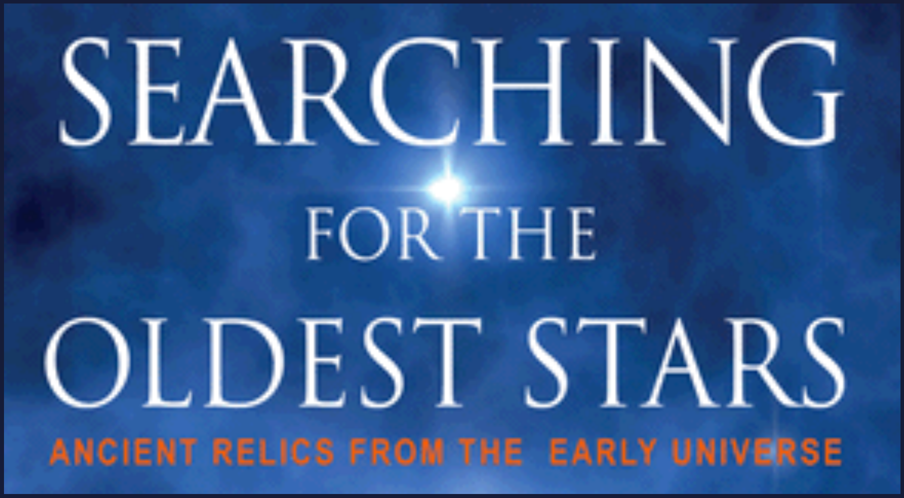

SEARCHING FOR THE OLDEST STARS

ANCIENT RELICS FROM THE EARLY UNIVERSE

Anna Frebel

Check out: annafrebel.com @annafrebel

Anna Frebel

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OVERVIEW

Introdution to metal-poor stars

- ✓ Astronomy jargon and nomenclature plus all the basics
- ✓ Early chemical evolution
- ✓ Neutron-capture signatures observed in metal-poor stars
- ✓ R-process in dwarf galaxy Reticulum II
- ✓ Question for YOU: what do you want to know?
  - ✓ Happy to talk about a variet of topics depending on interest
- ✓ Shameless ads: JINAbase, literature paper list, “Searching for the oldest stars”, video lectures

Class Discussion: Welcome!

Are you a

(A) theorist - astronomy
(B) theorist - nuclear physics
(C) observer
(D) experimentalist - nuclear physics
(E) other

Class Discussion: Metal-poor stars

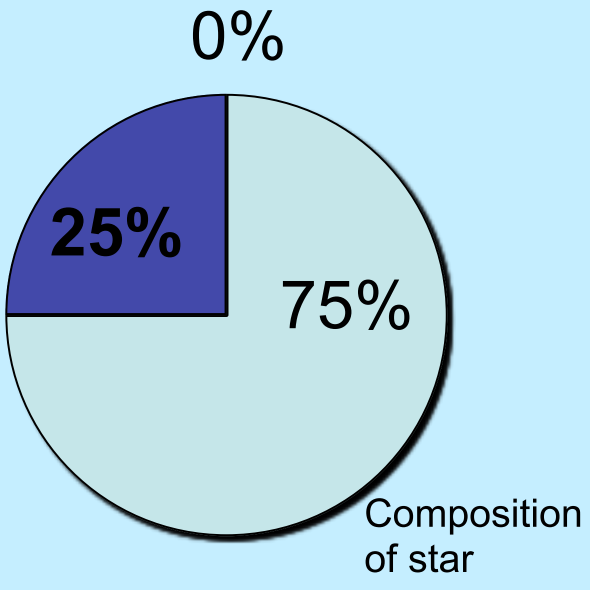
On a scale from 1 to 10 (1 = not so much; 10 = expert) how much do you know about observations/details of metal-poor stars?

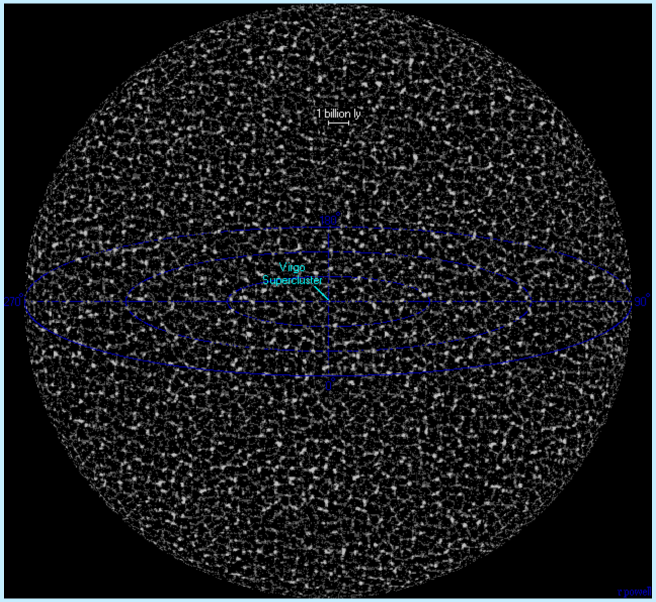
(A) 1-3
(B) 4-6
(C) 7-9
(D) 10-12

Stellar composition

One of the most fundamental concept in astronomy

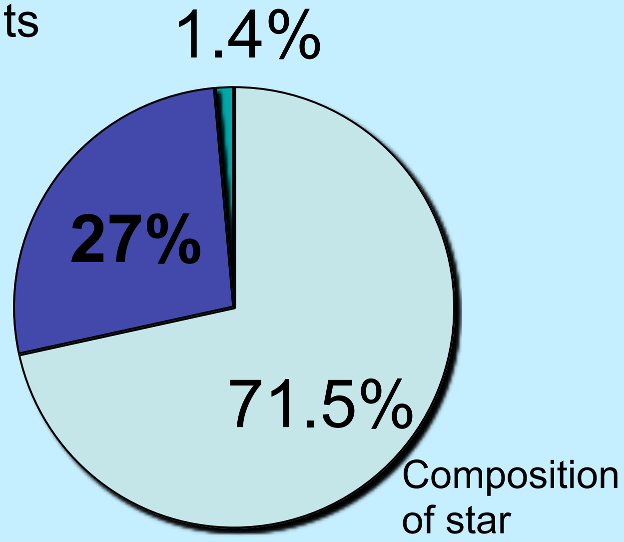
Universe
after Big
Bang
13.8 billion
yrs ago

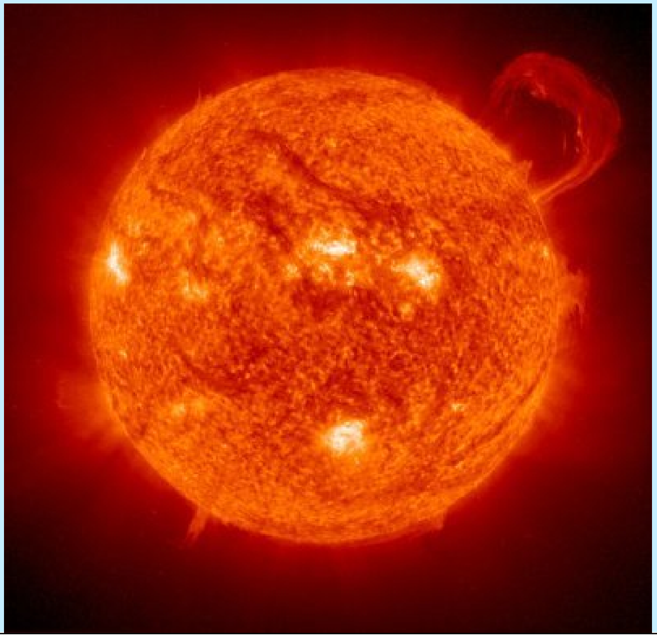




- ○ Hydrogen
- ● Helium
- ● Heavier elements

Sun
born 4.6
billion yrs
ago





Class Discussion:
Stellar evolution & nucleosynthesis

When the universe is twice its current age, the fraction of atoms in the universe that are hydrogen

(A) will be close to zero
(B) will be close to one
(C) should remain approximately constant
(D) will continue decreasing

Class Discussion:
Stellar evolution & nucleosynthesis

When the universe is twice its current age, the fraction of atoms in the universe that are hydrogen

D will continue decreasing

ASTRONOMER'S PERIODIC TABLE

In the
Universe
today

Hydrogen
1
H
1.0079

"X" ~ 71,5%

"Y" ~ 27%

Helium
2
He
4.0026

All other elements combined

Metals "Z" ~ 1.4%

Metallicity
Definition of log ε(X)

Stellar “abundances” are number density calculations with respect to H and the solar value

On a scale where H is 12.0:

$$\log \varepsilon(X) = \log_{10}\left(N_X / N_H\right) + 12$$

for element X

This quantity is the output of all model atmospheres!

i.e. MOOG code (by Chris Sneden) + Kurucz models -- all publicly available!

Definition: [Fe/H]

$$[\mathrm{Fe}/\mathrm{H}] = \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{star} - \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{sun}$$

where N_{Fe} and N_H is the no. of iron and hydrogen atoms per unit of volume respectively.

$$[\mathrm{O}/\mathrm{Fe}] = \log_{10}\left(\frac{N_{\mathrm{O}}}{N_{\mathrm{Fe}}}\right)_{star} - \log_{10}\left(\frac{N_{\mathrm{O}}}{N_{\mathrm{Fe}}}\right)_{sun}$$

$$= \left[\log_{10}(\frac{N_O}{N_H})_{star} - \log_{10}(\frac{N_O}{N_H})_{sun}\right] - \left[\log_{10}(\frac{N_{Fe}}{N_H})_{star} - \log_{10}(\frac{N_{Fe}}{N_H})_{sun}\right]$$

$$[A/H]-[B/H]=[A/B]$$ for elements A and B

Chemical abundance determination

Example:

You measure:

$\log \varepsilon\ (\mathrm{Mg})_{\mathrm{star}} = 5.96$; $\log \varepsilon\ (\mathrm{Fe})_{\mathrm{star}} = 5.50$

You look up:

$\log \varepsilon\ (\mathrm{Mg})_{\mathrm{sun}} = 7.60$; $\log \varepsilon\ (\mathrm{Fe})_{\mathrm{sun}} = 7.50$

Calculate: $[\mathrm{Mg/H}] = \log\varepsilon(\mathrm{Mg})_{\mathrm{star}} - \log\varepsilon(\mathrm{Mg})_{\mathrm{sun}} = -1.64$

=> metal-poor because subsolar!

(recall: $[\mathrm{Mg/H}] = 0$ is solar, by definition)

Calculate: $[\mathrm{Mg/Fe}] = [\mathrm{Mg/H}] - [\mathrm{Fe/H}] = -1.64 - (-2.0) = 0.36$

(alpha-enhanced compared to Sun, with positive ratio)

Solar abundances

Photospheric (='stellar' abundance)

- Anders, Grevesse & Sauval '89
- Grevesse & Sauval '98
- Asplund, Grevesse &Sauval '05
- Grevesse, Asplund & Sauval '07
- Asplund, Grevesse, Sauval & Scott '09

- reference element: H

Meteoritic (='star dust' grain analysis)

- Lodders 03
- Lodders, Palme & Gail 09

- reference element: Si

- Volatile elements depleted, incl. the most abundant elements: H, He, C, N, O, Ne cannot rely on meteorites to determine the primordial Solar System abundances for such elements

For each application, the most similarly obtained solar abundances should be use to minimize systematic uncertainties!

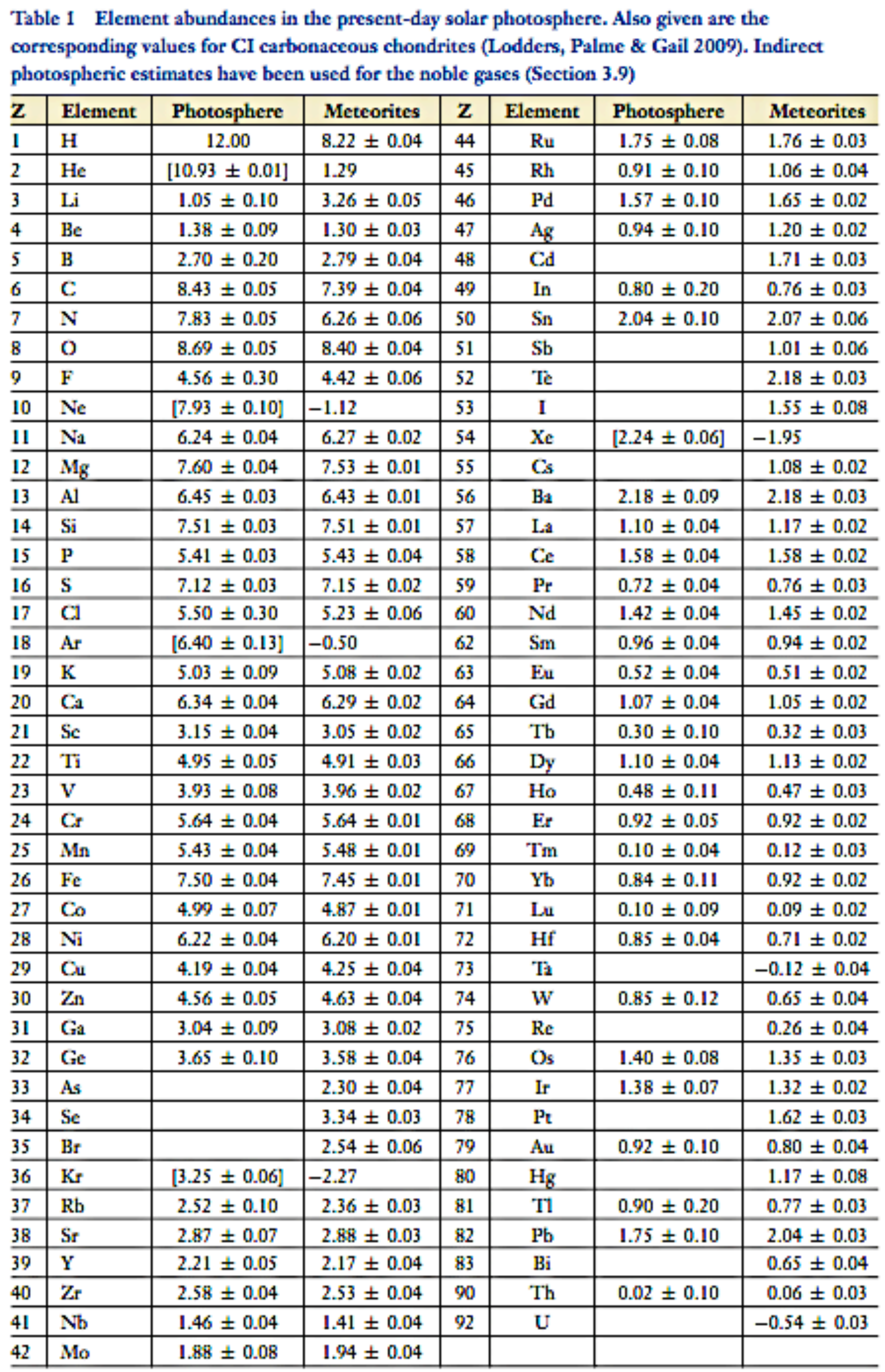


Table 1 Element abundances in the present-day solar photosphere. Also given are the corresponding values for CI carbonaceous chondrites (Lodders, Palme & Gail 2009). Indirect photospheric estimates have been used for the noble gases (Section 3.9)

Z	Element	Photosphere	Meteorites	Z	Element	Photosphere	Meteorites
1	H	12.00	8.22 ± 0.04	44	Ru	1.75 ± 0.08	1.76 ± 0.03
2	He	[10.93 ± 0.01]	1.29	45	Rh	0.91 ± 0.10	1.06 ± 0.04
3	Li	1.05 ± 0.10	3.26 ± 0.05	46	Pd	1.57 ± 0.10	1.65 ± 0.02
4	Be	1.38 ± 0.09	1.30 ± 0.03	47	Ag	0.94 ± 0.10	1.20 ± 0.02
5	B	2.70 ± 0.20	2.79 ± 0.04	48	Cd		1.71 ± 0.03
6	C	8.43 ± 0.05	7.39 ± 0.04	49	In	0.80 ± 0.20	0.76 ± 0.03
7	N	7.83 ± 0.05	6.26 ± 0.06	50	Sn	2.04 ± 0.10	2.07 ± 0.06
8	O	8.69 ± 0.05	8.40 ± 0.04	51	Sb		1.01 ± 0.06
9	F	4.56 ± 0.30	4.42 ± 0.06	52	Te		2.18 ± 0.03
10	Ne	[7.93 ± 0.10]	−1.12	53	I		1.55 ± 0.08
11	Na	6.24 ± 0.04	6.27 ± 0.02	54	Xe	[2.24 ± 0.06]	−1.95
12	Mg	7.60 ± 0.04	7.53 ± 0.01	55	Cs		1.08 ± 0.02
13	Al	6.45 ± 0.03	6.43 ± 0.01	56	Ba	2.18 ± 0.09	2.18 ± 0.03
14	Si	7.51 ± 0.03	7.51 ± 0.01	57	La	1.10 ± 0.04	1.17 ± 0.02
15	P	5.41 ± 0.03	5.43 ± 0.04	58	Ce	1.58 ± 0.04	1.58 ± 0.02
16	S	7.12 ± 0.03	7.15 ± 0.02	59	Pr	0.72 ± 0.04	0.76 ± 0.03
17	Cl	5.50 ± 0.30	5.23 ± 0.06	60	Nd	1.42 ± 0.04	1.45 ± 0.02
18	Ar	[6.40 ± 0.13]	−0.50	62	Sm	0.96 ± 0.04	0.94 ± 0.02
19	K	5.03 ± 0.09	5.08 ± 0.02	63	Eu	0.52 ± 0.04	0.51 ± 0.02
20	Ca	6.34 ± 0.04	6.29 ± 0.02	64	Gd	1.07 ± 0.04	1.05 ± 0.02
21	Sc	3.15 ± 0.04	3.05 ± 0.02	65	Tb	0.30 ± 0.10	0.32 ± 0.03
22	Ti	4.95 ± 0.05	4.91 ± 0.03	66	Dy	1.10 ± 0.04	1.13 ± 0.02
23	V	3.93 ± 0.08	3.96 ± 0.02	67	Ho	0.48 ± 0.11	0.47 ± 0.03
24	Cr	5.64 ± 0.04	5.64 ± 0.01	68	Er	0.92 ± 0.05	0.92 ± 0.02
25	Mn	5.43 ± 0.04	5.48 ± 0.01	69	Tm	0.10 ± 0.04	0.12 ± 0.03
26	Fe	7.50 ± 0.04	7.45 ± 0.01	70	Yb	0.84 ± 0.11	0.92 ± 0.02
27	Co	4.99 ± 0.07	4.87 ± 0.01	71	Lu	0.10 ± 0.09	0.09 ± 0.02
28	Ni	6.22 ± 0.04	6.20 ± 0.01	72	Hf	0.85 ± 0.04	0.71 ± 0.02
29	Cu	4.19 ± 0.04	4.25 ± 0.04	73	Ta		−0.12 ± 0.04
30	Zn	4.56 ± 0.05	4.63 ± 0.04	74	W	0.85 ± 0.12	0.65 ± 0.04
31	Ga	3.04 ± 0.09	3.08 ± 0.02	75	Re		0.26 ± 0.04
32	Ge	3.65 ± 0.10	3.58 ± 0.04	76	Os	1.40 ± 0.08	1.35 ± 0.03
33	As		2.30 ± 0.04	77	Ir	1.38 ± 0.07	1.32 ± 0.02
34	Se		3.34 ± 0.03	78	Pt		1.62 ± 0.03
35	Br		2.54 ± 0.06	79	Au	0.92 ± 0.10	0.80 ± 0.04
36	Kr	[3.25 ± 0.06]	−2.27	80	Hg		1.17 ± 0.08
37	Rb	2.52 ± 0.10	2.36 ± 0.03	81	Tl	0.90 ± 0.20	0.77 ± 0.03
38	Sr	2.87 ± 0.07	2.88 ± 0.03	82	Pb	1.75 ± 0.10	2.04 ± 0.03
39	Y	2.21 ± 0.05	2.17 ± 0.04	83	Bi		0.65 ± 0.04
40	Zr	2.58 ± 0.04	2.53 ± 0.04	90	Th	0.02 ± 0.10	0.06 ± 0.03
41	Nb	1.46 ± 0.04	1.41 ± 0.04	92	U		−0.54 ± 0.03
42	Mo	1.88 ± 0.08	1.94 ± 0.04				

Classification Scheme

	Range	Term	Acronym	#
Pop I stars	[Fe/H] ≥ +0.5	Super metal-rich	SMR	some
	[Fe/H] = 0.0	Solar	—	a lot!
Pop II stars	[Fe/H] ≤ –1.0	Metal-poor	MP	very many
	[Fe/H] ≤ –2.0	Very metal-poor	VMP	many
Extreme Pop II stars!	[Fe/H] ≤ –3.0	Extremely metal-poor	EMP	~100
	[Fe/H] ≤ –4.0	Ultra metal-poor	UMP	1
	[Fe/H] ≤ –5.0	Hyper metal-poor	HMP	2
	[Fe/H] ≤ –6.0	Mega metal-poor	MMP	--

Pop III stars [Fe/H] = – ∞

as suggested by Beers & Christlieb 2005

Update: Metal-poor star classifications

Frebel 2018, ARN&P, in prep

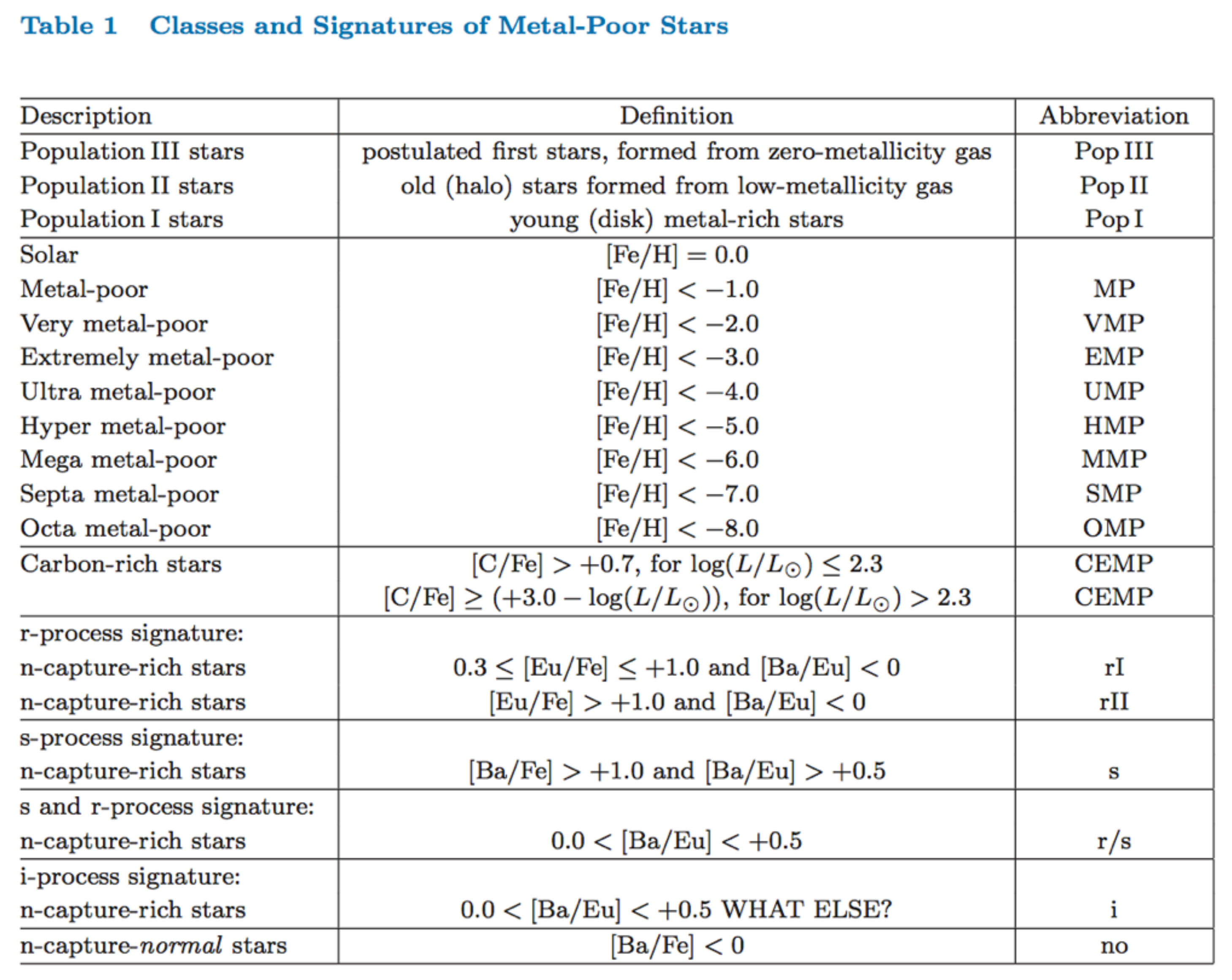


Table 1 Classes and Signatures of Metal-Poor Stars

Description	Definition	Abbreviation
Population III stars	postulated first stars, formed from zero-metallicity gas	Pop III
Population II stars	old (halo) stars formed from low-metallicity gas	Pop II
Population I stars	young (disk) metal-rich stars	Pop I
Solar	$[\mathrm{Fe/H}] = 0.0$	
Metal-poor	$[\mathrm{Fe/H}] < -1.0$	MP
Very metal-poor	$[\mathrm{Fe/H}] < -2.0$	VMP
Extremely metal-poor	$[\mathrm{Fe/H}] < -3.0$	EMP
Ultra metal-poor	$[\mathrm{Fe/H}] < -4.0$	UMP
Hyper metal-poor	$[\mathrm{Fe/H}] < -5.0$	HMP
Mega metal-poor	$[\mathrm{Fe/H}] < -6.0$	MMP
Septa metal-poor	$[\mathrm{Fe/H}] < -7.0$	SMP
Octa metal-poor	$[\mathrm{Fe/H}] < -8.0$	OMP
Carbon-rich stars	$[\mathrm{C/Fe}] > +0.7$, for $\log(L/L_\odot) \leq 2.3$	CEMP
	$[\mathrm{C/Fe}] \geq (+3.0 - \log(L/L_\odot))$, for $\log(L/L_\odot) > 2.3$	CEMP
r-process signature:		
n-capture-rich stars	$0.3 \leq [\mathrm{Eu/Fe}] \leq +1.0$ and $[\mathrm{Ba/Eu}] < 0$	rI
n-capture-rich stars	$[\mathrm{Eu/Fe}] > +1.0$ and $[\mathrm{Ba/Eu}] < 0$	rII
s-process signature:		
n-capture-rich stars	$[\mathrm{Ba/Fe}] > +1.0$ and $[\mathrm{Ba/Eu}] > +0.5$	s
s and r-process signature:		
n-capture-rich stars	$0.0 < [\mathrm{Ba/Eu}] < +0.5$	r/s
i-process signature:		
n-capture-rich stars	$0.0 < [\mathrm{Ba/Eu}] < +0.5$ WHAT ELSE?	i
n-capture-*normal* stars	$[\mathrm{Ba/Fe}] < 0$	no

Class Discussion: Metallicity

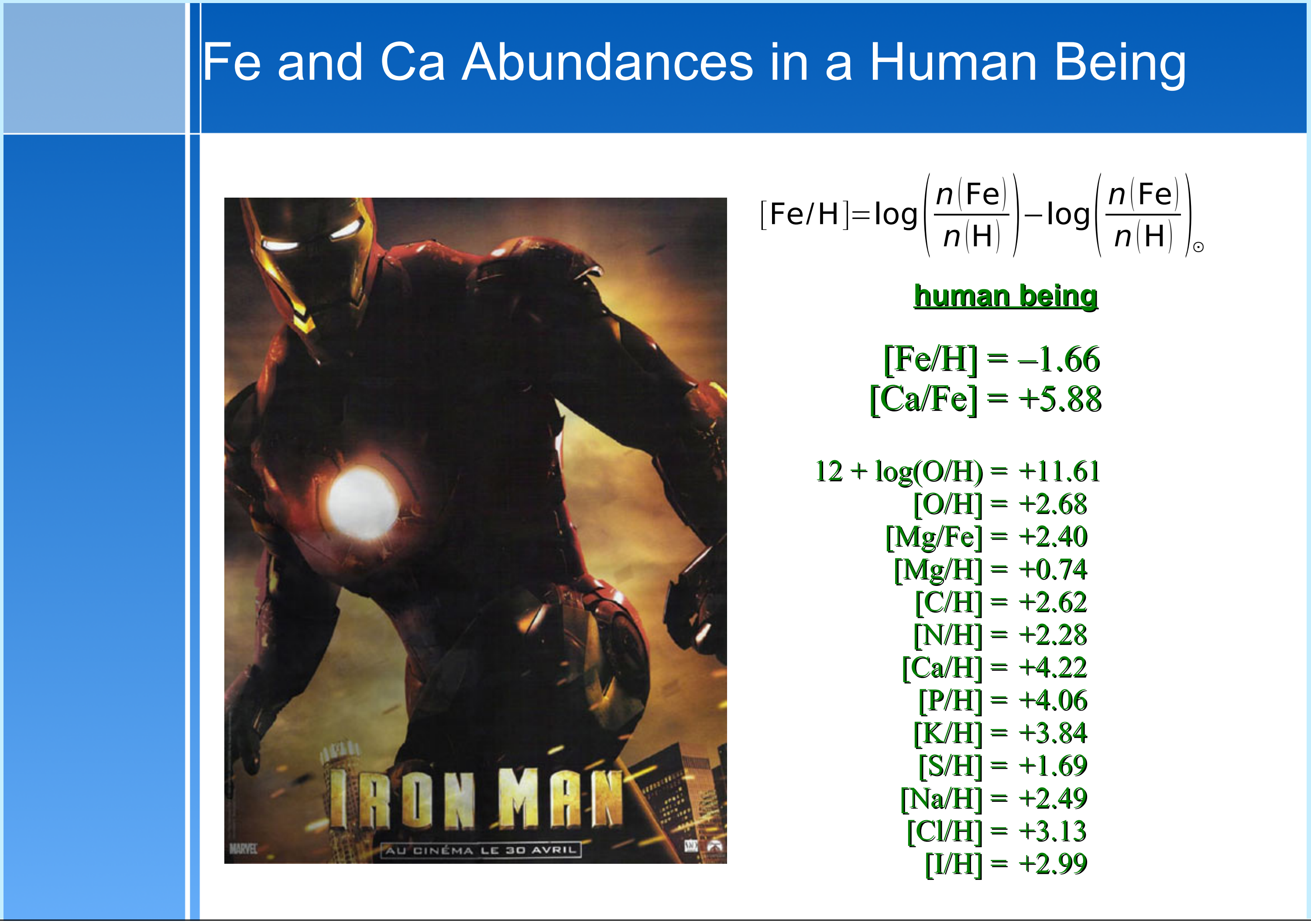
What is the [Fe/H] abundance of the human body?

(A) super metal-rich
(B) metal-rich
(C) metal-poor
(D) very metal-poor

Class Discussion: Metallicity

What is the [Fe/H] abundance of the human body?

