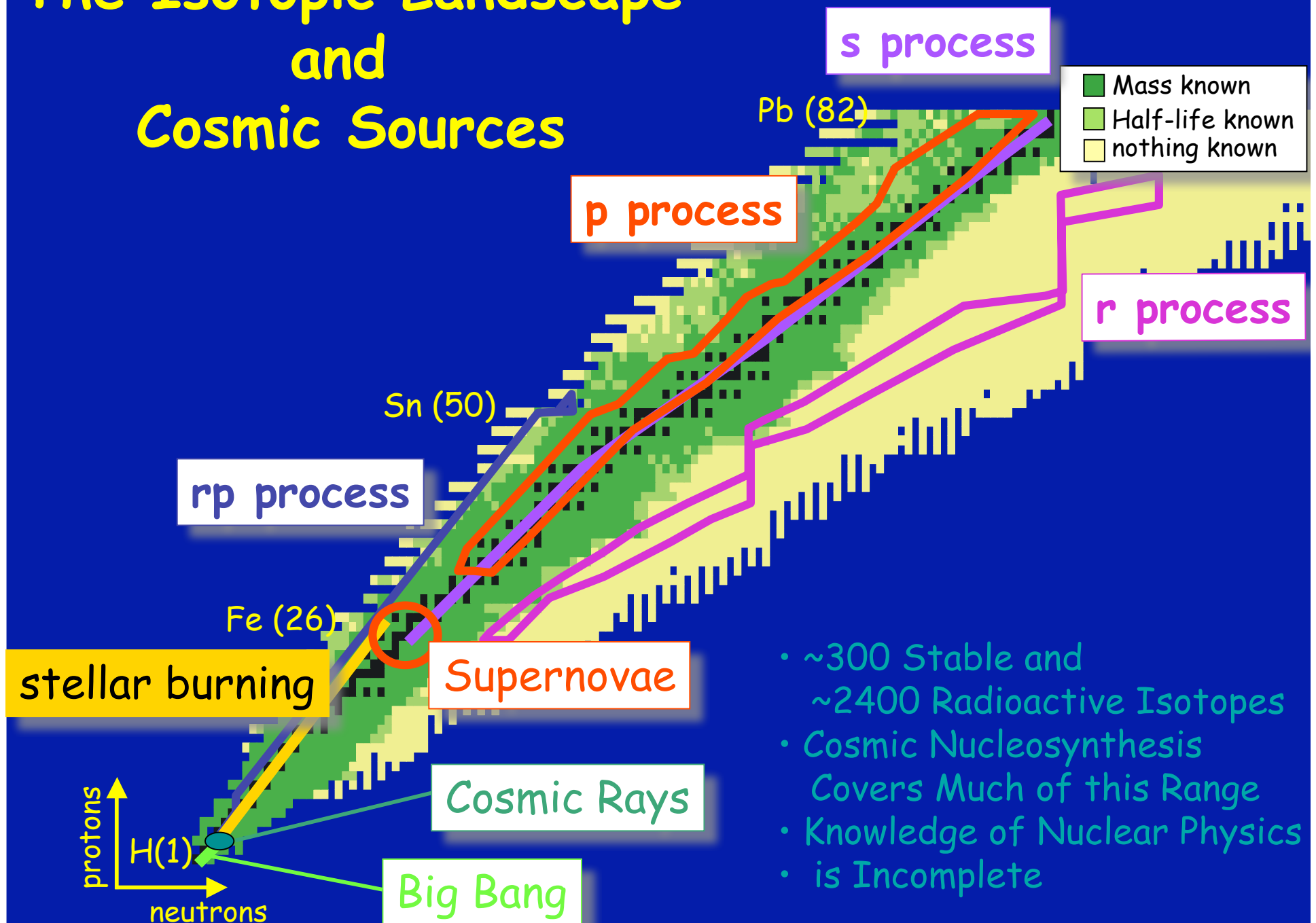


# Nucleosynthesis

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

<i>Rank</i>	<i>Z</i>	<i>Symbol</i>	<i>A</i>	<i>Nucleon Fraction</i>	<i>Source (process)</i>
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	<i>e</i> -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	<i>e</i> -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, <i>e</i> -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	<i>e</i> -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)

## 1. Hydrogen Burning

pp-cycles ->

CNO-cycle -> slowest reaction

$$T = (1-4) \times 10^7 \text{K}$$



s-process!

