Perspectives and theoretical challenges in electron scattering experiments on medium mass hypernuclei

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Collaborators

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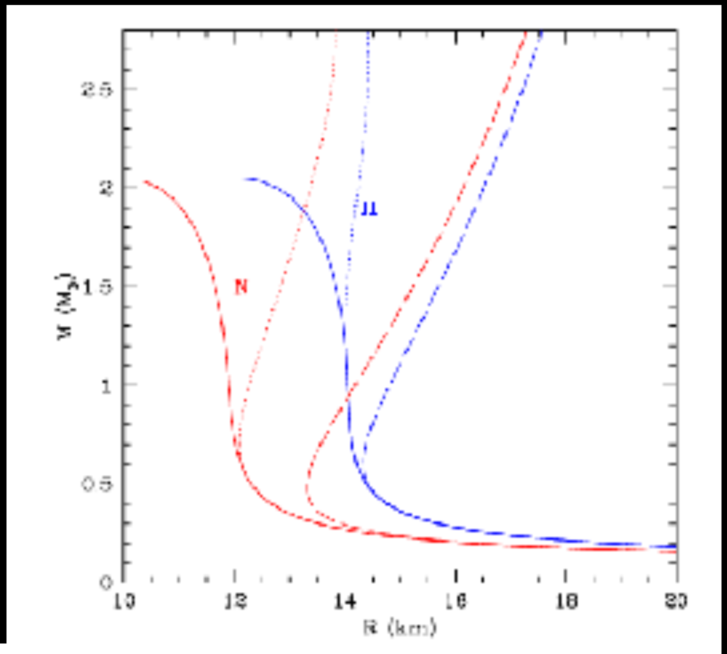
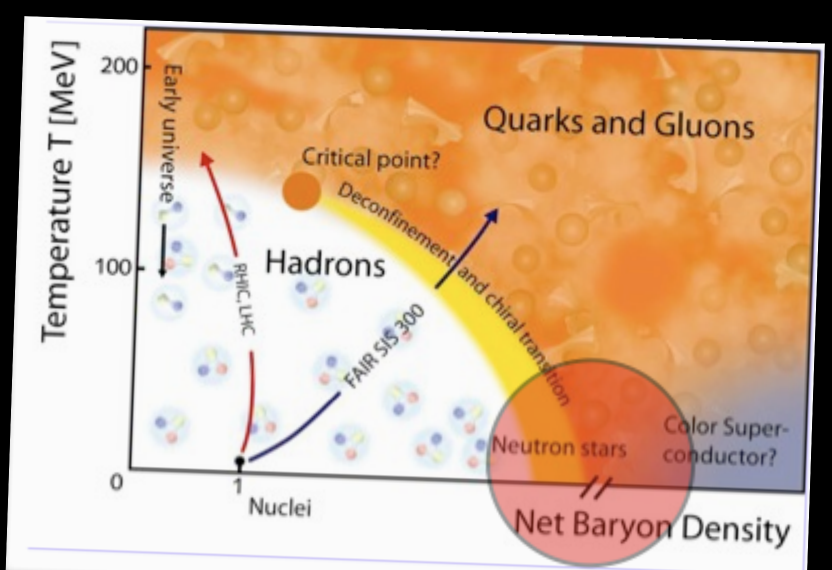
- **Stefano Gandolfi (LANL)**

Open questions...

ortin, M., Zdunik, J. L., Haensel, P., & Bejger, M. (2015).

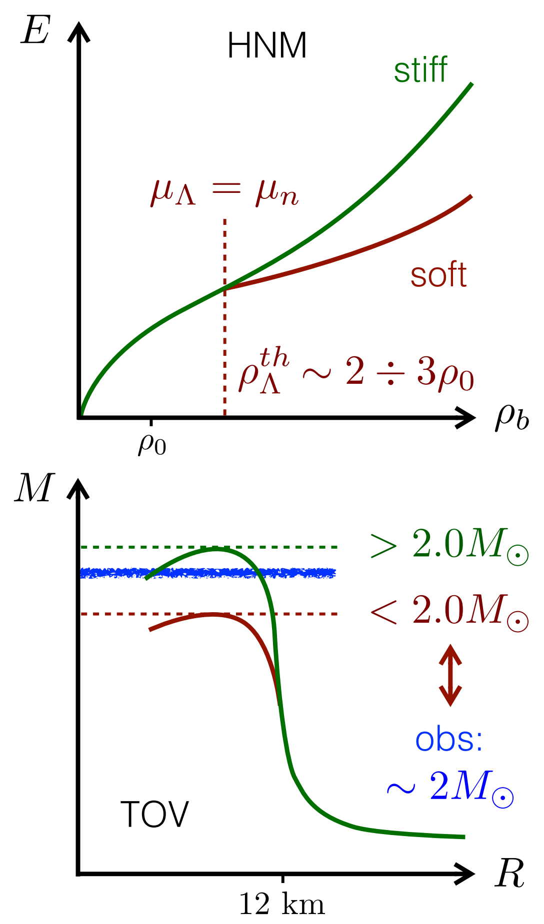


The *fine tuning* of the hyperon-nucleon interaction is essential to understand the behavior of matter in extreme conditions

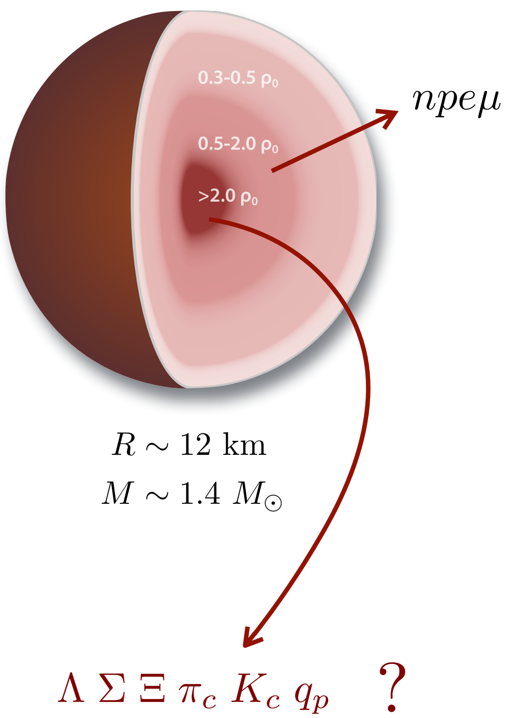


Far away from any possible perturbative treatment..

Equation of state



Neutron star structure



Internal composition still largely unknown

Gravitational waves

PRL 115, 091101 (2015) PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2015

Modeling the Complete Gravitational Wave Spectrum of Neutron Star Mergers

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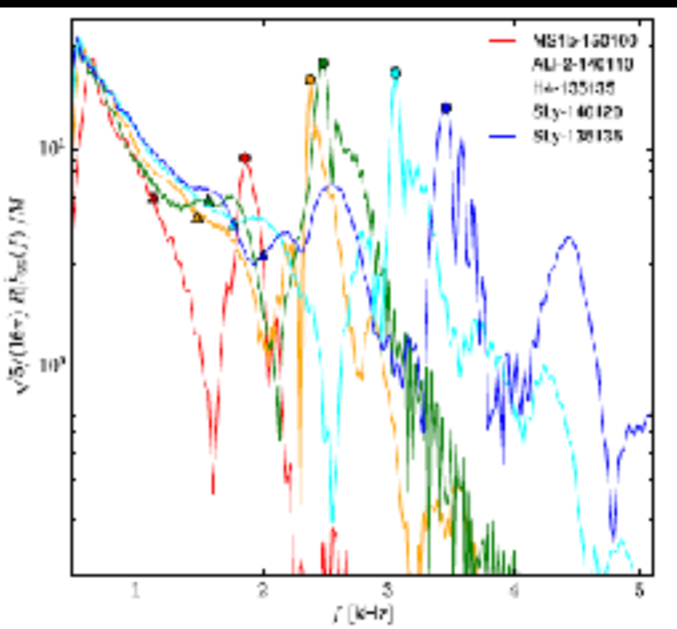
(Received 9 April 2015; revised manuscript received 11 June 2015; published 27 August 2015)

In the context of neutron star mergers, we study the gravitational wave spectrum of the merger remnant using numerical relativity simulations. Postmerger spectra are characterized by a main peak frequency f_2 related to the particular structure and dynamics of the remnant hot hypermassive neutron star. We show that f_2 is correlated with the tidal coupling constant κ_2^T that characterizes the binary tidal interactions during the late-inspiral merger. The relation $f_2(\kappa_2^T)$ depends very weakly on the binary total mass, mass ratio, equation of state, and thermal effects. This observation opens up the possibility of developing a model of the gravitational spectrum of every merger unifying the late-inspiral and postmerger descriptions.

Introduction.—Direct gravitational wave (GW) observations of binary neutron stars (BNS), late-inspiral merger and postmerger by ground-based GW interferometric experiments, can lead to the strongest constraints on the equation of state (EOS) of matter at supranuclear densities [1–7]. There are two ways to set such constraints (GW observations of BNS mergers can also constrain the source redshift [8,9]): (I) measure the binary phase during the last minutes of coalescence using matched filtered searches [1,3–5] and (II) measure the postmerger GW spectrum frequencies using burst searches [6,7].



Selected for a Viewpoint in Physics
PRL 119, 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

