# Properties of Lambda hypernuclei to constrain the symmetry energy

Wei-Zhou Jiang

*Department of Physics, Southeast University , Nanjing, China*

*Students: Rong-Yao Yang, Si-Na Wei*

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# Outline

I. Motivation
II. Λ hypernuclei in RMF
III. Some numerical results
IV. Summary

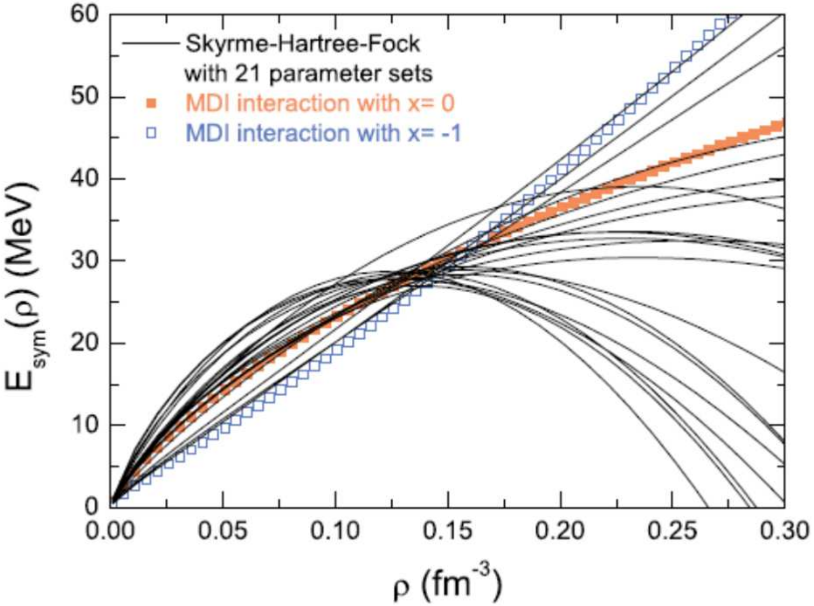



FIG. 1. (Color online) Density dependence of the nuclear symmetry energy $E_{\rm sym}(\rho)$ for 21 sets of Skyrme interaction parameters. The results from the MDI interaction with $x = -1$ (open squares) and 0 (solid squares) are also shown.

L.W.Chen,et.al., PRC72, 064309 (05)

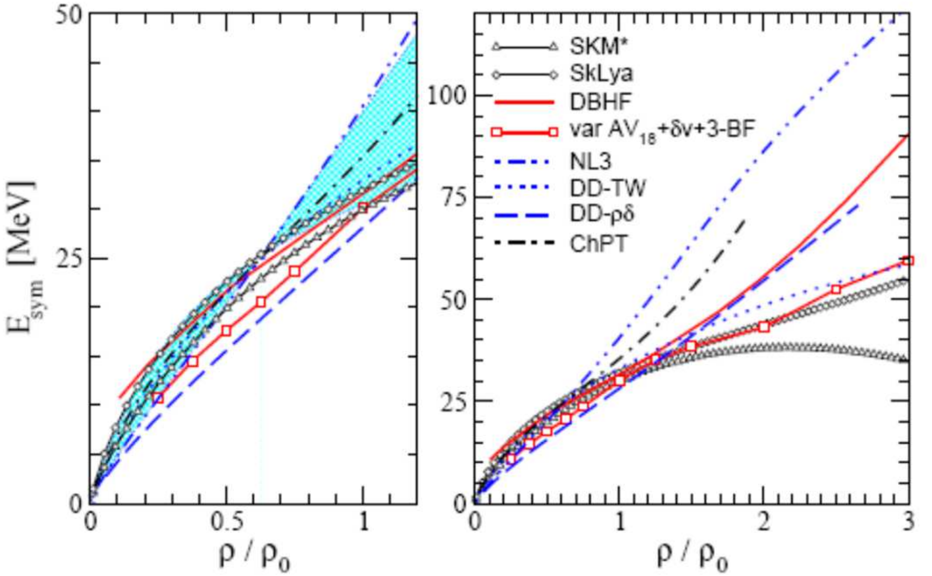
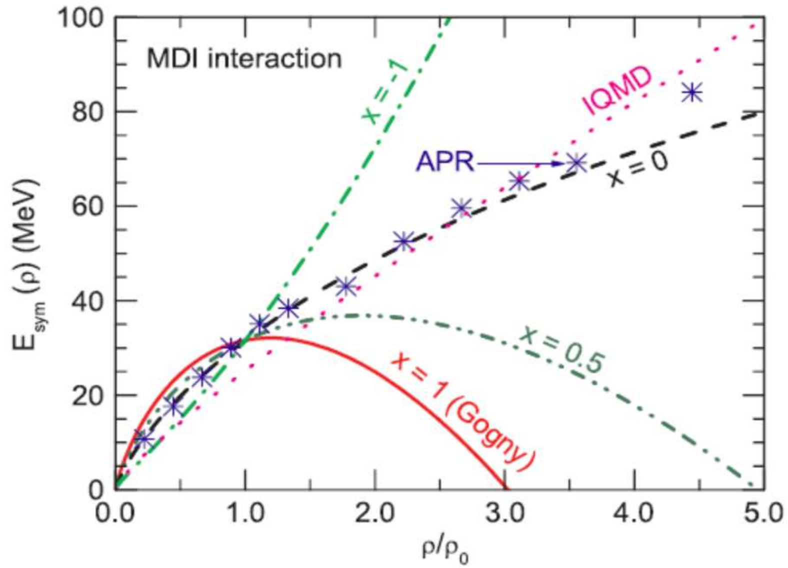
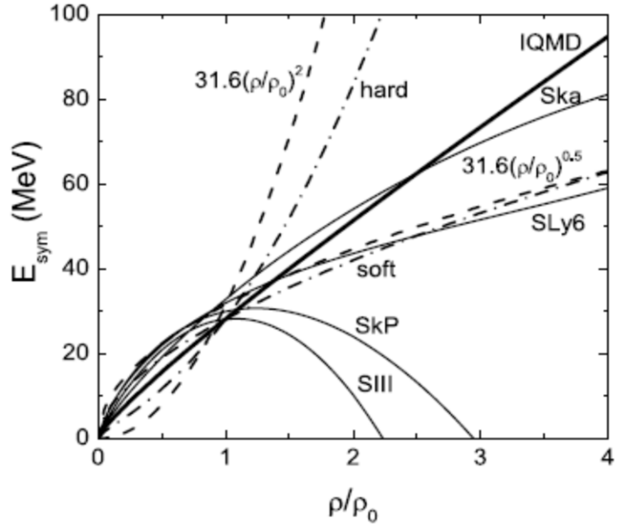