## 2. Helium Burning

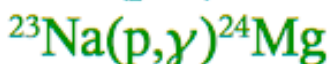


$$T = (1-2) \times 10^8 \text{K}$$

## 3. Carbon Burning



$$T = (6-8) \times 10^8 \text{K}$$



ongoing  
measurements of  
key fusion  
reactions at low  
energies

## 4. Neon Burning



$$T = (1.2-1.4) \times 10^9 \text{K}$$

$$30kT = 4\text{MeV}$$

## 5. Oxygen Burning



$$T = (1.5-2.2) \times 10^9 \text{K}$$



## 6. "Silicon" Burning

$$T = (3-4) \times 10^9 \text{K}$$

(all) photodisintegrations and capture reactions possible

⇒ thermal (chemical) equilibrium

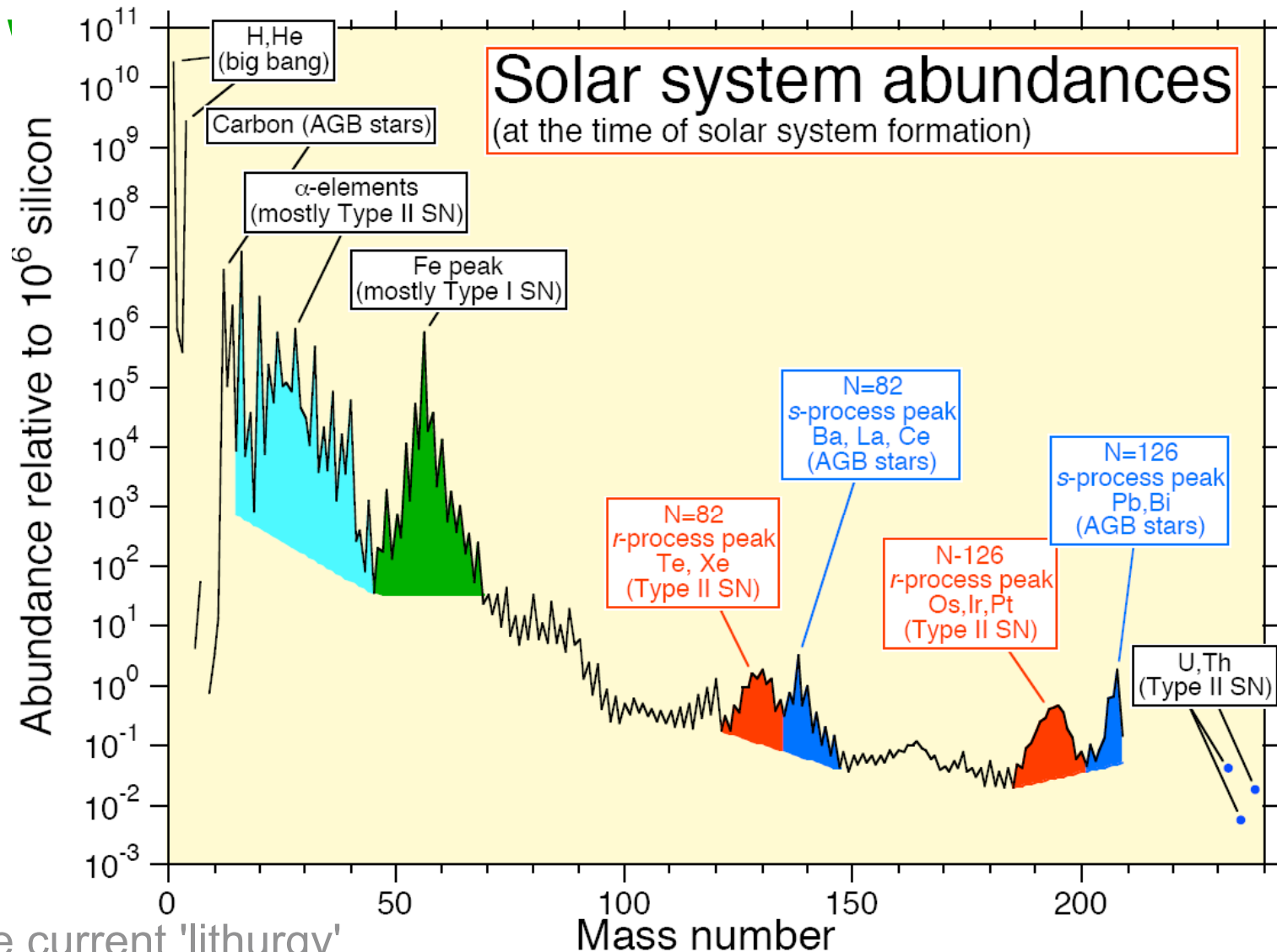


# Elemental Abundances

Table 2. Elemental Abundances

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

# One of the Key Tools of Astrophysics:

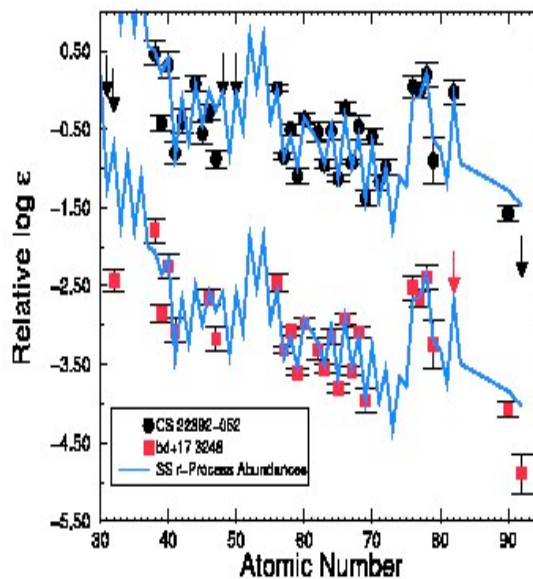
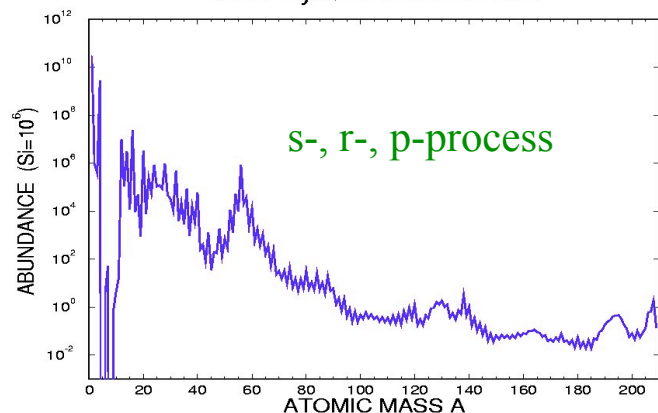


- ... the current 'lithurgy'
- > how much do we understand?

