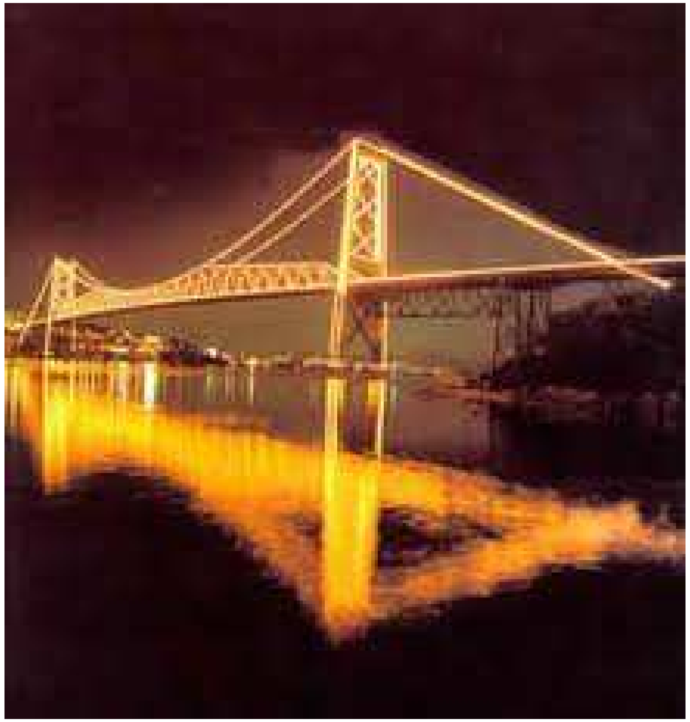
The role of stangeness in hadronic matter (in)stability: from hypernuclei to compact stars



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INCT 2016 - Adelaide

Are there strangeness driven phase transitions at low (liquid-gas) and high (stellar matter) densities?

Motivation: low densities

- Many hypernuclei have been synthetized lately.
- To describe/understand their properties, hadronic matter must have strange degrees of freedom.
- What's the influence of strangeness in the liquid-gas phase transition? Is strangeness an order parameter of the transition?
- RMF models are parameter dependent. How can we choose the meson-hyperon couplings based on known phenomenology?

Motivation: high densities

- The hyperon puzzle:
  - PSR J1614-2230 and PSR J0348+0432 (2 $M_\odot$) require very stiff EOS at large densities but heavy ion collisions point in opposite direction for $\rho < 5\rho_0$.
  - Hyperons are energetically favored, but soften the EoS; they are associated to first order phase transitions in many RMF models.
  - Strange vector mesons mediating the hyperon-hyperon interaction increases the maximum mass, just pushing away the hyperon threshold.
  - Meson-hyperon coupling constants are unknown: how to parametrize them in a less handwaving way as possible?
- Possible existence of instabilities in the strange sector are model dependent. How are they related to the values of the meson-hyperon couplings?

Formalism - RMF - (N)LWM

$$
\begin{aligned}
\mathcal{L}_{NLWM} \; = \; & \sum_j \overline{\psi}_j \left[\gamma^\mu \left(i\partial_\mu - g_{\omega j}\omega_\mu - g_{\phi j}\phi_\mu - g_{\rho j}\vec{\tau}\cdot\vec{\rho}_\mu \right) - \left(m_j - g_{\sigma j}\sigma - g_{\sigma^* j}\sigma^* \right) \right] \psi_j \\
& + \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2 \right) - \frac{1}{3} b M_N \left(g_{\sigma N}\sigma \right)^3 - \frac{1}{4} c \left(g_{\sigma N}\sigma \right)^4 \\
& + \frac{1}{2}\left(\partial_\mu\sigma^*\partial^\mu\sigma^* - m_\sigma^2\sigma^{*2} \right) \\
& - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu\omega^\mu \\
& - \frac{1}{4}\Phi_{\mu\nu}\Phi^{\mu\nu} + \frac{1}{2} m_\phi^2 \phi^\mu\phi_\mu \\
& - \frac{1}{4}\vec{R}_{\mu\nu}\cdot\vec{R}^{\mu\nu} + \frac{1}{2} m_\rho^2 \vec{\rho}_\mu\cdot\vec{\rho}^\mu \qquad (1)
\end{aligned}
$$

σ^* - strange scalar meson field, ϕ - strange vector meson field,
b, c - non-linear terms,
LWM - QHII, NLWM - GM1, $\quad g_{ij} = \chi_{ij} g_{iN}, \quad i = \sigma, \omega, \rho, \sigma^*, \phi.$

Hyperon couplings in the literature

- SU(6): $\chi_{\sigma\Lambda} = \chi_{\omega\Lambda} = 2/3$, $\chi_{\rho\Lambda} = 0$, $\chi_{\sigma^*\Lambda} = \chi_{\Phi\Lambda} = \sqrt{2}/3$

- Glendenning conjecture:

$$\frac{g_{Y\sigma}}{g_{N\sigma}} = 0.7, \quad \frac{g_{Y\omega}}{g_{N\omega}} = \chi_\omega \quad \frac{g_{Y\rho}}{g_{N\rho}} = \frac{I_{3B}}{I_{3N}}\chi_\rho, \tag{2}$$

  the ρ meson always couples to the isospin projection I_3; the value of χ_ρ is completely arbitrary:

  $\chi_{Y\omega} = \chi_{Y_\rho} = 0.783$ (GM1), 0.8 (GM3), 0.772 (NL3)

  so that $U_\Lambda^N = -28$ MeV.

