TOPoS

TURN-OFF PRIMORDIAL STARS

Paolo Molaro INAF-OATs

TOPoS COLLABORATION

TOPoS

P.I Eliabetta Caffau

Norbert Christlieb, Hans-Günter Ludwig, Simon Glover, Ralf Klessen, Andreas Koch ZAH, Heidelberg - Germany

Matthias Steffen Leibniz-Institut für Astrophysik Potsdam - Germany

Alessandro Chieffi, Marco Limongi, Paolo Molaro, Sofia Randich, Simone Zaggia INAF Italy

Piercarlo Bonifacio, Andy Gallagher, Roger Cayrel, Patrick François, François Hammer, Monique Spite, François Spite GEPI, Observatoire de Paris - France

Bertrand Plez Université de Montpellier - France

Vanessa Hill Université de Nice Sophia Antipolis, CNRS, Observatoire de la Côte d'Azur - France

Lorenzo Monaco Universidad Andrés Bello, Santiago - Chile

Luca Sbordone Pontificia Universidad Católica de Chile, Santiago - Chile

Lyudmila Mashonkina Institute of Astronomy, Russian Academy of Sciences - Russia

MERAC

l'Observatoire de Paris | GEPI

Galaxies Étoiles Physique et Instrumentation

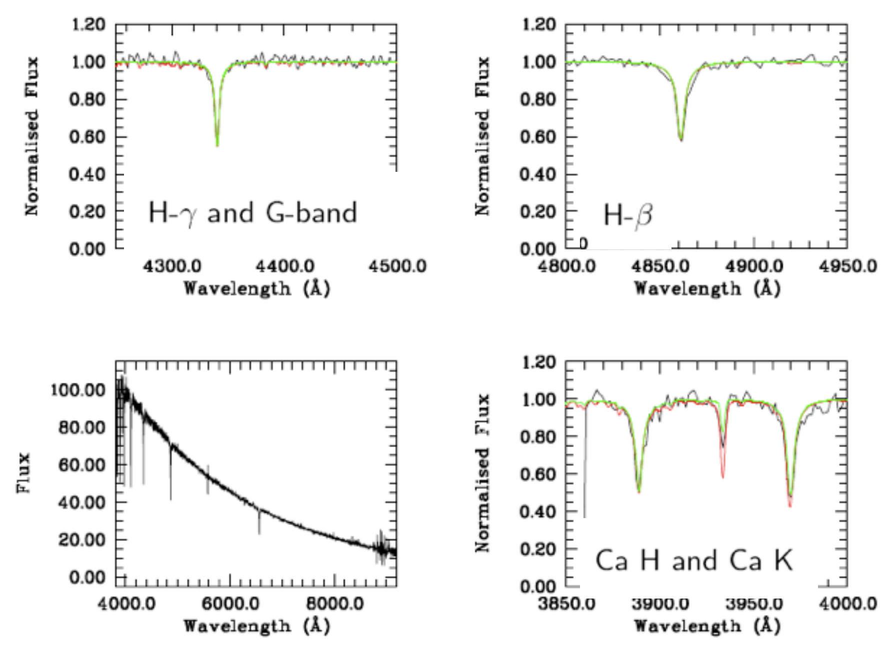
SCIENTIFIC AIMS

- Understand formation of low mass stars in low metallicity gas
  - Do zero-metal low mass stars exist?
  - If not: value of the “critical metallicity”
  - Derive the fraction of C-enhanced extremely metal-poor (CEMP) stars/“normal” extremely metal-poor (EMP) stars
- Lithium and the primordial nucleosynthesis predictions
  - Li abundance (Li destruction?) in EMP stars
- First massive stars
  - Masses of Pop III massive stars from chemical composition of a large sample of EMP stars

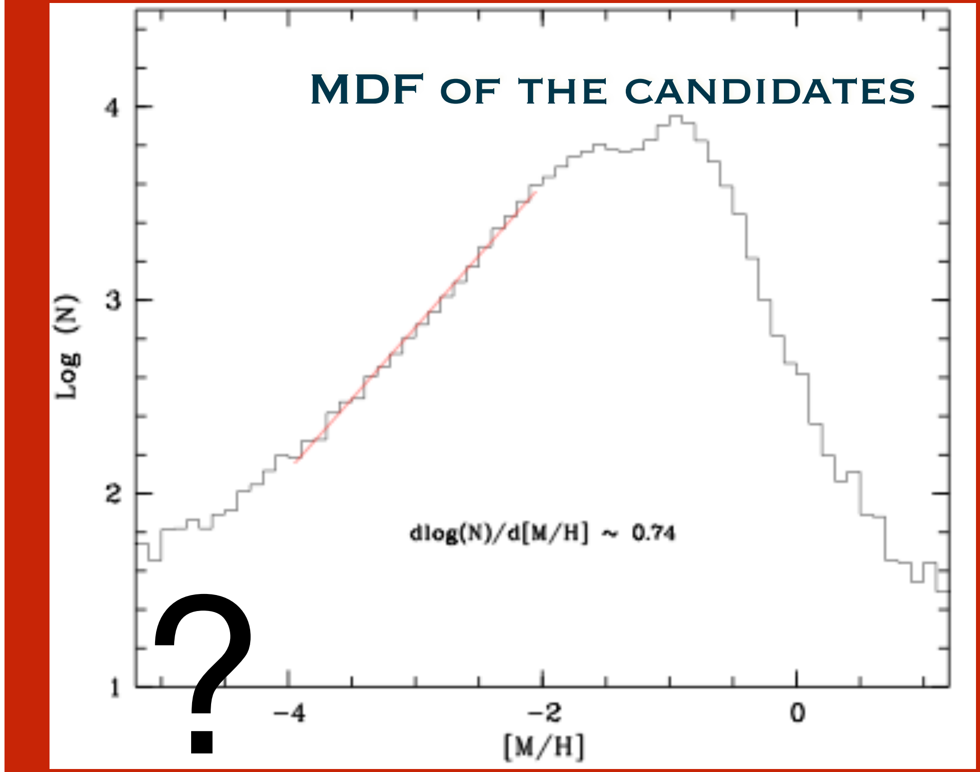
TOPoS in a Nutshell

- From SDSS-R9 pre-selection of **254335 TO** stars (Bonifacio & Caffau 2003) .
    - TO stars 0.18 <(g-z)<0.70 (5500 < Teff< 6600)
    - (u-g)>0.7 to exclude HB and White Dwarfs
    - g< 20
- From SDSS spectra (R~2000) metallicities for **182 807**

➡ **~ 750 with [Fe/H] < -3.5**

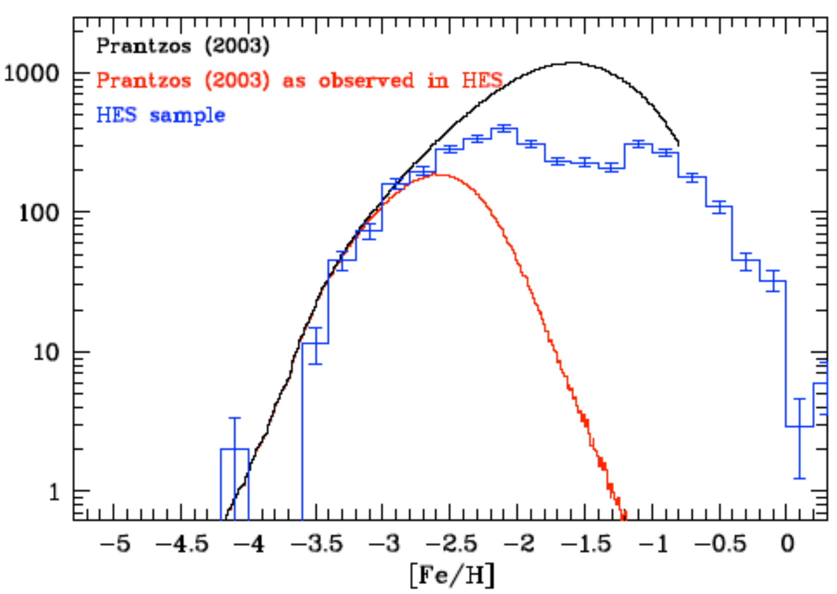


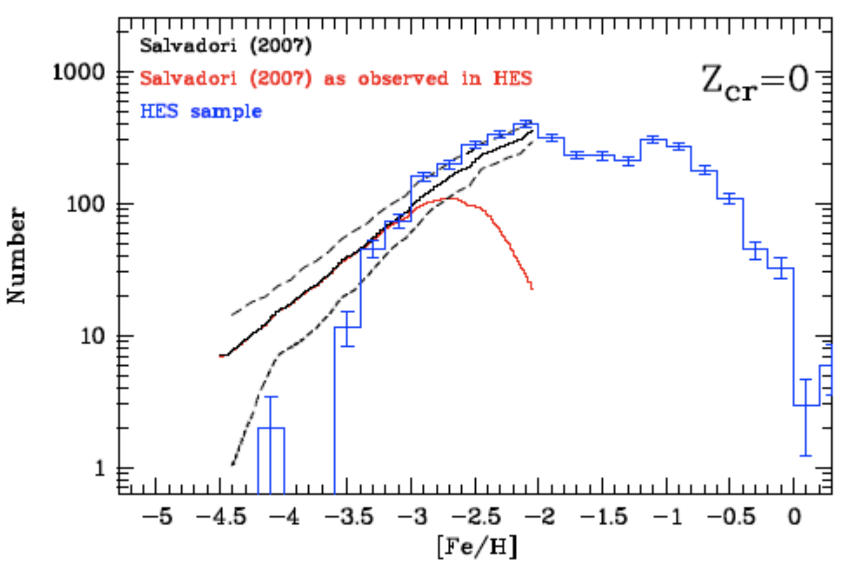
MDF of the candidates



?

never published!





The High Resolution bottleneck

- GTO X-Shooter (2010-2011)
- ESO Large Programme (PI E. Caffau) @ VLT-ESO 4 semesters (2012-2014)
  ➡ 150h: 120h X-Shooter & 30h UVES.
- + 4 approved “normal” programs, 82h UVES
- + 3 nights Subaru

High Resolution follow up:

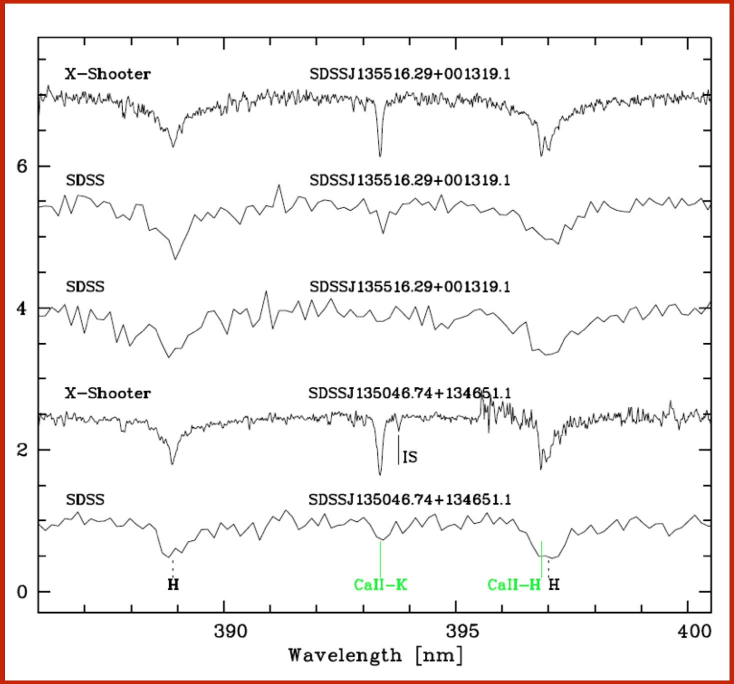
76 stars X-Shooter
30 stars with UVES
4 stars SUBARU