*Courtesy: Andy Davis*

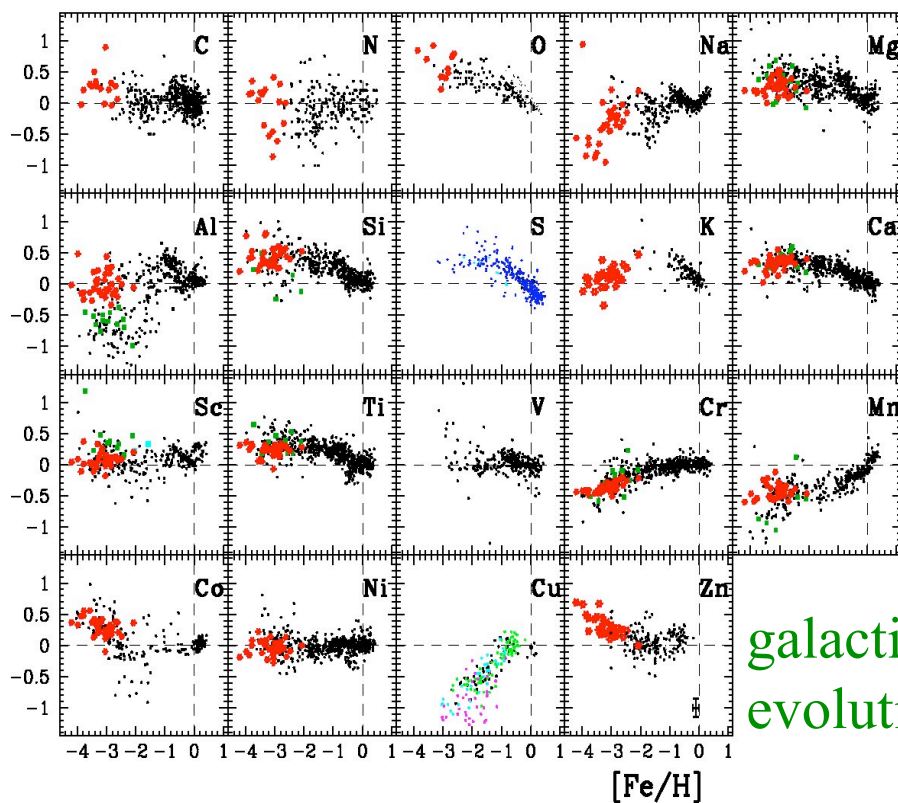
# SNe II and Ia

Solar System Abundances

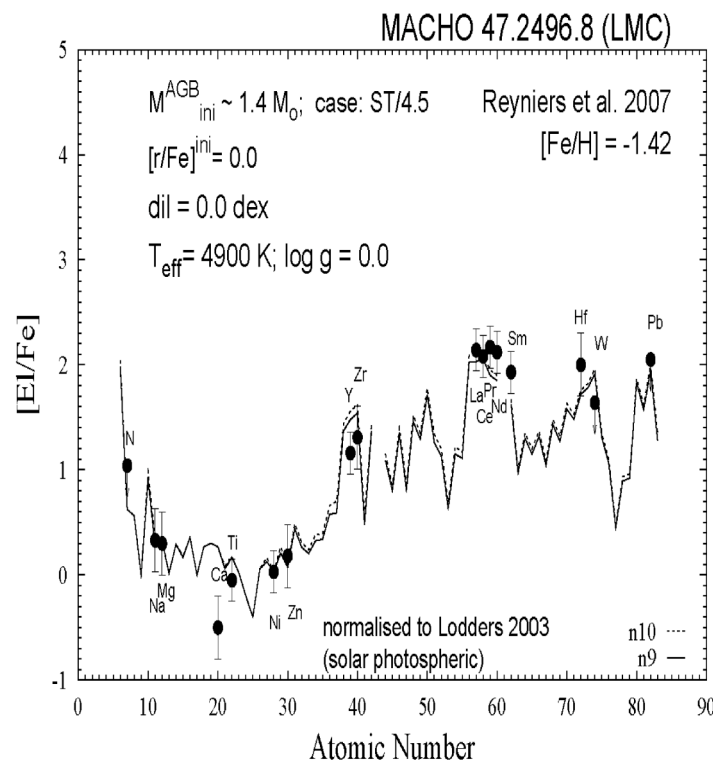


How do we understand:  
solar system abundances..

low metallicity stars ...



galactic  
evolution?



<b>1 (IA)</b>																	<b>18 (VIIIA)</b>
<b>Hydrogen</b> H 1 -259.34° +1-1 1.00794 91.0%																	<b>Helium</b> He 2 -272.2° 0 4.002602 8.9%
<b>2 (IIA)</b>																	
<b>Lithium</b> Li 3 -180.5° +1 6.941 1.86×10 <sup>-4</sup> %	<b>Beryllium</b> Be 4 -1287° +2 9.012182 2.38×10 <sup>-4</sup> %																
<b>Gallium</b> Ga 31 -30.26° +3 22.989770 0.000187%	<b>Magnesium</b> Mg 12 -1472° +2 24.3050 0.00350%																
<b>Potassium</b> K 19 -253.67° +1 39.0983	<b>Calcium</b> Ca 20 -29.15° +2 40.078	<b>Scandium</b> Sc 21 -29.15° +3 44.955910	<b>Titanium</b> Ti 22 -33.35° +4 47.867	<b>Vanadium</b> V 23 -33.6° +5 50.9415	<b>Chromium</b> Cr 24 -24.1° +6 51.9961	<b>Manganese</b> Mn 25 -161.7° +7 54.938049	<b>Iron</b> Fe 26 -27.1° +8 55.845	<b>Cobalt</b> Co 27 -15.9° +9 58.933200	<b>Nickel</b> Ni 28 -25.1° +10 58.6934	<b>Copper</b> Cu 29 -156° +11 63.546	<b>Zinc</b> Zn 30 -382° +12 65.39	<b>Gallium</b> Ga 31 -30.26° +3 69.723	<b>Germanium</b> Ge 32 -121° +4 72.61	<b>Arsenic</b> As 33 -120° +5 74.92160	<b>Selenium</b> Se 34 -49° +6 78.96	<b>Bromine</b> Br 35 -7.2° +7 79.904	<b>Krypton</b> Kr 36 -153.3° 0 83.80
<b>Si22</b> 6 ms 0+	<b>Si23</b>  ECp	<b>Si24</b> 102 ms 0+	<b>Si25</b> 220 ms 5/2+	<b>Si26</b> 2.234 s 0+	<b>Si27</b> 4.16 s 5/2+	<b>Si28</b>  92.23	<b>Si29</b>  4.67	<b>Si30</b>  3.10	<b>Si31</b> 157.3 m 3/2+	<b>Si32</b> 172 y 0+	<b>Si33</b> 6.18 s β-	<b>Si34</b> 2.77 s 0+	<b>Si35</b> 0.78 s β-	<b>Si36</b> 0.45 s 0+	<b>Si37</b>  β-n	<b>Si38</b>  0+	
<b>Al21</b>  ECp	<b>Al22</b> 70 ms ECp	<b>Al23</b> 0.47 s ECp	<b>Al24</b> 2.053 s 4+ *	<b>Al25</b> 7.183 s 5/2+ *	<b>Al26</b> 7.4E+S y 5+ *	<b>Al27</b>  100	<b>Al28</b> 2.2414 m β-	<b>Al29</b> 6.56 m β-	<b>Al30</b> 3.60 s β-	<b>Al31</b> 644 ms β-	<b>Al32</b> 33 ms β-	<b>Al33</b>  β-n	<b>Al34</b> 60 ms β-n	<b>Al35</b> 150 ms β-n	<b>Al36</b>  β-n	<b>Al37</b>  β-n	
<b>Mg20</b> 95 ms 0+	<b>Mg21</b> 122 ms (3/2,5/2)+	<b>Mg22</b> 3.857 s 0+	<b>Mg23</b> 11.317 s 3/2+	<b>Mg24</b>  0+	<b>Mg25</b>  5/2+	<b>Mg26</b>  0+	<b>Mg27</b> 9.458 m 1/2+	<b>Mg28</b> 20.91 h 0+	<b>Mg29</b> 1.30 s 3/2+	<b>Mg30</b> 335 ms 0+	<b>Mg31</b> 236 ms 0+	<b>Mg32</b> 120 ms 0+	<b>Mg33</b> 90 ms β-n	<b>Mg34</b> 20 ms β-n	<b>Mg35</b>  β-n	<b>Mg36</b>  β-n	
<b>Na19</b>  ECα	<b>Na20</b> 447.9 ms 2+	<b>Na21</b> 22.49 s 3/2+	<b>Na22</b> 2.6019 y 3+	<b>Na23</b>  100	<b>Na24</b> 14.9590 h 4+ *	<b>Na25</b> 59.1 s 5/2+	<b>Na26</b> 1.072 s 3+	<b>Na27</b> 301 ms 5/2+	<b>Na28</b> 30.5 ms 1+	<b>Na29</b> 44.9 ms 3/2	<b>Na30</b> 48 ms 2+	<b>Na31</b> 17.0 ms 3/2+	<b>Na32</b> 13.2 ms (3-,4-)	<b>Na33</b> 8.2 ms β-n	<b>Na34</b> 5.5 ms β-n	<b>Na35</b> 1.5 ms β-n	
<b>† Actinides</b>	<b>Th90</b> 1780° U 92 232.0381 1.09×10 <sup>10</sup> %	<b>Pa91</b> 1572° U 91 231.03588	<b>U92</b> 1135° U 92 238.0289	<b>Np93</b> 1343° Pu 93 [237]	<b>Pu94</b> 1267° Pu 94 [244]	<b>Am95</b> 1170° Am 95 [243]	<b>Cm96</b> 1345° Cf 96 [247]	<b>Bk97</b> 1065° Bk 97 [251]	<b>Cf98</b> 900° Cf 98 [252]	<b>Es99</b> 860° Es 99 [257]	<b>Fm100</b> 1527° Md 101 [258]	<b>Md101</b> 827° No 102 [259]	<b>No102</b> 827° Lr 103 [262]	<b>Lr103</b> 1627° Lr 103 [262]	<b>Lr104</b> 1627° Lr 104 [262]	<b>Lr105</b> 1627° Lr 105 [262]	

