初代星超新星による金属汚染と金属欠乏星形成

Metal pollution by Pop III supernovae and formation process of Pop II stars

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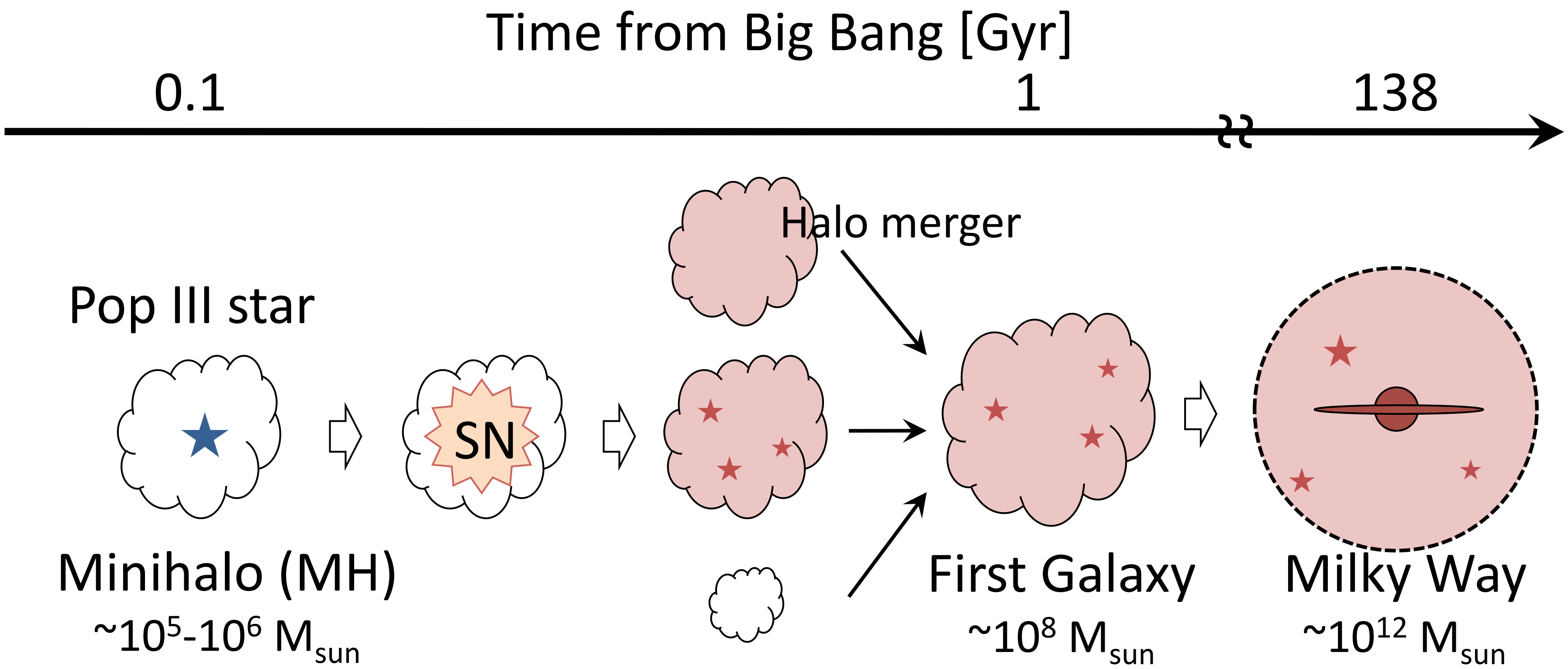
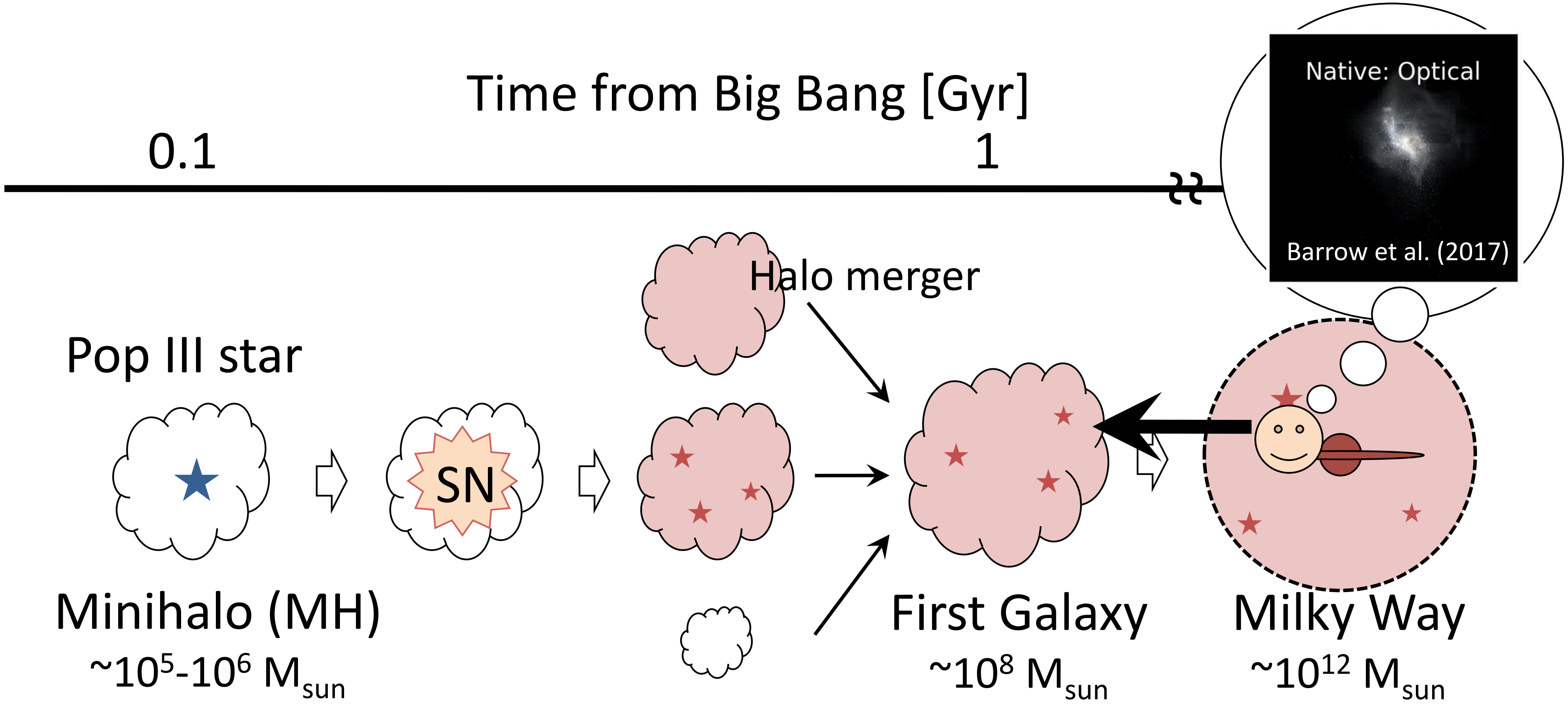
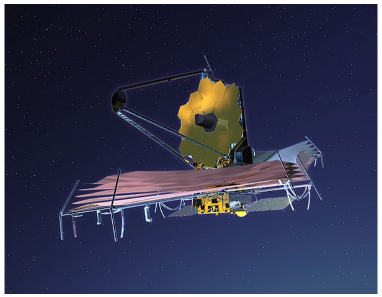
Final goal: to know the IMF and metal enrichment of early stars & galaxies



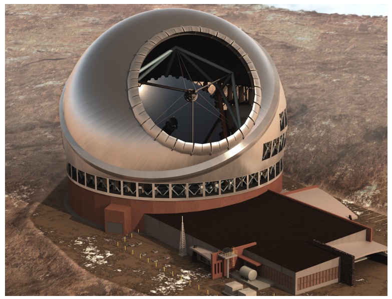
Approach1: Direct observation

(Wise et al. 2012; Xu et al. 2013; Kirk et al. 2017, 2018)

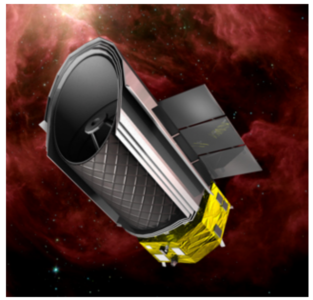




JWST



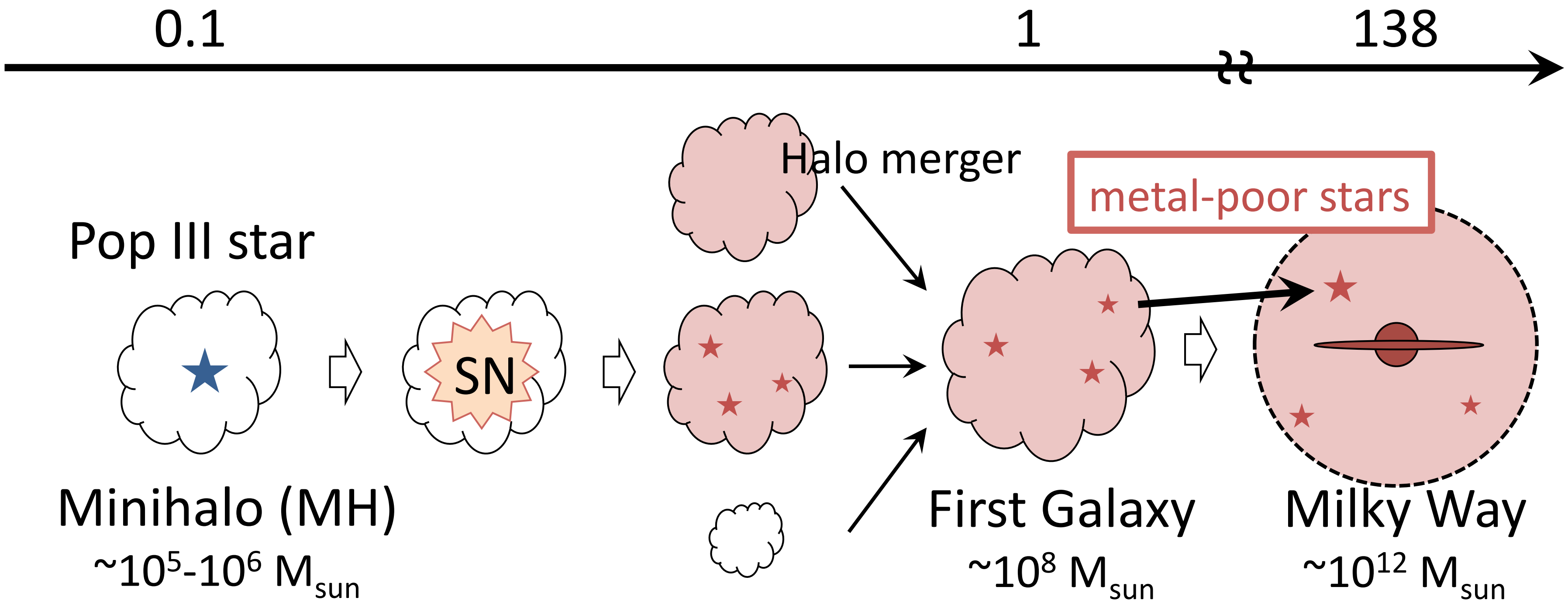
TMT



SPICA

Approach 2: To see ancient metal-poor stars in our vicinity

(Komiya et al. 2016, 2017; Ishiyama et al. 2016; Hartwig et al. 2015, 2018)



Near-field Cosmology

Galactic Archaeology

See Suda–san's talk

So far, 1400 metal-poor stars with [Fe/H]<−3 have been observed

Extremely metal-poor (EMP) stars

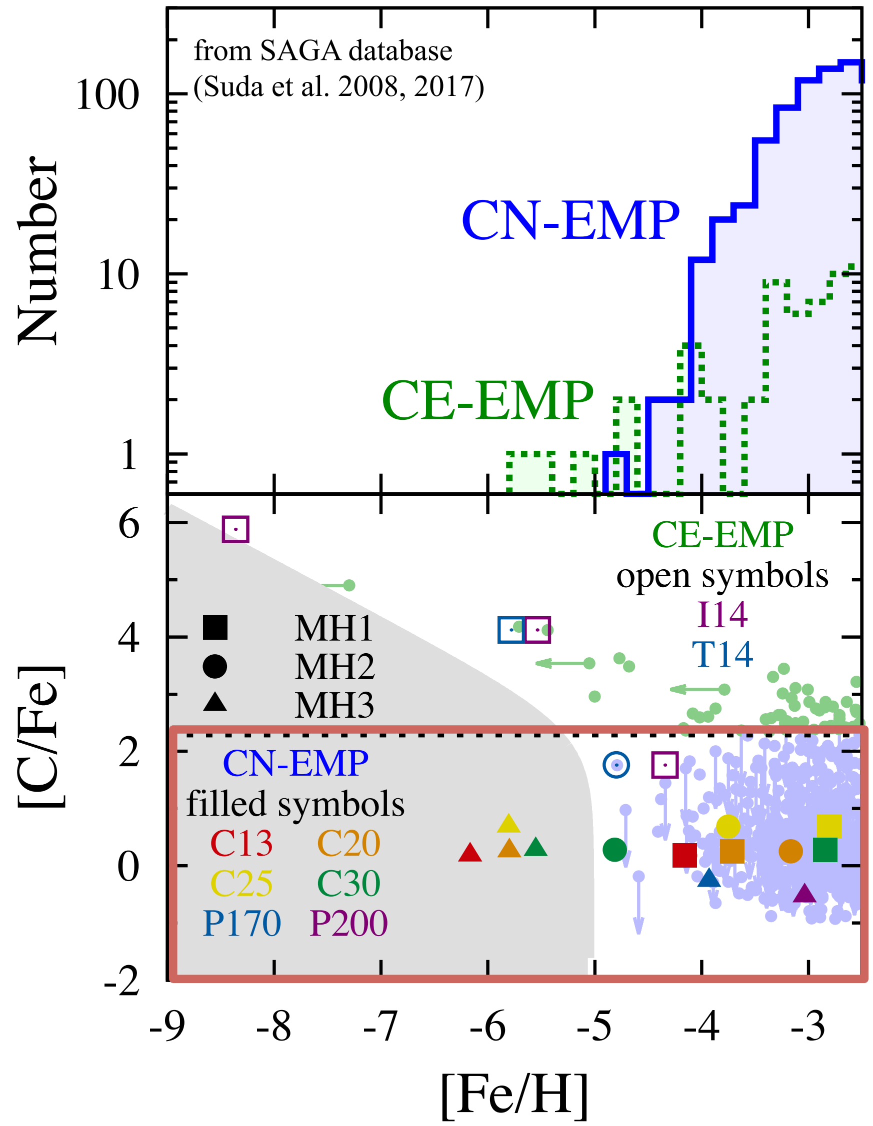
✓[Fe/H] < −3

✓considered to be formed in clouds enriched by a single or several SNe

(Ryan et al. 1996; Cayrel et al. 2004; Tilman's talk)

✓Classification

- ✓C-enhanced EMP (CE-EMP) stars
  [C/Fe] > 2.30
- ✓C-normal EMP (CN-EMP) stars
  [C/Fe] < 2.30

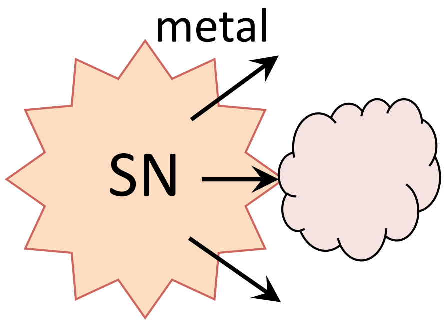


There are two enrichment processes. Which is dominated?

External Enrichment (EE)

Enrichment of neighboring halos

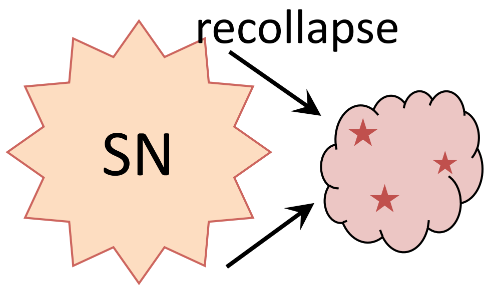
(Smith et al. 2015; Chen et al. 2016)



Internal Enrichment (IE)

Self-enrichment of Pop III star forming halo

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



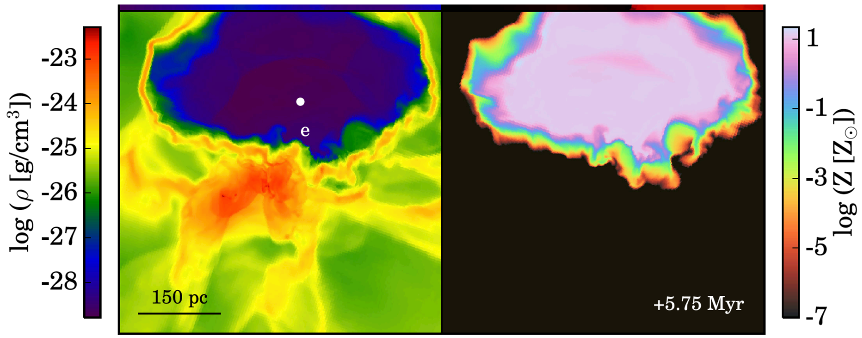
External enrichment (EE)

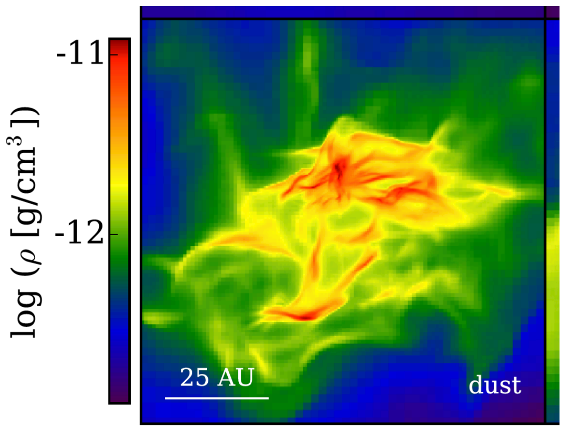
Smith et al. (2015)

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

✓Cosmological initial condition

✓Z = 2×10^5 $Z_\odot$





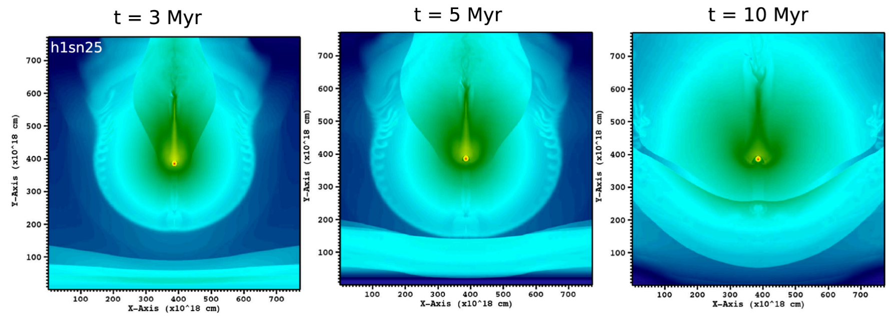
Cloud fragmentation by dust cooling

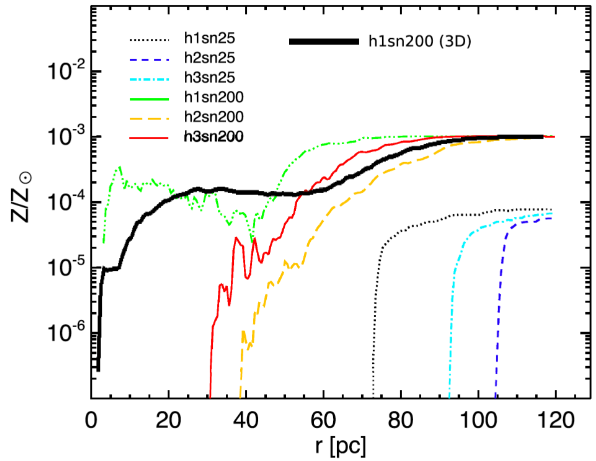
Chen et al. (2017)

✓M_{PopIII} = 25-200 $M_\odot$

✓Ideal initial conditions

✓Z = 2×10^5 $Z_\odot$





Metals do not penetrate into cloud center.

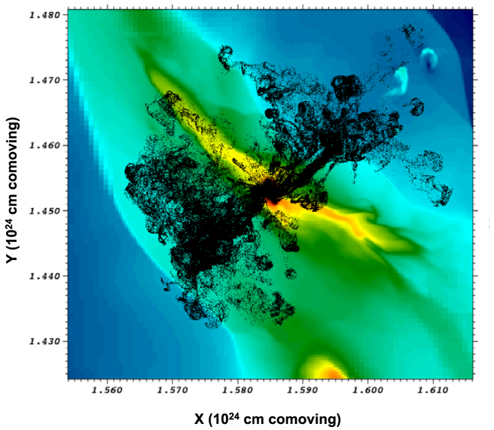
Internal enrichment (IE)

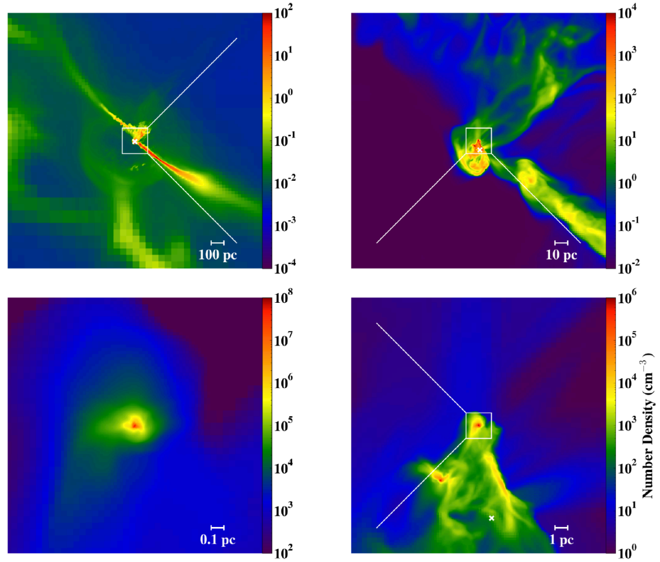
Ritter et al. (2012, 2015, 2016); Sluder et al. (2015)

✓ $(M_{\rm PopIII}, M_{\rm halo}) = (60\ M_\odot, 1\times10^6\ M_\odot)$

✓ Cosmological initial condition

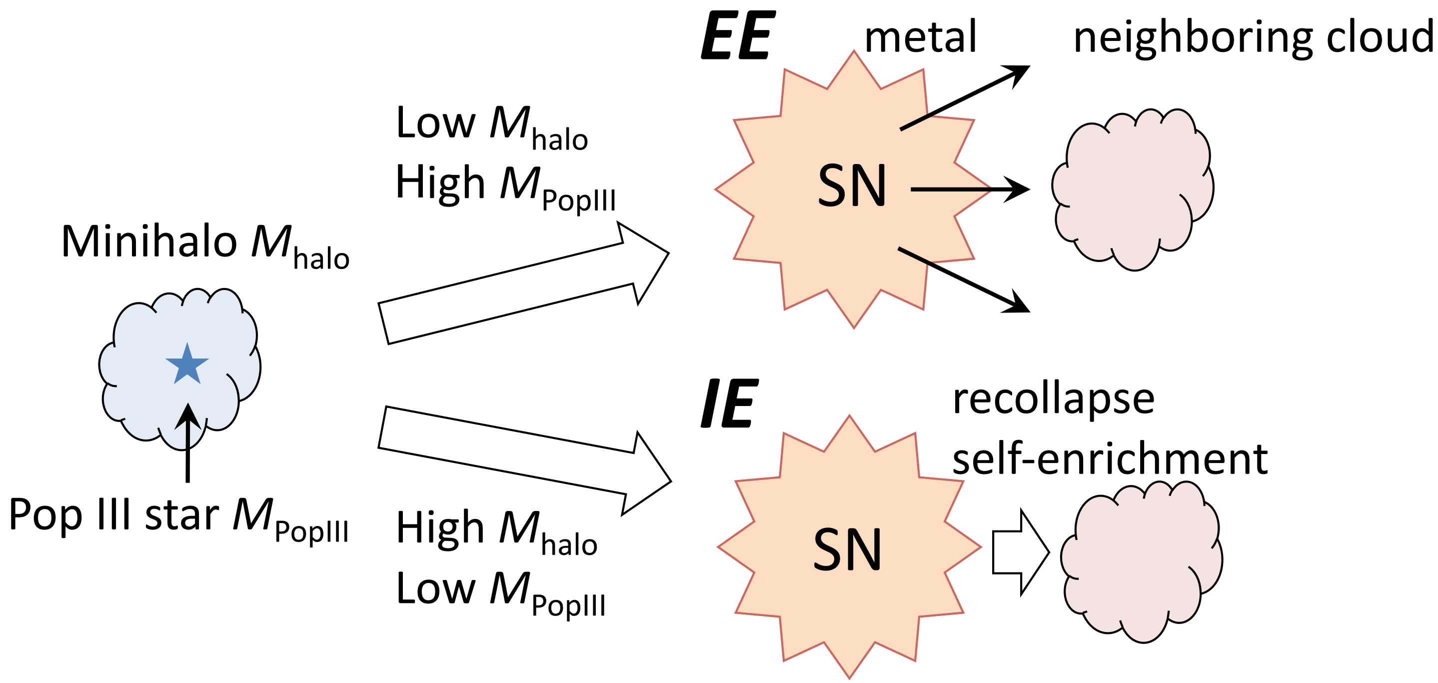
✓ $Z = 0.001\text{-}0.01\ Z_\odot$





However, earlier studies perform simulations with a single combination of $(M_{\rm PopIII}, M_{\rm halo})$.

Either EE or IE happens, depending on M_{halo} and M_{PopIII}

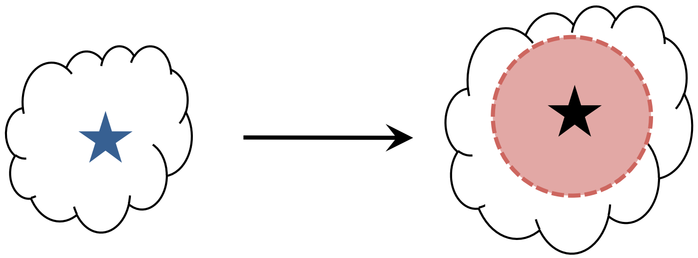


✓What is he condition for EE/IE?

✓Which mode IE or EE is dominant?

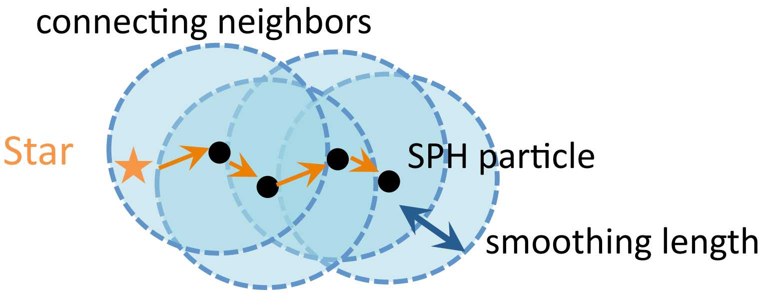
Numerical method

1. formation of H II region

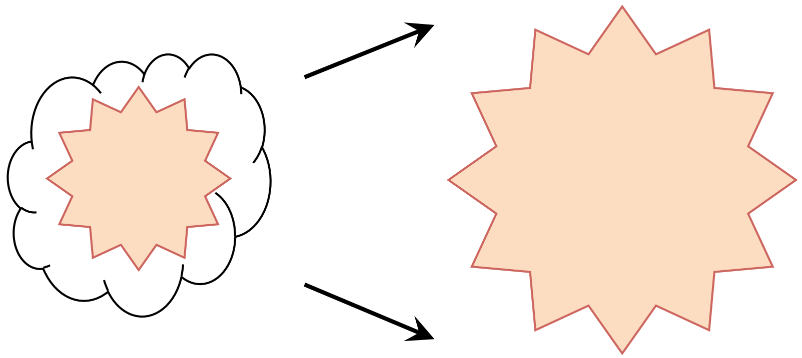


Followed until the lifetime t_{life} of Pop III stars

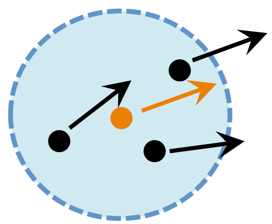
Radiation transfer (Susa 2006)



2. SN explosion + metal pollution



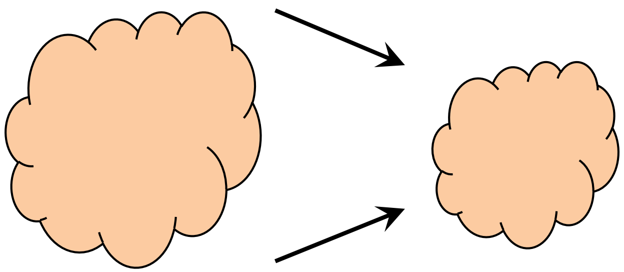
Thermal energy is added to 200 SPH particles around the Pop III star.



- We follow metal dispersion with tracer particles.
- Their velocity is interpolated from four neighboring SPH particles

Numerical method

3. Recollapse of Pop II cloud



We follow the recollapse of enriched clouds until the central density reaches to 10^3 /cc again.

