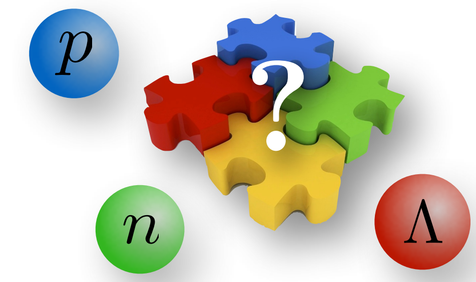
From hypernuclei to neutron stars: looking for the pieces of the puzzle



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- ✓ Alessandro Lovato, ANL
- ✓ Stefano Gandolfi, LANL
- ✓ Francesco Pederiva, Trento
- ✓ Francesco Catalano, Trento

Argonne NATIONAL LABORATORY

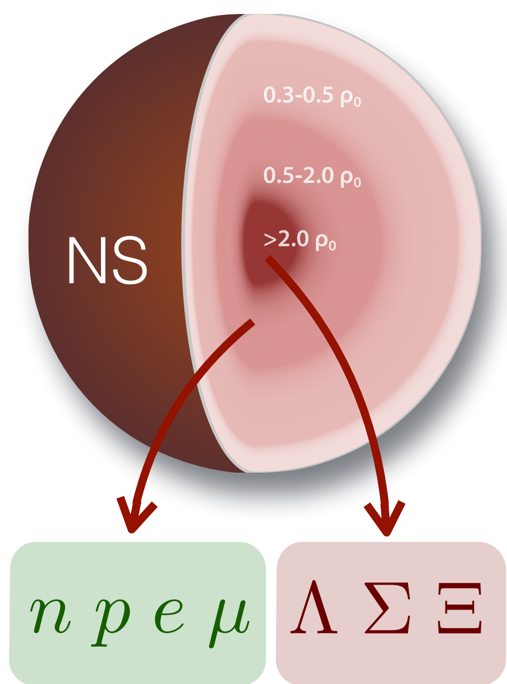
NUCLEI Nuclear Computational Low-Energy Initiative

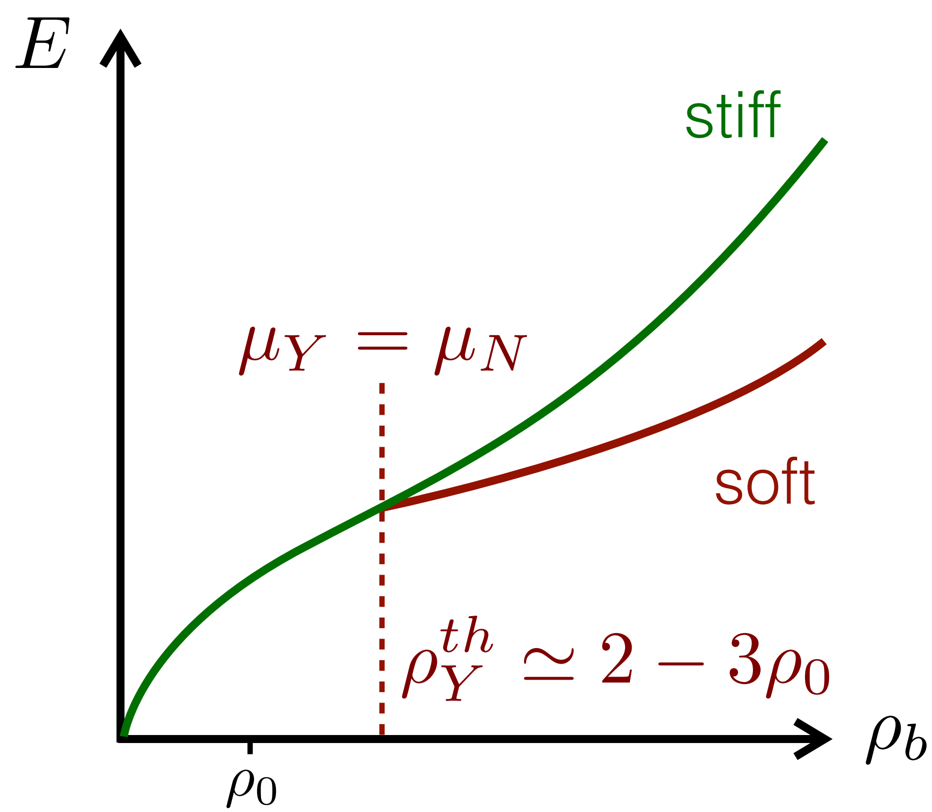
SciDAC Scientific Discovery through Advanced Computing

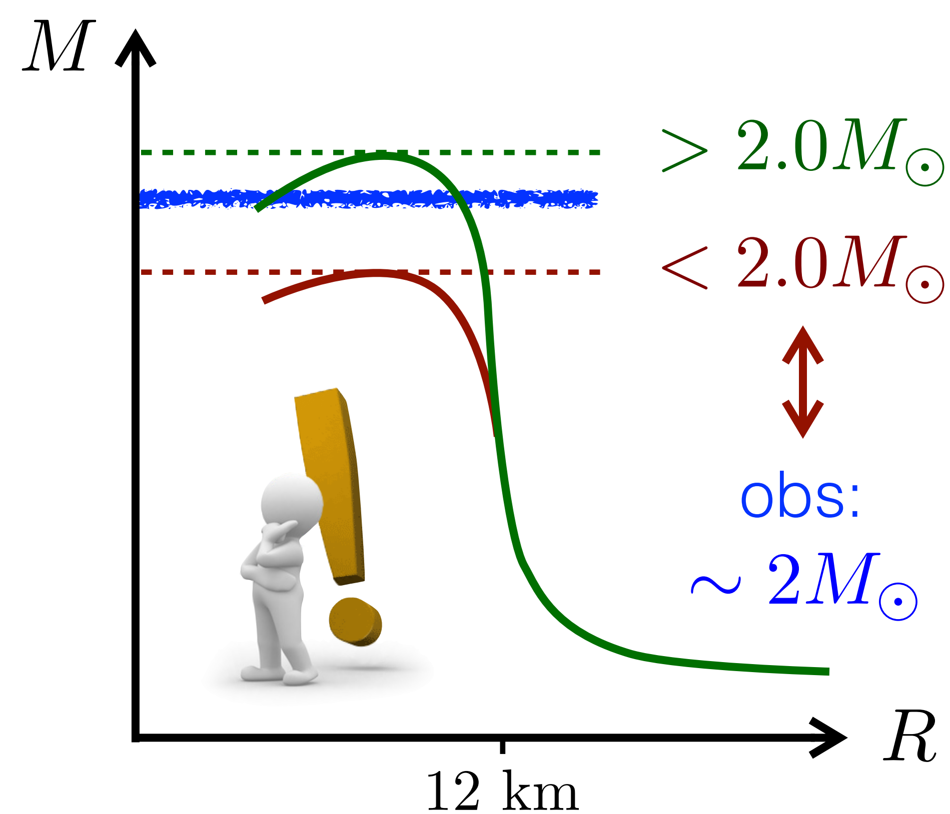
NERSC

HYP2015, September 8, 2015

Strangeness in neutron stars: the hyperon puzzle







Hyperon puzzle

- ✓ Indication for the appearance of hyperons in NS core
- ✓ Apparent inconsistency between theoretical calculations and observations