**Fig. 5.** Symmetry energy as a function of density as predicted by different models. The left panel shows the low density region while the right panel displays the high density range.

Fuchs, et.al., arXiv:nucl-th/0511070

# Diverse trends from data



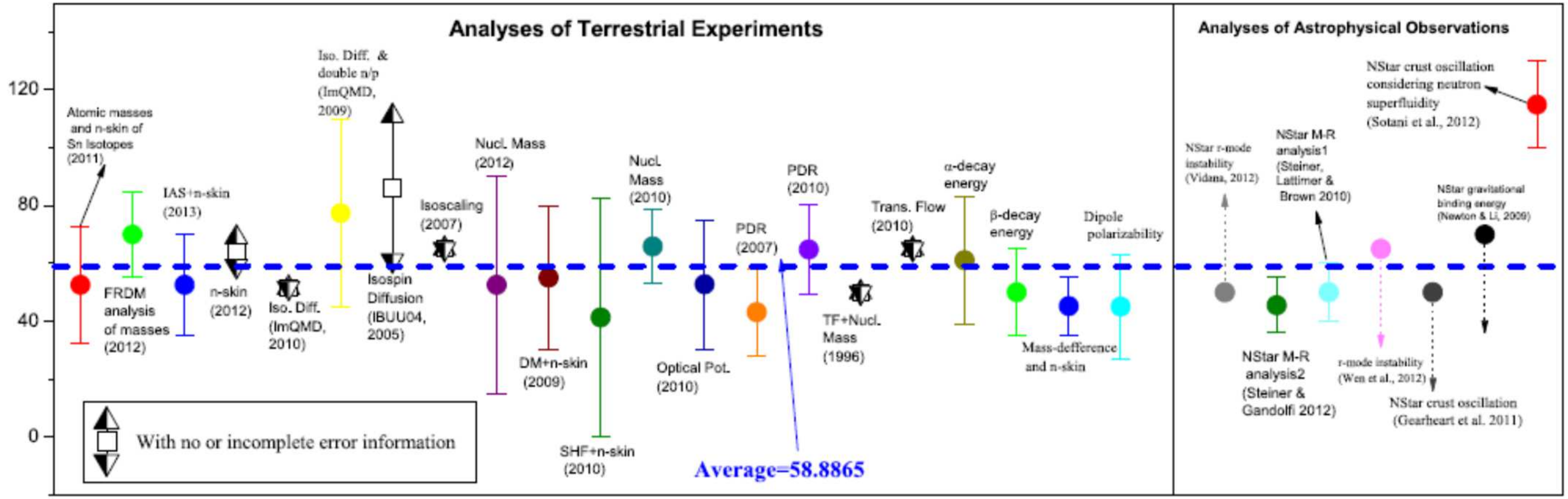

**1. Xiao, et.al PRL102, 062502 (2009)**

**2. Feng&Jin, PLB683 (2010) 140**

**3. P. Russotto,W. Trauntmann, Q.F. Li et al., PLB697, 471(2011)**

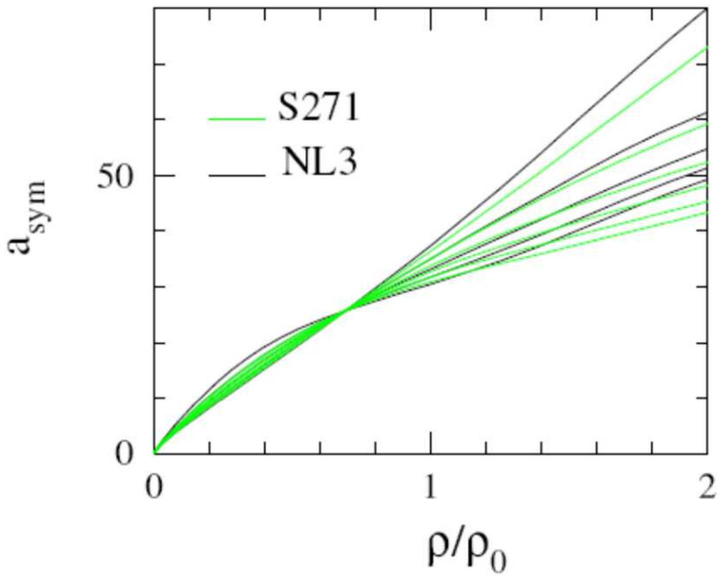
**31.6(ρ／ρ)$^{\gamma}$, with γ=0.9+/−0.4: almost linear**

