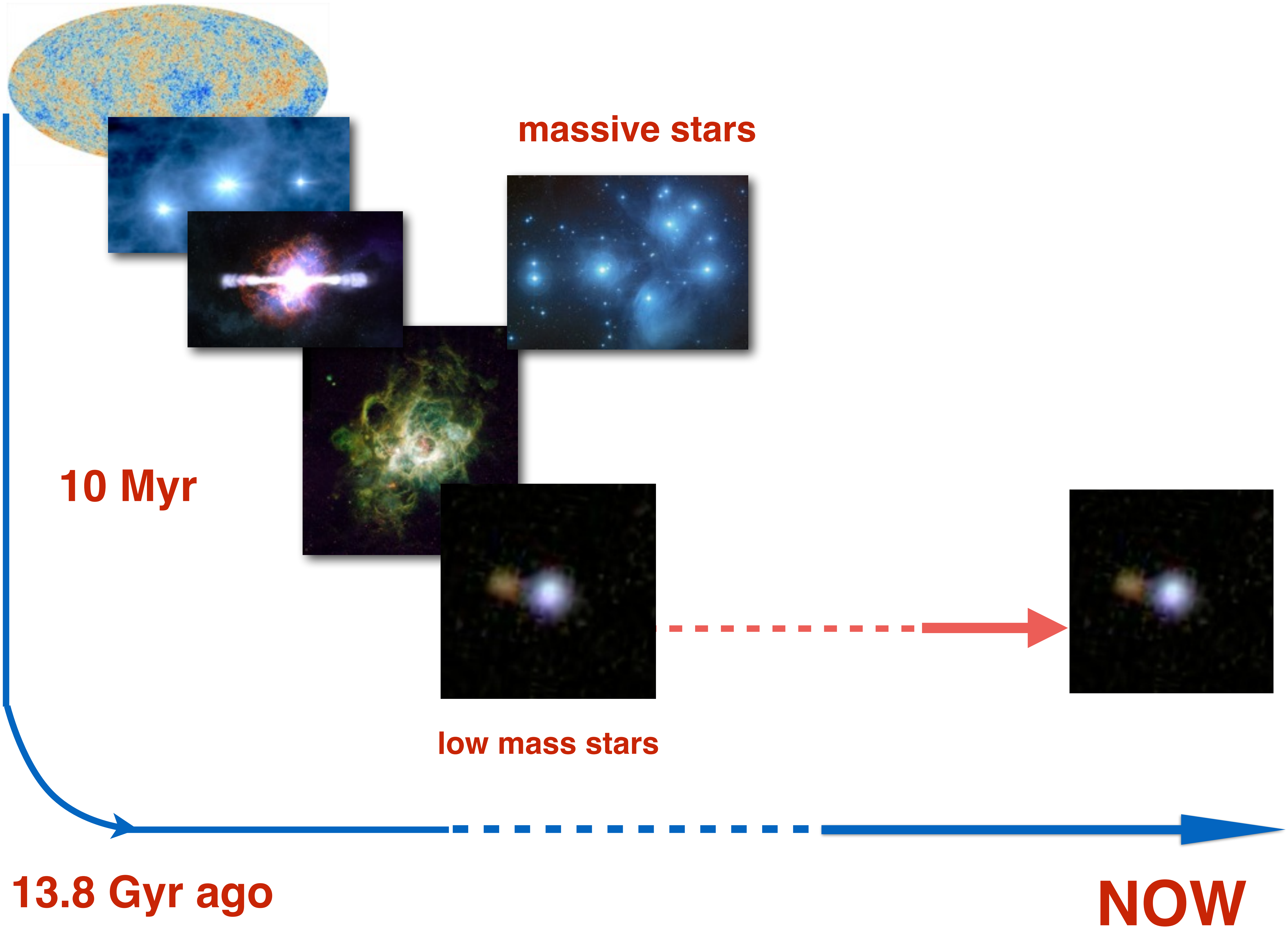
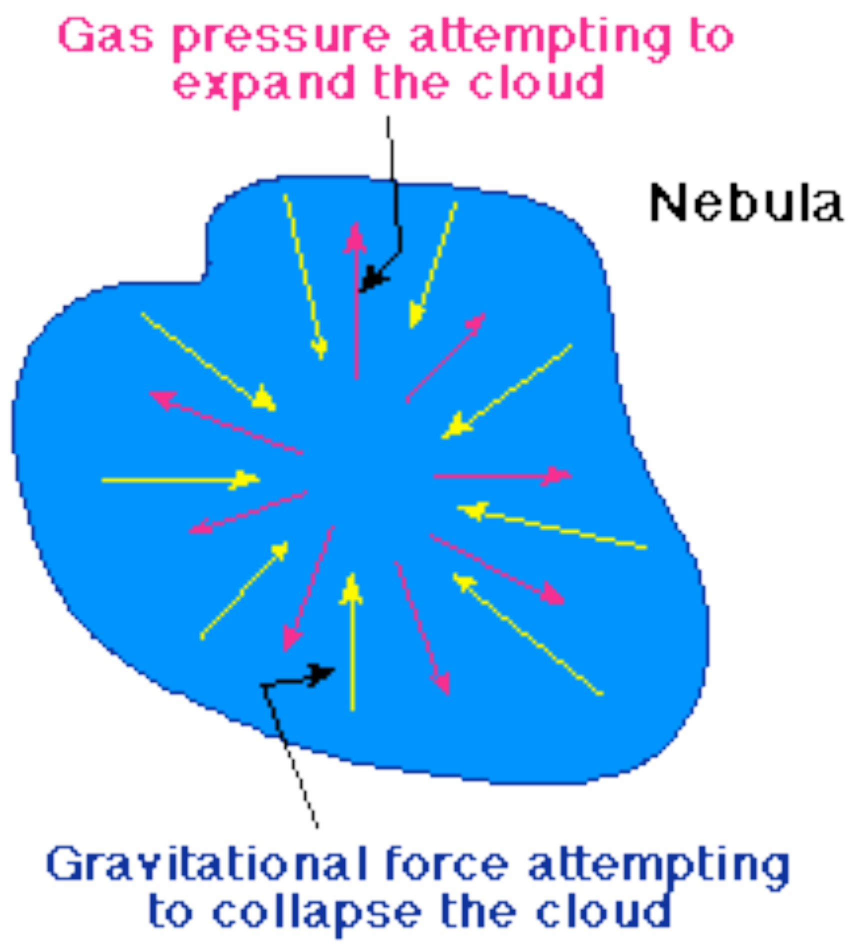
The dawn of star formation: a local perspective

Piercarlo Bonifacio

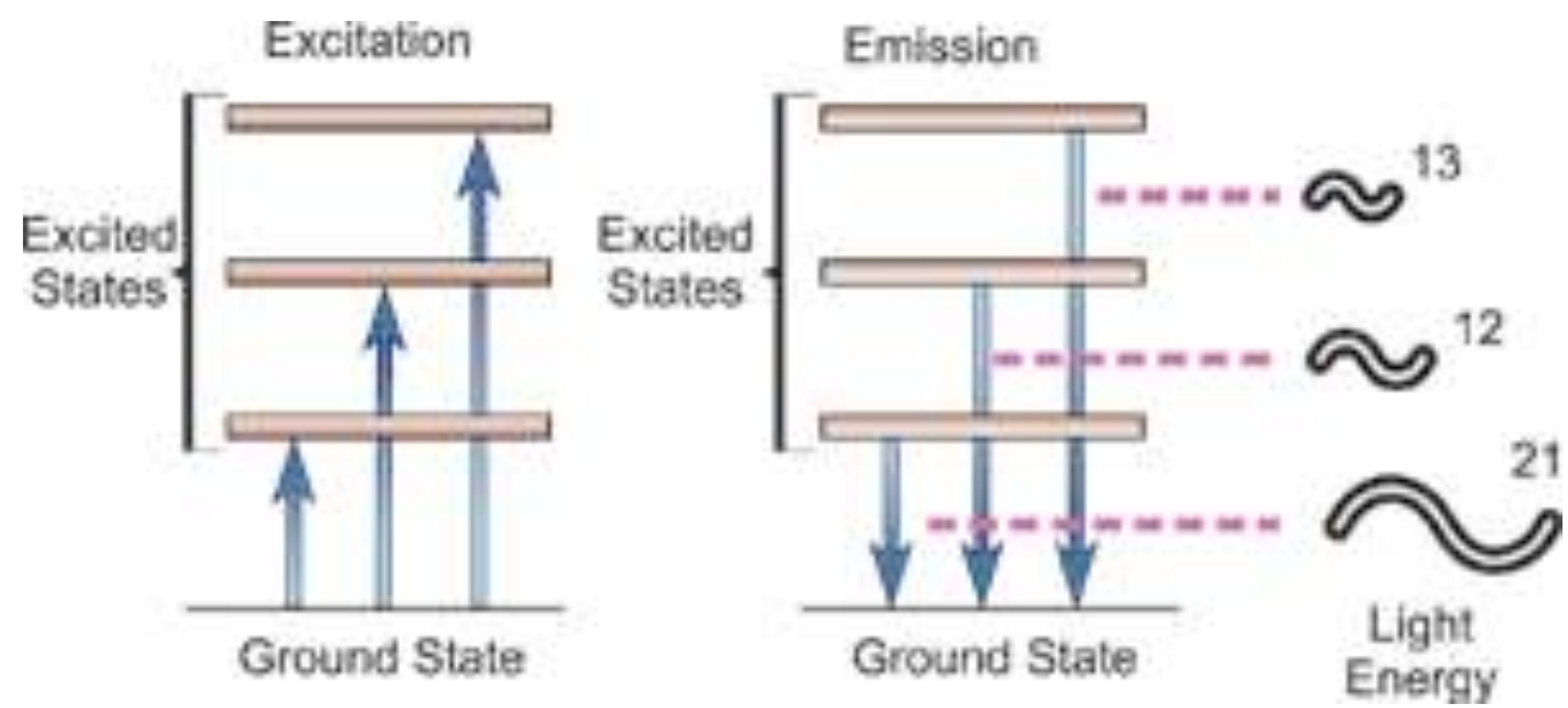


massive stars
10 Myr
low mass stars
13.8 Gyr ago
NOW



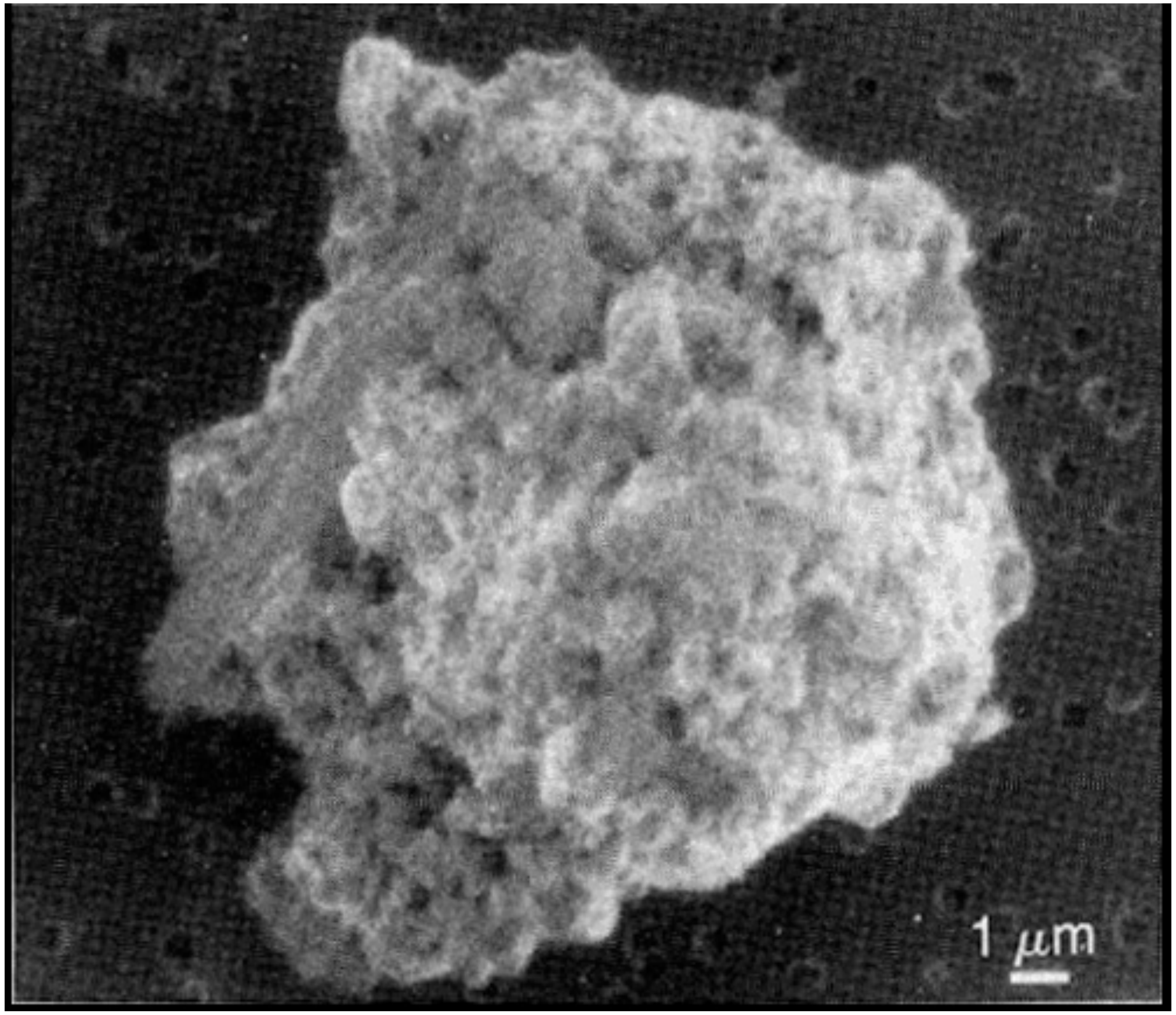
As a gas cloud contracts it heats, PV=nRT, thus also pressure increases, tends to balance the gravitational force. If the mass is small, contraction stops. To keep contracting I need to cool the gas.

Line cooling: collisional excitation, followed by radiative recombination.



Dust cooling

Dust grain collected from the Earth's orbital environment. Likely origin in the ISM.



Collisions with gas particles heat the grains. The energy is then radiated in the IR and these low-energy photons are not absorbed, thus the energy is effectively removed from the thermal pool.

Formation of low mass stars

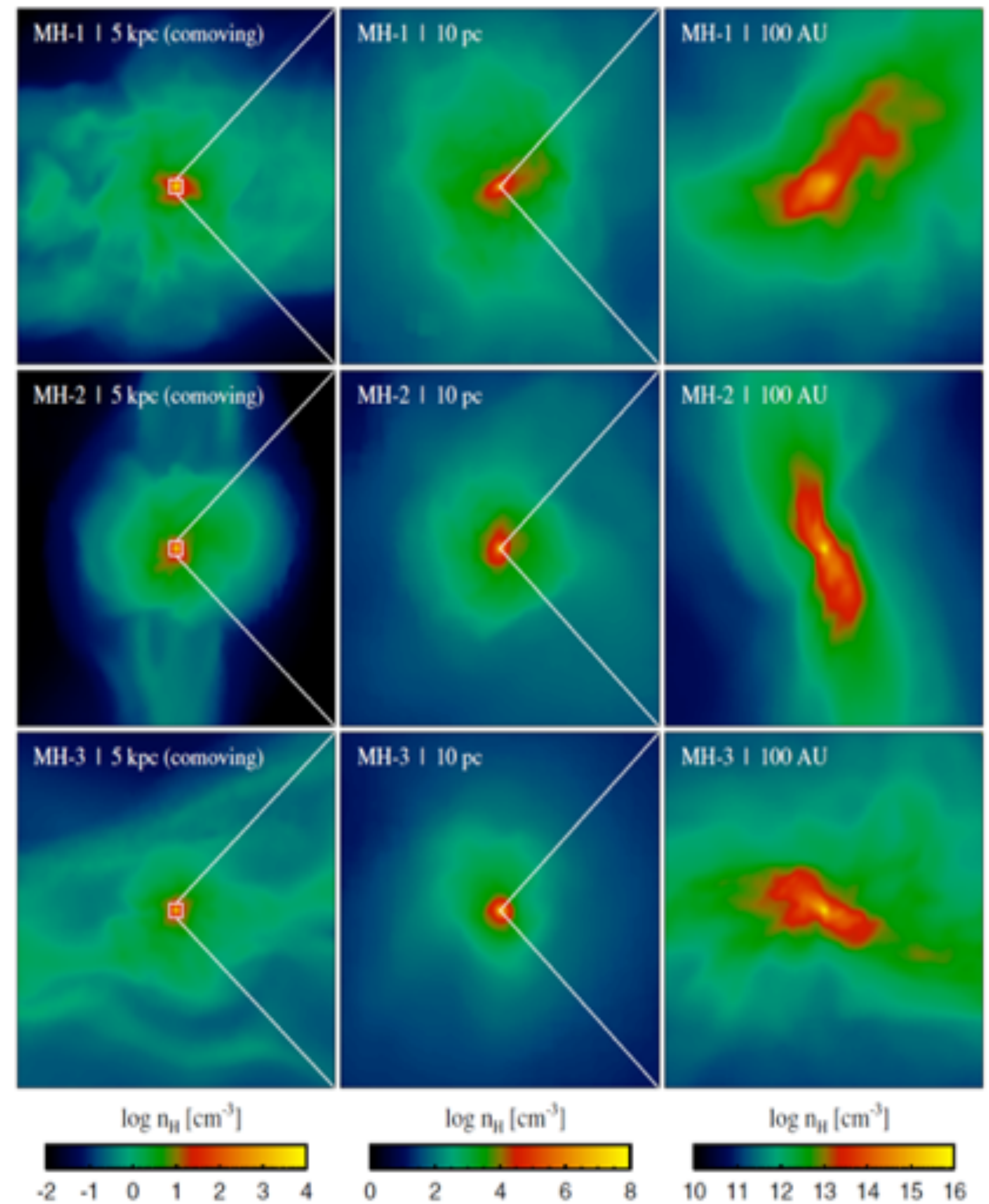
- Zero metallicity ⇒

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

- Metallicity > Zcr⇒

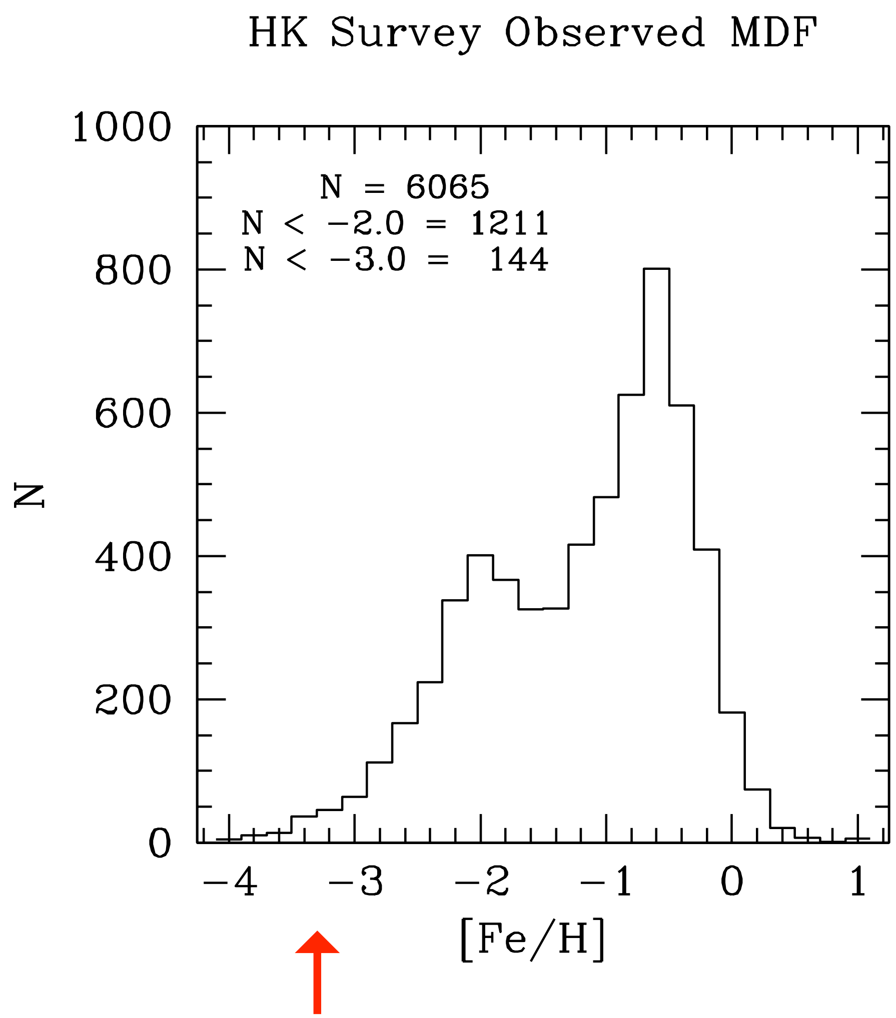
  ★ CII & OI fine structure cooling (Bromm & Loeb 2003)

