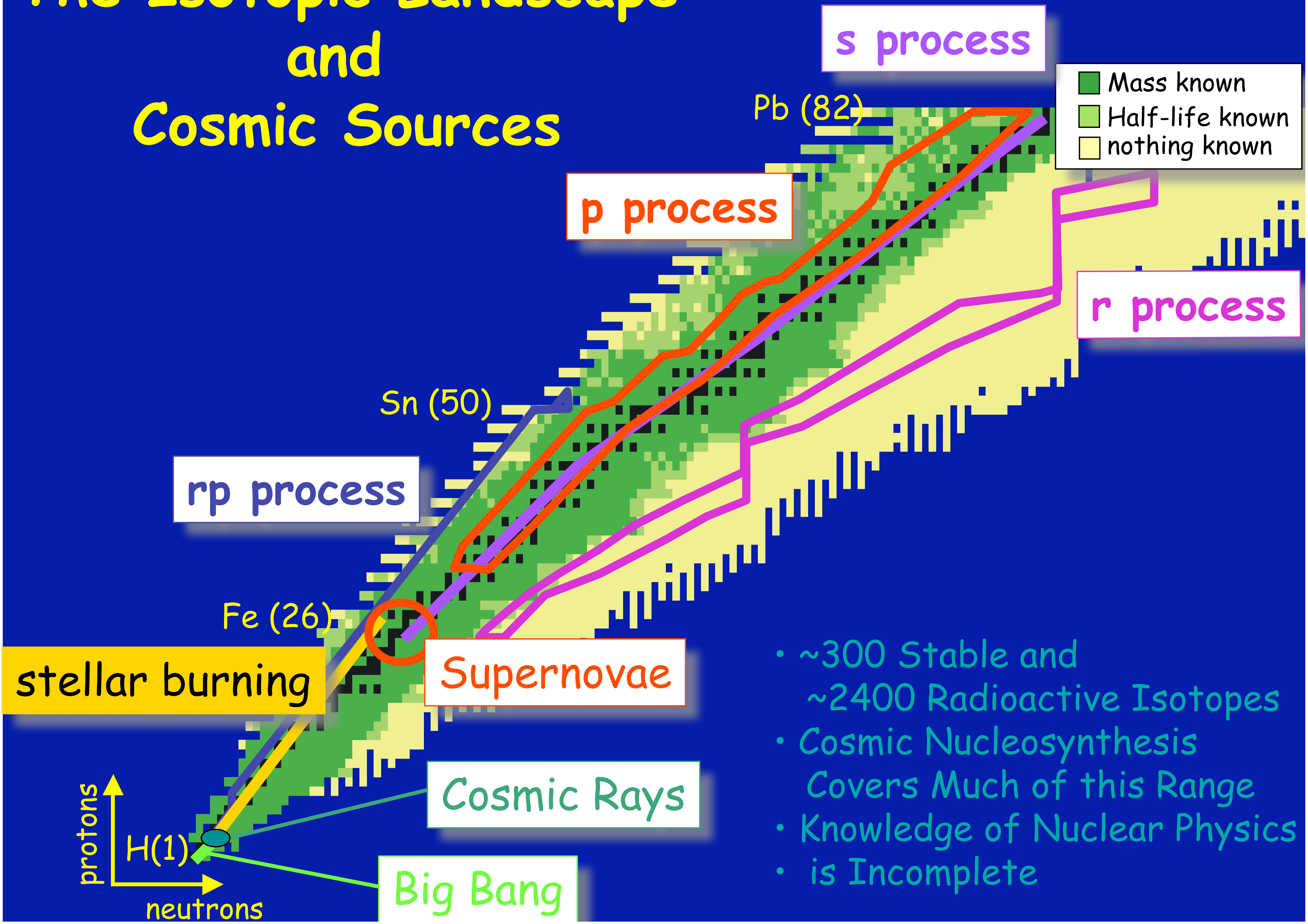
Nucleosynthesis

The Origin of the Elements

The Isotopic Landscape and Cosmic Sources



- ~300 Stable and ~2400 Radioactive Isotopes
- Cosmic Nucleosynthesis Covers Much of this Range
- Knowledge of Nuclear Physics
- is Incomplete

TABLE 2.1
The 25 Most Abundant Nuclei

Rank	*Z*	*Symbol*	*A*	*Nucleon Fraction*	*Source (process)*
1	1	H	1	7.057e-01	Big Bang
2	2	He	4	2.752e-01	Big Bang, CNO, pp
3	8	O	16	9.592e-03	Helium
4	6	C	12	3.032e-03	Helium
5	10	Ne	20	1.548e-03	Carbon
6	26	Fe	56	1.169e-03	*e*-process
7	7	N	14	1.105e-03	CNO
8	14	Si	28	6.530e-04	Oxygen
9	12	Mg	24	5.130e-04	Carbon
10	16	S	32	3.958e-04	Oxygen
11	10	Ne	22	2.076e-04	Helium
12	12	Mg	26	7.892e-05	Carbon
13	18	Ar	36	7.740e-05	Silicon, Oxygen
14	26	Fe	54	7.158e-05	*e*-process, Silicon
15	12	Mg	25	6.893e-05	Carbon
16	20	Ca	40	5.990e-05	Silicon, Oxygen
17	13	Al	27	5.798e-05	Carbon
18	28	Ni	58	4.915e-05	Silicon, *e*-process
19	6	C	13	3.683e-05	CNO
20	2	He	3	3.453e-05	Big Bang, pp
21	14	Si	29	3.448e-05	Carbon, Neon
22	11	Na	23	3.339e-05	Carbon
23	26	Fe	57	2.840e-05	*e*-process
24	14	Si	30	2.345e-05	Carbon, Neon
25	1	H	2	2.317e-05	Big Bang

Brief Summary of Burning Stages (Major Reactions)

s-process!

1. Hydrogen Burning — $T = (1\text{-}4)\times10^{7}$K
   - pp-cycles -> $^{1}H(p,e^{+}\nu)^{2}H$
   - CNO-cycle -> slowest reaction $^{14}N(p,\gamma)^{15}O$
2. Helium Burning — $T=(1\text{-}2)\times10^{8}$K
   - $^{4}He+^{4}He \Leftrightarrow {}^{8}Be$ $\quad$ $^{8}Be(\alpha,\gamma)^{12}C[(\alpha,\gamma)^{16}O]$
   - $^{14}N(\alpha,\gamma)^{18}F(\beta^{+})^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$ (n-source, alternatively $^{13}C(\alpha,n)^{16}O$)
3. Carbon Burning — $T=(6\text{-}8)\times10^{8}$K
   - $^{12}C(^{12}C,\alpha)^{20}Ne$ $\quad$ $^{23}Na(p,\alpha)^{20}Ne$
   - $^{12}C(^{12}C,p)^{23}Na$ $\quad$ $^{23}Na(p,\gamma)^{24}Mg$
4. Neon Burning — $T=(1.2\text{-}1.4)\times10^{9}$K
   - $^{20}Ne(\gamma,\alpha)^{16}O$
   - $^{20}Ne(\alpha,\gamma)^{24}Mg[(\alpha,\gamma)^{28}Si]$

   30kT = 4MeV
5. Oxygen Burning — $T=(1.5\text{-}2.2)\times10^{9}$K
   - $^{16}O(^{16}O,\alpha)^{28}Si$ $\quad$ $^{31}P(p,\alpha)^{28}Si$
   - ......,p)^{31}P ...,n)$^{31}S(\beta^{+})^{31}P$ $\quad$ $^{31}P(p,\gamma)^{23}S$
6. "Silicon" Burning — $T=(3\text{-}4)\times10^{9}$K

