Equation of state of Λ-neutron matter from QMC calculations

Francesco Pederiva

Physics Department - University of Trento
INFN - TIFPA, Trento Institute for Fundamental Physics and Applications

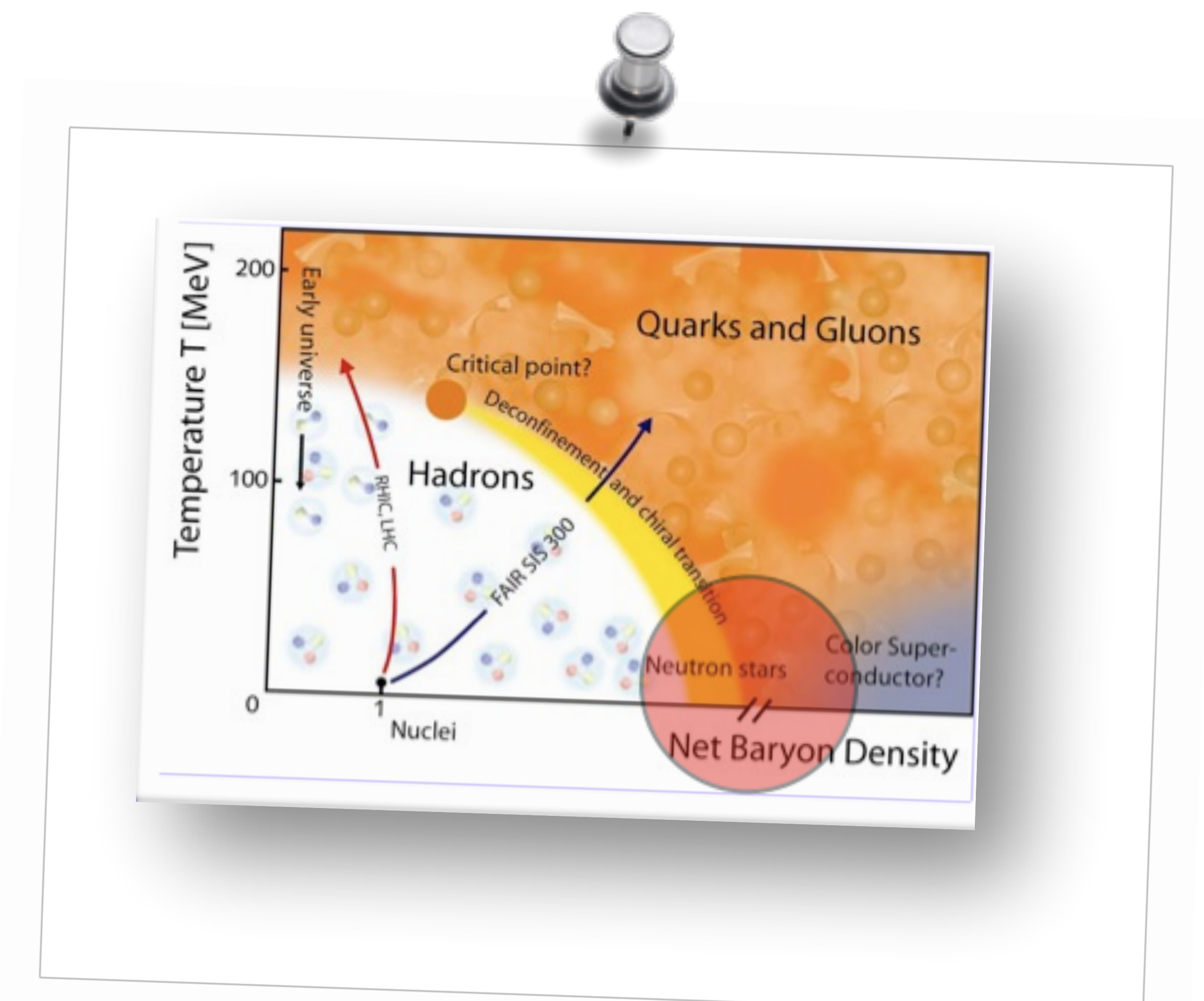
Collaborators

- Diego Lonardoni (ANL)
- Alessandro Lovato (ANL)
- Stefano Gandolfi (LANL)
- Francesco Catalano (Trento)

Strangeness in Nuclei & Neutron Stars, Pisa, May 20-21, 2015

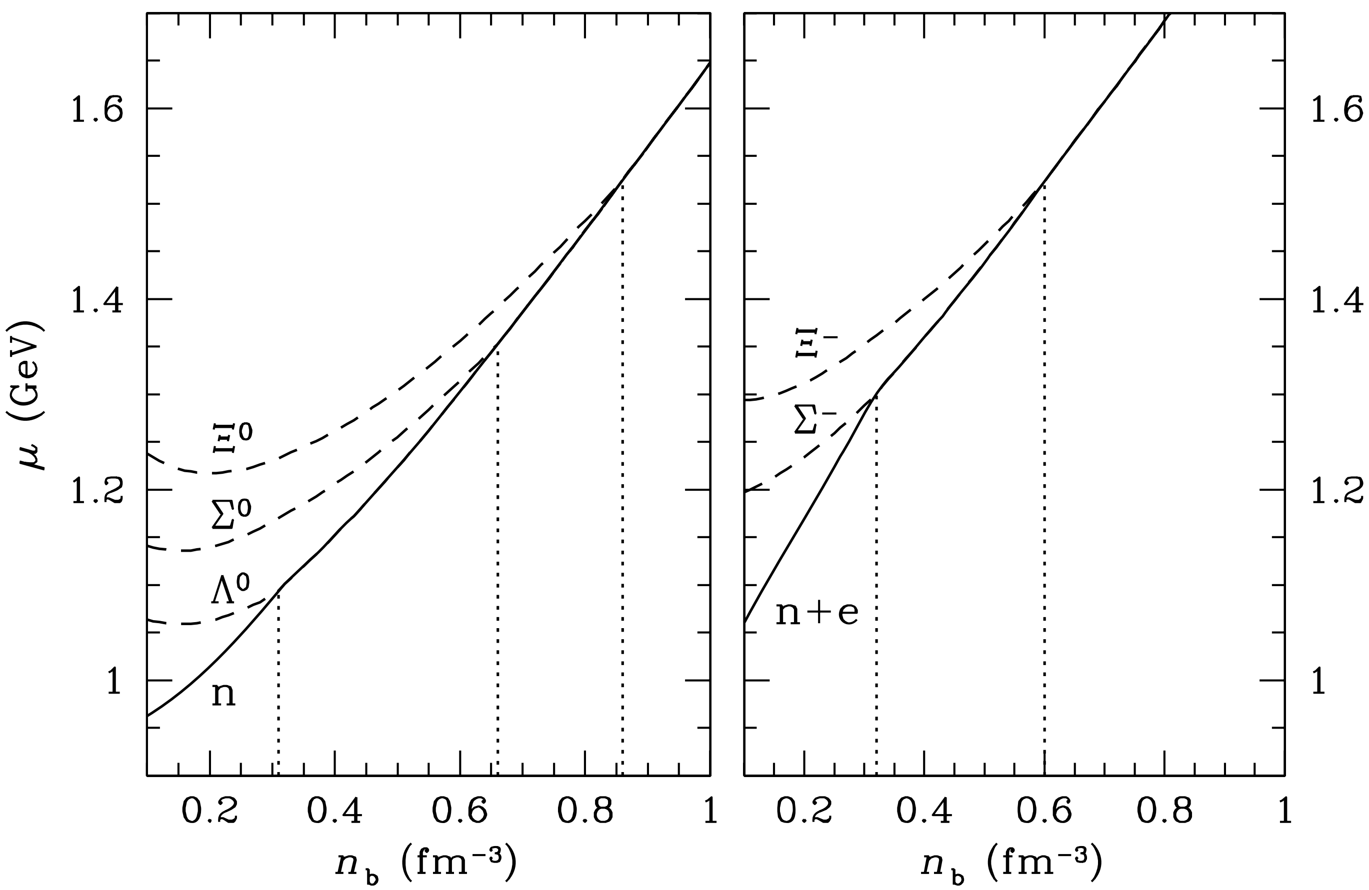
Outline

- The "hyperon puzzle" in neutron stars.
- A non-relativistic model of the hyperon(Λ)-nucleon interaction (for "normal" baryonic matter).
- Connection to the existing experimental data: computation of BE in hypernuclei by QMC.
- Infinite Λ-neutron matter and prediction for the NS structure.
- Conclusions



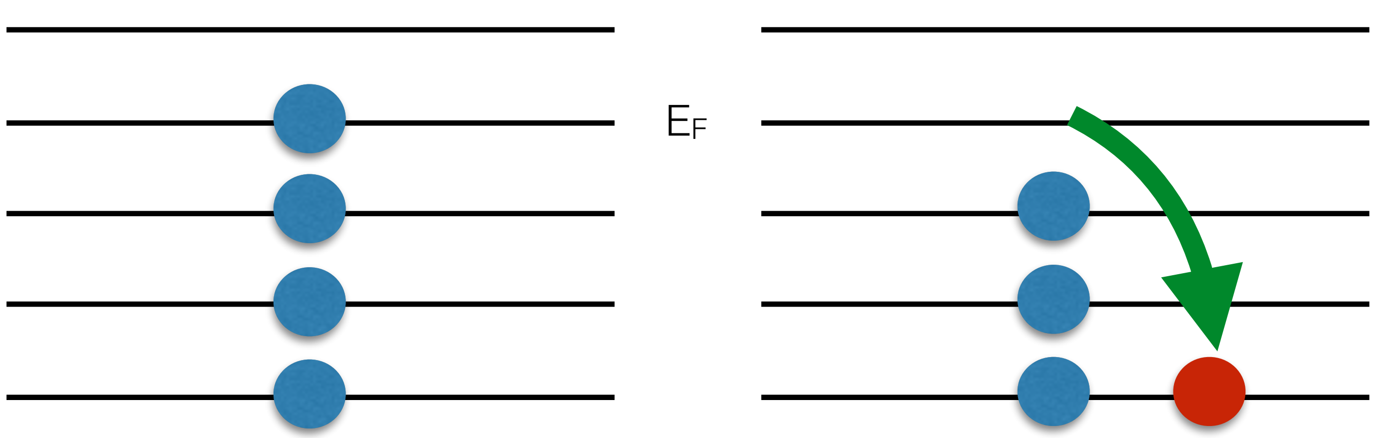
Hyperons in dense matter

P. Haensel, A.Y. Potekhin, D.G. Yakovlev, Neutron Stars 1, Springer 2007



A simple argument based on the properties of the Fermi gas tells us that at very large densities it is energetically favourable to change neutrons and protons into hyperons.

Hyperons might appear in the *inner core* of neutron stars.



When hyperons appear, energy is reduced!

Chemical equilibrium conditions:

$$Q=-1: \;\; \mu_{Y^-} = \mu_n + \mu_e$$

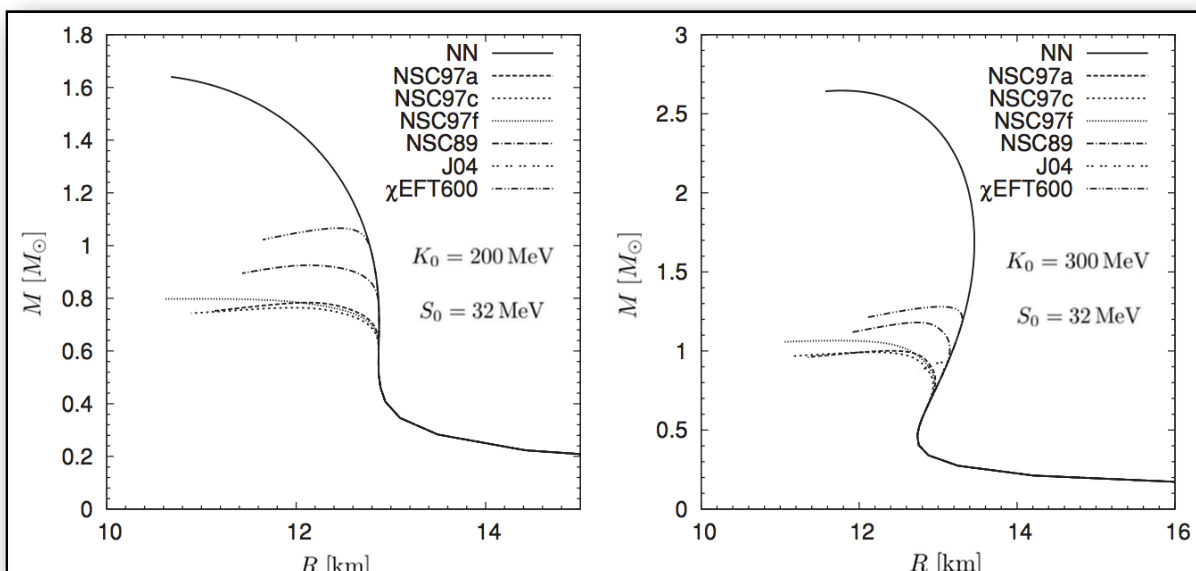
$$Q=0 \;\; : \;\; \mu_{Y^0} = \mu_n$$

$$Q=+1: \;\; \mu_{Y^+} = \mu_n - \mu_e$$

Hyperon puzzle

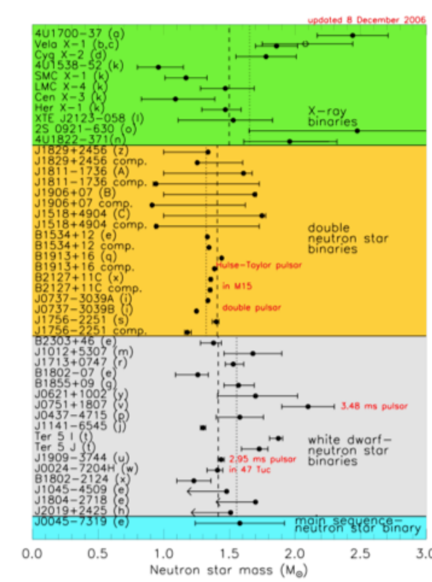
The appearance of hyperons has an immediate consequence on the equation of state: it makes it softer, i.e. the pressure coming from the baryon-baryon interaction is reduced.

Softer EoS ➠ lower star mass



H. Đapo, B.-J. Schaefer, and J. Wambach. Appearance of hyperons in neutron stars. Phys. Rev. C, 81(3): 035803 (2010) based on NN ("soft" and "stiff") EoS from M.Heiselberg, M.Hjort-Jensen, Phys. Rep. 328, 237 (2000)
See also the work of the Catania group (H.-J. Schulze, MM Baldo, F. Burgio et al.)

Until 2010 observed masses of NS were distributed around the Chandrashekar mass M_S=1.4 M⊙



Use of the equation of state of a p,n,e,μ leads to a maximum mass > 2 M⊙

⬇

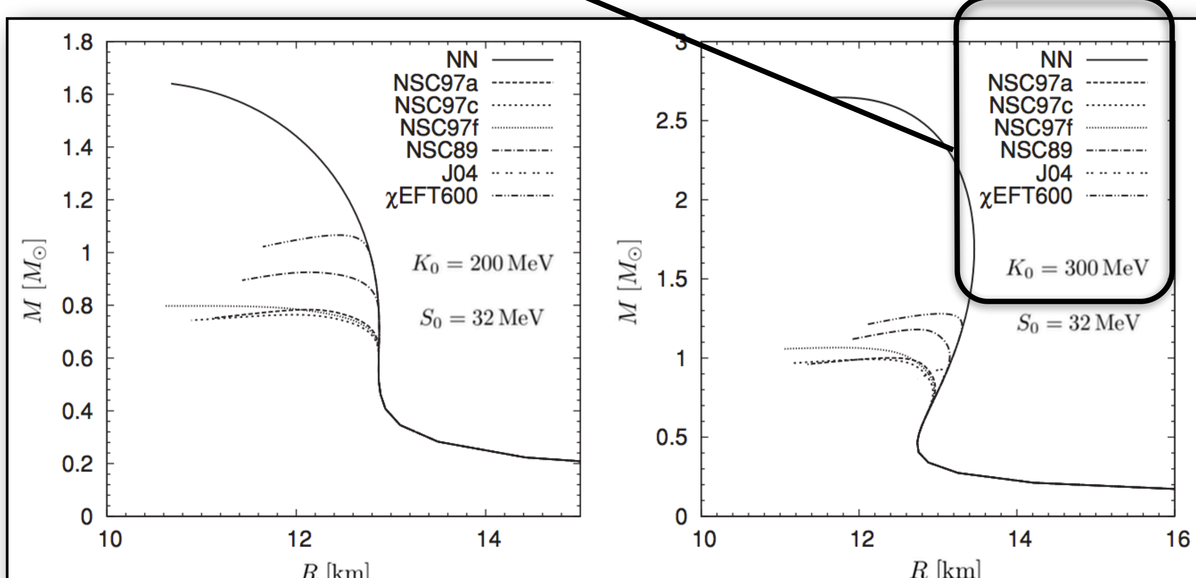
Soft EoS allowed: hyperons ok!

Hyperon puzzle

The appearance of hyperons has an immediate consequence on the equation of state: it makes it softer, i.e. the pressure coming from the baryon-baryon interaction is reduced.

Many hyperon-nucleon model interactions, giving differen EoS and different predictions.

