ANNA FREBEL EMMI '08 R-PROCESS IN THE OLDEST STARS

# Observing the signatures of the rapid neutron-capture process in the oldest Galactic stars

EMMI Kickoff Meeting

July 16-17, 2008

**Anna Frebel**
W. J. McDonald Fellow
McDonald Observatory
The University of Texas at Austin

# Why study the stars?


by: Apprentice to Galileo Galilei, 1636

# Outline

✓ **Introducing old, metal-poor stars**

Why are we interested & what is their role in the early Universe?

✓ **Unravelling the nucleosynthetic history of our "backyard"**

Metal-poor stars with huge amounts of rare earth elements

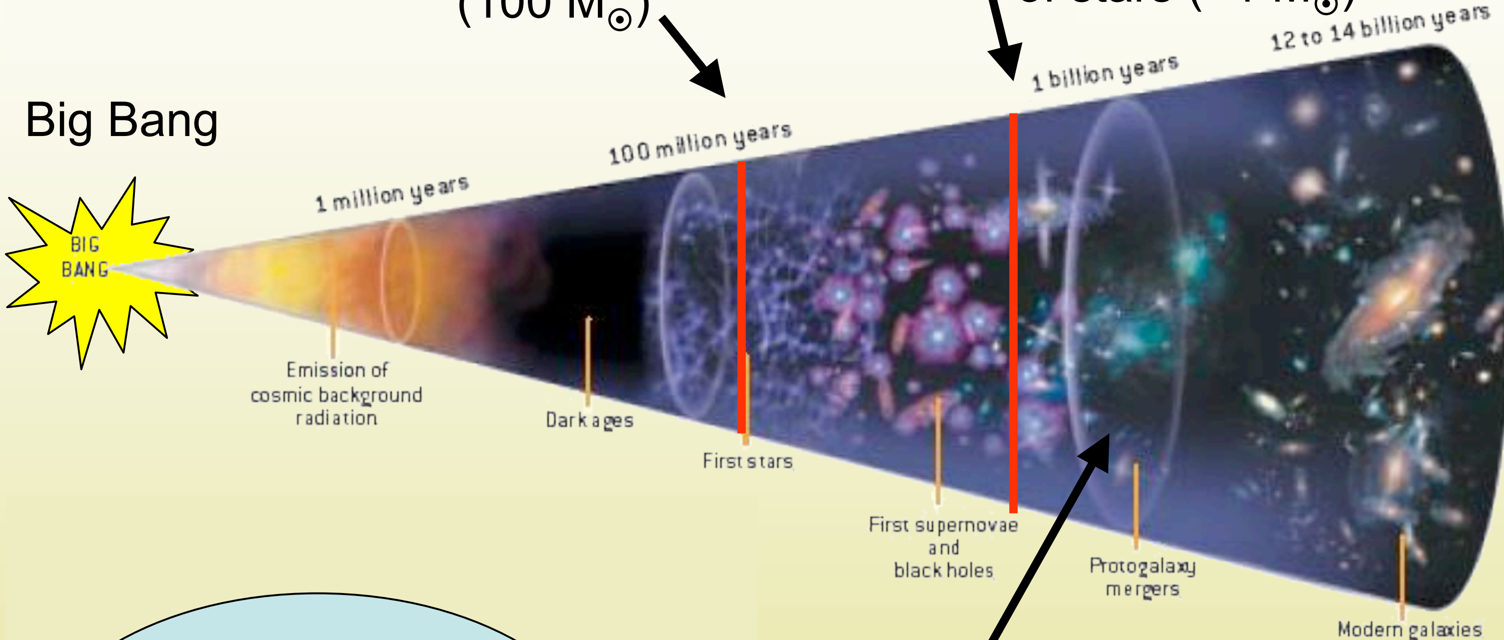
✓ **How old are the oldest stars?**

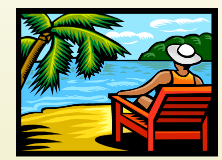
Detecting radioactive elements & actual age measurements

✓ **Where are we heading?**

Current challenges, new surveys & future opportunities

# A long time ago...



SCIENTIFIC AMERICAN
Larson & Bromm 2001

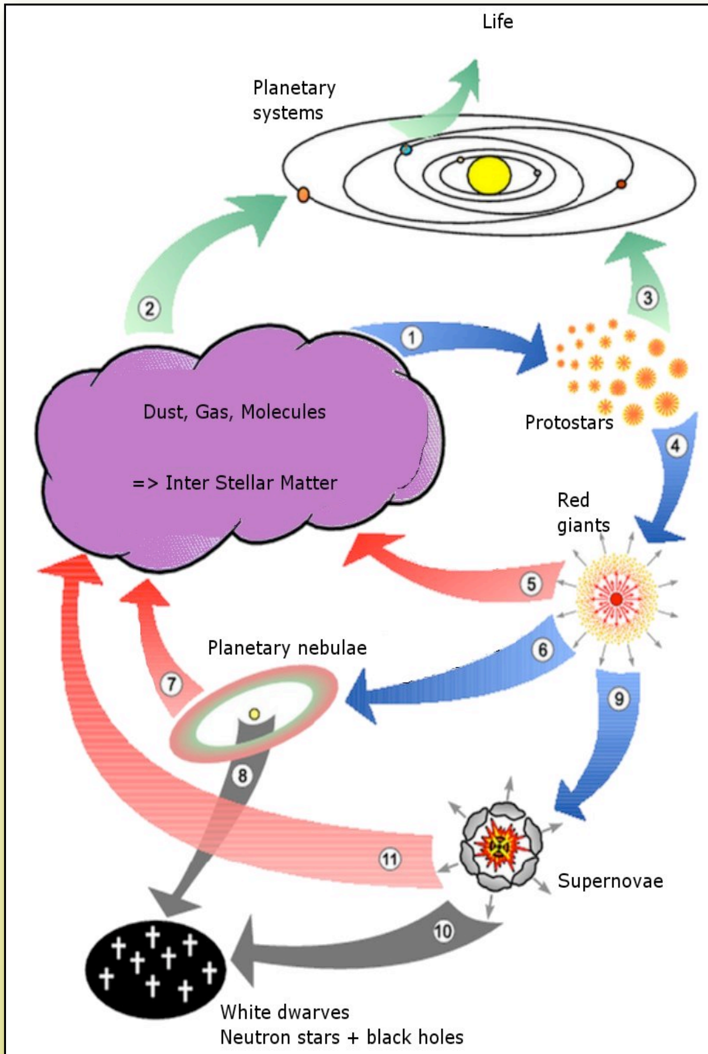
We want to find those stars from the $2^{nd}$ or later generations of stars!

Cosmic time (not to scale)

# Finding the needle in the Haystack

Old stars from the early Universe are extremely rare!

# CHEMICAL EVOLUTION




Zentrum fuer Astronomie und Astrophysik, TU Berlin

All the atoms (except H, He & Li) were created in stars!

Pop III: zero-metallicity stars
Pop II: old halo stars
Pop  I: young disk stars

**We are made of stardust!**

$\Rightarrow$ Old stars contain fewer elements (e.g. iron) than younger stars

We look for the stars with the least amounts of elements heavier than H and He!

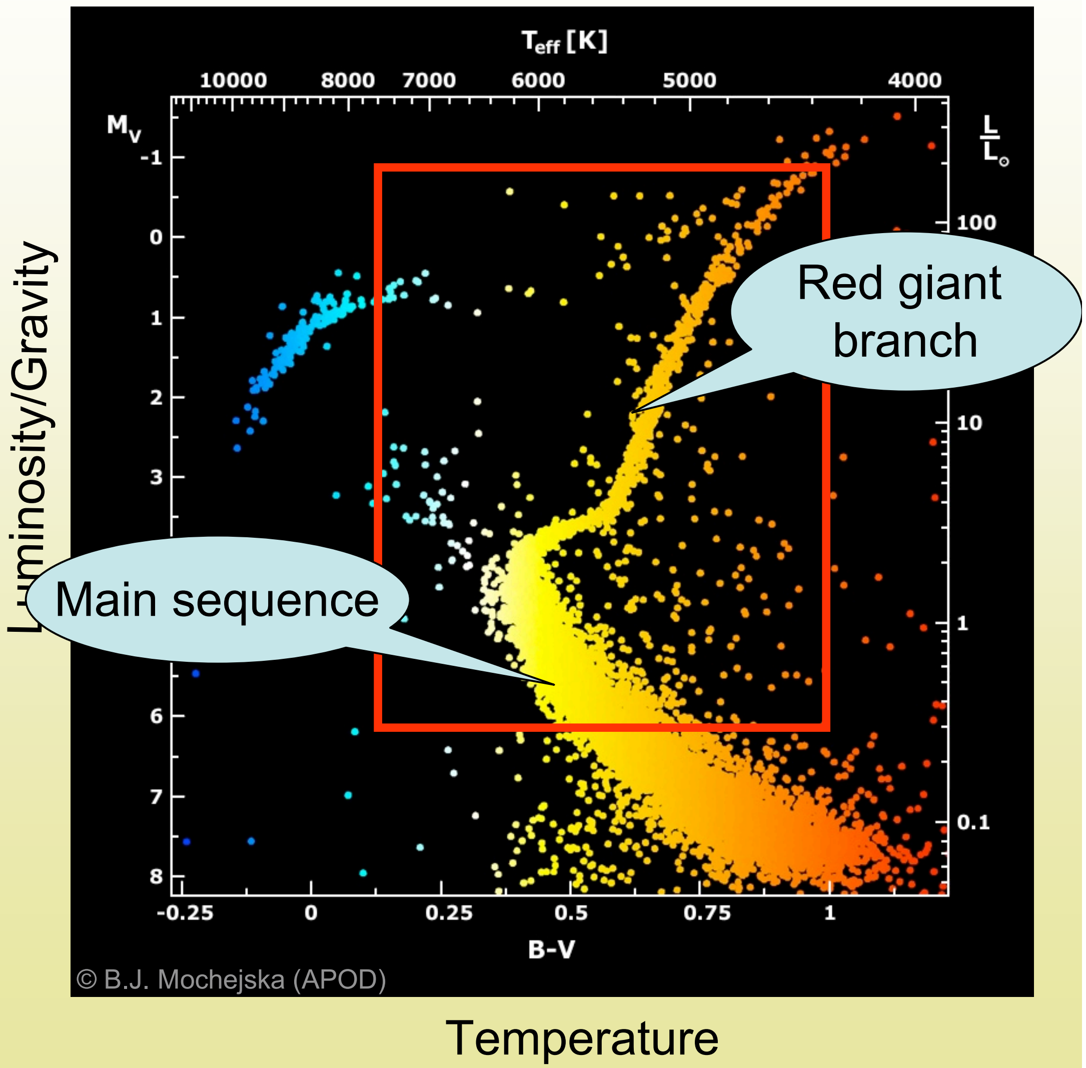
# Astronomer's favorite tool

**Hertzsprung-Russell-Diagram**

Stars spend ~90% of their lifetime on the main sequence

Main sequence and giant stars are "relatively unevolved"

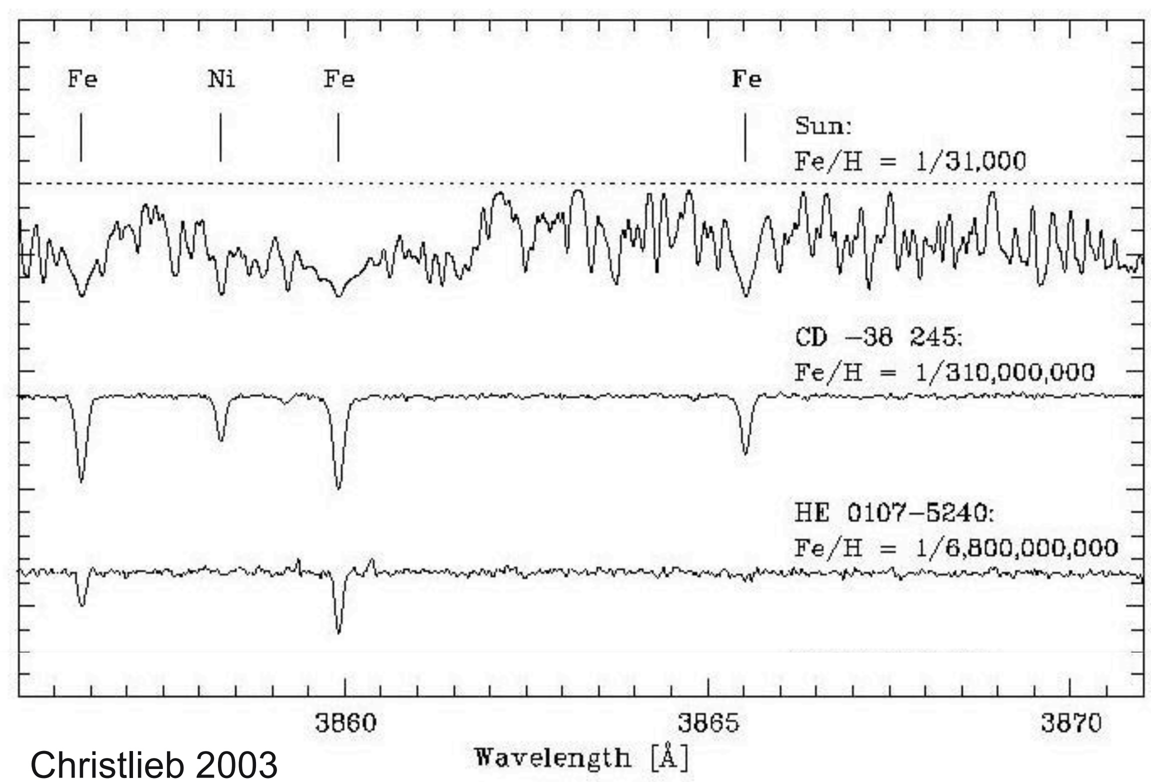
Their surface composition has not been changed by internal mixing process



# Taking a spectroscopic look



"Look-back time"




