Structure and Evolution of Stars

Lecture 22: Nucleosynthesis and Population III

- Nucleosynthesis – where did the elements come from?
    - nuclear burning
    - s-process
    - r-process
    - p-process

- Metallicity measures and Stellar Populations

- Where is Population III?

- *Star of the Week* #6: SMSSJ031300.36-670839.3 - the lowest metallicity star currently known

Binding Energy per Nucleon

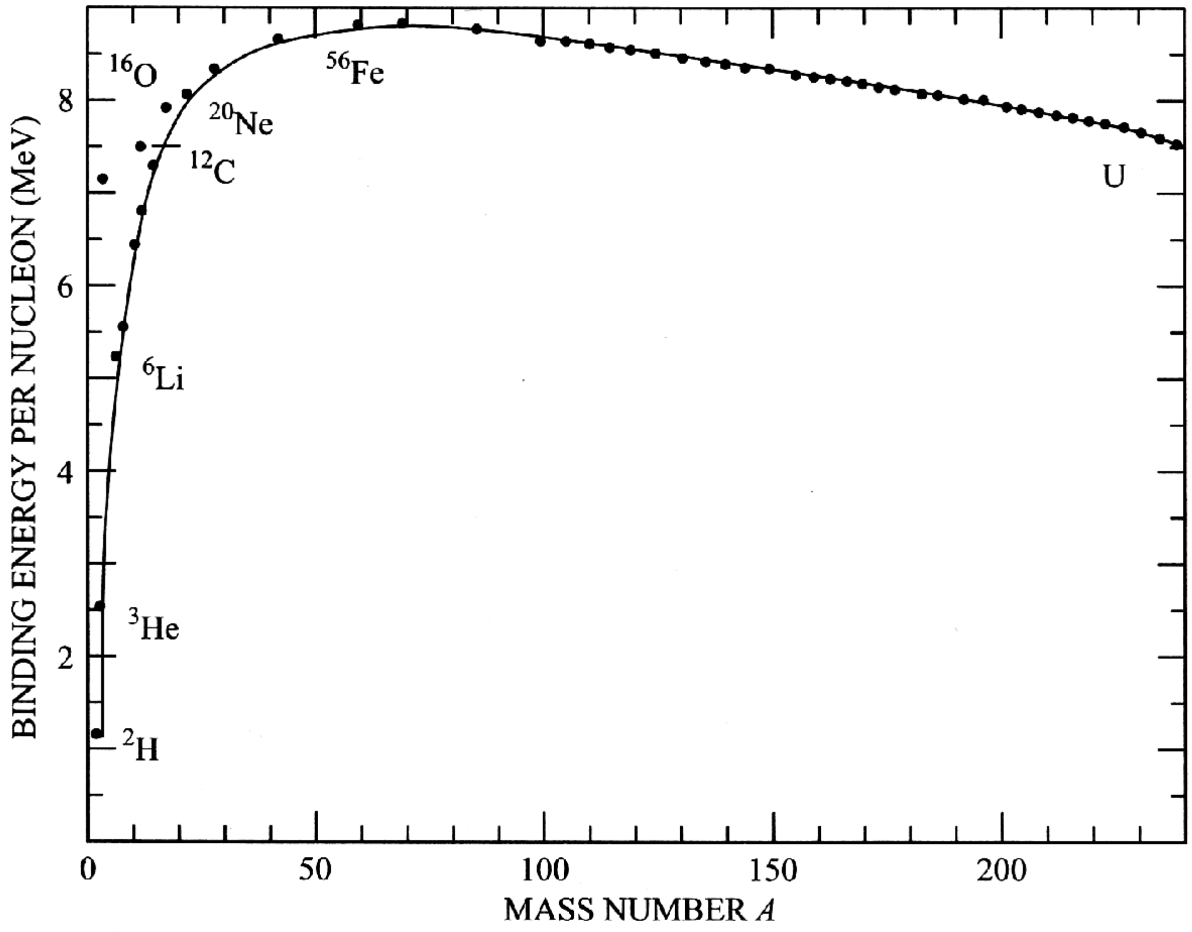


Fig. 1.3 Binding energy per nucleon for atomic nuclei. There is a broad maximum at mass number 56 which implies that energy is normally released when two light nuclei fuse to form a heavier nucleus provided the nucleus formed has a mass number less than 56

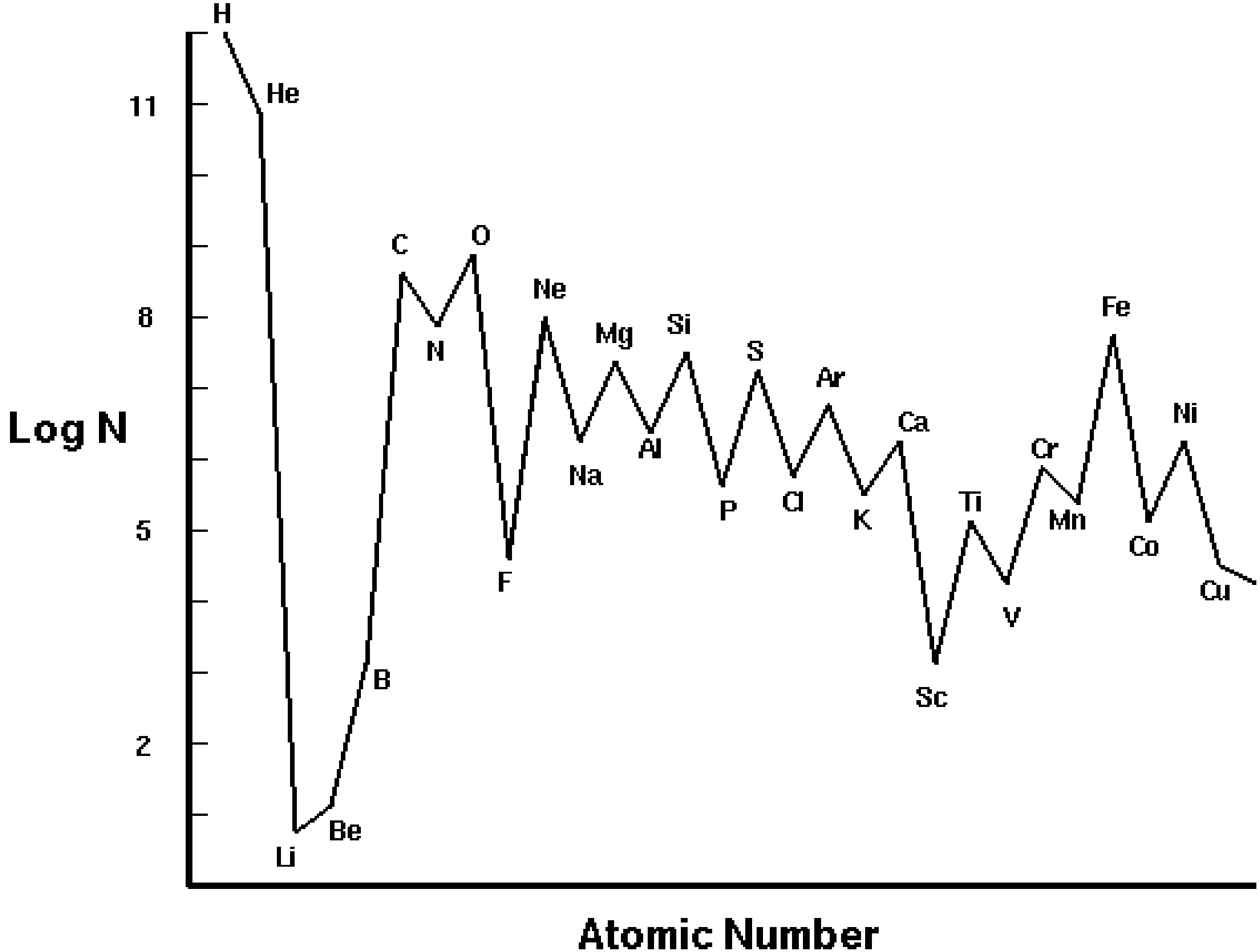
Origin of the Elements

• Massive stars provide primary source of even atomic mass elements from Carbon to Cr. However, little iron produced as large core mass of Fe collapses to form neutron star or black hole. Timescale for nucleosynthesis of elements by massive stars very short $<10^7$yr

• Thermonuclear detonation of C+O white dwarfs in binary systems – origin of Type Ia supernovae – runs through nuclear burning sequence all the way up to Fe and then disperses Iron into the interstellar medium. Type Ia supernovae are the principal source of Fe in the universe. Timescale for creation of a C+O white dwarf Type Ia supernova precursor much longer $\sim 10^9$yr

• Where do the rest of the elements come from?