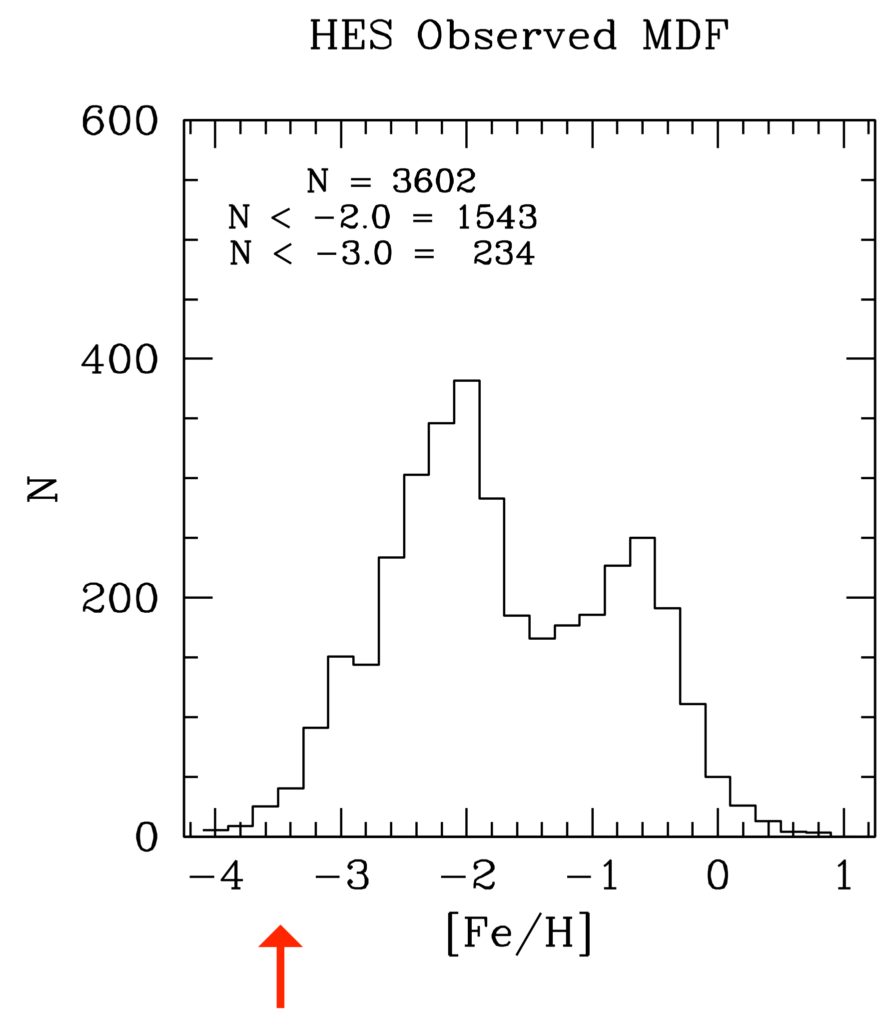
  ★ dust cooling + fragmentation (Schneider et al. 2011)



From Greif et al (2011)

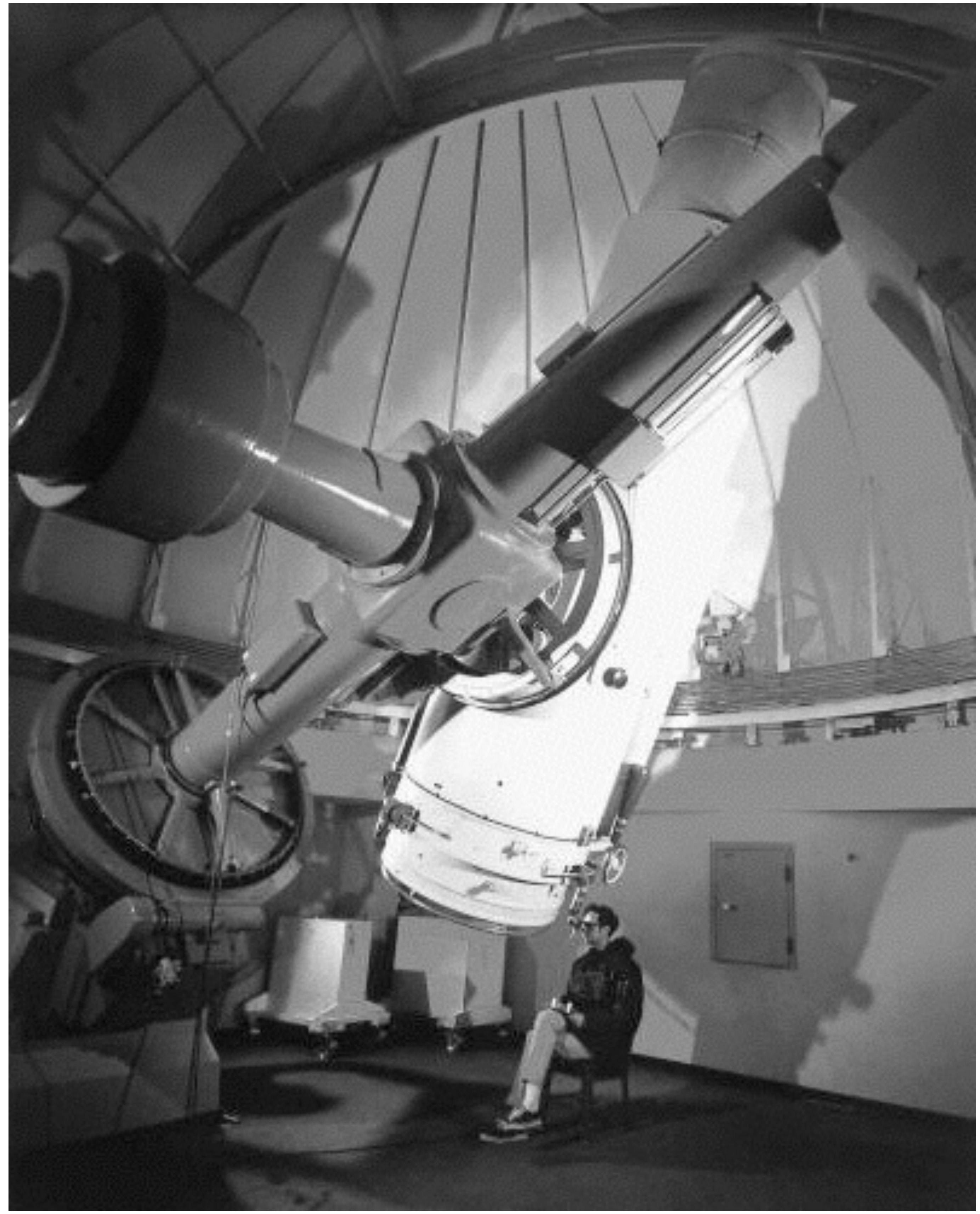
Such stars are exceedingly rare !!!!





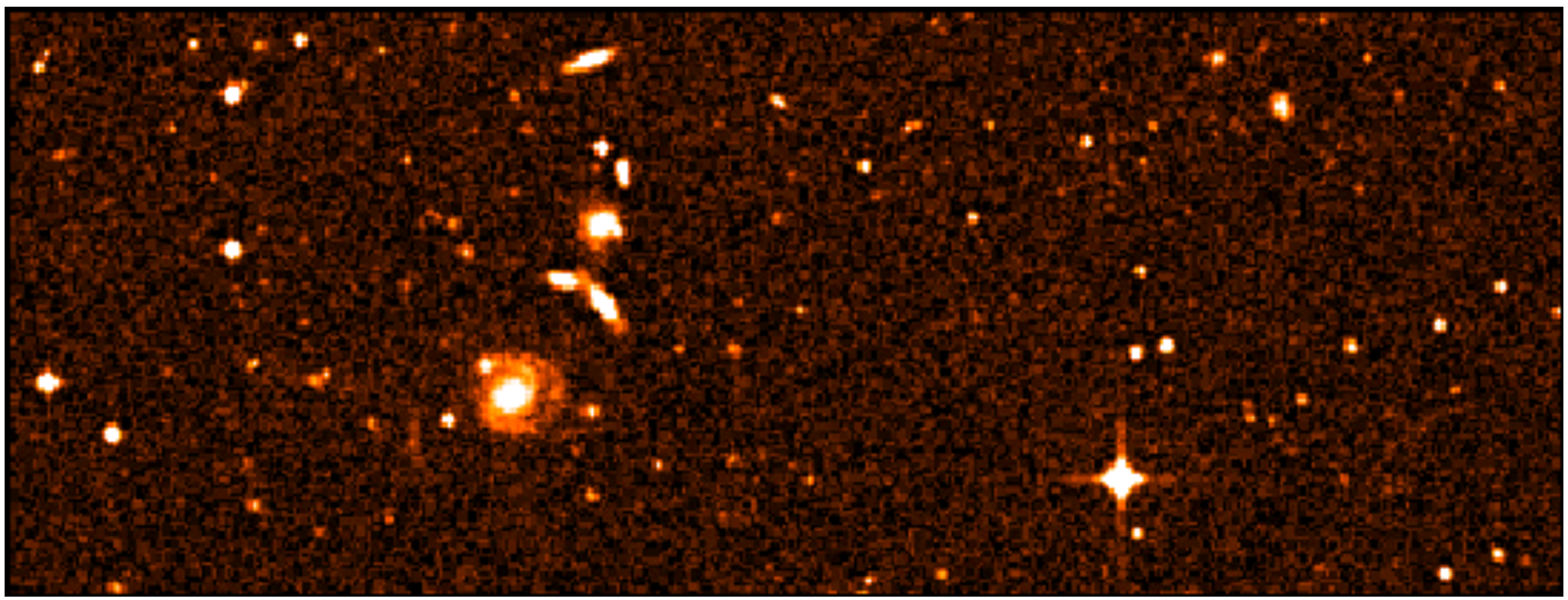
$$[X/Y] = \log(X/Y) - \log(X/Y)_\odot$$

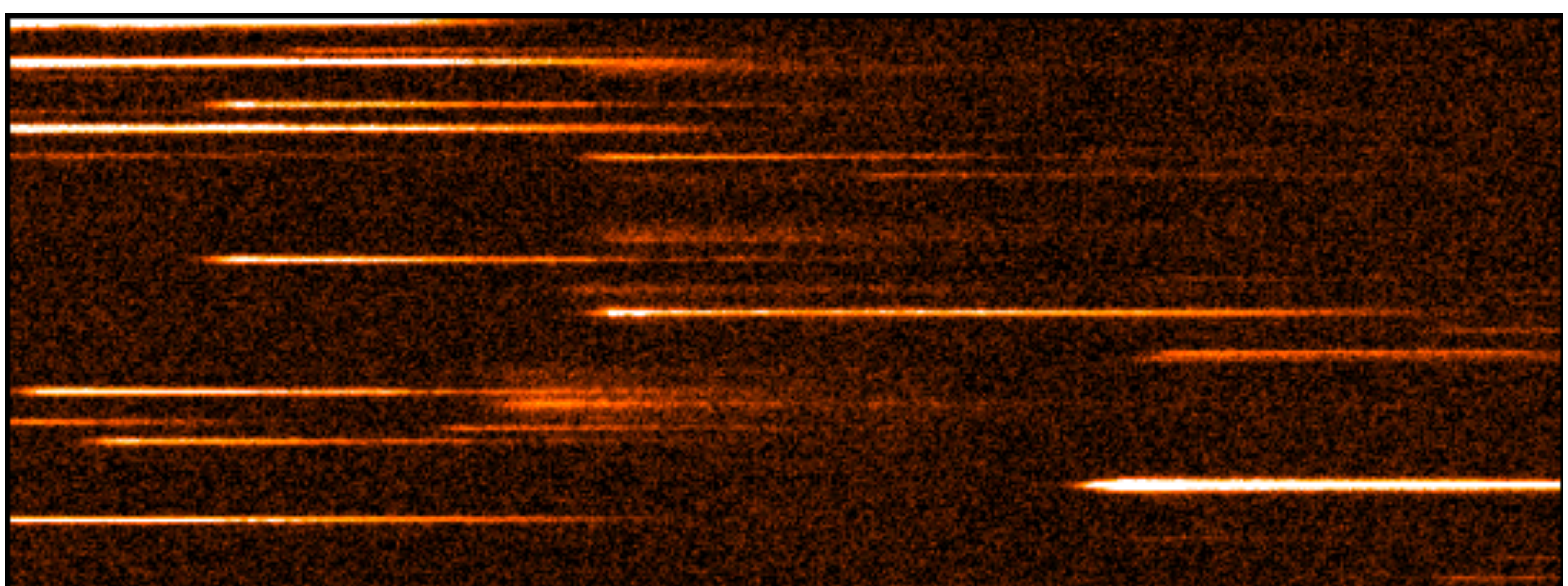
The main source for the EMP candidates in the 1980's 1990's was the HK objective prism survey. Short spectra (interference filter) centered on CaII K line, visually inspected with a binocular X10 microscope to select the candidates (Beers et al. 1985, 1992). Fairly deep, B< 15.5.
2800 deg2 North, 4100 deg2 South ~ 10000 MP candidates

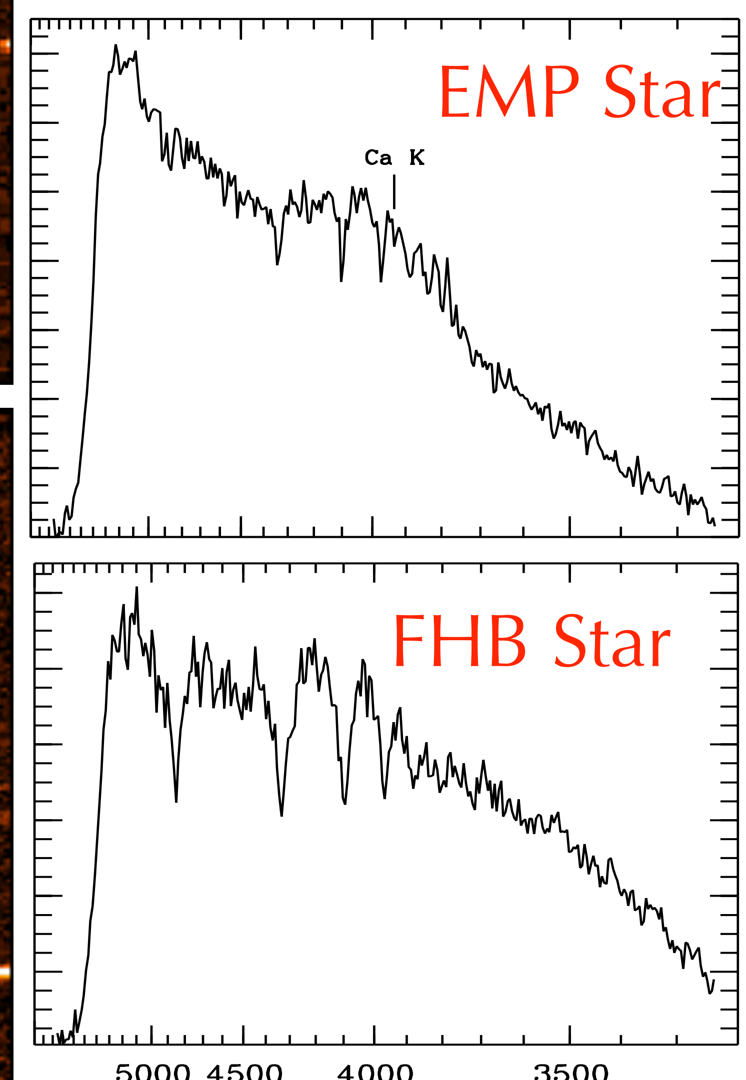


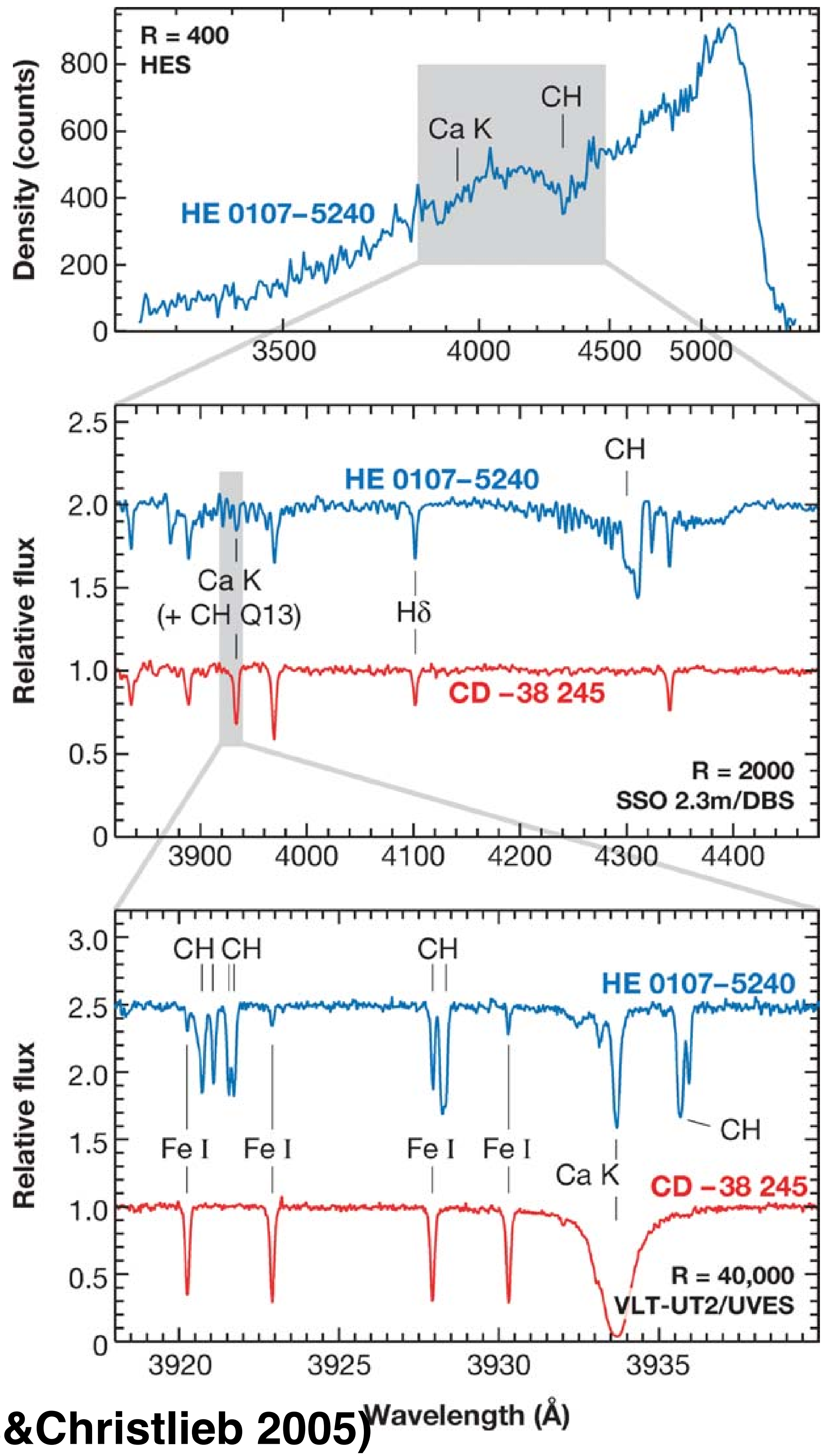
Curtis Schmidt Telescope at CTIO copyright NOAO/AURA/NSF

Towards the end of the 1990's also the Hamburg ESO objective prism Survey began to provide interesting candidates. Long spectra. Goes about 2 magnitudes deeper than HK (B< 17.5) again ~ 10000 candidates









(Beers&Christlieb 2005)

From the objective prism candidates one had to collect medium resolution spectroscopy ($R=\lambda/\Delta\lambda \sim 2000$) to confirm the metallicity and only after one could move to high resolution spectroscopy

