2017/12/19

超新星起源プレソーラーSiC粒子の形成

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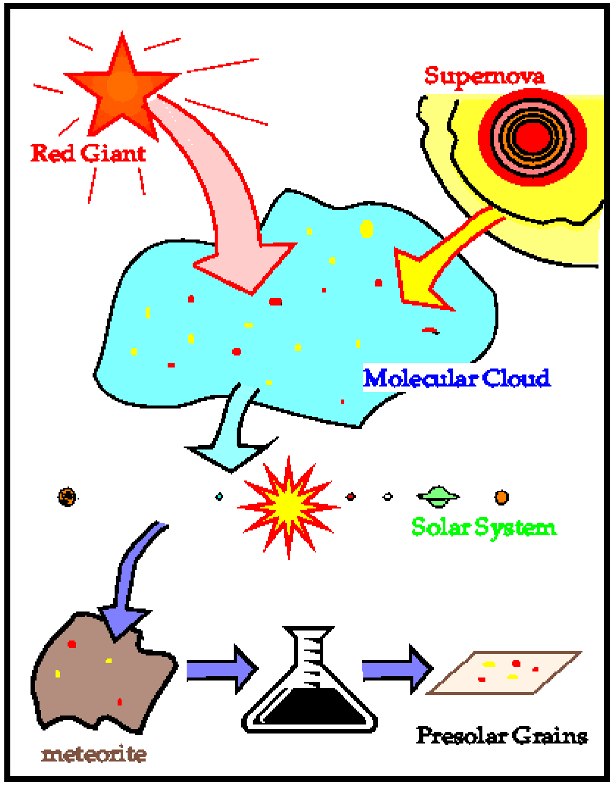
1-1. Presolar grains



http://presolargrains.net/

○ Presolar grains

- discovered in primitive meteorites
- showing peculiar isotopic compositions
  (different from the solar system's materials)
- thought to have formed in stars before the Sun was formed

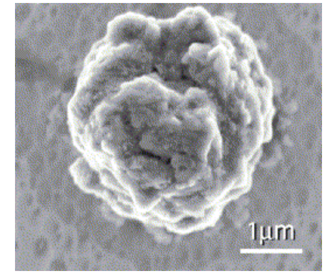
➜ **offering key information on**

- ・nuclear processes in the parent stars
- ・physical conditions in which they formed

- abundance (volume fraction): ~100-500 ppm (~0.1-0.5 %)
- mineral composition

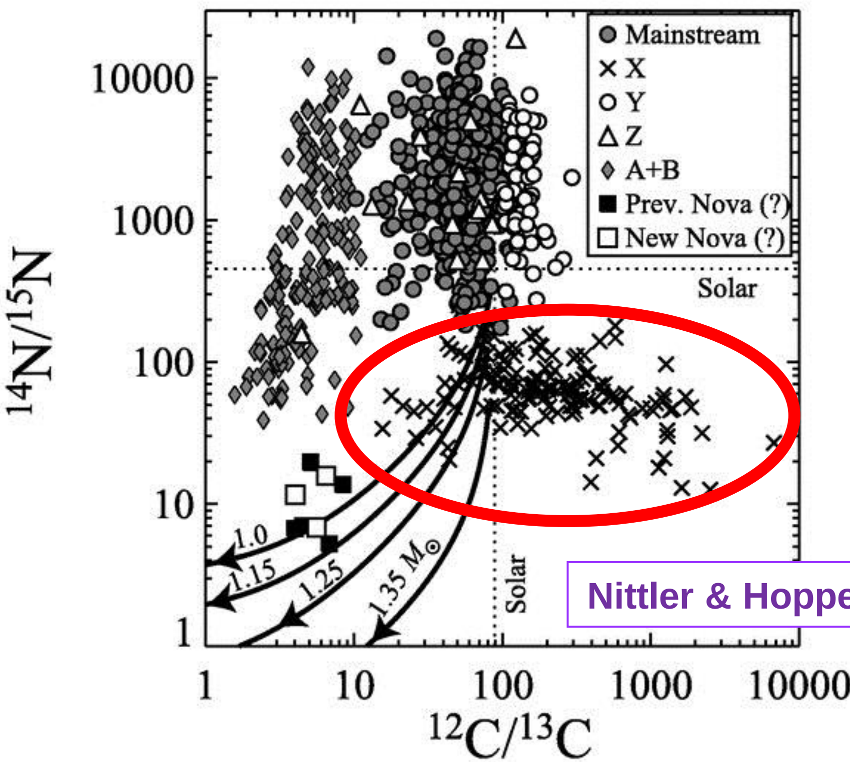
  graphite, SiC, TiC, Si_3N_4, Al_2O_3, $MgAl_2O_4$, Mg_2SiO_4, $MgSiO_3$ …

