Nuclear properties and the astrophysical *r* process

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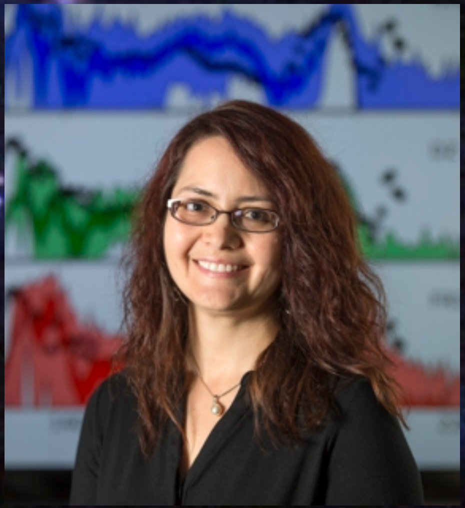

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FIRE

Fission In R-process Elements

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

Theory Alliance

FACILITY FOR RARE ISOTOPE BEAMS

JINA-CEE

Center for the Evolution of the Elements

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

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

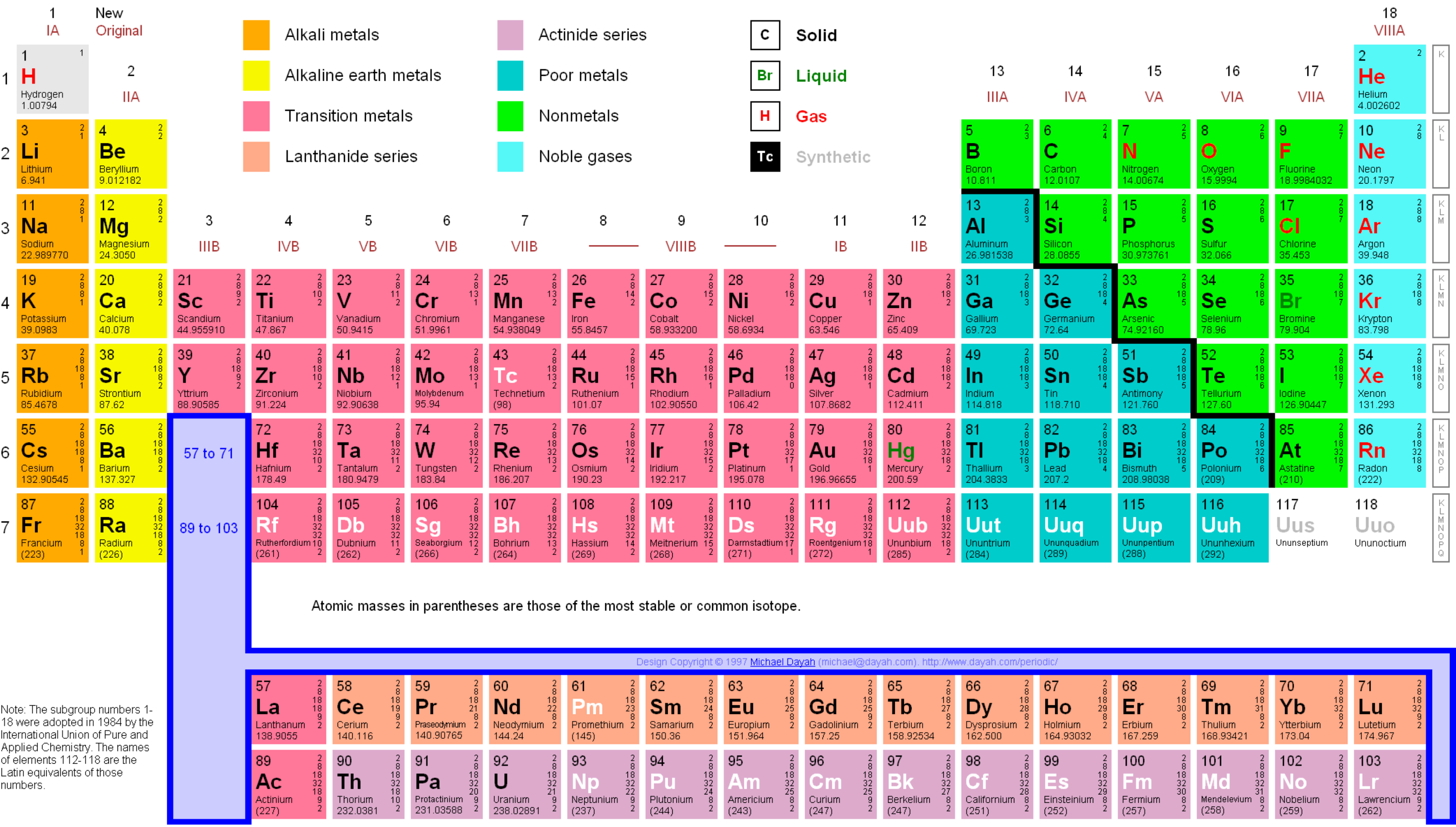
D – other

Nuclear properties and the astrophysical *r* process

What is the astrophysical origin of the heaviest elements??

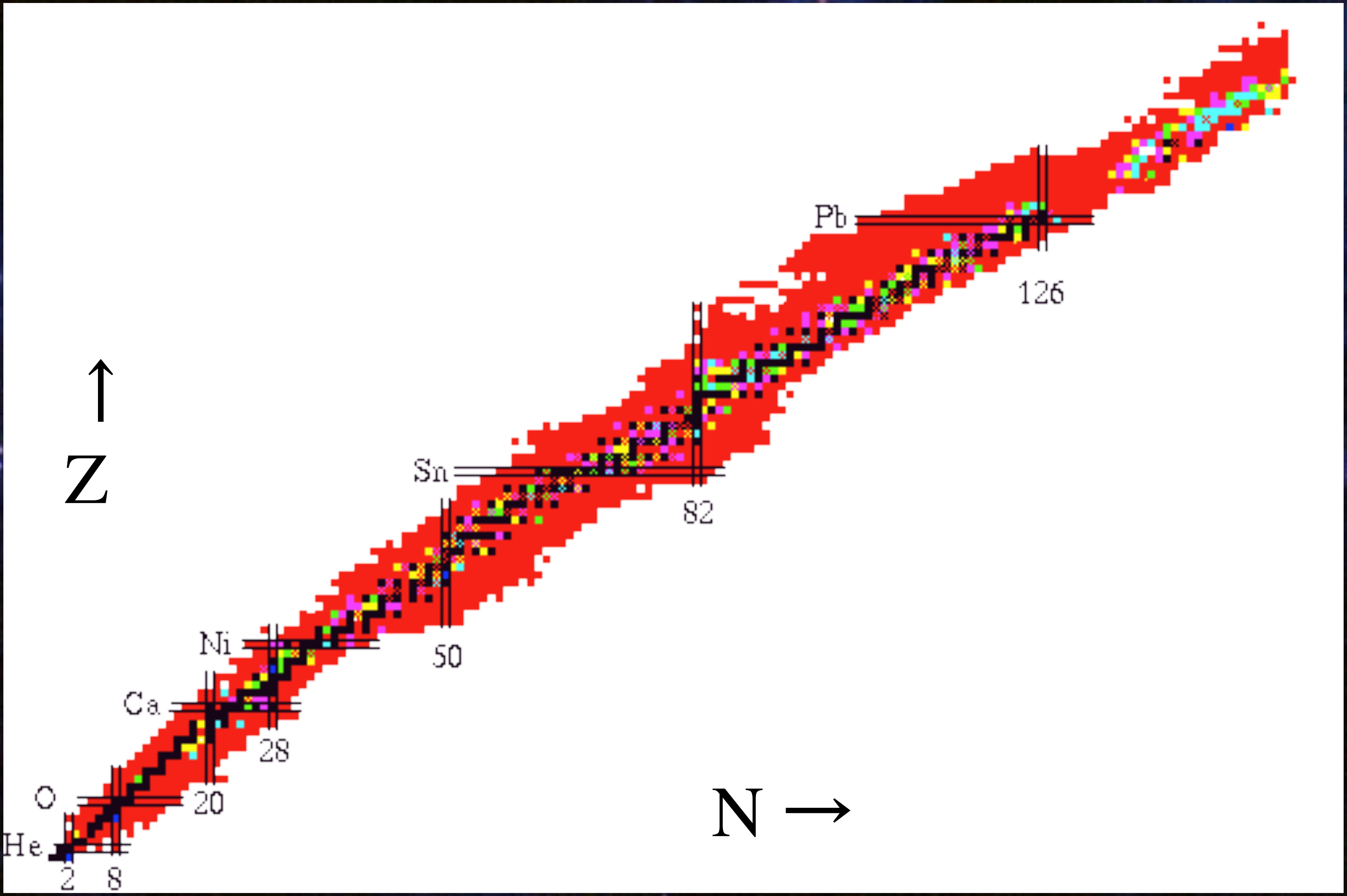
Class #	Subject
1	Introduction, chemical abundances
2	Origins of the elements up to the iron peak
3	Neutron capture nucleosynthesis, *r*-process dynamics
4	The r process: nuclear masses and lifetimes
5	The r process: neutron capture rates and fission

