Hydrodynamic simulations of collapsing gas clouds with low metallicities

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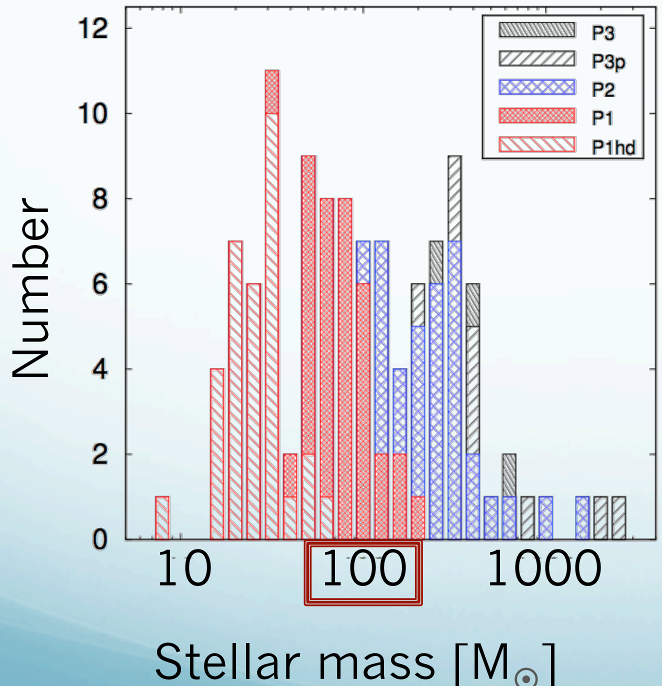
Pop III/II Transition

- **How and when does the transition of the stellar mass from massive Pop III to low-mass Pop I and II occur?**

(Hosokawa-san and Suda-san's talk)

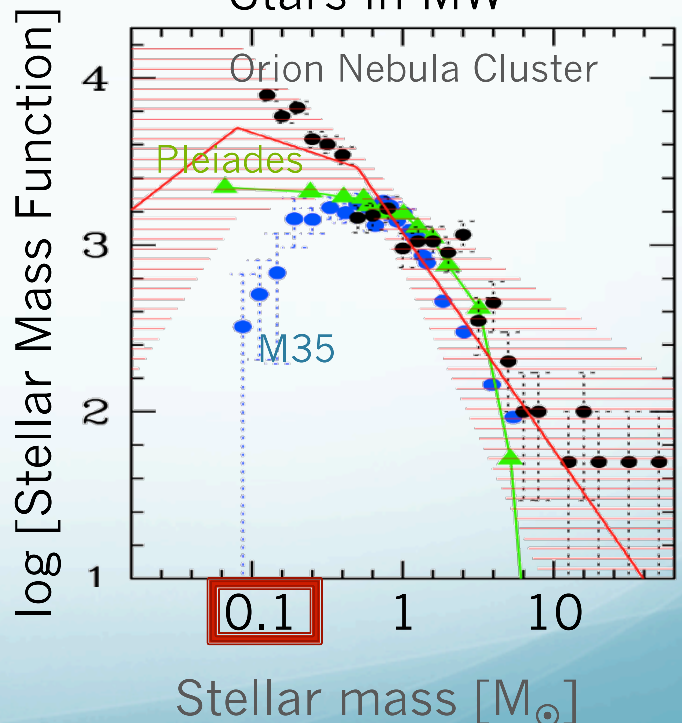
Massive Pop III stars



Hirano et al.(2014)

Stellar mass transition

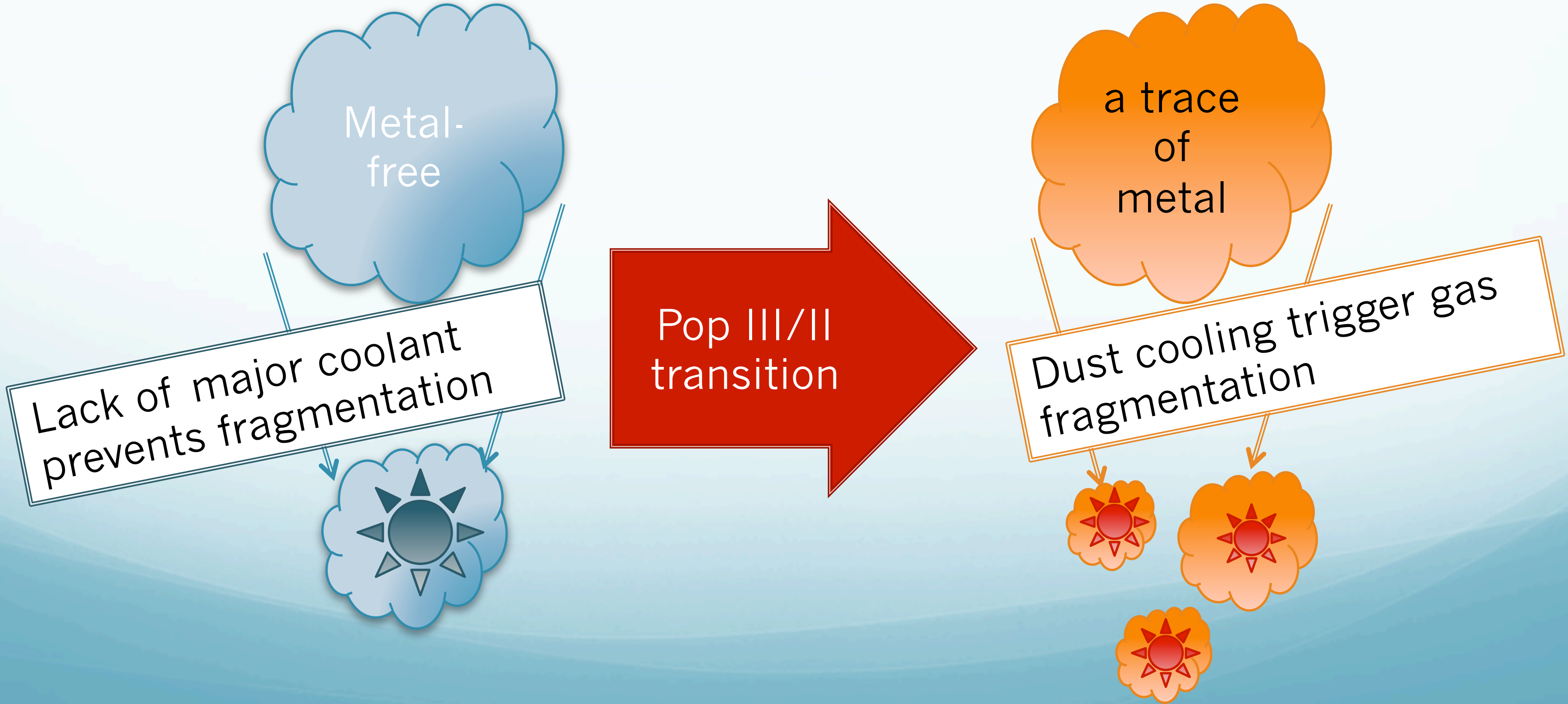
Stars in MW



Kroupa (2002)

Dust plays a *key role* in Pop III/II Transition

- Recent studies have revealed that additional gas cooling by **dust grains** trigger the gas fragmentation into low-mass clumps.
(Schneider et al.; Omukai et al.; Dopcke et al.; Chiaki et al.).

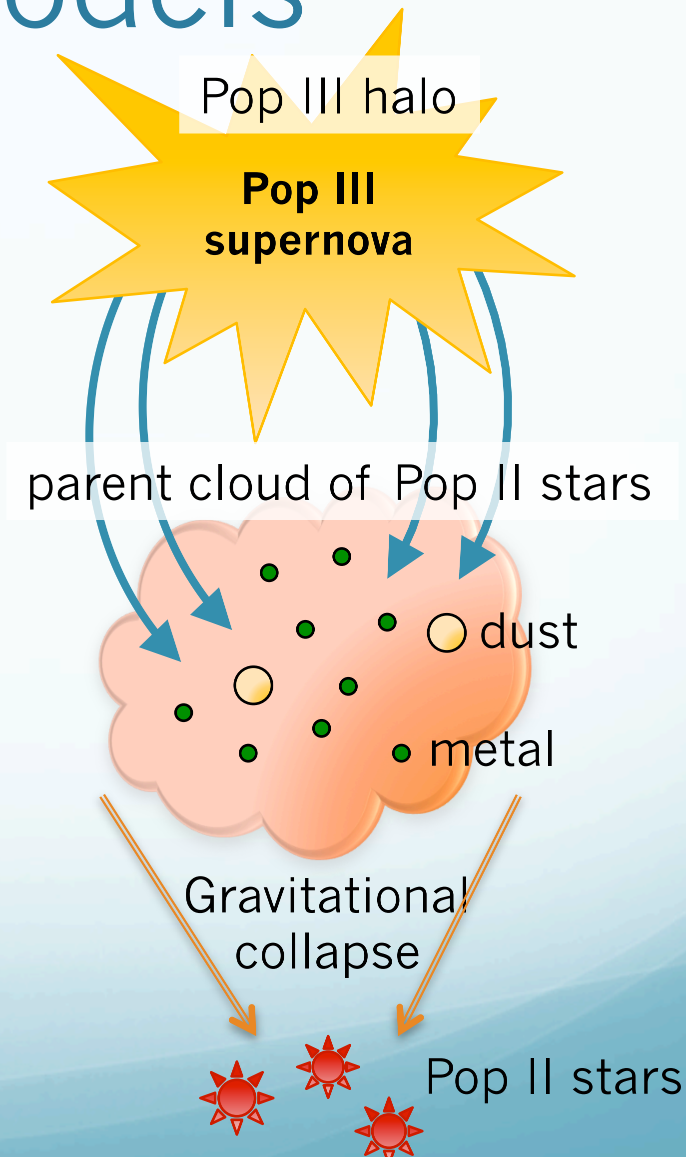


To study how & when Pop III/II Transition occurs,

- we estimate **the critical dust amount** above which dust cooling becomes effective to activate cloud fragmentation.
- Omukai et al. (2005) find that dust cooling becomes effective at $Z>10^{-5}\ Z_{\odot}$. corresponding to the dust-to-gas mass ratio $D_{crit}\sim1\times10^{-7}$.
- They employ the dust properties in the local universe.
  - total dust amount
  - composition of dust species (silicate, carbon, and so on)
  - size distribution

