CEMP star formation from faint supernova explosions

Gen Chiaki

John H. Wise

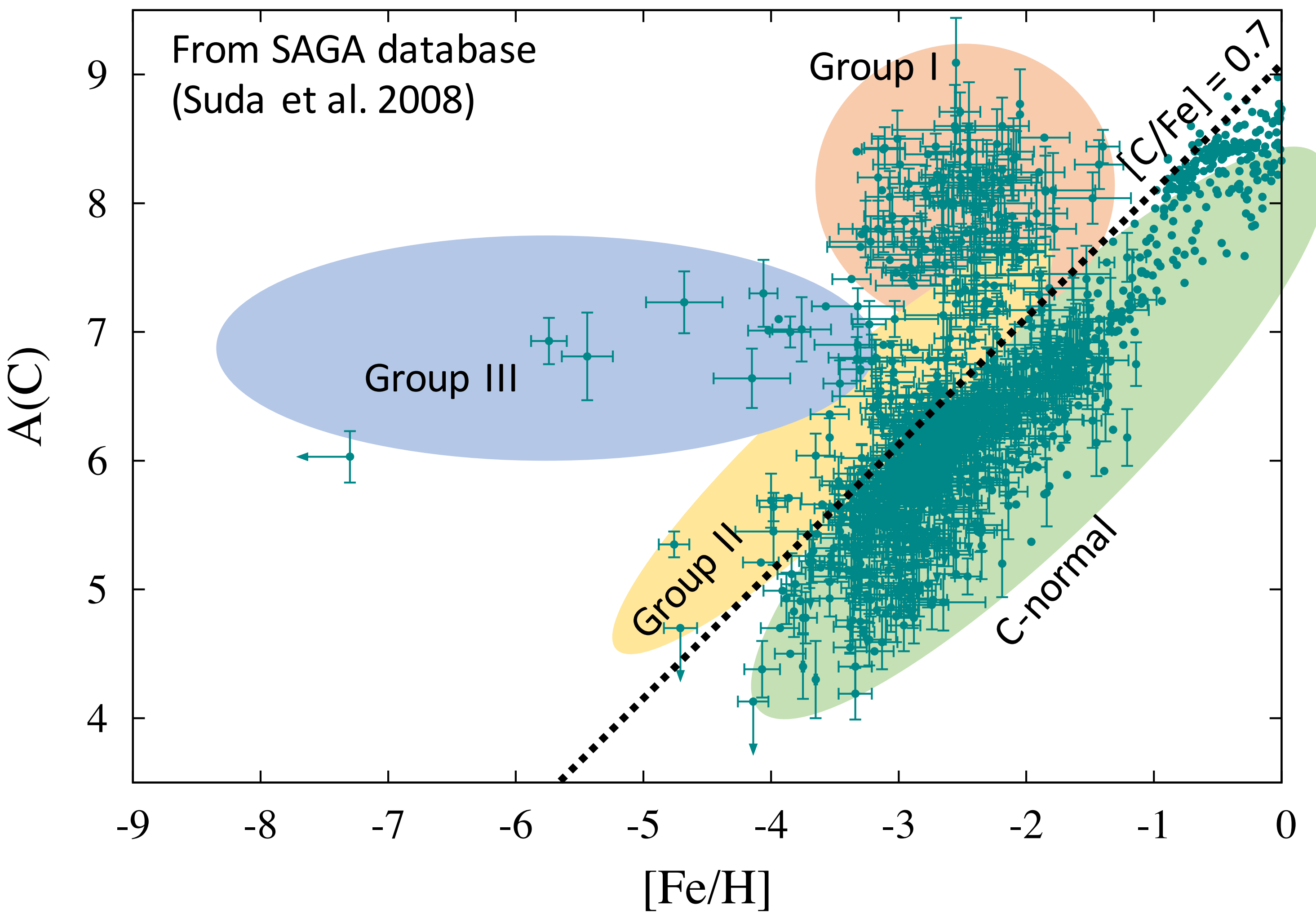
(Georgia Tech)

CEMP Stars as Probes of First-Star Nucleosynthesis, the IMF, and Galactic Assembly

September 12, 2019 @ Geneve

Origin of CEMP and EMP stars

Yoon et al. (2016, 2018); Tim & Jinmi's talks

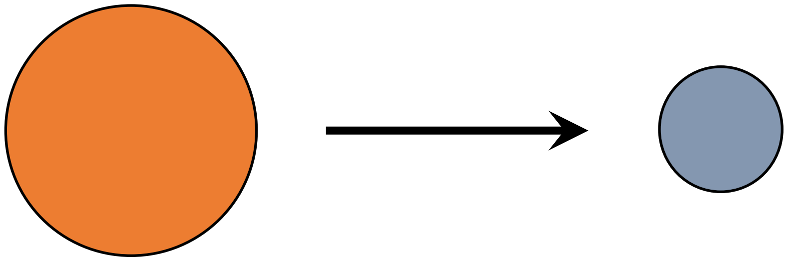


Origin of Group I stars

Extrinsic

- Binary transfer

(Suda et al. 2004)

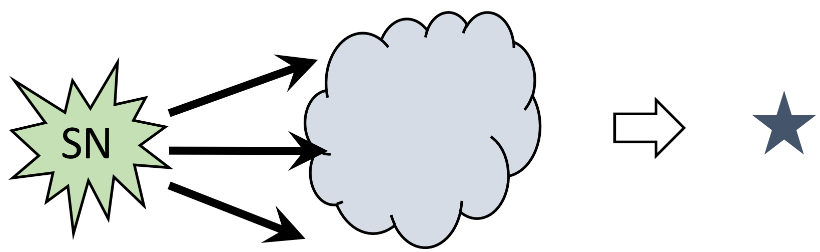


Origin of Group II/III stars

Intrinsic

- Enrichment from supernovae (SNe)

(Heger & Woosley 2002; Umeda & Nomoto 2002)



- Spinstar

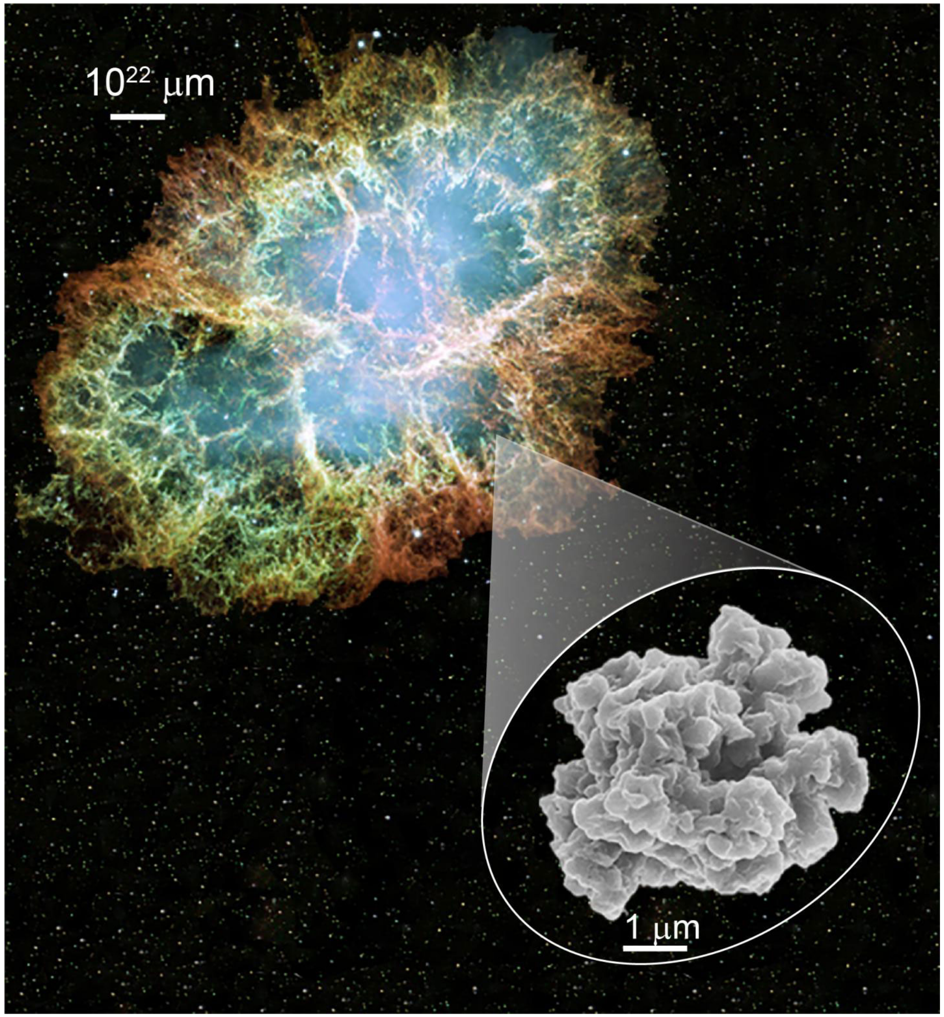
(Maynet et al. 2006)

- Binary transfer

(Suda et al. 2004)

SNe: the factory of dust grains

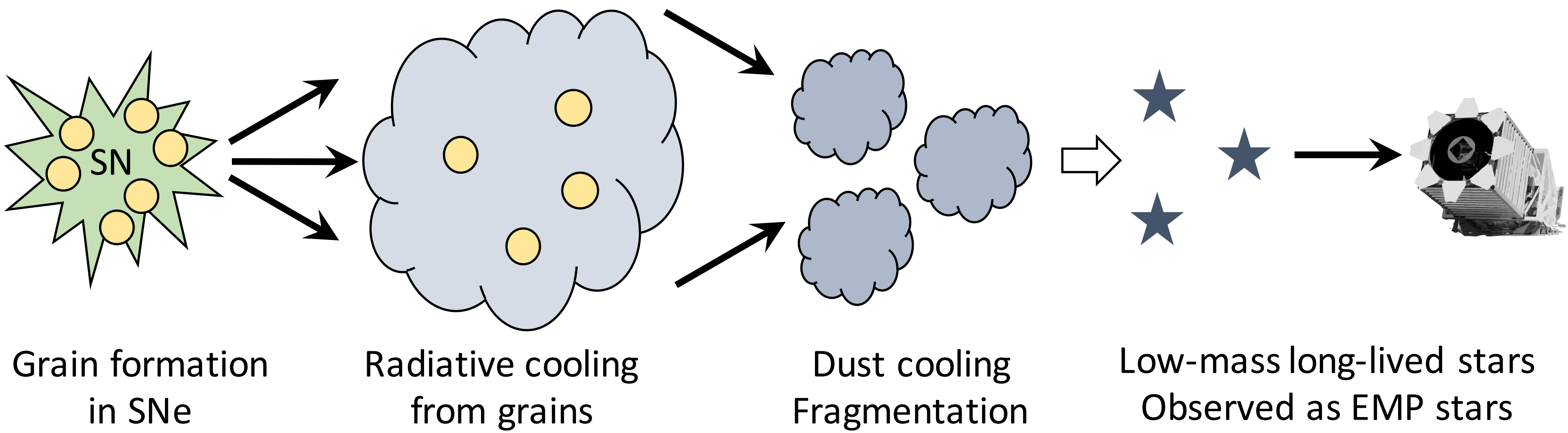
Todini & Ferrara (2001); Matsumoto et al. (2011)