TABLE 3 "Effective yields" of metal-poor stars

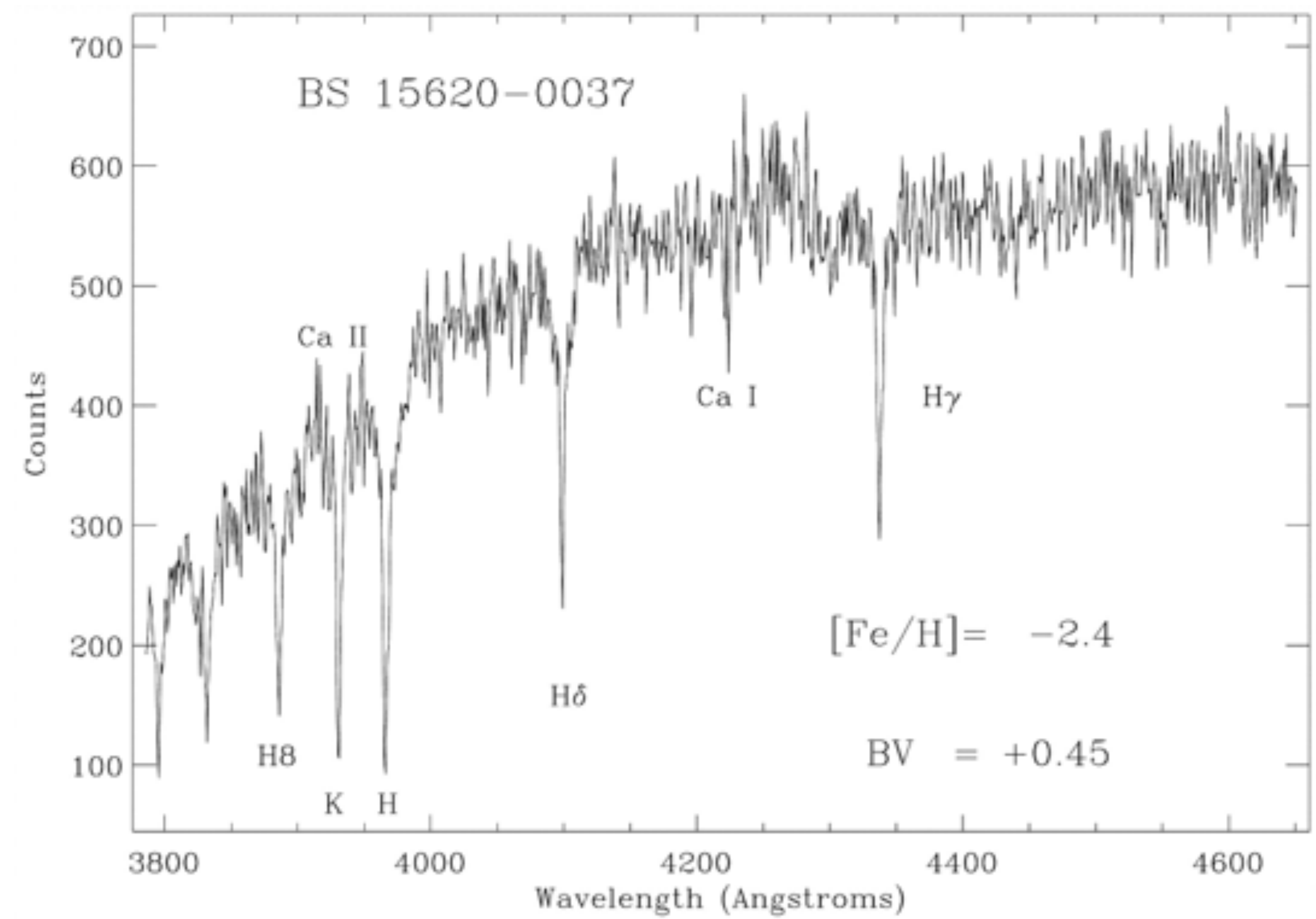
		[Fe/H]		
Survey	*N*	<-2.0	<-2.5	<-3.0
HK survey/no $B-V$	2614	11%	4%	1%
HK survey/with $B-V$	2140	32%	11%	3%
HES (faint turnoff stars)	571	59%	21%	6%
HES (faint giants)	643	50%	20%	6%

The HK follow-up

- In the 1990’s 4 groups started to do medium resolution spectroscocopic follow-up of the HK Survey, 2 in the South and 2 in the North

- In the North one group used IDS@INT (Rebolo, Allende Prieto, Garcia Lopez, Bonifacio, Molaro)

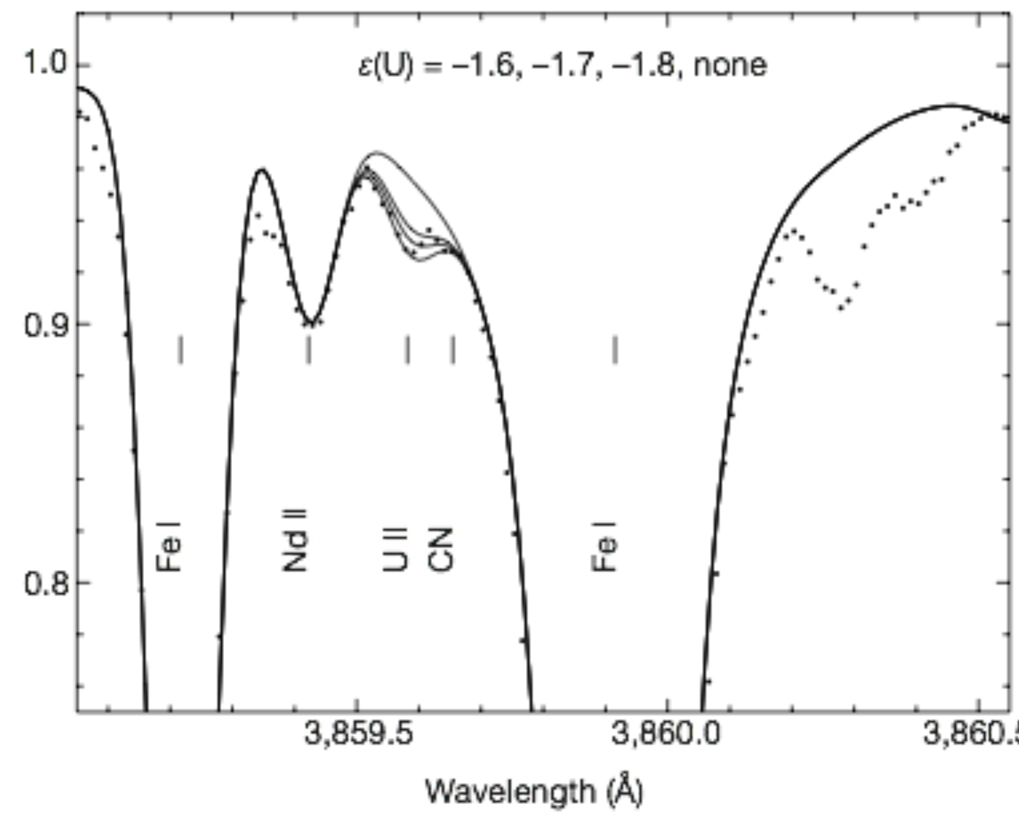
- In the South one group used ESO 1.5m (R. Cayrel, M. Spite, F. Spite, P. François)



IDS spectrum of a metal-poor star, from Allende Prieto et al. (2000) observations between March 1995 and June 1996

The “First Stars” project

- The idea was then to use VLT to do high resolution follow-up, I and P. Molaro joined the French, under the leadership of R. Cayrel.
- The “First Stars” collaboration, 18 refereed papers (1 letter in Nature).
- This changed my professional life because it was the basis on which I moved to Paris in 2005



First detection of U in a metal poor star (Cayrel et al. 2001, Hill et al. 2002)

The ESO Large Programme "First Stars"

P.I. Roger Cayrel

proposal 165.N-0276

proponents (in alphabetical order):

J.Andersen, B. Barbuy, T.C. Beers, P. Bonifacio, E. Depagne
P. François , V. Hill, P. Molaro, B. Nordström, B. Plez, F.Primas,
F. Spite, M. Spite

Joined the project later (in order of appearance):

T. Sivarani, F. Herwig, S. Andrievsky, J. Gonzalez Hernandez,
H.-G. Ludwig, E. Caffau, C. J. Hansen

Presented by P. Bonifacio

Turn Off Primordial Stars

PI E. Caffau

28 researchers
12 laboratories
7 countries

EMP stars selected from SDSS
76 stars with X-Shooter
30 stars with UVES
4 HDS (Subaru)

ESO Large Programme
150h @ VLT-ESO
4 semesters
120h X-Shooter
30h UVES

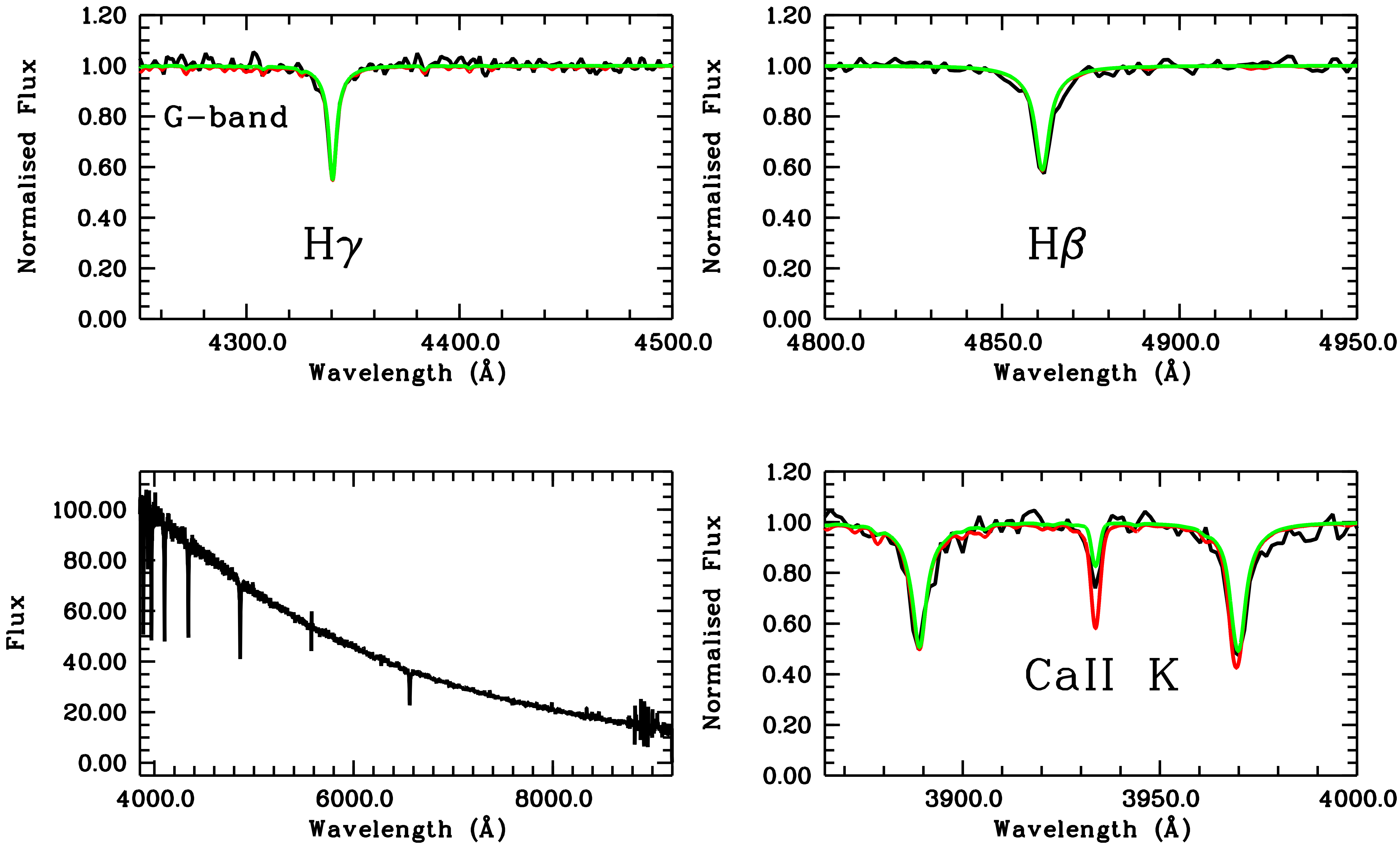
+ 4 approved "normal" programs, 82h UVES

+ 3 nights Subaru

- P. Bonifacio, E. Caffau, R. Cayrel, P. François, A. Gallagher, F. Hammer, S. Salvadori, M. Spite, F. Spite - **GEPI, Observatoire de Paris, France**
- Bertrand Plez - **Université de Montpellier, France**
- N. Christlieb, H.-G. Ludwig, S. Glover, D. Homeier, R. Klessen, A. Koch - **ZAH Heidelberg, Germany**
- M. Steffen - **Leibniz-Institut für Astrophysik Potsdam, Germany**
- B. Freytag - **Uppsala University Sweden**
- A. Chieffi, M. Limongi, P. Molaro, S. Randich, S. Zaggia - **INAF, Italy**
- L. Monaco - **Universidad Andrés Bello, Santiago, Chile**
- L. Sbordone - **Pontificia Universidad Católica de Chile, Santiago, Chile**
- L. Mashonkina - **Institute of Astronomy, Russian Academy of Sciences, Russia**
- S. Andrievskii, S. Korotin - **Astronomical Observatory, Odessa National University, Ukraine**

Main Questions

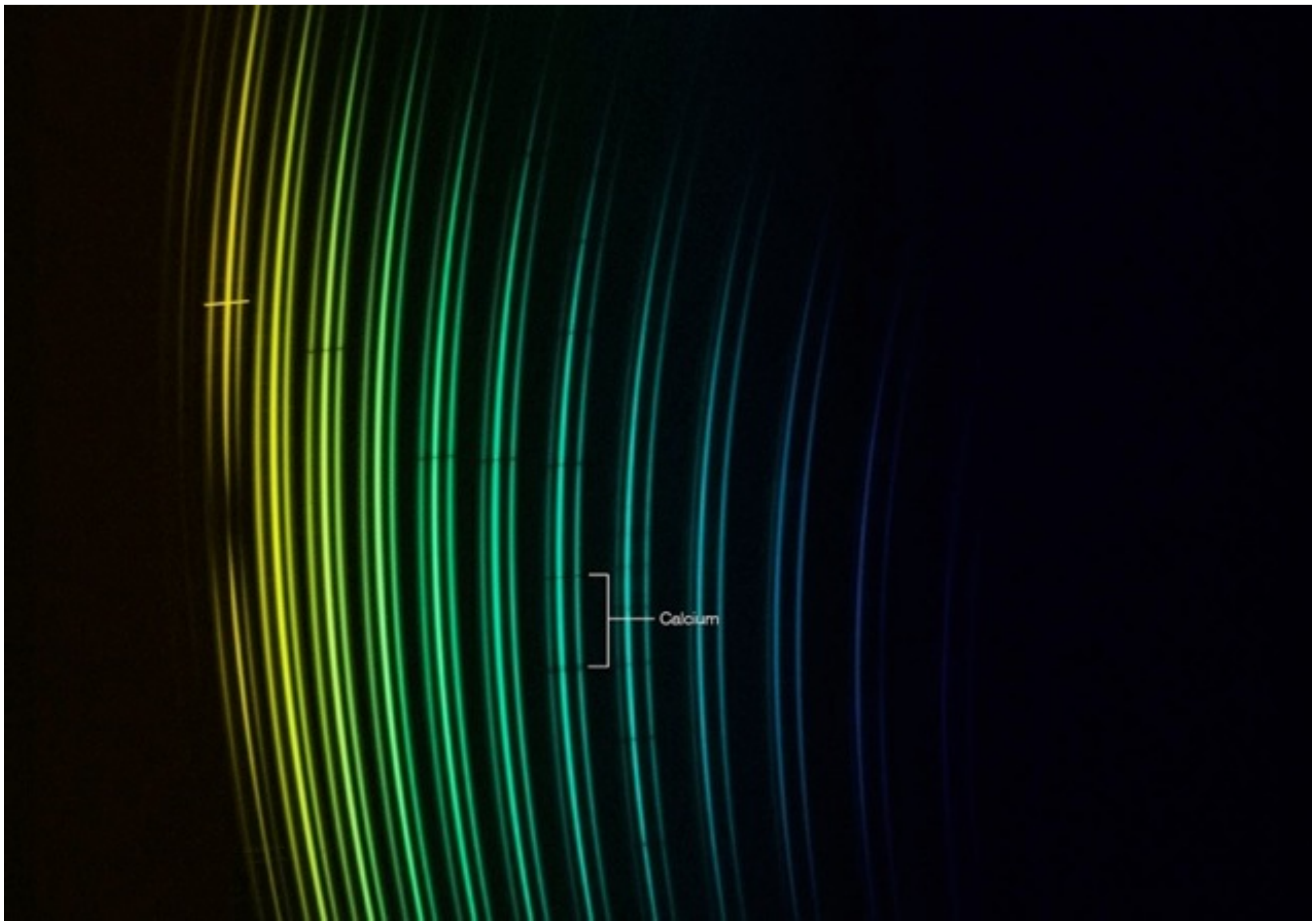
- **Understand formation of low mass stars in low metallicity gas**
  - Do zero-metal low mass stars exist?
  - If not: value of the "critical metallicity"
  - Derive the fraction of C-enhanced extremely metal-poor (CEMP) stars/"normal" extremely metal-poor (EMP) stars
- **Lithium and the primordial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



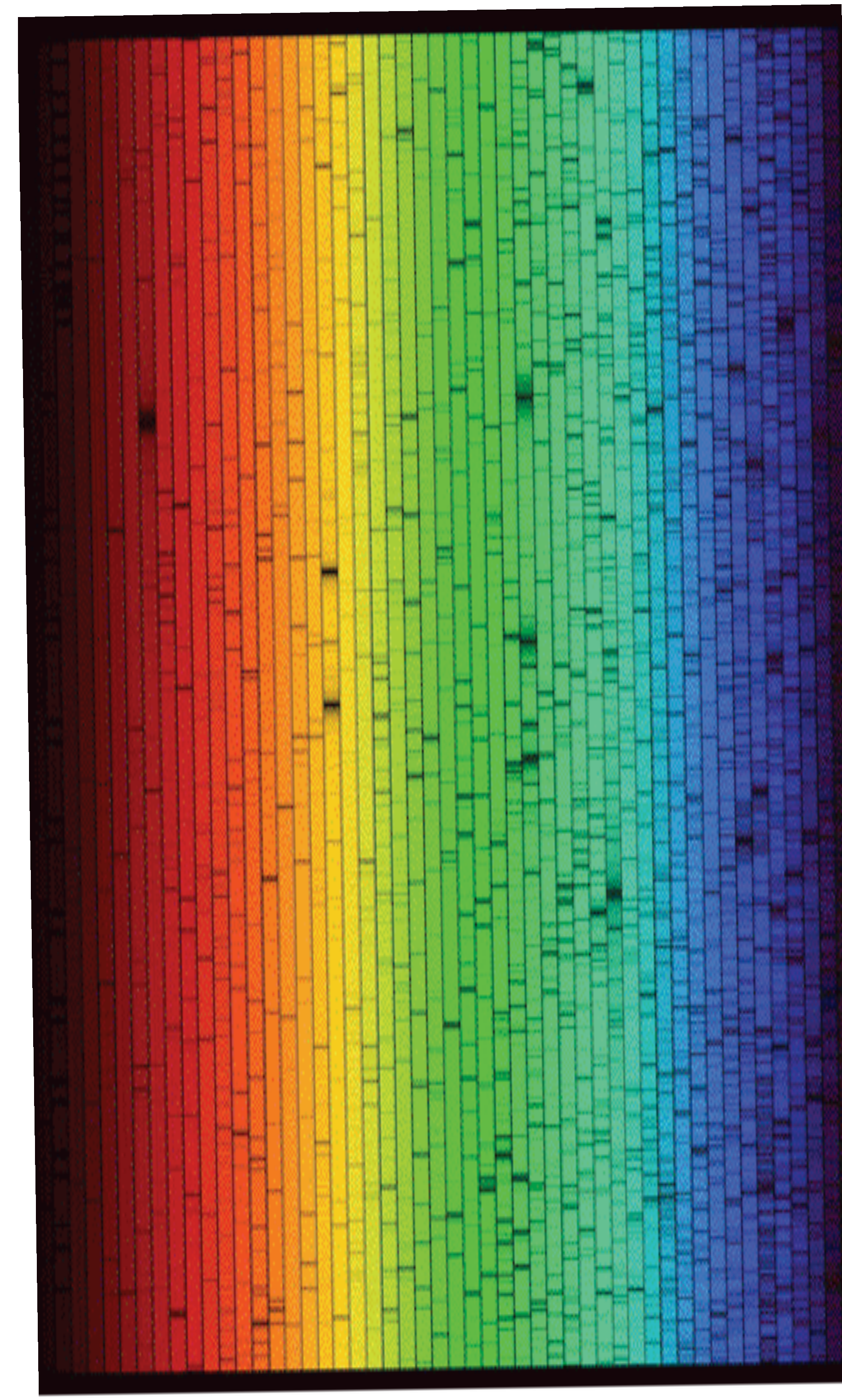
Automatic code to obtain abundance estimates from SDSS spectra

