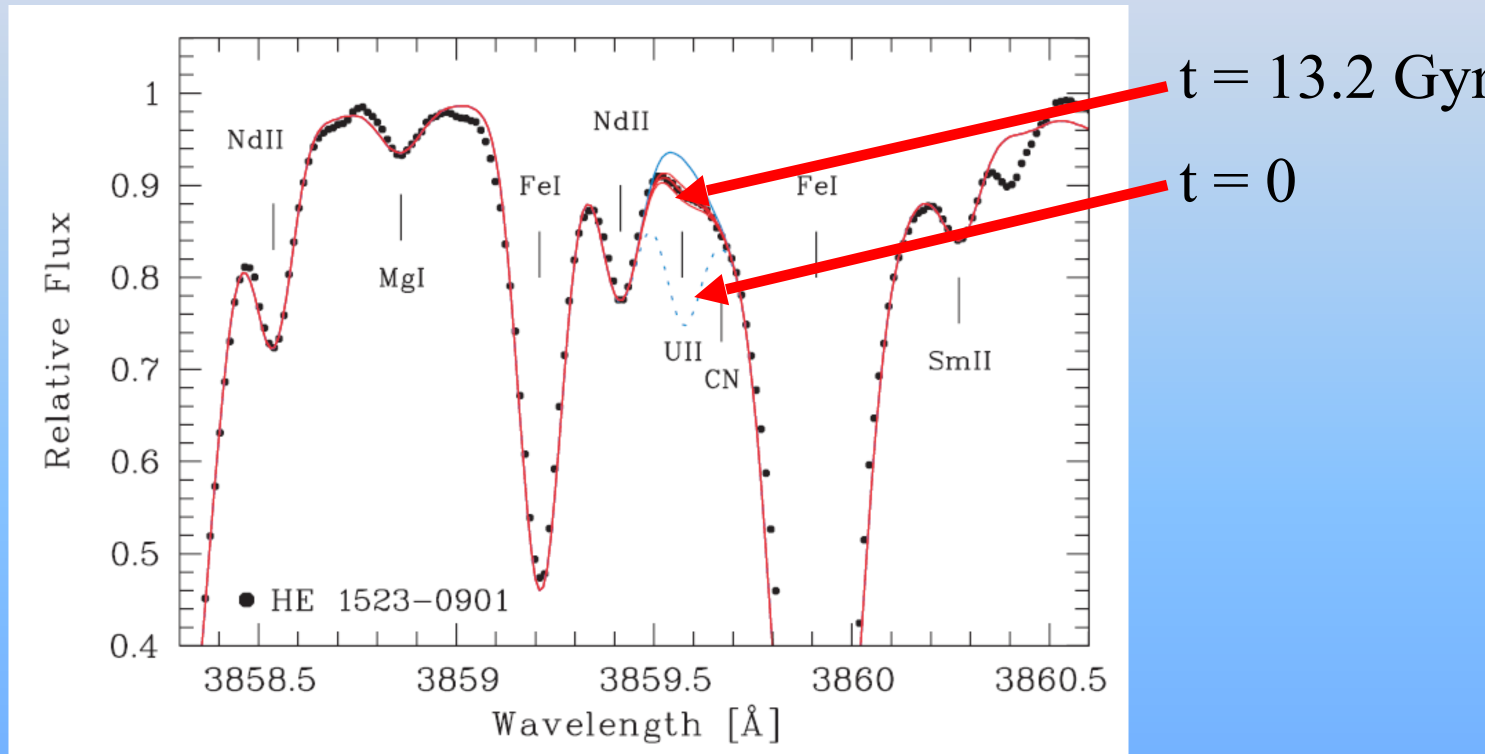
Age determination of metal-poor halo stars with nucleochronometry

Norbert Christlieb (ZAH)



RUPRECHT-KARLS-UNIVERSITÄT HEIDELBERG

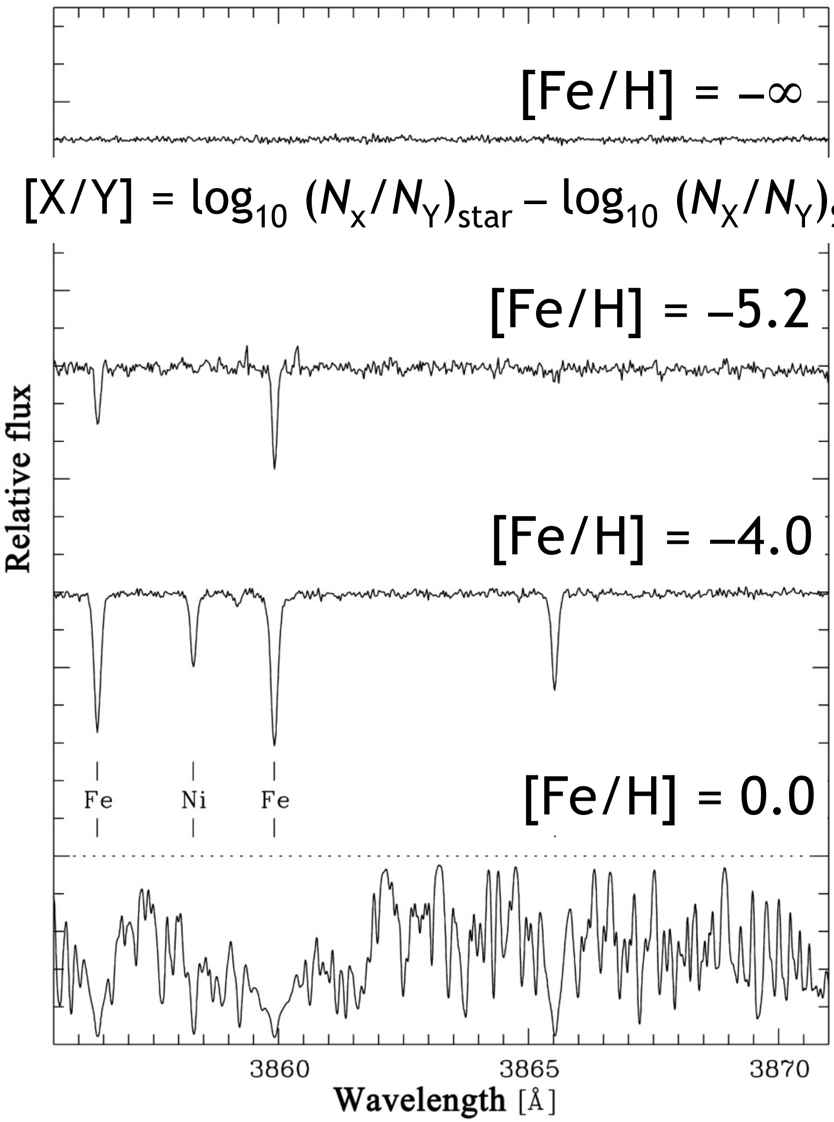
Deutsche Forschungsgemeinschaft
DFG

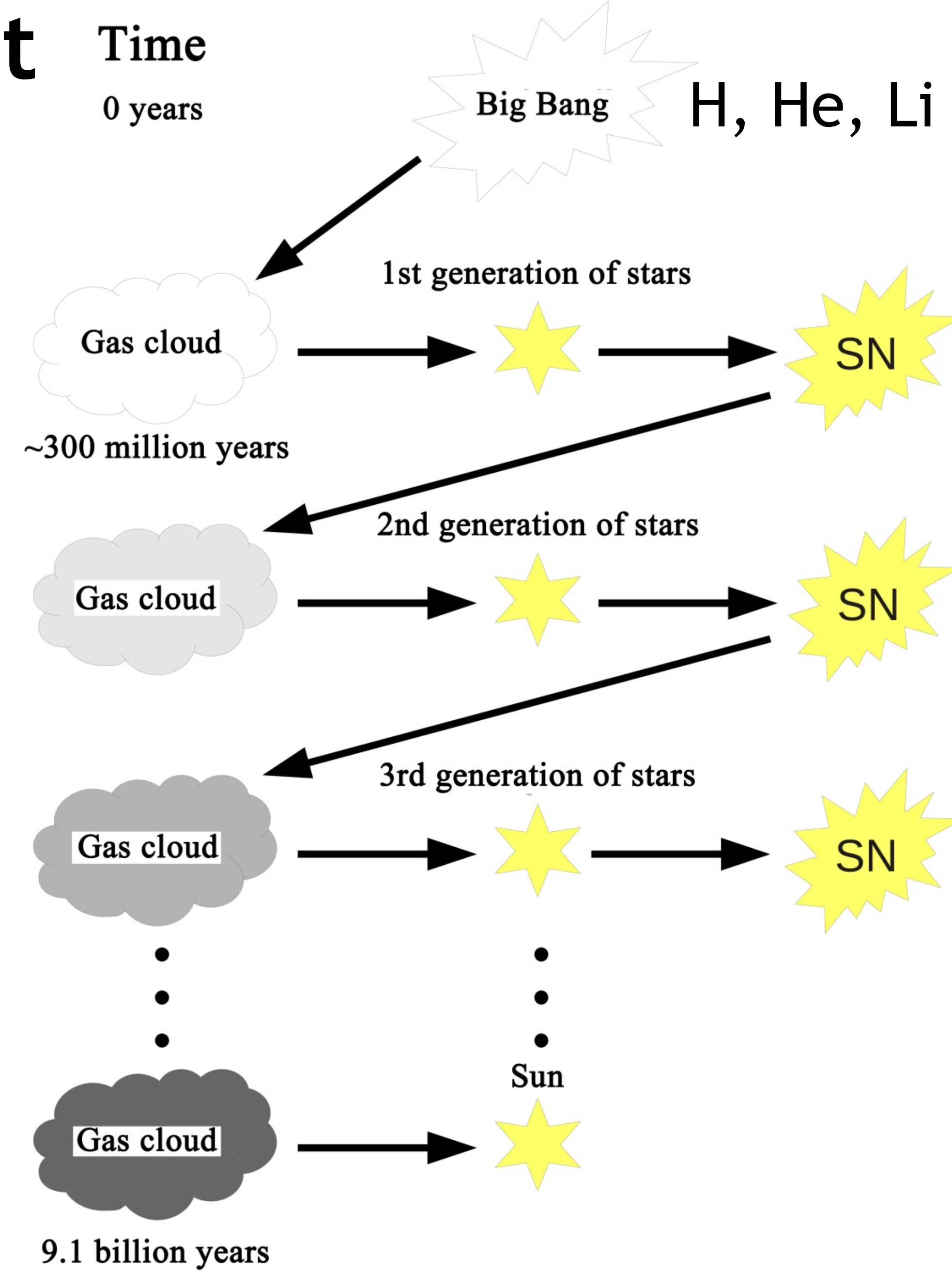
Contents

- Introductory remarks
- Finding metal-poor stars
- The most metal-poor stars currently known
- Nucleochronometric age determination of metal-poor stars: methods, uncertainties, results
- Conclusions

