Neutrinos and the *r*-process

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JINA Special School
Monday, May 14, 2007

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
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
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
55 Cs	56 Ba	*	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
87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

*** Lanthanides**	57 La	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
**** Actinides**	89 Ac	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

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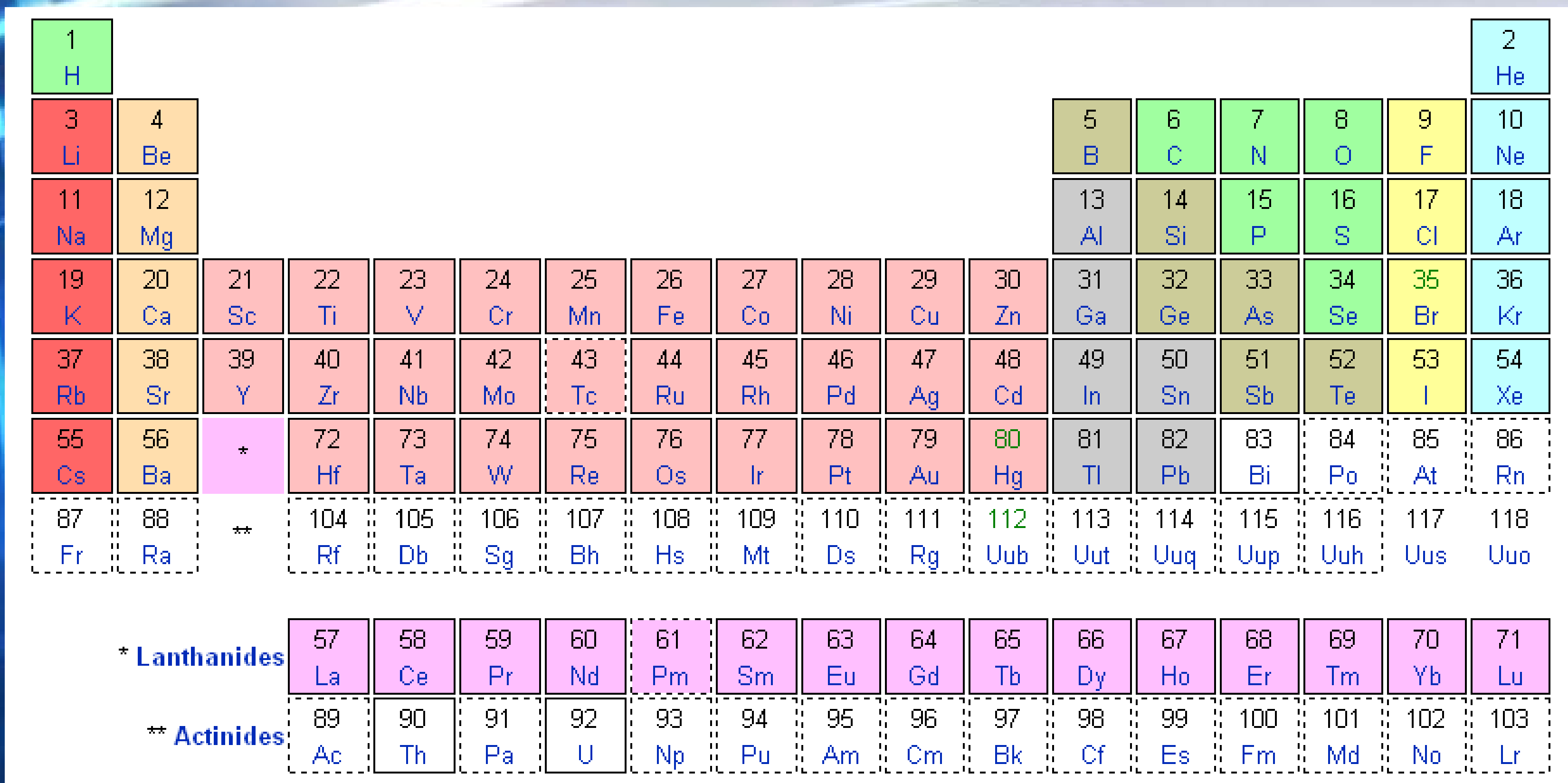
Big Bang… Cosmic Rays and Stellar Nucleosynthesis…