1-2. Presolar Type X SiC grains

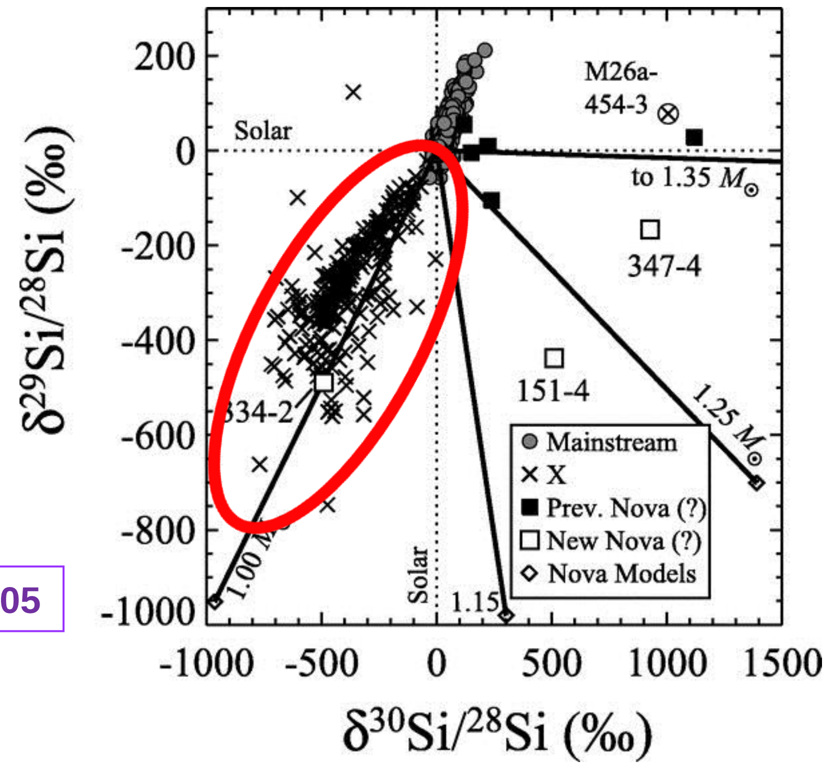


Nittler 2003

○ Presolar SiC grains (~10 ppm)



Nittler & Hoppe 2005



○ Type X SiC grains (~0.1 ppm, size: 0.1-20 µm)

- 12C/28Si rich, with excesses in 44Ca (44Ti), 49Ti (49V)

  ➜ originated from core-collapse supernovae

1-3. Long-lasting questions

○ Fact

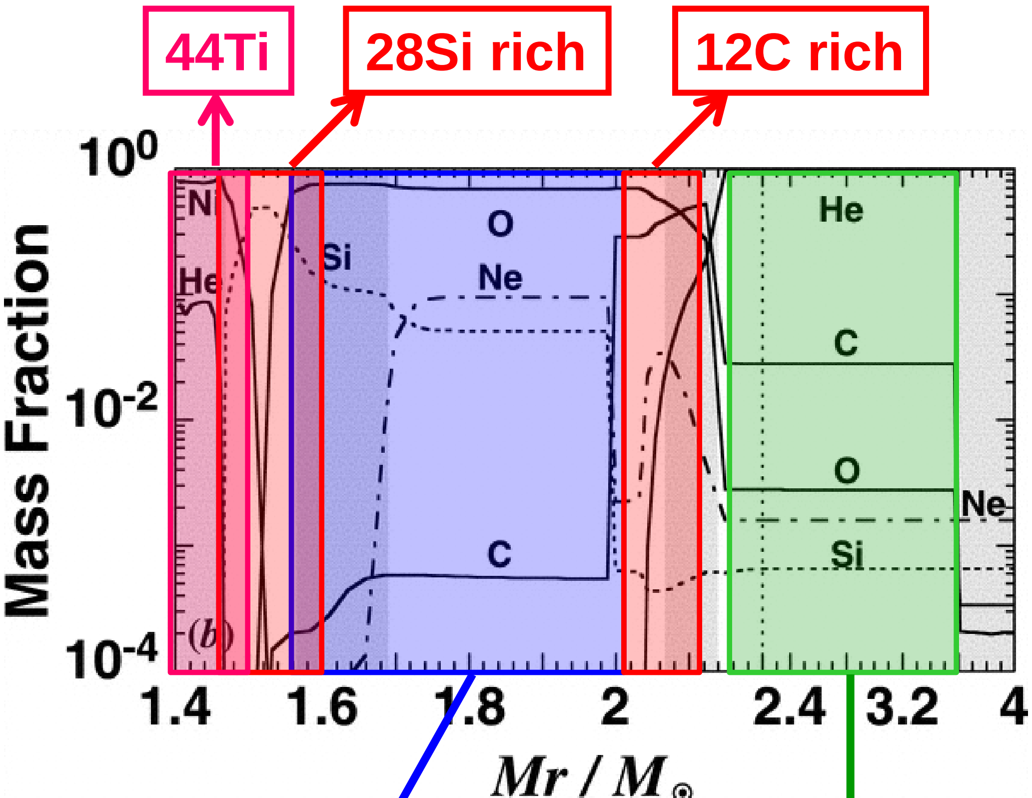
A fraction of presolar SiC grains is highly likely SN-origin

○ Question

How do these SiC grains form in the ejecta of core-collapse supernovae?