periodic table

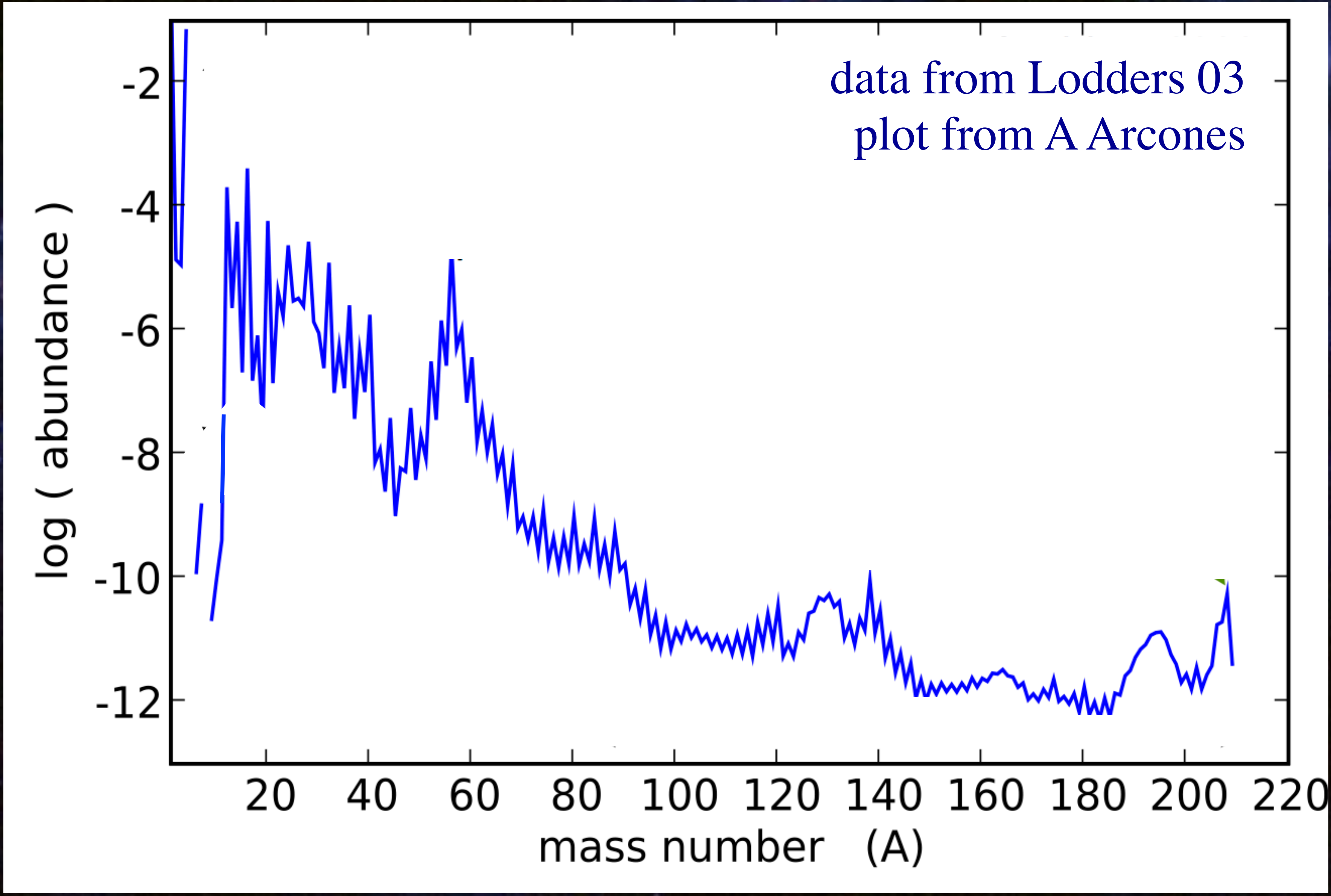


http://www.dayah.com/periodic/Images/periodic%20table.png

chart of the nuclides



solar system abundances



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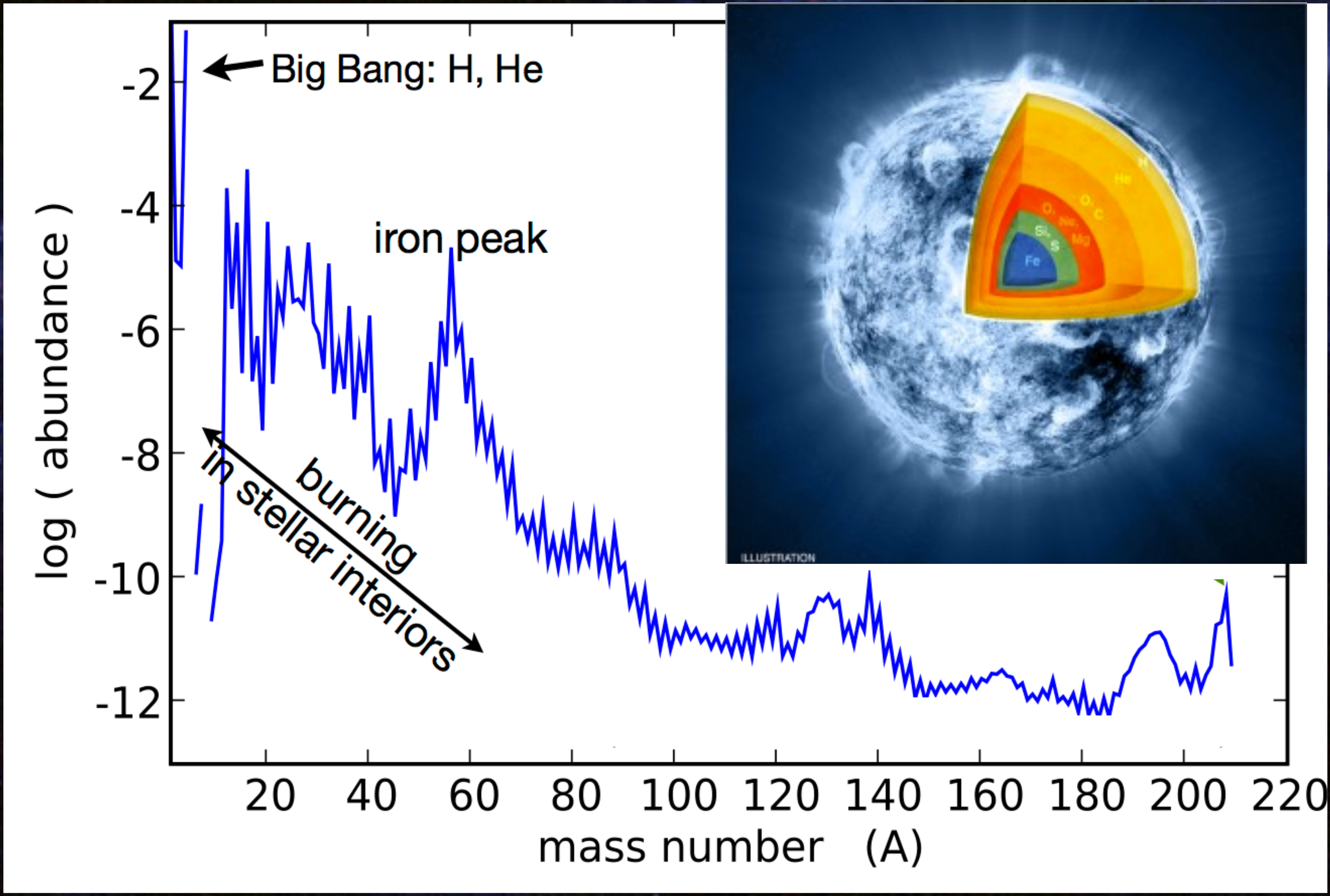

The Sun is currently powered by what fusion reactions?

A – H -> He

B – He -> C, O

C – C,O -> Si

D – Si -> Fe

The Sun is currently powered by w

A – H -> He

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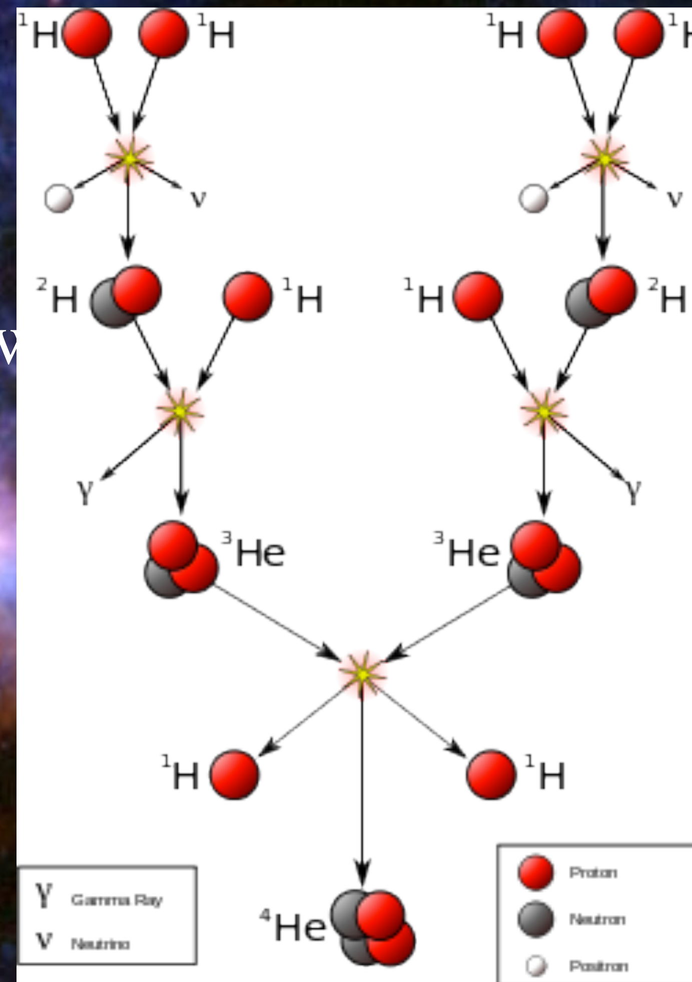

How far will fusion eventually proceed in the Sun's core?