(C) metal-poor



Fe and Ca Abundances in a Human Being

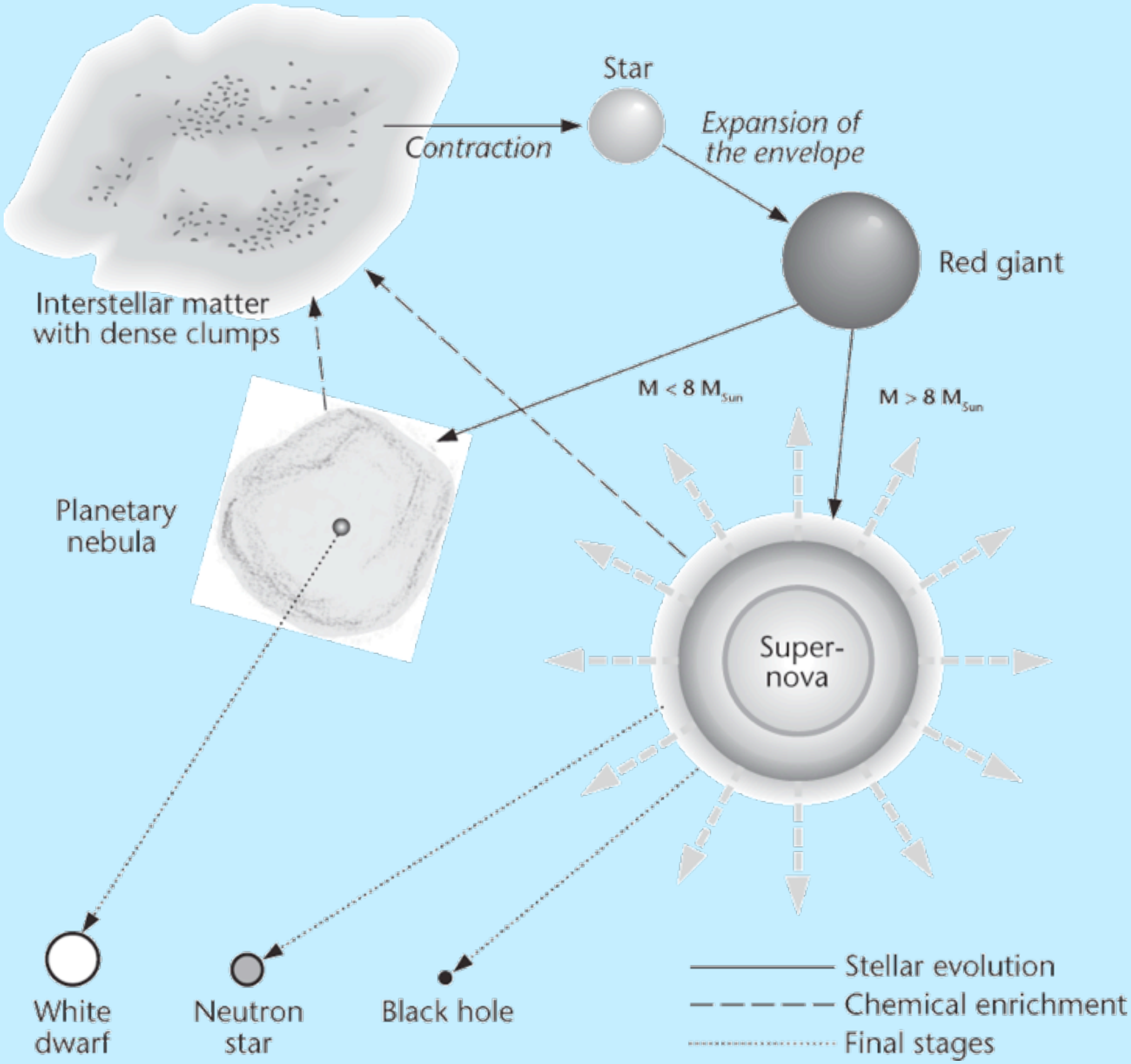
$$[\mathrm{Fe/H}] = \log\left(\frac{n(\mathrm{Fe})}{n(\mathrm{H})}\right) - \log\left(\frac{n(\mathrm{Fe})}{n(\mathrm{H})}\right)_{\odot}$$

human being

[Fe/H] = –1.66
[Ca/Fe] = +5.88

12 + log(O/H) = +11.61
[O/H] = +2.68
[Mg/Fe] = +2.40
[Mg/H] = +0.74
[C/H] = +2.62
[N/H] = +2.28
[Ca/H] = +4.22
[P/H] = +4.06
[K/H] = +3.84
[S/H] = +1.69
[Na/H] = +2.49
[Cl/H] = +3.13
[I/H] = +2.99

Cosmic cycle of matter



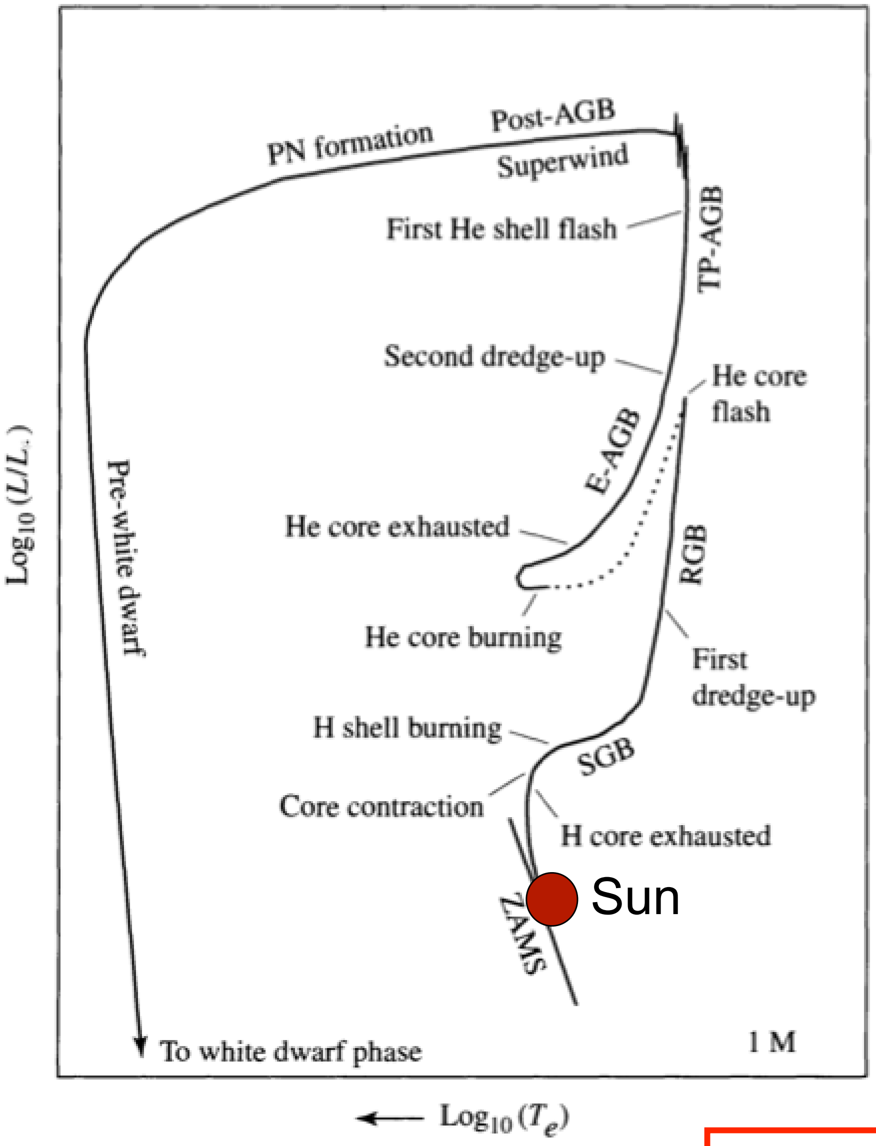


FIGURE 13.4 A schematic diagram of the evolution of a low-mass star of 1 $M_\odot$ from the zero-age main sequence to the formation of a white dwarf star (see Section 16.1). The dotted phase of evolution represents rapid evolution following the helium core flash. The various phases of evolution are labeled as follows: Zero-Age-Main-Sequence (ZAMS), Sub-Giant Branch (SGB), Red Giant Branch (RGB), Early Asymptotic Giant Branch (E-AGB), Thermal Pulse Asymptotic Giant Branch (TP-AGB), Post-Asymptotic Giant Branch (Post-AGB), Planetary Nebula formation (PN formation), and Pre-white dwarf phase leading to white dwarf phase.

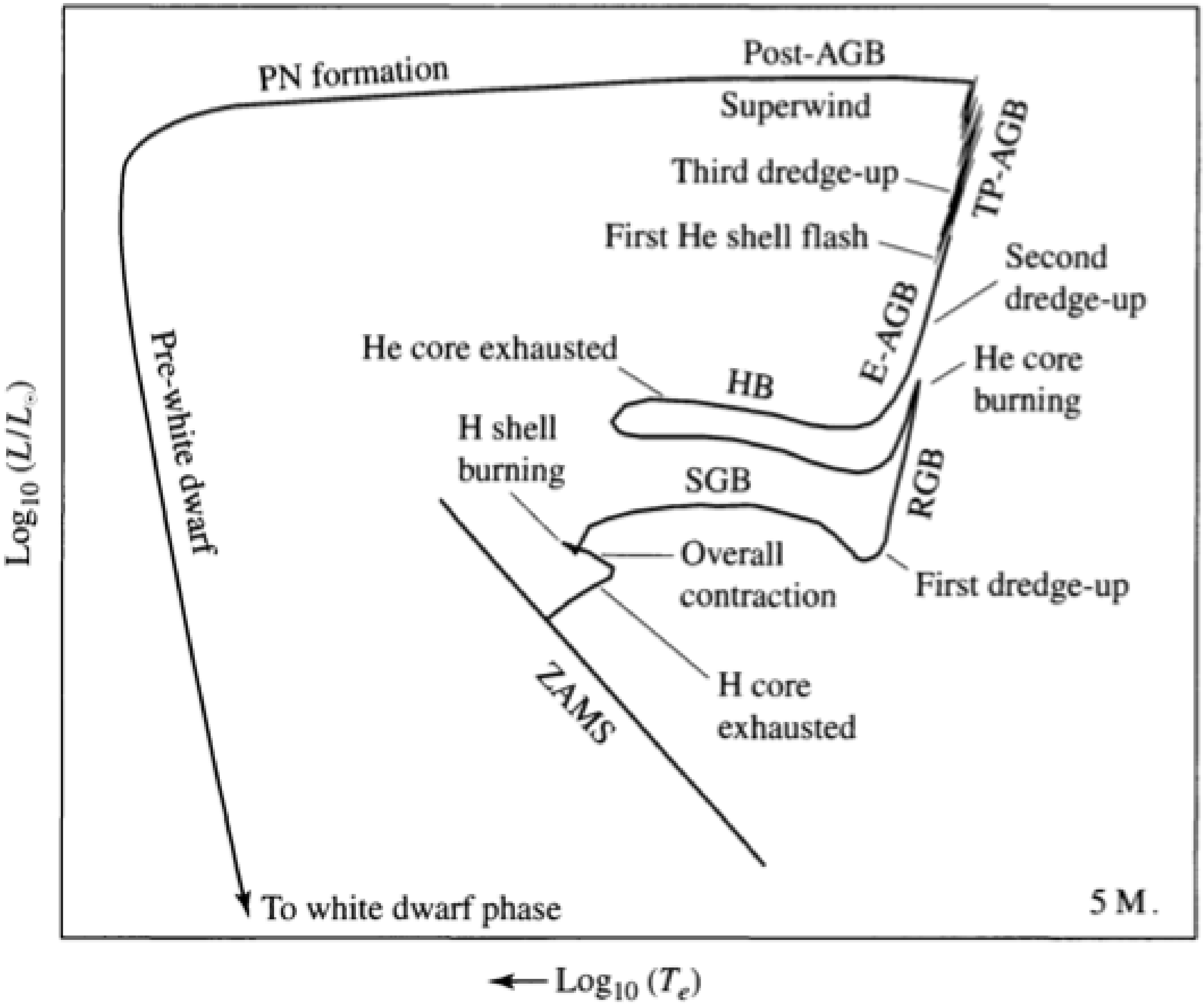


FIGURE 13.5 A schematic diagram of the evolution of an intermediate-mass star of 5 $M_\odot$ from the zero-age main sequence to the formation of a white dwarf star (see Section 16.1). The diagram is labeled according to Fig. 13.4 with the addition of the Horizontal Branch (HB).

Class Discussion:
Stellar interiors

If the center of the Sun be heated slightly, the nuclear reactions would faster and hence release more heat, so the Sun's core would

(A) collapse
(B) expand and hence cool back to its original temperature
(C) expand and hence heat up even more
(D) explode

Class Discussion: Stellar interiors

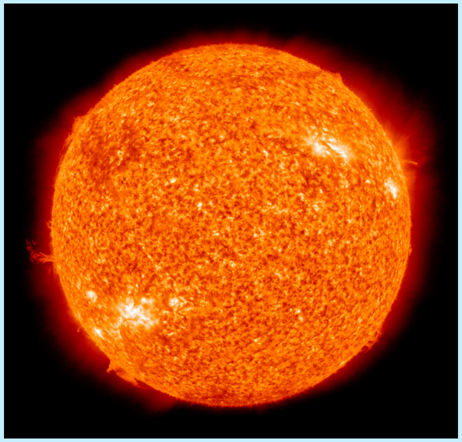
If the center of the Sun be heated slightly, the nuclear reactions would faster and hence release more heat, so the Sun’s core would

(A) expand and hence cool back to its original temperature

=> will reach hydrostatic equilibrium again, which depends on mass not T.

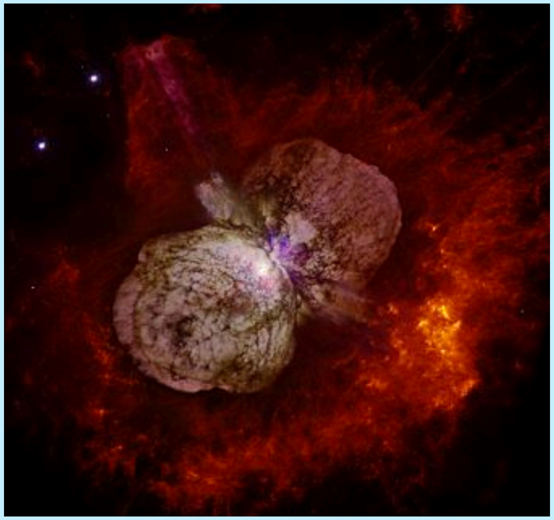
Stellar Lifetimes

- Total fuel to burn is the stellar mass



- **Low-mass stars** have rather long lives
- e.g. Sun: 10 billion yrs

- **High-mass stars** burn through their fuel faster and live shorter
- e.g. millions of years



Class Discussion: Stellar evolution & nucleosynthesis

Fusion in the core of a main sequence star changes the chemical composition in the core. What happens to the chemical composition of the rest of the star?

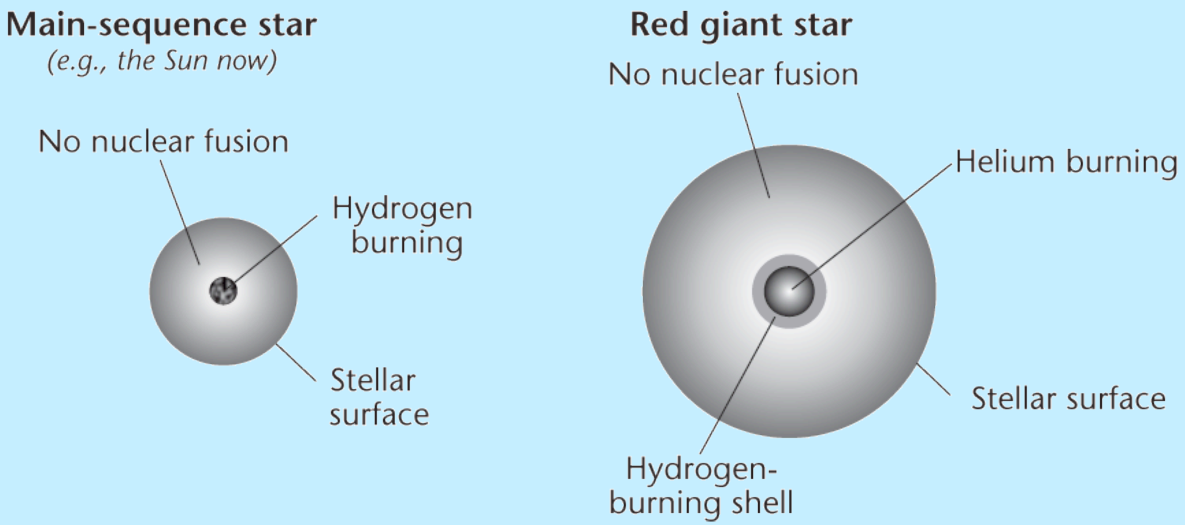
(A) We have no way to find out
(B) The chemical composition outside the core doesn’t change much
(C) The same changes occur outside the core as within the core
(D) Hydrogen becomes more abundant outside the core

Class Discussion:
Stellar evolution & nucleosynthesis

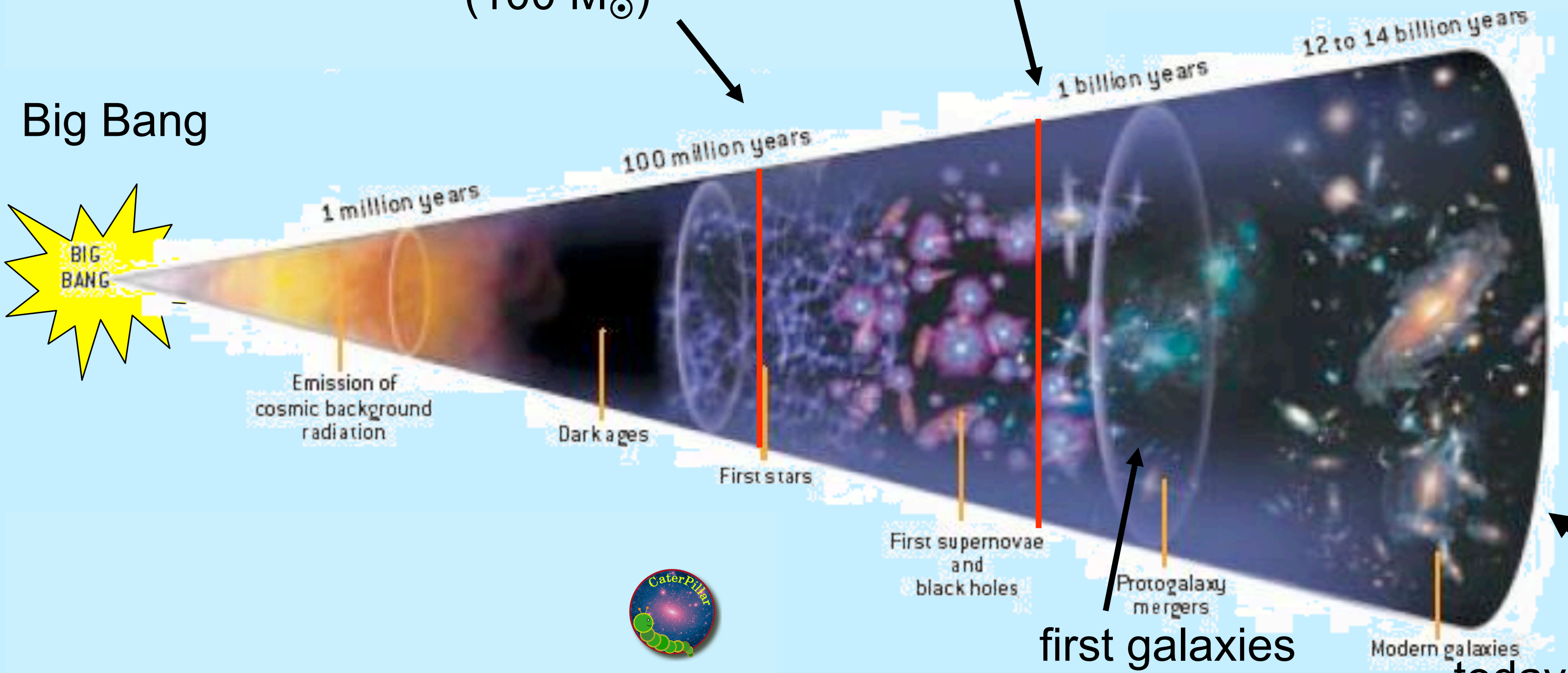
Fusion in the core of a main sequence star changes the chemical composition in the core. What happens to the chemical composition outside the core?

(B) The chemical composition outside the core doesn't change much

To the outer layers, the core is like in a galaxy far far away...



A long time ago...



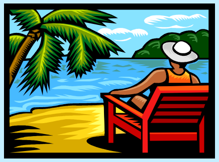
Big Bang

First stars
(100 $M_\odot$)

2nd and later generations
of stars (<1 $M_\odot$)

first galaxies

today



today's galaxies

SCIENTIFIC AMERICAN
Larson & Bromm 2001

Cosmic time (not to scale)

Red:
first star minihalos

Yellow:
first galaxies

How metal-poor can it get?

Classical example:

Early universe: primordial gas, first star makes metals (i.e., Fe)

How metal-poor is a second-generation star?

Available gas mass: 10^6 M_{sun} =>

Canonical SN Fe yield: 0.1 M_{sun} =>

$$N_H = \frac{M_{tot}}{m_H} = \frac{10^6 M_{sun}}{m_H}$$

$$N_{Fe} = \frac{M_{tot}}{m_{Fe}} = \frac{0.1 M_{sun}}{56 m_H}$$

$$[\mathrm{Fe}/\mathrm{H}] = \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{star} - \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{sun}$$

$$\frac{N_{Fe}}{N_H} = \frac{0.1 M_{sun}}{56 m_H} \times \frac{m_H}{10^6 M_{sun}} = \frac{10^{-7}}{56}$$

$$\log \varepsilon(Fe)_{sun} = \log(N_{Fe}/N_H)_{sun} + 12 = 7.50$$ (from Table)

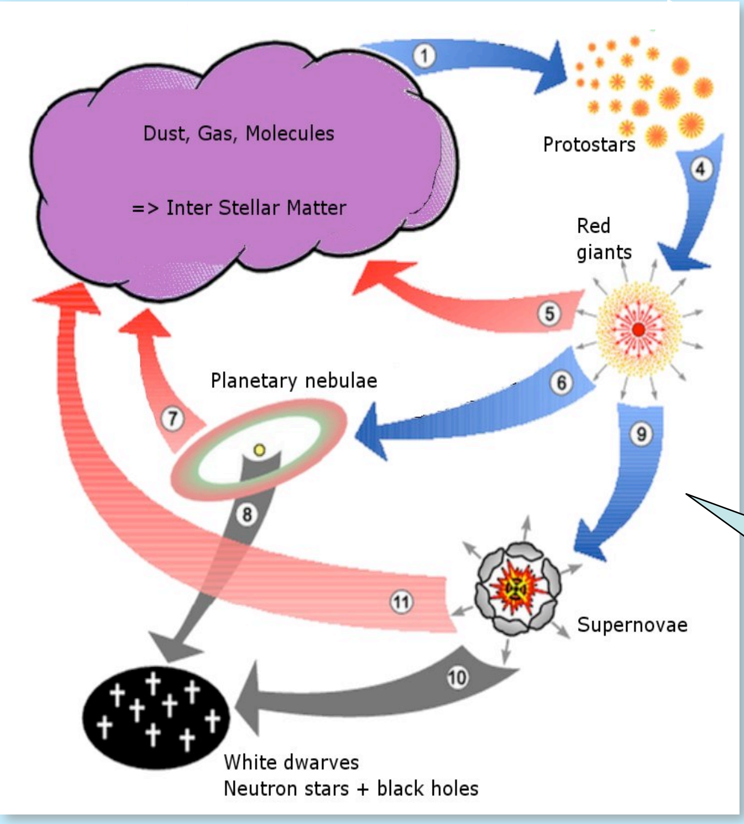
$$\Rightarrow \log(N_{Fe}/N_H)_{sun} = 7.50 - 12 = -4.50$$

$$\boxed{\Rightarrow [Fe/H] = \log(\frac{10^{-7}}{56}) - (-4.50) = -4.2}$$

~1/10,000 of the solar Fe abundance!

Chemical evolution

Chemical evolution & cosmic recycling



Zentrum fuer Astronomie und Astrophysik, TU Berlin

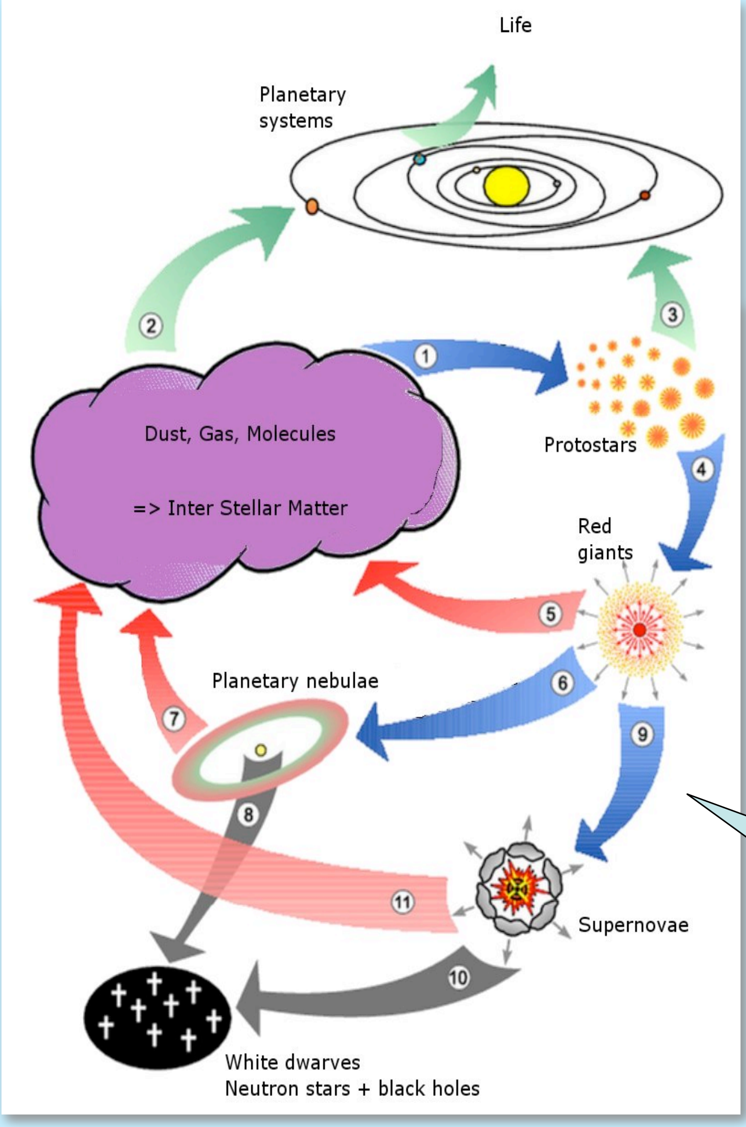
Stars are made from ~75% H and ~25% He, but:

⇒ Early stars contain little <u>of</u> all elements

⇒ Younger stars contain larger amounts

Old(er) stars contain the <u>least amounts</u> of elements heavier than H and He!

Chemical evolution



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Stars are made from ~75% H and ~25% He, but:

⇒ Early stars contain little <u>of</u> all elements

⇒ Younger stars contain larger amounts

<u>Examples</u>

Sun: contains 1.4 % heavy elements (by mass)

Oldest stars: 10^{-4} to 10^{-7} % heavy elements

Old(er) stars contain the <u>least amounts</u> of elements heavier than H and He!