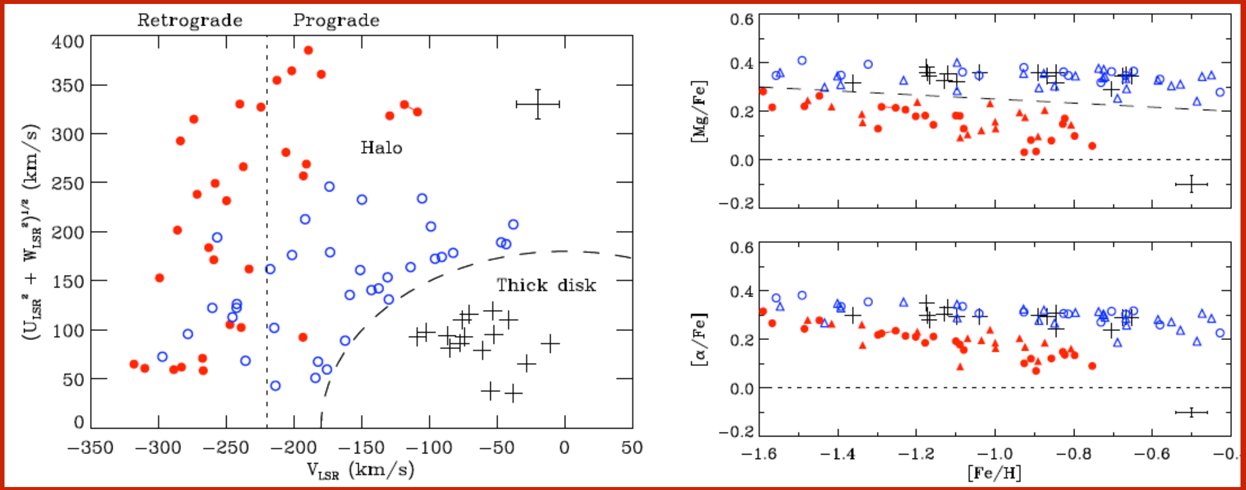
TOPoS HIGHLIGHTS

Bonifacio et al (2010)

- 5 stars X-Shooter (R~10000)
- [Fe/H] ~ -2.5
- but [Ca/H] ~ [Fe/H]: low alpha/Fe

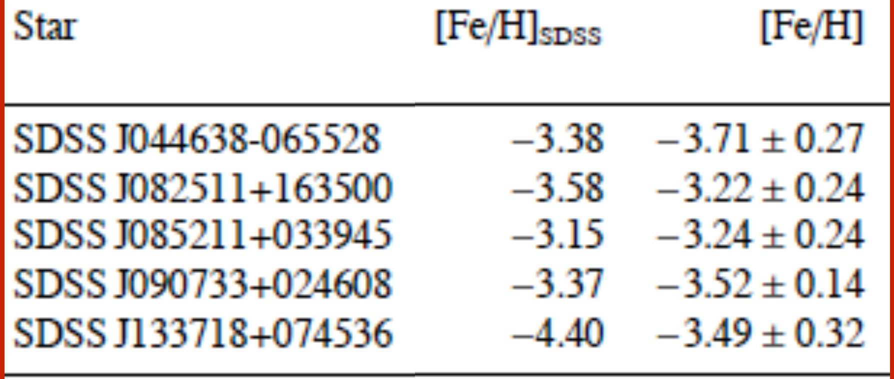
CaII H & K





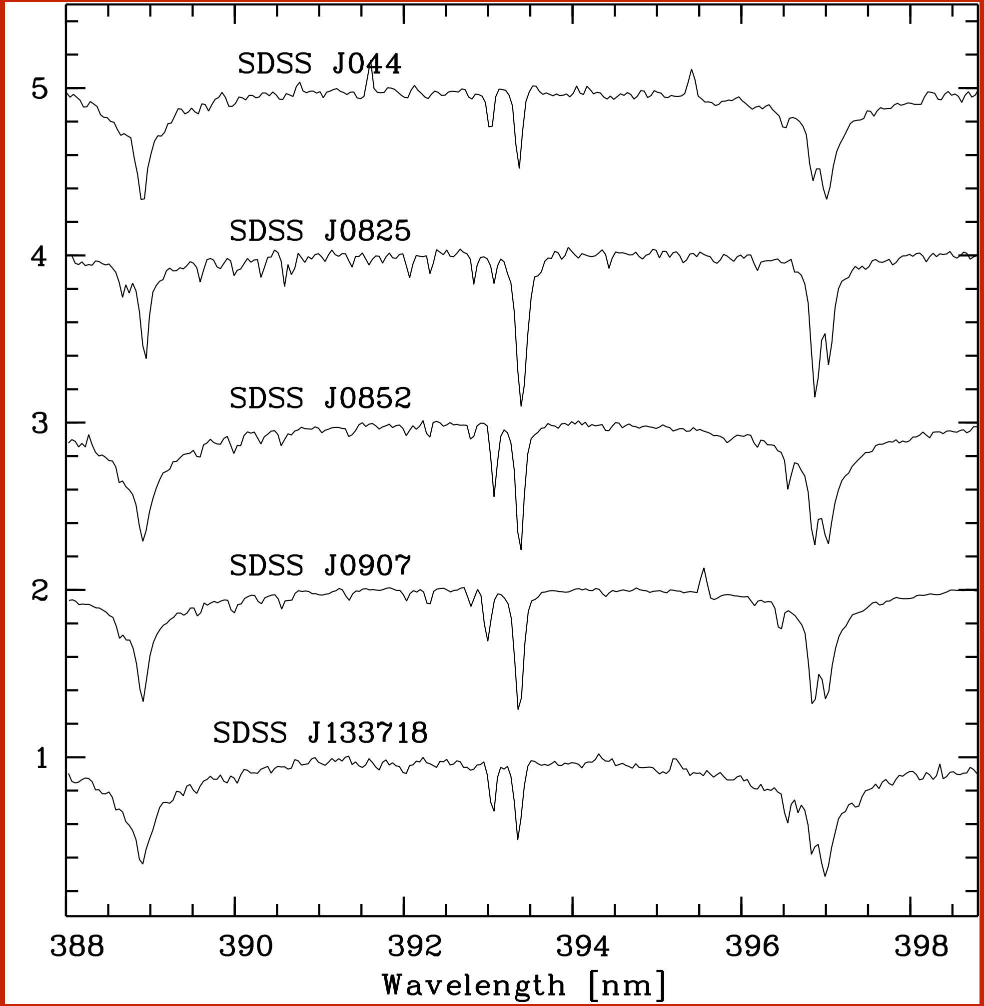
Nissen & Schuster 2010

Caffau et al (2011)



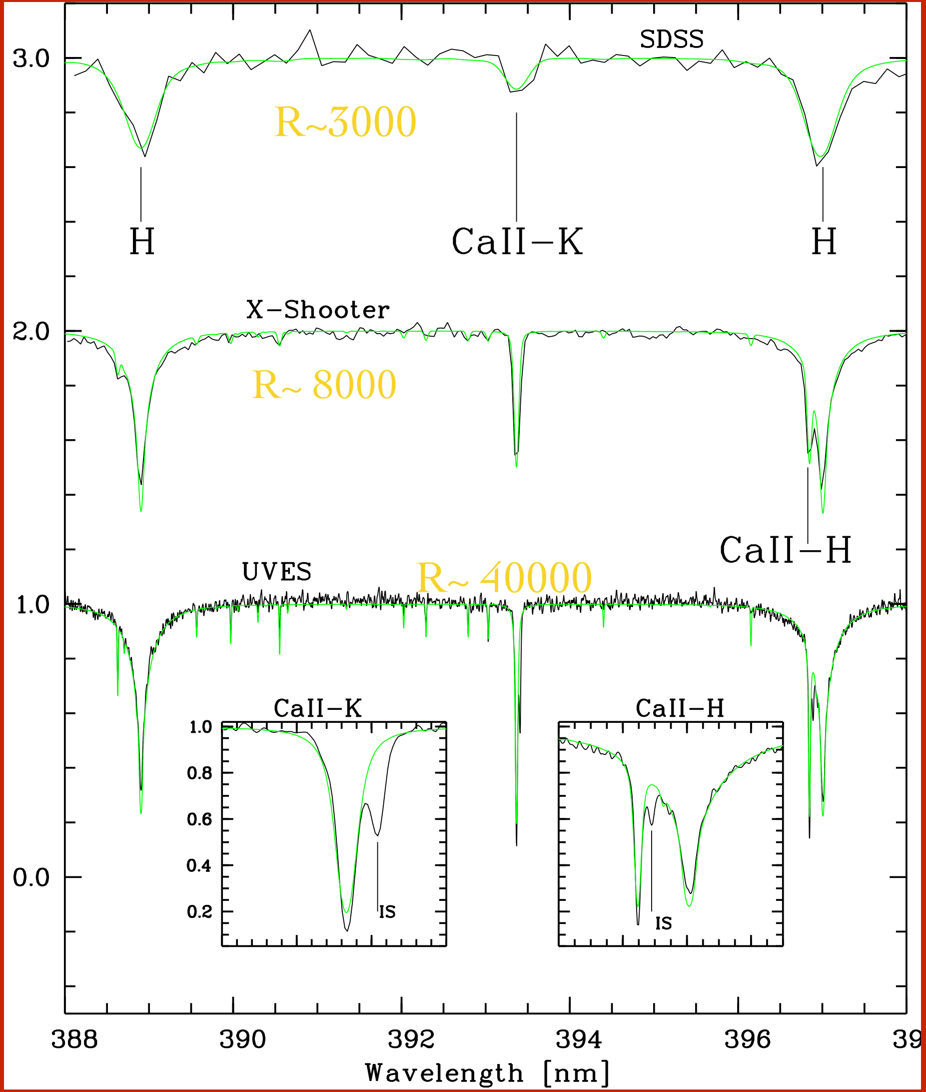
Star	$[Fe/H]_{SDSS}$	[Fe/H]
SDSS J044638-065528	−3.38	−3.71 ± 0.27
SDSS J082511+163500	−3.58	−3.22 ± 0.24
SDSS J085211+033945	−3.15	−3.24 ± 0.24
SDSS J090733+024608	−3.37	−3.52 ± 0.14
SDSS J133718+074536	−4.40	−3.49 ± 0.32

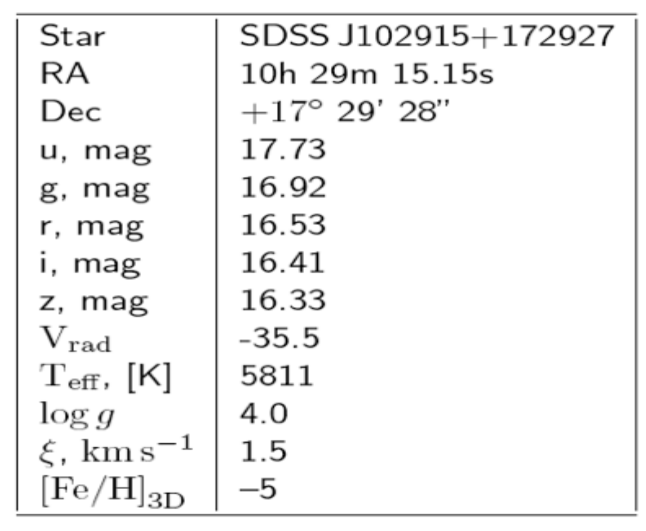
CaII H & K X-Shooter



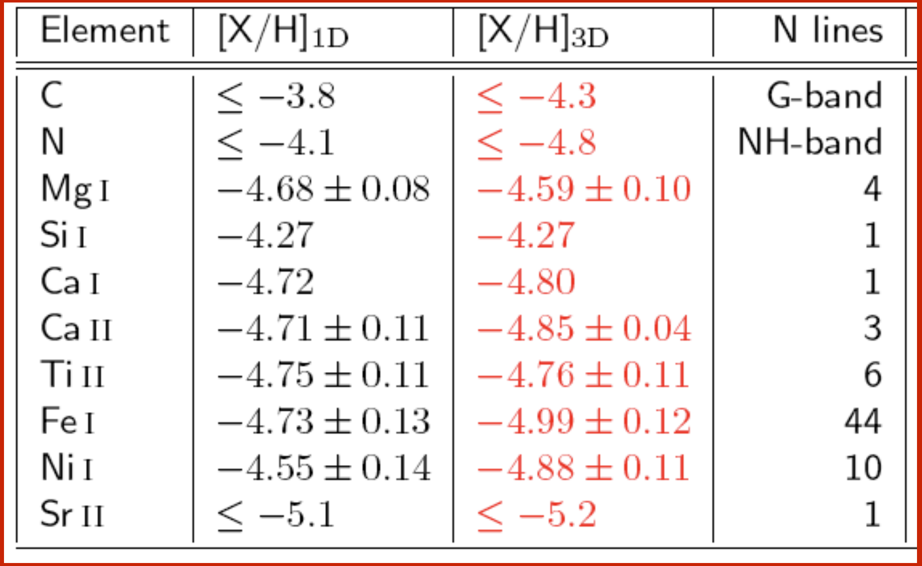
Caffau et al Nature 2011

SDSS J102915+172927





Star	SDSS J102915+172927
RA	10h 29m 15.15s
Dec	+17° 29' 28"
u, mag	17.73
g, mag	16.92
r, mag	16.53
i, mag	16.41
z, mag	16.33
$V_{\rm rad}$	-35.5
$T_{\rm eff}$, [K]	5811
$\log g$	4.0
ξ, $\rm km\,s^{-1}$	1.5
$[\rm Fe/H]_{3D}$	−5



