First stars and their local relics

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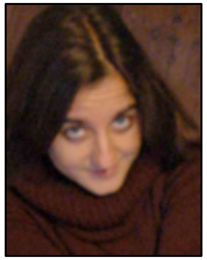

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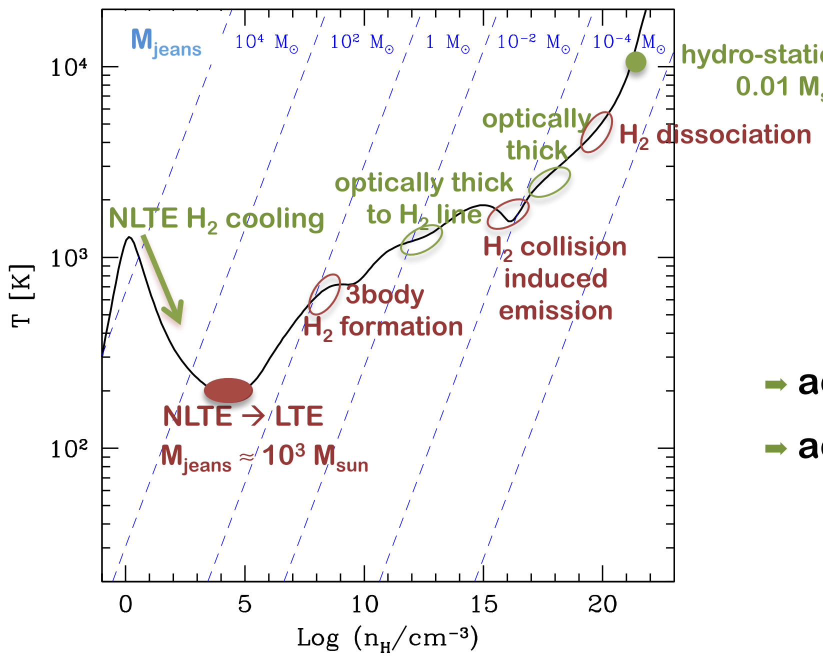
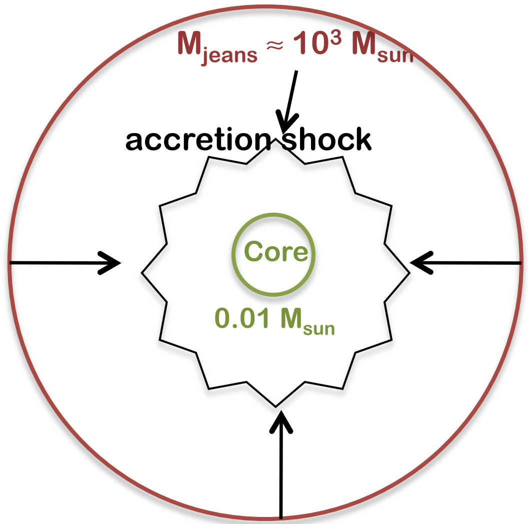
the formation of the first stars

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

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



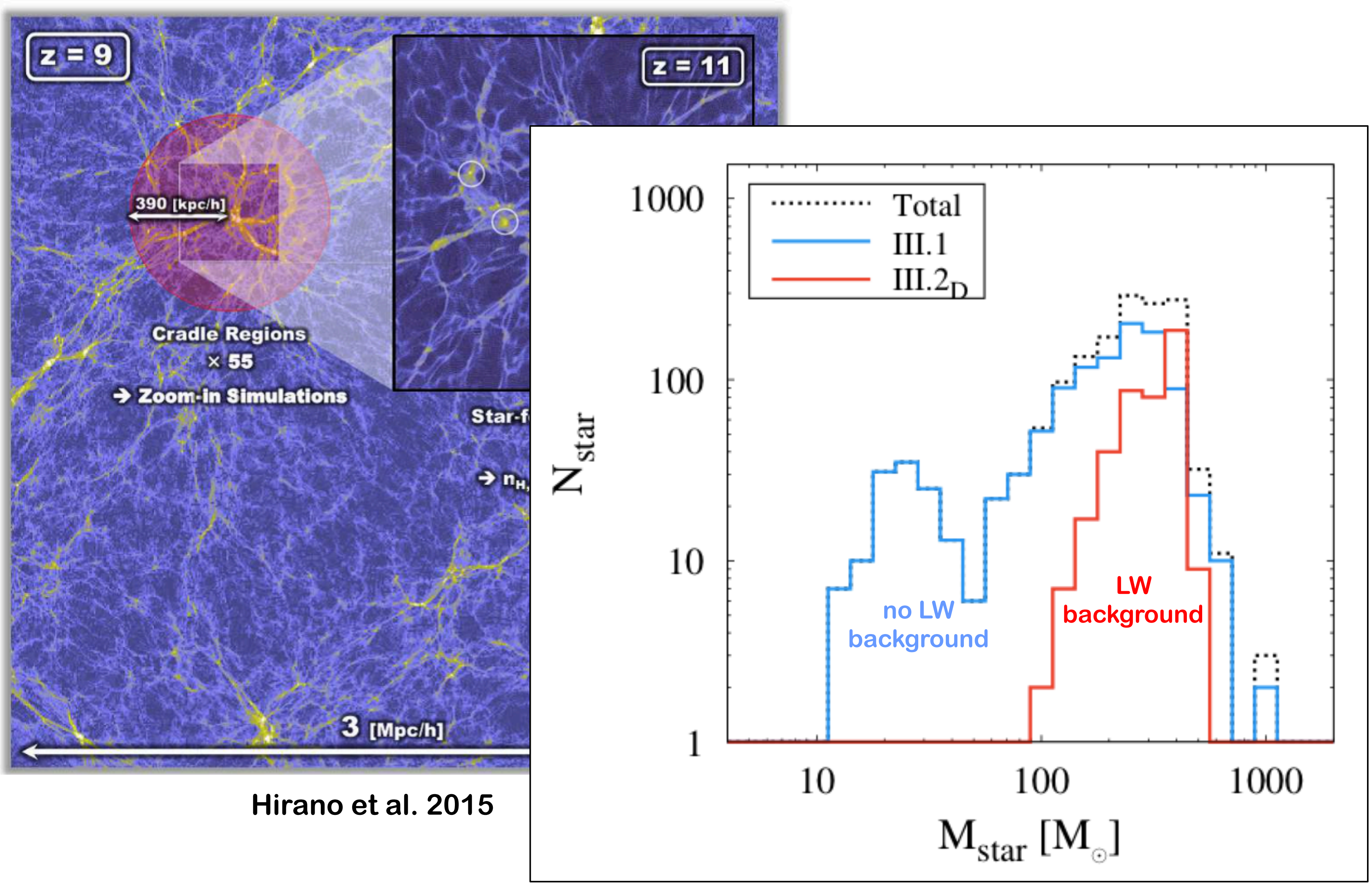
Omukai et al. 2005



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

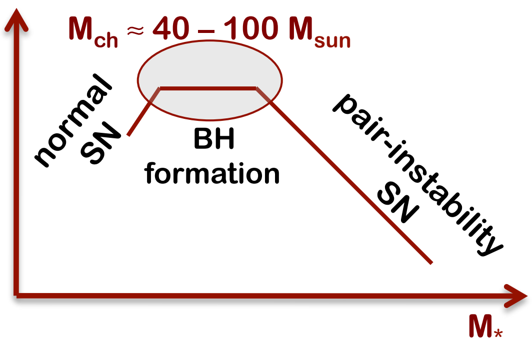
An ab-initio calculation of the Pop III IMF



Hirano et al. 2015

the end-products of Pop III stars

Pop III IMF ?