PRL 119, 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

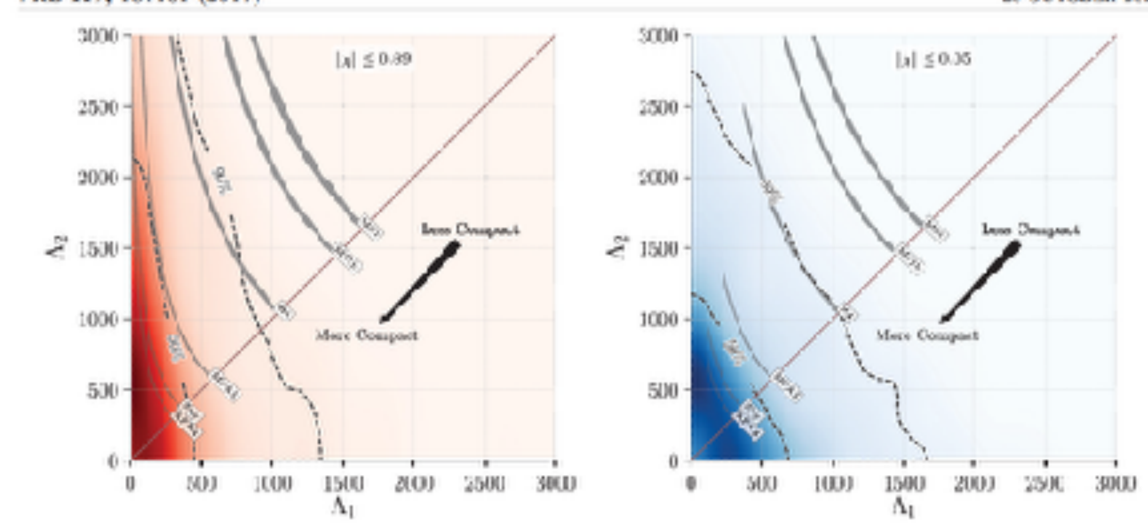


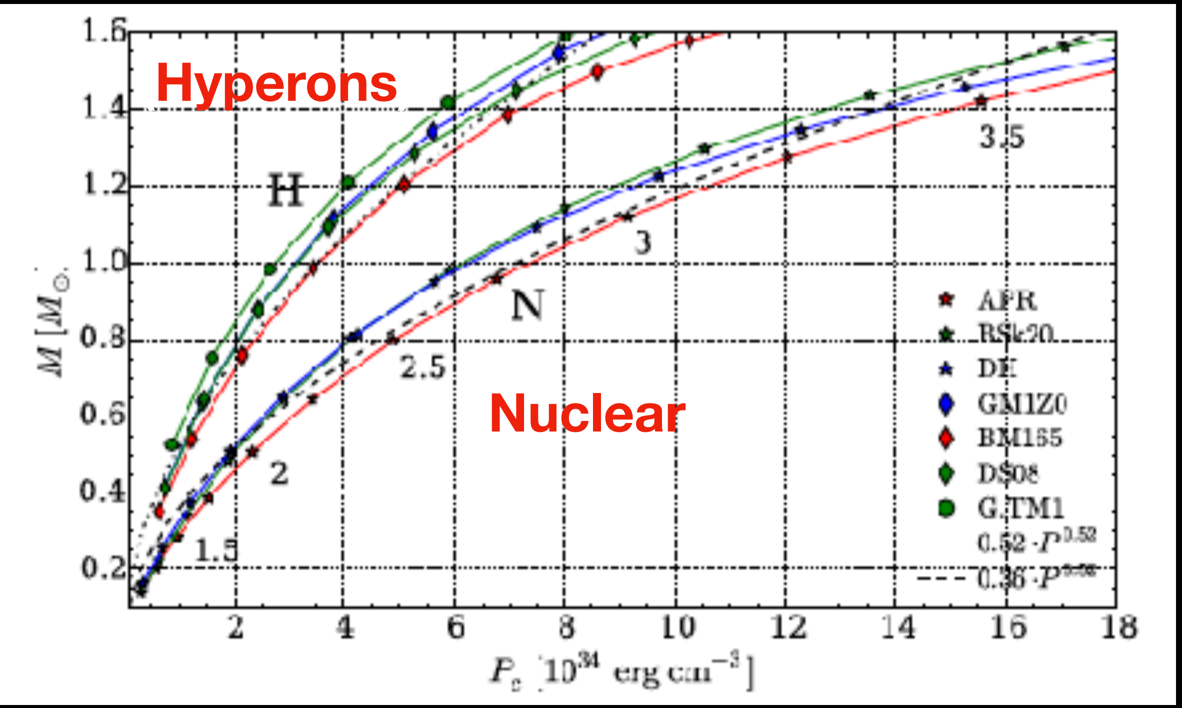
FIG. 5. Probability density for the tidal deformability parameters of the high and low mass components inferred from the detected signals using the post-Newtonian model. Contours enclosing 90% and 50% of the probability density are overlaid (dashed lines). The diagonal dashed line indicates the $\Lambda_1 = \Lambda_2$ boundary. The Λ_1 and Λ_2 parameters characterize the size of the tidally induced mass deformations of each star and are proportional to $k_2(R/m)^5$. Constraints are shown for the high-spin scenario $|\chi| \leq 0.89$ (left panel) and for the low-spin $|\chi| \leq 0.05$ (right panel). As a comparison, we plot predictions for tidal deformability given by a set of representative equations of state [156–160] (shaded filled regions), with labels following [161], all of which support stars of 2.01$M_\odot$. Under the assumption that both components are neutron stars, we apply the function $\Lambda(m)$ prescribed by that equation of state to the 90% most probable region of the component mass posterior distributions shown in Fig. 4. EOS that produce less compact stars, such as MS1 and MS1b, predict Λ values outside our 90% contour.

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})	$R^{(CL)}_{1.4}$ (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

Fortin, M., Zdunik, J. L., Haensel, P., & Bejger, M. (2015).



CONSTRAINING EoS

?

~ 18 orders of magnitude in between…

CONSTRAINING Nuclear Interactions

YN interaction

NON RELATIVISTIC:
write a Hamiltonian using a model potential and try to solve a many-body Schroedinger equation.

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

- 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.

Some hints from LQCD......

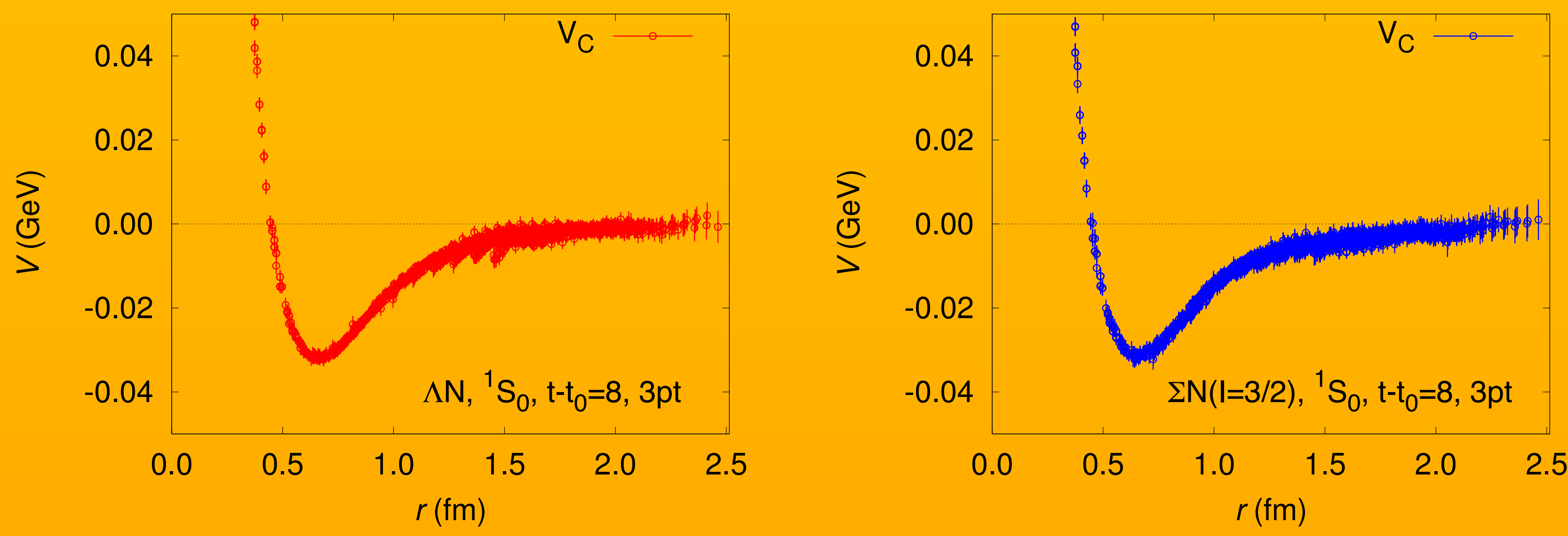


Fig. 10. Left: The central potential in the $^1S_0$ channel of the ΛN system in $2+1$ flavor QCD as a function of r. Right: The central potential in the $^1S_0$ channel of the $\Sigma N(I = 3/2)$ system as a function of r.

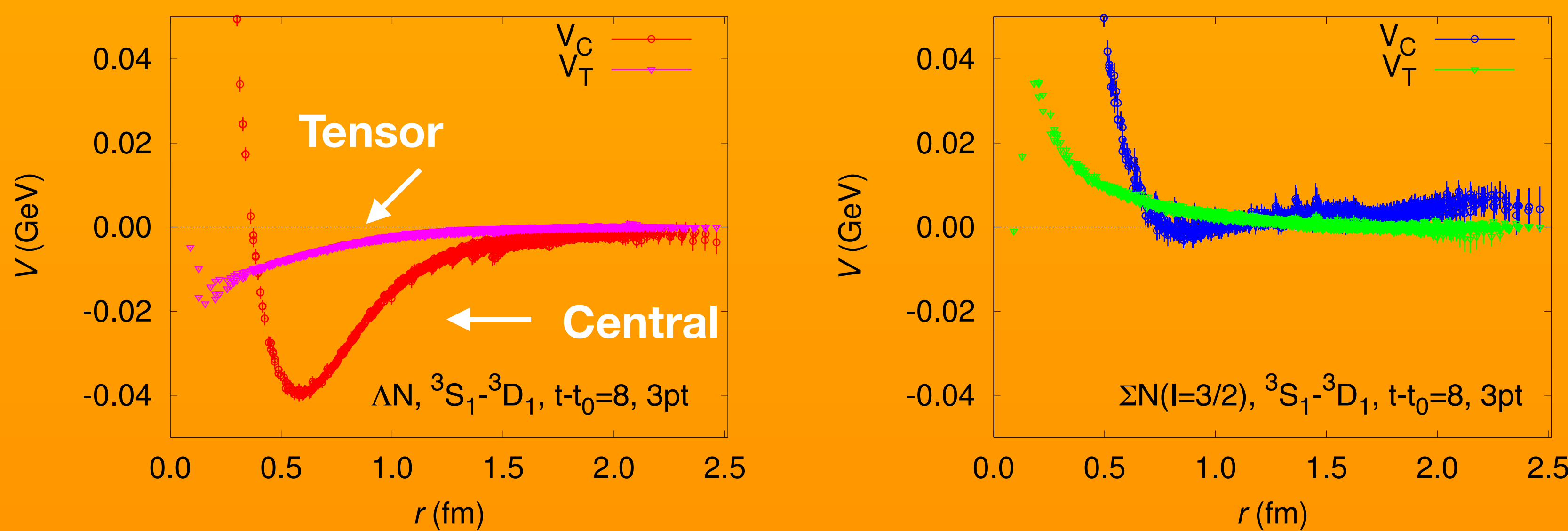


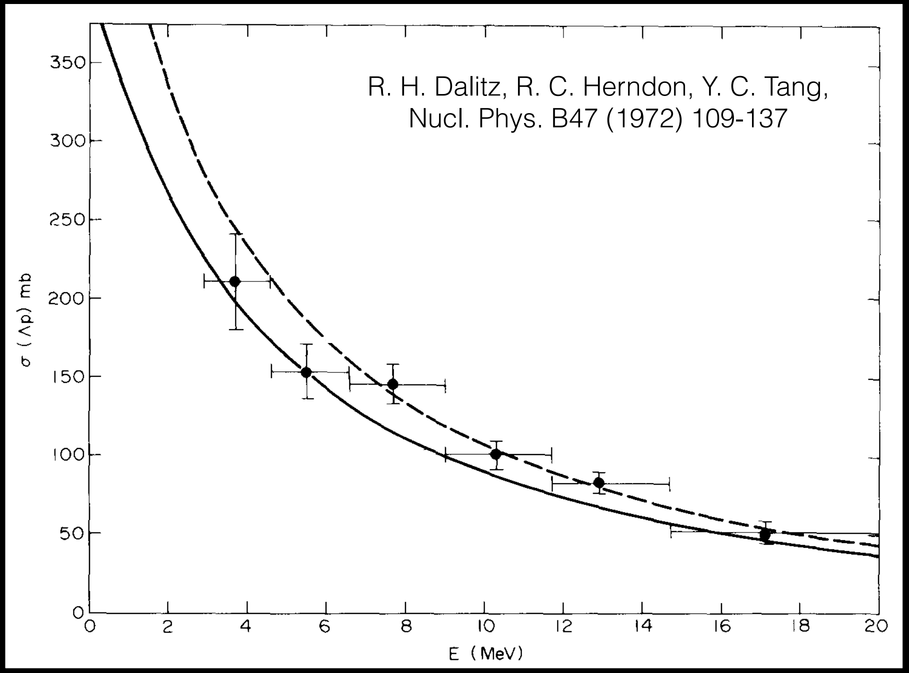
Fig. 11. Left: The central potential (circle) and the tensor potential (triangle) in the $^3S_1 -^3 D_1$

