The Oldest Stars in our Galaxy

or

A little tale of HE 1327-2326 & HE 1523-0901

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Why bother?

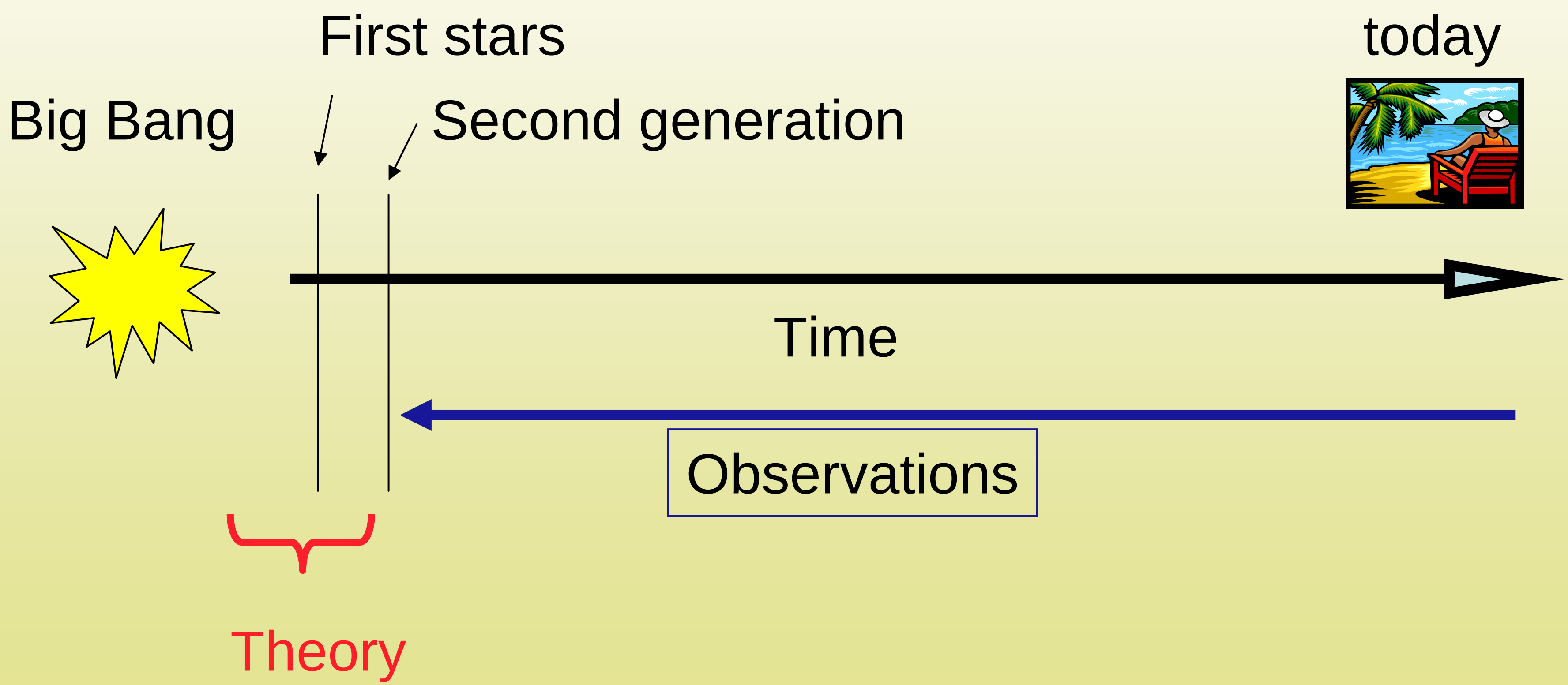
Metal-poor stars are “fossils” of the early Universe

We can learn about the formation of the elements and nucleosynthesis processes, and how the Universe became enriched with heavy elements

Metal-poor stars are ideal tracers of the chemical evolution of the Galaxy

They allow us to investigate how the first objects formed after the Big Bang (“closest relatives”)

Cosmic timeline



HE 1327-2326

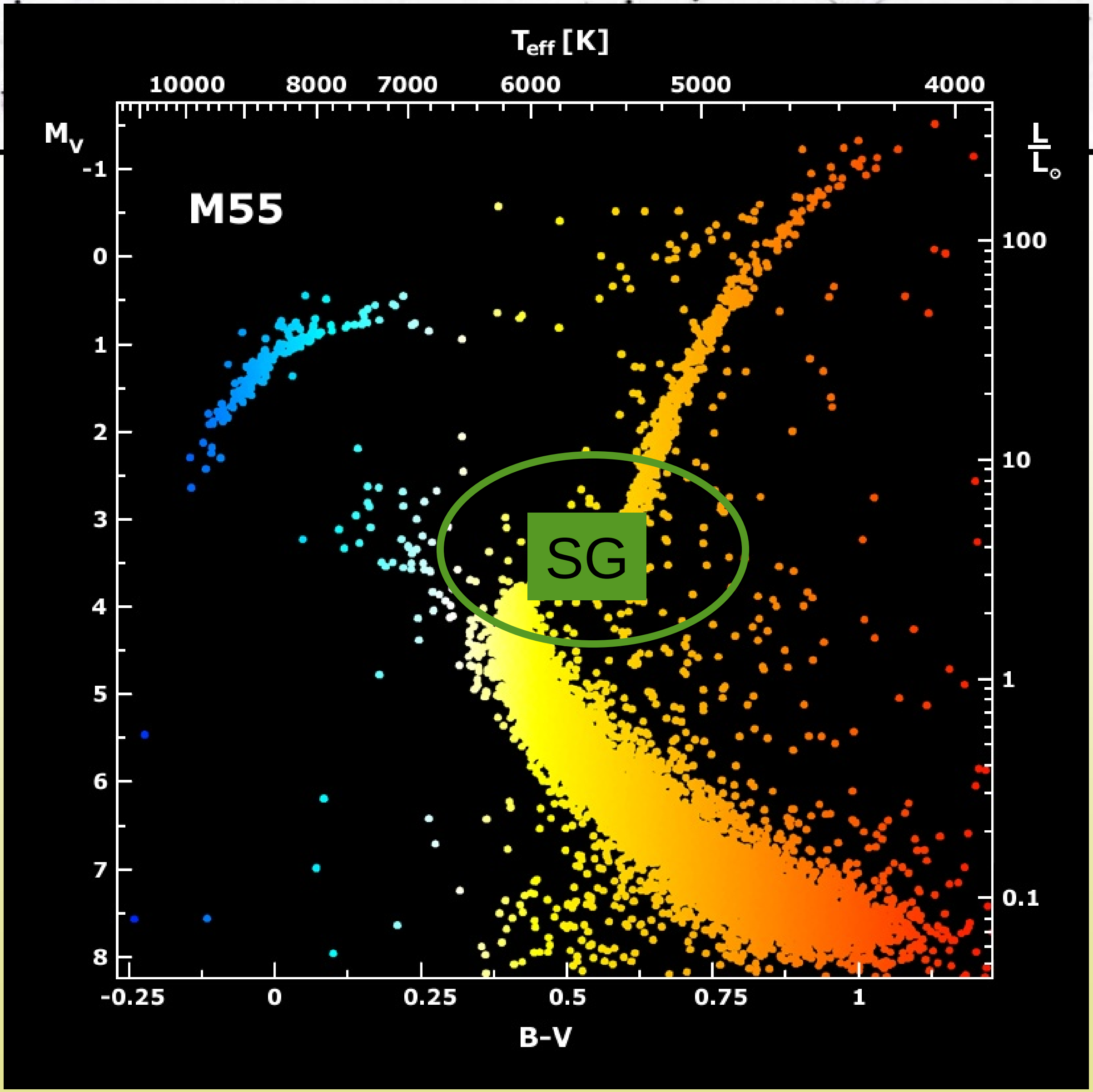
Basic and stellar parameters:

DSS

- Magnitude: B = 14.016 mag
- Colour: $(B-V)_0 = 0.40$ mag
- Reddening: $E(B-V) = 0.06 - 0.096$

- *BVRIK* photometry: $T_{\mathrm{eff}} = 6180 \pm 80$K (on Alonso et al. 1996 scale)
- Proper motion is μ = 0.0733 arcsec/yr
  => $M_V > 3.2$
  => surface gravity: log g = 3.7 (subgiant)
- Metallicity: [Fe/H] = -5.4

- Discovery spectrum: from the Subaru telescope (7 h)
- New near-UV spectrum from ESO/VLT (21 h)

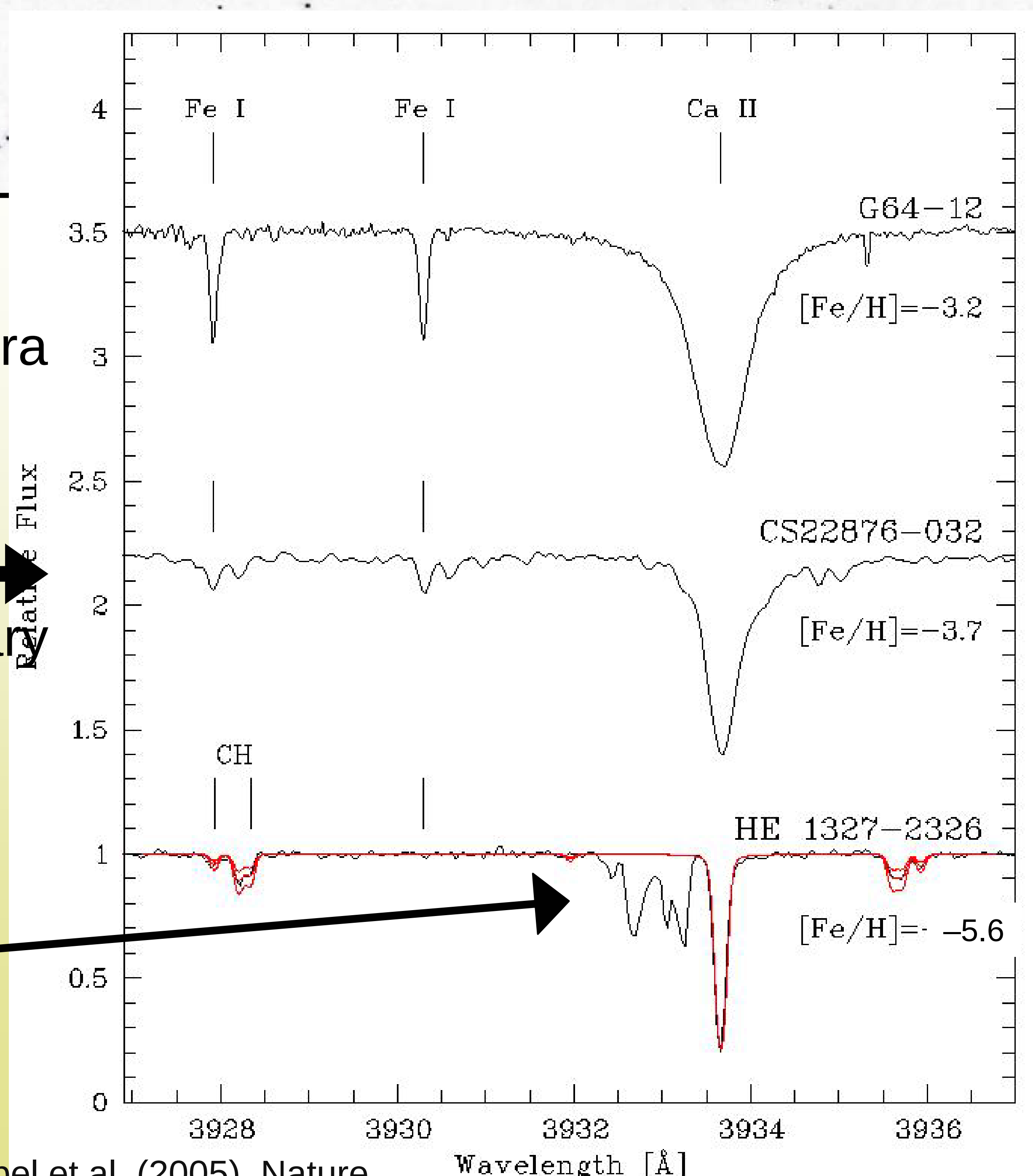

M55
T_{eff} [K]
10000
8000
7000
6000
5000
4000
M_V
-1
0
1
2
3
4
5
6
7
8
$\frac{L}{L_\odot}$
100
10
1
0.1
SG
-0.25
0
0.25
0.5
0.75
1
B-V

CaK line

High-resolution **Subaru/HDS** spectra (taken by W. Aoki)

