# *Impact of the strangeness on the structure of a neutron star*

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   - The model
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## Motivation

- observations of the binary millisecond pulsar J1614-2230 and estimation of the neutron star mass within the range $(1.97 \pm 0.04) M_{\odot}$ [a]
- this shifts the maximum neutron star mass $M_{max}$ towards rather high values
- and rules out most of the EOSs with hyperons - the models which involve exotic particles predict maximum neutron star masses well below $2M_{\odot}$
- there is a need to analyze whether it is possible to construct an EOS of neutron star matter which gives adequately high maximum mass despite including hyperons

[a] P. Demorest, T. Pennucci, S. Ransom, M. Roberts, and J. Hessels, Nature **467**, 1081 (2010)

## The model

Constituents of the model:

- baryons:
  - nucleons $n$, $p$
  - hyperons $\Lambda$, $\Sigma$, $\Xi$
- mesons:
  - scalar $\rightarrow \sigma$, $\sigma^*$
  - vector $\rightarrow \omega_\mu$, $\rho^a_\mu$, $\phi_\mu$
- leptons: electrons, muons

P. Papazoglou, D. Zschiesche, S. Schramm, J. Schaffner-Bielich, Ch. Stcker, W. Greiner, Phys. Rev. **C59**, 411 (1998)
P. Papazoglou, S. Schramm, J. Schaffner-Bielich, Ch. Stcker, W. Greiner, Phys. Rev.**C57**, 2576 (1998)

# Lagrangian of the model

$$
\begin{aligned}
\mathcal{L} &= \sum_B \overline{\psi}_B \left(\gamma^\mu i D_\mu - m_{eff,B}\right)\psi_B + \sum_{l=e,\mu} \overline{\psi}_l (i\gamma^\mu \partial_\mu - m_l)\psi_l \\
&+ \frac{1}{2}\partial^\mu \sigma \partial_\mu \sigma - \frac{1}{2}m_\sigma^2 \sigma^2 - \frac{1}{3}g_3\sigma^3 - \frac{1}{4}g_4\sigma^4 + \frac{1}{2}\partial^\mu \sigma^* \partial_\mu \sigma^* - \frac{1}{2}m_{\sigma^*}^2 \sigma^{*2} \\
&- \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} - \frac{1}{4}R^{\mu\nu a}R^a_{\mu\nu} - \frac{1}{4}\Phi^{\mu\nu}\Phi_{\mu\nu} + \frac{1}{2}m_\omega^2(\omega^\mu\omega_\mu) + \frac{1}{2}m_\rho^2(\rho^{\mu a}\rho^a_\mu) \\
&+ \frac{1}{2}m_\phi^2(\phi^\mu\phi_\mu) + \frac{1}{4}c_3(\omega^\mu\omega_\mu)^2 + \Lambda_V(g_{N\omega}g_{N\rho})^2(\omega^\mu\omega_\mu)(\rho^{\mu a}\rho^a_\mu) \\
&+ \frac{1}{8}c_3(\phi^\mu\phi_\mu)^2 + \frac{1}{4}\Lambda_V(g_{N\omega}g_{N\rho})^2(\phi^\mu\phi_\mu)^2 + \frac{1}{4}c_3(\rho^{\mu a}\rho^a_\mu)^2 \\
&+ \frac{1}{2}\left(\frac{3}{2}c_3 - \Lambda_V(g_{N\omega}g_{N\rho})^2\right)(\phi^\mu\phi_\mu)(\omega^\mu\omega_\mu + \rho^{\mu a}\rho^a_\mu)
\end{aligned}
$$

where

$D_\mu = \partial_\mu + i g_{B\omega}\omega_\mu + i g_{B\phi}\phi_\mu + i g_{B\rho} I_{3B}\tau^a \rho^a_\mu$

$\Omega_{\mu\nu} = \partial_\mu\omega_\nu - \partial_\nu\omega_\mu, \quad \Phi_{\mu\nu} = \partial_\mu\phi_\nu - \partial_\nu\phi_\mu, \quad R^a_{\mu\nu} = \partial_\mu\rho^a_\nu - \partial_\nu\rho^a_\mu$

$m_{eff,B} = m_B - g_{B\sigma}\sigma - g_{B\sigma^*}\sigma^*$

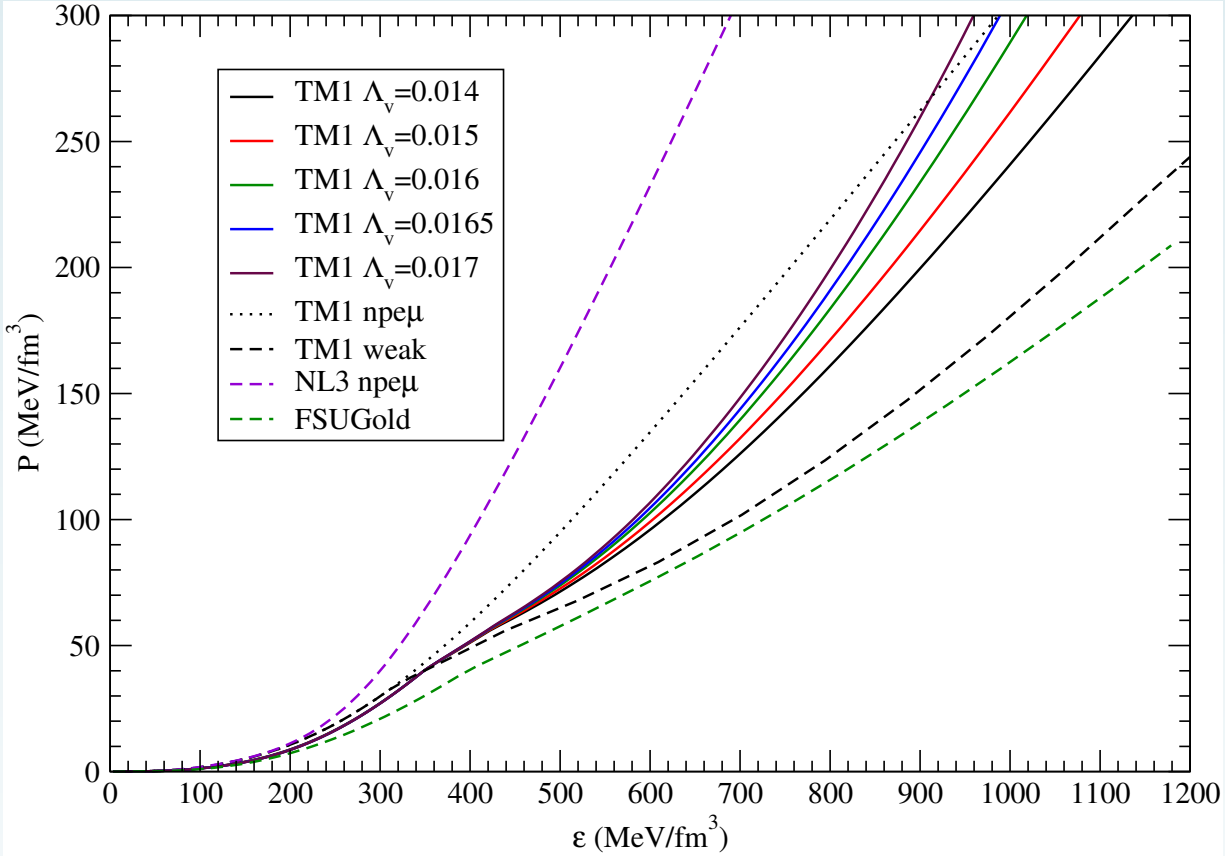
# Equation of state (RMF)

$$
\begin{aligned}
\mathcal{E} &= \frac{1}{2}m_\omega^2 w_0^2 + \frac{1}{2}m_\rho^2 r_0^2 + \frac{1}{2}m_\phi^2 f_0^2 + \frac{1}{2}m_\sigma^2 s_0^2 + \frac{1}{3}g_3 s_0^3 + \frac{1}{4}g_4 s_0^4 \\
&+ \frac{1}{2}m_{\sigma^*}^2 s_0^{*2} + \frac{3}{4}c_3 w_0^4 + 3\Lambda_V (g_\omega g_\rho)^2 w_0^2 r_0^2 + \frac{3}{4}c_3 r_0^4 + \frac{3}{8}c_3 f_0^4 \\
&+ \frac{3}{2}\left(\frac{3}{2}c_3 - \Lambda_V (g_\omega g_\rho)^2\right)(w_0^2 + r_0^2) f_0^2 + \frac{3}{4}\Lambda_V (g_\omega g_\rho)^2 f_0^4 \\
&+ \sum_B \frac{2}{\pi^2}\int_0^{k_{F,B}} k^2 dk \sqrt{k^2 + m_{eff,B}^2} + \mathcal{E}_L
\end{aligned}
$$