- SU(3): Depends on the original parameter set: **Luiz L. Lopes and Debora P. Menezes, Phys. Rev. C 89, 025805 (2014)**

Our prescription:

$\mathrm{U}_{\Lambda}^{N}(n_N) = -28$**MeV** is the potential one Λ feels due to the nuclear symmetric mean field:

$$U_{\Lambda}(\overbrace{n_N}^{\text{Sym}}, n_{\Lambda}) = \chi_{\omega\Lambda}(g_{\omega N}\omega_0) + \chi_{\phi\Lambda}(g_{\omega N}\phi_0) - \chi_{\sigma\Lambda}(g_{\sigma N}\sigma_0) - \chi_{\sigma^*\Lambda}(g_{\sigma N}\sigma_0^*) \,. \tag{3}$$

From the equations of motion, it becomes:

$$U_{\Lambda}^{N}(n_N) = \chi_{\omega\Lambda}\left(\frac{g_{\omega N}}{m_{\omega}}\right)^2 n_N - \chi_{\sigma\Lambda}\left(\frac{g_{\sigma N}}{m_{\sigma}}\right)^2 \left[\rho_N^s(\sigma) - b m_n \sigma^2 - c\sigma^3\right]. \tag{4}$$

$$\chi_{\omega\Lambda} = \frac{\chi_{\sigma\Lambda}\,\sigma|_{N=n_0} - 28\text{ MeV}}{\omega|_{N=n_0}}. \tag{5}$$

$U_\Lambda^\Lambda(n_\Lambda)$ is the potential one Λ feels due to field generated by the other Λs in a pure Λ matter; $\mathbf{U}_\Lambda^\Lambda\left(\frac{n_0}{5}\right) = -0.67$**MeV**

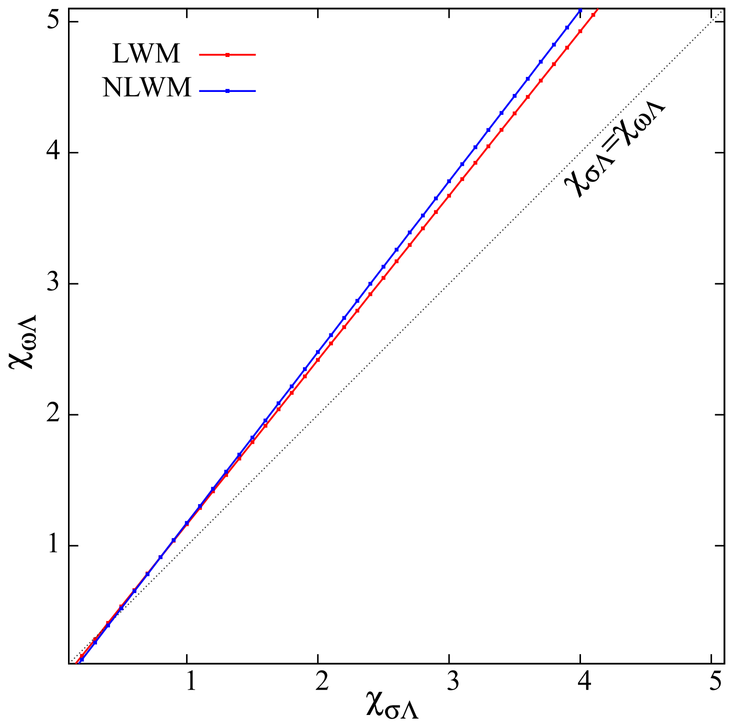
$$U_\Lambda^\Lambda(n_\Lambda) = \left[1 + \left(\frac{\chi_{\phi\Lambda}}{\chi_{\omega\Lambda}}\right)^2 \left(\frac{m_\omega}{m_\phi}\right)^2\right] (\chi_{\omega\Lambda})\,\omega - \left[1 + \left(\frac{\chi_{\sigma^*\Lambda}}{\chi_{\sigma\Lambda}}\right)^2 \left(\frac{m_\sigma}{m_{\sigma^*}}\right)^2\right] (\chi_{\sigma\Lambda})\,\Sigma \tag{6}$$

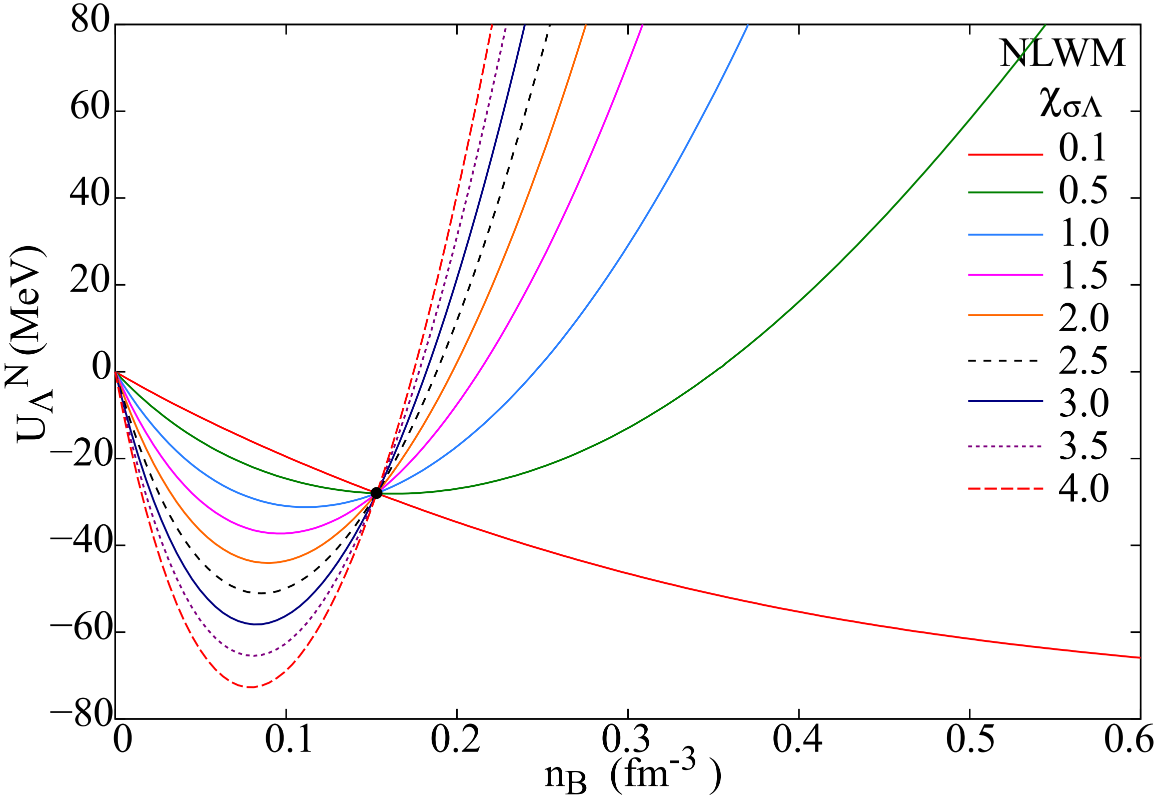
$$\Sigma = \sigma - \left(\frac{g_{\sigma N}}{m_\sigma}\right)^2 \left\{ \frac{\left(\frac{\chi_{\sigma^*\Lambda}}{\chi_{\sigma\Lambda}}\right)^2 \left(\frac{m_\sigma}{m_{\sigma^*}}\right)^2}{\left[1 + \left(\frac{\chi_{\sigma^*\Lambda}}{\chi_{\sigma\Lambda}}\right)^2 \left(\frac{m_\sigma}{m_{\sigma^*}}\right)^2\right]} \right\} \left(-b m_n \sigma^2 - c\sigma^3\right). \tag{7}$$

