Interplay between the symmetry energy and the strangeness content of neutron stars

Constança Providência

Centro de Física Computacional
Universidade de Coimbra, Portugal

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Motivation

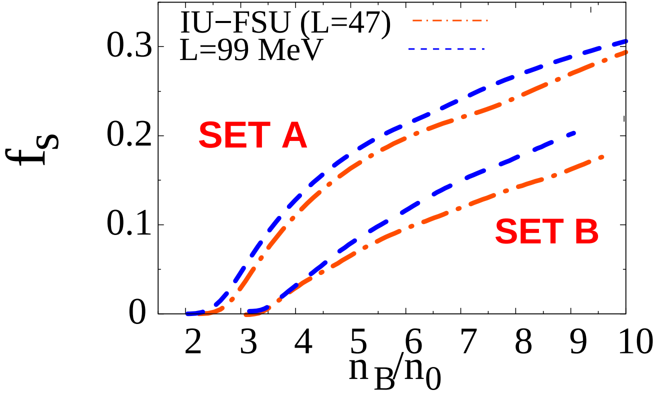
- How do compact star properties depend on the ϵ_{sym}?
  - strangeness content?
  - onset of the of strangeness?
  - the mass-radius curve of hyperonic stars?
- Which constraints on hyperon content are set by the recent measurement
  PSR J1614-2230: $1.97 \pm 0.04 M_\odot$ (Demorest et al (2010))
  PSR J0348+0432: $2.01 \pm 0.04\ M_\odot$ (Antoniadis et al (2013))?
  - Do 2 $M_\odot$ compact stars exclude strangeness from compact stars?

Hyperon content and *L*

Hyperon content depends on:

- hyperon-meson interaction
- properties of nucleonic EOS

  example: effect of $\epsilon_{sym}(\rho)$
  (L(IUFSU)= 47.2 MeV, L(set 7)=99.2 MeV)



Outline

Equation of state

Including Hyperons

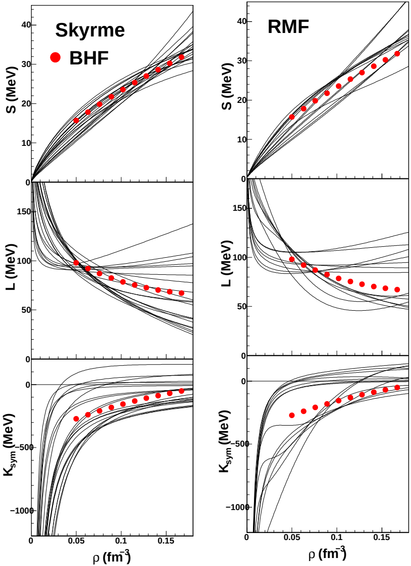
Compact stars: mass versus radius

Metastable hadronic stars

Compact stars: kaon condensation

Equation of state

Correlation between J, L and K_{sym}



(Ducoin *et al* PRC83)

Fitting of parameters to properties of nuclei:

ϵ_{sym}: crossing at ~ 0.12 fm^{-3}

L: tendency to cross at $\sim \rho/3\rho_0$

EOS

RMF Lagrangian for stellar matter

- Lagrangian density

$$\mathcal{L}_{NLWM} = \sum_{B=baryons} \mathcal{L}_B + \mathcal{L}_{mesons} + \mathcal{L}_l,$$

  - Nucleon contribution: $\mathcal{L}_B = \bar{\psi}_B \left[\gamma_\mu D^\mu_B - M^*_B\right] \psi_B,$
    $D^\mu_B = i\partial^\mu - g_{\omega B}\omega^\mu - \frac{g_{\rho B}}{2}\boldsymbol{\tau} \cdot \mathbf{b}^\mu - g_{\phi B}\phi^\mu$
    $M^*_B = M_B - g_{\sigma B}\sigma - g_{\sigma^* B}\sigma^*$
  - Meson contribution

$$\mathcal{L}_{mesons} = \mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\rho + \mathcal{L}_{\sigma^*} + \mathcal{L}_\phi + \mathcal{L}_{non-linear}$$

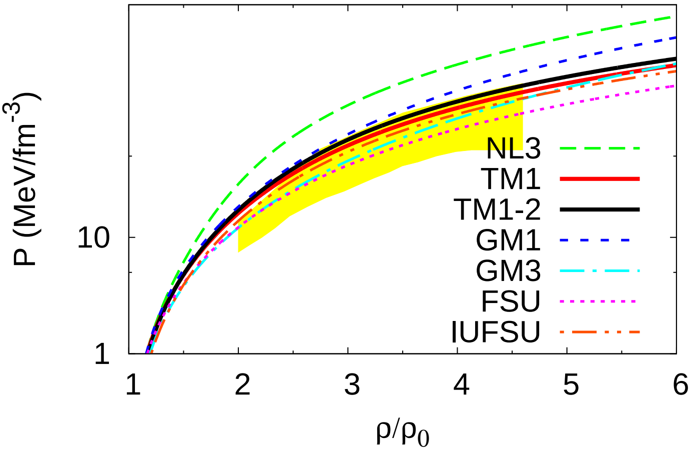
  - Lepton contribution: $\mathcal{L}_l = \sum_l \bar{\psi}_l \left[\gamma_\mu i\partial^\mu - m_l\right] \psi_l$

RMF: modeling the EOS and symmetry energy

- $\mathcal{L}_{non-linear}$

$$
\begin{aligned}
\mathcal{L}_{nl\sigma} &= -\frac{1}{3!}k\sigma^3 - \frac{1}{4!}\lambda\sigma^4 \\
\mathcal{L}_{nl\omega} &= \frac{1}{4!}\xi g_\omega^4 \left(\omega_\mu\omega^\mu\right)^2 \\
\mathcal{L}_{nl\rho\omega} &= \Lambda_v g_\rho^2 \vec{\rho}_\mu \cdot \vec{\rho}^\mu g_\omega^2 \omega_\mu\omega^\mu \\
\mathcal{L}_{nl\rho\sigma} &= \Lambda_\sigma g_\rho^2 \vec{\rho}_\mu \cdot \vec{\rho}^\mu g_\sigma^2 \sigma^2
\end{aligned}
$$