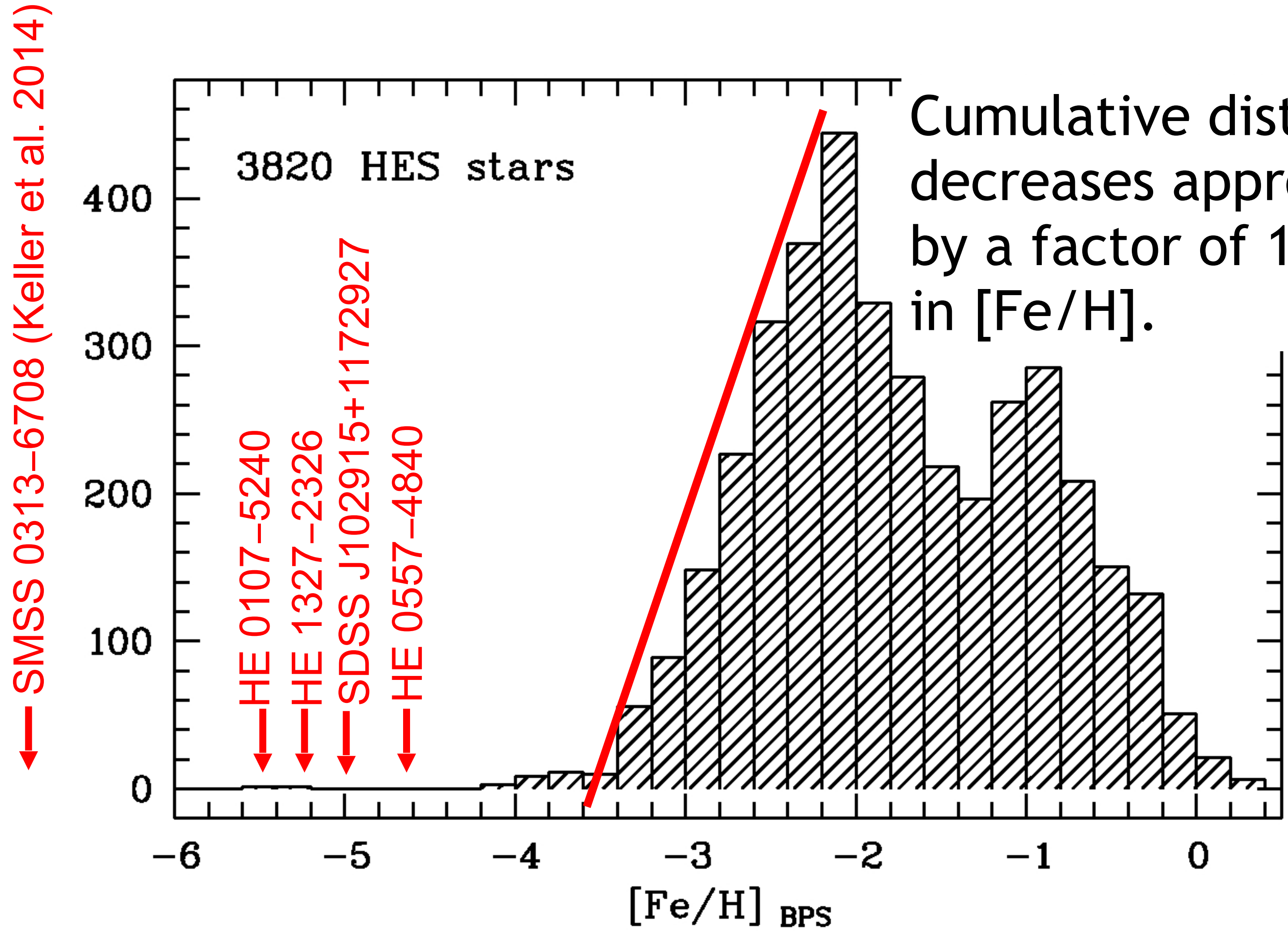
Chemical enrichment of the Universe

$$[X/Y] = \log_{10}(N_X/N_Y)_{star} - \log_{10}(N_X/N_Y)_{Sun}$$



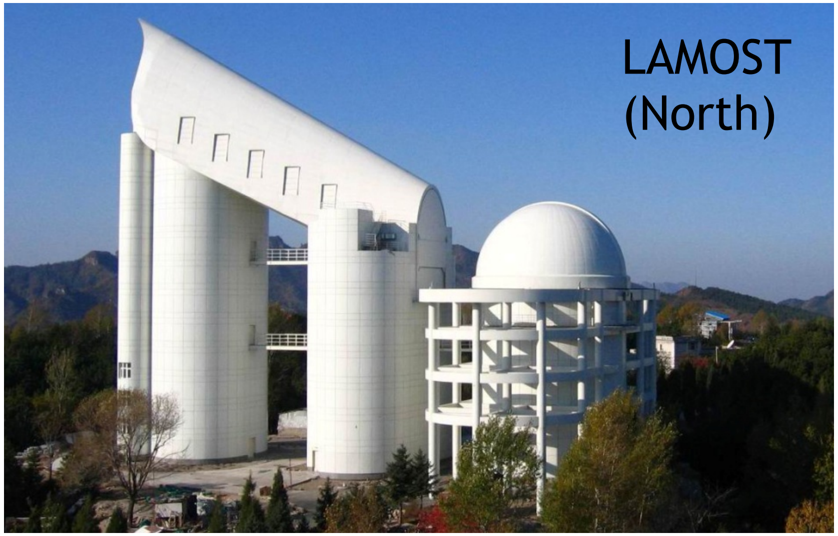


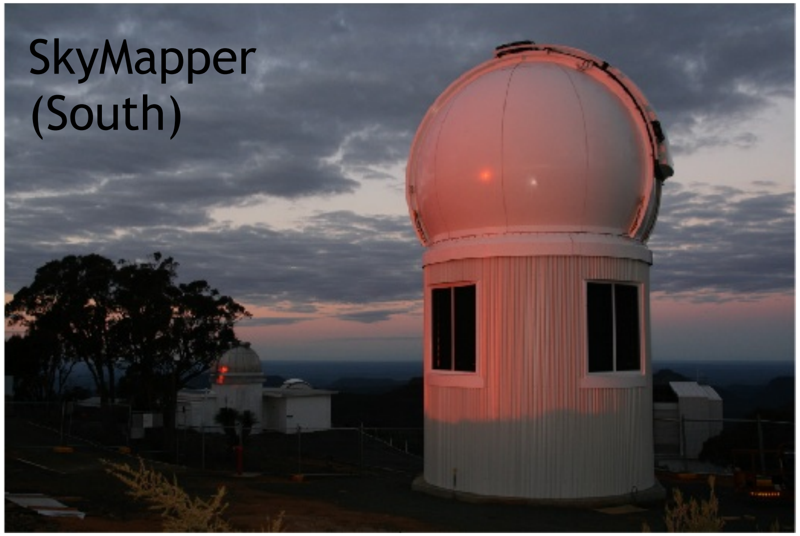
The metallicity distribution function of the Galactic halo



Cumulative distribution decreases approximately by a factor of 10 per dex in [Fe/H].

Past and present surveys





Survey	Effective sky coverage	Effective mag limit	***N*** < –3.0 (EMP)	***N*** < –5.0 (HMP)	People
HES	6,400 deg^2	B < 16.5	200	2	Christlieb et al.
SEGUE	1,000 deg^2	B < 19	(1,000)	(10)	Beers et al.; Caffau et al.
LAMOST	12,200 deg^2	B < 18.0	(3,000)	(30)	Zhao et al.
SSS	20,000 deg^2	B < 17.5	(2,500)	(25)	Keller et al.