# Equation of state (RMF)

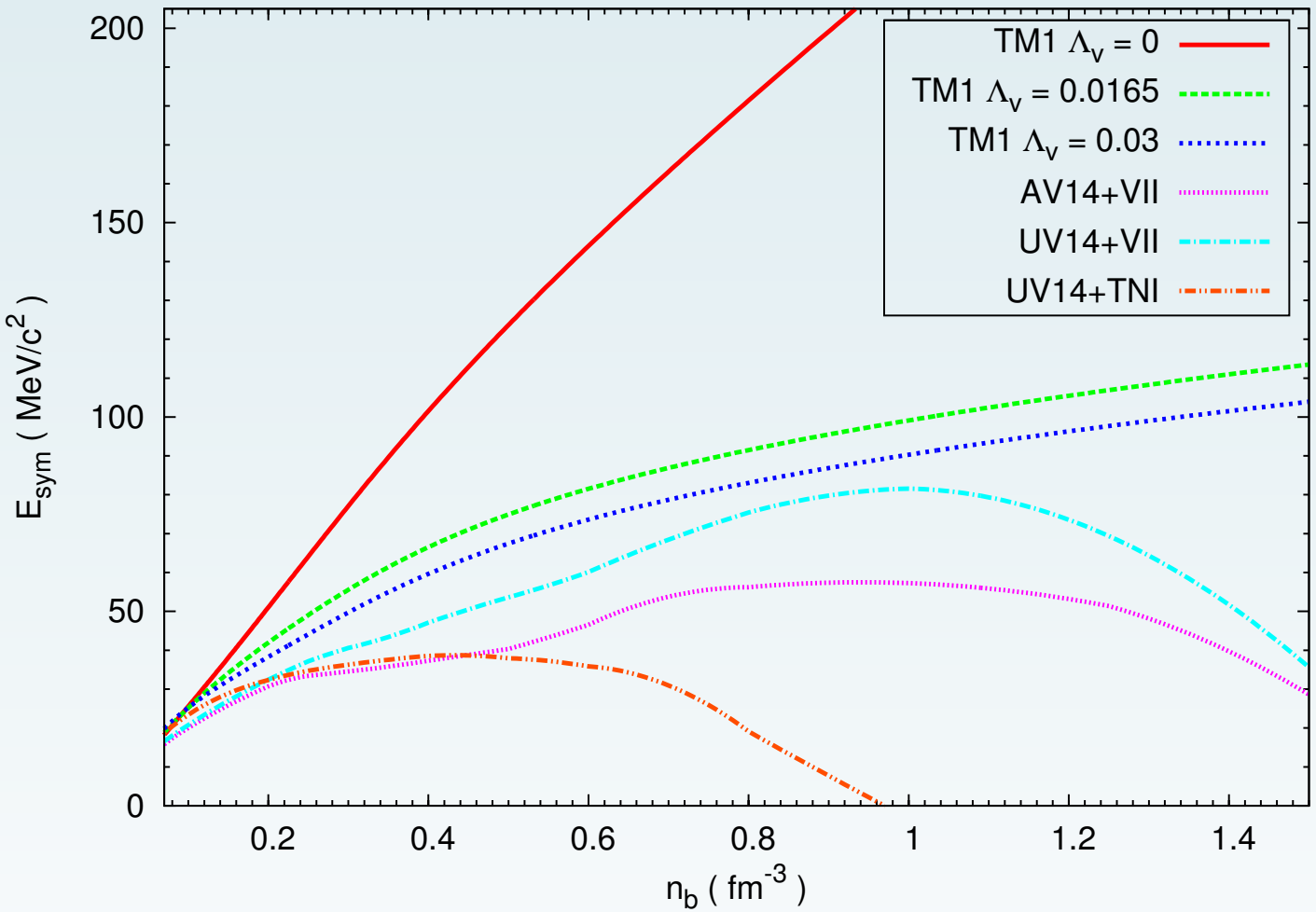
$$
\begin{aligned}
\mathcal{P} &= \frac{1}{2}m_\omega^2 w_0^2 + \frac{1}{2}m_\rho^2 r_0^2 + \frac{1}{2}m_\phi^2 f_0^2 - \frac{1}{2}m_\sigma^2 s_0^2 - \frac{1}{3}g_3 s_0^3 - \frac{1}{4}g_4 s_0^4 \\
&- \frac{1}{2}m_{\sigma^*}^2 s_0^{*2} + \frac{1}{4}c_3(w_0^4 + r_0^4) + \Lambda_V (g_\omega g_\rho)^2 w_0^2 r_0^2 \\
&+ \frac{1}{2}\left(\frac{3}{2}c_3 - \Lambda_V (g_\omega g_\rho)^2\right)(w_0^2 + r_0^2) f_0^2 \\
&+ \left(\frac{1}{8}c_3 + \frac{1}{4}\Lambda_V (g_\omega g_\rho)^2\right) f_0^4 \\
&+ \sum_B \frac{1}{3\pi^2}\int_0^{k_{F,B}} \frac{k^4 dk}{\sqrt{k^2 + m_{eff,B}^2}} + \mathcal{P}_L
\end{aligned}
$$

# Numerical results



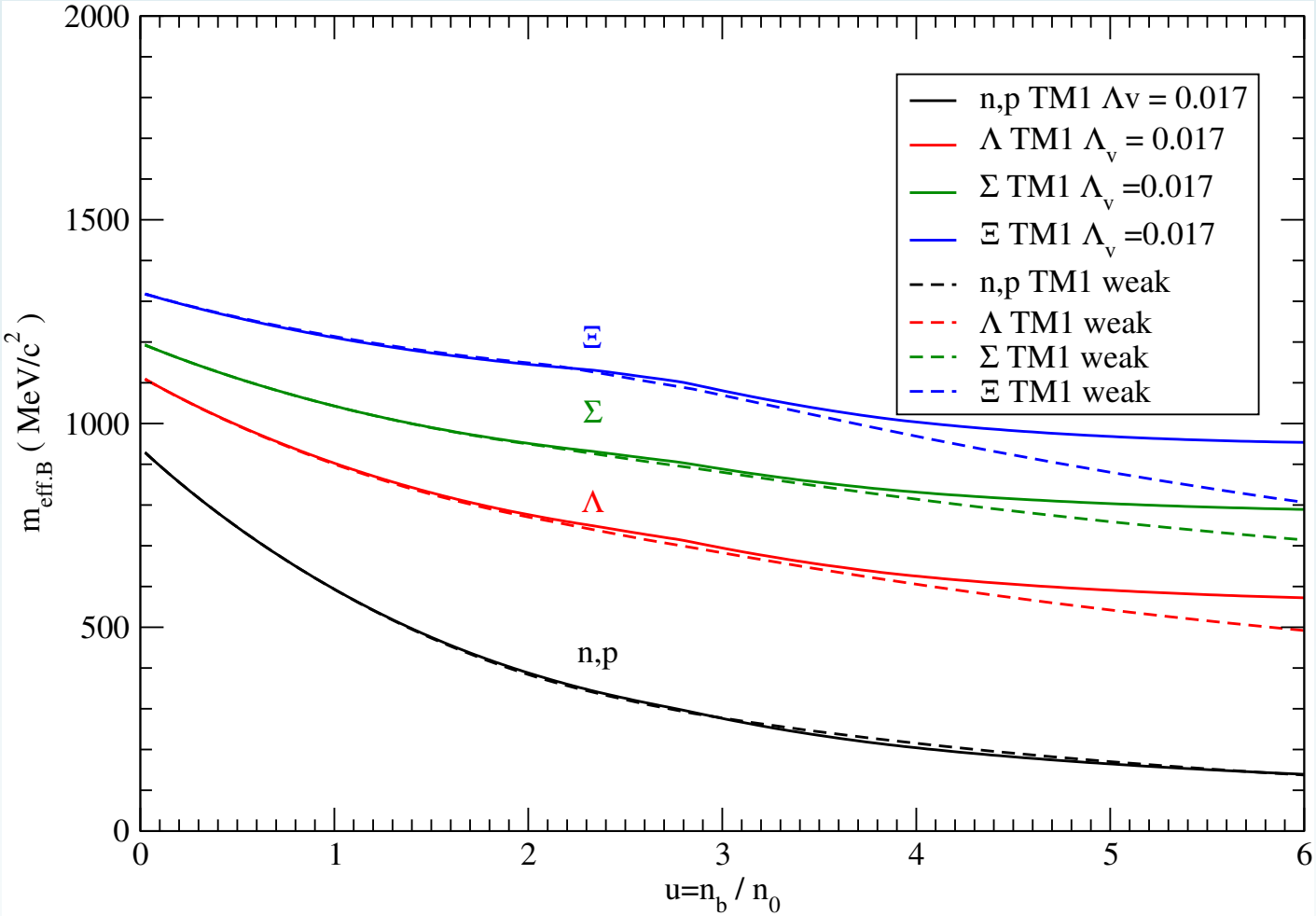

The EOS calculated for the nonlinear model for different values of the coupling strength $\Lambda_V$, the increase of $\Lambda_V$ produces a stiffer EOS. For comparison the results obtained for the non-strange matter for TM1[1], NL3[2] and FSUGold[3] parametrisation set are included. Black dotted line represents the case of the standard TM1 model extended by the inclusion of strange mesons which have been introduced in a minimal fashion.