RMF: modeling the EOS



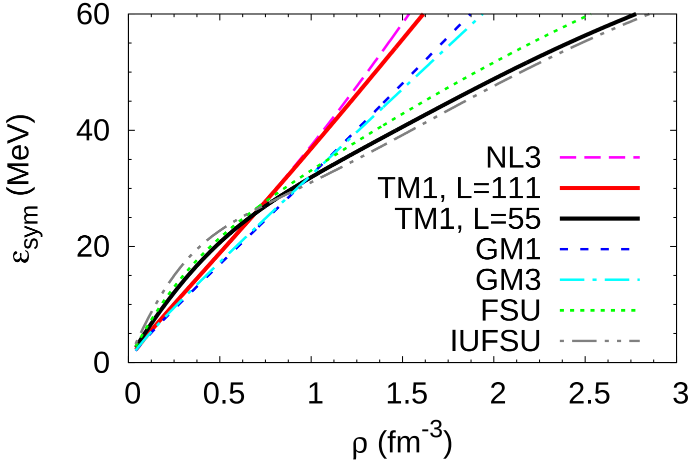
- yellow: constraints from flow of matter in nuclear collisions (Danielewicz 2002)

RMF: Non Linear Terms

ϵ_{sym} and L

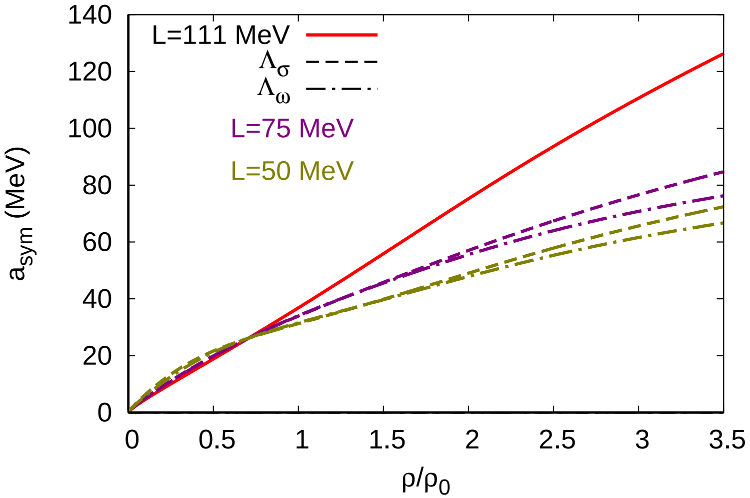
- $\omega - \rho$ and $\sigma - \rho$ terms
  - affect the density dependence of the symmetry energy (Horowitz& Piekerawicz 2001, Carriere et al 2003)
- $\omega - \rho$ term
  - FSU parametrization(Todd-Rutel & Piekerawicz2005)
    - constrained by ISGMR and IVGDR of ^{208}Pb and ^{90}Zr
    - EOS too soft at large densities ($M_{max} \sim 1.6 M_{\odot}$)
  - IU-FSU parametrization(Fattoyev et al PRC82)
    - similar ϵ_{sym} as FSU, harder EOS at high densities

RMF: symmetry energy



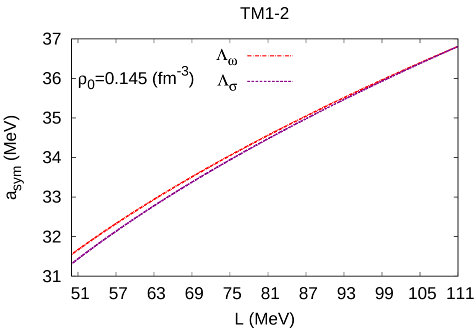
RMF: symmetry energy

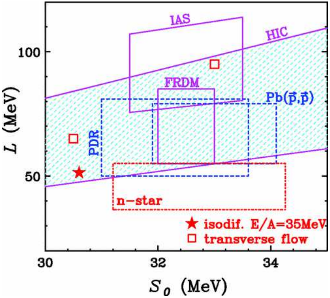
$\rho - \omega$ versus $\rho - \sigma$



RMF: symmetry energy

$\rho - \omega$ versus $\rho - \sigma$





experimental constraints (Tsang et al PRC86)

Including Hyperons

Meson Field Equations with Octet of Baryons

- σ meson

$$\sigma_0 = -\frac{\kappa}{2m_\sigma^2}\sigma_0^2 - \frac{\lambda}{6m_s^2}\sigma_0^3 + \frac{g_\sigma}{m_\sigma^2}\sum_B x_{sB}\ \rho_{sB}\,,$$

- ω meson

$$\omega_0 = \frac{g_\omega}{m^2_{\omega,eff}}\sum_B x_{vB}\ \rho_B\,,$$

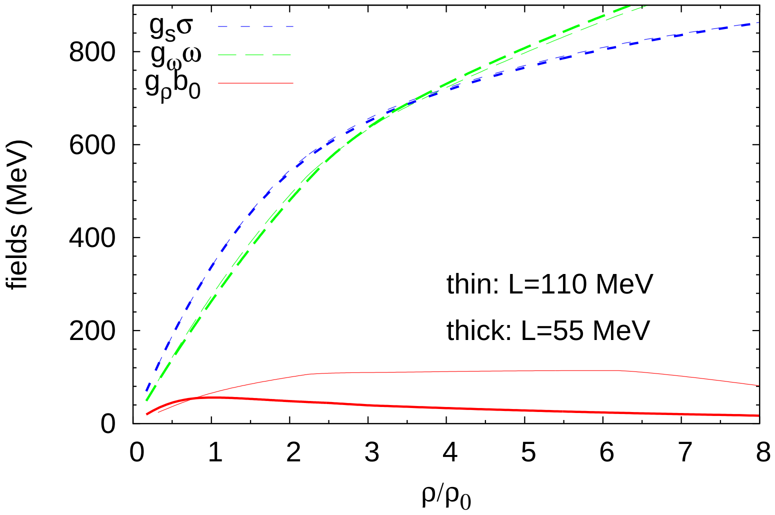
$$m^2_{\omega,eff} = m_\omega^2 + \frac{\xi}{6}g_\omega^4\omega_0^2 + 2\Lambda_\omega g_\omega^2 g_\rho^2 b_0^2$$