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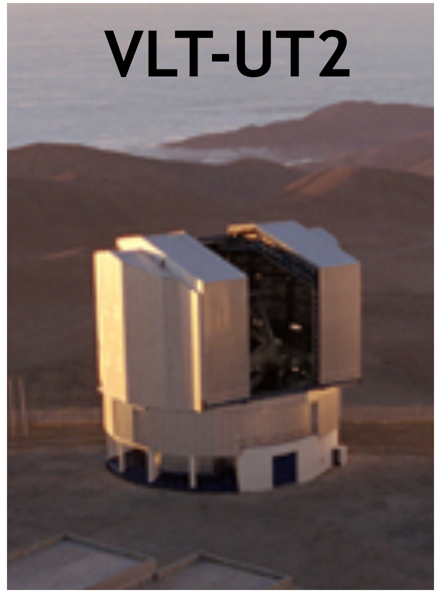

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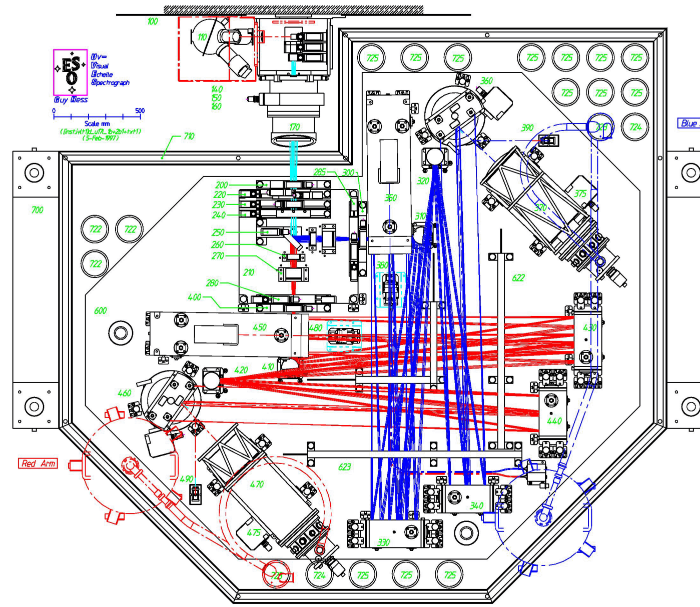

UVES

(two-arm cross-dispersed Échelle spectrograph => high spectral resolution *and* large wavelength coverage)

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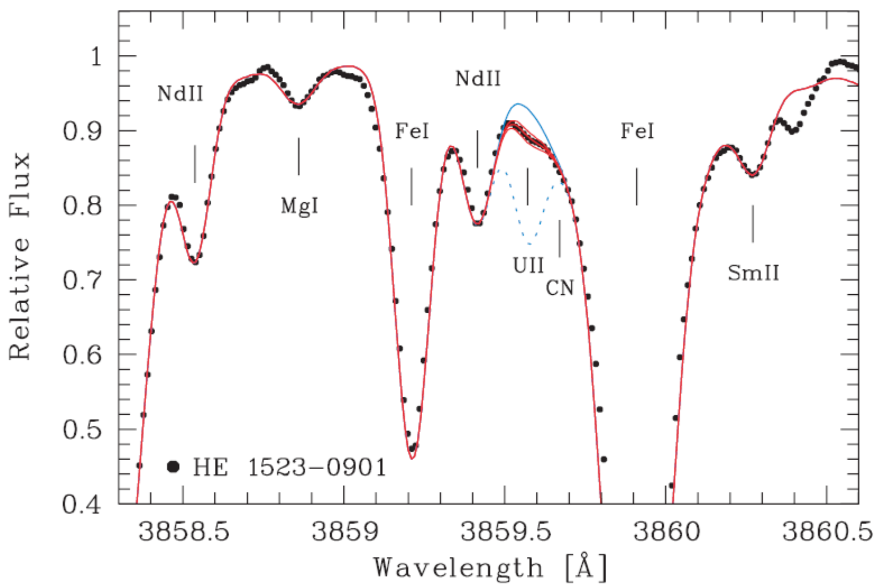
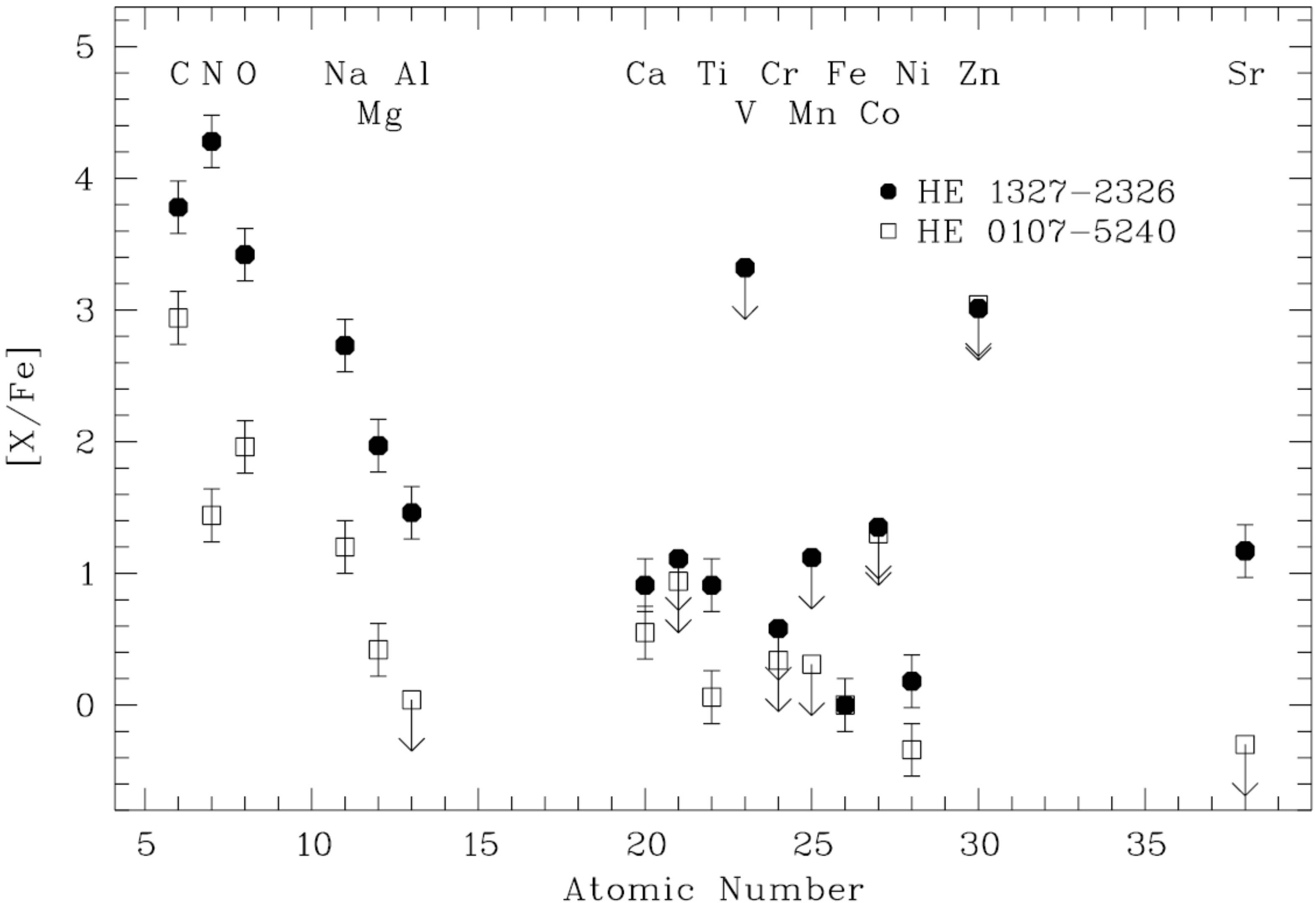
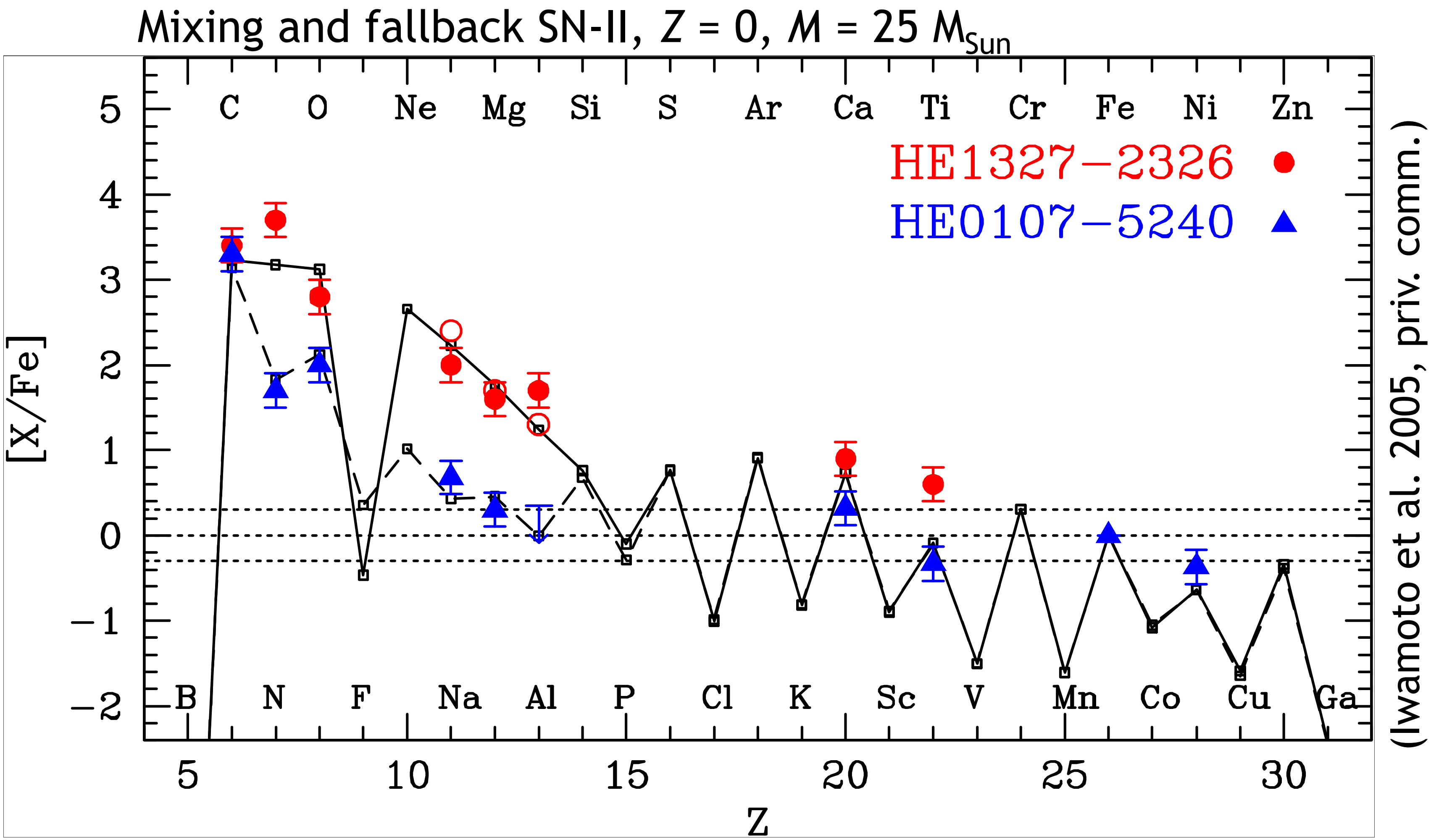


