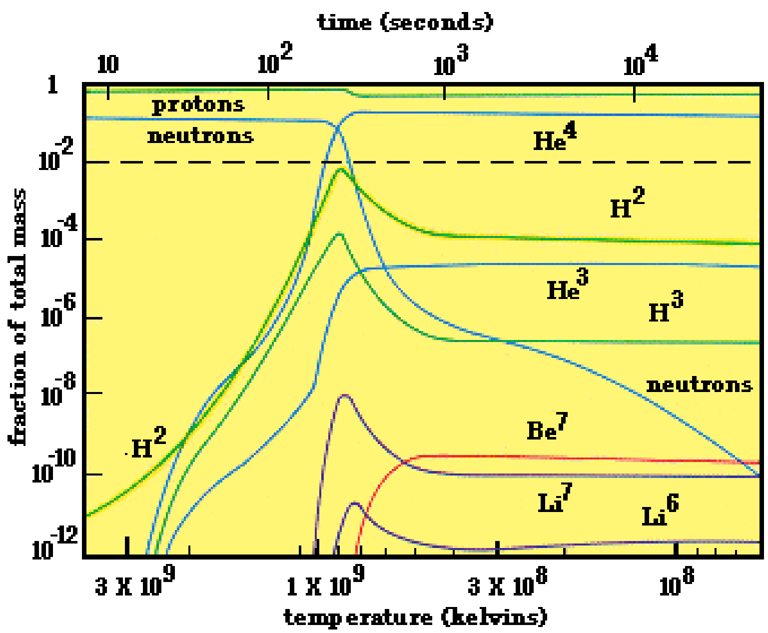
The Synthesis of the Elements

- In the beginning, there was only H and He. Early in the Big Bang, it was a soup of elementary particles. As the Universe expanded and cooled, there was a period of proton fusion into Helium.
- The Universe ran into the Be problem. Red giant cores get past this via the Triple-Alpha process, but the Universe expands right through this possibility and the density/temperature are quickly too low to synthesis any additional elements.

Big Bang Nucleosynthesis



- BB+1 second: electrons, photons, neutrons, protons
- BB+2 minutes: some H^2 (p+n) produced
- BB+4 minutes: He production+tiny amount of Be, B and Li
- That's all! Universe has expanded to 10^9K and a density of only 10 g/cm^2

Big Bang Nucleosynthesis

- Is this story right?
- Seems to be. The oldest stars in the Galaxy are deficient in the abundance of elements heavier than Helium (but show the predicted amount of He)
- The current record holder has Fe/H about 130,000 times smaller than the solar value.
- Not quite down to Big Bang abundances, but we are getting pretty close and still looking.

Chemical Evolution of the Universe

- So we need to find the sources of the vast majority of elements in the Periodic Table of the elements.
- We already know about some of the sources.

Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII	VII	VII	IB	IB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	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
5	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
6	55 Cs	56 Ba	57 *La	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
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110	111 111	112 112						

Naming conventions of new elements

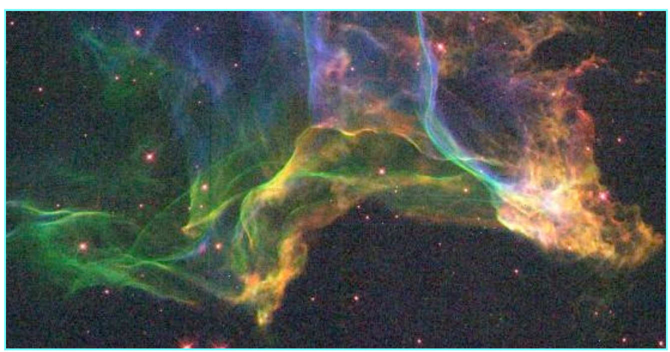
* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Chemical Evolution

- Low-mass stars synthesize `new' He, C, O during the main-sequence, RGB, HB and AGB phases.
- These freshly-minted elements are brought to the surface via convection and re-distributed via stellar winds and planetary nebulae into the interstellar medium to be incorporated into later generations of stars.

