Constraints on the isospin dependence of the lambda-nucleon force from hypernuclear binding energies

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Collaborators
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Outline

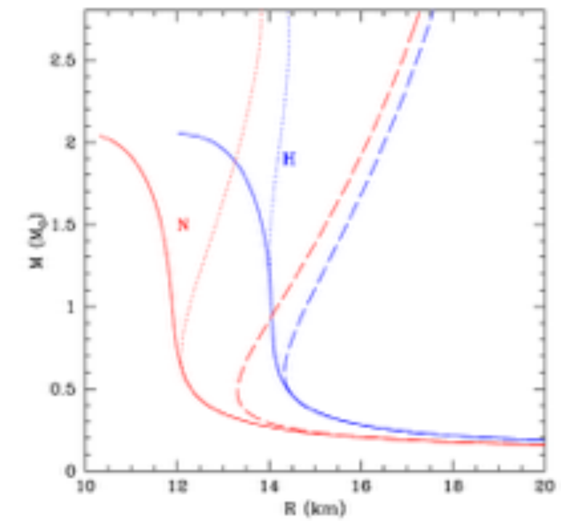
- Why do we care about details in the YN interaction
- A non-relativistic model of the hyperon(Λ)-nucleon interaction (for “normal” baryonic matter).
- Connection to the existing (and future?) experimental data: computation of BE in hypernuclei by QMC.
- Conclusions

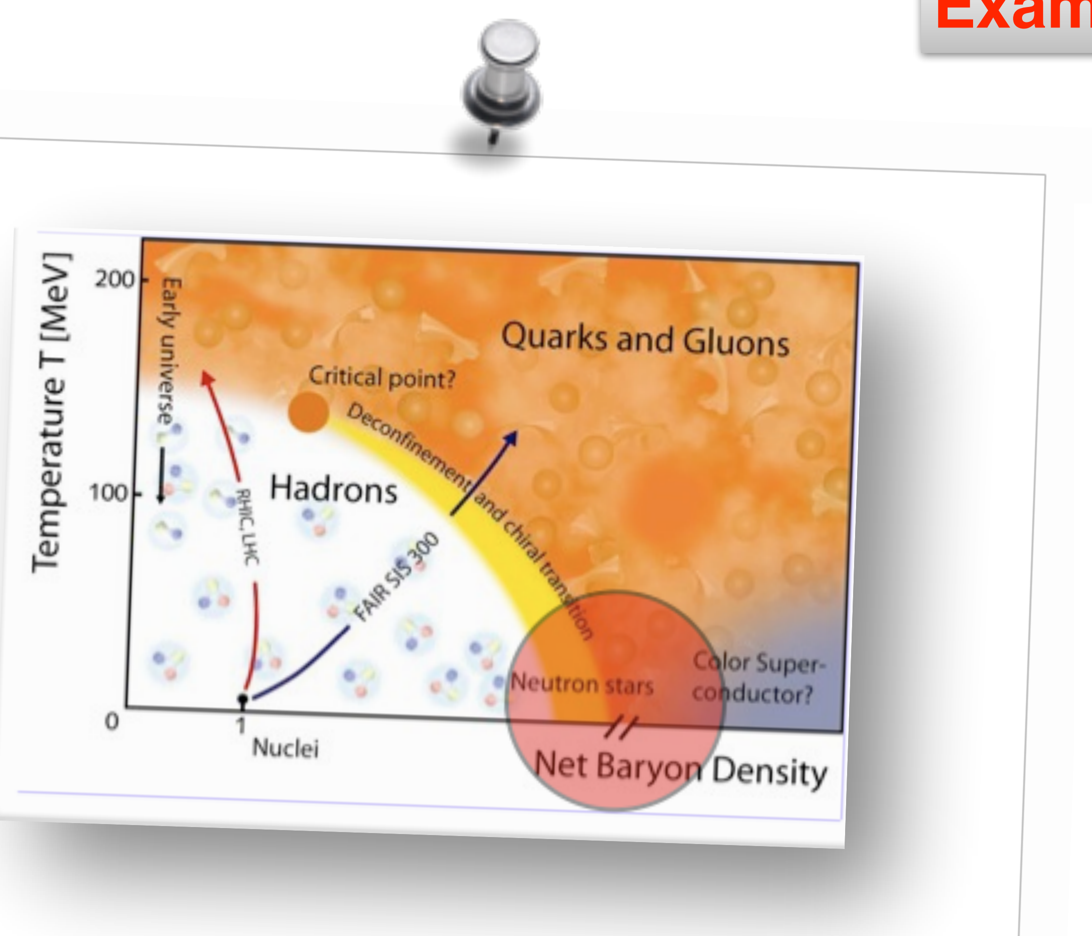
Open questions...

The *fine tuning* of the hyperon-nucleon interaction is essential to understand the behaviour of matter in extreme conditions.

Example: Neutron stars

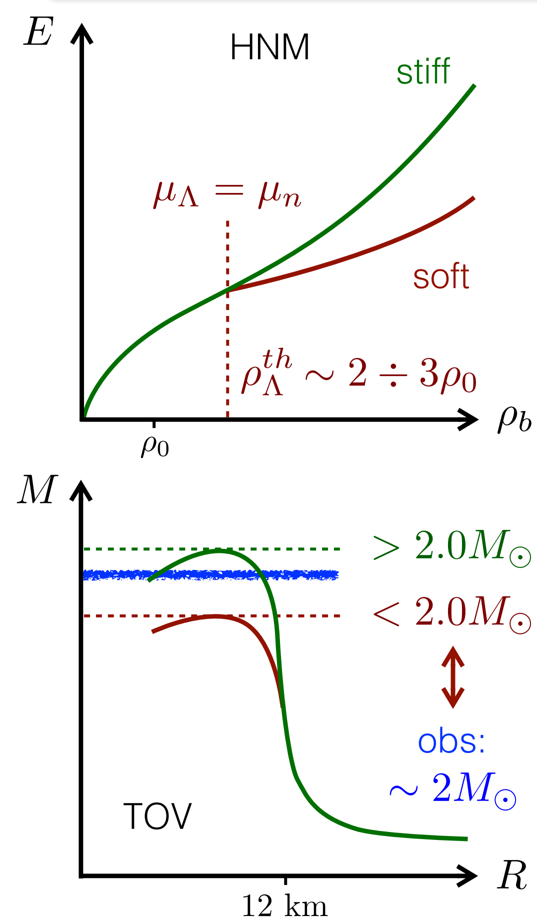
Fortin, M., Zdunik, J. L., Haensel, P., & Bejger, M. (2015). *Astronomy & Astrophysics*, *576*, A68.



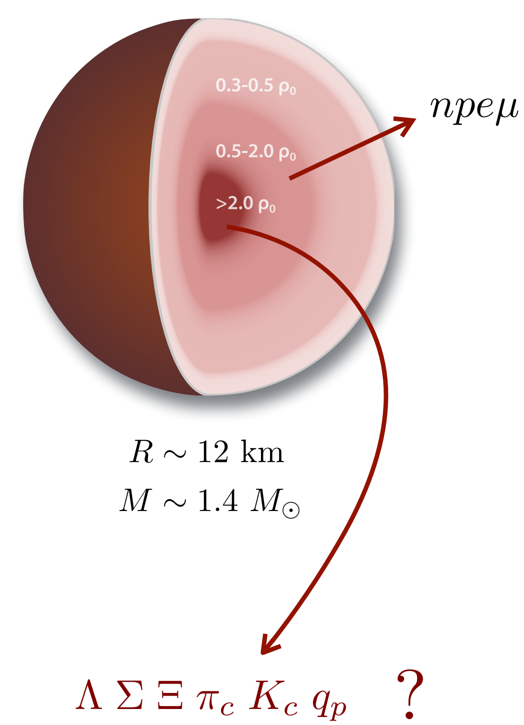


Far away from any possible perturbative treatment..

Equation of state



Neutron star structure

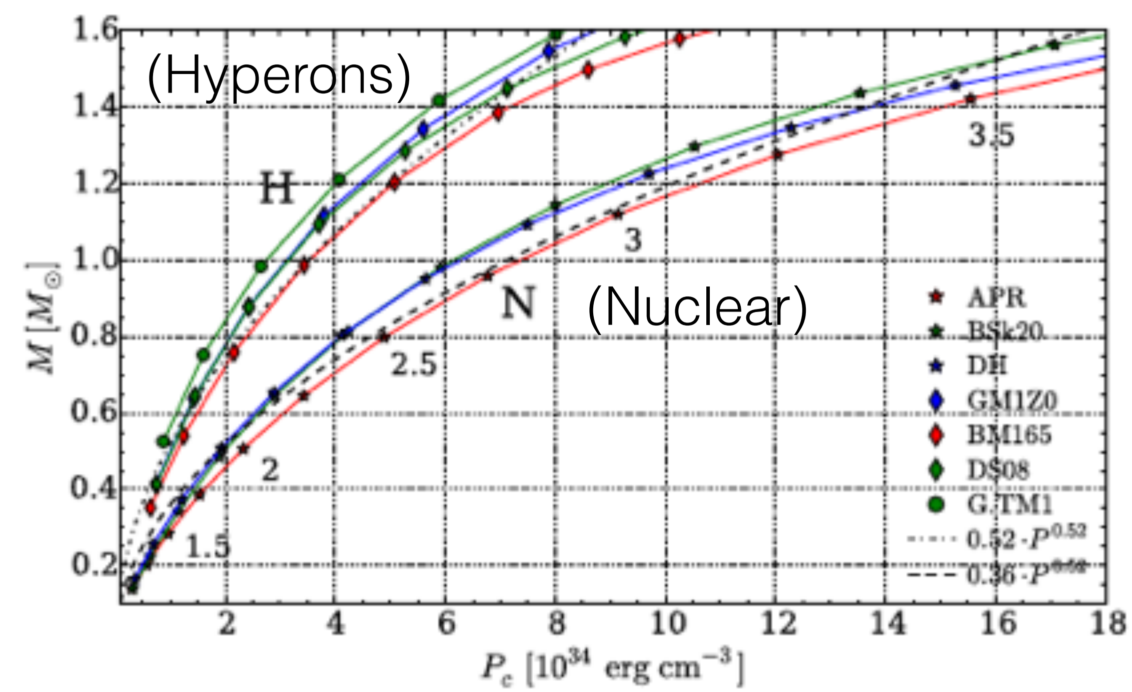


Internal composition still largely unknown

So many different models!

Table A.1. Parameters of the EOS and of NS models based on them.

EOS	$P(n_0)$ (10^{33} dyn cm^{-2})	$\rho(n_0)$ (10^{14} g cm^{-3})	$R_{1.4}^{(CL)}$ (km)	$R_{1.4}$ (km)	L_s (MeV)	$R_{M_{max}}$ (km)	M_{max} $M_\odot$
APR	3.05	2.72	15.01	11.34	59	9.93	2.19
BSk20	3.20	2.72	14.95	11.75	37	10.18	2.17
DH	3.60	2.72	15.03	11.73	46	9.99	2.05
BM165	6.45	2.74	15.46	13.59	74	10.68	2.03
DS08	7.58	2.74	15.52	13.91	88	12.02	2.05
GM1Z0	7.45	2.72	15.51	13.95	94	12.05	2.29
M.CQMCC	7.47	2.73	15.61	13.97	91	12.12	2.08
SA.BSR2	5.60	2.70	15.40	13.51	62	11.65	2.03
SA.TM1	9.58	2.82	16.35	14.86	110	12.52	2.10
G.TM1	8.78	2.75	15.91	14.51	110	12.51	2.06
M.TM1C	8.77	2.74	15.94	14.57	111	12.61	2.03
SA.NL3	8.91	2.72	16.14	15.02	118	12.83	2.32
M.NL3B	8.97	2.74	15.98	14.92	118	13.18	2.07
M.GM1C	7.45	2.72	15.61	14.06	94	12.28	2.14
SA.GM1	7.41	2.71	15.64	14.03	94	11.98	2.02
UU1	9.95	2.72	15.78	15.04	117	11.97	2.21
UU2	10.09	2.73	15.79	13.81	117	10.98	2.12



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BSk20	3.20	2.72	14.95	11.75	37	10.1[illegible]	2.17
DH	3.60	2.72	15.03	11.73	46	9.9[illegible]	2.05
BM165	6.45	2.74	15.46	13.59	74	10.6[illegible]	2.03
DS08	7.58	2.74	15.52	13.91	88	12.0[illegible]2	2.05
GM1Z0	7.45	2.72	15.51	13.95	94	12.0[illegible]5	2.29
M.CQMCC	7.47	2.73	15.61	13.97	91	12.[illegible]2	2.08
SA.BSR2	5.60	2.70	15.40	13.51	62	11.[illegible]5	2.03
SA.TM1	9.58	2.82	16.35	14.86	110	12.[illegible]2	2.10
G.TM1	8.78	2.75	15.91	14.51	110	12.[illegible]1	2.06
M.TM1C	8.77	2.74	15.94	14.57	111	12.6[illegible]1	2.03
SA.NL3	8.91	2.72	16.14	15.02	118	12.8[illegible]	2.32
M.NL3B	8.97	2.74	15.98	14.92	118	13.1[illegible]	2.07
M.GM1C	7.45	2.72	15.61	14.06	94	12.2[illegible]	2.14
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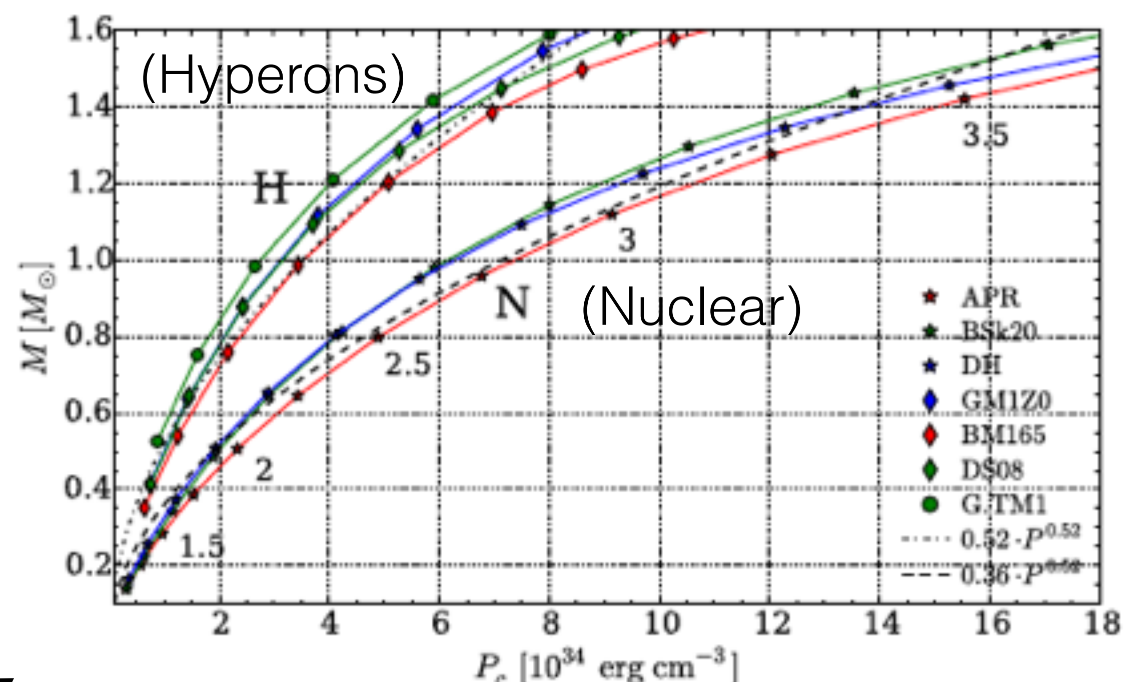
Fortin, M., Zdunik, J. L., Haensel, P., & Bejger, M.
Astronomy & Astrophysics, *576*, A68 (2015)