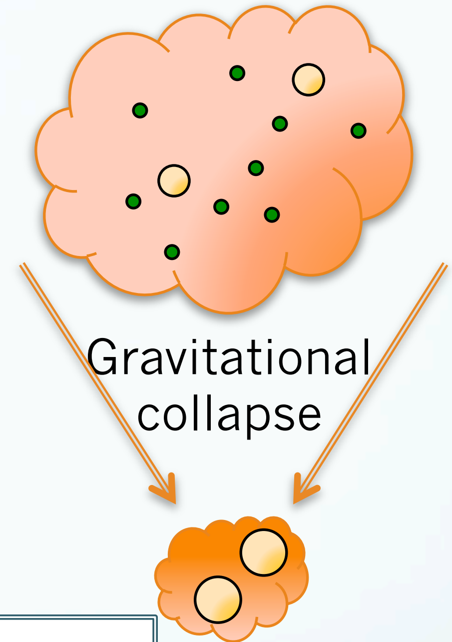
Initial Dust Properties: Supernova Models

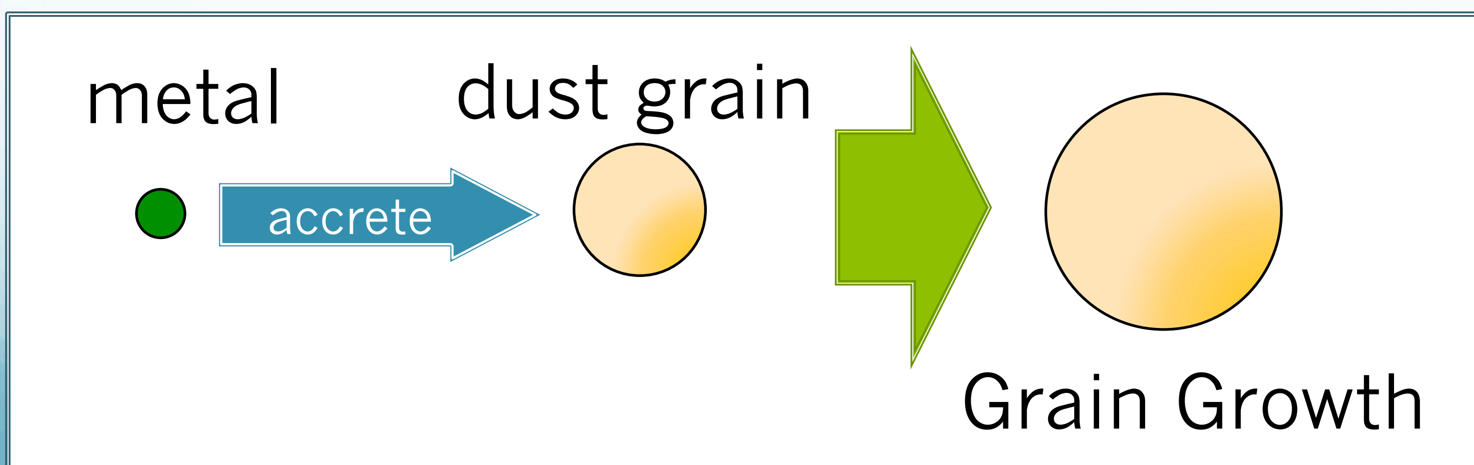
- However, in the early universe, dust properties are different from the local one.
  - Dust formation sites are limited to Pop III SNe, where grains are also destroyed partly.
- The dust properties in Pop II clouds should be given by the models of dust **formed/ destroyed in Pop III SNe**.
- This modifies the critical dust amount.
  - Schneider et al.(2006, 2012)
  - Chiaki et al.(2013, 2014)



The Dust Properties can be Altered by Grain Growth

- Accretion of gas-phase heavy elements onto grains (**Grain growth**) can reduce the critical dust amount
  - Nozawa et al.(2012); Chiaki et al.(2013, 2014)





What we have so far studied

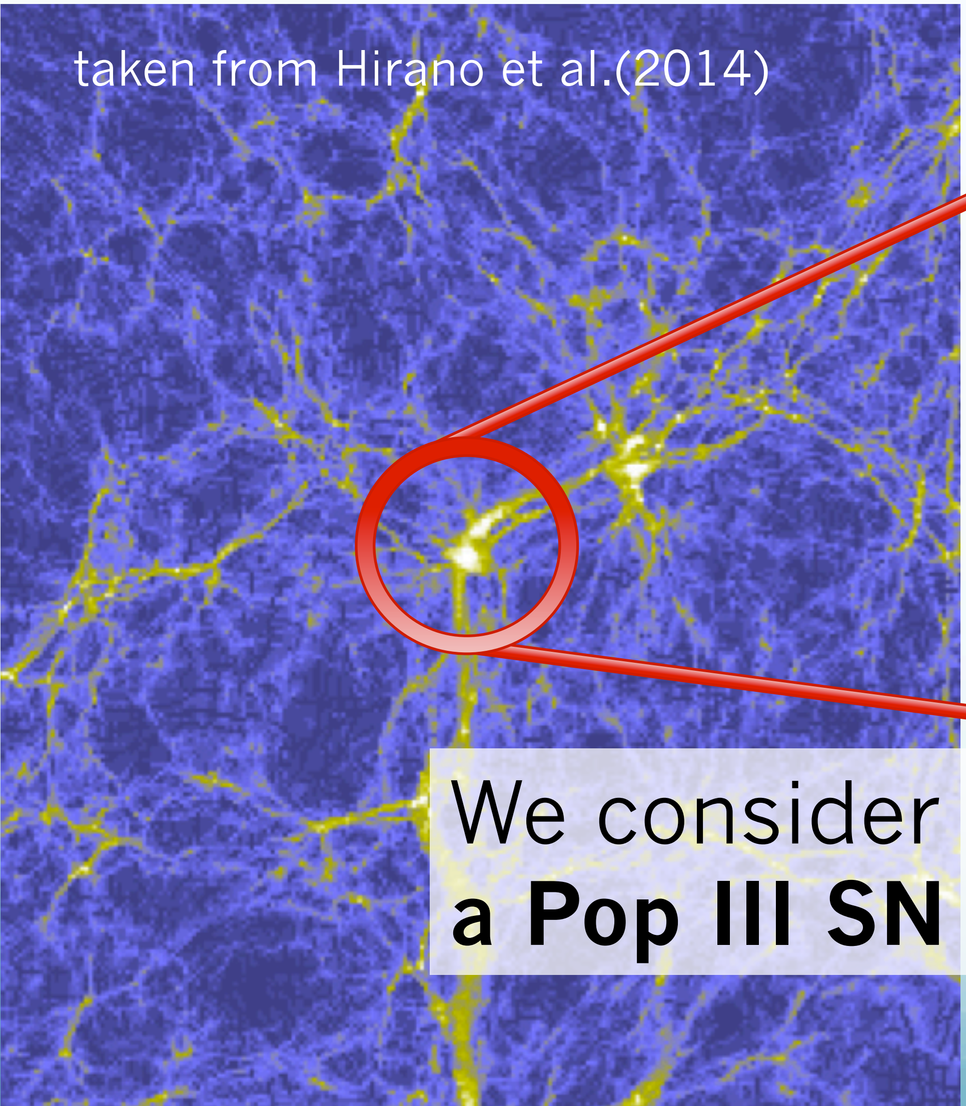
- Critical dust/gas mass ratio have been modified as
  - dust in the local universe (Omukai et al.2005)
    - **D_{cr} ~ 10^{-7}**
  - SN dust model (Schneider et al.2012)
    - **D_{cr} ~ $[0.81—11.6]\times10^{-8}$** (Chiaki et al. submitted)
  - + Grain growth (Chiaki et al. submitted to MN)
    - **D_{cr} ~ $[0.07—3.8]\times10^{-8}$**
- Both are crucial for Pop III/II transition!
- This has been revealed by our **one-zone** semi-analytic collapse calculations.

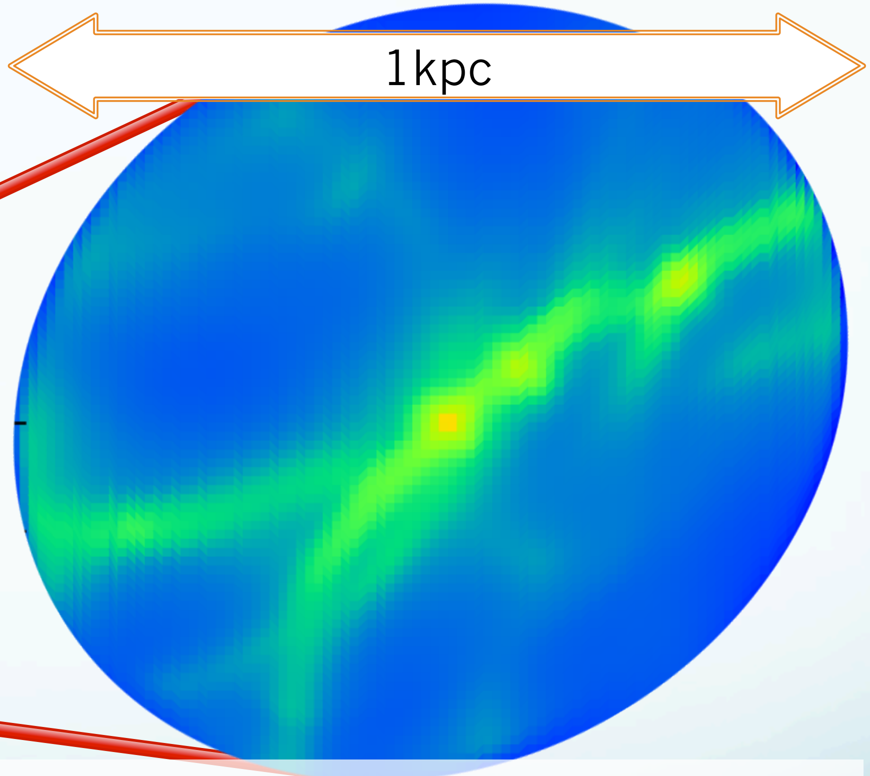
The Aim of This Study

- In the present work, we perform **three-dimensional hydrodynamic simulations**,
  - employing SN dust model
  - considering grain growth.
  - SPH code Gadget-3

- to reveal
  - How is **the initial mass (functions)** of low-metallicity stars?
  - How is the multi-dimensional effect on **the critical condition**?

