



NUCLEO-CHRONOMETRY OF THE OLDEST STARS

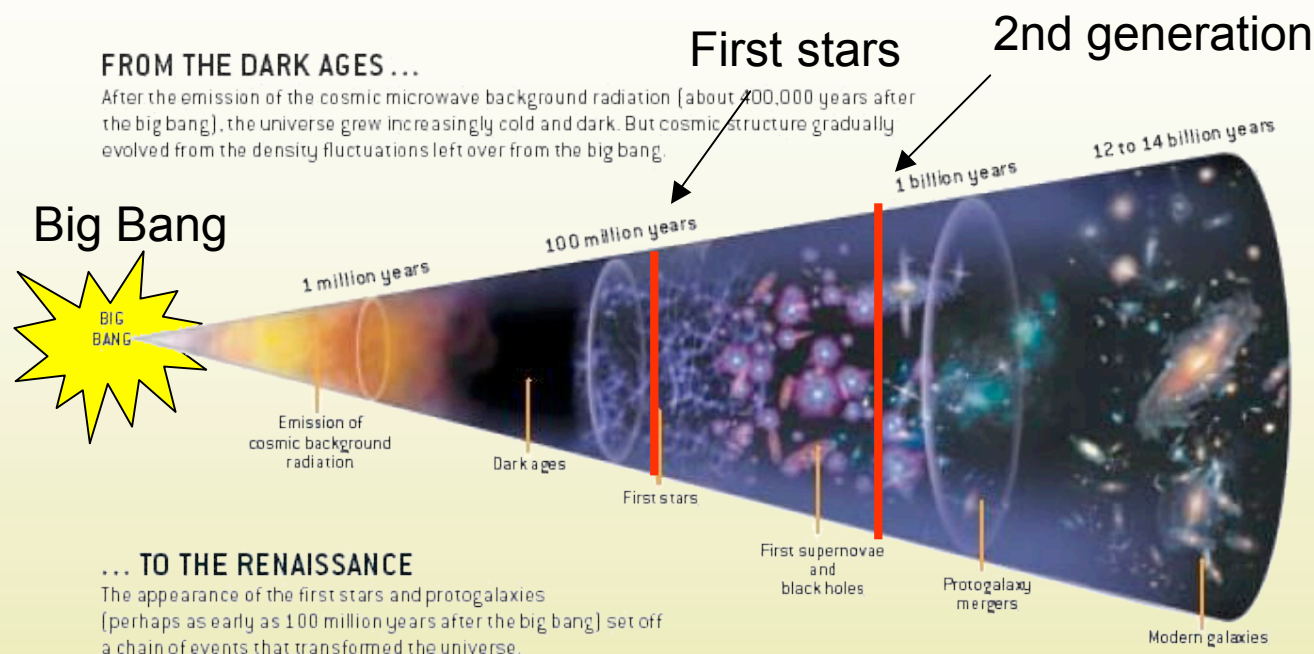
Anna Frebel

W. J. McDonald Fellow

McDonald Observatory

The University of Texas at Austin

COSMIC TIMELINE



... TO THE RENAISSANCE

The appearance of the first stars and protogalaxies (perhaps as early as 100 million years after the big bang) set off a chain of events that transformed the universe.

www.sciam.com

Larson & Bromm 2001
SCIENTIFIC AMERICAN ?

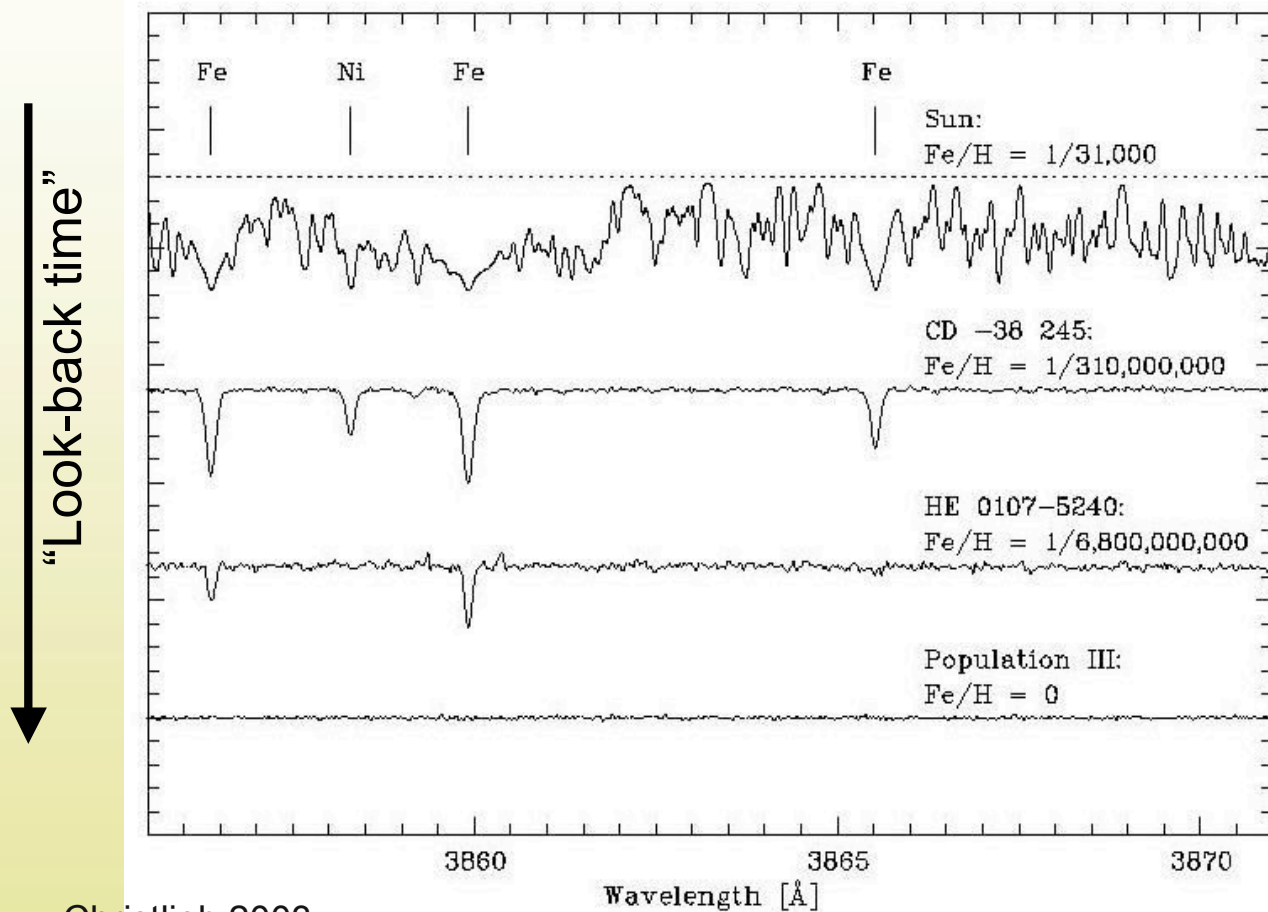
Theory

Observations

my research interest

Time

SPECTRAL COMPARISON



Christlieb 2003

[Fe/H]=0

[Fe/H]=-4

[Fe/H]=-5.3

*Pop III star
(just noise...?!?)*

$$[\text{Fe}/\text{H}] = \log(\text{NFe}/\text{NH})_* - \log(\text{NFe}/\text{NH})_{\odot}$$

WHAT CAN WE LEARN FROM METAL-POOR STARS?

