The first generations of stars

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MERAC

The first generations stars

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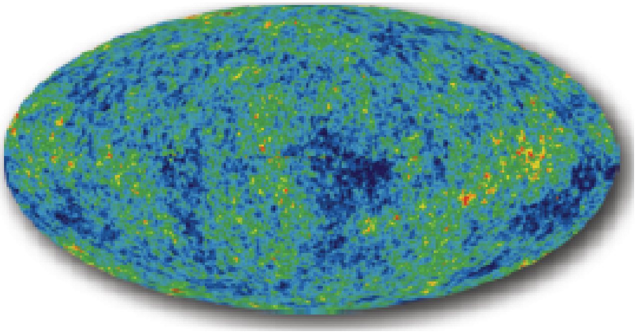
Main Questions

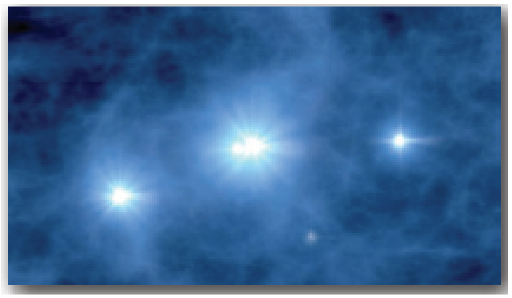
- **Understand formation of low mass stars in low metallicity gas**
  - **Do zero-metal low mass stars exist?**
  - **If not: value of the "critical metallicity"**
  - **Derive the fraction of C-enhanced extremely metal-poor (CEMP) stars/"normal" extremely metal-poor (EMP) stars**
- **Lithium and the 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**

The Universe emerging from the Big Bang

Only H, He, and traces of Li are present in the primordial gas

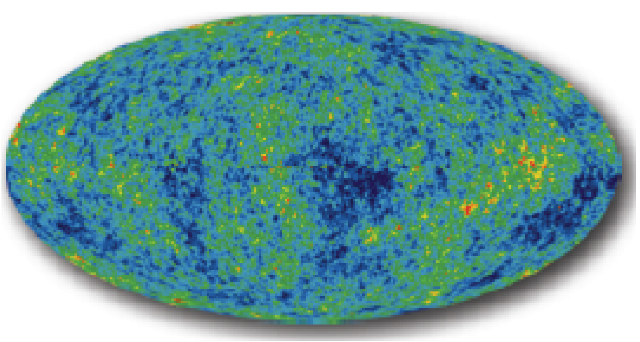


Formation of the first stars

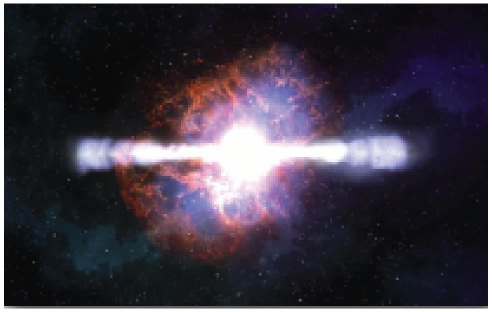


The first stars formed ~ 200 Myr after the Big Bang

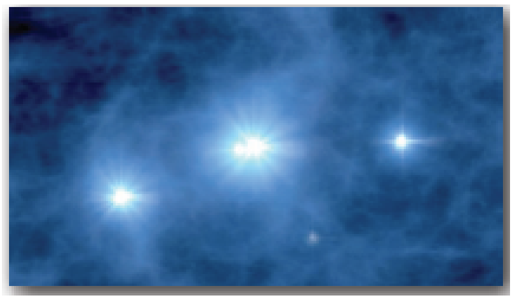
The cooling of the contracting material was inefficient due to the lack of metals and dust.

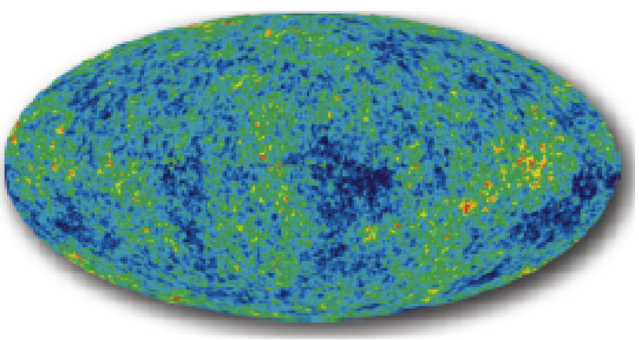


The first stars were most likely very massive (50-300 $M_\odot$)

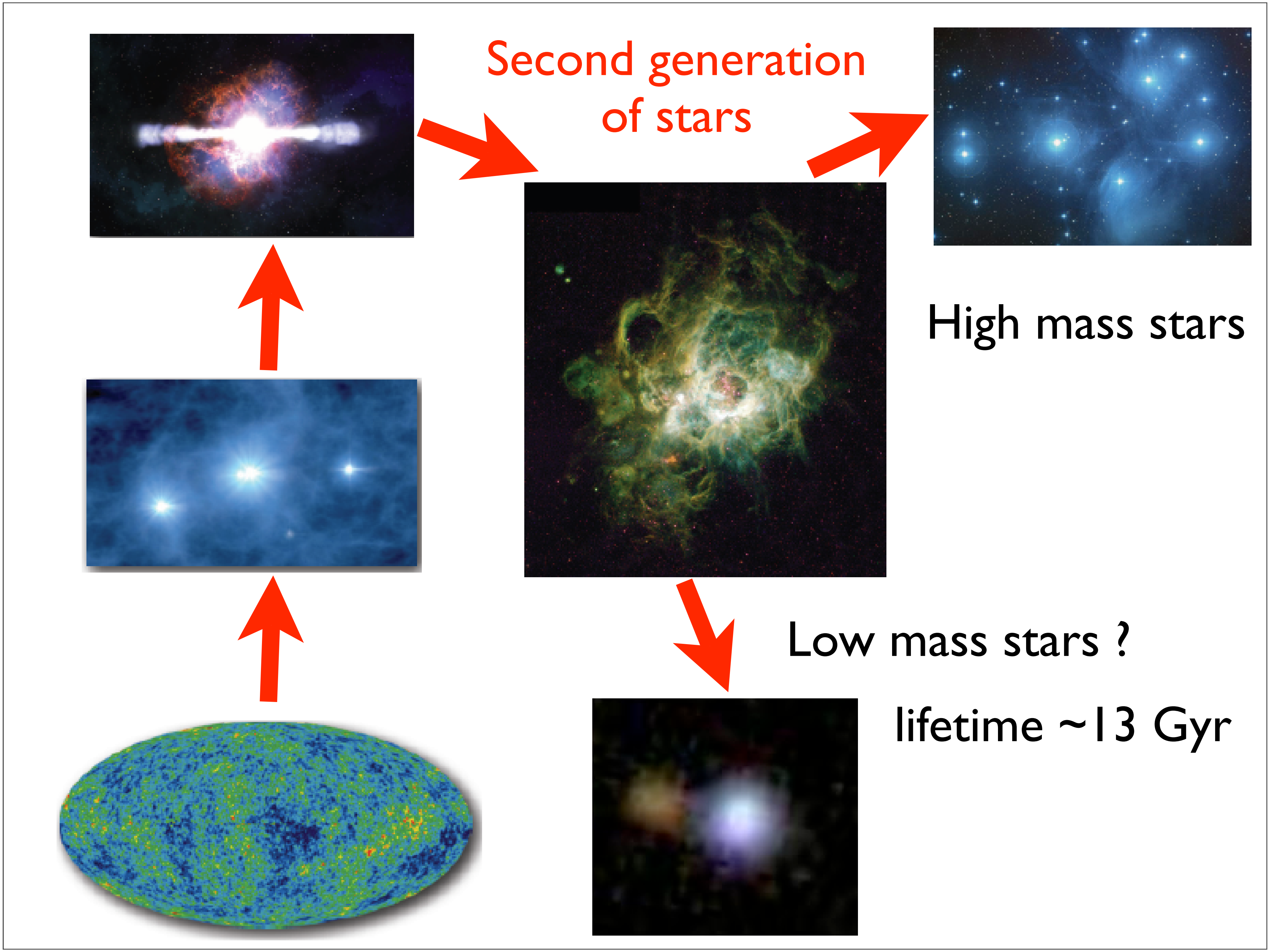


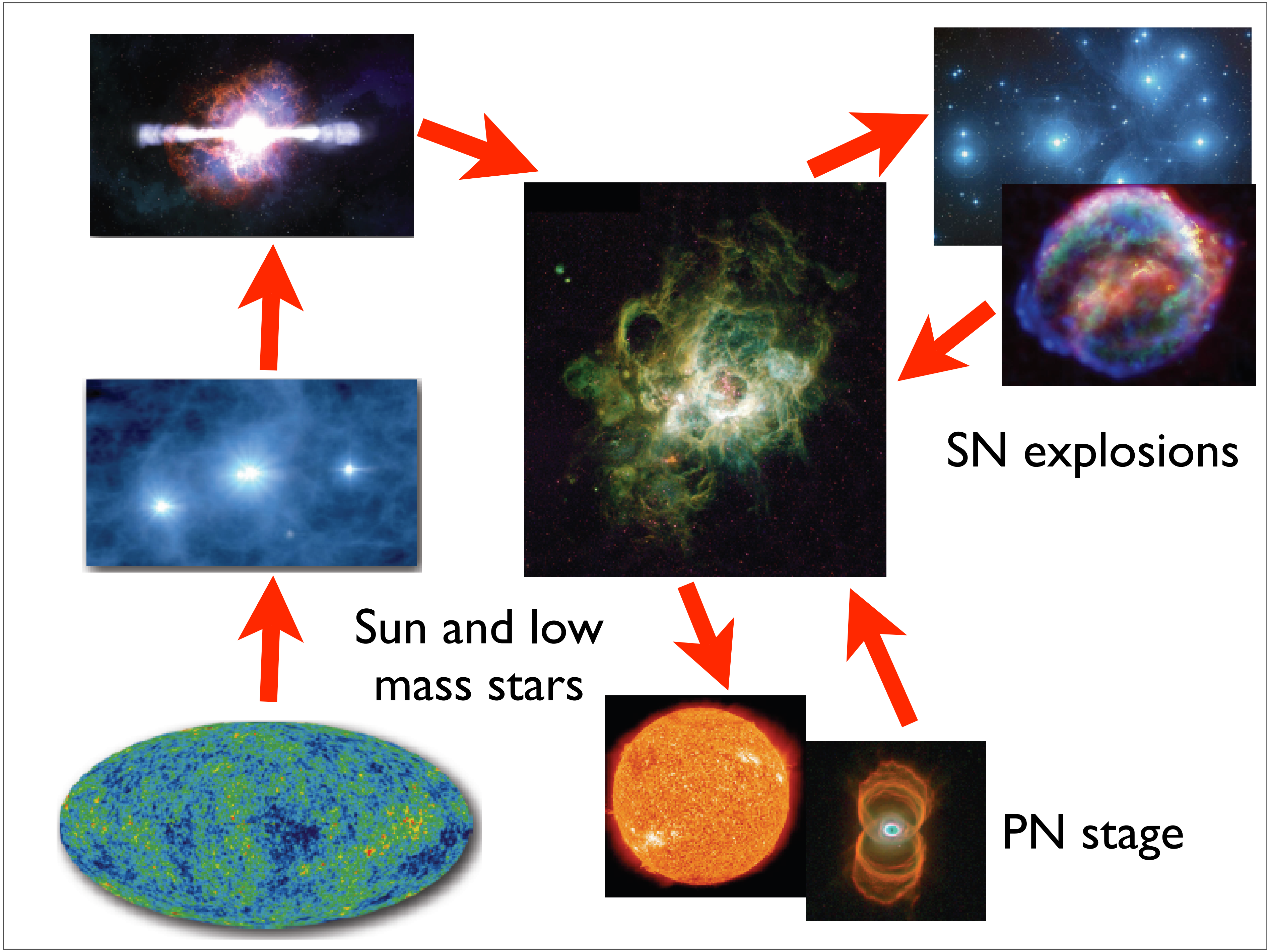
The first massive stars evolved rapidly and synthetised metals

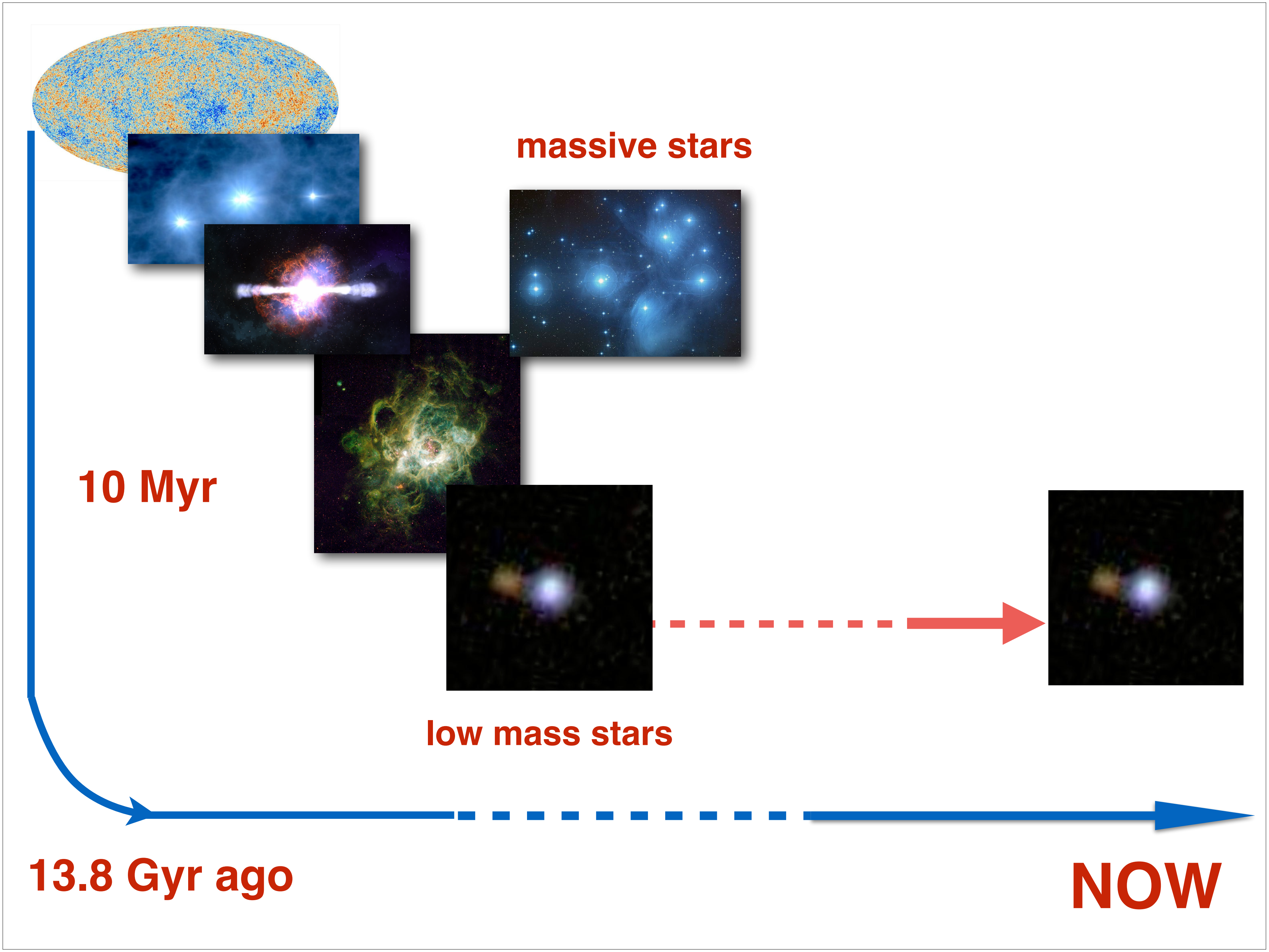




At the end of their lives (~10 Myr) they exploded as SN and polluted the ISM with the metals.

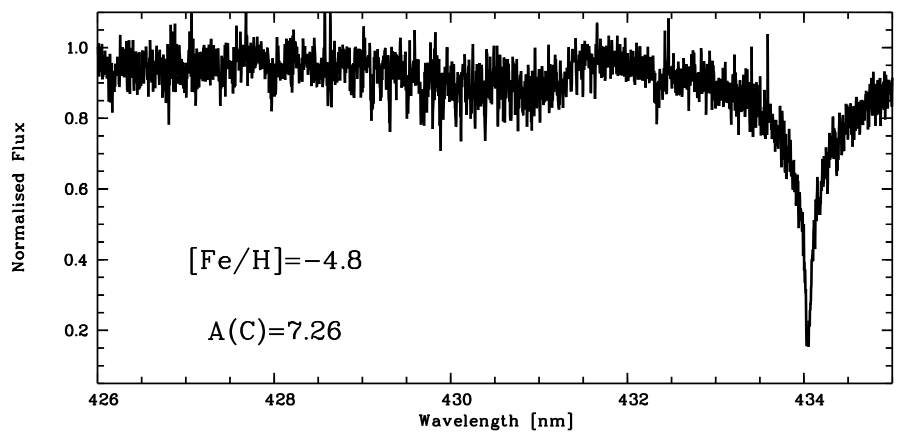

Second generation
of stars
High mass stars
Low mass stars ?
lifetime ~13 Gyr


SN explosions
Sun and low mass stars
PN stage


massive stars
10 Myr
low mass stars
13.8 Gyr ago
NOW

Formation of primordial mass stars shining today?

