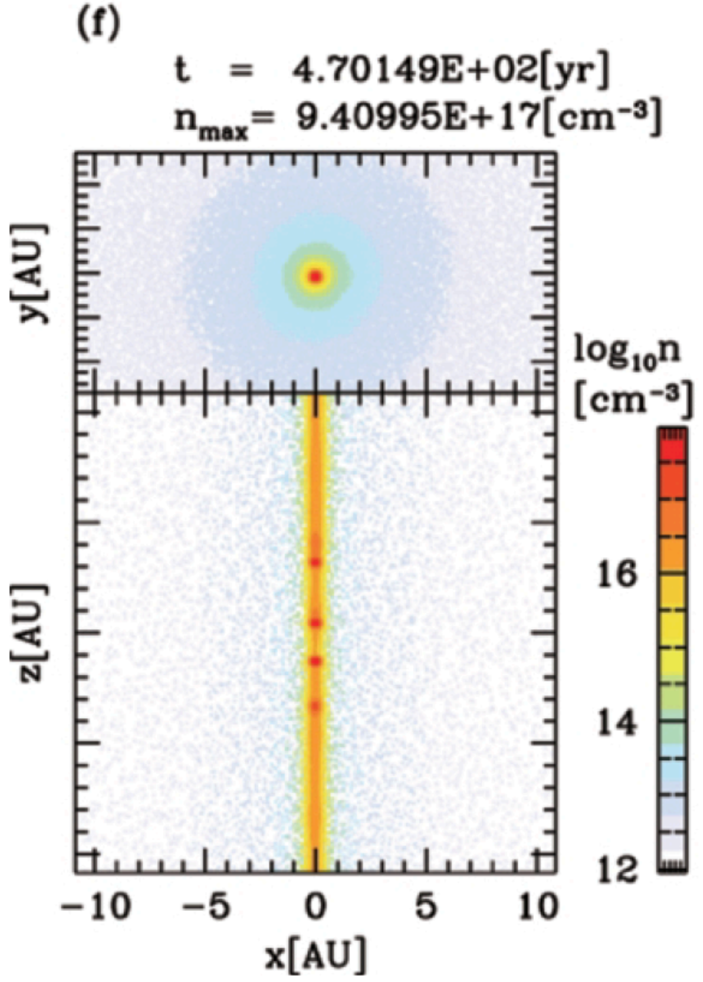

(e) O-bearing species


(a) Temperature

Dust cooling promotes cloud deformation and fragmentation

from an ideal initial condition (self-similar solution)





Tsuribe & Omukai (2006)

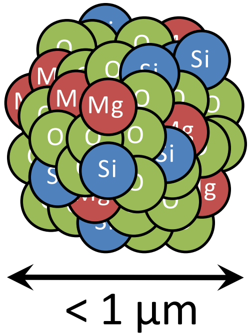
Especially, **dust grains** is crucial for the low-mass fragments.

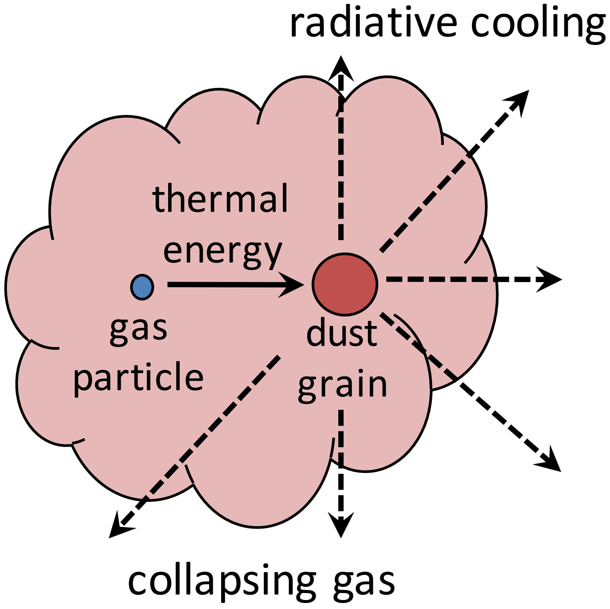
(Omukai 2000; Schneider et al. 2003; Safranek-shrader et al. 2014)

Dust grains

✓condensates of metal
✓solid particle

e.g. silicate grain ($MgSiO_3$)




radiative cooling

thermal energy

gas particle

dust grain

collapsing gas

✓Heat of gas particle is transferred to dust.
+
✓Dust grain is cooled by radiative cooling.

⇩

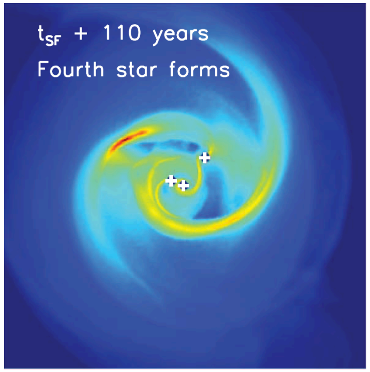
Net effect: Gas cooling

Dust cooling operates <u>**high density**</u> (~10^{14} cm^{-3}).
= **low** Jeans mass (~0.1 $M_\odot$)
→ Filament Fragmentation

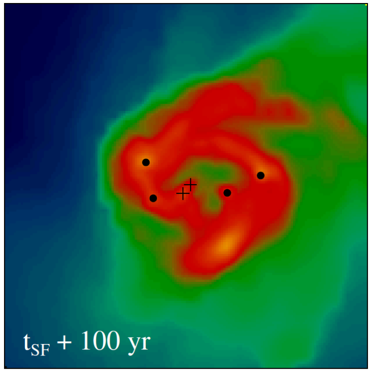
Mass scale of Pop III stars

Low mass (< 1 $M_\odot$)

Some researches predict **DF**.