- 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



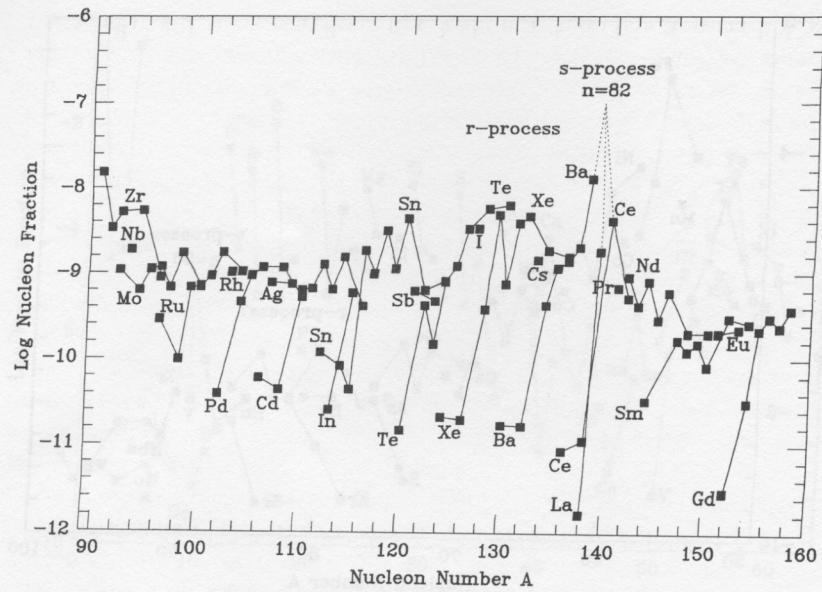


Fig. 2.4. Abundance ( $A = 90, 160$ )

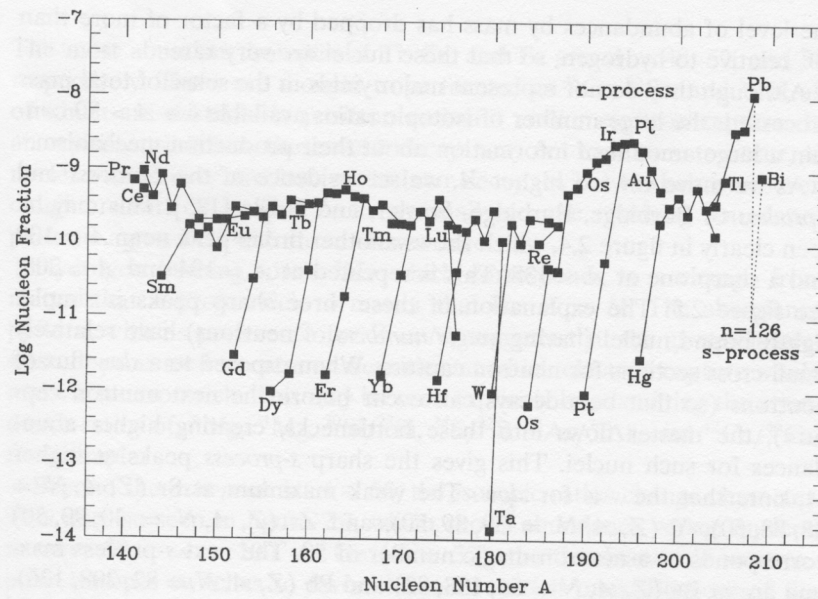
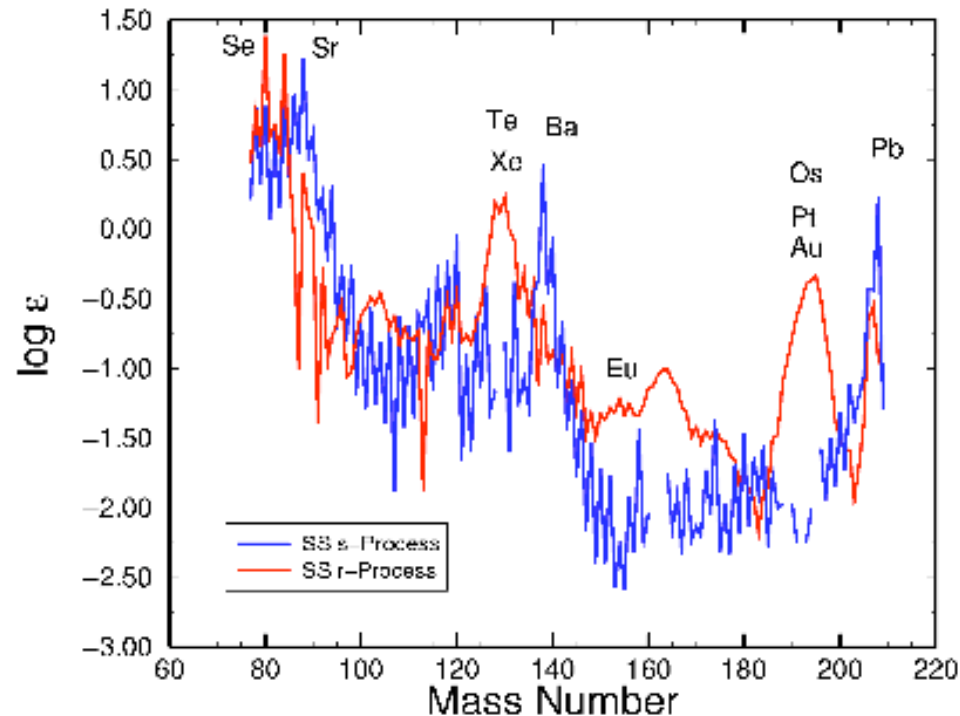


Fig. 2.5. Abundance ( $A = 140, 210$ )

