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First stars and their local relics

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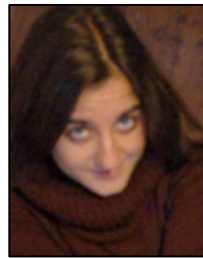
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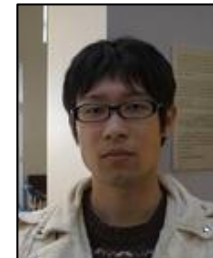
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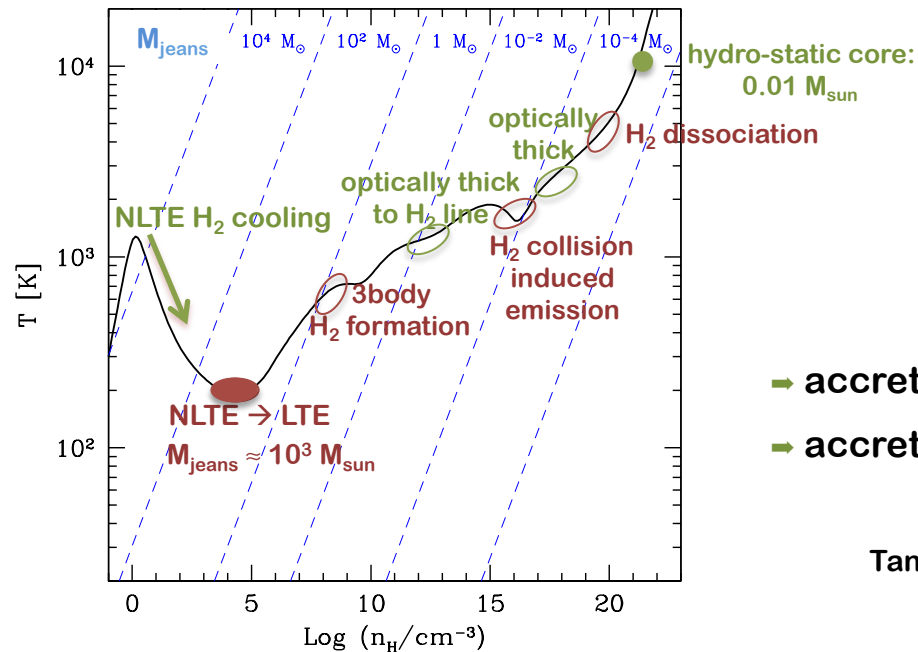
Kazu Omukai
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<http://www.oa-roma.inaf.it/FIRST/>

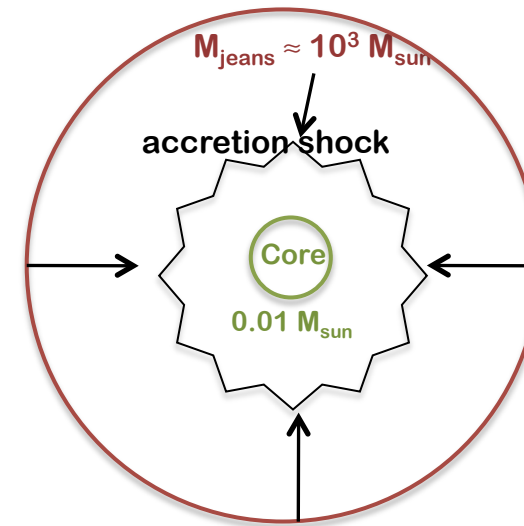
the formation of the first stars

Standard model for the formation of the first Pop III stars predicts an IMF dominated by high-mass stars

- ✓ collapse of $\approx 10^6 M_{\text{sun}}$ mini-halos at $z \approx 20$
- ✓ H_2 cooling
- ✓ gas cloud becomes Jeans unstable $M_{\text{jeans}} \approx 10^3 M_{\text{sun}}$



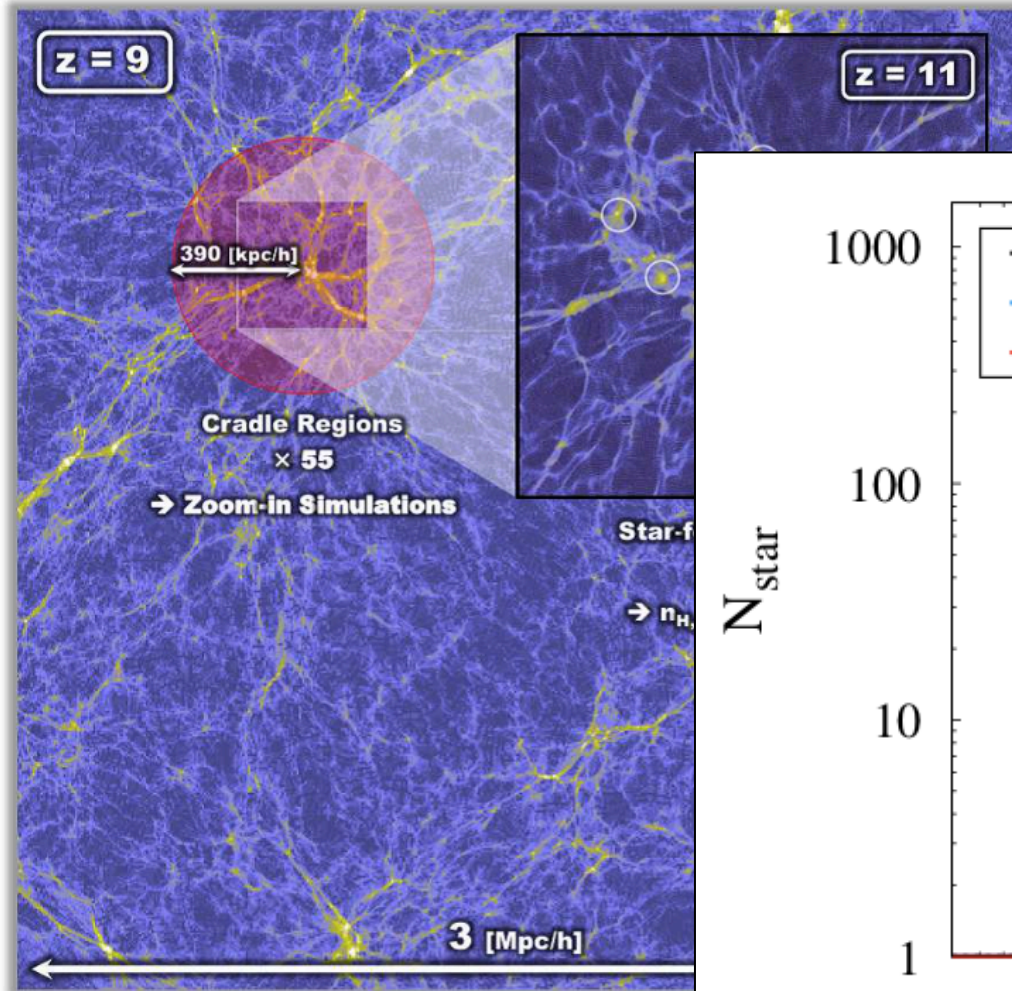
Omukai et al. 2005



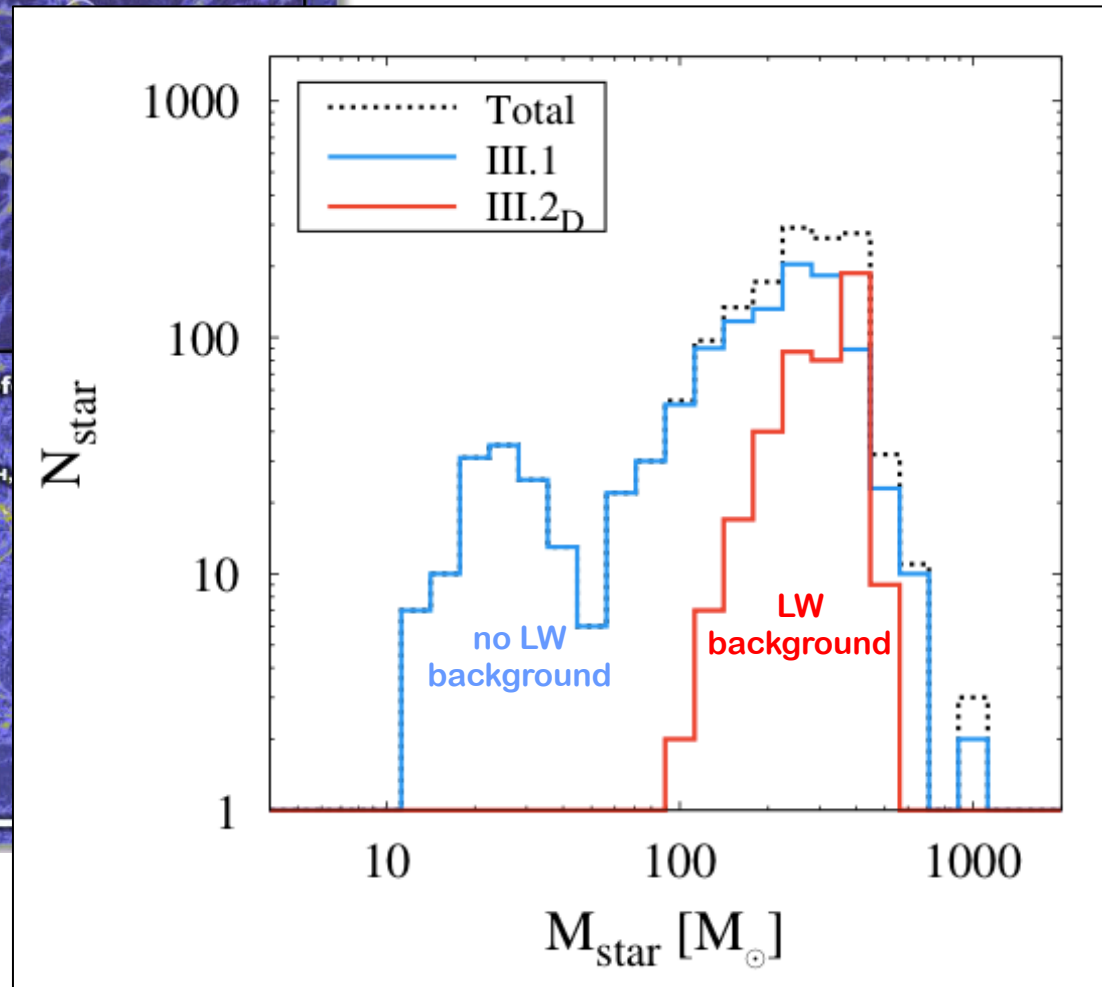
- ➡ accretion rate $dM/dt \approx M_J/t_{\text{ff}} \approx c_s^3/G \approx T^{3/2}$ (x 100 larger than @ Z_{sun})
- ➡ accreted gas mass $M_{\star} \equiv [10 - 1000] M_{\text{sun}}$

Omukai & Palla 2003; Bromm et al 2004; O'Shea et al. 2007;
Tan & McKee 2004; McKee & Tan 2008; Hosokawa et al. 2011, 2012;
Hirano+14, Susa+14; Hirano+15

