**Francesco's Legacy**
**Star Formation in Space and Time**

International Conference
June 5-9 2017
Istituto degli Innocenti
Firenze Italy

# Bridging the near and the far: constraints on first star formation from stellar archaeology

Raffaella Schneider
Sapienza University of Rome

Kyoto,First Stars IV 2012

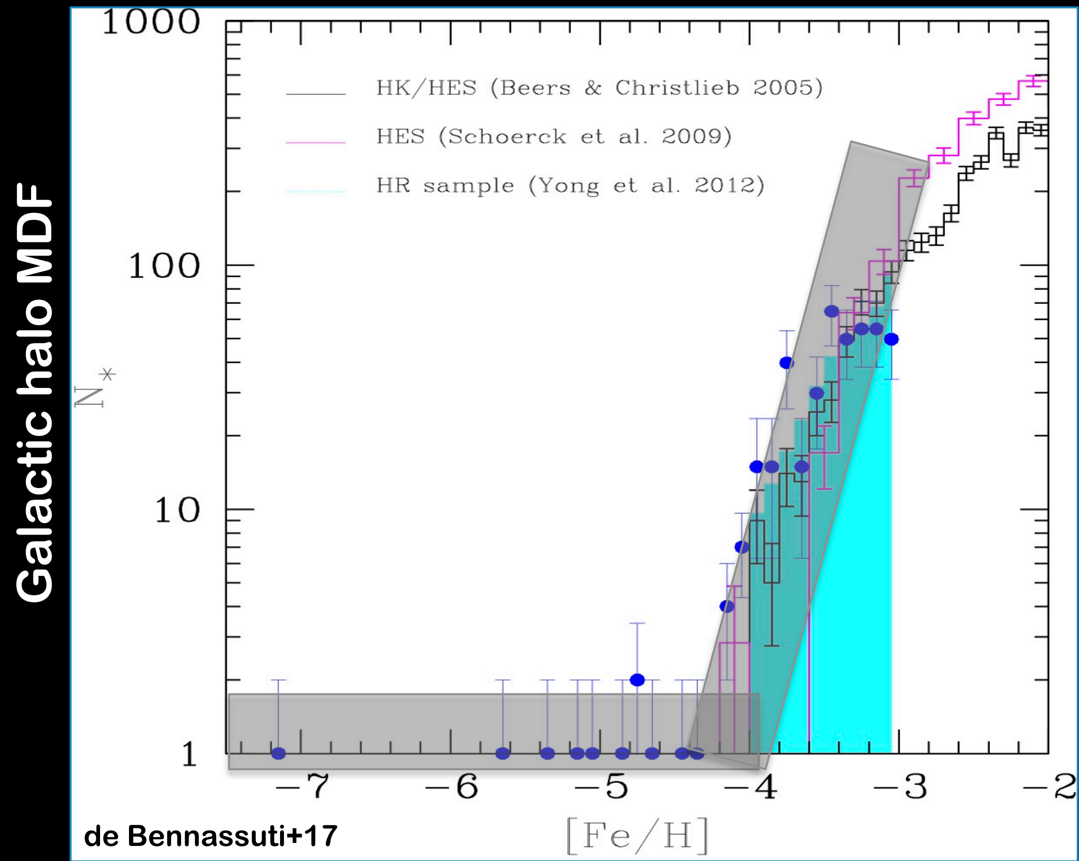

Kyoto,First Stars IV 2012

*"As we extend our investigation to the formation of the first stars, we reach the limits, in both time and space, of current knowledge"* Stahler & Palla, The Formation of stars, 2004

how can stellar archaeology help us bridge the gap in time and space?

# probing high-z SF with stellar archaeology

low mass metal-poor stars are fossil remnants of early star formation:
their metallicity distribution function (MDF) and surface elemental abundances
encode information on their formation efficiency and on the sources of metal enrichment




Beers & Christlieb 2005;Schörck et al. 2009; Christlieb 2013; Yong+2013

what are the processes that shape the low [Fe/H] tail of the MDF ?

# the most iron-poor stars in the Galactic halo

8 out of 9 can be classified as CEMP-no stars:
[C/Fe] > 0.7, no s-process elements, not associated to binary systems

| | | | |
|---|---|---|---|
| HE 0107–5240 | [Fe/H] = -5.39 | [C/Fe] = + 3.70 | Christilieb+02 |
| HE 1327–2326 | [Fe/H] = -5.66 | [C/Fe] = +4.26 | Frebel+05 |
| HE 0557–4840 | [Fe/H] =-4.81 | [C/Fe] = +1.65 | Norris+07 |
| SDSS J1069+1729 | [Fe/H] = -4.73 | [C/Fe] < 0.93 | Caffau+11 |
| SMSS 0313-0708 | [Fe/H] < -7.30 | [C/Fe] > 4.90 | Keller+14 |
| HE 0233–0343 | [Fe/H] = -4.68 | [C/Fe] = +3.46 | Hansen+14 |
| SDSS J1742+2531 | [Fe/H] = -4.80 | [C/Fe] = +3.56 | Caffau+14 |
| SDSS J1035+0641 | [Fe/H] < - 5.07 | [C/Fe] > 3.40 | Bonifacio+15 |
| SDSS J131326+0019 | [Fe/H] = -5 | [C/Fe] = + 3 | Allende-Prieto +15 |