Any theoretical studies have not yet realized the
formation of SiC grains in supernovae

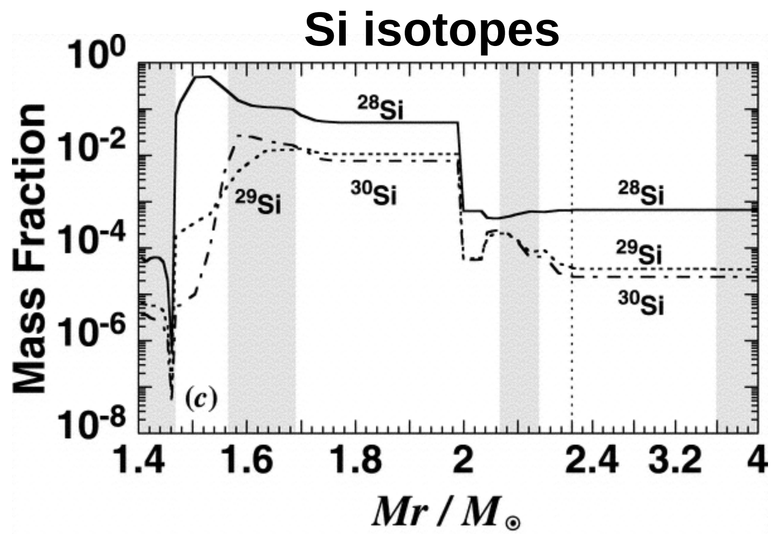
2-1. Elemental abundances in the SN ejecta

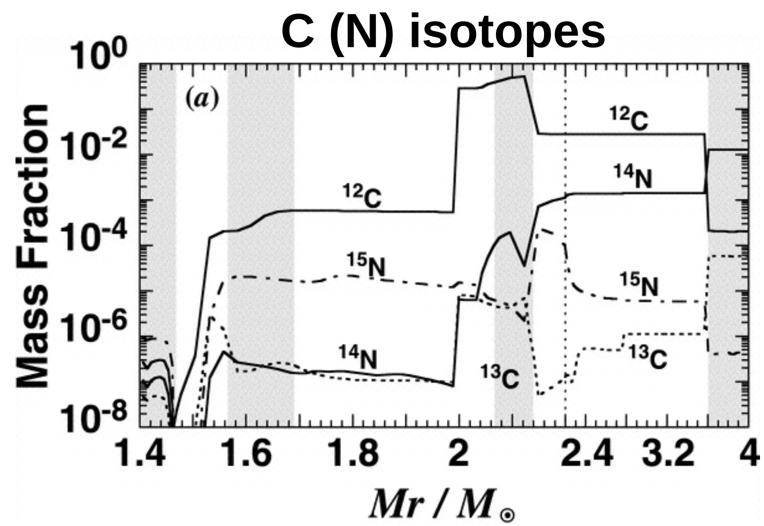


Yoshida 2007; 4 Msun He-core model (Mstar ~ 18 Msun)

