Hyperons in Nuclear Matter

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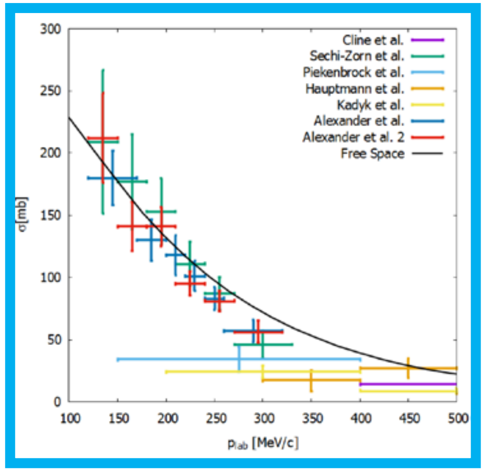
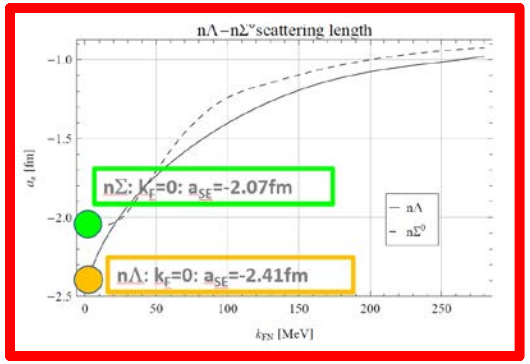
Today‘s Agenda

- GI-DBHF Theory: Covariant Approach to In-Medium BB-Physics
- Hypermatter, Hypernuclei, and Neutron Stars
- Induced Hyperon Self-Energies by the Background Isovector Mean-Field
- Views on Three-Body Interactions
- (Hypernuclear Production in Pion-Kaon Reactions)
- Summary

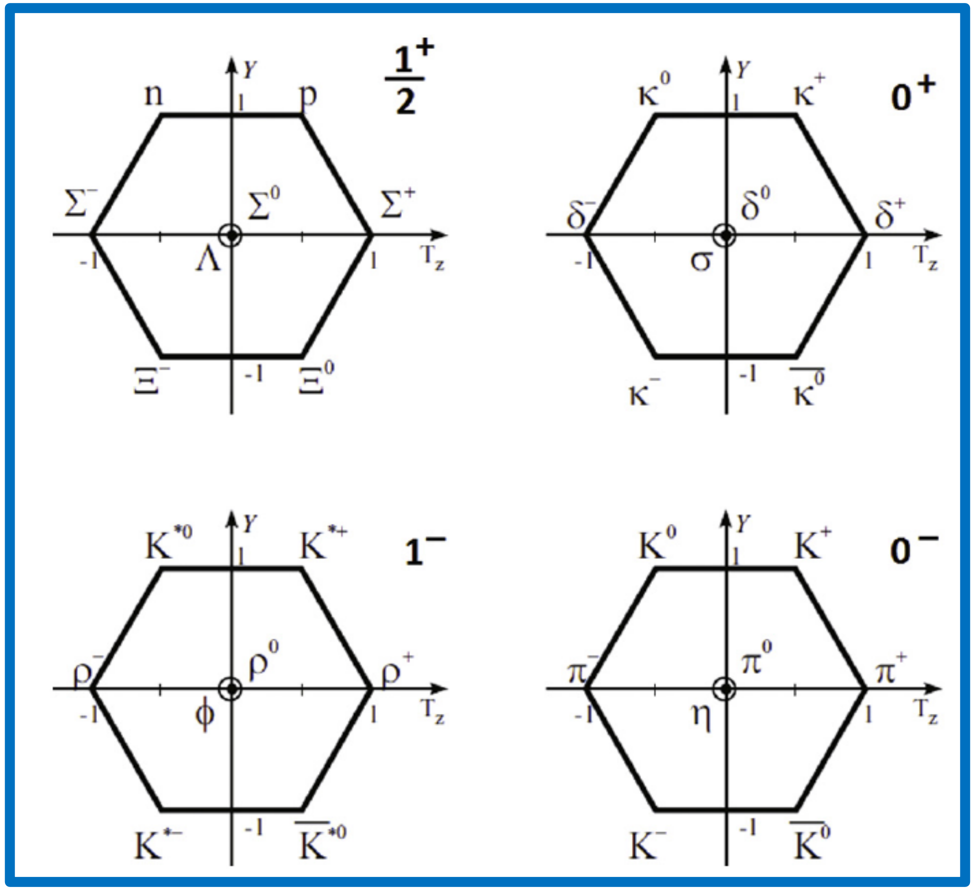
DBHF Description of In-Medium Baryon-Baryon Interactions