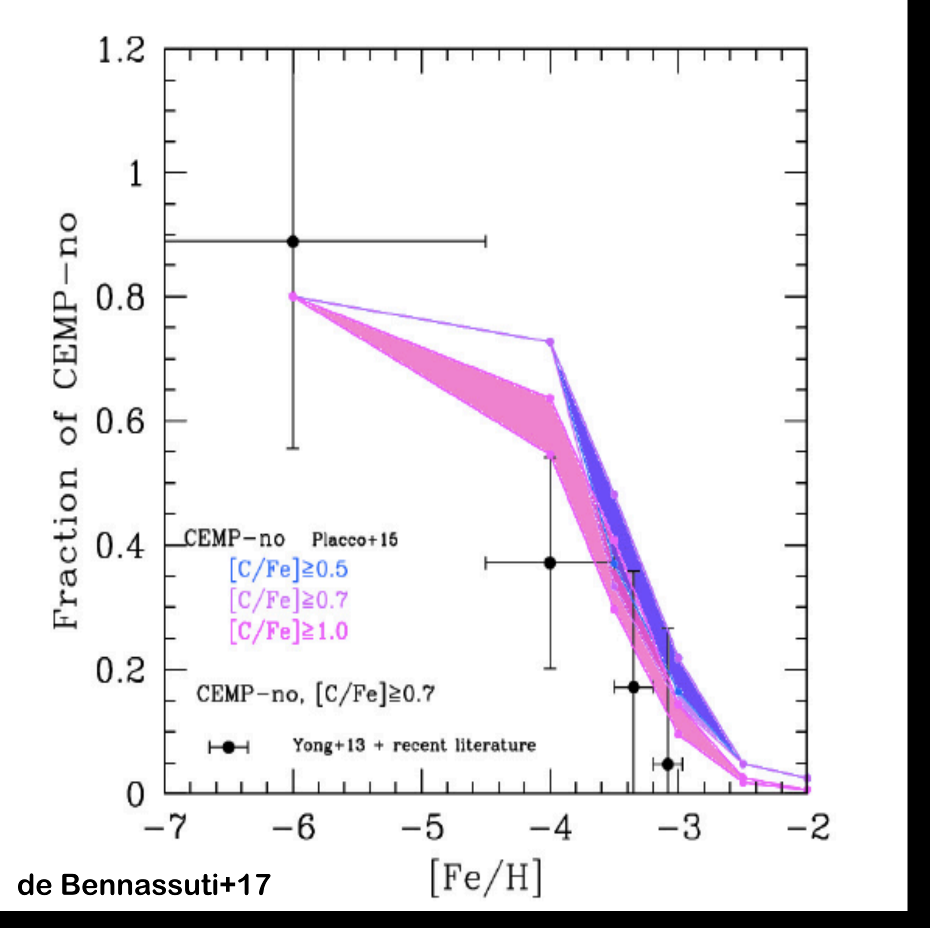
what is the origin of CEMP-no stars?

**Pop III faint/failed supernovae:** Umeda & Nomoto 03; Iwamoto+05; Joggerst+09; Marassi+14

**Massive rotating Pop III star:** Meynet+06; Maeder+15

# the carbonicity of metal-poor stars

**CEMP-no stars most likely appear at low [Fe/H]**



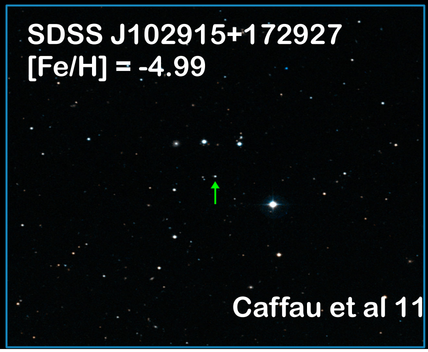

de Bennassuti+17

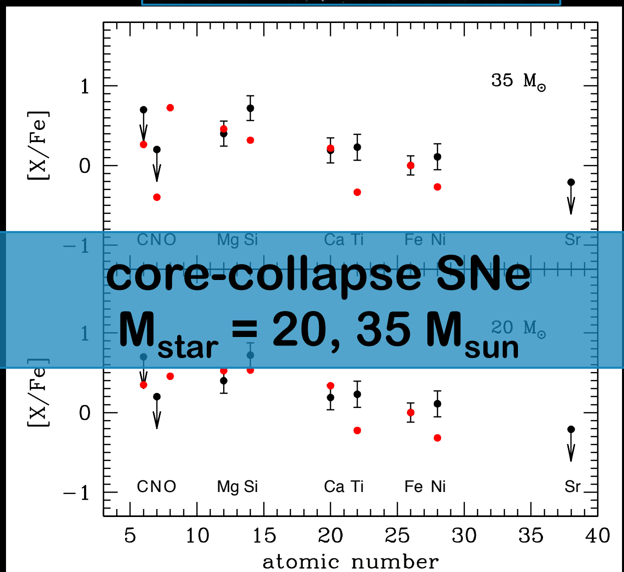
**Why does the C-enhanced fraction decrease with [Fe/H] ?**