O-rich (O/C >> 1)
29, 30Si rich

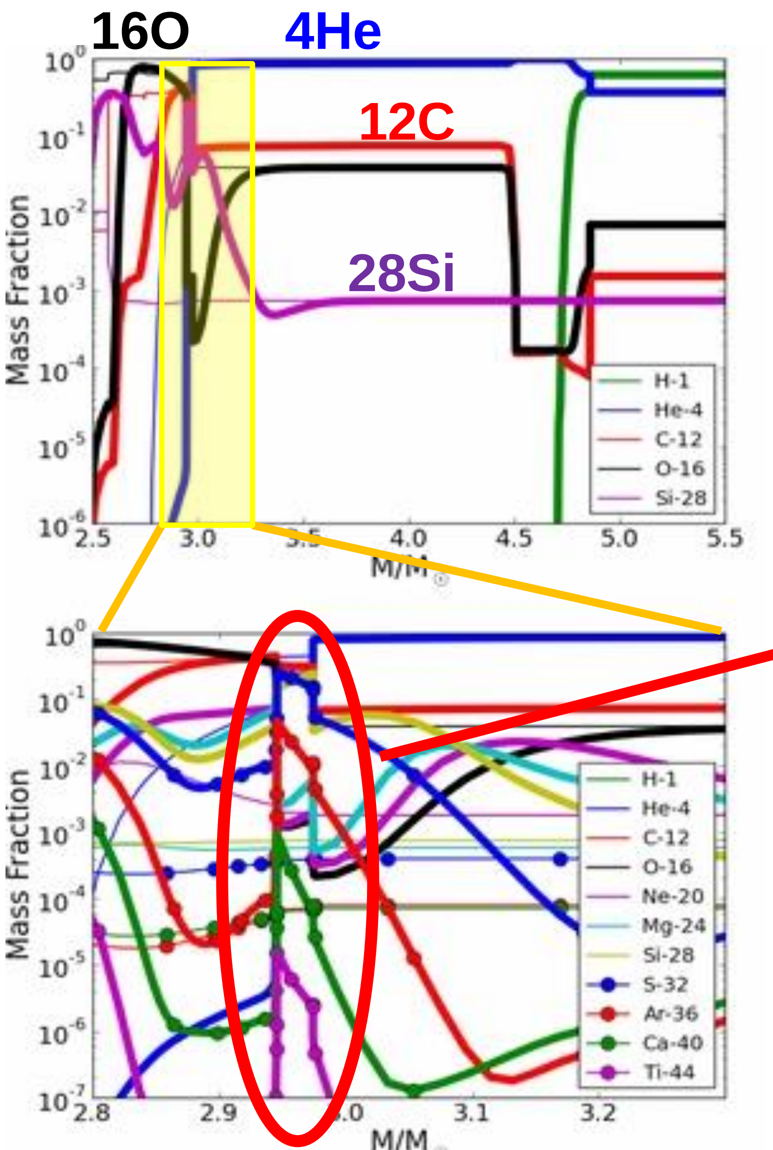
29, 30Si solar
14N rich





Needed unrealistic mixing of the ejecta

2-2. Possible formation site of SiC grains in SNe



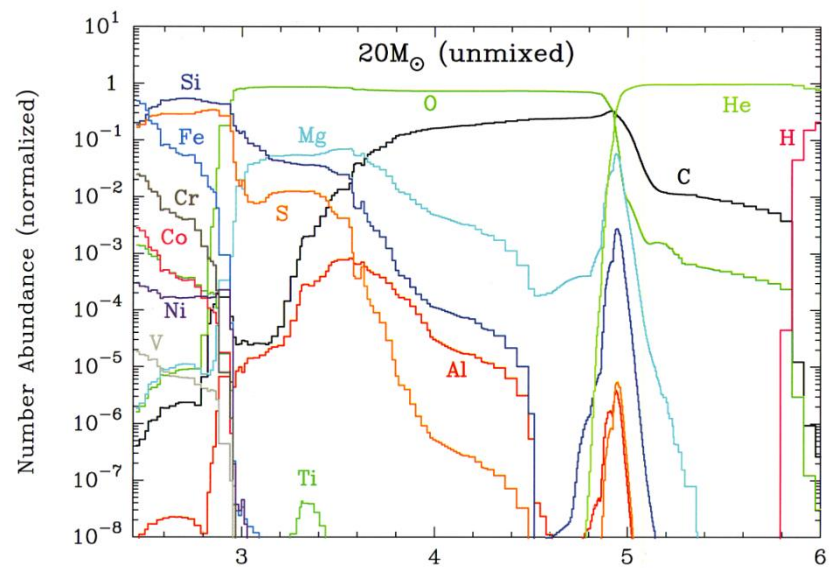
Pignatari+2013

○ Moderately energetic SNe

E_{kin} = (3-5)x10^{51} erg

(normal SNe : E_{kin} ~ 1x10^{51} erg)

explosive burning happens at the boundary between O-rich region and He-rich region



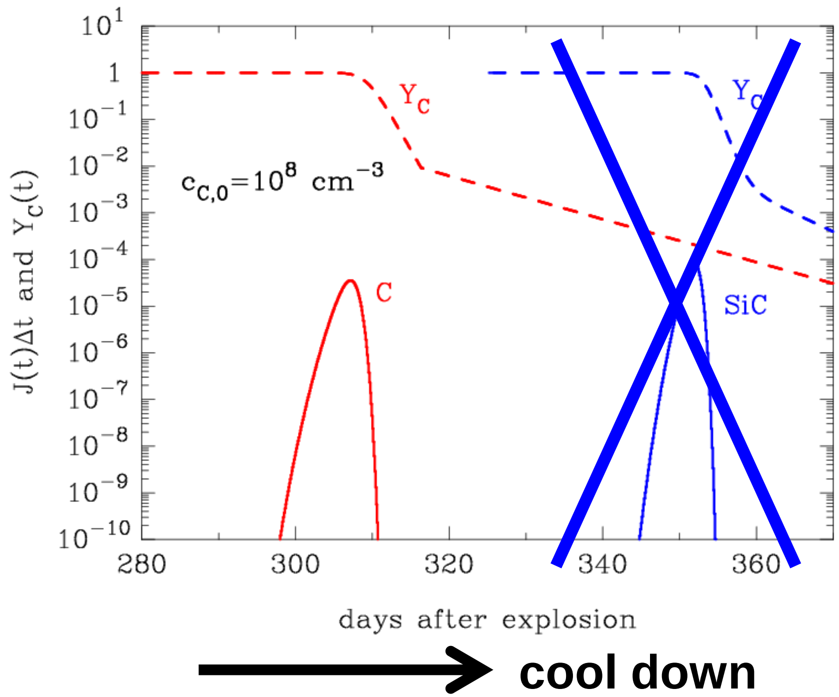
Umeda & Nomoto 2002

2-3. No formation of SiC in the calculations

○ Condensation temperature

- C grains : Tcon = 1700-2200 K
- SiC grains: Tcon = 1300-1800 K

➜ In C/Si-rich gas, C grains first condense to use up the gas-phase C atoms



○ Formation path of grains

$$C_n + C \longrightarrow C_{n+1}$$

$$(SiC)_n + Si + \text{C} \longrightarrow (SiC)_{n+1}$$

More efficient destruction of C grains (clusters)?