The abundance patterns of HE 0107−5240 and HE 1327−2326

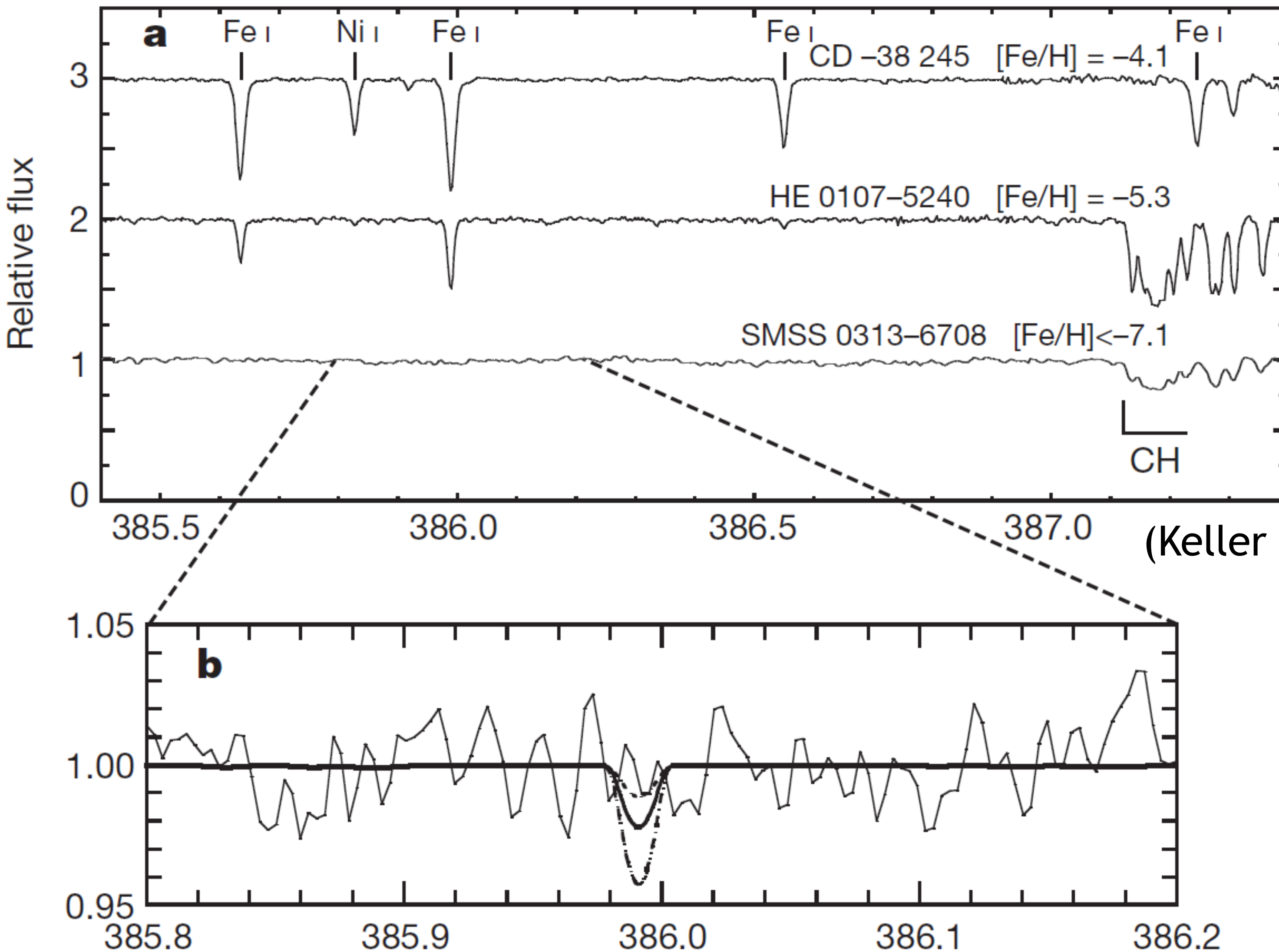


(Frebel et al. 2008, ApJ 684, 588)

Modeling the abundance patterns of HE 0107−5240 and HE 1327−2326

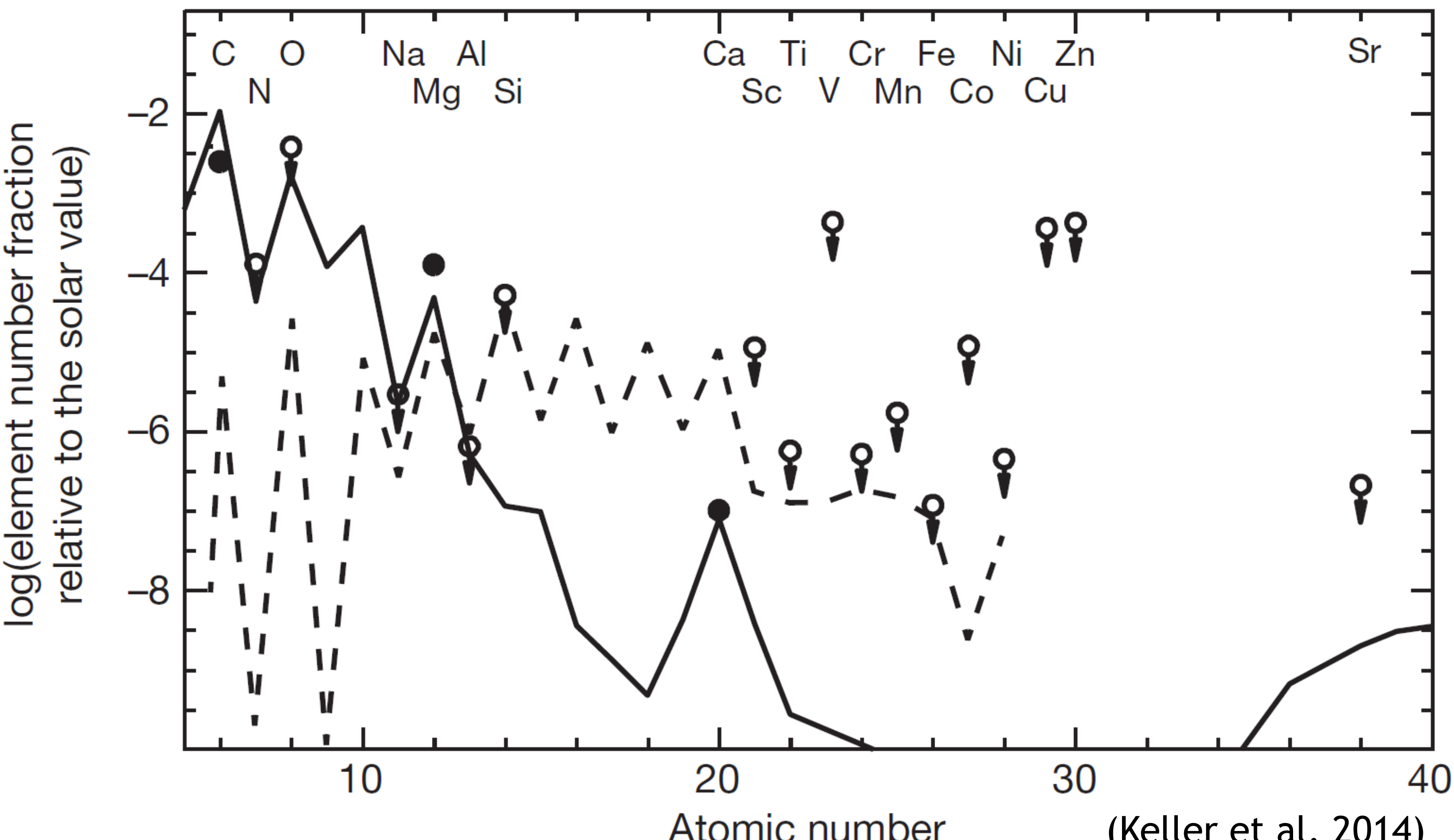


SMSS 0313−6708, [Fe/H] < −7.1



(Keller et al. 2014)

