GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

INSTITUT FÜR ASTROPHYSIK GÖTTINGEN

The low-metallicity ISM: Chemistry, Turbulence and Magnetic Fields
Göttingen, October 8-12

Probing the formation of the first low-mass stars with stellar archaeology

Raffaella Schneider
INAF/Osservatorio Astronomico di Roma

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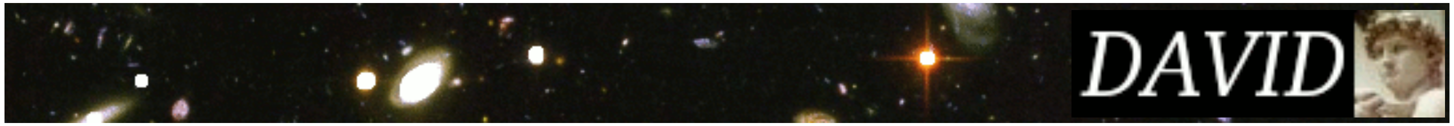
FIRST
THE FIRST STARS AND GALAXIES



DAVID http://www.arcetri.astro.it/david

Dark Ages VIrtual Department

A collaboration network for the study of Cosmology and the high redshift Universe


Simone Bianchi
INAF/OAArcetri

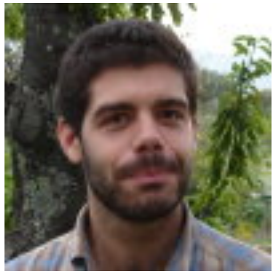

Benedetta Ciardi
MPA


Pratika Dayal
ROE-Edimburgh


Carmelo Evoli
Hamburg/DESY


Andrea Ferrara
SNS


Simona Gallerani
SNS


Fabio Iocco
IAP

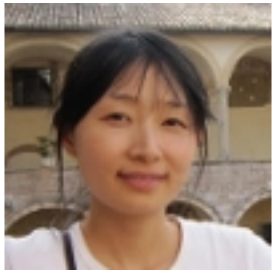

Francisco Shu-Kitaura
MPA


Antonella Maselli


Stefania Salvadori
Kapteyn Institute


Ruben Salvaterra
INAF/IAFS


Raffaella Schneider