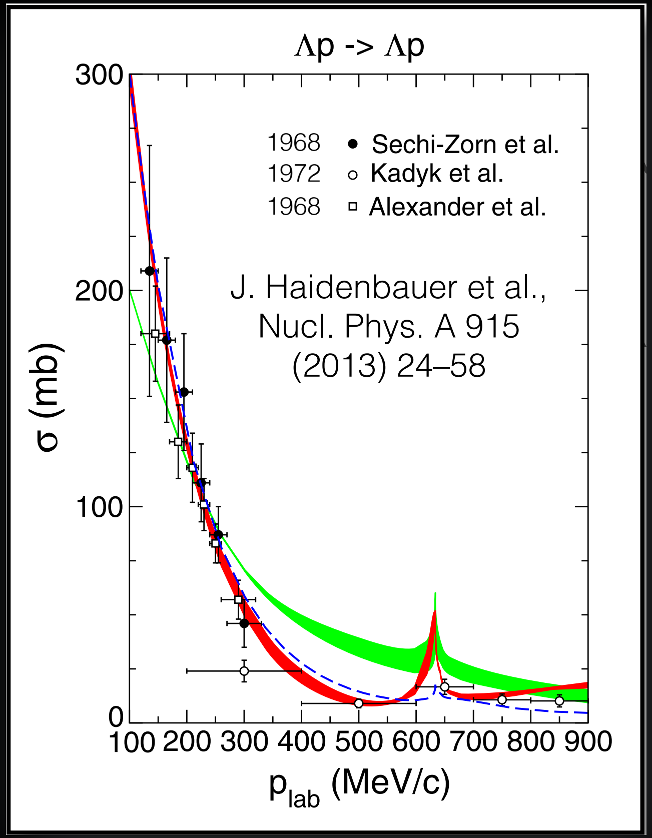
S. Aoki et al.
(HAL-QCD collaboration)

NB (again…): The potential is NOT an observable! Features like the hard core depend e.g. on the method used to reconstruct the kinetic energy.

Model Hyperon-nucleon interaction

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





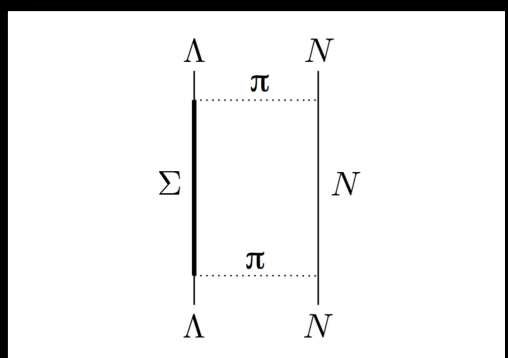
OUR CHOICE

- **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):

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

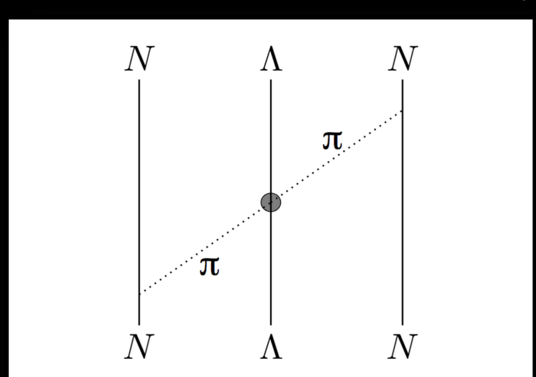


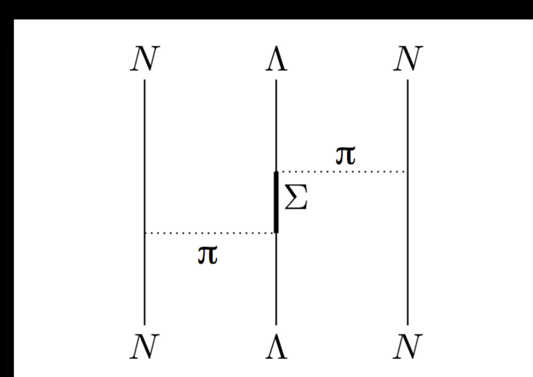
from Kaon exchange terms (not considered explicitly in our calculations)

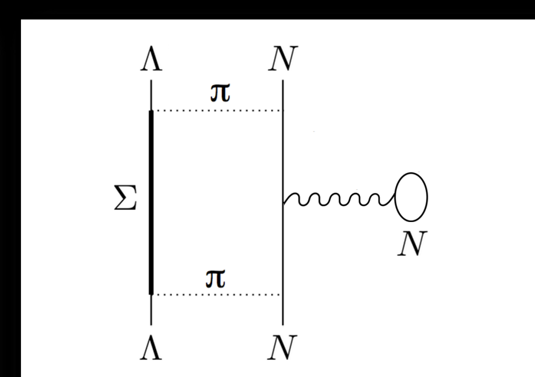
$$V_{\Lambda i}(r) = v_0(r) + v_0(r)\varepsilon(P_x - 1) + \frac{1}{4}v_\sigma T_\pi^2(m_\pi r)\boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_i$$

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

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







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

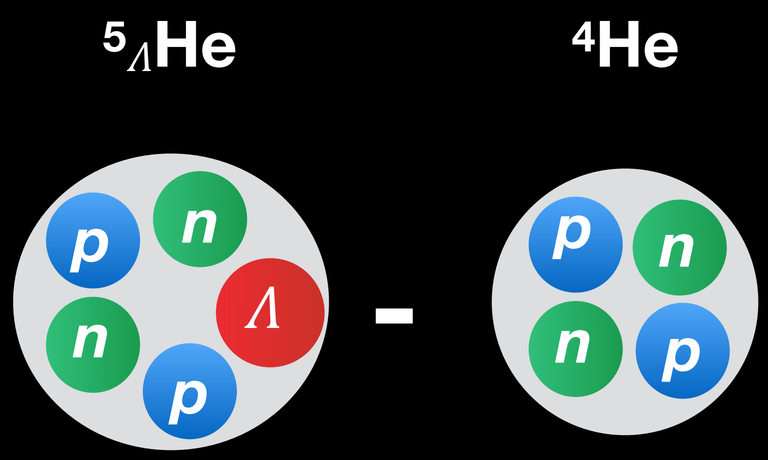
$$\begin{cases} V_{\Lambda ij}^{2\pi} = C_{2\pi}^{SW} \mathcal{O}_{\Lambda ij}^{2\pi,SW} + C_{2\pi}^{PW} \mathcal{O}_{\Lambda ij}^{2\pi,PW} \\ V_{\Lambda ij}^{D} = W^D\, T_\pi^2(m_\pi r_{\Lambda i})\, T_\pi^2(m_\pi r_{\Lambda j}) \left[1 + \frac{1}{6}\boldsymbol{\sigma}_\Lambda \cdot (\boldsymbol{\sigma}_i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

Parameters to be determined from calculations

Input from experiment

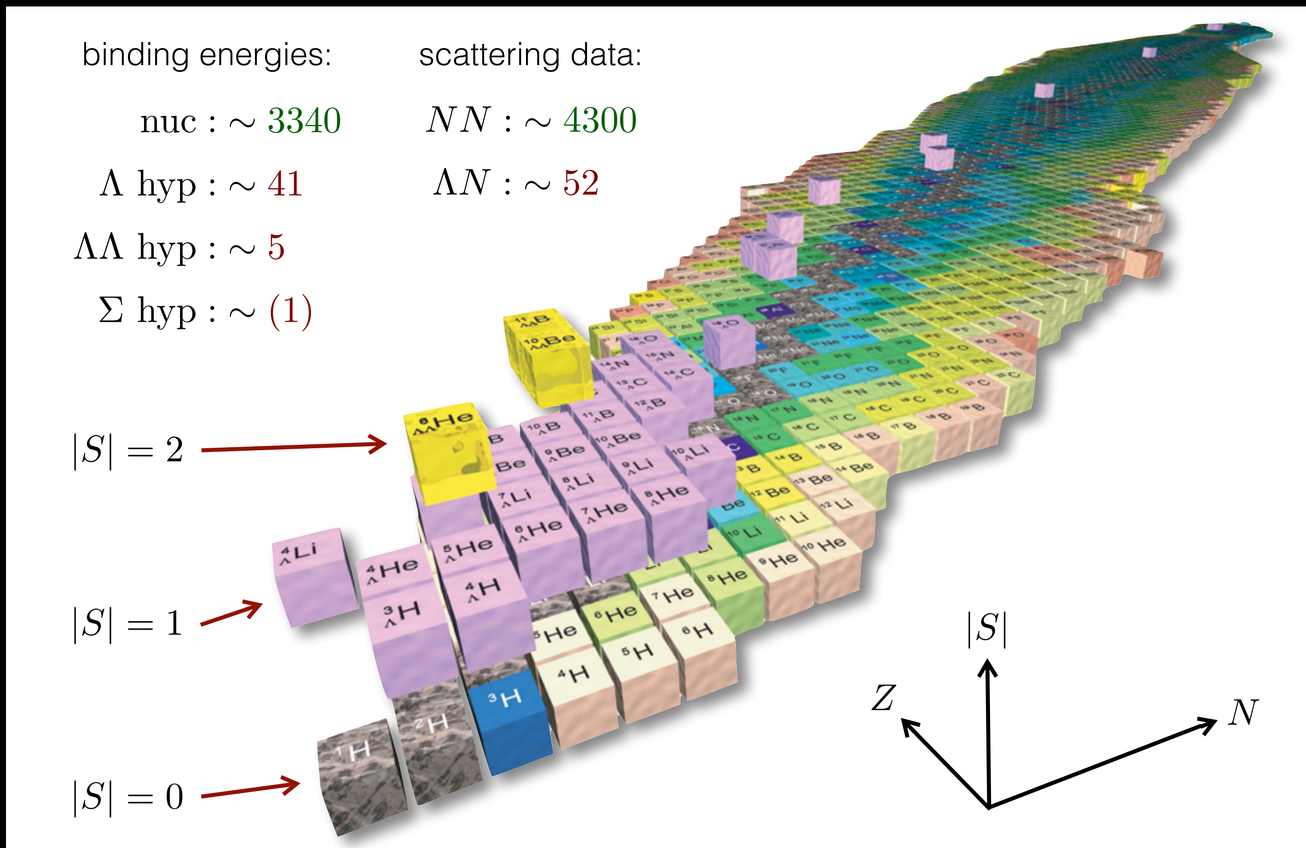
We need to fit the three body interaction against some experimental data. There are available several measurements of the binding energy of **Λ-hypernuclei**, i.e. nuclei containing a hyperon. The idea is to compute such binding energies. We can then compute the **hyperon separation energy:**