- ρ meson

$$b_0 = \frac{g_\rho}{m^2_{\rho,eff}}\sum_B x_{\rho B}\ t_{3B}\ \rho_B\,,$$

$$m^2_{\rho,eff} = m_\rho^2 + 2\Lambda_\omega g_\omega^2 g_\rho^2 \omega_0^2$$

Effect of L on fields strength



Hyperon-meson interaction

- SET B: $x_{\sigma j} = 0.8$ (Glendenning & Mozskowski 1991)
  - Accurately extrapolated value of the Λ hyperon binding in saturated nuclear matter

$$V_\Lambda = -28 = x_{\omega\Lambda} V_\omega - x_{\sigma\Lambda} V_\sigma$$

  - neutron stars masses $\rightarrow x_{\Lambda\sigma} \leq 0.9$
  - $x_{i\Sigma} = x_{i\Lambda} = x_{i\Xi}, \qquad i = \sigma,\ \omega,\ \rho$
- Quark meson coupling model
  - baryon effective mass: selfconsistently calculated bag energy
  - ω-meson coupling from binding of hyperons to nuclear matter

$$V_j = x_{\omega j} V_\omega + M_j^* - M_j$$

Hyperon-meson interaction

- Hypernuclei binging energy (SET A)
  - ω and ρ-hyperon couplings: SU(6) symmetry

$$\frac{1}{2}g_{\omega\Lambda} = \frac{1}{2}g_{\omega\Sigma} = g_{\omega\Xi} = \frac{1}{3}g_{\omega N}$$

  - σ-hyperon couplings: hypernuclei binding energies in SNM

$$V_j = x_{\omega j}\, V_\omega - x_{\sigma j}\, V_\sigma$$

$$V_\Lambda = -28\ \mathrm{MeV}\ ,\ \ V_\Sigma = 30\ \mathrm{MeV}\ ,\ \ V_\Xi = -18\ \mathrm{MeV}\ .$$

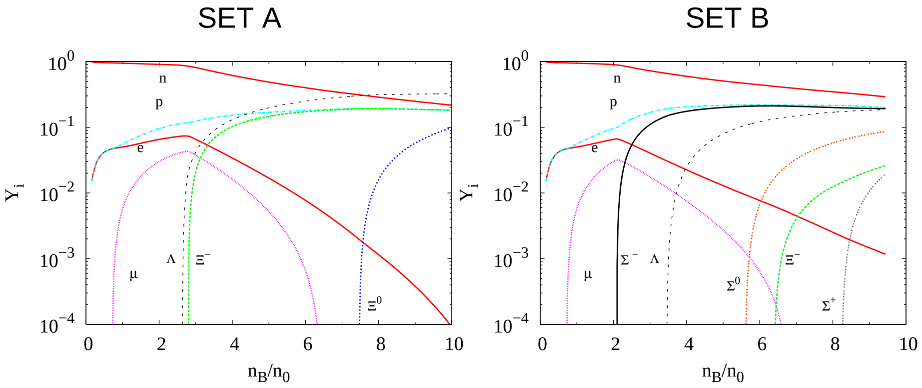
- AGS E885 collaboration (2000): $K^- + ^{12}\mathrm{C} \to K^+ + ^{12}_{\Xi}\mathrm{Be}$
  - " results are consistent with the theoretical predictions when a potential depth V_Ξ of 14 MeV or less is assumed"
- We will test the effect of changing V_Σ and V_Ξ

Hyperon-strange meson interaction

- Couplings ϕ,σ^*-nucleons
  - $g_{\phi N} = g_{\sigma^* N} = 0$
- Couplings ϕ-hyperons (su(6))
  - $2g_{\phi\Lambda} = 2g_{\phi\Sigma} = g_{\phi\Xi} = -\frac{2\sqrt{2}}{3} g_{\omega N}$
- Couplings σ^*-baryons: two options
  - weak attractive YY interaction
  - recent work of Gal and Millener (PLB2011) suggest ΛΛ is only slightly attractive:
    excess binding of 2Λ: $\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}He) = 0.67 \pm 0.17$MeV
  - we consider $g_{\sigma^* B} = 0$
- We will also relax su(6) constraint (Weissenborn et al PRC85 2012)