Softer EoS ➠ lower star mass



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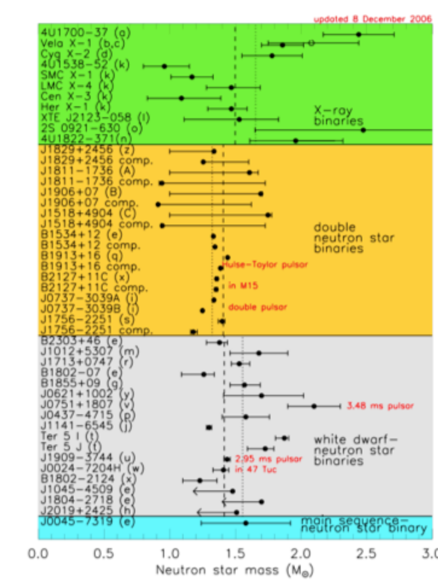

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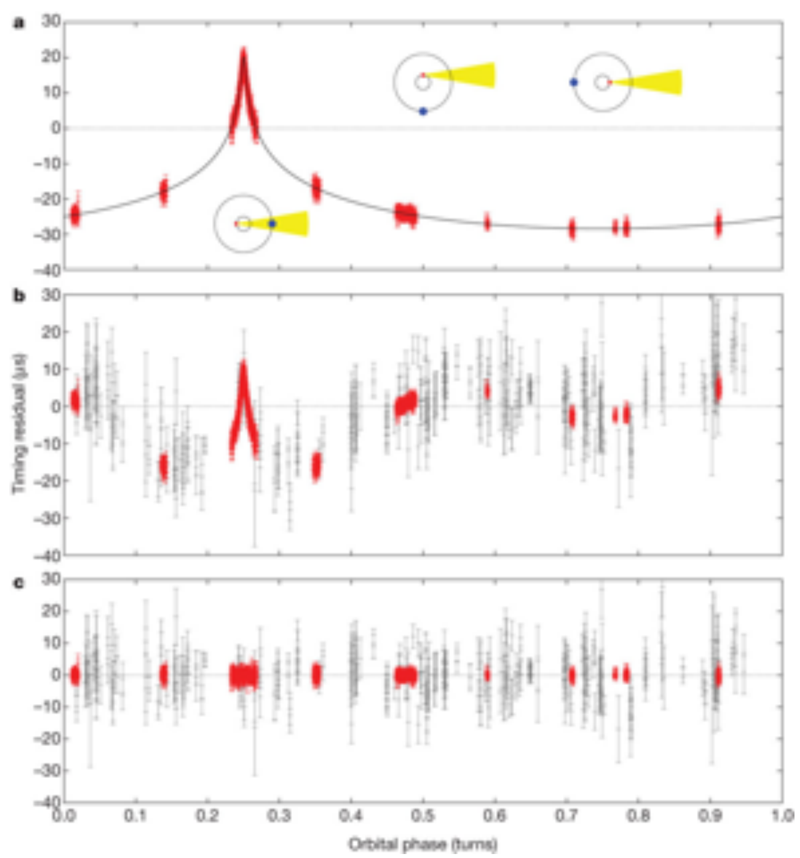
Hyperon Puzzle

Recently a few NS with a large mass were observed. by using Shapiro delay measurements. The first (2010) was PSRJ1614-2230 pulsar with **M=1.97(4)M⊙**.

(P. B. Demorest, T. Pennucci, S. M. Ransom, M. S. E. Roberts and J. W. T. Hessels. A two-solar-mass neutron star measured using Shapiro delay measurements, Nature 467, 1081 (2010).



Before 2010:

Maximum mass observed: 1.6M⊙

Maximum mass predicted without hyperons: 2.3⊙ (still ok in principle)

Maximum mass predicted with hyperons: 1.4-1.6M⊙ (good!)

After 2010:

Observed mass: 2.0M⊙

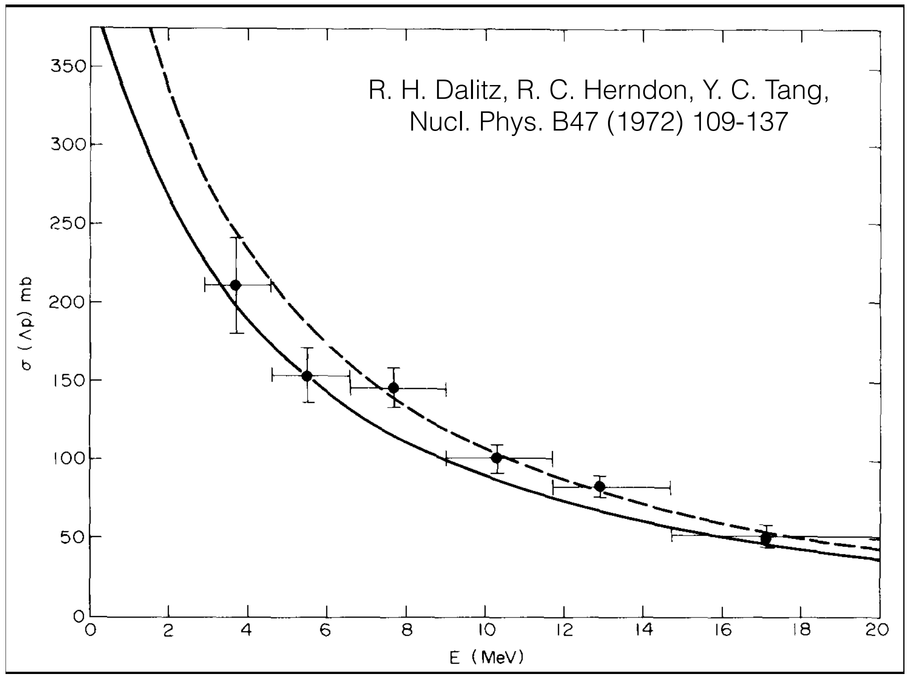
Maximum mass predicted without hyperons: 2.3M⊙ (good!)

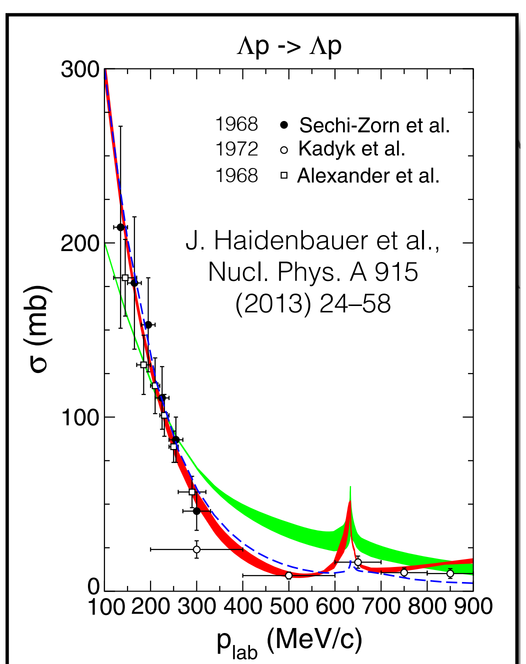
Maximum mass predicted with hyperons: 1.4-1.6M⊙ (very bad…)

In a non relativistic framework (= pure baryonic stars) hyperons are problematic

Model Hyperon-nucleon interaction

A fundamental ingredient to gain some understanding for this problem is to understand the structure of the baryon-baryon interaction.





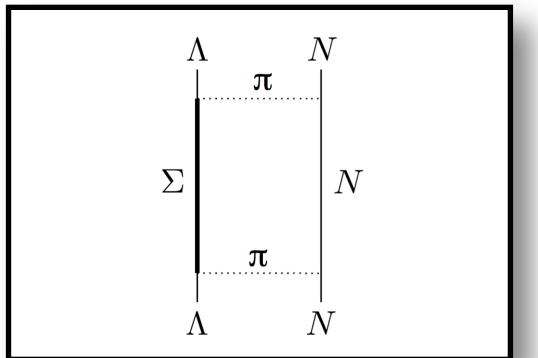
There are several ways of attacking the problem. This is our choice:

- **NON RELATIVISTIC APPROACH** (should be fine if the central density is not too large)
- **YN INTERACTION CHOSEN TO FIT EXISTING SCATTERING DATA** (with a hard-core)
- **PHENOMENOLOGICAL YNN THREE-BODY FORCES** with few parameters to be adjusted to reproduce light hypernuclei binding energies
- **ALL THE OTHER RESULTS ARE PREDICTIONS WITH NO OTHER ADJUSTABLE PARAMETERS** obtained from an *accurate solution of the Schroedinger equation*.

Model Hyperon-nucleon interaction

Model interaction (Bodmer, Usmani, Carlson):

A. Bodmer, Q. N. Usmani, and J. Carlson, Phys. Rev. C 29, 684 (1984).

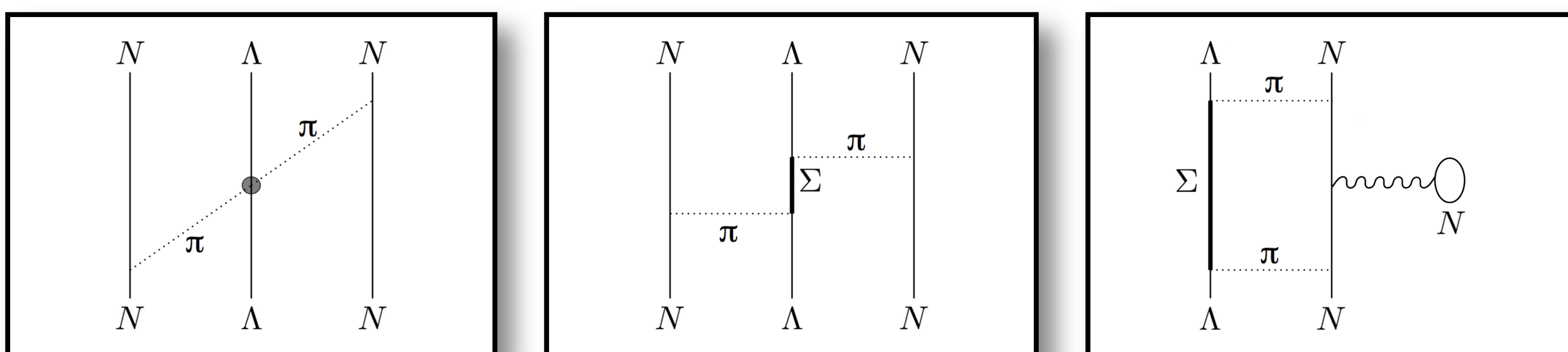


from Kaon exchange terms (not considered explicitly in our calculations)

$$V_{\Lambda i}(r) = v_0(r) + v_0(r)\varepsilon(P_x - 1) + \frac{1}{4}v_\sigma T_\pi^2(m_\pi r)\boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_i$$

Two-body potential: accurately fitted on p-*Λ* scattering data

Q. N. Usmani and A. R. Bodmer, Phys. Rev. C 60, 055215 (1999).



$$V_{\Lambda ij} = V_{\Lambda ij}^{2\pi} + V_{\Lambda ij}^{D}$$

$$\begin{cases} V_{\Lambda ij}^{2\pi} = C_{2\pi}^{SW}\mathcal{O}_{\Lambda ij}^{2\pi,SW} + C_{2\pi}^{PW}\mathcal{O}_{\Lambda ij}^{2\pi,PW} \\ V_{\Lambda ij}^{D} = W^D\, T_\pi^2(m_\pi r_{\Lambda i})\, T_\pi^2(m_\pi r_{\Lambda j}) \left[1 + \frac{1}{6}\boldsymbol{\sigma}_\Lambda \cdot (\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j)\right] \end{cases}$$

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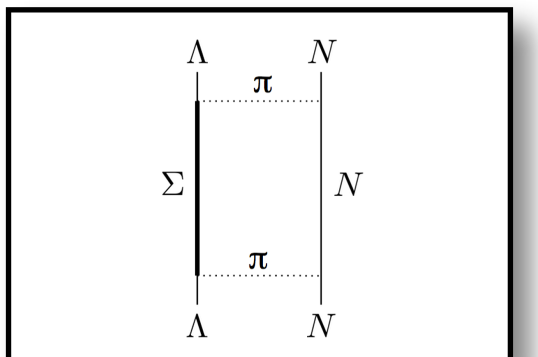

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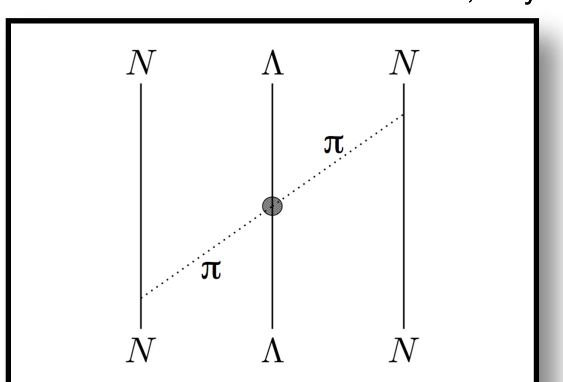

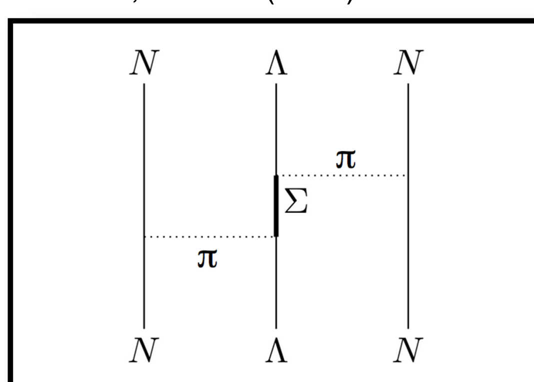

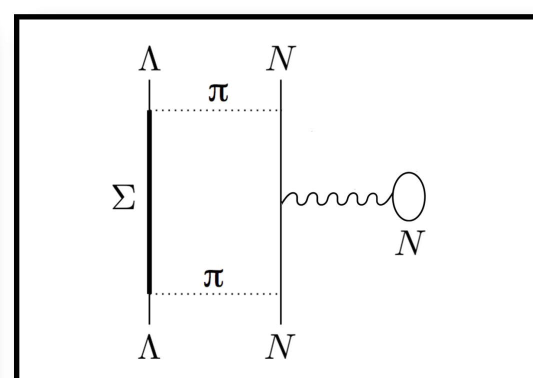

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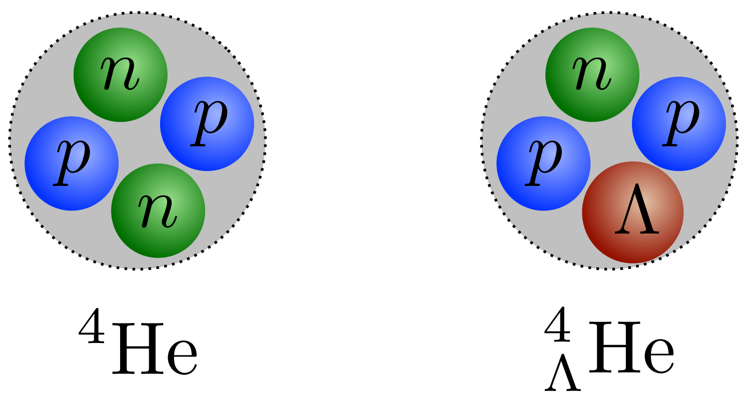
Parameters to be determined from calculations

Input from experiment

We need to fit the three body interaction against some experimental data. There are available several measurements of the binding energy of *Λ*-hypernuclei, i.e. nuclei containing a Λ hyperon. The idea is to compute such binding energies. We can then compute the **hyperon separation energy:**

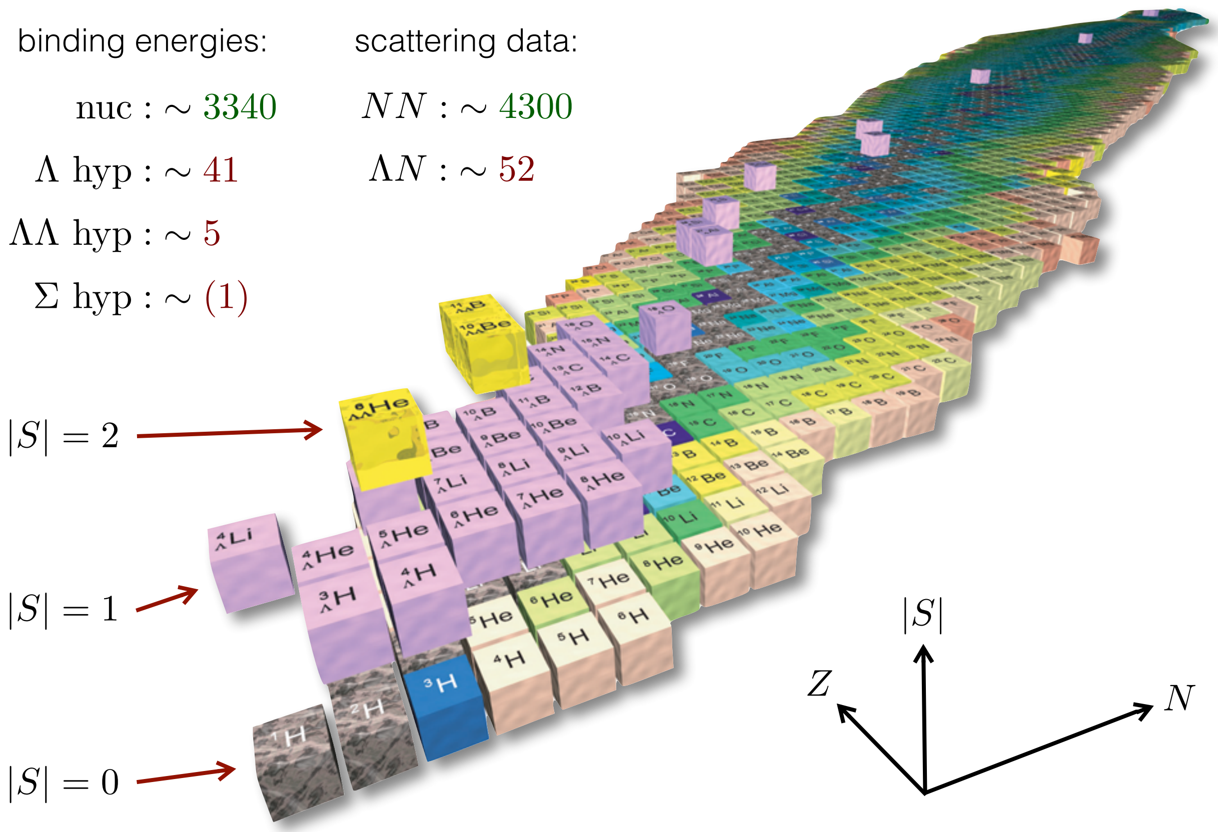
$$B_\Lambda = B_{hyp} - B_{nuc}$$

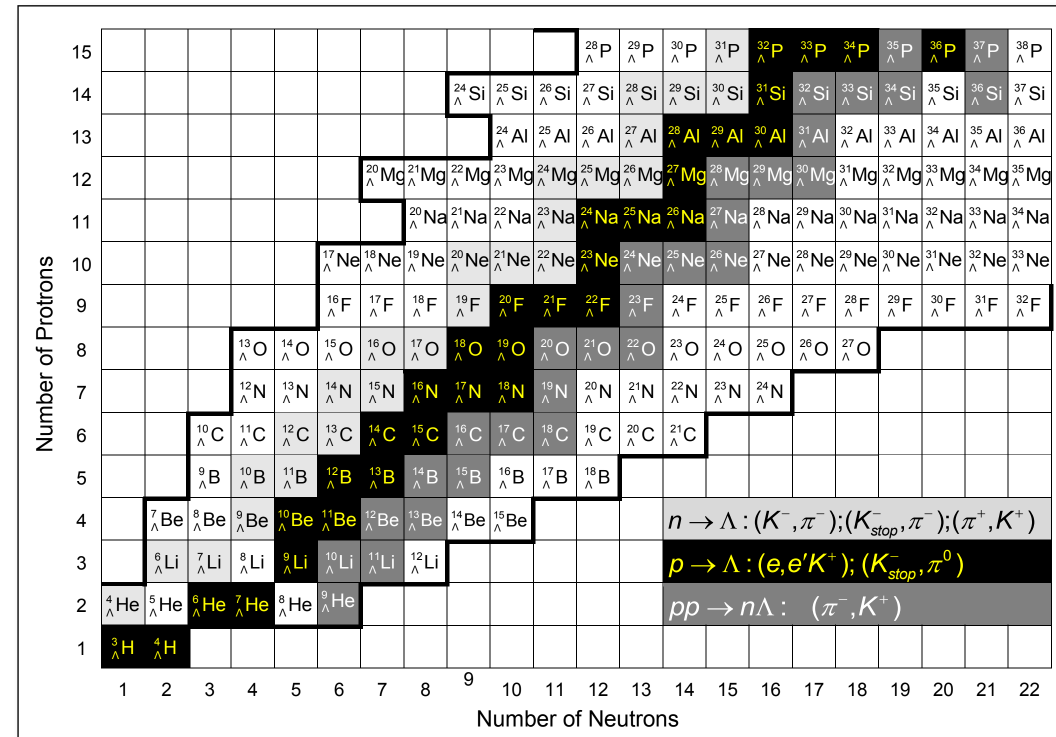


where B_{hyp} is the total binding energy of a hypernucleus with A nucleons and one Λ , and B_{nuc} is the total binding energy of the corresponding nucleus with A nucleons. This number can be used to gauge the coefficients in the nucleon-Λ interaction.

