Neutrinos in protoneutron star models

Monika Pieńkos

University of Silesia

Matter to the deepest

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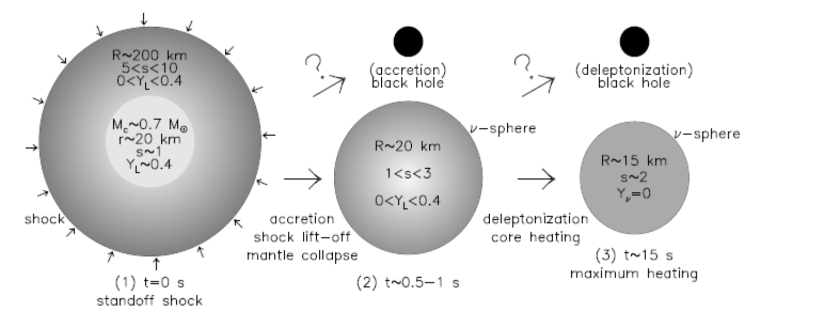
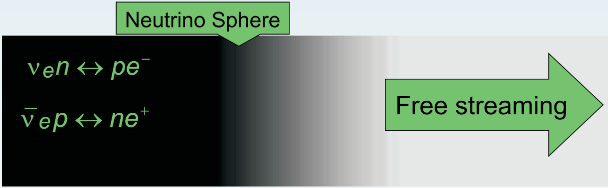


Evolution of neutron star (M. Prakash et al., Phys. Rep., **280**, 1 (1997))

- the post bounce phase: the low entropy core (s=1) and high entropy outer layer ($5 < s < 10$), both with trapped neutrinos (1)
- deleptonization of the outer layer (2)
- ν-free, high entropy (s=2) core, thermally produced neutrino pairs are emitted (3)
- neutrino cooling → cold catalyzed object

Neutrino interactions in the surronding medium

- neutrino - pair annihilation $\nu_e\bar{\nu_e} \leftrightarrow \nu_\mu\bar{\nu_\mu}$
- electron - positron annihilation $e^- + e^+ \leftrightarrow \nu + \bar{\nu}$
- nucleon - nucleon bremsstrahlung $NN \leftrightarrow NN\nu\bar{\nu}$
- scattering reactions $e^\pm + \nu \rightarrow e^\pm + \nu$, $N + \nu \rightarrow N + \nu$
- absorption processes $\nu_e + n \leftrightarrow e^- + p$, $\bar{\nu_e} + p \leftrightarrow e^+ + n$



Schematic picture of the ν_e and $\bar{\nu}_e$ spheres in a proto-neutron star

(M. T. Keil, astro-ph/0308228v1)

The models

Constituents of the model:

- baryons:
  - nucleons n, p
  - hyperons Λ, Σ, Ξ [a]
- mesons:
  - scalar $\longrightarrow \sigma$, σ^*
  - vector $\longrightarrow \omega_\mu$, ρ^a_μ, ϕ_μ
- leptons: electrons, muons, neutrinos

[a] only in the model of a hyperon star

Lagrangian of the model

$$
\begin{aligned}
\mathcal{L} &= \sum_B \overline{\psi}_B \left[\gamma^\mu i D_\mu - (M_B - g_{B\sigma}\sigma - g_{B\sigma^*}\sigma^*)\right]\psi_B \\
&+ \frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3}g_3\sigma^3 - \frac{1}{4}g_4\sigma^4 + \frac{1}{2}\partial^\mu\sigma^*\partial_\mu\sigma^* - \frac{1}{2}m_{\sigma^*}^2\sigma^{*2} \\
&+ \frac{1}{2}m_\omega^2(\omega^\mu\omega_\mu) + \frac{1}{2}m_\rho^2(\rho^{\mu a}\rho_\mu^a) + \frac{1}{2}m_\phi^2(\phi^\mu\phi_\mu) + \frac{1}{4}c_3(\omega^\mu\omega_\mu)^2 \\
&- \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} - \frac{1}{4}R^{\mu\nu a}R_{\mu\nu}^a - \frac{1}{4}\Phi^{\mu\nu}\Phi_{\mu\nu} + \sum_{l=e,\mu}\overline{\psi}_l(i\gamma^\mu\partial_\mu - m_l)\psi_l \\
&+ \Lambda_V(g_{N\omega}g_{N\rho})^2(\omega^\mu\omega_\mu)(\rho^{\mu a}\rho_\mu^a)
\end{aligned}
$$

$$\Psi_N = \begin{pmatrix} \psi_p \\ \psi_n \end{pmatrix}, \qquad \Psi_\Lambda = \psi_\Lambda,$$

$$\Psi_\Sigma = \begin{pmatrix} \psi_{\Sigma^+} \\ \psi_{\Sigma^0} \\ \psi_{\Sigma^-} \end{pmatrix}, \quad \Psi_\Xi = \begin{pmatrix} \psi_{\Xi^0} \\ \psi_{\Xi^-} \end{pmatrix}.$$

