In Search of the First Stars

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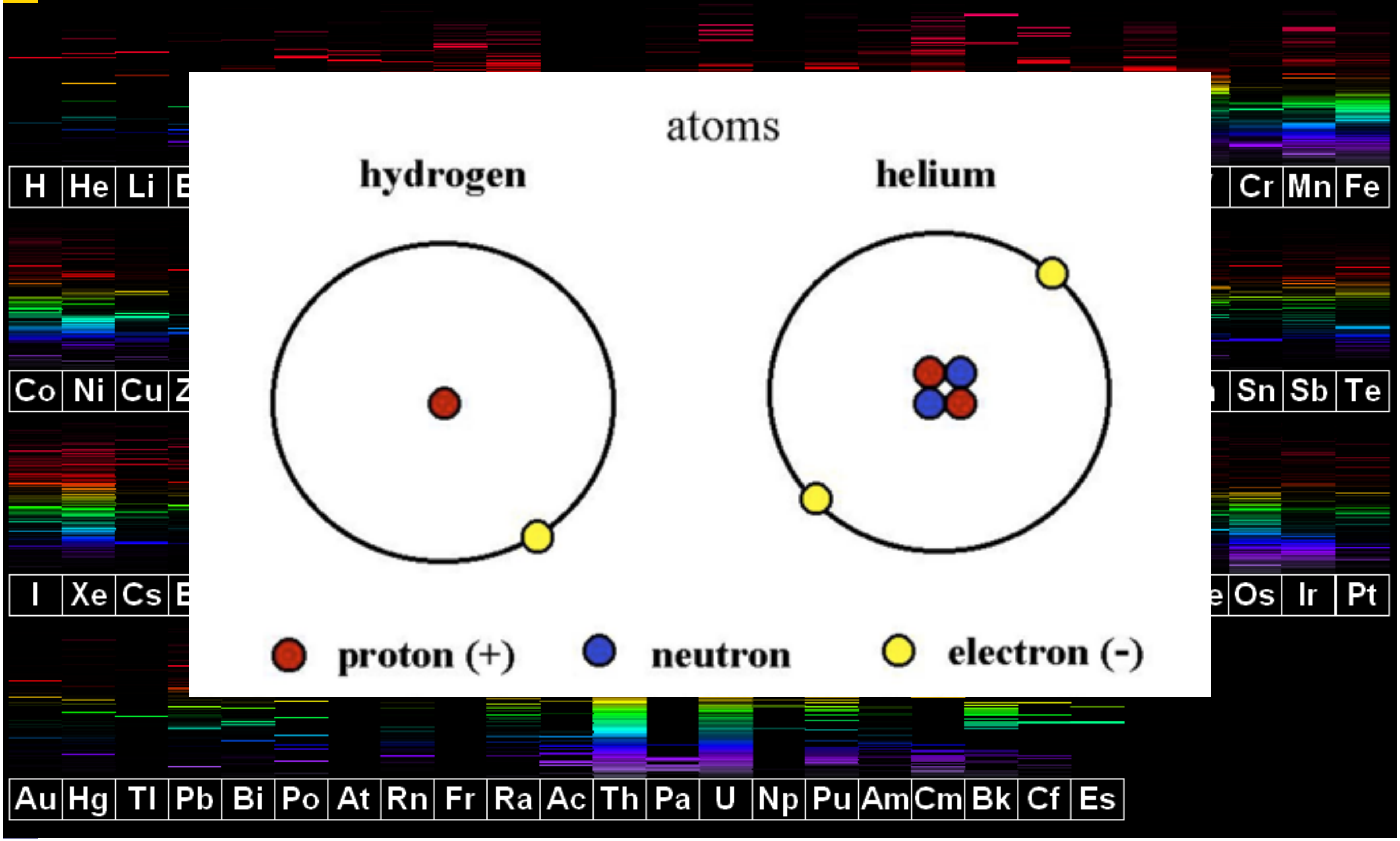
How did we come to be?

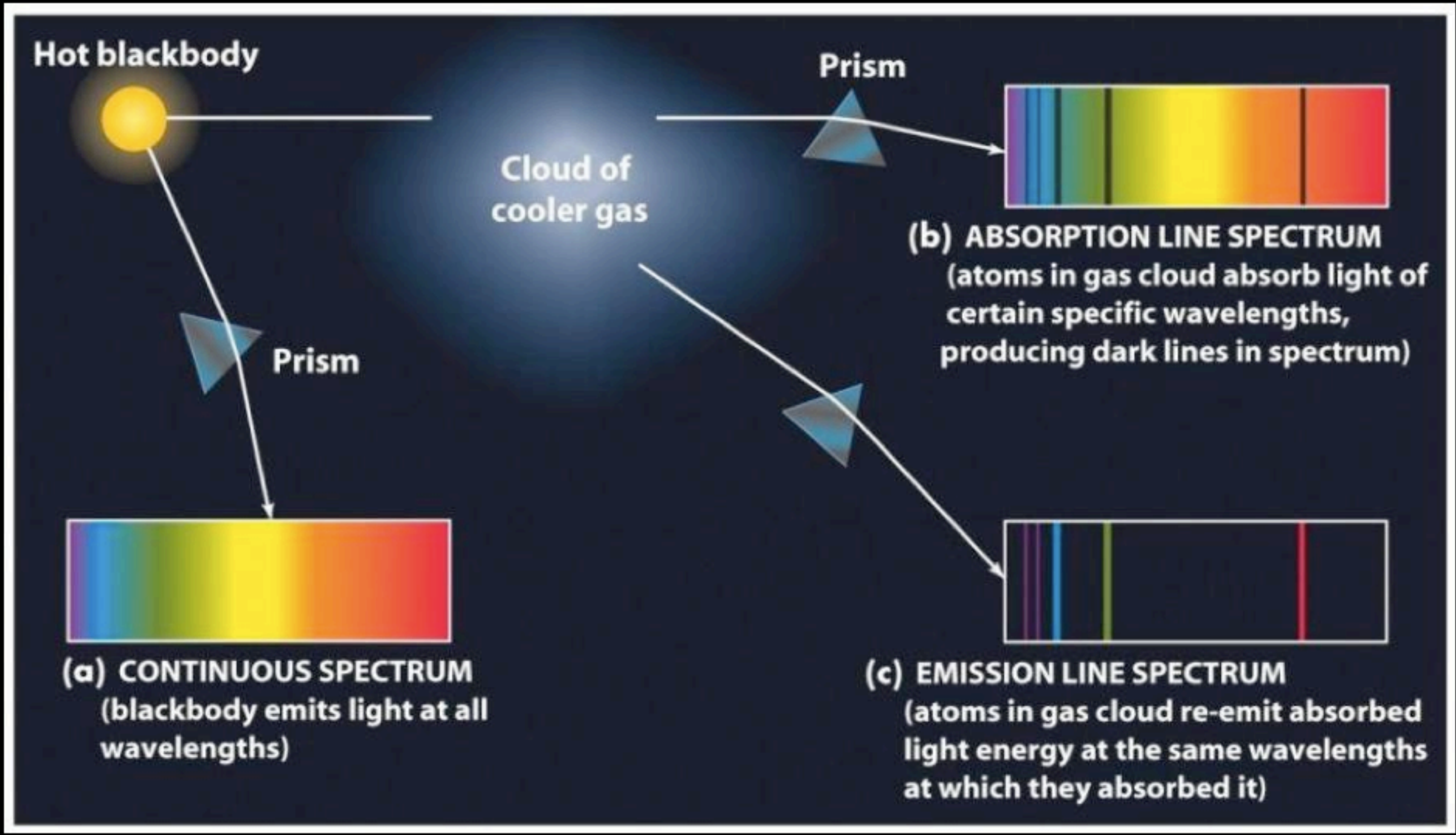
- Big Bang nucleosynthesis
- First stars & black holes
- Chemical evolution

Telescopes gather light from space...

...and tell us the Universe is full of matter



Emission versus absorption spectra



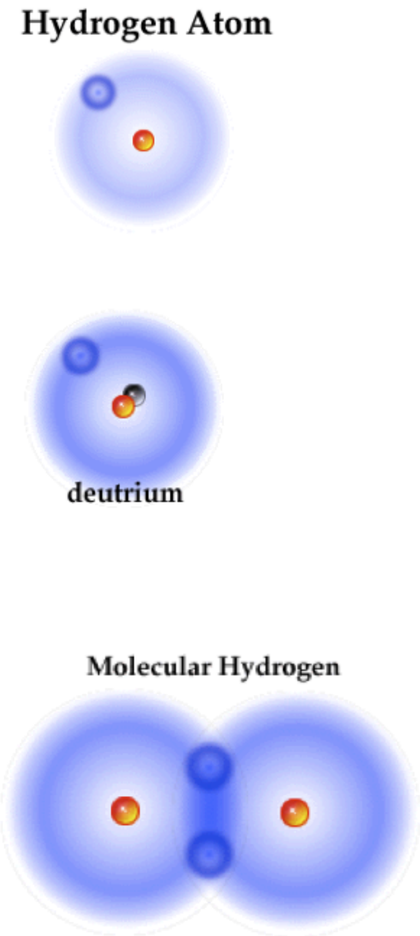
Where do the chemical elements come from?

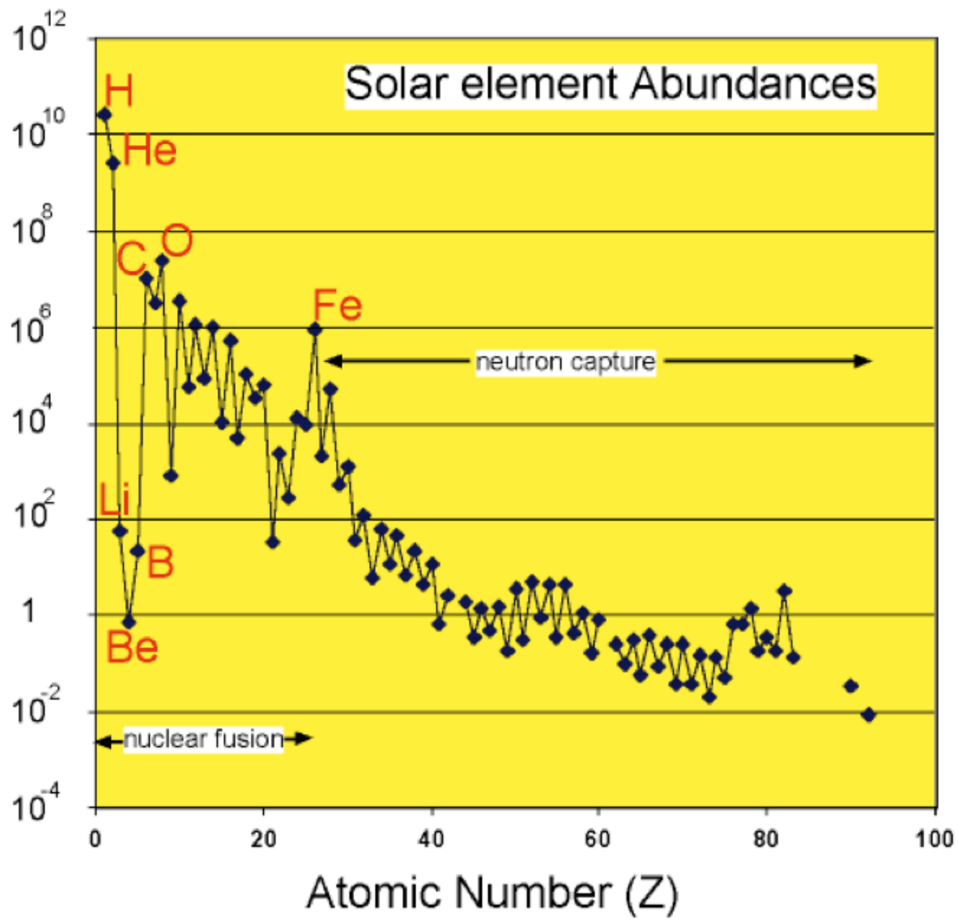
1 H																		2 He
3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
		*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
		**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

A full explanation requires knowledge of 4 things:

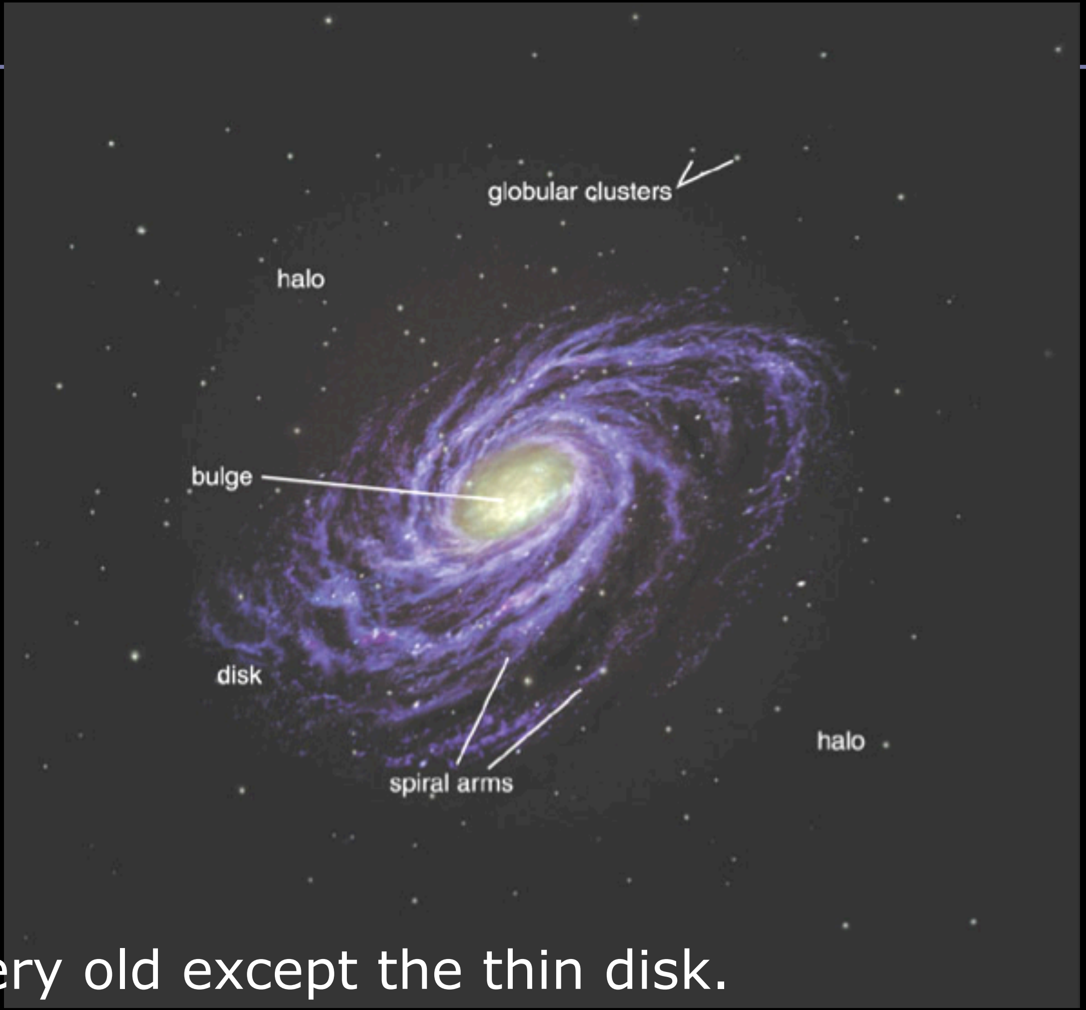
1. Big Bang 2. First stars 3. First black holes
4. Subsequent stellar formation & evolution

The elemental abundances from the Solar System (now seen in ancient stars too!)