Baryon and Meson $SU_f(3)$ –Multiplets and OBE Interactions





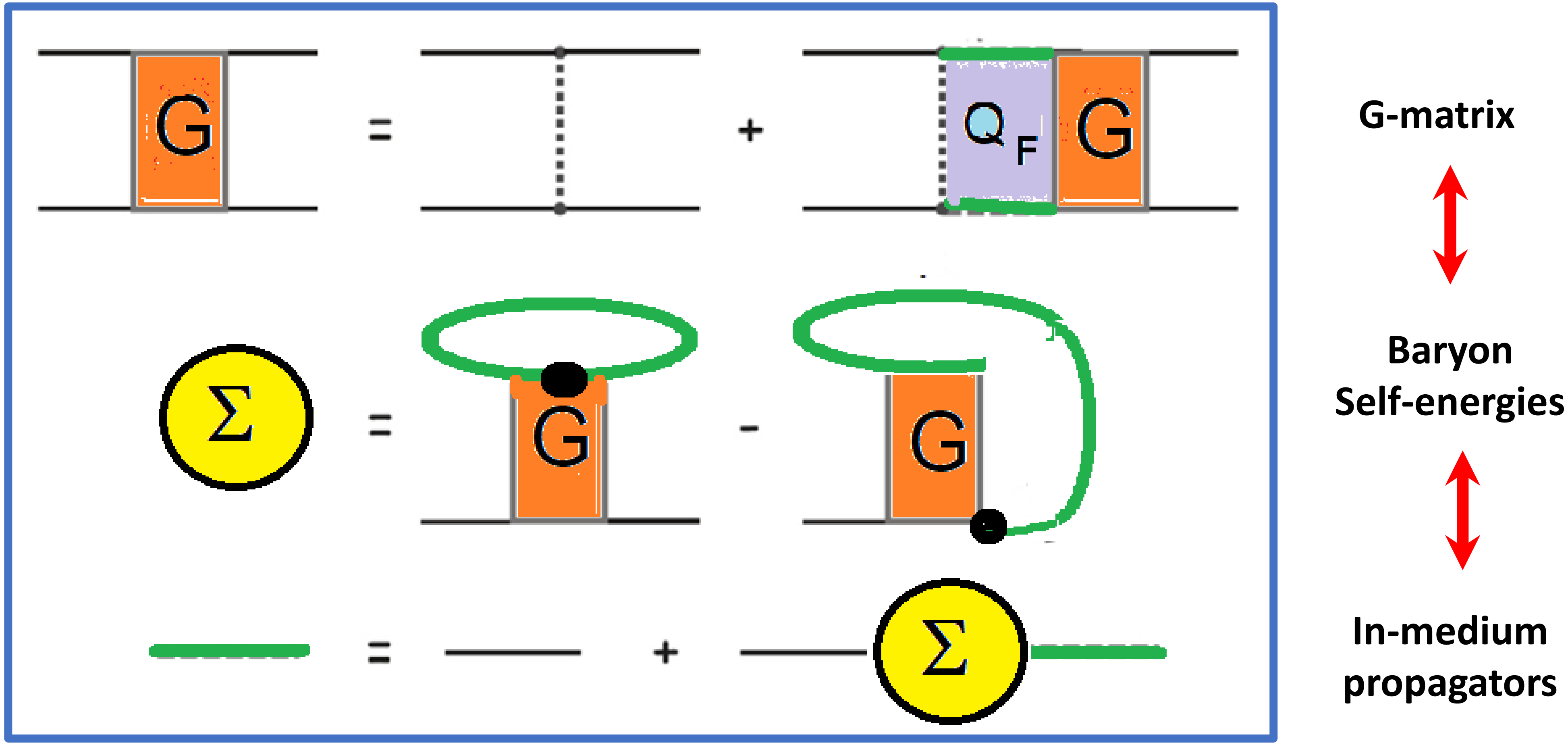
GI-OBE Results
M. Dhar



$$\mathcal{L} = \mathcal{L}_{\mathcal{B}} + \mathcal{L}_{\mathcal{M}} + \mathcal{L}_{int}$$

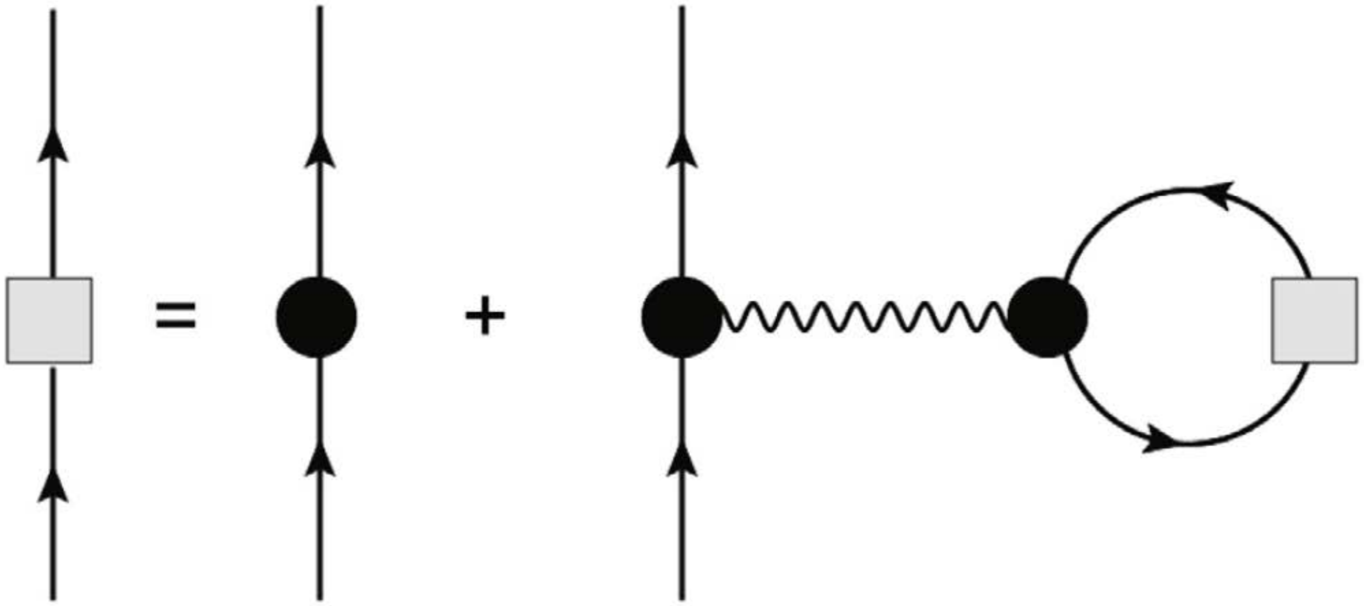
Nijmegen, Jülich, Giessen…

Dirac-Brueckner Hartree-Fock Theory
Self-Conistent Approach to In-Medium Interactions