# simulating the birth environment of C-normal and C-rich stars

Schneider et al. 2012; Klessen+12; Ji et al. 2013; Marassi et al.2014, 2015; Bovino et al. 2015, 2016

**C-normal star**



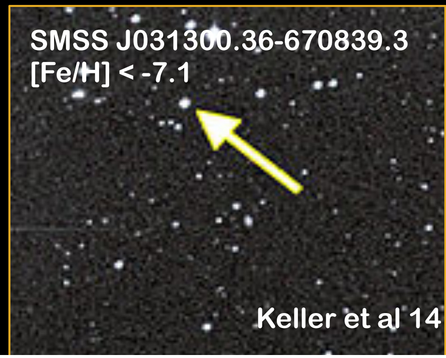



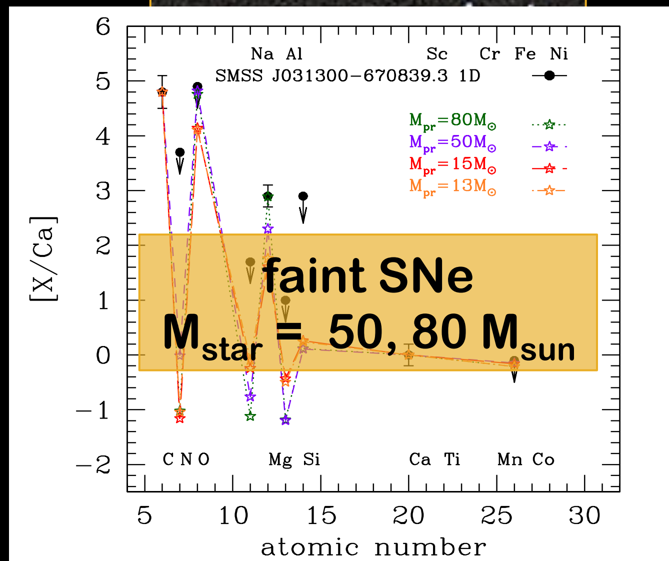

core-collapse SNe

$M_{star}$ = 20, 35 $M_{sun}$

Schneider et al. 2012

**C-enhanced star**



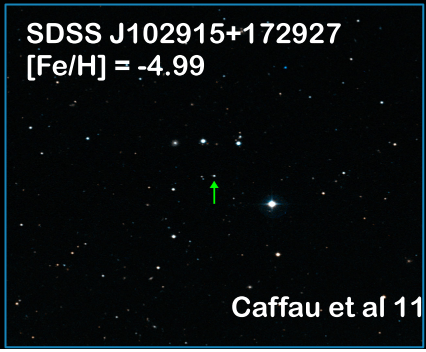



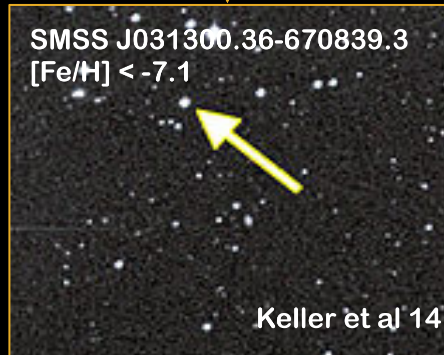

faint SNe

$M_{star}$ = 50, 80 $M_{sun}$

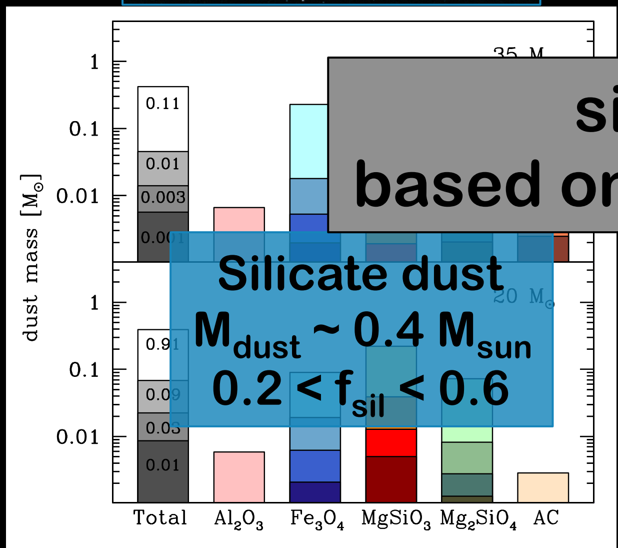
Marassi et al. 2014