(all) photodisintegrations and capture reactions possible

⇒ thermal (chemical) equilibrium

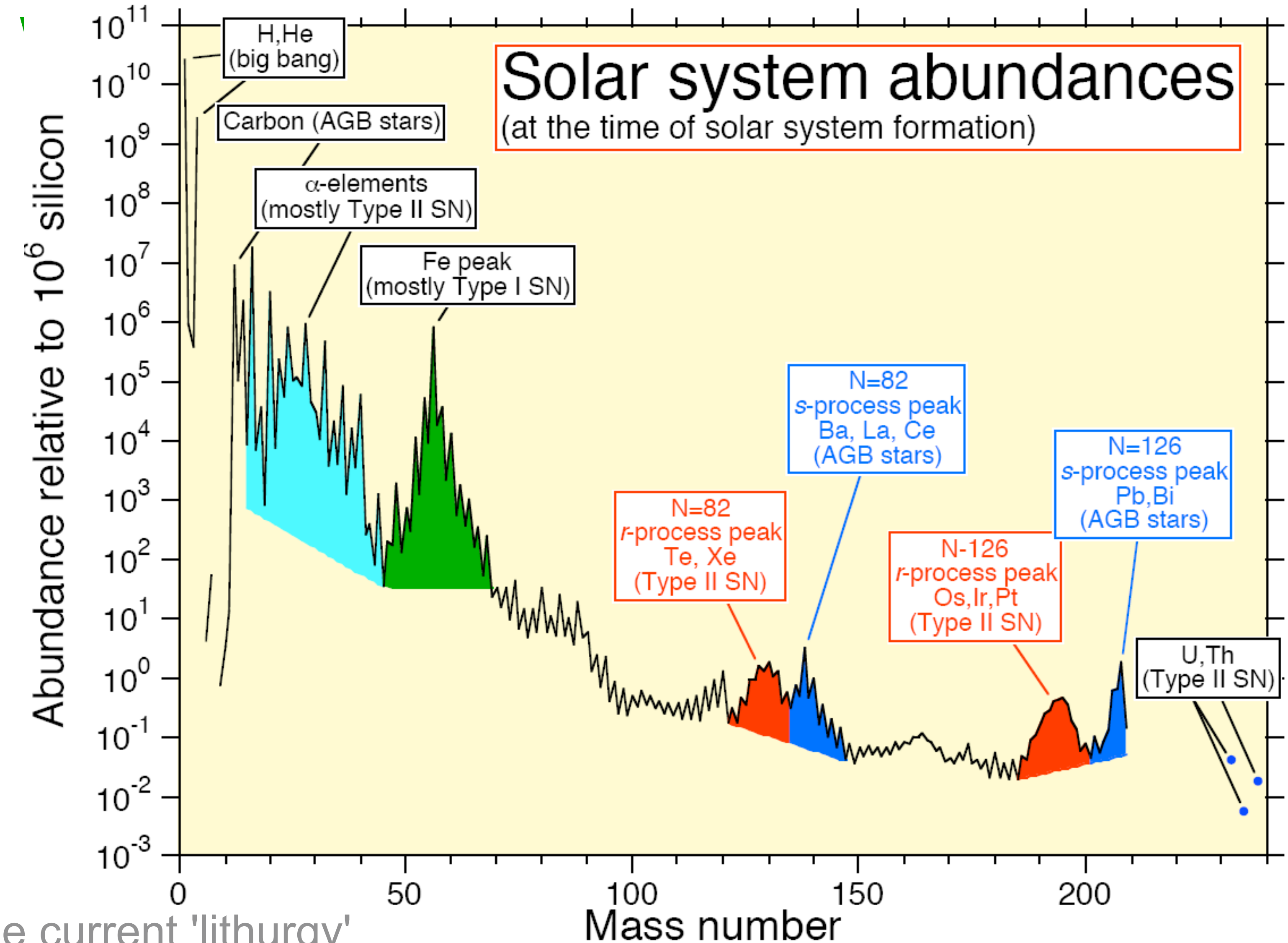
ongoing measurements of key fusion reactions at low energies

Elemental Abundances

Table 2. Elemental Abundances

Z	El	Solar System (%)	Abundance in the Earth's Crust (mg/kg)	Abundance in the Earth's Sea (mg/L)
1	H	91.0 *23*	1400	1.08×10^{5}
2	He	8.9 *5*	0.008	7×10^{-6}
3	Li	1.86×10^{-7} *17*	20	0.18
4	Be	2.38×10^{-9} *23*	2.8	5.6×10^{-6}
5	B	6.9×10^{-8} *7*	10	4.44
6	C	0.033	200	28
7	N	0.0102	19	0.5
8	O	0.078 *8*	4.61×10^{5}	8.57×10^{5}
9	F	2.7×10^{-6} *4*	585	1.3
10	Ne	0.0112 *16*	0.005	1.2×10^{-4}
11	Na	0.000187 *13*	2.36×10^{4}	1.08×10^{4}
12	Mg	0.00350 *13*	2.33×10^{4}	1290
13	Al	0.000277 *10*	8.23×10^{4}	0.002
14	Si	0.00326 *14*	2.82×10^{5}	2.2
15	P	3.4×10^{-5} *3*	1050	0.06
16	S	0.00168 *22*	350	905
17	Cl	1.7×10^{-5} *3*	145	1.94×10^{4}
18	Ar	0.000329 *20*	3.5	0.45
19	K	1.23×10^{-5} *9*	2.09×10^{4}	399
20	Ca	0.000199 *14*	4.15×10^{4}	412
21	Sc	1.12×10^{-7} *10*	22	6×10^{-7}
22	Ti	7.8×10^{-6} *4*	5650	0.001
23	V	9.6×10^{-7} *5*	120	0.0025
24	Cr	4.4×10^{-5} *3*	102	3×10^{-4}
25	Mn	3.1×10^{-5} *3*	950	2×10^{-4}
26	Fe	0.00294 *8*	5.63×10^{4}	0.002
27	Co	7.3×10^{-6} *5*	25	2×10^{-5}
28	Ni	0.000161 *8*	84	5.6×10^{-4}
29	Cu	1.70×10^{-6} *19*	60	2.5×10^{-4}
30	Zn	4.11×10^{-6} *18*	70	0.0049
31	Ga	1.23×10^{-7} *8*	19	3×10^{-5}
32	Ge	3.9×10^{-7} *4*	1.5	5×10^{-5}
33	As	2.1×10^{-8} *3*	1.8	0.0037
34	Se	2.03×10^{-7} *13*	0.05	2×10^{-4}
35	Br	3.8×10^{-8} *7*	2.4	67.3
36	Kr	1.5×10^{-7} *3*	1×10^{-4}	2.1×10^{-4}
37	Rb	2.31×10^{-8} *15*	90	0.12
38	Sr	7.7×10^{-8} *6*	370	7.9
39	Y	1.51×10^{-8} *9*	33	1.3×10^{-5}
40	Zr	3.72×10^{-8} *24*	165	3×10^{-5}
41	Nb	2.28×10^{-9} *3*	20	1×10^{-5}
42	Mo	8.3×10^{-9} *5*	1.2	0.01
43	Tc			
44	Ru	6.1×10^{-9} *3*	0.001	7×10^{-7}
45	Rh	1.12×10^{-9} *9*	0.001	
46	Pd	4.5×10^{-9} *3*	0.015	
47	Ag	1.58×10^{-9} *5*	0.075	4×10^{-5}
48	Cd	5.3×10^{-9} *3*	0.15	1.1×10^{-4}
49	In	6.0×10^{-10} *4*	0.25	0.02
50	Sn	1.25×10^{-8} *12*	2.3	4×10^{-6}
51	Sb	1.01×10^{-9} *18*	0.2	2.4×10^{-4}
52	Te	1.57×10^{-8} *16*	0.001	
53	I	2.9×10^{-9} *6*	0.45	0.06
54	Xe	1.5×10^{-8} *3*	3×10^{-5}	5×10^{-5}
55	Cs	1.21×10^{-9} *7*	3	3×10^{-4}
56	Ba	1.46×10^{-8} *9*	425	0.013
57	La	1.45×10^{-9} *3*	39	3.4×10^{-6}
58	Ce	3.70×10^{-9} *6*	66.5	1.2×10^{-6}
59	Pr	5.44×10^{-10} *13*	9.2	6.4×10^{-7}
60	Nd	2.70×10^{-9} *4*	41.5	2.8×10^{-6}
61	Pm			
62	Sm	8.42×10^{-10} *11*	7.05	4.5×10^{-7}
63	Eu	3.17×10^{-10} *5*	2.0	1.3×10^{-7}
64	Gd	1.076×10^{-9} *15*	6.2	7×10^{-7}
65	Tb	1.97×10^{-10} *4*	1.2	1.4×10^{-7}
66	Dy	1.286×10^{-9} *18*	5.2	9.1×10^{-7}
67	Ho	2.90×10^{-10} *7*	1.3	2.2×10^{-7}
68	Er	8.18×10^{-10} *11*	3.5	8.7×10^{-7}
69	Tm	1.23×10^{-10} *3*	0.52	1.7×10^{-7}
70	Yb	8.08×10^{-10} *13*	3.2	8.2×10^{-7}
71	Lu	1.197×10^{-10} *16*	0.8	1.5×10^{-7}
72	Hf	5.02×10^{-10} *10*	3.0	7×10^{-6}
73	Ta	6.75×10^{-11} *12*	2.0	2×10^{-6}
74	W	4.34×10^{-10} *22*	1.25	1×10^{-4}
75	Re	1.69×10^{-10} *16*	7×10^{-4}	4×10^{-6}
76	Os	2.20×10^{-9} *14*	0.0015	
77	Ir	2.16×10^{-9} *13*	0.001	
78	Pt	4.4×10^{-9} *3*	0.005	
79	Au	6.1×10^{-10} *9*	0.004	4×10^{-6}
80	Hg	1.11×10^{-9} *13*	0.085	3×10^{-5}
81	Tl	6.0×10^{-10} *6*	0.85	1.9×10^{-5}
82	Pb	1.03×10^{-8} *8*	14	3×10^{-5}
83	Bi	4.7×10^{-10} *4*	0.0085	2×10^{-5}
84	Po		2×10^{-10}	1.5×10^{-14}
85	At			
86	Rn		4×10^{-13}	6×10^{-16}
87	Fr			
88	Ra		9×10^{-7}	8.9×10^{-11}
89	Ac		5.5×10^{-10}	
90	Th	1.09×10^{-10} *6*	9.6	1×10^{-6}
91	Pa		1.4×10^{-6}	5×10^{-11}
92	U	2.94×10^{-11} *25*	2.7	0.0032