H.L., C. Fuchs, Phys.Lett.B 345 (1995) 355; Phys.Rev.C 52 (1995)
F. Dejong, H.L., Phys.Rev.C 57 (1998) 3099

Integral Equation for the „Dressed“ In-Medium Vertices

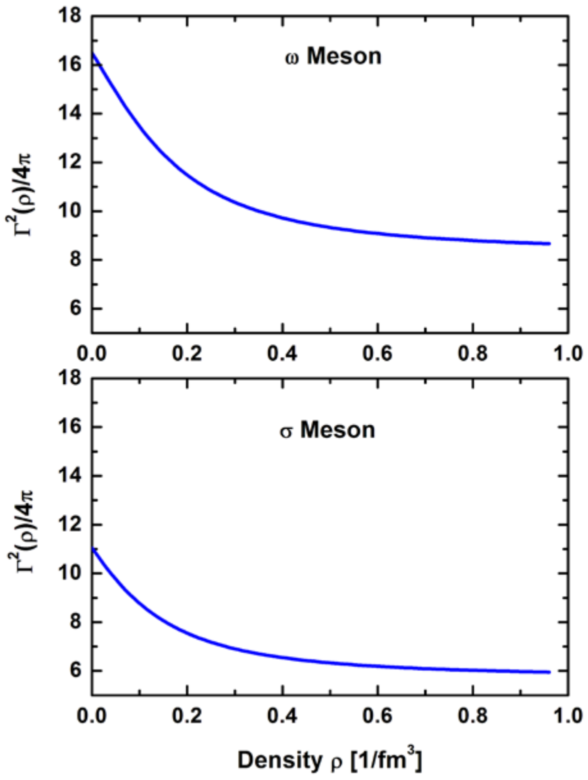


…in leading order:

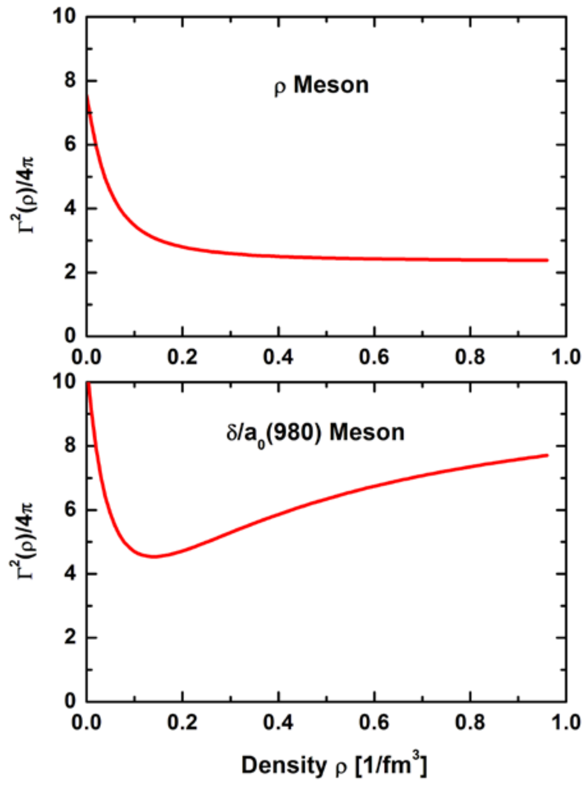
$$\Gamma_{\mathcal{B}\mathcal{B}'a}(q_s, k_F) \simeq \frac{1}{1 - \int dq' V_a \mathcal{G}^* Q_F}\Big|_{\mathcal{B}\mathcal{B}'} g_{\mathcal{B}\mathcal{B}'a}.$$