# Current constraints on the Slope parameter




From Li, Han, PLB727,276(2013)

# Symmetry energies in Relativistic models:




$$E_{sym} = \frac{\partial^2(\varepsilon/\rho)}{\partial\delta^2}\bigg|_{\delta=0} = \frac{1}{2}\left(\frac{g_\rho}{m_\rho^*}\right)^2 \rho + \frac{1}{6}\frac{k_F^2}{E_F^*}$$

$m_\rho \rightarrow m_\rho^*$ by isoscalar - isovector coupling

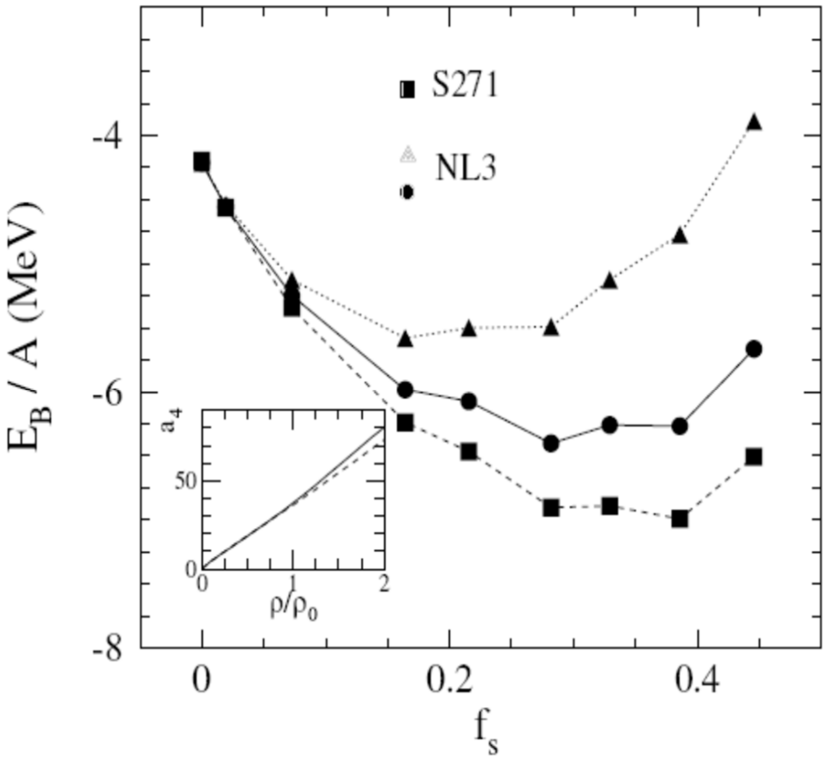
$$U\left(\sigma, \omega^\mu, b_0^\mu\right) = \frac{1}{3} g_2 \sigma^3 + \frac{1}{4} g_3 \sigma^4 - \frac{1}{4} c_3 \left(\omega_\mu \omega^\mu\right)^2 - 4 g_\rho^2 \left(\Lambda_s g_\sigma^2 \sigma^2 + \Lambda_v g_\omega^2 \omega_\mu \omega^\mu\right) b_{0\mu} b_0^\mu .$$

The density dependence of the symmetry energy in S271 and NL3

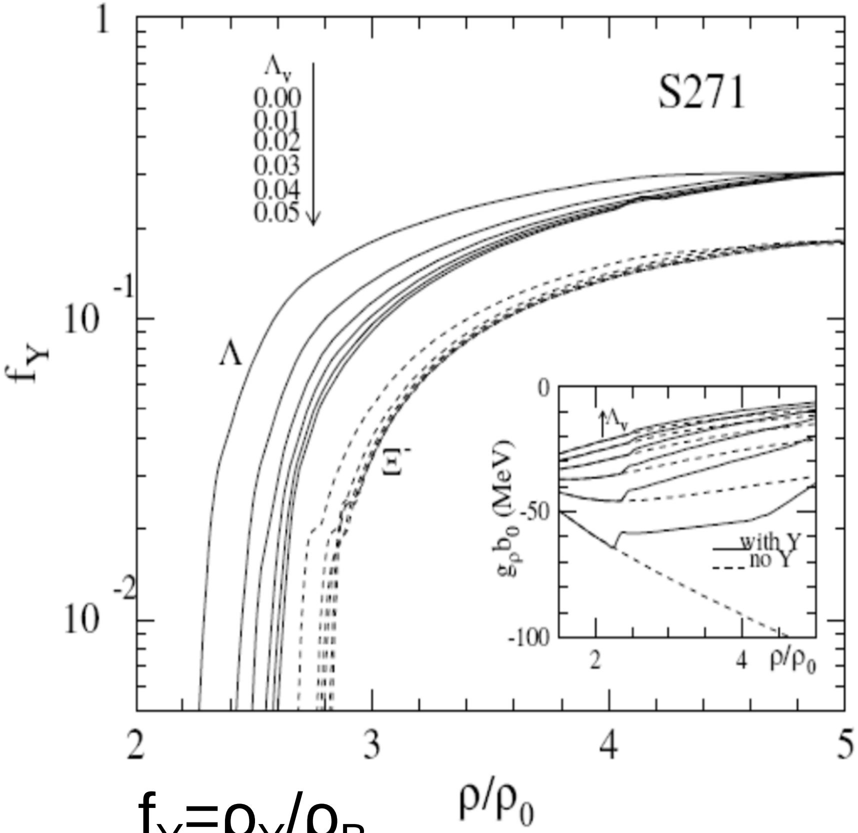
# Why to include isoscalar Λ hyperons in nuclear system?

