Formation Condition and Classification of Extremely Metal-Poor Stars:

Absent Region in the A(C)-[Fe/H] Plane

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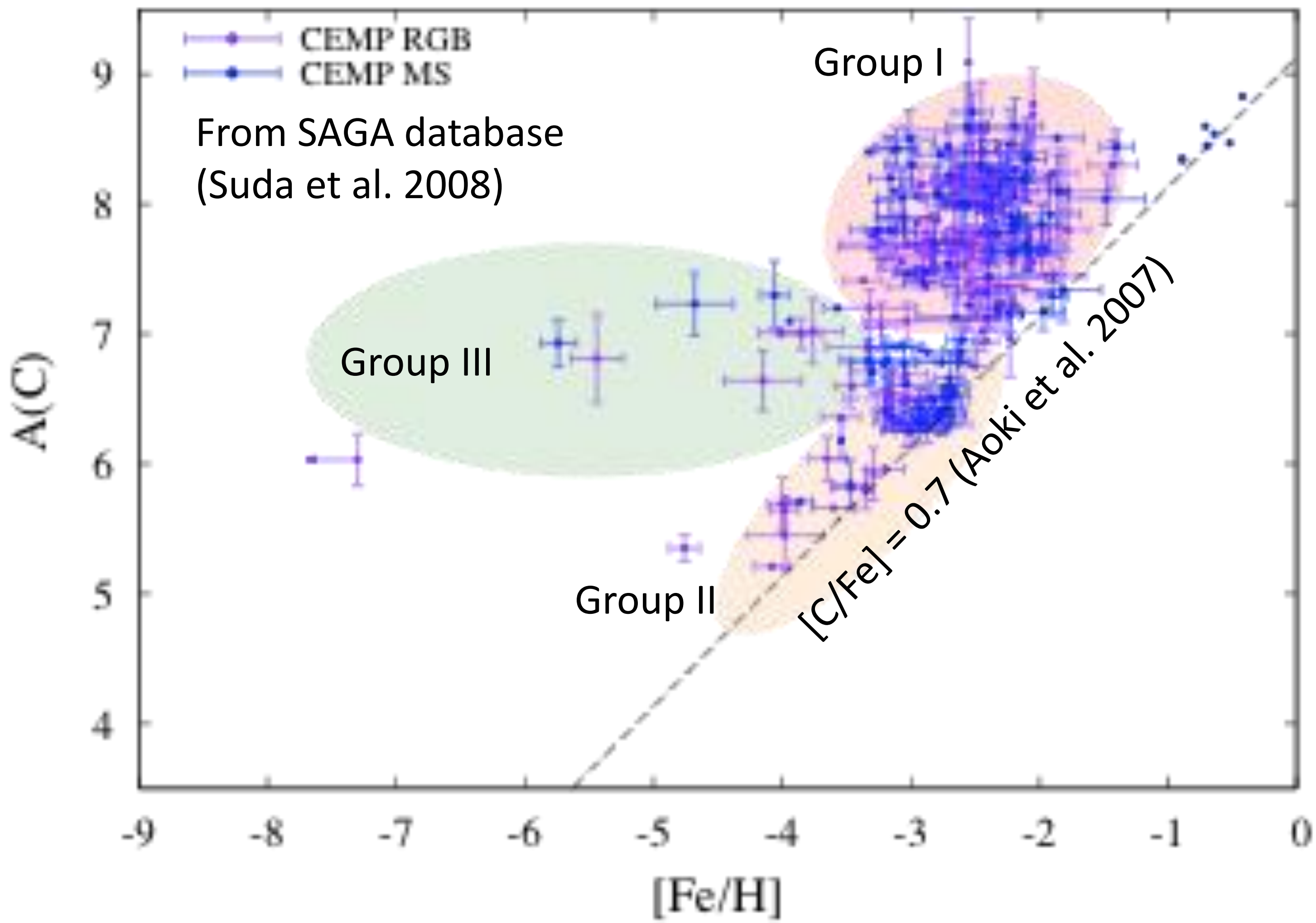
KONAN INFINITY

Chiaki, Tominaga, & Nozawa (2018, MNRAS, 472, L115) arXiv: 1710.04365

Sub-groups of CEMP stars

Yoon et al. (2016)



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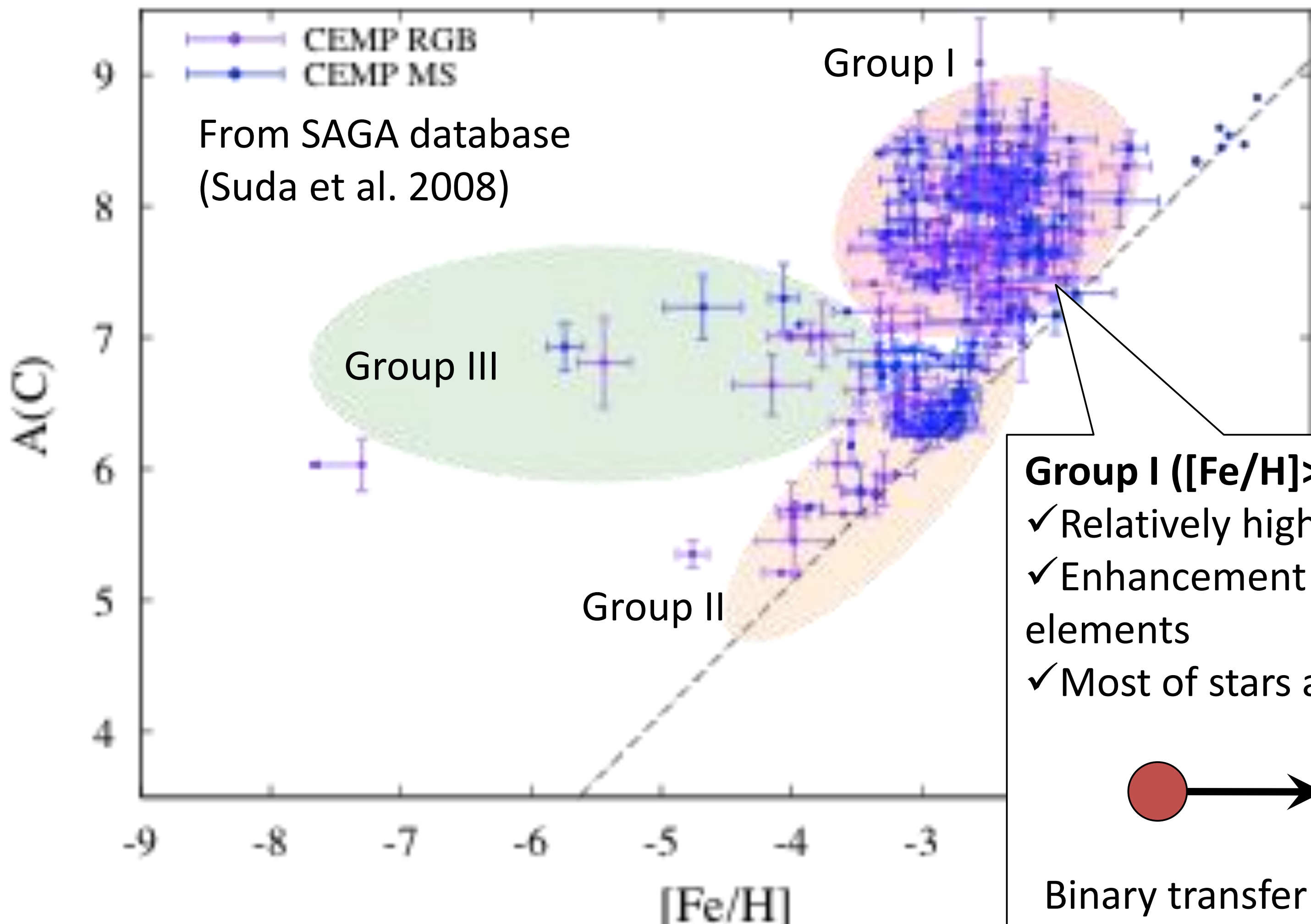


Group I ([Fe/H]>−3)

✓Relatively high Fe & C

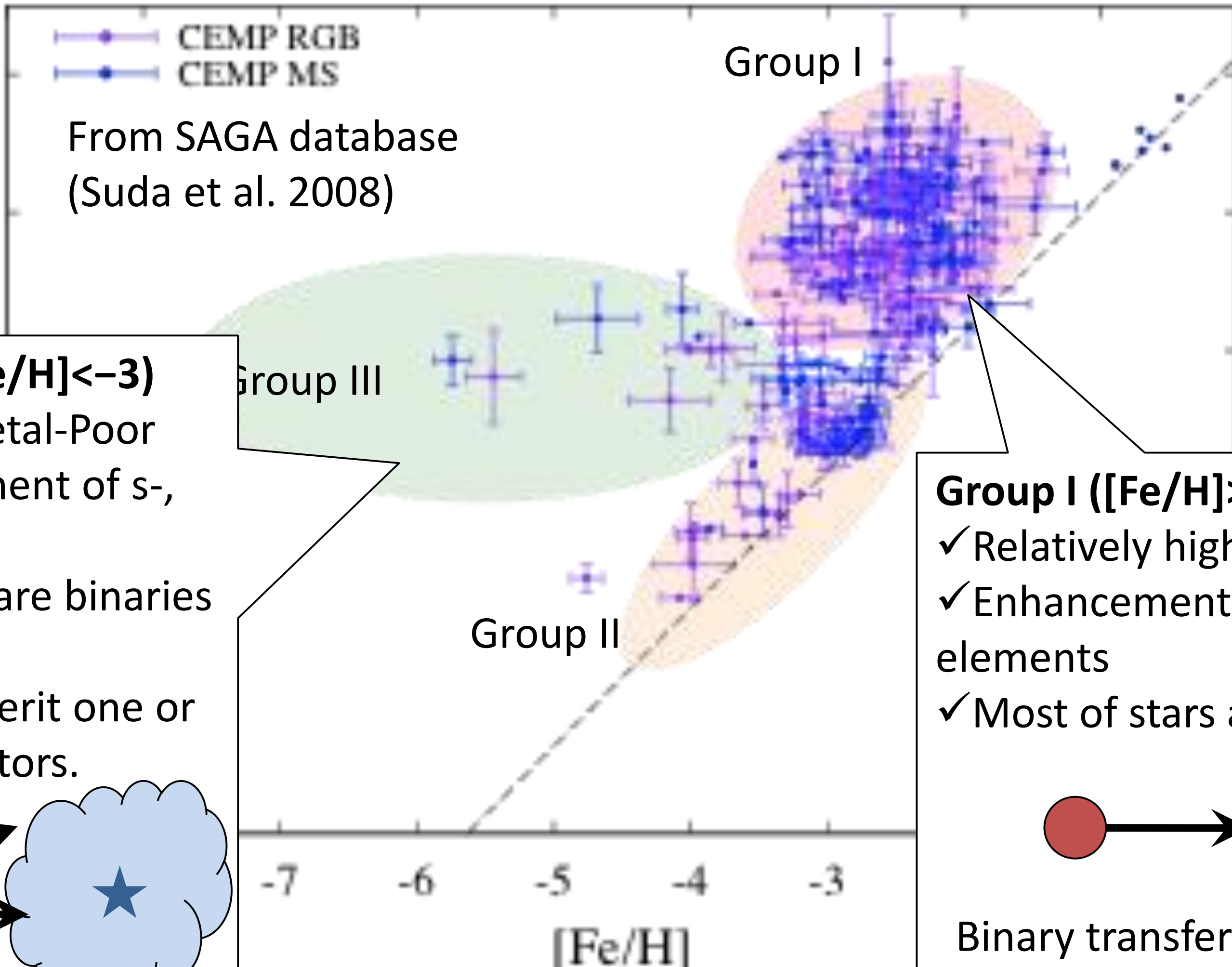
✓Enhancement of s-, r/s-elements

✓Most of stars are binary

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

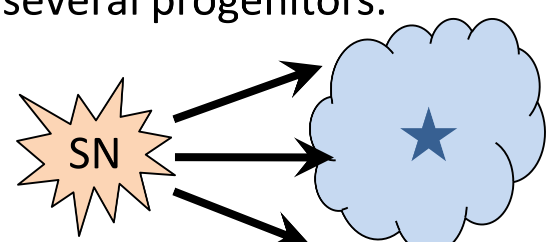
Sub-groups of CEMP stars

Yoon et al. (2016)