UV radiation, high-energy e, chemical reaction, …

➜ this may not do a good job

2-4. Formation of SiC grains via molecules

○ Previous works

$$C_n + C \longrightarrow C_{n+1}$$

$$(SiC)_n + Si + C \longrightarrow (SiC)_{n+1}$$

➜ accretion of Si/C atoms

○ This work

- accretion of SiC molecules

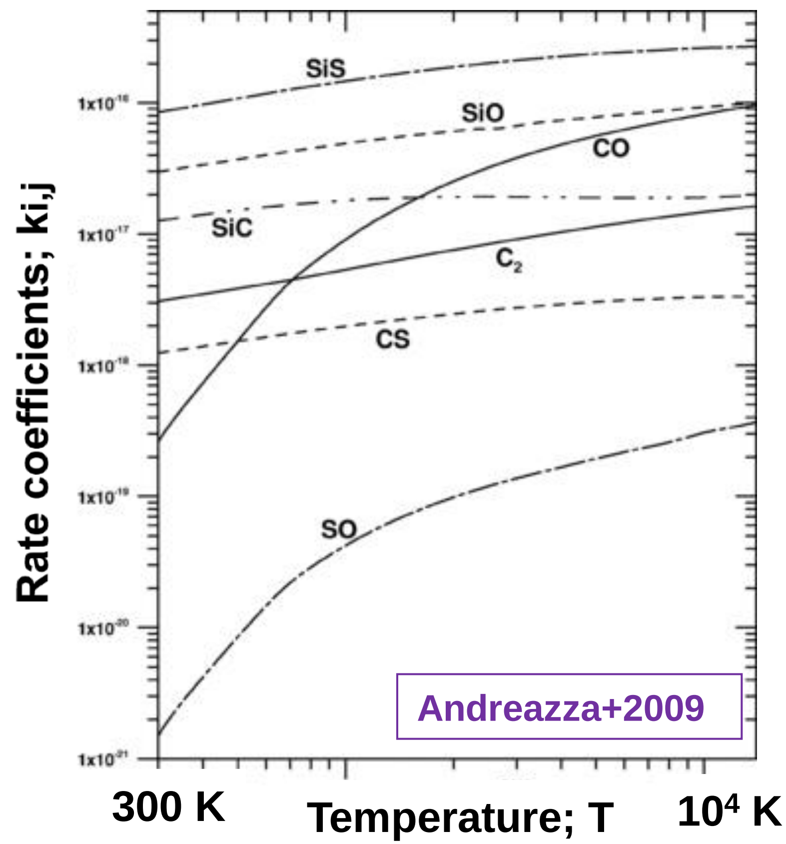
$$(SiC)_n + SiC \longrightarrow (SiC)_{n+1}$$

- coagulation

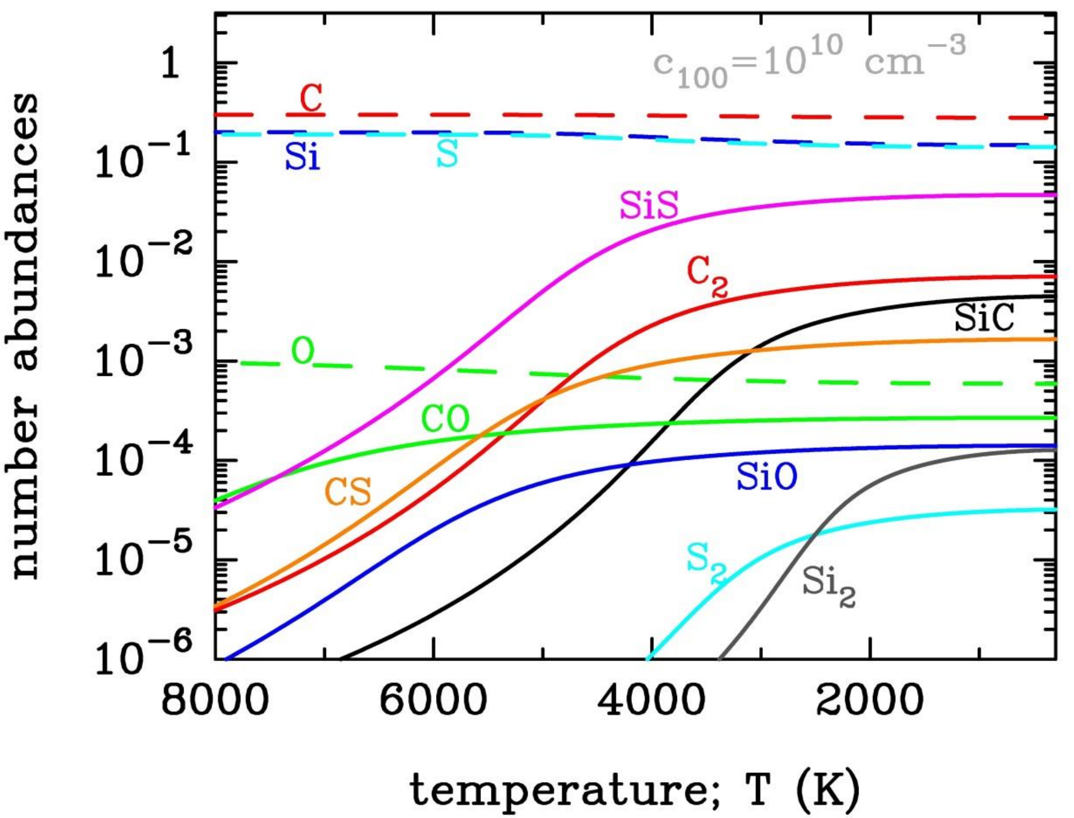
$$(SiC)_m + (SiC)_n \longrightarrow (SiC)_{m+n}$$