SDSS J102915+172927: the Caffau star

12 Feb 2011



IFU 4”x1.8” ==> 12”x0.6”
R~12600, 2700 sec S/N ~90

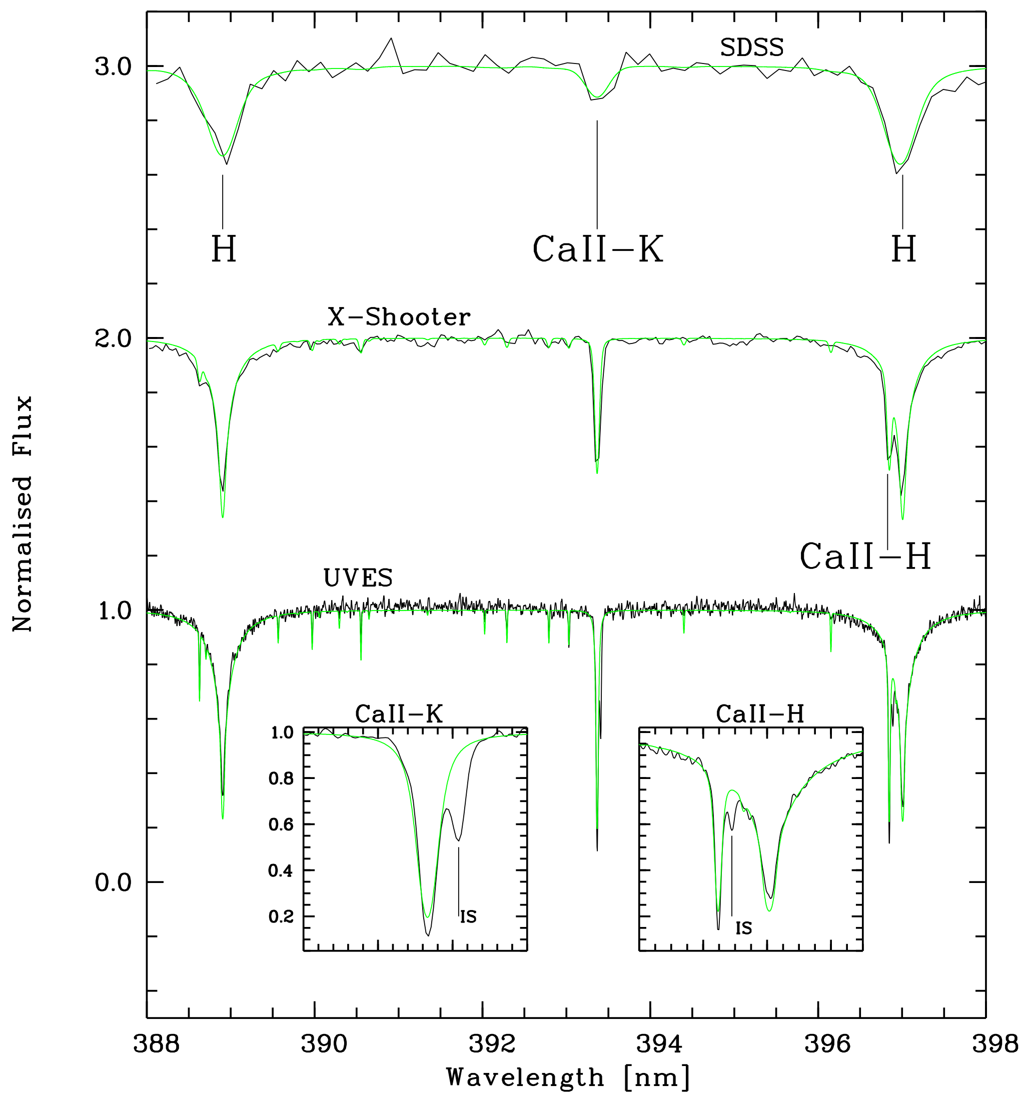


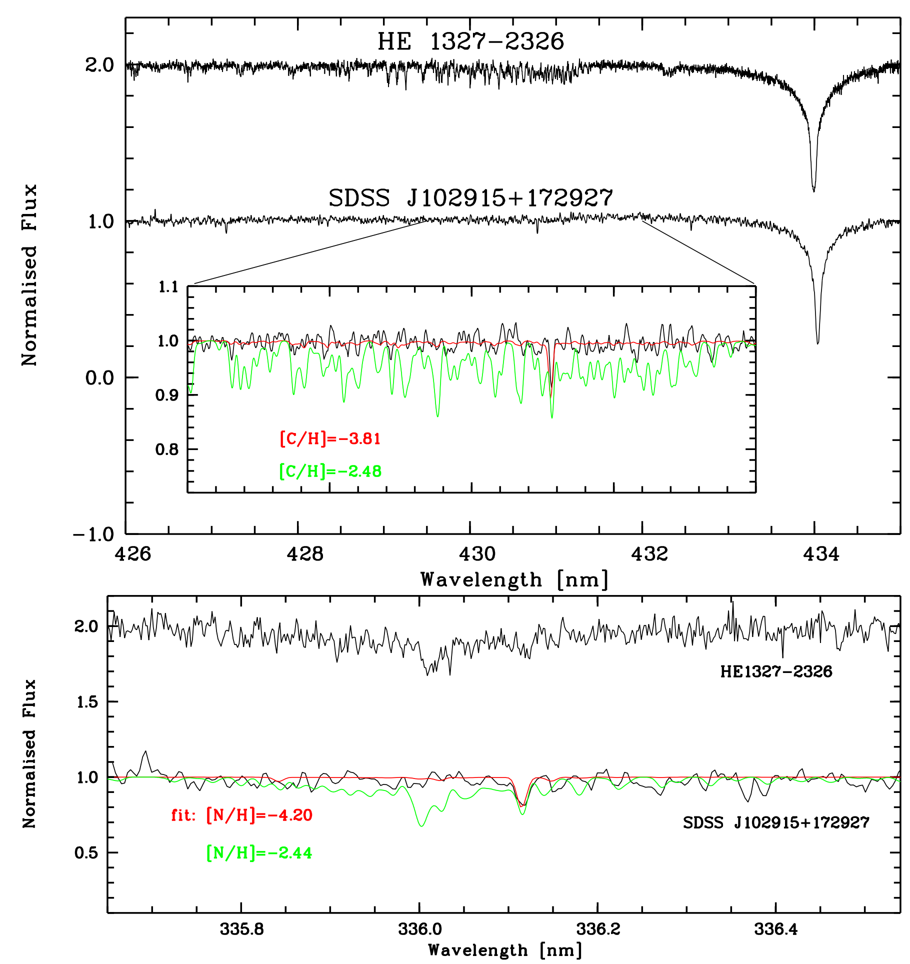
The Sun

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

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

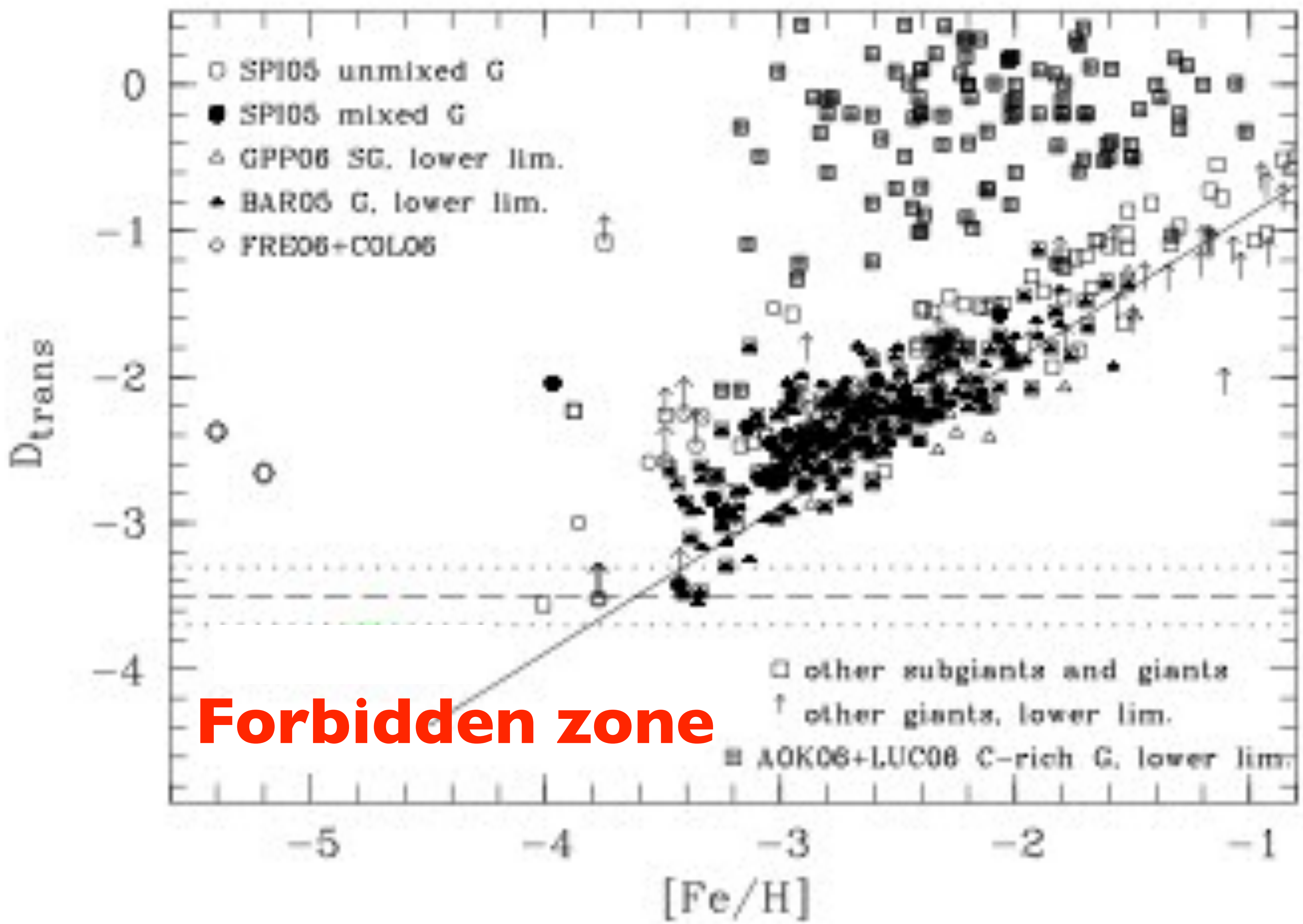


Figure from Frebel et al. 2007

But we have found a star in the forbidden zone

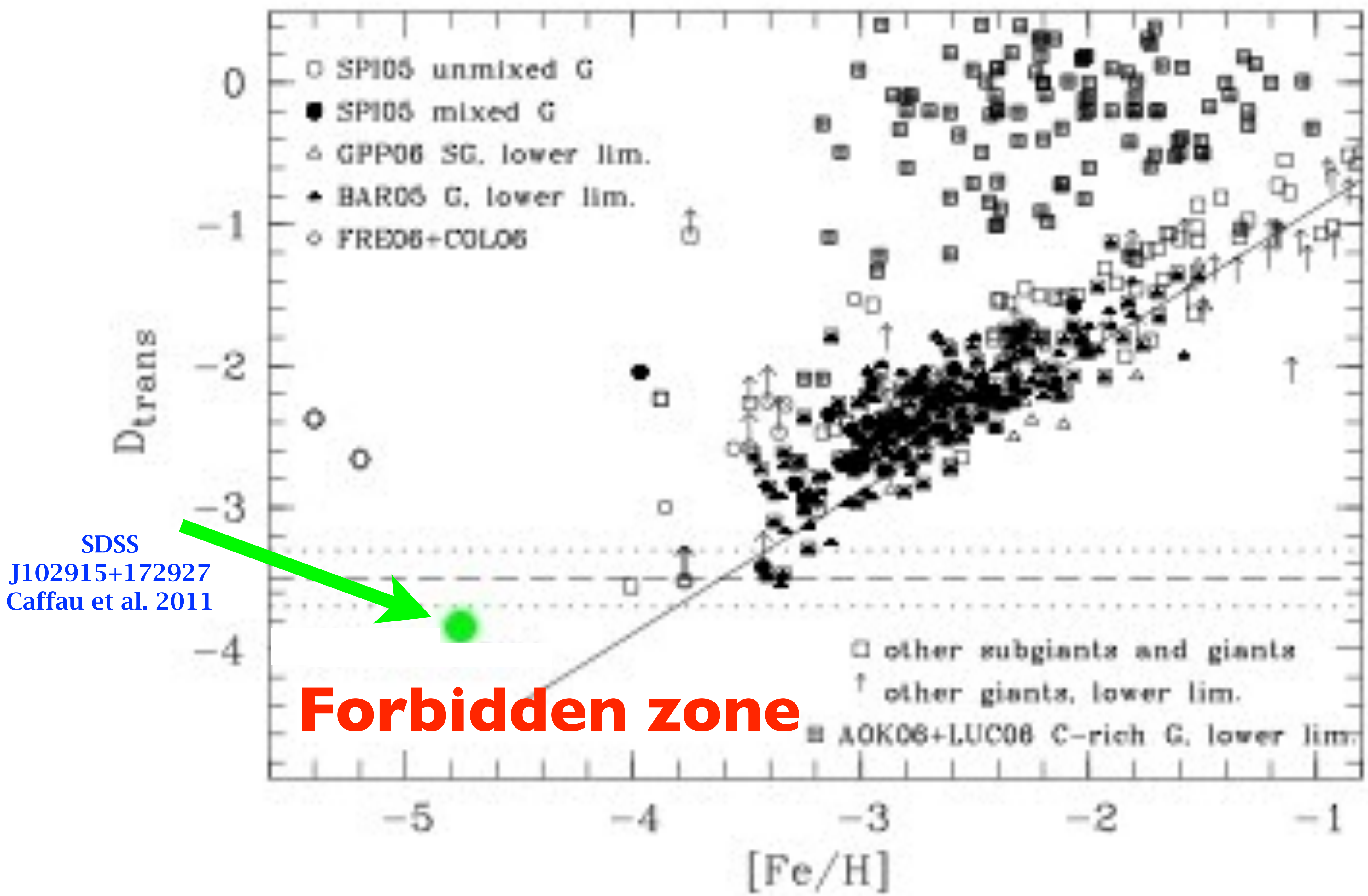
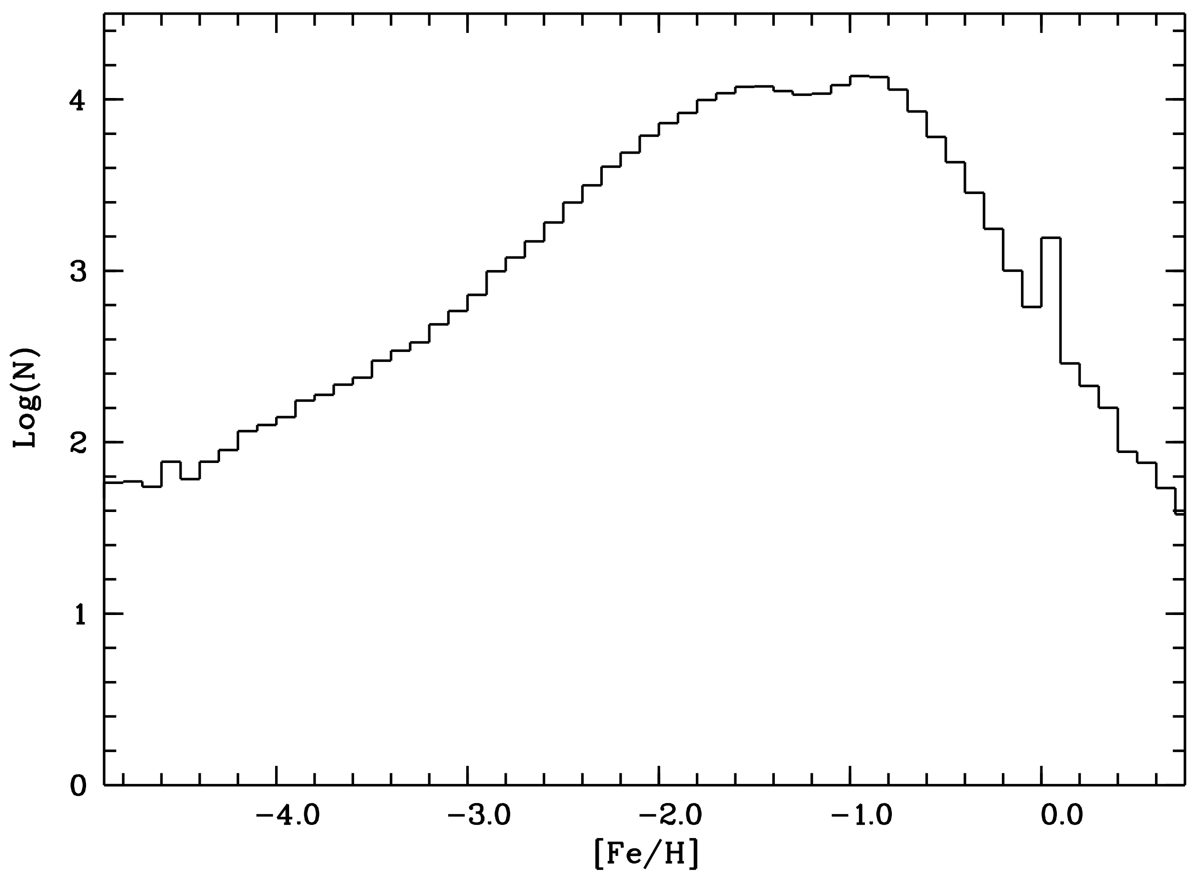


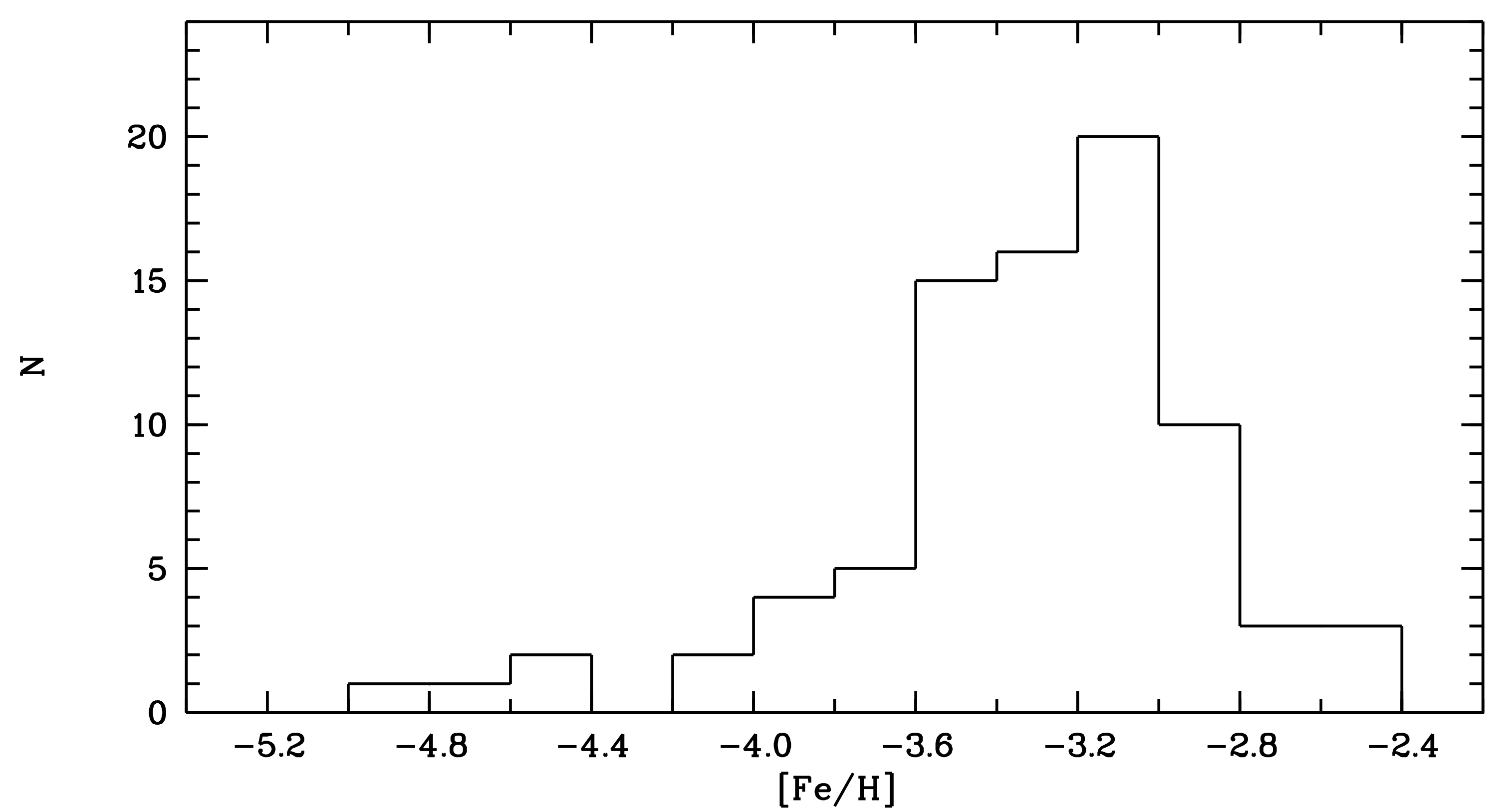
Figure from Frebel et al. 2007

Metallicity Distribution Function

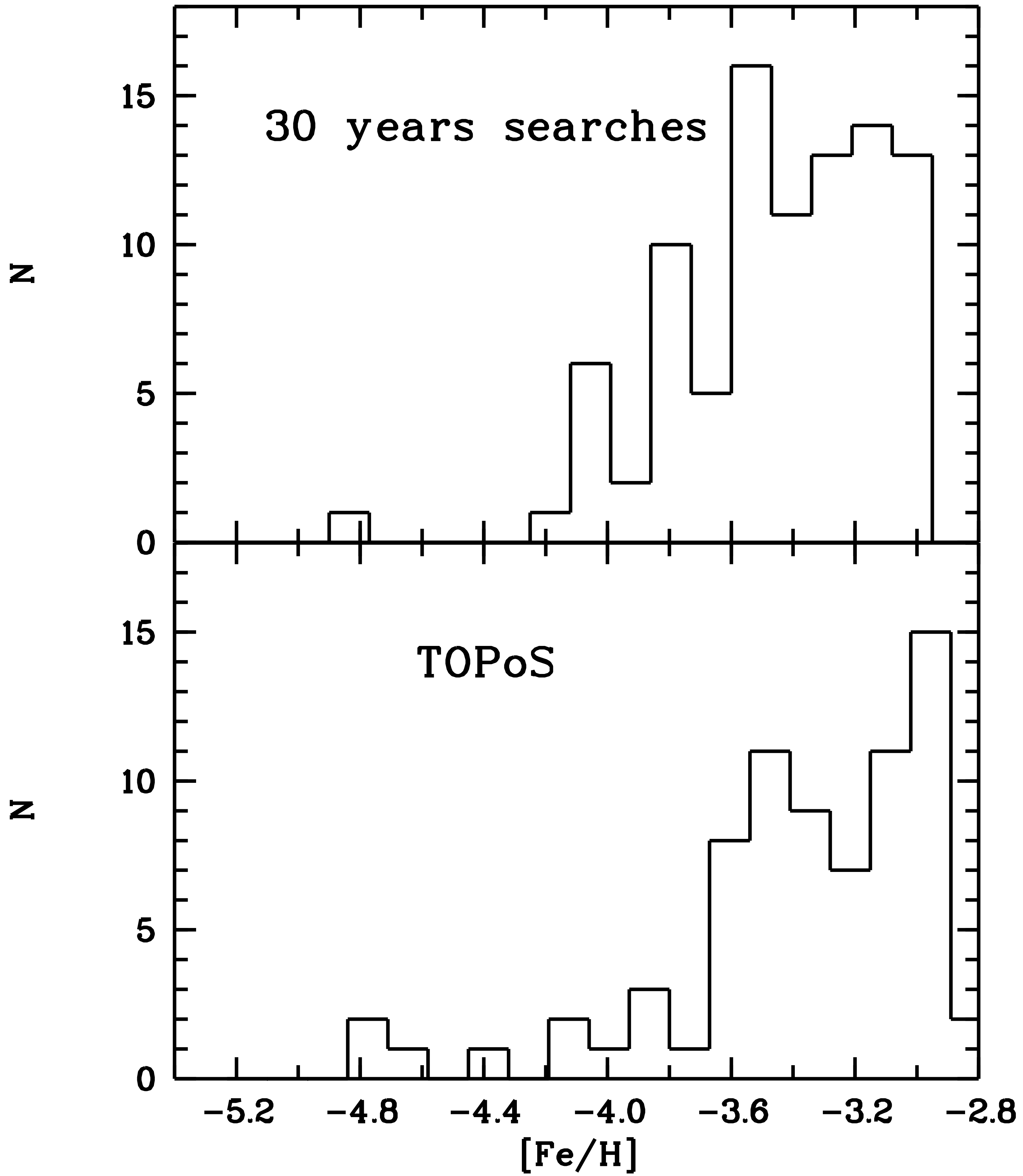


SDSS target observed at higher resolution (X-Shooter and UVES), sample of 87 stars, analysis not completed.

