A Solution to the Hyperon-Puzzle in Neutron Stars

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ΑΡΙΣΤΟΤΕΛΕΙΟ
ΠΑΝΕΠΙΣΤΗΜΙΟ
ΘΕΣΣΑΛΟΝΙΚΗΣ

Table of Contents

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

Table of Contents

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

Introduction

Neutron Stars (NS) are giant nuclei. Unique cosmic objects with

- baryonic content
- very high baryon densities ρ_B
- very high isospin asymmetries δ
- cold & equilibrated over long time scales
- Precise data for max. NS masses & NS radii estimations

$\Rightarrow$ Explore baryonic EoS at extremes (high ρ_B, high δ)
$\Rightarrow$ beyond terrestrial experiments (HIC)

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

Introduction

NS observations: large NS masses $M_{max} > 2M_{\odot}$

- EoS very stiff at very high ρ_B
- but EoS soft at high ρ_B (known from terrestrial HIC exp.)

$\Rightarrow$ Complex soft-stiff behaviour of Baryonic EoS with ρ_B
$\Rightarrow$ can be reproduced by state-of-the art models

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

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ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

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NS at very high densities: high nucleon momenta

- Baryons heavier than nucleons energetically allowed to co-exist
- NS composition: p,n,leptons and Hyperons in β-equilibrium

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

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High ρ_B baryonic EoS softens when hyperons are present

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

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Less available baryon energy $\Leftrightarrow$ less gravitational pressure

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

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Reduction of NS max. mass in presence of hyperons

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

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High ρ_B baryonic EoS softens when hyperons are present
Less available baryon energy $\Leftrightarrow$ less gravitational pressure
Reduction of NS max. mass in presence of hyperons

$\Rightarrow$ The hyperon-puzzle:

Observed high NS masses not reproduced by *state of the art* models when hyperons included in model calculations

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Introduction

Hyperon-puzzle: a persisting non-trivial issue

- Hyperon densities different from nucleon densities

ΑΡΙΣΤΟΤΕΛΕΙΟ
ΠΑΝΕΠΙΣΤΗΜΙΟ
ΘΕΣΣΑΛΟΝΙΚΗΣ

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ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

Introduction

Hyperon-puzzle: a persisting non-trivial issue

- Hyperon densities different from nucleon densities
- Hyperon momenta different from nucleonic momenta
- Not only density-, but momentum-dependence of hyperon potential important

Introduction

Hyperon-puzzle: a persisting non-trivial issue. We need

- Density & momentum-dependence of hyperon potential, or
- In-medium momentum-dependence of hyperon potential

Experimental knowledge about hyperons ($\Lambda, \Sigma^-, \Xi^-, \Omega^-$) only from:

- view single-Λ & double-Λ hypernuclei
- low-energy Λ & Σ^- nucleon free scattering
- HIC for Λ, but too many unknowns in theory (re-scattering)
- Ξ & Ω unexplored

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Introduction

Hyperon-puzzle: a persisting non-trivial issue. We need

- In-medium momentum-dependence of hyperon potential crucial, but
- poor exp. info about hyperon properties

Consequence:
No exp. info for in-medium hyperon potentials at finite s.p. momenta at baryon densities close to saturation & beyond

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Table of Contents

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

NLD for Neutron Stars: The NLD Model

Non-Linear Derivative (NLD) approach based on original QHD Lagrangian

$$\mathcal{L}_{NLD} = \sum_b \mathcal{L}_b + \sum_m \mathcal{L}_m + \sum_m \mathcal{L}_{int}^m , \quad b = p, n, \Lambda, \Sigma^{-,\pm}, \quad m = \sigma, \omega, \rho$$

NLD b-m Interaction with all higher-order derivative operators $\overleftarrow{\mathcal{D}}, \overrightarrow{\mathcal{D}}$

$$\mathcal{L}_{int}^m = \sum_b \frac{g_{mb}}{2} \left[\overline{\Psi}_b \overleftarrow{\mathcal{D}}_b \Gamma_m \Psi_b \varphi_m + \varphi_m \overline{\Psi}_b \Gamma_m \overrightarrow{\mathcal{D}}_b \Psi_b \right]$$

NLD operators $\overleftarrow{\mathcal{D}}, \overrightarrow{\mathcal{D}}$: infinite series of higher-order derivatives.
NLD formalism: fully covariant & thermodynamically consistent