Chemical Evolution II

- For more massive stars, `equilibrium' fusion reactions produce elements all the way up to Fe.
- Freshly made elements are delivered via stellar winds or, sometimes more spectacularly via supernova explosions



Chemical Evolution III

- What about the trans-Fe elements?
- Equilibrium fusion reactions of light elements don't proceed past Fe because of Fe's location at the peak of the curve of binding energy.
- However, in certain circumstances, supernovae for example, non-equilibrium reactions can build elements beyond Fe in the Periodic Table. Many of these are radioactive, but some are stable.

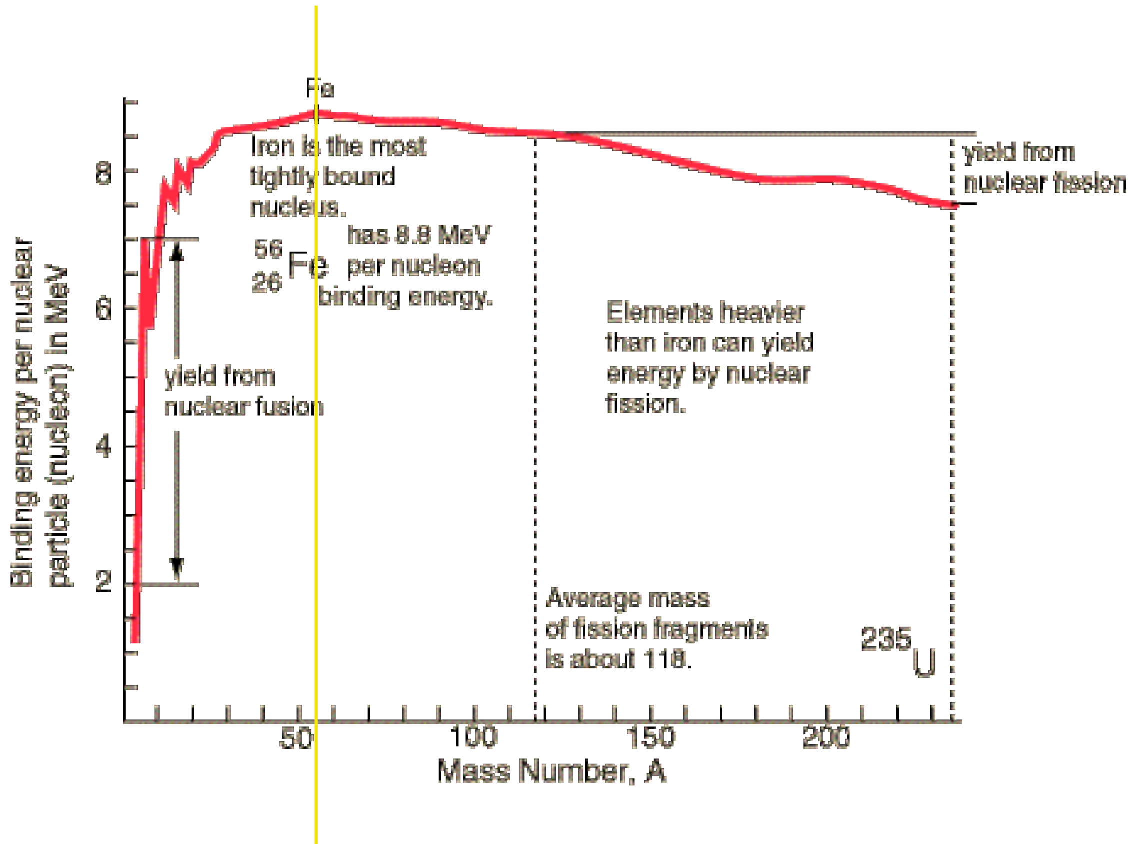
Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	——	VII	——	IB	IB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	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
5	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
6	55 Cs	56 Ba	57 *La	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
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110	111 111	112 112						

Naming conventions of new elements

* Lanthanide Series	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	71 Lu
+ Actinide Series	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	103 Lr

Remember, Fe is special



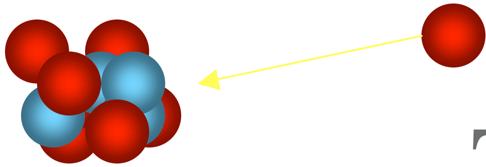
More binding energy/nucleon means less mass/nucleon

Neutron Capture Elements

- There are two principle paths to building the elements heavier than Fe. Both use the addition of neutrons to existing `seed' nuclei (neutrons have no charge so are much easier to add to positively-charged nuclei).