# simulating the birth environment of C-normal and C-rich stars



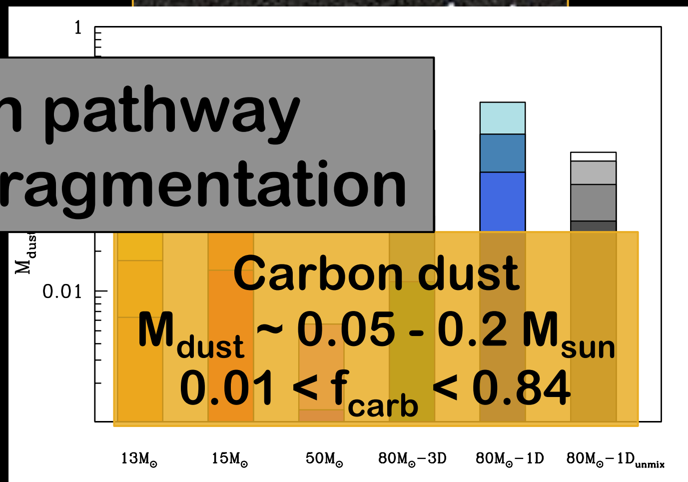




**single formation pathway**
**based on dust-driven fragmentation**




**Silicate dust**
$M_{dust} \sim 0.4\ M_{sun}$
$0.2 < f_{sil} < 0.6$

Schneider et al. 2012




**Carbon dust**
$M_{dust} \sim 0.05 - 0.2\ M_{sun}$
$0.01 < f_{carb} < 0.84$

Marassi et al. 2014

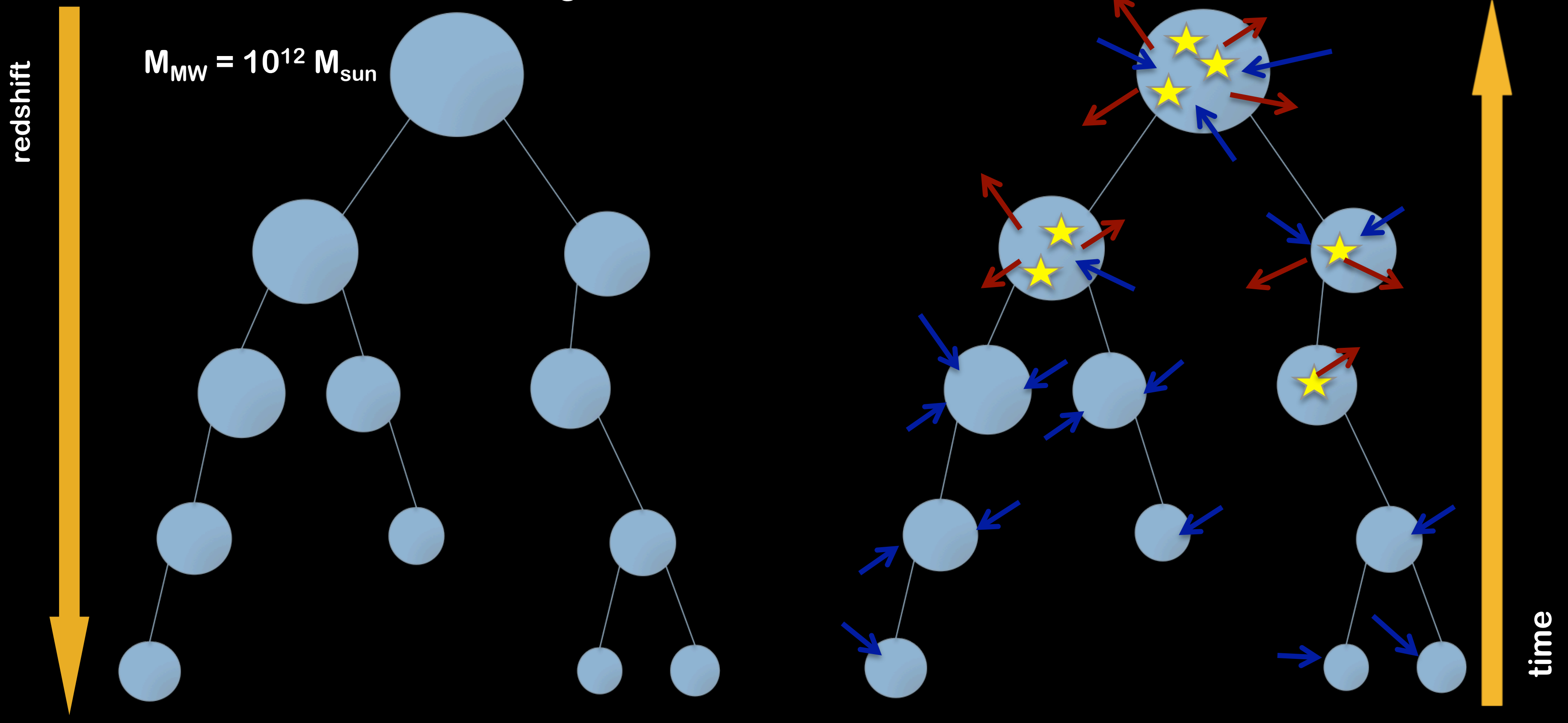
# GAMETE

## GAlaxy MErger Tree and Evolution

Salvadori et al. 2007, 2008, 2009, 2014, 2015; Valiante et al. 2011, 2014; de Bennassuti et al. 2014; Salvadori & Ferrara 2009,2012