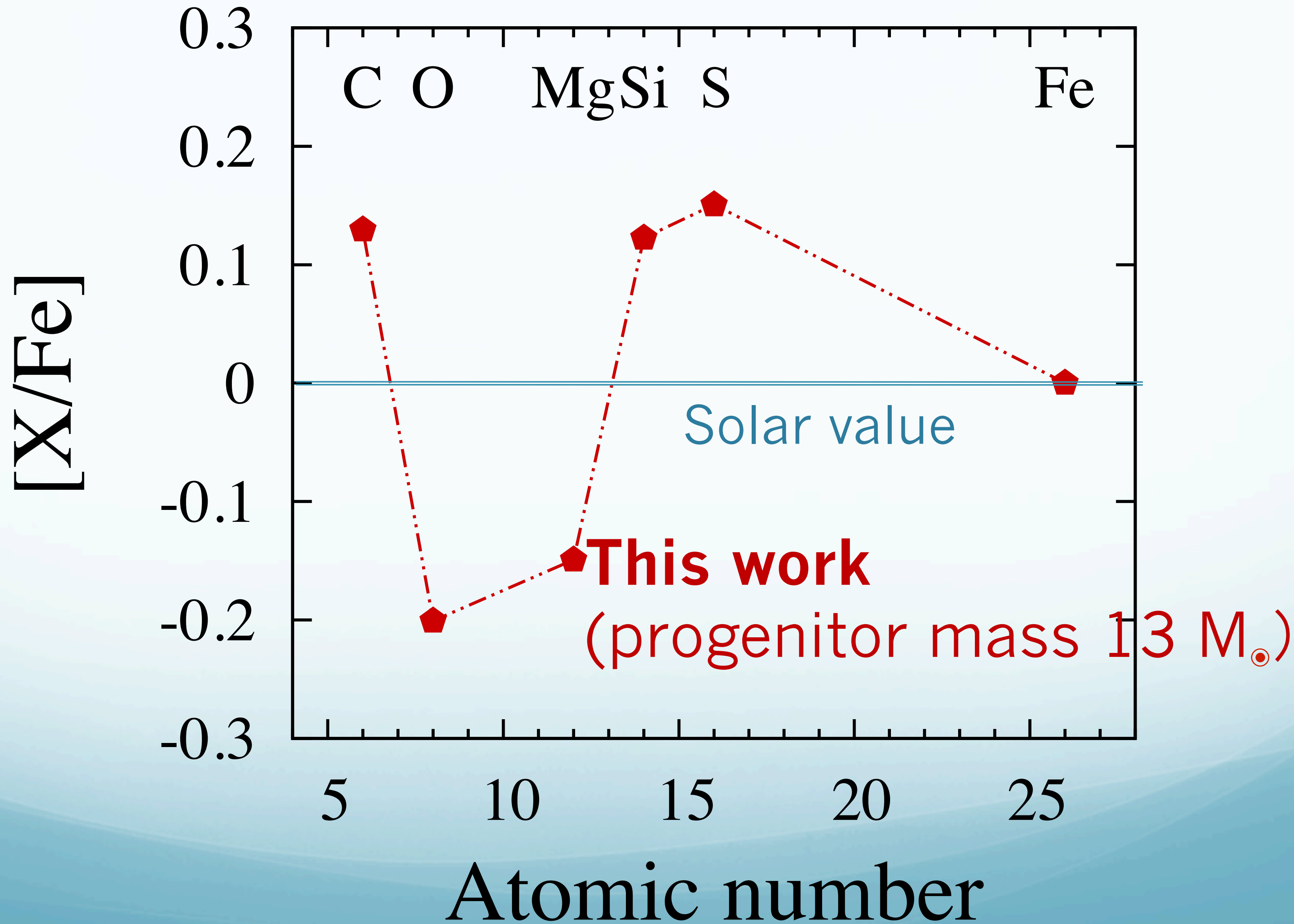
Initial Conditions: Cosmological Minihalo



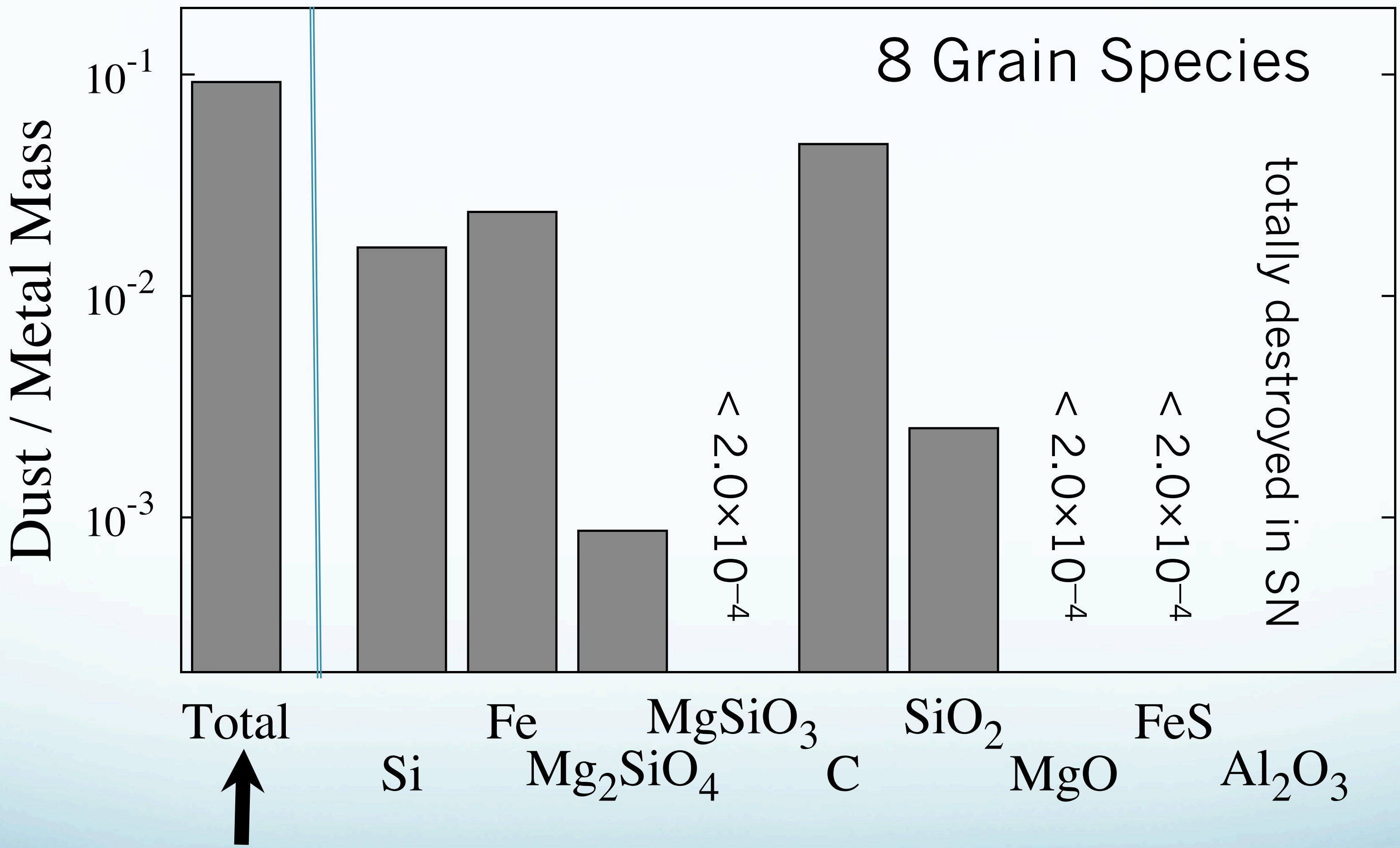


We consider this MH is polluted by **a Pop III SN** with metal and dust

Supernova Model gives Elemental Abundance



Supernova Model gives Initial Dust Amount



about 10 % of metal condenses into dust grains in this supernova with progenitor mass 13 $M_\odot$

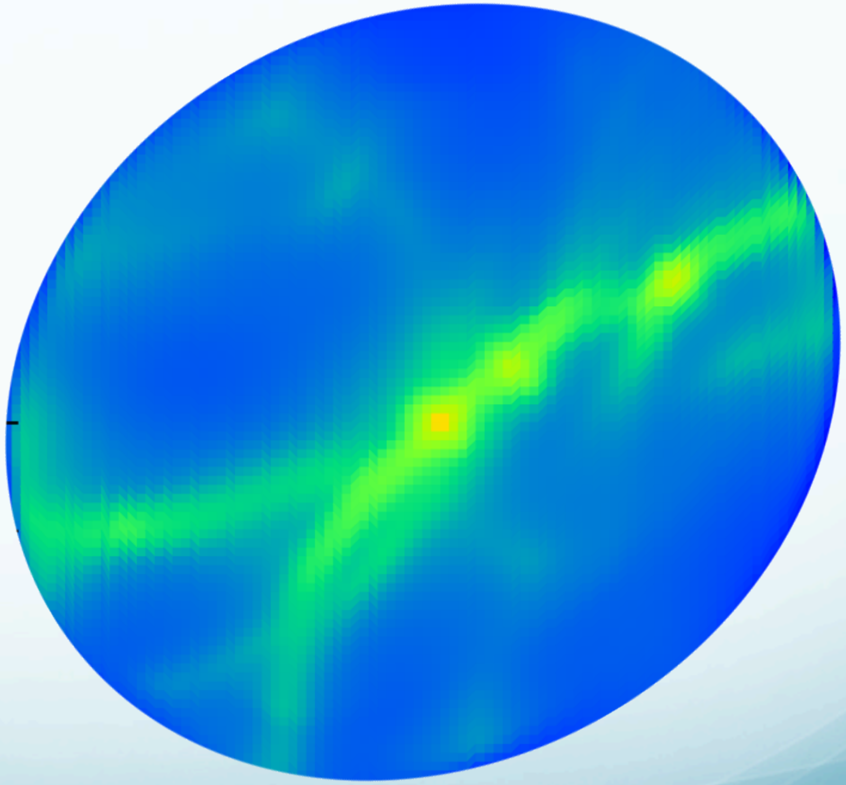
Initial Conditions: Cosmological Minihalo

