the Stellar path to the early universe

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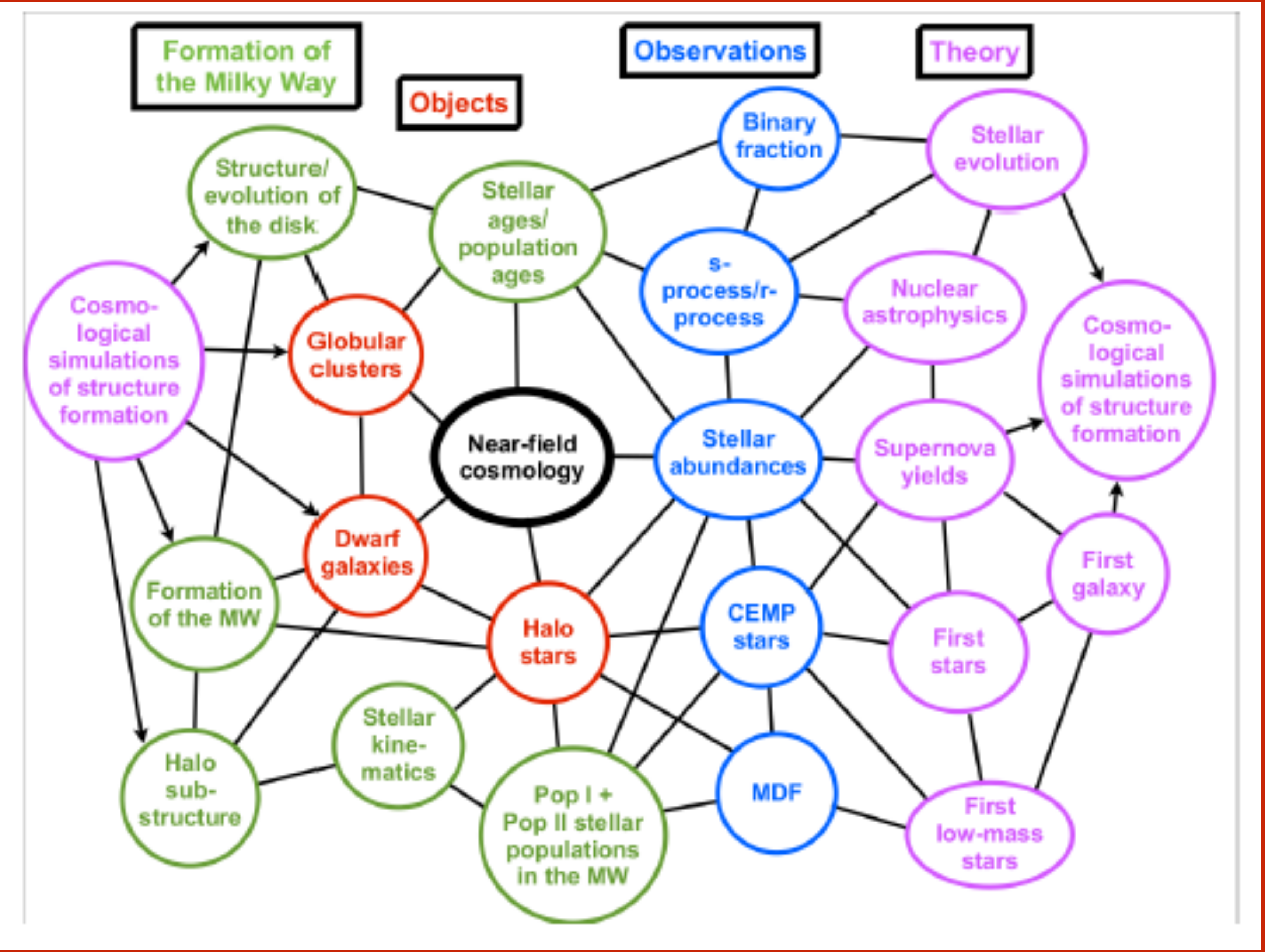
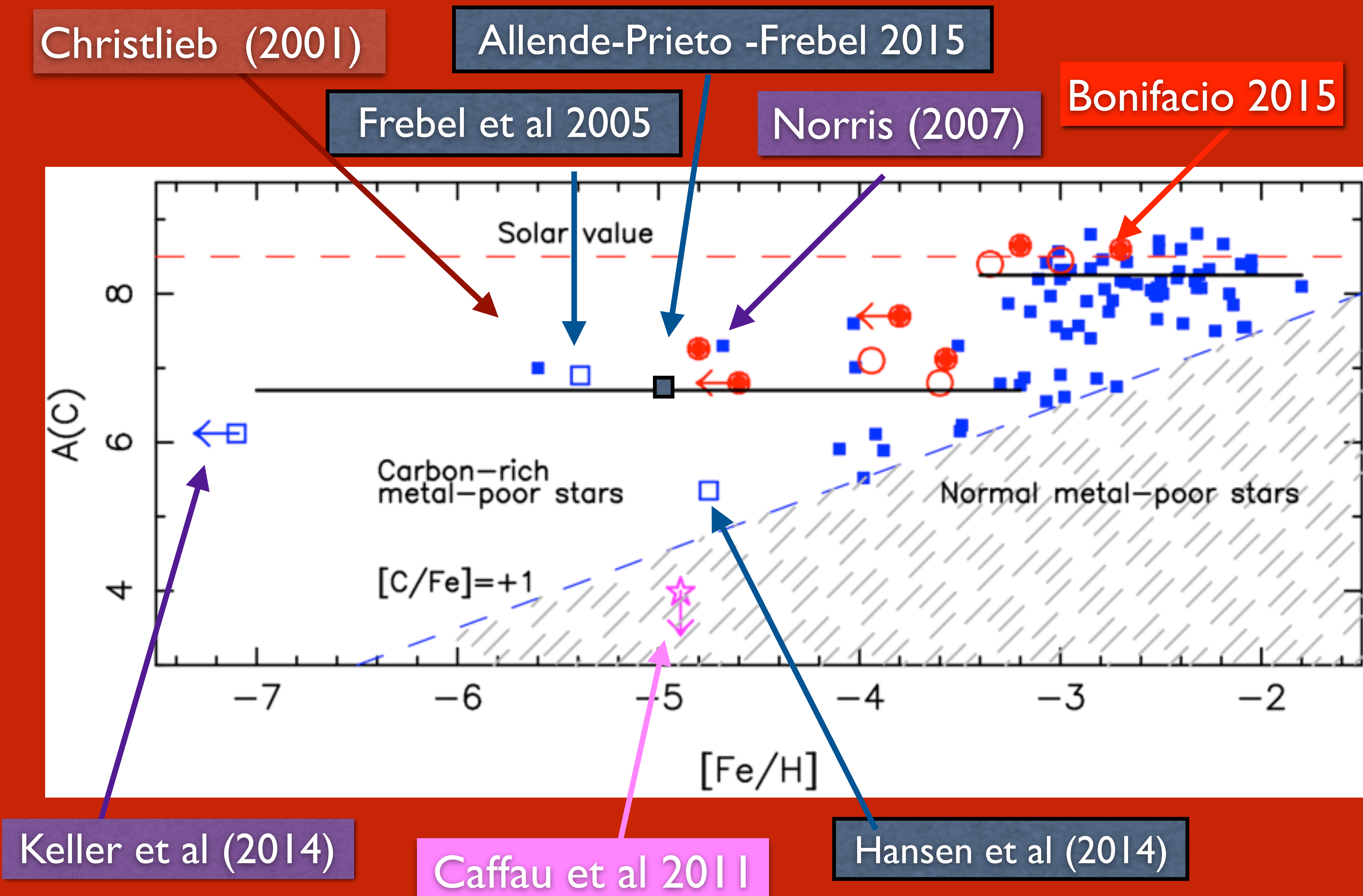
near-Field cosmology