Chemical evolution

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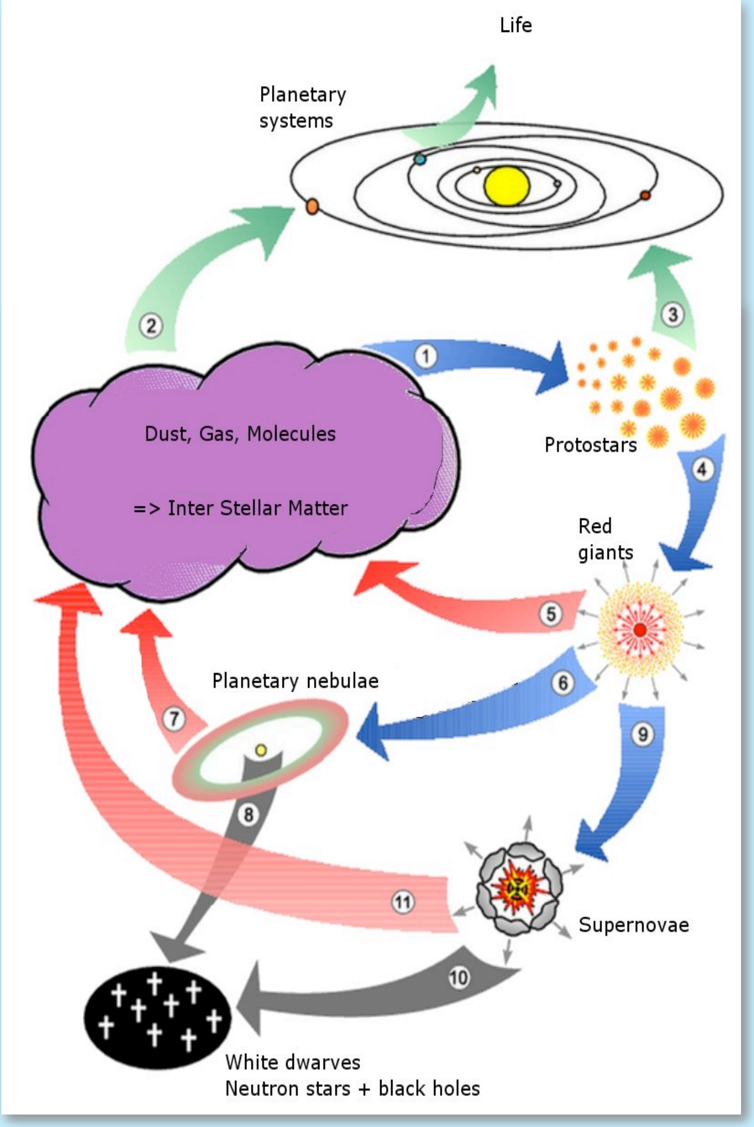
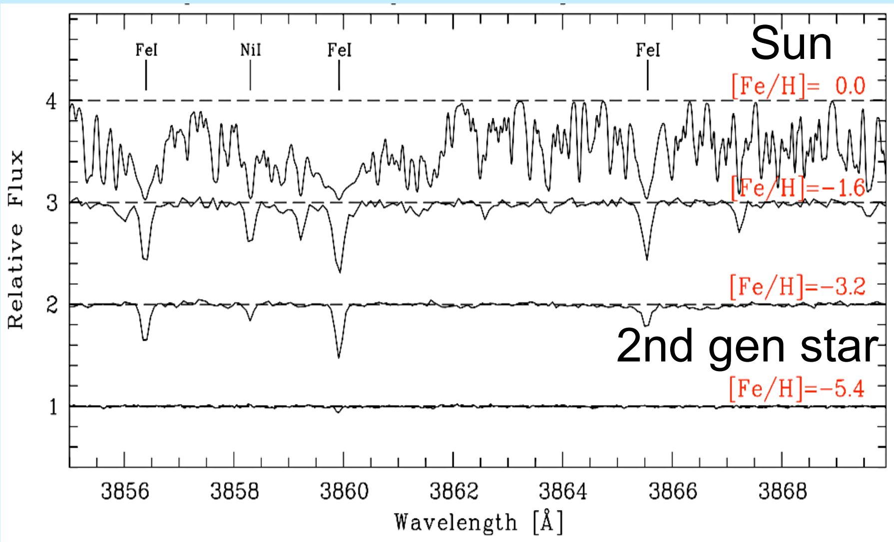


Stars are made from ~75% H and ~25% He, but:

⇒ Early stars contain little <u>of</u> all elements

⇒ Younger stars contain larger amounts

“Look-back time”

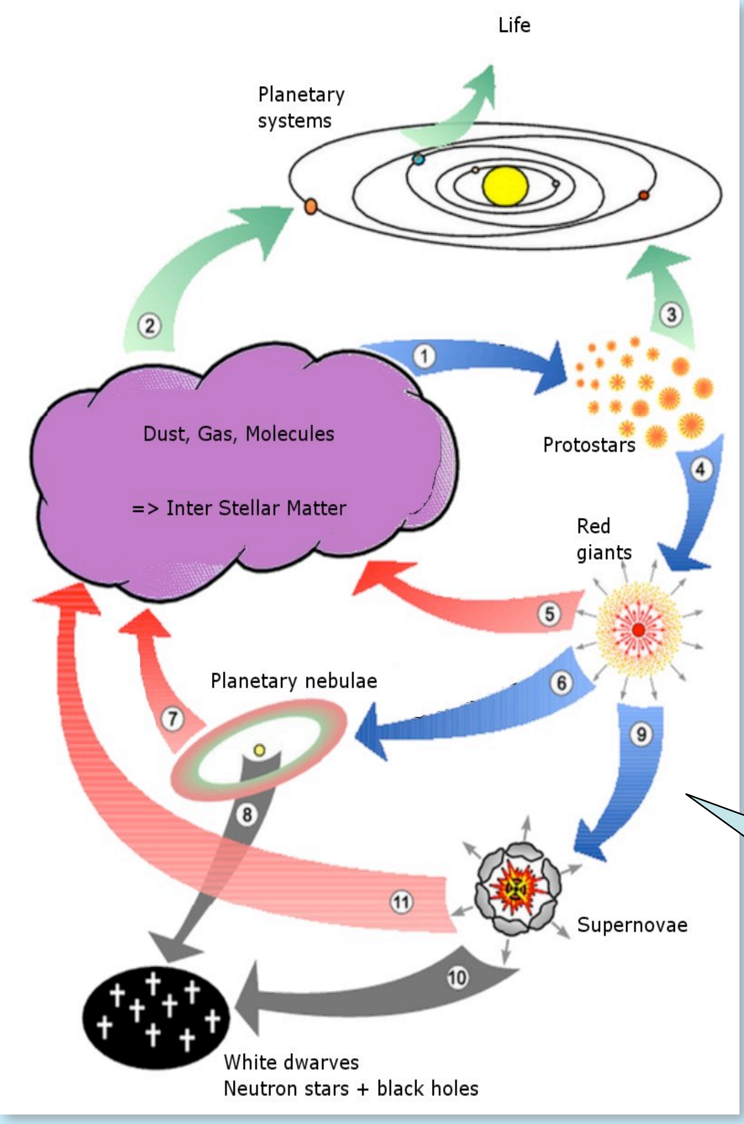


Galactic chemical evolution

Abundances are derived from integrated absorption line strengths

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

Chemical evolution



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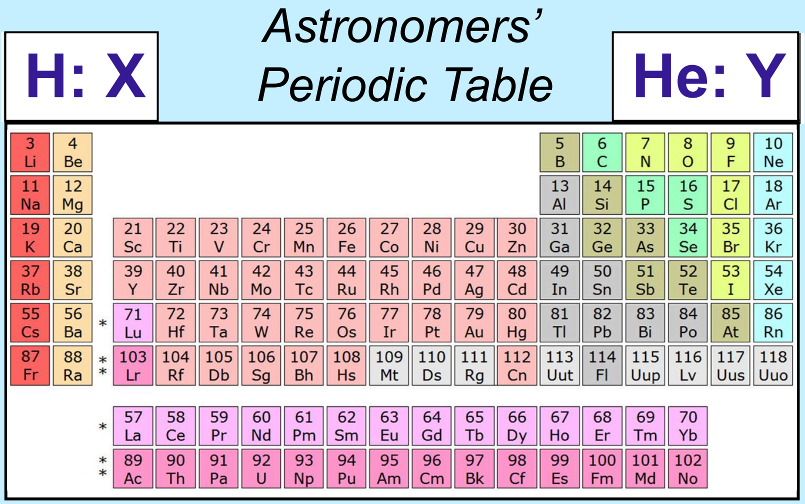


H: X

Astronomers' Periodic Table

He: Y

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 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	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		

With time, more and more of all elements were made!

Old(er) stars contain the least amounts of elements heavier than H and He!

Class Discussion:
Stellar evolution & nucleosynthesis

The chemical composition of the Sun 3 billion years ago was different from what it is now in that it had

(A) more hydrogen
(B) more helium
(C) actually stayed the same
(D) molecular hydrogen

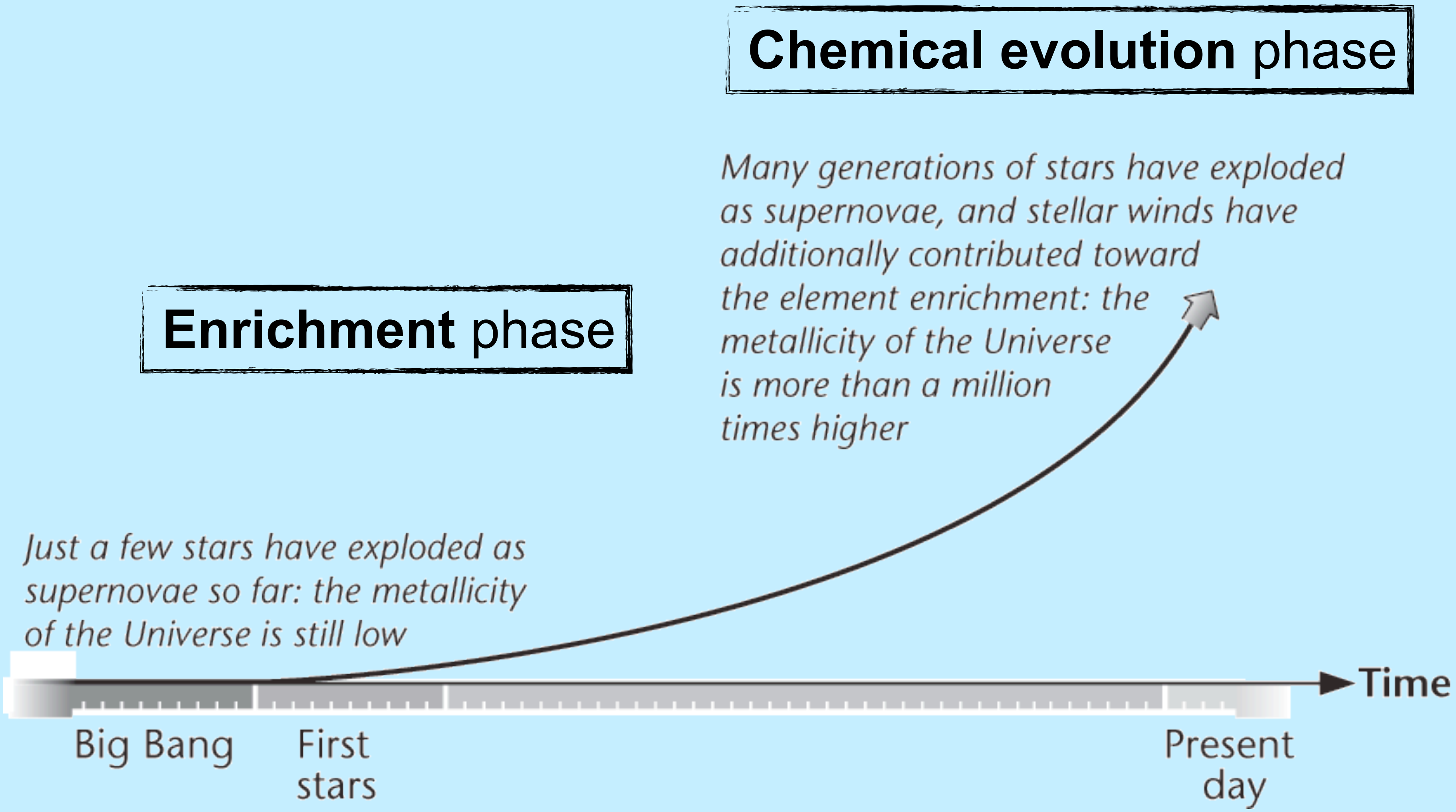
Class Discussion:
Stellar evolution & nucleosynthesis

The chemical composition of the Sun 3 billion years ago was different from what it is now in that it had

(A) more hydrogen

H has been converted to He since then. The Sun is still just converting H to He.

Chemical evolution



Enrichment phase

Just a few stars have exploded as supernovae so far: the metallicity of the Universe is still low

Chemical evolution phase

Many generations of stars have exploded as supernovae, and stellar winds have additionally contributed toward the element enrichment: the metallicity of the Universe is more than a million times higher

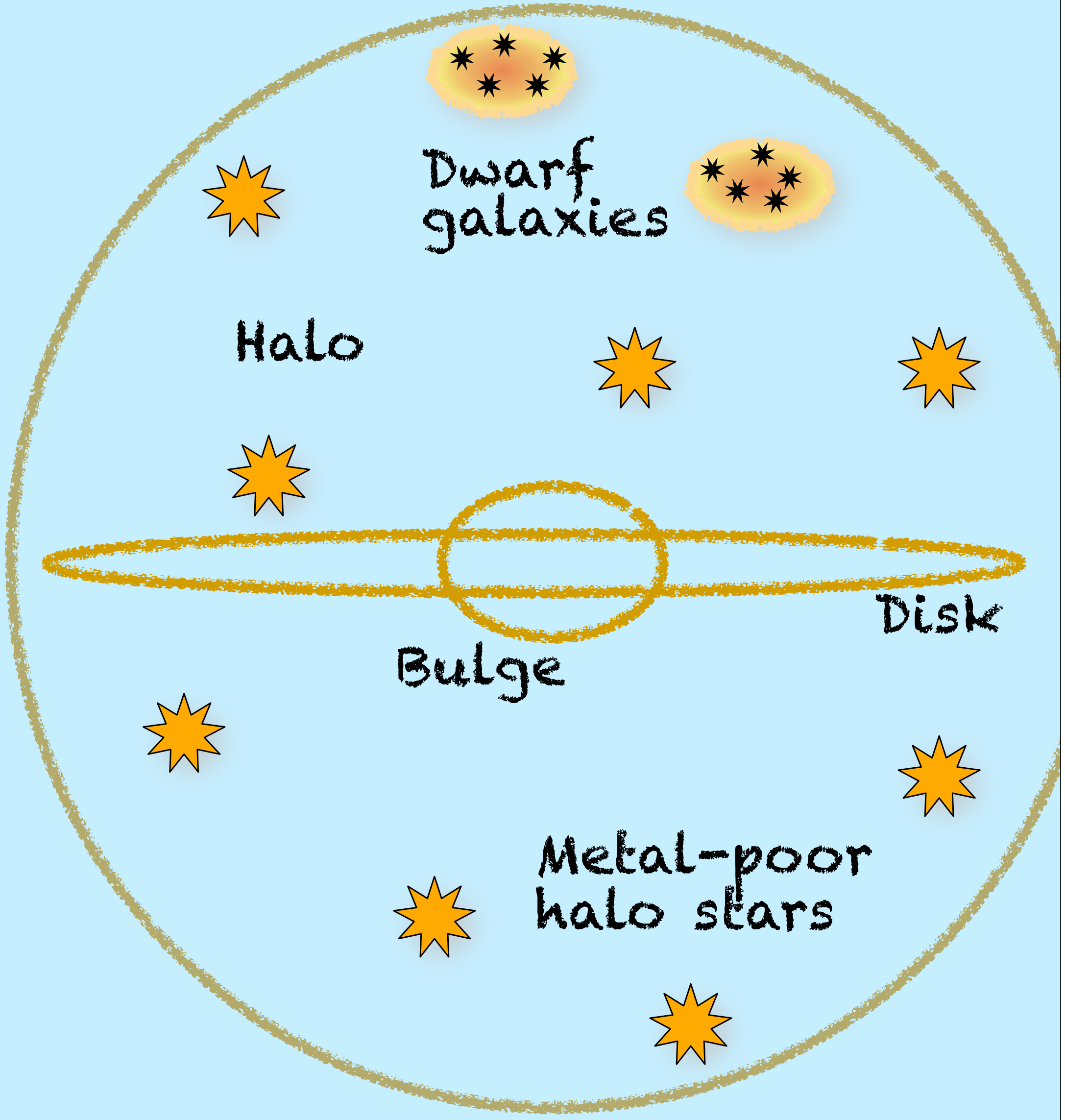
Where are metal-poor stars found in the Milky Way

Metal-poor stars are found in the halo, the bulge and dwarf galaxies

The disk and open and globular clusters do not contain stars with [Fe/H]<−2.3

=> Origin of halo and bulge stars is actually unknown

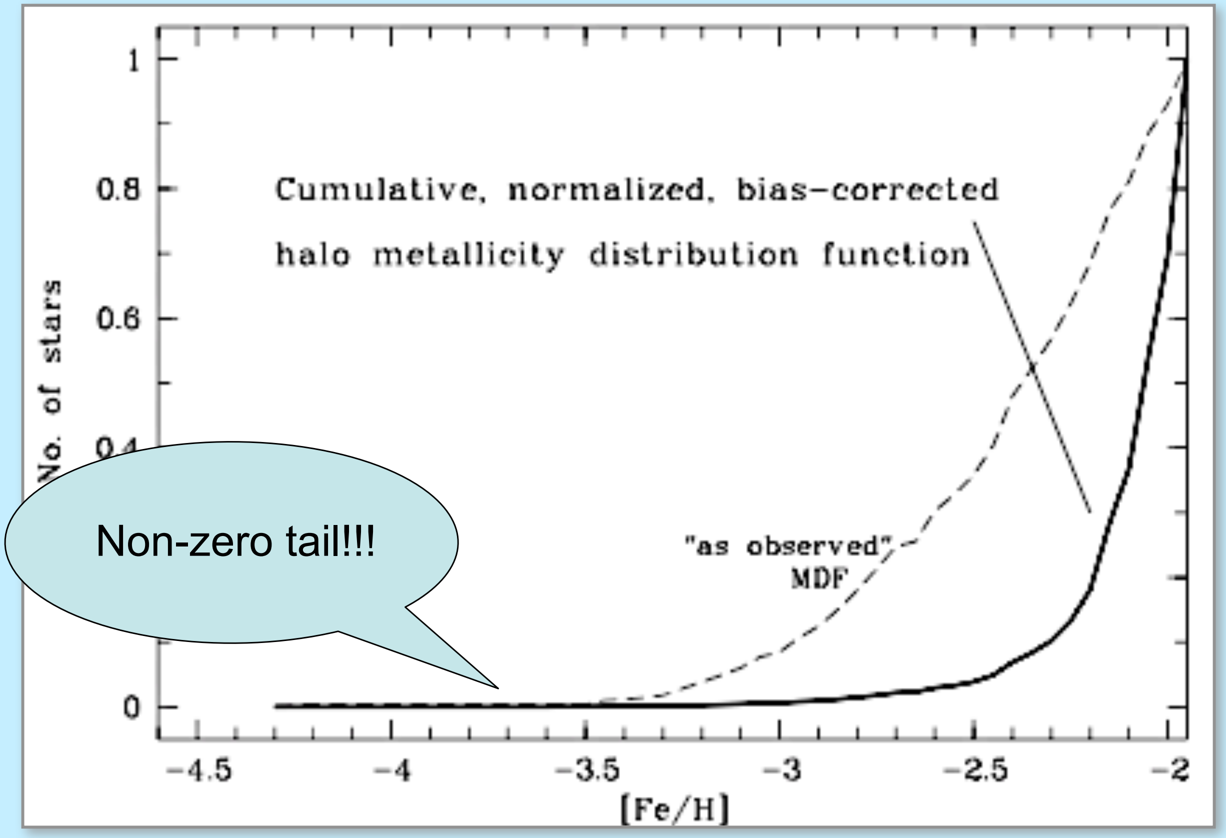
=> Trace chemical signature of their birth gas cloud wherever they formed



Halo Metallicity distribution function (MDF)

Previous ‘as observed’, raw MDF is **not** a realistic presentation!

(but shows that we have been doing a good job in finding these stars..)



Non-zero tail!!!

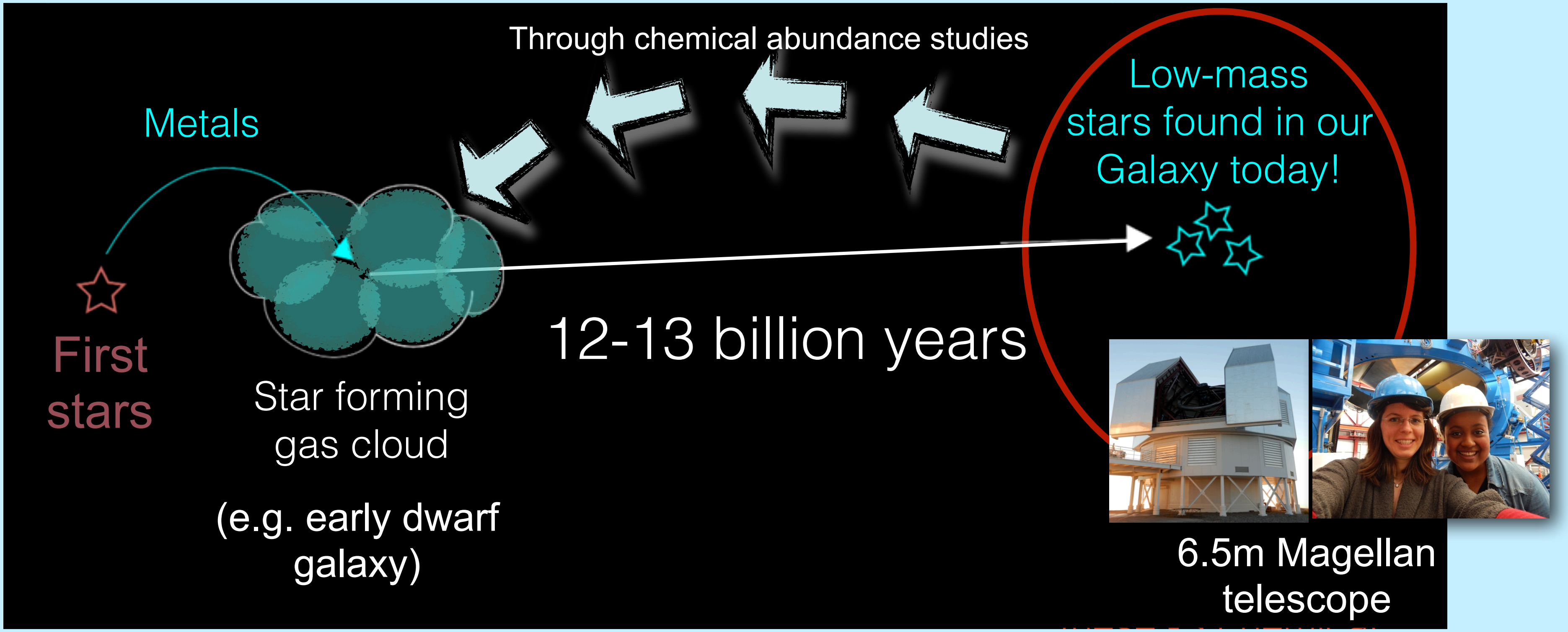
Schoerck et al. 2008

The most metal-poor stars are extremely rare but extremely important!

Stellar archaeology

Using metal-poor stars to probe the early universe

Low-mass stars with $M < 1\ M_\odot$: Lifetimes > 10 billion years => they are still around!



Through chemical abundance studies

Metals

First stars

Star forming gas cloud

(e.g. early dwarf galaxy)

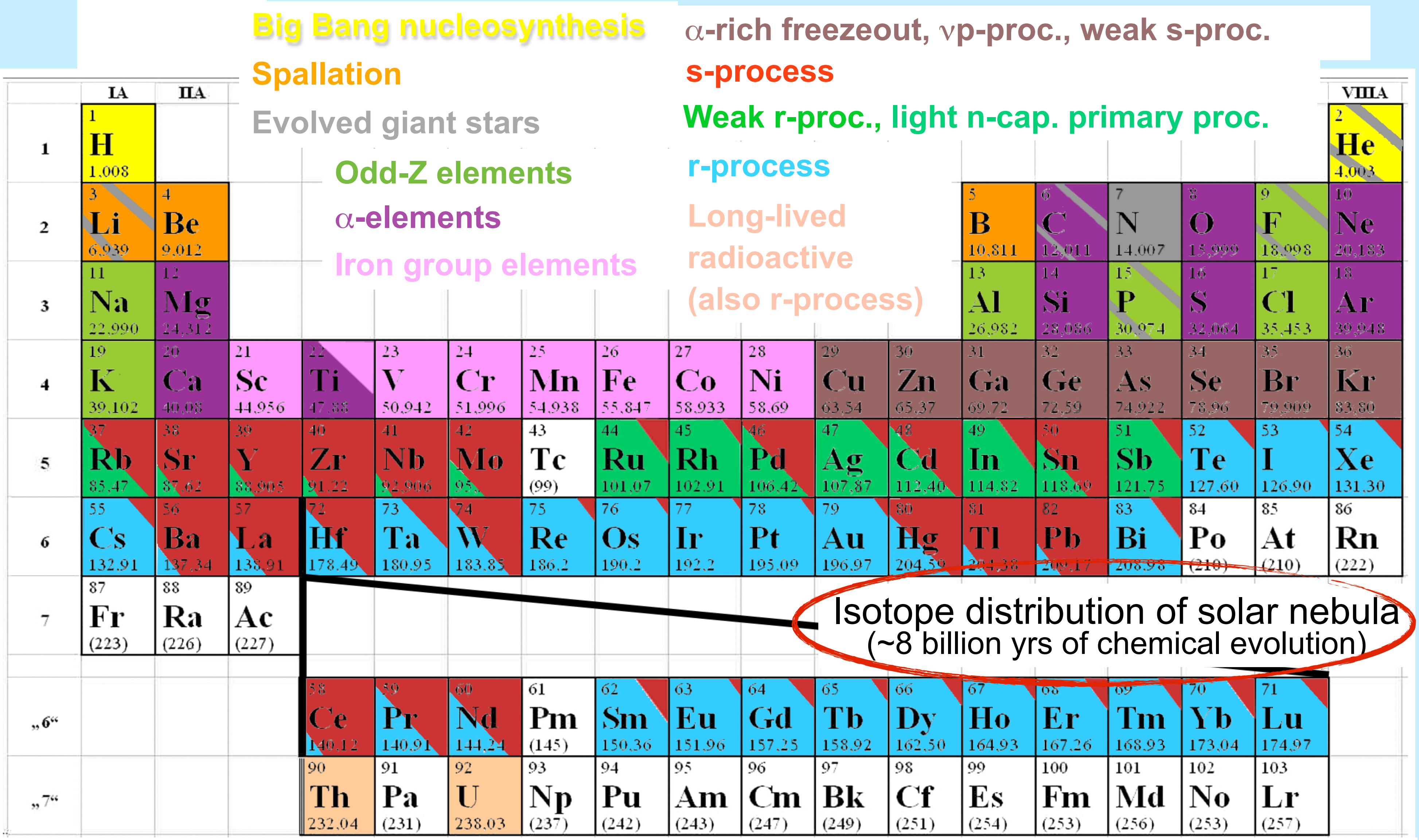
12-13 billion years

Low-mass stars found in our Galaxy today!

6.5m Magellan telescope

Galactic metal-poor stars are a great tool for near-field cosmology because they are the local equivalent of the high-redshift Universe!

THE (DETAILED) ASTRONOMER'S PERIODIC TABLE



Big Bang nucleosynthesis

Spallation

Evolved giant stars

Odd-Z elements

α-elements

Iron group elements

α-rich freezeout, νp-proc., weak s-proc.

s-process

Weak r-proc., light n-cap. primary proc.

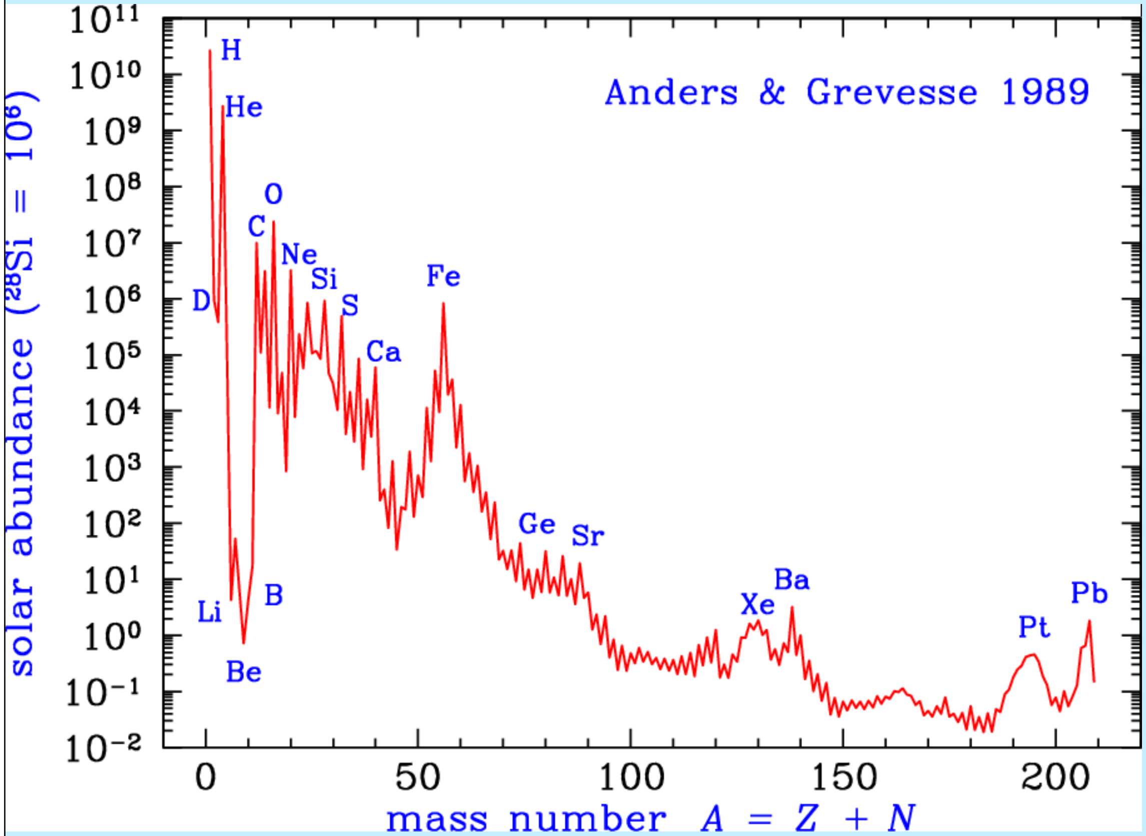
r-process

Long-lived radioactive (also r-process)

	IA	IIA																VIIIA
1	1 **H** 1,008																	2 **He** 4,003
2	3 **Li** 6,939	4 **Be** 9,012											5 **B** 10,811	6 **C** 12,011	7 **N** 14,007	8 **O** 15,999	9 **F** 18,998	10 **Ne** 20,183
3	11 **Na** 22,990	12 **Mg** 24,312											13 **Al** 26,982	14 **Si** 28,086	15 **P** 30,974	16 **S** 32,064	17 **Cl** 35,453	18 **Ar** 39,948
4	19 **K** 39,102	20 **Ca** 40,08	21 **Sc** 44,956	22 **Ti** 47,88	23 **V** 50,942	24 **Cr** 51,996	25 **Mn** 54,938	26 **Fe** 55,847	27 **Co** 58,933	28 **Ni** 58,69	29 **Cu** 63,54	30 **Zn** 65,37	31 **Ga** 69,72	32 **Ge** 72,59	33 **As** 74,922	34 **Se** 78,96	35 **Br** 79,909	36 **Kr** 83,80
5	37 **Rb** 85,47	38 **Sr** 87,62	39 **Y** 88,905	40 **Zr** 91,22	41 **Nb** 92,906	42 **Mo** 95,	43 **Tc** (99)	44 **Ru** 101,07	45 **Rh** 102,91	46 **Pd** 106,42	47 **Ag** 107,87	48 **Cd** 112,40	49 **In** 114,82	50 **Sn** 118,69	51 **Sb** 121,75	52 **Te** 127,60	53 **I** 126,90	54 **Xe** 131,30
6	55 **Cs** 132,91	56 **Ba** 137,34	57 **La** 138,91	72 **Hf** 178,49	73 **Ta** 180,95	74 **W** 183,85	75 **Re** 186,2	76 **Os** 190,2	77 **Ir** 192,2	78 **Pt** 195,09	79 **Au** 196,97	80 **Hg** 204,59	81 **Tl** 204,38	82 **Pb** 207,19	83 **Bi** 208,98	84 **Po** (210)	85 **At** (210)	86 **Rn** (222)
7	87 **Fr** (223)	88 **Ra** (226)	89 **Ac** (227)															
„6“				58 **Ce** 140,12	59 **Pr** 140,91	60 **Nd** 144,24	61 **Pm** (145)	62 **Sm** 150,36	63 **Eu** 151,96	64 **Gd** 157,25	65 **Tb** 158,92	66 **Dy** 162,50	67 **Ho** 164,93	68 **Er** 167,26	69 **Tm** 168,93	70 **Yb** 173,04	71 **Lu** 174,97	
„7“				90 **Th** 232,04	91 **Pa** (231)	92 **U** 238,03	93 **Np** (237)	94 **Pu** (242)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (249)	98 **Cf** (251)	99 **Es** (254)	100 **Fm** (253)	101 **Md** (256)	102 **No** (253)	103 **Lr** (257)	

Isotope distribution of solar nebula
(~8 billion yrs of chemical evolution)

Solar abundances



= combined product of 8 billion yrs of chemical evolution!