Nuclear Matter DBHF Mean-Field NN-Vertices

$$\Gamma_a^2(\rho) = \Sigma_{Na}(\rho)/\rho$$

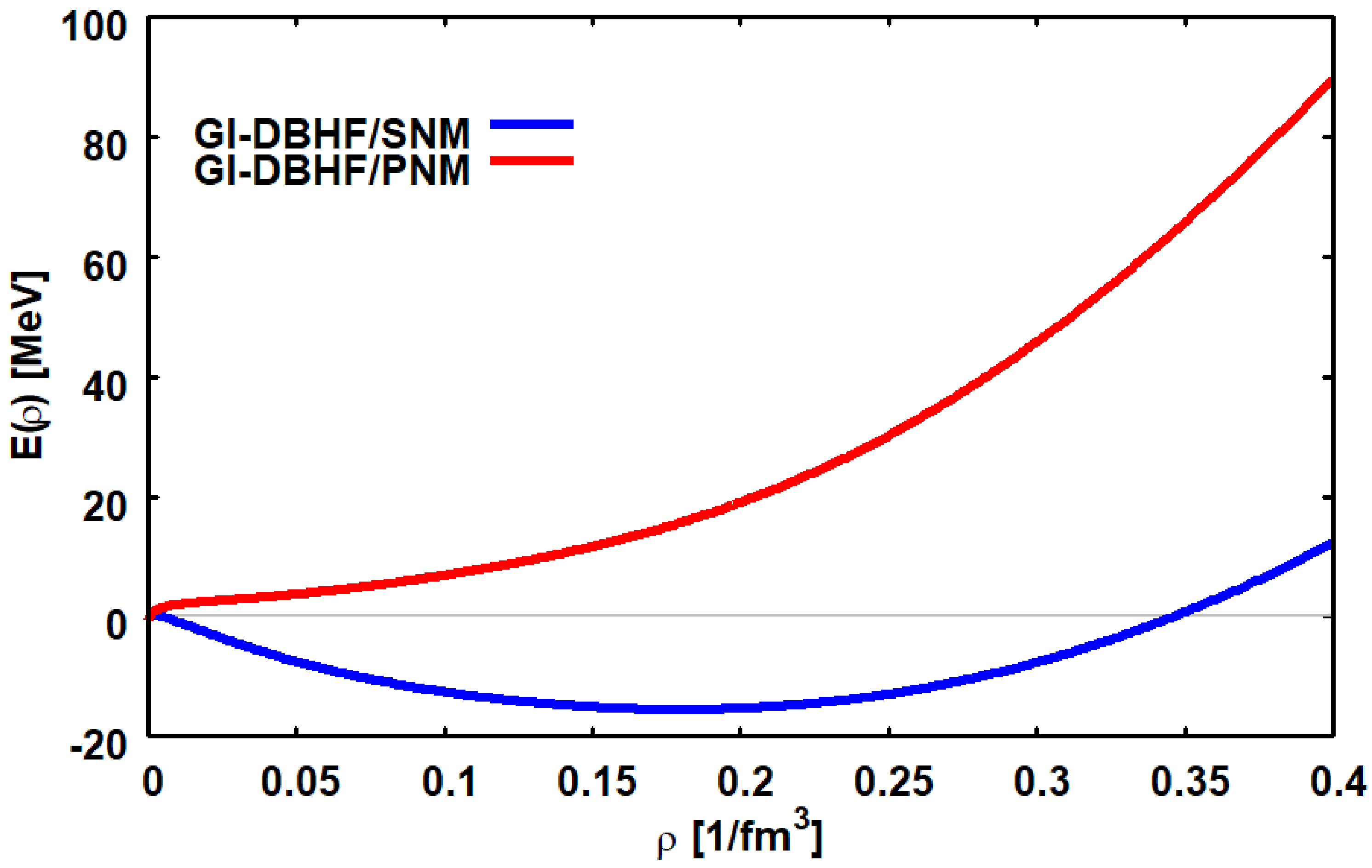


Isoscalar Vertices



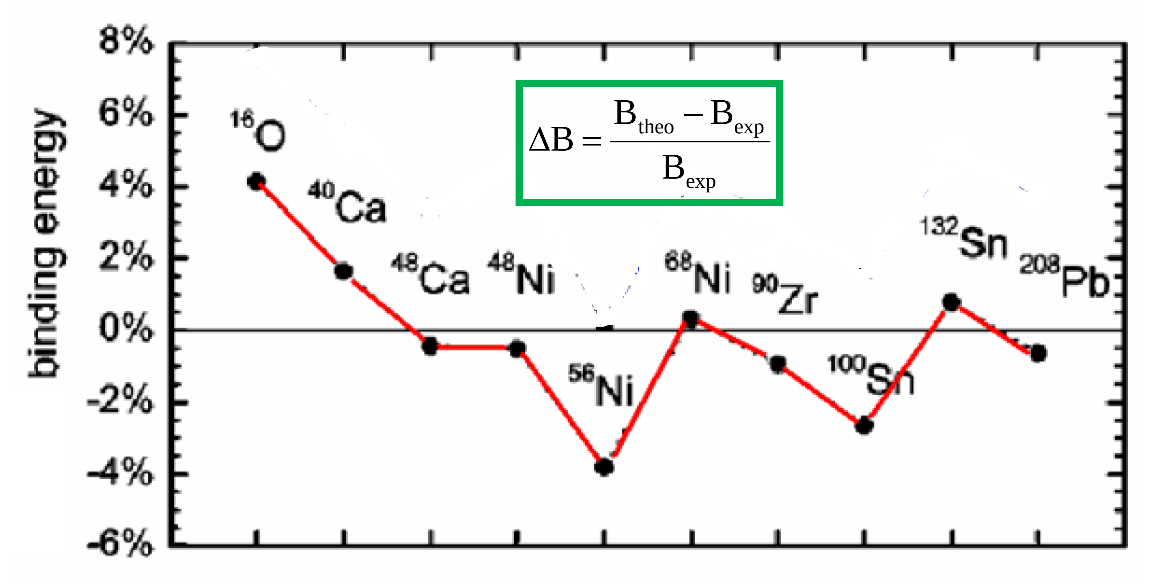
Isovector Vertices

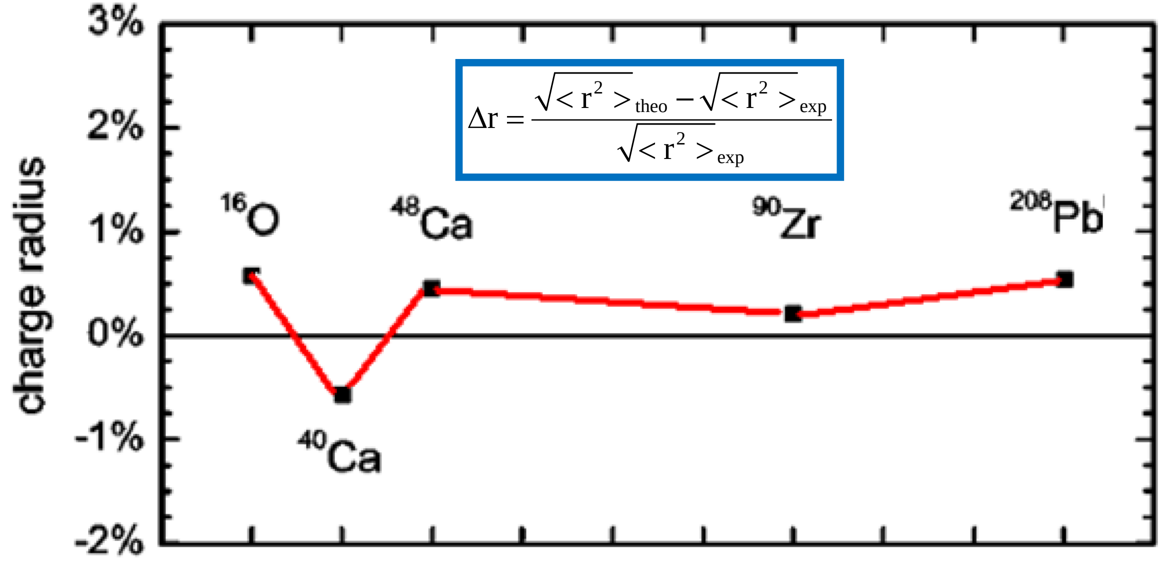
GI-DBHF Results for Infinite Nuclear Matter



• *Hofmann, Keil, Lenske, Phys.Rev.C* 64 (2001) 034314

GI-DBHF Results for Stable Nuclei: B(A) and Charge Radii





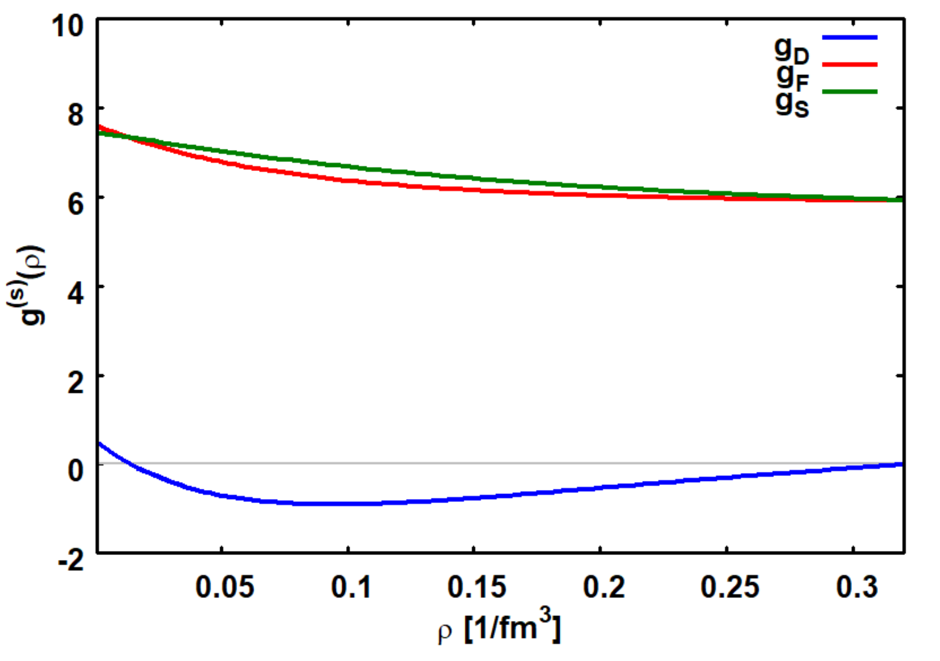
$$\mathcal{L} = \mathcal{L}_B + \mathcal{L}_M + \mathcal{L}_{int}$$

$$\mathcal{L}_{int} = \overline{\Psi}\hat{\Gamma}_\sigma(\hat{\rho})\Psi\Phi_\sigma - \overline{\Psi}\hat{\Gamma}_\omega(\hat{\rho})\gamma_\mu\Psi A^{(\omega)\mu} + \overline{\Psi}\hat{\Gamma}_\delta(\hat{\rho})\vec{\tau}\Psi\Phi_\delta - \overline{\Psi}\hat{\Gamma}_\rho(\hat{\rho})\gamma_\mu\vec{\tau}\Psi \mathbf{A}^{(\rho)\mu} - e\overline{\Psi}\hat{Q}\gamma_\mu\Psi A^{(\gamma)\mu} .$$