$M < 1 M_{\odot}$; lifetimes > 10 Gyr; turnoff stars and giants

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

- the origin and evolution of the elements
- the involved nucleosynthesis processes

⇒ ideal tracers of the chemical evolution of their host galaxy

- ⇒ chemical history
- ⇒ dynamical history
- ⇒ galaxy formation and evolution

Near-field cosmology

- abundance patterns provide constraints on the first SN yields
=> the first stars
- easily accessible local equivalent of the high-redshift Universe

REVIEWS OF MODERN PHYSICS

VOLUME 29, NUMBER 4

OCTOBER, 1957

B²FH

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*

XI. Variations in Chemical Composition among Stars, and Their Bearing on the Various Synthesizing Processes.....	620
A. Hydrogen Burning and Helium Burning.....	621
B. α Process.....	626
C. Synthesis of Elements in the Iron Peak of the Abundance Curve, and the Aging Effect as It Is Related to This and Other Types of Element Synthesis.....	626
D. s Process.....	627
E. r Process.....	629
F. p Process.....	629
G. x Process.....	629
H. Nuclear Reactions and Element Synthesis in Surfaces of Stars.....	629

E. r Process

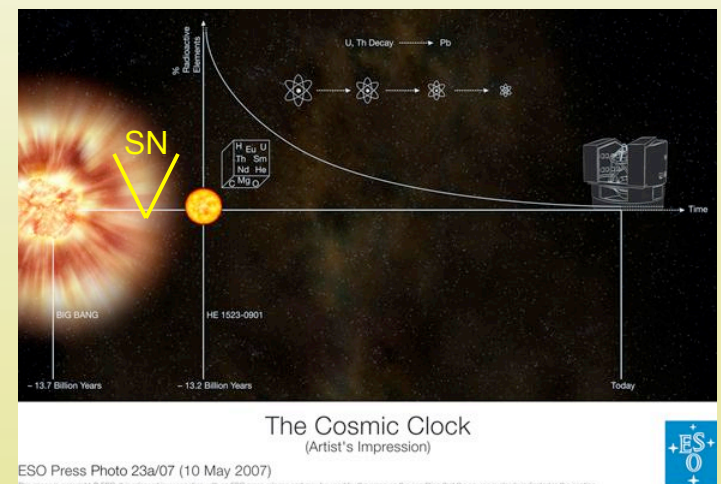
The outstanding piece of observational evidence that this takes place is given by the explanation of the light curves of supernovae of Type I as being due to the decay of Cf²⁵⁴ (Bu56, Ba56), together with some other isotopes produced in the r process. Further evidence can be obtained only by interpreting the spectra of Type I supernovae, a problem which has so far remained unsolved.

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

R-PROCESS ENHANCED STARS

(RAPID NEUTRON-CAPTURE PROCESS)

- Responsible for the production of heavy elements
- Most likely production site: SN type II => pre-enrichment
- Chemical “fingerprint” of previous nucleosynthesis event
- ~5% of metal-poor stars with $[\text{Fe}/\text{H}] < -2.5$ (Barklem et al. 05)
=> Only ~12 stars known so far with $[r/\text{Fe}] > 1.0$
- **Nucleo-chronometry:** obtain stellar ages from decaying Th, U and stable r-process elements (e.g. Eu, Os, Ir)



HALO METALLICITY DISTRIBUTION FUNCTION

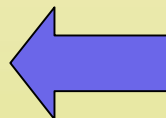
Plus

HE0557-4840, $[\text{Fe}/\text{H}] = -4.8$

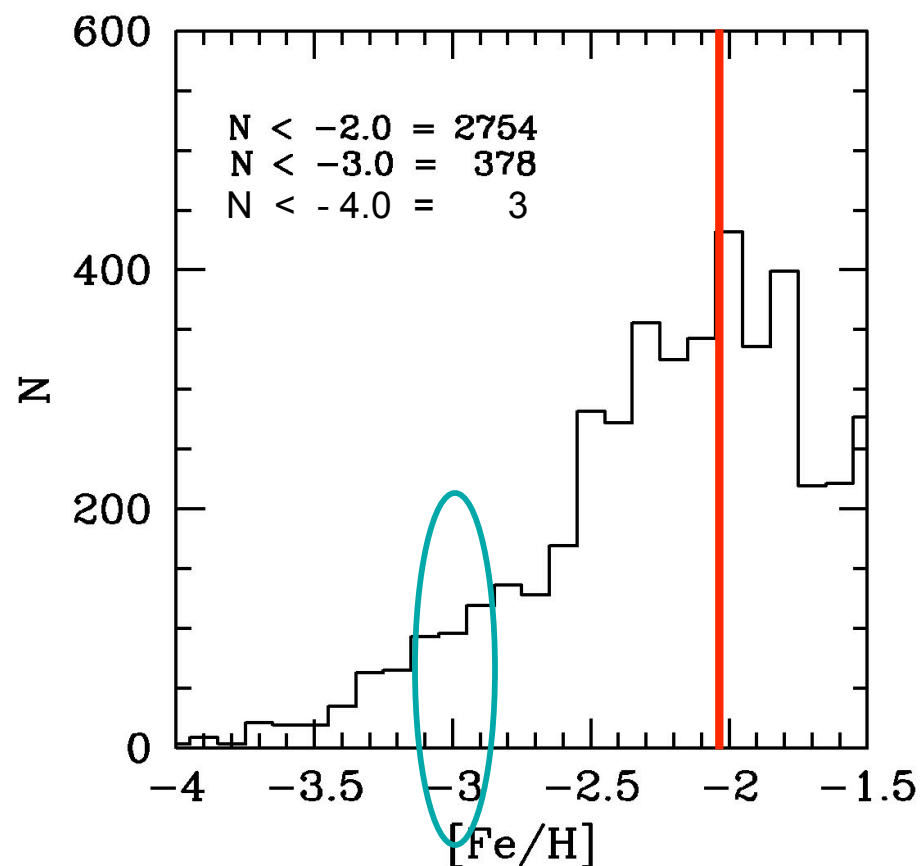
HE0107-5240, $[\text{Fe}/\text{H}] = -5.3$