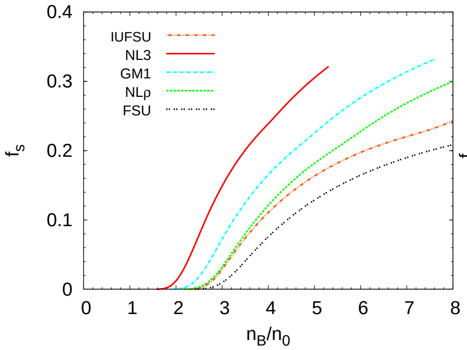
Particle fractions

Effect of the hyperon-meson interaction, Cavagnoli PRC84,065810

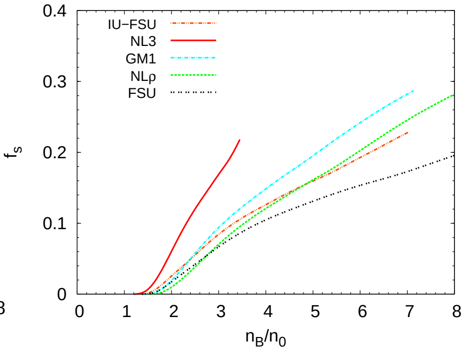


Chemical equilibrium

Hyperon content and hyperon-meson interaction



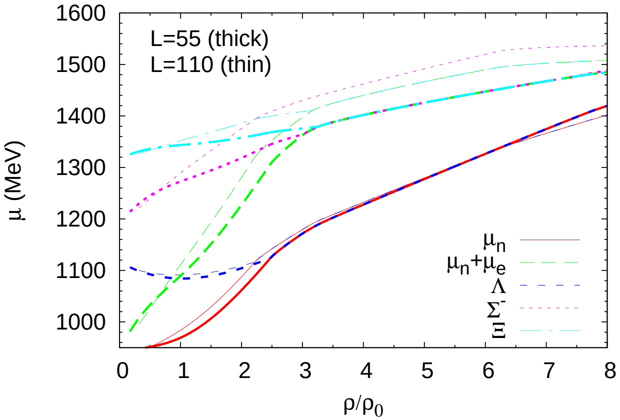
SET A



SET B

Chemical equilibrium

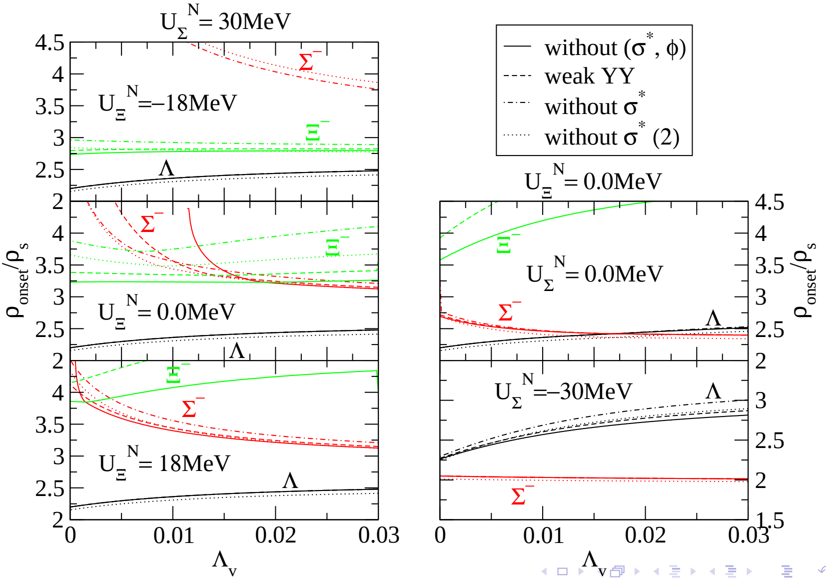
$V_\Lambda = -28$, $V_\Sigma = 30$, $V_\Xi = -18$ MeV, $L = 55$ and 110 MeV



- hyperon onset: $\mu_B = M_B^* + g_{\omega B} V_0 + g_{\rho B} t_B b_0 = \mu_n - q_B \mu_e$
- Small L favors negatively charged hyperons

Onset of strangeness

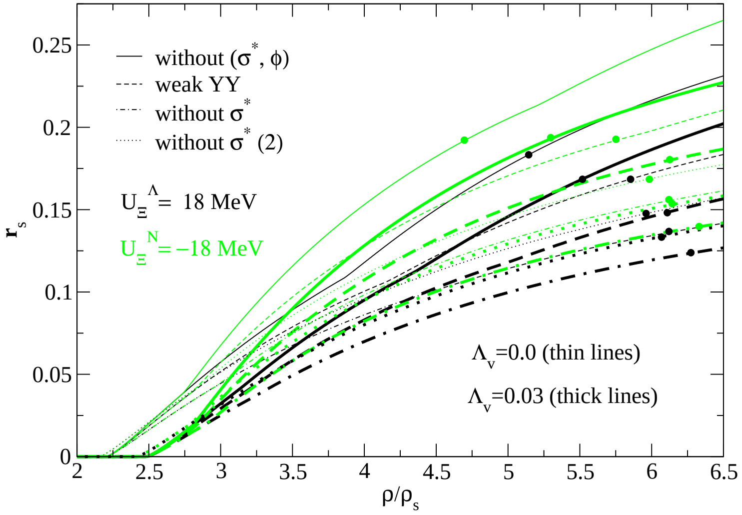
Effect of *L*



Testing hyperon-meson couplings

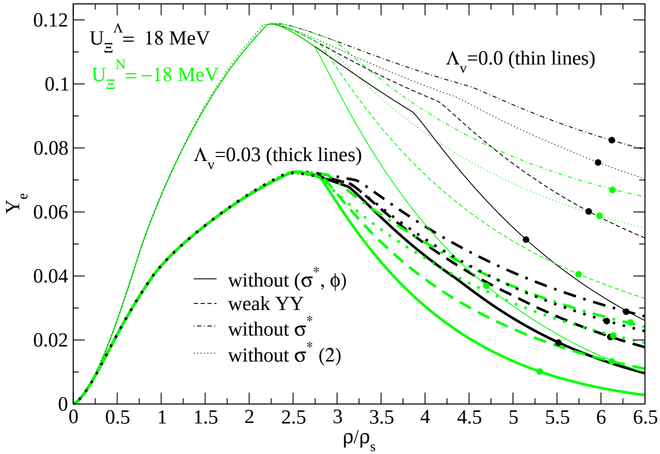
- nucleonic EOS: TM1 parametrization and modified versions
  - TM1 with $L = 110$ MeV,
  - TM1$\omega\rho$ term with $L = 55$ MeV
  - TM1-(2) with a reduction of 33% of the strength of the vector quartic term
  - all versions satisfy constraints from nuclear matter flow in HI collisions
- hyperonic interactions
  - fix $V_\Lambda = -28$ MeV, $V_\Sigma = 30$ MeV
  - vary V_Ξ
  - include σ^* and ϕ, weak coupling
  - include only ϕ

Hyperon fraction



- Smaller $L \rightarrow$ smaller hyperon fraction for a given density
- the strange meson reduces the strangeness fraction
- an harder EOS (TM1-2): larger strangeness fraction

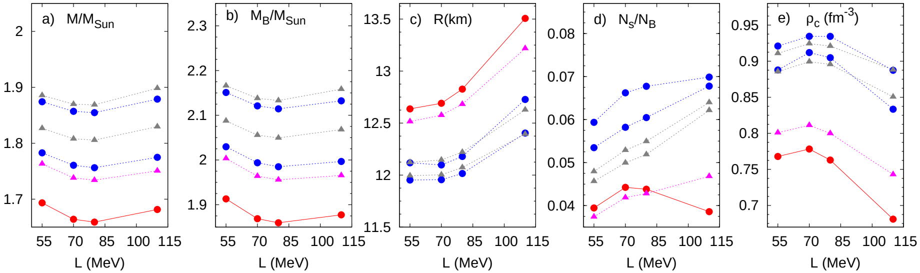
Electron fraction



- Smaller $L \to$ smaller electron fraction $\to$ larger ν fraction in neutrino trapped matter.
- strong influence of hyperon interaction