- **Change the matter density distribution by adding Λ without changing the isospin.**
- **Properties of finite and infinite systems with Λ's are sensitive to symmetry energy.**

# Multi- **Λ hypernuclei & hyperon-rich matter**




$f_s=n_\Lambda/n_B$




$f_Y=\rho_Y/\rho_B$

**Jiang, Nucl-th/0609024, PLB 642(2006)28**

# Production of Hypernuclei

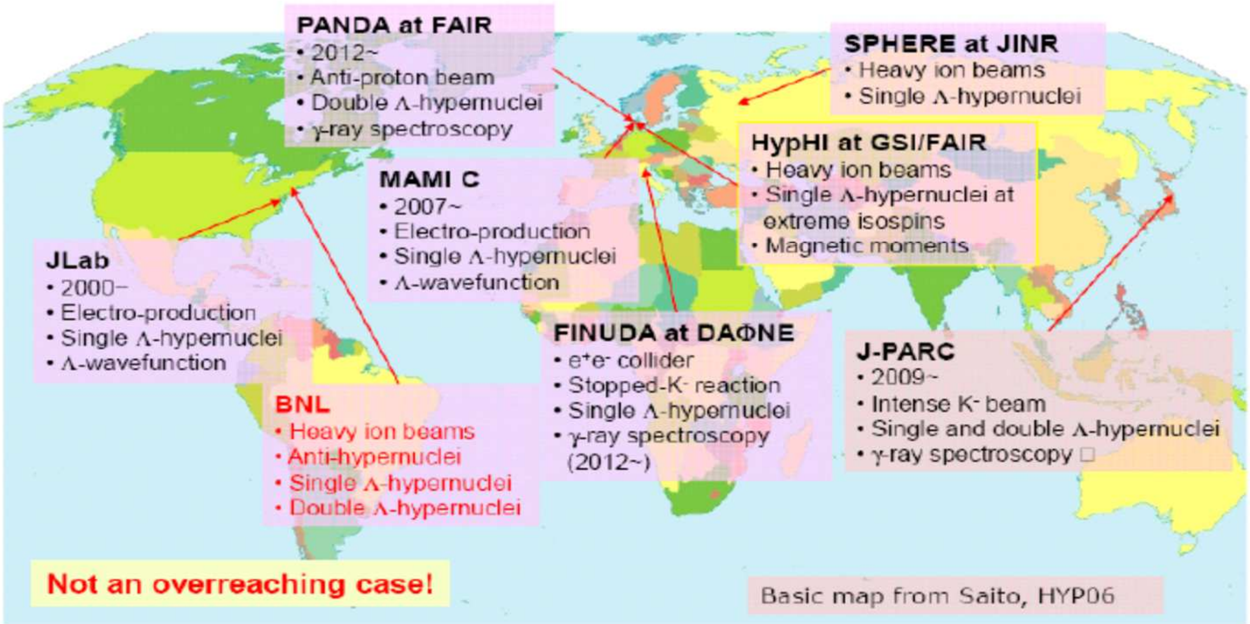
Strangeness exchange: $n(K^-, \pi^-)\Lambda$ CERN, BNL, KEK, DAPHNE
$p(K^-, \pi^\pm)\Sigma^\mp$

Associated production: $n(\pi^+, K^+)\Lambda$ BNL, KEK

Electroproduction: $p(e, e'K^+)\Lambda$ Jlab, MAMI

GSI/FAIR
•H.I. Collision
•p-$\bar{p}$ collision

## STAR International Hyper-nuclear network




Strangeness is conserved in Strong & e.m. interactions.

Hypernuclei live long enough to have sharp energy levels.

IMP of the CAS has a roadmap now.

More than 5 ΛΛ hypernuclei?



Courtesy of Samanta

# An idea from variation

- In parabolic approximation, the energy density function is

$$E(n, \delta) \approx E_0(n) + E_{\mathrm{sym}}\delta^2 \cdots$$

- The variation of symmetry energy should not affect the isoscalar part, e.g. the Λ binding in hypernuclei.
- However, in an integrated system with the coupling of the isoscalar and isovector, the variation of symmetry energy brings the rearrangement of the whole system and correspondingly the change of the isoscalar part.
- According to the variation principle, the separated isoscalar part should stay at extrema for the variation of the isovector part.

It's difficult to separate them in an integrated system. A nice example is the binding energy of the **Λ hyperons.**

# RMF

$$\mathcal{L} = \bar{\psi}_B\Big[i\gamma_\mu\partial^\mu - M_B + g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu\omega^\mu - g_{\rho B}\gamma_\mu\tau_3 b_0^\mu$$
$$+ \frac{f_{\omega B}}{2M_N}\sigma_{\mu\nu}\partial^\nu\omega_0^\mu - e\frac{1}{2}(1+\tau_c)\gamma_\mu A^\mu\Big]\psi_B$$
$$- U\big(\sigma, \omega^\mu, b_0^\mu\big) + \frac{1}{2}\big(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\big)$$
$$- \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$
$$+ \frac{1}{2}m_\rho^2 b_{0\mu}b_0^\mu - \frac{1}{4}A_{\mu\nu}A^{\mu\nu} + \mathcal{L}_Y$$

with

$$U\big(\sigma, \omega^\mu, b_0^\mu\big)$$
$$= \frac{1}{3}g_2\sigma^3 + \frac{1}{4}g_3\sigma^4 - \frac{1}{4}c_3\big(\omega_\mu\omega^\mu\big)^2$$
$$- 4g_\rho^2\big(\Lambda_s g_\sigma^2\sigma^2 + \Lambda_v g_\omega^2\omega_\mu\omega^\mu\big)b_{0\mu}b_0^\mu.$$