INAF/OARoma


Sunghye Baek
SNS


Marcos Valdes
SNS


Rosa Valiante
INAF/OARoma


Livia Vallini
SNS

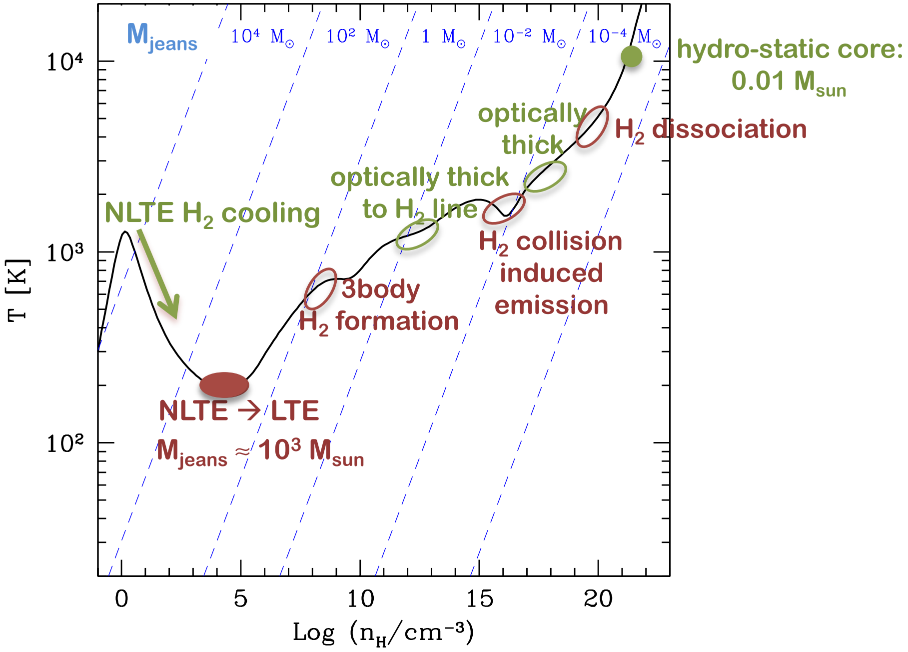

Andrei Meisinger
SNS


Stefania Pandolfi
DARK

star formation in primordial clouds

thermal evolution of Z = 0 gas as a 0^{th}-order reference case

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

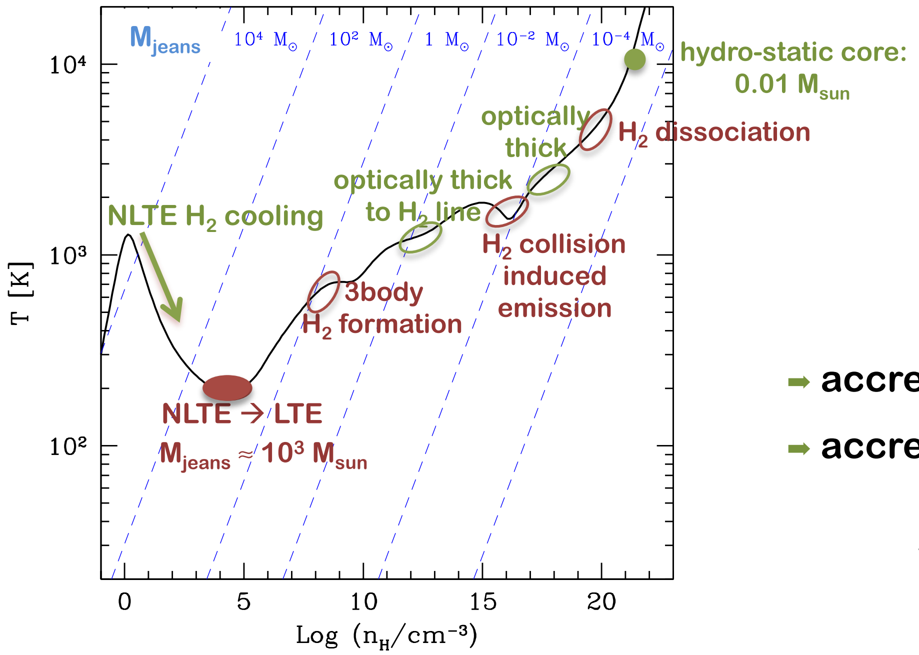


Omukai et al. 2005

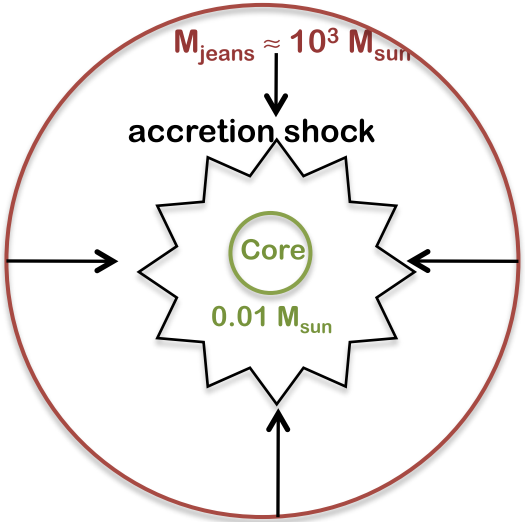
star formation in primordial clouds

thermal evolution of $Z = 0$ gas as a 0^{th}-order reference case

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



Omukai et al. 2005

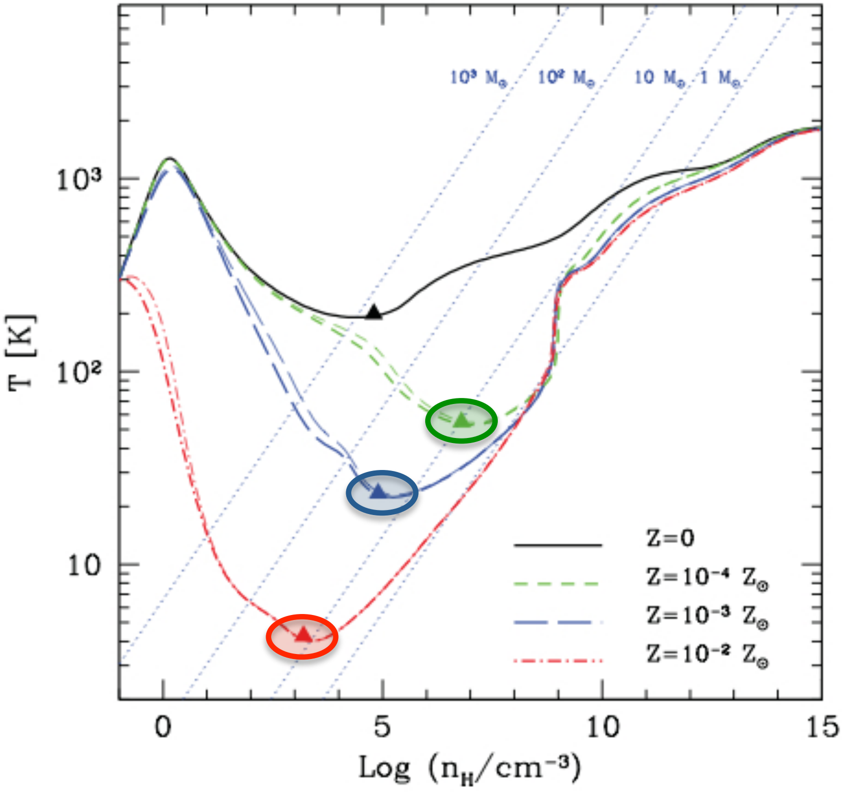


- ➡ accretion rate $dM/dt \approx M_J/t_{ff} \approx c_s^3/G \approx T^{3/2}$ (x 100 larger than Z_{sun})
- ➡ accreted gas mass $M_\star \cong [40 - 100]\ M_{sun}$

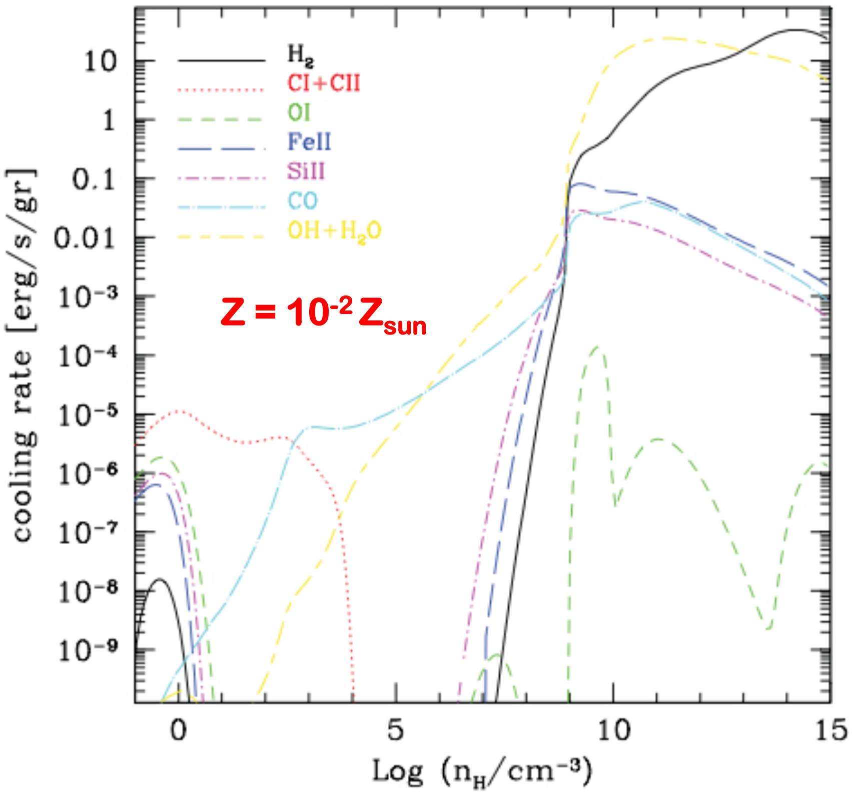
Omukai & Palla 2003; Bromm et al 2004; O’Shea et al. 2007;
Tan & McKee 2004; McKee & Tan 2008; Hosokawa et al. (2011)