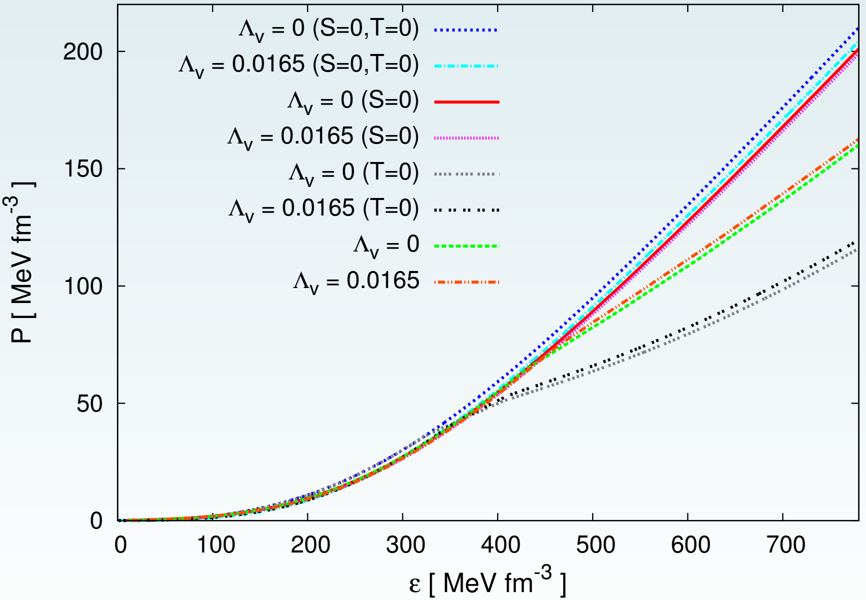
$$\begin{aligned} D_\mu &= \partial_\mu + ig_{B\omega}\omega_\mu + ig_{B\phi}\phi_\mu + ig_{B\rho} I_{3B}\tau^a\rho^a_\mu \\ \Omega_{\mu\nu} &= \partial_\mu\omega_\nu - \partial_\nu\omega_\mu \\ \Phi_{\mu\nu} &= \partial_\mu\phi_\nu - \partial_\nu\phi_\mu \\ R^a_{\mu\nu} &= \partial_\mu\rho^a_\nu - \partial_\nu\rho^a_\mu \end{aligned}$$