- The cooling (by radiation) of the contracting material was inefficient, due to lack of metals and dust
- Historically the first extremely iron-poor ([Fe/H]≤ -4.5) stars found are all C-, N- and O-enhanced, and others have been found
- My recent founding of new C-rich extremely metal-poor stars reinforces the theory on low-mass star formation with cooling through C II and O I fine-structure transitions radiate energy (collisional excitation and radiative de-excitation)



BUT . . .

According to the theory of Bromm & Loeb (2003) a minimal quantity of C and O is necessary to form low mass stars

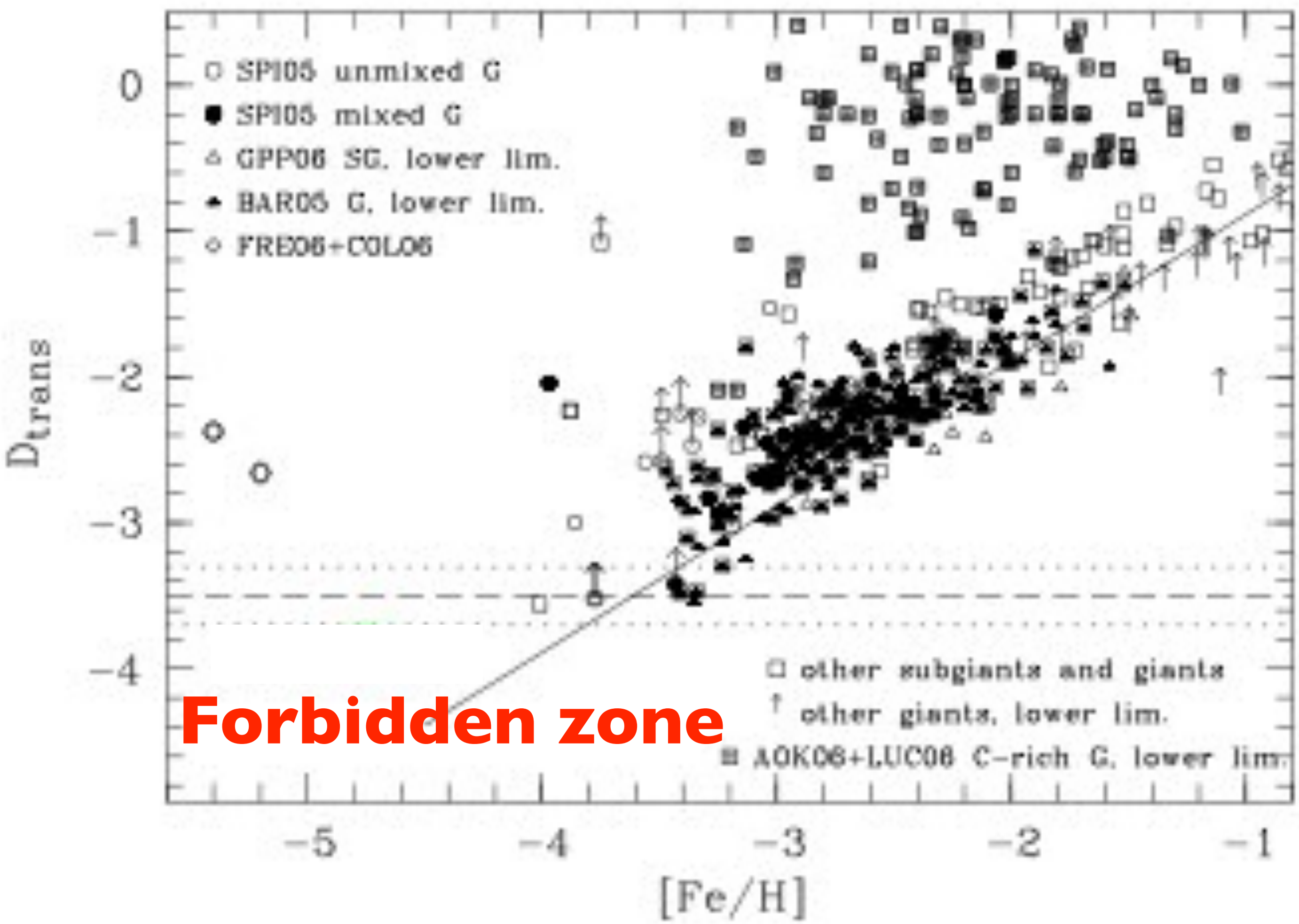
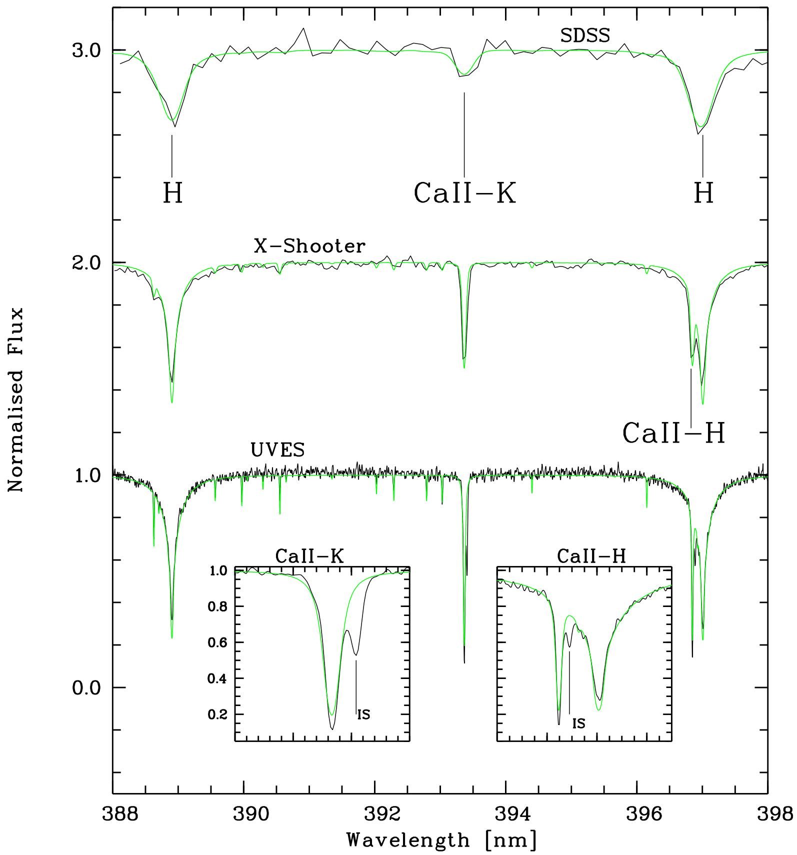


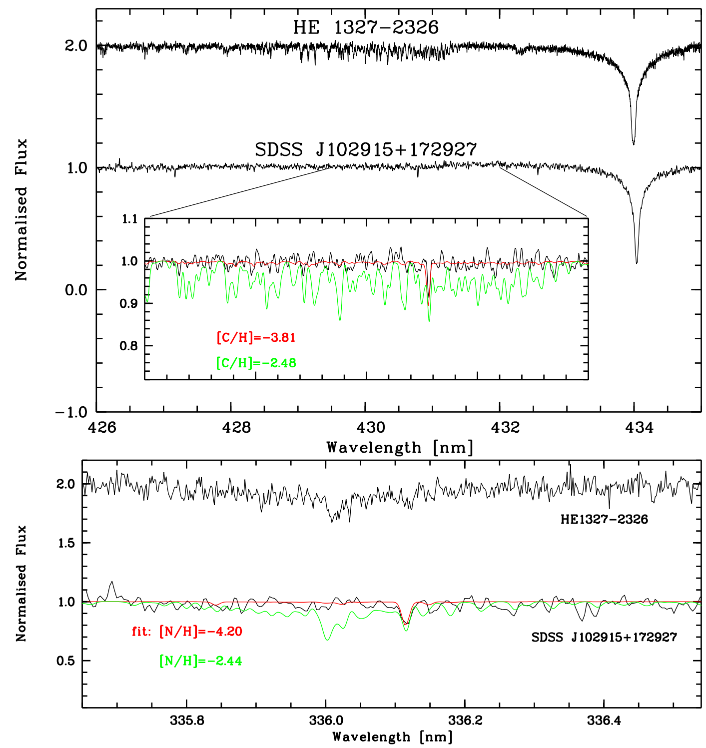
Figure from Frebel et al. 2007

The star that should not exist

- $[Fe/H]=-4.9$
- $[C/H]< -4.5$
- $Z = 5 \times 10^{-5} Z_{\odot}$

EMP star non-enhanced in C,N $\Longrightarrow$ over-abundance C not necessary to cool EMP gas





Caffau et al. (2011) Nature 2011, 477, 67

But we have found a star in the forbidden zone

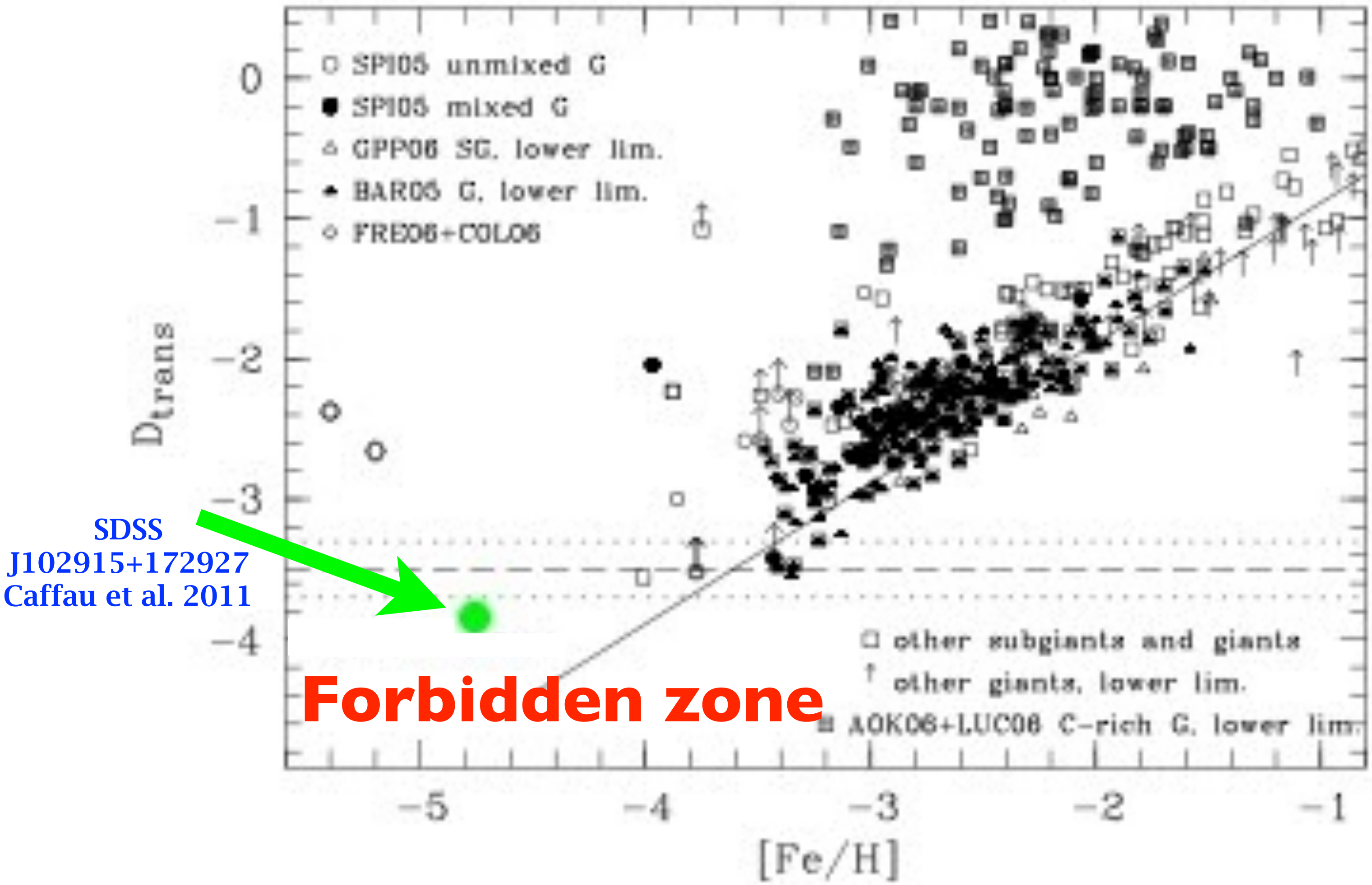


Figure from Frebel et al. 2007

Formation of low mass stars

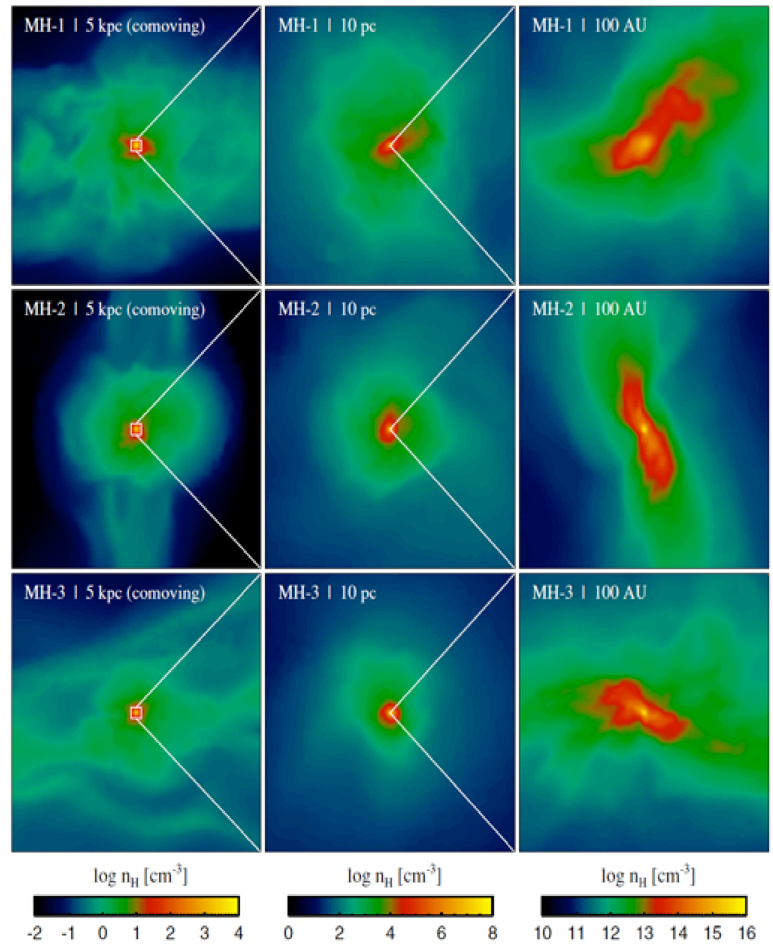
- Zero metallicity ⇒

  FRAGMENTATION (Clarke et al. 2011, **never observed**)

- Metallicity > Zcr⇒

  ★ CII & OI fine structure cooling (Bromm & Loeb 2003 ex. **HE 1327-2326**, **HE 0107-5240**)