[1] Y. Sugahara and H. Toki, Prog. Theor. Phys. **92**, 803 (1994)
[2] G. A. Lalazissis, J. Koenig, and P. Ring, Phys. Rev. C **55**, 540 (1997)
[3] B. Todd-Rutel and J. Piekarewicz, Phys. Rev. Lett. **95**, 122501 (2005)

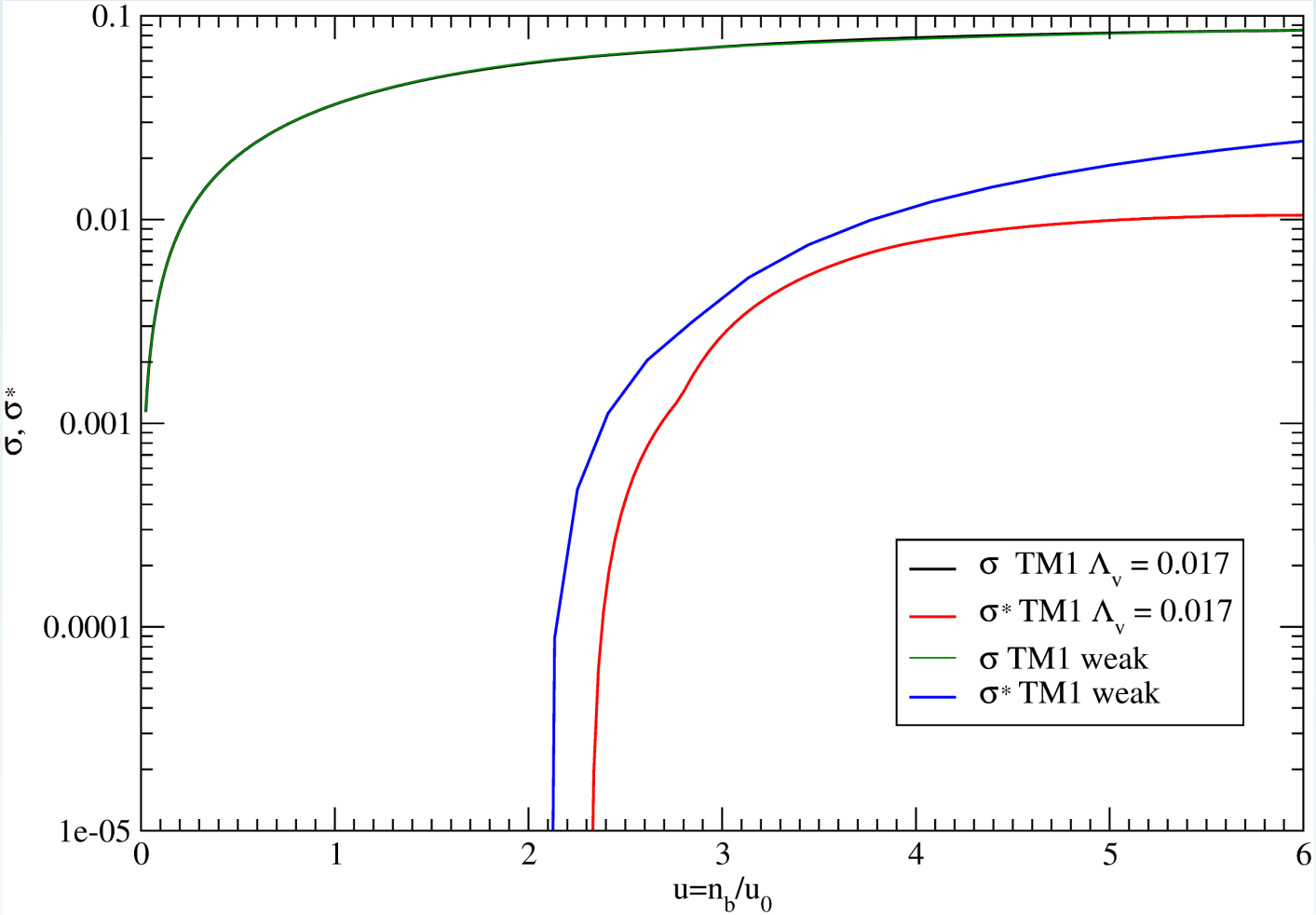



The density dependence of symmetry energy calculated for different values of parameter $\Lambda_V$. The inclusion of $\omega - \rho$ coupling softens the symmetry energy and leads to solution, which approaches that obtained for the AV14 and UV14 models with Urbana VII three nucleon potential[4].

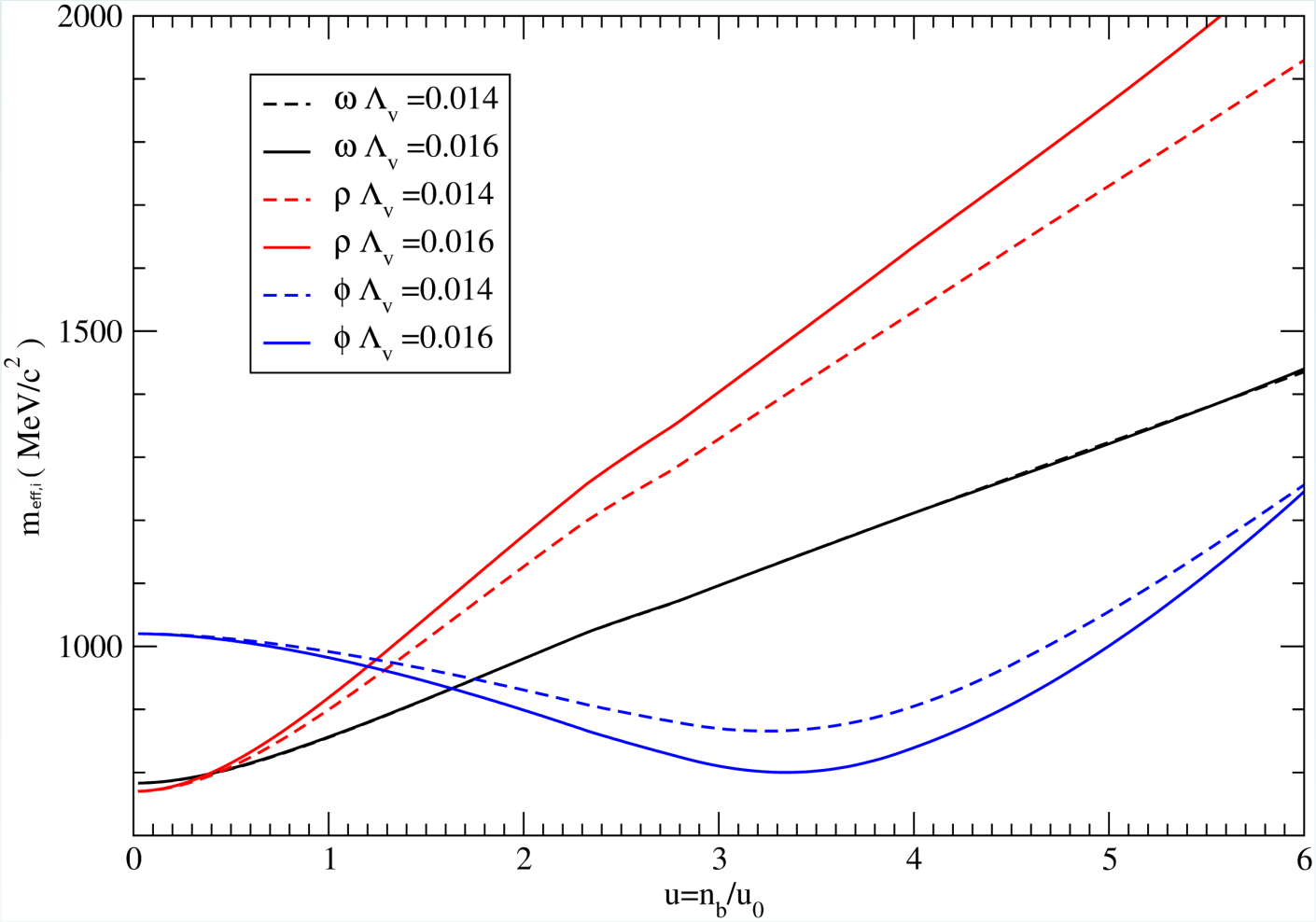
[4] R. B. Wiringa and V. Fiks, Phys. Rev. C **38**, 1010 (1988)