A – H -> He

B – He -> C, O

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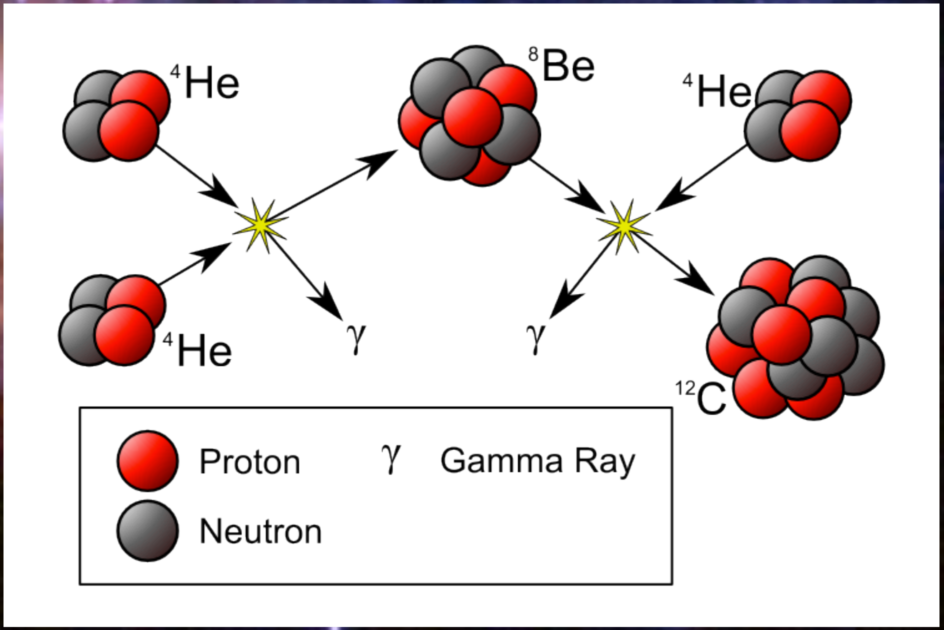

Fusion of silicon into iron requires a star…

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

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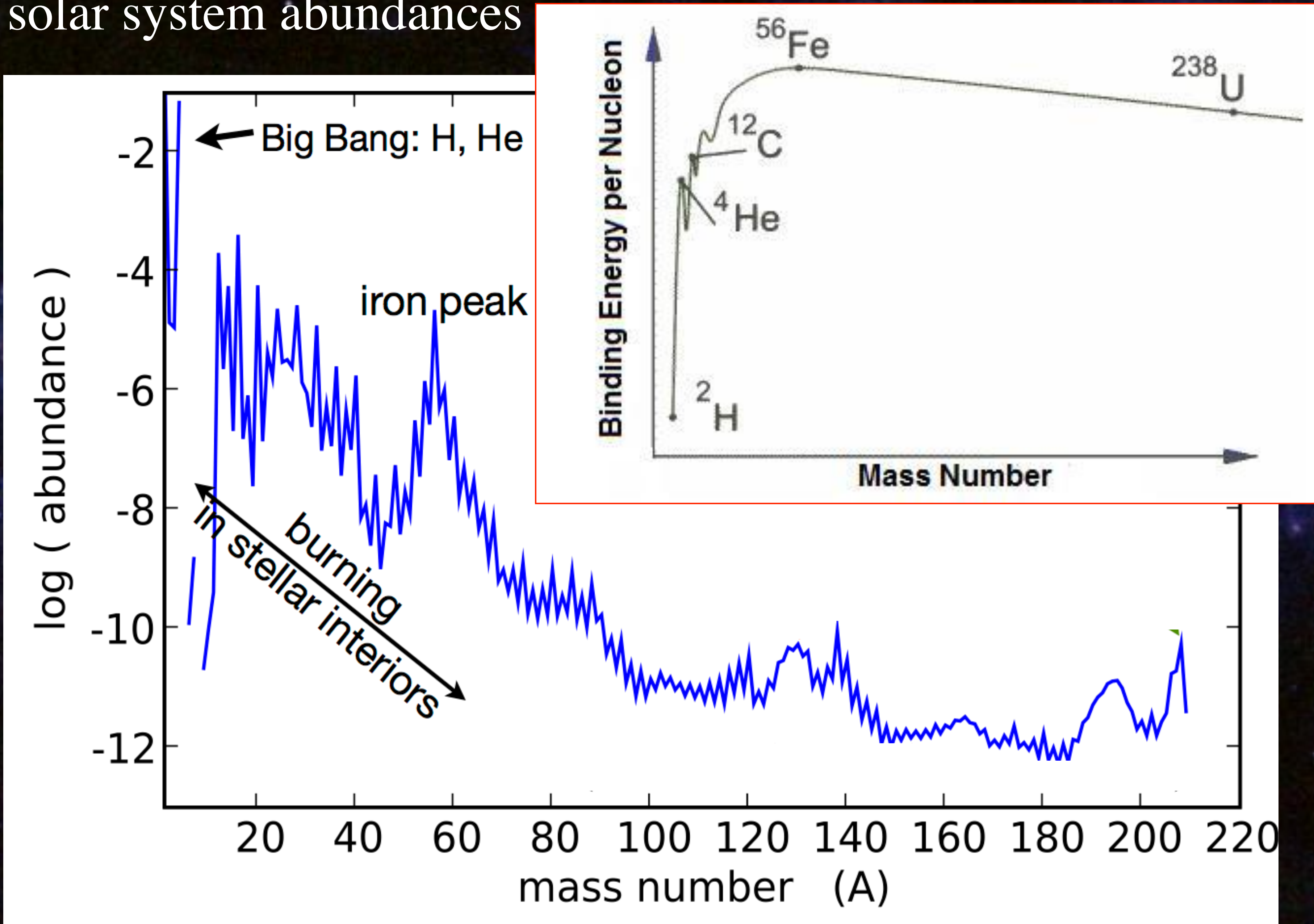