- GADGET-2 (Springel 2005)
- Non-eq. chemistry
  15 species
  e, H, H^+, H_2, H^-, H_2^+, HeH^+, He, He^+, He^{2+}, D, D^+, D^-, HD, and HD^+
  55 reactions including
  $H + \gamma \rightarrow H^+ + e$
  $H_2 + \gamma \rightarrow H + H$
- Radiative cooling
  H_2, HD ro-vib. cooling
  H, He, He^+ line, ion./rec. cooling
  Brems, & Compton
- Heating by ionizing photons

Wide range of M_{halo} and M_{PopIII} for initial conditions

Minihalos

	Halo	$M_{\mathrm{halo}}^{\mathrm{col}}$ [$M_\odot$]	$R_{\mathrm{halo}}^{\mathrm{col}}$ [pc]	z_{col}
LH	MH1	2.94e5	70.12	28.47
	MH2	3.89e5	79.52	27.52
HH	MH3	3.23e6	186.85	23.58

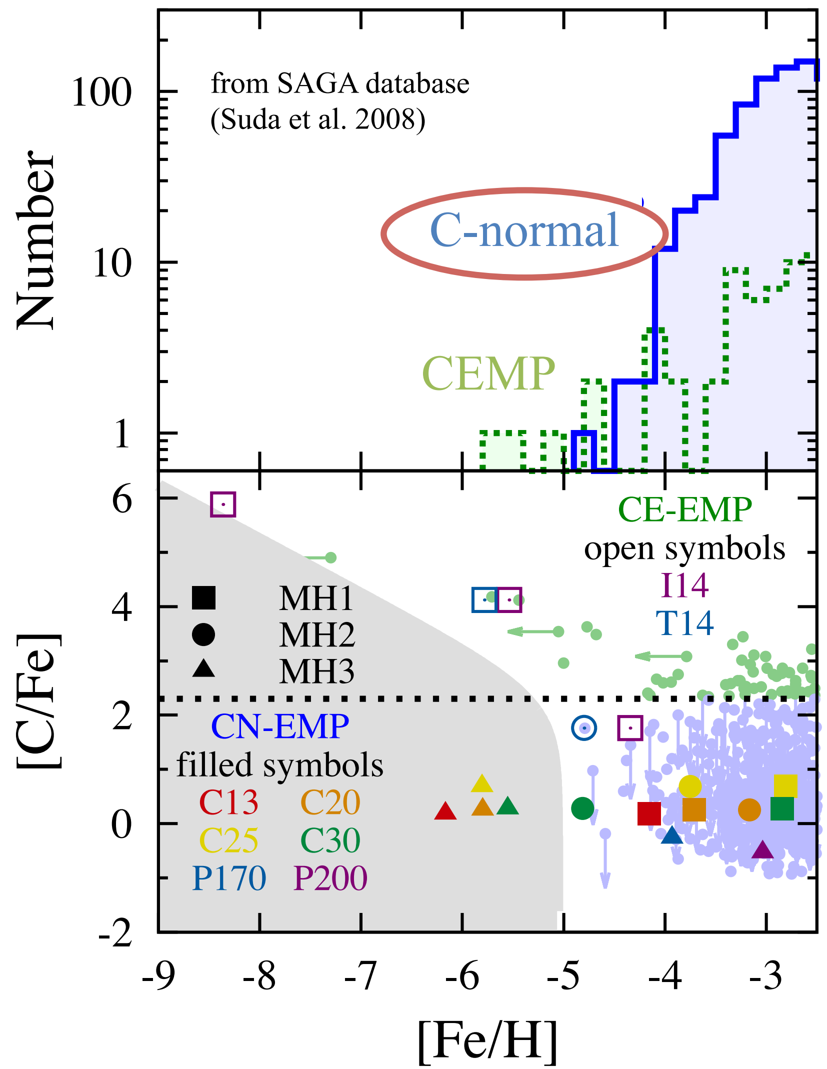
Pop III stars

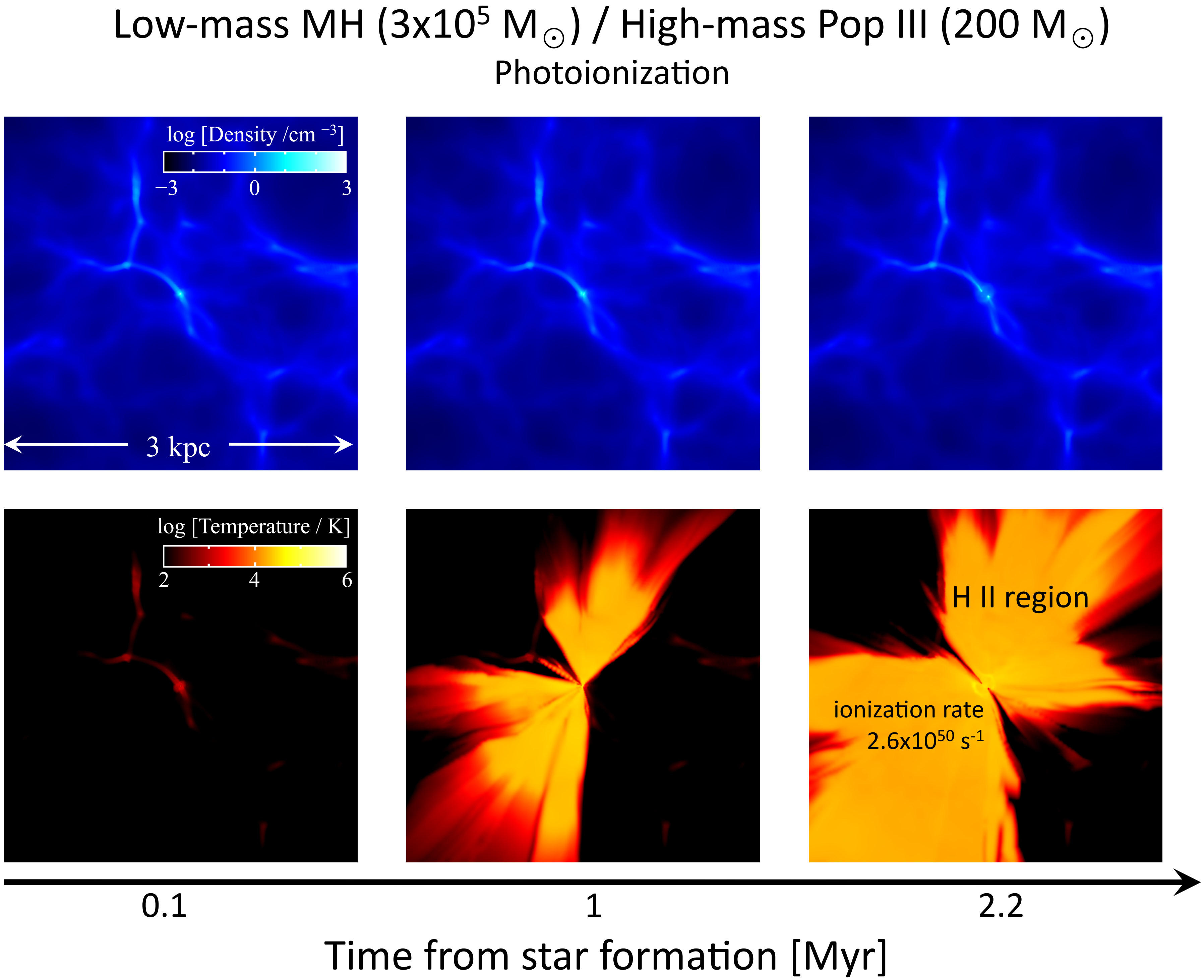
	M_{PopIII} [$M_\odot$]	t_{life} [Myr]	Q(H) [s^{-1}]	E_{SN} [10^{51} erg]	M_{met} [$M_\odot$]
CCSN	13	13.7	1.33e48	1	0.746
	20	8.43	4.72e48	1	2.56
	25	6.46	7.58e48	1	3.82
	30	5.59	1.33e49	1	7.18
PISN	170	2.32	2.16e50	20	83.4
	200	2.20	2.62e50	28	114.

Observations of EMP stars indicate that

✓For C-normal star, no stars with [Fe/H] < −5

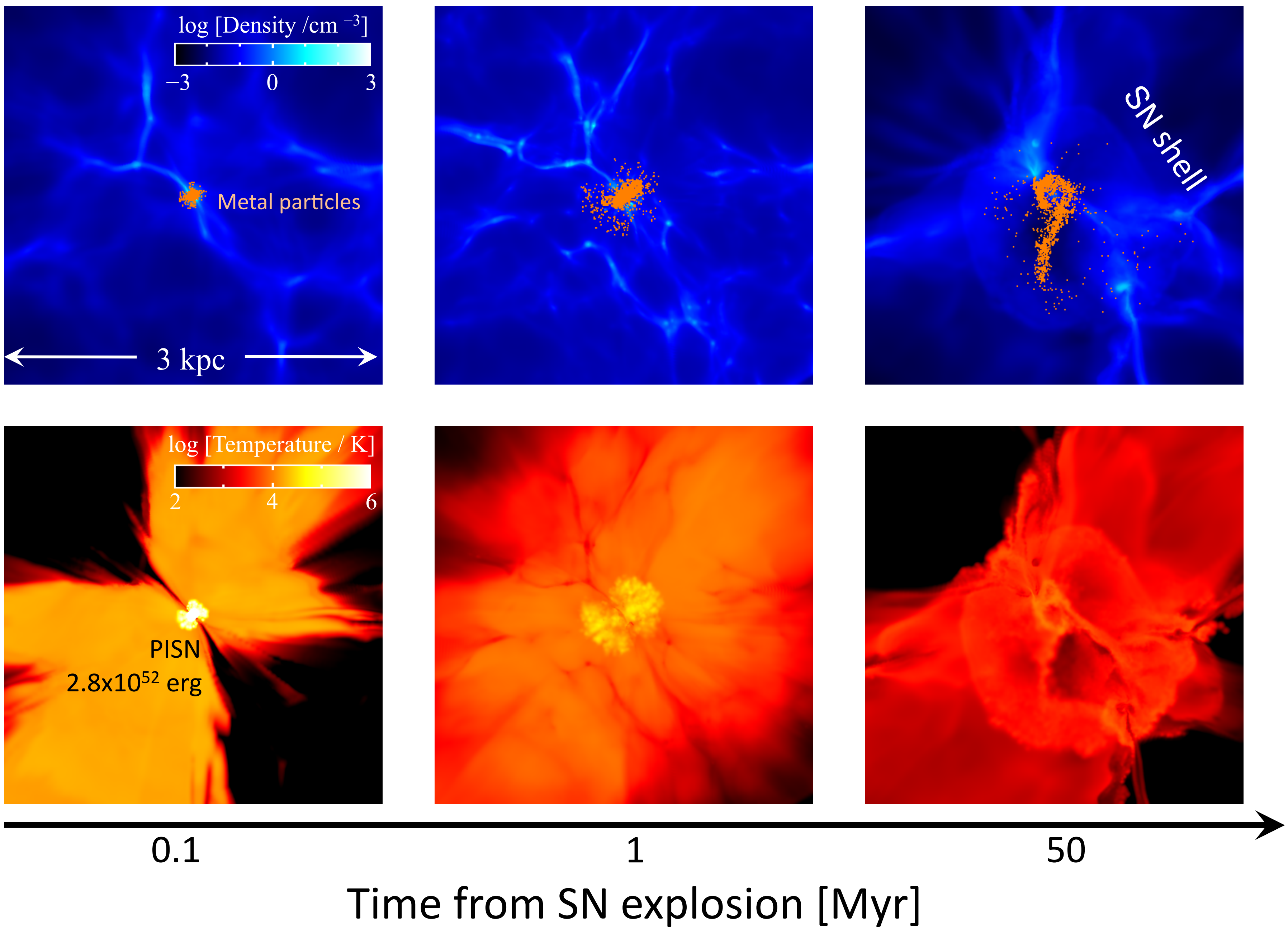
✓No stars with elemental abundance of PISNe



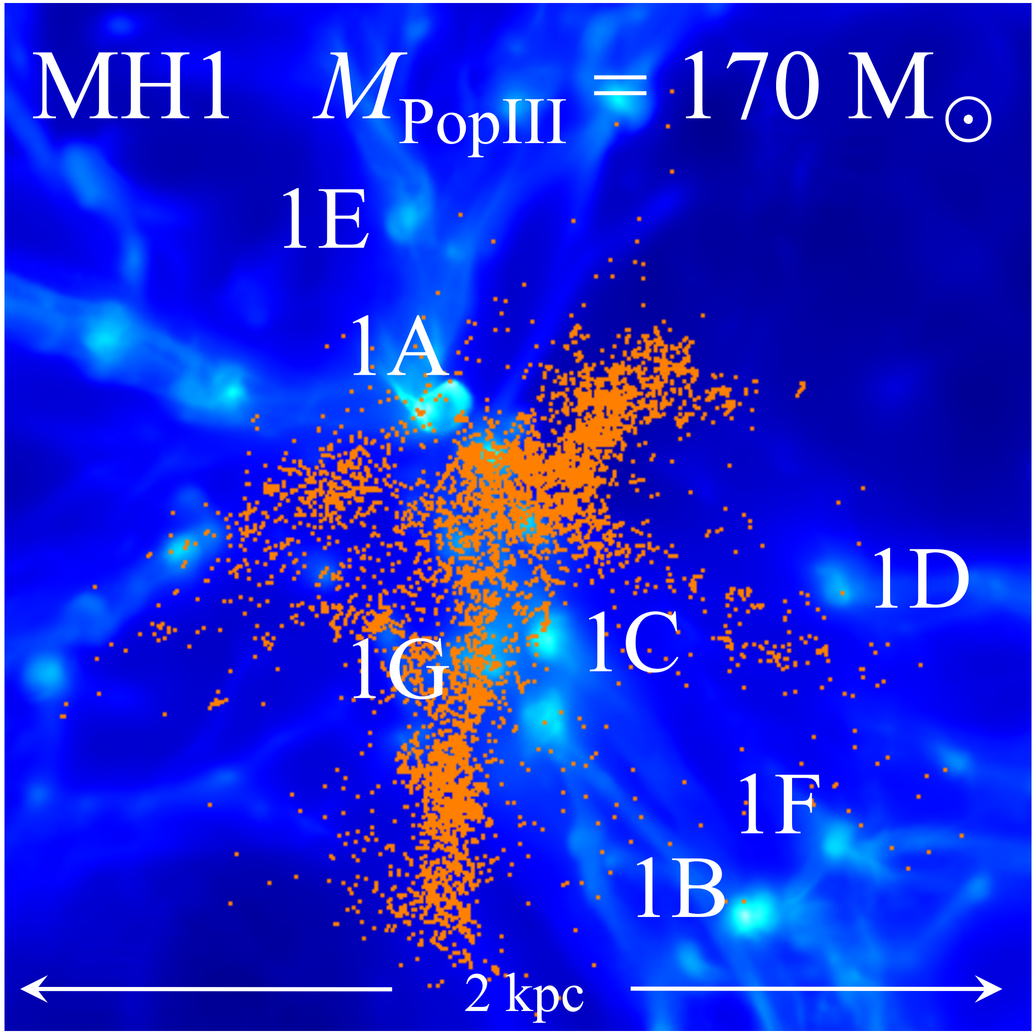

Low-mass MH (3x10^5 M$_\odot$) / High-mass Pop III (200 M$_\odot$)
Photoionization
log [Density /cm^{-3}]
−3
0
3
3 kpc
log [Temperature / K]
2
4
6
H II region
ionization rate
2.6x10^{50} s^{-1}
0.1
1
2.2
Time from star formation [Myr]

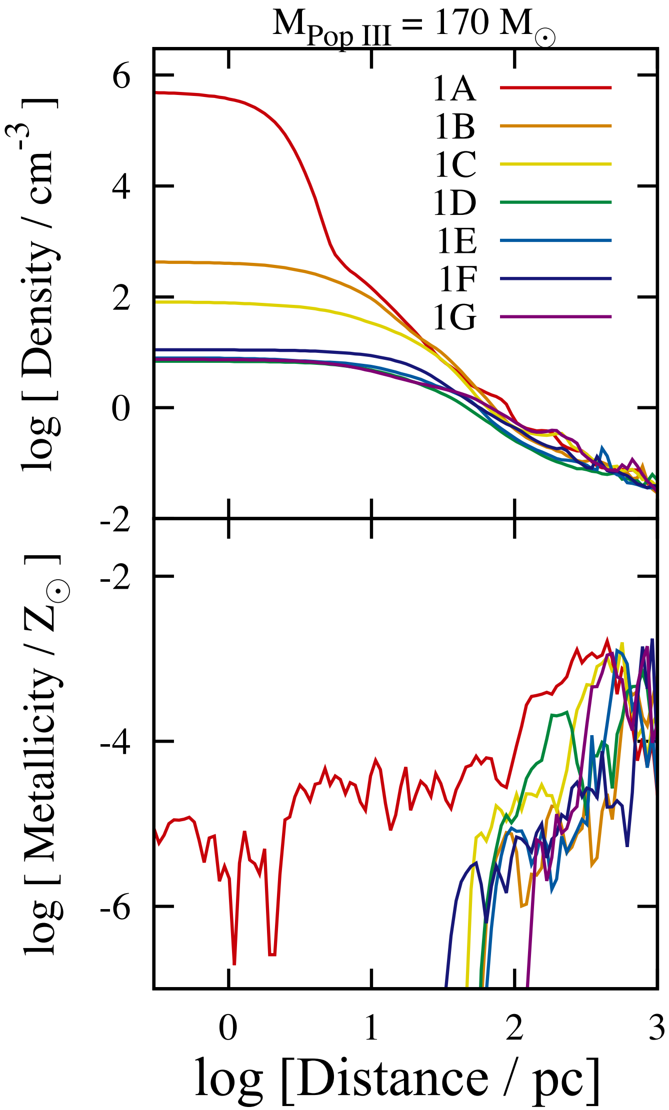
Low-mass MH ($3x10^5$ $M_\odot$) / High-mass Pop III (200 $M_\odot$)

SN explosion



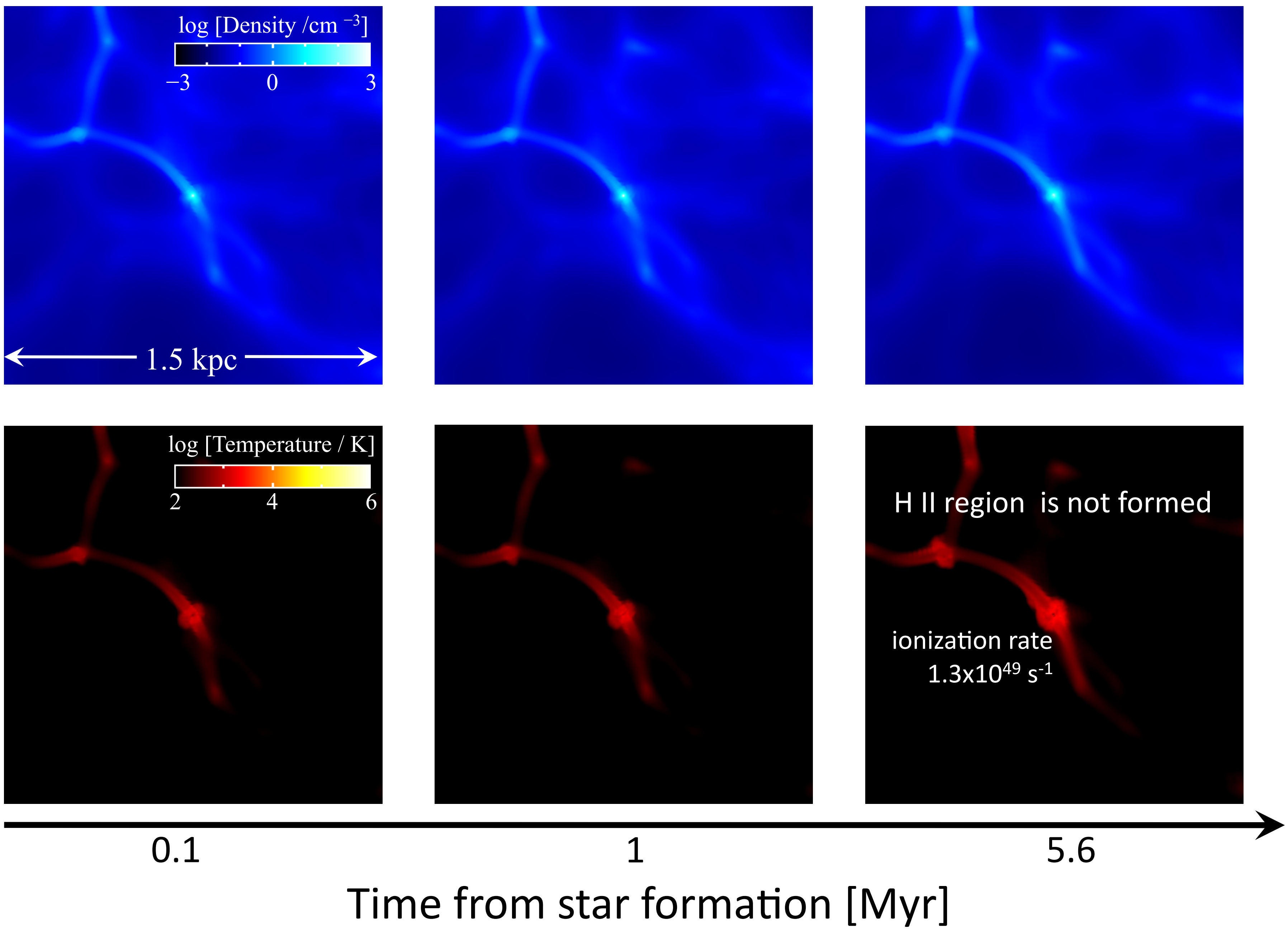
For small M_{halo} & large M_{PopIII}, EE takes place, but its efficiency is small.





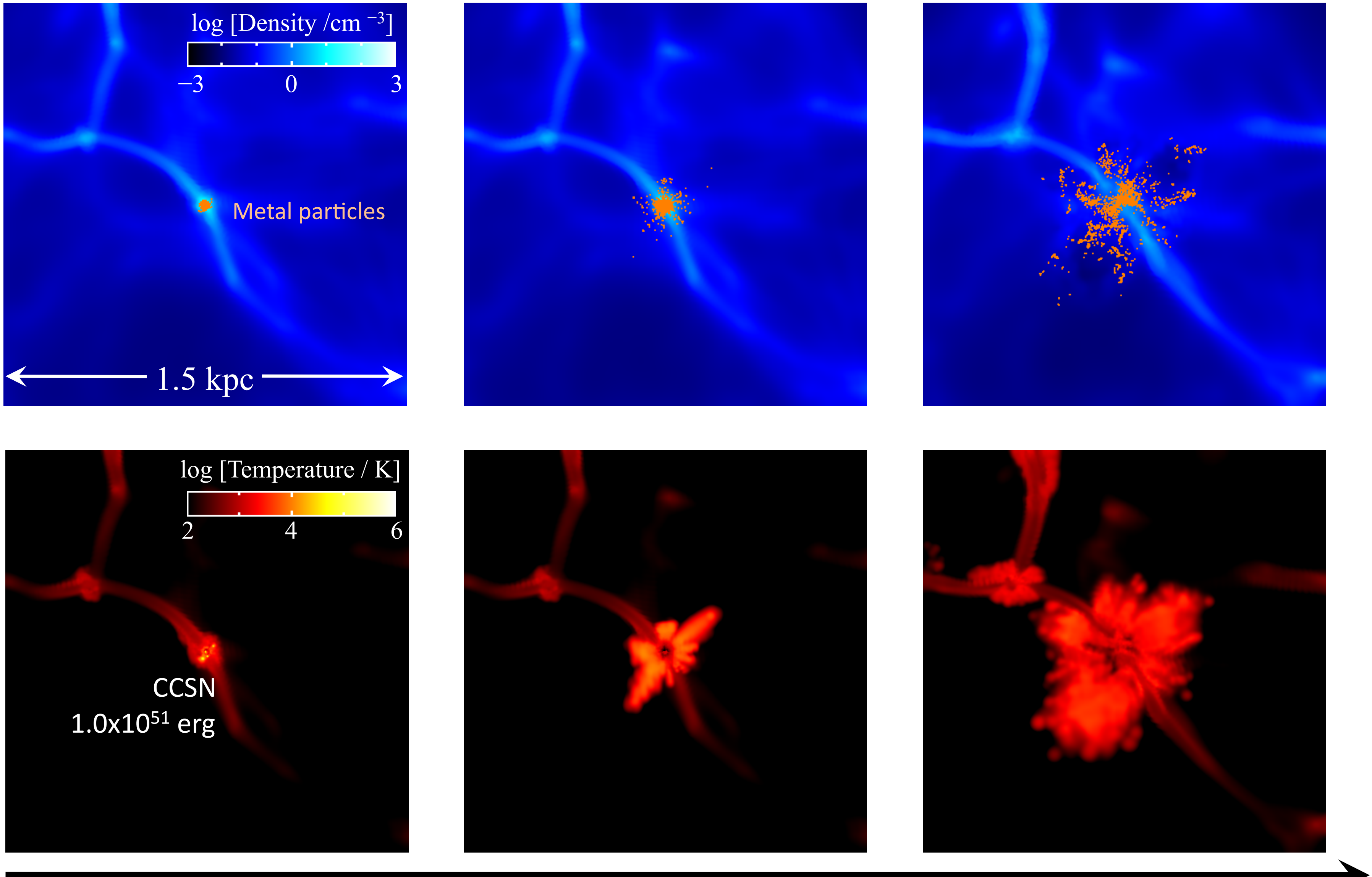
MH ($3x10^5$ $M_\odot$) / Low-mass Pop III (30 $M_\odot$)

Photoionization



MH (3x10^5 M$_\odot$) / Low-mass Pop III (30 M$_\odot$)

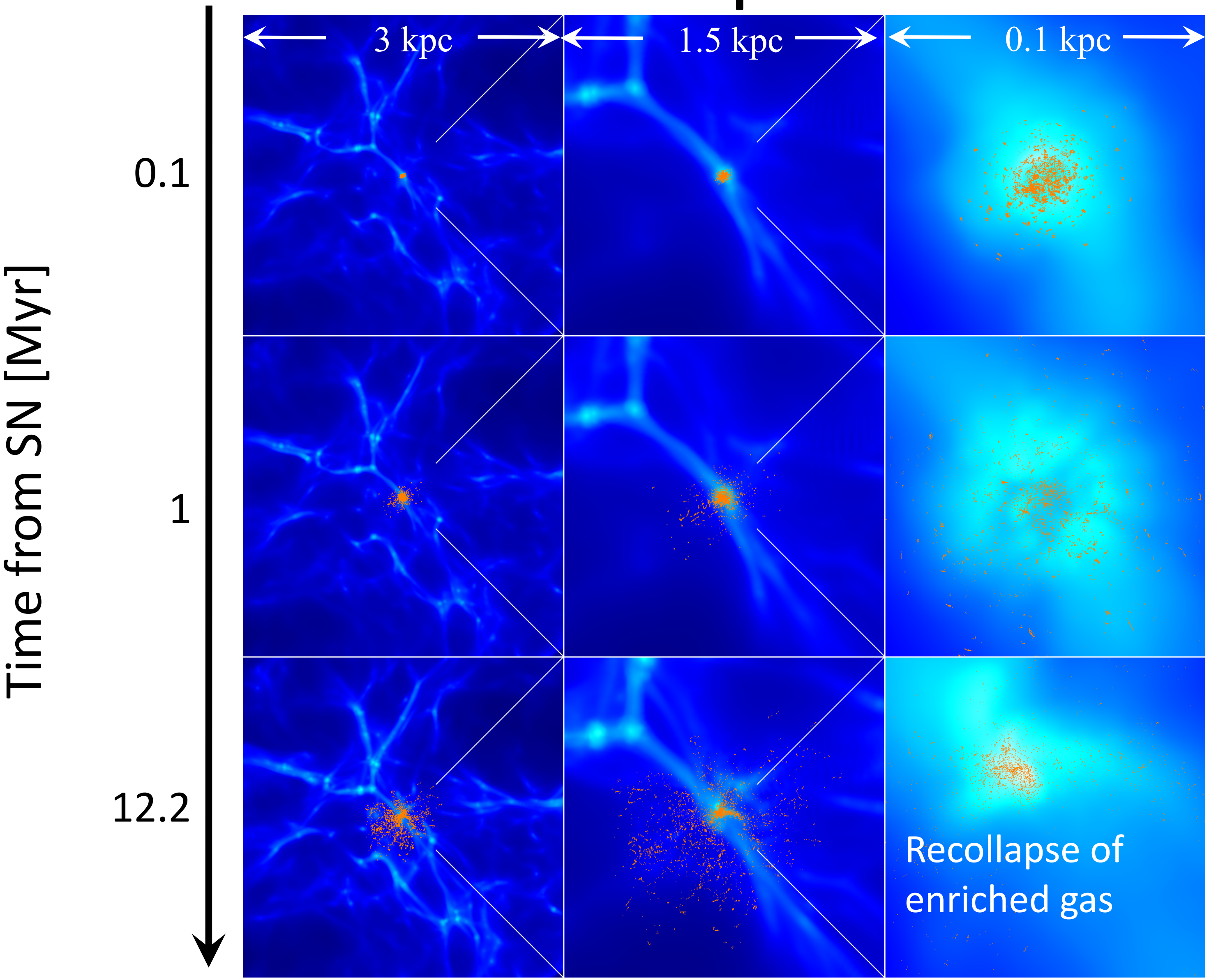
SN explosion



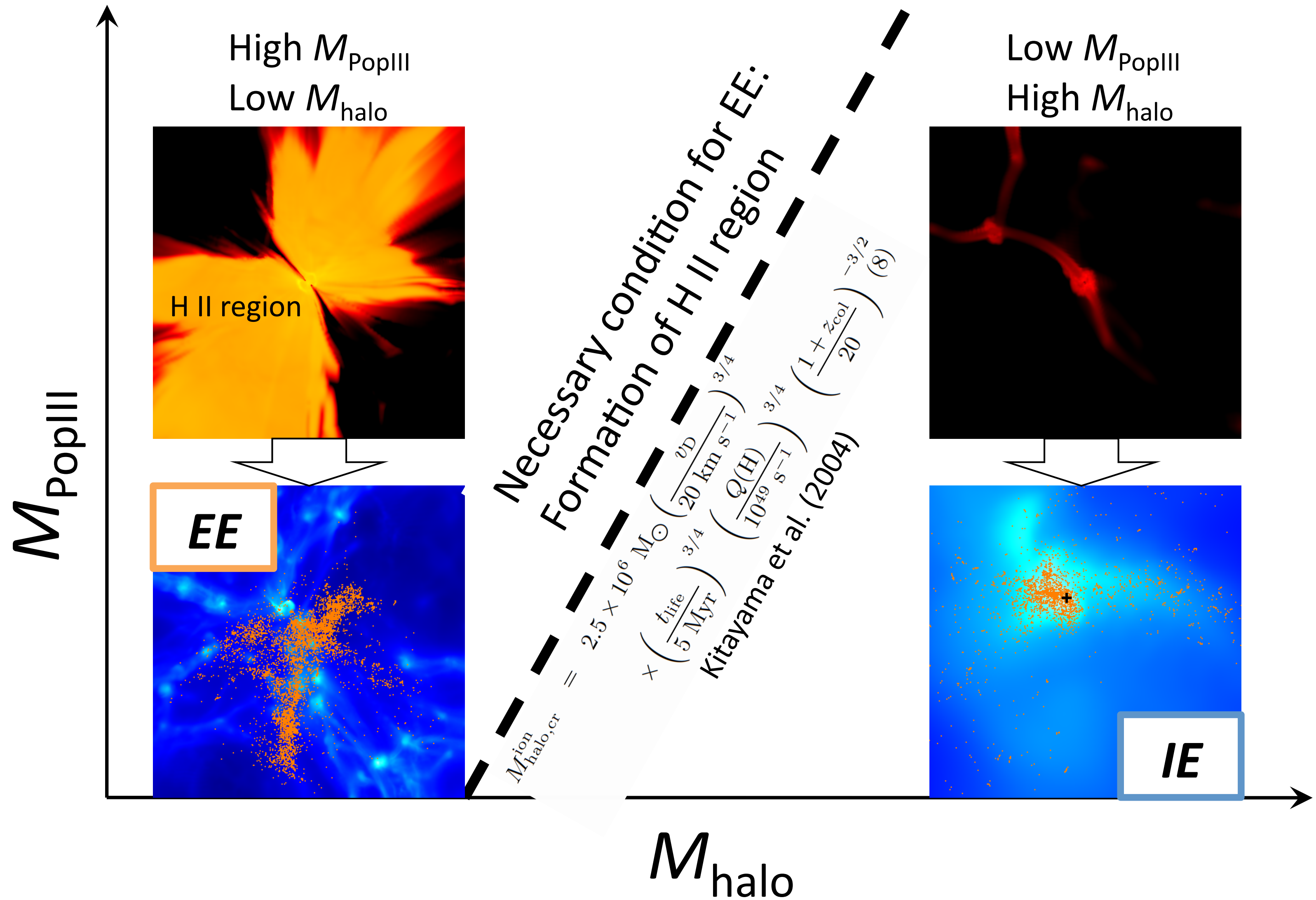
0.1 1 12.2

Time from SN explosion [Myr]

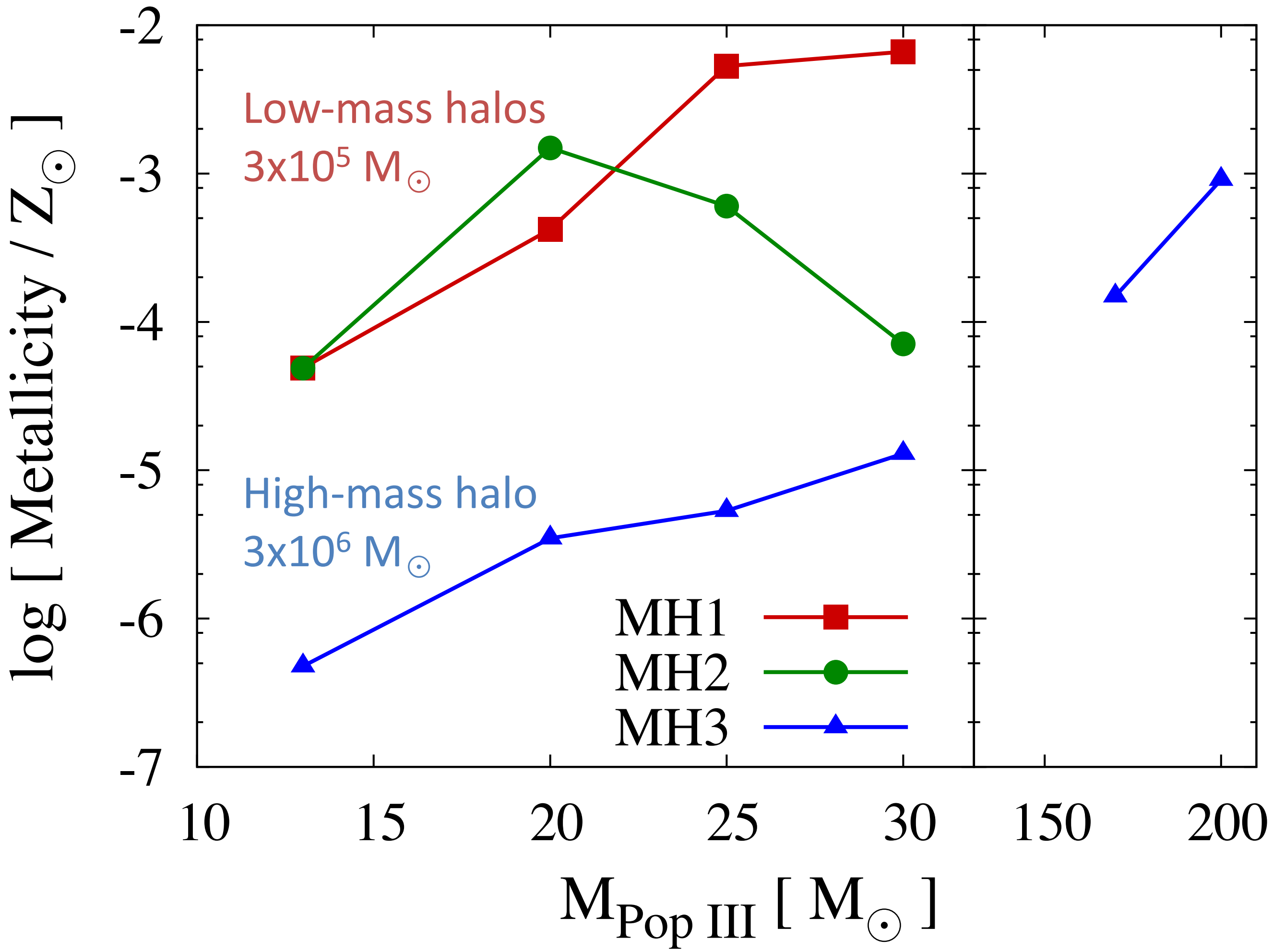
For relatively small M_{PopIII}, IE takes place.



