

Nuclear properties and the astrophysical *r* process

27th Jyväskylä Summer School

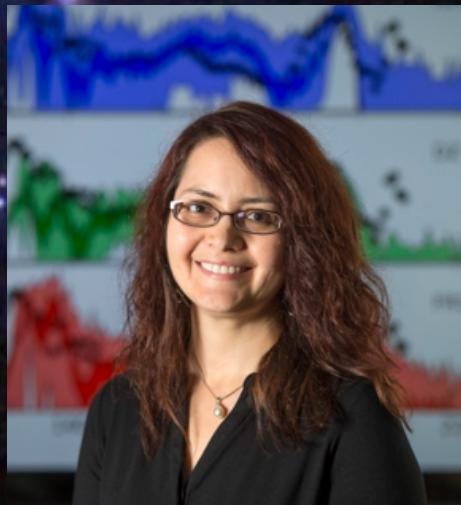
14.-18.8.2017

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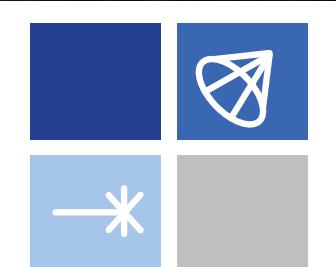


Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS



Fission In R-process Elements

The FIRE collaboration explores the role of fission in the rapid neutron capture or r-process of nucleosynthesis



JINA-CEE
Center for the Evolution
of the Elements

Welcome!

Are you a...

- A – Master's student
- B – PhD student
- C – postdoctoral researcher
- D – other

Welcome!

Are you a/an...

A – astronomer

B – theoretical nuclear physicist

C – experimental nuclear physicist

D – other

Nuclear properties and the astrophysical *r* process

What is the astrophysical origin of the heaviest elements??

Class #	Subject
1	Introduction, chemical abundances
2	Origins of the elements up to the iron peak
3	Neutron capture nucleosynthesis, <i>r</i> -process dynamics
4	The <i>r</i> process: nuclear masses and lifetimes
5	The <i>r</i> process: neutron capture rates and fission

periodic table

1 IA 1 H Hydrogen 1.00794	New Original	Alkali metals	Actinide series	c Solid	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
2 IA 2 He Helium 4.002602	K	Alkaline earth metals	Poor metals	Br Liquid	14 IIIA	15 IVA	16 VA	17 VIA	18 VIIA	2 He Helium 4.002602
3 IA 3 Li Lithium 6.941	IIA	Transition metals	Nonmetals	H Gas	15 IIIA	16 IVA	17 VA	18 VIA	19 VIIA	2 He Helium 4.002602
4 IA 4 Be Beryllium 9.012182	KL	Lanthanide series	Noble gases	Tc Synthetic	16 IIIA	17 IVA	18 VA	19 VIA	20 VIIA	2 He Helium 4.002602
11 IA 11 Na Sodium 22.989770	2 Mg Magnesium 24.3050	IIIIB	IVB	VIB	VIIB	VIIIB	—	VIIIB	—	18 VIIIA
12 IA 12 Mg Magnesium 24.3050	3 Mg Magnesium 24.3050	3 Sc Scandium 44.955910	4 Ti Titanium 47.867	5 V Vanadium 50.9415	6 Cr Chromium 51.9961	7 Mn Manganese 54.938049	8 Fe Iron 55.8457	9 Co Cobalt 58.933200	10 Ni Nickel 58.6934	11 Cu Copper 63.546
19 IA 19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.8457	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546
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37 IA 37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682
5 IA 5 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682
55 IA 55 Cs Cesium 132.90545	56 Ba Barium 137.327	57 to 71 57 to 71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655
6 IA 6 Cs Cesium 132.90545	56 Ba Barium 137.327	57 to 71 57 to 71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655
87 IA 87 Fr Francium (223)	88 Ra Radium (226)	89 to 103 89 to 103	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Hs Bohrium (264)	108 Mt Meitnerium (269)	109 Ds Darmstadtium (268)	110 Rg Roentgenium (271)	111 Uub Ununtrium (285)
7 IA 7 Fr Francium (223)	88 Ra Radium (226)	89 to 103 89 to 103	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Hs Bohrium (264)	108 Mt Meitnerium (269)	109 Ds Darmstadtium (268)	110 Rg Roentgenium (271)	111 Uub Ununtrium (285)
116 IA 116 Uuh Ununhexium (292)	117 Uus Ununseptium	118 Uuo Ununoctium (293)	115 Up Ununpentium (288)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uuh Ununhexium (292)	117 Uus Ununseptium	118 Uuo Ununoctium (293)	18 VIIIA	18 VIIIA

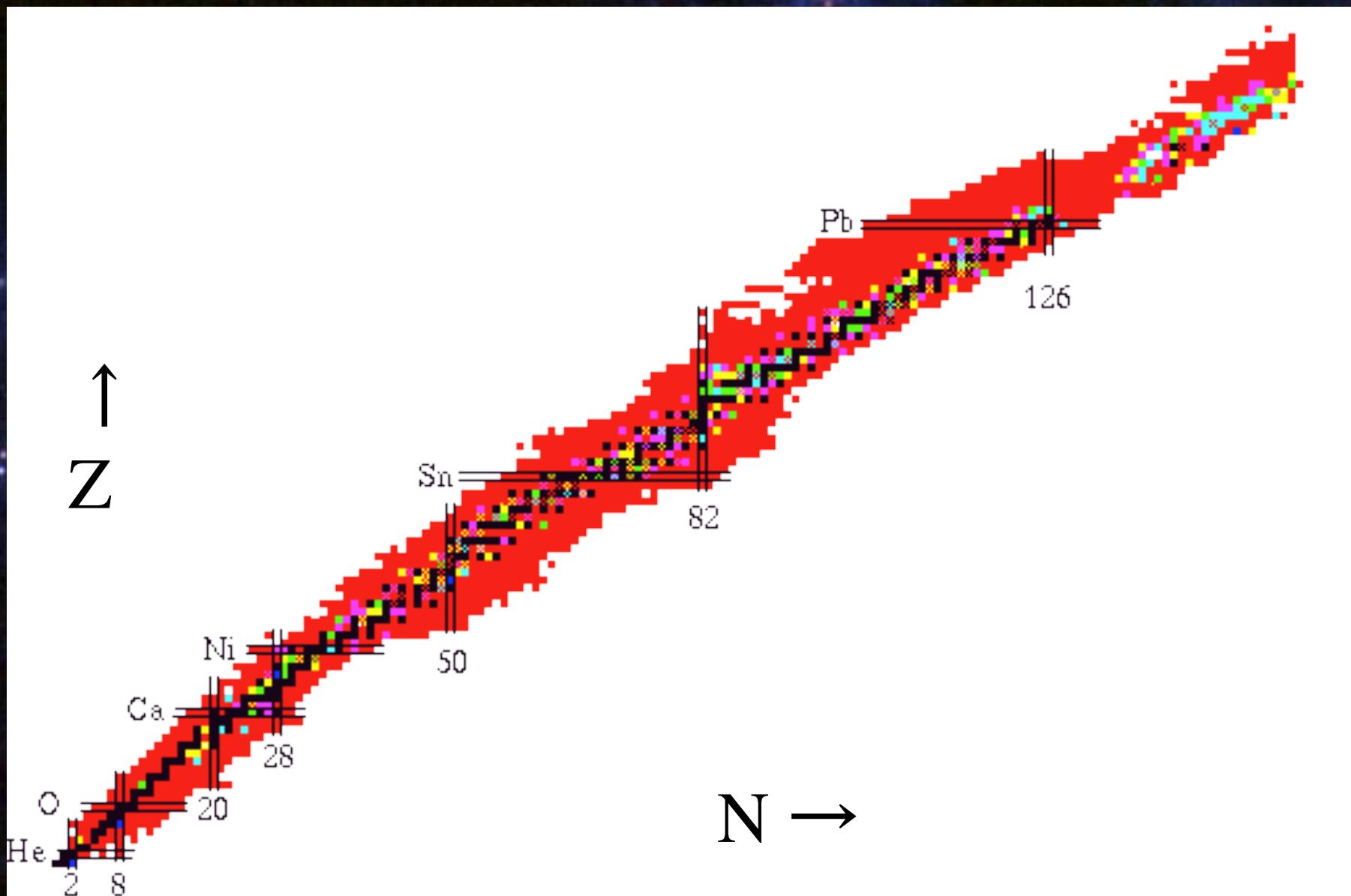
Atomic masses in parentheses are those of the most stable or common isotope.

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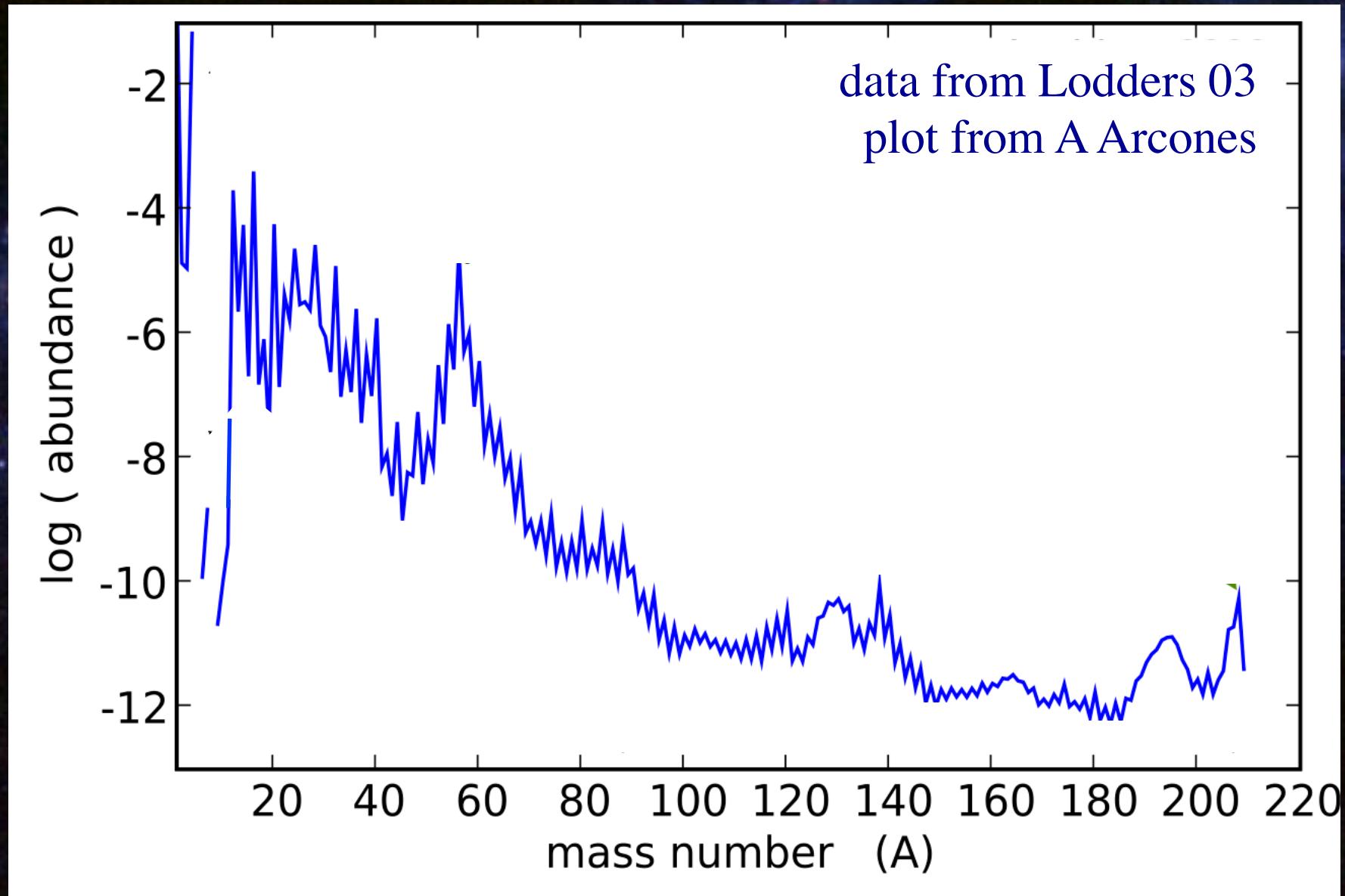
Note: The subgroup numbers 1-18 were adopted in 1984 by the International Union of Pure and Applied Chemistry. The names of elements 112-118 are the Latin equivalents of those numbers.