solar system abundances

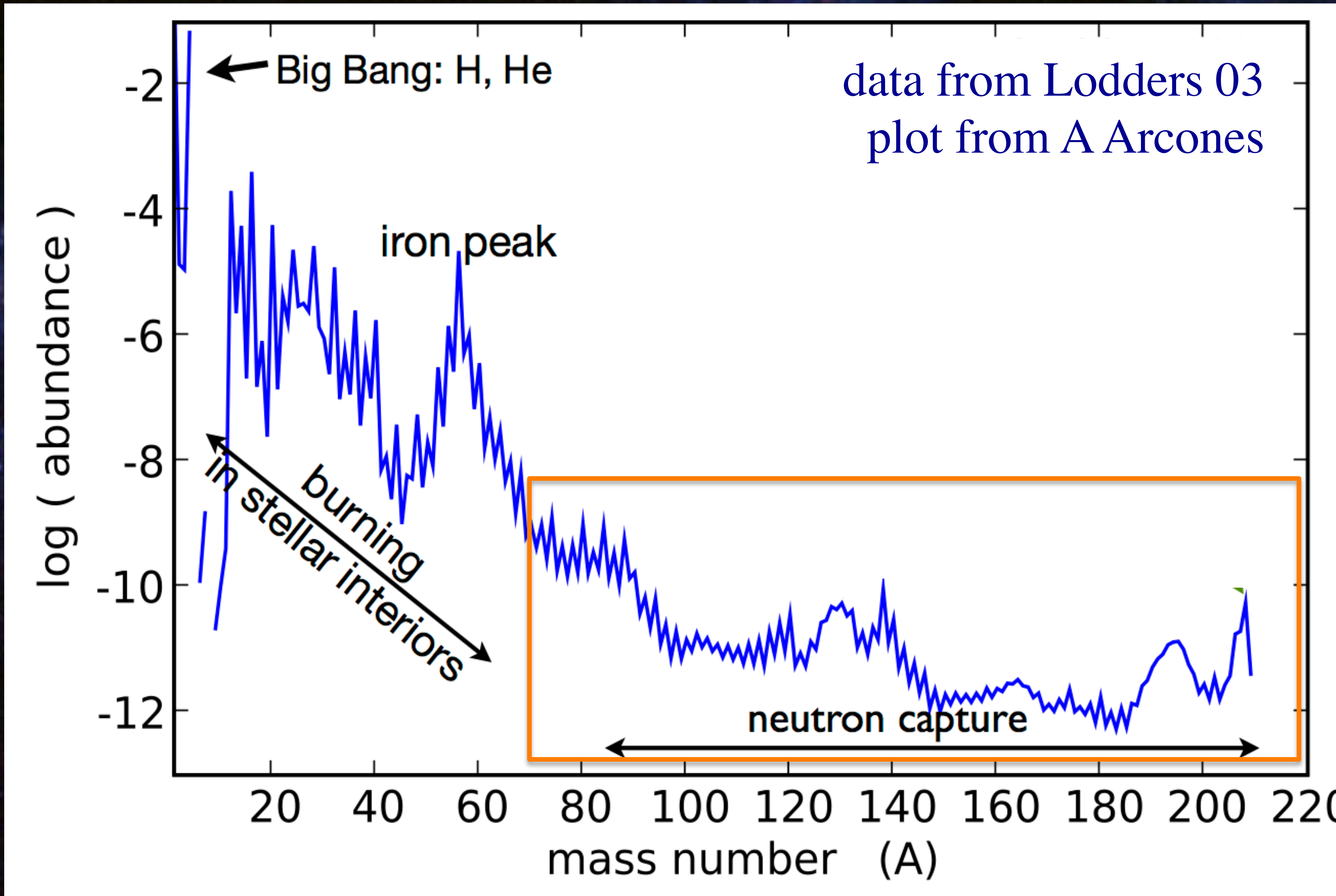
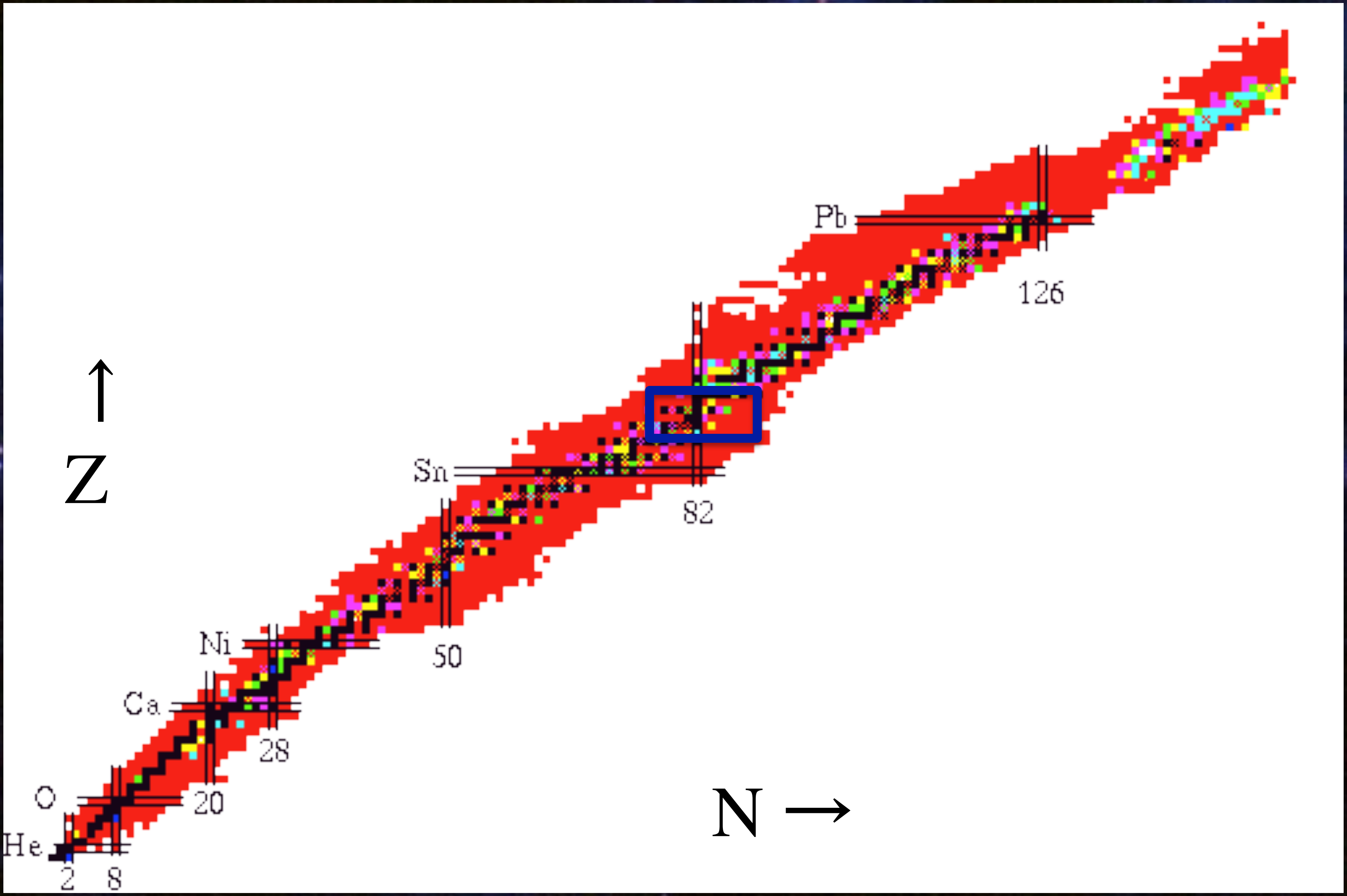