• Relative abundance, by number, of elements up to the Fe-peak shows systematic excess of even-numbered elements from nuclear burning in massive stars, including α-capture products (element+He…)



Origin of the Elements

• Have discussed the principal reactions that lead to energy generation via nuclear fusion. Also possible for nucleosynthesis to take place in non-equilibrium conditions where energy generation is not important

• The large Coulomb barriers for high-mass nuclei mean that interactions between such nuclei and protons rarely occurs

• In the case of interactions between heavy nuclei and neutrons there is no such barrier. Need a supply of free neutrons but interactions can occur at relatively low energies:

• nucleus plus neutron form heavier nucleus

$$ {}^{A}_{Z}\mathrm{X} + n \rightarrow {}^{A+1}_{Z}\mathrm{X} + \gamma $$

• nucleus may be stable or unstable to beta-decay

$$ {}^{A+1}_{Z}\mathrm{X} \rightarrow {}^{A+1}_{Z+1}\mathrm{X} + e^{-} + \overline{\nu} + \gamma $$

Origin of the Elements

• In case when the half-life for beta-decay is short compared to the timescale for neutron capture then obtain stable nuclei directly or via beta-decay - **s-process**, where s is for slow

• In case when the half-life for beta-decay is long compared to the timescale for neutron capture then obtain neutron-rich nuclei - **r-process**, where r is for rapid

• r-process takes place following core collapse in supernovae and possibly also close to young neutron stars – neutron star winds. Now (GW170817) from kilonovae – merging neutron stars

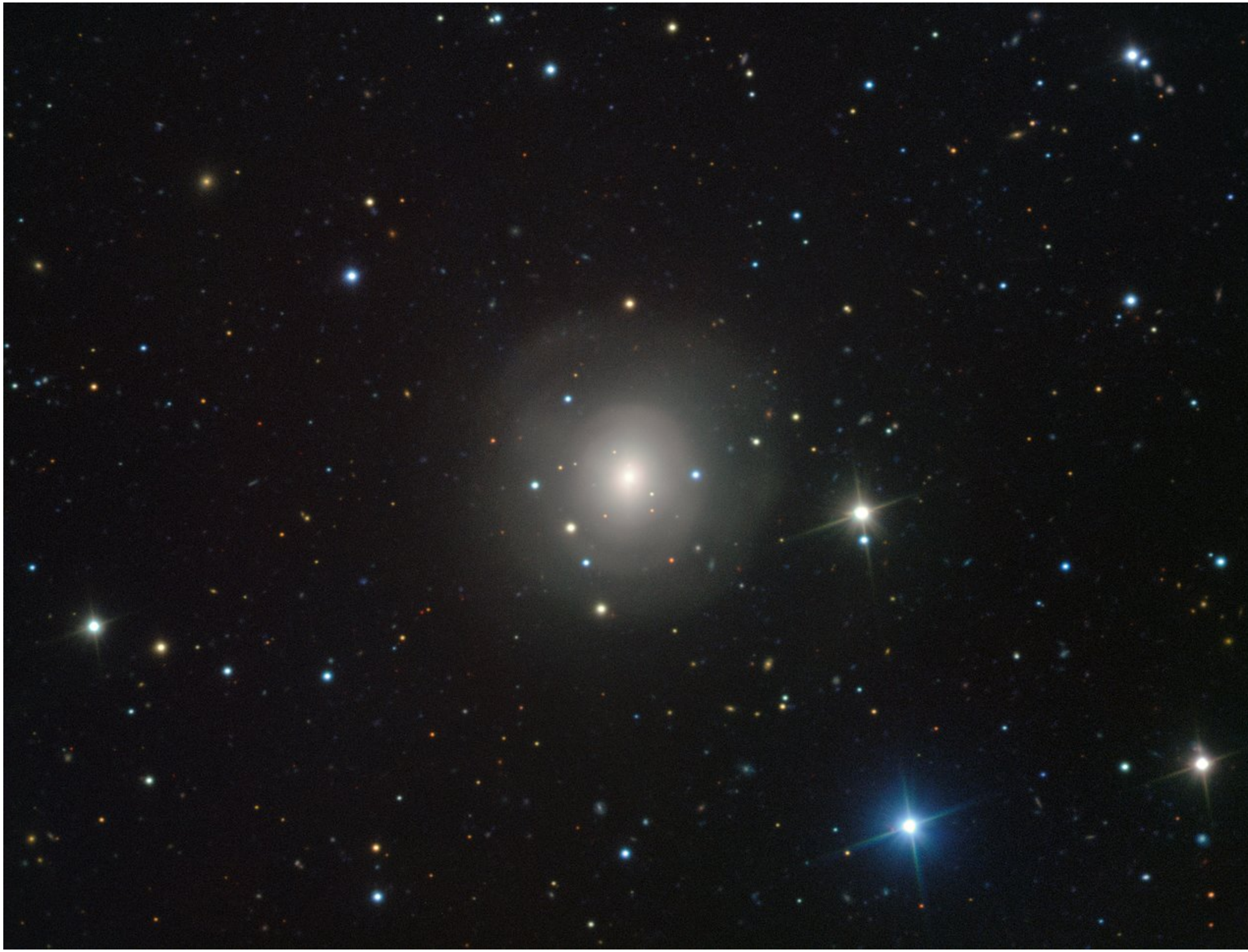
• s-process in the Helium-burning shell of asymptotic giant branch stars

• Detailed consideration shows that all but 35 of the elements can be produced via the s- and r-process

• Remaining elements do require proton-nuclei reactions **p-process**. Location not well-determined but supernovae favoured

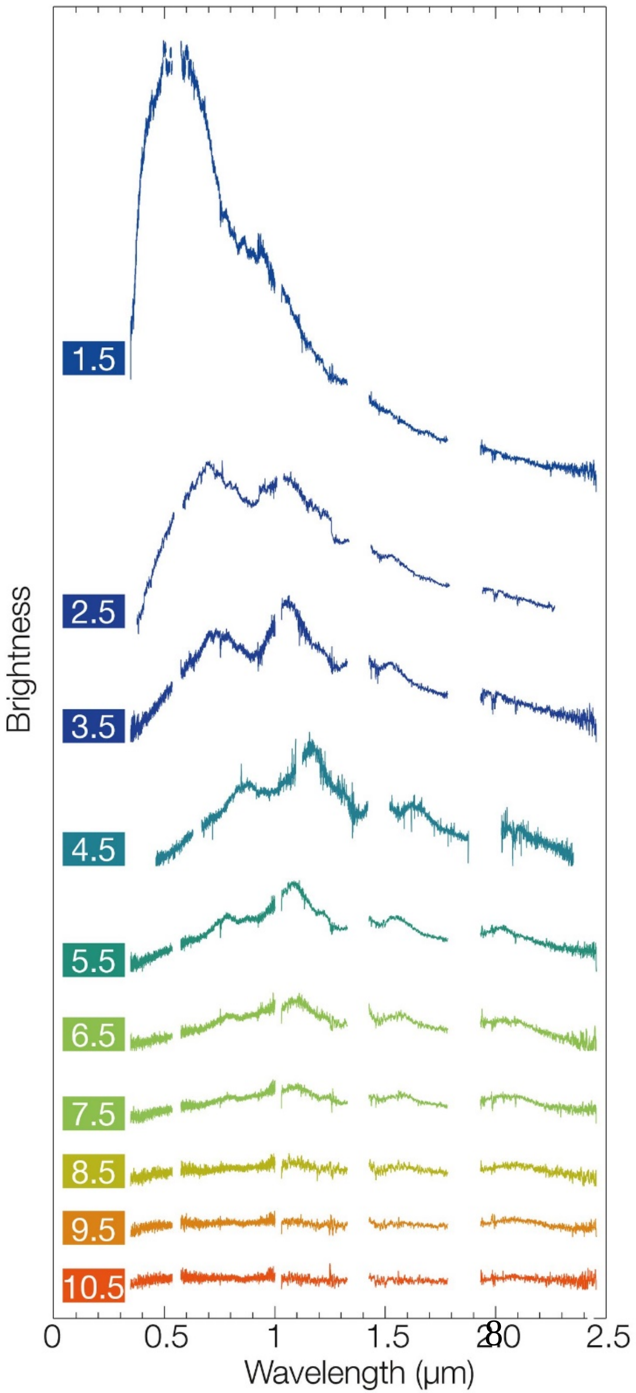
GW170817 in NGC4993 at ~40Mpc

Optical image from the ESO VLT



GW170817 – time sequence of optical through near infrared spectra
Evolution of the luminosity with time consistent with predictions of radioactive decay of of massive neutron-rich nuclides created by r-process

Importance of neutron-star mergers and resulting kilonovae for element creation via r-process in the Universe?