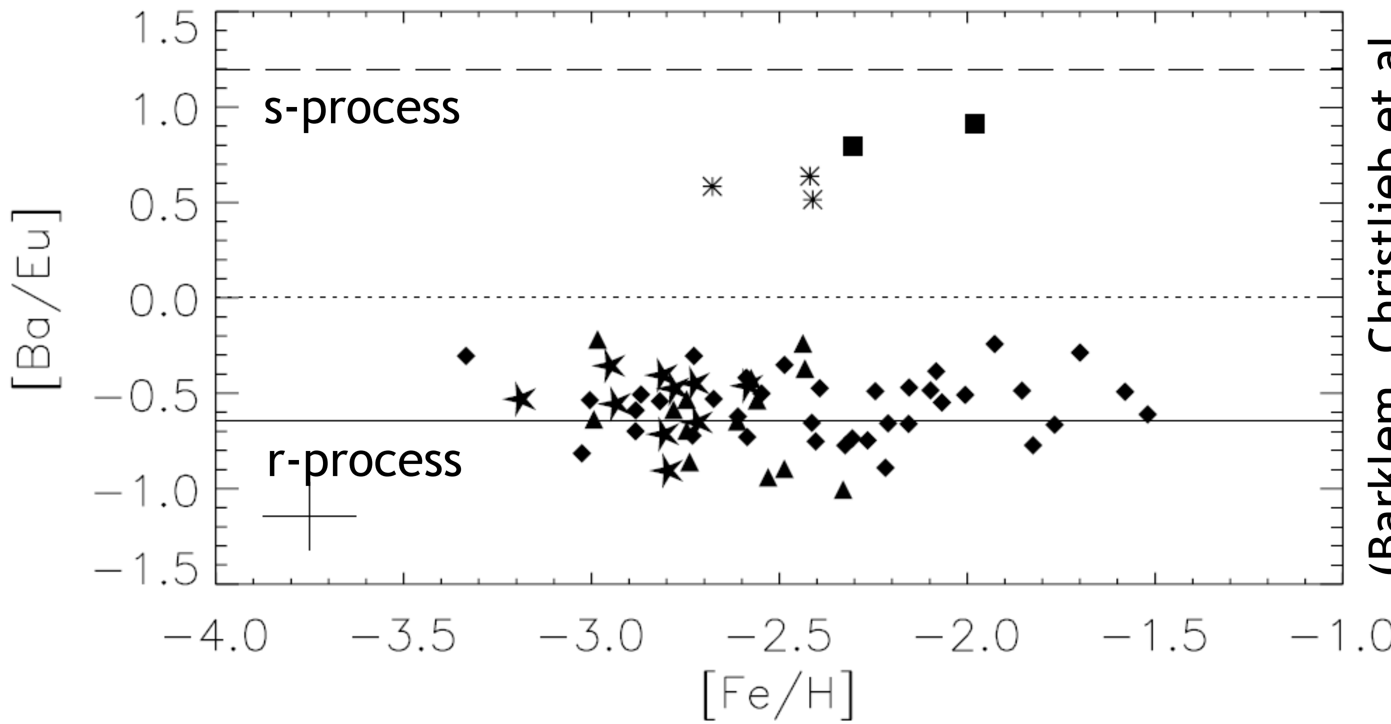
SMSS 0313−6708, [Fe/H] < −7.1



(Keller et al. 2014)

Metal-poor star sub-classes

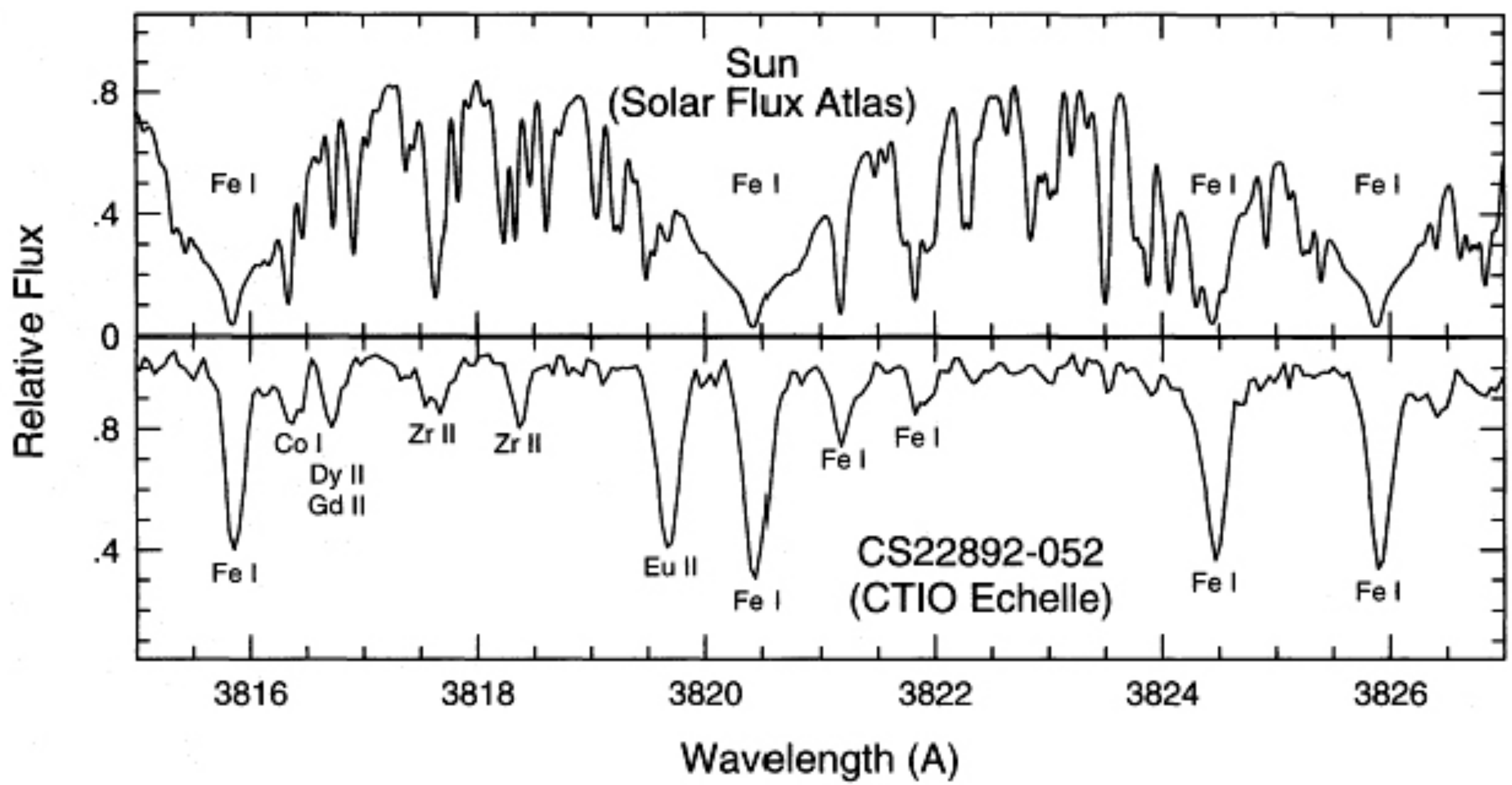
Neutron-capture-rich stars		Fraction
r-I	$0.3 < [Eu/Fe] < +1.0$ and $[Ba/Eu] < 0$	~15%
r-II	$[Eu/Fe] > +1.0$ and $[Ba/Eu] < 0$	~3%
s	$[Ba/Fe] > +1.0$ and $[Ba/Eu] > +0.5$	
r/s	$0.0 < [Ba/Eu] < +0.5$	



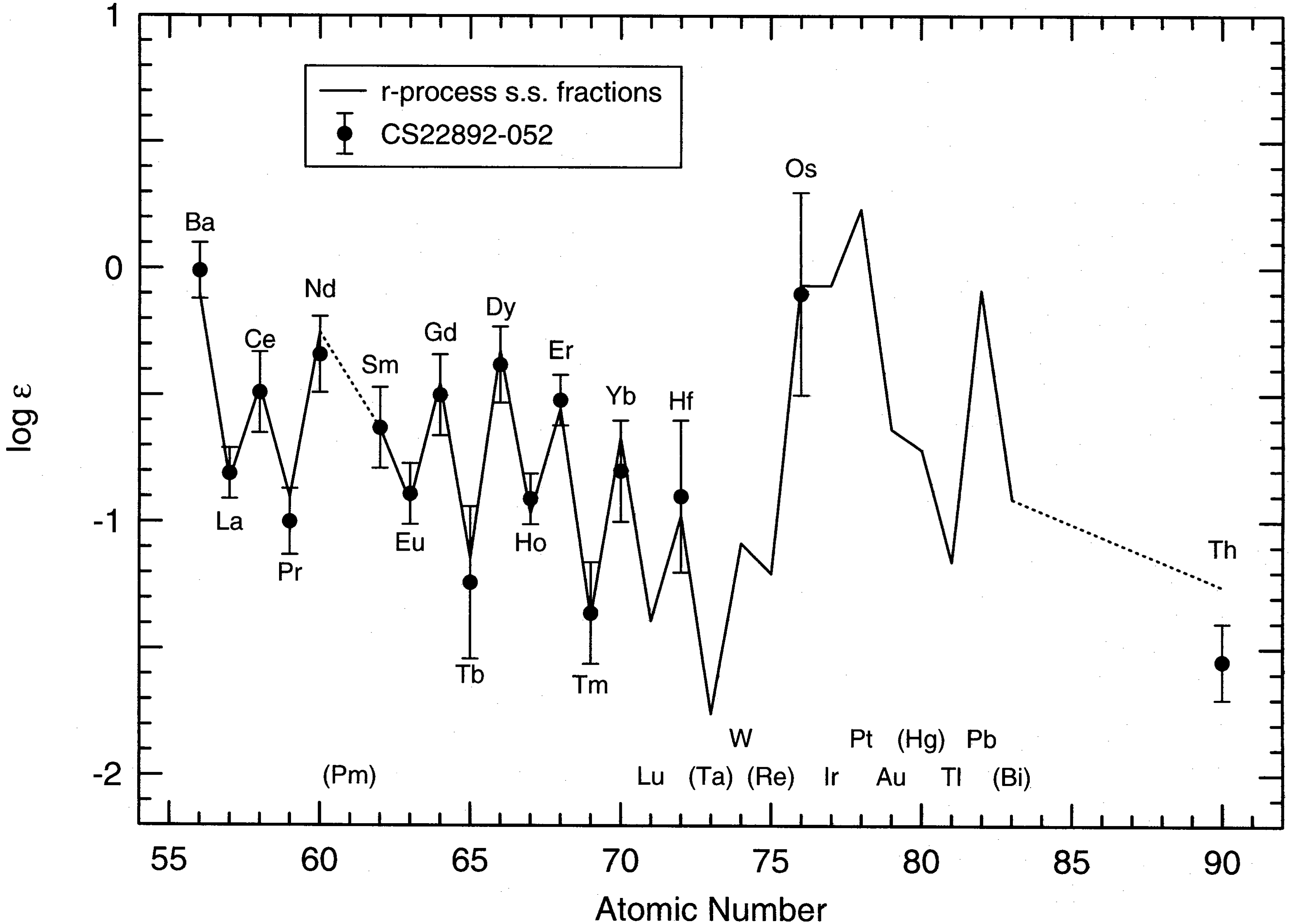
(Barklem, Christlieb et al. 2005, A&A 439, 129)