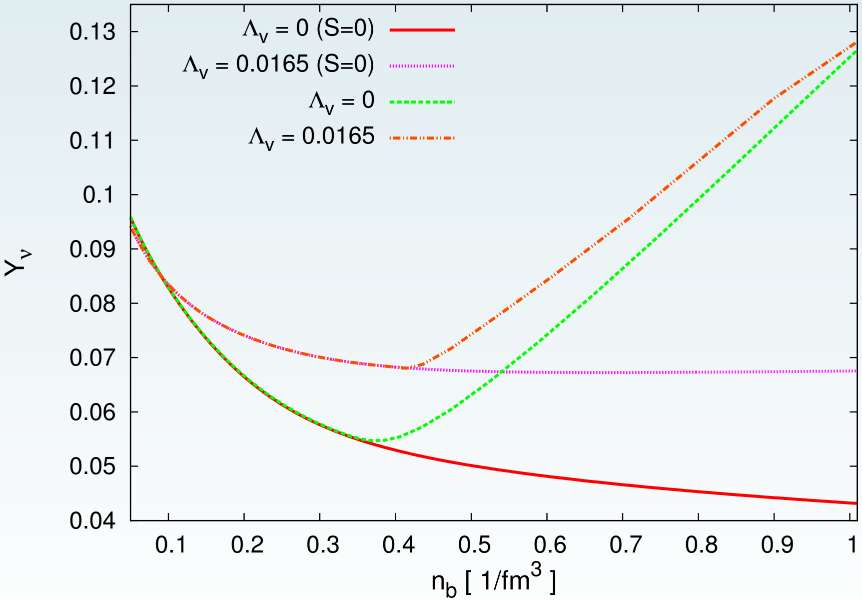
Equation of state

$$
\begin{aligned}
\varepsilon &= \frac{1}{2}m_\sigma s_0^2 + \frac{1}{3}s_0^3 + \frac{1}{4}s_0^4 + \frac{1}{2}m_{\sigma^*}s_0^{*2} + \frac{1}{2}m_\omega^2 w_0^2 + \frac{3}{4}c_3 w_0^4 + \\
&+ \frac{1}{2}m_\rho^2 r_0^2 + 3\Lambda_V (g_\omega g_\rho)^2 w_0^2 r_0^2 + \frac{1}{2}m_\phi^2 f_0^2 \\
&+ \sum_{i=B,l}\left\{\frac{2J_i+1}{(2\pi)^3}\int d^3k E_i^*(k)(f_i^+(k)+f_i^-(k))\right\} \\
P &= -\frac{1}{2}m_\sigma s_0^2 - \frac{1}{3}s_0^3 - \frac{1}{4}s_0^4 - \frac{1}{2}m_{\sigma^*}s_0^{*2} + \frac{1}{2}m_\omega^2 w_0^2 + \frac{1}{4}c_3 w_0^4 + \\
&+ \frac{1}{2}m_\rho^2 r_0^2 + \frac{1}{2}m_\phi^2 f_0^2 + \Lambda_V (g_\omega g_\rho)^2 w_0^2 r_0^2 + \\
&+ \sum_{i=B,l}\left\{\frac{2J_i+1}{3(2\pi)^3}\int d^3k \frac{k^2}{E_i^*}(k)(f_i^+(k)+f_i^-(k))\right\}
\end{aligned}
$$

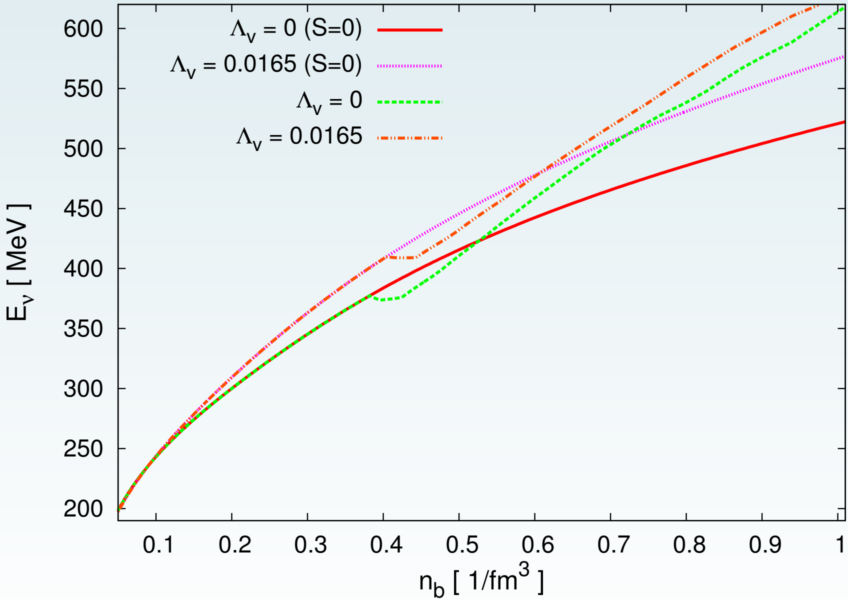
$$
\begin{aligned}
f_i^{\pm} &= \frac{1}{\exp\left[(E_i^{\star}(k) \mp \nu_i)/T\right] + 1} \\
\nu_i &= \mu_i - g_{i\omega} w_0 - g_{i\rho} r_{03} I_{3i} - g_{i\phi} f_0 \\
E_i^{\star}(k) &= \sqrt{k^2 + M_i^{\star 2}} \\
M_B^{\star} &= M_B - g_{B\sigma} s_0 - g_{B\sigma^{\star}} s_0^{\star} \\
M_l^{\star} &= m_l
\end{aligned}
$$