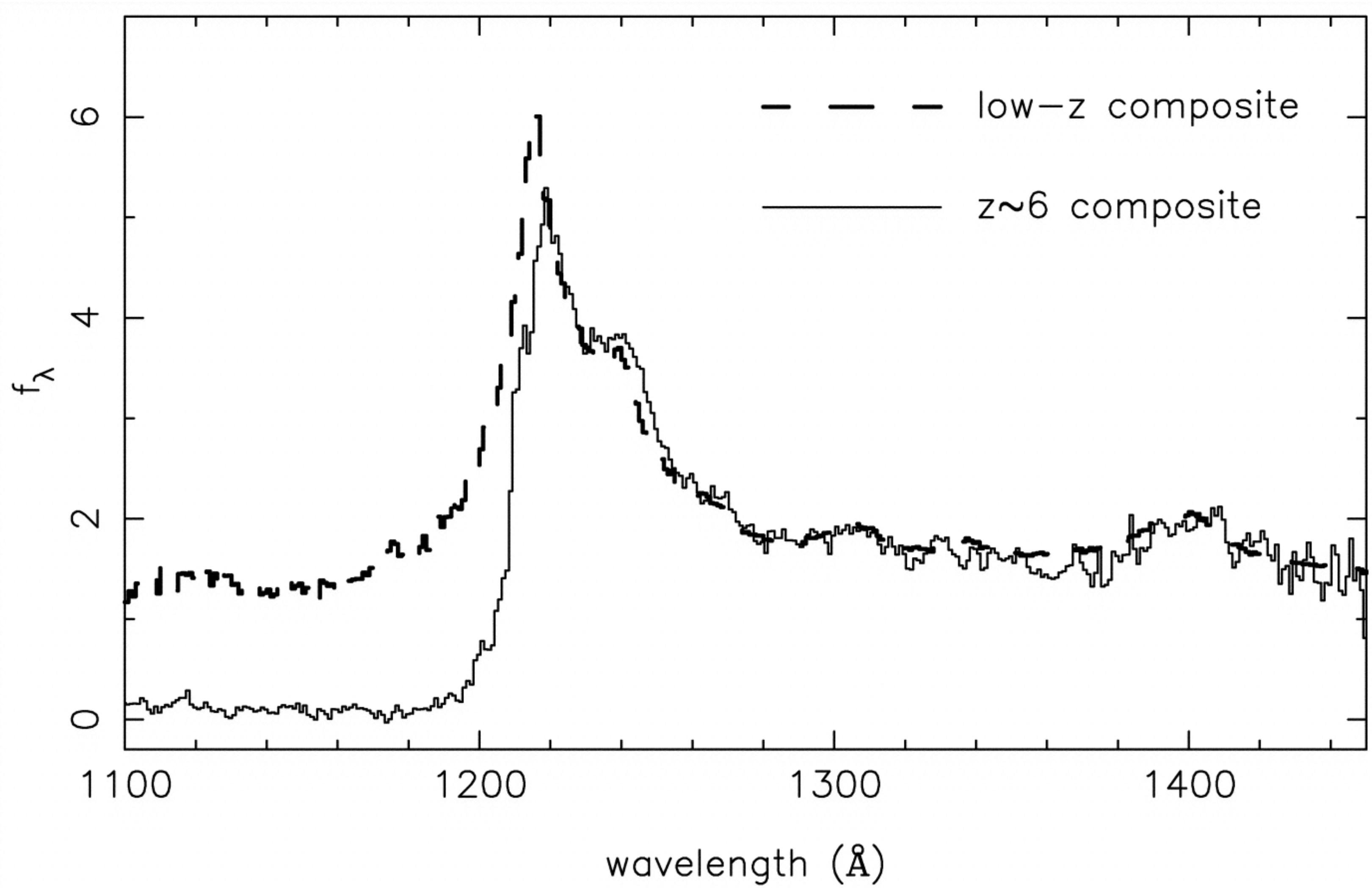
Stellar Populations: Metallicity

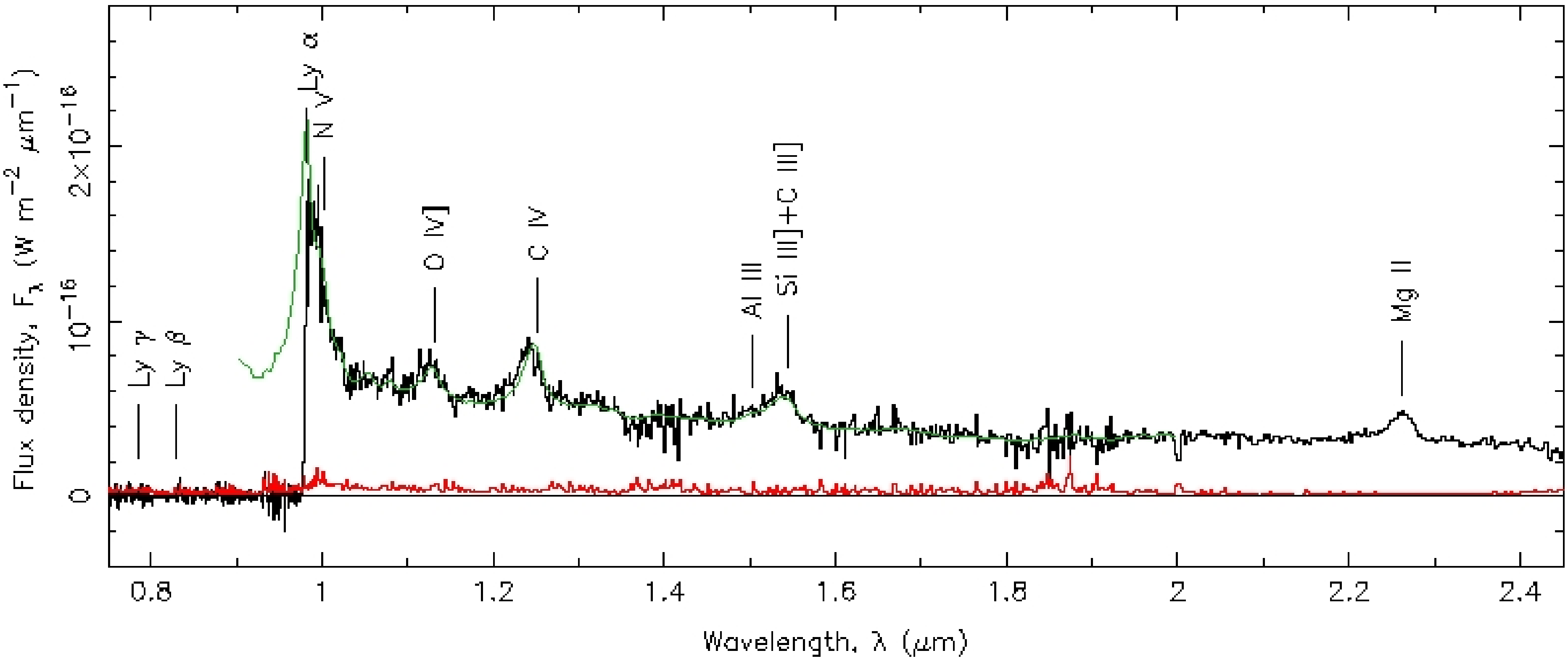
• The Sun is a typical Population I star, formed from gas that has experienced a number of generations/cycles of enrichment by massive stars and Type I supernovae. Population I stars comprise the stellar content of the disk of our Galaxy, with ages <9Gyr (white dwarf age for Galactic Disk – Lecture 19)

• The Halo of our Galaxy is made up predominantly of Population II stars that also have some evidence for enrichment from massive stars, although many of the stars possess only 1/100th of the heavy metals present in Population I stars like the Sun. Age of the Population II stars is ~11-13Gyr, almost as old as the universe

• Observations of high-redshift objects, even quasars, show direct evidence for early enrichment of gas due to nuclear burning in stars

• Composite spectra of *z*~6 quasars shows same abundances as quasars at lower redshift – gas enriched before *z*~6





J1120+0641, z=7.084 – most distant quasar known, 0.77 billion years after Big Bang. Still shows signatures of the same metal species with essentially the same abundances!

Stellar Populations: Where is Population III?

• Big-Bang nucleosynthesis calculations produce extremely tight constraints on the composition of the baryonic matter – H, He, Li and essentially nothing else

• Population II stars with ages >12Gyr are significantly enriched

• High-redshift objects, including quasars and star-forming galaxies show direct evidence for enrichment

• No alternative scheme for generating significant quantities of heavy elements is known

• Therefore follows that there must have been an earlier generation of stars before formation of Population II objects – **Population III**

Population III

• In Lecture 16 looked at what was known about the Initial Mass Function (IMF), noting the steep inverse dependence on stellar mass such that most of the mass of a collapsing gas cloud ends up in stars of low mass

• Observational evidence to date has found little evidence for significant variations in the form of the IMF (as a function of anything!)

• Population III, by definition, would have been formed from gas with essentially no heavy elements. Major change to the opacity and cooling processes operative during collapse of gas cloud

• A number of models have suggested that IMF would be skewed to much higher masses under such conditions – “Top heavy”

• If low mass stars were formed, they should be detectable today

• If only high-mass stars formed, then no Population III now but study of extreme Population II stars could reveal much about enrichment processes