Christlieb 2003

[Fe/H]= 0.0

[Fe/H]= –4.0

[Fe/H]= –5.3

Galactic chemical evolution

$$[Fe/H] = \log(N_{Fe}/N_H)_* - \log(N_{Fe}/N_H)_\odot$$

# Astronomer's Periodic Table



| hydrogen | helium |
|---|---|
| 1 | 2 |
| H | He |
| 1.0079 | 4.0026 |

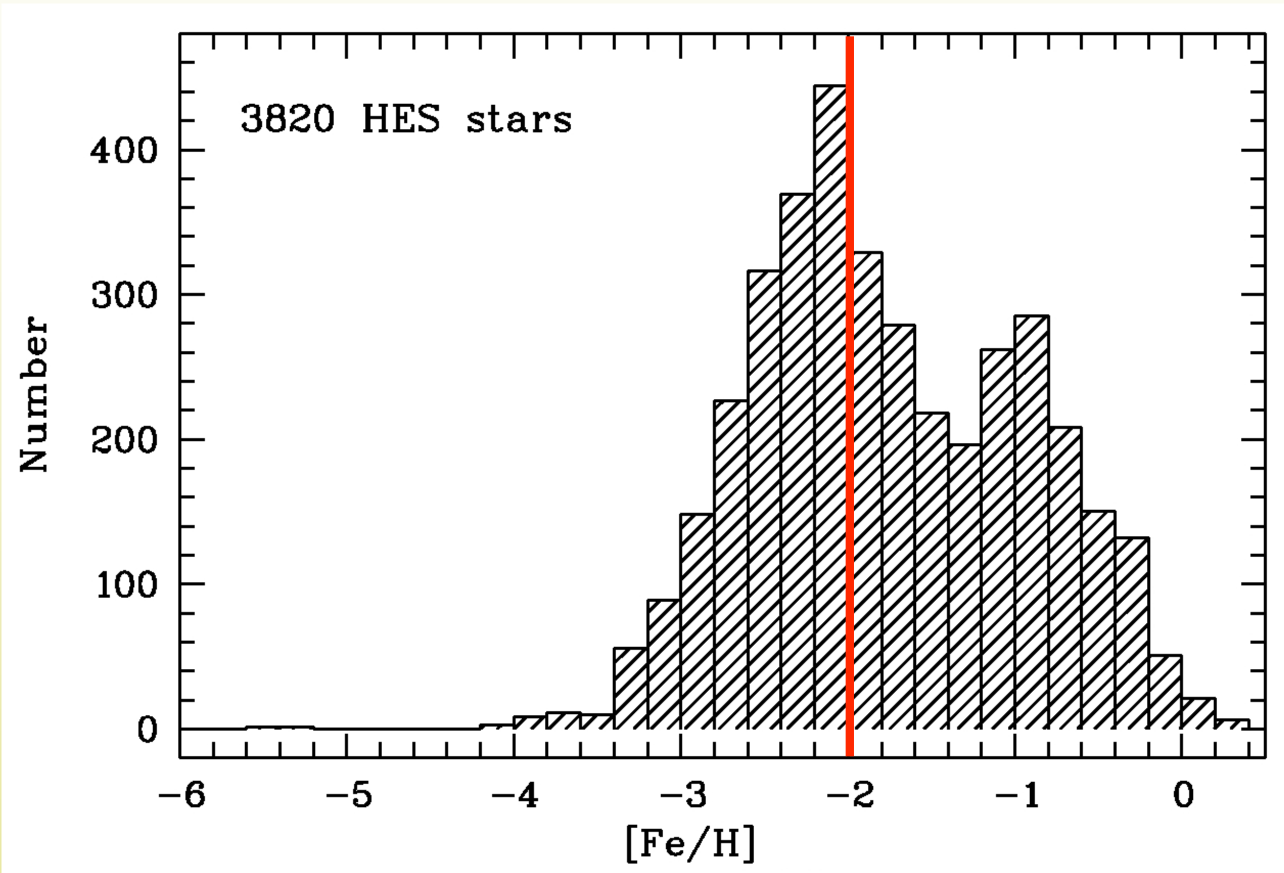
**Metals Z**

# Classification Scheme

| Range | Term | Acronym |
|---|---|---|
| [Fe/H] ≥ +0.5 | Super metal-rich | SMR |
| [Fe/H] = 0.0 | Solar | — |
| [Fe/H] ≤ –1.0 | Metal-poor | MP |
| [Fe/H] ≤ –2.0 | Very metal-poor | VMP |
| [Fe/H] ≤ –3.0 | Extremely metal-poor | EMP |
| [Fe/H] ≤ –4.0 | Ultra metal-poor | UMP |
| [Fe/H] ≤ –5.0 | Hyper metal-poor | HMP |
| [Fe/H] ≤ –6.0 | Mega metal-poor | MMP |

*as suggested by Beers & Christlieb 2005*

# Galactic Halo Metallicity distribution function




N. Christlieb 2008, priv. comm

# What can we learn from old halo stars?

Low-mass stars (M < 1 M☉)
⇒ lifetimes > 10 billion years
⇒ unevolved stars are still around!

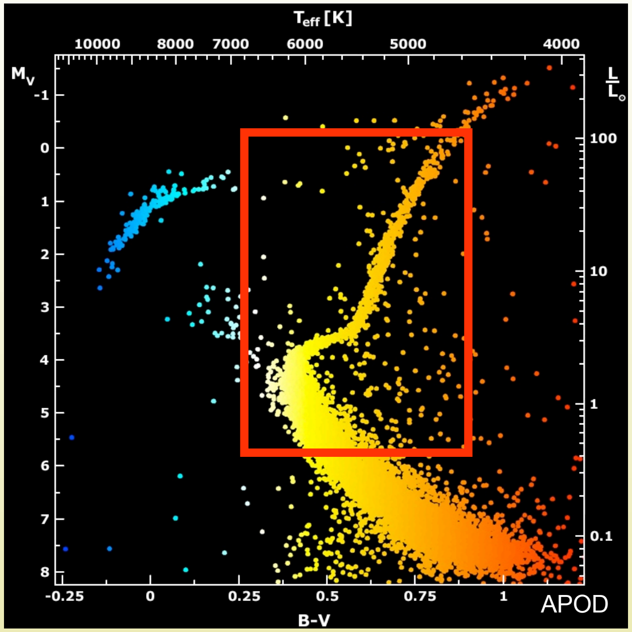
---

✓ Old stars are "fossils" of the early Universe
✓ Easily accessible local equivalent of the high-redshift Universe

From spectral analysis we learn:
- Origin and evolution of the elements
- Involved nucleosynthesis processes and sites
- Chemical and dynamical history

Hertzsprung-Russell-diagram

Gravity




Temperature

⇒ *Ideal tracers of the Galactic chemical evolution*
⇒ *Near-field cosmology*

REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

# Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

*Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California*

# B²FH



## 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 an r-process signature being discovered*!

# r-Process Enhanced Stars
## (rapid neutron-capture process)

- Responsible for the production of heavy elements

- Weak component:
  responsible for lighter (<Ba) neutron-capture elements
- Main component:
  responsible for heavier (>Ba) neutron-capture elements

- Most likely production site: SN type II => pre-enrichment

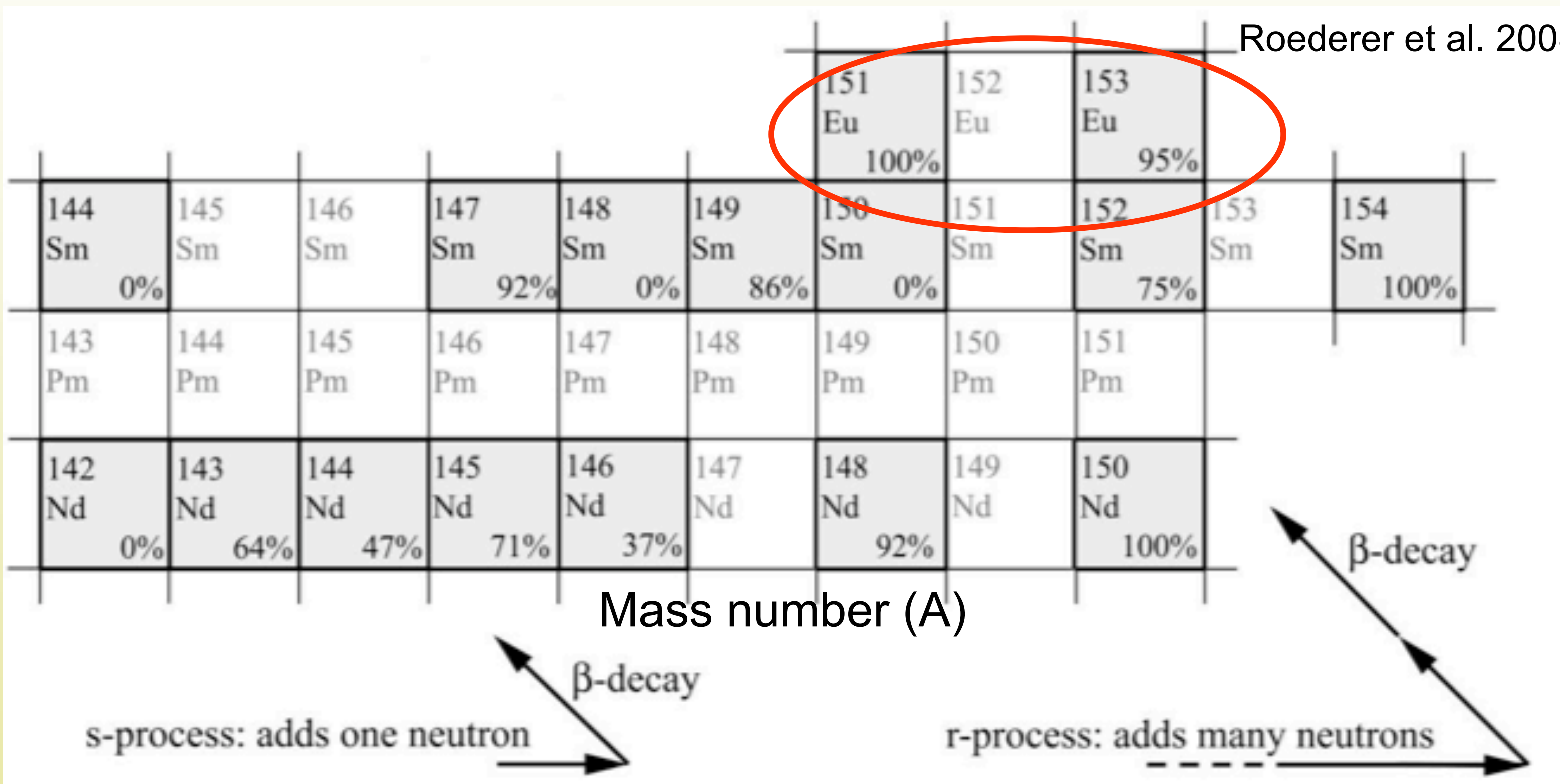
- Chemical "fingerprint" of previous nucleosynthesis event