chart of the nuclides



neutron capture pathways

figure generated using NuDat 2.5 by C. Magee

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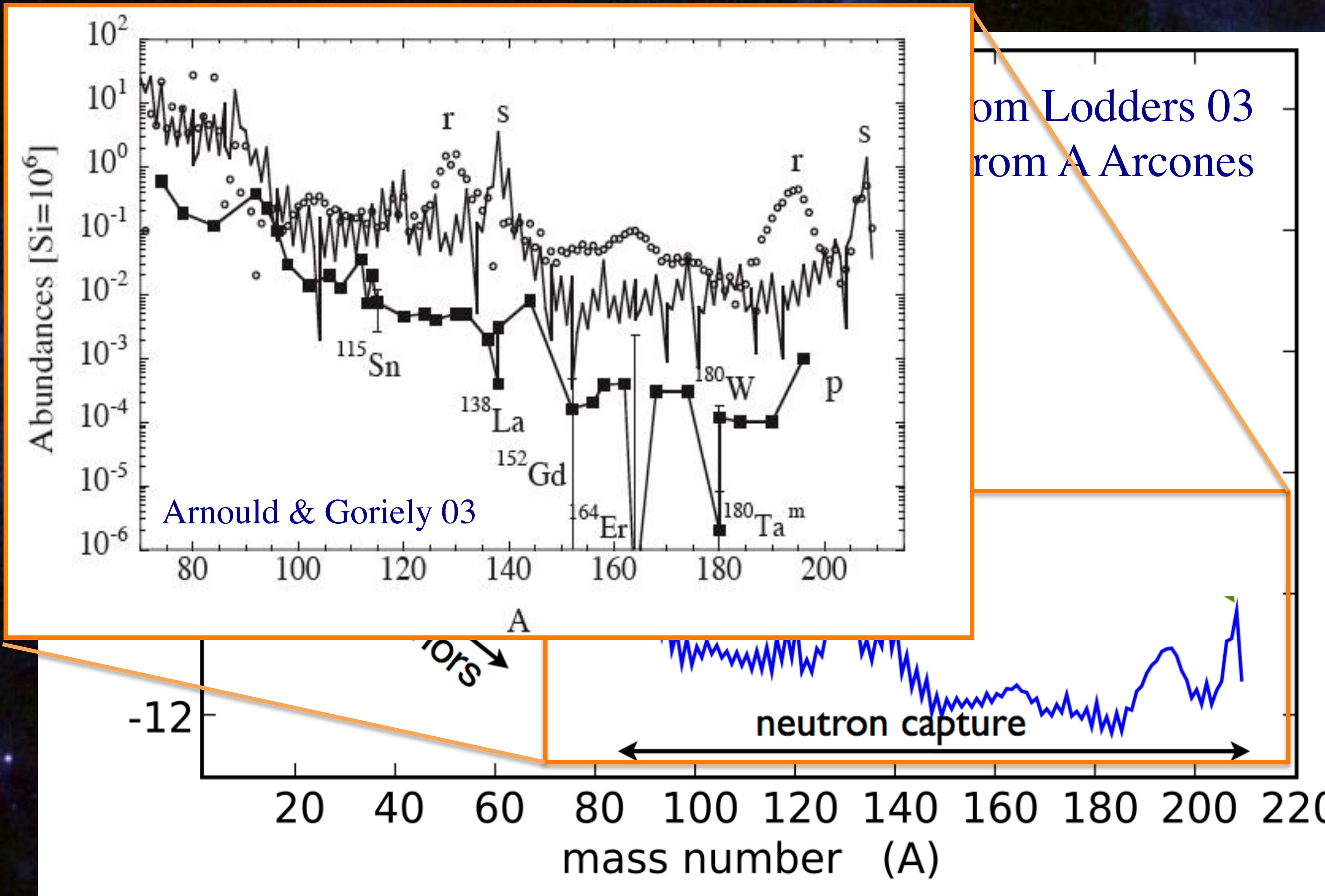
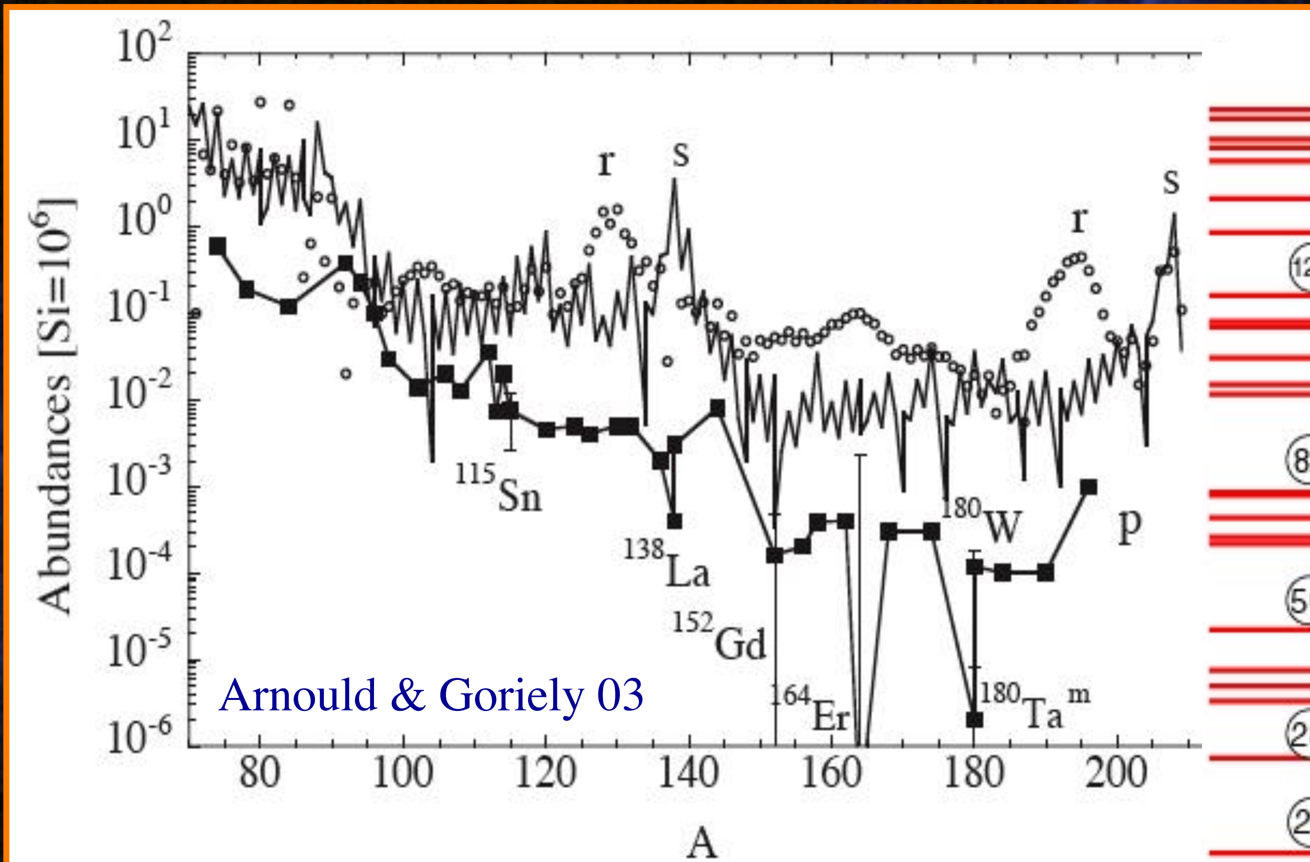
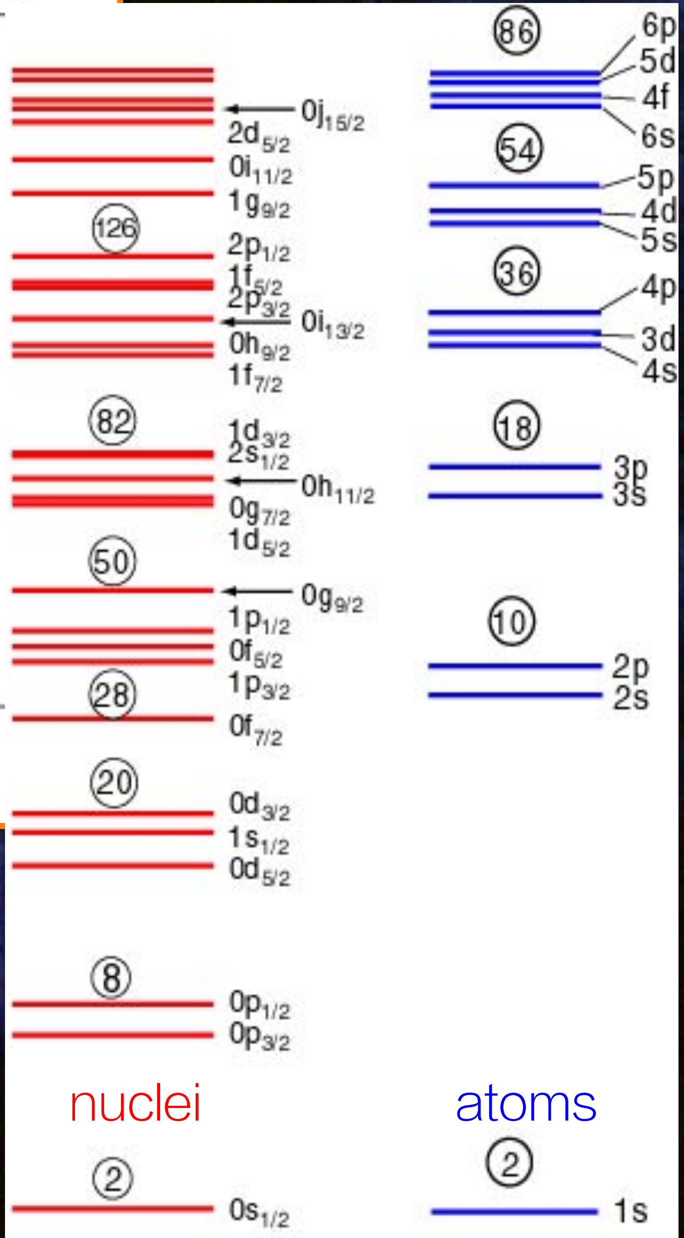
neutron capture abundances