<http://www.dayah.com/periodic/Images/periodic%20table.png>

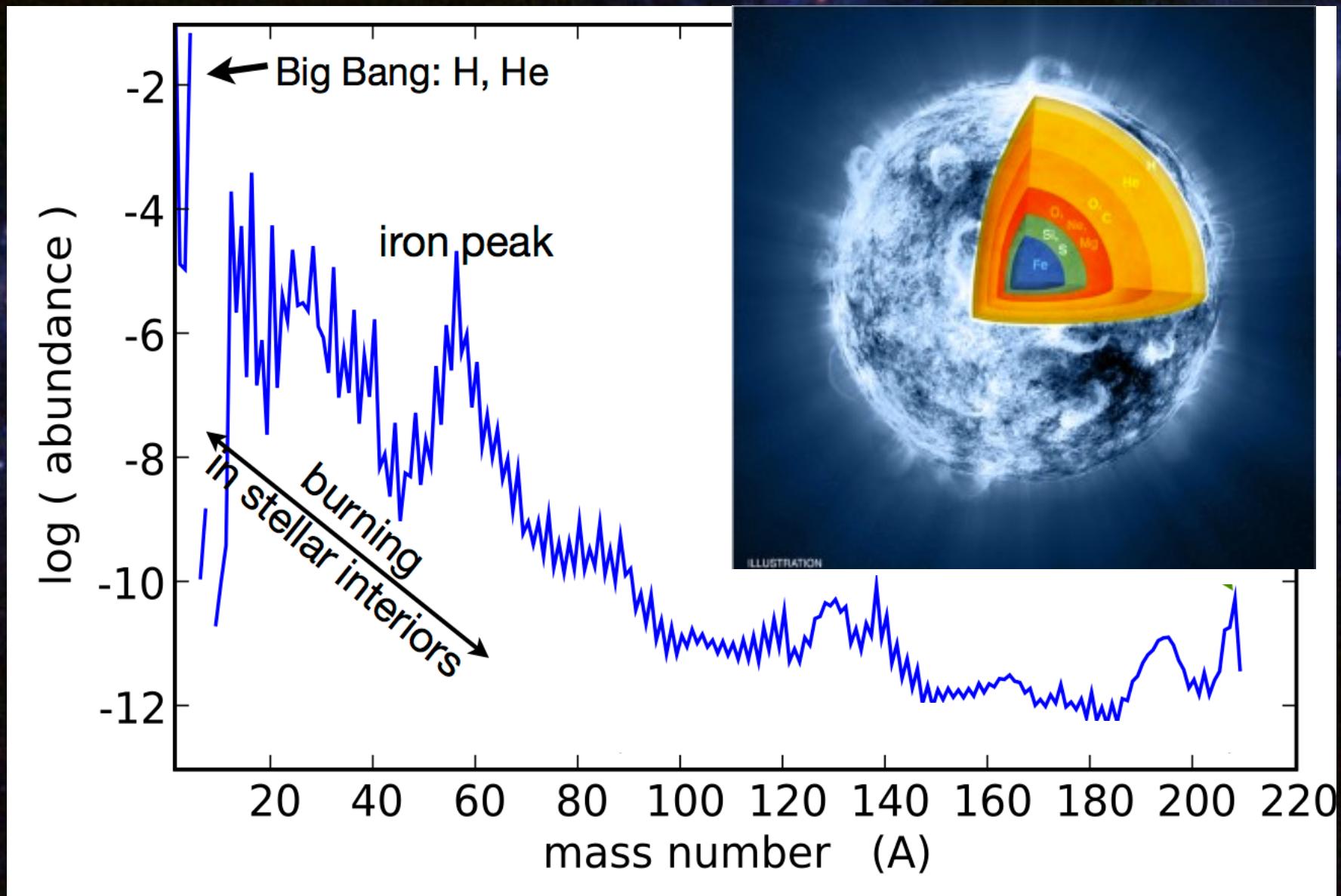
chart of the nuclides

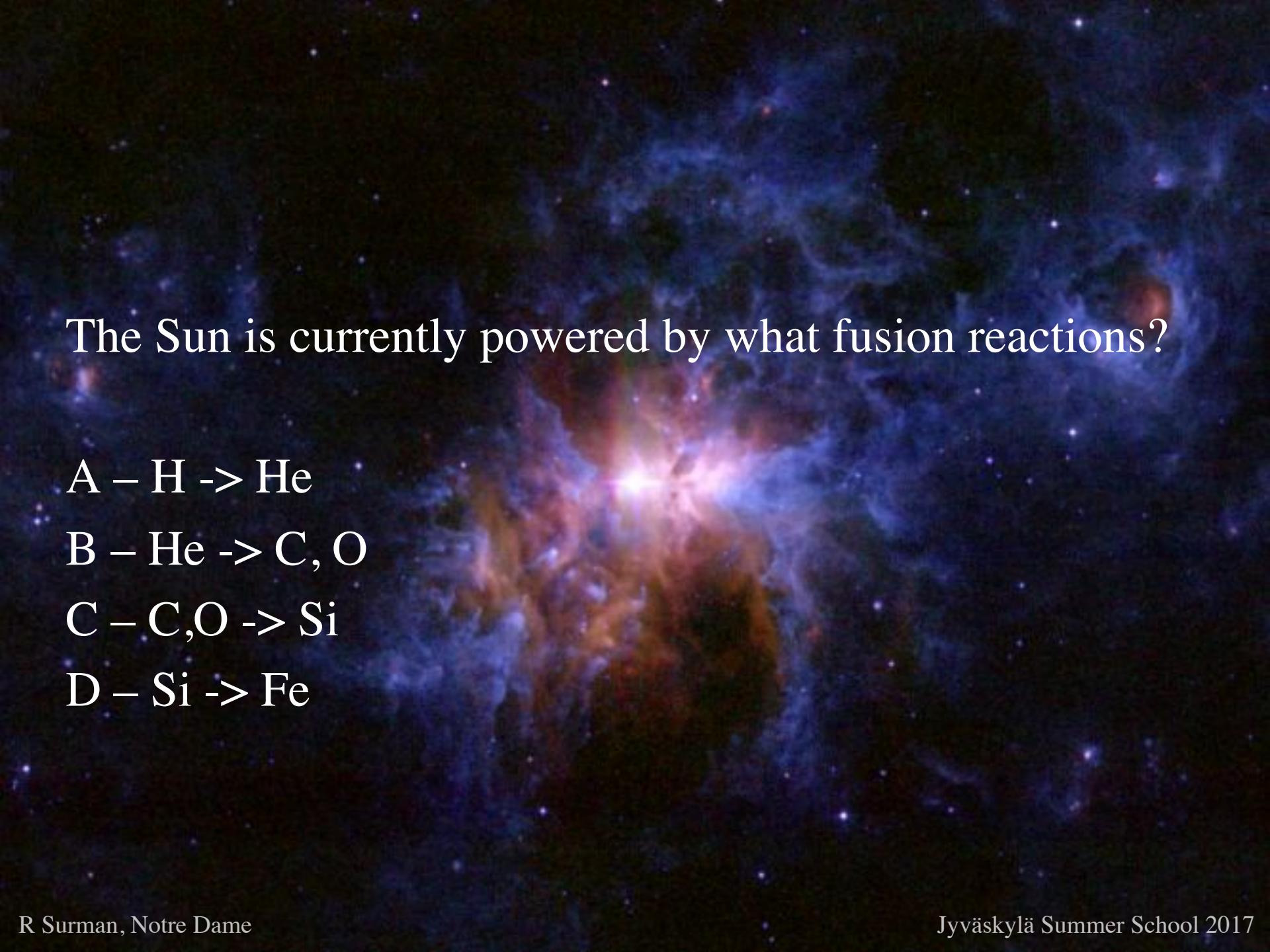


solar system abundances



solar system abundances





The Sun is currently powered by what fusion reactions?