Quantum Monte Carlo → YN interaction

Strangeness in QMC calculations

Quantum Monte Carlo (Auxiliary Field Diffusion Monte Carlo)

$$-\frac{\partial}{\partial\tau}|\psi(\tau)\rangle = (H - E_0)|\psi(\tau)\rangle \qquad \tau = it/\hbar \quad \text{imaginary time}$$

$$|\psi(\tau)\rangle = e^{-(H-E_0)\tau}|\psi(0)\rangle \xrightarrow{\tau\to\infty} c_0|\varphi_0\rangle \quad \text{projection}$$

✓ nucleon-nucleon phenomenological interaction: Argonne & Urbana

$$H = \sum_i \frac{p_i^2}{2m_N} + \sum_{i<j} v_{ij} + \sum_{i<j<k} v_{ijk}$$

2B: NN scattering + deuteron

3B: nuclei + nuclear matter

Strangeness in QMC calculations

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- ✓ nucleon-nucleon phenomenological interaction: Argonne & Urbana
- ✓ hyperon-nucleon phenomenological interaction: Argonne like

$$H = \sum_i \frac{p_i^2}{2m_N} + \sum_{i<j} v_{ij} + \sum_{i<j<k} v_{ijk}$$

$$+ \sum_\lambda \frac{p_\lambda^2}{2m_\Lambda} + \sum_{\lambda,i} v_{\lambda i} + \sum_{\lambda,i<j} v_{\lambda ij}$$

2B: Λp scattering + $A = 4$ CSB*

3B: no unique fit

Strangeness in QMC calculations

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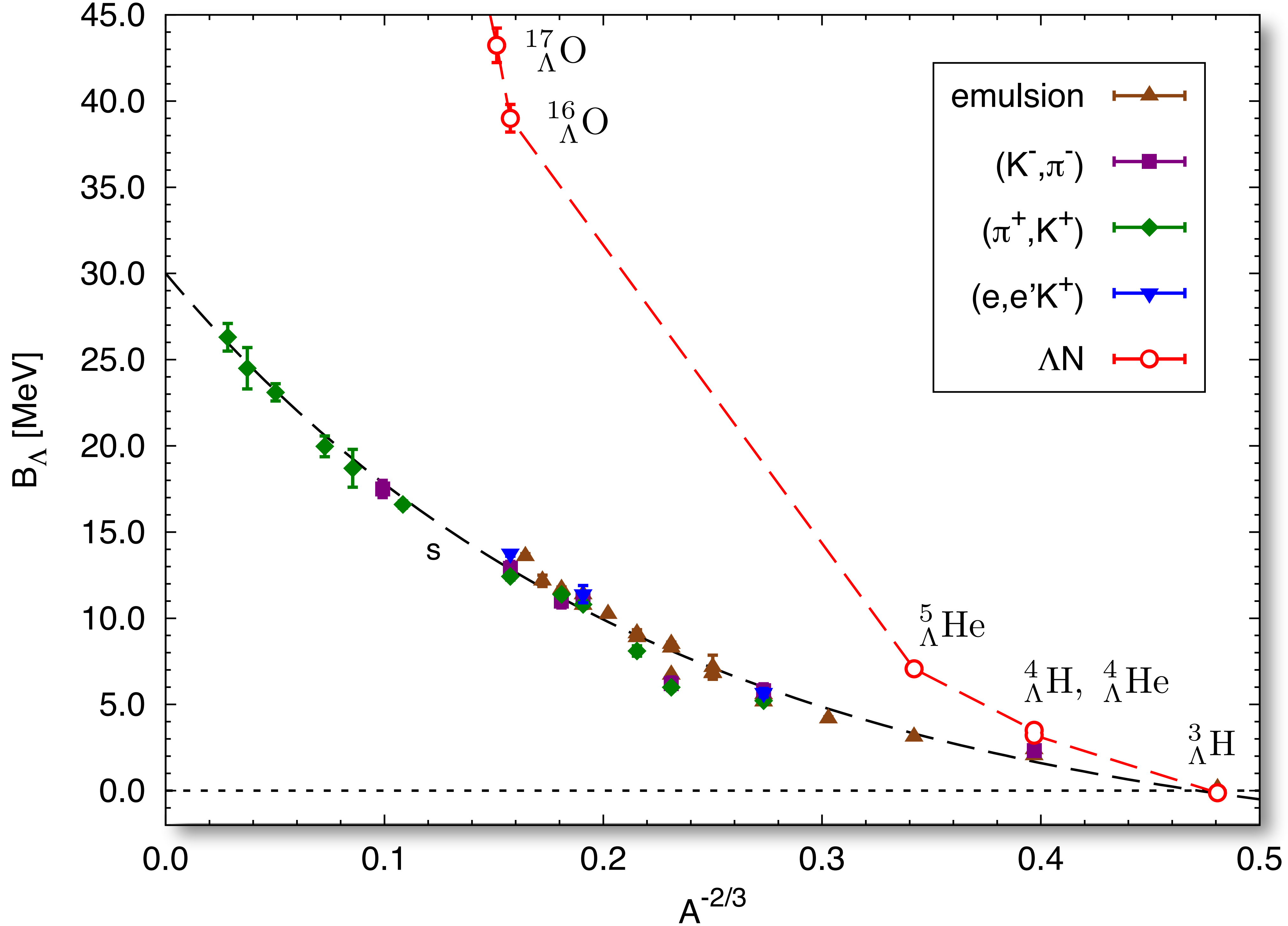
$$+ \sum_\lambda \frac{p_\lambda^2}{2m_\Lambda} + \sum_{\lambda,i} v_{\lambda i} + \sum_{\lambda,i<j} v_{\lambda ij}$$