cooling & fragmentation: line emission from molecules and metals

RS, Omukai, Bianchi & Valiante 2012



fragmentation mass scales > 10 M_{sun}



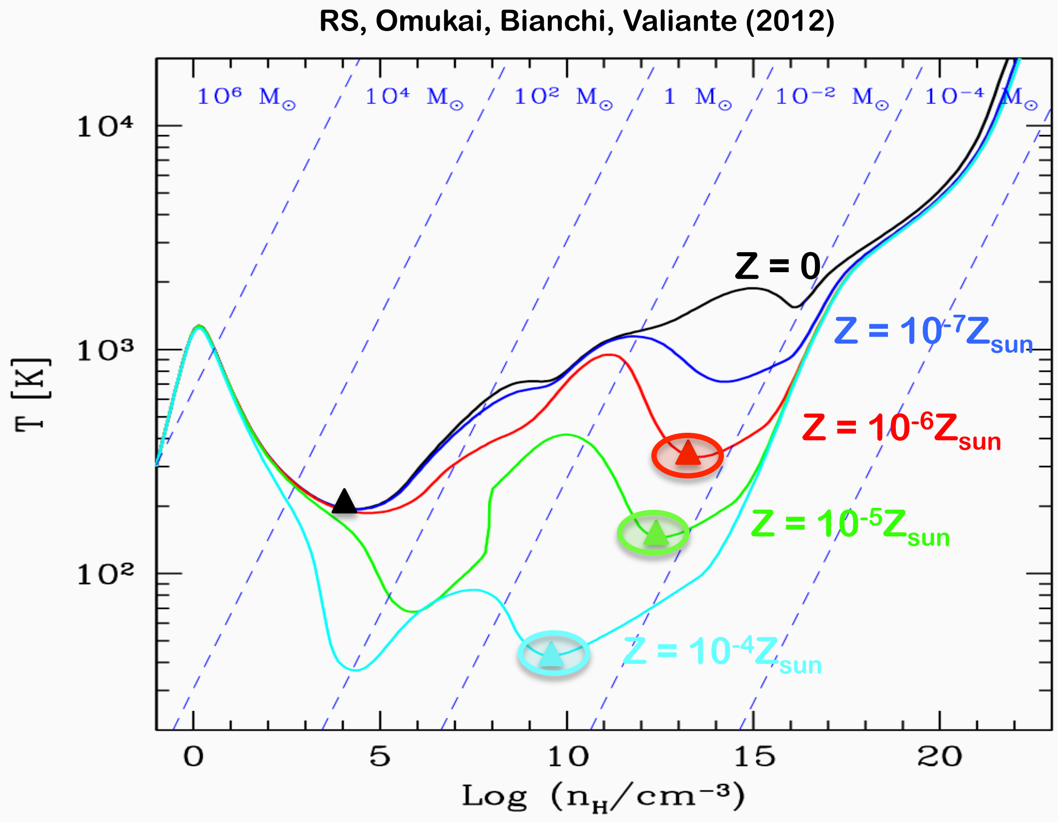
$Z = 10^{-2} Z_{sun}$

dominant coolants are OI, CII at $n_H < 10^3 cm^{-3}$

but CO, OH, H_2O are very important even at

$Z = 10^{-2} Z_{sun}$

cooling & fragmentation: thermal emission from dust grains



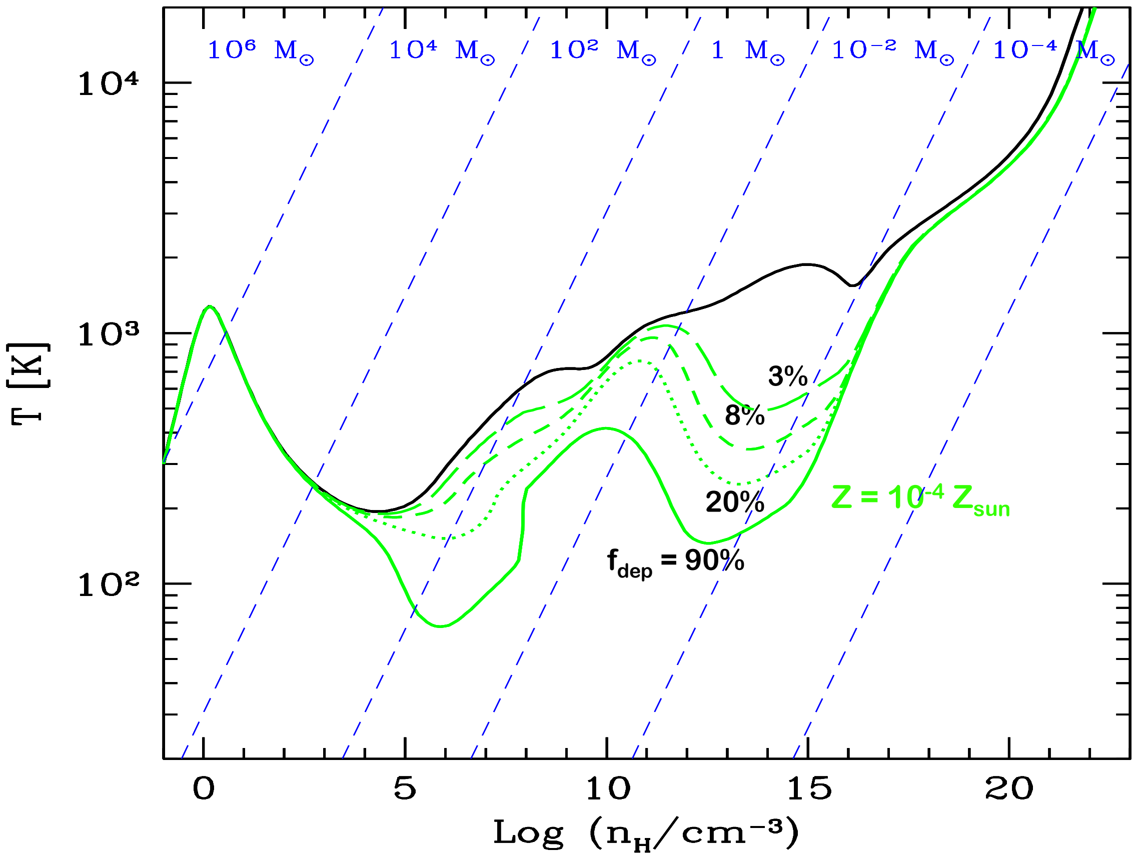
fragmentation mass scales < 1 M_{sun}

dust cooling is effective at $Z > 10^{-6}\ Z_{sun}$