The Sun reflects a mix of many different element production events

Asplund et al. 2009

log ε(X)$_{\mathrm{sun}}$

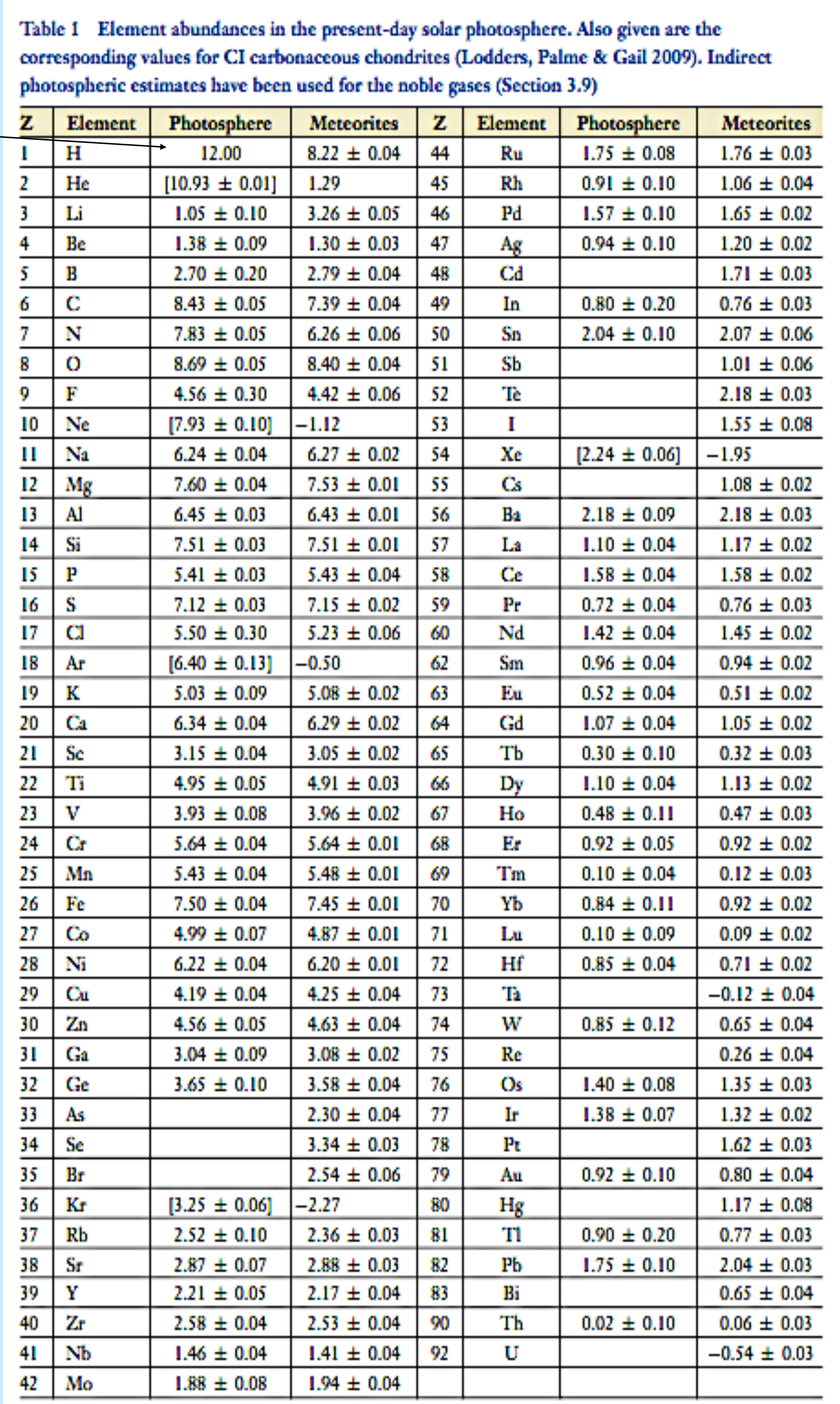


Table 1 Element abundances in the present-day solar photosphere. Also given are the corresponding values for CI carbonaceous chondrites (Lodders, Palme & Gail 2009). Indirect photospheric estimates have been used for the noble gases (Section 3.9)

Z	Element	Photosphere	Meteorites	Z	Element	Photosphere	Meteorites
1	H	12.00	8.22 ± 0.04	44	Ru	1.75 ± 0.08	1.76 ± 0.03
2	He	[10.93 ± 0.01]	1.29	45	Rh	0.91 ± 0.10	1.06 ± 0.04
3	Li	1.05 ± 0.10	3.26 ± 0.05	46	Pd	1.57 ± 0.10	1.65 ± 0.02
4	Be	1.38 ± 0.09	1.30 ± 0.03	47	Ag	0.94 ± 0.10	1.20 ± 0.02
5	B	2.70 ± 0.20	2.79 ± 0.04	48	Cd		1.71 ± 0.03
6	C	8.43 ± 0.05	7.39 ± 0.04	49	In	0.80 ± 0.20	0.76 ± 0.03
7	N	7.83 ± 0.05	6.26 ± 0.06	50	Sn	2.04 ± 0.10	2.07 ± 0.06
8	O	8.69 ± 0.05	8.40 ± 0.04	51	Sb		1.01 ± 0.06
9	F	4.56 ± 0.30	4.42 ± 0.06	52	Te		2.18 ± 0.03
10	Ne	[7.93 ± 0.10]	−1.12	53	I		1.55 ± 0.08
11	Na	6.24 ± 0.04	6.27 ± 0.02	54	Xe	[2.24 ± 0.06]	−1.95
12	Mg	7.60 ± 0.04	7.53 ± 0.01	55	Cs		1.08 ± 0.02
13	Al	6.45 ± 0.03	6.43 ± 0.01	56	Ba	2.18 ± 0.09	2.18 ± 0.03
14	Si	7.51 ± 0.03	7.51 ± 0.01	57	La	1.10 ± 0.04	1.17 ± 0.02
15	P	5.41 ± 0.03	5.43 ± 0.04	58	Ce	1.58 ± 0.04	1.58 ± 0.02
16	S	7.12 ± 0.03	7.15 ± 0.02	59	Pr	0.72 ± 0.04	0.76 ± 0.03
17	Cl	5.50 ± 0.30	5.23 ± 0.06	60	Nd	1.42 ± 0.04	1.45 ± 0.02
18	Ar	[6.40 ± 0.13]	−0.50	62	Sm	0.96 ± 0.04	0.94 ± 0.02
19	K	5.03 ± 0.09	5.08 ± 0.02	63	Eu	0.52 ± 0.04	0.51 ± 0.02
20	Ca	6.34 ± 0.04	6.29 ± 0.02	64	Gd	1.07 ± 0.04	1.05 ± 0.02
21	Sc	3.15 ± 0.04	3.05 ± 0.02	65	Tb	0.30 ± 0.10	0.32 ± 0.03
22	Ti	4.95 ± 0.05	4.91 ± 0.03	66	Dy	1.10 ± 0.04	1.13 ± 0.02
23	V	3.93 ± 0.08	3.96 ± 0.02	67	Ho	0.48 ± 0.11	0.47 ± 0.03
24	Cr	5.64 ± 0.04	5.64 ± 0.01	68	Er	0.92 ± 0.05	0.92 ± 0.02
25	Mn	5.43 ± 0.04	5.48 ± 0.01	69	Tm	0.10 ± 0.04	0.12 ± 0.03
26	Fe	7.50 ± 0.04	7.45 ± 0.01	70	Yb	0.84 ± 0.11	0.92 ± 0.02
27	Co	4.99 ± 0.07	4.87 ± 0.01	71	Lu	0.10 ± 0.09	0.09 ± 0.02
28	Ni	6.22 ± 0.04	6.20 ± 0.01	72	Hf	0.85 ± 0.04	0.71 ± 0.02
29	Cu	4.19 ± 0.04	4.25 ± 0.04	73	Ta		−0.12 ± 0.04
30	Zn	4.56 ± 0.05	4.63 ± 0.04	74	W	0.85 ± 0.12	0.65 ± 0.04
31	Ga	3.04 ± 0.09	3.08 ± 0.02	75	Re		0.26 ± 0.04
32	Ge	3.65 ± 0.10	3.58 ± 0.04	76	Os	1.40 ± 0.08	1.35 ± 0.03
33	As		2.30 ± 0.04	77	Ir	1.38 ± 0.07	1.32 ± 0.02
34	Se		3.34 ± 0.03	78	Pt		1.62 ± 0.03
35	Br		2.54 ± 0.06	79	Au	0.92 ± 0.10	0.80 ± 0.04
36	Kr	[3.25 ± 0.06]	−2.27	80	Hg		1.17 ± 0.08
37	Rb	2.52 ± 0.10	2.36 ± 0.03	81	Tl	0.90 ± 0.20	0.77 ± 0.03
38	Sr	2.87 ± 0.07	2.88 ± 0.03	82	Pb	1.75 ± 0.10	2.04 ± 0.03
39	Y	2.21 ± 0.05	2.17 ± 0.04	83	Bi		0.65 ± 0.04
40	Zr	2.58 ± 0.04	2.53 ± 0.04	90	Th	0.02 ± 0.10	0.06 ± 0.03
41	Nb	1.46 ± 0.04	1.41 ± 0.04	92	U		−0.54 ± 0.03
42	Mo	1.88 ± 0.08	1.94 ± 0.04				

Can galaxies have different metallicities?

ULTRA-FAINT DWARF GALAXY PROPERTIES (UFDs)

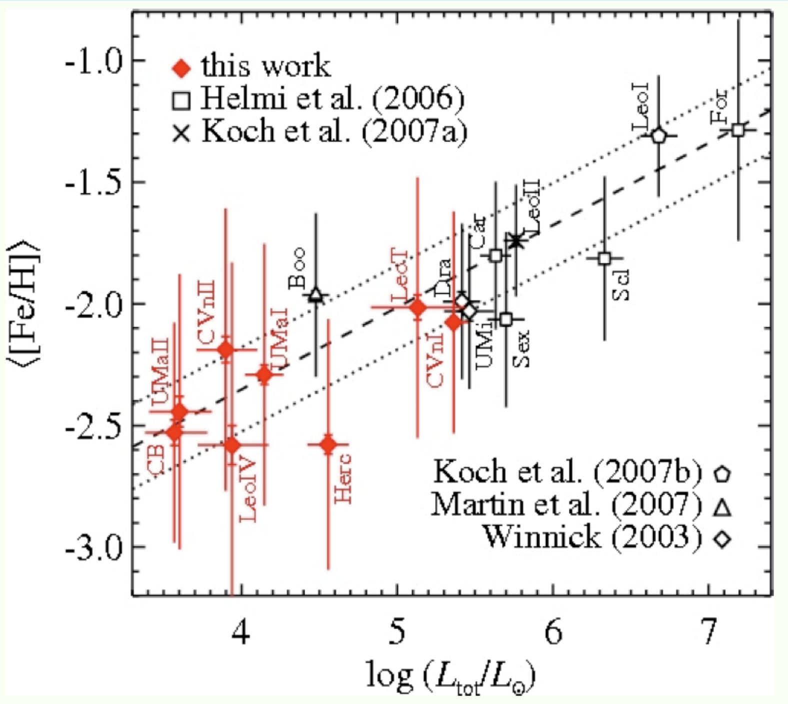
Low luminosity (300 - 3,000 L_{sun})

Dark matter-dominated (M/L > 100)

Metal-poor (mean [Fe/H] ~ −2)

Stars are old (mean age 13.3 +/− 1 Gyr)

Few bursts of star formation



Ultra-faint dwarfs

Classical dSphs

Ideal targets for Dwarf Galaxy Archaeology

Use entire galaxy as fossil record of the early universe!

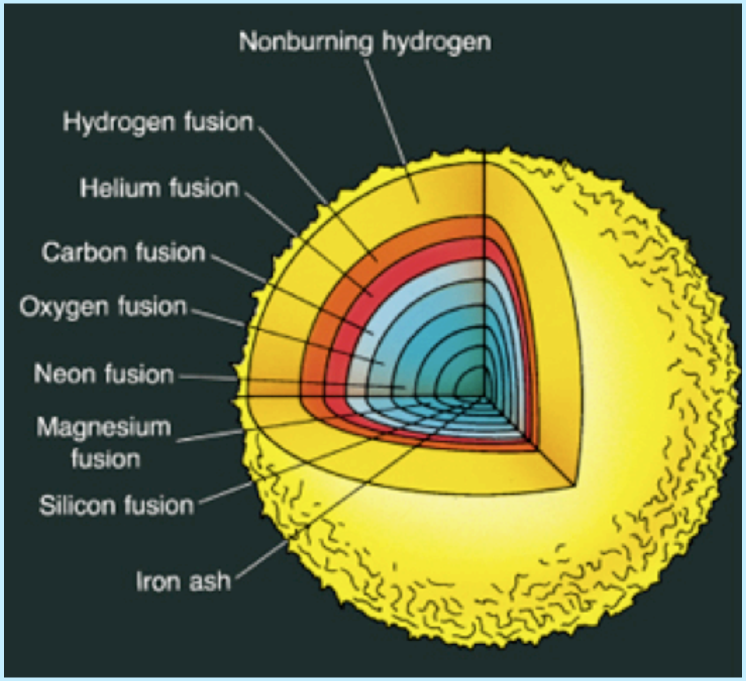
Bonus: get environmental information because we know where stars were born

Stars are the drivers of the chemical evolution of the universe

- **Long-lived low-mass stars:** nothing; but their WD (after too much mass-transfer in binary system) provide Fe, and little O, C, Mg
- **Longish-lived intermediate stars:** their AGB winds are main providers of C,O, neutron-capture elements in a galaxy
- **Short-lived massive stars:** supernova are gigantic fountains that blow new elements into the surrounding gas

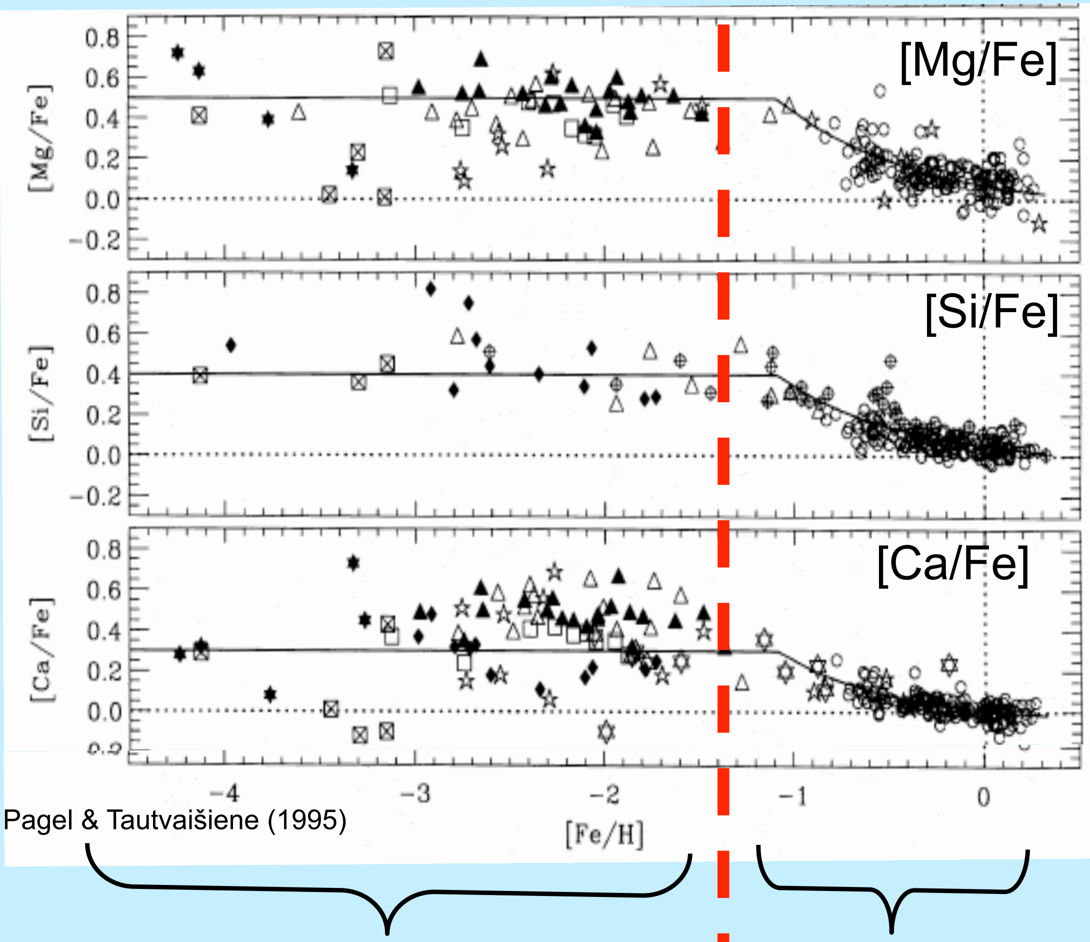
Abundance trends

α-elements



α-elements multiple of He: (C,O), Ne, Mg, Si, S, Ar, Ca, Ti (not pure)

Synthesis during stellar evolution and α-capture in supernova explosion of massive stars (>8 M⊙)



Pagel & Tautvaišiene (1995)

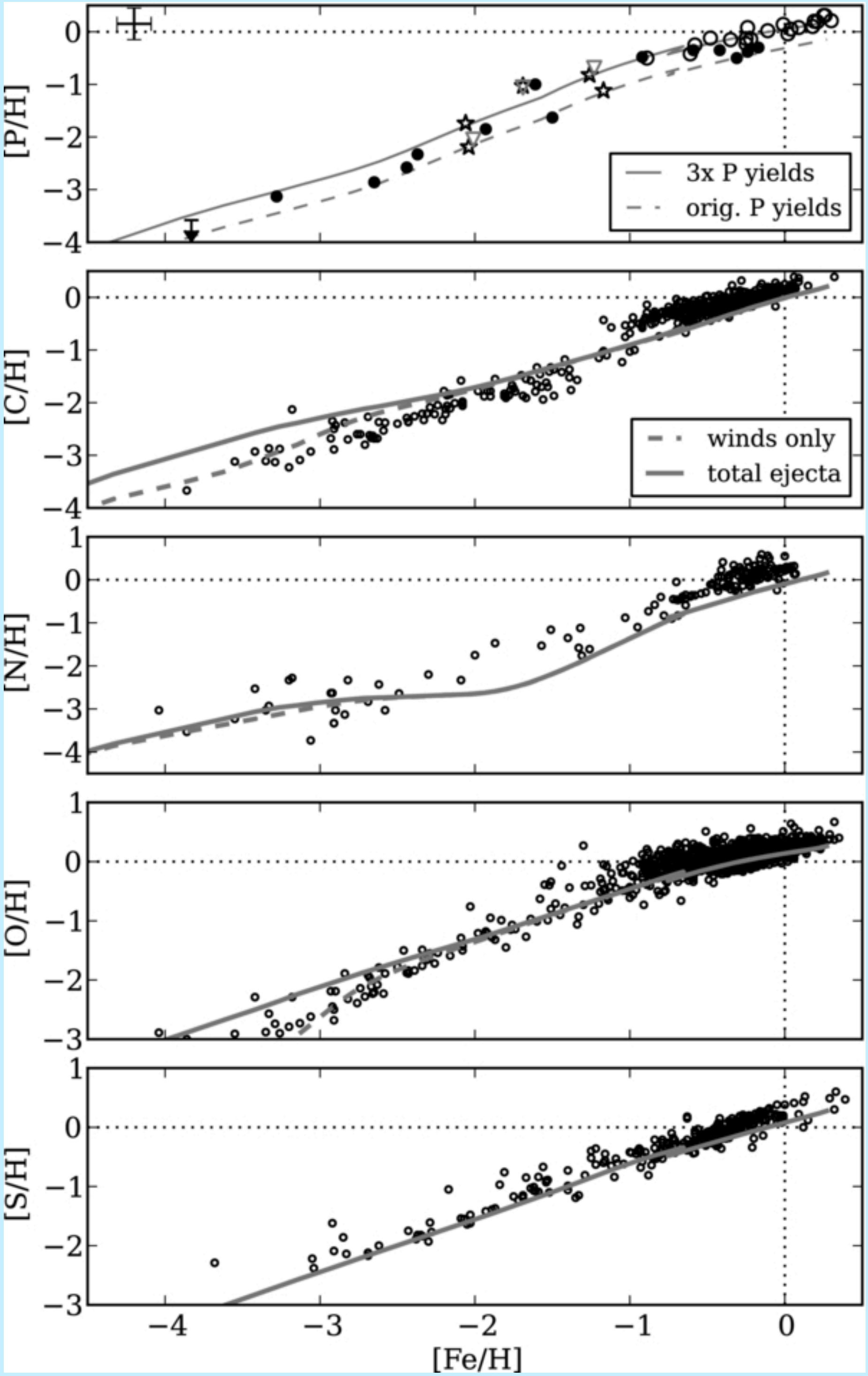
Fe and α-elements produced in the explosions of massive stars (SN type II)

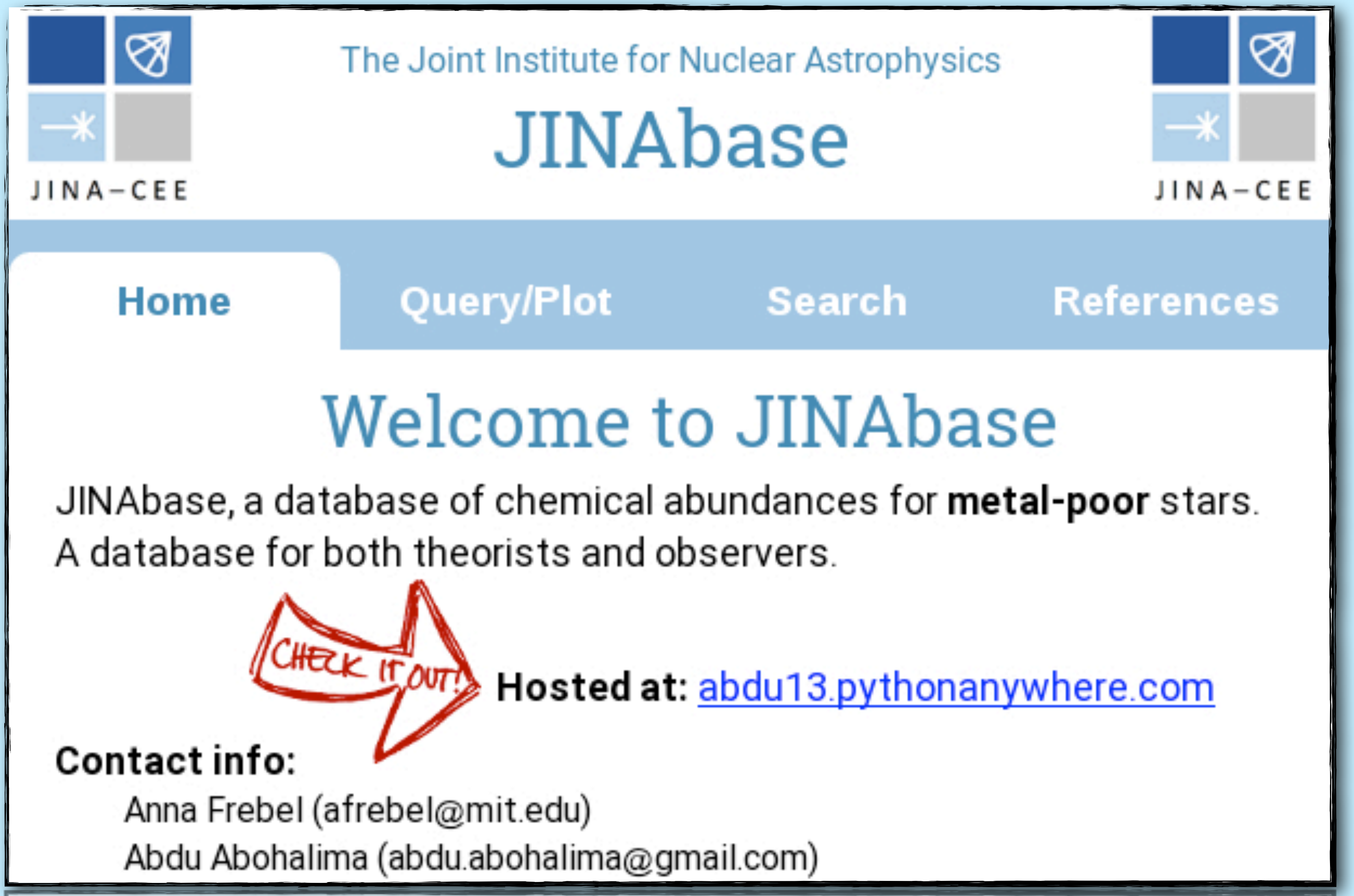
Fe-rich ejecta from the SN of low-mass stars (SN type Ia)

Elements of life

- Hydrogen
- Carbon
- Nitrogen
- Oxygen
- Sulfur
- Phosphorus

- Compared with results from chemical evolution modeling





The Joint Institute for Nuclear Astrophysics

JINAbase

Welcome to JINAbase

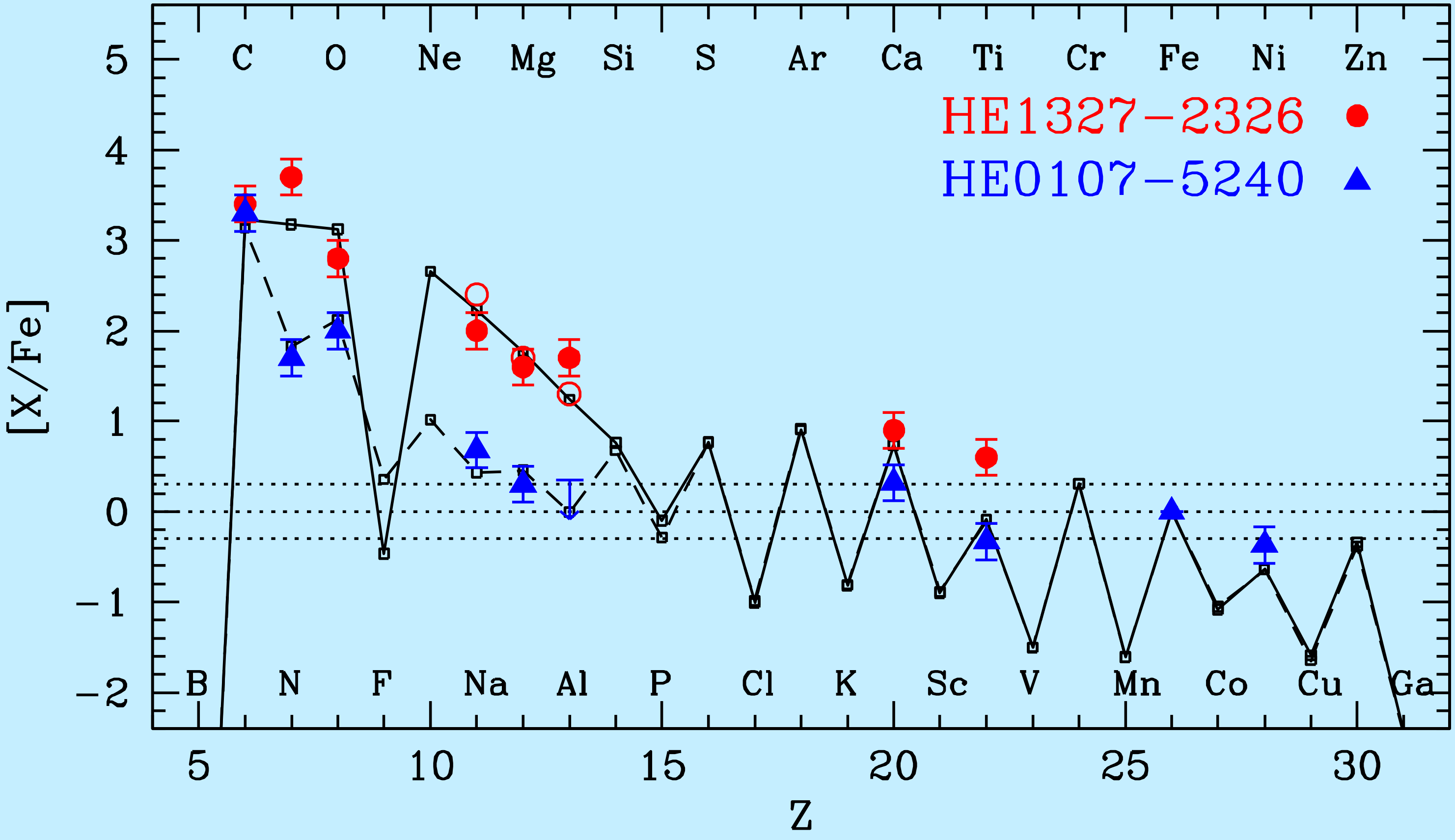
JINAbase, a database of chemical abundances for **metal-poor** stars.
A database for both theorists and observers.