Big Bang… Cosmic Rays and Stellar Nucleosynthesis…

…Neutron Capture and *rp*-process…

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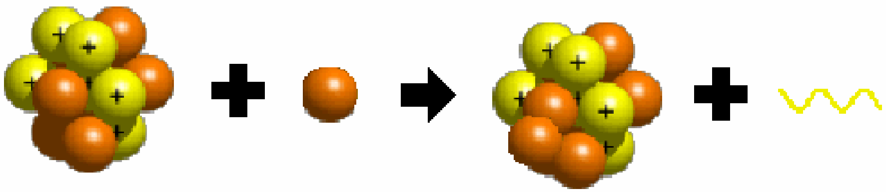
Big Bang… Cosmic Rays and Stellar Nucleosynthesis…

…Neutron Capture and *rp*-process… *r*-process

Neutron-Capture Nucleosynthesis

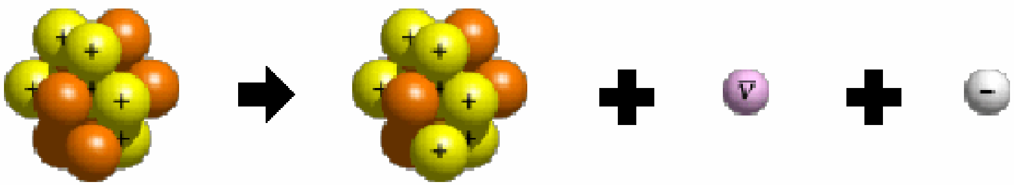
- S-process: Neutron capture slow compared to beta decay
- R-process: Neutron capture rapid compared to beta decay
- R-process peaks:
  - Strontium (A ~ 80)
  - Xenon (A ~ 130)
  - Europium (A ~ 165, rare earth)
  - Platinum (A ~ 195)