An ab-initio calculation of the Pop III IMF

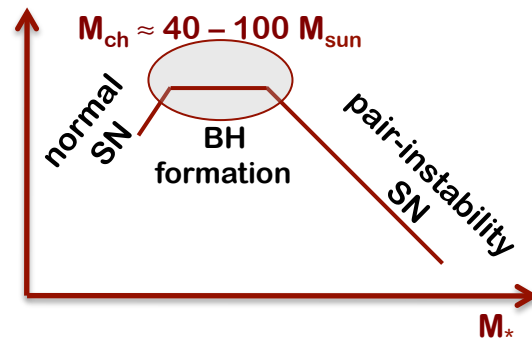


Hirano et al. 2015



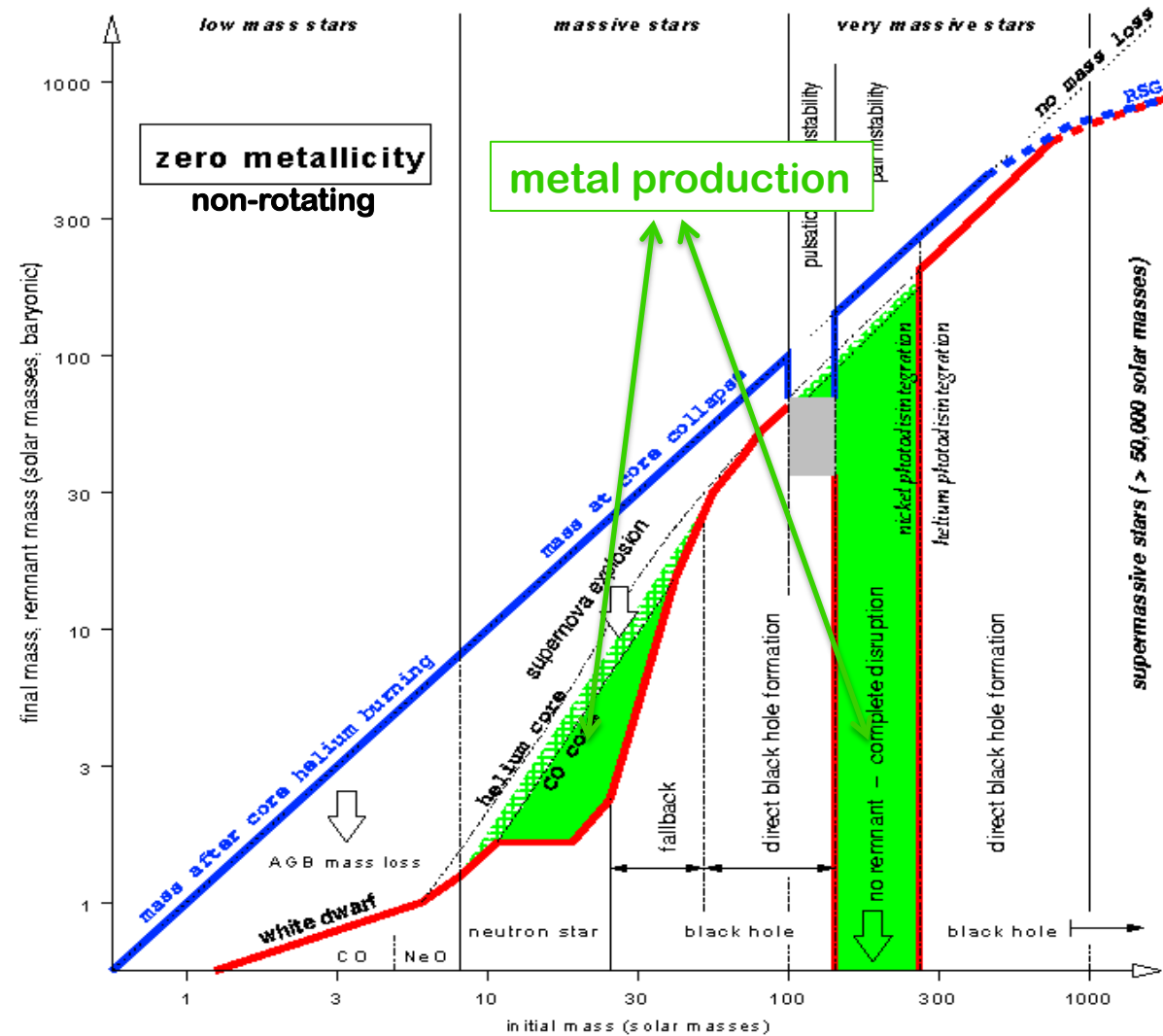
the end-products of Pop III stars

Pop III IMF ?



$10 M_{sun} < M_* < 40 M_{sun}$
metal production

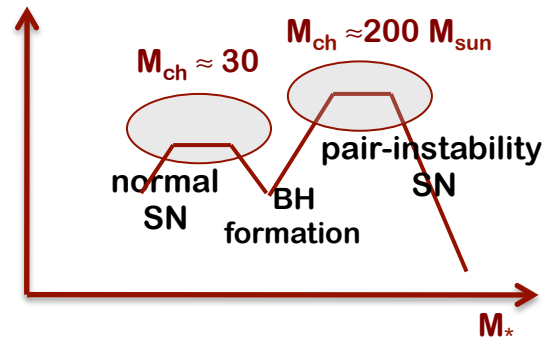
$140 M_{sun} < M_* < 260 M_{sun}$
metal production



Heger & Woosley (2002), Yoon et al (2012), Marassi et al. in prep

the end-products of Pop III stars

Pop III IMF ?

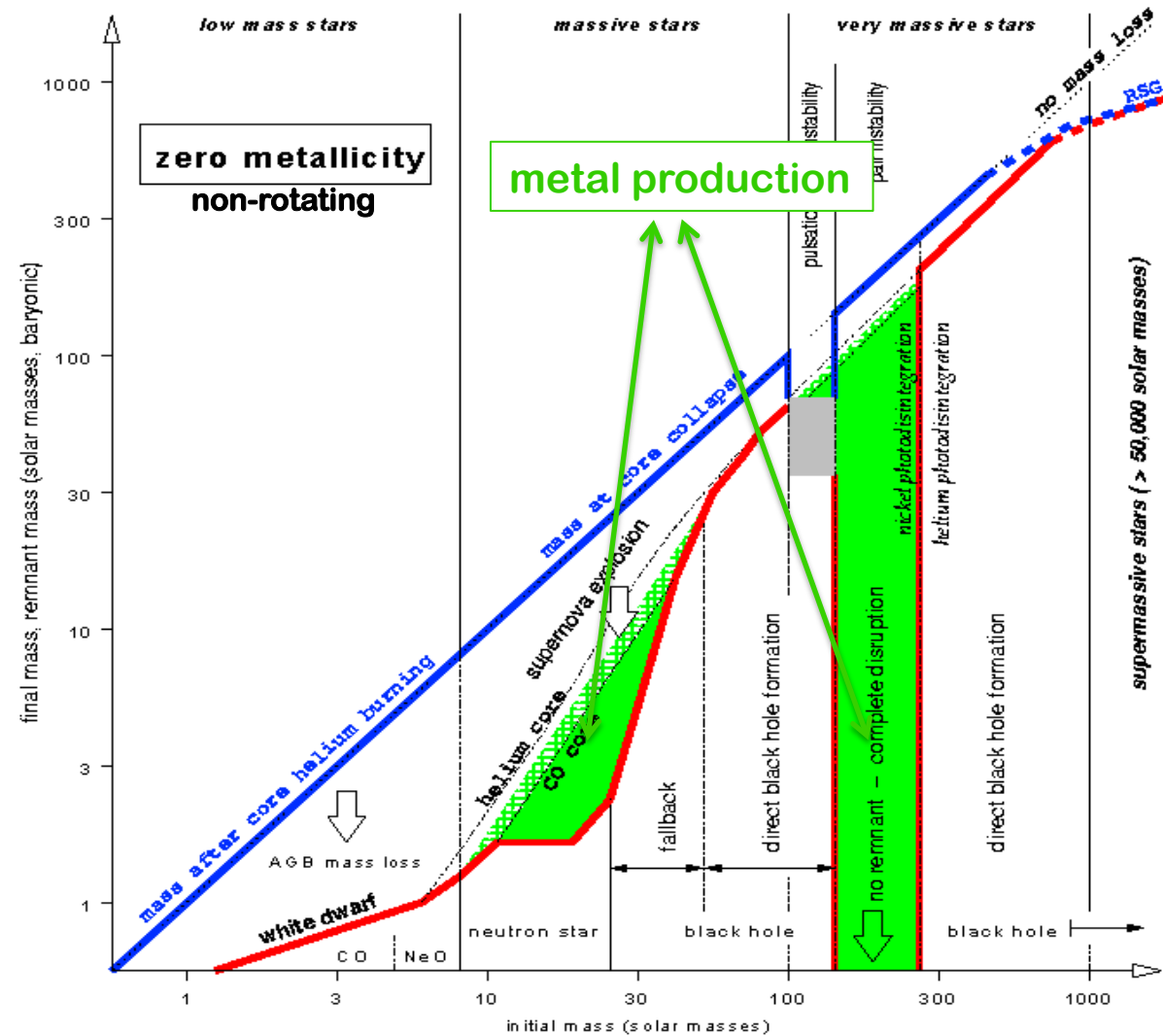


$10 M_{\odot} < M_* < 40 M_{\odot}$

metal production

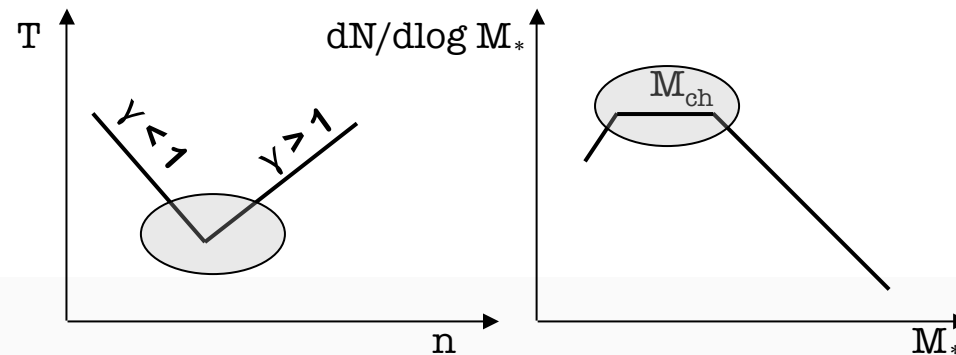
$140 M_{\odot} < M_* < 260 M_{\odot}$

metal production



Heger & Woosley (2002), Yoon et al (2012), Marassi et al. in prep

H₂, metal and dust-driven fragmentation: three different mass-scales



H₂-line cooling:

$$M_{\text{jeans}} \sim 10^3 M_{\text{sun}}$$

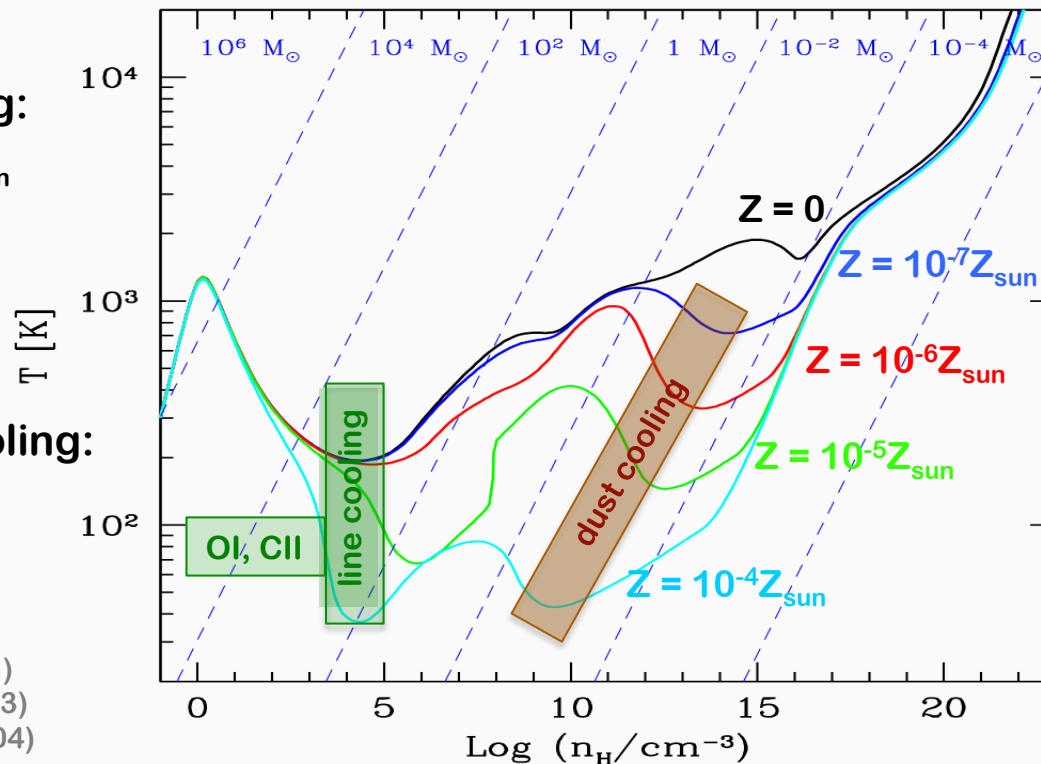
Abel+(2002)
Bromm+(2002)
Yoshida+(2008)

metal-line cooling:

$$Z > 10^{-4} Z_{\text{sun}}$$

$$M_{\text{jeans}} > 10 M_{\text{sun}}$$

Bromm et al. (2001)
Bromm & Loeb (2003)
Santoro & Shull (2004)



dust cooling:

$$Z > 10^{-6} Z_{\text{sun}}$$

$$M_{\text{jeans}} < 1 M_{\text{sun}}$$

RS et al. (2002,2003,2006),
Omukai et al. (2005)

stellar archaeology with the most metal poor stars

$[\text{Fe}/\text{H}] < -3$ $[\text{Fe}/\text{H}] < -5$

Survey	Effective sky coverage	Effective mag limit	$N < -3.0$ (EMP)	$N < -5.0$ (HMP)	People
HES	6,400 deg ²	$B < 16.5$	200	2	Christlieb et al.
SEGUE	1,000 deg ²	$B < 19$	(1,000)	(10)	Beers et al.; Caffau et al.
LAMOST	12,200 deg ²	$B < 18.0$	(3,000)	(30)	Zhao et al.
SSS	20,000 deg ²	$B < 17.5$	(2,500)	(25)	Keller et al.

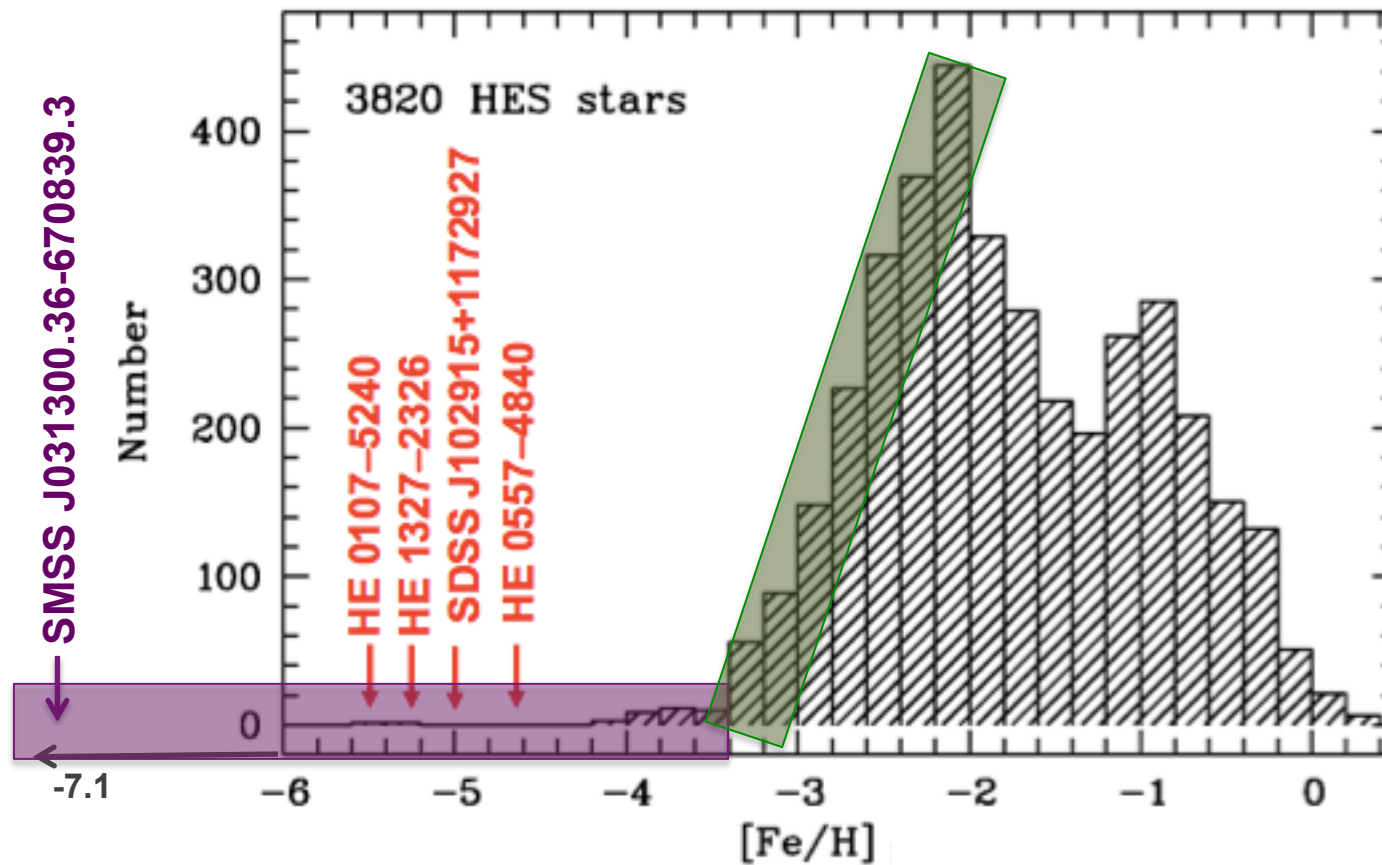
2014 Nature, 506, 463

A single low-energy, iron-poor supernova as the source of metals in the star SMSS J031300.36-670839.3

S. C. Keller¹, M. S. Bessell¹, A. Frebel^{*}, A. R. Casey¹, M. Asplund¹, H. R. Jacobson^{*}, K. Lind^{*}, J. E. Norris¹, D. Yong¹, A. Heger⁺, Z. Magic^Δ, G. S. Da Costa¹, B. P. Schmidt¹, & P. Tisserand¹

$[\text{Fe}/\text{H}] < -7.1$

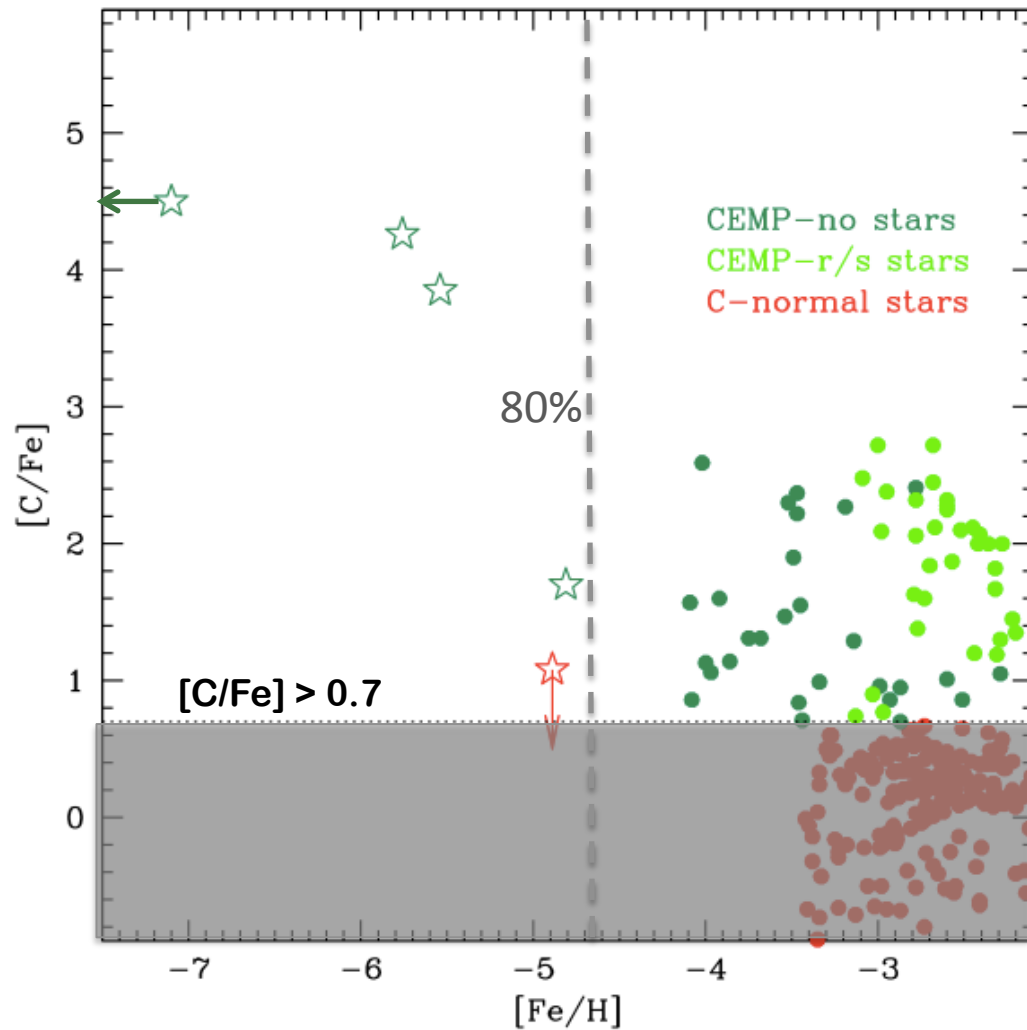
the metallicity distribution function of the Galactic halo



Schörck et al. 2009
Christlieb 2013

carbon-enhanced metal poor stars

~ 20 % of stars with $[\text{Fe}/\text{H}] < -2$ are C-enhanced: $[\text{C}/\text{Fe}] > 0.7$