Double lined spectroscopic binary

Interstellar Ca



Frebel et al. (2005), Nature

The oldest Stars

JINA Frontiers

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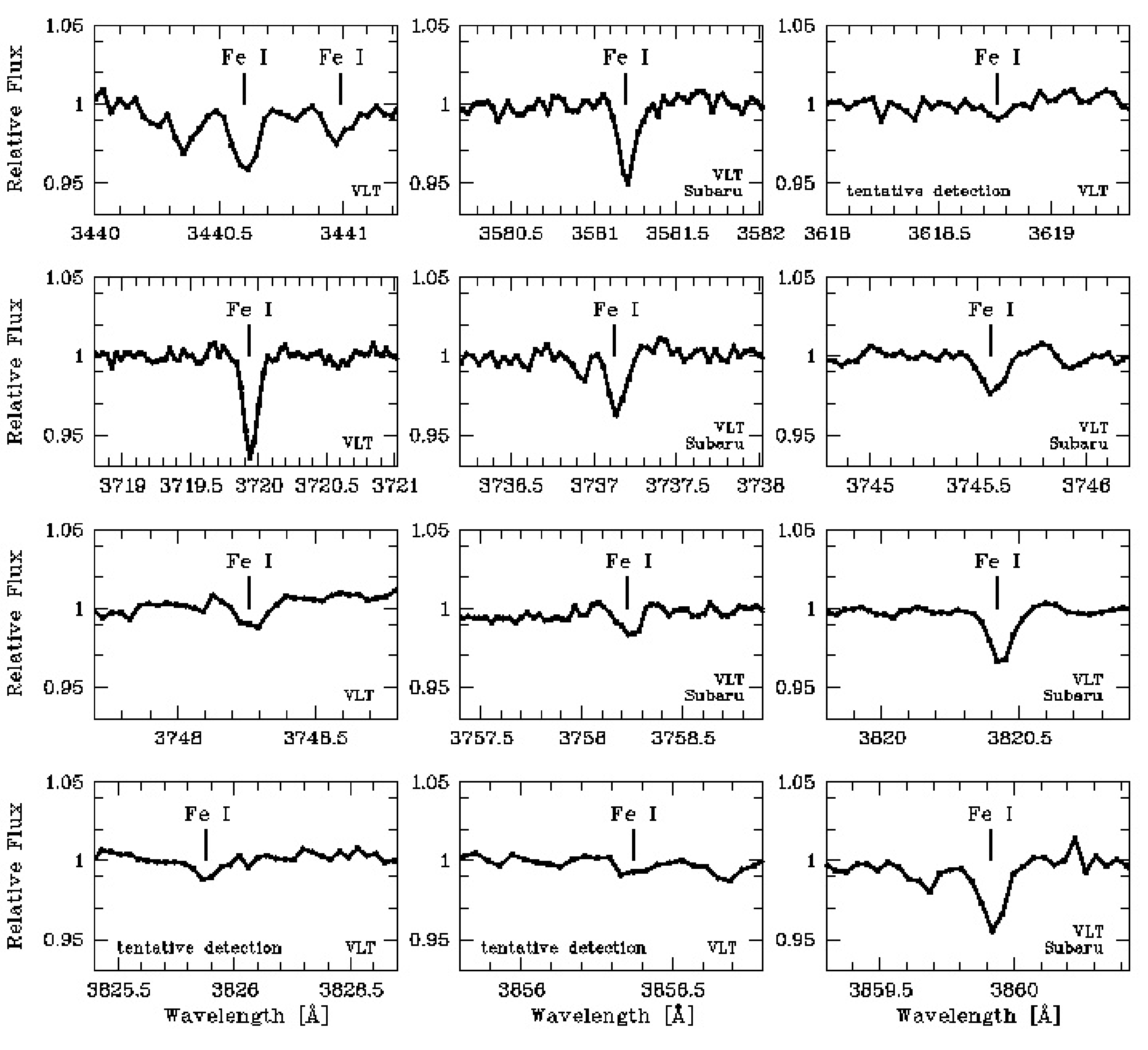
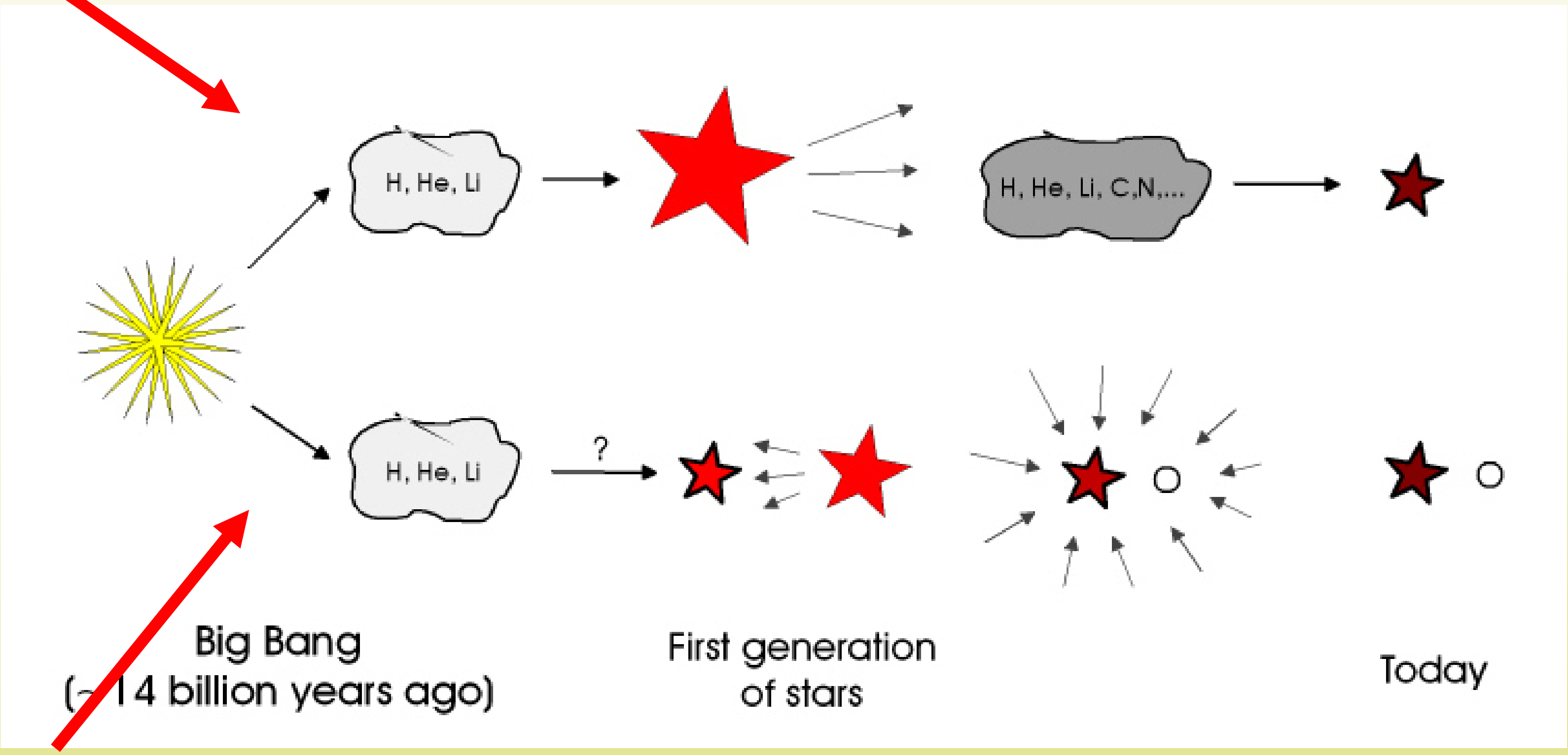


Frebel et al. 2007, ApJ submited

$[Fe/H]_{1D}$ = -5.7 => $\mathbf{[Fe/H]_{3D} = -5.9}$

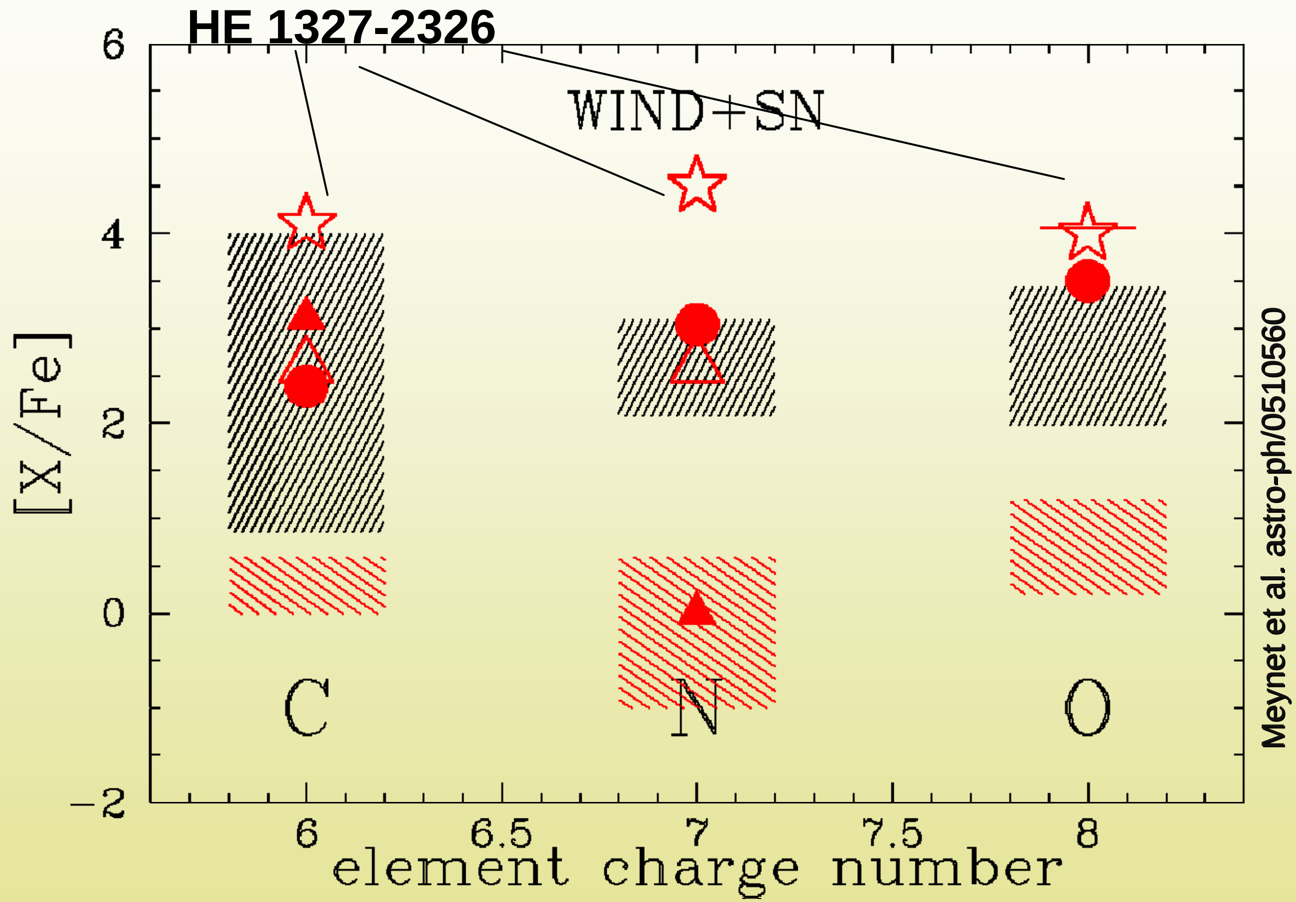
Possible Scenarios for the Origin of the Abundance Pattern

1. **By faint Pop III SN (mixing and fallback)**
2. **By Pop III stellar wind yields** **=> Pre-enrichment => Pop II star**
3. **By several Pop III SNe**



4. **Binary system with mass transfer** **=> Pop III star (unlikely...)**

Meynet/Maeder/Hirschi et al.



