The first generations of stars

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Galaxies Étoiles Physique et Instrumentation

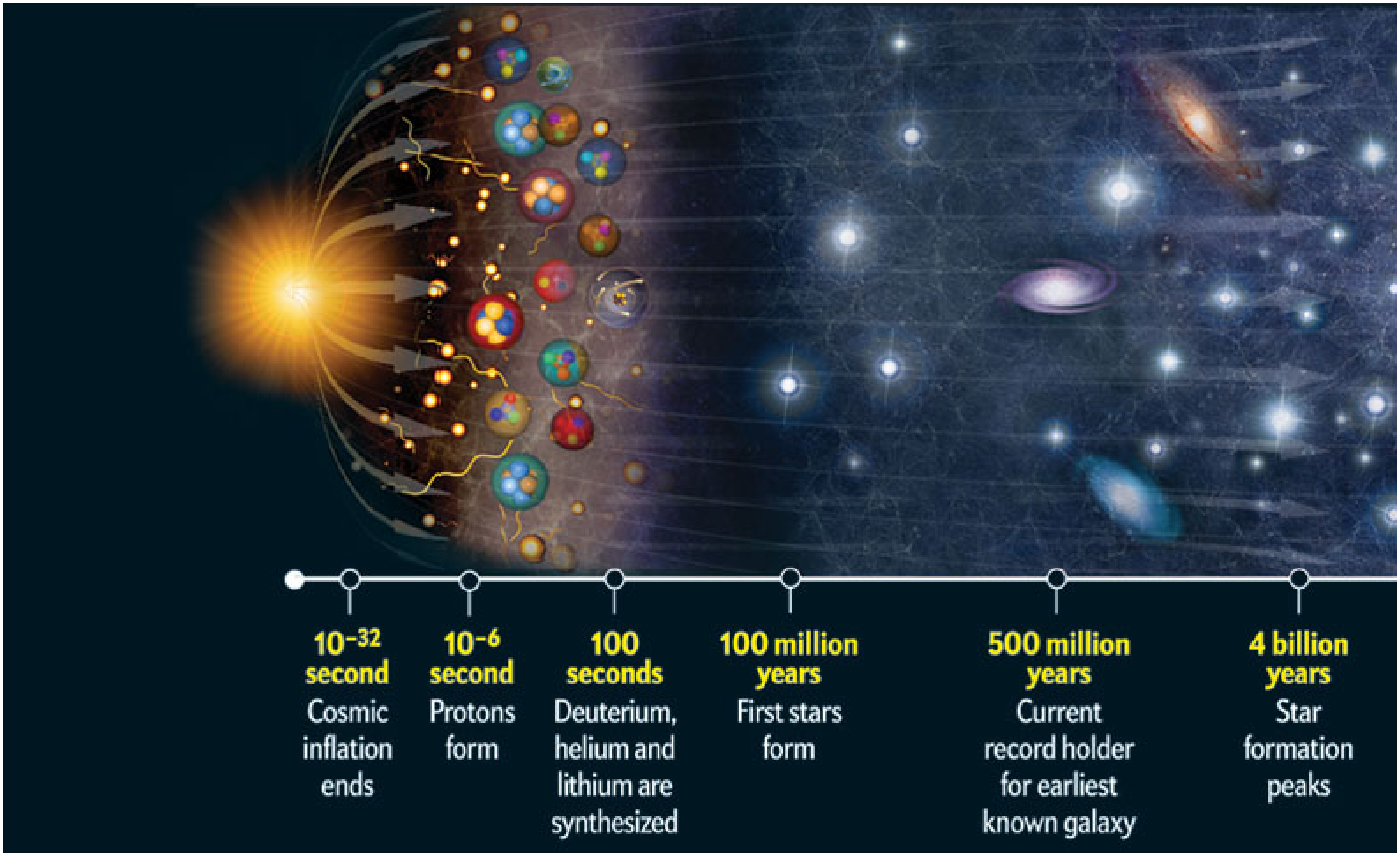
Primordial Universe

- **Understanding the Universe: we have now a picture on**
  - What the Universe is made of
  - For how long it has existed
  - How it will evolve in future

- **The knowledge is based on**
  - Investigations on supernovae
  - Observations of the large scale distribution of galaxies and intergalactic medium
  - Analysis of the cosmic background
  - **Observations of the first stars on the early Universe**
  - Studies of the nucleosynthesis during the BBN

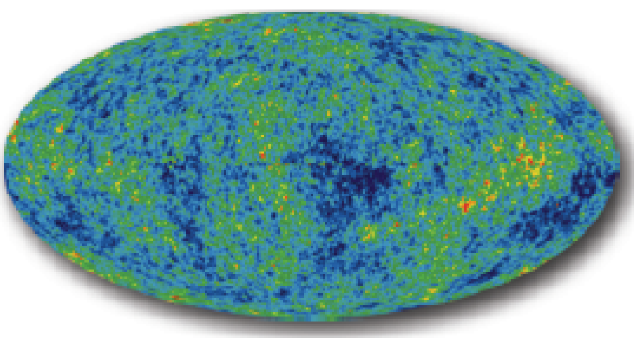
see Grant et al. 2017

First stars

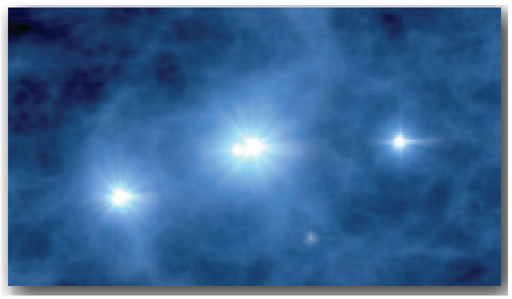

10^{-32} second
Cosmic inflation ends
10^{-6} second
Protons form
100 seconds
Deuterium, helium and lithium are synthesized
100 million years
First stars form
500 million years
Current record holder for earliest known galaxy
4 billion years
Star formation peaks

The Universe emerging from the Big Bang

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

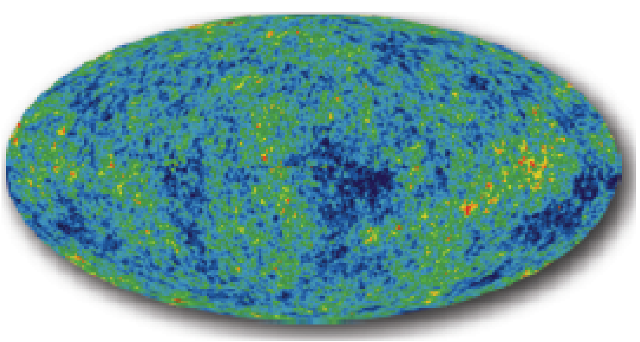


Formation of the first stars

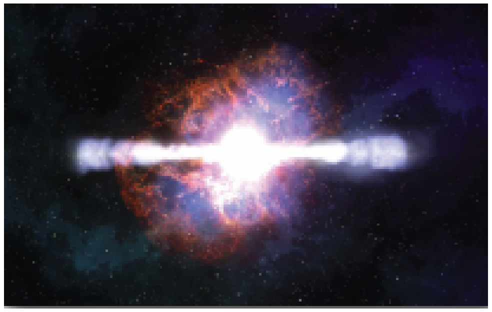


The first stars formed ~ 200 Myr after the Big Bang

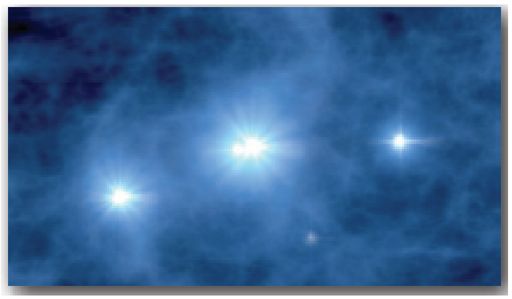
The cooling of the contracting material was inefficient due to the lack of metals and dust.

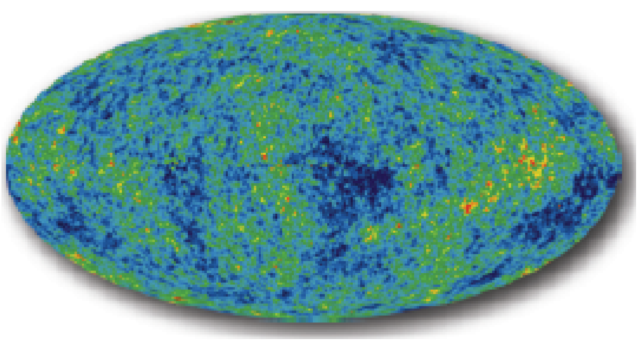


The first stars were most likely very massive (50-300 $M_\odot$)

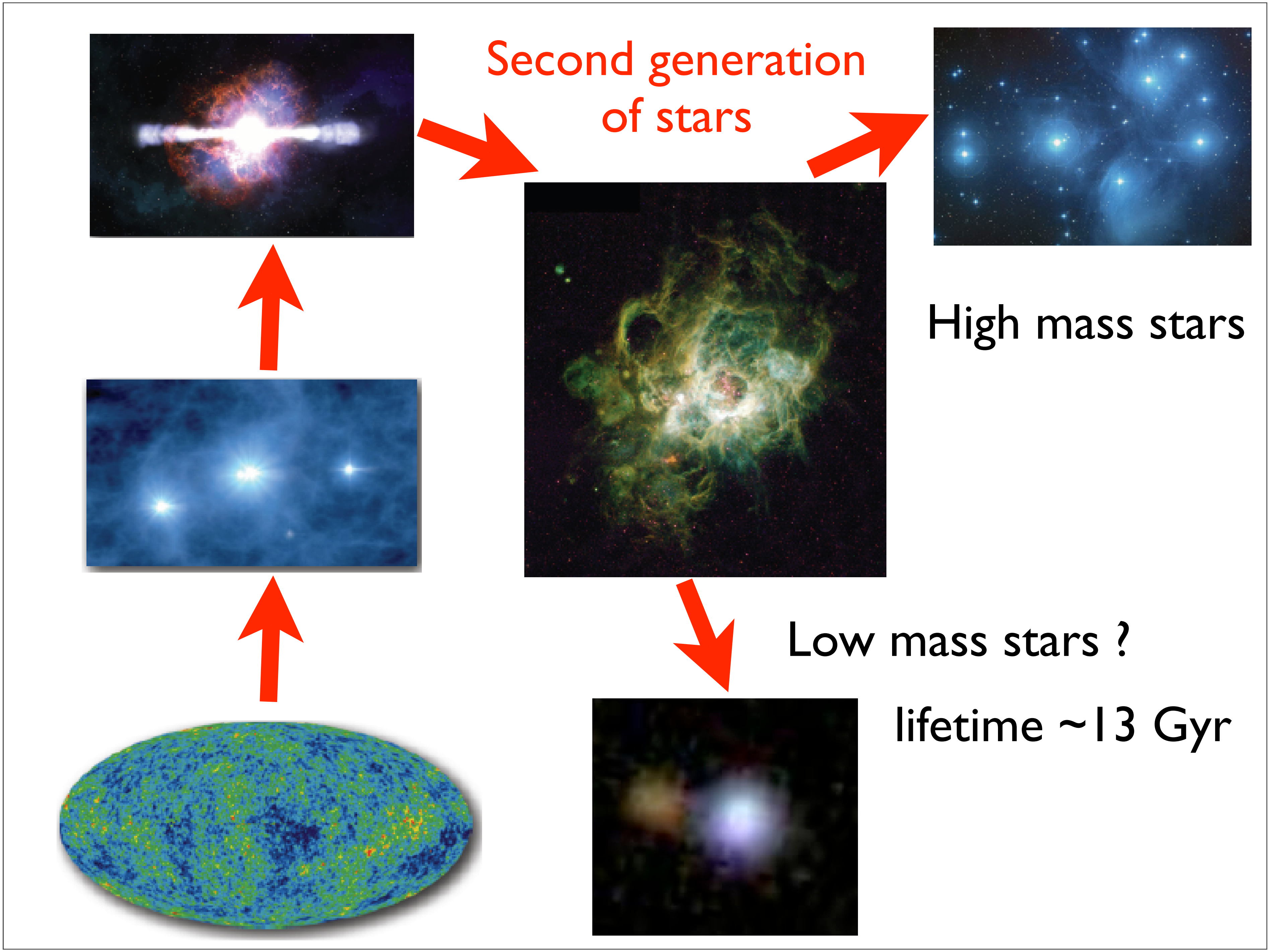


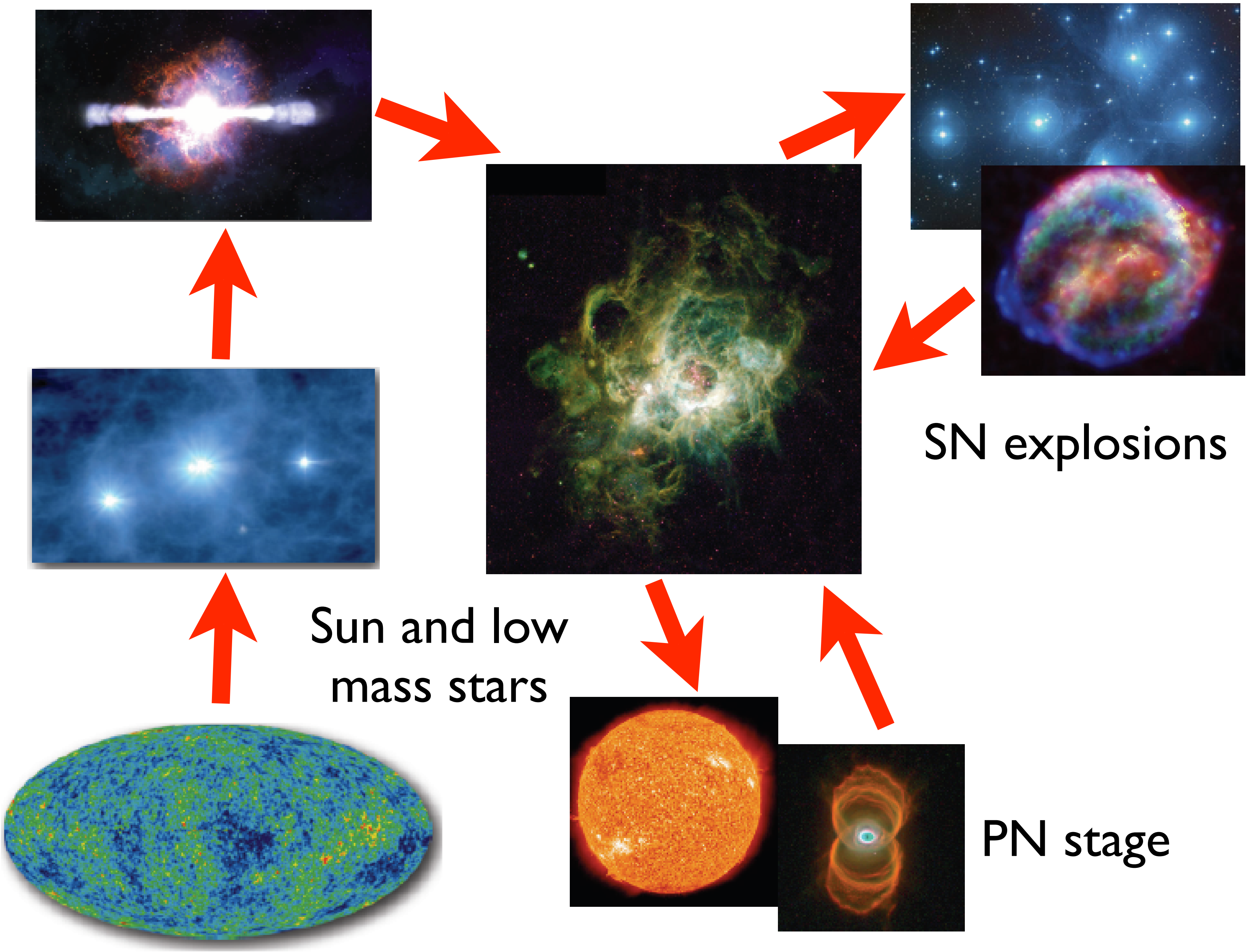
The first massive stars evolved rapidly and synthetised metals