$$\chi_{\phi\Lambda} = \left(\frac{m_\phi}{m_\omega}\right) \sqrt{\frac{U_\Lambda^\Lambda\left(\frac{n_0}{5}\right) + \left[1 + \left(\frac{\chi_{\sigma^*\Lambda}}{\chi_{\sigma\Lambda}}\right)^2 \left(\frac{m_\sigma}{m_{\sigma^*}}\right)^2\right] \chi_{\sigma\Lambda}\Sigma_0 - \chi_{\omega\Lambda}\omega_0}{\chi_{\omega\Lambda}\omega_0}}\,\chi_{\omega\Lambda}. \tag{8}$$

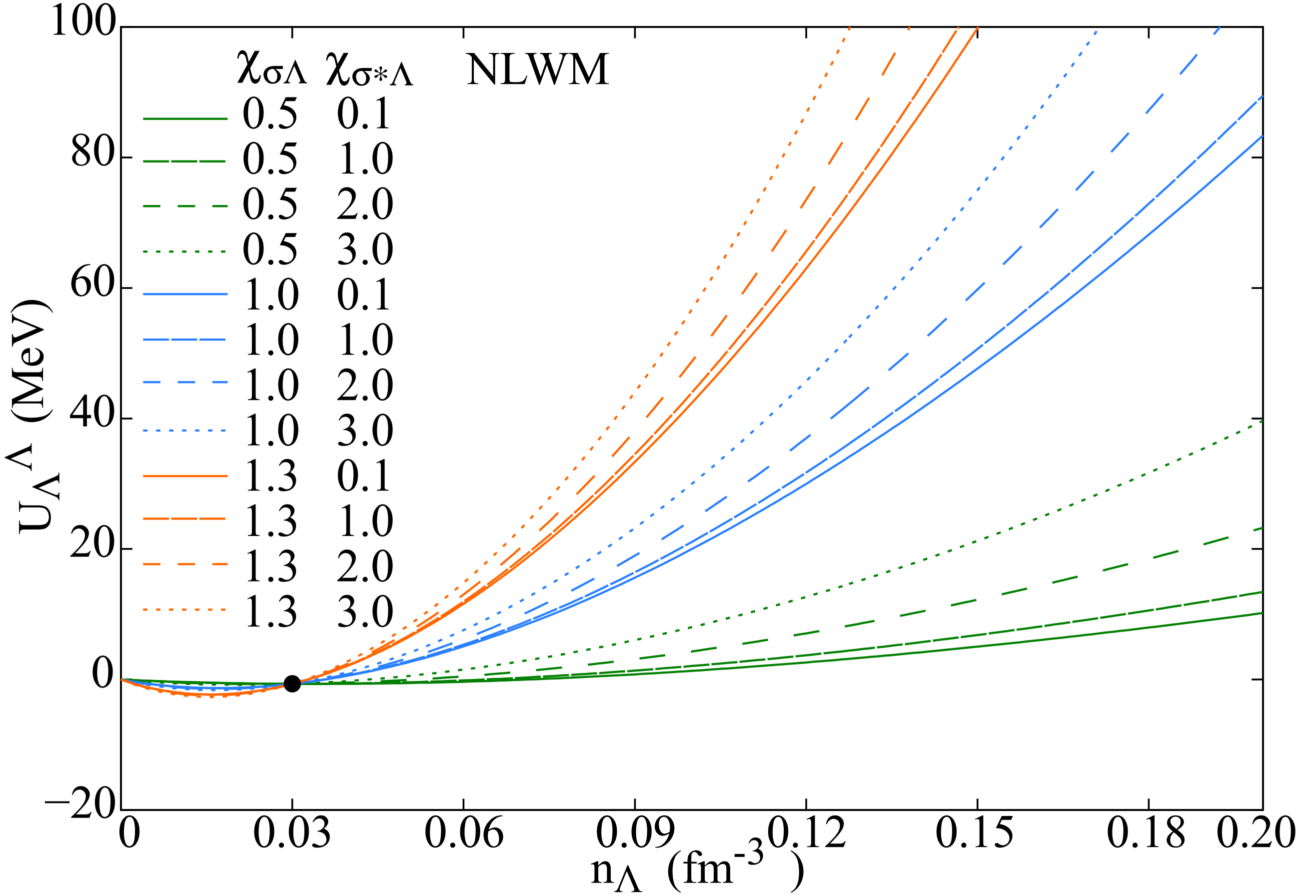
$$\Sigma_0 \equiv \Sigma\big|_{n_\Lambda = \frac{n_0}{5}}, \qquad \omega_0 \equiv \omega\big|_{n_\Lambda = \frac{n_0}{5}}$$