We consider the metallicities

- $Z=10^{-6}\ Z_{\odot}$
- $Z=10^{-4}\ Z_{\odot}$

corresponding to the dust-to-gas mass ratio, respectively,

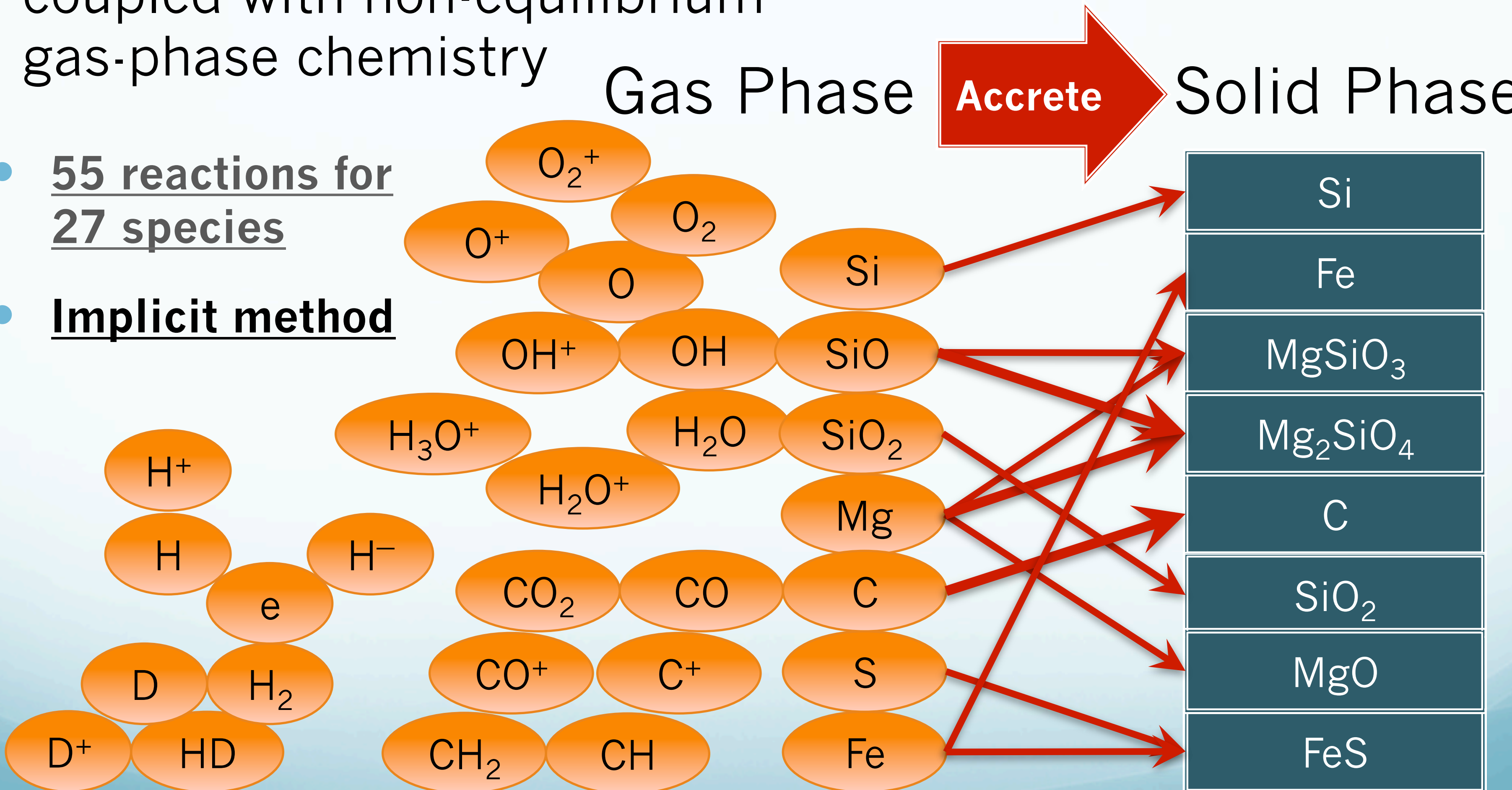
- $D_{ini}=2\times10^{-9}$
- $D_{ini}=2\times10^{-7}$



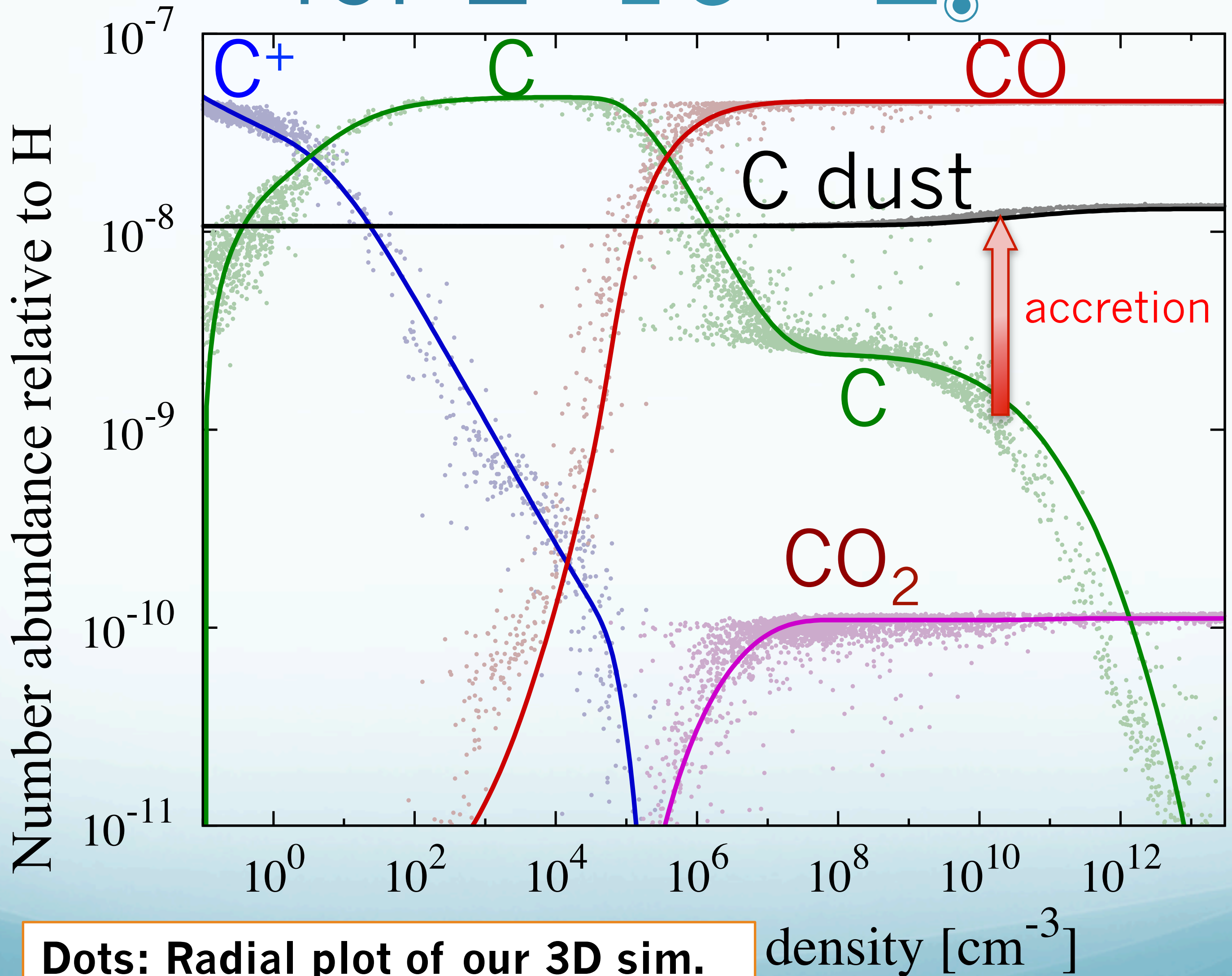
During cloud collapse, Grain Growth occurs

coupled with non-equilibrium gas-phase chemistry

- **55 reactions for 27 species**
- **Implicit method**



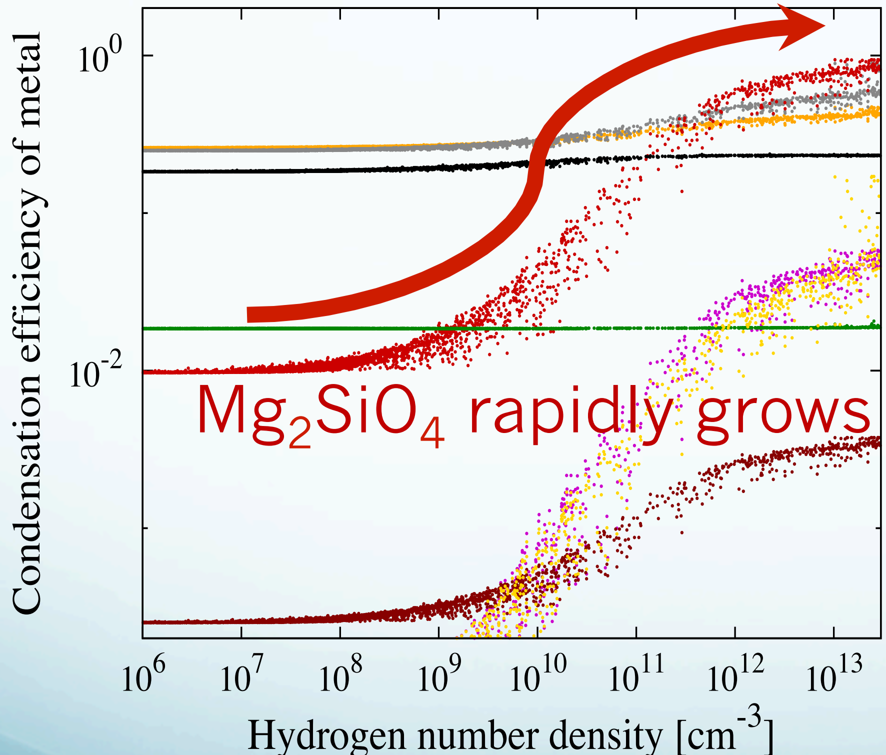
Chemical Evolution for $Z=10^{-4} Z_\odot$