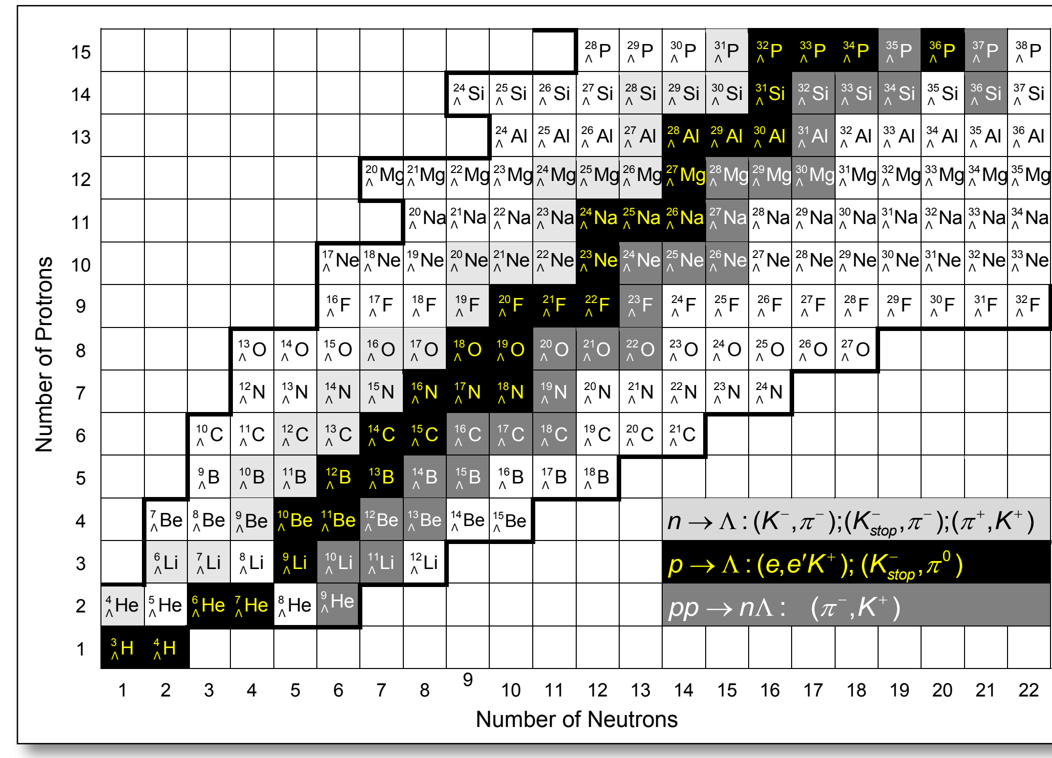
$$B_\Lambda = B_{hyp} - B_{nuc}$$



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.

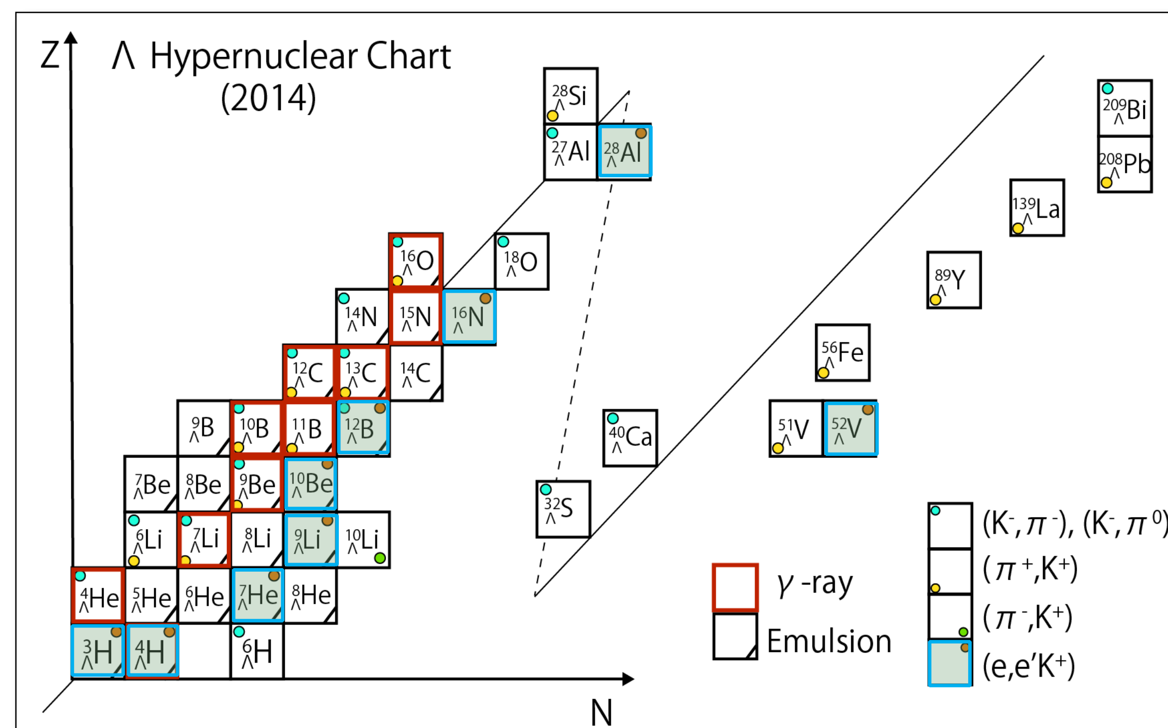
Existing data





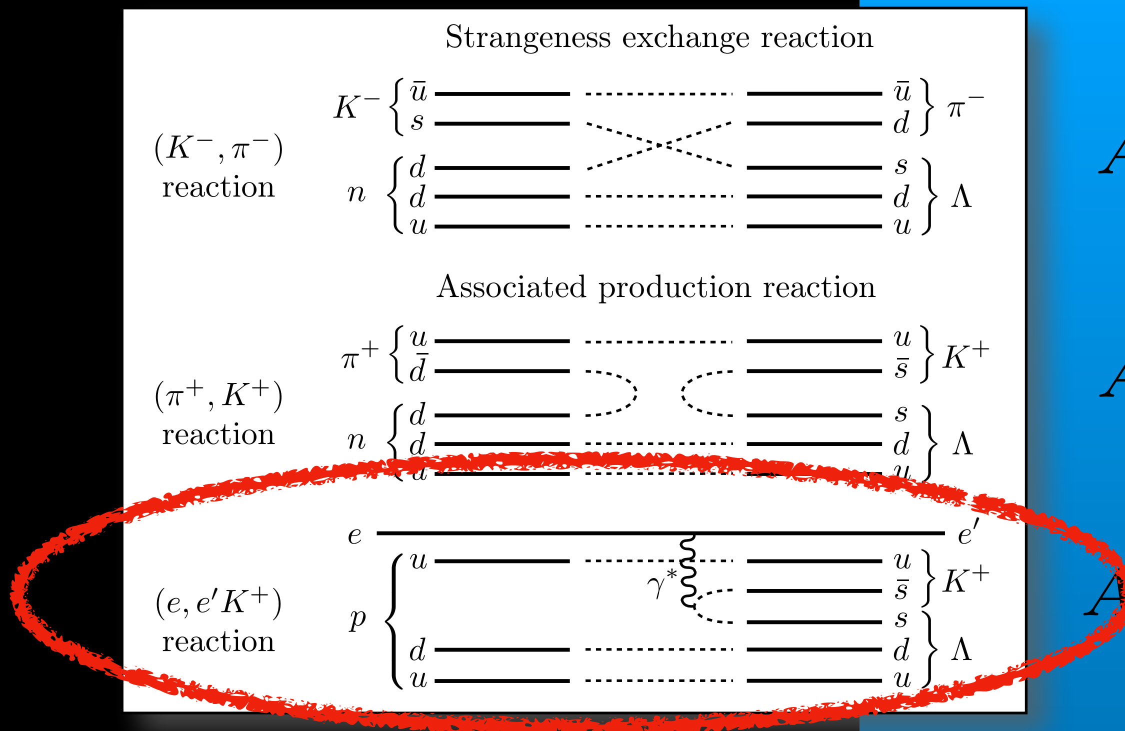
J. Pochodzalla, Acta Phys. Polon. B 42, 833– 842 (2011)

- 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)

Experiments!



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

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

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

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

Proposal to JLab PAC44 June 6 2016

An isospin dependence study of the ΛN interaction through the high precision spectroscopy of Λ-hypernuclei with electron beam

(update of the conditionally approved C12-15-008)

JLab Hypernuclear Collaboration

Spokespersons:

F. Garibaldi[1], P.E.C. Markowitz[2], S.N. Nakamura[3*], J.Reinhold[2], L. Tang[4,5], G.M. Urciuoli[1]

[1]Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Gr. Coll. Sanita', Viale Regina Elena 299, Rome, Italy
[2]Florida International University, Miami, Florida 33199, USA
[3]Department of Physics, Graduate School of Science, Tohoku University, Sendai, 980-8578, Japan
[4]Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA
[5]Department of Physics, Hampton University, Hampton, Virginia, 23668, USA

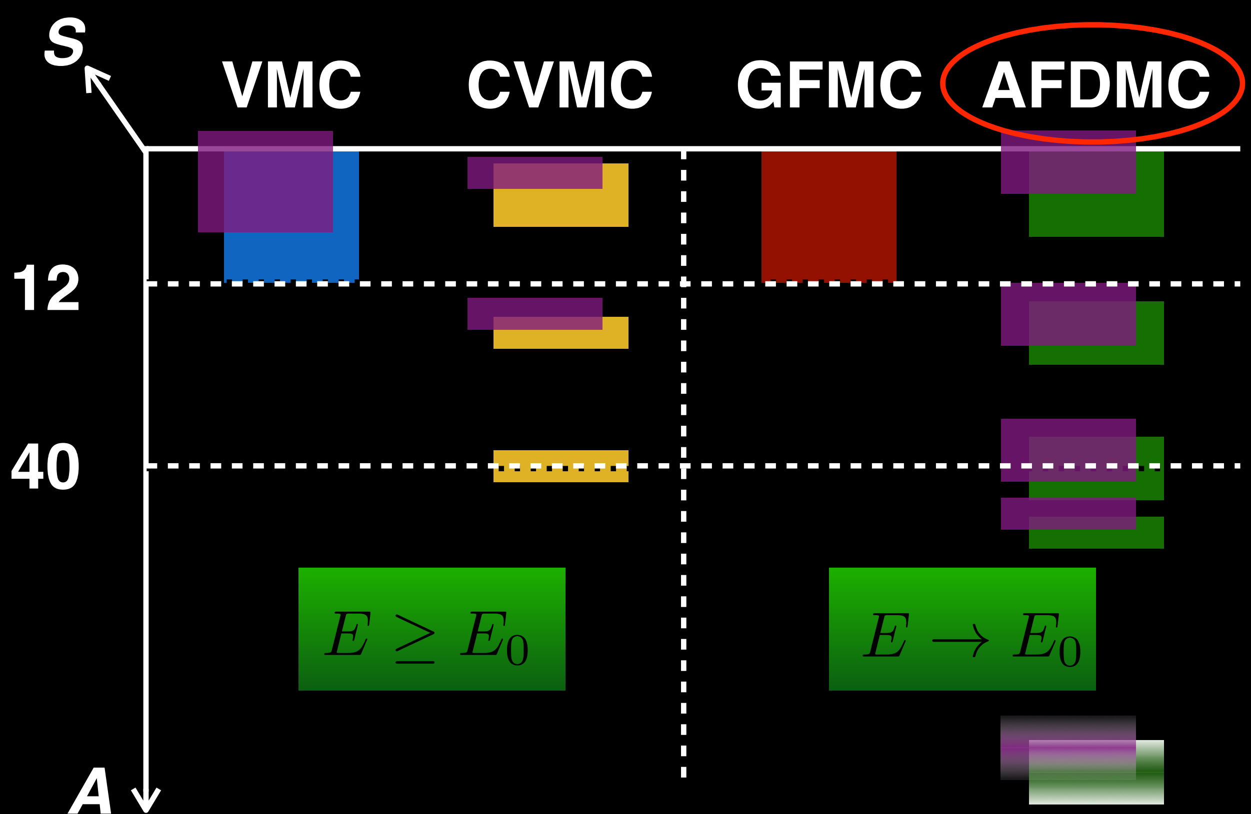
** Contact person*

APPROVED

Quantum Monte Carlo

***Method*: why Quantum Monte Carlo?**

i. **solve the many-body problem for strongly correlated systems in a non-perturbative fashion**
ii. **accurate description of ground-state properties**
iii. **statistical uncertainties**