fragmentation conditions depend on the dust-to-gas ratio

critical metallicity or dust-to-gas ratio?

RS, Omukai, Bianchi, Valiante (2012)

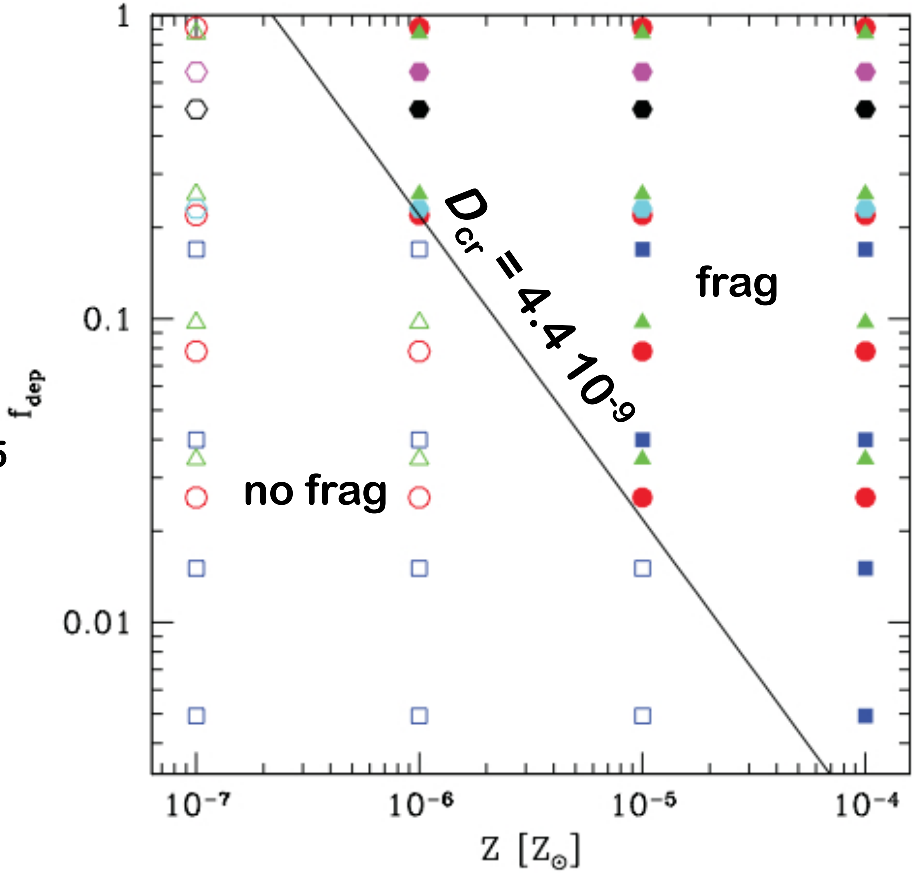


$f_{dep}=M_{dust}/(M_{met}+M_{dust})$

dust cooling depends on the absolute metallicity AND dust depletion factor
→ dust-to-gas ratio

minimal (chemical) conditions for the formation of the first low-mass stars

- ● 20 M_{sun} Z = 0
- ▲ 35 M_{sun} Z = $10^{-4} Z_{sun}$
- ■ 20 M_{sun} Z = $10^{-4} Z_{sun}$
- ● CCSN Schneider+06
- ⬢ PISN Schneider+06
- ● Local ISM Omukai+05