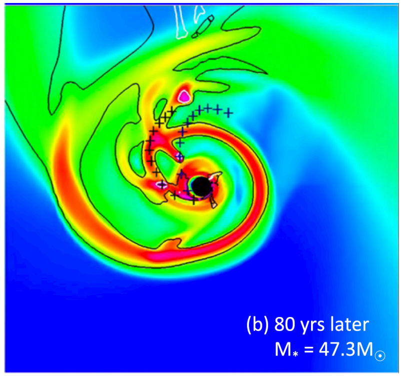
Clark et al. (2011)



Greif et al. (2012)

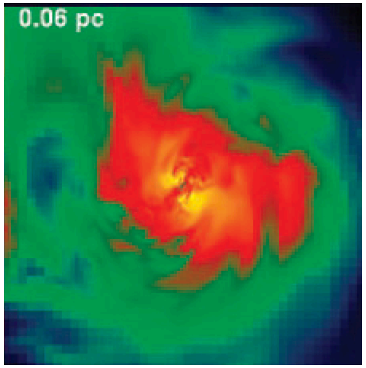
Note that the final fate of the fragments is <u>still unknown</u>.

Accretion onto primary protostar (Hosokawa et al. 2016)

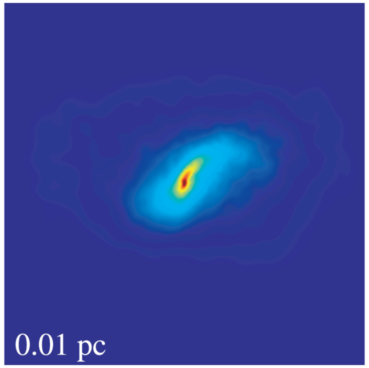


High mass (10-1000 $M_\odot$)

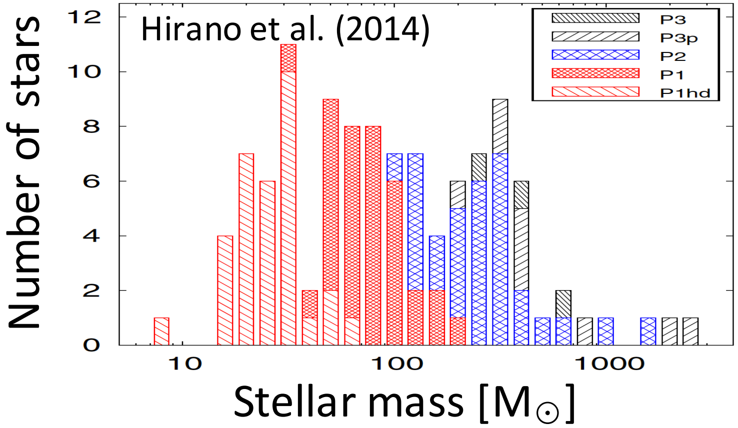
Clouds do not fragment.



Abel et al. (2002)