- the most metal poor stars in the Galactic halo (oldest?) present an unique opportunity to explore physical conditions of the earliest star formation of elements in the Universe (< 500 Myrs). In particular faint events which will be non observable at high redshift even with ELTs, (complementary to poor-DLA at high-z)
- insight into the Population III star progenitors responsible for the first chemical enrichment (stellar archeology)
- insight into the "Li problem" and   age of the Universe with nucleochronology



Formation of the Milky Way
Objects
Observations
Theory
Structure/ evolution of the disk
Stellar ages/ population ages
Binary fraction
Stellar evolution
Cosmo-logical simulations of structure formation
Globular clusters
s-process/r-process
Nuclear astrophysics
Cosmo-logical simulations of structure formation
Near-field cosmology
Stellar abundances
Supernova yields
Dwarf galaxies
Formation of the MW
Halo stars
CEMP stars
First stars
First galaxy
Halo sub-structure
Stellar kine-matics
Pop I + Pop II stellar populations in the MW
MDF
First low-mass stars

OVERVIEW



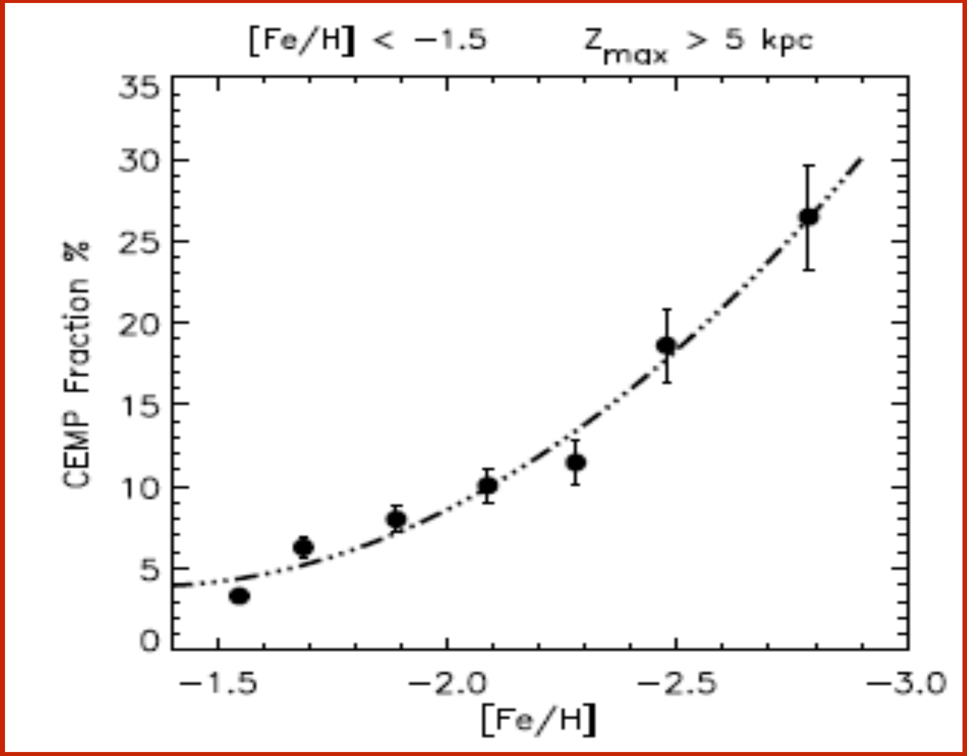
$[A/H] = \log_{10}(N_A/N_H)_\star - \log_{10}(N_A/N_H)_\odot$

9 stars with [Fe/H]<-4.5, but POP II

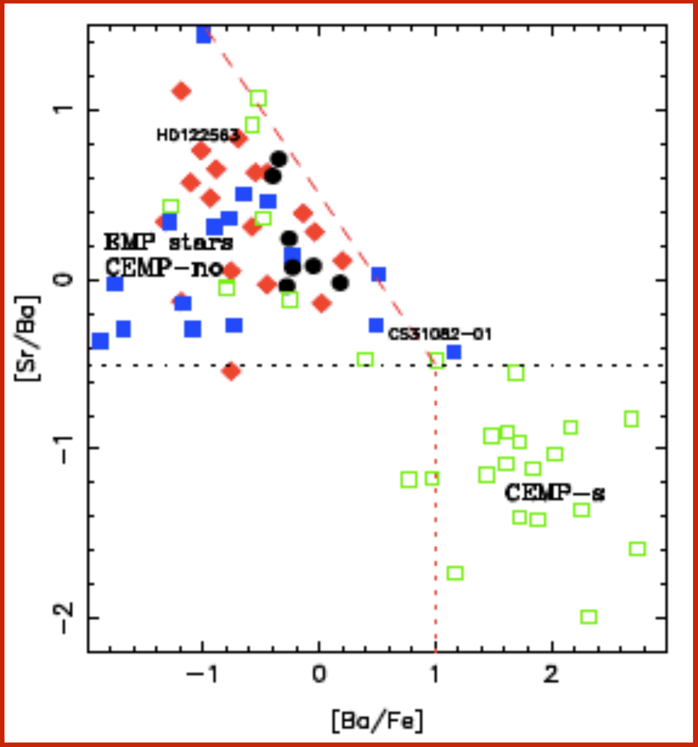
CEMP stars

- **CEMP stars: [Fe/H]<-2 ; [C/Fe]> +1.0**
- ~100% at [Fe/H] = -5 (?)
- origin?

From Spite et al 2014



Carollo et al 2011



CEMP-s, CEMP-r, CEMP-sr

CEMP-no

Prototype CEMP-no: CS 22957-027

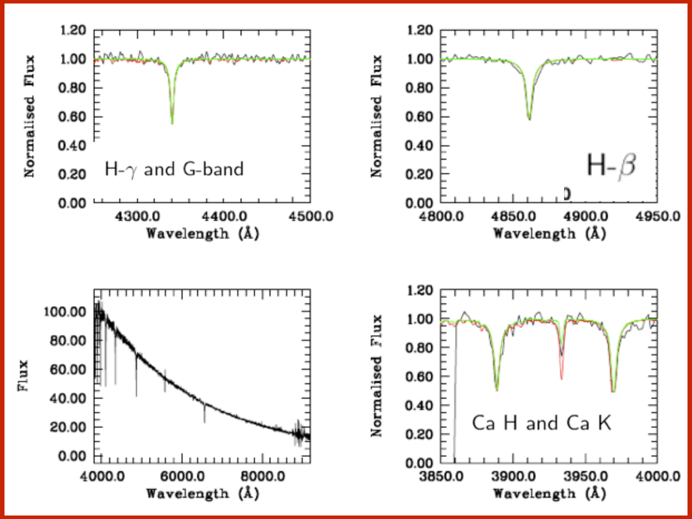
Bonifacio Molaro et al 1998

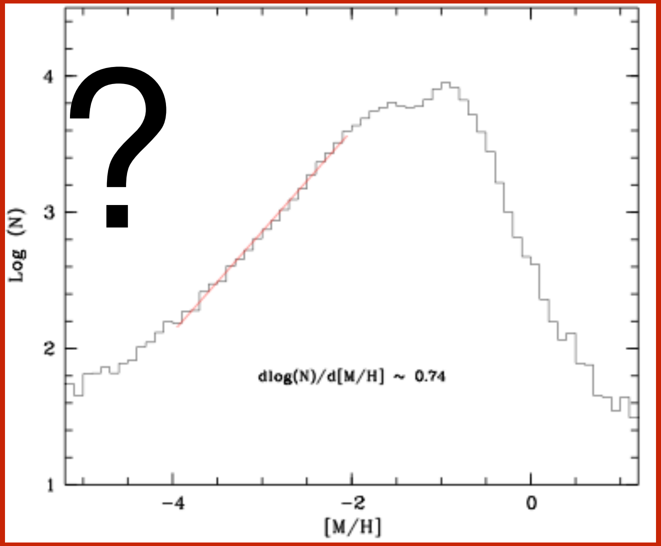
TOPoS in a Nutshell

- **SDSS-R9 pre-selection of 254335 TO stars.**
  - TO stars 0.18 <(g-z)<0.70 (5500 < Teff< 6600)
  - (u-g)>0.7 to exclude HB and White Dwarfs
  - g< 20
- **SDSS spectra (R~2000) metallicities for 182 807**