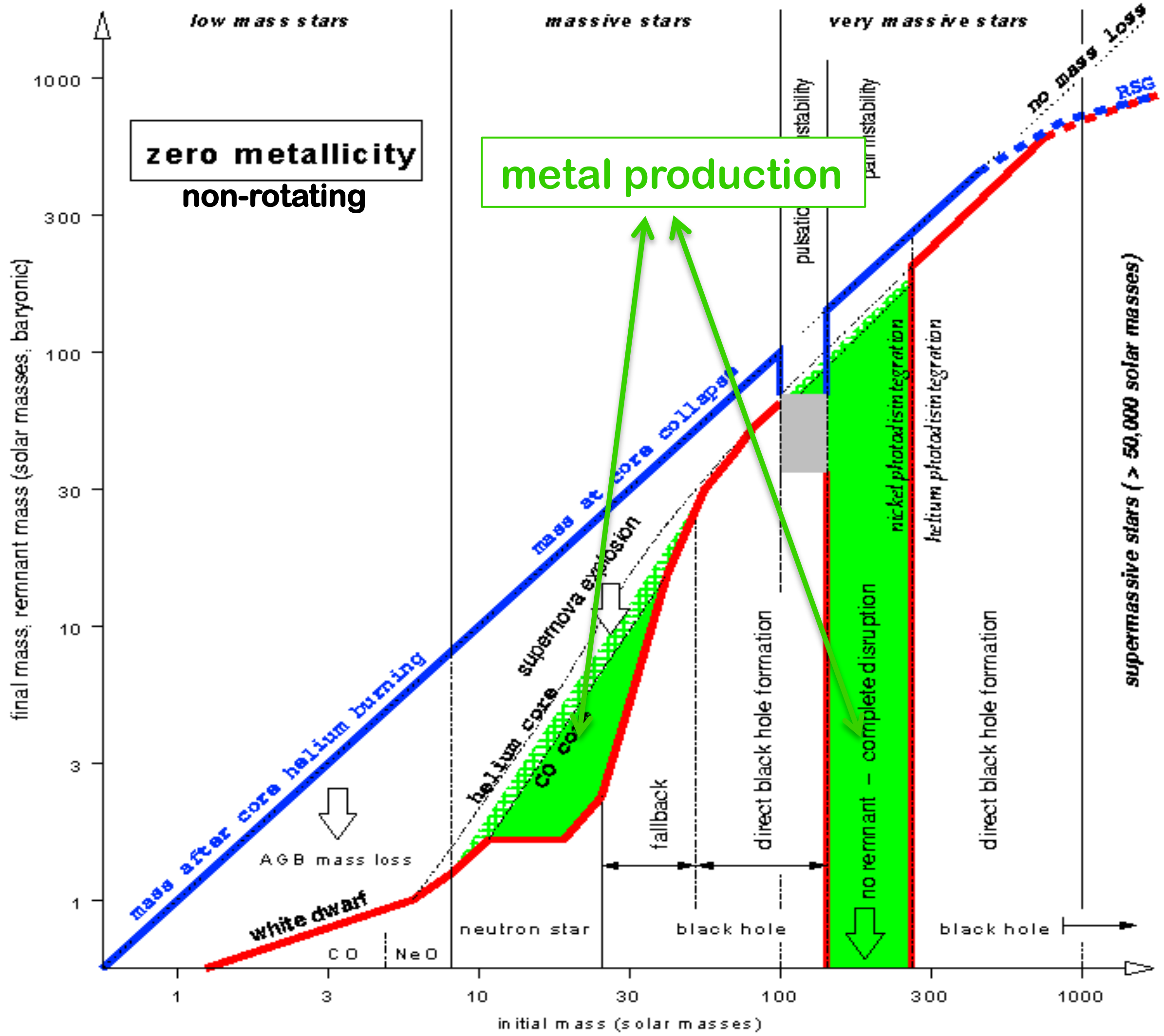


$10\ M_{sun} < M_* < 40\ M_{sun}$

metal production

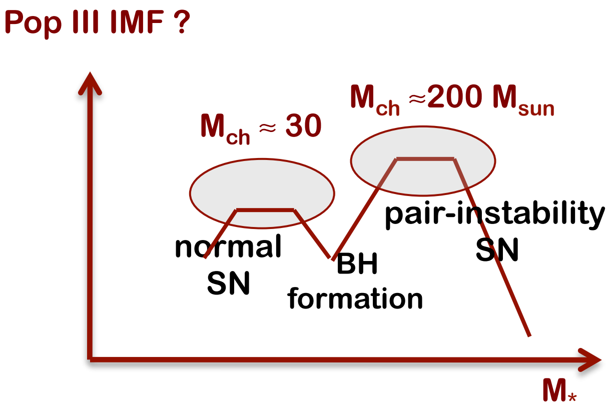
$140\ M_{sun} < M_* < 260\ M_{sun}$

metal production



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

the end-products of Pop III stars



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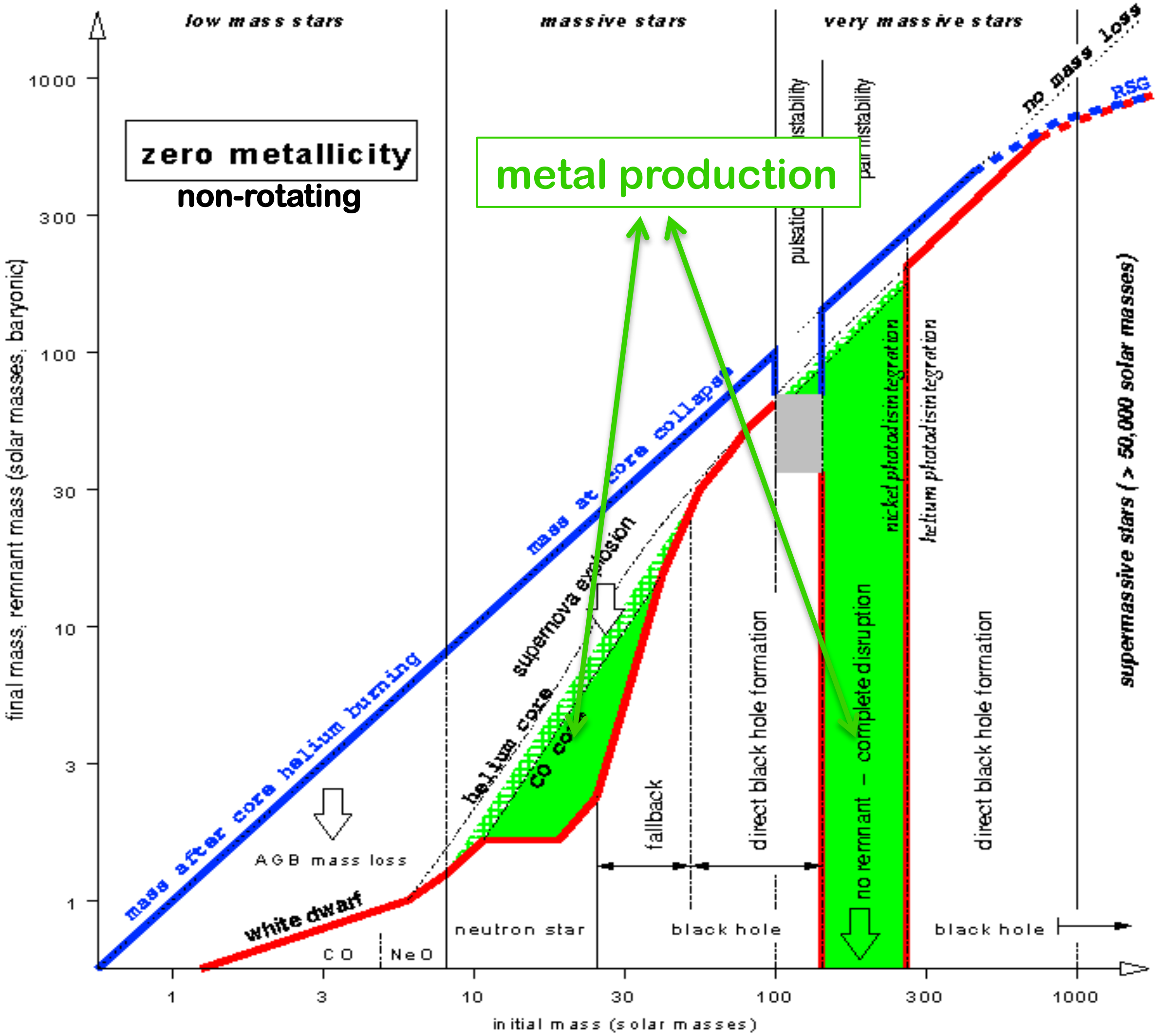
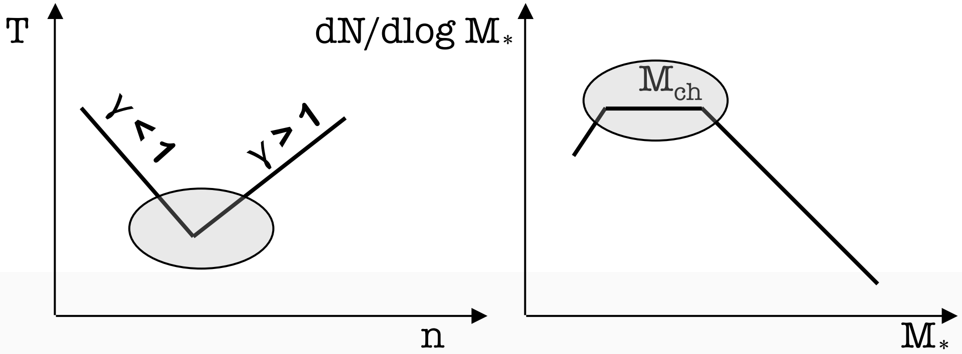


Heger & Woosley (2002), Yoon et al (2012), Marassi et al. in prep

H_2, metal and dust-driven fragmentation: three different mass-scales



H_2-line cooling:

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

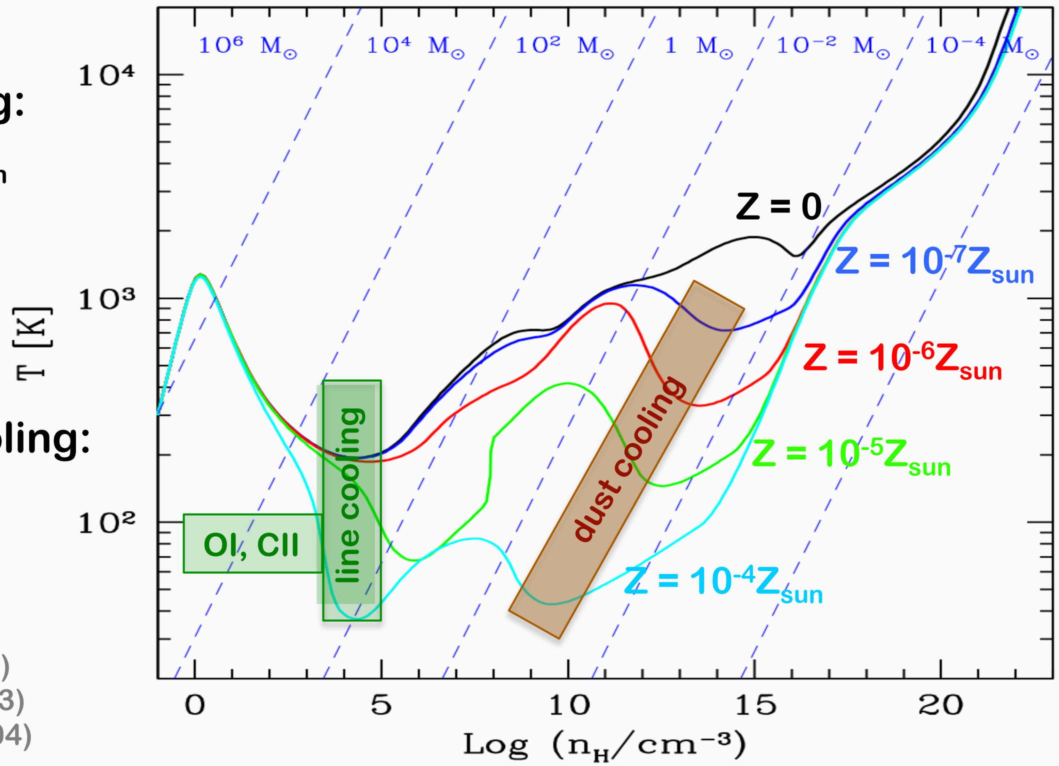
Abel+(2002)
Bromm+(2002)
Yoshida+(2008)

metal-line cooling:

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

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

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



dust cooling:

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

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

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

stellar archaeology
with the most metal poor stars

[Fe/H] < -3 [Fe/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.