Components of the Milky Way



Mostly very old except the thin disk.
But where are the truly ancient stars 0.8 M_o and smaller?

General Definitions

- **Metals** – chemical elements heavier than helium
- **Metallicity Z** – the mass fraction of metals ($Z_\odot$ = 0.0122, Asplund et al. 2005)
- **[Fe/H]** – the logarithm of the number fraction of iron nuclei to hydrogen nuclei relative to the abundance of iron in the sun ($\log(n_{Fe}/n_H)_\odot = -4.55$)
  - **Note: $[Fe/H]_\odot \equiv$ 0** in Sun by definition
- **Extremely metal-poor stars** – stars with [Fe/H] < –3.0, i.e., < 1/1000 of the solar iron abundance.
- **Chemical evolution** – the continuous enrichment of chemical elements (e.g., C, Fe, Au) in the interstellar medium (ISM) throughout cosmic history

Oldest stars

In a very naive model, metals increase with cosmic time, but solar abundances are observed to the highest redshifts.

It's not at all clear what the relationship is between [Fe/H] and age.

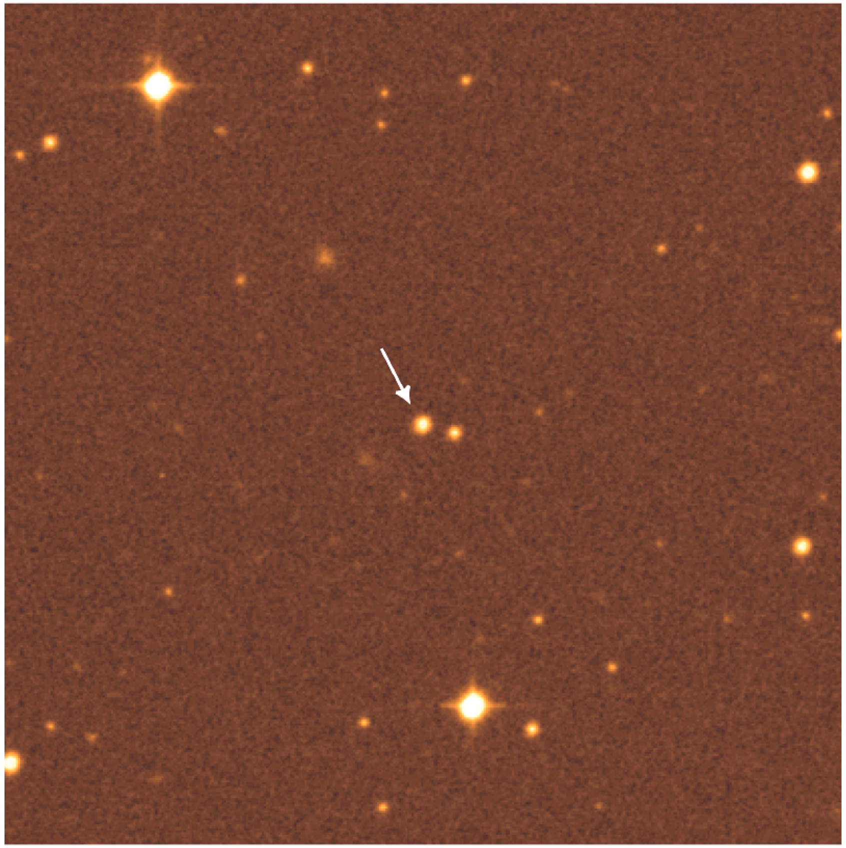
Most globulars are known to be ancient but have [Fe/H] > -2.

The most metal-poor stars are [Fe/H] < -5 and a few have radioactive ages indicating they **are** ancient.

But some stars with [Fe/H] ~ 0 will be just as ancient.

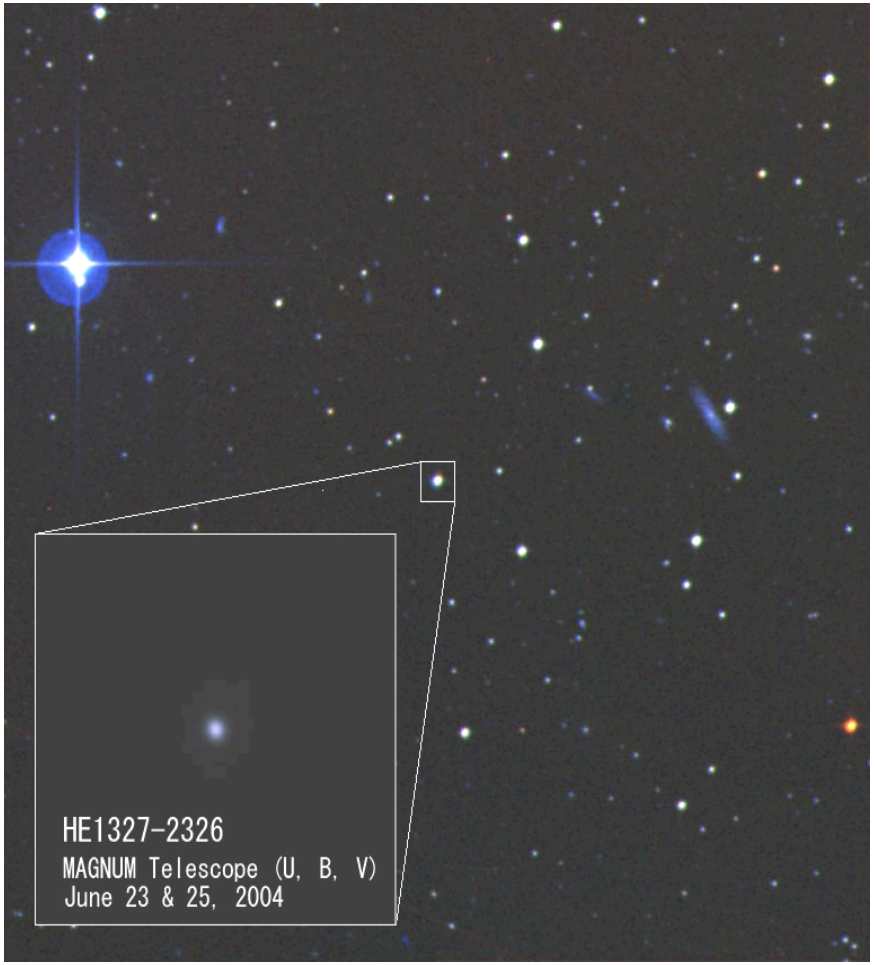
The existence of reliable ages for only a few stars is a problem. This could have made our job a lot easier.

The Oldest Stars in the Galaxy

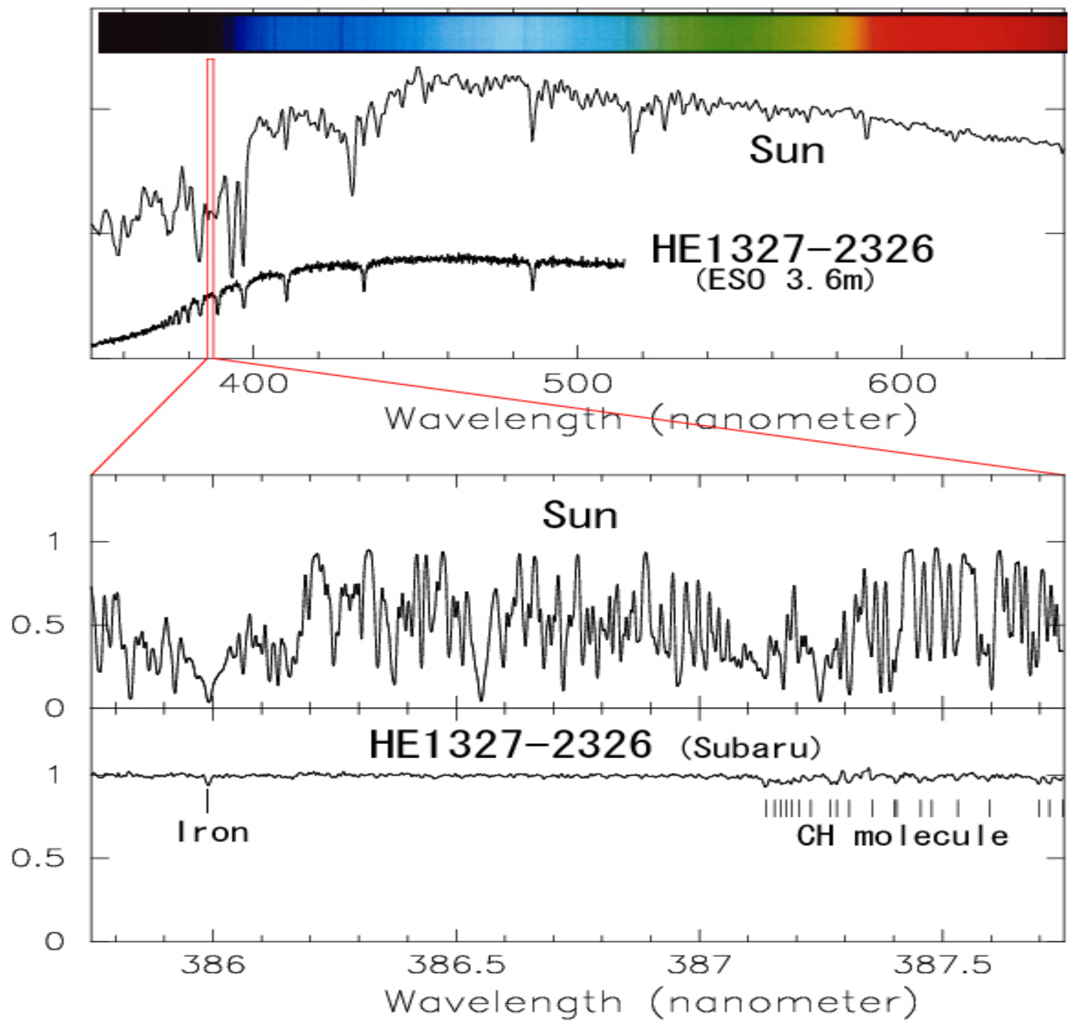


The Very Metal-Deficient Star HE 0107-5240

ESO PR Photo 25a/02 (30 October 2002)