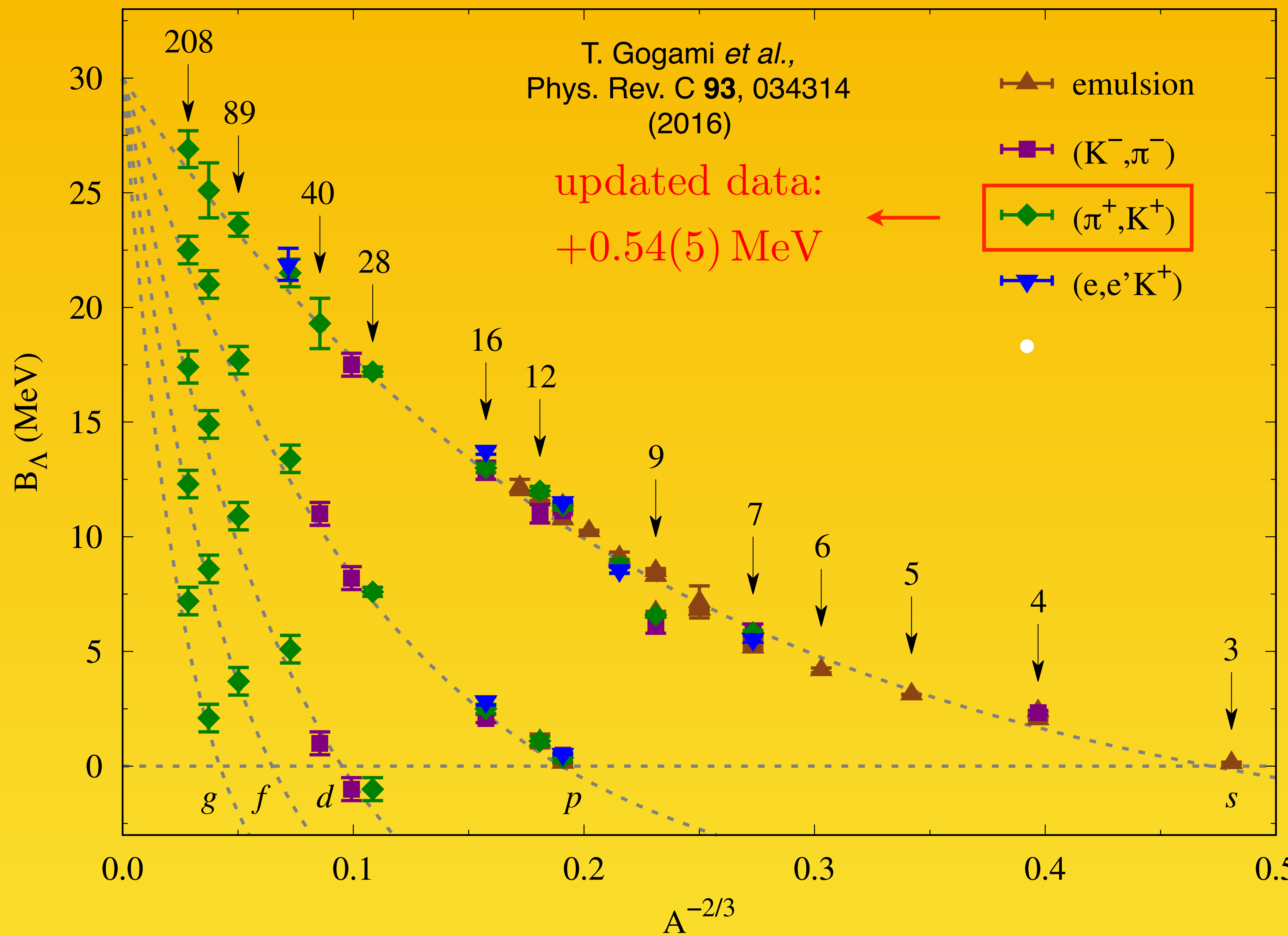


(C)VMC GFMC AFDMC	light systems	$A \leq 12$
CVMC AFDMC	light to medium-mass nuclei	$A \sim 50$
AFDMC	nuclear matter	$A = \infty$

$$\tau = \frac{it}{\hbar} : \; -\frac{\partial}{\partial \tau}|\psi(\tau)\rangle = (H - E_0)|\psi(\tau)\rangle \quad \longrightarrow \quad |\psi(\tau)\rangle = e^{-(H-E_0)\tau}|\psi(0)\rangle \overset{\tau\to\infty}{\longrightarrow} |\psi_0\rangle$$