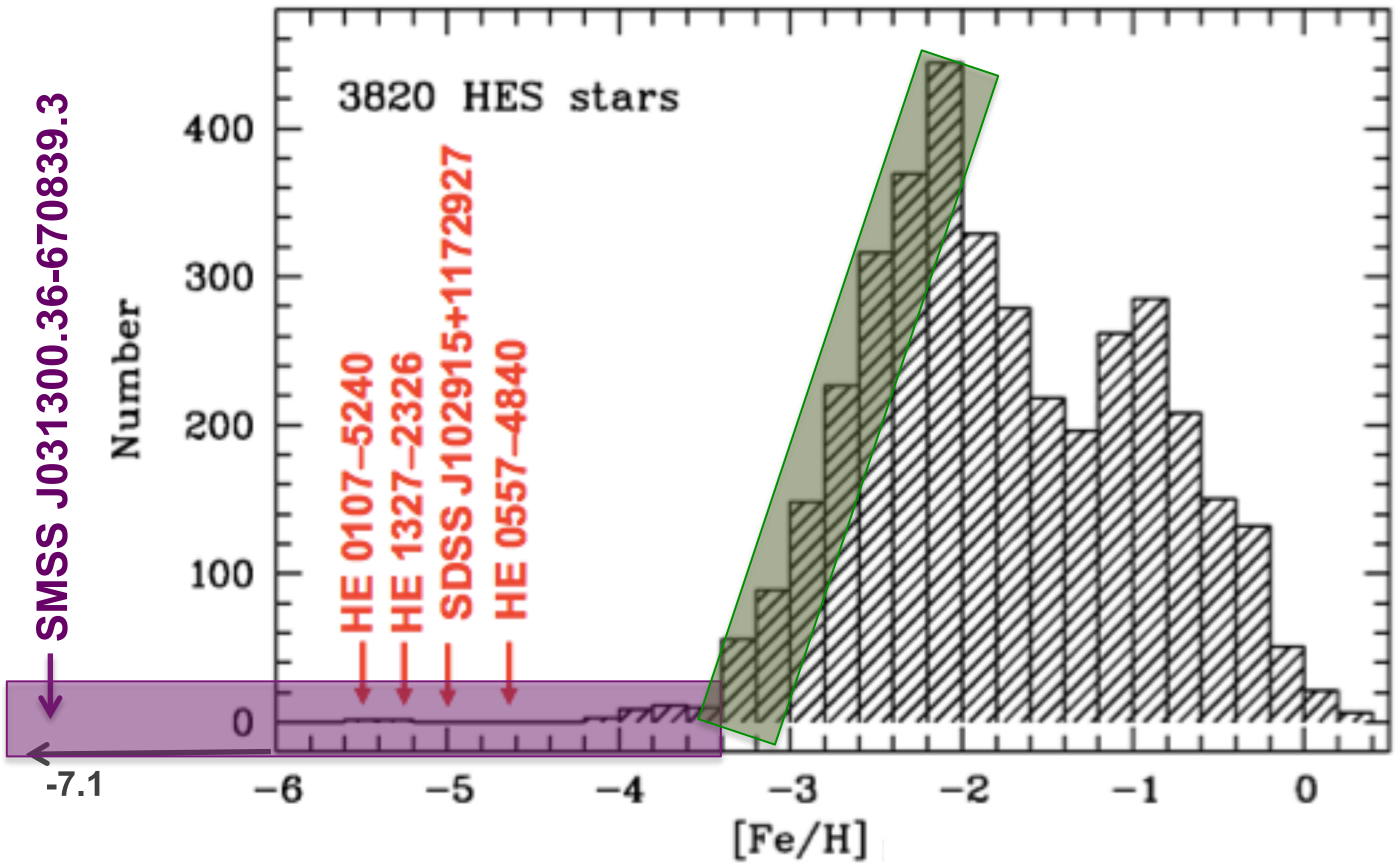
2014 Nature, 506, 463

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

S. C. Keller[\], M. S. Bessell[\], A. Frebel[*], A. R. Casey[\], M. Asplund[\], H. R. Jacobson[*], K. Lind[*], J. E. Norris[\], D. Yong[\], A. Heger[+], Z. Magic[△\], G. S. Da Costa[\], B. P. Schmidt[\], & P. Tisserand[\]

[Fe/H] < -7.1

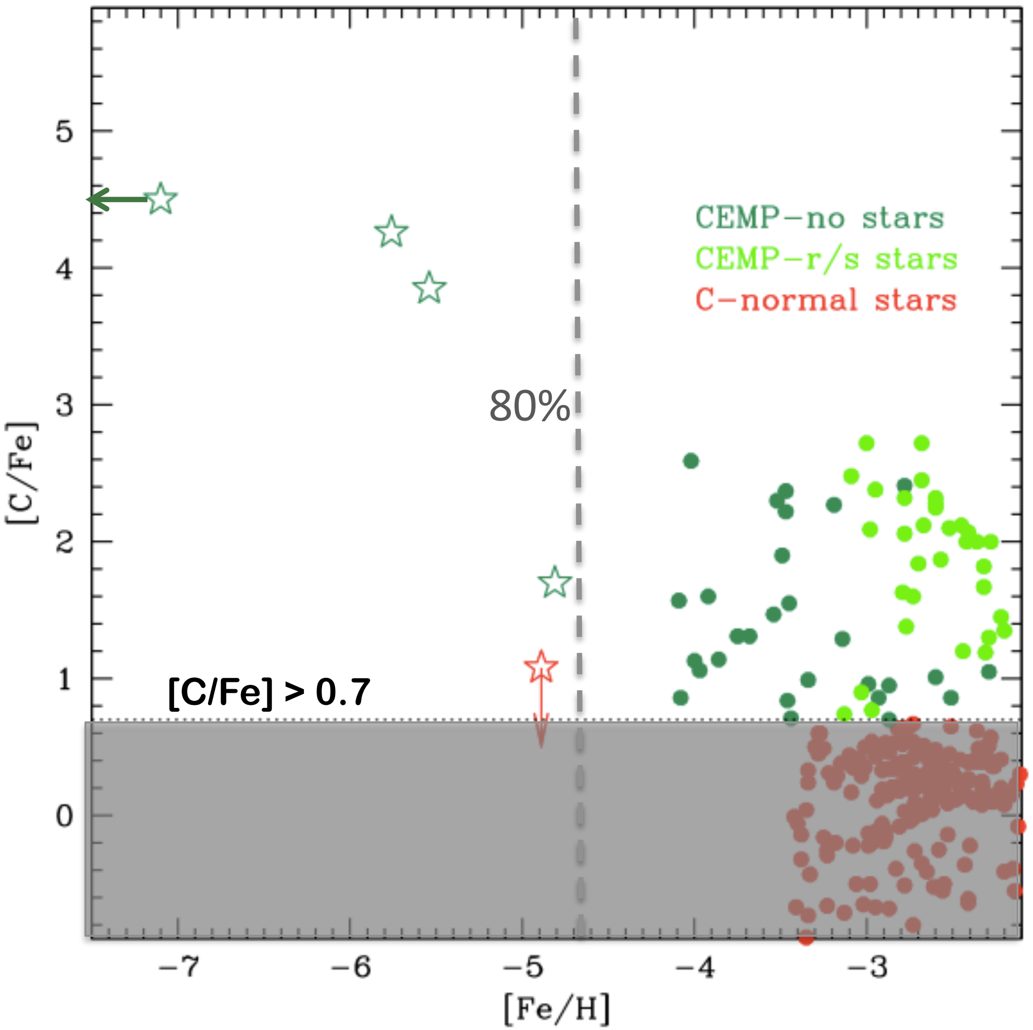
the metallicity distribution function of the Galactic halo