$\chi_{\omega\Lambda}$ **is constrained by** $\chi_{\sigma\Lambda}$ **and** $\chi_{\phi\Lambda}$ **is constrained by** $\chi_{\sigma^*\Lambda}$**.**



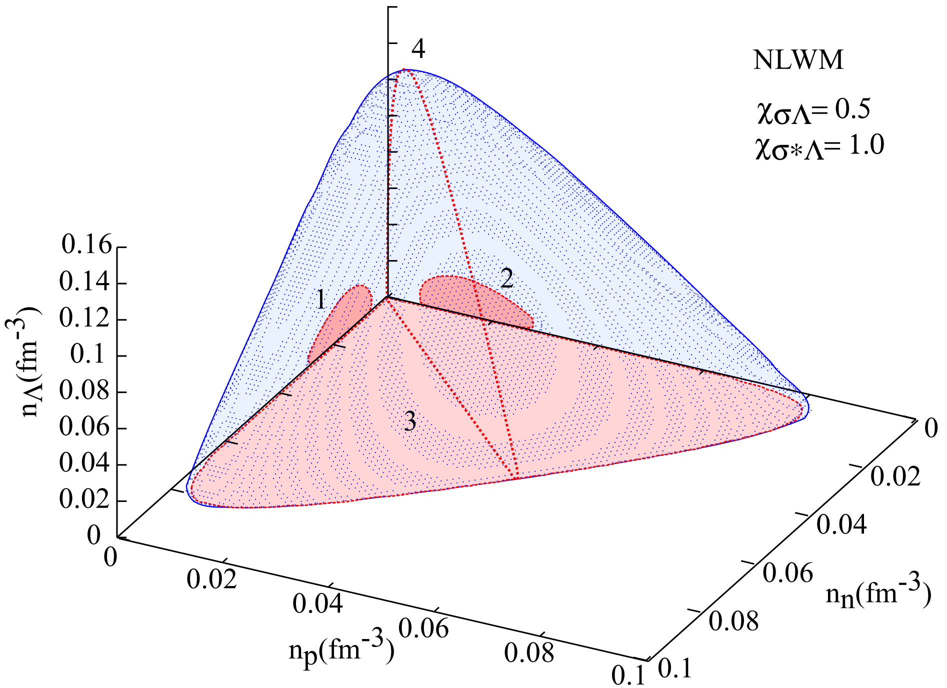


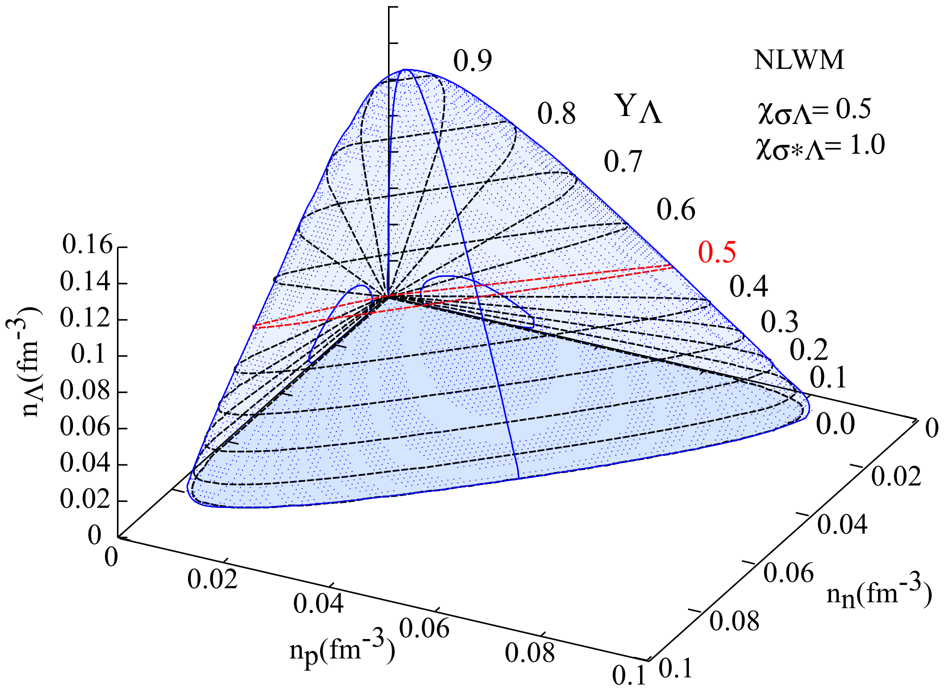
The increase of the $\chi_{\sigma\Lambda}$ **makes the potential more attractive at low densities AND more repulsive at high densities.**