dark matter halo merger tree

star formation and chemical evolution

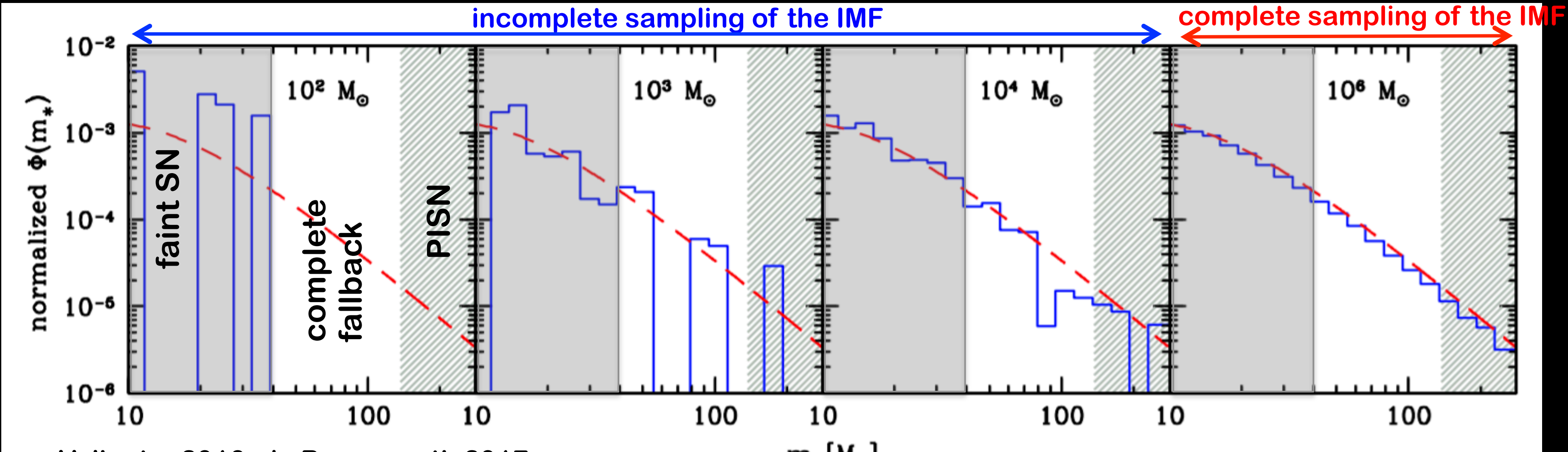



see also Tumlinson 2007, 2010; Komiya+2007, 2011, 2016; Hartwig+2015

# initial mass function of Pop III stars in mini-halos

$$\Phi(m) = \frac{dN}{dm} \propto m^{\alpha-1} \exp\left(-\frac{m_{ch}}{m}\right)$$