All masses compatible with the $2M_\odot$ constraint

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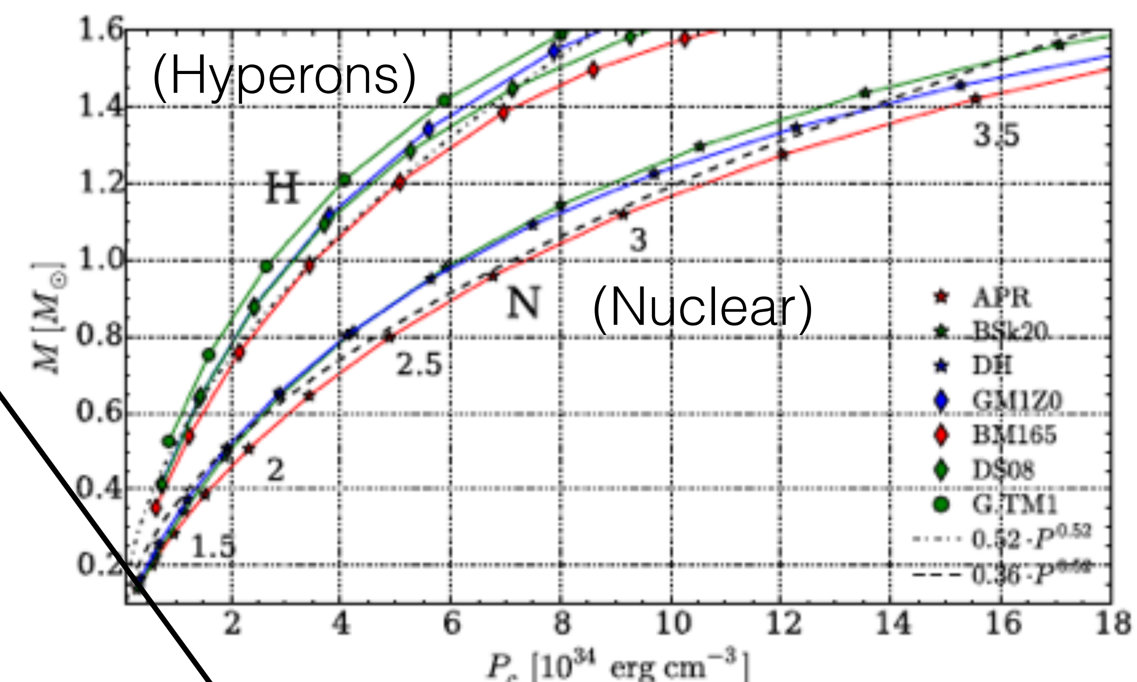

Radii roughly divided in two groups.

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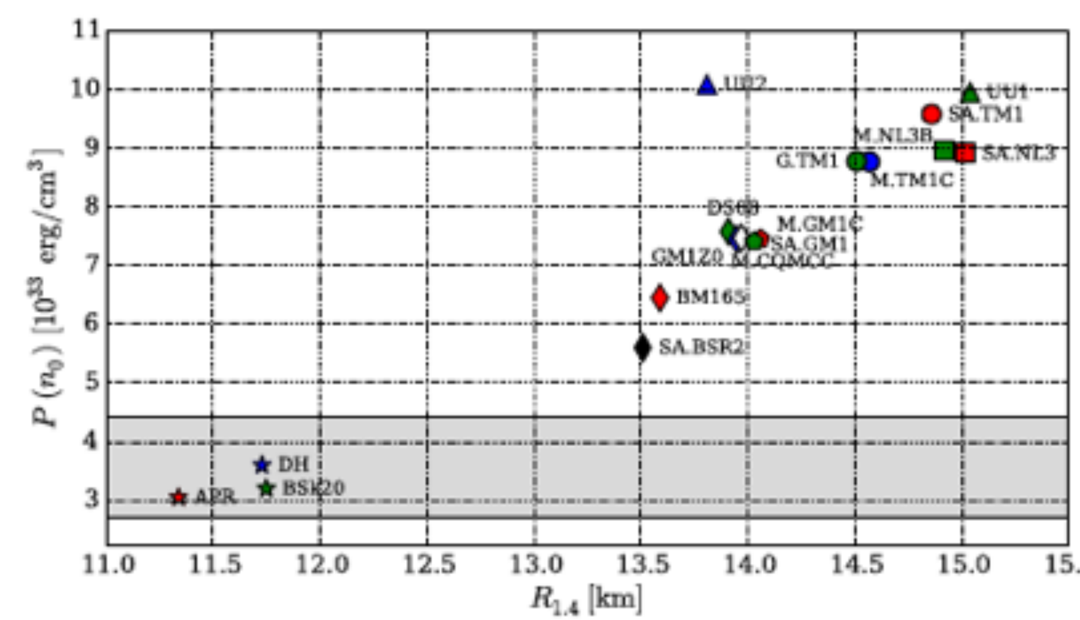


Many possible description of the YN interaction

NON RELATIVISTIC:

write an Hamiltonian including some potential and try to solve a many-body Schroedinger equation.

- The potential energy is **not an observable**: several different equivalent descriptions are possible.
- The interaction can be based on some more or less phenomenological scheme (fit the existing experimental data, rely on some systematic meson exchange model), or can be inferred from EFT systematic expansions.
- Only **accurate many-body calculations** can help distinguishing among different realisations of the potential.

RELATIVISTIC:

write a Lagrangian including relevant fields, and try to solve the field theoretical problem (usually RMF calculations are performed).

Some hints from LQCD.....

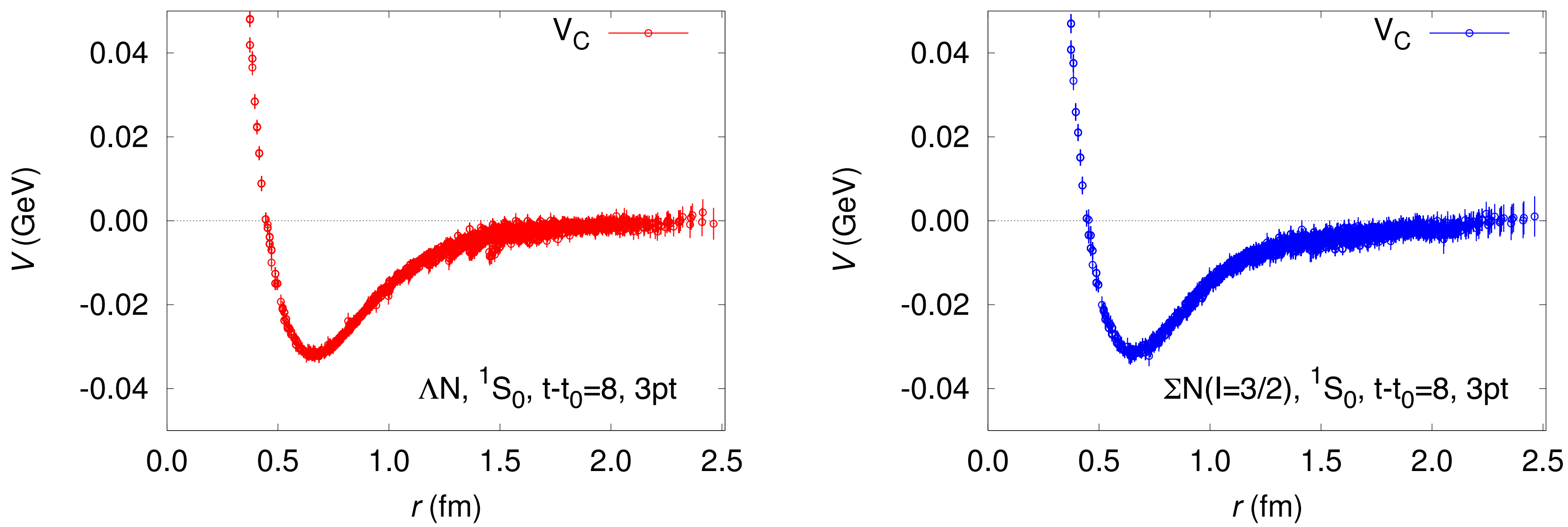


Fig. 10. Left: The central potential in the ${}^1S_0$ channel of the ΛN system in $2+1$ flavor QCD as a function of r. Right: The central potential in the ${}^1S_0$ channel of the $\Sigma N(I=3/2)$ system as a function of r.

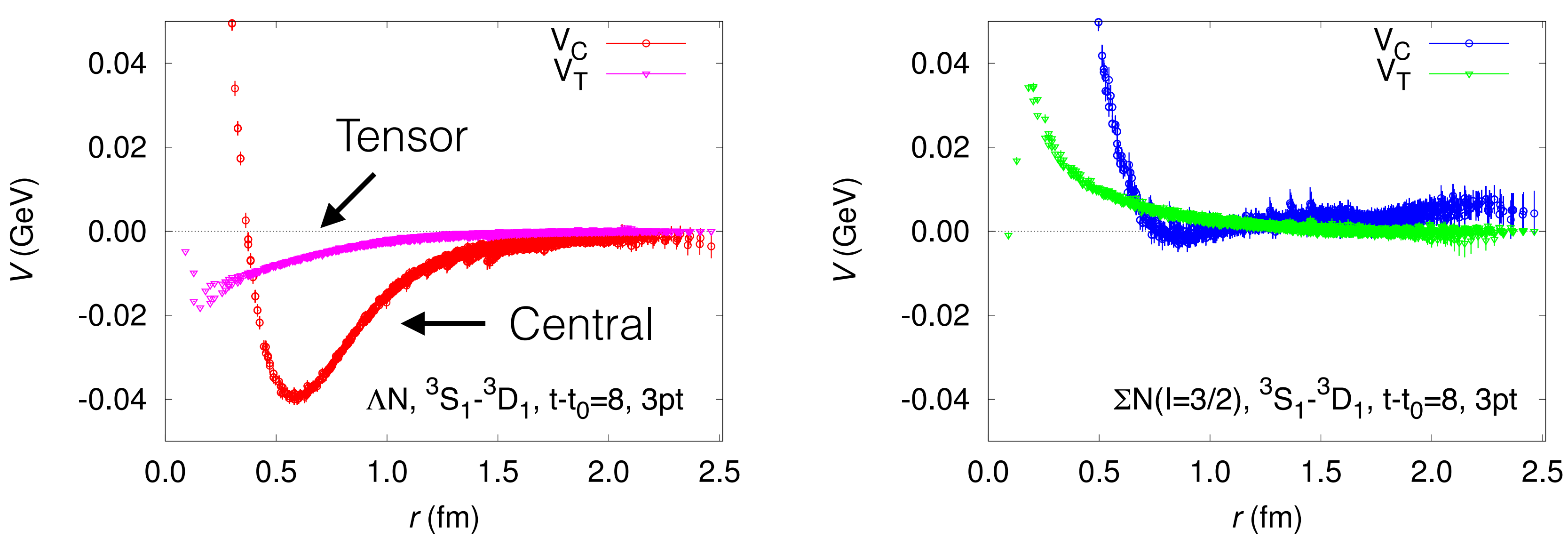
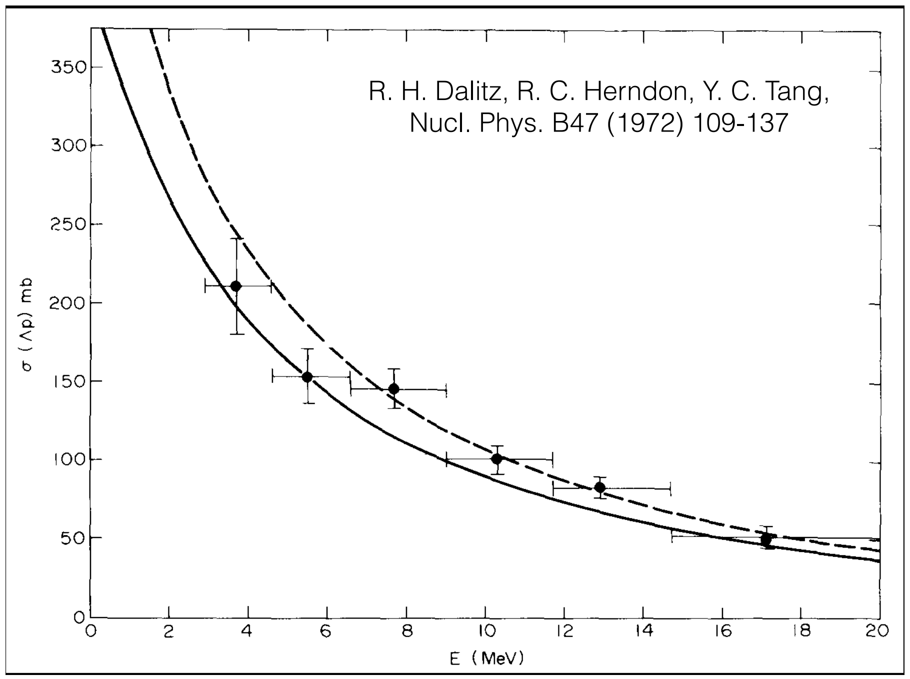