## s- and r-process Decomposition

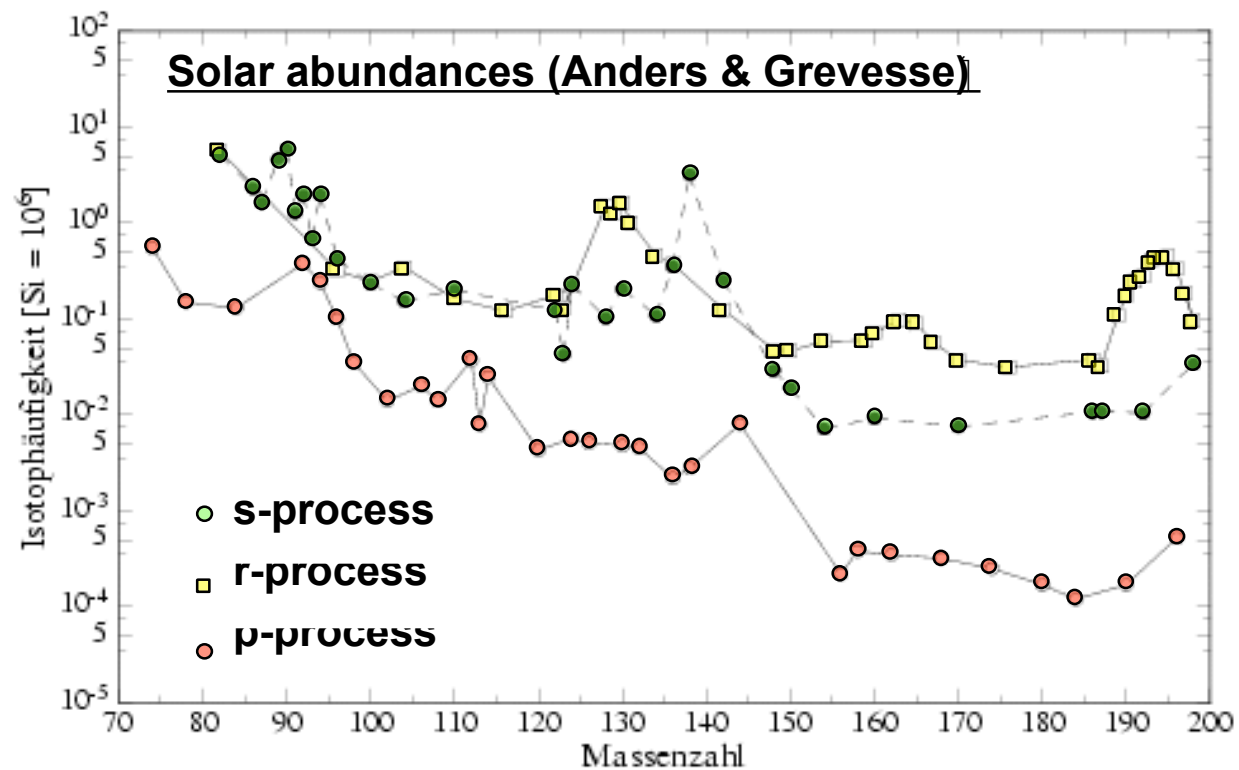


$$\begin{aligned}
 \dot{Y}(Z, A) &= -\lambda_{\beta}(Z, A)Y(Z, A) - \rho N_A \langle \sigma v \rangle_{n, \uparrow} Y_n Y(Z, A) \\
 &= -\lambda_{\beta}(Z, A)Y(Z, A) - \langle \sigma v \rangle_{n, \gamma} n_n Y(Z, A) \\
 &= -\frac{1}{\tau_{\beta}} Y(Z, A) - \frac{1}{\tau_{n, \uparrow}} Y(Z, A).
 \end{aligned}$$

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

Heavy Elements are made by **slow** and **rapid** neutron capture events

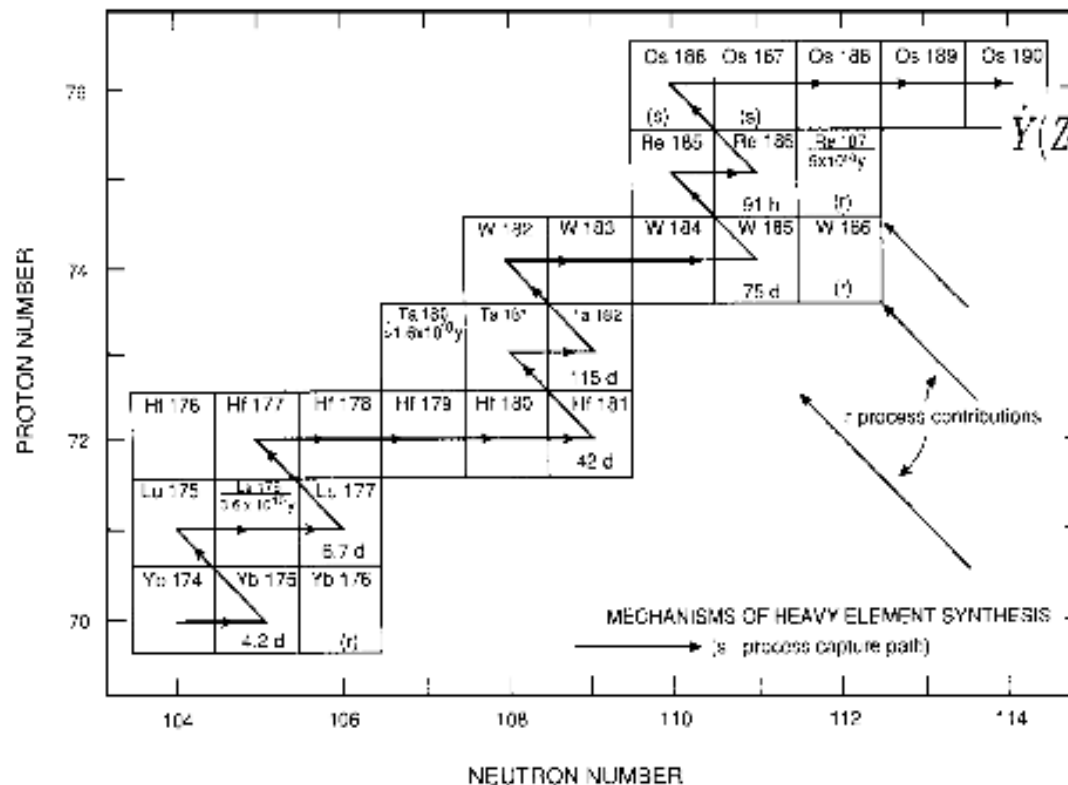
# The Heavy Elements





s-process

# s-process and steady flow



possible destruction of nucleus  $(Z, A)$

$$\begin{aligned}\dot{Y}(Z, A) &= -\lambda_{\beta-}(Z, A)Y(Z, A) - \rho N_A \langle \sigma v \rangle_{n,\gamma} Y_n Y(Z, A) \\ &= -\lambda_{\beta-}(Z, A)Y(Z, A) - \langle \sigma v \rangle_{n,\gamma} n_n Y(Z, A) \\ &= -\frac{1}{\tau_{\beta}} Y(Z, A) - \frac{1}{\tau_{n,\gamma}} Y(Z, A).\end{aligned}$$