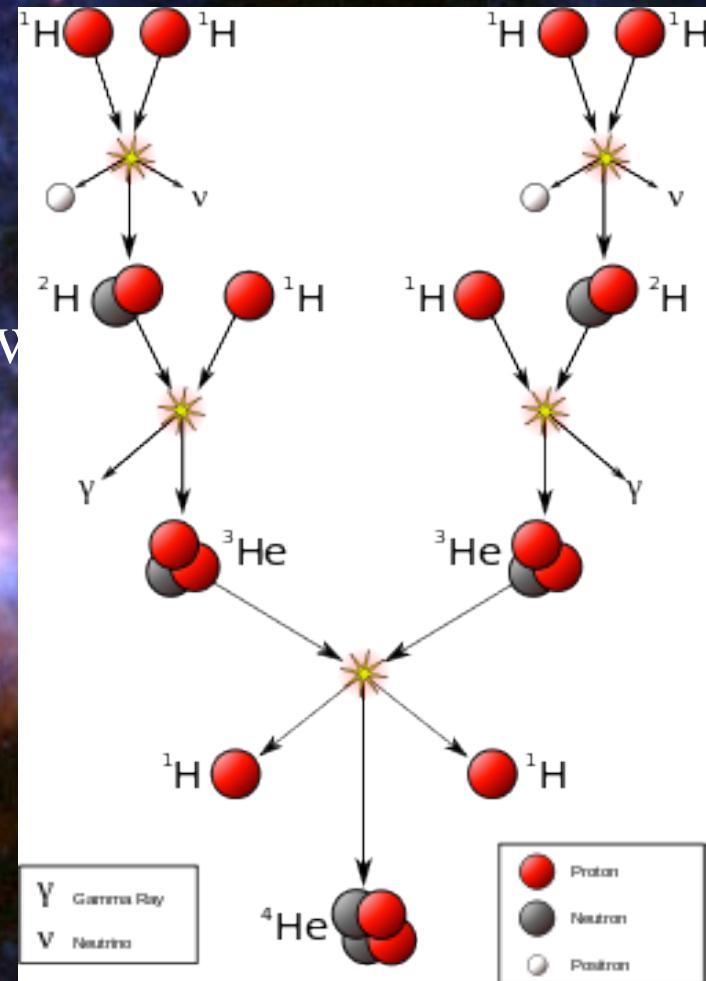
A – H -> He

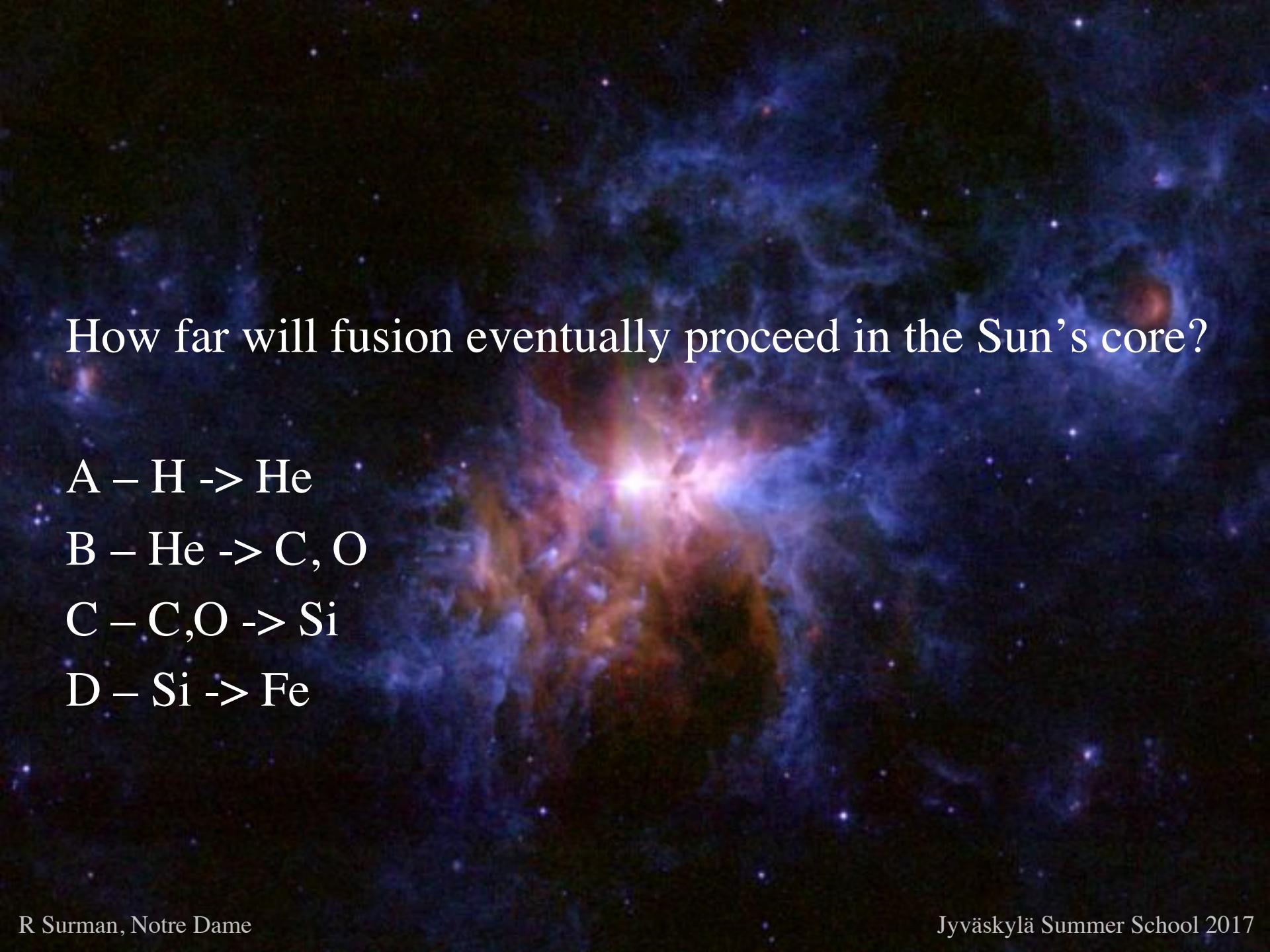
B – He -> C, O

C – C,O -> Si

D – Si -> Fe

The Sun is currently powered by v





How far will fusion eventually proceed in the Sun's core?

A – H \rightarrow He

B – He \rightarrow C, O

C – C,O \rightarrow Si

D – Si \rightarrow Fe

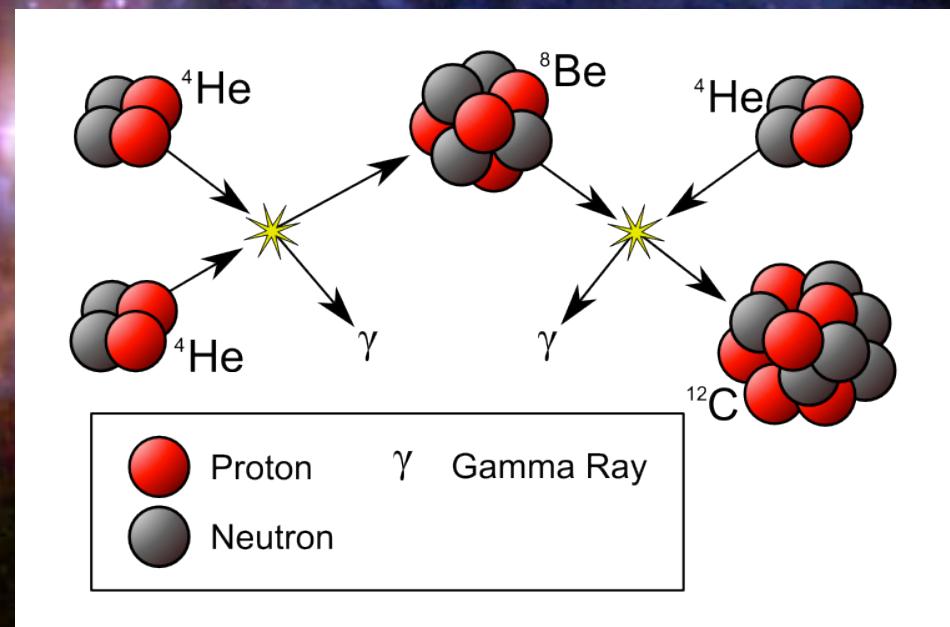
How far will fusion eventually proceed in the Sun's core?

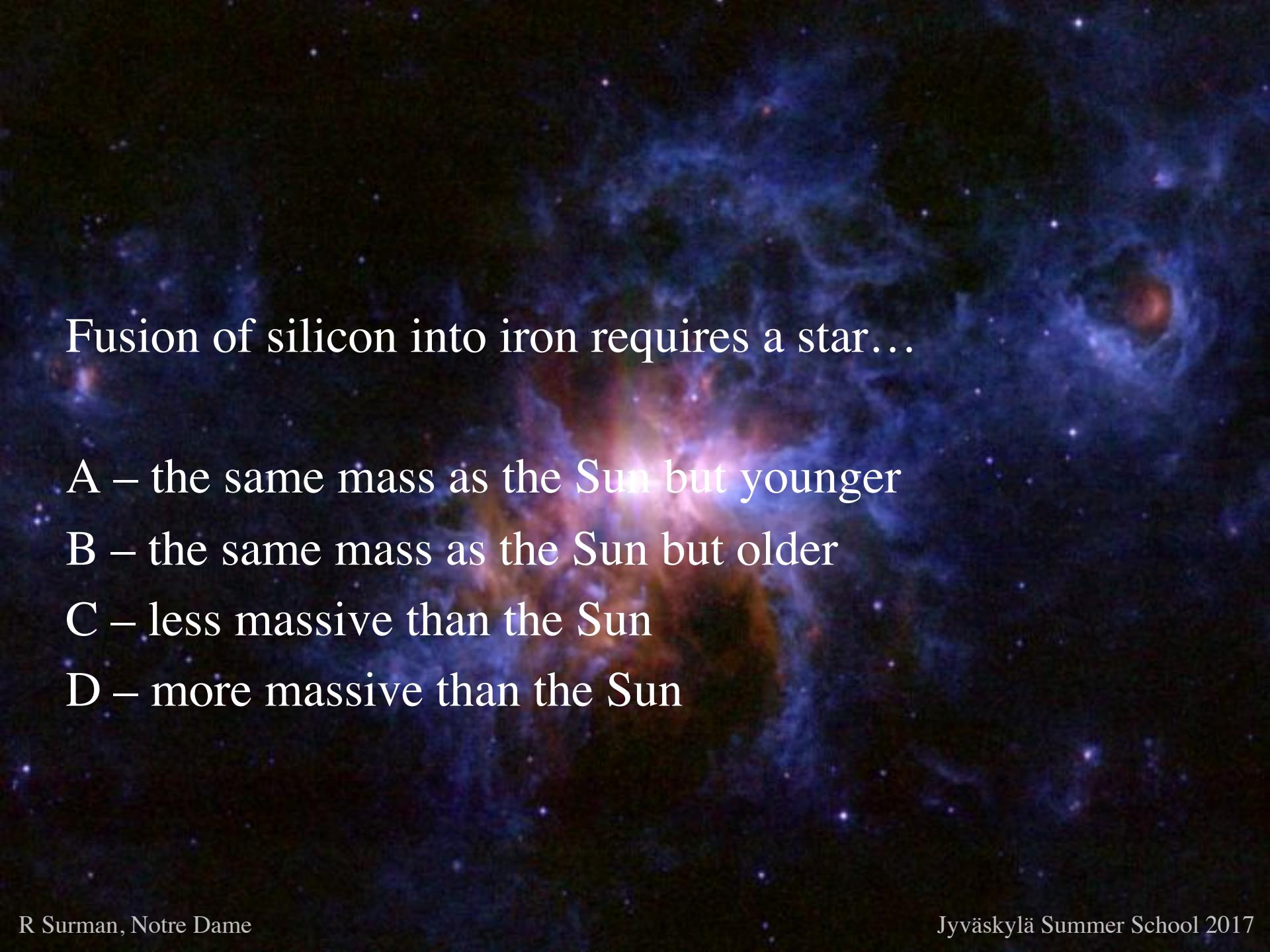
A – H \rightarrow He

B – He \rightarrow C, O

C – C,O \rightarrow Si

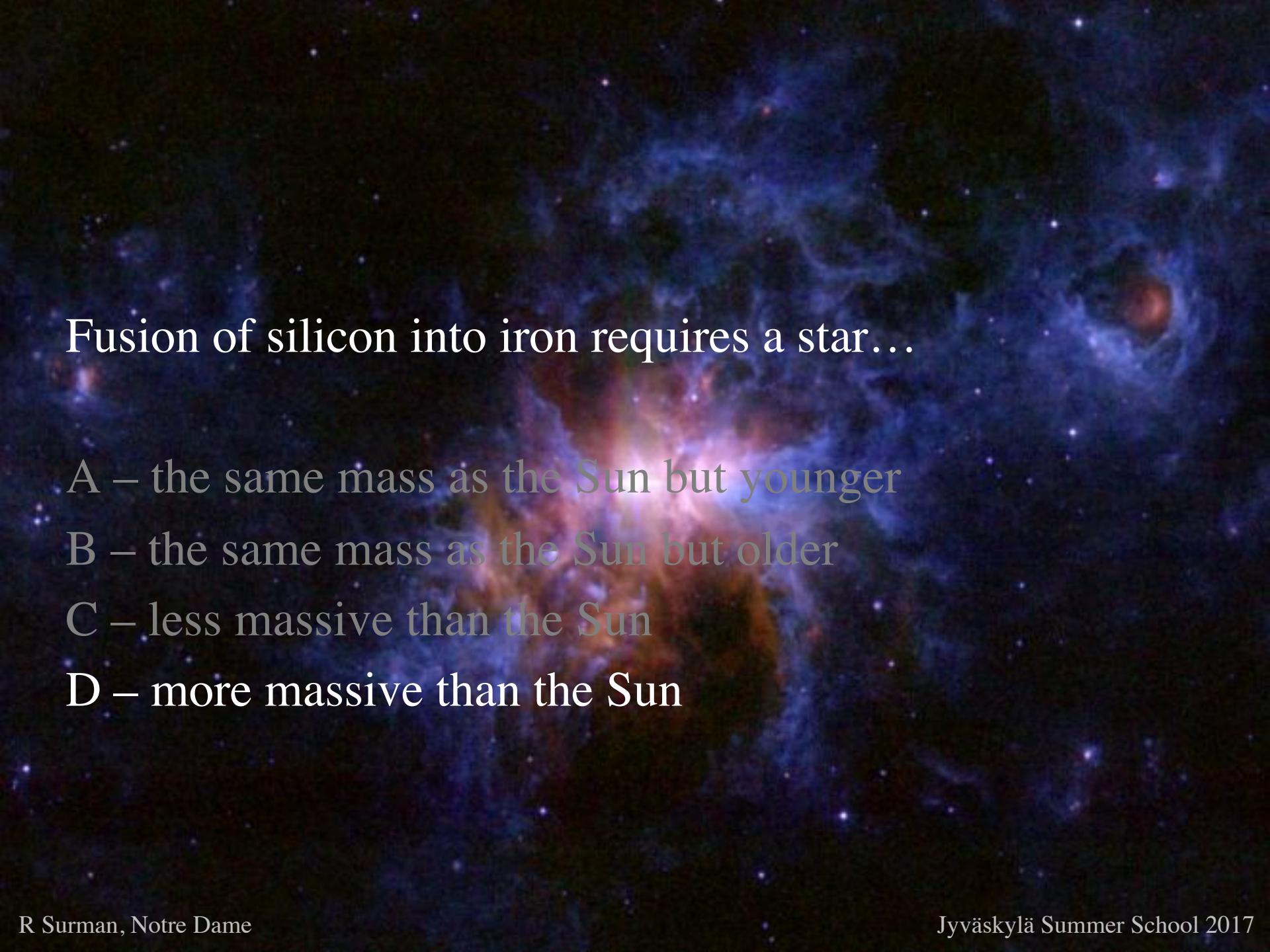
D – Si \rightarrow Fe





Fusion of silicon into iron requires a star...