rate coefficients of radiative association of molecules ki,j

$$\frac{dc_k^{\mathrm{mol}}}{dt} = k_{ij}(T)c_i c_j$$



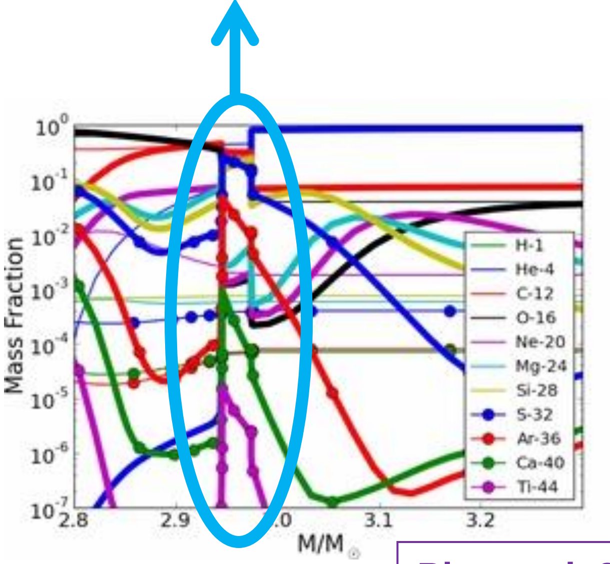
3-1. Formation of SiC molecules



Element	# abundance
He	0.3
C	0.3
O	0.001
Ne	0.001
Mg	0.002
Si	0.2
S	0.19
Ar	0.006

$$c(t) = c_{100}\left(\frac{t}{100\ \mathrm{day}}\right)^{-3}\quad \mathrm{cm}^{-3}$$

$$T(t) = 10^4\left(\frac{t}{100\ \mathrm{day}}\right)^{-1}\quad \mathrm{K}$$



Pignatari+2013

3-2. Equation of dust formation

○ Master equations of dust growth

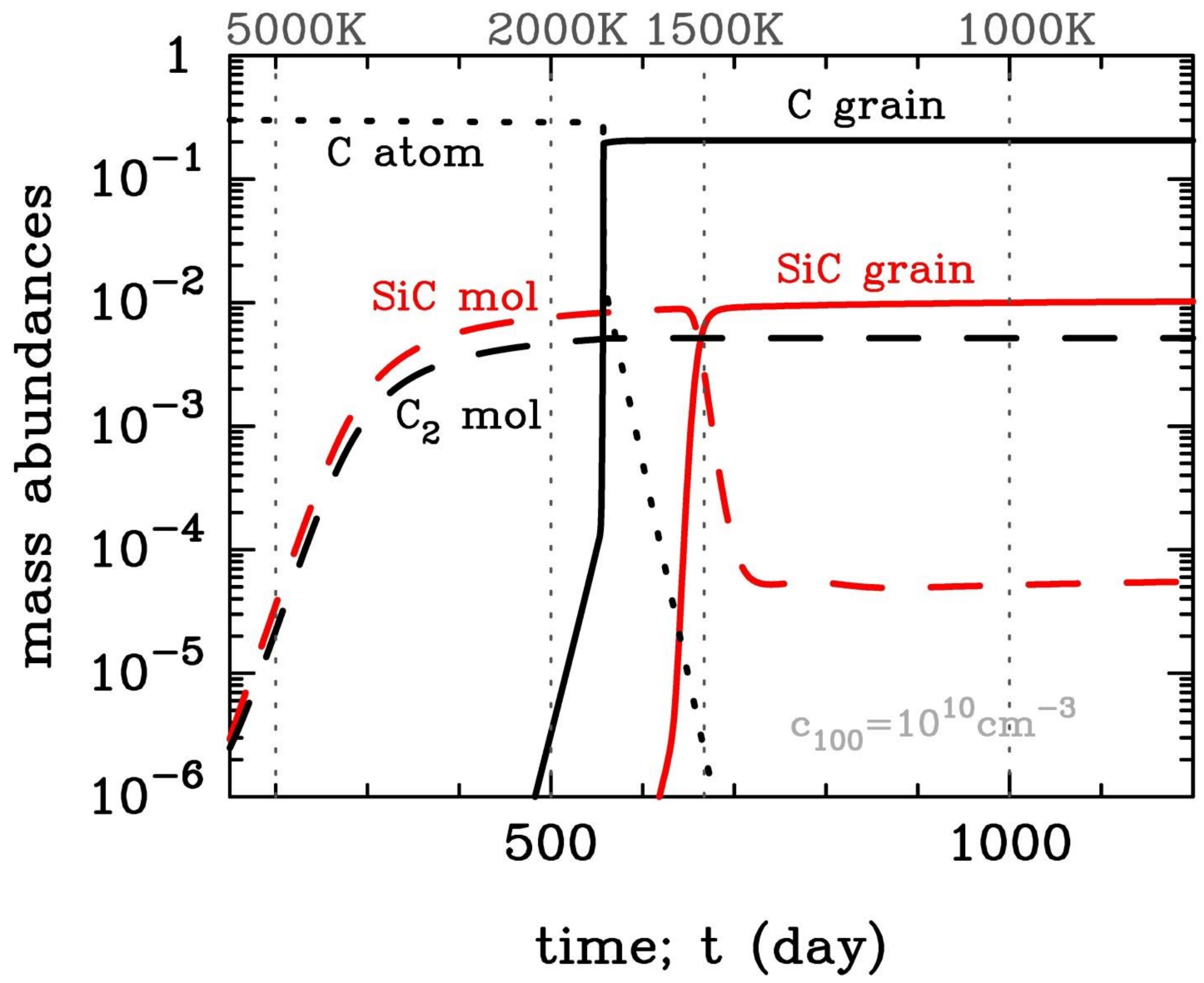
$$\frac{dc_n}{dt} = \frac{1}{2}\sum_{i=1}^{n-1} K_{i,n-i}(T) c_i \left(c_{n-i} - c_n e^{\gamma_{i,n-1}}\right) - c_n \sum_{l=1}^{n_{\max}} K_{n,l}(T)\left(c_l - c_{n+l} e^{\gamma_{l,n}}\right)$$