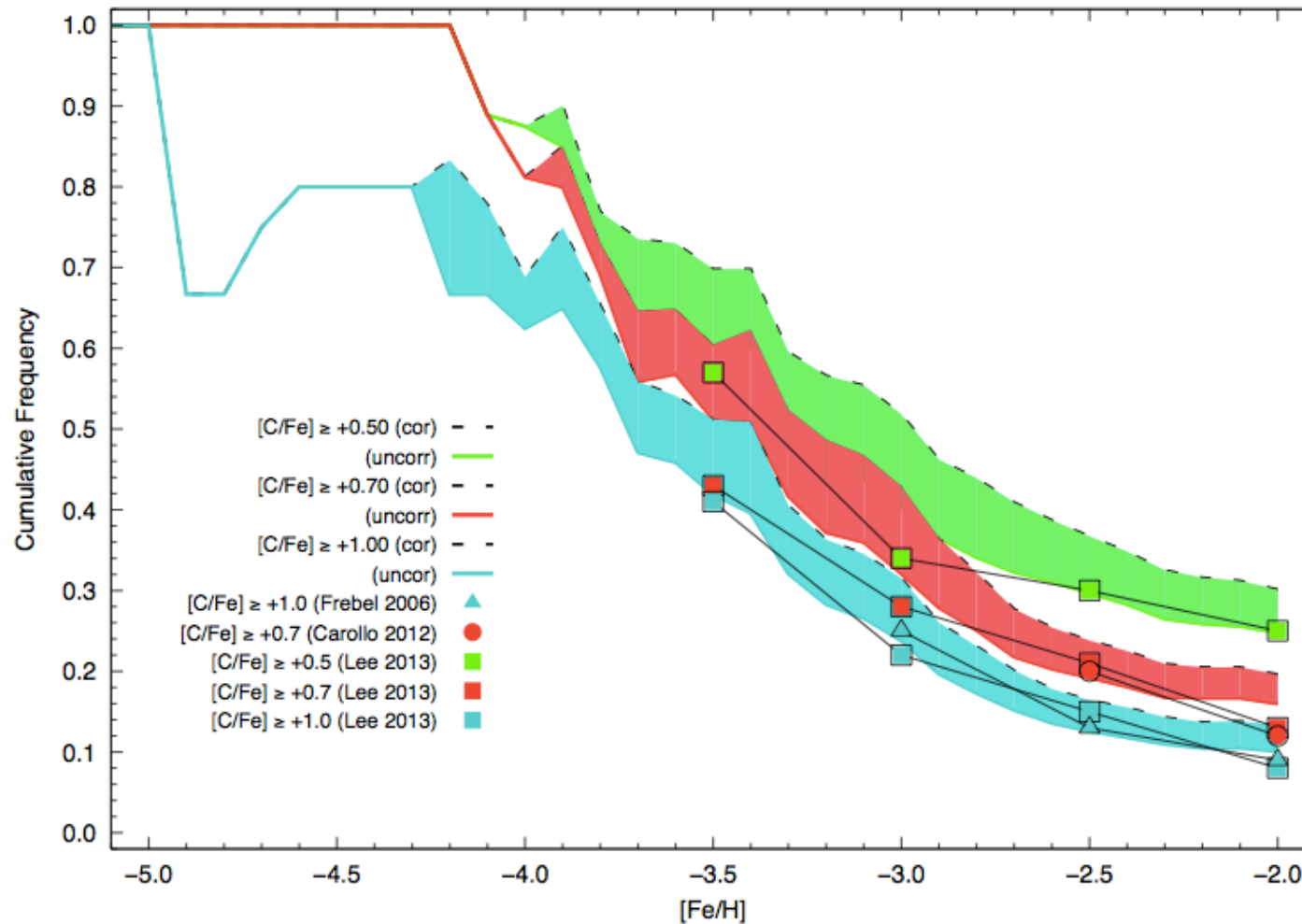
CEMP – r/s
mass transfer from an AGB companion
in binary systems

CEMP – no
metal yields from faint SNe with
mixing/fallback

Yong et al. 2013; Norris et al. 2013

The frequency of CEMP-no stars

Placco et al. 2014



$[Fe/H] \leq -2.0$, 20% exhibit $[C/Fe] \geq +0.7$

$[Fe/H] \leq -3.0$, 43% exhibit $[C/Fe] \geq +0.7$

$[Fe/H] \leq -4.0$, 81% exhibit $[C/Fe] \geq +0.7$

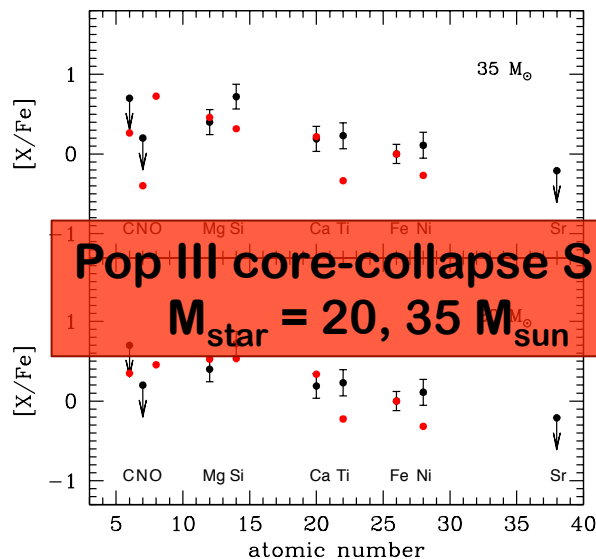
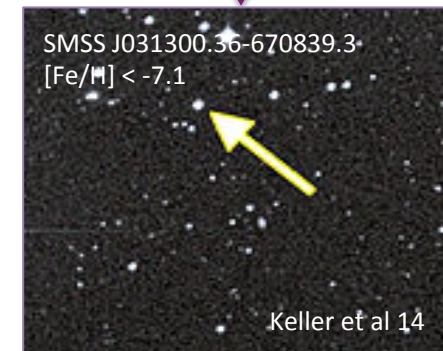
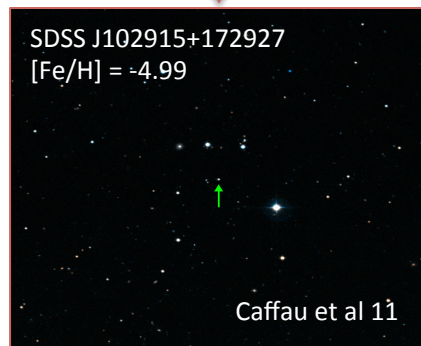
Questions that we want to address:

What are the formation pathways of C-normal and C-rich stars?

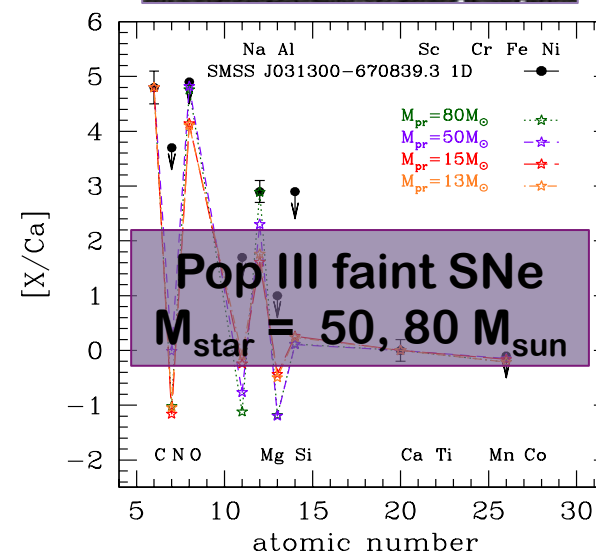
What are the physical processes that shape the low-[Fe/H] tail of the MDF ?

Why is the relative fraction of C-normal and C-rich stars varying with [Fe/H] ?

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

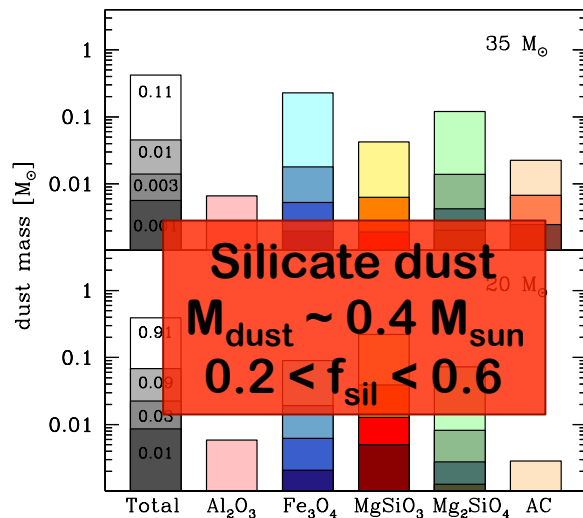
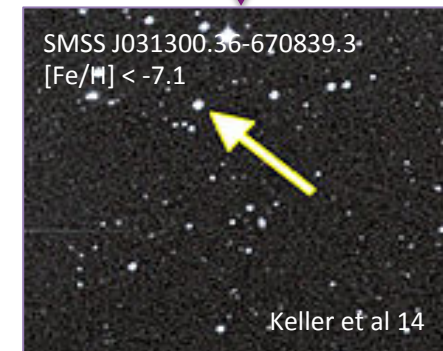
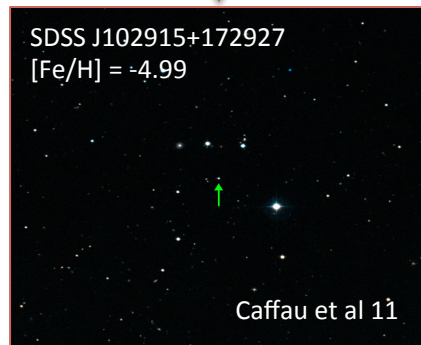