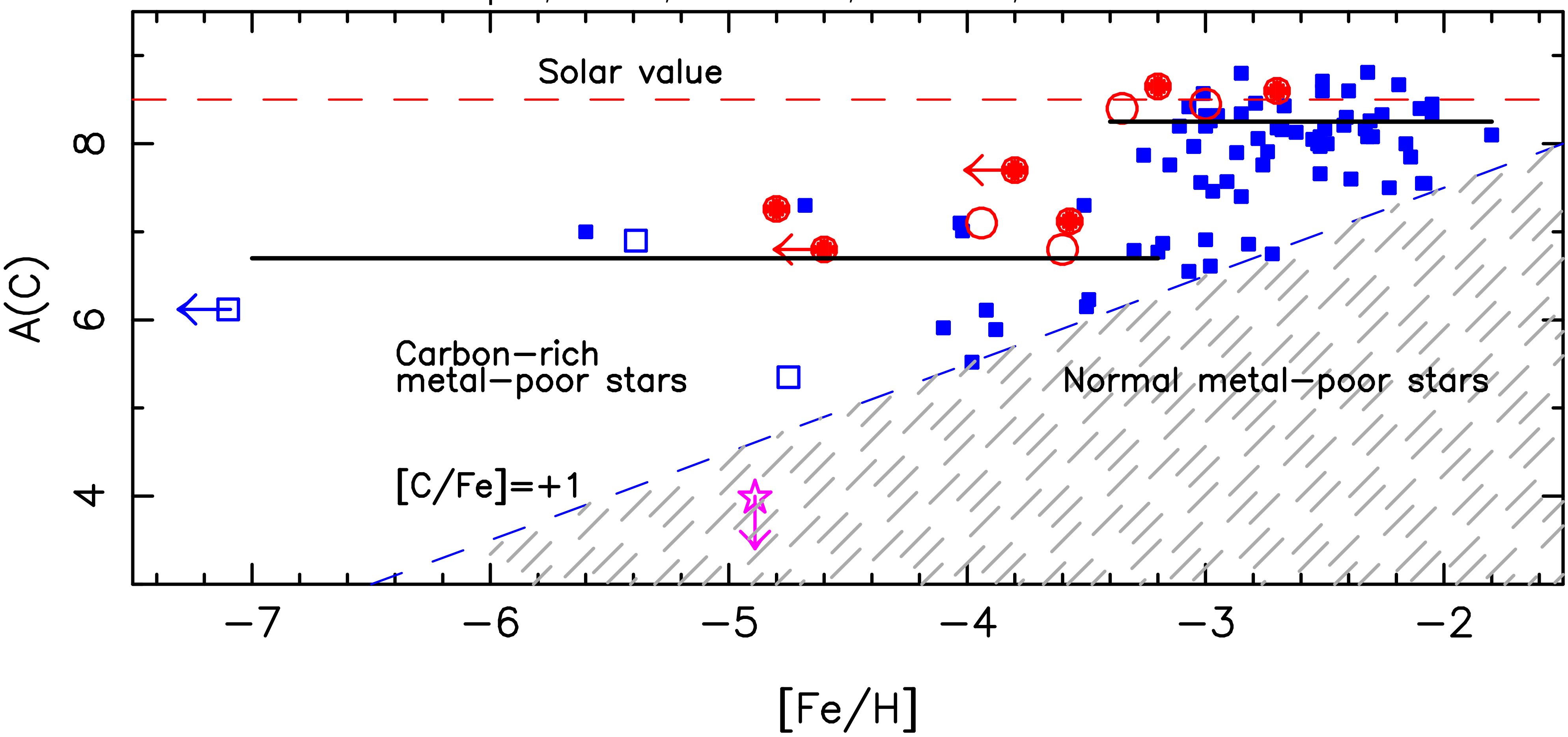
  ★ dust cooling + fragmentation (Schneder et al. 2011, ex. **SDSS J102915+172927**)



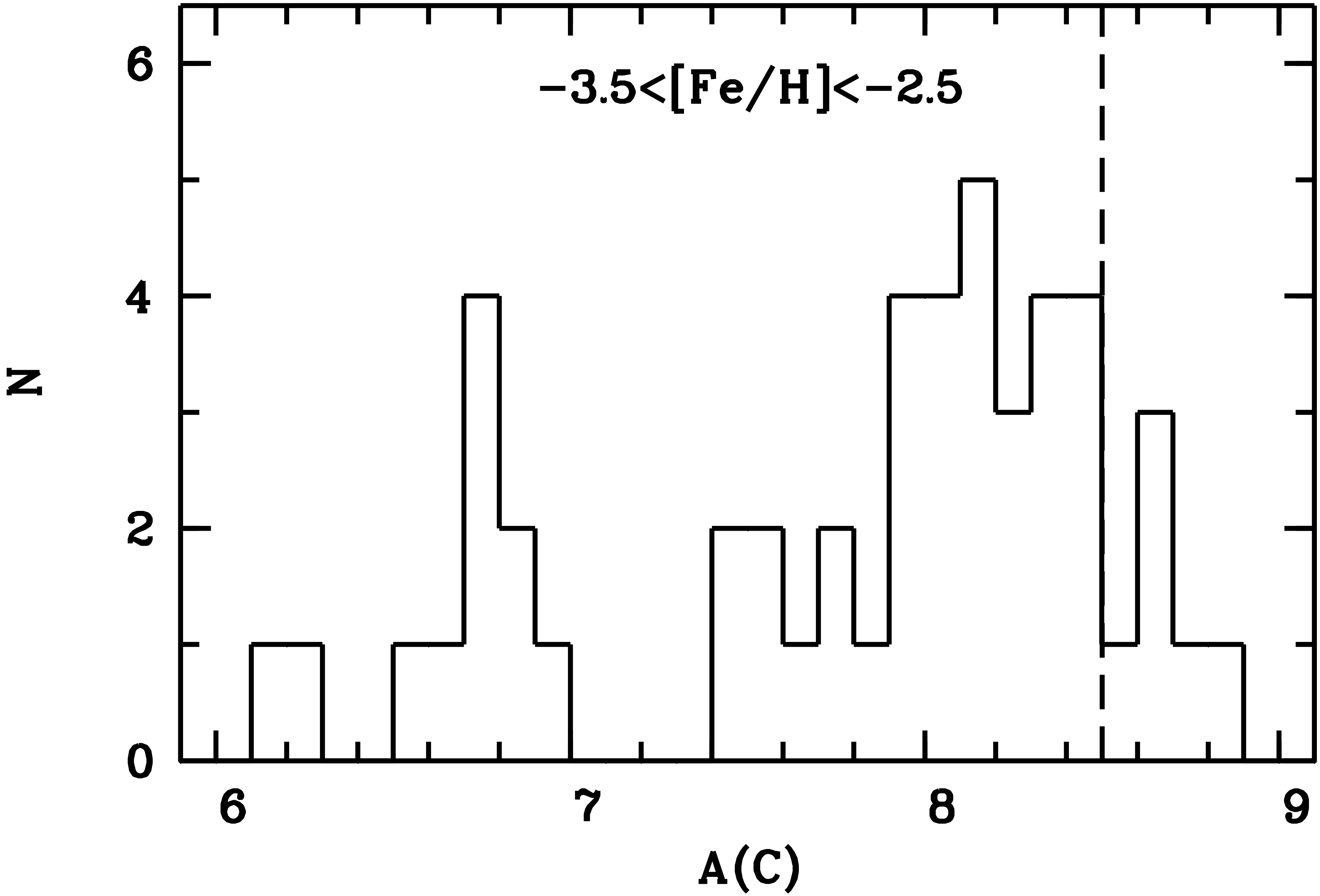
From Greif et al (2011)

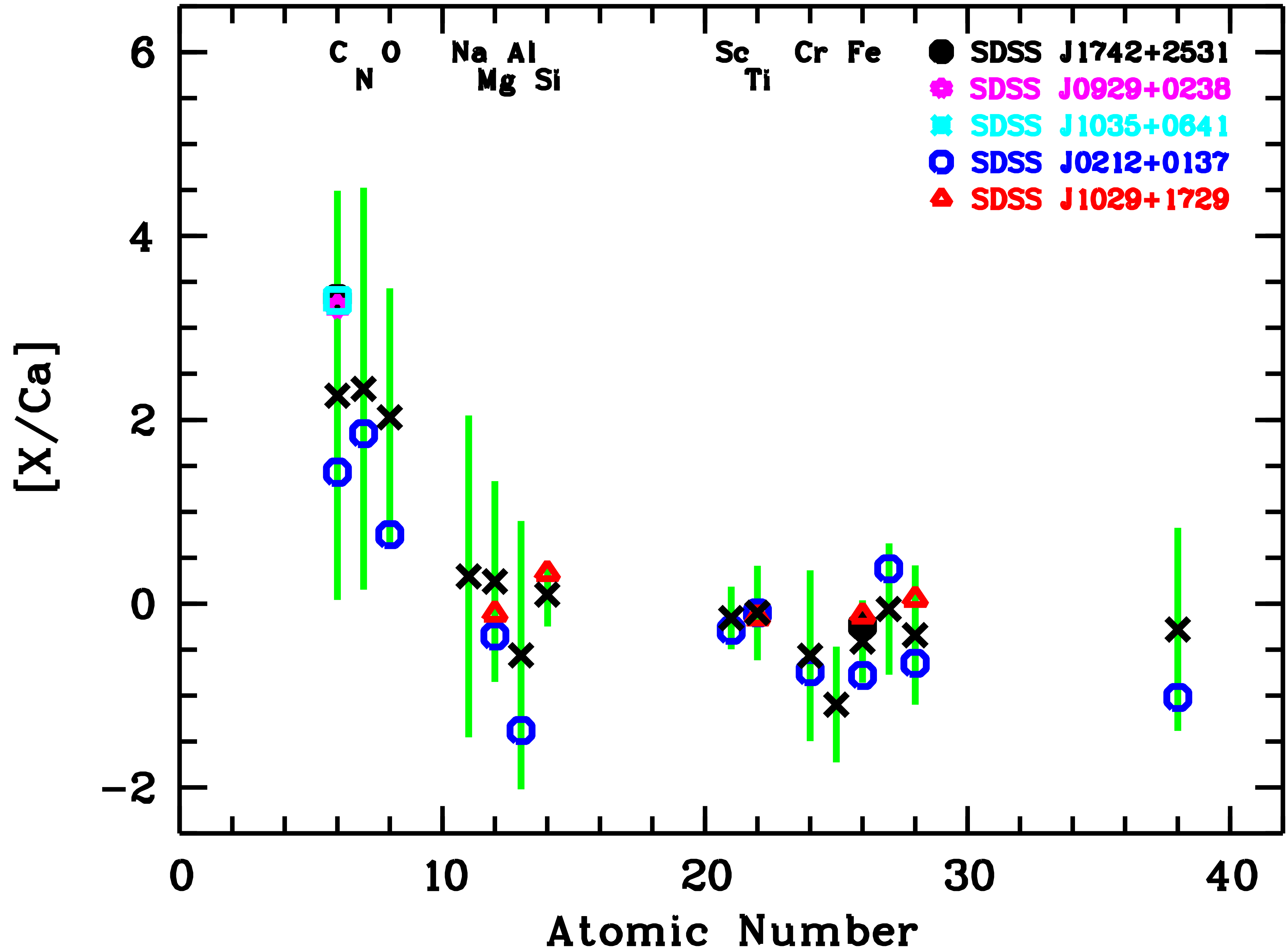
CEMP

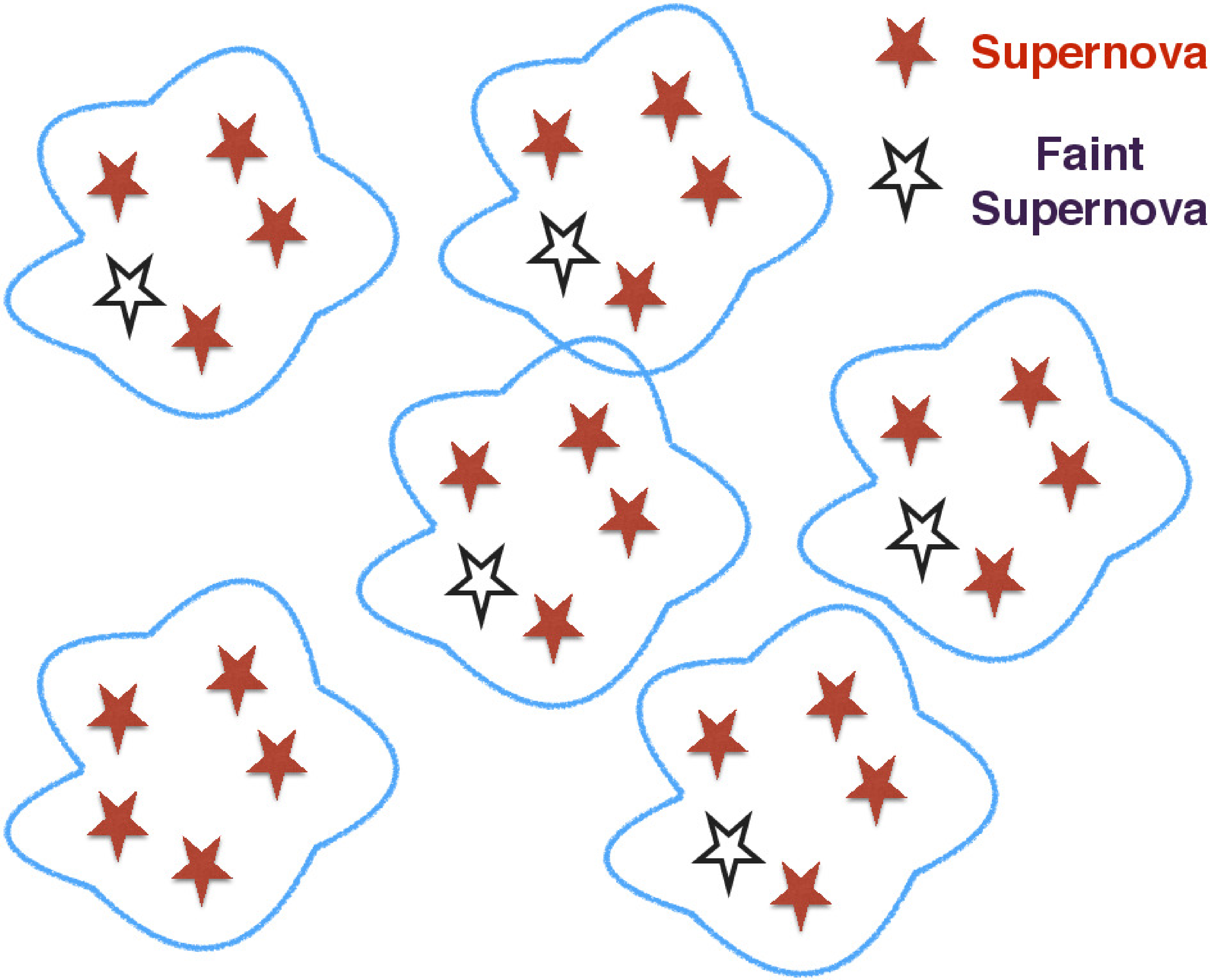
Spite, Caffau, et al. 2013, A&A 552, 107



CEMP




C
N
O
Na
Mg
Al
Si
Sc
Ti
Cr
Fe
SDSS J1742+2531
SDSS J0929+0238
SDSS J1035+0641
SDSS J0212+0137
SDSS J1029+1729
[X/Ca]
Atomic Number
6
4
2
0
−2
0
10
20
30
40