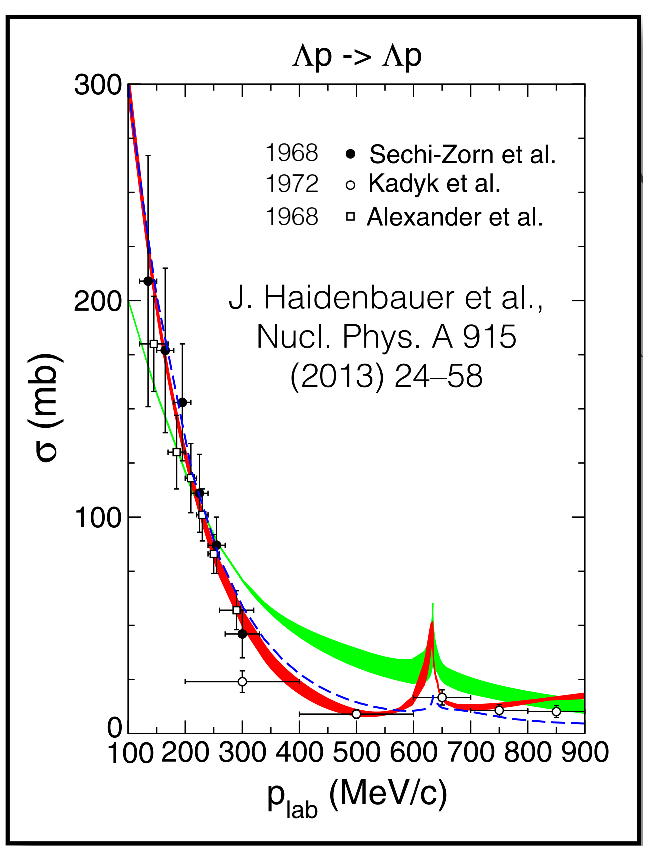
Fig. 11. Left: The central potential (circle) and the tensor potential (triangle) in the ${}^3S_1 -{}^3 D_1$ channel of the ΛN system as a function of r. Right: The central potential (circle) and the tensor potential (triangle) in the ${}^3S_1 -{}^3 D_1$ channel of the $\Sigma N(I=3/2)$ system as a function of r.

S. Aoki et al. (HAL-QCD collaboration)

Model Hyperon-nucleon interaction

In order to gain some understanding, we need to set up some scheme.





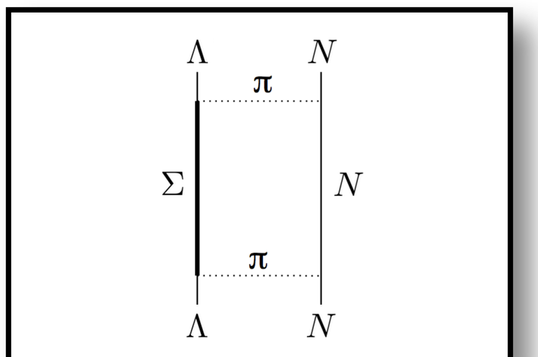
OUR CHOICE

- **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 the fewest possible parameters to be adjusted to reproduce light hypernuclei binding energies
- **ALL OF 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).

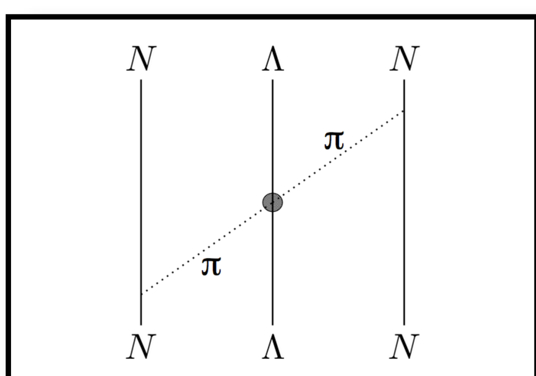


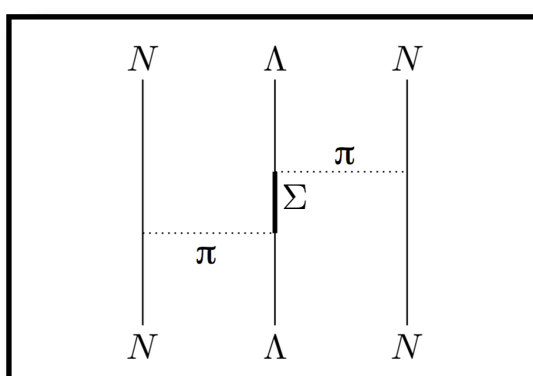
from Kaon exchange terms (not considered explicitly in our calculations)

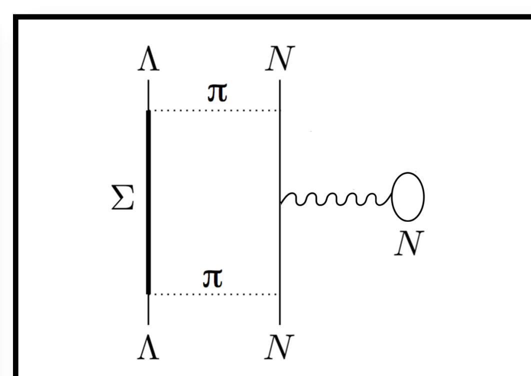
$$V_{\Lambda i}(r) = v_0(r) + v_0(r)\varepsilon(P_x - 1) + \frac{1}{4} v_\sigma T_\pi^2(m_\pi r) \boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_i$$

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

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







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

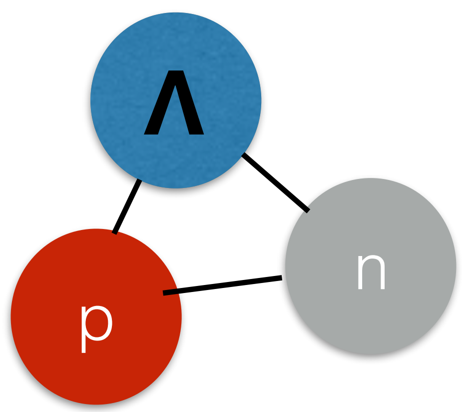
$$\begin{cases} V_{\Lambda ij}^{2\pi} = \boxed{C_{2\pi}^{SW}} \mathcal{O}_{\Lambda ij}^{2\pi, SW} + \boxed{C_{2\pi}^{PW}} \mathcal{O}_{\Lambda ij}^{2\pi, PW} \\ V_{\Lambda ij}^{D} = \boxed{W^D} T_\pi^2(m_\pi r_{\Lambda i})\, T_\pi^2(m_\pi r_{\Lambda j}) \left[1 + \frac{1}{6} \boldsymbol{\sigma}_\Lambda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

Parameters to be determined from calculations

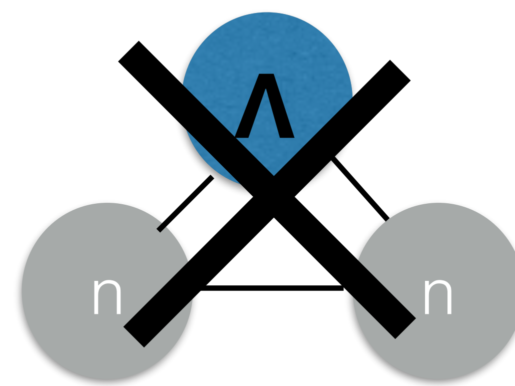
Non trivial isospin dependence in the three-body sector?

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



Pauli repulsion

On can try o do 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.

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

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

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

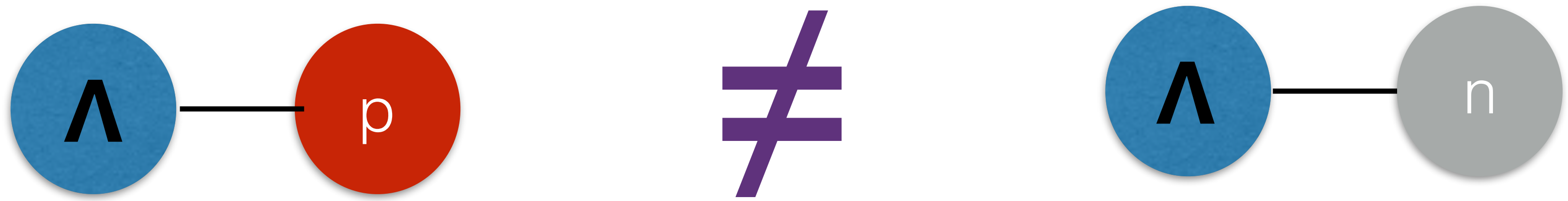
$$v^{2\pi,S} = C_S O^{2\pi,S}_{ij\lambda}\vec{\tau}_i \cdot \vec{\tau}_j$$

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

$$v^{\tau\tau}_{ij\lambda} = \frac{3}{4}(C_T - 1)v^P_{ij\lambda} + \frac{1}{4}(3 + C_T)v^P_{ij\lambda}\vec{\tau}_i \cdot \vec{\tau}_j$$

Charge symmetry breaking

Obviously one also has to consider CSB interactions



This adds a further parameter in the interaction:

$$v_{\lambda i}^{CSB} = C_\tau \, T_\pi^2 \left(r_{\lambda i} \right) \tau_i^z$$

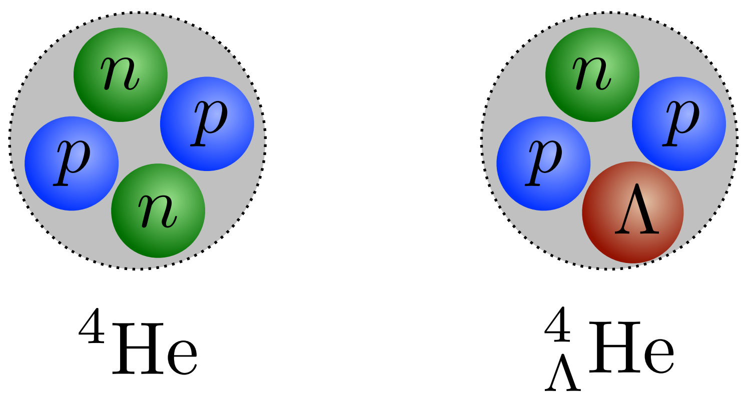
A. R. Bodmer, Q. N. Usmani, Phys.Rev.C 31, 1400 (1985)

Notice that no spin dependence has been added here. CSB interaction can be clearly seen in light nuclei. **What about heavier hypernuclei?**