Schneider et al. 2012

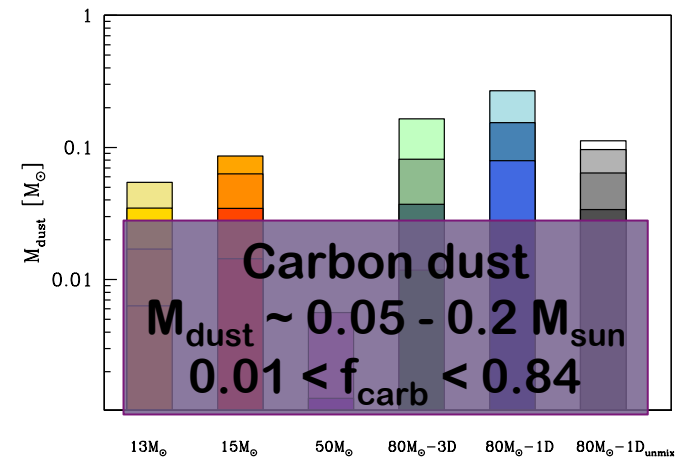


Marassi et al. 2014

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

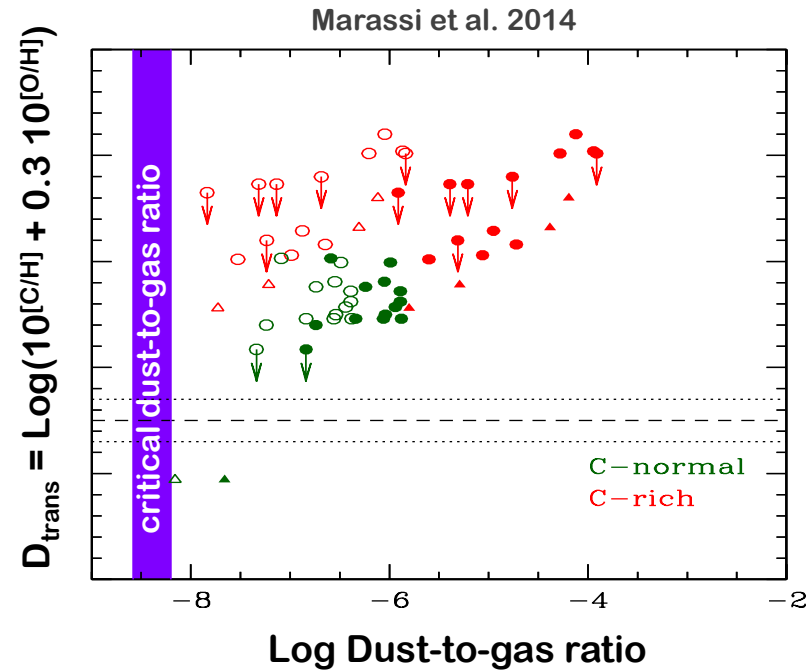


Schneider et al. 2012

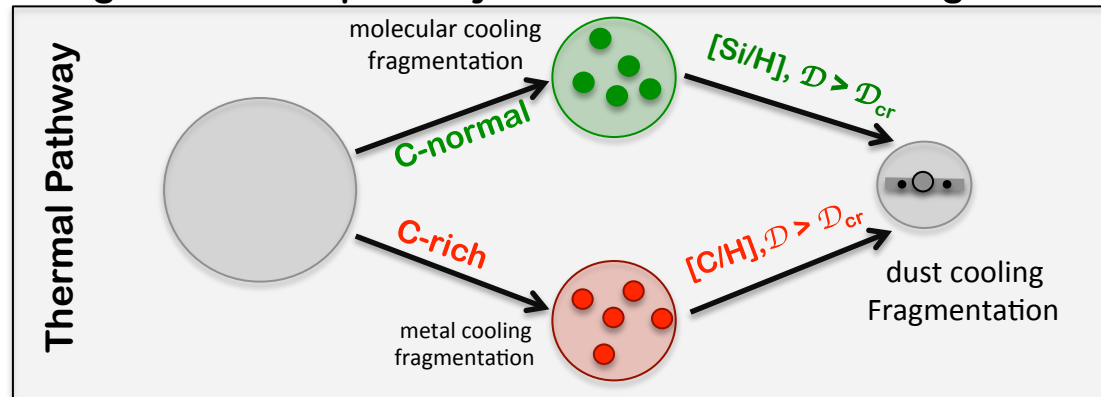


Marassi et al. 2014

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

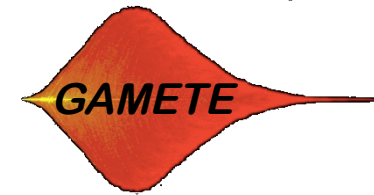


a single formation pathway based on dust-driven fragmentation



GAMETE

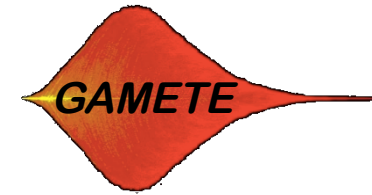
GAlaxy MErger Tree and Evolution



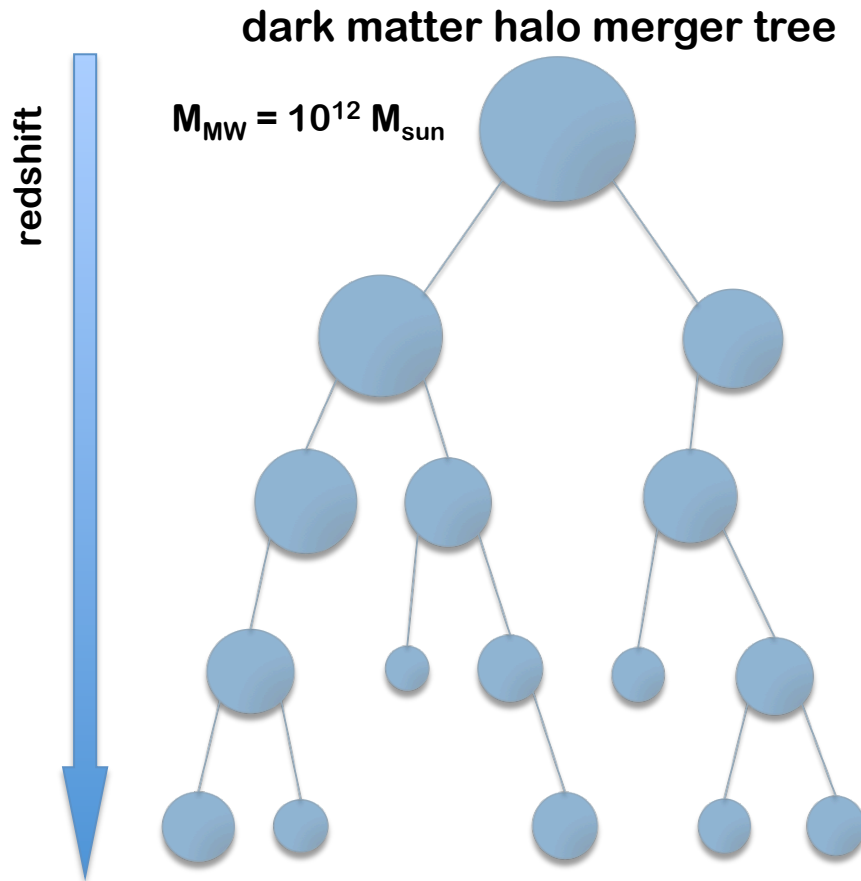
Salvadori et al. 2007, 2008, 2009; Valiante et al. 2011, 2014; de Bennassuti et al. 2014

GAMETE

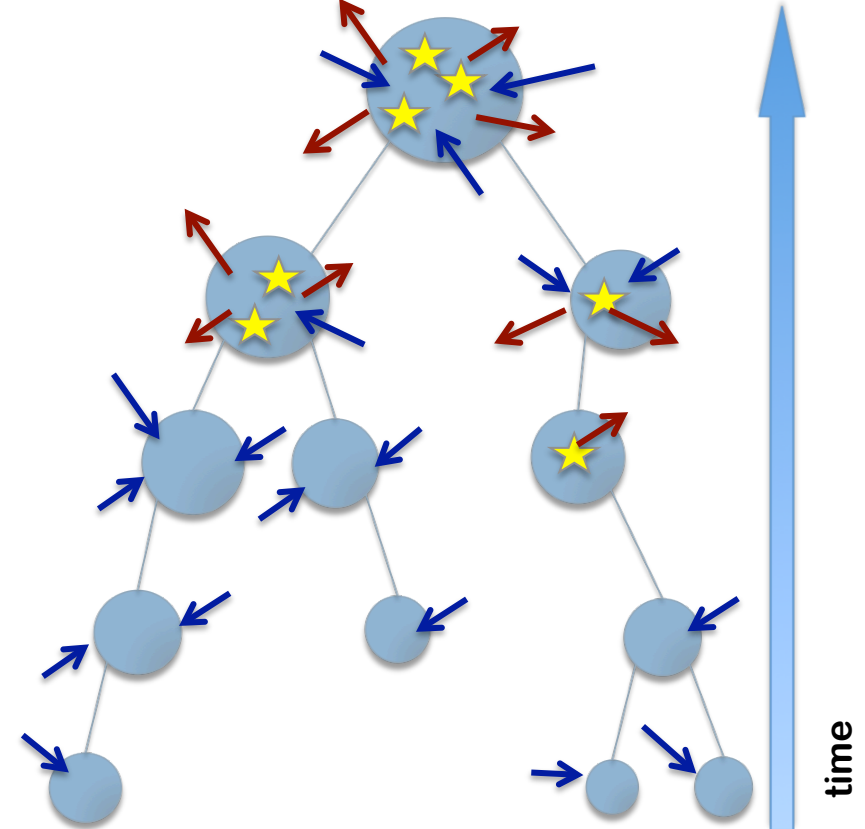
Galaxy MErger Tree and Evolution



Salvadori et al. 2007, 2008, 2009; Valiante et al. 2011, 2014; de Bennassuti et al. 2014