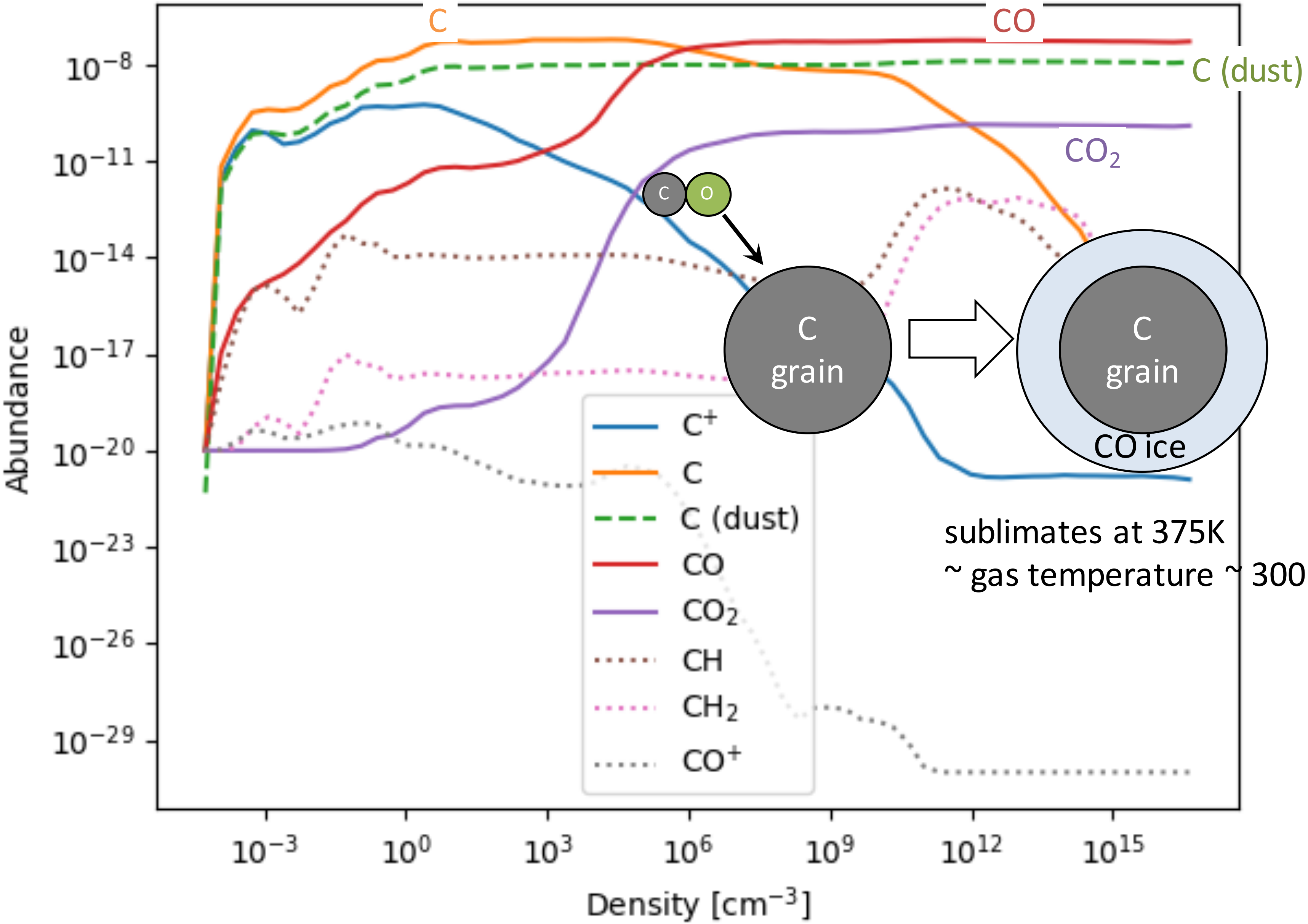


Yoshida et al. (2006)



Note that the simulation imposed some simplification (2D RHD in accretion phase).

Carbon grain



sublimates at 375K

~ gas temperature ~ 300 K

Sticking coefficient of grain growth

In this study, the sticking coeff. α_i is set unity.
(Kozasa & Hasegawa 1987, 1989)

for α_i = 0.1, the grain growth hardly affect the critical metallicity Z_{cr} as

$$(Z_{cr}/10^{-5.5}\,Z_{\odot}) = (f_{dep,0}/3.5)^{-0.92}$$

Dust growth rate for grain species *i*

$$\left(\frac{dr}{dt}\right)_i = \boxed{\alpha_i}\left(\frac{4\pi}{3}a^3_{ij,0}\right)\left(\frac{kT}{2\pi m_{i1}}\right)^{1/2} n_{i1}(t)$$

Cross-section

Thermal velocity of gas

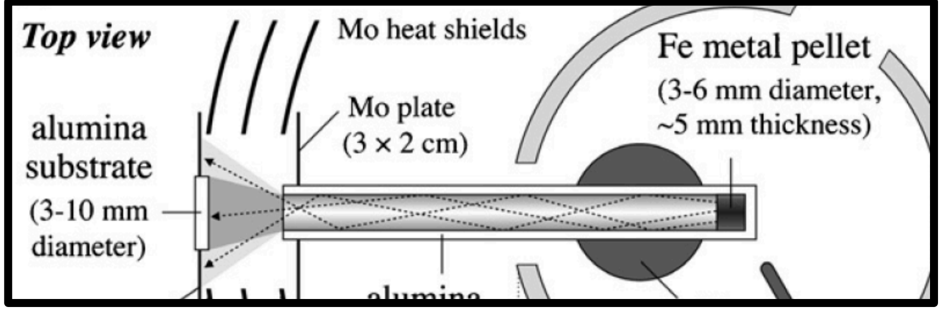
✓α_i is still uncertain but considered to be 0.1—1

✓Several groups estimate the sticking coefficient.

Theoretical approach
Leitch-Delvin & Williams (1985).
•interaction of a lattice and an incident particle

Carbon atom→	Graphite	α=0.4
Deuterium→	Silicate	α=1.0
Deuterium→	Oxide	α=0.5

Laboratory experiment
Tachibana et al. (2011).
"Although the data are scattered to some extent, all of the measured condensation fluxes are close to the ideal value. This indicates that α_c (=α_i) is close to unity irrespective of α_e (= evaporation efficiency), *because the effect of re-evaporation from the condensates must be small due to the large values of S ."*



Method: modified GRACKLE + ENZO
Huge reaction networks

48 primordial chemistry

$H + e^- \rightarrow H^+ + 2e^-$
$H^+ + e^- \rightarrow H + \gamma$
$He + e^- \rightarrow He^+ + 2e^-$
$He^+ + e^- \rightarrow He + \gamma$
$He^+ + e^- \rightarrow He^{++} + 2e^-$
$He^{++} + e^- \rightarrow He^+ + \gamma$
$H + e^- \rightarrow H^- + \gamma$
$H + H^- \rightarrow H_2 + e^-$
$H + H^+ \rightarrow H_2^+ + \gamma$
$H_2^+ + H \rightarrow H_2{}^* + H^+$
$H_2 + H^+ \rightarrow H_2^+ + H$
$H_2 + e^- \rightarrow 2H + e^-$
$H_2 + H \rightarrow 3H$
$H^- + e^- \rightarrow H + 2e^-$
$H^- + H \rightarrow 2H + e^-$
$H^- + H^+ \rightarrow 2H$
$H^- + H^+ \rightarrow H_2^+ + e^-$
$H_2^+ + e^- \rightarrow 2H$
$H_2^+ + H^- \rightarrow H + H_2$
$D^+ + e^- \rightarrow D + \gamma$
$D + H^+ \rightarrow D^+ + H$
$D^+ + H \rightarrow D + H^+$
$D + H \rightarrow HD + \gamma$
$D + H_2 \rightarrow H + HD$
$HD^+ + H \rightarrow H^+ + HD$
$D^+ + H_2 \rightarrow H^+ + HD$