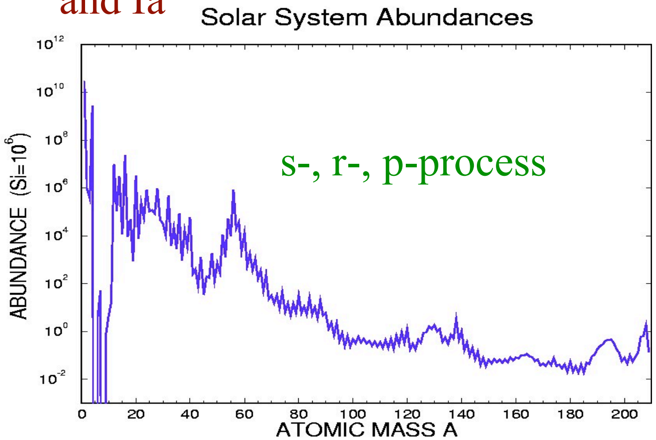
One of the Key Tools of Astrophysics:



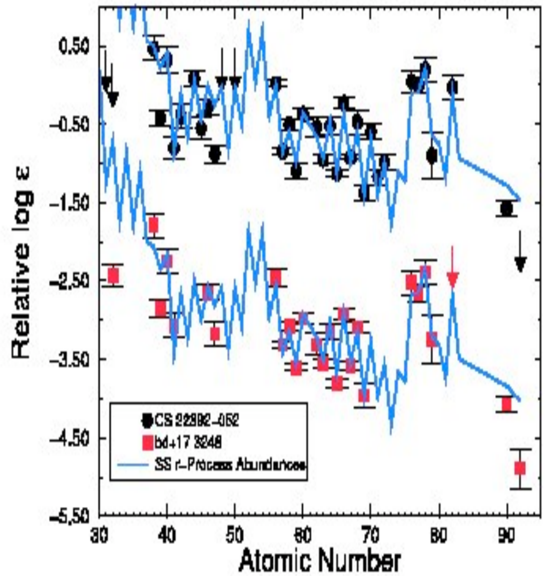
– ... the current 'lithurgy'

-> how much do we understand?

SNe II
and Ia

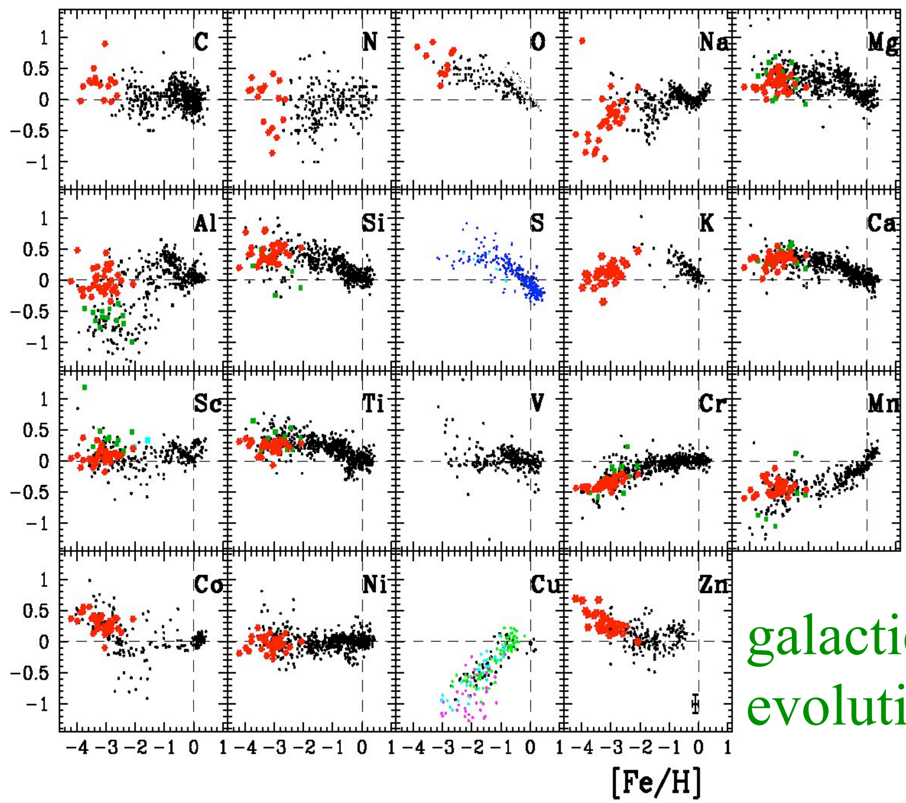


s-, r-, p-process

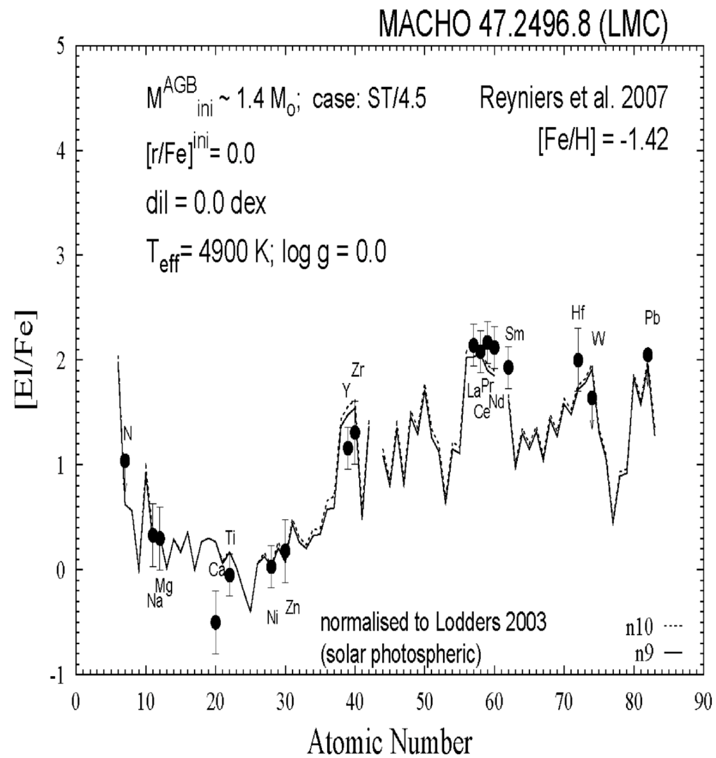


How do we understand:
solar system abundances..