Results

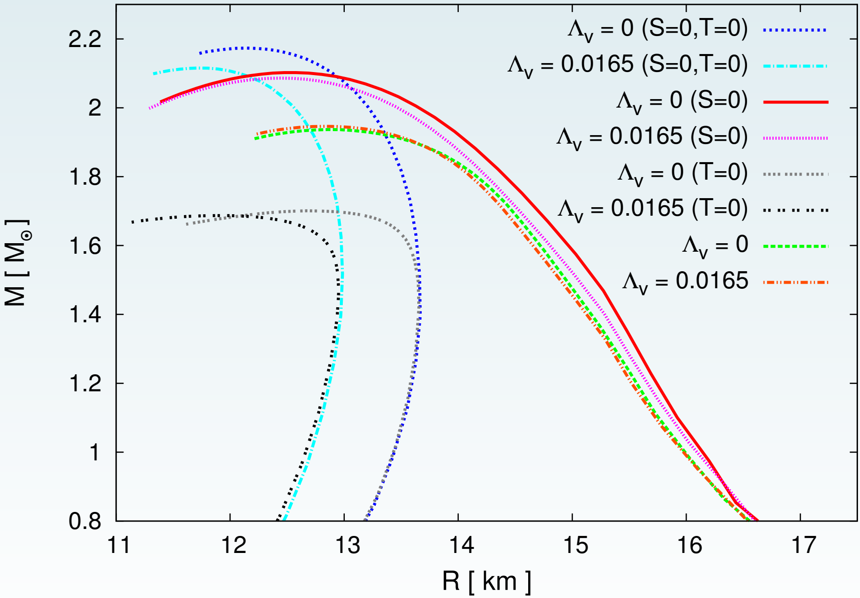

Λv = 0 (S=0,T=0)
Λv = 0.0165 (S=0,T=0)
Λv = 0 (S=0)
Λv = 0.0165 (S=0)
Λv = 0 (T=0)
Λv = 0.0165 (T=0)
Λv = 0
Λv = 0.0165
P [MeV fm-3]
ε [MeV fm-3]
0
50
100
150
200
0
100
200
300
400
500
600
700

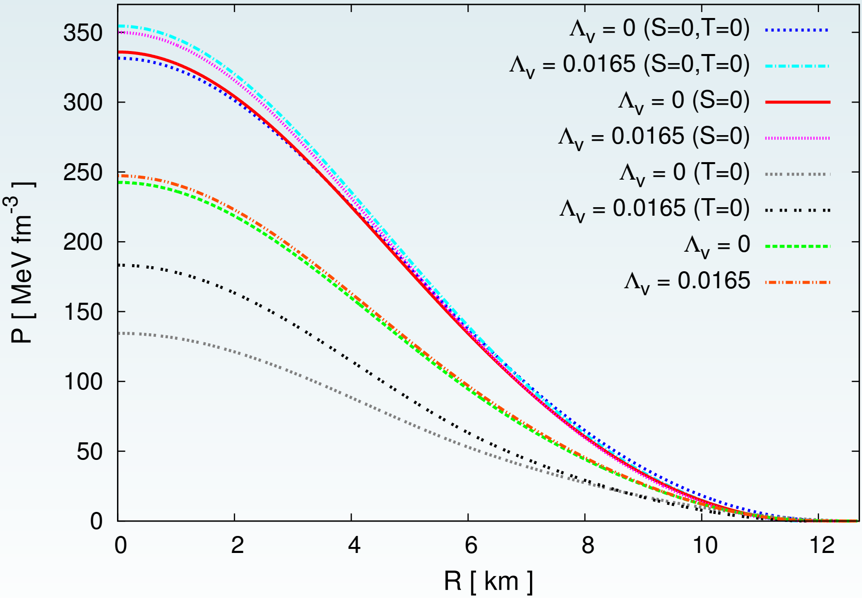


Λv = 0 (S=0)
Λv = 0.0165 (S=0)
Λv = 0
Λv = 0.0165
Yν
nb [1/fm3]
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11
0.12
0.13
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