use QMC to fit hyp. exp. data

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

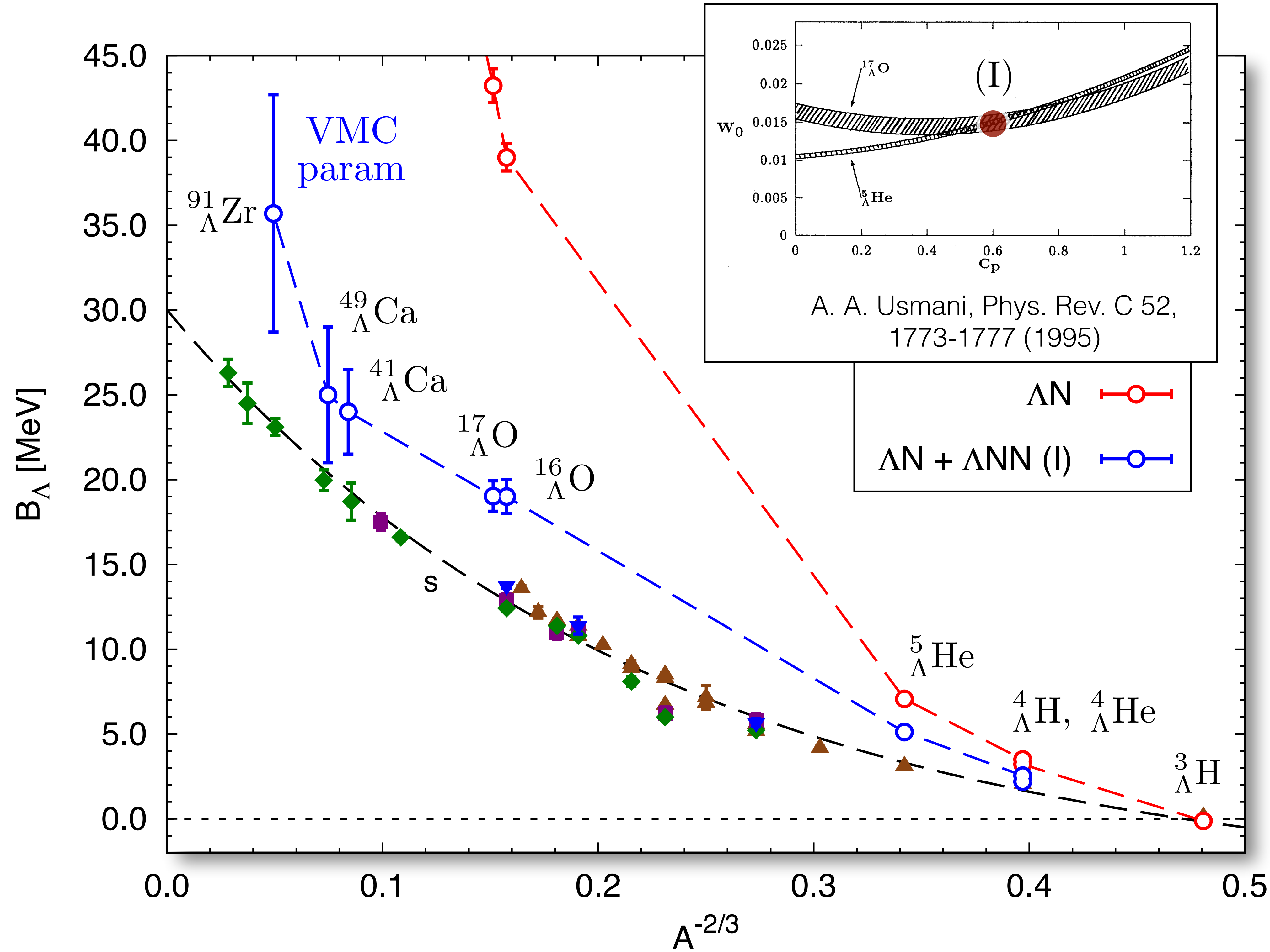
3B: no unique fit

Strangeness in nuclei



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

Strangeness in nuclei