HE1327-2326, $[\text{Fe}/\text{H}] = -5.4$

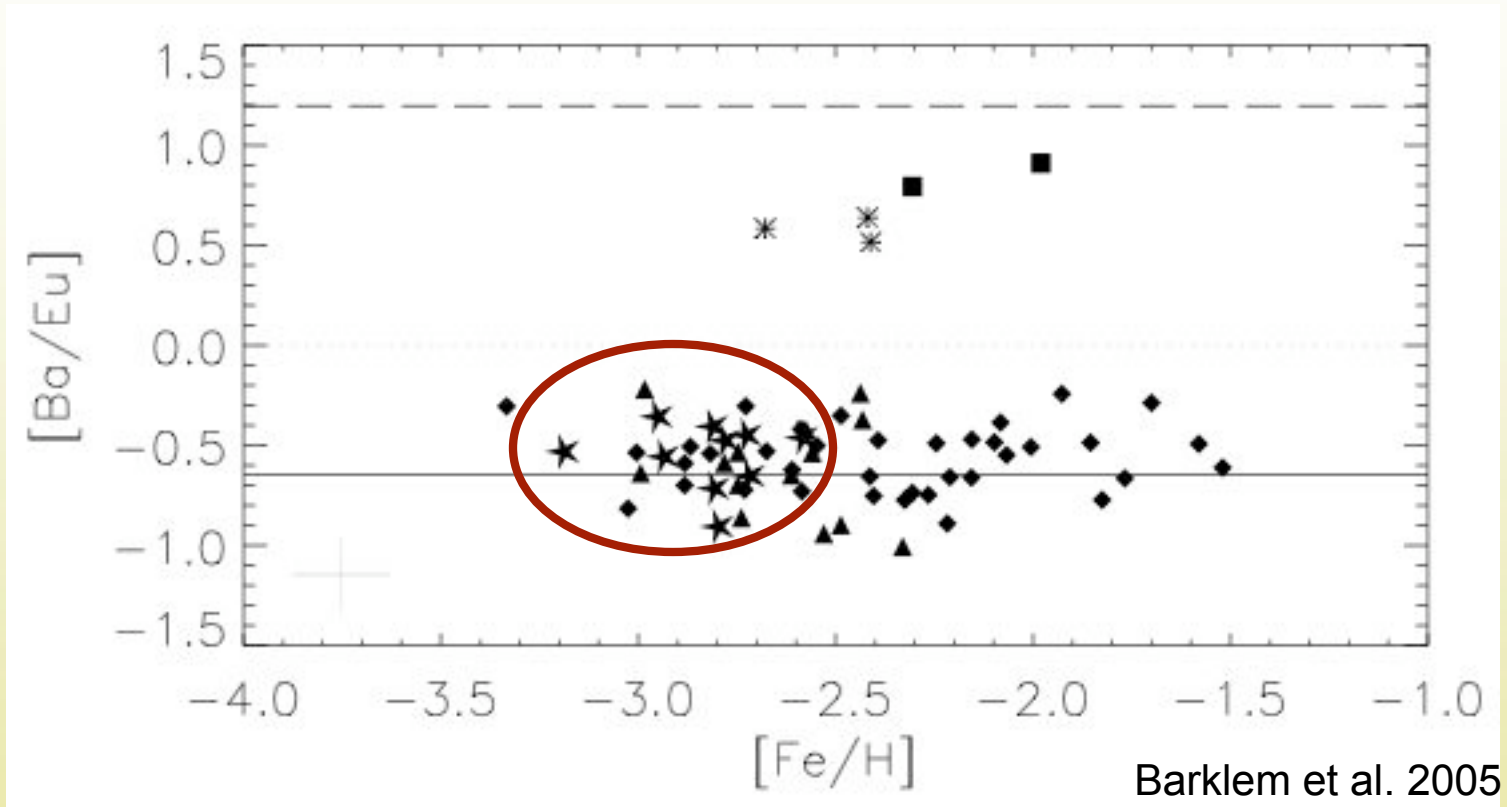
The Big Bang



HK/HES MDF (Low Metallicity Tail)



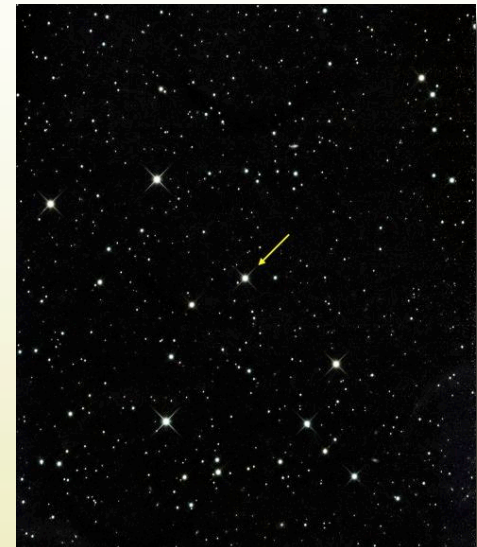
WHERE ARE R-RICH STARS?



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.: $T_{\text{eff}} = 4630 \pm 70\text{K}$
- Surface gravity: $\log g = 1.0$ (red giant)
- Metallicity: $[\text{Fe}/\text{H}] = -3.0$
- Frebel et al. 2007, ApJ 660, L117
- Frebel et al. 2008, in prep.



© Anthony Aylomamitis

WE MADE NO. 5!

5 A st unc

HE 1523-0901, an 11th-magnitude star, is one of the oldest stars known. HE 1523-0901 formed about 500 million years after the Big Bang.

Studies of the cosmic microwave background suggest the universe's first stars fired up a few minutes after the Big Bang. Astronomers think the first stars lived for only a few million years, blowing up as supernovae and seeding the universe with heavy elements like iron, so important for planet formation.

"The lifetime of the very first stars was probably only a few hundred million years," says Frebel. "That's a very short time in cosmic terms." At the end of its life, HE 1523-0901 exploded as a supernova, seeding the surrounding space with heavy elements like iron, so important for planet formation.

To learn about the first stars, Frebel and her team looked at the Milky Way's oldest stars, which contain very little iron. That's where HE 1523-0901 fits in. "That's where HE 1523-0901 fits in," Frebel says. "Very few stars dis- cover this kind of thing. I'm looking at a rare sub-

Because uranium decays at a predictable rate, it's a natural clock. Better yet, the speed of light is constant, so it's a natural "clock" — a time-keeper. "We can now use several different 'clocks' — tritium, potassium, and others — to date these stars, not just one as in the past," Frebel says. "It's this fact that makes these stars so valuable."

Theorists provide a standard model for the evolution of these "clock" elements the-

SPECIAL ISSUE Astronomy The world's best-selling astronomy magazine TOP 10 STORIES 2007



THE YEAR'S HOTTEST STORIES!