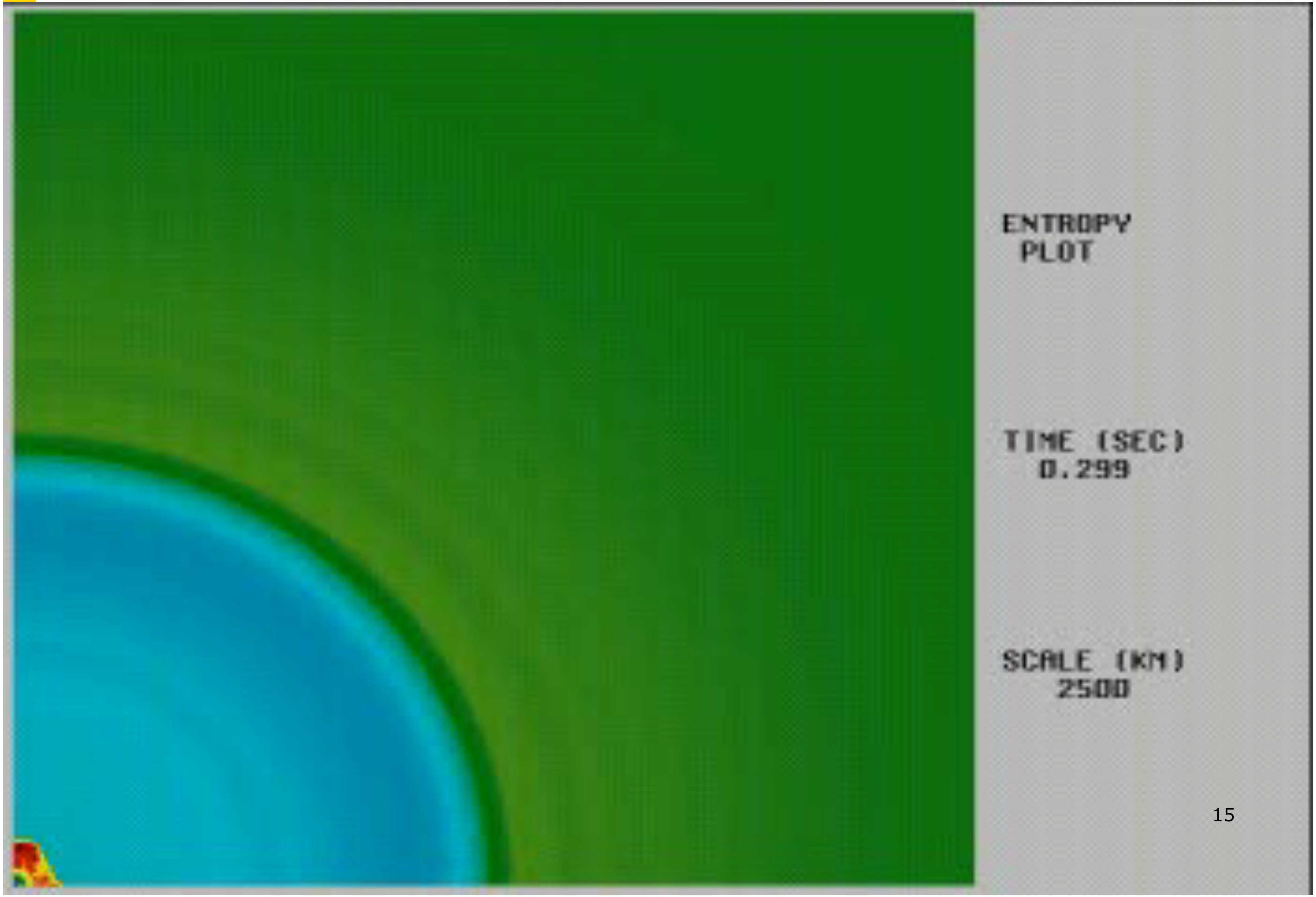
Spectrum of HE 1327-2326



Gas and DM build up over cosmic time to make the Galaxy

The final product showing the gas, dust & stars

Simulation of a SN explosion

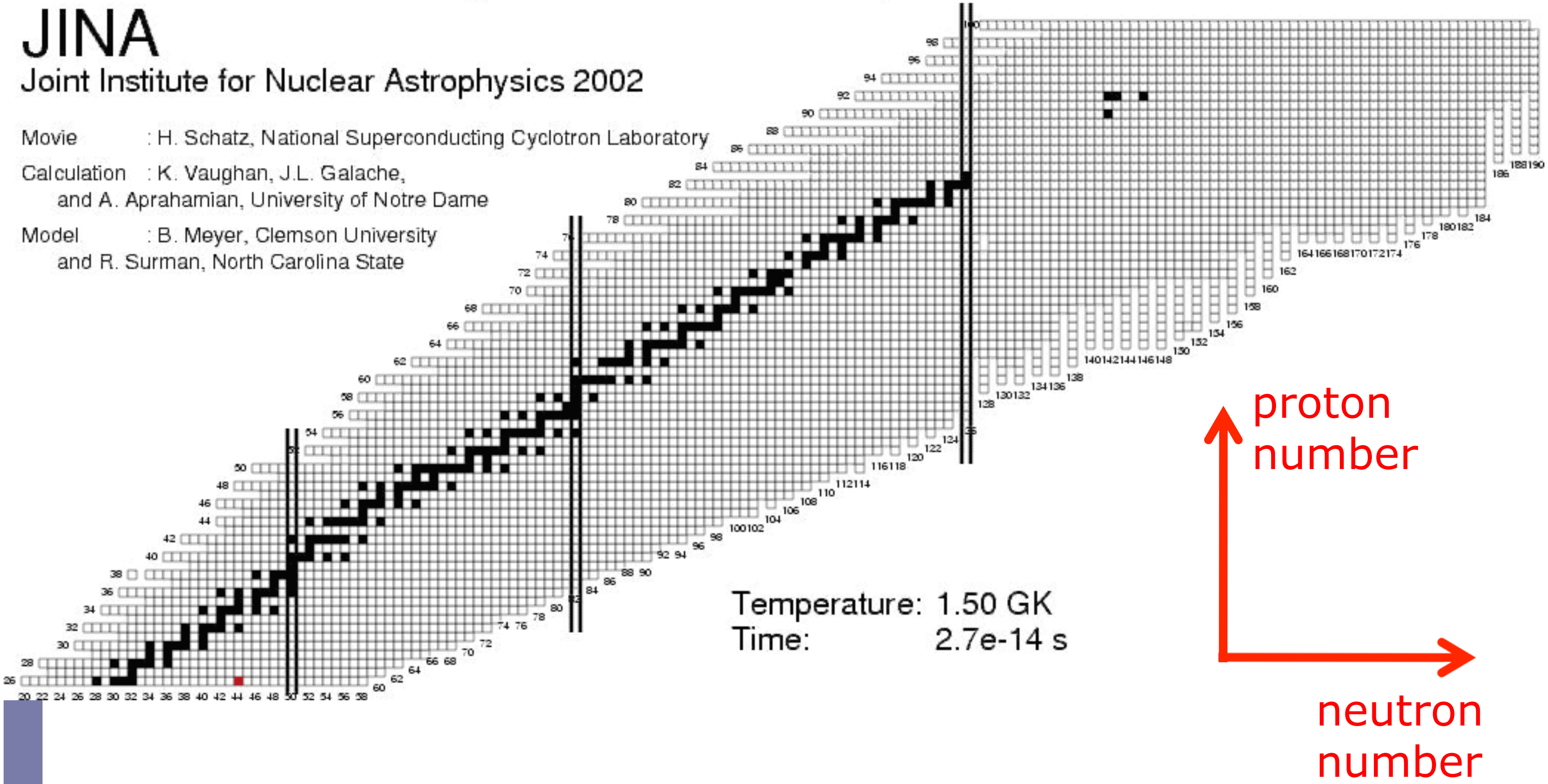


Neutron-capture nucleosynthesis

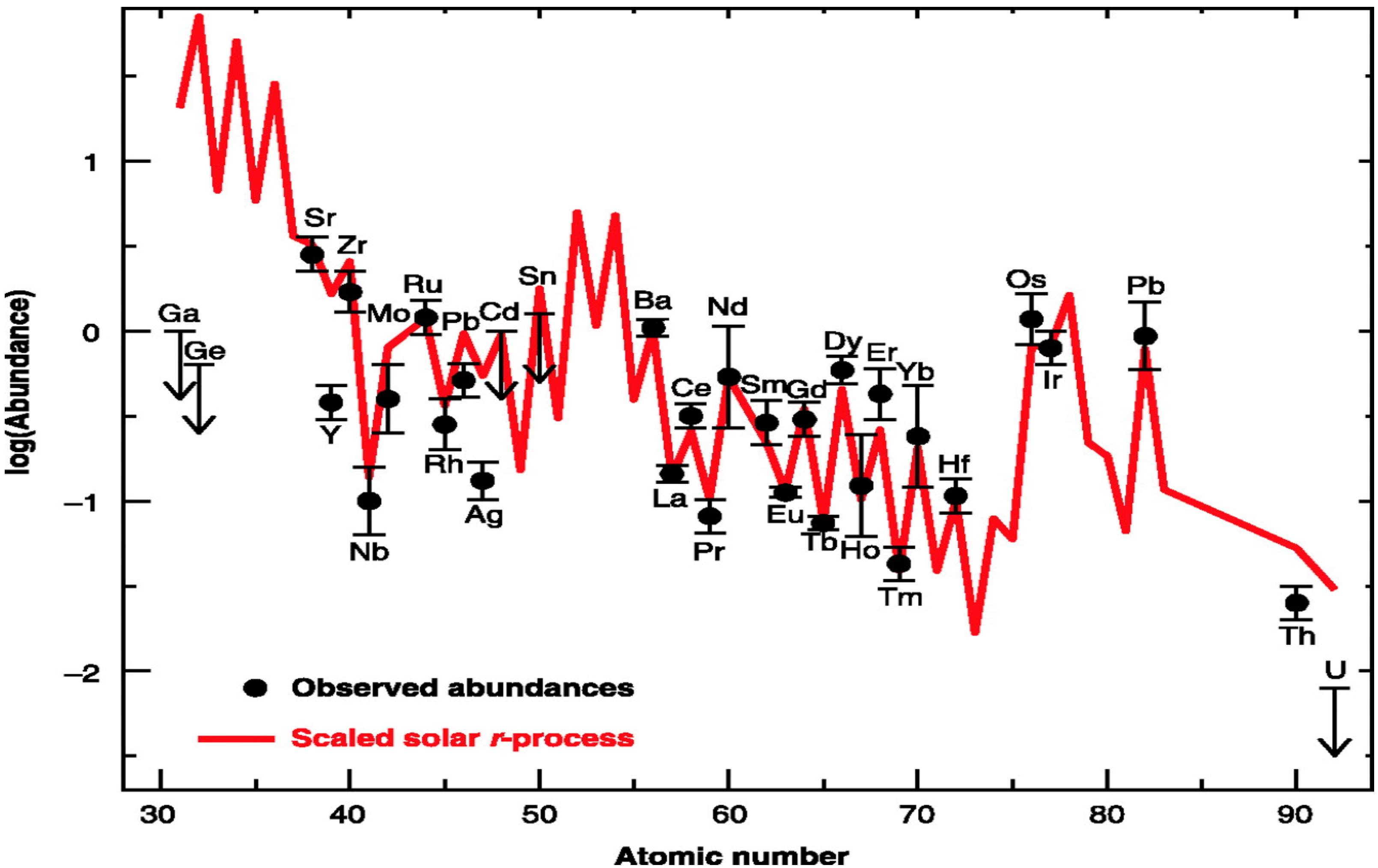
- The s(low) neutron-capture process: β-decay times of "stepping stone" products *shorter* than neutron-capture timescales.
- The r(apid) neutron-capture process: β-decay times of "stepping stone " *longer* than neutron-capture timescales.
- In solar system material, e.g. Ba is 85% s-process, and Eu is 97% r-process; Nd is 53%/47% r/s.
- Actinides, like Th and U, can *only* be produced by r-process, since s-process terminates at ^{209}Bi.

r-process movie (copyright H. Schatz, MSU/JINA)

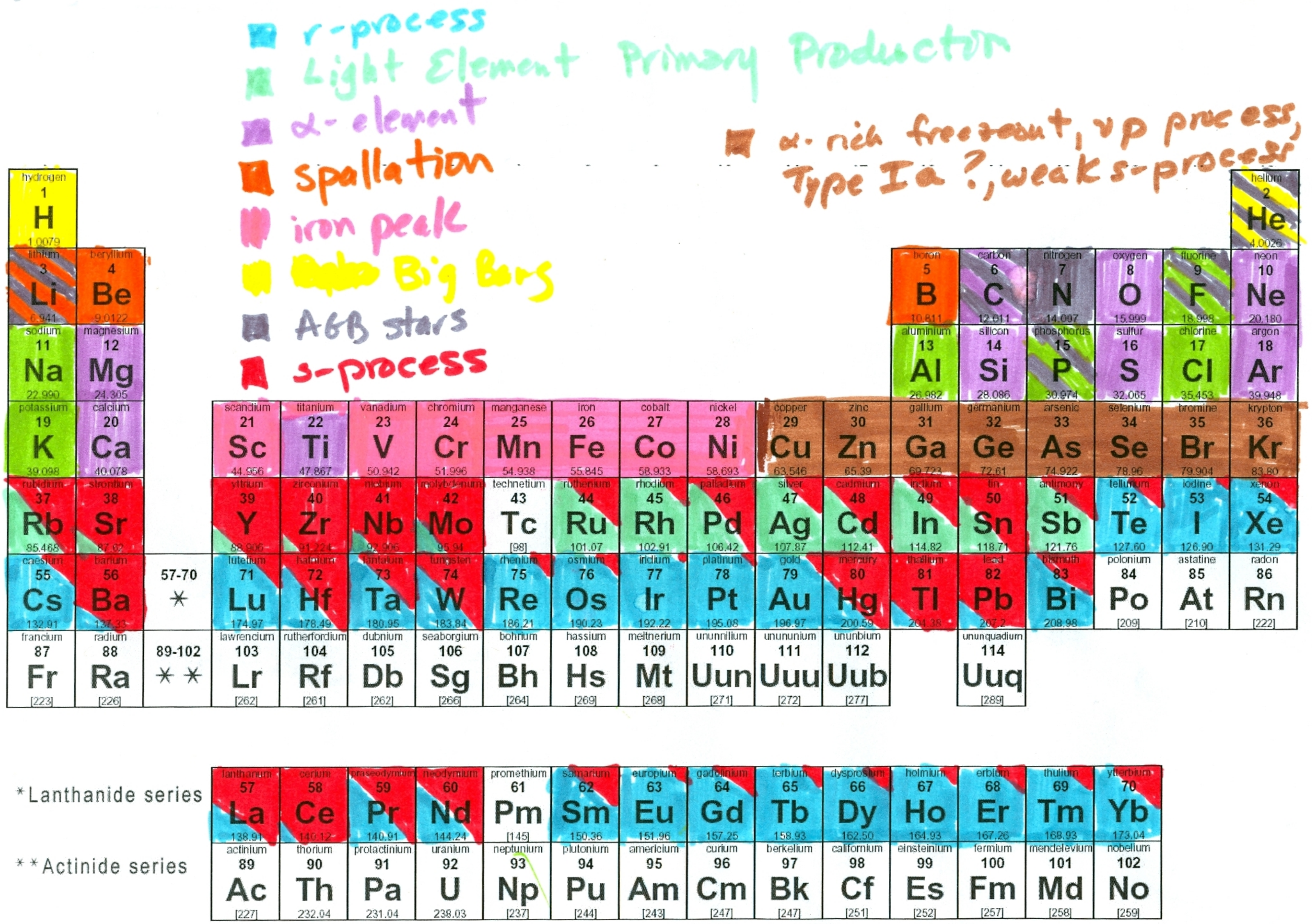
Nucleosynthesis in the r-process



The r-process Pattern for the Metal-poor Star CS 22892-052

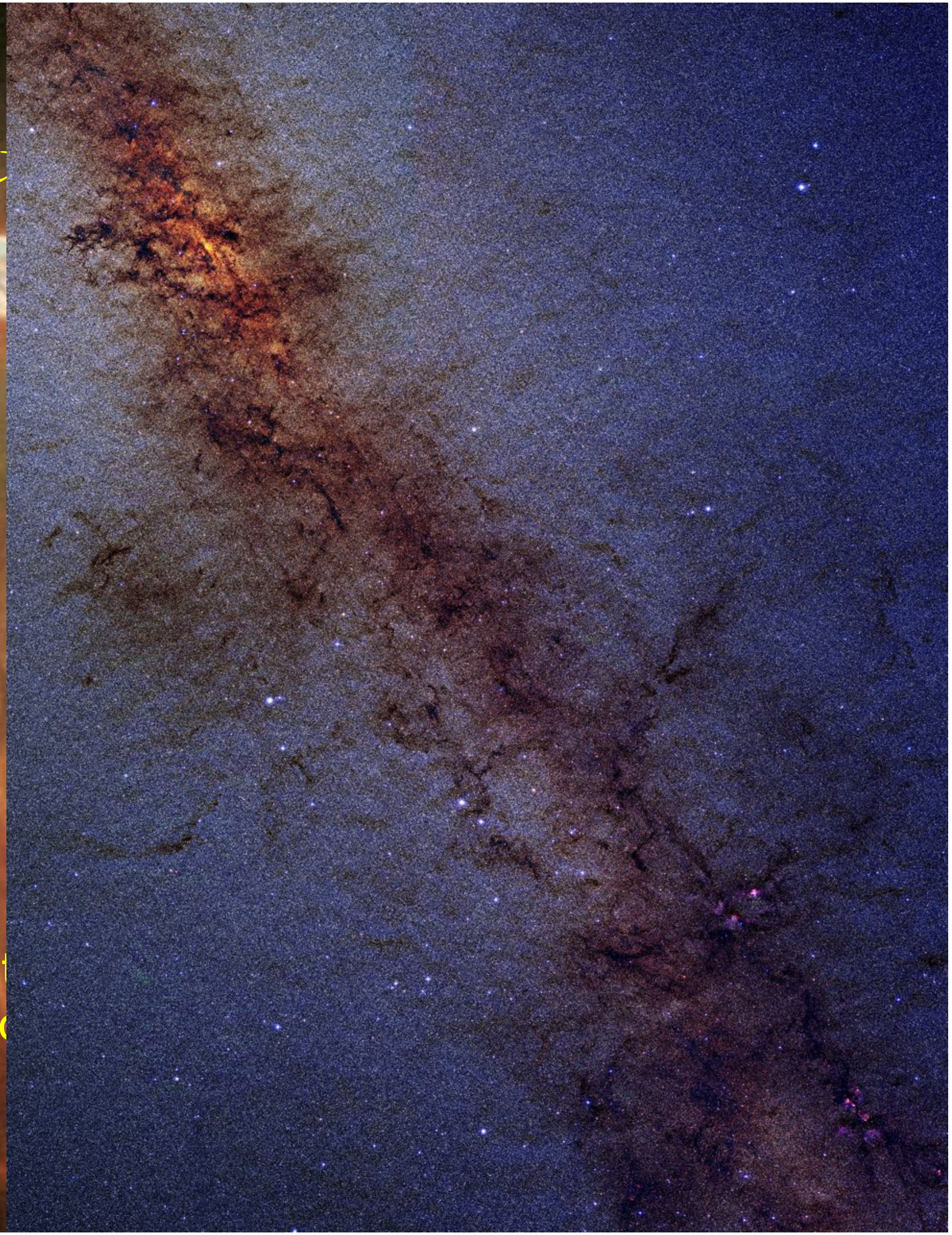


The many elements tell you about many physical processes



The s-process occu

This is a hugely important
5-8 M_o on the Asymptotic



How to age a star?