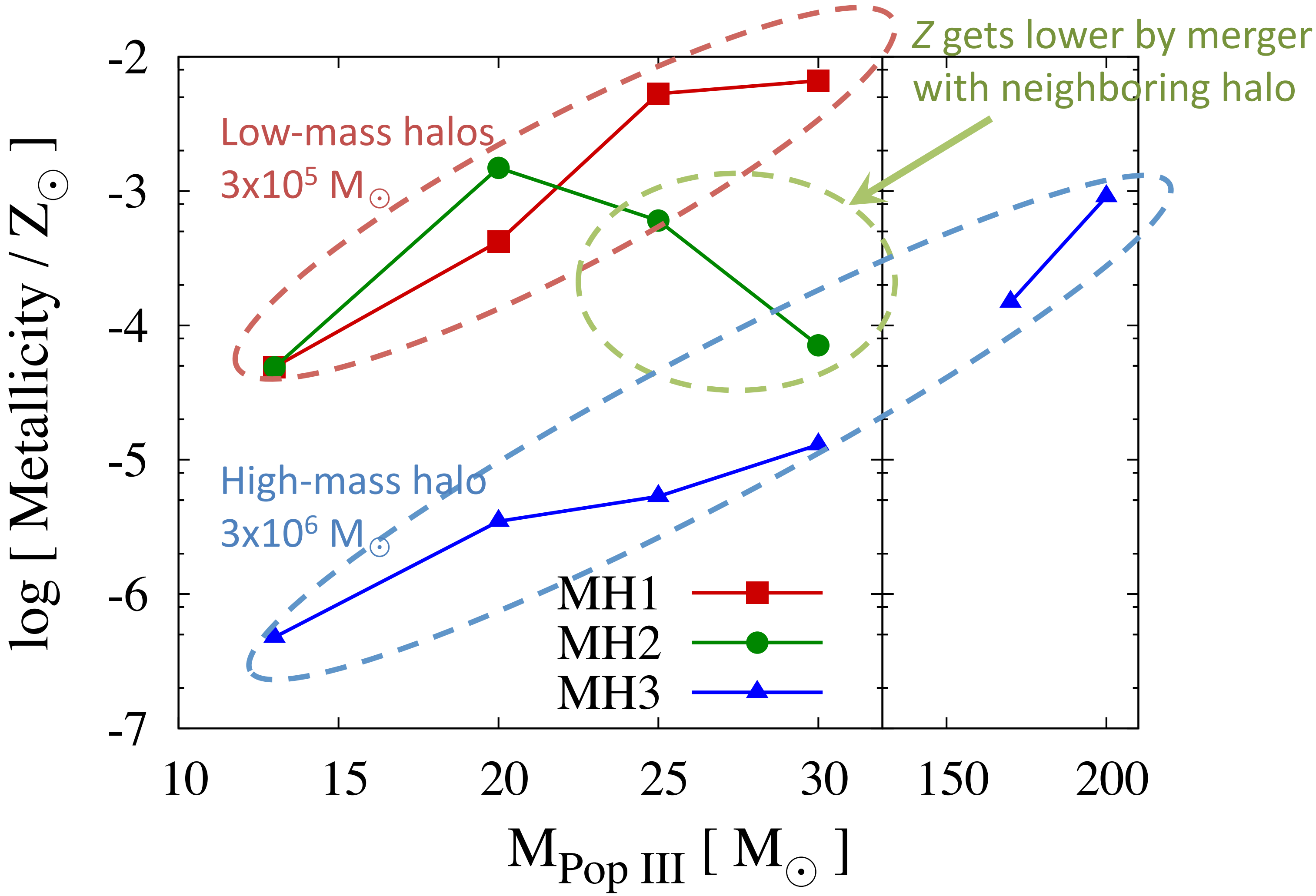
Condition for EE/IE



Self-enriched halos have a wide range of metallicities −7<[Fe/H]<−3

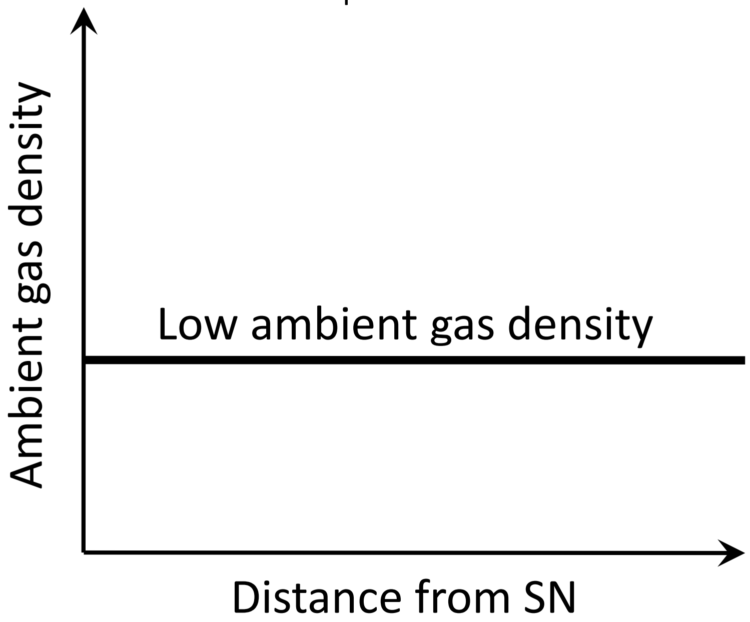


Higher M_{halo} + Lower M_{PopIII} → Lower Z



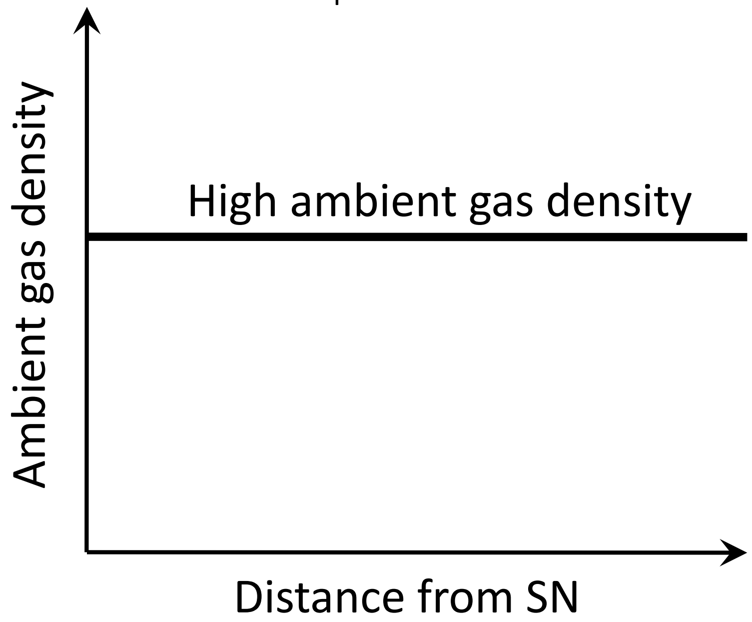
Dependency of Z on M_{halo} and M_{PopIII} in the IE cases

Small M_{halo}
Large M_{PopIII}



H II region is formed
→ambient gas density < 1 cm^{-3}
(Kitayama et al. 2004)

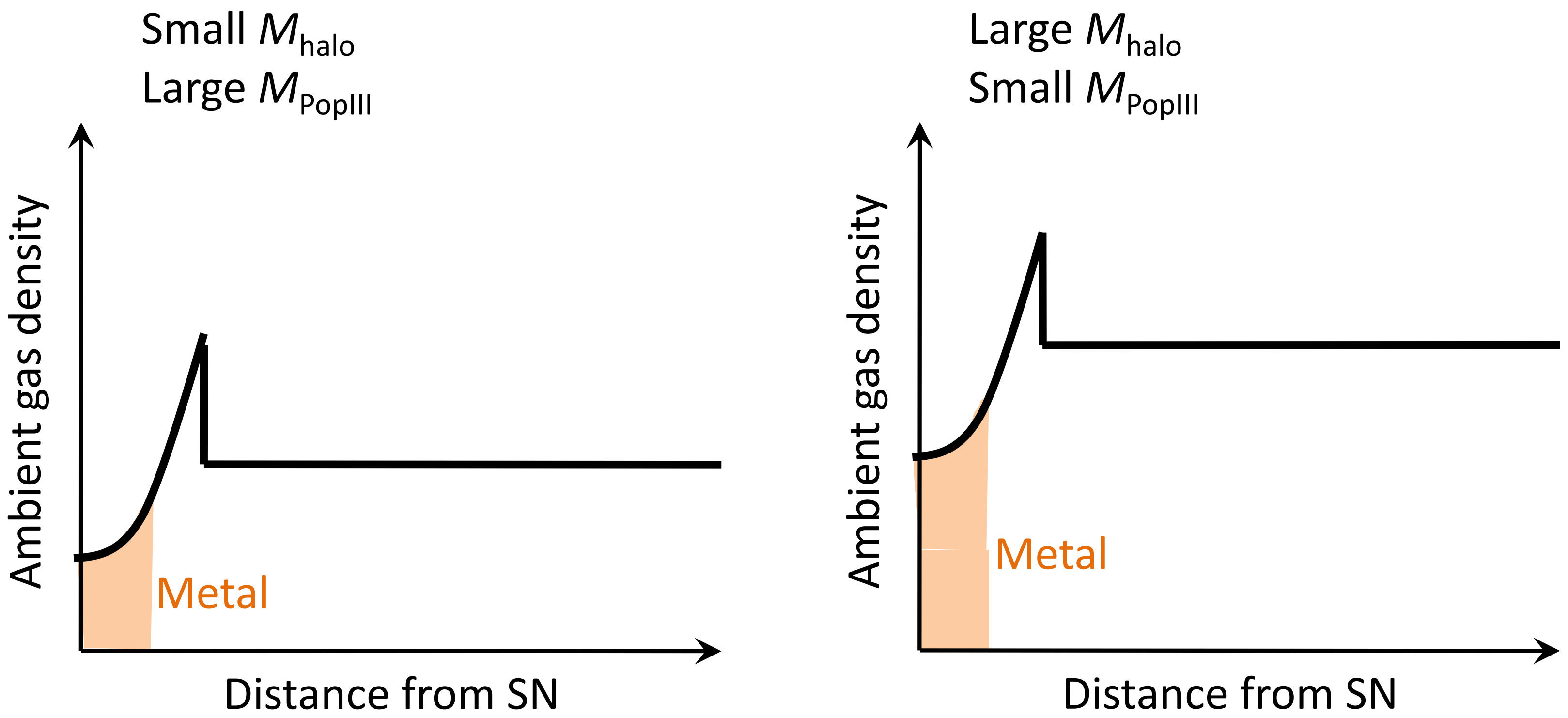
Large M_{halo}
Small M_{PopIII}



H II region is not formed
→ambient gas density > 1 cm^{-3}

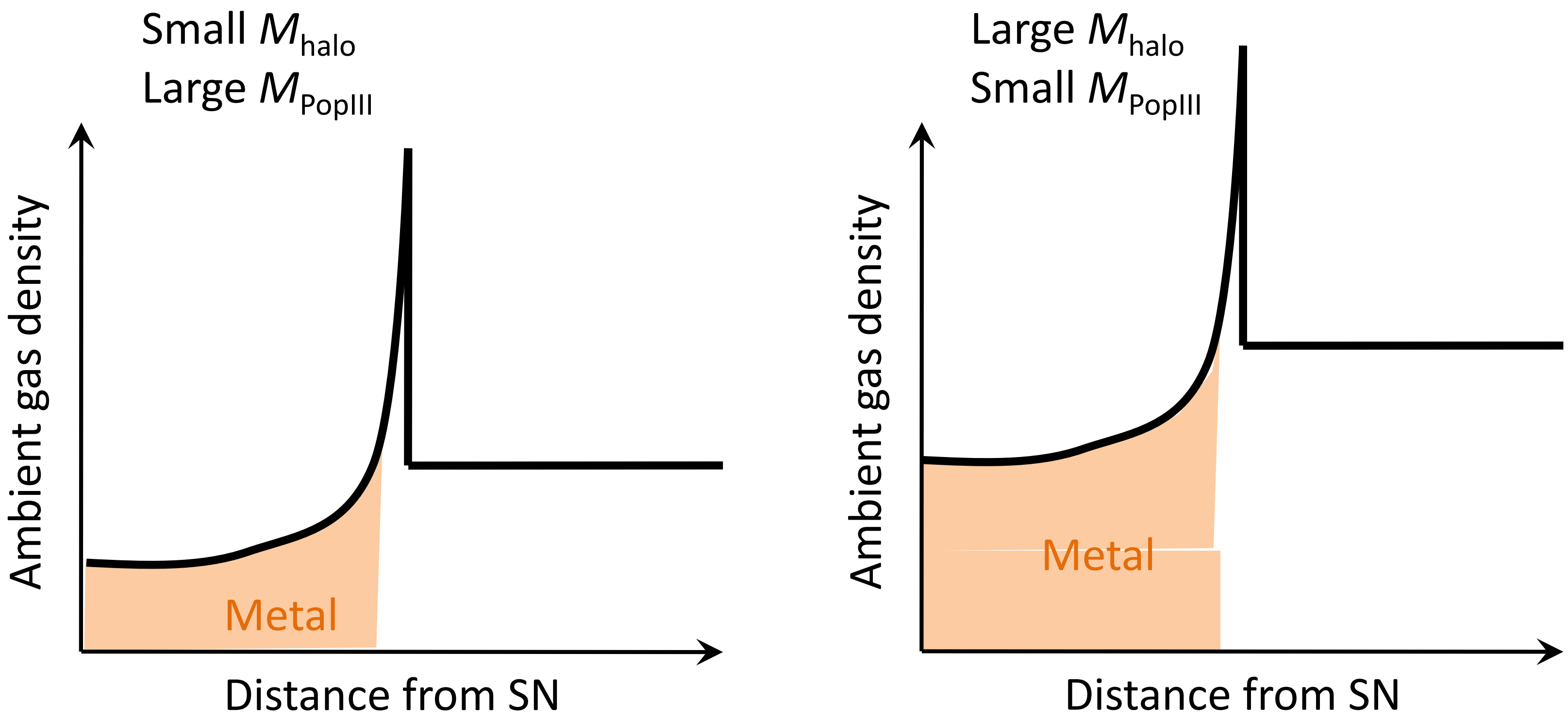
(Chiaki, Yoshida, & Kitayama 2013)

Dependency of Z on $M_{\rm halo}$ and $M_{\rm PopIII}$ in the IE cases



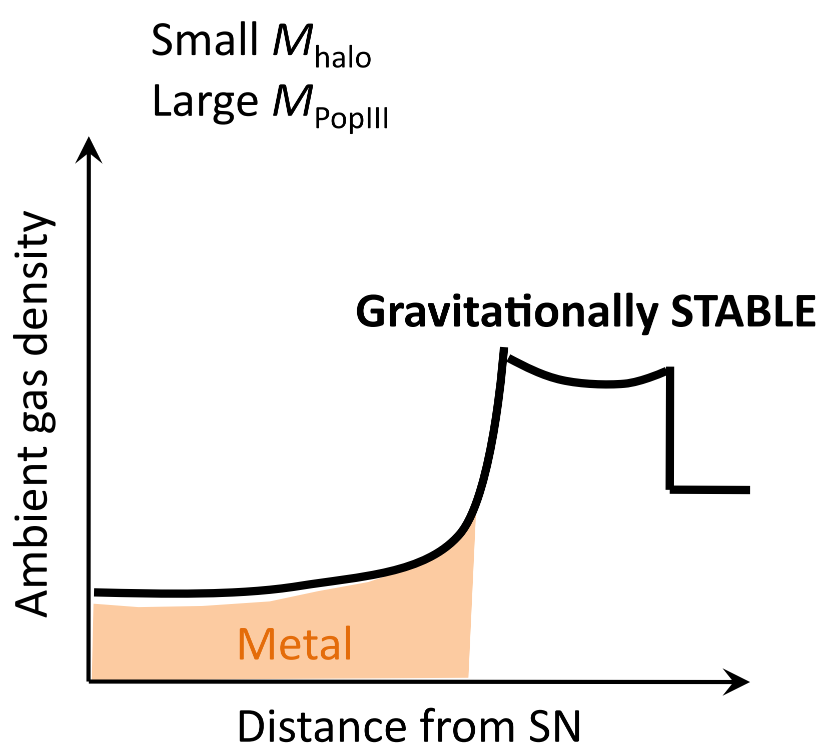
Inefficient radiative cooling
Sedov-Taylor phase

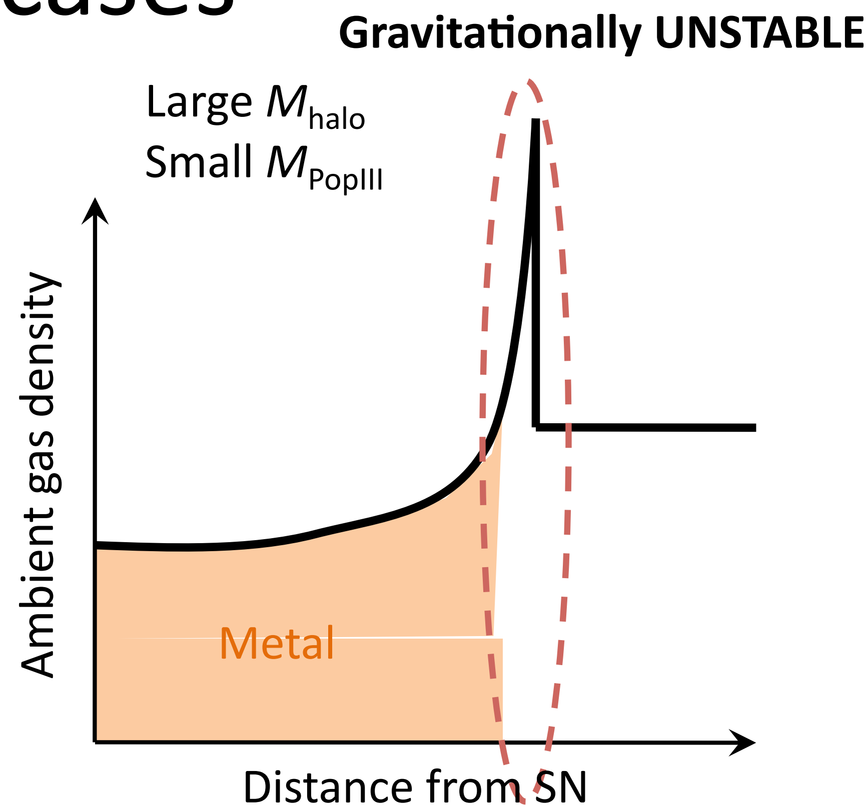
Dependency of Z on M_{halo} and M_{PopIII} in the IE cases



Efficient radiative cooling
Pressure-driven snowplough phase

Dependency of Z on M_{halo} and M_{PopIII} in the IE cases





Central part is cooled

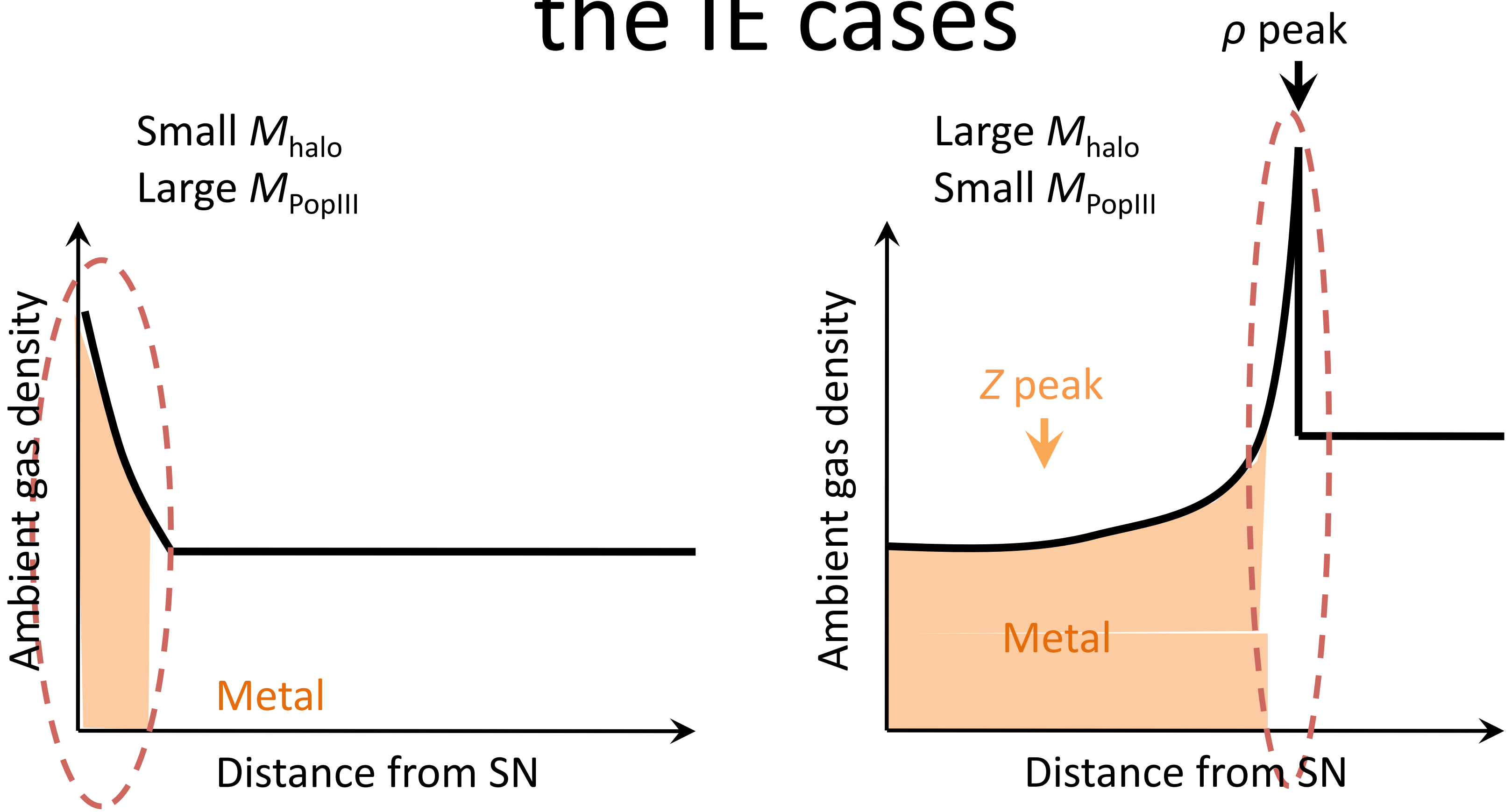
Momentum-conserving snowplough phase

Shell is still gravitationally stable.

Large cooling rate ($\propto$ Density^2)

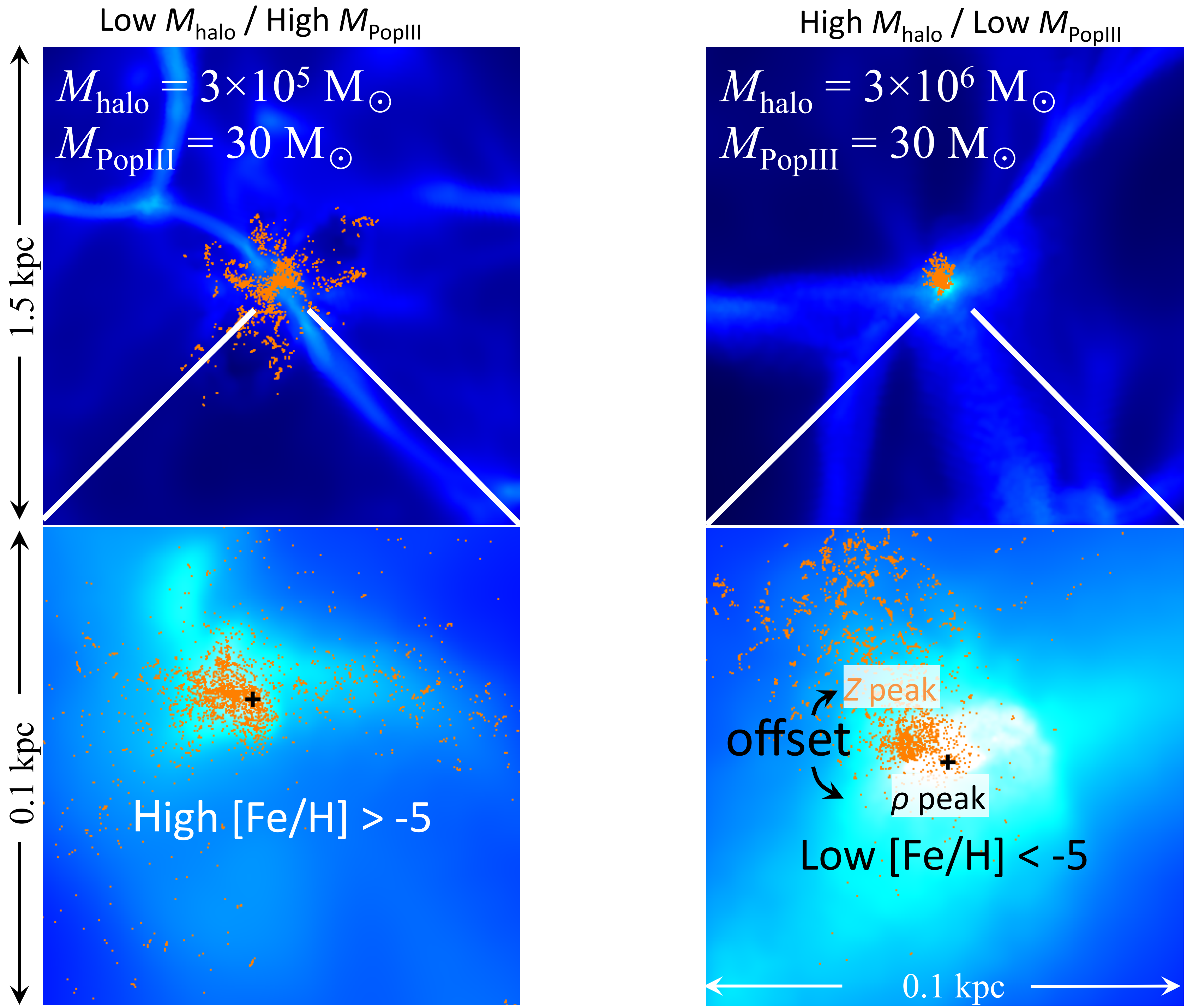
Shell becomes gravitationally unstable during shell expansion

Dependency of Z on M_{halo} and M_{PopIII} in the IE cases



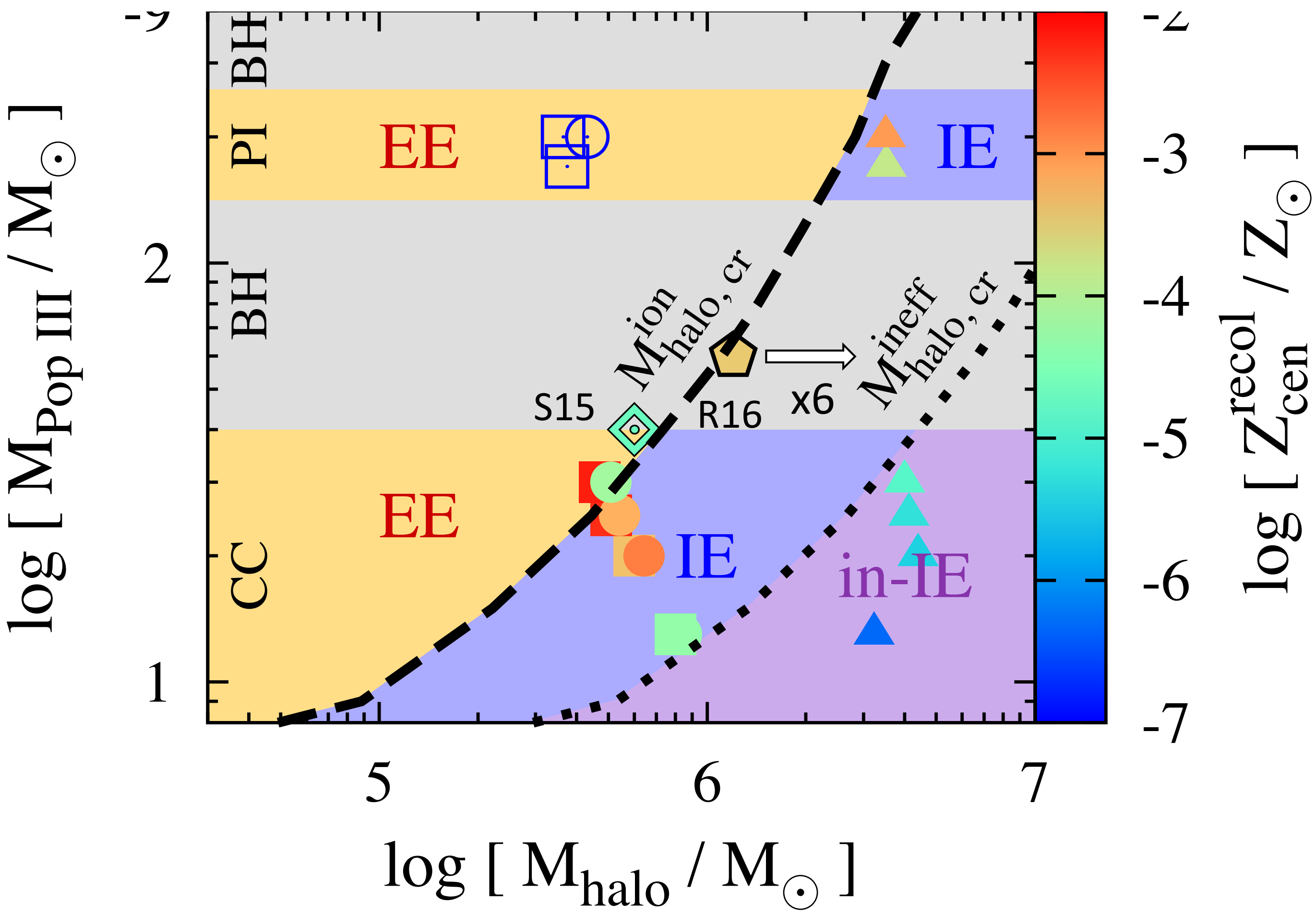
✓Recollapse only after fall back
✓**Coincidence** between ρ and Z peaks
✓Z in recollapsing region is relatively high ([Fe/H] > −3)