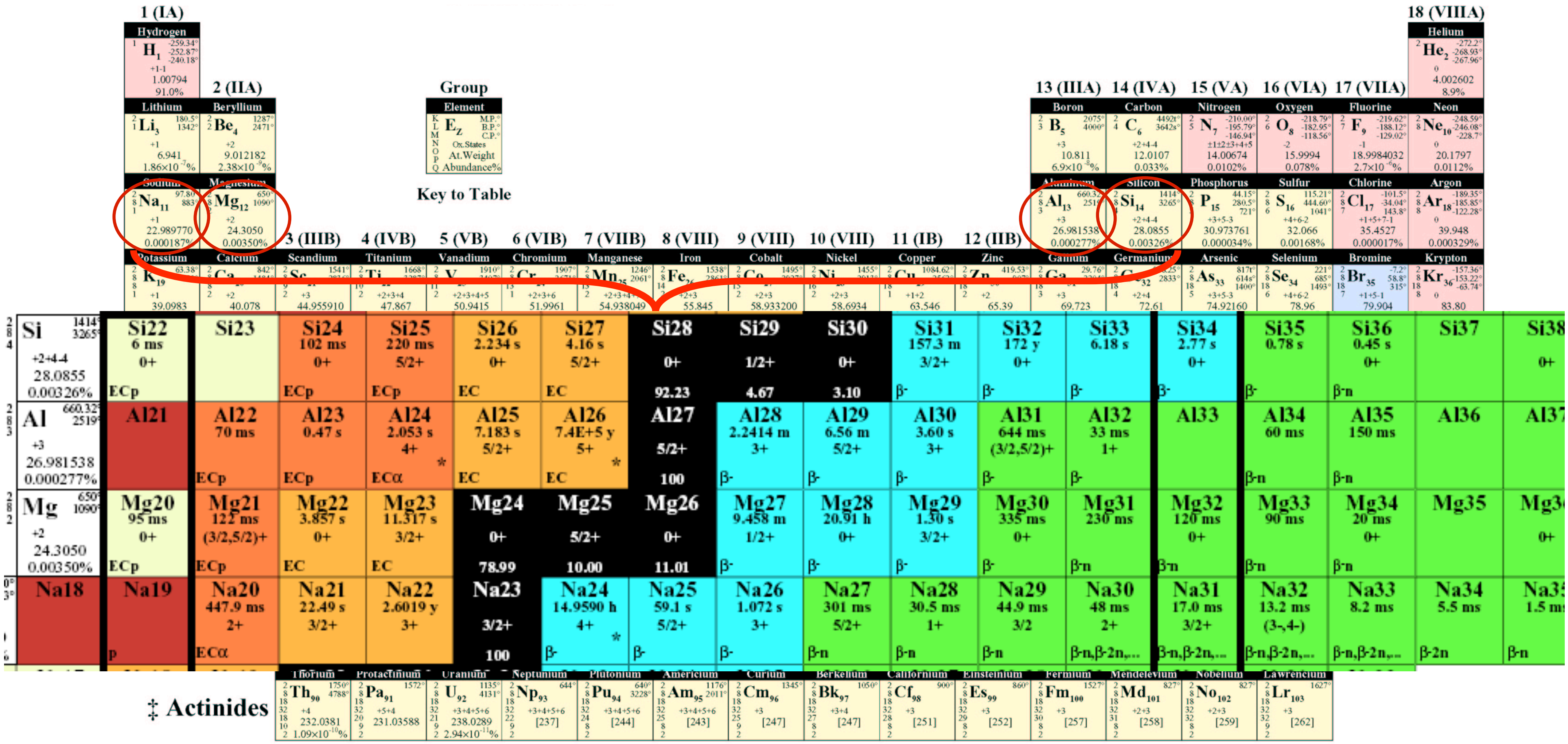
low metallicity stars ...



galactic
evolution?



From Atomic to Nuclear Physics



– Cosmic Nucleosynthesis Produces New **Isotopes**

- Diagnostics of Nuclear Fusion Reactions
  → Thermodynamic Variables in Hot (GK) Sites

s- and r-processes

The Origin of the Heaviest Elements

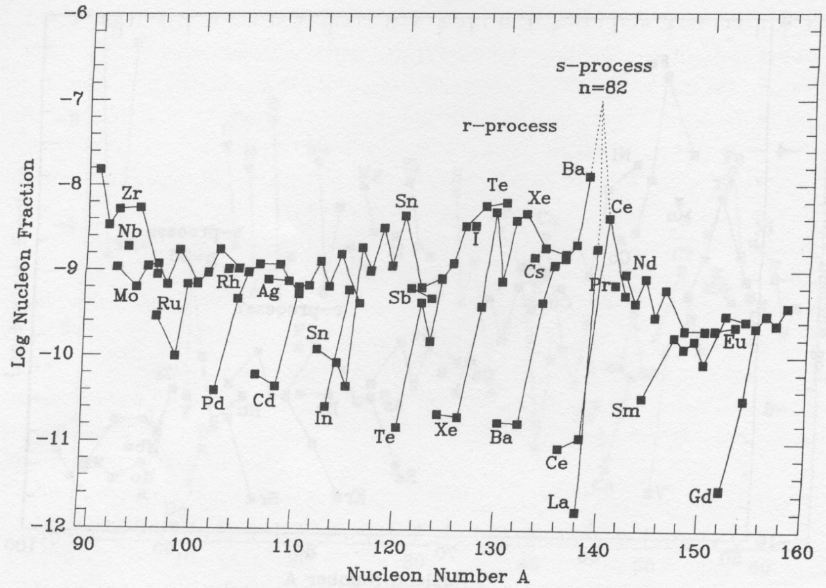


Fig. 2.4. Abundance ($A = 90, 160$)