  S-process (slow addition of neutrons)

  R-process (rapid addition of neutrons)



The S-process

- The S-process stands for the Slow addition of neutrons to nuclei. The addition of a n° produces heavier isotope of a particular element. However, if an electron is emitted (this is called beta-decay), the nucleus moves one step up the periodic table.

S-Process

- `Slow' here means that rate of n^o captures is low compared to the beta-decay rate.
- It really is slow, sometimes 100's of years go by between neutron captures.

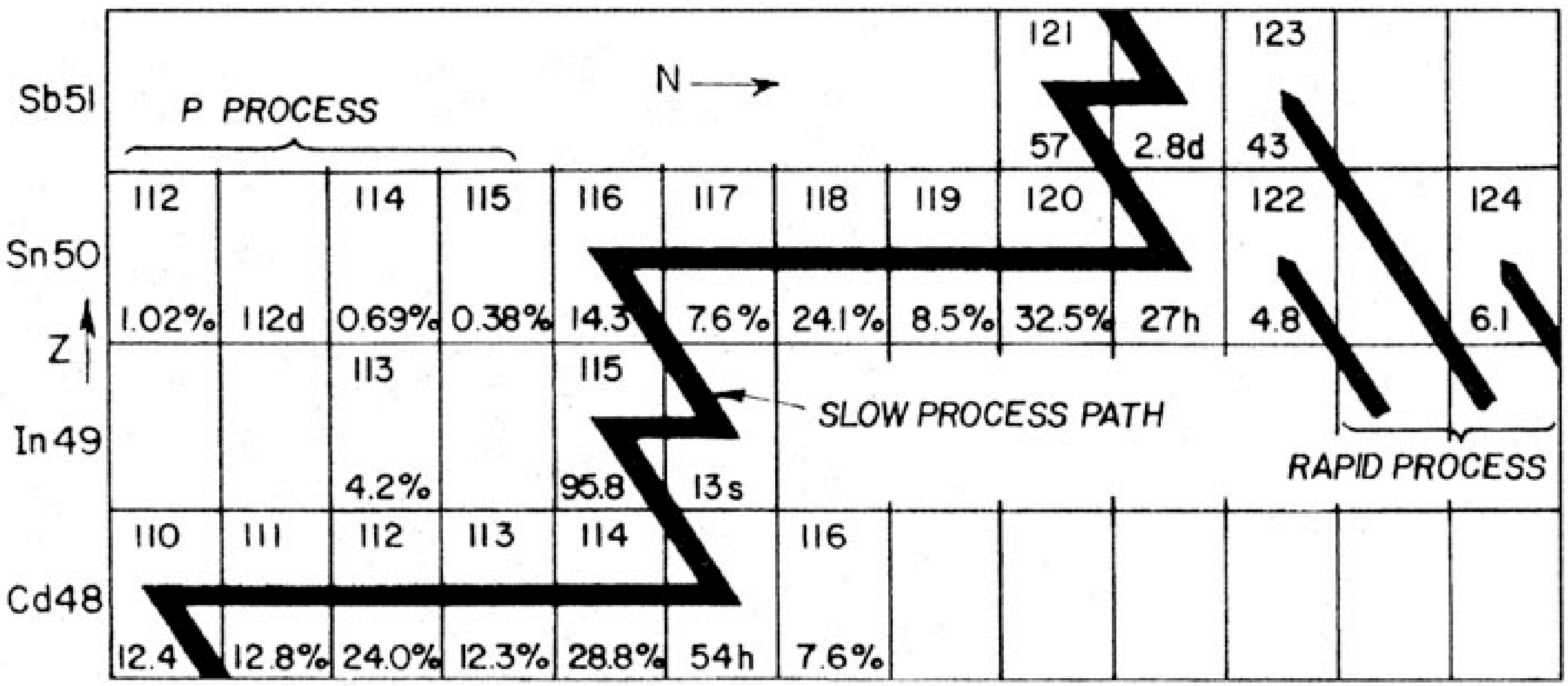
$$Fe^{56} + n^o \rightarrow Fe^{57}$$

$$Fe^{57} \rightarrow Co^{57} + e^{-}$$

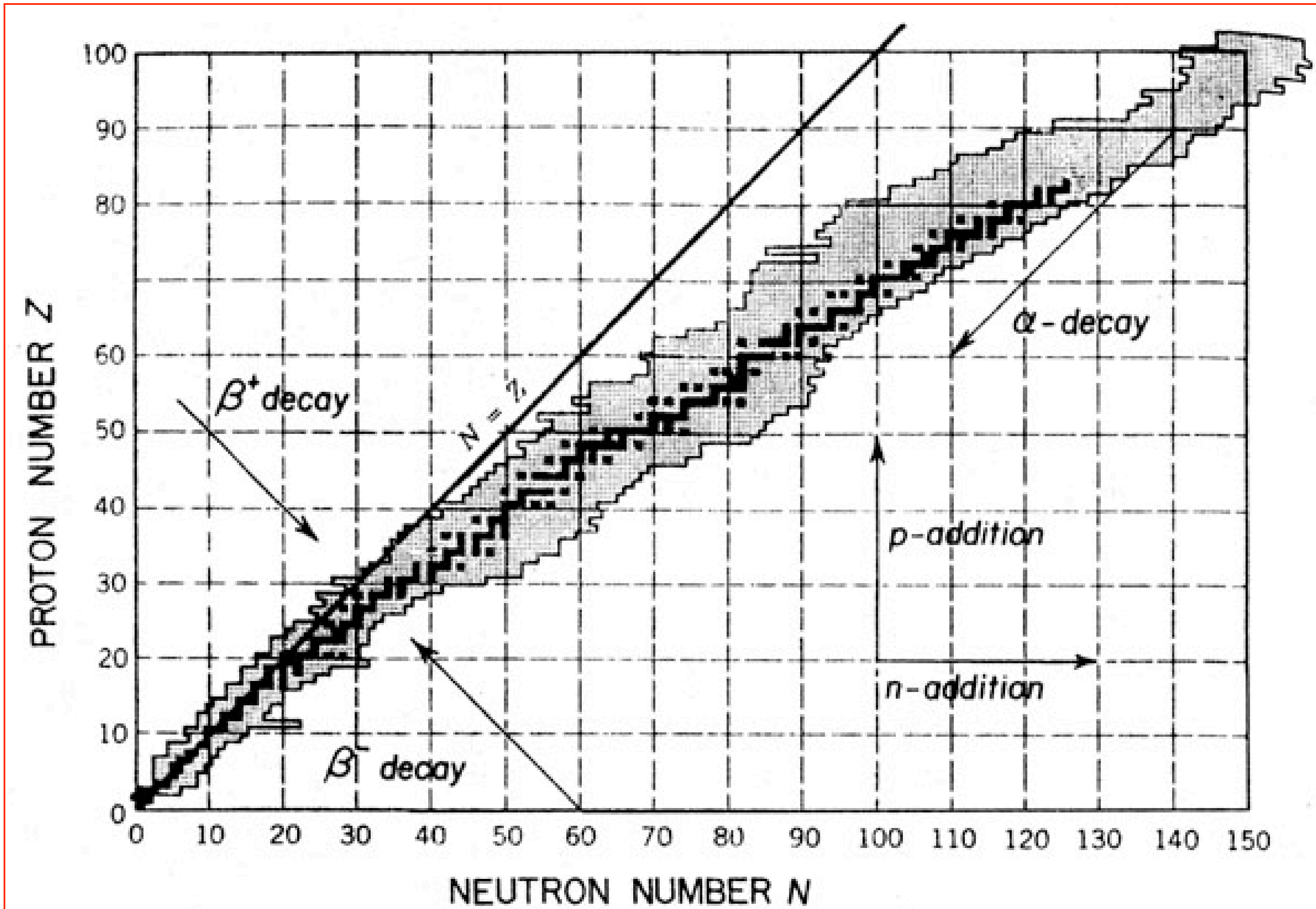
Here a neutron changed into a proton by emitting an electron