Star of the Week: #6

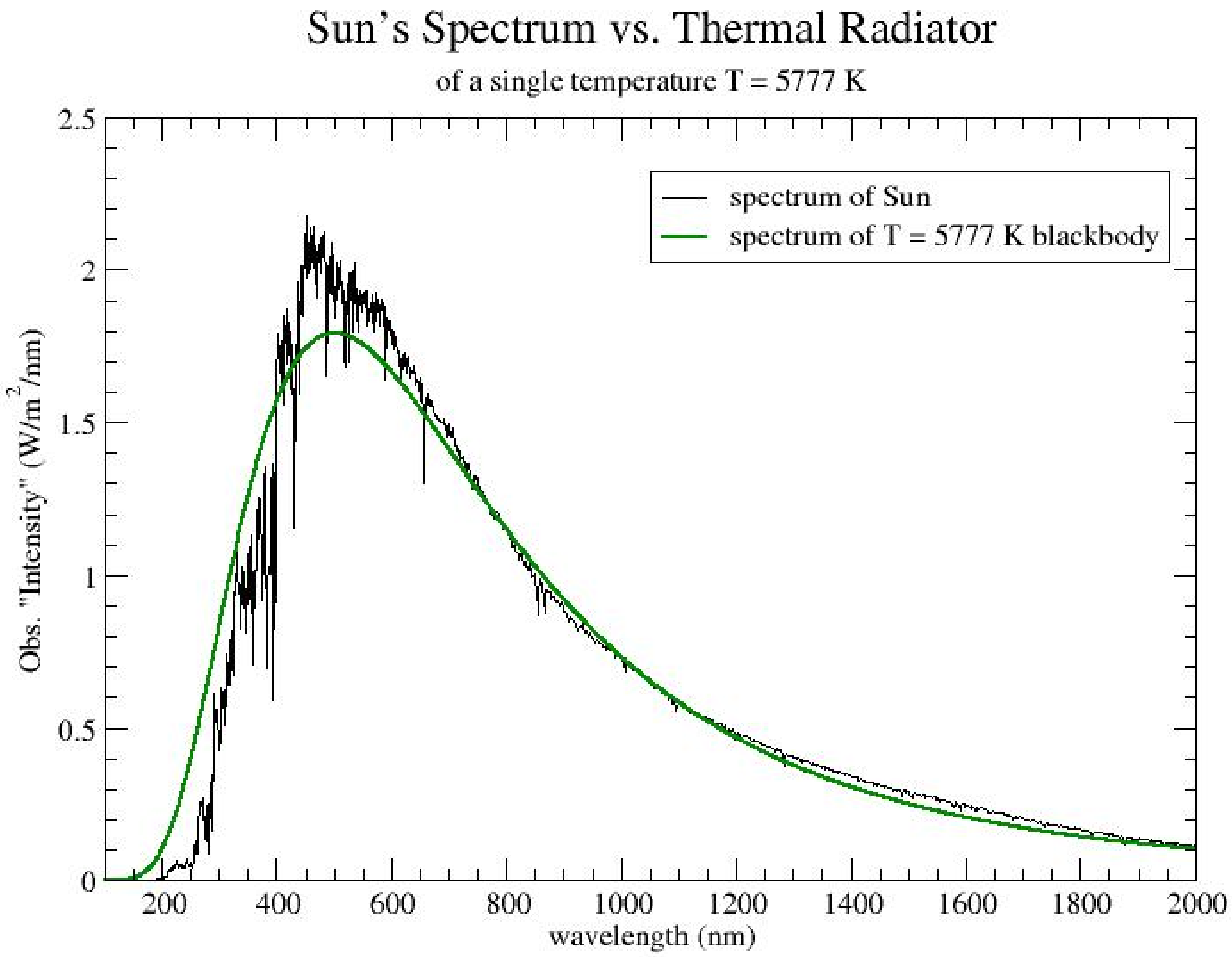
Keller et al. 2014, *Nature*, 506, 463

• SMSSJ0313-6708 the lowest metallicity star known

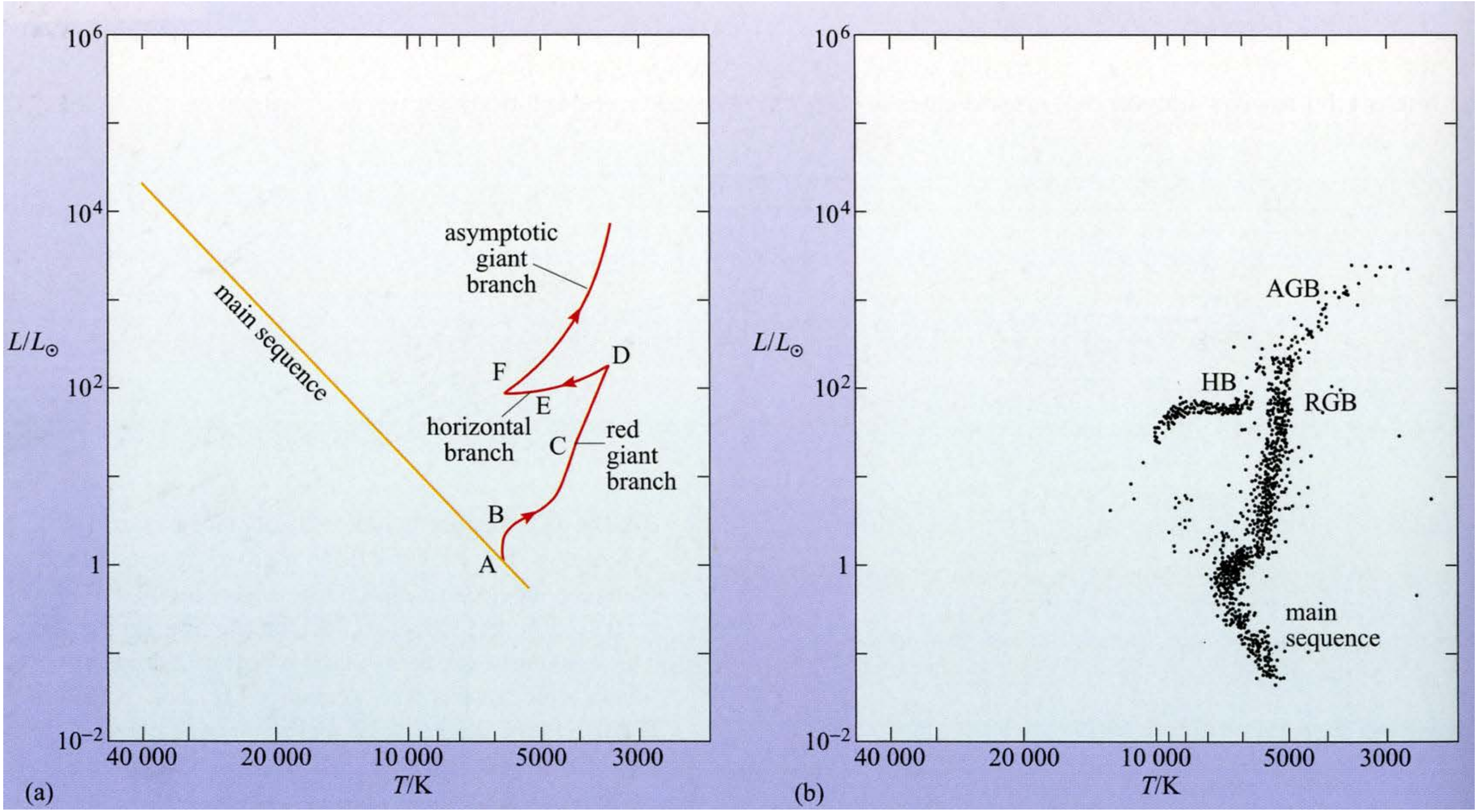
• A star in the Galaxy Halo with a magnitude V=14.7 ascending the giant branch, at a distance of ~5kpc

• How does one set about trying to find Population III stars?

- Requires a multi-stage process
- Not easy and objects are rare
- Search for stars of Mass ~0.7-0.8M_{sun} evolved off main sequence up the giant branch (luminous, visible to large distances)



Most stellar spectra are well approximated by blackbodies but majority of bound-bound opacity from metals affects wavelengths below 4000 Angstroms, i.e. in the U-band



10^6
10^4
10^2
1
10^{-2}
$L/L_\odot$
main sequence
asymptotic
giant
branch
F
D
E
horizontal
branch
C
red
giant
branch
B
A
40 000
20 000
10 000
5000
3000
T/K
(a)
AGB
HB
RGB
main
sequence
(b)

Initial Survey to Identify Potential Candidates

- Need low-resolution spectra, or, now, with high accuracy-photometry, to identify stars that show low absorption below 4000 Angstroms
- Historically, until last fifteen years, “objective-prism” spectra employed
- New wide-field photometric surveys allow accurate (few percent, i.e. 0.02 mag) colours to be acquired for relatively faint stars
- Australian SKYMAPPER survey – 1.35m telescope, u,v,g,r,i,z passbands -3500-9000 Angstroms
- At fixed g-i colour (longward of 4000A to get stellar temperature), look for stars that are blue in u-v (measures across the 4000A-break) – after one in a million (or more!)

• Telescope is a giant wide-field camera, aperture 1.2m, field of view 6.4 × 6.4 degrees (12 moon diameters)

• Northern and southern hemispheres surveyed in *BVRI* bands by UKSTU and Mount Palomar Schmidt Telescope

• Objective-prism exposures from placing very large thin prism over the telescope entrance aperture

• Various other smaller Schmidt telescopes have undertaken systematic objective-prism surveys

Objective-prism image (on photographic film): poor-mans spectroscopy

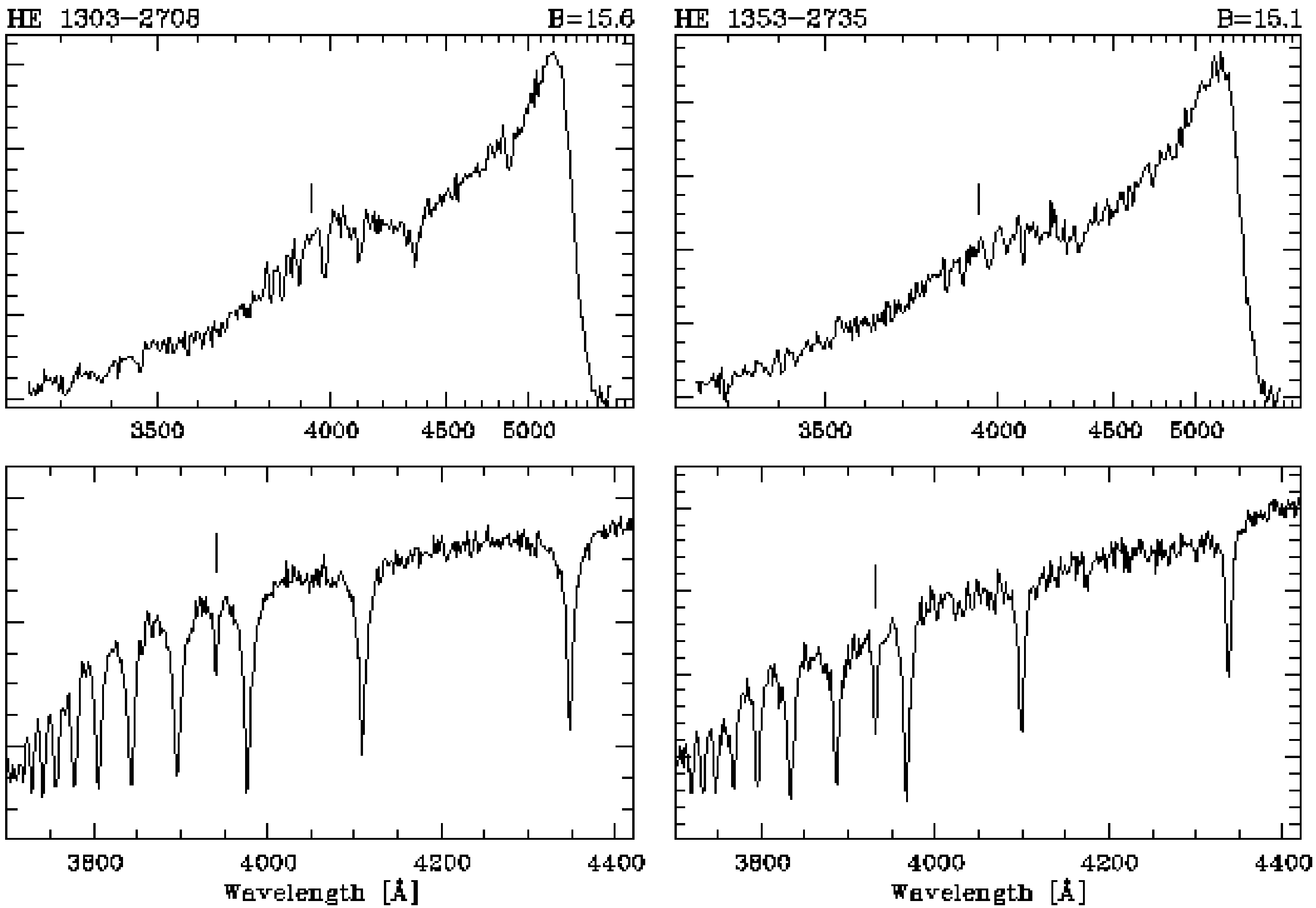
Effective for objects brighter than the sky background level