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

NLD for Neutron Stars: The NLD Model

Relevant NLD equations: meson-fields

$$m_\sigma^2 \sigma + \frac{\partial U}{\partial \sigma} = \sum_b g_{\sigma b} \frac{\kappa}{(2\pi)^3} \int\limits_{|\vec{p}| \leq p_{F_b}} d^3p \frac{m_b^*}{E_b^*} \mathcal{D}_b^\sigma(p)$$

$$m_\omega^2 \omega = \sum_b g_{\omega b} \frac{\kappa}{(2\pi)^3} \int\limits_{|\vec{p}| \leq p_{F_b}} d^3p \, \mathcal{D}_b^\omega(p)$$

with momentum dependent (MD) regulators D_b^m for each b-m vertex

ΑΡΙΣΤΟΤΕΛΕΙΟ
ΠΑΝΕΠΙΣΤΗΜΙΟ
ΘΕΣΣΑΛΟΝΙΚΗΣ

NLD for Neutron Stars: The NLD Model

Relevant equations: baryon fields

$$\left[\gamma_\mu(p^\mu - V_b^\mu(p)) - m_b^\star(p)\right] u_b(p) = 0 \text{ with } m_b^\star(p) = M_b - S_b(p)$$

with MD vector $V_b^\mu(p)$ & scalar $S_b(p)$ baryon selfenergies

$$\begin{aligned} V_b^\mu(p) =& g_{\omega b}\, \omega^\mu\, \mathcal{D}_b^\omega(p) + \tau_{3b} g_{\rho b}\, \rho^\mu\, \mathcal{D}_b^\rho(p) \\ S_b(p) =& g_{\sigma b} \sigma \mathcal{D}_b^\sigma(p) \end{aligned}$$

NLD-regulators: generic monopole-like form

$$\mathcal{D}(p) = \frac{\Lambda_1^2}{\Lambda_2^2 + p^2}$$ with cut-offs $\Lambda_{1,2}$ for each b & each b-m vertex.

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

NLD for Neutron Stars: The NLD Model

NLD features: regulators $\mathcal{D}(p)$ show up

- implicitly in source terms of meson-field equations
- explicitly in baryon self-energies

Non-trivial density (ρ_B) & momentum (p) potential dependencies

Non-trivial soft-stiff EoS behavior with ρ_B

non-trivial soft-stiff MD of in-medium s.p. baryon energies

$$\mathbf{E_b(p)} = \sqrt{\mathbf{p^2} + (\mathbf{M_b} - \mathbf{S_b(p)})^2} + \mathbf{V_b^0(p)}$$

$\Rightarrow$**new hyperon threshold effects in NS matter**

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

NLD for Neutron Stars: NLD for β-equilibrium

NS description: p,n,e & hyperons (Λ, $\Sigma^{0,\pm}$) imposing

- charge neutrality & ρ_B conservation & β-equilibrium

$\Rightarrow$ Simultaneous treatment of

- $\sum_b q_b \rho_b - \rho_e = 0$ & $\rho_B = \sum_b \rho_b$ & meson-field equations
- $\mu_b = \mu_n - q_b\, \mu_e$ with $\mu_b = \sqrt{p_{F_b}^2 + m_b^{*2}} + V_b^0$

Results:

- baryon (b) Fermi-momenta p_{F_b} from solution (if any) of
  $\mu_b = \sqrt{p^2 + (M_b - S_b(p))^2} + V_b^0(p)$ at $p = p_{F_b}$
  with MD selfenergies

$\mu_Y = E_Y \Rightarrow$ threshold conditions for particles heavier than neutron
$\Rightarrow$ strangeness (Y) threshold conditions

Table of Contents

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

Strangeness Threshold Effects: Conventional Models

Conventional hyperon (Y) threshold effect:

- s.p. energy $E_Y(p) = \sqrt{p^2 + (M_Y - S_Y)^2} + V_Y^0$
  always monotonically increasing function vs p
- hyperon Y will be populated as solution of $\mu_Y = E_Y(p_{F_Y})$
  if $\mu_n - q_Y \mu_e$ exceeds hyperon's lowest energy $E_Y(0)$:
  $\mu_Y = \mu_n - q_Y \mu_e > E_Y(0)$
- applies to conventional RMF models, (no MD selfenergies)
- Norman K. Glendenning, Astrophys. J. **293** (1985) 470