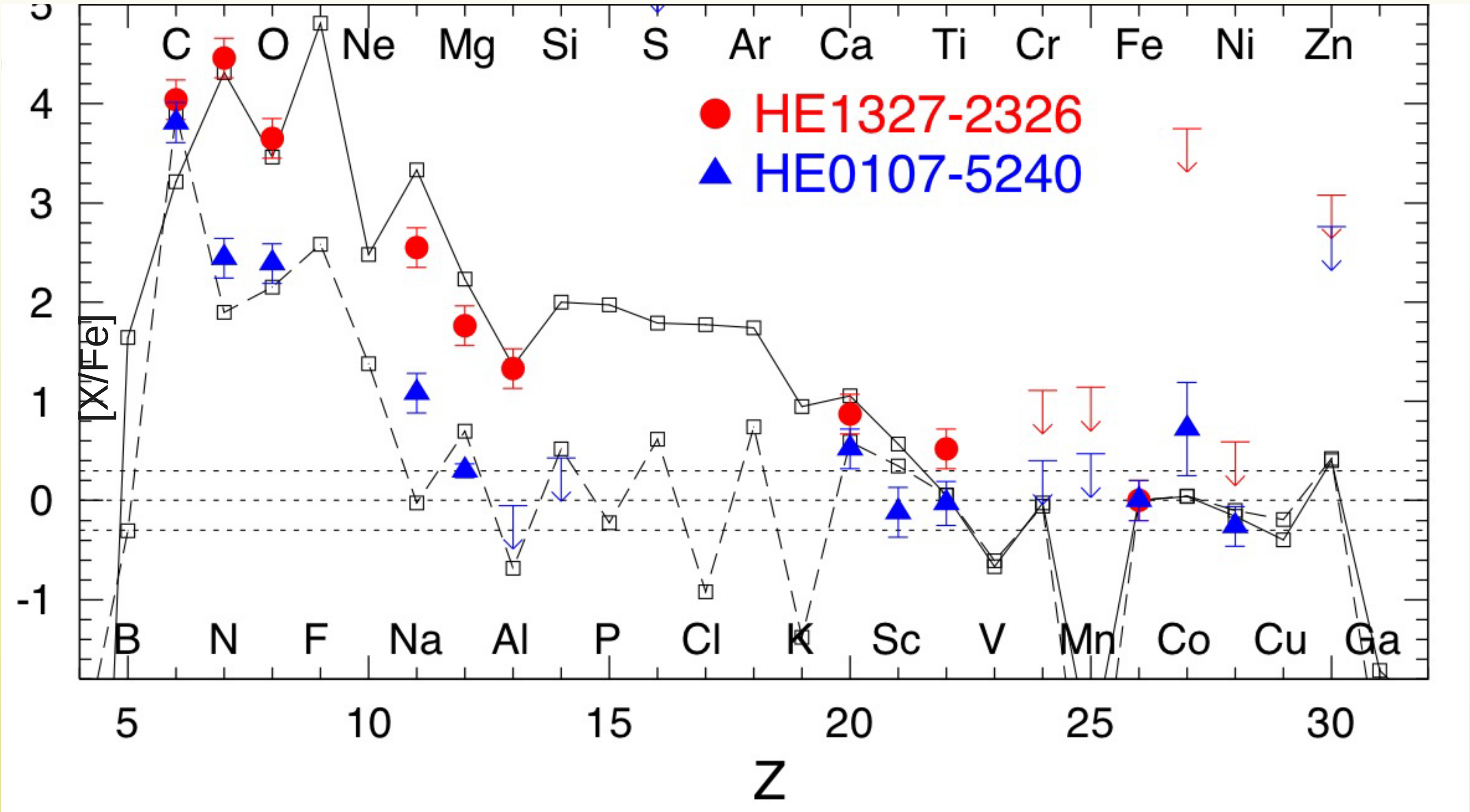
$60M_\odot$

v_{ini}=800km/s

Solid circles: [Fe/H]=–6.6 with rotation   stars: HE 1327–2326

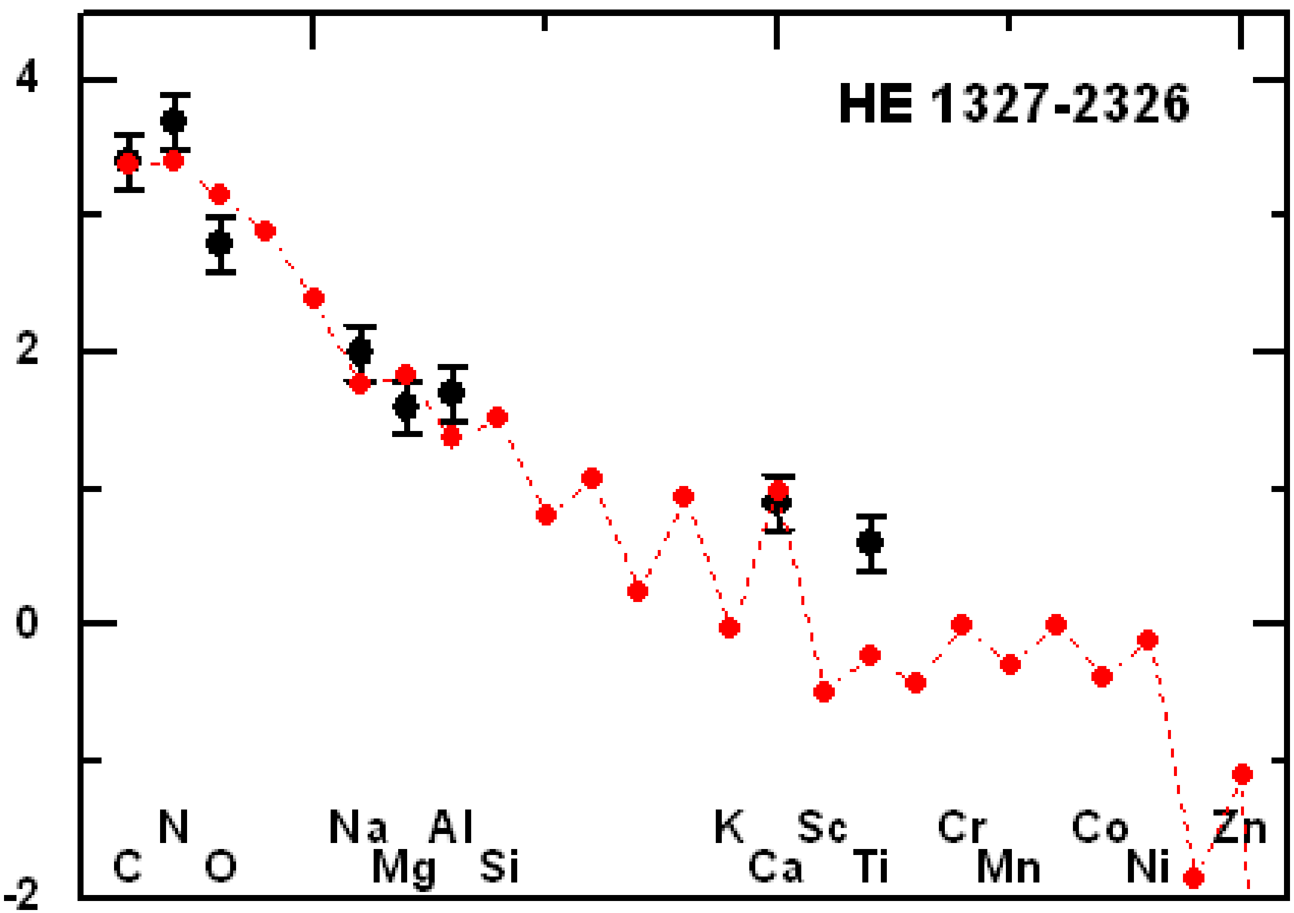
Solid triangles: [Fe/H]=–6.6 without rotation   empty triangles: G77-61

Tominaga/Iwamoto/ Umeda/Nomoto et al.



Tominaga et al. 2007

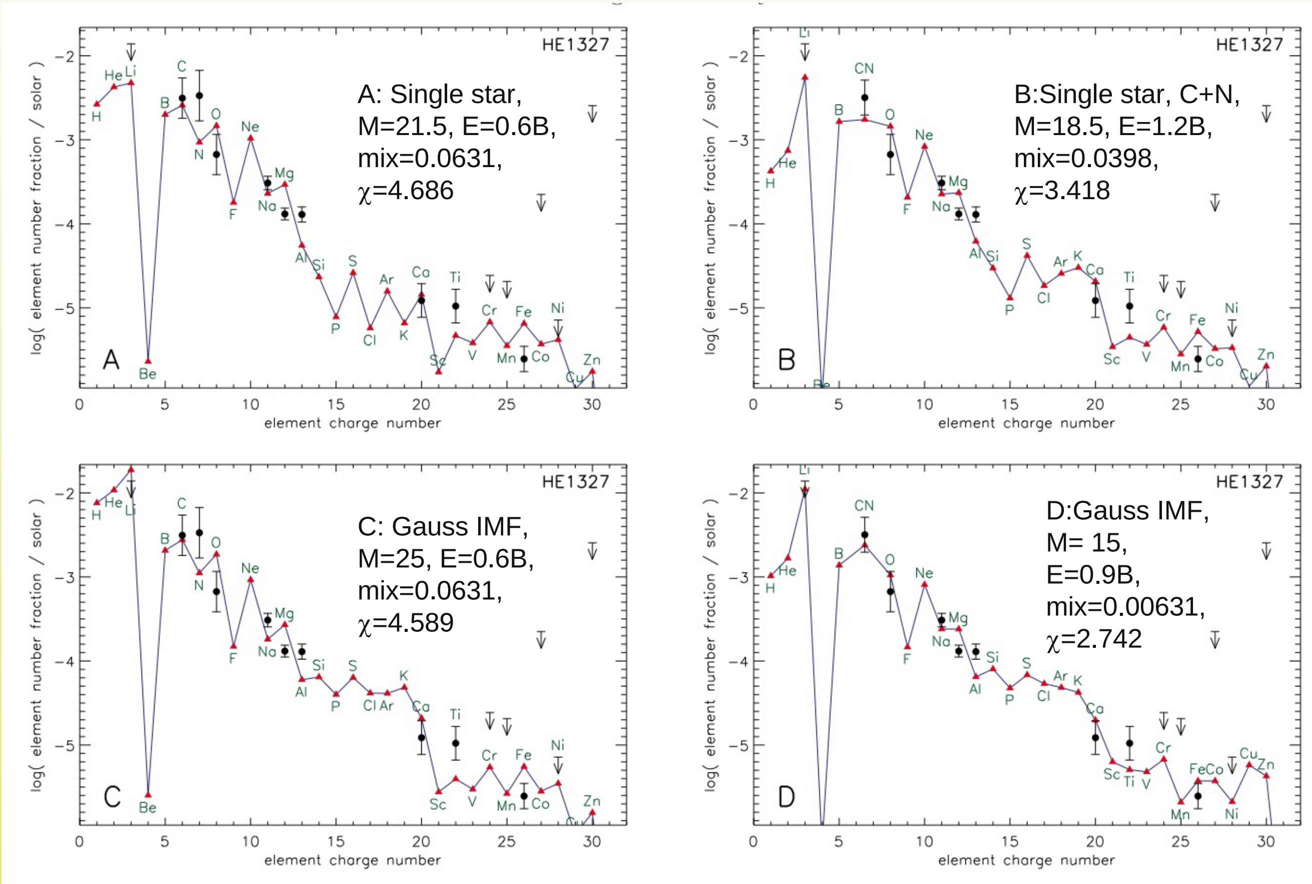
Chieffi & Limongi



Chieffi & Linomgi, priv. comm.

Heger & Woosley

- new SN yields with Z=0
- individual and integrated yields
- fits of metal-poor data



Heger & Woosley, in prep.

The observer's task:

...provide the best possible abundances so they can be accurately modeled!

(and we are trying really hard..!)

Abundance Analysis

Observers use 1D LTE plane-parallel (in most cases) model atmospheres to convert the measured equivalent widths of the absorption lines observed in the stellar spectrum into actual abundances.

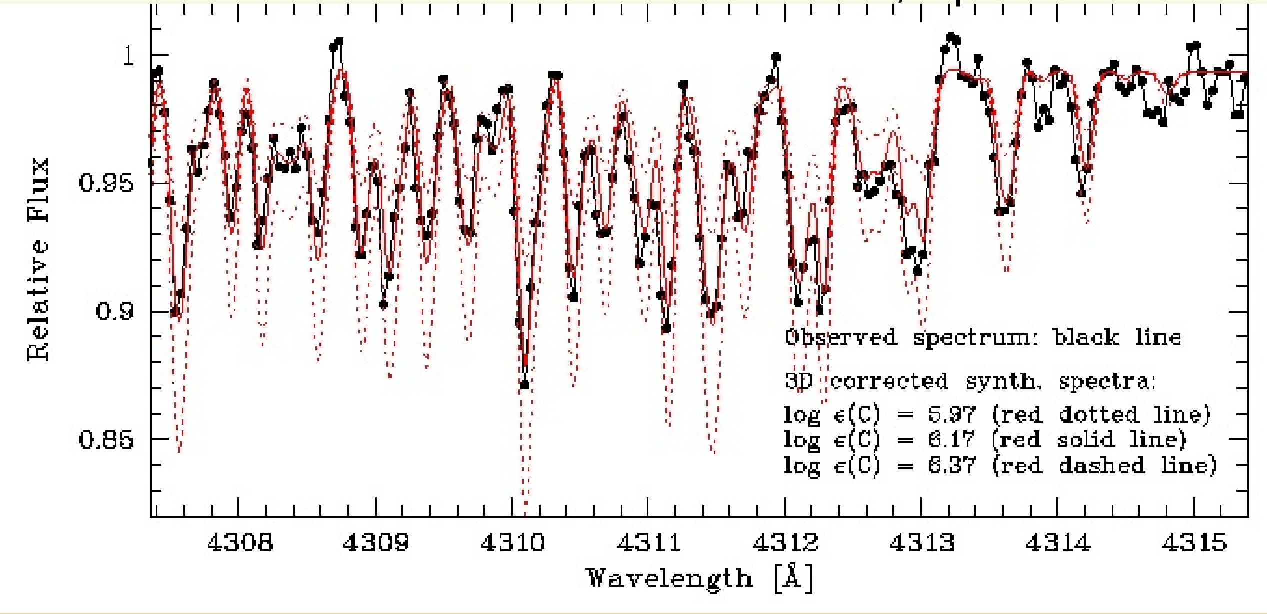
Obviously, there are some limitations to 1D and to LTE...! However, 3D models are hardly available.