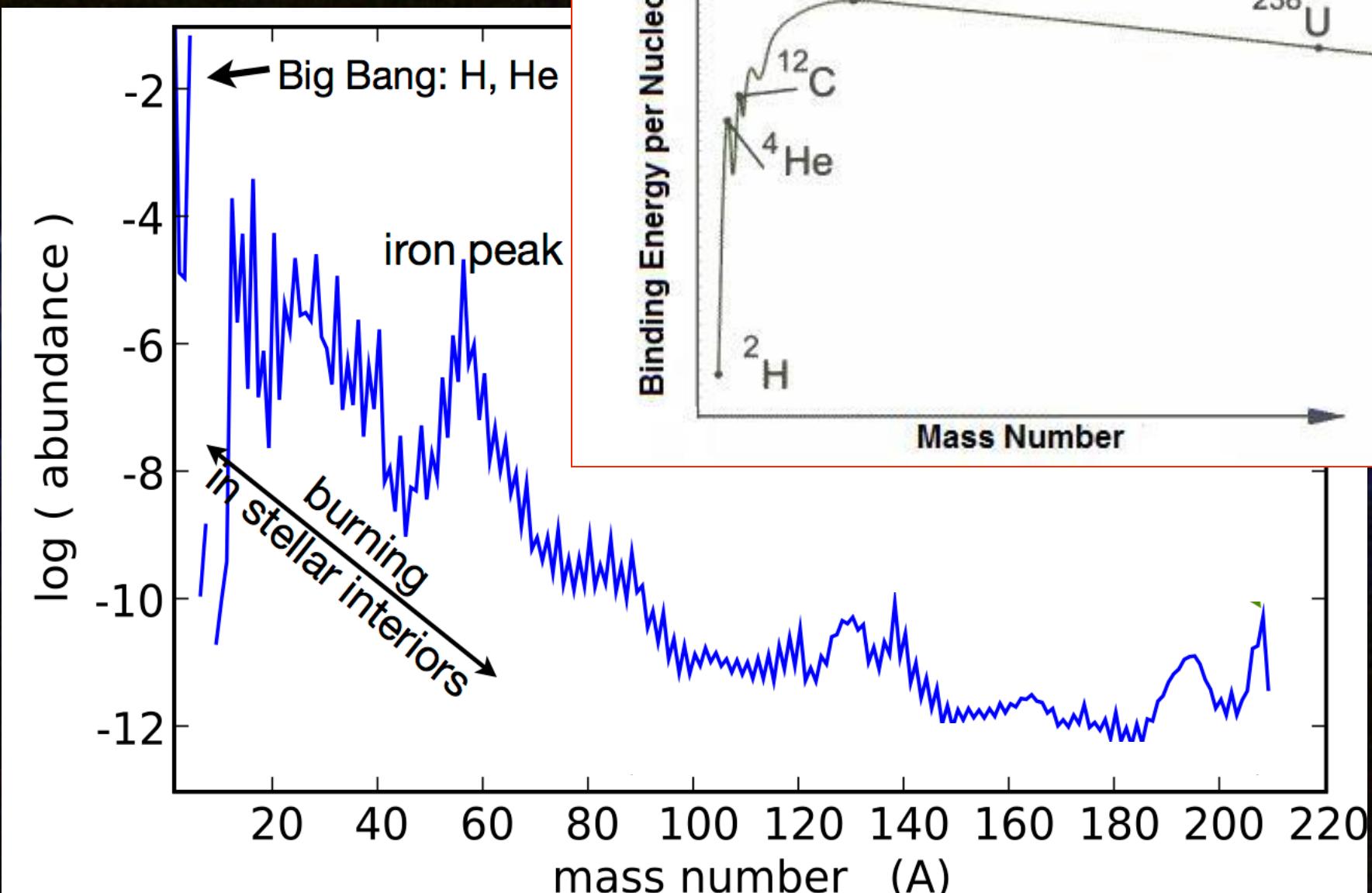
- A – the same mass as the Sun but younger
- B – the same mass as the Sun but older
- C – less massive than the Sun
- D – more massive than the Sun



Fusion of silicon into iron requires a star...

- A – the same mass as the Sun but younger
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- C – less massive than the Sun
- D – more massive than the Sun

solar system abundances



solar system abundances

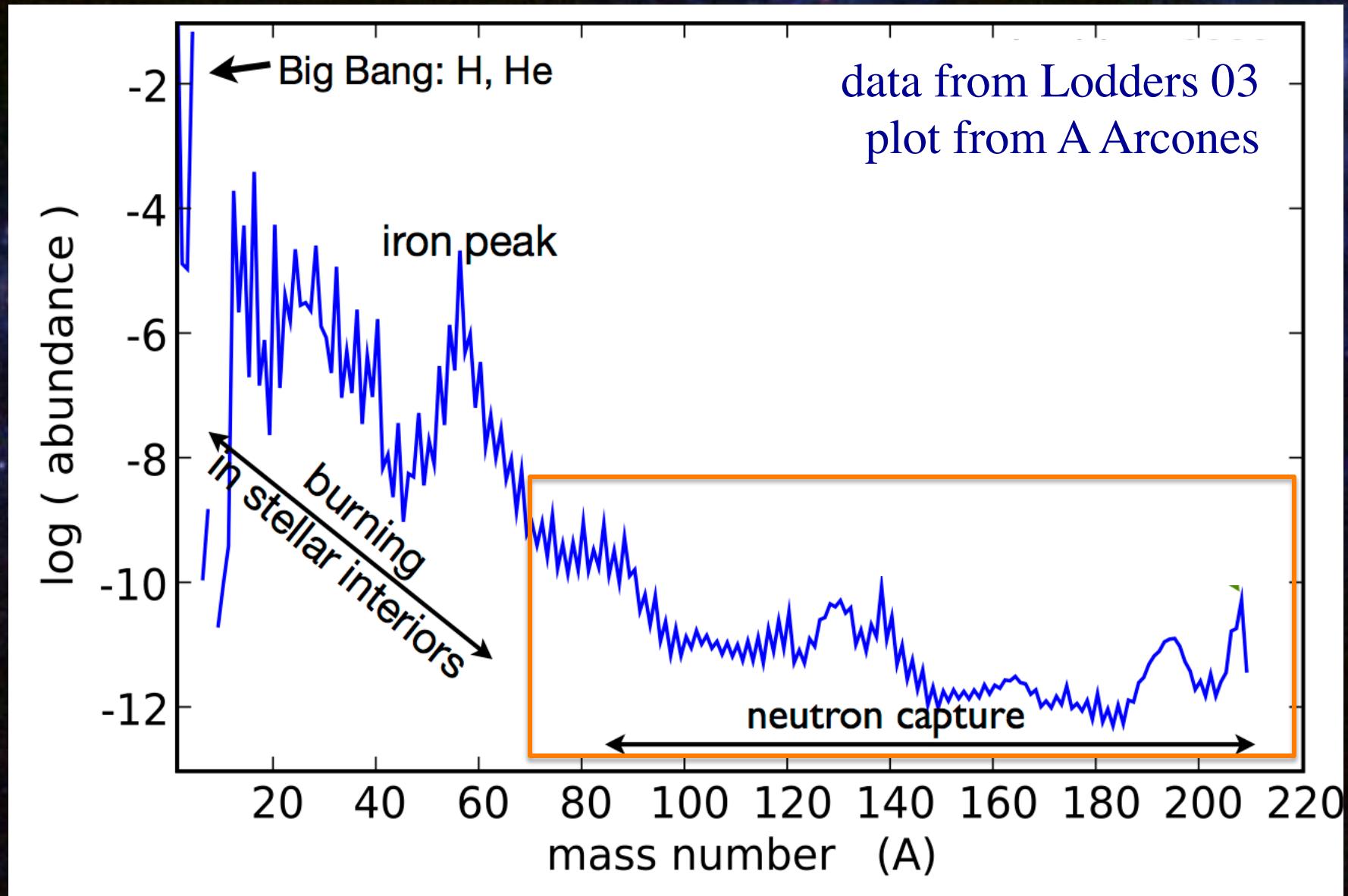
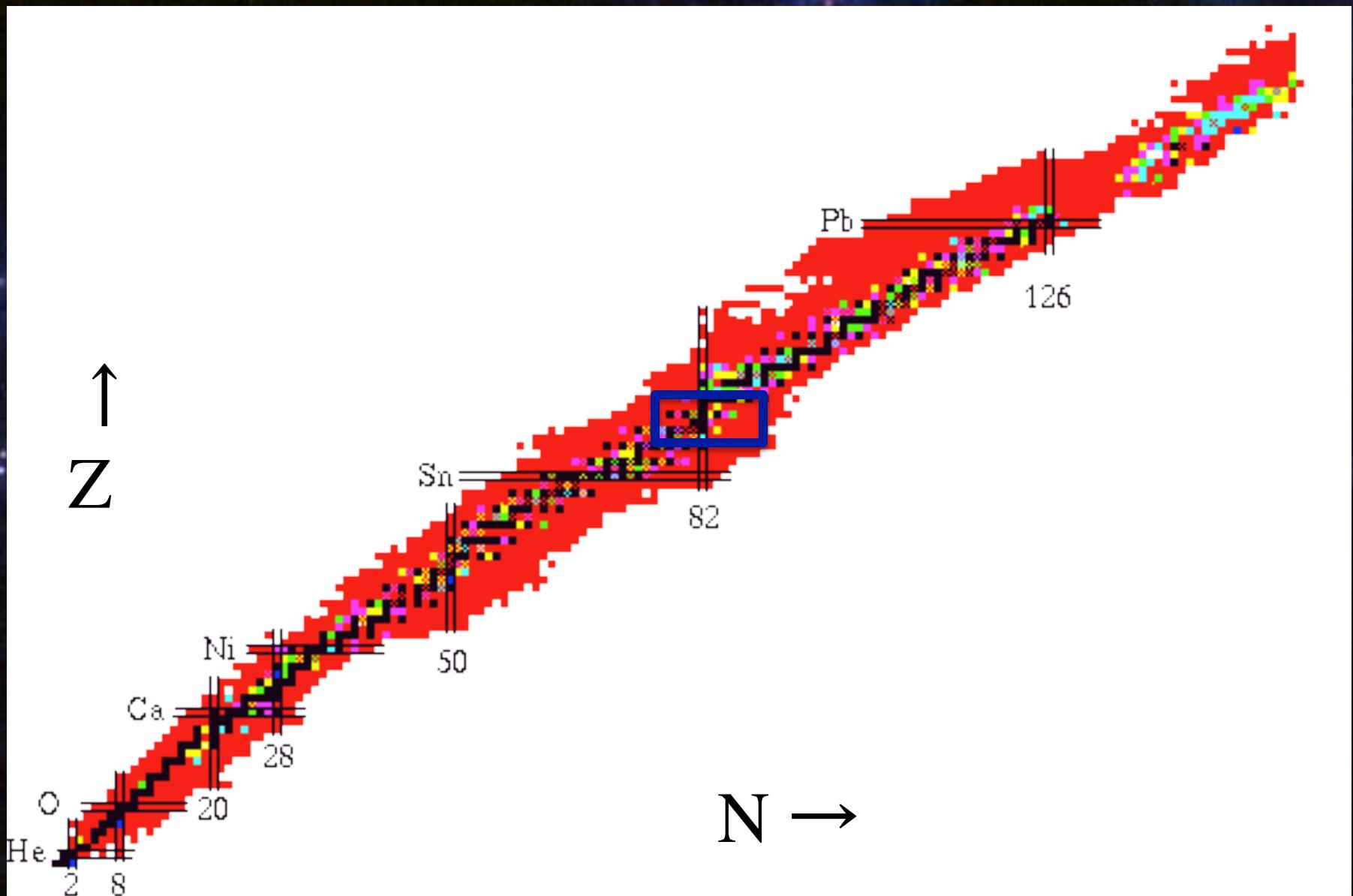