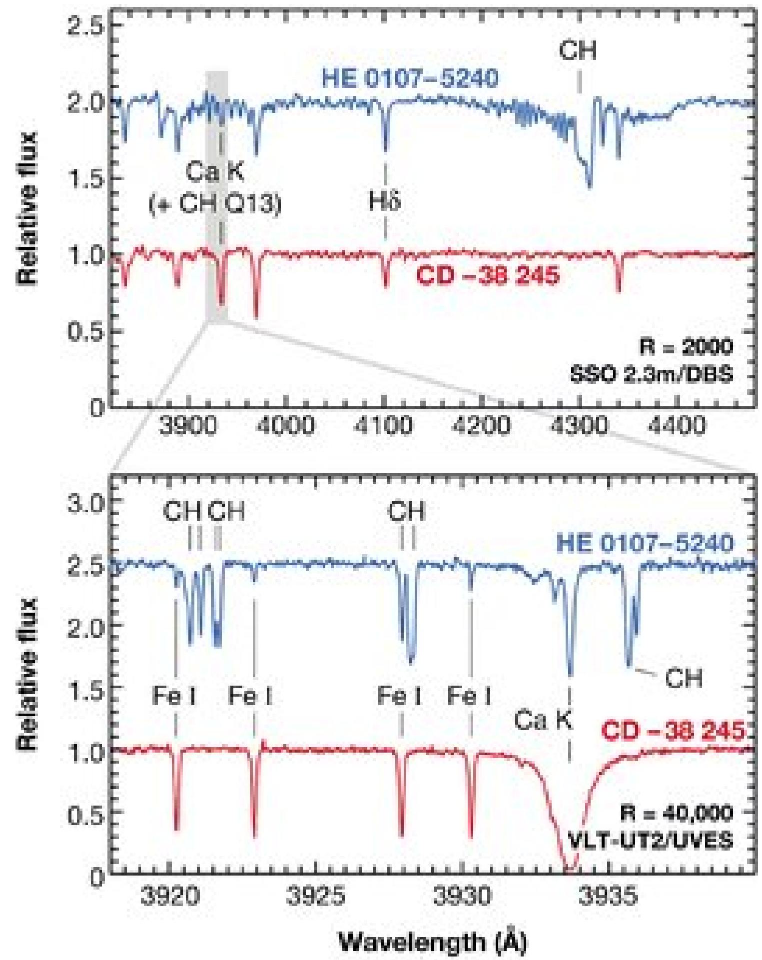

Supernova
Faint Supernova

Working plan

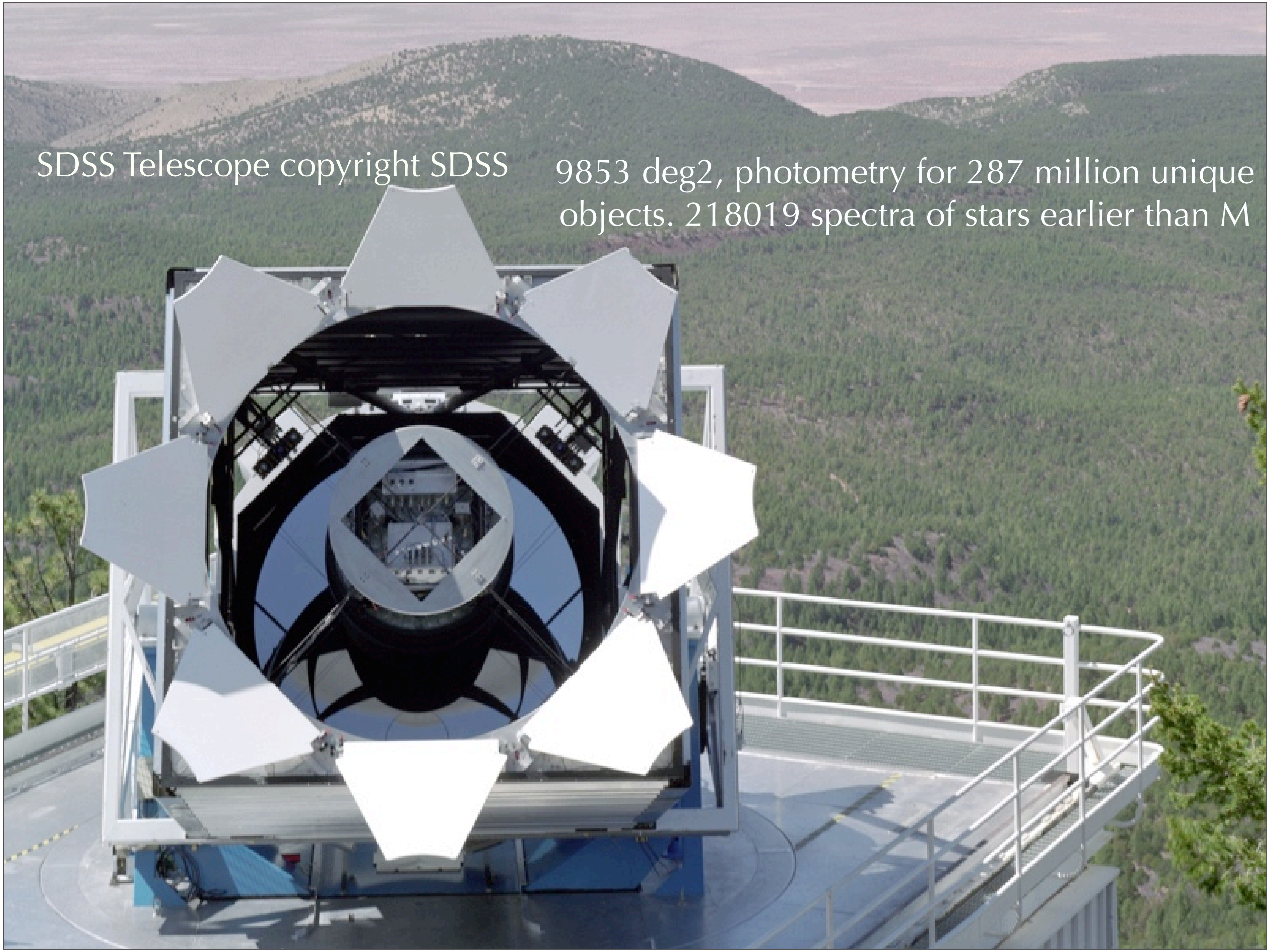
- Selection of EMP candidates
- Follow-up observation at intermediate/high resolution
- 1D-LTE analysis
- Computation of 3D corrections and NLTE effects
- Calibration of the low-resolution data
- Derivation metallicity distribution function (MDF)

Searching for and analysing EMP stars

- Stars of extremely low metallicity (EMP) are exceedingly rare
- To select them large amount of observations is needed
- Large databases available at low resolution
- Spectra of EMP stars show few lines and these are weak
- Follow-up at higher resolution is necessary

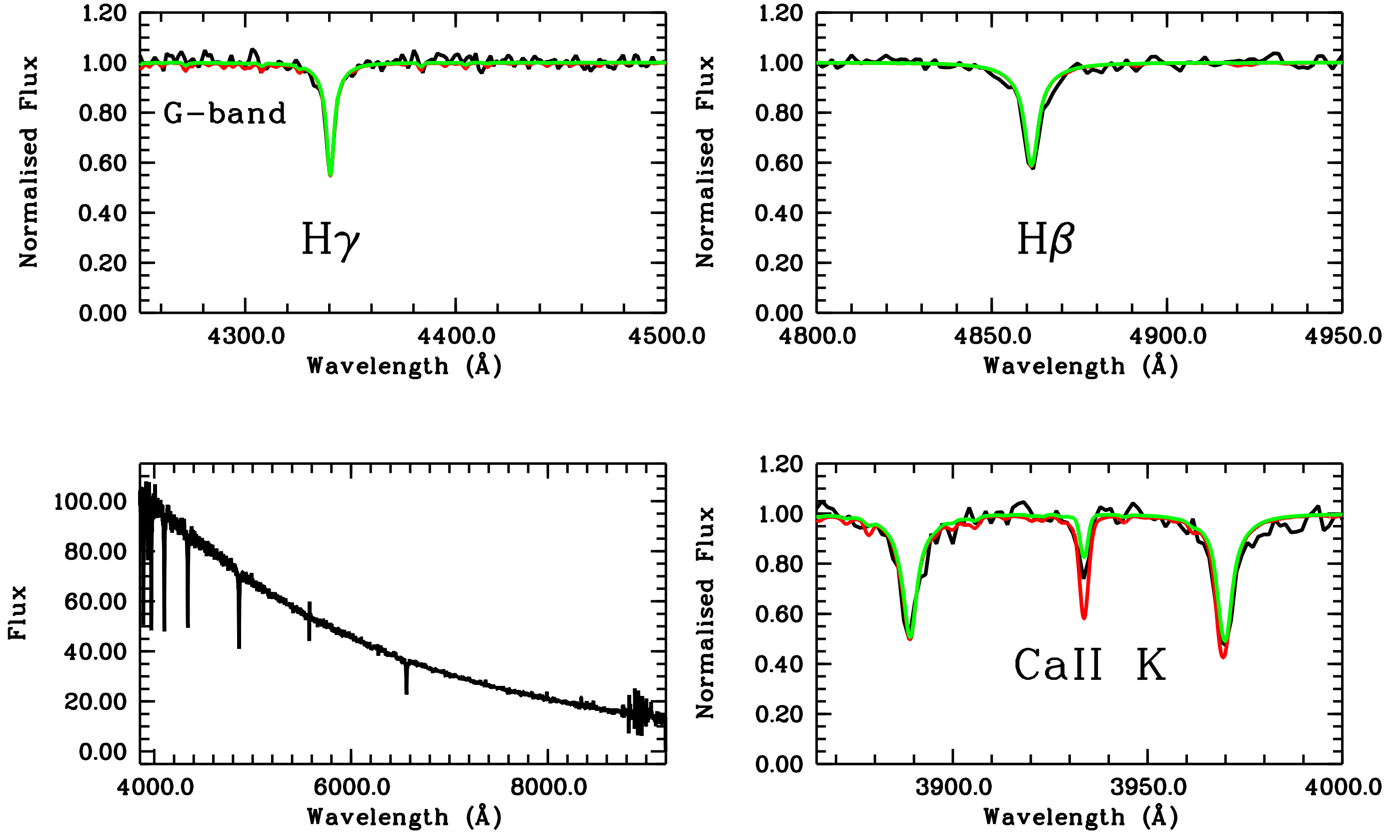


Beers, TC and Christlieb, N. 2005
Annu. Rev. Astron. Astrophys. 43: 531–80


SDSS Telescope copyright SDSS
9853 deg2, photometry for 287 million unique objects. 218019 spectra of stars earlier than M

Selection

- Limited information derived from R=2 000 resolution spectra + photometry
- Many such spectra available from several surveys, essential for searching for rare objects
- Extremely metal-poor stars can be extracted from low resolution surveys
  - **150 000 SDSS spectra** (potentially TO stars) analysed automatically
  - final selection by visual inspection



Caffau et al. A&A 2011

Observed spectrum and over-imposed synthetic spectra [Fe/H]=-3.0 and [Fe/H]=-4.0

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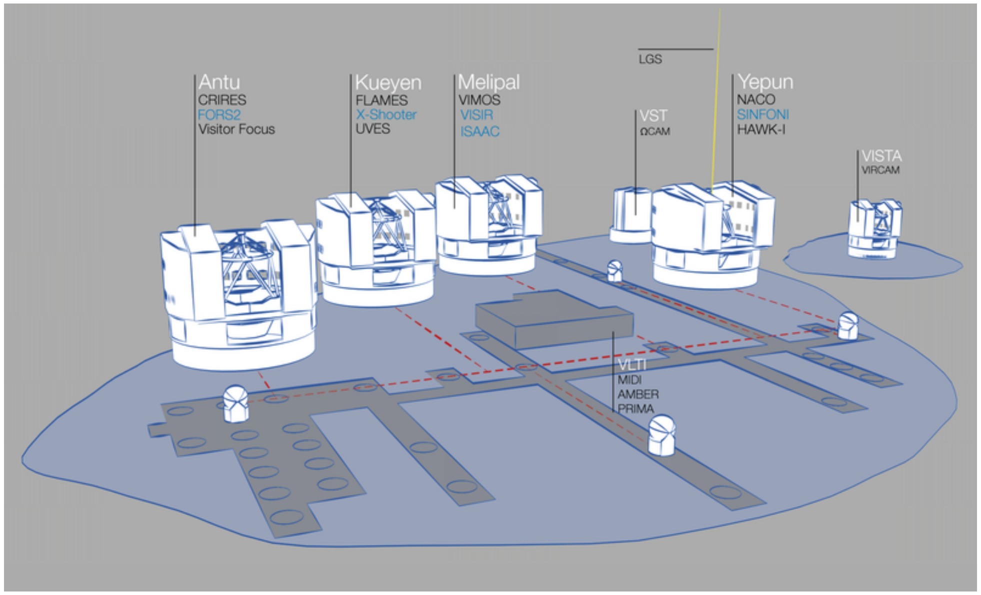
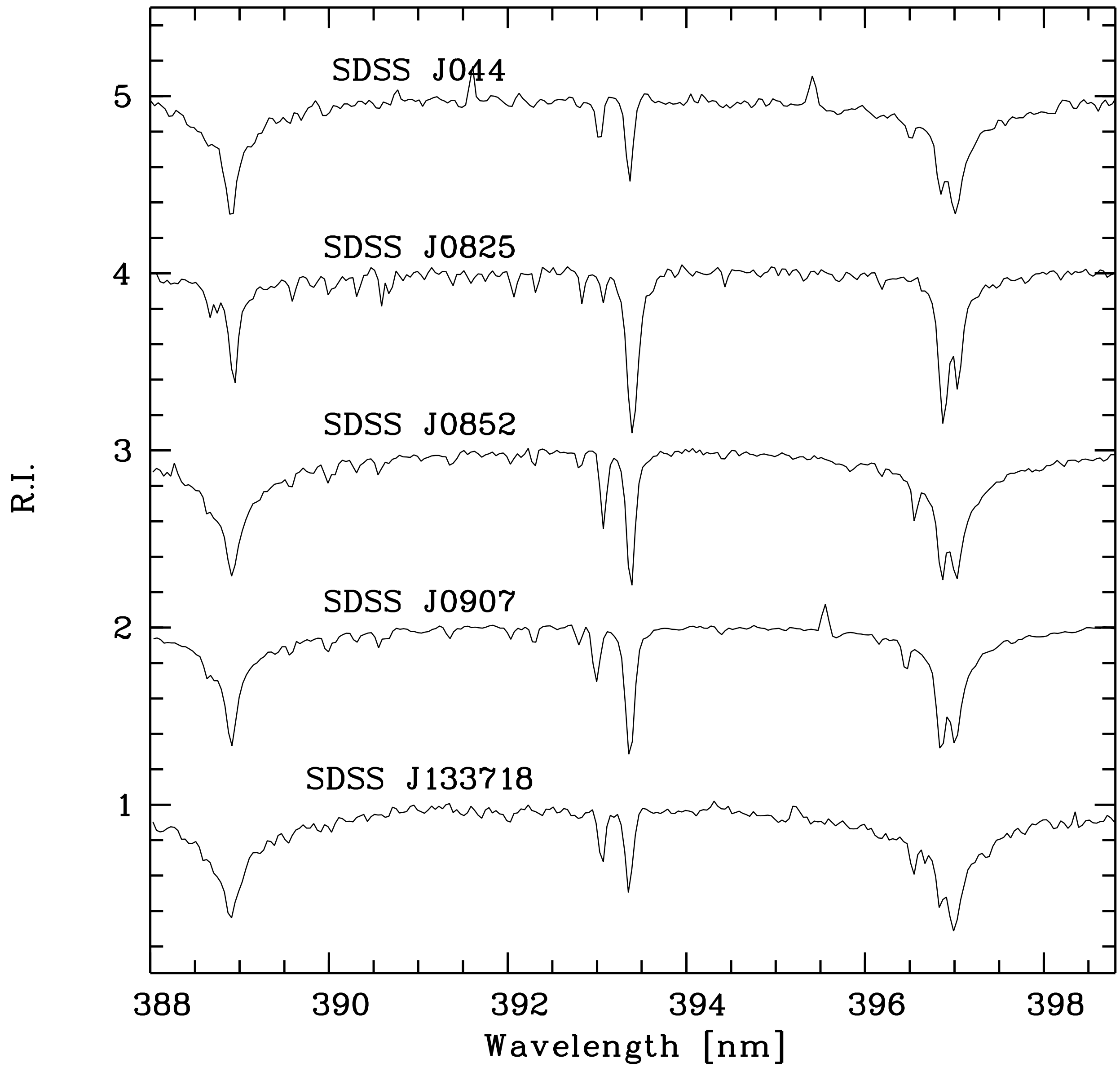
Follow-up observations facility: Paranal



European Southern Observatory - ESO

Metal-poor star selected from SDSS and observed with the spectrograph X-Shooter at VLT - February 2011