Schörck et al. 2009
Christlieb 2013

carbon-enhanced metal poor stars

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

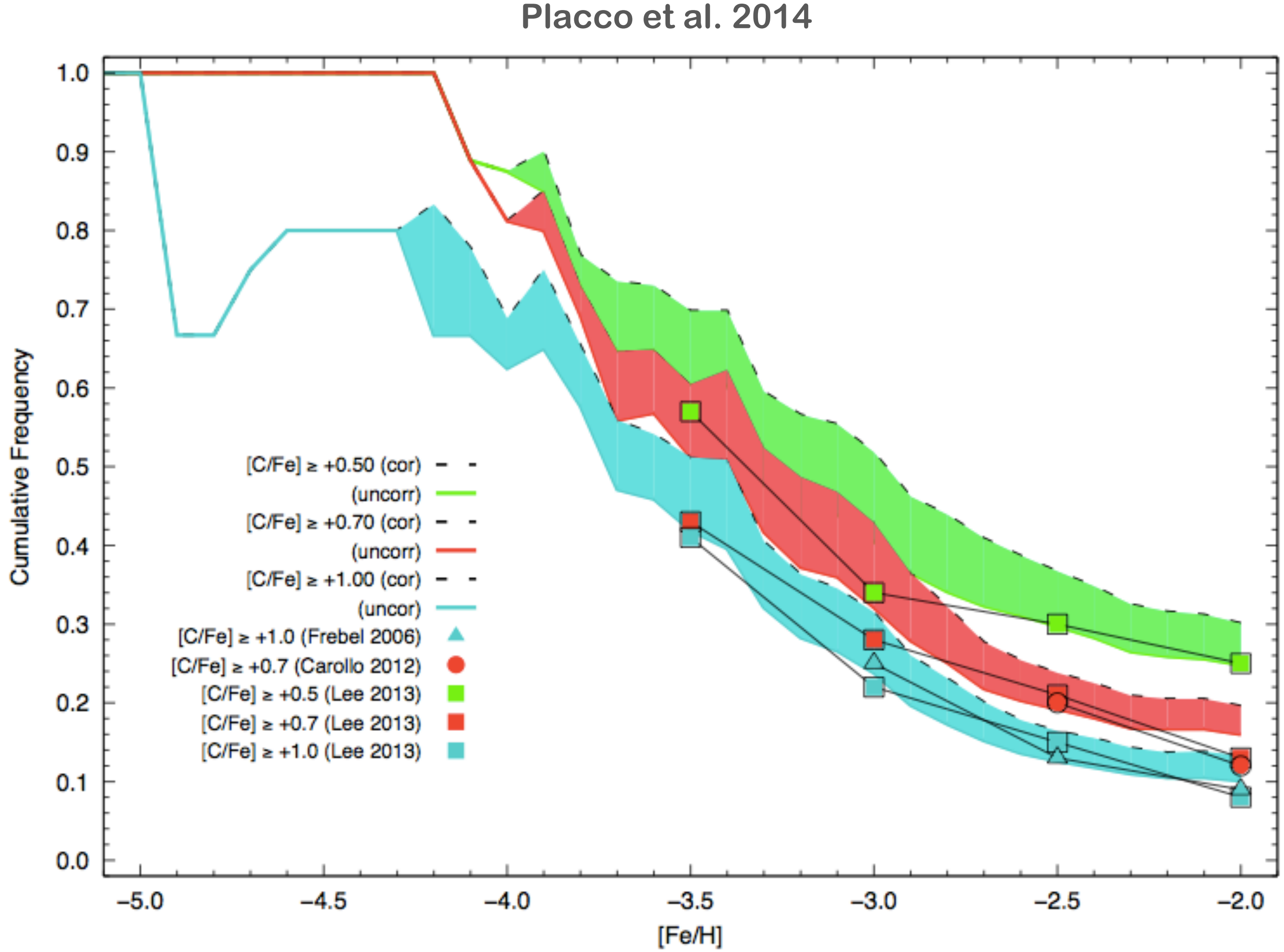


Yong et al. 2013; Norris et al. 2013

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

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

The frequency of CEMP-no stars



[Fe/H]≤ −2.0, 20% exhibit [C/Fe]≥ +0.7

[Fe/H]≤ −3.0, 43% exhibit [C/Fe]≥ +0.7

[Fe/H]≤ −4.0, 81% exhibit [C/Fe]≥ +0.7

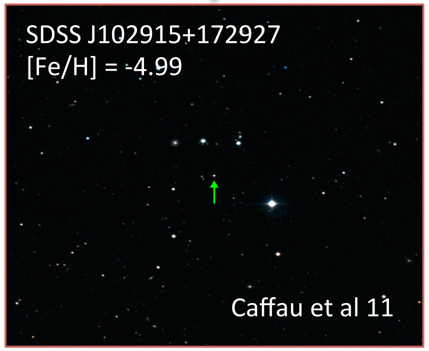
Questions that we want to address:

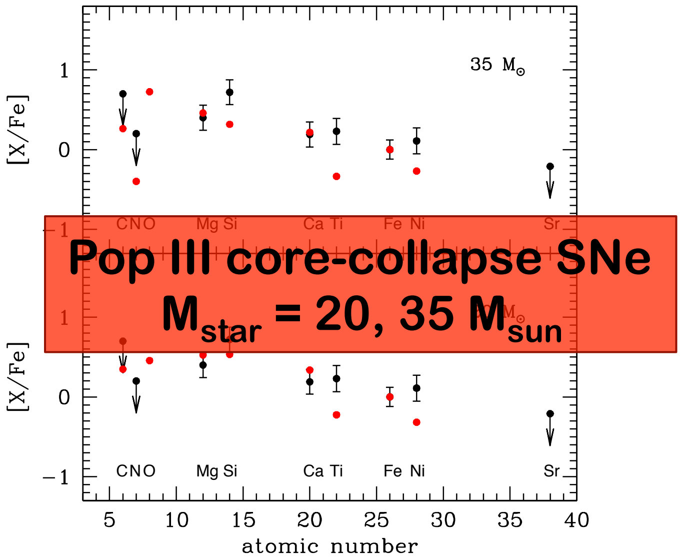
What are the formation pathways of C-normal and C-rich stars?

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

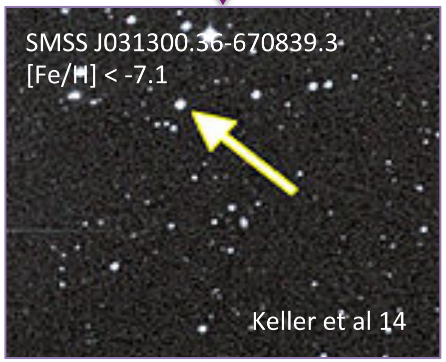
Why is the relative fraction of C-normal and C-rich stars varying with [Fe/H] ?

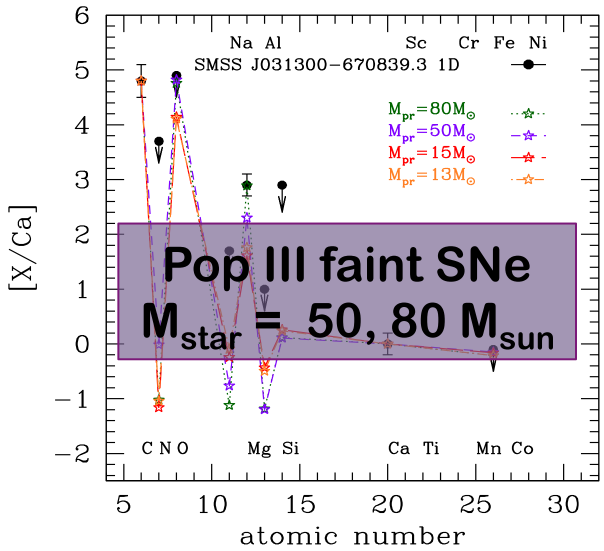
simulating the birth environment of C-normal and C-rich stars





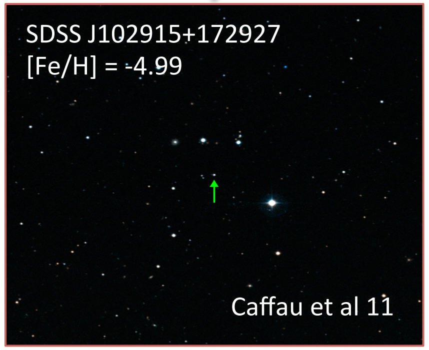
Schneider et al. 2012

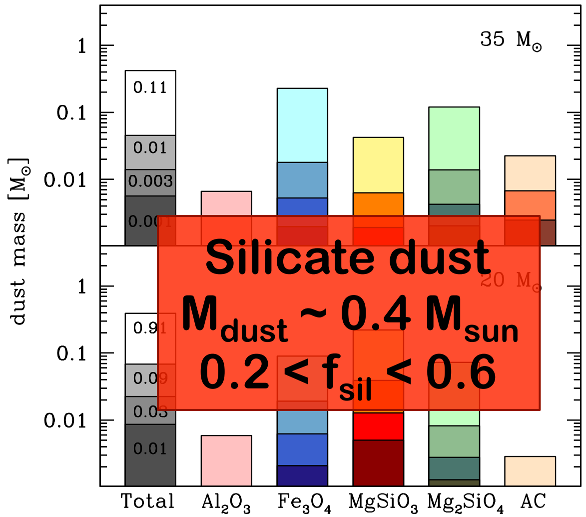




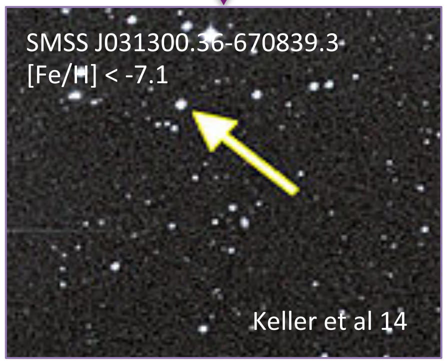
Marassi et al. 2014

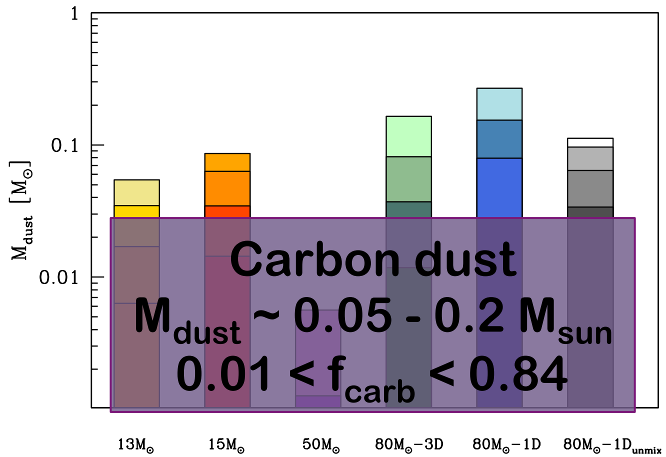
simulating the birth environment of C-normal and C-rich stars