chart of the nuclides



neutron capture pathways



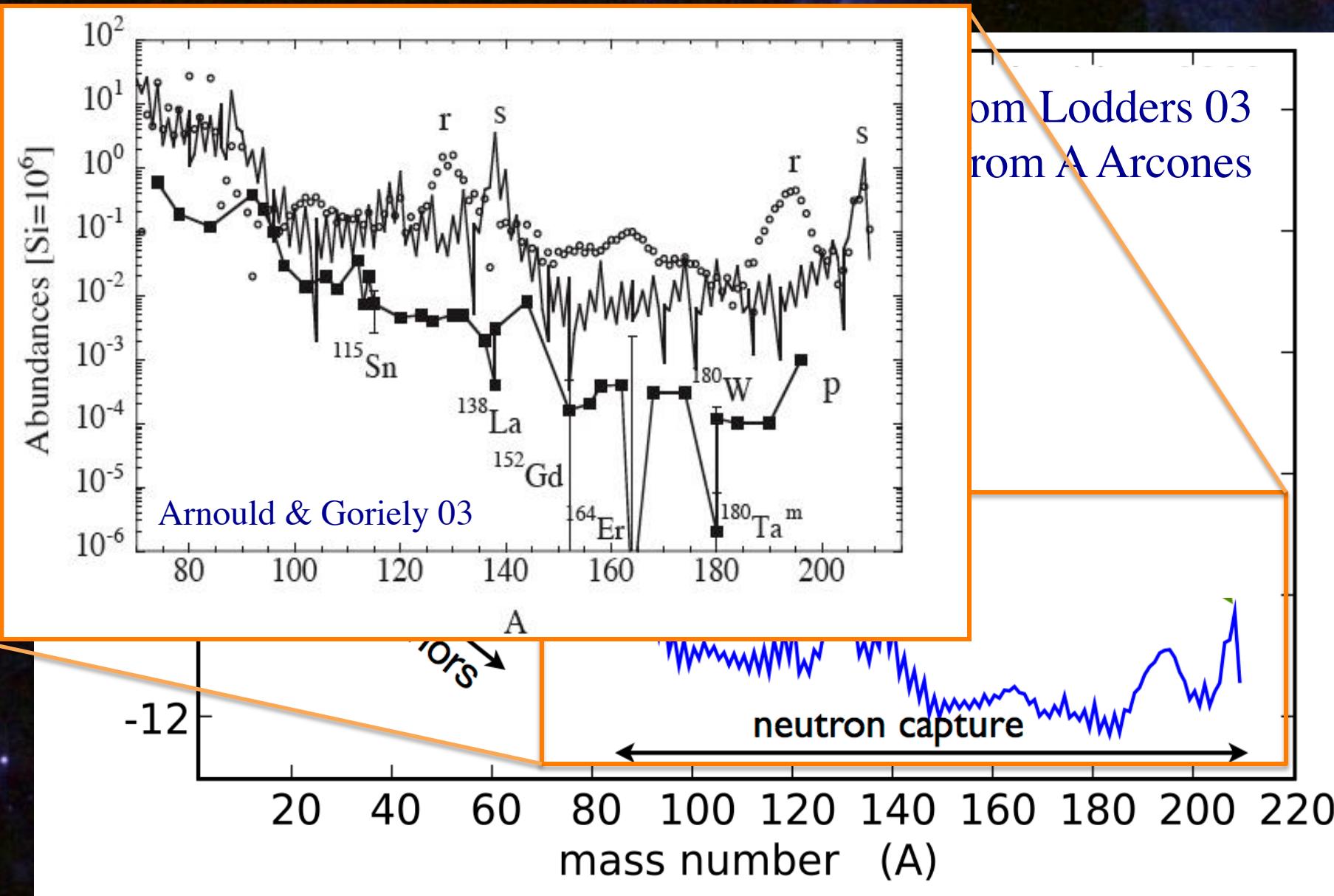
figure generated using NuDat 2.5 by C. Magee

neutron capture pathways

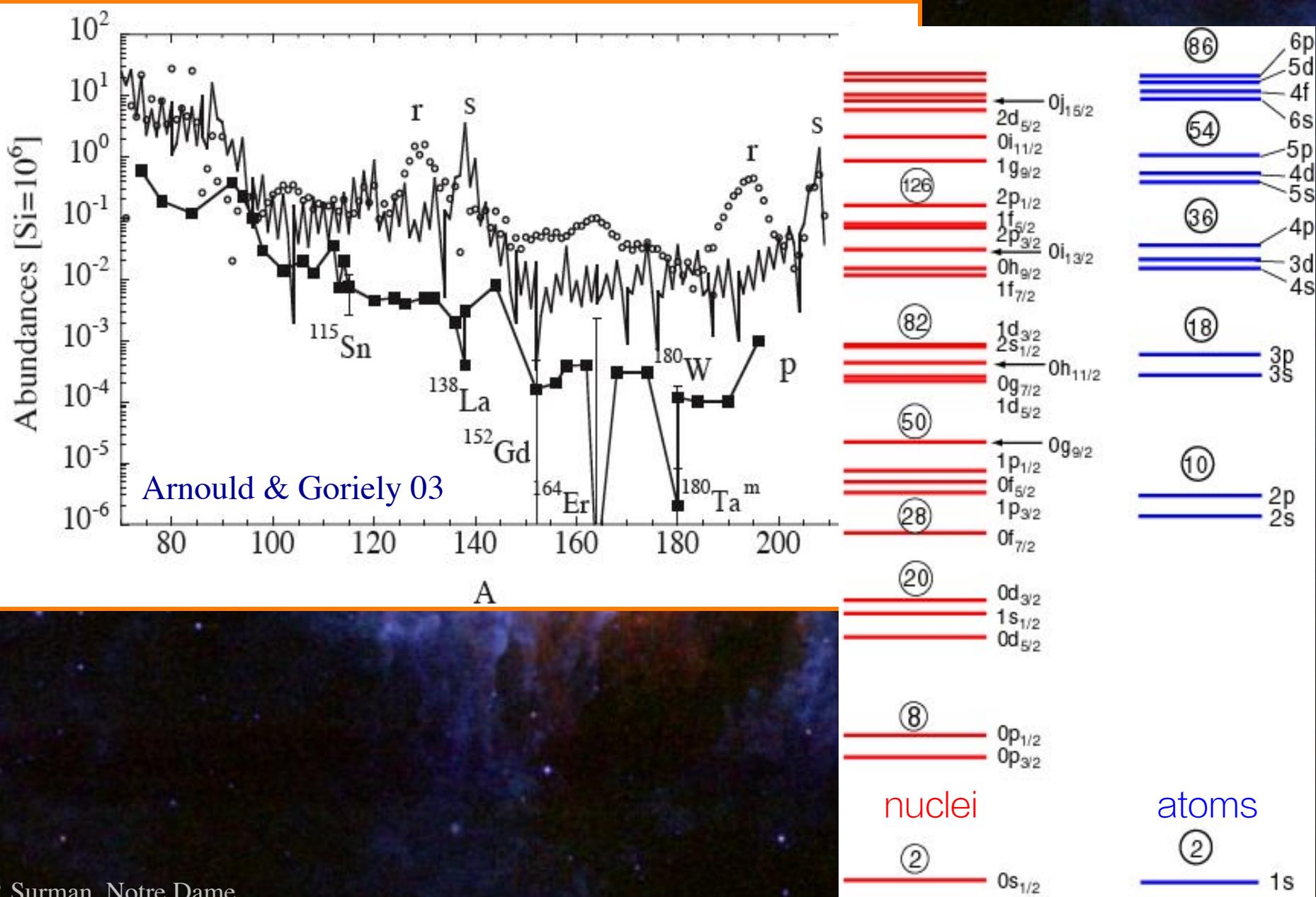


figure generated using NuDat 2.5 by C. Magee

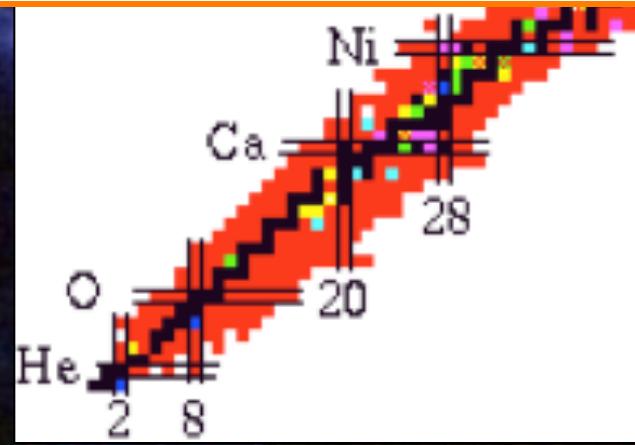
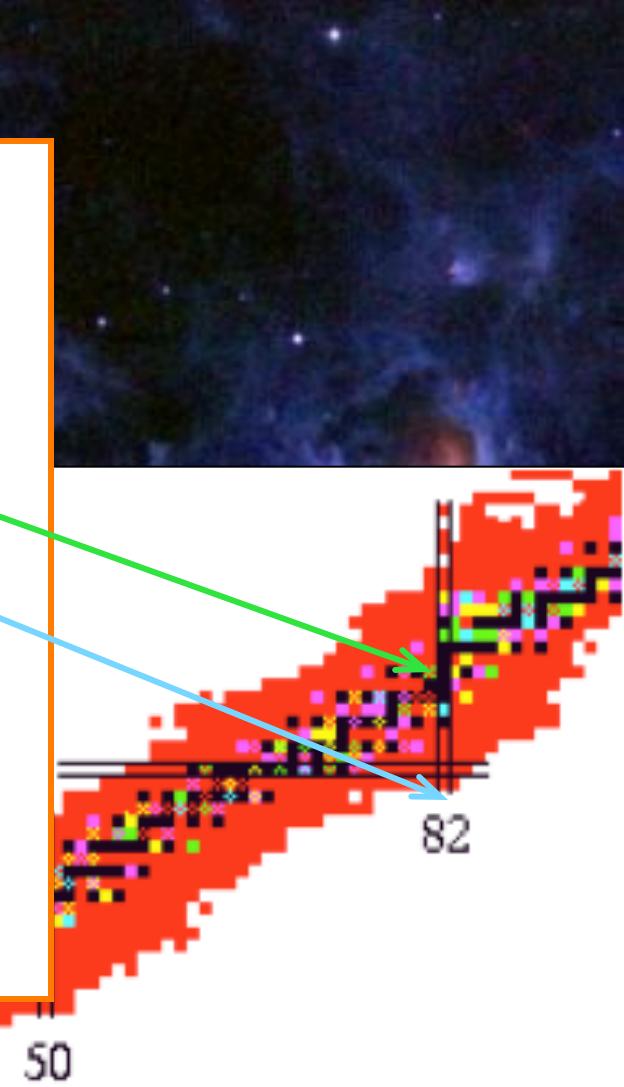
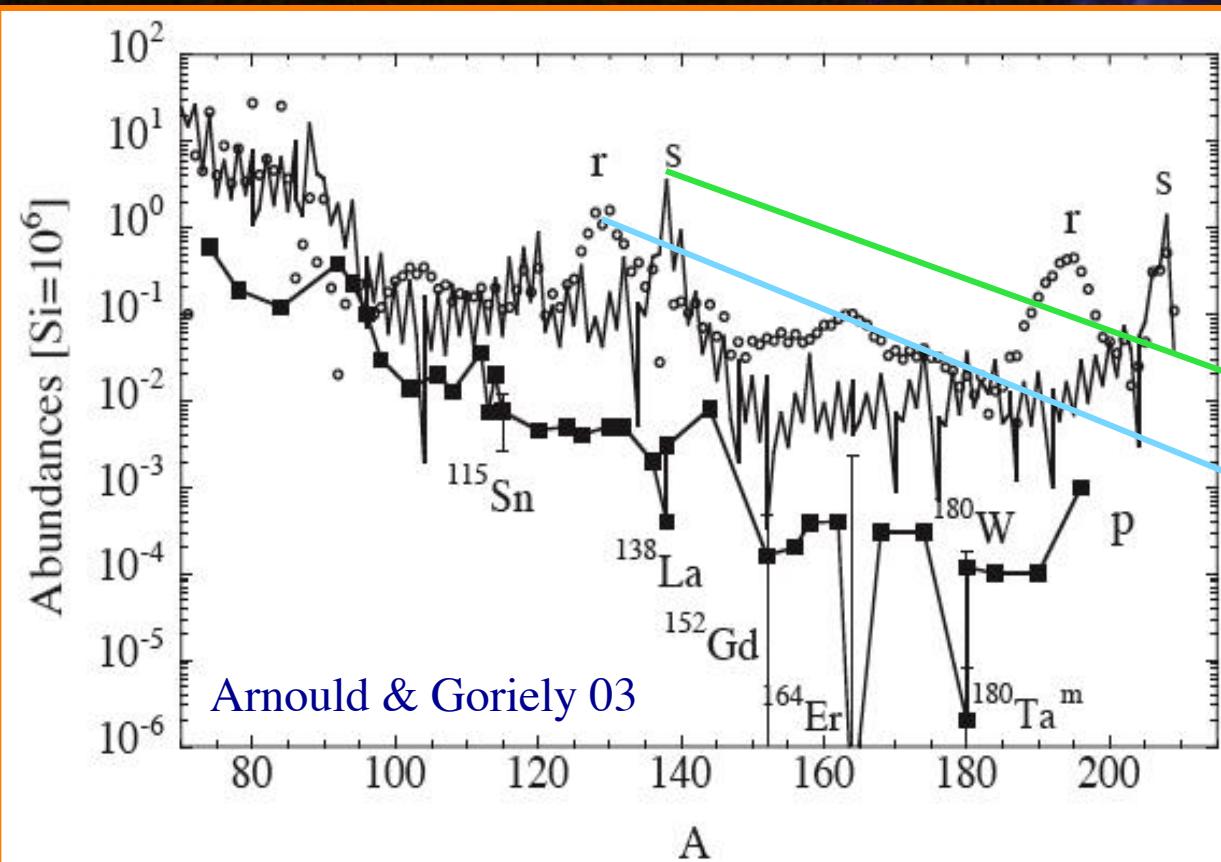
neutron capture abundances