Carbon (G-band at 4313A)

Frebel et al. 05 estimated 1D $[C/Fe]_{LTE} = 4.3$

New result is 3D $[C/Fe]_{LTE} = 3.7$

Frebel et al. 2007, ApJ submitted



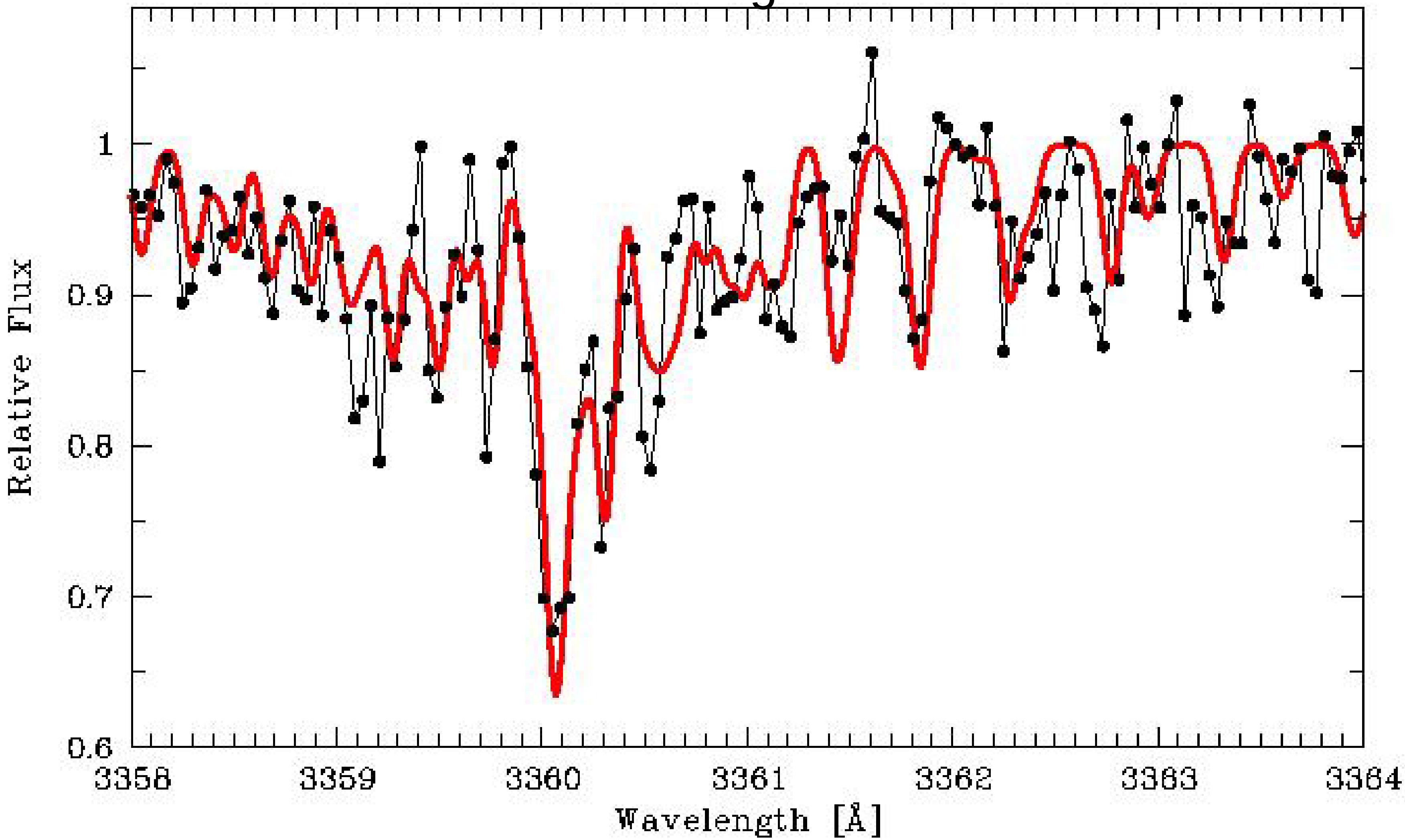
3D corrections:

Collet et al. 06 presented 3D model atmosphere of HE 1327-2326

- For CNO: 3D correction as fct. of excitation potential of the molecular lines
- We have now turned these corrections into new 3D abundances as derived from CH, OH and NH

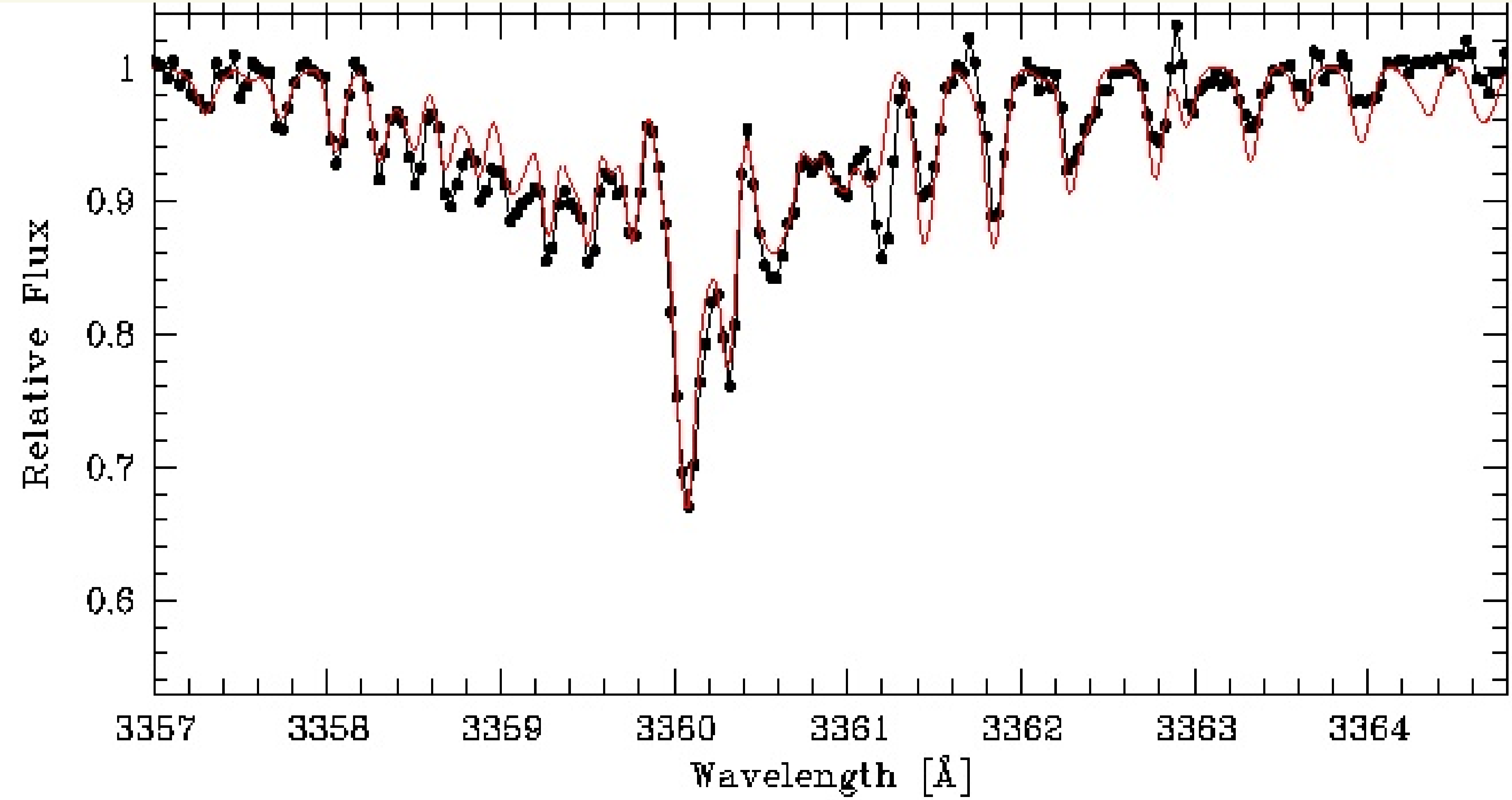
Nitrogen (NH 3360 A)

Subaru data with fit from original ‘1D’ linelist



Nitrogen

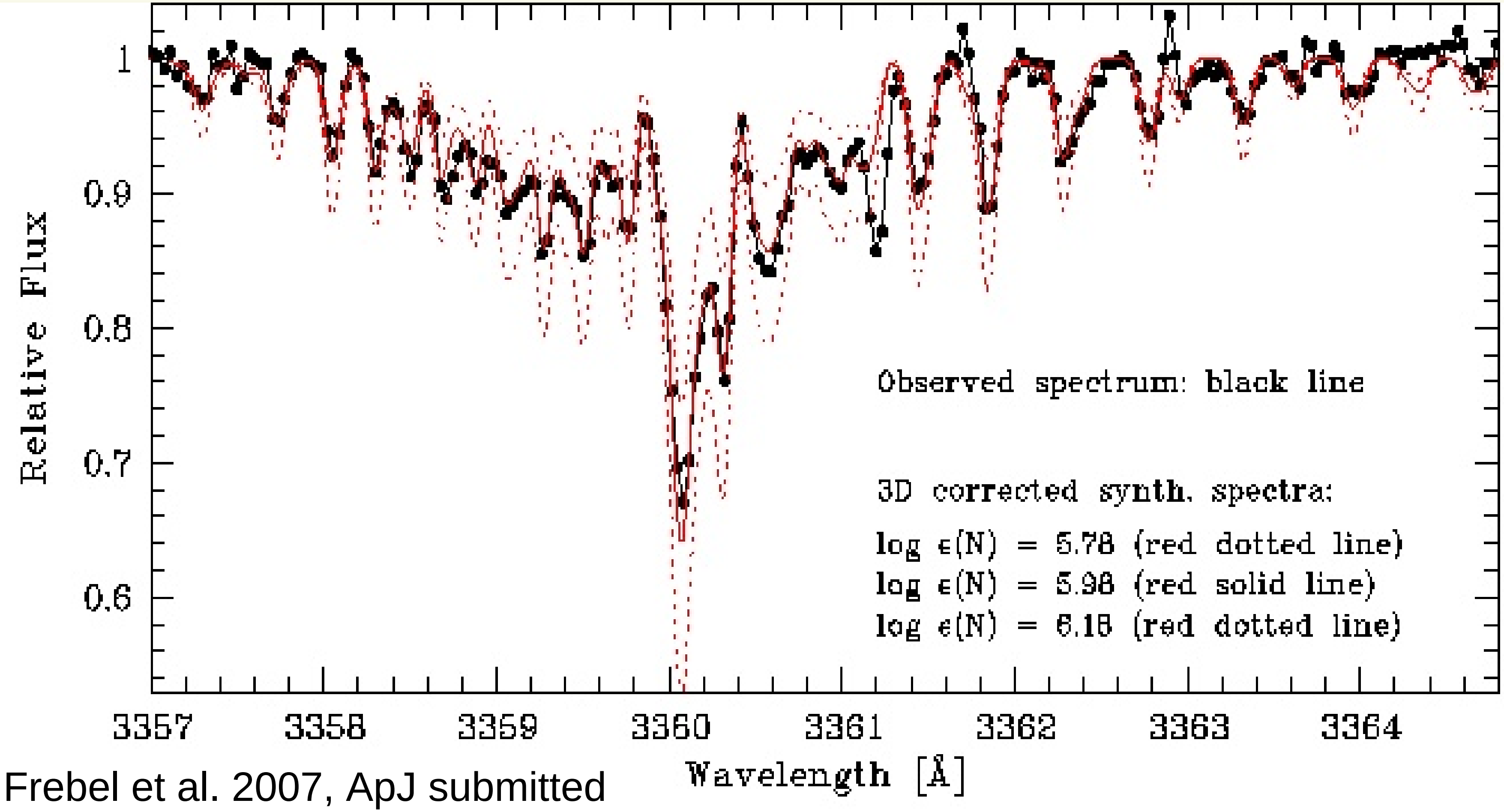
VLT data with fit based on original ‘1D’ linelist