MDF from SDSS-DR9 (182.807 TO stars)

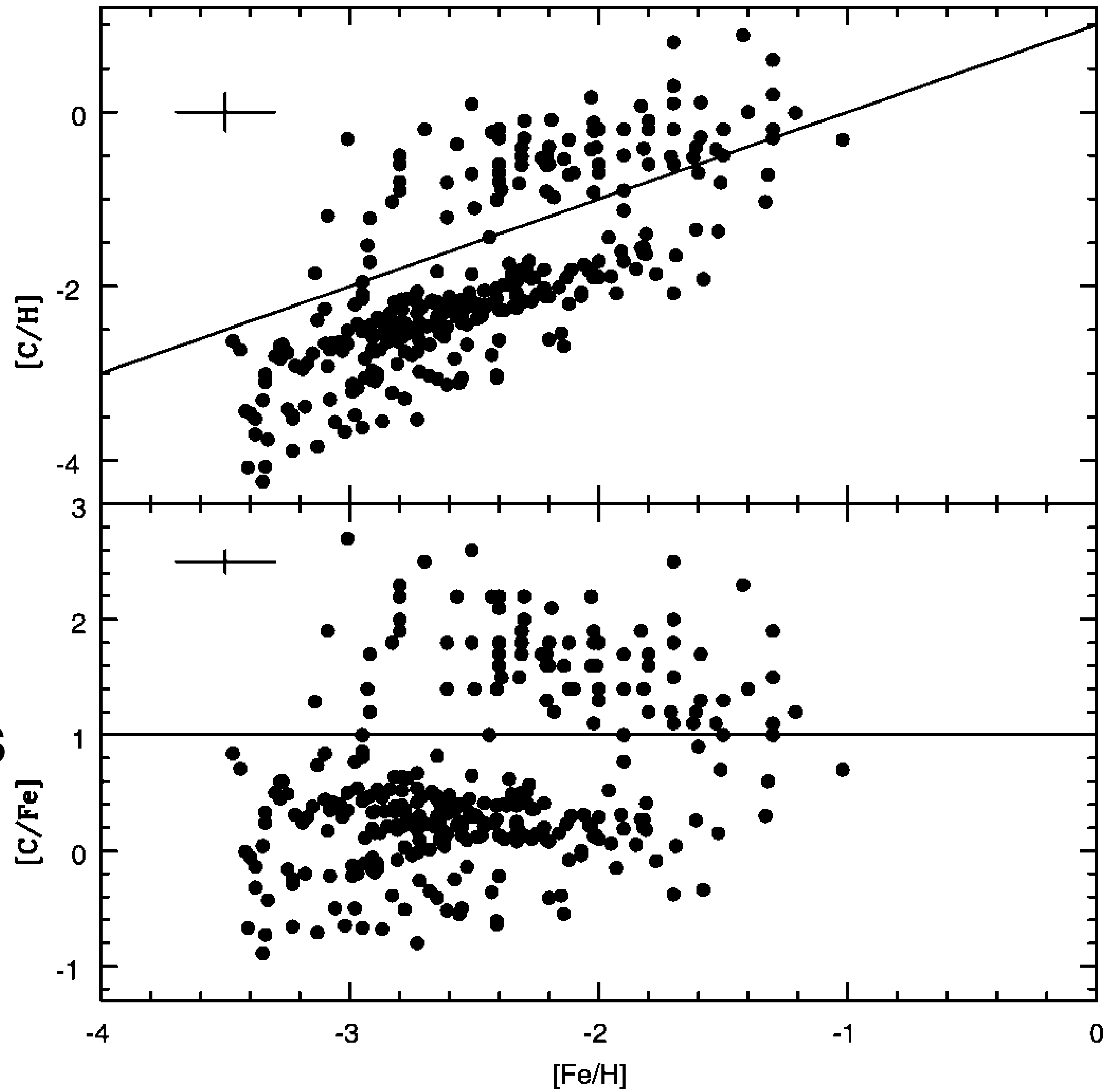


The TOPOS contribution



CEMP stars

For over twenty years it has been known that among low metallicity stars there is a large fraction of "carbon-enhanced stars". Larger in fact than among solar-metallicity stars. The actual fraction is debated 15%—35%, in any case rising with lowering metallicity

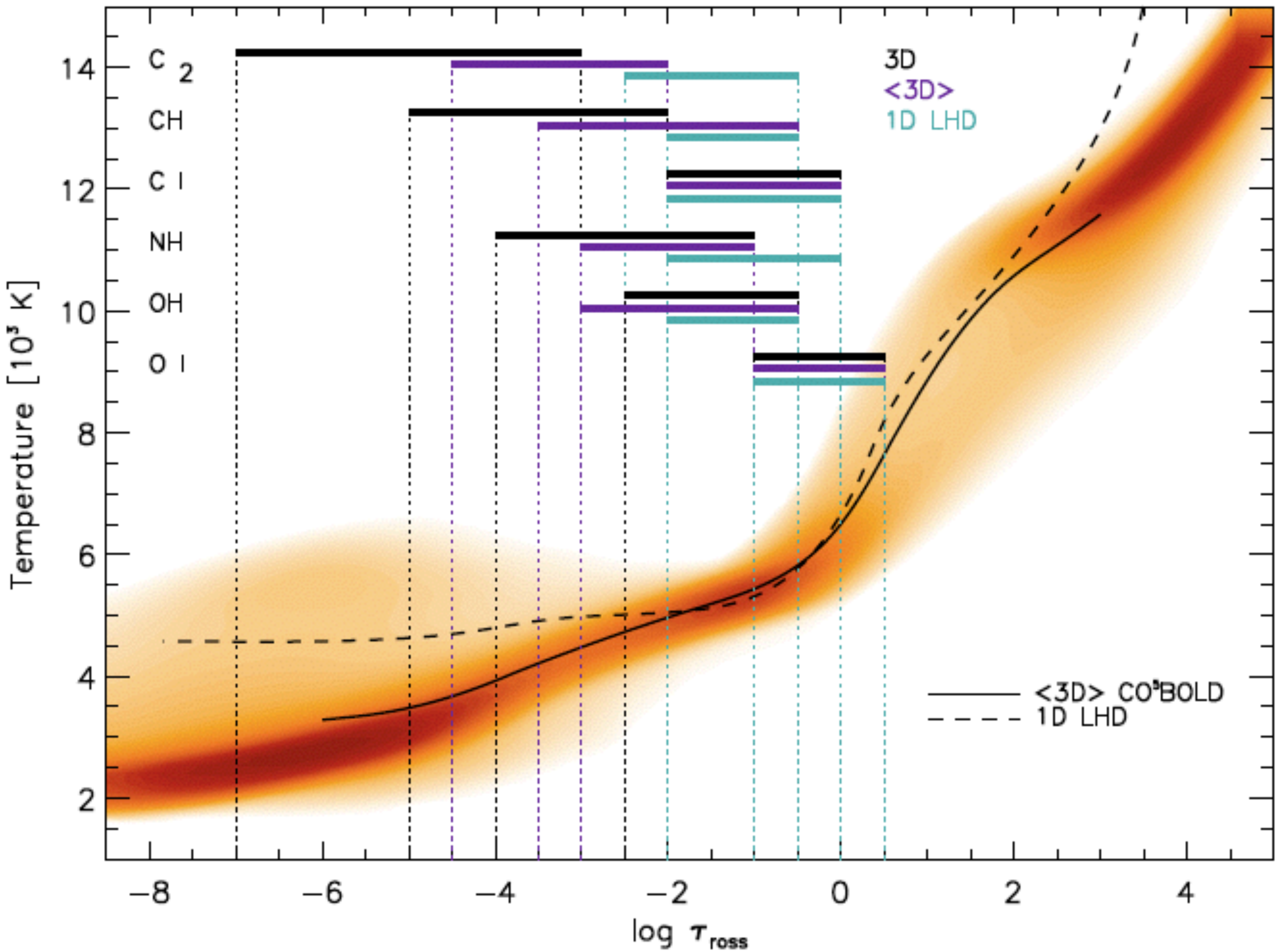


Lucatello et al. (2005)

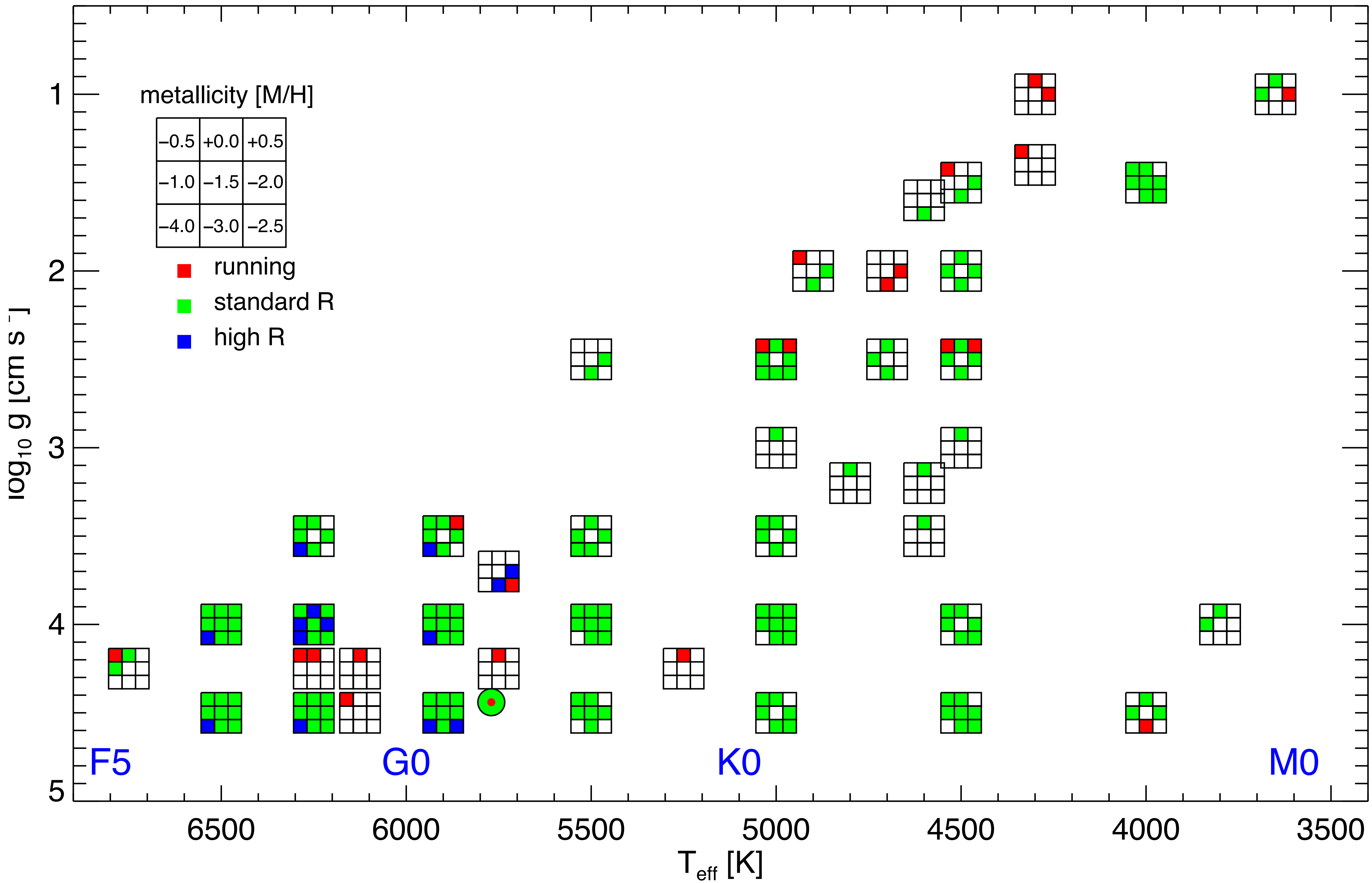
Definitions of CEMP (Carbon Enhanced Metal-Poor)

- Traditional: [C/Fe] > 1.0
- some authors suggest [C/Fe] > 0.7, but such a definition may be ambiguous
- In any case, empirical, no theoretical basis for it
- At metallicity < -3.0 the information on the C abundance comes mainly from the CH G-band

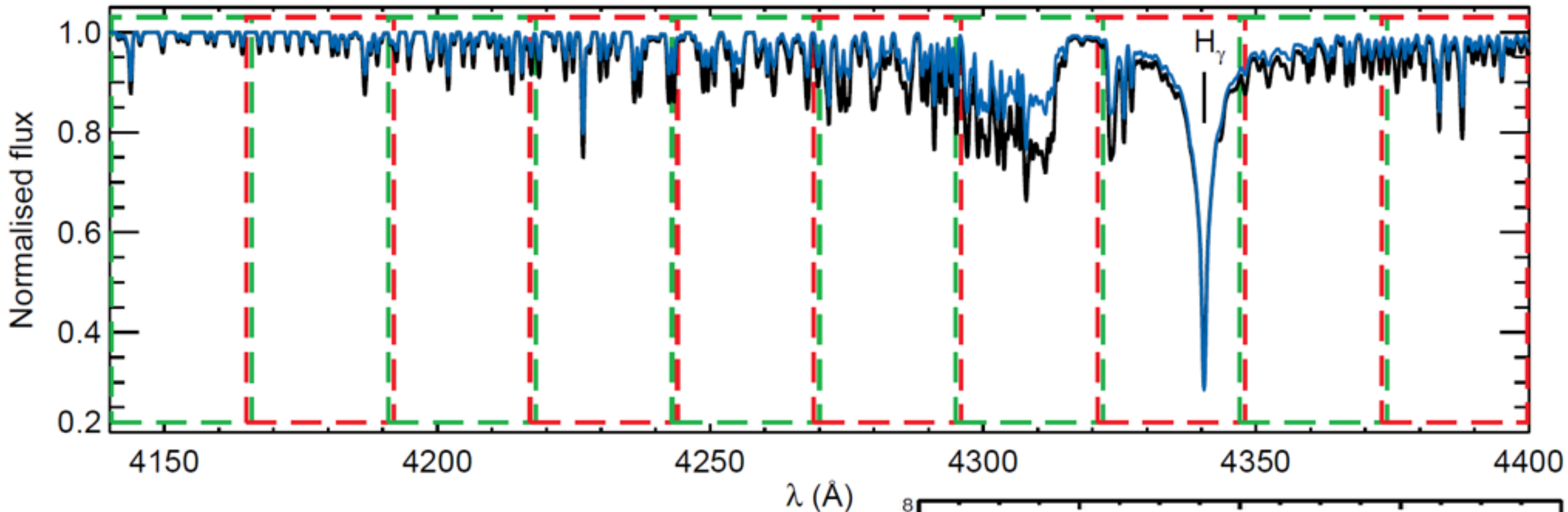
But molecular bands are strongly dependent on granulation effects ! (Behara et al. 2010)



CIFIST grid of 3D hydro models



Molecular bands in 3D



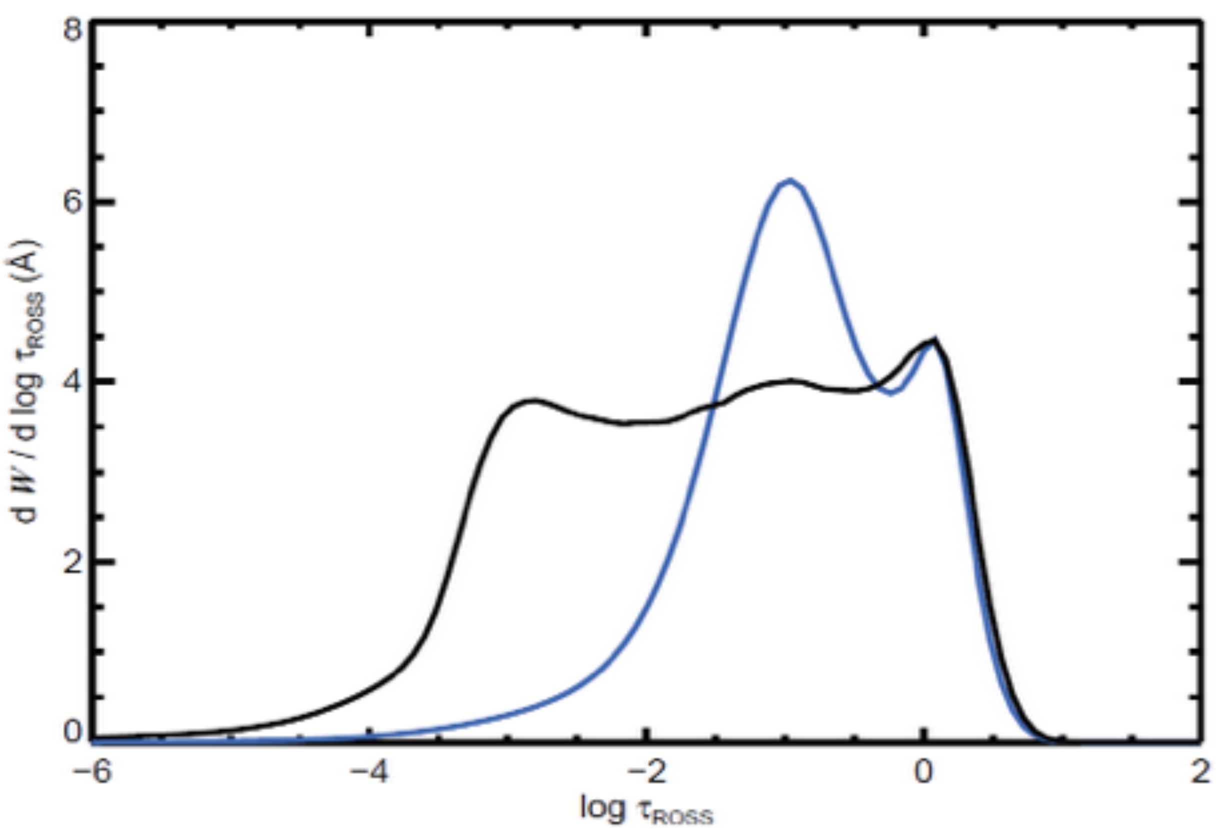
Stellar Parameters (T_{eff}/log g/[Fe/H])
6250 K/4.0/-3.0