✓Recollapse during shell expansion
✓**Offset** between ρ and Z peaks
✓Z in recollapsing region is relatively low ([Fe/H] < −3)



Low $M_{\rm halo}$ / High $M_{\rm PopIII}$
High $M_{\rm halo}$ / Low $M_{\rm PopIII}$
$M_{\rm halo} = 3\times10^5\ {\rm M}_\odot$
$M_{\rm PopIII} = 30\ {\rm M}_\odot$
$M_{\rm halo} = 3\times10^6\ {\rm M}_\odot$
$M_{\rm PopIII} = 30\ {\rm M}_\odot$
1.5 kpc
0.1 kpc
High [Fe/H] > -5
Z peak
offset
ρ peak
Low [Fe/H] < -5
0.1 kpc

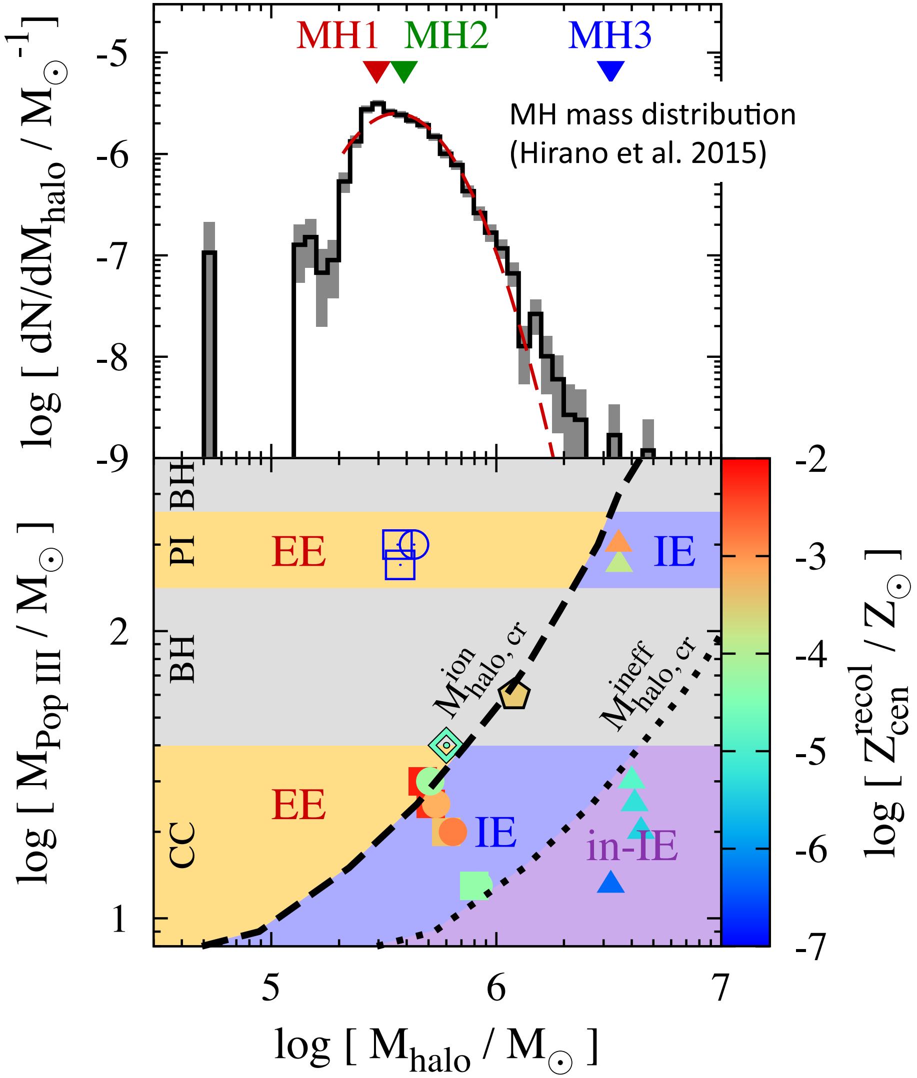
We regard IE mode with [Fe/H]<−5 as `Ineffective IE' mode



Open symbol: EE
Closed symbol: IE

S15: Smith et al. (2015)
R16: Ritter et al. (2016)

PISN: EE in almost all cases
CCSN: IE in most cases



SN	Enr. mode	$[\mathrm{Fe/H}]^{\mathrm{recol}}_{\mathrm{cen}}$	Fraction flat IMF	Fraction Salpeter IMF
PI	EE	$< [\mathrm{Fe/H}]_{\mathrm{cr}}$	$\simeq 1$	$\simeq 1$
	IE	$> [\mathrm{Fe/H}]_{\mathrm{cr}}$	4.60×10^{-6}	7.23×10^{-6}
CC	EE	$< [\mathrm{Fe/H}]_{\mathrm{cr}}$	0.423	0.127
	IE	$> [\mathrm{Fe/H}]_{\mathrm{cr}}$	0.566	0.824
	in-IE	$< [\mathrm{Fe/H}]_{\mathrm{cr}}$	0.011	0.049

PISN

✓EE in almoast all cases

✓To detect EMP stars ($-5 < [\mathrm{Fe/H}] < -2.5$), 10^5-10^6 stars need to be observed.

CCSN

✓IE is the dominant mode.

✓The fraction of EE is non-negligible (10-40%).

✓However, stars with $[\mathrm{Fe/H}] < -5$ have not been observed so far,

→which indicates the critical metallicity (Omukai 2000; Schneider et al. 2002)

Summary and Conclusion

In this work, to investigate

- metal enrichment process by Pop III SNe
- metallicity range of metal-poor star forming region,

we perform numerical simulations of SN remnants of Pop III stars in a range of

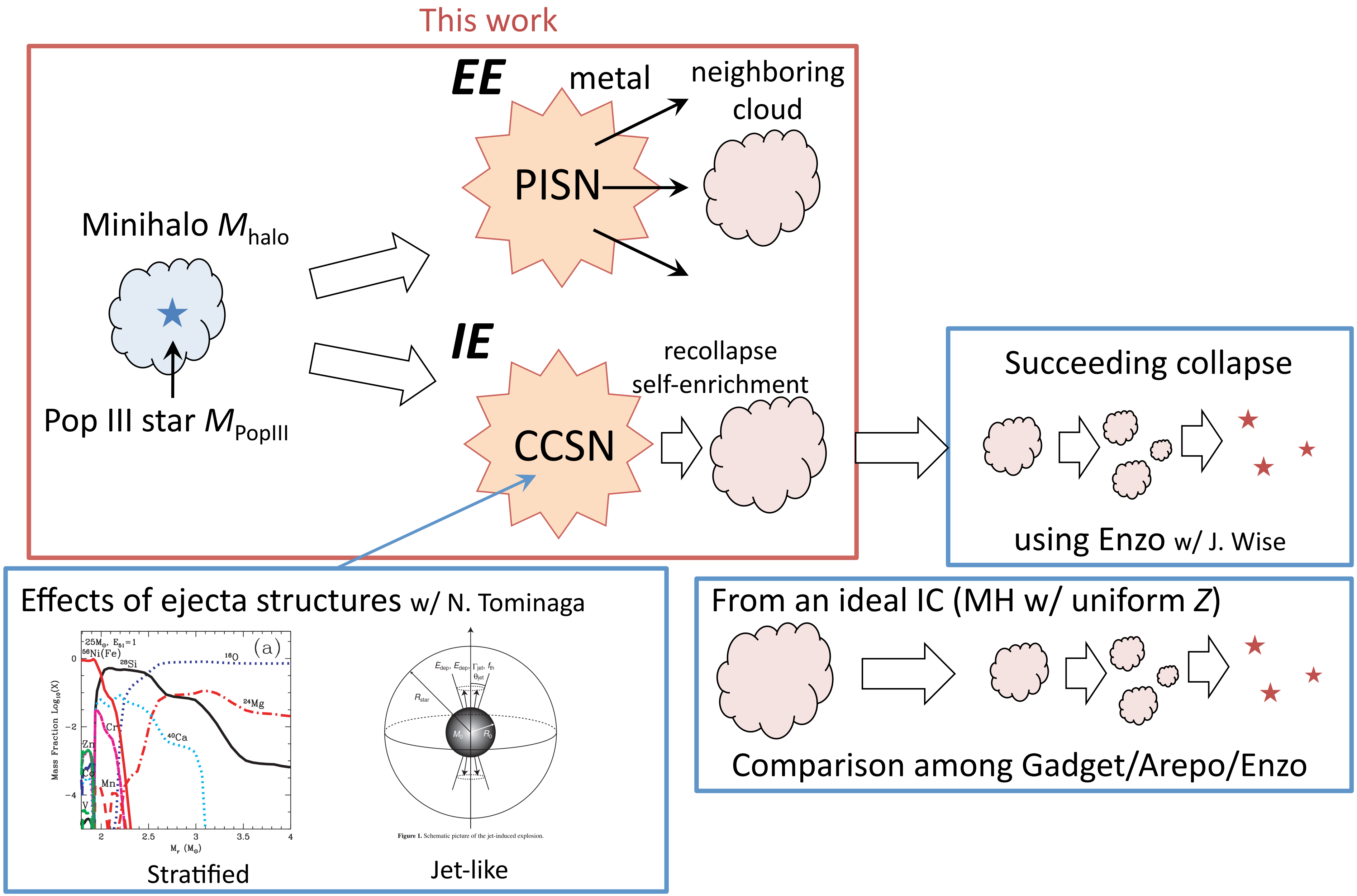
- minihalo masses (M_{halo})
- Pop III stellar masses (M_{PopIII})

Consequently,

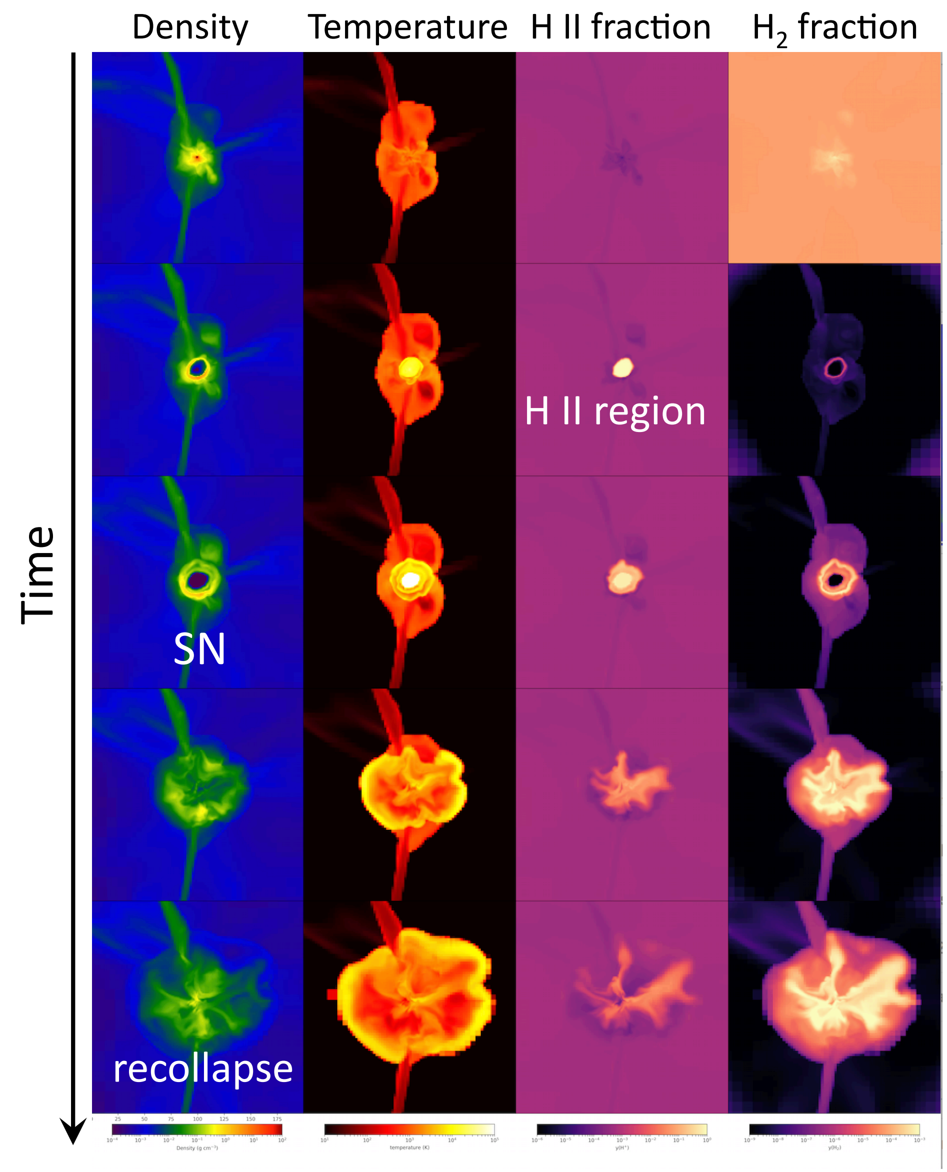
- we show that either IE or EE occurs in a sequence of simulations.
  - EE is ineffective mode, and the metallicity in the enriched region is [Fe/H] < −5.
  - The recollapsing regions formed by IE have a wide range of metallicities −7 < [Fe/H] < −3.
    - Although metallicity is [Fe/H] < −5 for sufficiently large M_{halo} / small M_{PopIII},
    - mass distributions of MH and Pop III reproduce tiny fraction（1-5%）.
- The different enrichment modes for PISNe and CCSNe
  - For PISNe, EE takes place in almost all relevant mass range of MHs.
    - consistent with the current observation by which EMP stars with elemental abundance of PISNe have not been observed.
  - For CCSNe, IE takes place in most cases (57-82% of MHs).
    - Non-negligible fraction of MH (13-42%), EE occurs.
      - All 1400 EMP stars ever observed have larger elemental abundance than the critical.
      - This indicates the critical metallicity above which metal/dust cooling induce low-mass star formation mode.

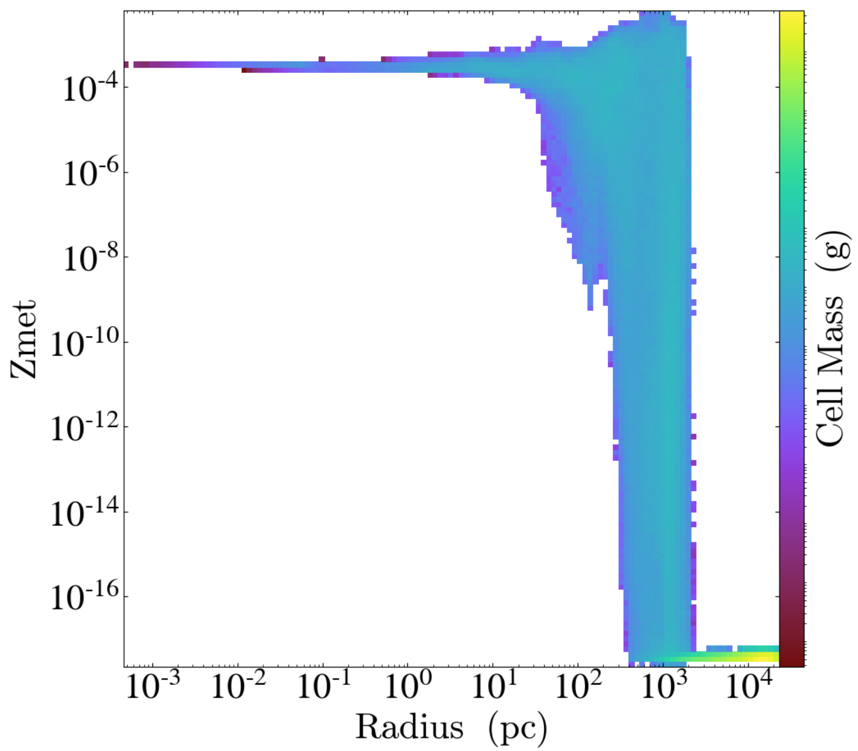
The formation of observed EMP stars can be explained by IE from CCSNe.

Ongoing works



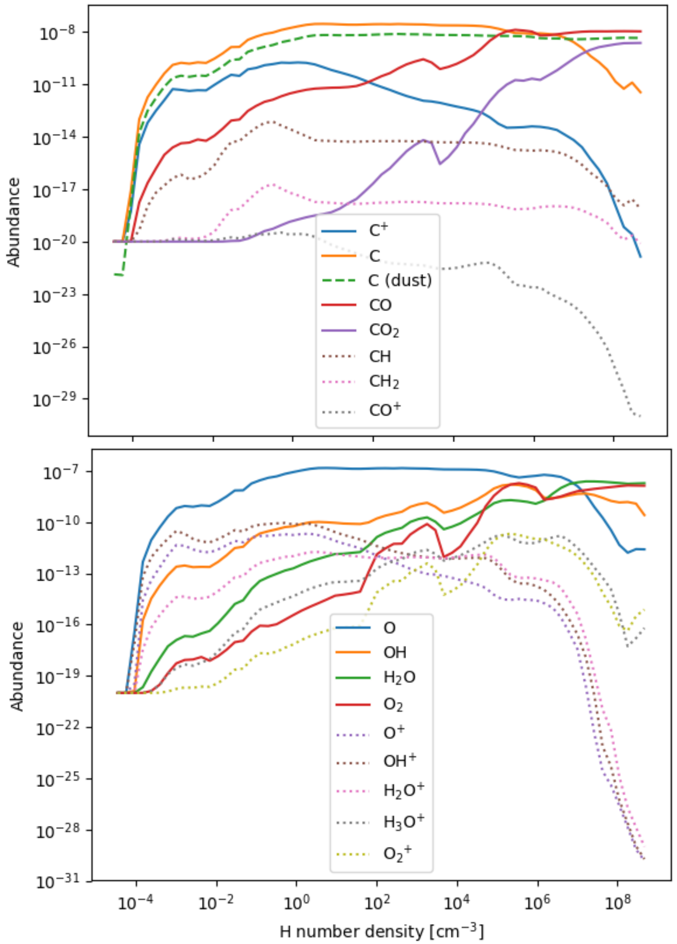
Succeeding evolution of recollapsing region w/ Enzo

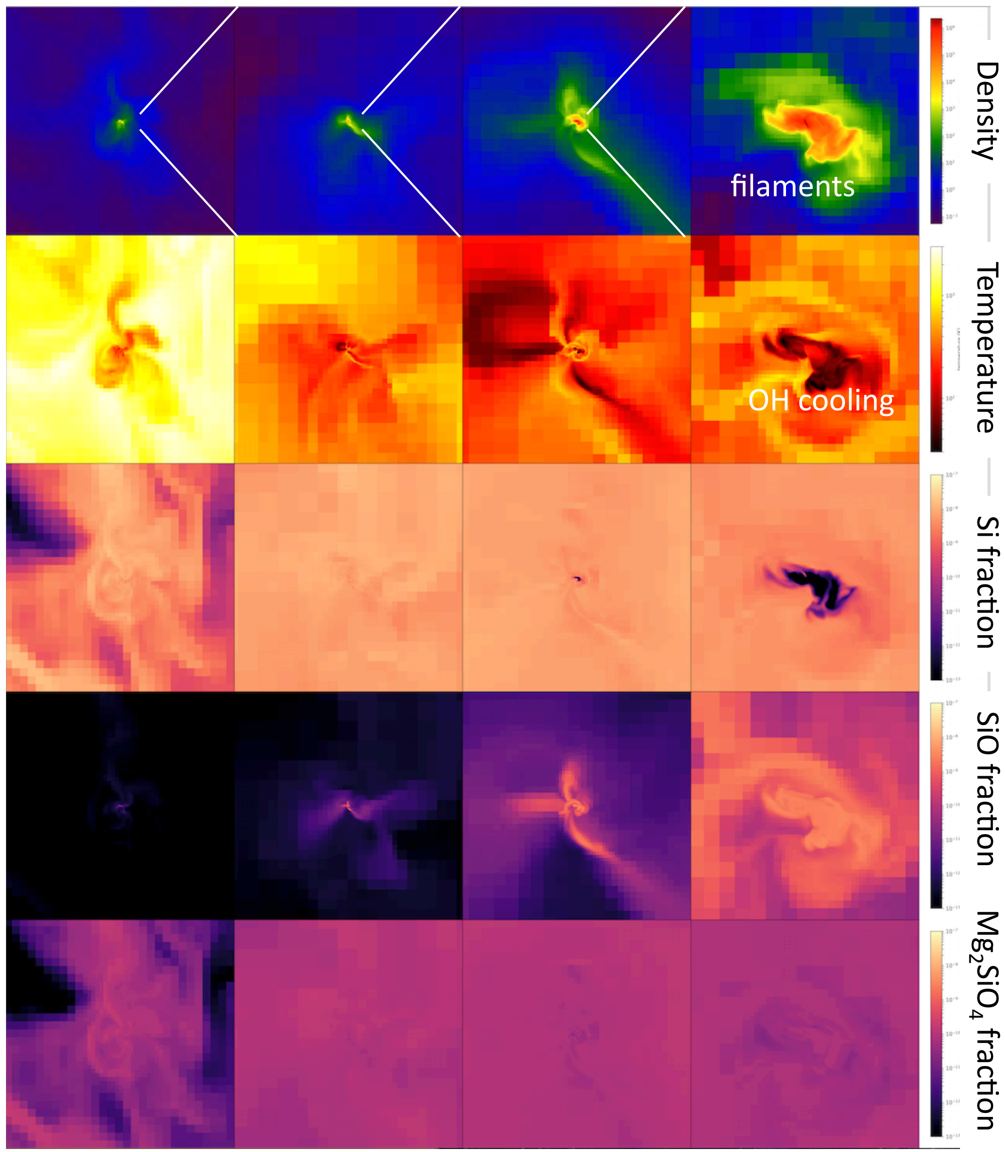




The metallicity in the recollapsing region is ~ 10^{-4} $Z_{\odot}$

Succeeding evolution of recollapsing region w/ Enzo

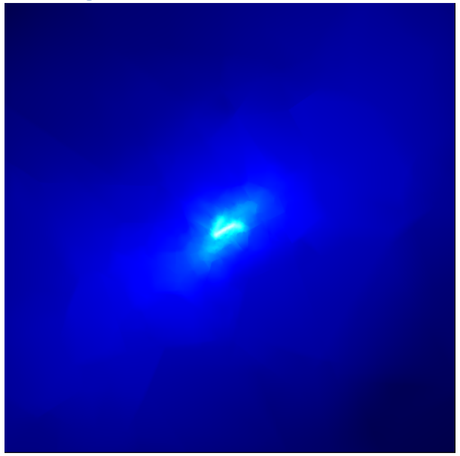




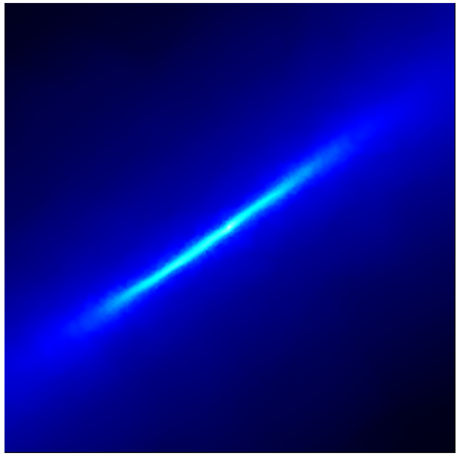
successfully solves **48 species** in recollapsing region.

Comparison project
Collapse of a MH with $10^{-4} Z_\odot$

Arepo



$\lambda_J/\Delta x = 10$

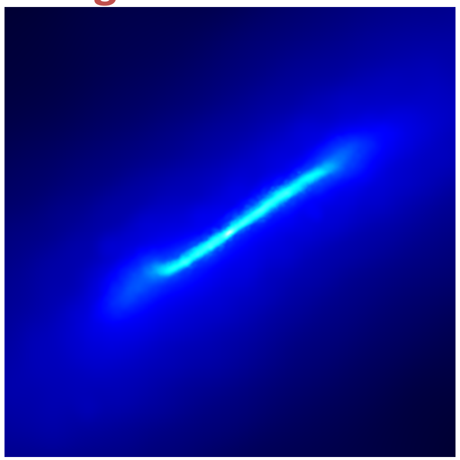


20

64

128

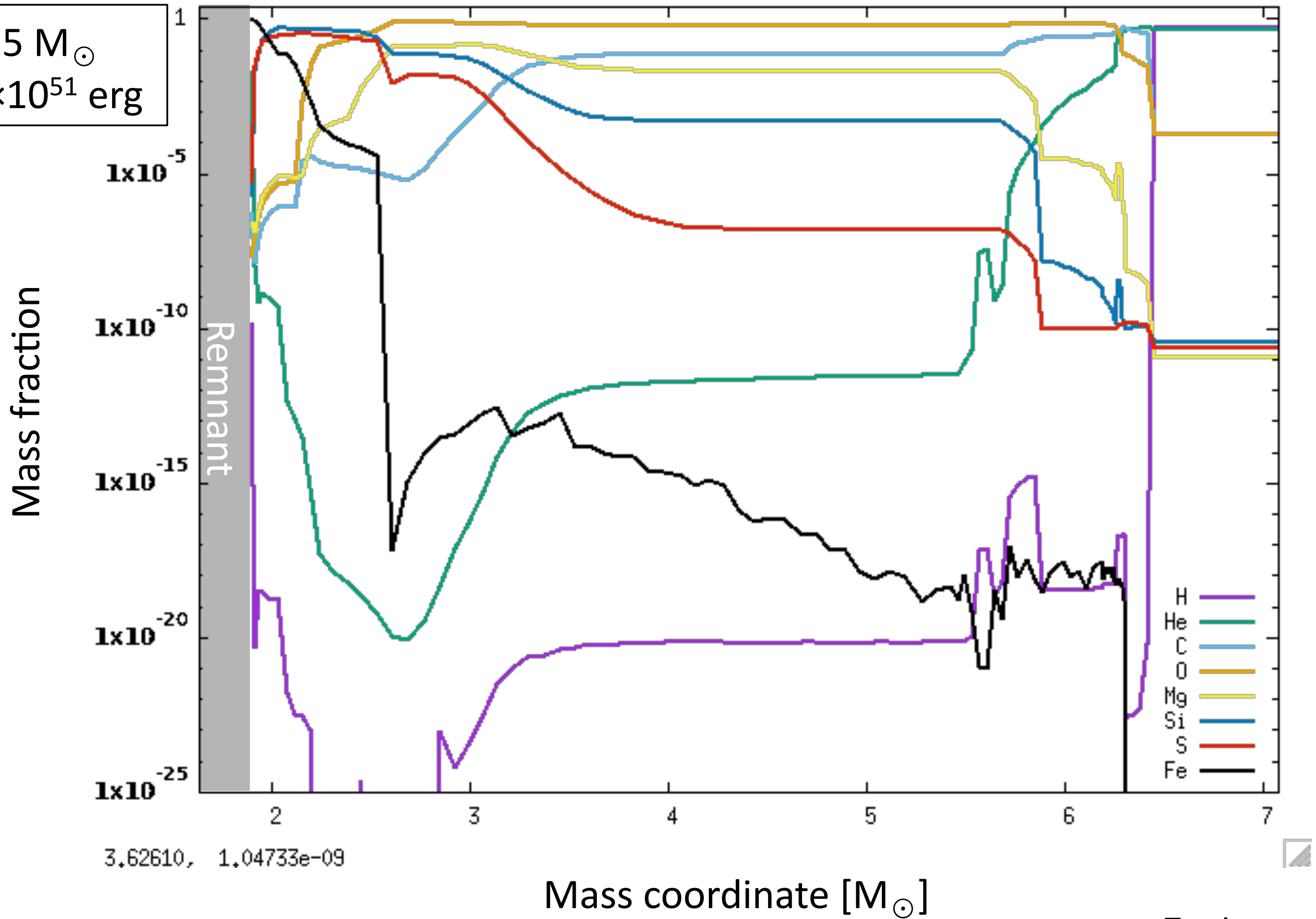
Gadget



$\lambda_J/\Delta x = 10$

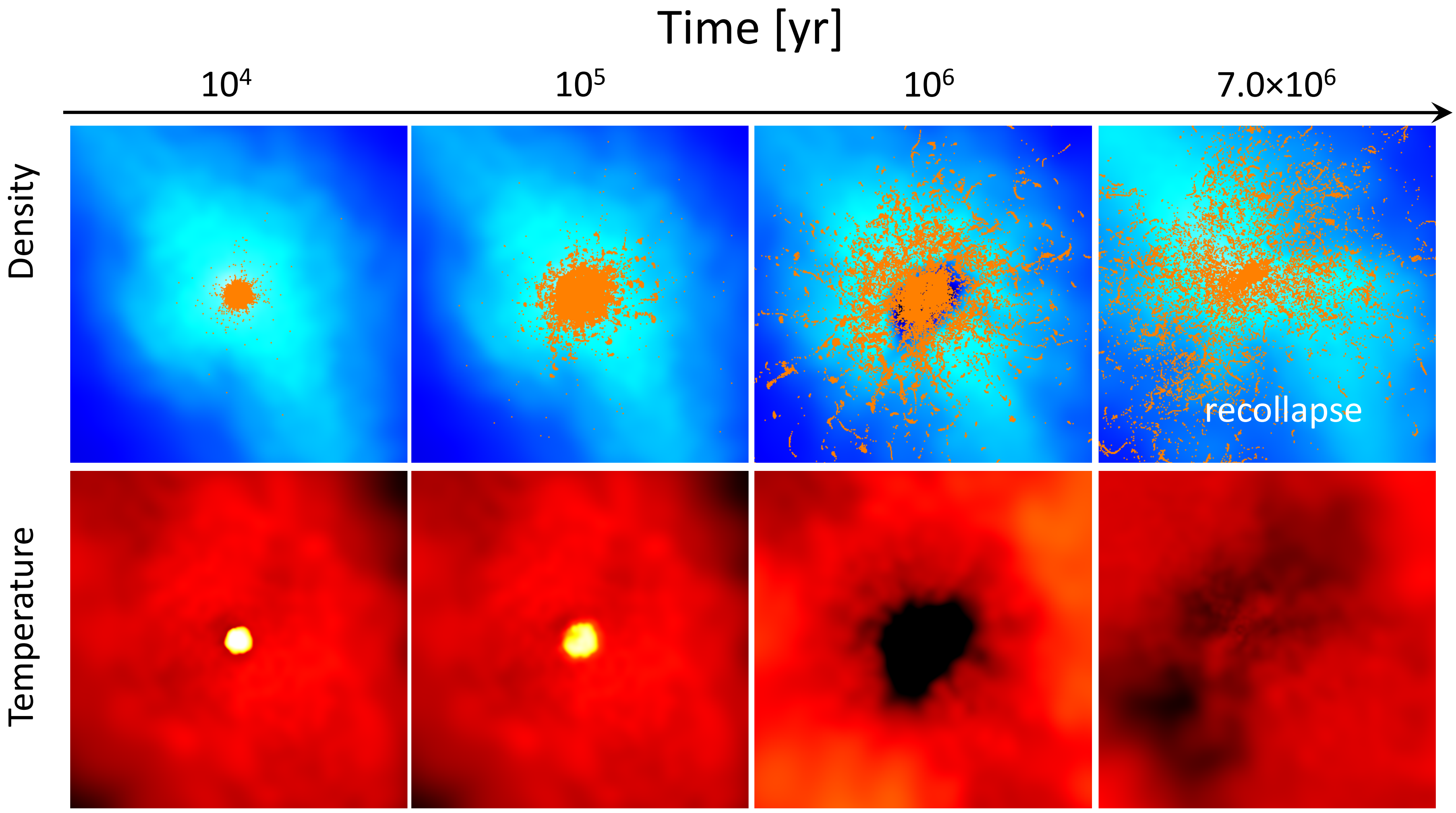
Non-uniform ejecta structures

M_{PopIII} = 25 $M_\odot$
$E_{\mathrm{SN}} = 0.7\times10^{51}$ erg

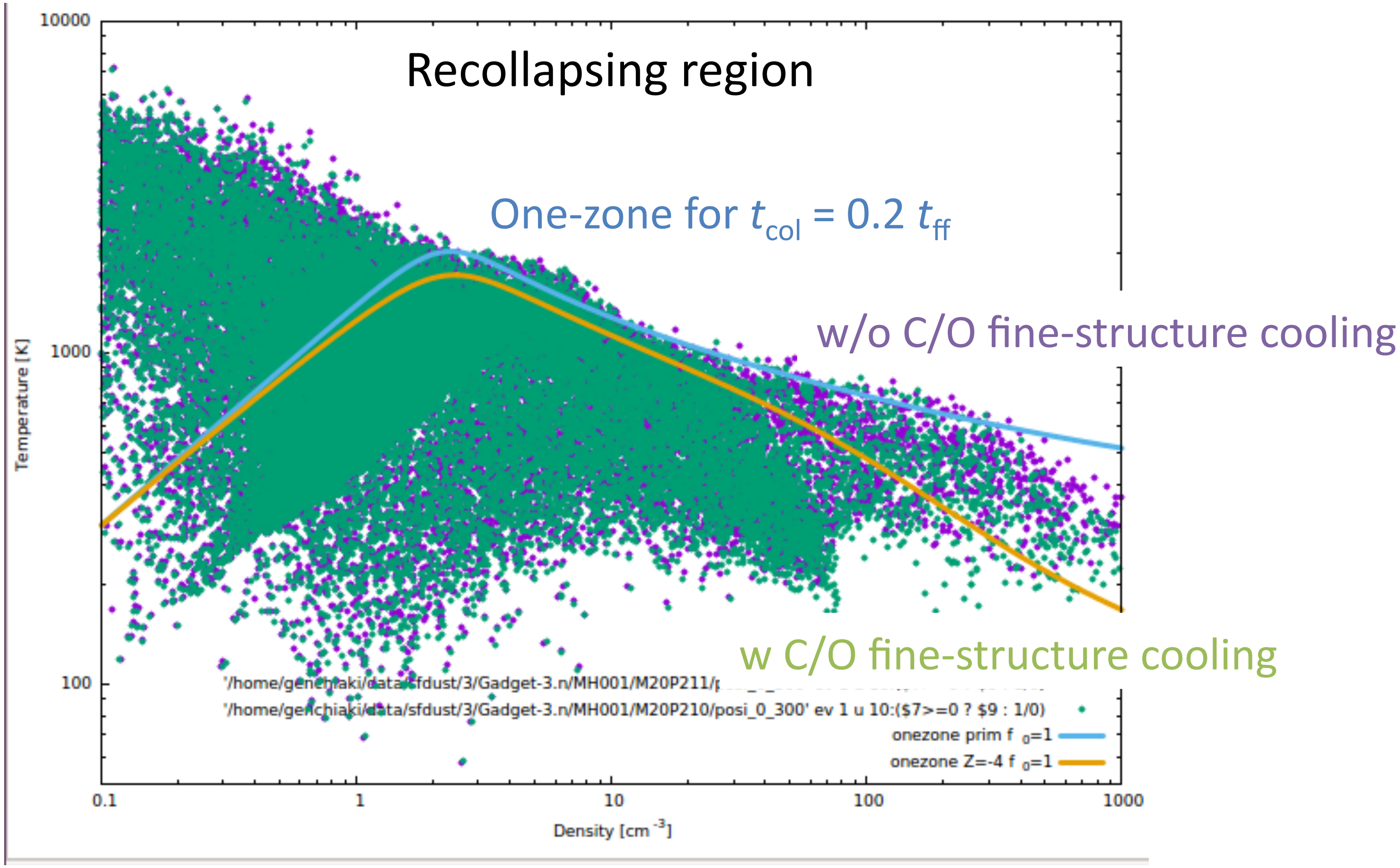


Tominaga et al. (2007)