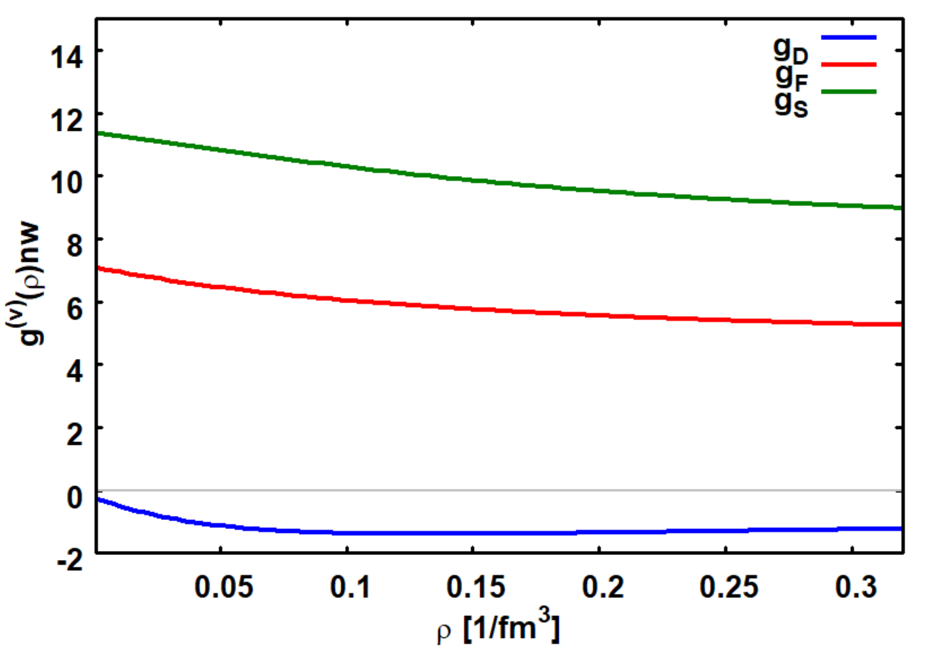
•*Hofmann, Keil, Lenske, Phys.Rev.C* 64 (2001) 034314

Derived Fundamental SU(3)-Vertices

$$g_D^{(m)} = \frac{1}{4}\left(3g_{NNa} - \sqrt{3}g_{NNf}\right) \quad ; \quad g_F^{(m)} = \frac{1}{4}\left(g_{NNa} + \sqrt{3}g_{NNf}\right)$$



Scalar



Vector

H.L., M. Dhar, Lect.Notes Phys. 948 (2018) 161
H.L., M. Dhar et al, Prog.Part.Nucl.Phys. 98 (2018) 119

Hypermatter and Hypernuclei

Covariant GI-DBHF Approach to Hypermatter and Hypernuclei

Meson Mean-Fields

$$\left(-\nabla^2 + m_\omega^2\right) V_\omega^0 = g^*_{NN\omega}(\rho_{\mathcal{B}})\left(\rho_p + \rho_n\right) + g^*_{\Lambda\Lambda\omega}(\rho_{\mathcal{B}})\rho_\Lambda$$

$$\left(-\nabla^2 + m_\rho^2\right) V_\rho^0 = g^*_{NN\omega}(\rho_{\mathcal{B}})\left(\rho_p - \rho_n\right)$$

$$-\nabla^2 V_\gamma^0 = e_p \rho_p^{(c)}$$

$$\left(-\nabla^2 + m_\sigma^2\right) \Phi_\sigma = g^*_{NN\sigma}(\rho_{\mathcal{B}})\left(\rho_p^{(s)} + \rho_n^{(s)}\right) + g^*_{\Lambda\Lambda\sigma}(\rho_{\mathcal{B}})\rho_\Lambda^{(s)}$$

$$\left(-\nabla^2 + m_\delta^2\right) \Phi_\delta = g^*_{NN\delta}(\rho_{\mathcal{B}})\left(\rho_p^{(s)} - \rho_n^{(s)}\right),$$

Baryon total density

$$\rho_{\mathcal{B}}(r) = \rho_p(r) + \rho_n(r) + \rho_\Lambda(r)$$

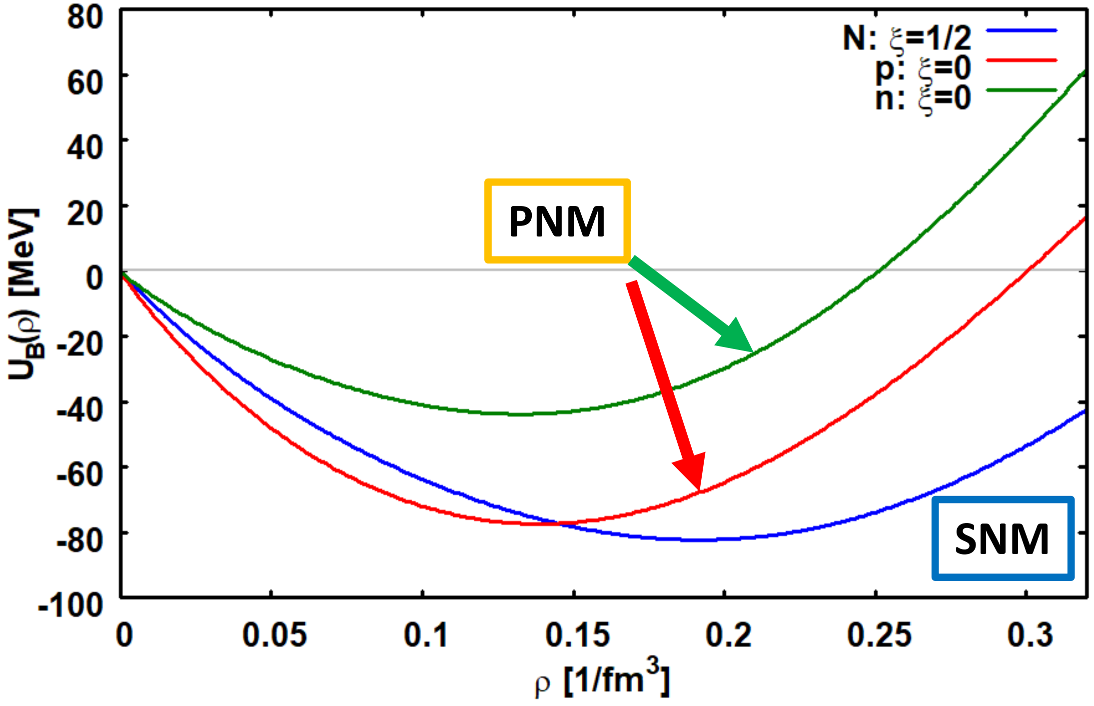
Baryon Self-Energies

$$\Sigma_B^{(s)}(r) = g^*_{BB_\sigma}(\rho_{\mathcal{B}})\Phi_\sigma(r) + \langle\tau_3\rangle_B g^*_{BB_\delta}(\rho_{\mathcal{B}})\Phi_\delta(r).$$