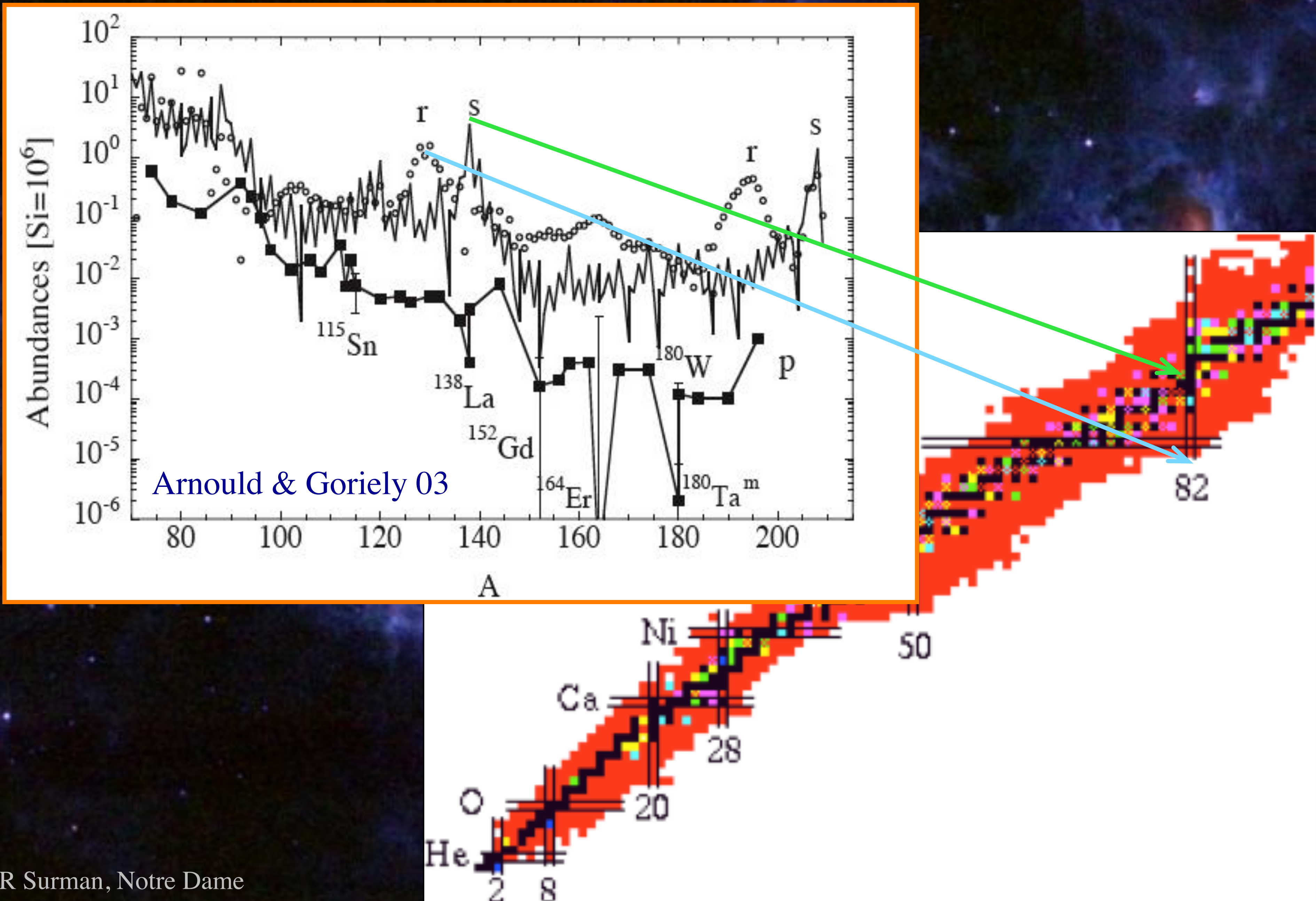


neutron capture abundances

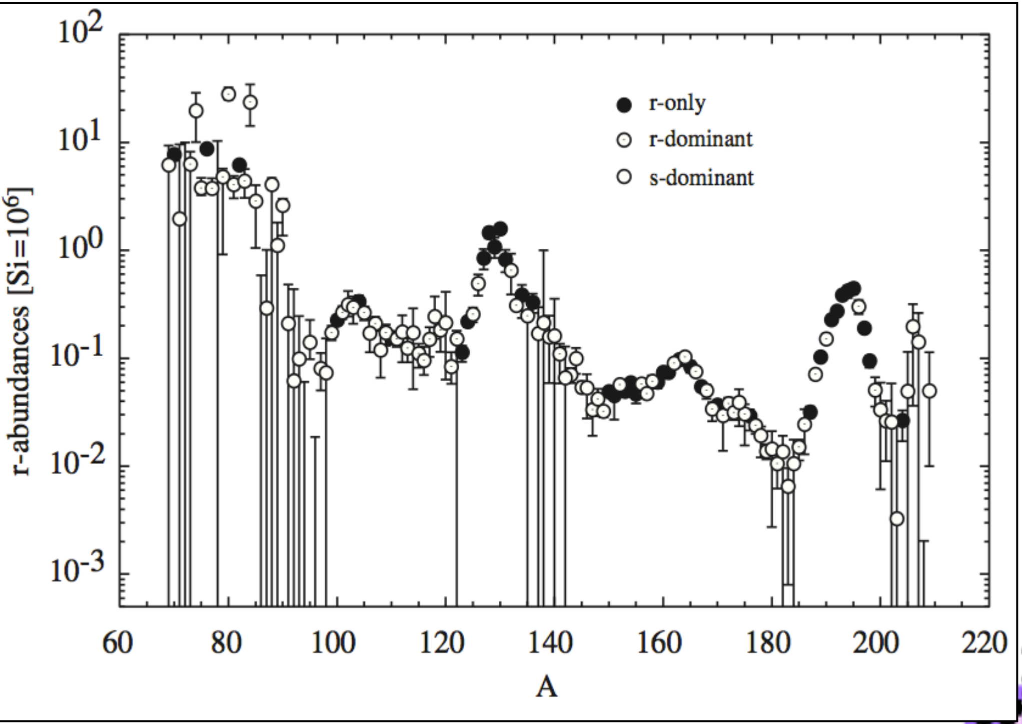




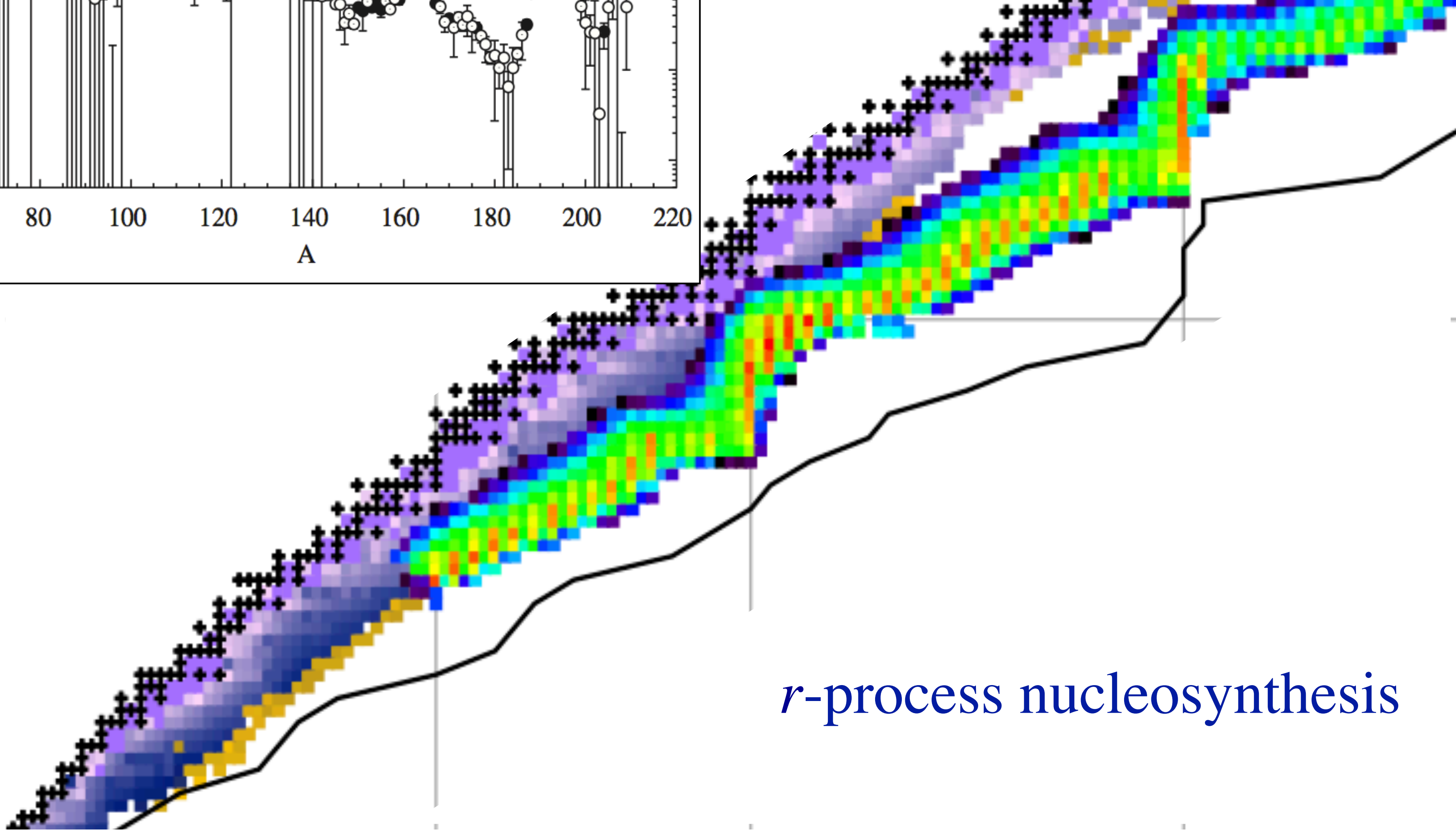
neutron capture abundances



R Surman, Notre Dame



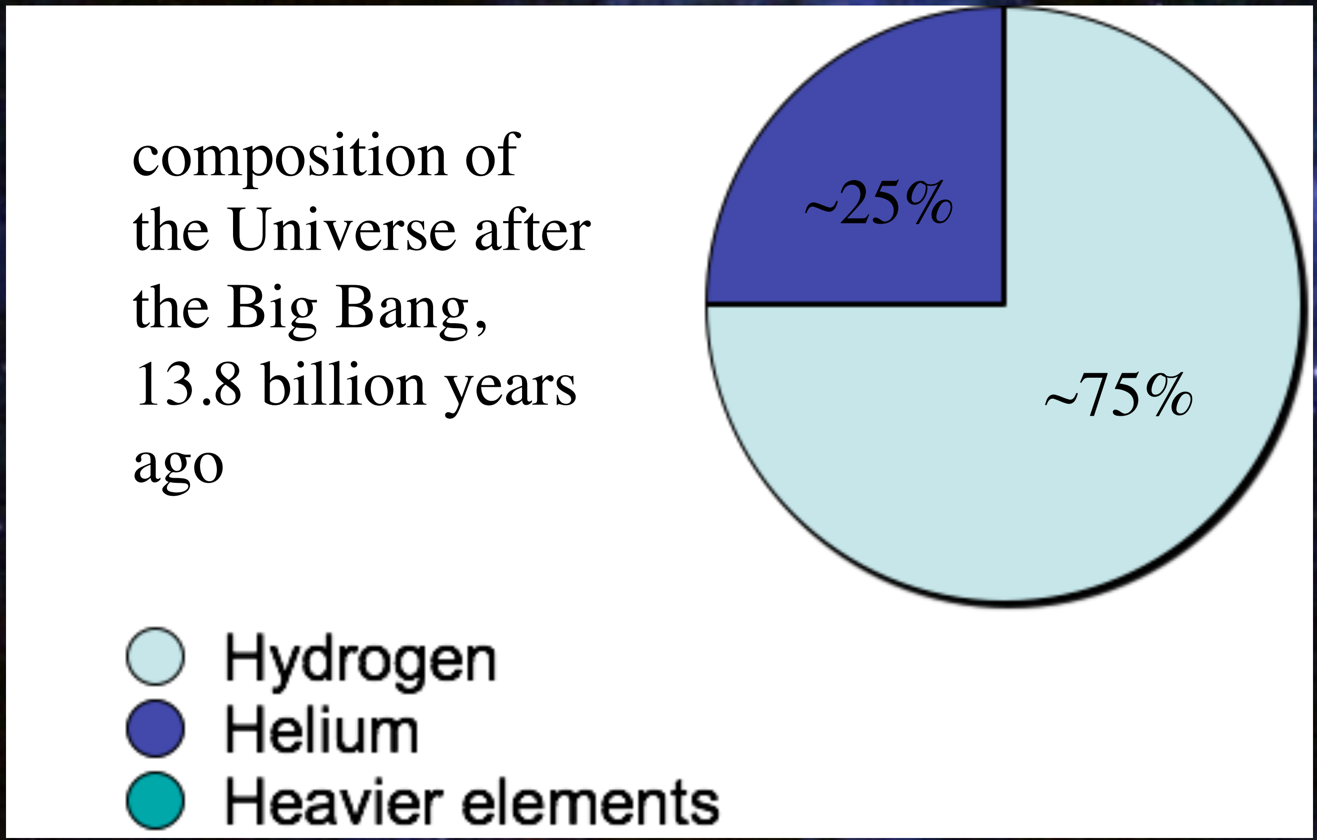
solar system
r-process
residuals



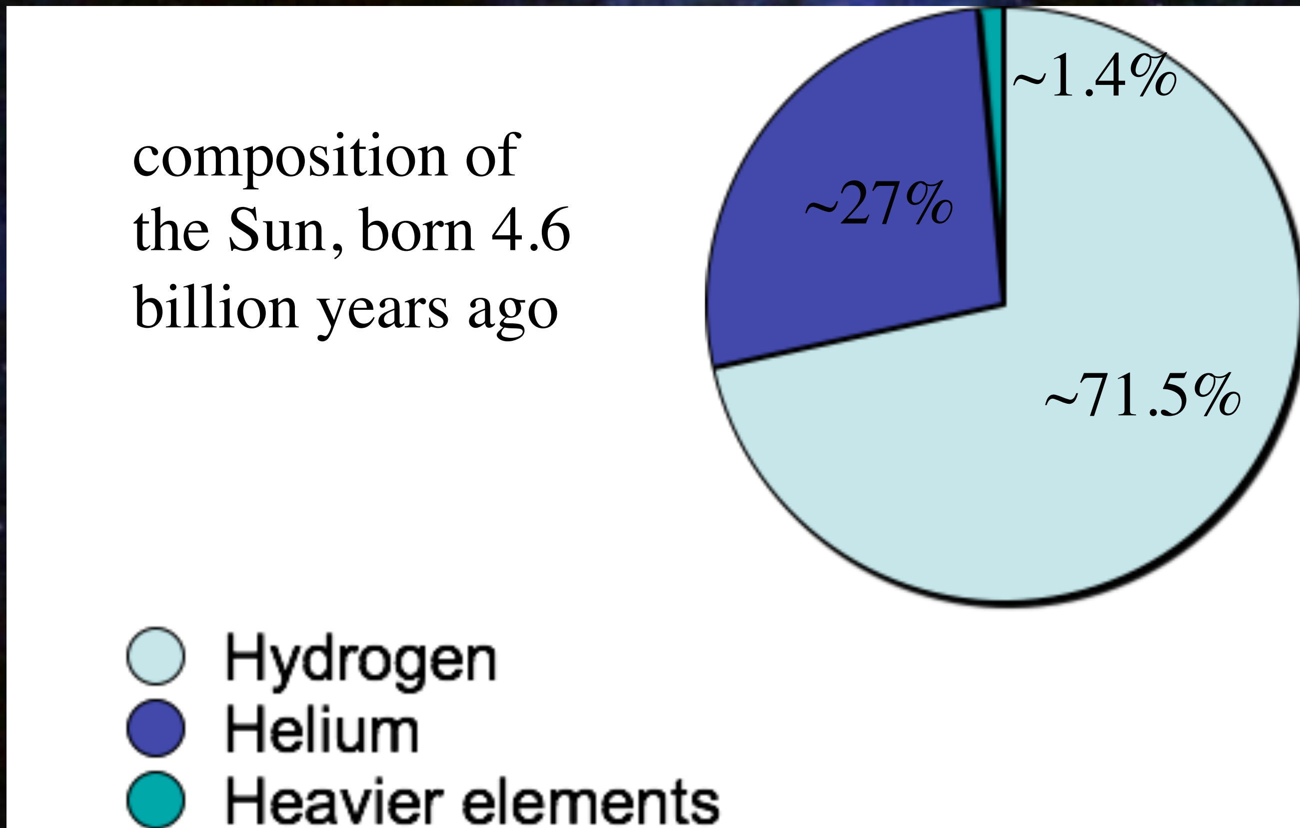
r-process nucleosynthesis

Check out: annafrebel.com @annafrebel

stellar composition



stellar composition



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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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]

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

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

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

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

for elements A and B.

chemical abundance determination

Example:

You measure:

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

You look up:

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