Hosted at: abdu13.pythonanywhere.com

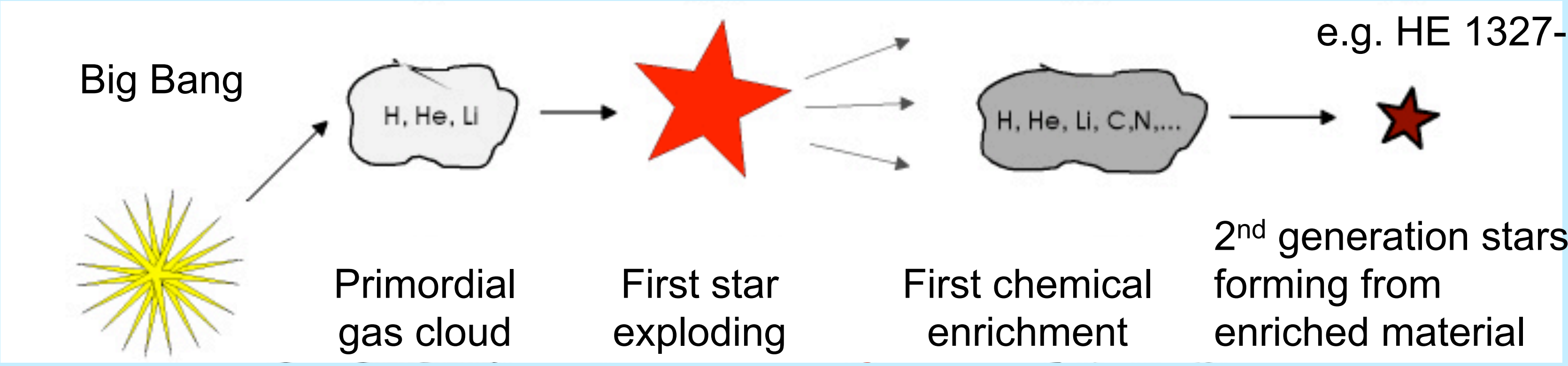
Contact info:
Anna Frebel (afrebel@mit.edu)
Abdu Abohalima (abdu.abohalima@gmail.com)

Abundance patterns

- Stellar chemical abundances are compared with supernova elemental yields => reconstruct the first stars in the universe
- Learn about chemical evolution!
-



How and when did these early stars form?



e.g. HE 1327-2326

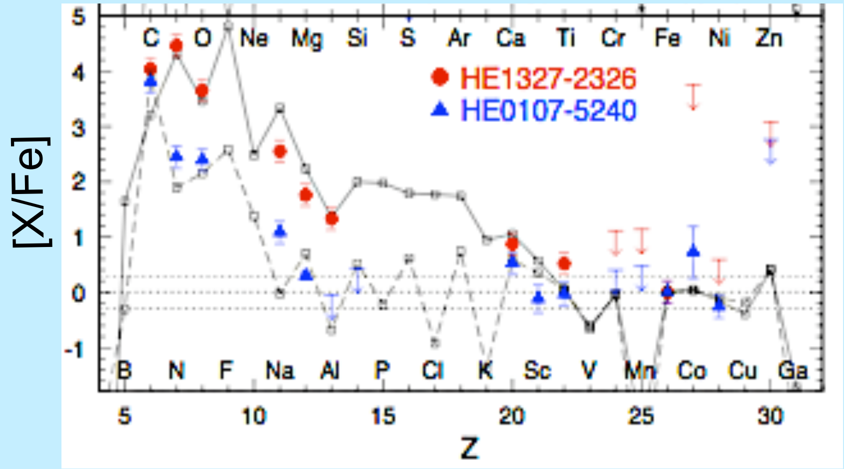
Big Bang

Primordial
gas cloud

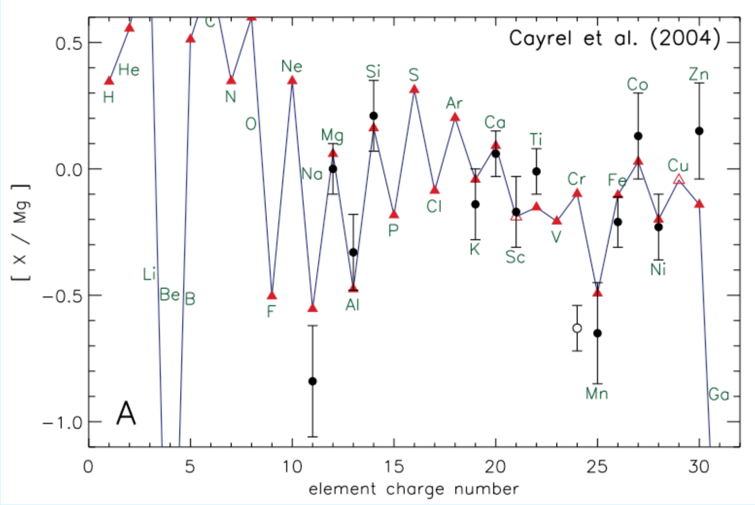
First star
exploding

First chemical
enrichment

2nd generation stars
forming from
enriched material



Tominaga et al. 2007

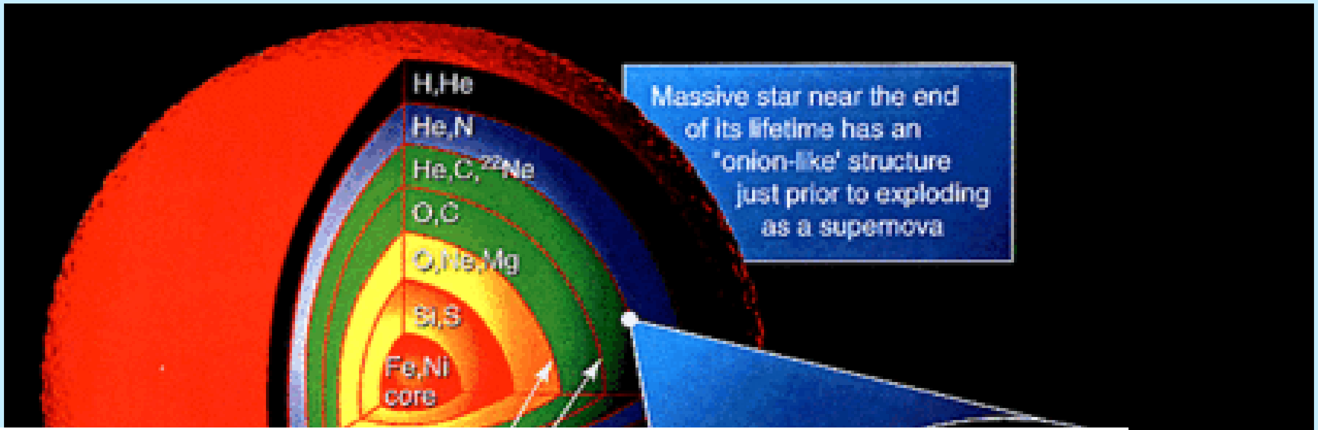


Heger & Woosley 2008

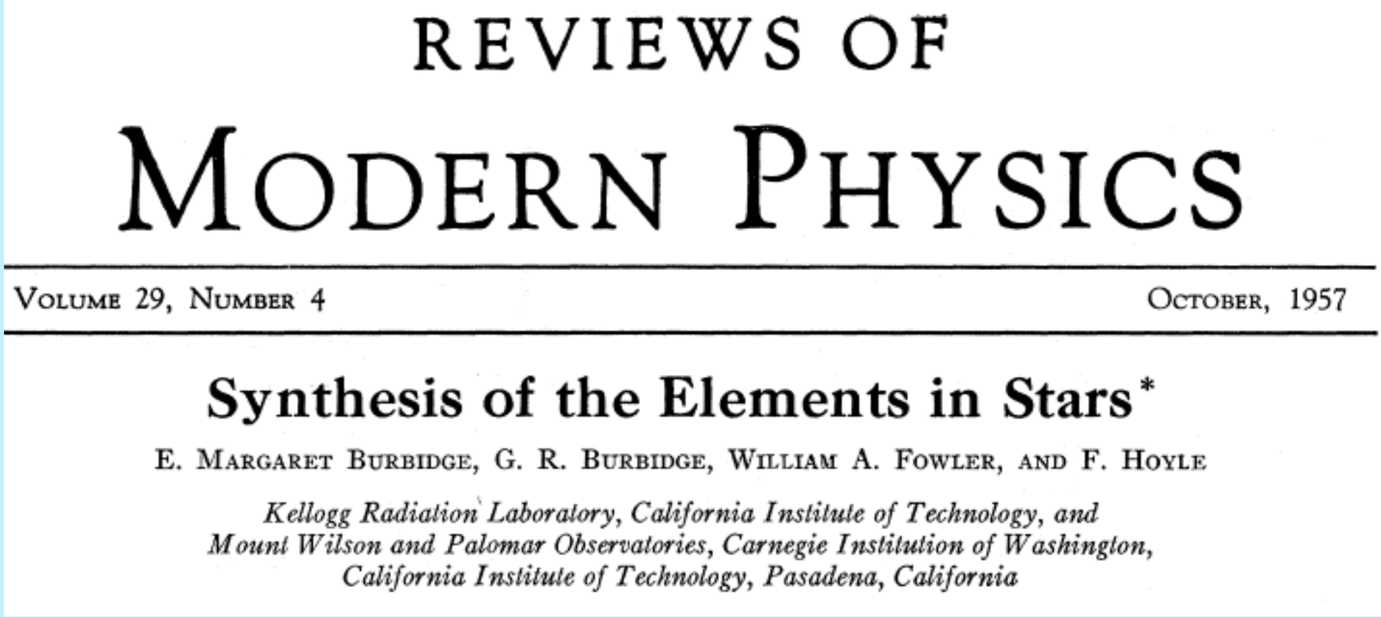
Why important?

Metal-poor stars provide the only available diagnosis for zero-metallicity Pop III nucleosynthesis and early chemical enrichment

Heavy element nucleosynthesis



Massive star near the end of its lifetime has an 'onion-like' structure just prior to exploding as a supernova



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

All elements heavier than Li, Be, B are made during stellar evolution, supernova explosions and their remnants

Most important reactions in stellar nucleosynthesis:

- **Hydrogen burning:**
  - The proton-proton chain
  - The CNO cycle
- **Helium burning:**
  - The triple-alpha process
  - The alpha process

All textbooks, wikipedia
....

- **Burning of heavier elements:**
  - Carbon burning process
  - Neon burning process
  - Oxygen burning process
  - Silicon burning process

Timmes+ ~95
Woosely&Weaver 1995
Heger & Woosley 2008

- **Production of elements heavier than iron:**
  - Neutron capture:
    - The R-process
    - The S-process
  - Proton capture:
    - The Rp-process
  - Photo-disintegration:
    - The P-process

Many details not known, but models out there

Update: Metal-poor star classifications

Frebel 2018, ARN&P, in prep

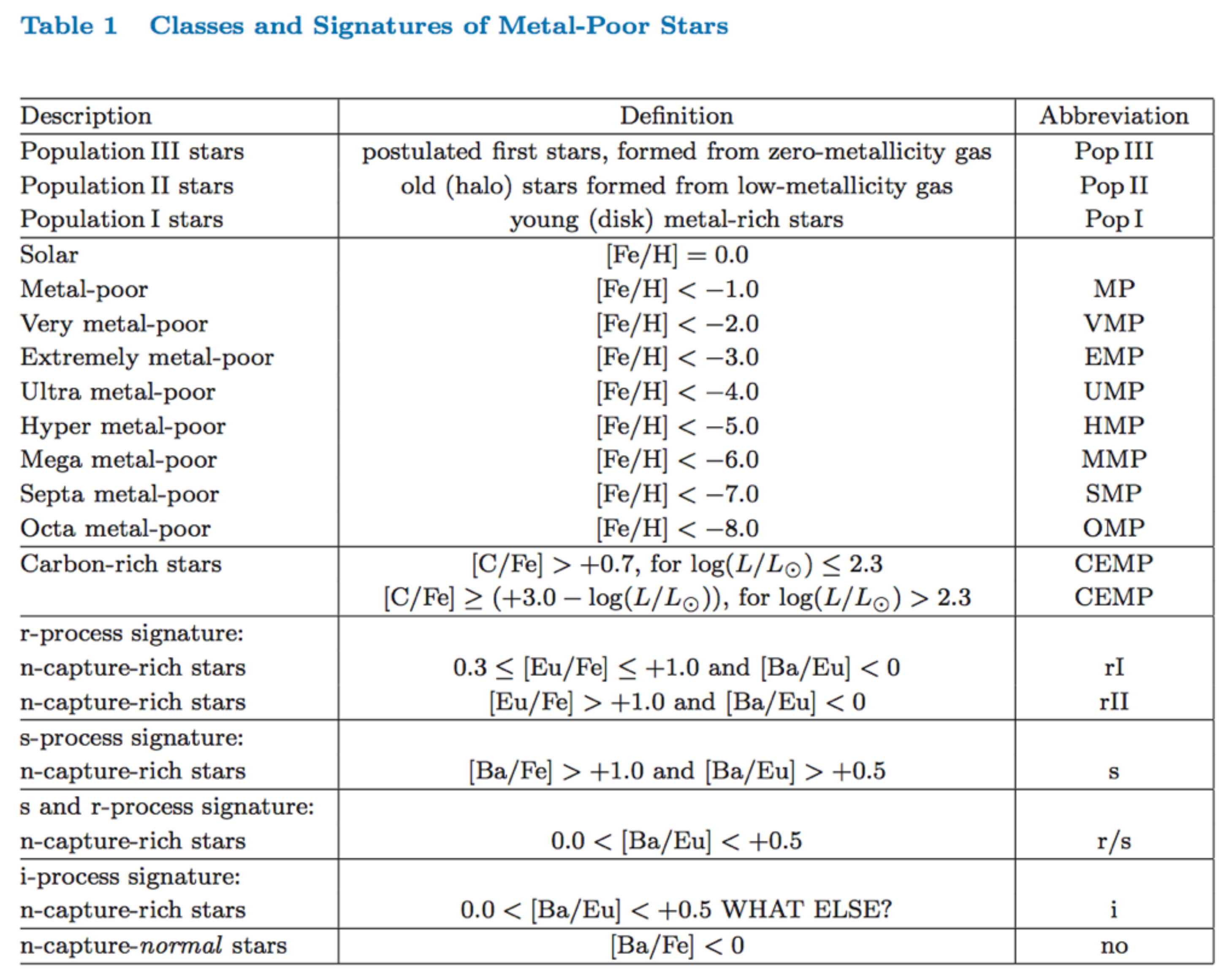
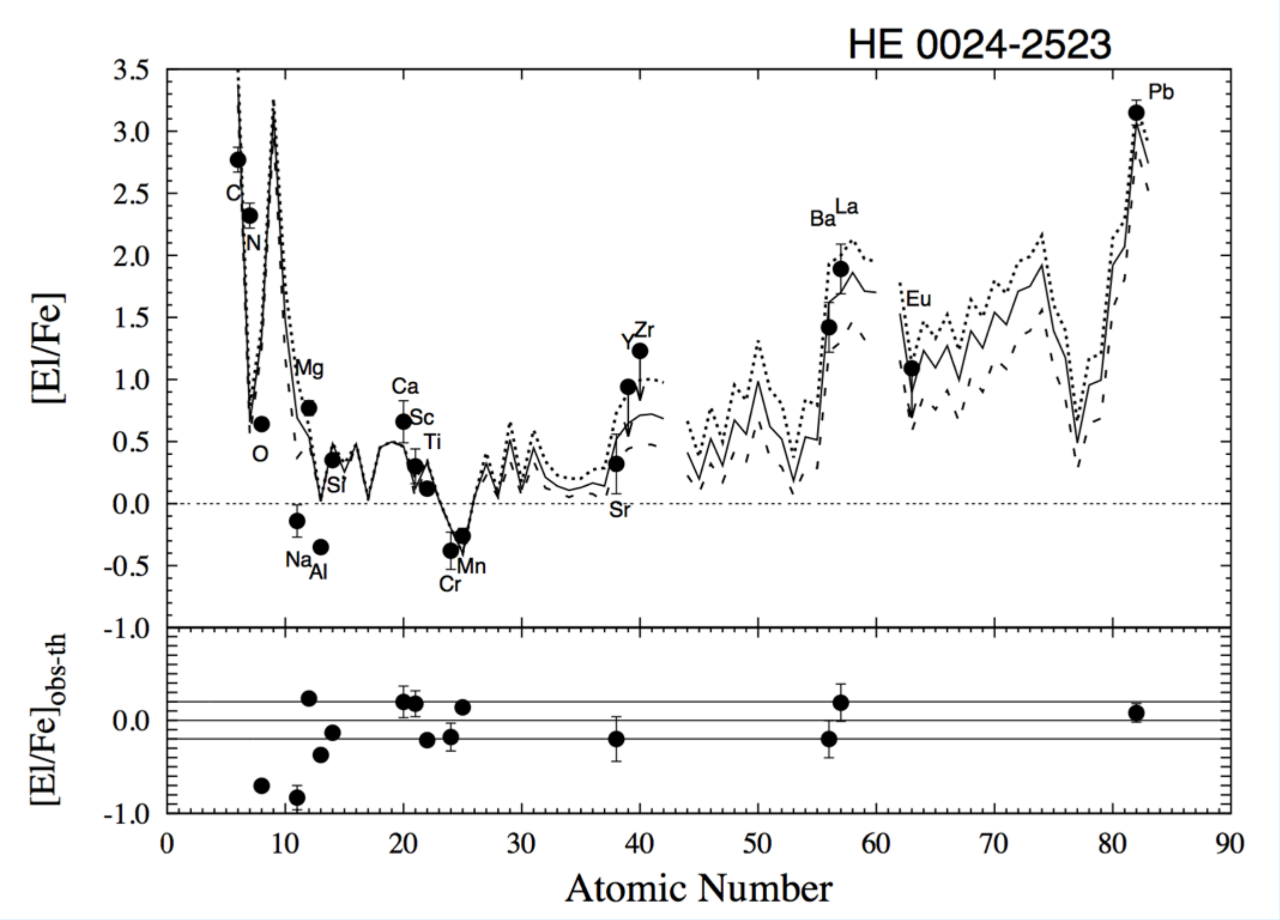


Table 1 Classes and Signatures of Metal-Poor Stars

Description	Definition	Abbreviation
Population III stars	postulated first stars, formed from zero-metallicity gas	Pop III
Population II stars	old (halo) stars formed from low-metallicity gas	Pop II
Population I stars	young (disk) metal-rich stars	Pop I
Solar	$[\mathrm{Fe/H}] = 0.0$	
Metal-poor	$[\mathrm{Fe/H}] < -1.0$	MP
Very metal-poor	$[\mathrm{Fe/H}] < -2.0$	VMP
Extremely metal-poor	$[\mathrm{Fe/H}] < -3.0$	EMP
Ultra metal-poor	$[\mathrm{Fe/H}] < -4.0$	UMP
Hyper metal-poor	$[\mathrm{Fe/H}] < -5.0$	HMP
Mega metal-poor	$[\mathrm{Fe/H}] < -6.0$	MMP
Septa metal-poor	$[\mathrm{Fe/H}] < -7.0$	SMP
Octa metal-poor	$[\mathrm{Fe/H}] < -8.0$	OMP
Carbon-rich stars	$[\mathrm{C/Fe}] > +0.7$, for $\log(L/L_\odot) \leq 2.3$	CEMP
	$[\mathrm{C/Fe}] \geq (+3.0 - \log(L/L_\odot))$, for $\log(L/L_\odot) > 2.3$	CEMP
r-process signature:		
n-capture-rich stars	$0.3 \leq [\mathrm{Eu/Fe}] \leq +1.0$ and $[\mathrm{Ba/Eu}] < 0$	rI
n-capture-rich stars	$[\mathrm{Eu/Fe}] > +1.0$ and $[\mathrm{Ba/Eu}] < 0$	rII
s-process signature:		
n-capture-rich stars	$[\mathrm{Ba/Fe}] > +1.0$ and $[\mathrm{Ba/Eu}] > +0.5$	s
s and r-process signature:		
n-capture-rich stars	$0.0 < [\mathrm{Ba/Eu}] < +0.5$	r/s
i-process signature:		
n-capture-rich stars	$0.0 < [\mathrm{Ba/Eu}] < +0.5$ WHAT ELSE?	i
n-capture-*normal* stars	$[\mathrm{Ba/Fe}] < 0$	no

s-process

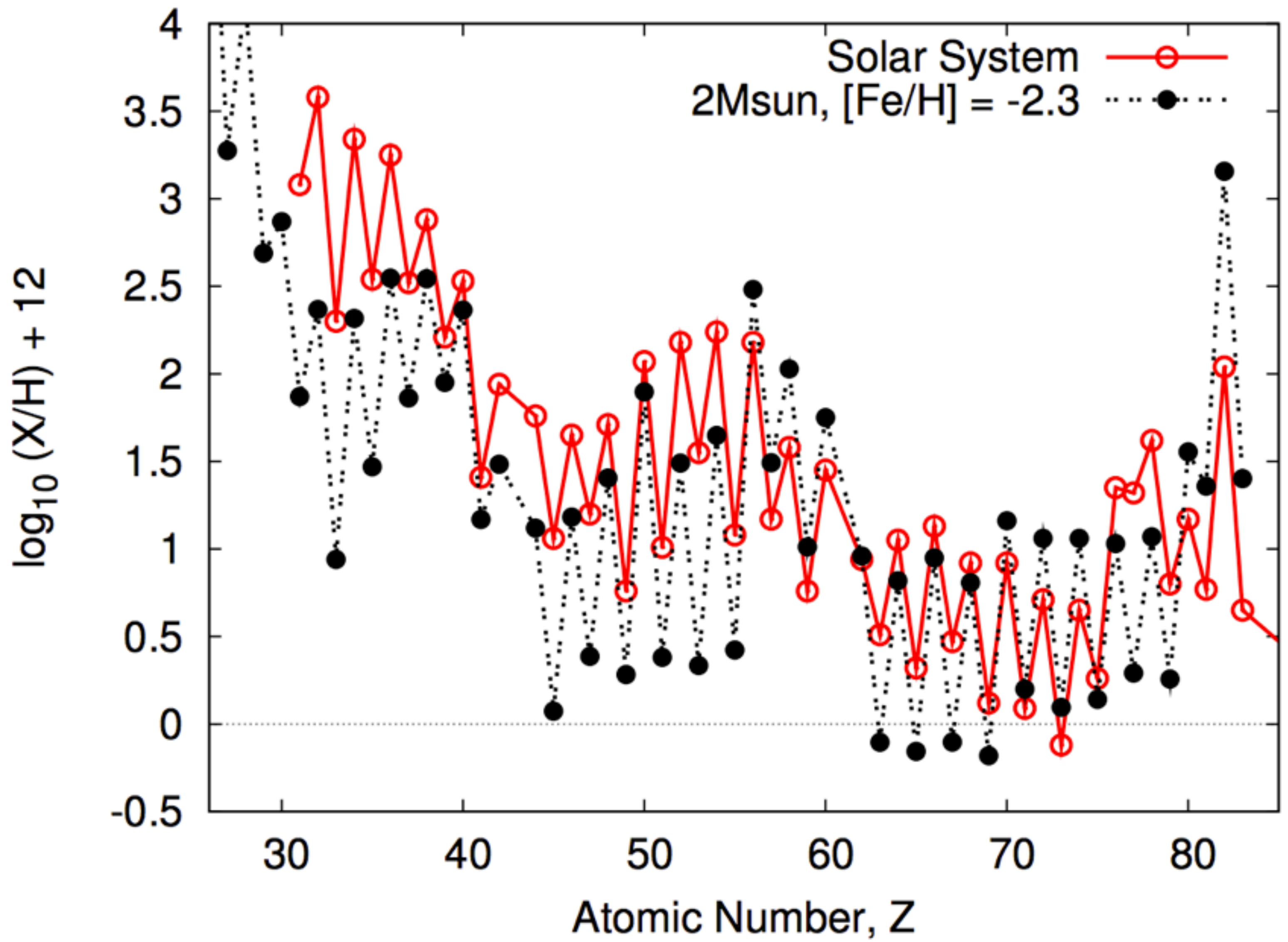
metal-poor star formed as part of binary system; receives mass transfer of C-rich, s-rich material from companion that undergoes AGB phase



Bisterzo et al. 2012, data from Lucatello et al. 2003

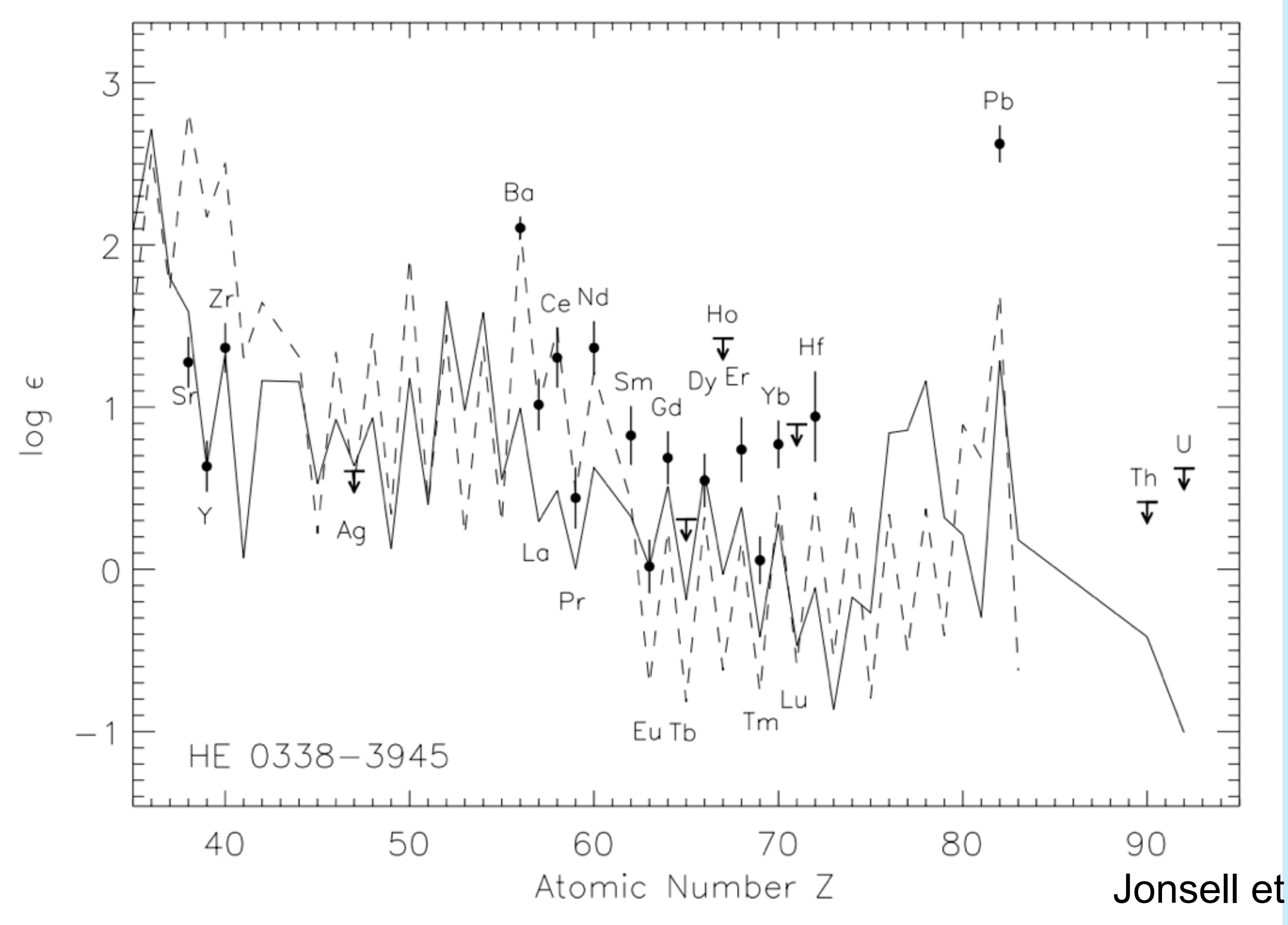
s-process: solar and at low-met

Number of seed nuclei determine s-process signature;
more Pb at low [Fe/H]



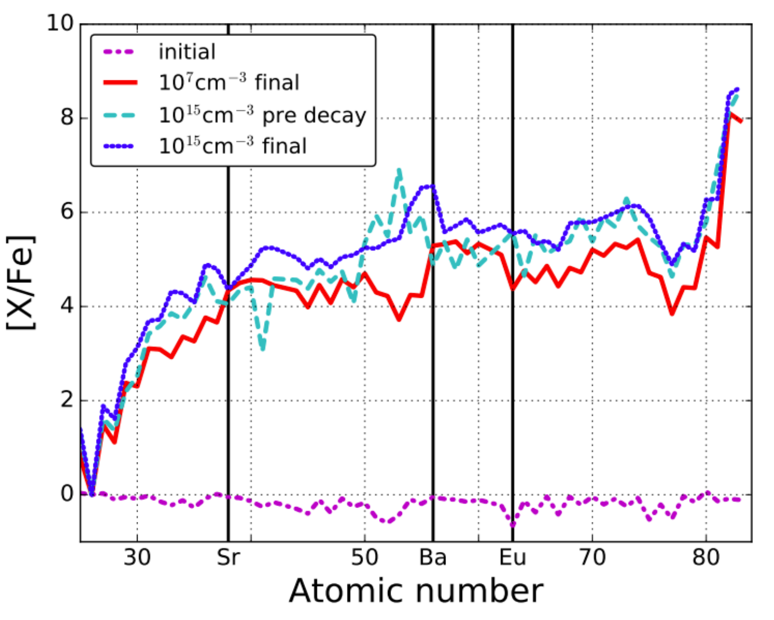
~~“r/s” star~~ => i-process star

Stars enriched by neither a clean s-proc nor r-proc signature
Characteristic: looks like s-proc but enhanced Eu



Jonsell et al. 2006

intermediate (i)-process



Low-metallicity AGB stars
with low CNO content

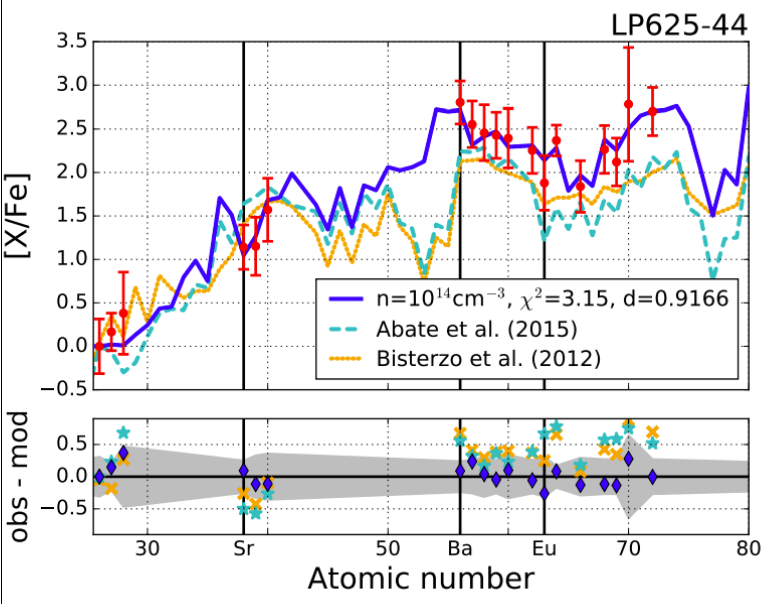
=> intershell convection zone (during thermal pulse) penetrates up into H burning shell
=> draws protons down to hotter region
=> protons react w/ 12C in intershell to form 13C
=> neutron source 13C (α, n)16 O
(**= proton ingestion episodes)**

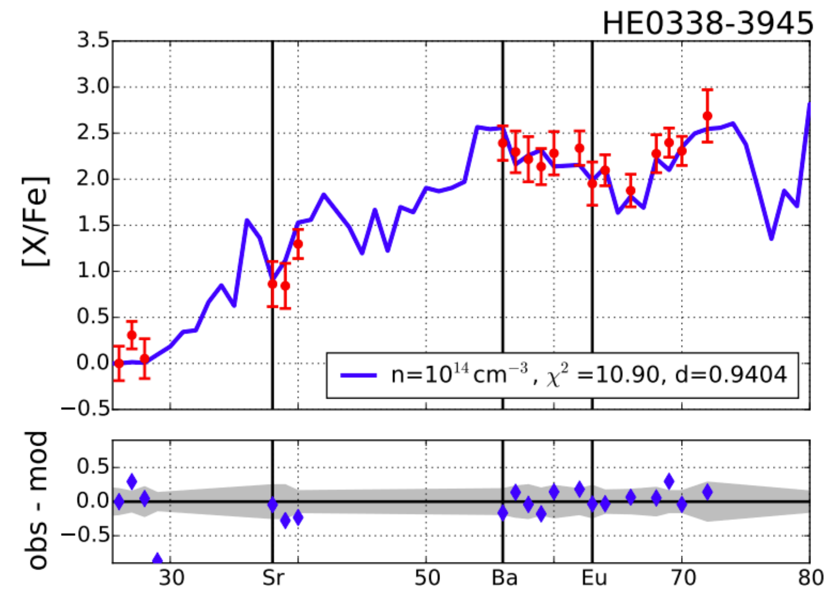
=> high neutron densities, up to
n = 10^{15} cm^{-3}

TABLE 2
FIT PARAMETERS FOR EACH CEMP-s/r STAR: NUMBER OF MEASUREMENTS THE FIT IS BASED ON, NEUTRON DENSITY n, DILUTION FACTOR d AND MINIMUM χ^2.

