Neutrino-induced nucleosynthesis in supernovae

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Helmholtz International Summer School

"NUCLEAR THEORY AND ASTROPHYSICAL APPLICATIONS"

BLTP, JINR

Dubna, August 7 - 17, 2007

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Introduction

Two basic types of supernovae (SNe):

Thermonuclear SNe (Type Ia)

Explosive carbon burning (^{12}C+^{12}C ® ^{56}Ni)
in a degenerate *Chandrasekhar mass* (~1.4$M_{\odot}$) white dwarf.
The white dwarf turns out to be totally disrupted in
the explosion — no stellar remnant is left!

The total energy of electromagnetic radiation is of »6´10^{49}erg
and comes from the ^{56}Ni®^{56}Co®^{56}Fe decay.
The explosion energy E_{exp} is of »10^{51}erg and comes from
the explosive carbon burning into ^{56}Ni , almost all the E_{exp}
resides in the kinetic energy of expanding envelope.

Core-collapse SNe (all other Types but Ia)

The SN outburst is triggered by the gravitational collapse of the "iron" core of a mass $M_{Fe}=(1.2–2)\ M_{\odot}$ **into a neutron star. About** (10–15)% $M_{Fe}c^2$ **is radiated in the form of neutrinos and antineutrinos of all the flavors (e,** m, t**):**

$$\boxed{\mathbf{E}_{n\tilde{n}} = (\mathbf{3}-\mathbf{5})\times\mathbf{10}^{\mathbf{53}}\,\mathrm{erg}}$$

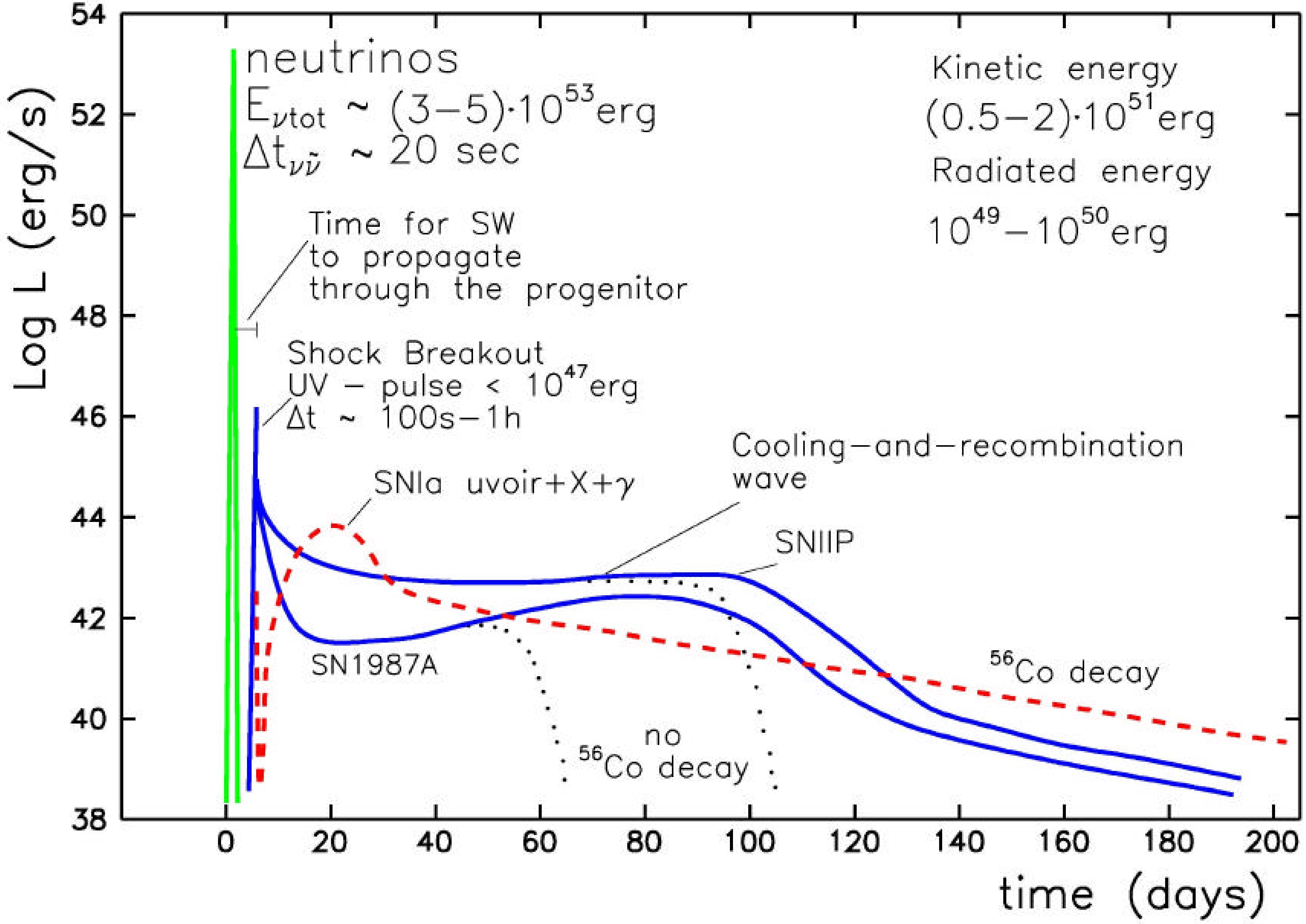
The explosion energy (kinetic energy of the envelope expansion):

$$\boxed{\mathbf{E_{exp} = (0.5 - 2)\,{}^{\prime}\,10^{51}}\mathrm{erg}}$$

it comes from the shock wave created at the boundary between a new-born neutron star and the envelope to be expelled.

$$\mathrm{E_{exp}} / \mathrm{E}_{n\tilde{n}} \approx 3\times10^{-3}\ \ !!$$

Schematic Supernova «light curves»



Dynamics of gravitational collapse

Dynamical stability

Expanding force:

$$F_E \sim 4\pi R^2 P$$

Contracting force:

$$F_G \sim GM^2/R^2$$

$$\rho = \rho_0 (R_0/R)^3$$

$$P = P_0 (\rho/\rho_0)^\gamma$$

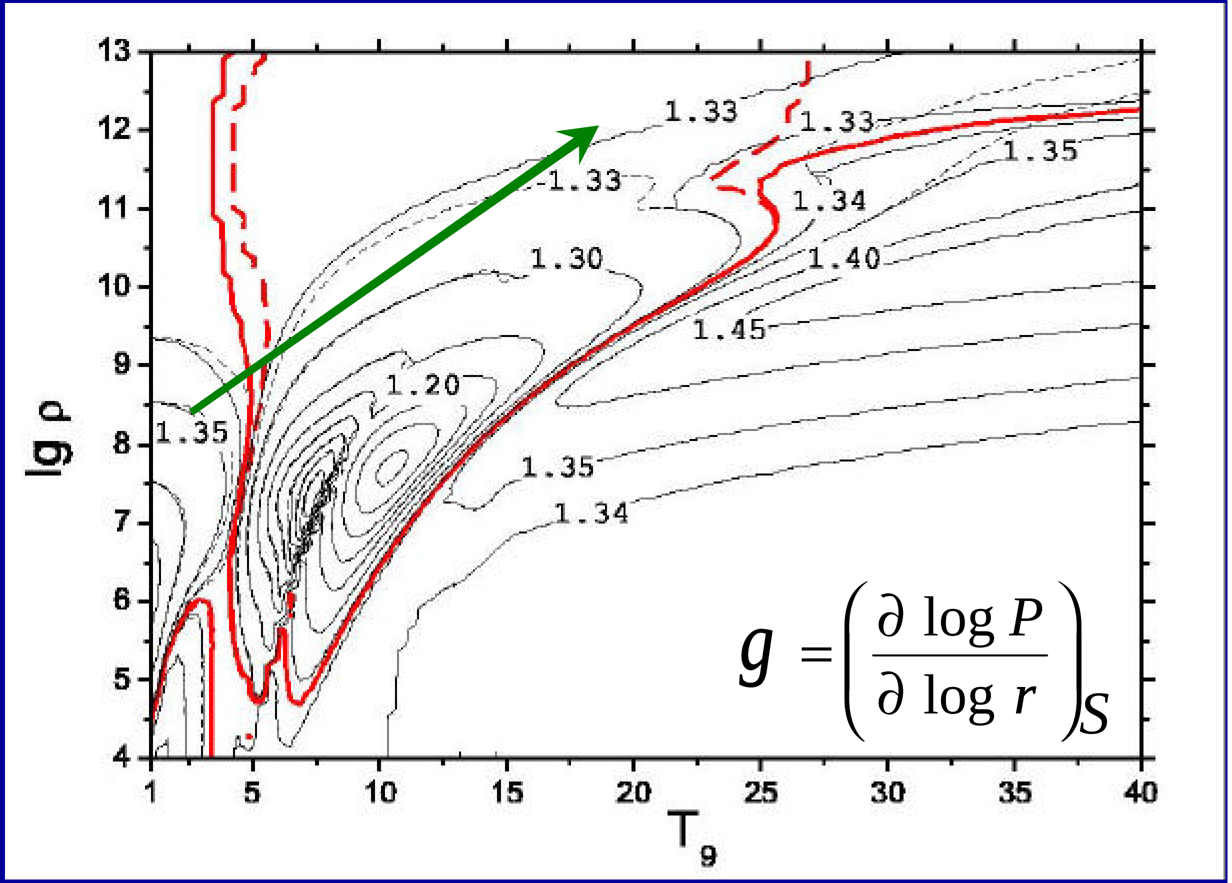
$$F_E \sim 1/R^{3\gamma-2}$$

$$F_G \sim 1/R^2$$

Stability: $3\gamma - 2 > 2$

$$\boxed{\gamma > 4/3}$$

Nadyozhin & Yudin (2005):



$$\gamma = \left(\frac{\partial \log P}{\partial \log \rho}\right)_S$$

$$^{56}\mathrm{Fe} \rightleftarrows 26\,\mathrm{p} + 30\,\mathrm{n}$$

Nuclear Statistical Equilibrium (NSE)

Dynamics of gravitational collapse

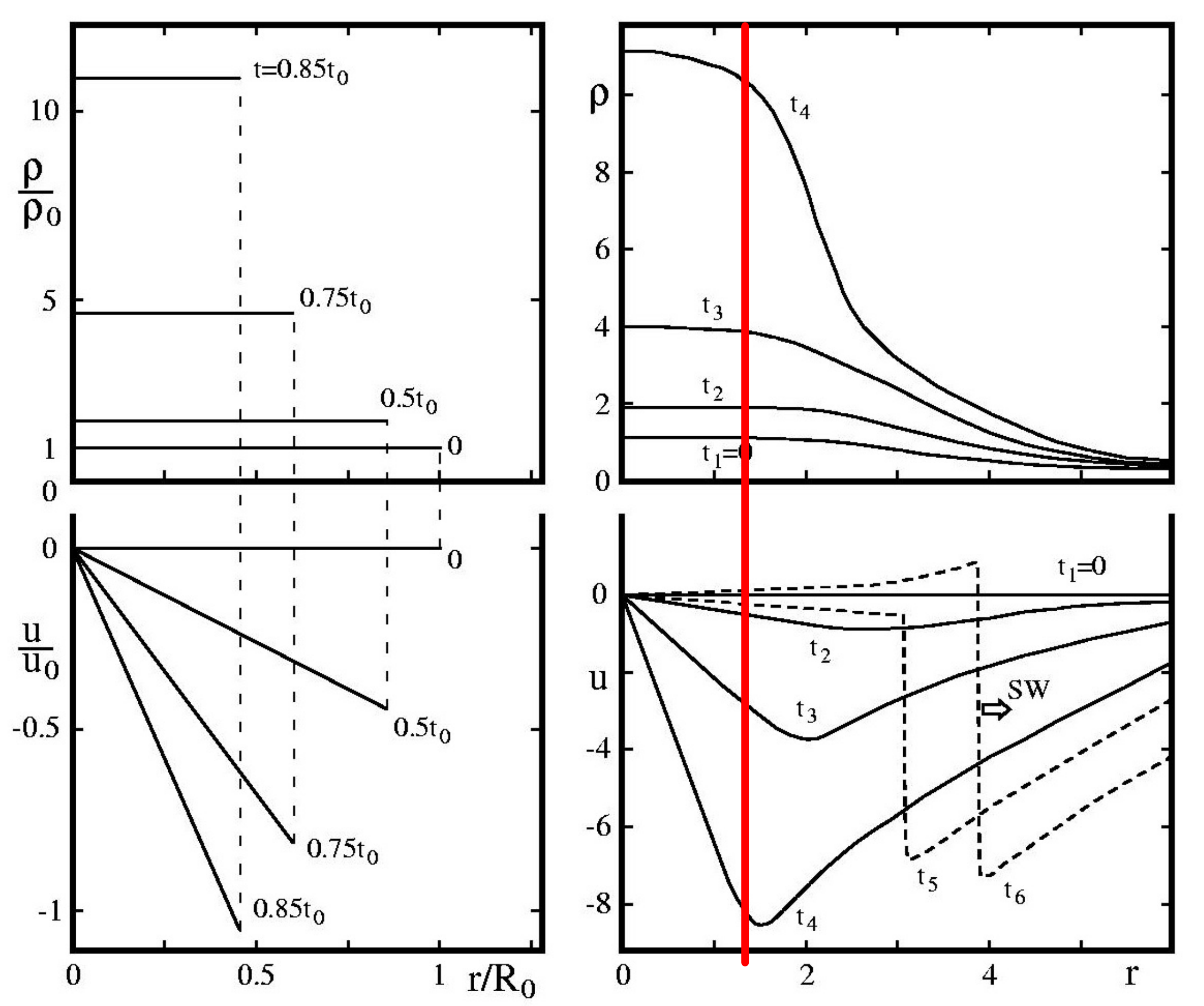
Initial “free fall”. Accreting shock wave