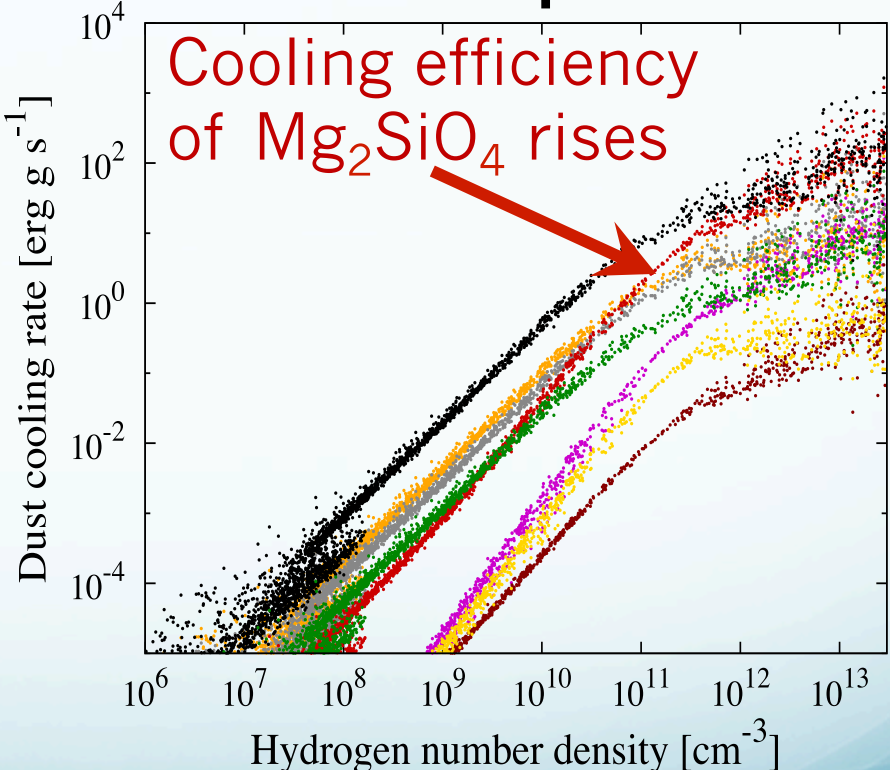
Dots: Radial plot of our 3D sim.
Curves: One-zone calc.

Grain Growth for $Z=10^{-4}\,Z_\odot$

Amount of each dust species

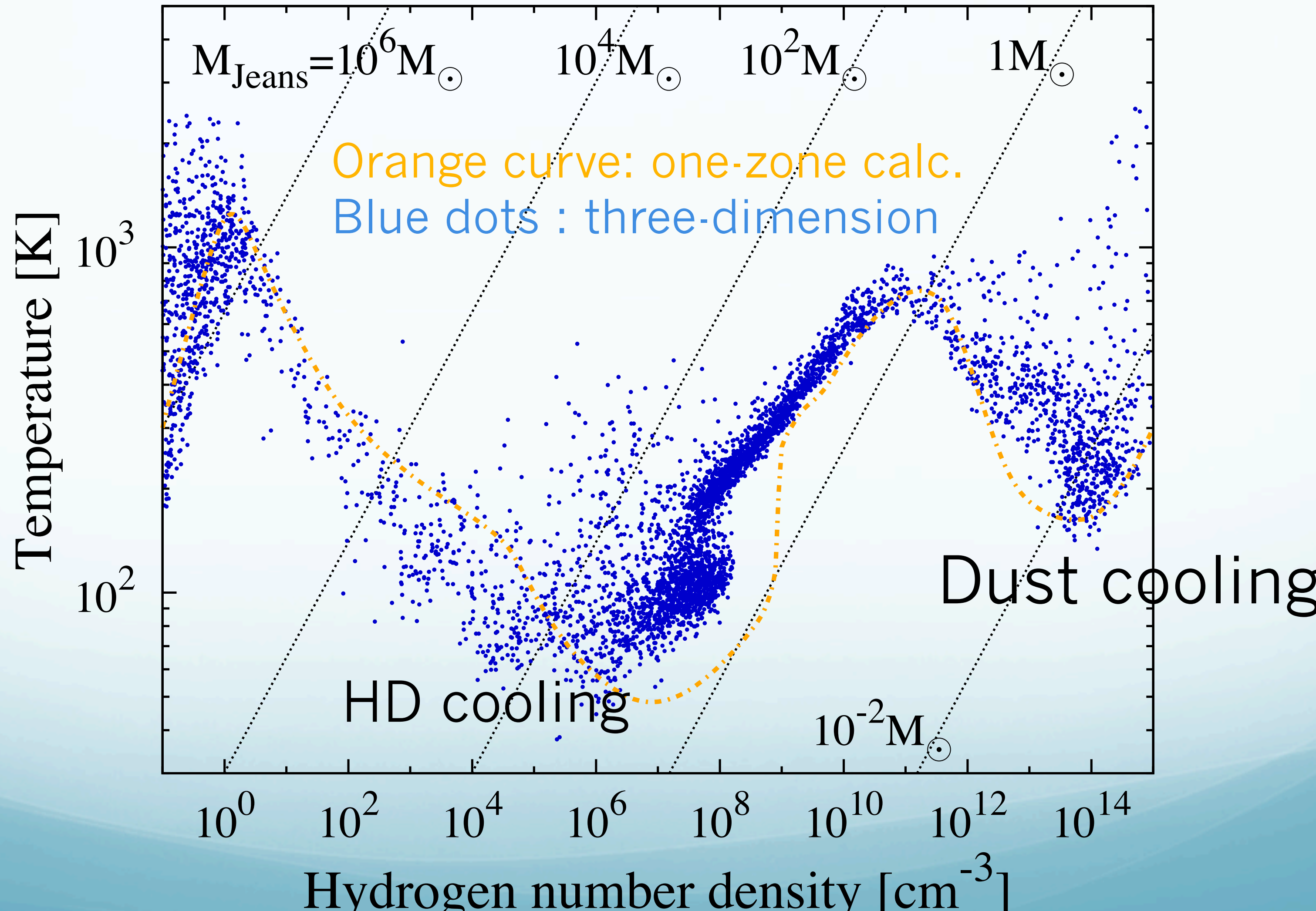


Cooling efficiency of each dust species

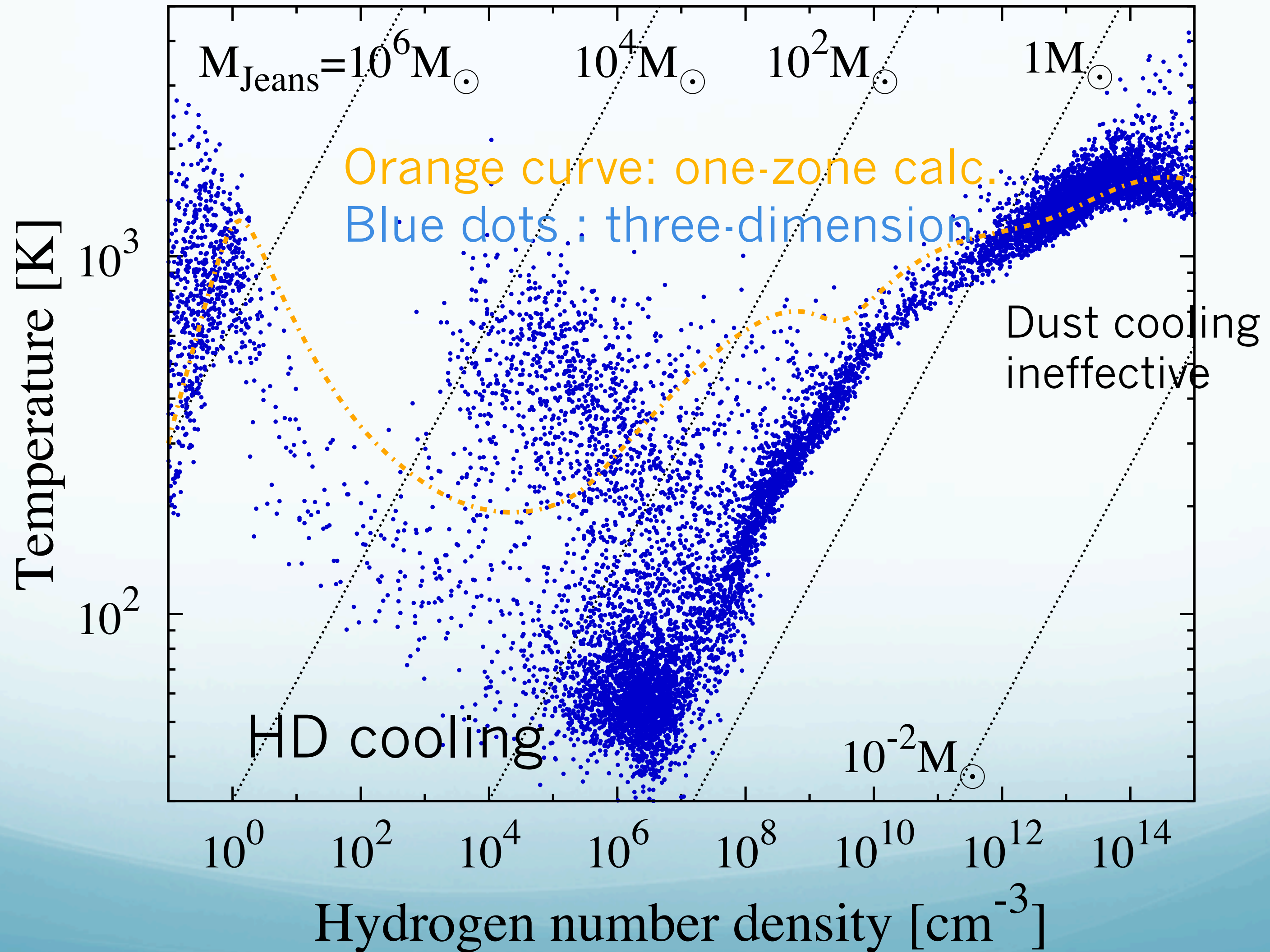


black: C
orange: Si
grey: Fe
green: SiO_2
red: Mg_2SiO_4
brown: MgO
pink: $MgSiO_3$
yellow: FeS