Non-uniform ejecta structures: Evolution of SN shells

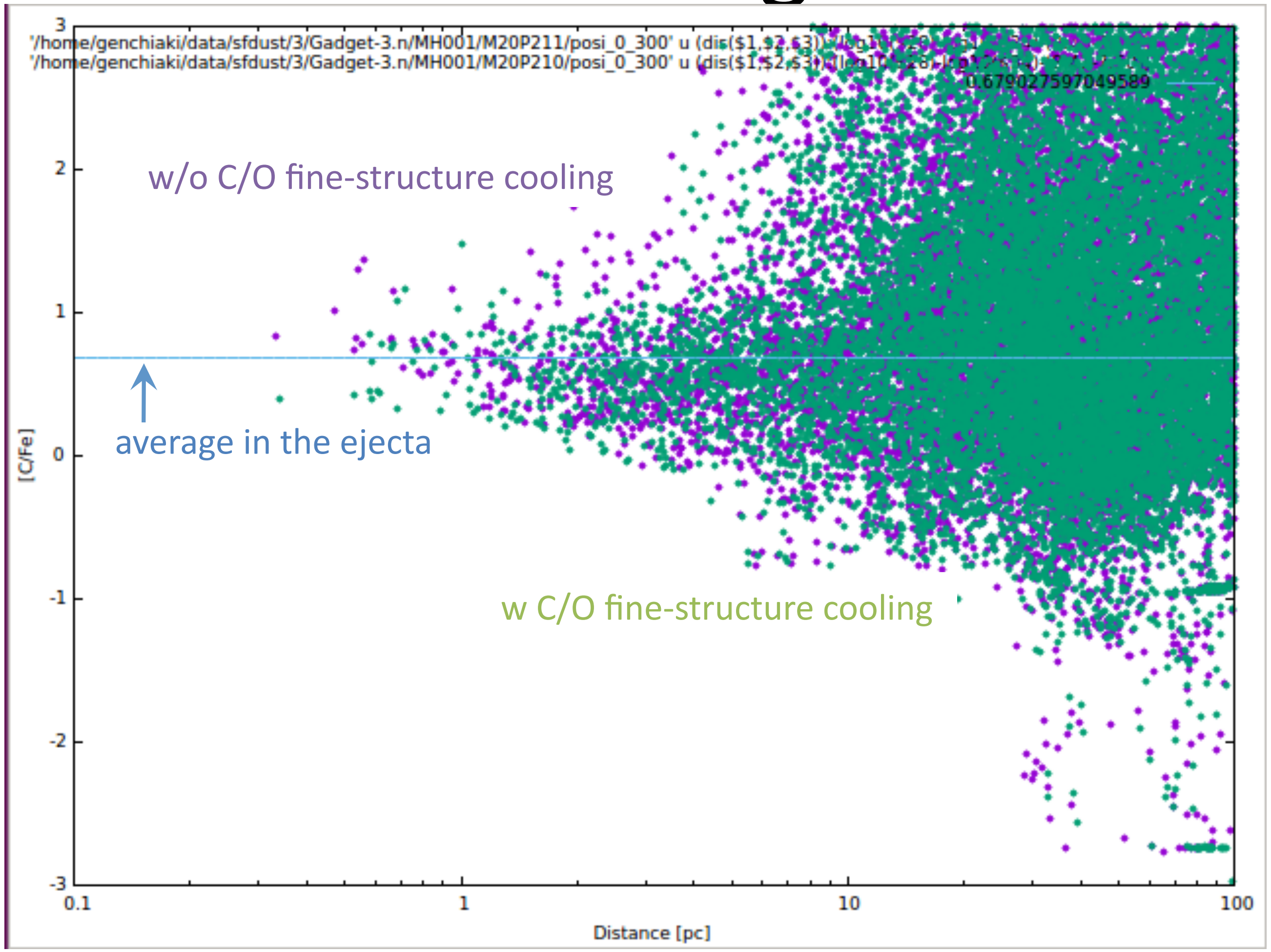


Non-uniform ejecta structures: Fine-structure cooling does not affect



We find that C/O fine-structure cooling hardly works because the dynamical time is small (~0.2 t_{ff}).

Non-uniform ejecta structures do not affect resulting abundances

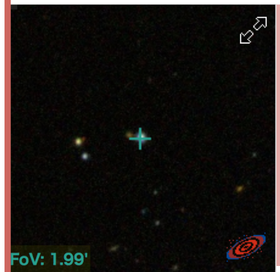


The abundance ratio [C/Fe] is not affected by the structure of the ejecta.
consistent with [C/Fe] for the uniform ejecta ([C/Fe]=0.67; blue line) within 0.1 dex

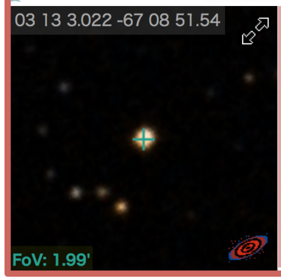
Metal-poor stars are clue to nucleosynthesis in the early Universe

Recently, in the galactic halo,
✓**Metal-Poor**（MP; [Fe/H] < 0）
✓long-lived（**low-mass**; $M_* < 0.8\ M_\odot$）
stars have been observed.

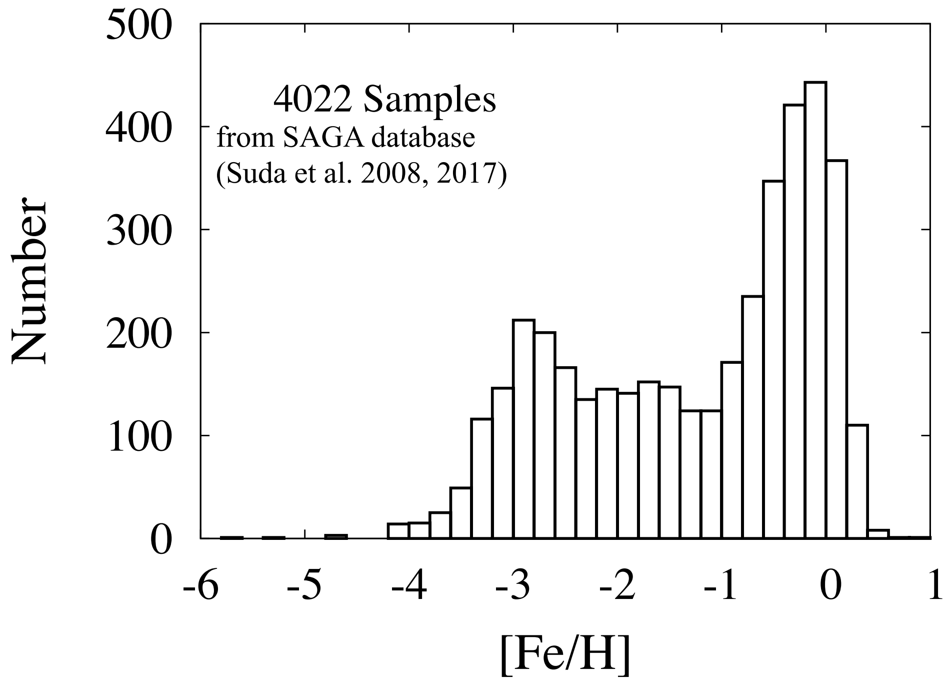
Examples:



SDSS J102915+172927
- Caffau et al. (2011)
- $Z<4.5\times10^{-5}\ Z_\odot$
- $0.8\ M_\odot$



SMSS J031300.36-670839.3
- Keller et al. (2014)
- [Fe/H]<−7.1
- $0.5\ M_\odot$



[Fe/H] = log [*n*(Fe)/n(H)]−log [*n*(Fe)/n(H)]

Their origins are intensively studied because they possibly inherit nucleosynthetic features of their progenitors, even Pop III stars.

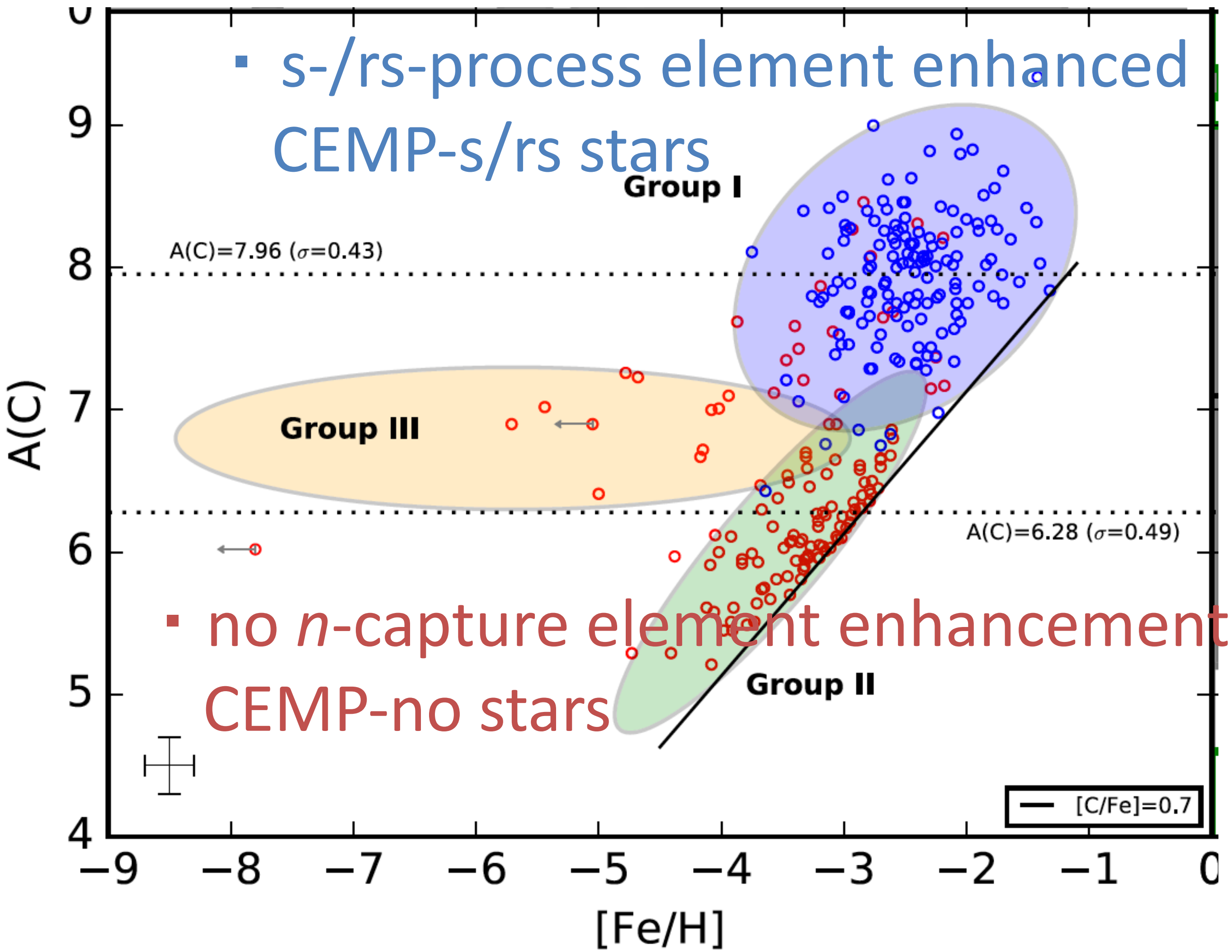
Classification of MP stars to constrain their origins

(Beers & Christlieb 2005)

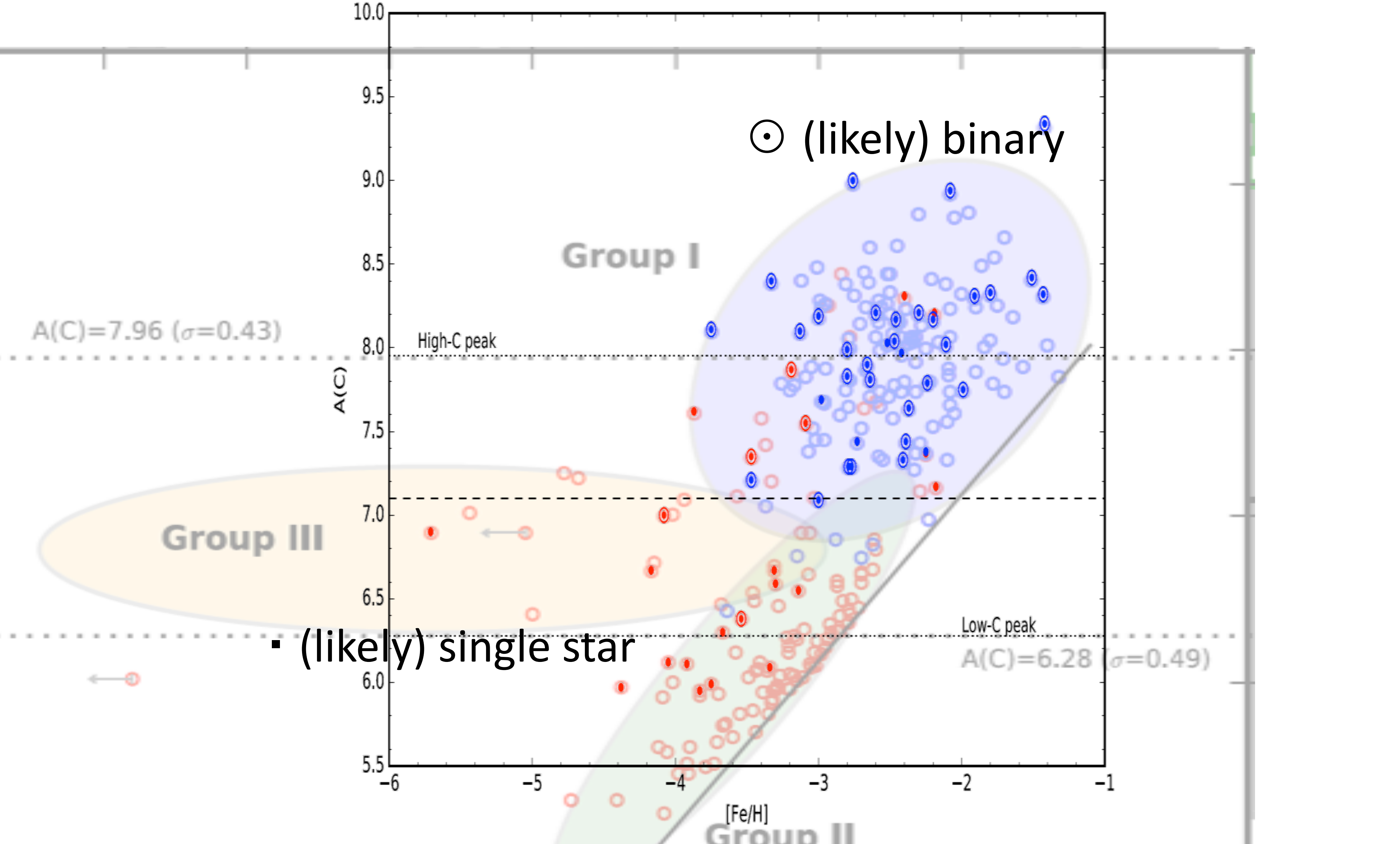
Neutron-capture-rich stars	
r-I	$0.3 \le [\mathrm{Eu/Fe}] \le +1.0$ and $[\mathrm{Ba/Eu}] < 0$
r-II	$[\mathrm{Eu/Fe}] > +1.0$ and $[\mathrm{Ba/Eu}] < 0$
s	$[\mathrm{Ba/Fe}] > +1.0$ and $[\mathrm{Ba/Eu}] > +0.5$
r/s	$0.0 < [\mathrm{Ba/Eu}] < +0.5$
Carbon-enhanced metal-poor stars	
CEMP	$[\mathrm{C/Fe}] >$ ~~+1.0~~ ⇨ 0.7 (Aoki et al. 2007)
CEMP-r	$[\mathrm{C/Fe}] > +1.0$ and $[\mathrm{Eu/Fe}] > +1.0$
CEMP-s	$[\mathrm{C/Fe}] > +1.0$, $[\mathrm{Ba/Fe}] > +1.0$, and $[\mathrm{Ba/Eu}] > +0.5$
CEMP-r/s	$[\mathrm{C/Fe}] > +1.0$ and $0.0 < [\mathrm{Ba/Eu}] < +0.5$
CEMP-no	$[\mathrm{C/Fe}] > +1.0$ and $[\mathrm{Ba/Fe}] < 0$

New classification of CEMP stars
Yoon-Beers diagram

(Yoon et al. 2016)

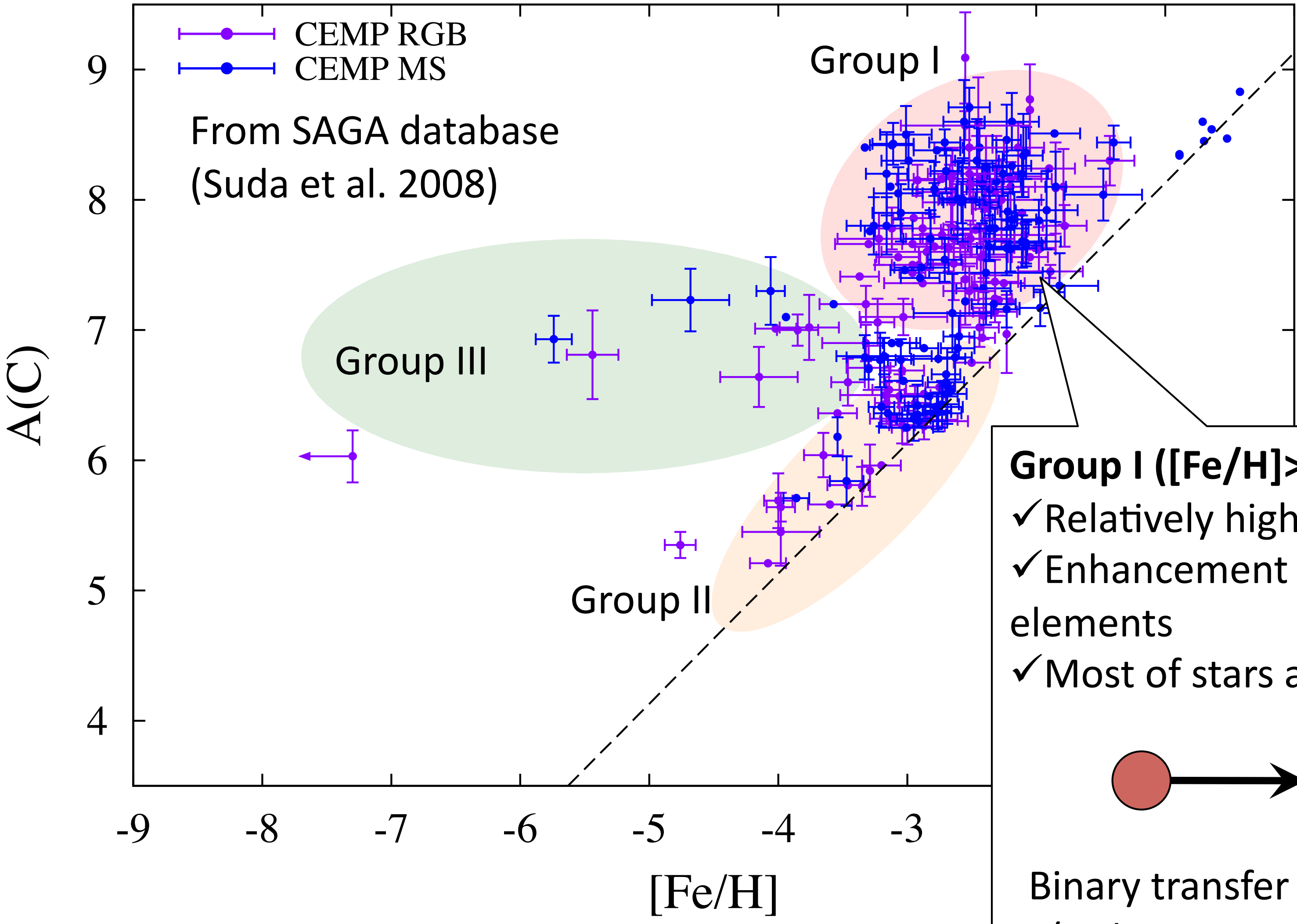


Binarity



⊙ (likely) binary
▪ (likely) single star
Group I
Group II
Group III
A(C)=7.96 (σ=0.43)
A(C)=6.28 (σ=0.49)
High-C peak
Low-C peak
A(C)
[Fe/H]
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
−6
−5
−4
−3
−2
−1

n-capture element enhancement and binality → binary transfer



Group I ([Fe/H]>−3)

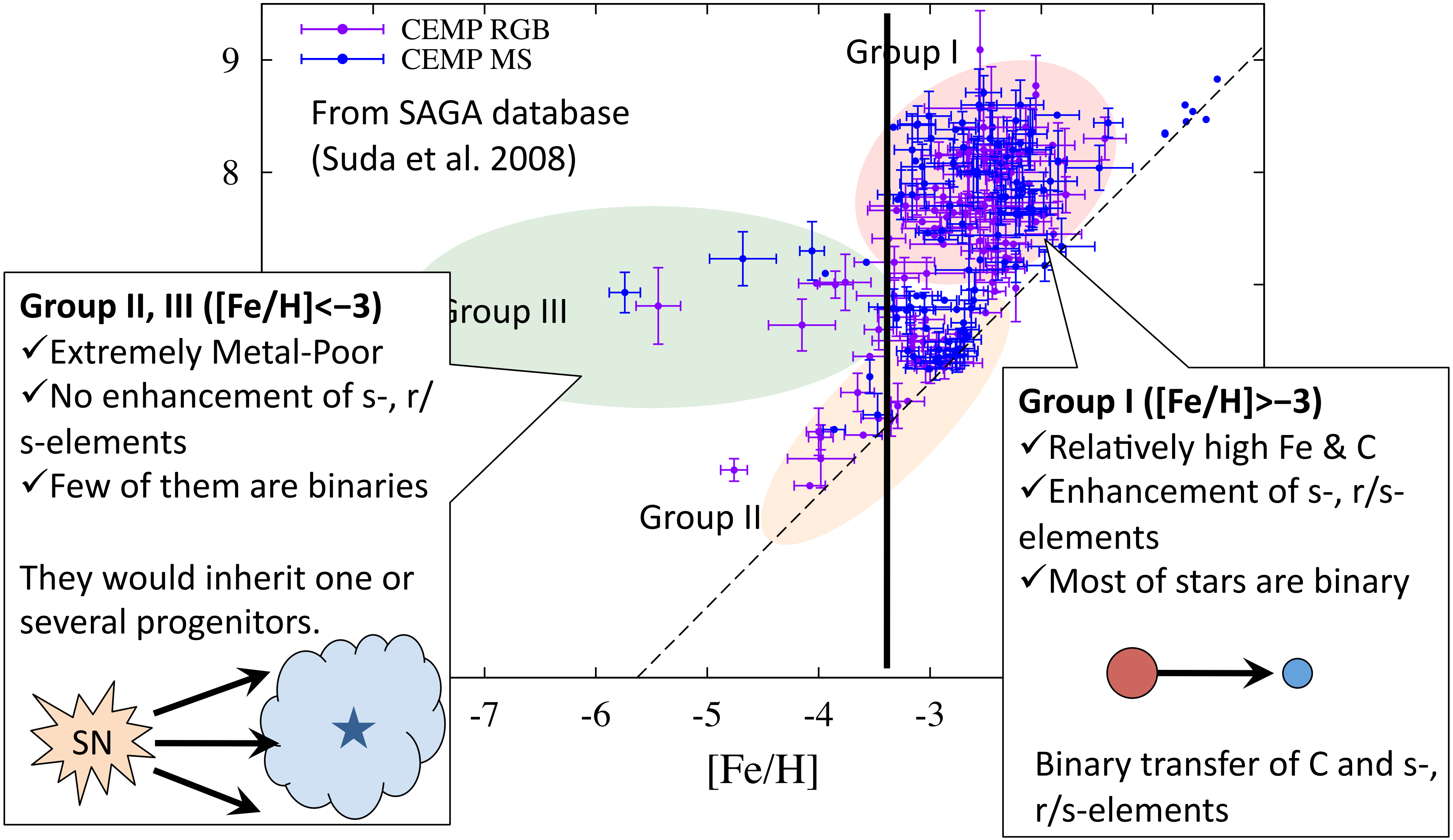
✓Relatively high Fe & C

✓Enhancement of s-, r/s-elements

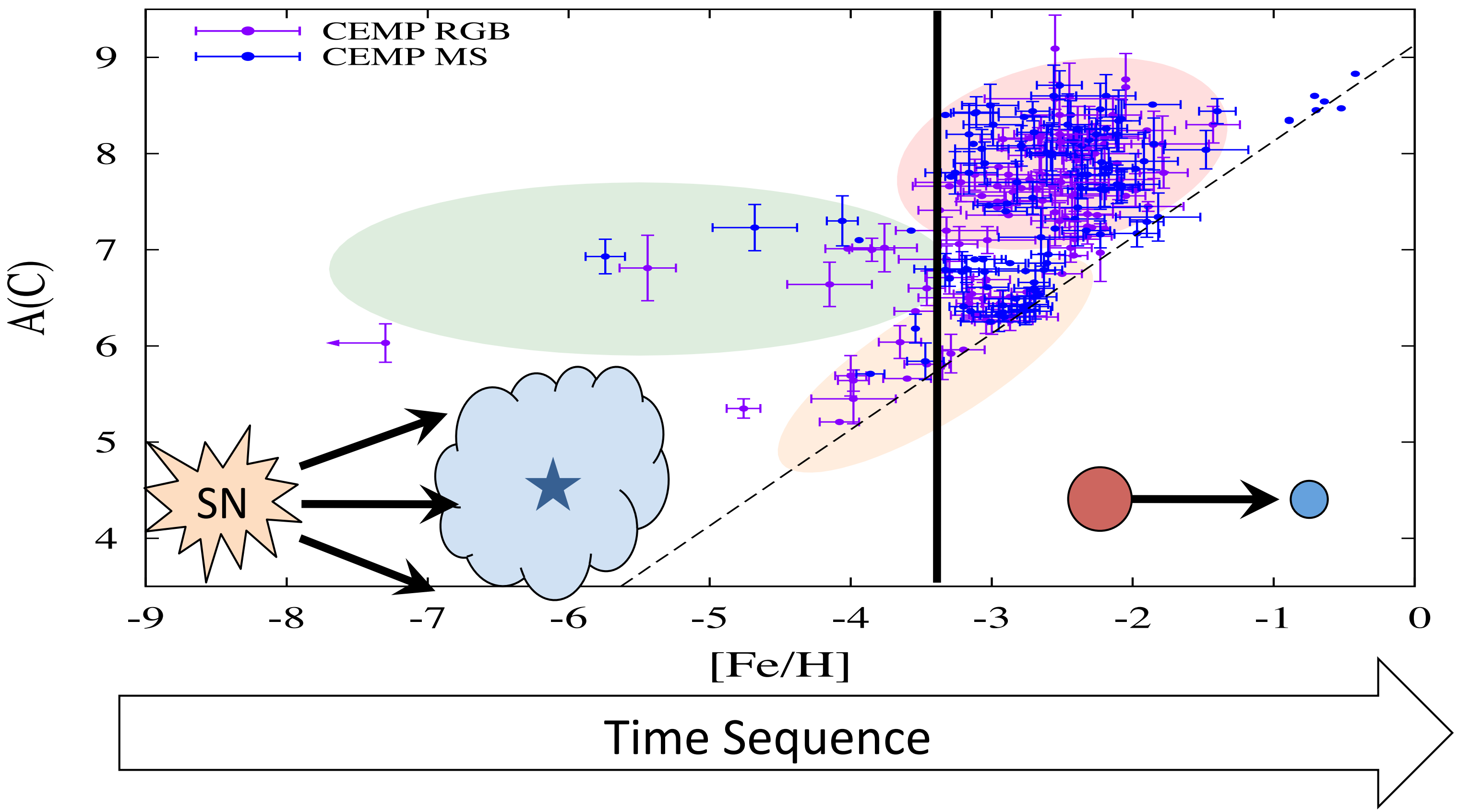
✓Most of stars are binary

Binary transfer of C and s-, r/s-elements

no *n*-capture element enhancement and no binarity → SN origin



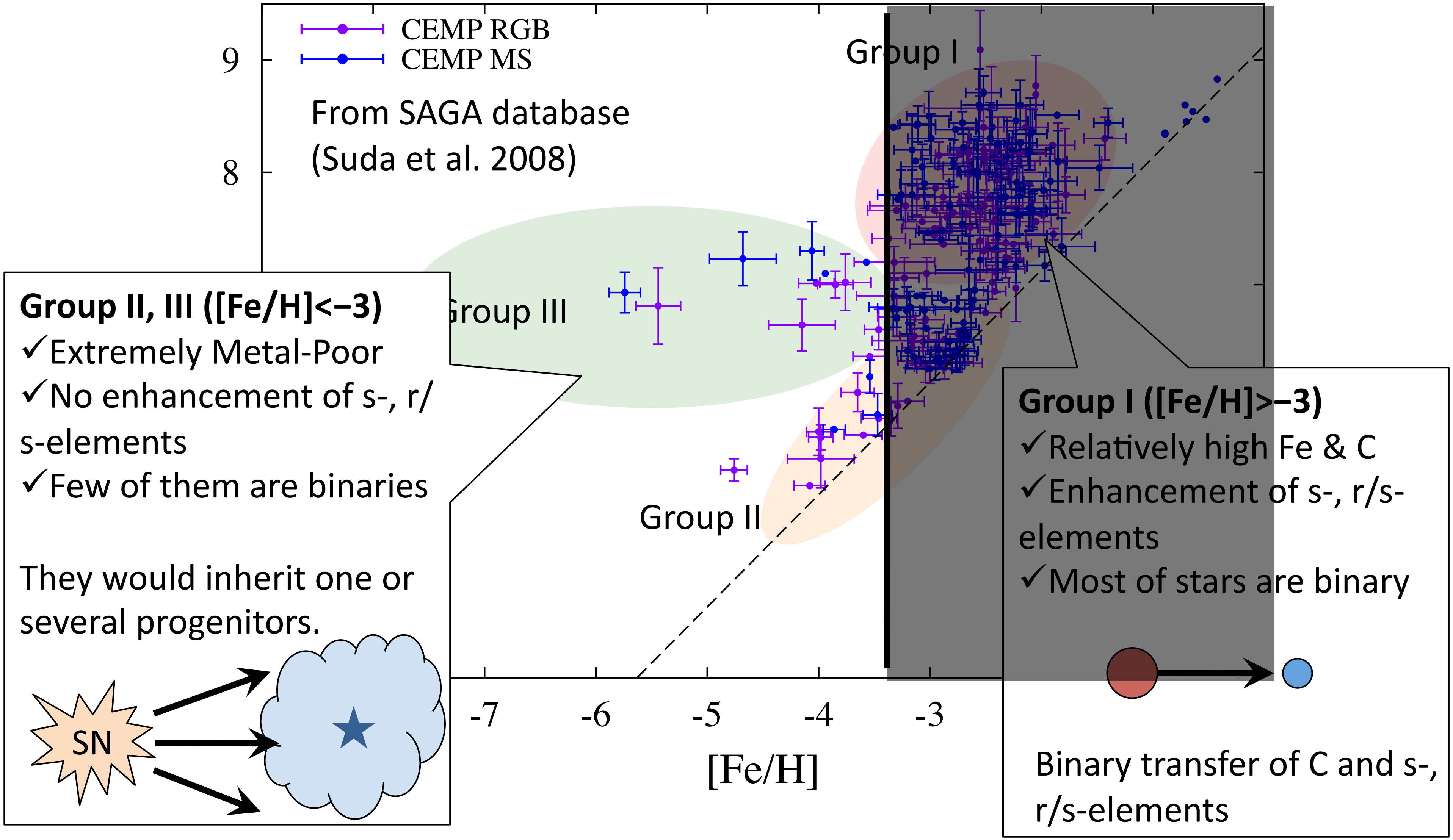
Transition of progenitors



If increase of [Fe/H] is equivalent to time sequence,
We can consider that
the progenitor is transitioned from massive SNe to low-mass binary companion at [Fe/H] ~ −3.5.