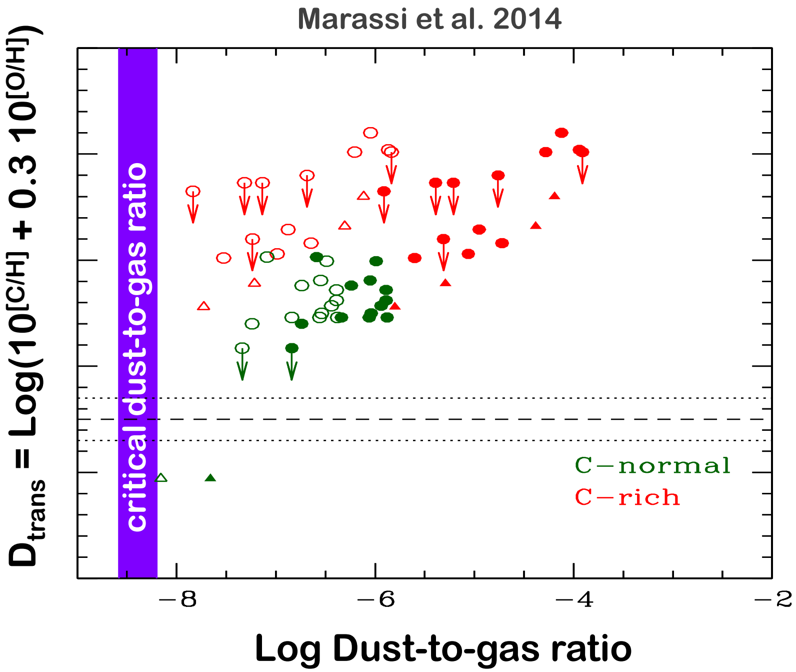
Schneider et al. 2012



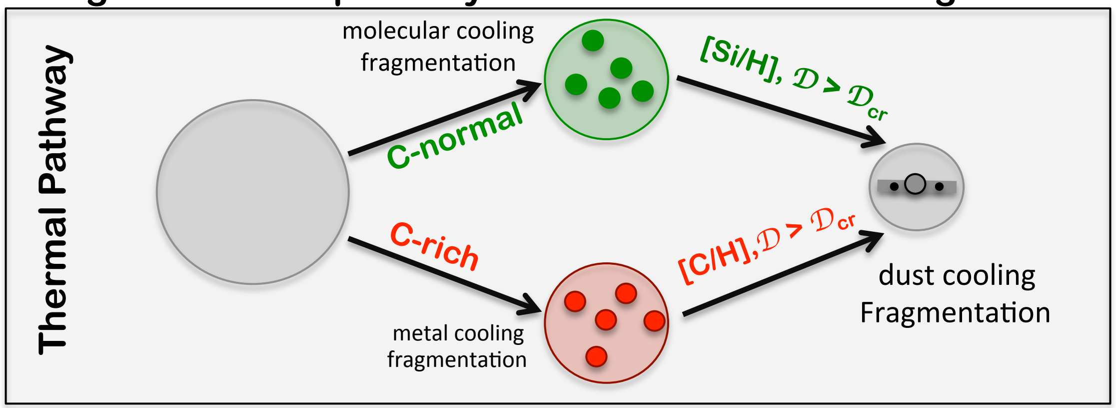


Marassi et al. 2014

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

GAMETE

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

GAMETE

GAlaxy MErger Tree and Evolution

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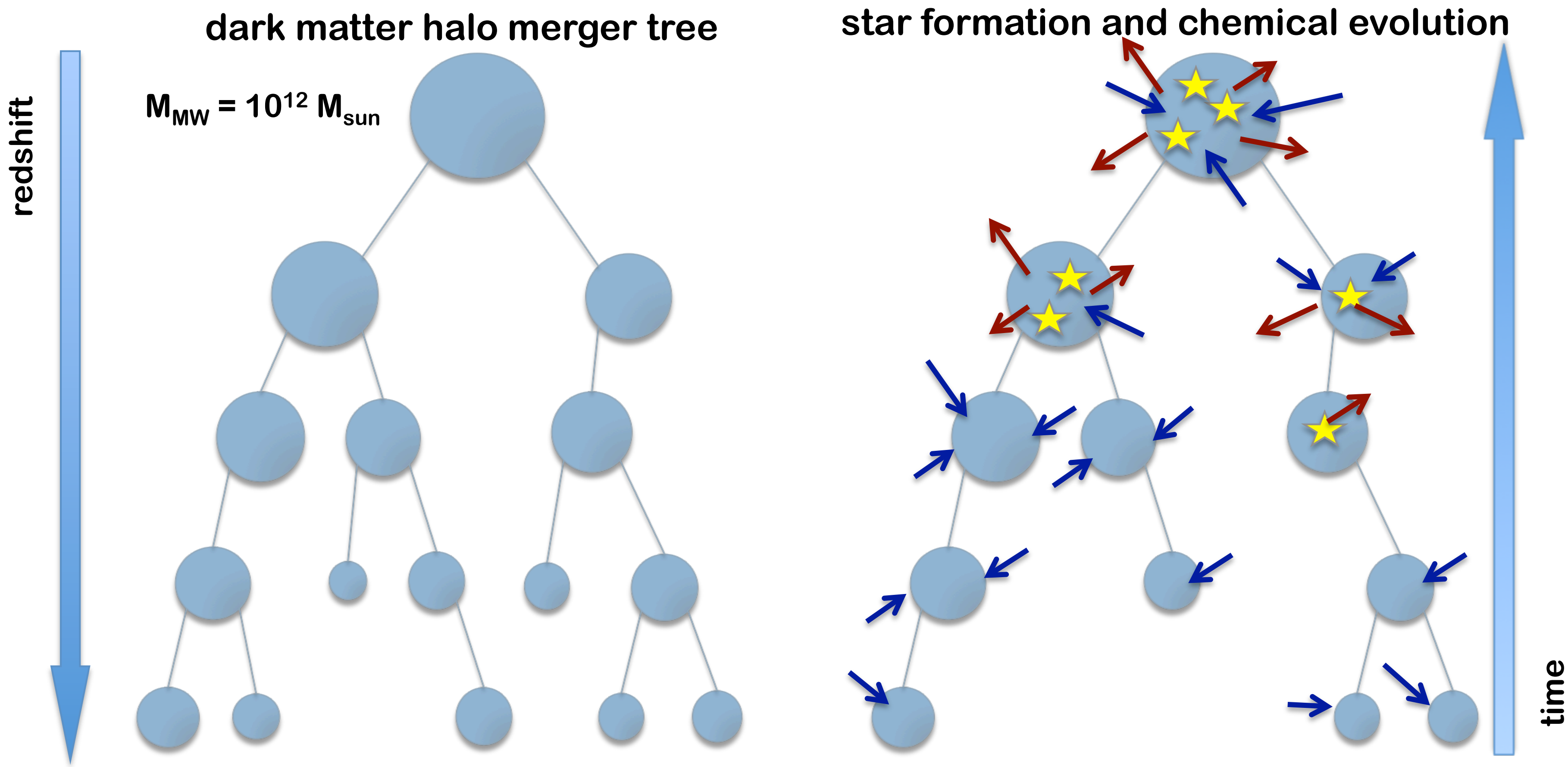
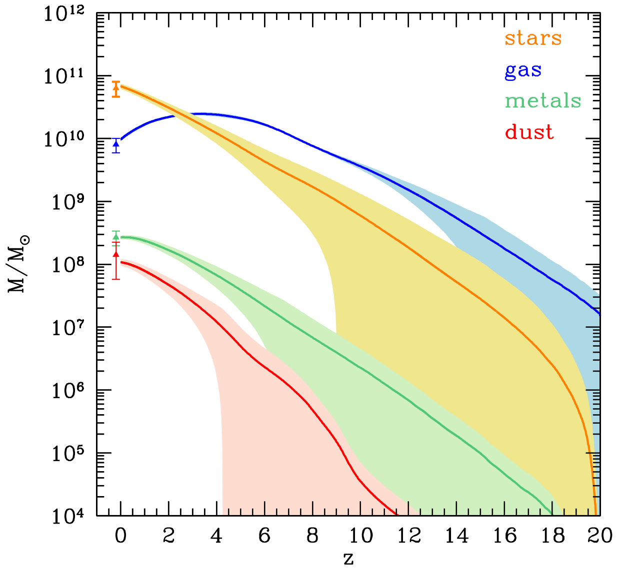
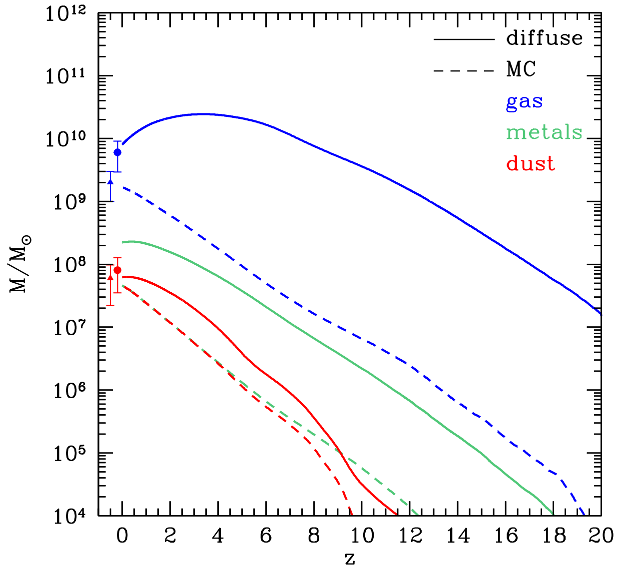