$m_{ch} = 20\ M_{sun}$ $\alpha = 1.35$ $m_* = [10 – 300]\ M_{sun}$

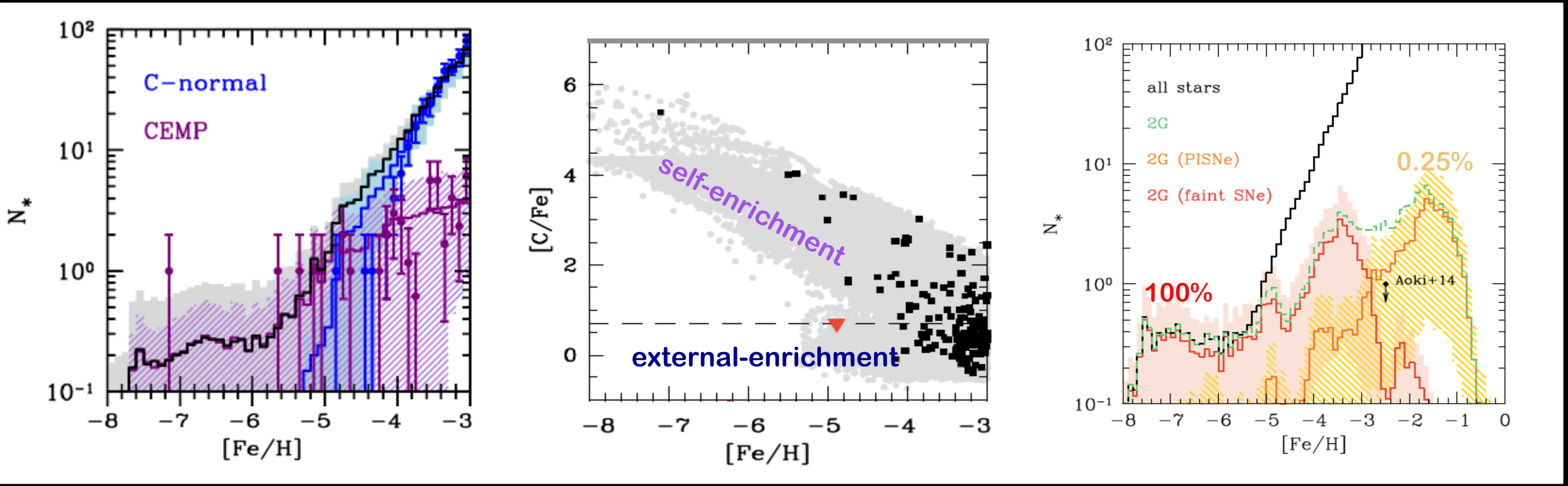



Valiante+2016; de Bennassuti+2017

Pop III stars forming in mini-halos have a low probability to explode as PISN

# probing high-z SF with stellar archaeology

Tumlinson+2007; Salvadori+2007; Komiya+2009,2010, 2015; Ji et al. 2013; Hartwig+15; de Bennassuti+15,16; Ishiyama+16




de Bennassuti+2014, 2017

Lessons learnt:

Pop III nucleosynthetic signatures dominated by faint supernovae

the formation of the first low mass stars is driven by dust cooling at very low metallicities

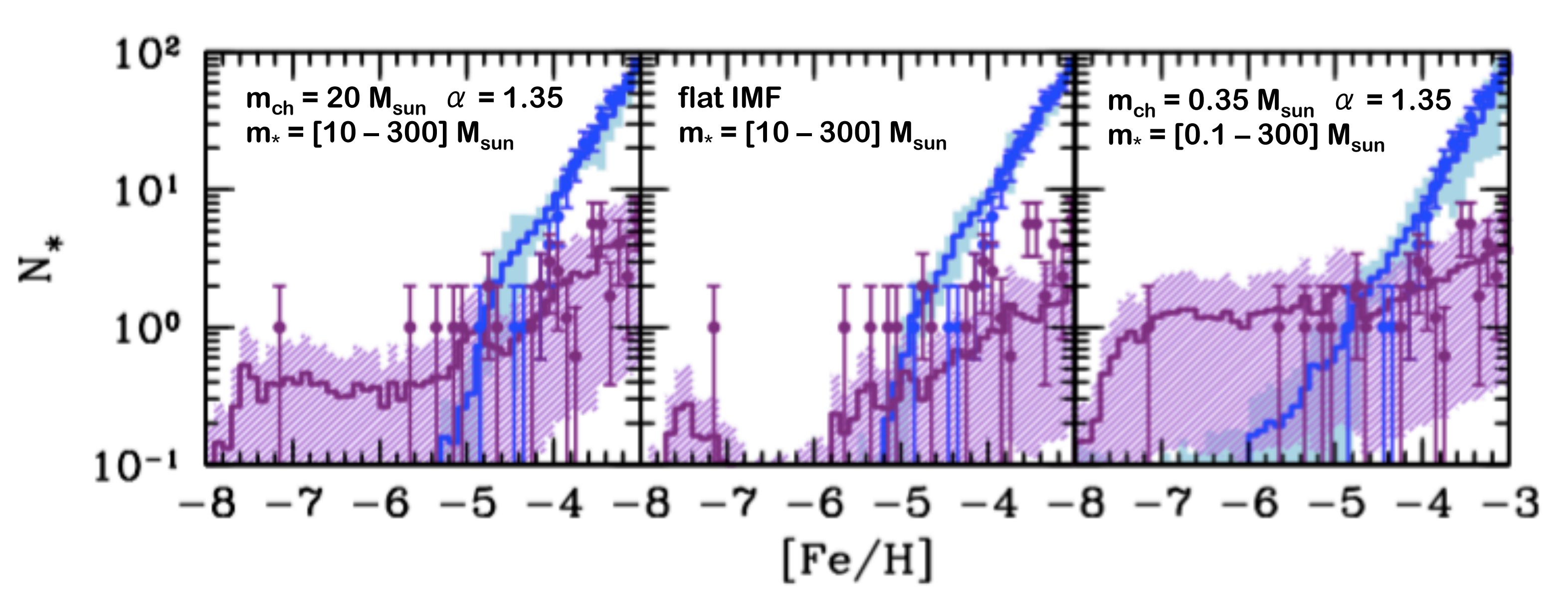
the low-[Fe/H] tail of the MDF is dominated by second-generation stars:

- 50% of CEMP-no stars with [Fe/H] < -3 are imprinted by Pop III faint SNe
- a few % of the total halo stars at -4 < [Fe/H] < -1 are imprinted by Pop III PISN

# constraints on the Pop III initial mass function

Tumlinson+2007; Salvadori+2007; Komiya+2009,2010, 2015; Ji et al. 2013; Hartwig+15; de Bennassuti+15,16; Ishiyama+16

de Bennassuti+2017




Lessons learnt:

a flat Pop III IMF with m = [10 – 300] $M_{sun}$ is currently disfavored by data

a Pop III IMF with mch ~ 0.35 Msun and extending to 0.1 Msun is still consistent with data:

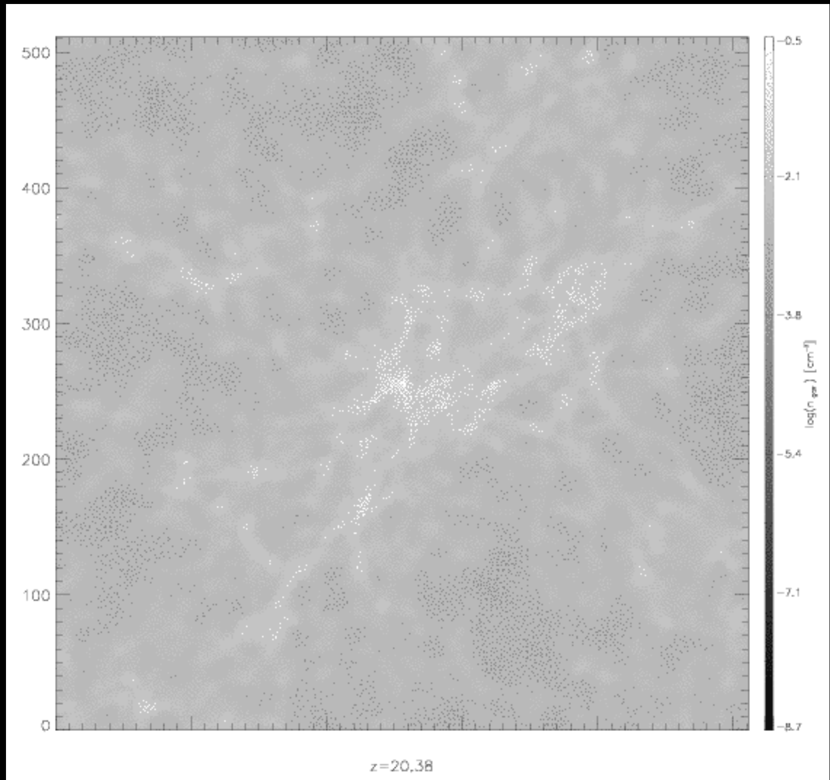
- 30% of CEMP stars at [Fe/H] < -5 are imprinted by faint SNe AND AGB stars: should show s-process
- 0.15 % of stars at [Fe/H] < -3 are truly metal-free

with better statistics we will be able to prove/disprove the existence of Pop III stars with m < 10 $M_{sun}$