$$K_{i,j}(T) = \alpha_{\rm s}\pi(a_i + a_j)^2 \left(\frac{8kT}{\pi m_{i,j}}\right)^{\frac{1}{2}}$$

$$\gamma_{i,n-i}(T) = \frac{4\pi a_0^2 \sigma}{kT}\left[(n-1)^{\frac{2}{3}} - (n-i-1)^{\frac{2}{3}} - (i-1)^{\frac{2}{3}}\right] - \ln S_i$$

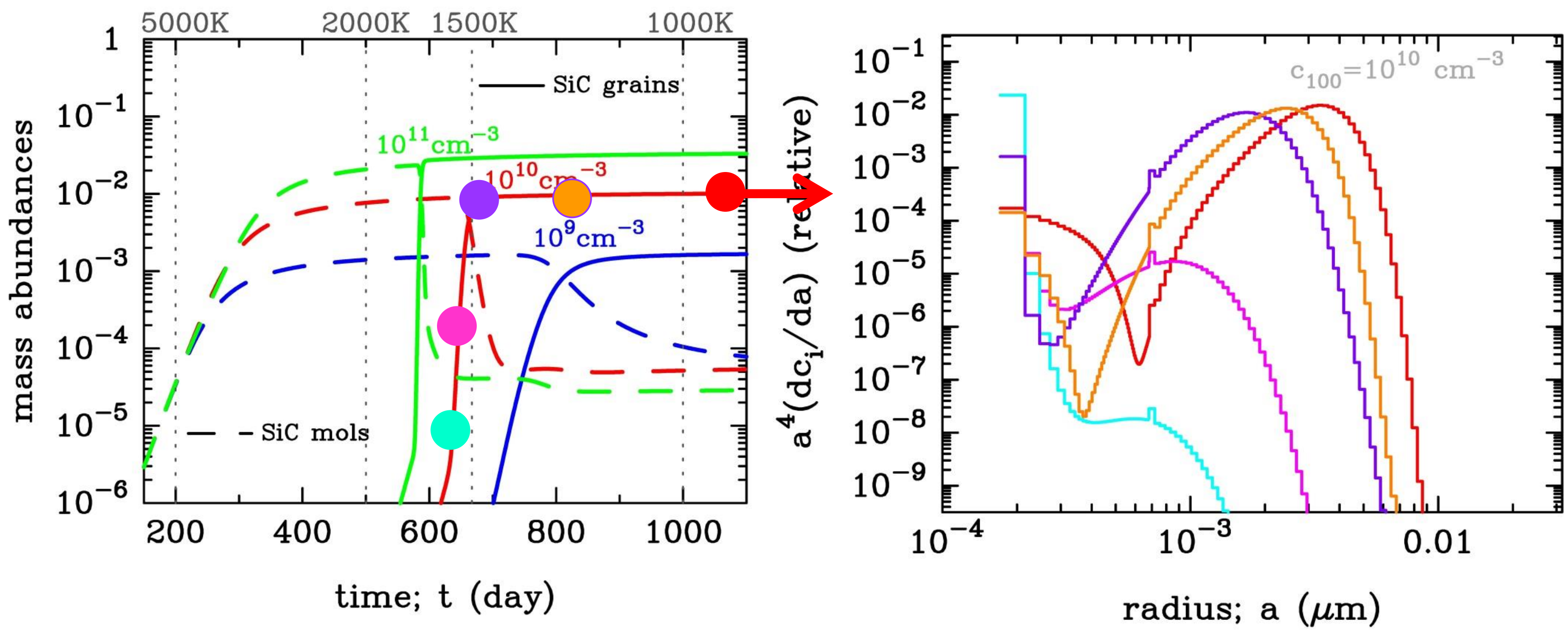
taking account of nucleation and grain growth through gas accretion and coagulation between grains simultaneously!

3-3. Can SiC grains form in the SN ejecta?



Yes, the formation of SiC grains is possible !

3-4. Formation process of SiC grains



○ Formation of SiC grains is possible !!