From testing Einstein's relativity, to brilliant Comet McNaught, an earthlike exoplanet, the first 3-D dark-matter map, and more. p. 28

PLUS:

Jupiter's 5 deepest mysteries p. 38

Earth's impact craters mapped p. 60

Observe celestial odd couples p. 64

The colliding Antennae galaxies gleam with new stars. But don't expect fireworks when the Andromeda Galaxy crashes into us.

www.Astronomy.com



BONUS! 2008 night-sky guide pullout inside

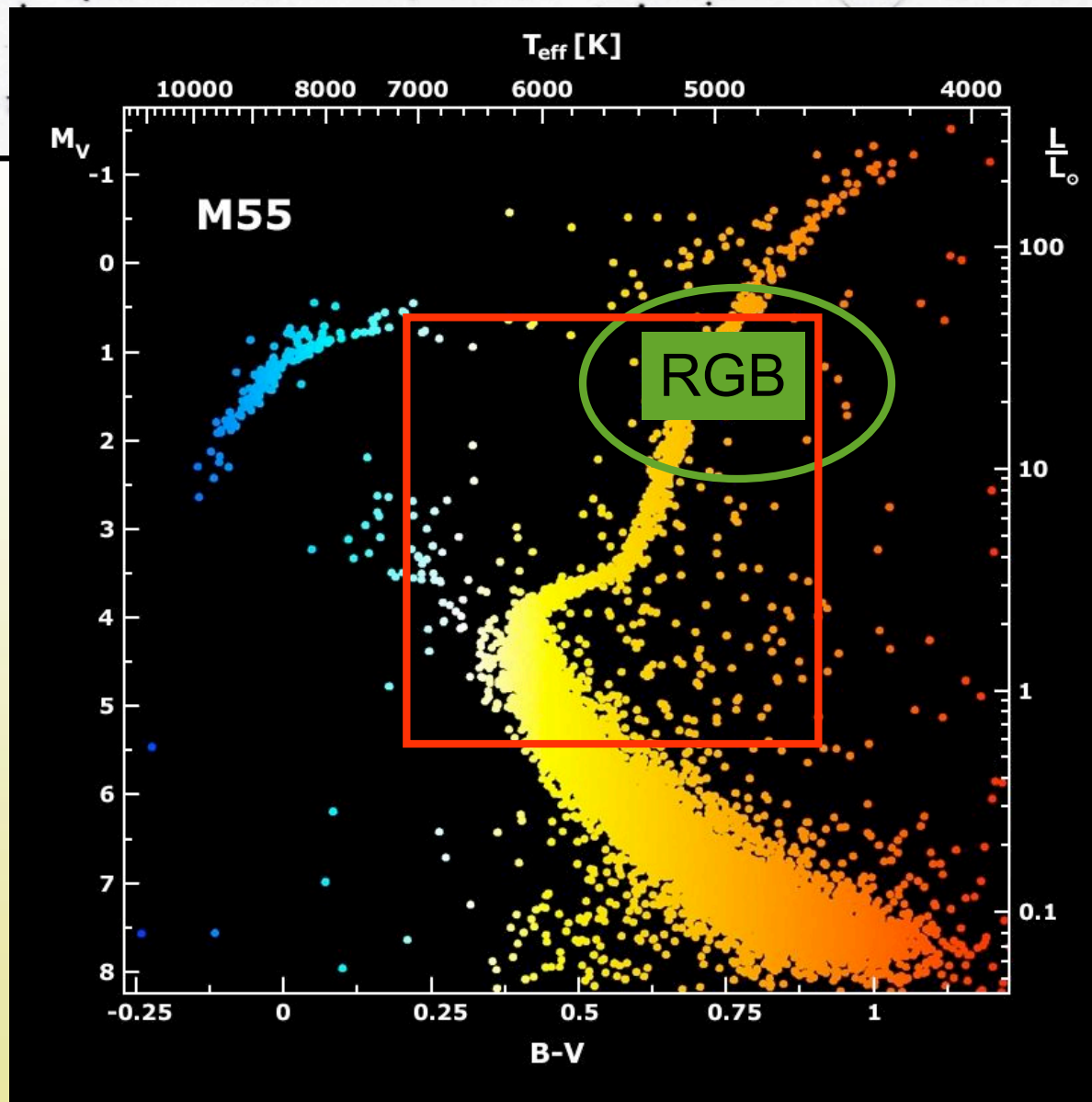
a handle on how hot and mas-

helps constrain state-of-the-art models. "Only now are computers getting better at simulations," says Frebel. "But the observations, and the old stars, are still a puzzle."

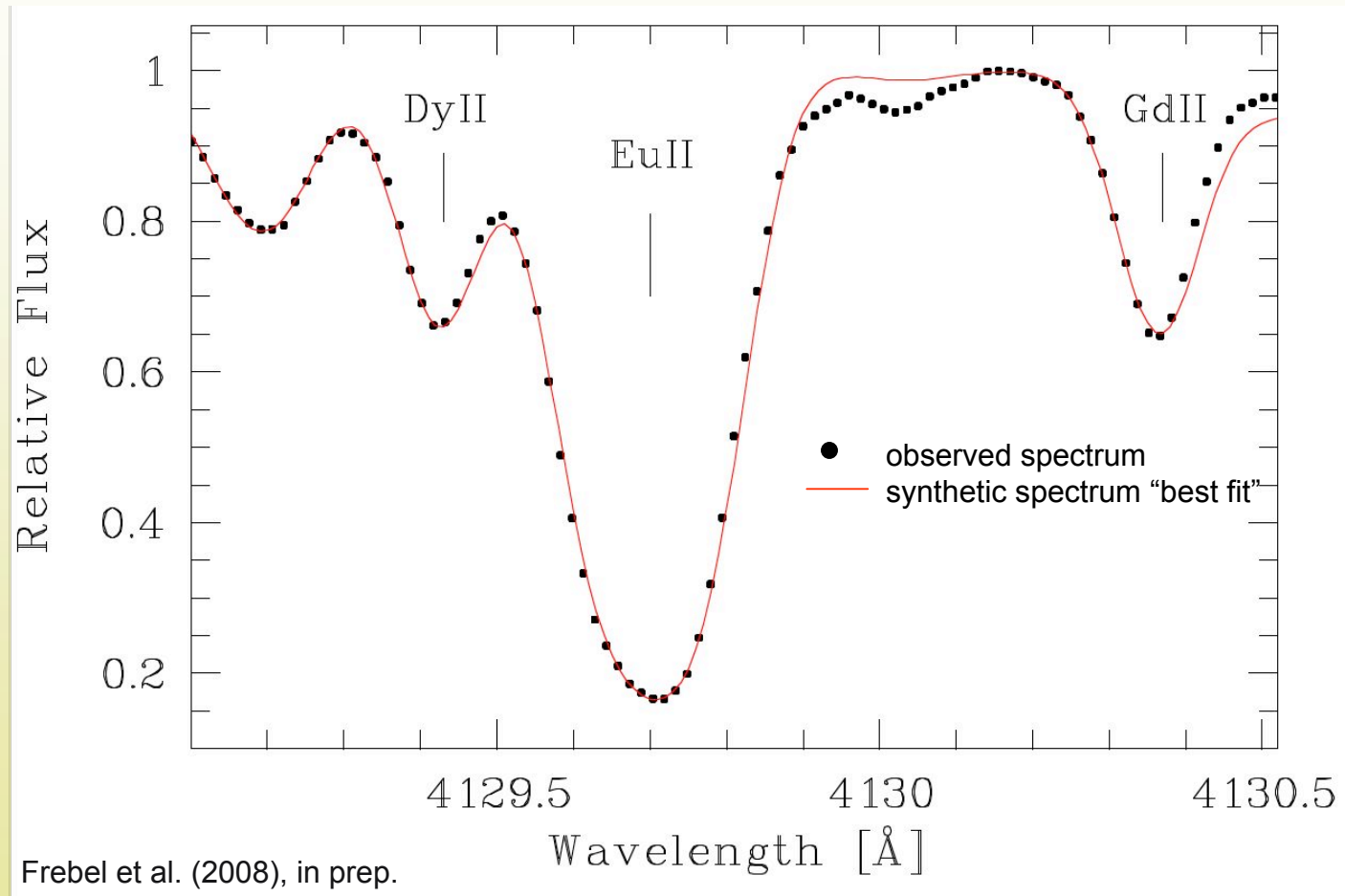
For the Sun's birth, Frebel says, "We take a bit of poetic license and say, 'Well,' Frebel says, 'the truth.'"