- The S-process can produce elements up to #83 - Bismuth. There are peaks in the Solar System abundance of heavy elements at ^{38}Sr, ^{56}Ba and ^{82}Pb. These are easily understood in the context of the S-process and `magic' numbers of neutrons.
- The site of the S-process is AGB stars during and between shell flashes. The n^o source is a by-product of C^{13}+He^4 -> O^{16}
- ^{43}Tc is an s-process nucleus and proof that it is in operation in AGB stars.

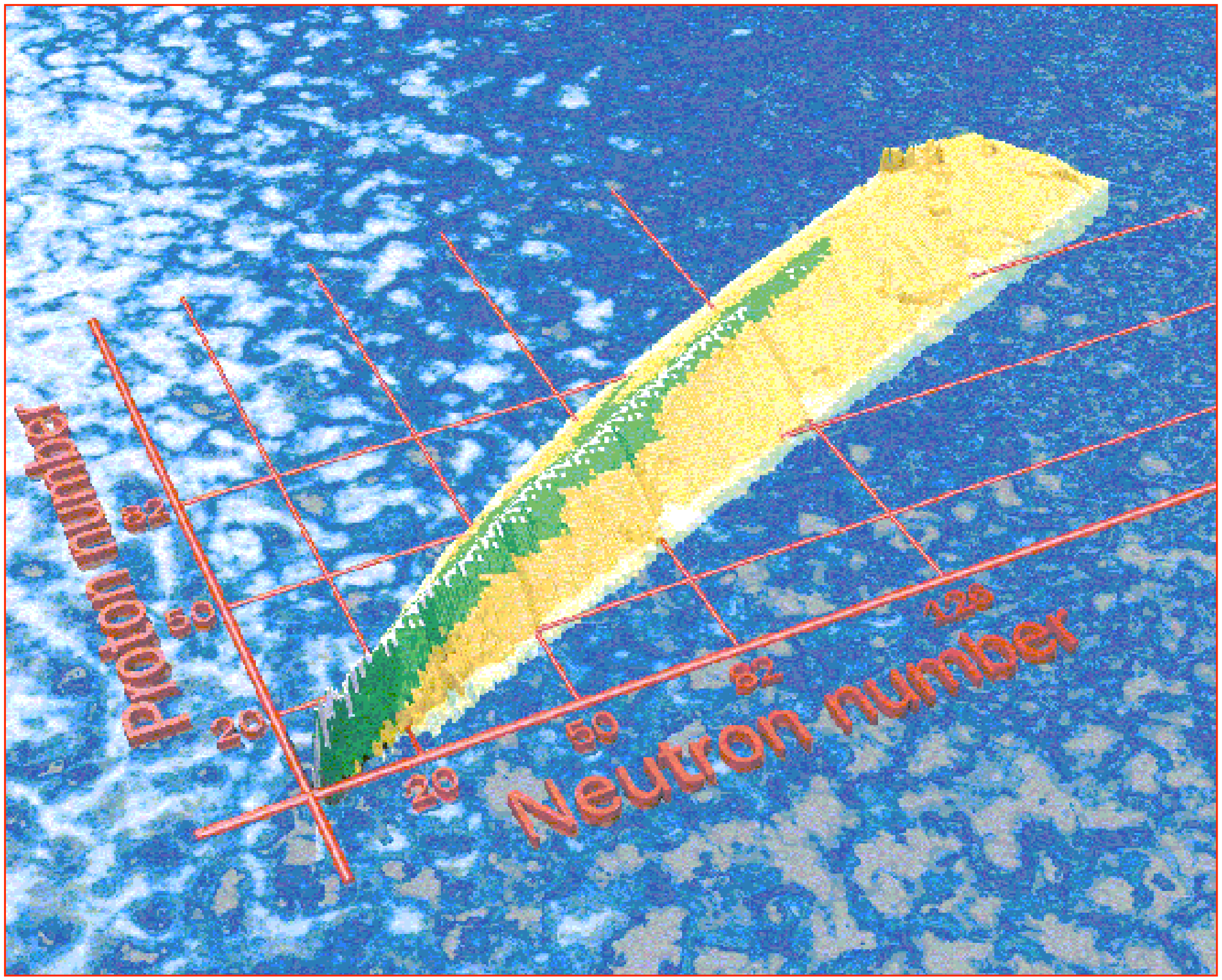
S-process path