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

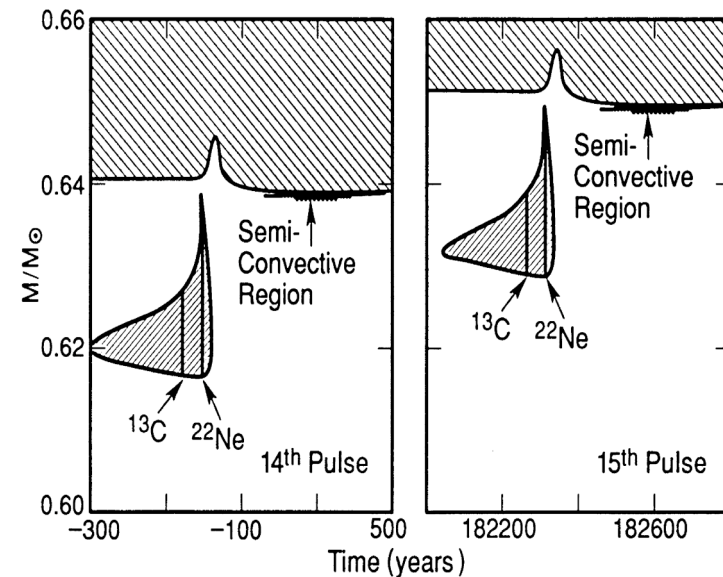
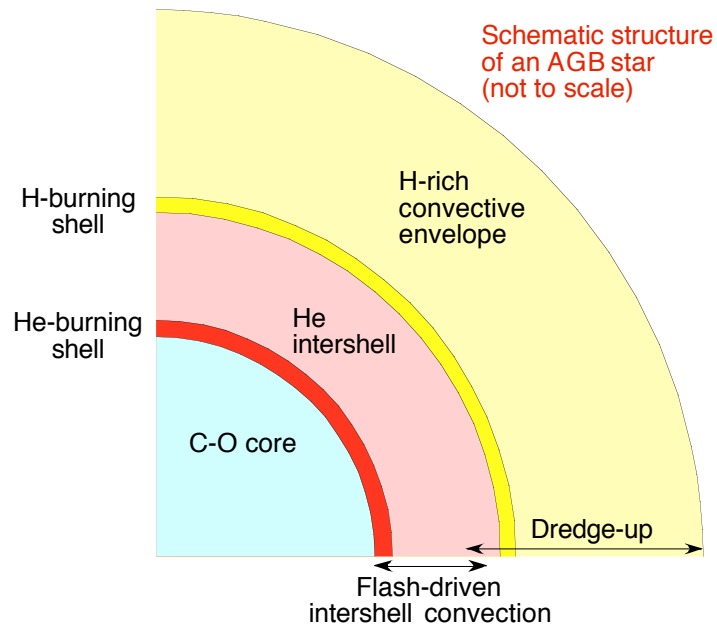
only one nucleus per  $A$   
needs to be considered!

$$\dot{Y}(A) = n_n \langle \sigma v \rangle_{n,\gamma} Y(A-1) - n_n \langle \sigma v \rangle_{n,\gamma} Y(A) \quad \text{in case of steady flow } = 0$$

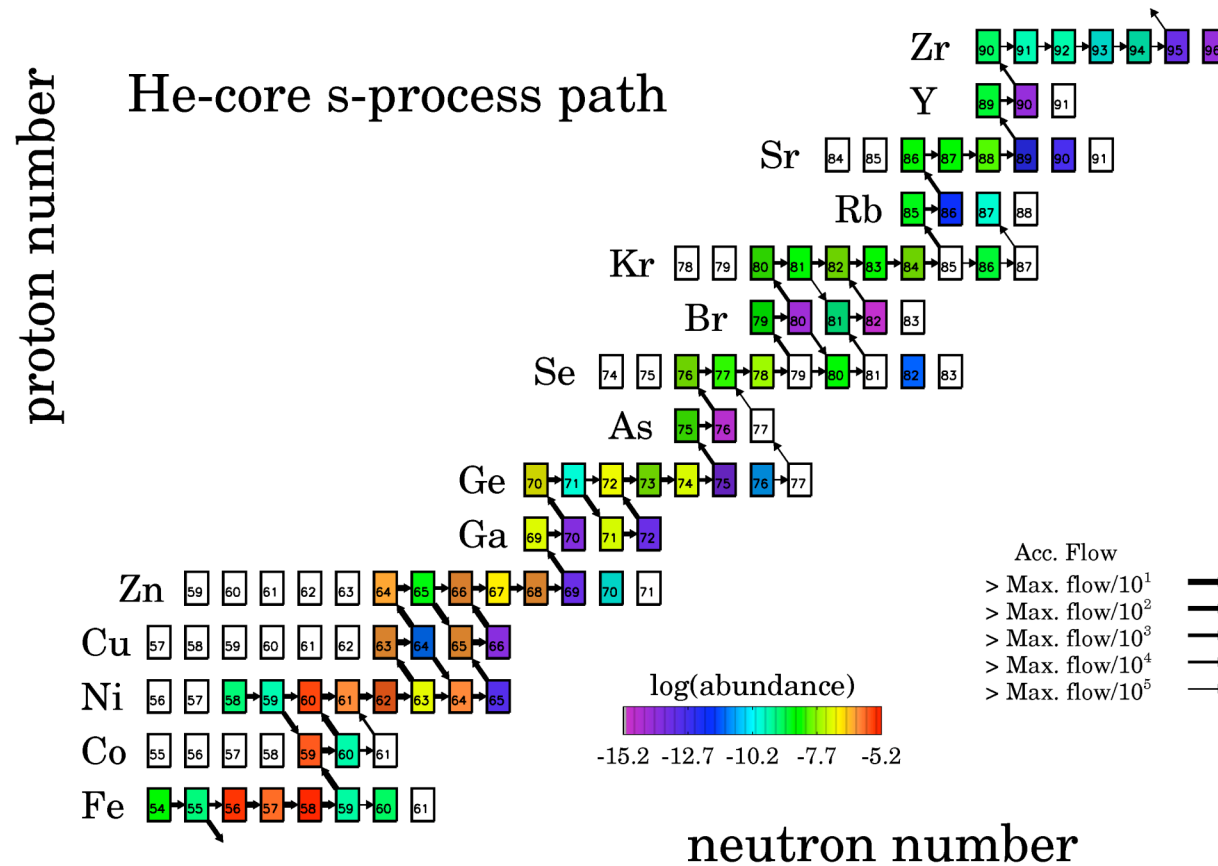
$$\sigma \approx 1/v, \langle \sigma v \rangle = \sigma(v)v \quad \text{therefore}$$