HE 1523-0901 is one of the oldest stars known. It lies 7,500 light-years away in the constellation Cygnus. The star's 13.2-billion-year age makes it a "fossil" in the cosmic clock elements. ESO



WHAT ELEMENTS CAN WE SEE IN HE 1523-0901?



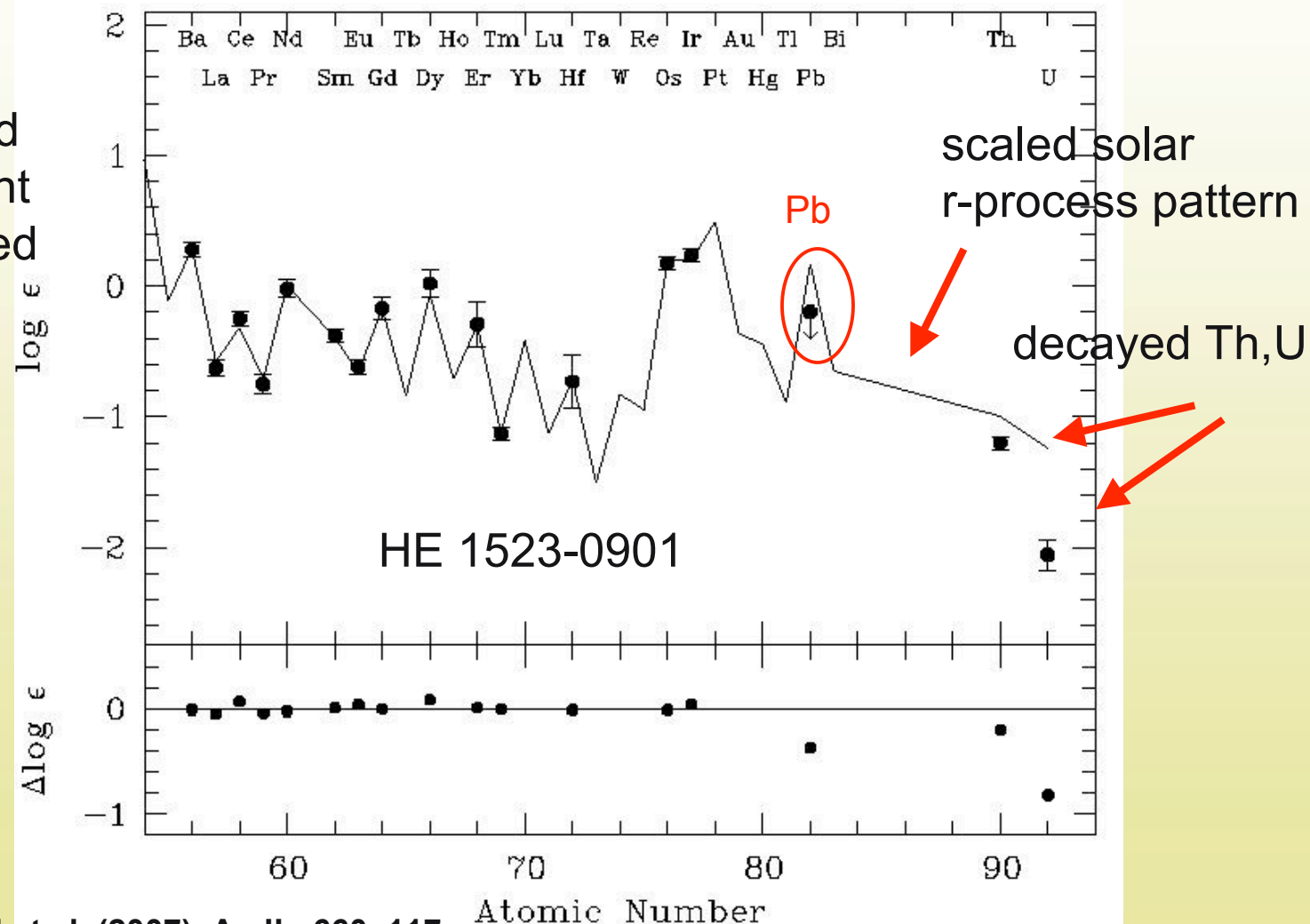
Lanthanides or rare earth elements: i.e. Eu, Gd, Dy

HEAVY NEUTRON-CAPTURE ELEMENTS IN STARS

	alkali metals I A			alkaline earth metals II A												nonmetals					noble gases 0															
Period 1	1	H 1.01 Hydrogen														5	6	7	8	9	10															
Period 2	3	Li 6.94 Lithium	4	Be 9.01 Beryllium											13	14	15	16	17	18																
Period 3	11	Na 22.99 Sodium	12	Mg 24.31 Magnesium											21	22	23	24	25	26																
					transition metals																															
					III B	IV B	V B	VI B	VII B	VIII		IB	IIB																							
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) Darmstadtium	111	(272) Roentgenium	112	(277) Copernicium			114	(281) Flerovium			116	(289) Livermorium			118	(293) Oganesson
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		