Hypernuclei data

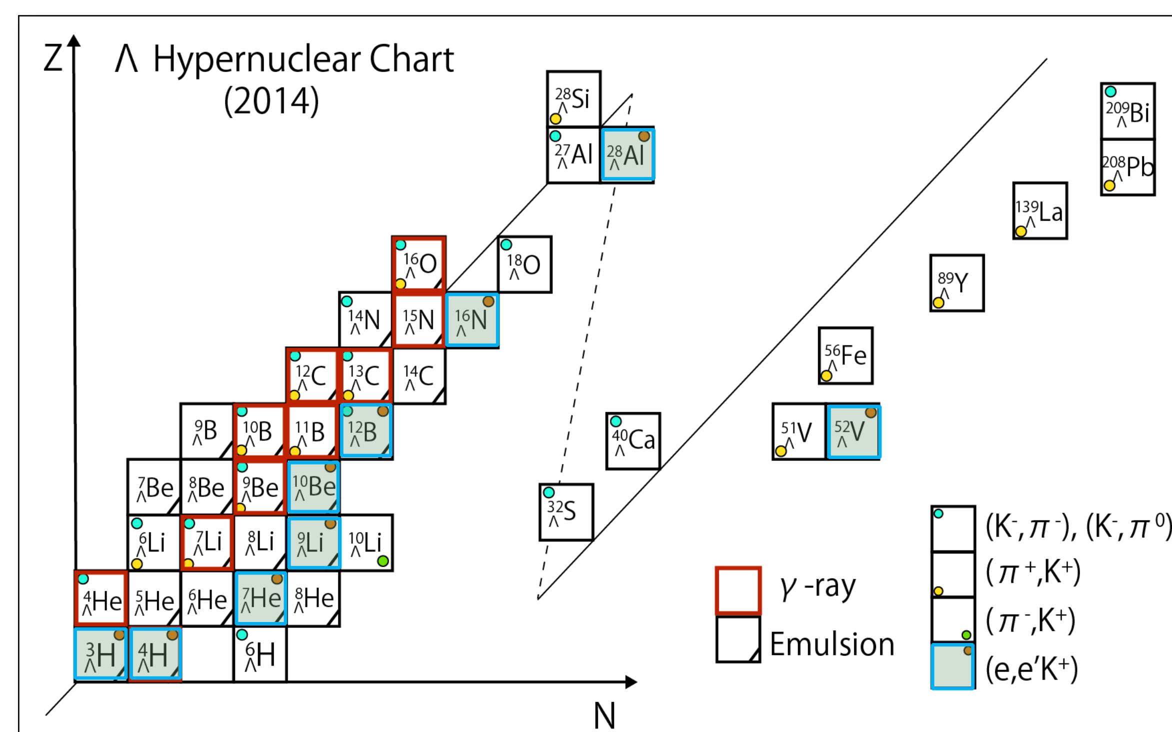
binding energies:	scattering data:
nuc : ~ 3340	$NN : \sim 4300$
Λ hyp : ~ 41	$\Lambda N : \sim 52$
$\Lambda\Lambda$ hyp : ~ 5	
Σ hyp : $\sim (1)$	





J. Pochodzalla, Acta Phys. Polon. B 42, 833– 842 (2011)

- The available data are very limited.
- There are several planned and ongoing systematic measurements.
- At present no proposals for gathering more Λ-nulceon scattering data
- Essentially no information on $\Lambda\Lambda$ interaction
- (Almost) nothing on Σ or Ξ hypernulcei



S. N. Nakamura, Hypernuclear workshop, JLab, May 2014
updated from: O. Hashimoto, H. Tamura, Prog. Part. Nucl. Phys. 57, 564 (2006)

Projection Monte Carlo

We compute ground state energies of nuclei by means of projection Monte Carlo methods. The ground state of a many-body system is computed by applying an "imaginary time propagator" to an arbitrary state that has to be non-orthogonal to the ground state (power method):

$$\langle R|\Psi(\tau)\rangle = \langle R|e^{-(\hat{H}-E_0)\tau}|R'\rangle\langle R'|\Psi(0)\rangle$$

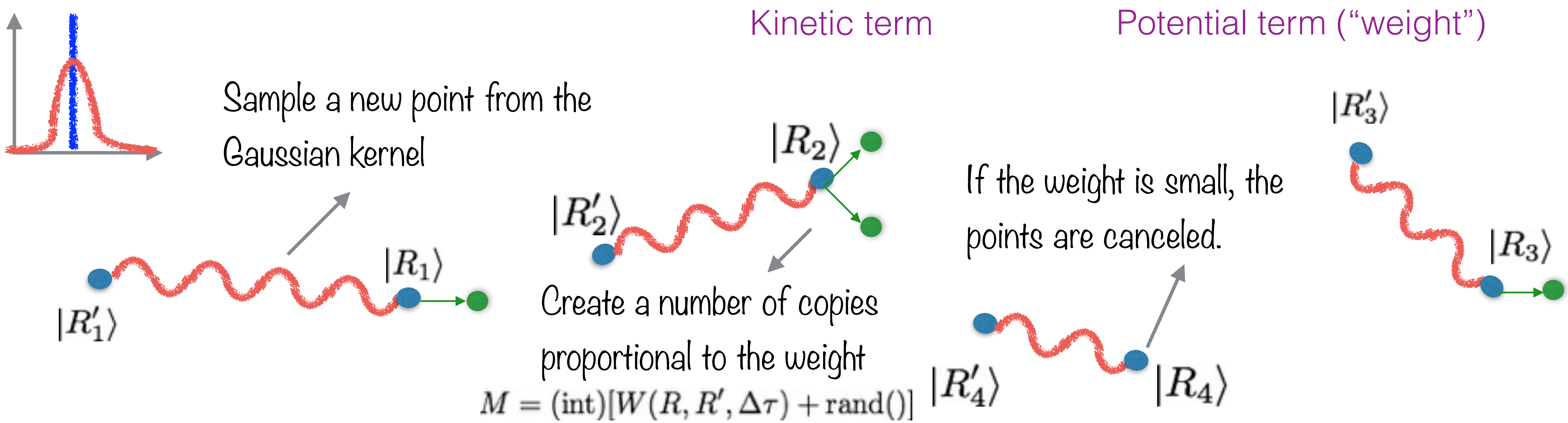
In the limit of "short" τ (let us call it "$\boldsymbol{\Delta\tau}$"), the propagator can be broken up as follows (Trotter-Suzuki formula):

$W(R, R', \Delta\tau)$

$$\langle R|e^{-(\hat{H}-E_0)\Delta\tau}|R'\rangle \sim e^{-\frac{(R-R')^2}{2\frac{\hbar}{m}\Delta\tau}}\, e^{-\left(\frac{V(R)+V(R')}{2}-E_0\right)\Delta\tau}$$

Kinetic term

Potential term ("weight")

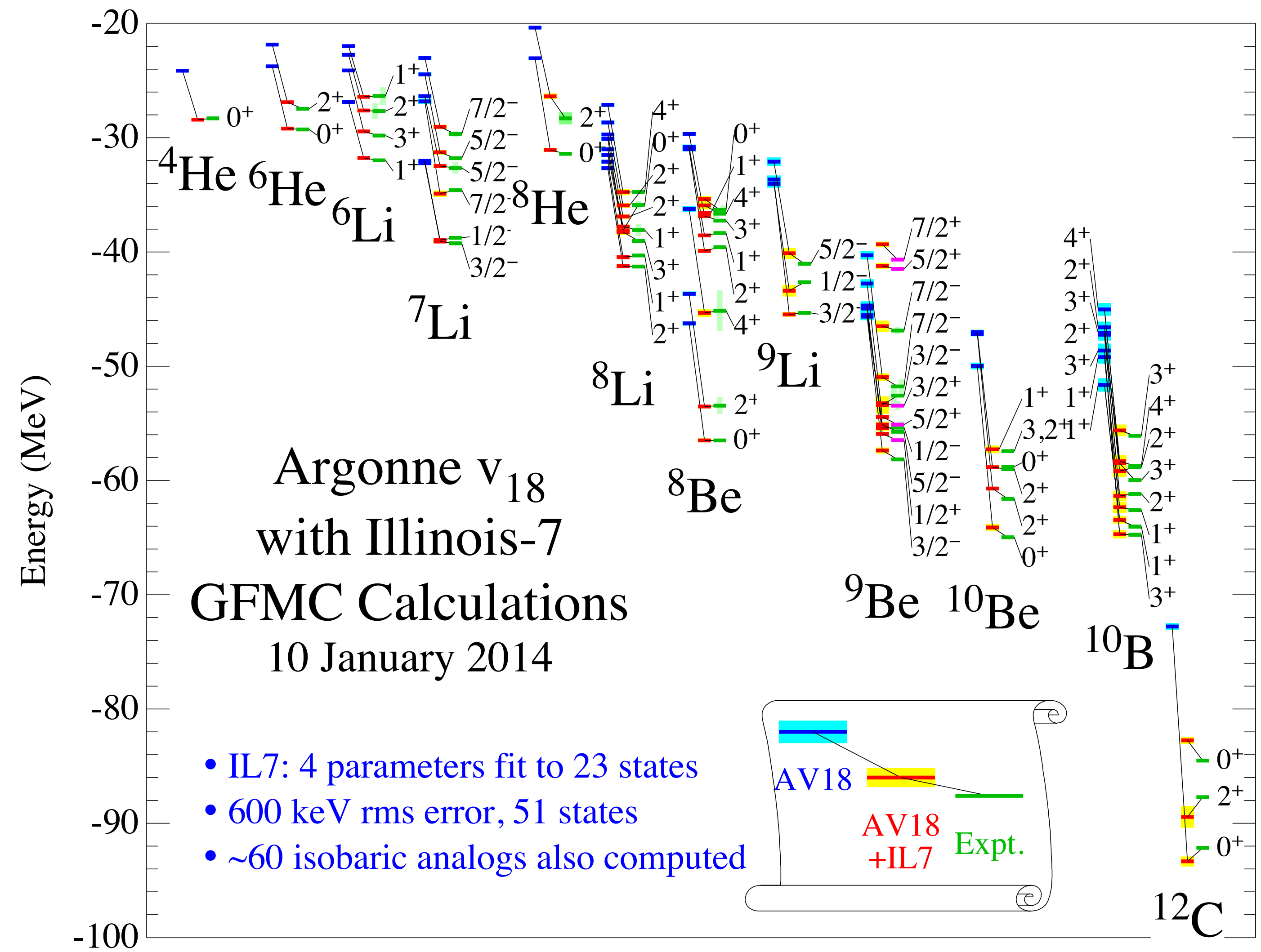


Many-nucleon systems

PROBLEM

for realistic many-nucleon Hamiltonians, propagators must be evaluated on wave functions that have a number of components exponentially growing with A (spin/isospin singlet/triplet state for each pair of nucleons)

Very accurate results have been obtained in the years for the ground state and some excitation properties of nuclei with A≤12 by the Argonne based group (GFMC calculations by Pieper, Wiringa, Carlson, Schiavilla…). These calculations include two- and three-nucleon interactions.



Courtesy of R. Wiringa, ANL

Auxiliary Field Diffusion Monte Carlo (AFDMC)

Stefano Fantoni & Kevin Schmidt, 1999

The computational cost of GFMC can be reduced by introducing a way of sampling over the space of states, rather than summing explicitly over the full set.
For simplicity let us consider only one of the terms in the interaction.
We start by observing that:

Linear combination of spin operators for different particles

$$\sum_{i<j} v(r_{ij}) \vec{\sigma}_i \cdot \vec{\sigma}_j = \frac{1}{2} \sum_{i;\alpha,j;\beta} \sigma_{i;\alpha} A_{i;\alpha,j;\beta} \sigma_{j;\beta} = \sum_{n=1}^{3A} \lambda_n \hat{O}_n^2$$

Then, we can linearize the operatorial dependence in the propagator by means of an integral transform:

auxiliary fields→Auxiliary Field Diffusion Monte Carlo

$$e^{-\frac{1}{2}\lambda \hat{O}_n^2 \Delta\tau} = \frac{1}{\sqrt{2\pi}} \int dx e^{-\frac{x^2}{2}} e^{-x\sqrt{\lambda\Delta\tau}\hat{O}_n}$$

K. E. Schmidt and S. Fantoni, Phys. Lett. B 446, 99 (1999).
S. Gandolfi, F. Pederiva, S. Fantoni, and K. E. Schmidt, Phys. Rev. Lett. 99, 022507 (2007)

Hubbard-Stratonovich transformation

Auxiliary Field Diffusion Monte Carlo (AFDMC)

The operator dependence in the exponent has become linear.

In the Monte Carlo spirit, the integral can be performed by sampling values of x from the Gaussian $e^{-\frac{x^2}{2}}$. For a given x the action of the propagator will become:

$$e^{-x\sqrt{\lambda\Delta\tau}\hat{O}_n}|S\rangle = \prod_{k=1}^{3A} e^{-x\sqrt{\lambda\Delta\tau}\phi_n^k\sigma_k}|S\rangle$$

In a space of spinors, each factor corresponds to a rotation induced by the action of the Pauli matrices

The sum over the states has been replaced by rotations sampling!

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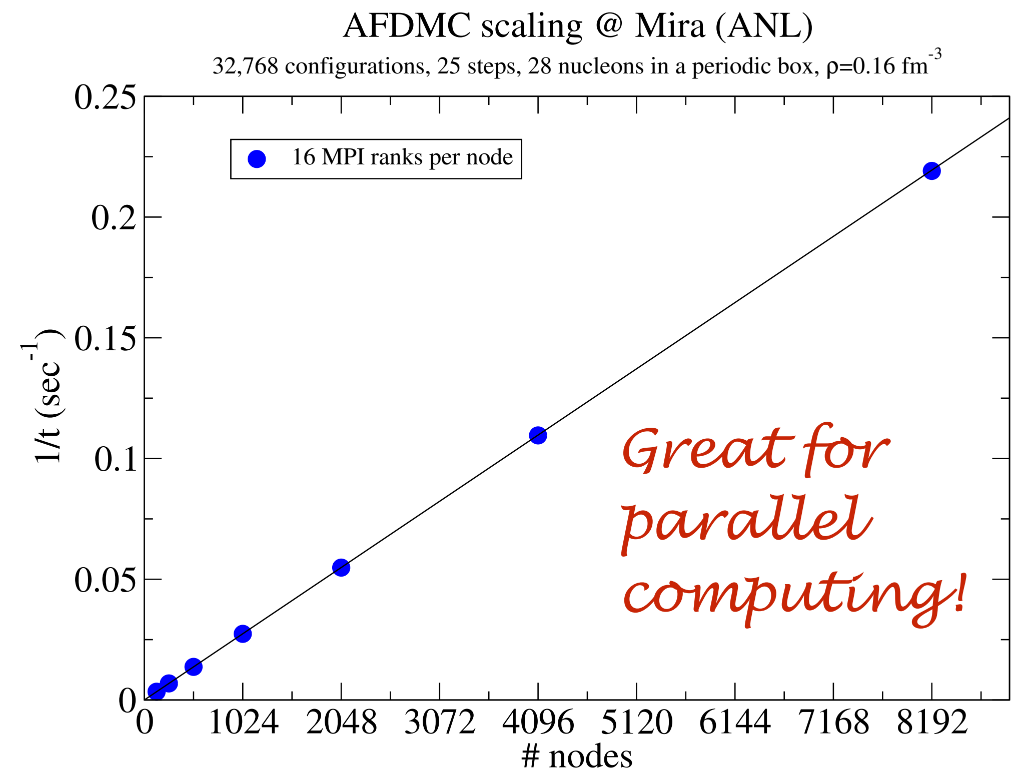
Auxiliary Field Diffusion Monte Carlo (AFDMC)

The crucial advantage of AFDMC is that the scaling of the required computer resources is no longer exponential: **the cost scales as A^3** (the scaling required by the computation of the determinants in the antisymmetric wave functions) → **LARGER SYSTEMS ACCESSIBLE!**



Problems

- The HS transformation can be used ONLY FOR THE PROPAGATOR Accurate wave functions require an operatorial dependence! "Cluster expansion" introduced and working!
- Extra variables → larger fluctuations and autocorrelations.
- Some problems in treating nuclear spin-orbit.
- Three-body forces (extremely important in nuclear physics) cannot be implemented in all cases

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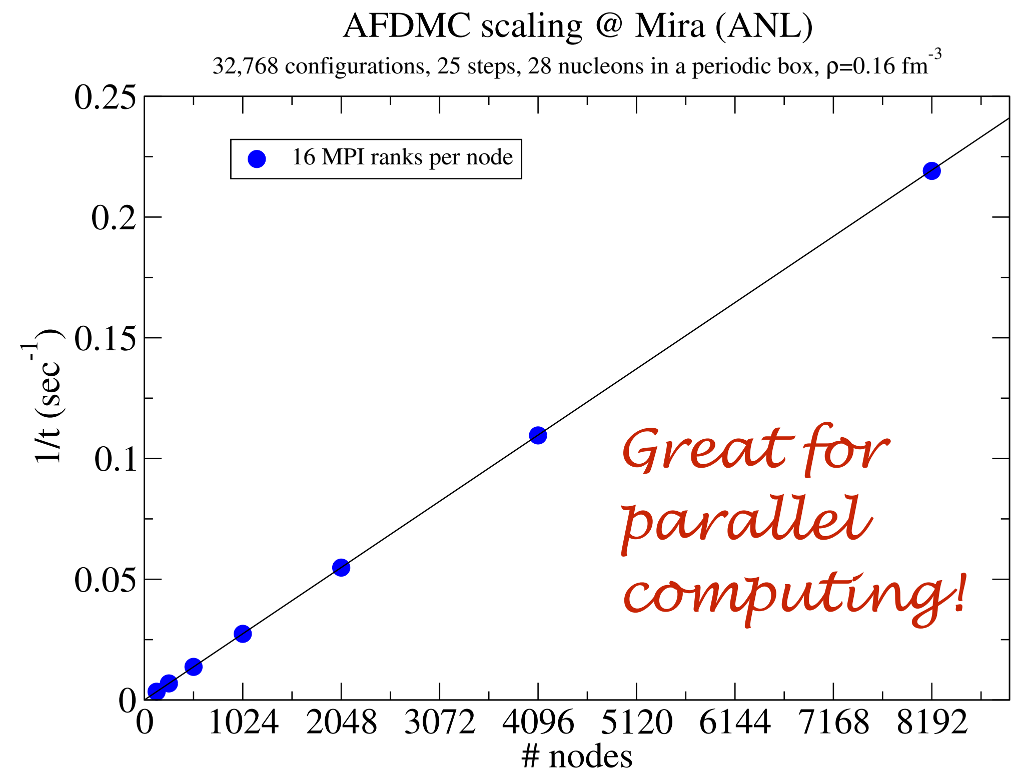

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Progress!