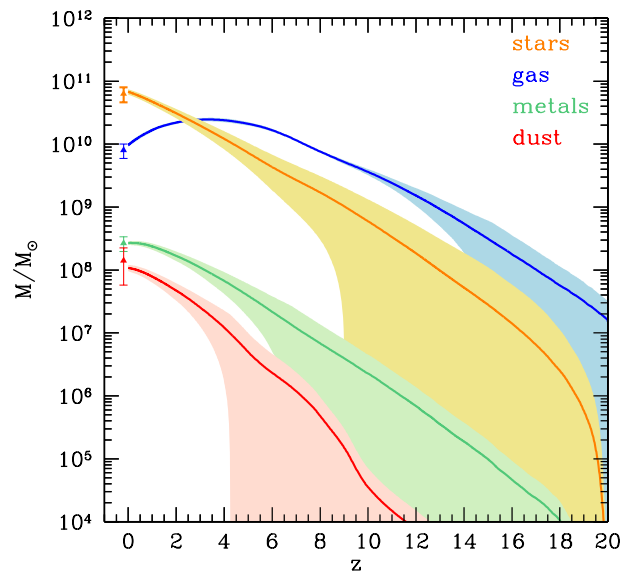


star formation and chemical evolution

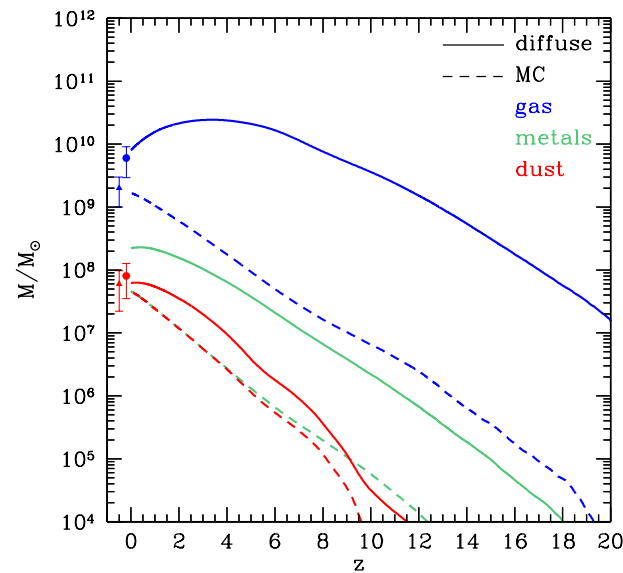


The MW and its dusty progenitors

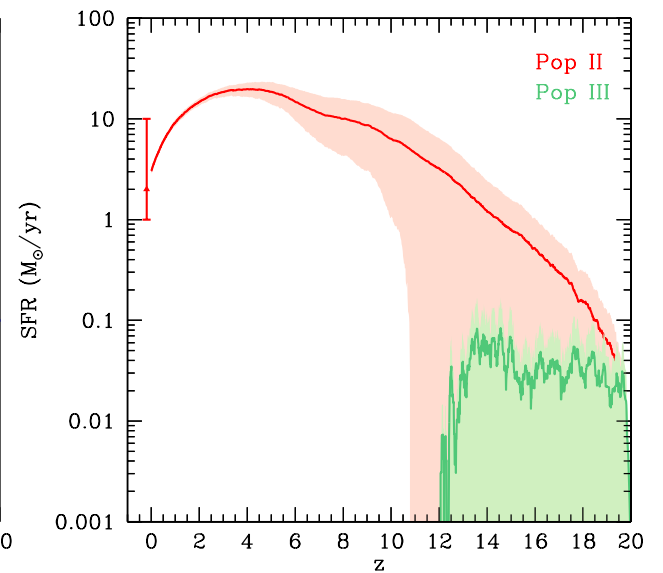
global properties of the MW



2-phase structure of the ISM



Pop III and Pop II SFRs

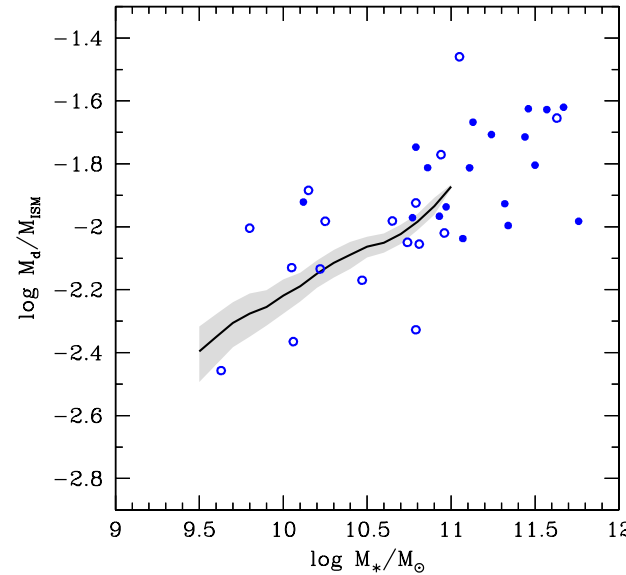
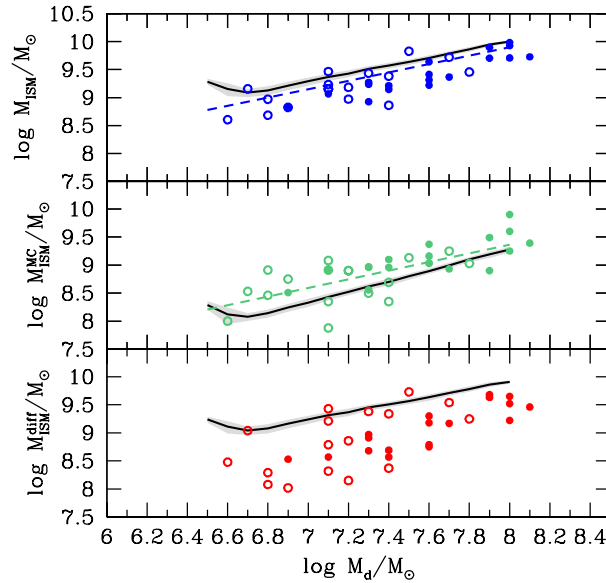


— average over 50 independent merger trees
 1- σ

The MW and its dusty progenitors

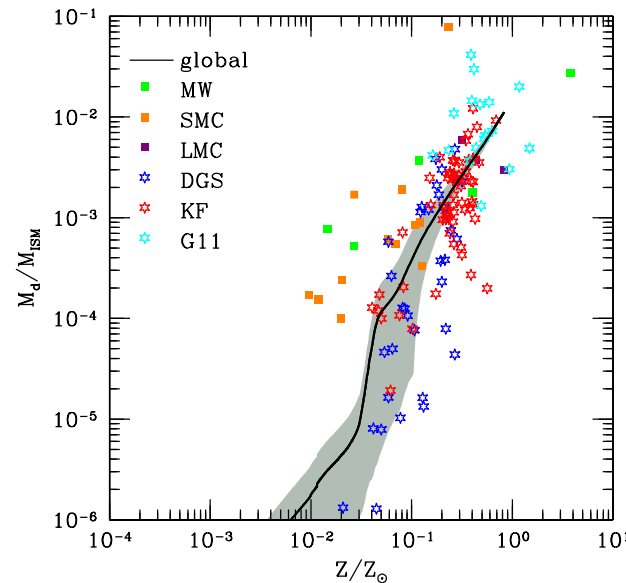
de Bennassuti et al 2014

gas and dust scaling relations



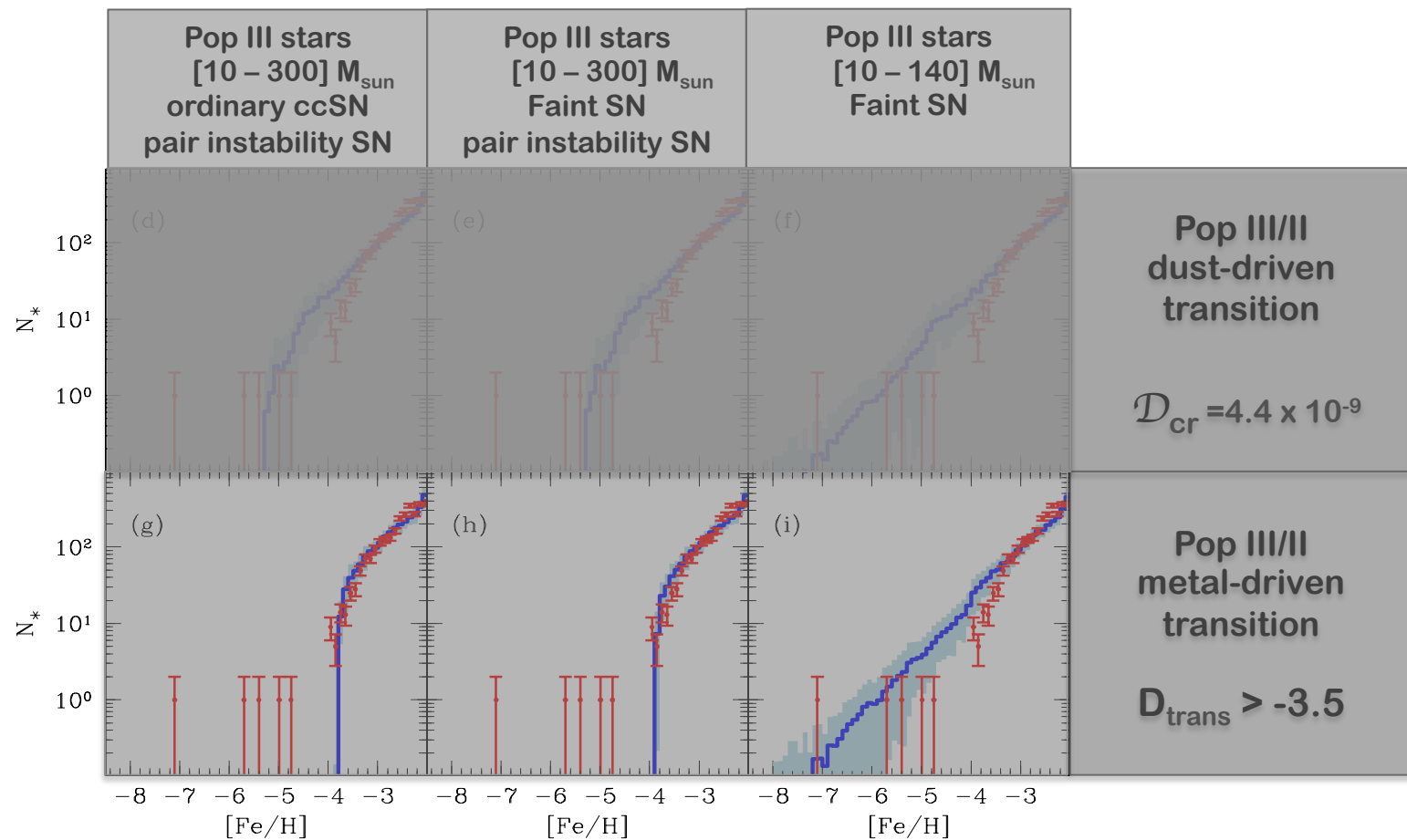
data points:
sample of local
Virgo galaxies
Corbelli et al. (2012)

dust-to-gas ratio vs metallicity



data points:
sample of GRB hosts
 $0.1 < z < 6.3$ Zafar & Watson (2013)
Local dwarfs Galametz et al. (2011)
Madden et al. (2013),
Remy-Ruyer et al. (2014)