- ~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

**Nucleo-chronometry**:
obtain stellar ages from decaying Th, U and stable r-process elements (e.g. Eu, Os, Ir)

# S- VS. R-PROCESS PATHS

grey: naturally occurring isotopes

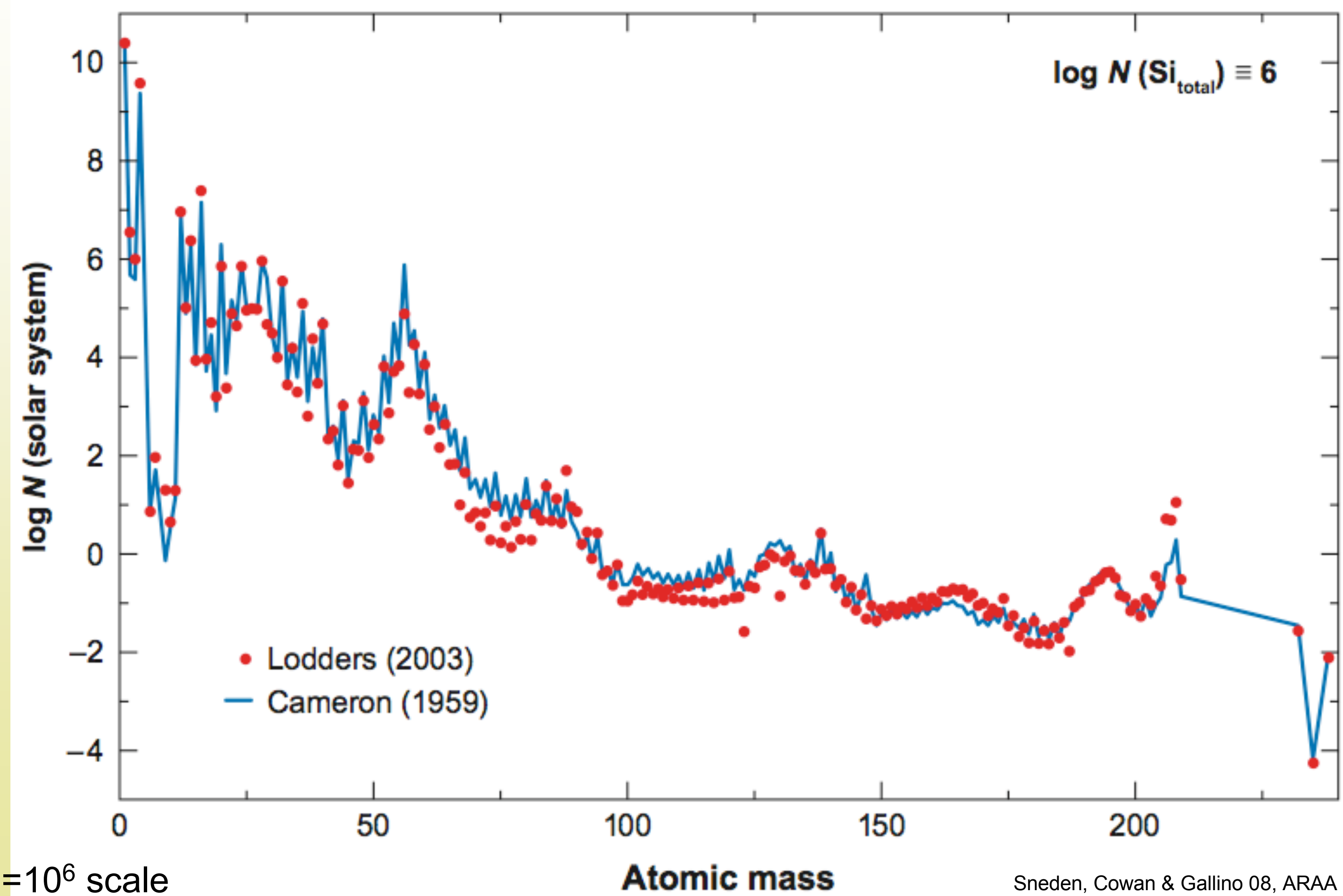



slow neutron-capture process

rapid neutron-capture process

# Solar system abundances "historic" vs today's



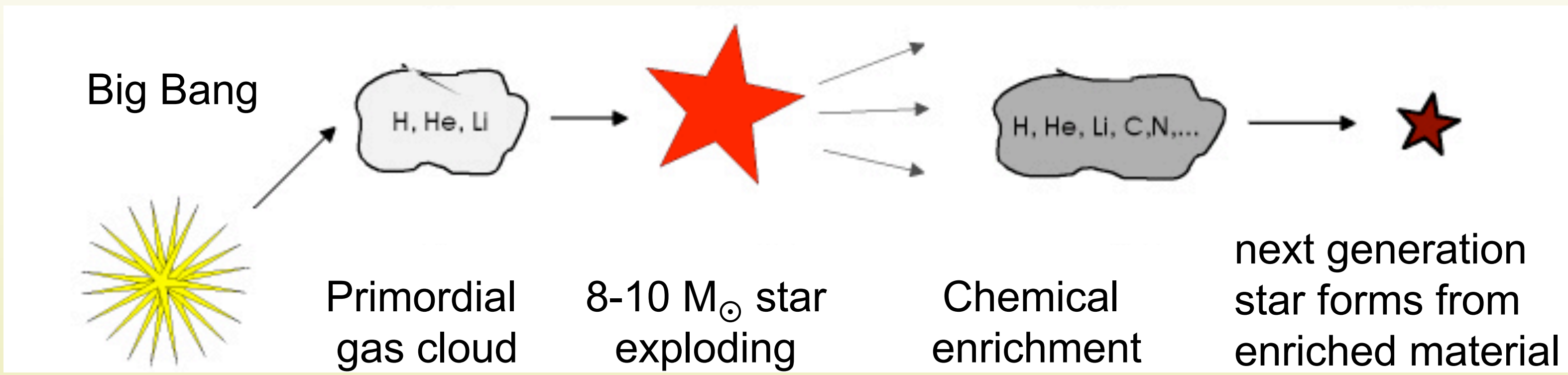


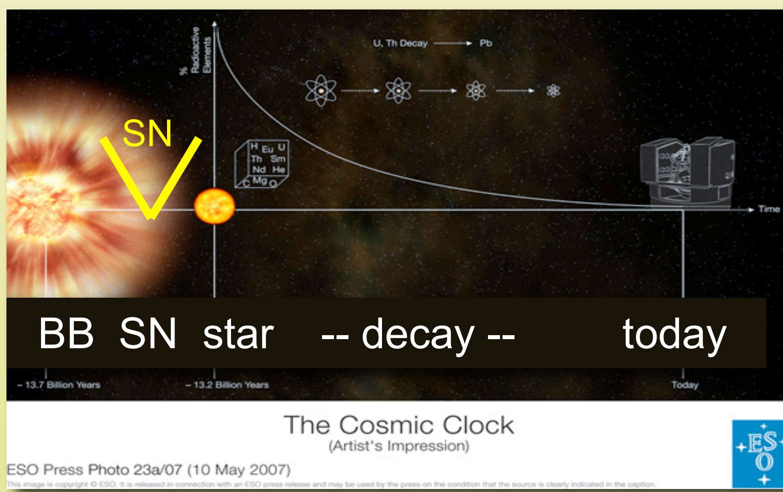

Si =$10^6$ scale (meteoritic)

Sneden, Cowan & Gallino 08, ARAA

# How and when did r-process stars form?

*Star explodes as supernova and ejects the metals into the interstellar medium*



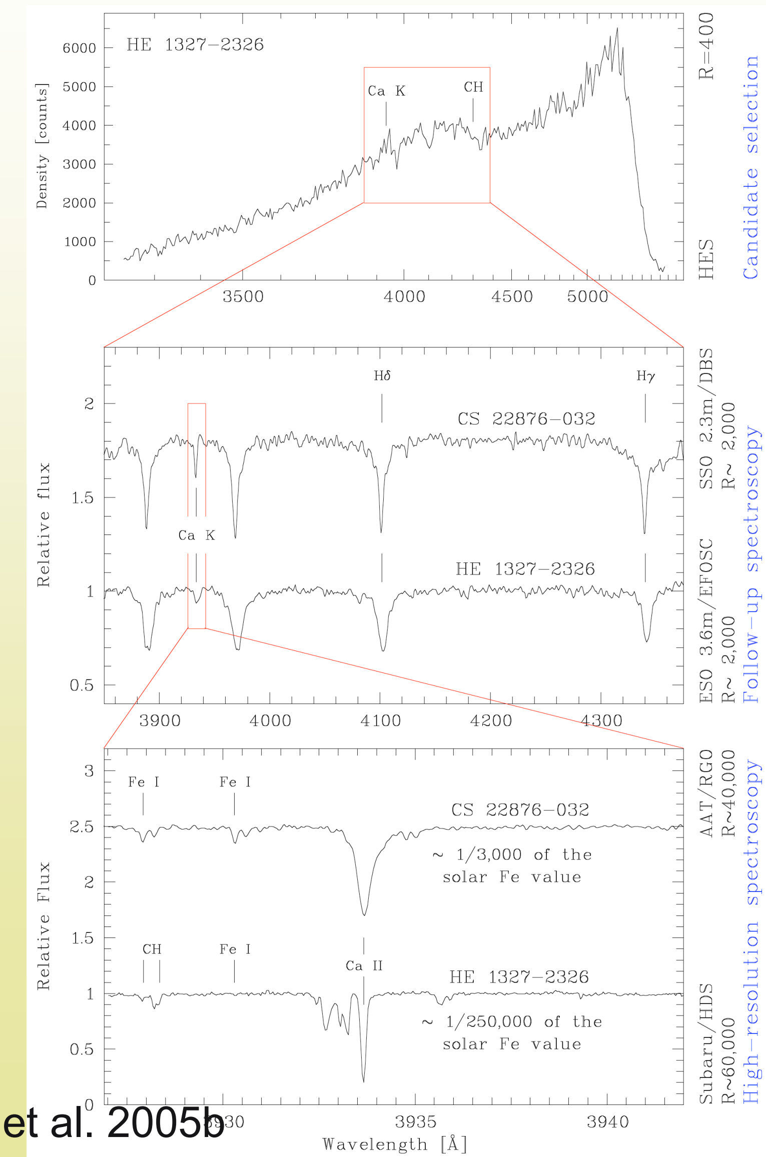
# Metal-poor stars from the Hamburg/ESO survey I

**Three observational steps to find metal-poor stars**

1. Sample selection and visual inspection:
   Find appropriate candidates

2. Follow-up spectroscopy (medium resolution):
   Derive estimate for [Fe/H] from the Ca II K line

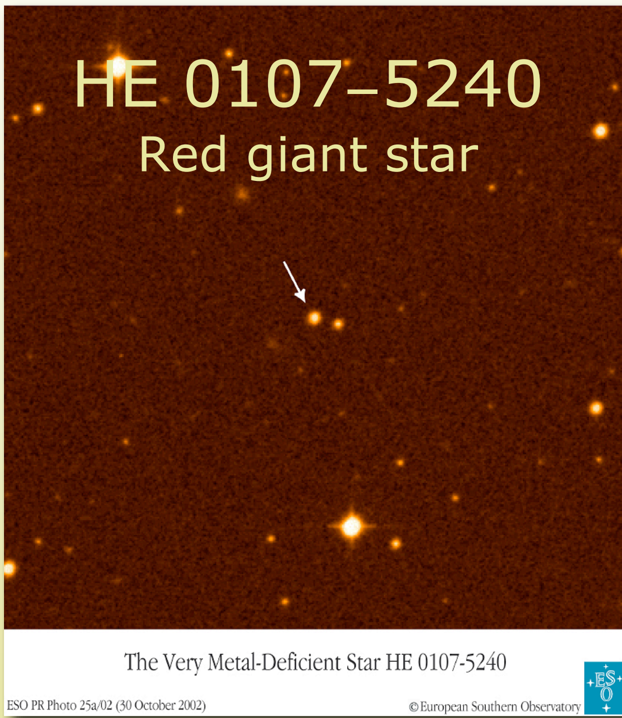
3. High-resolution spectroscopy:
   Detailed abundances analysis



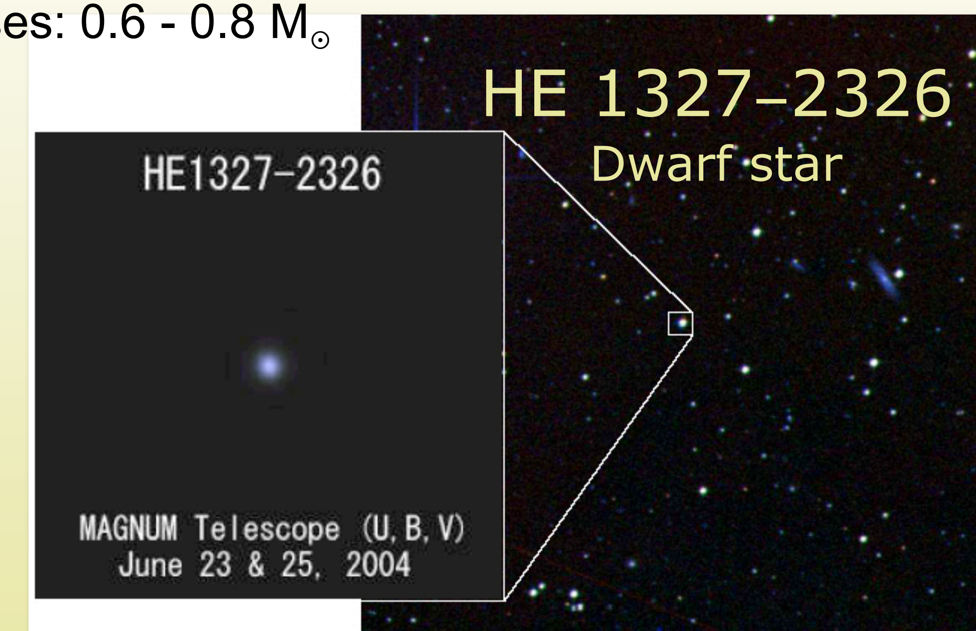

Frebel et al. 2005b

# Metal-poor stars from the Hamburg/ESO survey II

Biggest success of the stellar part of the survey:
**Discovery of the most iron-deficient stars**




Masses: 0.6 - 0.8 $M_{\odot}$




**$[Fe/H]_{NLTE}$ = –5.2**

Christlieb et al. (2002), Nature 419, 904
Christlieb et al. (2004), ApJ 603, 708
Bessell et al. (2004), ApJ 612, L61

**$[Fe/H]_{NLTE}$ = –5.4**

Frebel et al. 2005, Nature 434, 871
Frebel et al. 2006, ApJ 638, L17
Aoki, Frebel et al. 2006, ApJ 639, 897
Frebel et al. 2008, ApJ in press

# Metal-poor stars from the Hamburg/ESO survey III

→ **Hamburg/ESO r-process enhanced star survey (HERES)**
Largest dedicated effort with the Very Large Telescope (VLT) at the European Southern Observatory to discover r-process enhanced stars (lead by N. Christlieb)

Results based on „snapshot" spectra of 350 stars:

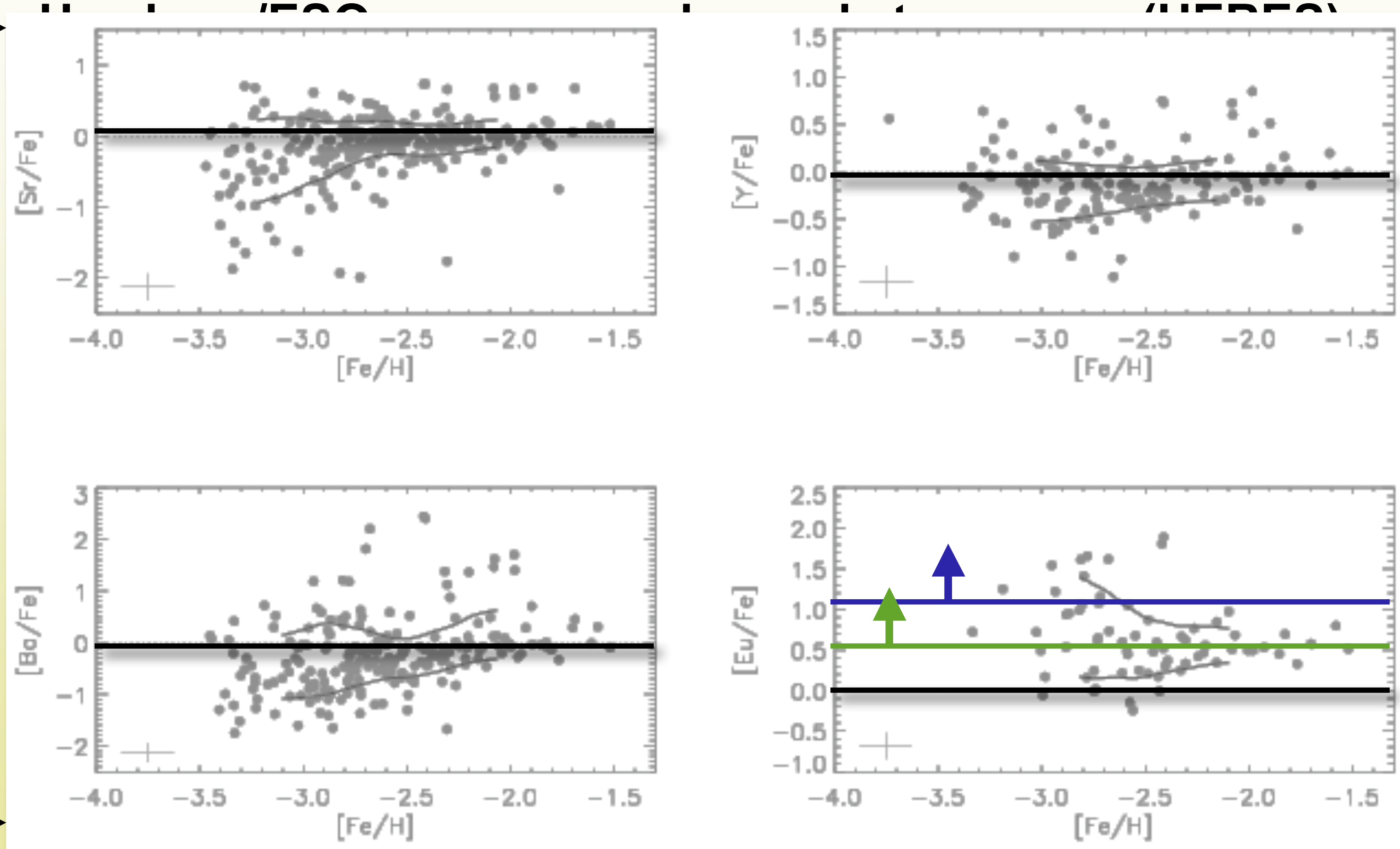
- 10 new strongly r-process enhanced ([r/Fe] > 1.0) stars.