Neutron Capture

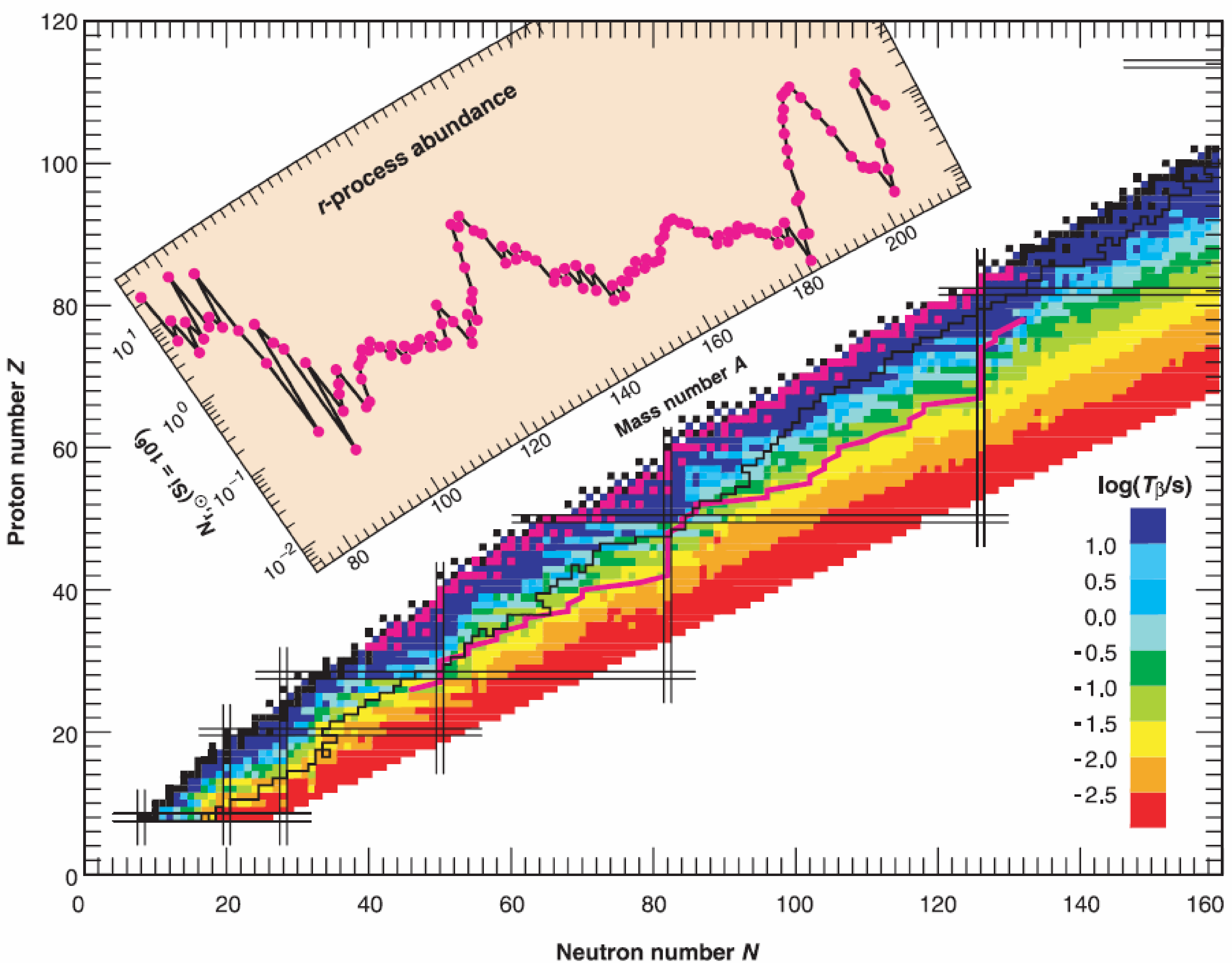


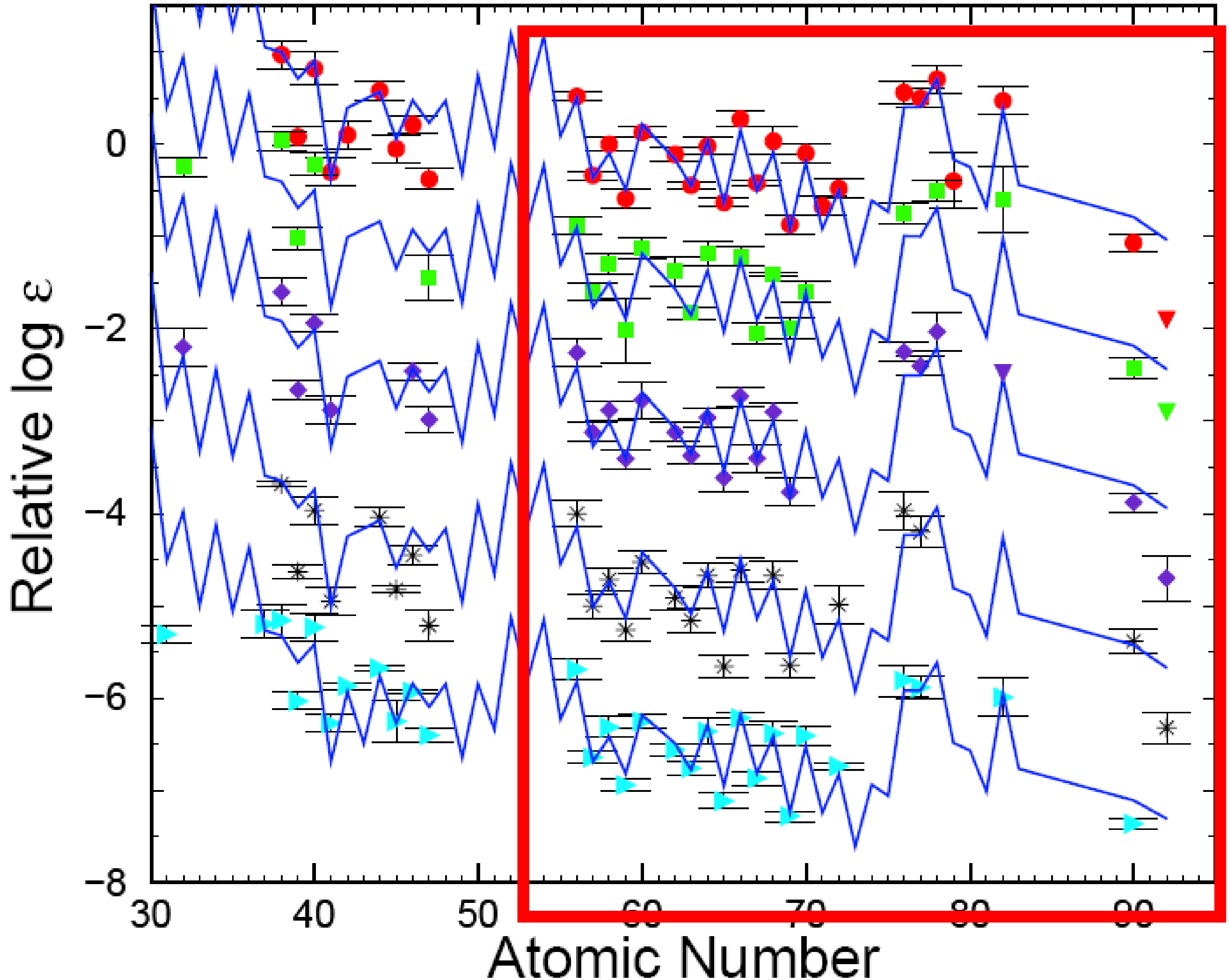
$$A(Z,N) + n \rightarrow A(Z,N+1) + \gamma$$