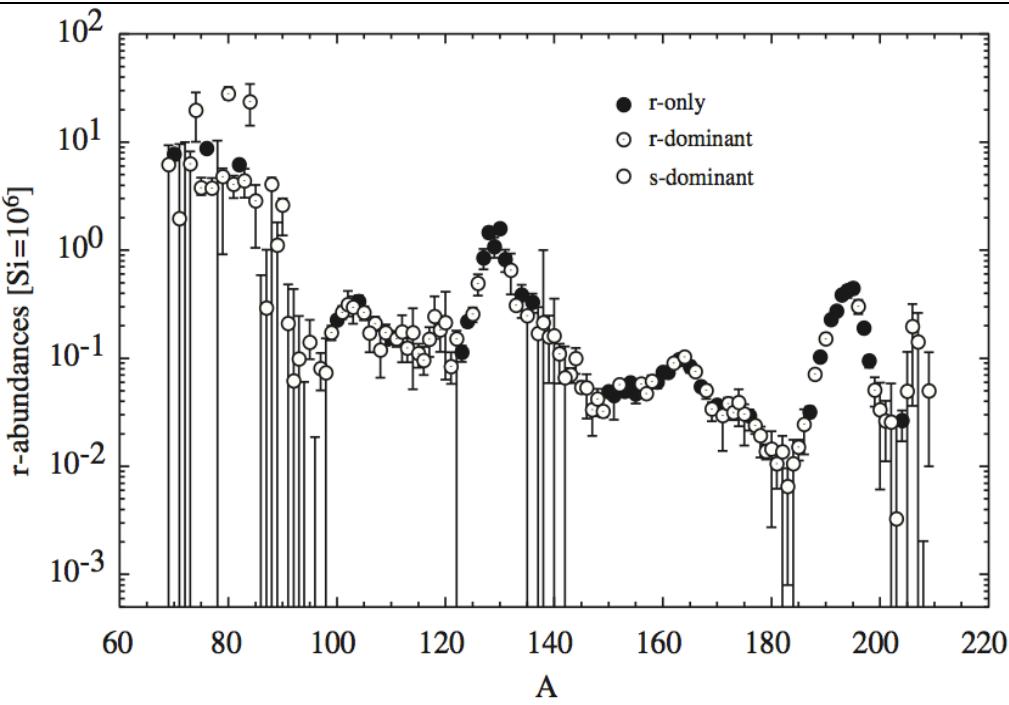


neutron capture abundances

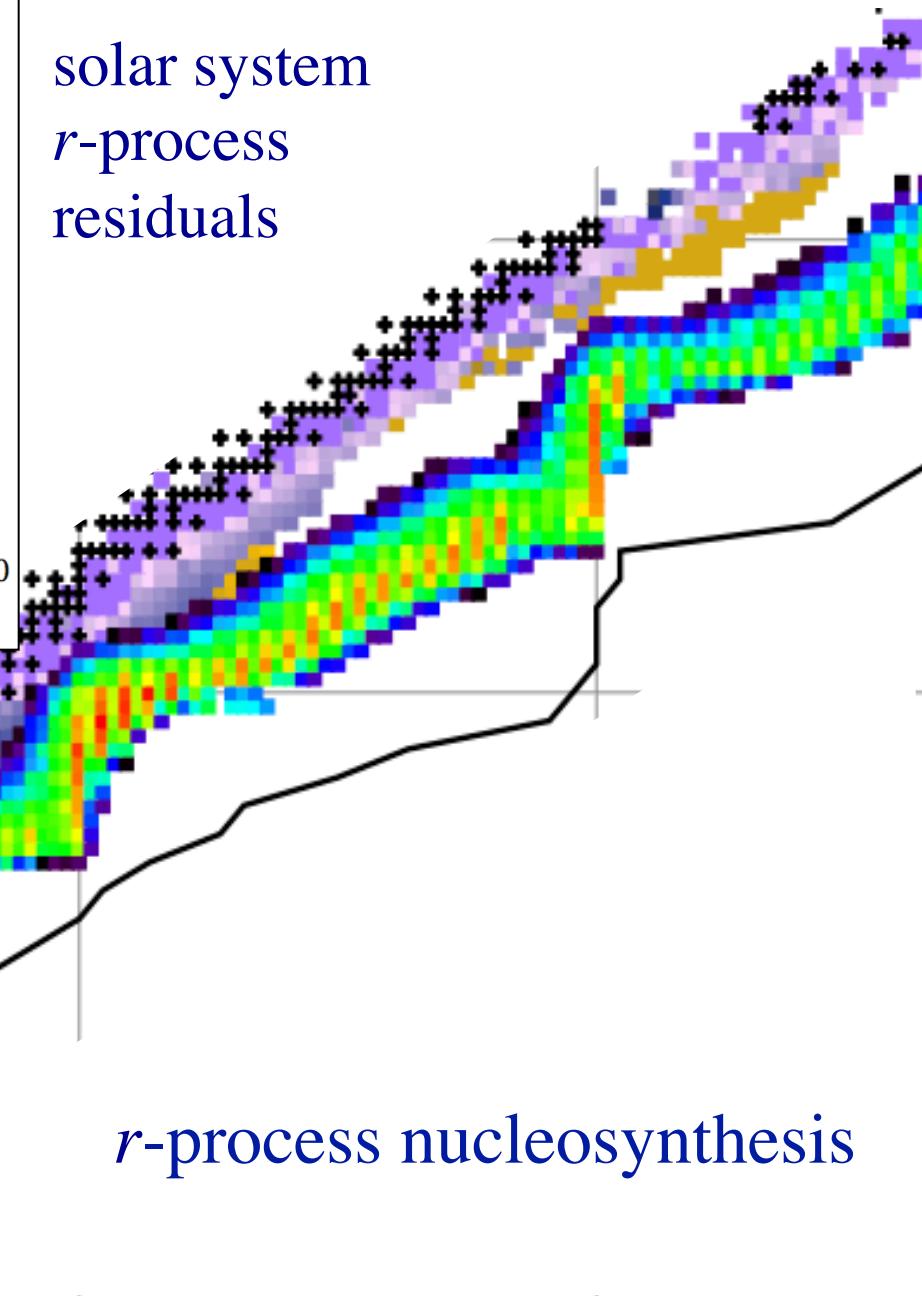


neutron capture abundances





solar system
r-process
residuals





SEARCHING FOR THE OLDEST STARS

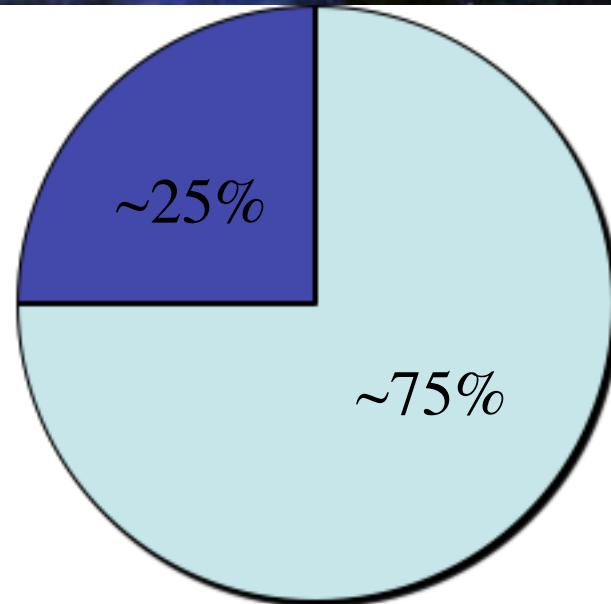
ANCIENT RELICS FROM THE EARLY UNIVERSE

Anna Frebel



stellar composition

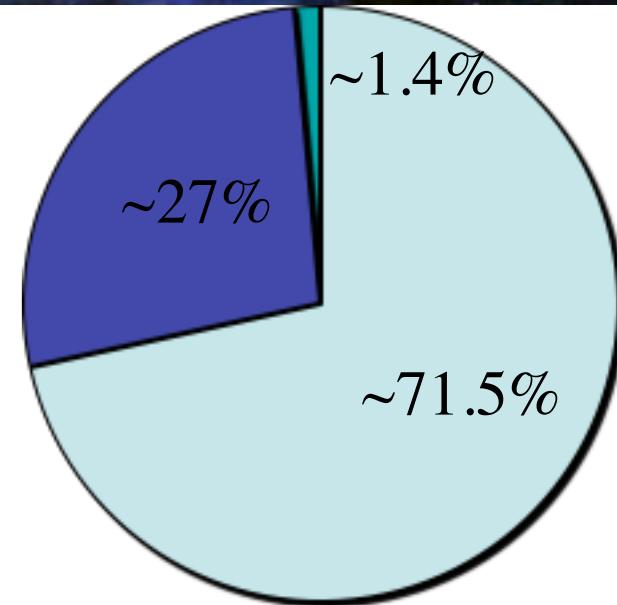
composition of
the Universe after
the Big Bang,
13.8 billion years
ago