Compact stars: mass versus radius

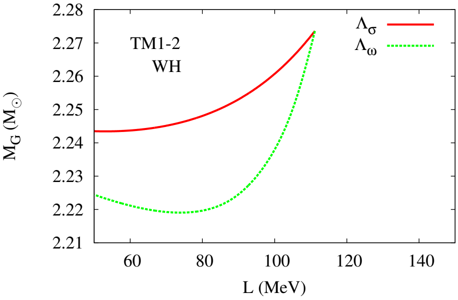
Maximum mass stars

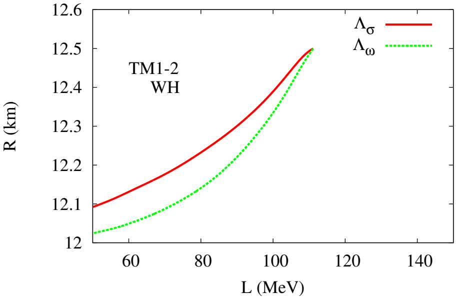


- $U_\Lambda = -28$ MeV, $U_\Sigma = 30$ MeV,
- $U_\Xi = -18$ MeV without (circles) (**red**), with (**blue**) YY
  $U_\Xi = +18$ MeV without (triangles) (**pink**), with (**grey**) YY

Maximum mass stars

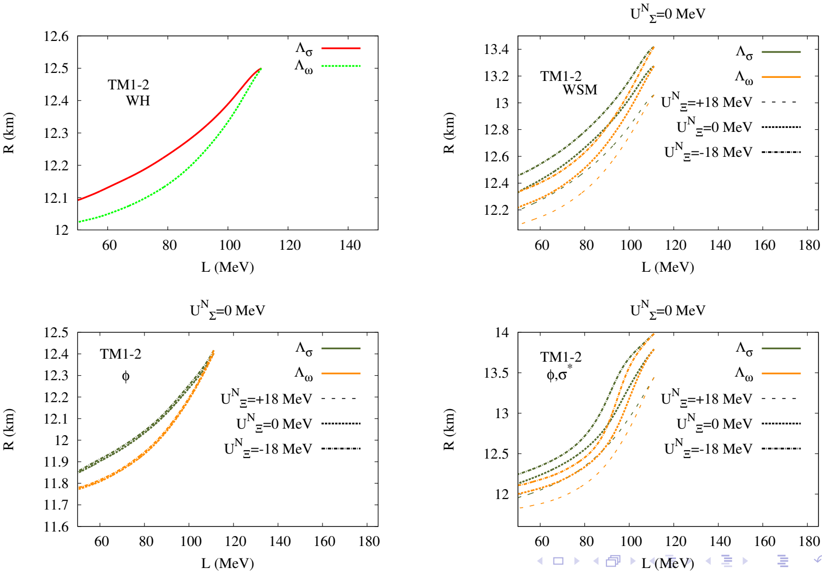
no hyperons, TM1-2, L=111 MeV





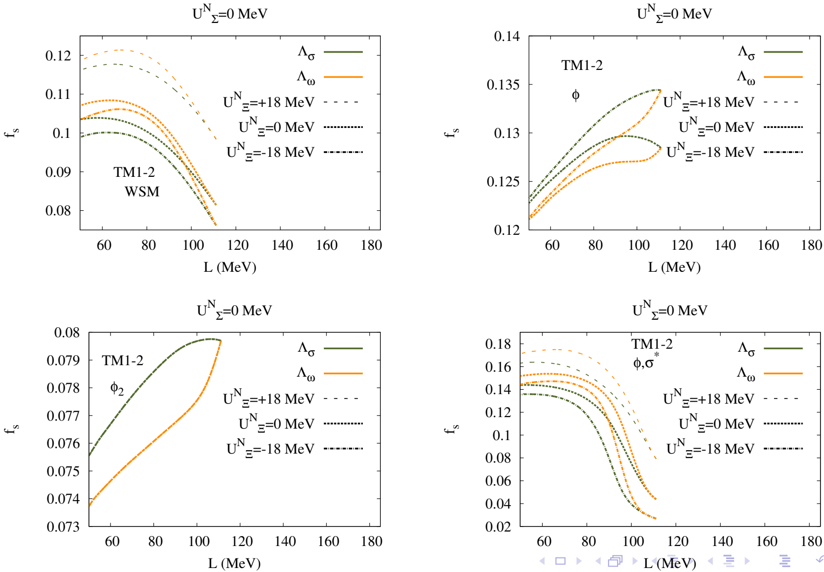
Radius of maximum mass stars

$U_\Lambda = -28$ MeV, $U_\Lambda = 30$ MeV



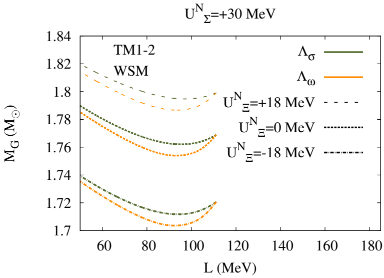
Strangeness content of maximum mass stars

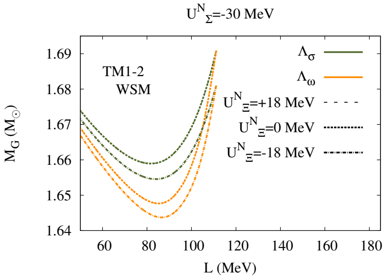
$U_\Lambda = -28$ MeV, $U_\Lambda = 30$ MeV