ID	$N_{\rm obs}$ $(31 \leq Z \leq 80)$	$\log\left(n/{\rm cm}^{-3}\right)$	d	χ^2_{min}
BS16080-175	3	12	0.991	2.0
BS17436-058	3	13	0.989	0.2
CS22881-036	7	12	0.985	5.1
CS22898-027	11	14	0.937	5.7
CS22948-027	9	13	0.965	5.9
CS29497-030	15	14	0.957	8.1
CS29526-110	7	14	0.966	2.7
CS31062-012	7	14	0.971	3.2
CS31062-050	22	15	0.916	26.5
HD187861	8	12	0.978	0.5
HD224959	8	13	0.969	3.7
HE0131-3953	6	14	0.969	0.4
HE0143-0441	8	14	0.947	9.0
HE0338-3945	16	14	0.940	10.9
HE1105+0027	6	14	0.953	1.2
HE1305+0007	10	14	0.858	7.6
HE2148-1247	12	14	0.937	14.4
HE2258-6358	17	14	0.973	23.4
LP625-44	16	14	0.917	3.2
SDSSJ0912+0216	16	14	0.938	373.7

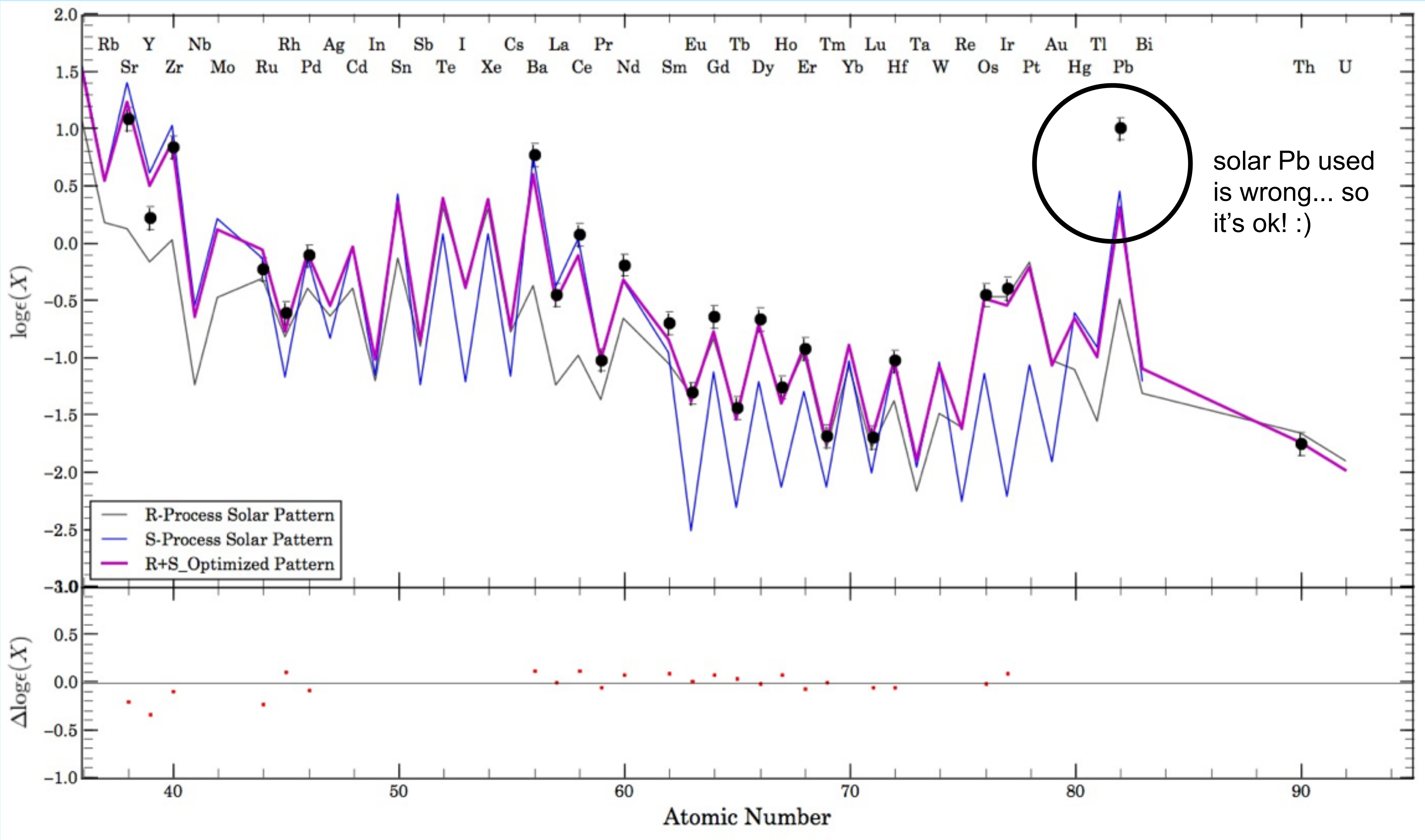
Hampel et al. 2016





The first true r+s star!

An s-process star with [Fe/H] = -2.3
that formed from r-process enhanced gas!

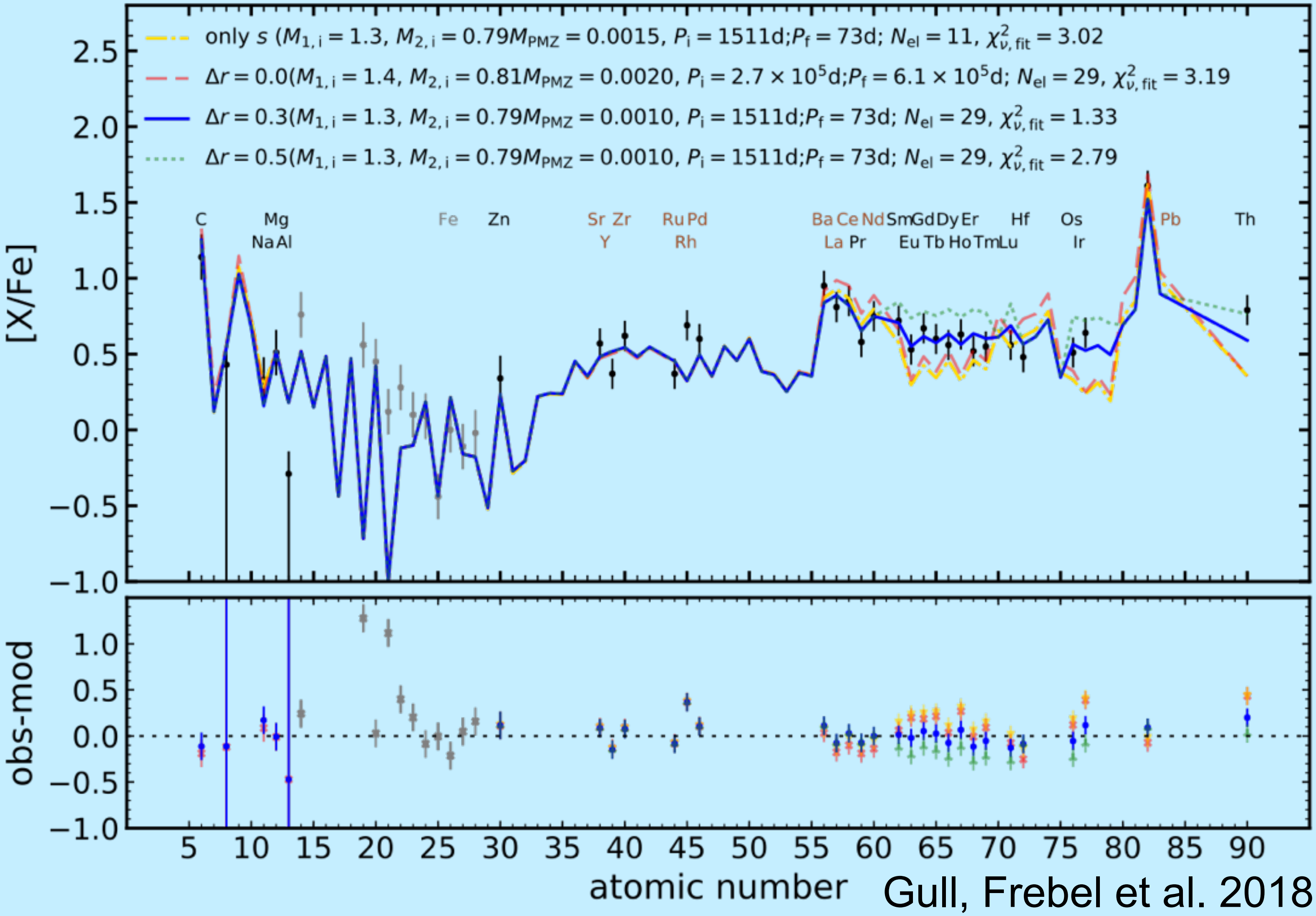


solar Pb used
is wrong... so
it’s ok! :)

Gull, Frebel et al. 2018, in prep

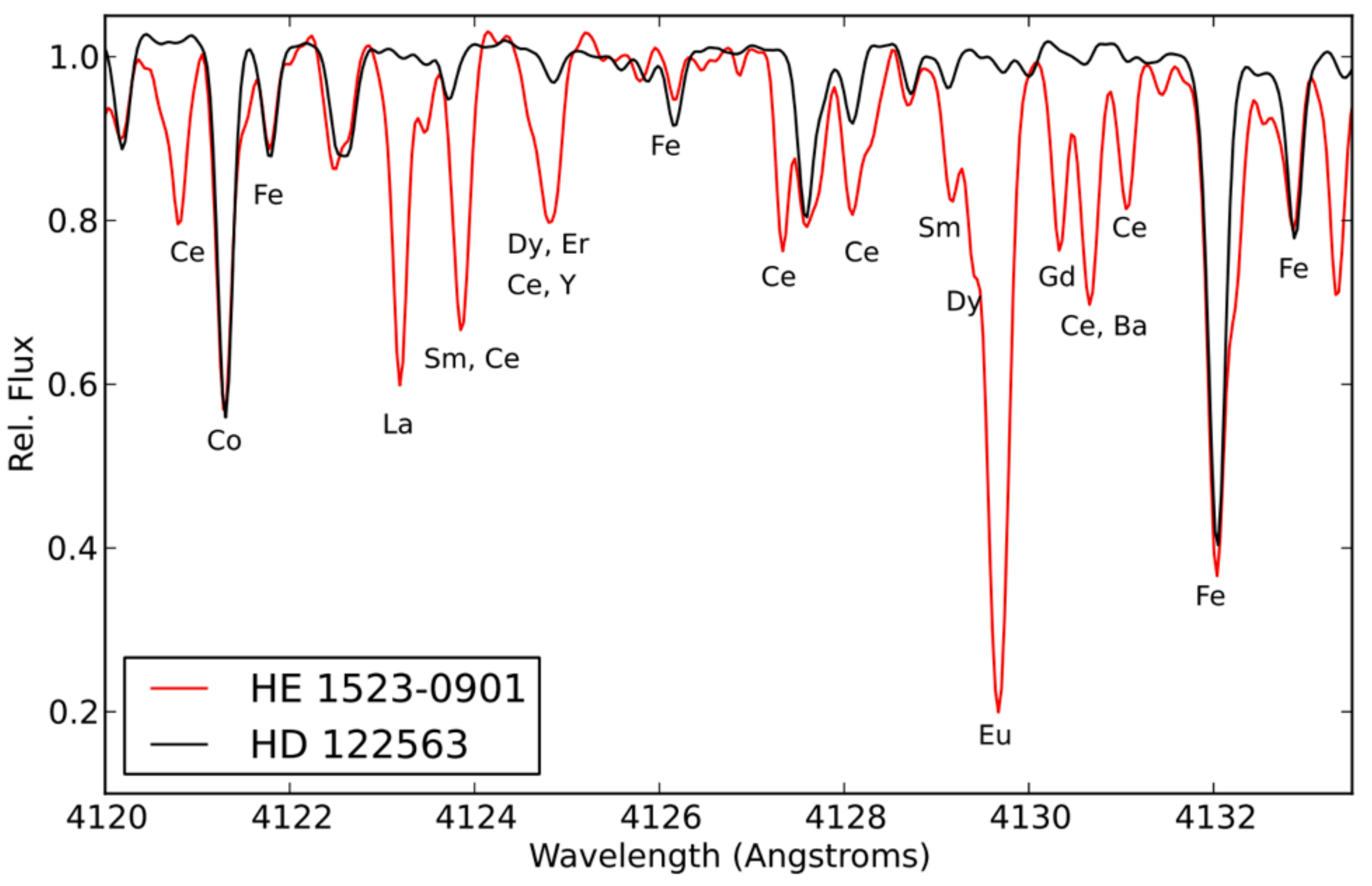
The first true r+s star!

An s-process star with [Fe/H] = -2.3
that formed from r-process enhanced gas!



Gull, Frebel et al. 2018, in prep

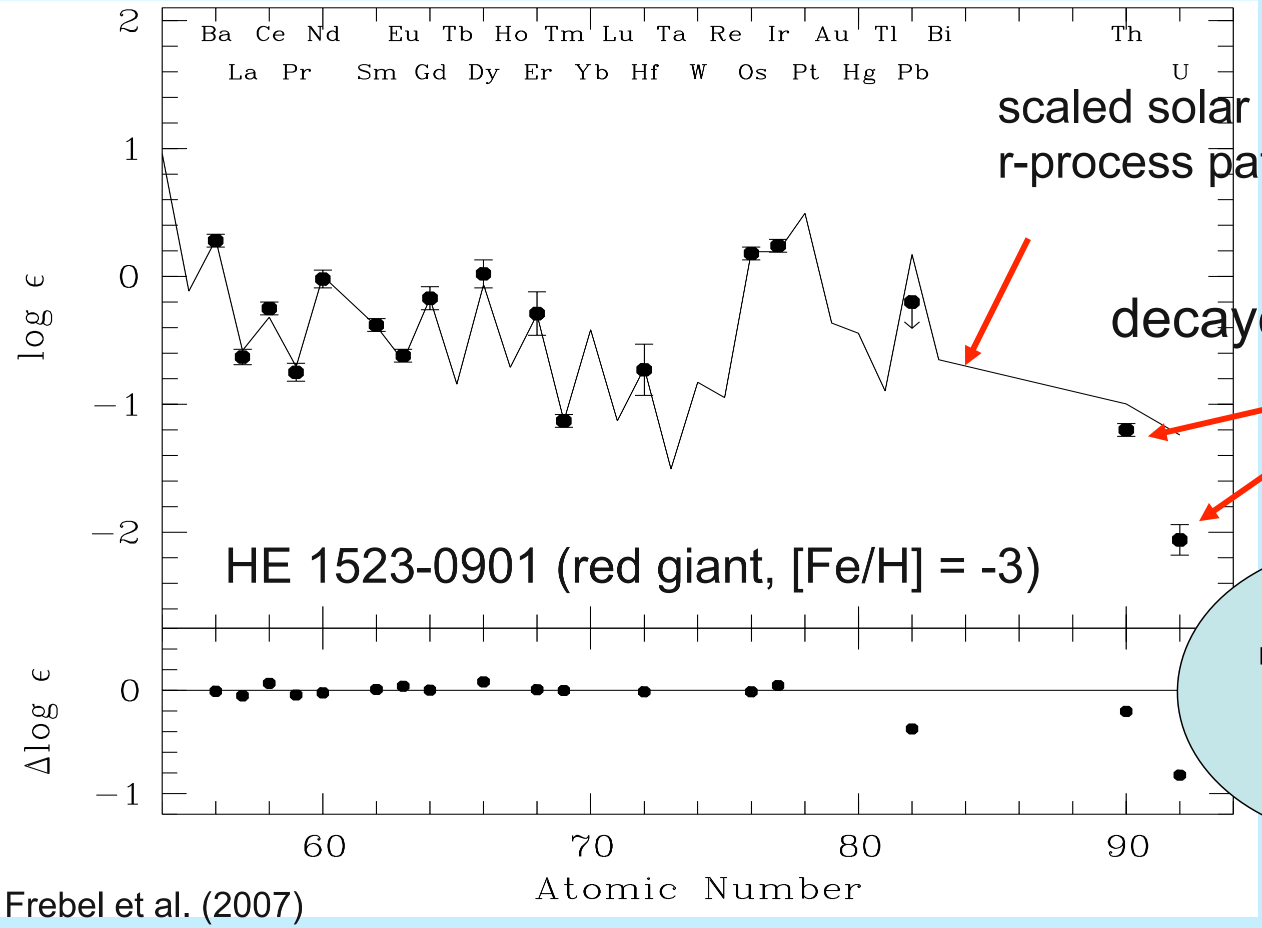
r-process signature in the spectrum



r-process

Does the r-process occur in SNe or neutro star mergers?

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



scaled solar r-process pattern

decayed Th,U

HE 1523-0901 (red giant, [Fe/H] = -3)

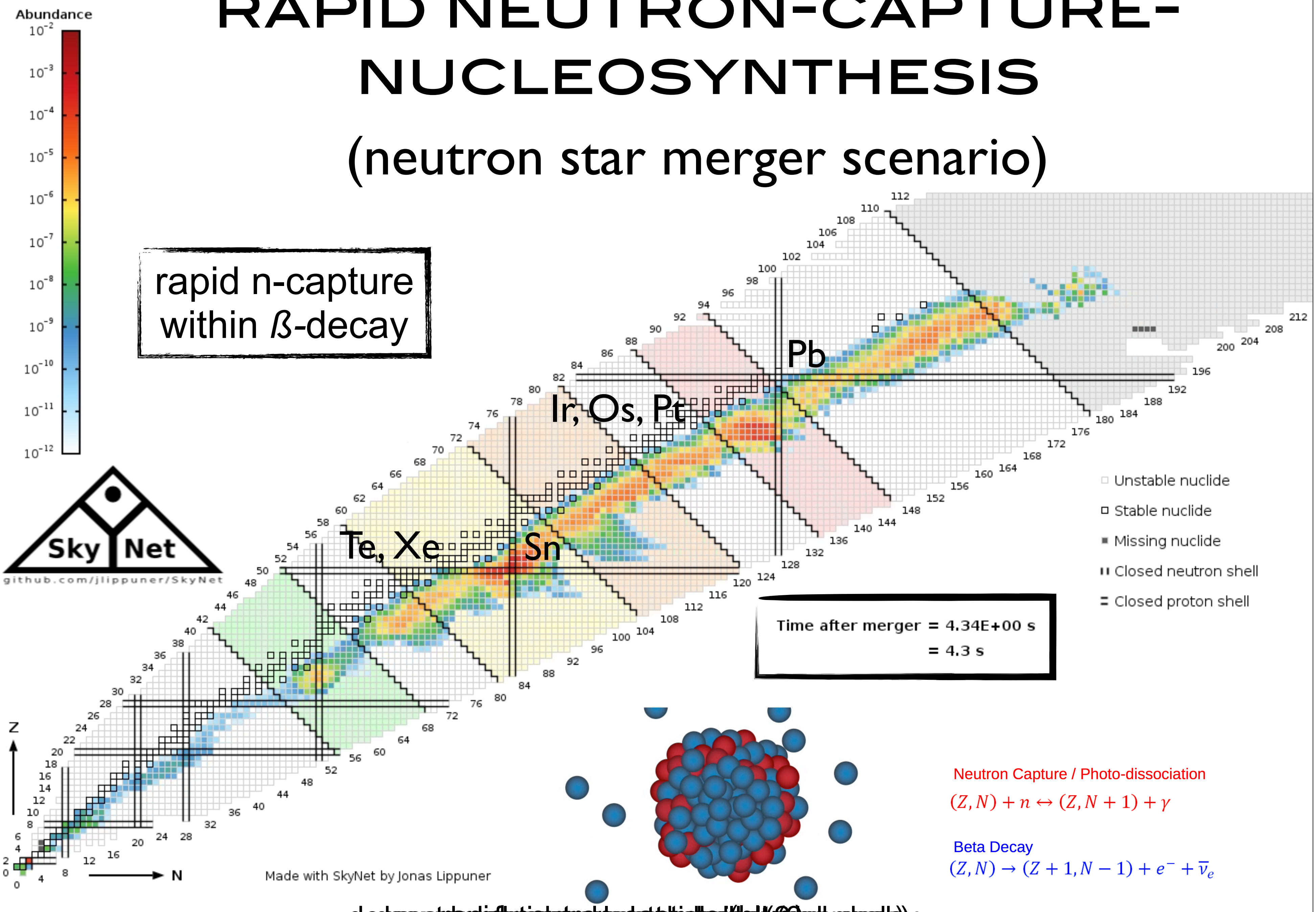
Frebel et al. (2007)

According to metal-poor star abundances, the r-process is universal!

RAPID NEUTRON-CAPTURE-NUCLEOSYNTHESIS

(neutron star merger scenario)

rapid n-capture
within ß-decay



Neutron Capture / Photo-dissociation

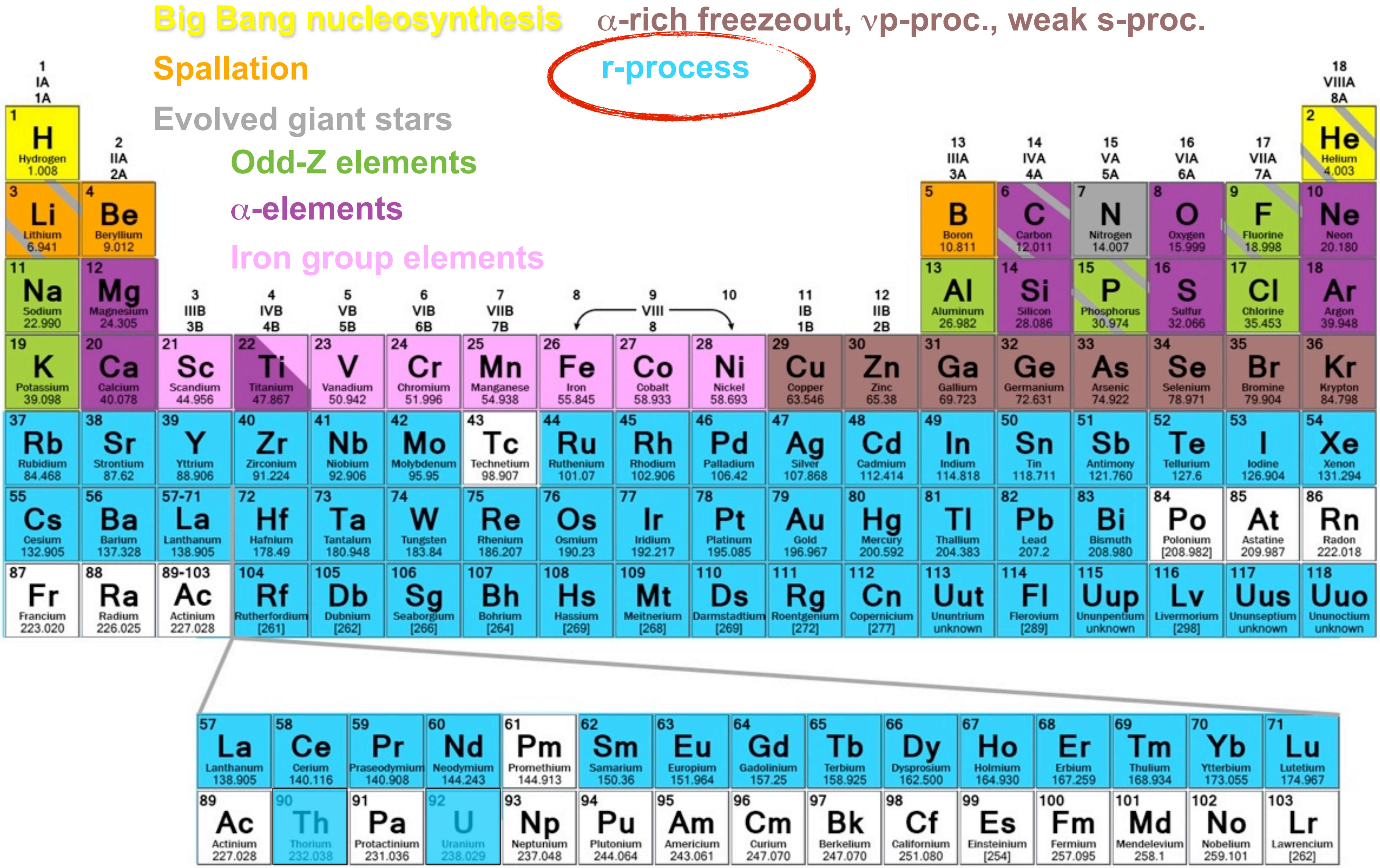
$(Z,N)+n \leftrightarrow (Z,N+1)+\gamma$

Beta Decay

$(Z,N) \rightarrow (Z+1,N-1)+e^{-}+\overline{\nu}_e$

[illegible]
to stability

THE (DETAILED) ASTRONOMER'S PERIODIC TABLE



Big Bang nucleosynthesis

Spallation

Evolved giant stars

Odd-Z elements

α-elements

Iron group elements

α-rich freezeout, νp-proc., weak s-proc.

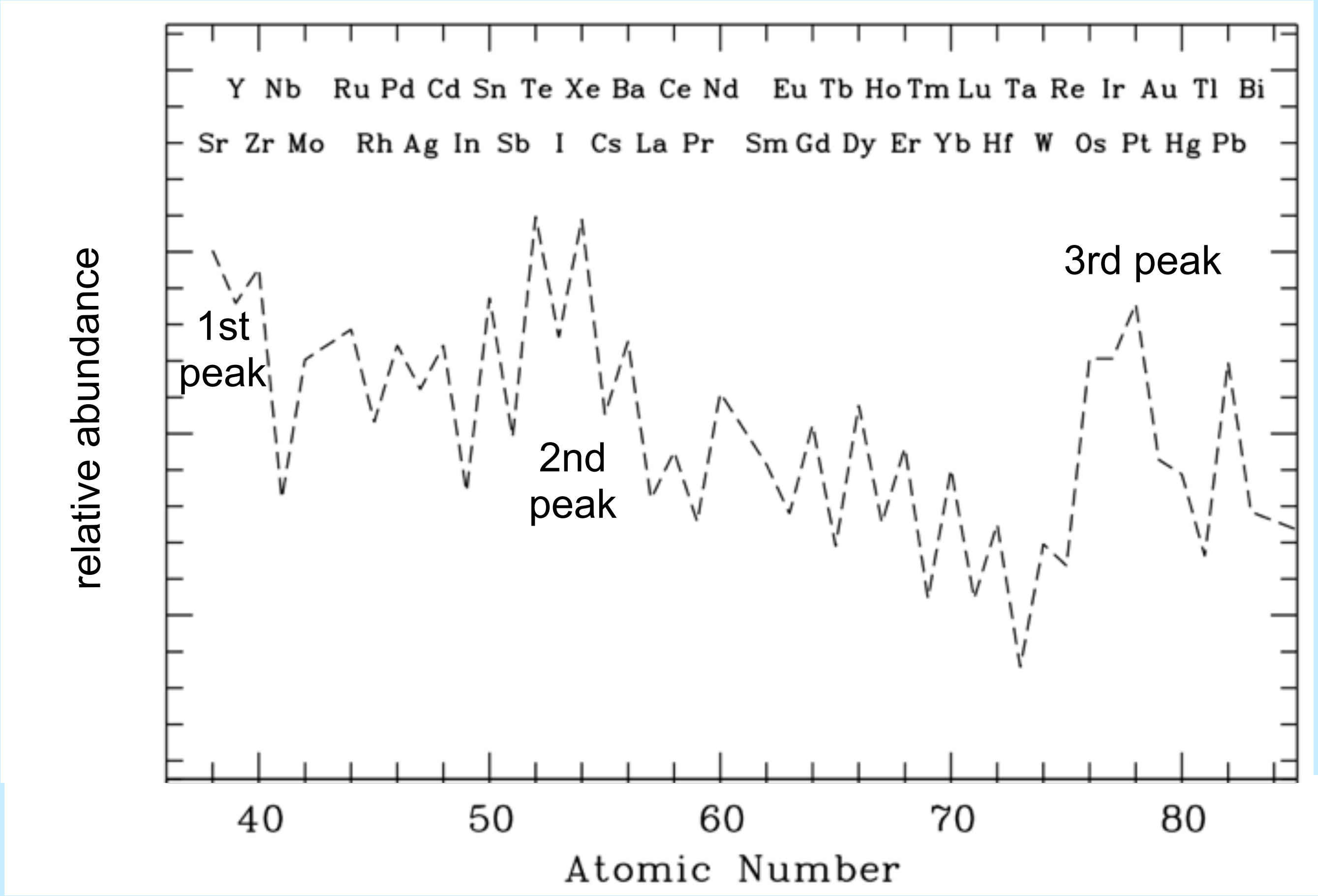
r-process

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71 La Lanthanum 138.905	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Ac Actinium 227.028	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

r-process pattern

neutron-capture r-process elemental pattern

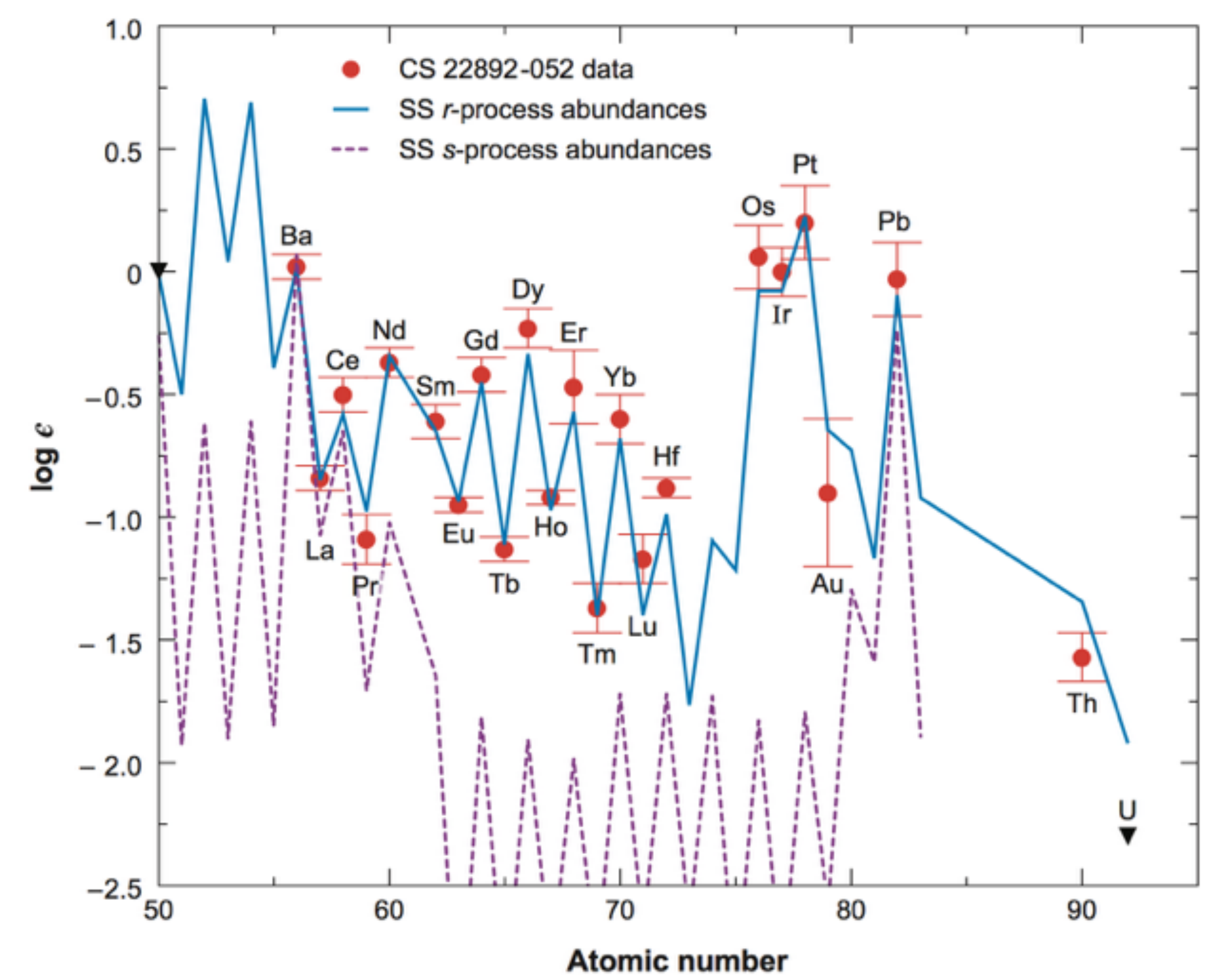


Universal r-process pattern observed in metal-poor stars

r-process abundance **patterns** are the same in the Sun and old metal-poor stars

r-process stars are all extremely metal-poor: [Fe/H]~−3.0

(= 1/1000th of solar Fe value)



Sneden et al. 2008

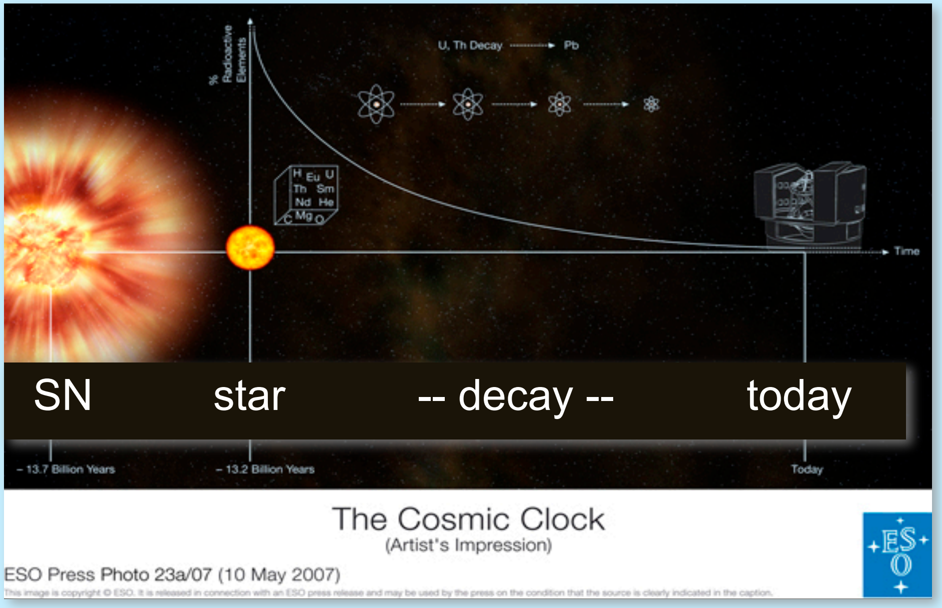
Definition: $[Fe/H] = \log_{10}(N_{Fe}/N_H)_{star} - \log_{10}(N_{Fe}/N_H)_{Sun}$

Nucleo-chronometry of the oldest stars

- Need r-process metal-poor stars
- They display the chemical “fingerprint” of previous nucleosynthesis event (only “visible” in the oldest stars because of low metallicity)

- ~5% of metal-poor stars with $[Fe/H] < -2.5$ (Barklem et al. 05)
  $\Rightarrow$Only 15-20 stars known so far with $[Eu/Fe] > 1.0$

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



The Cosmic Clock
(Artist's Impression)

ESO Press Photo 23a/07 (10 May 2007)

[Th and U can also be measured in the Sun, but the chemical evolution has progressed too far; required are old, metal-poor stars from times when only very few SNe had exploded in the universe]

The Age of HE 1523-0901

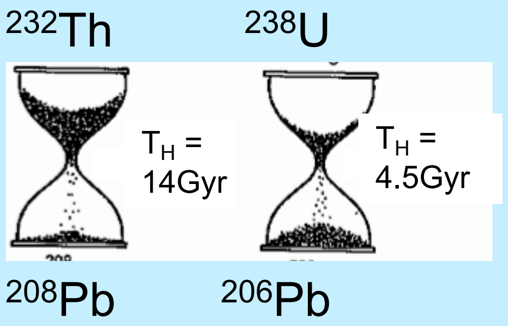
Ages can be obtained from comparison of observed abundance ratio of a radioactive element (such as Thorium, Uranium) to a stable r-process element (such as Europium, Osmium, Iridium) and a theoretically derived initial production ratio.