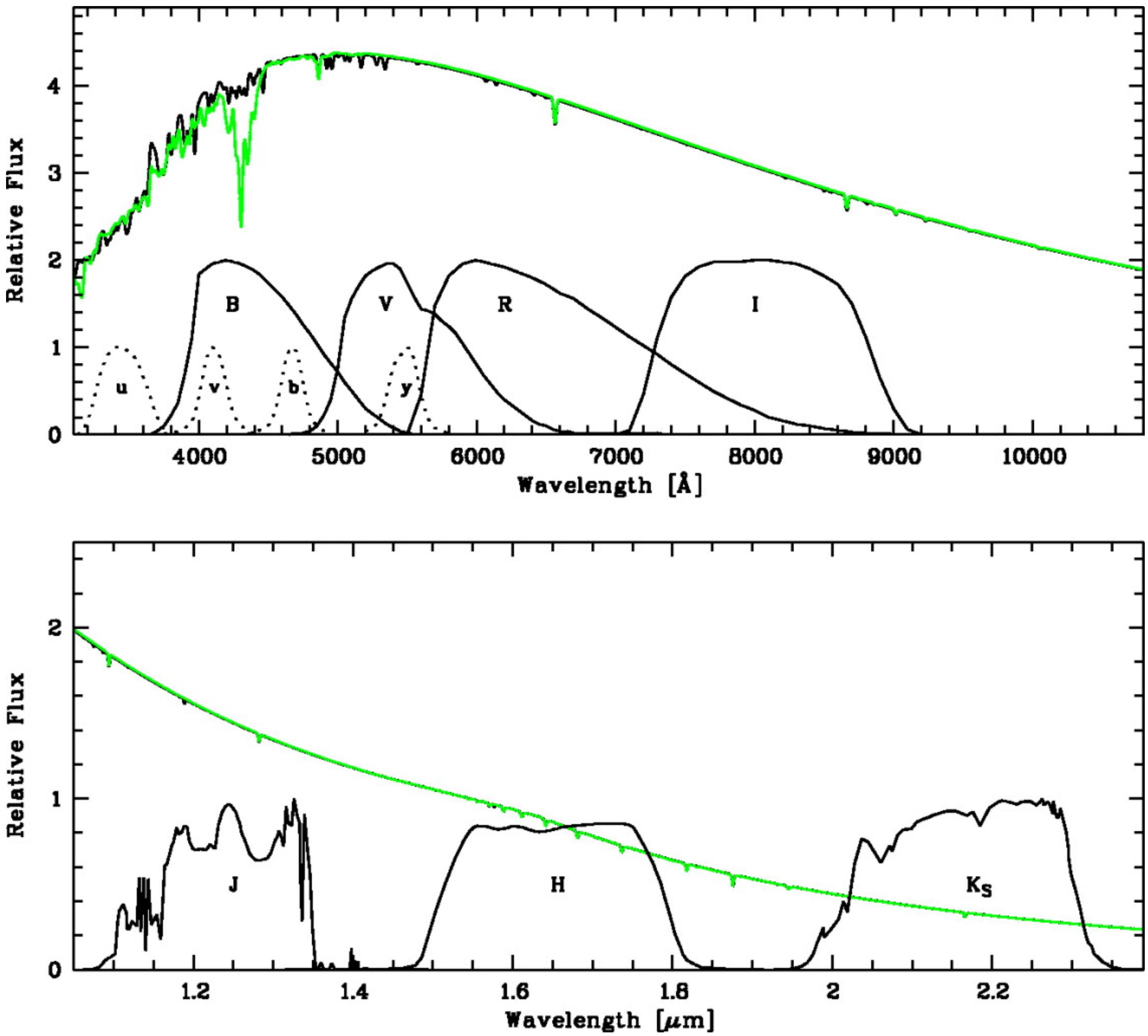
Easy to acquire and still the source of the majority of stellar spectra in existence

Digitize the objective-prism exposures, derive a wavelength-scale and look for stars that have small or non-existent depressions at <4000 Angstroms and no strong metal lines