➡ ~ 750 with [Fe/H] < -3.5

➡ ~ 100 studied at high resolution





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TOPoS HIGHLIGHTS

Caffau et al Nature 2011

Bonifacio et al (2015)

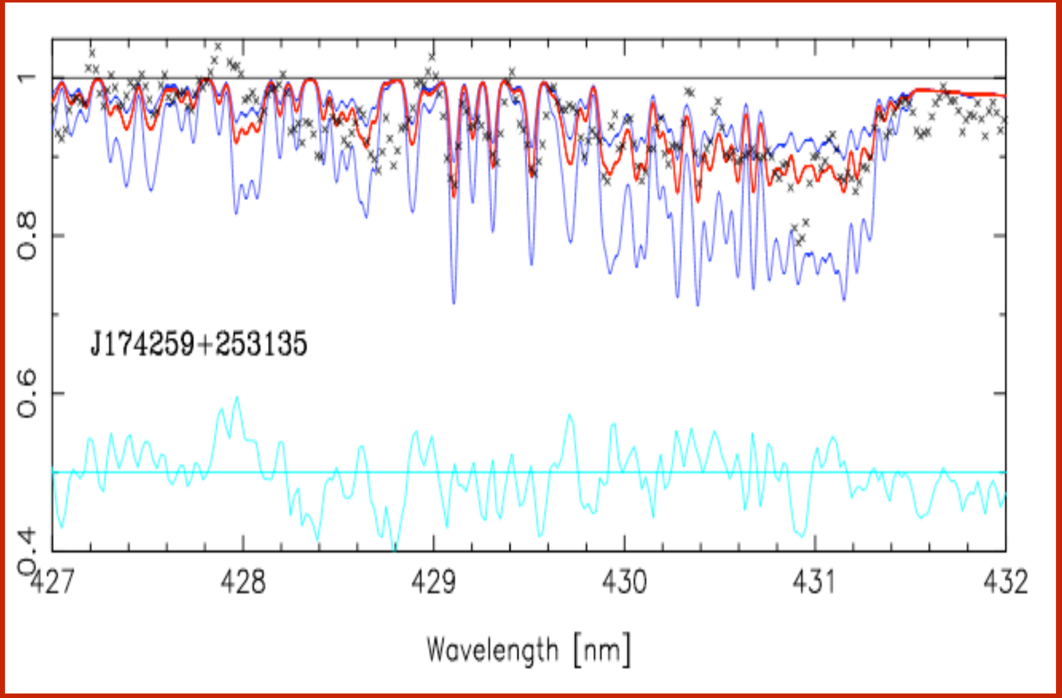
1 EMP stars with [Fe/H] ~ -4.5

2 (3?) CEMP stars with [Fe/H]< -4.5

SDSS1742+2531

$T_{\rm eff}$	log g[a]	ξ^b	[Fe/H]	[Ca/H]
6345	4.0	1.5	−4.80	−4.56

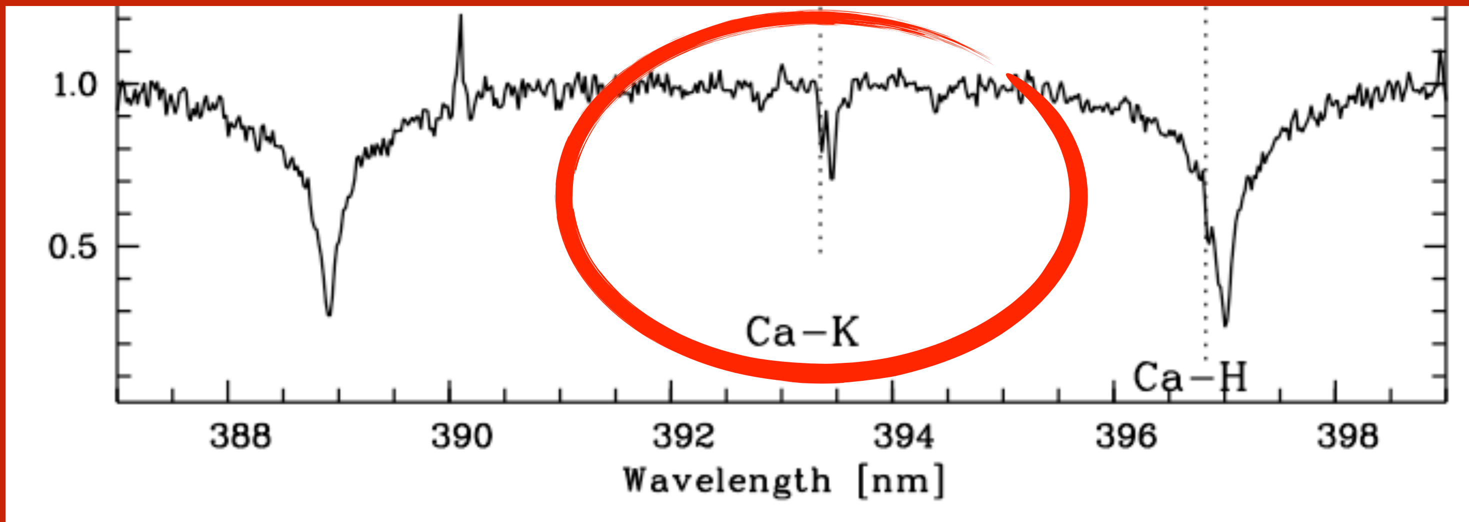
Ion	λ nm	χ eV	log gf	EW pm	A(X)
Li I	6707.761[a]	0.00	−0.009	< 0.83	< 1.8[b]
O I	777.1941	9.15	0.369	< 1.00	< 6.92
Na I	588.9951	0.00	0.117	< 0.90	< 2.14
Mg I	518.3604	2.72	−0.239	< 1.00	< 3.07
S I	921.2863	6.53	0.420	< 1.10	< 4.61
Ca I	422.6728	0.00	0.265	< 1.00	< 1.62
Ca II	393.3663	0.00	0.105	syn	1.79
Ca II	396.8469	0.00	−0.200	syn	1.76
Ca II	854.2091	1.70	−0.514	6.20	1.72
Ca II	866.2141	1.69	−0.770	5.20	1.79
Fe I	382.0425	0.86	0.119	2.40	2.73
Fe I	382.5881	0.92	−0.037	1.90	2.80
Fe I	385.9911	0.00	−0.710	1.90	2.63
Sr II	407.7709	0.00	0.167	< 1.40	< −1.25
Ba II	4554.029	0.00	0.170	< 1.50	< −0.97
Molecular bands					
element	molecule		band		A(X)
C	CH		G-band		7.26