Element	$[\rm X/H]_{1D}$	$[\rm X/H]_{3D}$	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

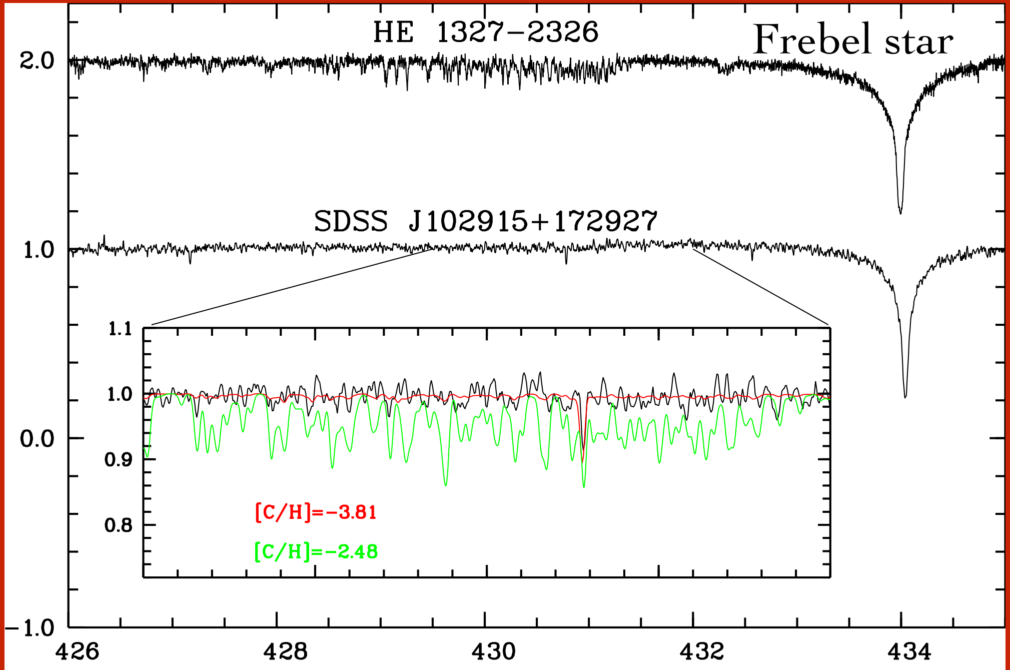
[Ca/H]~ -4.8!

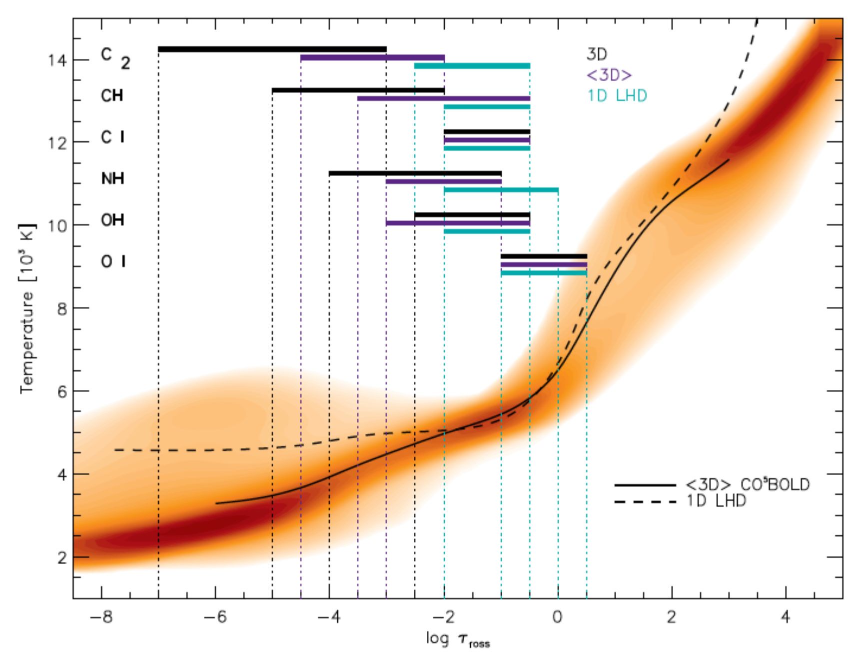
[Fe/H]~ -5.0 !

d= 1.27+/- 0.15 Kpc

carbon

CH: G-band at 430 nm

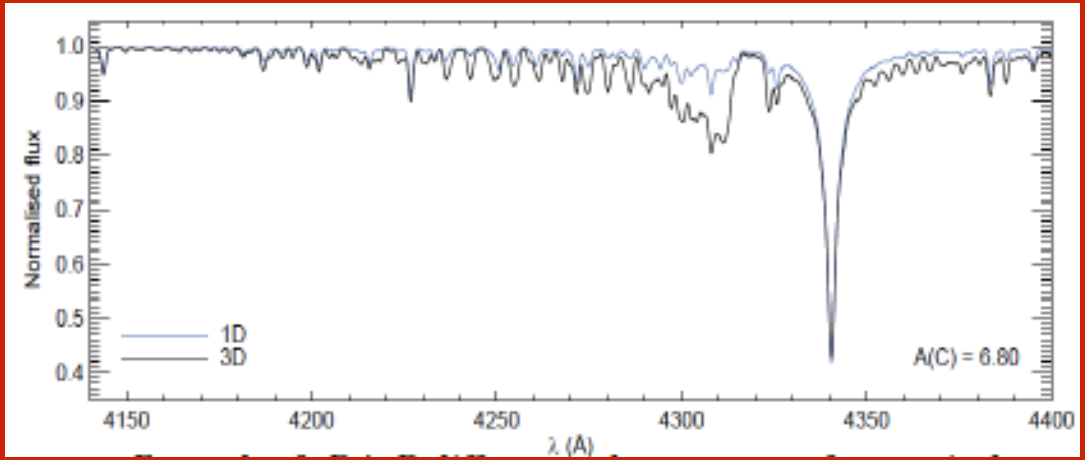




From Behara (2010)

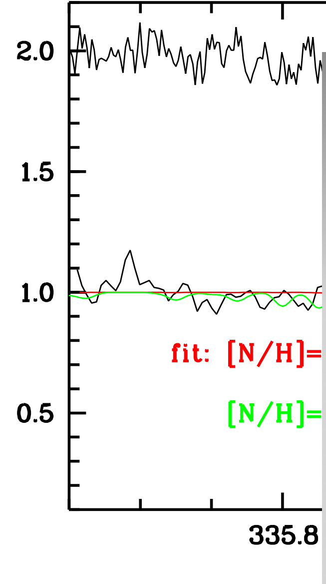
[C/H] < -4.3 (3D)

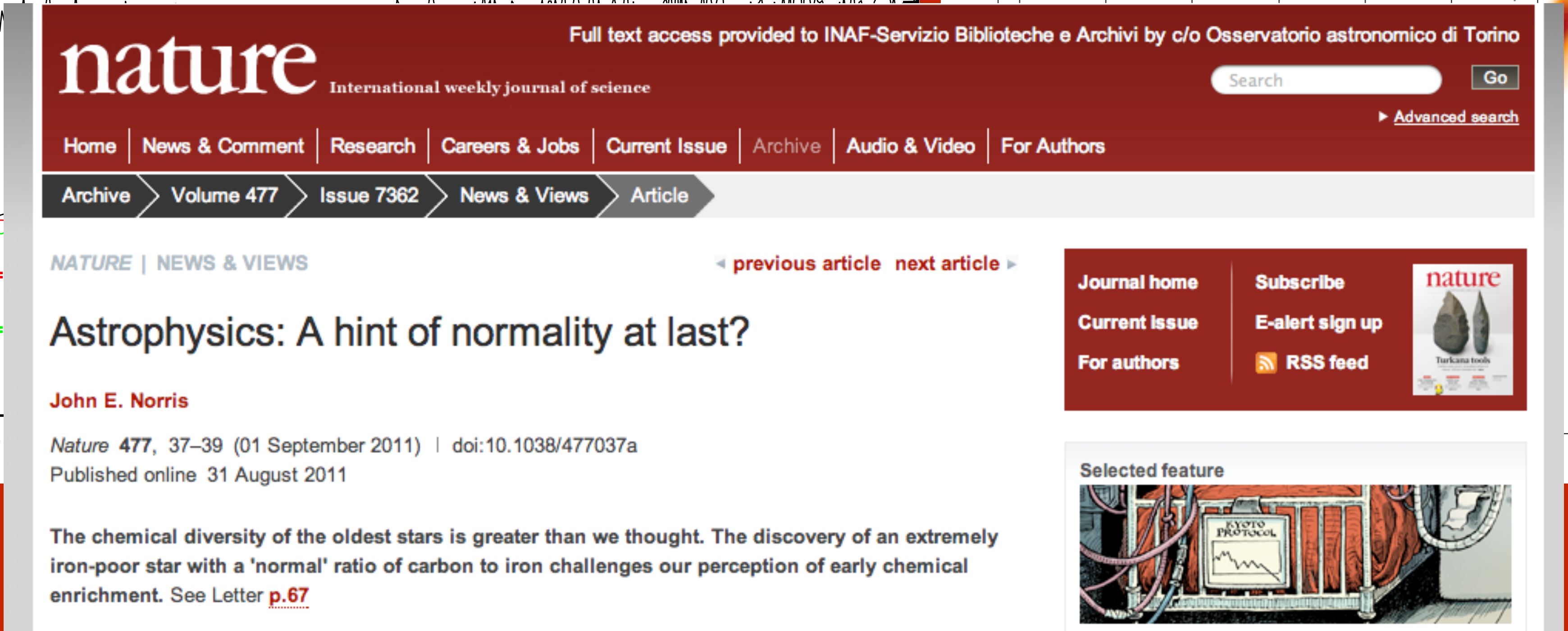
Example of 3D/1D difference for a TO EMP star



nitrogen

NH band at 336 nm,





NATURE | NEWS & VIEWS

Astrophysics: A hint of normality at last?

John E. Norris

Nature **477**, 37–39 (01 September 2011) | doi:10.1038/477037a
Published online 31 August 2011

The chemical diversity of the oldest stars is greater than we thought. The discovery of an extremely iron-poor star with a 'normal' ratio of carbon to iron challenges our perception of early chemical enrichment. See Letter p.67

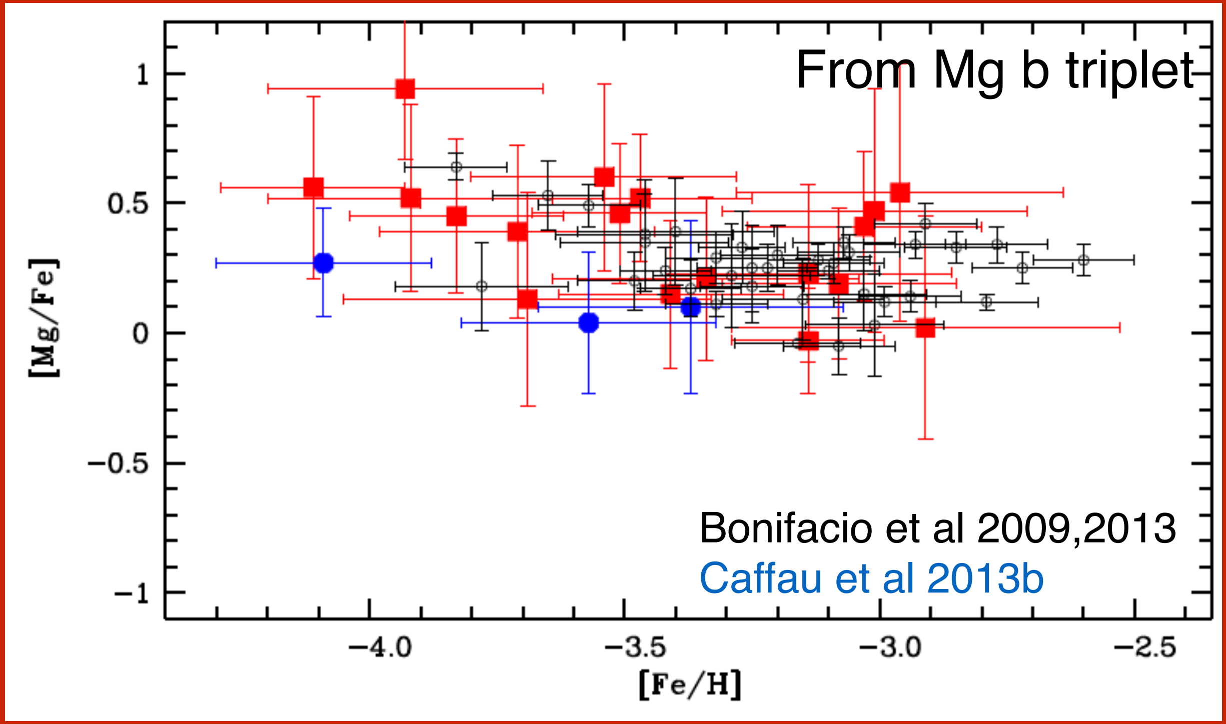
[C/H]~ [N/H] ~ [Fe/H]~ -5

Oxygen?