A homogeneous sphere of a mass M_0 and radius R_0 : $r_0 = \frac{3}{4p}\frac{M_0}{R_0^3}$

$$t_0 = p\sqrt{R_0^3/(8GM_0)}$$

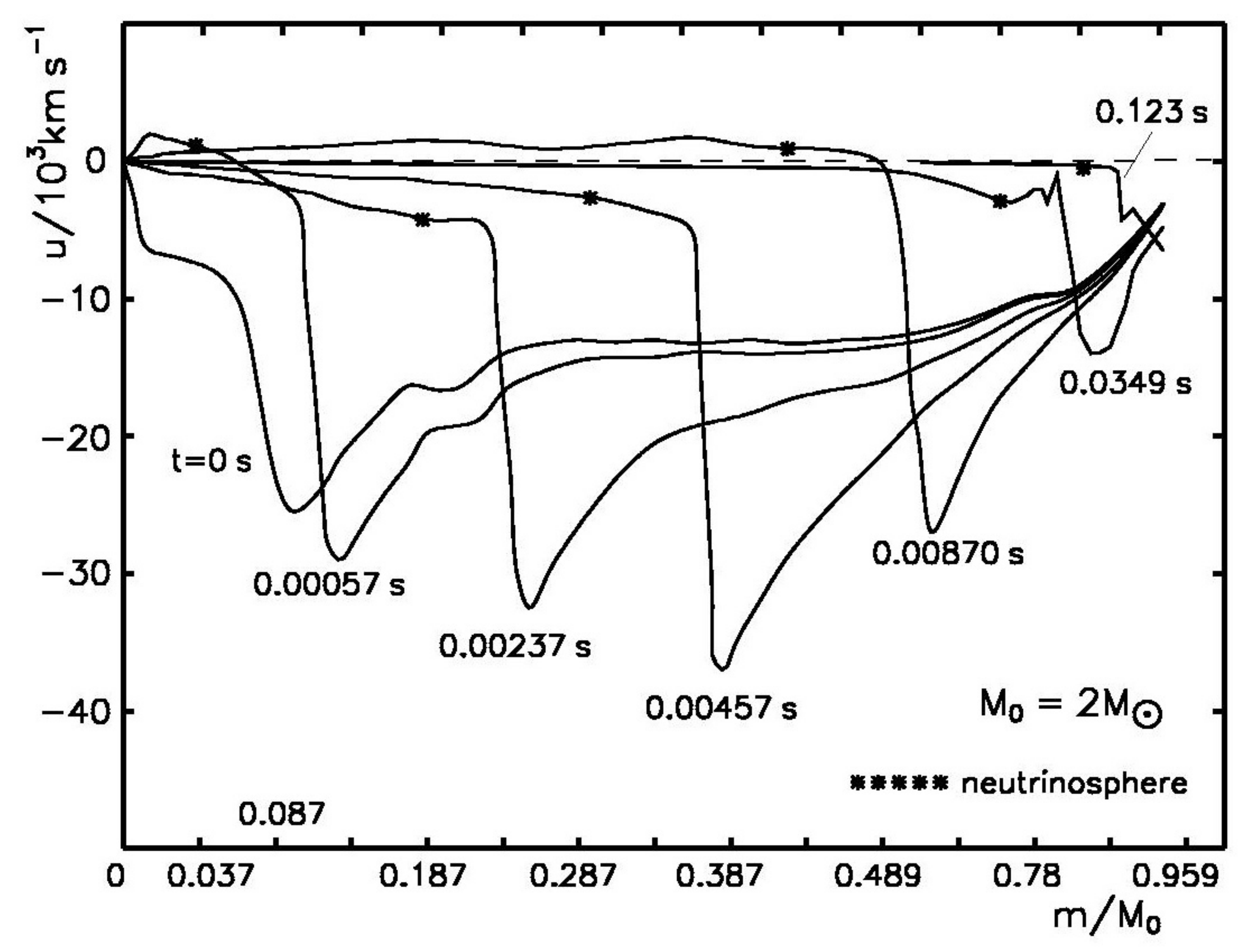
$$t_0 \approx 1 \text{ sec}$$

$$u_0 = \sqrt{2GM_0/R_0}$$



Schematic view

Dynamics of gravitational collapse

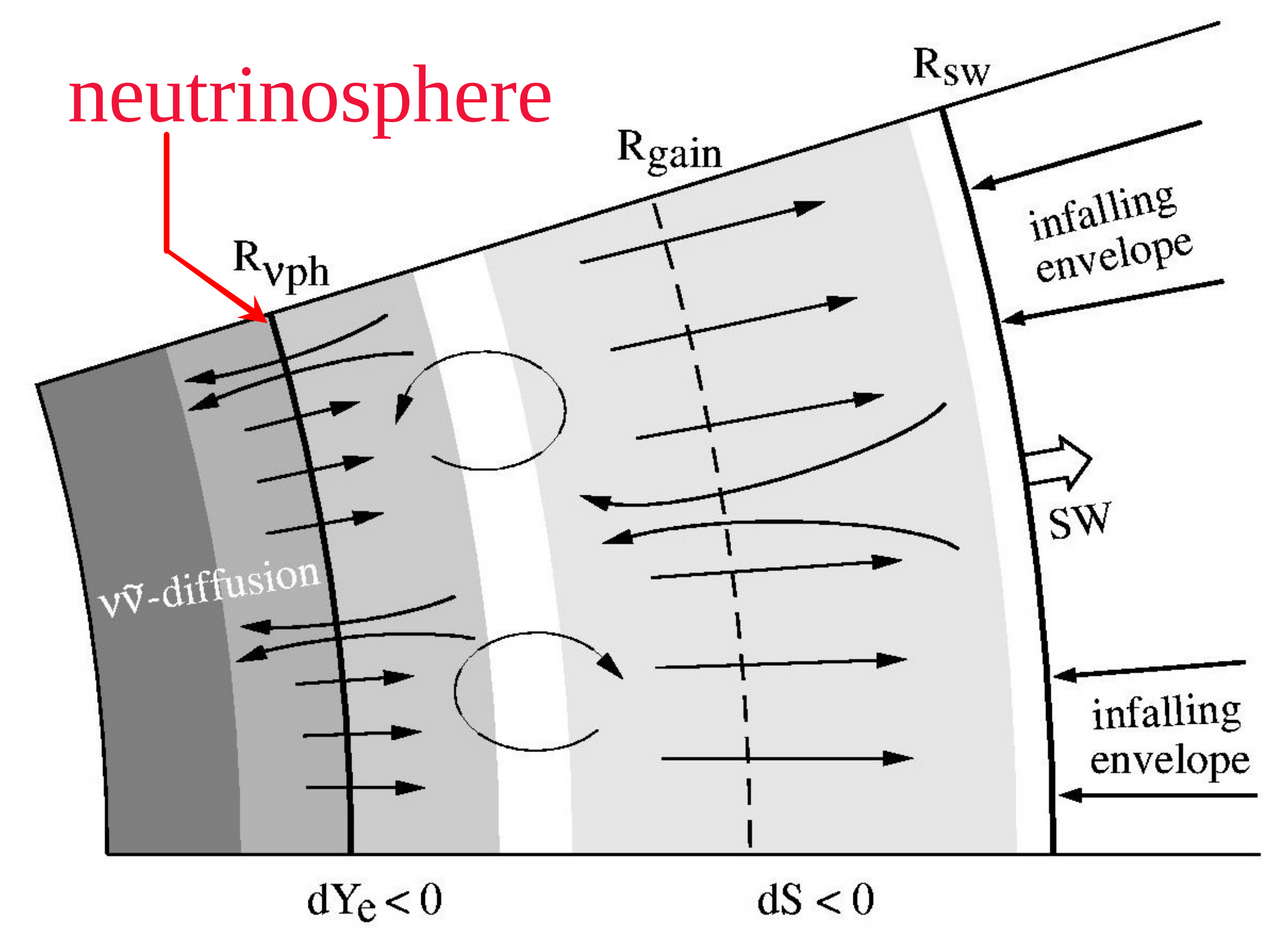


Collapse of a $2M_\odot$ iron stellar core

(based on Nadyozhin 1977)

Dynamics of gravitational collapse

Expulsion of supernova envelope (how?)



Dynamics of gravitational collapse

Total energy liberated

The total energy liberated is equal to the neutron star gravitational binding energy E_{g}:

$$E_{\mathrm{g}} = \left(M_{\mathrm{Fe}} - M_{\mathrm{g}}\right)\mathrm{c}^2$$

M_{Fe} – initial mass of the iron core before collapse

M_{g} – The gravitational mass of a neutron star measured by a distant observer that connected with M_{Fe} by *(Lattimer & Yahil 1989)*

$$M_{\mathrm{Fe}} = M_{\mathrm{g}} + 0.084\, M_{\mathrm{g}}^2 \Longrightarrow \boxed{E_{\mathrm{g}} = 1.5\times10^{53} M_{\mathrm{g}}^2 \ \mathrm{erg}}$$

$(M_{\mathrm{Fe}}, M_{\mathrm{g}}$ are in $M_{\odot})$

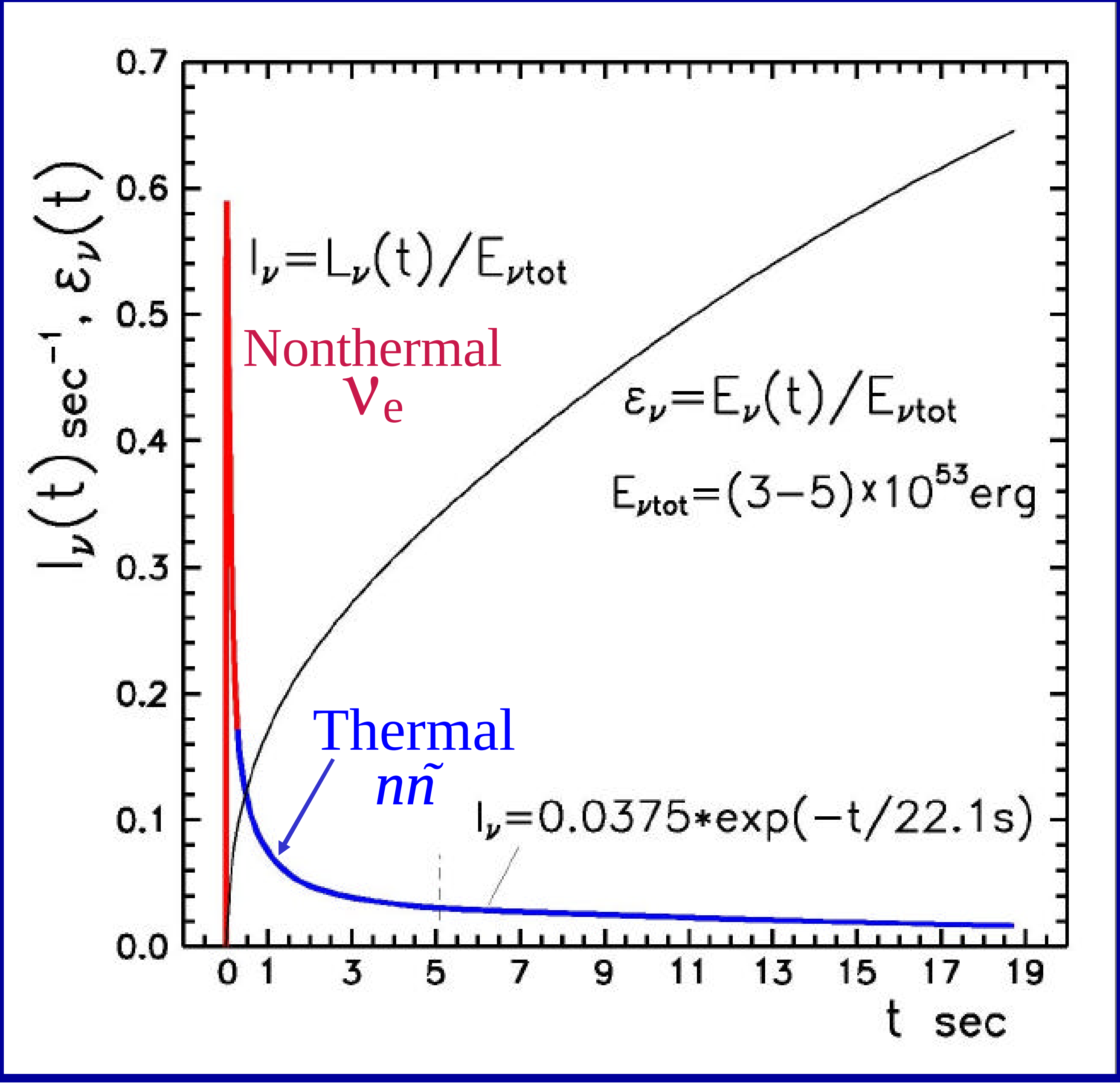
N - total number of nucleons in the neutron star

M_{Fe}	M_{g}	$E_{\mathrm{g}}/10^{53}$ erg	$N/10^{57}$	E_{g}/N MeV
1.10	1.01	1.54	1.33	73
1.40	1.27	2.40	1.67	90
1.70	1.51	3.41	2.03	105
2.00	1.74	4.56	2.38	120
2.30	1.97	5.84	2.74	133

$$\boxed{\mathrm{E}_{n\tilde{n}} \approx E_{\mathrm{g}}}$$

The properties of the Neutrino flux

Cumulative neutrino "light" curve (based on Nadyozhin 1978)



The properties of the Neutrino flux

Total energy radiated. Characteristic time.