Nitrogen

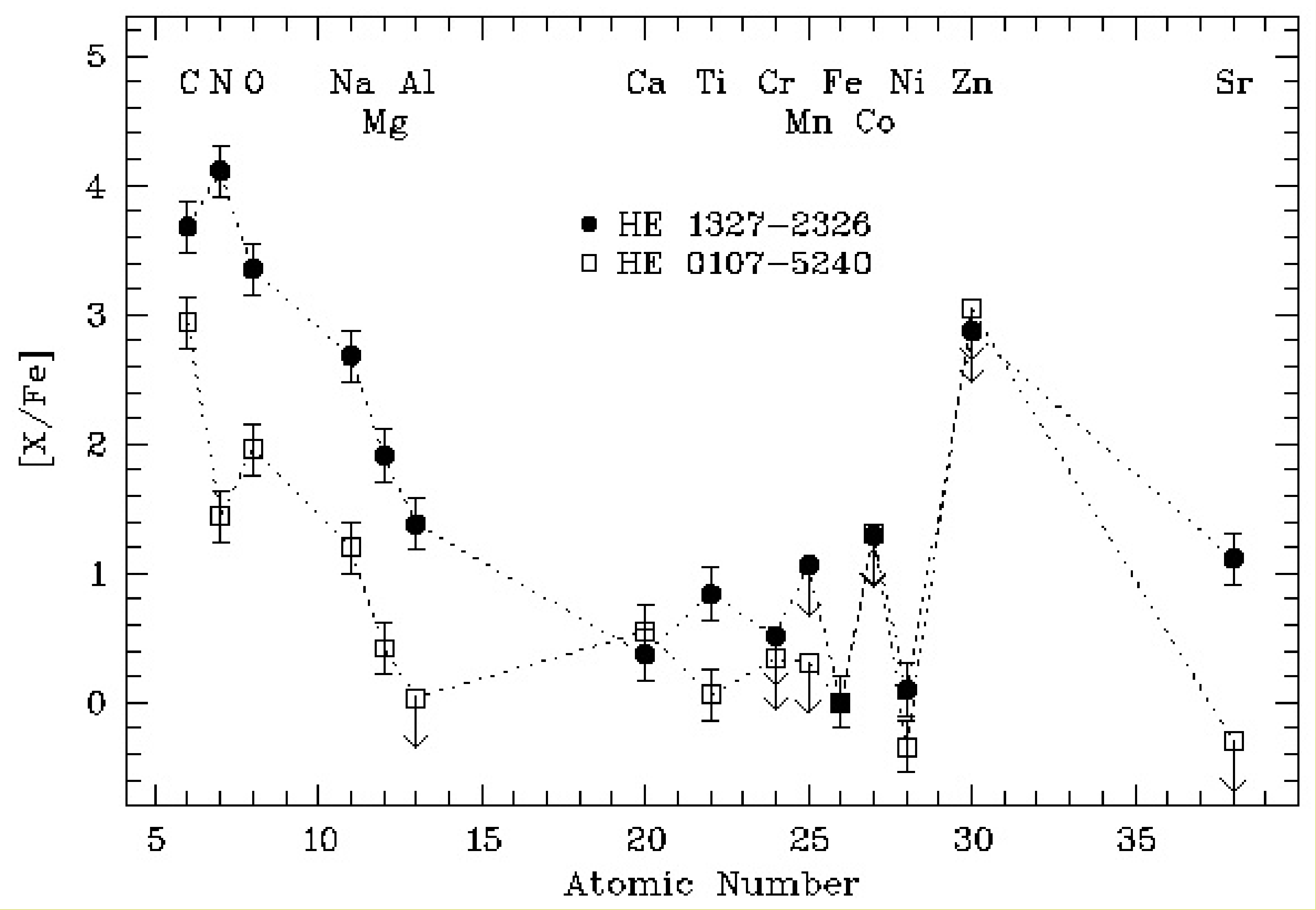
Frebel et al. 05 estimated 1D $[N/Fe]_{LTE} = 4.6$

New result is 3D $[N/Fe]_{LTE} = 4.1$



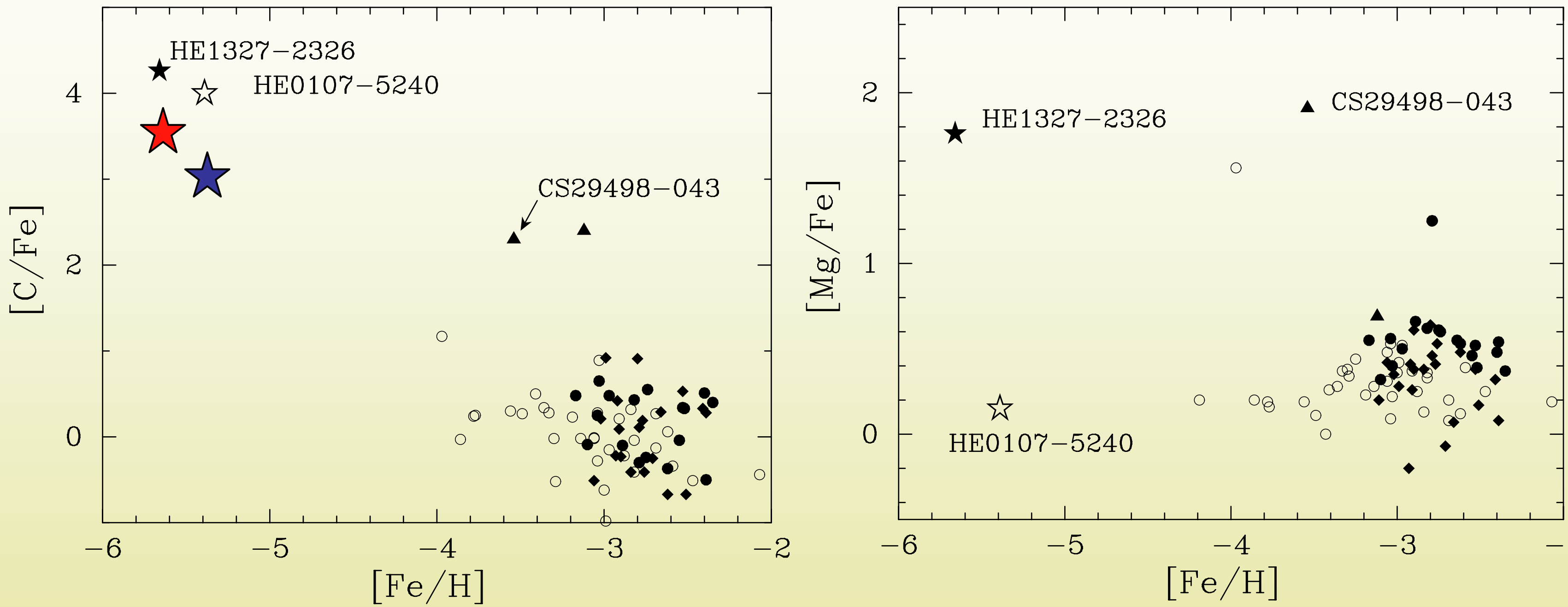
Frebel et al. 2007, ApJ submitted

3D abundances



Frebel et al. 2007, ApJ submitted

What is so Special About HE 1327–2326?

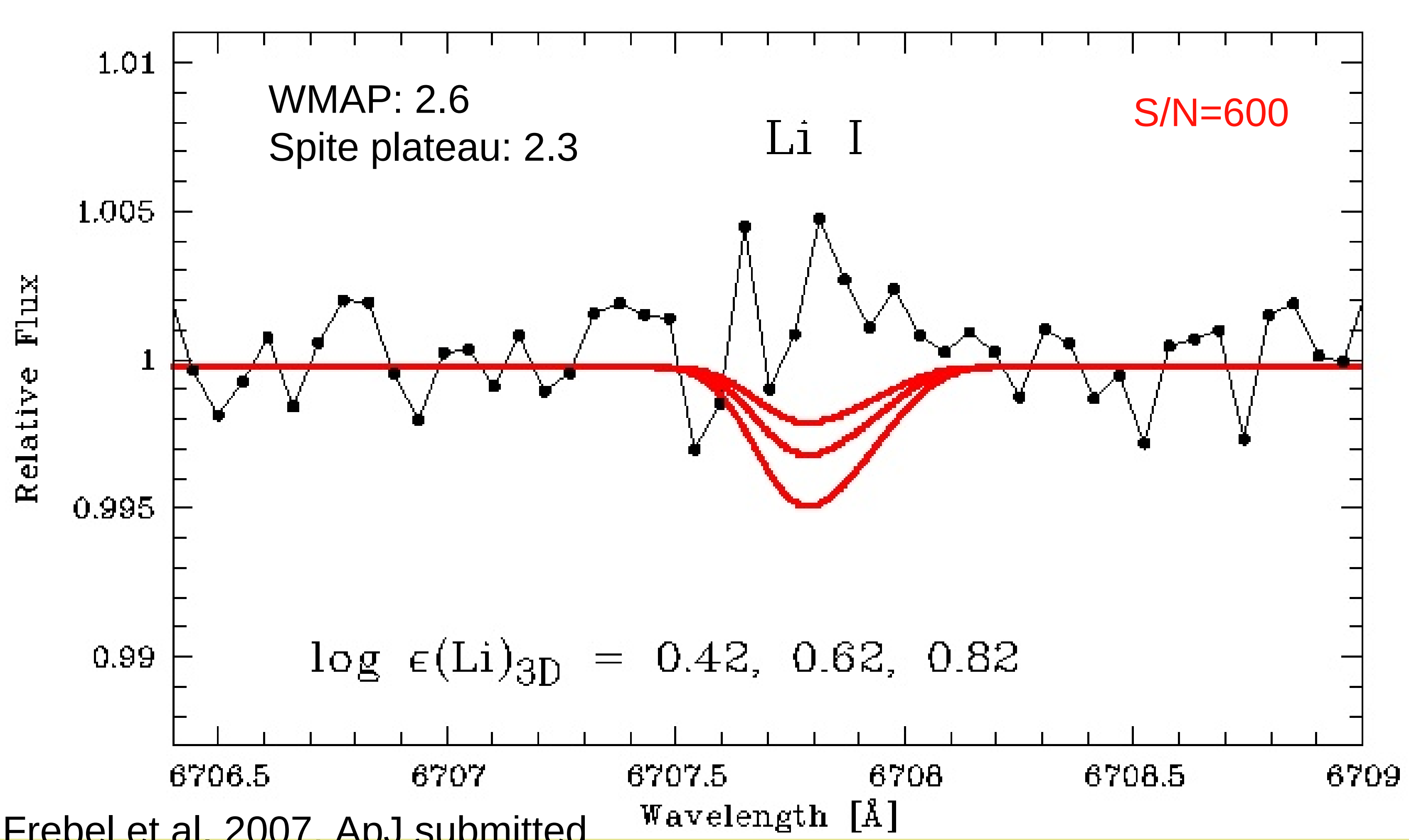


Aoki, Frebel et al. 2006

HE 1327–2326 has a very different chemical signature compared with the more metal-rich stars! So does HE 0107–5240 (Christlieb et al. 2002, 2004)

This is crucial observational information for the study of the early Universe

(New) Upper Limit on Li Abundance

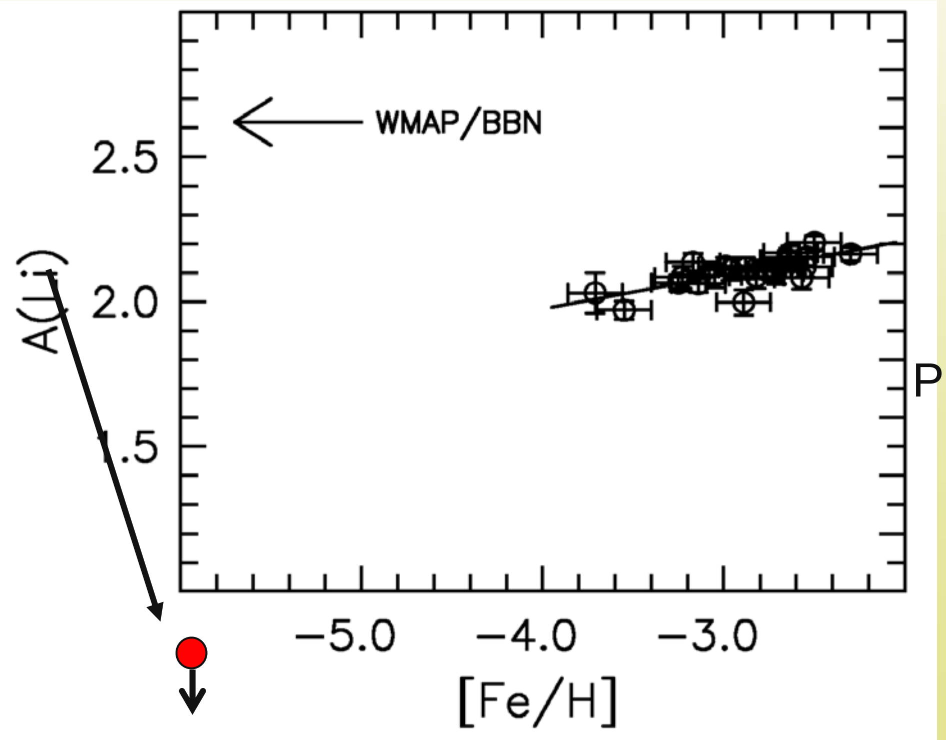


Frebel et al. 2007, ApJ submitted

The Lithium Riddle

Really low Li abundance!!