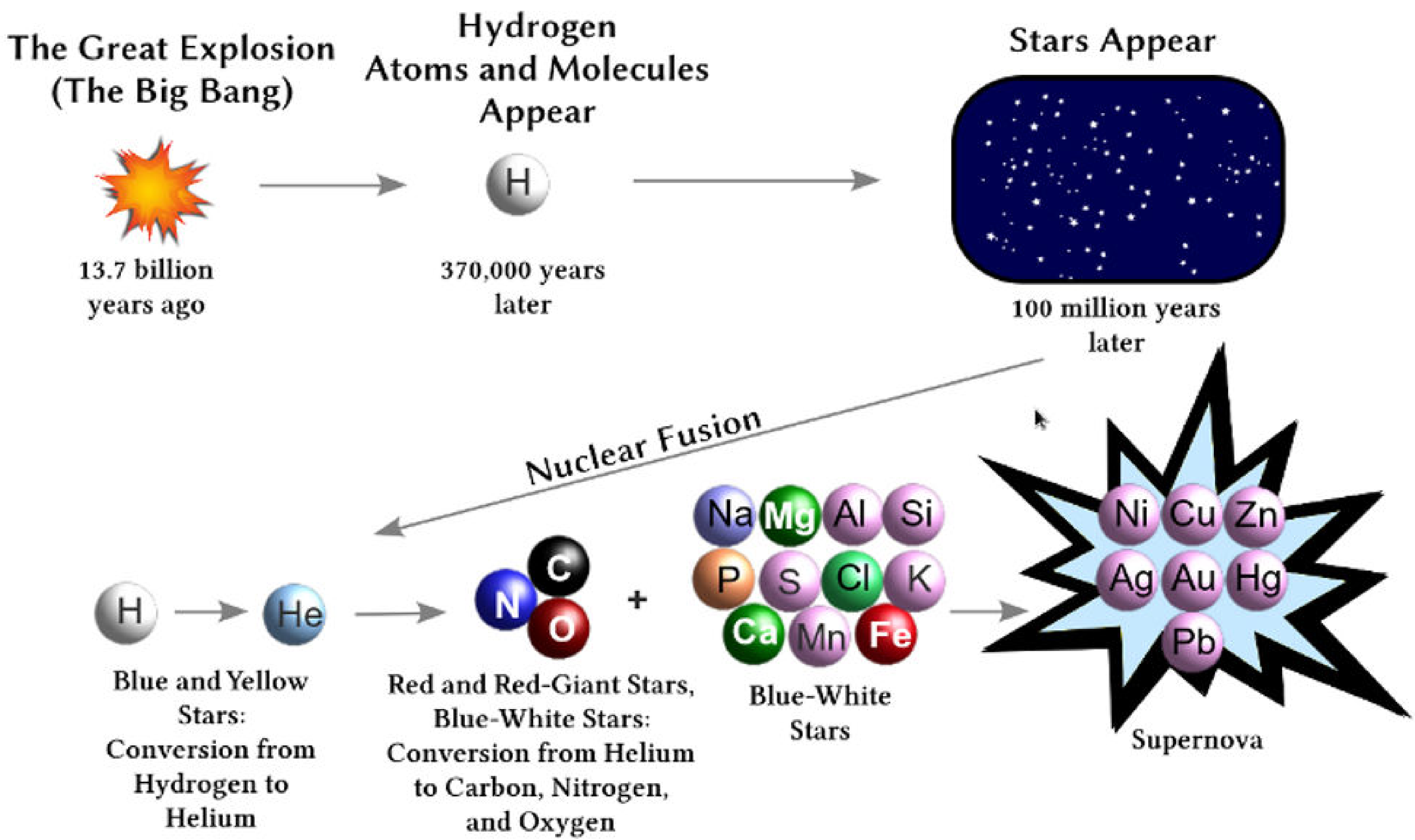




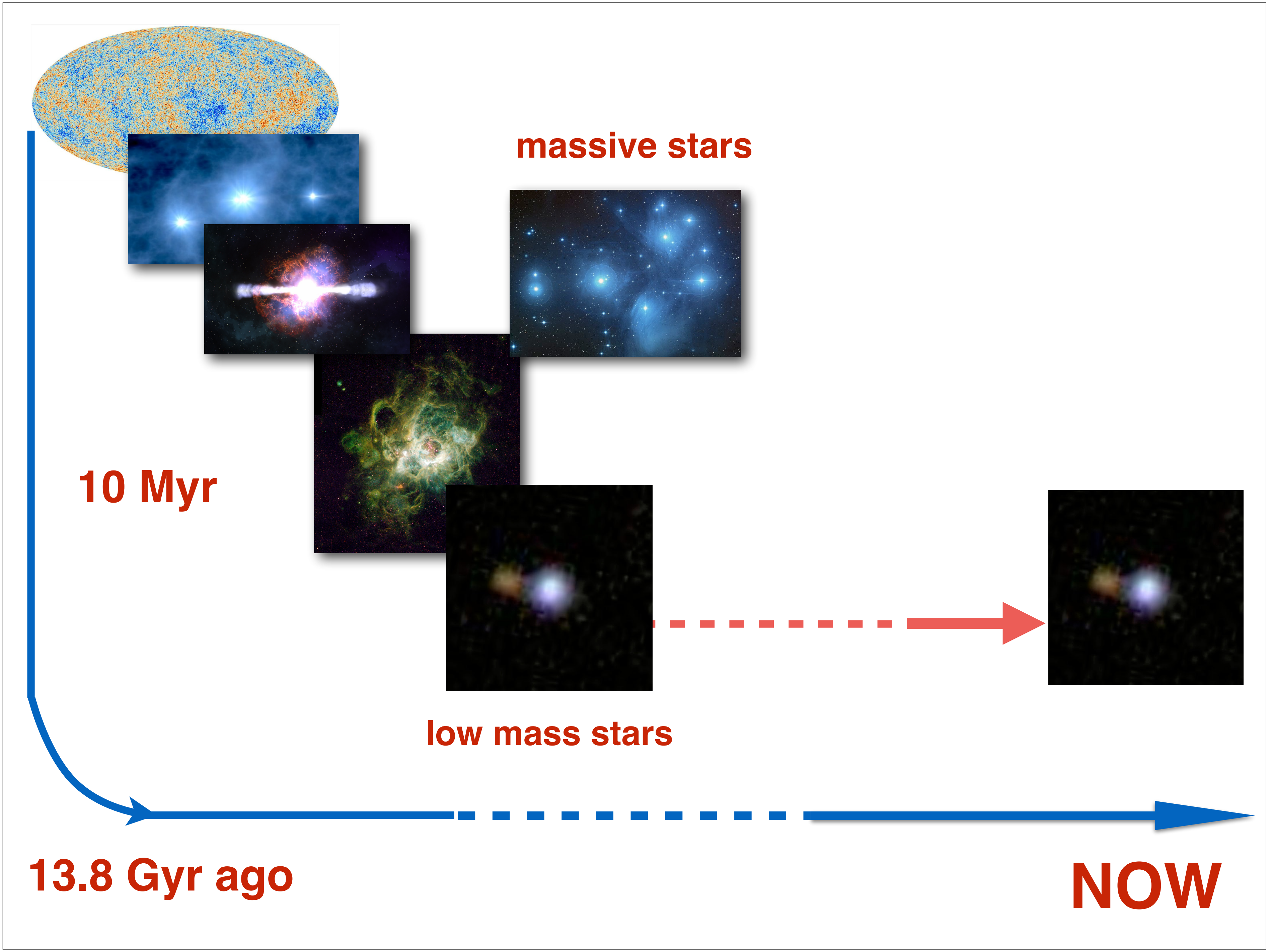
At the end of their lives (~10 Myr) they exploded as SN and polluted the ISM with the metals.


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


SN explosions
Sun and low mass stars
PN stage



The Great Explosion (The Big Bang)
13.7 billion years ago
Hydrogen Atoms and Molecules Appear
H
370,000 years later
Stars Appear
100 million years later
Nuclear Fusion
H
He
Blue and Yellow Stars: Conversion from Hydrogen to Helium
C
N
O
Red and Red-Giant Stars, Blue-White Stars: Conversion from Helium to Carbon, Nitrogen, and Oxygen
+
Na Mg Al Si
P S Cl K
Ca Mn Fe
Blue-White Stars
Ni Cu Zn
Ag Au Hg
Pb
Supernova

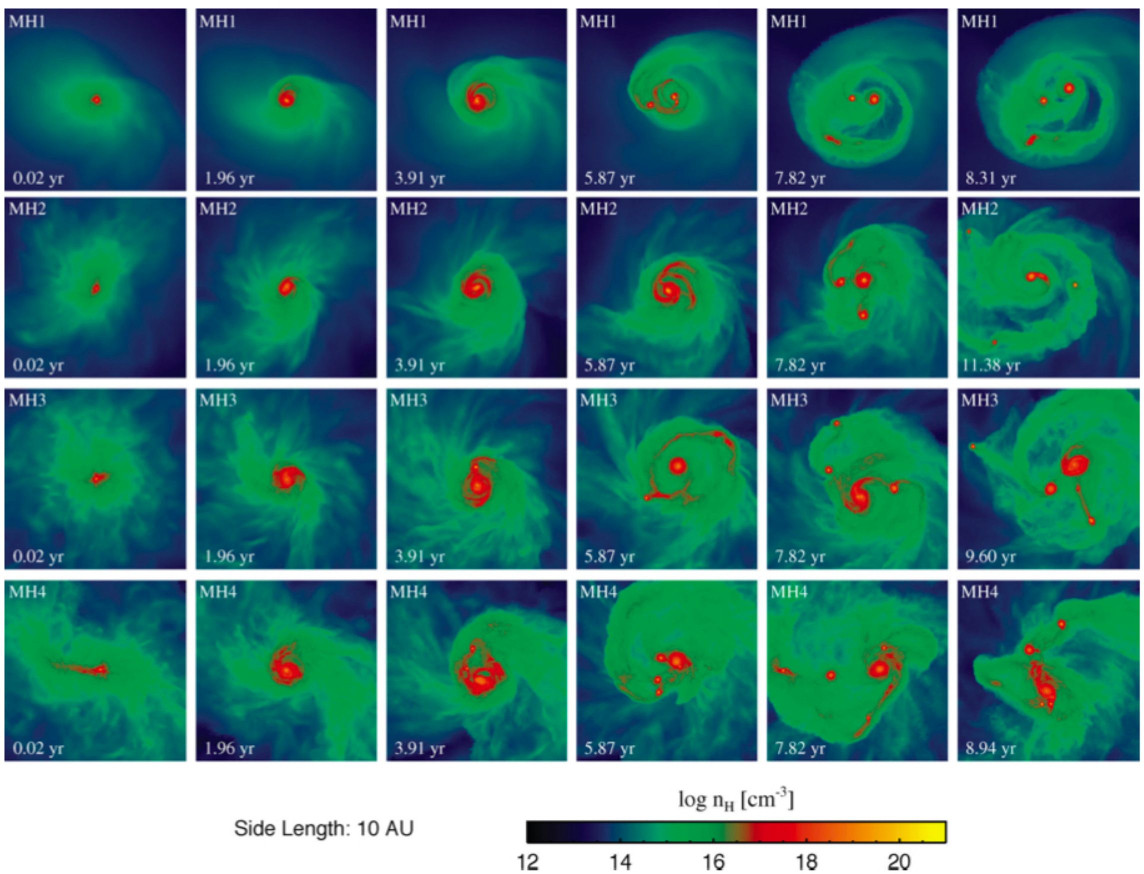

massive stars
10 Myr
low mass stars
13.8 Gyr ago
NOW

First stars

- Formation of Population III (PopIII) stars
  - end of cosmic dark age
  - start of increasing complexity
- Pop III stars
  - source of first hydrogen-ionising photons $\Longrightarrow$ initiation reionisation Universe
  - contribute to the large-angle polarisation of cosmic microwave background (CMB) photons
  - in principle possible to be observed as hyper-energetic supernova or gamma-ray bursts, at the moment of their violent end

First stars

- Pop III stars expected to form
  - in dark matter (DM) mini-halos of masses $\sim 10^6 \mathrm{M}_\odot$
  - at $z \sim 20 - 30$



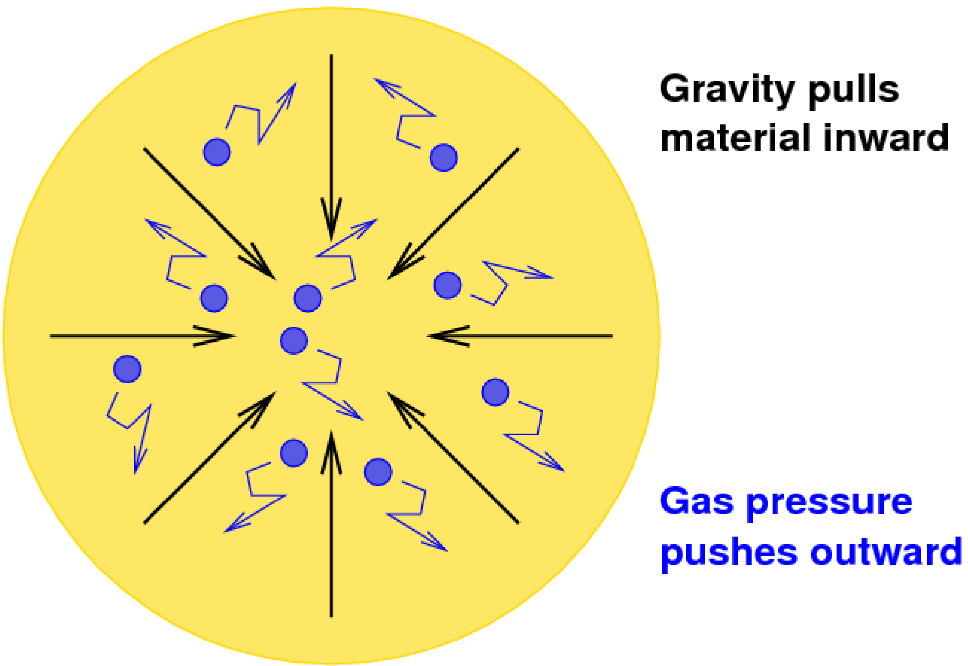
Stacy et al. 2012

Mini-halo

- Mini-halo
  - the primordial density field randomly enhanced over surrounding matter
  - gravity could amplify this perturbation
  - they could decouple from the general expansion of background Universe
  - they could have turned around and collapsed
  - typical (virial) temperature of the gas in mini-halo below 10^4 K, temperature of efficient cooling due to atom H
  - higher temperature would have not allowed the gas to cool, so to collapse

First stars

- To form a star
  - gas has to collapse
  - collapsing gas heats $\Longrightarrow$ cooling needed
  - primordial material very inefficient for cooling



H2 cooling

- H_2 formation
  - With no dust grain that facilitate molecule formation, molecule form in gas phase
  - H_2 molecule has high degree symmetry (not easy radiation)
  - radiation only via magnetic quadrupole
  - so it is difficult to form from collision of two H
- In ISM dust grain serve as catalysts, grain absorb excess of kinetic energy
- In early Universe no dust, instead
  - $\mathrm{H} + e^- \rightarrow \mathrm{H}^- + \gamma$ then $\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + e^-$
    - e^- as catalyst, present in recombination epoch ($z \approx 1100$)
    - formation H_2 stops when e^- are recombined
- In mini-halo the larger the virial temperature the larger the asymptotic H_2 abundance $f_{\mathrm{H}_2} \propto \mathrm{T}_{\mathrm{vir}}^{1.5}$

Mass mini-halo

- To form a galaxy (Rees-Ostriker-Silk criterion) needed
  - cooling timescale shorter than dynamical timescale: $t_{\rm cool} < t_{\rm dyn}$
- Minimum mass at $z \sim 20 - 30$ of about $10^6 \mathrm{M}_\odot$

Accretion

- End initial collapse: small ($\approx 10^{-2}\mathrm{M}_\odot$, similar to Pop I) protostellar core formed at centre minihalo

- Protostellar accretion in Pop. III stars believed to be much larger than today
  - higher temperature in star forming clouds due to limited ability of the gas to cool below ≈ 200 K accessible to H_2 cooling
  - typical accretion rates about 100 times larger to gas forming Pop. I stars

- Pop. III stars would be expected to reach $100\mathrm{M}_\odot$ or more but
  - material falling in the centre of minihalo has angular momentum (e.g. Clark et al. 2011, Grief et al. 2011,2012) $\Longrightarrow$ rotational disc is fed $\Longrightarrow$ there is gravitational instability, the disc is subject to global perturbation
  - To anable useful fragmentation: cooling time scale $<$ orbital time scale (Gammie criterion, 2001)

Fragmentation

- According to simulations disc fragments in small multiple systems, also with binaries (dominating Greif et al.2012, present Turk et al. 2009)
- Lower limit mass for single star not much dependent on metallicity
  - this lower limit important for possibility to observe Pop. III stars
    - if $\mathrm{M} \leq 0.8\mathrm{M}_\odot$ life longer than age Universe
    - according to simulations (Clark et al. 2011, Greif et al. 2011) some fragments could be Pop. III survivors
- Upper limit mass: simplistic $\mathrm{M} \sim 500 - 600\mathrm{M}_\odot$ (Bromm & Loeb 2004), more sophisticated $\mathrm{M} \sim 140\mathrm{M}_\odot$ (McKee & Tan 2008) more sophisticated $\mathrm{M} \sim 30 - 60\mathrm{M}_\odot$ (Hosokawa et al. 2011)

