Strangeness in nuclei and neutron stars: a challenging puzzle

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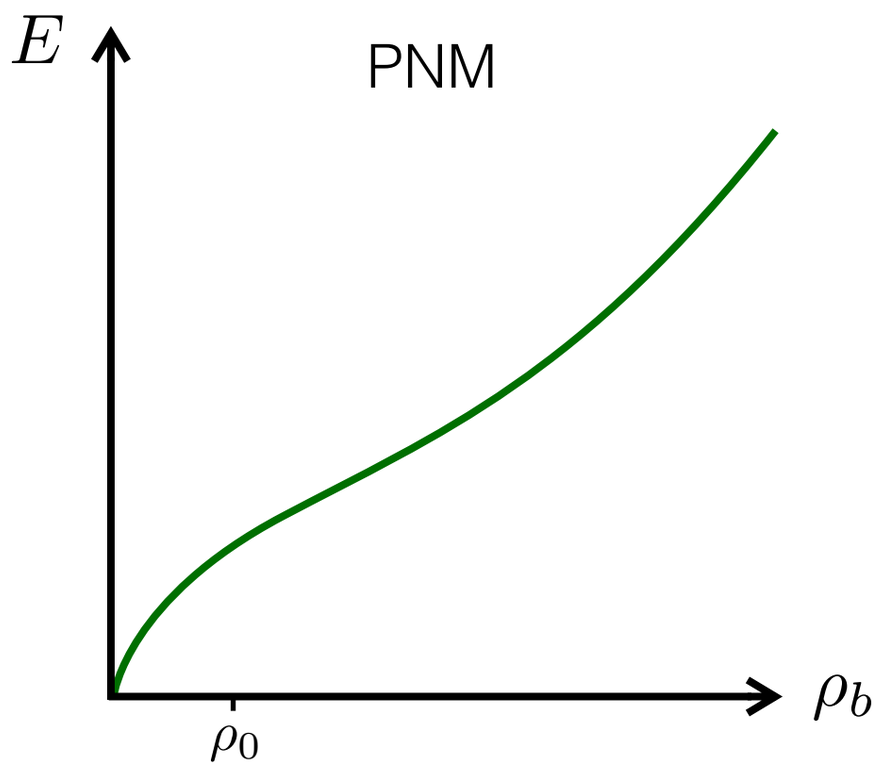
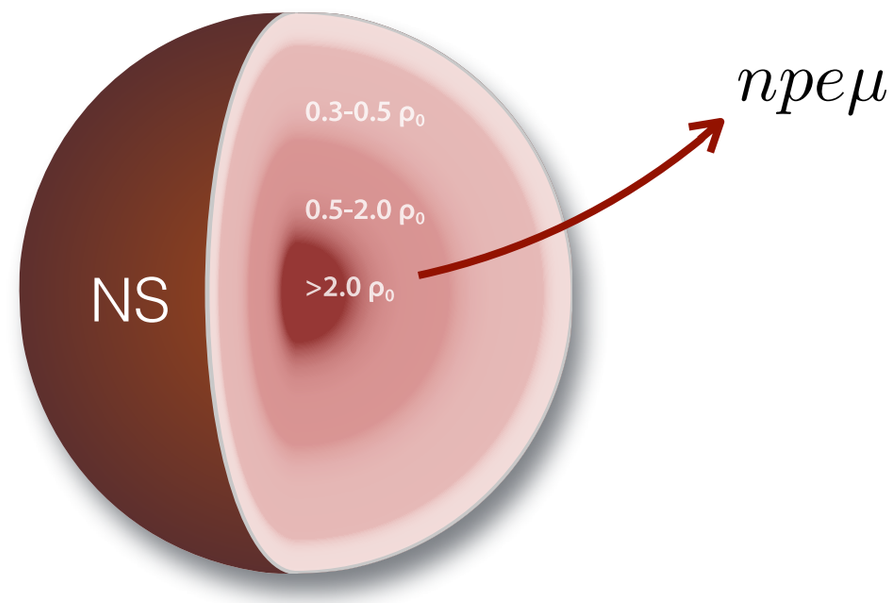
Outline

- ✓ Strangeness in neutron stars:
  - the hyperon puzzle
- ✓ Strangeness in nuclei:
  - hypernuclei & experimental inputs
- ✓ The project:
  - Auxiliary Field Diffusion Monte Carlo (AFDMC)
  - hyperon-nucleon interaction
- ✓ Results:
  - hypernuclei
  - hyper-neutron matter → neutron stars
- ✓ Conclusions & Perspectives