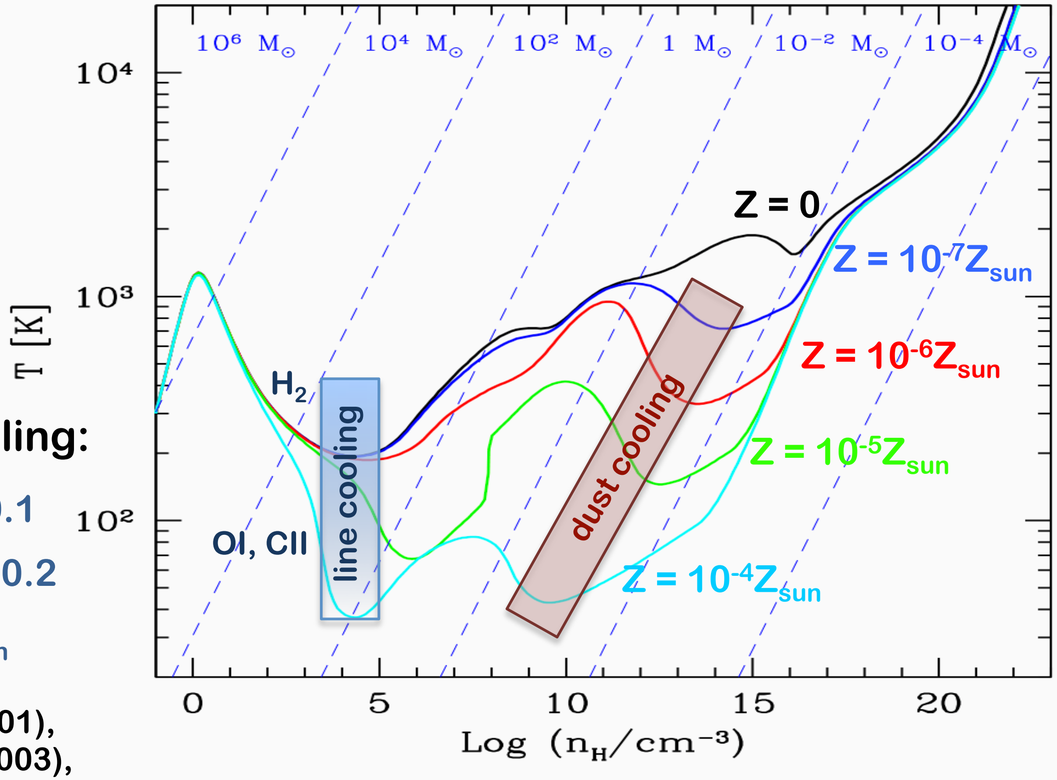
Energy transfer rate between gas and dust > Compressional heating rate

total grain cross section per unit dust mass ←

$$\mathcal{S}\mathcal{D}_{cr} > 1.4 \times 10^{-3} \mathrm{cm}^2/\mathrm{gr} \left[\frac{T}{10^3 \mathrm{K}}\right]^{-1/2} \left[\frac{n_{\mathrm{H}}}{10^{12} \mathrm{cm}^{-3}}\right]^{-1/2}$$

RS, Omukai, Bianchi, Valiante (2012)

two epochs of fragmentation: two different fragmentation scales



metal-line cooling:

$[C/H]_{cr} = -3.5 \pm 0.1$

$[O/H]_{cr} = -3.05 \pm 0.2$

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

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

dust cooling:

$Z_{cr} > 10^{-6} Z_{sun}$

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

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

observational constraints from stellar archaeology

Samples of metal-poor stars in the Galactic halo and dwarf galaxies

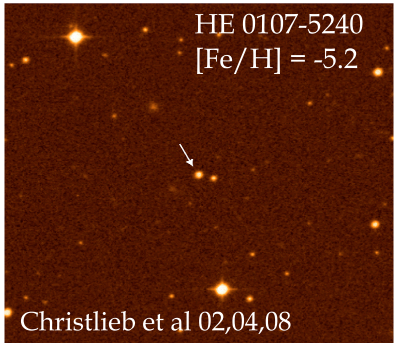
HK survey	Beers, Preston, Schectman 85/92	*Galactic halo stars*
Hamburg/**ES**o	Wisotzki et al 00; Christlieb et al 03	
Sloan**D**igital**S**ky**S**urvey	York et al 00	→ *Halo structure*
Dwarf**A**bundances&**R**adialvelocity**T**eam	Tolstoy et al 06	→ *Dwarf galaxies*

Main observables:

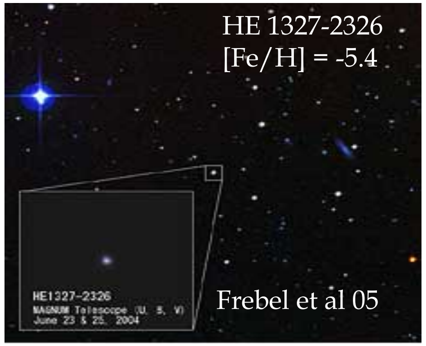
- → Metallicity Distribution Function (MDF)
- → Stellar abundances

no metal-free star has been detected but several hyper metal (Fe)-poor stars have been found