Beta Minus Decay



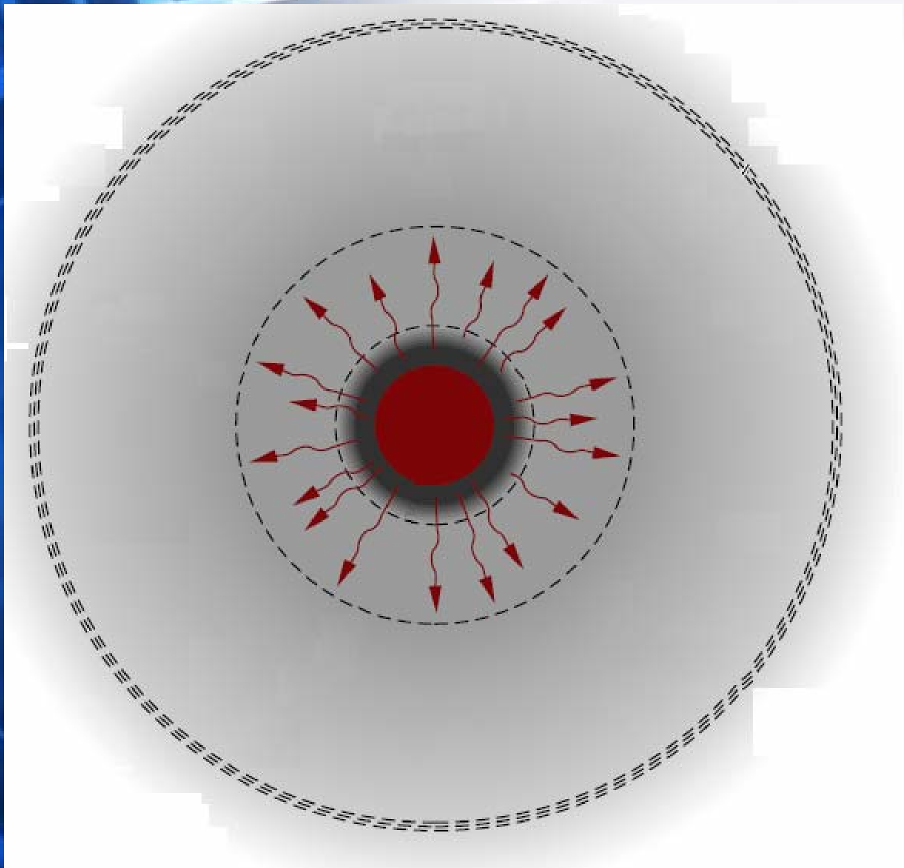
$$A(Z,N) \rightarrow A(Z+1,N-1) + \bar{\upsilon}_e + e^-$$


r-process abundance
Mass number A
$N_{r,\odot}$ (Si = 10^6)
Proton number Z
Neutron number N
log(T_β/s)
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5