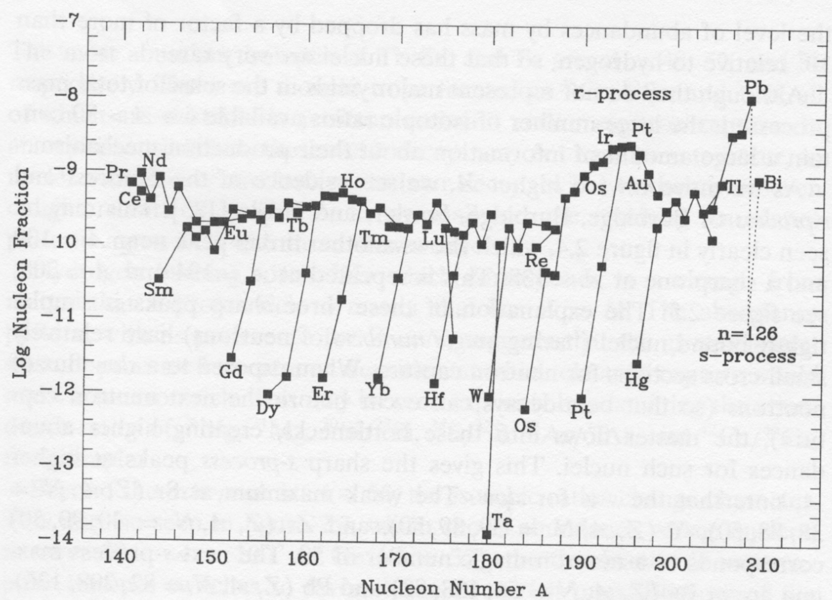
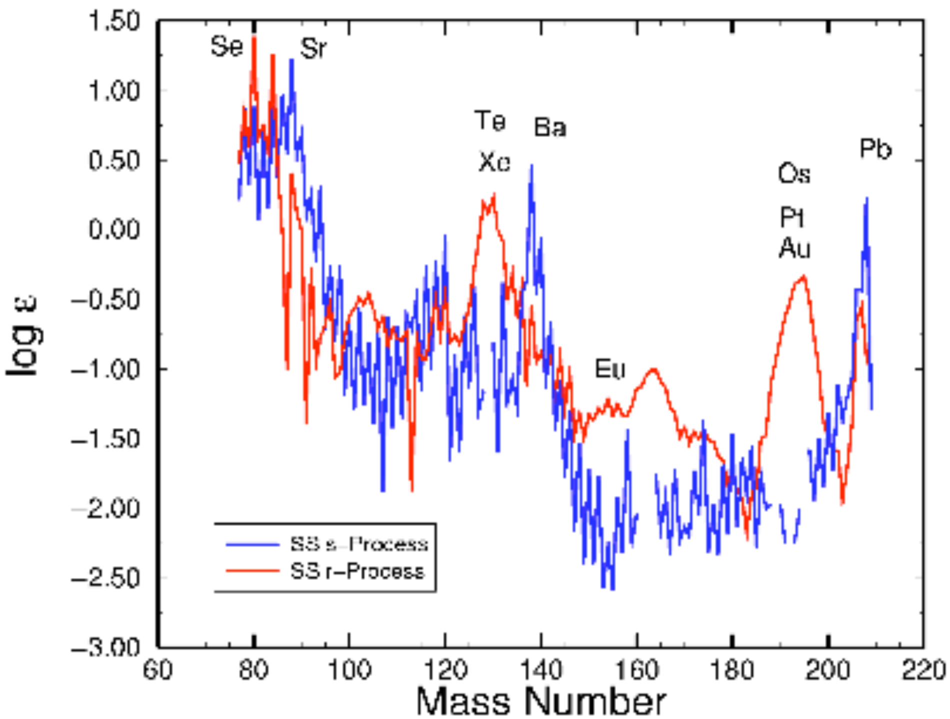


Fig. 2.5. Abundance ($A = 140, 210$)

s- and r-process Decomposition

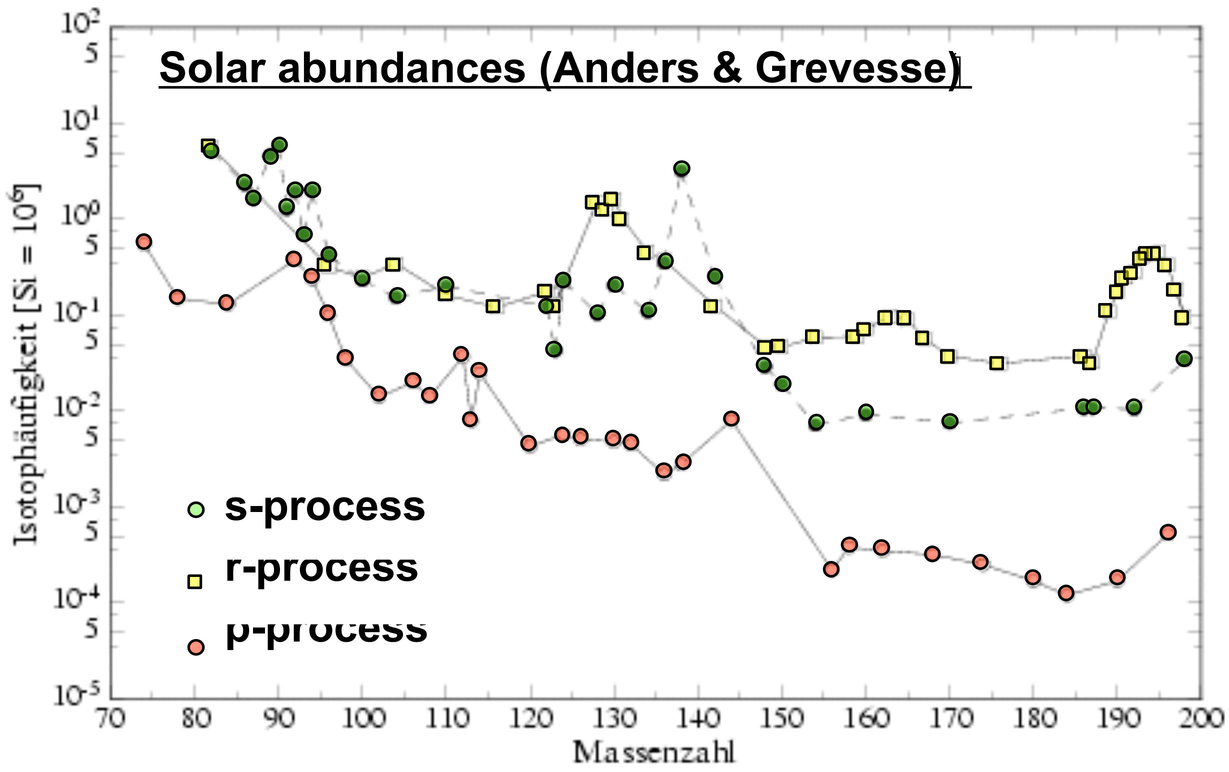


$$\dot{Y}(Z,A) = -\lambda_{\beta^-}(Z,A)Y(Z,A) - \rho N_A < \sigma v >_{n,\gamma} Y_n Y(Z,A)$$
$$= -\lambda_{\beta^-}(Z,A)Y(Z,A) - < \sigma v >_{n,\gamma} n_n Y(Z,A)$$
$$= -\frac{1}{\tau_\beta}Y(Z,A) - \frac{1}{\tau_{n,\gamma}}Y(Z,A).$$

which timescale is shorter? neutron capture inverse proportional to n_n !