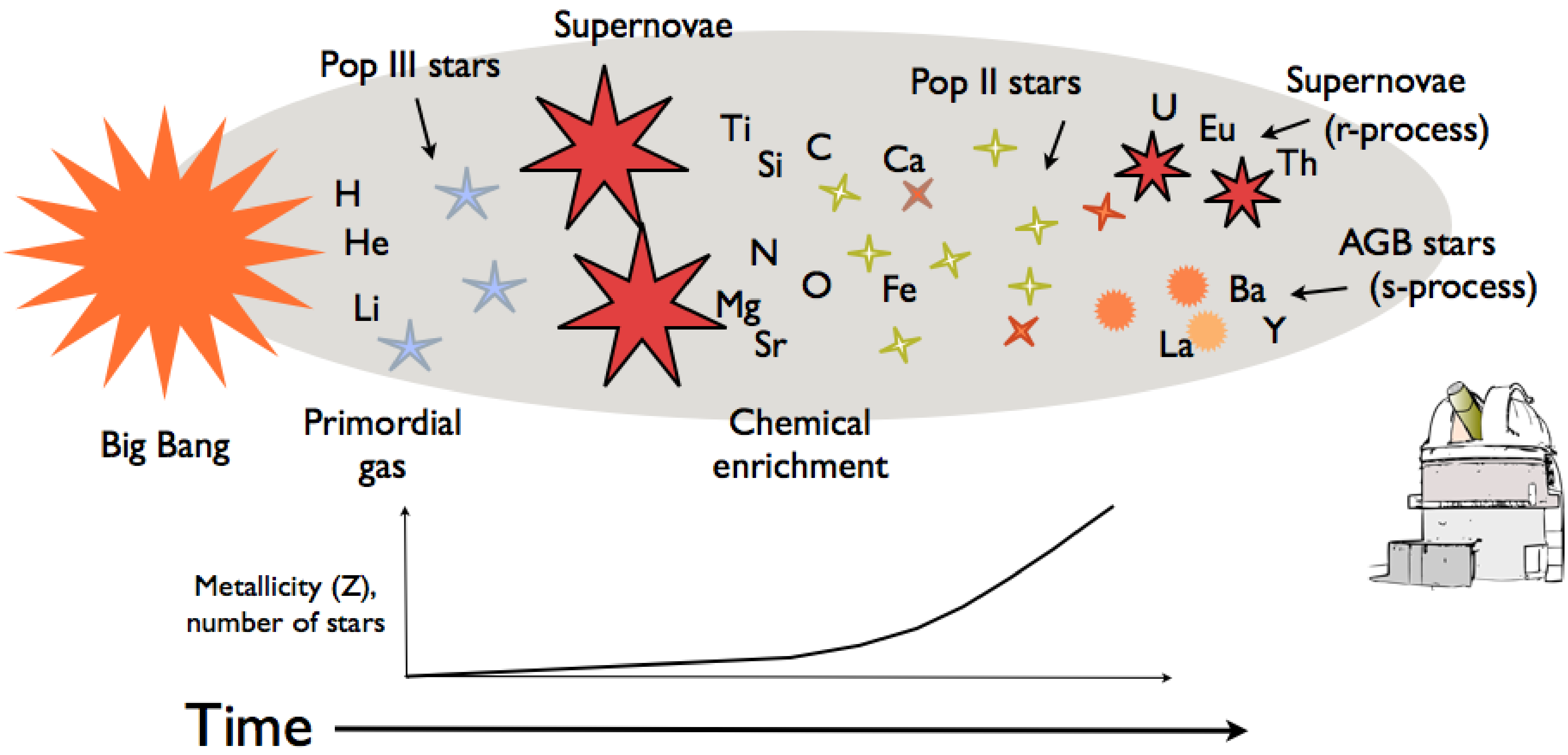
High-mass stars

- No detection at high redshift of high-mass Pop III stars
  - They are too faint
  - Type O6 Main Sequence star: $\mathrm{M} = 40\,\mathrm{M}_{\odot}$, Mag$\sim -6$ ....
  - A $40\mathrm{M}_{\odot}$ not observable "in situ"
    - at $z \sim 8$ or even $z \sim 6$ not observable $(\mathrm{mag} > 40)$
    - cluster on ~ 100000 such stars $\mathrm{mag} \sim 30$
    - from shape Lym α emission discernible Pop III star forming region observable with JWST

Low-mass stars

- From a theoretical point of view a low-mass Pop III star could have been formed (Clark et al. 2011)
- A low-mass star has to be close to be detected
- No detection of Pop III stars in the Solar "vicinity"
  - At present no low-mass first generation star observed
    - It could have been observed but missed because polluted by the enriched gas
    - It could be that they are rare objects and we did not observe yet enough stars to have observed one of them
  - High-mass stars are exploded by long time

The second stellar generation

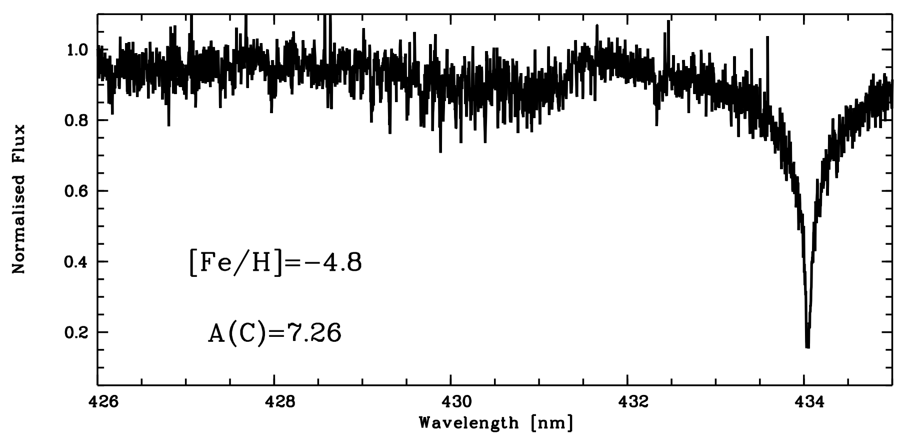


The second stellar generation

- Explosion of Pop III massive stars enriched the gas (dilution of metals synthesised by the star with primordial gas)
- Still the amount of metals is low to allow an efficient cooling
  - a minimum critical metallicity ($\mathrm{Z_{cr}}$) of the gas cloud necessary to form low-mass stars?
  - $\mathrm{[C/H]_{cr}}$ and $\mathrm{[O/H]_{cr}}$, C II and O I fine structure line cooling (Bromm & Loeb 2003), e.g. HE 1327–2326 and HE 0107–5240
    - fine structure line cooling, excitation via collision of C II and O I with e^- or H, radiative de-excitation
    - $\mathrm{[C/H]_{cr}} \sim -3.5 \pm 0.1$ and $\mathrm{[O/H]_{cr}} \sim -3.05 \pm 0.2$
  - presence of dust + fragmentation (Schneider 2012), e.g. SDSS J102915+172927

Second generation of stars shining today?

- Historically the first extremely iron-poor ([Fe/H]≤ -4.5) stars found are all C-, N- and probably O-enhanced, and others have been found (Christileb et al. 2002)
- Out of 11 stars known at present with [Fe/H]≤ -4.5 only one is C-normal
- Derive C abundance from stellar spectra is usually not a problem



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

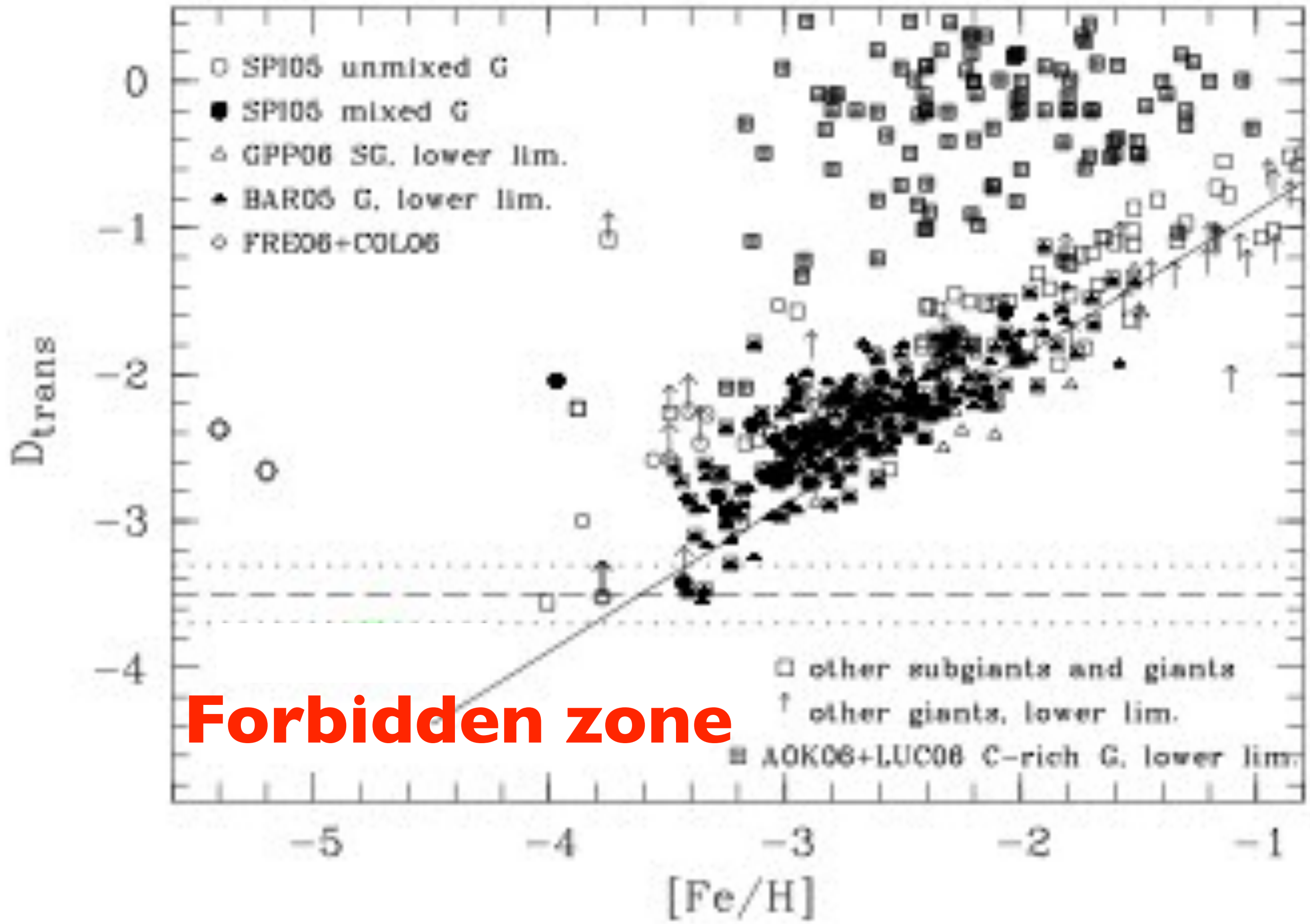
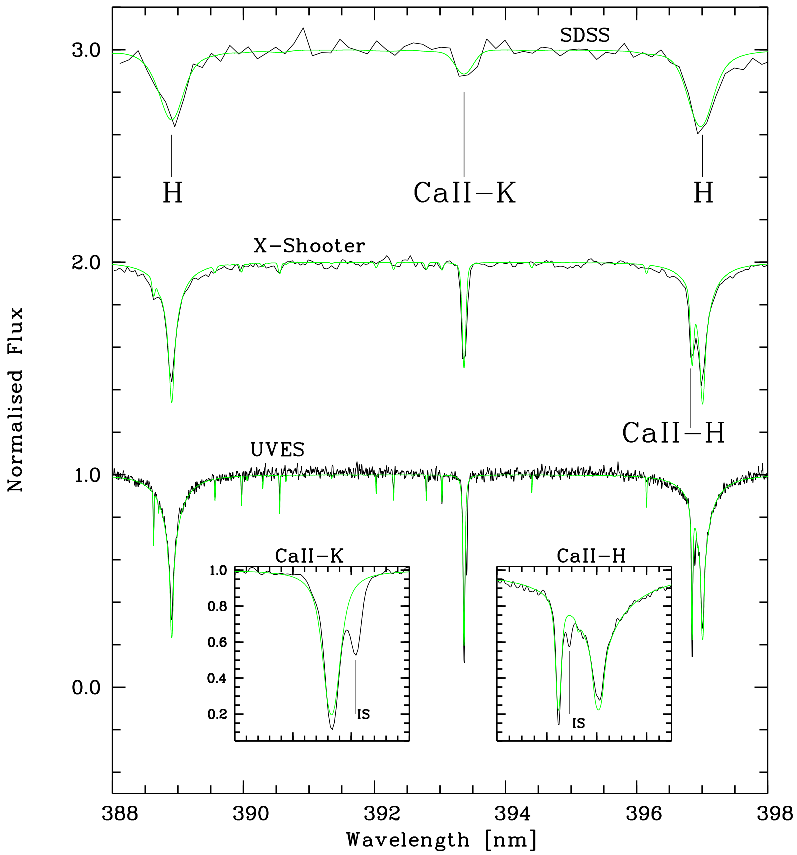