Relative log ε
Atomic Number
0
−2
−4
−6
−8
30
40
50
60
70
80
90

Neutrino Driven Wind



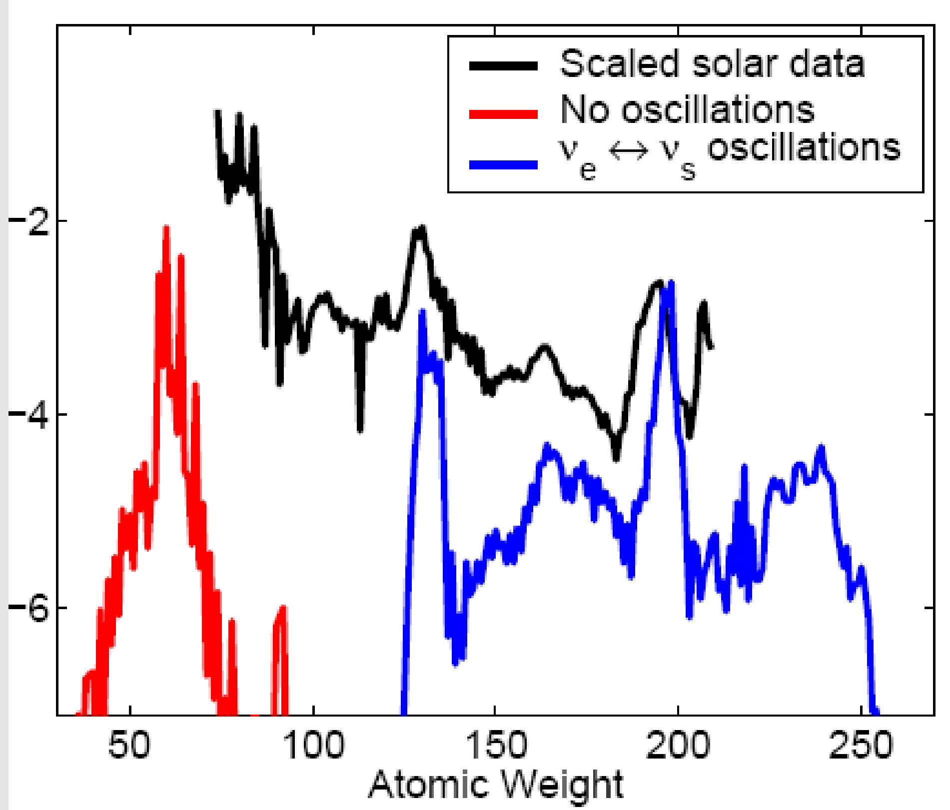
- Proto-neutron Star
  - Radius ~ 10-15 km
  - Mass ~ 1.4 $M_{\odot}$
- ~ 99% of energy into

  υ_e , υ_μ , υ_τ , $\overline{\upsilon}_e$, $\overline{\upsilon}_\mu$, $\overline{\upsilon}_\tau$
- Mean Energies
  - $\langle E\upsilon_e \rangle$ ~ 11 MeV
  - $\langle E\overline{\upsilon}_e \rangle$ ~ 16 MeV

$\overline{\upsilon}_e + p \rightarrow n + e^+$ favored over $\upsilon_e + n \rightarrow p + e^-$