The MW and its dusty progenitors

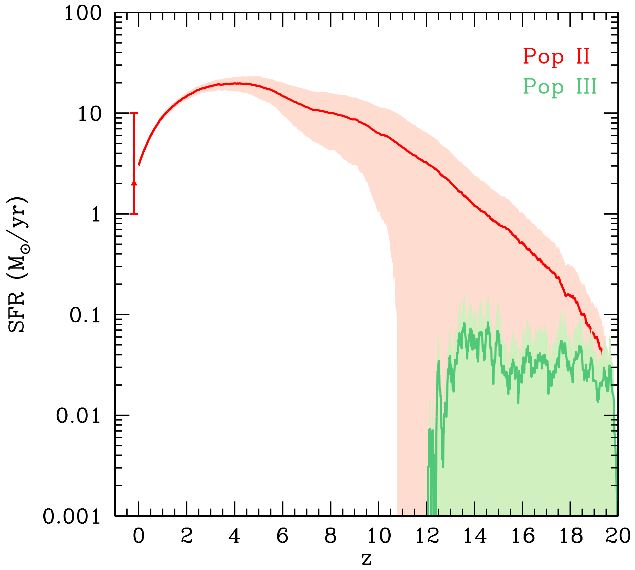
global properties of the MW



2-phase structure of the ISM



Pop III and Pop II SFRs



average over 50 independent merger trees

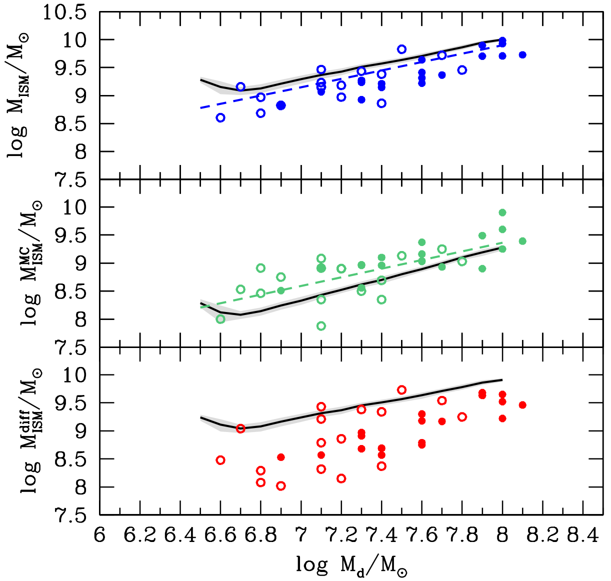
1 – σ

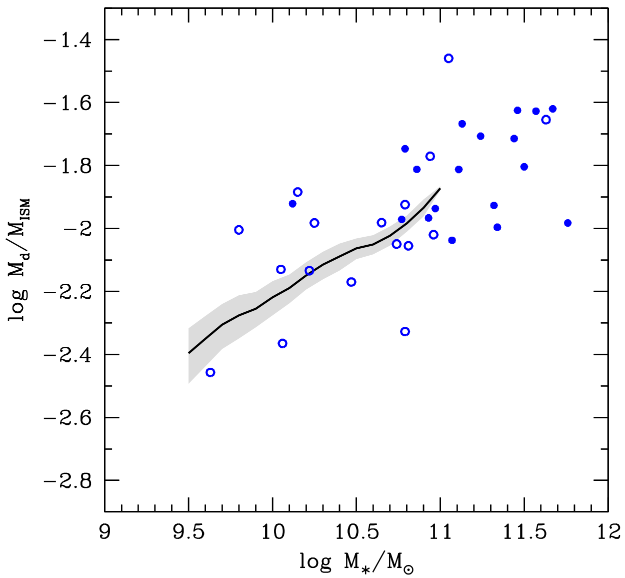
de Bennassuti et al 2014

The MW and its dusty progenitors

de Bennassuti et al 2014

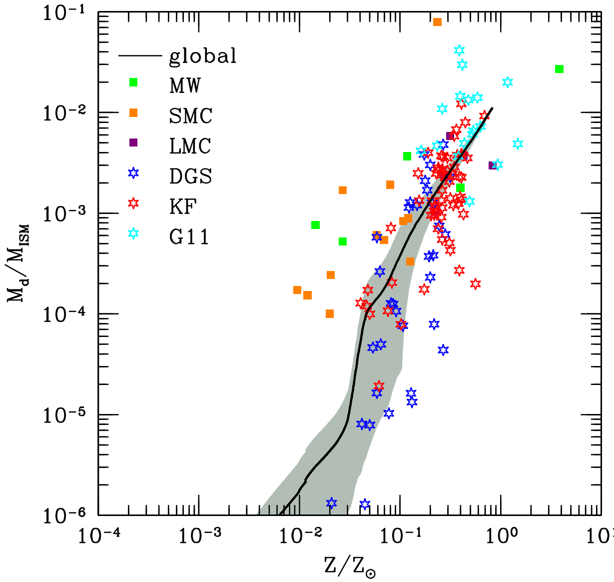
gas and dust scaling relations





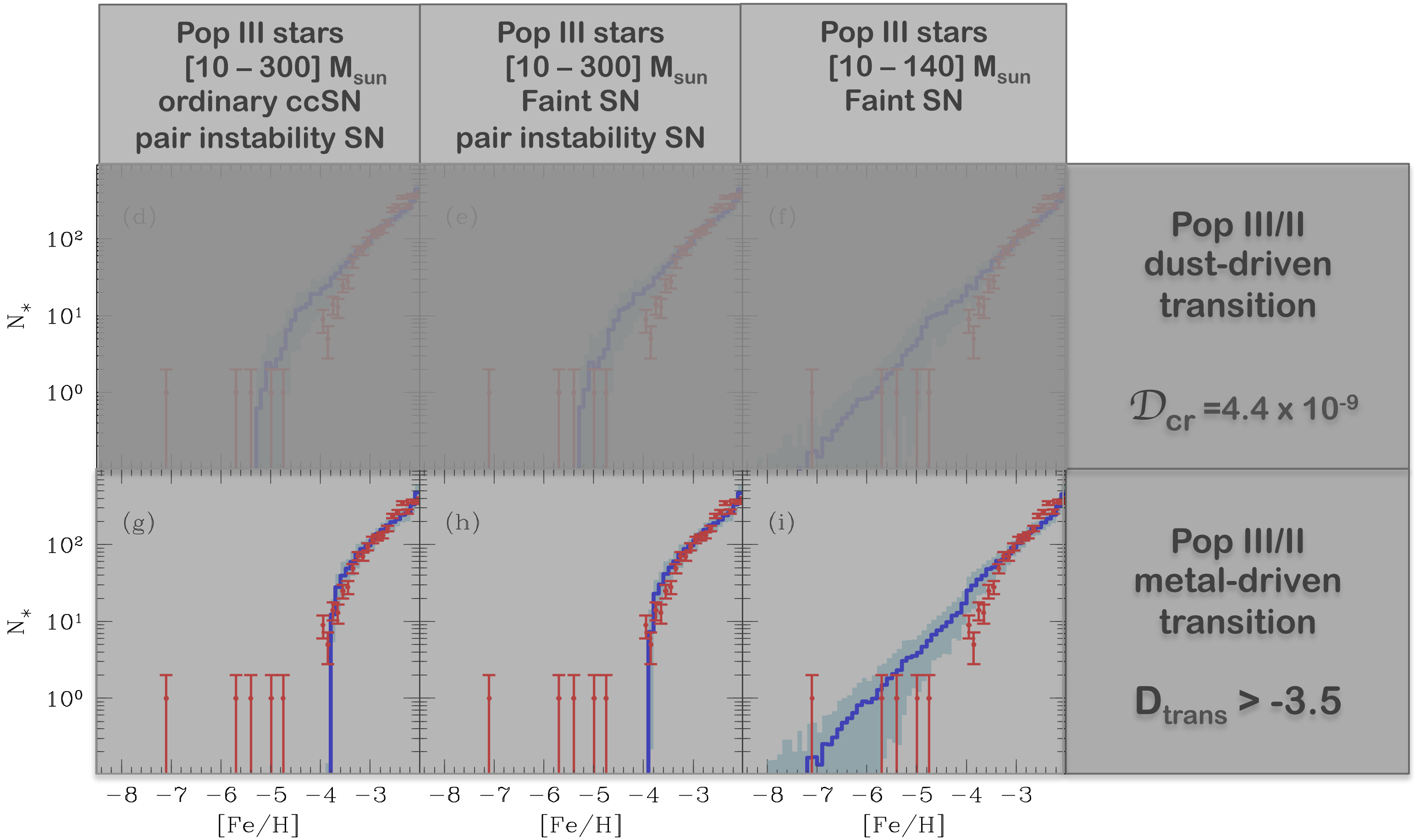
data points:
sample of local
Virgo galaxies
Corbelli et al. (2012)