Done for Th/Eu for 20-30 stars (Sneden+96, Cayrel+ 01, Johnson+Bolte 02, Christlieb+04)

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

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

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



Element ratio	Age [billion yrs]
Th/Eu	11.5
Th/Os	10.7
Th/Ir	15.0
U/Eu	13.2
U/Os	12.9
U/Ir	14.1
U/Th	13.0
average age	**~13 billion years**

Frebel et al. (2007)

WMAP age of the Universe: 13.8 Gyr

A new uranium star

Placco et al. 2017

12.4+-0.9 billion years from U/X

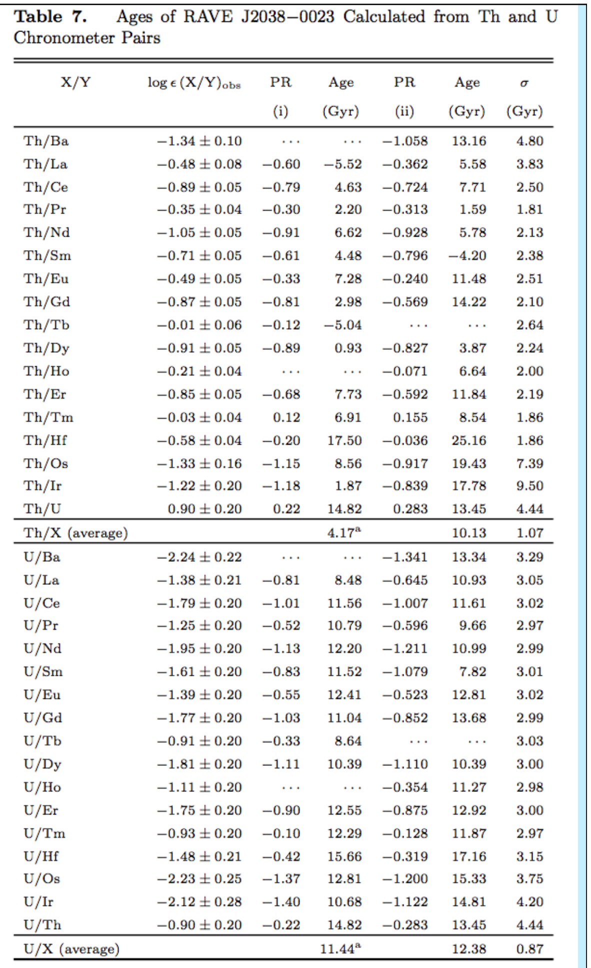
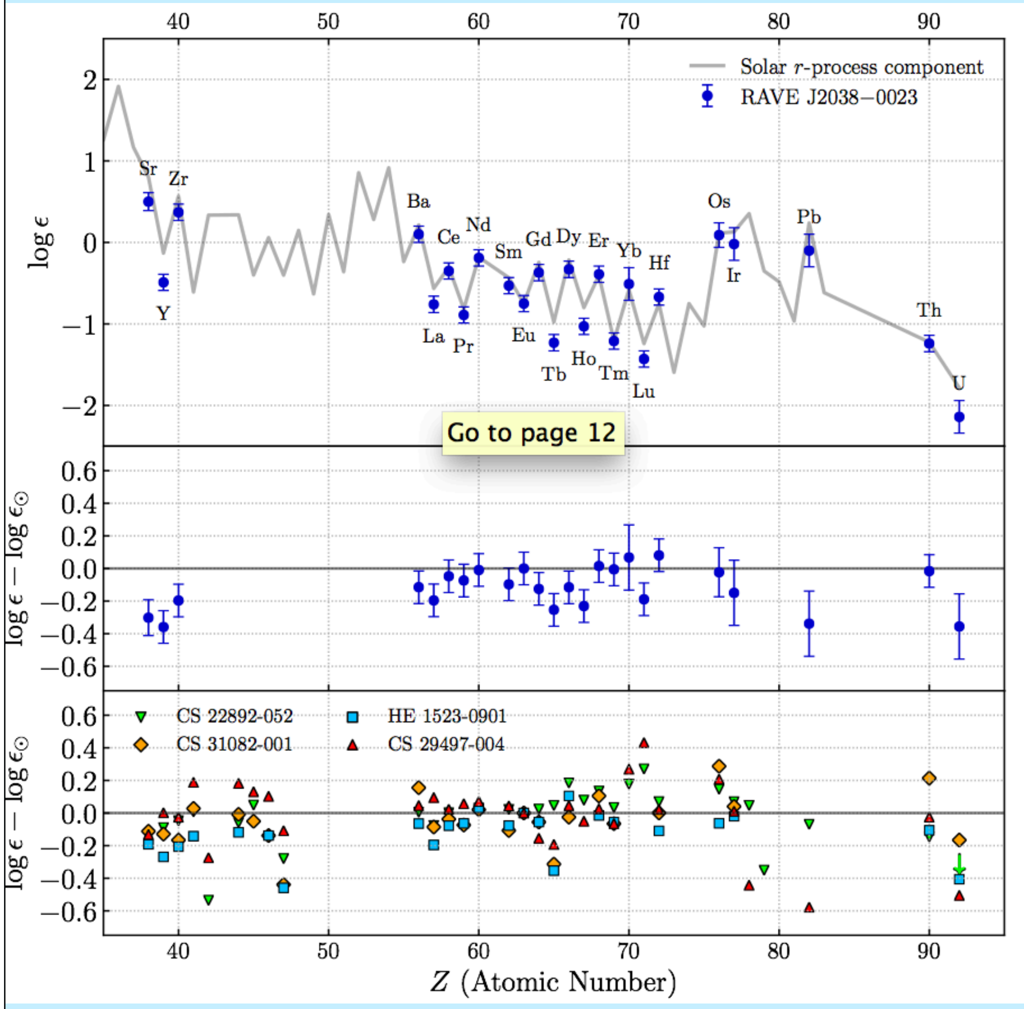
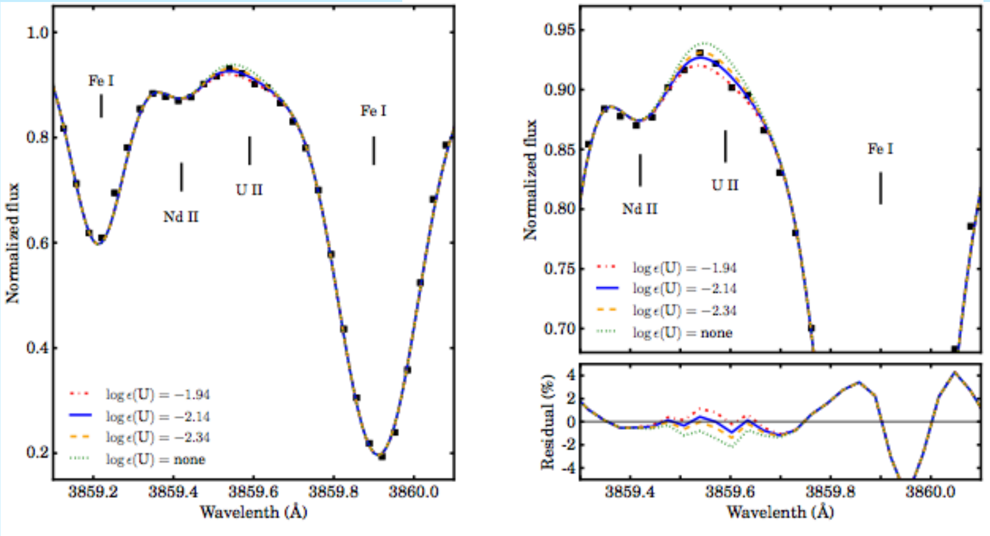


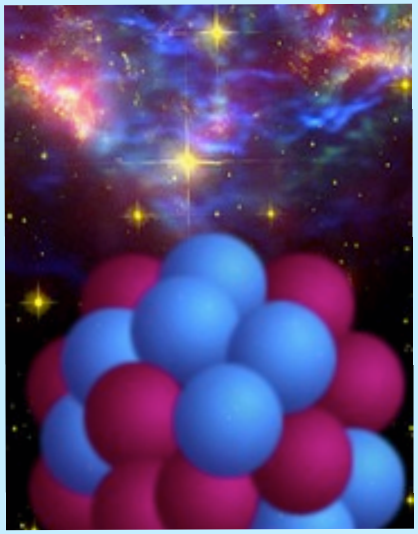
Table 7. Ages of RAVE J2038−0023 Calculated from Th and U Chronometer Pairs

X/Y	$\log\epsilon\,(X/Y)_{\rm obs}$	PR (i)	Age (Gyr)	PR (ii)	Age (Gyr)	σ (Gyr)
Th/Ba	-1.34 ± 0.10	···	···	−1.058	13.16	4.80
Th/La	-0.48 ± 0.08	−0.60	−5.52	−0.362	5.58	3.83
Th/Ce	-0.89 ± 0.05	−0.79	4.63	−0.724	7.71	2.50
Th/Pr	-0.35 ± 0.04	−0.30	2.20	−0.313	1.59	1.81
Th/Nd	-1.05 ± 0.05	−0.91	6.62	−0.928	5.78	2.13
Th/Sm	-0.71 ± 0.05	−0.61	4.48	−0.796	−4.20	2.38
Th/Eu	-0.49 ± 0.05	−0.33	7.28	−0.240	11.48	2.51
Th/Gd	-0.87 ± 0.05	−0.81	2.98	−0.569	14.22	2.10
Th/Tb	-0.01 ± 0.06	−0.12	−5.04	···	···	2.64
Th/Dy	-0.91 ± 0.05	−0.89	0.93	−0.827	3.87	2.24
Th/Ho	-0.21 ± 0.04	···	···	−0.071	6.64	2.00
Th/Er	-0.85 ± 0.05	−0.68	7.73	−0.592	11.84	2.19
Th/Tm	-0.03 ± 0.04	0.12	6.91	0.155	8.54	1.86
Th/Hf	-0.58 ± 0.04	−0.20	17.50	−0.036	25.16	1.86
Th/Os	-1.33 ± 0.16	−1.15	8.56	−0.917	19.43	7.39
Th/Ir	-1.22 ± 0.20	−1.18	1.87	−0.839	17.78	9.50
Th/U	0.90 ± 0.20	0.22	14.82	0.283	13.45	4.44
Th/X (average)			4.17[a]		10.13	1.07
U/Ba	-2.24 ± 0.22	···	···	−1.341	13.34	3.29
U/La	-1.38 ± 0.21	−0.81	8.48	−0.645	10.93	3.05
U/Ce	-1.79 ± 0.20	−1.01	11.56	−1.007	11.61	3.02
U/Pr	-1.25 ± 0.20	−0.52	10.79	−0.596	9.66	2.97
U/Nd	-1.95 ± 0.20	−1.13	12.20	−1.211	10.99	2.99
U/Sm	-1.61 ± 0.20	−0.83	11.52	−1.079	7.82	3.01
U/Eu	-1.39 ± 0.20	−0.55	12.41	−0.523	12.81	3.02
U/Gd	-1.77 ± 0.20	−1.03	11.04	−0.852	13.68	2.99
U/Tb	-0.91 ± 0.20	−0.33	8.64	···	···	3.03
U/Dy	-1.81 ± 0.20	−1.11	10.39	−1.110	10.39	3.00
U/Ho	-1.11 ± 0.20	···	···	−0.354	11.27	2.98
U/Er	-1.75 ± 0.20	−0.90	12.55	−0.875	12.92	3.00
U/Tm	-0.93 ± 0.20	−0.10	12.29	−0.128	11.87	2.97
U/Hf	-1.48 ± 0.21	−0.42	15.66	−0.319	17.16	3.15
U/Os	-2.23 ± 0.25	−1.37	12.81	−1.200	15.33	3.75
U/Ir	-2.12 ± 0.28	−1.40	10.68	−1.122	14.81	4.20
U/Th	-0.90 ± 0.20	−0.22	14.82	−0.283	13.45	4.44
U/X (average)			11.44[a]		12.38	0.87



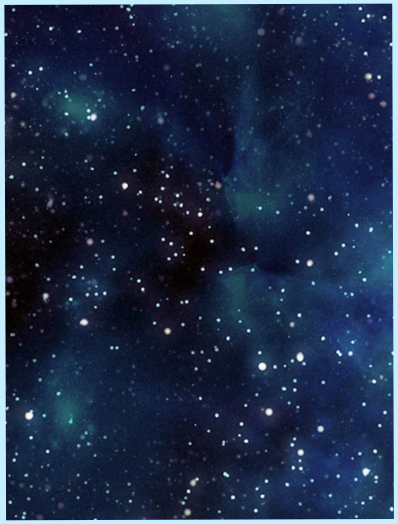


The Story of Reticulum II



Nuclear Astrophysics

Cosmic origin of the chemical elements



Stellar Archaeology

Clues to the astrophysical site of r-process nucleosynthesis

Dwarf Galaxy Archaeology

Ancient, clean chemical enrichment signatures

THE BIG QUESTION

★ **What is the (dominant) astrophysical site of the r-process?**

- ➡ Core-collapse supernovae
- ➡ Neutron star mergers
- ➡ Others (e.g., jet-driven supernovae)

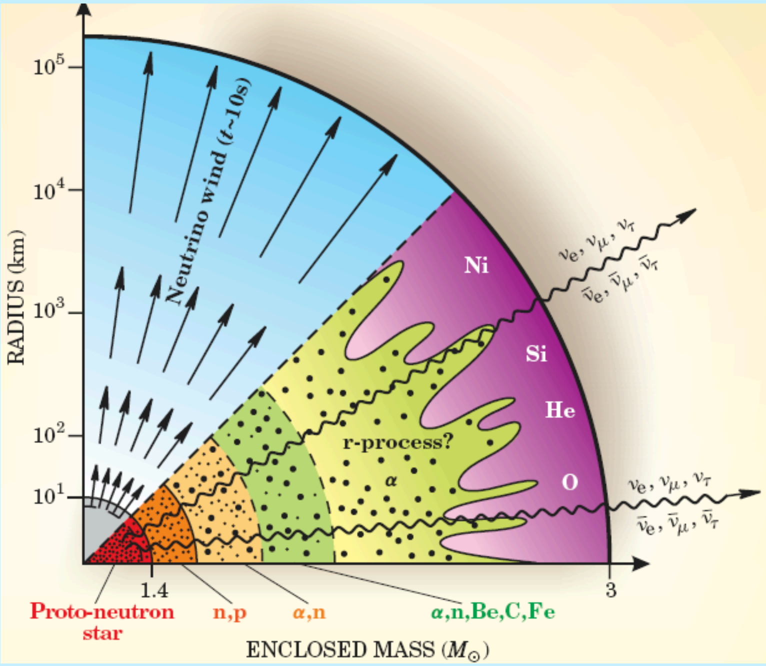
★ **What is the rate and yield of the event?**

★ **Is the dominant site changing over cosmic time?**

Core-collapse supernova

(death of a massive star with M > 8 $M_\odot$)

Supernovae are <u>common</u>; produce light elements w/ Z<30 in their cores
Responsible for these light elements when observed in metal-poor stars



Woosley & Janka 2005

Theoretical element yield:

~10^{-6} M_{sun} of total r-process material

=> ~$10^{-7.5}$ M_{sun} of Eu (per event)

Pros

✓Metal-poor stars only have one/few progenitors
✓Provides the fast enrichment needed; small & steady r-process yields

Con Theoretical difficulties for r-process nucleosynthesis to produce elements heavier than Ba (e.g. Arcones et al.)

NEUTRON STAR BINARY MERGER

(TWO COMPACT SUPERNOVA REMNANTS)

Pros Easily produces elements heavier than Ba

Cons Rare One binary per ~1000- 2000 supernovae
Long(er) enrichment timescale => Inspiral time >100 Myr

Delay time too long to occur before metal-poor stars form??

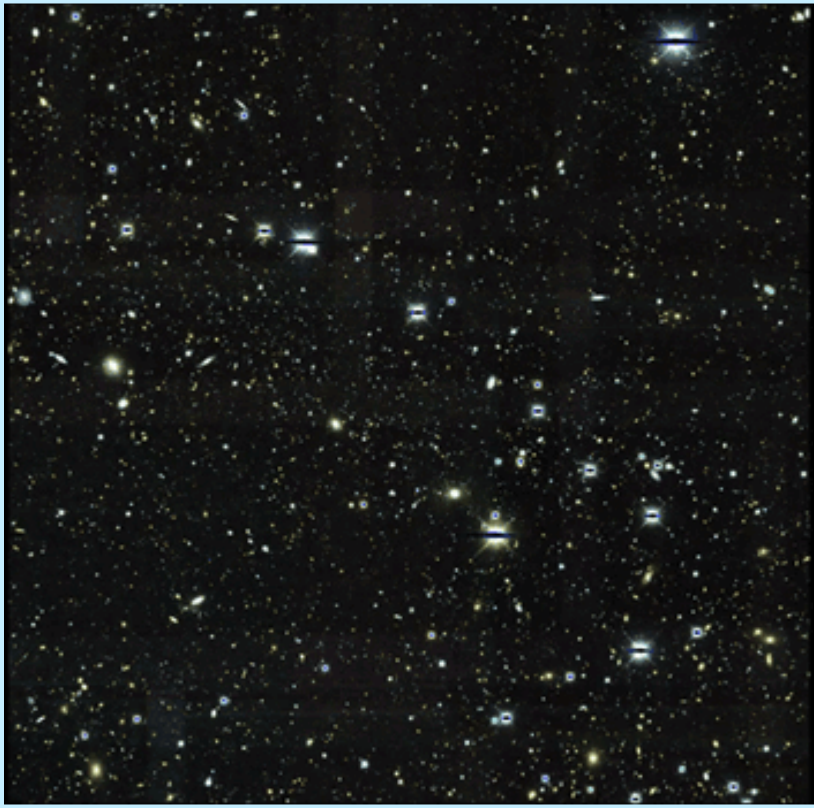
Yield: ~10^{-3} -10^{-2} M_{sun} of r-process material (across all n-cap elements)

=> ~$10^{-4.5}$ M_{sun} of Eu (per event)

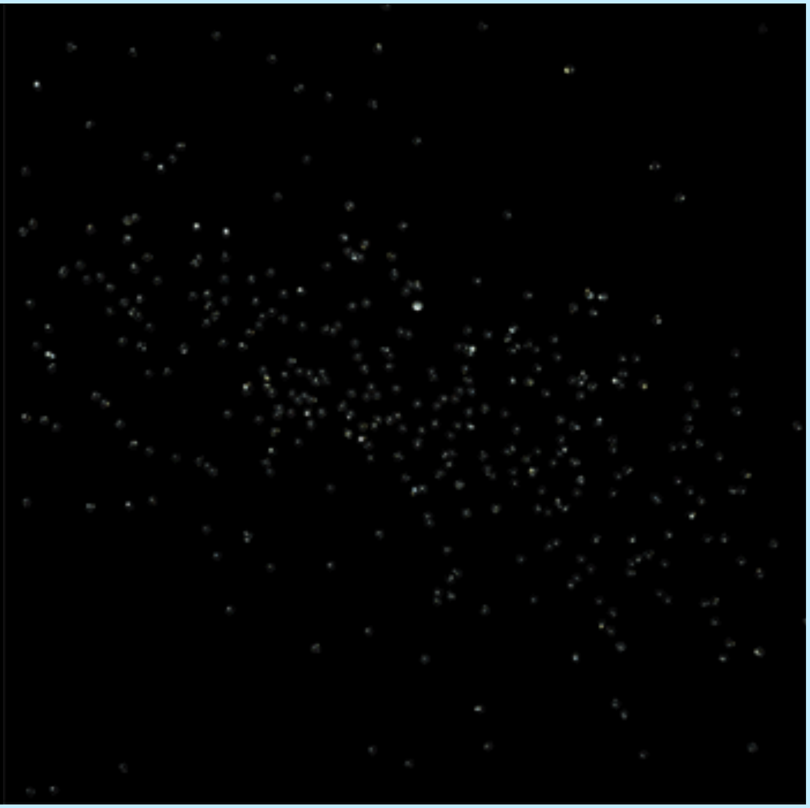
Additional (indirect) evidence for local r-process nucleosynthesis

1) Short gamma-ray bursts: Afterglow from decay of radioactive r-process elements detected (Tanvir et al. 13)
2) Radioactive deep sea measurements suggest local neutron star mergers (Wallner et al. 15, Hotokezaka et al.15)

Meet Reticulum II



All stars



Reticulum II stars

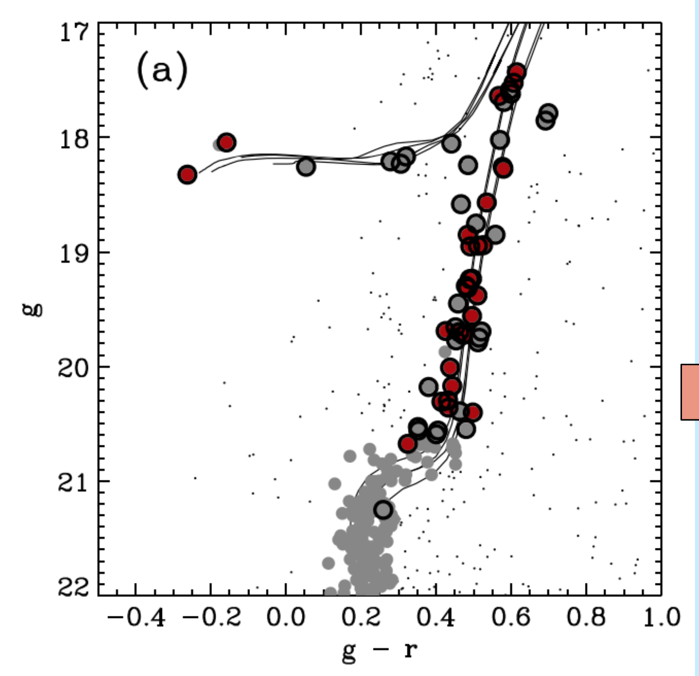
(Dark Energy Survey, 2015)

MAGELLAN OBSERVATIONS

Simon et al. 2015: radial velocity members confirm Ret II to be a galaxy

Brightest members (V=17-19) observable with high-resolution spectroscopy

=> Ji et al. (2015) spent 2-3 hours on each of 9 brightest targets (~23h)



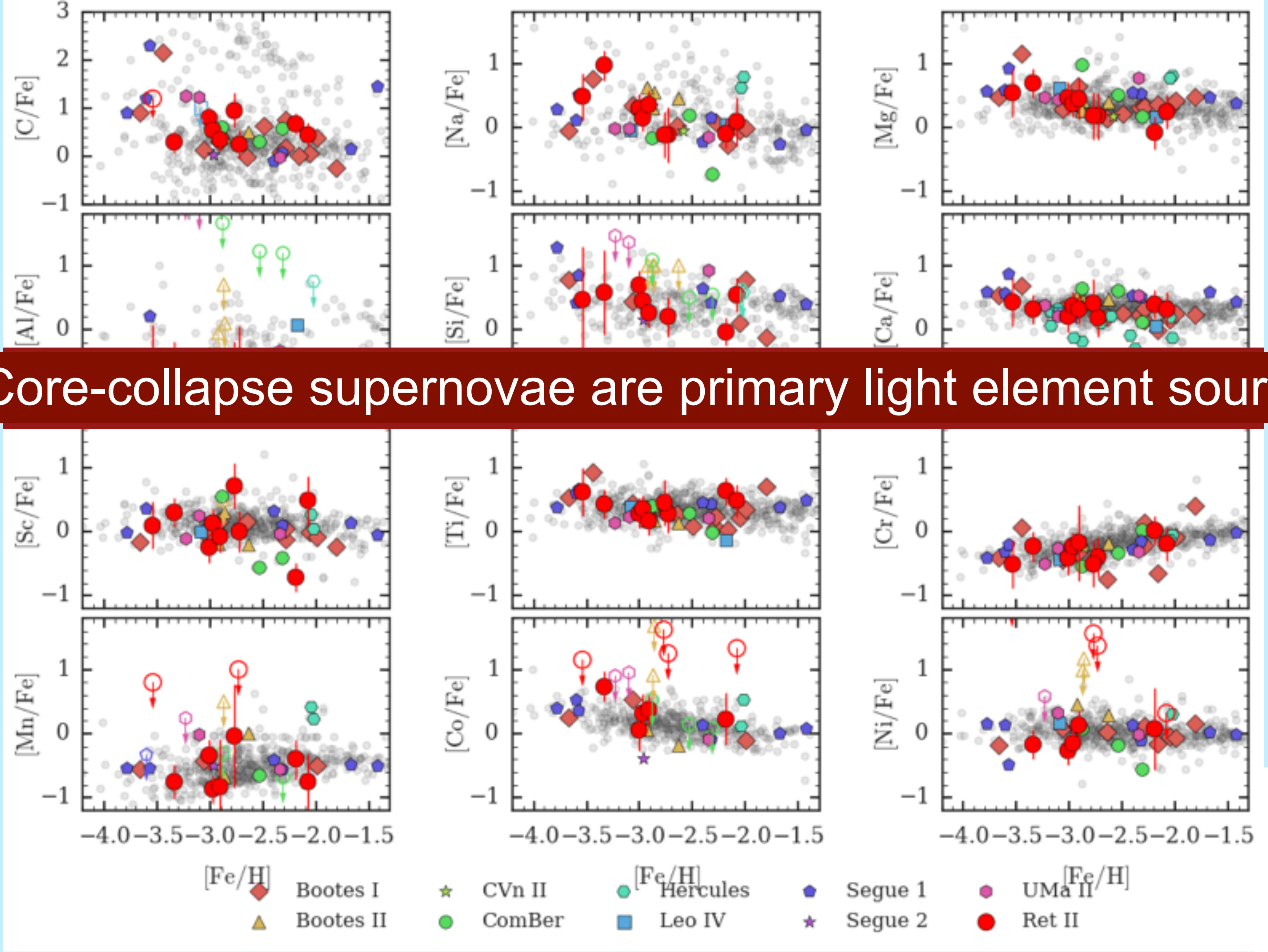
Color-magnitude-diagram of Ret II
(red = confirmed members)

Clay 6.5m Magellan telescope
(on left) at Las Campanas Observatory, Chile

Light element abundances

(C, Na, Mg, Al, Si, Ca, Sc, Ti, Cr, Mn, Co, Ni)