(See Suda-san's talk)

We here focus on extremely metal-poor (EMP) stars with [Fe/H] < −3



Group II, III ([Fe/H]<−3)

✓Extremely Metal-Poor

✓No enhancement of s-, r/s-elements

✓Few of them are binaries

They would inherit one or several progenitors.

Group I ([Fe/H]>−3)

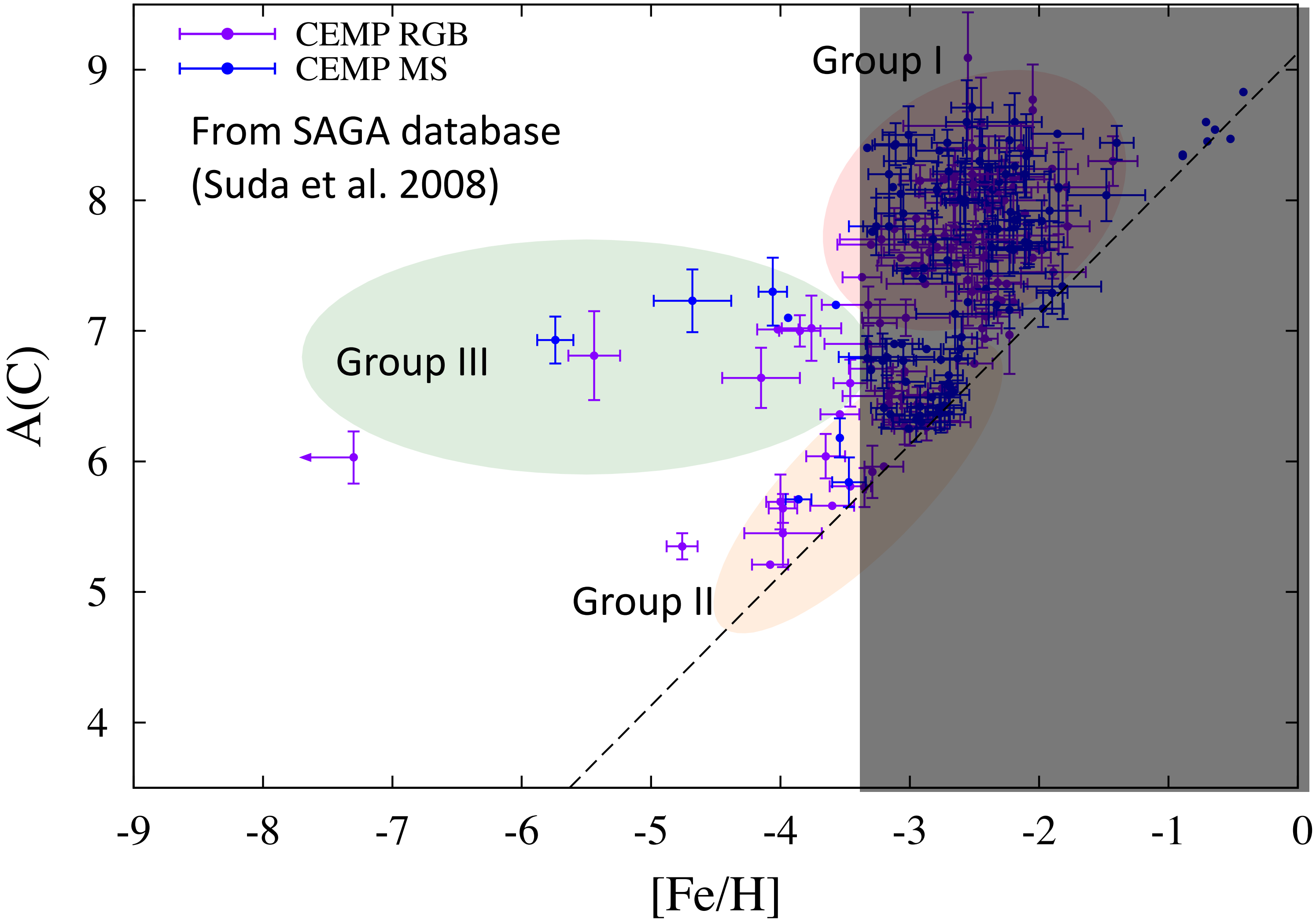
✓Relatively high Fe & C

✓Enhancement of s-, r/s-elements

✓Most of stars are binary

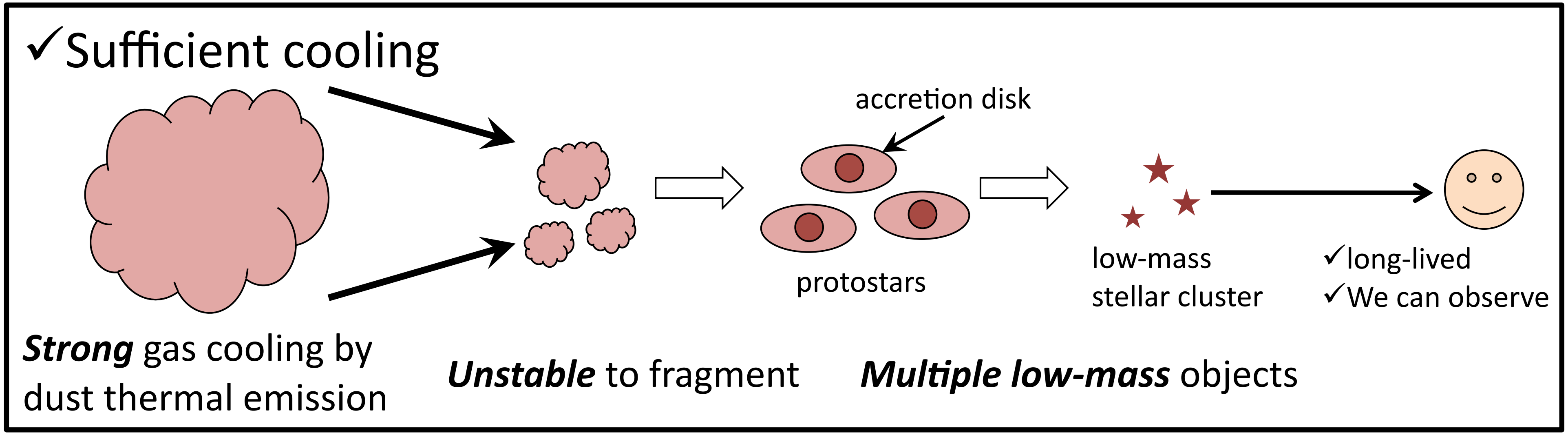
Binary transfer of C and s-, r/s-elements

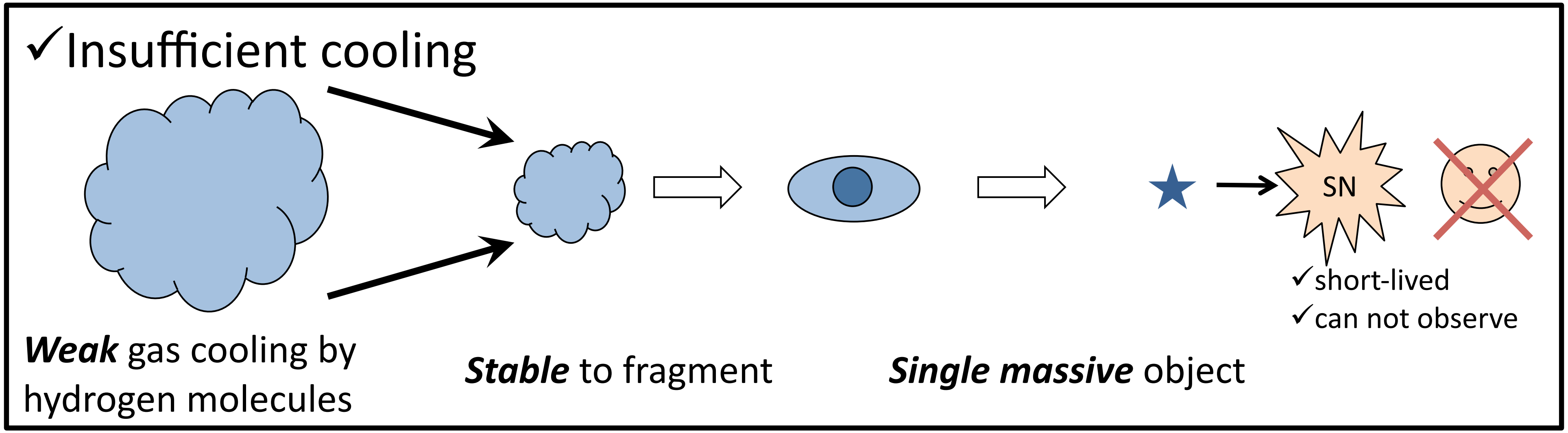
Can low-mass stars be formed with extremely low metallicity?



Radiative cooling determines the process of cloud collapse

(Omukai 2000; Schneider et al. 2003; Dopcke et al. 2011, 2013; Bromm et al. 2014; Safranek-Shrader 2014, 2016)

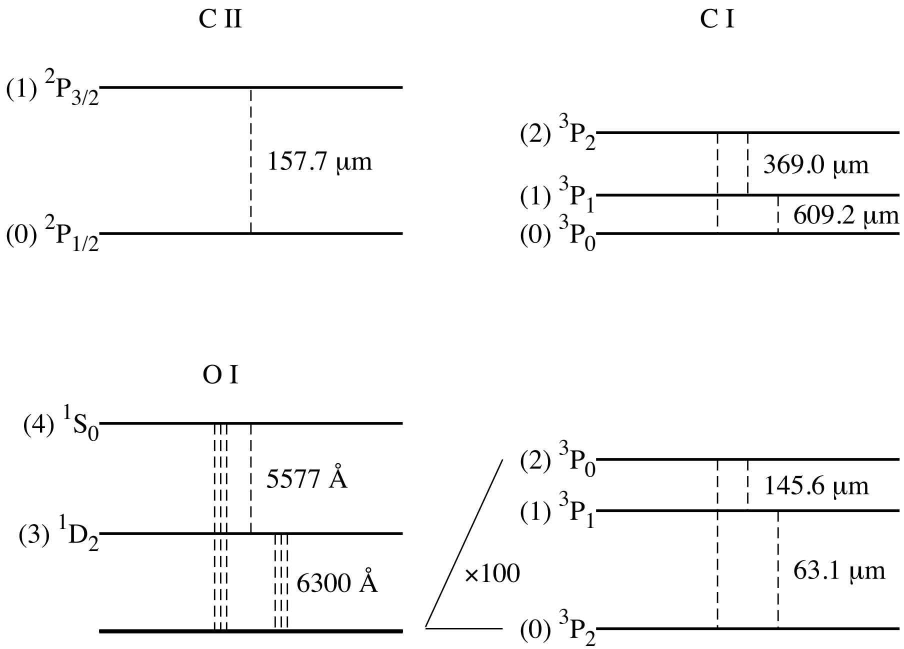


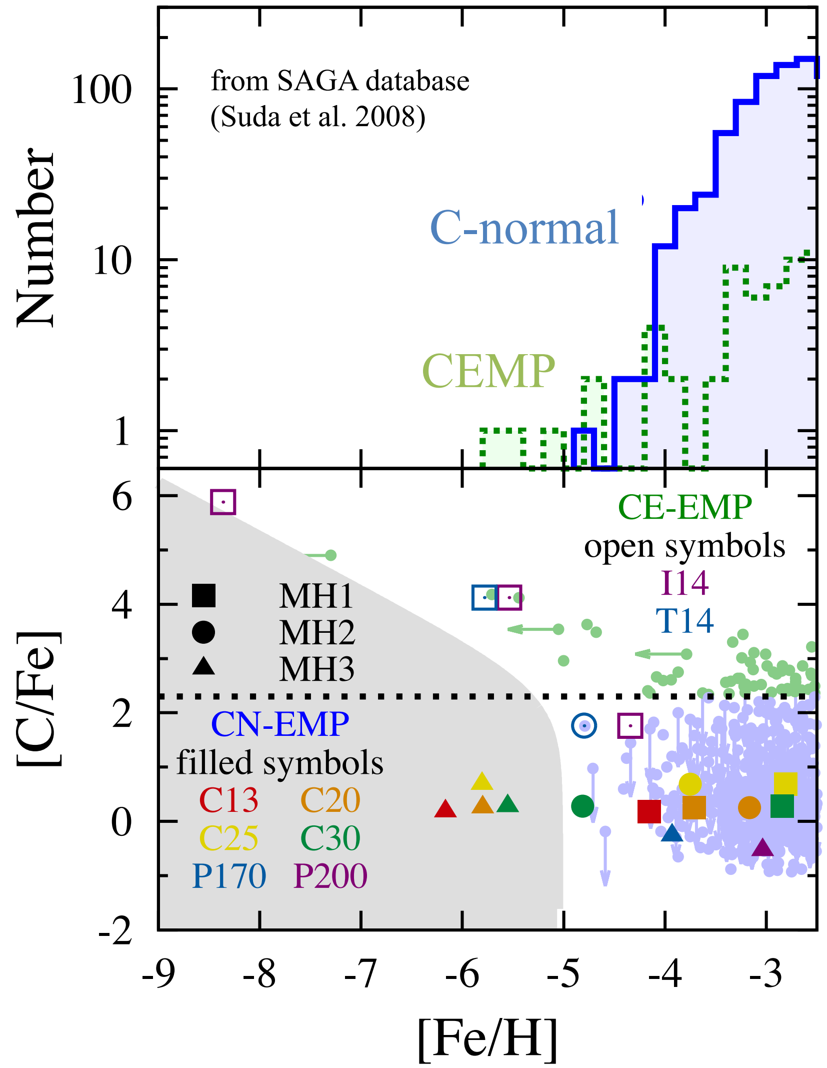


Scenario1: C/O fine−structure cooling

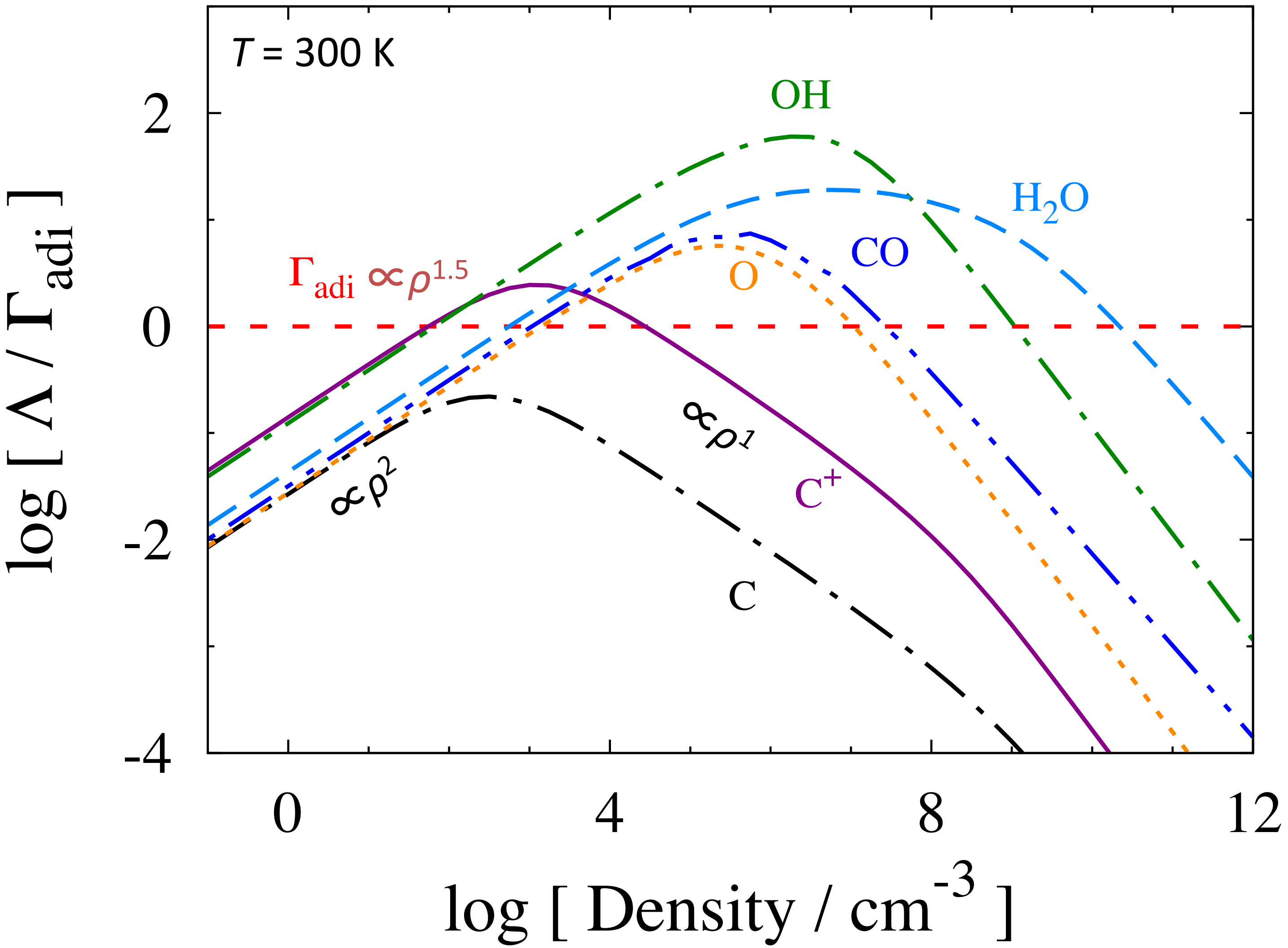
(Bromm & Loeb 2003; Frebel 2005)

To explain the formation of CEMP stars. The CEMP fraction increases with lower metallicity.



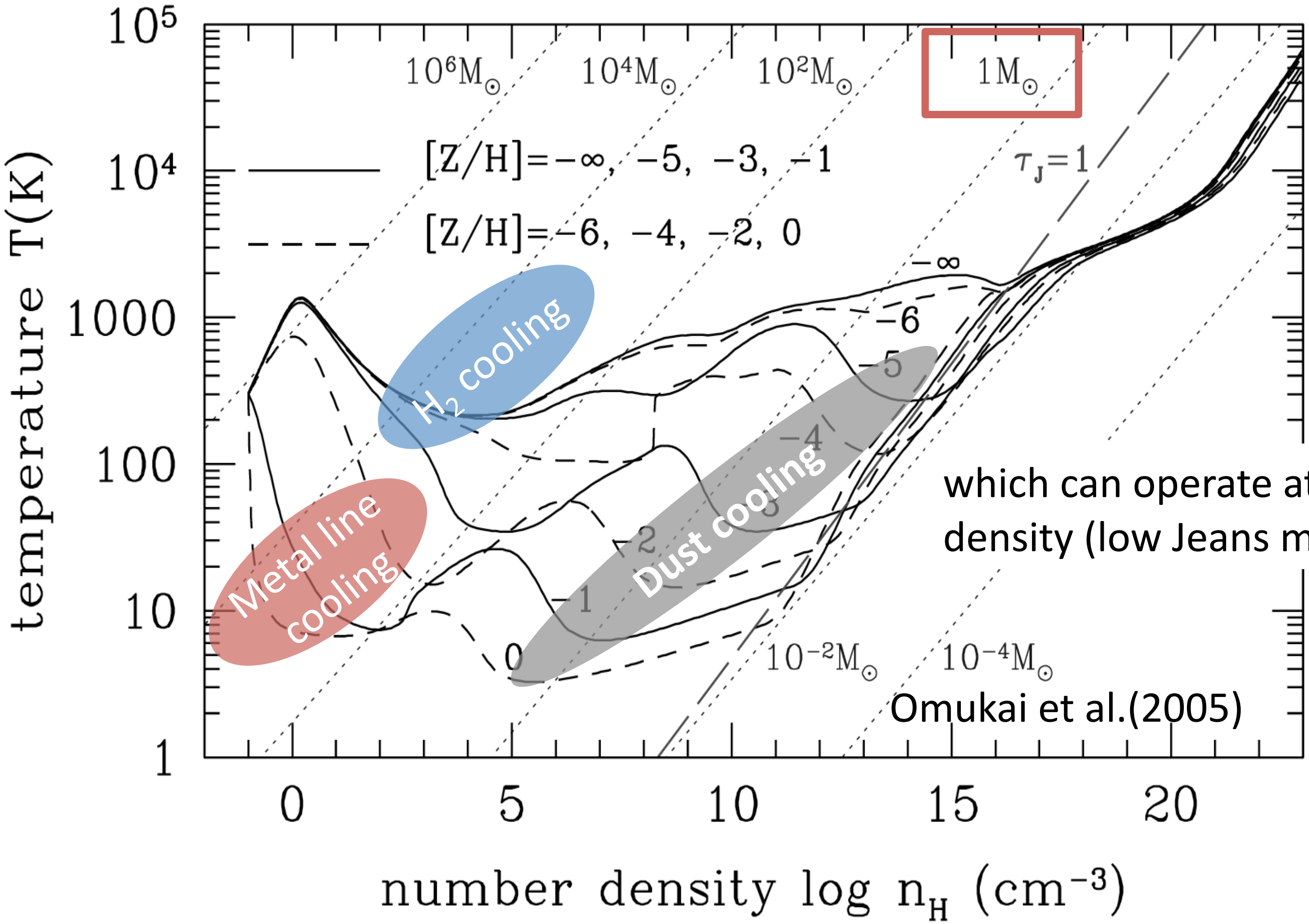


C/O cooling becomes ineffective at low density/high Jeans mass



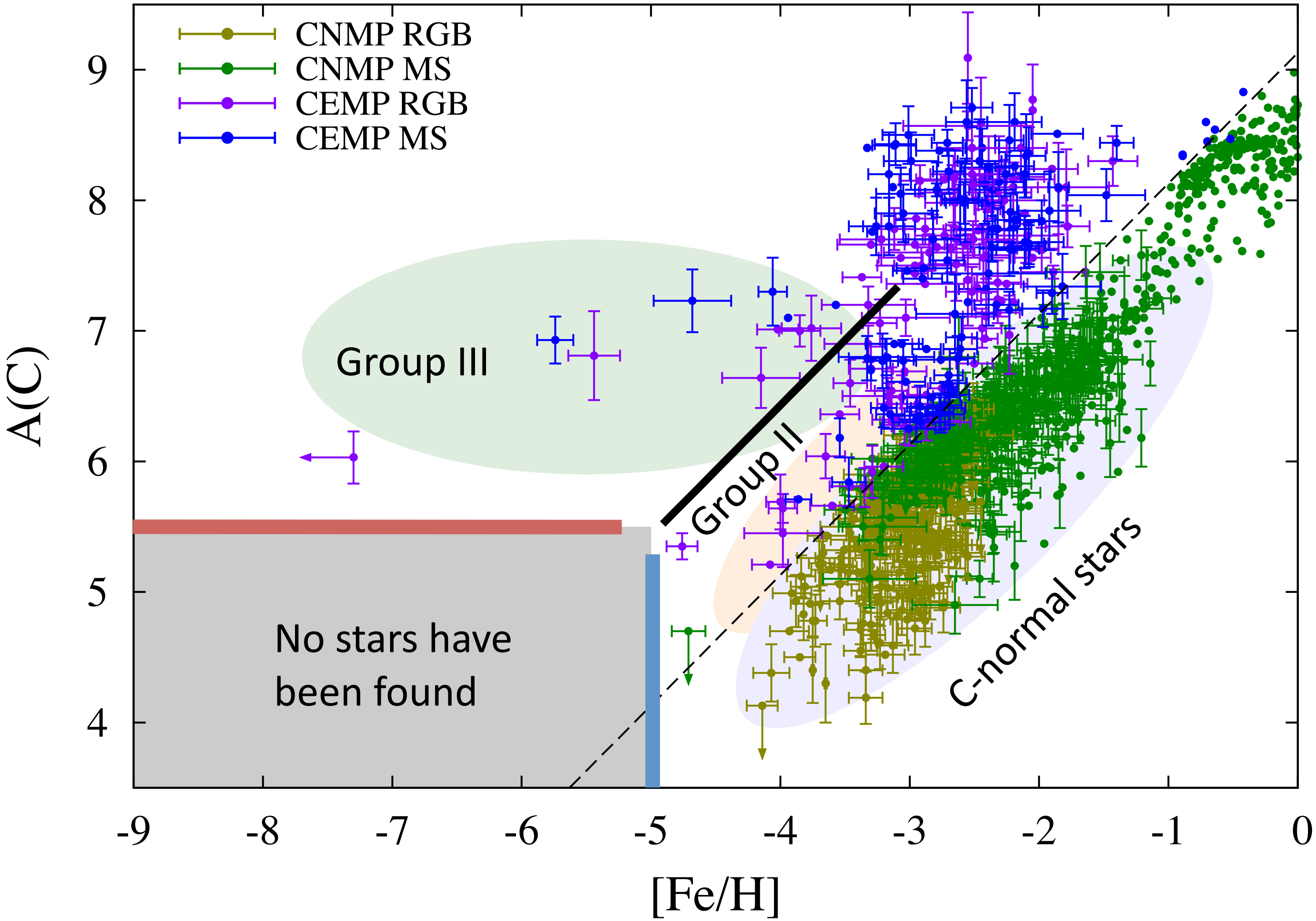
Scenario 2: Dust cooling

(Omukai 2000; Schneider et al. 2003)



which can operate at high density (low Jeans mass).