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

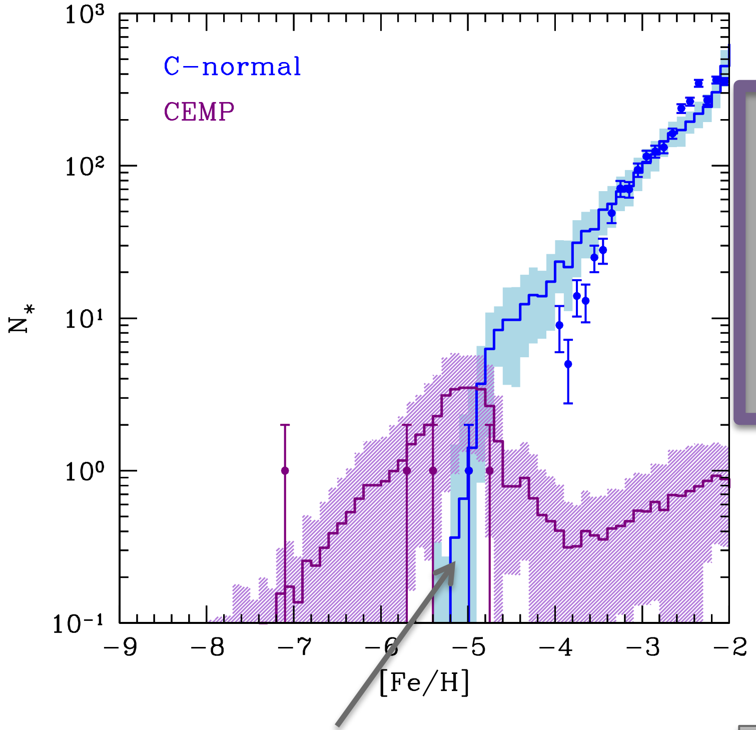


Pop III stars IMF → [10-140] M_{sun} and explode as faint SN

Pop III/II transition criterium → degenerate with the Pop III IMF

de Bennassuti et al 2014

Metallicity distribution of C-rich stars

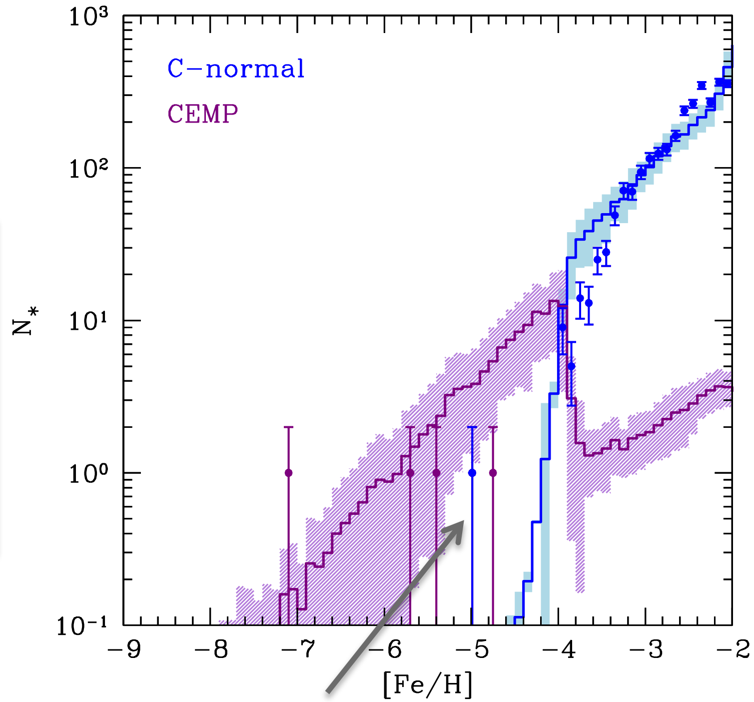


Pop III/II
dust-driven
transition

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

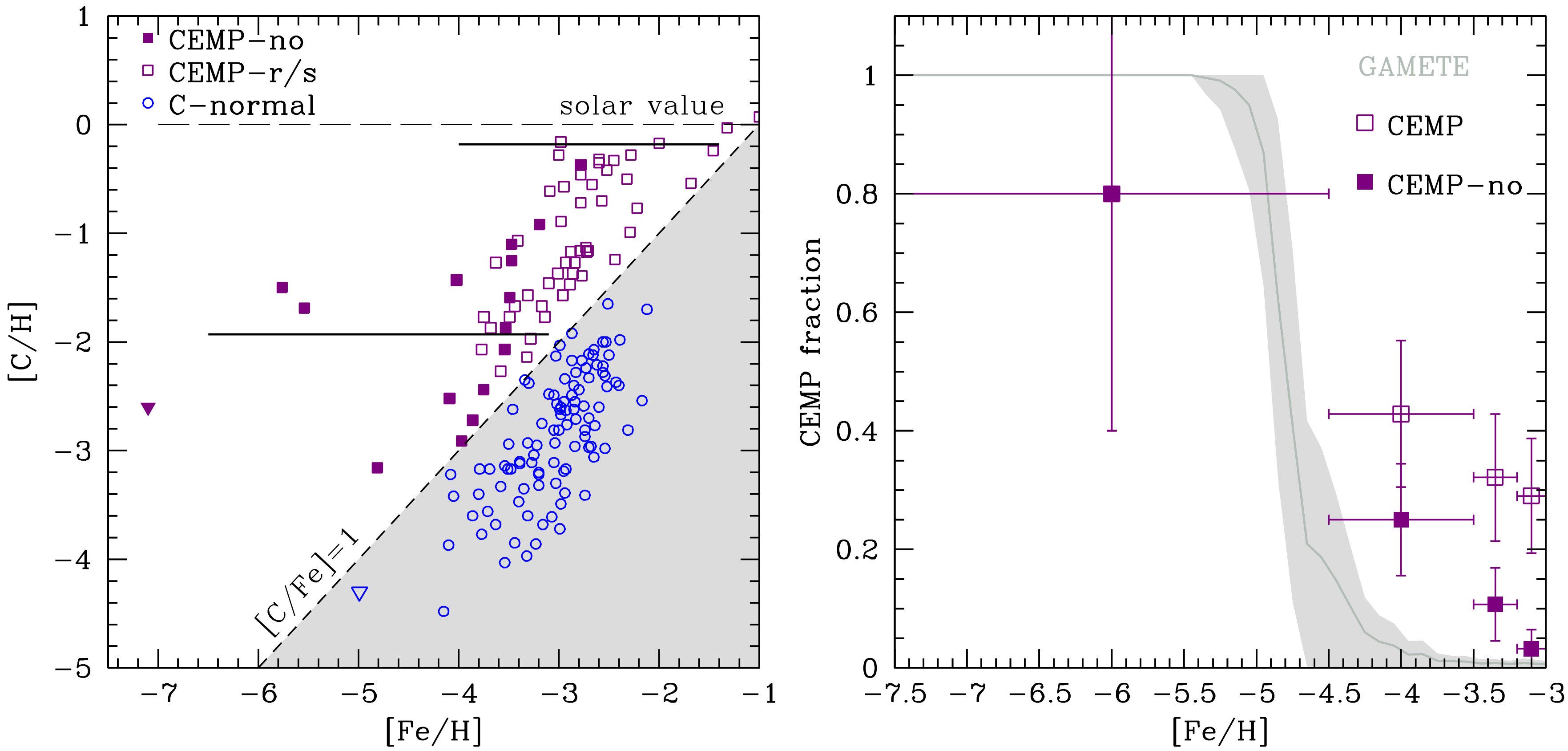
Pop III/II
metal-driven
transition

$D_{trans} > -3.5$



de Bennassuti et al 2014

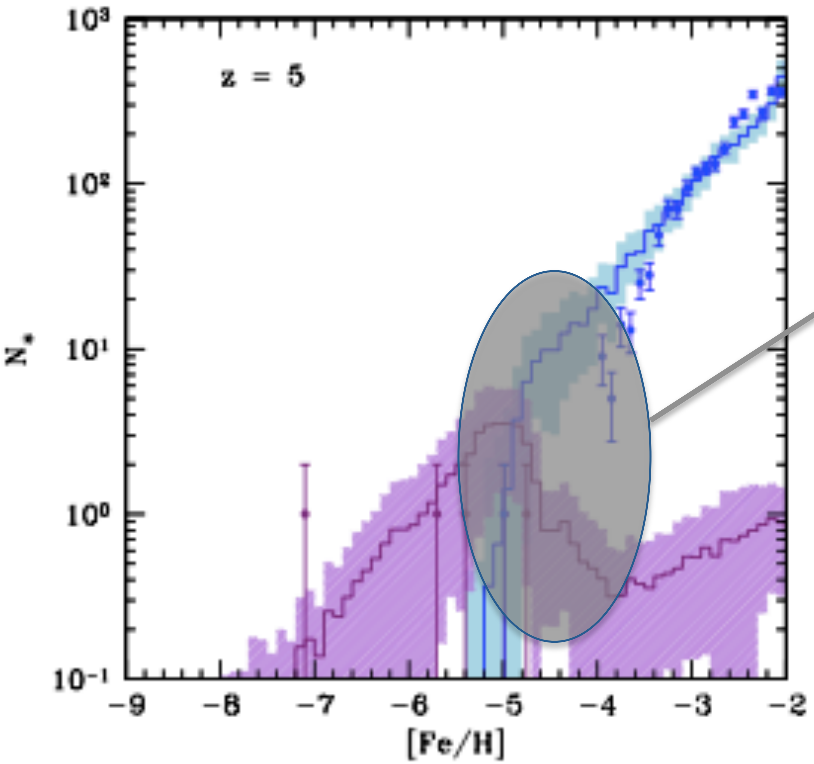
Relative fraction of C-rich and C-normal stars



data points from Yong et al. (2013)

de Bennassuti et al 2014

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



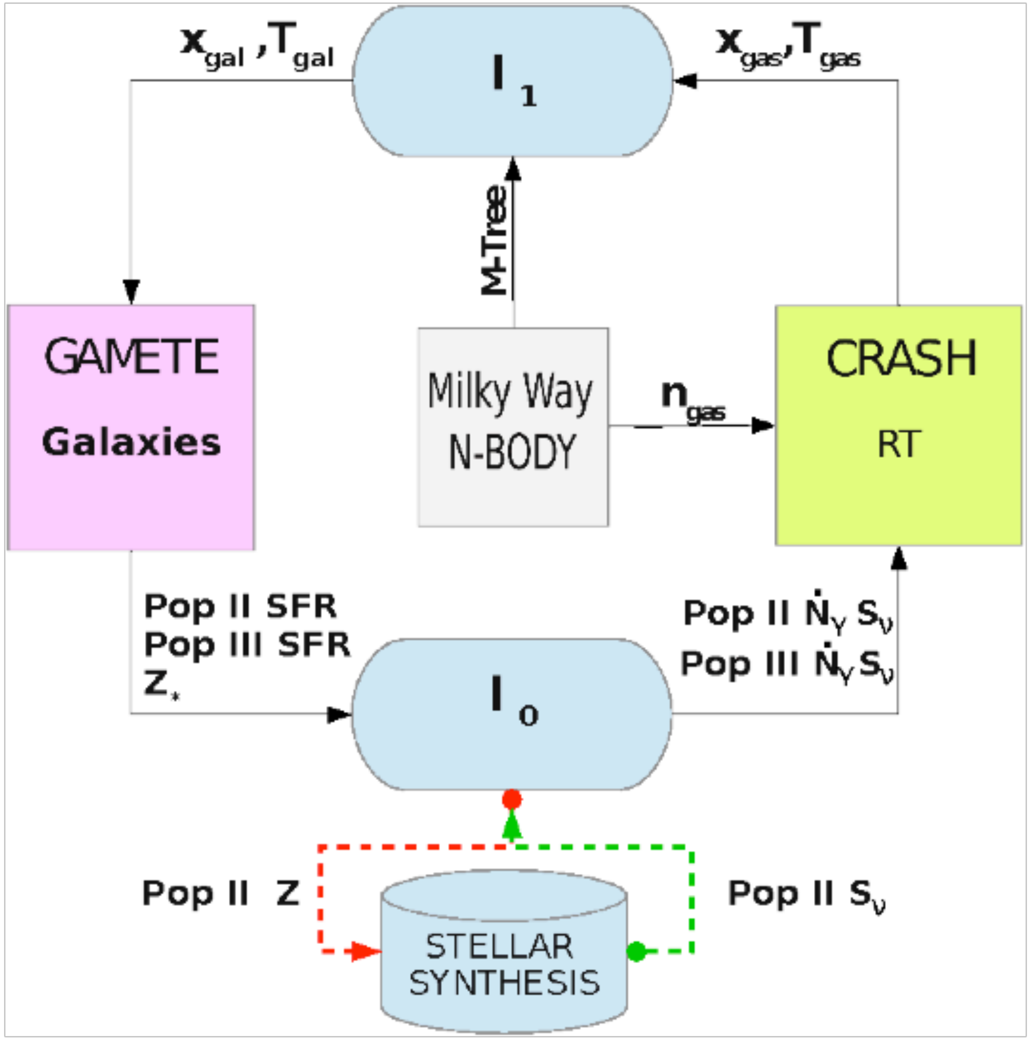
the “excess” stars are predicted to form at 15 < z < 5

interplay between chemical and radiative feedback effects

de Bennassuti et al 2014

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)