Two example objective-prism spectra – no Ca visible

Intermediate resolution follow-up spectra of the same objects – see Ca



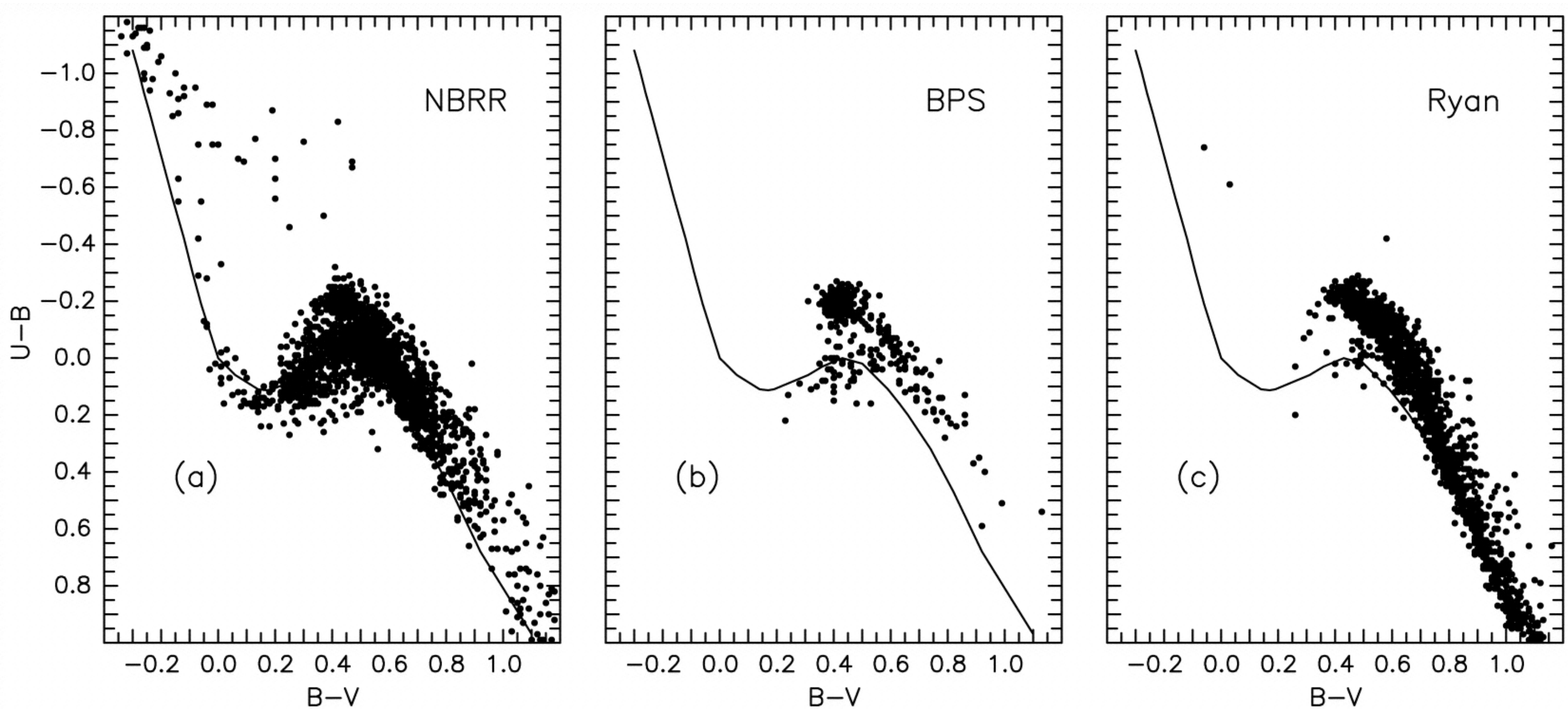


HE 0107-5240

$T_{\rm eff}$ from broad-band colours - Blackbody fit

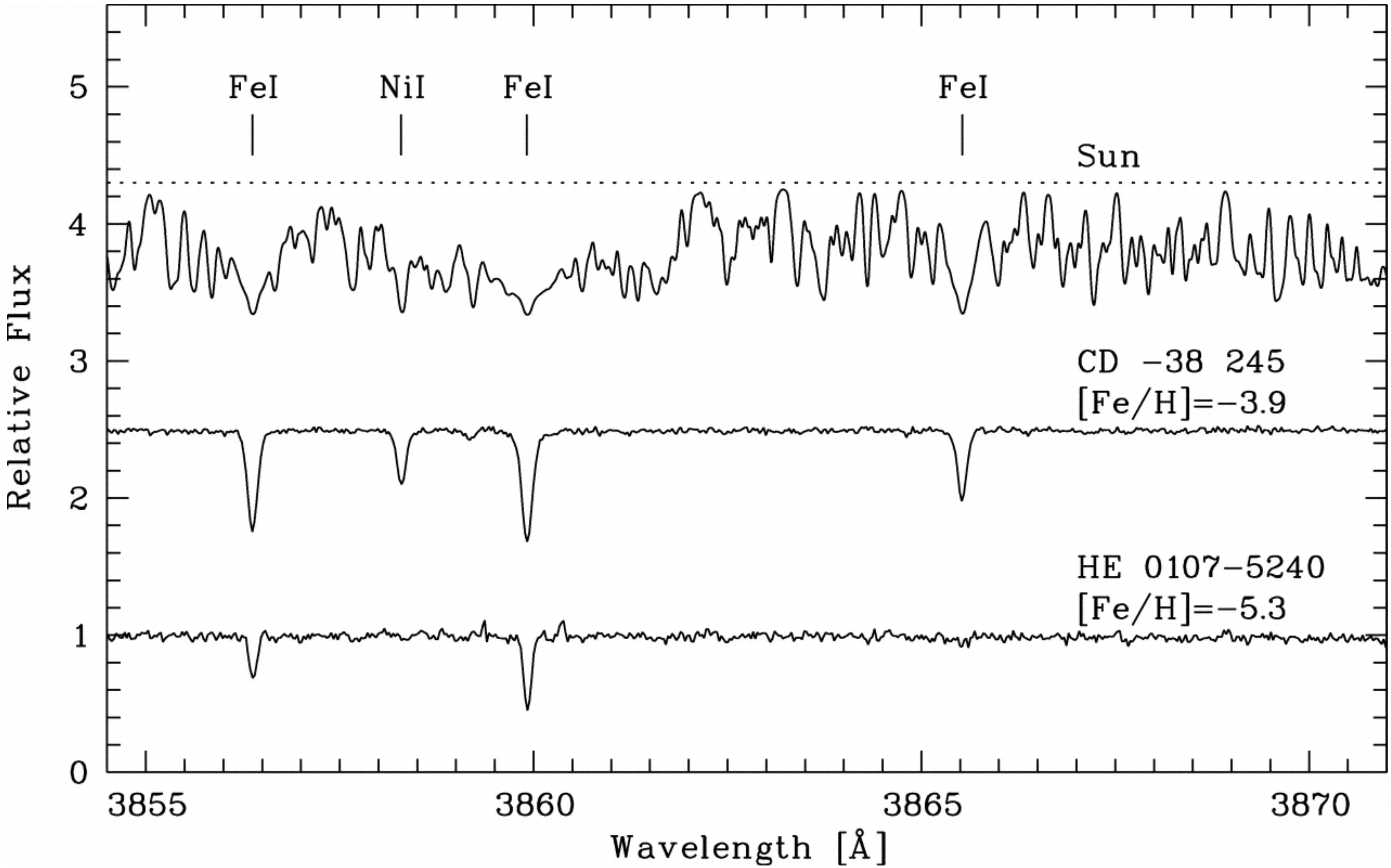
$T_{\rm eff}$ =5100±150K

Candidate list of UV-bright stars through accurate uvgriz or *UBV* photometry – candidates lie blueward (in *U*-*B*) of the main sequence of Population I stars in the two-colour diagram

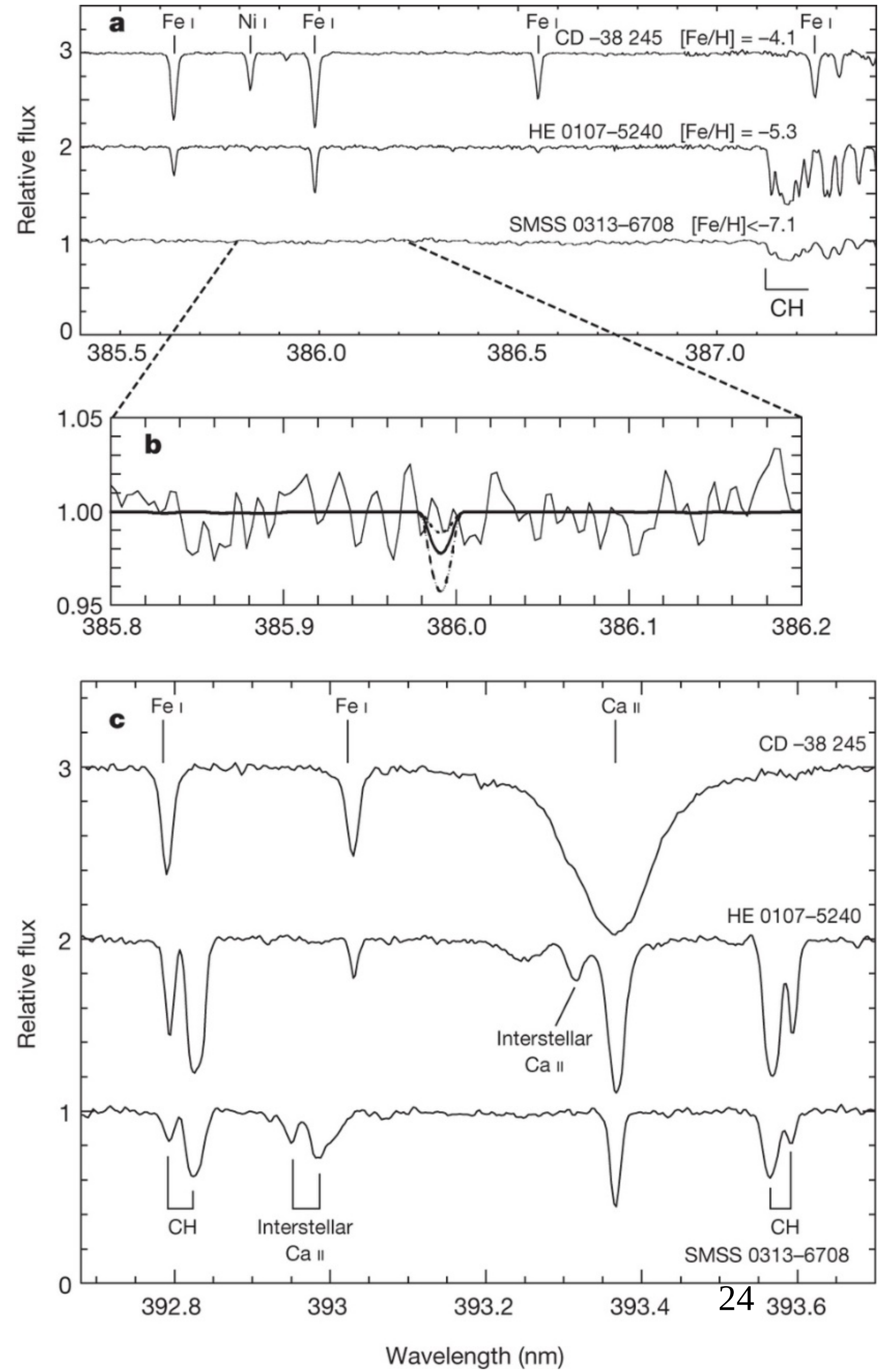


Need to exclude very blue white dwarfs and quasars – (a) top left

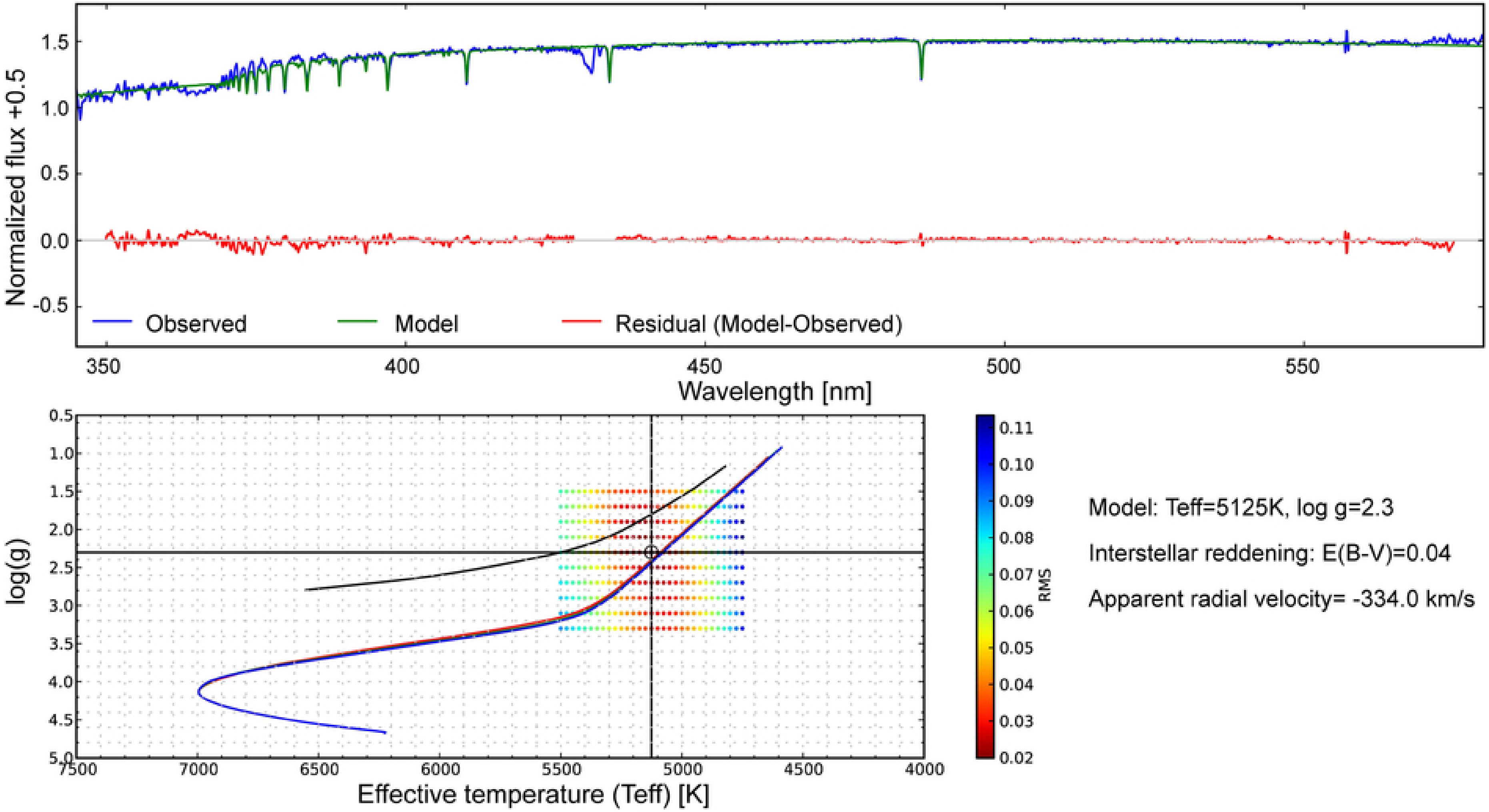
High-resolution ESO VLT spectrum for HE 0107-5240) (previous record holder): metallicity determination [Fe/H]=-5.3±0.2