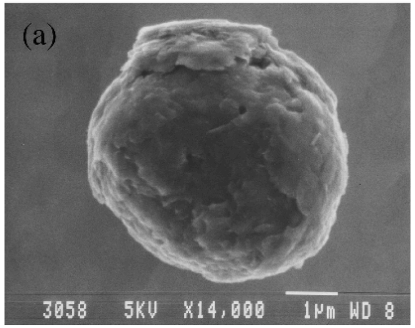
Two critical abundances:
$A_{cr}(C) \sim 6$, $[Fe/H]_{cr} \sim -5$



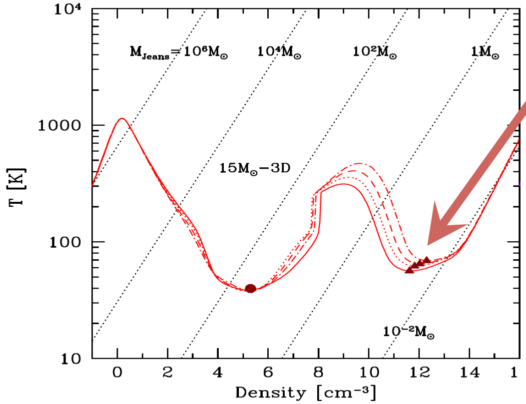
For the formation of C-enhanced/ normal EMP stars, carbon/silicate grains are important

Carbonaceous grains

✓Composition: C



Lodders & Amari (2005)



Carbon grain cooling

⇩

Low-mass fragmentation

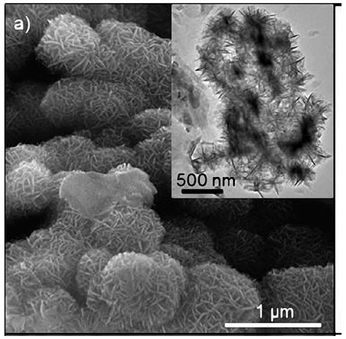
⇩

Critical C abundance is defined

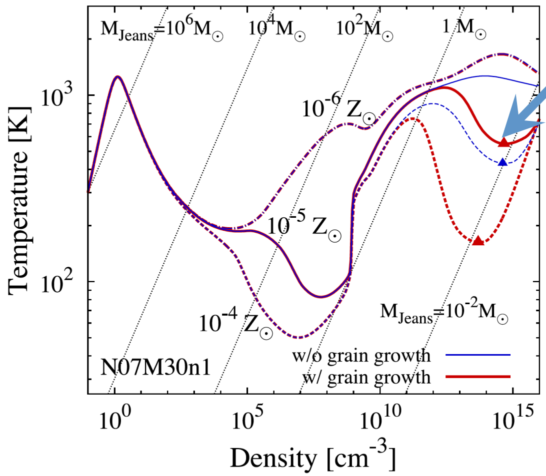
Marassi et al. (2014)

Silicate grains

✓Composition: O, Si, Mg, …



Moyce et al. (2015)



Silicate grain cooling

⇩

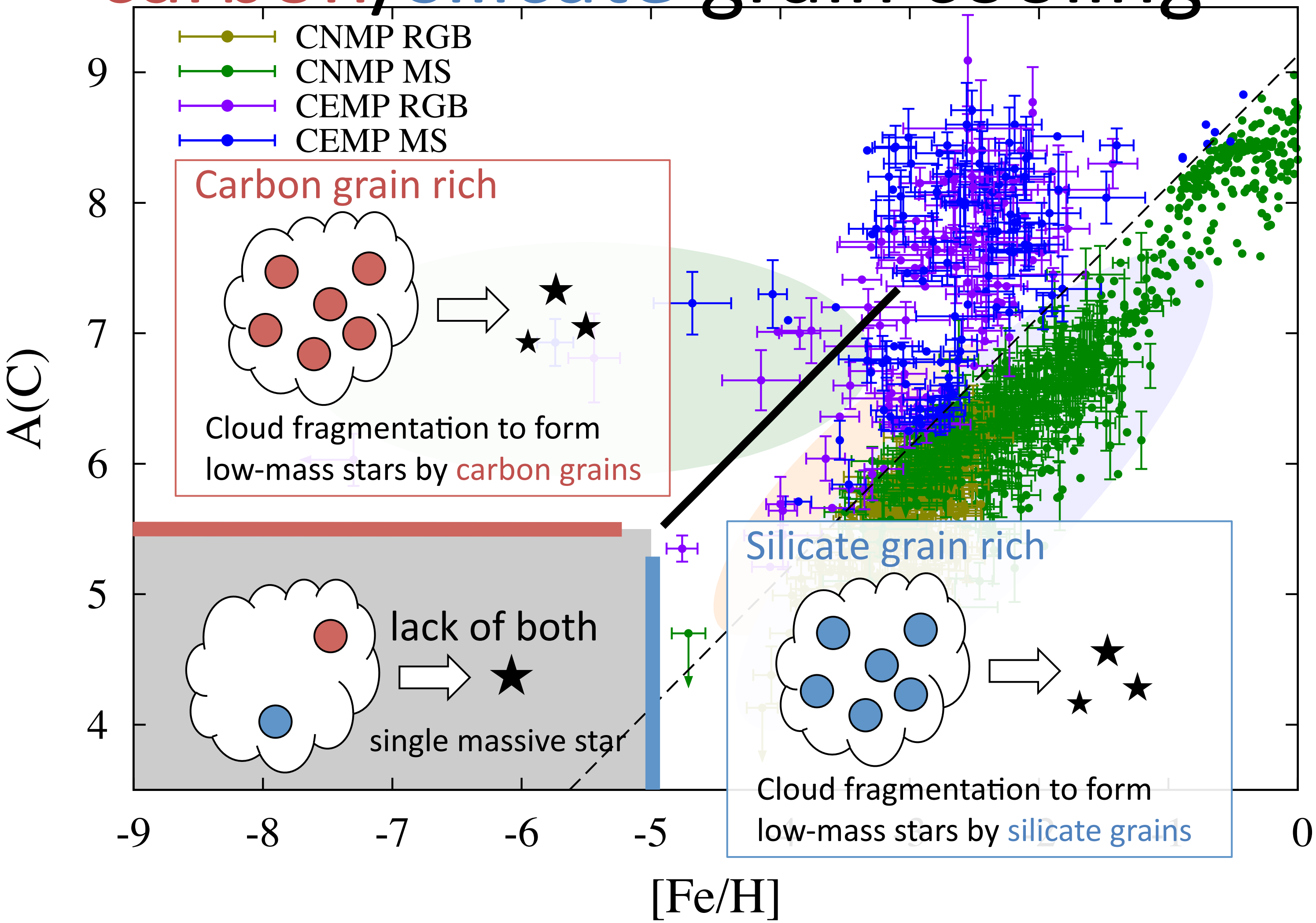
Low-mass fragmentation

⇩

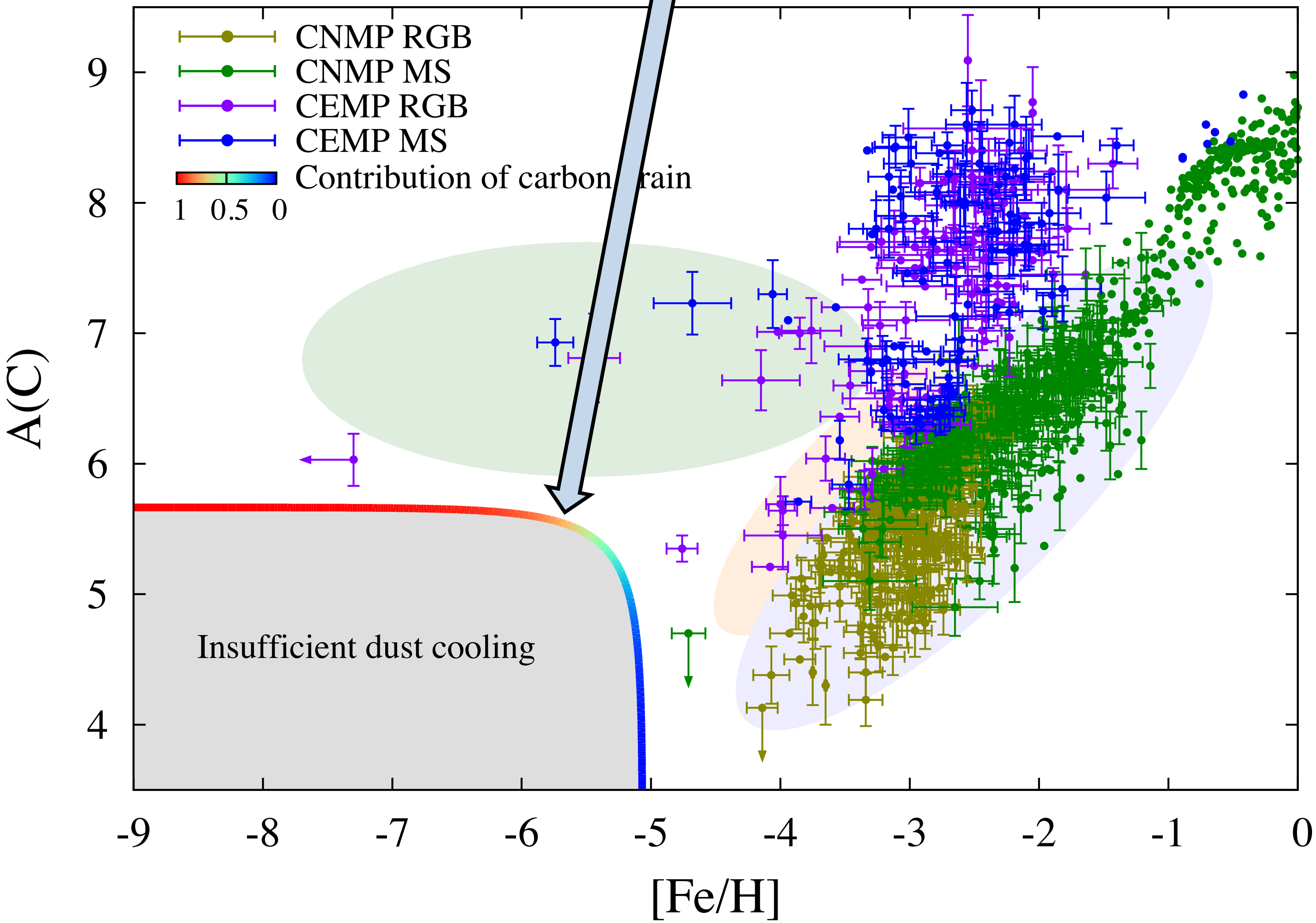
Critical Mg and Si abundance is defined

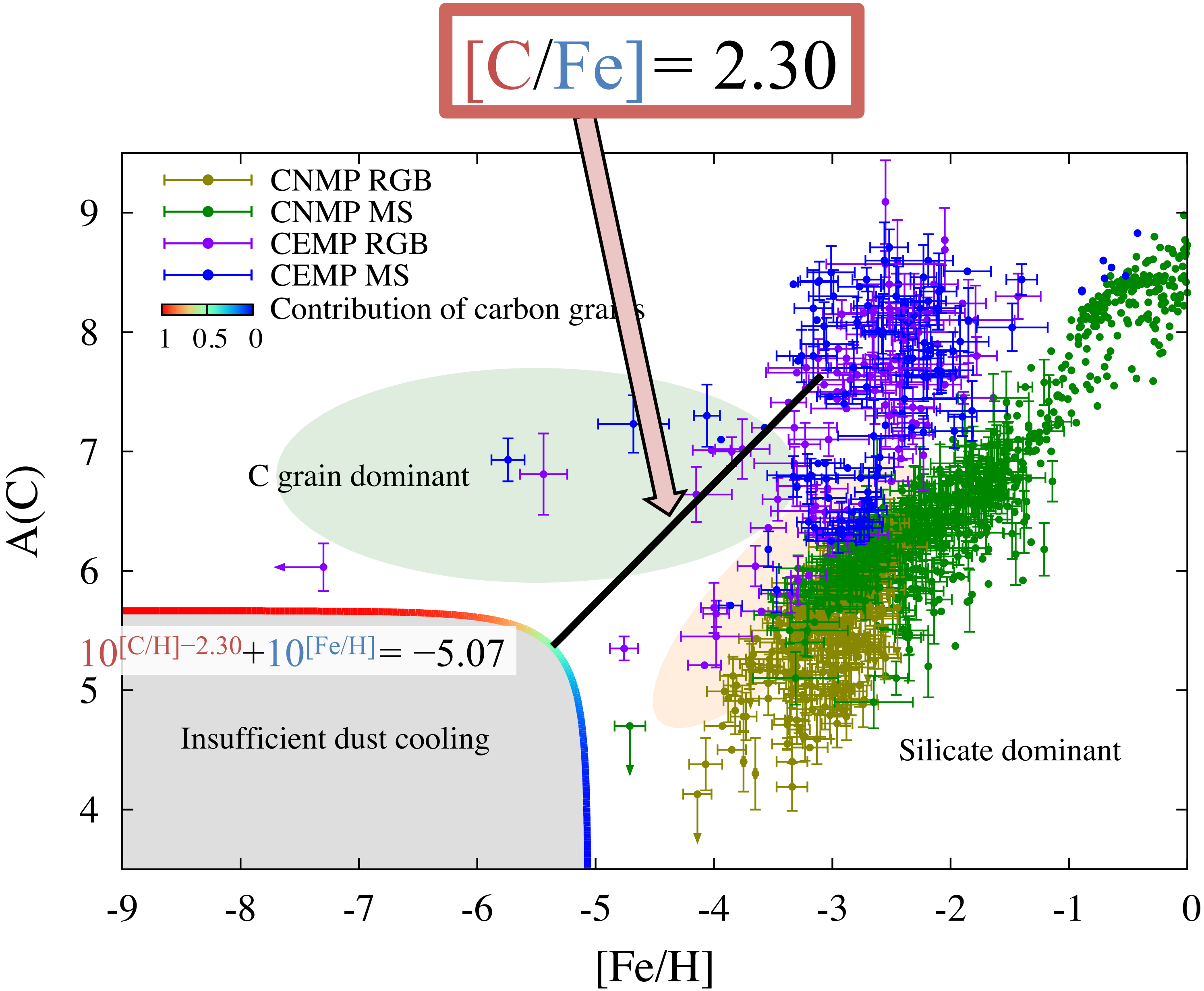
Chiaki et al. (2015)

Only *two* classes where low-mass star formation is triggered by carbon/silicate grain cooling



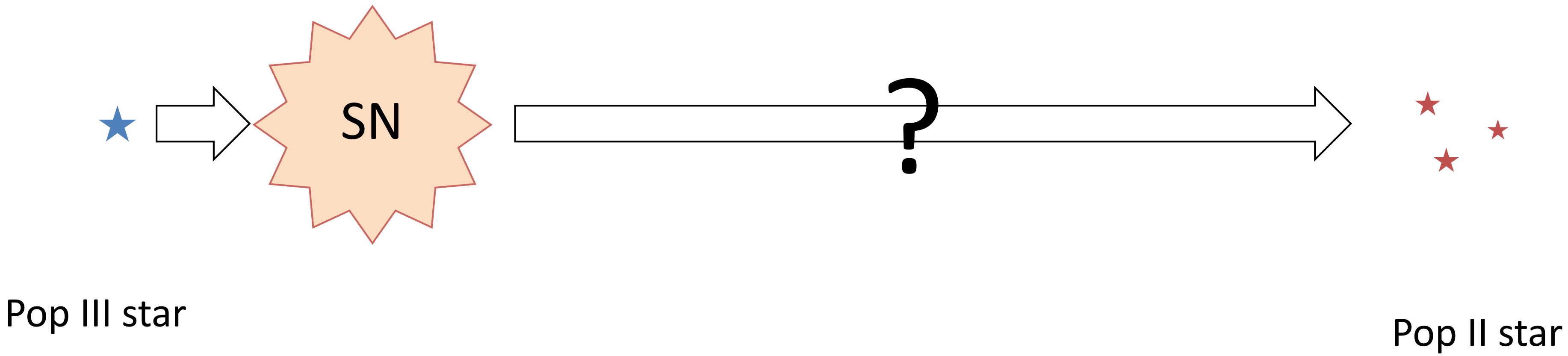
$$10^{[C/H]-2.30}+10^{[Fe/H]} = -5.07$$





[C/Fe]= 2.30
CNMP RGB
CNMP MS
CEMP RGB
CEMP MS
Contribution of carbon grains
1 0.5 0
C grain dominant
$10^{[C/H]-2.30}+10^{[Fe/H]}= -5.07$
Insufficient dust cooling
Silicate dominant
A(C)
[Fe/H]

How do the EMP star-forming clouds acquire metal/dust?

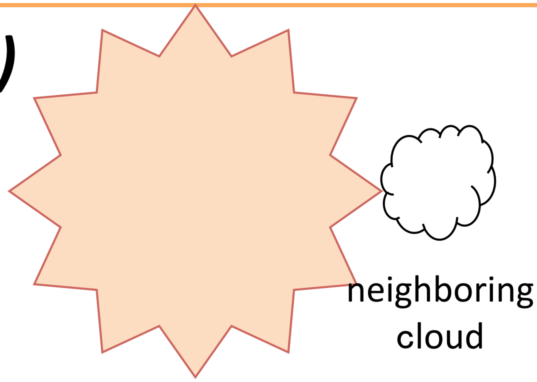


Two enrichment mode: external enrichment (EE)/internal enrichment (IE)

External Enrichment (EE)

Enrichment of neighboring halos

(Smith et al. 2015; Chen et al. 2016)

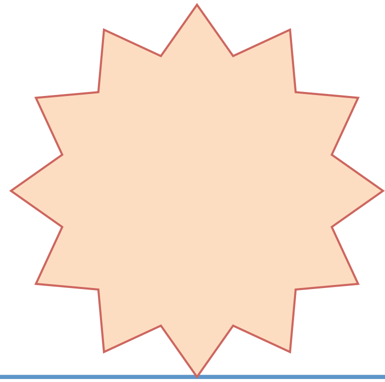


Pop III star

Internal Enrichment (IE)

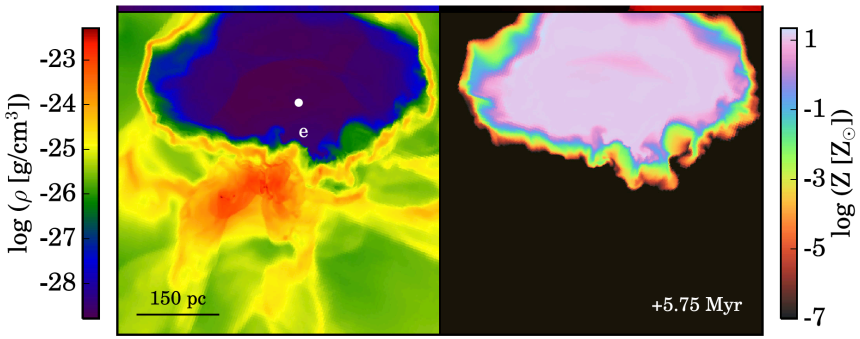
Self-enrichment of Pop III star forming halo

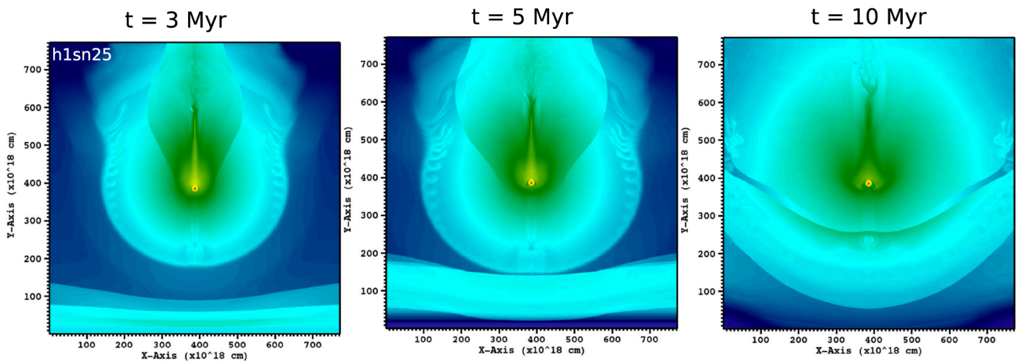
(Ritter et al. 2012, 2015, 2016, Sluder et al. 2016)

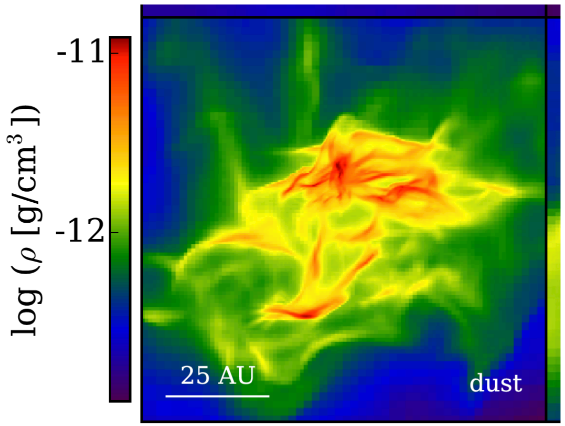


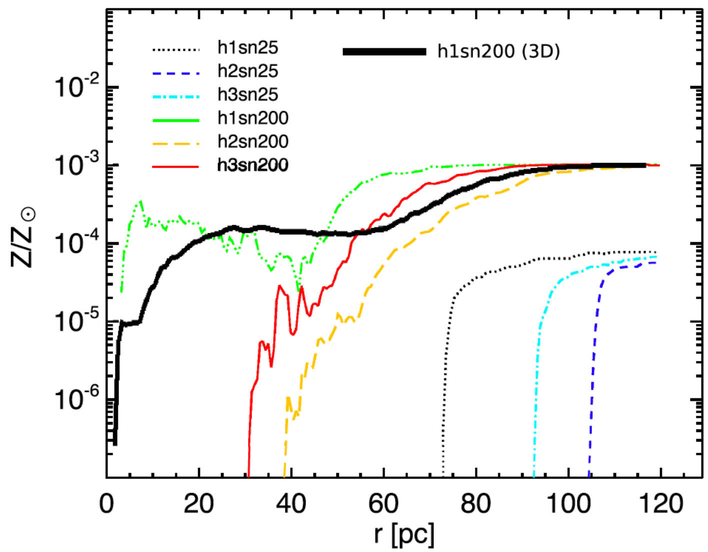
Pop II star

External enrichment

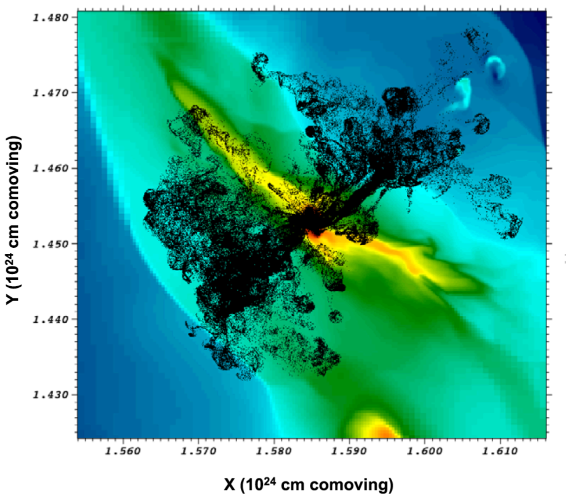


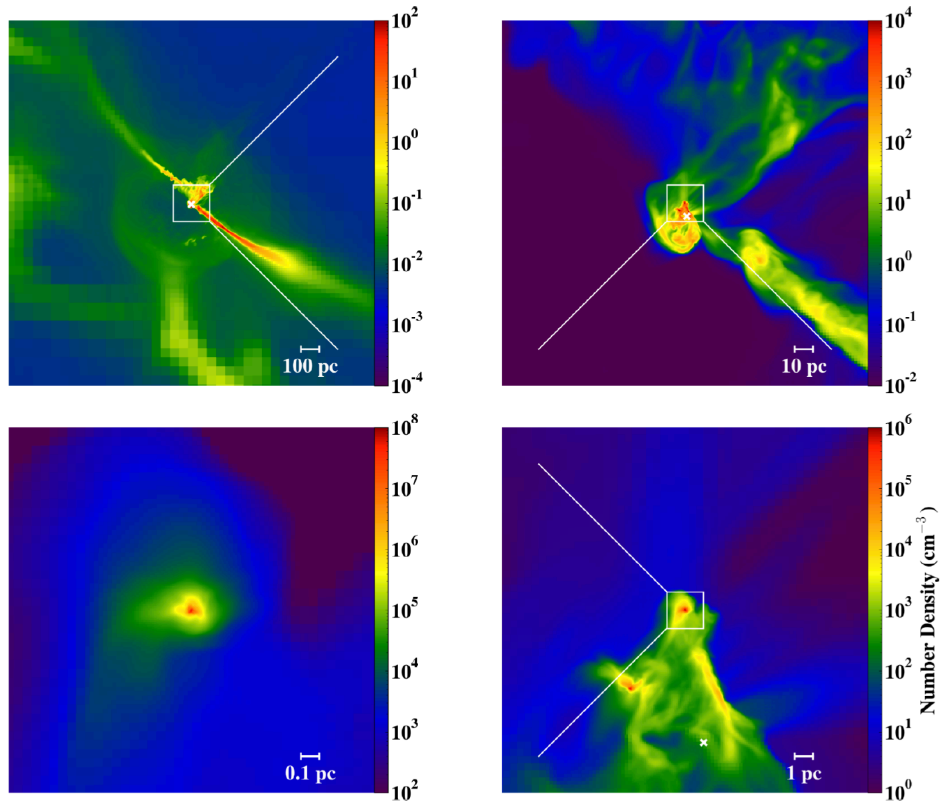




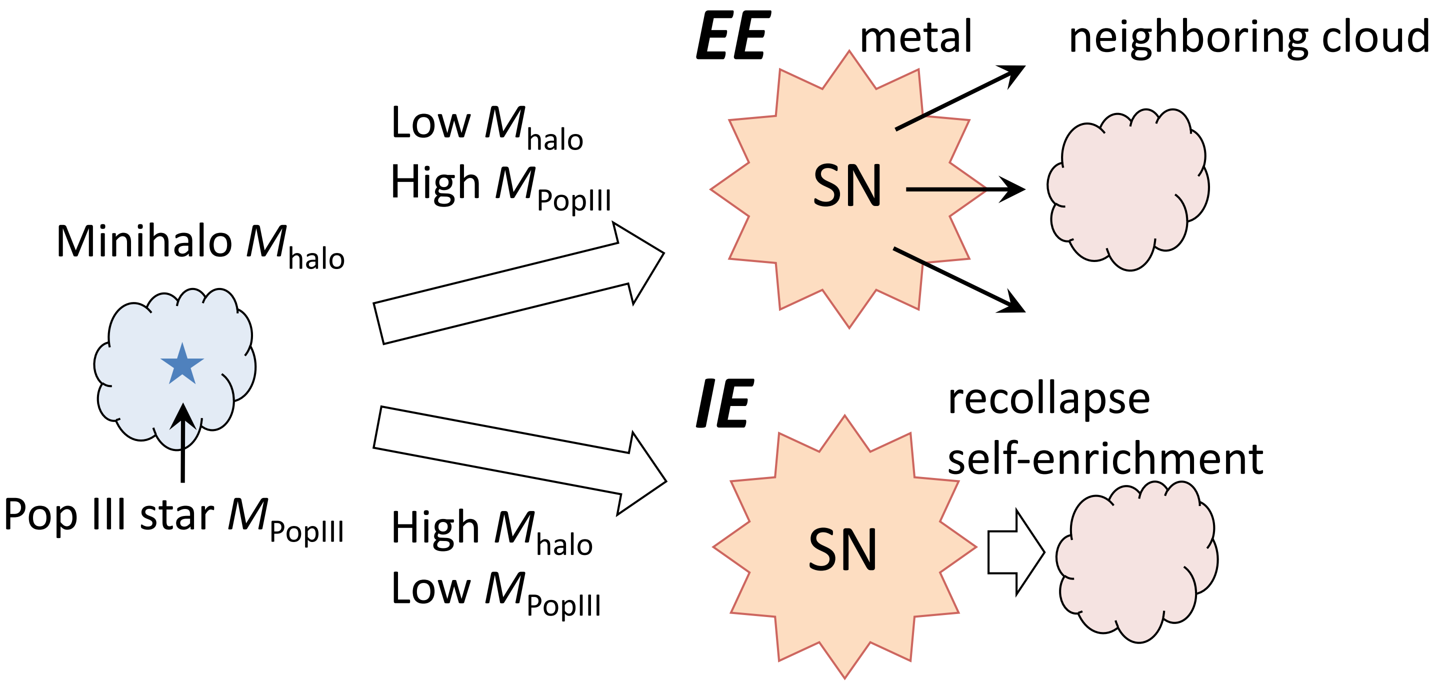


Internal enrichment





Either EE or IE happens, depending on M_{halo} and M_{PopIII}



✓What is he condition for EE/IE?

✓Which mode IE or EE is dominant?

Method

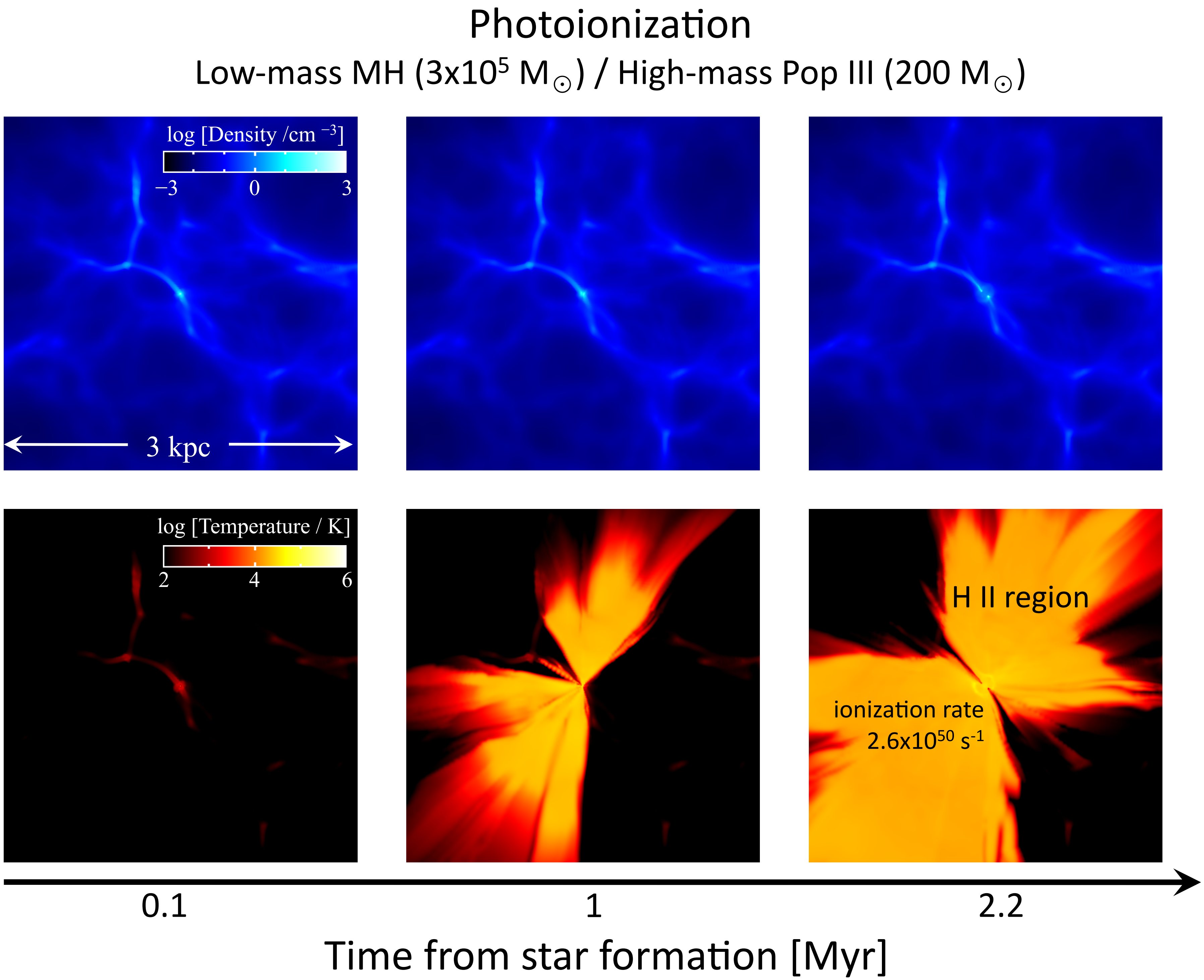
- ☹ GADGET-2 (Springel 2005)
- Non-eq. chemistry
  15 species
  e, H, H^+, H_2, H^-, H_2^+, HeH^+, He, He^+, He^{2+}, D, D^+, D^-, HD, and HD^+
  53 reactions
- Radiative transfer
  $H + \gamma \rightarrow H^+ + e$
  $H_2 + \gamma \rightarrow H + H$
- Radiative cooling
  H_2, HD ro-vib. cooling
  H, He, He^+ line, ion./rec. cooling
  Brems, & Compton
- Heating by ionizing photons

Target halos

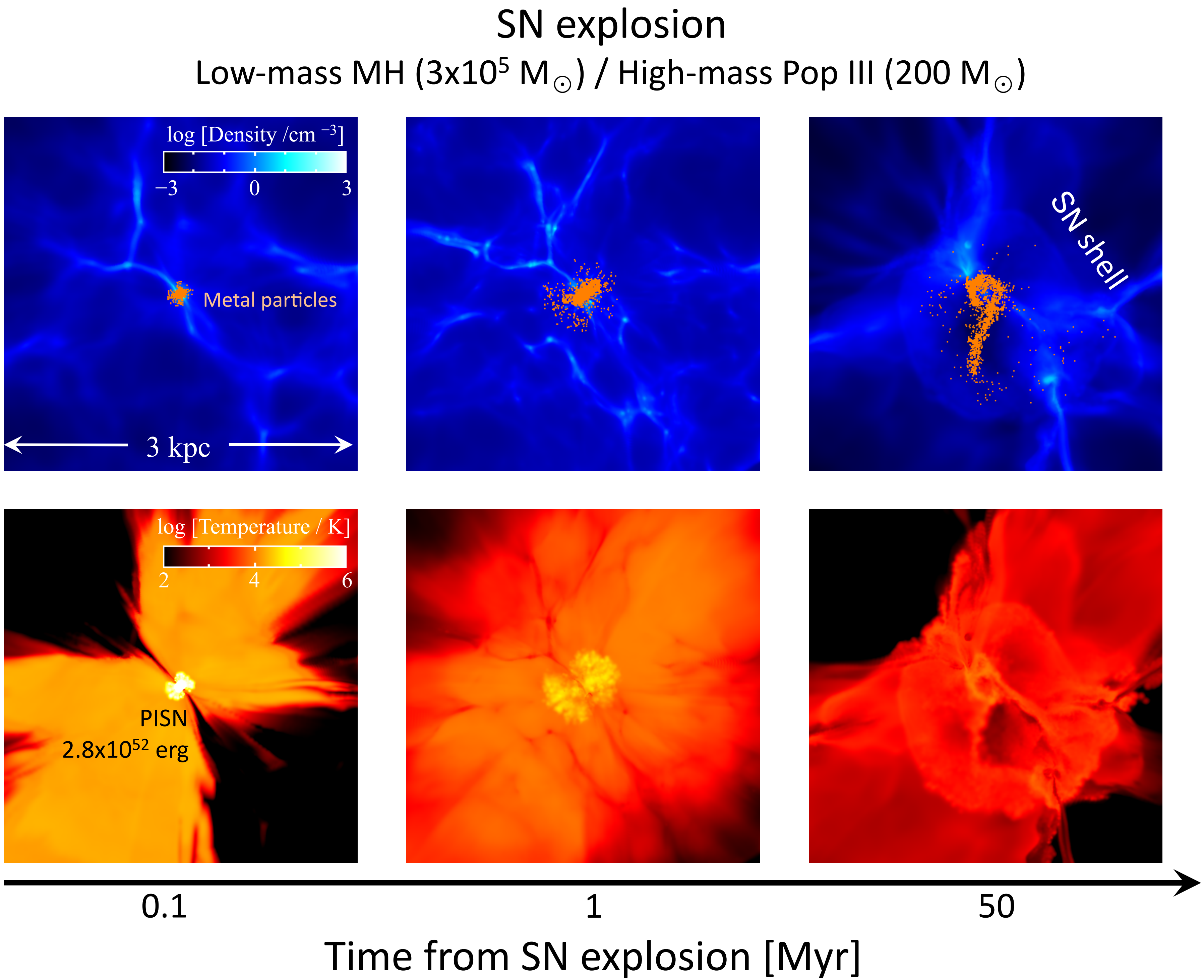
Halo	M_{halo}^{col} [$M_\odot$]	R_{halo}^{col} [pc]	z_{col}
MH1	2.94e5	70.12	28.47
MH2	3.89e5	79.52	27.52
MH3	3.23e6	186.85	23.58

Pop III stars

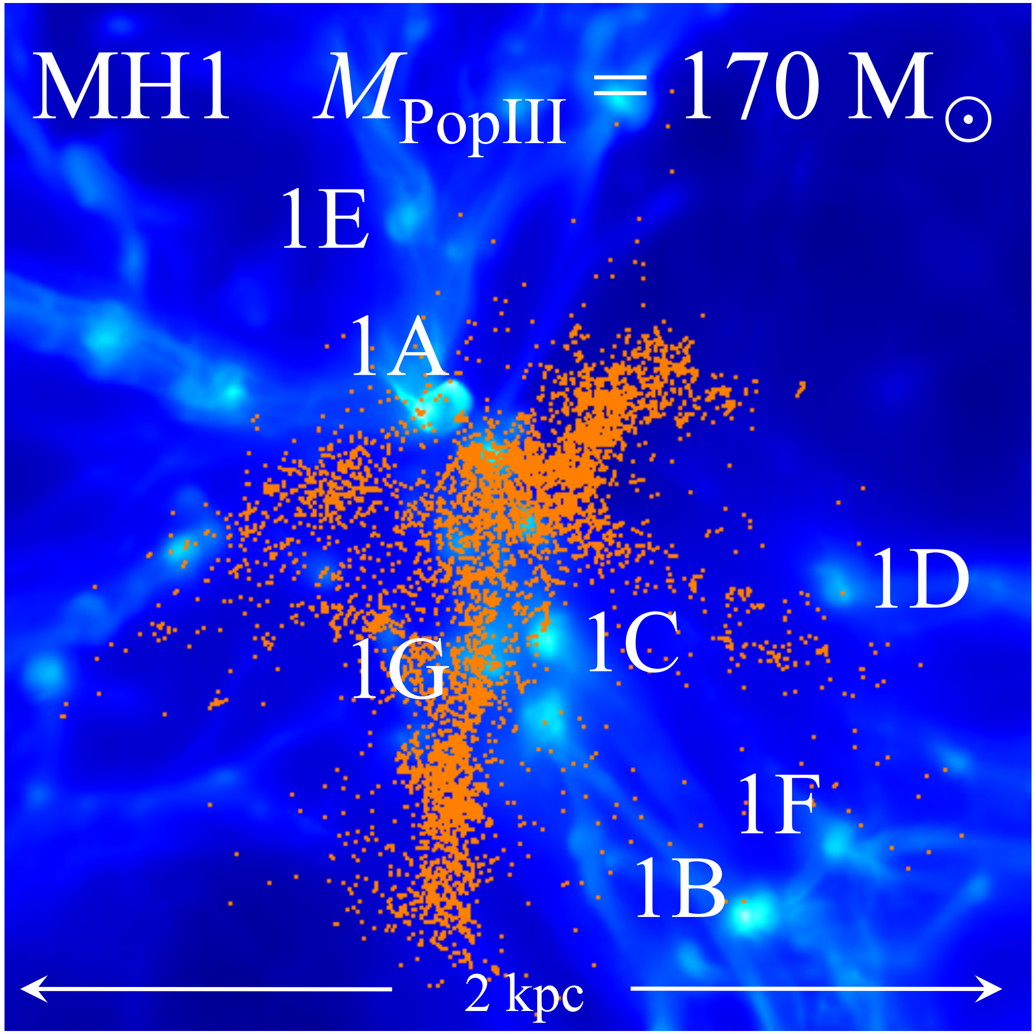
M_{PopIII} [$M_\odot$]	t_{life} [Myr]	Q(H) [s^{-1}]	E_{SN} [10^{51} erg]	M_{met} [$M_\odot$]
13	13.7	1.33e48	1	0.746
20	8.43	4.72e48	1	2.56
25	6.46	7.58e48	1	3.82
30	5.59	1.33e49	1	7.18
170	2.32	2.16e50	20	83.4
200	2.20	2.62e50	28	114.