Estimating the ages of stars

Cluster

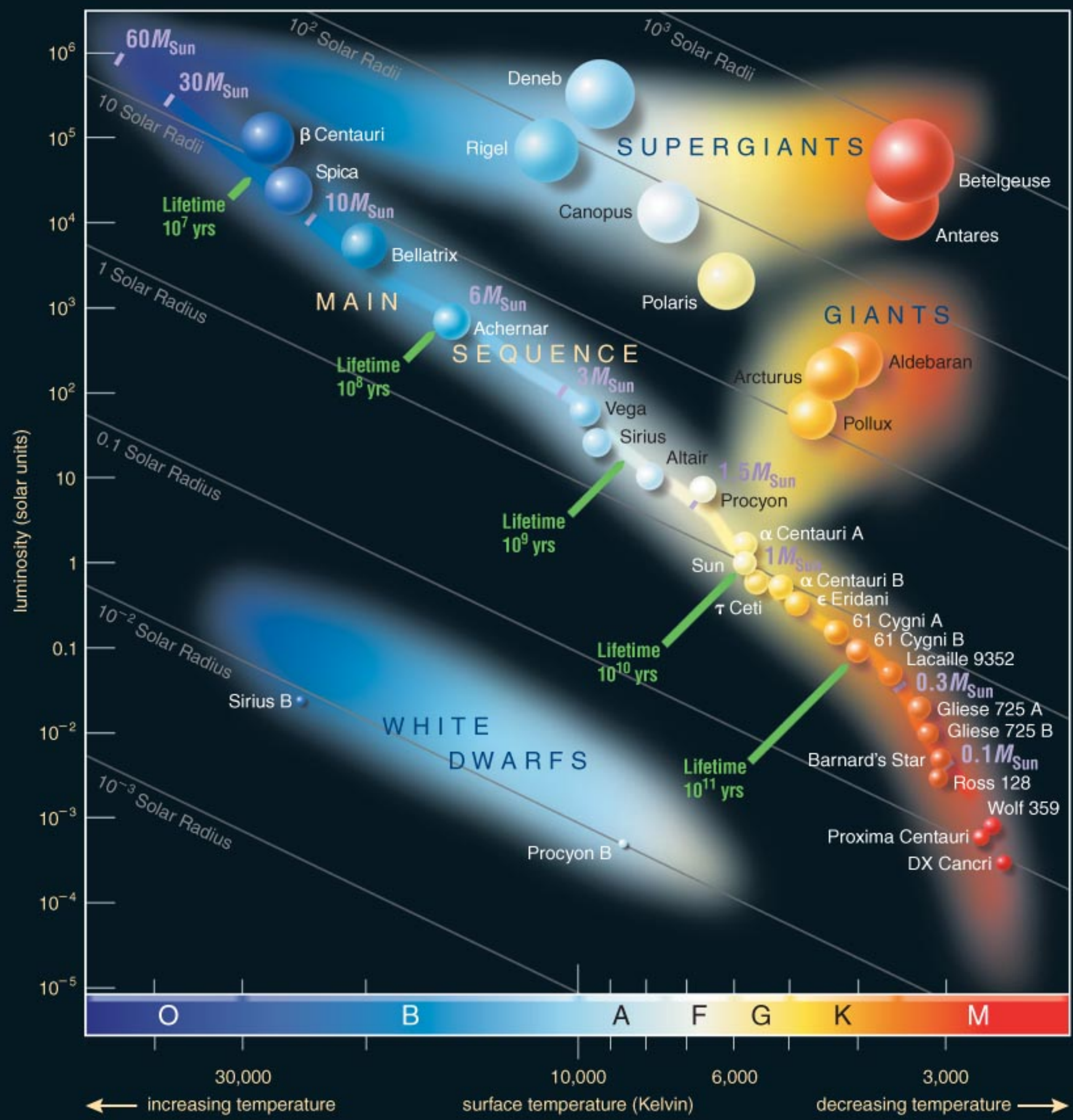
- Main Sequence Turnoff
- White Dwarf Cooling

Individual

Difficult to do for all stars, except the Sun (4.57±0.02 Gyr)

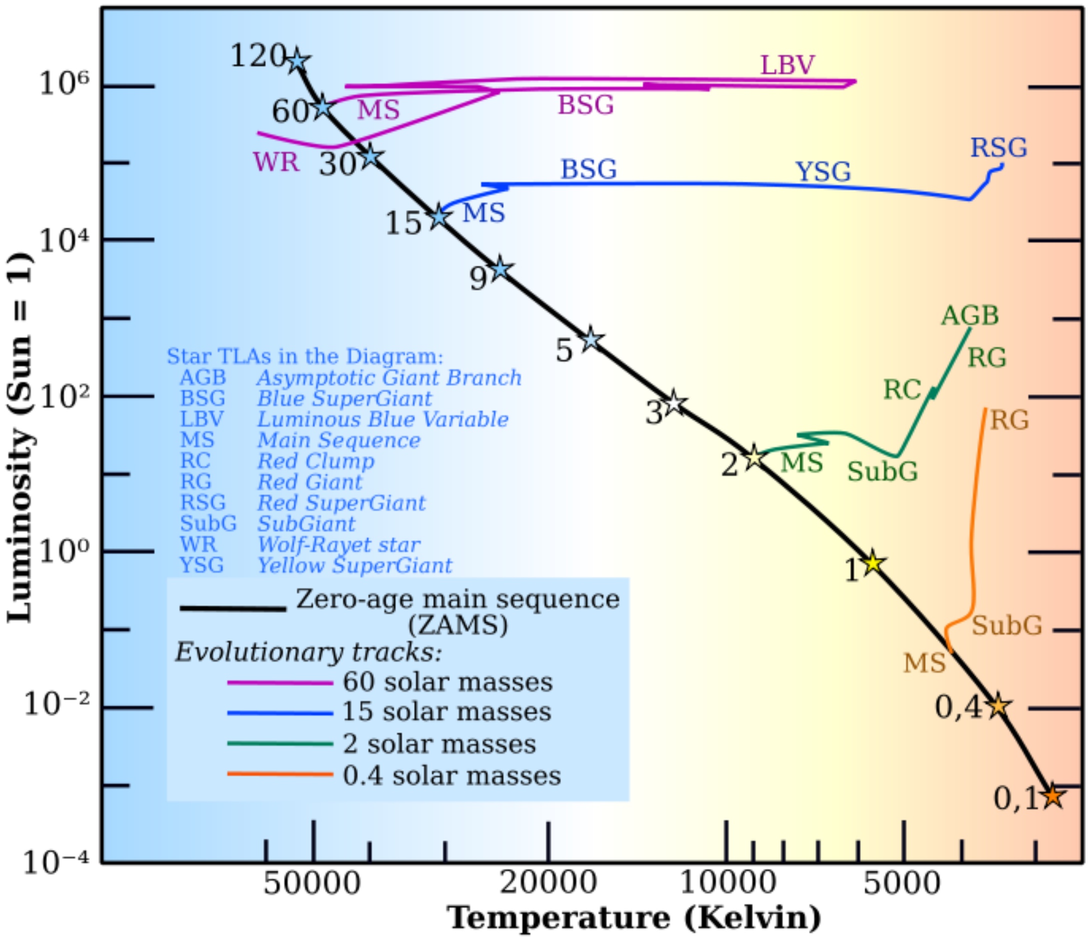
- Nucleo-Cosmochronology
  - Beryllium measurements
  - Radioactive dating
- Gyrochronology
- Asteroseismology (the best of all!)

H-R diagram



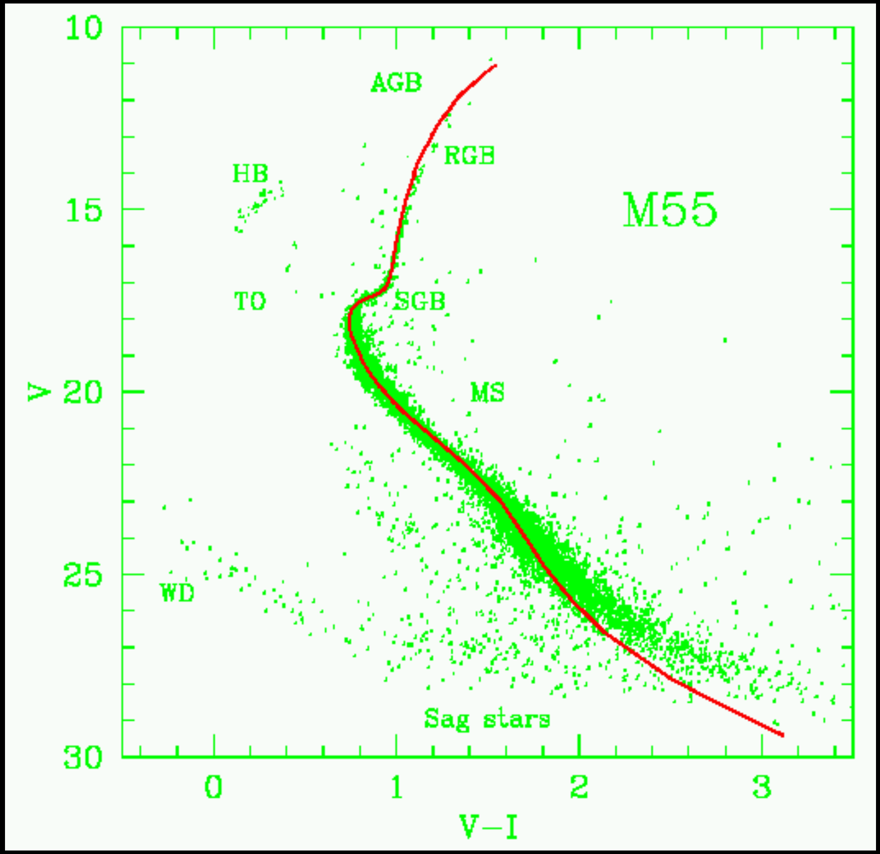
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
10^-5
60 M Sun
30 M Sun
10 M Sun
6 M Sun
3 M Sun
1.5 M Sun
1 M Sun
0.3 M Sun
0.1 M Sun
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^-2 Solar Radius
10^-3 Solar Radius
Deneb
Rigel
SUPERGIANTS
Betelgeuse
Antares
Canopus
Polaris
β Centauri
Spica
Bellatrix
Achernar
MAIN
SEQUENCE
GIANTS
Aldebaran
Arcturus
Pollux
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^10 yrs
Lifetime 10^11 yrs
Vega
Sirius
Altair
Procyon
α Centauri A
Sun
α Centauri B
ε Eridani
τ Ceti
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
WHITE
DWARFS
Procyon B
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

How far removed from the zero age main sequence?



This is much easier to do for a star **cluster** cf. to a single star

Determining the Age of M55



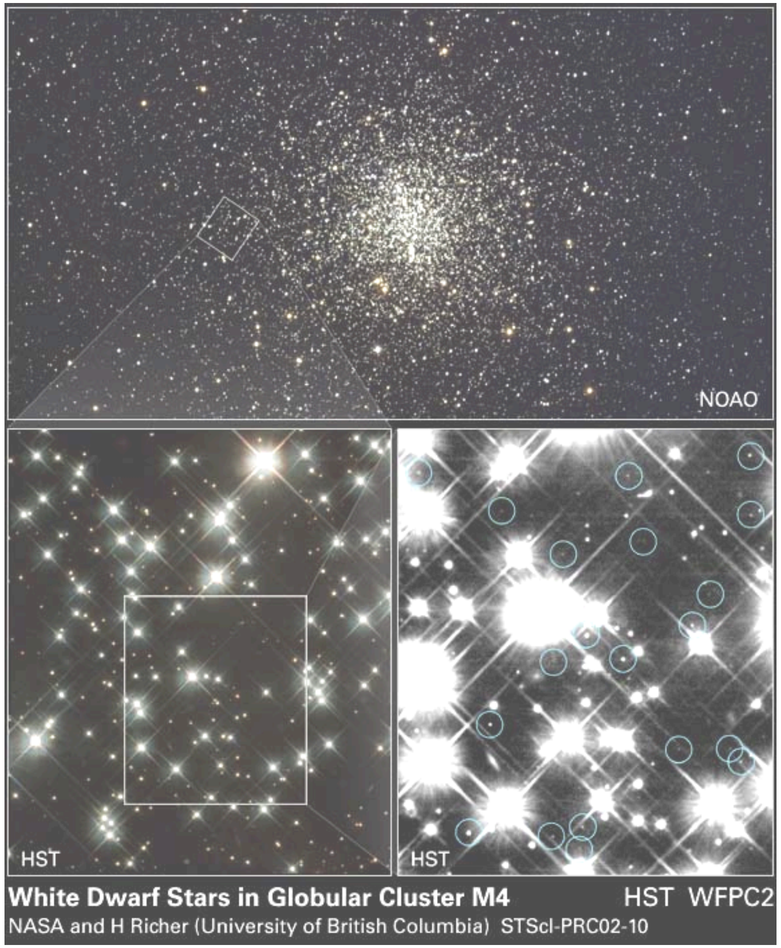
Isochrone: **14 Gyr**; Z = 0.0004, i.e., [Fe/H] = −1.5

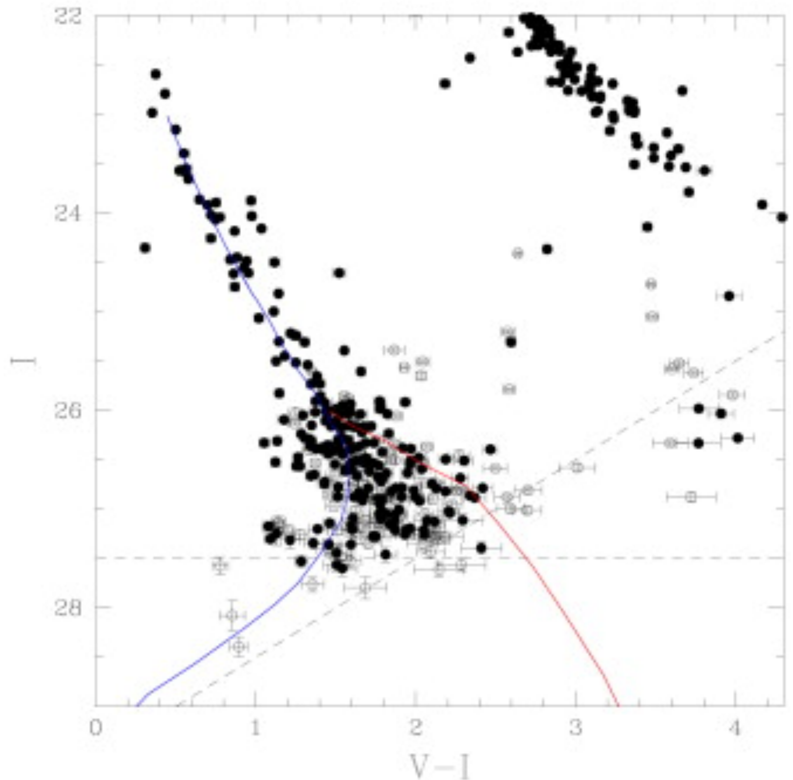
White Dwarf Cooling as a Chronometer

Basic idea:

- Take as deep an image of a globular cluster as possible.
- Identify and measure the luminosities of the **dimmest** white dwarfs.
- Compare with theoretical cooling sequences of white dwarfs.