[C/H]= -1.24

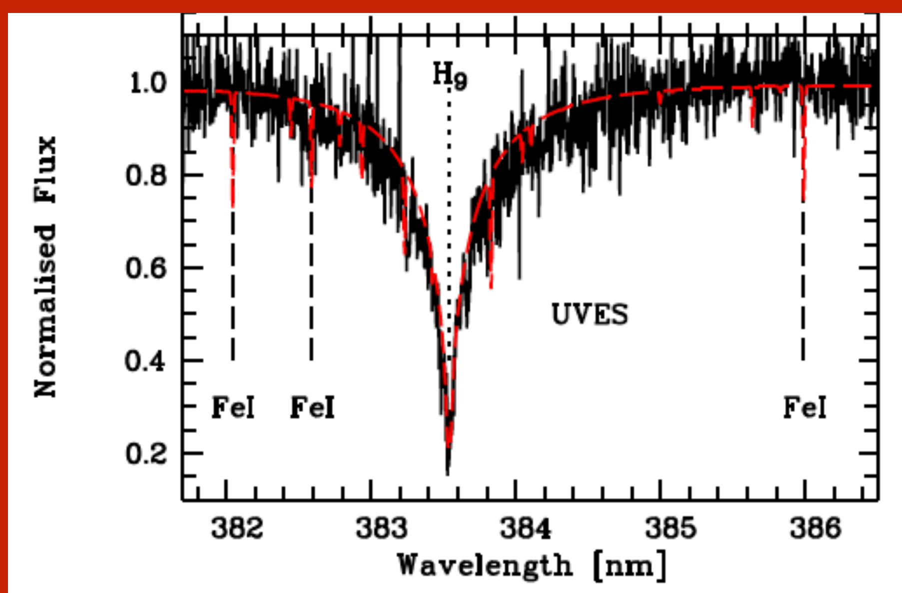
[C/Fe]= +3.5

SDSS J1035+0641



[Ca/H] = -5.0

[C/H]= -1.7



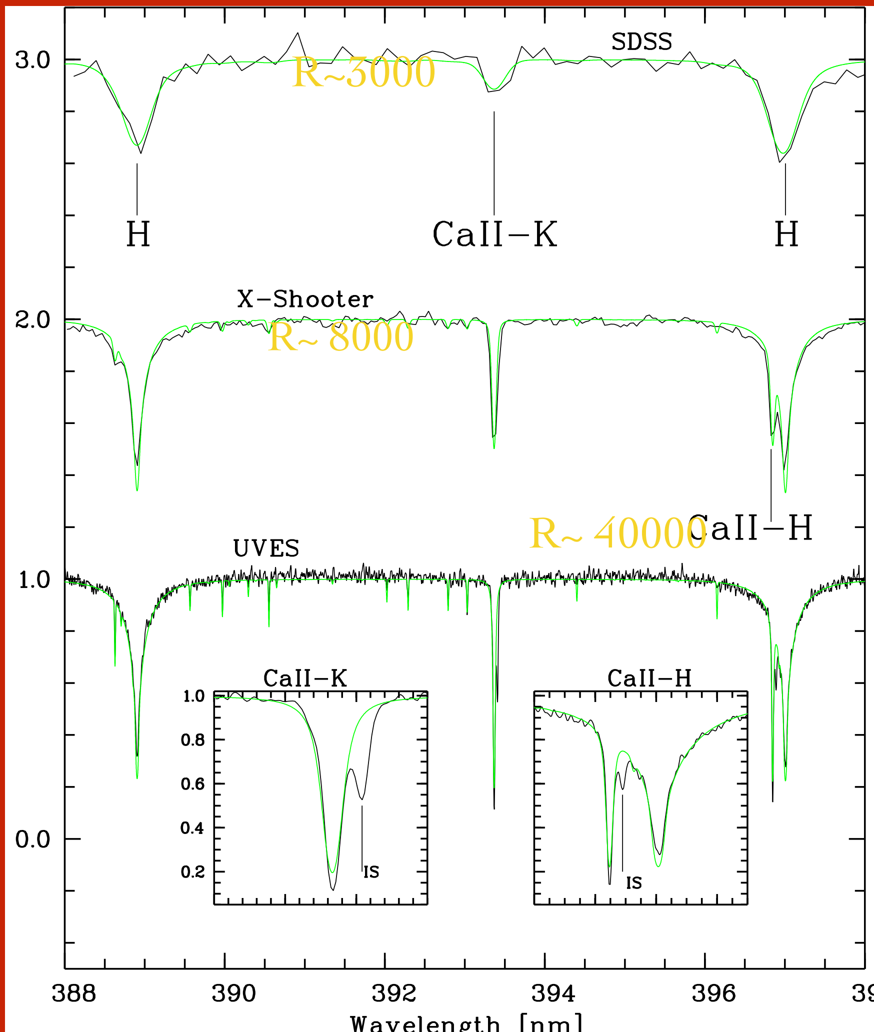
UVES R~37000 11x3000 sec

Fe not measured
[Fe/H]< -4.6

Ca => [Fe/H] ~ -5.3

Caffau et al Nature 2011

SDSS J102915+172927



[Fe/H]~ -5.0 !

[Ca/H]~ -4.8!

Element	$[X/H]_{1D}$	$[X/H]_{3D}$	N lines
C	≤ -3.8	≤ -4.3	G-band
N	≤ -4.1	≤ -4.8	NH-band
Mg I	-4.68 ± 0.08	-4.59 ± 0.10	4
Si I	-4.27	-4.27	1
Ca I	-4.72	-4.80	1
Ca II	-4.71 ± 0.11	-4.85 ± 0.04	3
Ti II	-4.75 ± 0.11	-4.76 ± 0.11	6
Fe I	-4.73 ± 0.13	-4.99 ± 0.12	44
Ni I	-4.55 ± 0.14	-4.88 ± 0.11	10
Sr II	≤ -5.1	≤ -5.2	1

[C/H]~ [N/H] ~ [Fe/H]~ -5

d= 1.27+/- 0.15 Kpc

The most metal poor Z object

Low-mass very metal poor stars exist!

First Stars (PopIII)

- PopIII formed in DM minihalos of ~ 10^6 Msun, at z~20-30 (some 100-200 Myr after BB) (Tegmark et al 1997)

- Primordial gas cooling is from H2, HD (Galli Palla 2013) Minimum Mass to fragment is the Jeans Mass:

$$M_J \simeq 400 M_\odot (T/200\,\mathrm{K})^{3/2} (n/10^4\,\mathrm{cm}^{-3})^{-1/2}$$

- Massive first generation of stars:
  - leaving BH remnant 25< M <140 Msun, or M> 260 Msun
  - PISN 140 < M < 260 => strong odd-even effect

- Any fingerprint? Do they really form?

Low-mass formation

- Small masses requires extra cooling:

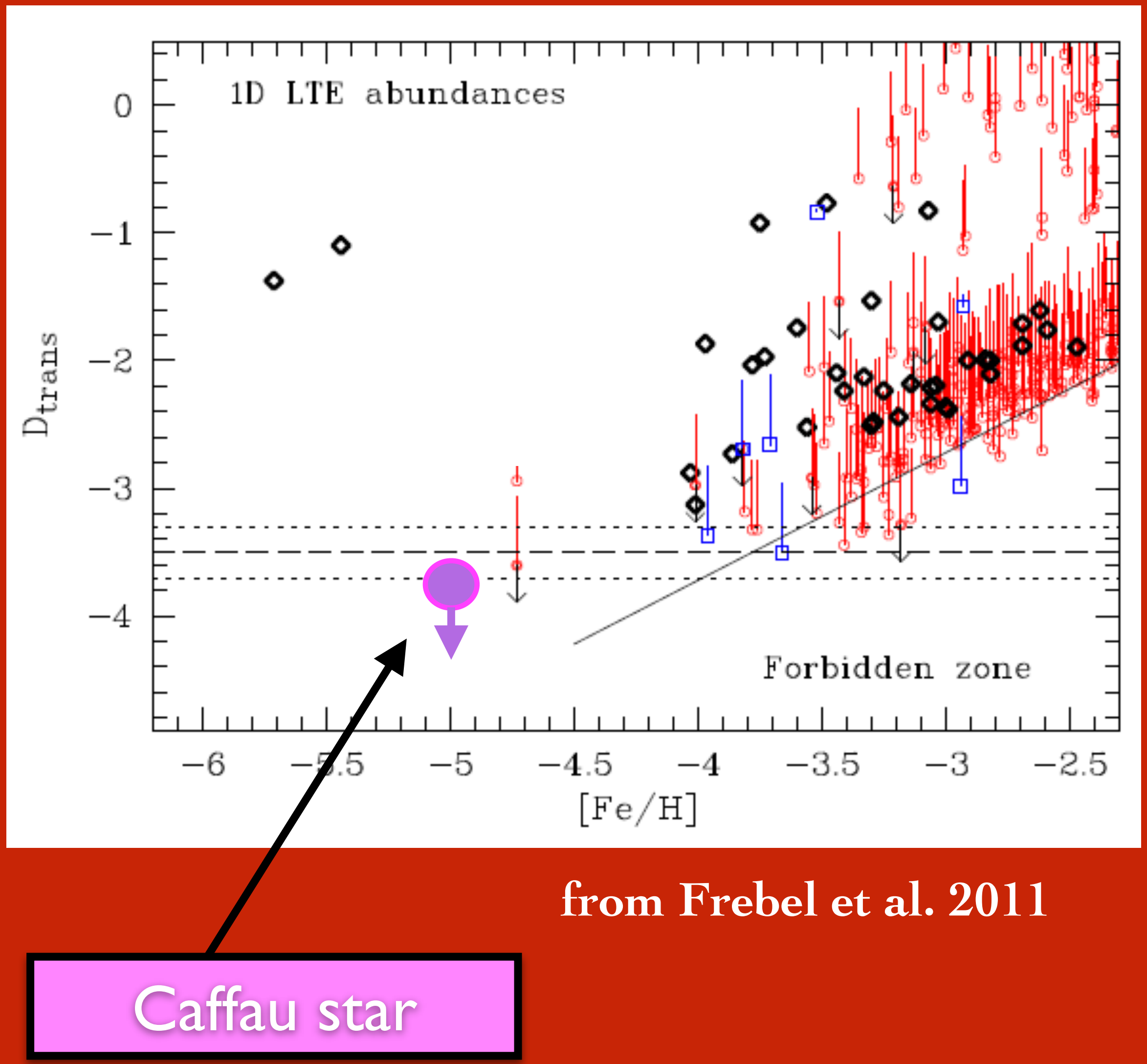
  -CII and OI are the coolants (Bromm & Loeb 2003) (IP CI is 11.26 eV ionized before HI)

- Critical metallicity:

  Radiative Cooling rate > free-fall compressional heating

  ➡ [C/H]c ~ -3.5 ± 0.1

  ➡ [O/H]c ~ -3.05 ± 0.2



from Frebel et al. 2011

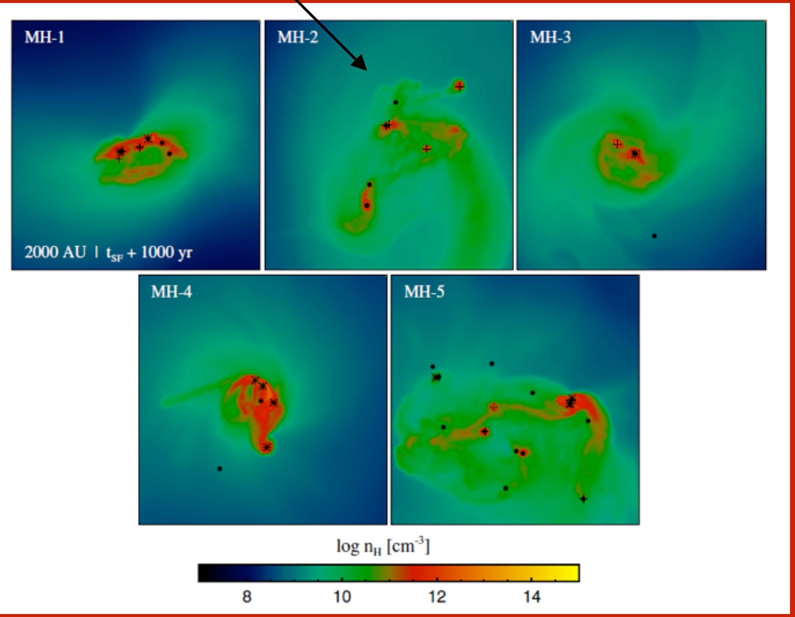
CEMP are above the critical metallicity !
Caffau star is below the critical metallicity !

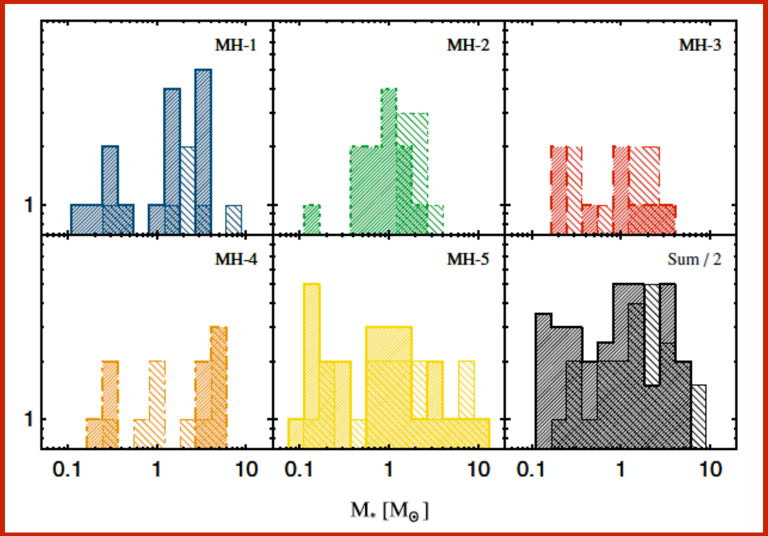
The Caffau star require new mechanisms for mass formation:

- **Fragmentation:**
  possible fragmentation of primordial gas in minihalos induced by turbulence => flat distribution of masses (Clark et al 2008, Greif et al 2011). => PopIII of solar mass??

- **Dust cooling + fragmentation**
  critical metallicity [Z/H]c ~ -5 (Schneider et al 2011)