Why *metal-poor* r-II stars?

- Presumably pre-enriched only by a single (or a few) nucleosynthesis event(s).
- Enhanced contrast between absorption lines of "plain" metals and lines of neutron-capture elements.

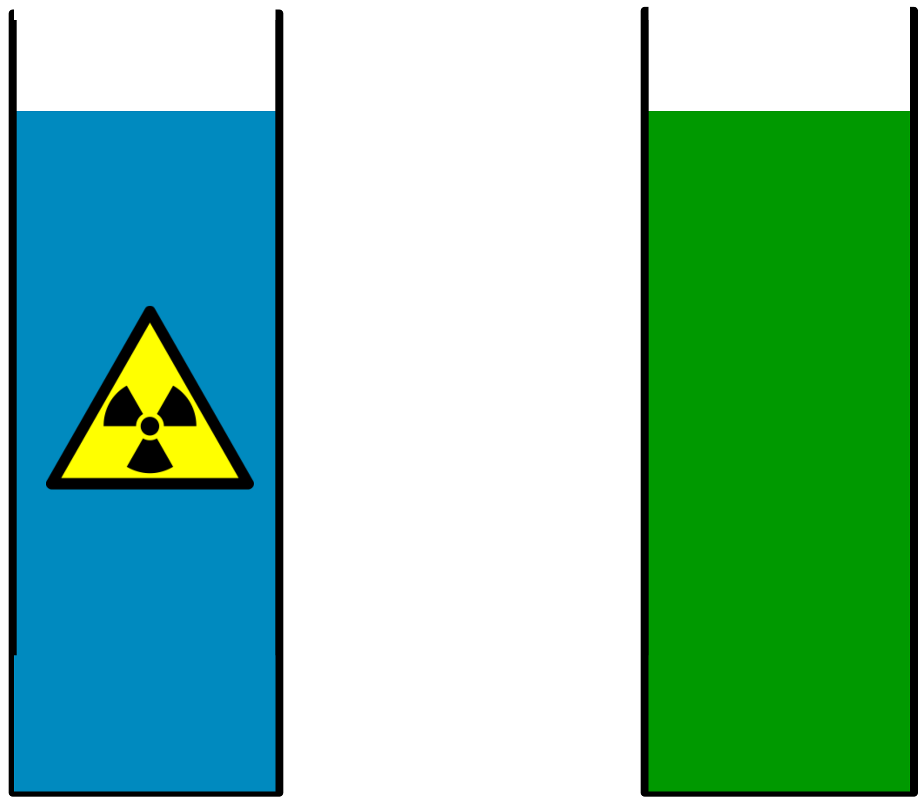


CS 22892–052, the “classical” r-II star



Sneden et al. (1996)

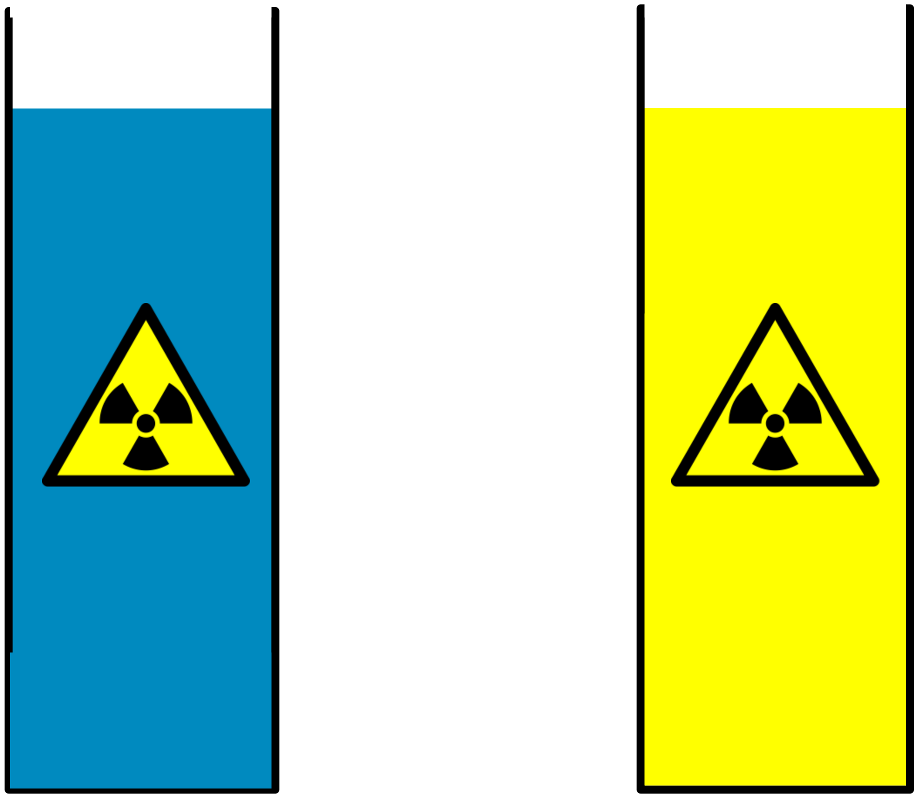
Age determination with radioactive isotopes



Uranium-238
Half-life:
4,468 billion years

Europium
(stable)

Age determination with radioactive isotopes



Uranium-238
Half-life:
4,468 billion years

Thorium-232
Half-life:
14,05 billion years

Nucleochronometry

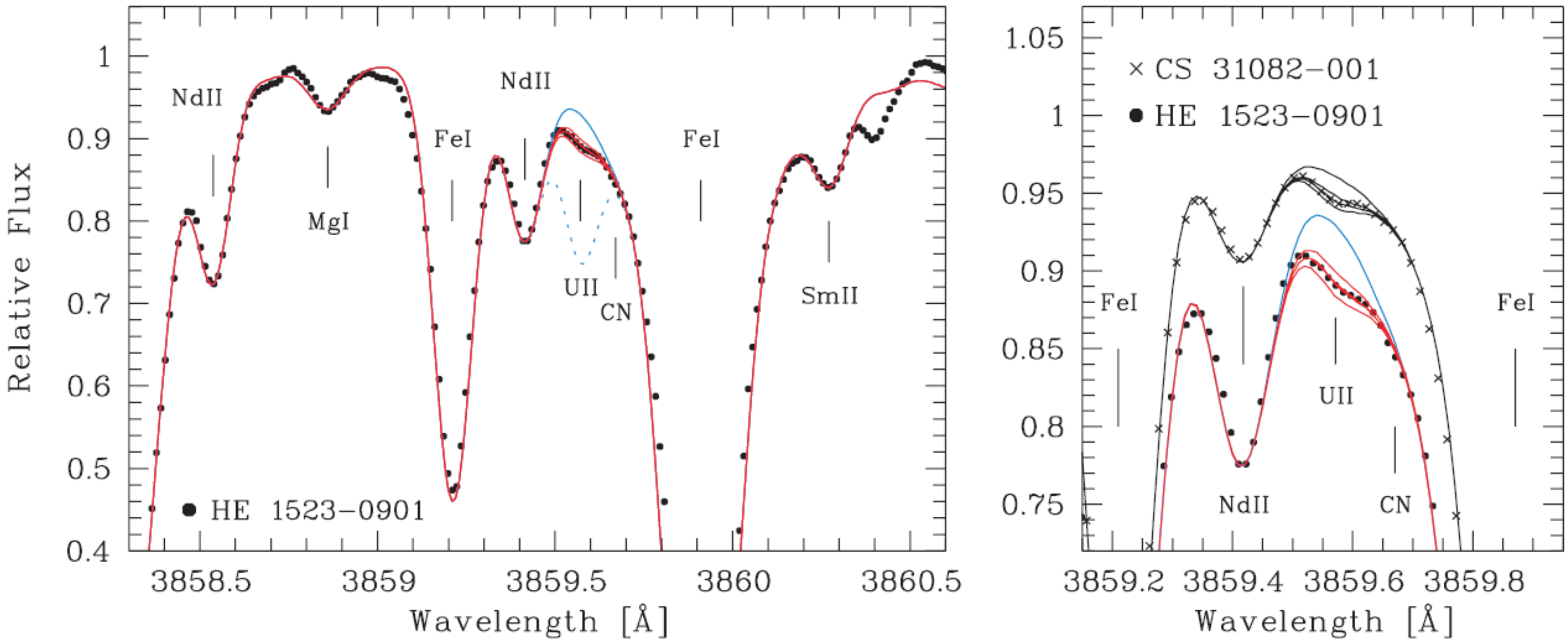
^{232}Th: Half-life 14.05 Gyr
^{238}U: Half-life 4.468 Gyr

$$\Delta t = 46.7[\log(\mathrm{Th}/r)_{\mathrm{initial}} - \log(\mathrm{Th}/r)_{\mathrm{now}}]\,\mathrm{Gyr}$$
$$\Delta t = 14.8[\log(\mathrm{U}/r)_{\mathrm{initial}} - \log(\mathrm{U}/r)_{\mathrm{now}}]\,\mathrm{Gyr}$$
$$\Delta t = 21.8[\log(\mathrm{U}/\mathrm{Th})_{\mathrm{initial}} - \log(\mathrm{U}/\mathrm{Th})_{\mathrm{now}}]\,\mathrm{Gyr}$$