White Dwarfs in M4

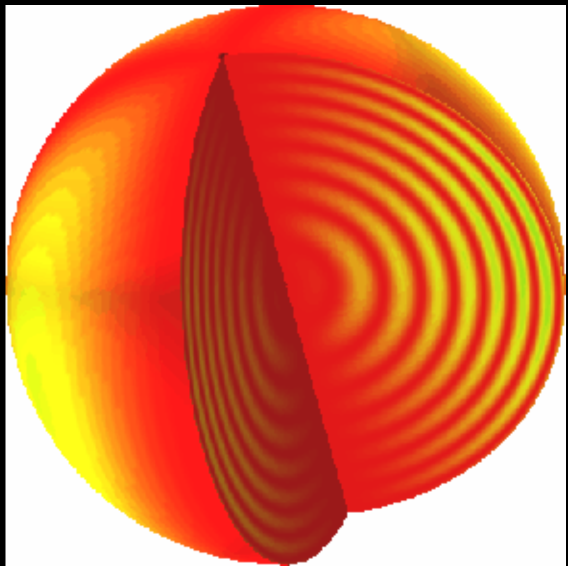


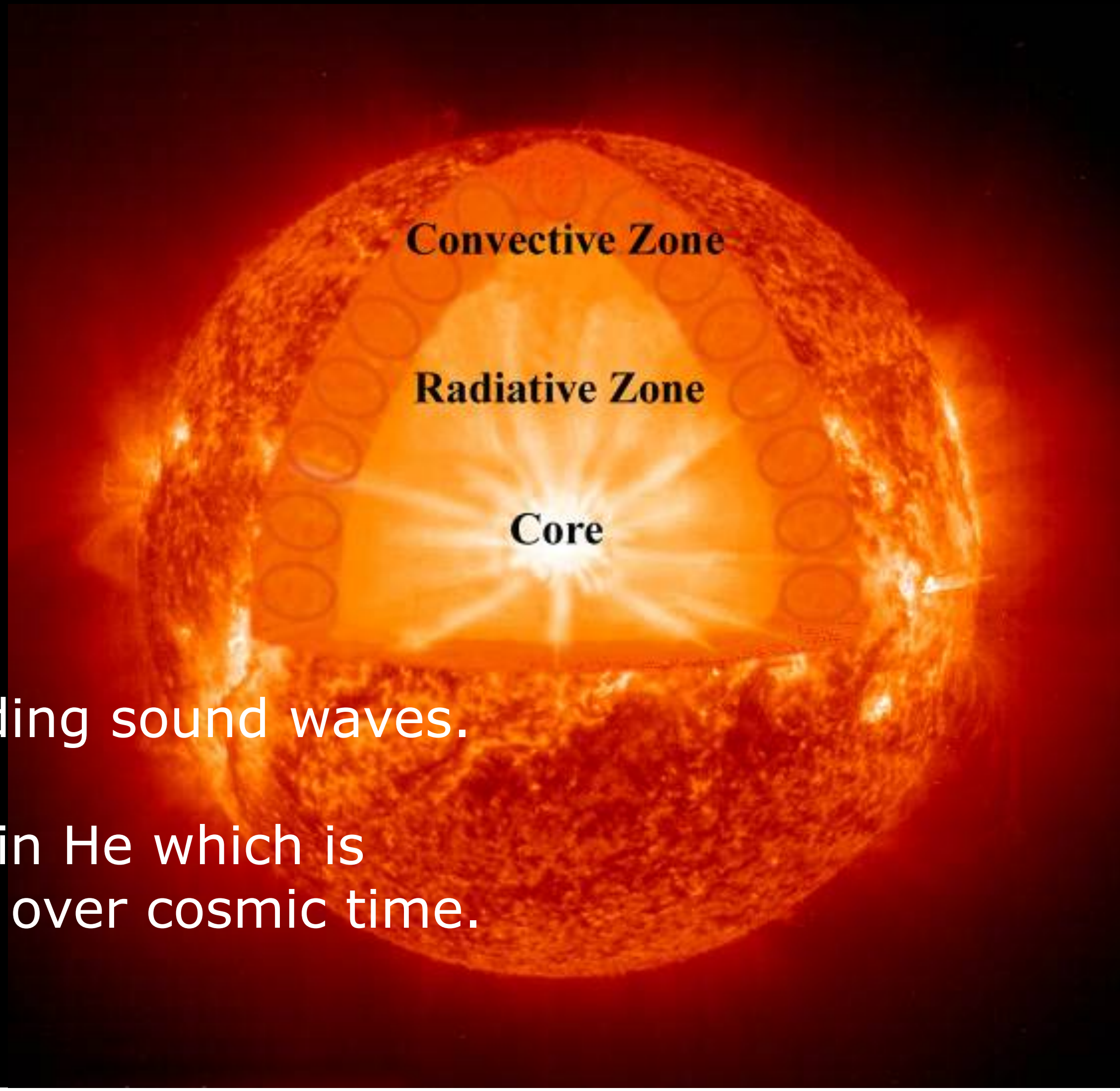


Estimated age: 12.7 ± 0.7 Gyr

Hansen et al. (2002)

Asteroseismology

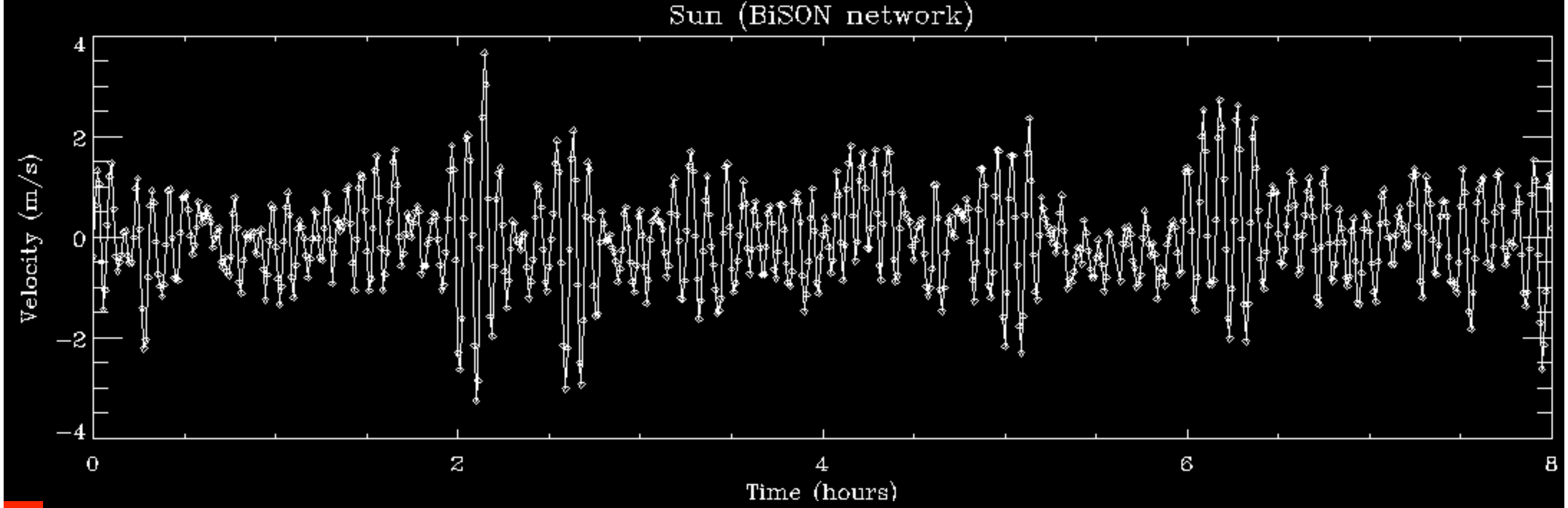




Oscillations are standing sound waves.

Sound travels faster in He which is
being slowly cooked over cosmic time.

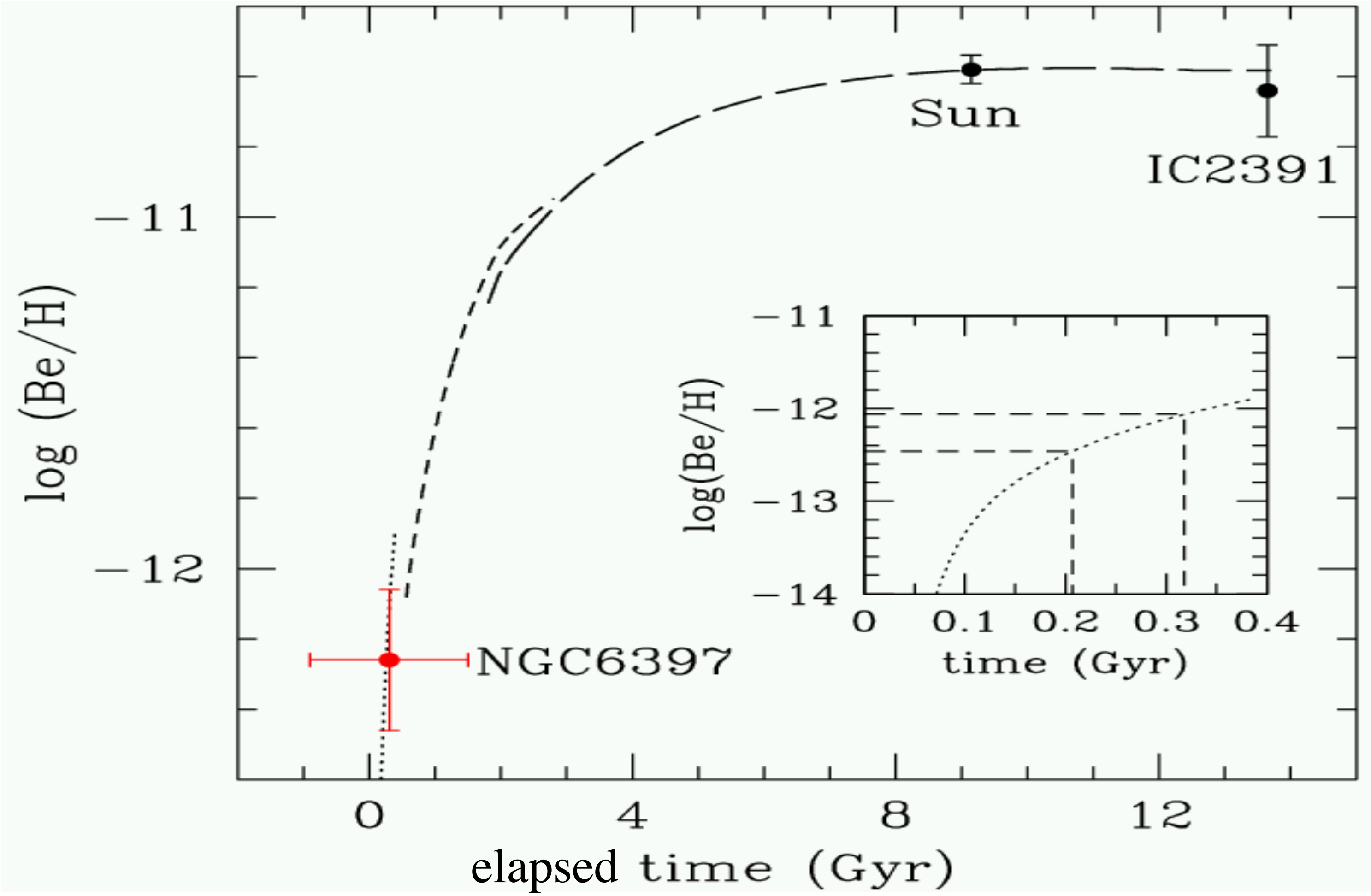
Doppler velocities of the Sun



Beryllium as a Chronometer

- Be is **uniquely** produced by cosmic ray spallation of CNO-nuclei in the ISM.
- Galactic cosmic rays (GCRs) are high-energy particles (H, He, C, N, O) accelerated to near-light speeds in supernova shocks.
- Global, ”instantaneous” spreading of GCRs ⇒ homogeneous distribution of Be in the Galaxy at any given time.
- **Abundance of Be in stars determines their age.**

The "Be age" of NGC 6397



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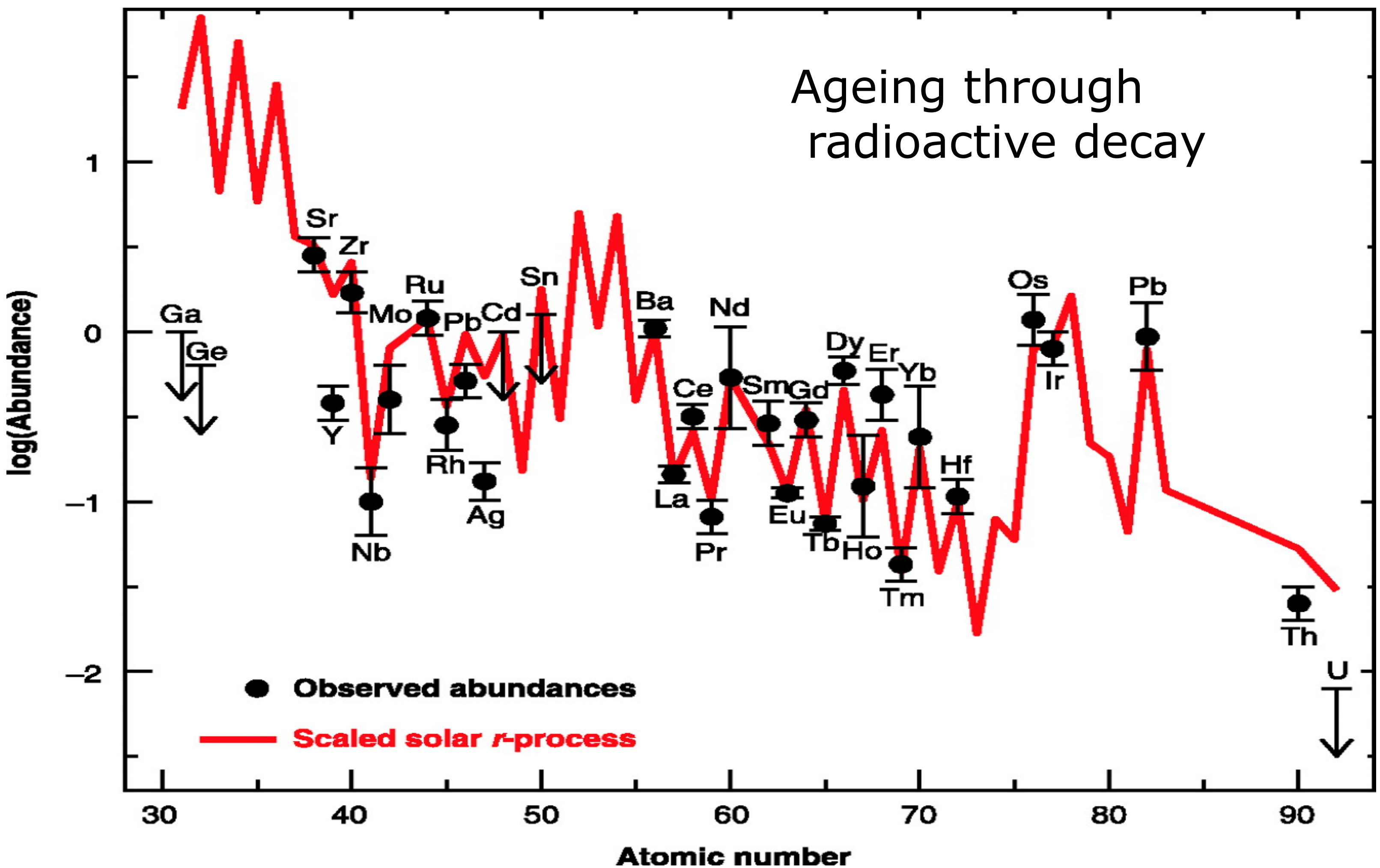