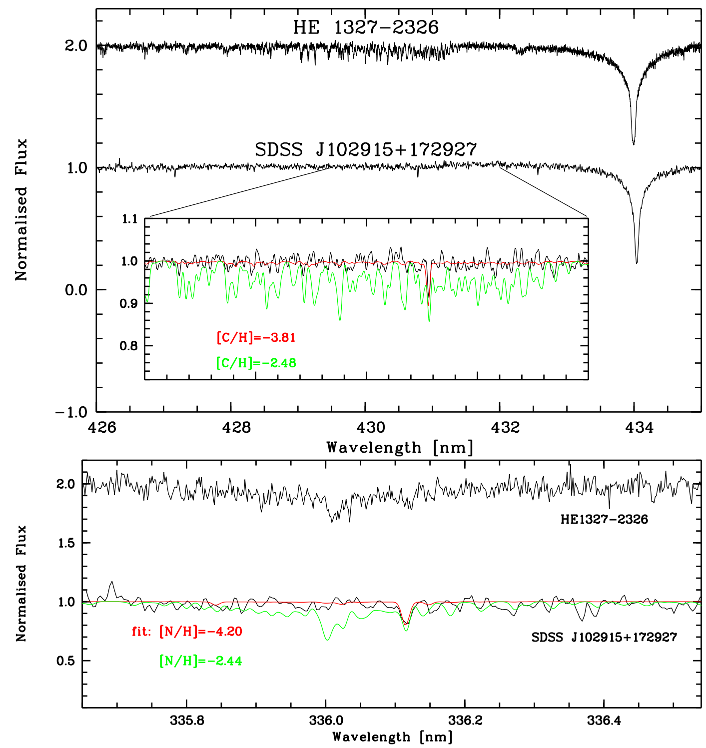
Figure from Frebel et al. 2007

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

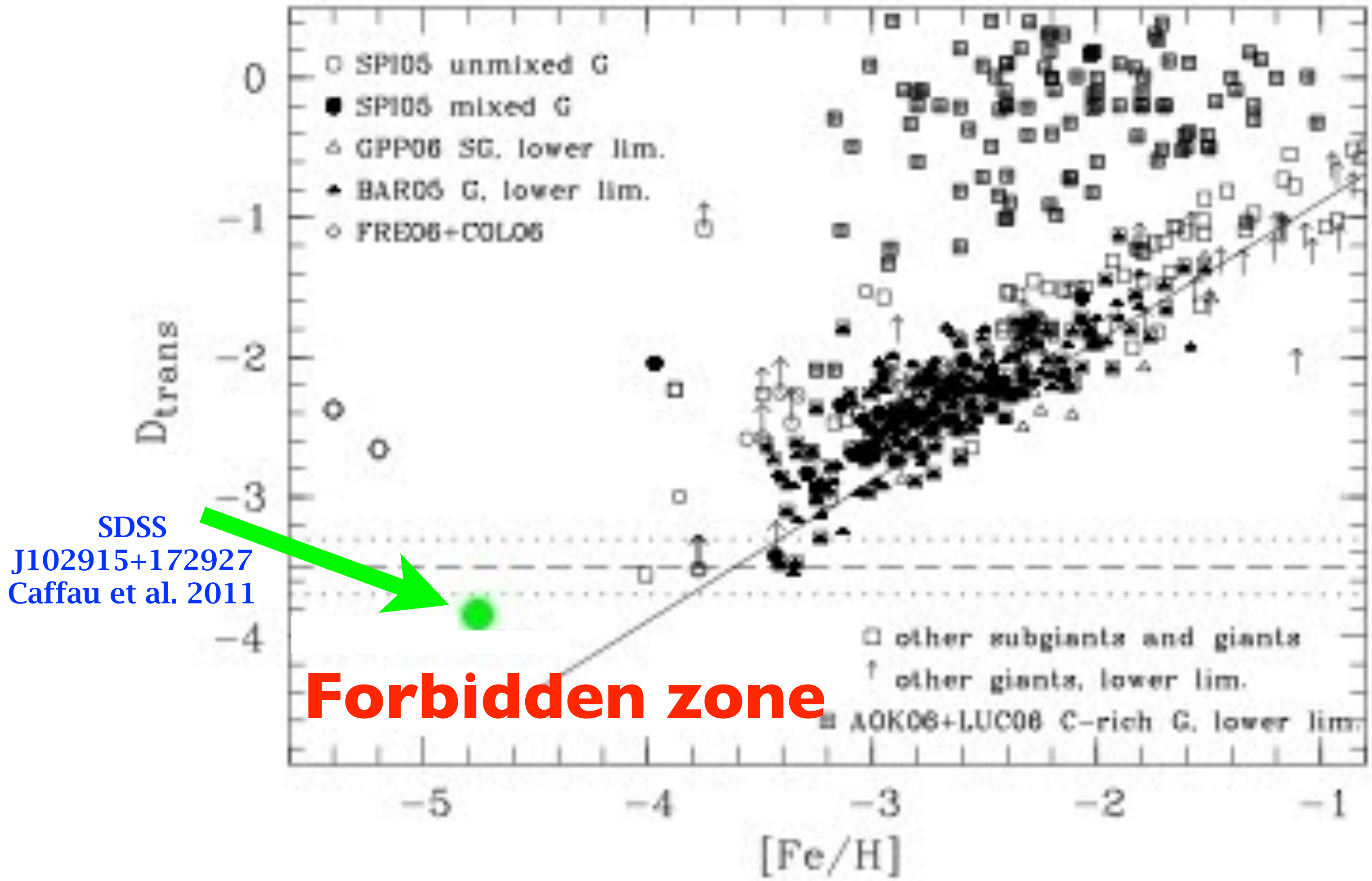
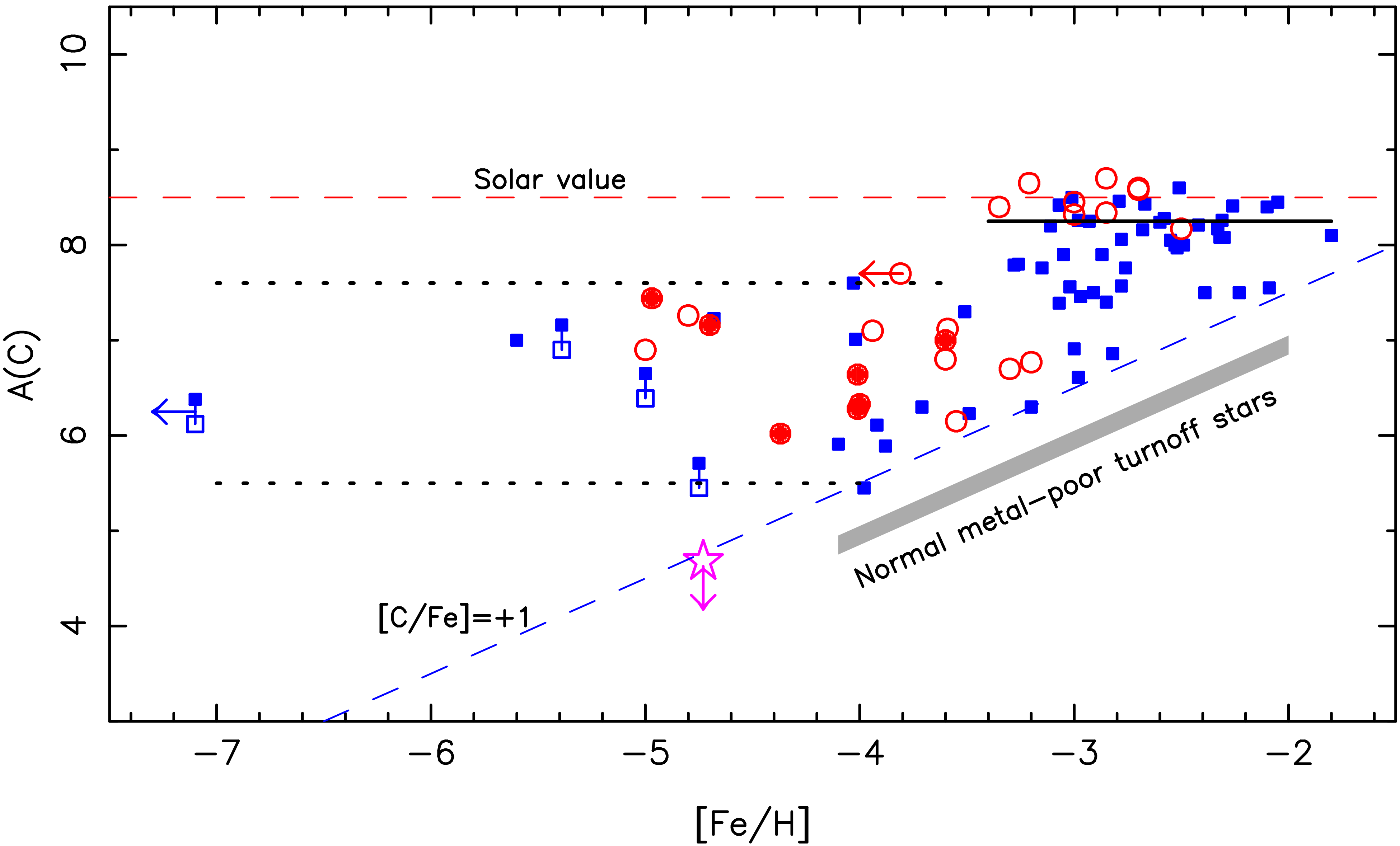


Figure from Frebel et al. 2007

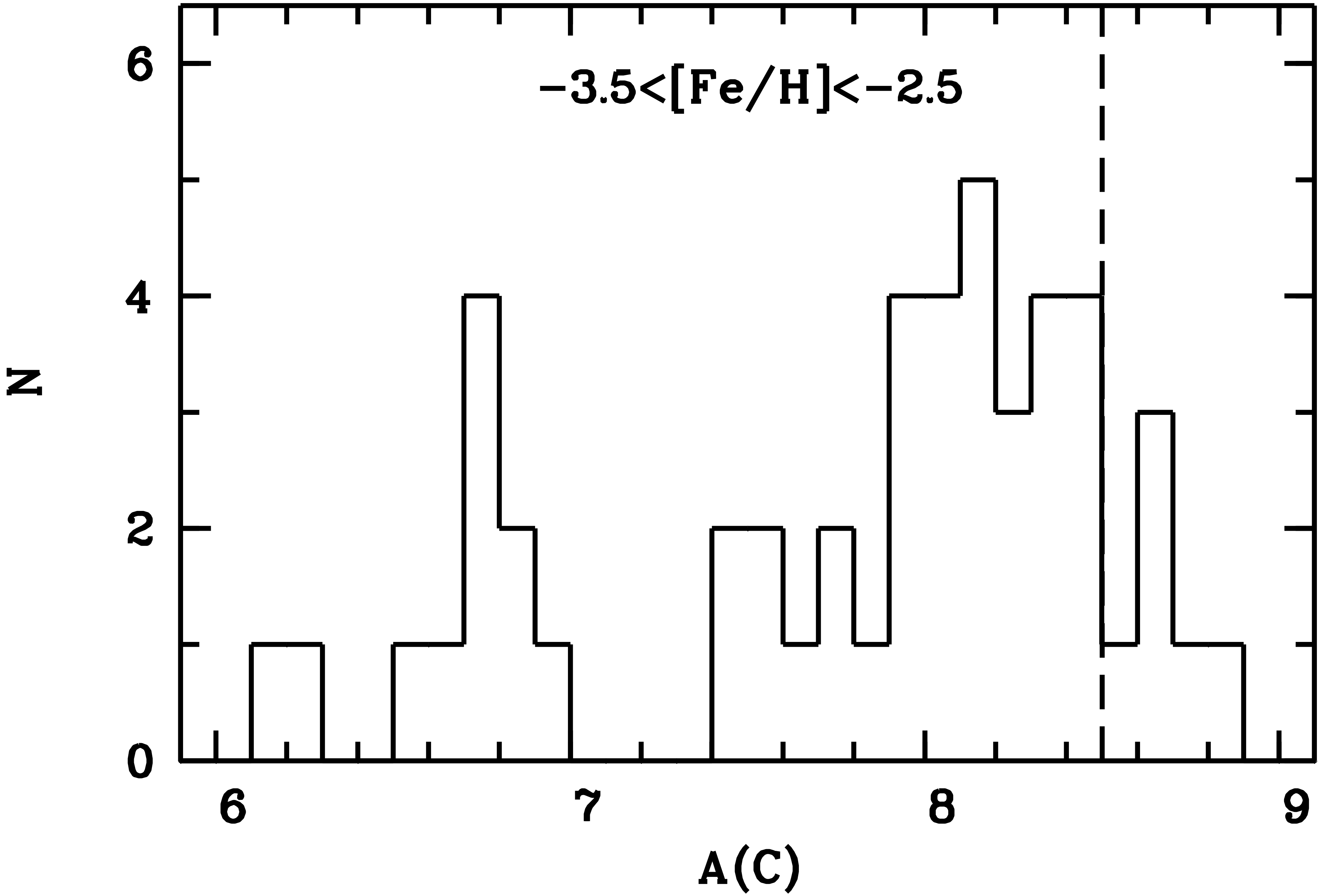
- Probably both cooling process at work
  - fine structure line cooling (e.g. HE 1327-2326)
  - dust cooling (e.g. SDSS J102915+172927)

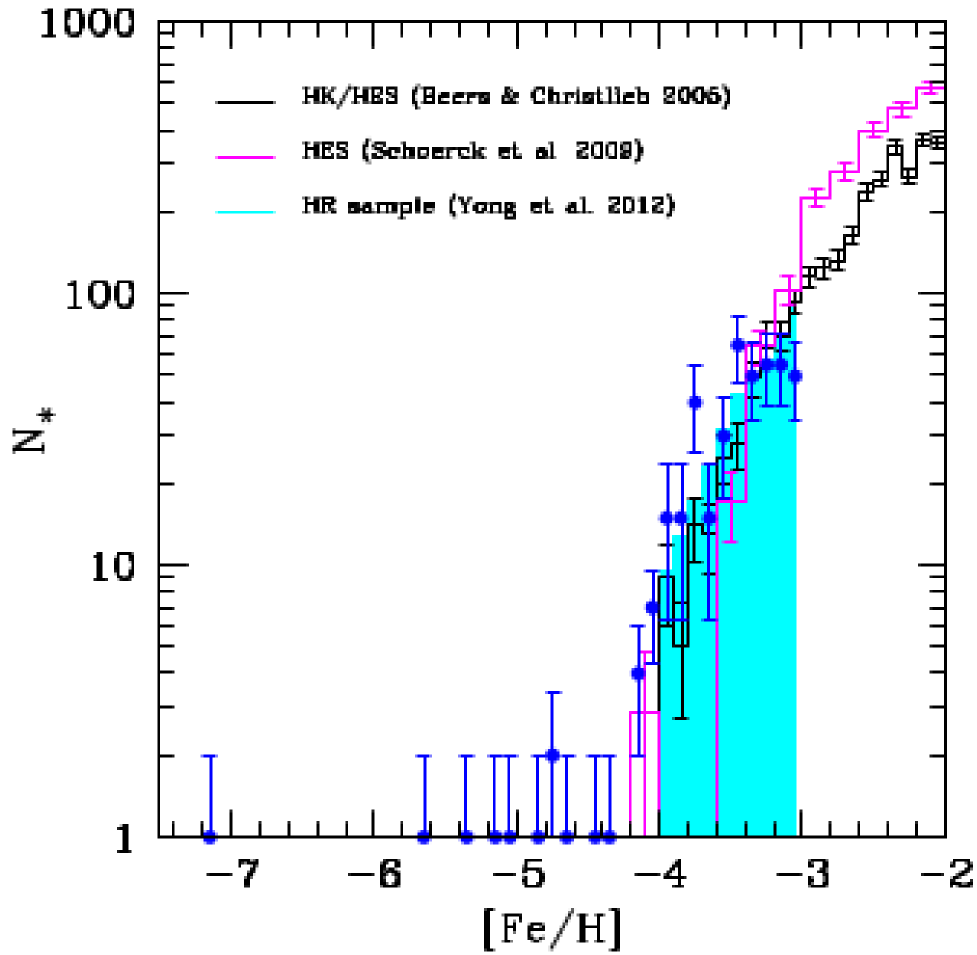
CEMP



Solar value
[C/Fe]=+1
Normal metal–poor turnoff stars
A(C)
[Fe/H]
10
8
6
4
−7
−6
−5
−4
−3
−2

CEMP





MDF for $[\mathrm{Fe/H}] \leq -3.0$ from four samples (normalised to same sample-size)

uncorrected Young et al. 2003 (to be compared to the light blue) added with data of the stars with $[\mathrm{Fe/H}] < -4.0$ from the literature

de Bennassuti et al. 2017

MDF

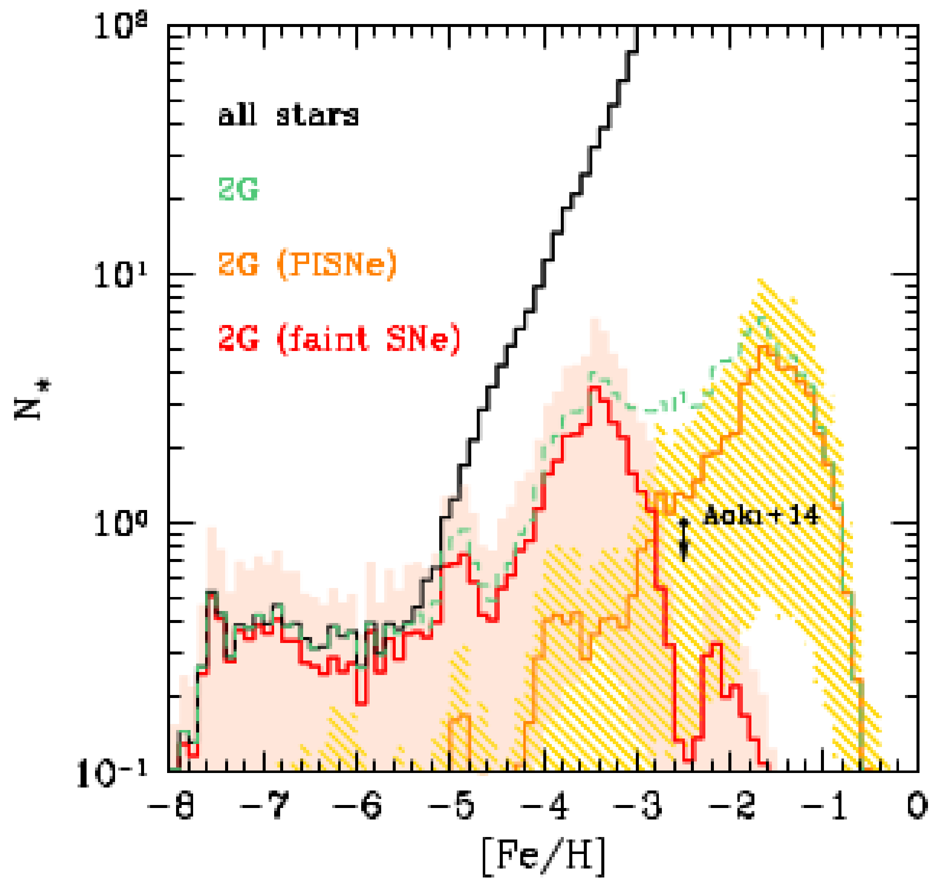
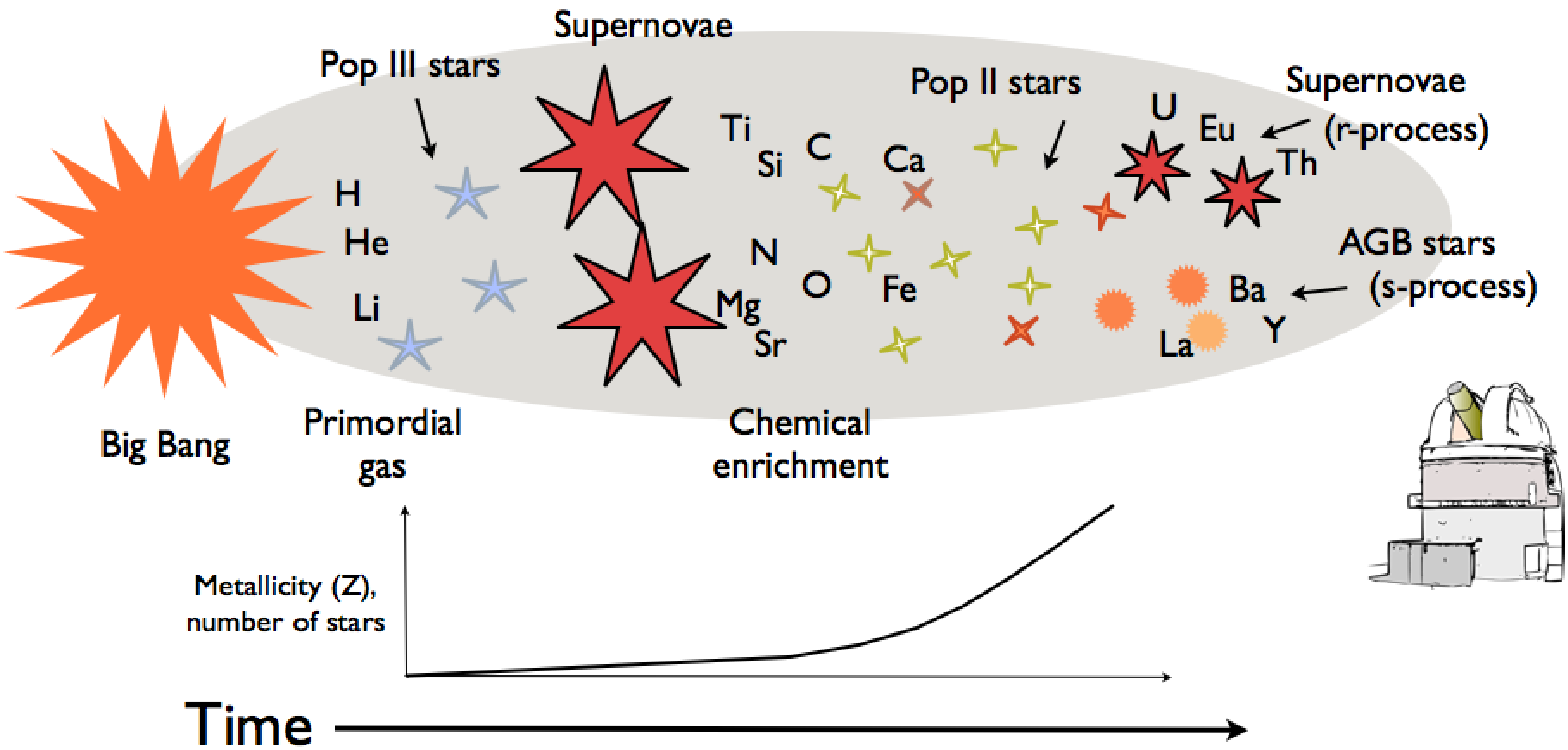


Figure 9. Simulated average MDF for all stars (black histogram) and for 2G stars (dashed green histogram), selecting them as stars formed in environments where metals come mostly (>50 per cent) from Pop III stars. The red (orange) histogram represents 2G stars with a dominant (>50 per cent) metal contribution from Pop III faint SNe (PISNe) and the filled (striped-dashed) region represents the 1σ dispersion. The upper limit at [Fe/H] = −2.5 represents the recent observation of a star with chemical imprint of PISNe (Aoki et al. 2014).