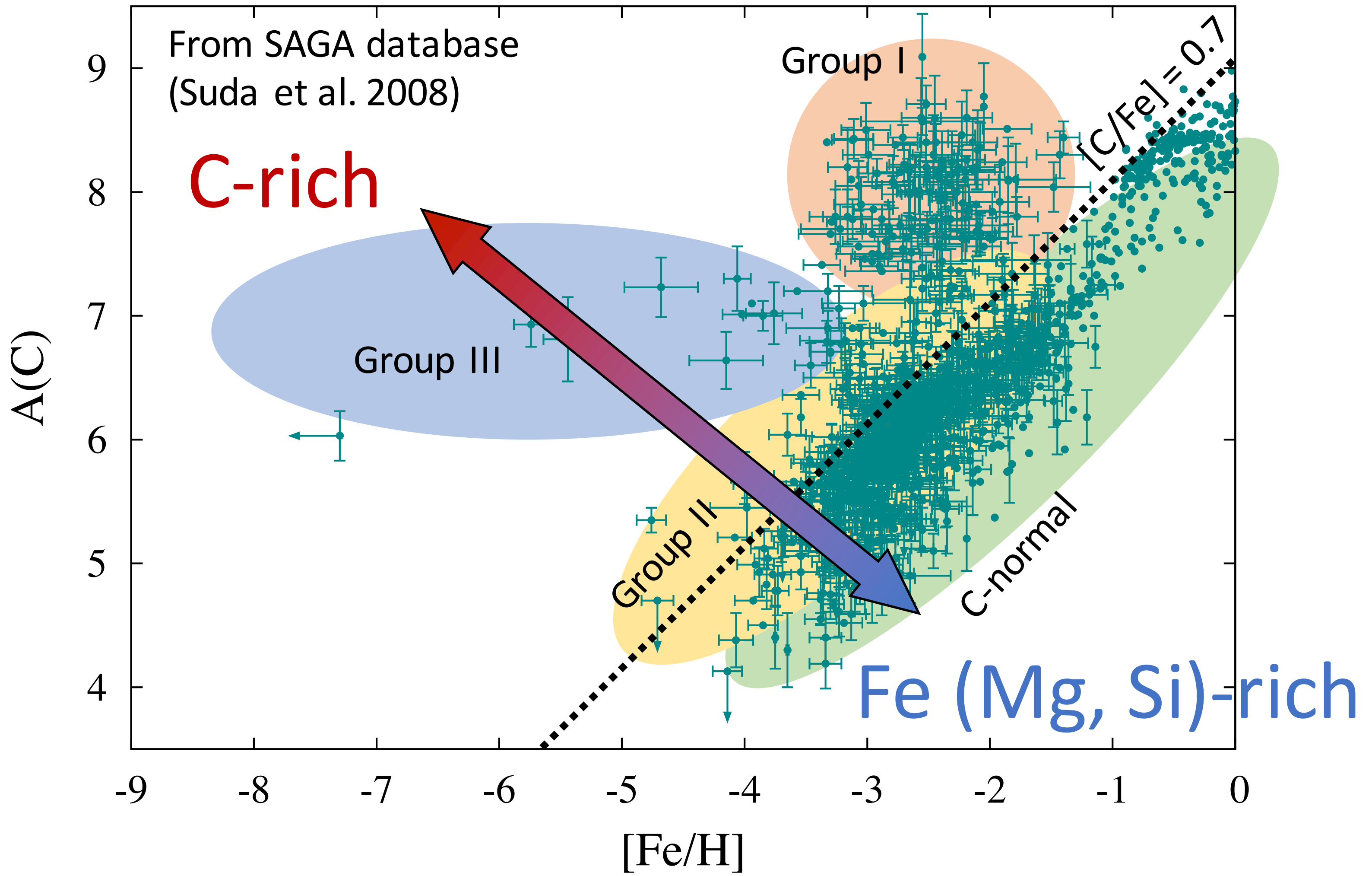
© NASA and Larry Nittler

Role of grains in star formation

Omukai (2000); Schneider et al. (2003)



Origin of CEMP and EMP stars

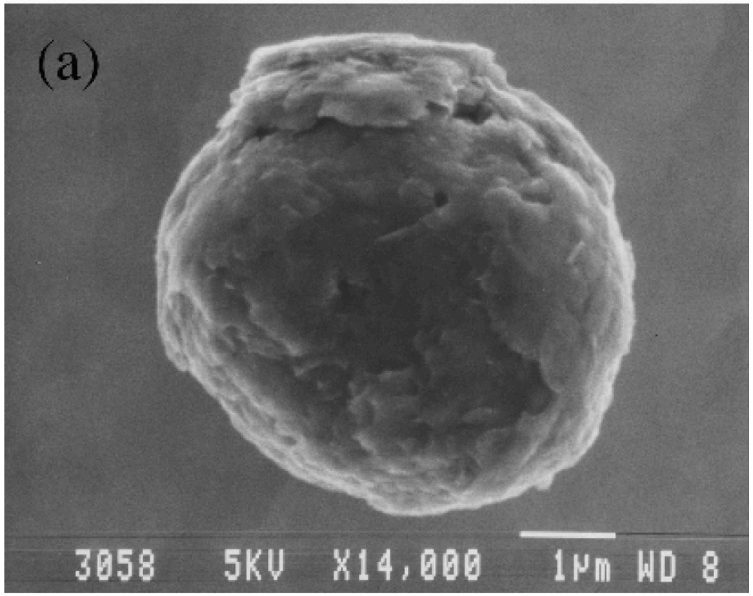


Two major grain species

Todini & Ferrara (2001); Matsumoto et al. (2011)

Carbonaceous grains

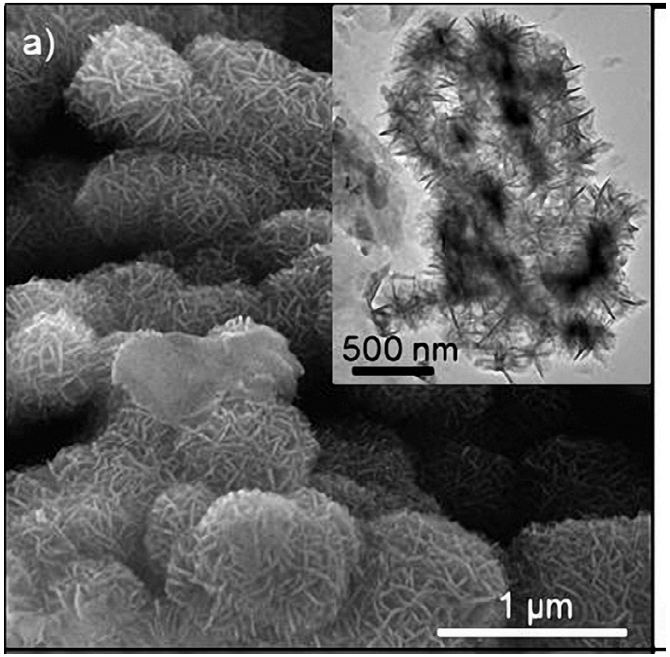
✓Composition: C



Lodders & Amari (2005)

Silicate grains

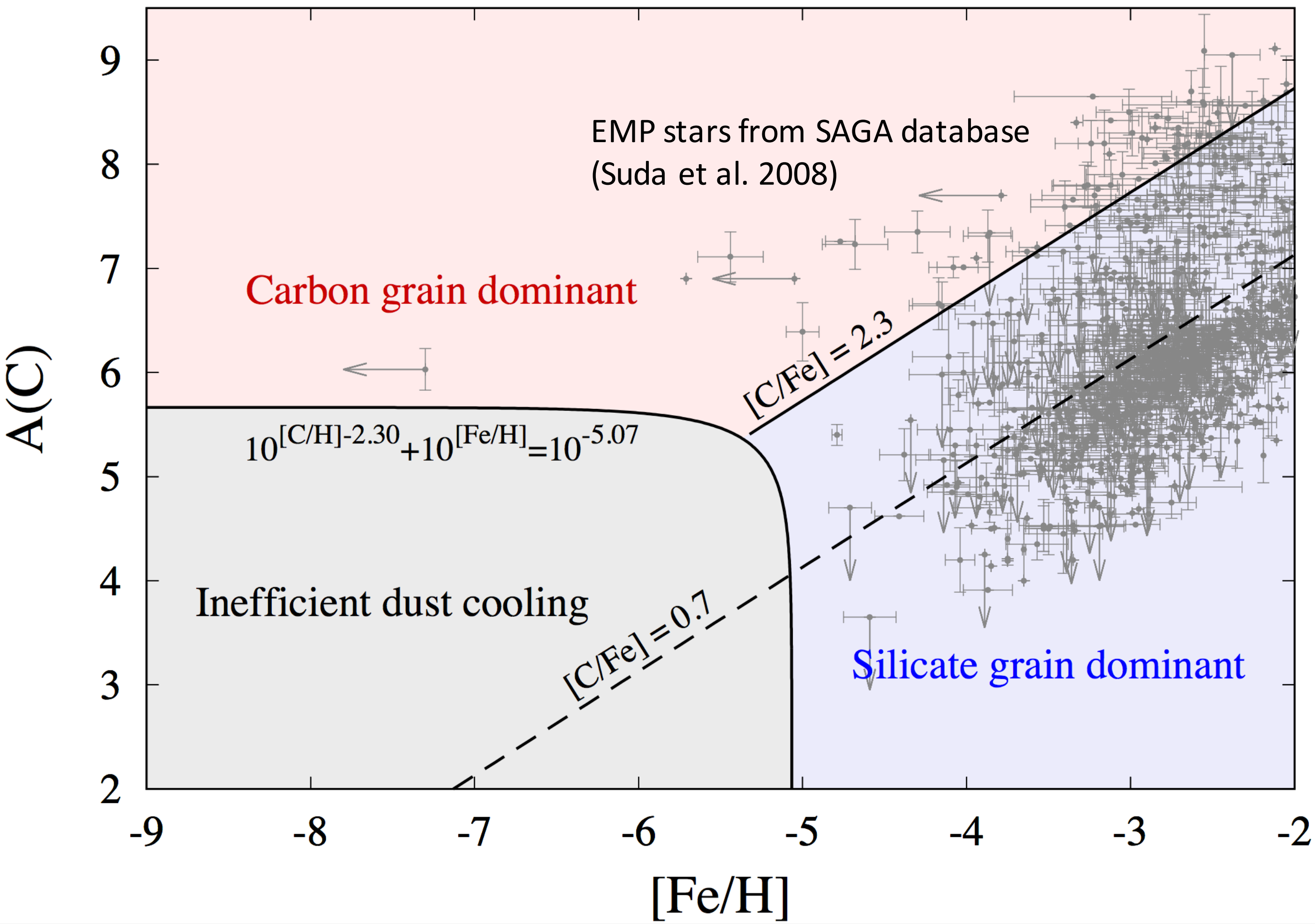
✓Composition: O, Si, Mg, …



Moyce et al. (2015)