...other evolved stars display Li!



Primordial Li value:

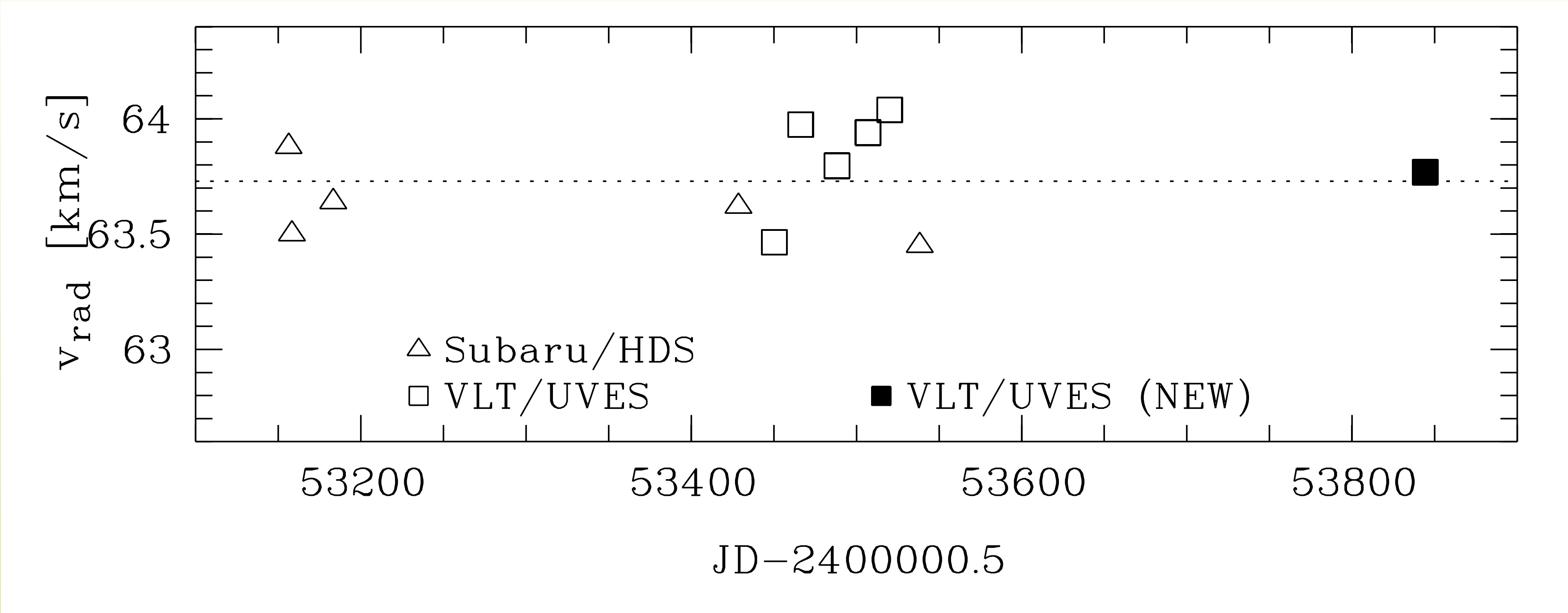
- WMAP: log ε (Li)=2.6 (Spergel et al. 06)
- Ryan et al. value at [Fe/H]=–3.5: log ε (Li)=2.0
- Our current upper limit: log ε (Li)<0.6

Possible reasons for Li depletion:

- HE1327-2326 could be a fast rotator
- Accretion of Li-depleted material from binary companion

Radial Velocity Variations??

May-Jun 2004 Mar-Jul 2005 Apr 06



based on Frebel et al. 2006, 638, L117

<v> = 63.7 km/s

B²FH

REVIEWS OF
MODERN PHYSICS
VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

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"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

E. r Process

The outstanding piece of observational evidence that this takes place is given by the explanation of the light curves of supernovae of Type I as being due to the decay of Cf^{254} (Bu56, Ba56), together with some other isotopes produced in the r process. Further evidence can be obtained only by interpreting the spectra of Type I supernovae, a problem which has so far remained unsolved.

... there are old stars with r-process enhancement being discovered!

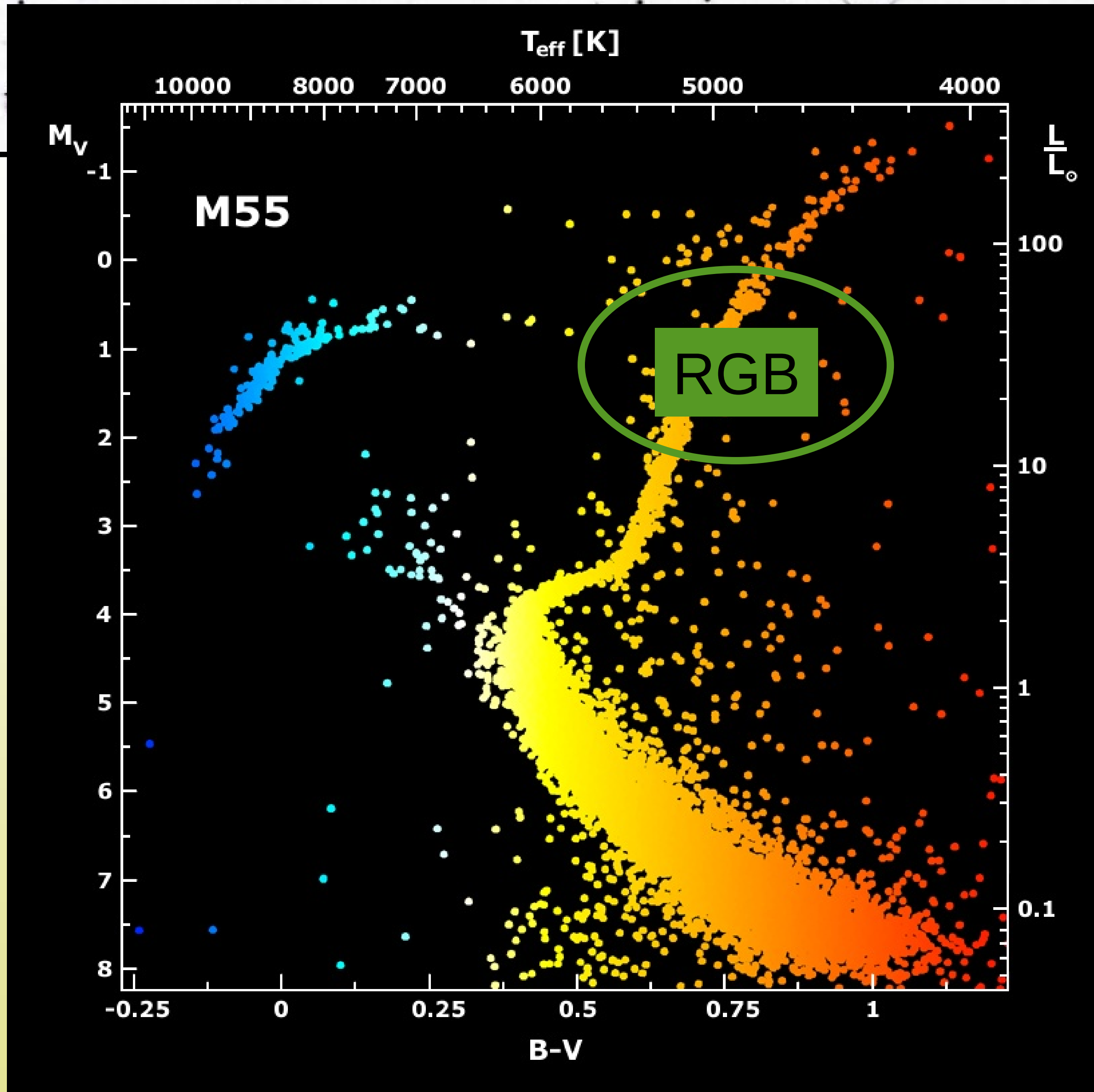
HE 1523-0901

Basic and stellar parameters:

© Anthony Ayiomamitis

- Magnitude: B = 12.1 mag
- Colour: $(B-V)_0 = 0.70$ mag
- Reddening: $E(B-V) = 0.02$

- *BVRIJHK* photometry:
  $T_{eff} = 4630 \pm 70$K (on Alonso et al. 1996 scale)
- Surface gravity: $\log g = 1.0$ (ionisation equilibrium)
  => red giant
- Metallicity: [Fe/H] = -3.0



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r-Process Enhanced Stars

(rapid neutron-capture process)

- Responsible for the production of heavy elements
- Possible production site: SN type II
- ~5% of metal-poor stars with [Fe/H] < – 2.5 (Barklem et al. 05)
  => Only ~12 stars known so far with [r/Fe] > 1.0
- Chemical "fingerprint" of previous nucleosynthesis event
- **Nucleo-chronometry**: w/ Th, U and stable r-process elements (e.g. Eu, Os, Ir)

Heavy neutron-capture elements in stars

alkali metals I A — alkaline earth metals II A — transition metals — nonmetals — noble gases O

	I A	II A	III B	IV B	V B	VI B	VII B	VIII	VIII	VIII	I B	II B	III A	IV A	V A	VI A	VII A	O
Period 1	1 H 1.01 Hydrogen																	2 He 4.00 Helium
Period 2	3 Li 6.94 Lithium	4 Be 9.01 Beryllium											5 B 10.81 Boron	6 C 12.01 Carbon	7 N 14.01 Nitrogen	8 O 16.00 Oxygen	9 F 19.00 Fluorine	10 Ne 20.18 Neon
Period 3	11 Na 22.99 Sodium	12 Mg 24.31 Magnesium											13 Al 26.98 Aluminum	14 Si 28.09 Silicon	15 P 30.97 Phosphorus	16 S 32.07 Sulfur	17 Cl 35.45 Chlorine	18 Ar 39.95 Argon
Period 4	19 K 39.10 Potassium	20 Ca 40.08 Calcium	21 Sc 44.96 Scandium	22 Ti 47.88 Titanium	23 V 50.94 Vanadium	24 Cr 52.00 Chromium	25 Mn 54.95 Manganese	26 Fe 55.85 Iron	27 Co 58.93 Cobalt	28 Ni 58.70 Nickel	29 Cu 63.55 Copper	30 Zn 65.39 Zinc	31 Ga 69.72 Gallium	32 Ge 72.61 Germanium	33 As 74.92 Arsenic	34 Se 78.96 Selenium	35 Br 79.90 Bromine	36 Kr 83.80 Krypton
Period 5	37 Rb 85.47 Rubidium	38 Sr 87.62 Strontium	39 Y 88.91 Yttrium	40 Zr 91.22 Zirconium	41 Nb 92.91 Niobium	42 Mo 95.94 Molybdenum	43 Tc (98) Technetium	44 Ru 101.07 Ruthenium	45 Rh 102.91 Rhodium	46 Pd 106.4 Palladium	47 Ag 107.87 Silver	48 Cd 112.41 Cadmium	49 In 114.82 Indium	50 Sn 118.71 Tin	51 Sb 121.74 Antimony	52 Te 127.60 Tellurium	53 I 126.90 Iodine	54 Xe 131.29 Xenon
Period 6	55 Cs 132.91 Cesium	56 Ba 137.33 Barium	Lanthanide series (see below)	72 Hf 178.49 Hafnium	73 Ta 180.94 Tantalum	74 W 183.85 Tungsten	75 Re 186.21 Rhenium	76 Os 190.23 Osmium	77 Ir 192.22 Iridium	78 Pt 195.08 Platinum	79 Au 196.97 Gold	80 Hg 200.59 Mercury	81 Tl 204.38 Thallium	82 Pb 207.2 Lead	83 Bi 208.98 Bismuth	84 Po (209) Polonium	85 At (210) Astatine	86 Rn (222) Radon
Period 7	87 Fr (223) Francium	88 Ra 226.03 Radium	Actinide series (see below)	104 Rf (261) Rutherfordium	105 Db (262) Dubnium	106 Sg (263) Seaborgium	107 Bh (262) Bohrium	108 Hs (265) Hassium	109 Mt (266) Meitnerium	110 (269)	111 (272)	112 (277)		114 (281)		116 (289)		118 (293)

rare earth elements—Lanthanide series														
57 La 138.91 Lanthanum	58 Ce 140.12 Cerium	59 Pr 140.91 Praseodymium	60 Nd 144.24 Neodymium	61 Pm (145) Promethium	62 Sm 150.4 Samarium	63 Eu 151.96 Europium	64 Gd 157.25 Gadolinium	65 Tb 158.93 Terbium	66 Dy 162.50 Dysprosium	67 Ho 164.93 Holmium	68 Er 167.26 Erbium	69 Tm 168.93 Thulium	70 Yb 173.04 Ytterbium	71 Lu 174.97 Lutetium

Actinide series														
89 Ac 227.03 Actinium	90 Th 232.04 Thorium	91 Pa 231.04 Protactinium	92 U 238.03 Uranium	93 Np 237.05 Neptunium	94 Pu (244) Plutonium	95 Am (243) Americium	96 Cm (247) Curium	97 Bk (247) Berkelium	98 Cf (251) Californium	99 Es (252) Einsteinium	100 Fm (257) Fermium	101 Md (258) Mendelevium	102 No (259) Nobelium	103 Lr (260) Lawrencium

Cosmo-Chronometry

Age estimates can be obtained from a comparison of an observed abundance ratio of a radioactive element (such as Th, U) to a stable r-process element (such as Eu, Os, Ir) and a theoretically derived initial production ratio.