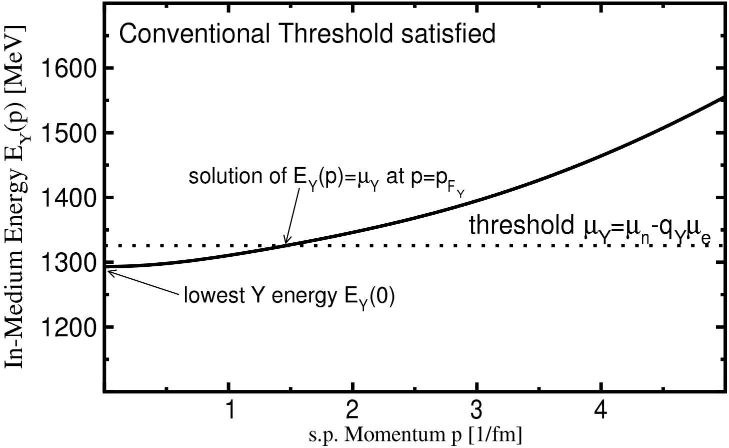
$$\mu_n - q_B \mu_e \geq g_{\omega B} \omega_0 + g_{\rho B} \rho_{03} I_{3B} + m_B - g_{\sigma B} \sigma \ . \qquad (64)$$

When the left side equals or exceeds the right, the baryon species *B* will be populated.

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

Strangeness Threshold Effects: Conventional Models

Conventional model calculation, β-equilibrium at high ρ_B
$\Rightarrow$ hyperon Y produced at Fermi-momentum p_{F_Y}



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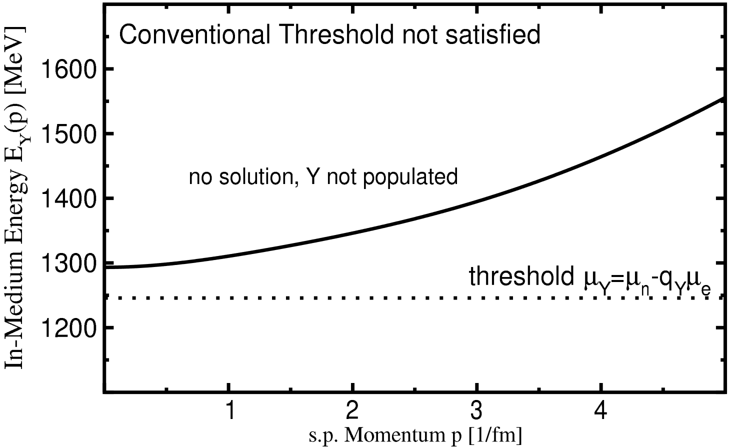
Strangeness Threshold Effects: Conventional Models

Conventional model calculation, β-equilibrium at high ρ_B

$\Rightarrow$ hyperon Y not produced



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Strangeness Threshold Effects: NLD Model

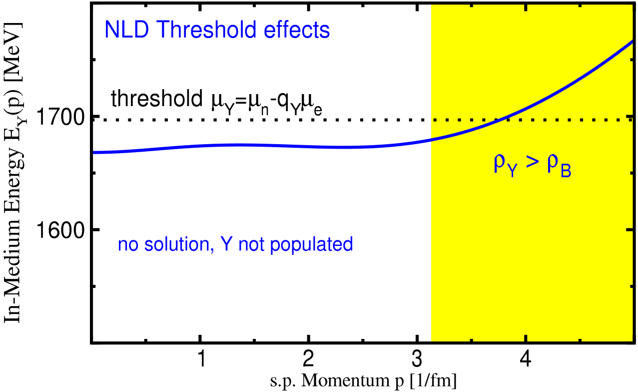
NLD hyperon (Y) threshold novel effects in β-equilibrium:

- s.p. energy $E_Y(p) = \sqrt{p^2 + (M_Y - S_Y^2(p))} + V_Y^0(p)$
  not necessarily increasing function vs p
- hyperon Y may not be populated
  even when $\mu_n - q_Y\mu_e$ exceeds hyperon's lowest energy $E_Y(0)$:
  $\mu_Y = \mu_n - q_Y\mu_e > E_Y(0)$
- applies to NLD model
  (explicit p-dependence in selfenergies)

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

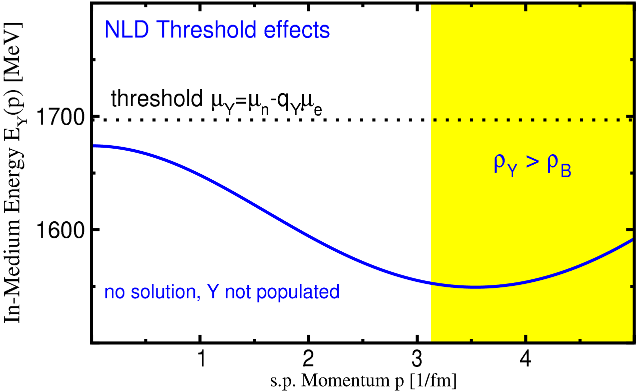
Strangeness Threshold Effects: NLD Model