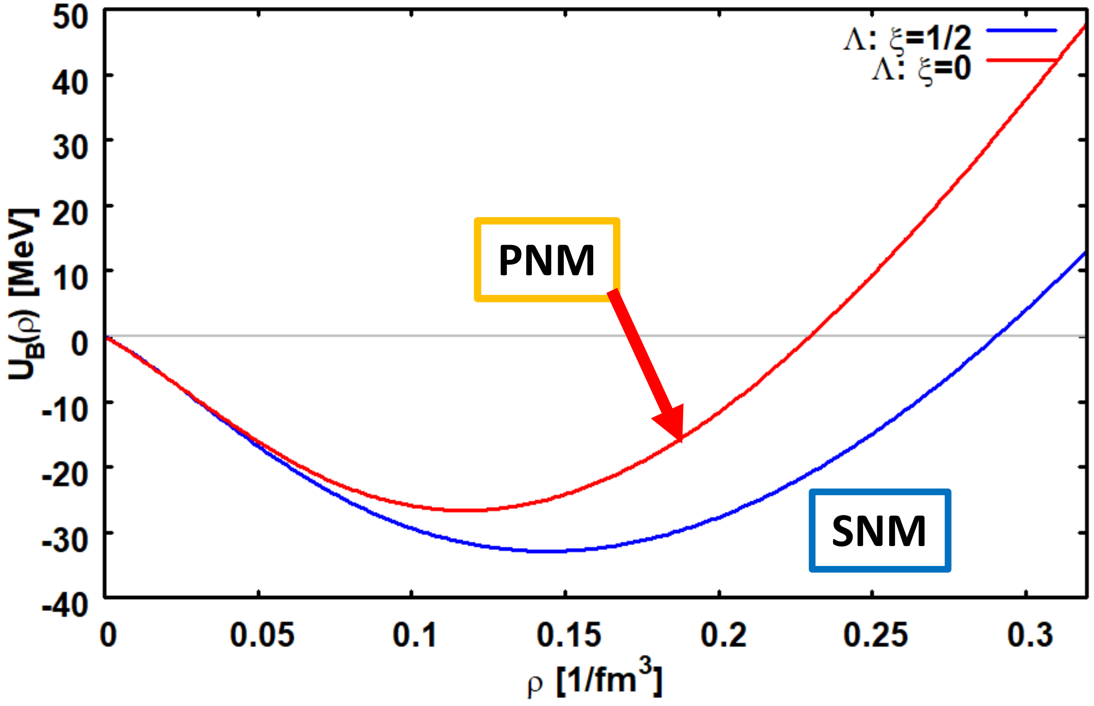
$$\Sigma_B^{(d)}(r) = g^*_{BB\omega}(\rho_{\mathcal{B}})V_\omega^0(r) + \langle\tau_3\rangle_B g^*_{BB\rho}(\rho_{\mathcal{B}})V_\rho^0(r) + q_B V_\gamma^0(r).$$