and strange meson included

$$\mathcal{L}_Y = \overline{\psi}_Y[g_{\sigma^* Y}\sigma^* - g_{\phi Y}\gamma_\mu\phi^\mu]\psi_Y + \frac{1}{2}(\partial_\mu\sigma^*\partial^\mu\sigma^* - m_{\sigma^*}^2\sigma^{*2})$$
$$-\frac{1}{4}(\partial^\mu\phi^\nu - \partial^\nu\phi^\mu)(\partial_\mu\phi_\nu - \partial_\nu\phi_\mu) + \frac{1}{2}m_\phi^2\phi_\mu\phi^\mu$$

- Equations of Motion In RMF:

$$\left(\frac{d^2}{dr^2} + \frac{2}{r}\frac{d}{dr} - m_\phi^2\right)\phi(r) = -s_\phi(r)$$

$$s_\phi(r) = \begin{cases} g_\sigma \rho_s + 8 g_\sigma^2 g_\rho^2 \Lambda_s \sigma b_0^2 - g_2 \sigma^2(r) - g_3 \sigma^3(r) & \sigma \\ g_\omega \rho_B - c_3 \omega_0^3 - 8 g_\omega^2 g_\rho^2 \Lambda_v \omega b_0^2 & \omega \\ g_\rho \rho_3 - 8 g_\rho^2 b_0 \left(g_\omega^2 \Lambda_v \omega_0^2 + g_\sigma^2 \Lambda_s \sigma_0^2\right) & \rho \\ e\rho_c = e \sum_\alpha^A \frac{2j_\alpha+1}{4\pi r^2}\left(G_\alpha^2(r) + F_\alpha^2(r)\right)(1+t)/2 & \text{photon} \end{cases}$$

For Baryons

$$\frac{dG_\alpha}{dr} = (M_N^*(r) - V(r) + E_\alpha)F_\alpha - \left(\frac{\kappa}{r} - U_2^\rho(r) - U_3^\rho(r)\right)G_\alpha$$

$$\frac{dF_\alpha}{dr} = (M_N^*(r) + V(r) - E_\alpha)G_\alpha + \left(\frac{\kappa}{r} - U_2^\rho(r) - U_3^\rho(r)\right)F_\alpha$$

$$M_N^*(r) = M_N - V^\sigma(r)$$

$$V(r) = g_\omega(r)\omega_0(r) + g_\rho b_0(r) t + e\left(\frac{1+t}{2}\right)A_0 - U_1^\rho(r)$$

$$V^\sigma(r) = g_\sigma(r)\sigma(r)$$

# Parameters for Λ

$$g_{\omega\Lambda} = \frac{2}{3} g_{\omega N}, \; g_{\rho\Lambda} = 0.$$

$g_{\sigma\Lambda}$ is determined by $U_\Lambda^{(N)} = -30$ MeV

$g_{\phi\Lambda} = -\sqrt{2}/3 g_{\omega N}$, from SU(6) relation,

$g_{\sigma^*\Lambda}$ is determined by the values of $\Delta B_{\Lambda\Lambda}$ of $^{10}_{\Lambda\Lambda}$Be.

RMF parameter set: NL3

$U_\Lambda^{(\Xi)}$ as a parameter, $e.g. -51, -30, -15 MeV$

$g_{\sigma^*\Lambda}/g_{\sigma N} = 0.76, 0.62, 0.52$

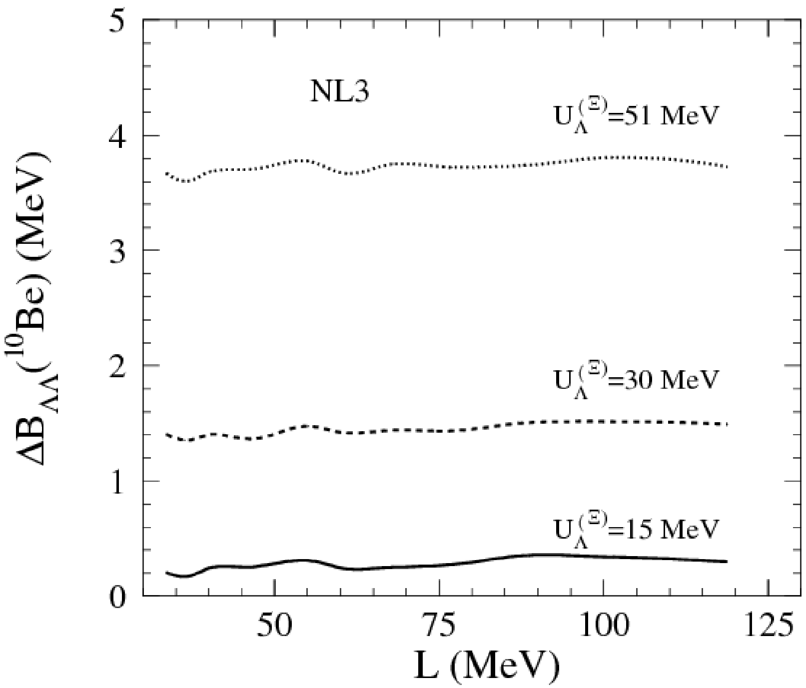
The small ωΛΛ tensor coupling is fitted to the vanishing s.o. splitting of Λ in $^{16}_{\Lambda}$O