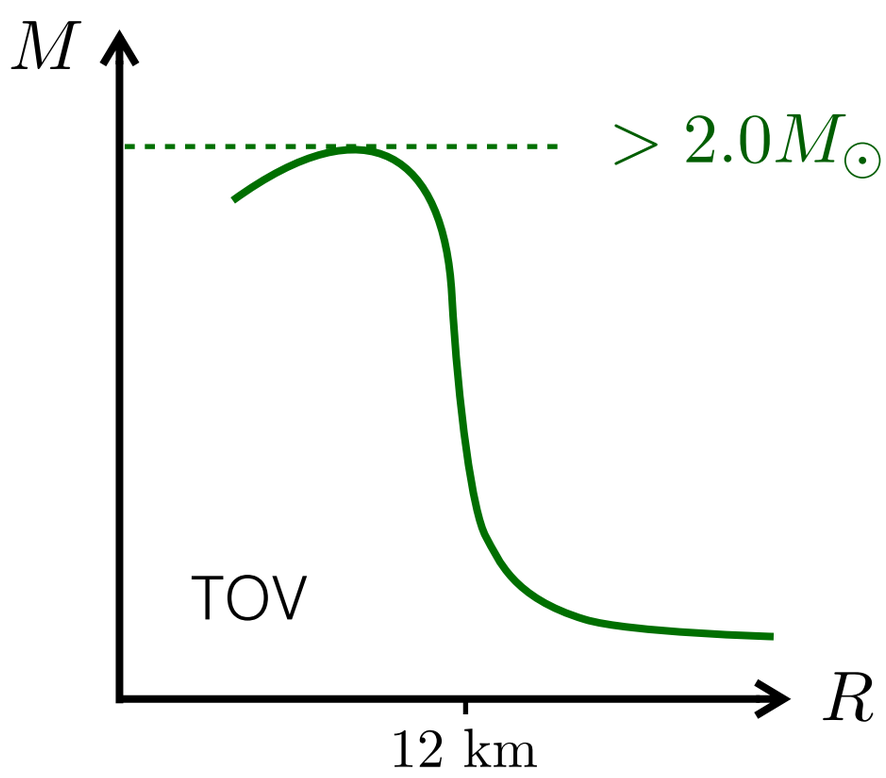
Strangeness in neutron stars



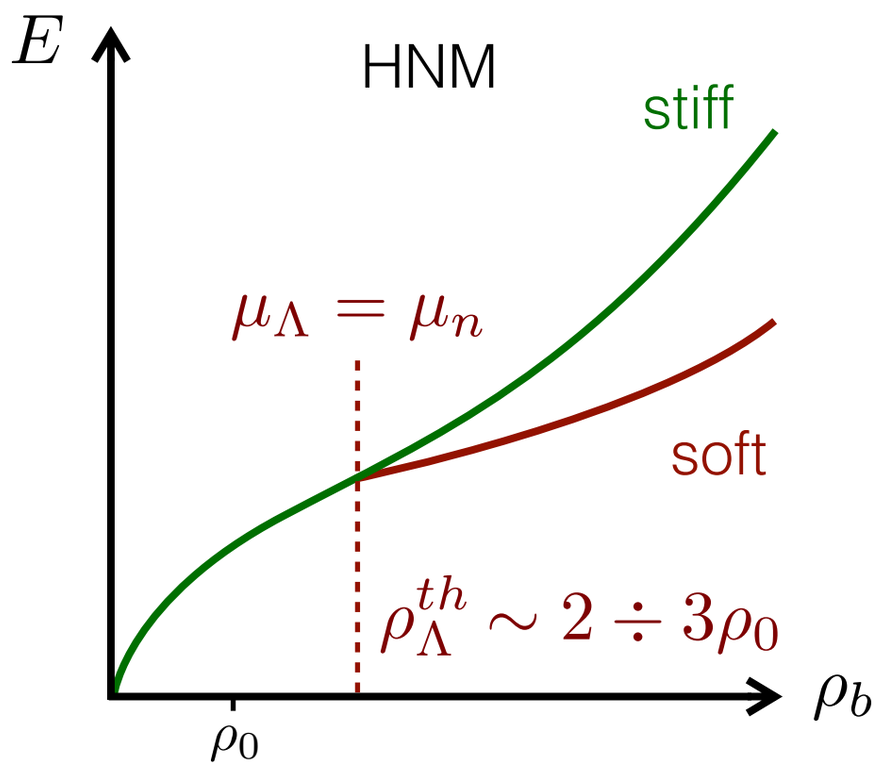


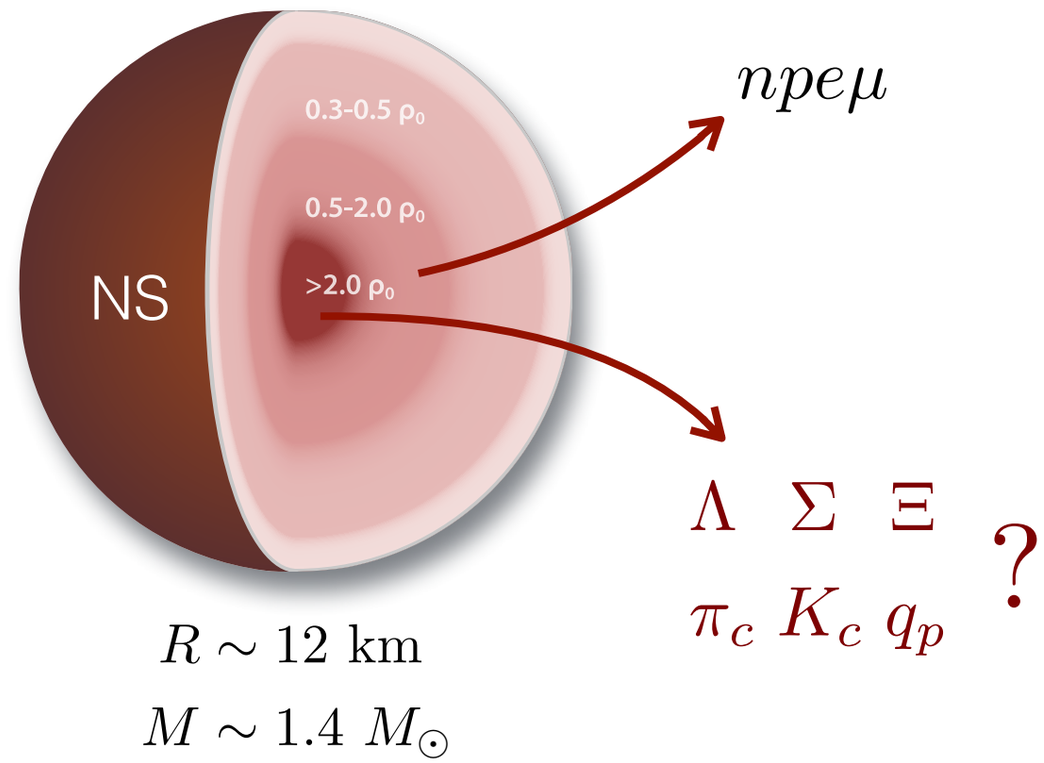
$R \sim 12$ km

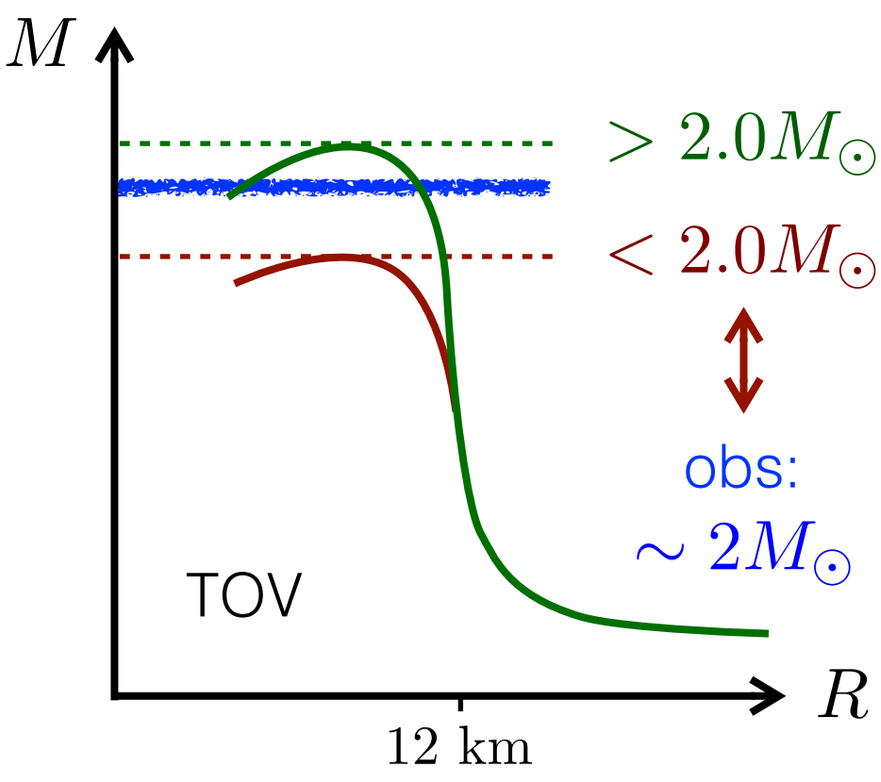
$M \sim 1.4\ M_\odot$