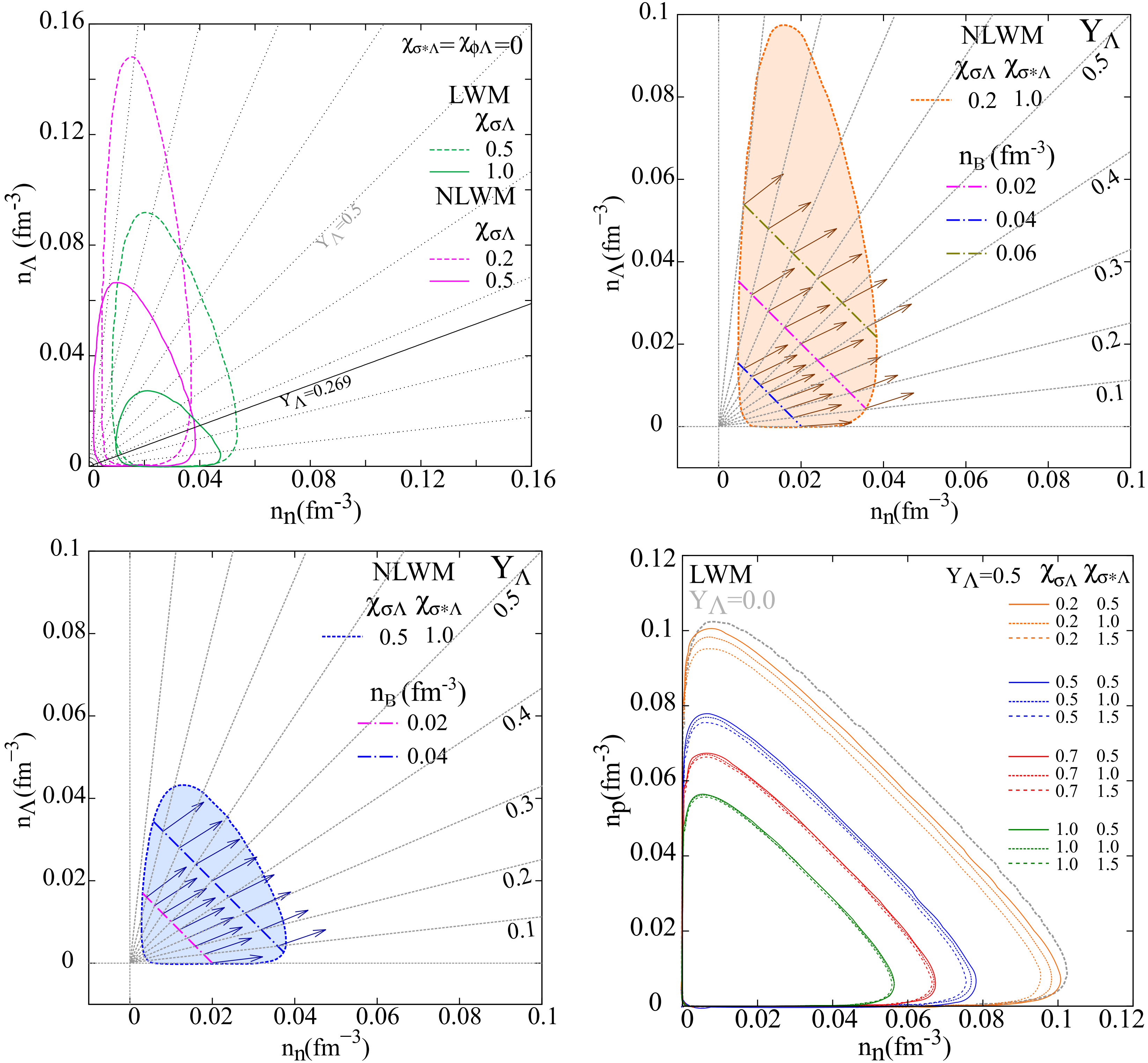
The increase of $\chi_{\sigma^*\Lambda}$ increases the repulsion at high densities, but it is not the dominant feature.

Spinodals - Low densities





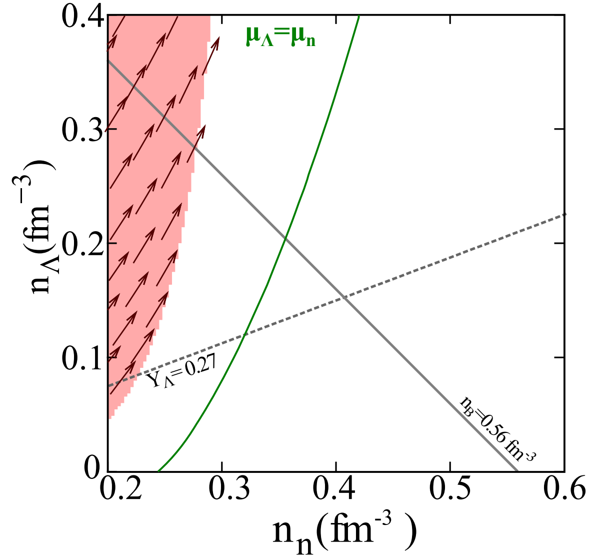
1 $n - \Lambda$ **plane; 2** $p - \Lambda$ **plane; 3** $n - p$ **plane; 4** $N - \Lambda (Y_p = Y_n)$ **plane**