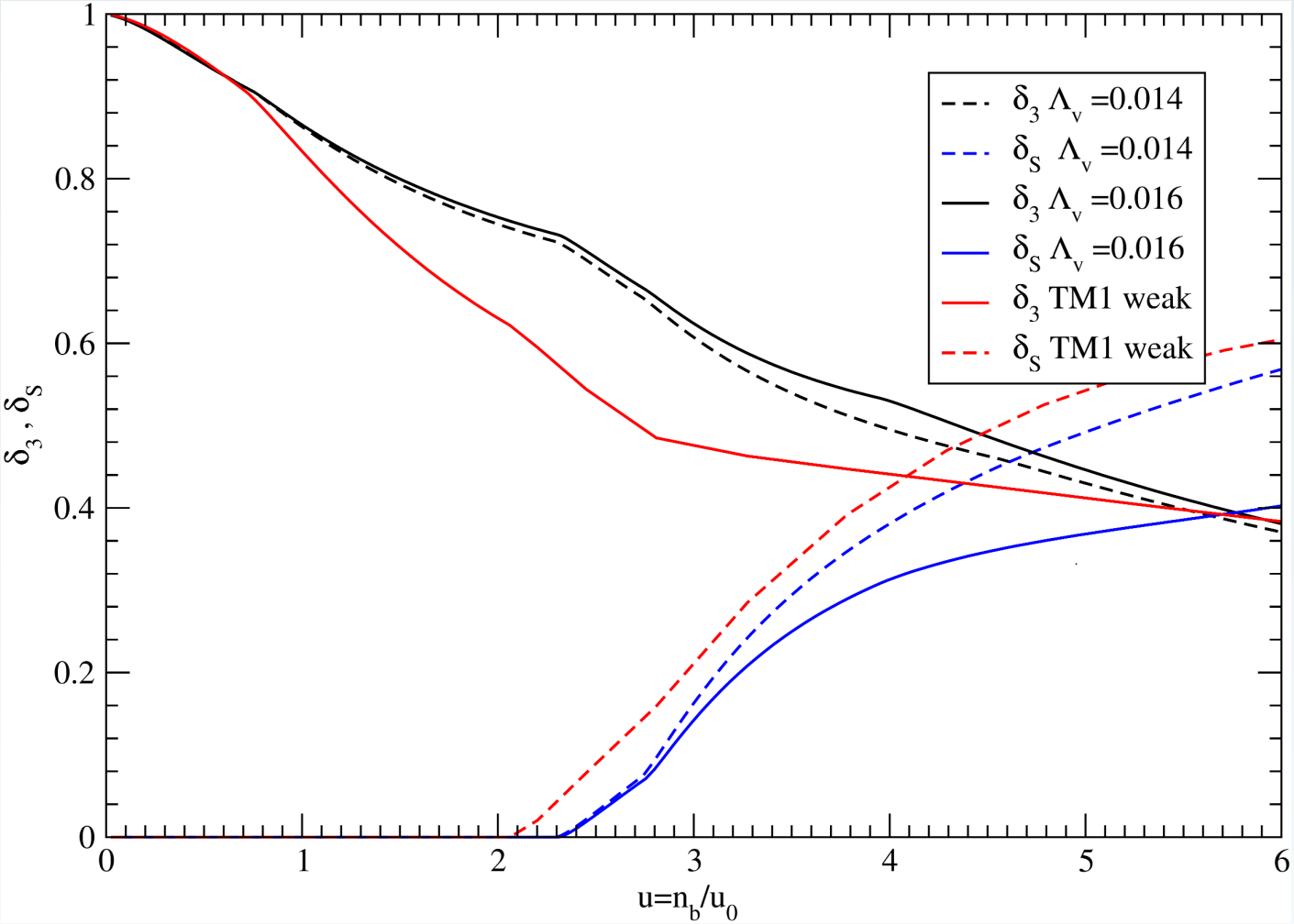

The effective baryon masses as a function of relative baryon density calculated for the nonlinear model, for $\Lambda_V = 0.017$ and for the TM1-weak model. The reduction of the nucleon mass in nonlinear model is essentialy the same as that obtained in the TM1-week model. The effective masses of strange baryons in the case of nonlinear model drop less rapidly than in the case of TM1-weak model.



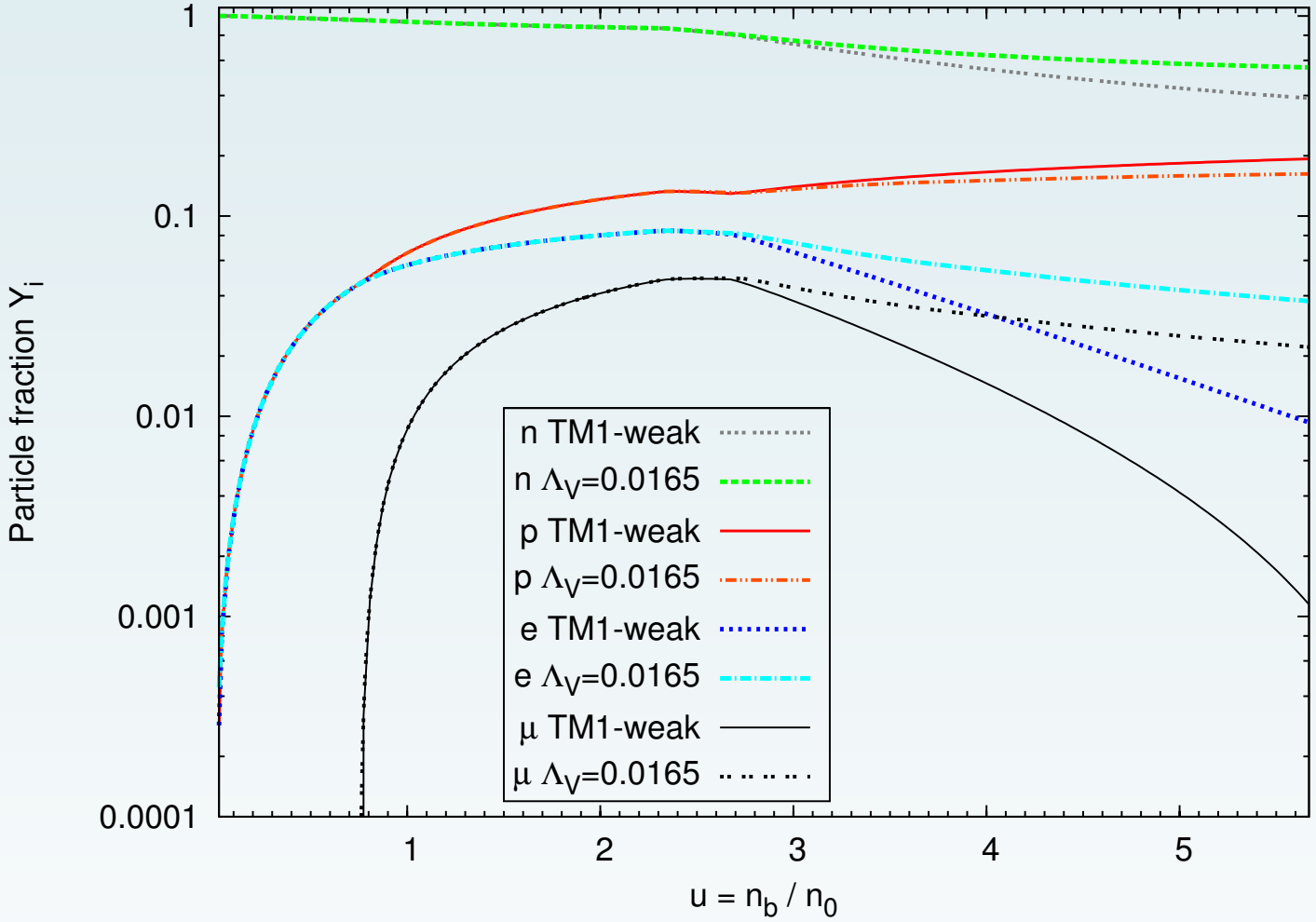

The scalar mesons $\sigma$ and $\sigma^*$ as a function of baryon density. For comparison the results obtained for the TM1-weak model have been included. The presence of nonlinear couplings between vector mesons modifies the density dependence of strange scalar meson leaving the nonstrange scalar meson almost unchanged.