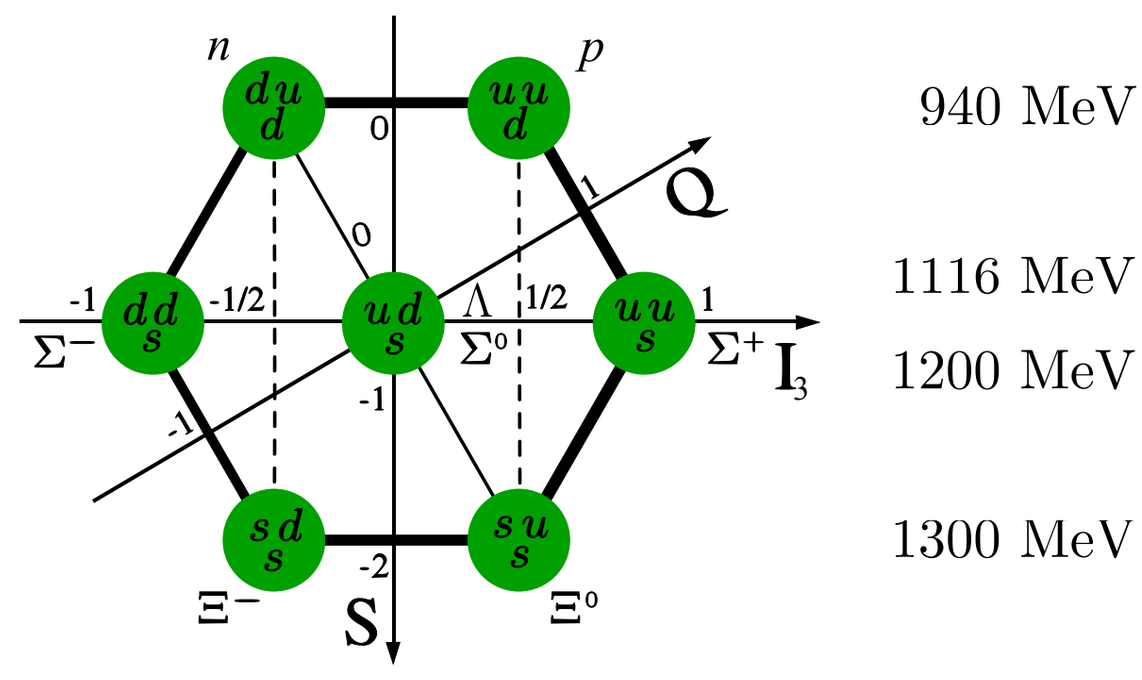


Strangeness in neutron stars









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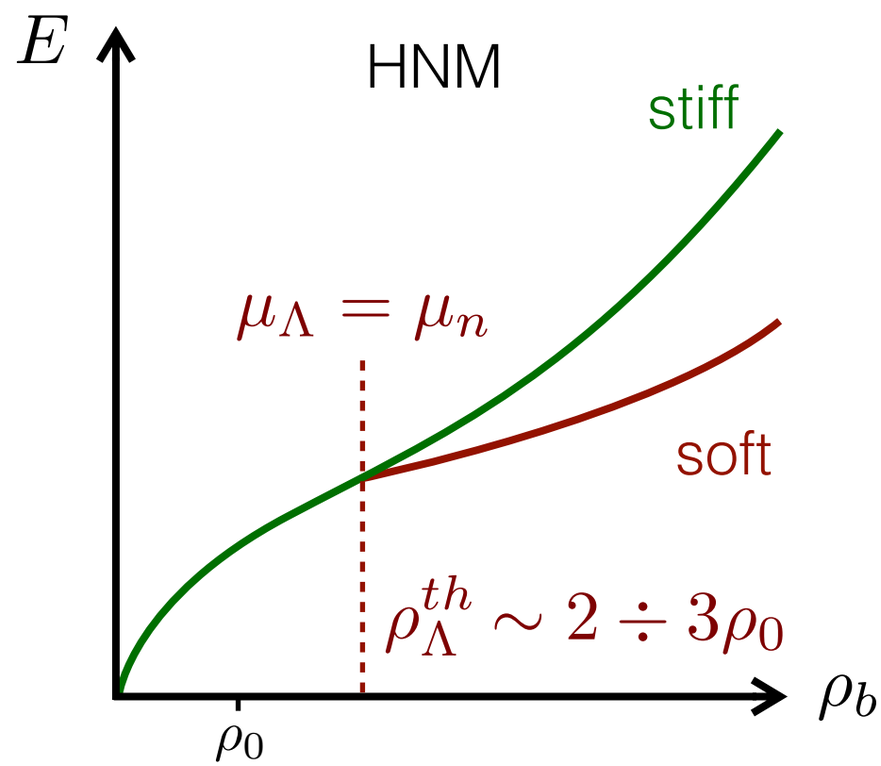
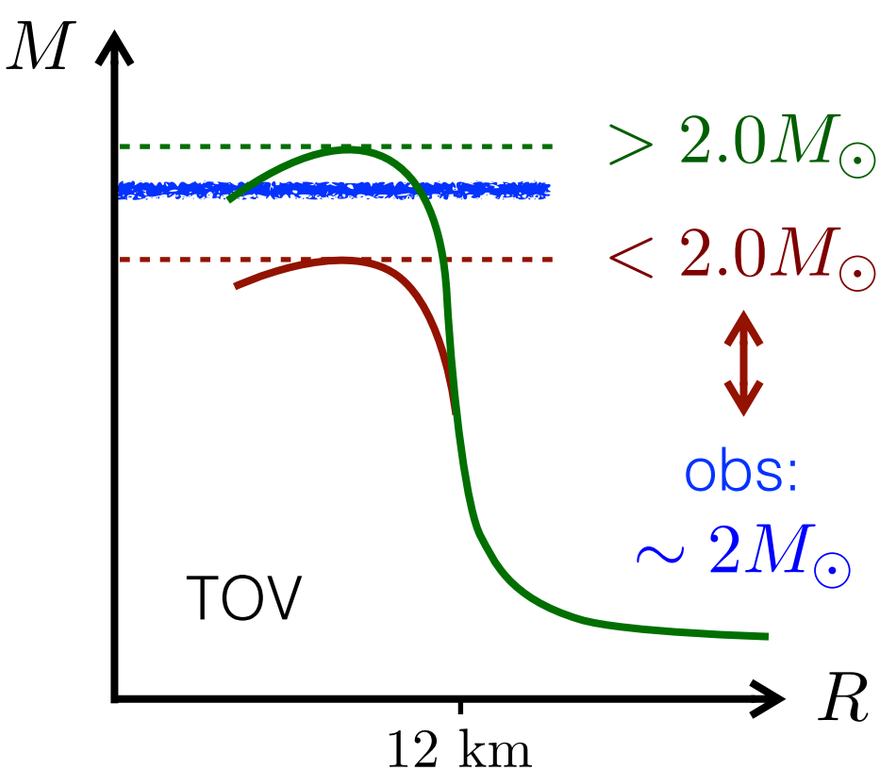