| Event | $^{A}_{\Lambda\Lambda}$Z | $\Xi^-$ captured | $B_{\Lambda\Lambda} - B_{\Xi^-}$ (MeV) | $\Delta B_{\Lambda\Lambda} - B_{\Xi^-}$ (MeV) | Level | $B_{\Lambda\Lambda}$ (MeV) | $\Delta B_{\Lambda\Lambda}$ (MeV) |
|---|---|---|---|---|---|---|---|
| NAGARA | $^{6}_{\Lambda\Lambda}$He | $^{12}$C | $B_{\Lambda\Lambda} = 6.79 + 0.91 B_{\Xi^-} (\pm 0.16)$<br>$\Delta B_{\Lambda\Lambda} = 0.55 + 0.91 B_{\Xi^-} (\pm 0.17)$ | | 3$D$ | 6.91 | 0.67 |
| MIKAGE | $^{6}_{\Lambda\Lambda}$He | $^{12}$C | 9.88 ± 1.71 | 3.64 ± 1.71 | 3$D$ | 10.01 | 3.77 |
| | $^{11}_{\Lambda\Lambda}$Be | $^{14}$N | 21.95 ± 2.67 | 3.73 ± 2.71 | 3$D$ | 22.12 | 3.94 |
| DEMACHI-YANAGI | $^{10}_{\Lambda\Lambda}$Be* | $^{12}$C | 11.77 ± 0.13 | -1.65 ± 0.15 | 3$D$ | 11.90 | -1.52 |
| | | | | | $Ex(^{10}_{\Lambda\Lambda}$Be*$) \simeq 2.8$ MeV | | |
| HIDA | $^{11}_{\Lambda\Lambda}$Be | $^{16}$O | 20.60 ± 1.27 | 2.38 ± 1.34 | 3$D$ | 20.83 | 2.61 |
| | $^{12}_{\Lambda\Lambda}$Be | $^{14}$N | 22.31 ± 1.21 | – | 3$D$ | 22.48 | – |
| E176 | $^{13}_{\Lambda\Lambda}$B | $^{14}$N | – | – | 3$D$ | 23.3 ± 0.7 | 0.6 ± 0.8 |
| Danysz | $^{10}_{\Lambda\Lambda}$Be | – | Reconstructed by decay daughters | | | 14.7 ± 0.4 | 1.3 ± 0.4 |

Nakazawa,et al.J. Phys. Conf. Series **569** (2014) 012082

# Some numerical results

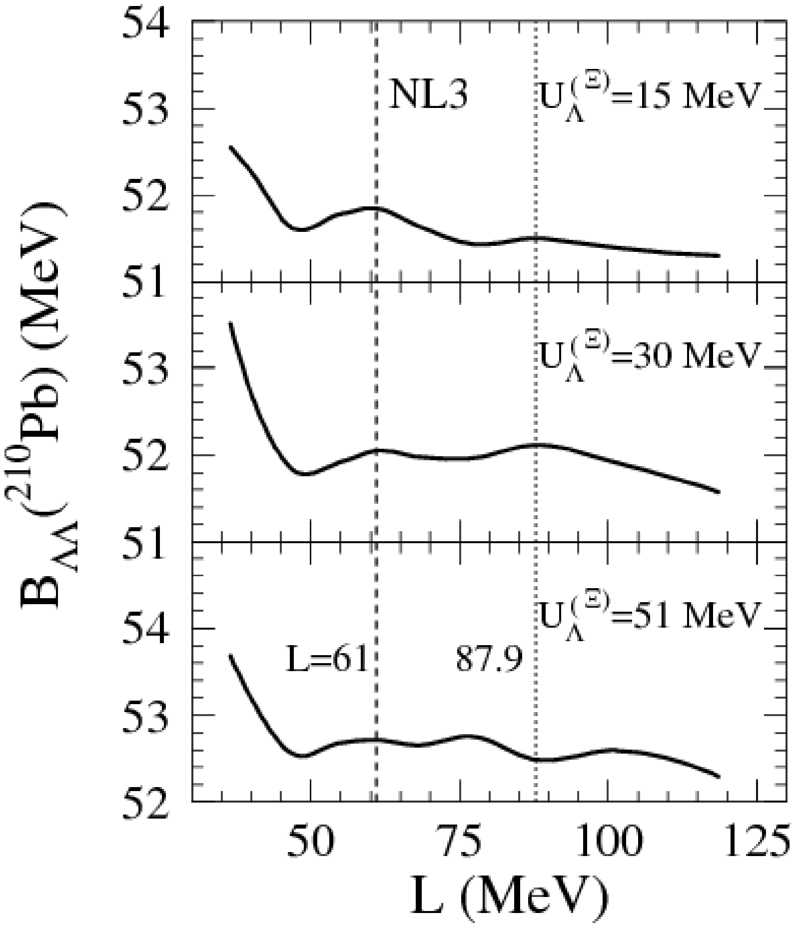
$$\Delta B_{\Lambda\Lambda}(^{10}_{\Lambda\Lambda}\mathrm{Be}) = B_{\Lambda\Lambda}(^{10}_{\Lambda\Lambda}\mathrm{Be}) - 2B_{\Lambda}(^{9}_{\Lambda\Lambda}\mathrm{Be})$$