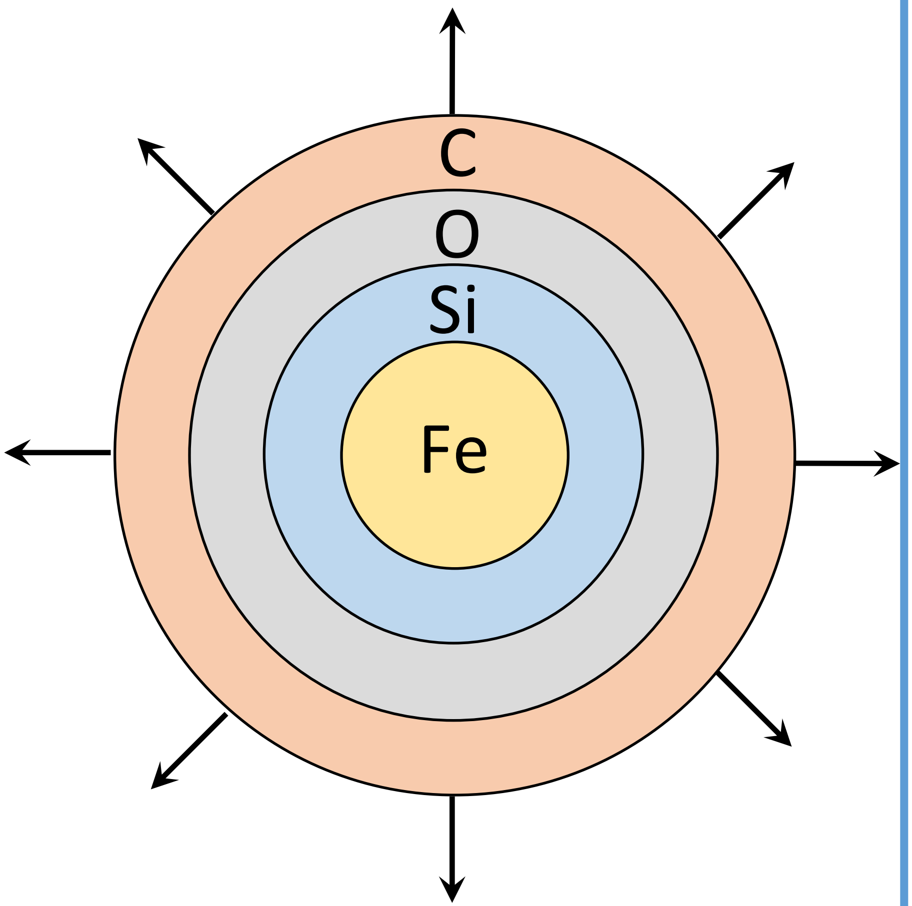
Group II and III star formation through carbon/silicate grains

Chiaki, Tominaga & Nozawa (2017, MNRAS, 472, L115)



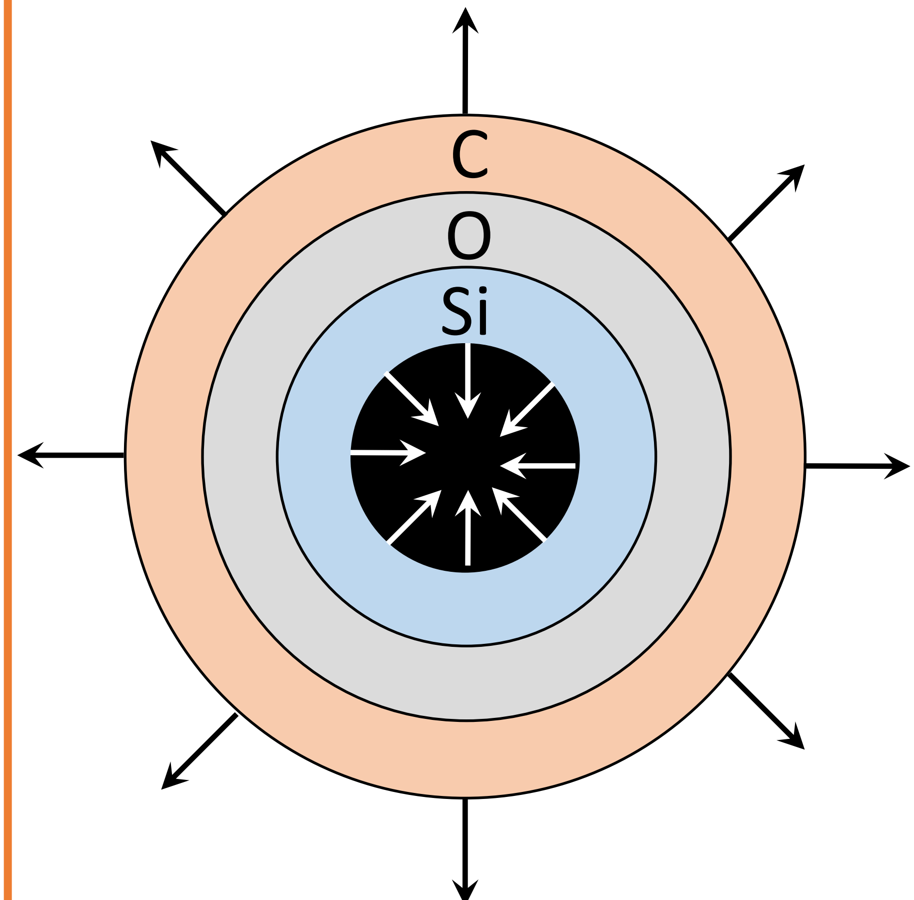
Group II and III CEMP stars

Group II - normal type II

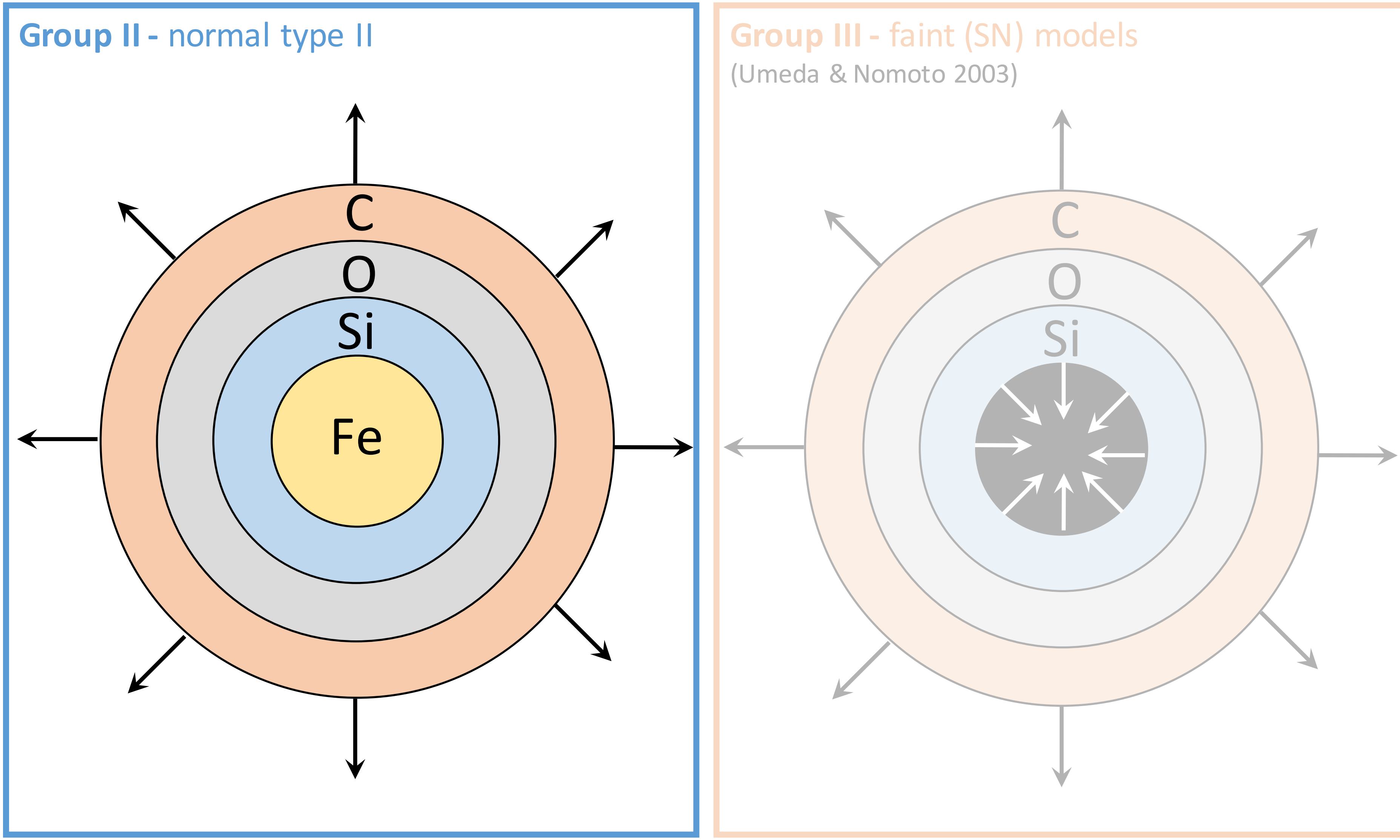


Group III - faint (SN) models

(Umeda & Nomoto 2003)



Normal Type II SNe



Numerical method

AMR/N-body Code

ENZO (Bryan et al. 2014)

Chemistry/cooling

GRACKLE (Smith et al. 2017)