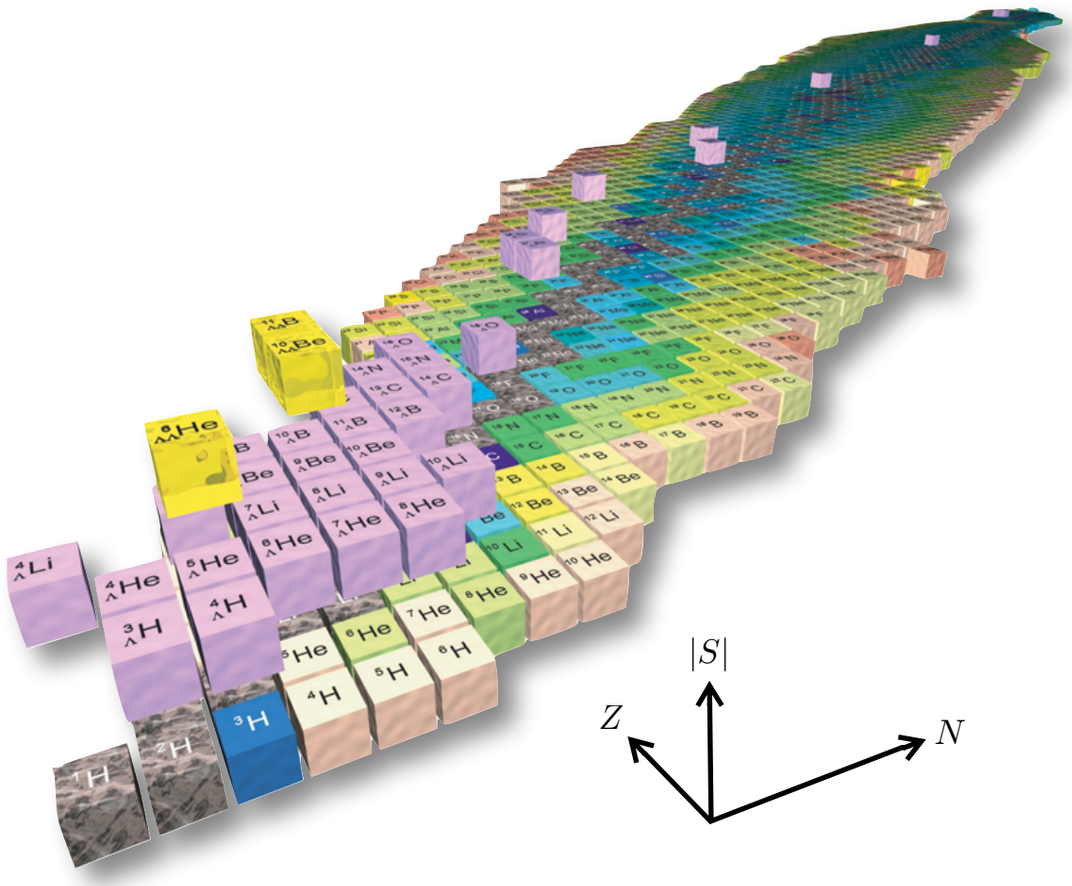
Hyperon puzzle

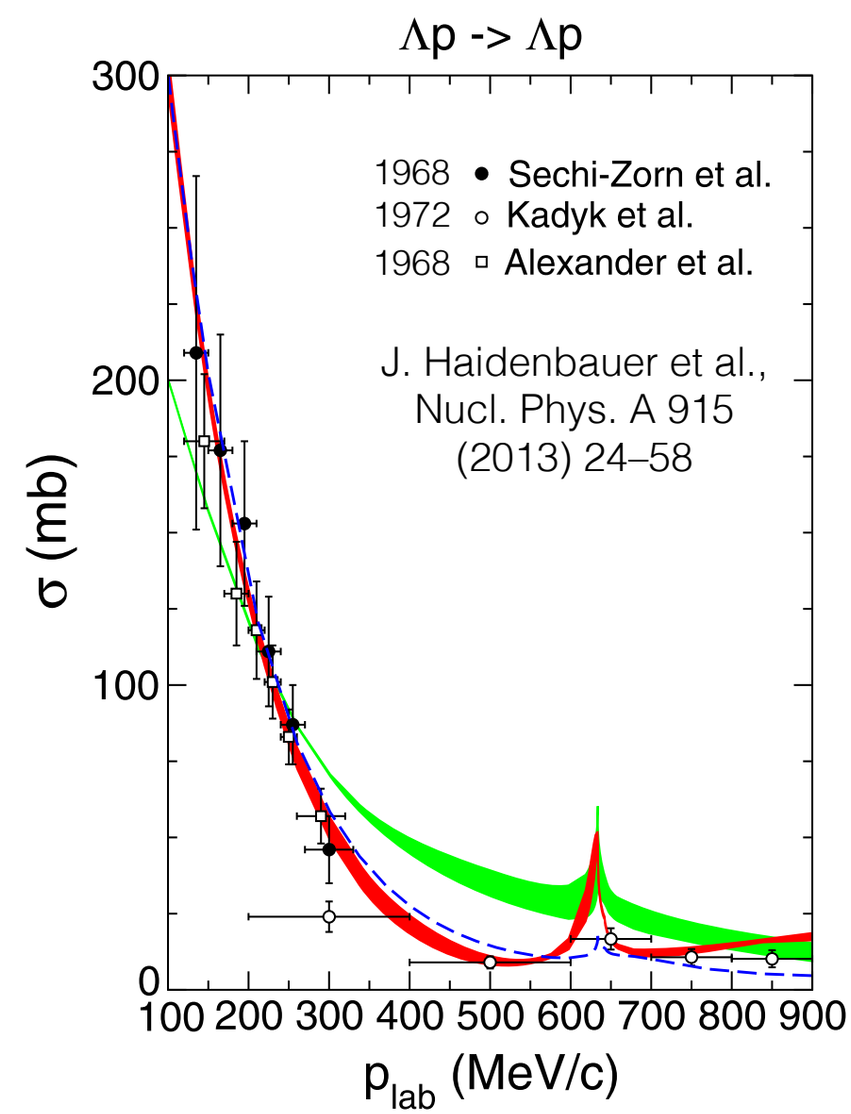
- ✓ Theoretical indication for hyperons in NS core: softening of the EoS
- ✓ Observation of massive NS: stiff EoS
- ✓ Magnitude of the softening: strongly model dependent

⇩

- ✓ Interactions poorly known
- ✓ Non trivial many-body problem: very dense system, strong interactions

Strangeness in nuclei





binding energies:		scattering data:	
nuc :	~ 3340	NN :	~ 4300
Λ hyp :	~ 41	ΛN :	~ 52
$\Lambda\Lambda$ hyp :	~ 5		
Σ hyp :	$\sim (1)$		

- ✓ Interactions poorly known
- ✓ Non trivial many-body problem: very dense system, strong interactions

The project: AFDMC

- Diffusion Monte Carlo

$$|\psi(\tau + d\tau)\rangle = \mathrm{e}^{-(H-E_T)d\tau}\,|\psi(\tau)\rangle \xrightarrow{\tau \to \infty} \text{ground state}$$

$$\downarrow$$

$$\mathcal{P} \sim \mathrm{e}^{-\frac{1}{2}\lambda d\tau \mathcal{O}^2} \longrightarrow |\psi(\tau + d\tau)\rangle \sim 2^A \text{ components}$$

- Auxiliary Field Diffusion Monte Carlo

Idea: single particle wave function + Hubbard-Stratonovich transformation

$$|\psi\rangle \sim \bigotimes_i |\varphi_i\rangle \quad \sim A \qquad \mathrm{e}^{-\frac{1}{2}\lambda\mathcal{O}^2} = \frac{1}{\sqrt{2\pi}}\int dx\, \mathrm{e}^{-\frac{x^2}{2}+\sqrt{-\lambda}\,x\mathcal{O}}$$

AFDMC:

finite systems: $A \sim 90$

infinite systems: $A \sim 140$

- Interactions poorly known
- Non trivial many-body problem: very dense system, strong interactions

The project: hyperon-nucleon interaction

Quantum Monte Carlo (Auxiliary Field Diffusion Monte Carlo)

↓

- ✓ 2b+3b nucleon-nucleon phenom. interaction: Argonne & Urbana
- ✓ 2b+3b hyperon-nucleon phenom. interaction: Argonne like

Bodmer, Usmani, Carlson et al.

→ VMC calculations: light hypernuclei

→ CVMC calculations: A=17

↓

- pion exchange model
- local in coordinate space
- explicit 2-body and 3-body terms
- hard-core repulsion
- charge symmetry breaking terms

$$H = T_{\rm N} + V_{\rm NN} + V_{\rm NNN}$$
$$+ T_{\Lambda} + V_{\Lambda \rm N} + V_{\Lambda \rm NN}$$

↓

suitable for AFDMC calculations

The project: hyperon-nucleon interaction

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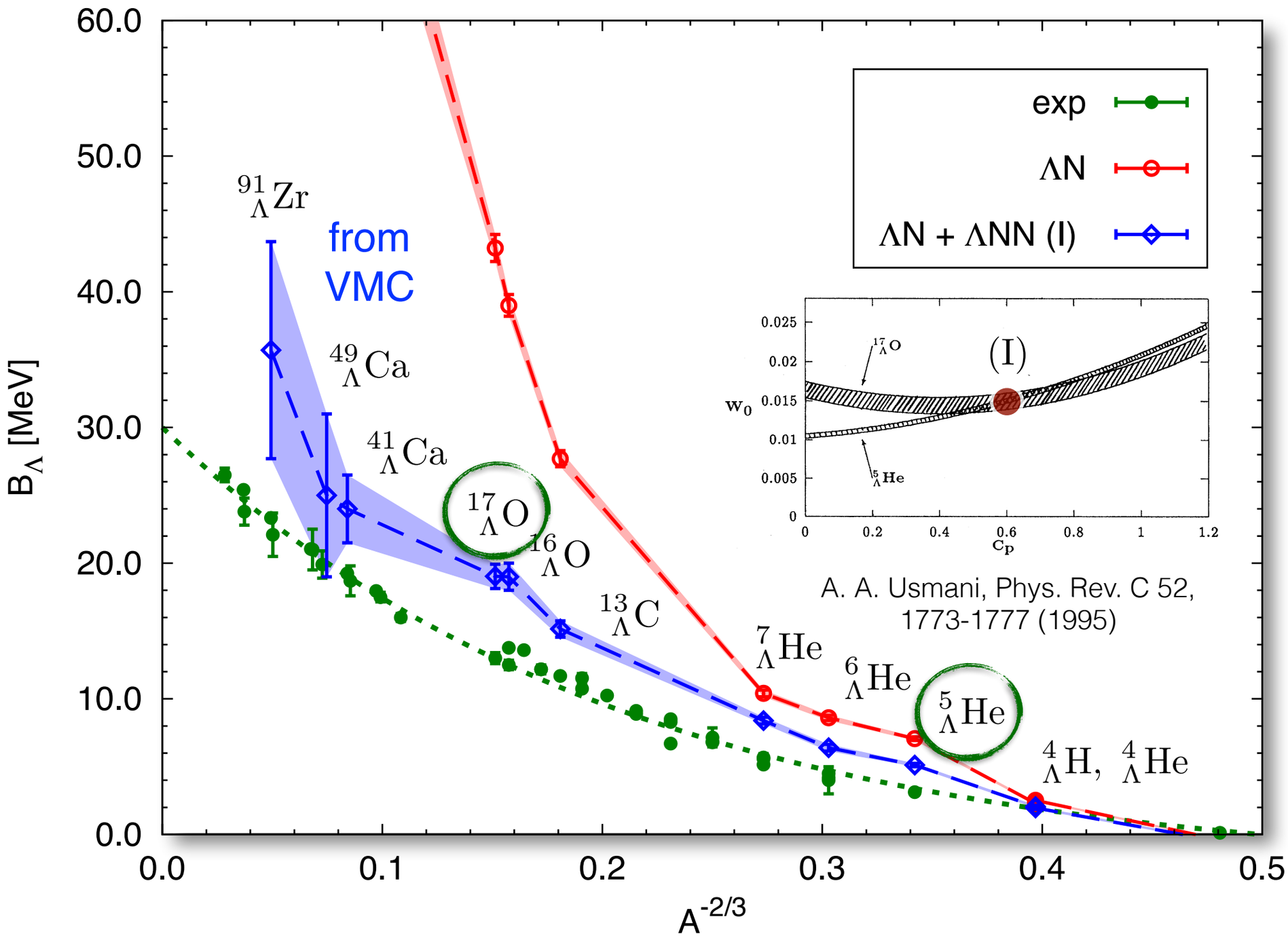
ΛN scattering data