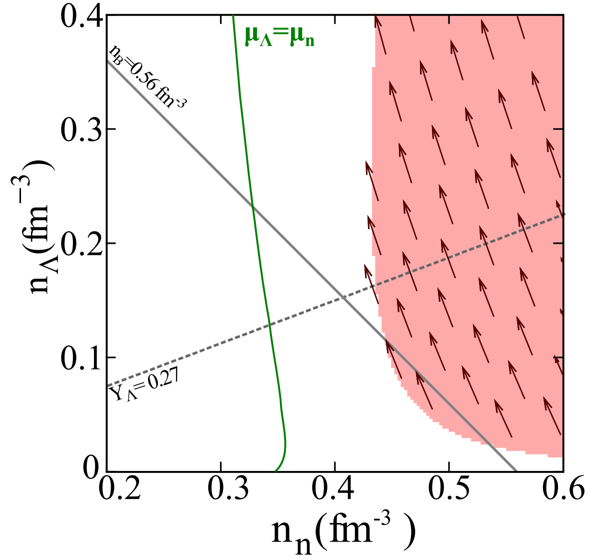
χσ*Λ= χφΛ =0
LWM
χσΛ
0.5
1.0
NLWM
χσΛ
0.2
0.5
YΛ=0.5
YΛ=0.269
nΛ (fm-3)
nn(fm-3)
NLWM
YΛ
χσΛ χσ*Λ
0.2 1.0
nB (fm-3)
0.02
0.04
0.06
0.5
0.4
0.3
0.2
0.1
nΛ(fm-3)
nn(fm-3)
NLWM
YΛ
χσΛ χσ*Λ
0.5 1.0
nB (fm-3)
0.02
0.04
0.5
0.4
0.3
0.2
0.1
nΛ(fm-3)
nn(fm-3)
LWM
YΛ=0.0
YΛ=0.5 χσΛ χσ*Λ
0.2 0.5
0.2 1.0
0.2 1.5
0.5 0.5
0.5 1.0
0.5 1.5
0.7 0.5
0.7 1.0
0.7 1.5
1.0 0.5
1.0 1.0
1.0 1.5
np(fm-3)
nn(fm-3)

High densities

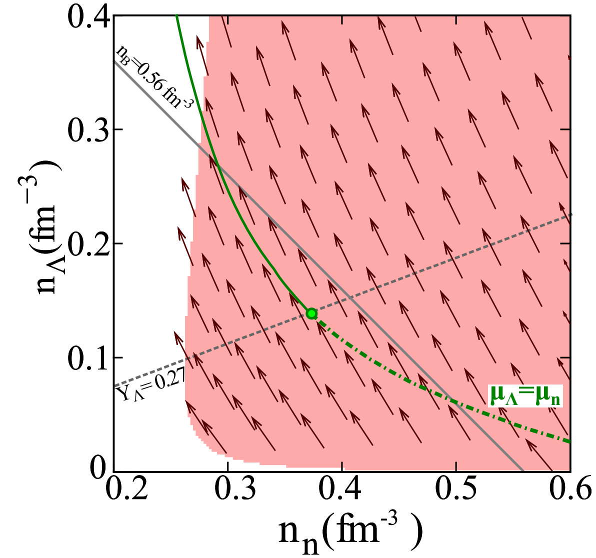
Non-relativistic *ab-initio* models: D, Lonardoni, A. Lovato, S. Gandolfi and F. Pederiva, PRL 114, 092301 (2015)