(Total number of known „r-II"-stars increased by a factor of more than 4, from 3 to 13!)

- 40 „mildly" r-process enhanced (0.3 < [r/Fe] < 1.0) stars found

→ **Bright Hamburg/ESO survey sample** (lead by A. Frebel) is also being used to find r-process stars

# Metal-poor stars from the Hamburg/ESO survey III



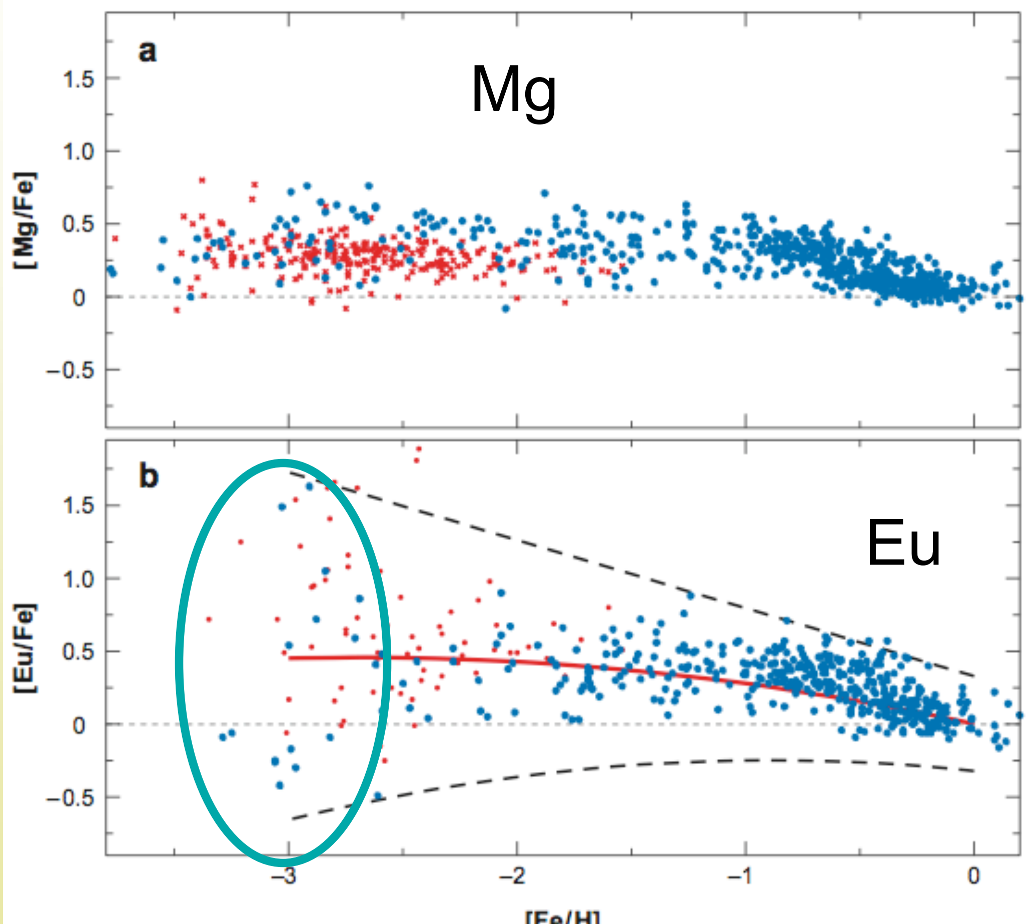

also being used to find r-process stars

# Early Galactic Nucleosynthesis

- Little scatter
- ~0.3 overabundance
- Significant Mg prod. in early Universe by massive stars (which also produce the Fe)

- Large scatter
- Some large overabundances
- Rare production event in the early Universe

r-process nucleosynthesis is not coupled with that of Fe, Mg (produced by different SN mass ranges)



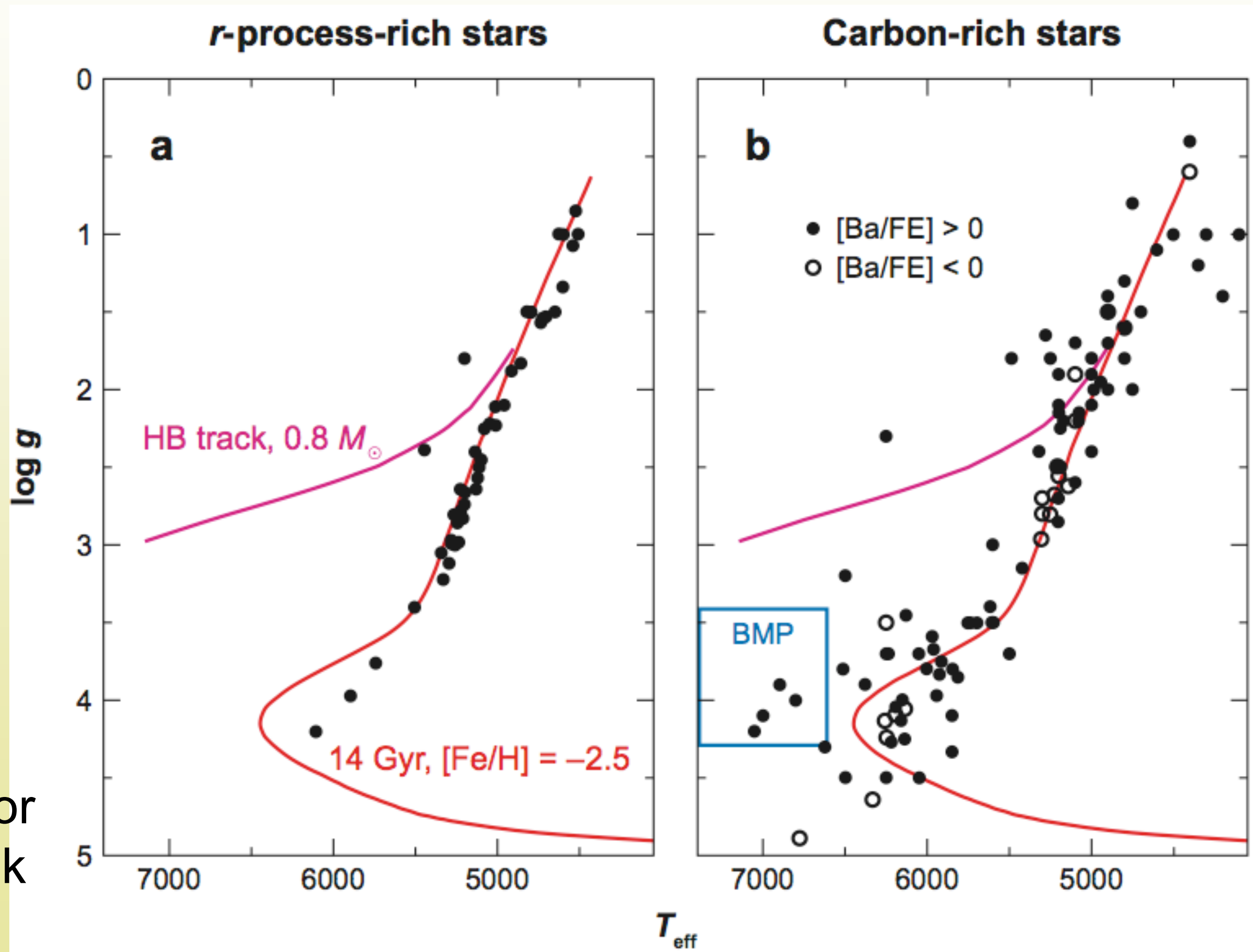

Sneden, Cowan & Gallino 08, ARAA

Early Universe today's

# Hertzsprung-Russell Diagram

14 Gyr isochrone (Demarque et al 2004)

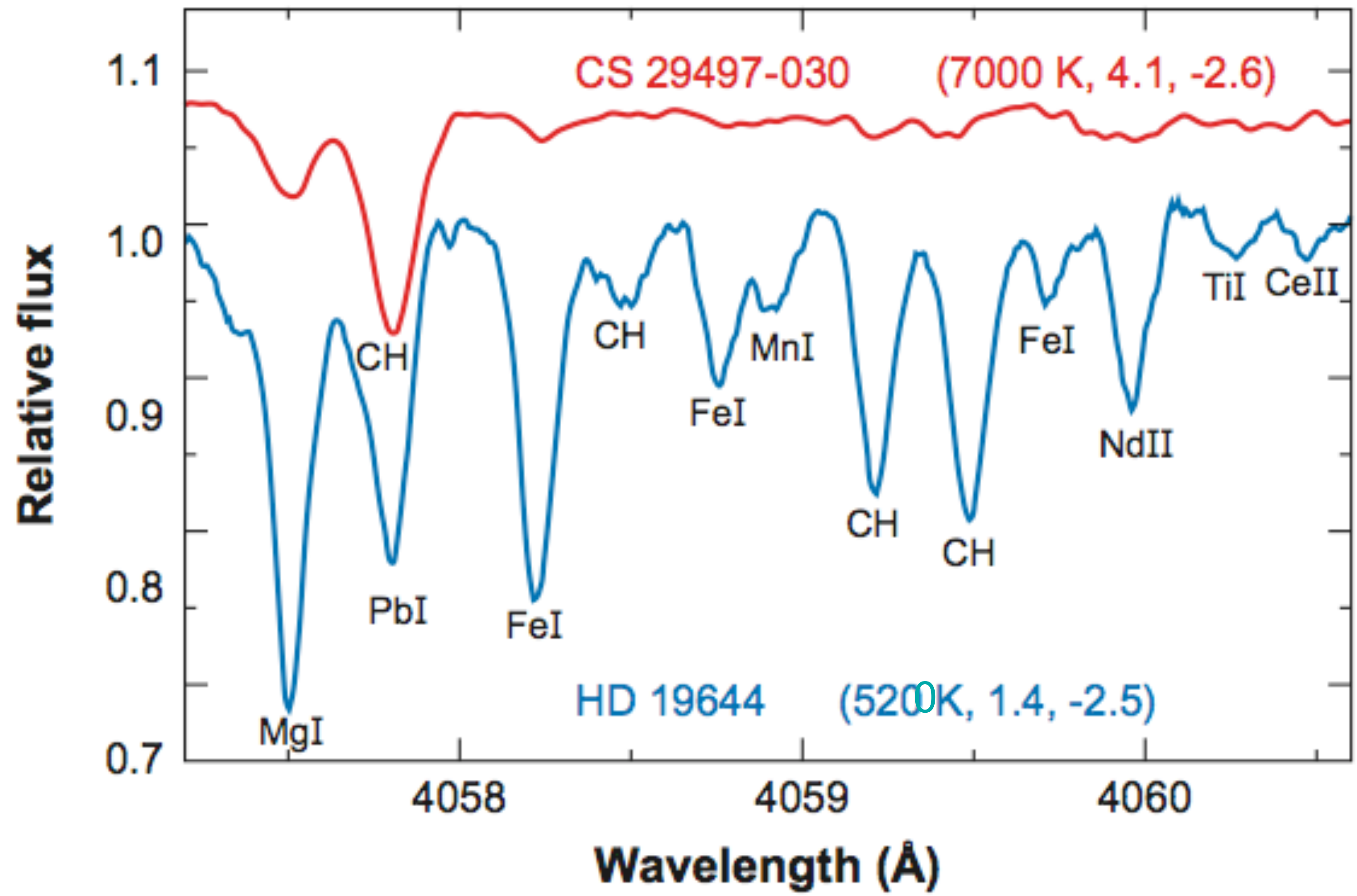
0.8 M⊙ horizontal branch evol. track (Cassisi et al. 2004)