$A = 4$ asymmetry

no unique form: fit on exp data

$$B_\Lambda = E({}^{A-1}Z) - E({}^{A}_{\Lambda}Z)$$

Results: hypernuclei



A. A. Usmani, Phys. Rev. C 52, 1773-1777 (1995)

D. L., F. Pederiva, S. Gandolfi, Phys. Rev. C 89, 014314 (2014)

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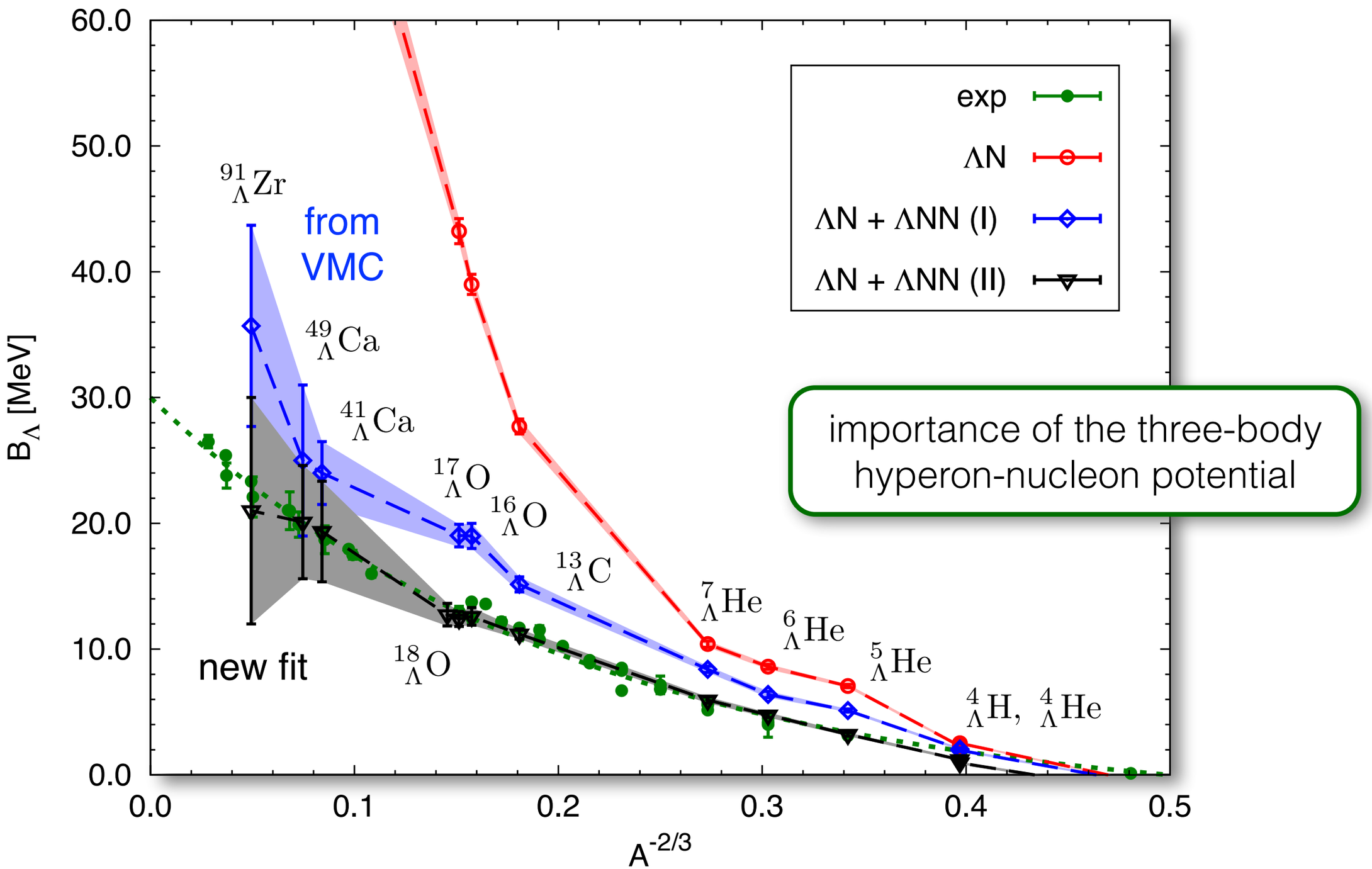