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

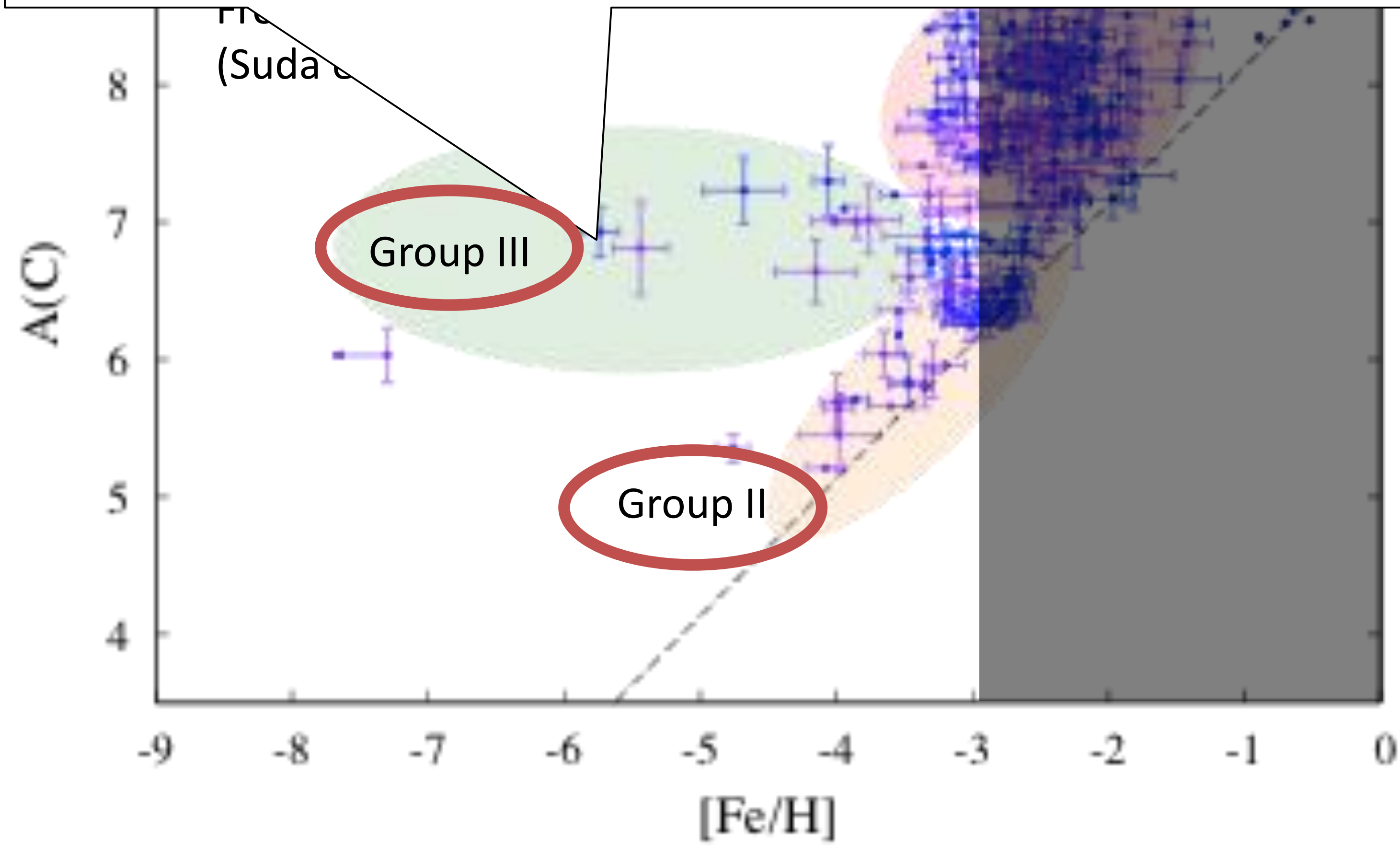
Binary transfer of C and s-, r/s-elements

CEMP-no stars

✓mainly in [Fe/H]<-3

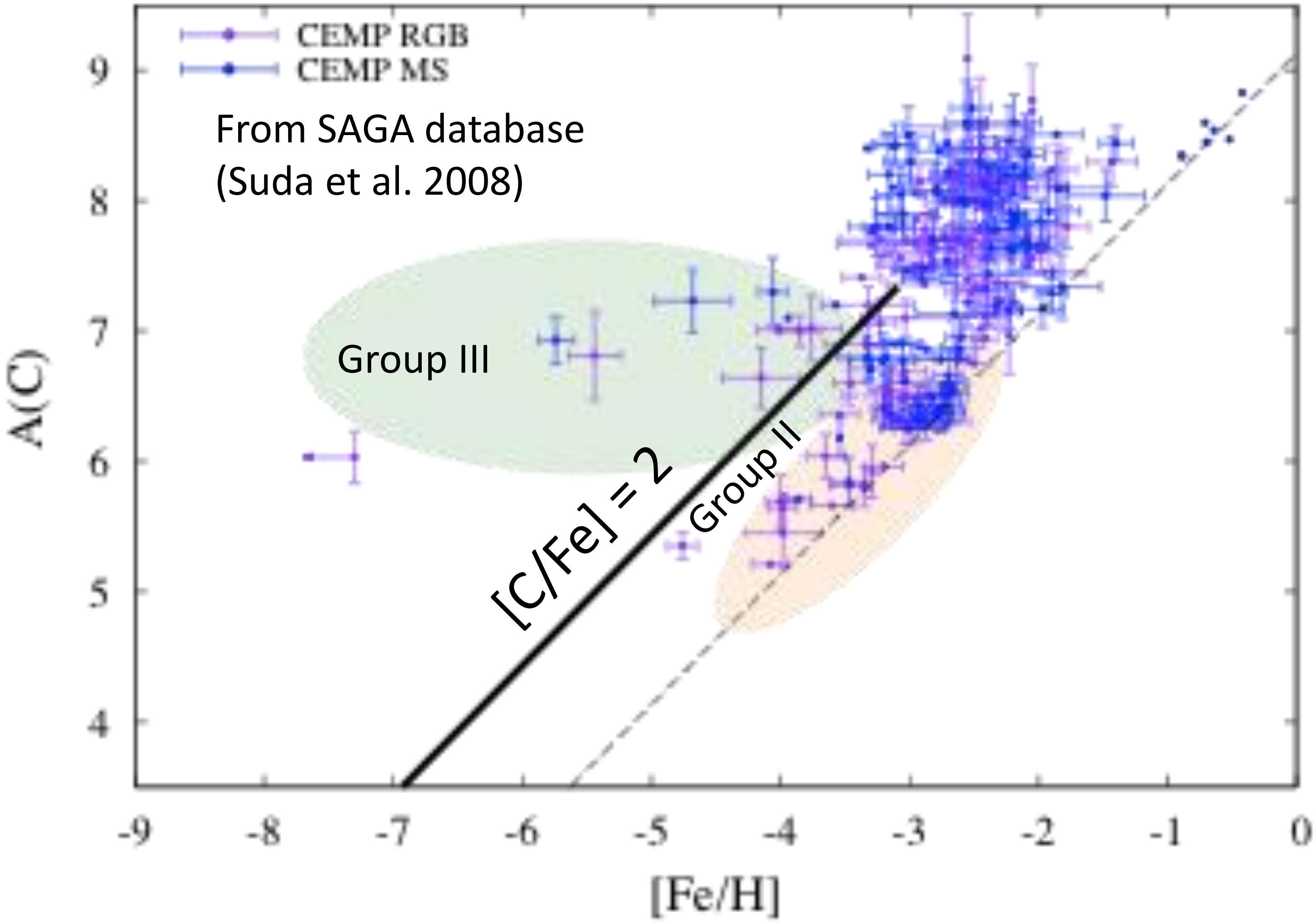
✓consist of Groups II and III

✓And what is the physical origin of the discrimination of Groups II and III?



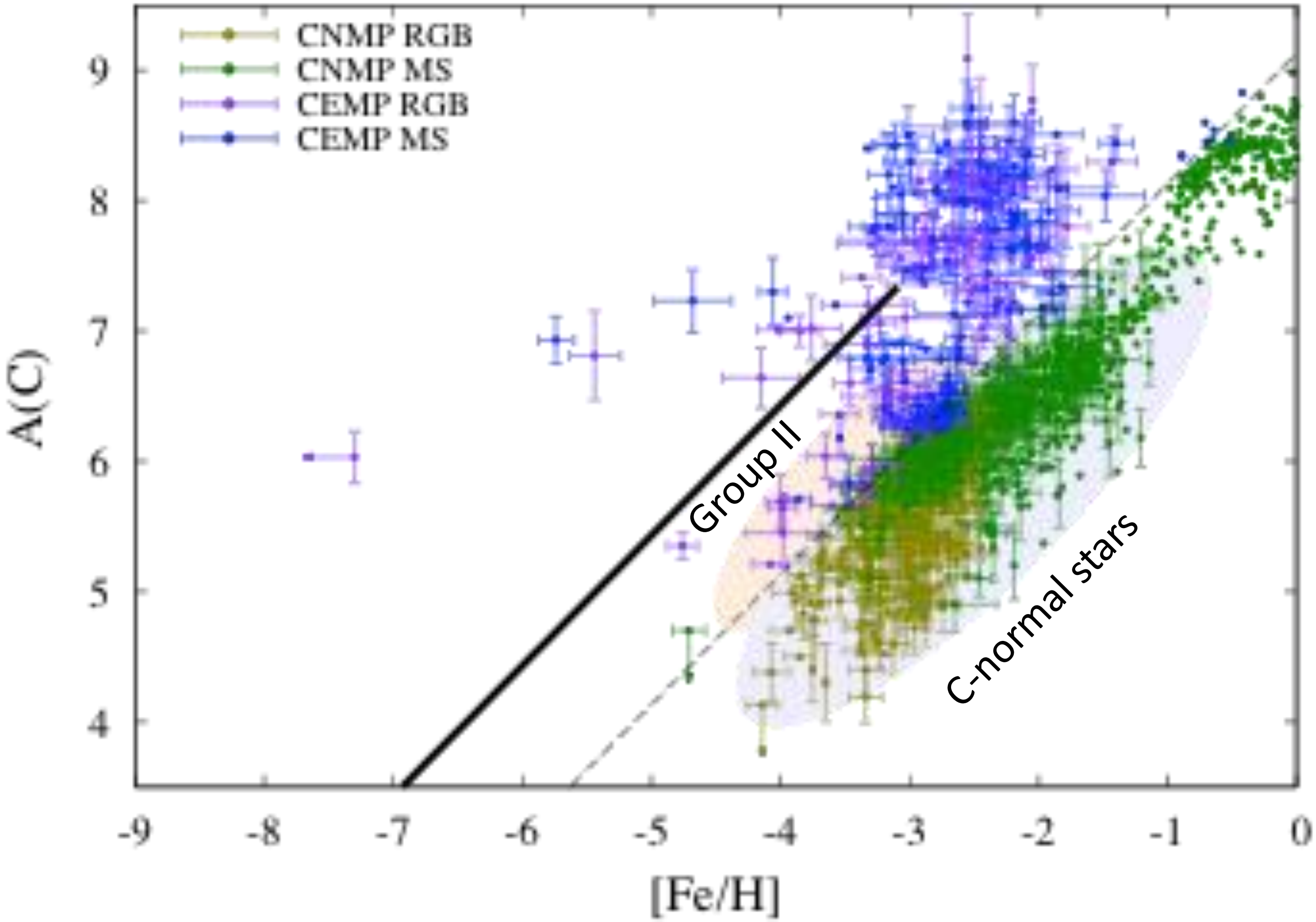
Our findings (1/3)

- ✓Group III stars show large C-enhancement ([C/Fe] > 2)
- ✓Group II stars show moderate C-enhancement ([C/Fe] < 2)



Our findings (2/3)

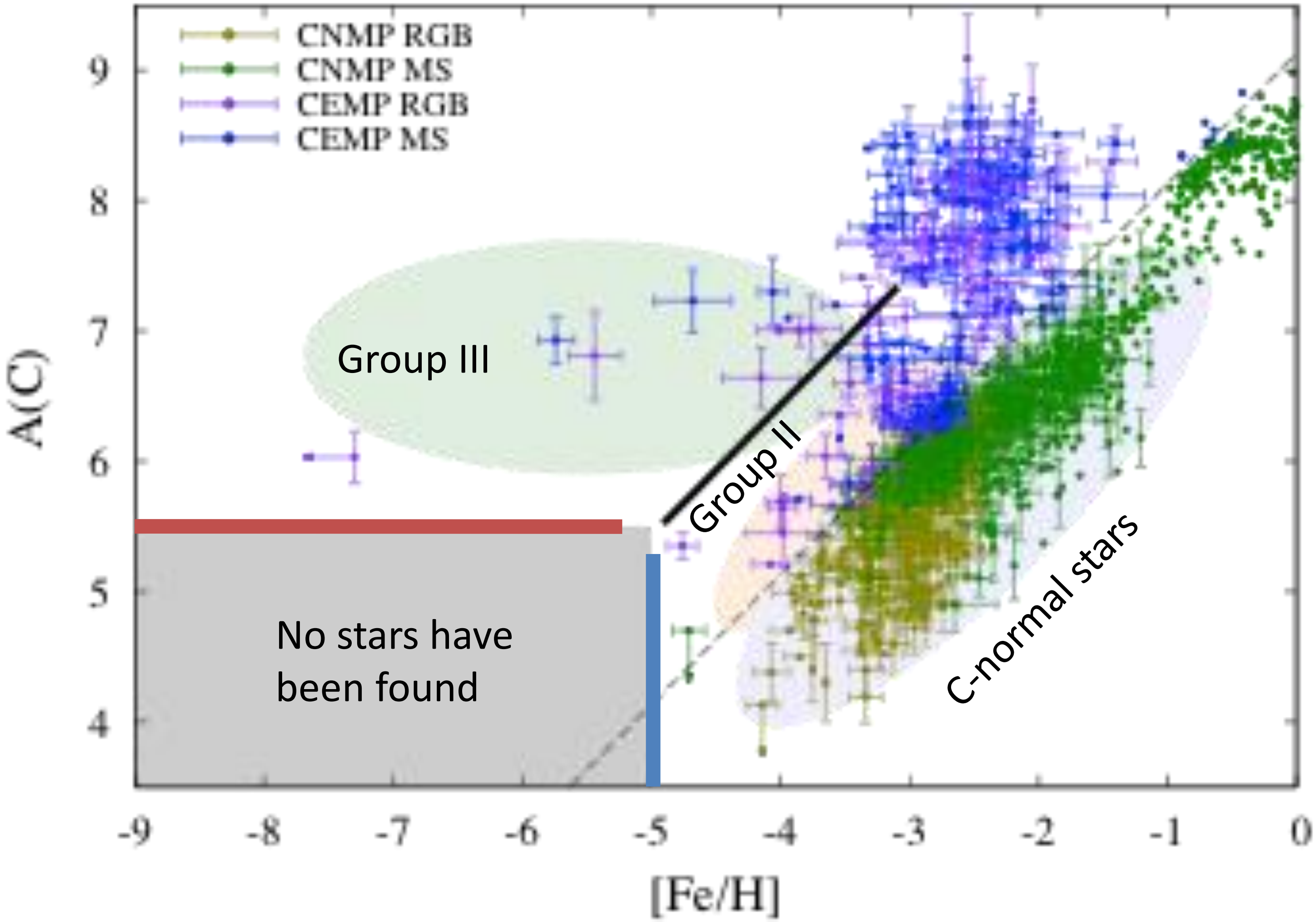
✓The distribution of Group II appears to continuously connect with that of C-normal stars.