Results

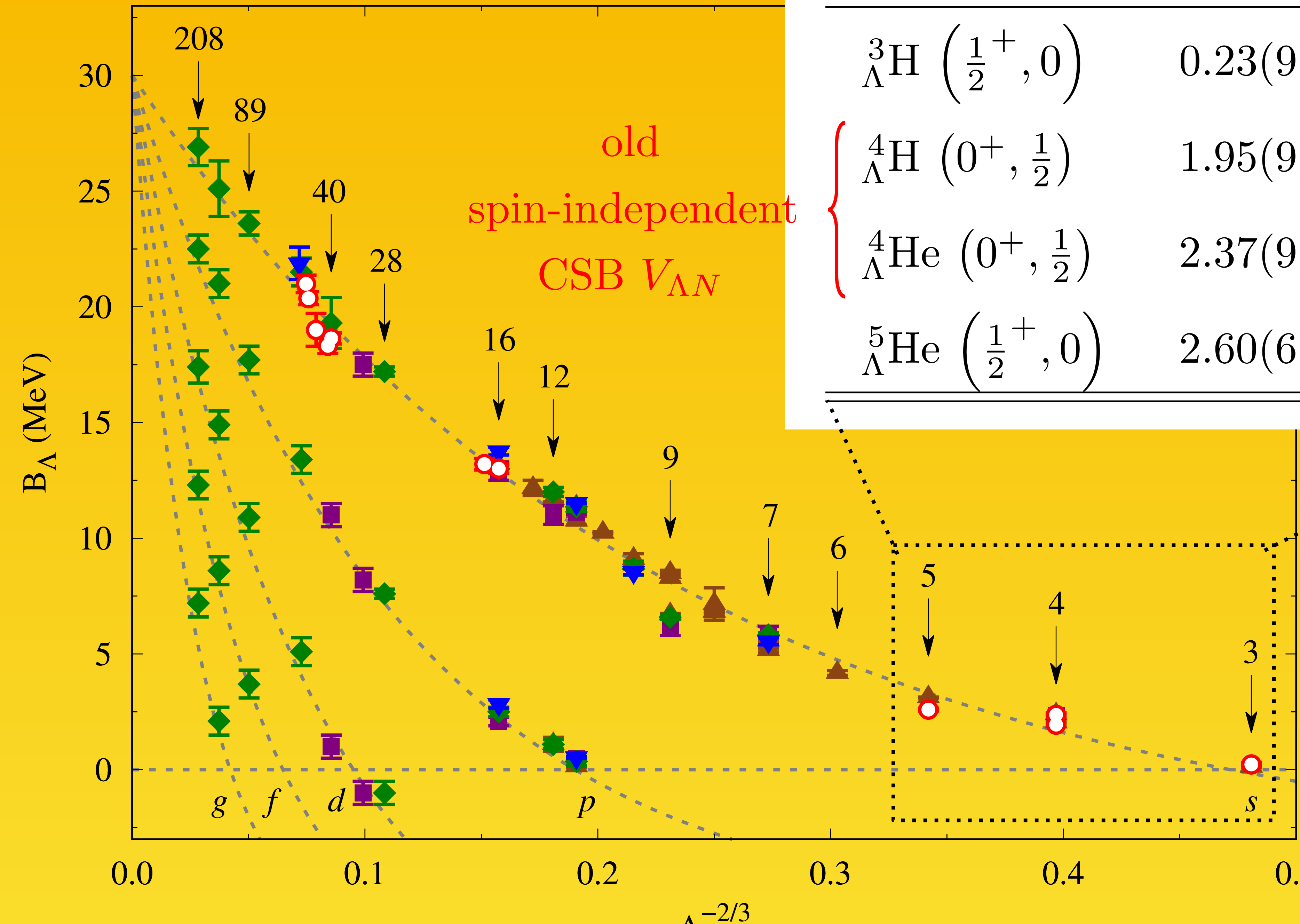
AFDMC: Λ hypernuclei



D. Lonardoni and FP, arXiv:1711.07521

Results

AFDMC: **Λ hypernuclei**

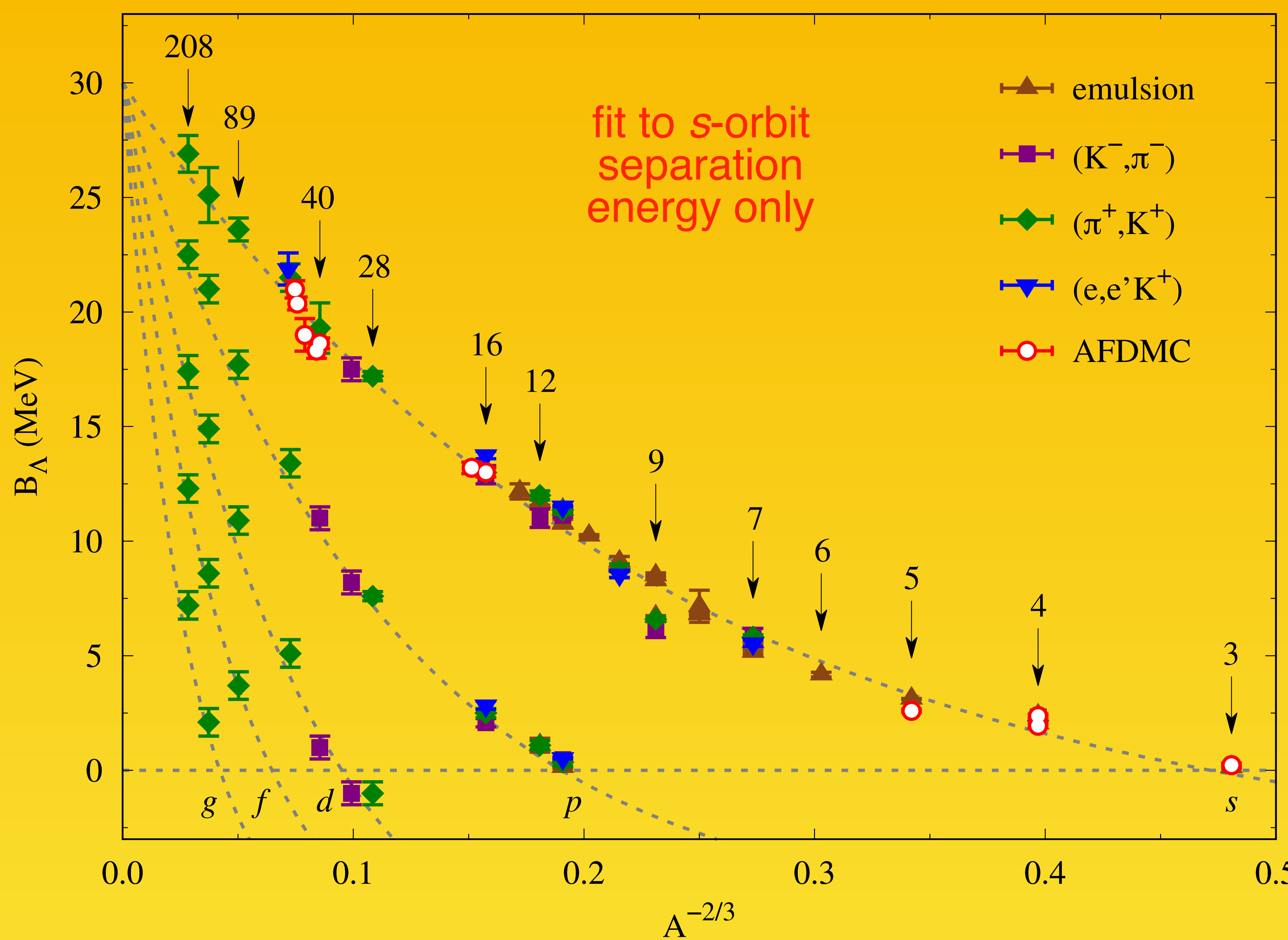


${}^{A}_{\Lambda}Z\ (J^\pi, T)$	B_Λ	Exp
${}^{3}_{\Lambda}\mathrm{H}\ \left(\frac{1}{2}^+, 0\right)$	0.23(9)	0.13(5)
${}^{4}_{\Lambda}\mathrm{H}\ \left(0^+, \frac{1}{2}\right)$	1.95(9)	~~2.16(8)~~ 2.04(4)
${}^{4}_{\Lambda}\mathrm{He}\ \left(0^+, \frac{1}{2}\right)$	2.37(9)	2.39(3)
${}^{5}_{\Lambda}\mathrm{He}\ \left(\frac{1}{2}^+, 0\right)$	2.60(6)	3.12(2)

D. Lonardoni and FP, arXiv:1711.07521

Results

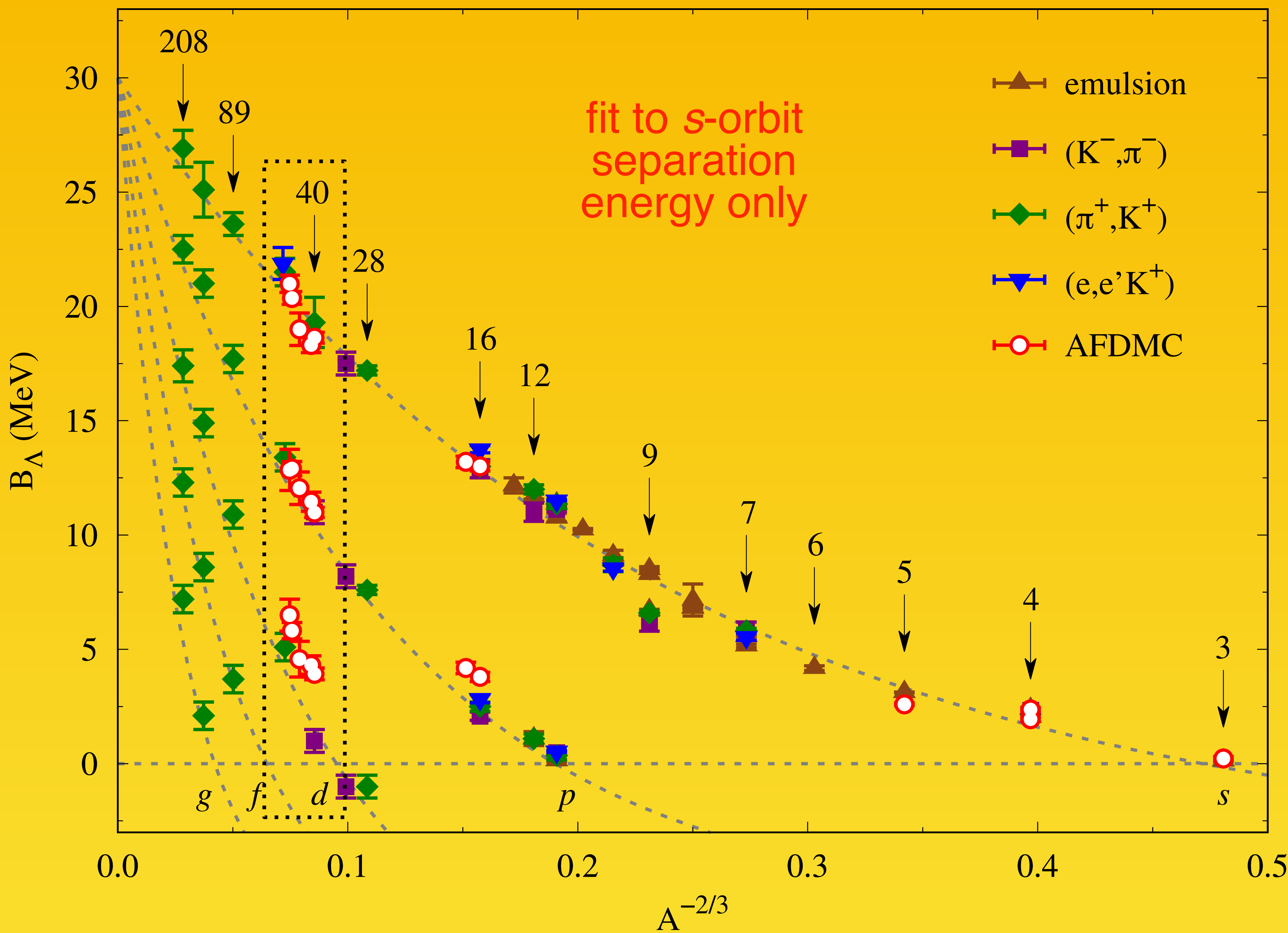
AFDMC: Λ hypernuclei



D. Lonardoni and FP, arXiv:1711.07521

Results

AFDMC: Λ hypernuclei

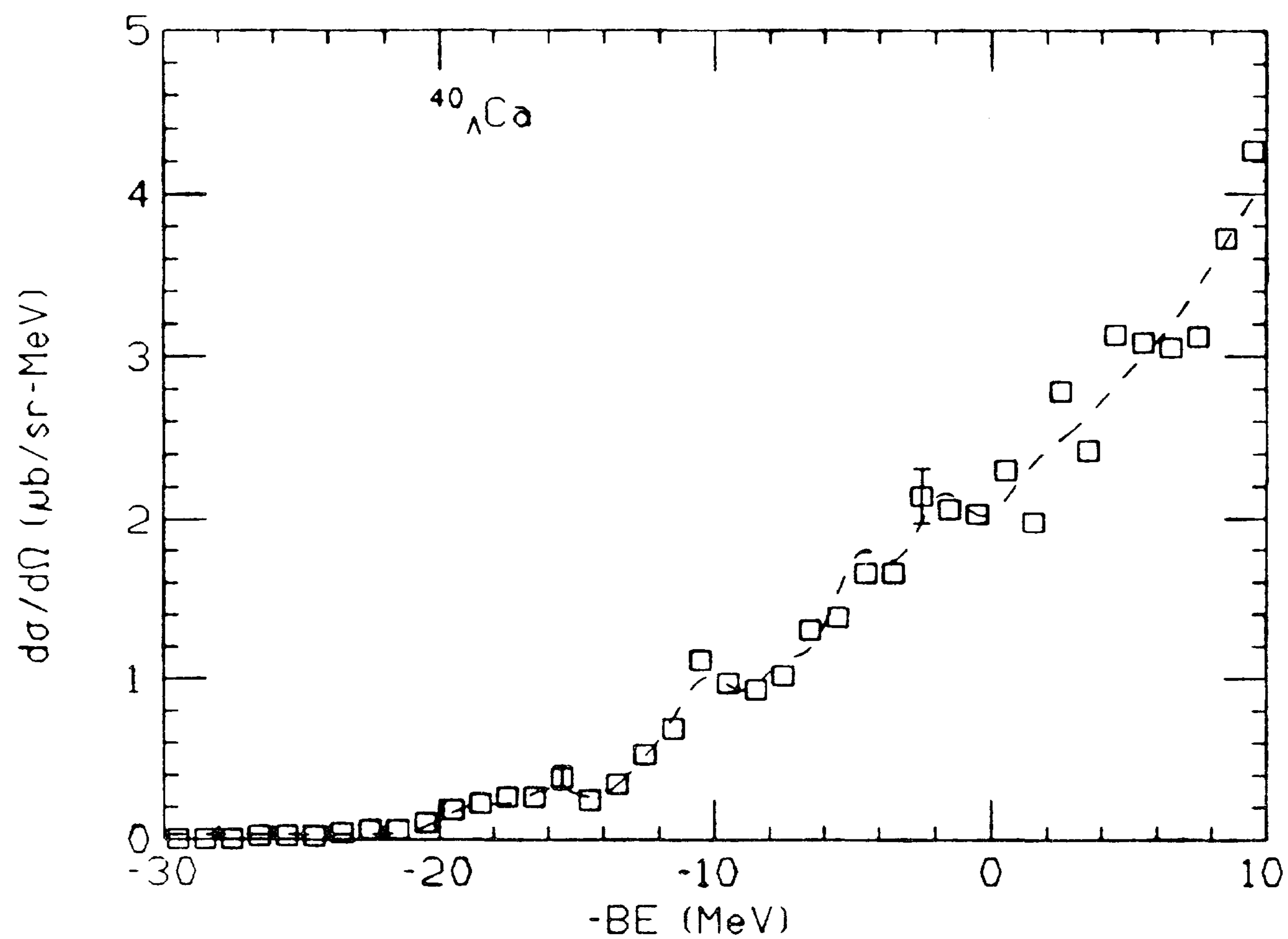


D. Lonardoni and FP, arXiv:1711.07521

Results

AFDMC: Λ-hypernuclei

	$^{A}_{\Lambda}\mathrm{Z}\ (J^\pi, T)$	s-orbit	p-orbit	d-orbit
AFDMC	$^{40}_{\Lambda}\mathrm{K}$	$\left(2^+, \frac{1}{2}\right)$ 18.6(3)	$\left(3^-, \frac{1}{2}\right)$ 11.0(3)	$\left(4^+, \frac{1}{2}\right)$ 3.9(3)
	$^{41}_{\Lambda}\mathrm{Ca}$	$\left(\frac{1}{2}^+, 0\right)$ 18.3(4)		
	$^{45}_{\Lambda}\mathrm{Ca}$	$\left(\frac{1}{2}^+, 2\right)$ 19.0(8)		
	$^{48}_{\Lambda}\mathrm{K}$	$\left(1^+, \frac{9}{2}\right)$ 20.4(4)		
	$^{49}_{\Lambda}\mathrm{Ca}$	$\left(\frac{1}{2}^+, 4\right)$ 21.0(5)		
Exp	$^{40}_{\Lambda}\mathrm{Ca}$	$\left(2^+, \frac{1}{2}\right)$ 19.3(1.1)		
	$^{51}_{\Lambda}\mathrm{V}$	$(?, 2)$ 21.5(6)		
	$^{52}_{\Lambda}\mathrm{V}$	$\left(3^-, \frac{5}{2}\right)$ 21.9(7)		
		$\left(4^-, \frac{5}{2}\right)$ 21.9(7)		