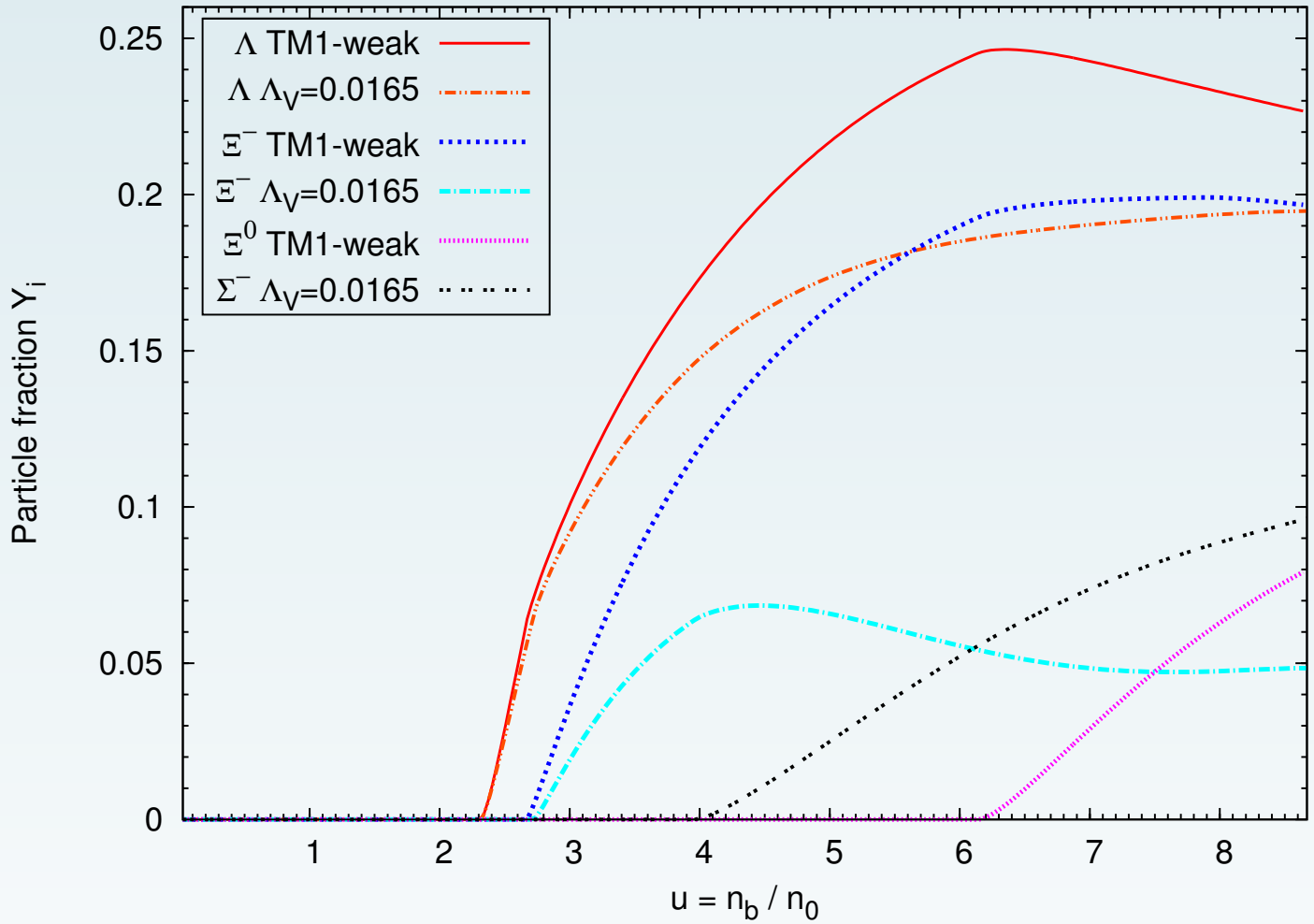

The effective meson masses as a function of baryon number density calculated for the nonlinear model, for $\Lambda_V = 0.014$ and $\Lambda_V = 0.016$. An analysis of the density dependence of the effective $\rho$ and $\phi$ vector meson masses led to the conclusion that their modification was produced by a strong $\Lambda_V$ dependence, especially in the high density limit. The effective mass of the $\omega$ meson is almost independent of the value of parameter $\Lambda_V$.



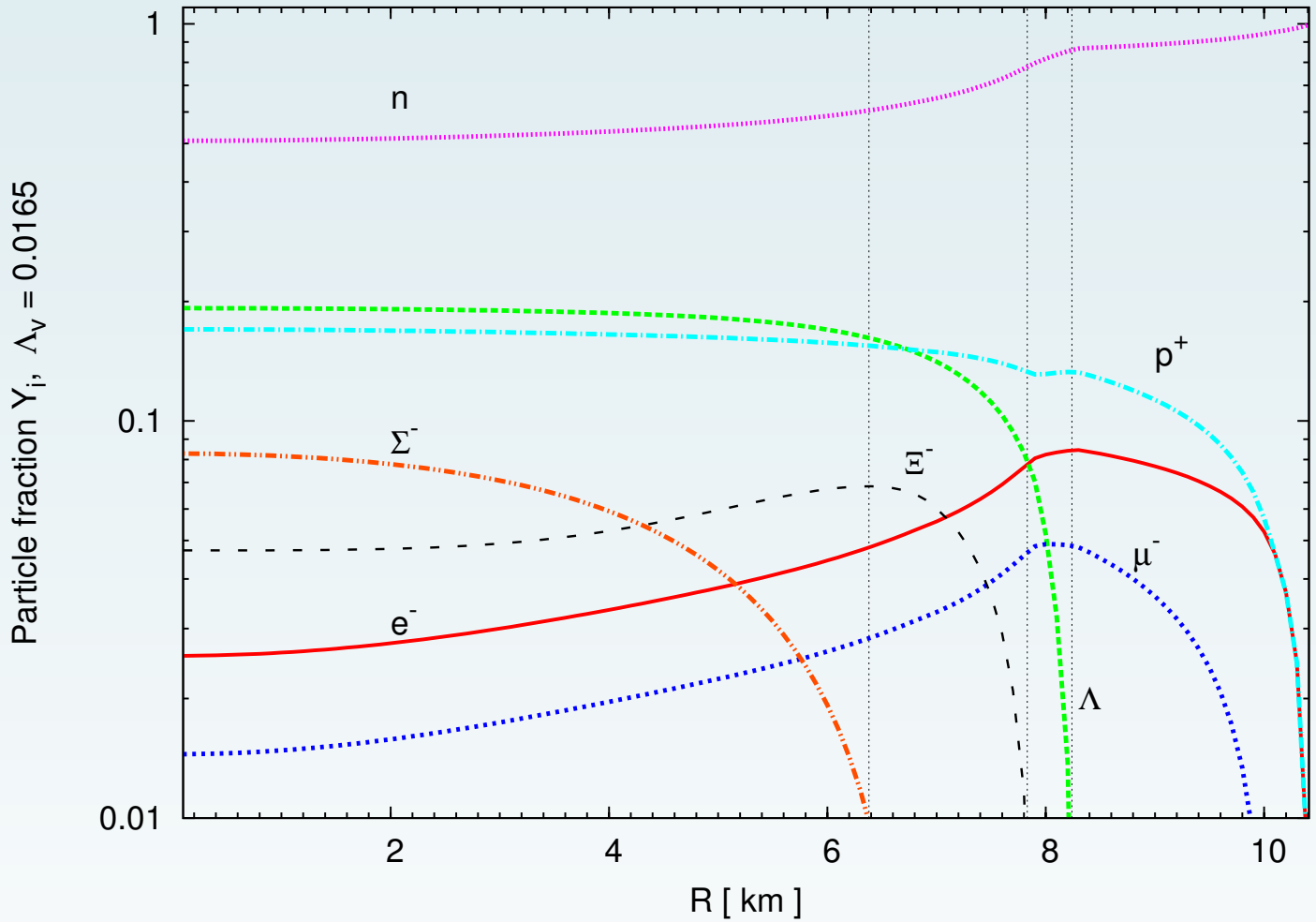

The asymmetry parameters $f_a = \delta_3$ and $f_S = 3\delta_S$ as a function of baryon number density calculated for the nonlinear model, for different values of $\Lambda_V$ and for the TM1-weak model. The nonlinear model leads to a system with an enhanced asymmetry and a considerably reduced strangeness. An increase of parameter $\Lambda_V$ causes the matter to become more asymmetric.