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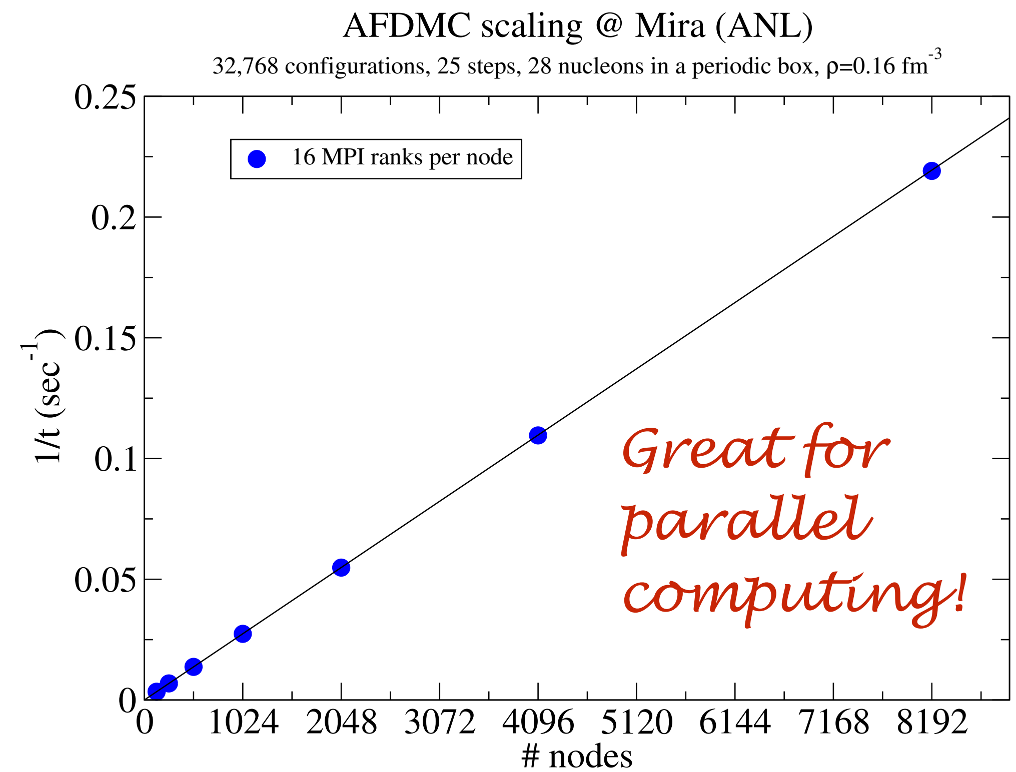

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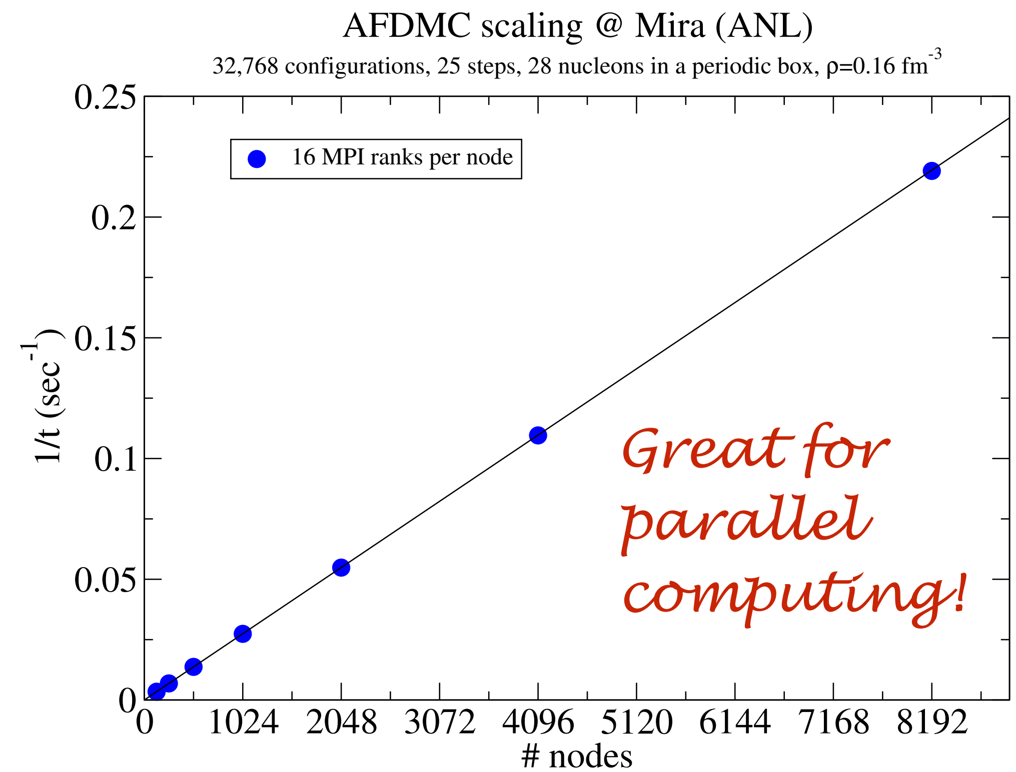

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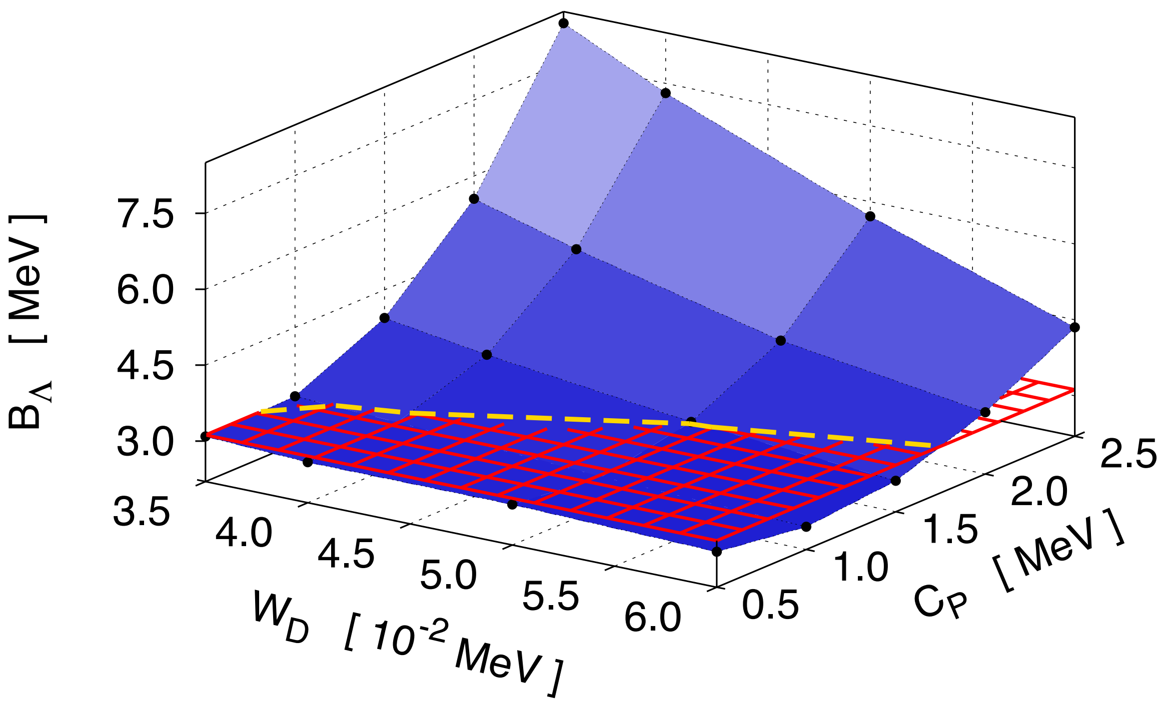
Input from experiment

$$B_\Lambda = B_{hyp} - B_{nuc}$$

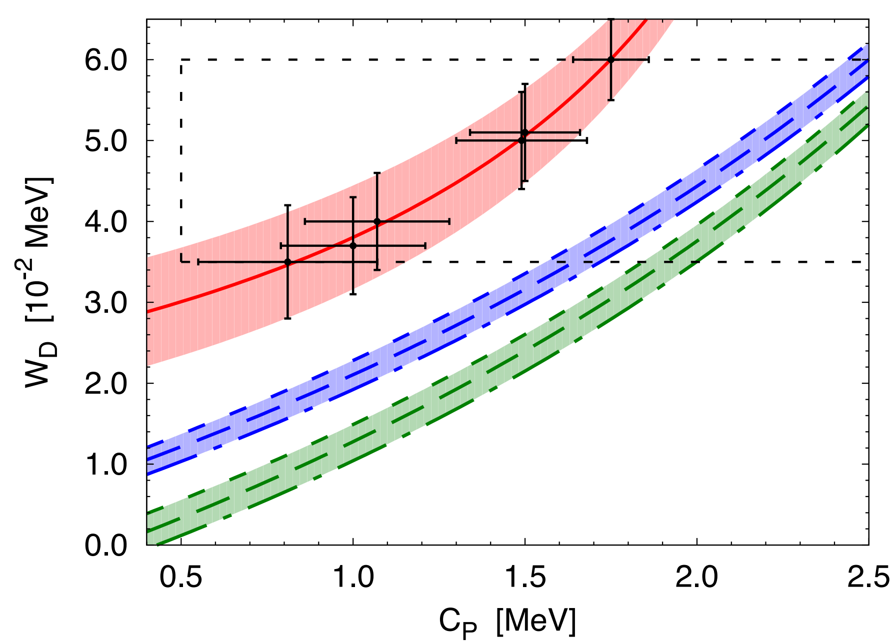
$$H = T + AV4' + UIX_c + V_{\Lambda N} + V_{\Lambda NN}$$

$$H = T + AV4' + UIX_c$$



Assumption: use of a simplified NN interaction cancel in the difference and therefore the estimate of BΛ is accurate (verified!)

Only two parameters are relevant (one of them is essentially ineffective)



Hypernuclei

The *nucleon-nucleon* interaction that we use in our hypernuclear calculations is not the full realistic one, but the simpler AV4'+ the central (repulsive) term of the Urbana IX
potential (UIX_c). Despite this simplification, the description of closed shell nuclei is at leas "not unrealistic". Here we report some results.

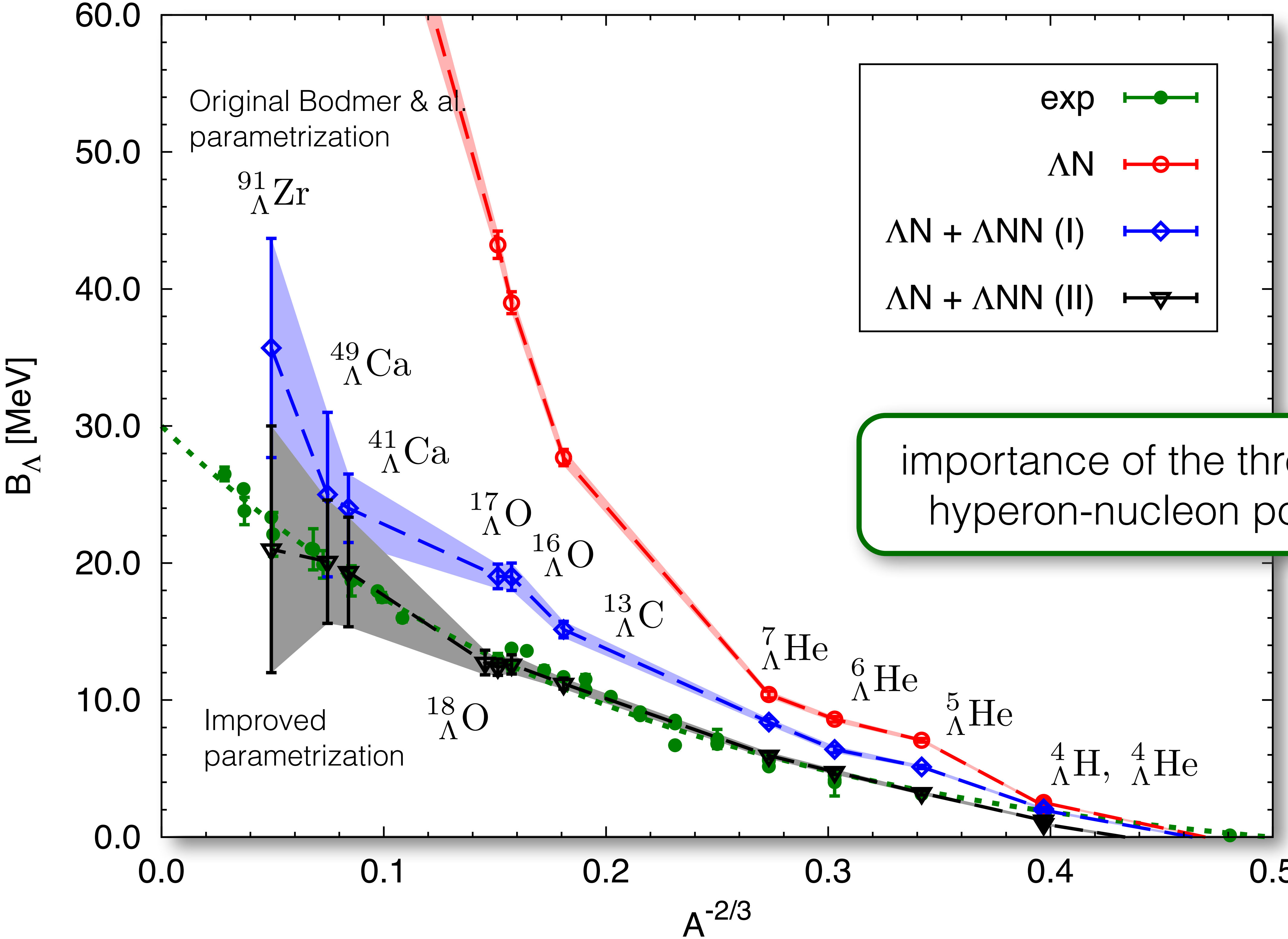
preliminary

	AV4′	AV4′+UIX_c	exp	
^{4}He	-32.67(8)	-26.55(7)	-28.295	$\sim$ 6%
^{16}O	-176.8(6)	-119.5(3)	-127.619	
^{40}Ca	-597(3)	-381.9(8)	-342.051	$\sim$ 12%
^{48}Ca	-645(3)	-414(1)	-416.001	$\sim$ 0.5%

	Hamiltonian	AFDMC	GFMC
^{4}He	AV4′	-32.67(8)	-32.88(6)
	AV4′+UIX_c	-26.55(7)	-26.82(8)