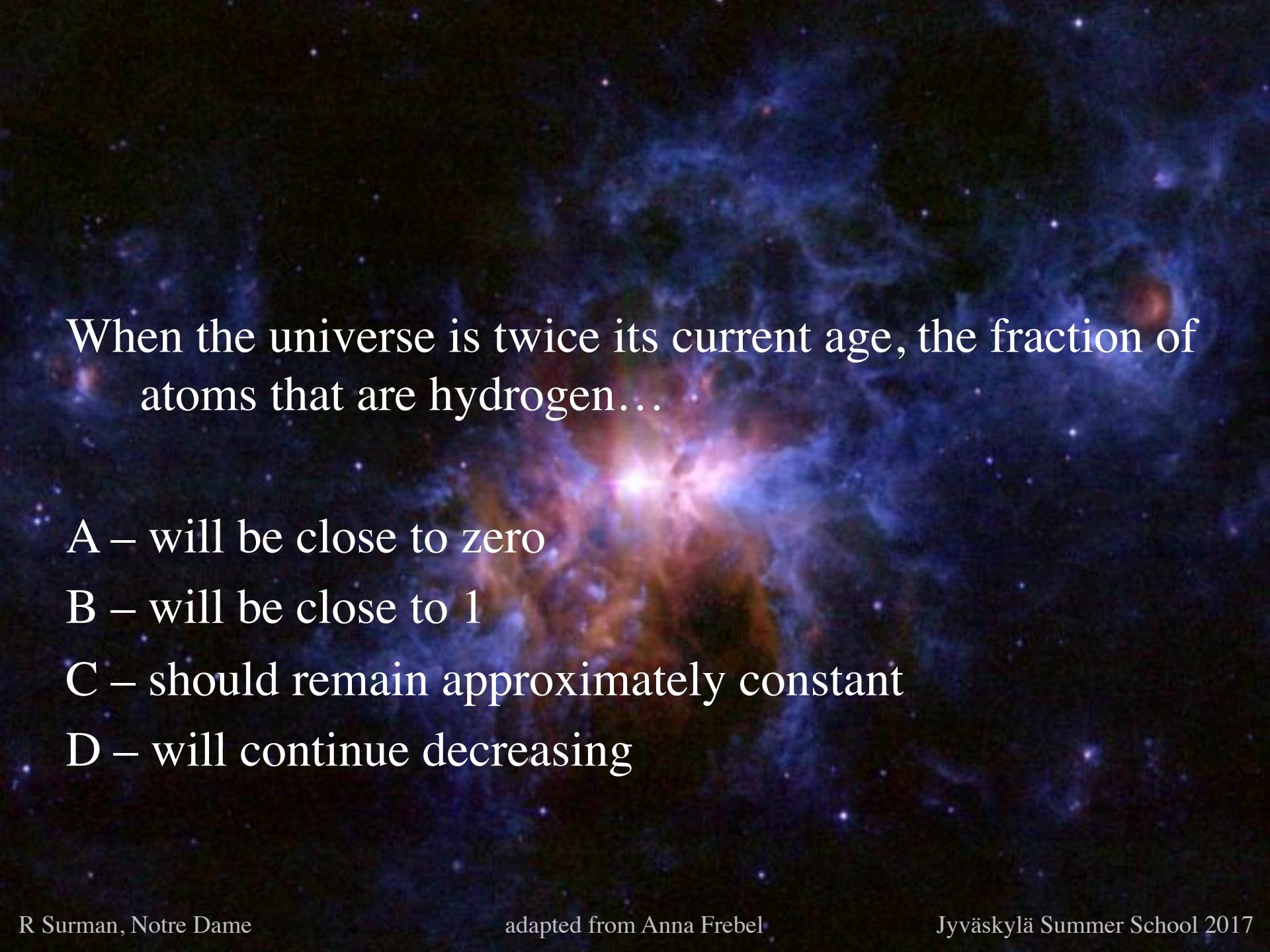
- Hydrogen
- Helium
- Heavier elements

stellar composition

composition of
the Sun, born 4.6
billion years ago

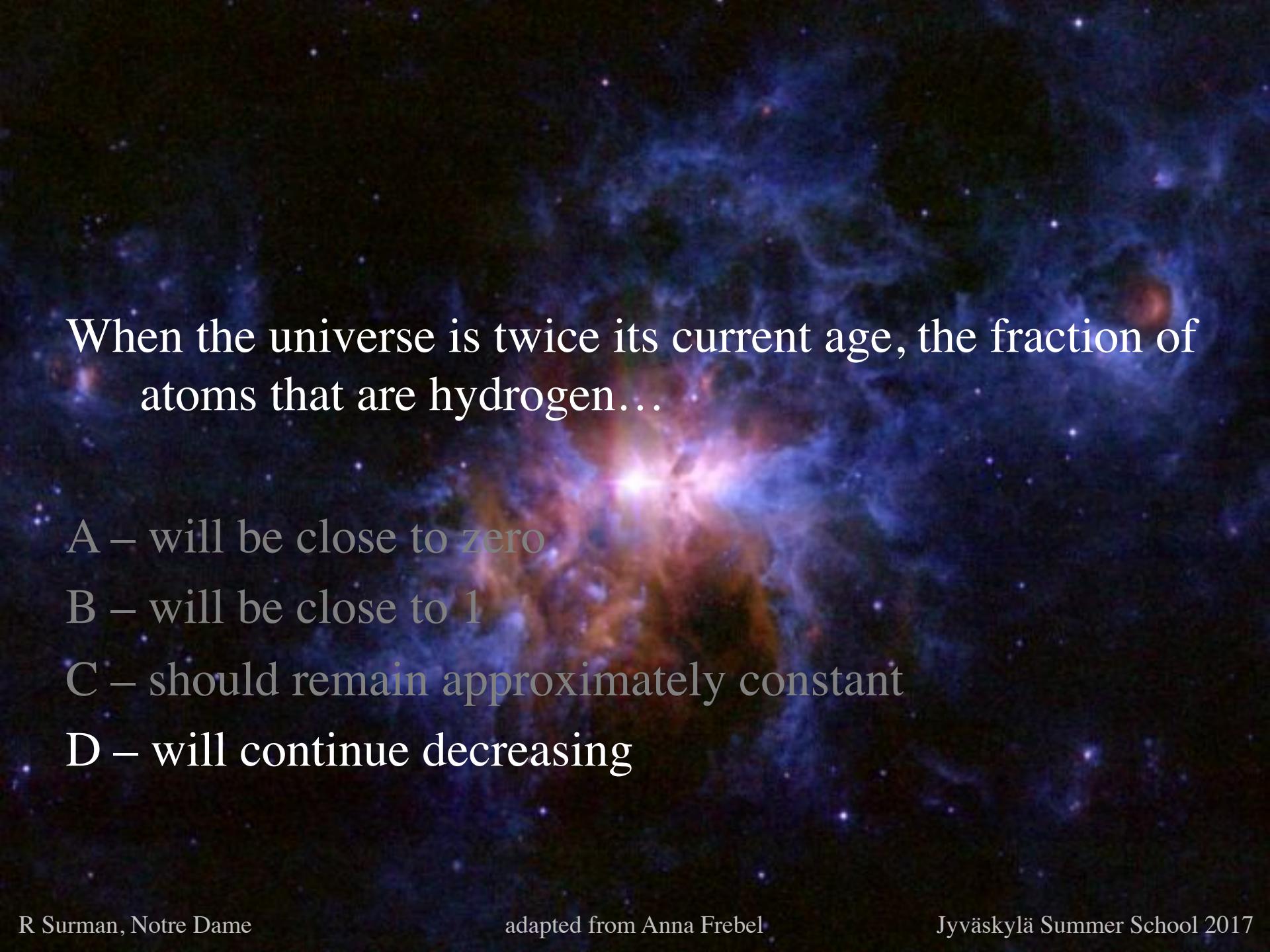


- Hydrogen
- Helium
- Heavier elements



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

- A – will be close to zero
- B – will be close to 1
- C – should remain approximately constant
- D – will continue decreasing



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- A – will be close to zero
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- C – should remain approximately constant
- D – will continue decreasing

terminology: stellar abundances

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

terminology: [Fe/H]

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

where N_{Fe} and N_{H} are the number of iron and hydrogen atoms per unit of volume, respectively.

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

$$[A/H] - [B/H] = [A/B]$$

for elements A and B.

chemical abundance determination

Example:

You measure:

$$\log \epsilon (\text{Mg})_{\text{star}} = 5.96; \quad \log \epsilon (\text{Fe})_{\text{star}} = 5.50$$

You look up:

$$\log \epsilon (\text{Mg})_{\text{sun}} = 7.60; \quad \log \epsilon (\text{Fe})_{\text{sun}} = 7.50$$

Calculate: [Mg/H] =

Calculate: [Mg/Fe] =

chemical abundance determination

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$$\log \epsilon (\text{Mg})_{\text{sun}} = 7.60; \quad \log \epsilon (\text{Fe})_{\text{sun}} = 7.50$$

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

\Rightarrow metal-poor because subsolar!

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

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

(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

Table I 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	80	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				