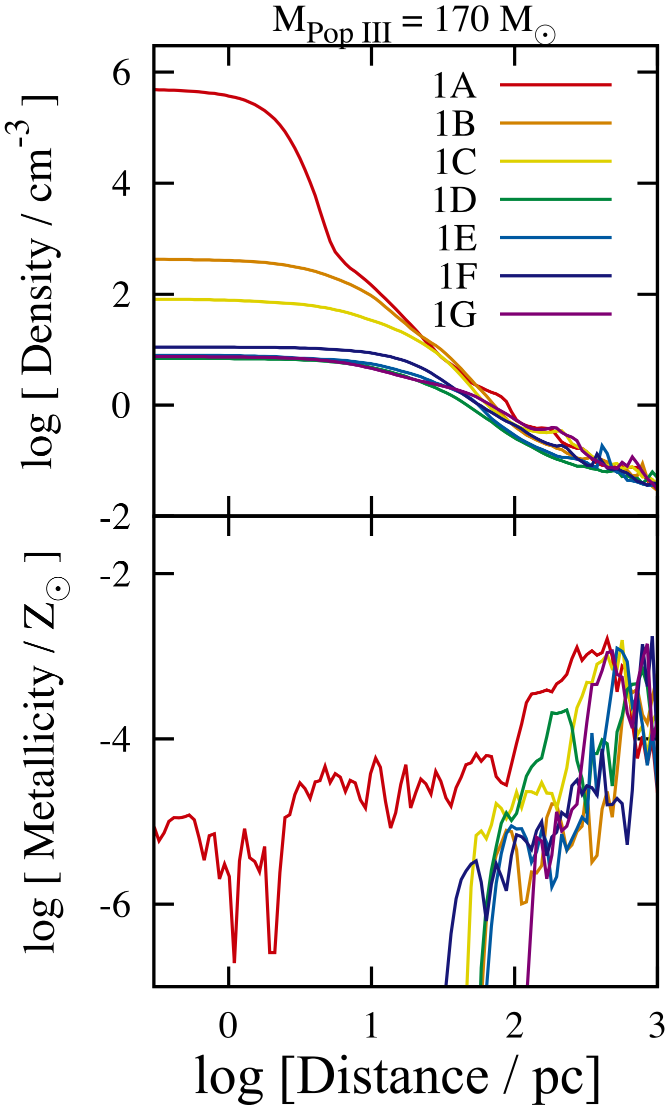


Photoionization
Low-mass MH (3x10^5 M_⊙) / High-mass Pop III (200 M_⊙)
log [Density /cm^-3]
−3
0
3
3 kpc
log [Temperature / K]
2
4
6
H II region
ionization rate
2.6x10^50 s^-1
0.1
1
2.2
Time from star formation [Myr]


SN explosion
Low-mass MH (3x10^5 M☉) / High-mass Pop III (200 M☉)
log [Density /cm ^-3]
−3
0
3
Metal particles
3 kpc
SN shell
log [Temperature / K]
2
4
6
PISN
2.8x10^52 erg
0.1
1
50
Time from SN explosion [Myr]

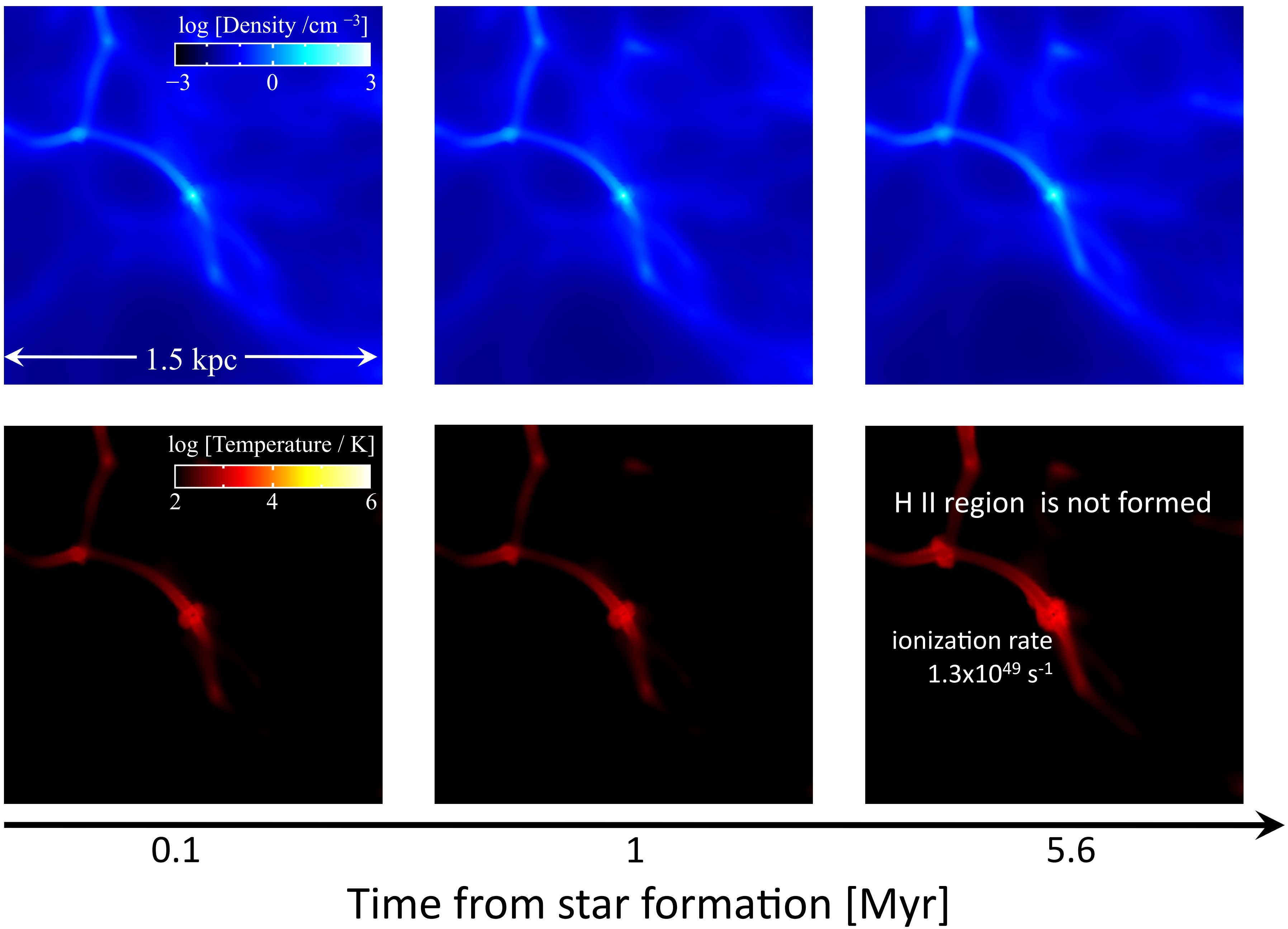
For small M_{halo} & large M_{PopIII}, EE takes place, but its efficiency is small.

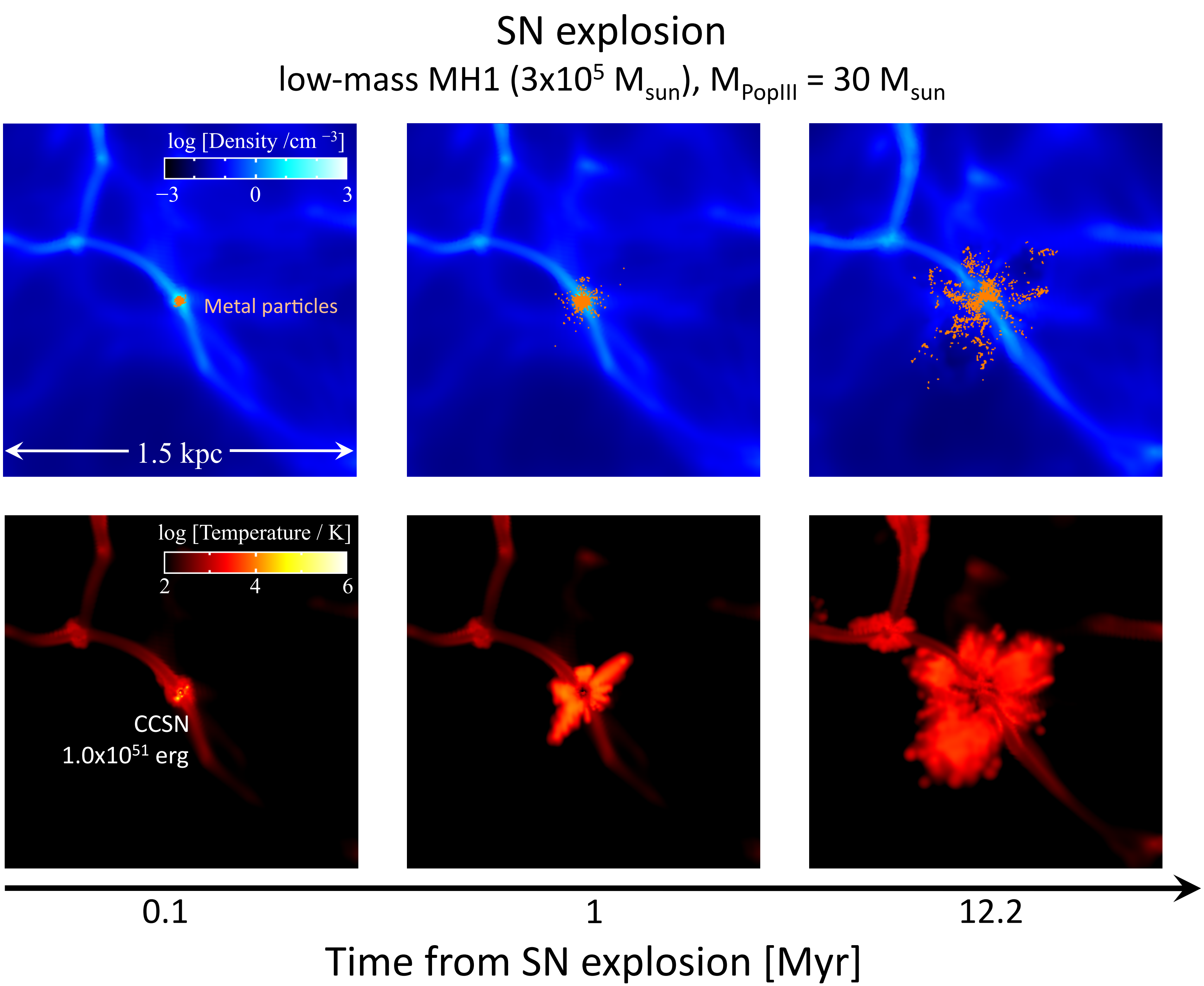




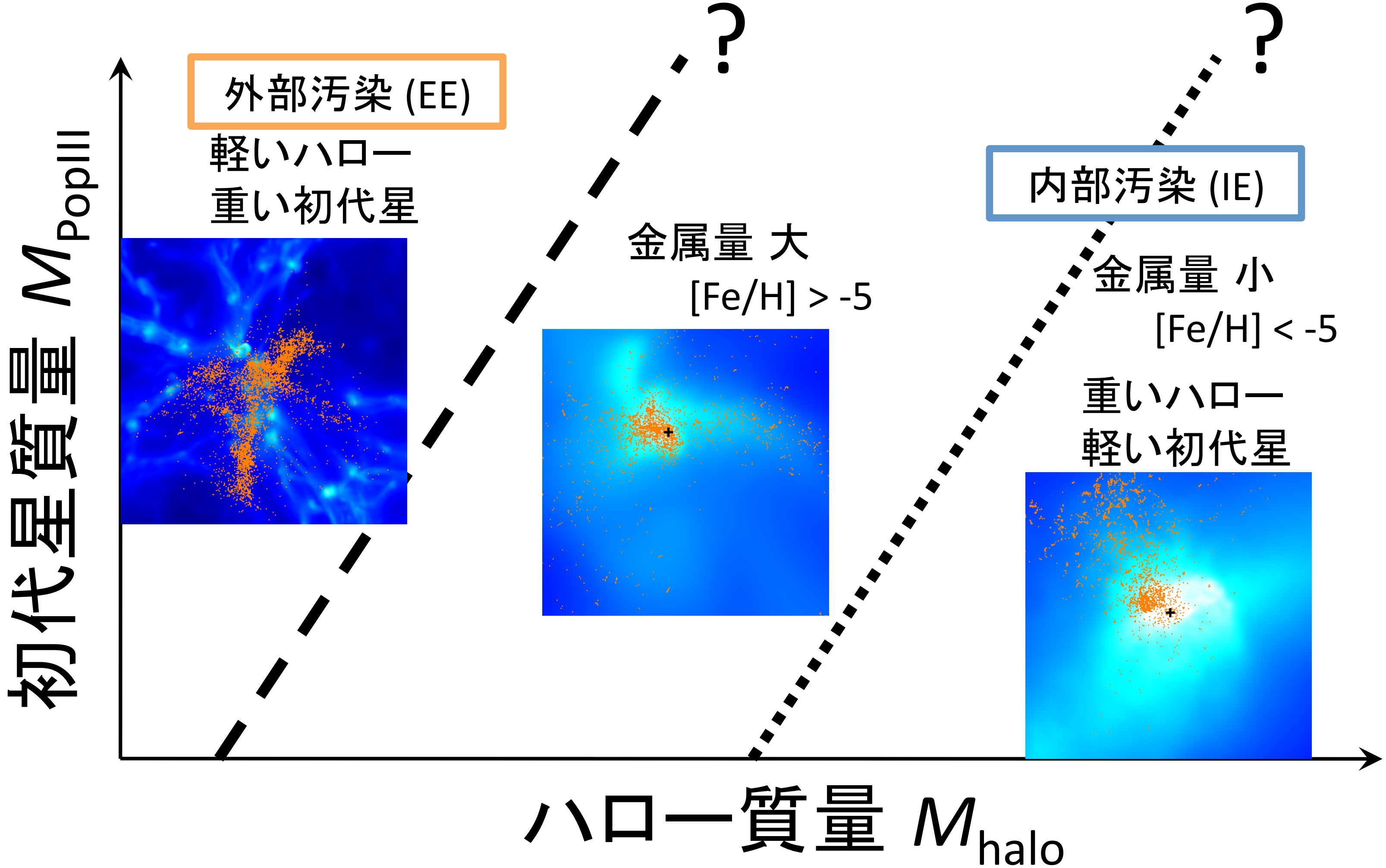
Photoionization

low-mass MH1 (3×10^5 M_{sun}), M_{PopIII} = 30 M_{sun}

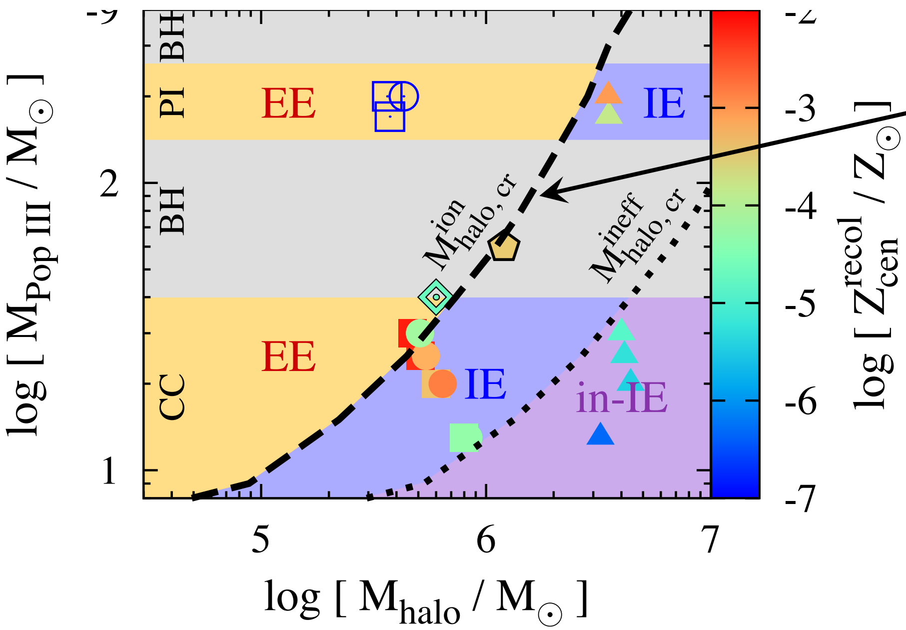


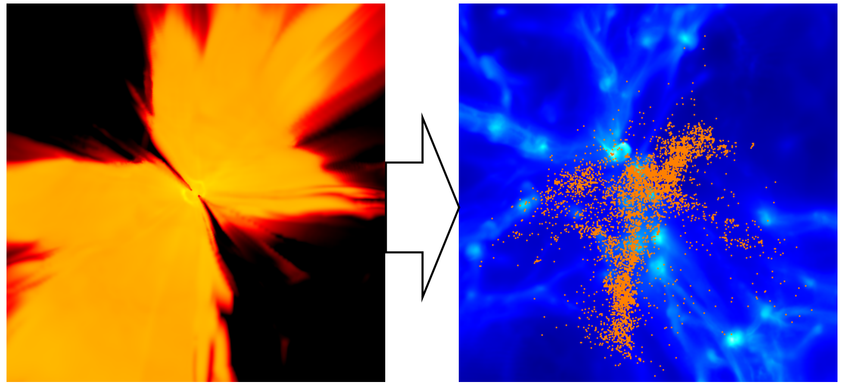

SN explosion
low-mass MH1 (3x10^5 M_sun), M_PopIII = 30 M_sun
log [Density /cm ^-3]
−3
0
3
Metal particles
1.5 kpc
log [Temperature / K]
2
4
6
CCSN
1.0x10^51 erg
0.1
1
12.2
Time from SN explosion [Myr]

では、どのような条件で EE/IE は起こるのか?



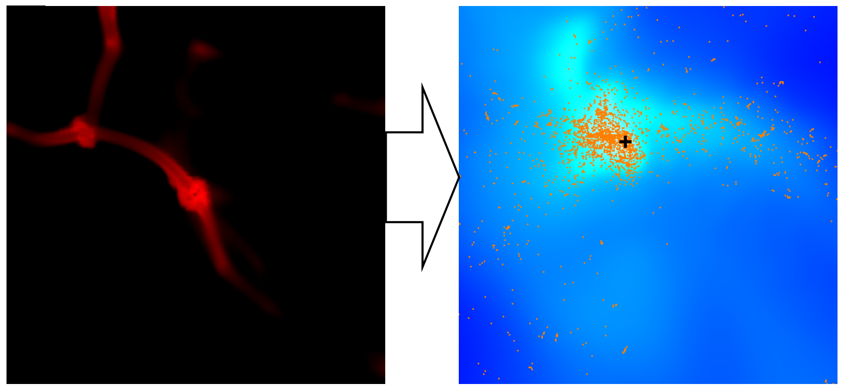
IE/EE の条件





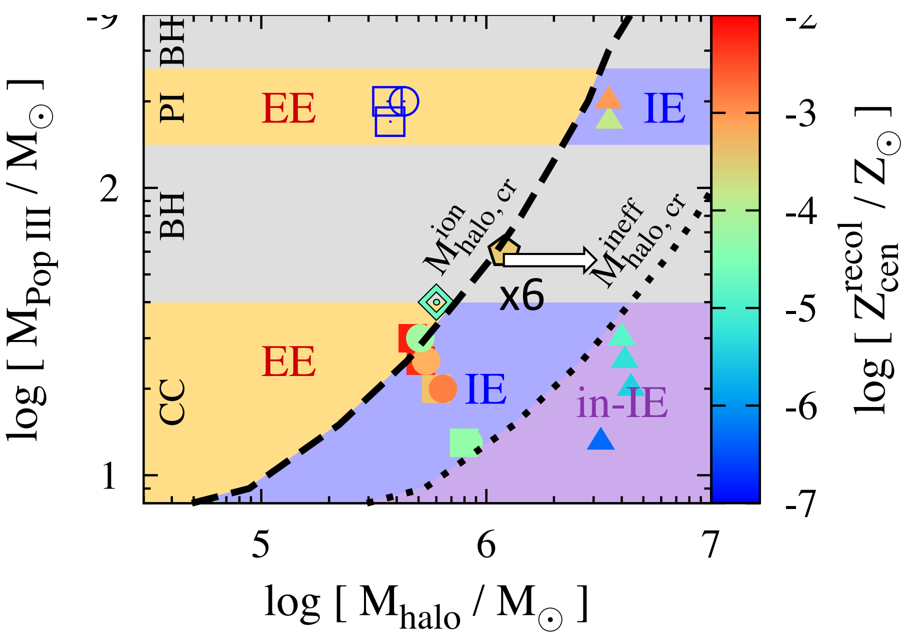
H II 領域形成が EE を起こす必要条件 (Kitayama & Yoshida 2005)

$$M^{\rm ion}_{\rm halo,cr} = 2.5\times10^{6}\ {\rm M}_\odot \left(\frac{v_{\rm D}}{20\ {\rm km\ s^{-1}}}\right)^{3/4} \times \left(\frac{t_{\rm life}}{5\ {\rm Myr}}\right)^{3/4} \left(\frac{Q({\rm H})}{10^{49}\ {\rm s^{-1}}}\right)^{3/4} \left(\frac{1+z_{\rm col}}{20}\right)^{-3/2} \quad (8)$$



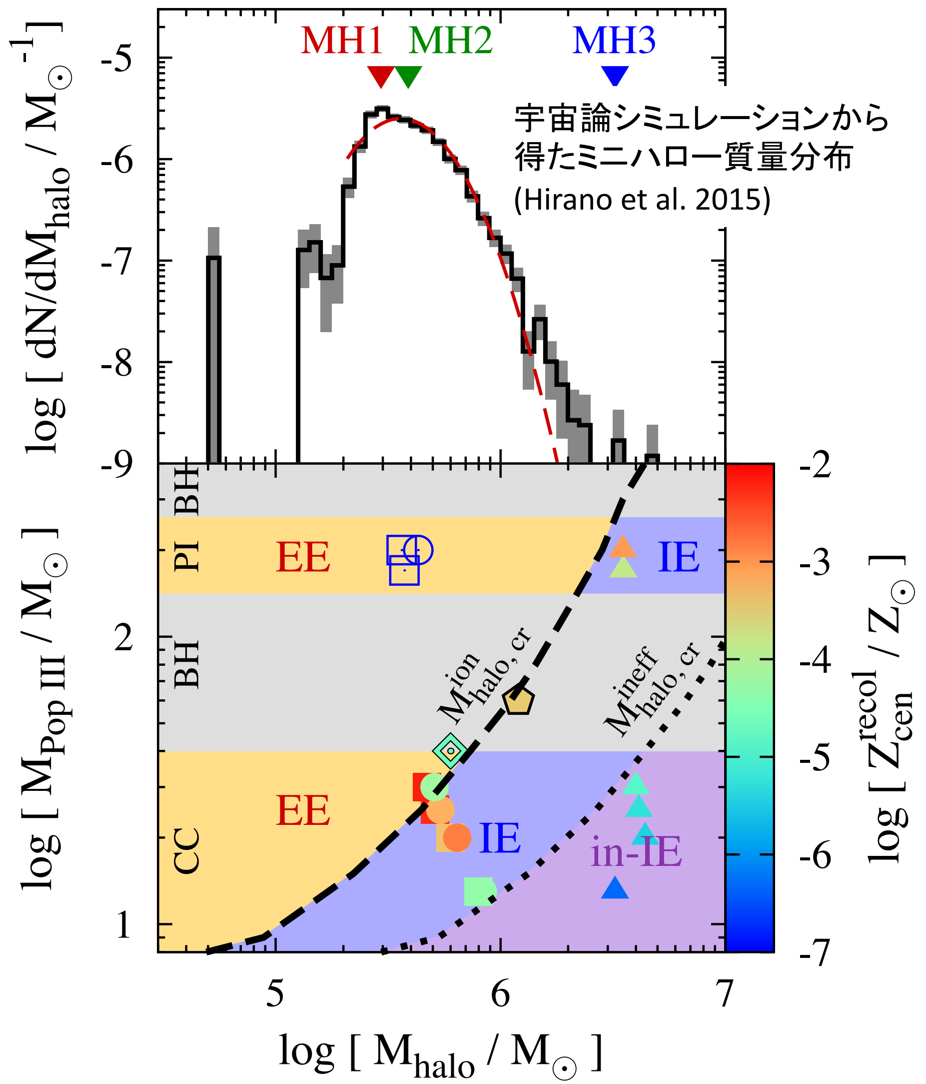
IE のうち、特に [Fe/H] < −5 を与える場合を`ineffective IE’モードとして区別

ineffective IE モードの条件
シミュレーションから、
$$M_{\rm halo} > M_{\rm halo,cr}^{\rm ineff} = 6\ M_{\rm halo,cr}^{\rm ion}$$



これらの条件と、
✓ハロー質量分布(Hirano et al. 2015)
✓初代星質量分布 (flat/ Salpeter)
を使って、どのモードが支配的かを計算

PISN: ほぼ EE
CCSN: IE と EE が半々



SN	Enr. mode	$[\mathrm{Fe/H}]^{\mathrm{recol}}_{\mathrm{cen}}$	Fraction flat IMF	Fraction Salpeter IMF
PI	EE	$< [\mathrm{Fe/H}]_{\mathrm{cr}}$	$\simeq 1$	$\simeq 1$
	IE	$> [\mathrm{Fe/H}]_{\mathrm{cr}}$	4.60×10^{-6}	7.23×10^{-6}
CC	EE	$< [\mathrm{Fe/H}]_{\mathrm{cr}}$	0.423	0.127
	IE	$> [\mathrm{Fe/H}]_{\mathrm{cr}}$	0.566	0.824
	in-IE	$< [\mathrm{Fe/H}]_{\mathrm{cr}}$	0.011	0.049

PISN の場合
✓ほぼ EE ([Fe/H] < −5)
✓−5 < [Fe/H] < −2.5 の範囲で PISN の兆候をもつ星を探すためには 10^5-10^6 個の星が必要

CCSN の場合
✓IE が支配的だが、
✓EE も無視できない割合起こる (10-40%)
✓しかし、[Fe/H]<−5の星が見つかっていない
→臨界金属量を示唆 (Omukai 2000; Schneider et al. 2002)

まとめと結論

本研究では

- 初代星による支配的な金属汚染過程
- 金属欠乏星形成領域の金属量分布

を調べるため、初代星の輻射/超新星フィードバックを幅広いパラメータ領域

- ハロー質量 (M_{halo})
- 初代星質量 (M_{PopIII})

に対して数値シミュレーションした。

その結果、

- 一連のシミュレーションで、内部汚染(IE) と外部汚染 (EE) が起こり得ることが初めてわかった。
  - EE は非効率的であり、汚染領域の金属量は [Fe/H] < −5 にとどまった。
  - IE により再収縮領域は幅広い金属量分布がを持つことがわかった。
    - 十分重いハロー質量/軽い初代星質量では、金属量が [Fe/H] < −5 となるが、
    - ミニハローと初代星のの質量分布関数を考慮すると、その割合は低い（1-5%）。
- PISN と CCSN で、汚染過程は異なる。
  - PISN の場合、ほぼ全てのミニハローに対し EE となる。
    - 現在の観測では PISN の兆候をもつ金属欠乏星が見られていないことと整合
  - CCSN の場合、
    - IE は大半のミニハローに対して起こる。
      - 観測されている金属欠乏星の金属量の範囲と一致
    - EE になるミニハローは 10-40% と、無視できない
      - 1400 個の金属欠乏星を観測して、[Fe/H] < −5 となる星は数個しか見つかっていない。
      - 臨界金属量の存在を示唆。

現在観測されている金属欠乏星の形成は、CCSN の IE によって説明できる。

Their elemental abundance ratio is clue to nucleosynthesis of Pop III SNe

Ishigaki et al. (2018)