P. H. Pile *et al.*, Phys. Rev. Lett **66**, 2585 (1991)

D. Lonardoni and FP, arXiv:1711.07521

Results

AFDMC: Λ-hypernuclei

${}^{A}_{\Lambda}\mathrm{Z}\ (J^\pi, T)$	s-orbit	p-orbit	d-orbit	
${}^{40}_{\Lambda}\mathrm{K}$	$(2^+, \frac{1}{2})$ 18.6(3)	$(3^-, \frac{1}{2})$ 11.0(3)	$(4^+, \frac{1}{2})$ 3.9(3)	
			$\left(\frac{5}{2}^+, 0\right)$ 4.3(4)	
			$\left(\frac{5}{2}^+, 2\right)$ 4.6(8)	
			$(3^+, \frac{9}{2})$ 5.8(4)	
			$\left(\frac{5}{2}^+, 4\right)$ 6.5(7)	
			$(4^+, \frac{1}{2})$ 1.0(5)	?
			(?, 2) 5.1(6)	
			—	
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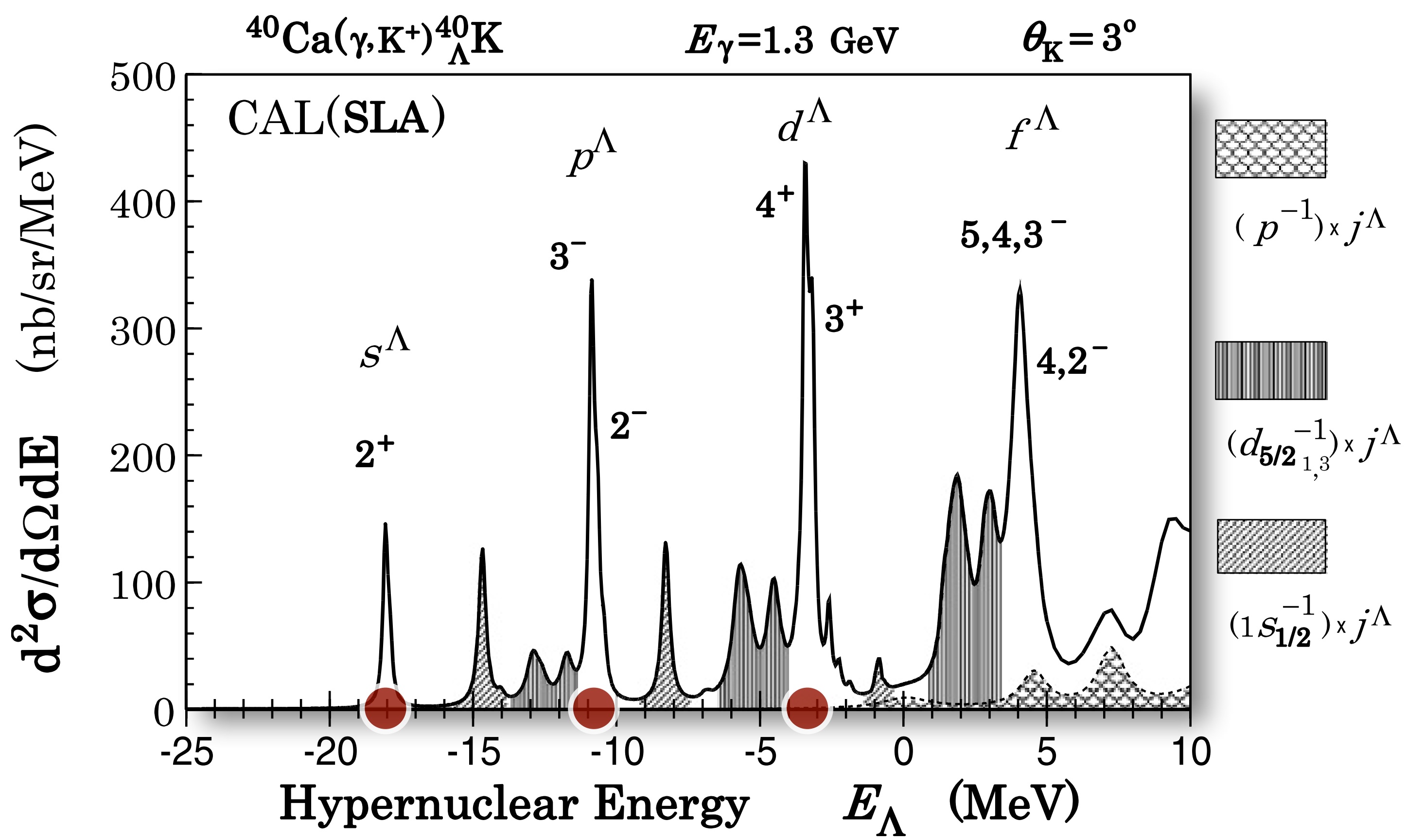

P. Bydžovský *et al.*, Nucl. Phys. A **881** (2012) 199-217

$B_\Lambda^s \simeq 18.0\,\mathrm{MeV} \quad \mathrm{B}_\Lambda^\mathrm{p} \simeq 10.7\,\mathrm{MeV} \quad \mathrm{B}_\Lambda^\mathrm{d} \simeq 3.3\,\mathrm{MeV}$

Results

AFDMC: Λ-hypernuclei

AFDMC

${}^{A}_{\Lambda}\mathrm{Z}\ (J^\pi, T)$	s-orbit	p-orbit	d-orbit
${}^{40}_{\Lambda}\mathrm{K}$	$(2^+, \frac{1}{2})$ 18.6(3)	$(3^-, \frac{1}{2})$ 11.0(3)	$(4^+, \frac{1}{2})$ 3.9(3)
${}^{41}_{\Lambda}\mathrm{Ca}$	$\left(\frac{1}{2}^+, 0\right)$ 18.3(4)	$\left(\frac{3}{2}^-, 0\right)$ 11.5(4)	$\left(\frac{5}{2}^+, 0\right)$ 4.3(4)
${}^{45}_{\Lambda}\mathrm{Ca}$	$\left(\frac{1}{2}^+, 2\right)$ 19.0(8)	$\left(\frac{3}{2}^-, 2\right)$ 12.1(8)	$\left(\frac{5}{2}^+, 2\right)$ 4.6(8)
${}^{48}_{\Lambda}\mathrm{K}$	$(1^+, \frac{9}{2})$ 20.4(4)	$(2^-, \frac{9}{2})$ 12.9(4)	$(3^+, \frac{9}{2})$ 5.8(4)
${}^{49}_{\Lambda}\mathrm{Ca}$	$\left(\frac{1}{2}^+, 4\right)$ 21.0(5)	$\left(\frac{3}{2}^-, 4\right)$ 12.9(9)	$\left(\frac{5}{2}^+, 4\right)$ 6.5(7)

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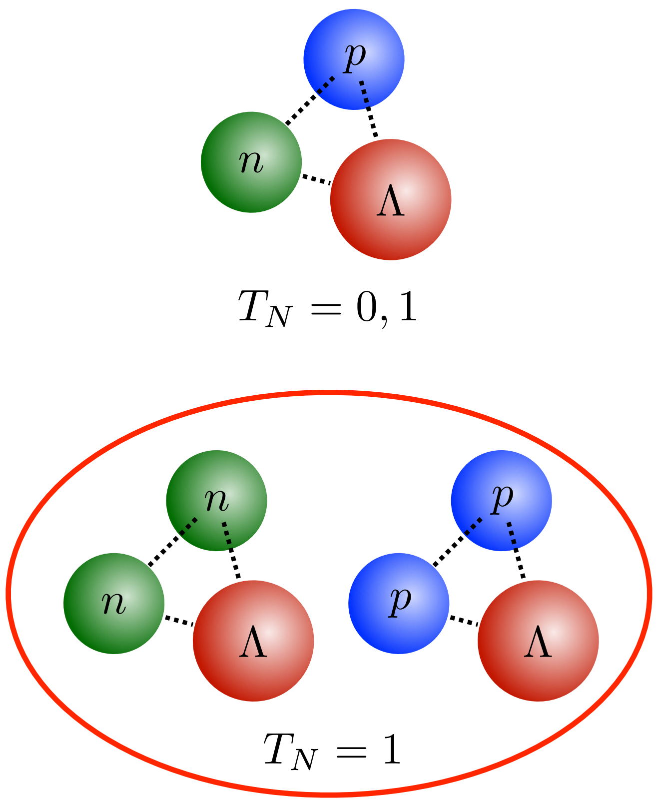
$^{40}\mathrm{Ca}\,(e, e'K^+)\,{}^{40}_{\Lambda}\mathrm{K}$