reasonable single particle densities and radii

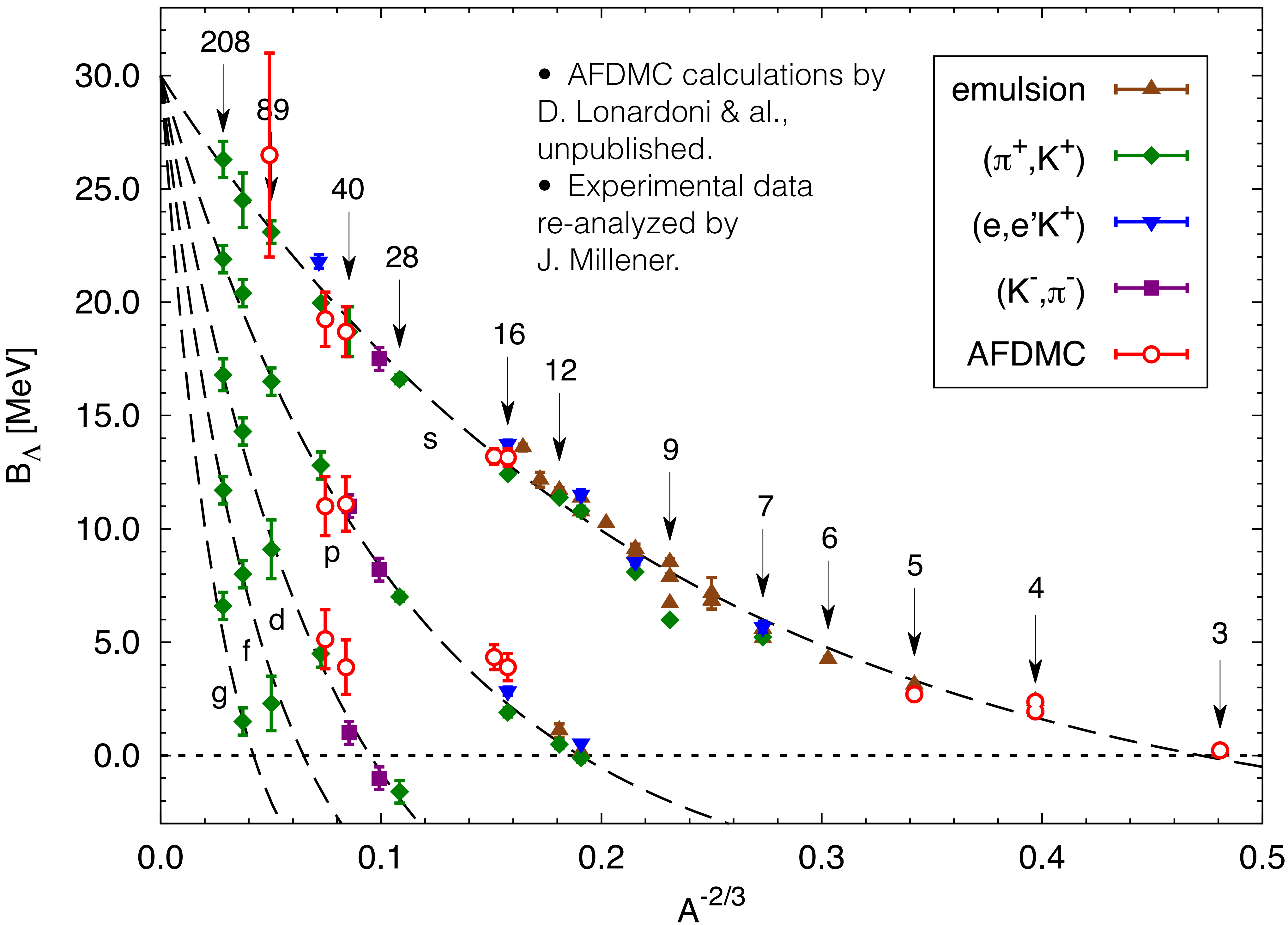
Hypernuclei



importance of the three-body hyperon-nucleon potential

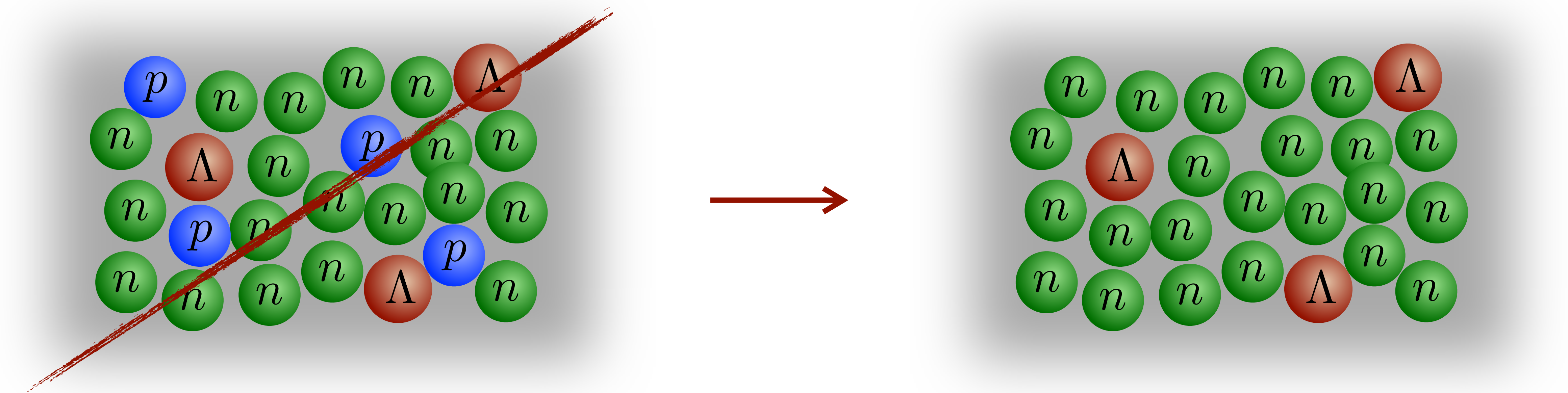
Diego Lonardoni, FP, Stefano Gandolfi ys. Rev. C 89, 014314 (2014)

Hypernuclei



Calculations can ber performed also for excited states: more information available on the structure of the interaction (e.g. spin orbit? charge symmetry breaking?)

Λ-neutron matter



hyper-nuclear matter → hyper-neutron matter

PNM → hyperon fraction → energy per particle: $E_{\rm HNM} \equiv E_{\rm HNM}(\rho_b, x_\Lambda)$

PNM → hyperon fraction → energy density: $\mathcal{E}_{\rm HNM} \equiv \mathcal{E}_{\rm HNM}(\rho_b, x_\Lambda)$

equilibrium condition : chemical potentials

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

Λ-neutron matter

neutrons
+
lambdas

$$\begin{cases} \rho_b = \rho_n + \rho_\Lambda \\ x_\Lambda = \dfrac{\rho_\Lambda}{\rho_b} \end{cases} \qquad \begin{cases} \rho_n = (1 - x_\Lambda)\rho_b \\ \rho_\Lambda = x_\Lambda \rho_b \end{cases}$$

$$E_{\mathrm{HNM}}(\rho_b, x_\Lambda) = \Big[E_{\mathrm{PNM}}((1 - x_\Lambda)\rho_b) + m_n\Big](1 - x_\Lambda) + \Big[E_\Lambda^F(x_\Lambda \rho_b) + m_\Lambda\Big] x_\Lambda + f(\rho_b, x_\Lambda)$$

Problem1: limitation in x_Λ due to simulation box

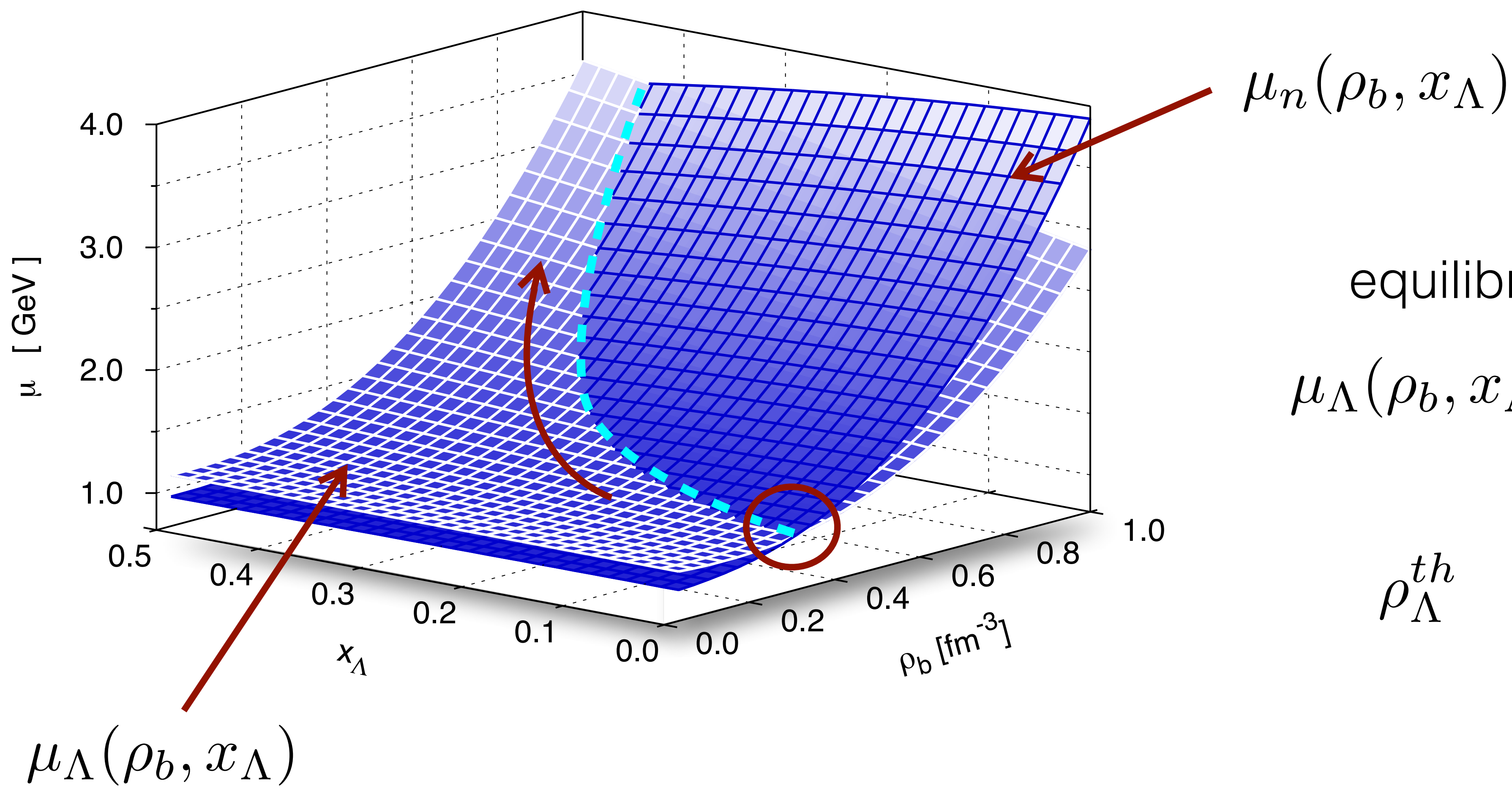
Problem2: finite size effects

Problem3: fitting procedure

$f(\rho_b, x_\Lambda)$ cluster expansion $\dfrac{\rho_\Lambda \rho_n}{\rho_b}$, $\dfrac{\rho_\Lambda \rho_n \rho_n}{\rho_b}$, ~~$\dfrac{\rho_\Lambda \rho_\Lambda \rho_n}{\rho_b}$~~ , ~~$\dfrac{\rho_\Lambda \rho_n \rho_n \rho_n}{\rho_b}$~~

Λ-neutron matter

$$\begin{cases} \mu_n(\rho_b, x_\Lambda) = E_{\rm PNM}(\rho_n) + \rho_n \dfrac{\partial E_{\rm PNM}}{\partial \rho_n} + m_n + f(\rho_b, x_\Lambda) + \rho_b \dfrac{\partial f}{\partial \rho_n} \\ \mu_\Lambda(\rho_b, x_\Lambda) = E_\Lambda^F(\rho_\Lambda) + \rho_\Lambda \dfrac{\partial E_\Lambda^F}{\partial \rho_\Lambda} + m_\Lambda + f(\rho_b, x_\Lambda) + \rho_b \dfrac{\partial f}{\partial \rho_\Lambda} \end{cases}$$

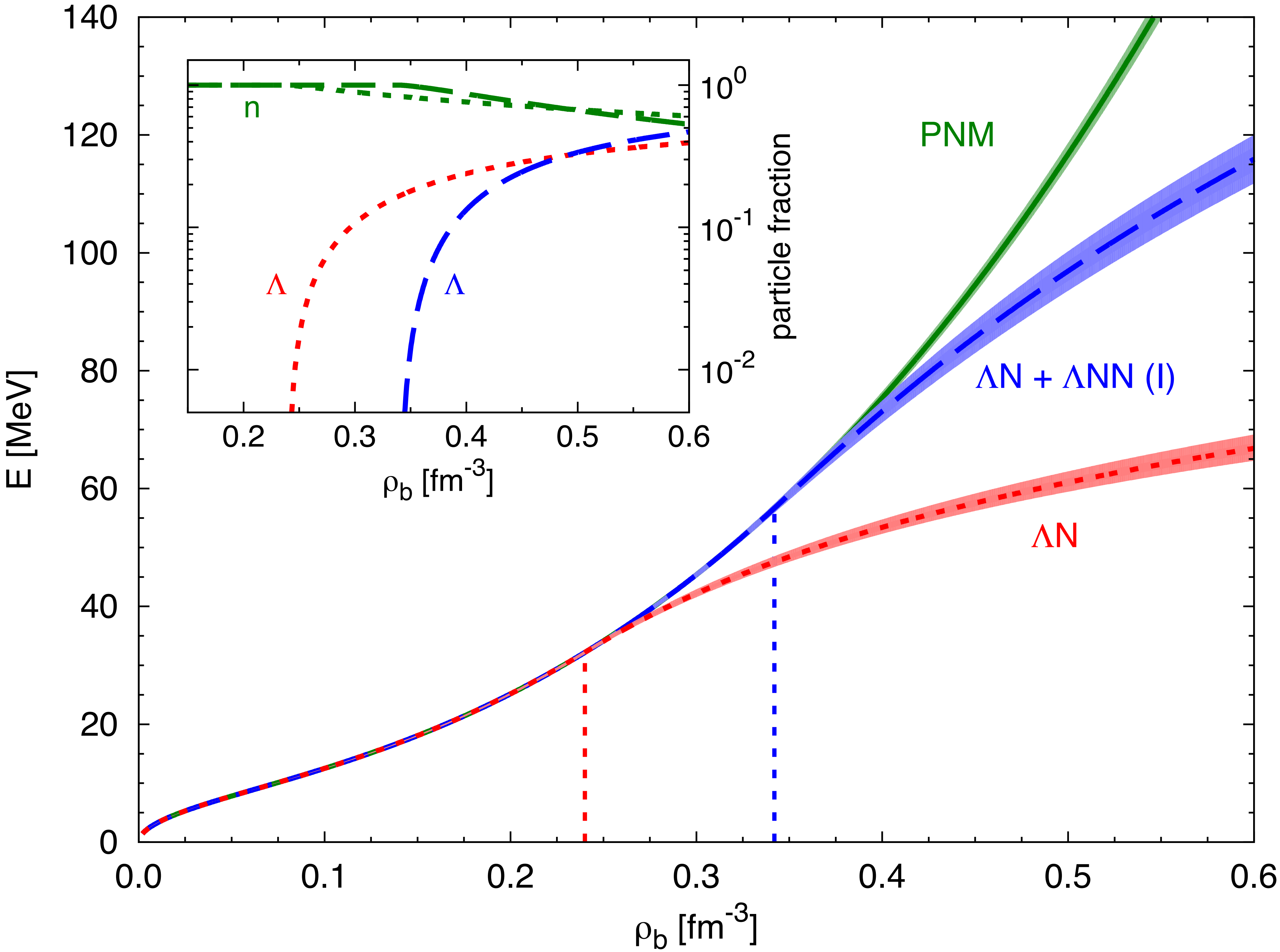


equilibrium condition:

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

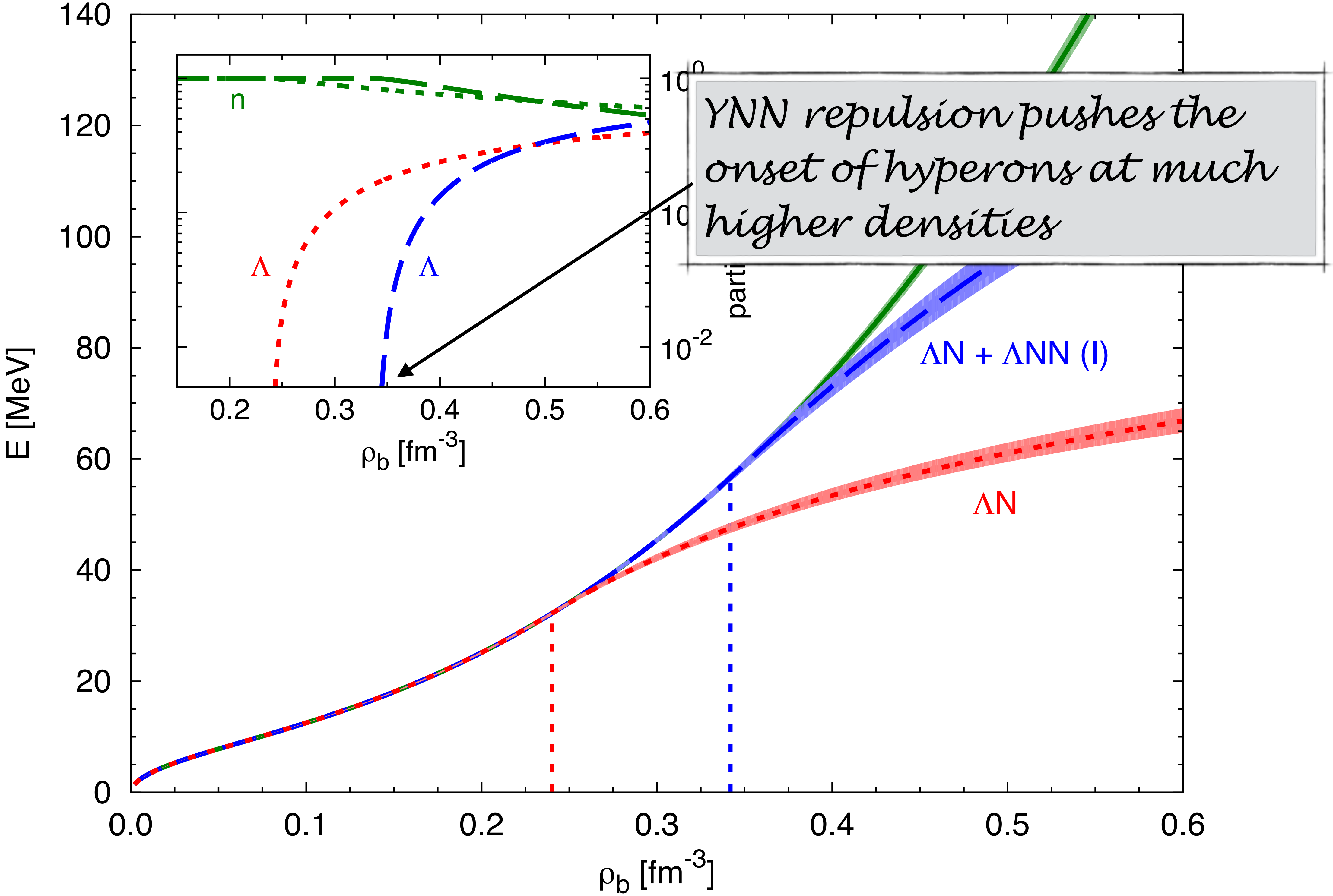
$$\rho_\Lambda^{th} \quad @ \quad x_\Lambda \to 0$$