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

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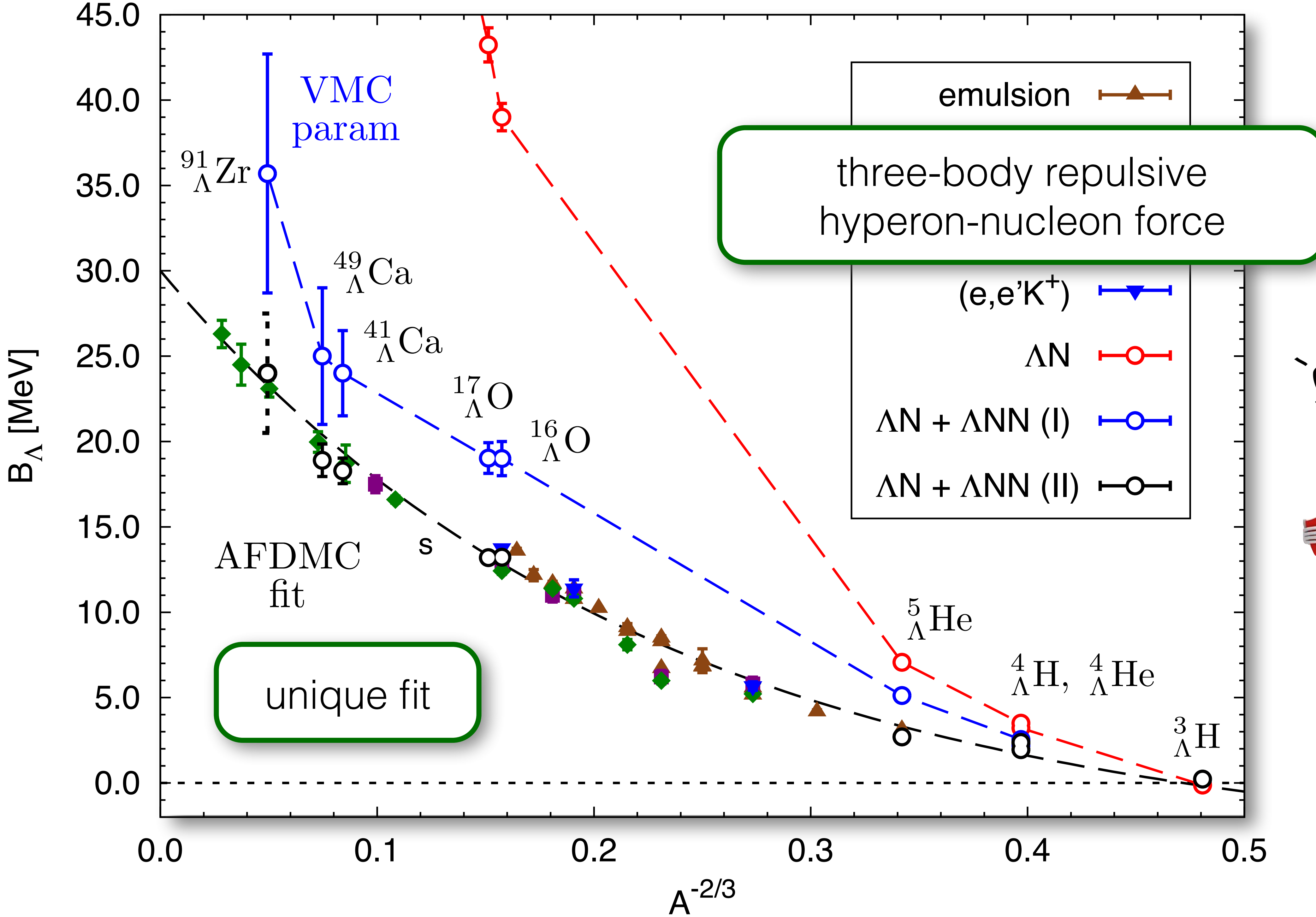
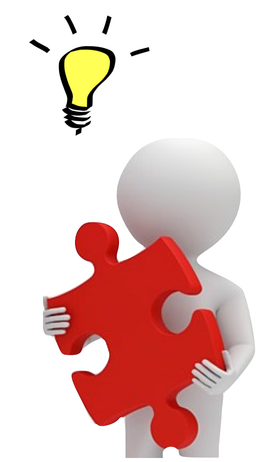
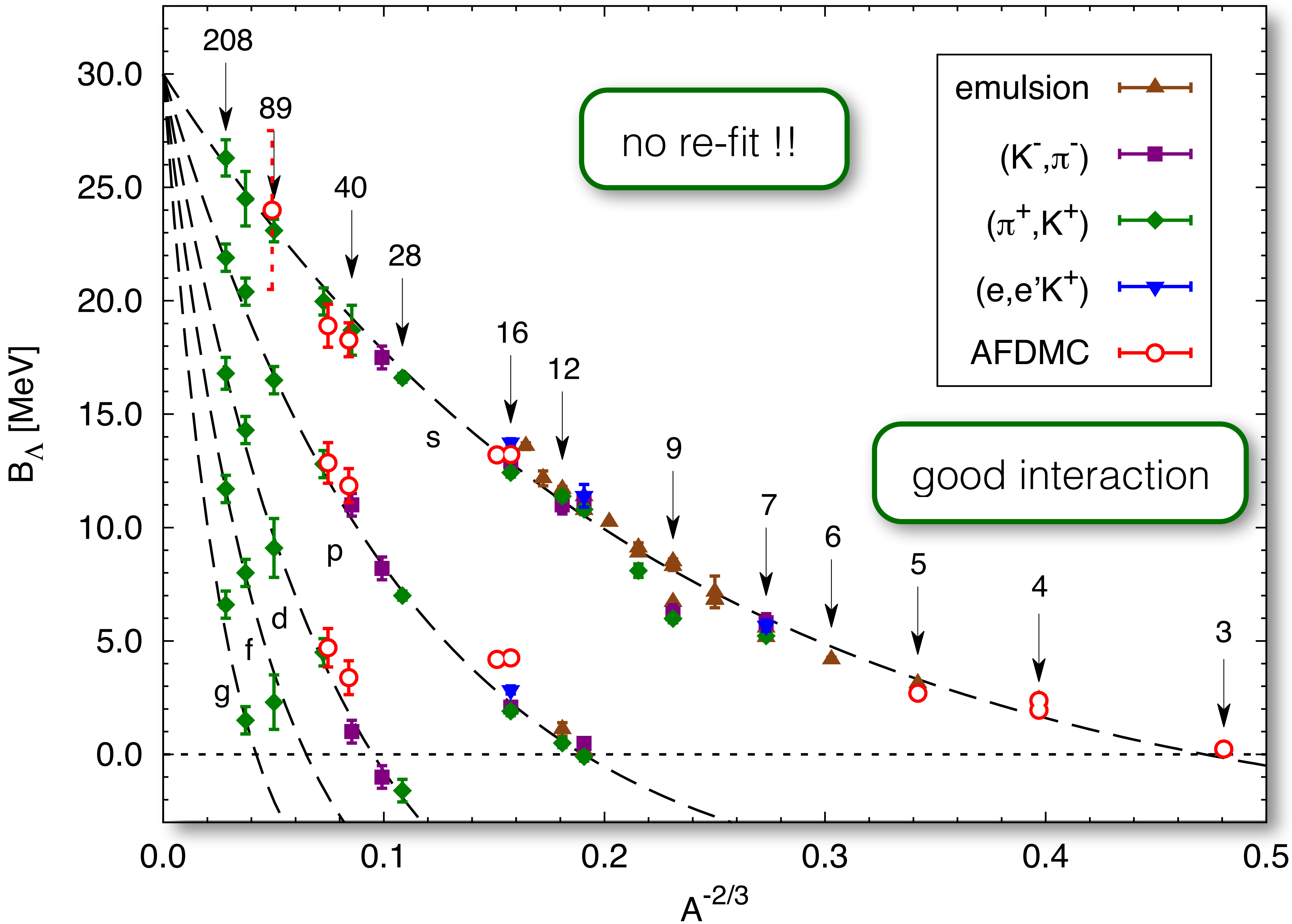