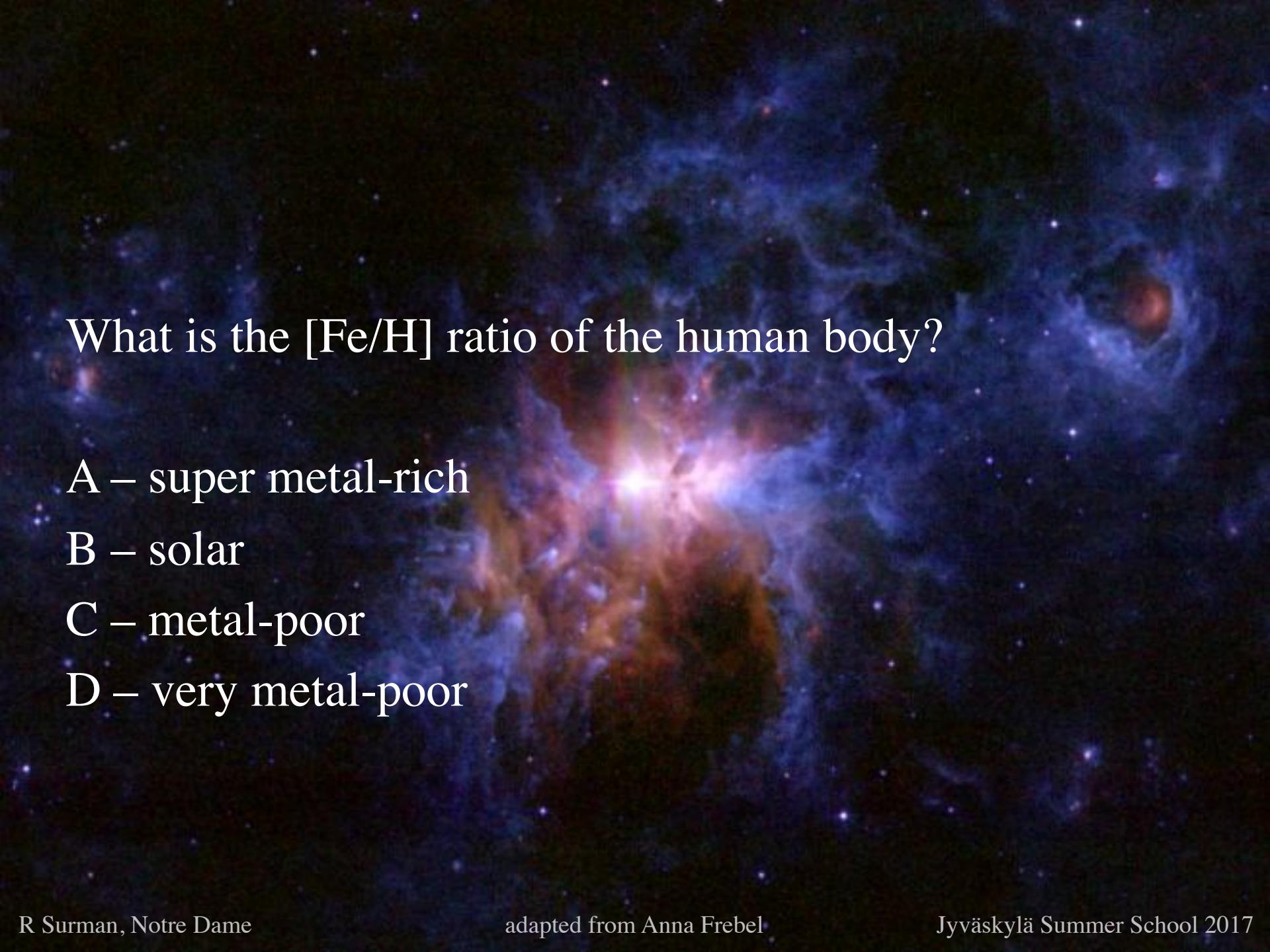
adapted from Anna Frebel

classification scheme

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

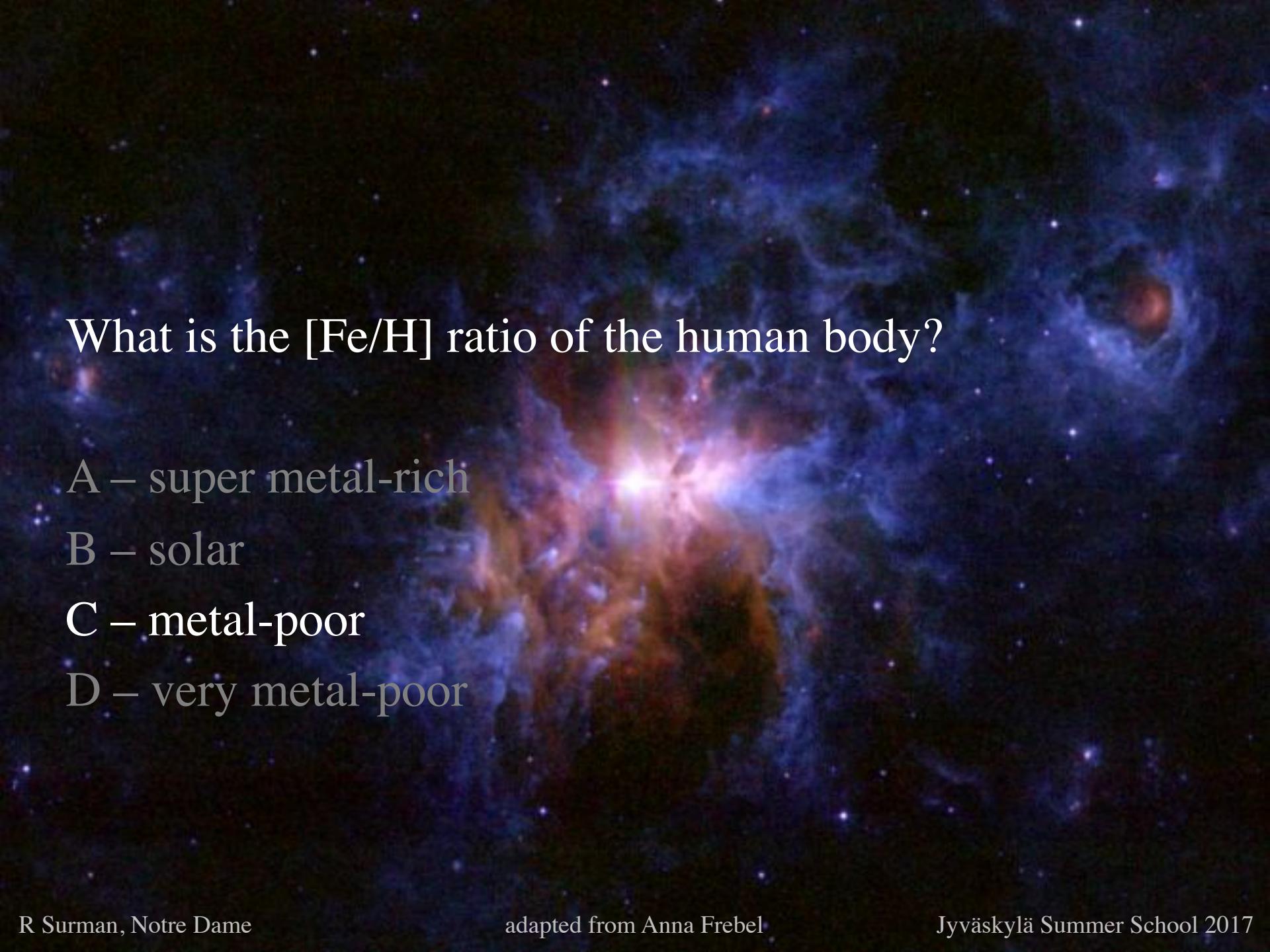
Pop III stars $[\text{Fe}/\text{H}] = -\infty$

as suggested by Beers & Christlieb 2005



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

- A – super metal-rich
- B – solar
- C – metal-poor
- D – very metal-poor



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

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Fe and Ca Abundances in a Human Being



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

human being

$$\begin{aligned} [\text{Fe}/\text{H}] &= -1.66 \\ [\text{Ca}/\text{Fe}] &= +5.88 \end{aligned}$$

$$\begin{aligned} 12 + \log(\text{O}/\text{H}) &= +11.61 \\ [\text{O}/\text{H}] &= +2.68 \\ [\text{Mg}/\text{Fe}] &= +2.40 \\ [\text{Mg}/\text{H}] &= +0.74 \\ [\text{C}/\text{H}] &= +2.62 \\ [\text{N}/\text{H}] &= +2.28 \\ [\text{Ca}/\text{H}] &= +4.22 \\ [\text{P}/\text{H}] &= +4.06 \\ [\text{K}/\text{H}] &= +3.84 \\ [\text{S}/\text{H}] &= +1.69 \\ [\text{Na}/\text{H}] &= +2.49 \\ [\text{Cl}/\text{H}] &= +3.13 \\ [\text{Li}/\text{H}] &= +2.99 \end{aligned}$$

chemical evolution

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

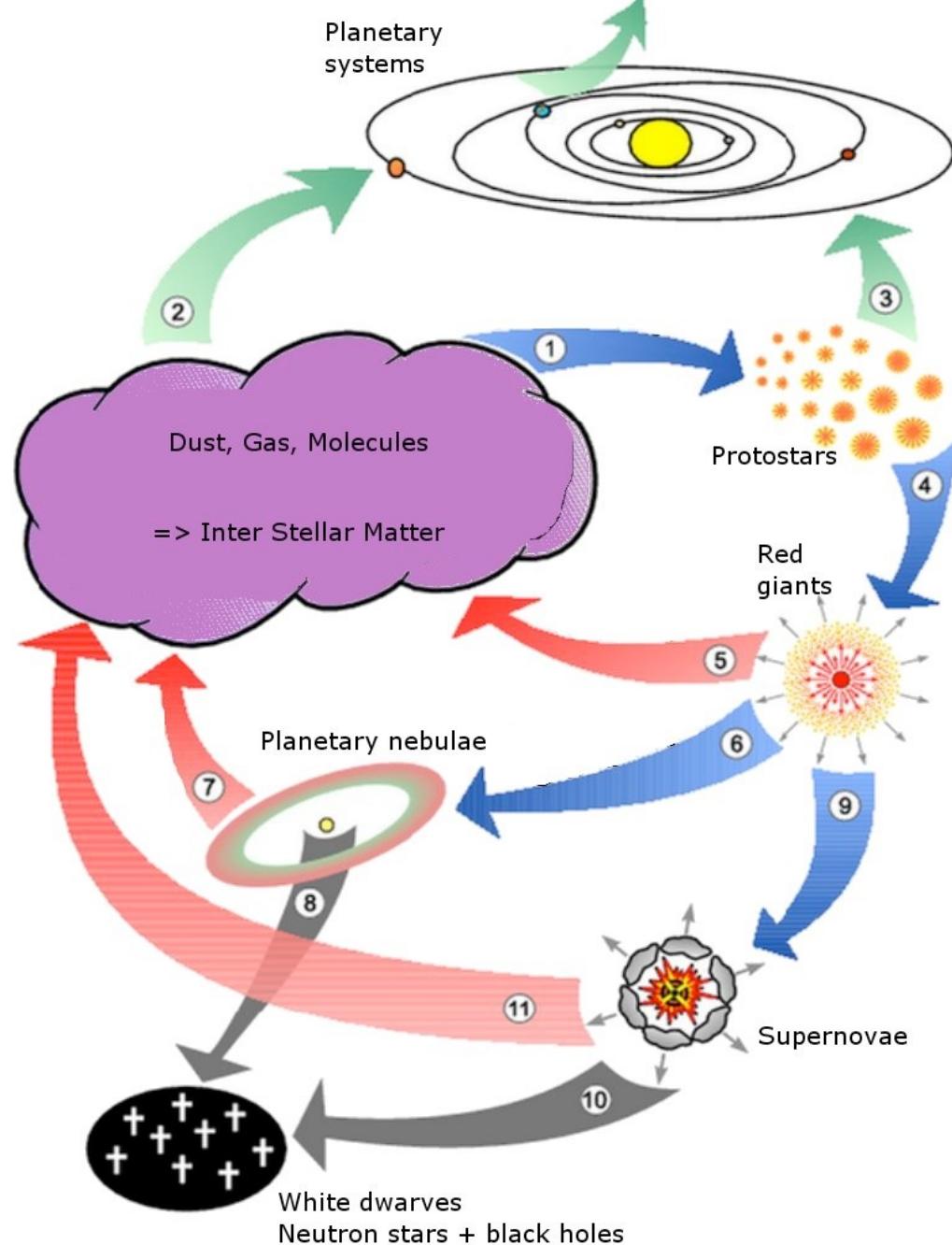
Early stars contain little of all elements

Younger stars contain larger amounts

Examples:

Sun: contains 1.4 % heavy elements
(by mass)

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



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: $10^6 M_{\text{sun}}$ =>

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

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: $10^6 M_{\text{sun}}$ =>

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

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

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

$$[\text{Fe}/\text{H}] = \log_{10} \left(\frac{N_{Fe}}{N_H} \right)_{\text{star}} - \log_{10} \left(\frac{N_{Fe}}{N_H} \right)_{\text{sun}} \quad \frac{N_{Fe}}{N_H} = \frac{0.1 M_{\text{sun}}}{56 m_H} \times \frac{m_H}{10^6 M_{\text{sun}}} = \frac{10^{-7}}{56}$$

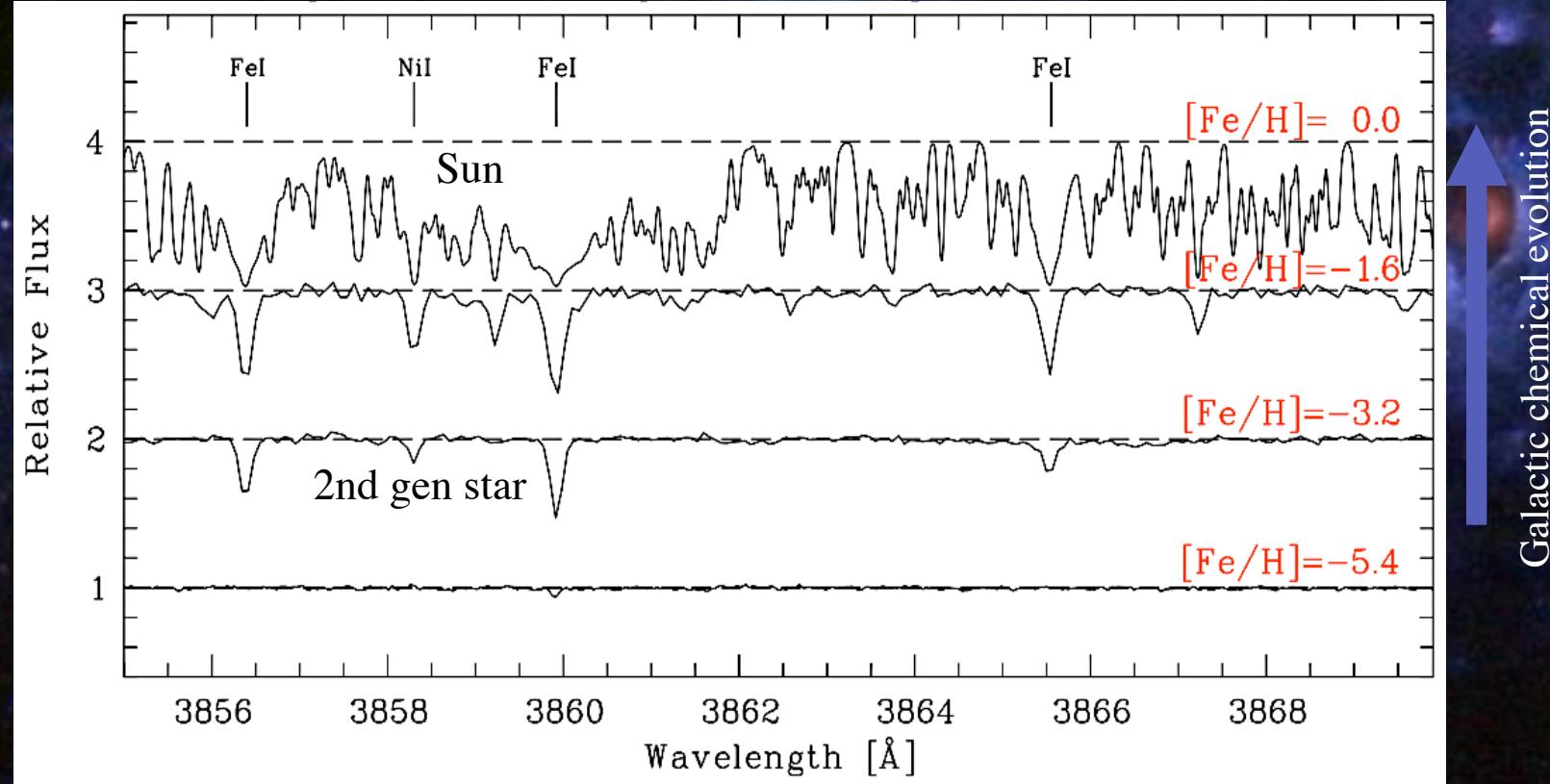
$$\log \epsilon(Fe)_{\text{sun}} = \log(N_{Fe} / N_H) + 12 = 7.50 \quad (\text{from Table})$$

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

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

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

chemical evolution



Abundances are derived from
integrated absorption line strengths

chemical evolution