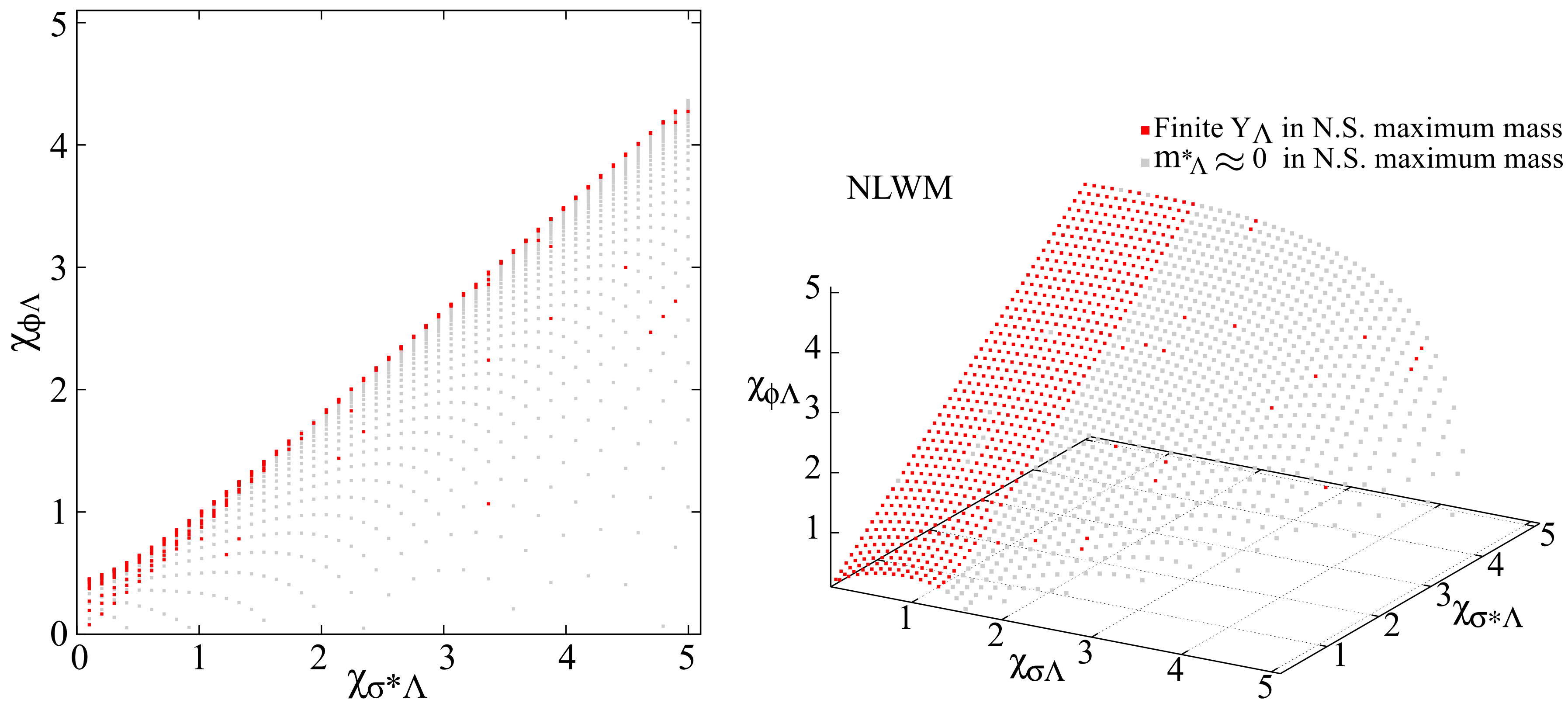
2-body interaction



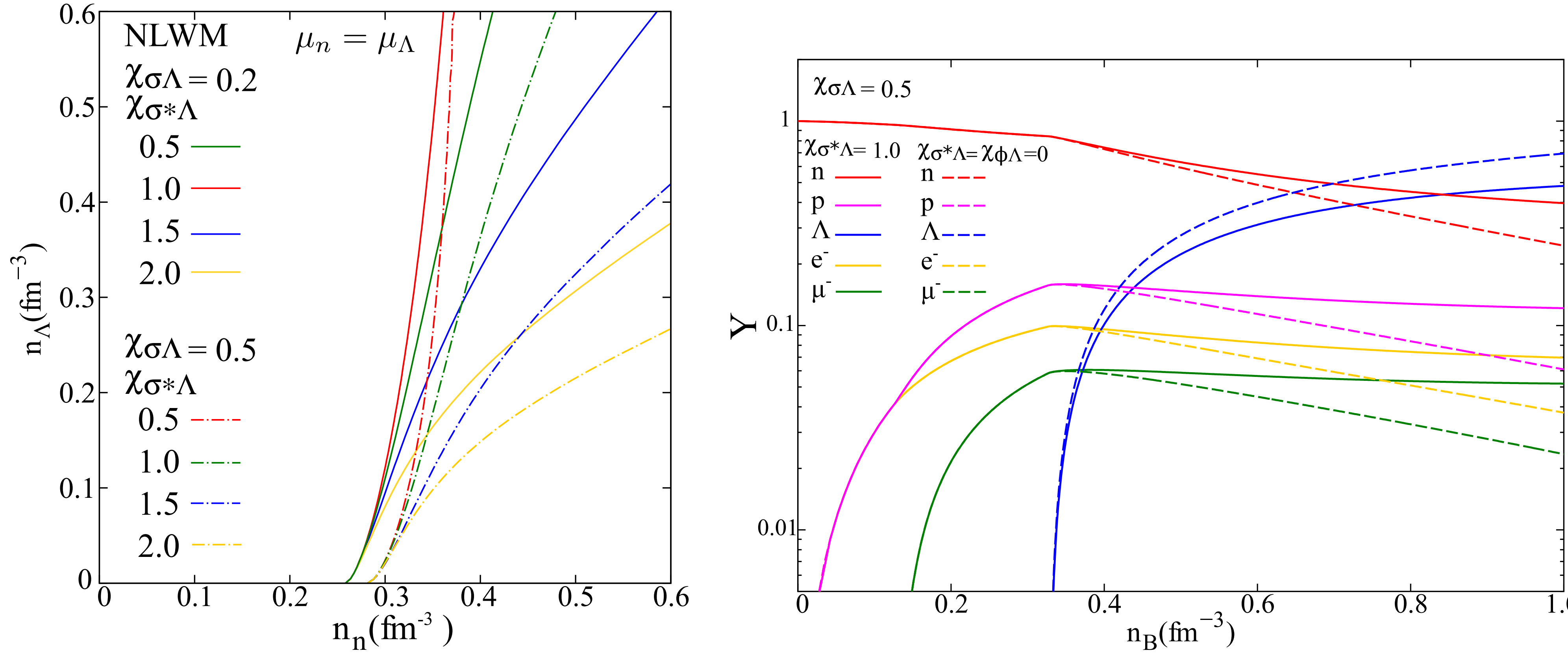
3-body interaction (I)



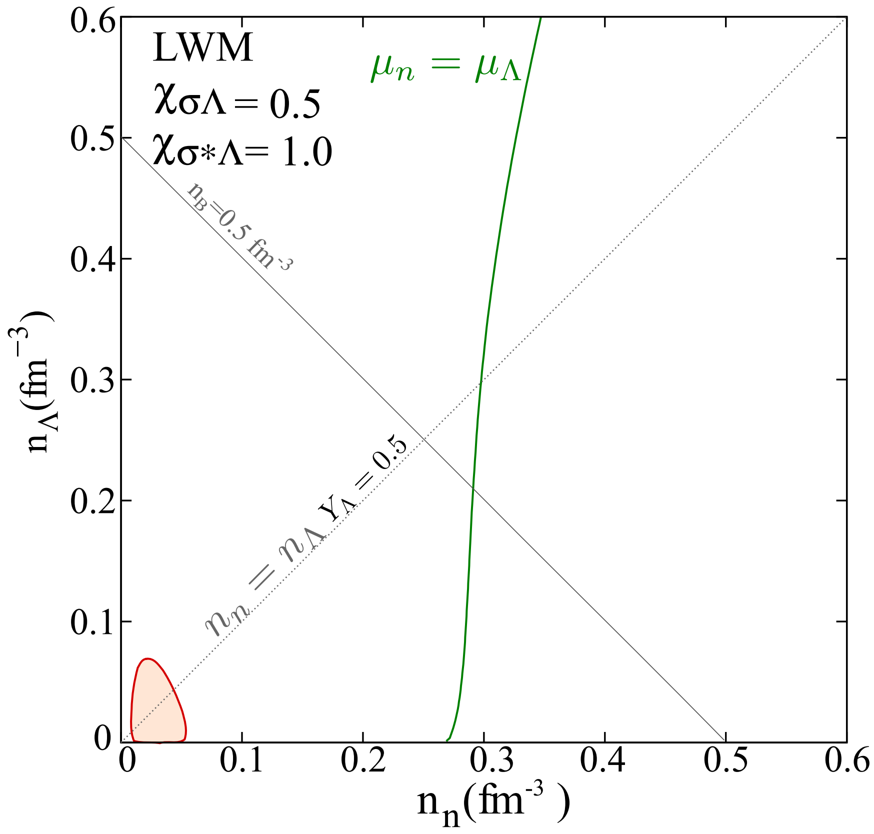
3-body interaction (II)