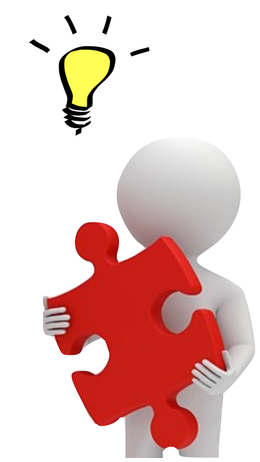


D. L., F. Pederiva, S. Gandolfi, Phys. Rev. C 89, 014314 (2014)

F. Pederiva, F. Catalano, D. L., A. Lovato, S. Gandolfi, arXiv:1506.04042 (2015)

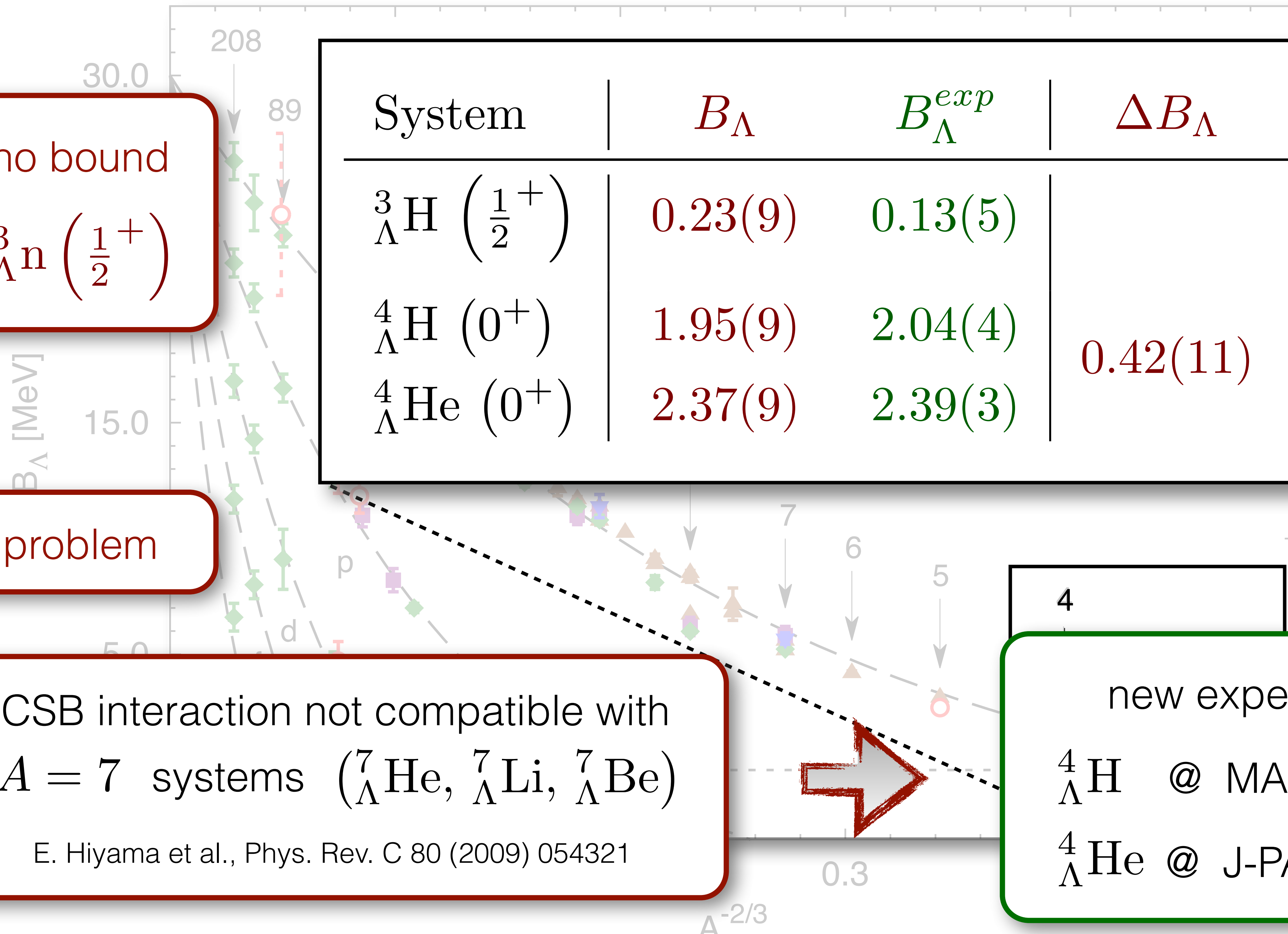
Strangeness in nuclei





F. Pederiva, F. Catalano, D. L., A. Lovato, S. Gandolfi, arXiv:1506.04042 (2015)

Strangeness in nuclei: light



System	B_Λ	B_Λ^{exp}	ΔB_Λ	ΔB_Λ^{exp}
${}^{3}_{\Lambda}\mathrm{H}\ \left(\frac{1}{2}^{+}\right)$	0.23(9)	0.13(5)		
${}^{4}_{\Lambda}\mathrm{H}\ (0^{+})$	1.95(9)	2.04(4)	0.42(11)	0.35(6)
${}^{4}_{\Lambda}\mathrm{He}\ (0^{+})$	2.37(9)	2.39(3)		

no bound

${}^{3}_{\Lambda}\mathrm{n}\ \left(\frac{1}{2}^{+}\right)$

problem

CSB interaction not compatible with

$A = 7$ systems $\left({}^{7}_{\Lambda}\mathrm{He},\ {}^{7}_{\Lambda}\mathrm{Li},\ {}^{7}_{\Lambda}\mathrm{Be}\right)$

E. Hiyama et al., Phys. Rev. C 80 (2009) 054321

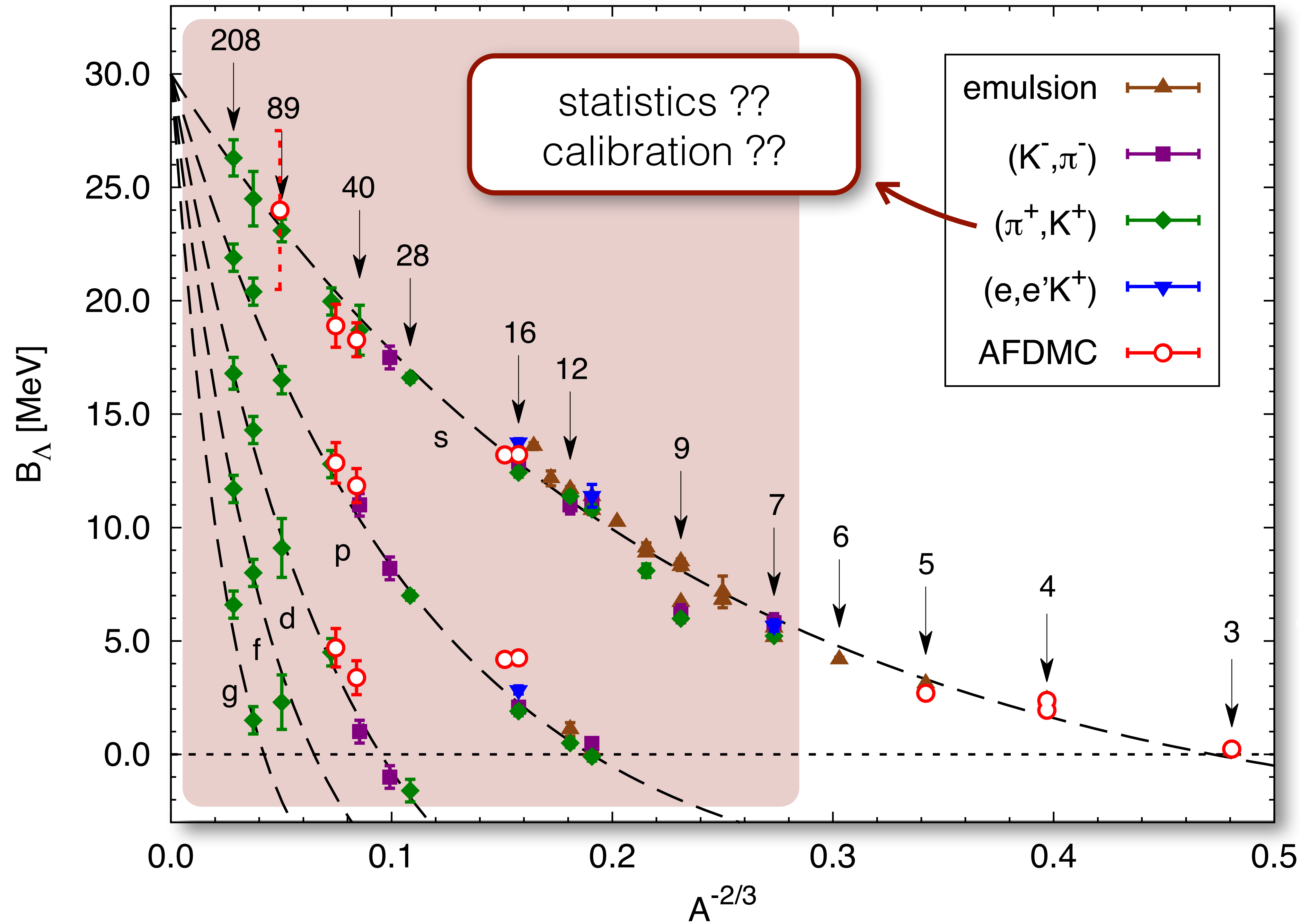
new experiments:

${}^{4}_{\Lambda}\mathrm{H}$ @ MAMI, JLab

${}^{4}_{\Lambda}\mathrm{He}$ @ J-PARC

D. L., A. Lovato, S. Gandolfi, F. Pederiva, arXiv:1508.04722 (2015)

Strangeness in nuclei: medium-heavy



F. Pederiva, F. Catalano, D. L., A. Lovato, S. Gandolfi, arXiv:1506.04042 (2015)

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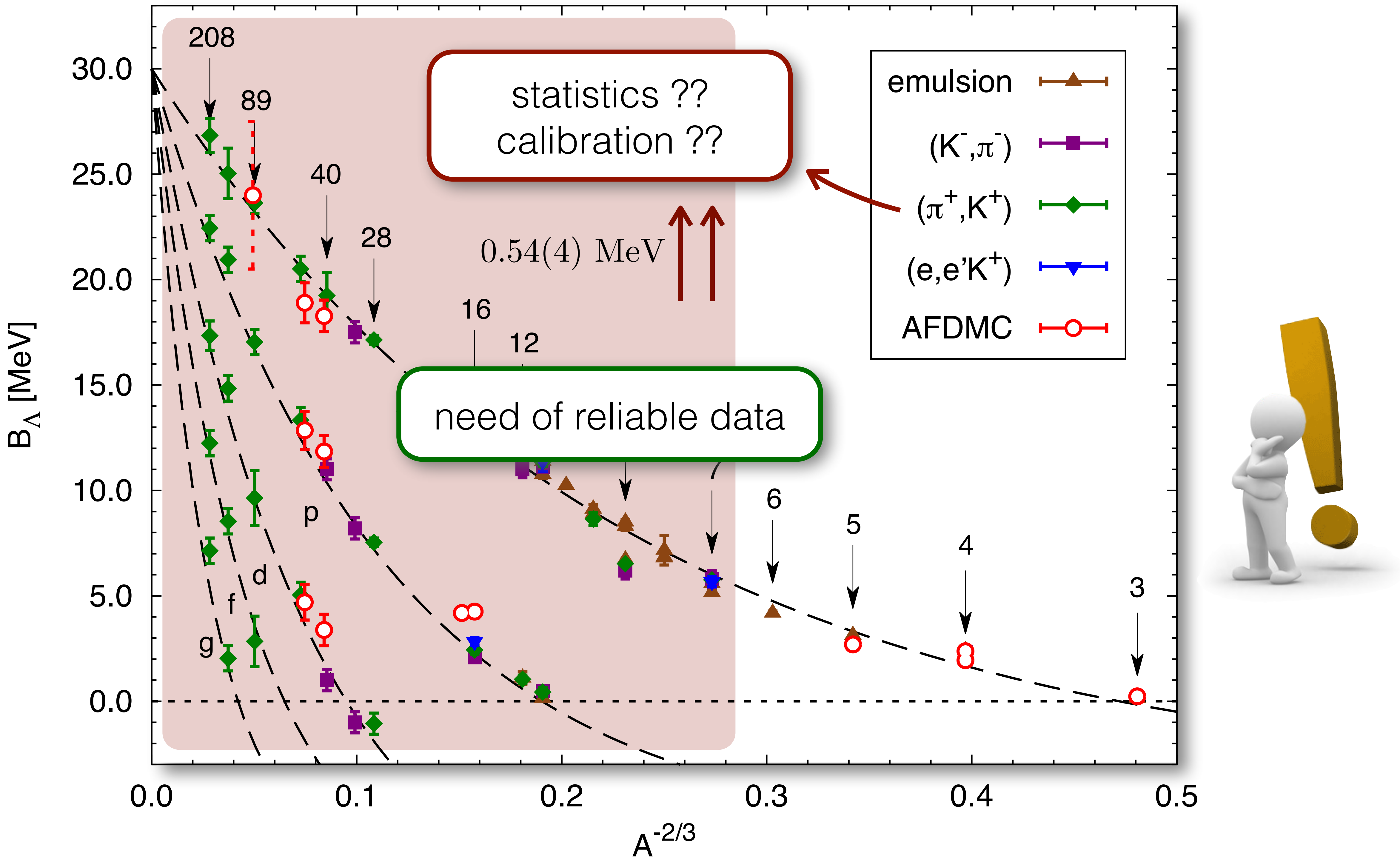
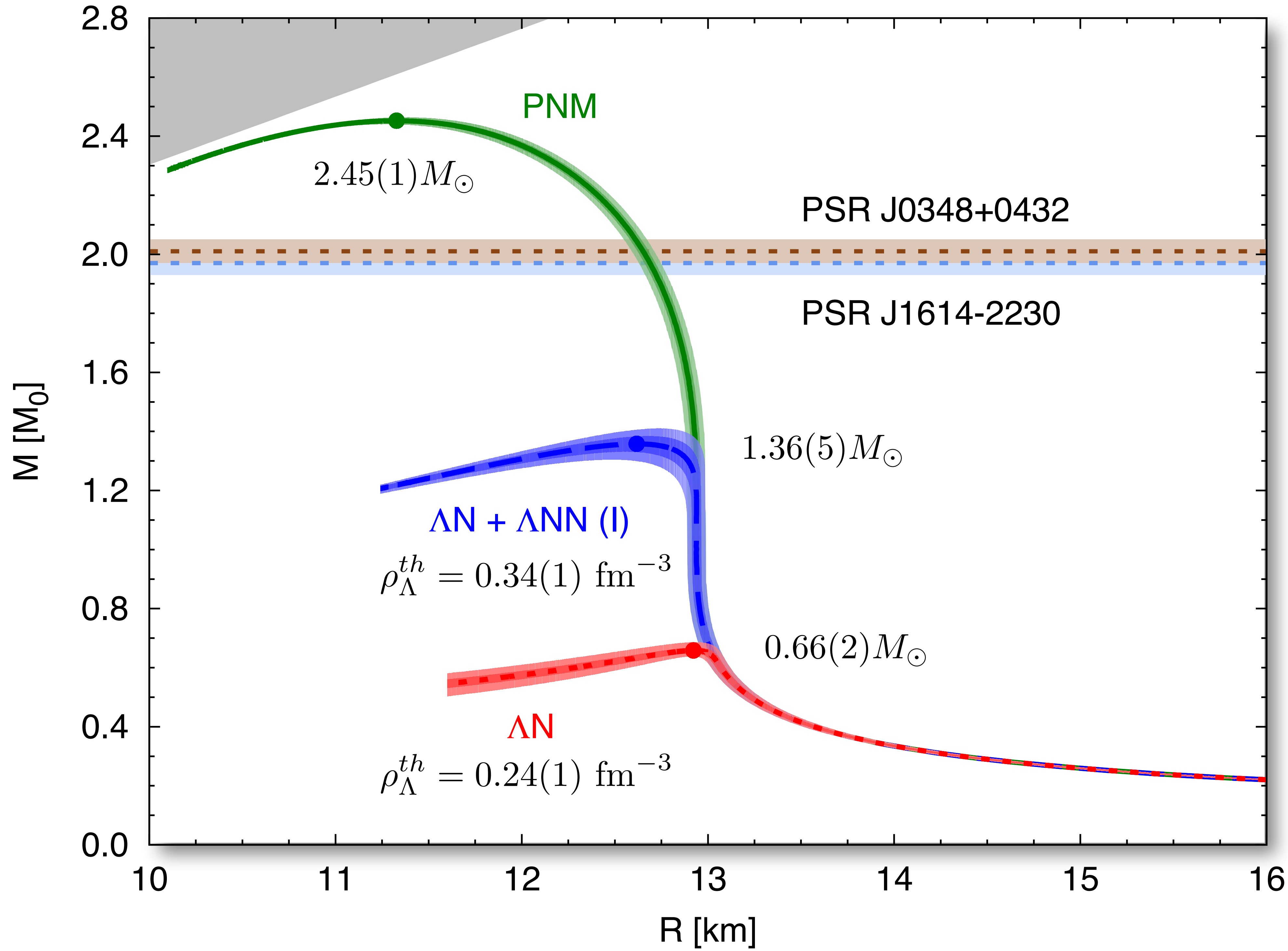