dots are stars with M< 1 Msun

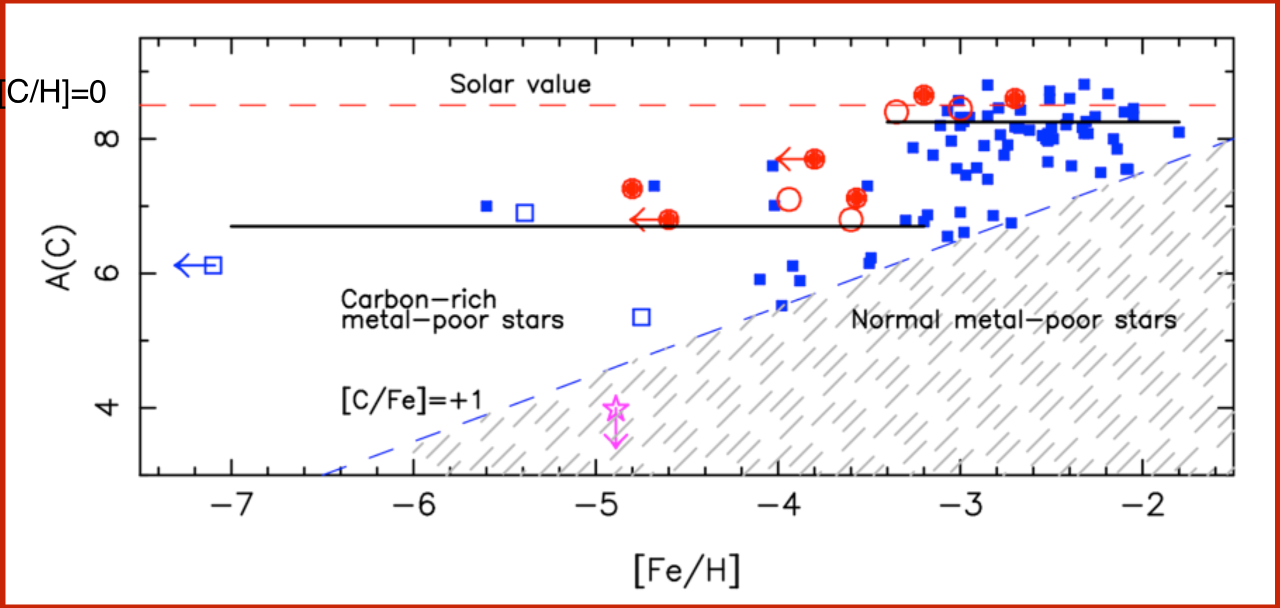


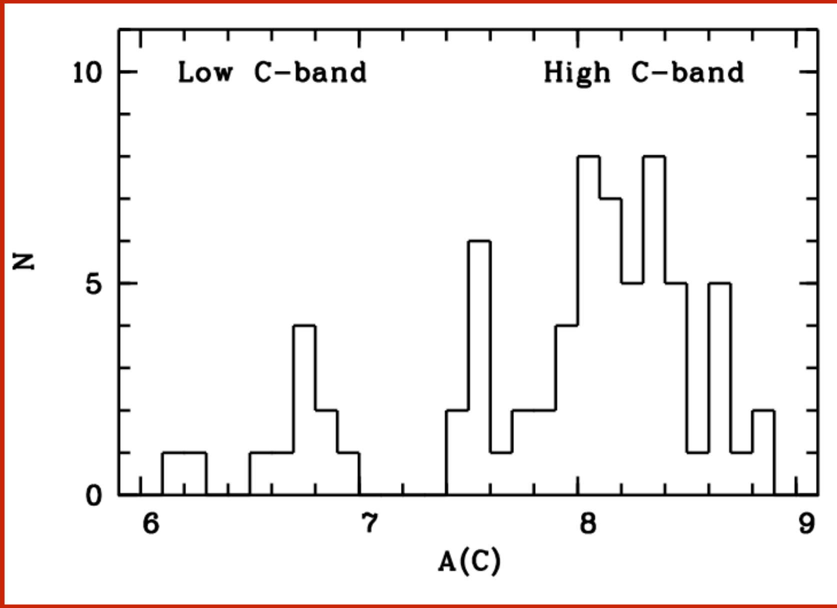


Greif et al 2011

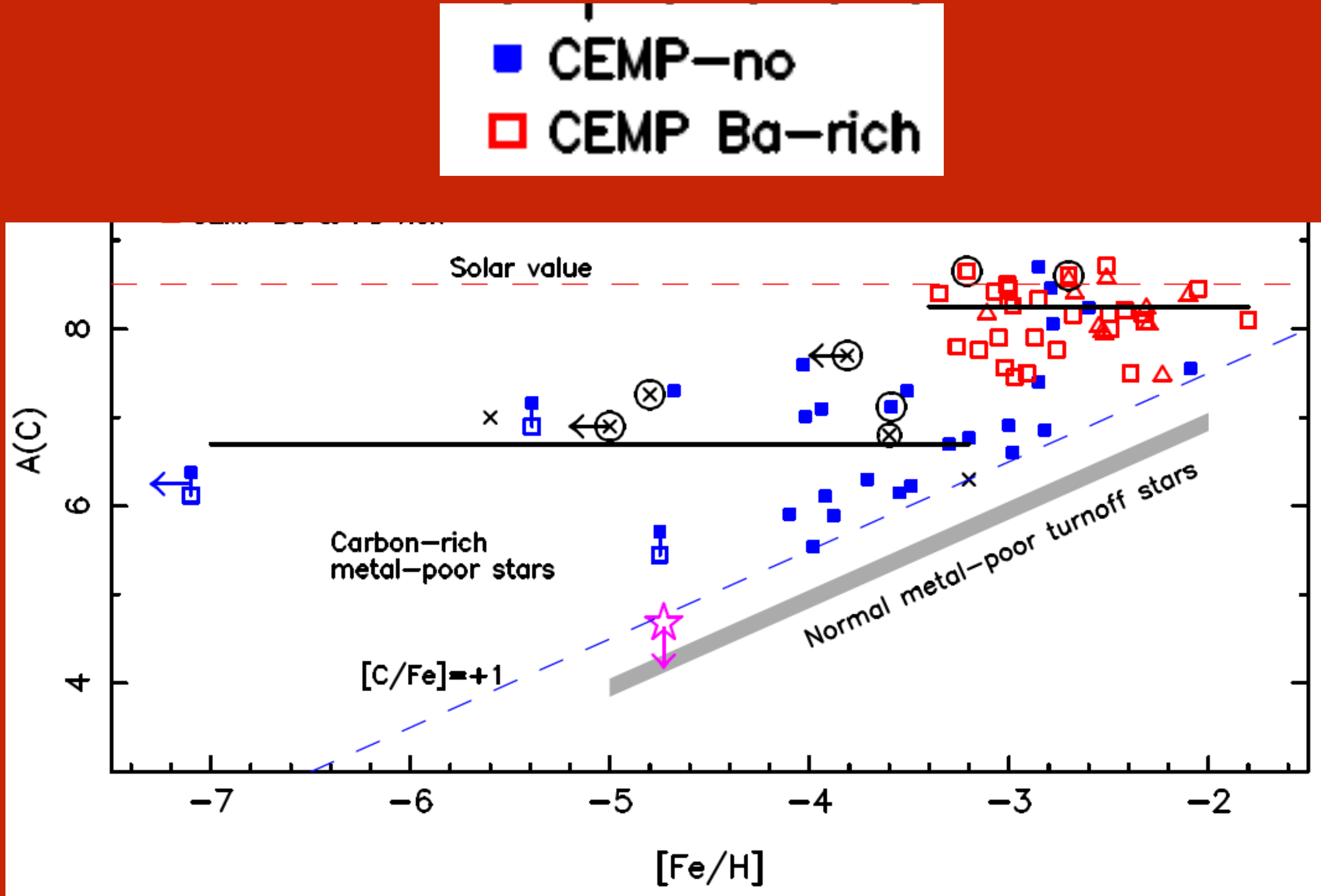
POLLUTERS

The [Fe/H] < -4.5 are "second" generation (PopII).
What about the polluters?





- **Carbon is unrelated to metallicity. Bimodal?**
  ➡ **Two populations: Low-Carbon, High-Carbon** (Spite et al 2013)
  ➡ **The two populations separate at low metallicity**