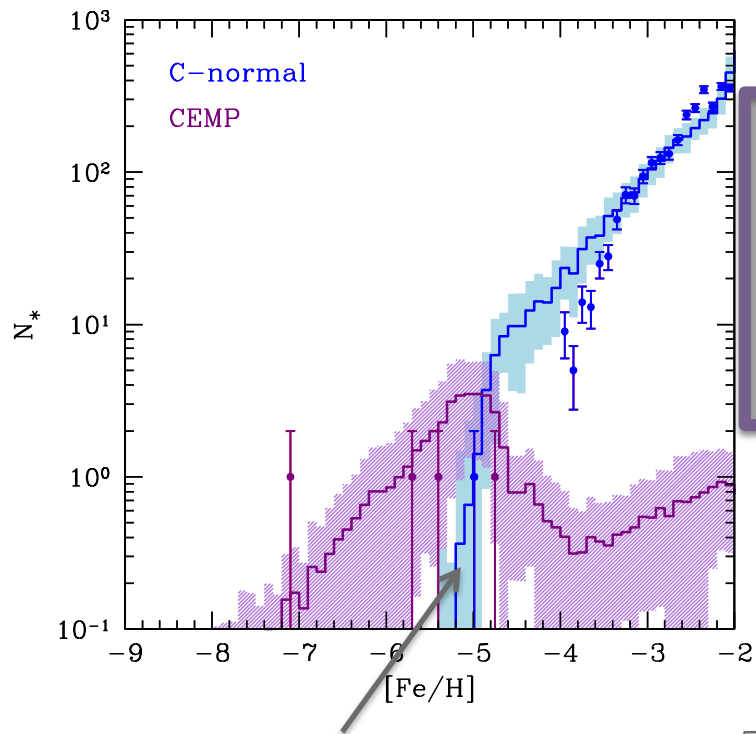
The low-[Fe/H] tail of the MDF



Pop III stars IMF $\rightarrow [10-140] M_{\text{sun}}$ and explode as faint SN

Pop III/II transition criterium $\rightarrow$ degenerate with the Pop III IMF

Metallicity distribution of C-rich stars

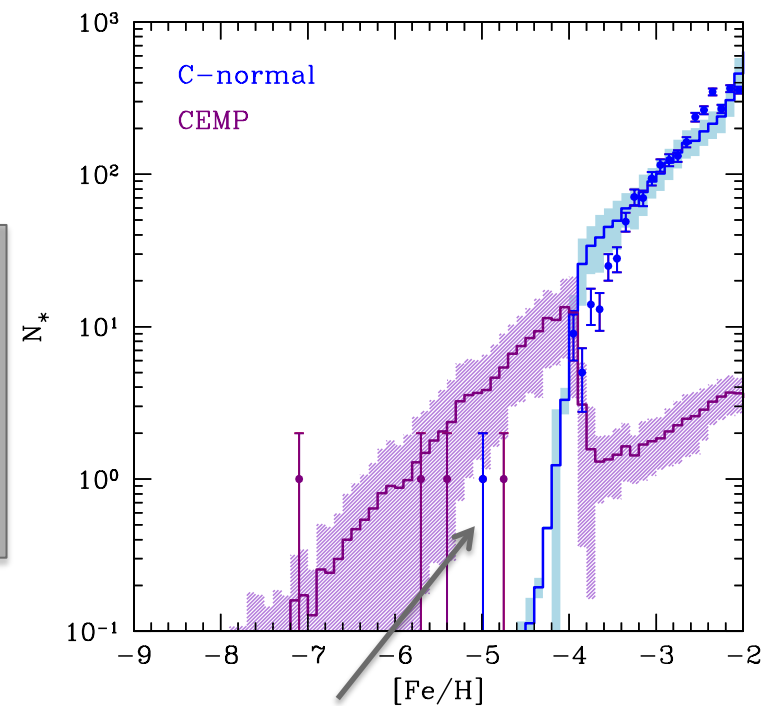


Pop III/II
dust-driven
transition

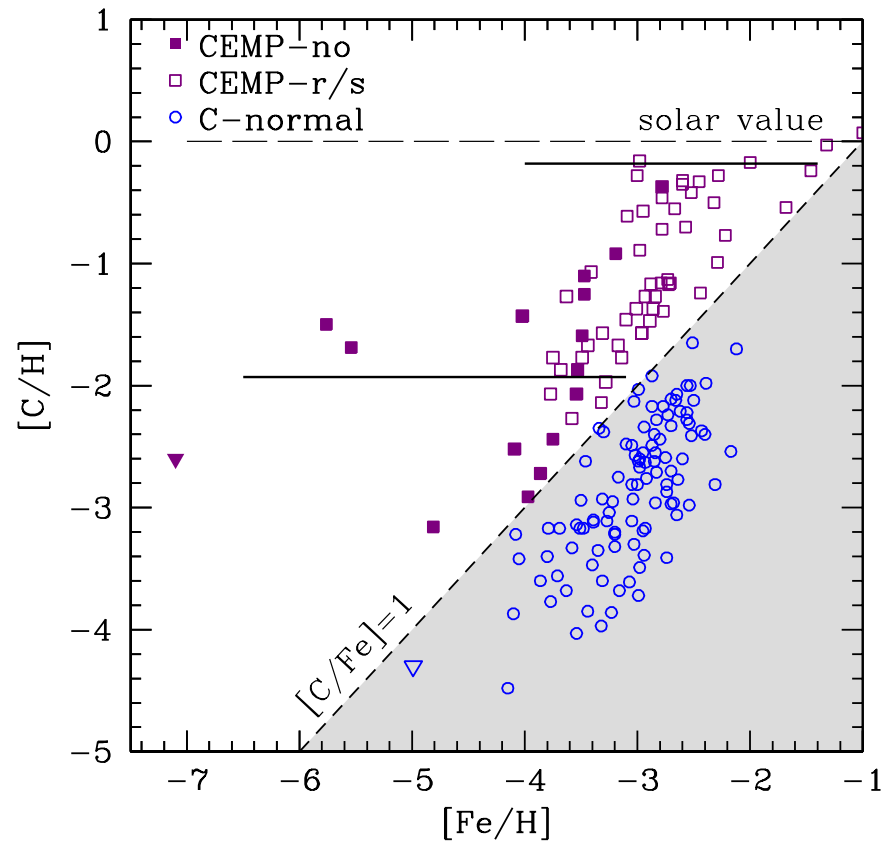
$$\mathcal{D}_{\text{cr}} = 4.4 \times 10^{-9}$$

Pop III/II
metal-driven
transition

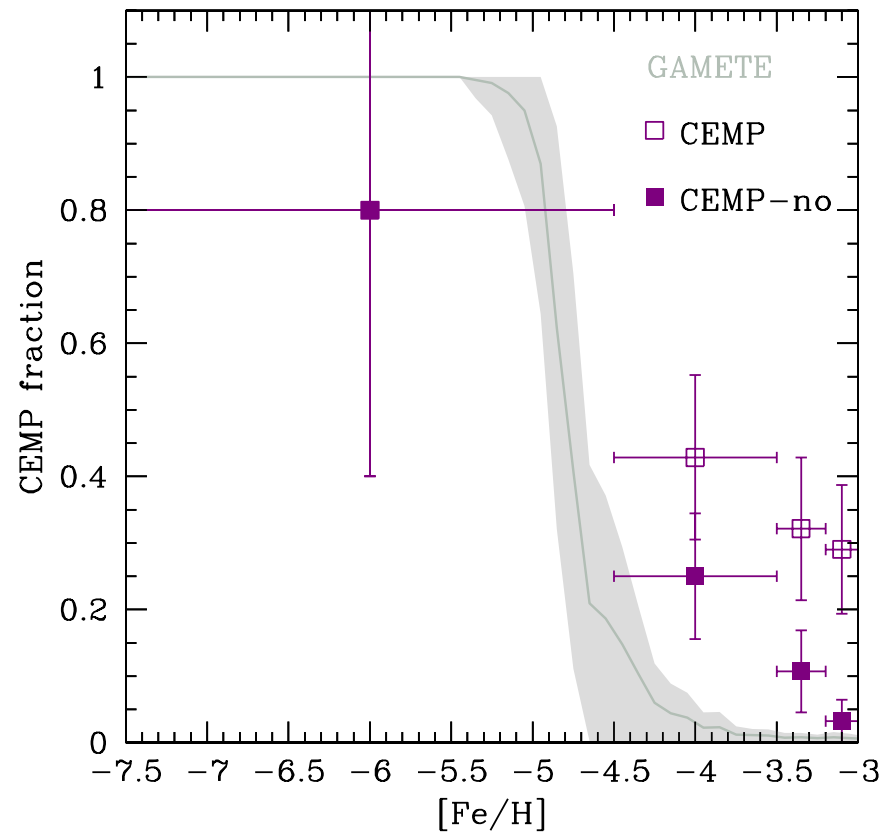
$$D_{\text{trans}} > -3.5$$



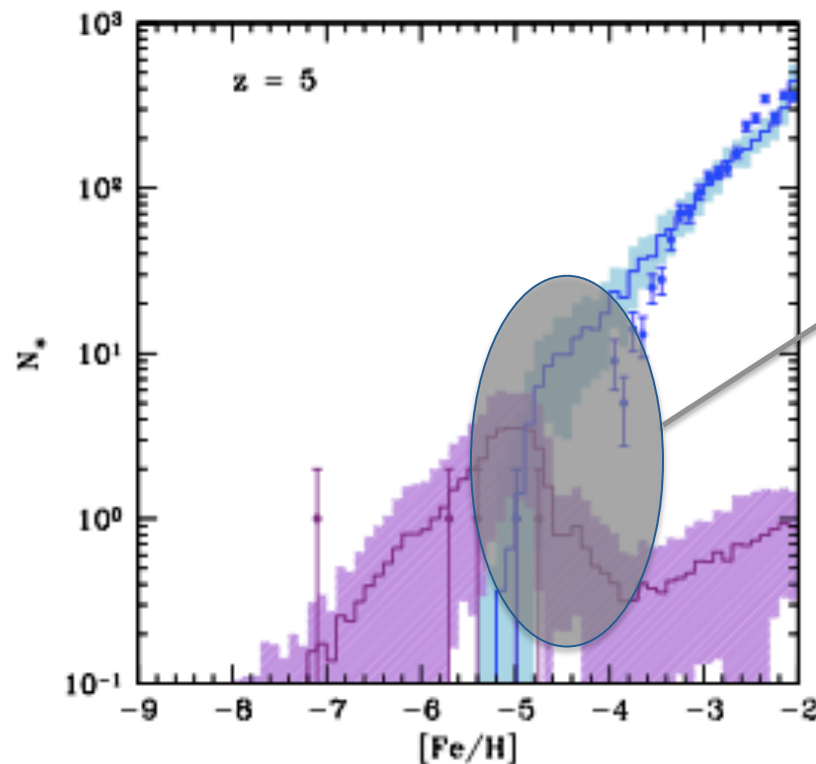
Relative fraction of C-rich and C-normal stars



data points from Yong et al. (2013)



When do the low- $[\text{Fe}/\text{H}]$ tail of the MDF of C-rich and C-normal stars form?

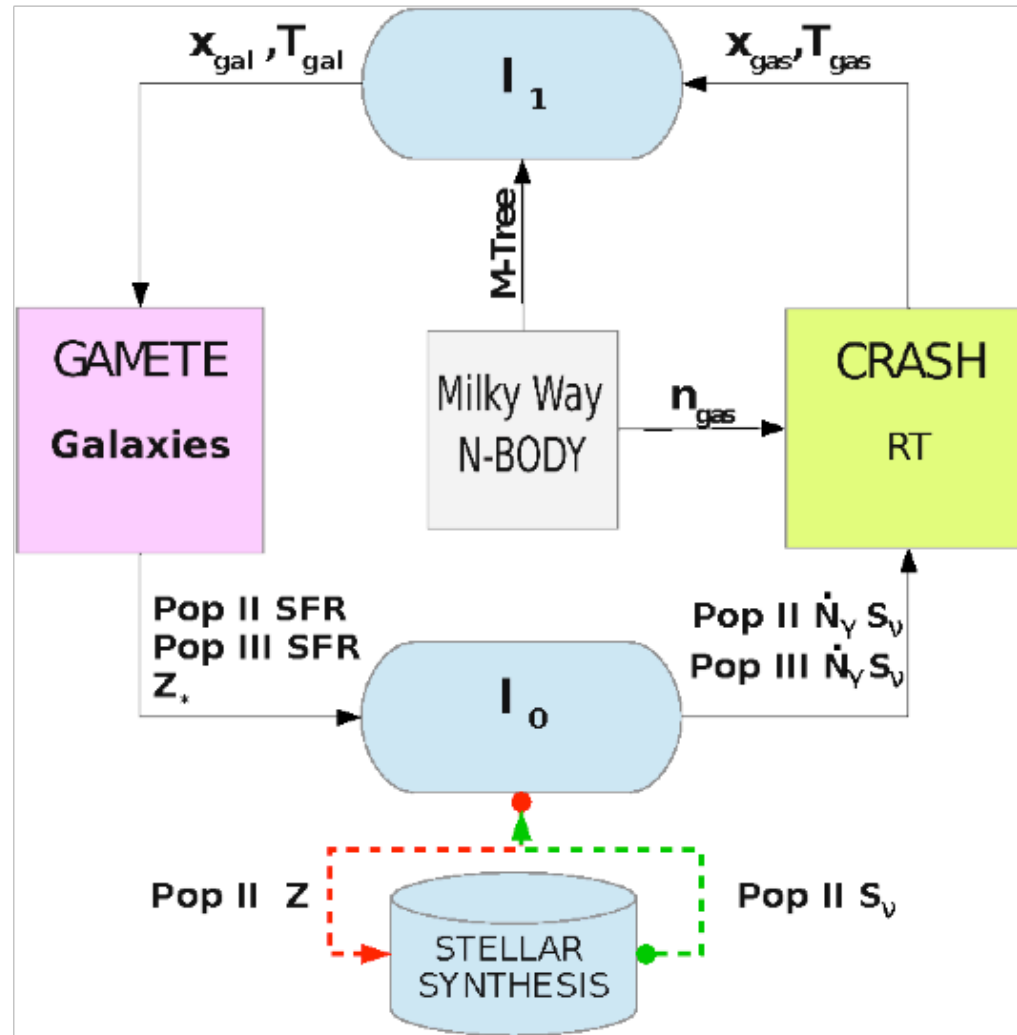


the “excess” stars are
predicted to form
at $15 < z < 5$

interplay between chemical
and radiative feedback effects

Galaxy formation with radiative and chemical feedback

GAMESH, a new pipeline integrating the latest release of cosmological radiative transfer code CRASH (Graziani+ 2013) with the semi-analytic model of galaxy formation GAMETE, powered by an N-body simulation (Salvadori+2010, Kawata+2010)