A(C) = 7.39
A(N) = 6.78
A(O) = 7.66
C/O = 0.54

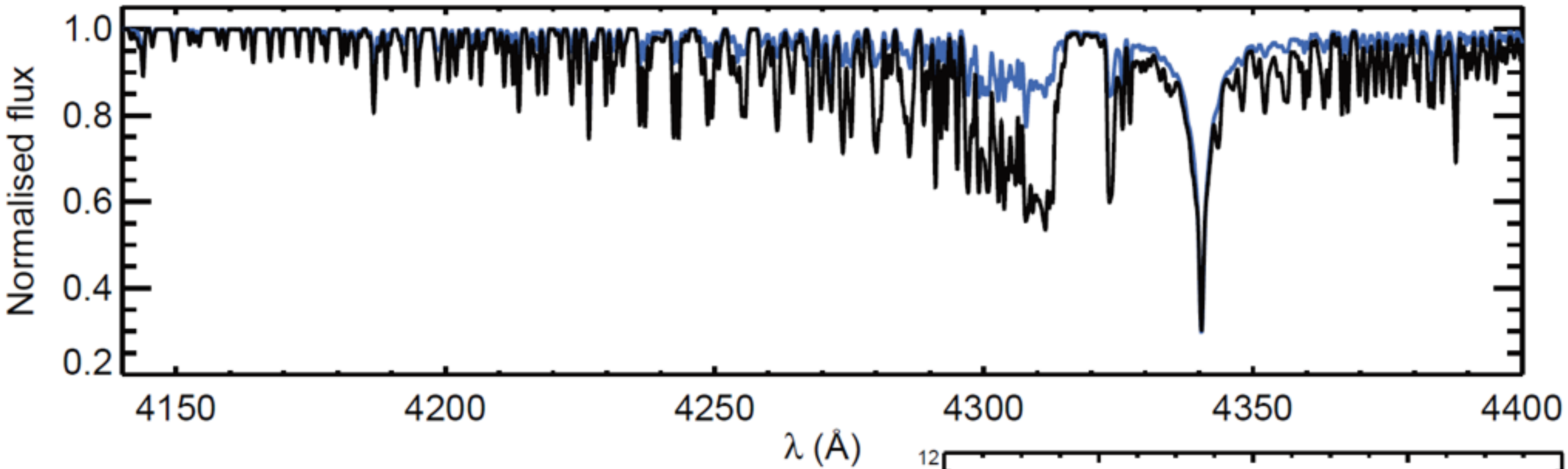
Gallagher et al (2016 A&A 593, A48)

1D

3D



Molecular bands in 3D

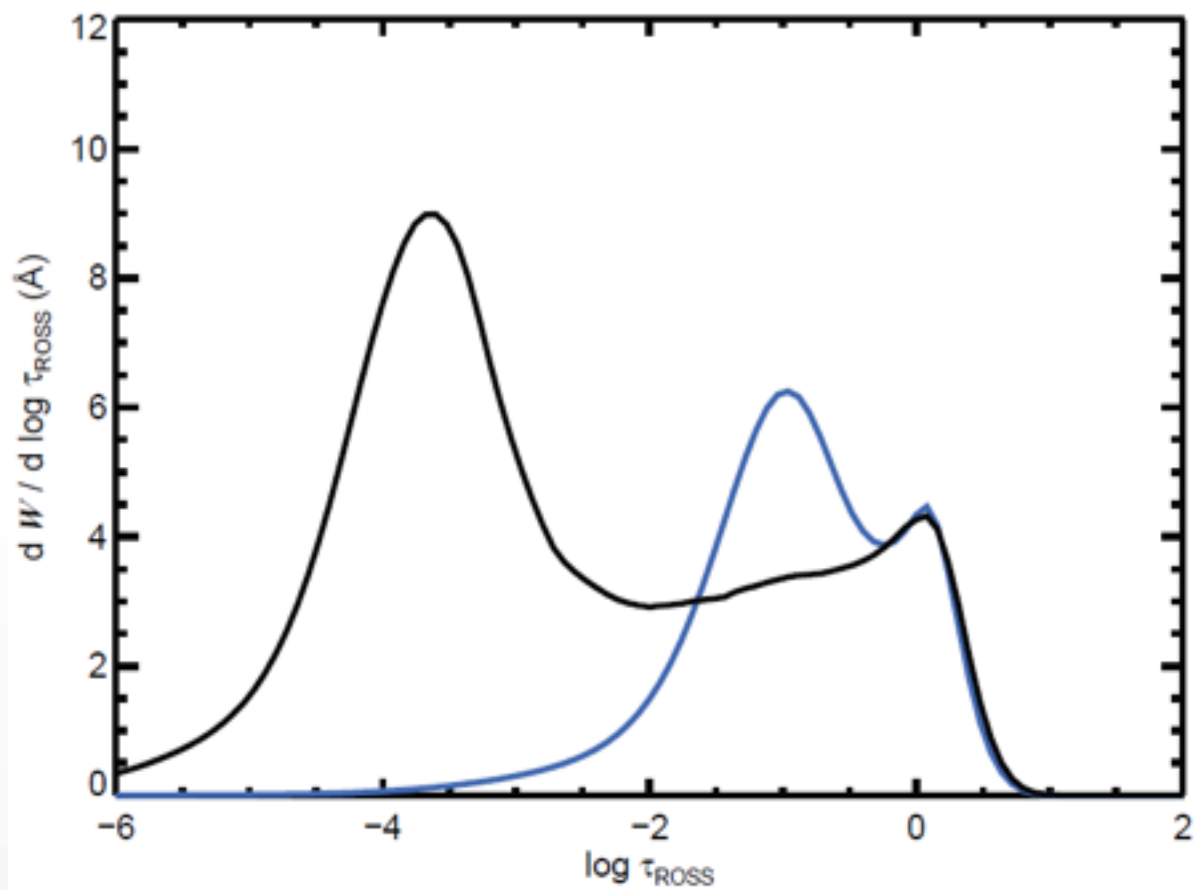


Stellar Parameters (T_{eff}/log g/[Fe/H])
6250 K/4.0/-3.0

A(C) = 7.39
A(N) = 6.78
A(O) = 6.06
C/O = 21.4

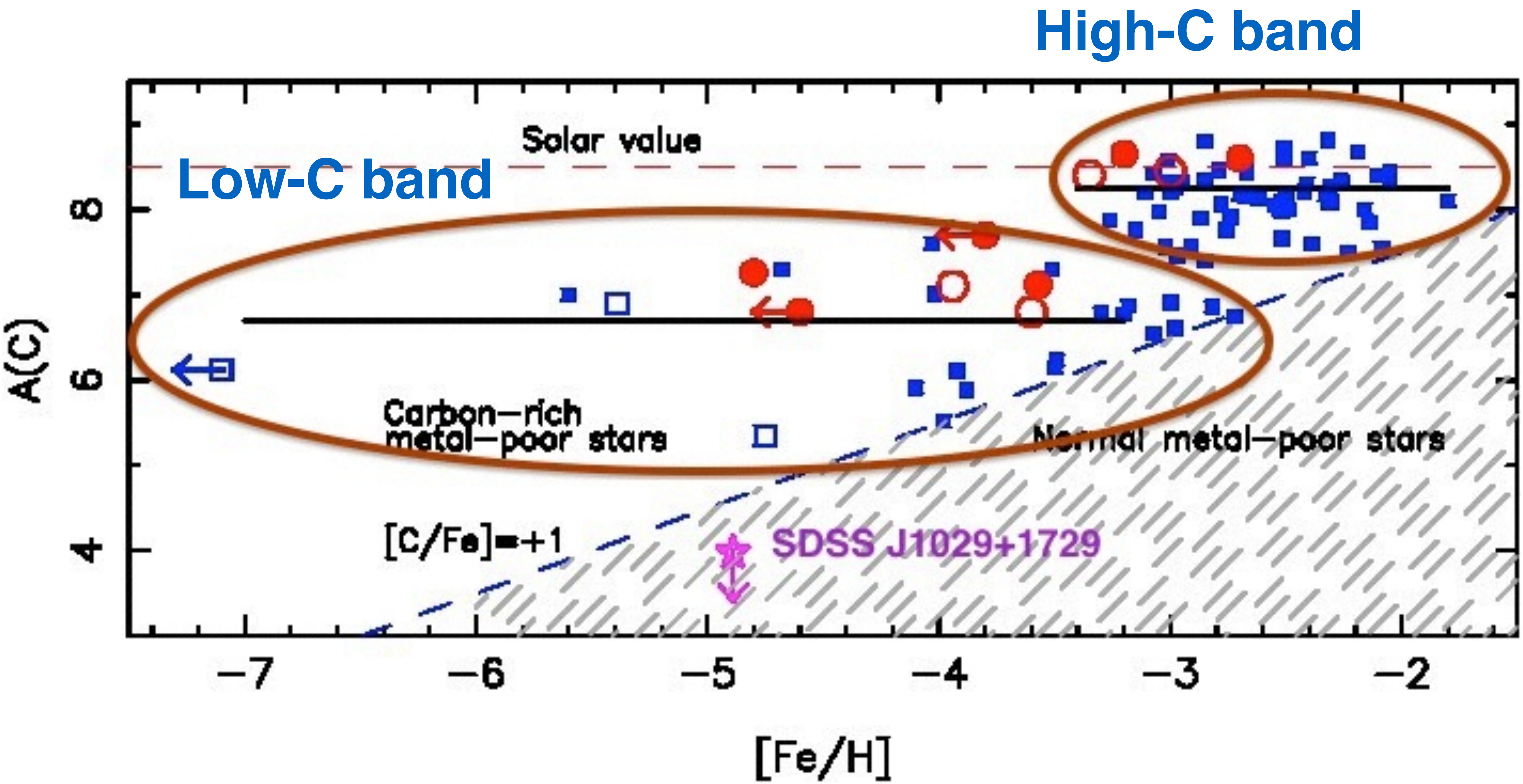
1D

3D



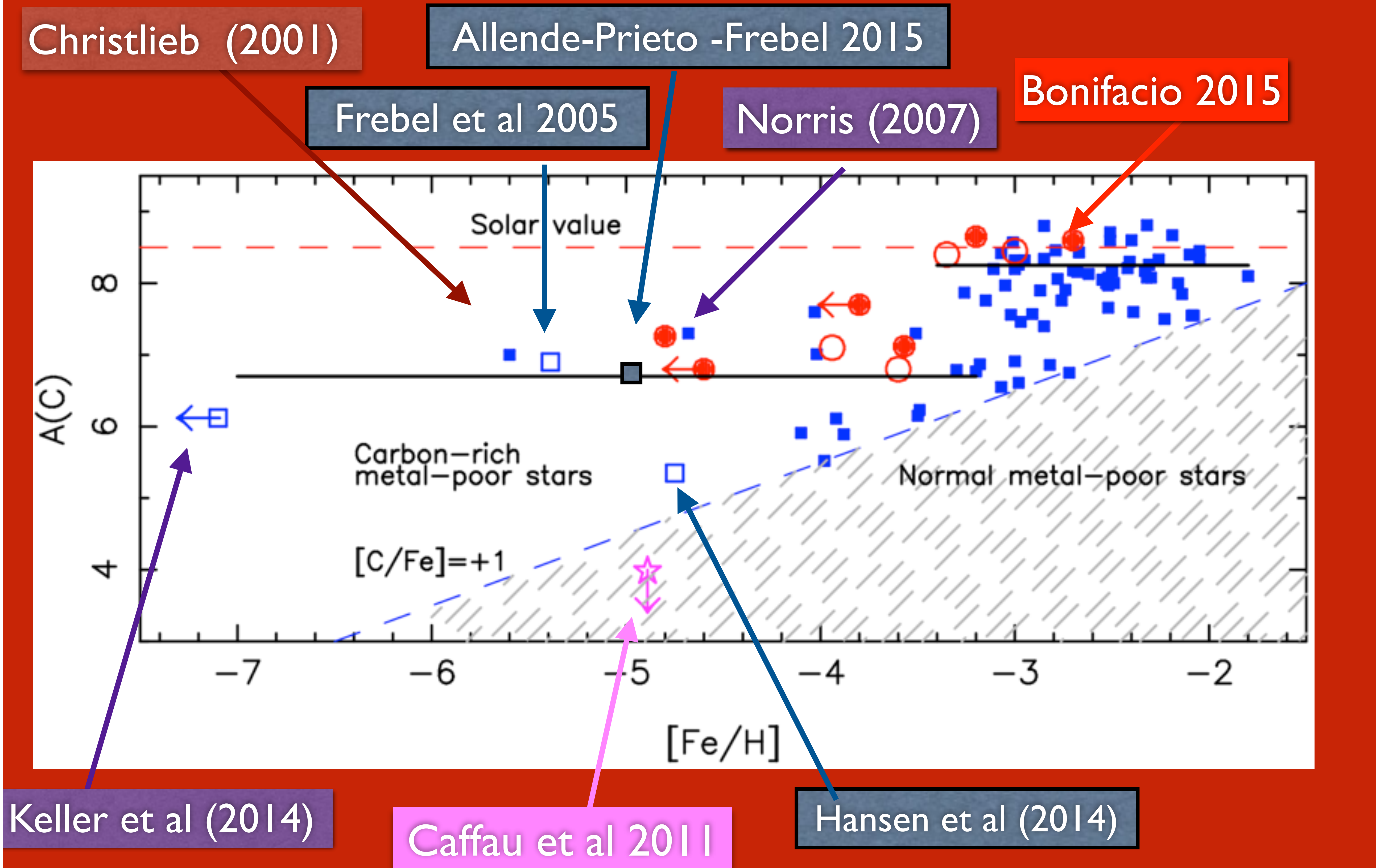
Gallagher et al (2016 A&A 593, A48)