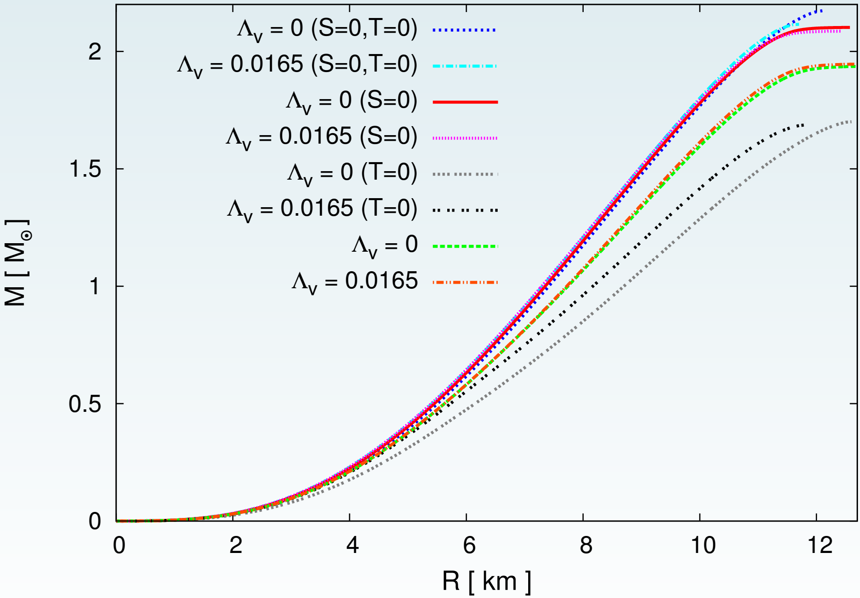


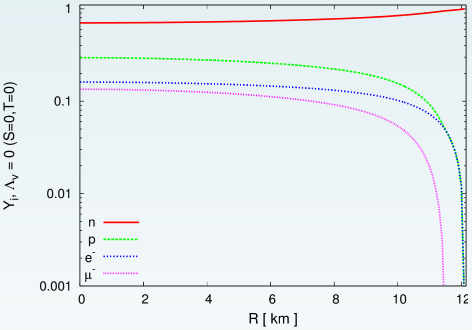
Λv = 0 (S=0)
Λv = 0.0165 (S=0)
Λv = 0
Λv = 0.0165
Eν [MeV]
nb [1/fm3]
600
550
500
450
400
350
300
250
200
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

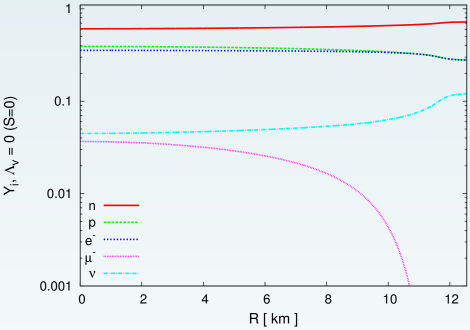

Λ_v = 0 (S=0,T=0)
Λ_v = 0.0165 (S=0,T=0)
Λ_v = 0 (S=0)
Λ_v = 0.0165 (S=0)
Λ_v = 0 (T=0)
Λ_v = 0.0165 (T=0)
Λ_v = 0
Λ_v = 0.0165
M [$M_\odot$]
R [km]
2.2
2
1.8
1.6
1.4
1.2
1
0.8
11
12
13
14
15
16
17

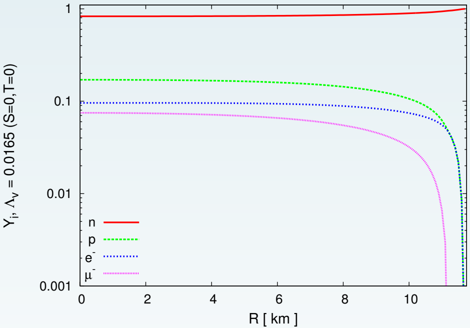


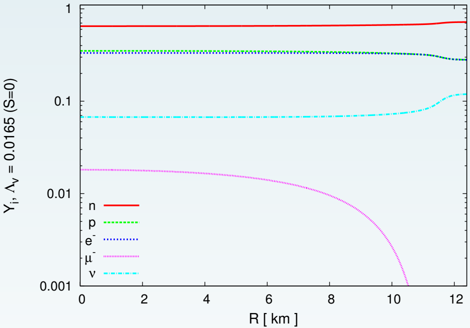
P [MeV fm^{-3}]
R [km]
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
Λ_v = 0 (S=0,T=0)
Λ_v = 0.0165 (S=0,T=0)
Λ_v = 0 (S=0)
Λ_v = 0.0165 (S=0)
Λ_v = 0 (T=0)
Λ_v = 0.0165 (T=0)
Λ_v = 0
Λ_v = 0.0165