The U/Th-ratio as a Chronometer

For the radioactive decay of U and Th, we have

$$n_U(\Delta T) = n_U(0) \times 2^{-\Delta T/\tau_U},$$

and

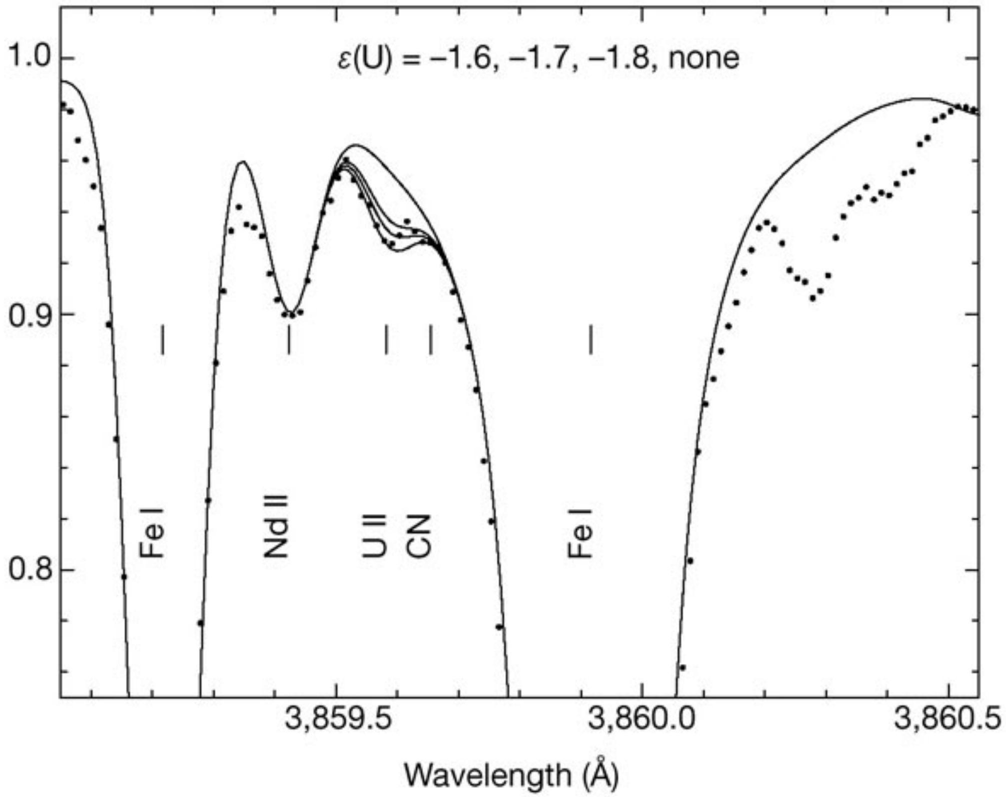
$$n_{Th}(\Delta T) = n_{Th}(0) \times 2^{-\Delta T/\tau_{Th}}.$$

Thus, taking the ratio $n_U(\Delta T)/n_{Th}(\Delta T) \equiv (U/Th)_{obs}$

$$\Delta T = 21.8\left[\log(U/Th)_0 - \log(U/Th)_{obs}\right] Gyr$$

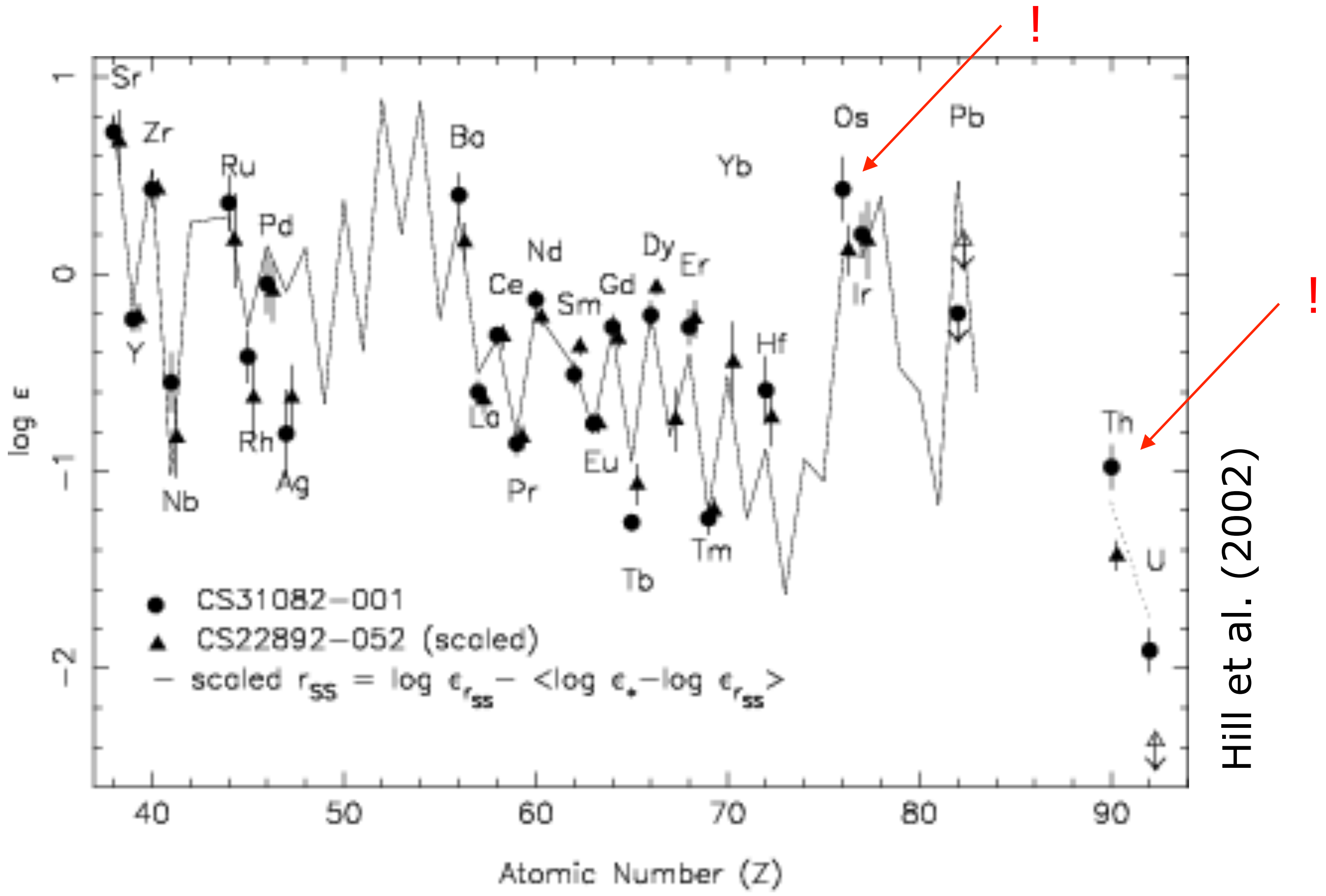
CS 31082-001: we just barely detect Uranium

(Cayrel et al. 2001, Nature 409, 691; Hill et al. 2002, A&A 387, 560)



This gives us an age based on **radioactivity** over the past 13 Gyr!

The abundance pattern of CS 31082-001

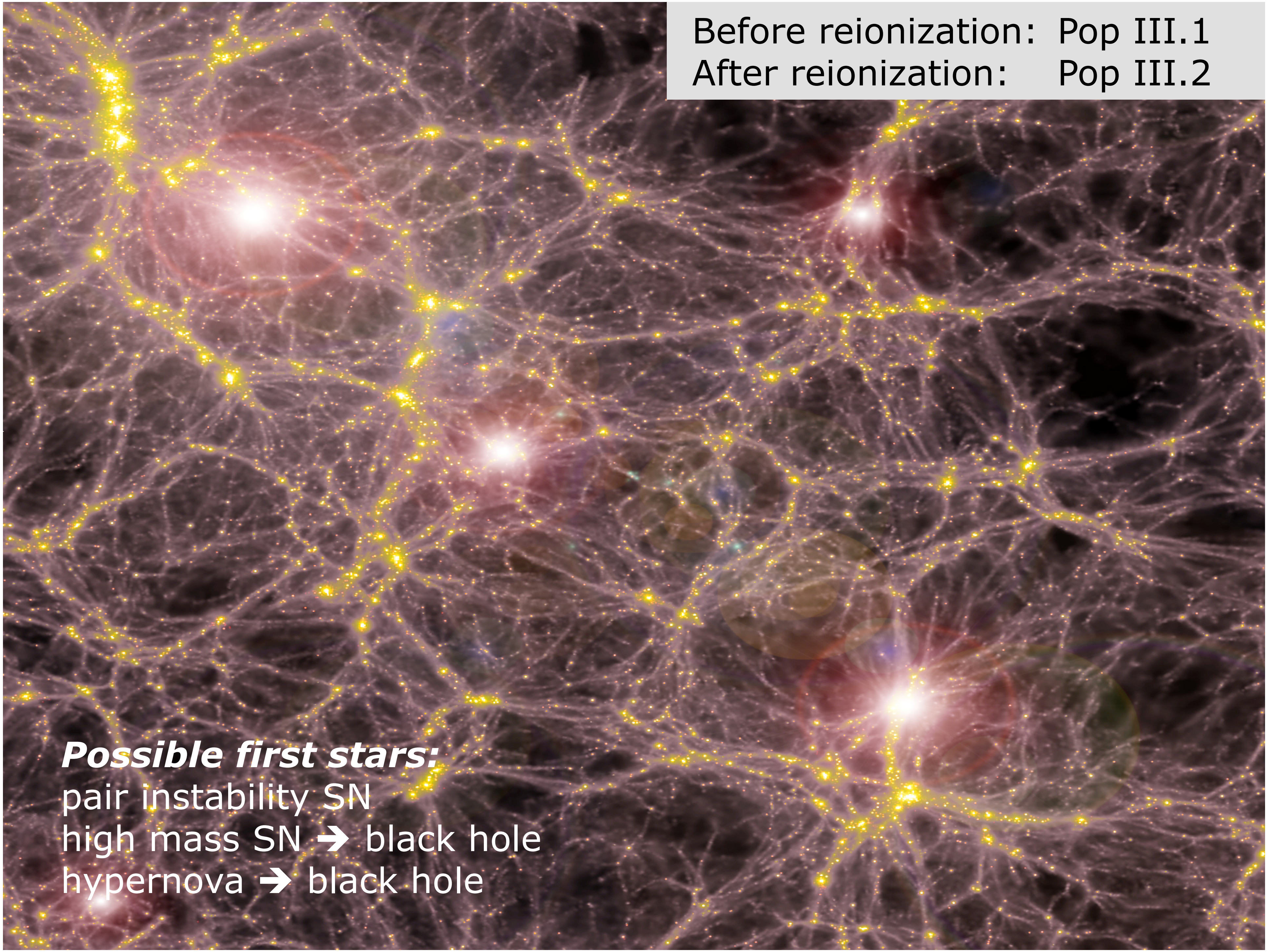


Hill et al. (2002)

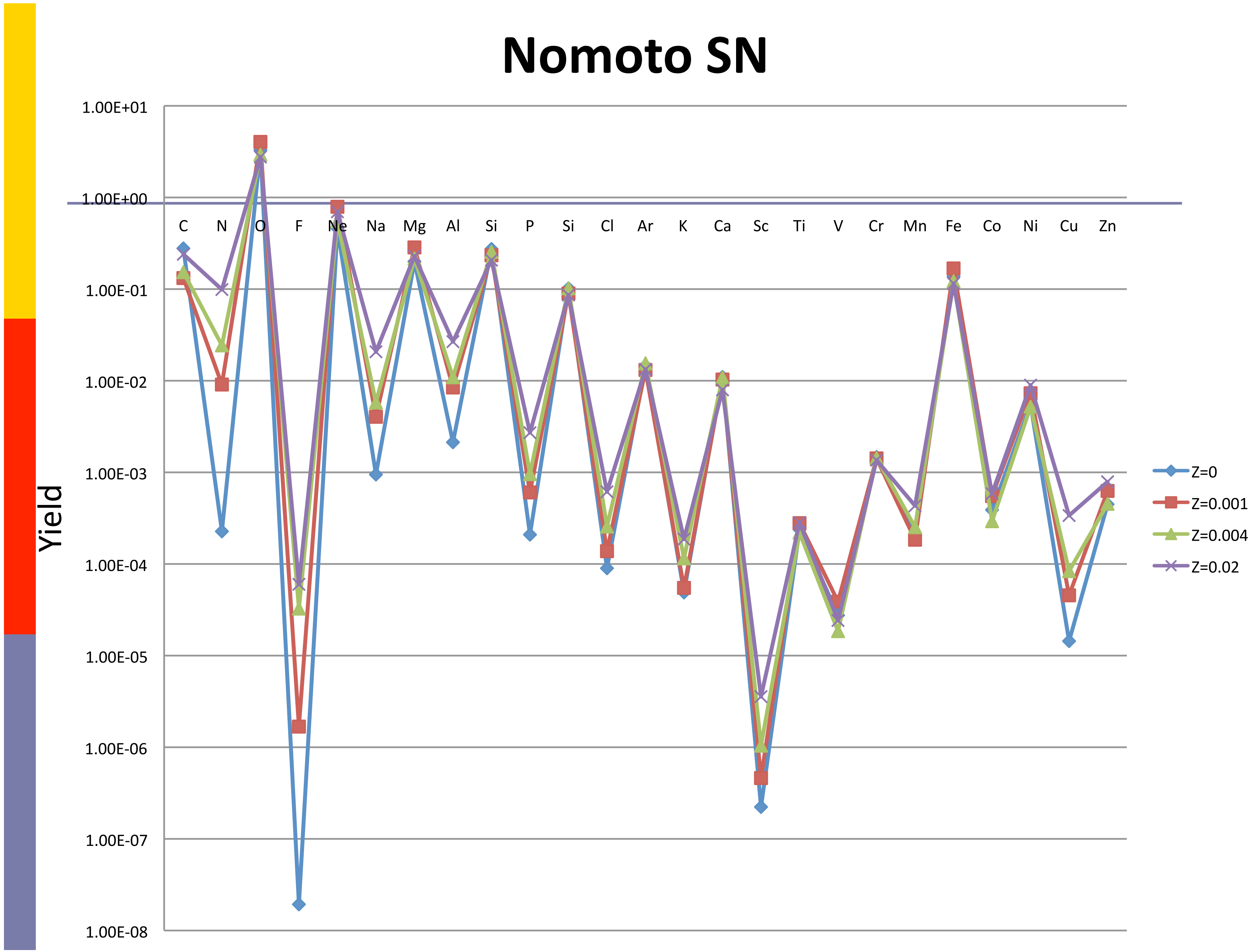
Lower Limits to the Age of the Universe

- Globular clusters
  - Main-sequence turnoff in GCs: 12.6 ± 1.8 Gyr.
  - White Dwarf cooling sequence in M4: 12.7 ± 0.7 Gyr.
- Extremely metal-poor stars
  - Beryllium abundance in NGC 6397: 13.2 ± 0.06 Gyr.
  - U/Th-ratio in CS 31082-001: 14.0 ± 2.4 Gyr.
  - U/Th-ratio in BD +17º3248: 13.8 ± 4 Gyr.
- **Cf. WMAP: 13.7 ± 0.2 Gyr.**

What were the first stars like?