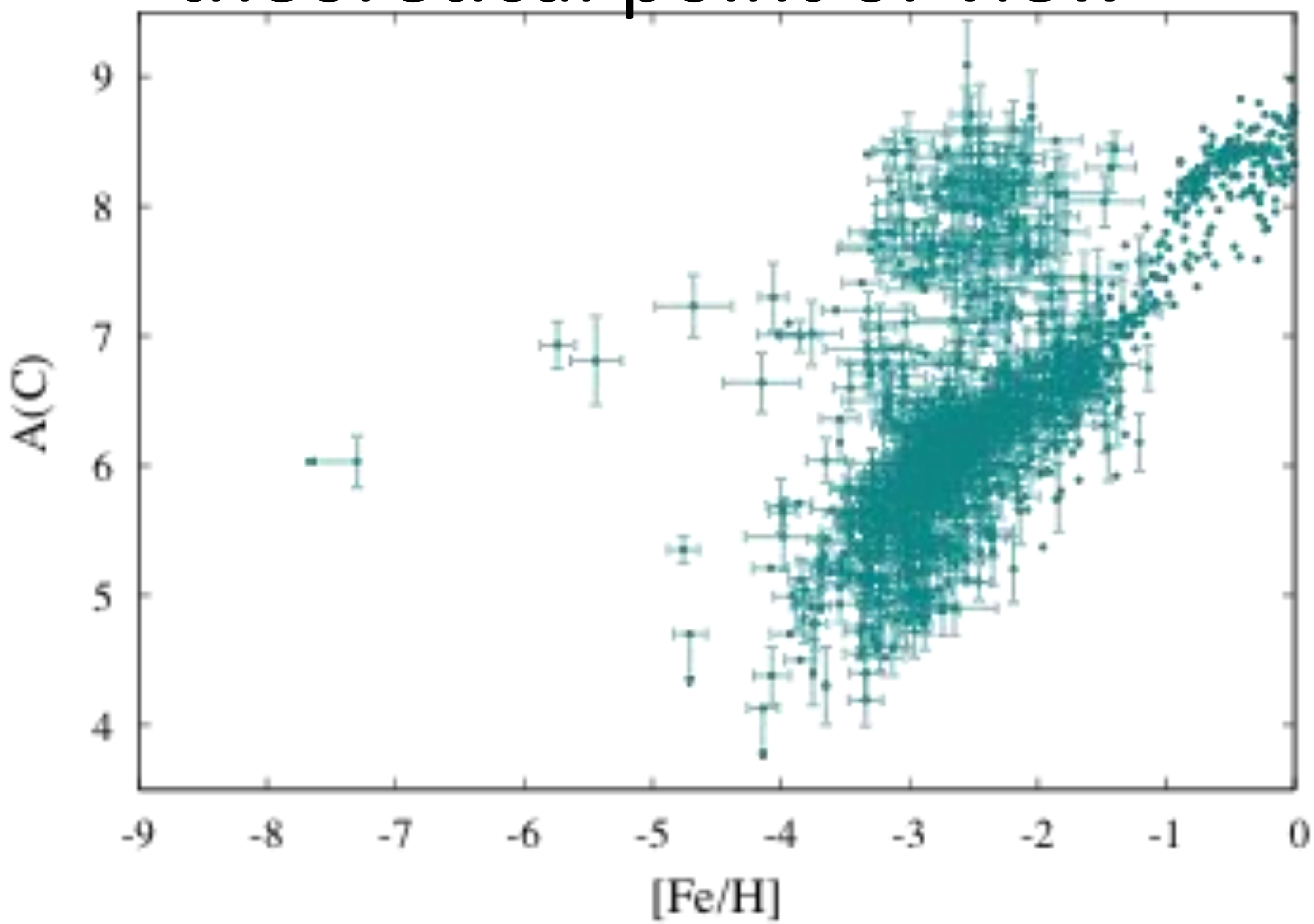
Our findings (3/3)

✓Stars with large C-enhancement show lower limit of $A_{cr}(C)$~6

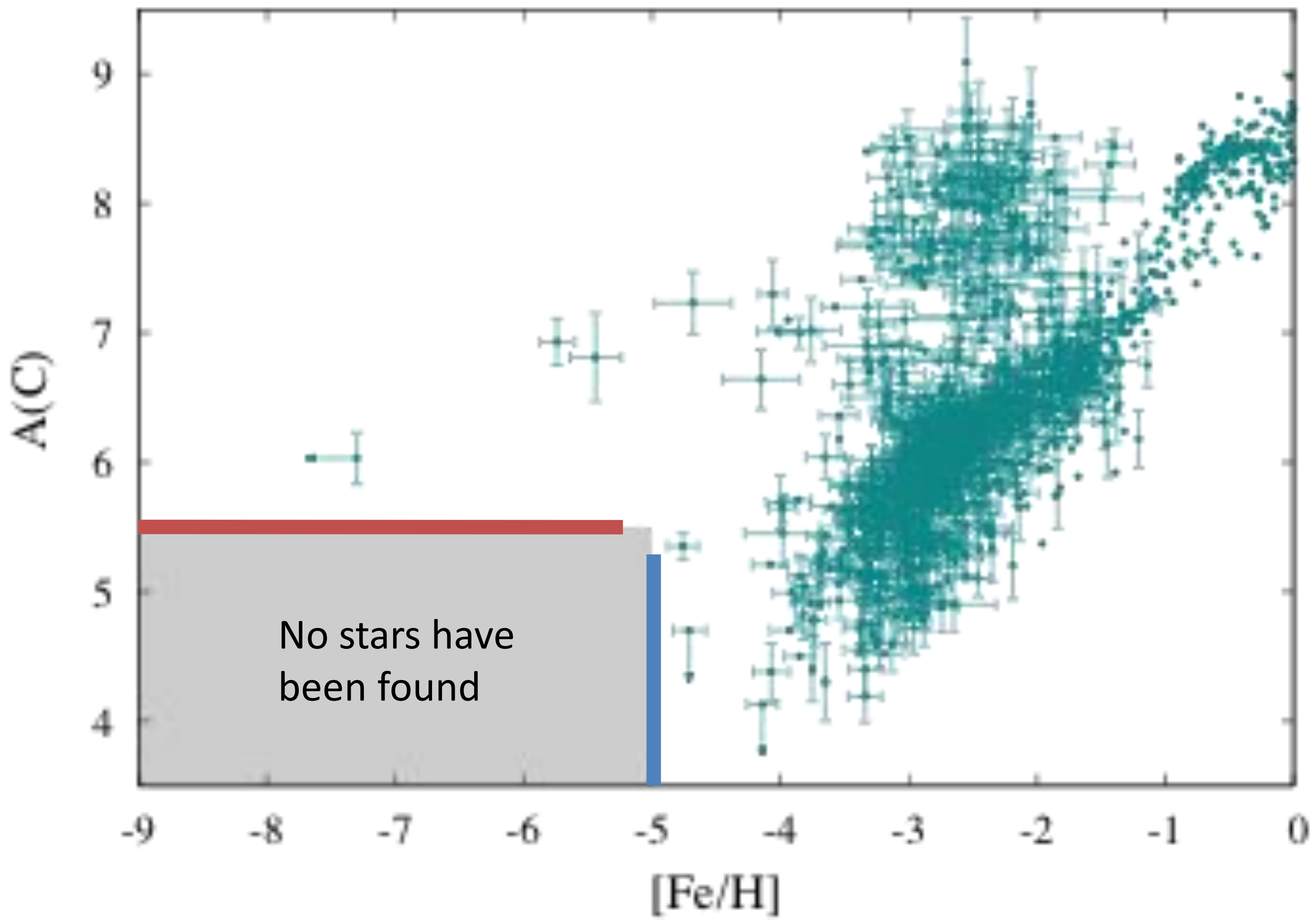
✓Stars with moderate C-enhancement show lower limit of $[Fe/H]_{cr} \sim -5$



In this work, we reconsider the classification of EMP stars from a theoretical point of view

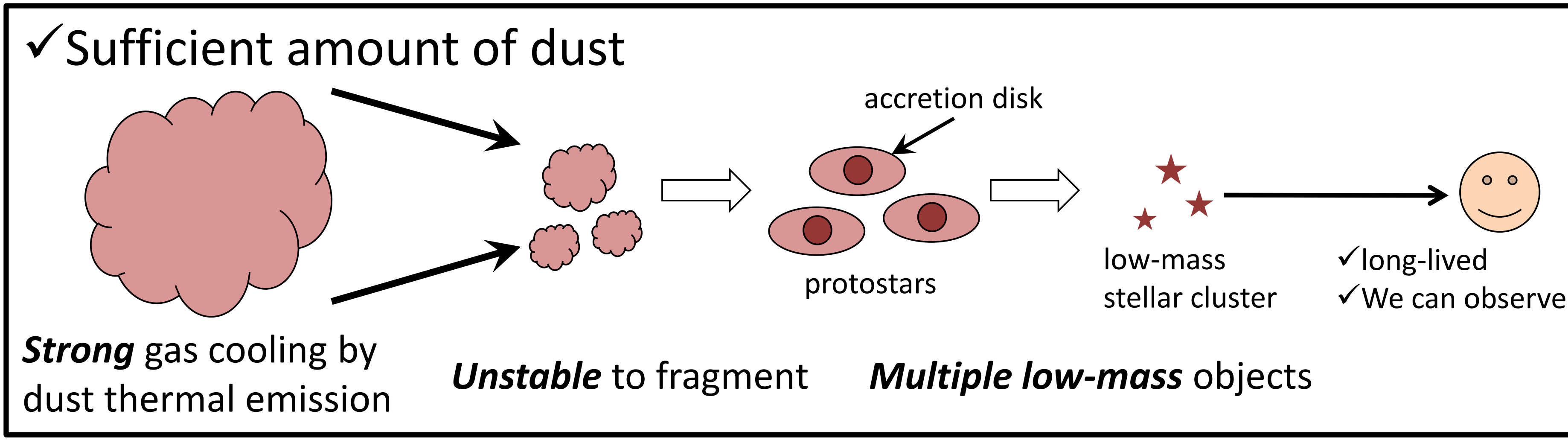


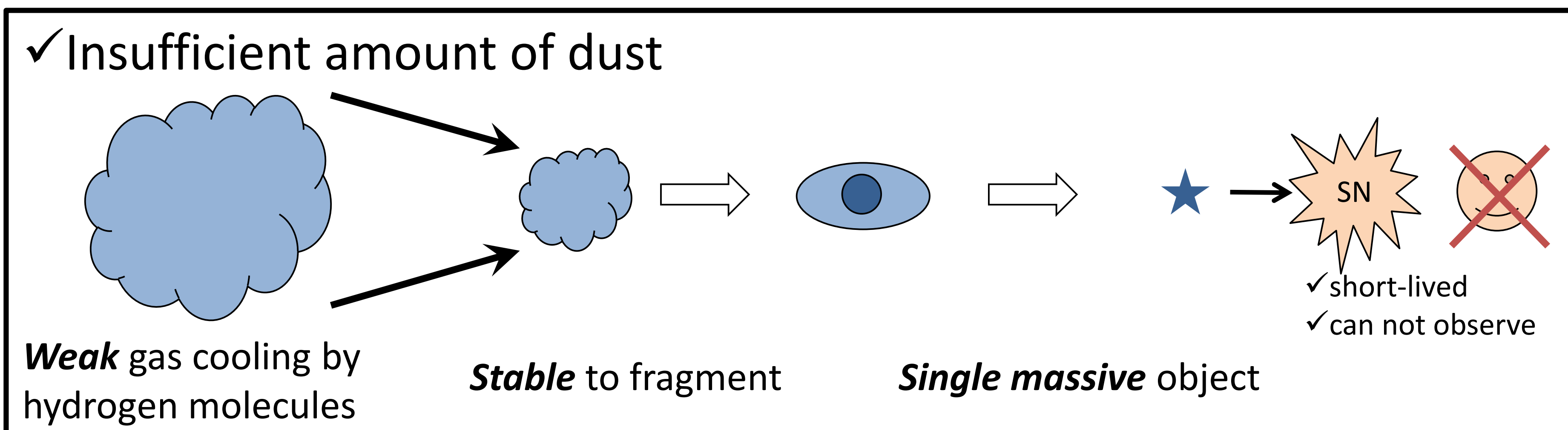
First, we focus on the lower-limits of A(C) & [Fe/H]