In terms of Z:
the most metal poor object

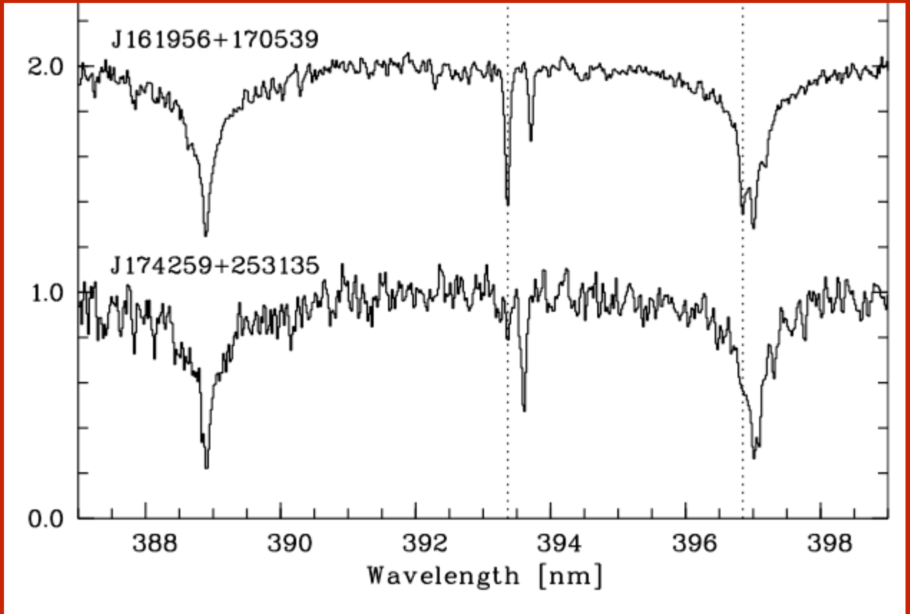
Caffau et al (2013a)

Caffau et al (2013b)



19 stars X-Shooter IFU mode
-4.1 < [Fe/H] <-2.9
SDSSJ1247-0341 [Fe/H] = -4.1
Model atmosferes OSMARCS
Synthetic spectrum

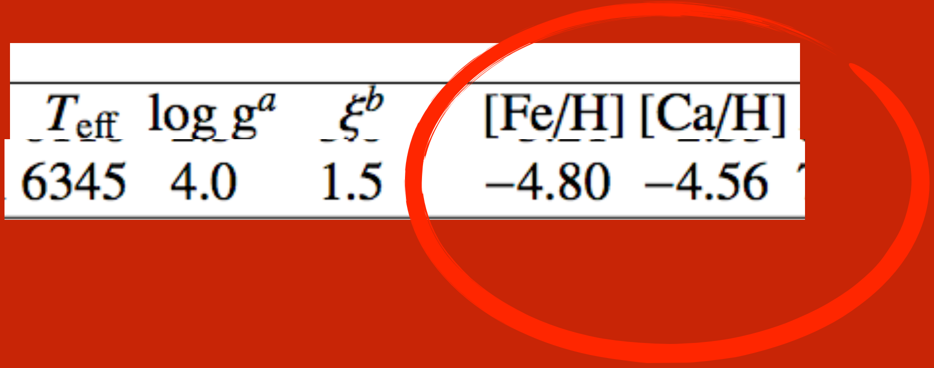
- 4 stars X-Shooter
- [Fe/H] < -3.3
- SDSS1742+2531 [Ca/H]< -4.5



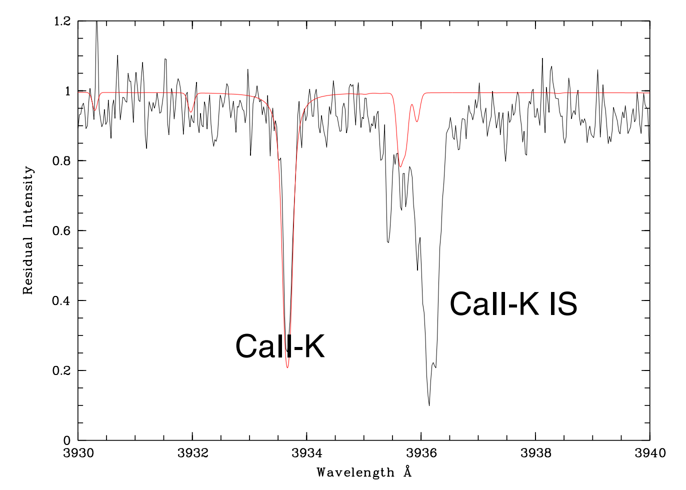
Bonifacio et al (2015)

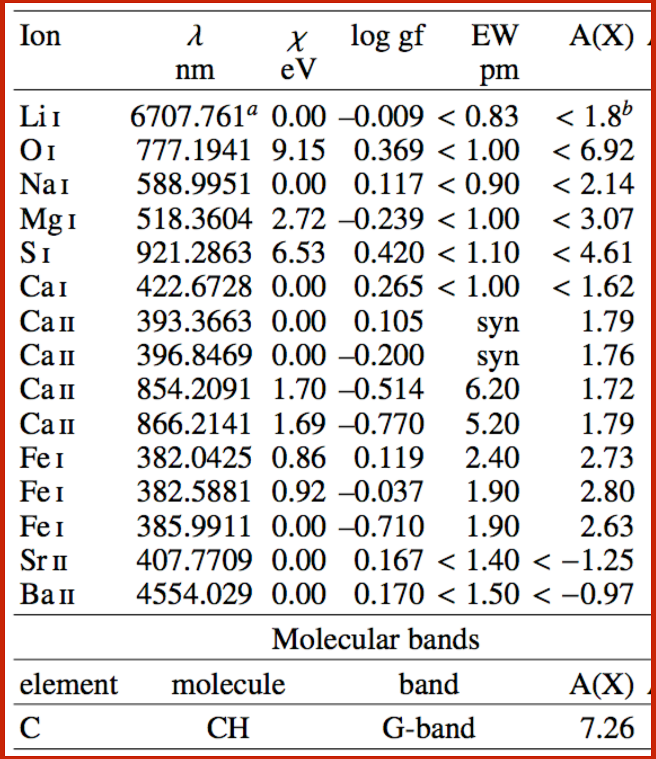
UVES 29x3000 sec exp
R~47000

re-analysis of SDSS1742+2531



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

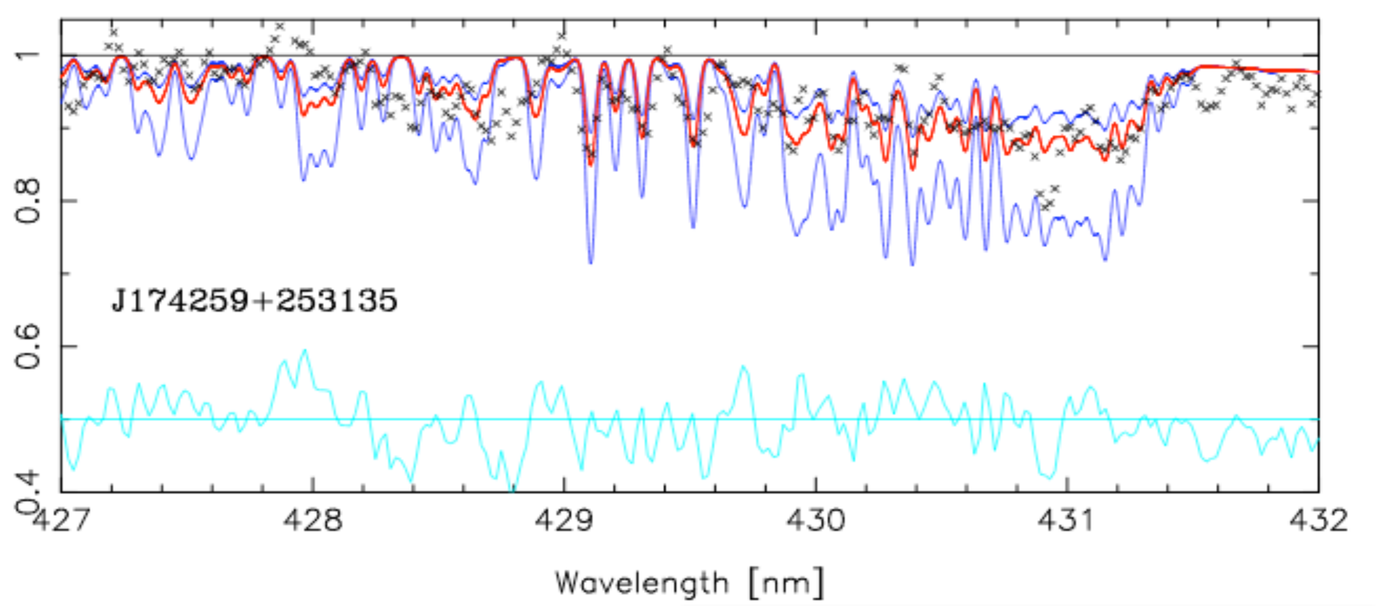




Ion	λ nm	χ eV	log gf	EW pm	A(X)
Li I	6707.761^{a}	0.00	−0.009	< 0.83	< 1.8^{b}
O I	777.1941	9.15	0.369	< 1.00	< 6.92
Na I	588.9951	0.00	0.117	< 0.90	< 2.14
Mg I	518.3604	2.72	−0.239	< 1.00	< 3.07
S I	921.2863	6.53	0.420	< 1.10	< 4.61
Ca I	422.6728	0.00	0.265	< 1.00	< 1.62
Ca II	393.3663	0.00	0.105	syn	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

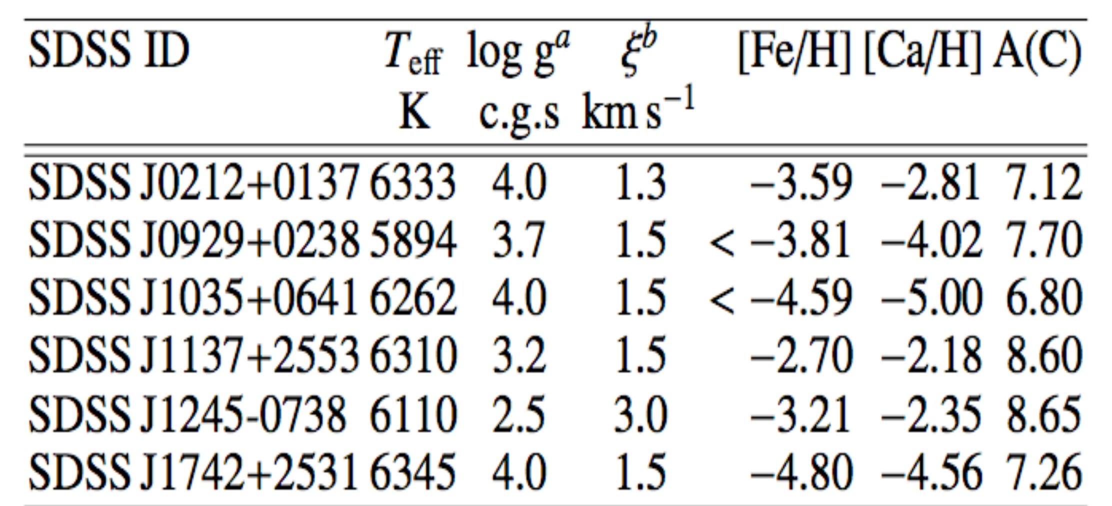
element	molecule	band	A(X)
C	CH	G-band	7.26



[C/H]= -1.24 +/- 0.4

[C/Fe]=3.5

Bonifacio et al (2015)

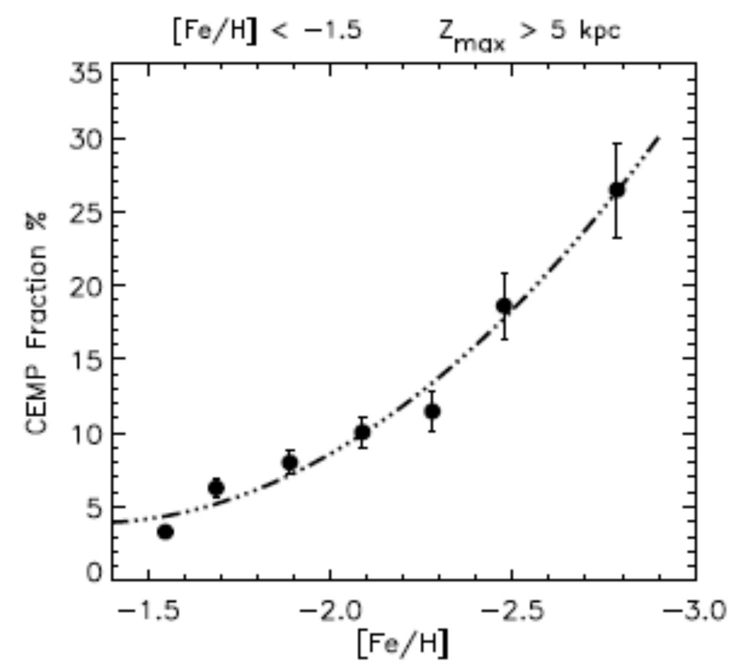


SDSS ID	$T_{\rm eff}$ K	log g^a c.g.s	ξ^b km s^{-1}	[Fe/H]	[Ca/H]	A(C)
SDSS J0212+0137	6333	4.0	1.3	−3.59	−2.81	7.12
SDSS J0929+0238	5894	3.7	1.5	< −3.81	−4.02	7.70
SDSS J1035+0641	6262	4.0	1.5	< −4.59	−5.00	6.80
SDSS J1137+2553	6310	3.2	1.5	−2.70	−2.18	8.60
SDSS J1245-0738	6110	2.5	3.0	−3.21	−2.35	8.65
SDSS J1742+2531	6345	4.0	1.5	−4.80	−4.56	7.26

\+ 5 new CEMP!