- Condensation temperature is higher for higher gas density
- Dust growth proceeds on a short timescale through rapid accretion of molecules
- Coagulation makes the average radius by about a factor of 2

3-5. Size distribution of SiC grains formed

○ Timescale of collision

$$\tau_{\rm coll}^{-1} = \pi S_{i,j} \langle v \rangle c_i$$

– Timescale of gas accretion onto 0.001um-sized grains

$$\tau_{\rm acc} \simeq 0.028 \text{ day } \left(\frac{a_{ij}}{0.001\ \mu{\rm m}}\right)^{-2} \left(\frac{T}{1500\ {\rm K}}\right)^{-\frac{1}{2}} \left(\frac{m_{ij}}{40 m_{\rm H}}\right)^{\frac{1}{2}} \left(\frac{c_{\rm tot}}{3\times 10^7\ {\rm cm}^{-3}}\right)^{-1} \left(\frac{A_i}{5\times 10^{-3}}\right)^{-1}$$

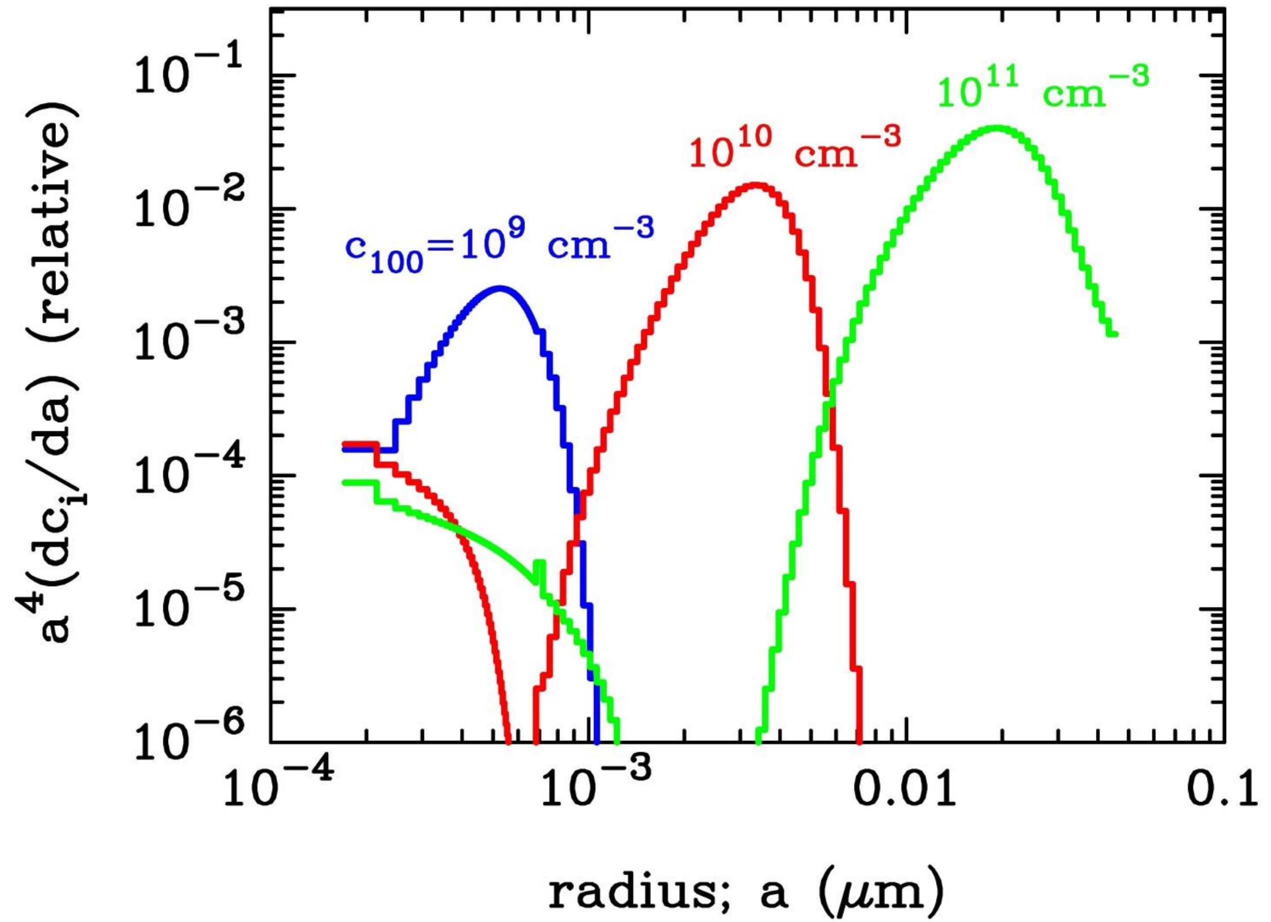
– Timescale of coagulation between 0.001um-sized grains

$$\tau_{\rm coag} \simeq \tau_{\rm acc} \left(\frac{1}{4\sqrt{2}}\right) (10^3)^{\frac{1}{2}} 10^3 \simeq 155 \ \ \text{day}$$

– Timescale of gas expansion

$$\tau_{\rm exp} = \left(\frac{1}{c}\left|\frac{dc}{dt}\right|\right)^{-1} = \frac{t}{3} \simeq 220 \ \ \text{day}$$

3-6. Size distribution of SiC grains formed



- **Radius of newly formed grains is larger for higher gas density**
- **In the density range considered in this study, grain radius is not large enough to reproduce ones observed in presolar SiC grains**

4. Summary of this talk

We investigate the formation of SiC grains in the ejecta of supernovae, self-consistently treating

- **formation of SiC molecules**
- **growth of SiC grains via accretion of molecules**
- **growth of SiC grains via grain-grain coagulation**

We have realized, for the first time, the formation of SiC grains (but with small radii of < 0.1 μm…)

calculations for more dense cases needed to
achieve the formation of SiC grains as large as
presolar Type-X SiC grains (a > 0.1 μm)