$[Fe/H] = -3.71 \pm 0.27$

$[Fe/H] = -3.22 \pm 0.24$

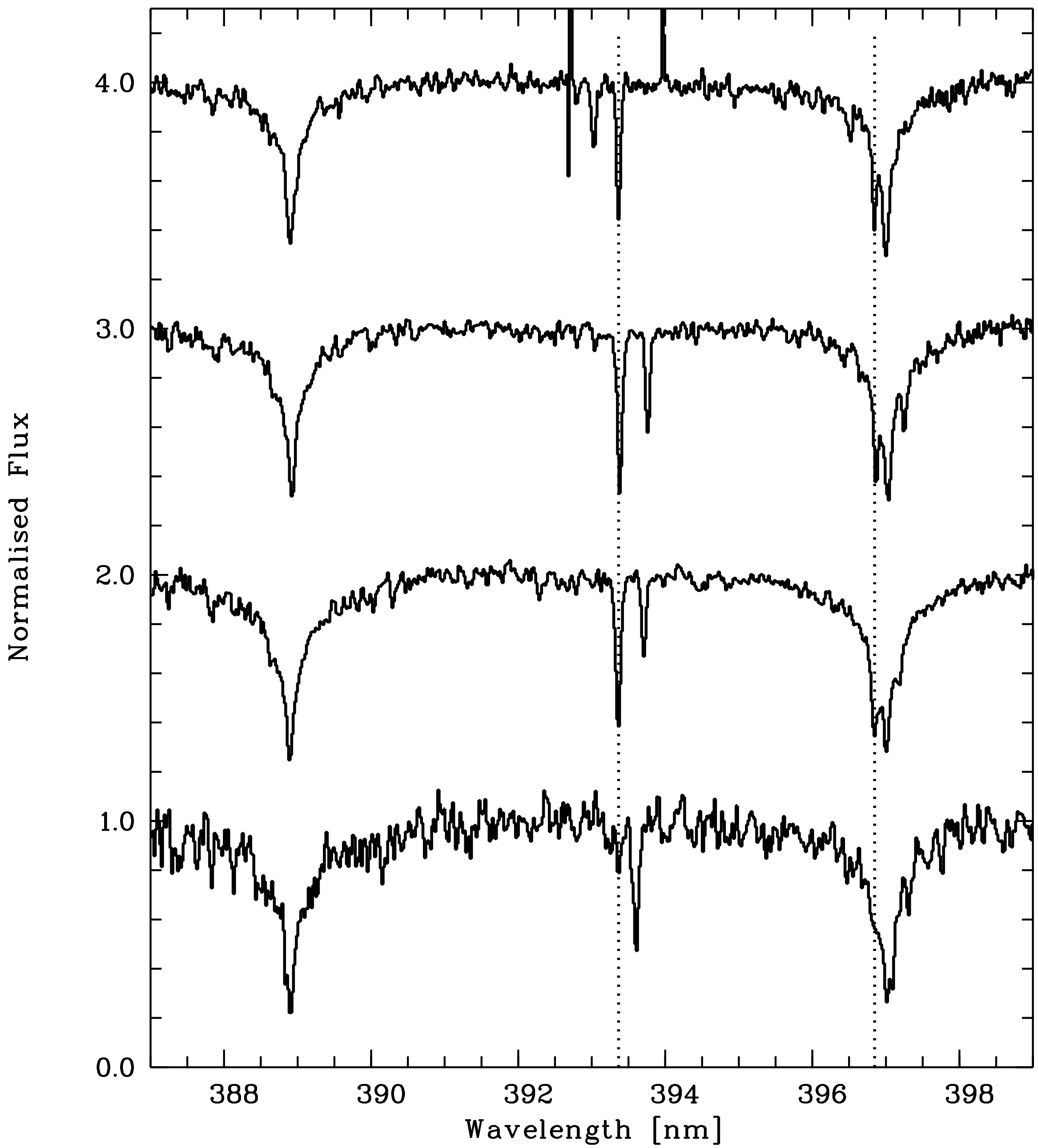
$[Fe/H] = -3.24 \pm 0.24$

$[Fe/H] = -3.52 \pm 0.14$

$[Fe/H] = -3.49 \pm 0.32$

Caffau et al. 2011 A&A

Other interesting stars from the GTO July 2012



[Fe/H]=−4.1

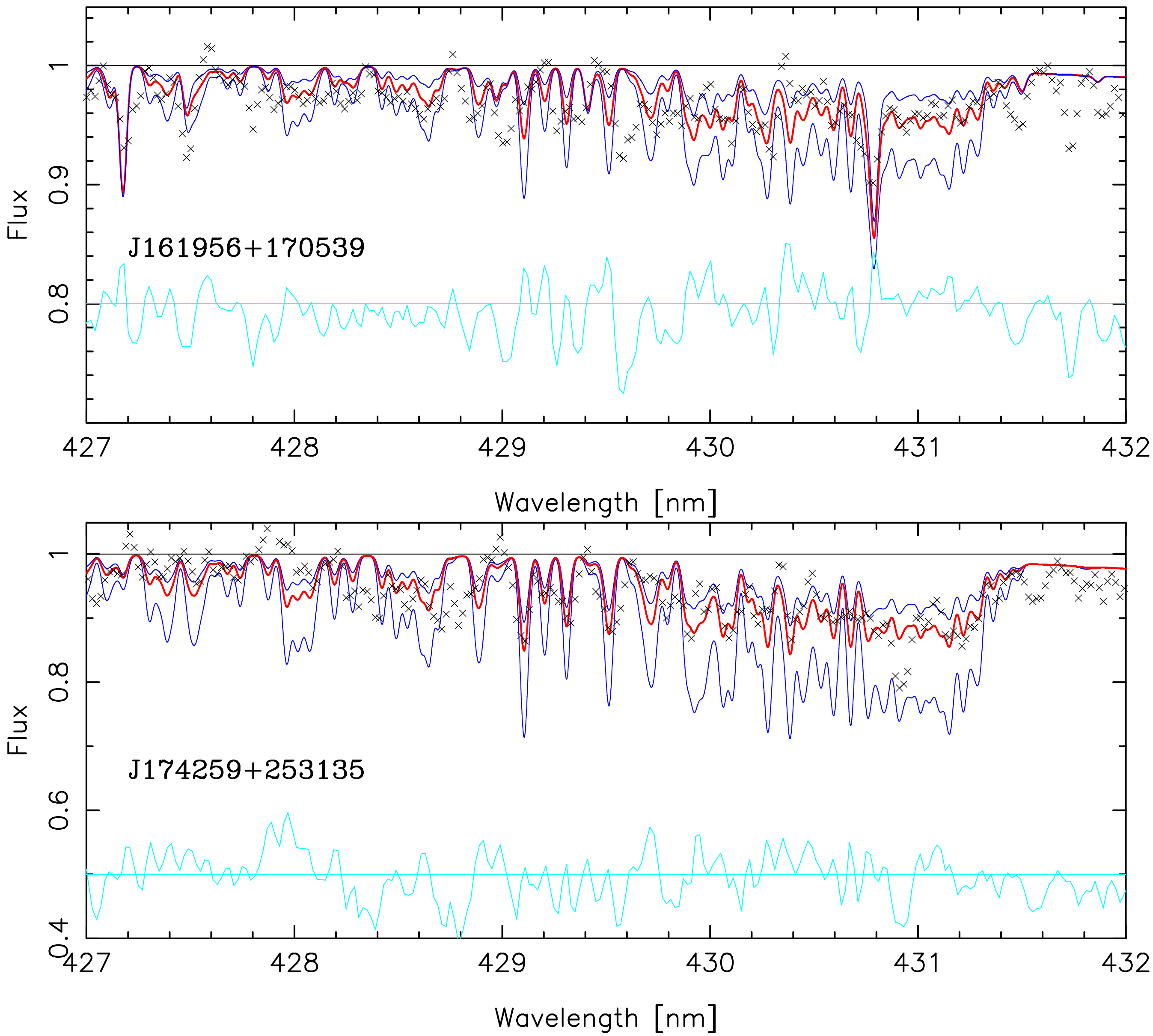
α low

CEMP, α low

CEMP, [Fe/H]=-4.8

Caffau et al. 2013 A&A

Two more CEMP stars



SDSS J161956+150539
6191/4.0/–3.57
A(C)=7.1

SDSS J174259+253135
6345/4.0/–5.00
A(C)=7.4

Observations: high resolution follow-up

Turn Off Primordial Stars

PI Elisabetta Caffau
20 researchers
10 laboratories
5 countries

Tragets: Turn-Off stars

- Large Programme Observations:
  - 120 h X-Shooter (medium resolution)
  - 30 h UVES (high resolution)
- Other observations:
  - 82 h UVES
  - 3 night X-Shooter
  - 3 nights Subaru

- Present/Future
  - CoI of the Gaia ESO Survey: 300 nights @FLAMES-VLT 2012-2016
  - Gaia satellite observations (expected in 2015)
  - High-resolution observations: UVES and X-Shooter @ESO, Subaru, LBT, . . .

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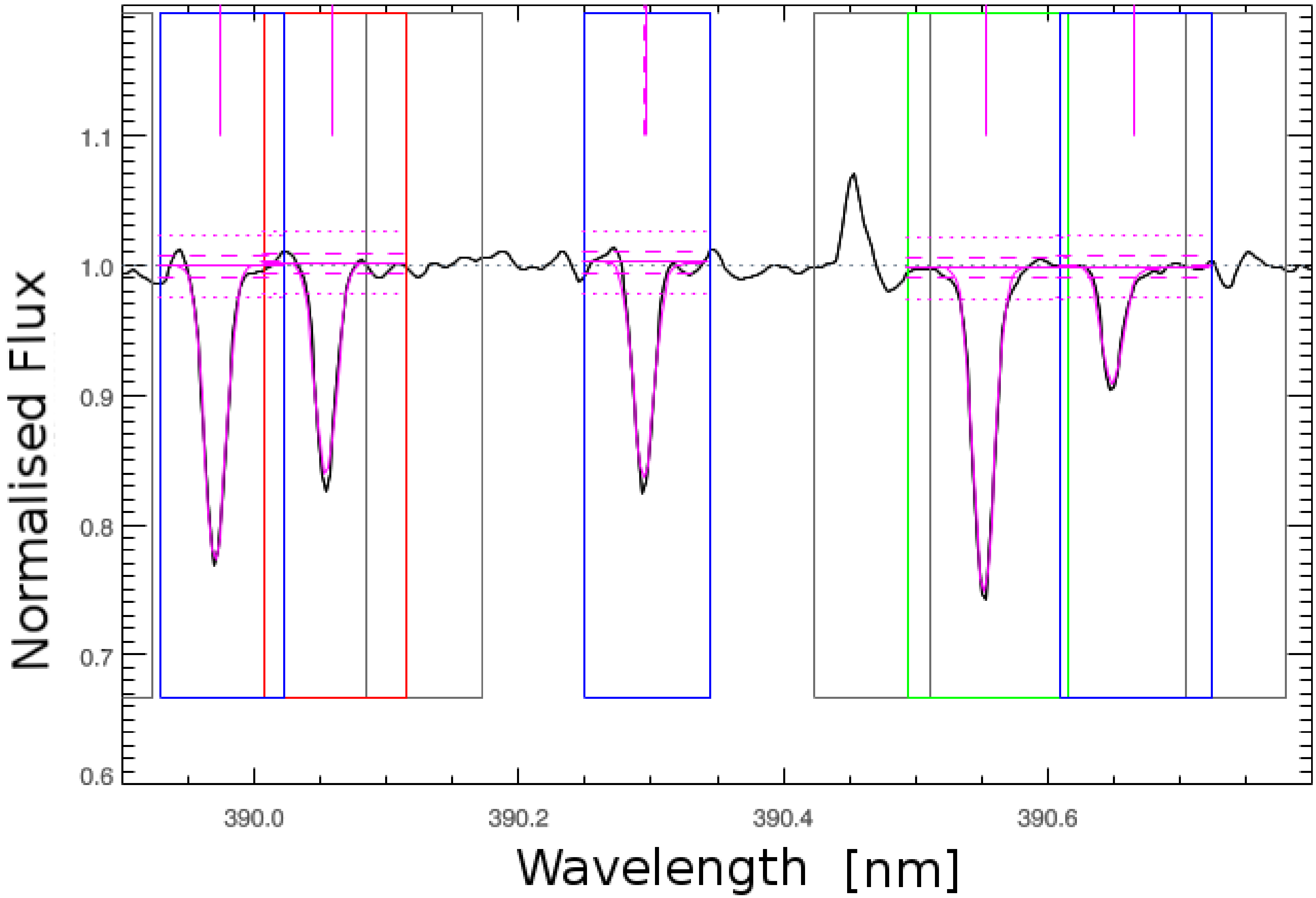
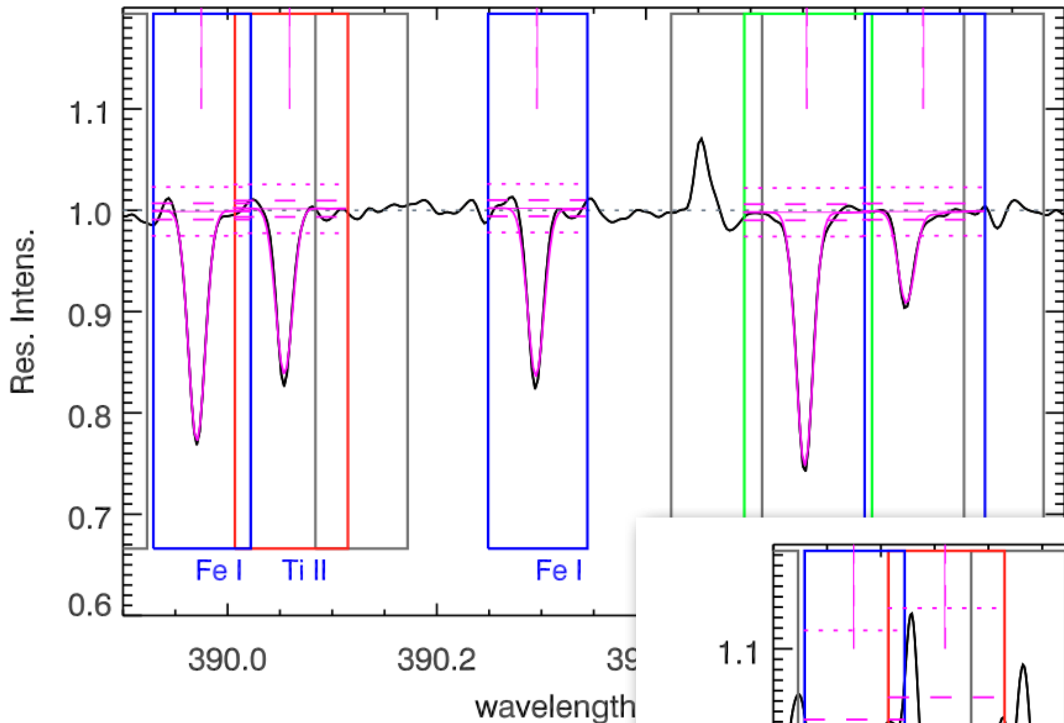
Analysis of high resolution spectra: automatic code MyGIsFOS