Abundance Yields

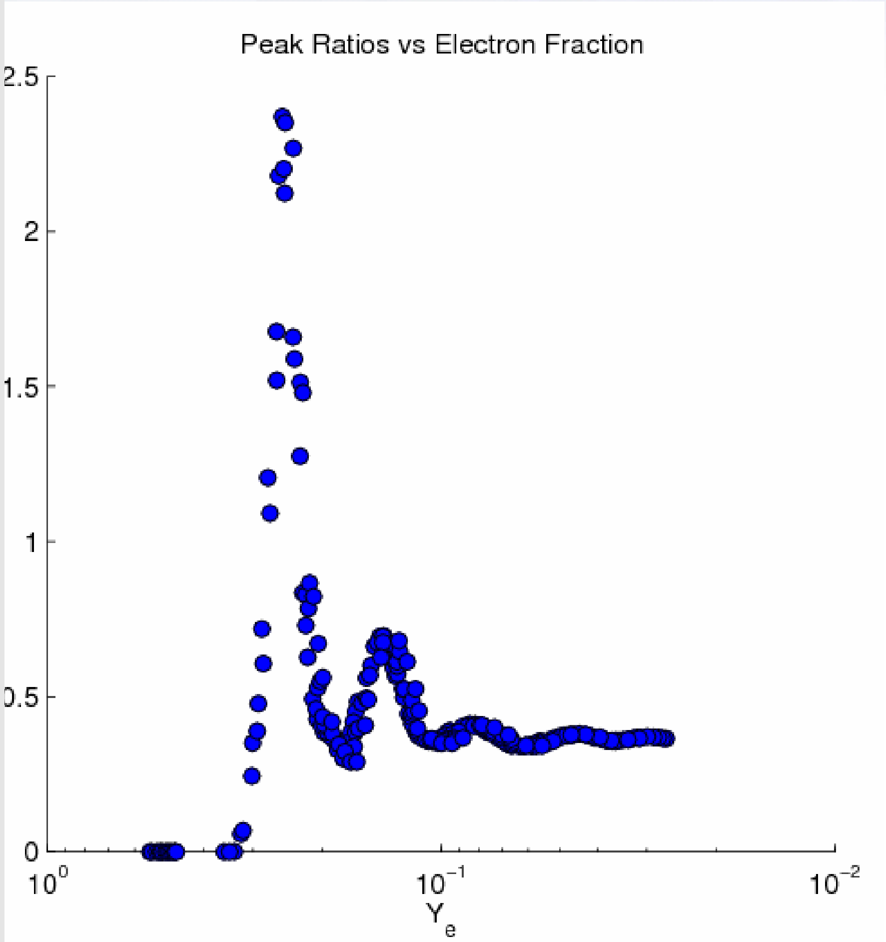
- Traditional Core-collapse Supernova Does Not Produce The *r*-process
- Active-Sterile Neutrino Oscillations Result In *r*-process Element Production



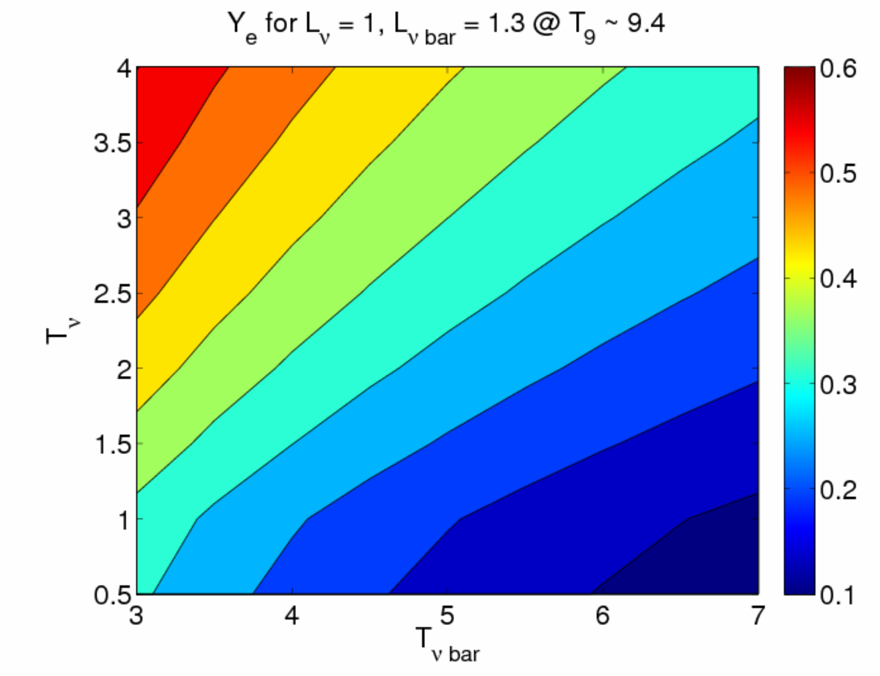
Phys.Rev. D73 (2006) 093007, J. Beun, G.C. McLaughlin, R. Surman, W.R. Hix