Box size

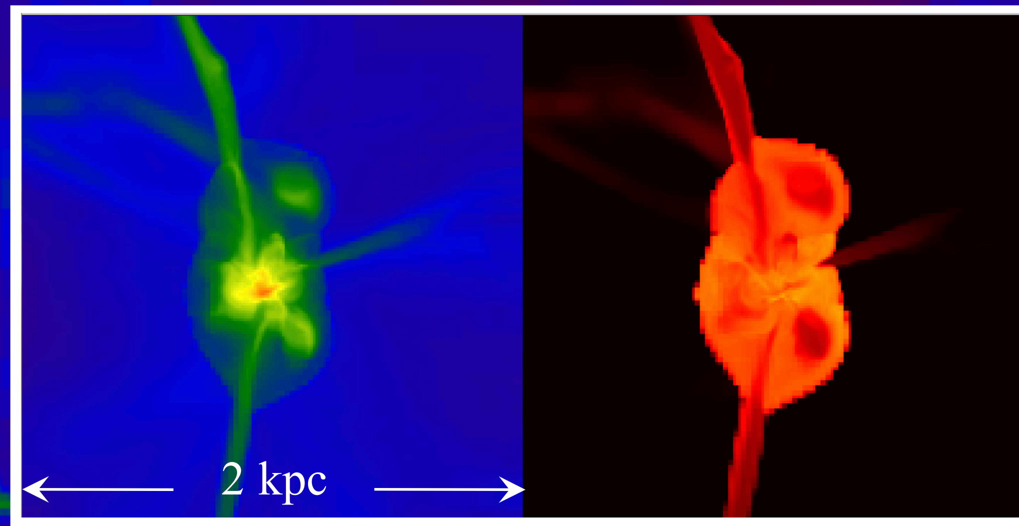
300 ckpc (periodic)

Top grid

64^3

Resolution

Jeans length / 64



Minihalo

✓ $z_{\mathrm{form}} = 12.1$

✓ $R_{\mathrm{halo}} = 287$ kpc

✓ $M_{\mathrm{halo}} = 1.77 \times 10^6\ M_\odot$

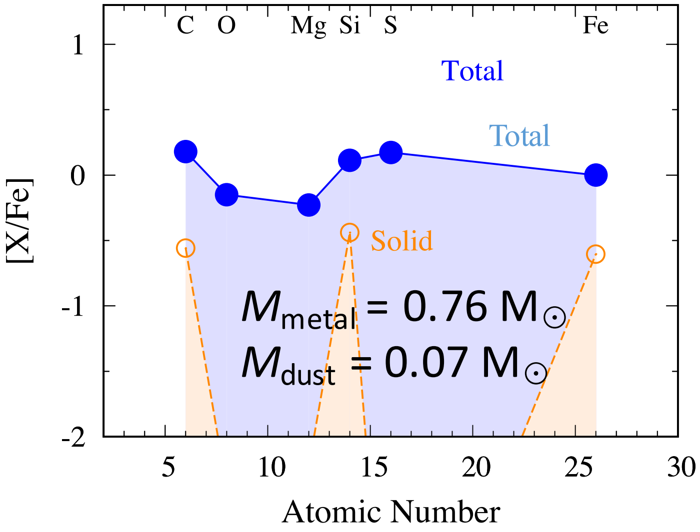
Box size (300 comoving kpc)

Normal Type II SNe

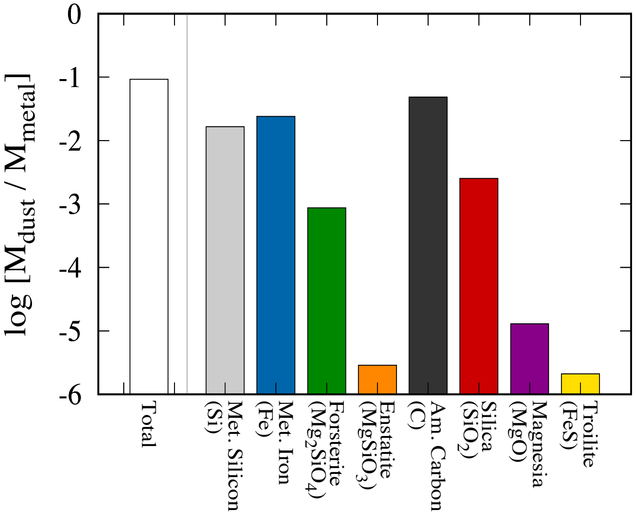
Nozawa et al. (2007)

M_{pr} [M⊙]	E_{SN} [10^{51} erg]	M(met) [M⊙]	M(C) [M⊙]	M(Fe) [M⊙]	M(dust) [M⊙]	M(silicate) [M⊙]
13	1	0.746	0.197	6.98×10^{-2}	6.90×10^{-2}	6.48×10^{-4}