$Z \approx 7\ 10^{-3}\ Z_{sun}$

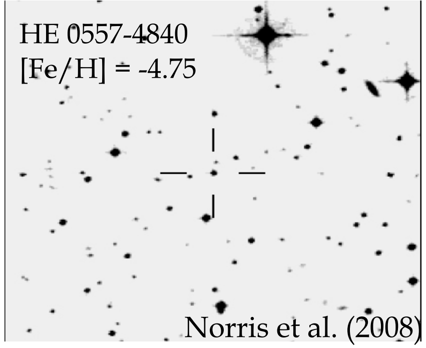

HE 0107-5240
[Fe/H] = -5.2
Christlieb et al 02,04,08

$Z \approx 2\ 10^{-2}\ Z_{sun}$

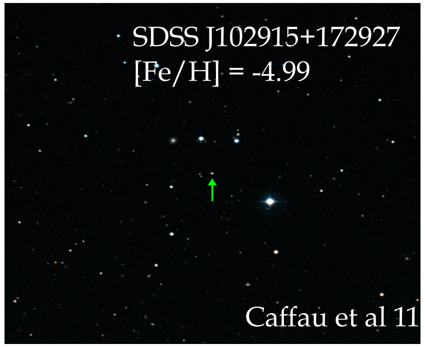


HE 1327-2326
[Fe/H] = -5.4
Frebel et al 05

$Z \approx 10^{-3}\ Z_{sun}$


HE 0557-4840
[Fe/H] = -4.75
Norris et al. (2008)

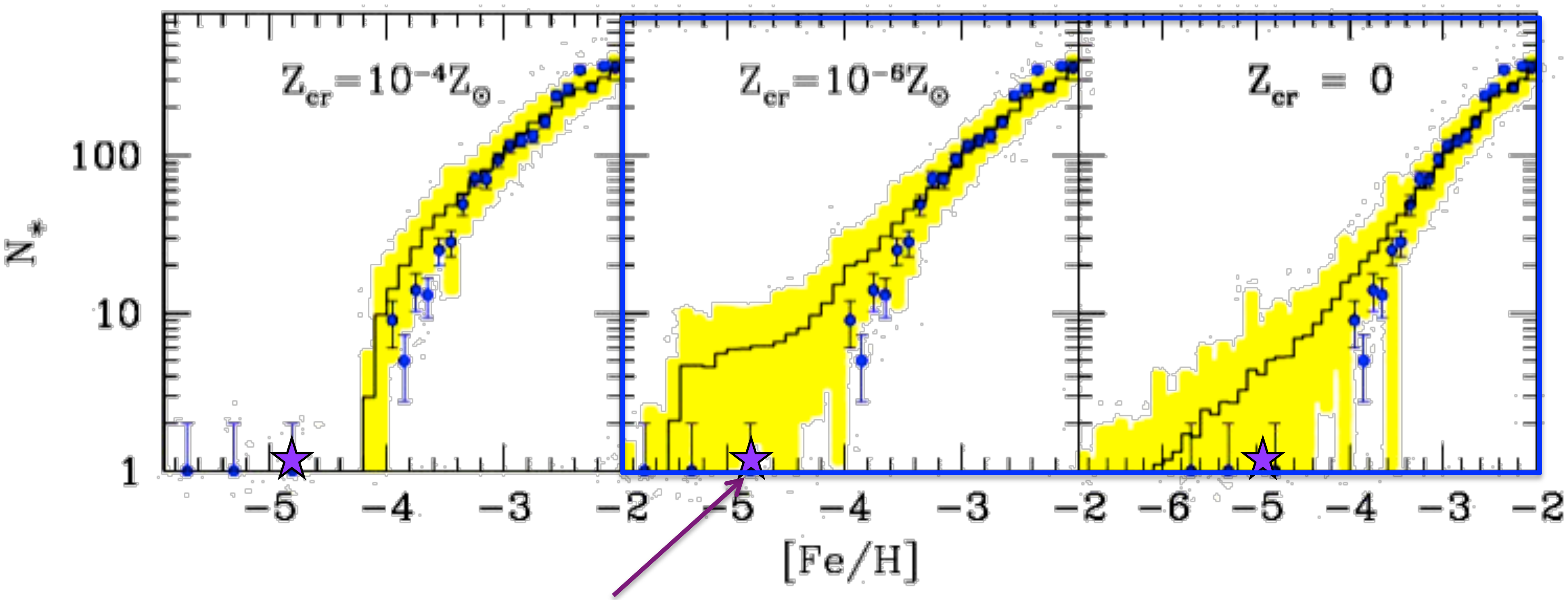
$Z < 4.5\ 10^{-5}\ Z_{sun}$


SDSS J102915+172927
[Fe/H] = -4.99
Caffau et al 11

stellar archaeology: observed MDF

Salvadori, Schneider & Ferrara (2007)

universal Salpeter IMF



SDSS J102915+172927 star observed by Caffau+(2011) requires $Z_{cr} \leq 4.5\ 10^{-5}\ Z_{sun}$

RS et al. (2012)

F_o = # metal-free stars / # observed stars [Fe/H] < -2.5 < $F_{obs} = 8.7\ 10^{-4}$

(Oey 2003; Tumlinson 2006)

Z_{crit}/Z_{sun}	F_o
10^{-4}	<< F_{obs}
10^{-6}	<< F_{obs}
0	$7.5\ 10^{-3}$

the formation of the primitive star SDSS 102915 relies on dust ?

RS, Omukai, Limongi, Ferrara, Salvaterra, Chieffi, Bianchi (2012)

Reconstruct the birth environment of SDSS 102915:

1. Fit the observed surface elemental abundances with SN models
2. Use these SN models to compute the associated dust yields
3. Follow the thermal evolution during the collapse of the parent cloud of SDSS 102915 to check for fragmentation conditions