De Bennassuti et al. 2017

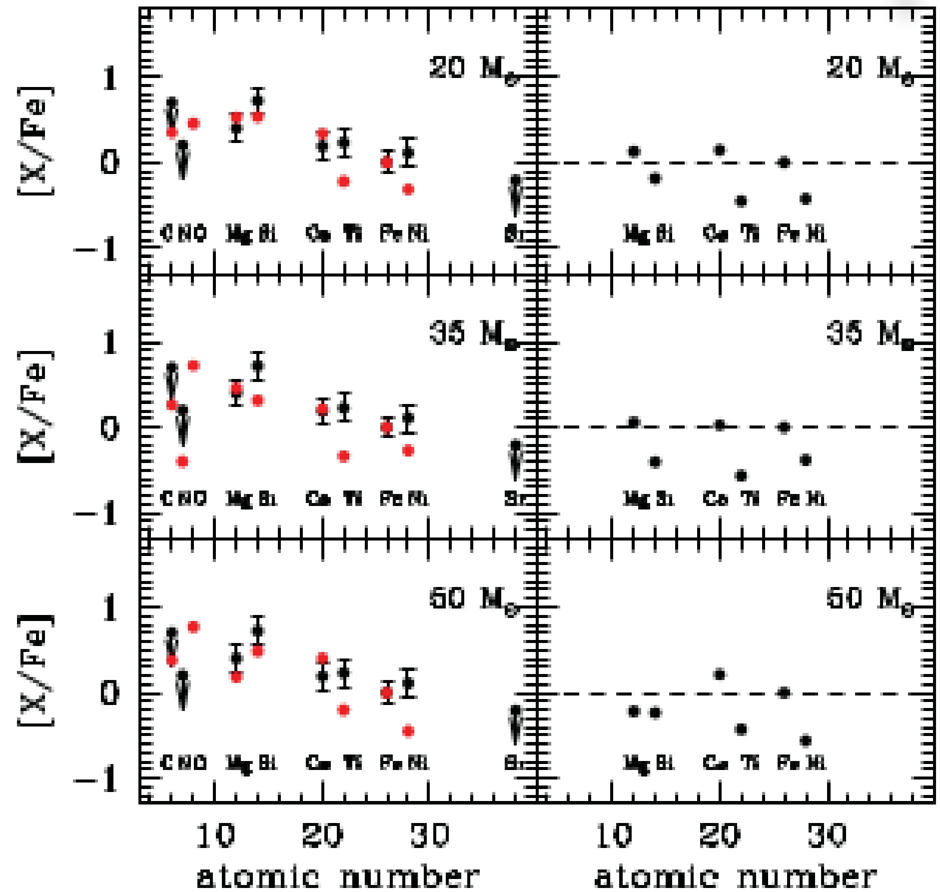
Theoretical predictions can explain the large fraction (with respect to “normal” stars) of CEMP stars we observe

The second stellar generation



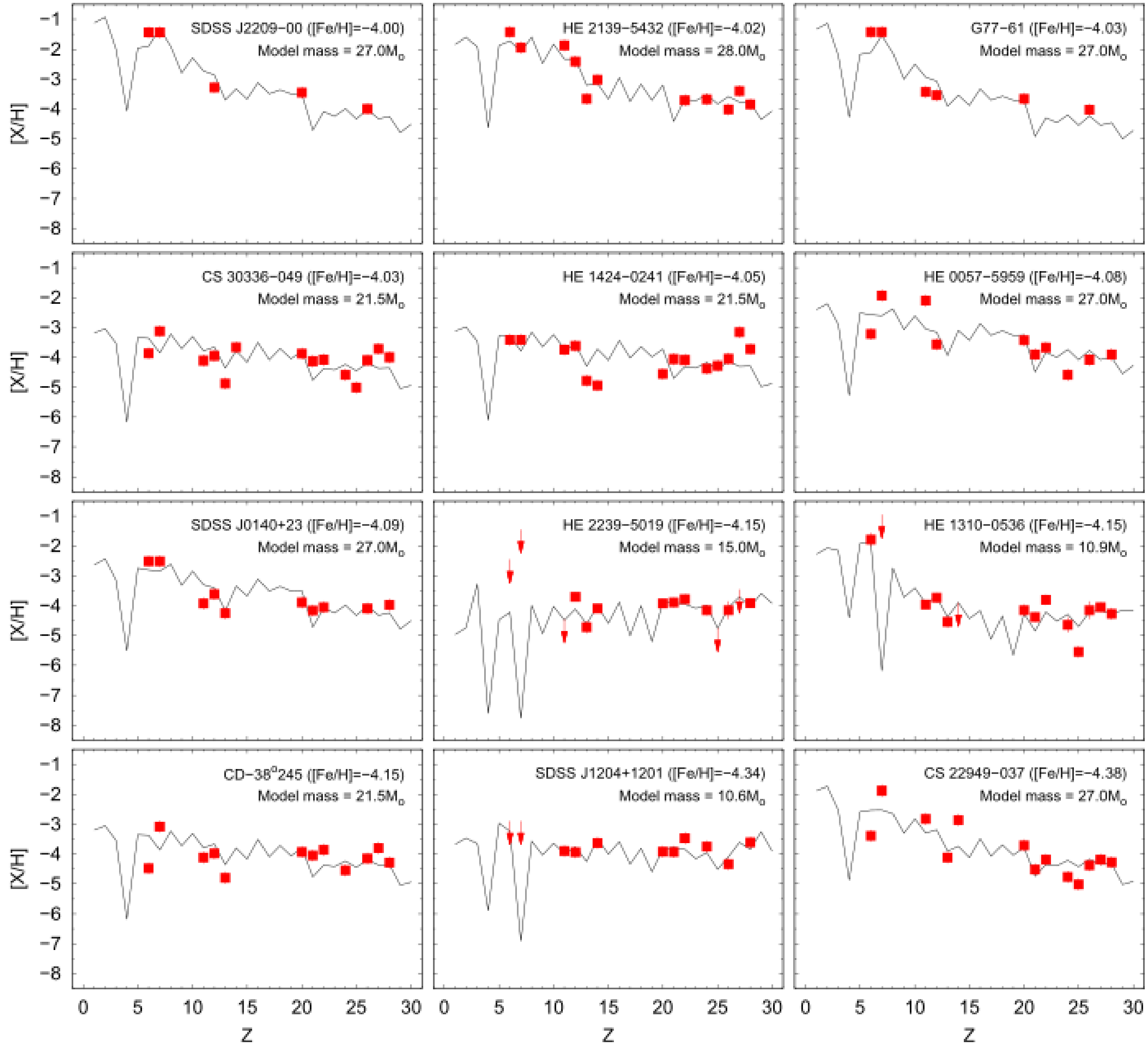
SDSS J102915+172927

Schneider et al. 2012, MNRAS 423, L60

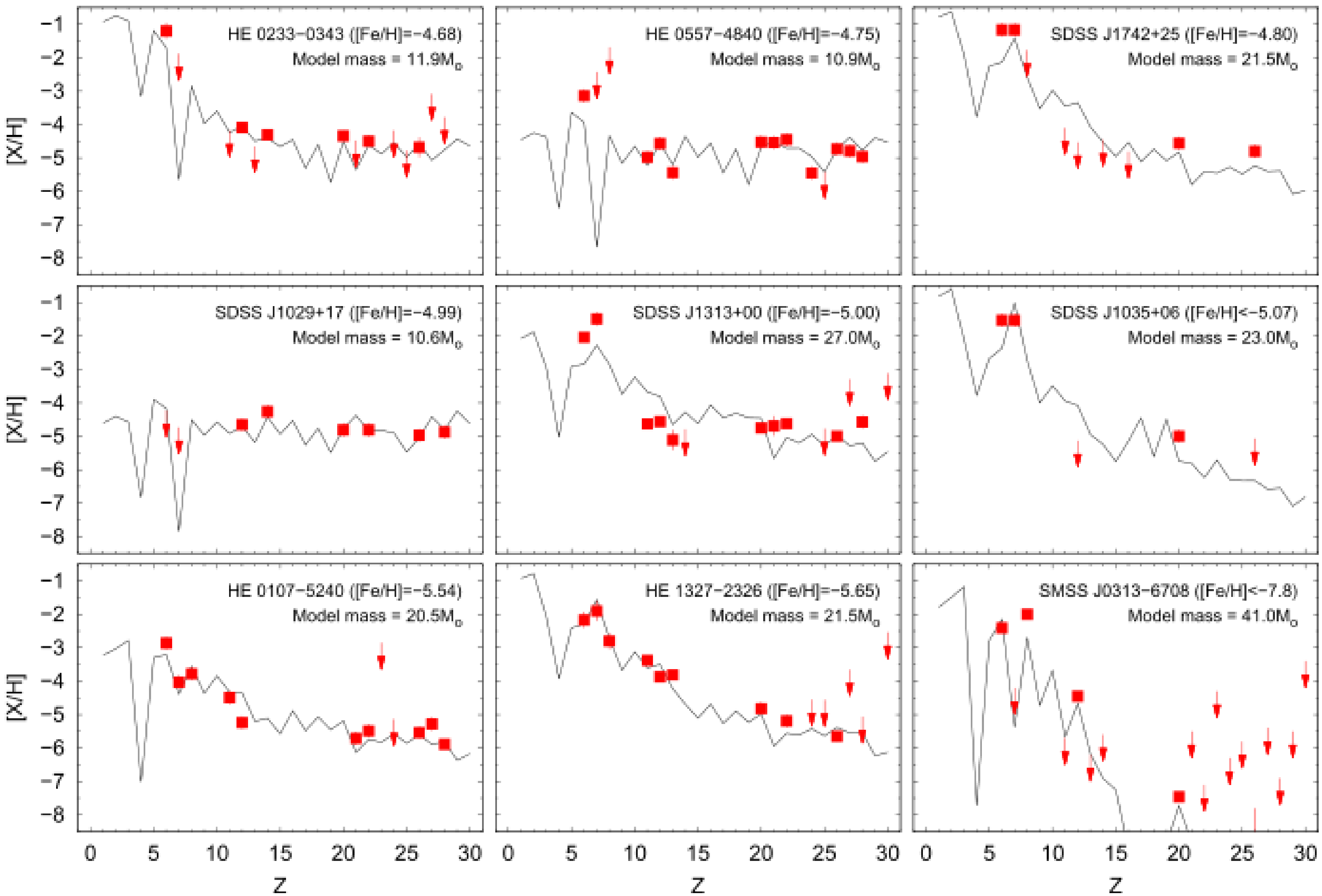


SDSS J102915+172927 formed due to dust cooling from primordial gas enriched by the explosion of one 20-35 $M_\odot$ Pop III star

Placco et al. 2015, ApJ 809, 136



Placco et al. 2015, ApJ 809, 136



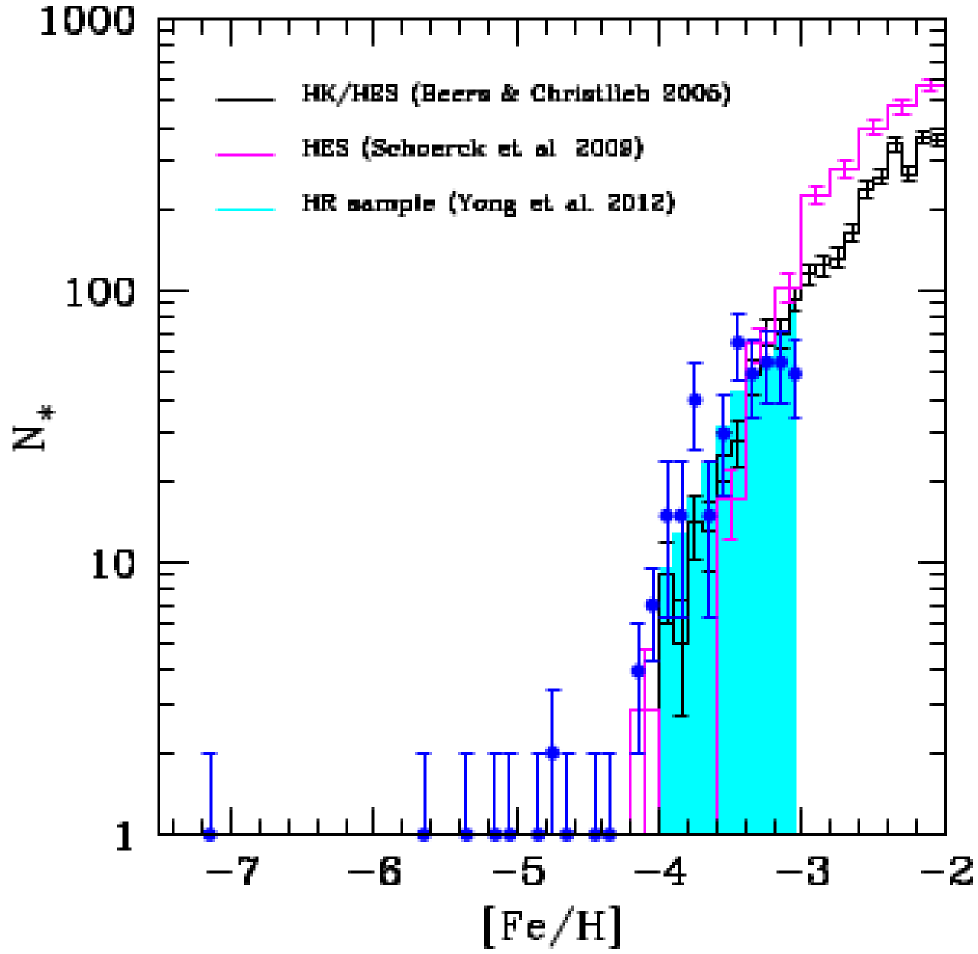
Masses PopIII stars

- From the chemical analysis of the EMP stars
  - Pop III stars were not very massive
  - Masses of tens $M_\odot$ can explain the chemical composition of the second stellar generation
- Theoretical models can disagree by factor two but agrees on the order of magnitude
  - e.g. SDSS J102915+172927 from a Pop III star of
    - $\sim 25\,M_\odot$ according to Schneider et al. 2012
    - $10.6\,M_\odot$ according to Placco et al. 2015

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
  - spectra at low resolution (e.g. SDSS, Lamost)
  - narrow band photometry to be associated to wide-band photometry (e.g. Pristine)
- Spectra of EMP stars show few lines and these are weak
- Follow-up at higher resolution is necessary

EMP extremely rare:



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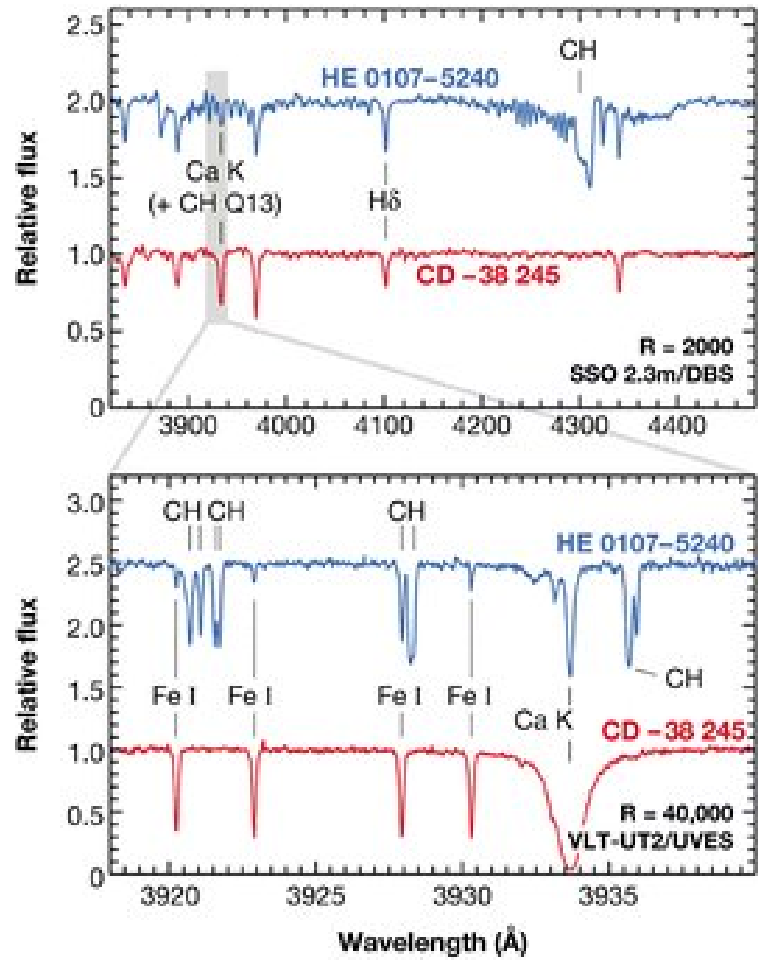
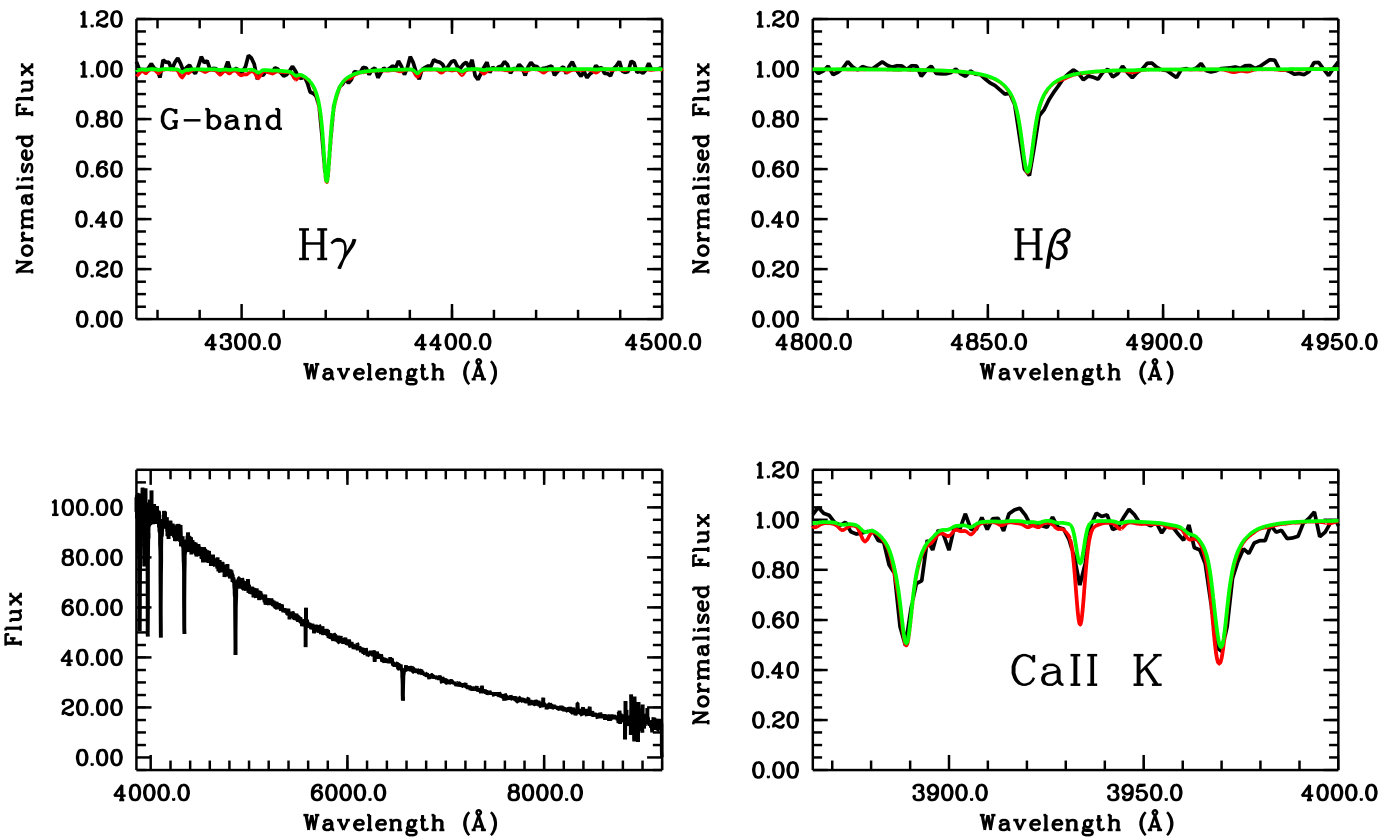


Beers, TC and Christlieb, N. 2005
Annu. Rev. Astron. Astrophys. 43: 531–80

Selection

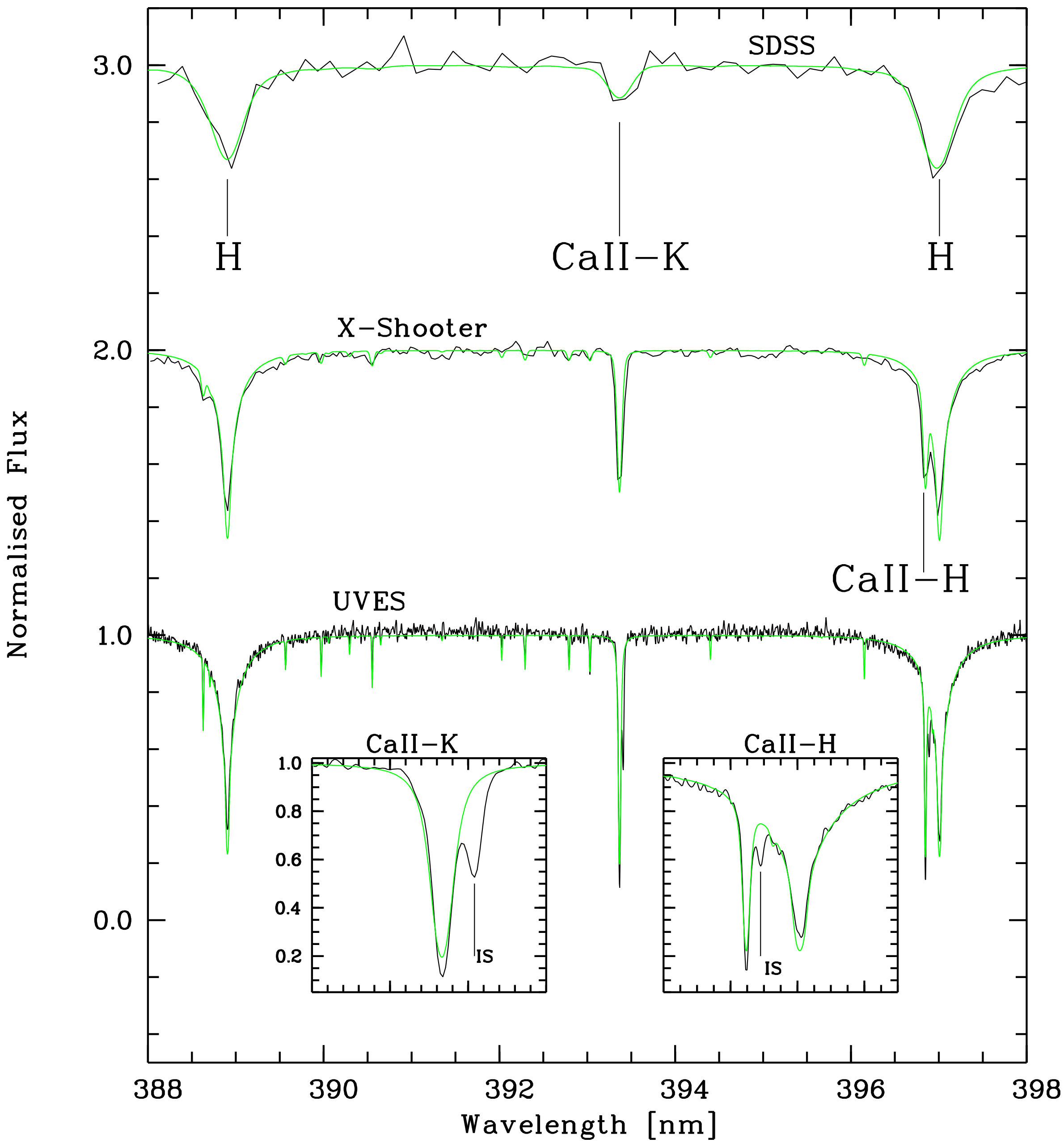
- Limited information derived from R=2 000 resolution spectra + photometry
- Many such spectra available from several surveys, essential for searching for rare objects
- Extremely metal-poor stars can be extracted from low resolution surveys
  - ∼**200 000 SDSS spectra** (potentially TO stars) analysed automatically
  - final selection by visual inspection