Total energy radiated :

$$\mathbf{E}_{\nu\tilde{\nu}} \approx E_{\gamma} = (2.4-4.6)\times 10^{53}\,\mathrm{erg} \quad (\text{for } 1.4 \le M_{\mathrm{Fe}} \le 2)$$

$$(10\%-13\% \text{ of } M_{\mathrm{Fe}}\mathrm{c}^2)$$

Nonthermal component :

$$\text{Mostly } \nu_{\mathrm{e}}:\ \mathrm{E}_{\nu_\mathrm{e}} \le (1-2)\times 10^{52}\,\mathrm{erg} \approx 0.05\,\mathbf{E}_{\nu\tilde{\nu}}\ ,$$

$$\varepsilon_{\nu_\mathrm{e}} \approx 15-20\ \mathrm{MeV}, \quad \Delta\mathrm{t} \approx (0.01-0.02)\ \mathrm{sec}$$

Thermal component :

$$\mathrm{E}_{\nu_\mathrm{e}} \approx \mathrm{E}_{\nu_\mu} \approx \mathrm{E}_{\nu_\tau} \approx \tfrac{1}{3}\mathbf{E}_{\nu\tilde{\nu}} \quad (\nu_i \equiv \nu_i + \tilde{\nu}_i,\ i = \mathrm{e}, \mu, \tau)$$

$$\varepsilon_{\nu_\mathrm{e},\tilde{\nu}_\mathrm{e}} \approx 10-12\ \mathrm{MeV}, \quad \varepsilon_{\nu_\mu,\tilde{\nu}_\mu} \approx \varepsilon_{\nu_\tau,\tilde{\nu}_\tau} \approx 25\ \mathrm{MeV}\ ,$$

$$\Delta\mathrm{t} \approx (10-20)\ \mathrm{sec} \quad (\varepsilon - \text{ individual energy of neutrinos}).$$

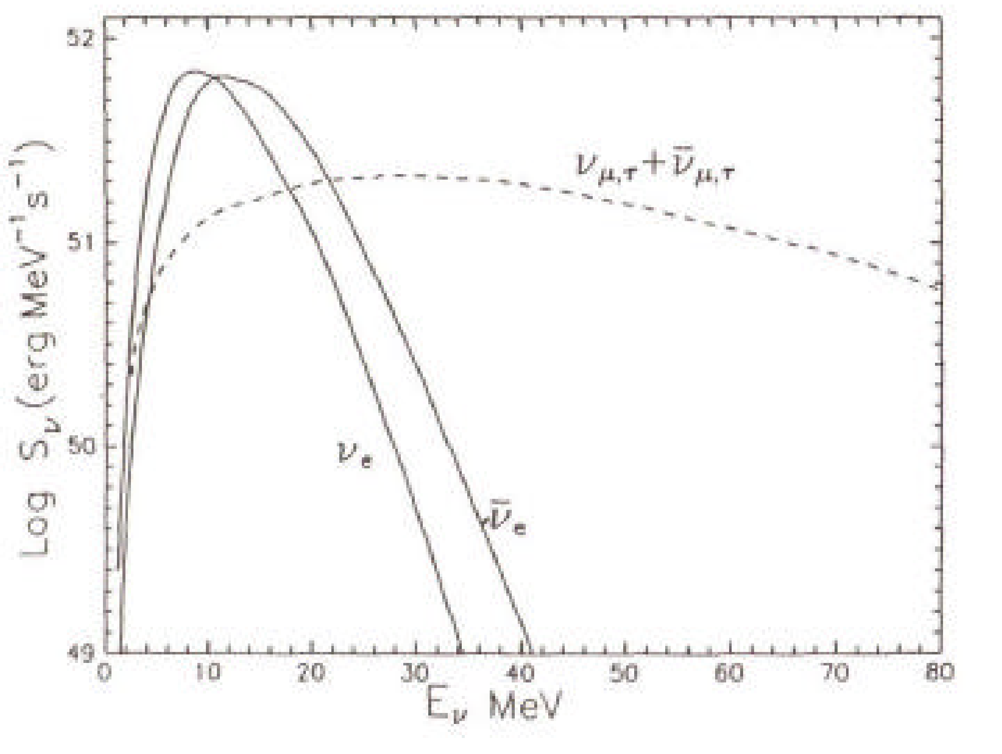
The properties of the Neutrino flux

Energy spectra.

Fermi- Dirac law:

$$S_n \sim \frac{e_n^3}{1+\exp\left(\dfrac{e_n}{kT_{n\,\mathrm{ph}}} - y_{n\,\mathrm{ph}}\right)},$$

$(y_{n\,\mathrm{ph}} \approx 0)$.



High-energy cutoff

(*relevant to* $n_e, \tilde{n}_e$):

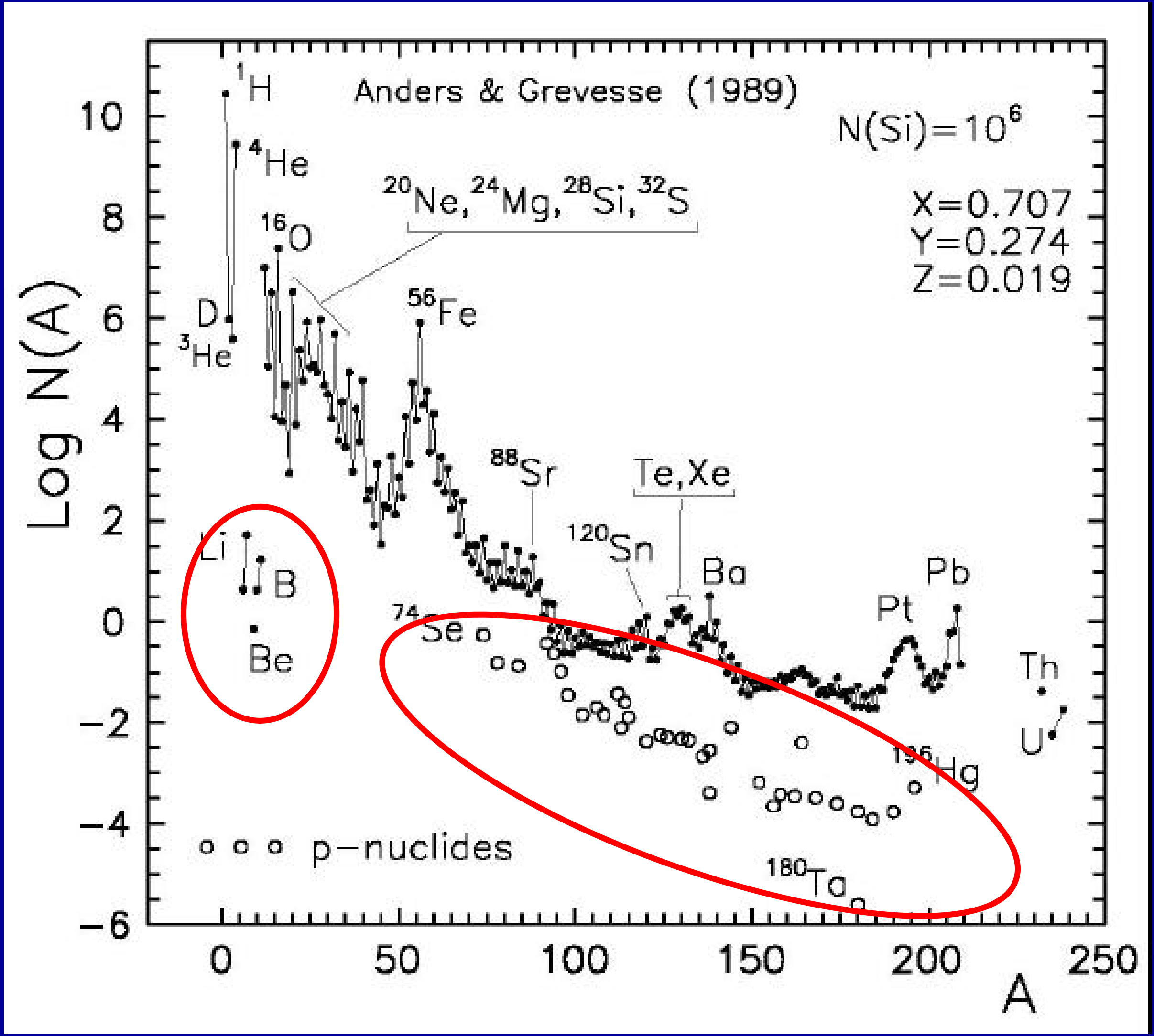
$$T_{n\,\mathrm{ph}} \approx 4 \text{ MeV for } n_e, \tilde{n}_e$$

$$T_{n\,\mathrm{ph}} \approx 8 \text{ MeV for } n_m, n_t$$

$$S_n \sim \frac{e_n^3 \exp\left[-a\left(\dfrac{e_n}{kT_{n\,\mathrm{ph}}}\right)^2\right]}{1+\exp\left(\dfrac{e_n}{kT_{n\,\mathrm{ph}}}\right)}, \quad (a \approx 0.02-0.04).$$

Basics of the Neutrino Nucleosynthesis

Light elements and p-nuclei



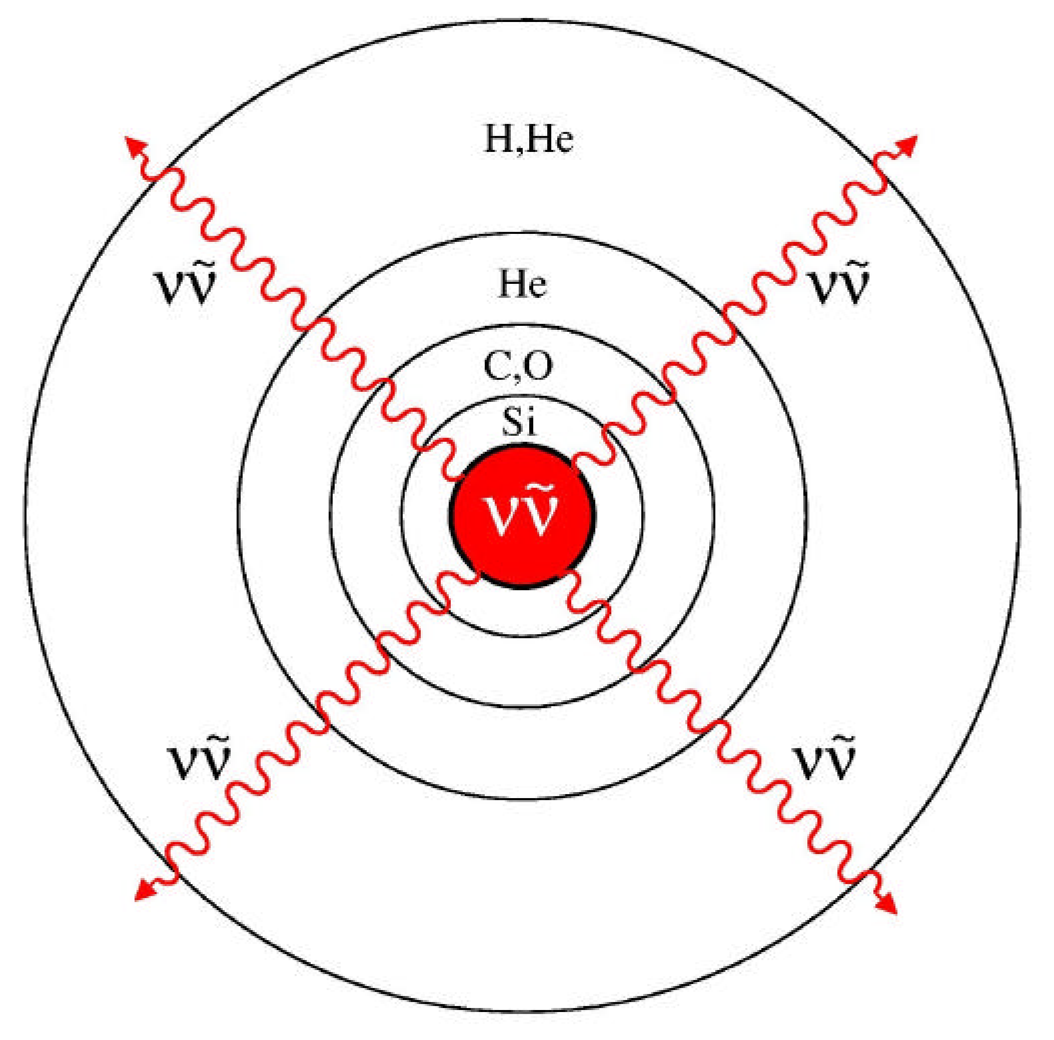
Cosmic abundance of elements

^{180}Ta exists in its excited (isomeric)
state ($\mathrm{E}_{\mathrm{ex}} = 75.4\,\mathrm{keV}$, $J^{p} = 9^{-}$)
abundance = 0.00012 ^{181}Ta
$\mathrm{T}_{1/2}(^{180}\mathrm{Ta}) > 1.2\times10^{15}$ y

The ground state ($J^{p} = 1^{+}$)
b^{-}decays: $\mathrm{T}_{1/2} = 8.15$ h
into ^{180}W

Basics of the Neutrino Nucleosynthesis

Presupernova shell structure:



A spatial scanning of Gamov’s sub Coulomb-barrier penetration factor !!