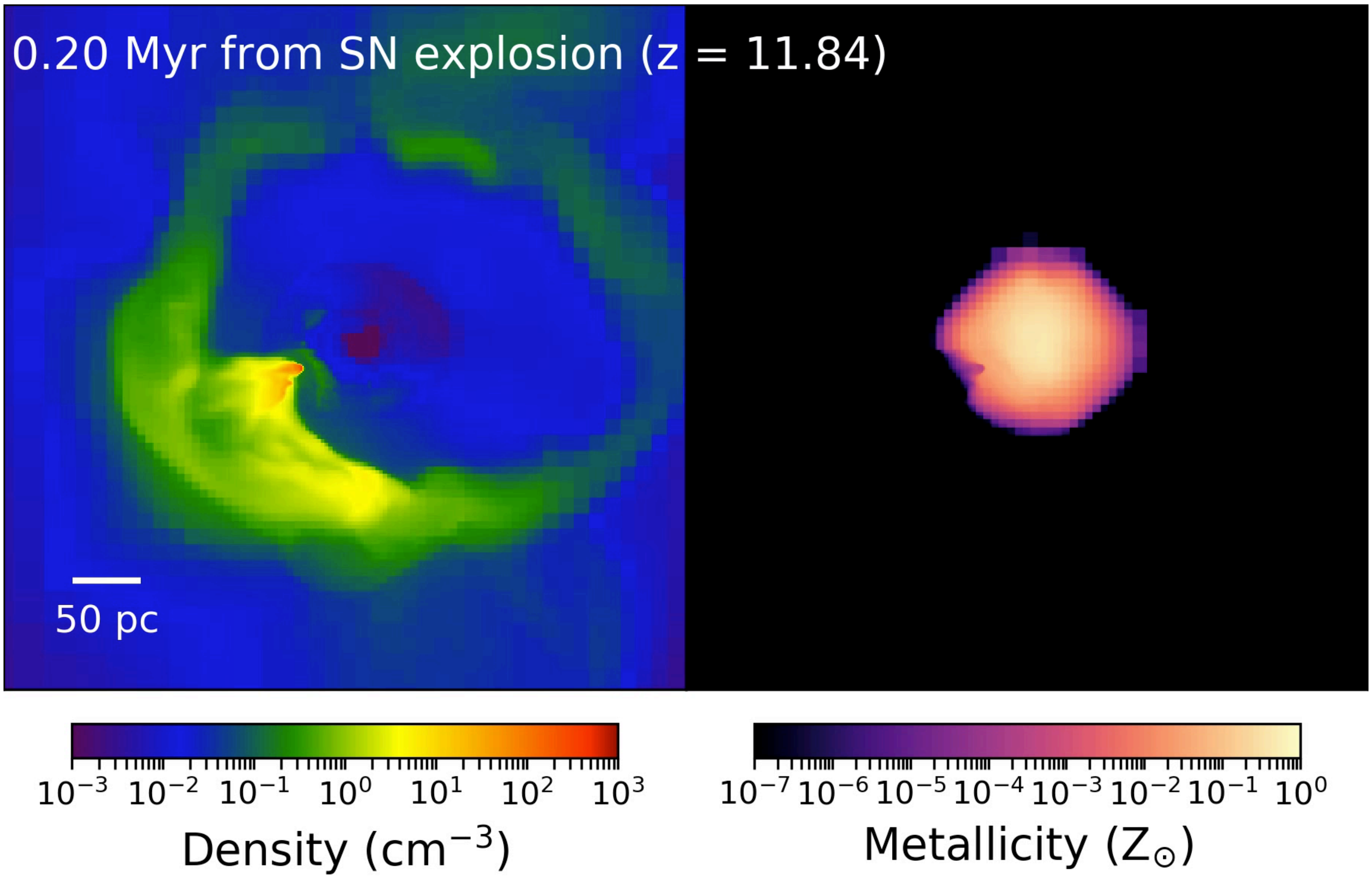
Elemental abundance



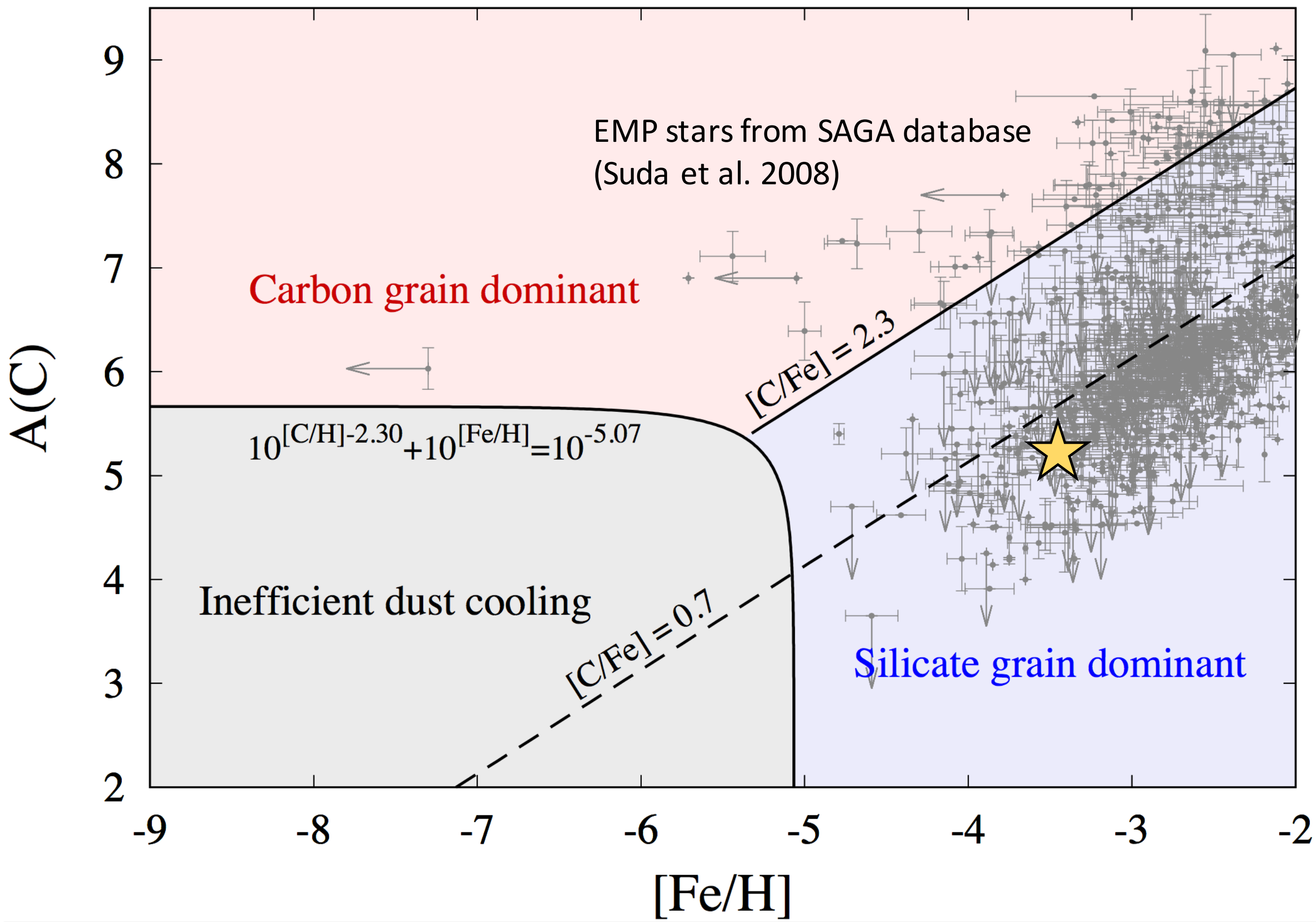
Initial dust abundance



Self-enrichment of the cloud

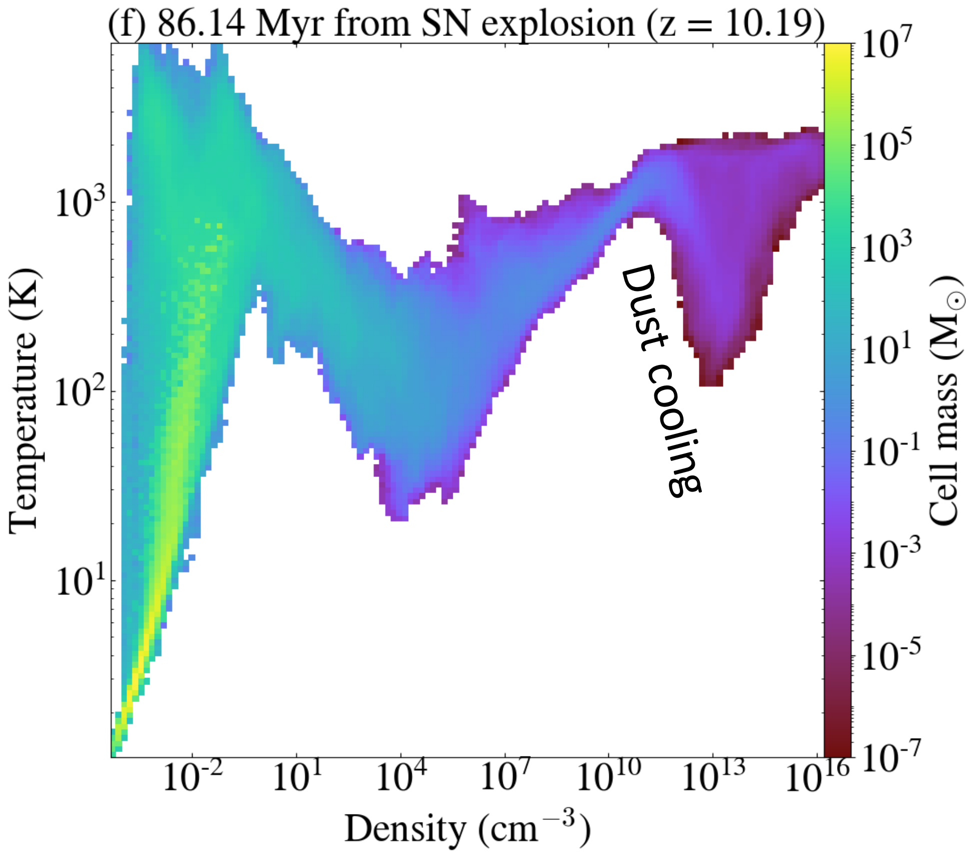


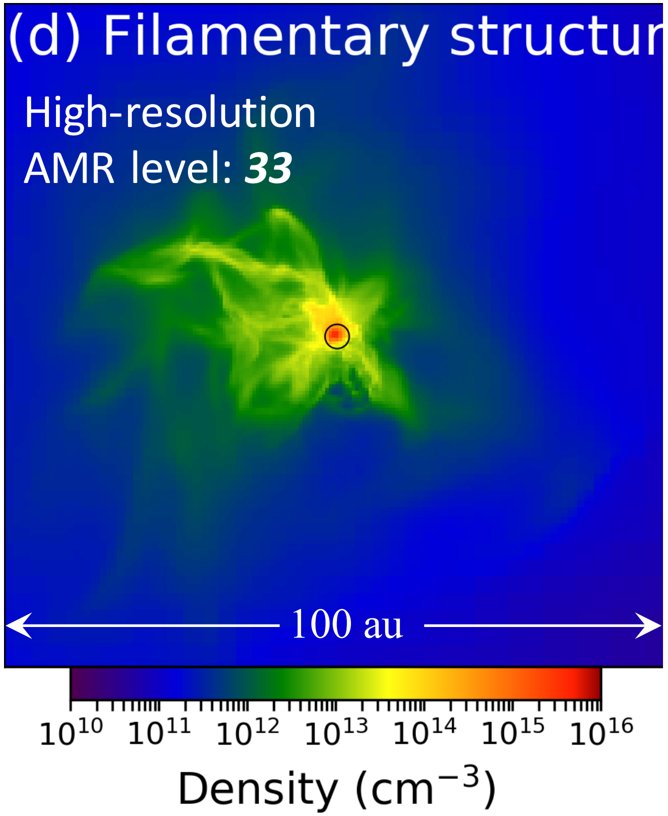
Origin of C-normal stars: Enrichment of normal Type II SNe



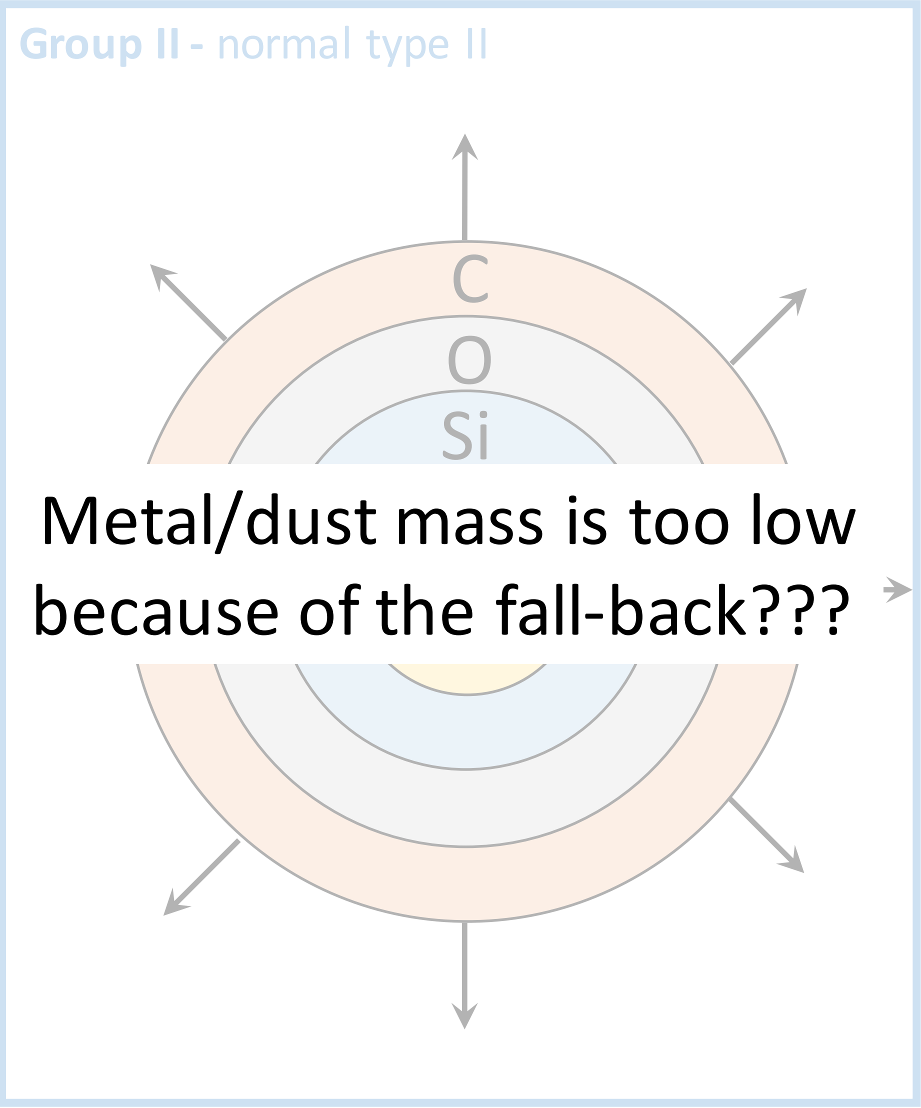
Filamentary structures induced by dust cooling