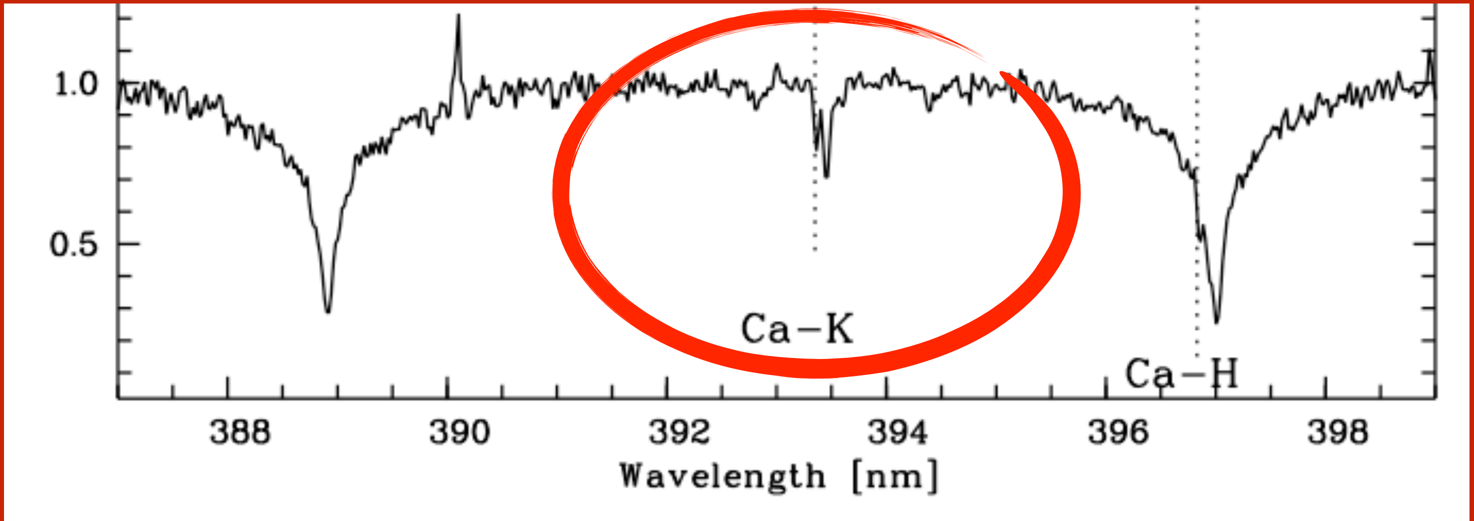
CEMP stars

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



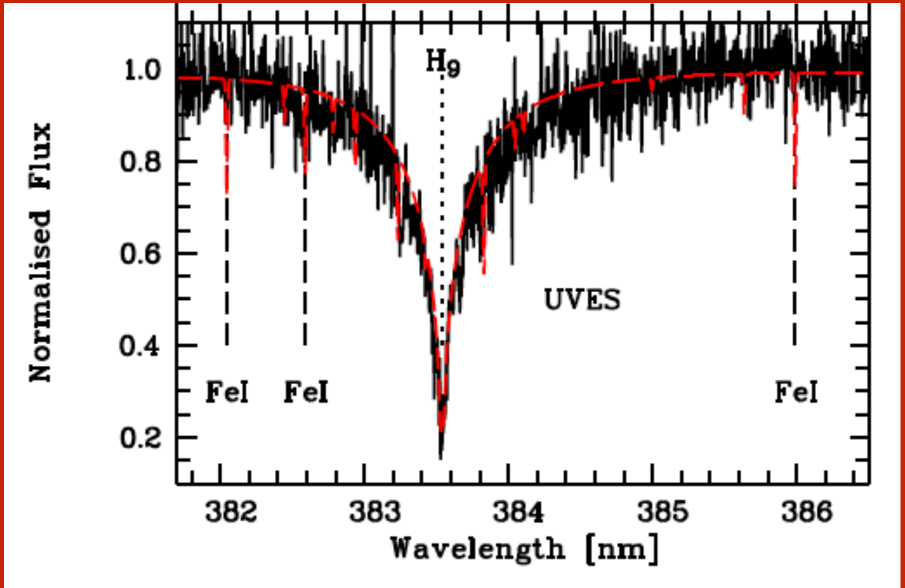
Carollo et al 2011

SDSS J1035+0641



[Ca/H] = -5.0

[C/H]= -1.7



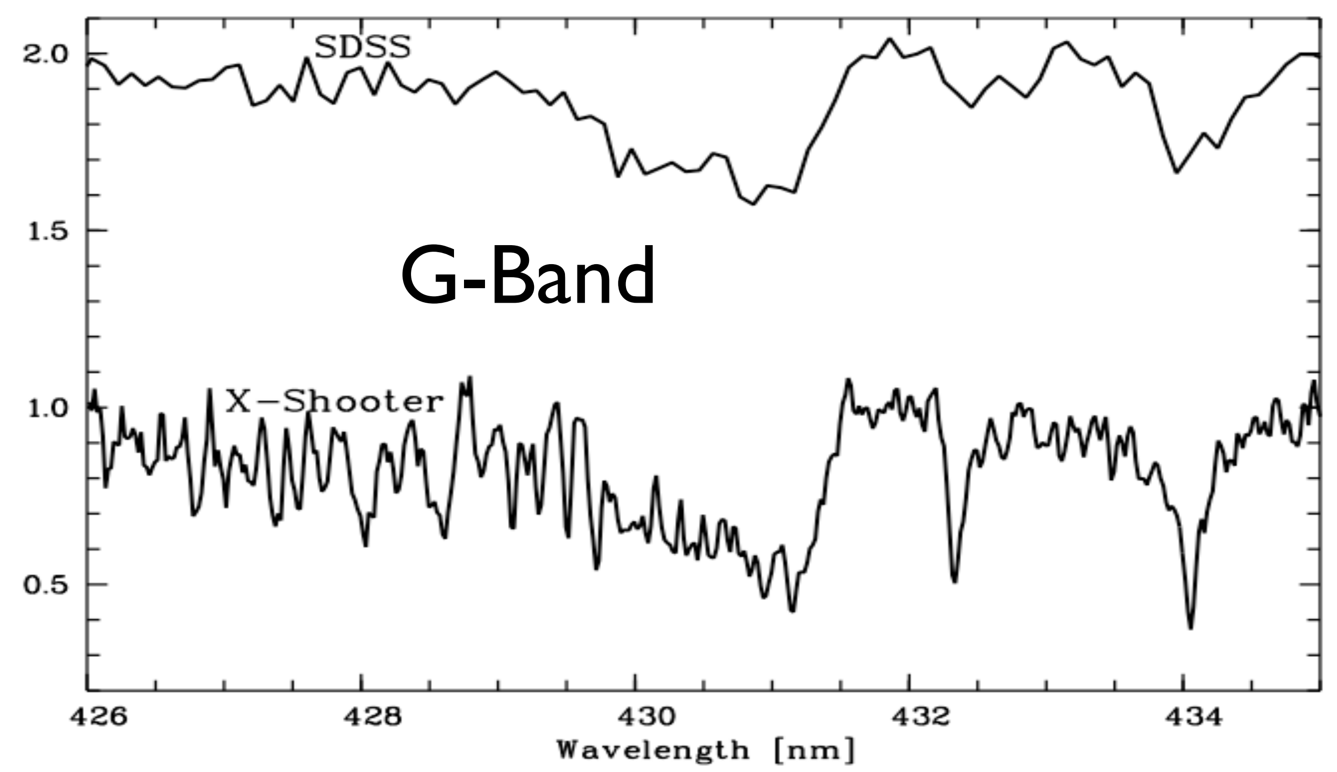
UVES R~37000 11x3000 sec

Fe not measured
[Fe/H]< -4.6

From Ca abundance =>
[Fe/H] ~ -5.3

SDSS J0929+0238

$T_{\rm eff}$	log g
5894	3.7



[C/H] ~ -0.7

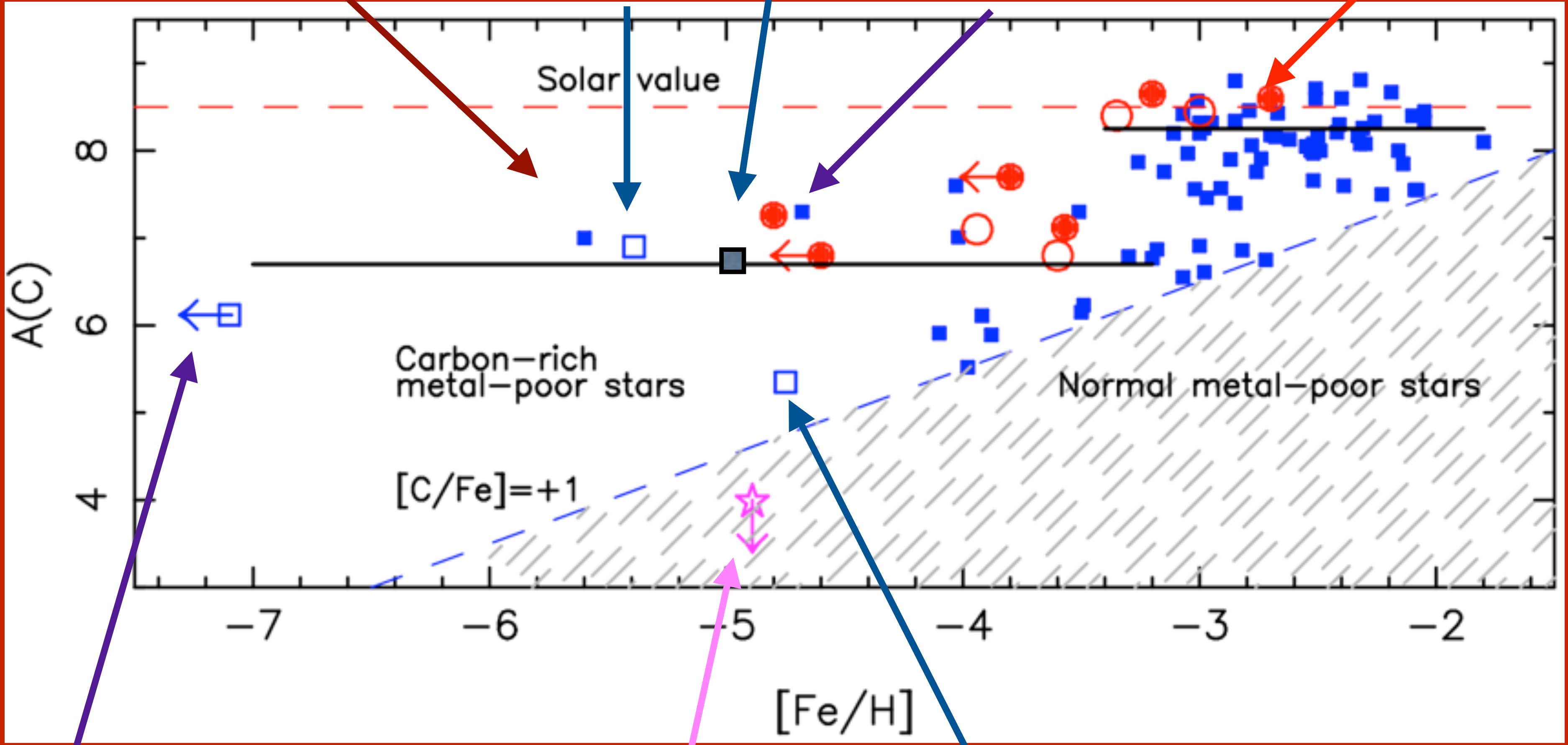
[Ca/H] ~ -4.02

[Fe/H] ? ~ -4.3

[C/Fe] ~ 3

The other are 3 CEMP stars with [Fe/H] ~ -3.0

9 stars with [Fe/H]<-4.5



Christlieb (2001)