Basics of the Neutrino Nucleosynthesis

Magnitude of the neutrino-induced transformations

$$n + A \rightarrow B + c + \cdots$$

$$\frac{\mathrm{d}n}{\mathrm{d}t} = -n \frac{L_n(t)}{\langle e_n \rangle} \frac{\langle s_{nA} \rangle}{4p r^2}$$

$n -$ density of species A

$$\left| \frac{dn}{n} \right| = \underbrace{\int_0^\infty \frac{L_n(t)}{\langle e_n \rangle}\, \mathrm{d}t}_{N_n \,-\, \text{total number of radiated neutrinos}} \frac{\langle s_{nA} \rangle}{4p r^2} = N_n \frac{\langle s_{nA} \rangle}{4p r^2} = \boxed{10^{-2} - 10^{-5}}$$

Basics of the Neutrino Nucleosynthesis

Magnitude of the neutrino-induced transformations

$$\nu + A \rightarrow B + c + \cdots \qquad (1)$$

$$\frac{\mathrm{d}n}{\mathrm{d}t} = -n\frac{L_\nu(t)}{\langle\varepsilon_\nu\rangle}\frac{\langle\sigma_{\nu A}\rangle}{4\pi r^2}$$

n – density of species A

$$\left|\frac{dn}{n}\right| = \underbrace{\int_0^\infty \frac{L_\nu(t)}{\langle\varepsilon_\nu\rangle}\,\mathrm{d}t}\frac{\langle\sigma_{\nu A}\rangle}{4\pi r^2} = N_\nu\frac{\langle\sigma_{\nu A}\rangle}{4\pi r^2} = \boxed{10^{-2} - 10^{-5}}$$

N_ν – total number of radiated neutrinos participating in reaction (1)

Typical values:

$$\boxed{N_\nu \sim 10^{57},\ \ \langle\sigma_{\nu A}\rangle \approx 10^{-42} - 10^{-44}\,\mathrm{cm}^2\ ,\ \ r = 10^8 - 10^9\,\mathrm{cm}}$$

- # Basics of the Neutrino Nucleosynthesis

The role of shock wave

$$T_{\mathrm{WW}} = \left(\frac{3E}{4\pi a R_0^3} \right)^{1/4} = 2.37 \times 10^9 \, E_{51}^{0.25} (R_{09})^{-0.75} \;\; \mathrm{K}$$

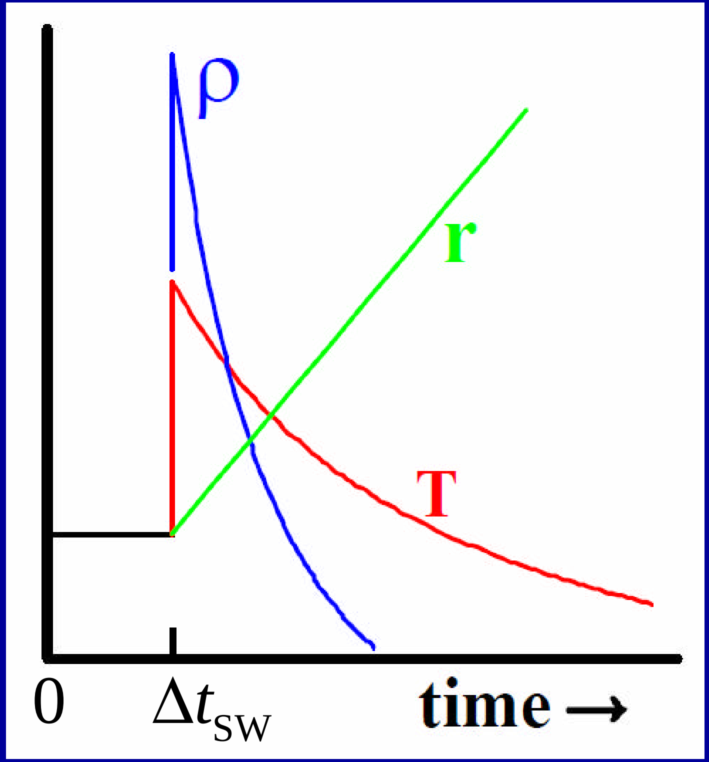
$$t_{\mathrm{u}} = 3.83 \times 10^{-3} \, \rho_0^{0.5} E_{51}^{-0.5} \, (R_{09})^{2.5} \;\; \mathrm{s}$$

$$T(t) = \frac{T_{\mathrm{p}}}{1 + \xi_{\mathrm{T}} \, t/t_{\mathrm{u}}}, \qquad T_{\mathrm{p}} = \xi_{\mathrm{p}} T_{\mathrm{WW}},$$

$$\rho(t) = \rho_{\mathrm{p}} \left(\frac{T}{T_{\mathrm{p}}} \right)^3, \qquad \rho_{\mathrm{p}} = 7\rho_0 \,,$$

$$R(t) = R_0 \, (1 + \xi_{\mathrm{r}} t/t_{\mathrm{u}}) \,,$$

$$\Delta t_{\mathrm{SW}} = \xi_{\mathrm{SW}} \, E_{51}^{-0.38} \, (R_0/10^9 \mathrm{cm})^{1.4} \;\; \mathrm{s},$$



x ~1 are adjustable parameters

Nadyozhin & Deputovich (2002)

T_{WW} – Weaver & Woosley (1980) temperature

<u>Neutrino Nucleosynthesis of p-nuclei</u>

p - process

Creation of some 30 isotopes (from ^{74}Se up to ^{196}Hg) that can be produced by the neutron capture neither in the s-process nor in the r-process (bypassed or p-nuclei)

The mechanisms of the production:

- The (p,γ) and (γ,n) reactions at high temperatures (T_9= 3–5)
- The neutrino resonance captures and scattering (GT & IA resonances)

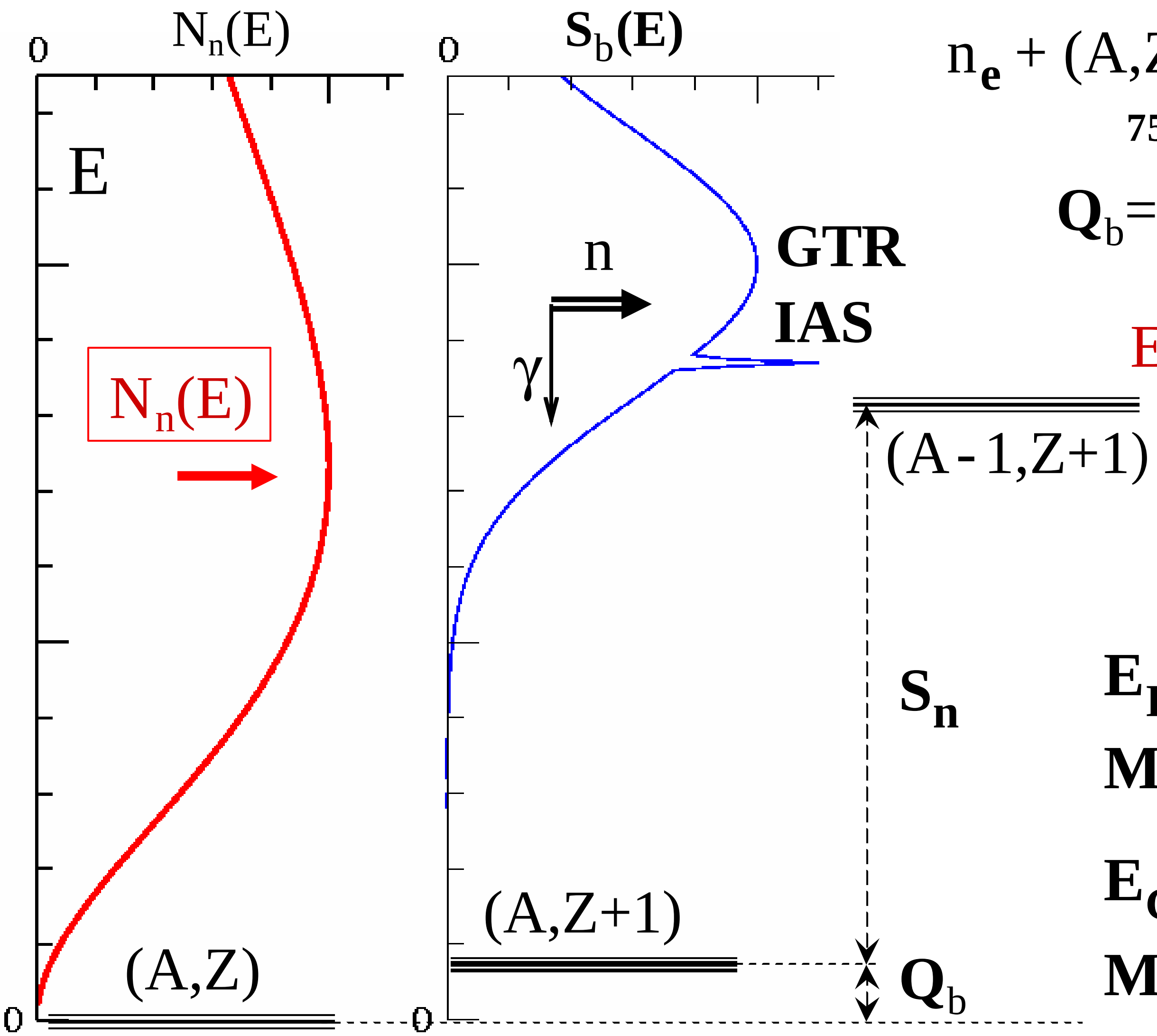
The main neutrino-induced process is

$$\boxed{\begin{aligned} & n_{\mathrm{e}} + (A,Z) \rightarrow (A,Z+1)^{*} + \mathrm{e}^{-} \\ & (A,Z+1)^{*} \rightarrow (A-1,Z+1)_{\mathrm{bps}} + \mathrm{n} \end{aligned}}$$

$$n_{\mathbf{e}} + (A,Z) \Rightarrow \mathbf{e^-} + \mathbf{n} + (A-1, Z+1)$$

$\mathbf{^{75}As}$ $\mathbf{^{74}Se}$

$\mathbf{Q_b}=0.86$, $\mathbf{S_n}=8.075$ **MeV**



$$E_n > \mathbf{S_n} + \mathbf{Q_b}$$

$$\mathbf{E_{IAS} = 1.44\, Z/A^{1/3} - 1.13}$$

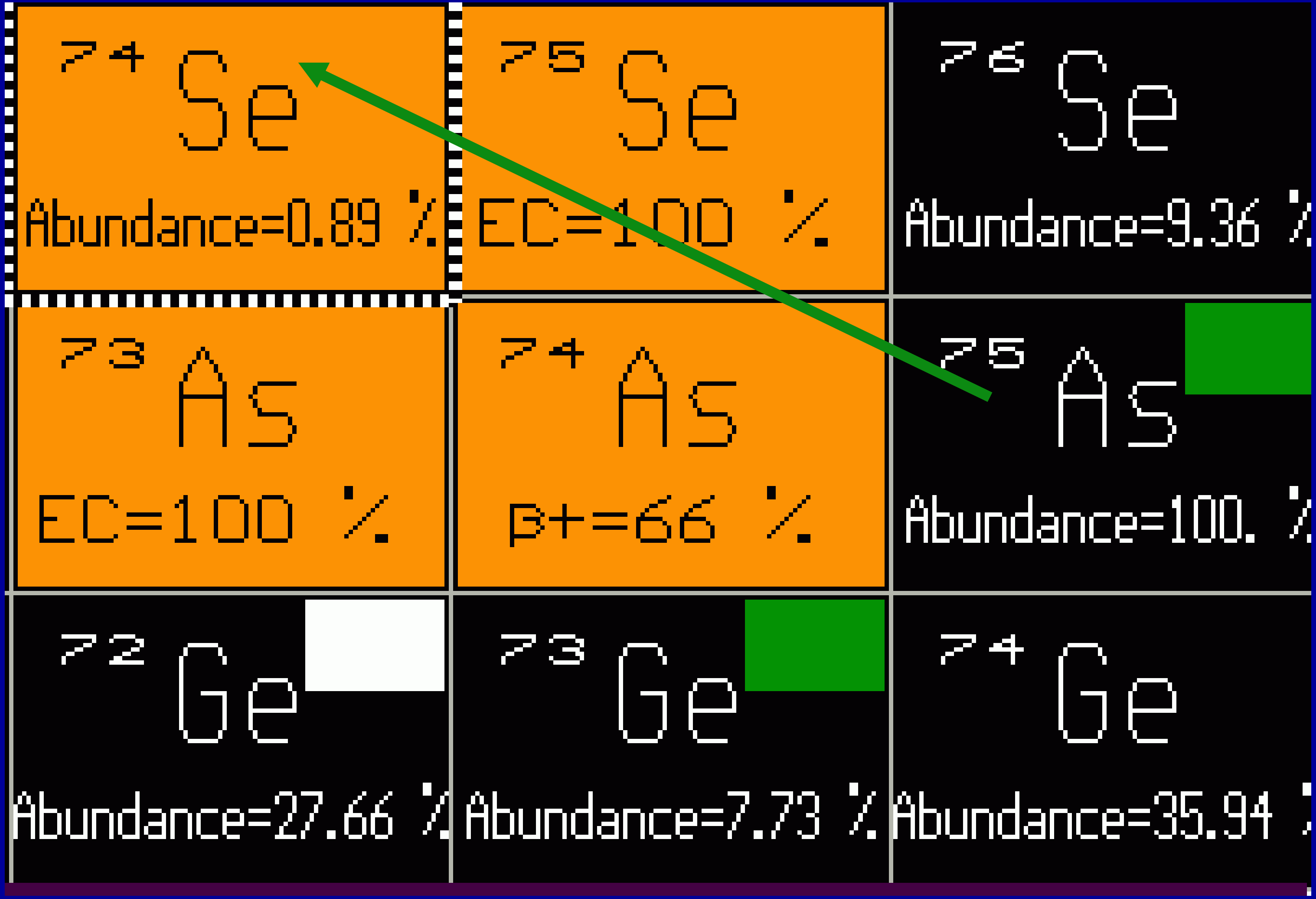
$$\mathbf{M^2_{IAS} \approx (N - Z)}$$

$$\mathbf{E_{GTR} \approx E_{IAS} + (1 - 3) MeV}$$

$$\mathbf{M^2_{GTR} \approx 3\,(N - Z)\, e^2_q}$$

Gaponov Yu.V., Lyutostansky Yu. S., *Sov. J. Nucl. Phys.* (1974)
Domogatskii G.V., Nadyozhin D.K., *Sov. Astronomy* (1978)
Panov I.V., *Astronomy Letters* (1994)