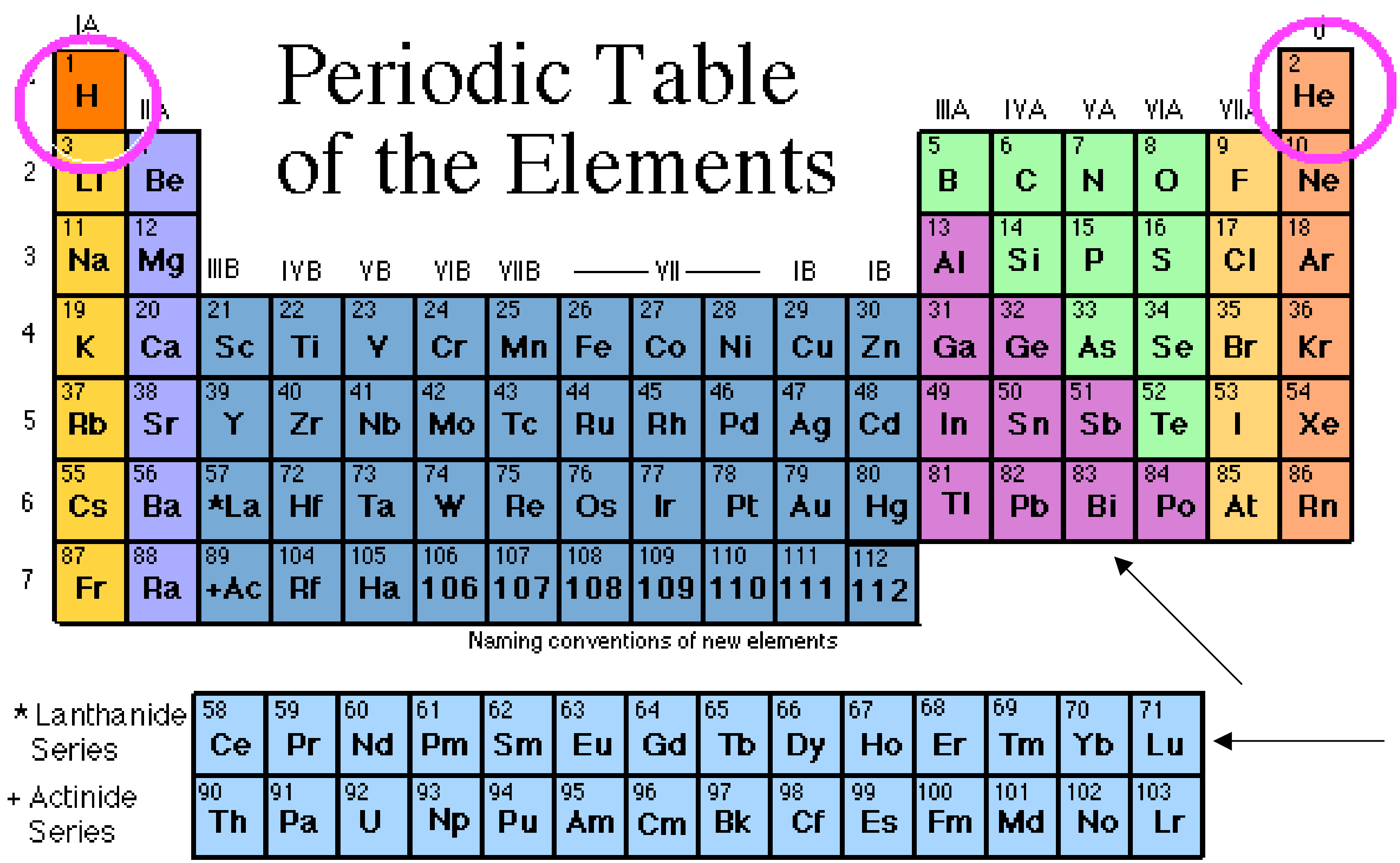


Nuclear mass - neutrons+protons

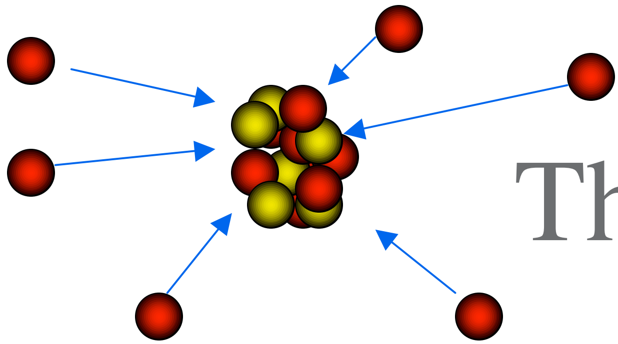


PROTON NUMBER Z
NEUTRON NUMBER N
N = Z
β+ decay
β− decay
α - decay
p-addition
n-addition
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150


Proton number
20
50
82
Neutron number
20
50
82
126

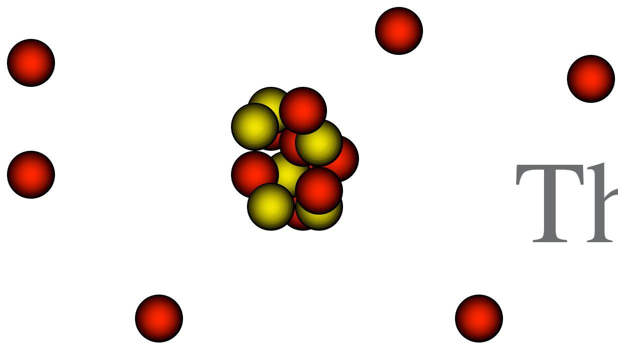


Add 5 neutrons to Fe and undergo 2 beta-decays. What element?



The R-process

- The R-process is the Rapid addition of neutrons to existing nuclei. Rapid here means that many neutrons are added before a beta-decay occurs.
- First build up a VERY heavy isotope, then as beta-decays occur you march up in atomic number and produce the REALLY HEAVY STUFF.



The R-process

- For this to happen need a big burst of neutrons. The most promising place with the right conditions is in a SNII explosion right above the collapsed core.
- We see an overabundance of R-process elements in the oldest stars. As the early chemical enrichment of the Galaxy was through SNII, this is evidence of SNII as the source of r-process elements