# stellar archaeology along the MW assembly with radiative and chemical feedback with GAMESH

**GAMESH: GAMETE + dark matter simulation coupled to the radiative transfer code CRASH**

Graziani+15, 17



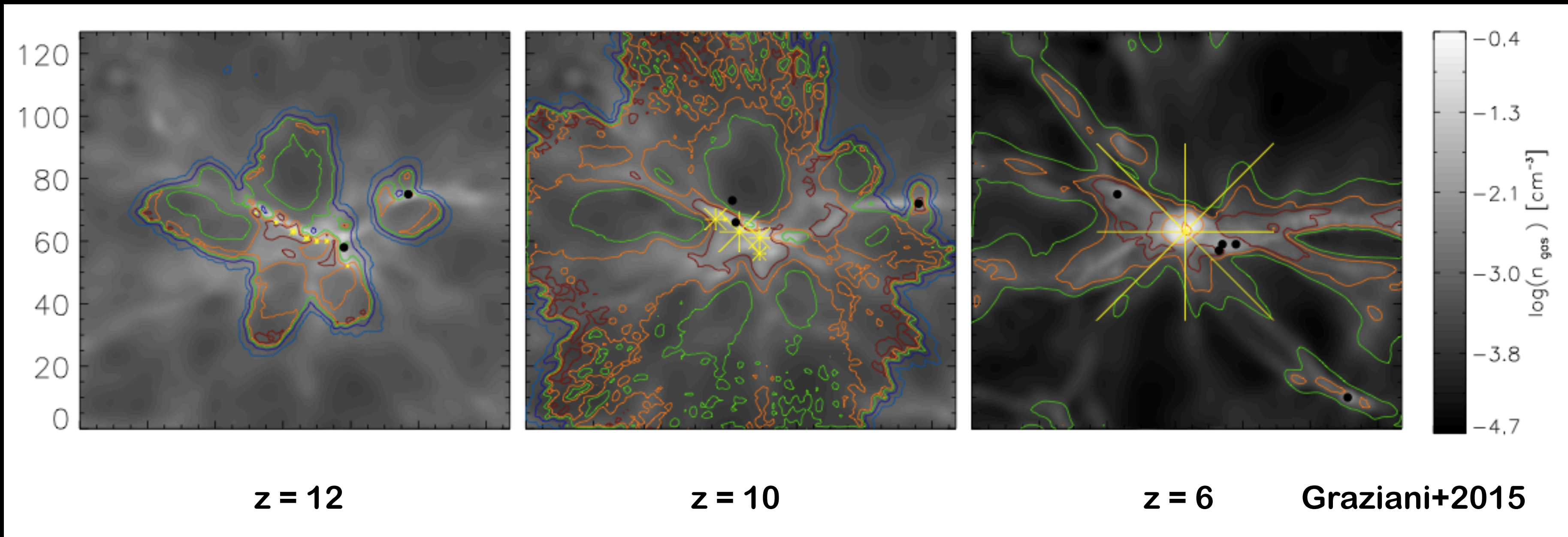

Dark matter simulation of the Milky Way galaxy in Planck cosmology GCD+ code with multi-resolution technique (Kawata & Gibson 03):

Low-res spherical region of $R_l \sim 20\ h^{-1}$ Mpc taken from a low-res cosmological simulation

High-res spherical region of $R_h \sim 2\ h^{-1}$ Mpc with $M_p = 3.4 \times 10^5\ M_{sun}$

# effects of inhomogeneous radiative feedback

cell units 1 cell = 15.6 $h^{-1}$ kpc

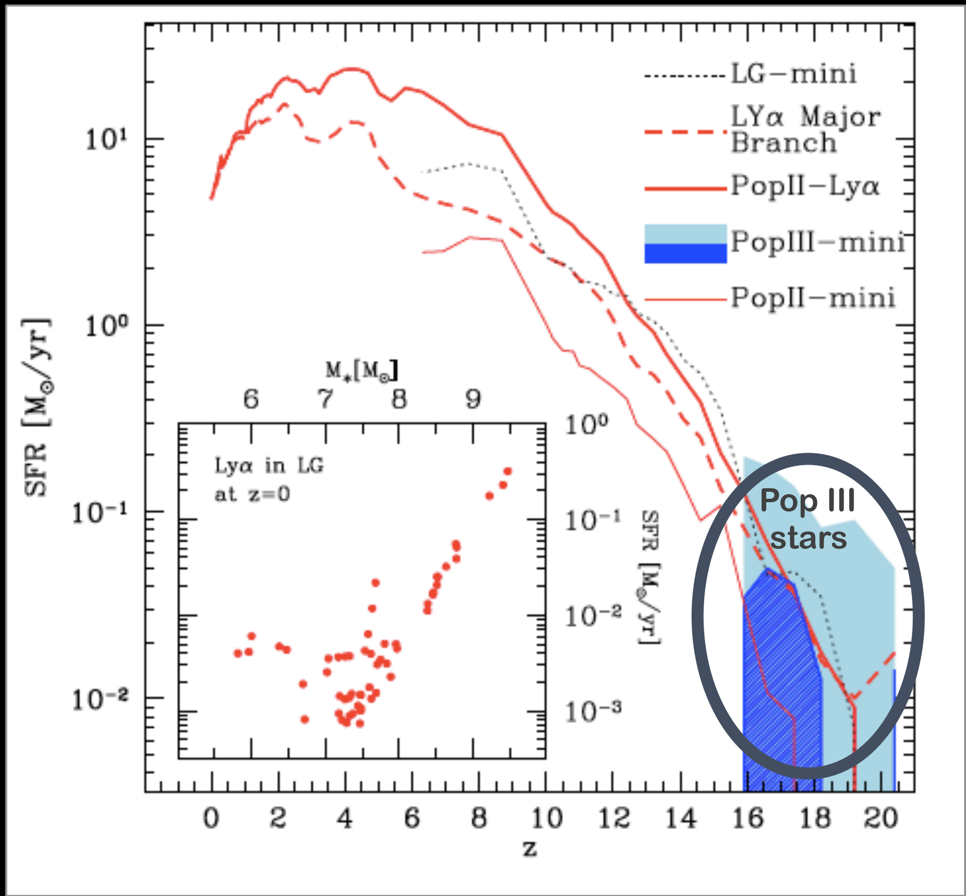



Temperature contours:
T ~ 100  4 x $10^3$  $10^4$  1.3 x $10^4$  1.5 x $10^4$ K

star forming regions in the plane are represented by yellow asterisks
black dots indicate regions where star formation is suppressed by radiative feedback

# tracing Pop III stars along the history of dark and luminous MW progenitors

Graziani+2017




due to chemical and radiative feedback effects, Pop III stars dominate the SFH at z > 16 and are confined to form in DM mini-halos: traces of early Pop III stars may be found in external galaxies of the Local Group

# Conclusions

*"As we extend our investigation to the formation of the first stars, we reach the limits, in both time and space, of current knowledge."* Stahler & Palla, The Formation of stars, 2004

although primordial stars were formed in the distant past, some of our greatest clues to the process of their formation are likely to come from our local Galactic neighborhood

on the theoretical side:
accurate modeling is required to interpret observations
→ GAMESH!

on the observational side:
larger statistical sample of MP stars with [Fe/H] < -3 can constrain the Pop III IMF