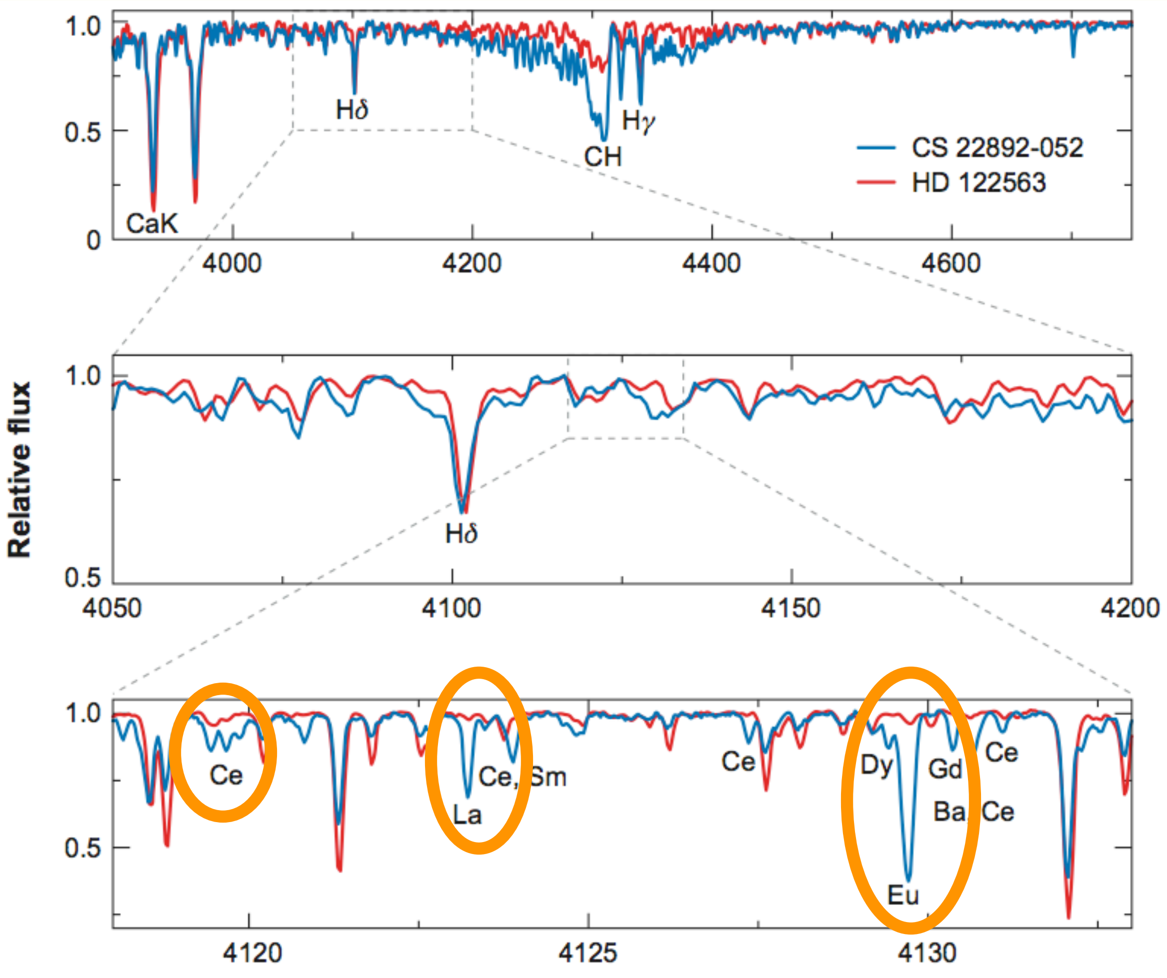

⇒ Cool giants with strong absorption lines

Very important for detection of weak absorption lines

# Hotter/Cooler Stars



# Observing neutron-capture elements

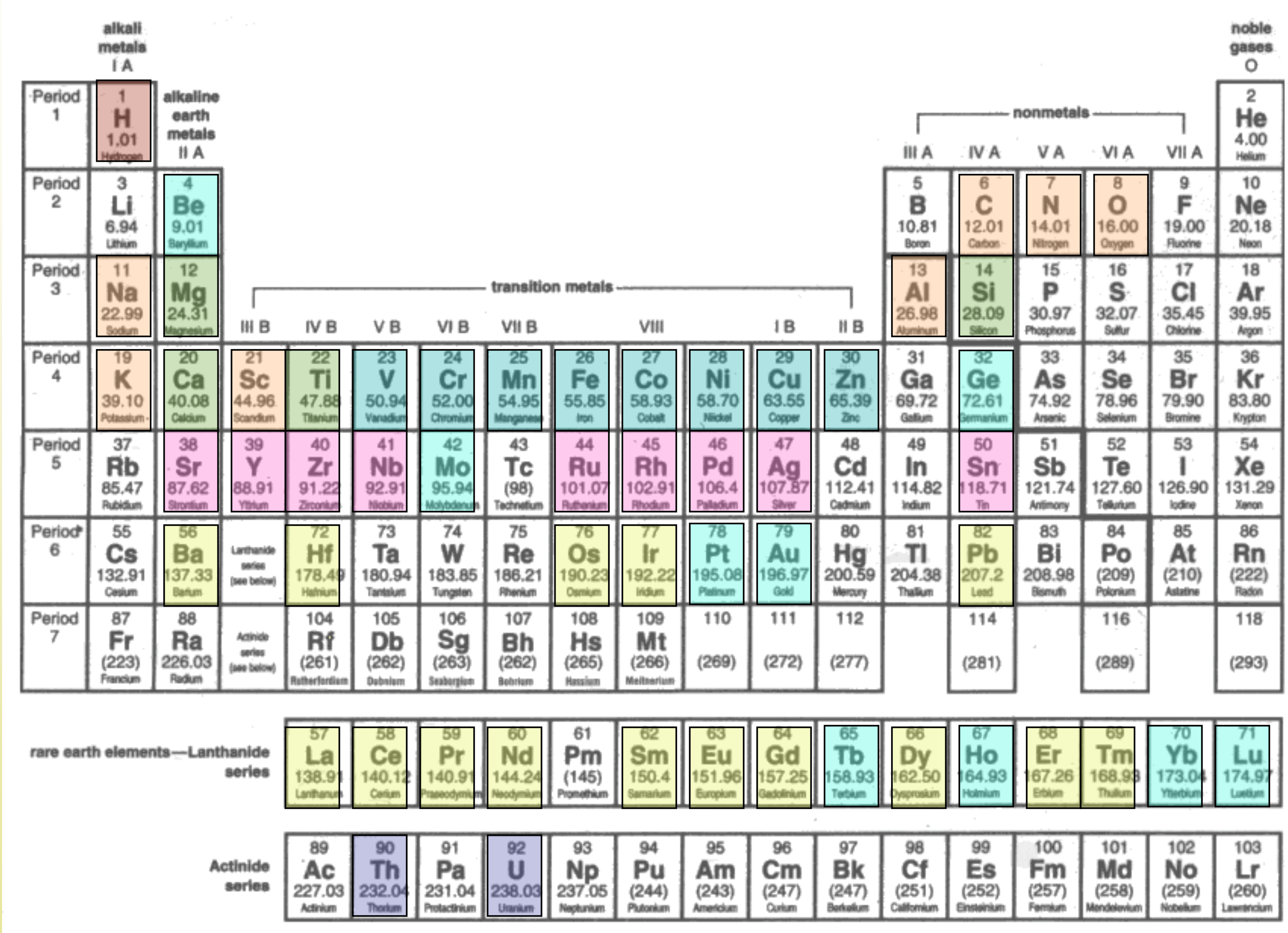



Sneden, Cowan & Gallino 08, ARAA

HD 122563:
r-process deficient star

CS 22892-052:
r-process strong star

# My Cosmic Lab: HE 1523-0901




Anna Frebel

EMMI '08

r-process in the oldest stars

# RAPID NUCLEOSYNTHESIS EVIDENCE: HE 1523-0901

Basic and stellar parameters:

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

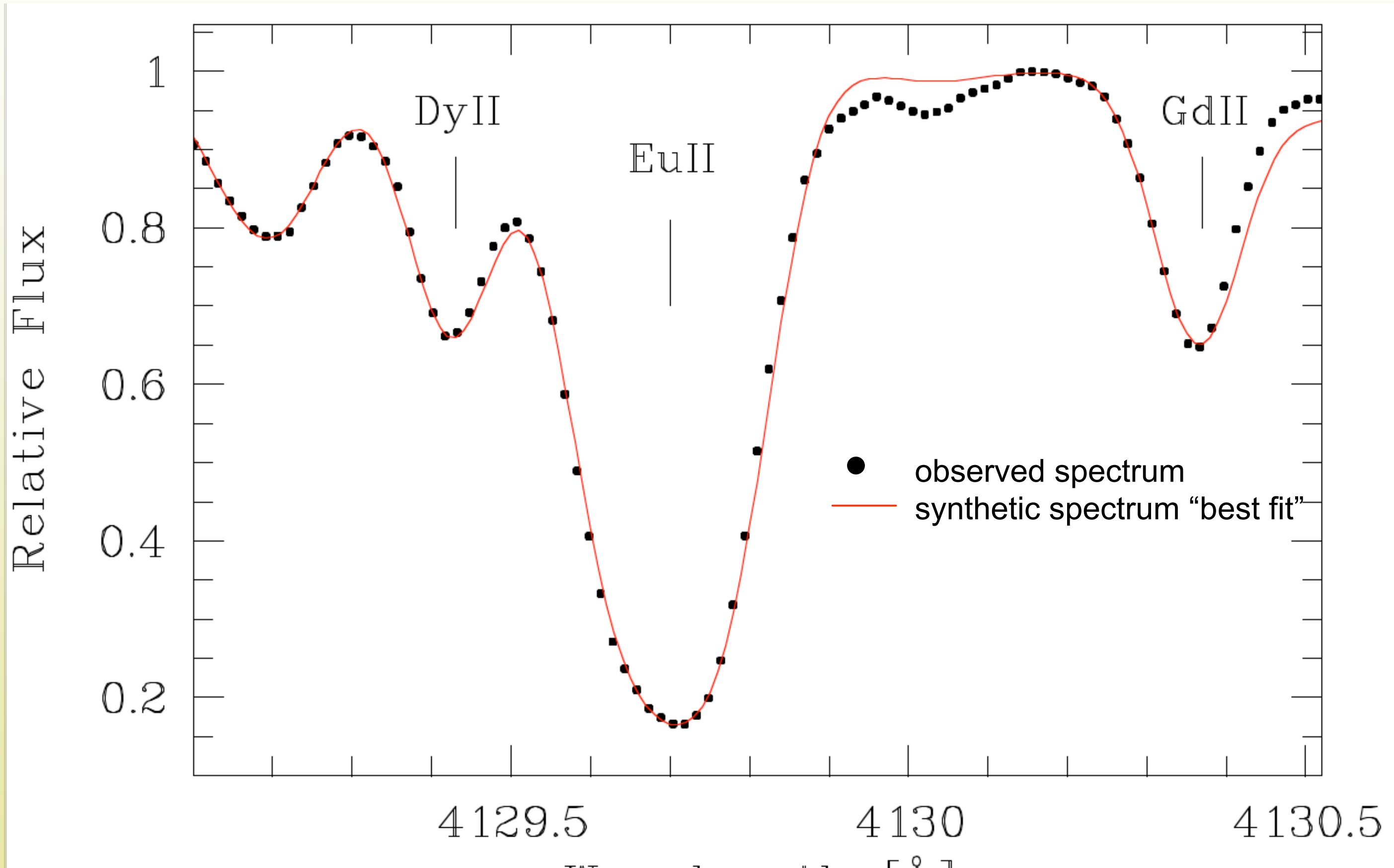
- Effective temp.: $T_{eff} = 4630 \pm 70$K
- Surface gravity: log $g$ = 1.0 (red giant)
- Metallicity: [Fe/H] = −3.0
  "Extremely metal-poor star"

- Frebel et al. 2007, ApJ 660, L117
- Frebel et al. 2008, in prep.

© Anthony Ayiomamitis
(Greek amateur astronomer)


HE 1523-0901 was No. 5!

# What elements can we see in HE 1523-0901?




Frebel et al. (2008), in prep.

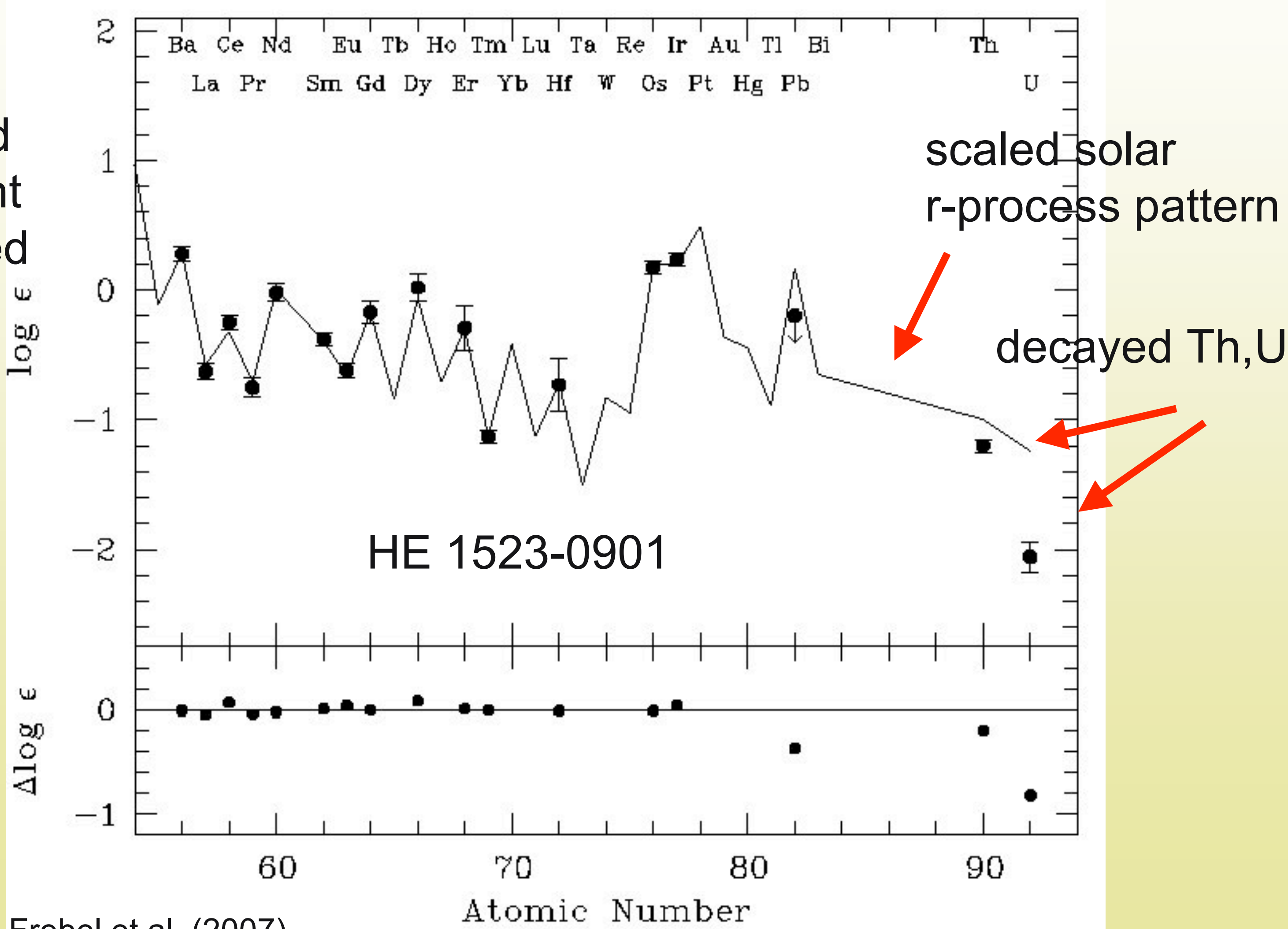
Lanthanides or rare earth elements: i.e. Eu, Gd, Dy