Allende-Prieto -Frebel 2015

Frebel et al 2005

Norris (2007)

Bonifacio 2015

Keller et al (2014)

Caffau et al 2011

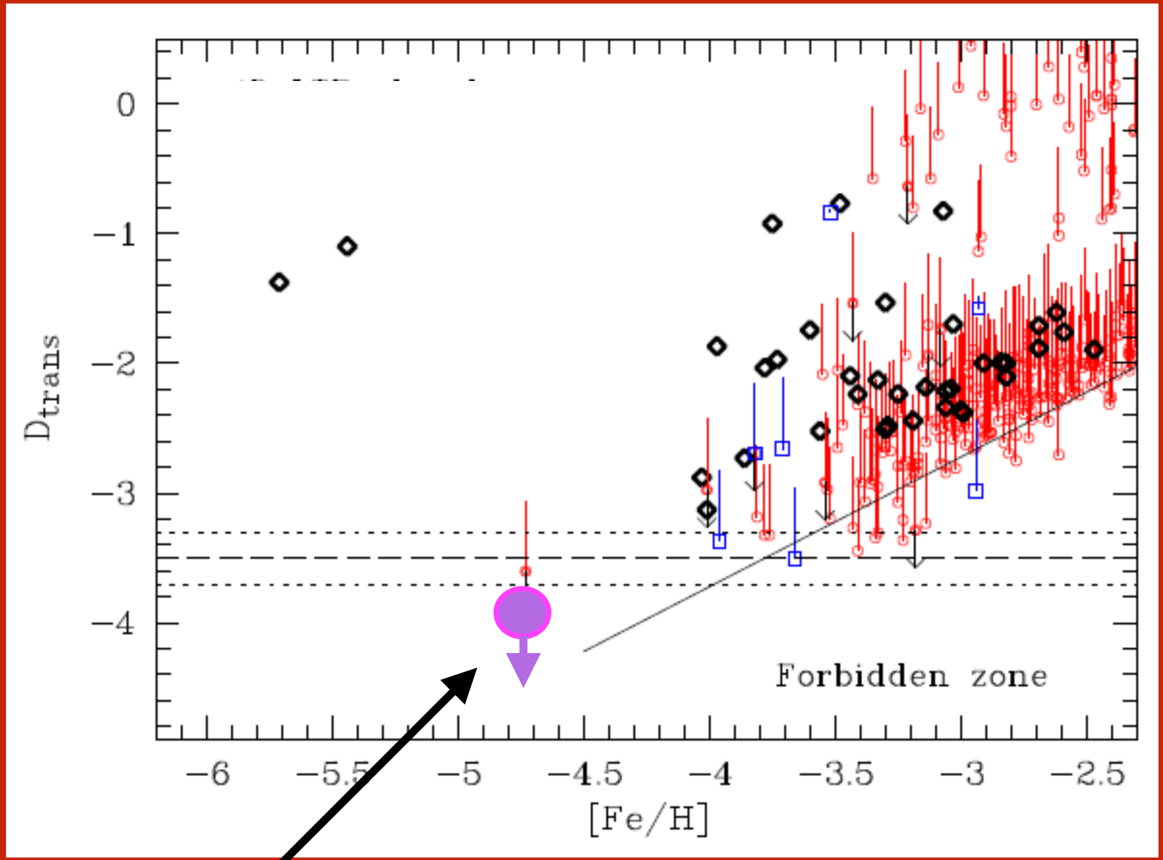
Hansen et al (2014)

Low-mass metal poor stars exist

- Small masses requires cooling to form:
  - CII and OI the most important coolants (Bromm & Loeb 2003)
  - IP CI is 11.26 eV ionized before HI by UV photons of SN
- Critical metallicity: radiative cooling rate > free-fall compressional heating

➡ $[C/H]_c \sim -3.5 \pm 0.1$

➡ $[O/H]_c \sim -3.05 \pm 0.2$



Caffau star

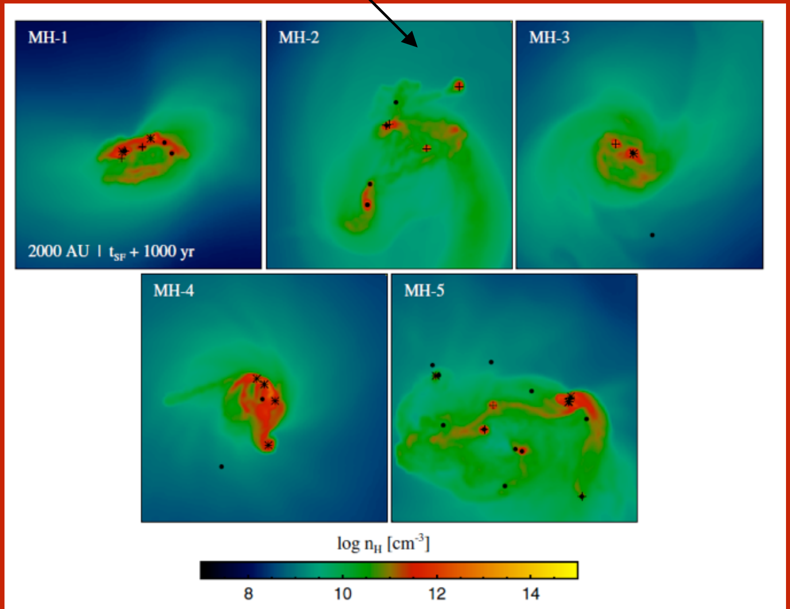
from Frebel et al. 2011

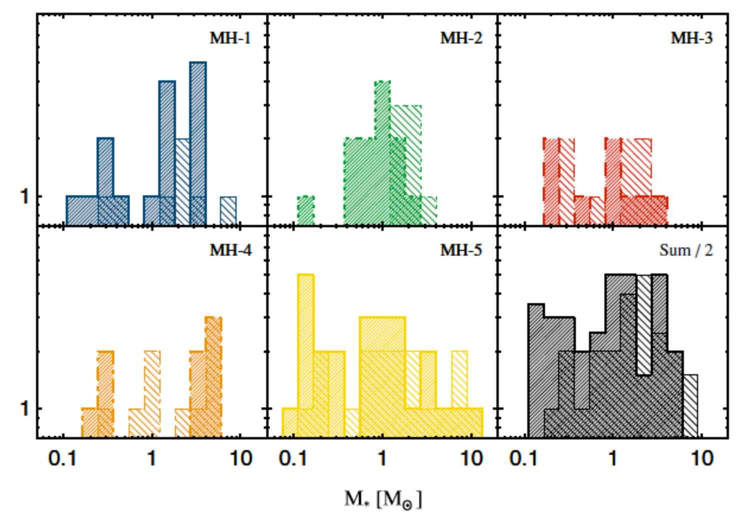
The CEMP are above the critical metallicity but the Caffau star is below the minimum amount of C to form low-mass stars

The Caffau star require new mechanisms for low mass formation: dust cooling or fragmentation

From Greif et al 2011

dots are stars with M< 1 Msun





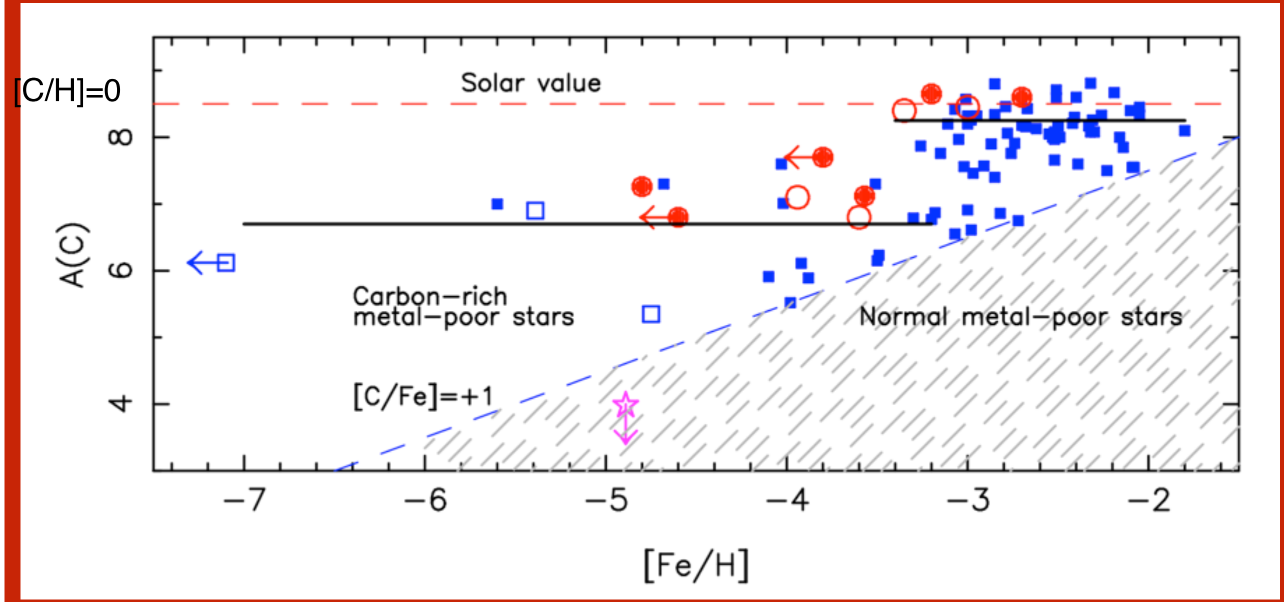
- Dust cooling + fragmentation (Schneider et al 2011)

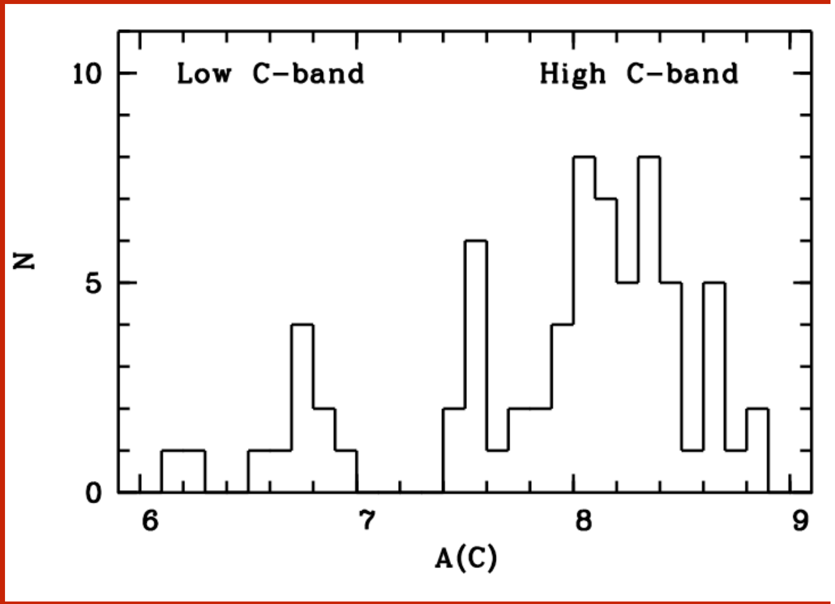
- Fragmentation: possible fragmentation of primordial gas in minihalos induced by turbulence (Clark et al 2008, Greif et al 2011). Flat distribution of masses

PROGENITORS

These are second generation stars. What about their progenitors

Bimodal C abundance?