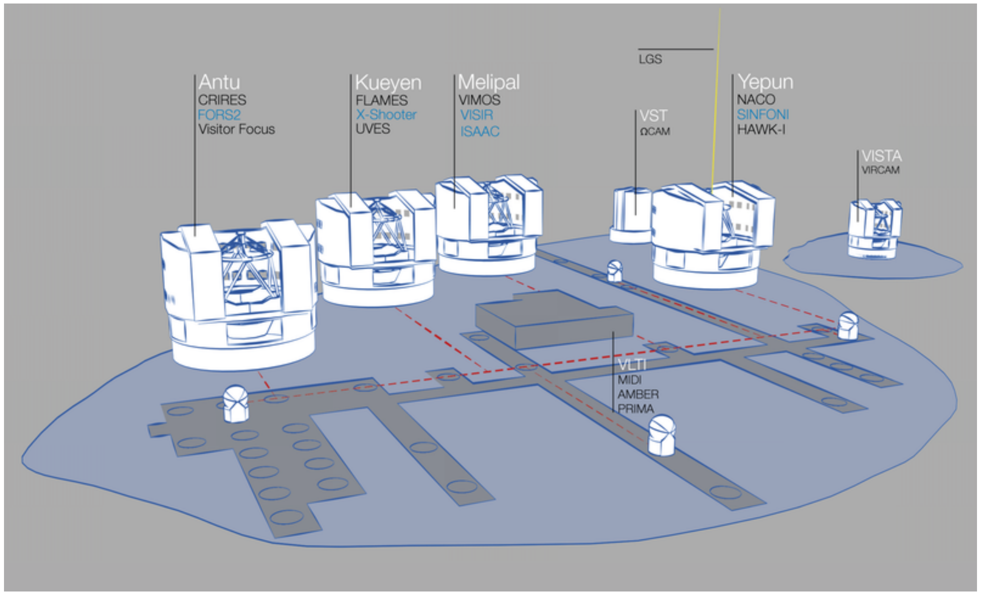
Caffau et al. A&A 2011

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

Low/High spectral resolution

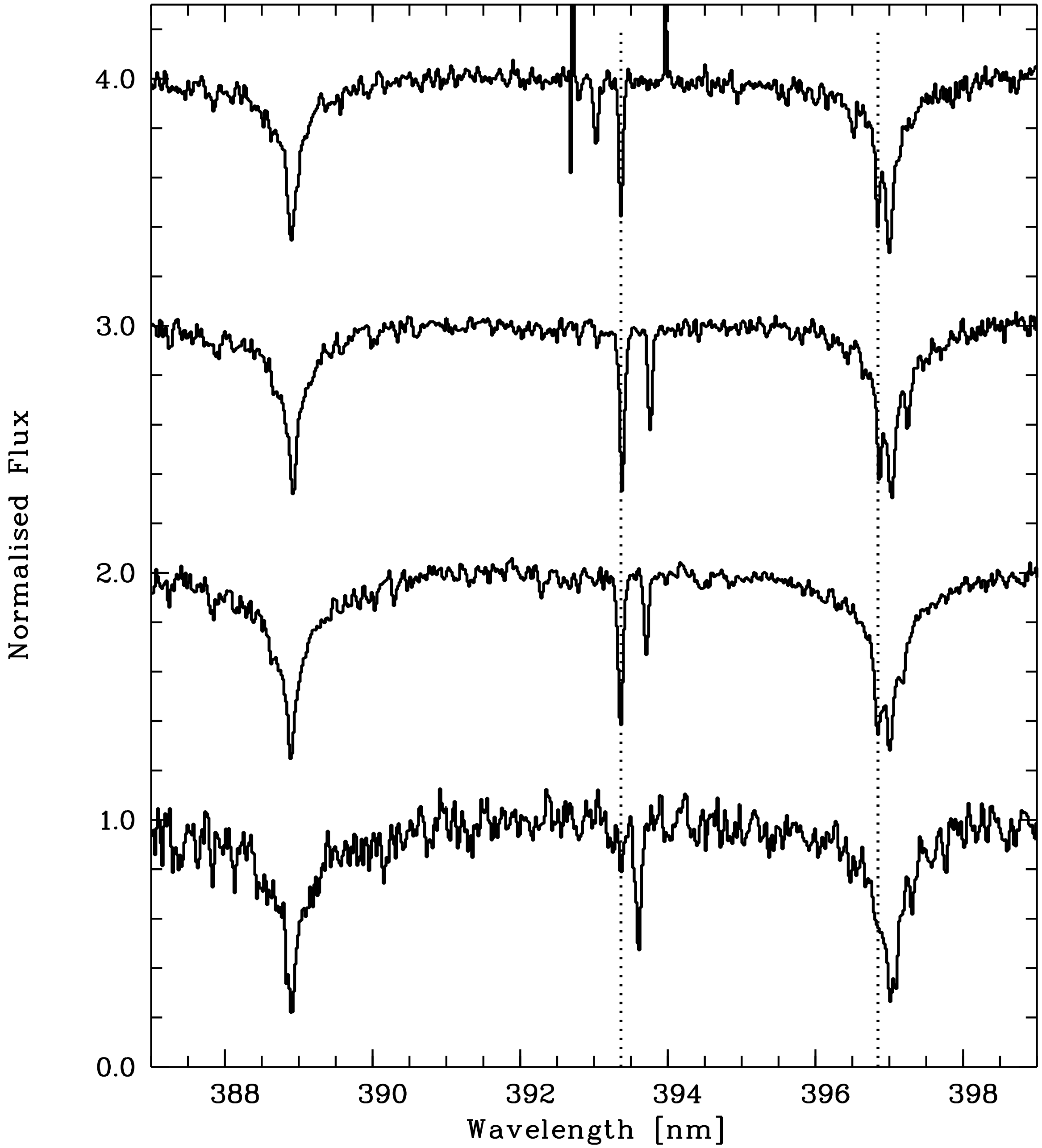


Follow-up observations facility: Paranal



European Southern Observatory - ESO

Interesting stars from the X-Shooter GTO July 2012



[Fe/H]=−4.1

α low

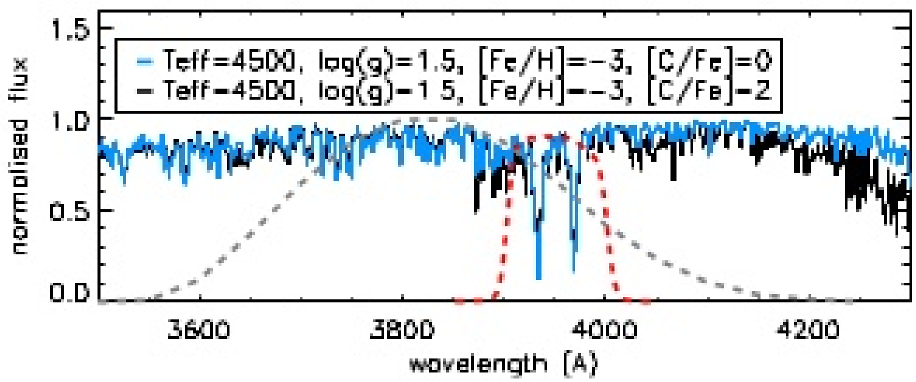
CEMP, α low

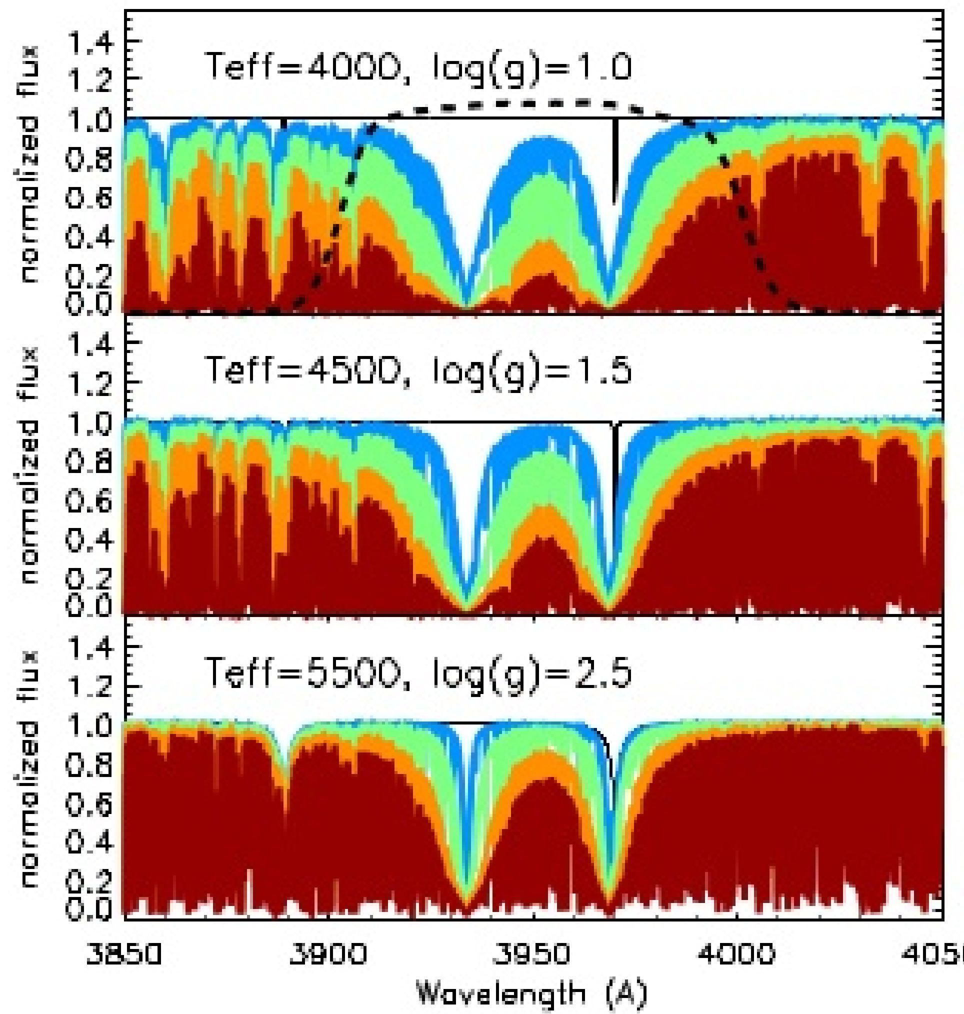
CEMP, [Fe/H]=-4.8

Caffau et al. 2013 A&A

Pristine

Narrow-band photometry centred on the Ca-H and -K lines
PIs: Else Starkenburg and Nicolas Martin





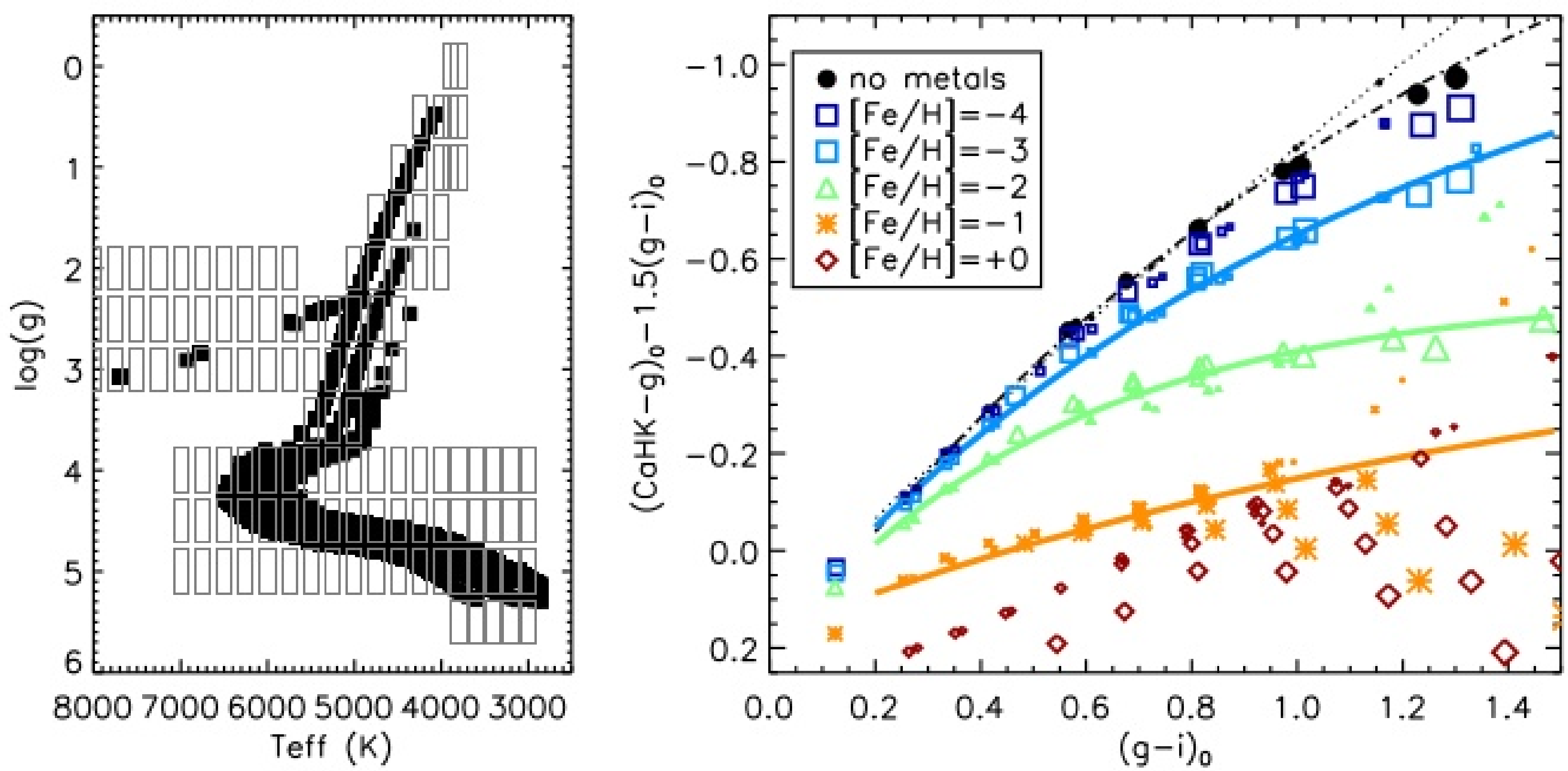


Figure 3. Left: Besançon model prediction (black points) and the spectral synthesis grid used in these tests (grey) in Teff, log(g) space. Spectra are computed for the full parameter space for [Fe/H]$= -4.0, -3.0, -2.0, -1.0$ and $+0.0$. Right: All predicted stars are matched to their most representative spectrum in the grid and colours are calculated for the spectra. This panel demonstrates how combinations of broad-band Sloan colours and the new narrow band filter cleanly separate the various metallicity stars in the sample. Additionally, the most metal-poor stellar atmosphere models are run with no metal absorption lines, resulting in the black circles. The coloured lines represent exponential fits to the symbols of metallicities [Fe/H]$= -1, -2$ and -3 and no metals (same colour-coding, redwards of $g - i = 1.0$ the giant branch is followed instead of the main sequence dwarfs).

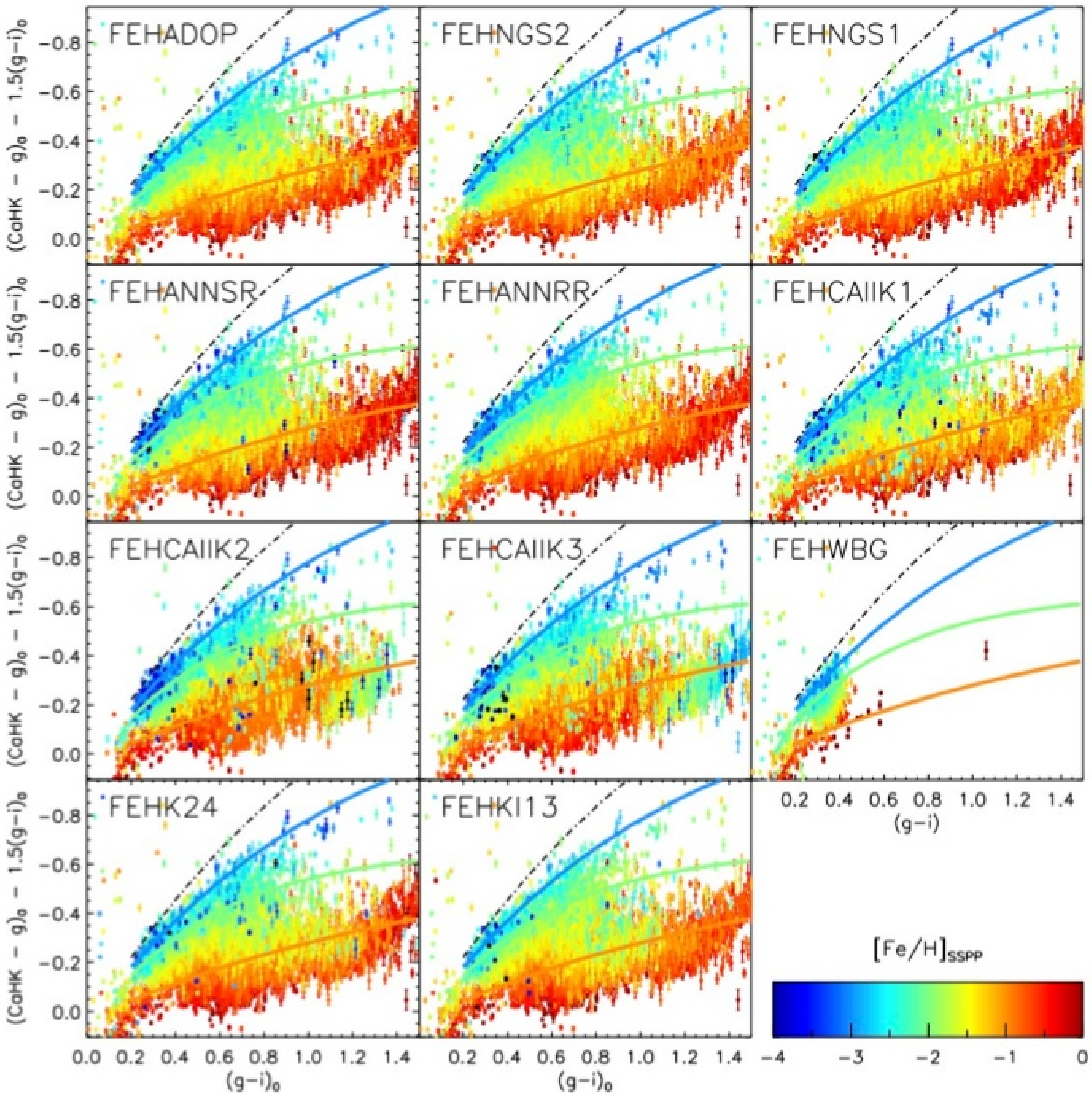
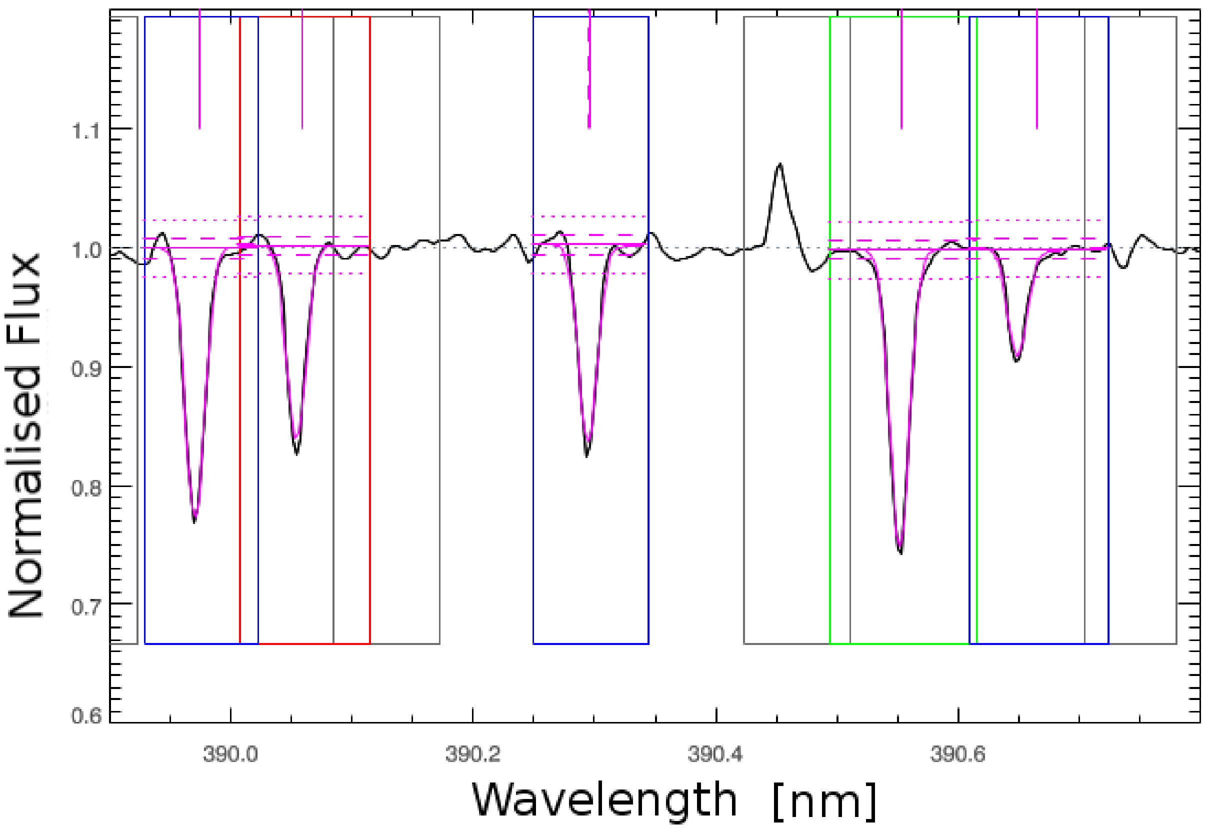


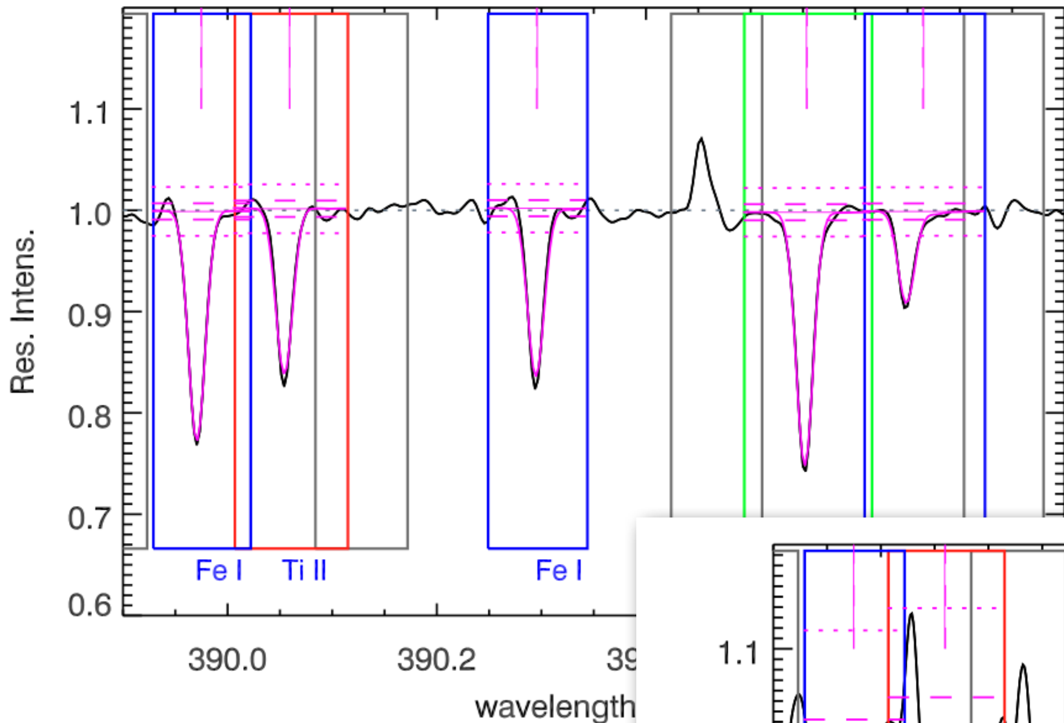
Figure 11. Distribution of stars in common between SDSS/SEGUE and *Pristine* in the $CaHK_0$, g_0, and i_0 colour-colour space. Stars are colour-coded by their SDSS/SEGUE metallicity. The coloured lines are fits to synthetic spectra model predictions for stars with [Fe/H] $= -1.0, -2.0, -3.0$, and with no metal lines (orange, green, blue, and black, respectively), as defined in Figure 3 and shifted to fit the data (see text for details). Each panel corresponds to a different metallicity output from the SDSS stellar parameter pipeline SSPP. Quality cuts are described in the text.