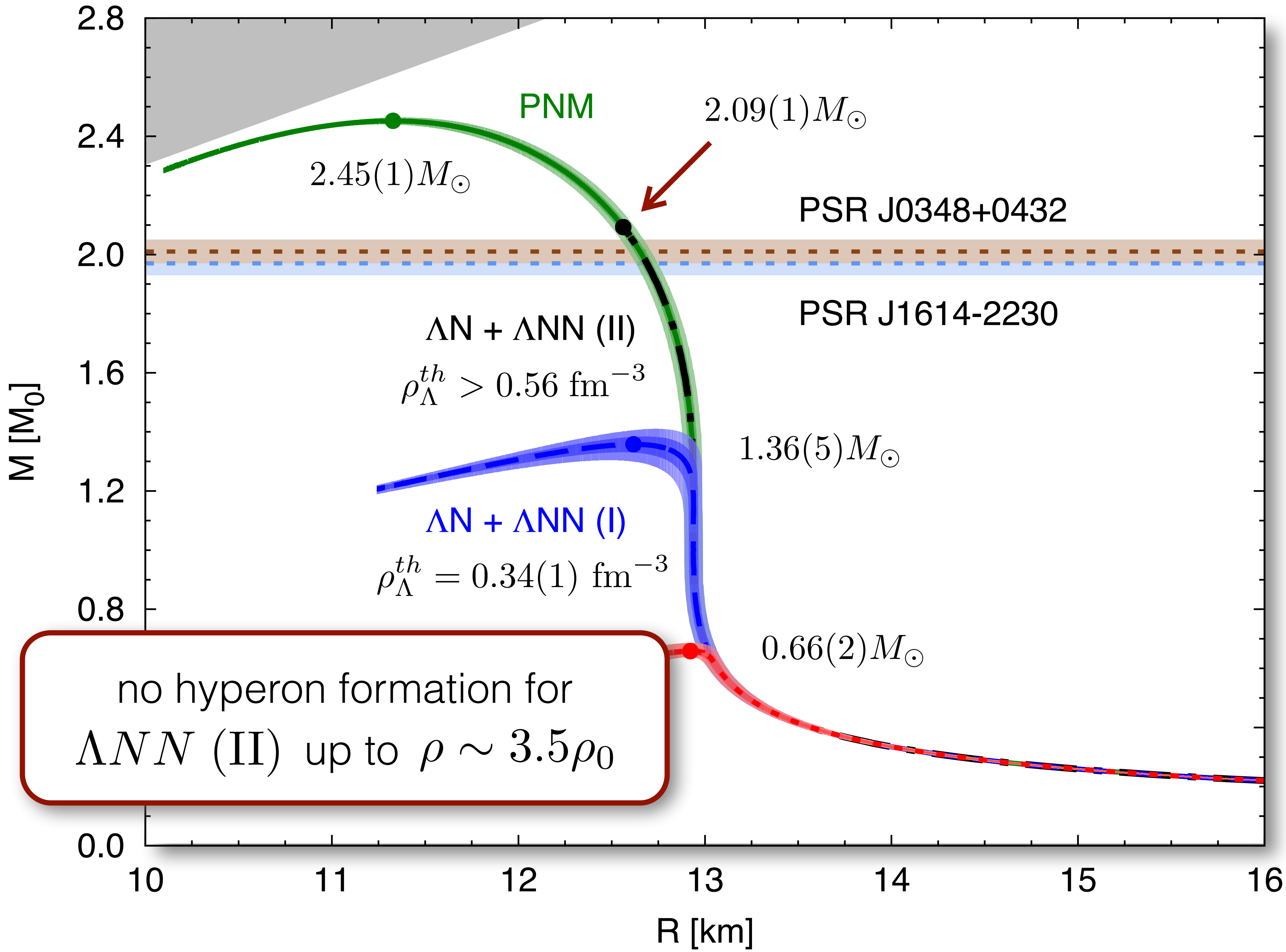
F. Pederiva, F. Catalano, D. L., A. Lovato, S. Gandolfi, arXiv:1506.04042 (2015)
S. N. Nakamura & T. Gogami talks

Strangeness in neutron stars



D. L., A. Lovato, S. Gandolfi, F. Pederiva, Phys. Rev. Lett. 114, 092301 (2015)

Strangeness in neutron stars



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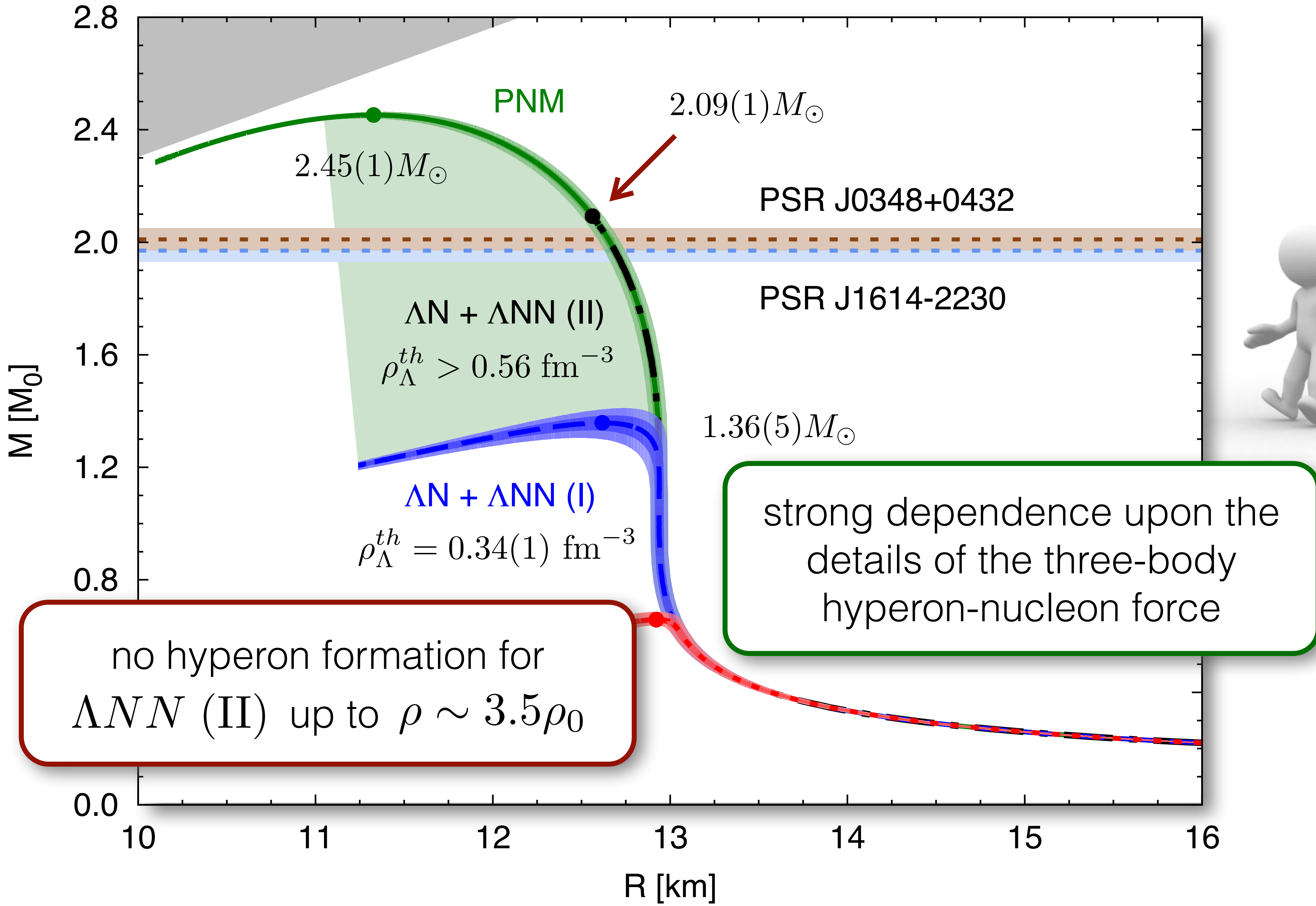