The lower-limits reflect dust amounts required for cloud fragmentation

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

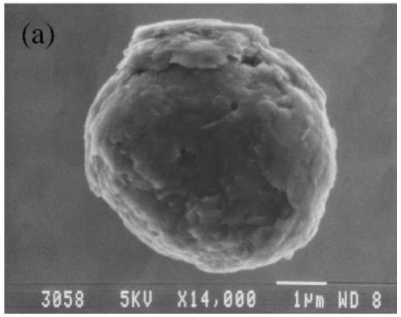




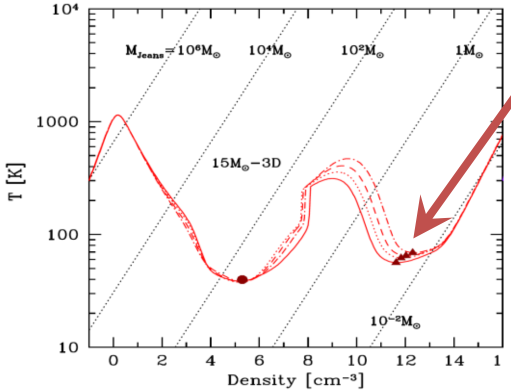
For the formation of C-enhanced/normal EMP stars, carbon/silicate grains are important

Carbonaceous grains

✓Composition: C



Lodders & Amari (2005)



Carbon grain cooling

⇩

Low-mass fragmentation

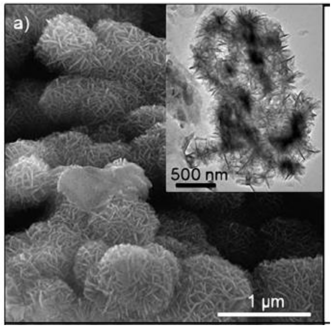
⇩

Critical C abundance is defined

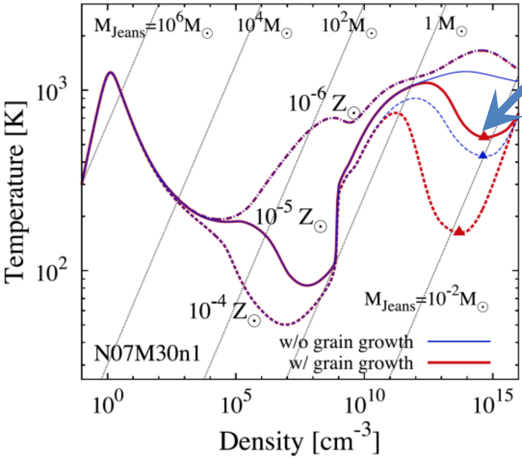
Marassi et al. (2014)

Silicate grains

✓Composition: O, Si, Mg, …



Moyce et al. (2015)



Silicate grain cooling

⇩

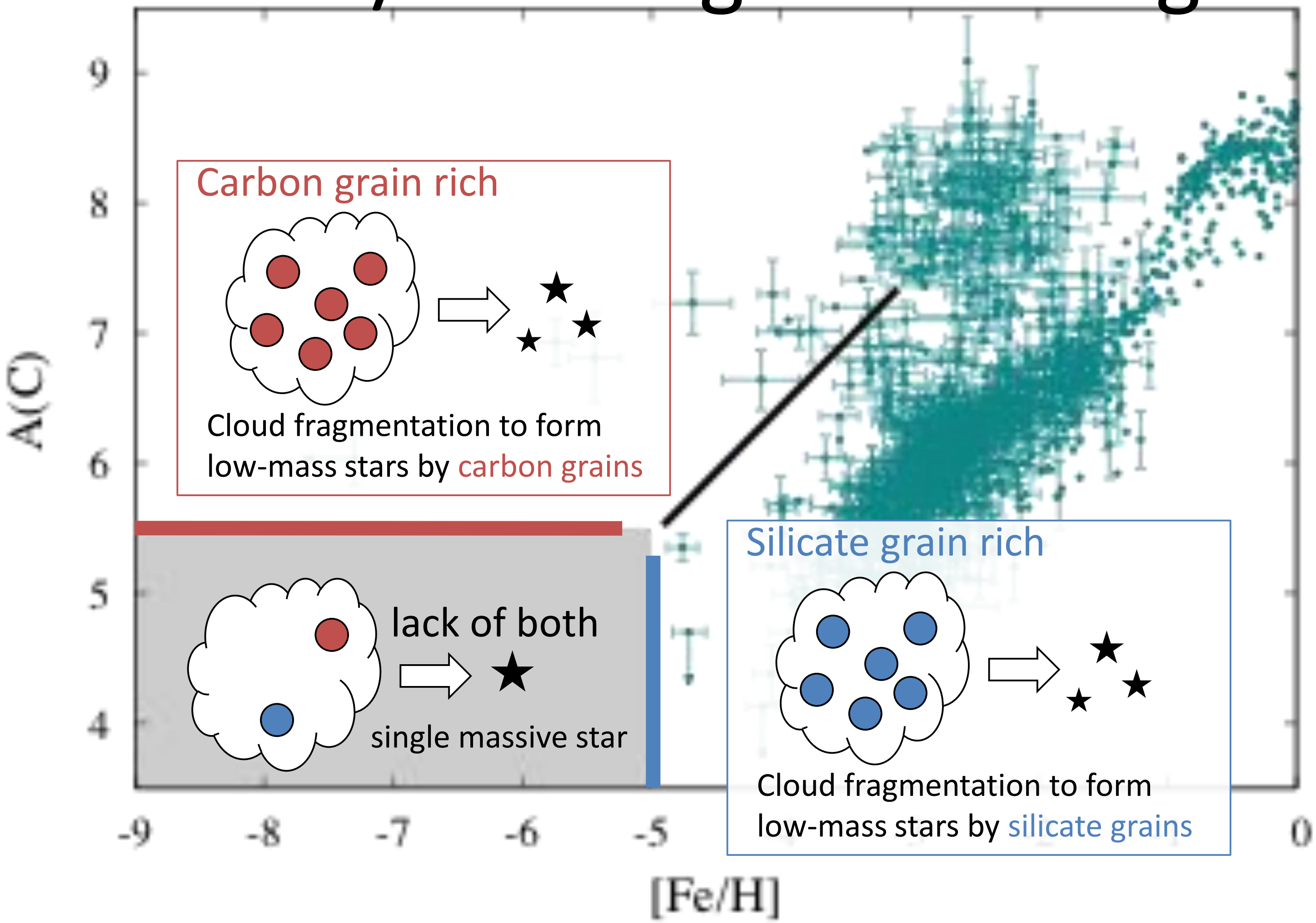
Low-mass fragmentation

⇩

Critical Mg and Si abundance is defined

Chiaki et al. (2015)

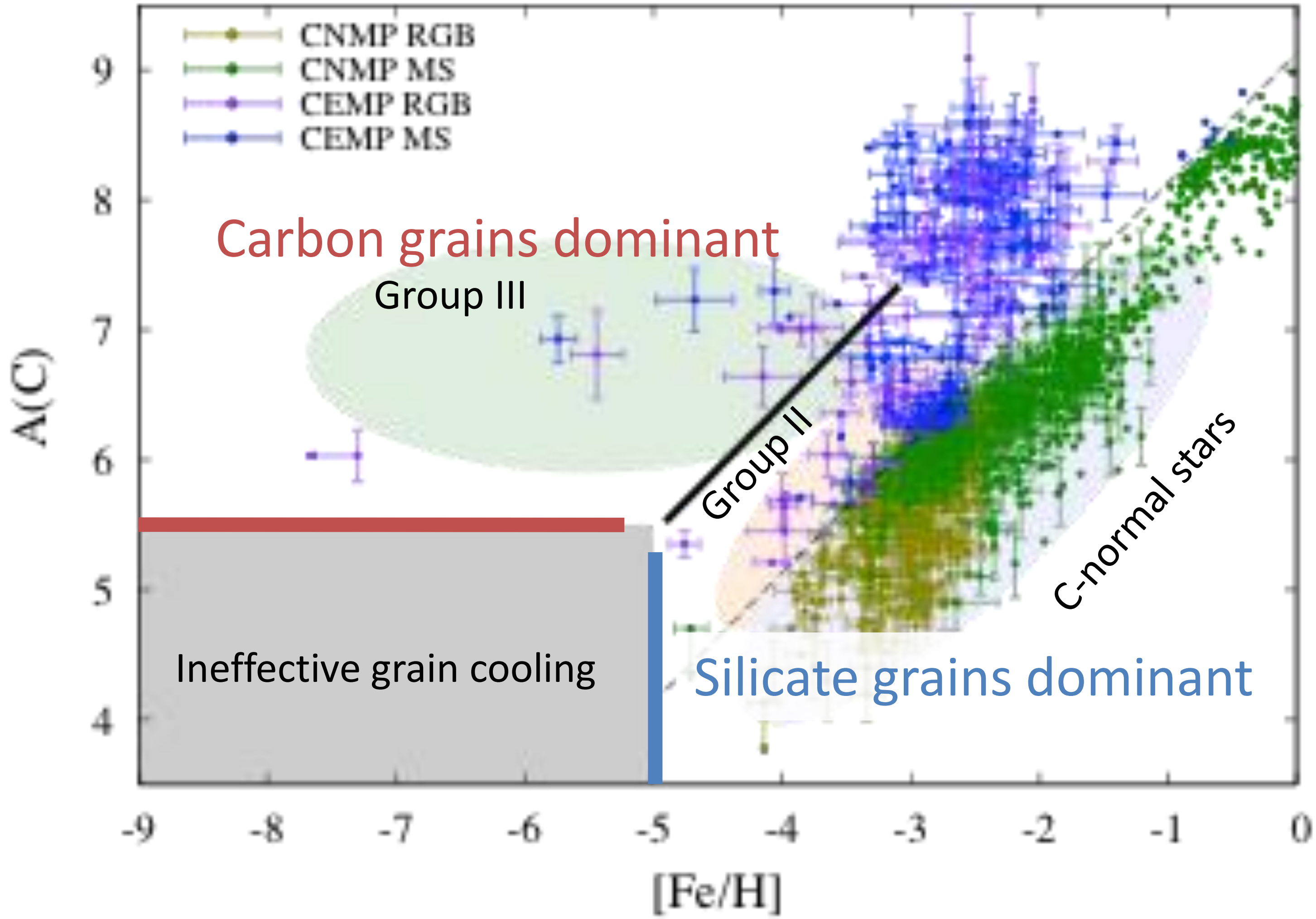
Only ***two*** classes where low-mass star formation is triggered by carbon/silicate grain cooling