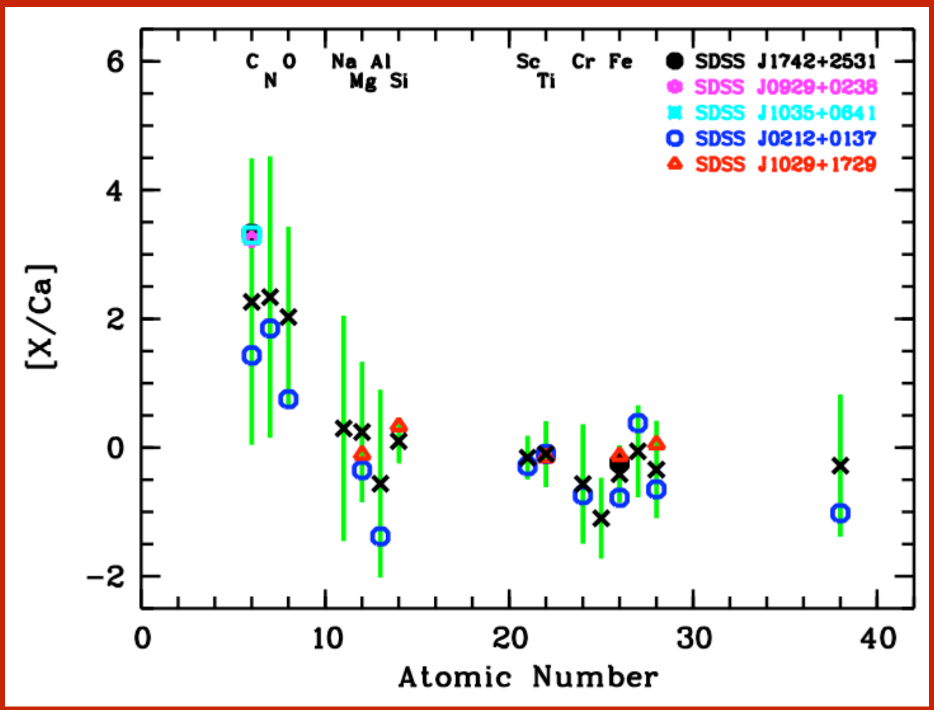


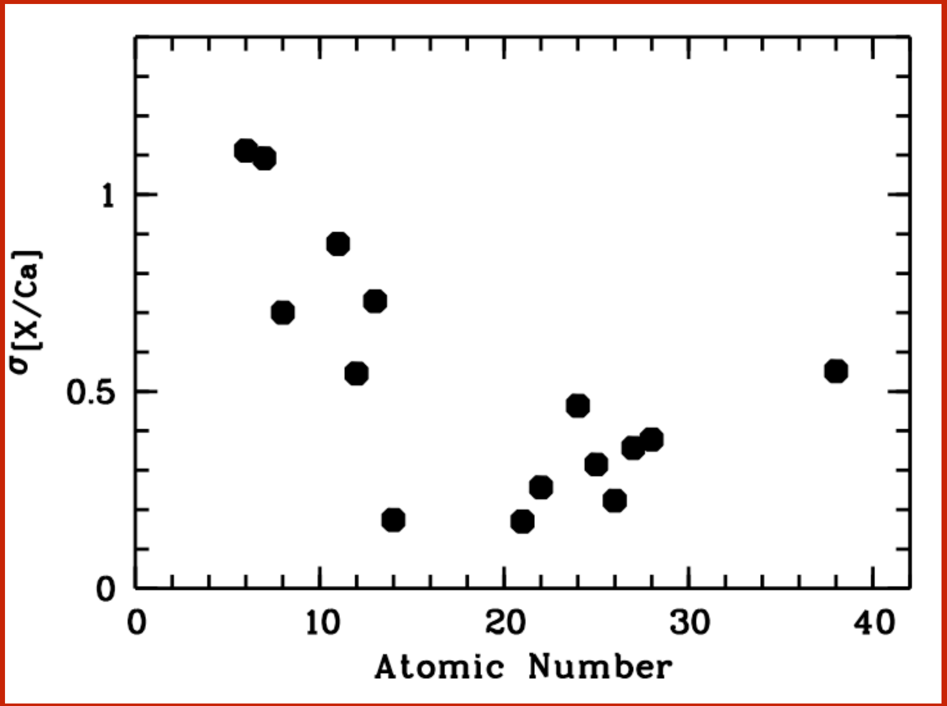
High-C: ~ all CEMP-s. Binaries, s-elements from AGB companion?

(Lucatello et al 2005, Starkerburg et al 2014)

Low-C: all CEMP-no. No binaries, origin?

Chemical abundances relative to Ca





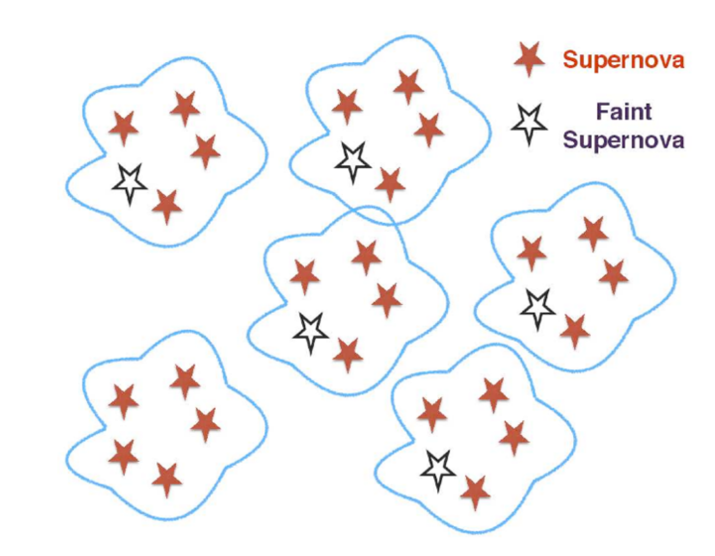
light elements (<Si) are variable
heavy elements (>Si) are ~ constant

Progenitors of CEMP-no?

- **Multiple SNae: Faint SNae + CCSN** (Limongi et al 2003)

  - **Energy ~ 10^{50} erg,**
  - **vel ejecta <1000 km/s,**
  - **Ni_{56} mass ~ 0.001 Msun**

  ➡ **In Faint SNae only most superficial layers are ejected + classical CCSN for the heavier elements**

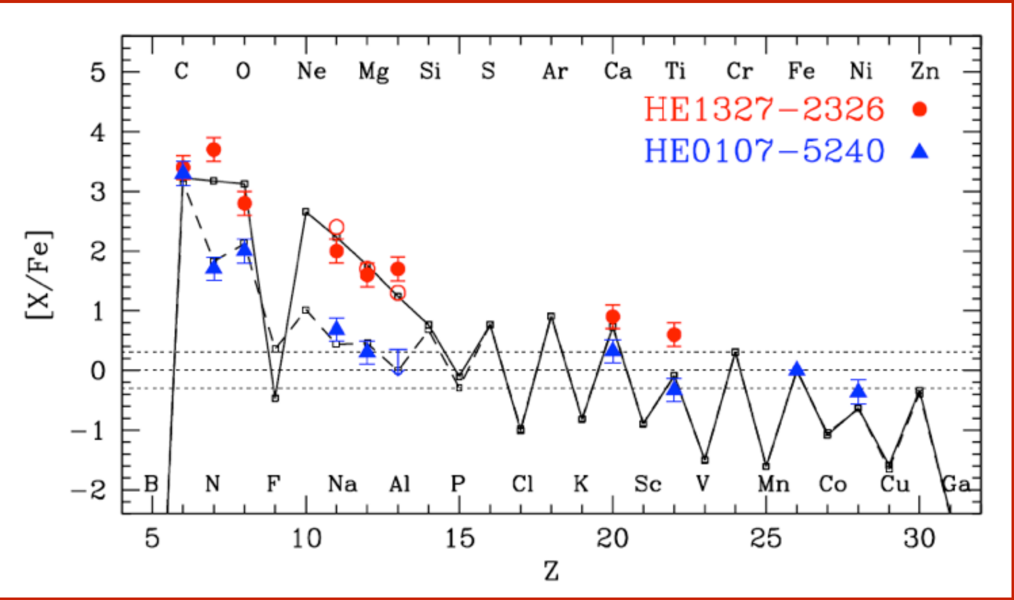


~ Mini-halo model of Cooke e Madau (2014)

- Fall-back models of Nomoto et al (2006)