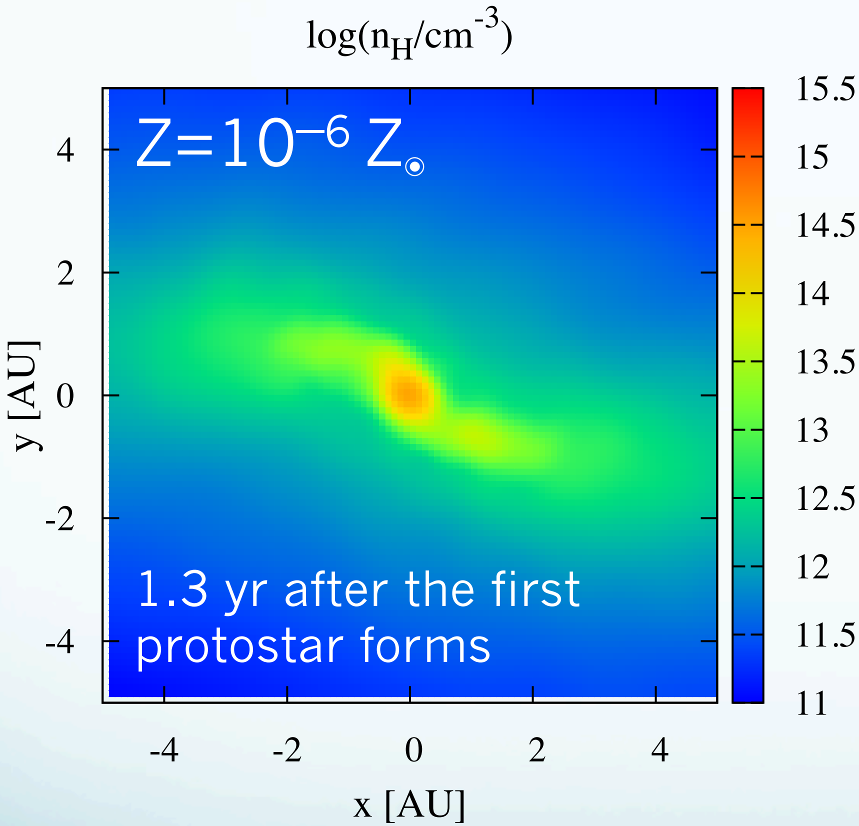
Thermal Evolution of Gas for $Z=10^{-4} Z_\odot$

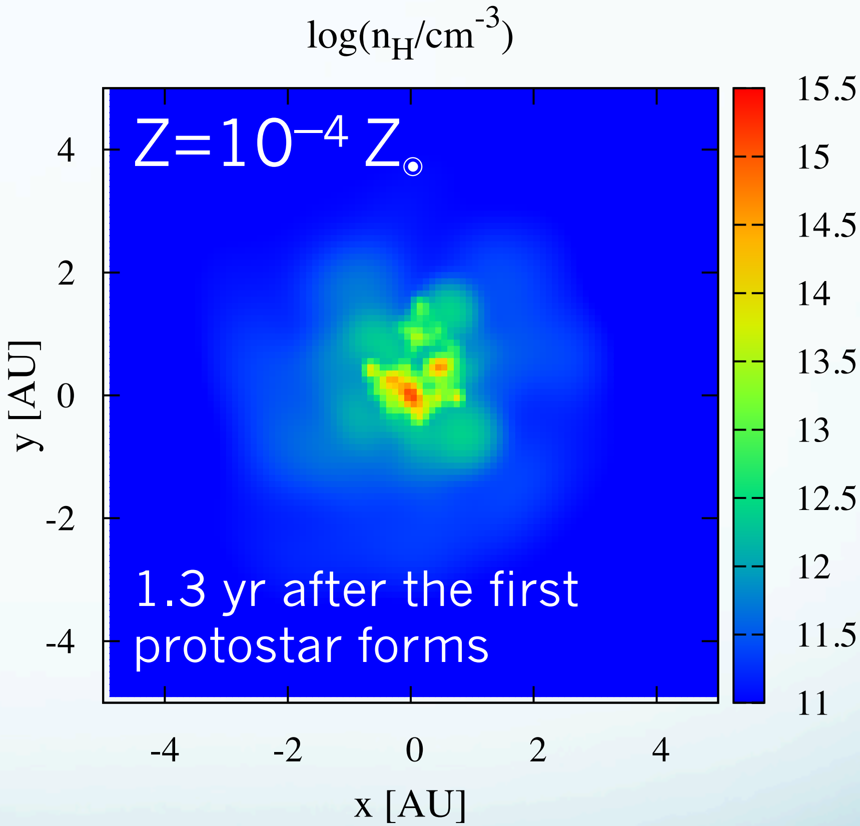


Thermal Evolution of Gas for $Z=10^{-6} Z_{\odot}$



Dust-Induced Gas Fragmentation



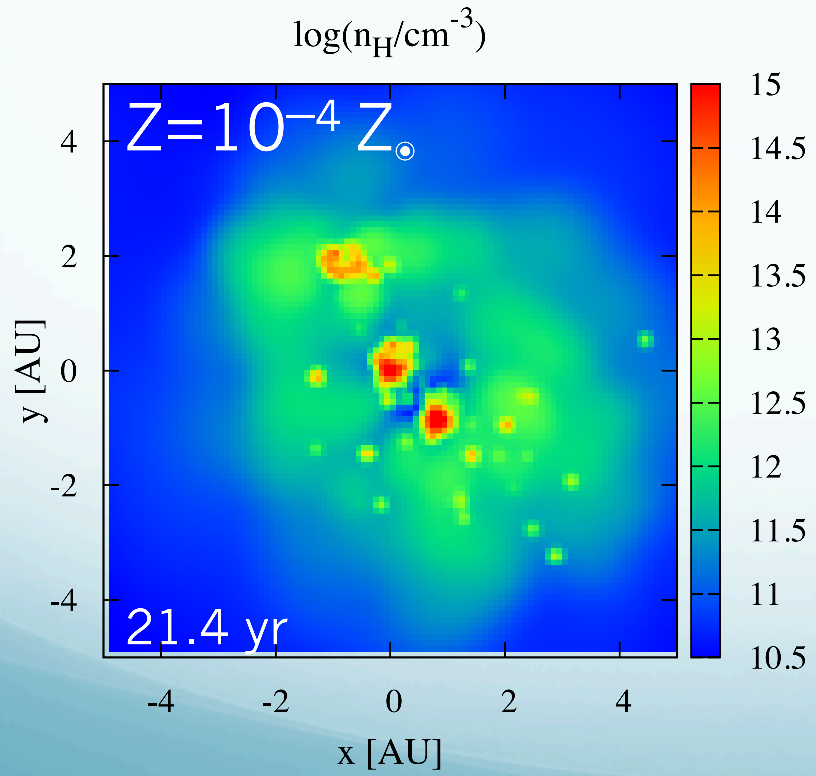


insufficient dust cooling
The gas does not fragment

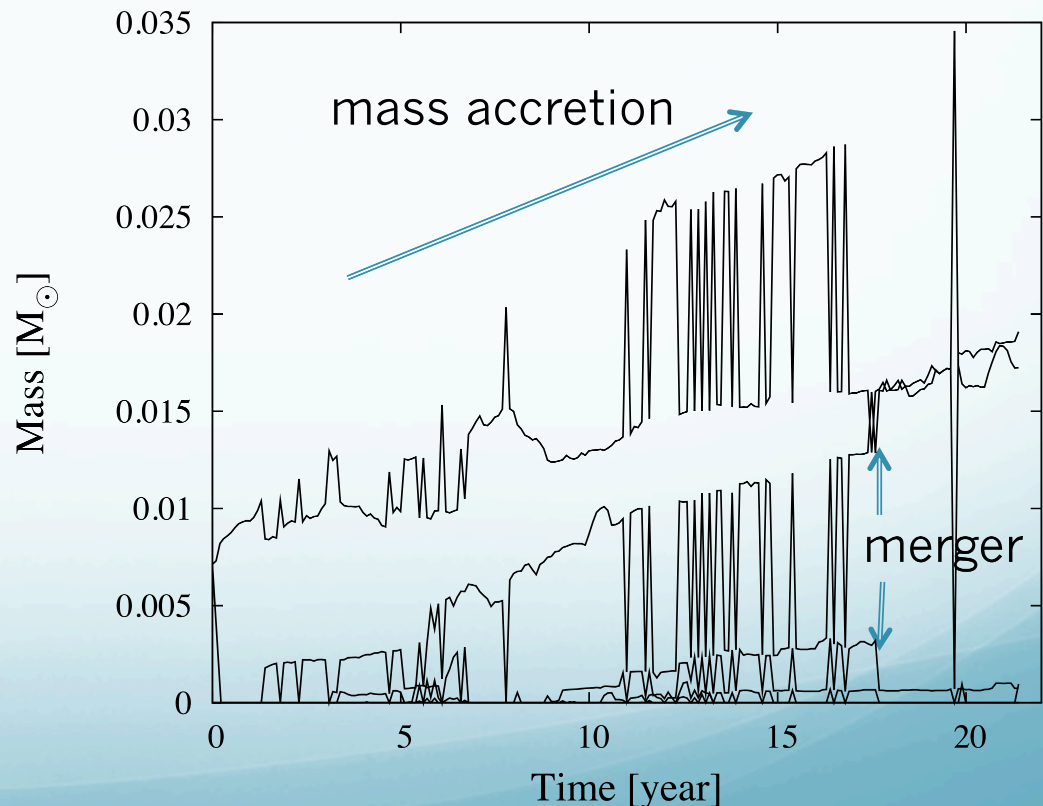
sufficient dust cooling
The gas fragments