Calculate: [Mg/H] =

Calculate: [Mg/Fe] =

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

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

=> metal-poor because subsolar!

(recall: [Mg/H] = 0 is solar, by definition)

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

(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

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

Pop I stars

Pop II stars

Extreme Pop II stars!

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

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

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

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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

chemical evolution

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

Early stars contain little of all elements

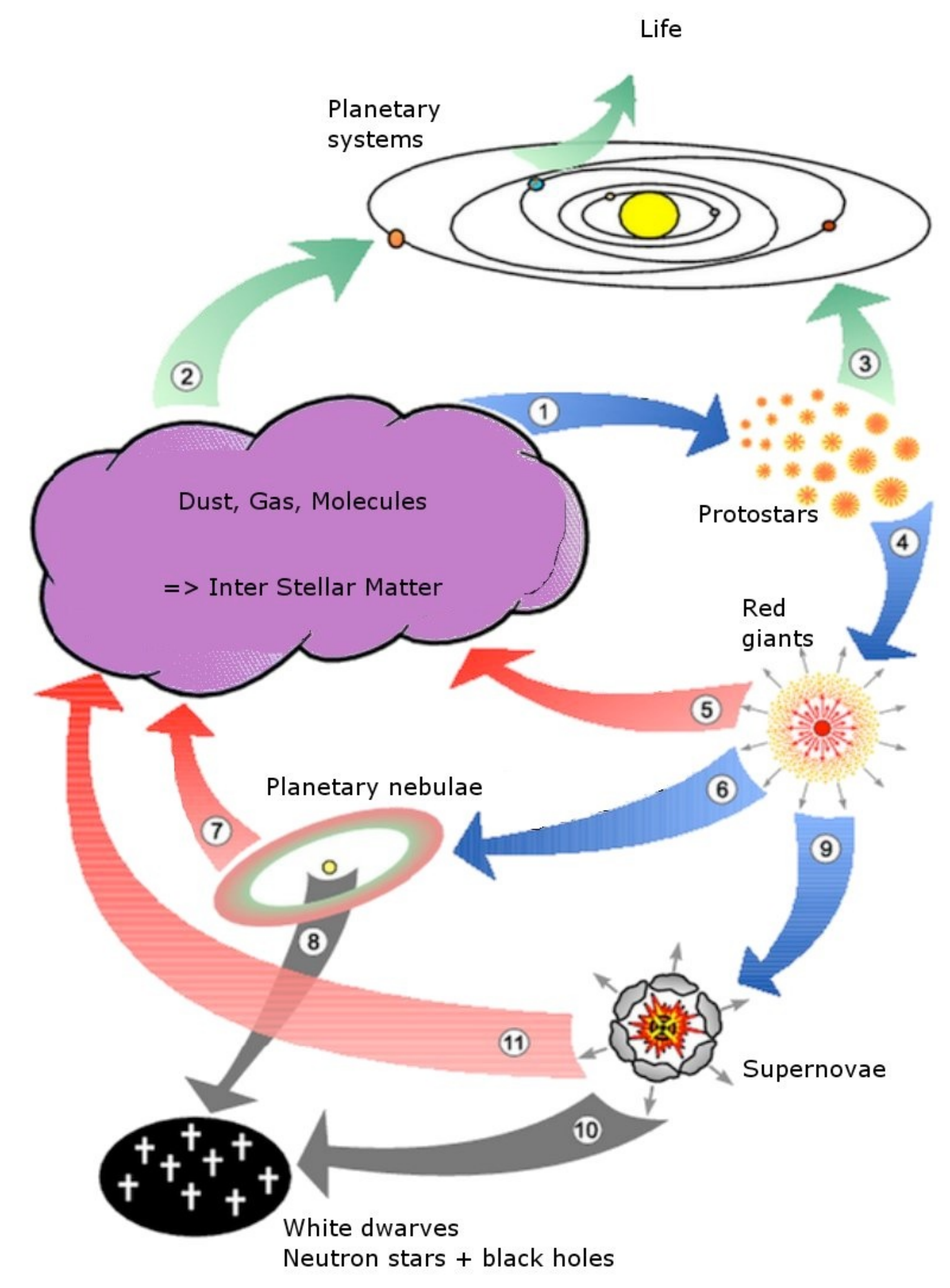
Younger stars contain larger amounts

Examples:

Sun: contains 1.4 % heavy elements (by mass)