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:**

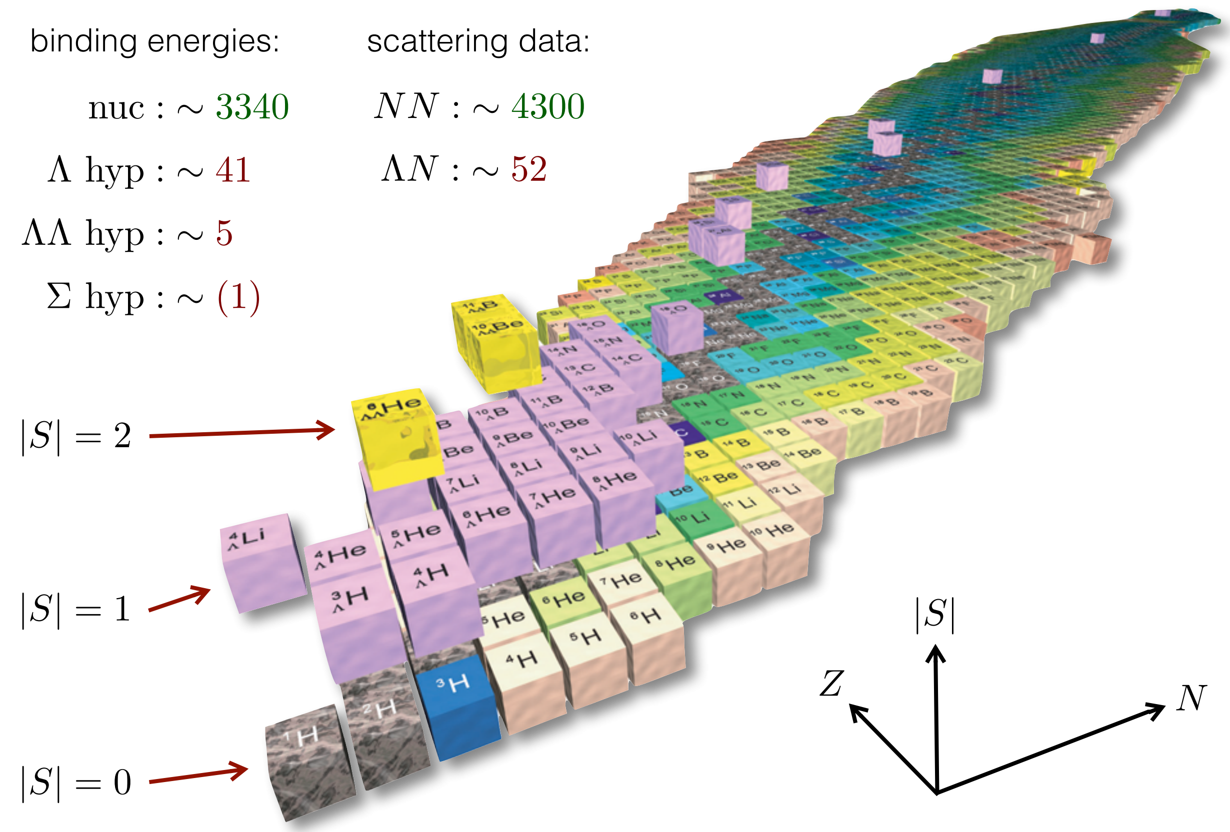
$$B_\Lambda = B_{hyp} - B_{nuc}$$

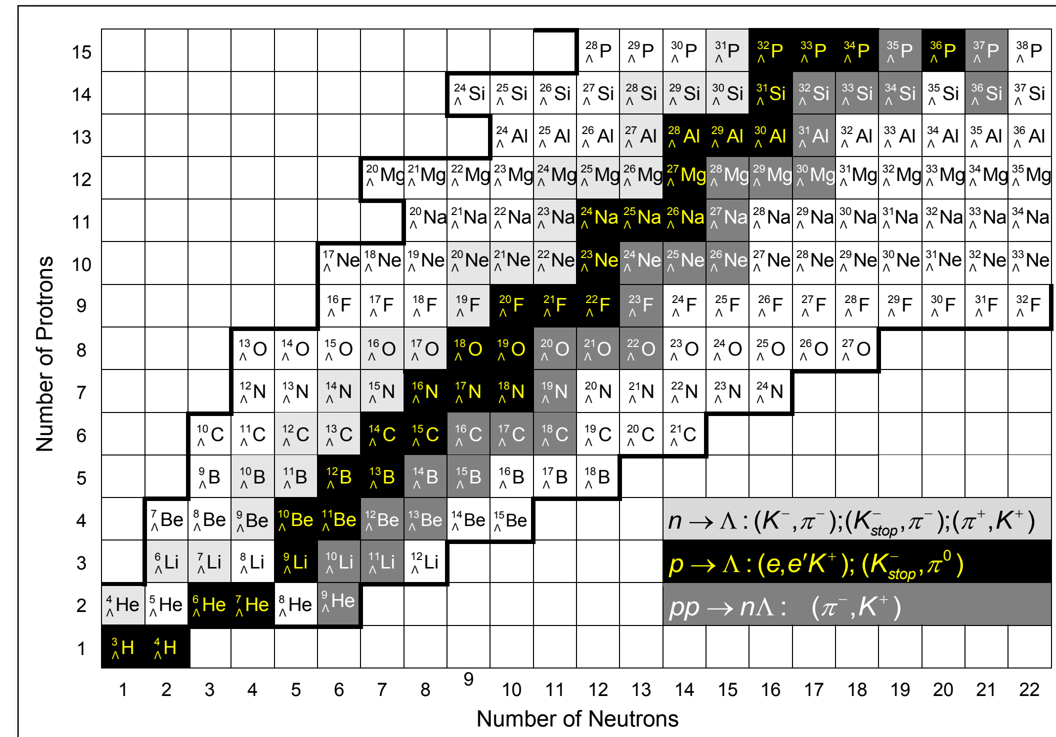


where B_{hyp} is the total binding energy of a hypernucleus with A nucleons and one Λ, and B_{nuc} is the total binding energy of the corresponding nucleus with A nucleons. This number can be used to gauge the coefficients in the nucleon-Λ interaction.

Hypernuclei data

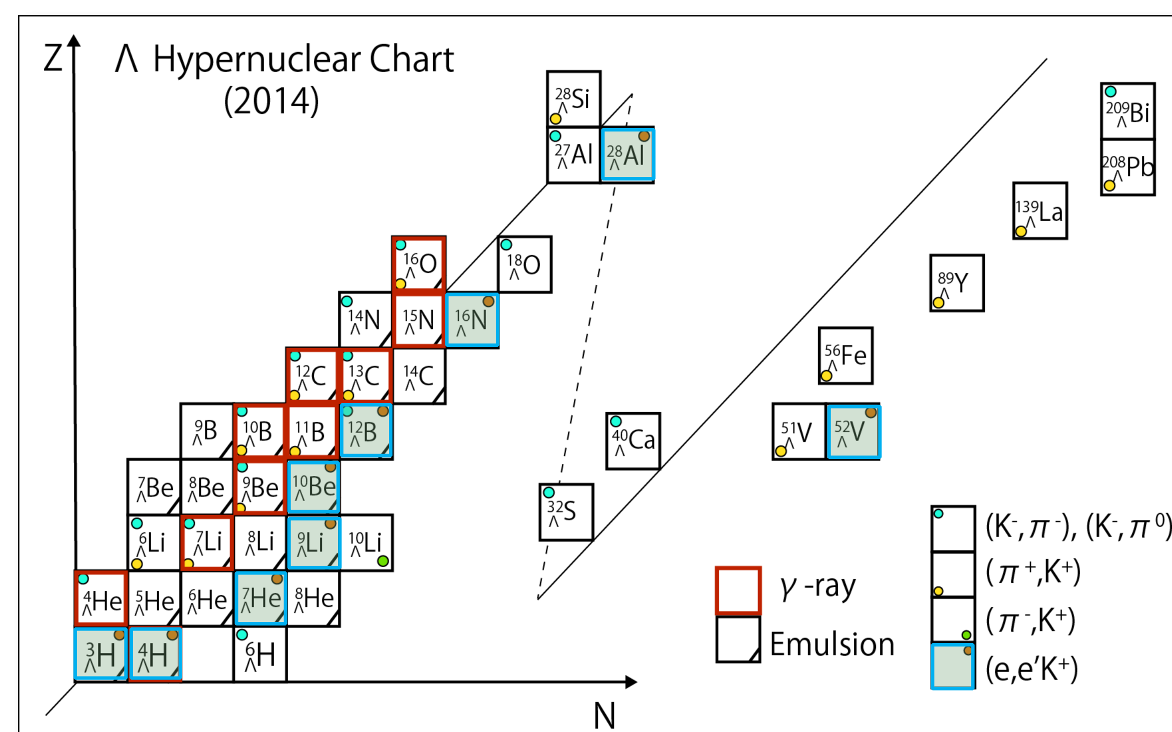
binding energies:	scattering data:
nuc : ~ 3340	$NN : \sim 4300$
Λ hyp : ~ 41	$\Lambda N : \sim 52$
$\Lambda\Lambda$ hyp : ~ 5	
Σ hyp : $\sim (1)$	





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-nucleon 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)

Many-Body theory: 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):

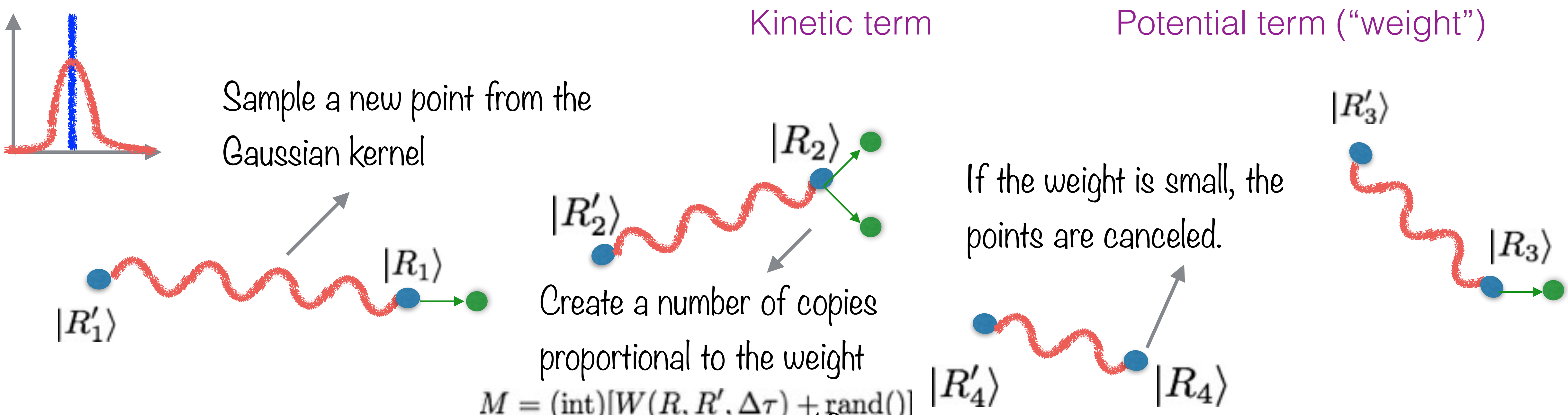
$$\langle R|\Psi(\tau)\rangle = \langle R|e^{-(\hat{H}-E_0)\tau}|R'\rangle\langle R'|\Psi(0)\rangle$$

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")

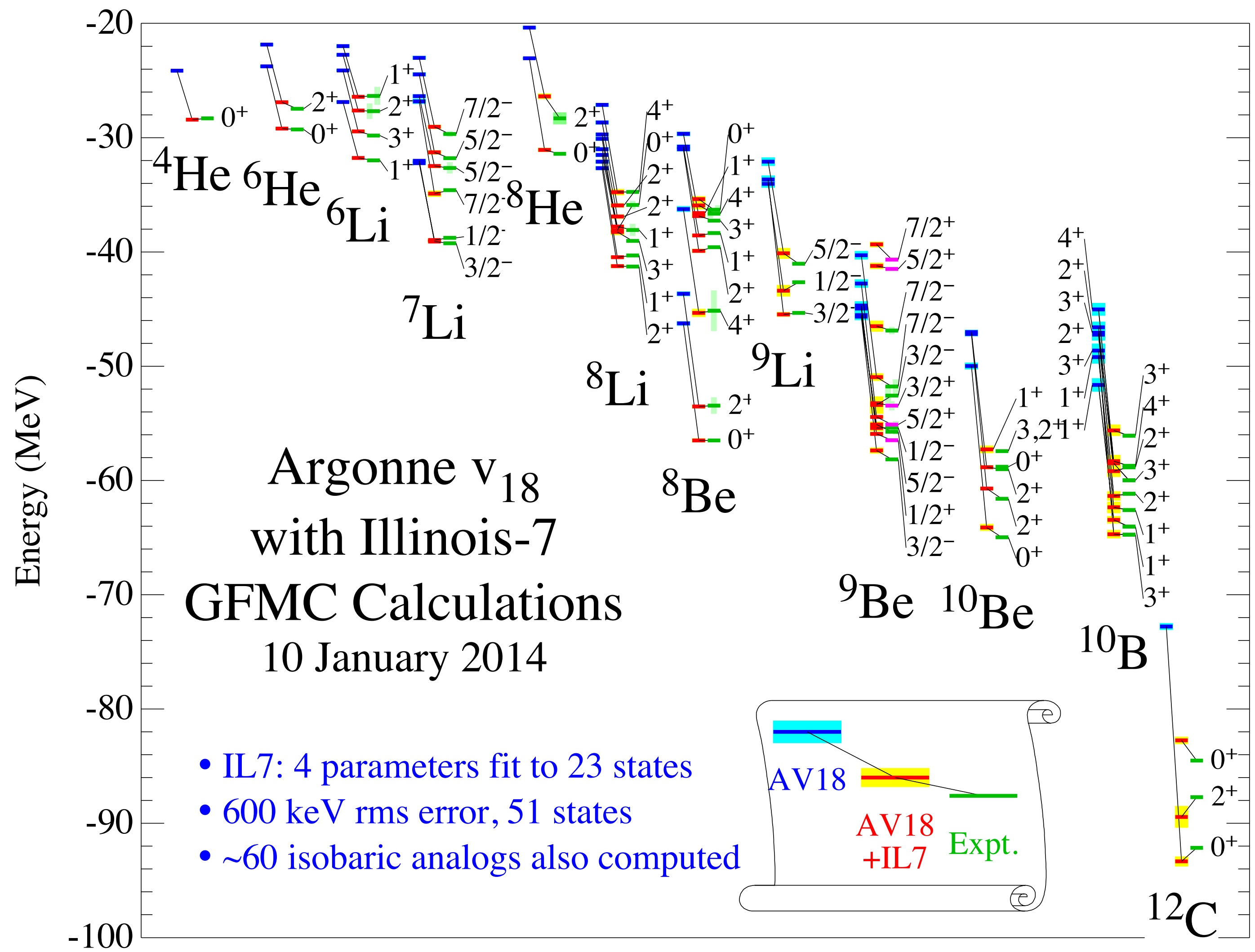


Many-nucleon systems

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

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

Hubbard-Stratonovich transformation

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)

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:

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

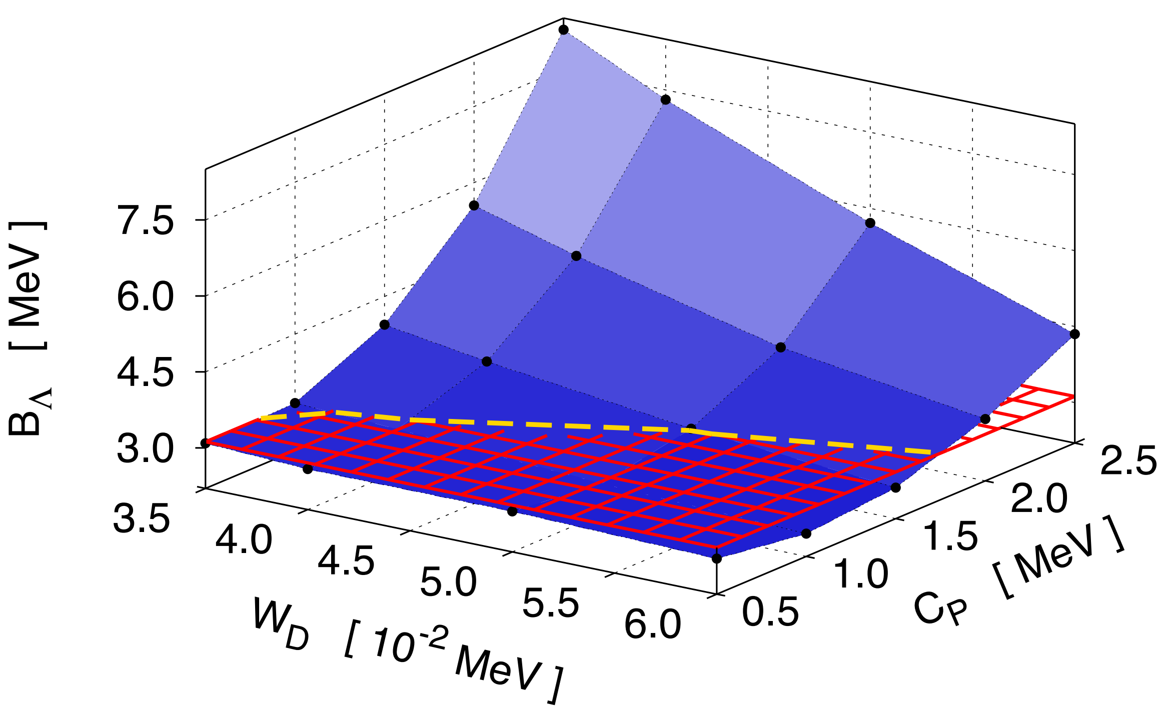
In a space of spinors, each factor corresponds to a rotation induced by the action of the Pauli matrices