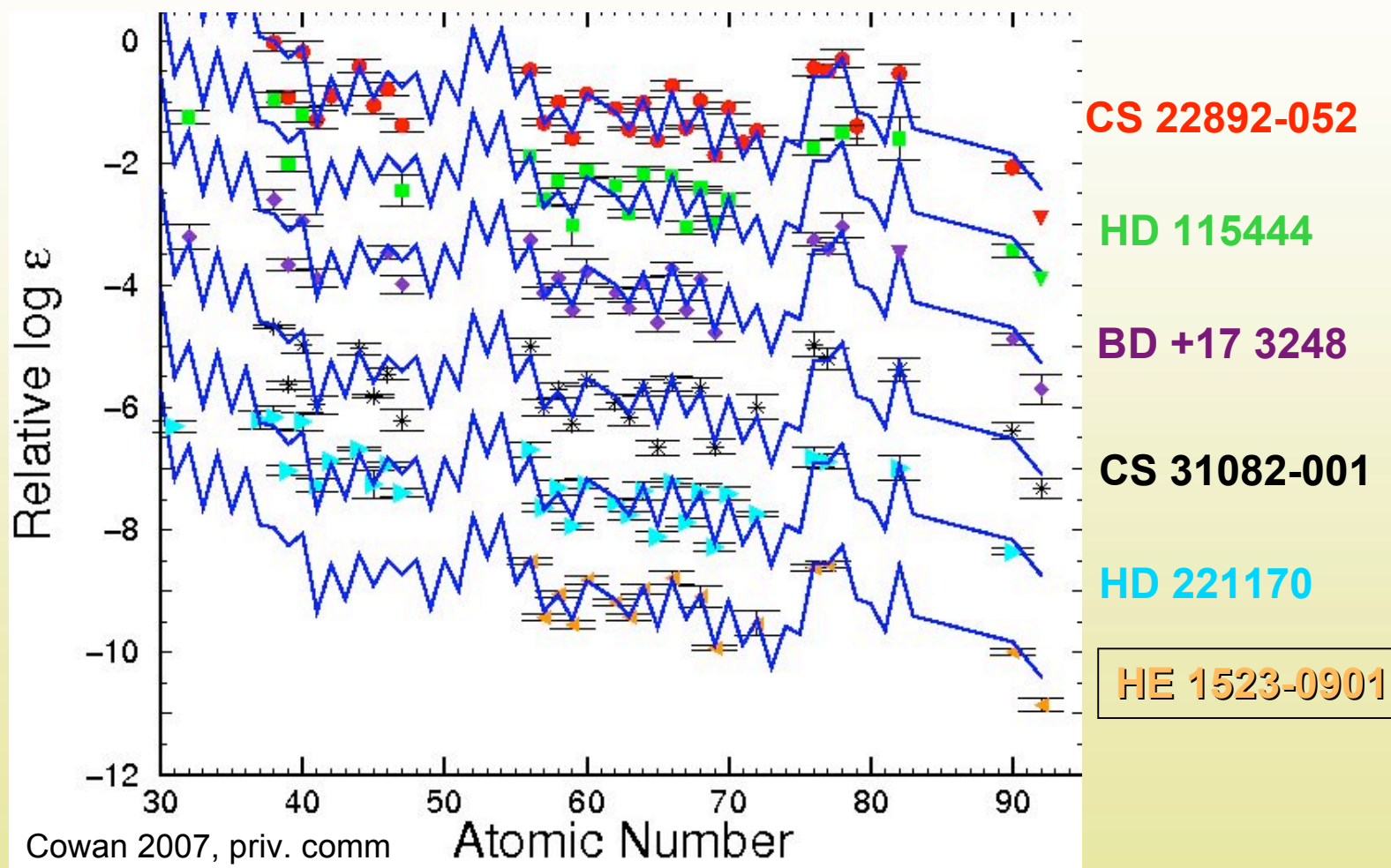
THE R-PROCESS PATTERN

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



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

HIGH-PRECISION AT WORK



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

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
 – “famous” example: CS22892-052
 ~14-15Gyr; (Snedden et al. 96,03)

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

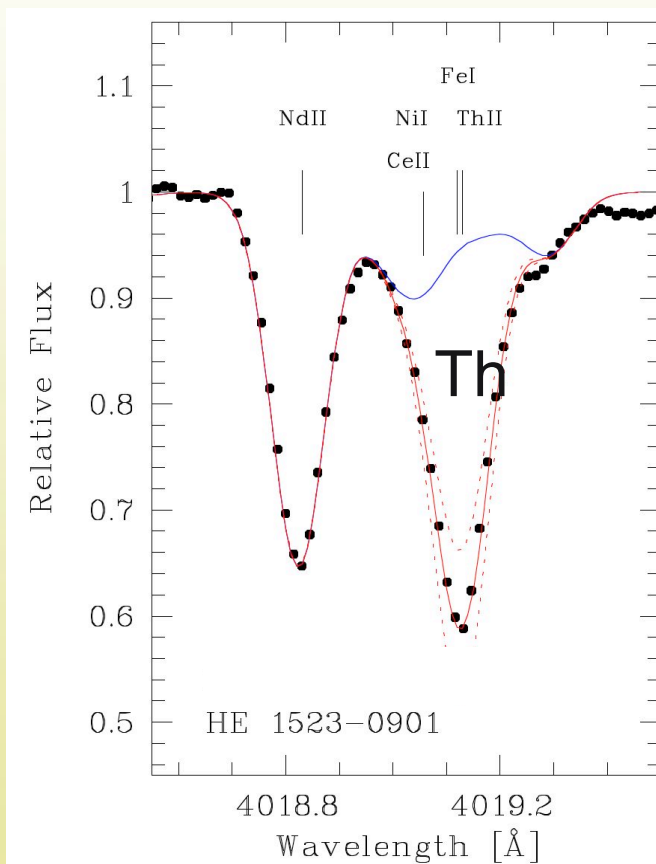
$$\Delta t = 14.8 * (\log (U/r)_0 - \log (U/r)_{obs})$$

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

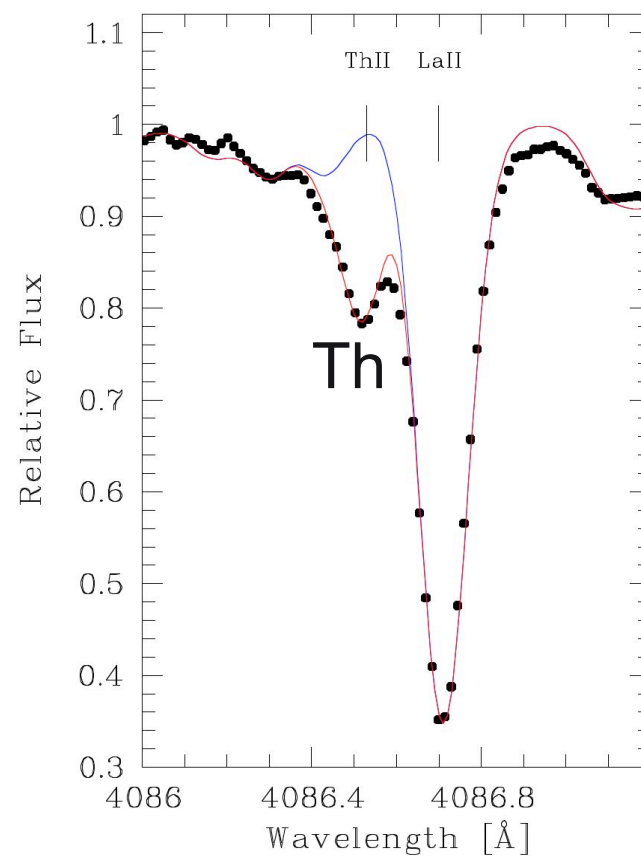
U/Th: Uranium only confidently measured
 in **one** star before: CS31082-001
 ~14Gyr (Cayrel et al. 01, Hill et al. 02);

=> Ultimate goal: Use as many chronometers as possible
 (+ beat down any errors...)!