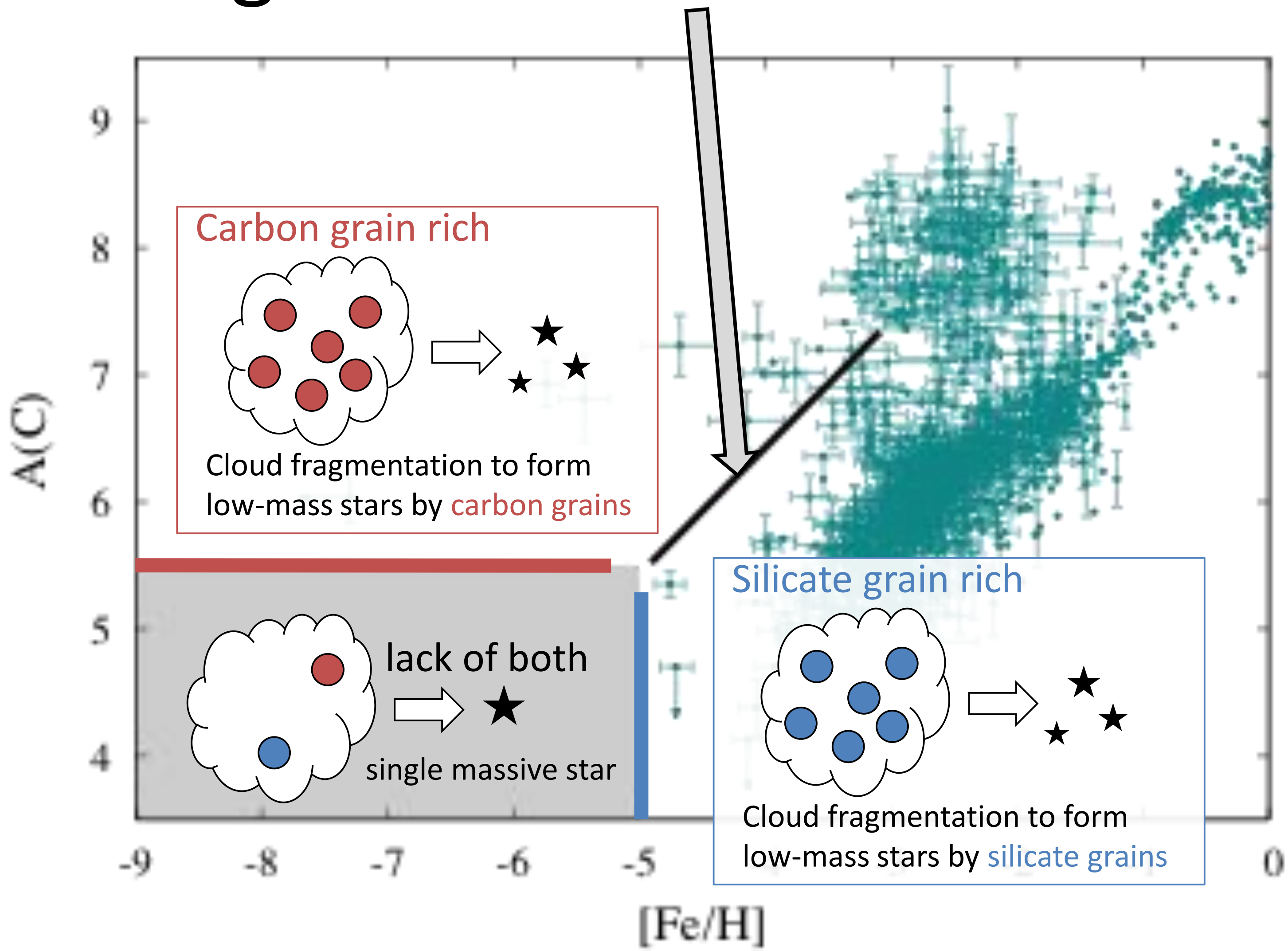
Interestingly,

✓For Group III star formation, carbon grains are dominant.

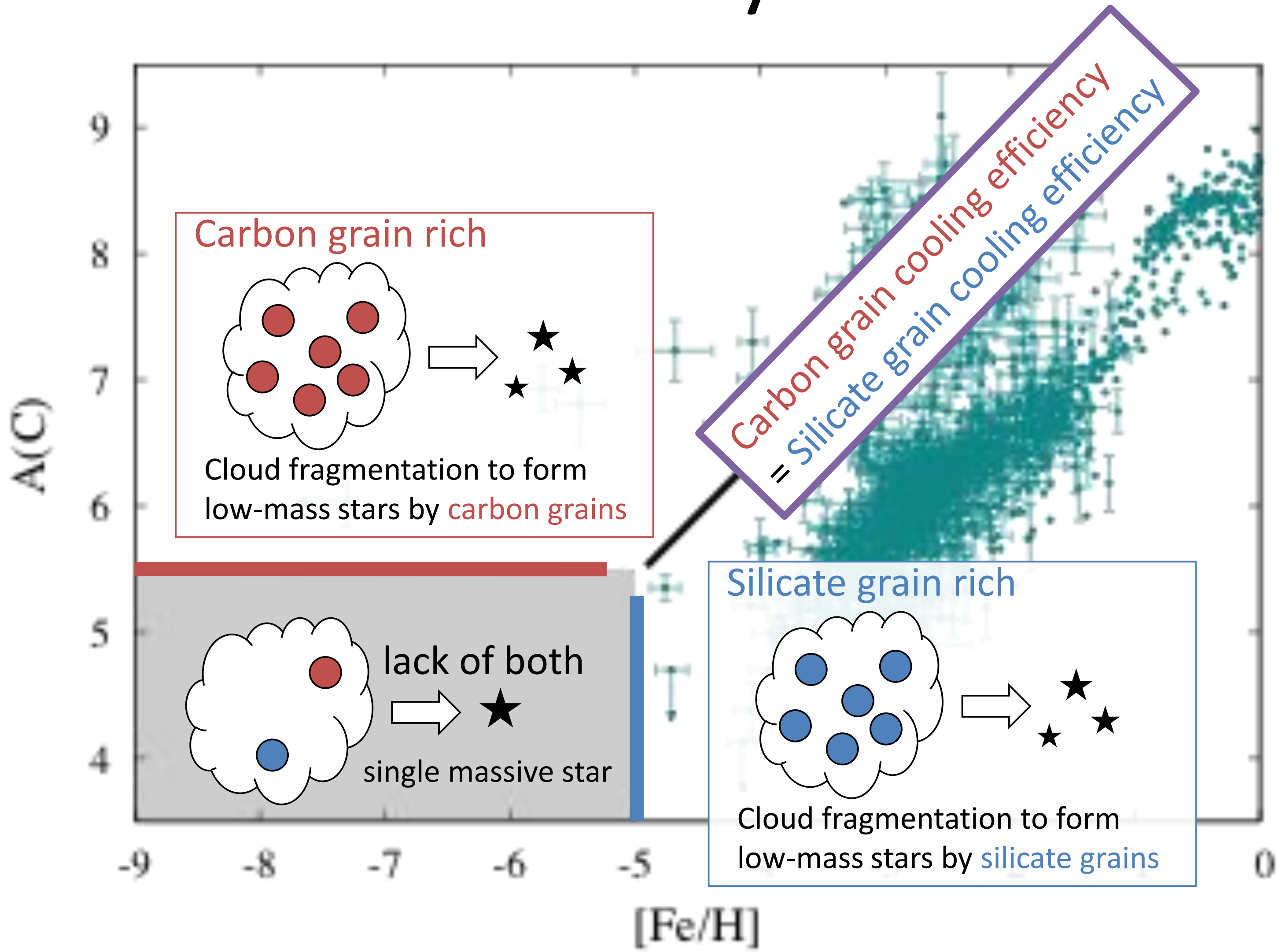
✓For Group II and C-normal star formation, silicate are dominant.



So, let's estimate the boundary dividing EMP stars into two classes



The condition established on this boundary is



We need estimate the carbon and silicate grain cooling efficiency

Carbon grain cooling efficiency = Silicate grain cooling efficiency

? ?

To estimate the cooling efficiencies, we need dust properties:

- ✓ condensation efficiency of metal into dust
- ✓ dust size

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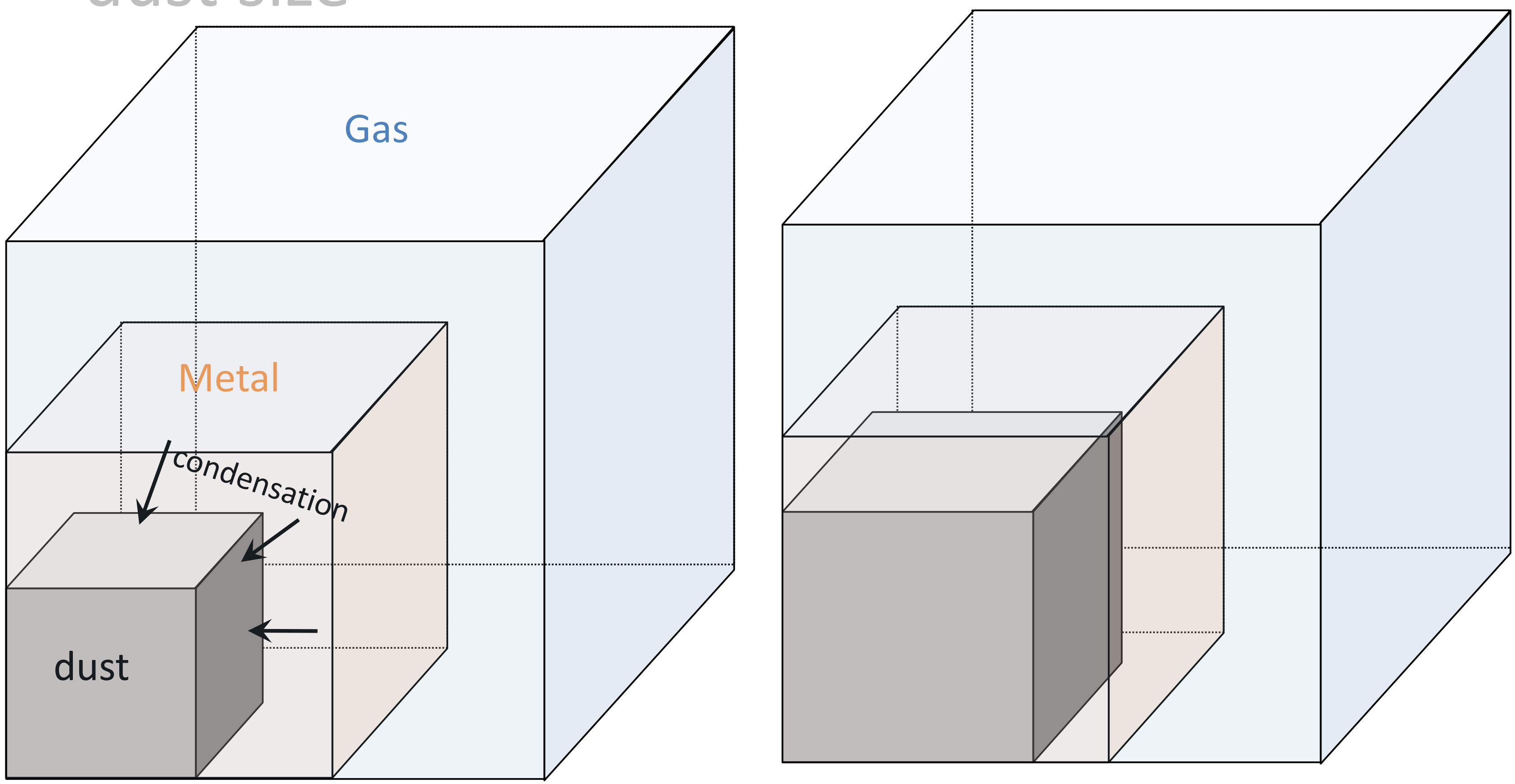
- ✓dust size

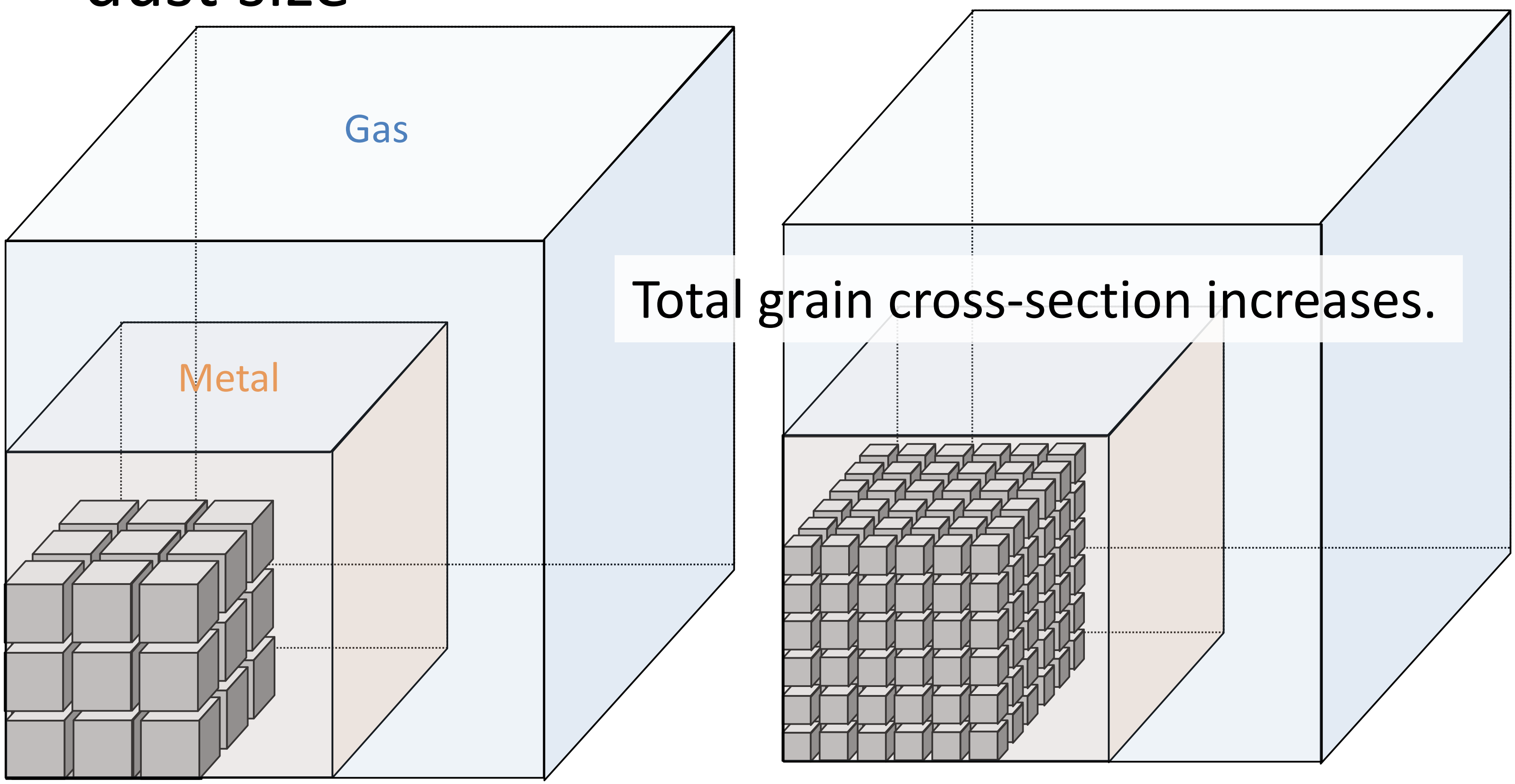


Larger condensation efficiency → Larger cooling efficiency

To estimate the cooling efficiencies, we need dust properties:

✓condensation efficiency of metal into dust

✓dust size



Smaller dust size→ Larger cooling efficiency

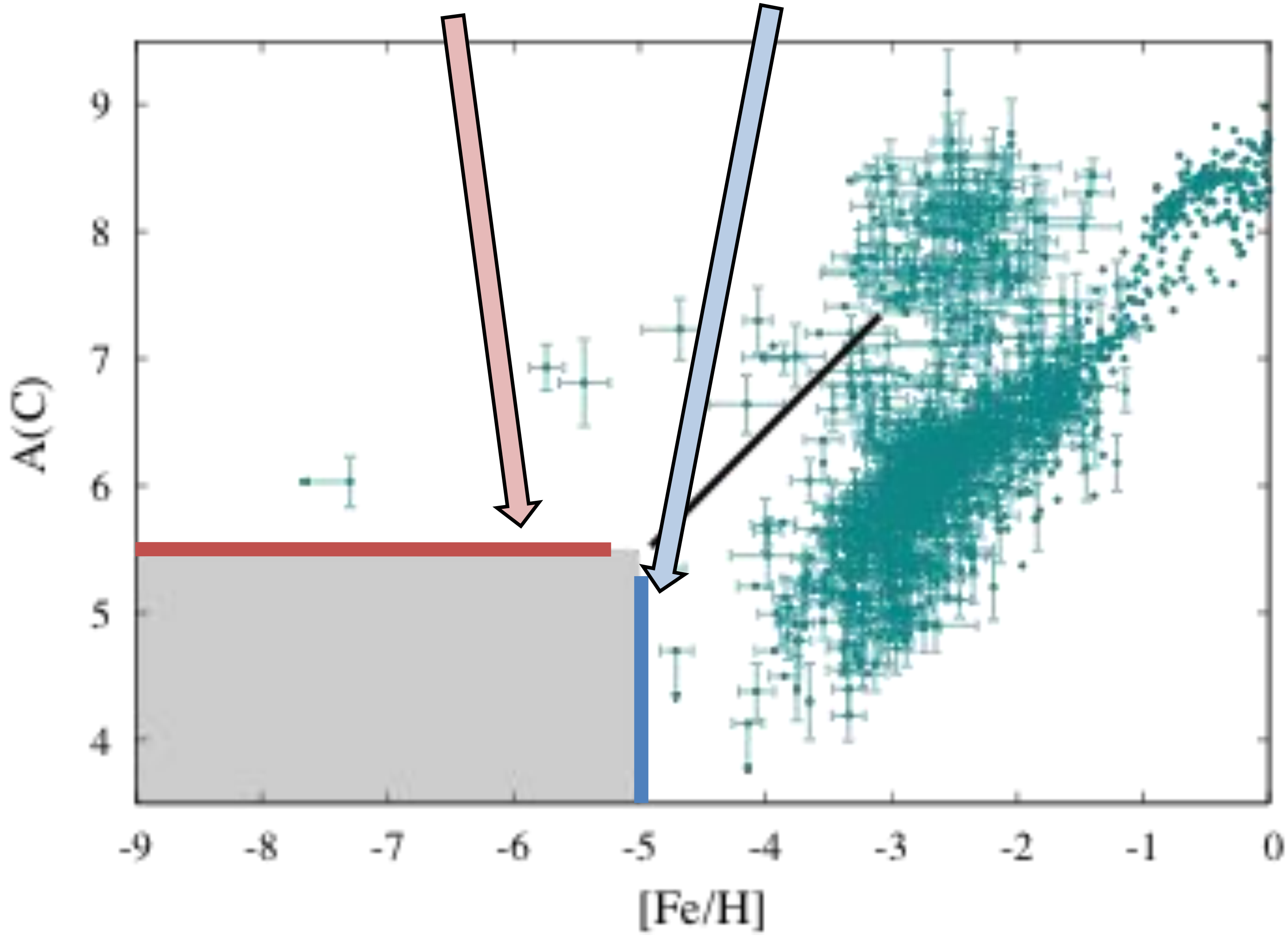
How can we determine these dust properties in the early Universe?

✓Direct measurement.
→Too hard to directly measure them by observations.

✓Earlier studies estimate them by theoretical models.
(Schneider et al. 2006; Chiaki et al. 2013, 2014, 2015; Marassi et al. 2014, 2015)
→Model dependent…

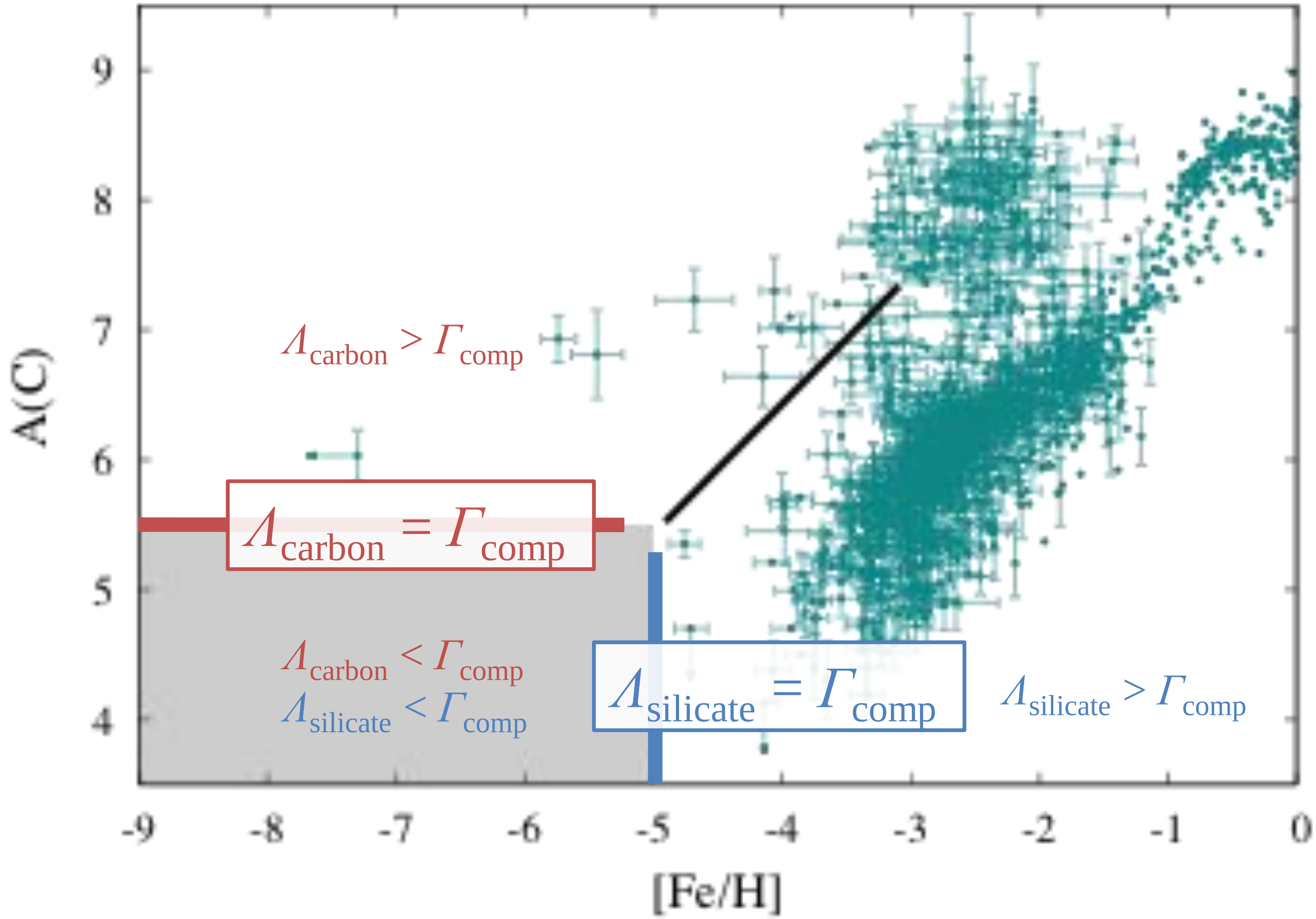
So, we here present a new way to estimate the dust properties.

We pay attention to $A_{cr}(C)$ & $[Fe/H]_{cr}$



On the critical lines, energy balance equations are established

dust cooling rate Λ_{dust} = gas compressional heating Γ_{comp}



Energy balance equation on the critical lines

Dust cooling rate:

grain cross section — gas thermal velocity

$$\Lambda_{\mathrm{dust}} = (2kT_{\mathrm{gas}} - 2kT_{\mathrm{dust}})\,(\sigma_{\mathrm{dust}} v_{\mathrm{gas}}) n_{\mathrm{gas}} n_{\mathrm{dust}}$$

Hydrogen mass fraction — molecular weight of dust — condensation efficiency

$$\approx \frac{3X_{\mathrm{H}}\,\mu_{\mathrm{dust}} m_{\mathrm{H}} n_{\mathrm{H}}^{2} v_{\mathrm{gas}}}{4\varsigma_{\mathrm{dust}}} \frac{f_{\mathrm{dust}\leftarrow\mathrm{metal}}}{r_{\mathrm{dust}}^{\mathrm{cool}}} y_{\mathrm{metal}}$$

dust bulk density ~g cm^{-3} — metal number fraction — average grain radius

Gas compressional heating:

$$\Gamma_{\mathrm{comp}} = \frac{n_{\mathrm{gas}} k T_{\mathrm{gas}}}{t_{\mathrm{collapse}}}$$

collapse timescale = free-fall time

Energy balance equation on the critical lines

$$\frac{3\mu_{\rm dust} X_{\rm H}}{4\varsigma_{\rm dust}\, r_{\rm dust}^{\rm cool} / f_{\rm dust\leftarrow metal}}\, y_{\rm metal} = 1.4\times 10^{-2}\ {\rm g\ cm^{-1}}$$

Energy balance equation on the critical lines

$$\begin{cases} A_{\rm cr}({\rm C}) \sim 6 \\ [{\rm Fe/H}]_{\rm cr} \sim -5 \end{cases}$$

$$\Downarrow$$

$$\frac{3\mu_{\rm dust} X_{\rm H}}{4\varsigma_{\rm dust}\, r_{\rm dust}^{\rm cool} / f_{\rm dust\leftarrow metal}}\, y_{\rm metal} = 1.4\times 10^{-2}\ {\rm g\ cm^{-1}}$$

$$\Downarrow$$

We can estimate **grain size / condensation efficiency** as

$$\begin{cases} r_{\rm carbon} / f_{\rm carbon\leftarrow C} \sim 10\ \mu{\rm m} \\ r_{\rm silicate} / f_{\rm silicate\leftarrow Mg} \sim 0.1\ \mu{\rm m} \end{cases}$$

We consider that they are valid for all EMP stars.

We can reconstruct the critical lines with these dust properties.