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

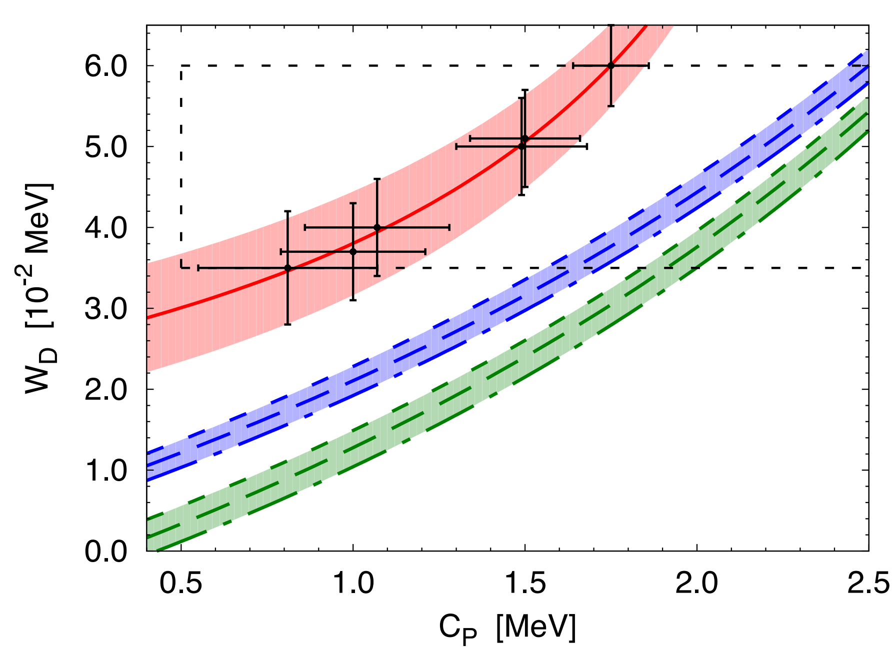
Input from experiment

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

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



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)

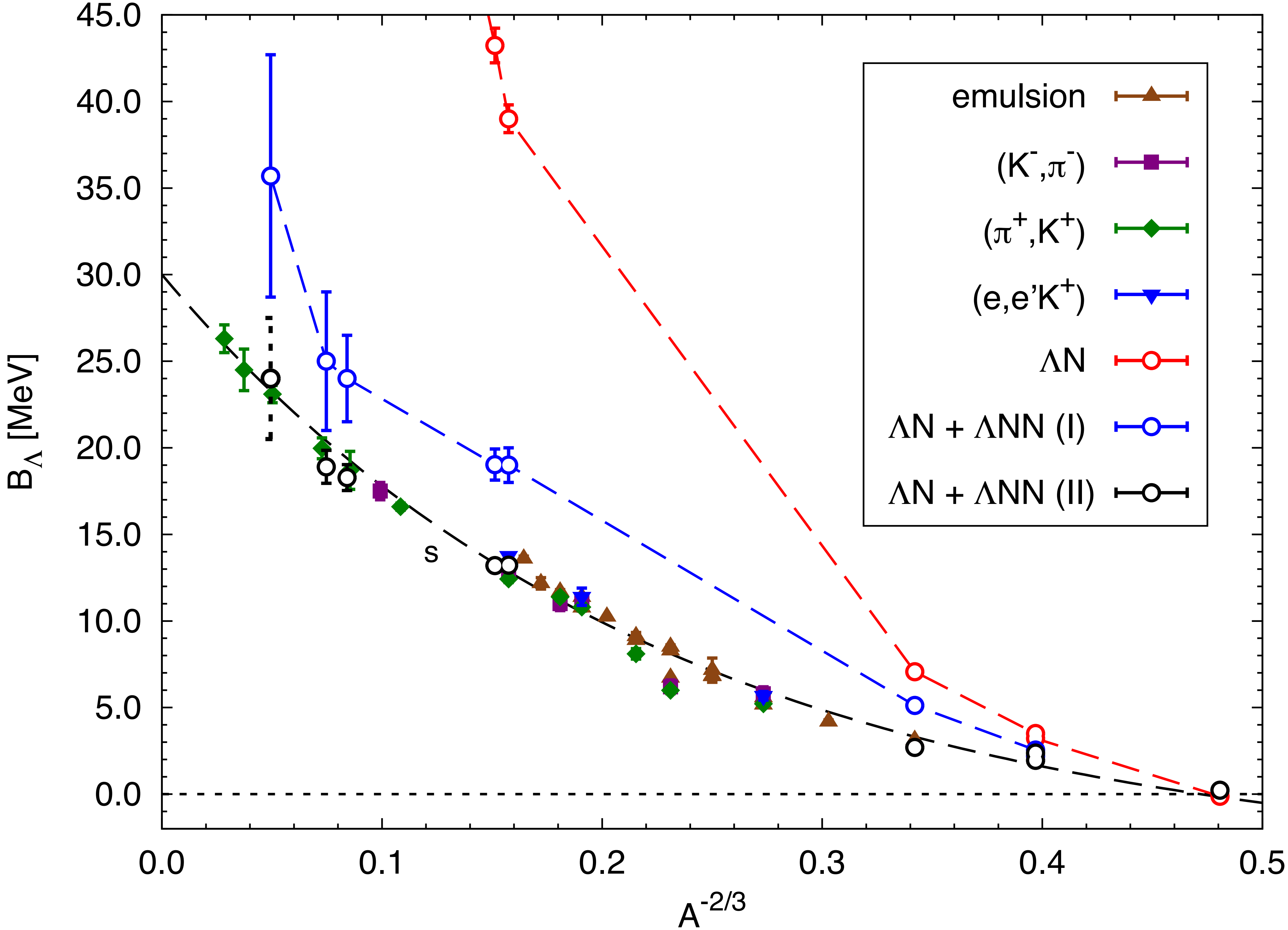
Hypernuclei

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 not so bad. Here we report some results.

nucleus	AV4′	AV6′	AV7′	AV4′+UIX$_c$	exp
^{4}He (0^+)	-32.83(5)	-27.09(3)	-25.7(2)	-26.63(2)	-28.295
^{15}O $(\frac{1}{2}^-)$	–	–	–	-99.43(2)	-111.955
^{16}O (0^+)	-180.1(4)	-115.6(3)	-90.6(4)	-119.9(2)	-127.619
^{39}K $(\frac{3}{2}^+)$	–	–	–	-360.8(2)	-333.724
^{40}Ca (0^+)	-597(3)	-322(2)	-209(1)	-383.3(3)	-342.051
^{44}Ca (0^+)	–	–	–	-397.8(5)	-380.960
^{47}K $(\frac{1}{2}^+)$	–	–	–	-386.3(2)	-400.199
^{48}Ca (0^+)	-645(3)	–	–	-413.2(3)	-416.001

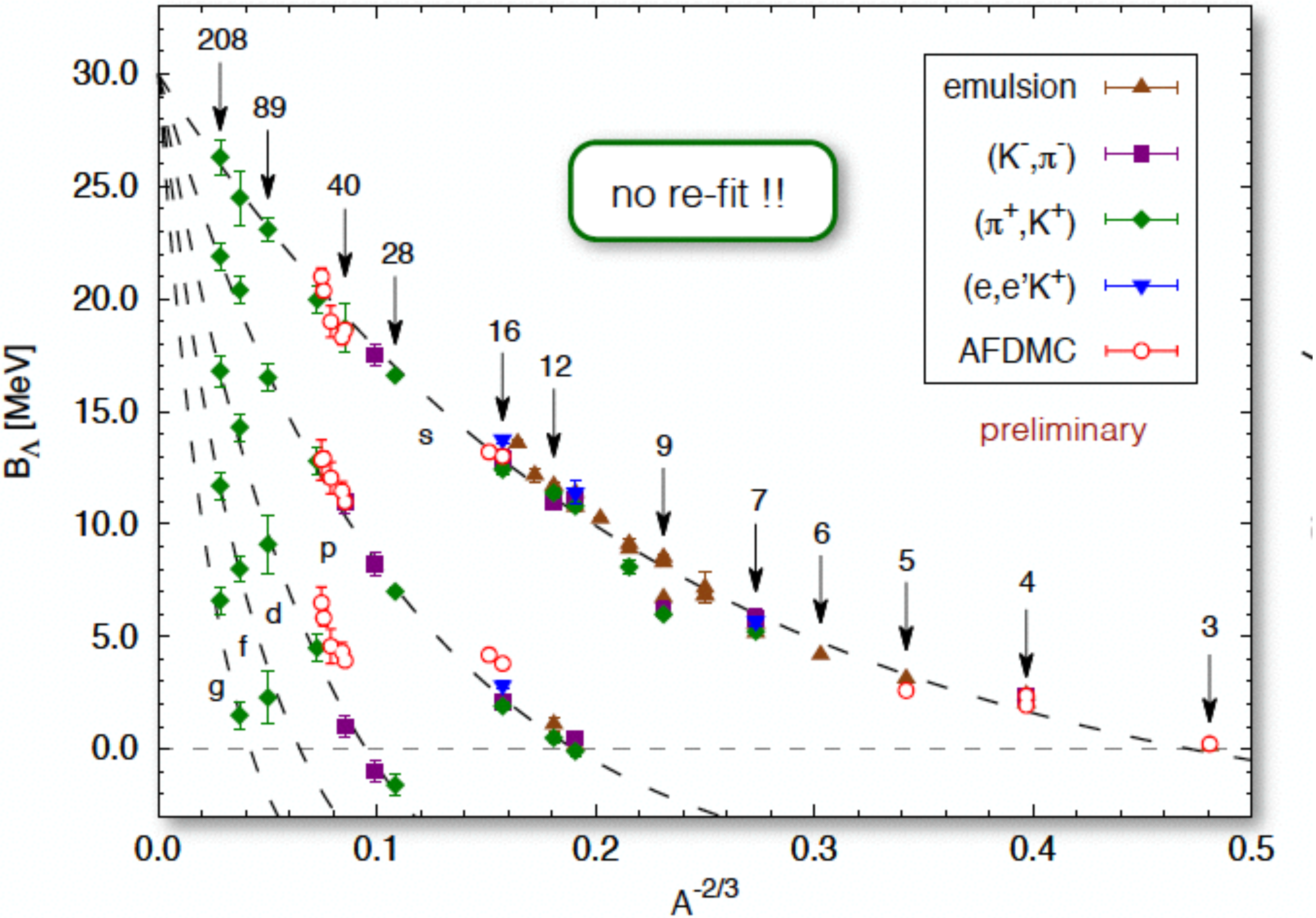
preliminary

Hypernuclei



Diego Lonardoni, Alessandro Lovato, FP, Stefano Gandolfi

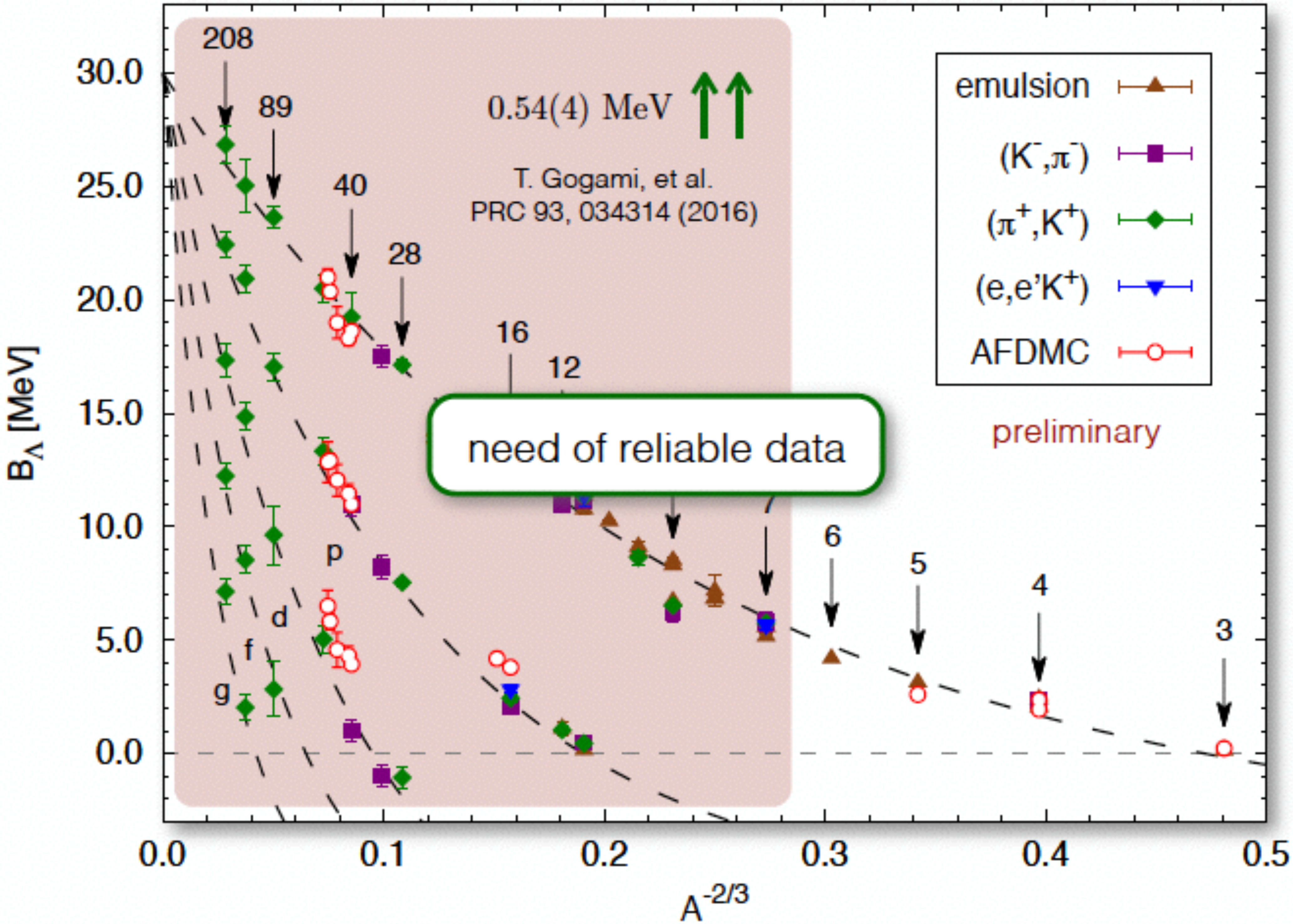
Hypernuclei



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)