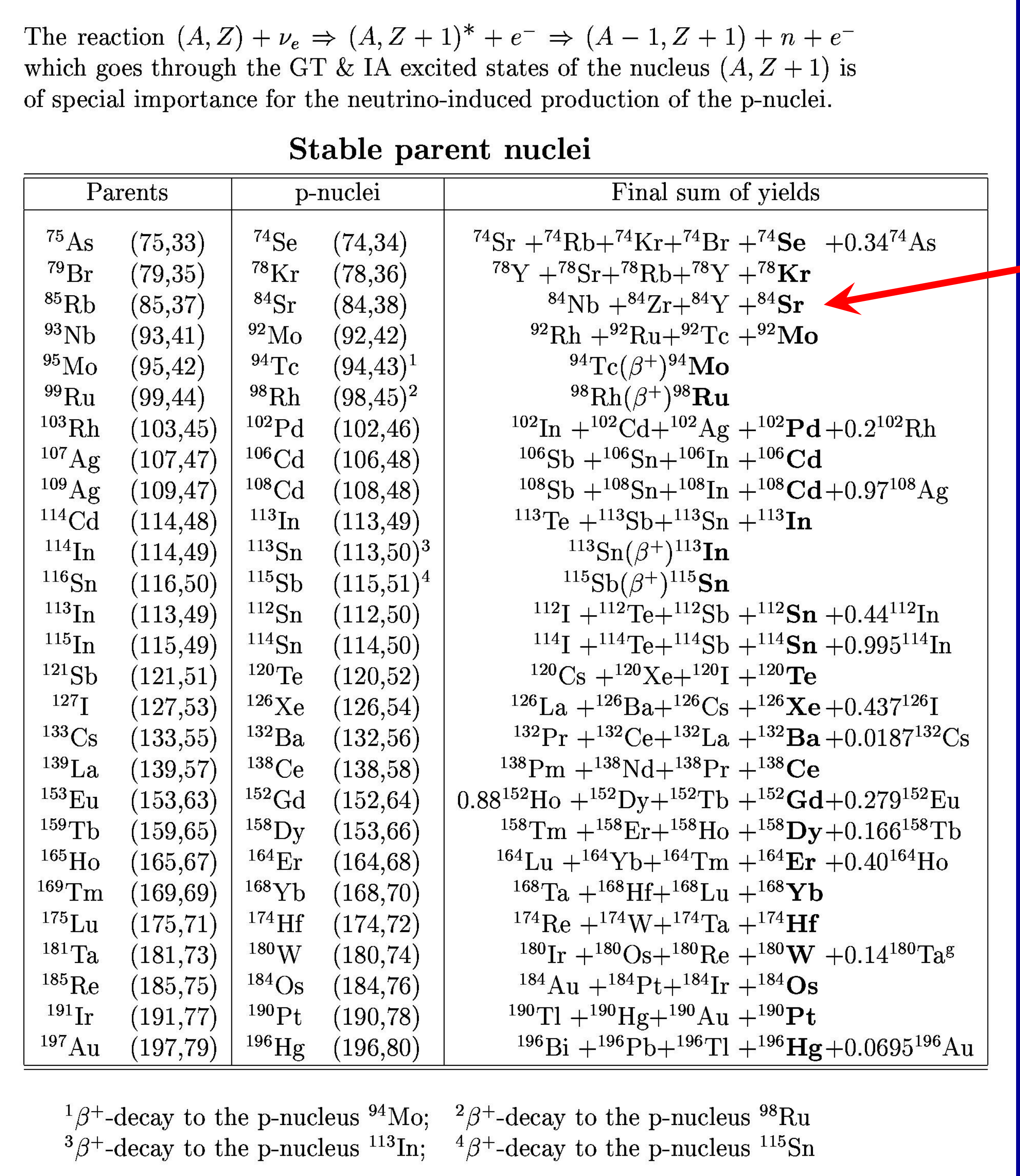
Neutrino Nucleosynthesis of p-nuclei



^{74}Se Abundance=0.89 %	^{75}Se EC=100 %	^{76}Se Abundance=9.36 %
^{73}As EC=100 %	^{74}As β+=66 %	^{75}As Abundance=100. %
^{72}Ge Abundance=27.66 %	^{73}Ge Abundance=7.73 %	^{74}Ge Abundance=35.94

$$n_e + {}^{75}\mathrm{As} \Rightarrow e^- + n + {}^{74}\mathrm{Se}$$

Neutrino Nucleosynthesis of p-nuclei



The reaction $(A,Z)+\nu_e \Rightarrow (A,Z+1)^* + e^- \Rightarrow (A-1,Z+1)+n+e^-$ which goes through the GT & IA excited states of the nucleus $(A,Z+1)$ is of special importance for the neutrino-induced production of the p-nuclei.

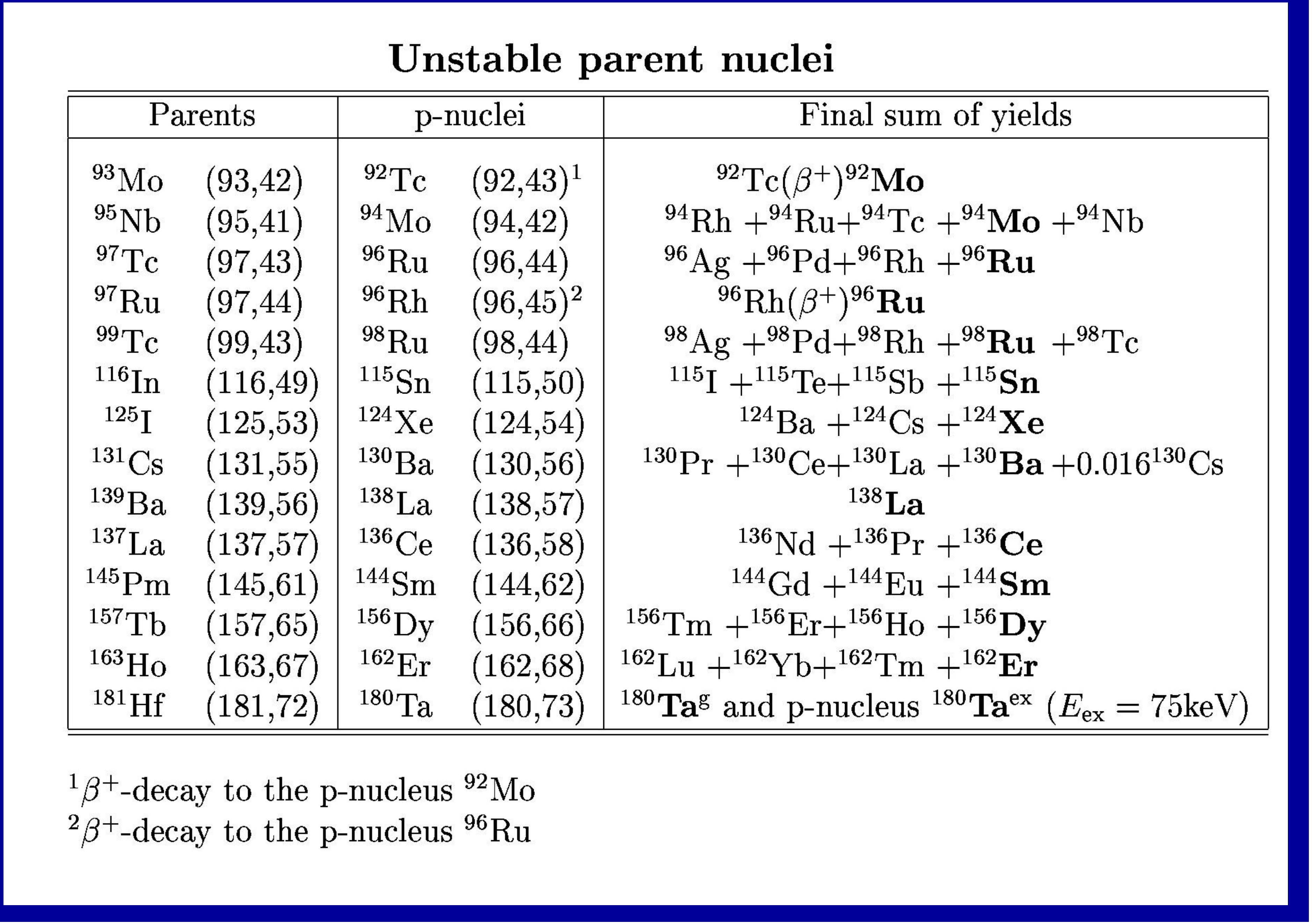
Stable parent nuclei

Parents		p-nuclei		Final sum of yields
^{75}As	(75,33)	^{74}Se	(74,34)	^{74}Sr + ^{74}Rb+^{74}Kr+^{74}Br + ^{74}**Se** +0.34^{74}As
^{79}Br	(79,35)	^{78}Kr	(78,36)	^{78}Y + ^{78}Sr+^{78}Rb+^{78}Y + ^{78}**Kr**
^{85}Rb	(85,37)	^{84}Sr	(84,38)	^{84}Nb + ^{84}Zr+^{84}Y + ^{84}**Sr**
^{93}Nb	(93,41)	^{92}Mo	(92,42)	^{92}Rh + ^{92}Ru+^{92}Tc + ^{92}**Mo**
^{95}Mo	(95,42)	^{94}Tc	(94,43)^1	^{94}Tc(β^+)^{94}**Mo**
^{99}Ru	(99,44)	^{98}Rh	(98,45)^2	^{98}Rh(β^+)^{98}**Ru**
^{103}Rh	(103,45)	^{102}Pd	(102,46)	^{102}In + ^{102}Cd+^{102}Ag + ^{102}**Pd**+0.2^{102}Rh
^{107}Ag	(107,47)	^{106}Cd	(106,48)	^{106}Sb + ^{106}Sn+^{106}In + ^{106}**Cd**
^{109}Ag	(109,47)	^{108}Cd	(108,48)	^{108}Sb + ^{108}Sn+^{108}In + ^{108}**Cd**+0.97^{108}Ag
^{114}Cd	(114,48)	^{113}In	(113,49)	^{113}Te + ^{113}Sb+^{113}Sn + ^{113}**In**
^{114}In	(114,49)	^{113}Sn	(113,50)^3	^{113}Sn(β^+)^{113}**In**
^{116}Sn	(116,50)	^{115}Sb	(115,51)^4	^{115}Sb(β^+)^{115}**Sn**
^{113}In	(113,49)	^{112}Sn	(112,50)	^{112}I + ^{112}Te+^{112}Sb + ^{112}**Sn** +0.44^{112}In
^{115}In	(115,49)	^{114}Sn	(114,50)	^{114}I + ^{114}Te+^{114}Sb + ^{114}**Sn** +0.995^{114}In
^{121}Sb	(121,51)	^{120}Te	(120,52)	^{120}Cs + ^{120}Xe+^{120}I + ^{120}**Te**
^{127}I	(127,53)	^{126}Xe	(126,54)	^{126}La + ^{126}Ba+^{126}Cs + ^{126}**Xe**+0.437^{126}I
^{133}Cs	(133,55)	^{132}Ba	(132,56)	^{132}Pr + ^{132}Ce+^{132}La + ^{132}**Ba**+0.0187^{132}Cs
^{139}La	(139,57)	^{138}Ce	(138,58)	^{138}Pm + ^{138}Nd+^{138}Pr + ^{138}**Ce**
^{153}Eu	(153,63)	^{152}Gd	(152,64)	0.88^{152}Ho + ^{152}Dy+^{152}Tb + ^{152}**Gd**+0.279^{152}Eu
^{159}Tb	(159,65)	^{158}Dy	(153,66)	^{158}Tm + ^{158}Er+^{158}Ho + ^{158}**Dy**+0.166^{158}Tb
^{165}Ho	(165,67)	^{164}Er	(164,68)	^{164}Lu + ^{164}Yb+^{164}Tm + ^{164}**Er** +0.40^{164}Ho
^{169}Tm	(169,69)	^{168}Yb	(168,70)	^{168}Ta + ^{168}Hf+^{168}Lu + ^{168}**Yb**
^{175}Lu	(175,71)	^{174}Hf	(174,72)	^{174}Re + ^{174}W+^{174}Ta + ^{174}**Hf**
^{181}Ta	(181,73)	^{180}W	(180,74)	^{180}Ir + ^{180}Os+^{180}Re + ^{180}**W** +0.14^{180}Ta^{g}
^{185}Re	(185,75)	^{184}Os	(184,76)	^{184}Au + ^{184}Pt+^{184}Ir + ^{184}**Os**
^{191}Ir	(191,77)	^{190}Pt	(190,78)	^{190}Tl + ^{190}Hg+^{190}Au + ^{190}**Pt**
^{197}Au	(197,79)	^{196}Hg	(196,80)	^{196}Bi + ^{196}Pb+^{196}Tl + ^{196}**Hg**+0.0695^{196}Au

[1] β^+-decay to the p-nucleus ^{94}Mo; [2] β^+-decay to the p-nucleus ^{98}Ru
[3] β^+-decay to the p-nucleus ^{113}In; [4] β^+-decay to the p-nucleus ^{115}Sn

To find the final yield of a p-nucleus, marked in bold, one has to sum the yields of a number of ß-unstable nuclei that can exist in nuclear network

Neutrino Nucleosynthesis of p-nuclei



Unstable parent nuclei

Parents		p-nuclei		Final sum of yields
^{93}Mo	(93,42)	^{92}Tc	(92,43)[1]	$^{92}\mathrm{Tc}(\beta^+)^{92}\mathbf{Mo}$
^{95}Nb	(95,41)	^{94}Mo	(94,42)	$^{94}\mathrm{Rh} + ^{94}\mathrm{Ru} + ^{94}\mathrm{Tc} + ^{94}\mathbf{Mo} + ^{94}\mathrm{Nb}$
^{97}Tc	(97,43)	^{96}Ru	(96,44)	$^{96}\mathrm{Ag} + ^{96}\mathrm{Pd} + ^{96}\mathrm{Rh} + ^{96}\mathbf{Ru}$
^{97}Ru	(97,44)	^{96}Rh	(96,45)[2]	$^{96}\mathrm{Rh}(\beta^+)^{96}\mathbf{Ru}$
^{99}Tc	(99,43)	^{98}Ru	(98,44)	$^{98}\mathrm{Ag} + ^{98}\mathrm{Pd} + ^{98}\mathrm{Rh} + ^{98}\mathbf{Ru} + ^{98}\mathrm{Tc}$
^{116}In	(116,49)	^{115}Sn	(115,50)	$^{115}\mathrm{I} + ^{115}\mathrm{Te} + ^{115}\mathrm{Sb} + ^{115}\mathbf{Sn}$
^{125}I	(125,53)	^{124}Xe	(124,54)	$^{124}\mathrm{Ba} + ^{124}\mathrm{Cs} + ^{124}\mathbf{Xe}$
^{131}Cs	(131,55)	^{130}Ba	(130,56)	$^{130}\mathrm{Pr} + ^{130}\mathrm{Ce} + ^{130}\mathrm{La} + ^{130}\mathbf{Ba} + 0.016^{130}\mathrm{Cs}$
^{139}Ba	(139,56)	^{138}La	(138,57)	$^{138}\mathbf{La}$
^{137}La	(137,57)	^{136}Ce	(136,58)	$^{136}\mathrm{Nd} + ^{136}\mathrm{Pr} + ^{136}\mathbf{Ce}$
^{145}Pm	(145,61)	^{144}Sm	(144,62)	$^{144}\mathrm{Gd} + ^{144}\mathrm{Eu} + ^{144}\mathbf{Sm}$
^{157}Tb	(157,65)	^{156}Dy	(156,66)	$^{156}\mathrm{Tm} + ^{156}\mathrm{Er} + ^{156}\mathrm{Ho} + ^{156}\mathbf{Dy}$
^{163}Ho	(163,67)	^{162}Er	(162,68)	$^{162}\mathrm{Lu} + ^{162}\mathrm{Yb} + ^{162}\mathrm{Tm} + ^{162}\mathbf{Er}$
^{181}Hf	(181,72)	^{180}Ta	(180,73)	$^{180}\mathbf{Ta}^{\mathrm{g}}$ and p-nucleus $^{180}\mathbf{Ta}^{\mathrm{ex}}$ $(E_{\mathrm{ex}} = 75\mathrm{keV})$

[1] β^+-decay to the p-nucleus ^{92}Mo

[2] β^+-decay to the p-nucleus ^{96}Ru

Neutrino Nucleosynthesis of p-nuclei

There is also a need in the cross-sections of a number of reactions involving muon and tau neutrinos and antineutrinos. Specifically, we need the total cross-section of the neutral-current excitation followed by the emission of a neutron for the following processes. The cross-section has to be averaged over the Fermi–Dirac spectra of zero chemical potential and with temperatures $kT = 6,\ 8,\ 10\,\mathrm{MeV}$.