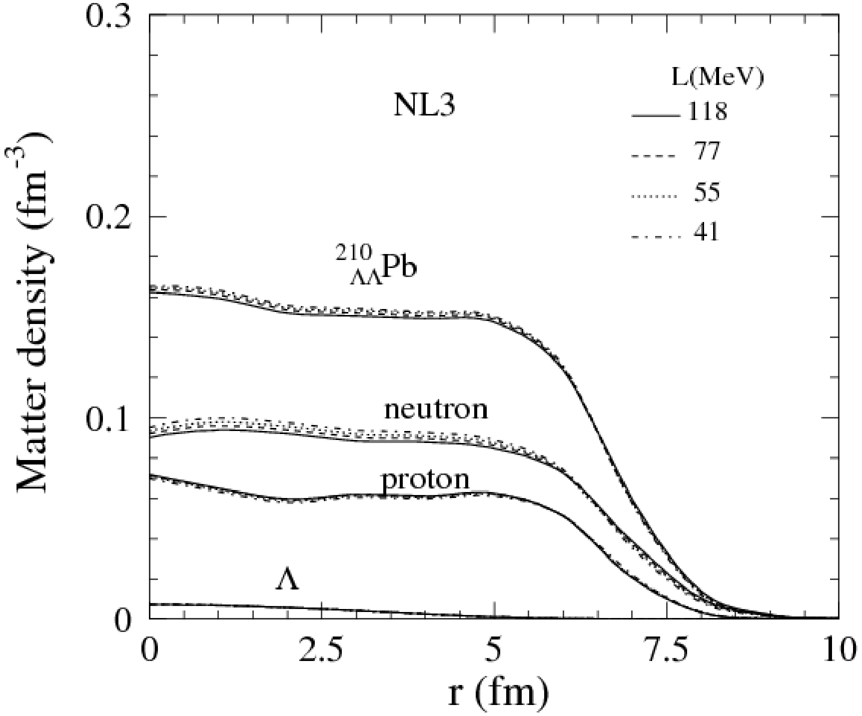



Danysz et al. NPA49,121(1963)

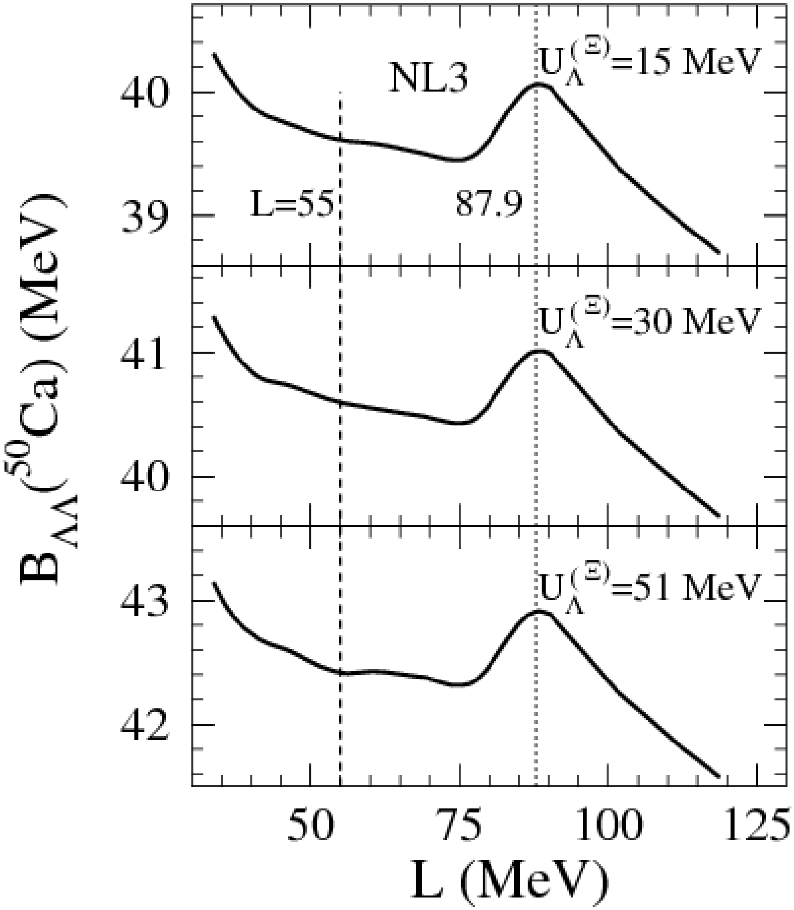
Subtraction of excitation energy
of daughter nucleus? Nakazawa,et al.,
J. Phys. Conf. Series **569** (2014) 012082

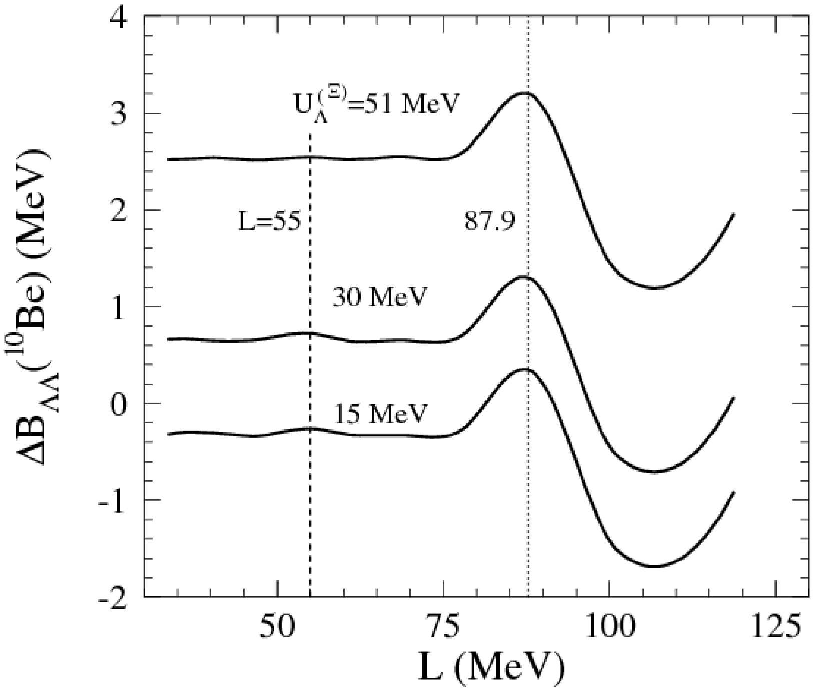
# ${}^{210}_{\Lambda\Lambda}\mathrm{Pb}$ with a flat matter distribution