  ➡ 25 M_{sun}: a large fraction of Fe is falling back onto the BH

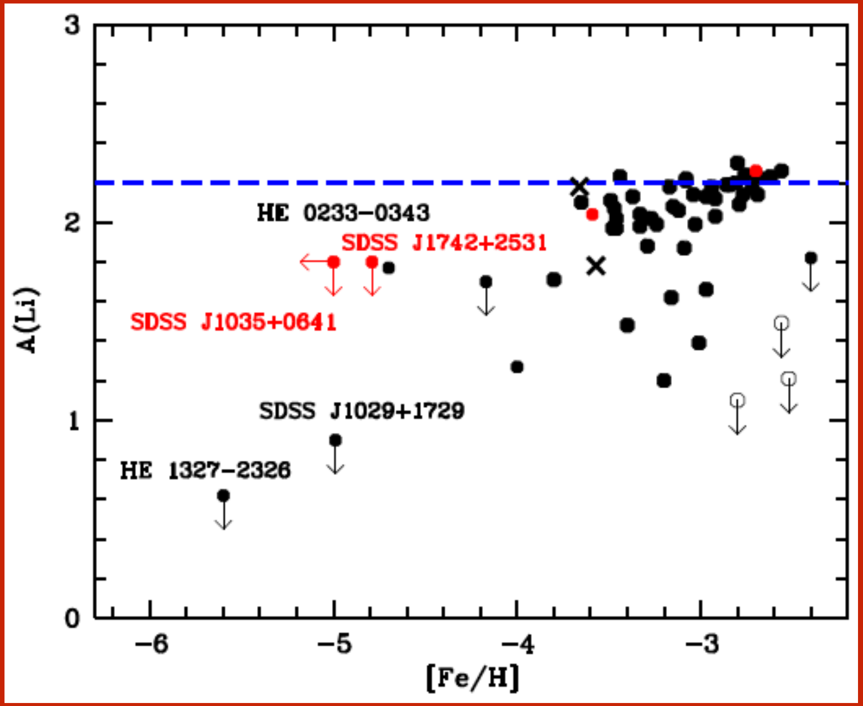
  ➡ henancement of C and light elements

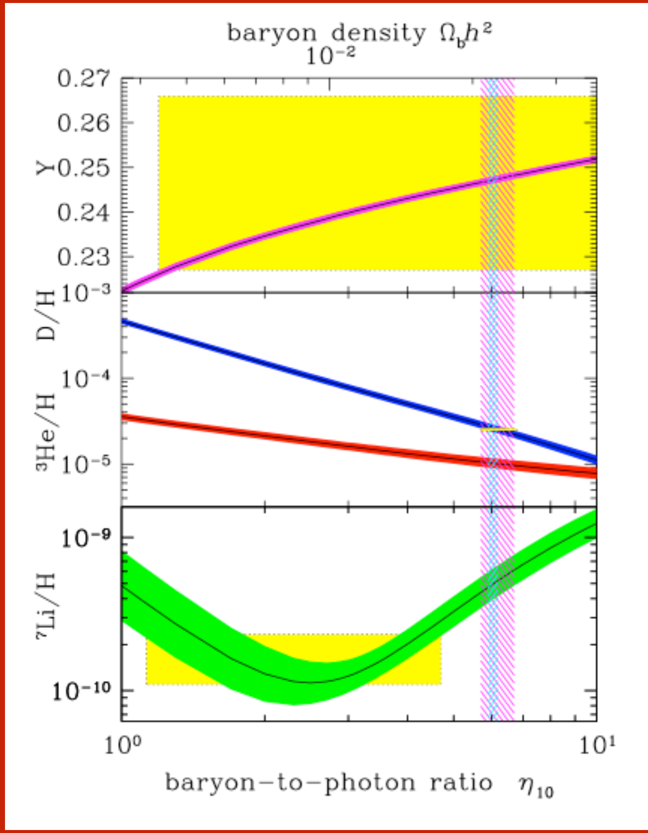


- Rotating Model (Maynet & Meder 2006)

Lithium

5 dwarf stars (4 CEMP & 1 C-normal) have Teff of the Spite plateau but show no Li.





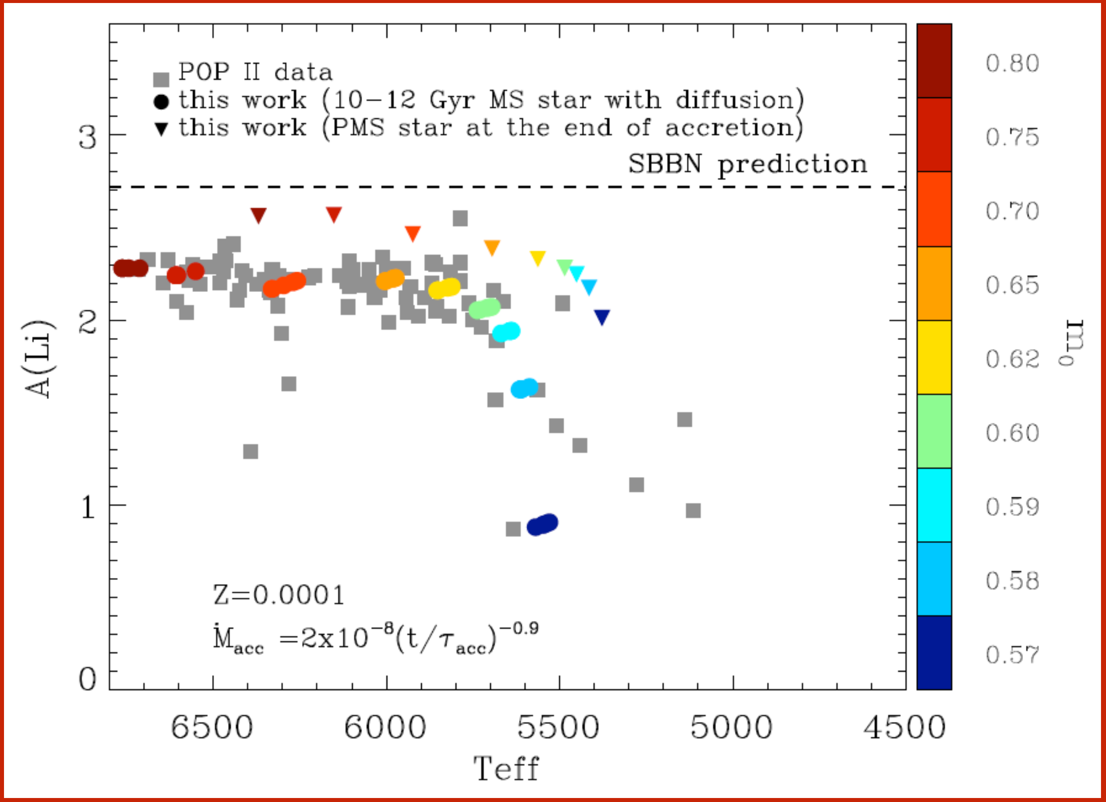
Planck, D/H: A(^{7}Li) = 2.72

"melting" of Li at [Fe/H] ~ -3
(Sbordone et al 2013)

➡ stellar origin of the Li Cosmological problem

New proposal: PreMain Sequence Li depletion and late Li accretion

Fu, Bressan, Molaro, Amico 2016



In CEMP or EMP with [Fe/H]<-4.5 Li could be low because:

- accretion is lower due to the small mass and shorter since the stars are hotter
- PreMS depletion is higher due to the small mass (~ 0.6 Msun)

Conclusions

- our survey successful: 100 stars studied, 3(4) stars with [Fe/H]<-4.5 (30-40%)
- EMP star   with [Fe/H]< -4.5 show that solar masses stars must form also at the lowest metallicity (not expected!).
- Likely two different mechanisms at work: one for the CEMP and one for the "normal" stars
- CEMP-no is the main root for first low-mass stars formation. “normal” metal poor stars exist dawn to [Fe/H]~ -5 (proportion 1:9)
- both   CEMP or normal dwarfs show absence of Li => possible   stellar origin of   the primordial Li problem