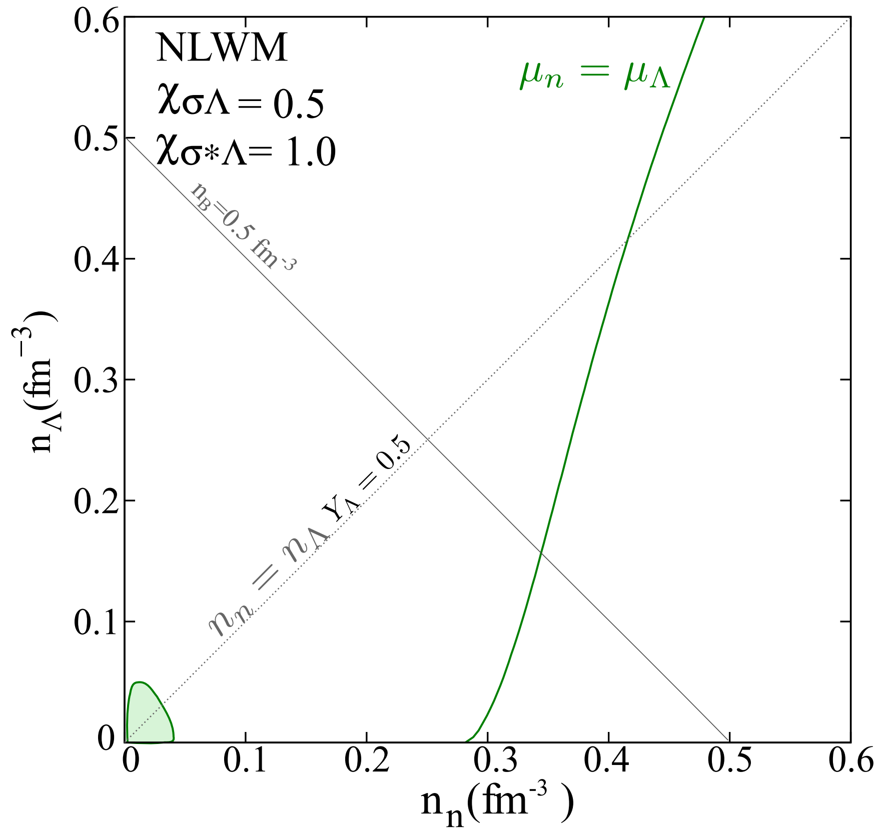


Gray points = parameters for which there is no convergence in stellar matter; Λ effective mass becomes negative; $\chi_\rho = 1.5$ was fixed in such a way that Λ hyperons appear before Σ^-.



If $\chi_{\sigma\Lambda} > 1$, no hyperons appear; $\chi_{\sigma^*\Lambda}$ do not alter the onset of hyperons.





No instabilities at high densities with RMF models !!!

Stellar Matter - 8 baryons included

NLWM - $\chi_{\sigma H} = 0.2$, $\chi_{\rho H} = 1.0$							
$\chi_{\sigma^* H}$	$M_{\rm max}$ (M$_\odot$)	R (km)	ϵ_c (fm^{-4})	n_c(fm^{-3})	Y^c_Λ	Y^c_H	$n^\Lambda_{\rm Lim}$(fm^{-3})
0.5	–	–	–	–	–	–	–
1.0	–	–	–	–	–	–	–
3.5	2.09	10.73	7.35	1.09	0.02	0.18	0.30
4.0	2.14	10.93	7.00	1.05	0.01	0.15	0.30
NLWM - $\chi_{\sigma H} = 0.8$, $\chi_{\rho H} = 1.0$							
$\chi_{\sigma^* H}$	$M_{\rm max}$ (M$_\odot$)	R (km)	ϵ_c (fm^{-4})	n_c(fm^{-3})	Y^c_Λ	Y^c_H	$n^\Lambda_{\rm Lim}$(fm^{-3})
0.5	2.24	11.83	5.84	0.90	0.14	0.33	0.42
1.0	2.25	11.78	5.90	0.90	0.11	0.26	0.42
3.5	2.32	11.78	5.86	0.89	0.00	0.08	0.42
4.0	2.32	11.80	5.84	0.88	0.00	0.06	0.42

The increase of the $\chi_{\sigma\Lambda}$ ($\chi_{\sigma^*\Lambda}$) makes the potential U^N_Λ (U^Λ_Λ) more repulsive at high densities and the EoS becomes stiffer. - $M_{\rm max} <$ 1.44 (M$_\odot$)

Conclusions - Low densities

- At subsaturation densities, the existence of a n-Λ liquid-gas phase transition is the result of a very clear hadronic matter instability.

- If n-p-Λ matter is investigated, the instability is still present, strangeness being an order parameter of the phase transition, which means that dilute strange matter is expected to be unstable with respect to hyperclusters.

- Liquid-gas phase transition is slightly quenched by the inclusion of Λs.

Conclusions - High densities

- **Once the meson-hyperon couplings are constrained to satisfy hypernuclear experimental potentials, no instability at super-saturation densities is found. Non-relativistic model produces** *pathological* **results.**

- **Hence, a strangeness driven phase transition only takes place in neutron star matter if quarks are present.**

- **Using our prescription, massive stars with small radii are obtained, in accordance with recent observational and theoretical results.**

James R. Torres, Francesca Gulminelli and Debora P Menezes, PRC 93, 024306 (2016); James R. Torres, Francesca Gulminelli and Debora P Menezes, arXiv: 1608.05108

Thank you