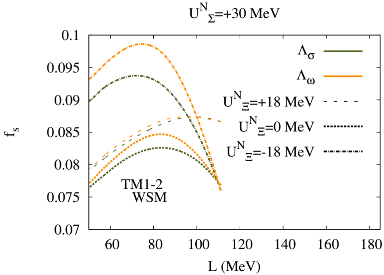


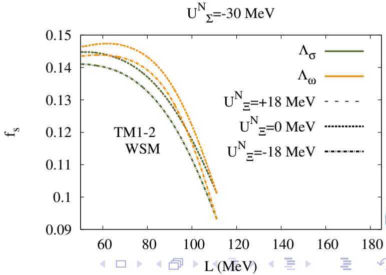
Maximum mass stars

$U_\Lambda = -28$ MeV, $g_\phi = 0$, $g_{\sigma *} = 0$



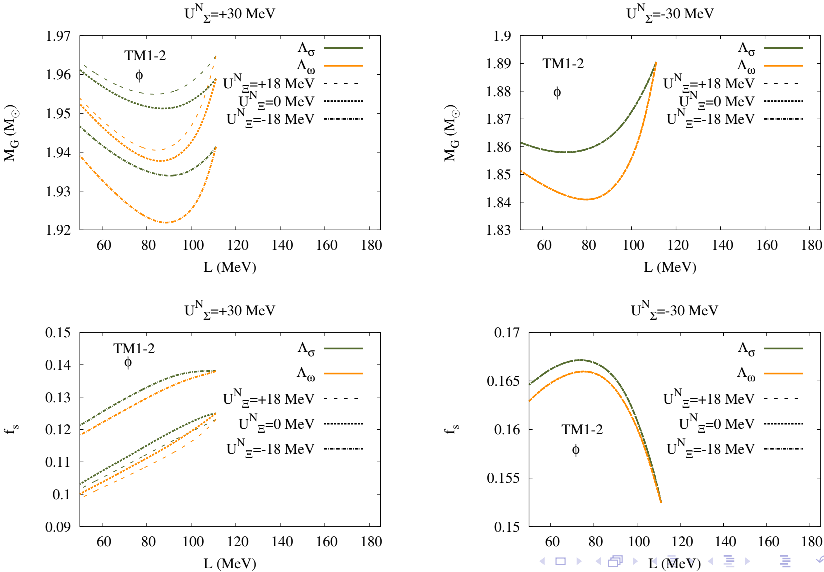






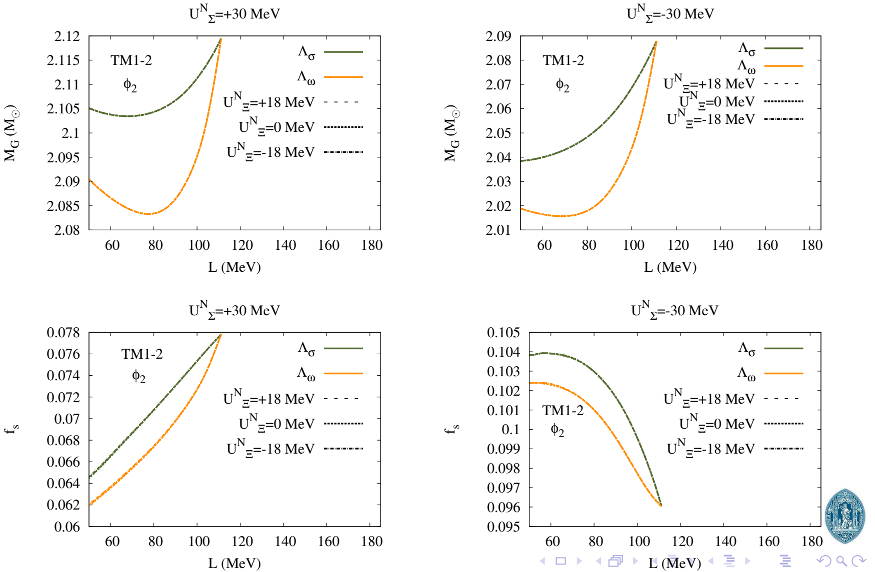
Maximum mass stars

including meson-ϕ: $U_\Lambda = -28$ MeV, $g_\phi = g_\phi(su(6))$, $g_{\sigma*} = 0$



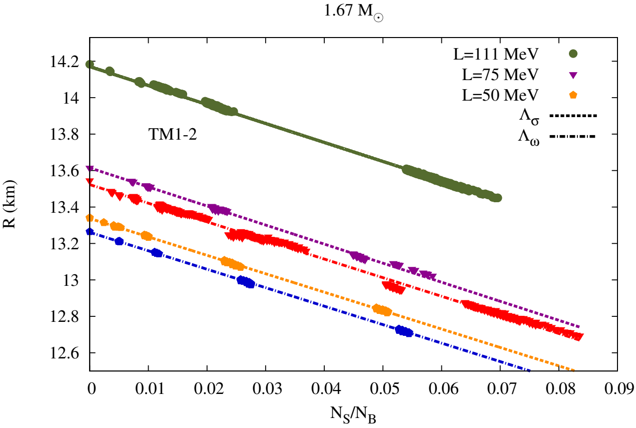
Maximum mass stars

beyond su(6), $U_\Lambda = -28$ MeV, $g_\phi = 2g_\phi(su(6))$, $g_{\sigma *} = 0$



Radius versus strangeness

Star with M=1.67 $M_\odot$



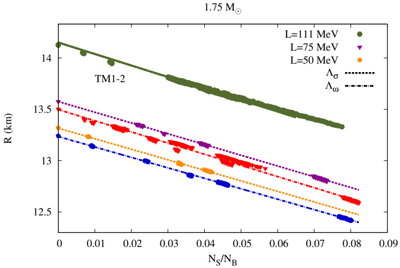
slope($L = 110$)=-10.72 $\pm$0.0719% km

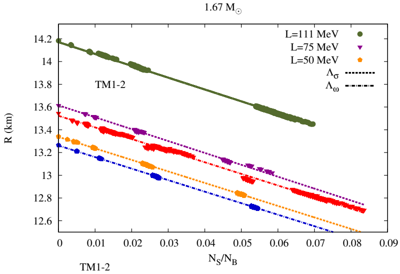
$L = 75$, slope(Λ_v)=-10.2132 $\pm$0.2348% km, slope(Λ_σ)=-10.4567 $\pm$0.4225% km

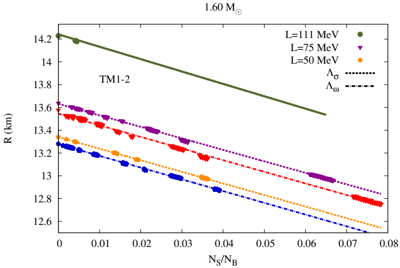
$L = 50$, slope(Λ_v)=-10.1327 $\pm$0.1586% km, slope(Λ_σ)=-10.1152 $\pm$0.1694% km