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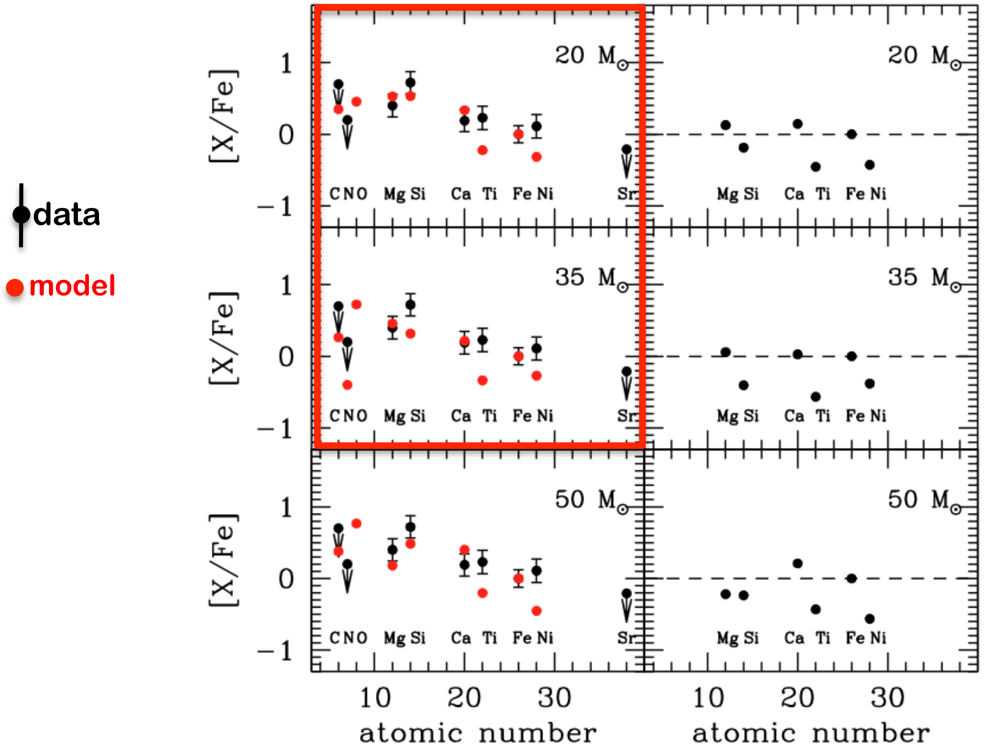

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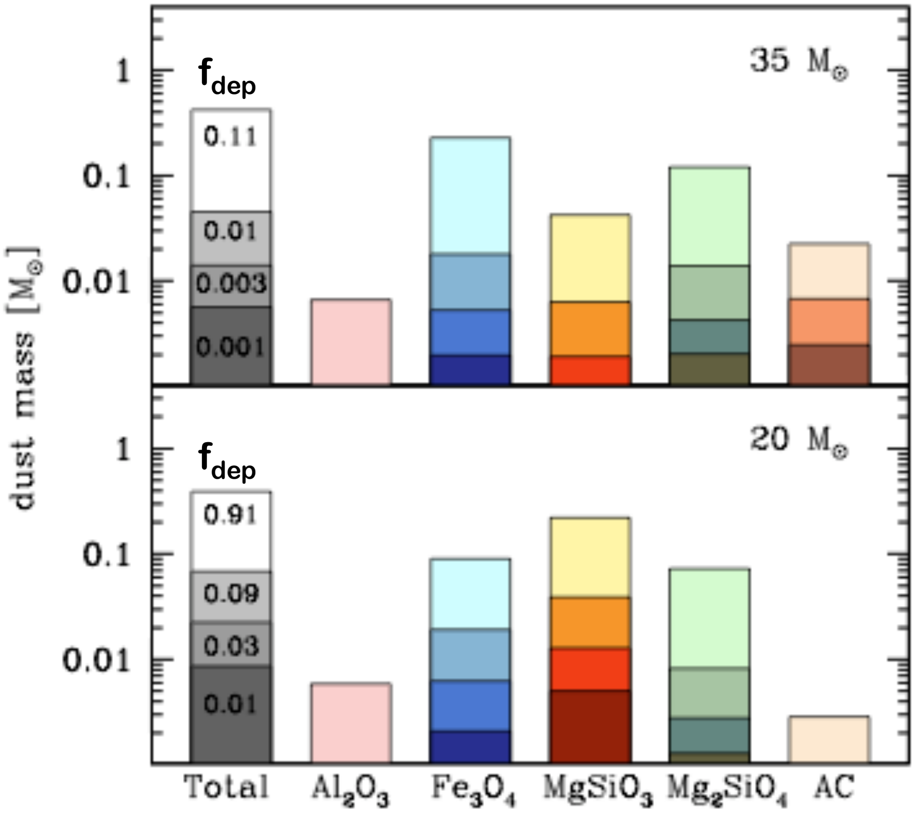