$HD + H \rightarrow H_2 + D$
$HD + H^+ \rightarrow H_2 + D^+$
$D + H^+ \rightarrow HD^+ + \gamma$
$D^+ + H \rightarrow HD^+ + \gamma$
$HD^+ + e^- \rightarrow H + D$
$D + e^- \rightarrow D^- + \gamma$
$D^+ + D^- \rightarrow 2D$
$H^+ + D^- \rightarrow D + H$
$H^- + D \rightarrow H + D^-$
$D^- + H \rightarrow D + H^-$
$D^- + H \rightarrow HD + e^-$
$H + H + H \rightarrow H_2 + H$
$H + H + H_2 \rightarrow H_2 + H_2$
$H_2 + H_2 \rightarrow H + H + H_2$
$H + H \rightarrow H^+ + e^- + H$
$He + H^+ \rightarrow He^+ + H$
$He^+ + H \rightarrow He + H^+$
$He + H^+ \rightarrow HeH^+ + \gamma$
$He + H^+ \rightarrow HeH^+ + \gamma$
$He + H_2^+ \rightarrow HeH^+ + H$
$He^+ + H \rightarrow HeH^+ + \gamma$
$HeH^+ + H \rightarrow He + H_2^+$
$HeH^+ + e^- \rightarrow He + H$

H_2 formation on grain surfaces

$2H + grain \rightarrow H_2$

38 metal chemistry

$H + CH \rightarrow C + H_2$
$H + CH_2 \rightarrow CH + H_2$
$H + OH \rightarrow H_2 + O$
$H + H_2O \rightarrow OH + H_2$
$H + O_2 \rightarrow OH + O$
$C + H_2 \rightarrow CH + H$
$\boxed{O + H_2 \rightarrow OH + H}$
$H^+ + O \rightarrow O^+ + H$
$H_2 + CH \rightarrow CH_2 + H$
$\boxed{H_2 + OH \rightarrow H_2O + H}$
$2OH \rightarrow H_2O + O$
$OH + CO \rightarrow CO_2 + H$
$C + H \rightarrow CH + \gamma$
$\boxed{C + OH \rightarrow CO + H}$
$C + O_2 \rightarrow CO + O$
$O + H \rightarrow OH + \gamma$
$2O \rightarrow O_2 + \gamma$
$O + CH \rightarrow CO + H$
$O + OH \rightarrow O_2 + H$
$H^+ + OH \rightarrow OH^+ + H$
$H^+ + H_2O \rightarrow H_2O^+ + H$

$H^+ + O_2 \rightarrow O_2^+ + H$
$C^+ + OH \rightarrow CO^+ + H$
$C^+ + O_2 \rightarrow O^+ + CO$
$O^+ + H \rightarrow H^+ + O$
$O^+ + H_2 \rightarrow OH^+ + H$
$OH^+ + H_2 \rightarrow H_2O^+ + H$
$H_2O^+ + H_2 \rightarrow H_3O^+ + H$
$CO^+ + H \rightarrow H^+ + CO$
$C^+ + e \rightarrow C + \gamma$
$OH^+ + e \rightarrow O + H$
$H_2O^+ + e \rightarrow OH + H$
$H_2O^+ + e \rightarrow O + H_2$
$H_3O^+ + e \rightarrow H_2O + H$
$H_3O^+ + e \rightarrow OH + 2H$
$O_2^+ + e \rightarrow 2O$
$H_2 + C \rightarrow CH_2 + \gamma$
$\boxed{Si + OH \rightarrow SiO + H}$
$Si + O_2 \rightarrow SiO + O$
$SiO + OH \rightarrow SiO_2 + H$

10 grain growth reactions

$Si(g) \rightarrow Si(s)$
$Fe(g) \rightarrow Fe(s)$
$2Mg(g) + SiO(g) + 3H_2O(g) \rightarrow Mg_2SiO_4(s) + 3H_2(g)$
$Mg(g) + SiO(g) + 2H_2O(g) \rightarrow MgSiO_3(s) + 2H_2(g)$
$3Fe(g) + 4H_2O(g) \rightarrow Fe_3O_4(s) + 4H_2(g)$
$C(g) \rightarrow C(s)$
$SiO_2(g) \rightarrow SiO_2(s)$
$Mg(g) + H_2O(g) \rightarrow MgO(s) + H_2(g)$
$Fe(g) + S(g) \rightarrow FeS(s)$
$2Al(g) + 3H_2O(g) \rightarrow Al_2O_3(s) + 3H_2(g)$

(g) gas-phase, (s) solid-phase

Method: modified GRACKLE + ENZO

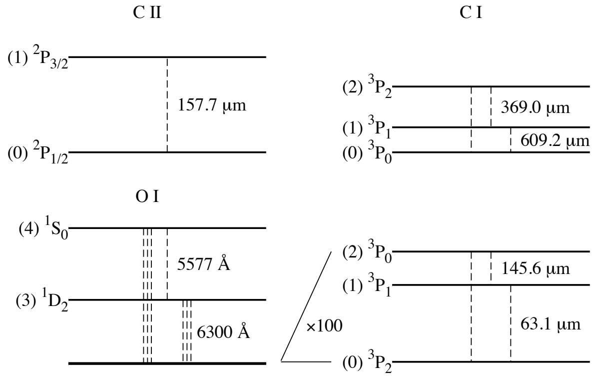
Radiative cooling

C II, C I, and O I fine-structure cooling

calculate level populations

opacity for each transition line (Sobolev approx.)

integrate cooling rates



H_2 ro-vibration transition line cooling

3 vibrational levels

20 rotational levels

HD rotation transition line cooling

3 vibrational levels

CO, OH, and H_2O rotation transition line

interpolated from tables presented by

CO (Omukai et al. 2010)

OH (Neufeld & Kaufman 1993)