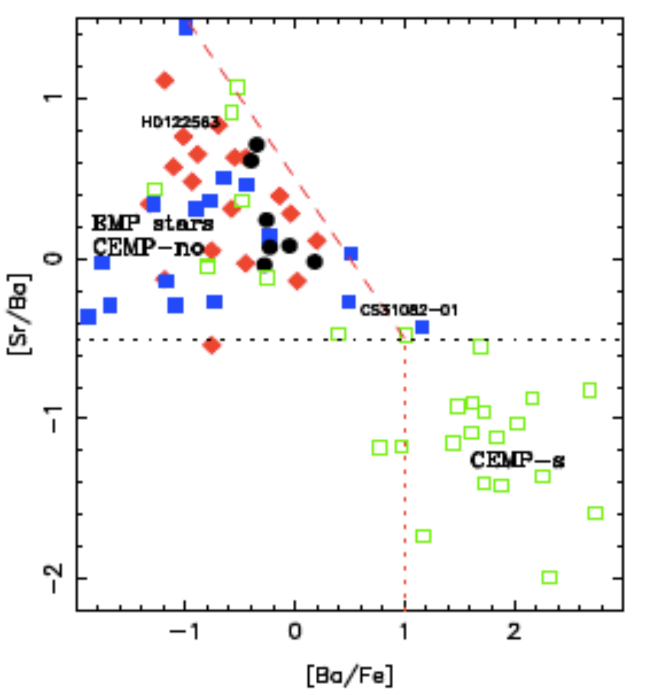


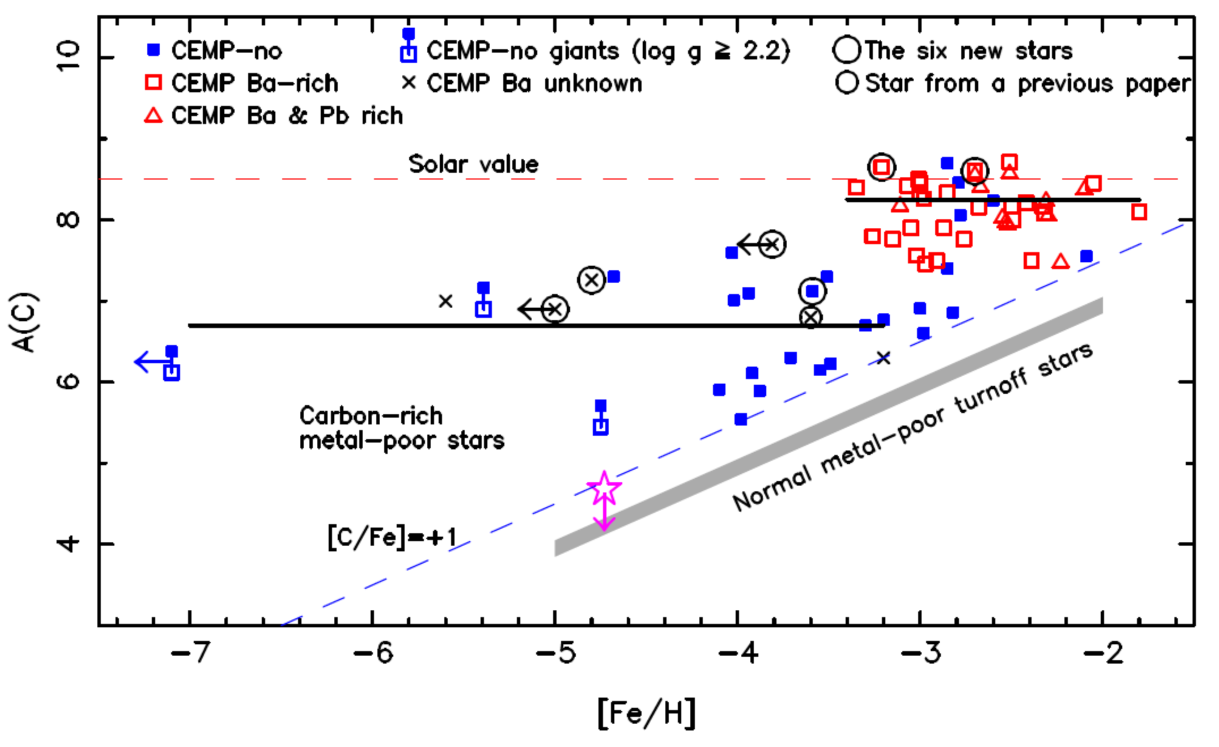


- Carbon is unrelated to metallicity
- Two populations: Low-Carbon, High-Carbon (Spite et al 2013)
- The two populations are well separated at low metallicity

TAXONOMY OF THE CEMPS (Beers Christlieb 2005):

CEMPs, CEMP-r, CEMPsr
CEMP-no





From Spite et al 2014

HighC: ~ **All** CEMP-s, binaries, from AGB companion (Lucatello et al 2005, Starkerburg et al 2014)

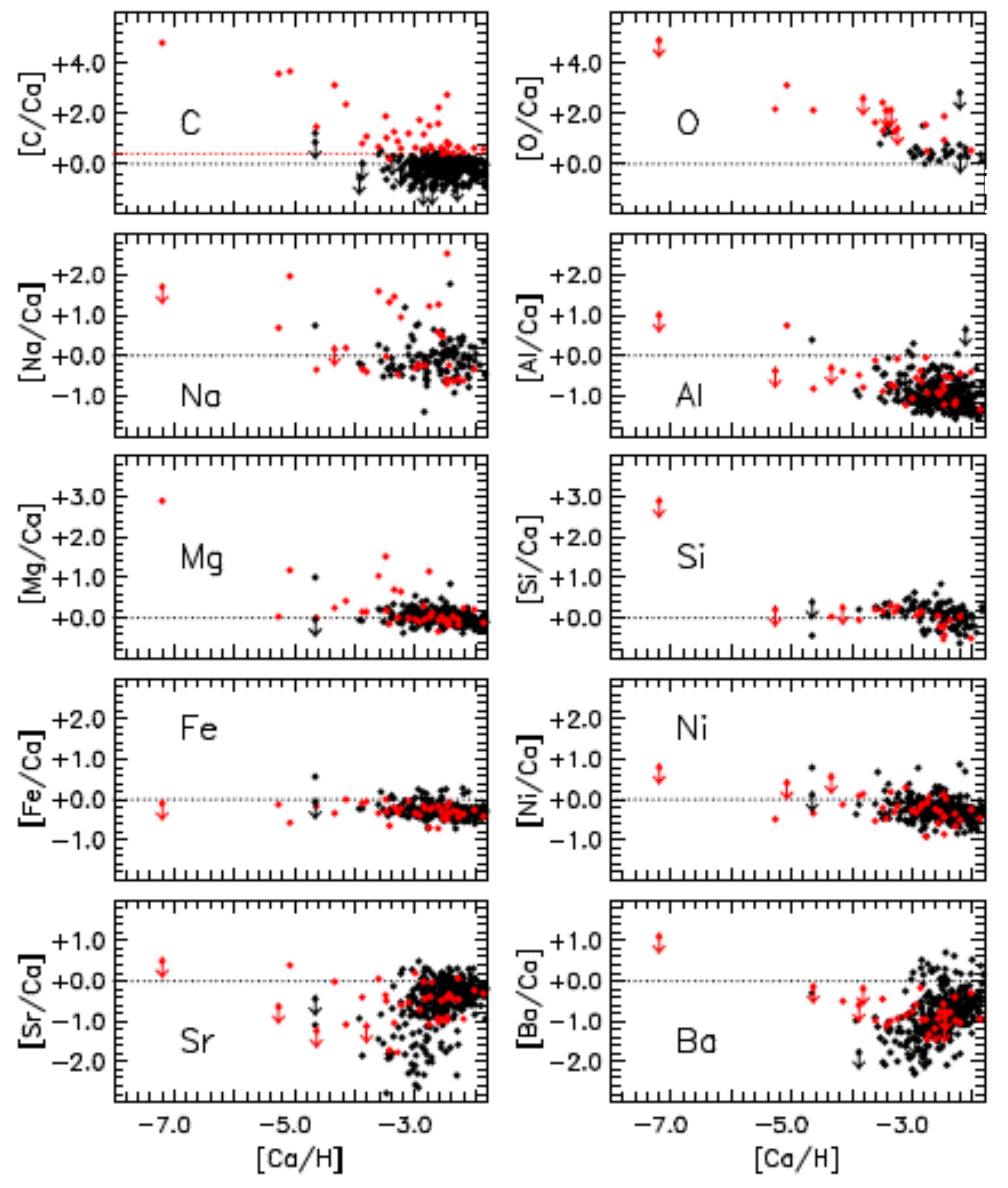
LowC: all CEMP-no, no binaries, origin?

Prototype CEMP-no:
CS 22957-027 Bonifacio Molaro Beers Vladilo 1998; Norris et al 1997

RELATIVE ABUNDANCES

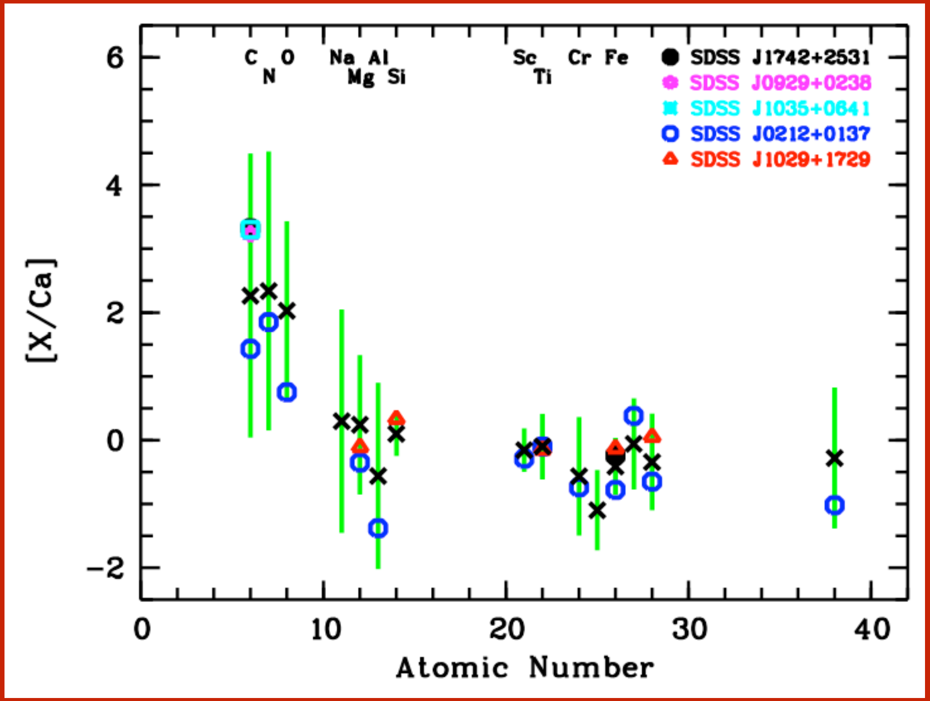
[X/Ca]

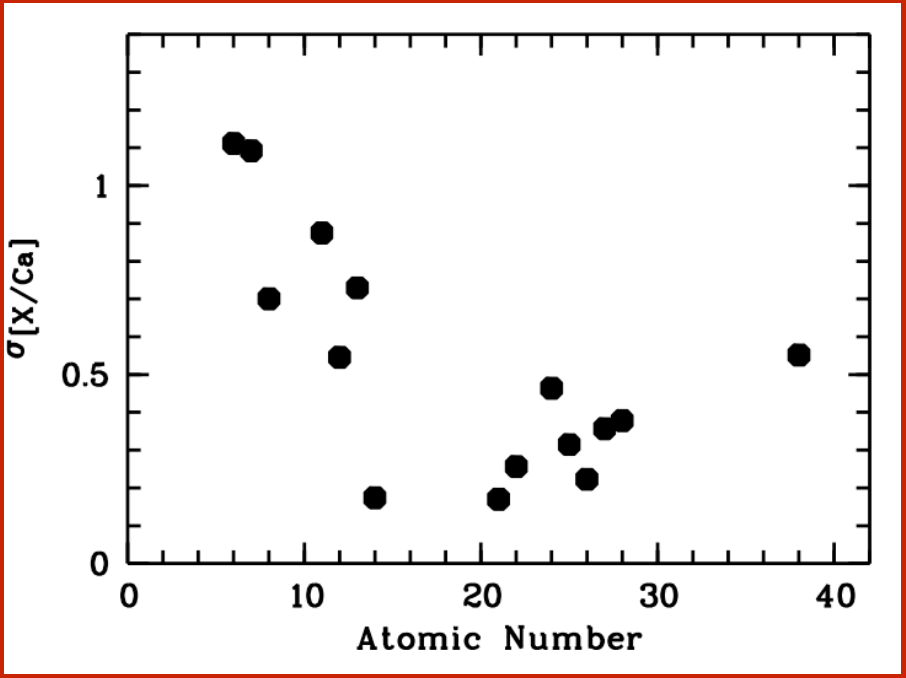
Frebel Norris 2015



red the CEMP
black C-normal

9- UMP-CEMP have a bizarre pattern





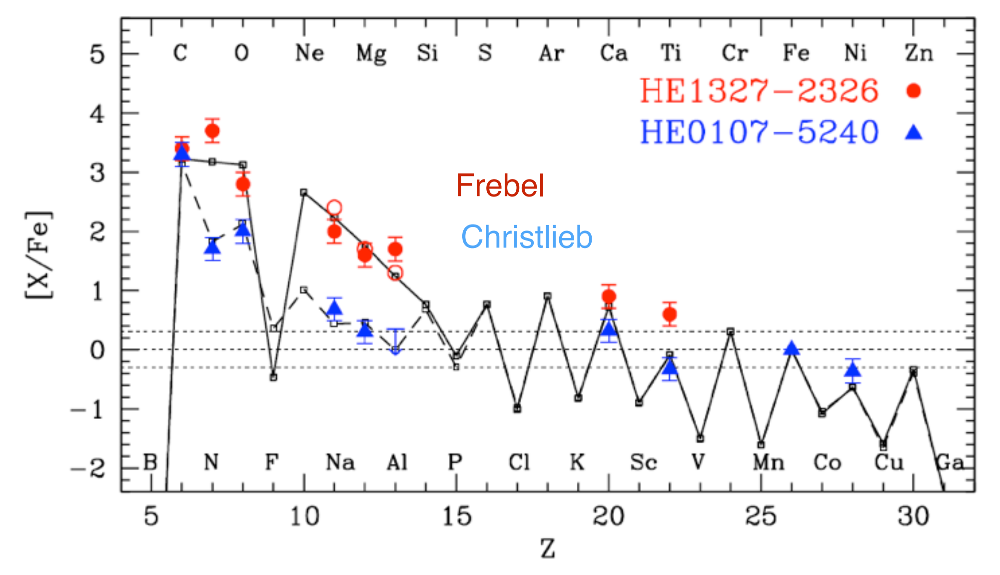
Rel. Abundances of light elements (< Si) variable
Rel. Abundances of heavier elements very constants

PROGENITORS?