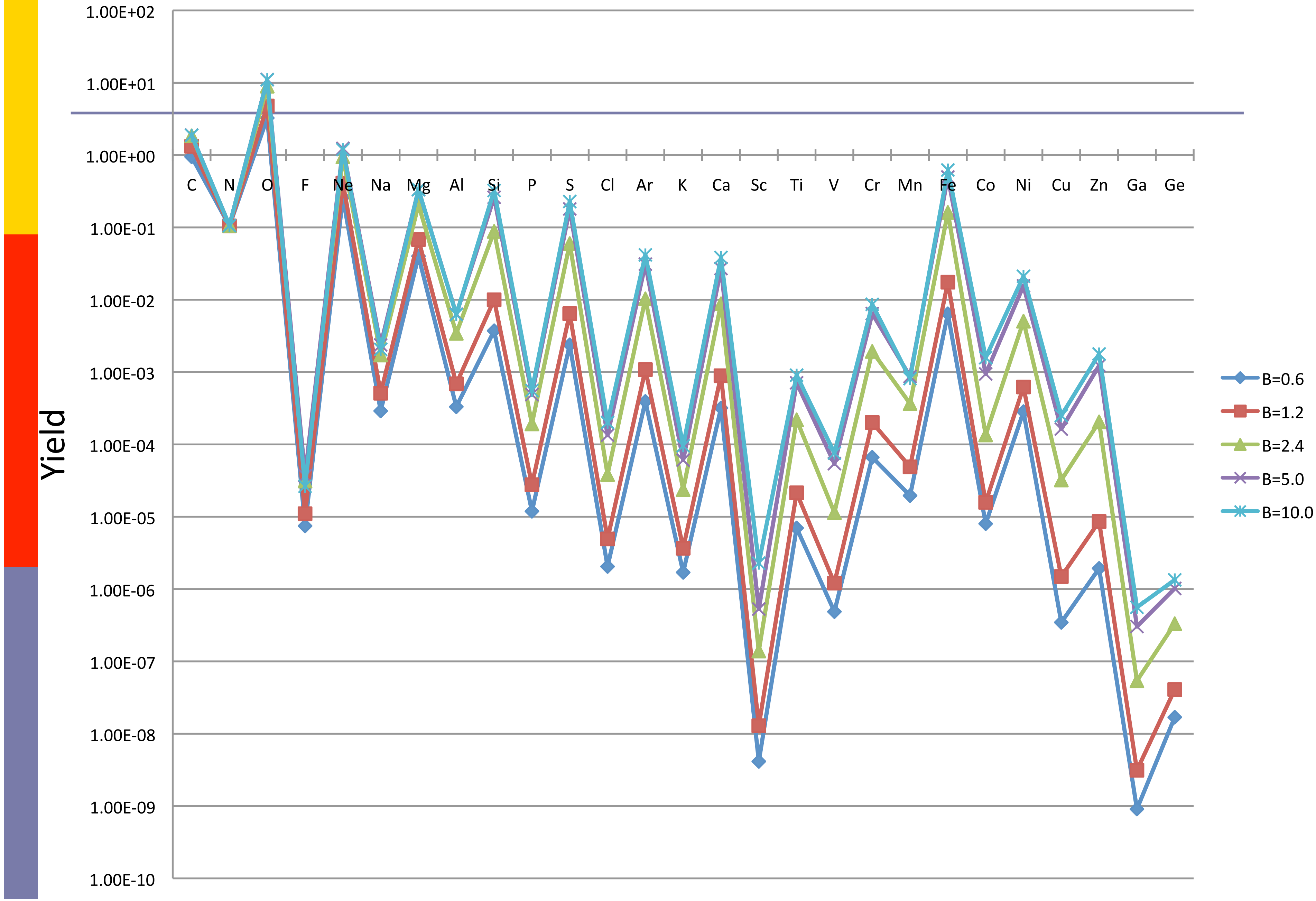

Before reionization: Pop III.1
After reionization: Pop III.2
Possible first stars:
pair instability SN
high mass SN ➔ black hole
hypernova ➔ black hole

Nomoto SN

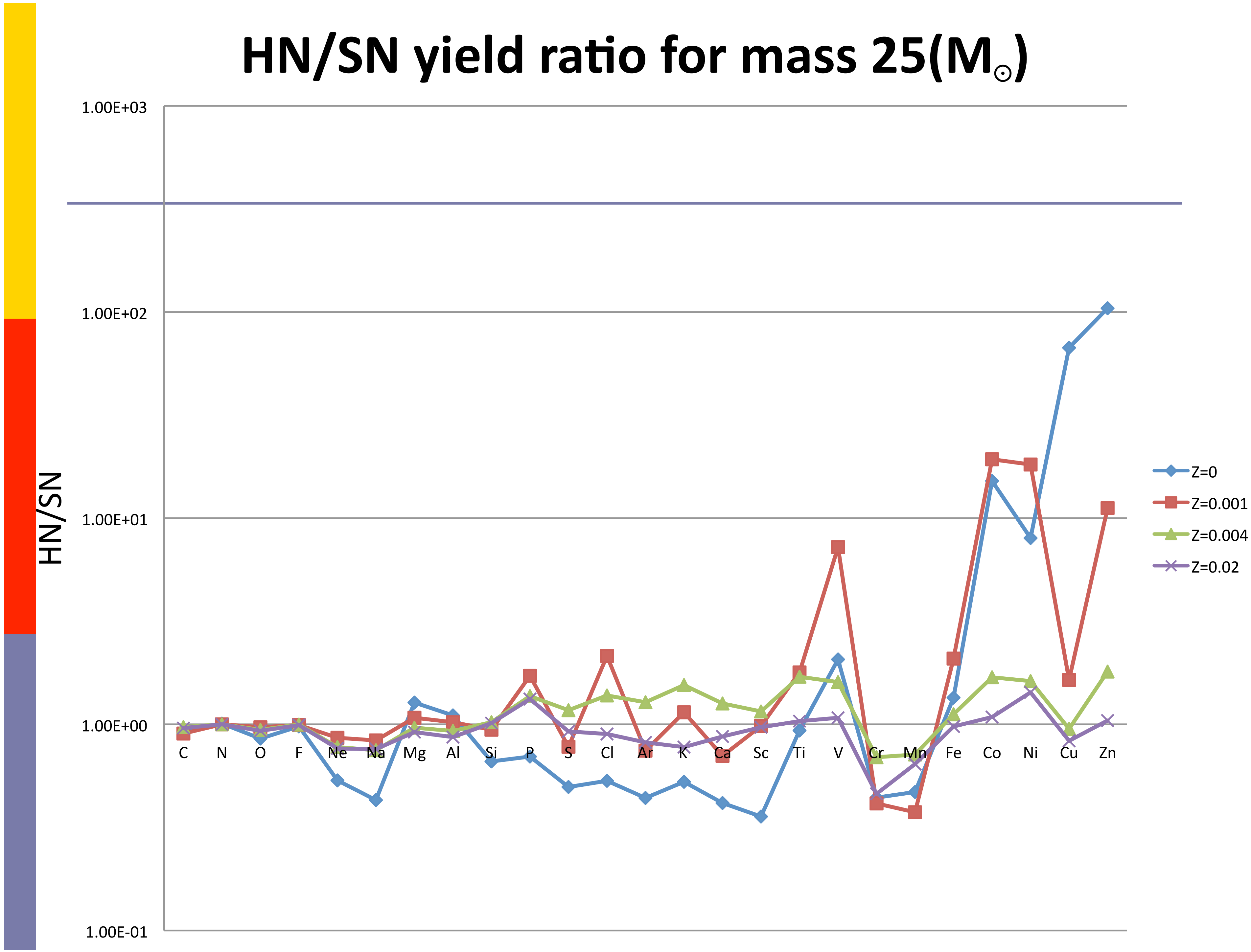


Yield
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
C
N
O
F
Ne
Na
Mg
Al
Si
P
Si
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Z=0
Z=0.001
Z=0.004
Z=0.02

Woosley Explosion Energy Effects

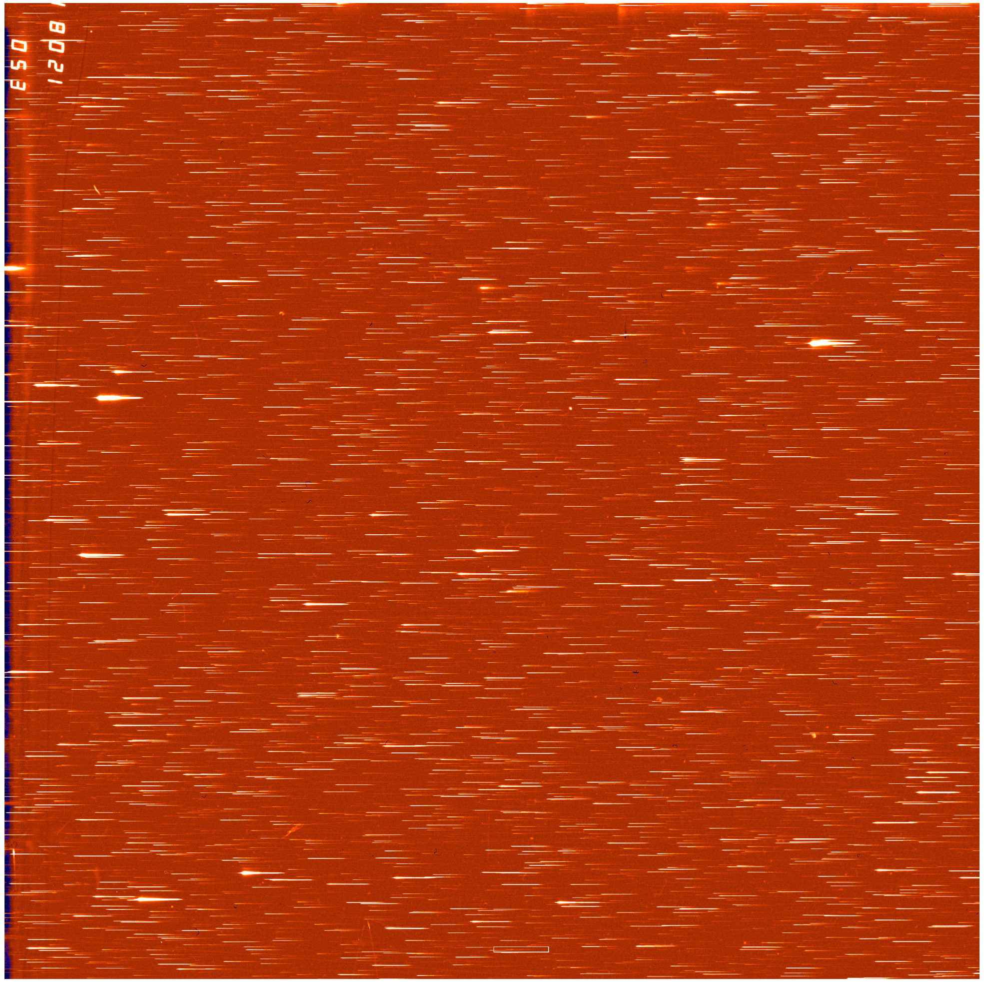


HN/SN yield ratio for mass 25($M_\odot$)



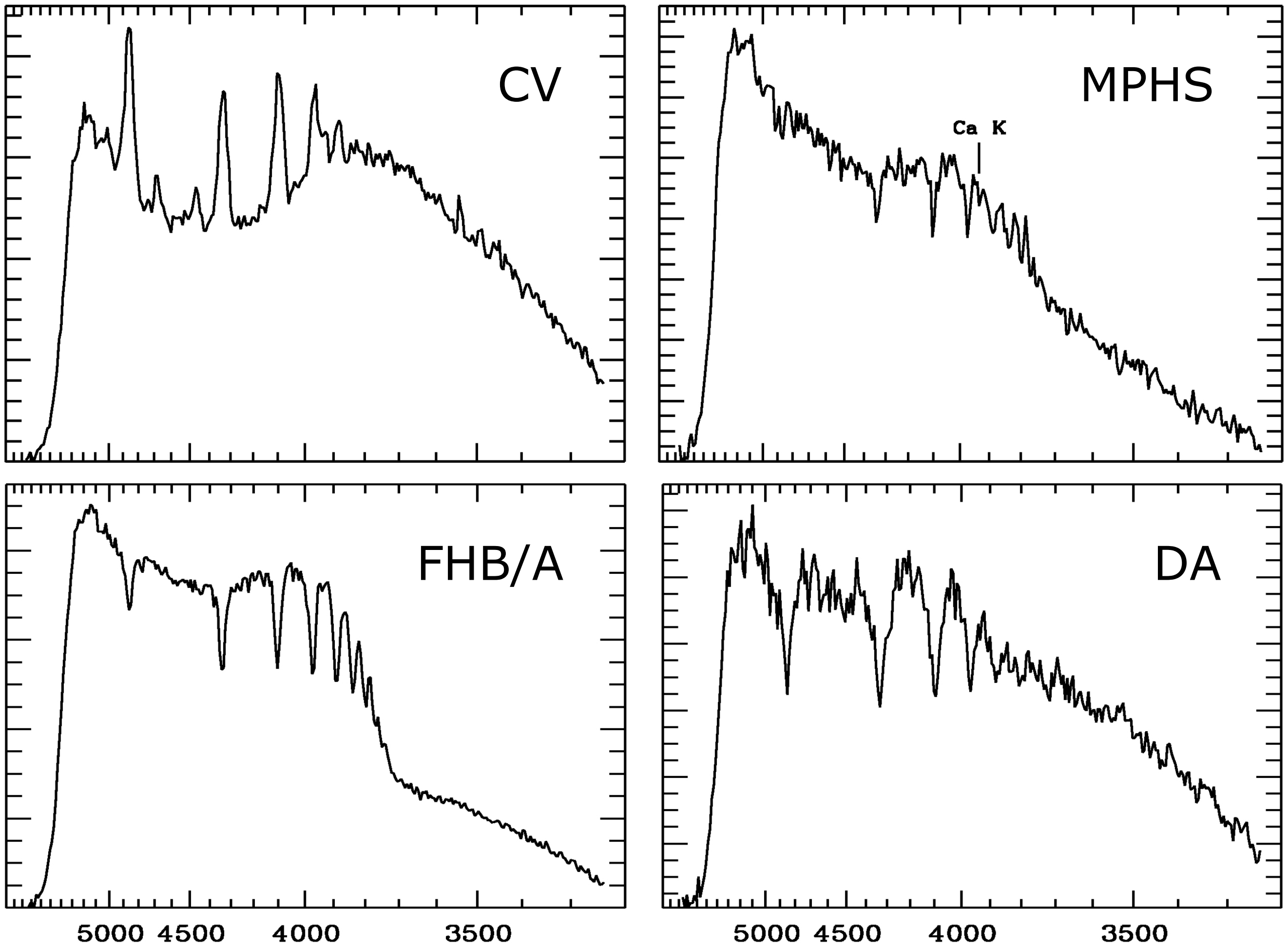
How to find the most ancient stars?