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

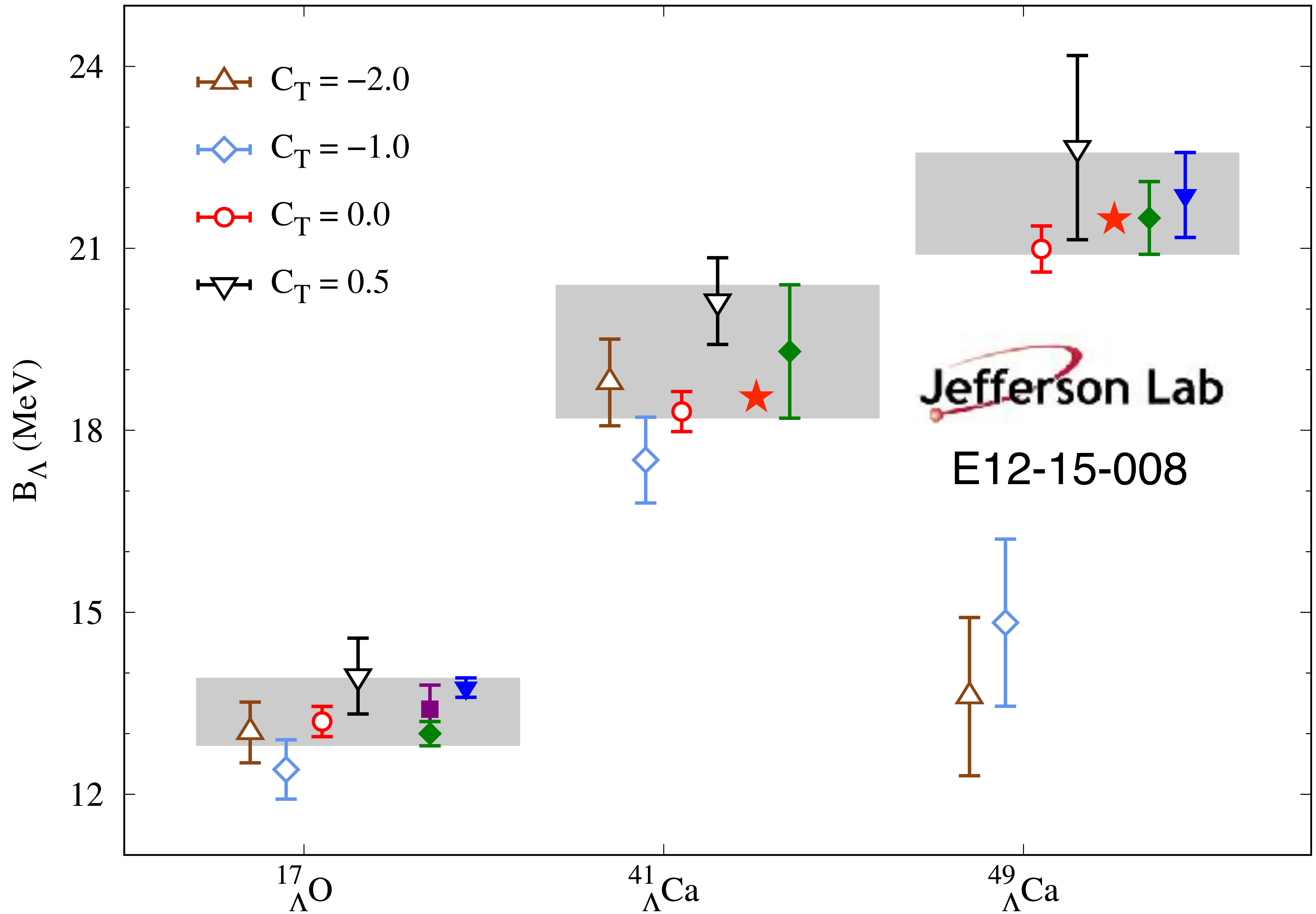
D. Lonardoni and FP, arXiv:1711.07521

Results

AFDMC: Λ-hypernuclei



control parameter C_T

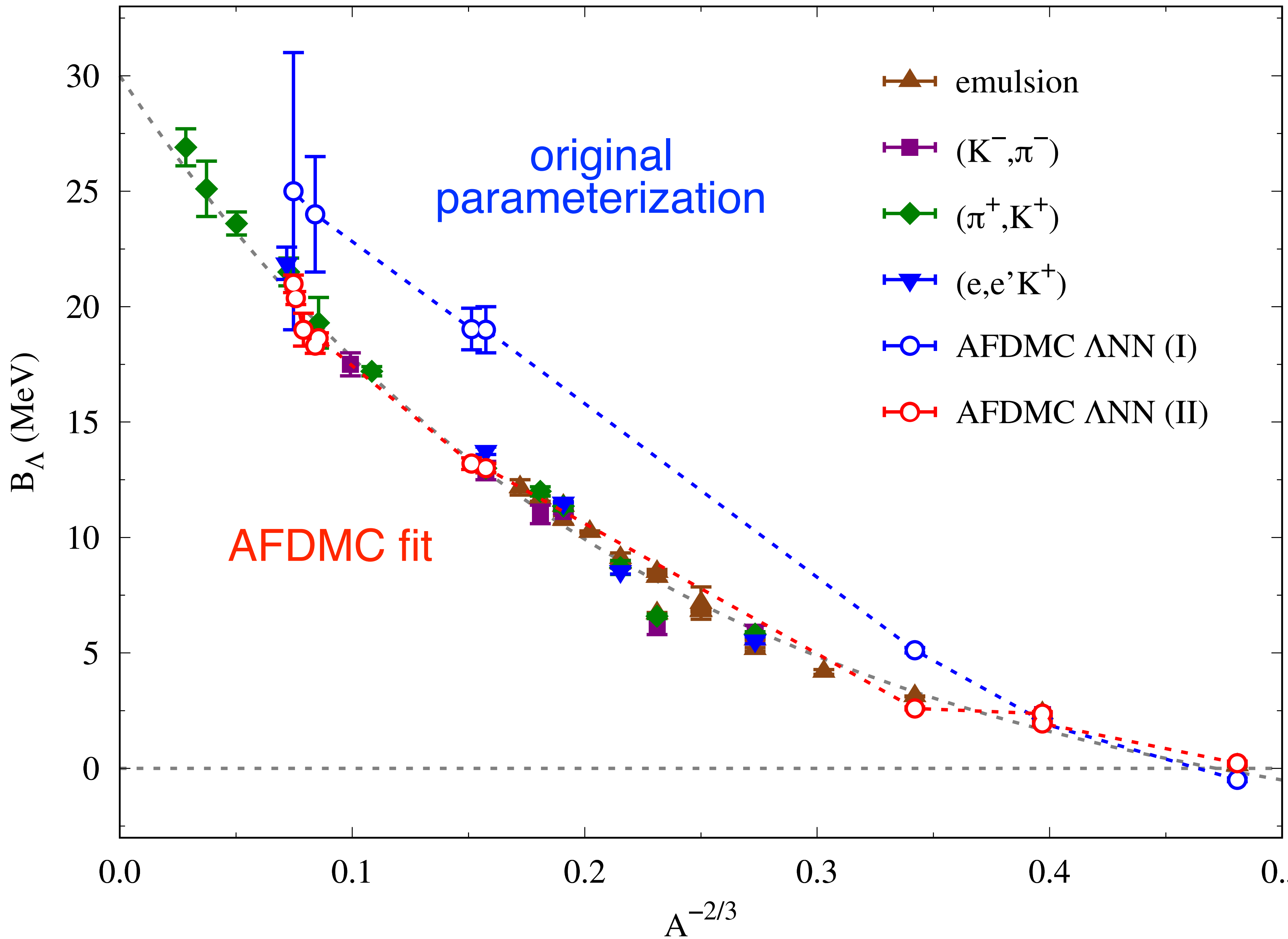


is AFDMC sensitive to a nucleon-isospin dependence of the ΛNN force?

D. Lonardoni and FP arXiv:1711.07521

Results

AFDMC: Λ-hypernuclei

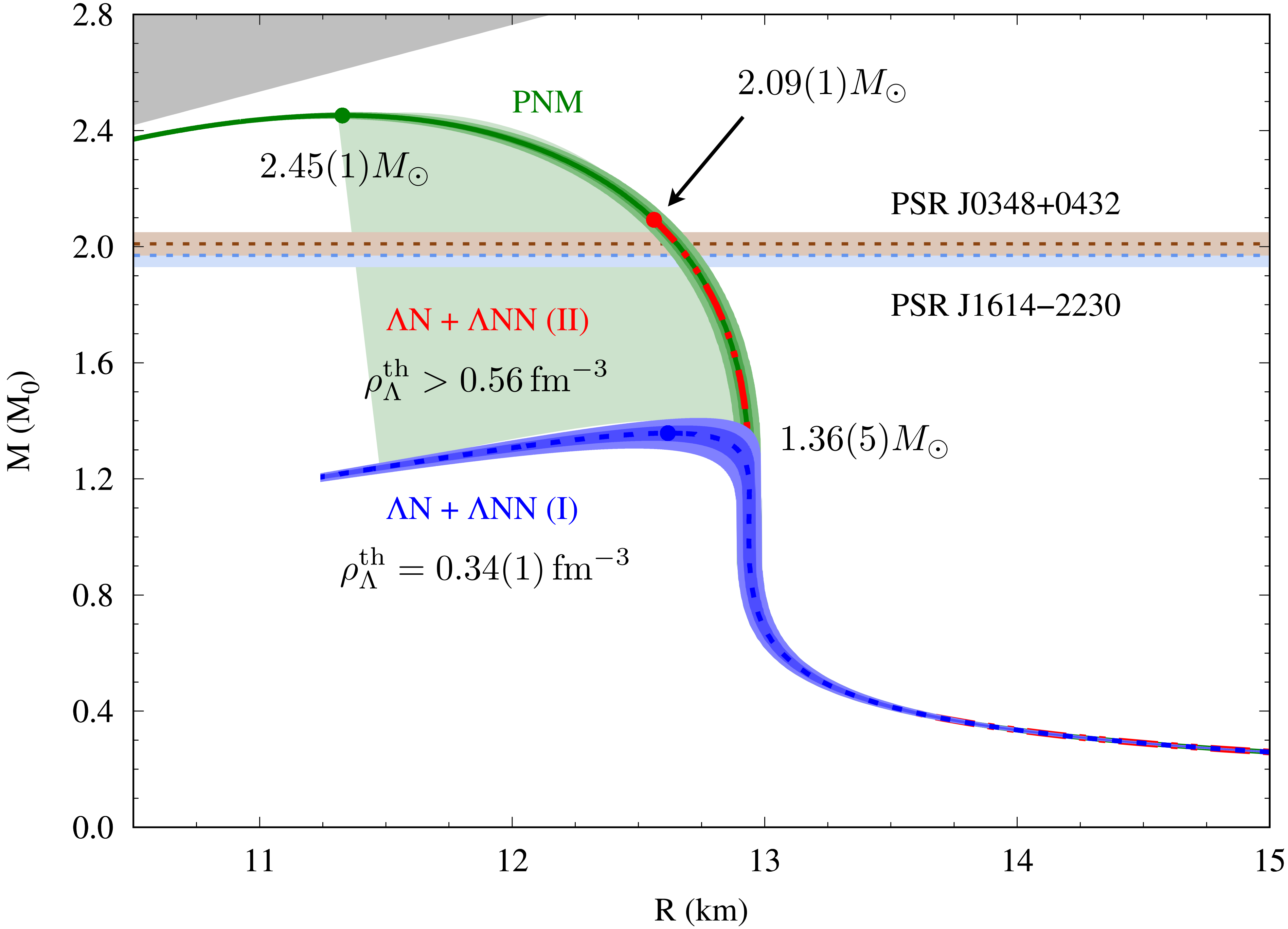


D. Lonardoni *et al.*, Phys. Rev. C 89, 014314 (2014)

D. Lonardoni and FP, arXiv:1711.07521

Results

AFDMC: Λ-hypermatter



D. Lonardoni *et al.*, Phys. Rev. Lett. **114**, 092301 (2015)

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.
- 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 > $2\rho_0$. Accurate spectroscopy of n-rich medium mass hypernuclei in ~ two years. But the community badly needs more p-Λ scattering data. Improved LQCD calculations will help adding pieces to the puzzle to complete the picture.