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

Zentrum fuer Astronomie und Astrophysik, TU Berlin



adapt

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} =>

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} =>

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

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

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

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

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

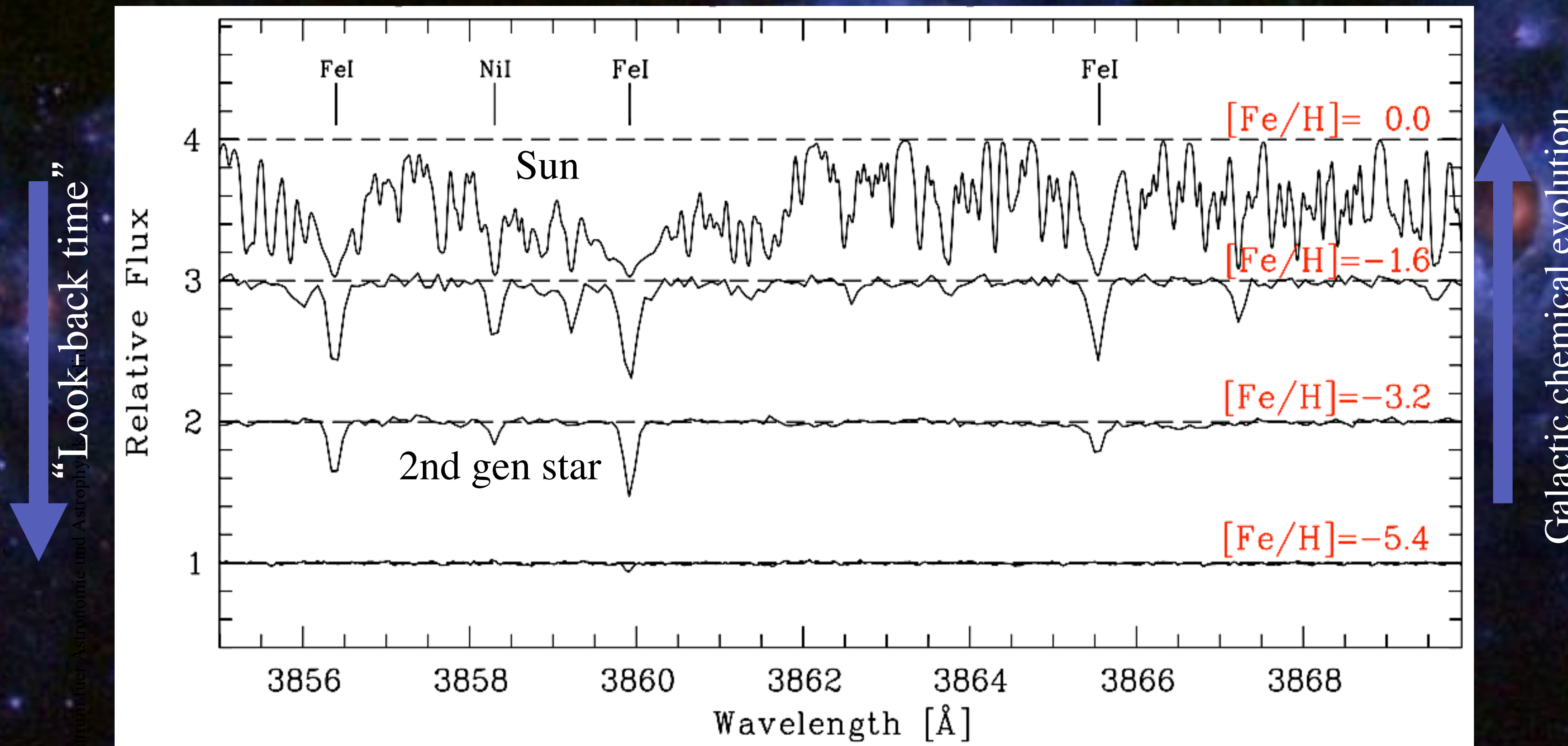
(from Table)

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

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

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

chemical evolution



Abundances are derived from
integrated absorption line strengths

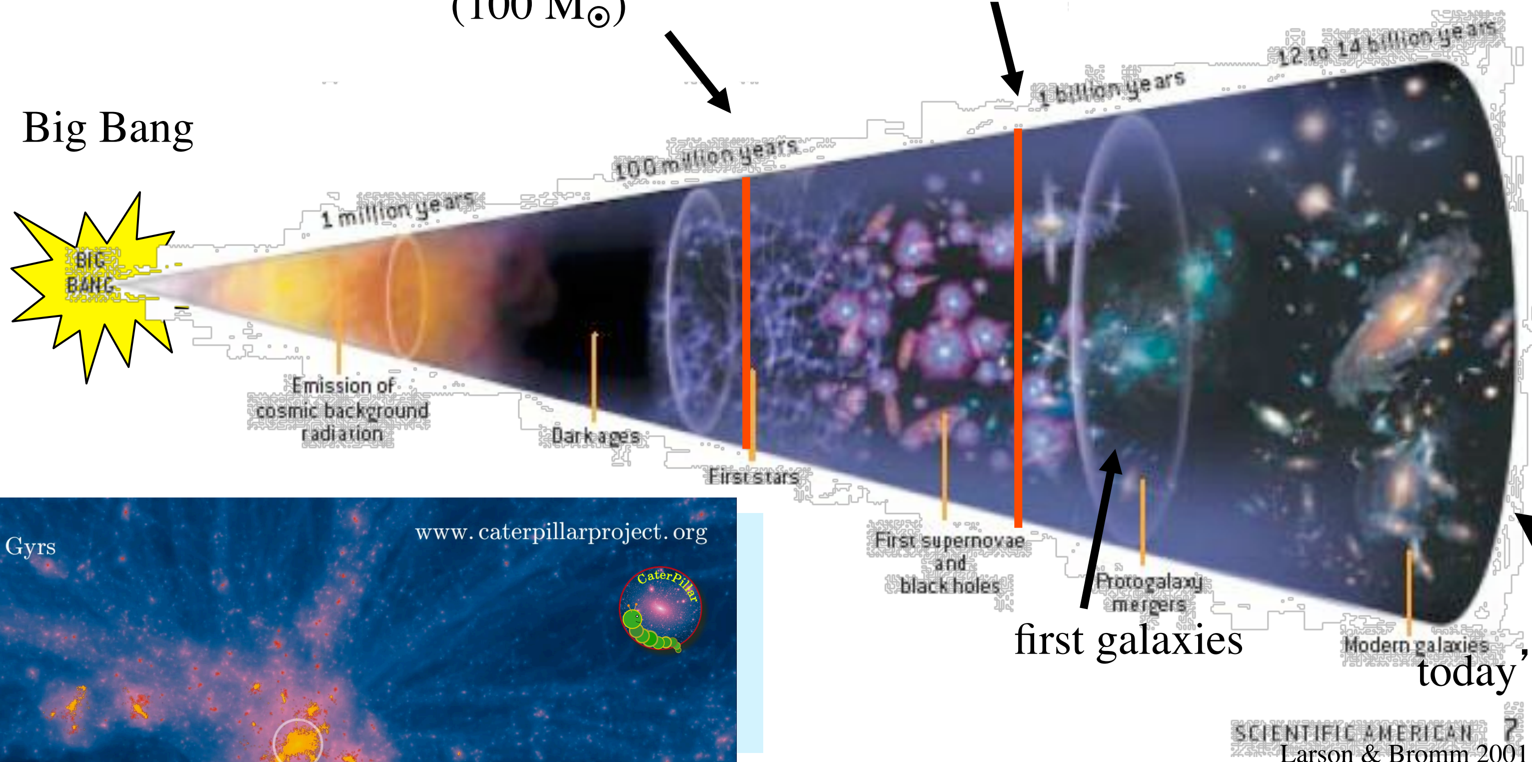
chemical evolution

First stars (100 $M_\odot$)

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

Big Bang

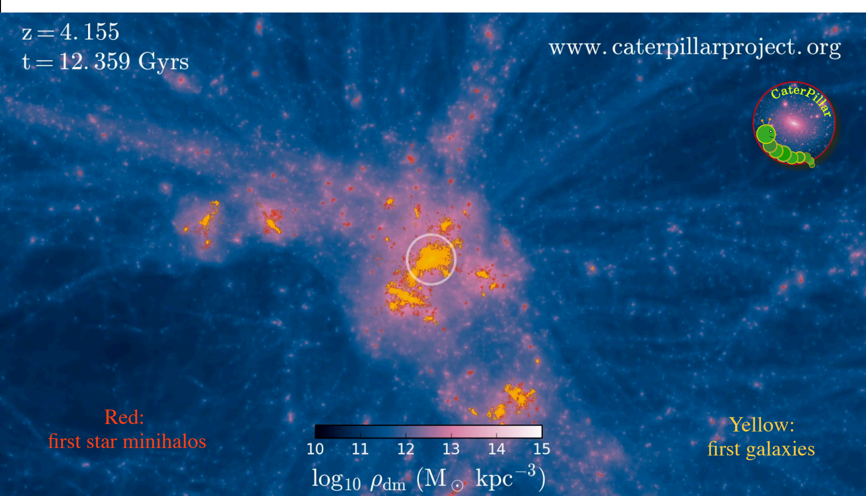
today



first galaxies

today's galaxies

Larson & Bromm 2001



Cosmic time (not to scale)