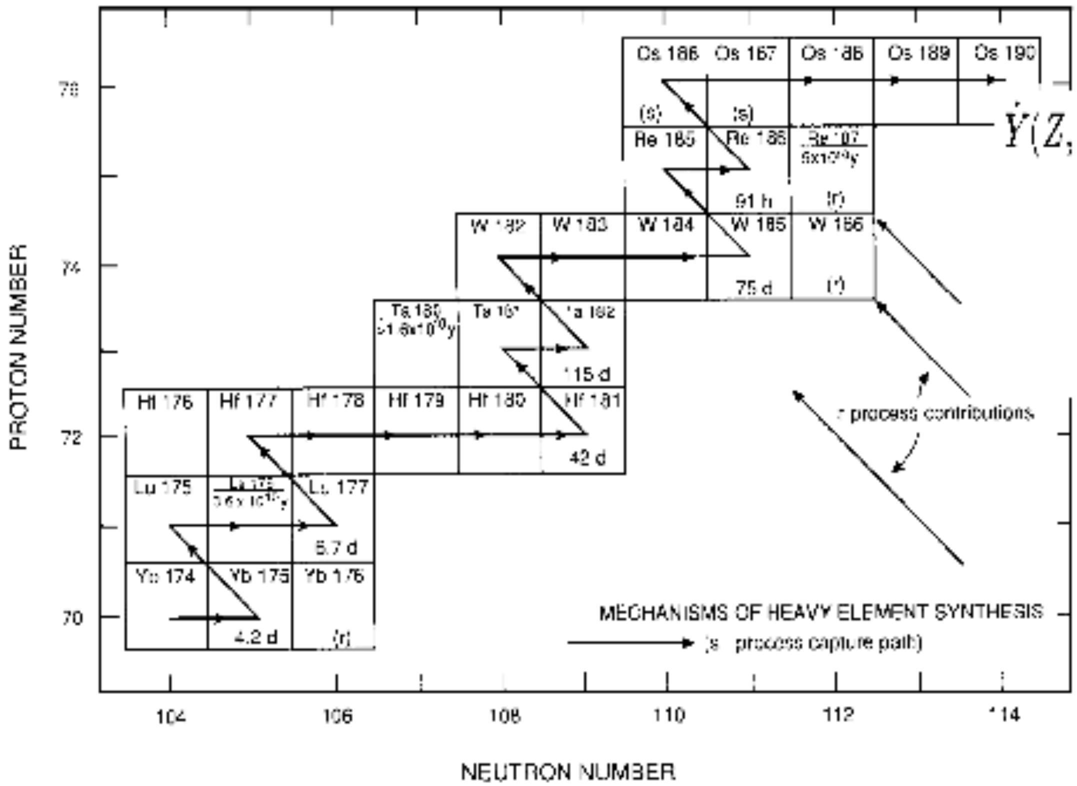
Heavy Elements are made by slow and rapid neutron capture events

The Heavy Elements



s-process

s-process and steady flow



possible destruction of nucleus (Z,A)

$$\dot{Y}(Z,A) = -\lambda_{\beta^-}(Z,A)Y(Z,A) - \rho N_A < \sigma v >_{n,\gamma} Y_n Y(Z,A)$$
$$= -\lambda_{\beta^-}(Z,A)Y(Z,A) - < \sigma v >_{n,\gamma} n_n Y(Z,A)$$
$$= -\frac{1}{\tau_\beta} Y(Z,A) - \frac{1}{\tau_{n,\gamma}} Y(Z,A).$$

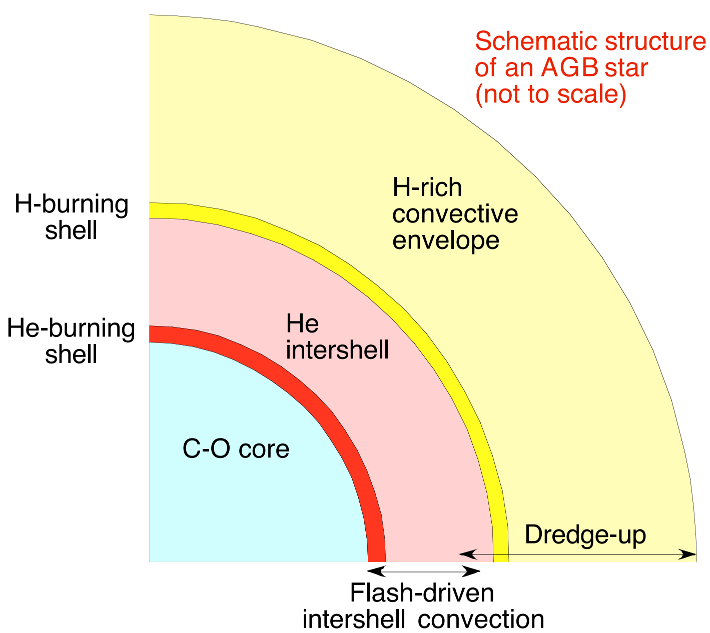
$\tau_n > \tau_\beta$ beta-decay to (Z+1,A)

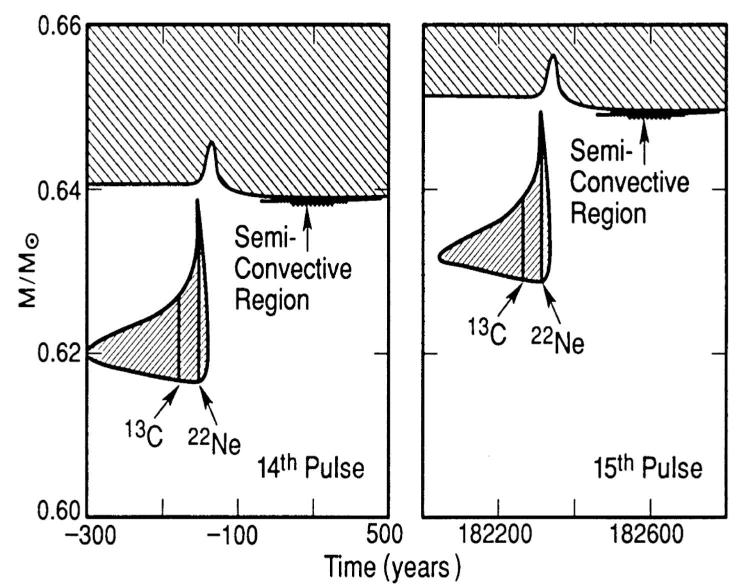
only one nucleus per A
needs to be considered!

$$\dot{Y}(A) = n_n < \sigma v >_{n,\gamma} Y(A-1) - n_n < \sigma v >_{n,\gamma} Y(A)$$ in case of steady flow =0

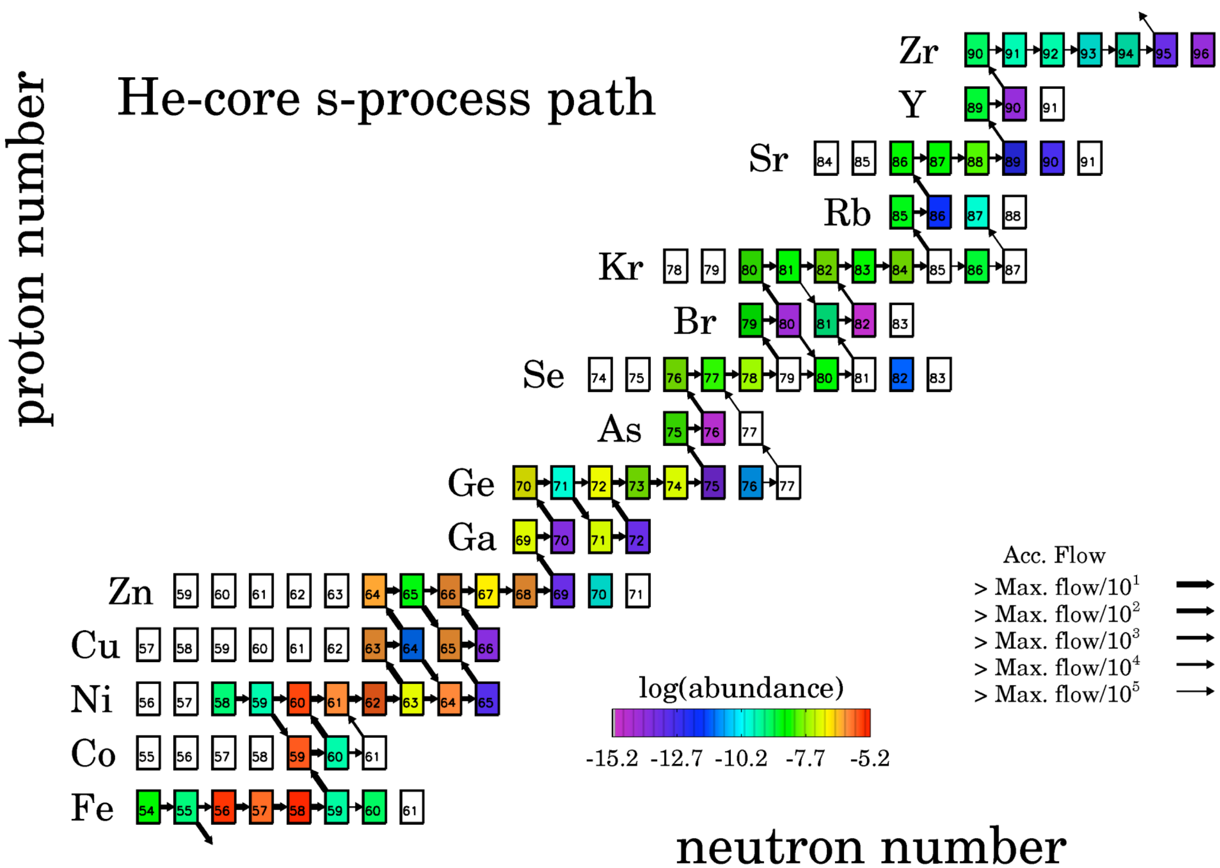
$\sigma \approx 1/v, < \sigma v > = \sigma(v)v$ therefore $\sigma(A-1, 30 \text{ keV})Y(A-1) = \sigma(A, 30 \text{ keV})Y(A)$