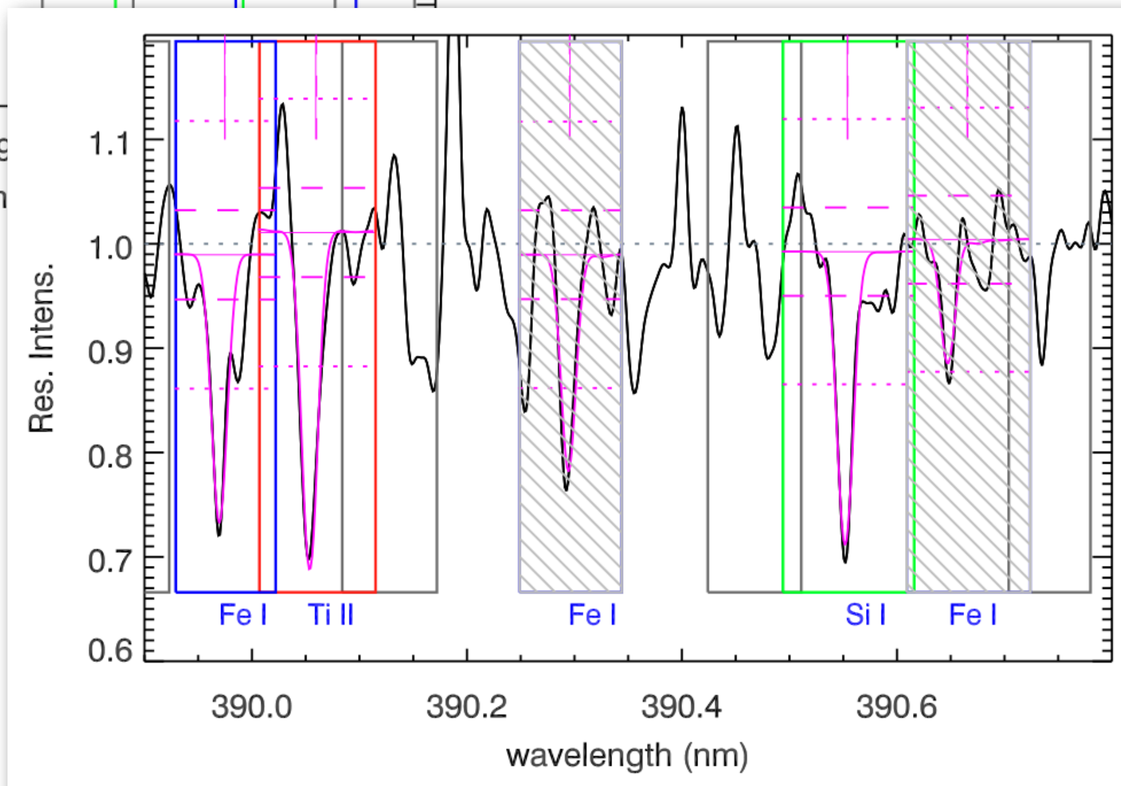


Data quality: UVES

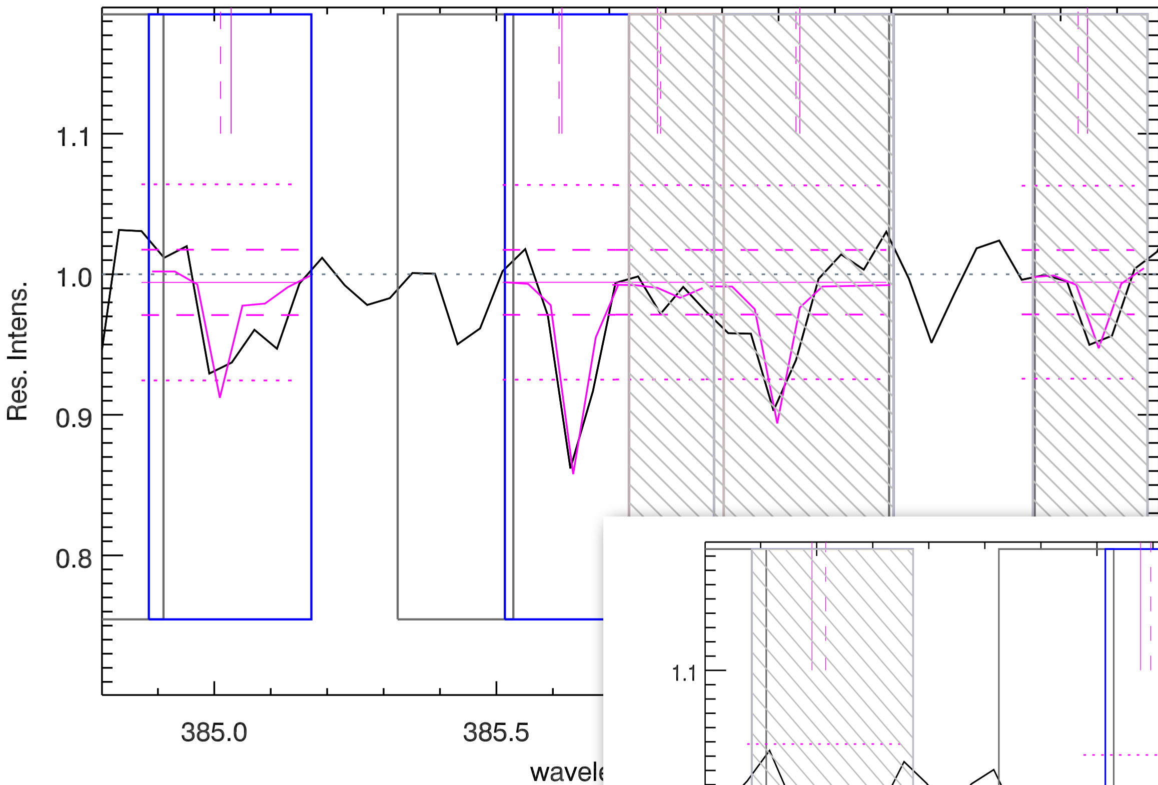


6422 K
[Fe/H] -3.27
S/N~110

6452 K
[Fe/H] -3.29
S/N~32

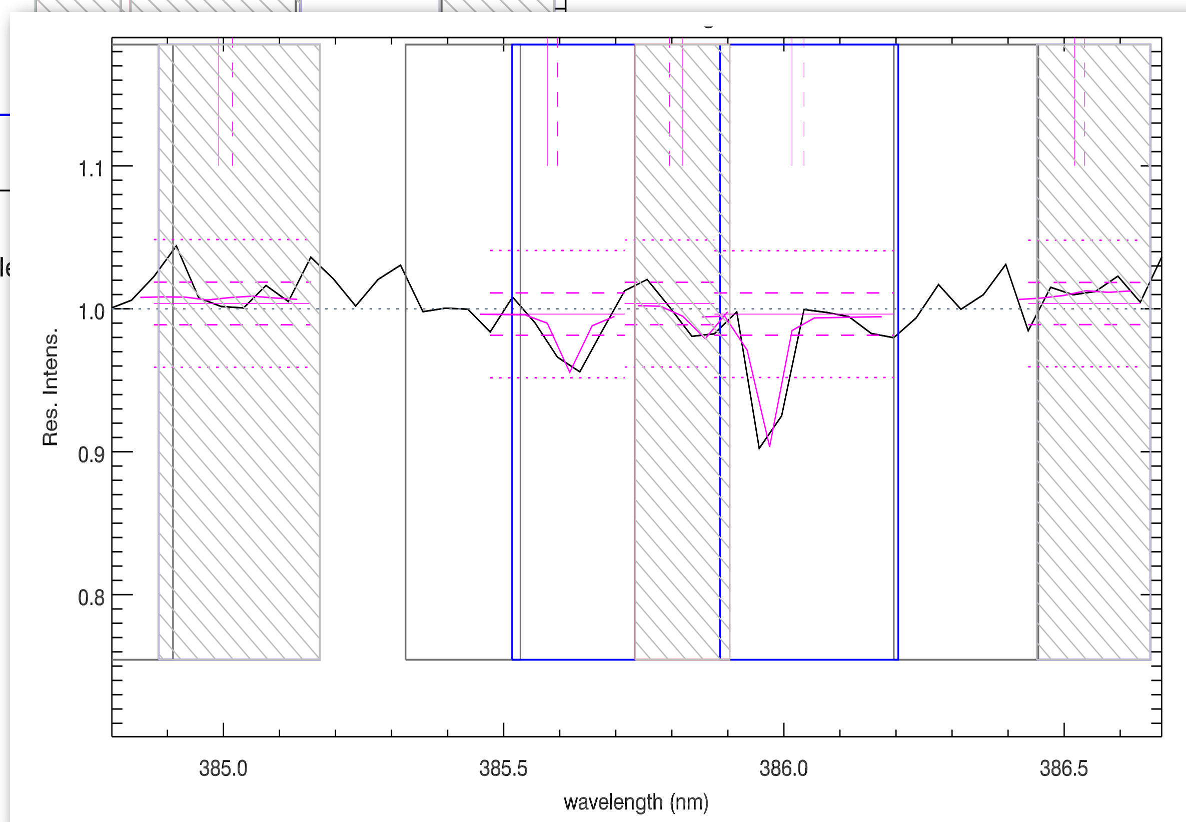


Data quality: X-Shooter



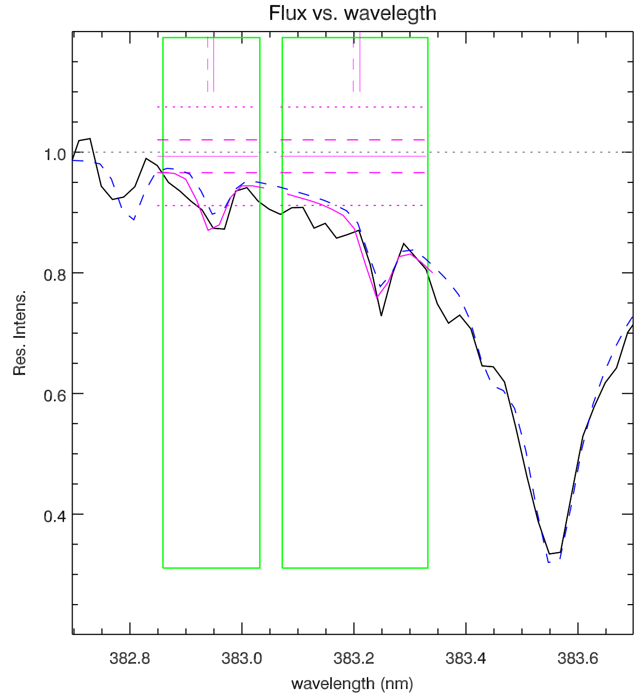
6392 K
[Fe/H] -3.13
S/N~40

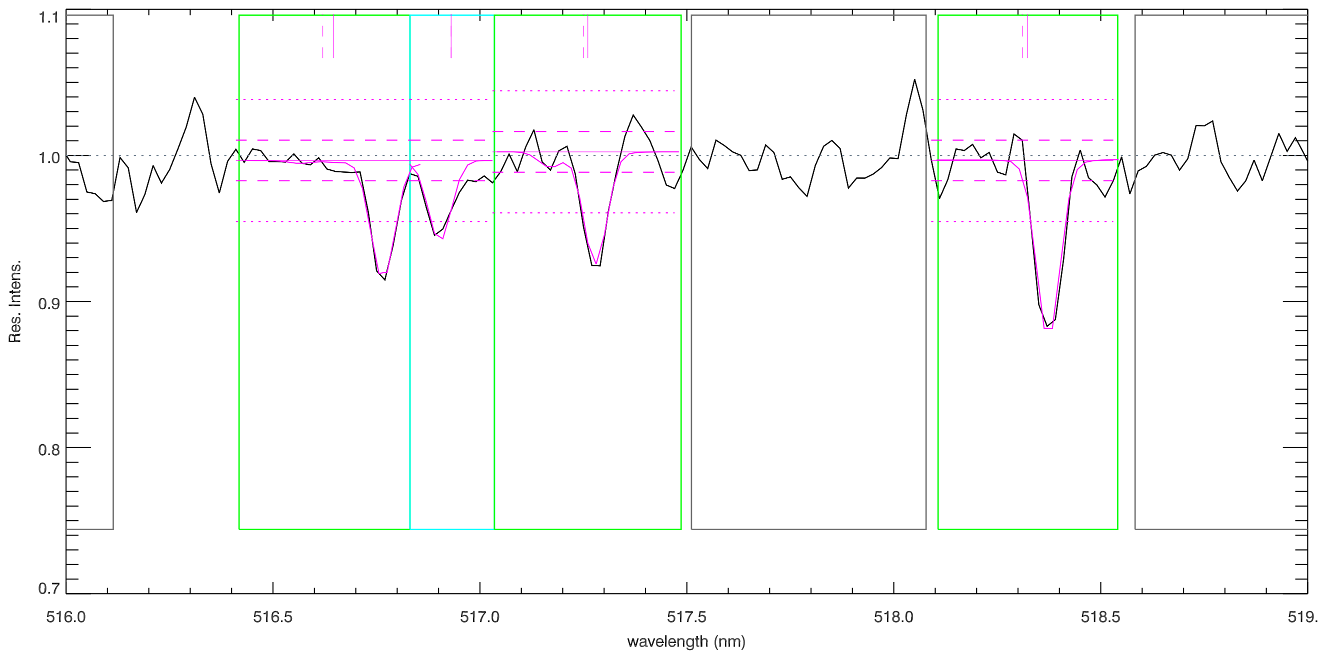
6332 K
[Fe/H] -4.1
S/N~70



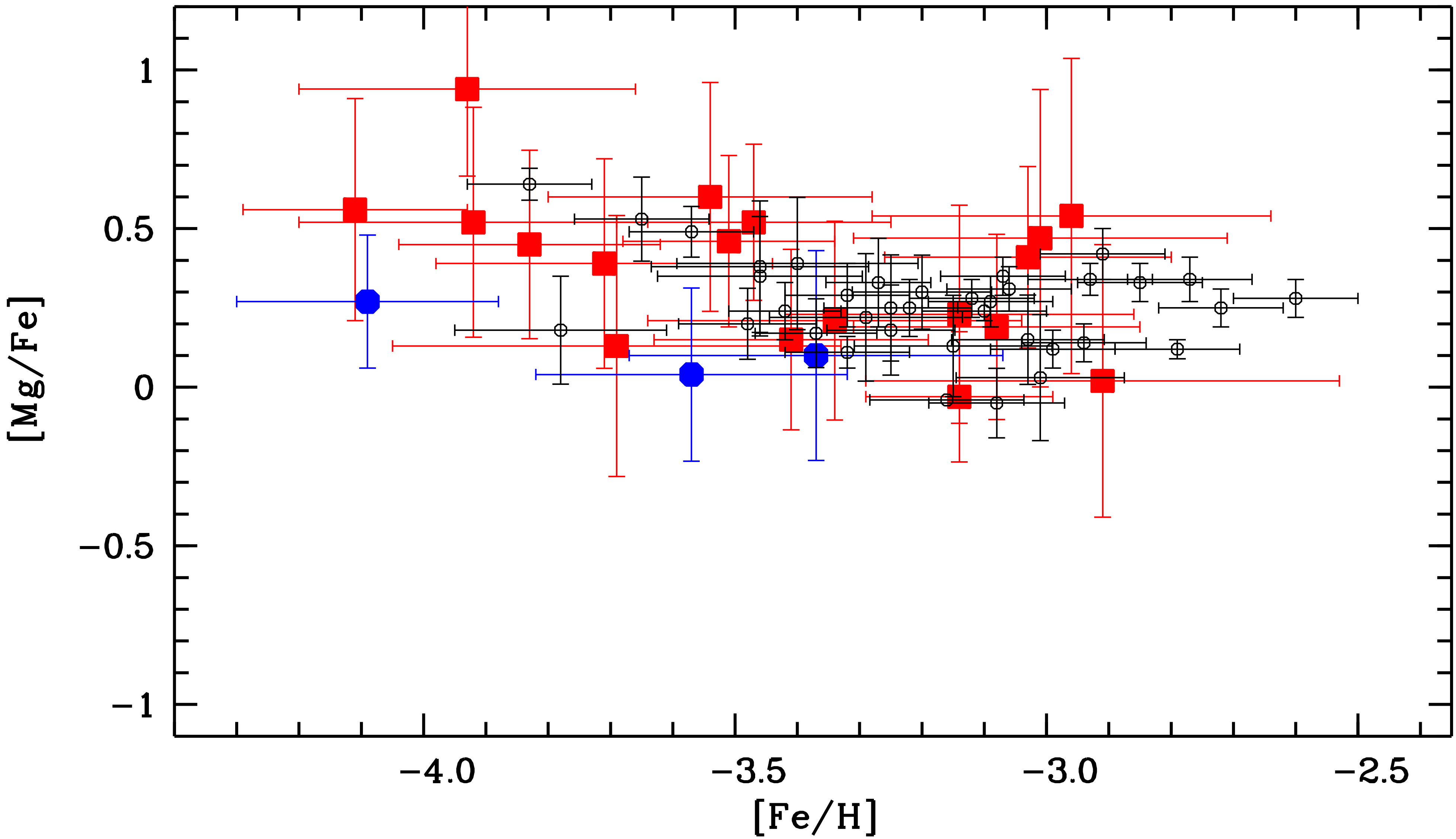
MgI lines

for [α/Fe] determination



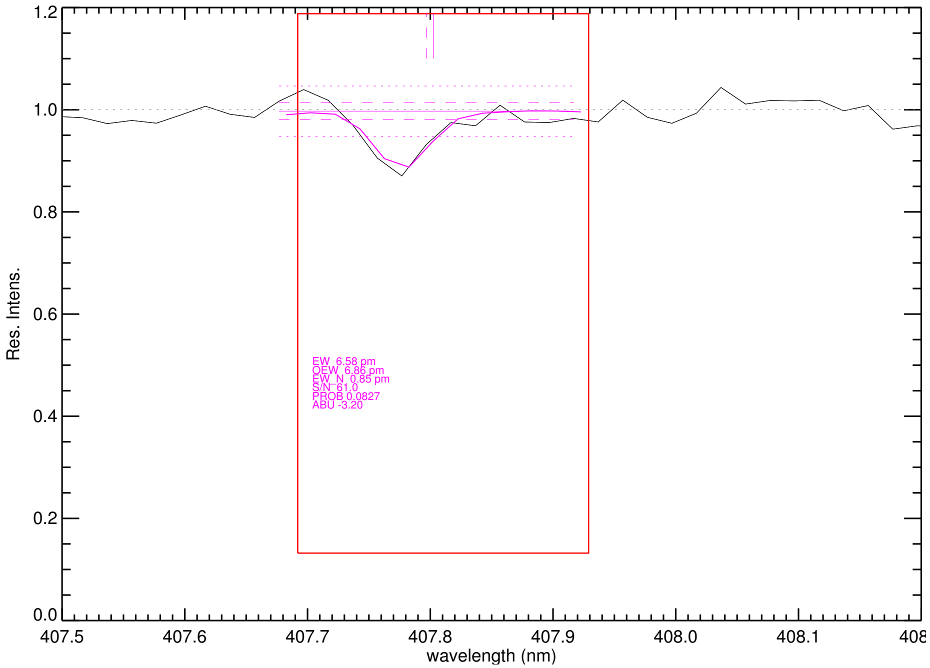


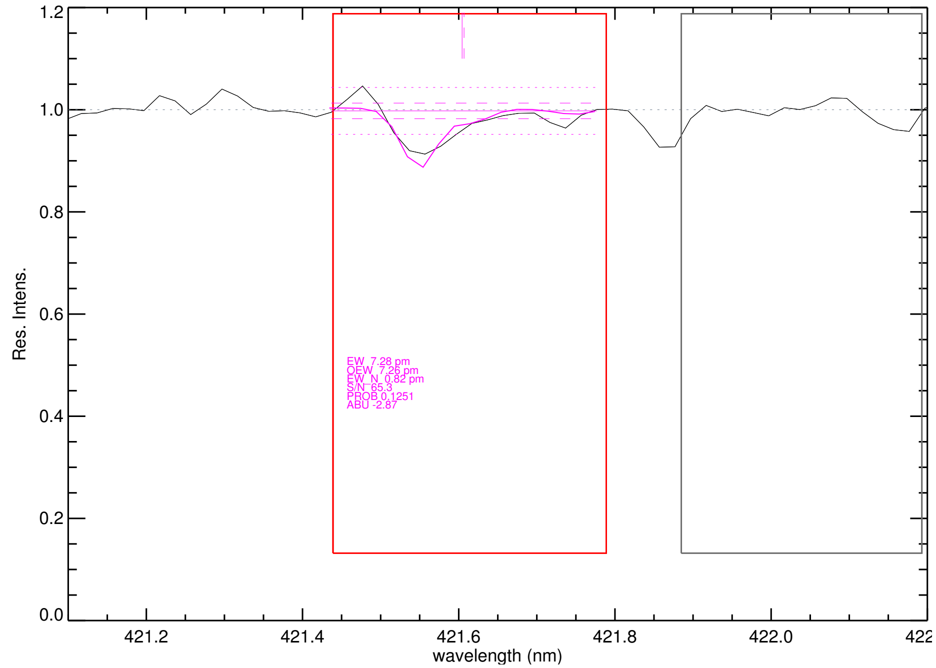
[Mg/Fe] vs. [Fe/H]