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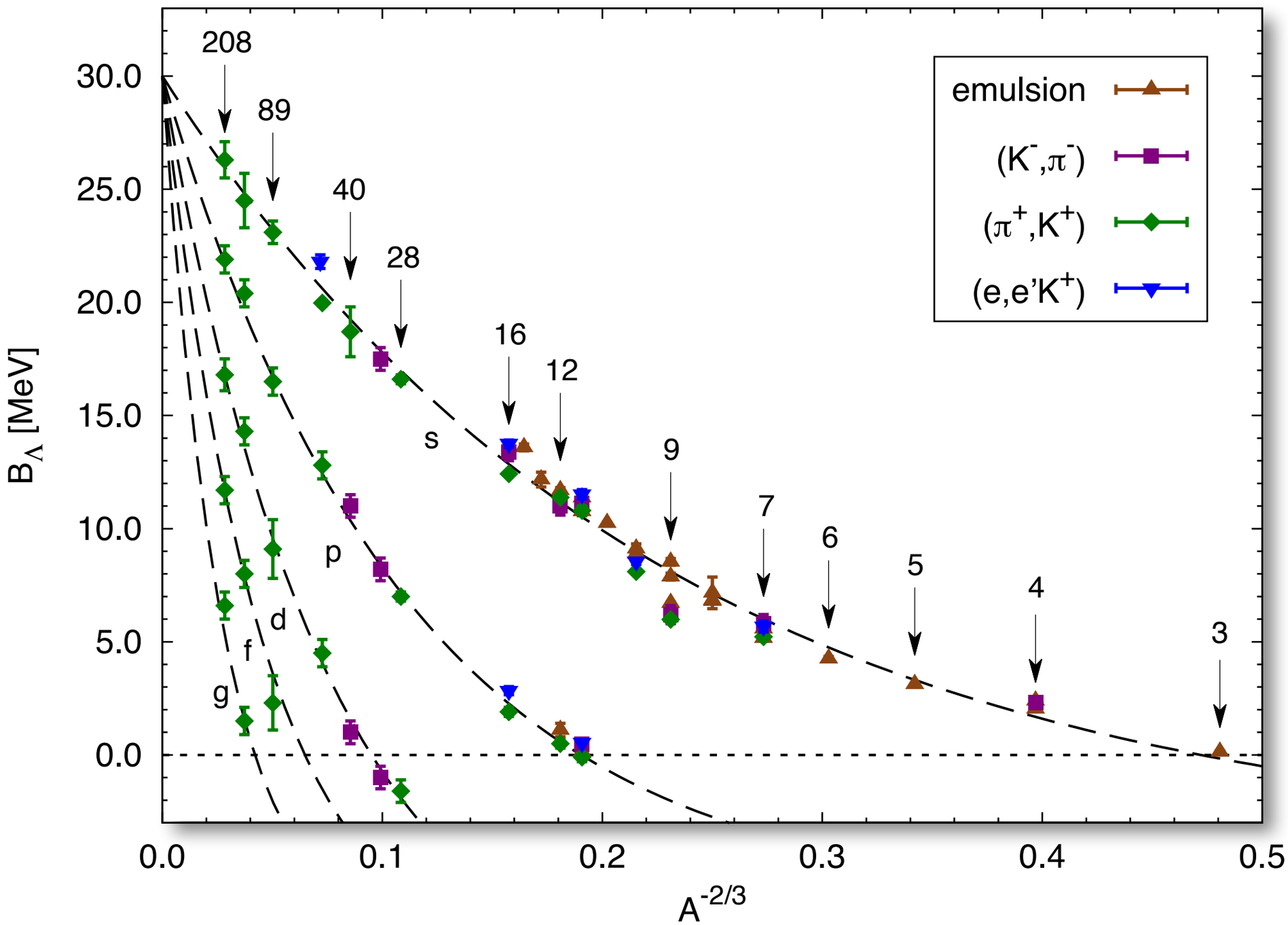
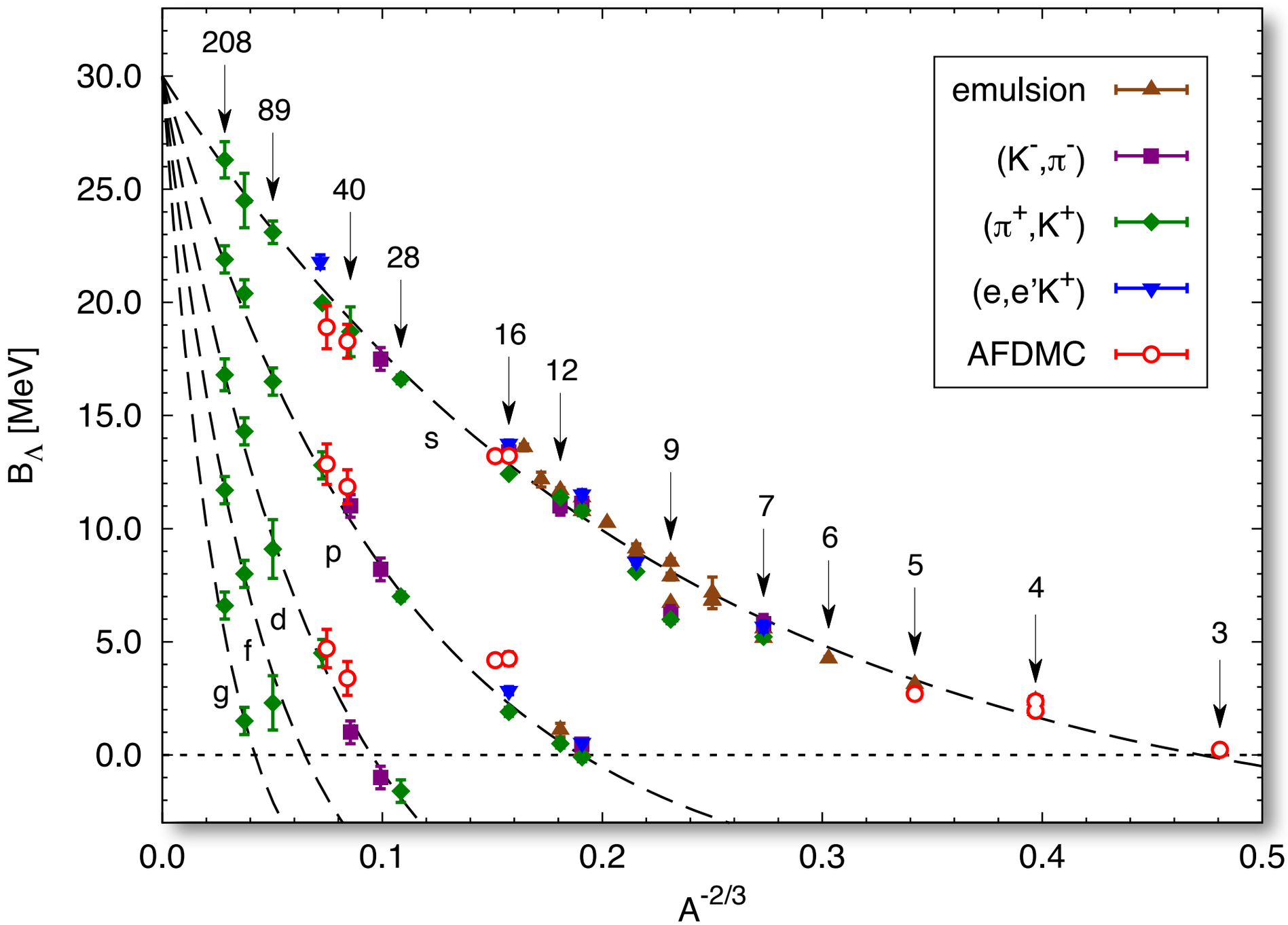


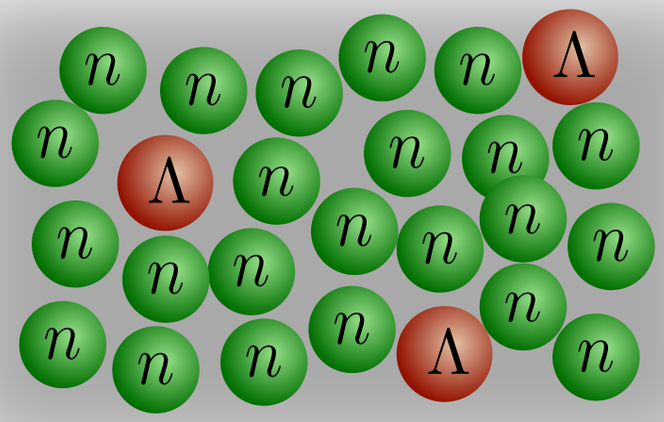
D. L., S. Gandolfi, F. Pederiva, in preparation