σ(log (Th/r)) = 0.1 dex <=> σ(Age) = 4.7 Gyr
σ(log (U/r)) = 0.1 dex <=> σ(Age) = 1.5 Gyr
σ(log (U/Th))= 0.1 dex <=> σ(Age) = 2.2 Gyr

Detection of uranium

Frebel et al. (2007, ApJ 660, L117)



log ε(U) = −2.06

Q: How many atoms of uranium per hydrogen atom are there in this star?

A: $\log \varepsilon(\mathrm{U}) = \log_{10} (N_\mathrm{U}/N_\mathrm{H}) + 12 = -2.06$ => 1 in ~10^{14}!

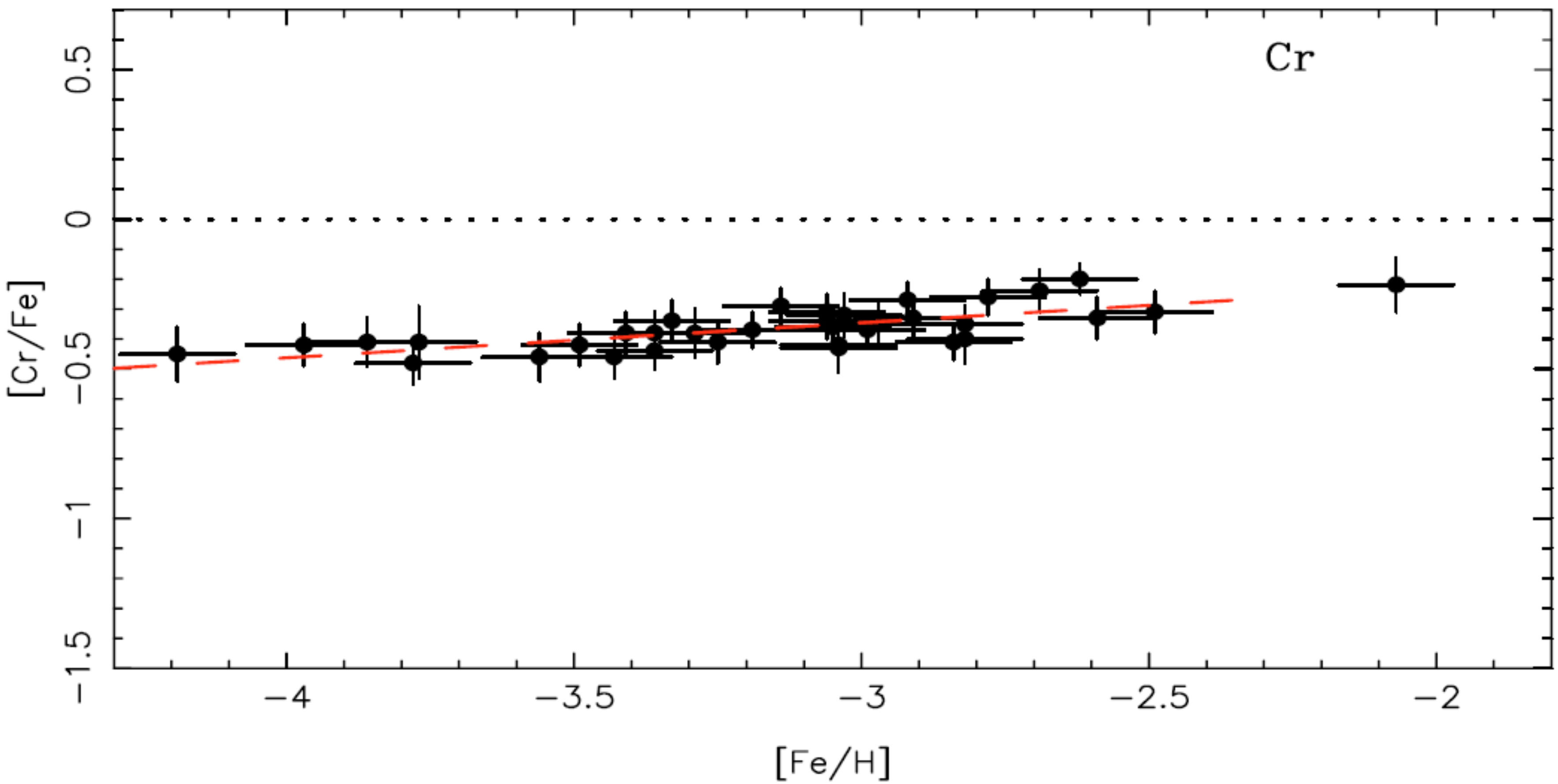
…but very high spectral resolution ($R = \lambda/\Delta\lambda > 60{,}000$) and signal-to-noise ratio ($S/N > 500$) needed, therefore limited to bright ($V < 12$) stars.

Typical abundance uncertainties

Cause	**Type**	**Uncertainty**
Stellar parameters	systematic	0.1-0.3 dex
NLTE	systematic	0.05-0.5 dex
3D (atomic species)	systematic	0.05-0.4 dex
3D (molecules)	systematic	0.3-1.0 dex
Atomic data	random	0.05-0.2 dex

Quantity	**Uncertainty**
[X/Y] or log(X/Y)	0.05-0.2 dex
log ε(X) differential	0.02-0.1 dex
log ε(X) absolute	0.1-0.5 dex

Precision of abundance ratios



Cayrel et al. (2004, A&A 416, 1117)

The age of HE 1523−0901

(Frebel et al. 2007, ApJ 660, L117)

X/Y	log (PR)[a]	Ref.	log $\epsilon(X/Y)_{obs}$	Age (Gyr)	Uncertainties[b] (Gyr)
U/Eu	−0.55	2	−1.44	13.2	1.9/0.6/0.4/0.2/1.6
U/Os	−1.37	2	−2.24	12.9	1.9/0.6/1.2/0.3/1.6
U/Ir	−1.40	2	−2.30	13.3	1.9/0.3/0.3/0.7/1.6
	−1.298	3	−2.30	14.8	1.9/0.3/0.3/0.8/1.6
U/Th	−0.301	4	−0.86	12.2	2.8/0.4/0.9/0.4/2.2
	−0.29	5	−0.86	12.4	2.8/0.4/0.9/0.4/2.2
	−0.256	3	−0.86	13.1	2.8/0.5/1.0/0.5/2.2
	−0.243	6	−0.86	13.4	2.8/0.4/0.8/0.4/2.2
	−0.22	2	−0.86	13.9	2.8/0.4/0.9/0.4/2.2

T_{eff}/log g/v_{micr}/PR.

- Weighted average is 13.2 ± 2 Gyr.