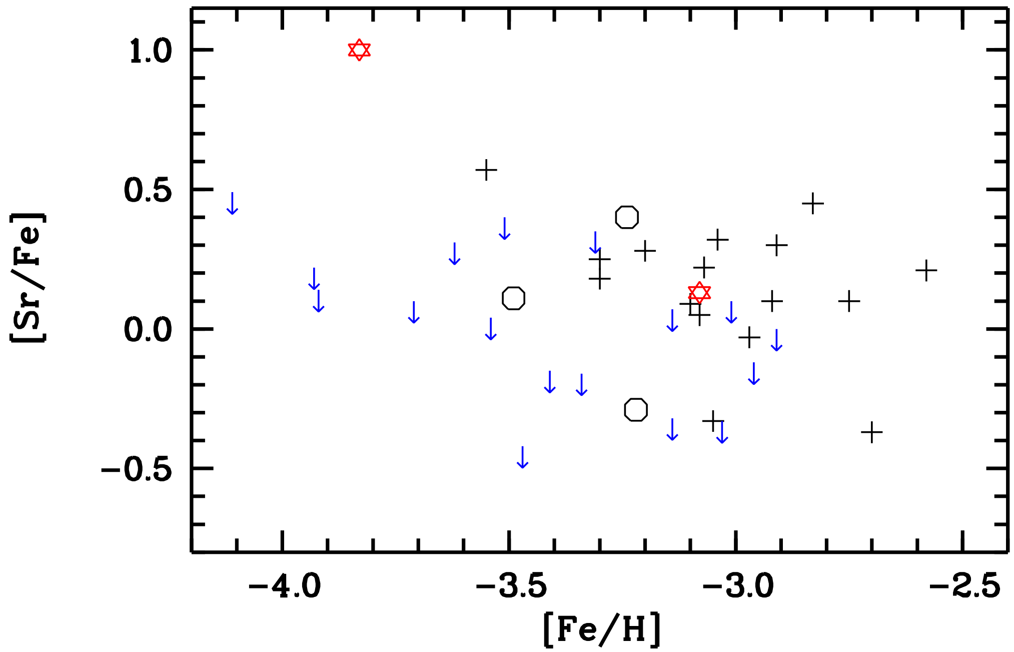


Caffau et al. (2013)

Strontium

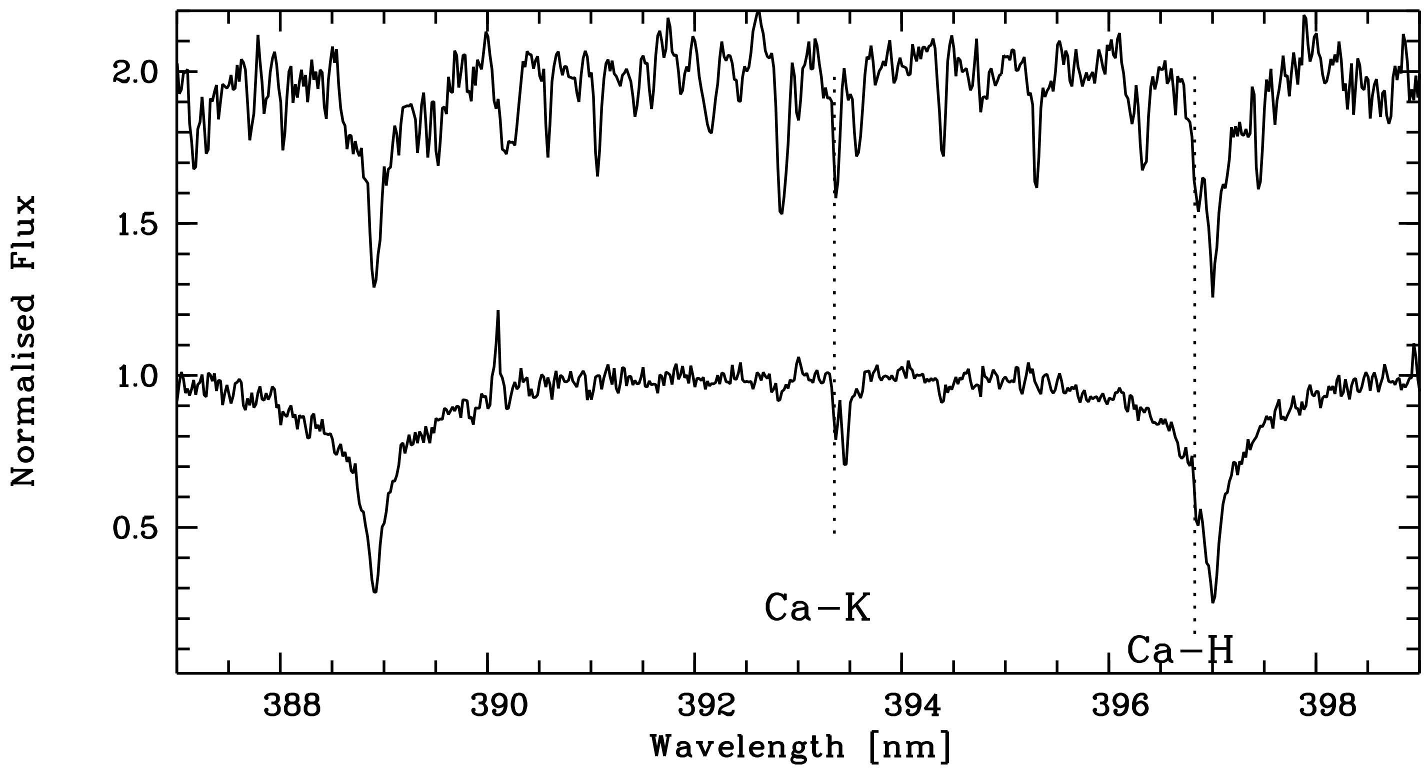

Res. Intens.
wavelength (nm)
EW_6.58 pm
OEW_6.86 pm
EW_N_0.85 pm
S/N_61.0
PROB 0.0827
ABU -3.20


Res. Intens.
wavelength (nm)
EW_7.28 pm
OEW_7.26 pm
EW_N_0.82 pm
S/N_65.3
PROB 0.1251
ABU -2.87


[Sr/Fe]
[Fe/H]

TOPoS: first results

- **105 TO stars selected**
  - **100 stars with $[Fe/H] \le -3$ (doubled known sample);**
  - **28 stars with $[Fe/H] \le -3.5$;**
  - **6 stars with $[Fe/H] \le -4$ (9 stars known before our program);**
  - **4 stars with $[Fe/H] \le -4.5$ of which three CEMP.**



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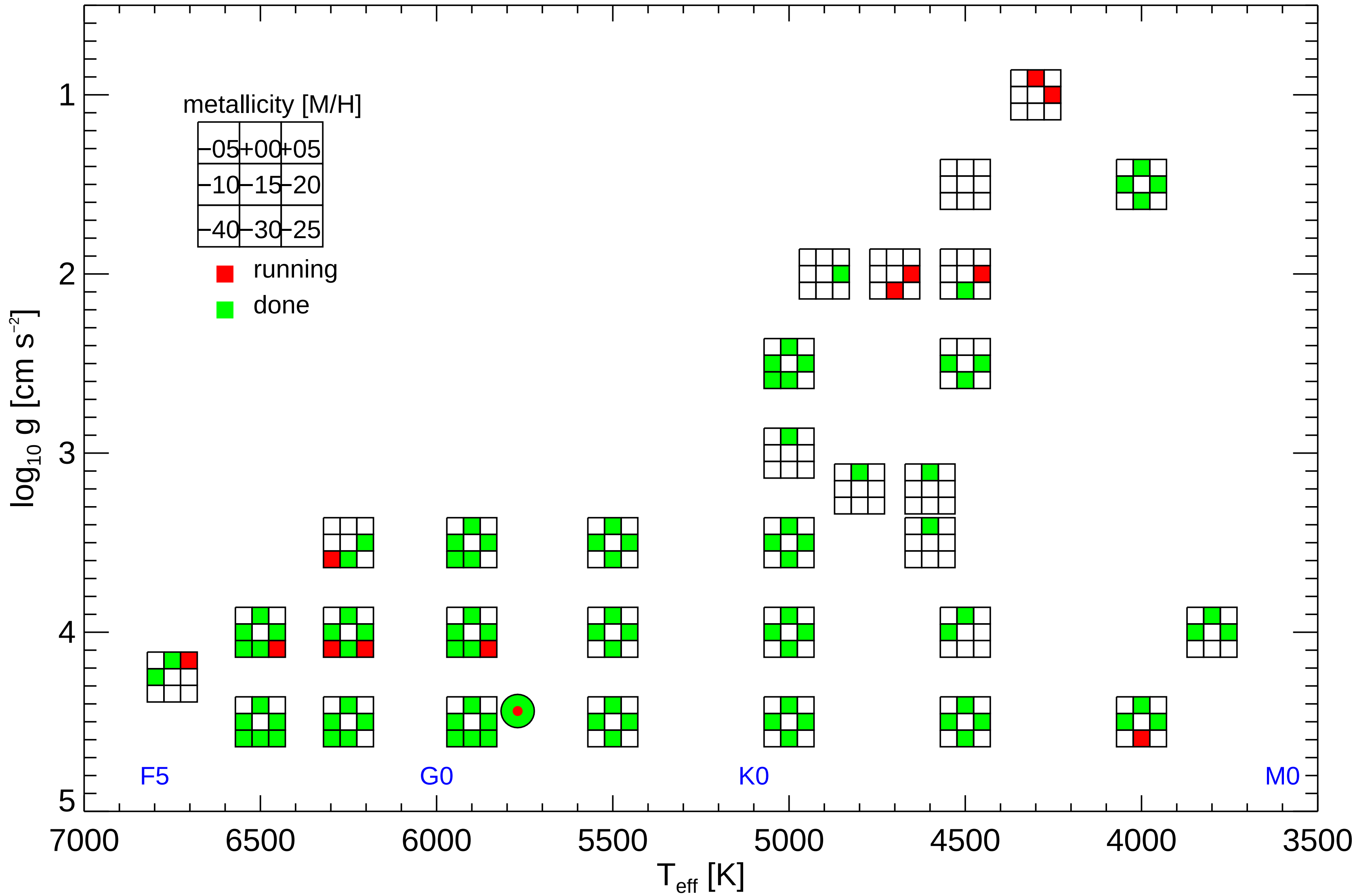
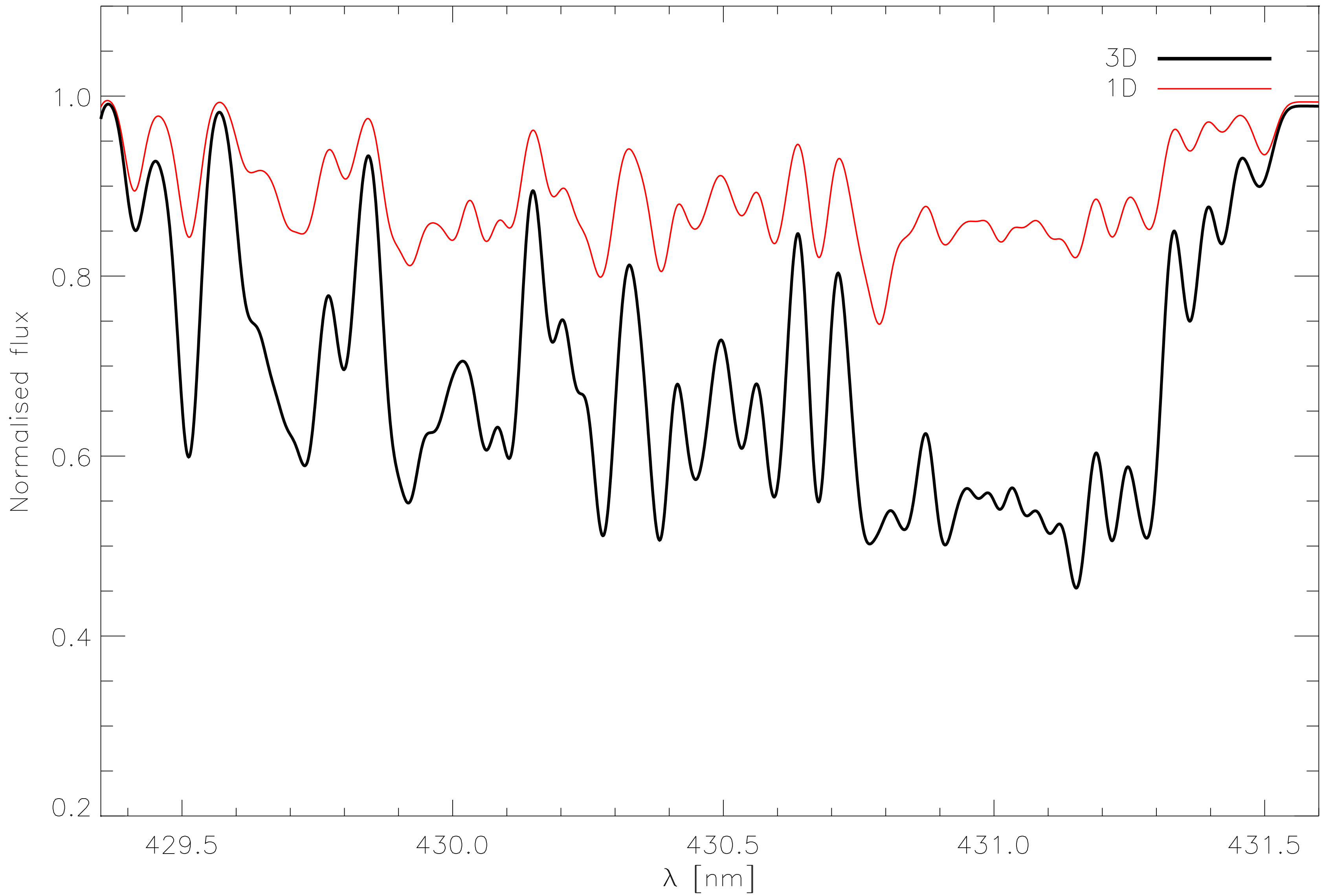
The CIFIST