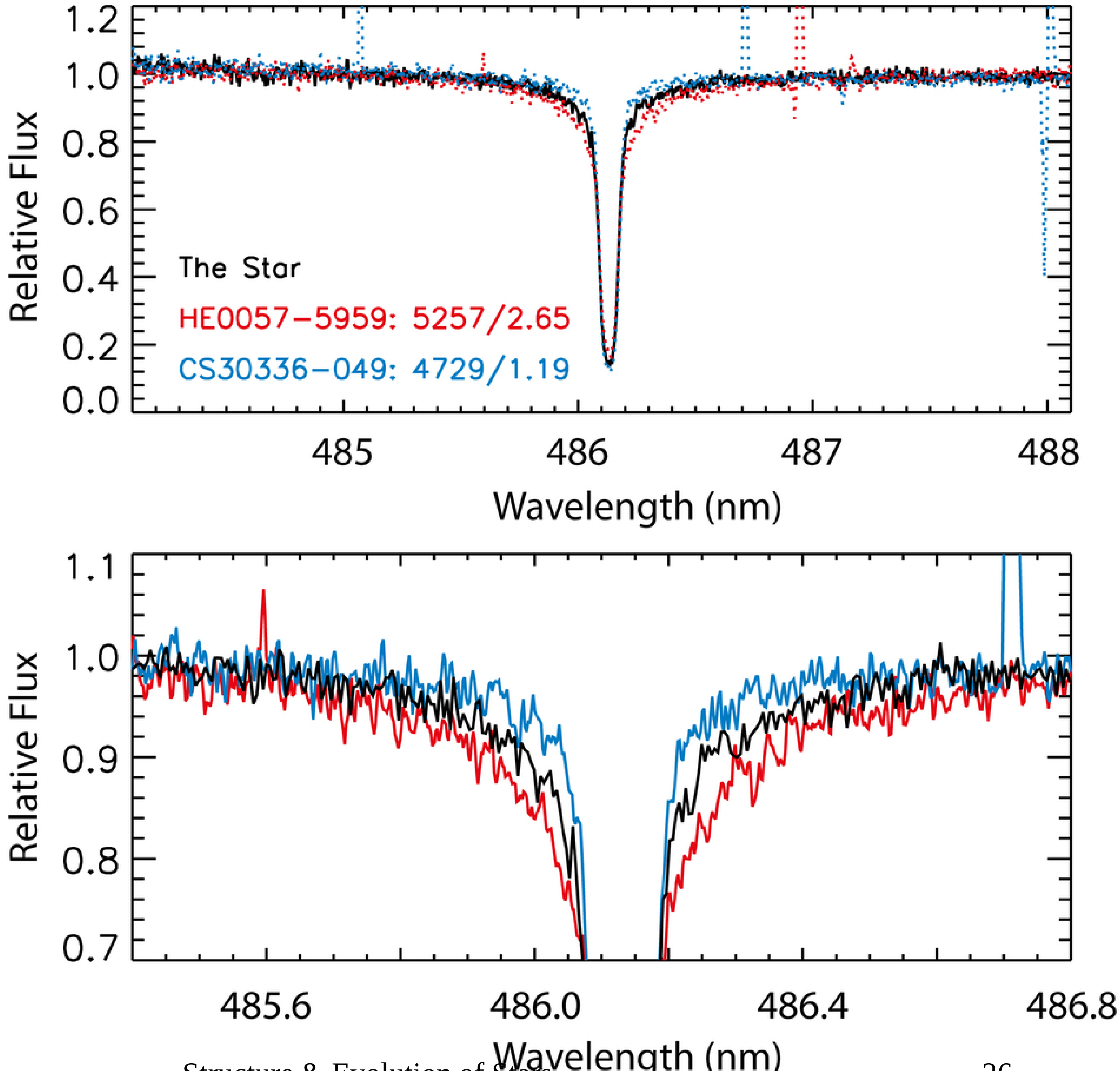
● Initial candidate list from photometry or objective-prism spectra
● Then follow-up promising looking candidates with moderate-resolution spectra to identify candidates with [Fe/H]<-3 (or thereabouts)
● Finally, obtain high signal-to-noise ratio, high-resolution spectra of candidates – need 6.5, 8 or 10m diameter telescopes
● Spectrum of J0313-6708 compared to previous lowest metallicity stars known