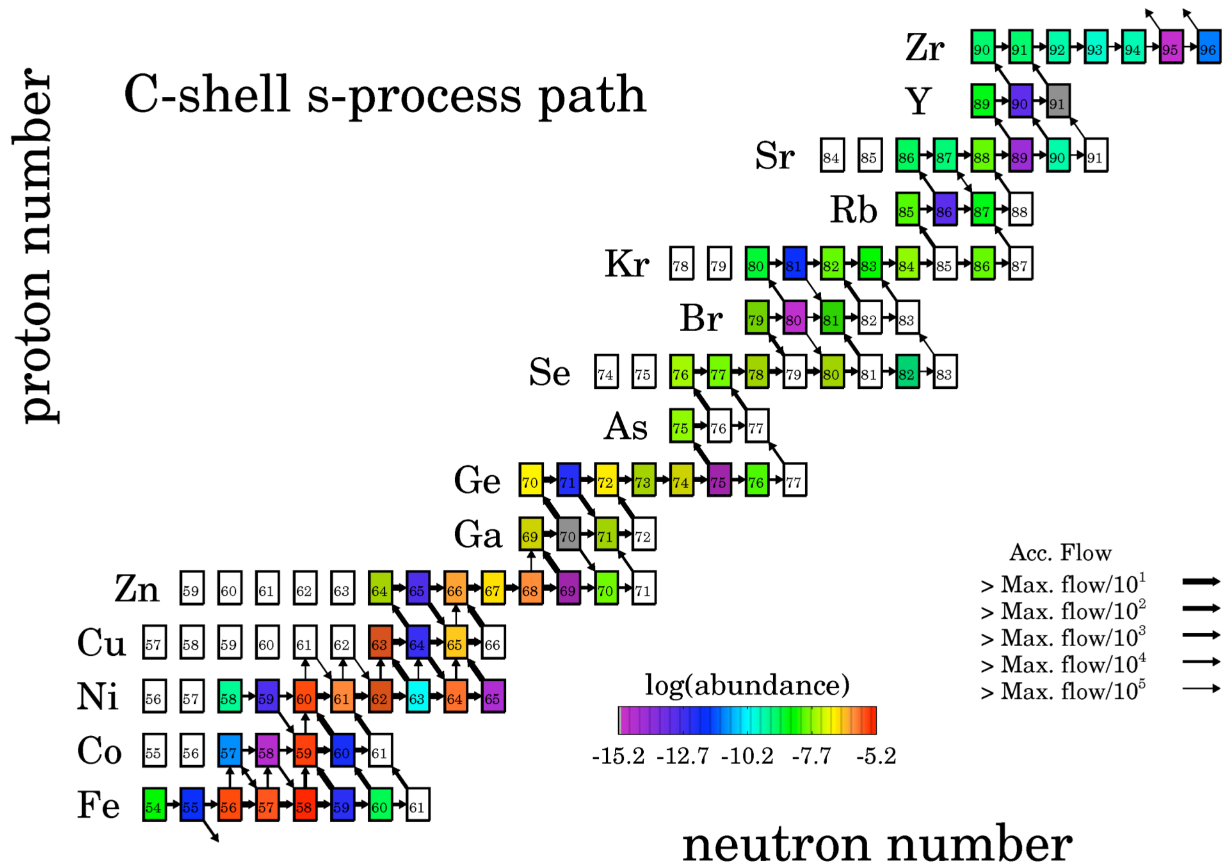
in low and intermediate mass stars the H- and He-shells are located at small distances. They do not burn in a constant fashion. If the H-burning zone is on, it creates He fuel. After sufficient He is produced in an unburned He-rich zone (leading to sufficient densities and temperatures), He is ignited. The burning is not stable, as the amount of energy created in a shallow zone is not sufficient to lift the overlaying H-shell which would cause expansion + cooling, i.e. steady burning. Instead He-burning, being dependent on the density squared burnes almost explosively (flash), causing then a stronger expansion which even stops H-burning in the H-shell. This behavior repeats in recurrent flashes. H is mixed into the unburned He fuel.





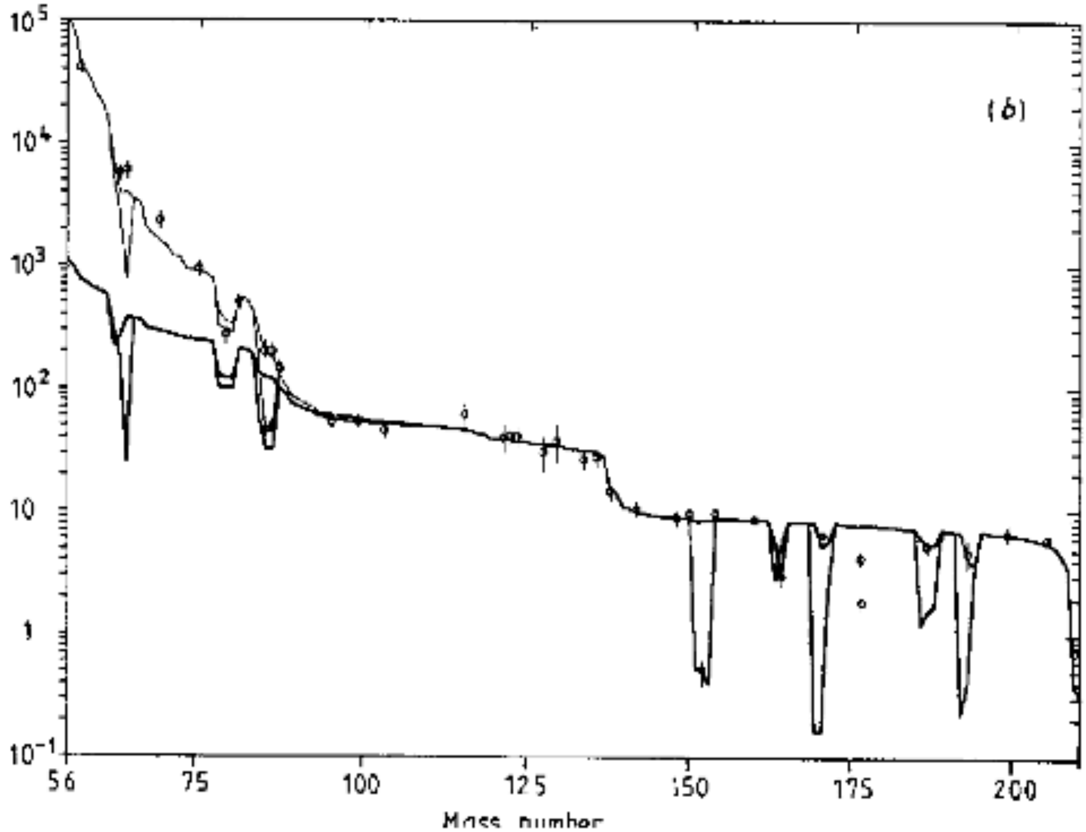
s-process reaction paths in core He and C-burning