In general, both carbon and silicate grains contribute to gas cooling. Therefore,

$$\frac{3\mu_{\rm carbon} X_{\rm H}}{4\varsigma_{\rm carbon}\, r_{\rm carbon}^{\rm cool} / f_{\rm carbon \leftarrow C}}\, y_{\rm C} + \frac{3\mu_{\rm silicate} X_{\rm H}}{4\varsigma_{\rm silicate}\, r_{\rm silicate}^{\rm cool} / f_{\rm silicate \leftarrow Mg}}\, y_{\rm Mg} = 1.4 \times 10^{-2}\ {\rm g\ cm^{-1}}$$

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using
$$\begin{cases} r_{\rm carbon} / f_{\rm carbon\leftarrow C} \sim 10\ \mu{\rm m} \\ r_{\rm silicate} / f_{\rm silicate\leftarrow Mg} \sim 0.1\ \mu{\rm m} \end{cases}$$

$$10^{[{\rm C/H}]-1.93} + 10^{[{\rm Mg/H}]} = -4.70$$

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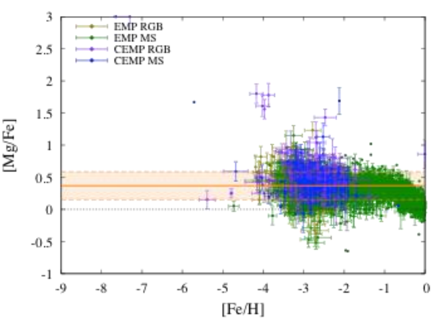
$$10^{[\mathrm{C/H}]-1.93} + 10^{[\mathrm{Mg/H}]} = -4.70$$

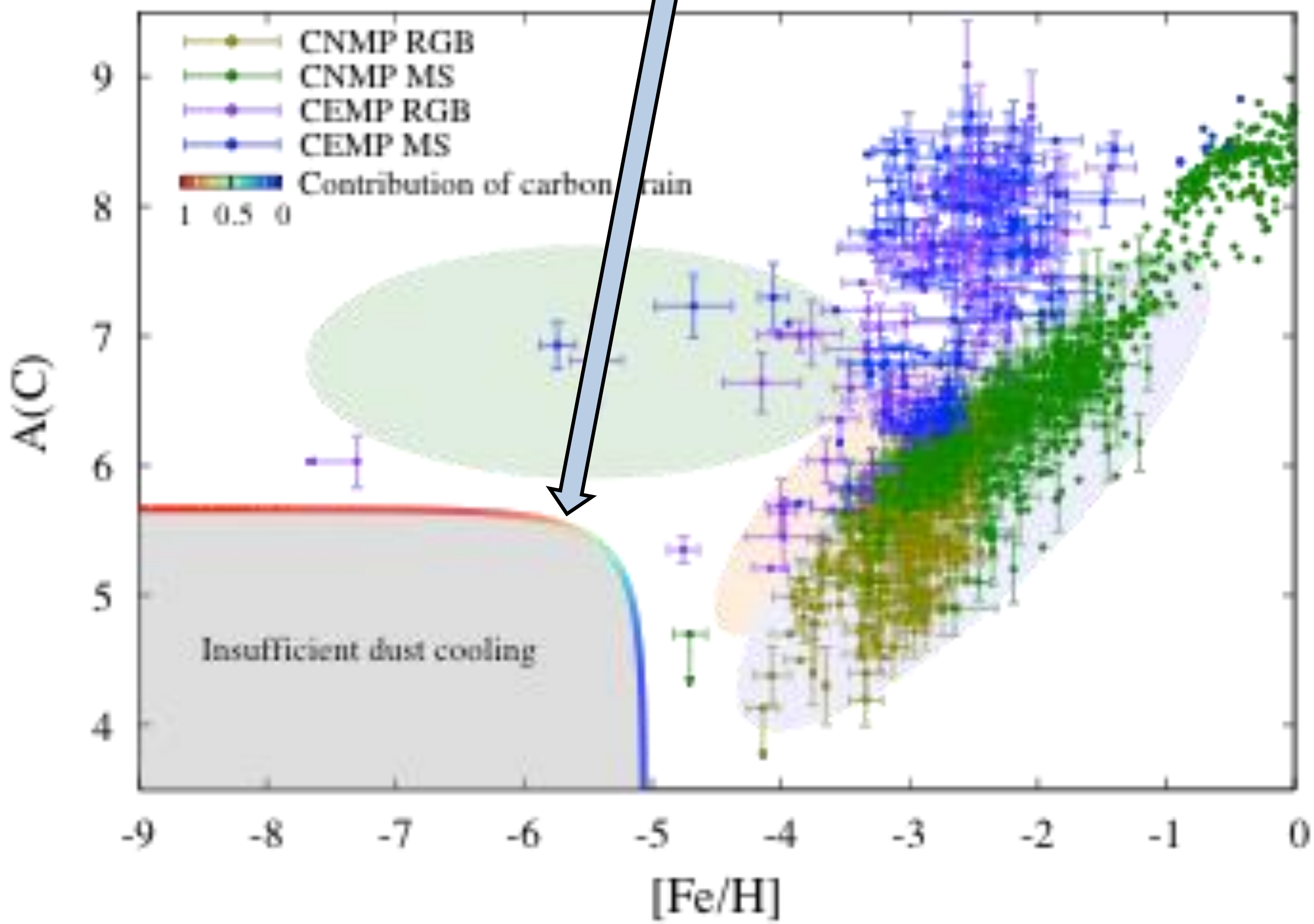


from average [Mg/Fe] = 0.368 of EMP stars,

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

$$\left\{ \begin{array}{l} r_{\mathrm{carbon}} / f_{\mathrm{carbon}\leftarrow \mathrm{C}} \sim 10\ \mu\mathrm{m} \\ r_{\mathrm{silicate}} / f_{\mathrm{silicate}\leftarrow \mathrm{Mg}} \sim 0.1\ \mu\mathrm{m} \end{array} \right.$$

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

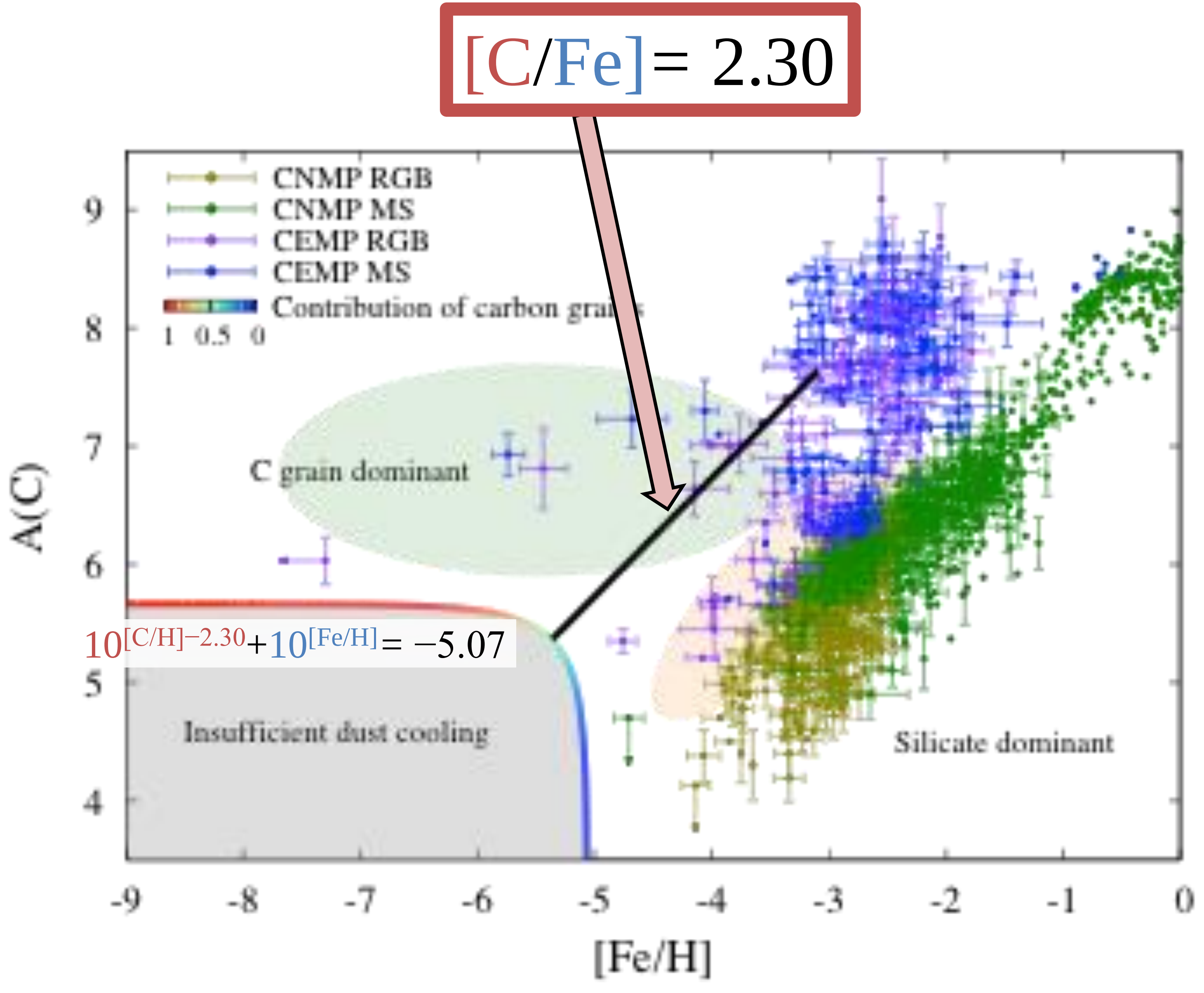


Finally, the boundary of two regions with carbon and silicate is

Carbon grain cooling efficiency = Silicate grain cooling efficiency

$$\frac{3\mu_{\rm carbon} X_{\rm H}}{4\varsigma_{\rm carbon}\, r^{\rm cool}_{\rm carbon} / f_{\rm carbon\leftarrow C}}\, y_{\rm C} = \frac{3\mu_{\rm silicate} X_{\rm H}}{4\varsigma_{\rm silicate}\, r^{\rm cool}_{\rm silicate} / f_{\rm silicate\leftarrow Mg}}\, y_{\rm Mg}$$

$$[{\rm C}/{\rm Fe}] = 2.30$$



[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]
9
8
7
6
5
4
-9
-8
-7
-6
-5
-4
-3
-2
-1
0

A_{cr}(C) & [Fe/H]$_{cr}$ suggest the larger carbon grains than silicate

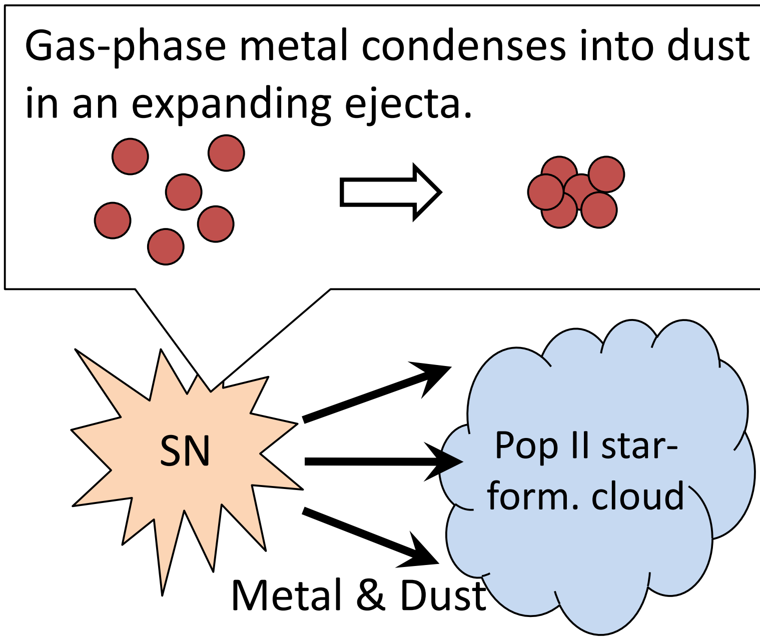
$$\begin{cases} r_{\mathrm{carbon}} / f_{\mathrm{carbon}\leftarrow\mathrm{C}} \sim 10\ \mu\mathrm{m} \\ r_{\mathrm{silicate}} / f_{\mathrm{silicate}\leftarrow\mathrm{Mg}} \sim 0.1\ \mu\mathrm{m} \end{cases}$$

We confirm it from a model calculation.

•Dust grains in the early universe are mainly supplied by supernovae (SNe) of first (Pop III) stars (Todini & Ferrara 2001).

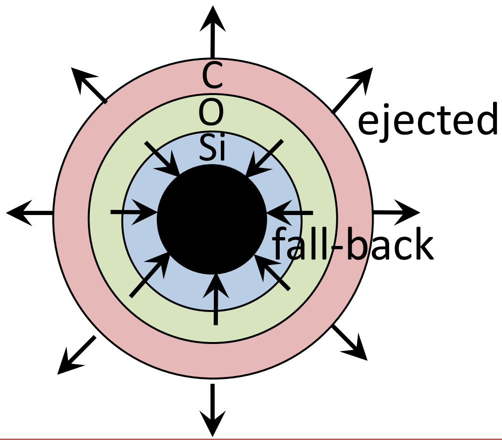
•We calculate condensation of metals in an expanding ejecta.