Th/Eu: "most commonly" used chronometer

- Th is "relatively easy" measurable in r-process stars
- "famous" example: CS22892-052: 14-15Gyr; Sneden et al. 96,03

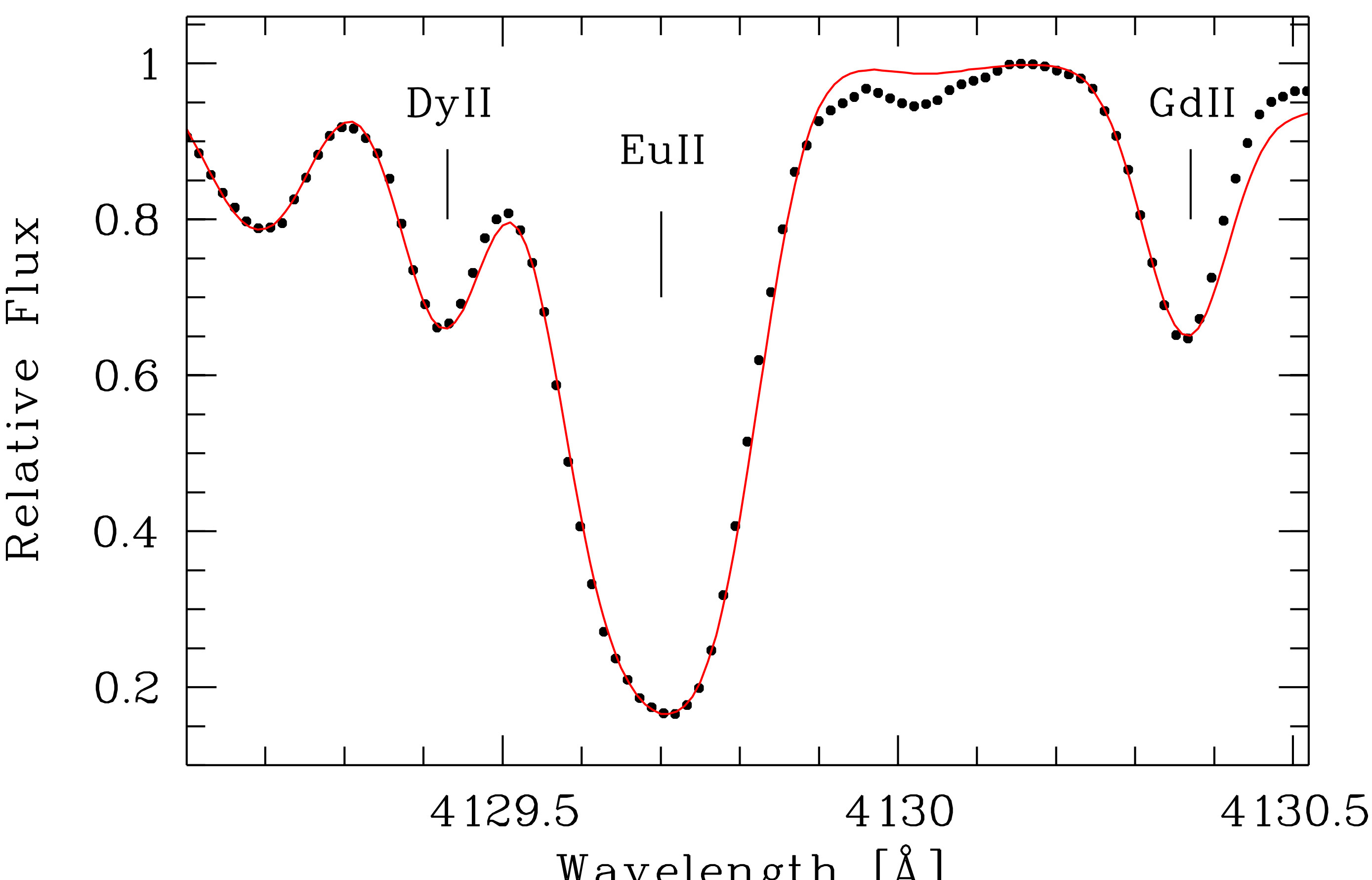
U/Th: Uranium so far *only confidently measured in one star*

-- CS31082-001: U/Th: ~14Gyr (Cayrel et al. 01, Hill et al. 02);

- one known with tentative, one with detection (Hill et al. 2007, in prep.)

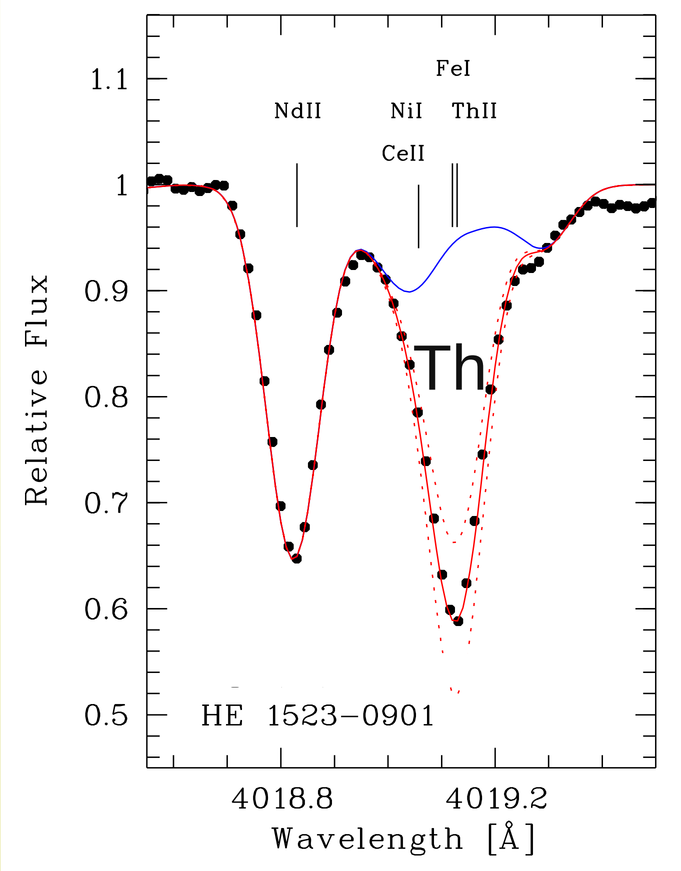
$\Rightarrow$ Ultimate goal: Use as many chronometers as possible (+ beat down any errors...)!

Abundances of HE 1523-0901



Frebel et al. (2007), in prep.

Th II Line 4019Å

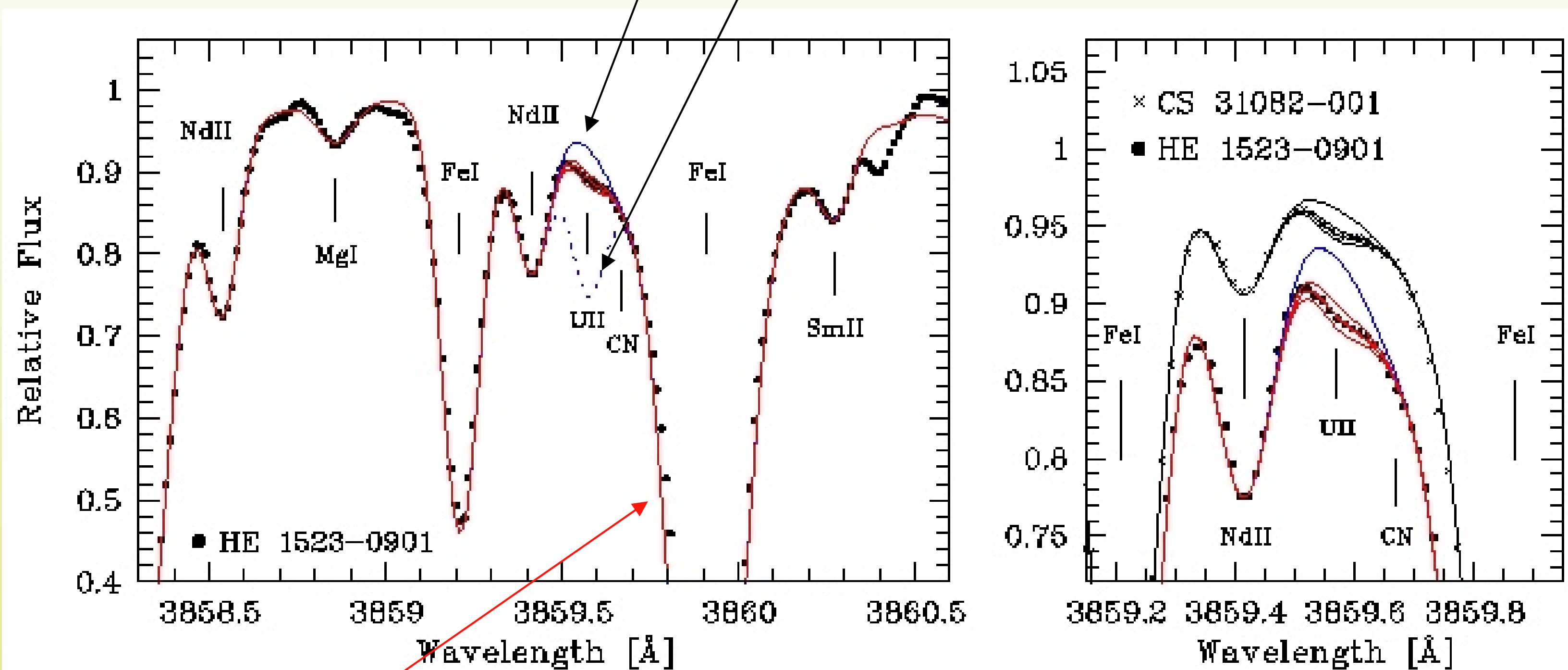


Frebel et al. (2007), in prep.