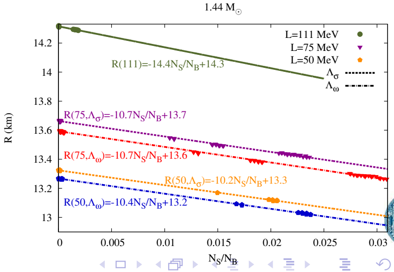
Radius versus strangeness

Star with M=1.75 $M_\odot$









Hyperons in compact stars

- Strangeness content in compact stars
  - smaller for a smaller L if U_Σ repulsive, or ϕ present and no $\sigma*$ (first onset of Λ)
  - larger for a smaller L otherwise (first onset of Σ^-)
- Mass/radius properties of compact stars
  - sensitive to the high density dependence of the EOS and the hyperon interaction
  - R is clearly correlated with L
  - smaller radius for a smaller L,
    larger differences for U_Σ attractive, inclusion of $\phi + \sigma^*$
    $\rightarrow$ can be as high as 2 km (with σ^*), 1 km (no ϕ, σ^*)
    $\rightarrow$ larger with $\omega - \rho$ term
    - uncertainty in $U_{hyperon}$ (U_Ξ, U_Σ, and σ^*, ϕ)) : $\lesssim 0.6\, M_\odot$
  - R is correlated with the strangeness fraction
  - $2\, M_\odot$ stars: do not exclude hyperons taking into account our lack of knowledge on the EOS at high densities and hyperon interaction

Metastable hadronic stars

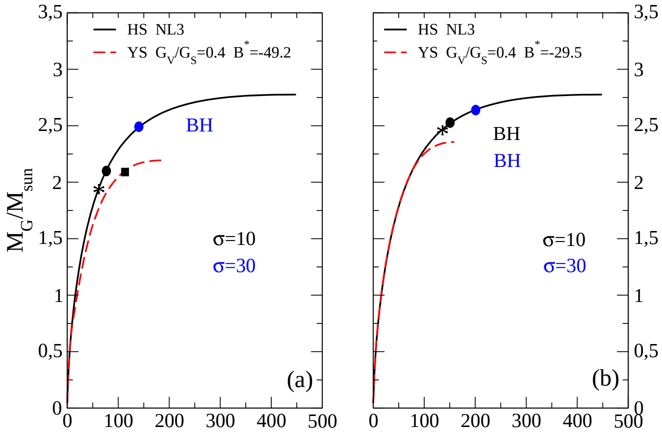
- How does the symmetry energy affect the evolution of a metastable hadronic star?
- Nucleonic EOS+ su(3) NJL for quark matter
- Total pressure quark matter

$$p = p(NJL) + 2G_V \sum_{i=u,d,s} n_i^2 - p_0 - B^*$$

- vector term, extra effective bag parameter
  - $B^* \rightarrow$ defines hadron-quark phase transition (Plagiara&Schaffner-Bielich2008)
  - with vector contribuition $\rightarrow$ stiffer quark EOS
- Nucleation
  - The Gibbs conditions are imposed
  - central pressure $P > P_0$: hadronic phase is metastable $\rightarrow$ stable quark matter as result of a nucleation process
  - Free energy difference: system with/without quark matter droplet

$$U(\mathcal{R}) = \frac{4}{3}\pi n_{Q^*}(\mu_{Q^*} - \mu_H)\mathcal{R}^3 + 4\pi\sigma\mathcal{R}^2$$

Star evolution



- Final configuration is not a blackhole if
  - G_V is strong enough: stiff quark EOS
  - B^* allows a hadron-quark phase transition a low enough ρ
- if $B^* > -49.2$ MeV/fm^3: transition to BH

Effect of the strangeness

- $B^* = -39.46\ \left(\text{MeVfm}^3\right)$

Model	σ $\left(\frac{\text{MeV}}{\text{fm}^2}\right)$	P_0 $\left(\frac{\text{MeV}}{\text{fm}^3}\right)$	$M(P_0)$ $(M_\odot)$	M_{cr} $(M_\odot)$	M_{fin} $(M_\odot)$	M_{max}^{YS} $(M_\odot)$
TM1-2						
N	25	35.93	1.31	1.94	1.95	1.97
N	30			2.04	BH	1.97
NY (L=55)	13	24.96	1.092	1.90	1.89	1.90
NY (L=110)	11.5	14.16	0.925	1.83	1.82	1.90

- Not all stable hybrid stars are populated after nucleation!
- smaller $L \rightarrow$ nucleation at larger ρ, allows larger hybrid stars.

Compact stars: kaon condensation

Kaons in stellar matter

- Kaplan and Nelson (PLB15,57 1986) suggested that the interaction of the K^- with the nuclear medium reduces its mass within chiral perturbation theory
- $\rightarrow$ being a boson it can condense in a zero momentum state and replace electrons as the neutralizing agent in charge neutral matter.
- Existence of a kaon condensate has strong implications in star properties which could be observed: stronger neutrino fluxes, or late low mass blackhole formation.

Including kaons in RMF EOS

- Kaon effective lagrangian density (Glendenning&Schäffner99)

$$\mathcal{L}_K = \mathcal{D}^*_\mu K^* \mathcal{D}^\mu K - m_K^* K^* K ,$$

$$\mathcal{D}_\mu = \partial_\mu + i g_{\omega K} \omega_\mu + i \frac{1}{2} g_{\rho K} \, \vec{\tau} \cdot \mathbf{b}_\mu . \quad m_K^* = m_K - g_{\sigma K} \sigma$$

- Let $K = f_K e^{iEt}$ in equation of motion

$$\left(D^\mu D_\mu + m_K^{*2} \right) K = 0$$

- get dispersion relation for the kaons

$$\omega_{K^-} = {m_K^*}^2 - g_{\omega K} \omega_0 - \frac{1}{2} g_{\rho K} b_{03} .$$

RMF EOS with kaons: parameters

- mass: vacuum mass 497 MeV
- meson-kaon couplings:
  - Vector mesons coupling: simple quark model and isopsin counting rules