R-process in the oldest stars    EMMI '08    Anna Frebel

# The r-Process Pattern

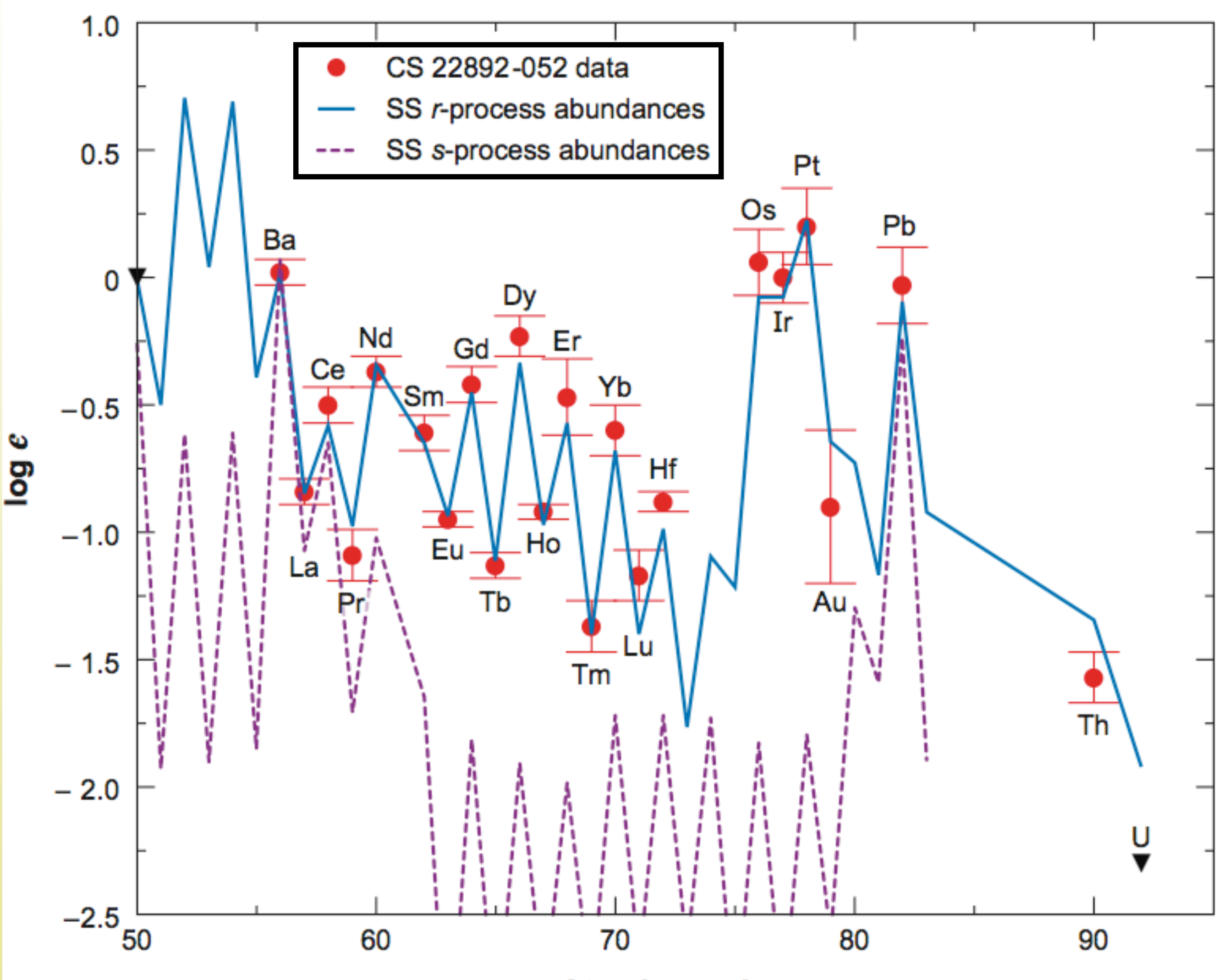


Very good agreement with scaled solar r-process pattern for Z>56




Frebel et al. (2007)

# Comparison w/ r- and s-process patterns

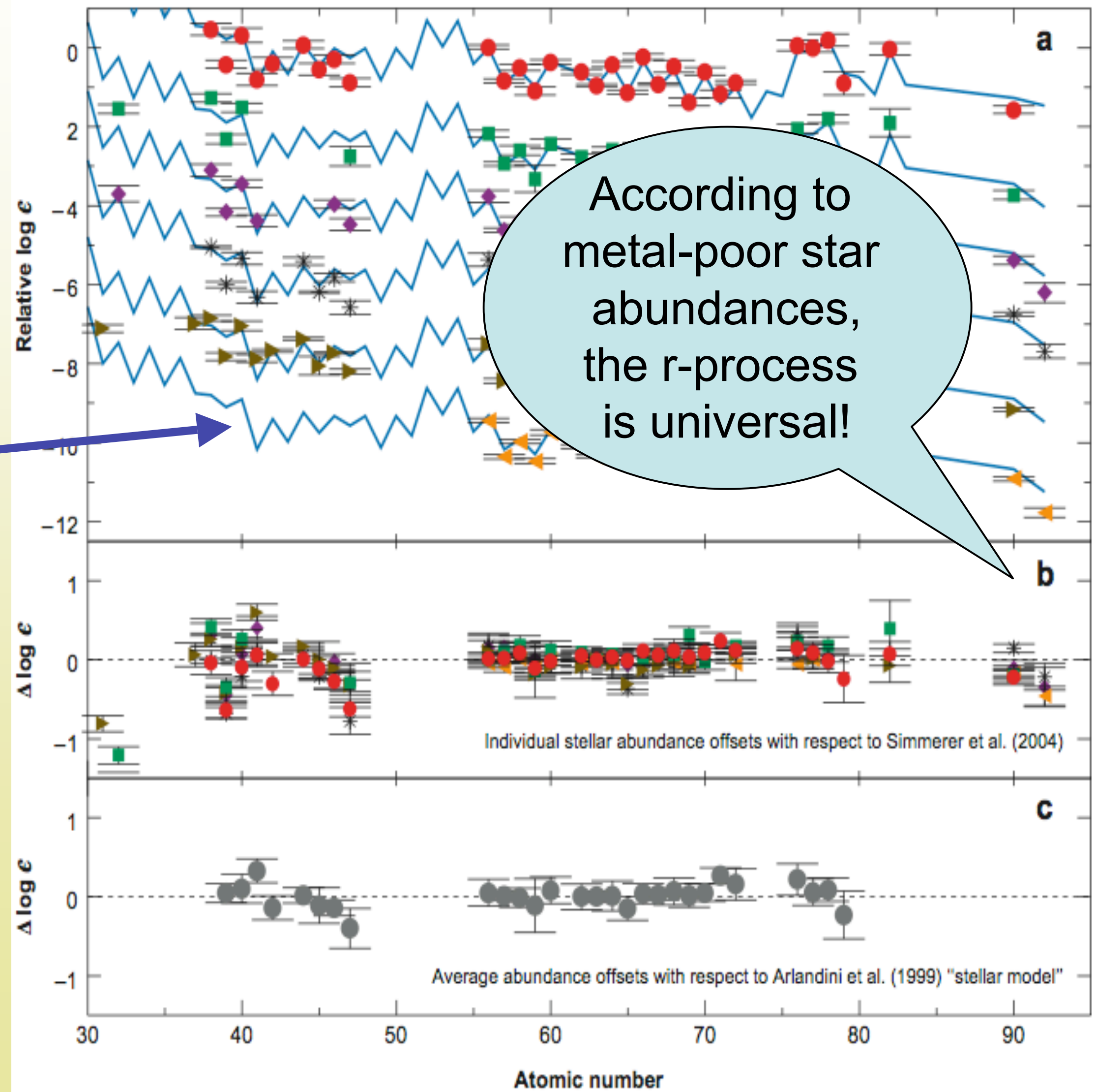



Sneden, Cowan & Gallino 08, ARAA

# Precision at work

- CS 22892-052: Sneden et al. (2003)
- HD 115444: Westin et al. (2000)
- BD+17°324817: Cowan et al. (2002)
- CS 31082-001: Hill et al. (2002)
- HD 221170: Ivans et al. (2006)
- HE 1523-0901: Frebel et al. (2007)

Scaled *solar system* neutron-capture element pattern!



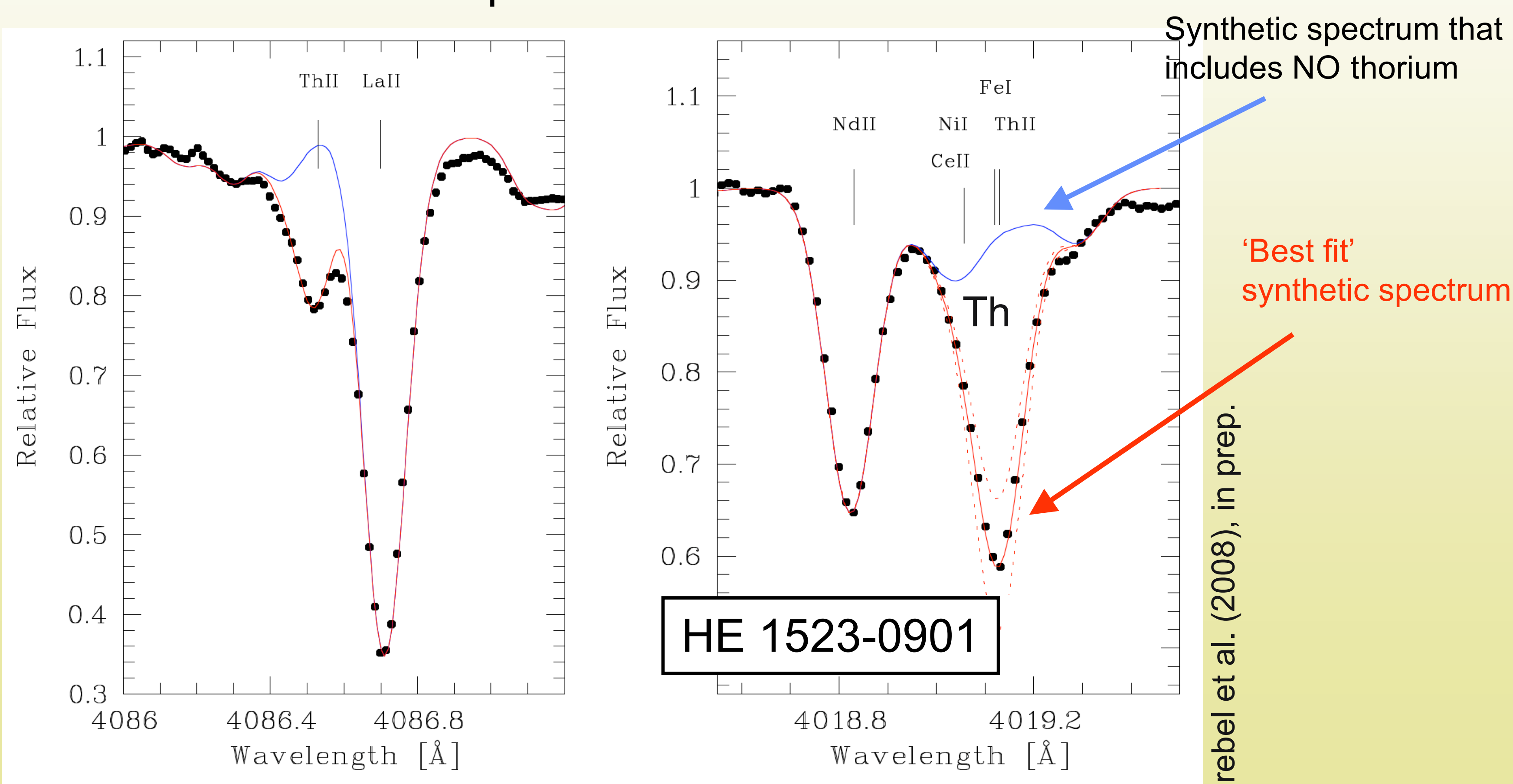

Individual stellar abundance offsets wrt to Simmerer et al. 2004

Average abundance offset wrt to Arlandini et al 1999 ("stellar model")

Sneden, Cowan & Gallino 08, ARAA

# Thorium II Lines in HE 1523-0901

Abundance:
Synthetic spectrum (based on atomic data and model atmosphere) to match observed spectrum

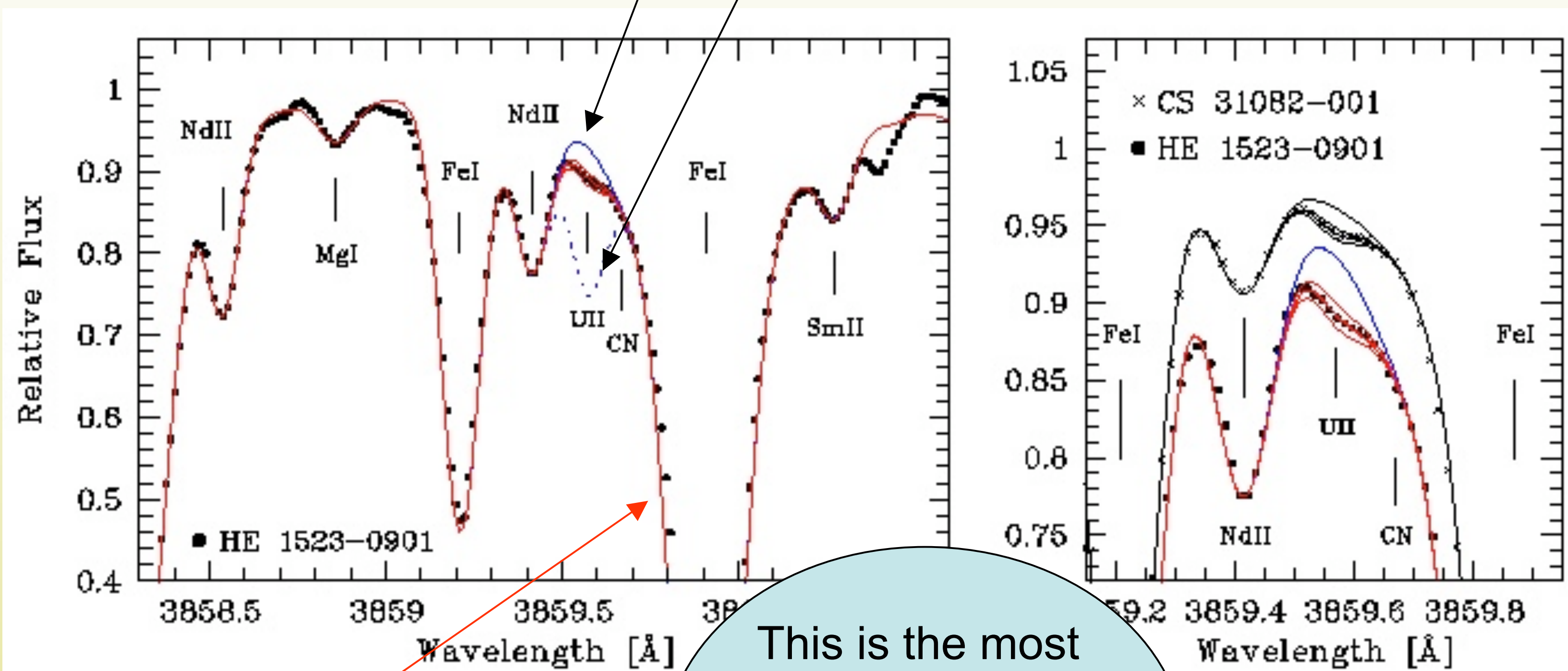



Frebel et al. (2008), in prep.