Results: hypernuclei



D. L., S. Gandolfi, F. Pederiva, in preparation

Results: hyper-neutron matter



hyper-neutron matter

PNM → hyperon fraction → energy per particle

equilibrium condition: chemical potentials

$$\mu_\Lambda(\rho_b, x_\Lambda) = \mu_n(\rho_b, x_\Lambda)$$

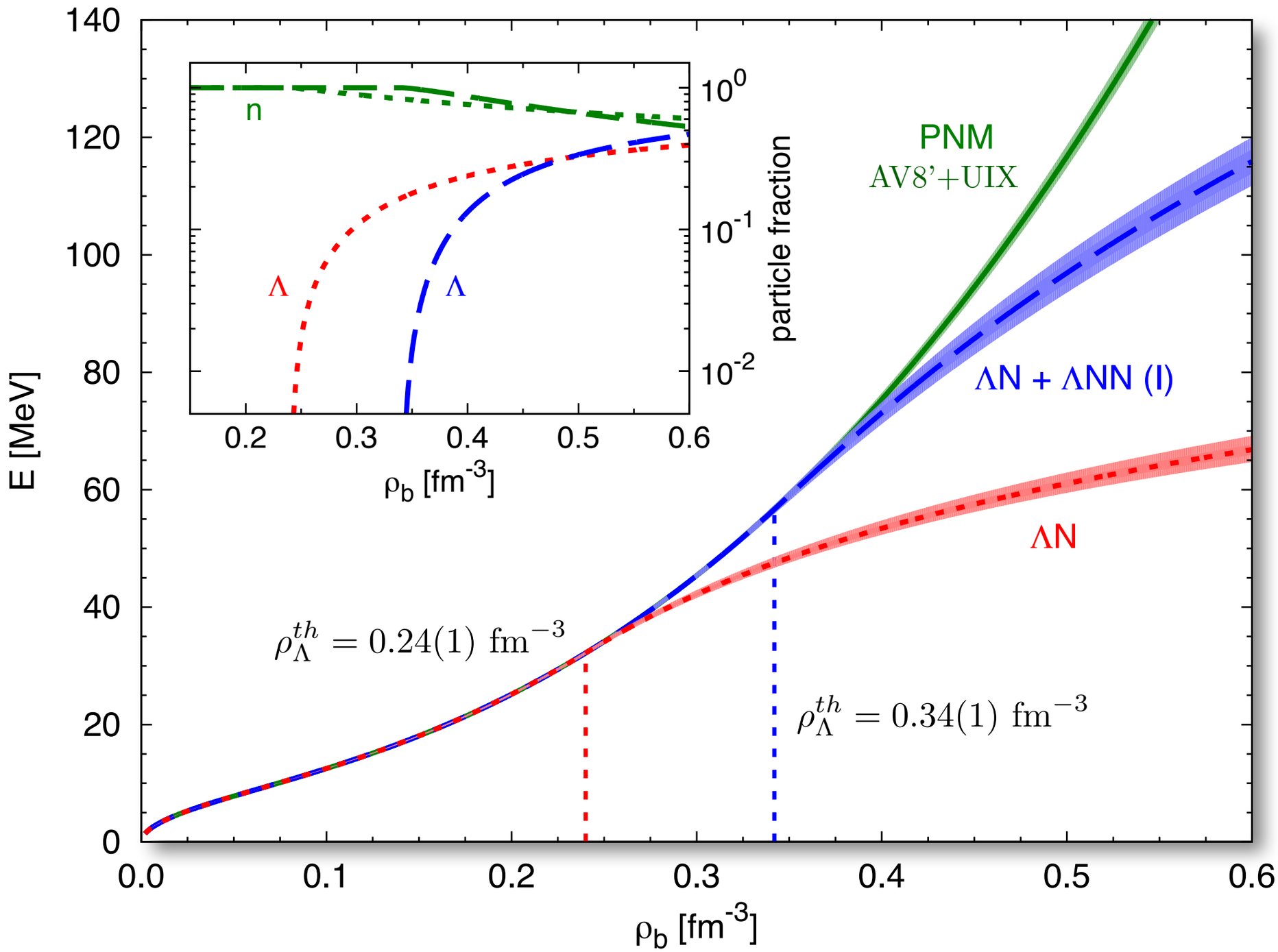
$$\Rightarrow \quad x_\Lambda \equiv x_\Lambda(\rho_b)$$

EoS
$$\begin{cases} E_{\rm HNM} & \equiv & E_{\rm HNM}(\rho_b) \\ \mathcal{E}_{\rm HNM} & \equiv & \mathcal{E}_{\rm HNM}(\rho_b) \\ P_{\rm HNM} & \equiv & P_{\rm HNM}(\rho_b) \end{cases}$$

$\Rightarrow$ TOV
$$\begin{cases} M(R) \\ M_{\rm max} \end{cases}$$

AFDMC: neutrons + lambdas → $E_{\rm HNM} \equiv E_{\rm HNM}(\rho_b, x_\Lambda)$

Results: hyper-neutron matter



D. L., A. Lovato, S. Gandolfi, F. Pederiva, arXiv:1407.4448 [nucl-th] (2014), submitted to Phys. Rev. Lett.

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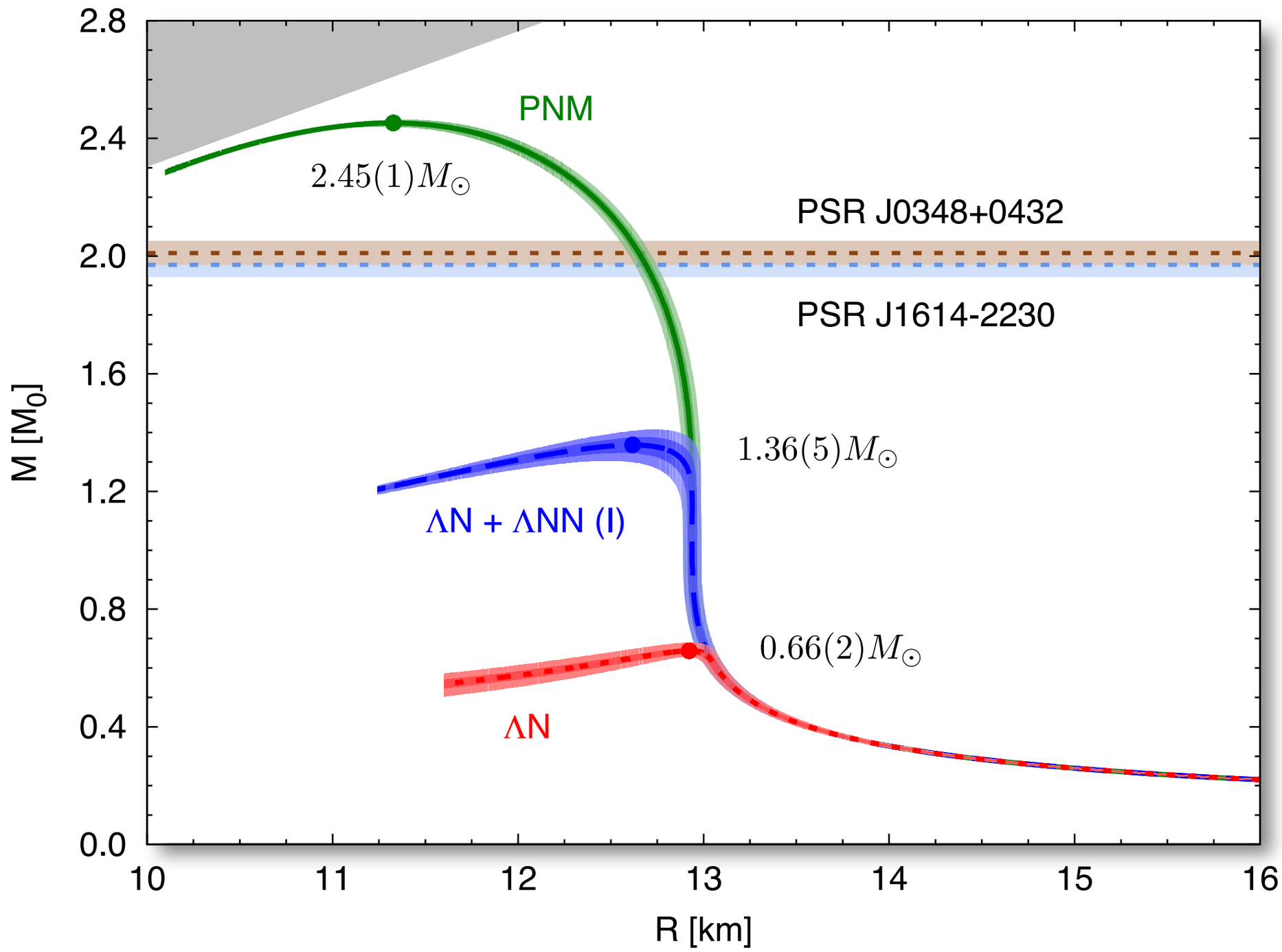