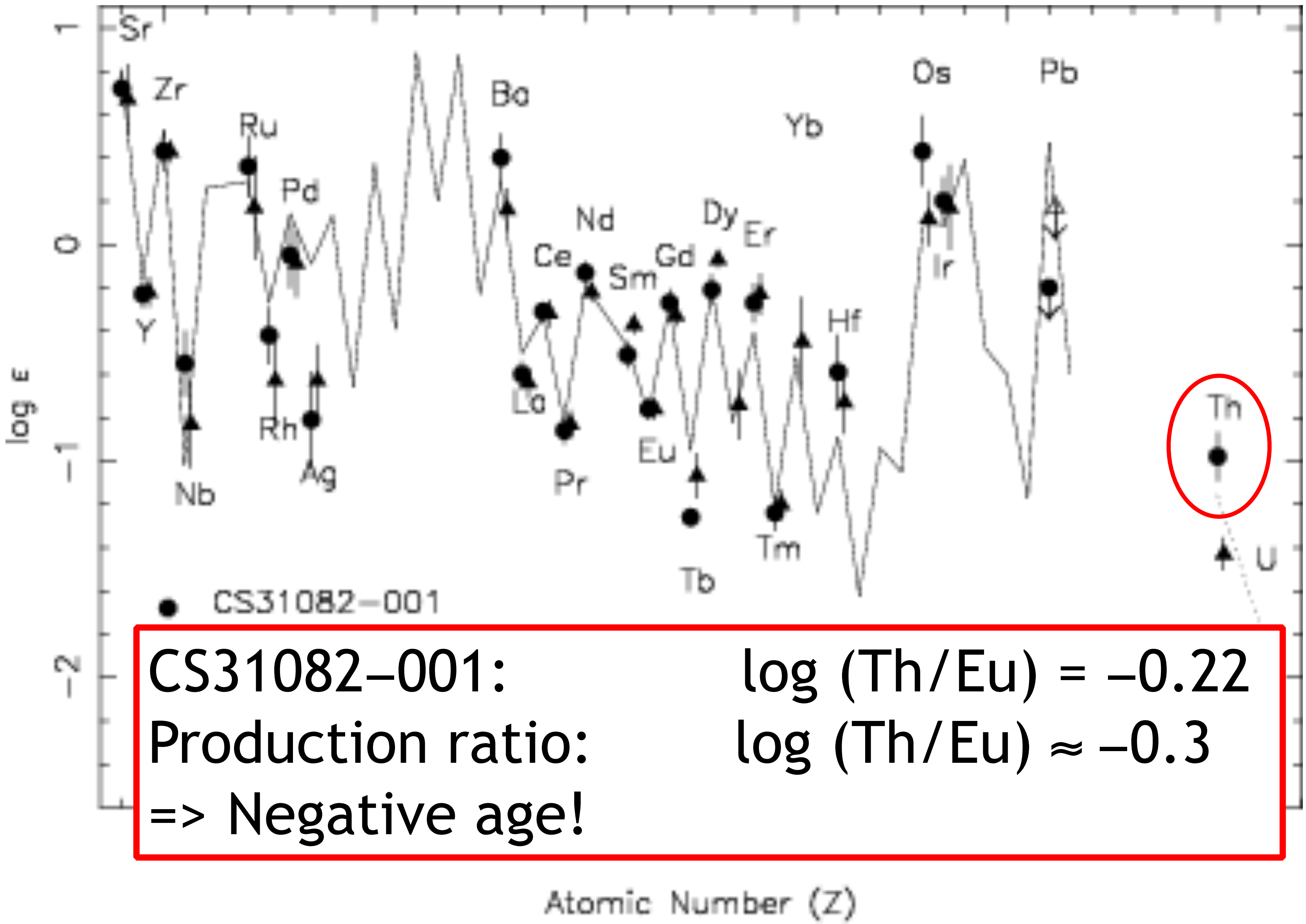
Production ratios

	log (Th/Eu)	log (U/Th)
Goriely & Arnould		–0.301
Cowan et al. (2002)	–0.295	–0.256
Schatz et al. (2002)	–0.33	–0.22
Wanajo et al. (2002)		–0.29
Sneden et al. (2003)	–0.377	
Kratz et al. (2007)	–0.344	–0.195

σ(log (Th/r)) = 0.1 dex <=> σ(Age) = 4.7 Gyr

σ(log (U/Th)) = 0.1 dex <=> σ(Age) = 2.2 Gyr

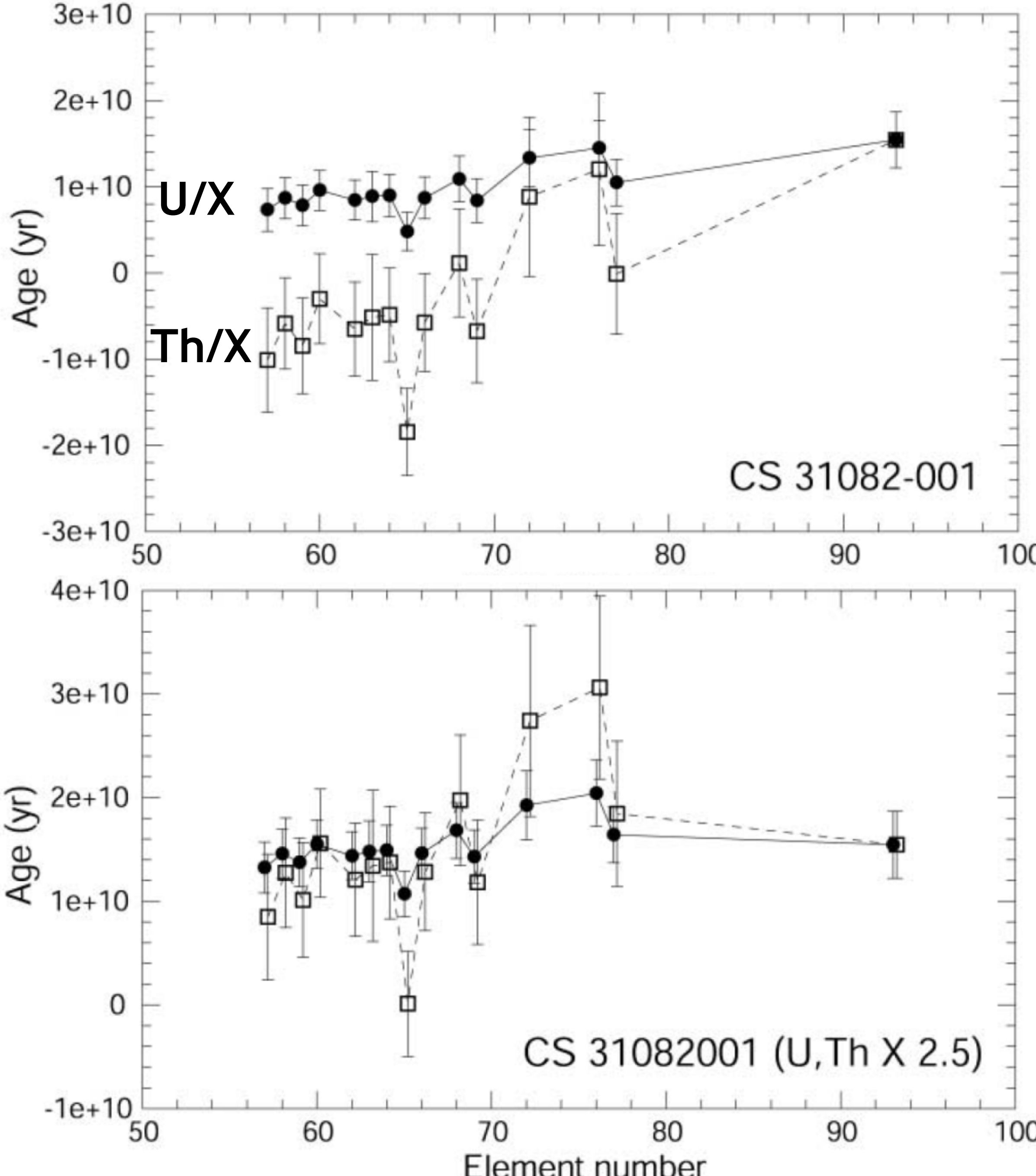
The abundance pattern of CS 31082-001



CS31082−001: log (Th/Eu) = −0.22
Production ratio: log (Th/Eu) ≈ −0.3
=> Negative age!

Hill et al. (2002 A&A 387, 560)

The “actinide boost”



Schatz et al. (2002)

Currently known r-II stars

Star	T_{eff}	log *g*	[Fe/H]	[Eu/Fe]	[Ba/Eu]	log(Th/Eu)	Refs.
CS22892-052	4880	1.8	−2.95	+1.54	−0.35	−0.62	Sneden et al. (1996, 2000)
CS31082-001	4920	1.9	−2.78	+1.66	−0.48	−0.22	Cayrel et al. (2001), Hill et al. (2002)
CS22183-031	5250	2.8	−2.93	+1.20	−0.78		Honda et al. (2004)
CS29497-004	5010	2.2	−2.81	+1.62	−0.41	−0.51	HERES; Christlieb et al. (2004)
HE 0430−4901	5300	3.1	−2.72	+1.16	−0.66		HERES
HE 0432−0923	5130	2.6	−3.19	+1.25	−0.53		HERES
HE 1127−1143	5220	2.6	−2.73	+1.08	−0.45		HERES
HE1219−0312	5060	2.3	−2.96	+1.38	−0.73	−0.23	HERES; Hayek et al. (2009)
HE 2224+0143	5200	2.7	−2.58	+1.05	−0.46		HERES; Mashonkina et al. (201X)
HE 2327−5642	5050	2.2	−2.95	+1.22	−0.56	−0.31	HERES; Mashonkina et al. (2010)
HE1226−1149	5100		−2.90	+1.7	−0.60		Keck/Cohen et al. (in prep.)
HE 1523−0901	4630	1.0	−2.95	+1.8	−0.34	−0.58	Frebel et al. (2007)
CS31078-018	5260	2.8	−2.85	+1.2	−0.51	−0.18	Lai et al. (2008)
SDSS J2357−0052	5000	4.8	−3.4	+1.9	−0.80	< −0.32	Aoki et al. (2010)

Red: actinide boost stars (4 out of 7) -- only Th/U chronometer works
Green: „normal“ r-II stars (3 out of 7) -- all chronometer pairs work
Black: Th not yet detected

Conclusions

- The most metal-poor stars are valuable probes of the earliest phases of Galactic chemical evolution.
- Nucleochronometric age determination of metal-poor stars is possible with precisions of up to ± **2 Gyr**.
- However, this is a method that is **not applicable to large samples of stars**, because it works only for a rare subclass of metal-poor stars, and only for bright stars, due to the high data quality that is required.
- "Rare" means: 0.001 (halo star fraction) · 0.1 (EMP) · 0.03 (r-II stars) · 0.5 (non-actinide boost) = about **1 in a million stars** in the Solar neighbourhood.

ZENTRUM FÜR ASTRONOMIE

- **First Stars V home**
- Scientific rationale
- Program
- Venue
- Abstract submission
- Registration
- General information
- Travel information
- Social events
- Important dates
- Participants
- SOC
- LOC
- Contact

First Stars V

When?

1-5 August 2016

Where?

Heidelberg Convention Center, Germany

Who?

The SOC and LOC co-chairs are Norbert Christlieb and Ralf Klessen.

Why?

The past two decades have seen enormous progress in our theoretical and observational understanding of first star and galaxy formation and the implications of these processes for subsequent cosmic evolution. These advances have been documented in four international conferences, First Stars I-IV, held in Garching in 1999, Pennsylvania in 2003, Santa Fe in

www.lsw.uni-heidelberg.de/FirstStarsV