Dust-Induced Gas Fragmentation

Final snapshot of our simulation



Time evolution of fragment masses

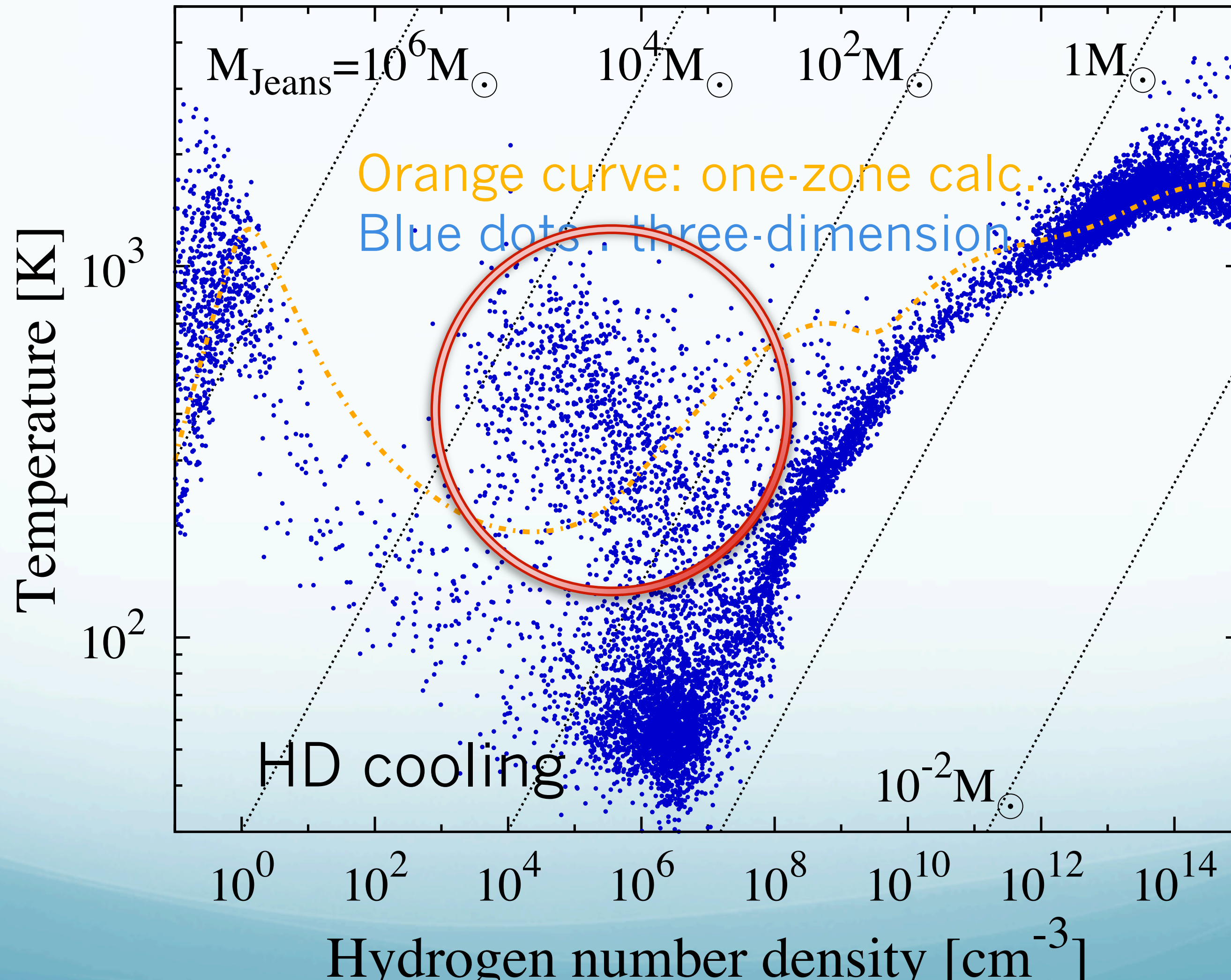


Summary

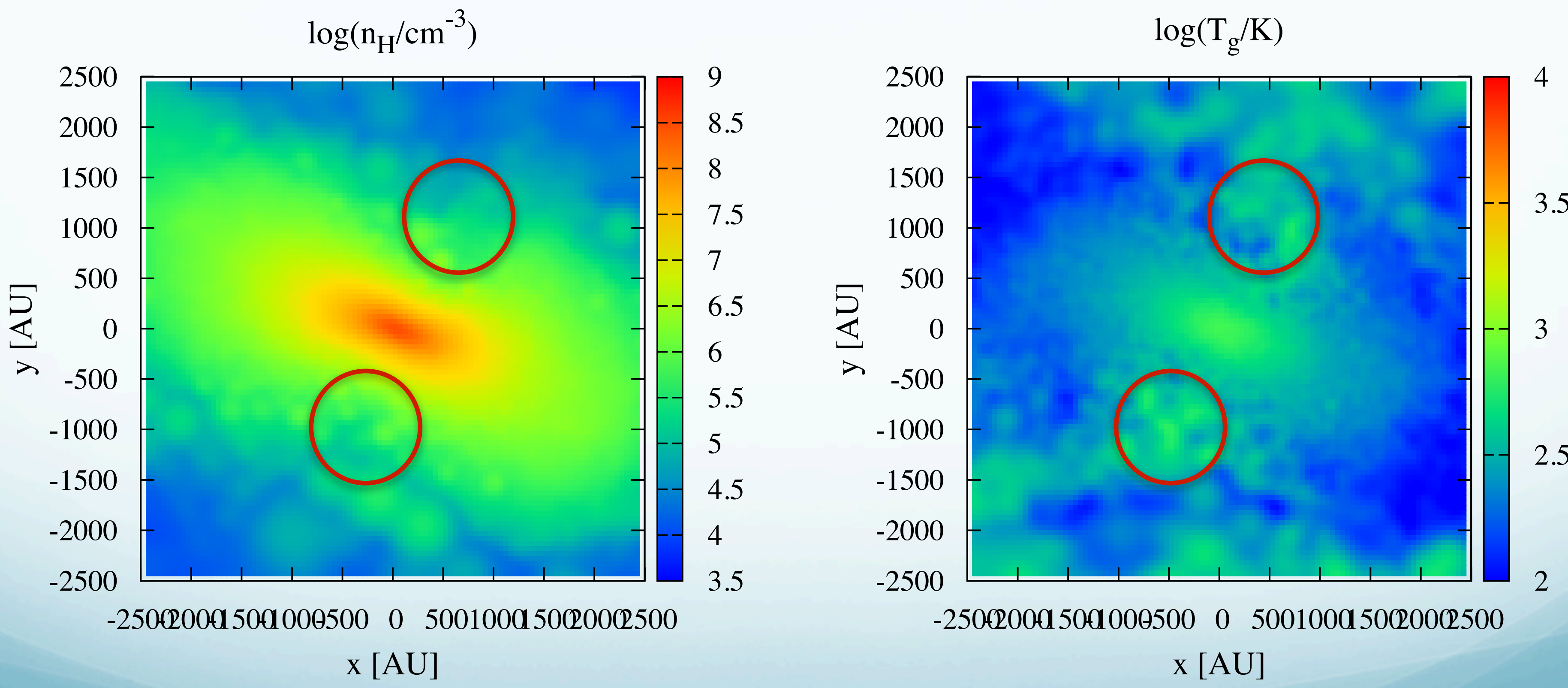
- We perform three-dimensional hydrodynamic calculations for low-metallicity clouds,
- employing the realistic dust models:
  - SN dust model
  - Grain growth
- Dust cooling can trigger gas fragmentation into the low-mass clumps with 0.001, 0.017 and 0.019 M_{sun} 21.4 yr after the first protostar formation.
- The critical metallicity for this case lies between $Z=10^{-6}\ Z_{\odot}$ and $Z=10^{-4}\ Z_{\odot}$.