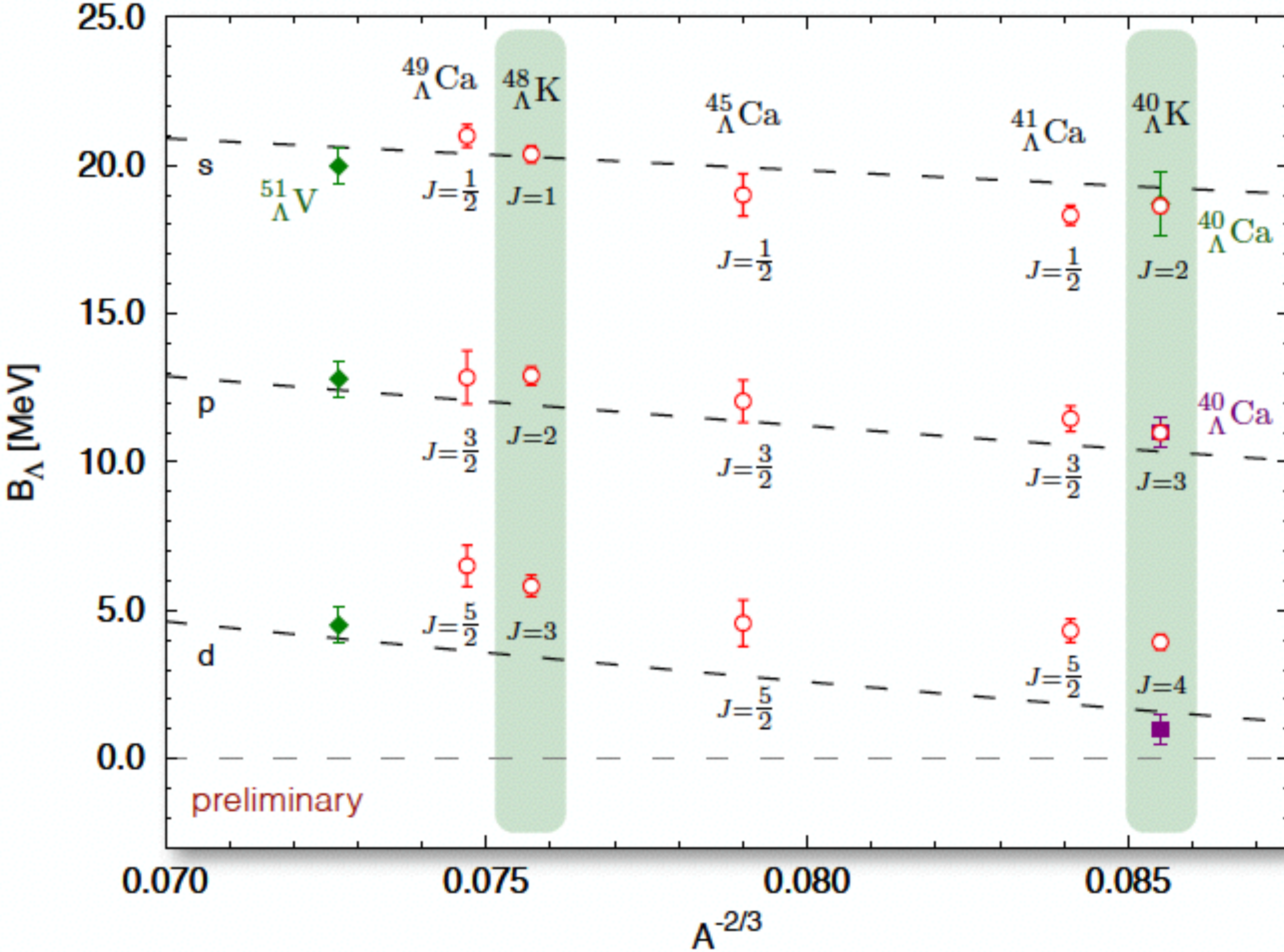
Hypernuclei



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

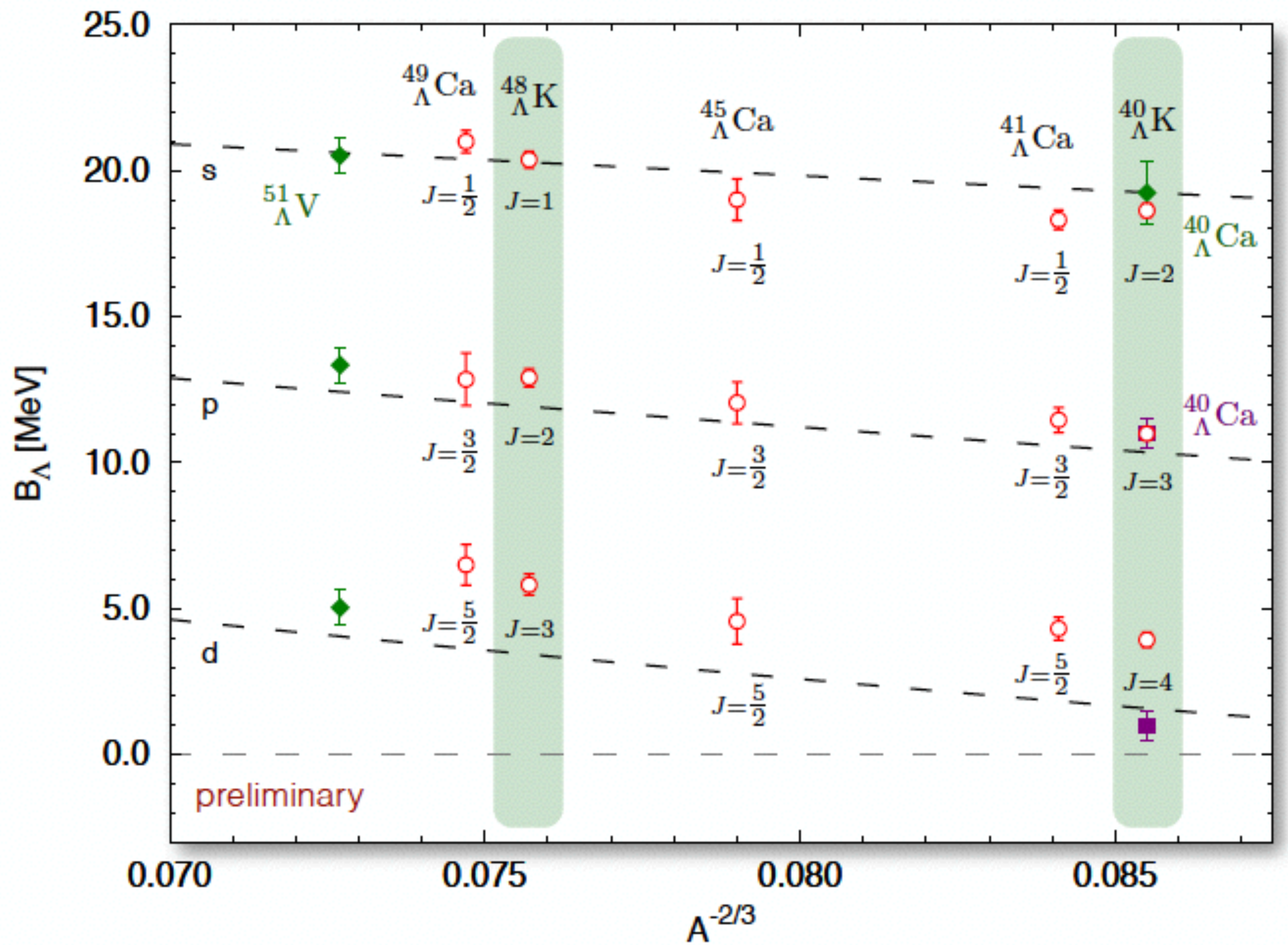
F. Pederiva, F. Catalano, D. L., A. Lovato, S. Gandolfi, arXiv:1506.04042 (2015)

Hypernuclei



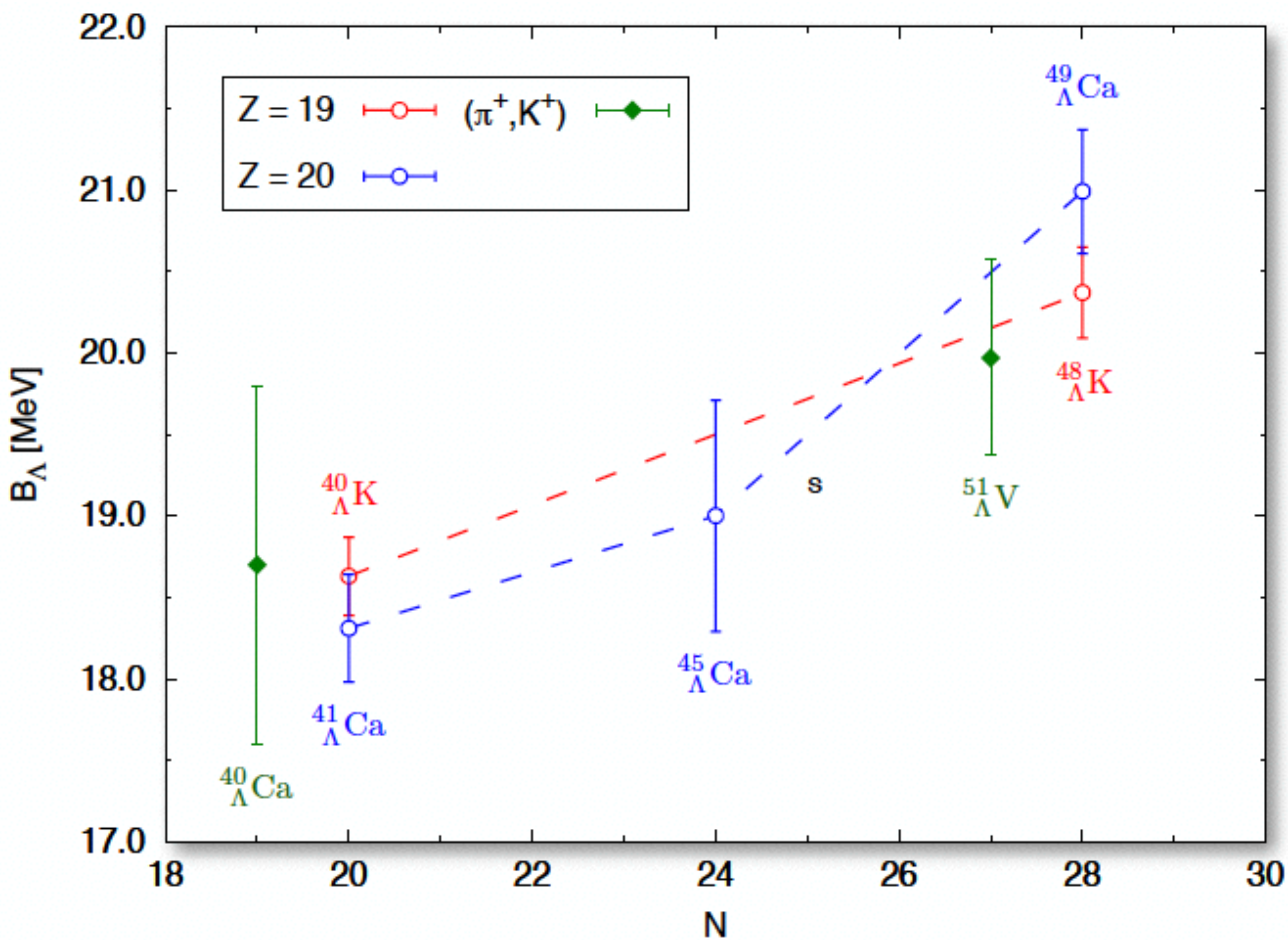
^{48}Ca$(e, e'K^+)^{48}_{\Lambda}$K ^{40}Ca$(e, e'K^+)^{40}_{\Lambda}$K