# Uranium in HE 1523-0901

Synthetic spectrum that includes NO uranium

Synthetic spectrum with U abundance if it had NOT decayed




Frebel et al. (2007)

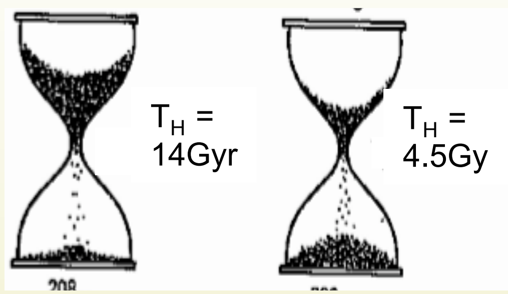
‘Best fit’ synthetic spectrum

This is the most reliable U detection! Only *two more* stars have measured U abundances.

This is the only available li … ngth range!

# Cosmo-Chronometry relies on observations..

$^{232}Th$ $^{238}U$




$^{208}Pb$ $^{206}Pb$

$$\Delta t = 46.8 * (\log (Th/r)_0 - \log (Th/r)_{obs})$$

$$\Delta t = 14.8 * (\log (U/r)_0 - \log (U/r)_{obs})$$

$$\Delta t = 21.8 * (\log (U/Th)_0 - \log (U/Th)_{obs})$$

Th/Eu: "most commonly" used chronometer
"famous" example: CS22892-052
~14-15Gyr; (Sneden et al. 96,03)

U/Th: Uranium only confidently measured
in **one** star before: CS31082-001
~14Gyr (Cayrel et al. 01, Hill et al. 02);

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

=> Ultimate goal: Use as many chronometers as possible

# The Age of HE 1523-0901

| Element ratio | Age [billion yrs] | $\sigma_{obs/Teff/log\ g/vmicr/PR}$ |
|---|---|---|
| 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 age** | **~13 billion years** | |

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

WMAP age of the Universe: 13.7 Gyr

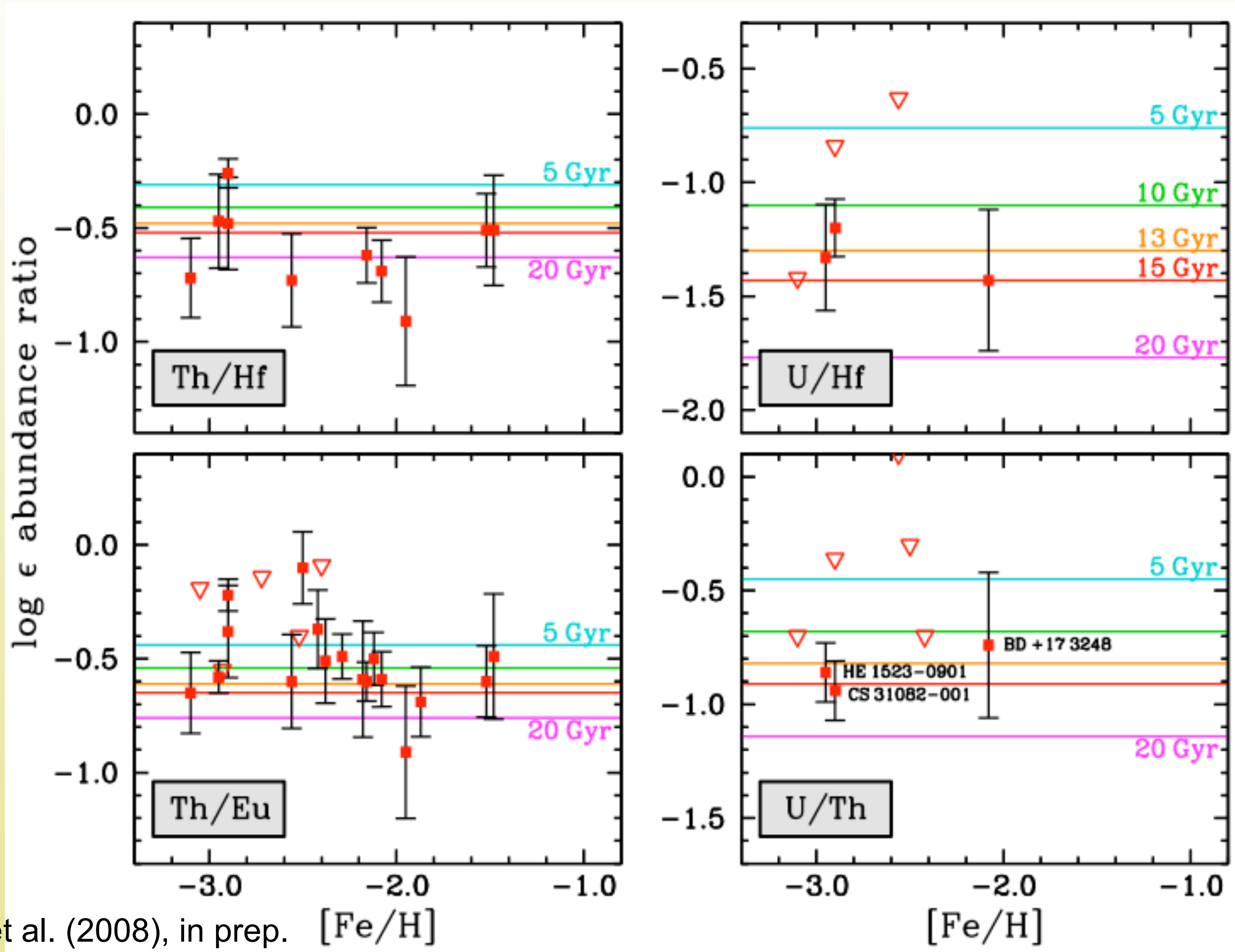
The first time more than one chronometer could be employed in a star to measure the age!

⇒ Confirms the old age of metal-poor stars and their low-mass (to reach old age)

⇒ Independent lower limit for the age of the Universe

# Chronometric Ages

Initial production ratios for nucleosynthesis taken from Schatz et al. 2002




Roederer et al. (2008), in prep.

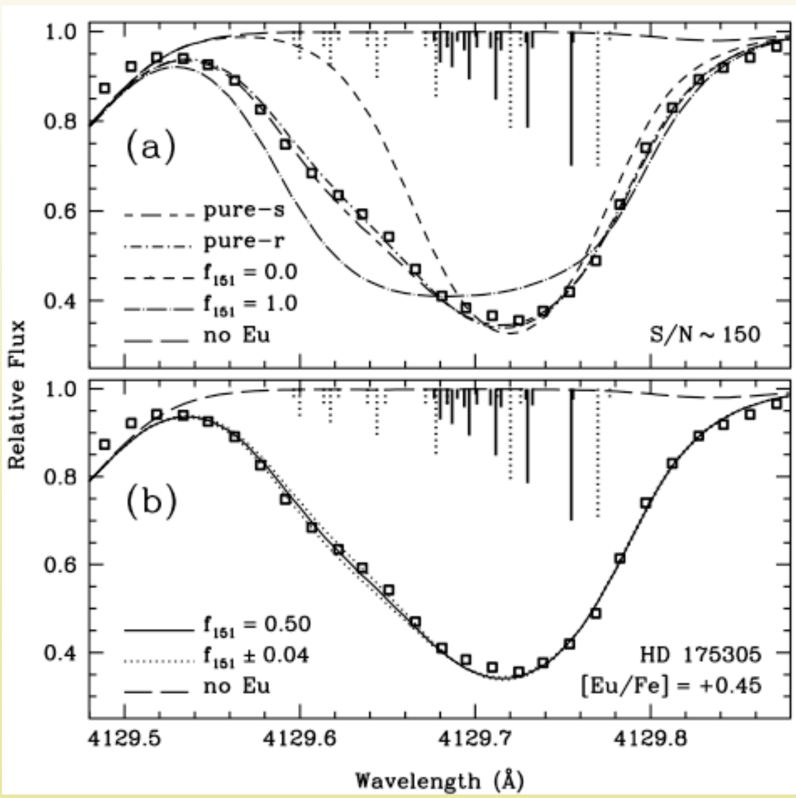
# "Reverse engineering" or: let the observers make some predictions

- Assume age for star, e.g. 13 Gyr
- Take observed ratios (at face value) & calculate initial prod. ratios
- Need star(s) with many measured chronometer ratios.
  Only available so far: HE 1523-0902 => *NEED MORE STARS!!!*

| Ratio | Observed ratios | Derived initial prod. ratio derived from HE1523-0901 | Derived ages (Gyr) | Stars |
|---|---|---|---|---|
| Th/Eu | -0.62, -0.51, -0.60, -0.60 | -0.222 | 18.6, 13.5, 17.7, 17.7 | CS 22892-052, BD 17 3248, HD221170, HD 115444 |
| Th/Os | -1.59, -1.63 | -1.022 | 26.6, 28.5 | CS 22892-052, BD 17 3248 |
| Th/Ir | -1.47, -1.48 | -1.082 | 18.2, 18.6 | CS 22892-052, BD 17 3248 |
| U/Eu | -1.33 | -0.562 | 11.4 | BD 17 3248 |
| U/Os | -2.45 | -1.362 | 16.1 | BD 17 3248 |
| U/Ir | -2.30 | -1.422 | 13.0 | BD 17 3248 |
| U/Th | -0.82 | -0.344 | 10.4 | CS 31082-001 |

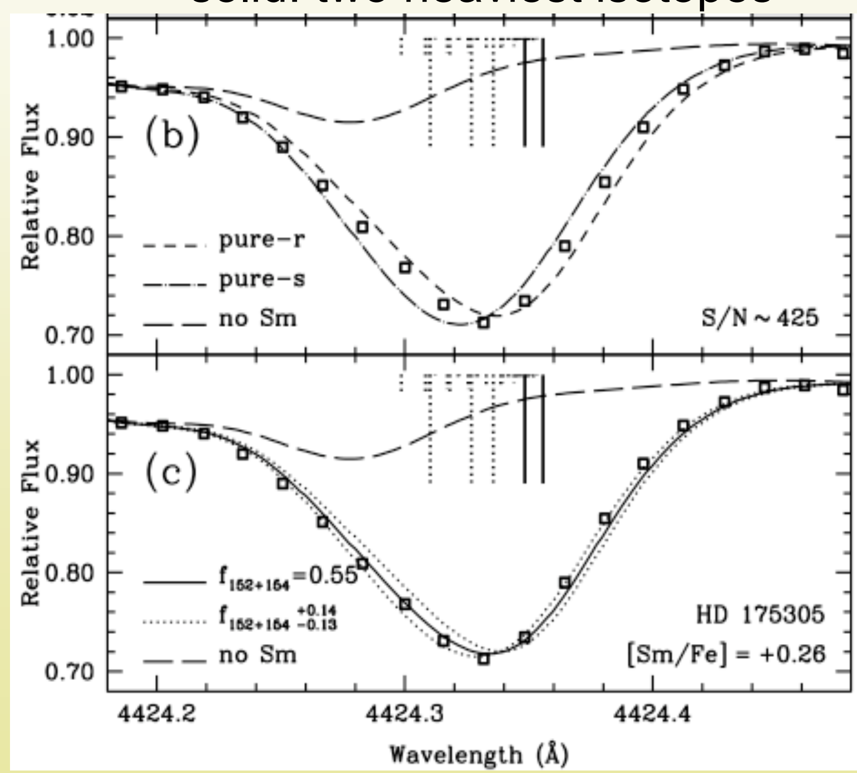
# Measuring isotope ratios in an r-process star