- Hypernova models of Nomoto et al (2006)

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

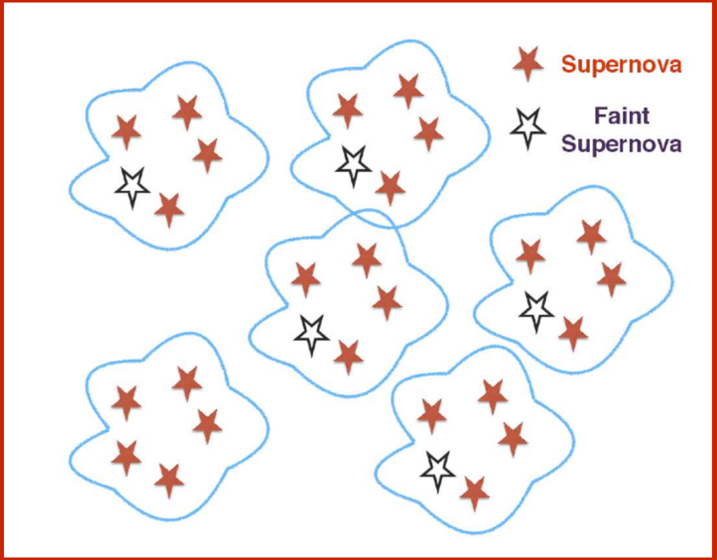
  - but one model for one star!



- Faint SN model (Limongi et al (2003), Cooke e Madau (2014))

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

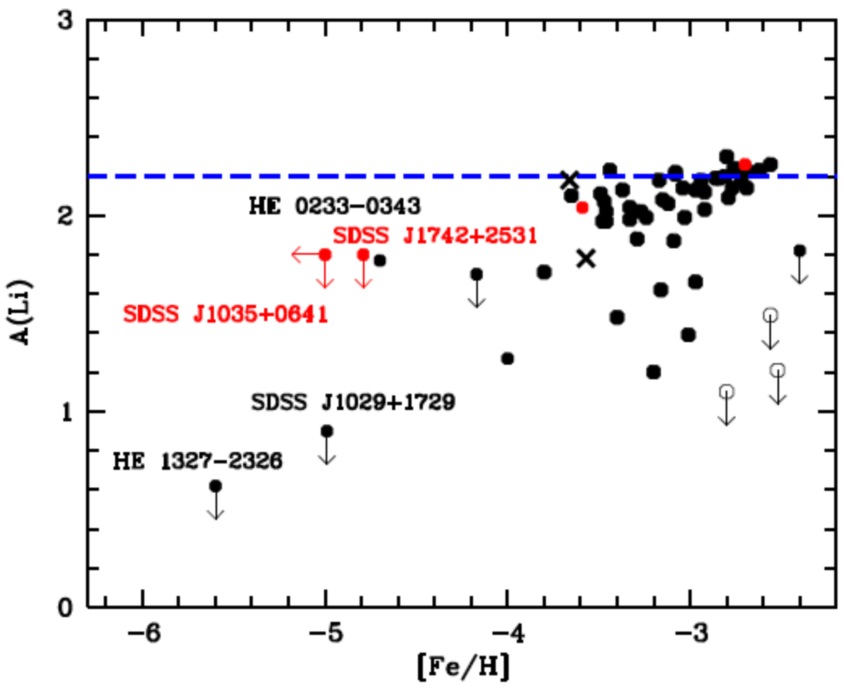
  ➡ only most superficial layers are ejected
  \+ classical +SN for the heavier elements

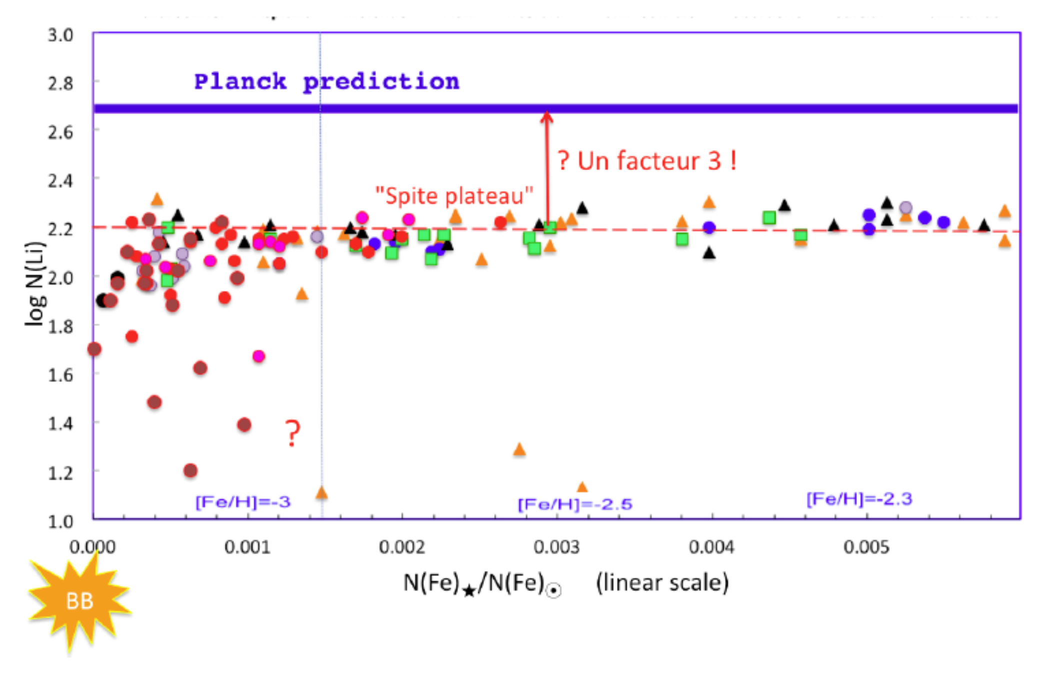


Lithium

5 TO stars have a Teff of the Spite plateau but show no Li.

also SDSS1029+1729 (Caffau star) no CEMP

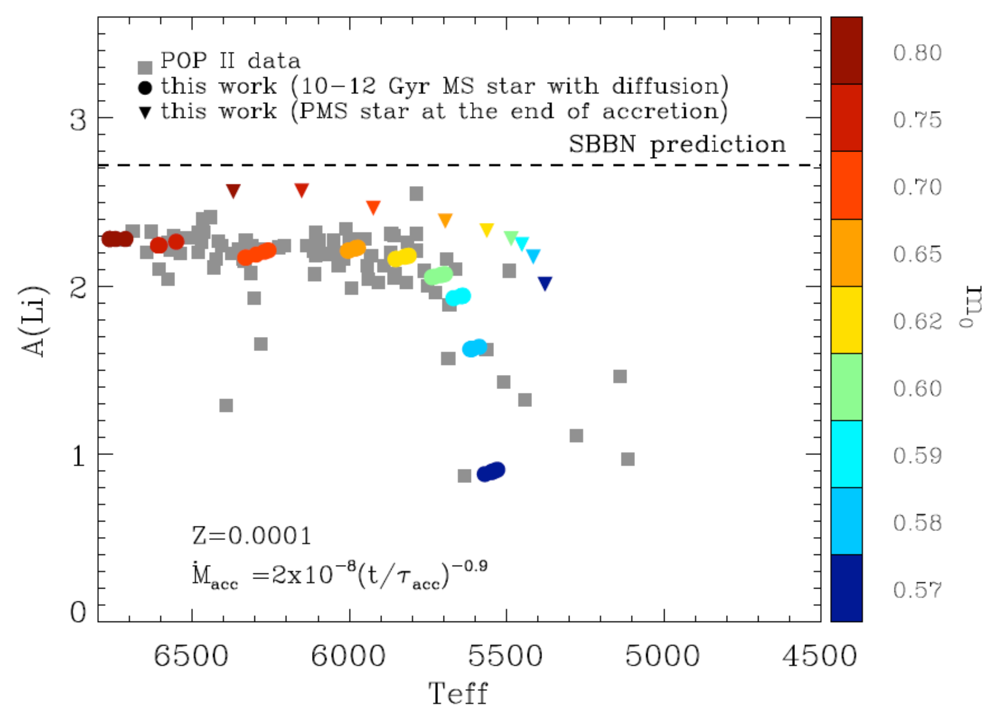




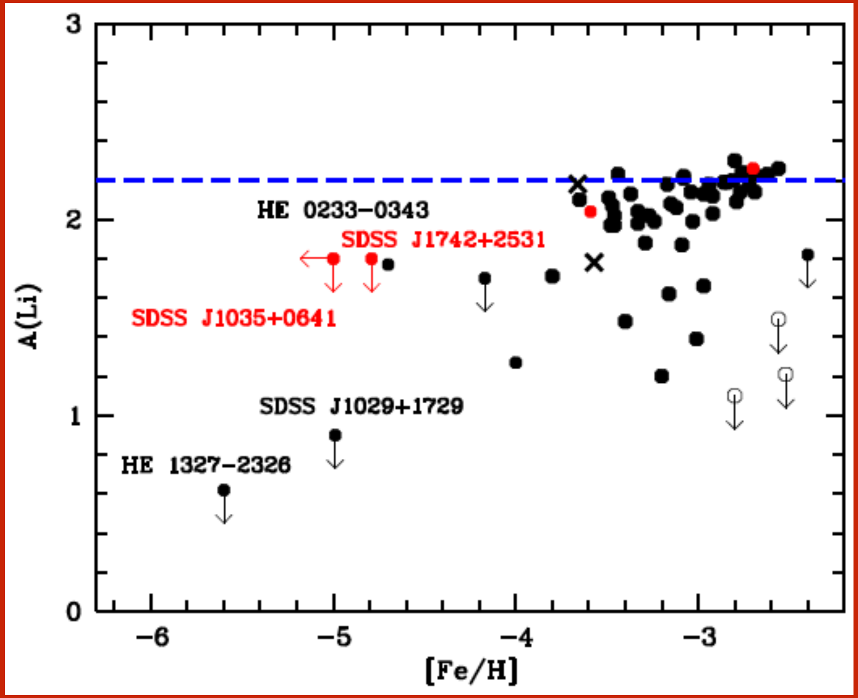
"melting" of Li at [Fe/H] ~ -3 (Sbordone et al 2013)

=> probable stellar origin of the Li Cosmological problem

Fu, Bressan, Molaro, Amico 2016



PreMain Sequence depletion and late accretion



In the EMP Li could be low because:

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

CONCLUSIONS

- TOPoS successful: 100 stars studied, 3(4) stars with [Fe/H]<-4.5 (30-40%)
- The EMP star show that stars with solar masses must form also at the lowest metallicity. Likely two main mechanisms at work: one for the CEMP and one for the C-normal
- CEMP-no is the main root for first low-mass stars formation.
- “C-normal” metal poor stars exist dawn to [Fe/H]~ -5 (proportion 1:9)
- TO CEMP or C-normal show absence of Li. This suggests a stellar origin of the primordial Li problem