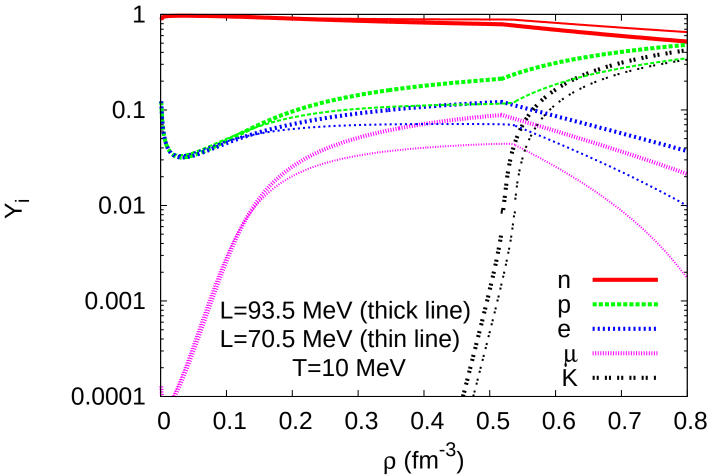
$$g_{\omega K} = \frac{1}{3} g_{\omega} \qquad g_{\rho K} = g_{\rho}$$

  - Scalar coupling: from optical potential of kaon in symmetric nuclear matter

$$V_K = m_K^* - g_{\omega K}\omega_0 - m_K = -g_{\sigma K}\sigma - g_{\omega K}\omega_0$$

  - Kaonic atom data (see Gal, PTP sup. 186(2010)) $V_K(\rho = 0) = -(50 - 200) MeV$,
  - $V_K(\rho_0) = -125$ MeV, a value suggested by chiral models

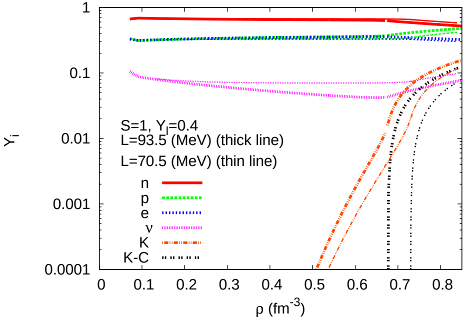
Effect of symmetry energy on kaon condensation

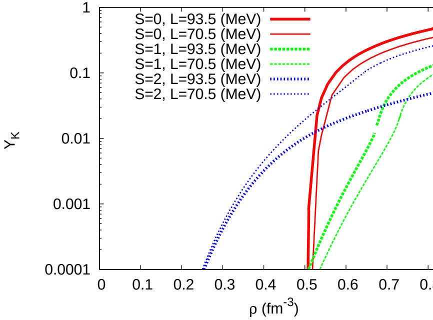


- A smaller L $\rightarrow$ smaller kaon fraction for a given ρ
- A smaller $L$$\rightarrow$ larger neutrino content

Effect of symmetry energy on kaon condensation

Warm matter with trapped neutrino, $S = 1$ and $Y_l = 0.4$

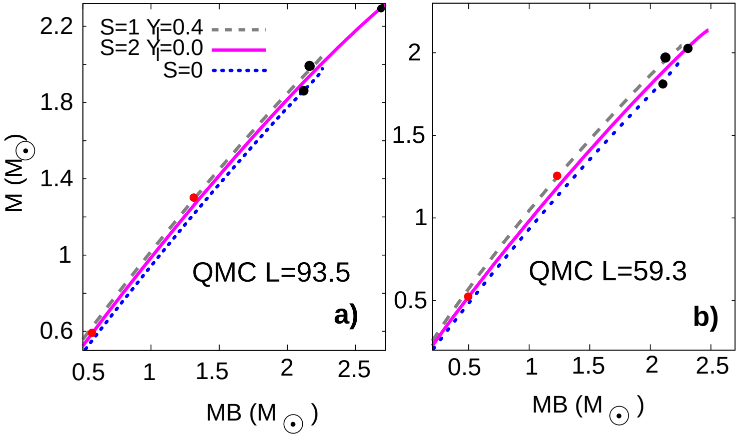




- The EOS with the smaller L has a smaller kaon and larger ν content
- large L may prevent condensation in hot matter

Effect of symmetry energy on star evolution

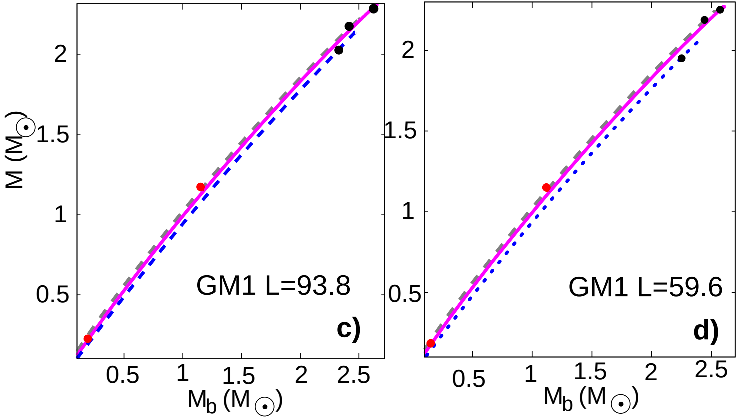
QMC



- Within QMC: smaller $L \rightarrow$ larger of chance low mass black-hole formation

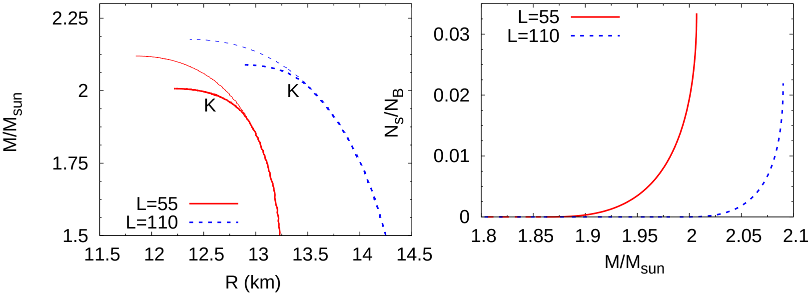
Effect of symmetry energy on star evolution

GM1



- Kaon content is larger within GM1: larger effects

Effect of symmetry energy on kaon condensation



- The EOS with the smaller L has a larger strangeness content
- Consequences for stars:
  - larger kaon content corresponds to a smaller electron content $\rightarrow$ larger neutrino fluxes

Collaborators

- Daniel Bizarro, Isaac Vidaña (UC)
- Aziz Rabhi (Tunes University, Tunisia)
- Prafulla K. Panda (C.V. Raman College Eng., India)
- Debora Menezes, Rafael Cavagnoli (UFSC, Brazil)

Thank you !