Λ-neutron matter



Equation of state from AFDMC calculations

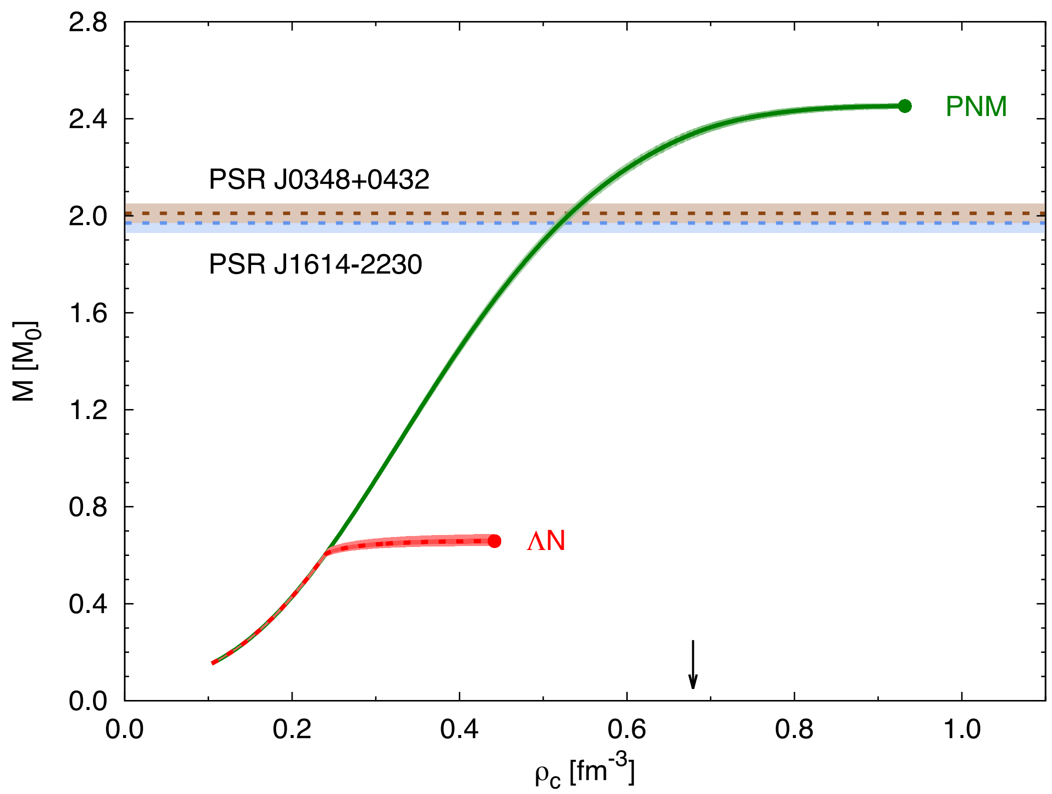
Λ-neutron matter



Equation of state from AFDMC calculations

Neutron star structure

Neutron star structure



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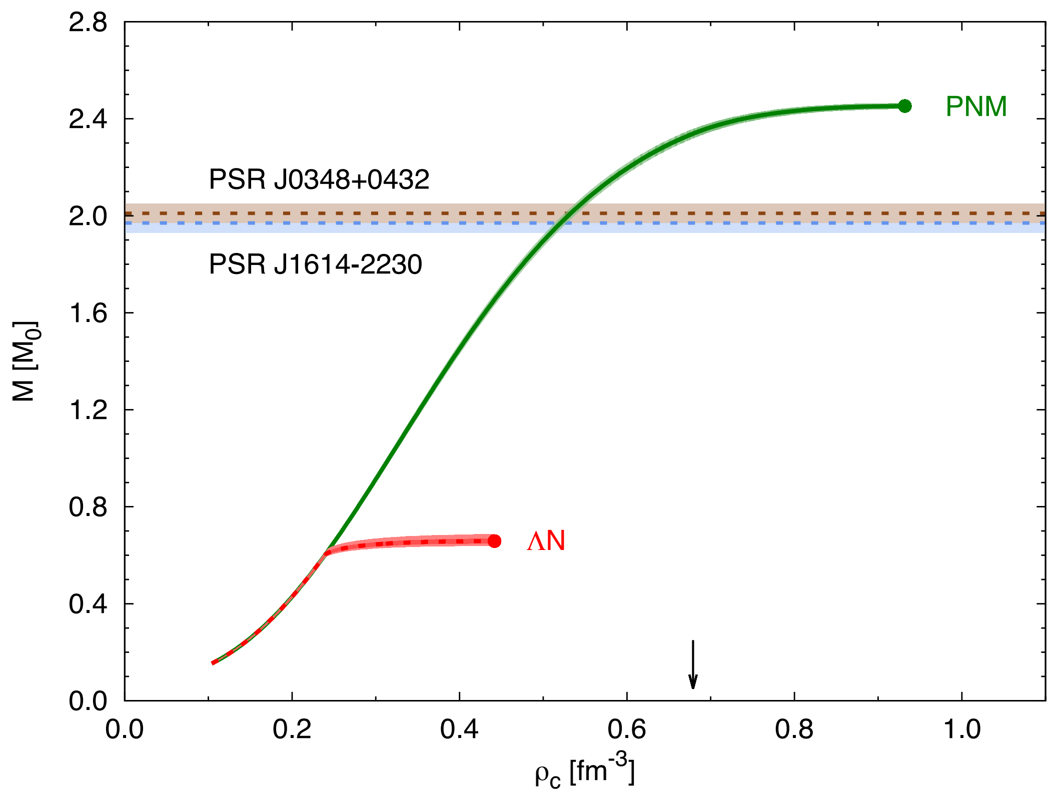

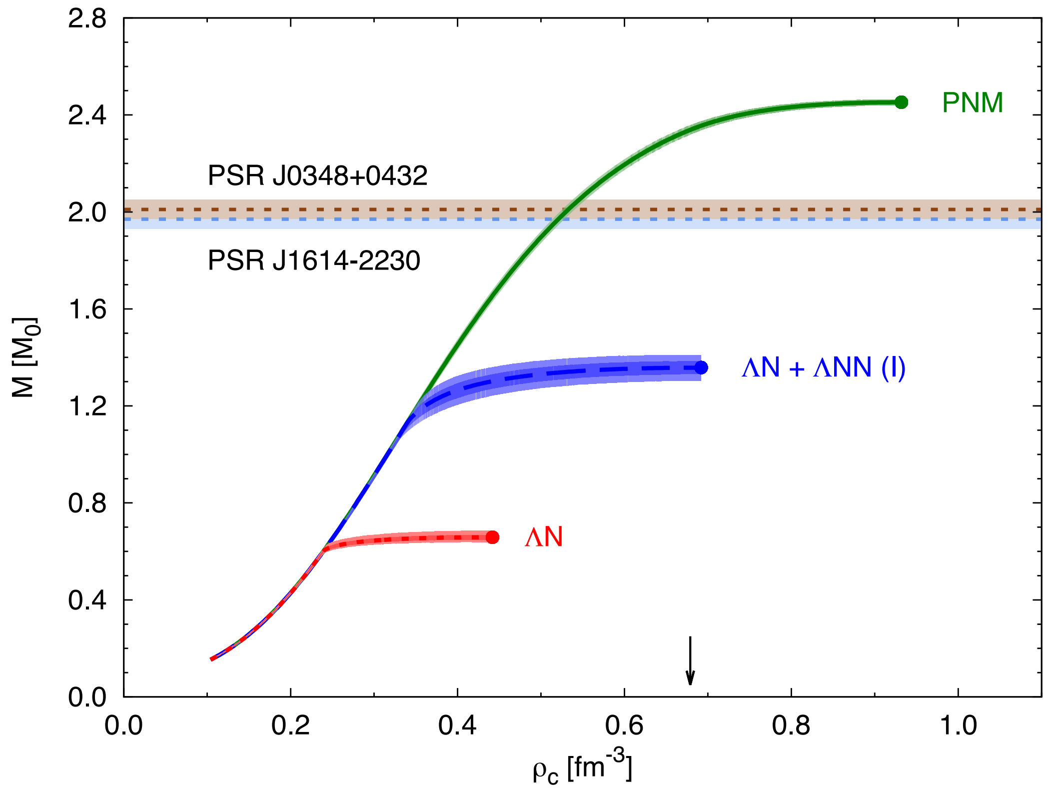

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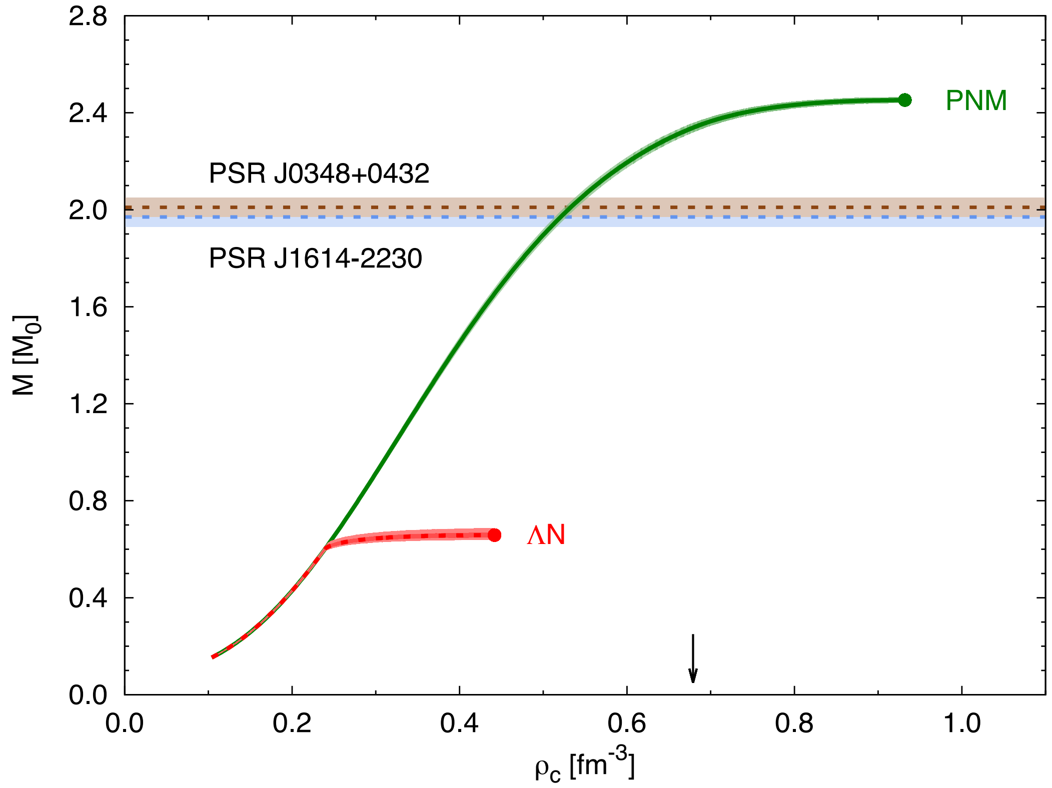

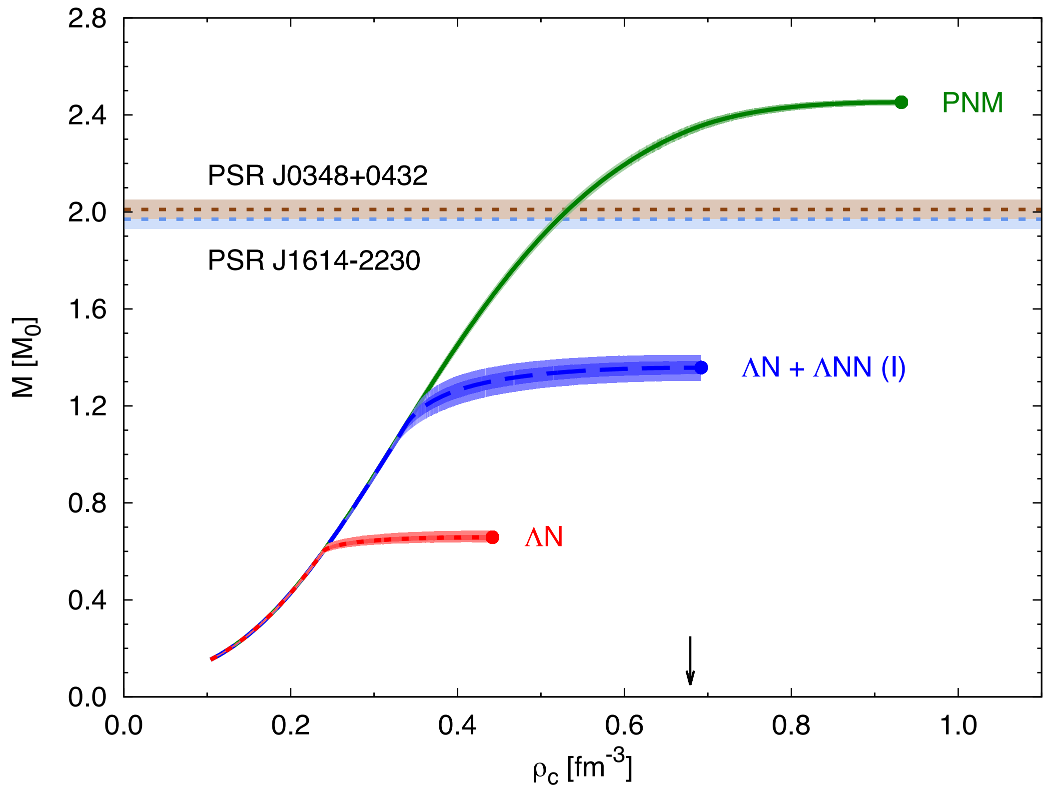

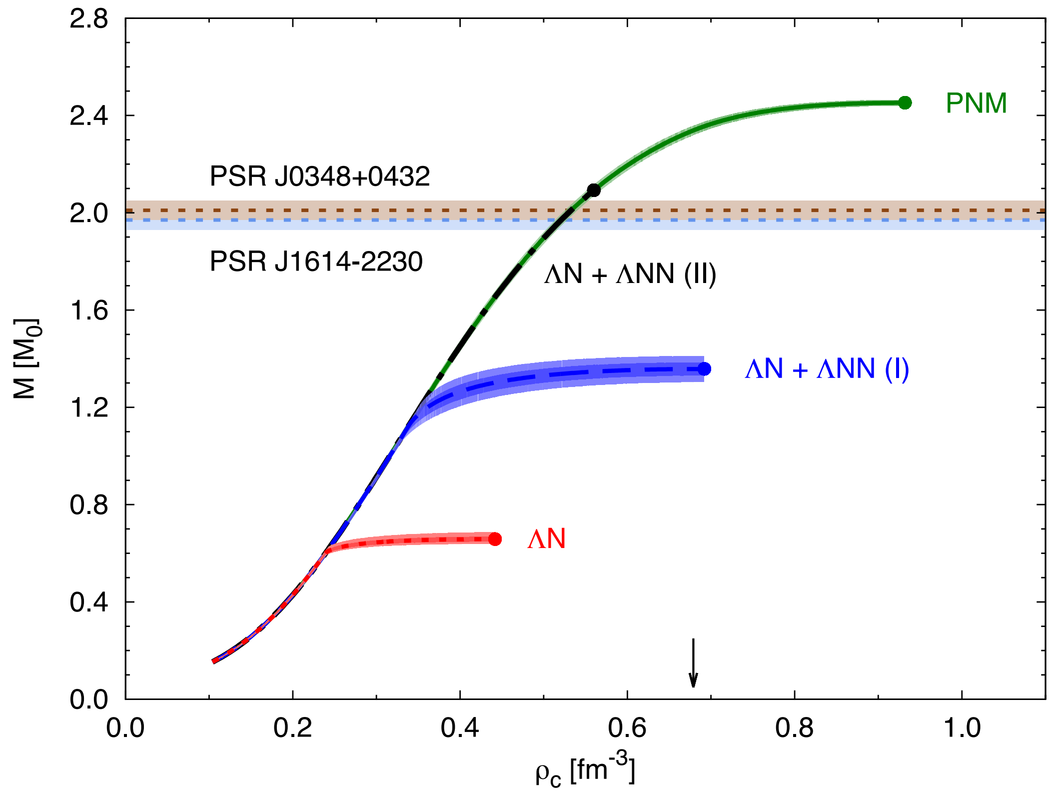

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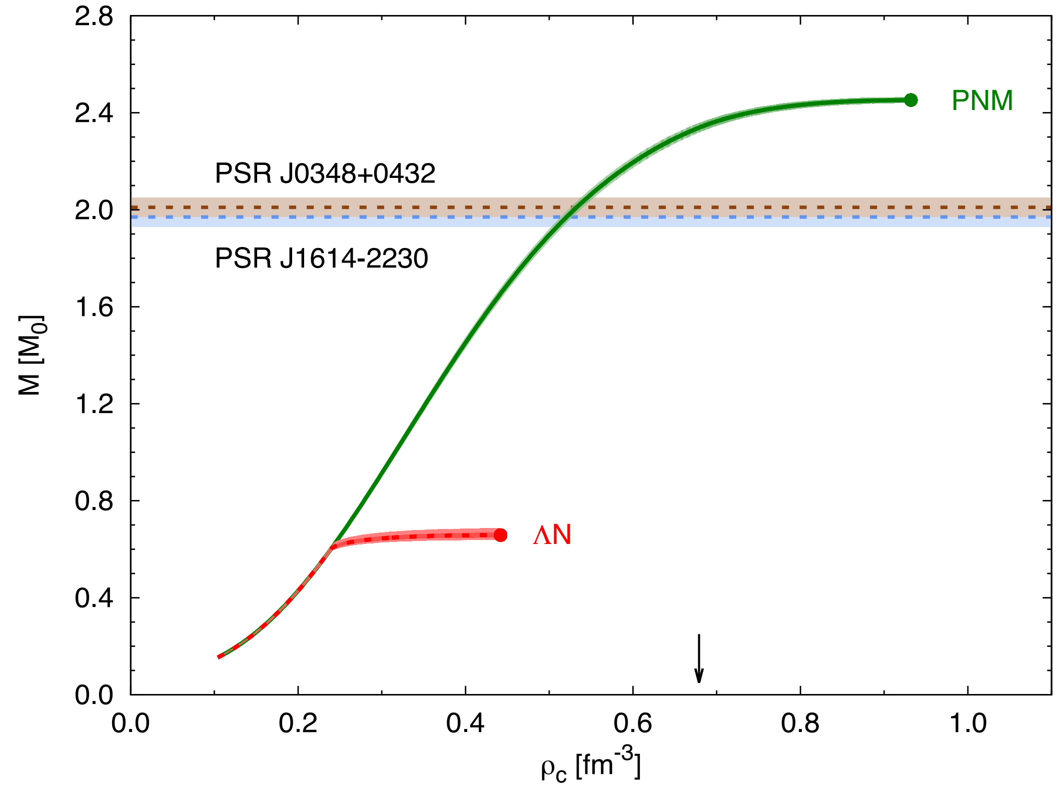
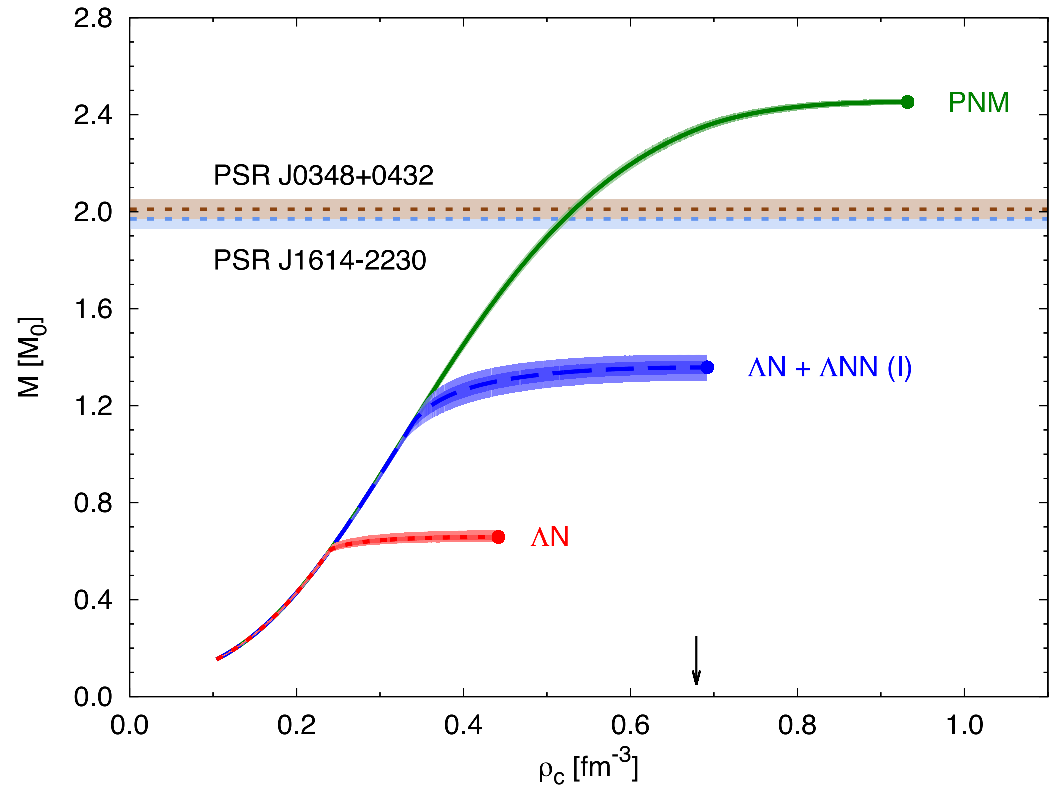
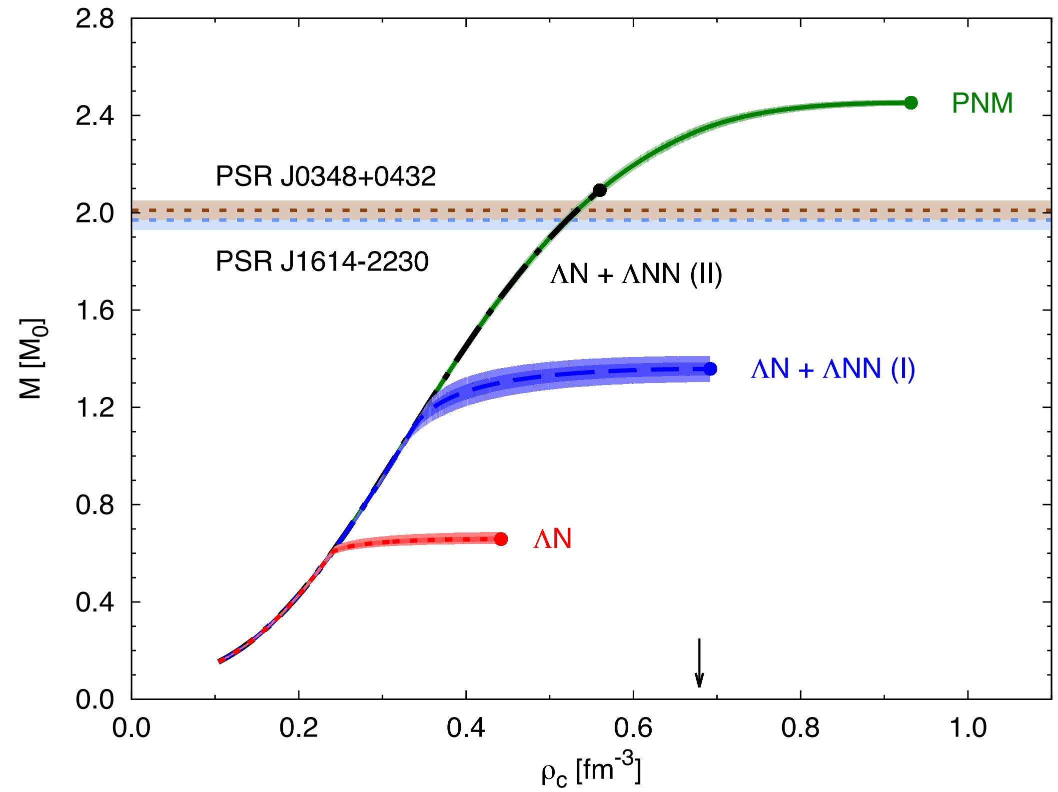