H_2O (Neufeld et al. 1995)

from N_{mol}, T, and n_{H2} of each cell

Dust cooling

calculated for each grain size bin

interpolated from a table

Density

Temperature

Metallicity

Dust Density

Dust cooling rate

Dust continuum opacity

H_2 formation rate on dust

Grain growth rate

for each dust species in each cell

Method: modified GRACKLE + ENZO

Add fields

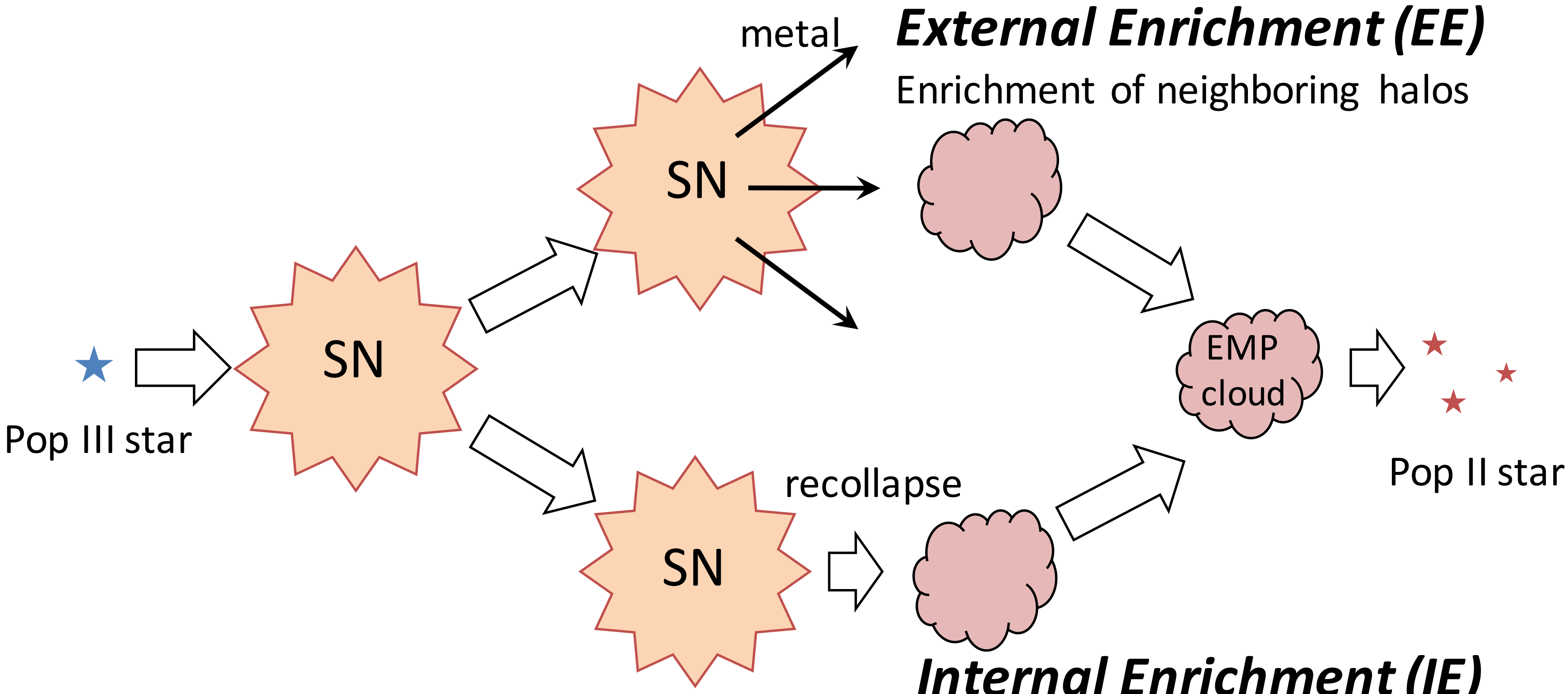
```
 if (MultiSpecies)  {
    DataLabel[i++]  = ElectronName;          e-
    DataLabel[i++]  = HIName;                H
    DataLabel[i++]  = HIIName;               H+
    DataLabel[i++]  = HeIName;               He
    DataLabel[i++]  = HeIIName;              He+
    DataLabel[i++]  = HeIIIName;             He++
    if (MultiSpecies  > 1) {
      DataLabel[i++]  = HMName;              H-
      DataLabel[i++]  = H2IName;             H2
      DataLabel[i++]  = H2IIName;            H2+
    }
    if (MultiSpecies  > 2) {
      DataLabel[i++]  = DIName;              D
      DataLabel[i++]  = DIIName;             D+
      DataLabel[i++]  = HDIName;             HD
    }
#ifdef  USE_GRACKLE
    if (MultiSpecies  > 3) {
      DataLabel[i++]  = HeHIIName;           HeH+
      DataLabel[i++]  = DMName;              D-
      DataLabel[i++]  = HDIIName;            HD+
    }
    if (MultiSpecies  > 10) {
      DataLabel[i++]  = CIName;              C
      DataLabel[i++]  = CIIName;             C+
      DataLabel[i++]  = COName;              CO
      DataLabel[i++]  = CO2Name;             CO2
      DataLabel[i++]  = OIName;              O
      DataLabel[i++]  = OHName;              OH
      DataLabel[i++]  = H2OName;             H2O
      DataLabel[i++]  = O2Name;              O2
      DataLabel[i++]  = SiIName;             Si
      DataLabel[i++]  = SiOIName;            SiO
      DataLabel[i++]  = SiO2IName;           SiO2
      DataLabel[i++]  = CHName;              CH
      DataLabel[i++]  = CH2Name;             CH2
      DataLabel[i++]  = COIIName;            CO+
      DataLabel[i++]  = OIIName;             O+
      DataLabel[i++]  = OHIIName;            OH+
      DataLabel[i++]  = H2OIIName;           H2O+
      DataLabel[i++]  = H3OIIName;           H3O+
      DataLabel[i++]  = O2IIName;            O2+
      DataLabel[i++]  = MgName;              Mg
      DataLabel[i++]  = AlName;              Al
      DataLabel[i++]  = SName;               S
      DataLabel[i++]  = FeName;              Fe
    }
    if (MultiSpecies  > 20)  {
      DataLabel[i++]  = SiMName;             Si (dust)
      DataLabel[i++]  = FeMName;             Fe (dust)
      DataLabel[i++]  = Mg2SiO4Name;         Mg2SiO4 (dust) }
      DataLabel[i++]  = MgSiO3Name;          MgSiO3 (dust)  } Silicate dust
      DataLabel[i++]  = Fe3O4Name;           Fe3O4 (dust)
      DataLabel[i++]  = AmCName;             C (dust)
      DataLabel[i++]  = SiO2DName;           SiO2 (dust)
      DataLabel[i++]  = MgOName;             MgO (dust)
      DataLabel[i++]  = FeSName;             FeS (dust)
      DataLabel[i++]  = Al2O3Name;           Al2O3 (dust)
    }
#endif
  }
```