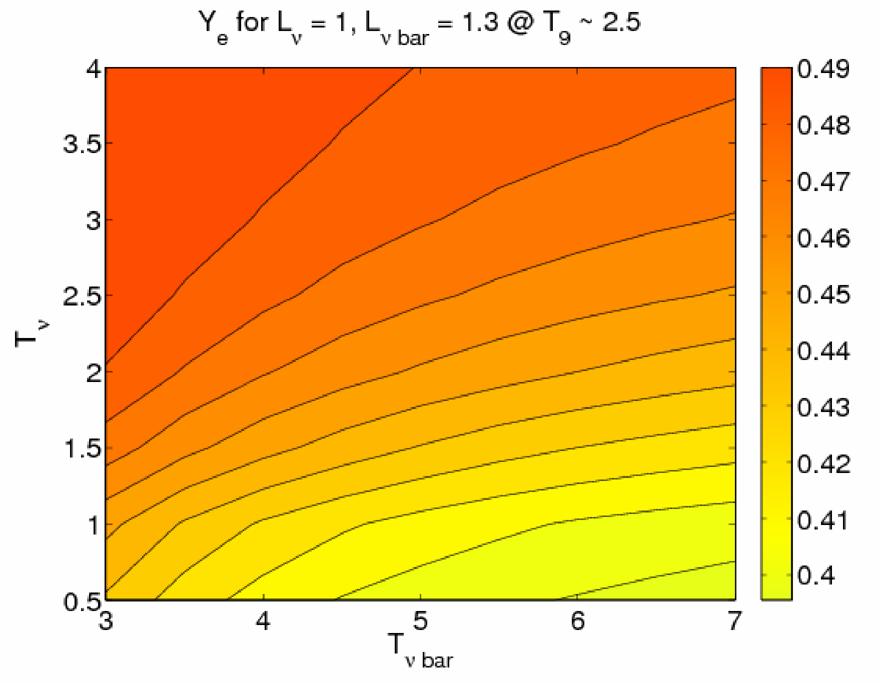
Abundance: Fission Cycling

- Progressively Lower Electron Fractions Converge To A Single *r*-process Pattern
- Asymptotic Value Dependent on Fission Model



Electron Fraction: Mean Neutrino Energy

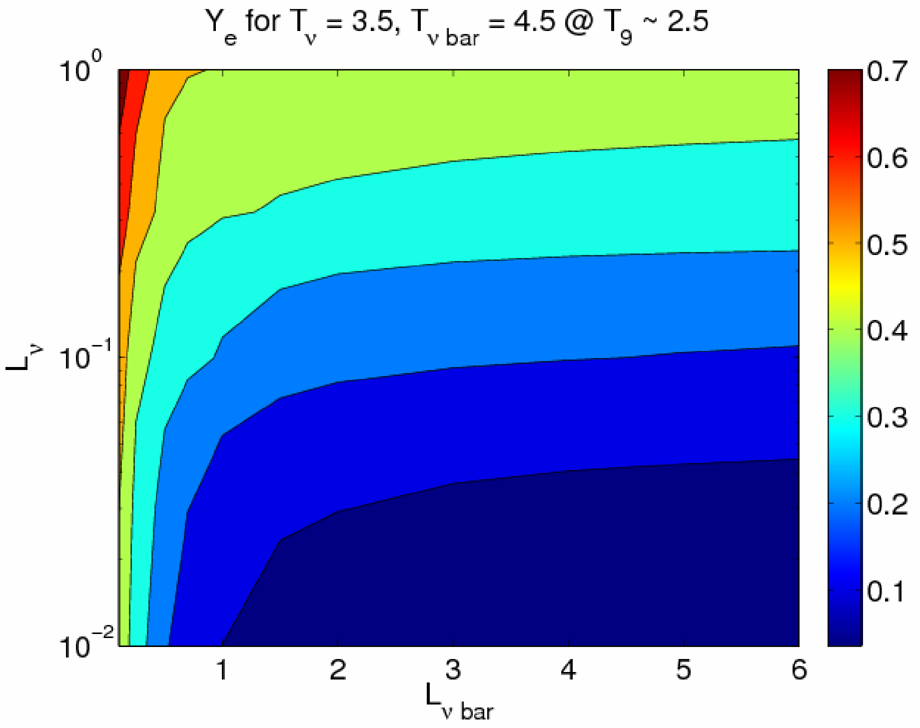




Variation of Neutrino and Anti-Neutrino Energies does not lead to neutron-rich environments