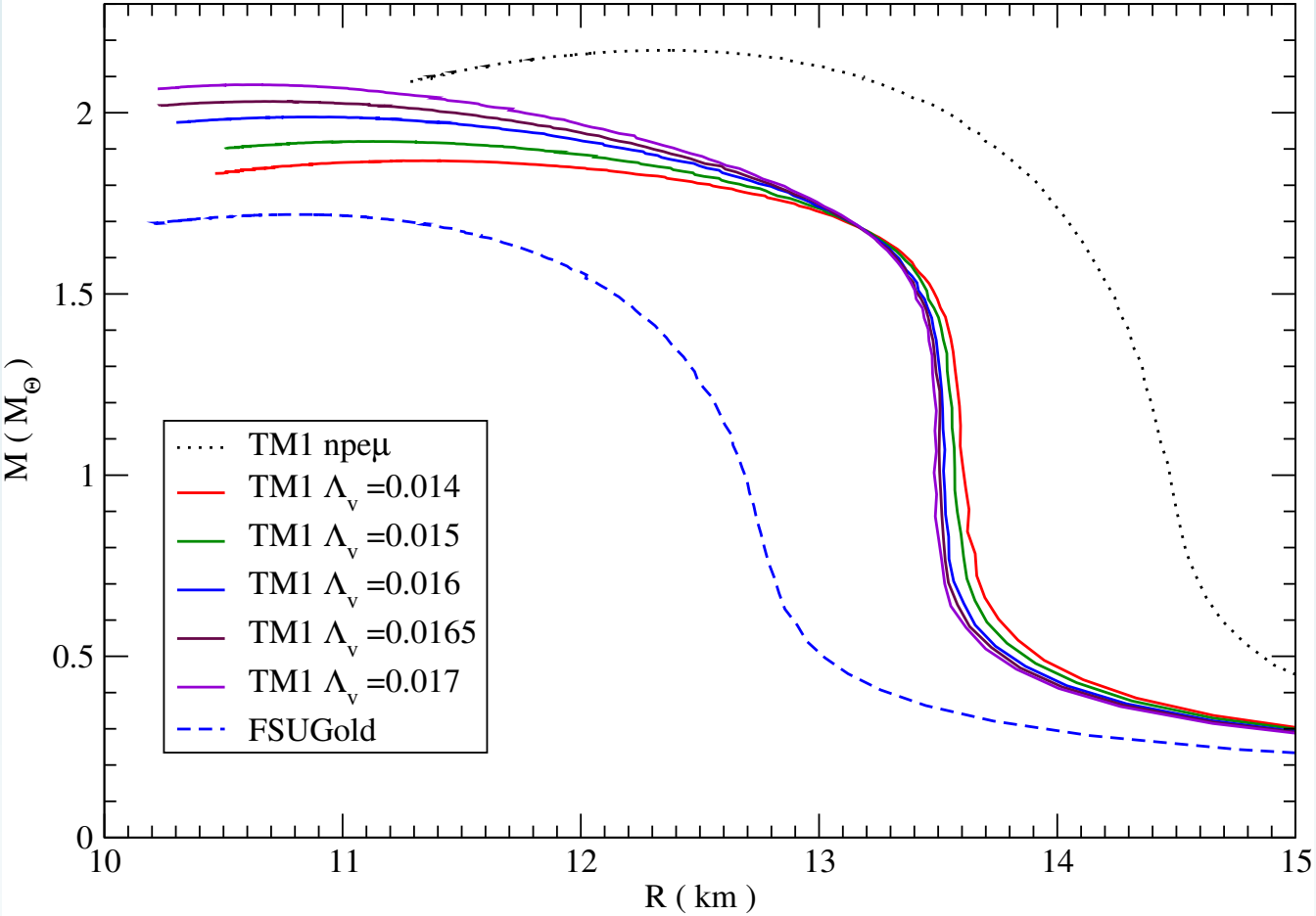

Relative concentrations of nucleons and leptons calculated for the nonlinear model, for the fixed value of parameter $\Lambda_V = 0.0165$. For comparison the results obtained for the TM1-weak model has been included. The important findings concern the concentration of leptons, which are more highly populated in the case of the nonlinear model.




Relative concentrations of strange baryons calculated for the nonlinear model, for the fixed value of parameter $\Lambda_V = 0.0165$. For comparison the results obtained for the TM1-weak model has been included. It is evident that the additional nonlinear couplings between vector mesons modify chemical composition of the neutron star shifting the onset point to higher densities and reduces the strangeness content of the system.

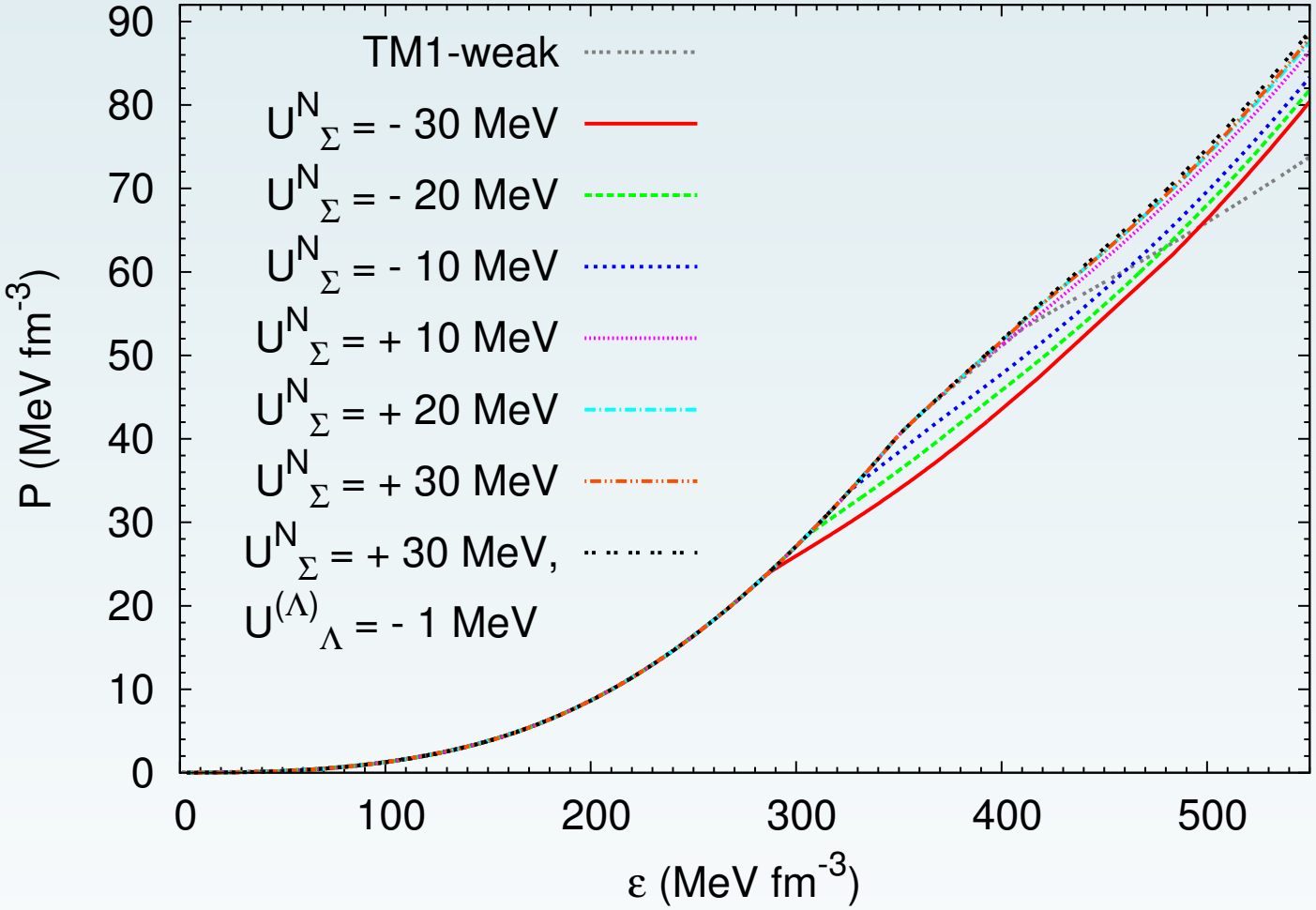



The particle fraction $Y_i = \frac{n_i}{n_b}$ as a function of the radius of the neutron star, for the maximal mass configuration. Calculations has been done on the basis of nonlinear model with $\Lambda_V = 0.0165$. The dotted vertical lines point the threshold densities for particular hyperons. The first hyperon that appears is $\Lambda$ and it is followed by $\Xi^-$ and $\Sigma^-$.