A scanned HES plate

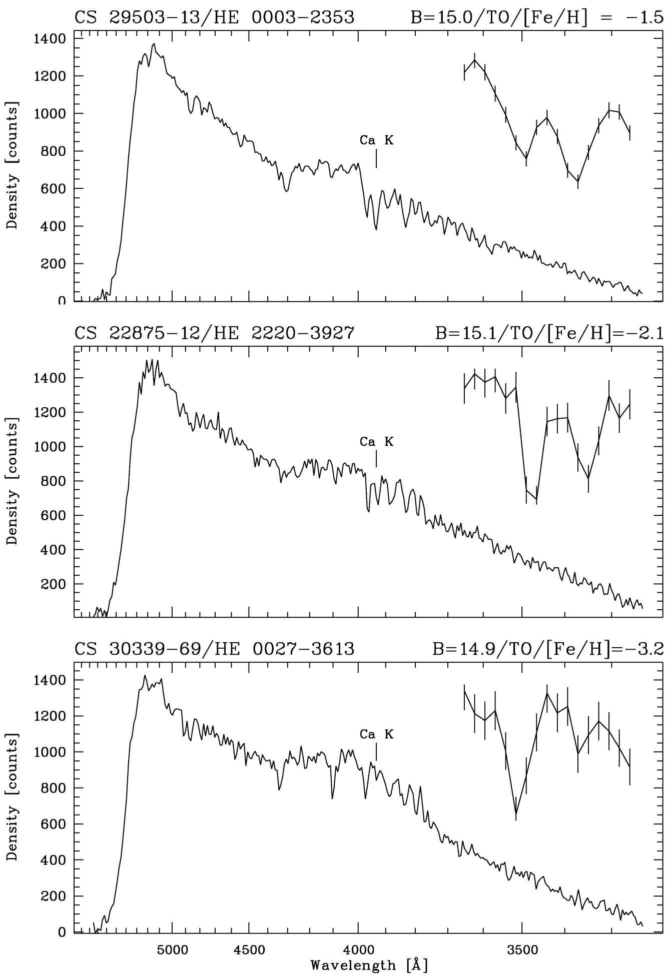


- 5 x 5 deg on the sky
- Mag. range: approx. $12 < B_J < 17.5$ (but depending on plate quality; i.e., background, seeing)
- On average 10,000 objects (but strongly depending on galactic latitude *b*)
- Kodak IIIa-J emulsion => 3200-5300Å
- Spectral resolution typically 10Å at Ca K (but depending on seeing)

Extracted HES spectra



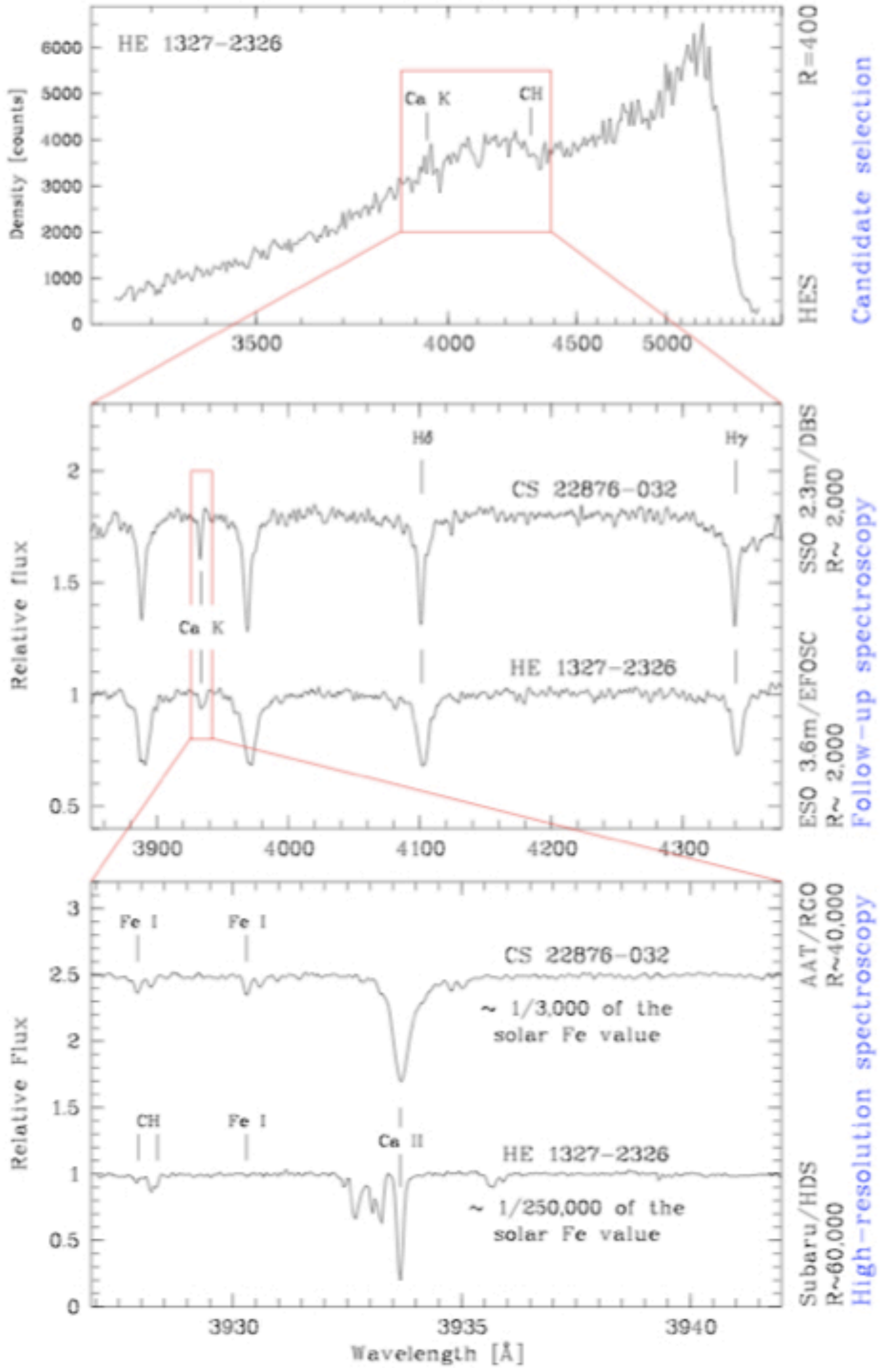
HES spectra of metal-poor stars



These are *candidates*, which need confirmation by moderate-resolution follow-up spectroscopy.

A large survey is required that provides low-resolution spectra to search for metal-poor stars. Those spectra need to cover the strong calcium absorption (Ca II K) line at 3933 A. The strength of this line indicates the metal-deficiency of the star. If the line is sufficiently weak, an object is selected as a candidate metal-poor star. For my work, I have used the Hamburg/ESO survey.

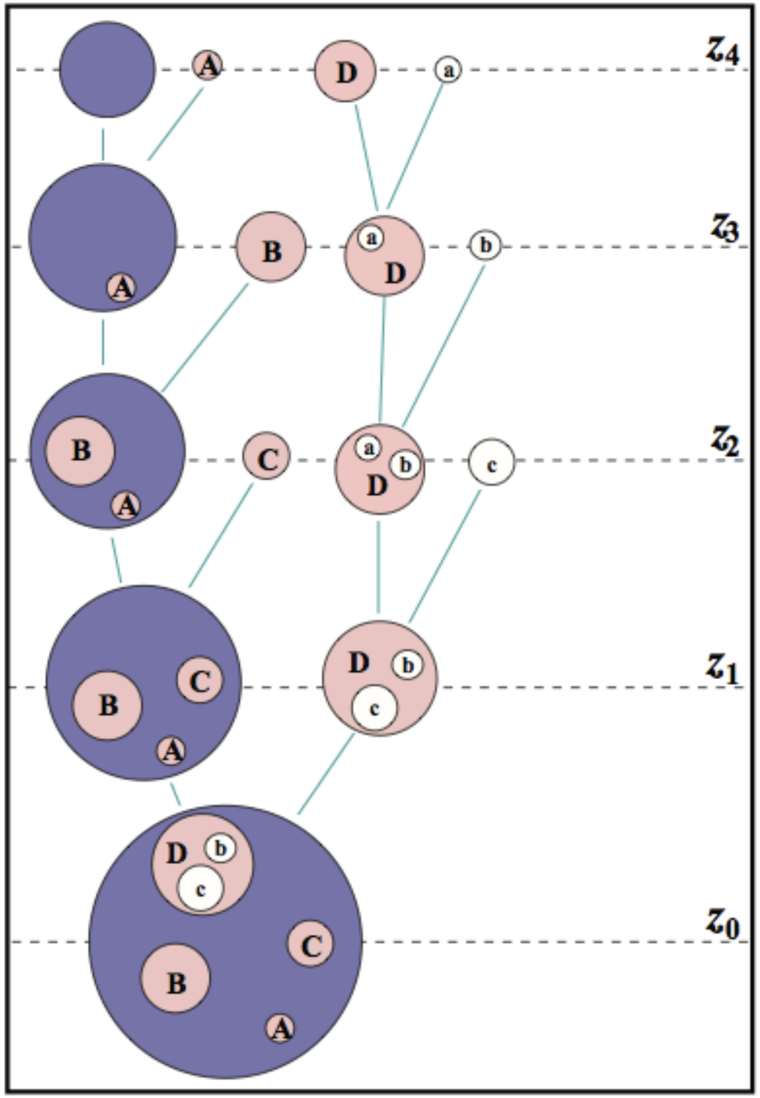
For all the candidates, medium-resolution spectra are required to get a better information of the Ca II K line strength. This line is the best indicator for the overall metallicity of the star in such spectra, and provides good estimates of the iron (Fe) abundance. The Fe abundance is commonly used to trace the overall metallicity.



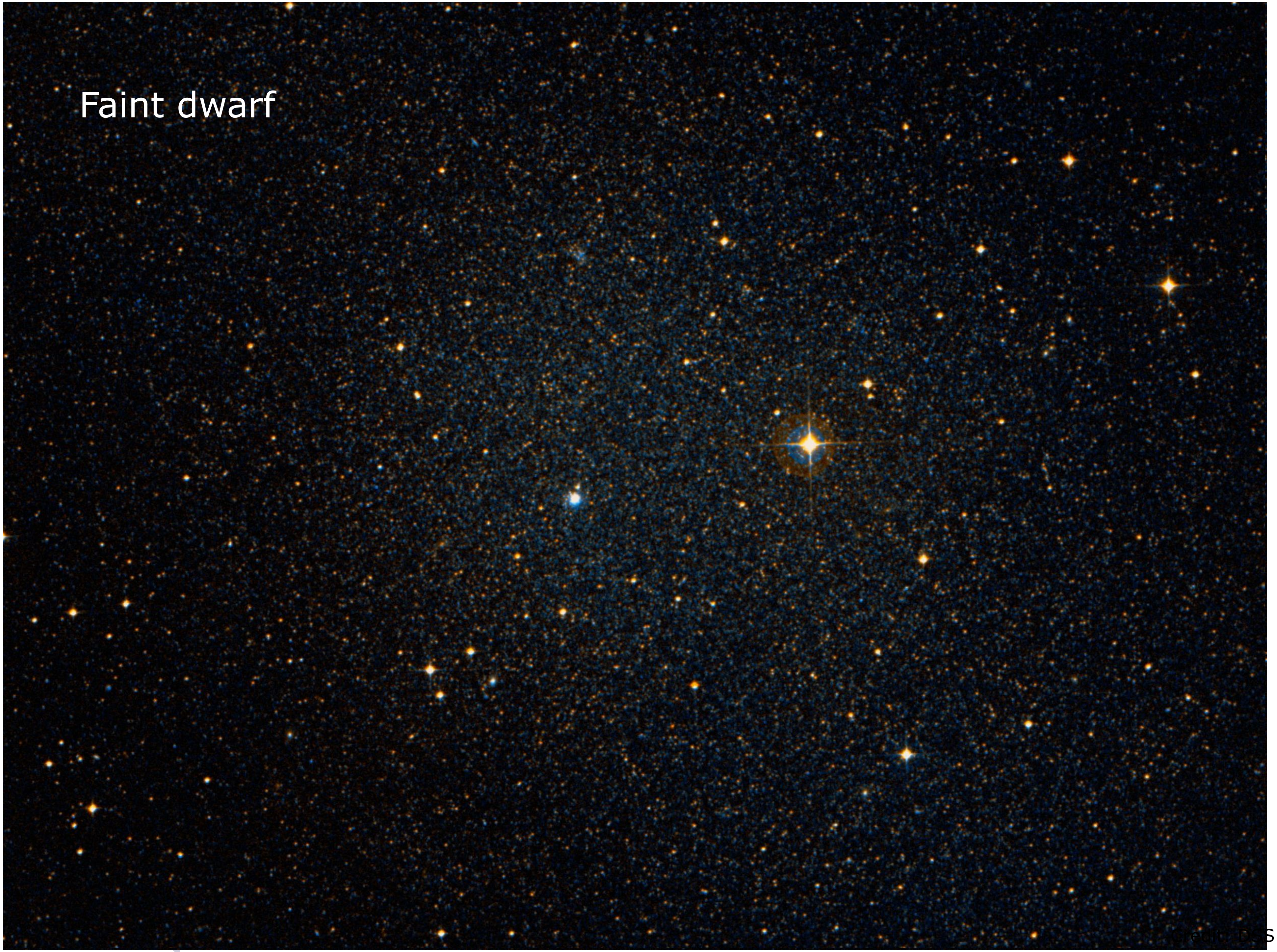
Where do we look for these gems?

The standard paradigm might suggest galaxy nuclei, but these stars would occur at **all** [Fe/H]

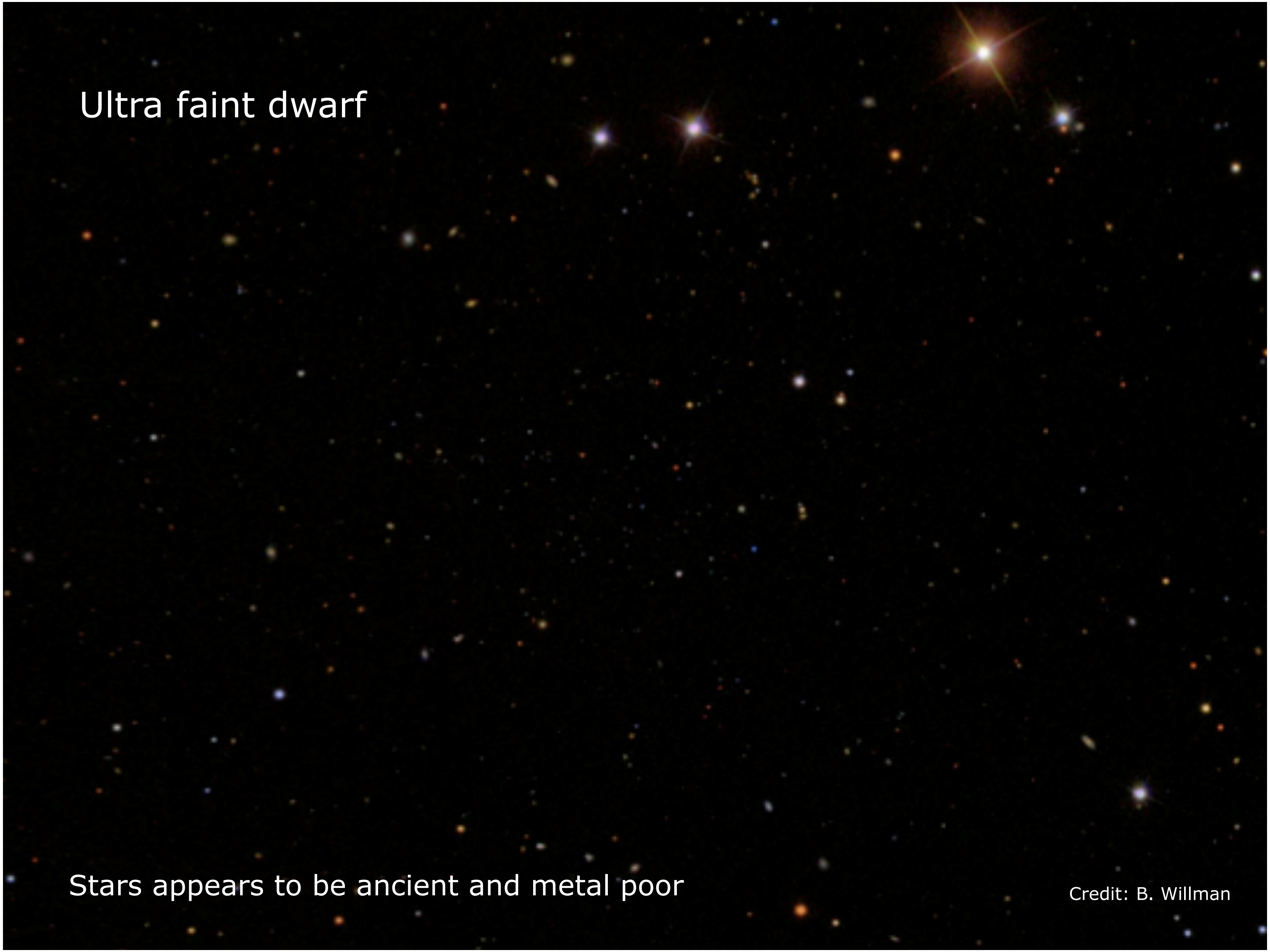
A new paradigm is **ultra faint dwarf galaxies**...




Luminous dwarf
Credit: NOAO



Credit: DSS


Ultra faint dwarf
Stars appears to be ancient and metal poor
Credit: B. Willman

Outlook and conclusions

A new place to look – ultrafaint dwarfs

(Karlsson, Bromm & Bland-Hawthorn 2011,
Reviews of Modern Physics)

THE END