•1D hydrodynamics calculation
✓Radiative transfer
✓energy deposition of ^{56}Ni decay
(Iwamoto et al. 2000)

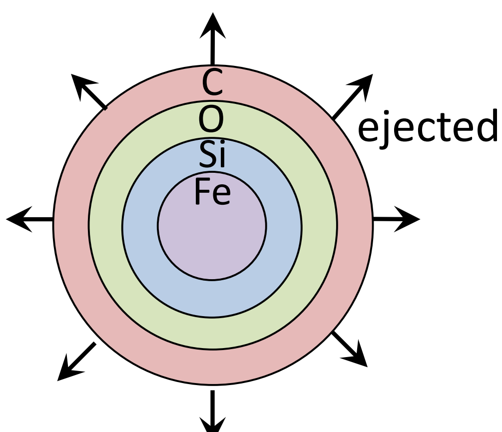


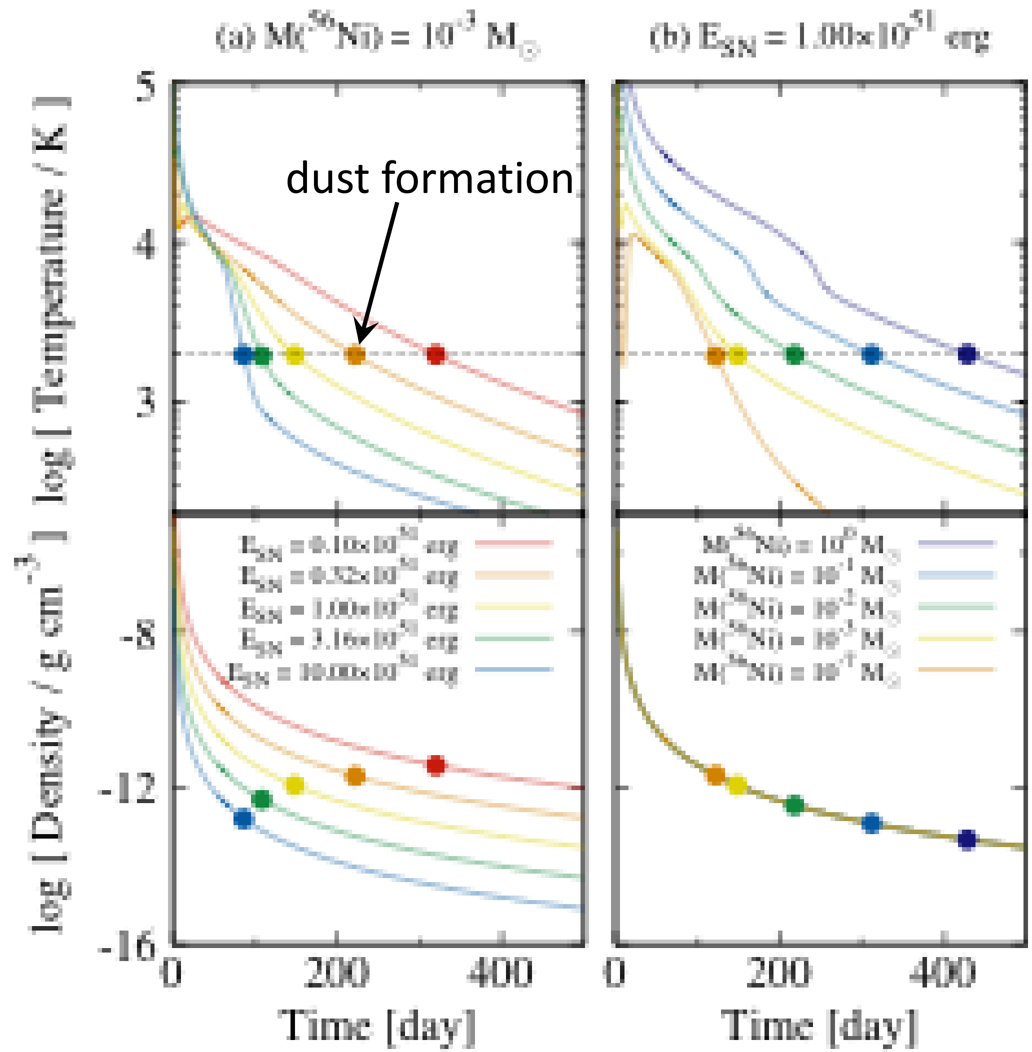
SN models

CEMP stars - faint (SN) models
(Umeda & Nomoto 2003)

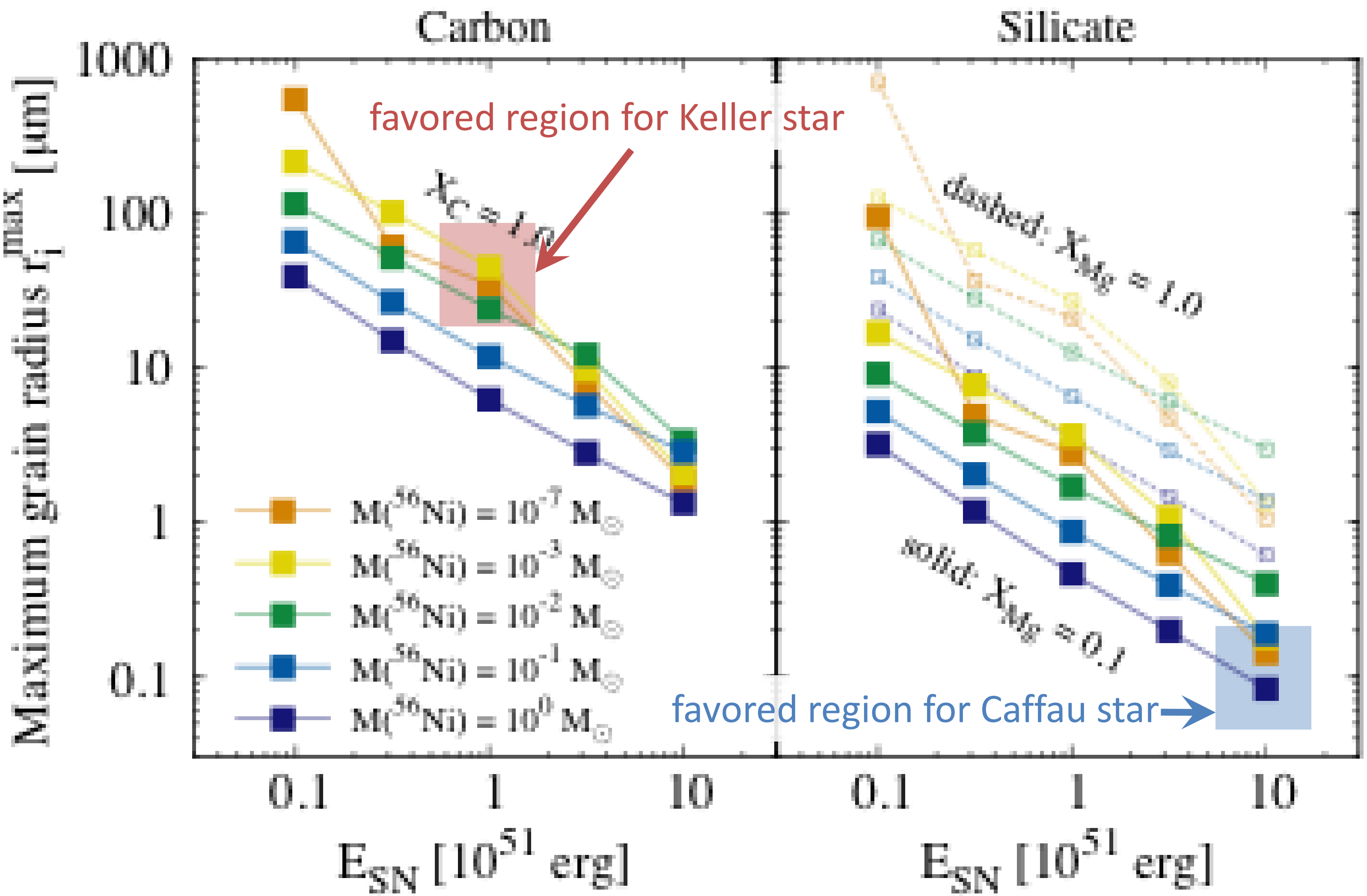


C-normal stars - normal type II



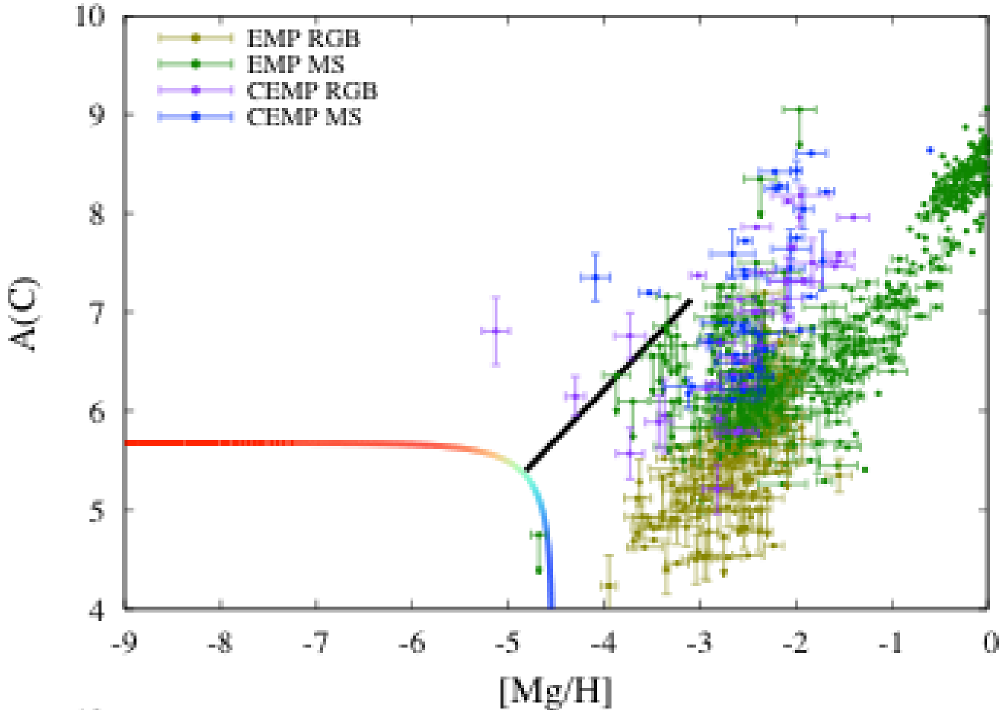


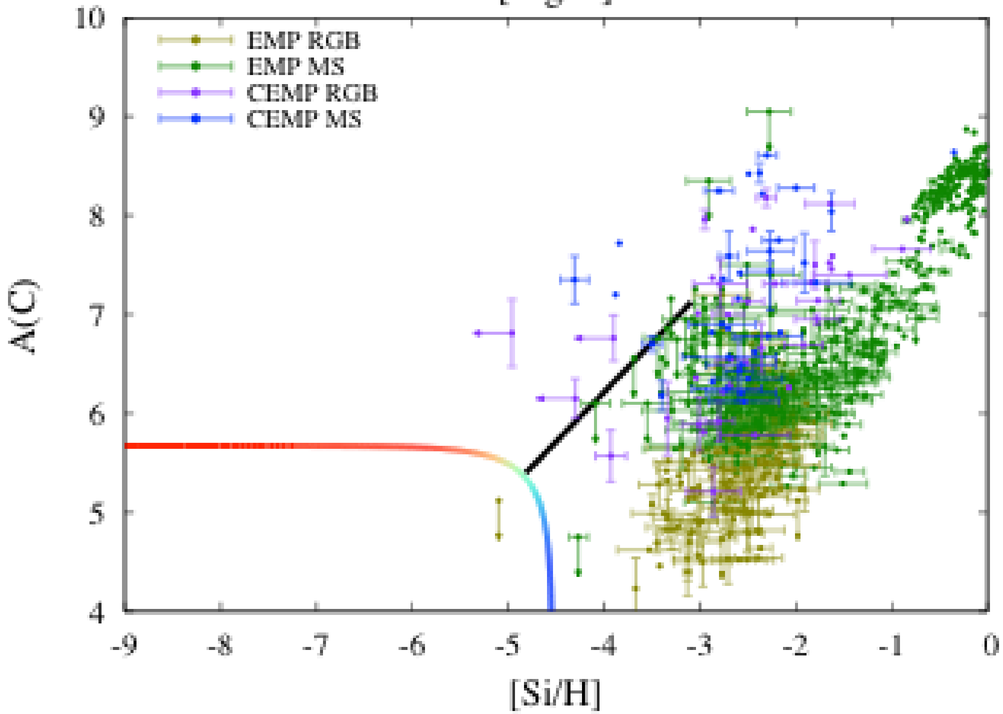
The model predicts larger carbon grains than silicate!



Summery

- We reconsider the classification of EMP stars from a theoretical point of view
  - ✓Stars formed through cloud fragmentation induced by carbon grains ([C/Fe]$\gtrsim$2)
  - ✓Stars formed through cloud fragmentation induced by silicate grains ([C/Fe]$\lesssim$2)
- From the critical abundances $A_{cr}(\mathrm{C})$ and $[\mathrm{Fe/H}]_{cr}$, we derive the dust properties in EMP star-forming clouds as
  - ✓$r_{\mathrm{carbon}} / f_{\mathrm{carbon} \leftarrow \mathrm{C}} \sim 10\ \mu\mathrm{m}$
  - ✓$r_{\mathrm{silicate}} / f_{\mathrm{silicate} \leftarrow \mathrm{Mg}} \sim 0.1\ \mu\mathrm{m}$
- Using the dust properties, we reconstruct the critical condition for low-mass EMP star formation as
  - ✓$10^{[\mathrm{C/H}]-2.30} + 10^{[\mathrm{Fe/H}]} = -5.07$
- The boundary of two classes is estimated as
  - ✓$[\mathrm{C/Fe}] = 2.30$


EMP RGB
EMP MS
CEMP RGB
CEMP MS
A(C)
[Mg/H]
10
9
8
7
6
5
4
-9
-8
-7
-6
-5
-4
-3
-2
-1
0


EMP RGB
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A(C)
[Si/H]
10
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