Within this model the repulsion needed to correctly describe hypernuclear binding energy is so strong that **hyperons would not be present in $2M_\odot$ stars!**



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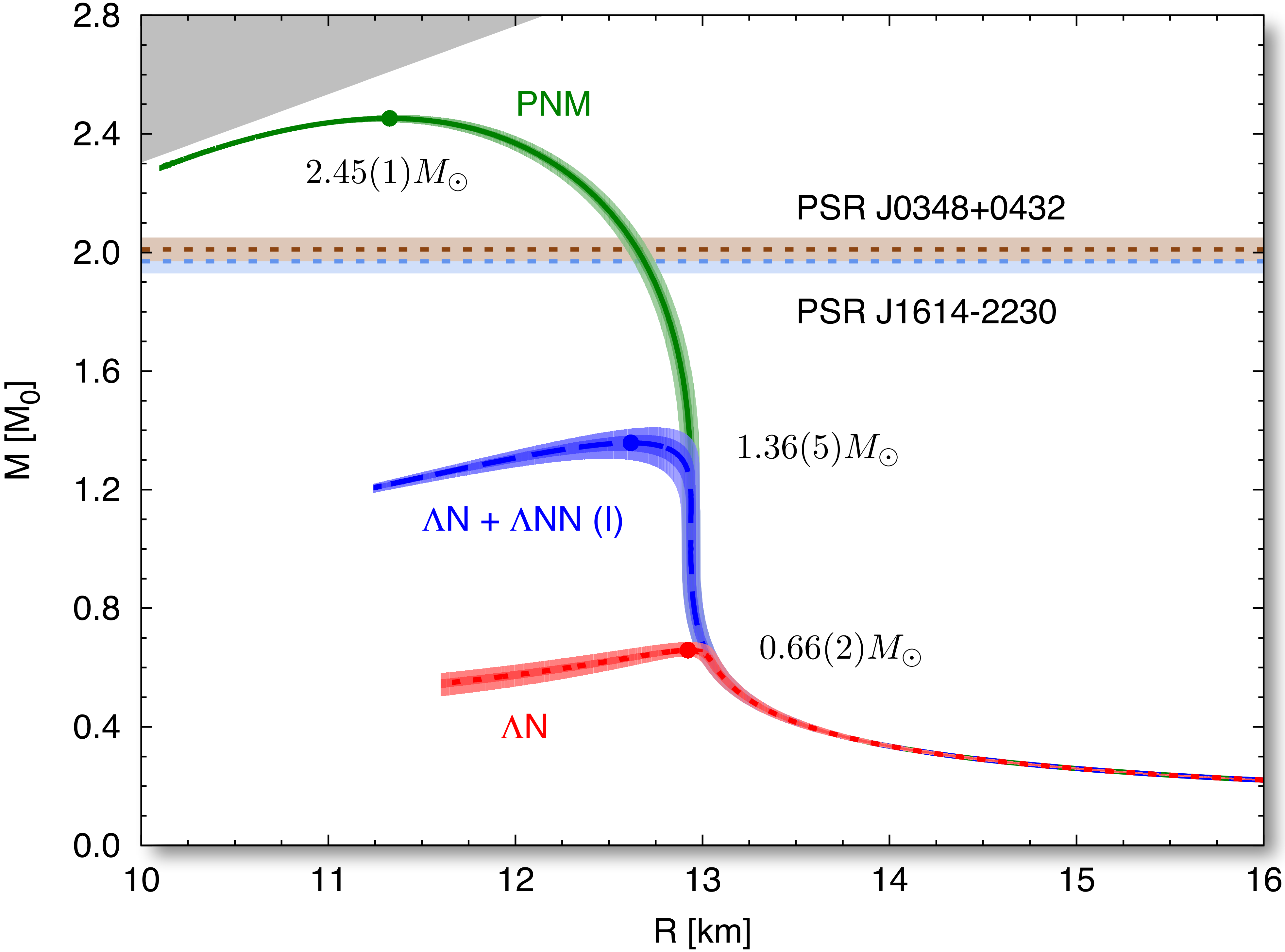

Diego Lonardoni, A. Lovato, S. Gandolfi, FP, arXiv:1407.4448 [nucl-th], submitted to Phys. Rev. Lett.

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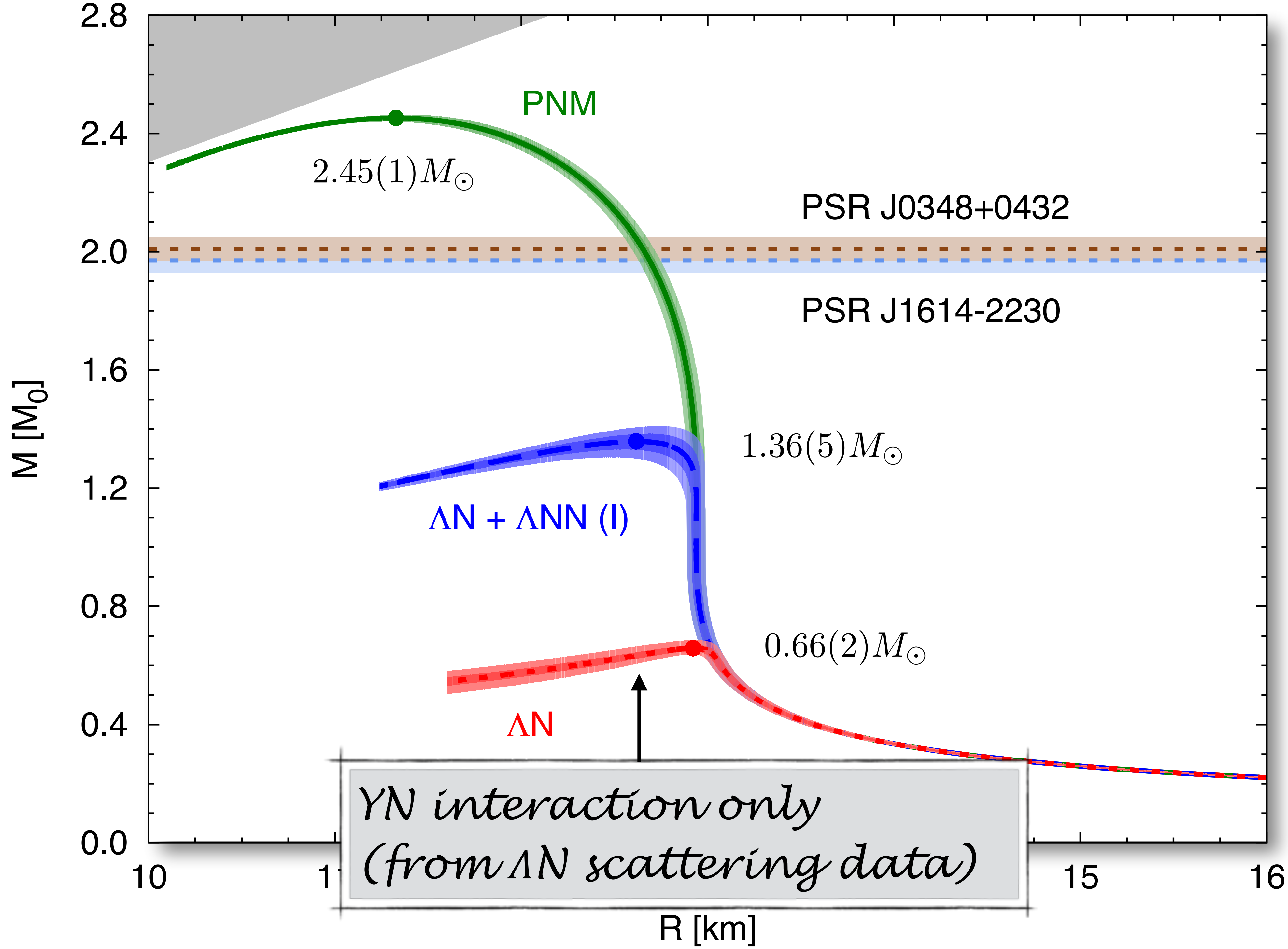

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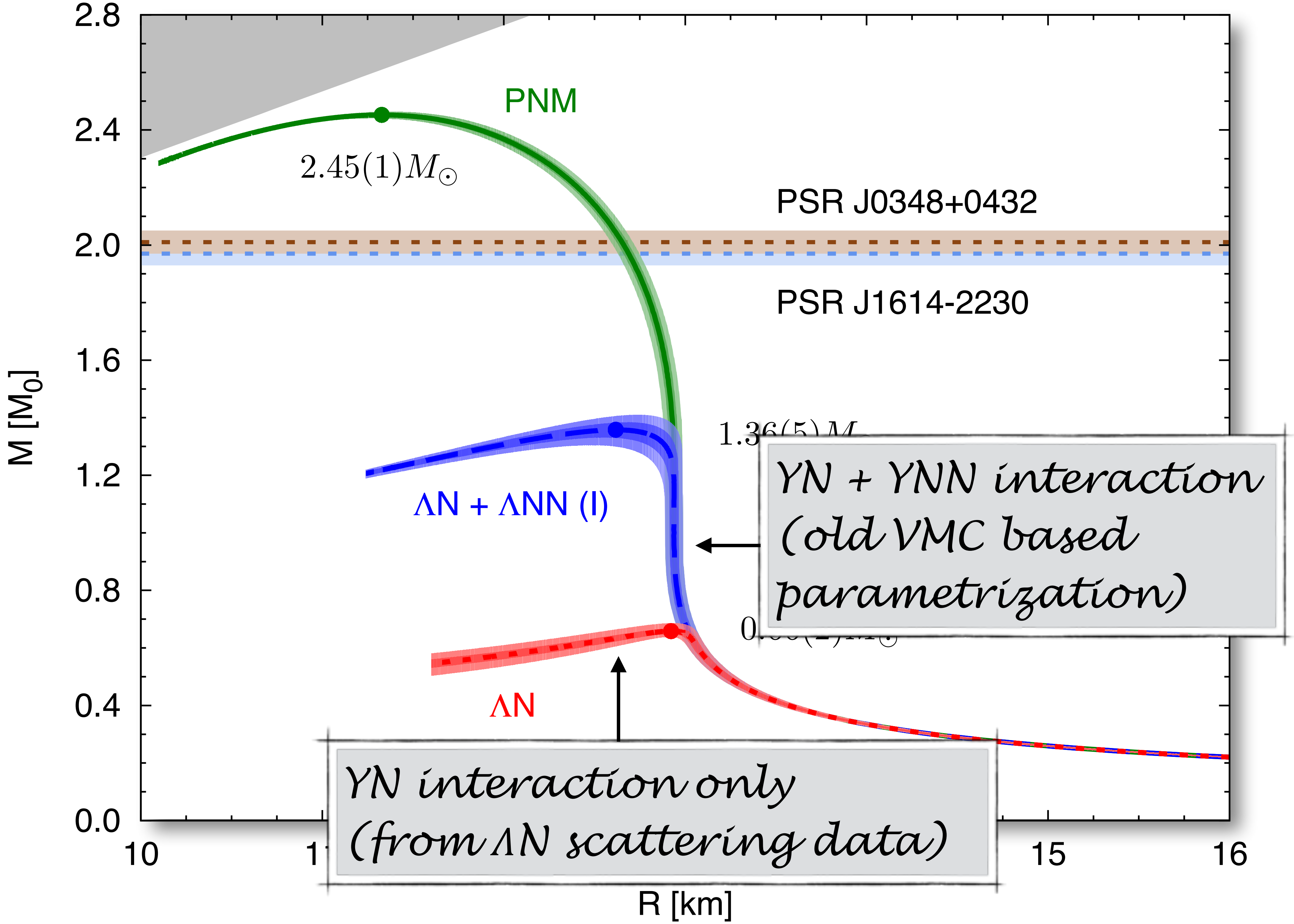

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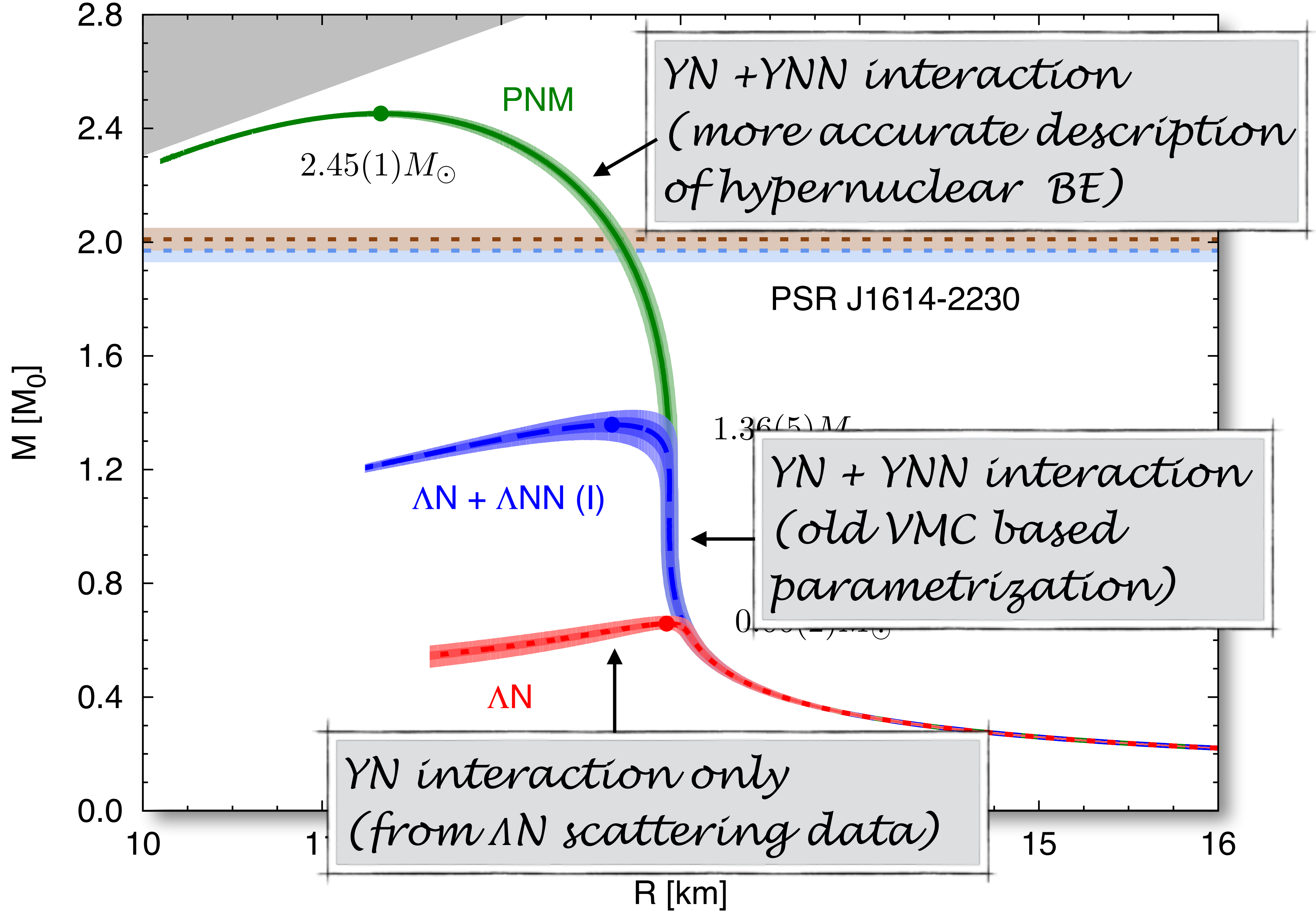

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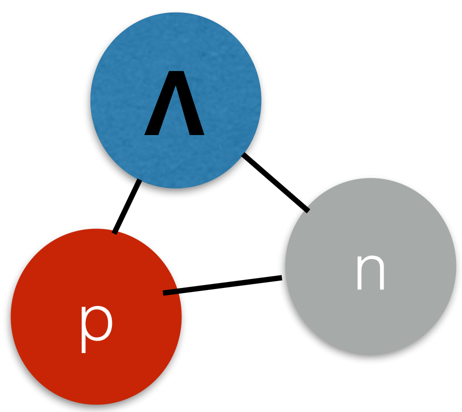
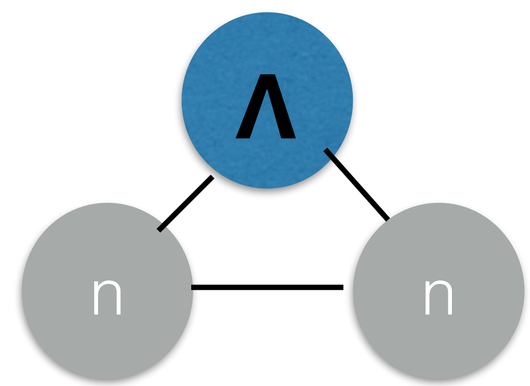
Can we really constrain ΛNN interaction from hyper nuclear data?