THORIUM II LINES IN HE 1523-0901



Frebel et al. (2007) ApJL

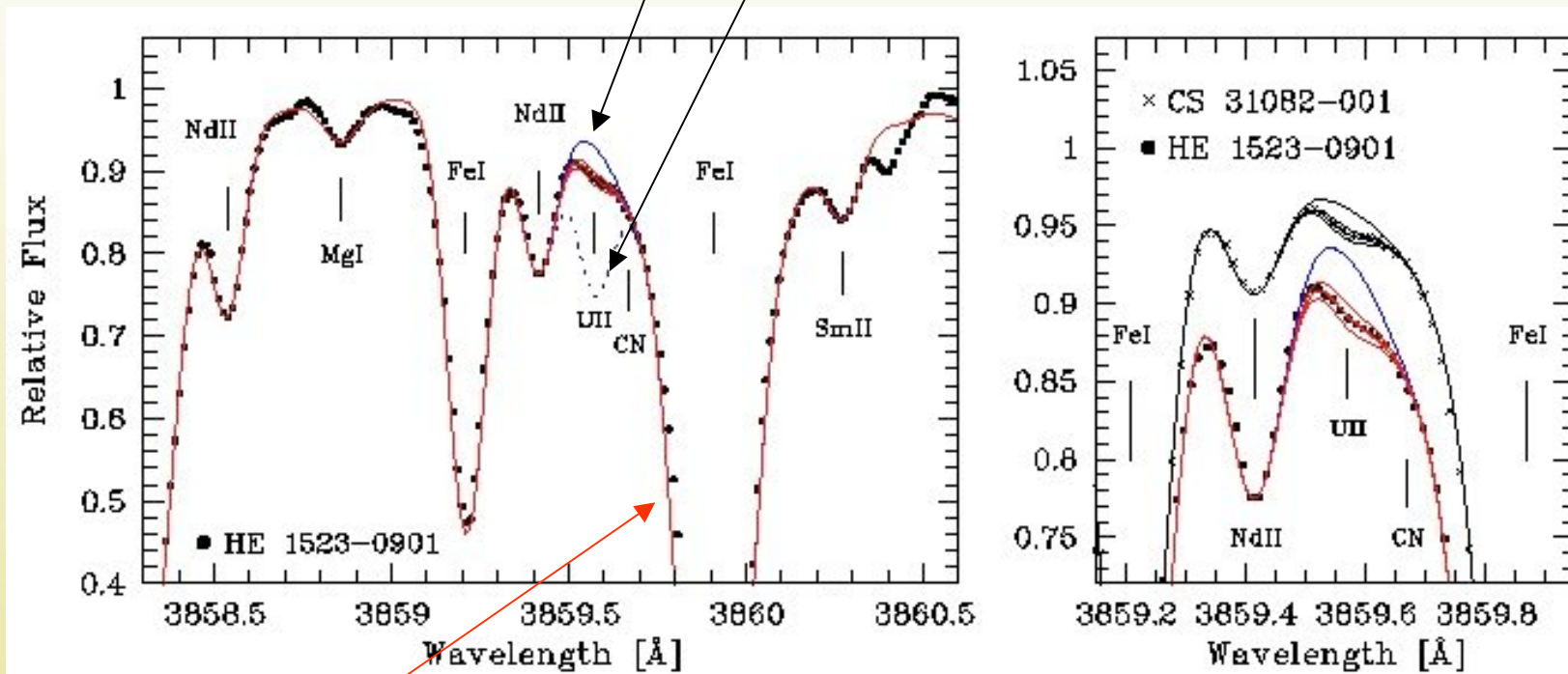


Frebel et al. (2008), in prep.

U II AT 3859Å IN HE 1523-0901

Synthetic spectrum that includes NO uranium

Synthetic spectrum with U abundance if it had NOT decayed



'Best fit' synthetic spectrum

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

THE AGE OF HE 1523-0901

Ratio	Age	$\sigma_{\text{obs/Teff/log g/vmicr/PR}}$
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

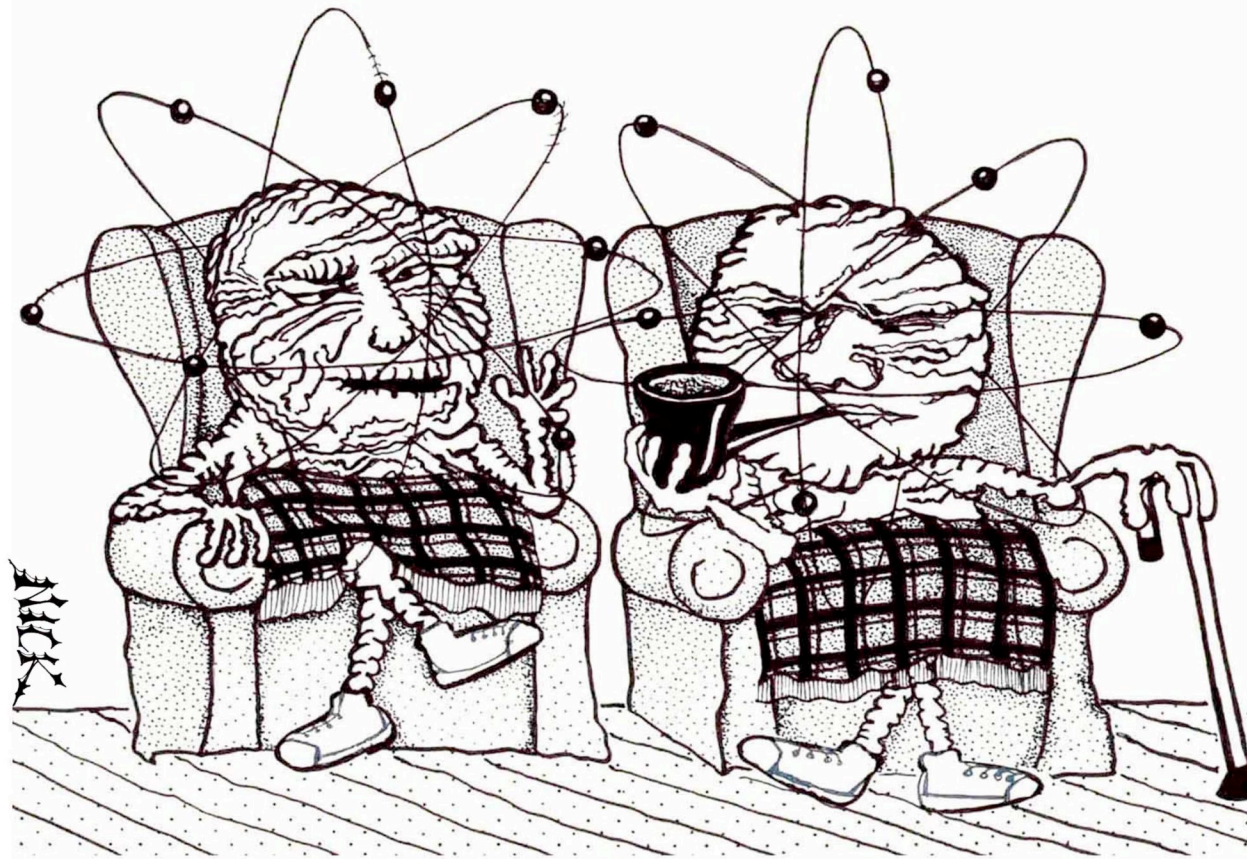
The first time more than one chronometer
could be employed in a star to measure the age!