Abundance determination

Good-quality spectra are secured
investigation to derive chemical composition
constraints on masses Pop III stars

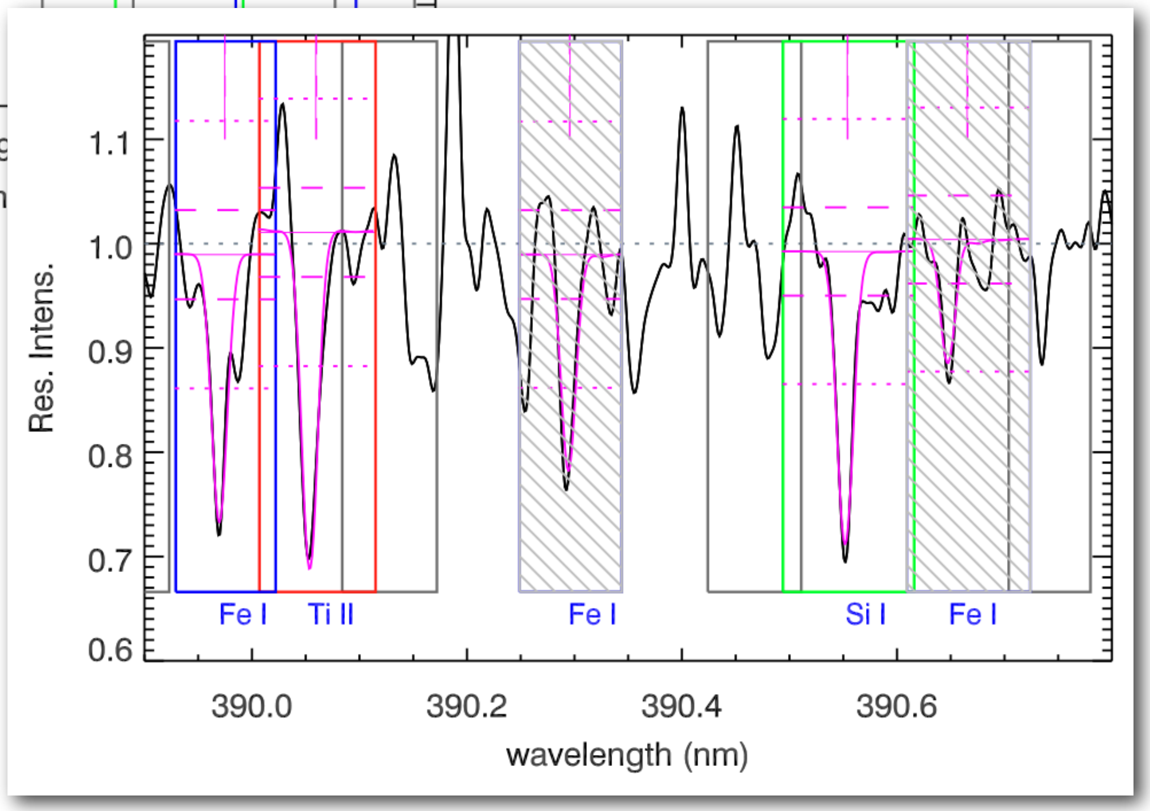


Data quality: UVES

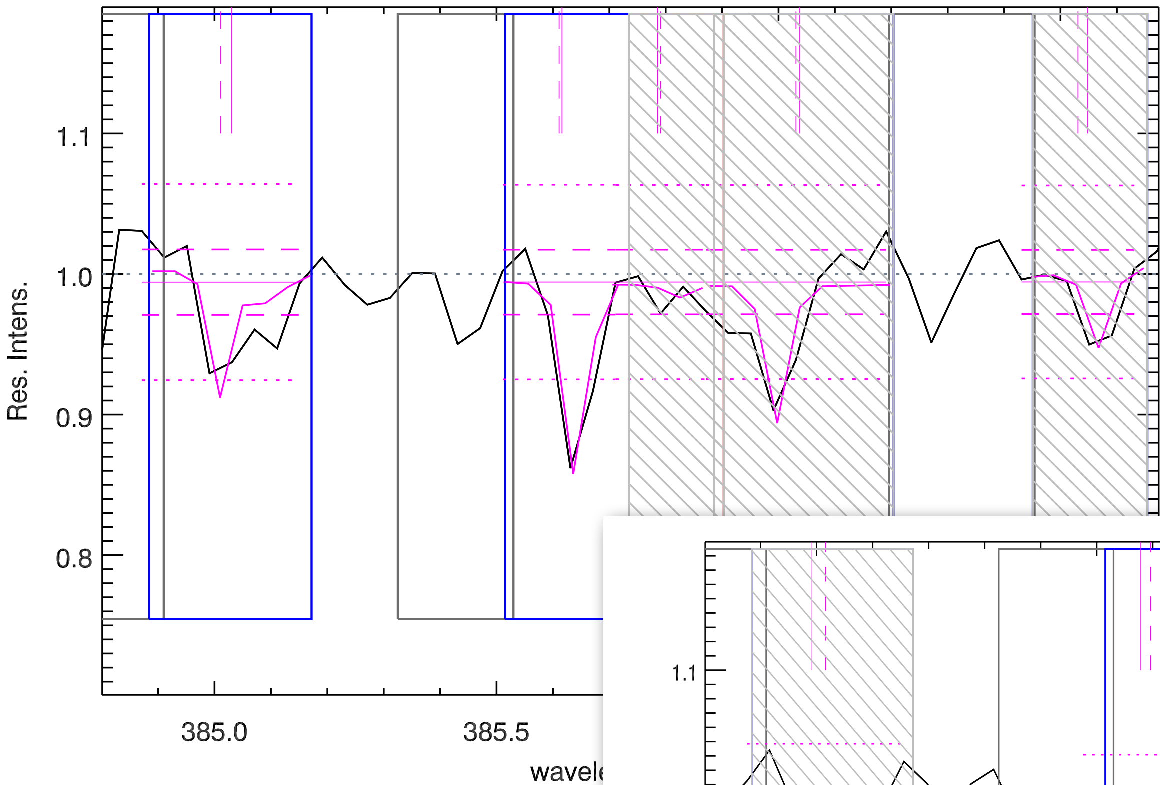


6422 K
[Fe/H] -3.27
S/N~110

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

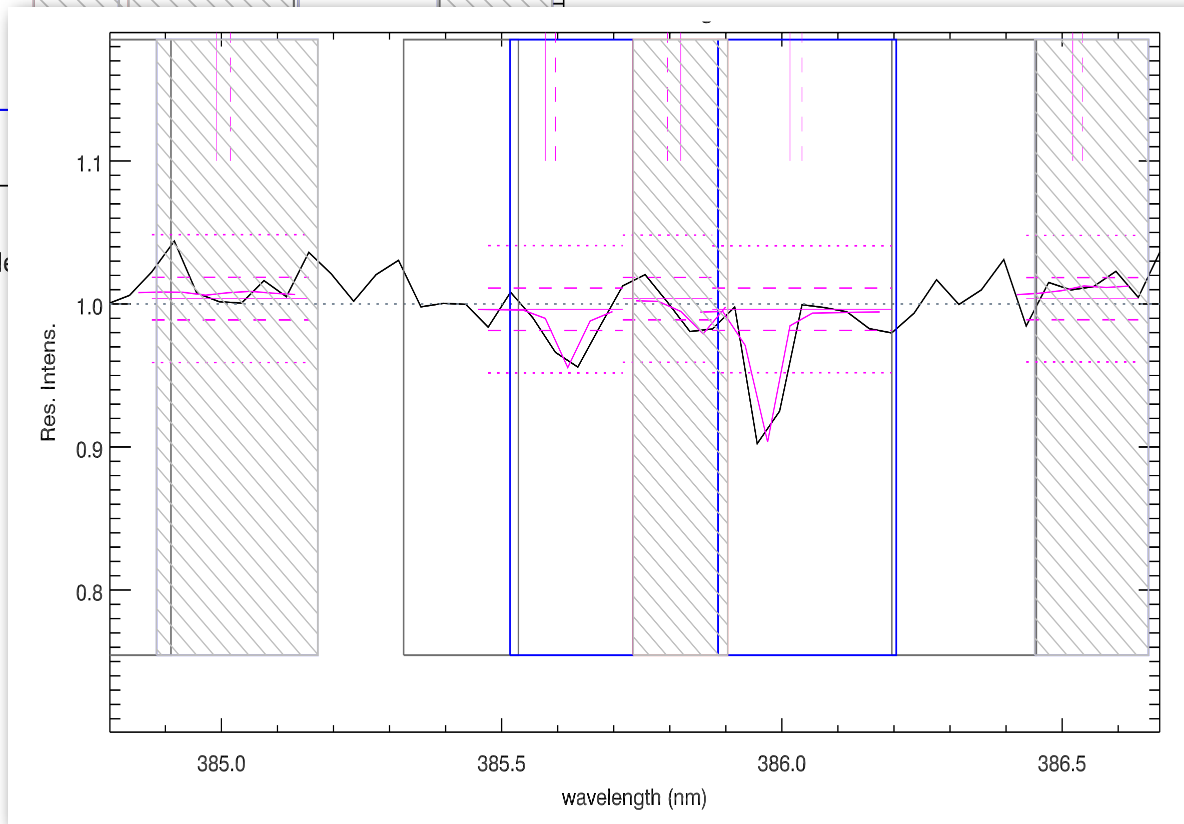


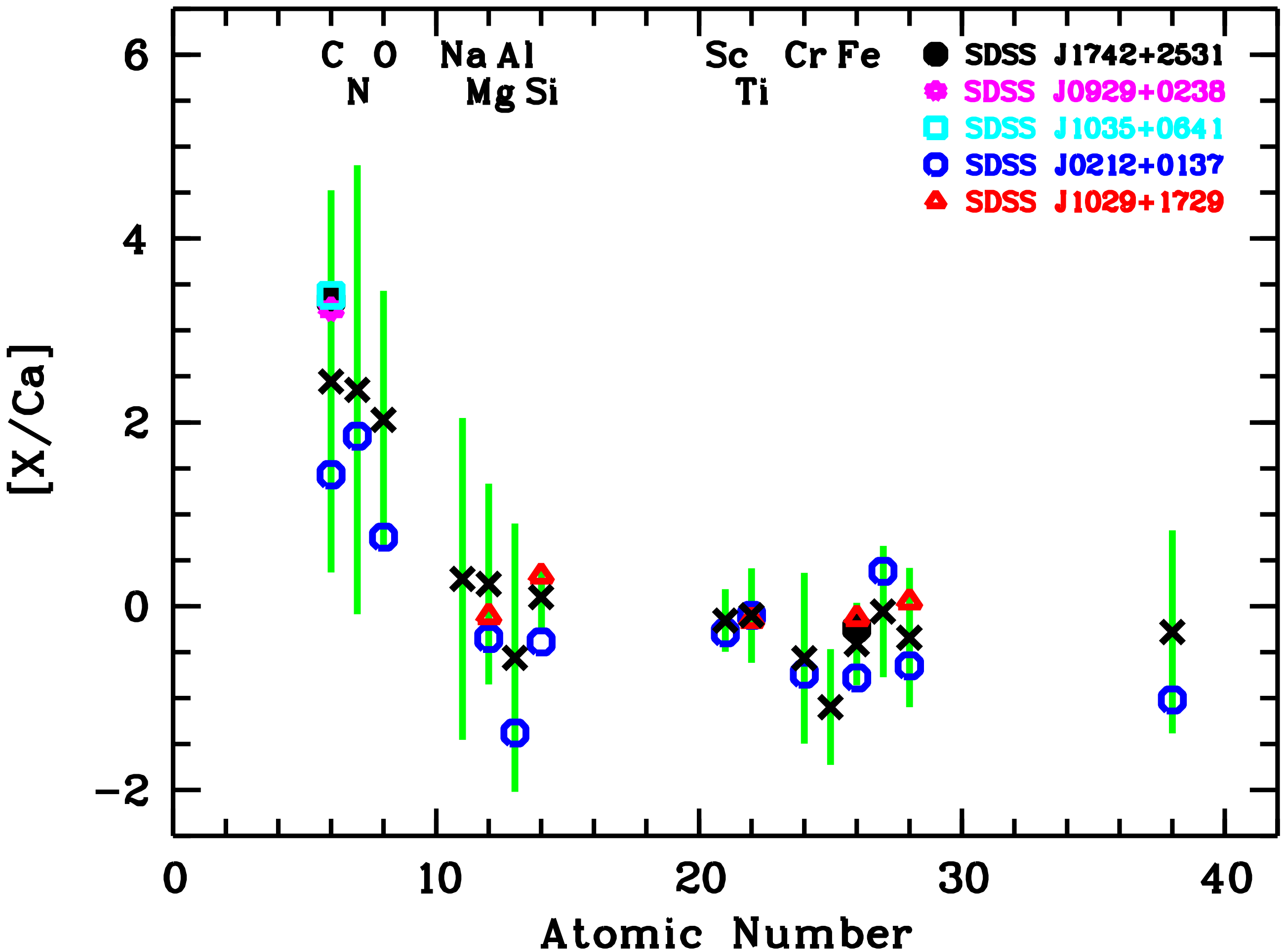
Data quality: X-Shooter



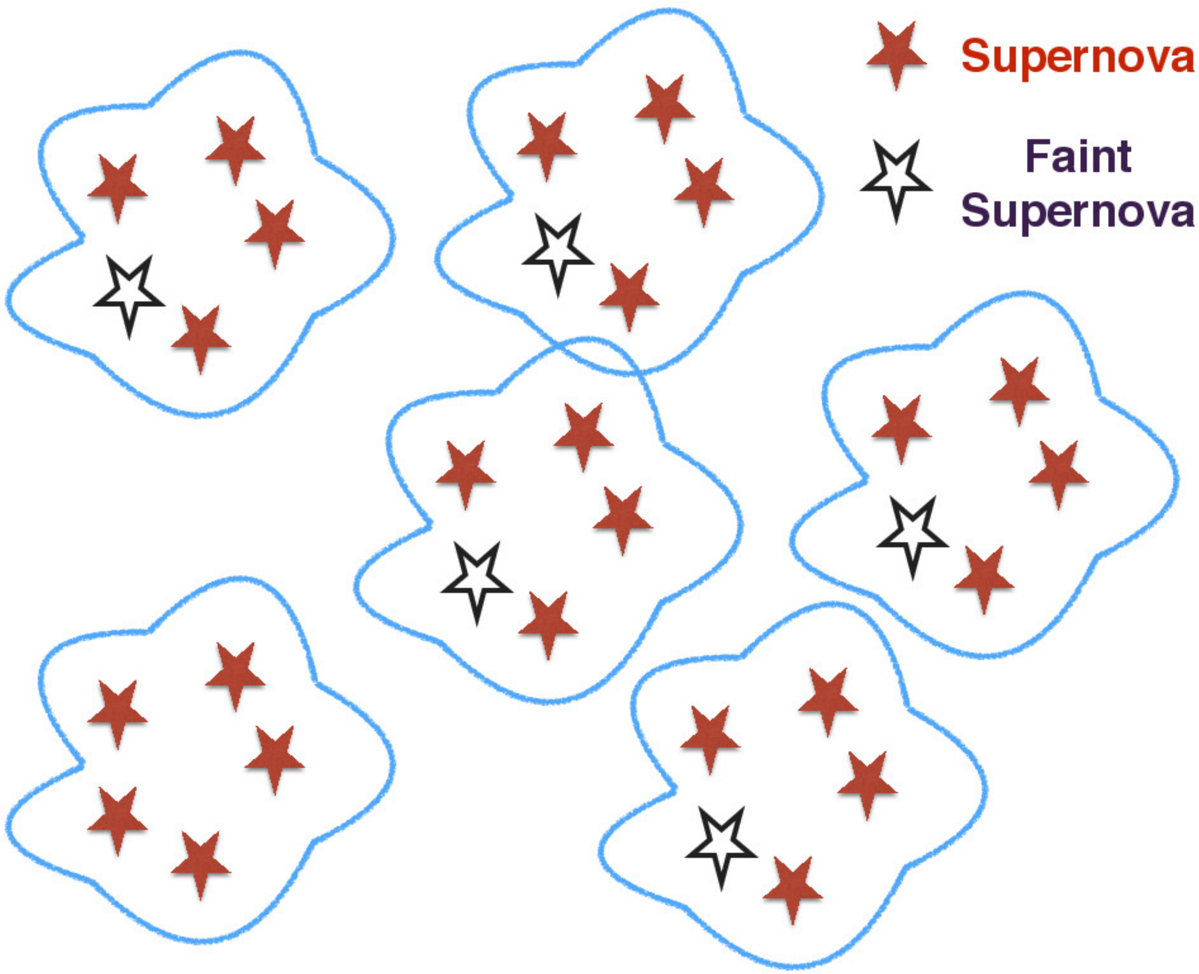
6392 K
[Fe/H] -3.13
S/N~40

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





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


Supernova
Faint Supernova

Still we could observe the zero-metal star!