U II at 3859Å

Synthetic spectrum that includes NO uranium

Synthetic spectrum with U abundance if it had NOT decayed

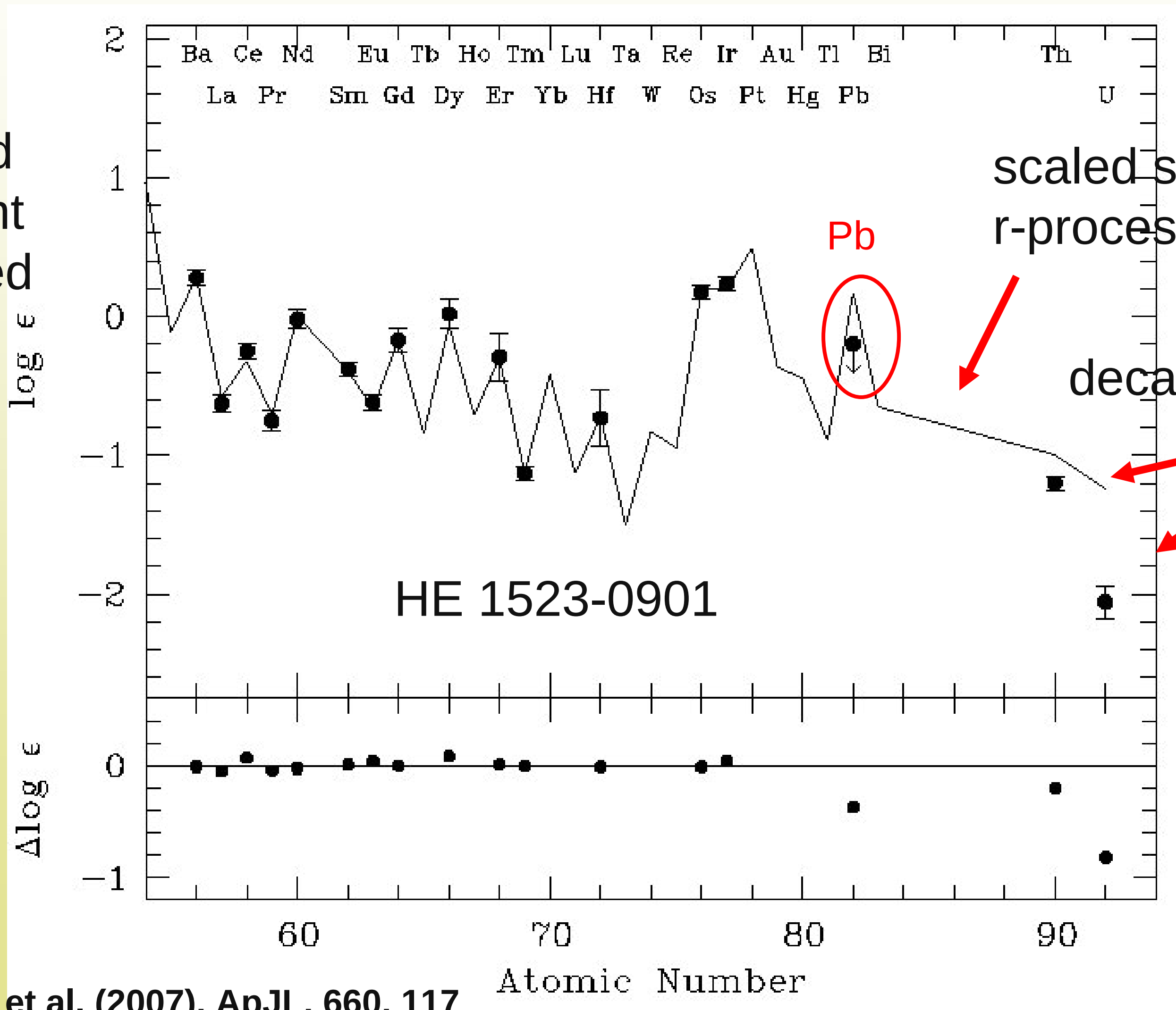


Frebel et al. (2007), ApJL, 660, 117

'Best fit' synthetic spectrum

The r-Process Pattern

Very good agreement with scaled solar r-process pattern for Z>56

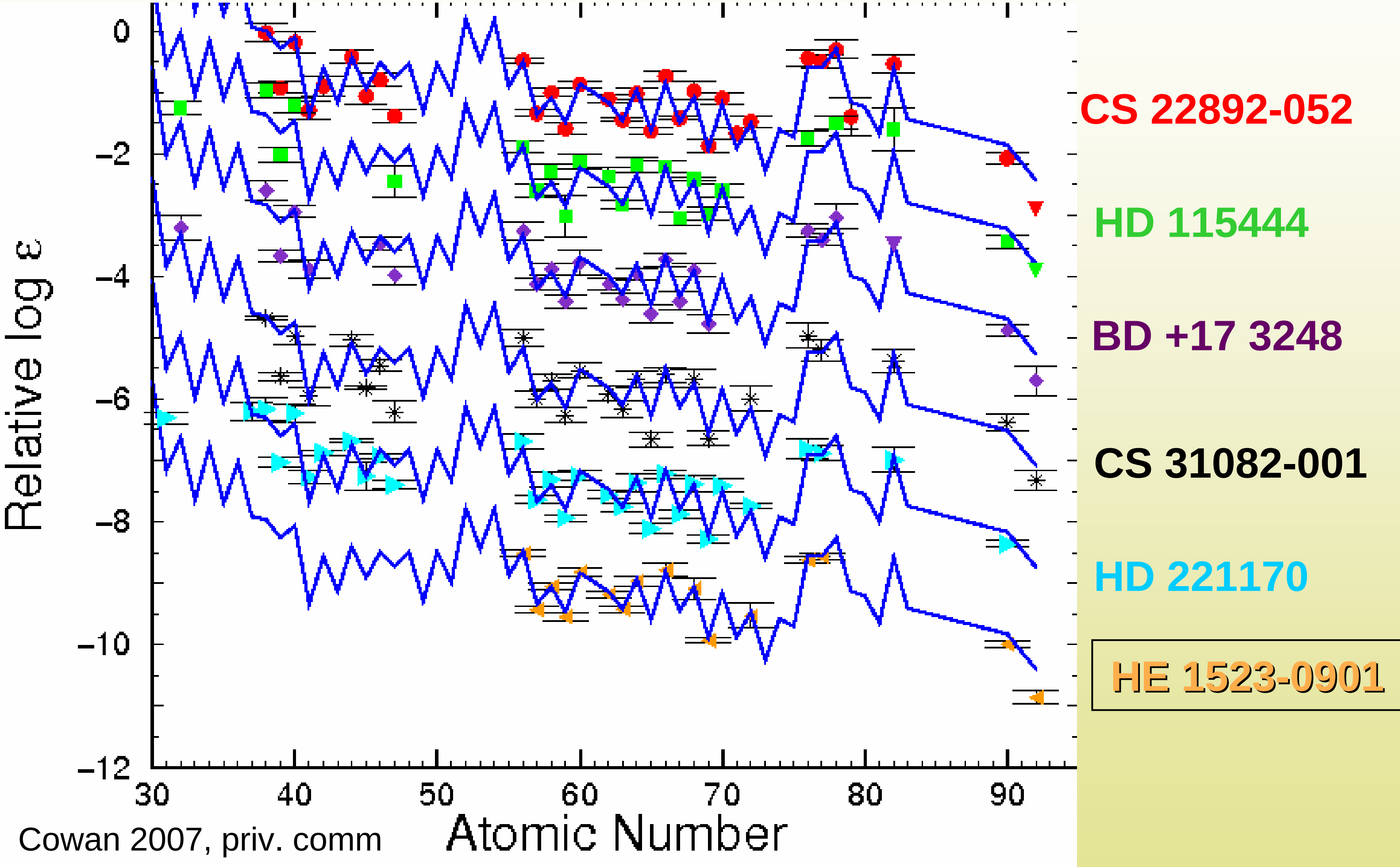


scaled solar r-process pattern

decayed Th,U

Frebel et al. (2007), ApJL, 660, 117

Precision at work



They all have the same abundance pattern, particularly in the heavy n-c elements!

The Age of HE 1523-0901

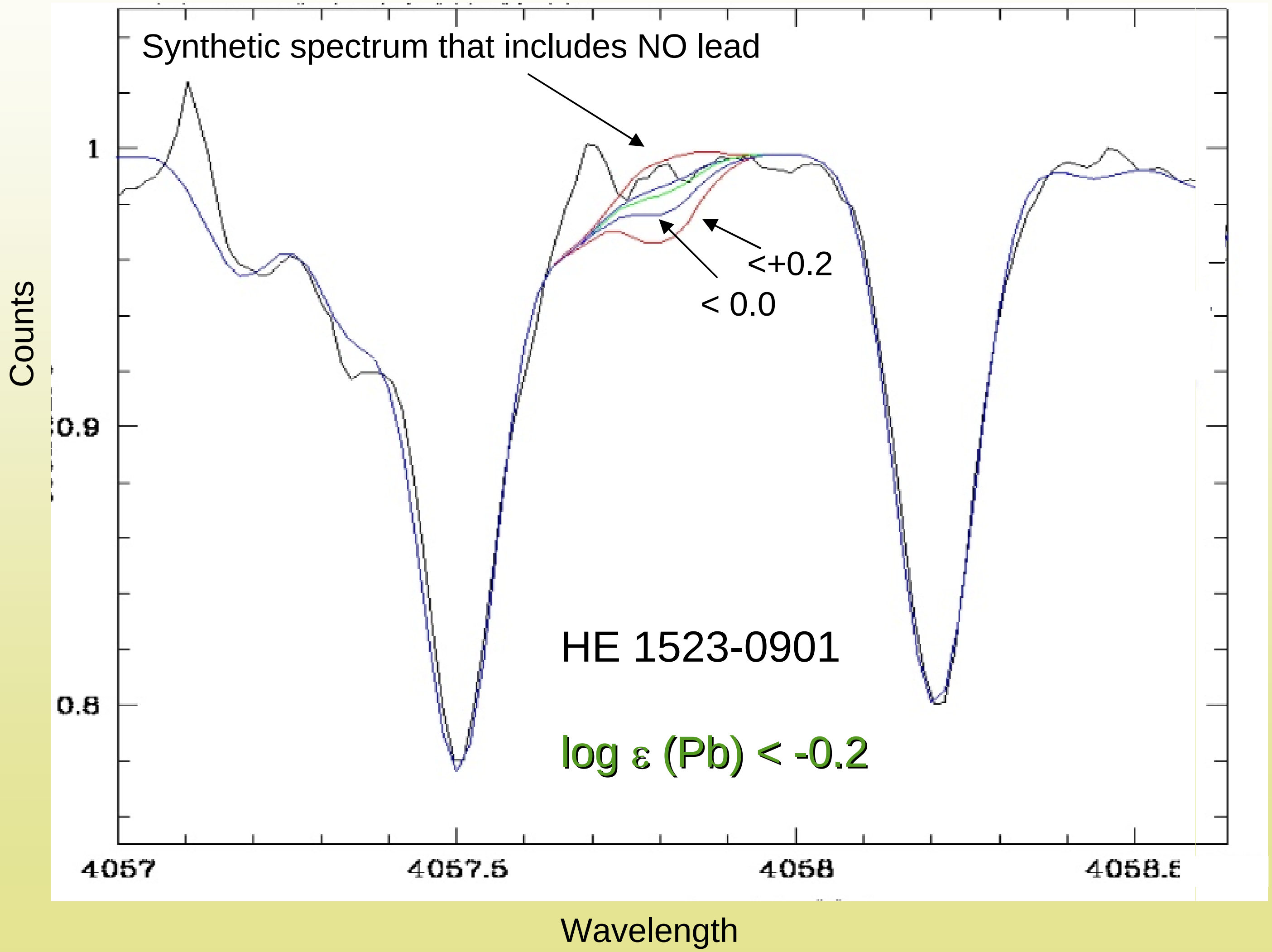
Ratio	Age	$\sigma_{obs/Teff/log\ g/vmicr/PR}$
Th/Eu	11.5	3.3/3.4/0.6/0.6/5.6
Th/Os	10.7	3.3/2.8/5.6/0.0/5.6
Th/Ir	15.0	3.3/2.0/2.9/1.5/5.6
U/Eu	13.2	1.9/0.6/0.4/0.2/1.6
U/Os	12.9	1.9/0.6/1.2/0.3/1.6
U/Ir	14.1	1.9/0.3/0.3/0.8/1.6
U/Th	13.0	2.9/0.4/0.9/0.4/2.2
average	**13.2 Gyr**	

Age of HE 1523-0901:

WMAP: 13.7 Gyr

The first time more than one chronometer could be employed in a star to measure the age!

Lead at 4058Å



Decaying into lead...

$t=13.2$ Gyr, $\tau(^{238}U)=4.47$, $\tau(^{232}Th)=14.05$, $\log\varepsilon(Th)=-1.20$, $\log\varepsilon(U)=-2.06$

$^{238}U \Rightarrow {}^{206}Pb$ $\log\varepsilon(Pb) = -1.231$ (from obs.)

$^{232}Th \Rightarrow {}^{208}Pb$ $\log\varepsilon(Pb) = -1.237$ (from obs.)

$^{235}U \Rightarrow {}^{207}Pb$ $\log\varepsilon(Pb) = -1.125$ (theoretical)

==============================

total Pb from decay: $\log\varepsilon(Pb) = -0.72$

current observed Pb upper limit: $\log\varepsilon(Pb) < -0.2$

$\Rightarrow$ S/N of 500+ needed to attempt detection!

Lead production

Pb production channels:

known Pb abundance in HE 1523-0901 will help disentangle what the different production channels are:

- Pb production from decay of Th and U
- additional prod. channels that do not go via the actinide path

Solar r-process Pb abundance:

Pb abundance in HE 1523-0901 is already *lower* than scaled solar r-process pattern: in line with claim that s-process can produce large amounts of lead (e.g. Goriely&Siess 2001, van Eck et al. 2003)

What we all could/should do...!

Observational:

- More telescope time for Pb abundance in HE 1523-0901
- More stars with detected U + Pb are needed to further constrain nucleosynthesis processes of the heaviest elements & contribution of Pb to the r- and s-processes
- Any fainter stars will require 30m telescopes to achieve very high S/N ratio necessary for the U + Pb detections

Theoretical:

- Best possible production ratios for Th/r and U/r are needed to refine cosmo-chronometry
- Detailed knowledge of nucleosynthesis processes that are responsible for the lighter and heavier n-c elements (w.r.t. scaled solar r-process pattern)

Conclusion

- The recently discovered star HE 1327–2326 holds the record for the most iron-poor star known ($[FeI/H]_{3D} = -5.9$). Several promising SN pre-enrichment scenarios reproduce the abundance pattern.
- HE 1523–0901 is a newly discovered r-process enhanced star with a U detection. For the first time, all three available chronometer pairs (Th/r, U/r, U/Th) can be measured in the star, and the age was derived to be 13.2 Gyr. The Pb is very low.
- Outlook @ UT: **A new metal-poor stars observing program** with the **Hobby-Eberly-Telescope** "The chemical compositions of our Galactic Halo" (w/ Chris Sneden, Carlos Allende Prieto and others) w/ targets from SDSS/SEGUE, HKII & bright HES samples