✓15 primordial species
✓23 metal species
✓10 dust species

CosmologySimulationInitialize.C

There are two ways of the first enrichment.

(Ritter et al. 2012, 2015, 2016; Sluder et al. 2015; Smith et al. 2015; Chen et al. 2017; Chiaki et al. 2018)



External Enrichment (EE)

Enrichment of neighboring halos

Internal Enrichment (IE)

Self-enrichment of Pop III star forming halo

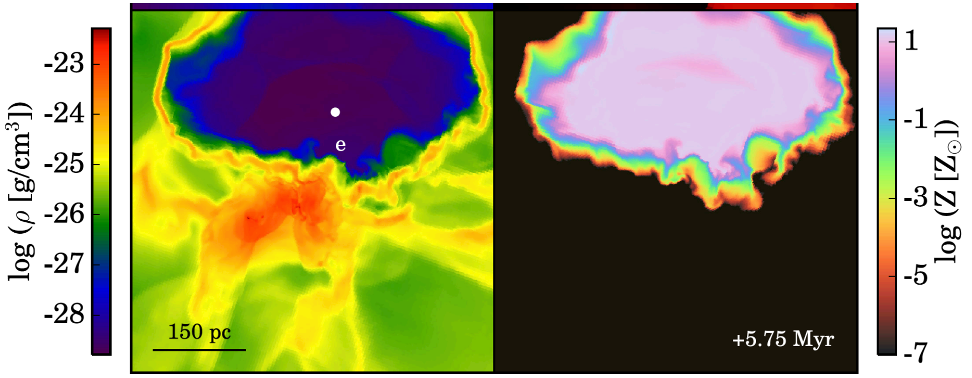
For EE, a previous work follow whole process of Pop II star formation.

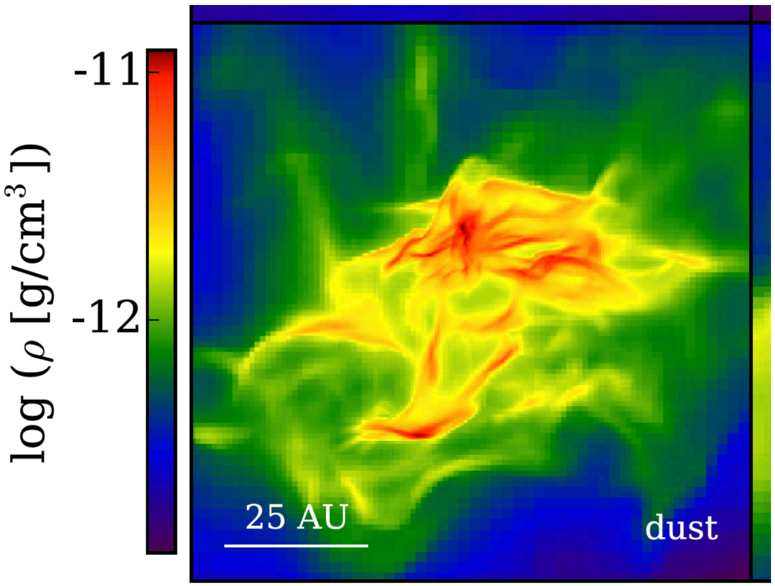
Smith et al. (2015)

✓($M_{\rm PopIII}$, $M_{\rm halo}$) = (40 $M_\odot$, 5 × 10^5 $M_\odot$)