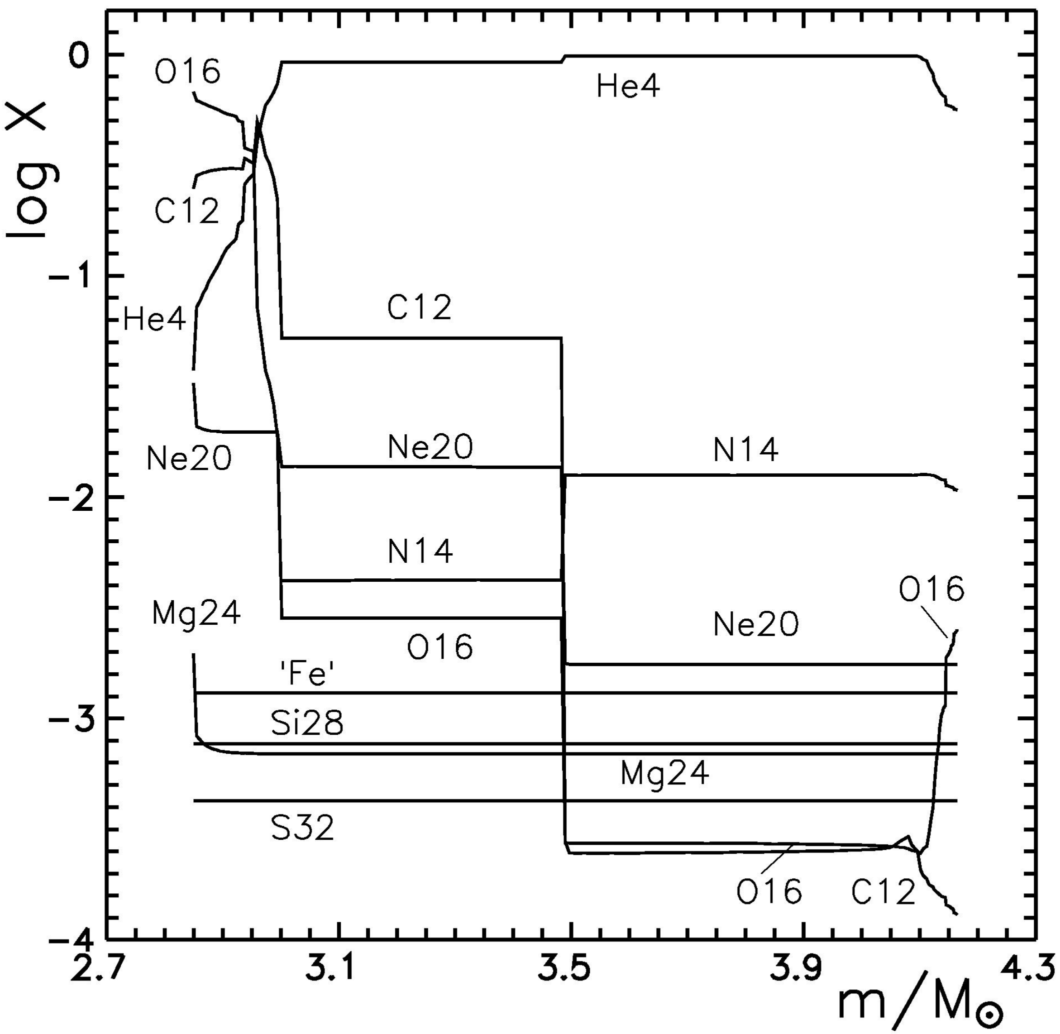
Stable nuclei	Unstable nuclei
${}^{95}\mathrm{Mo}(\nu,\nu')^{95}\mathrm{Mo}^{*}\Longrightarrow{}^{94}\mathbf{Mo}+\mathrm{n}$	${}^{97}\mathrm{Ru}(\nu,\nu')^{97}\mathrm{Ru}^{*}\Longrightarrow{}^{96}\mathbf{Ru}+\mathrm{n}$
${}^{99}\mathrm{Ru}(\nu,\nu')^{99}\mathrm{Ru}^{*}\Longrightarrow{}^{98}\mathbf{Ru}+\mathrm{n}$	${}^{113}\mathrm{Sn}(\nu,\nu')^{113}\mathrm{Sn}^{*}\Longrightarrow{}^{112}\mathbf{Sn}+\mathrm{n}$
${}^{116}\mathrm{Sn}(\nu,\nu')^{116}\mathrm{Sn}^{*}\Longrightarrow{}^{115}\mathbf{Sn}+\mathrm{n}$	${}^{114}\mathrm{In}(\nu,\nu')^{114}\mathrm{In}^{*}\Longrightarrow{}^{113}\mathbf{In}+\mathrm{n}$
${}^{139}\mathrm{La}(\nu,\nu')^{139}\mathrm{La}^{*}\Longrightarrow{}^{138}\mathbf{La}+\mathrm{n}$	${}^{125}\mathrm{Xe}(\nu,\nu')^{125}\mathrm{Xe}^{*}\Longrightarrow{}^{124}\mathbf{Xe}+\mathrm{n}$
${}^{181}\mathrm{Ta}(\nu,\nu')^{181}\mathrm{Ta}^{*}\Longrightarrow{}^{180}\mathbf{Ta}^{\mathrm{ex}}+\mathrm{n}$	${}^{127}\mathrm{Xe}(\nu,\nu')^{127}\mathrm{Xe}^{*}\Longrightarrow{}^{126}\mathbf{Xe}+\mathrm{n}$
	${}^{131}\mathrm{Ba}(\nu,\nu')^{131}\mathrm{Ba}^{*}\Longrightarrow{}^{130}\mathbf{Ba}+\mathrm{n}$
	${}^{137}\mathrm{Ce}(\nu,\nu')^{137}\mathrm{Ce}^{*}\Longrightarrow{}^{136}\mathbf{Ce}+\mathrm{n}$
	${}^{145}\mathrm{Sm}(\nu,\nu')^{145}\mathrm{Sm}^{*}\Longrightarrow{}^{144}\mathbf{Sm}+\mathrm{n}$
	${}^{157}\mathrm{Dy}(\nu,\nu')^{157}\mathrm{Dy}^{*}\Longrightarrow{}^{156}\mathbf{Dy}+\mathrm{n}$
	${}^{163}\mathrm{Er}(\nu,\nu')^{163}\mathrm{Er}^{*}\Longrightarrow{}^{162}\mathbf{Er}+\mathrm{n}$

The p-nuclei are marked in bold, ν stands for $\nu_\mu, \tilde{\nu}_\mu, \nu_\tau$, and $\tilde{\nu}_\tau$.

Neutrino Nucleosynthesis in Helium Shell

He shell

Neutrino Nucleosynthesis in Helium Shell



Composition of a 15 $M_\odot$ solar metallicity ($Z_\odot$) presupernova He-shell (*Woosley, Heger et al.*)

Neutrino Nucleosynthesis in Helium Shell

The key reactions:

$$\boxed{{}^{4}\mathrm{He}(n,n'\mathrm{n})\,{}^{3}\mathrm{He}\,,\qquad {}^{4}\mathrm{He}(n,n'\mathrm{p})\,{}^{3}\mathrm{H}}$$

Thermonuclear network (code I)

$$\mathrm{p} + \mathrm{n} \rightarrow \mathrm{D}\,;\ {}^{4}\mathrm{He}(\mathrm{T},g)\,{}^{7}\mathrm{Li}\,;\ {}^{4}\mathrm{He}({}^{3}\mathrm{He},g)\,{}^{7}\mathrm{Be}\,;\ (\mathrm{T} \equiv {}^{3}\mathrm{H})$$

$${}^{7}\mathrm{Li}(a,g)\,{}^{11}\mathrm{B}\,;\ {}^{7}\mathrm{Be}(a,g)\,{}^{11}\mathrm{C}\,;\qquad (a \equiv {}^{4}\mathrm{He})$$

$$.\ \ .\ \ .\ \ .\ \ {}^{13}\mathrm{C}(\mathrm{n},g)\,{}^{14}\mathrm{C}\,,\ {}^{13}\mathrm{C}(a,\mathrm{n})\,{}^{16}\mathrm{O}\ .\ \ .\ \ .\ \ .$$

+

About 160 thermonuclear reactions and beta-decays connecting 40 nuclides from n and p through ^{24}Mg

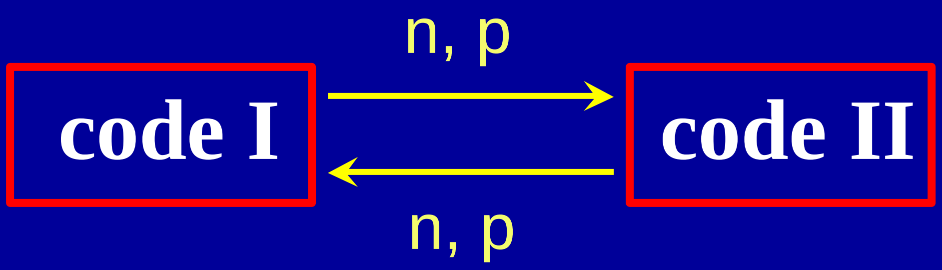
The rates are from the Fowler et al., Thielemann et al., Angulo et al. data bases.

Neutrino Nucleosynthesis in Helium Shell

Thermonuclear network (code II)

deals with ~1300 heavy nuclides up to the atomic number Z=60 (Nd)

The rates of the n, p, and α-captures are from
Cowan et al. (1991).
The β-decay rates are from Kratz et al. (1993).



Iterative adjustment

Nadyozhin, Panov, Blinnikov, AA **335**, 207 (1998)

Neutrino Nucleosynthesis in Helium Shell

Neutrino-nuclear interactions included

$$^{4}\mathrm{He}(n,n'\mathrm{n})^{3}\mathrm{He}\ , \qquad ^{4}\mathrm{He}(n,n'\mathrm{p})^{3}\mathrm{H}$$

$$^{12}\mathrm{C}(n,n'\mathrm{n})^{11}\mathrm{C}\ , \qquad ^{12}\mathrm{C}(n,n'\mathrm{p})^{11}\mathrm{B}$$

$$^{12}\mathrm{C}(n,n'{}^{3}\mathrm{He})^{9}\mathrm{Be}\ , \qquad ^{14}\mathrm{N}(n,n'a)^{10}\mathrm{B}$$

$$^{16}\mathrm{O}(n,n'\mathrm{n})^{15}\mathrm{O}\ , \qquad ^{16}\mathrm{O}(n,n'\mathrm{p})^{15}\mathrm{N}$$

$$^{20}\mathrm{Ne}(n,n'\mathrm{n})^{19}\mathrm{Ne}\ , \qquad ^{20}\mathrm{Ne}(n,n'\mathrm{p})^{19}\mathrm{F}$$

$$\mathrm{p}(\tilde{n}_{\mathrm{e}},\mathrm{e}^{+})\mathrm{n}$$

$$n \equiv n_{m,t}\,,\tilde{n}_{m,t}$$

The neutrino cross-sections from:

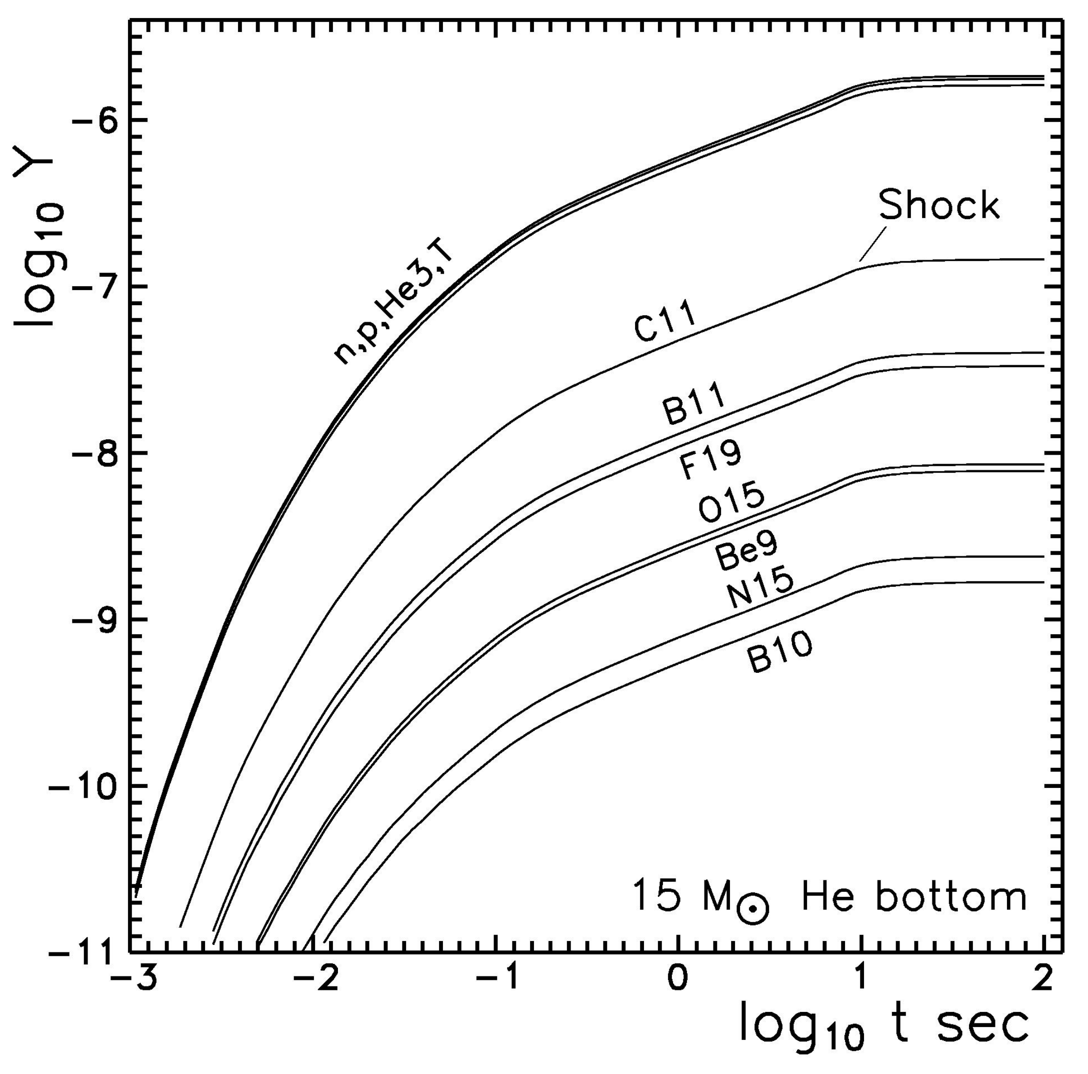
Woosley, Hartmann, Hoffman, Haxton (1990)
Heger, Kolbe, Haxton, Langanke et al. (2003)
Domogatsky, Svetlana Imshennik (1982)
Domogatsky, Nadyozhin, Eramzhyan (1978)

The cross-sections are averaged over the μ and τ neutrino-antineutrino spectra given by the Fermi-Dirac distributions with T=8 MeV and zero chemical potential ($\langle E_\nu \rangle$ = 25 MeV).