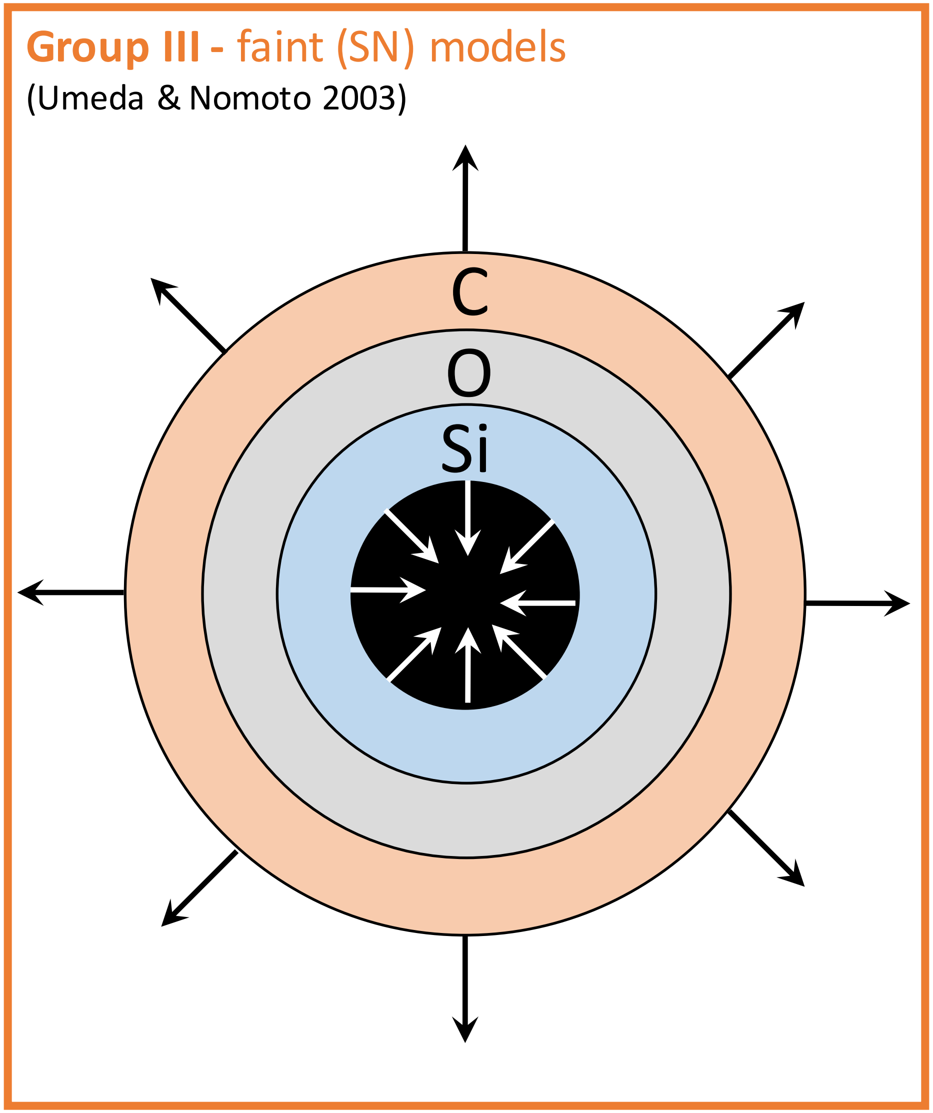
Chiaki & Wise (2019, MNRAS, 482, 3933)





Faint SNe

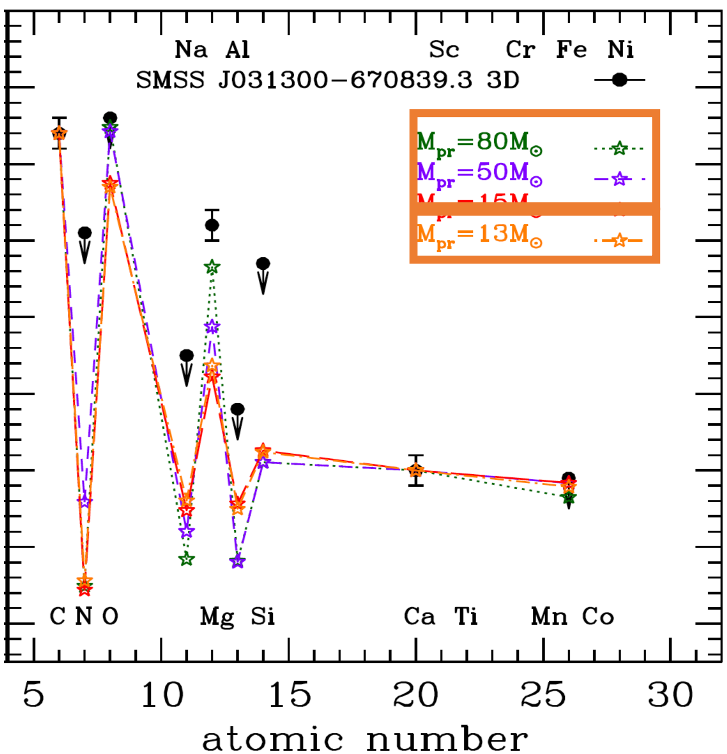

Group II - normal type II
C
O
Si
Metal/dust mass is too low
because of the fall-back???


Group III - faint (SN) models
(Umeda & Nomoto 2003)
C
O
Si

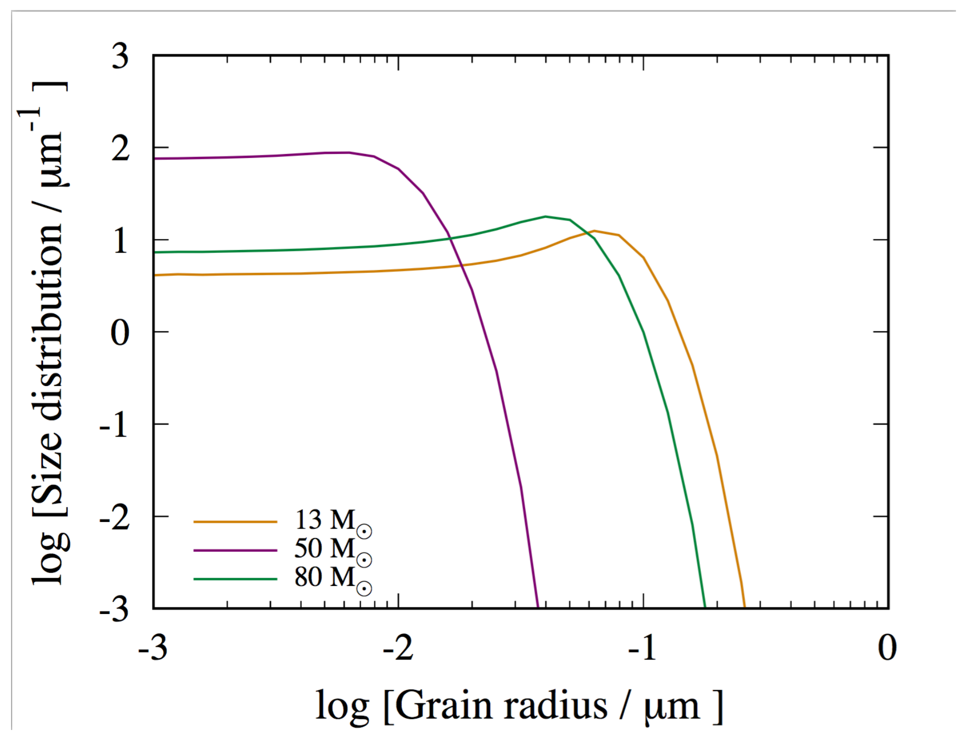
Progenitor models Marassi et al. (2014)

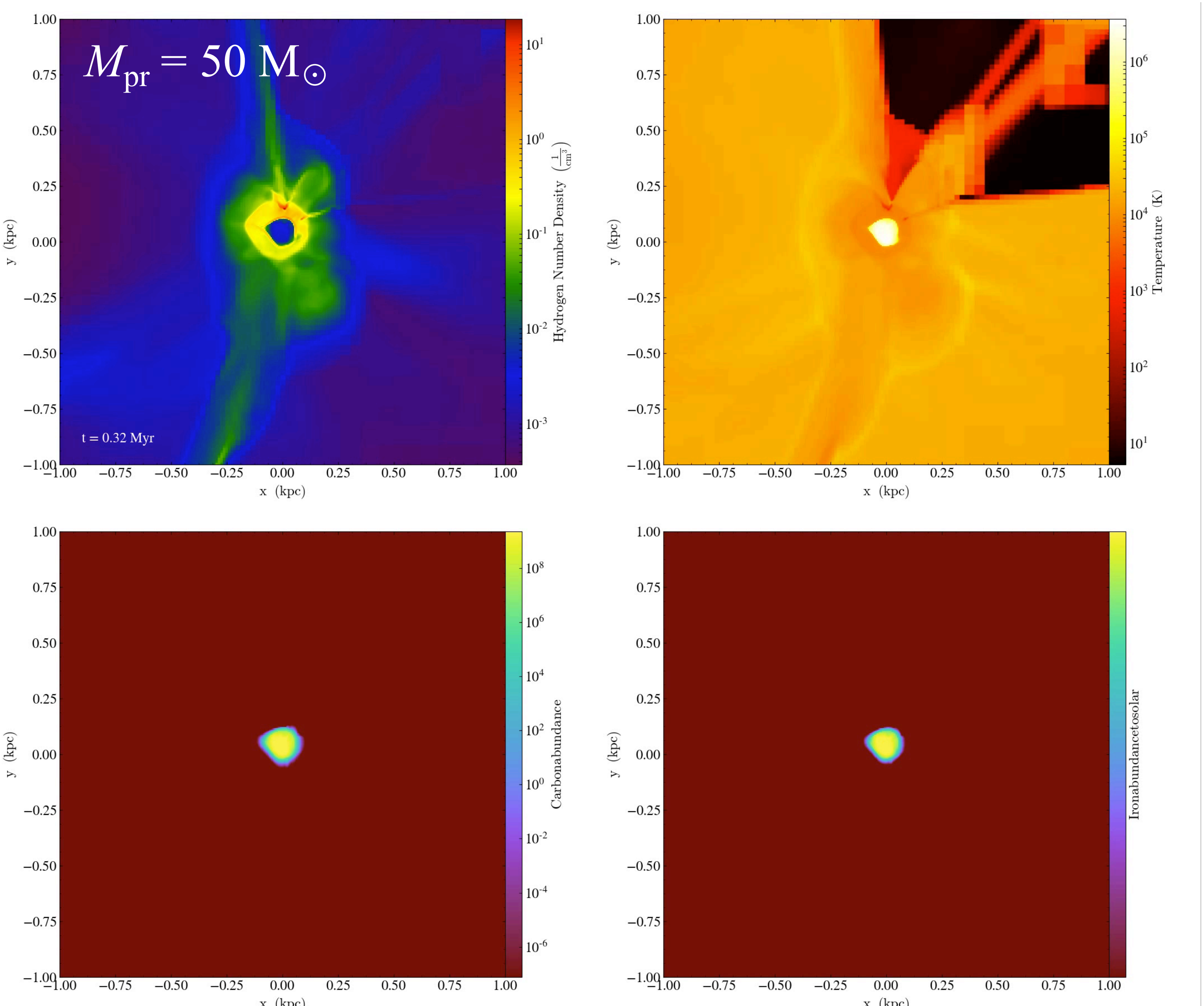
M_{pr} [M⊙]	E_{SN} [10^{51} erg]	M(met) [M⊙]	M(C) [M⊙]	M(O) [M⊙]	M(dust) [M⊙]	M(C,dust) [M⊙]
13	0.5	9.71×10^{-2}	6.50×10^{-2}	3.21×10^{-2}	1.70×10^{-2}	1.70×10^{-2}
50	2.6	3.54	0.988	2.55	3.89×10^{-4}	3.89×10^{-4}
80	5.2	4.31	1.09	3.21	3.74×10^{-2}	3.74×10^{-2}