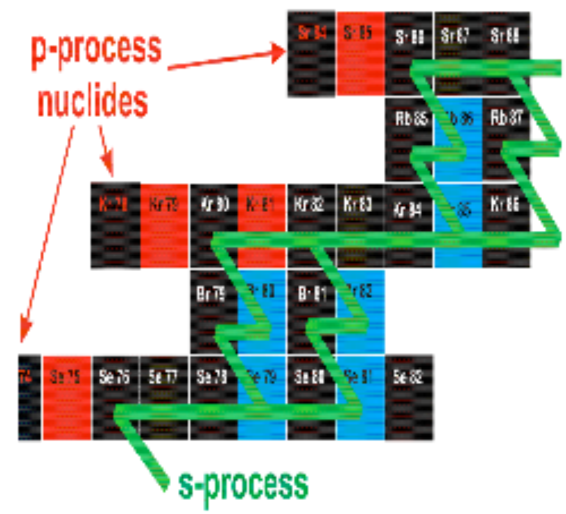




higher temperatures and neutrons densities lead to different branchings (The et al. 2007)

The sigma*N-curve





double values due to branchings

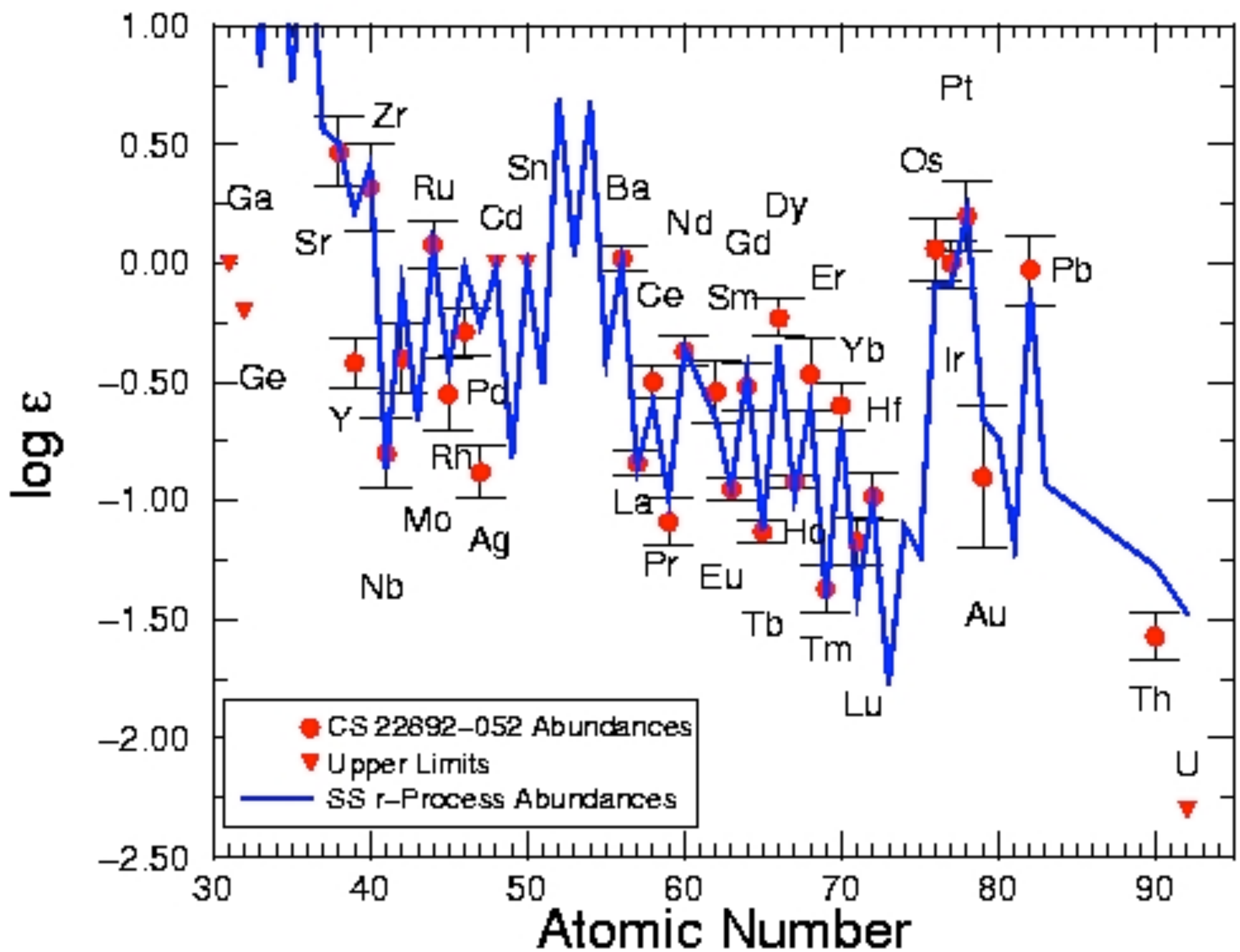
a complete steady flow is not given, but in between magic numbers (where the neutron capture cross sections are small) almost attained!

r-process

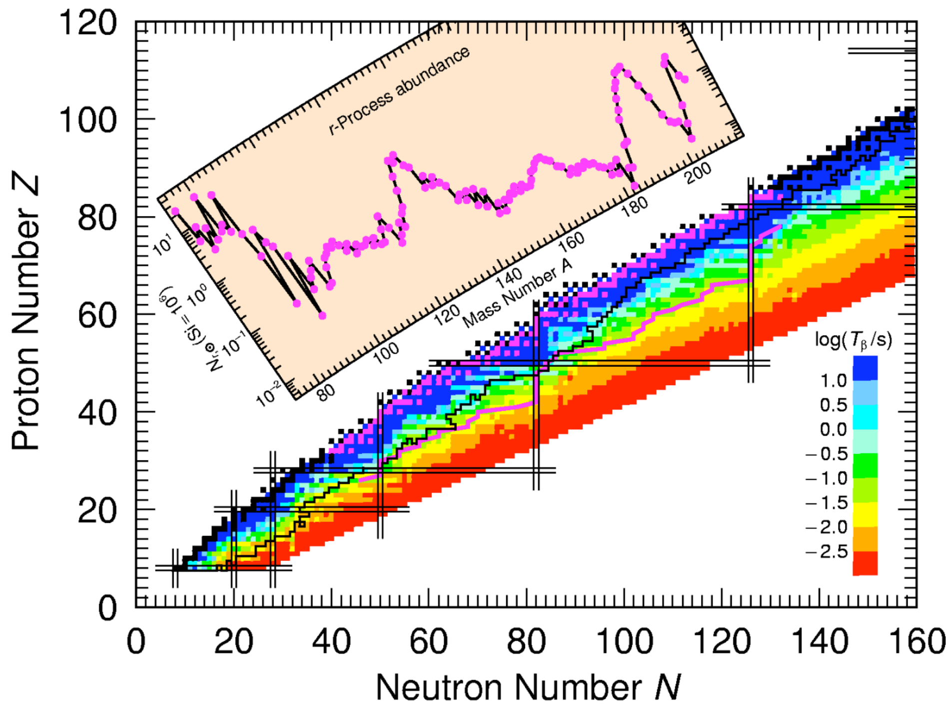
Site?

Readdressing Chemical Evolution in Galaxies as a function of metallicity:
CS22892-052: A pure r-process star at [Fe/H]=-3.1

(Cowan et al. 2005)



High neutron densities lead to nuclei far from stability



Nuclear Reactions to be considered: (n,γ), (γ,n)

(β,xn), (β,f), (n,f), inelastic ν-scattering, (ν_e,e^-) ......

Transmutation by Rapid Neutron Addition