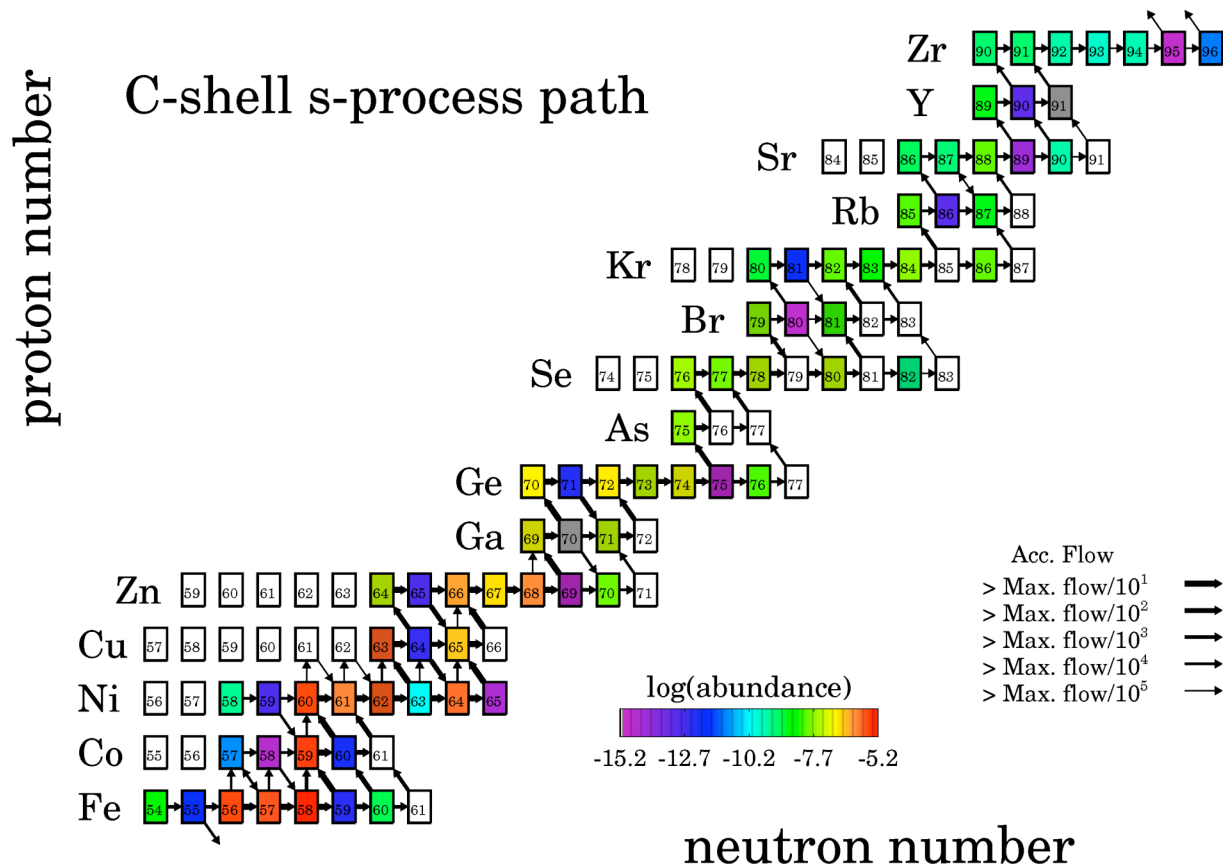
$$\sigma(A-1, 30 \text{ keV})Y(A-1) = \sigma(A, 30 \text{ keV})Y(A)$$

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 burns 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.



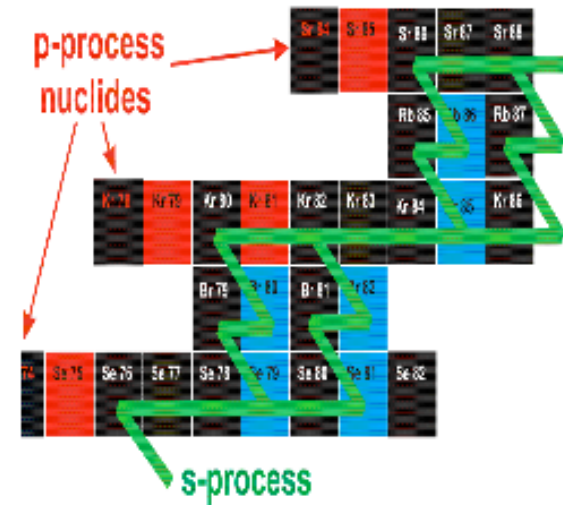
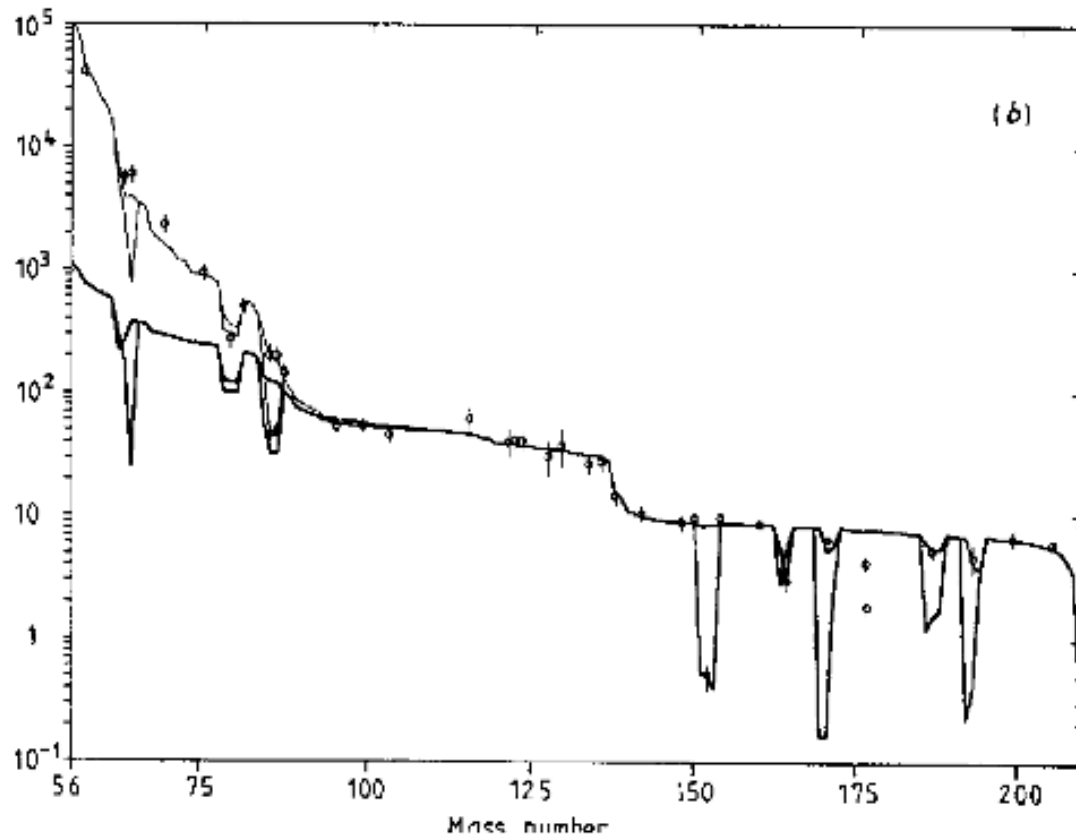
# s-process reaction paths in core He and C-burning