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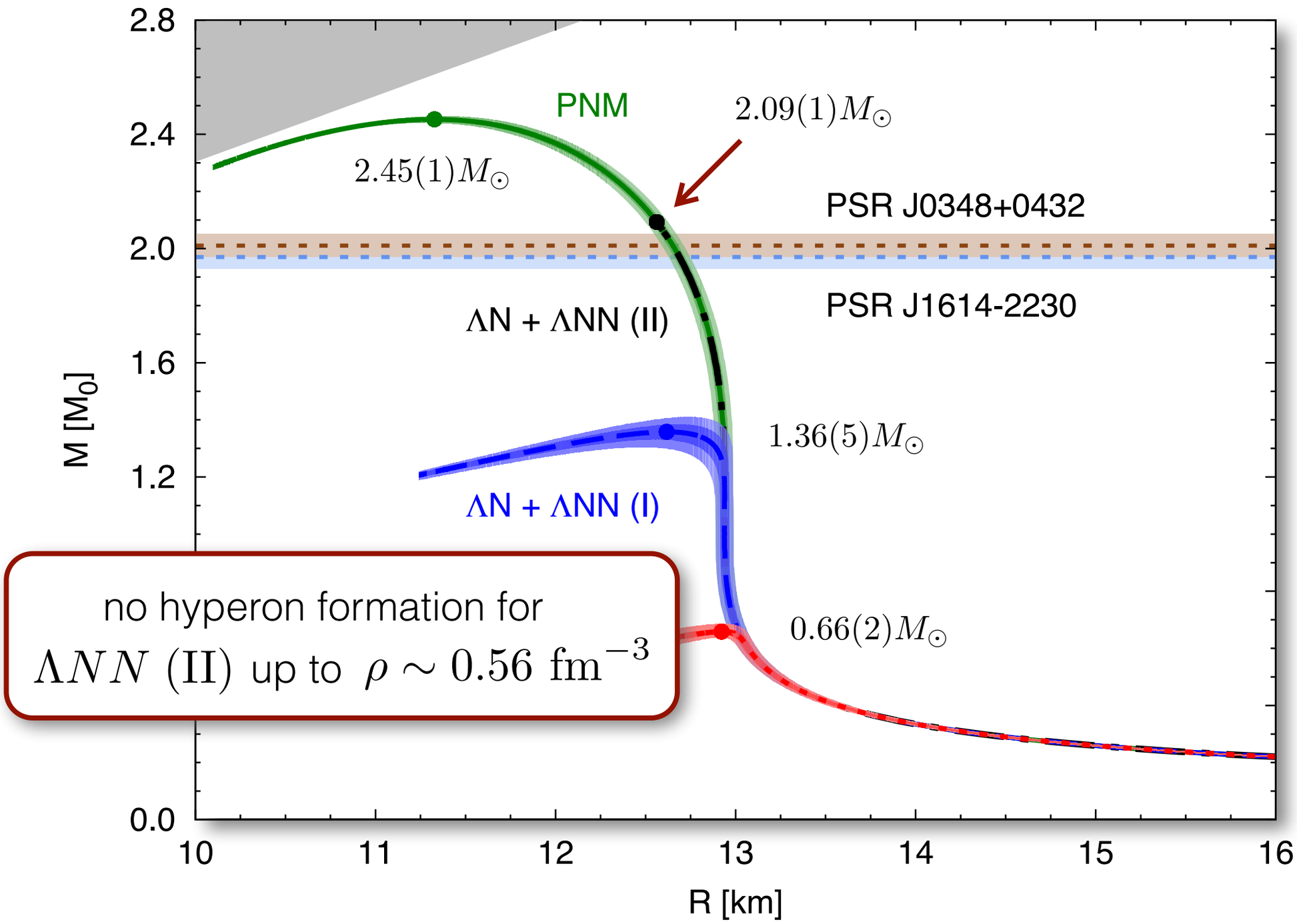

no hyperon formation for
ΛNN (II) up to $\rho \sim 0.56$ fm^{-3}

D. L., A. Lovato, S. Gandolfi, F. Pederiva, arXiv:1407.4448 [nucl-th] (2014), submitted to Phys. Rev. Lett.

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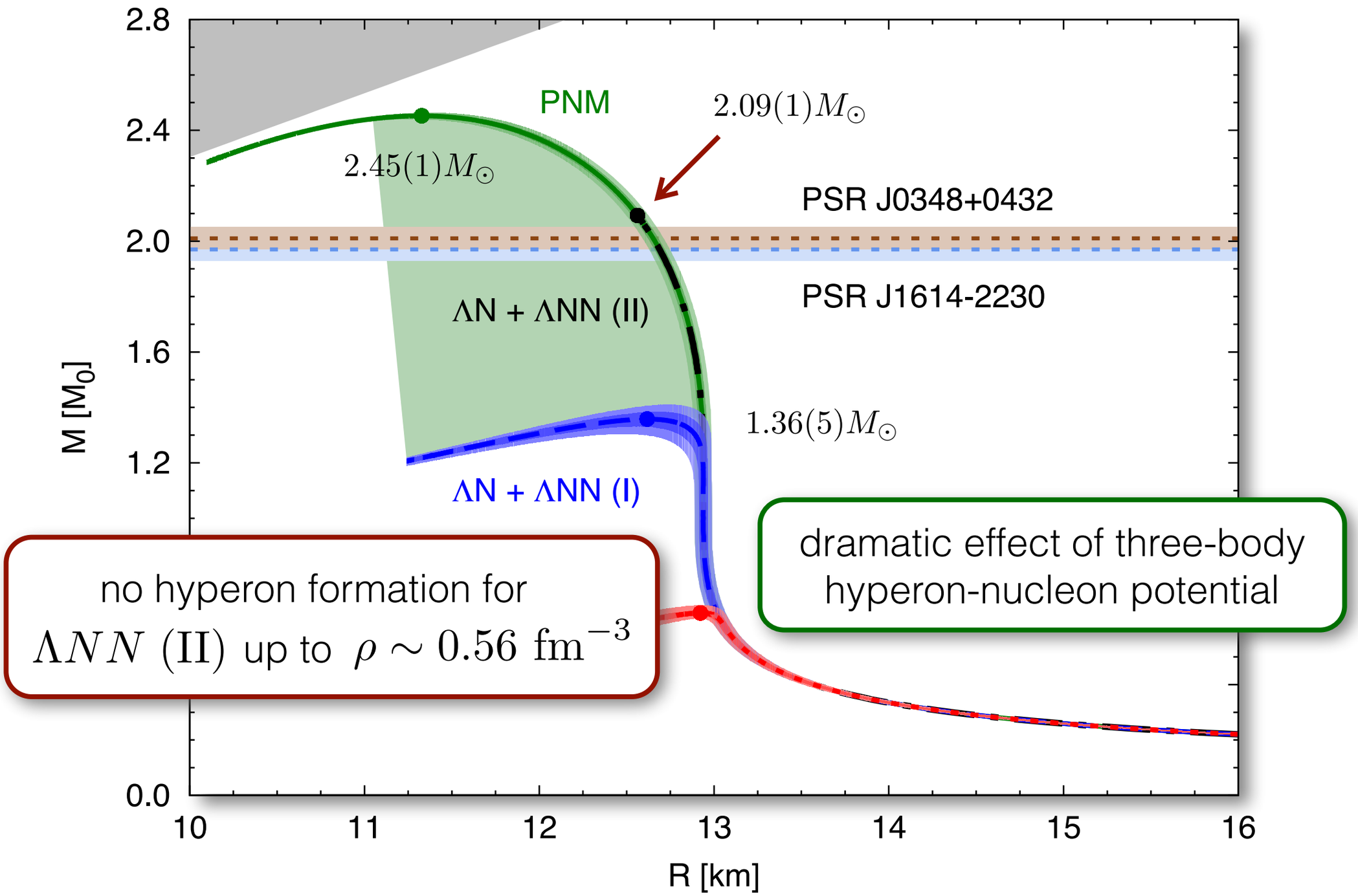

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Conclusions & Perspectives

- ✓ Status
  - development of a Quantum Monte Carlo algorithm for hypernuclear systems
  - the three-body hyperon-nucleon interaction plays a fundamental role in both finite and infinite hypernuclear systems
  - more constraints on the nature of hyperon-neutron forces are needed before drawing any conclusion on the role played by hyperons in neutron stars
  - *hyperon puzzle* still not solved

- ✓ Needs & Developments
  - experimental inputs: scattering data, energy spectrum (gs+exc), CSB effect, exotic neutron rich hypersystems
  - NN(N) and YN(N) different potentials: Nijmegen, chiral, (isospin projected)
  - benchmark calculations
  - realistic (hyper)nuclear matter in beta equilibrium