The carbon abundances in CEMP stars are bimodal

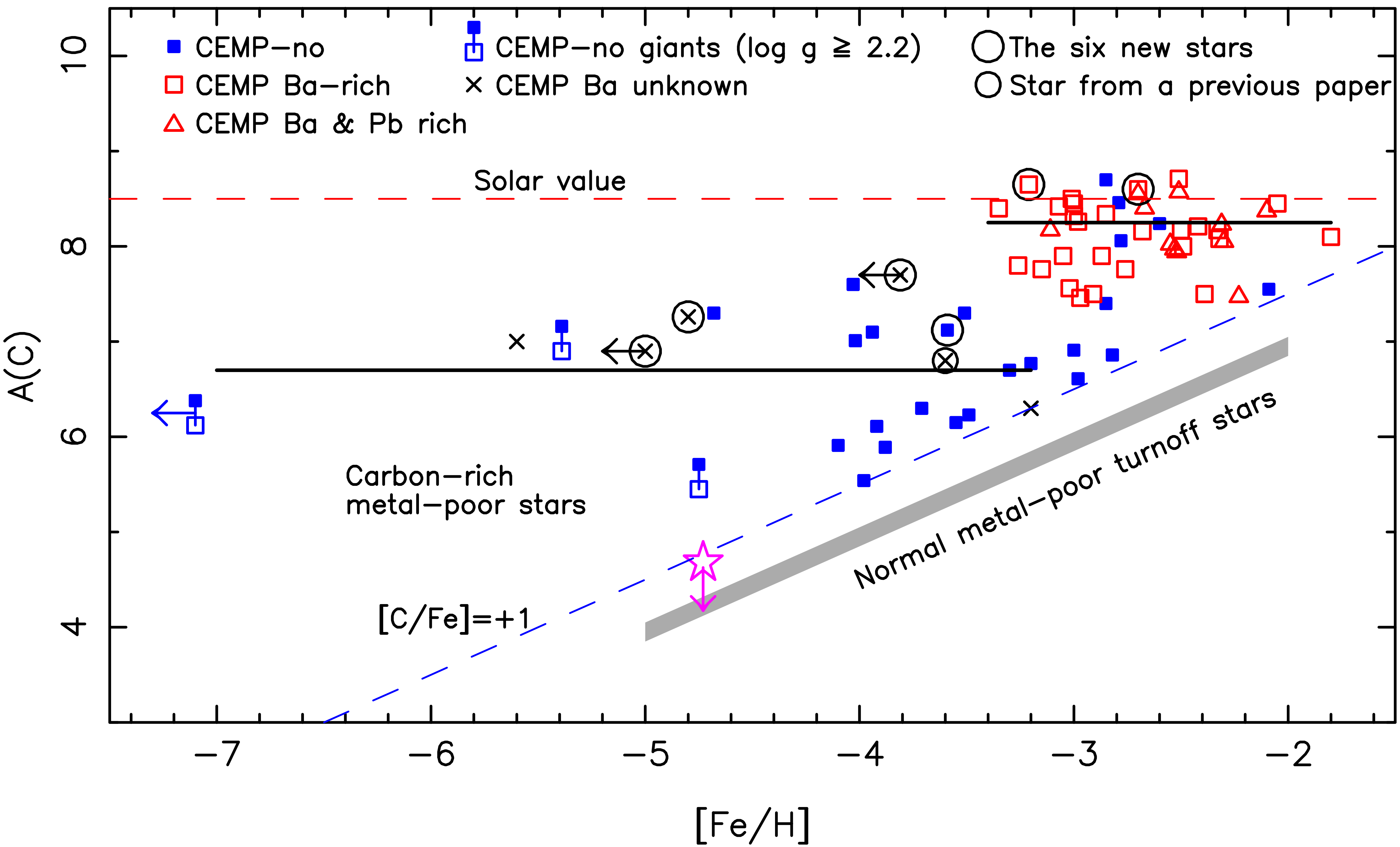


Bonifacio et al. 2015 A&A 579, A28

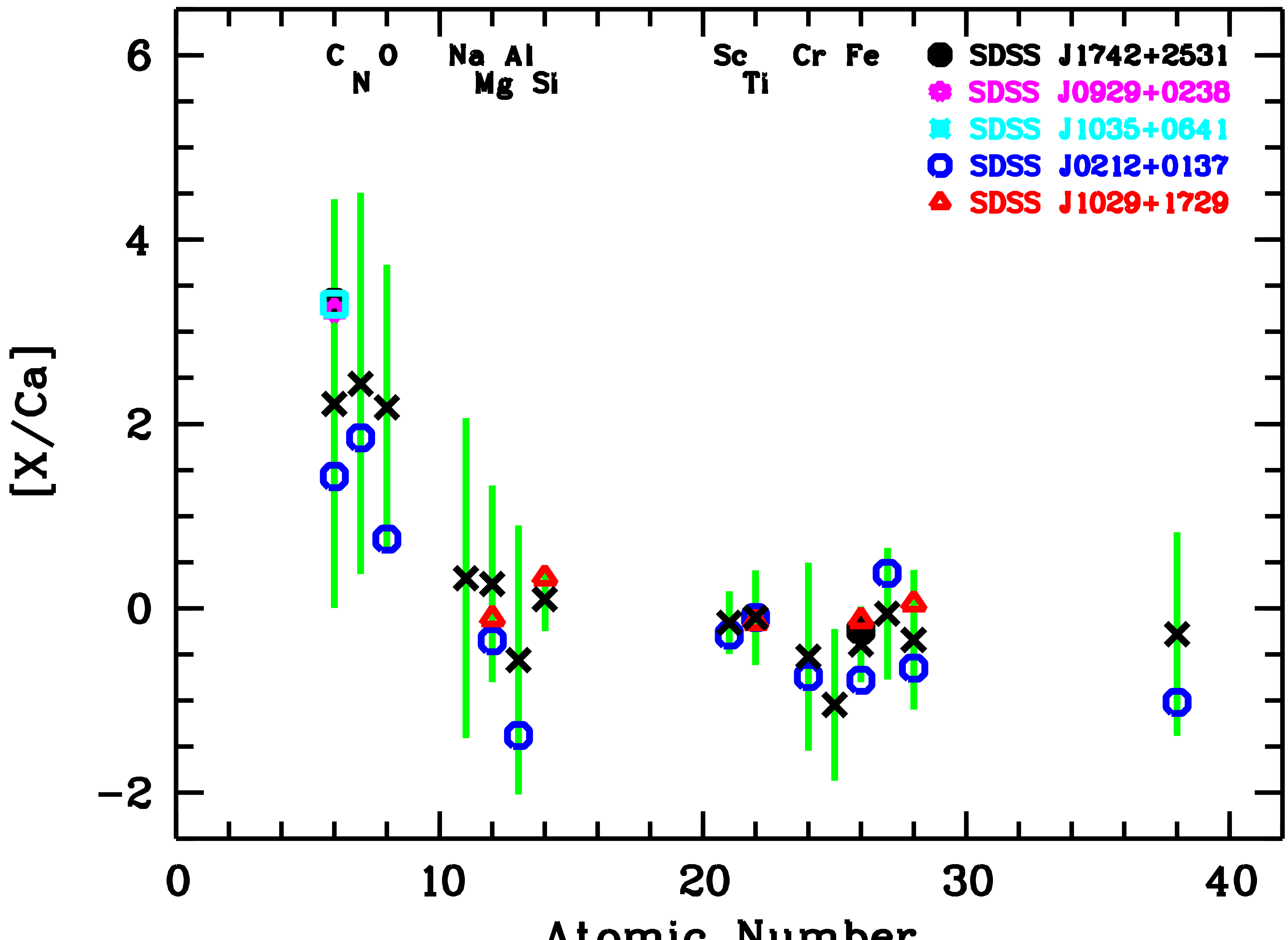
9 stars with [Fe/H]<-4.5

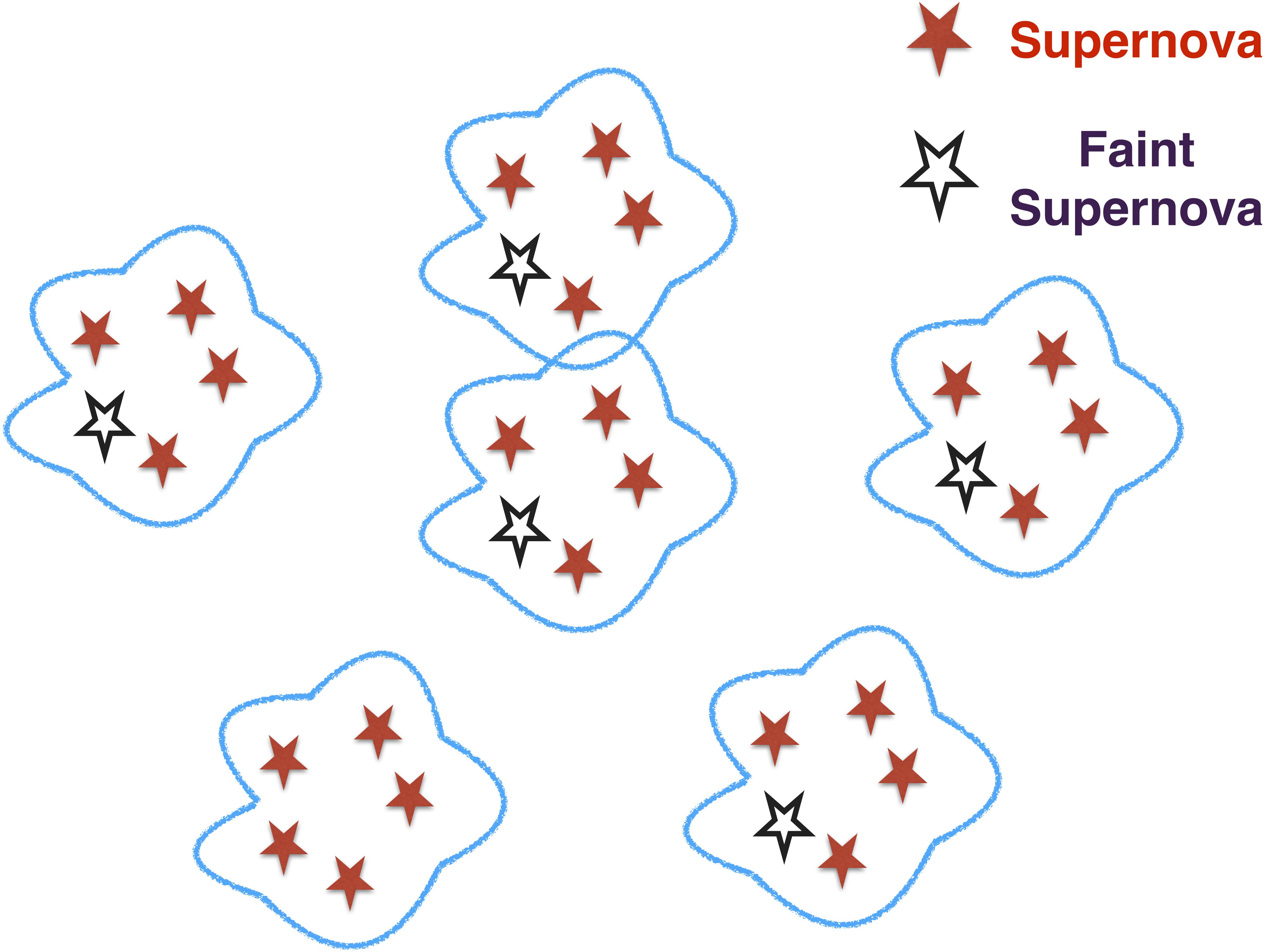


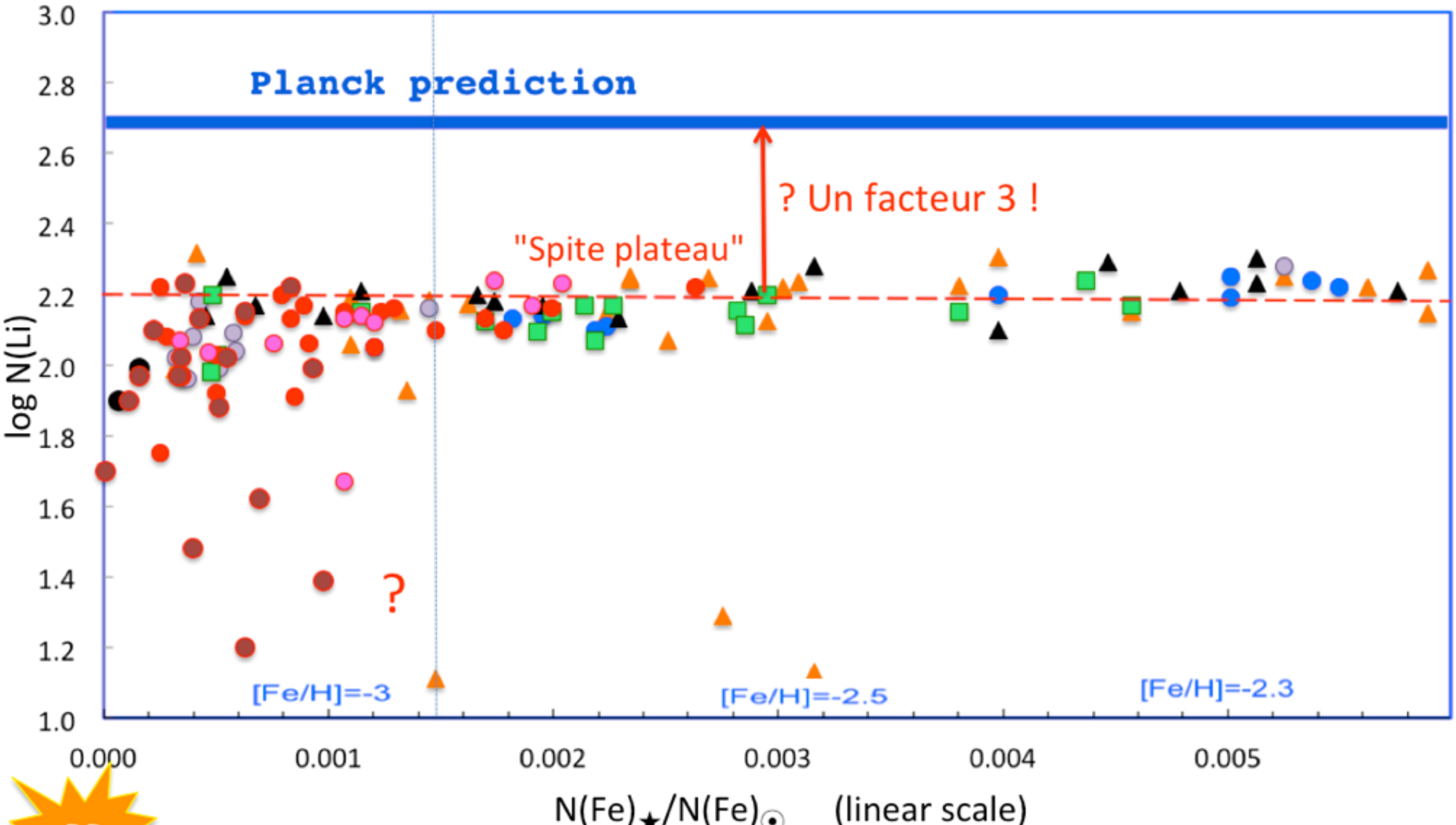
The carbon abundances in CEMP stars are bimodal



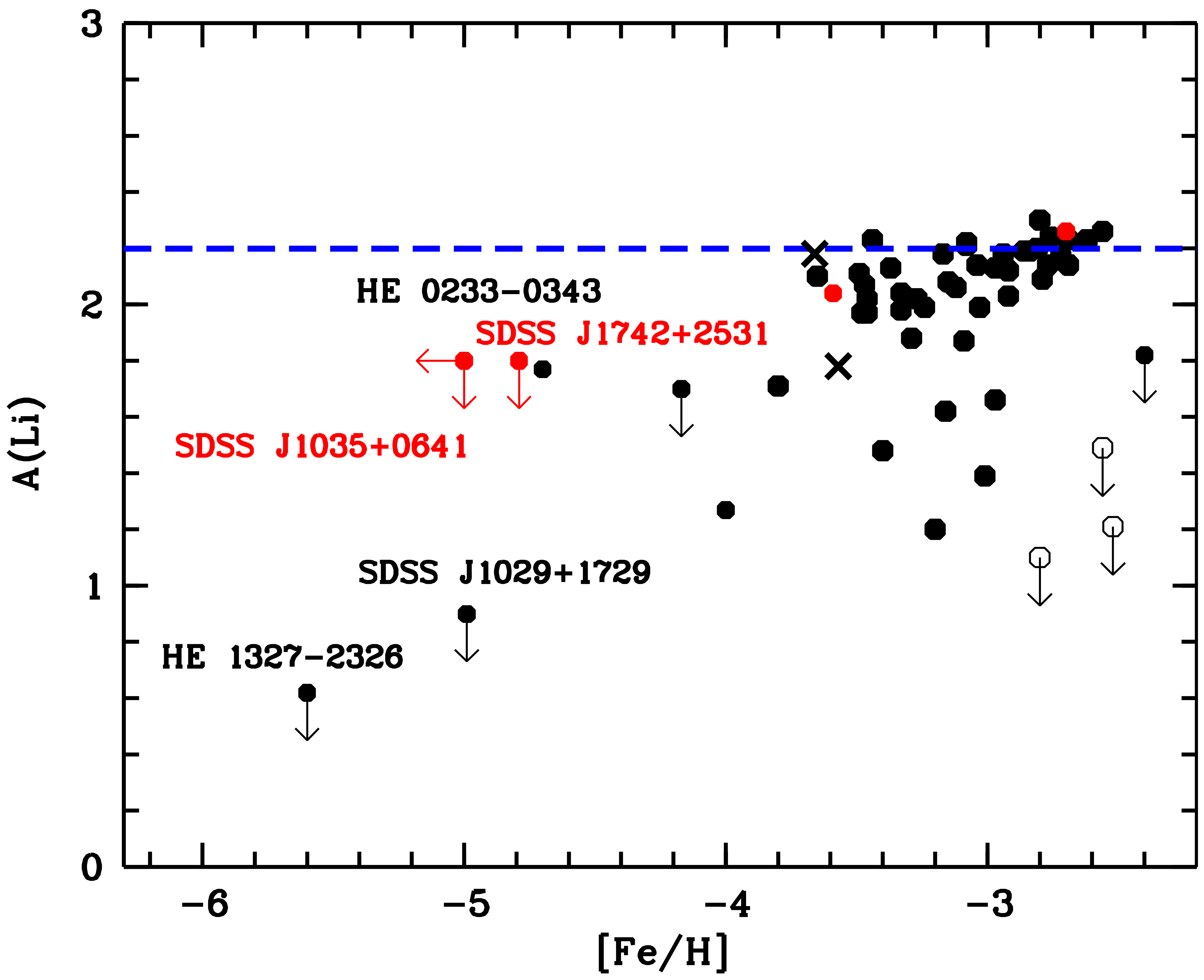
Bonifacio et al. 2015 A&A 579, A28


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


Planck prediction
? Un facteur 3 !
"Spite plateau"
?
[Fe/H]=-3
[Fe/H]=-2.5
[Fe/H]=-2.3
log N(Li)
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.000
0.001
0.002
0.003
0.004
0.005
N(Fe)★/N(Fe)☉ (linear scale)

BB



3
2
1
0
−6
−5
−4
−3
[Fe/H]
A(Li)
HE 0233−0343
SDSS J1742+2531
SDSS J1035+0641
SDSS J1029+1729
HE 1327−2326

Three possible scenarios to explain Li-depletion

1. EMP low mass stars were all formed by fragmentation of higher mass clouds. They remain fast rotators through pre-MS. Rotational mixing leads to Li destruction.

2. Pre-MS always depletes all the Li, late accretion of unprocessed material restores the Li to some extent (Molaro, Bressan, Fu,…). EMP stars lack or have an inefficient late-accretion phase

3. Within the DM mini-halo a significant fraction of the mass (50% ?) is rapidly processed through massive stars, this leads to Li depletion. Low-mass stars only form from this pre-processed material (also some metals ?).

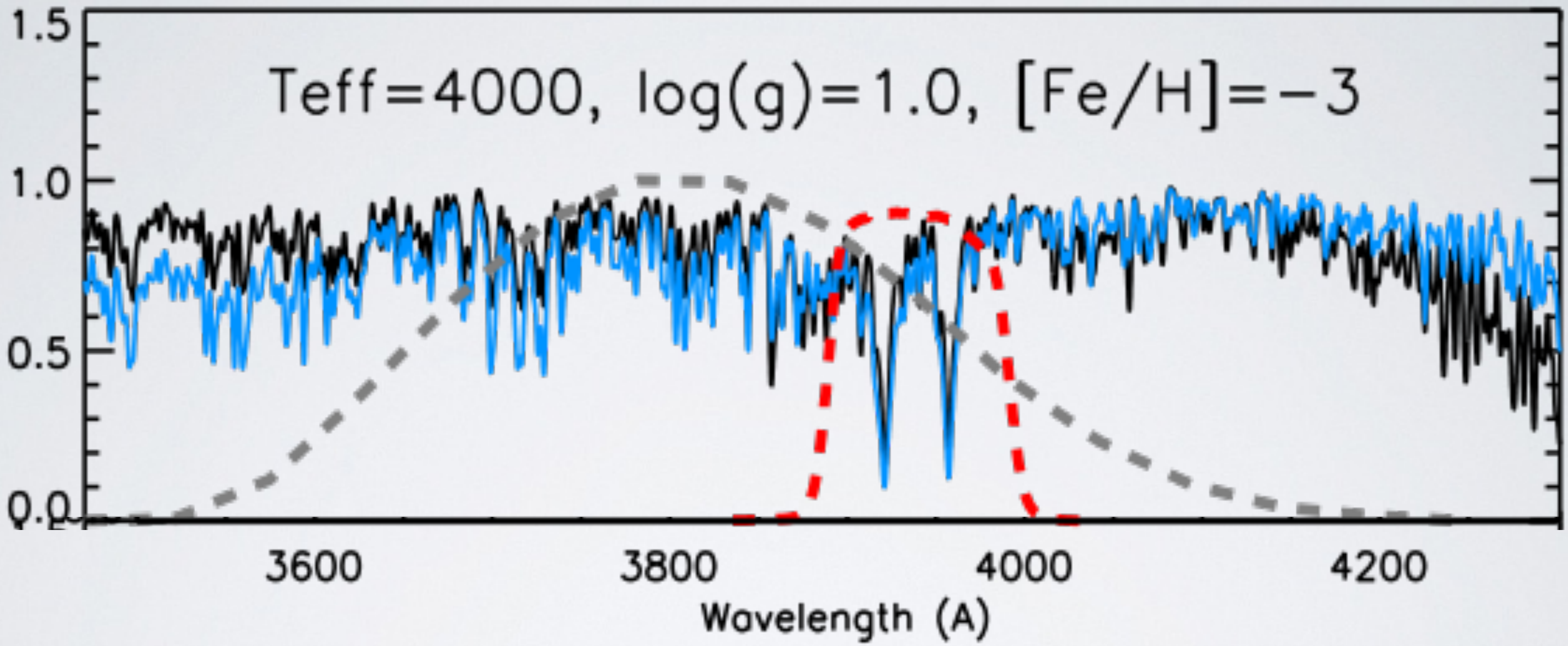
What is in the future ?

Researching the “Pristine” Galaxy

PI: Else Starkenburg & Nicolas Martin. Co-Is: Piercarlo Bonifacio, Elisabetta Caffau, Raymond Carlberg, Patrick Cote, Patrick Francois, Stephen Gwyn, Vanessa Hill, Rodrigo Ibata, Pascale Jablonka, Julio Navarro, Alan McConnachie, Ruben Sanchez-Janssen, Kim Venn, Kris Youakim

Leibniz Institute for astrophysics Potsdam (AIP), Observatoire astronomique de Strasbourg, Observatoire de Paris (GEPI), University of Victoria, University of Toronto, NRC-Herzberg, Observatoire de la Cote d'Azur