“REVERSE ENGINEERING”

- 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: HE 1523-0902 so far => NEED MORE STARS!!!

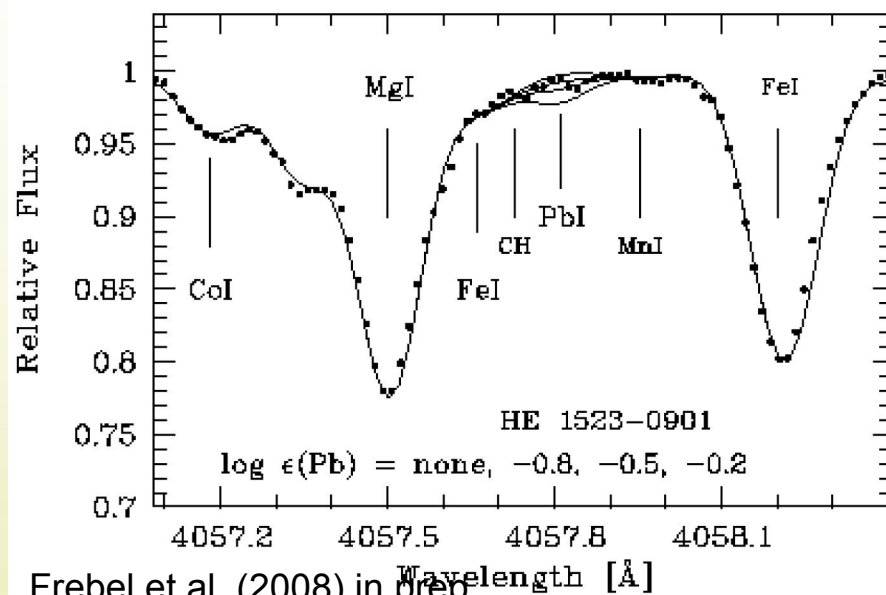
Ratio	observed ratio	derived initial prod. ratio derived from HE1523-0901	derived ages (Gyr)	stars
Th/Eu	-0.62, -0.51, -0.60, -0.60	-0.222	18.6, 13.5, 17.7, 17.7	CS 22892-052, BD 17 3248, HD221170, HD 115444
Th/Os	-1.59, -1.63	-1.022	26.6, 28.5	CS 22892-052, BD 17 3248
Th/Ir	-1.47, -1.48	-1.082	18.2, 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

At the home for old atoms...

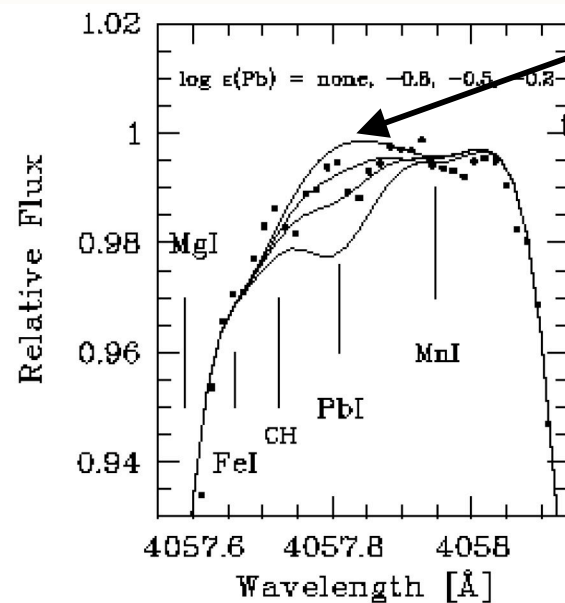


"When I was young I used to feel so alive and dangerous! Would you believe I started life as a uranium-238? Then one day I accidentally ejected an alpha particle. Now look at me—a spent old atom of lead-206. It seems that all my life since then has been nothing but decay, decay, decay..."

LEAD AT 4058Å

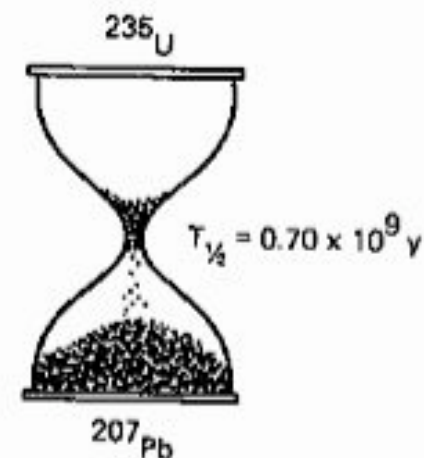
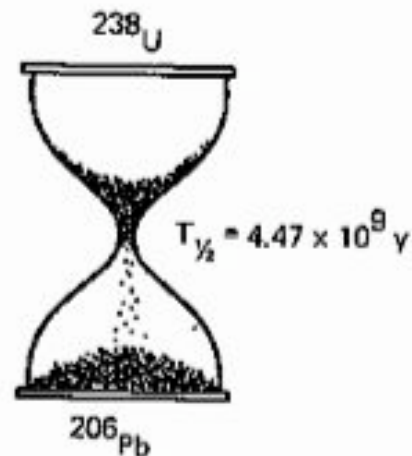
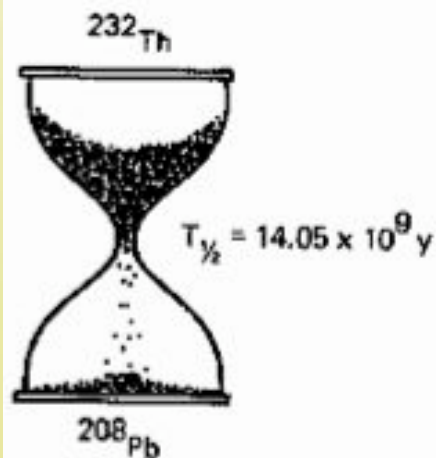


Frebel et al. (2008) in prep.



Synthetic spectrum
that includes NO lead

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



SUMMARY

- HE 1523-0901 is an ideal candidate for difficult neutron-capture line measurements, e.g., has the yet best U detection
- For the first time, all three available chronometer pairs (Th/r, U/r, U/Th) are measured in one star (7 ratios so far)
- The derived age is 13.2 Gyr; but large systematic uncertainties!
- In HE1523-0901: attempt to measure good Hf (existing data) and Pt (HST data) for Th/Hf, U/Hf and Th/Pt, U/Pt
- Reverse-engineering: use stars to obtain initial production ratio to get ages of other stars, but: we need more stars to play this game!

Thank you!

Question/comments/requests for figures? email me: anna@astro.as.utexas.edu