**Eu** relative strength of hyperfine components
dotted: $^{151}$Eu; solid: $^{153}$Eu




$f_{151}$=0.50+-0.04

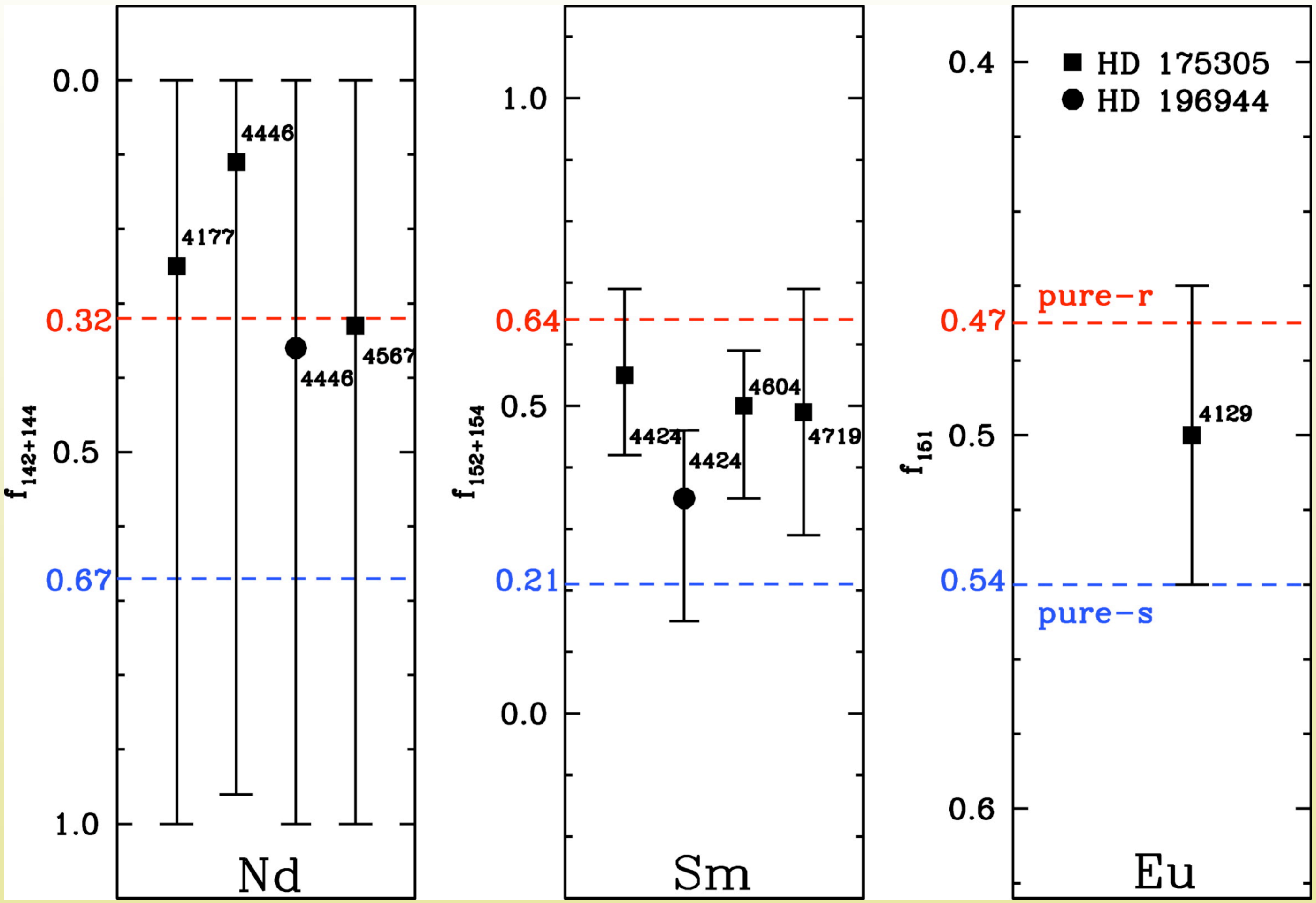
**Sm** relative strength of hyperfine components
dashed: lighter 5 isotopes;
solid: two heaviest isotopes




$f_{152+154}$=0.55+0.14-0.13

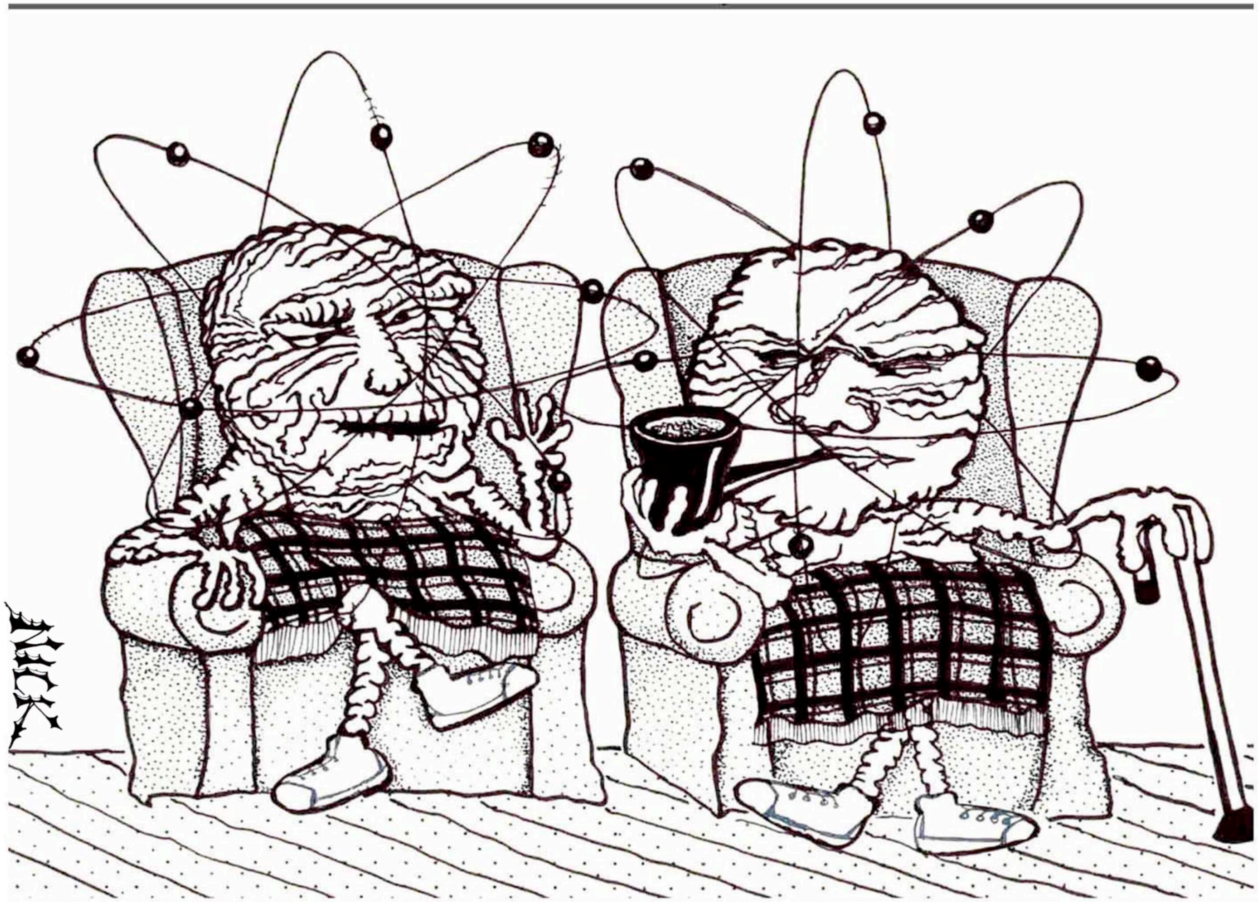
Roederer et al. 2008

# IT'S A TOUGH LIFE...



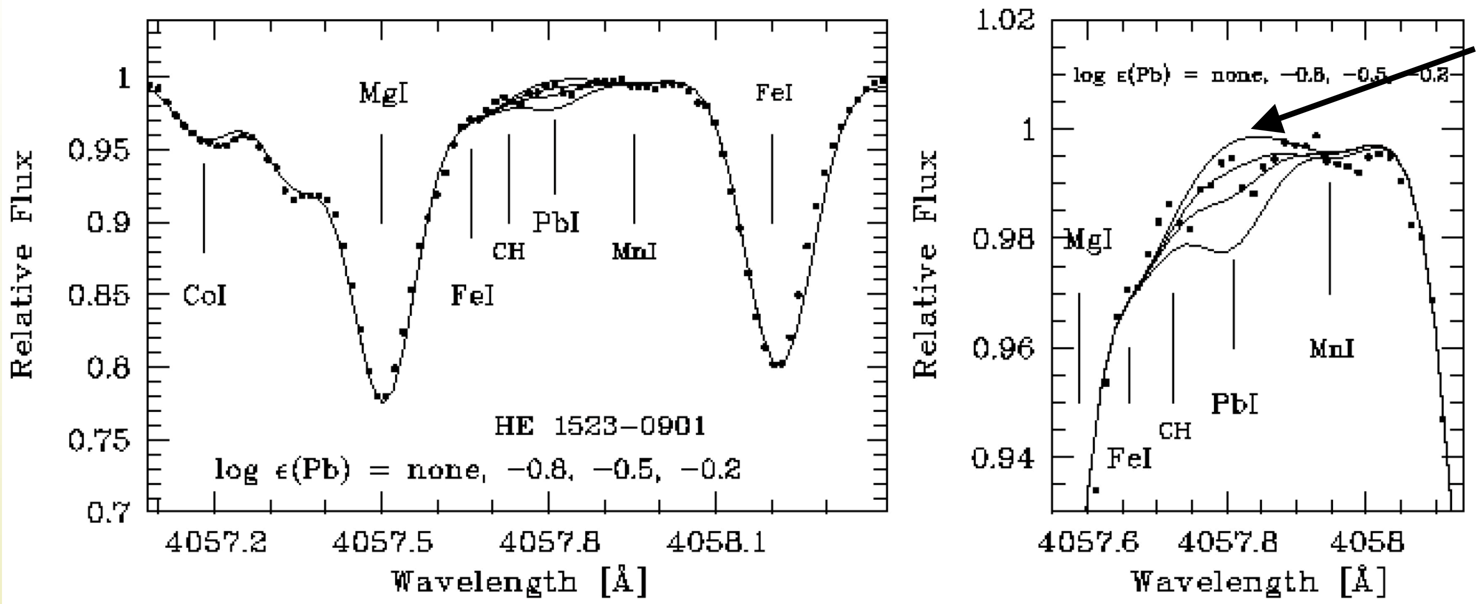

Roederer et al. 2008

**At the home for old atoms...**



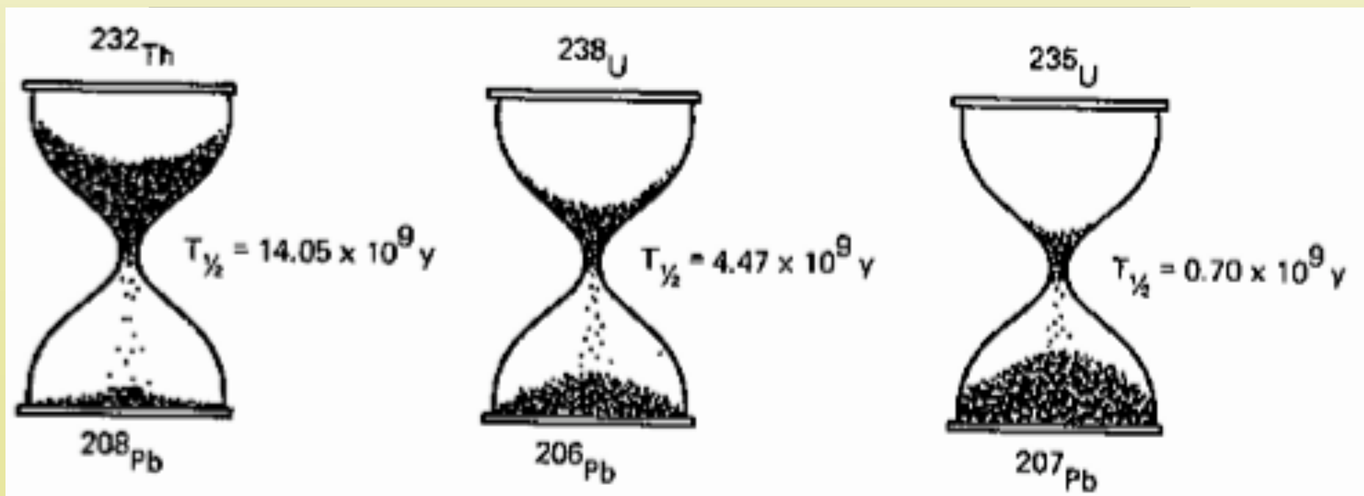
*"When I was young I used to feel so alive and dangerous! Would you believe I started life as a uranium-238? Then one day I accidentally ejected an alpha particle. Now look at me—a spent old atom of lead-206. It seems that all my life since then has been nothing but decay, decay, decay..."*

# Lead in HE 1523-0901




Synthetic spectrum that includes NO lead

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



# Lead production



**Pb production channels:**

- Pb production from decay of Th and U
- additional production channels

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

**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)

*More observational data needed to attempt the difficult lead measurement!!*

# Lead abundance prediction

| | t=0 | t=13 Gyr | HE 1523-0901 | CS31082-001 |
|---|---|---|---|---|
| **log(Th/U)** | **0.26** | **0.84** | **0.86** | **0.89** |
| **log(Th/Pb)** | **-1.327** | **-1.316** | **>-1.0** | **-0.43** |
| **log(U/Pb)** | **-2.208** | **-2.161** | **>-1.9** | **-1.32** |
| **log(Pb)** | **-0.426** | **-0.346** | **<-0.2** | **-0.55** |

good agreement...!

...bad agreement!

Classical “waiting-point r-process model” calculations (by KL Kratz)

# Conclusion

**Observations**

- ✓ Stars are cosmic lab for studying the r-process
- ✓ Ideally, a whole suite of chronometers (= element ratios) is employed to obtain stellar ages
- ✓ Confirm the (assumed) old age of these stars
- ✓ Independent lower limit to age of the Universe
- ✓ Ages have large systematic uncertainties

**Theory wish list & Future work**

- ➢ More stars with detected U + Pb are needed to further constrain nucleosynthesis processes
- ➢ Best possible production ratios are needed!
- ➢ Reverse-engineering: initial production ratios from stars
- ➢ Any fainter stars will require 30m telescopes to achieve very high S/N ratio necessary for the U + Pb detections

**Combining the chemical abundances and ages of old halo stars, their kinematic information, and the theoretical understanding of nucleosynthesis & star formation processes in the early Universe will provide us with new, exciting insight into the formation history of our Galaxy!**

# Good luck EMMI!

"All men have the stars," he answered, "but they are not the same things for different people. For some, who are travelers, the stars are guides. For others they are no more than little lights in the sky. **For others, who are scholars, they are problems**. [..]. But all these stars are silent. You --you alone-- will have the stars as no one else has them--" [..]

The Little Prince