✓Cosmological initial condition

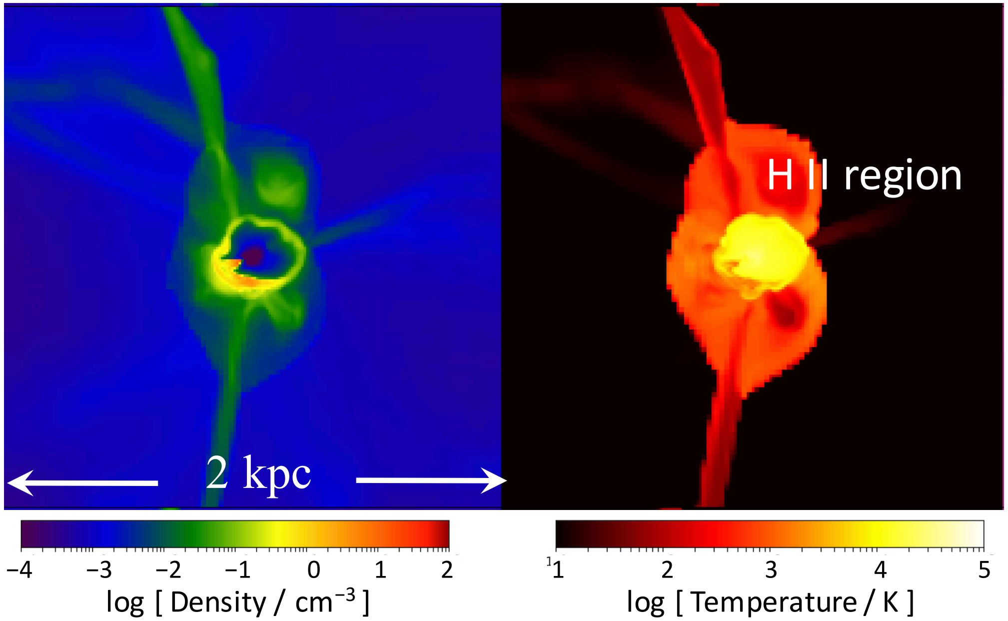
✓$Z = 2 \times 10^{-5}\ Z_\odot$





Cloud fragmentation by dust cooling

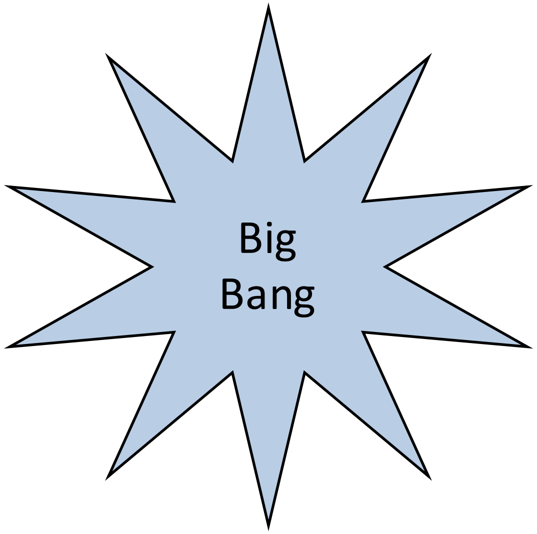
Photoionization by Pop III star



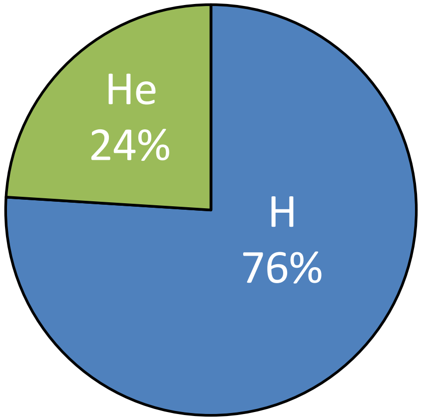
H I ionization photon emission rate
1.1×10^{48} s^{-1}