Elemental abundance



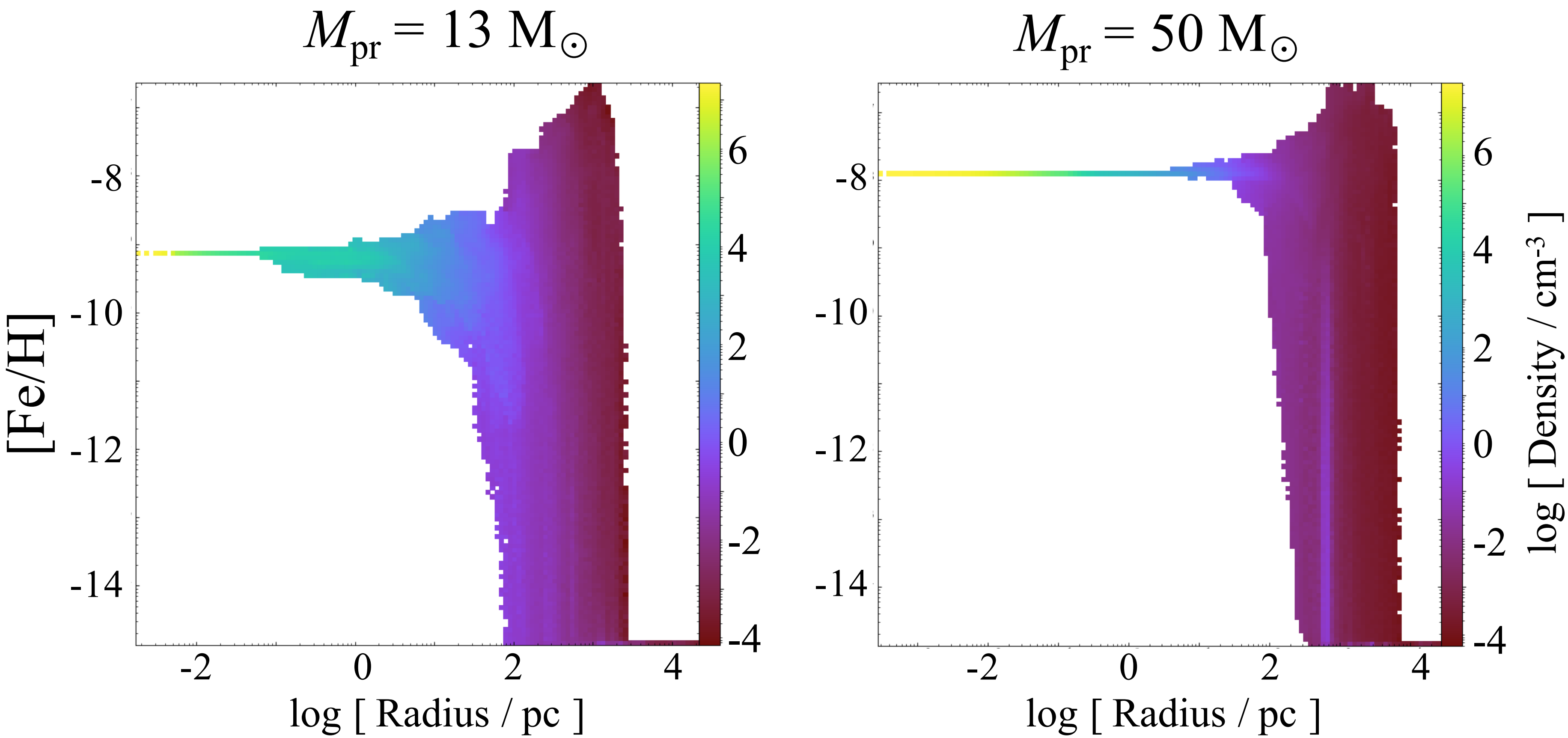
Size distribution of carbon grains





$M_{pr} = 50\ M_\odot$
t = 0.32 Myr
Hydrogen Number Density $\left(\frac{1}{cm^3}\right)$
Temperature (K)
Carbonabundance
Ironabundancetosolar
x (kpc)
y (kpc)

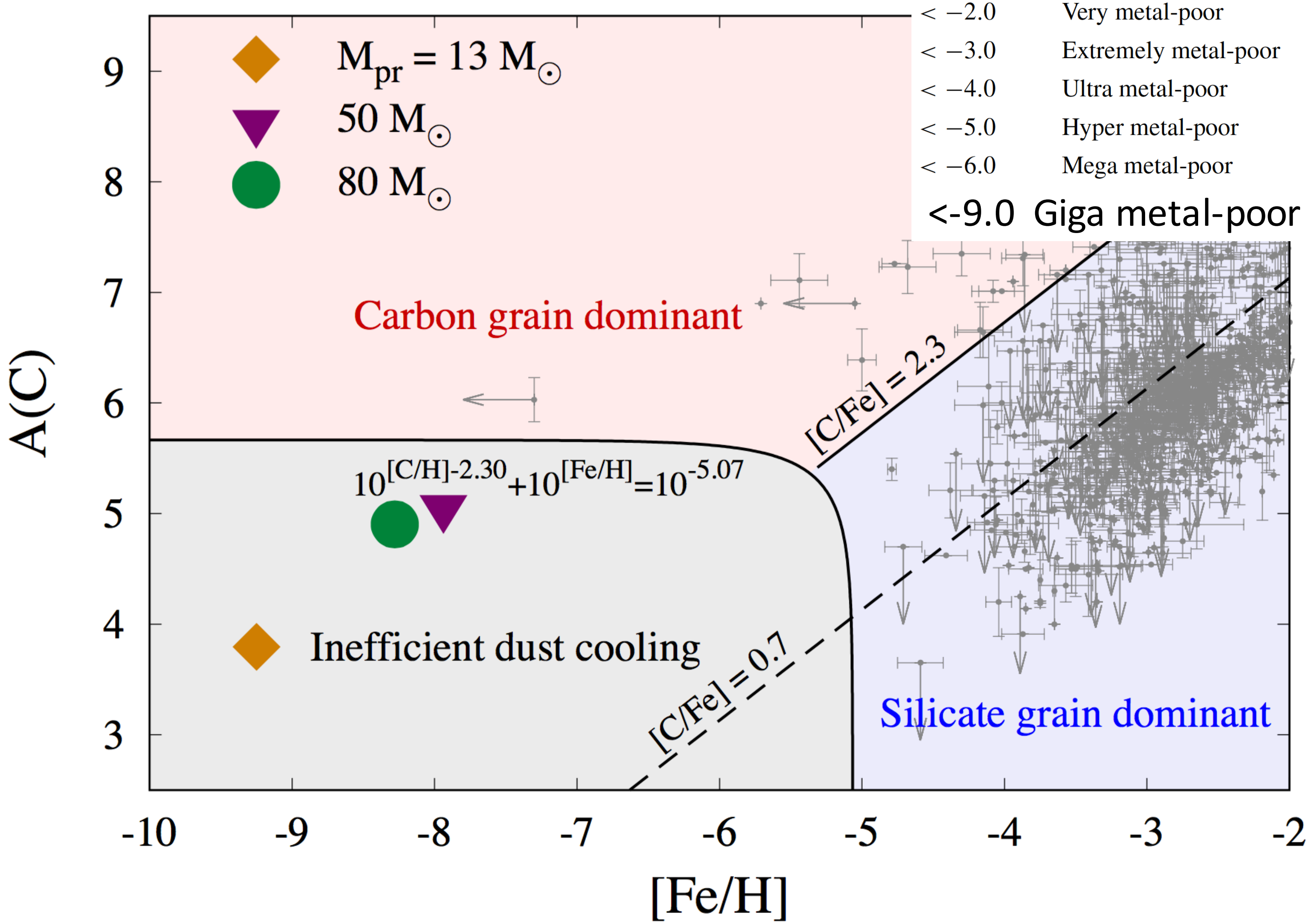
Metallicity distribution in recollapsing clouds