In hypernuclei it is possible that the ΛNN interaction is not well constrained, especially in the isospin triplet channel:

NN isospin singlet



NN isospin triplet



We are doing the exercise of re-projecting the interaction in the isospin singlet and triplet channels and try to explore the dependence of the hypernuclei binding energy on the relative strength.

$$v^{2\pi,P} = -\frac{C_P}{6}\left\{X_{i\lambda}, X_{\lambda j}\right\}\vec{\tau}_i\cdot\vec{\tau}_j$$

$$v^{2\pi,S} = C_S O^{2\pi,S}_{ij\lambda}\vec{\tau}_i\cdot\vec{\tau}_j$$

$$v^{\tau\tau}_{ij\lambda} = -3v^{P}_{ij\lambda}\hat{P}^{T=0}_{ij} + C_T v^{P}_{ij\lambda}\hat{P}^{T=1}_{ij}$$

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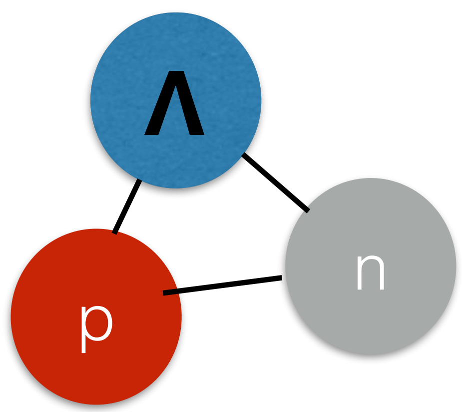

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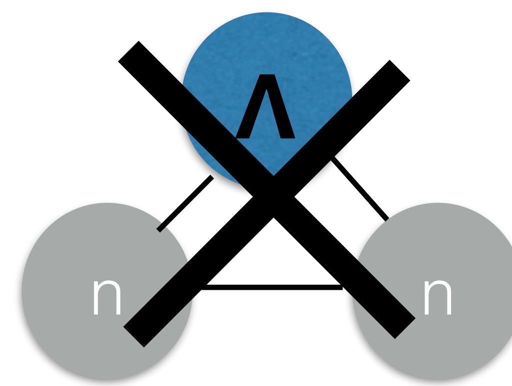

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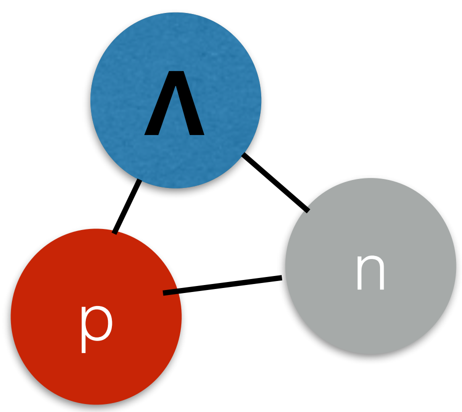

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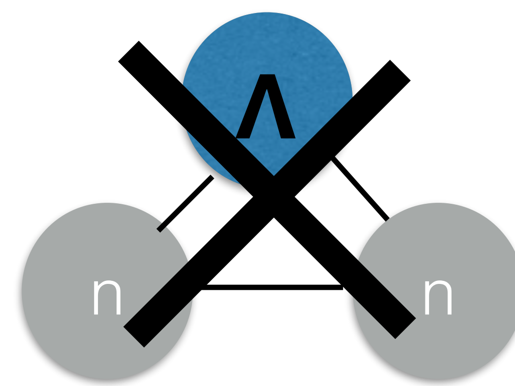

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C_T=1 gives the original potential, but we can choose an **arbitrary value**.
$C_T < 1 \Rightarrow$ more repulsion

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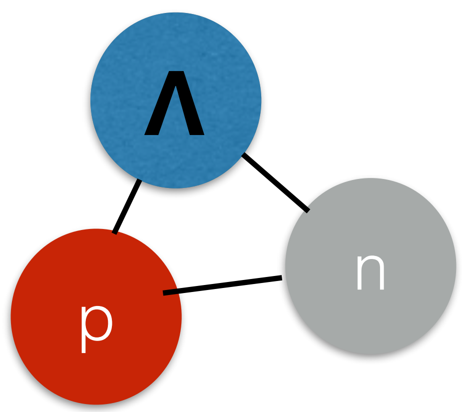

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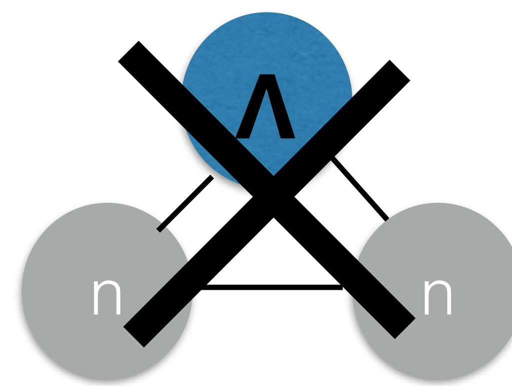

Pauli repulsion

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must be **negative on average** to give repulsion

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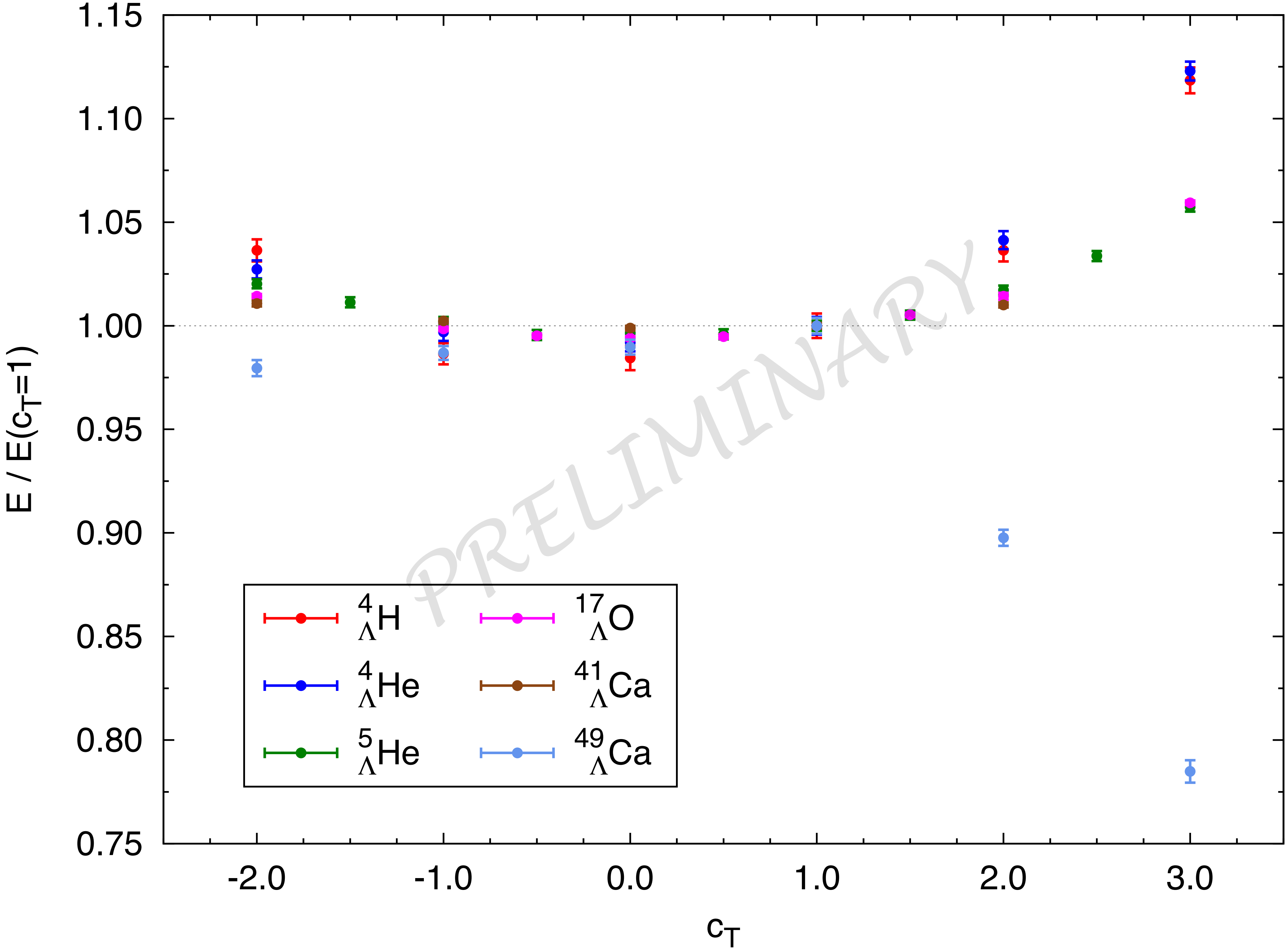

Francesco Catalano, Diego Lonardoni, FP, unpublished

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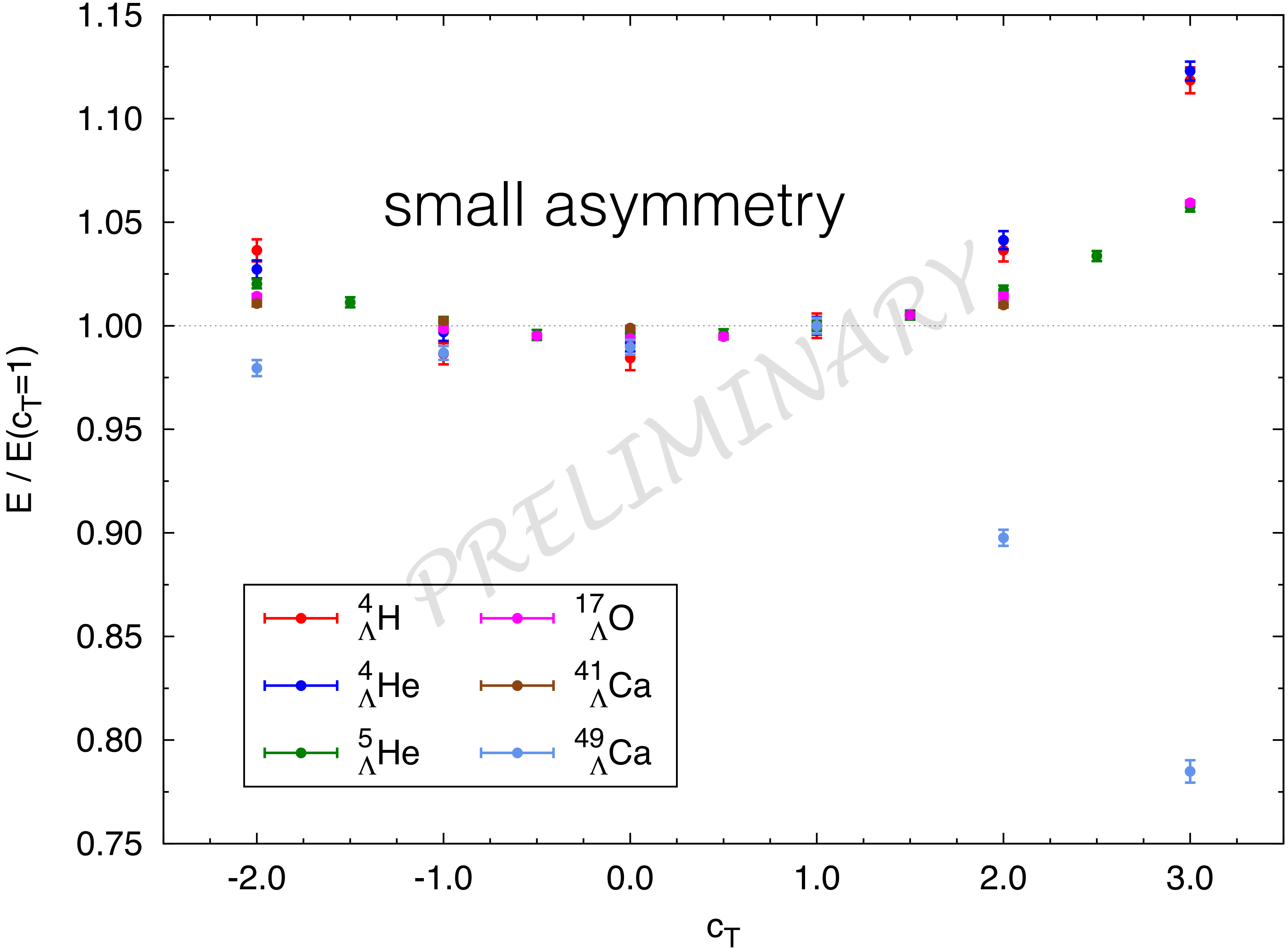

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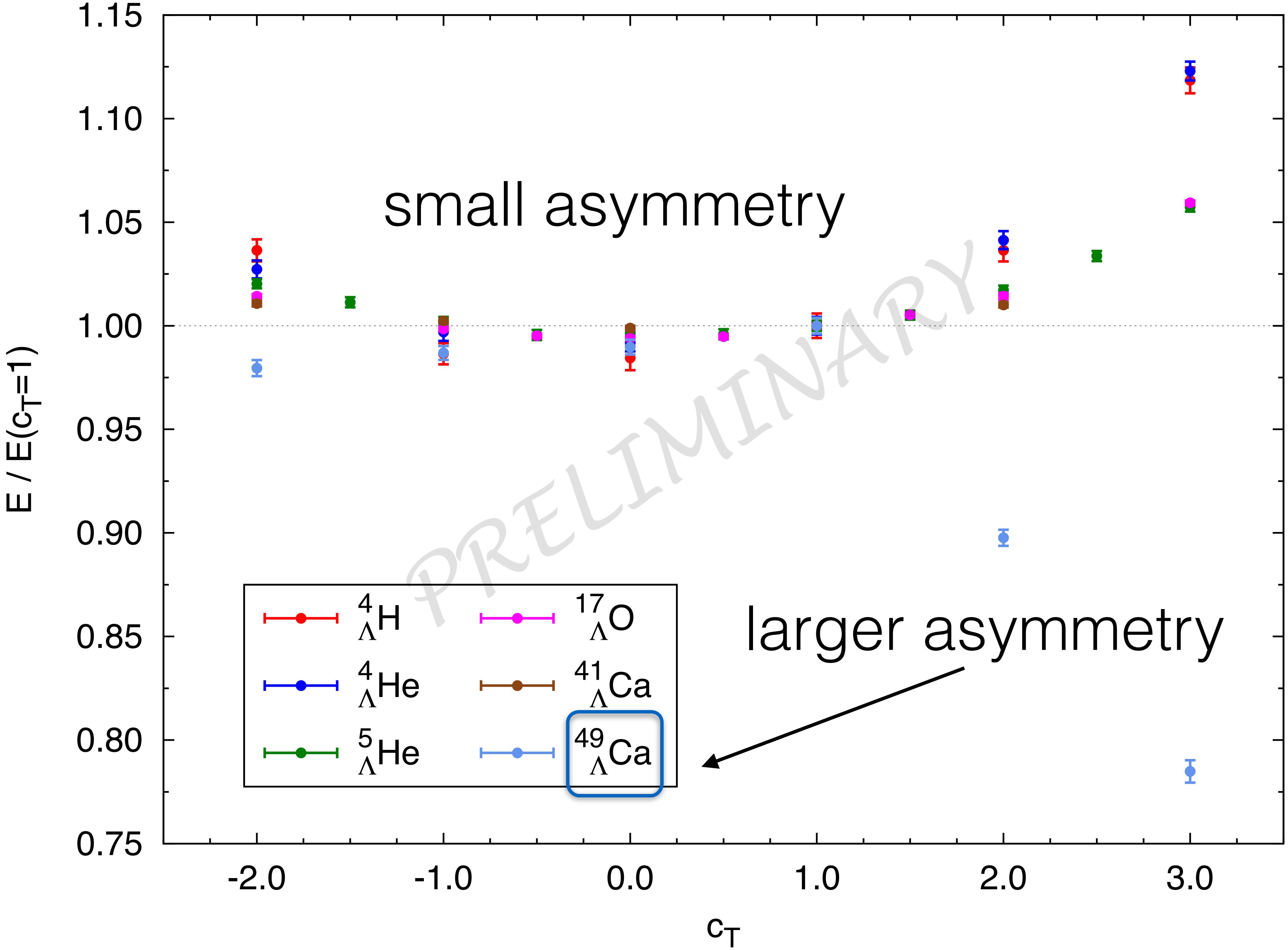

Francesco Catalano, Diego Lonardoni, FP, unpublished

Conclusions

Status

- The three-body hyperon-nucleon force provides the necessary repulsion to reproduce the ground state physics of medium-light hypernuclei
- The three-body hyperon-nucleon interaction plays a fundamental role in the softening of the EoS and for the consequent reduction of the predicted maximum mass.

Needs & Developments

- experimental inputs: scattering data, energy spectrum (gs+exc), CSB effects
- benchmark calculations
- different NN(N) and YN(N) potentials: Nijmegen, chiral, isospin
- projected realistic (hyper)nuclear matter in beta equilibrium
- medium-heavy mass hypernuclei [(e,e',K), proposal submitted at JLab]