The Ca H&K filter



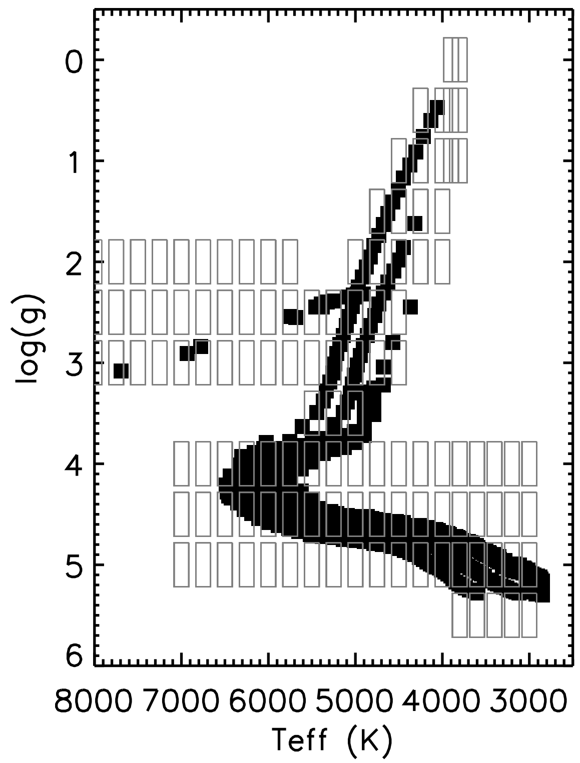
[Fe/H] = –3.0

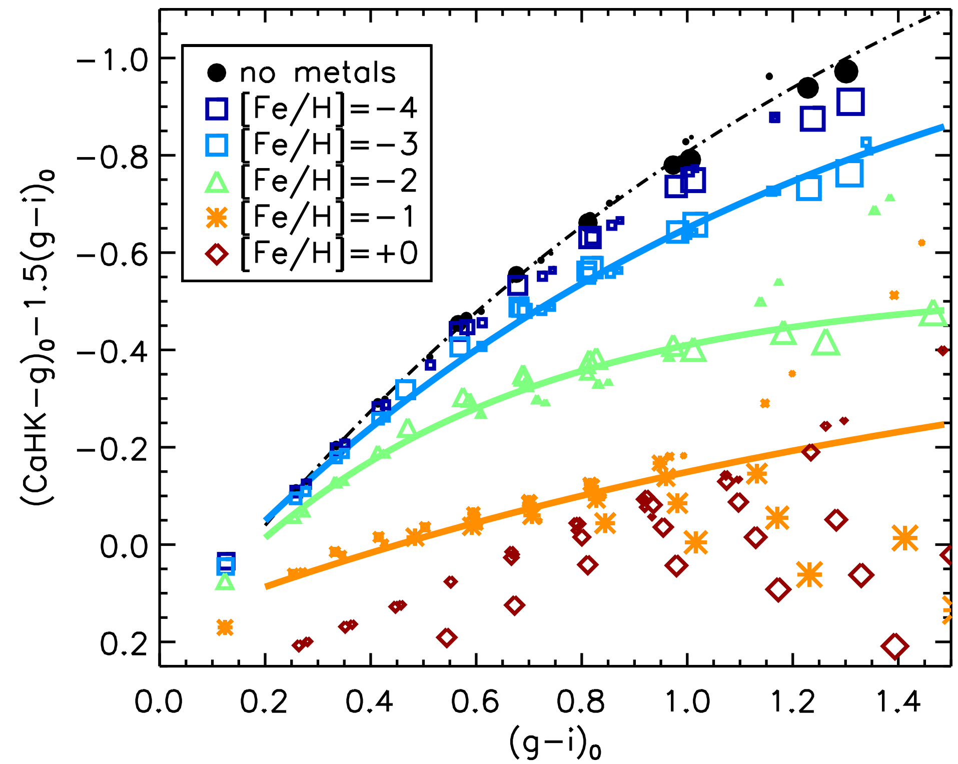
[Fe/H] = –3.0, [C/Fe] = +1

- *Pristine filter is narrower than the Skymapper filter*

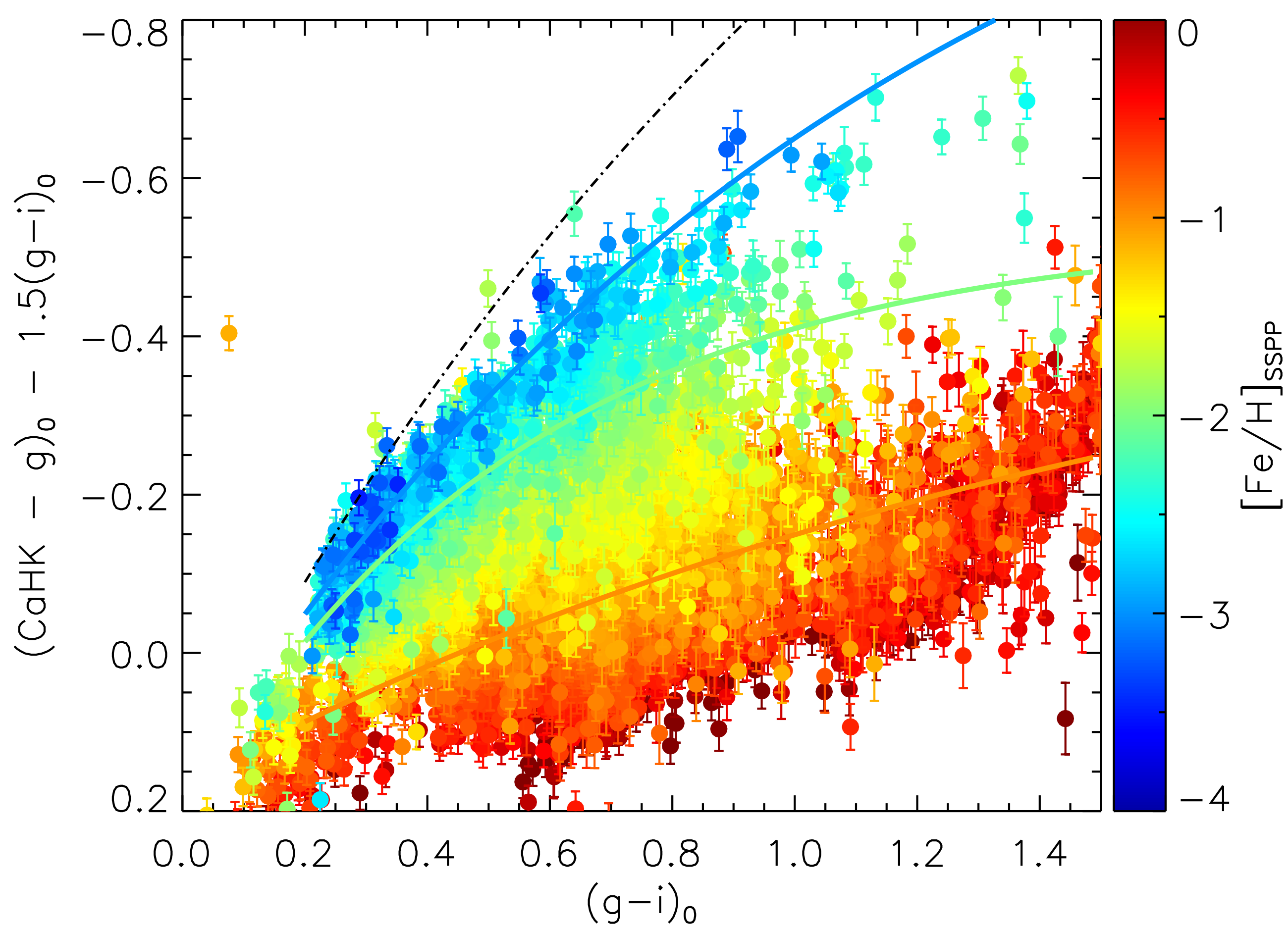
courtesy of E. Starkenburg

The theory





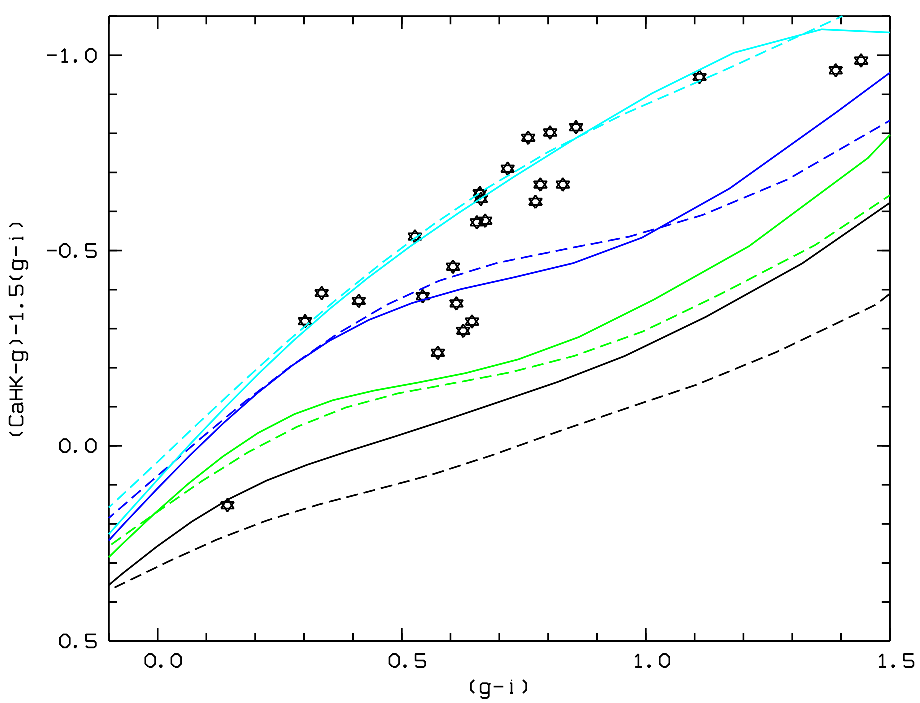
The observations (SDSS metallicities)



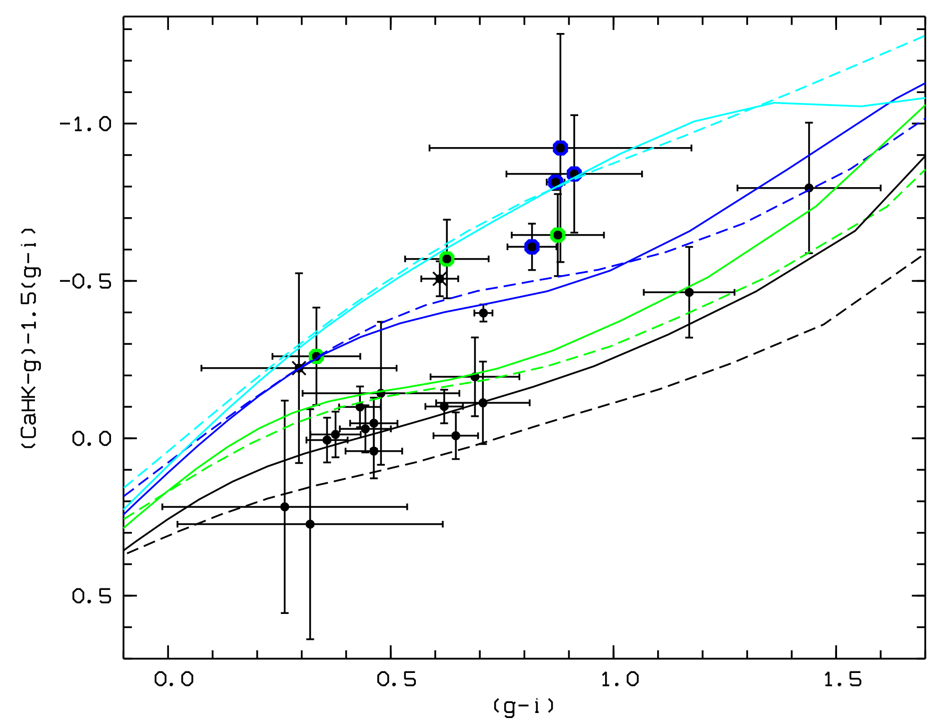
Starkenburg et al. 2017 MNRAS in press, arXiv: 1705.01113 (Paper I)

It is important to have also good broad-band photometry

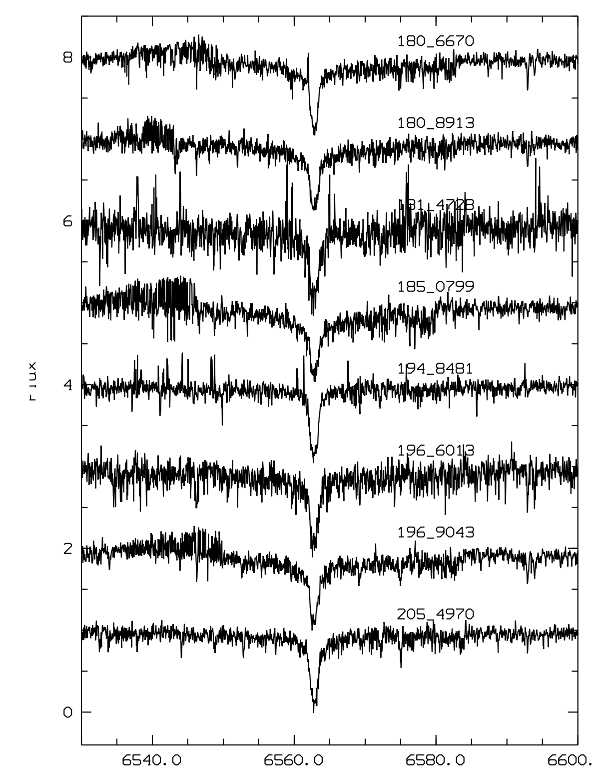
SDSS



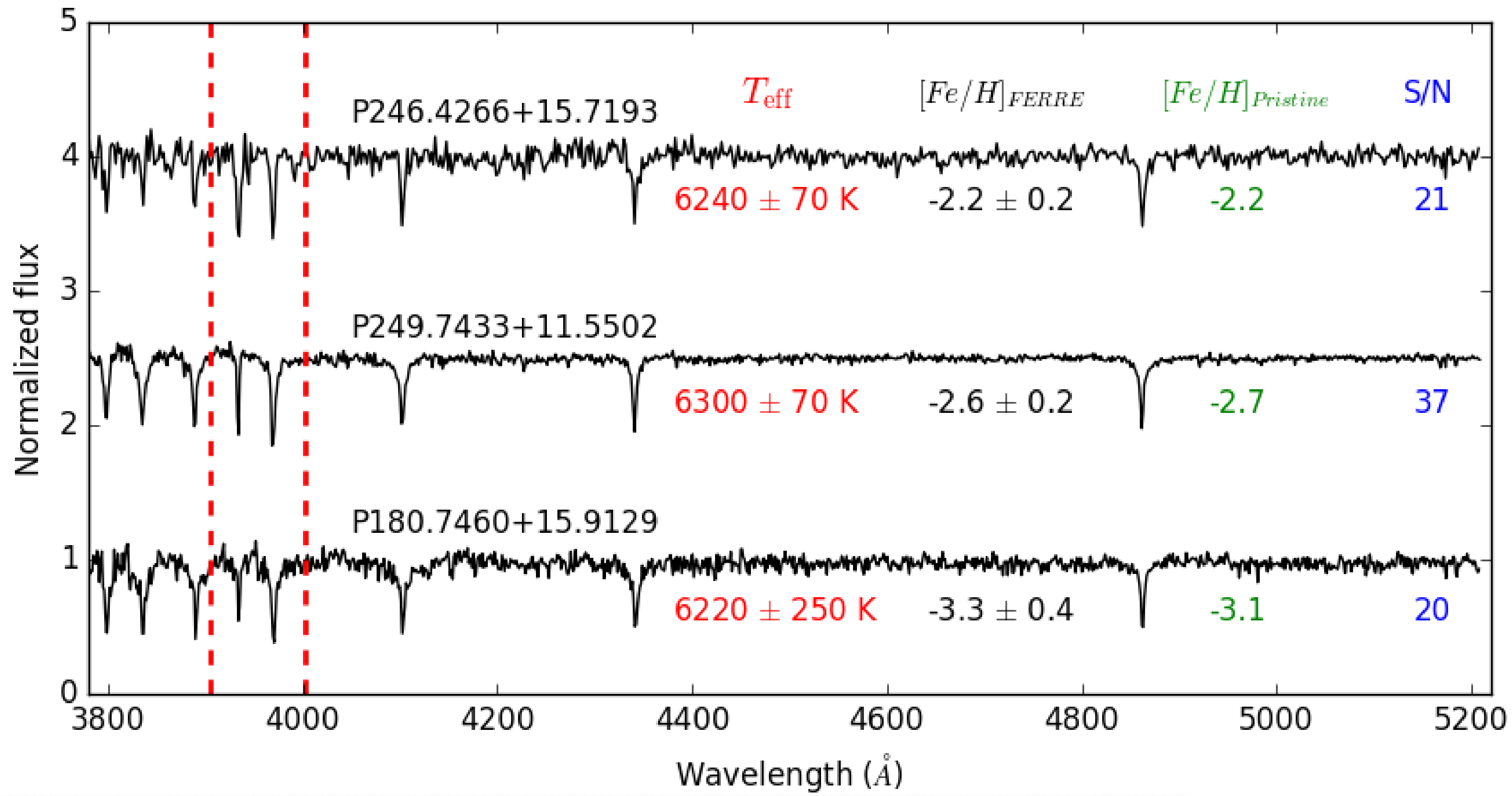
APASS



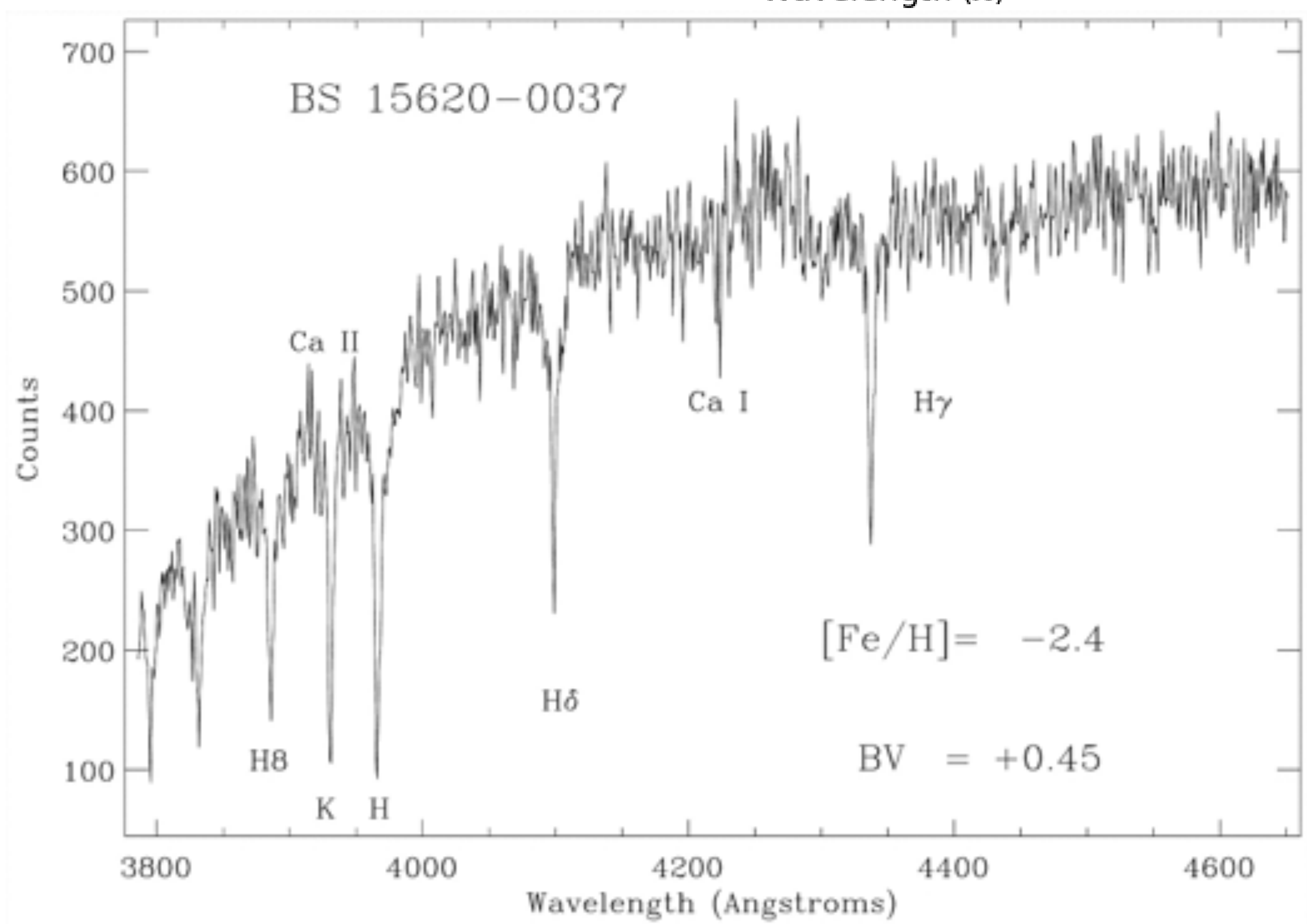
FEROS observation of a sample of bright stars. The initial photometric estimates were wrong. This because the SDSS photometry is not good below g~15. Things are fixed if you use APASS instead. (Caffau et al. 2017 AN submitted; Paper II)



IDS 2016
Youakim et al. submitted to MNRAS ; Paper III



IDS 1995-1996
Allende Prieto et al. 2000



There are some fine points on calibrating HK photometry

Şeyma Çalışkan[1,*], Tolgahan Kılıçoğlu[1], Doğuş Özuyar[1], Piercarlo Bonifacio[2], Elisabetta Caffau

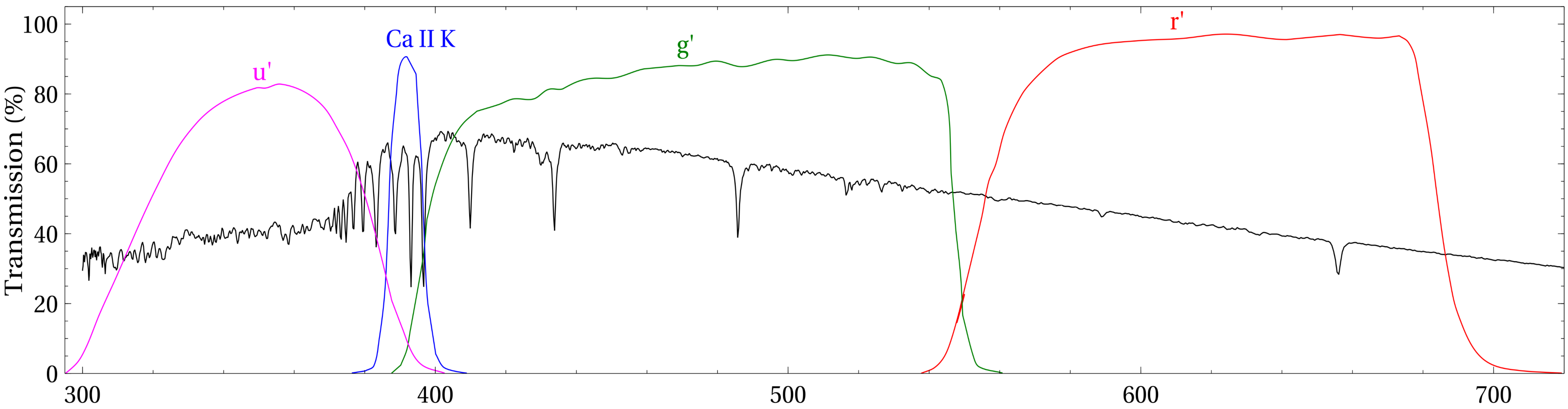
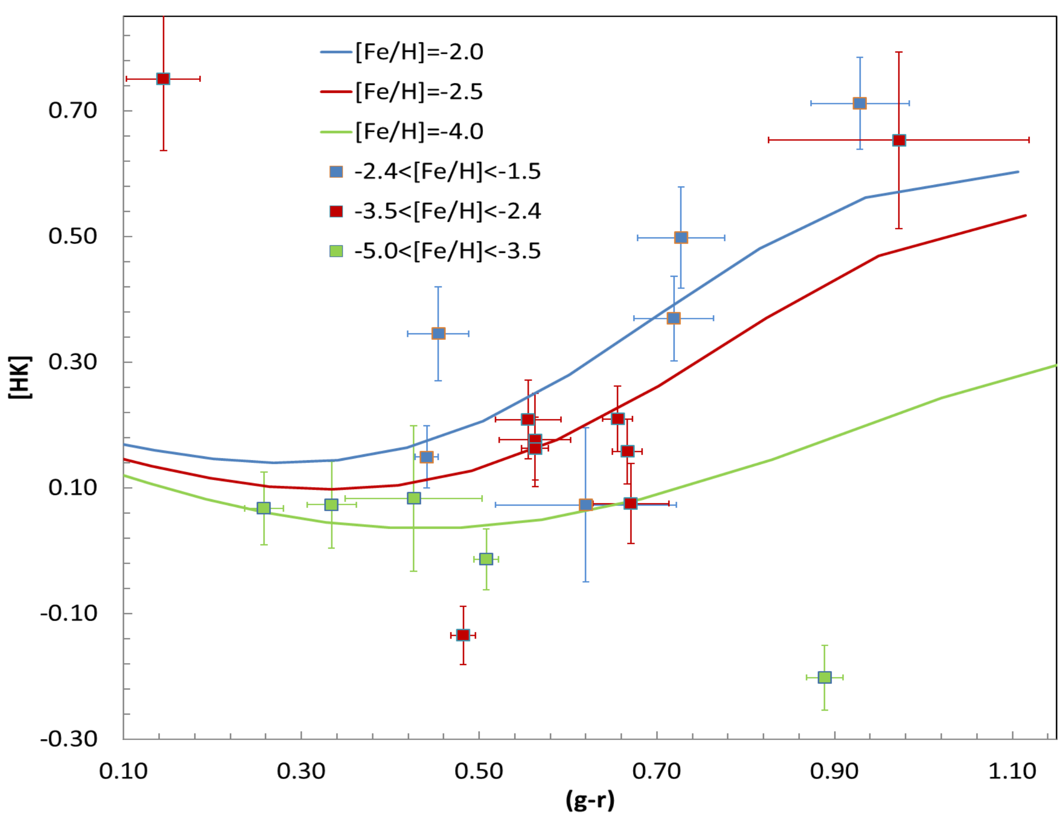


Figure 1. Transmission curves of TUG-T100 u'g'r'CaK



If you want to “tie in” into the SDSS system and compare to theoretical models you need to observe the SDSS primary standards. These are mostly too bright for CFHT. We are doing HK observations with the 1m TUG observatory, to established a fully homogeneous system. Eventually we hope to cross-calibrate TUG and CFHT filters.

Next steps

- The calibration of the CFHT HK colour is already very good (Youakim et al. 2017) when compared to other surveys.

Survey	**[Fe/H] <-3**	**[Fe/H] <-2.5**	**-3 <[Fe/H] <-2**
Pristine	22%	70%	85%
HES	3.8%	22%	40%
SC14	3.8%	-	32%

- With the current observations we are aiming at further improving it, especially for the bin below [M/H]= -3.0

- The improved calibration will be used to select a large sample for follow-up in the WEAVE Galactic Archeology Survey.

Thank you !