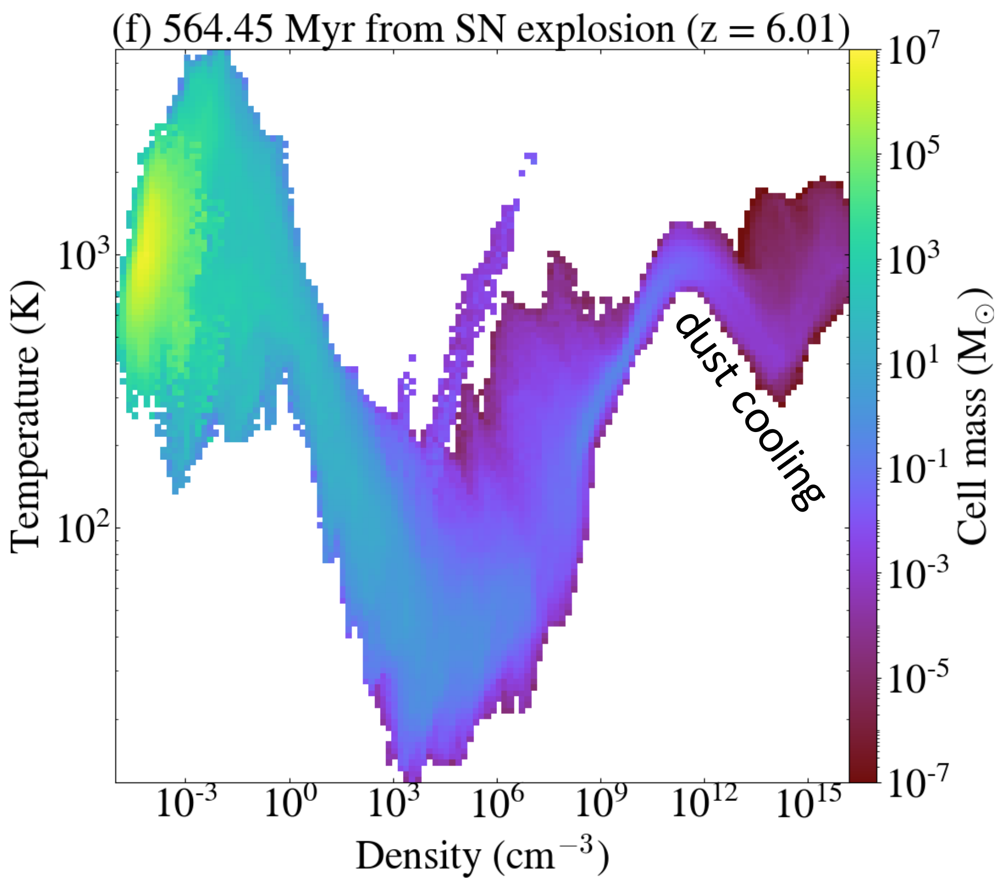
Resulting metallicity

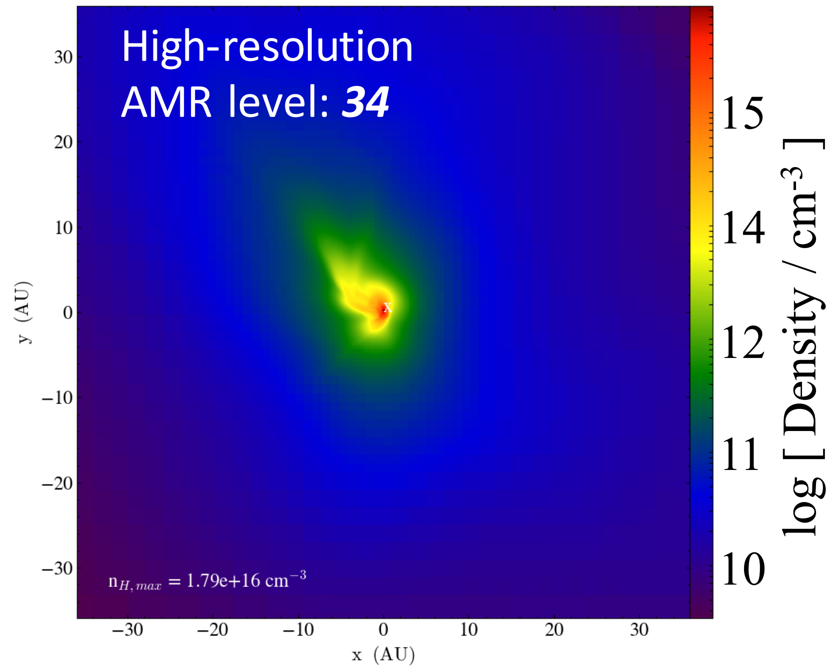
Beers & Christlieb (2005)

[Fe/H]	Term	Acronym
$> +0.5$	Super metal-rich	SMR
~ 0.0	Solar	—
< -1.0	Metal-poor	MP
< -2.0	Very metal-poor	VMP
< -3.0	Extremely metal-poor	EMP
< -4.0	Ultra metal-poor	UMP
< -5.0	Hyper metal-poor	HMP
< -6.0	Mega metal-poor	MMP
<-9.0	Giga metal-poor	GMP



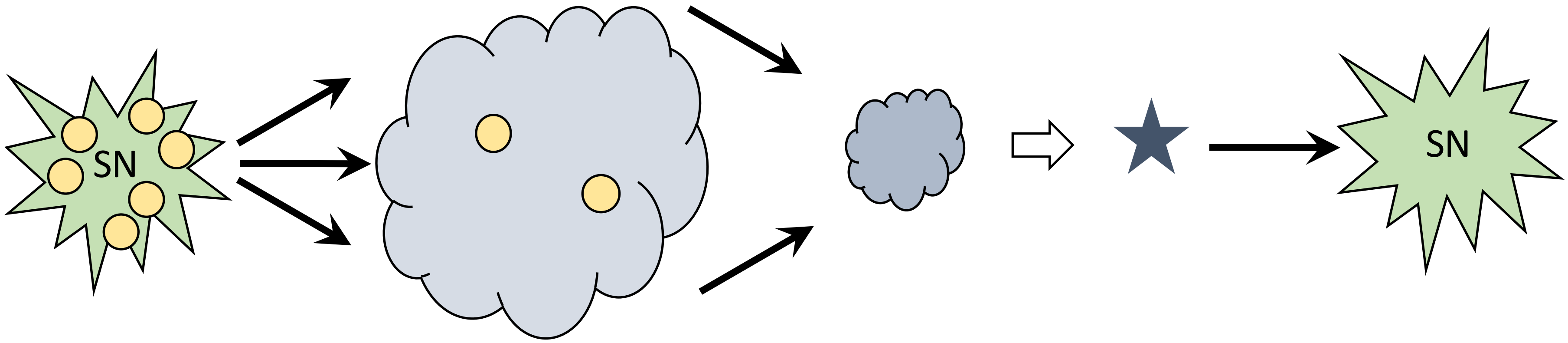
Poor dust cooling
The cloud collapses stably.





Role of grains in star formation

Omukai (2000); Schneider et al. (2003)



Grain formation in SNe

Metal/dust-poor cloud

Collapse stably against frag.

Massive star formation

Too short lifetime to be observed

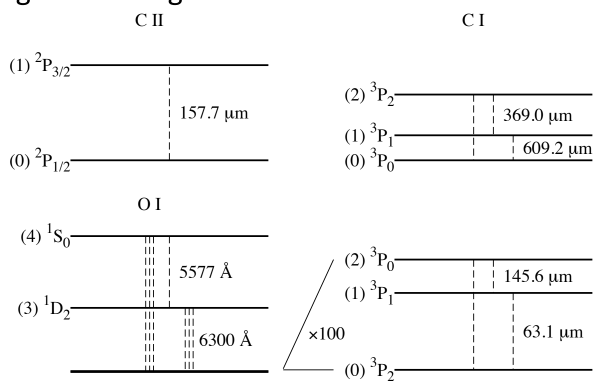
Conclusion

- What is the origin of CEMP stars?
- Can enrichment from a single faint SN explain this?
  - ➢ NO
- Metallicity in the self-enriched halo is too small.
    - A(C) = 3.80-5.06 for M_{pr} = 13-80 $M_{\odot}$
  - ➢ Clouds collapse stably against fragmentation.
  - ➢ Massive stars which can not survive will form.
- Enrichment more than twice is required.
  - multi-enrichment (Tilman's talk)
- Or other mechanisms
  - binary transfer (Suda et al. 2004)
  - spinstar (Meynet et al. 2006; Arthur's talk)
  - jet-like SNe (Tominaga et al. 2009; Rana's talk)

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
Huge reaction networks

48 primordial chemistry

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

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

H_2 formation on grain

$2H + \text{grain} \to H_2$

38 metal chemistry

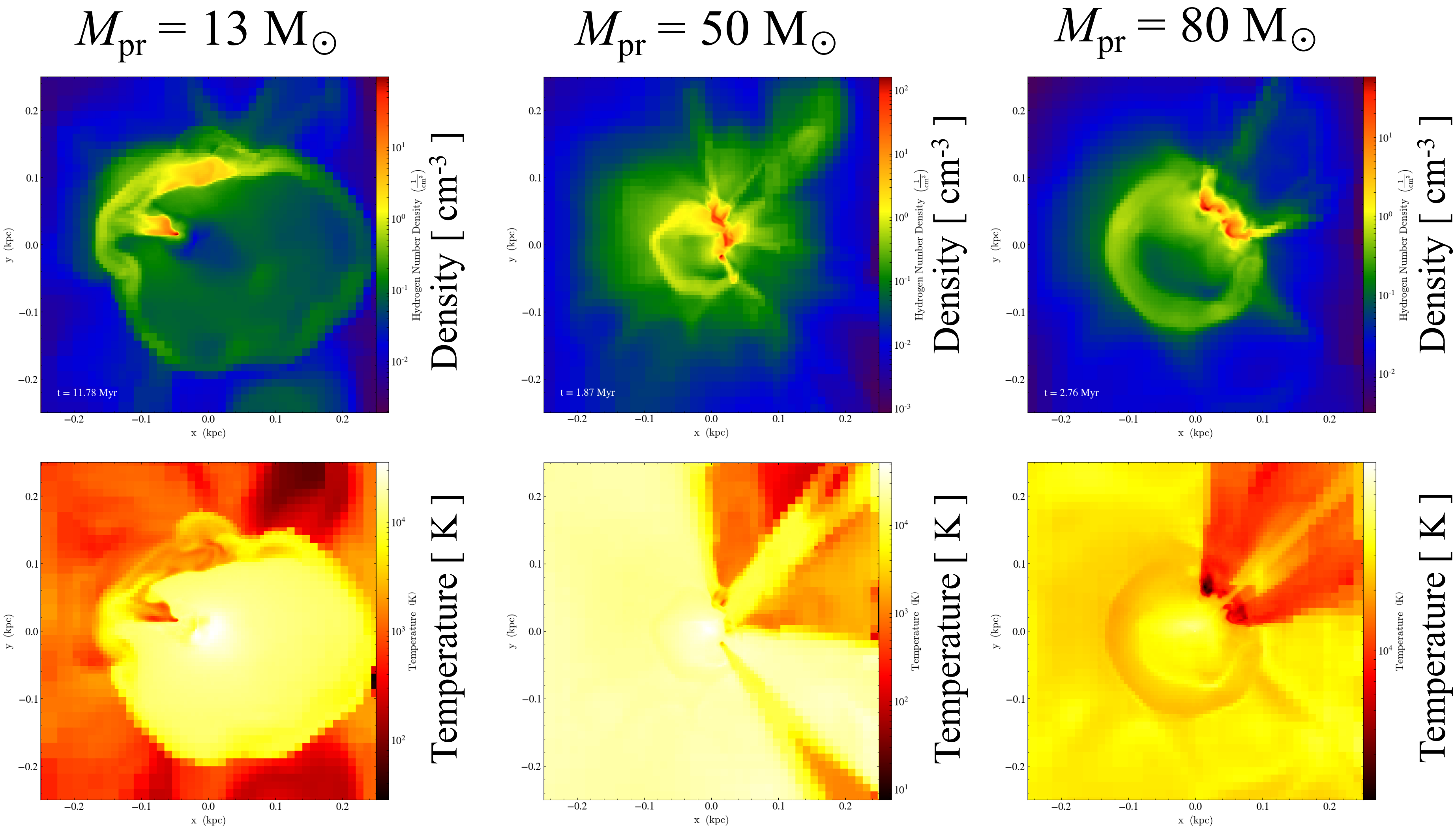
$H + CH \to C + H_2$
$H + CH_2 \to CH + H_2$
$H + OH \to H_2 + O$
$H + H_2O \to OH + H_2$
$H + O_2 \to OH + O$
$C + H_2 \to CH + H$
$O + H_2 \to OH + H$
$H^+ + O \to O^+ + H$
$H_2 + CH \to CH_2 + H$
$H_2 + OH \to H_2O + H$
$2OH \to H_2O + O$
$OH + CO \to CO_2 + H$
$C + H \to CH + \gamma$
$C + OH \to CO + H$
$C + O_2 \to CO + O$
$O + H \to OH + \gamma$
$2O \to O_2 + \gamma$
$O + CH \to CO + H$
$O + OH \to O_2 + H$
$H^+ + OH \to OH^+ + H$
$H^+ + H_2O \to H_2O^+ + H$

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

10 grain growth reactions

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

Formation of H II region



Collapse of enriched cloud with $M_{pr} = 80\ M_\odot$