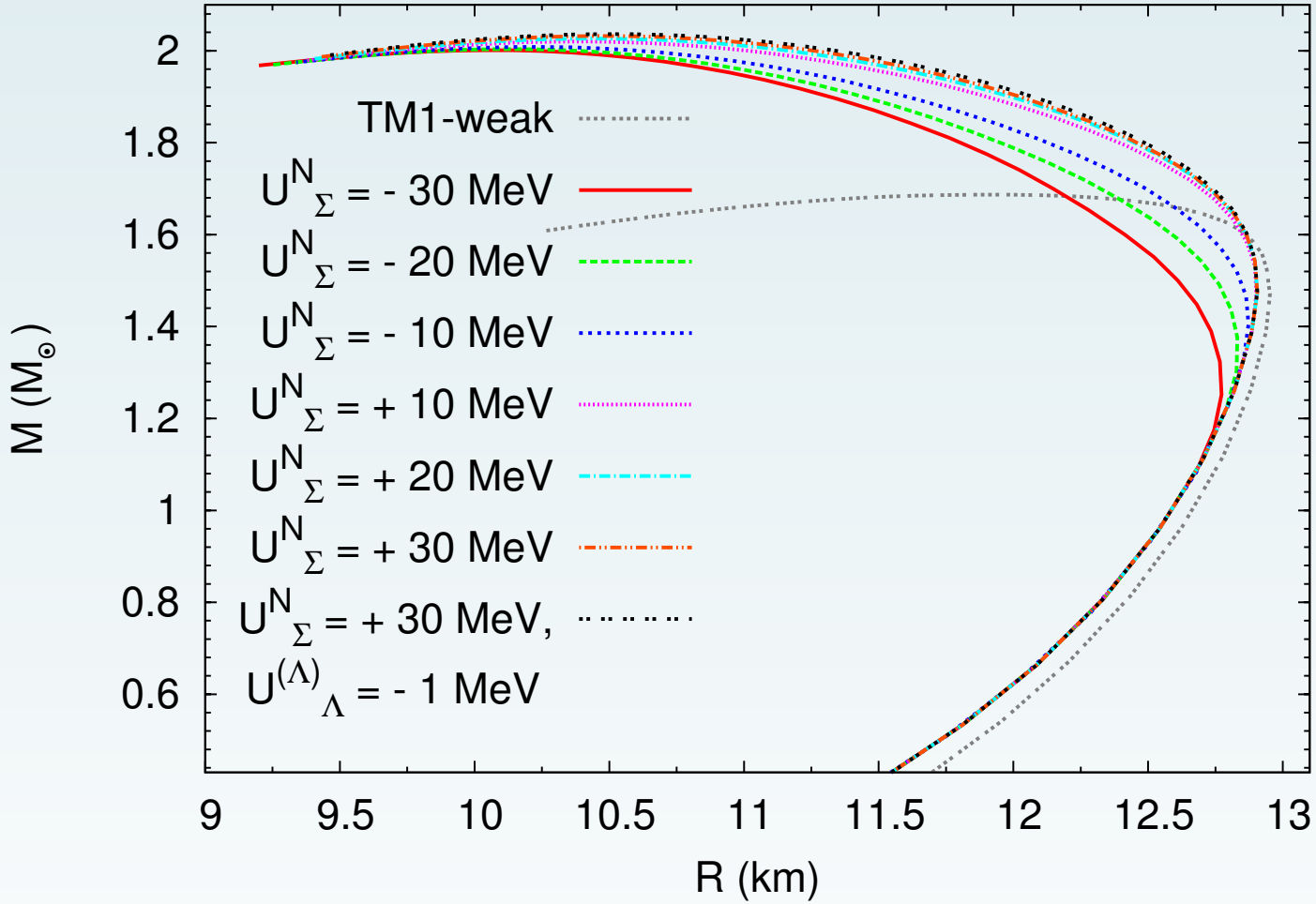



The mass–radius relations calculated for the nonlinear model for different values of parameter $\Lambda_V$. The higher value of $\Lambda_V$, the higher the maximum mass. The results obtained for both the TM1 parameterisation in the case when the matter of the neutron star comprises only nucleons and for FSUGold parameter set[5] are included.

[5] B. Todd-Rutel and J. Piekarewicz, Phys. Rev. Lett. **95**, 122501 (2005)




The pressure vs density calculated for different values of the $U_\Sigma^N$ potential (attractive and repulsive), the very weak $U_\Lambda^{(\Lambda)}$ case has been icluded. The change of $U_\Sigma^N$ does not lead to sufficiently high stiffening of the EoS.




The mass – radius relation calculated for different values of the $U_\Sigma^N$ potential (attractive and repulsive), the very weak $U_\Lambda^{(\Lambda)}$ case has been icluded. Differences between values of maximal mass are rather small.

## Conclusions

- in the case when hyperons are included additional repulse in the system is indispensable
- the model with the extended vector - meson sector leads to EOS that is much stiffer then the one constructed on the basis on the minimal model
- $U_{\Sigma}^{N}$ potential change does not result in a sufficiently high stiffening of the EOS
- a characteristic feature of the model is the change of the effective baryon and meson masses with particular emphasis on the effective $\phi$ meson mass; there is a range of density for which the effective $\phi$ meson mass decreases

Baryon–vector meson coupling constants, $g_{B\omega} = (1 - x_B) g_{N\omega}$ and $x_B$ counts the contribution of strange quarks, $g_{N\omega} \equiv g_\omega$ and $g_{N\rho} \equiv g_\rho$.

| Baryon (B) | $x_B$ | $g_{B\omega}$ | $g_{B\phi} = x_B g_{N\omega}$ | $g_{B\rho}$ |
|---|---|---|---|---|
| n | 0 | $g_\omega$ | 0 | $g_\rho$ |
| p | 0 | $g_\omega$ | 0 | $g_\rho$ |
| $\Lambda$ | $\frac{1}{3}$ | $\frac{2}{3} g_\omega$ | $-\frac{\sqrt{2}}{3} g_\omega$ | 0 |
| $\Sigma$ | $\frac{1}{3}$ | $\frac{2}{3} g_\omega$ | $-\frac{\sqrt{2}}{3} g_\omega$ | $2 g_\rho$ |
| $\Xi$ | $\frac{2}{3}$ | $\frac{1}{3} g_\omega$ | -2$\frac{\sqrt{2}}{3} g_\omega$ | $g_\rho$ |

The critical value of the parameter $\Lambda_{V,cr}$ calculated for the selected parameterisations and the incompressibility $K_0$ taken at the saturation density.

| Parameter set | $c_3$ | $\Lambda_{V,cr}$ | $K_0$ (MeV) |
|---|---|---|---|
| NL3 [6] | 0 | - | 271 |
| FSUGold [7] | 418.39 | 0.0517 | 230 |
| TMA [8] | 151.59 | 0.0318 | 318 |
| TM1* [9] | 134.624 | 0.0215 | 281.1 |
| TM1 [10] | 71.3 | 0.0156 | 281.1 |
| TM2 [11] | 84.5318 | 0.0186 | 343.8 |

[6] G. A. Lalazissis, J. Koenig, and P. Ring, Phys. Rev. C **55**, 540 (1997)
[7] B. Todd-Rutel and J. Piekarewicz, Phys. Rev. Lett. **95**, 122501 (2005)
[8] H. Toki, D. Hirata, Y. Sugahara, K. Sumiyoshi, and I. Tanihata, Nucl. Phys. A **588**, c357(1995)
[9] M. Del Estal, M. Centelles, X. Vinas, and S. K. Patra, Phys. Rev. C **63**, 024314 (2001)
[10] Y. Sugahara and H. Toki, Prog. Theor. Phys. **92**, 803 (1994)
[11] Y. Sugahara and H. Toki, Nucl. Phys. A 579, 557 (1994)

The scalar coupling constants.