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

# The $\sigma \cdot N$ -curve



double values due to branchings

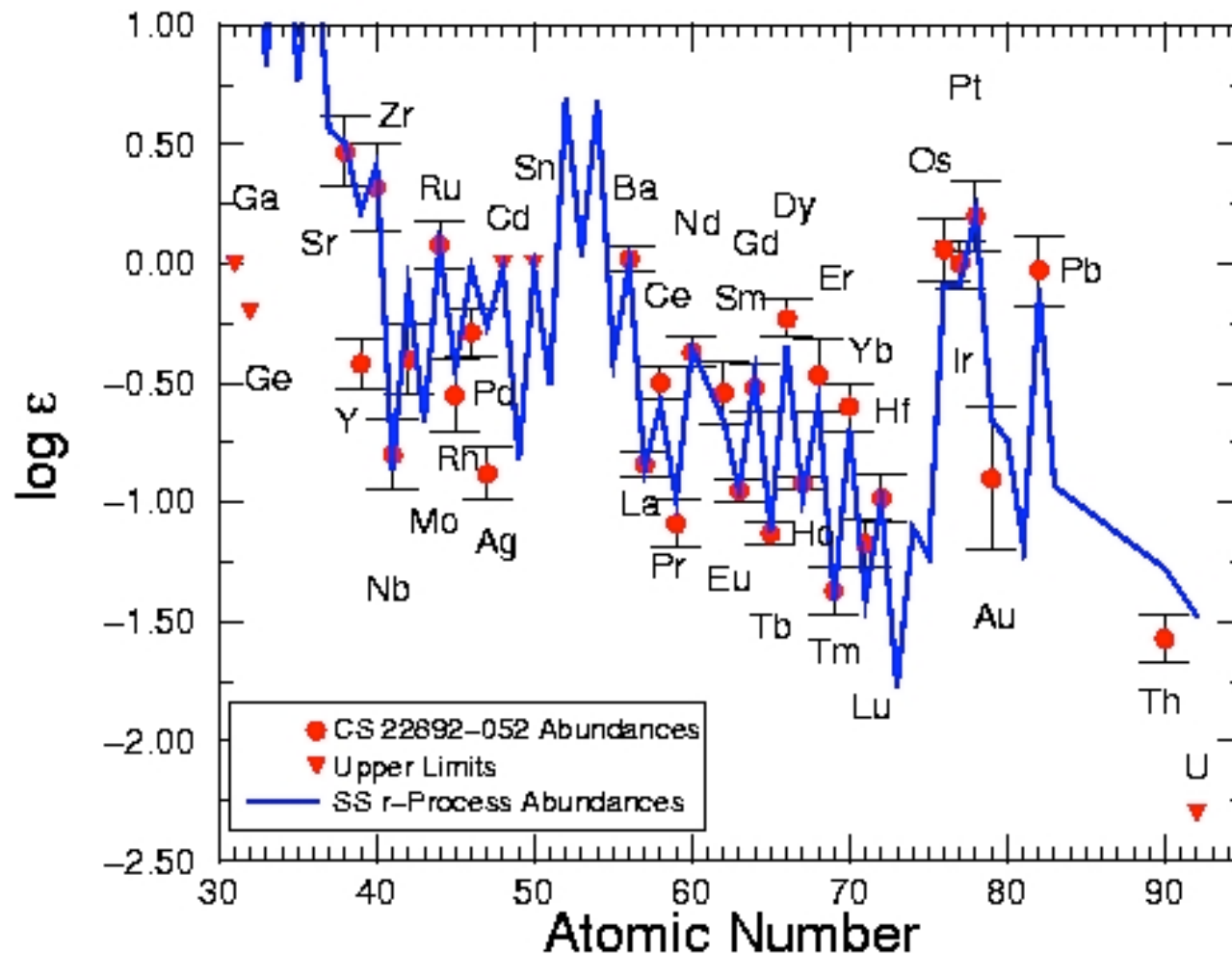
a complete steady flow is not given, but in between magic numbers (where the neutron capture cross sections are small) almost attained!

r-process

Site?

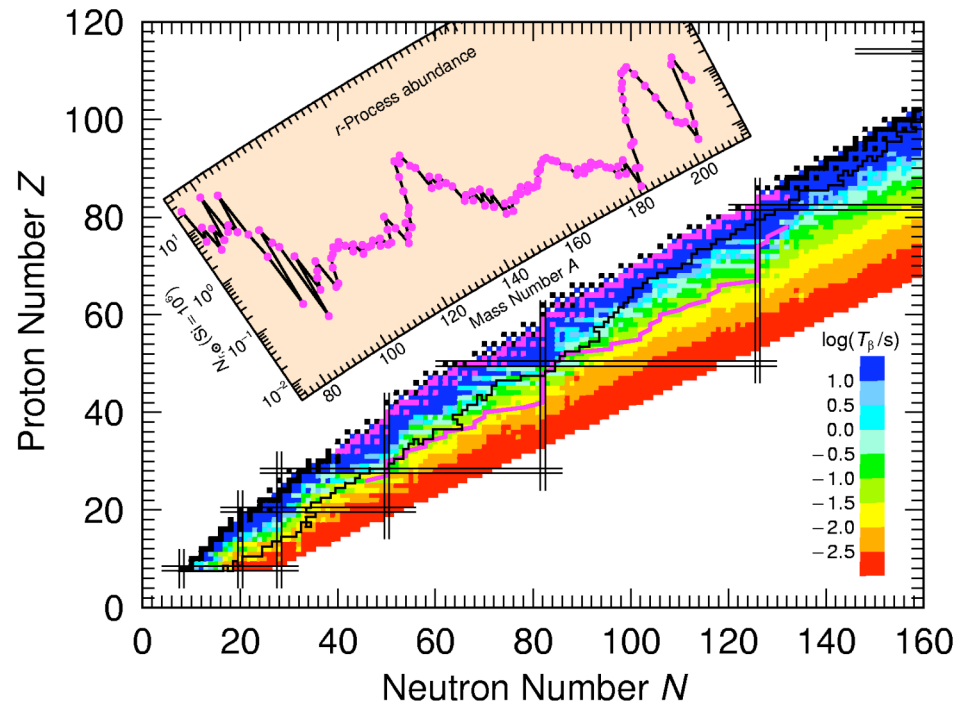
Readdressing Chemical Evolution in Galaxies as a  
function of metallicity:  
CS22892-052: A pure r-process star at  $[\text{Fe}/\text{H}]=-3.1$

(Cowan et al. 2005)





# High neutron densities lead to nuclei far from stability



Nuclear Reactions to be considered:  $(n, \gamma)$ ,  $(\gamma, n)$   
 $(\beta, xn)$ ,  $(\beta, f)$ ,  $(n, f)$ , inelastic  $\nu$ -scattering,  $(\nu_e, e^-)$  .....

# Transmutation by Rapid Neutron Addition

## Nucleosynthesis in the r-process

JINA

Joint Institute for Nuclear Astrophysics 2002

Movie : H. Schatz, National Superconducting Cyclotron Laboratory

Calculation : K. Vaughan, J.L. Galache,  
and A. Aprahamian, University of Notre Dame

Model : B. Meyer, Clemson University  
and R. Surman, North Carolina State