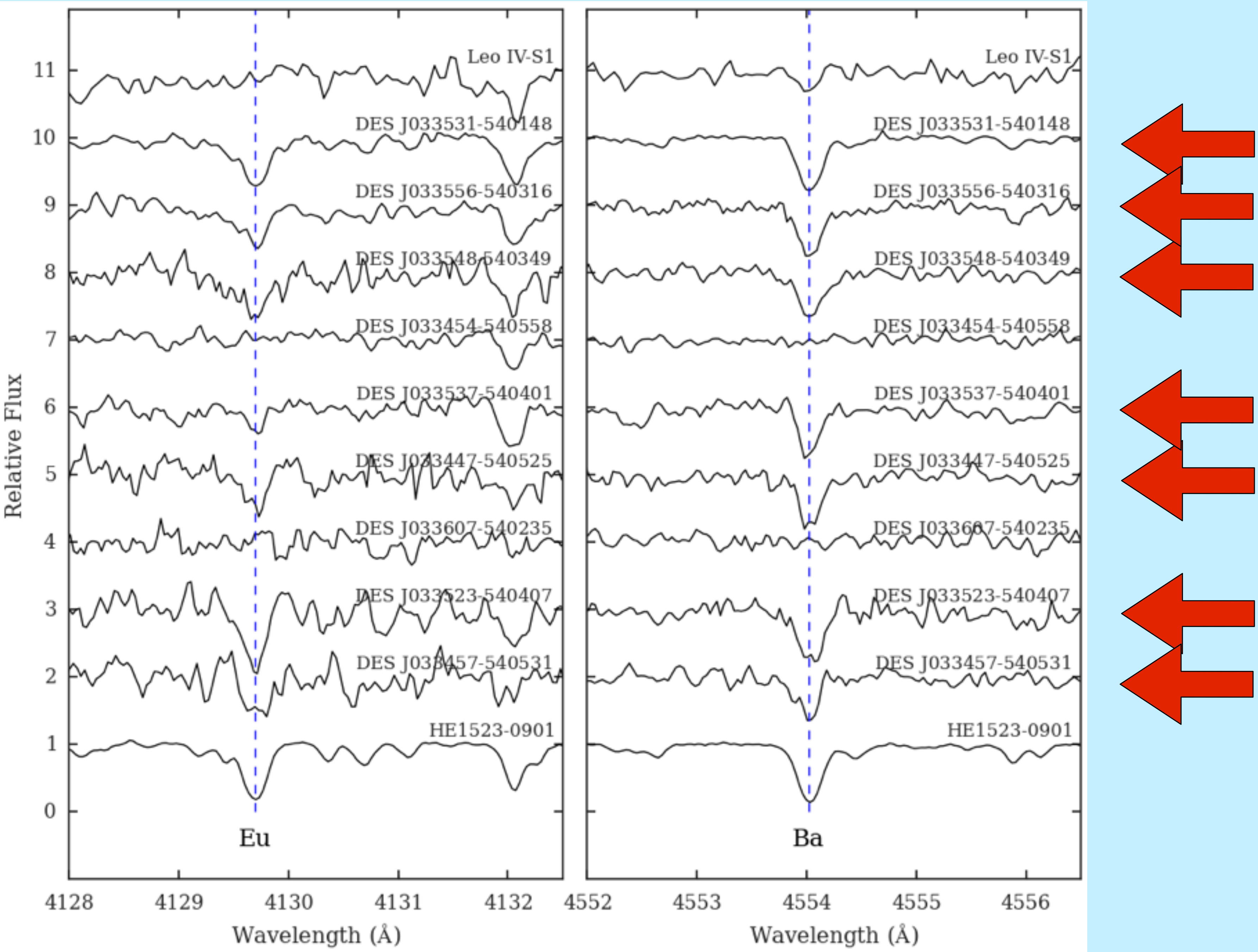
Reticulum II stars have same abundances as typical metal-poor halo stars



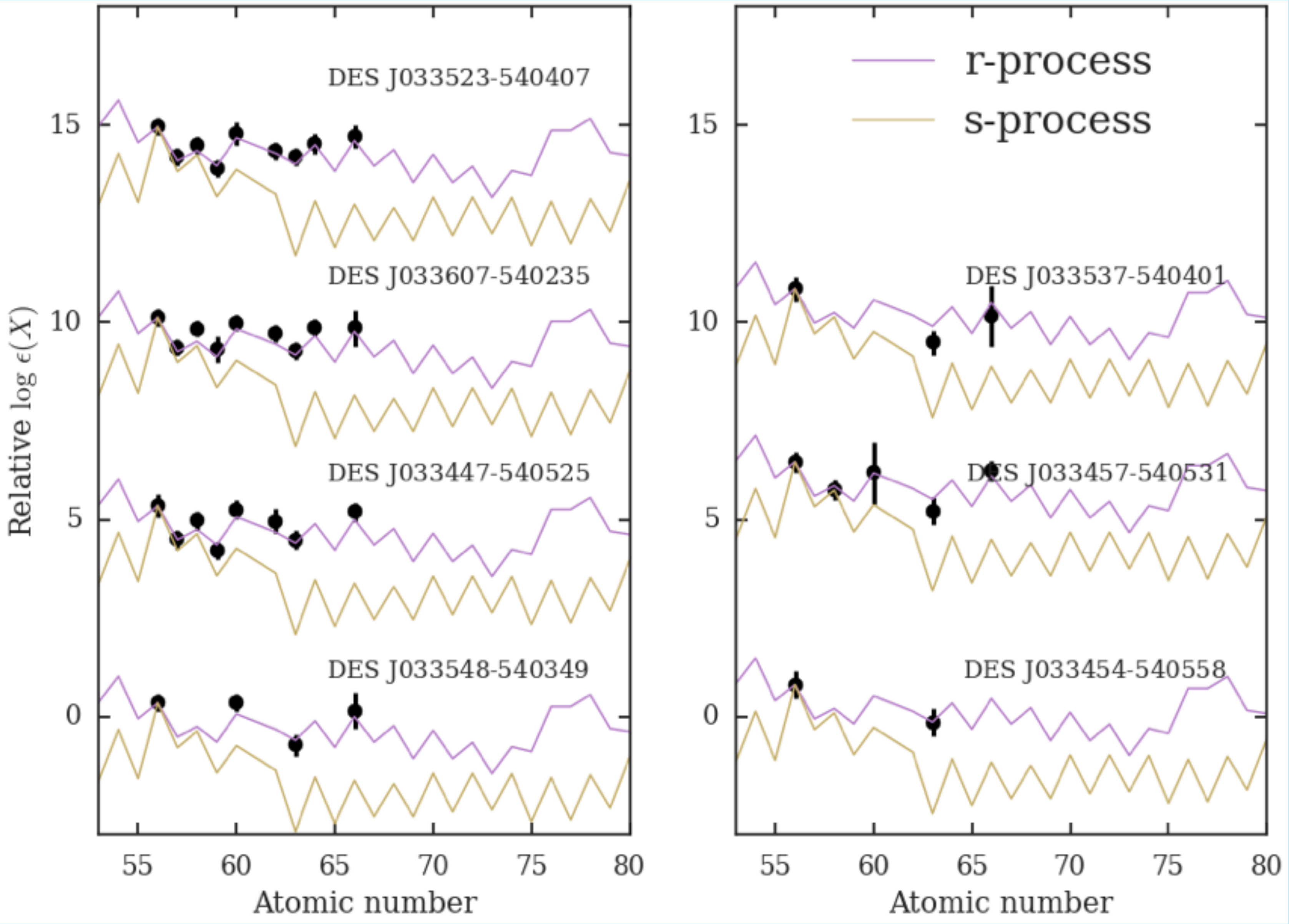
Core-collapse supernovae are primary light element source

Ji et al 2016, *Nature*, 531, 610

gray dots
metal-poor halo stars

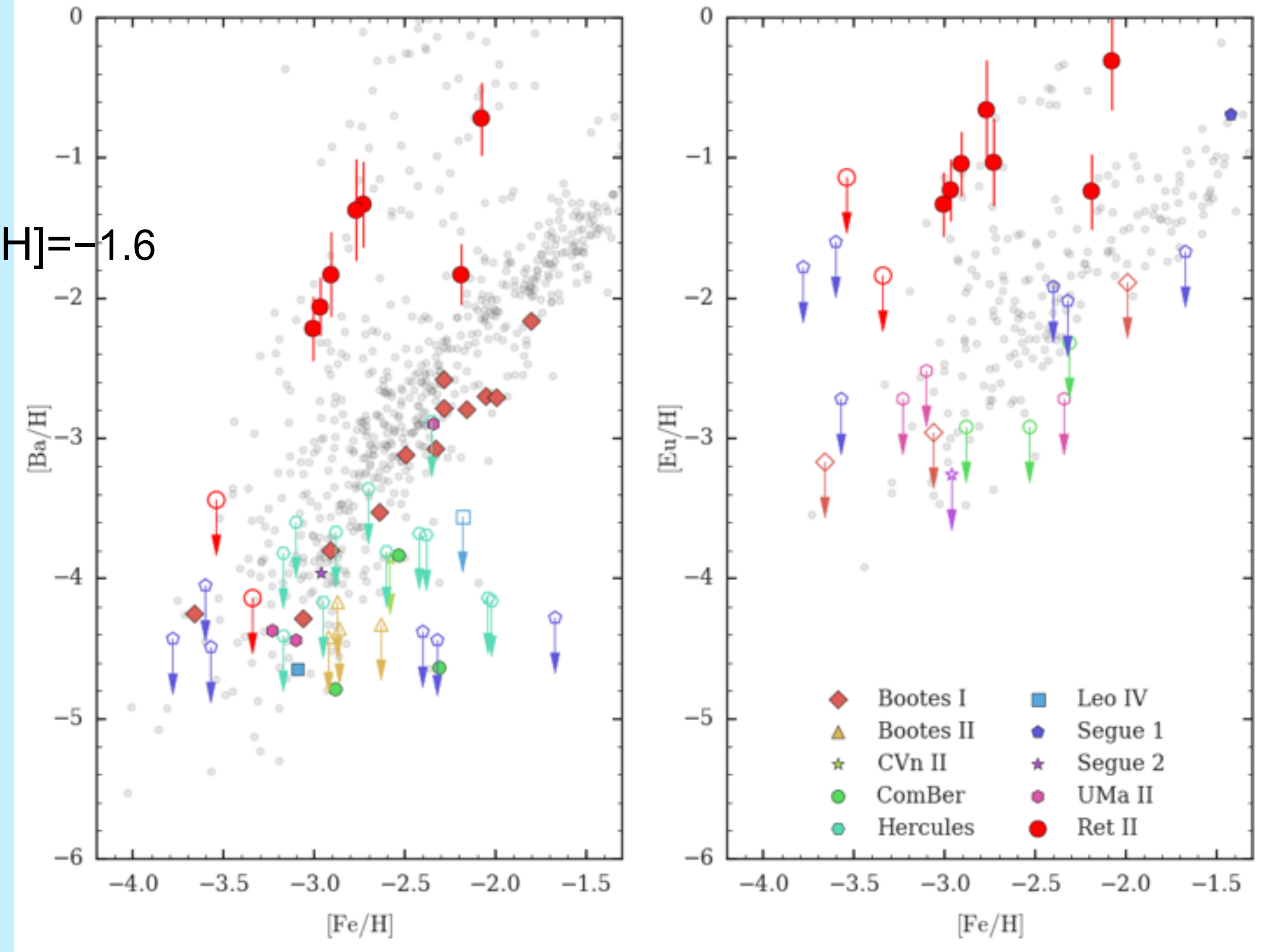

Relative Flux
0
1
2
3
4
5
6
7
8
9
10
11
Leo IV-S1
DES J033531-540148
DES J033556-540316
DES J033548-540349
DES J033454-540558
DES J033537-540401
DES J033447-540525
DES J033607-540235
DES J033523-540407
DES J033457-540531
HE1523-0901
Eu
Ba
4128
4129
4130
4131
4132
4552
4553
4554
4555
4556
Wavelength (Å)
Wavelength (Å)

All seven Ret II stars display the r-process pattern



Ji et al 2016, *Nature*, 531, 610

Ret II stars:
<u>> 100x higher</u> n-capture element abundances than other UFDs



[Ba/H]=−1.6

[Eu/H]=−1

DWARF GALAXY ARCHAEOLOGY

(= USING AN ENTIRE DWARF GALAXY TO STUDY THE EARLY UNIVERSE)

How Rare?

Population of 10 UFDs:

➡1 of 10 r-process events

➡Est. stellar mass of ***all*** UFDs: ~2000 SNe expected

➡Consistent w/ expected NSM rate of 1 per 1000-2000 SNe

(LIGO will deliver answer in 2+ yrs)

How Prolific?

Estimate gas mass of UFD:

Total gas in UFD galaxy

➡Max. dilution mass: ~10^7 M_{sun}

Gas swept up by a 10^{51}erg energy injection into typical ISM

➡Min. dilution mass: ~10^5 M_{sun}

Back-of-the-envelope calculation

Mix NSM yield mass of $10^{-4.5}$ M_{sun} into 10^6 M_{sun} of H gas (can NOW be estimated!)

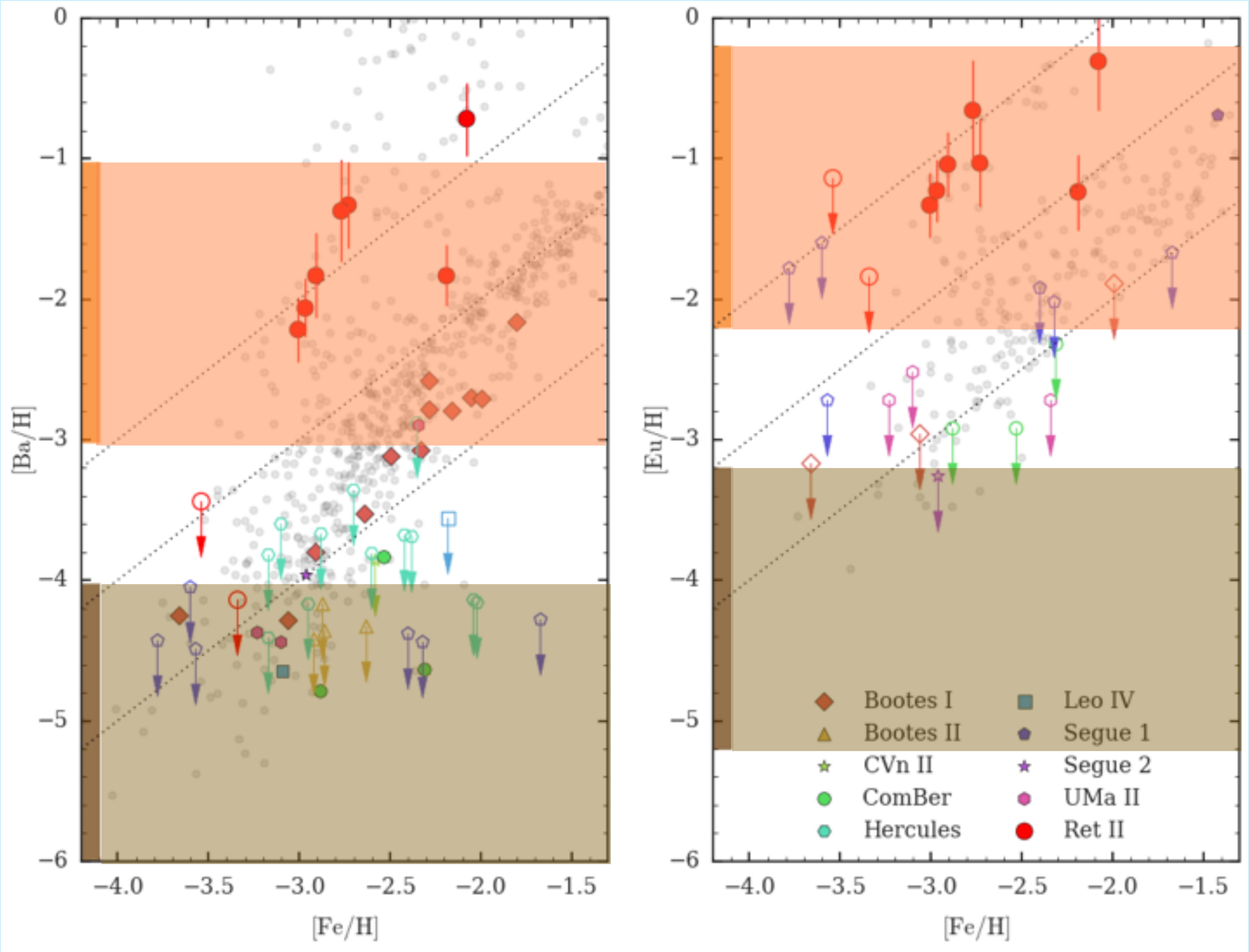
=> [Eu/H] = −1.2 is abundance of next-generation star

=> Agrees with Ret II abundance results!

RET II ABUNDANCES CONSISTENT W/ NEUTRON-STAR MERGER YIELD

Neutron star merger

Supernova

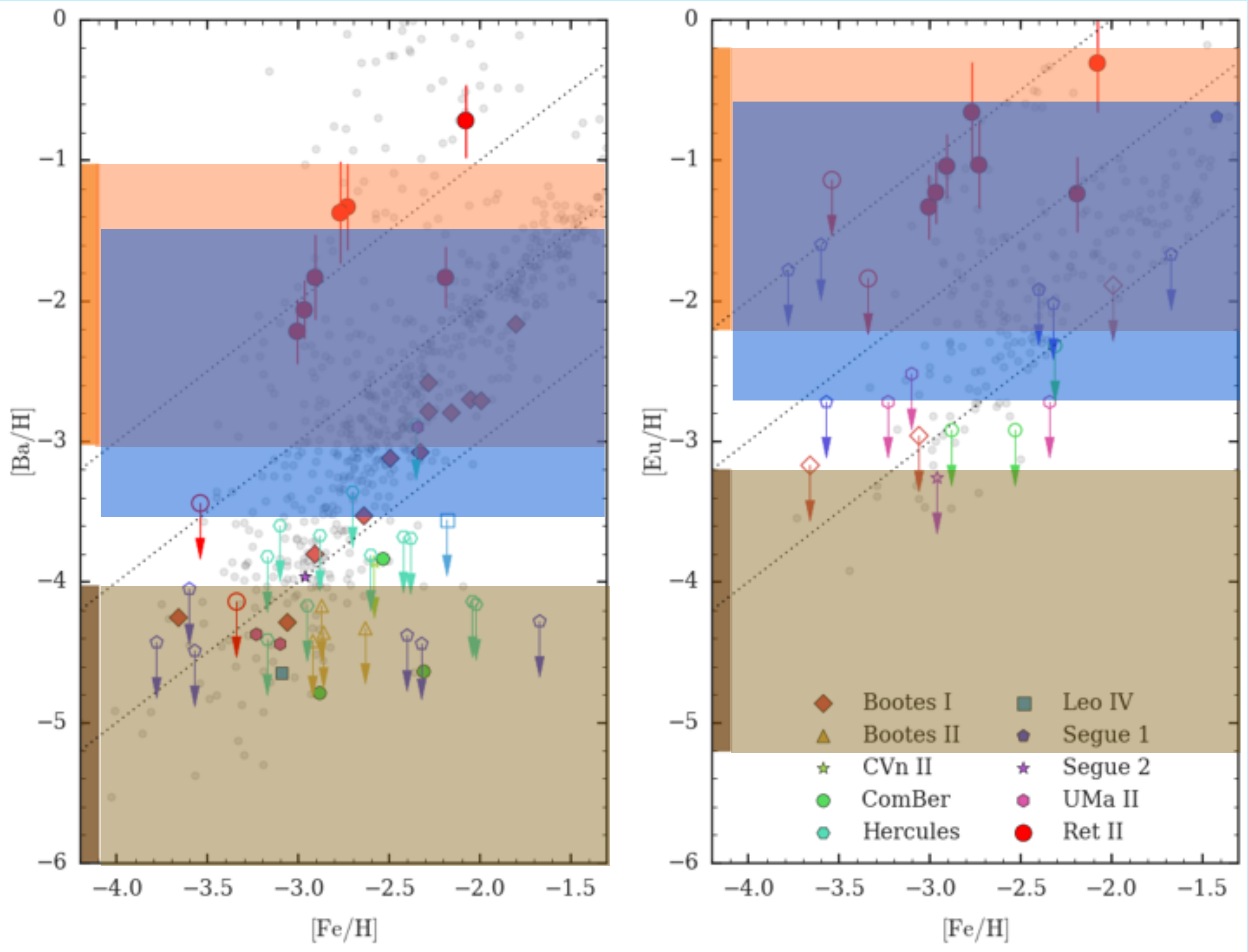


Ji et al 2016, *Nature*, 531, 610

Rare and prolific jet-driven supernova remains possibility

Neutron star merger

Supernova

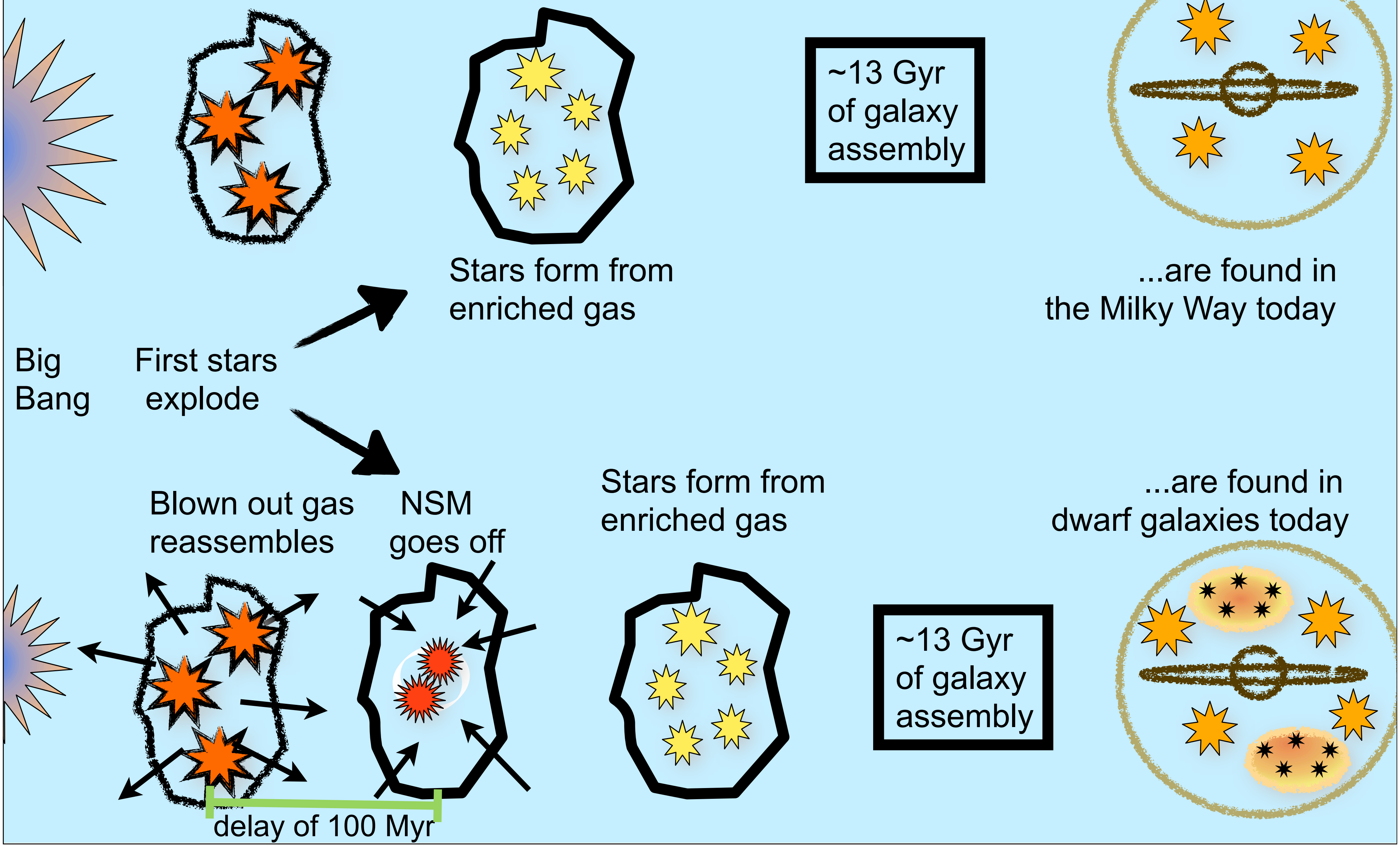


Jet-driven supernova

(e.g. Winteler et al. 2012)

...but ordinary supernovae remain ruled out!

ENRICHMENT AND STAR FORMATION TIMELINE



Big Bang

First stars explode

Stars form from enriched gas

~13 Gyr of galaxy assembly

...are found in the Milky Way today

Blown out gas reassembles

NSM goes off

delay of 100 Myr

Stars form from enriched gas

~13 Gyr of galaxy assembly

...are found in dwarf galaxies today

Answers to the Big Question

★ What is the (dominant) astrophysical site of the r-process?

- ➡ Core-collapse supe ➡No, but a rare and prolific site
- ➡ Neutron star me ➡Consistent w/ Ret II abundances
- ➡ Others (e.g., jet-driven super ➡Remain possible

★ What is the rate and yield of the event?

➡ ~1 event per 2000 SN; $\sim 10^{-2.5}$ M_{sun} of r-process

★ Is the dominant site changing over cosmic time?

➡Probably not!

Selected literature

- **Metal-poor stars:**
- Frebel & Norris 2015, ARA&A

- **Neutron-capture elements:**
- Sneden et al. 2008, ARA&A
- Jacobson & Frebel 2014, JPhysG

- **R-process in dwarf galaxies:**
- Ji et al. 2016a,b, Nature/ApJ
- Roederer et al. 2016, MNRAS

- NOT A COMPLETE LIST -- SEND ME MORE TO ADD HERE!

The Cosmic Origin on the Chemical elements

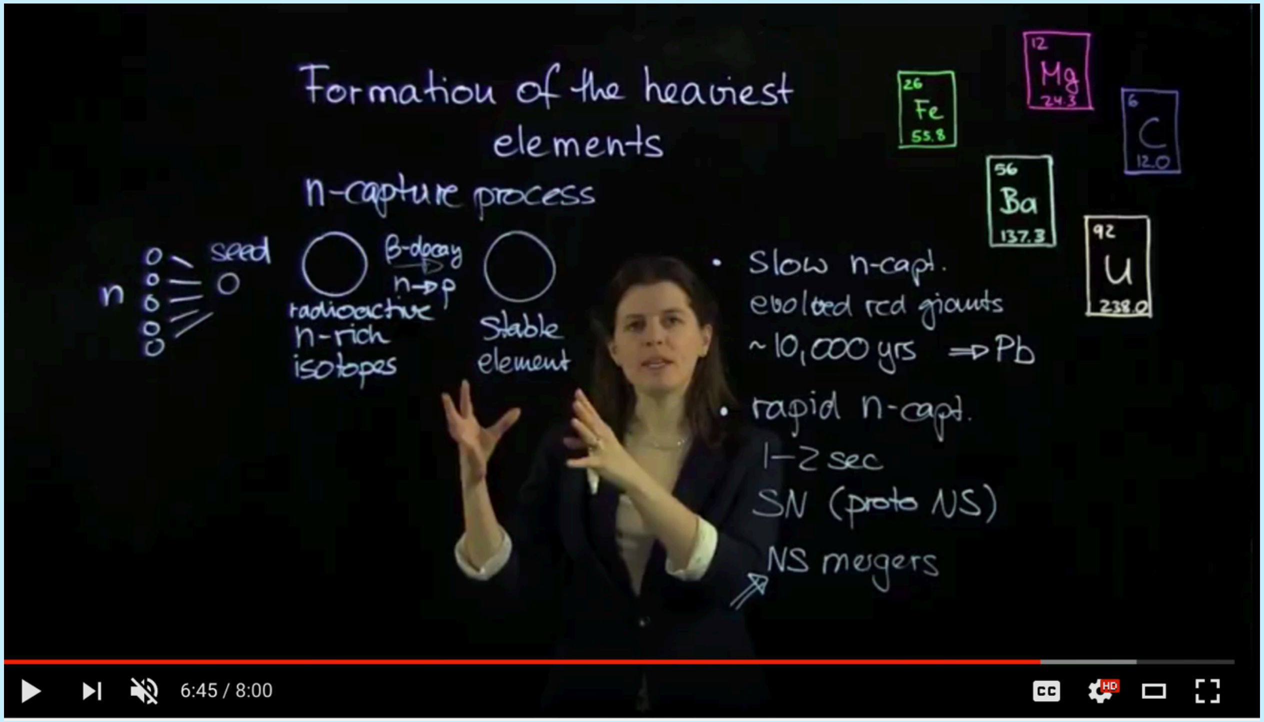
Popular science book

all about stars, elements,
discoveries & telescopes

~270 pages
Princeton University Press

11 episodes (5 to 8min) on YouTube

https://www.youtube.com/channel/UC3cyRVDoePNf_rLQlwKpdeg



Use in the classroom, with research/PhD students, for your own entertainment or as outreach material

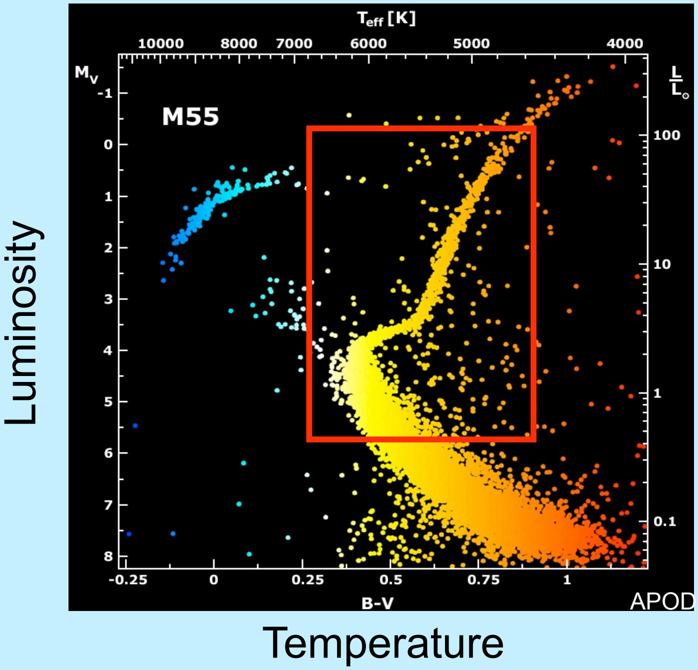
What we learn from stellar abundances of old stars

Low-mass stars ($M < 1\,M_\odot$)

⇒ lifetimes > 10 billion years

⇒ unevolved stars are still around!

Hertzsprung-Russell-diagram



APOD

Using “fossil” metal-poor stars to reconstruct...

- ✓ Origin and evolution of chemical elements
- ✓ Relevant nucleosynthesis processes and sites
- ✓ Chemical and dynamical history of the Galaxy
- ✓ Lower limit to the age of the Universe

... and to provide constraints

- ✓ Nature of the first stars & initial mass function
- ✓ Nucleosynthesis & chemical yields of first/early SNe
- ✓ Early star & early galaxy formation processes
- ✓ Hierarchical merging of galaxies (observed abundances are ‘end product’ that have to be reproduced by any comprehensive galaxy formation model)
- ✓ Formation of the galactic halo by detailed understanding of its stellar content

Galactic metal-poor stars are a great tool for near-field cosmology because they are the local equivalent of the high-redshift Universe!