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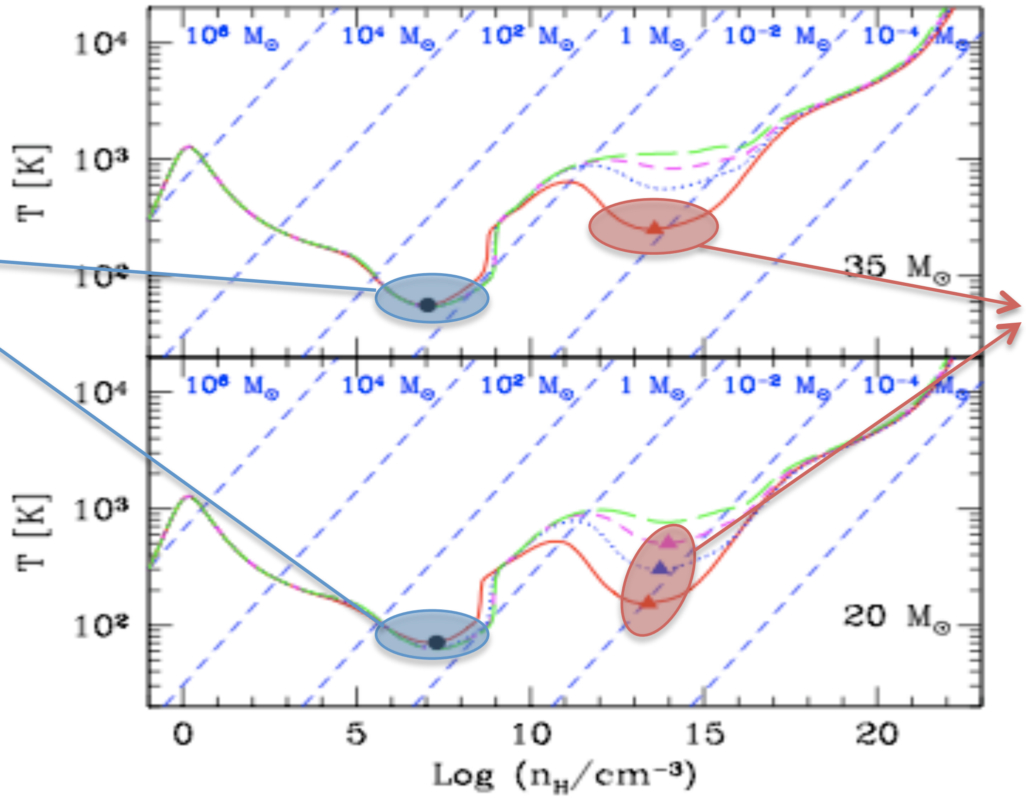


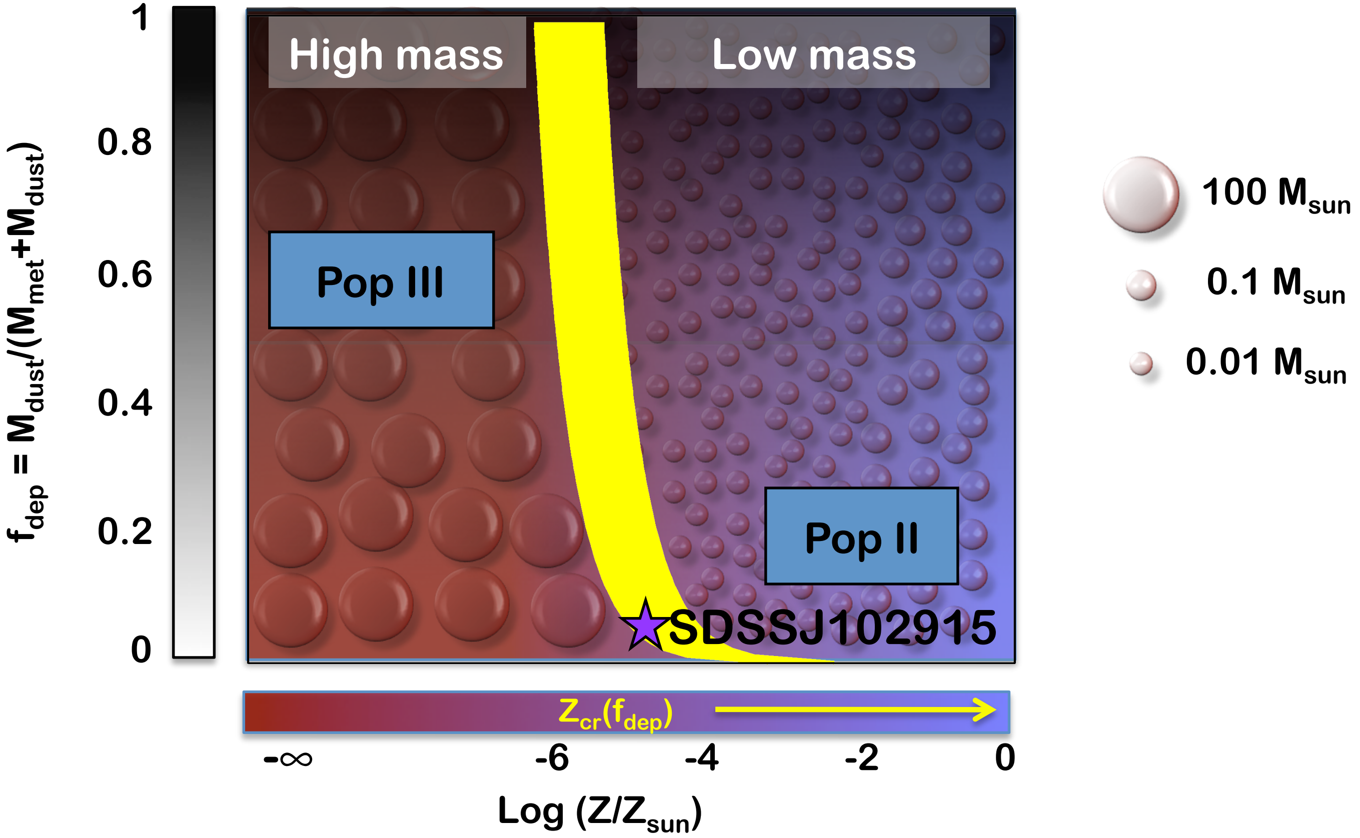
$Z = 4.5\ 10^{-5}\ Z_{sun}$

OH cooling
$M_{jeans} \approx 10\ M_{sun}$

dust cooling
$M_{jeans} \approx [0.05 -0.1]\ M_{sun}$

critical metallicity scenario

SDSS J102915 provides a strong evidence in support of the dust-driven transition



the observed properties of SDSS J102915 constrain the SN progenitors to have masses ≈ [20 – 40] M_{sun} and to release ≈ [0.01 –0.4] M_{sun} of dust in the surrounding medium

RAPID DUST ENRICHMENT AT HIGH REDSHIFT