The post-shock temporal behavior of temperature, density, and radius from:

Nadyozhin, Deputovich (2002)

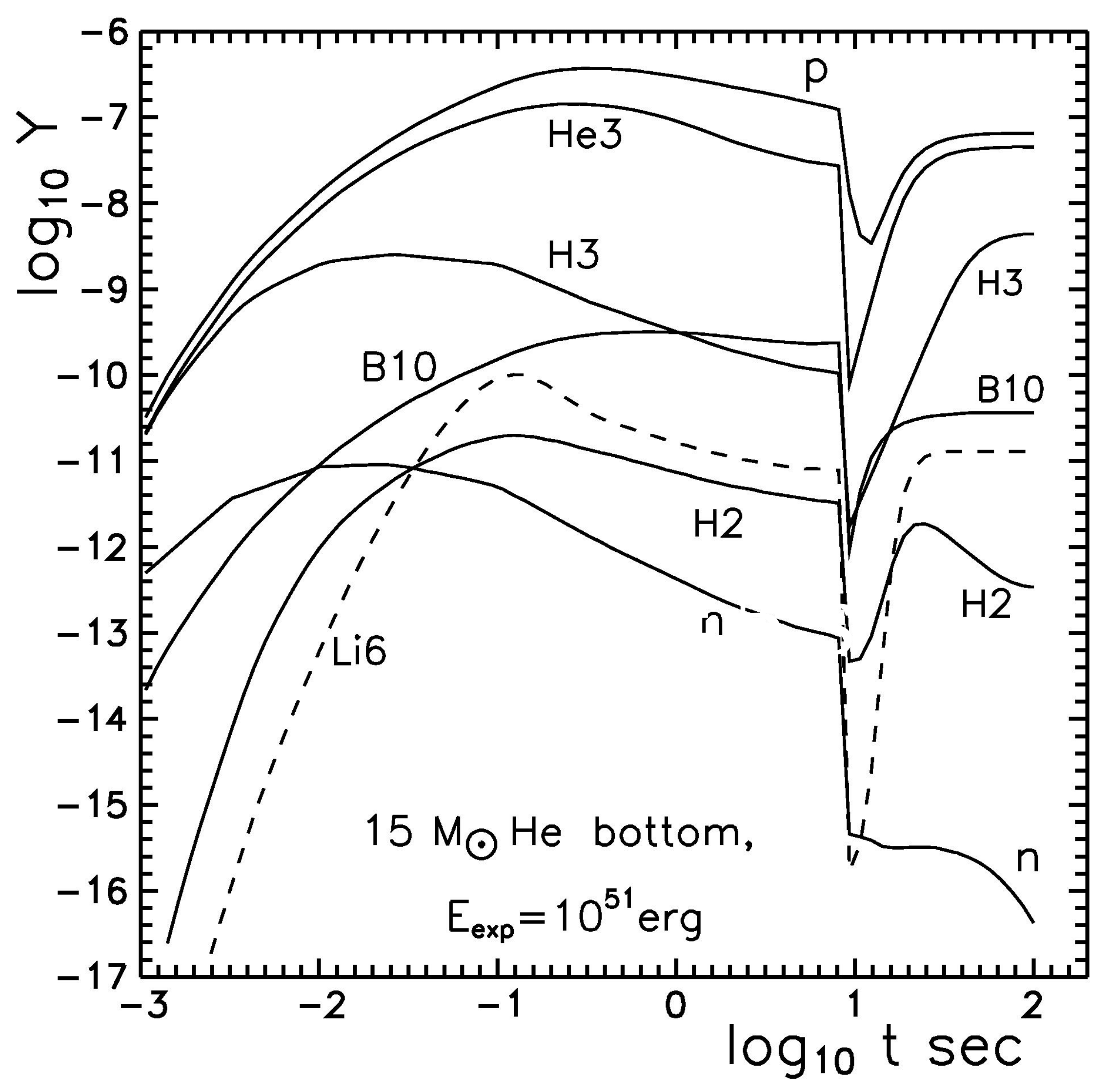
Neutrino Nucleosynthesis in Helium Shell



No thermonuclear processing !

(only ν-induced interactions!)

Neutrino Nucleosynthesis in Helium Shell



Post-shock burning and recreation I

(**Y** versus time **t**)

$E_{exp}=10^{51}$erg

$T_{peak}=6.5\ 10^8$K

$r_{peak}=5.3\ 10^3$

Shock arrives at $\Delta t_{SW} \approx 8$ s

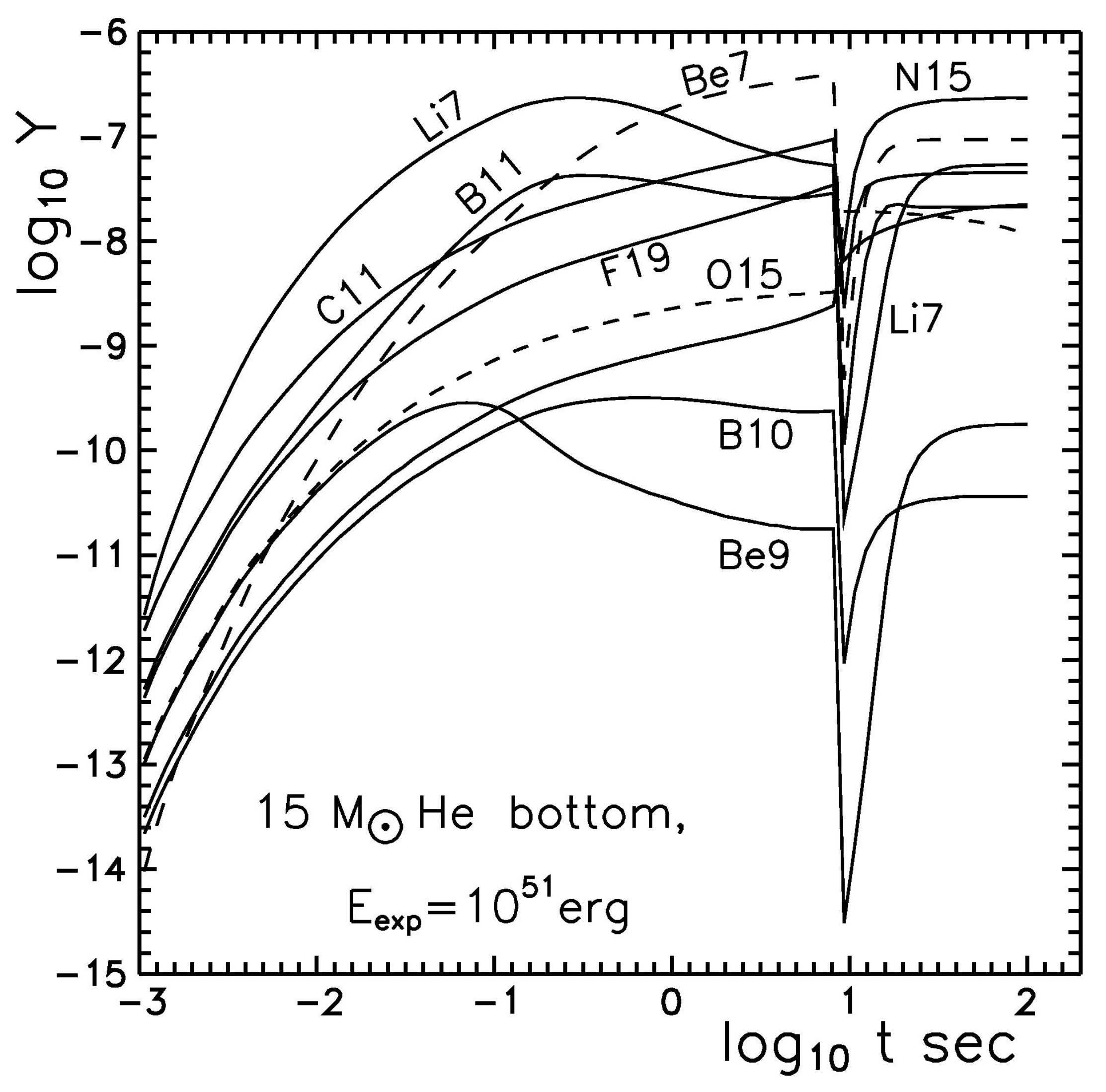
Post shock characteristic time $\Delta t = 5$ s

$$Y_j \equiv \frac{m_u}{r} n_j$$

number of nuclides

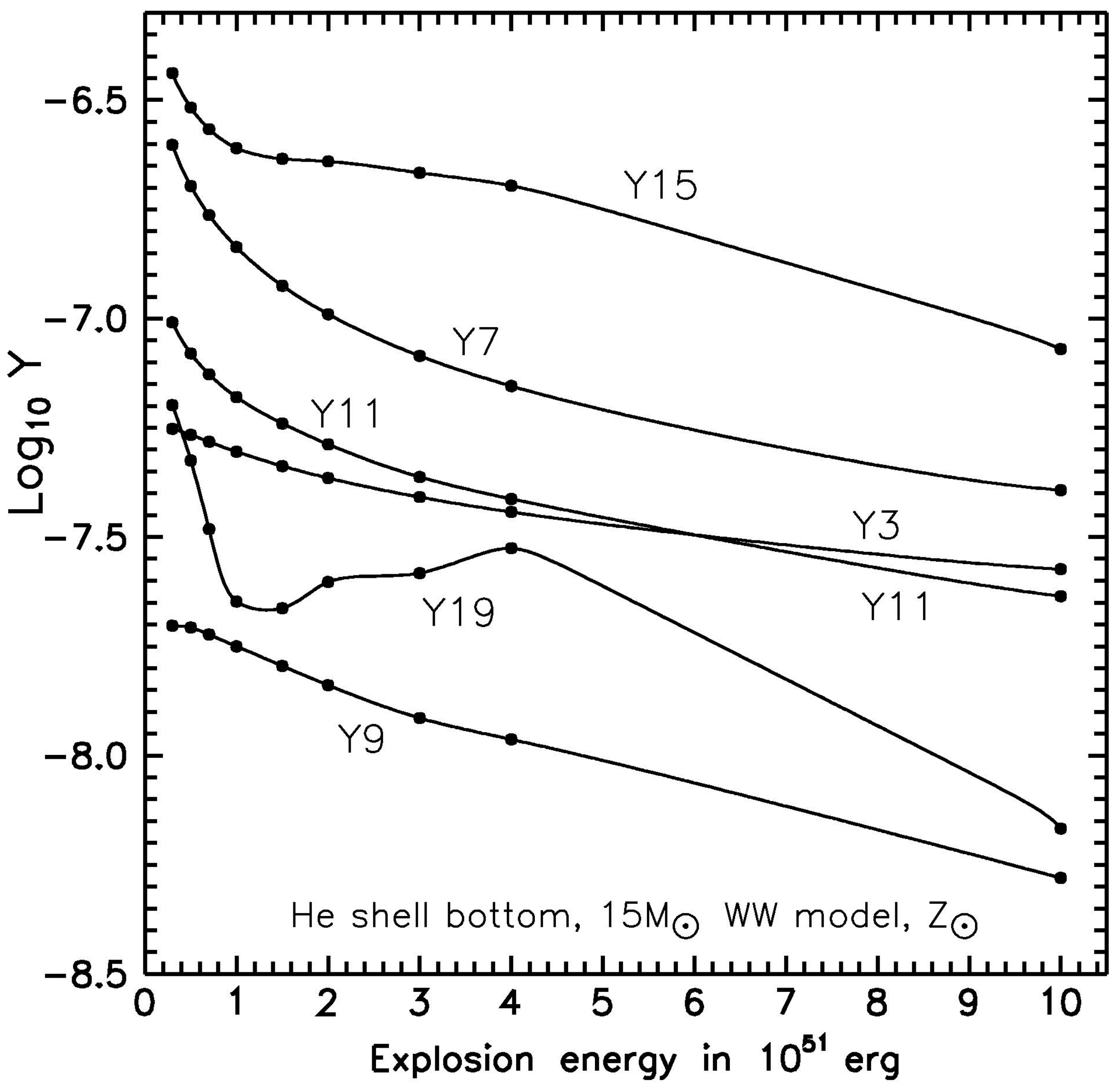
j per barion

Neutrino Nucleosynthesis in Helium Shell



Post-shock burning and recreation II

(**Y** versus time **t**)



Bottom of He-shell: Final yields versus E_{exp}

(Here Y9 = actual Y9 × 100)