Electron Fraction: Neutrino Luminosity

- Neutrino Reduction Necessary For Low Electron Fractions In The Core-Collapse Supernova Environment



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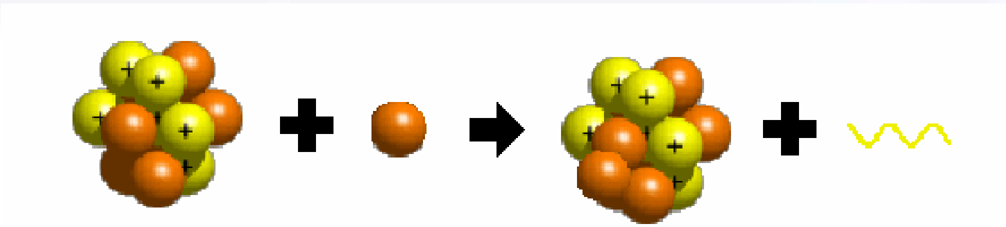

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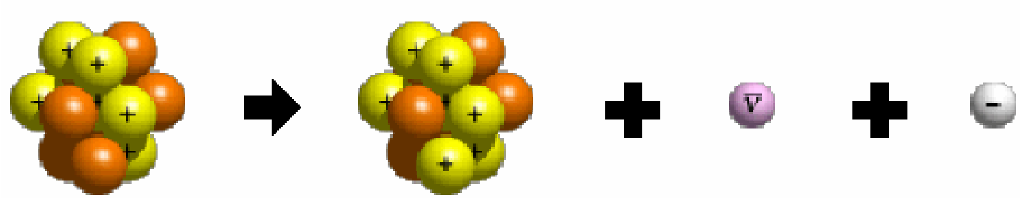

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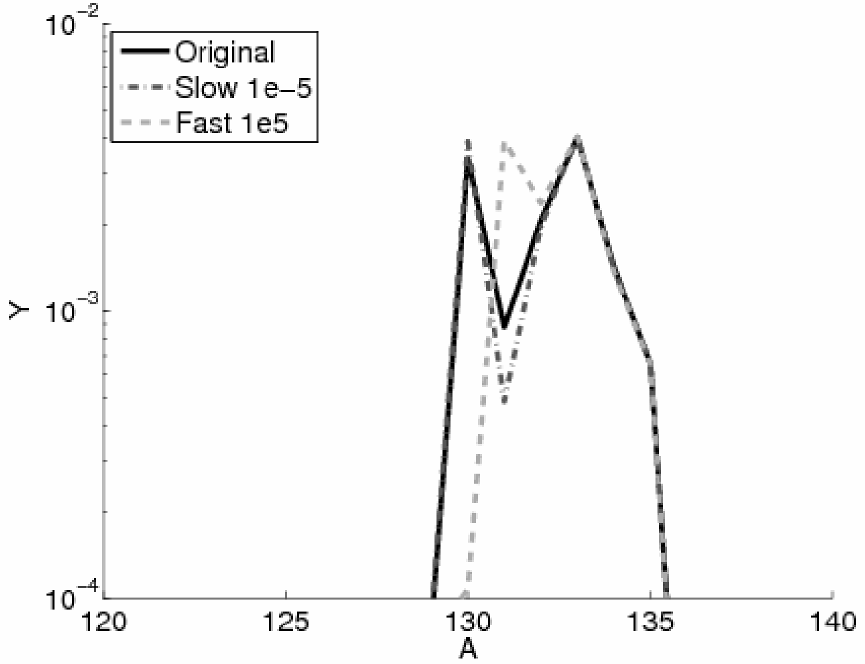
N=80 Neutron Capture Rates



Halo Star Comparison

- Fission creates seed nuclei around second peak
- This provides a connection between the peaks seen in Halo Stars