Hypernuclei



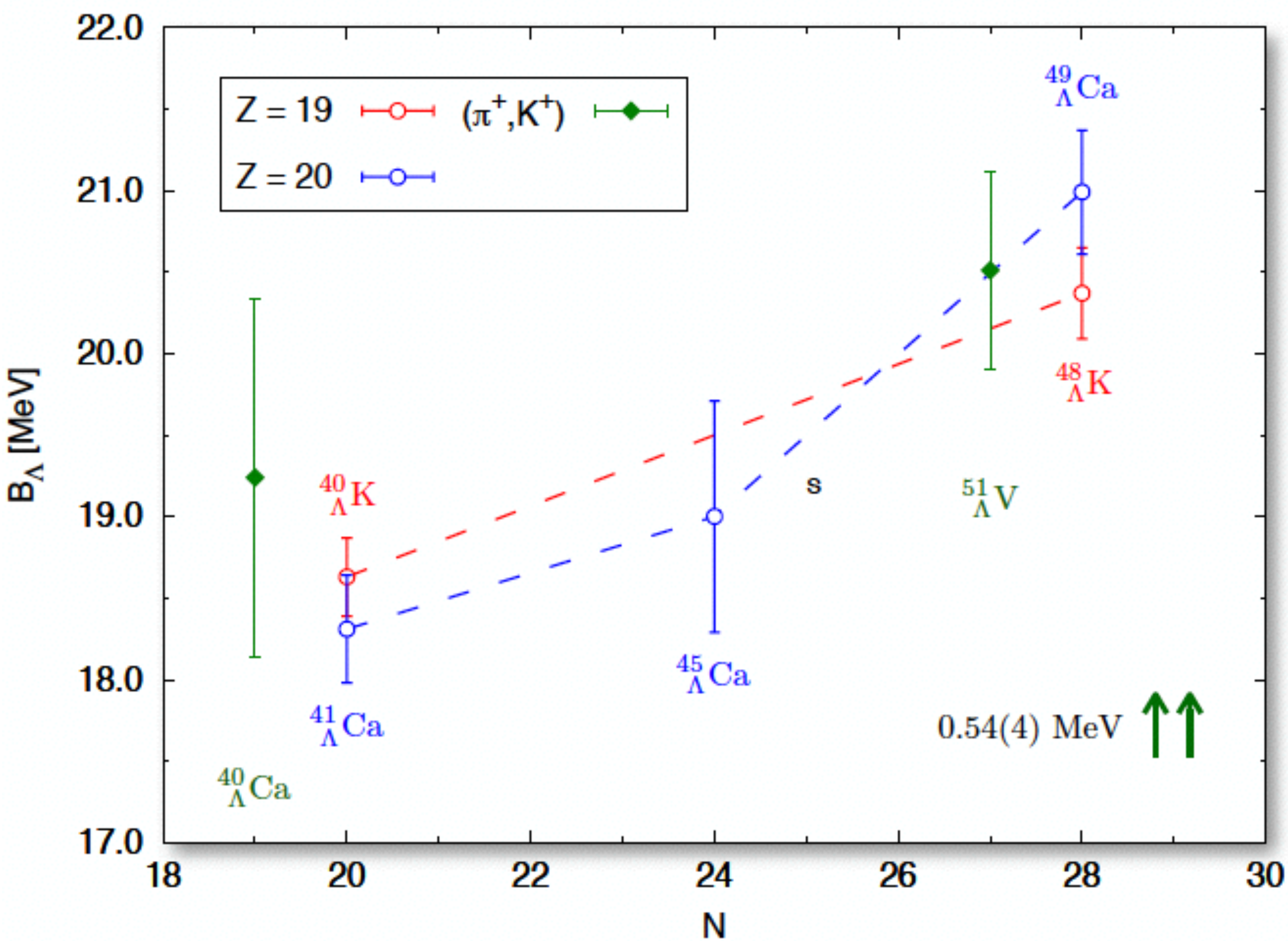
$^{48}\mathrm{Ca}(e,e'K^{+})^{48}_{\Lambda}\mathrm{K}$ $^{40}\mathrm{Ca}(e,e'K^{+})^{40}_{\Lambda}\mathrm{K}$

Hypernuclei



preliminary

Hypernuclei



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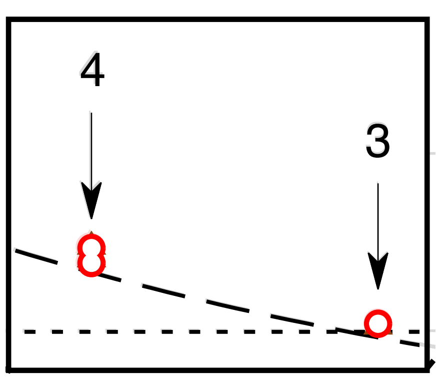
Charge symmetry breaking

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)		
${}^{4}_{\Lambda}\mathrm{H}\ (1^{+})$	0.35(11)	1.00(6)	0.41(14)	0.24(8)
${}^{4}_{\Lambda}\mathrm{He}\ (1^{+})$	0.76(10)	1.24(6)		



CSB interaction not compatible with

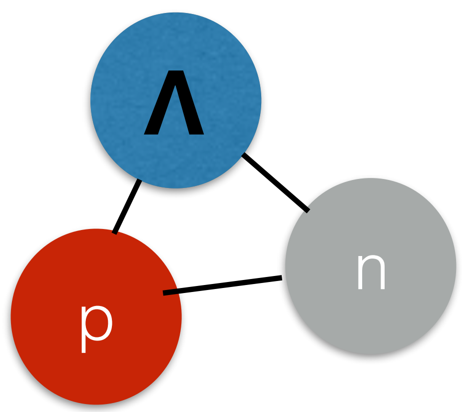
$A = 7$ systems $({}^{7}_{\Lambda}\mathrm{He},\ {}^{7}_{\Lambda}\mathrm{Li},\ {}^{7}_{\Lambda}\mathrm{Be})$

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

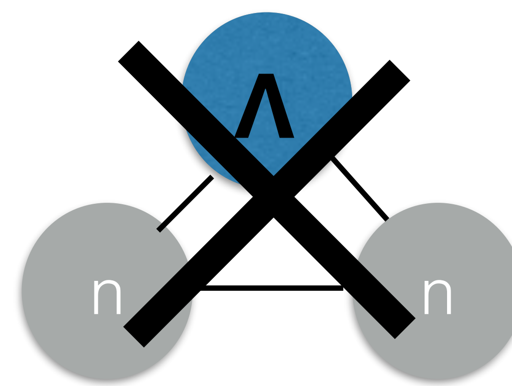
Can we really constrain ΛNN interaction from hyper nuclear data?

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



Pauli repulsion

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.

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

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

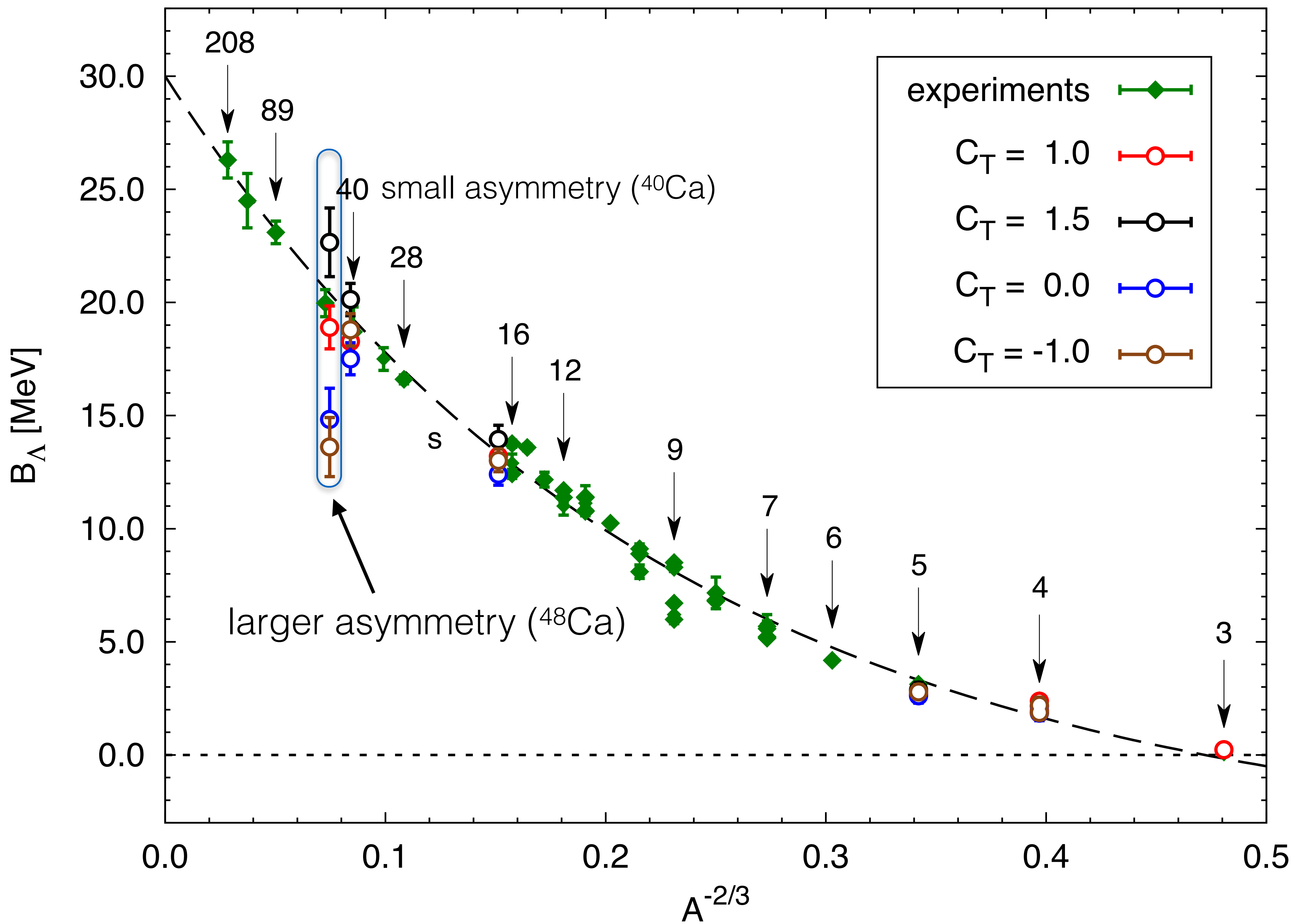
$$v^{2\pi,P} = -\frac{C_P}{6}\{X_{i\lambda}, X_{\lambda j}\}\,\vec{\tau}_i \cdot \vec{\tau}_j$$

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

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

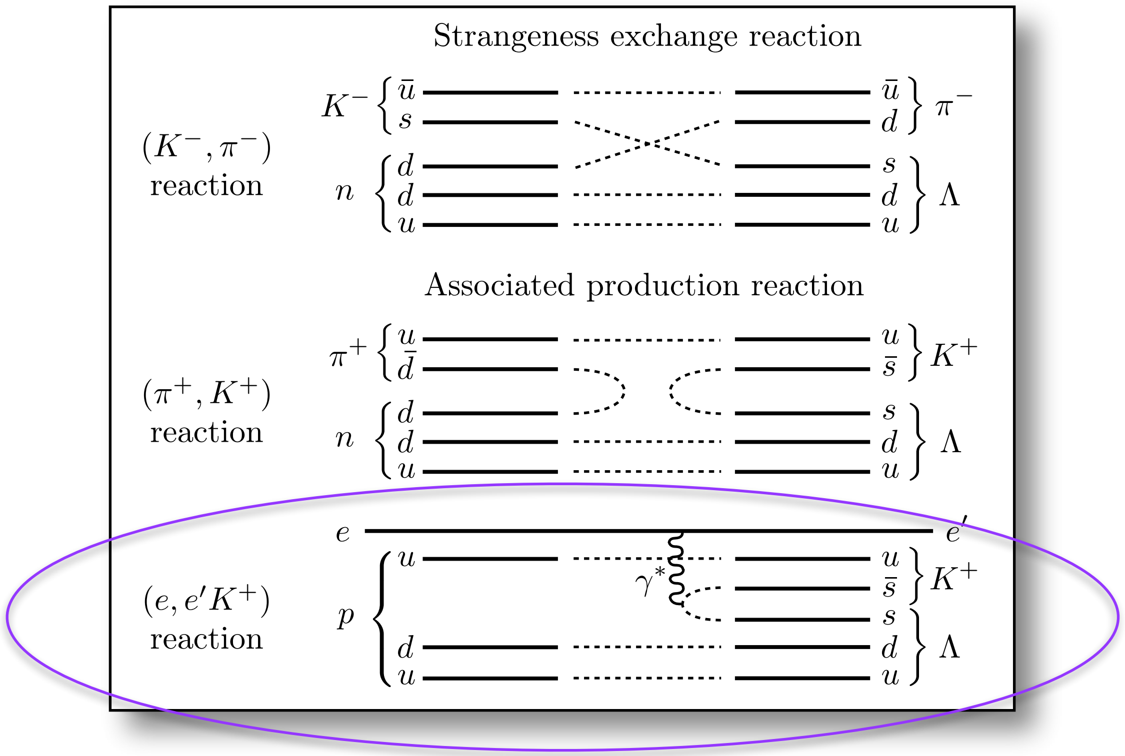
$$v^{\tau\tau}_{ij\lambda} = \frac{3}{4}(C_T - 1)v^P_{ij\lambda} + \frac{1}{4}(3 + C_T)v^P_{ij\lambda}\vec{\tau}_i \cdot \vec{\tau}_j$$

Can we really constrain the interaction from hyper nuclear data?