Appendix

Thermal Evolution of Gas for $Z=10^{-6} Z_{\odot}$



Gas deformation due to HD cooling

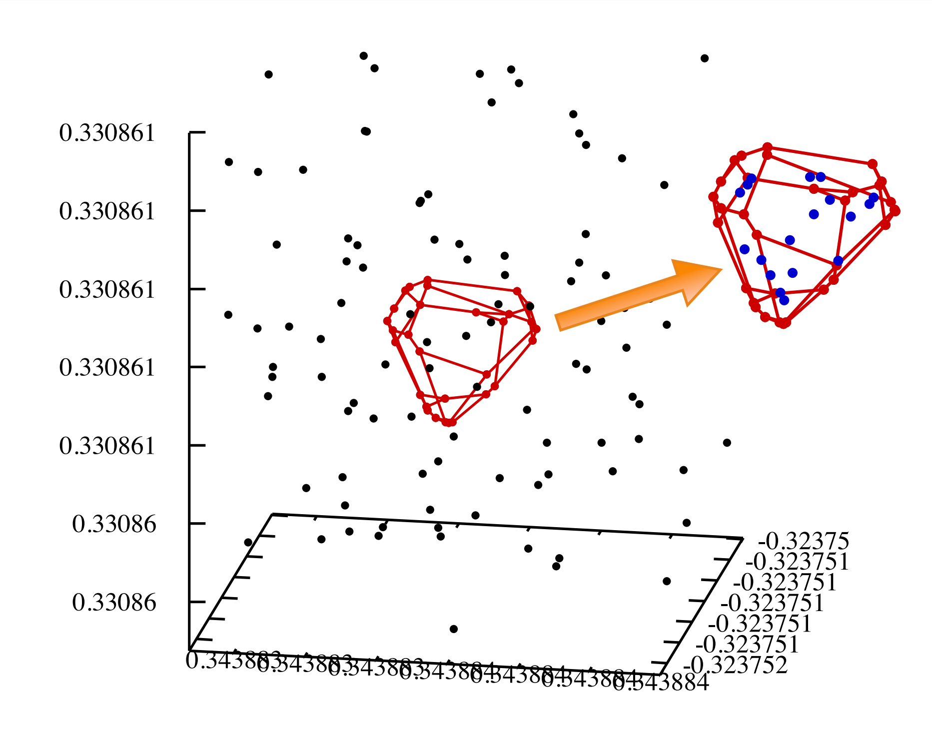


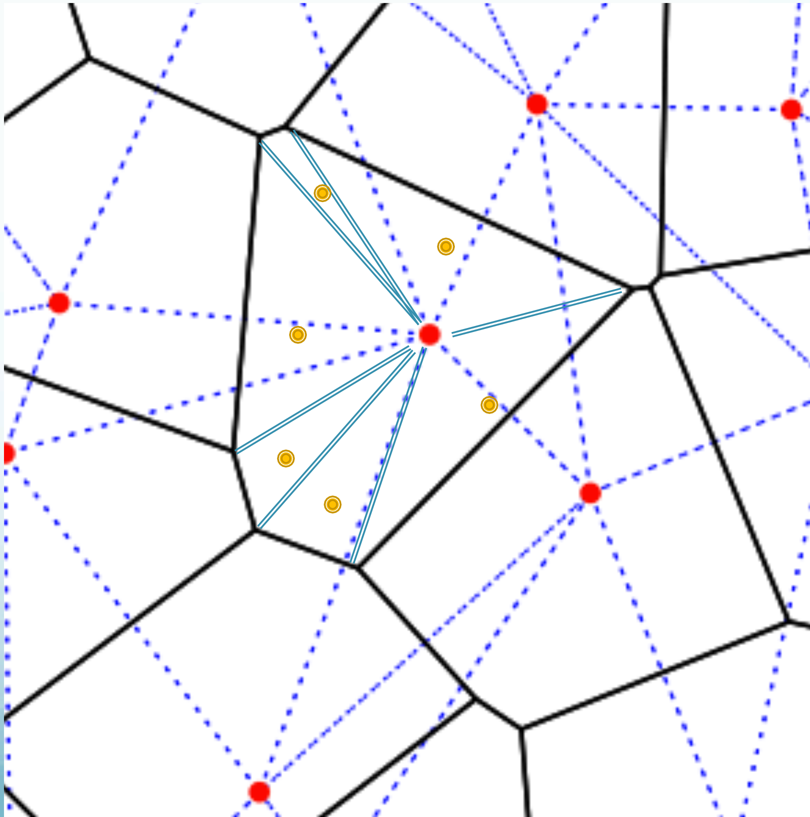
Gas Cooling

- Line cooling
  - OI (5 levels), CI (3 levels), CII (2 levels)
  - H_2 (v=0—2, J=0—19), HD (J=0—3)
  - CO, OH, H_2O
  - Escape fraction calculated for each line (Sobolev approximation for 3 directions)
- Continuum cooling
  - CIE
  - dust (sum of the values **for each species and size**)
  - Escape fraction calculated for each dust species and size

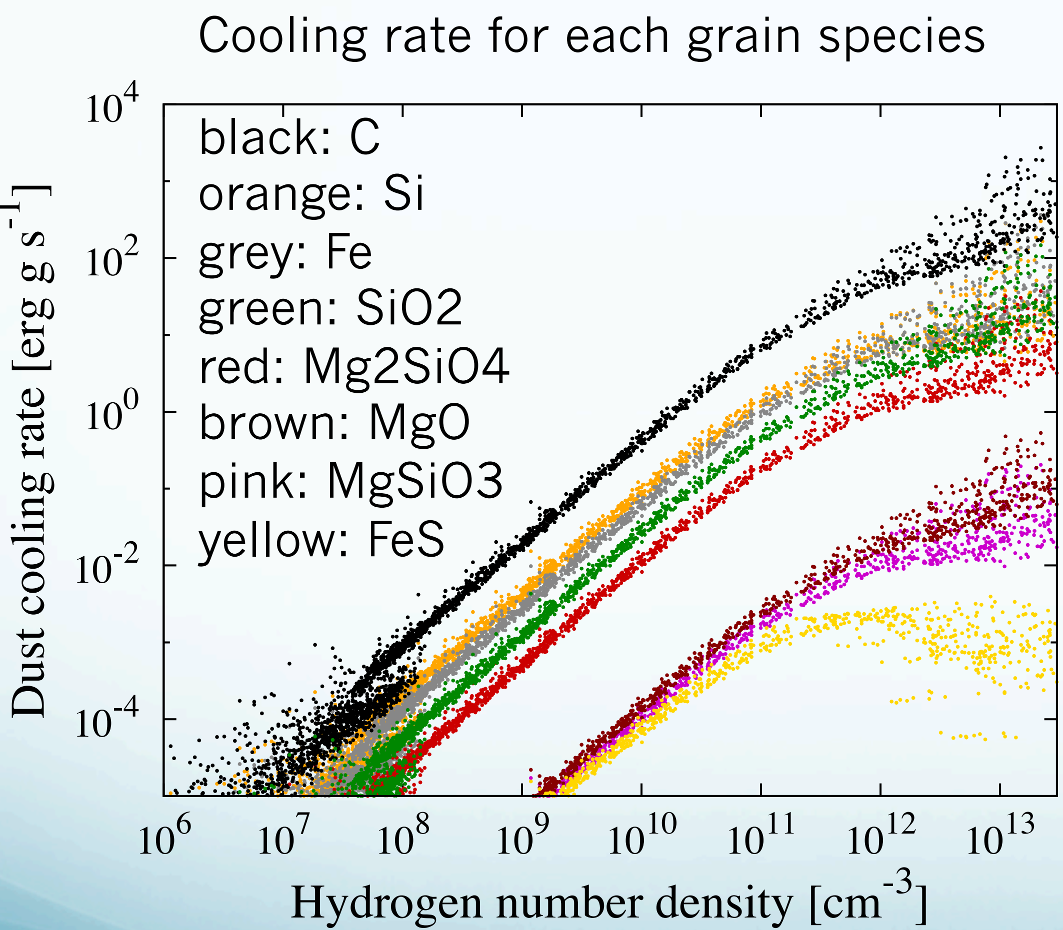
Particle Splitting with the Voronoi Tessellation

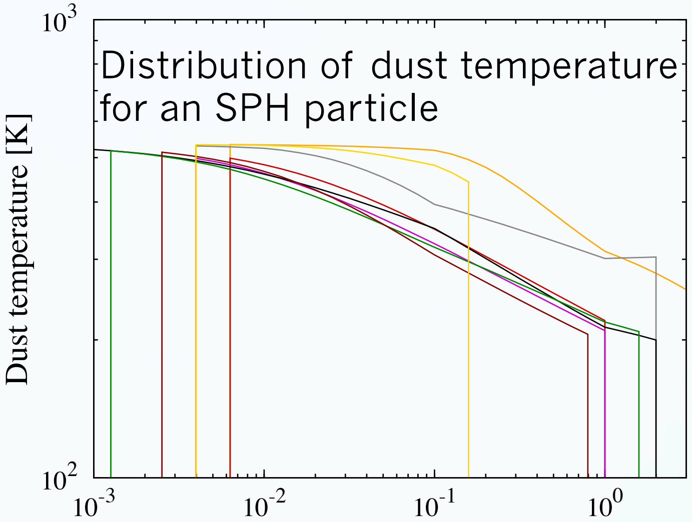
- We put daughter particles at the center of mass of the tetrahedra defined by the Voronoi tessellation.
  - The mass of the daughter particle is proportional to the volume of the tetrahedra.

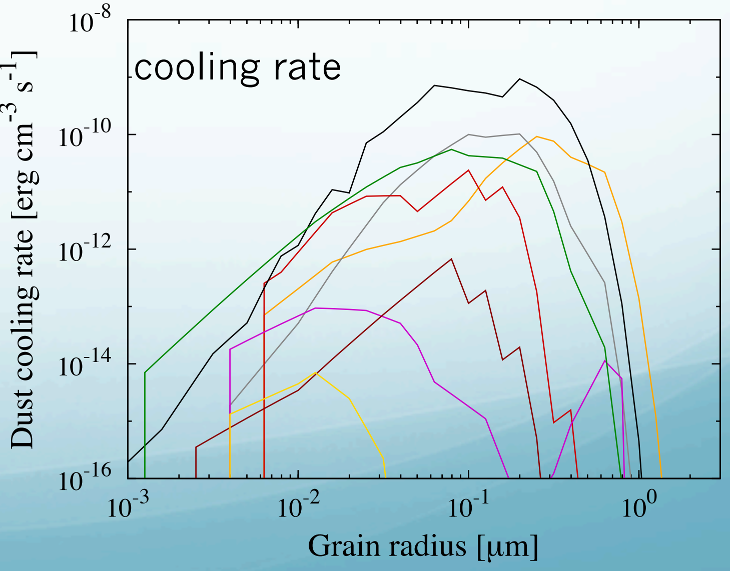




Dust Cooling Rate for Each Species and Size







W/O grain growth

Supernova Model gives Initial Size Distribution