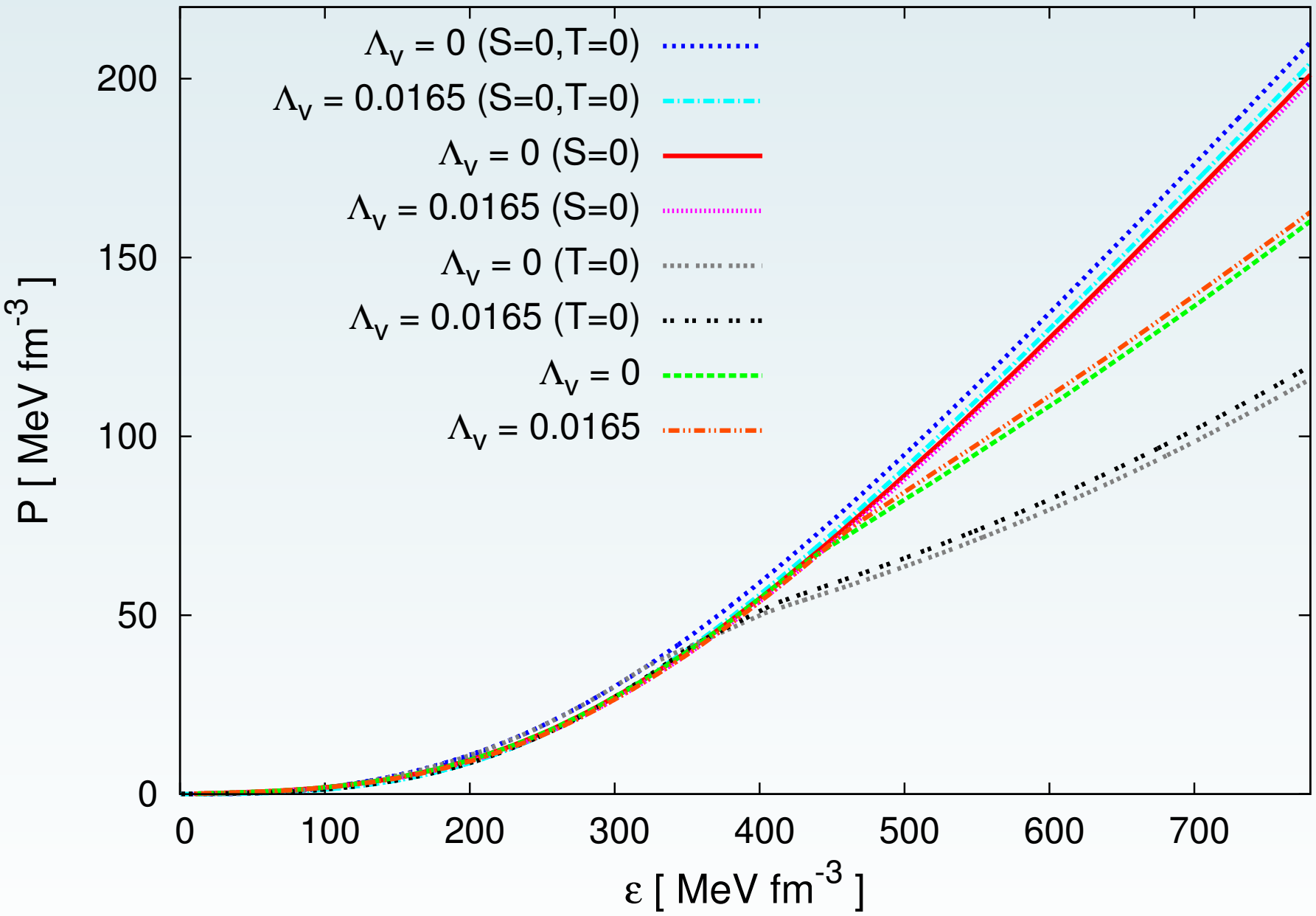
| $g_{\sigma\Lambda}$ | $g_{\sigma\Xi}$ | $g_{\sigma\Sigma}$ | $g_{\sigma^*\Lambda}$ | $g_{\sigma^*\Xi}$ | $g_{\sigma^*\Sigma}$ |
|---|---|---|---|---|---|
| 6.169 | 3.201 | 4.476 | 5.262 | 11.623 | 5.626 |

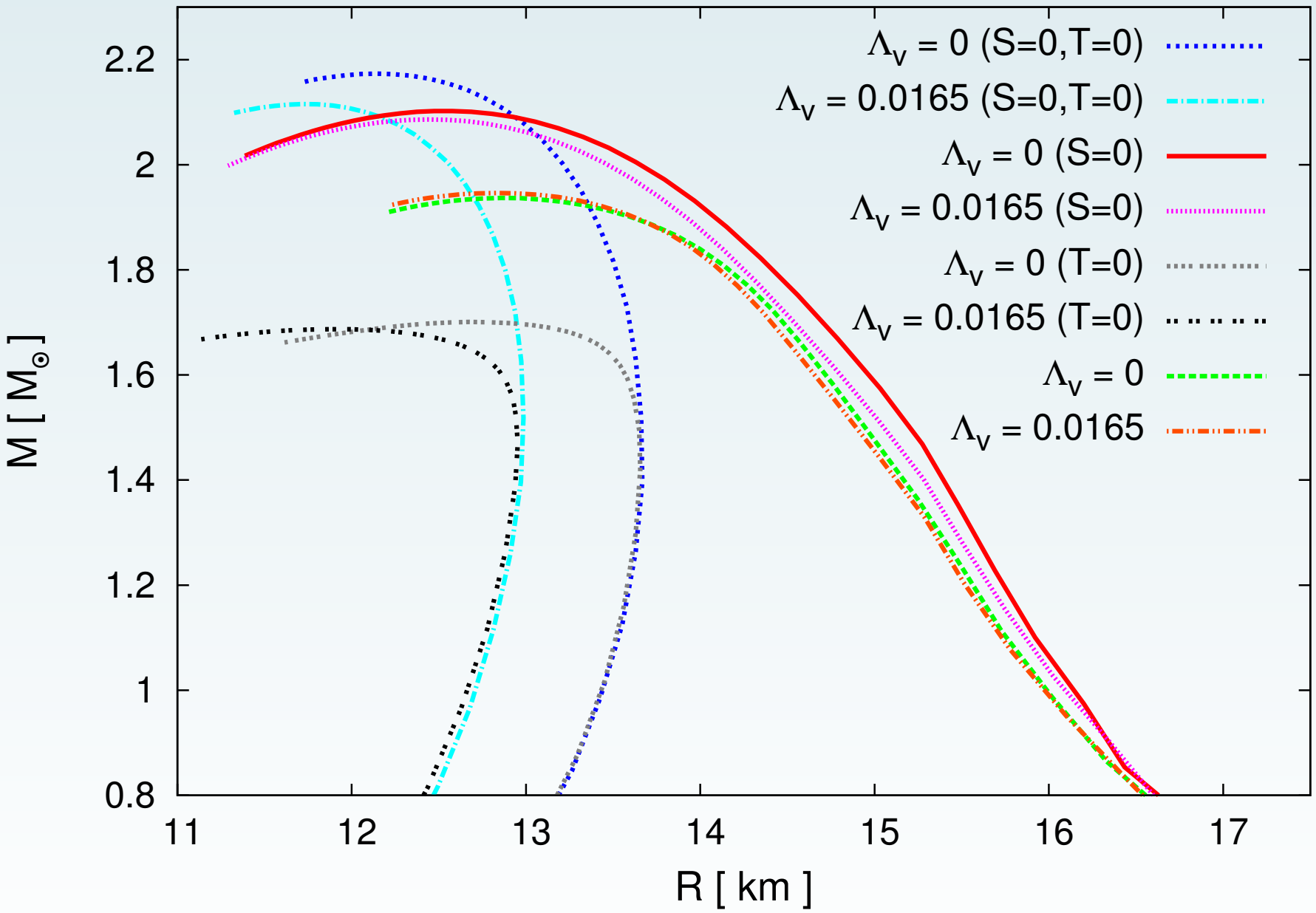
TM1 parameter set[12] with the extended isovector sector

| TM1 | | |
|---|---|---|
| $m_\sigma = 511.2$ MeV | $g_\sigma = 10.029$ | $g_3 = 7.2325$ fm$^{-1}$ |
| $m_\omega = 783$ MeV | $g_\omega = 12.614$ | $g_4 = 0.6183$ |
| $m_\rho = 770$ MeV | $g_\rho = 9.264$ | $c_3 = 71.0375$ |

| TM1 nonlinear (isovector sector) | | | | |
|---|---|---|---|---|
| $\Lambda_V$ | 0 | 0.016 | 0.0165 | 0.017 |
| $g_\rho$ | 9.2644 | 10.003 | 10.037 | 10.071 |

[12] Y. Sugahara and H. Toki, Prog. Theor. Phys. **92**, 803 (1994)


$\Lambda_v$ = 0 (S=0,T=0)
$\Lambda_v$ = 0.0165 (S=0,T=0)
$\Lambda_v$ = 0 (S=0)
$\Lambda_v$ = 0.0165 (S=0)
$\Lambda_v$ = 0 (T=0)
$\Lambda_v$ = 0.0165 (T=0)
$\Lambda_v$ = 0
$\Lambda_v$ = 0.0165
P [ MeV fm$^{-3}$ ]
0
50
100
150
200
0
100
200
300
400
500
600
700
ε [ MeV fm$^{-3}$ ]


$\Lambda_v$ = 0 (S=0,T=0)
$\Lambda_v$ = 0.0165 (S=0,T=0)
$\Lambda_v$ = 0 (S=0)
$\Lambda_v$ = 0.0165 (S=0)
$\Lambda_v$ = 0 (T=0)
$\Lambda_v$ = 0.0165 (T=0)
$\Lambda_v$ = 0
$\Lambda_v$ = 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