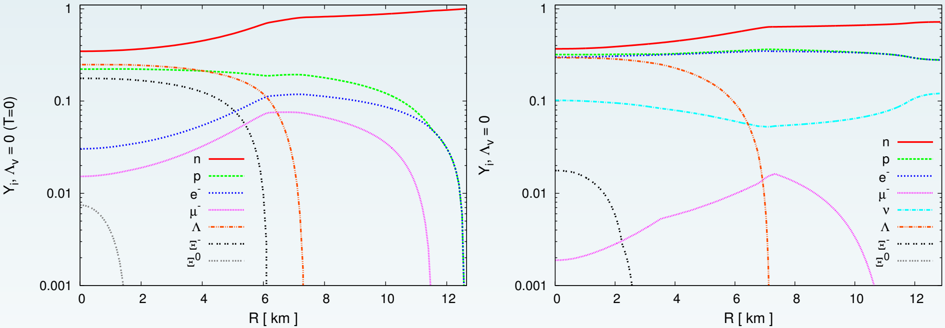

Λv = 0 (S=0,T=0)
Λv = 0.0165 (S=0,T=0)
Λv = 0 (S=0)
Λv = 0.0165 (S=0)
Λv = 0 (T=0)
Λv = 0.0165 (T=0)
Λv = 0
Λv = 0.0165
M [M⊙]
R [km]
0
0.5
1
1.5
2
0
2
4
6
8
10
12

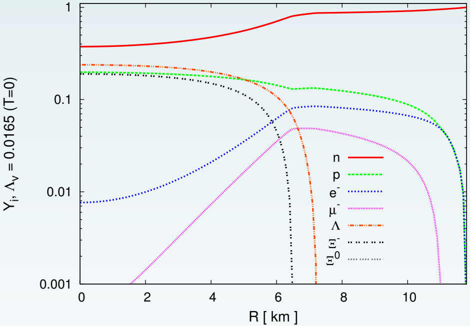

1
0.1
0.01
0.001
Y_i, Λ_ν = 0 (S=0,T=0)
n
p
e^-
μ^-
0
2
4
6
8
10
12
R [km]


1
0.1
0.01
0.001
Y_i, Λ_ν = 0 (S=0)
n
p
e^-
μ^-
ν
0
2
4
6
8
10
12
R [km]

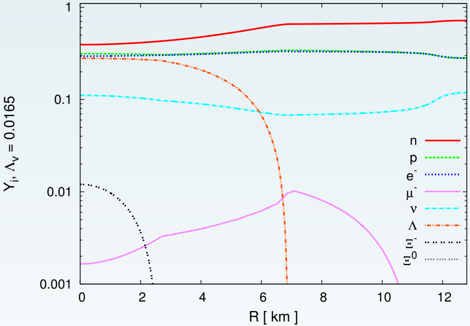

1
0.1
0.01
0.001
0
2
4
6
8
10
R [km]
Y_i, Λ_ν = 0.0165 (S=0,T=0)
n
p
e-
μ-


1
0.1
0.01
0.001
0
2
4
6
8
10
12
R [km]
Y_i, Λ_ν = 0.0165 (S=0)
n
p
e-
μ-
ν


Yi, Λν = 0 (T=0)
1
0.1
0.01
0.001
0 2 4 6 8 10 12
R [km]
n
p
e-
μ-
Λ
Ξ-
Ξ0
Yi, Λν = 0
1
0.1
0.01
0.001
0 2 4 6 8 10 12
R [km]
n
p
e-
μ-
ν
Λ
Ξ-
Ξ0



Y_i, Λ_V = 0.0165 (T=0)
1
0.1
0.01
0.001
0
2
4
6
8
10
R [km]
n
p
e⁻
μ⁻
Λ
Ξ⁻
Ξ0



Y_i, Λ_V = 0.0165
1
0.1
0.01
0.001
0
2
4
6
8
10
12
R [km]
n
p
e⁻
μ⁻
ν
Λ
Ξ⁻
Ξ0

		R_ν [km]	R_* [km]	E_ν [MeV]
$S = 0$	$\Lambda_V = 0$	12.5758	12.5773	55.2786
	$\Lambda_V = 0.0165$	12.4417	12.4404	57.17
$S \neq 0$	$\Lambda_V = 0$	12.858	12.8567	48.2799
	$\Lambda_V = 0.0165$	12.8313	12.8303	57.5677

Conclusions

- model with trapped neutrinos leads to stiffer EoS
- hyperons modify density dependence of neutrinos energy and affect relative concentration of neutrinos
- neutrinos change significantly chemical composition of a star
- neutrinos shift the hyperon onset point to the higher densities
- Λ_V parameter modifies location of a neutrinosphere