Nucleosynthesis just after Big Bang

< 3 minutes

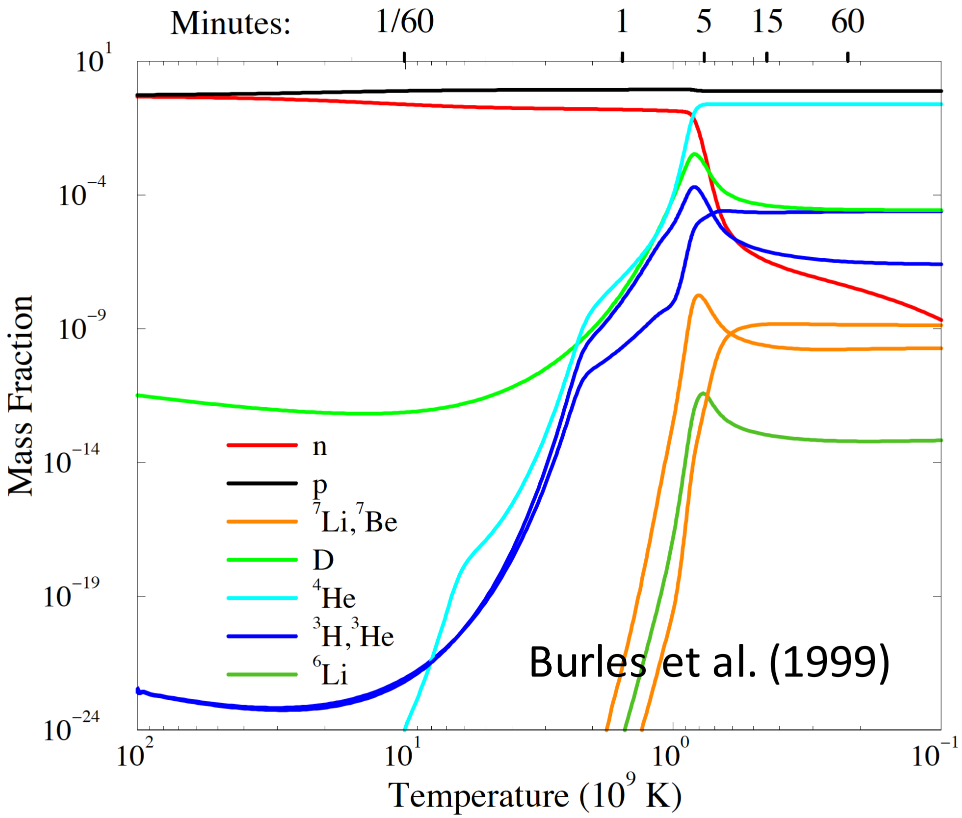


Mass fraction



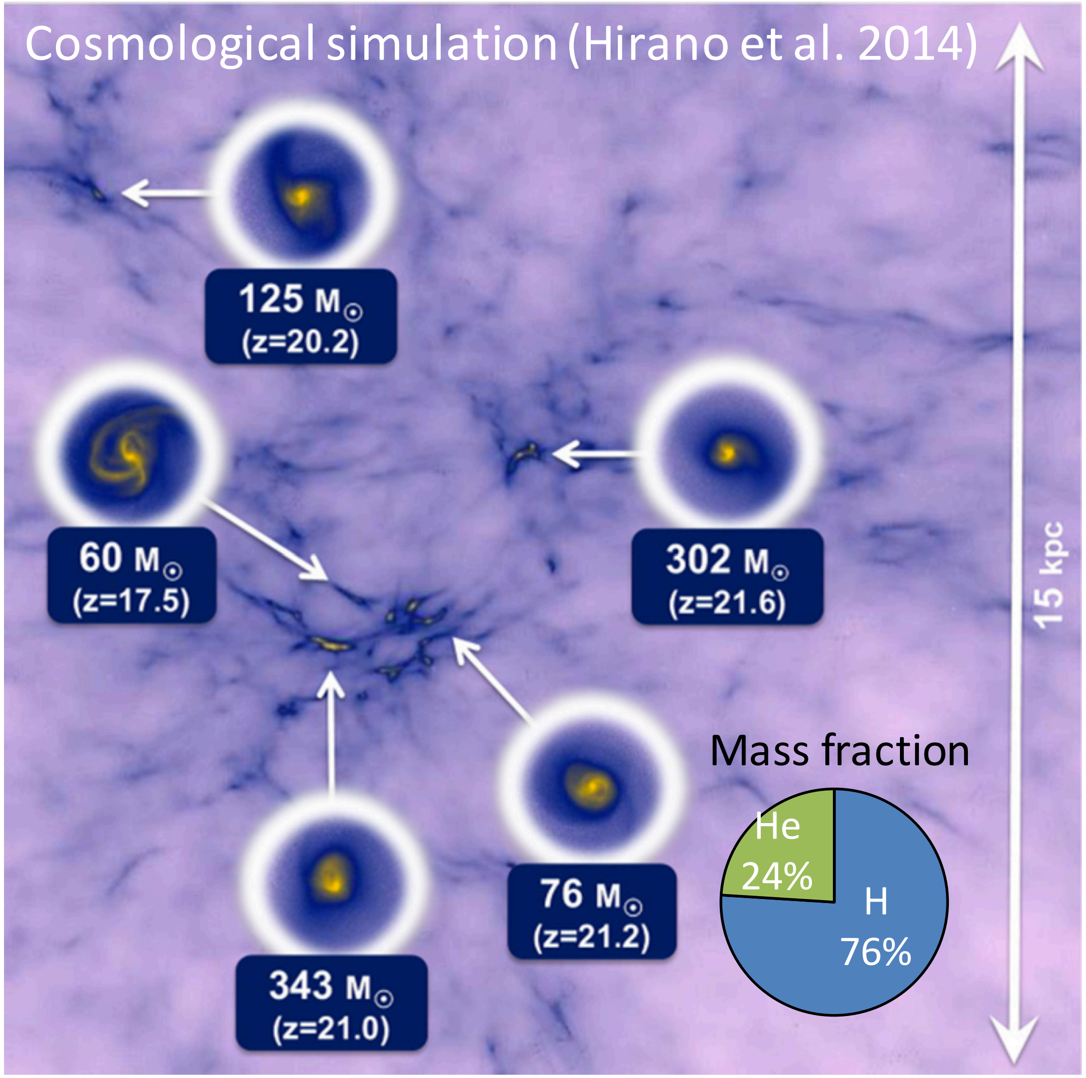
✓The first nucleosynthesis happens within the first ~3 minutes from Big Bang.

✓**Only H and He** (and tiny fraction of Li) are synthesized.



Burles et al. (1999)

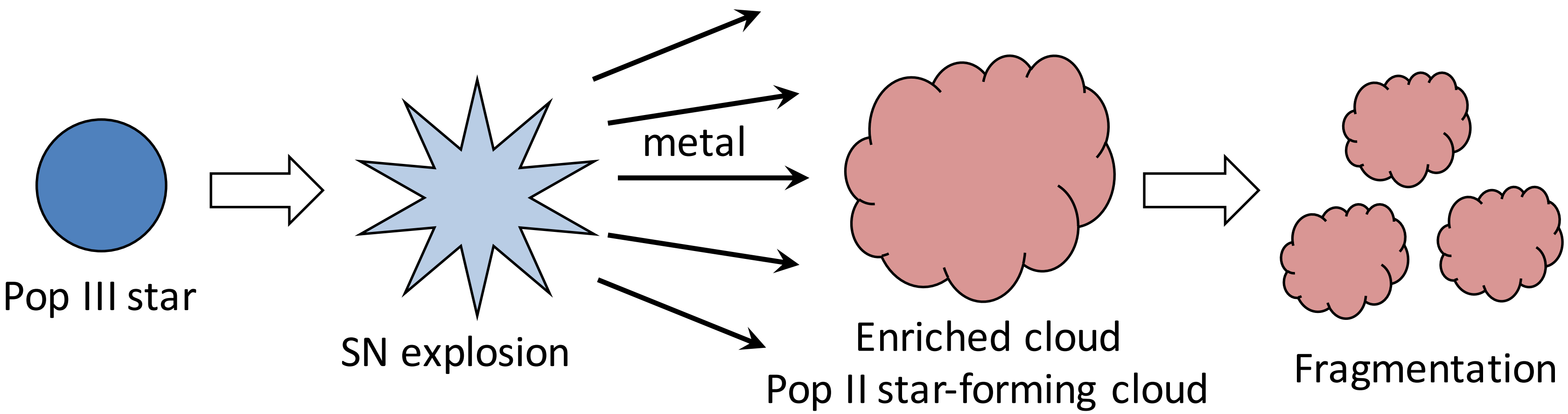
The **first stars** are born in the **metal-free** gas.



Cosmological simulation (Hirano et al. 2014)

The first stars (**Population III stars**) are formed in the different environment from the present-day stars.

To see this, we follow Pop III → Pop II star formation by numerical simulations.



Pop III star

SN explosion

metal

Enriched cloud
Pop II star-forming cloud

Fragmentation