Francesco Catalano, Diego Lonardoni, FP

New experiments needed



$$^{A}Z(K^-,\pi^-)^{A}_{\Lambda}Z$$

$$^{A}Z(\pi^+,K^+)^{A}_{\Lambda}Z$$

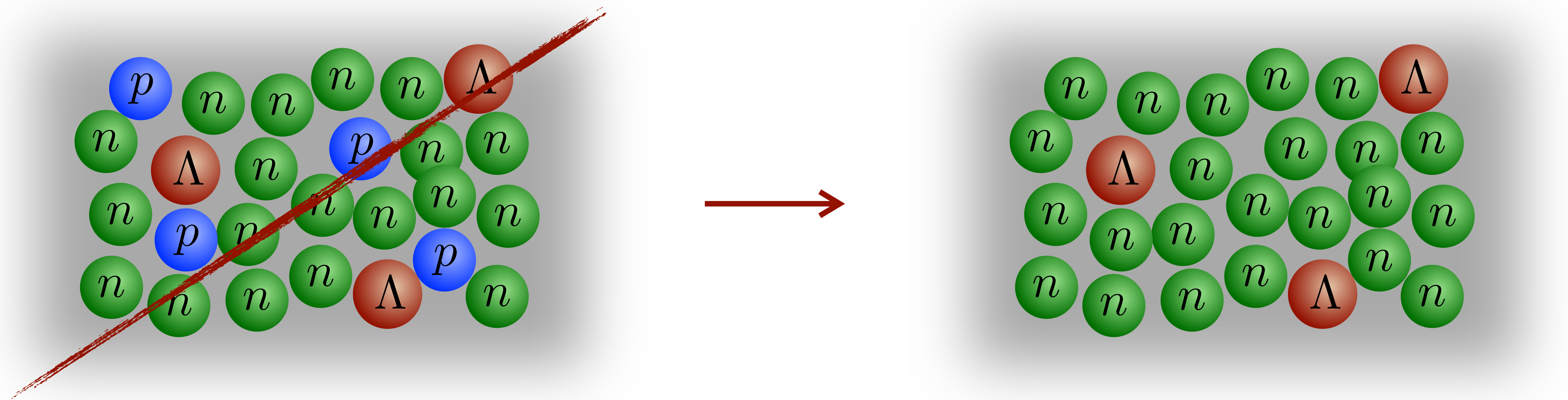
$$^{A}Z(e,e'K^+)^{A}_{\Lambda}[Z-1]$$

Proposal presented at JLAB:

“A study of the **Λ**-N interaction through the high precision spectroscopy of **Λ**-hypernuclei with electron beam” (spokepersons: S. Nakamura, F. Garibaldi, P.E.C. Markowitz, J. Reinhold, L. Tang, G.M. Urciuoli)

Including measurements of $^{48}{}_{\Lambda}$K and $^{40}{}_{\Lambda}$K, but hopefully also light hypernuclei and hyper-Pb (EoS…)

Λ-neutron matter



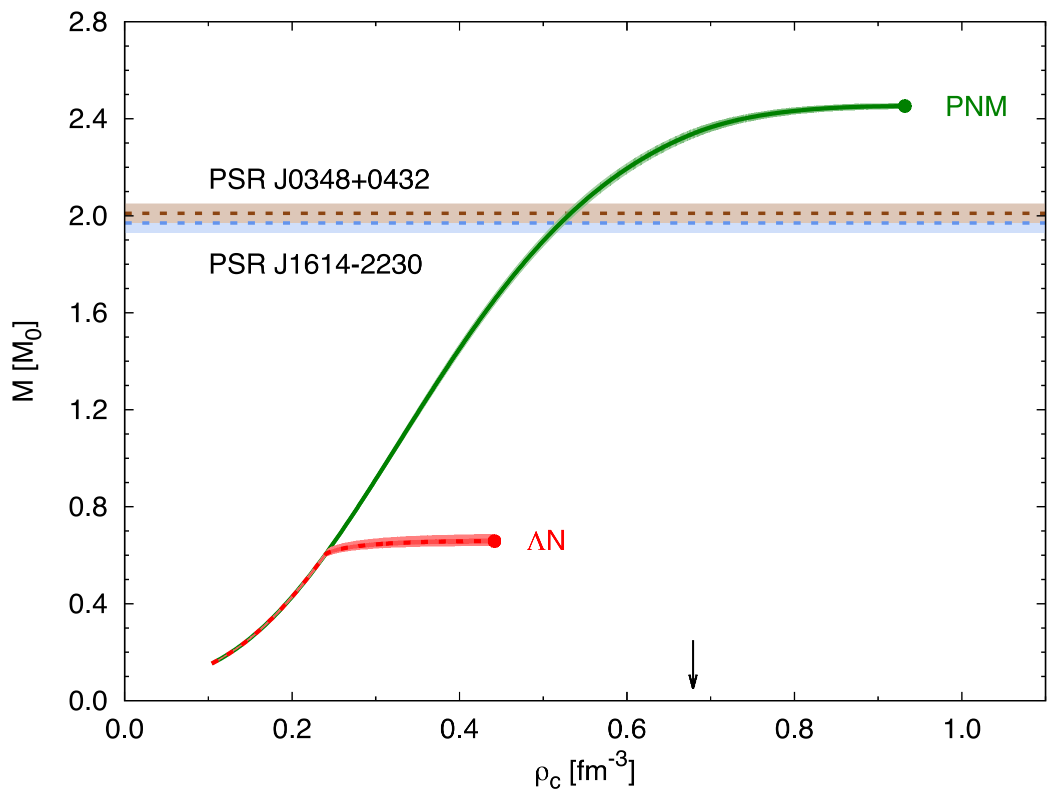
hyper-nuclear matter → hyper-neutron matter

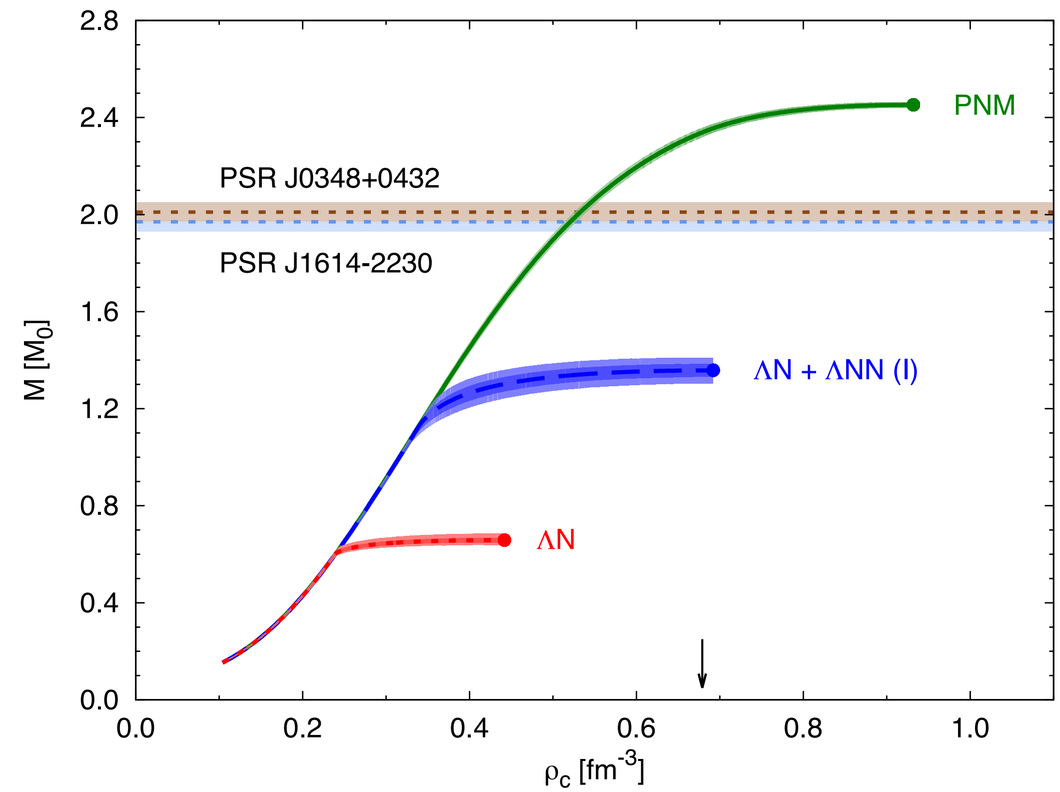
PNM → hyperon fraction →

- energy per particle: $E_{\mathrm{HNM}} \equiv E_{\mathrm{HNM}}(\rho_b, x_\Lambda)$
- energy density: $\mathcal{E}_{\mathrm{HNM}} \equiv \mathcal{E}_{\mathrm{HNM}}(\rho_b, x_\Lambda)$

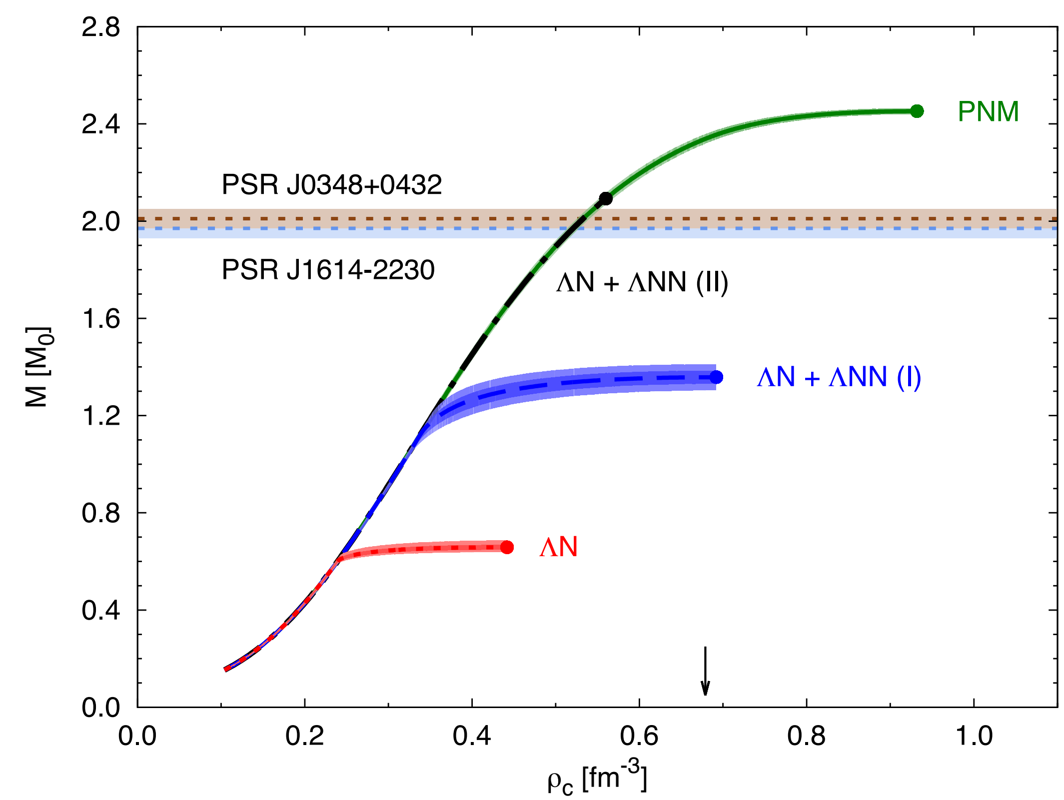
equilibrium condition : chemical potentials $\mu_\Lambda(\rho_b, x_\Lambda) = \mu_n(\rho_b, x_\Lambda)$ ⇒ $x_\Lambda \equiv x_\Lambda(\rho_b)$

Neutron star structure

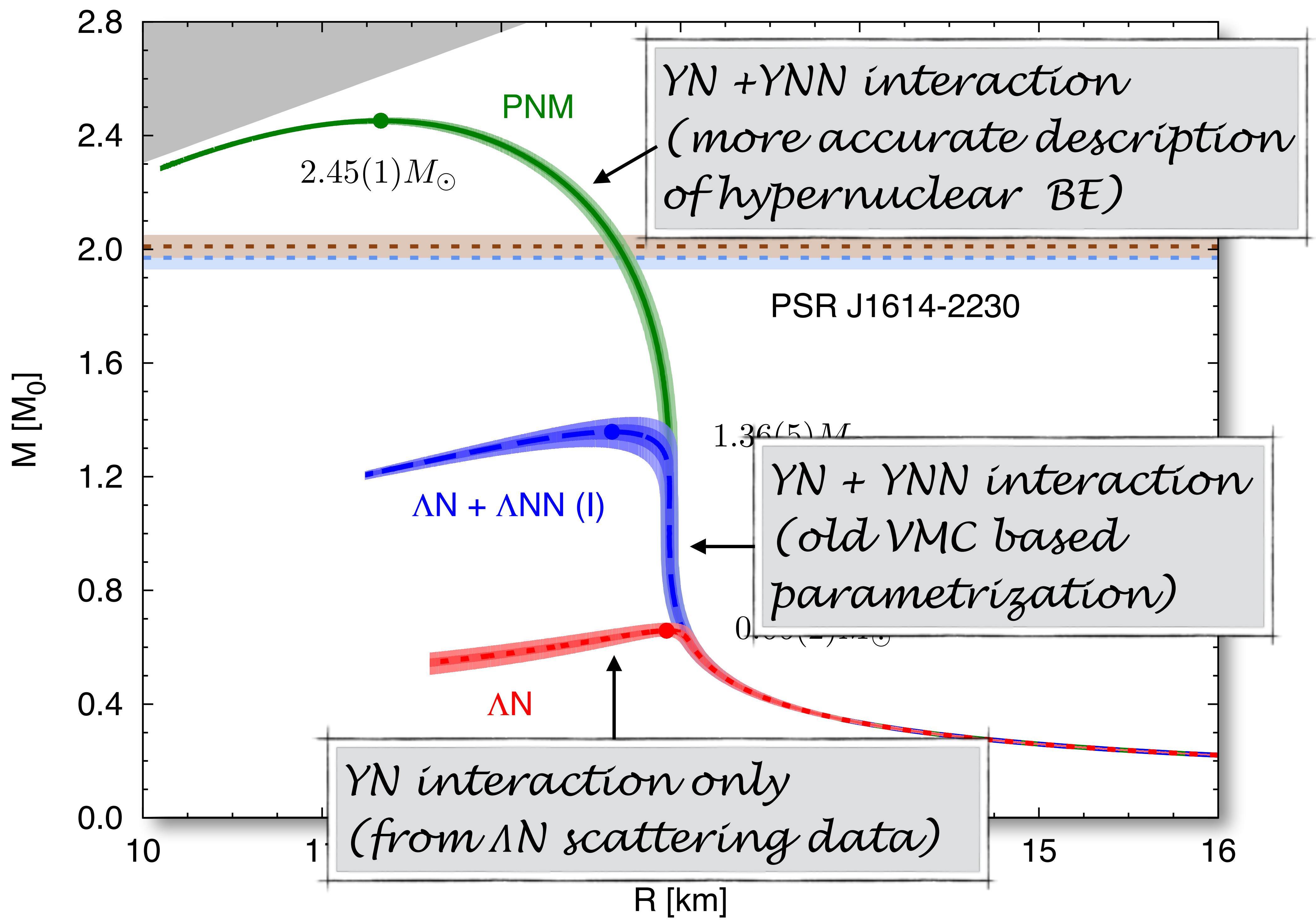




Within this model the repulsion needed to correctly describe hypernuclear binding energy is so strong that **hyperons would not be present in $2M_\odot$ stars!**



Neutron star structure



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

Conclusions

- Our philosophy in attacking the problem of the hyperon-nucleon interaction: **we do not want to add more information than the one that experiments can give us.** Having too many parameters will result in a substantially **arbitrary prediction of the EoS**, and consequently **adjustable predictions on the Neutron Star structures**.

- AFDMC calculations are evolving. Better accuracy, better performance. This reflects on the work on hypernuclei Accessible systems: definitely A=90. For heavier systems one can possibly use alternative approaches.

- At this point there is real need of accurate experiments on hypernuclei in order to be able to gain more insight on NS interior at densities $> 2\rho_0$.