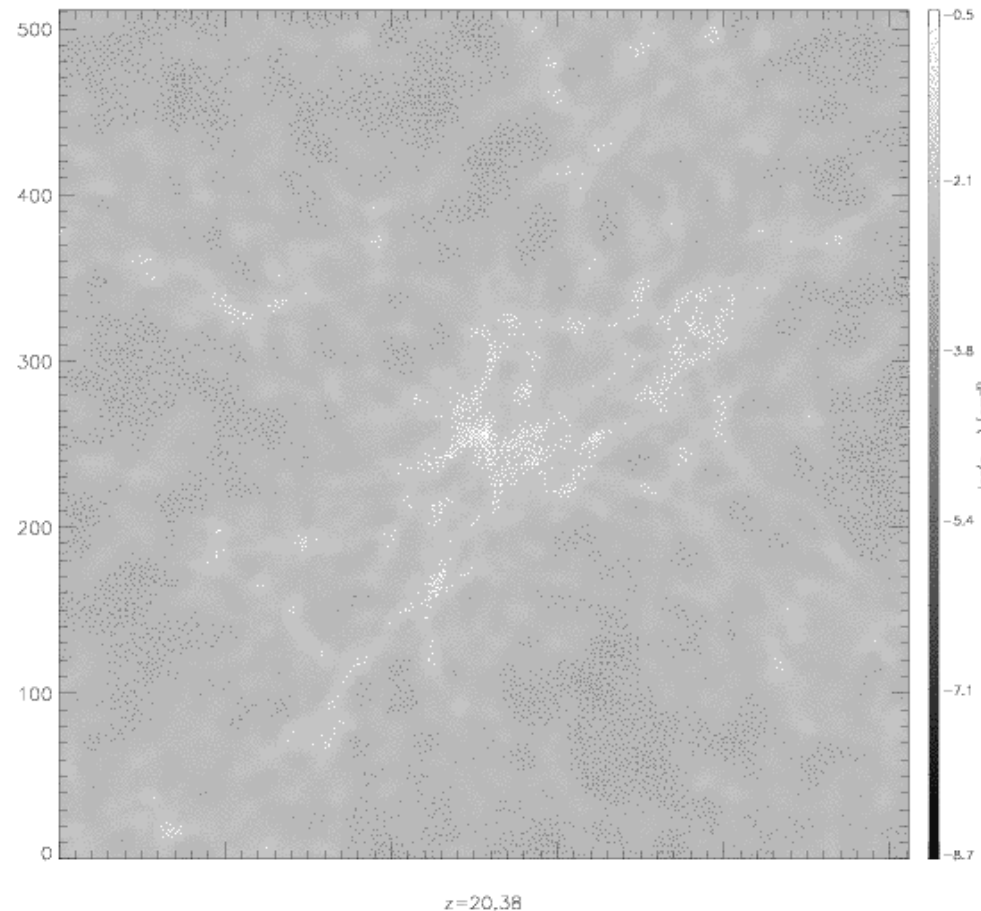
The cosmic assembly of the Milky Way

N-body simulation of a MW-sized halo in Planck cosmology

GCD+ code with multi-resolution technique (Kawata & Gibson 03):

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

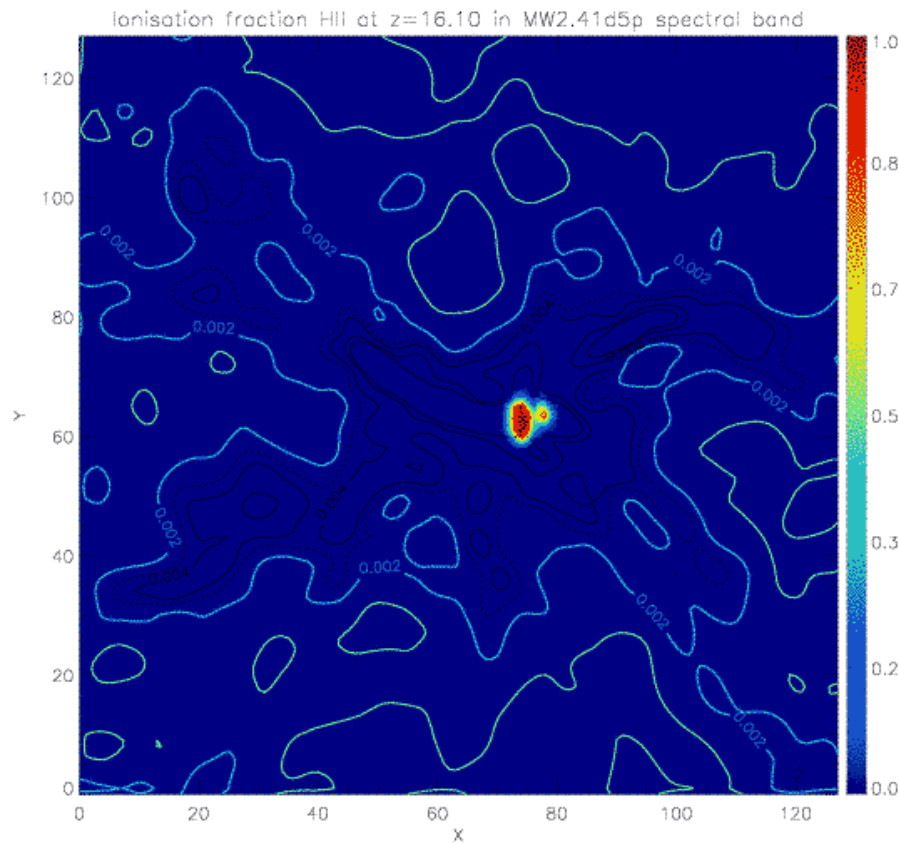
High-res spherical region of $R_h \sim 2 h^{-1} \text{ Mpc}$ with $M_p = 3.4 \times 10^5 M_{\text{sun}}$



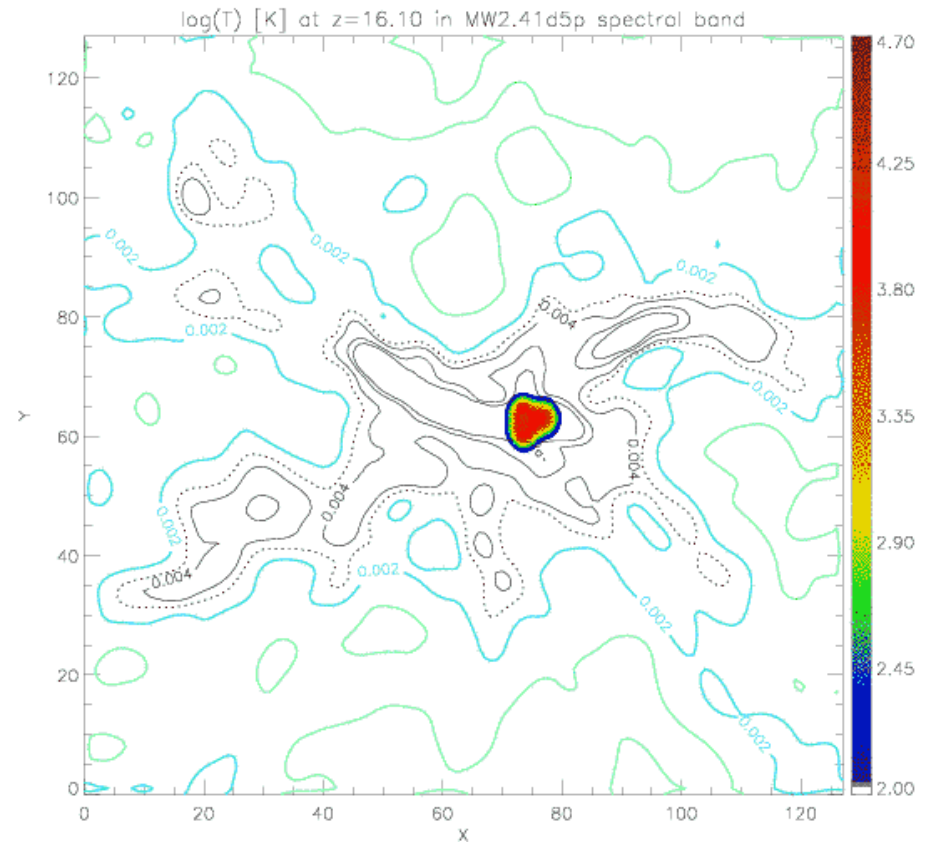
Graziani+2015

The Milky Way reionisation simulation

redshift evolution of the HII fraction



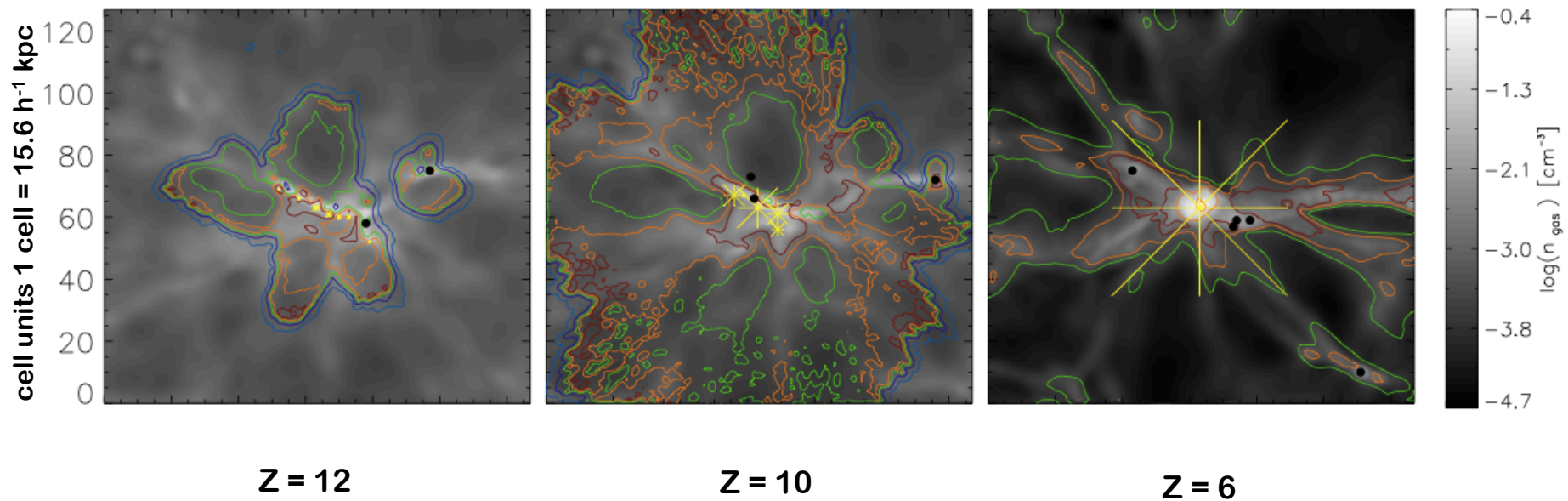
and of the gas temperature



Slice cuts (distances in cell units 1 cell = $15.6 h^{-1}$ kpc)

The Milky Way reionisation simulation

effects of inhomogeneous radiative feedback



Temperature contours:

$T \sim 100, 4 \times 10^3, 10^4, 1.3 \times 10^4, 1.5 \times 10^4 \text{ K}$

Summary

- ✳ the Pop III IMF is likely to be top-heavy and characterized by masses of 10s – 1000s M_{sun}
- ✳ metals and dust grains produced by the first Pop III SNe have important effects on the stellar mass scales
- ✳ dust grains condensed in the ejecta of the first SN allow the formation of the first low mass stars $\leq 1 M_{\text{sun}}$ at $Z_{\text{cr}} > 10^{-6} Z_{\text{sun}}$
- ✳ stellar archaeology is a fundamental benchmark for theoretical models