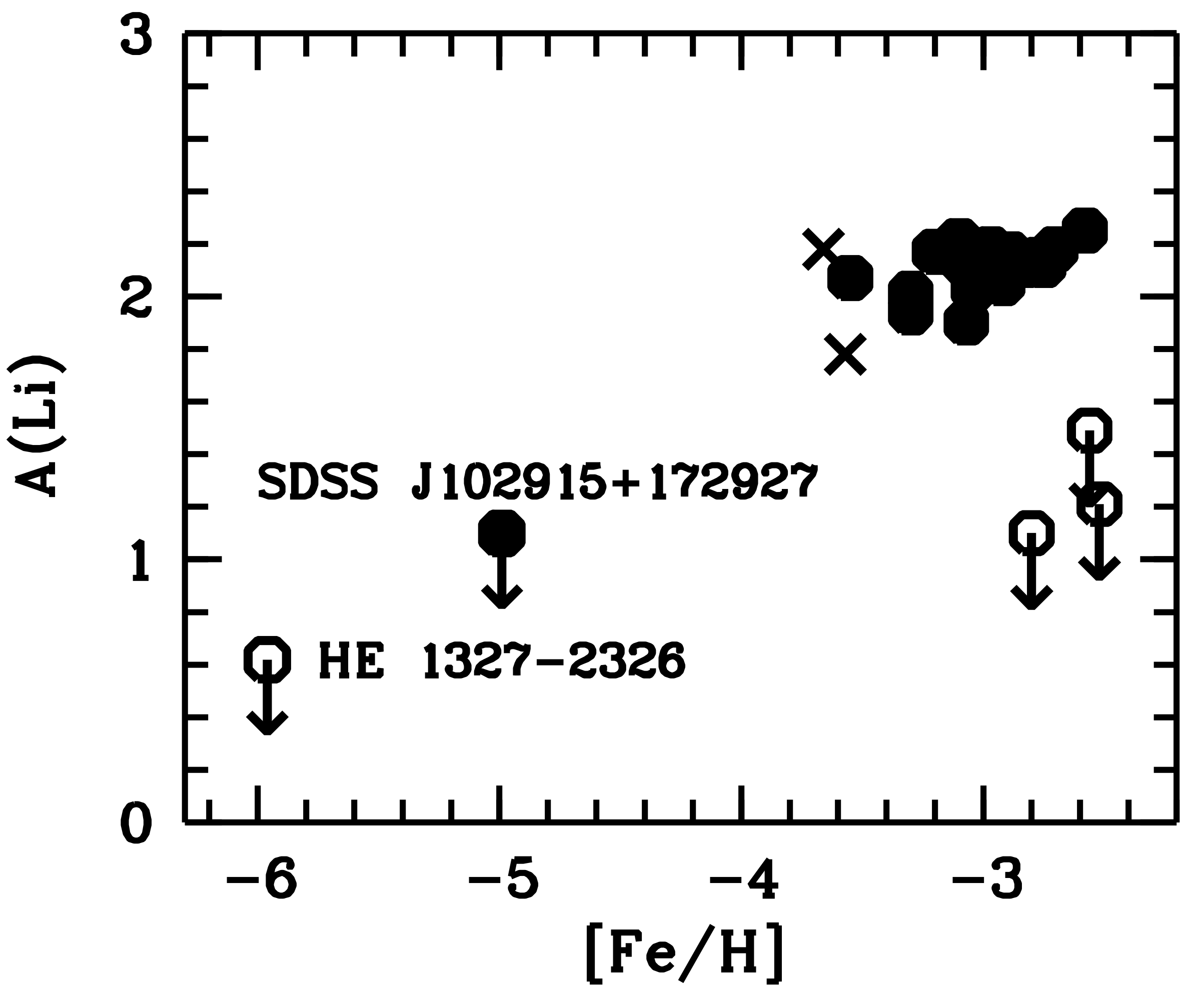
metallicity [M/H]
−05
+00
+05
−10
−15
−20
−40
−30
−25
running
done
1
2
3
4
5
log$_{10}$ g [cm s^{-2}]
F5
G0
K0
M0
7000
6500
6000
5500
5000
4500
4000
3500
T$_{eff}$ [K]

The G-band

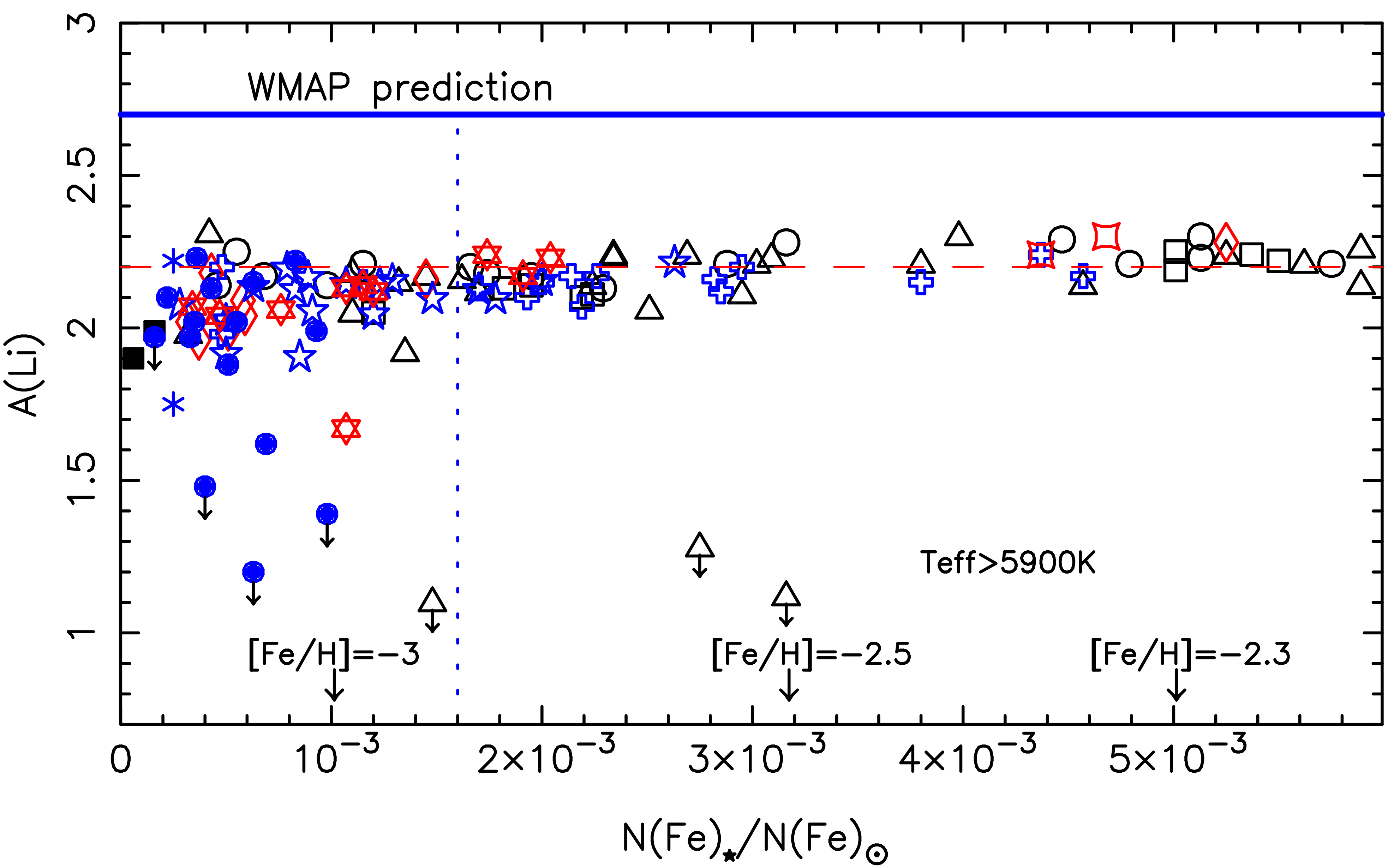


From A. Gallagher

NLTE analysis: Li, C, N, O, Si; Na, Mg, Sr, Ba (Andrievsky); Fe (Mashonkina)



Spite plateau



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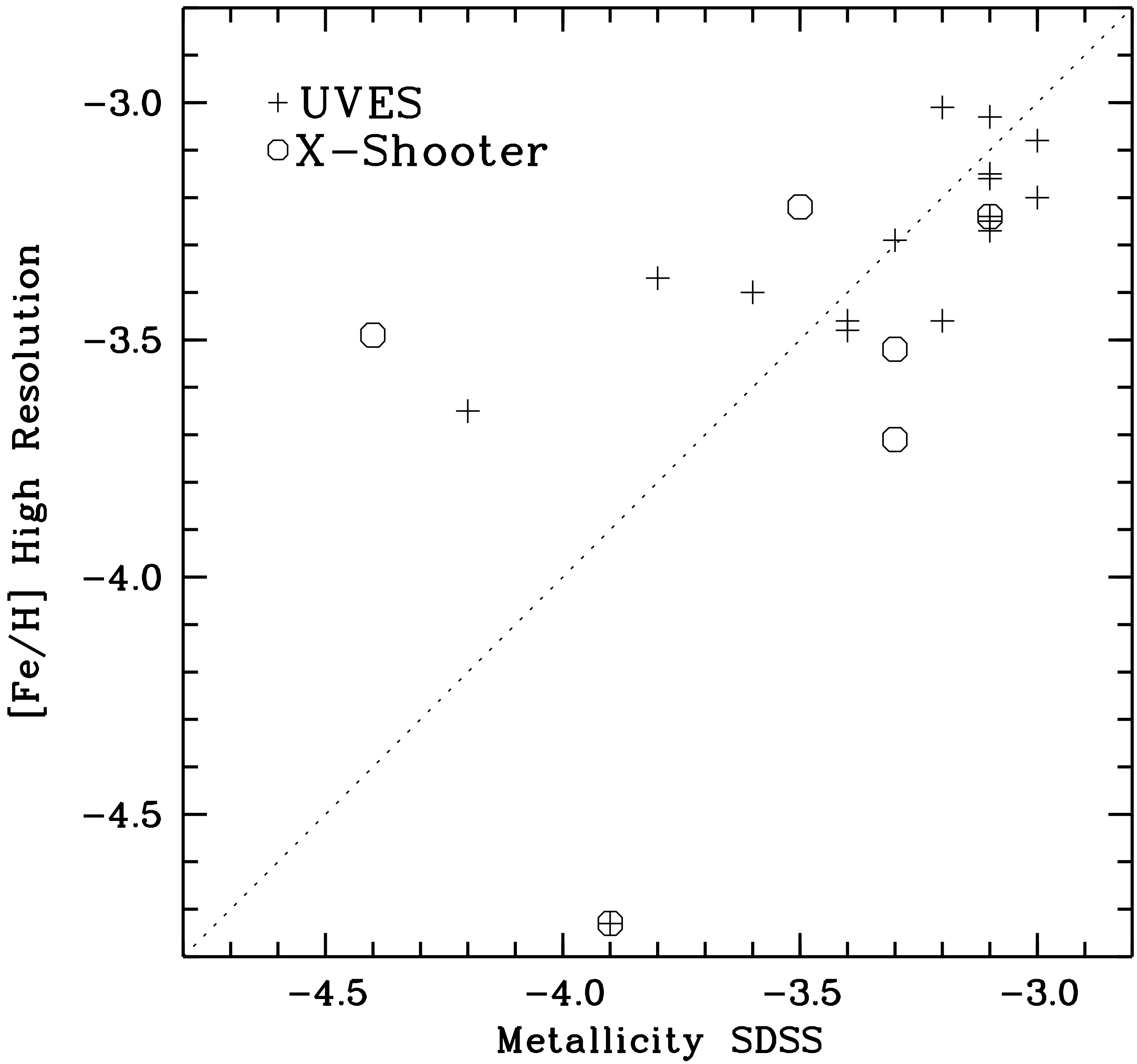
Calibration



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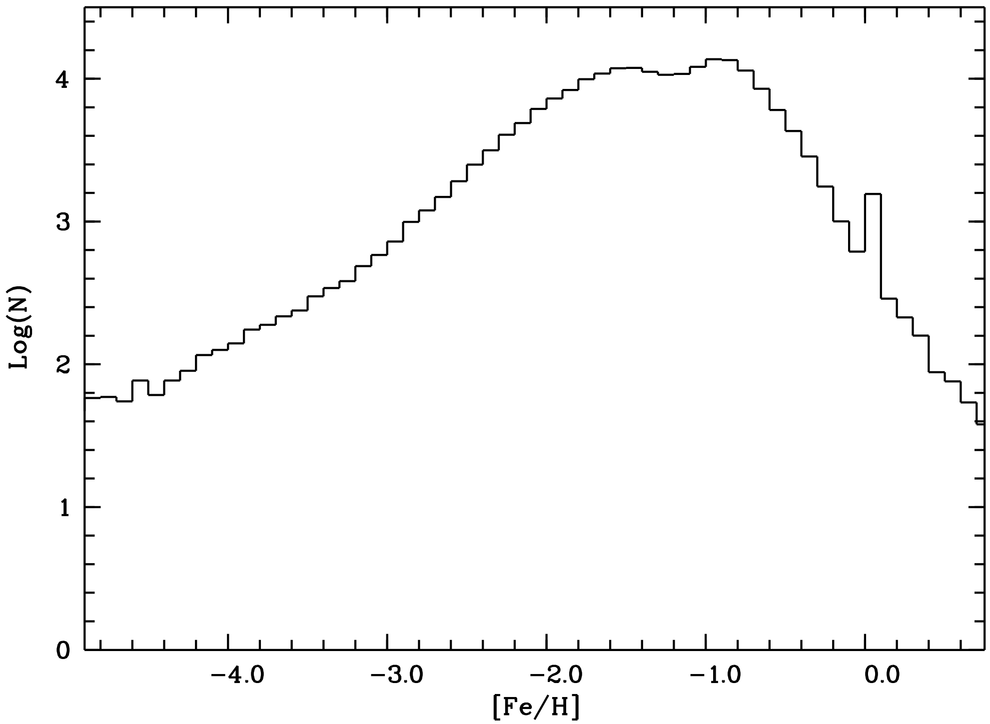
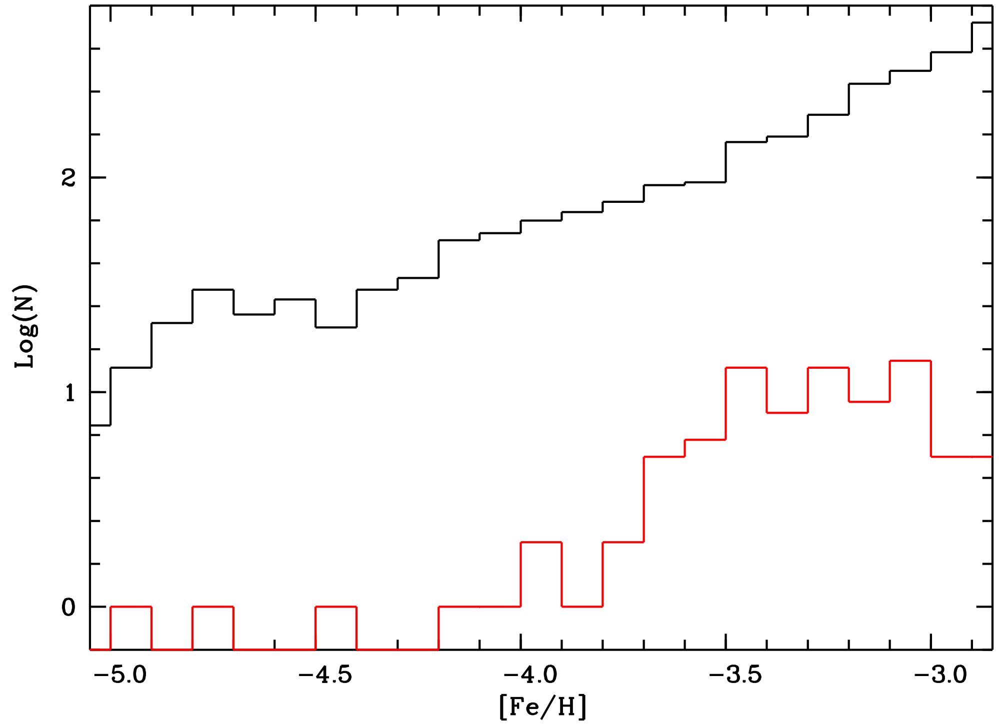
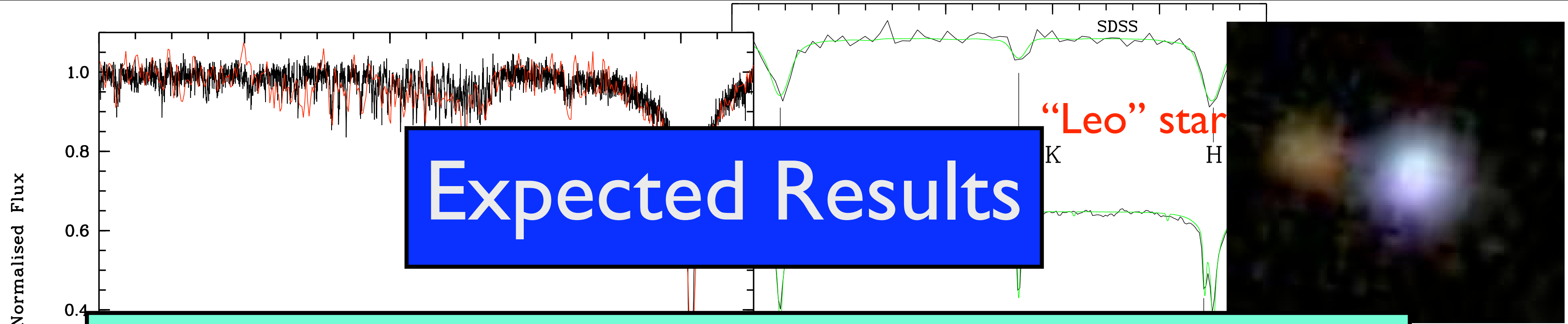
Metallicity Distribution Function





MDF from SDSS-DR9 (182 807 TO stars)

MP-component of MDF SDSS-DR9 TO stars with $g < 19.5$ and observable from Paranal compared with a sample of 39 stars we analysed



Expected Results

- ★ Do zero-metal low mass stars exist ? (yes/no)
- ★ If not: value of the “critical metallicity”
- ★ Fraction of CEMP/”normal” EMP stars
- ★ Li abundances (Li destruction ?)
- ★ Masses of Pop III massive stars from chemical composition of a large sample of EMP stars