Graziani+2015

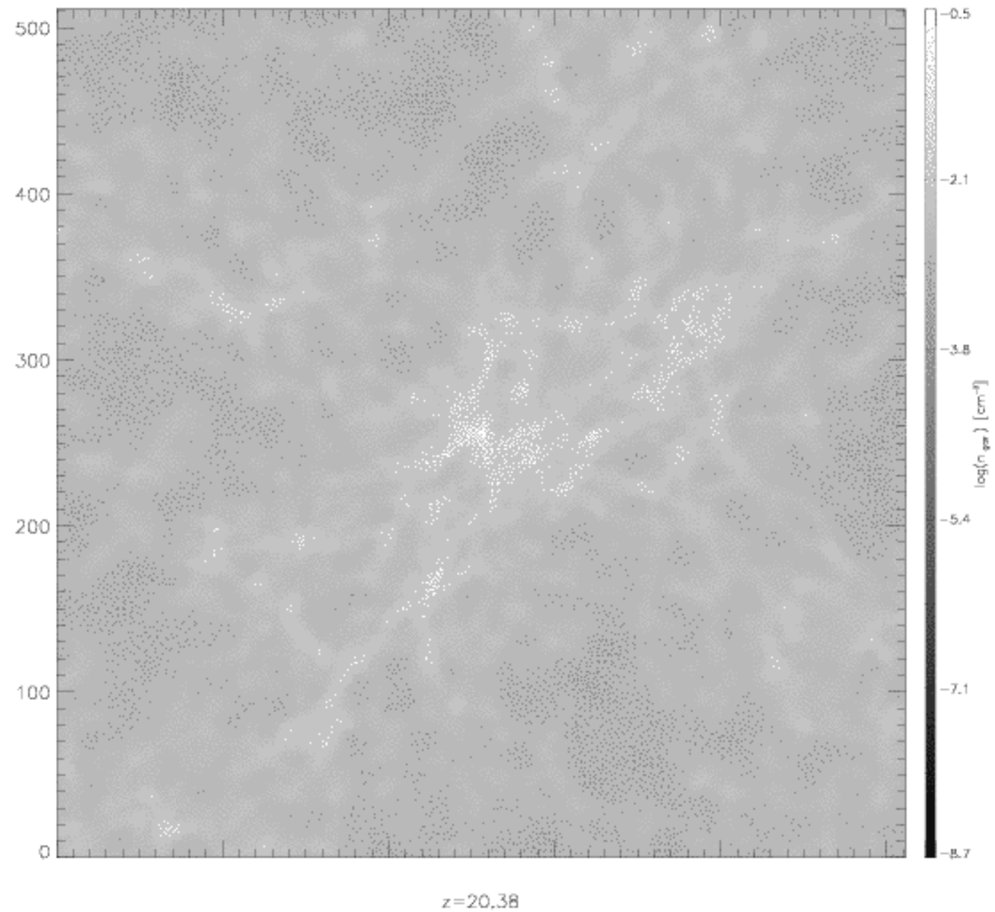
The cosmic assembly of the Milky Way

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

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

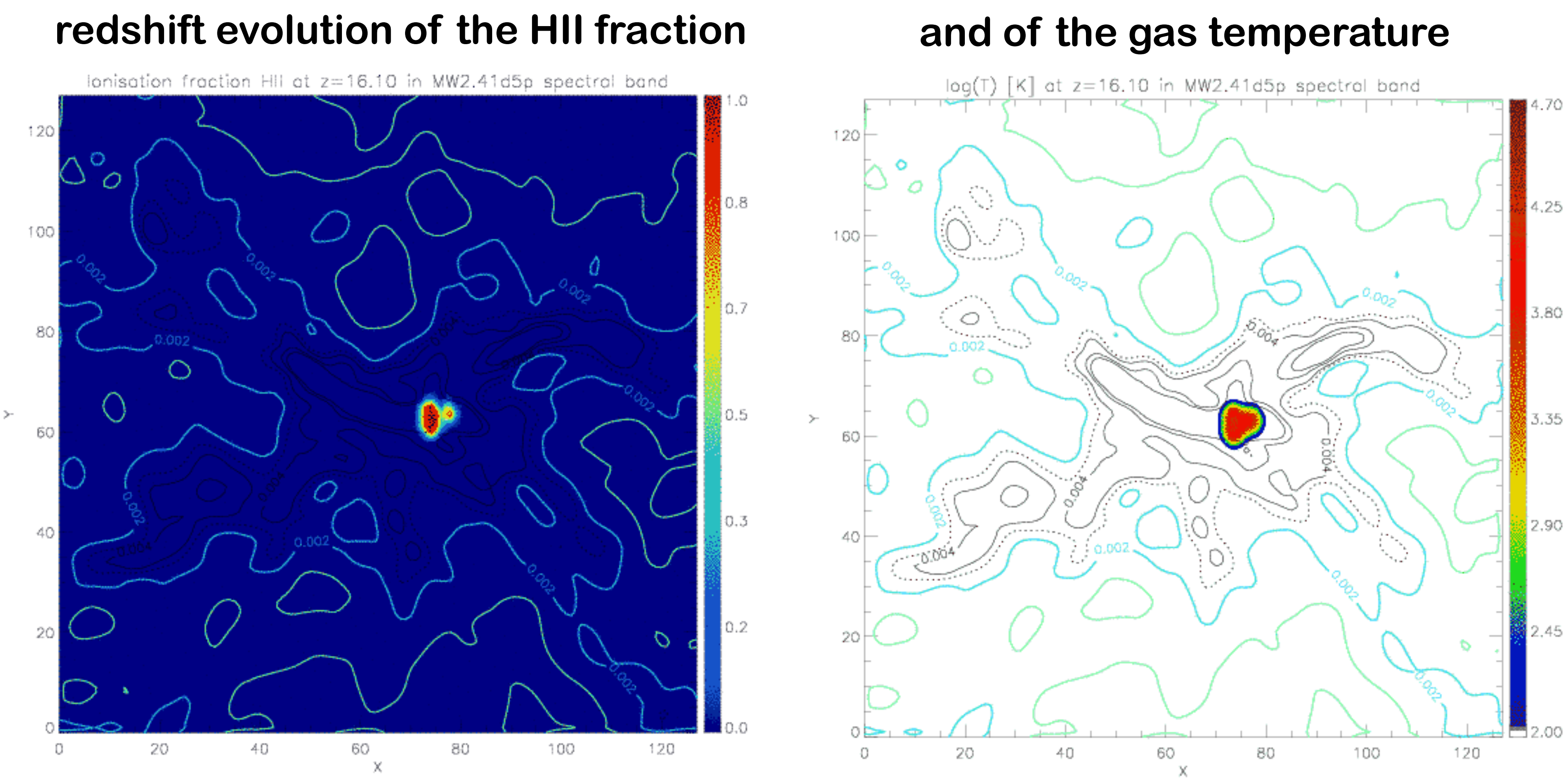
Low-res spherical region of R_l ~ 20 h^{-1} Mpc taken from a low-res cosmological simulation

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



Graziani+2015

The Milky Way reionisation simulation

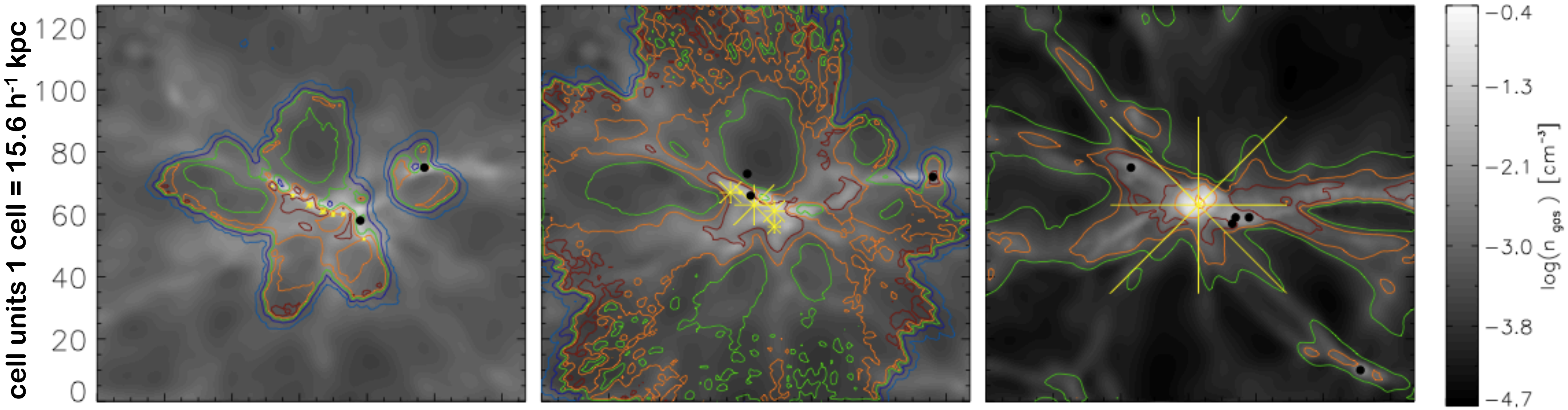


Slice cuts (distances in cell units 1 cell = 15.6 h^{-1} kpc)

Graziani+2015

The Milky Way reionisation simulation

effects of inhomogeneous radiative feedback



Z = 12 **Z = 10** **Z = 6**

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

Graziani+2015

Summary

- the Pop III IMF is likely to be top-heavy and characterized by masses of 10s – 1000s Msun

- 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 $\leq 1\ M_{sun}$ at $Z_{cr} > 10^{-6}\ Z_{sun}$

- stellar archaeology is a fundamental benchmark for theoretical models