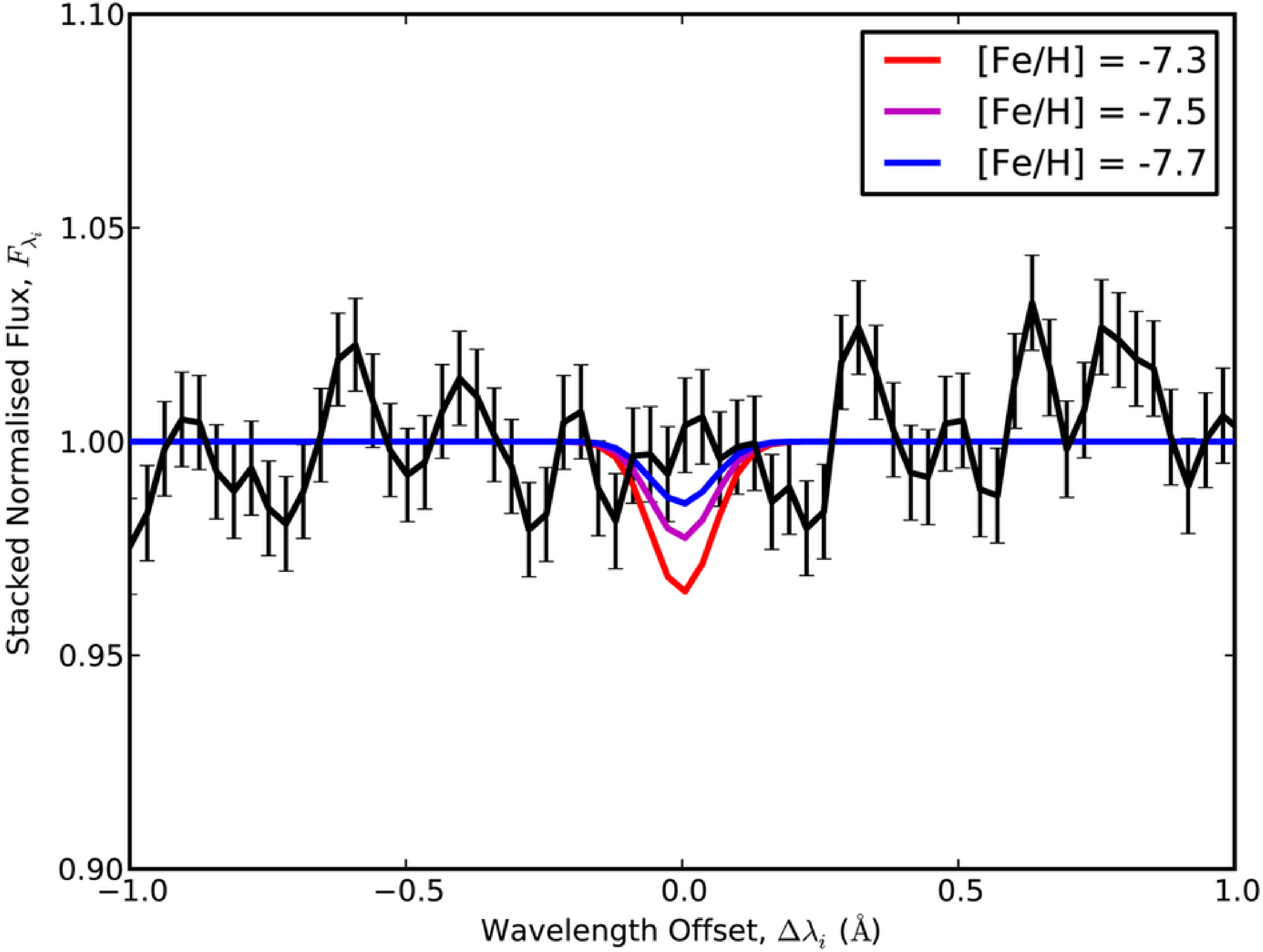


Need accurate model for star for accurate [X/H] measures

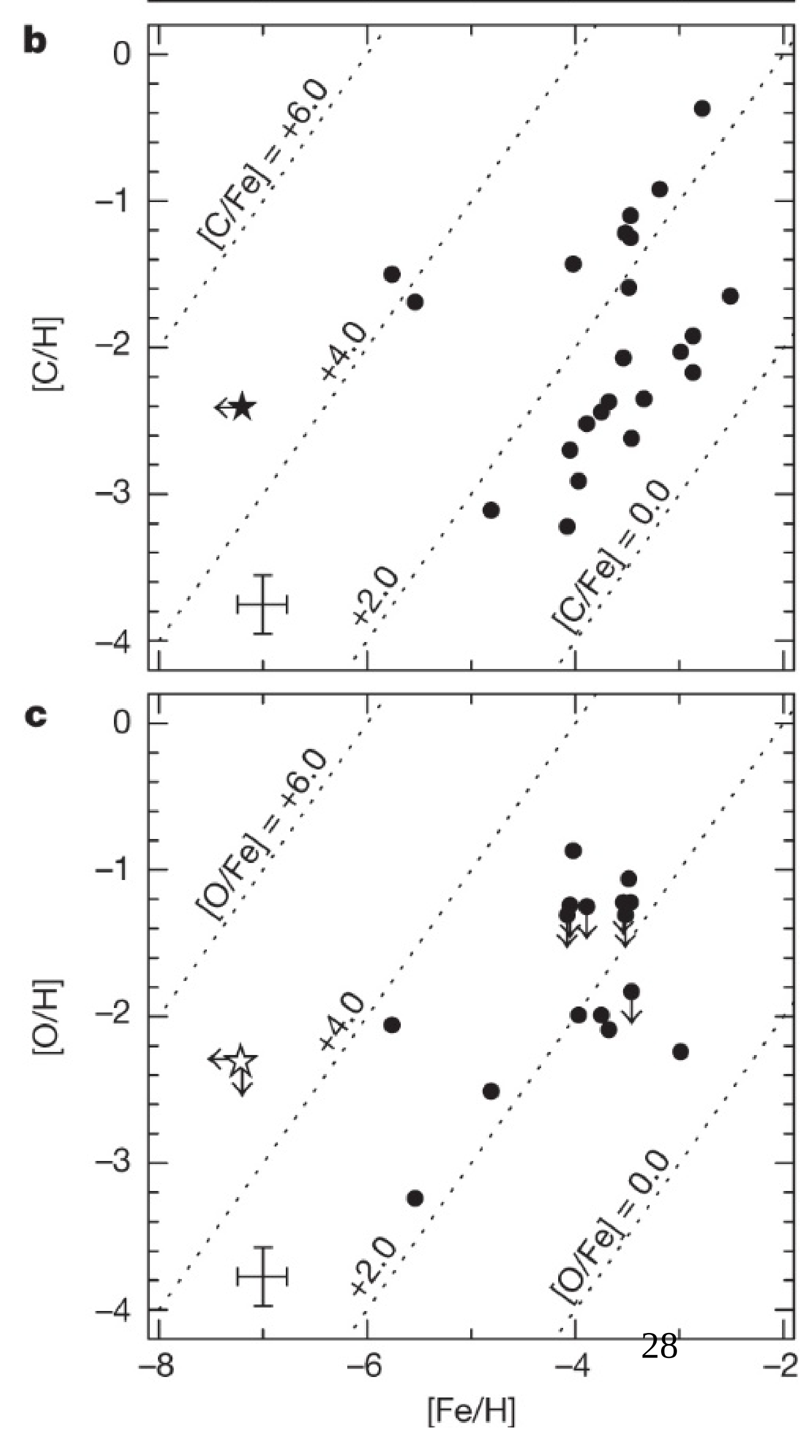


Double-check model using Hydrogen Balmer line – surface gravity, T,… Compare to stars that bracket physical properties





[Fe/H] limits extraordinarily low – previous lowest -5.3



● Element abundance ratios compared to other low-metallicity stars. Carbon and Oxygen typical but [Mg/Ca] high. [X-axis for plot above same as for plots to the right]

HE 0107-5240: (nearly) Population III only explanation?

• Population III star + contamination by accretion of interstellar gas

• Post asymptotic giant branch star (a few have [Fe/H]=-4.8) where various elements (Fe, Ca, Mg) have formed dust grains which are then lost via mass-loss (Eddington Luminosity for dust grains low). However, other elements do not deplete onto dust and C, N, O and Zn should have ~Solar abundances. In HE 0107-5240, Zn observed to be extremely under-abundant. Dredge-up of nuclear products from deep inside star to surface layers possible

• Some effects evident due to interaction with companion star

• Extreme Population II with potential for constraining enrichment history of gas at the epoch first stars form

SMSSJ0313-6708: Abundance Results

Can look at abundance of elements relative to Fe

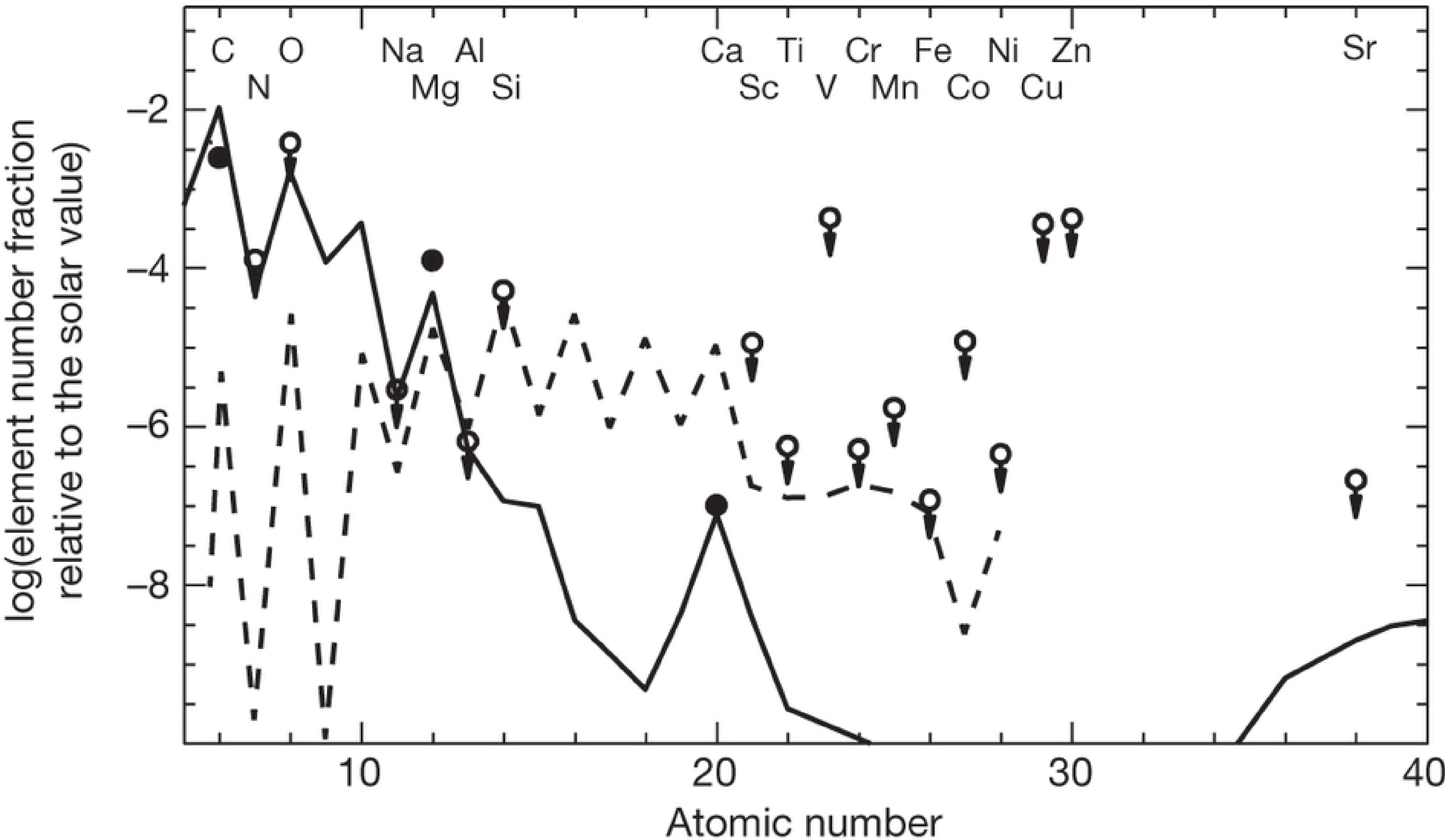
• [Fe/H] incredibly low – formed before SN Type Ia enrichment

• Carbon, oxygen and [probably] nitrogen much less depleted

• A high [Mg/Ca] ratio

Compare to values of element production from models of Population III supernovae:

a) 60 M_{Sun} star –familiar production of CNO plus Mg and Ca because core T higher due to reduced opacity in star
b) 200 M_{Sun} star – generates higher mass elements with CNO greatly reduced as fused into heavier elements



J0313-6708 abundance ratios versus Population III supernovae models – solid-line 60M_{Sun} star, dashed-line 200M_{Sun} star

Lecture 22: Summary

• Origin of elements requires a number of non-equilibrium processes – r-, s- and p-process - to complement result of thermonuclear burning inside stars
• Enrichment with heavy elements has very different timescales depending on process – Type II supernovae cf. Type Ia supernovae
• Improved searches for low-mass stars from Population III can provide constraints on the IMF at very early timed
• Detailed abundance studies of the lowest metallicity Population II stars offer prospect of understanding the nature of star-formation for Population III
• Extremely low-metallicity stars now known, eg. J0313-6708, but definitive confirmation of evolutionary state difficult and their use in the context of understanding Population III star-formation still requires much effort

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