NLD hyperon (Y) threshold novel effects in β-equilibrium:
soft MD Y-potential at high $\rho_B \Rightarrow$ soft $E_Y(p)$
$\Rightarrow$ **no solution, even with satisfied threshold**



Strangeness Threshold Effects: NLD Model

NLD hyperon (Y) threshold novel effects in β-equilibrium:
very soft MD Y-potential at high $\rho_B \Rightarrow$ soft $E_Y(p)$
$\Rightarrow$ **no solution, even with satisfied threshold**



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Strangeness Threshold Effects: NLD Model

NLD hyperon (Y) other threshold effects in β-equilibrium:
non-trivial MD Y-potential at high ρ_B
$\Rightarrow$ non-trivial $E_Y(p)$ behavior $\Rightarrow$ a "solution" shows up
Not appeared in calculations so far, but interpretation under study

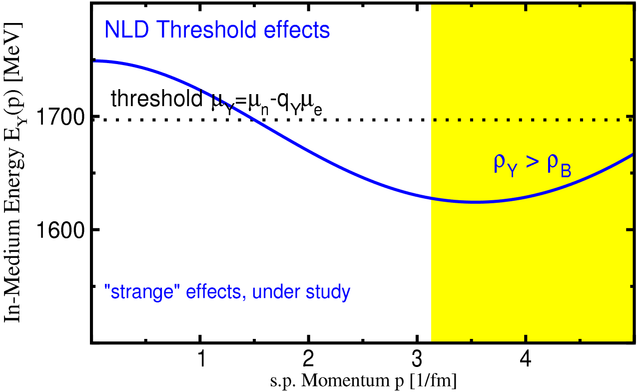

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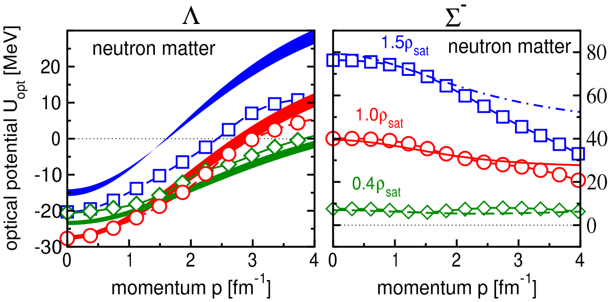
Table of Contents

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

NLD Results: Y-Potentials in nuclear matter

NLD parameters fitted to most recent χEFT calculations at $\rho_{\rm sat}$



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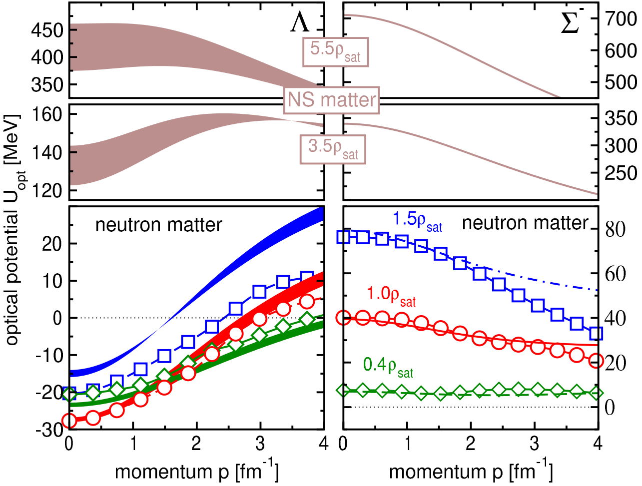
NLD Results: Y-Potentials in nuclear & NS matter

NLD predictions at NS densities: generic soft p-dependent behavior



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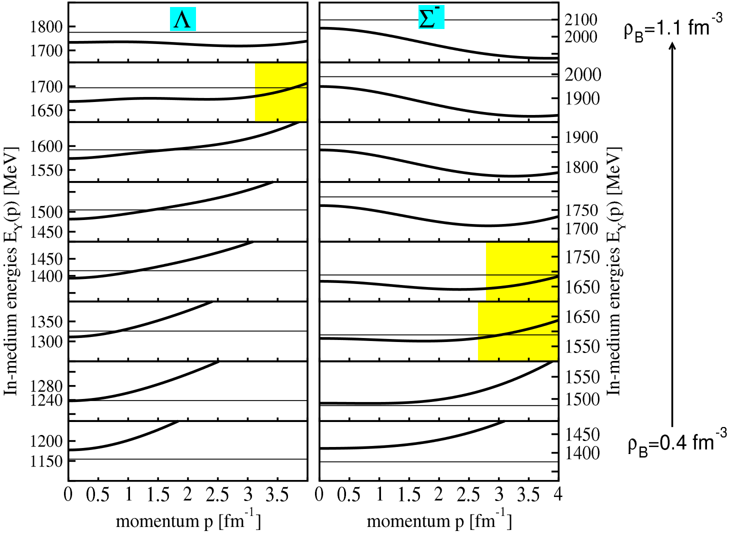
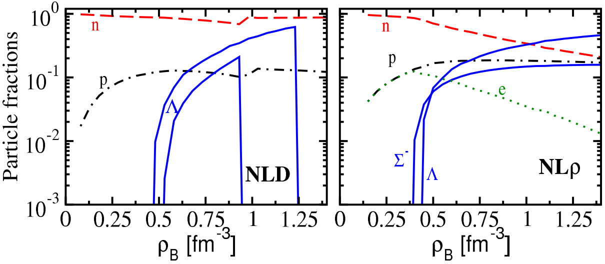
NLD strangeness threshold effects at relevant NS-densities:



NLD Results: Particle Fractions

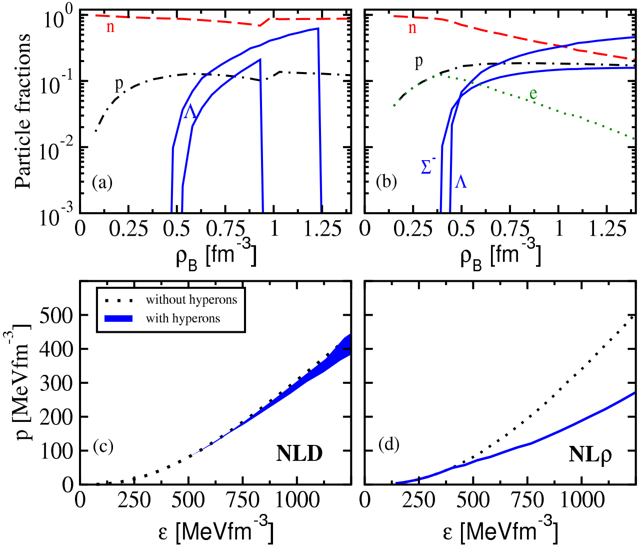
NLD calculations for NS matter with Λ, Σ^-, Σ^0 and Σ^+



ΑΡΙΣΤΟΤΕΛΕΙΟ
ΠΑΝΕΠΙΣΤΗΜΙΟ
ΘΕΣΣΑΛΟΝΙΚΗΣ

NLD Results: Particle Fractions & EoS

NLD calculations for NS matter with Λ, Σ^-, Σ^0 and Σ^+



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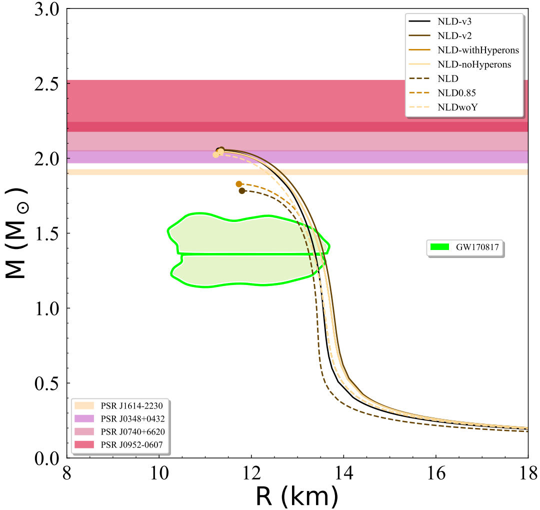
ΠΑΝΕΠΙΣΤΗΜΙΟ
ΘΕΣΣΑΛΟΝΙΚΗΣ

NLD Results: MR-Diagram (PRELIMINARY)

NLD calculations for NS matter with Λ, Σ^-, Σ^0 and Σ^+ (with A.K. Pegios, Ch. Moustakidis)



ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

Table of Contents

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

Conclusions & Outlook

- NLD model: properly accounted for MD Y-potentials
- MD Y-potentials induce new effects on Y-thresholds in NS matter
- Significant suppression & limitation of strangeness in NS matter
- NS EoS maintains its stiffness with hyperons
- NS max. mass $M \approx (2.05 - 2.15)\ M_{\odot}$ without and with hyperons

Momentum dependence of hyperon potentials necessary to resolve the persisting Hyperon-Puzzle

Under study/in progress

- Interpret some new strangeness threshold effects
- Include double-strangeness Ξ^- in calculations
- Readjust neutron matter EoS for better NS radius & NS cooling (soft E_{sym} at ρ_{sat})

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