D. L., A. Lovato, S. Gandolfi, F. Pederiva, Phys. Rev. Lett. 114, 092301 (2015)

Strangeness in nuclei

3-body interaction → fit on symmetric hypernuclei

ΛNN force: no dependence on singlet or triplet nucleon isospin state

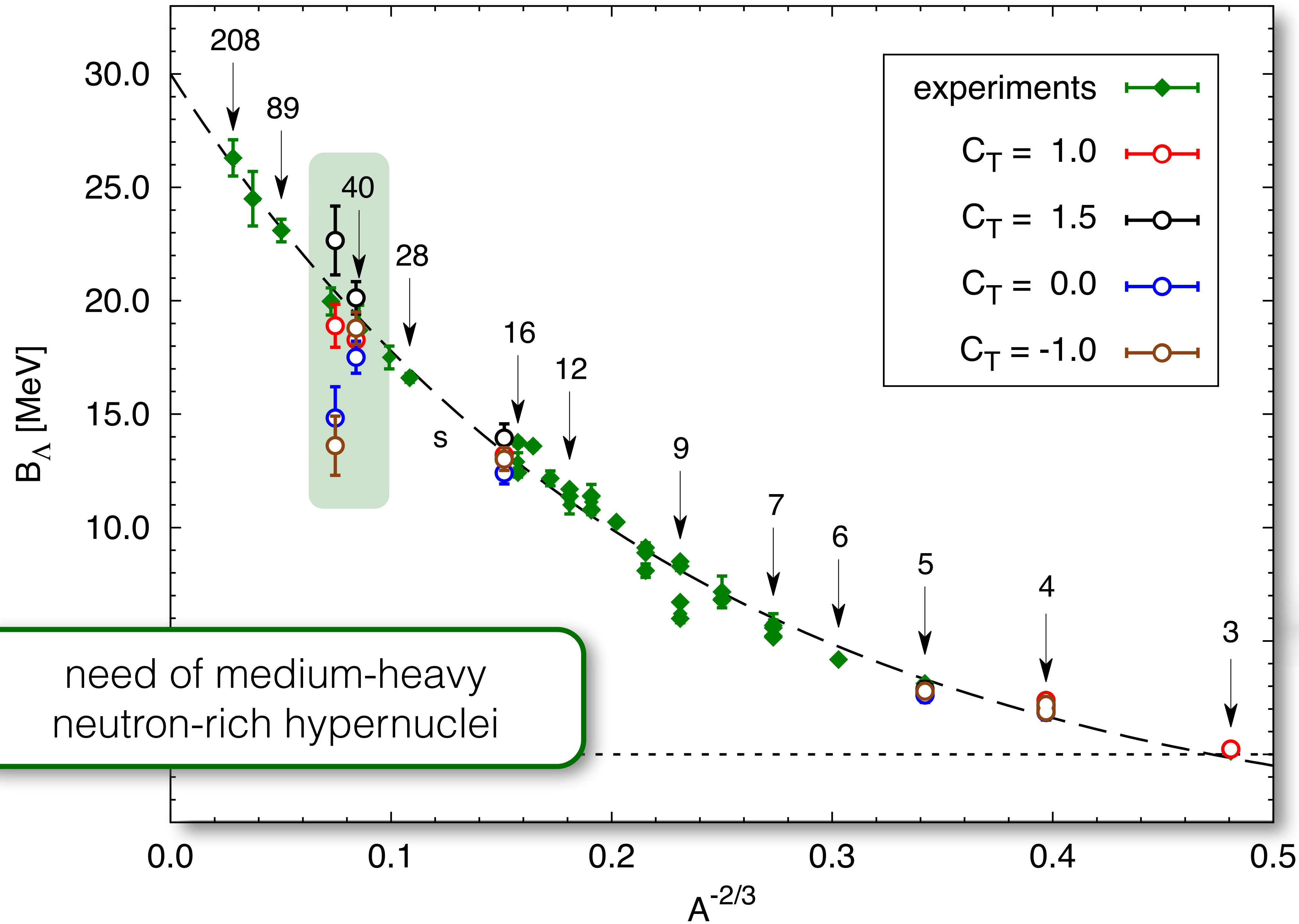
$$\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j = -3\,\mathcal{P}^{T=0} + \mathcal{P}^{T=1} \quad \longrightarrow \quad -3\,\mathcal{P}^{T=0} + C_T\,\mathcal{P}^{T=1}$$

isospin projectors

control parameter:
strength and sign of the nucleon isospin triplet channel

sensitivity study:
light- & medium-heavy hypernuclei

Strangeness in nuclei



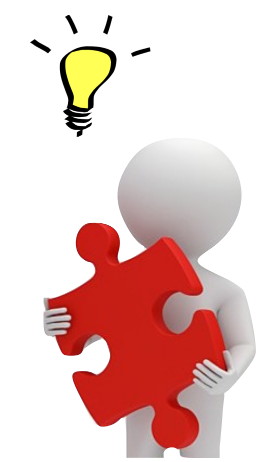
need of medium-heavy neutron-rich hypernuclei

F. Pederiva, F. Catalano, D. L., A. Lovato, S. Gandolfi, arXiv:1506.04042 (2015)

Conclusions

- ✓ The observation of massive neutron stars reopened the debate about the presence of hyperons in the inner core
  - no general agreement among theoretical calculations
  - hyperon puzzle not yet solved: new hints?

- ✓ We developed a quantum Monte Carlo algorithm to study finite and infinite hypernuclear systems:
  - a repulsive three-body ΛNN force is needed to reproduce the experimental Λ separation energies for light- and medium-heavy hypernuclei
  - the predicted neutron star equation of state and maximum mass strongly depend upon the details of the three-body ΛNN force



- ✓ Need of more constraints on hypernuclear interactions before drawing conclusions on the role played by hyperons in neutron stars
  - accurate experimental investigation: medium-heavy neutron-rich hypernuclei
  - accurate theoretical investigation