R-process

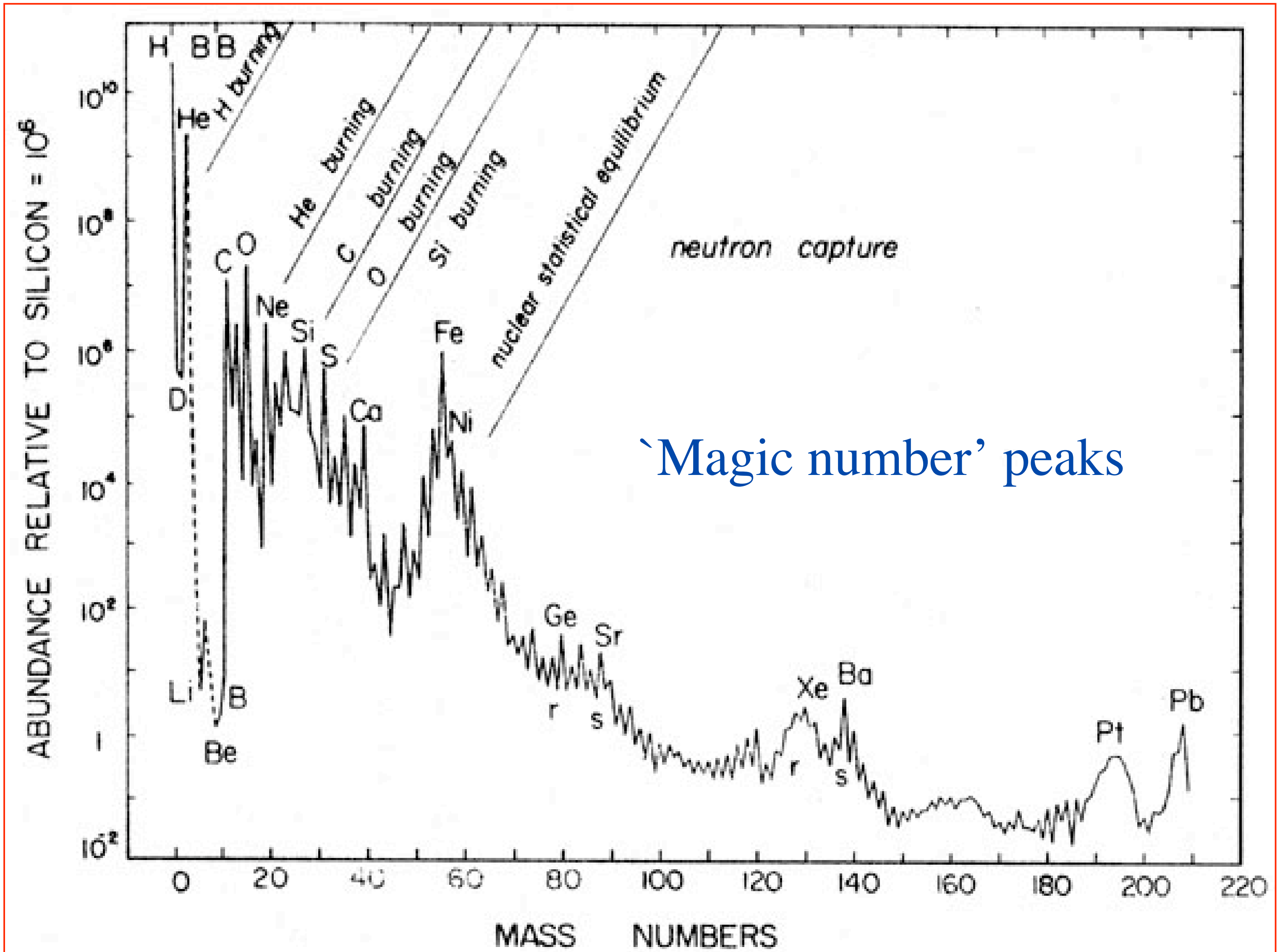
- If we look at the Crab Nebula or other SNII remnants we don't see r-process elements.
- We DO see regions of enhanced O, Si, Ne and He which appear to reflect the `onion skin' structure of the massive star progenitor.

Solar Composition by Mass

H ……….78.4%
He……….19.8%
O ………. 0.8%
C ……….. 0.3%
N ……….. 0.2%
Ne ……… 0.2%
Si ………. 0.04%
Fe ………. 0.04%

Gold……..0.000000009%
($2.1 x 10^{24} at $300/ounce)

Big Bang
Low-mass stars
High-mass stars
R-process
S-process



`Magic number' peaks
ABUNDANCE RELATIVE TO SILICON = 10^6
MASS NUMBERS
H
BB
H burning
He burning
C burning
O burning
Si burning
nuclear statistical equilibrium
neutron capture
He
D
Li
Be
B
C
O
Ne
Si
S
Ca
Fe
Ni
Ge
Sr
r
s
Xe
Ba
r
s
Pt
Pb
10^{10}
10^8
10^6
10^4
10^2
1
10^{-2}
0
20
40
60
80
100
120
140
160
180
200
220