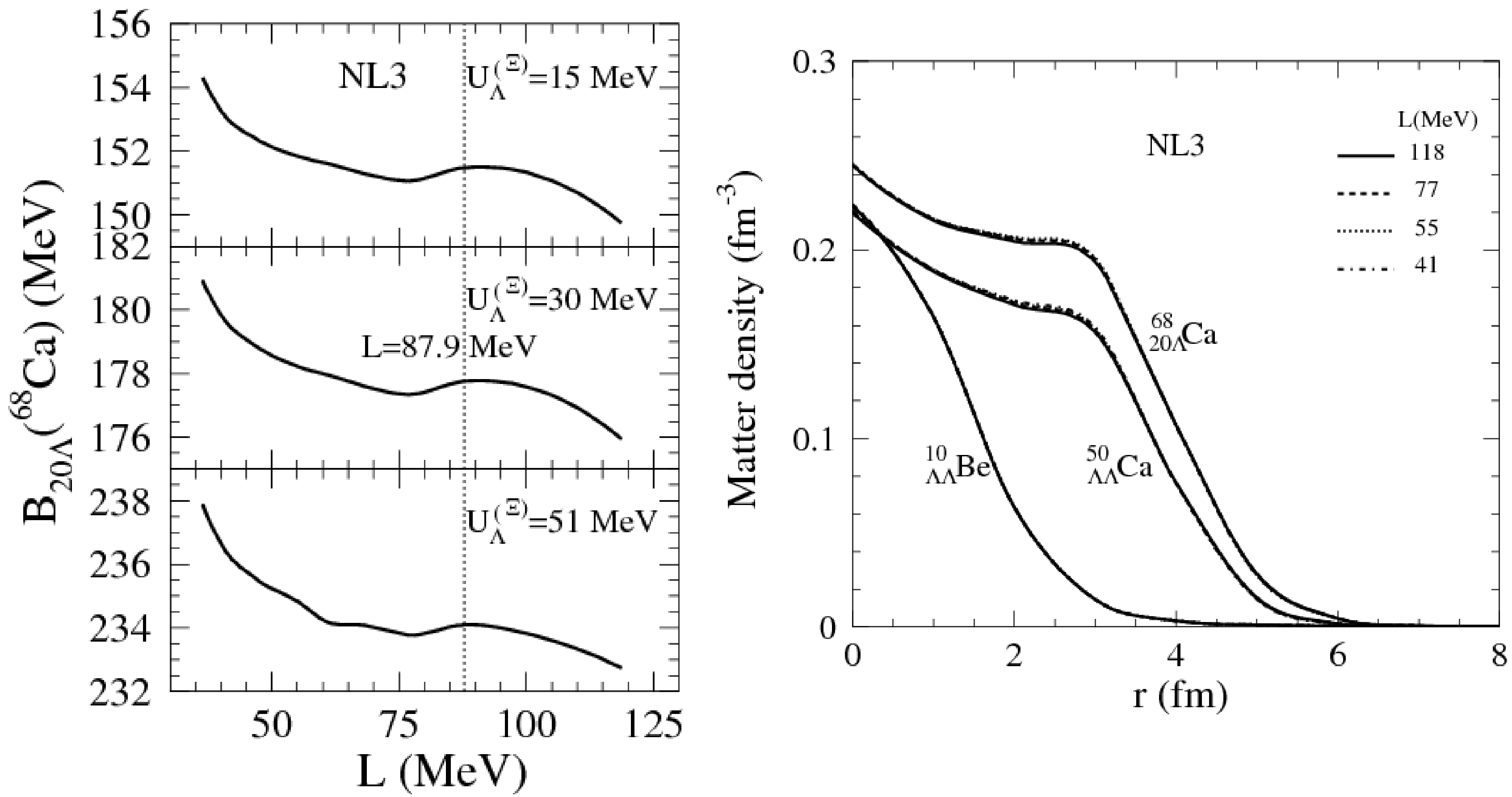



$^{50}_{\Lambda\Lambda}\mathrm{Ca}$



# ${}^{68}_{20\Lambda}\mathrm{Ca}$ , matter density distributions




It has similar surface to ${}^{50}_{\Lambda\Lambda}\mathrm{Ca}$ but has a large core density

# Summary

- ✓ Using the RMF parameter set NL3, properties of $\Lambda$ hypernuclei were studied.
- ✓ Variation of symmetry energy leads to extrema of $\Lambda$ bindings in hypernuclei.
- ✓ The separation energy of $\Lambda$'s in heavy nuclei shows double extrema with decreasing the slope of the symmetry energy.
- ✓ In lighter systems that are created with a larger core density , the double extrema reduce to the single extremum at the larger slope.
- ✓ It would be an indication of a stiffening of symmetry energy at higher densities.
- ✓ Model independence? Should check the model dependence!

Thank you
for your
attention!