Neutrino Nucleosynthesis in Helium Shell

$$Y3 = {}^{3}\mathrm{He} + {}^{3}\mathrm{H} \quad (T_{1/2} = 12.33\ \mathrm{y})$$

$$Y7 = {}^{7}\mathrm{Li} + {}^{7}\mathrm{Be} \quad (T_{1/2} = 53.29\ \mathrm{d})$$

$$Y9 = {}^{9}\mathrm{Be}$$

$$Y11 = {}^{11}\mathrm{B} + {}^{11}\mathrm{C} \quad (T_{1/2} = 20.4\ \mathrm{m})$$

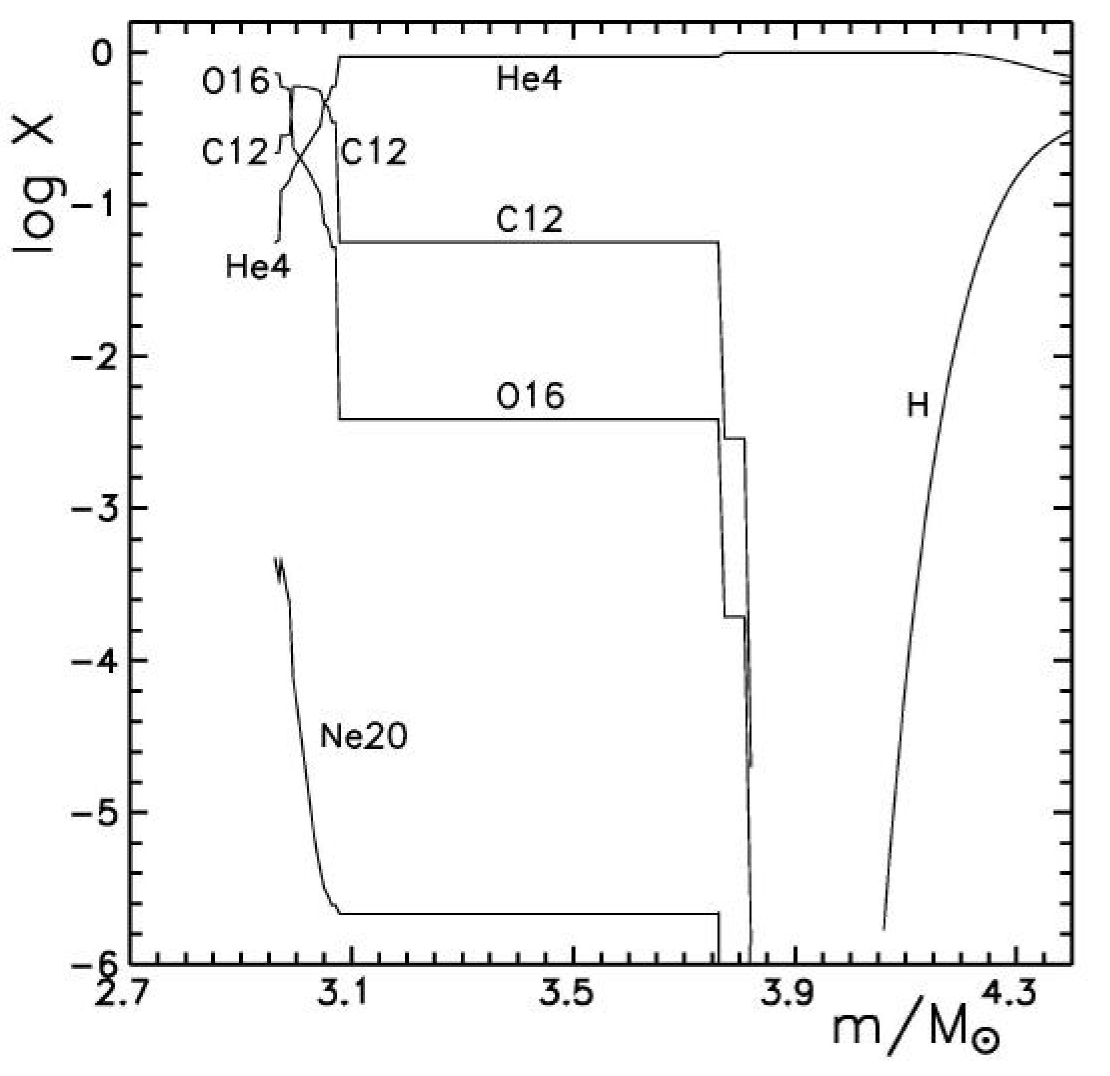
$$Y15 = {}^{15}\mathrm{N} + {}^{15}\mathrm{O} \quad (T_{1/2} = 122\ \mathrm{s})$$

$$Y19 = {}^{19}\mathrm{F} + {}^{19}\mathrm{Ne} \quad (T_{1/2} = 17.3\ \mathrm{s})$$

Neutrino Nucleosynthesis in Helium Shell

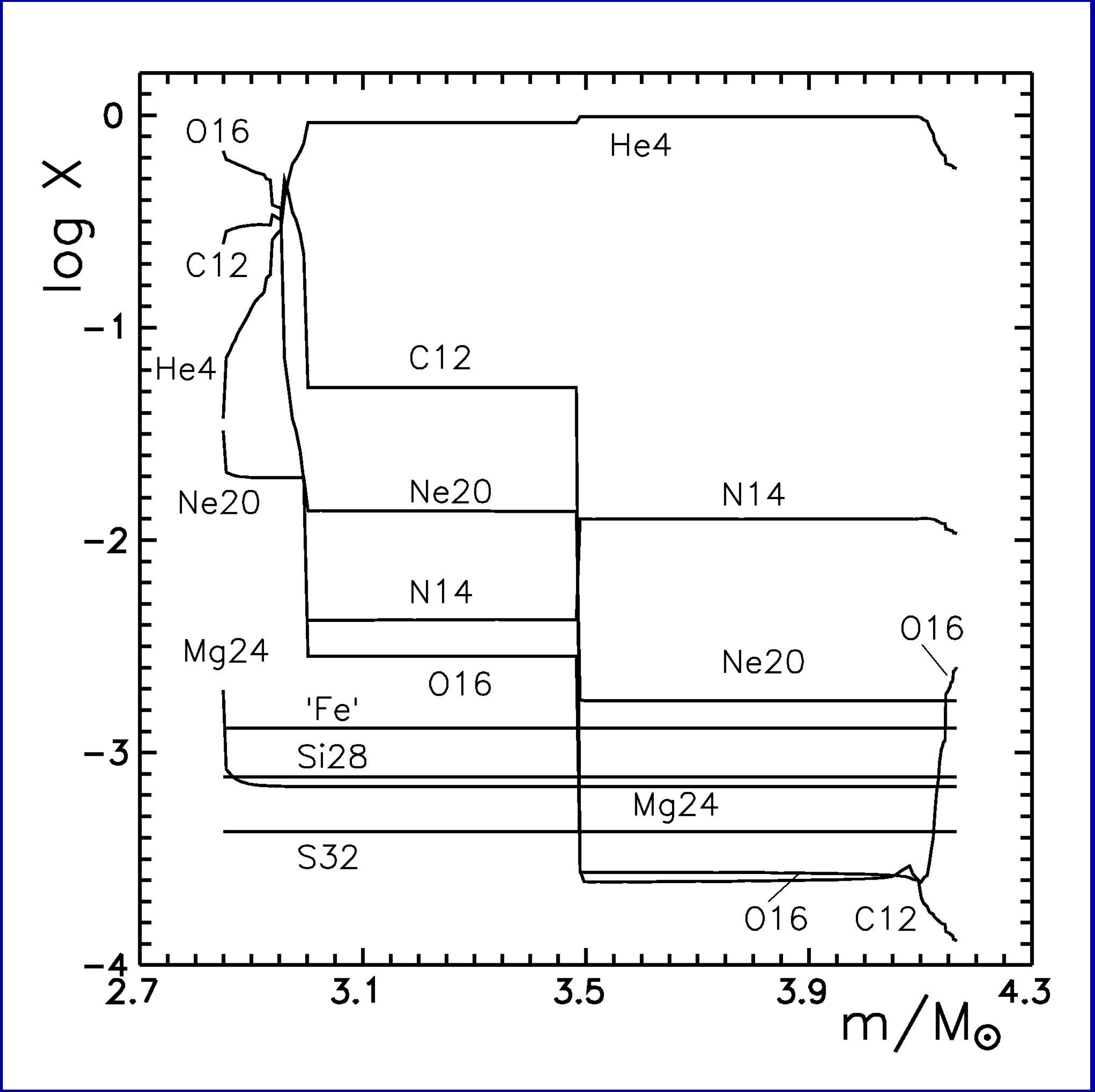
Neutrino-driven weak r-process component in the helium shell of poor-metal stars

Neutrino Nucleosynthesis in Helium Shell



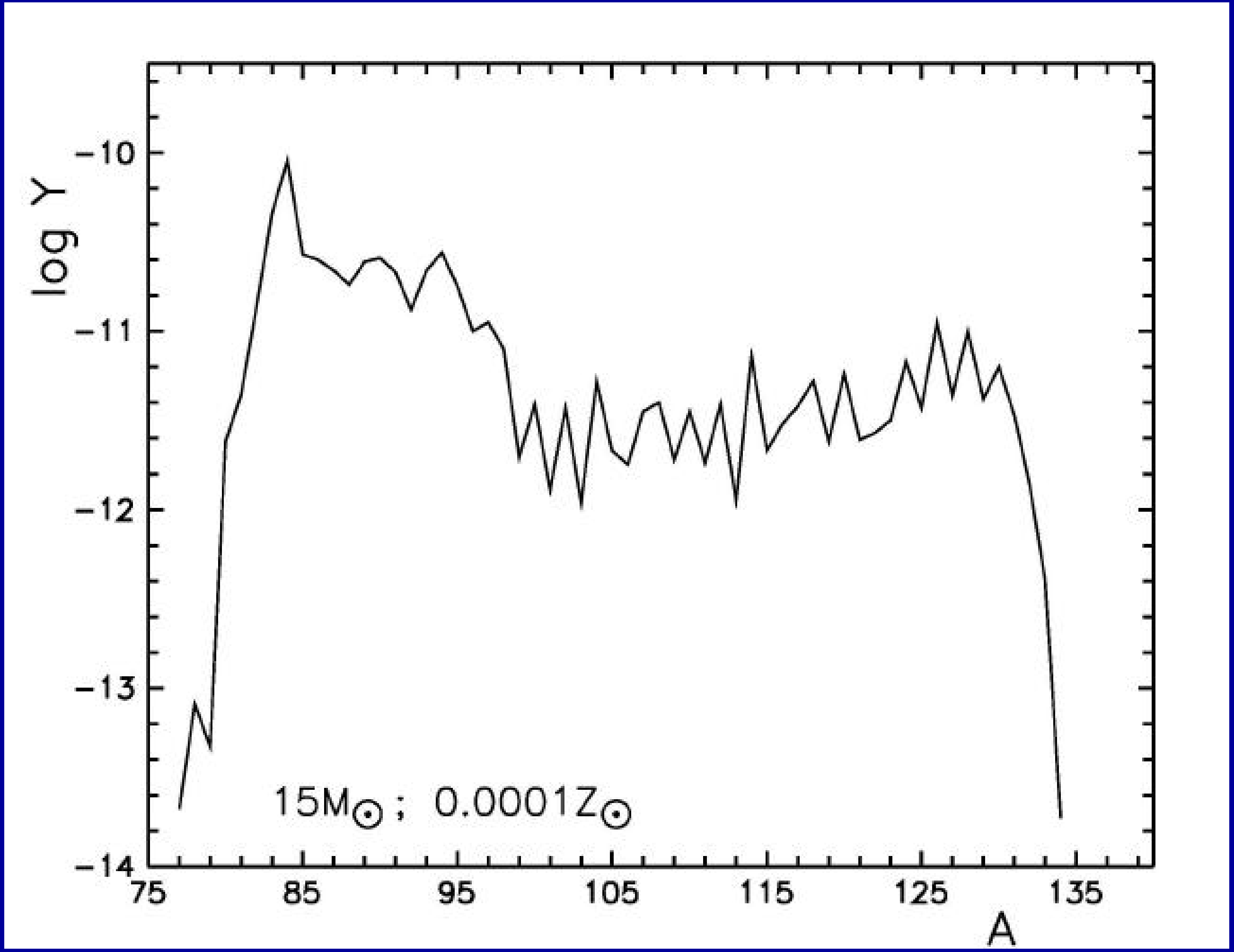
Composition of a 15 M$_\odot$ poor-metal (Z=0.0001 Z$_\odot$) presupernova He-shell (*Woosley, Heger et al*.)

Neutrino Nucleosynthesis in Helium Shell



Composition of a 15 $M_\odot$ solar metallicity ($Z_\odot$) presupernova He-shell (*Woosley, Heger et al.*)

Neutrino Nucleosynthesis in Helium Shell



On average 50 neutrons were captured per Fe-seed
Nadyozhin, *Panov* *Astron. Lett.* **33**, 385 (2007)

Main issues

1. Creation of some 30 isotopes (from ^{74}Se up to ^{196}Hg) that can be produced neither in the s-process nor in the r-process (bypassed or p-nuclei)

2. Creation of ^{7}Li, ^{11}B, ^{9}Be (in He-shell and in CO-shell)
There is no need in hypothetical low-energy (E<100 MeV) CR

^{6}Li comes from CR;
^{7}Li comes from BBN + CR + NN;
^{9}Be comes from CR + NN;
^{10}B comes from CR;
^{11}B comes from CR + NN;

No problem with large cosmic ratios ^{7}Li/^{6}Li and ^{11}B/^{10}B

3. Creation of rare isotopes such as ^{19}F, ^{15}N and some others

4. Possibility to reproduce at least a weak component of the r-process in He-shell

5. Neutrino induced acceleration of heavy nuclide fission

6. Evaporation of free neutrons due to the neutrino inelastic scattering off heavy nuclides (helps to drive the r-process)

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see a remarkable review:

Woosley S.E., Heger A. and Weaver T.A.

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Acknowledgement

It is a pleasure to thank
the NTAA Organizing Committee
for warm hospitality and financial support

Some results reported in this lecture were supported
by the Swiss-Russian grant SNF #IB7320-110996
and grant # 04-02-16793-a of the Russian Foundation
of Basic Research