Nucleon and Λ Mean-Field Potentials

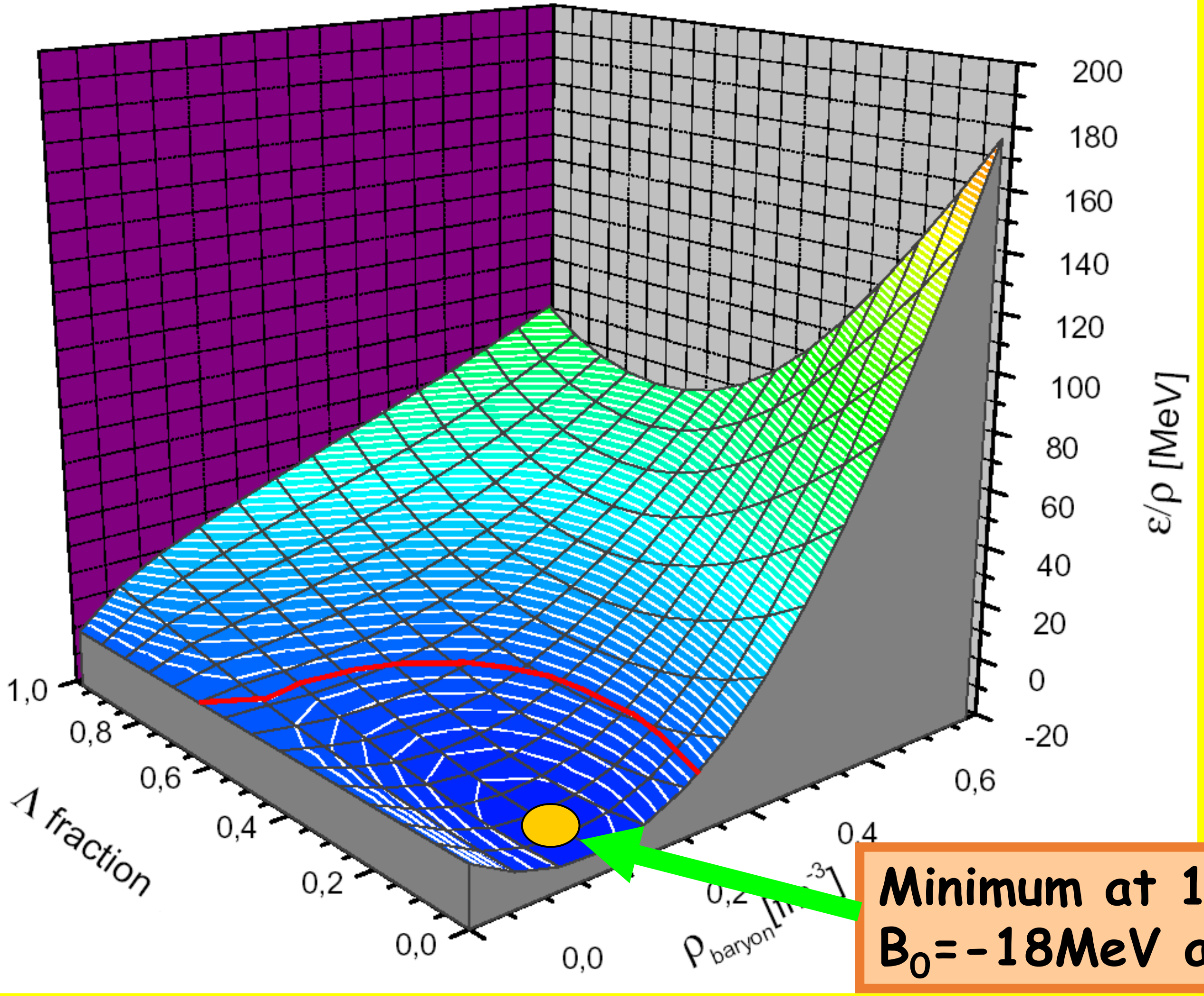
Nucleons



Λ-Hyperon



GI-DBHF Hypermatter „Equation of State“
(Binding Energy per Baryon)

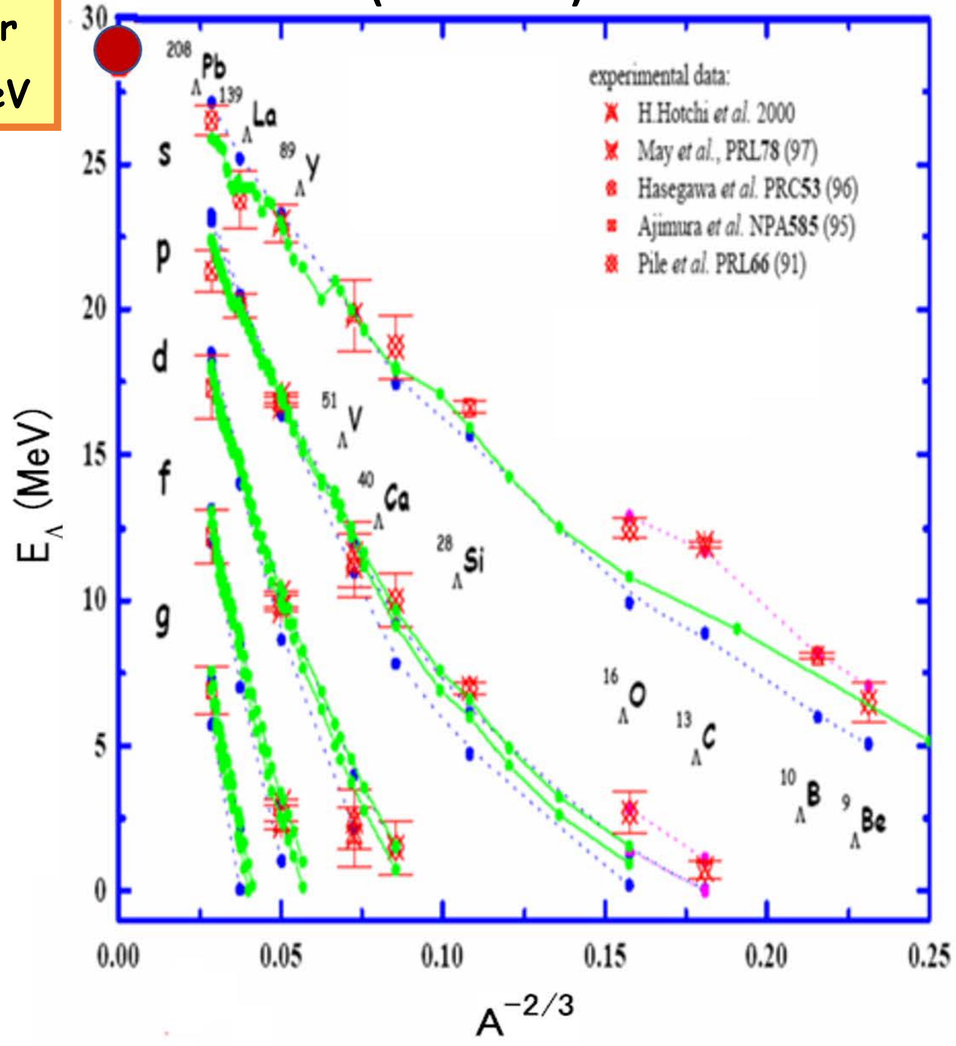


Minimum at 10% Λ-content:
B_0=-18MeV at ρ_0=0.21fm^{-3}

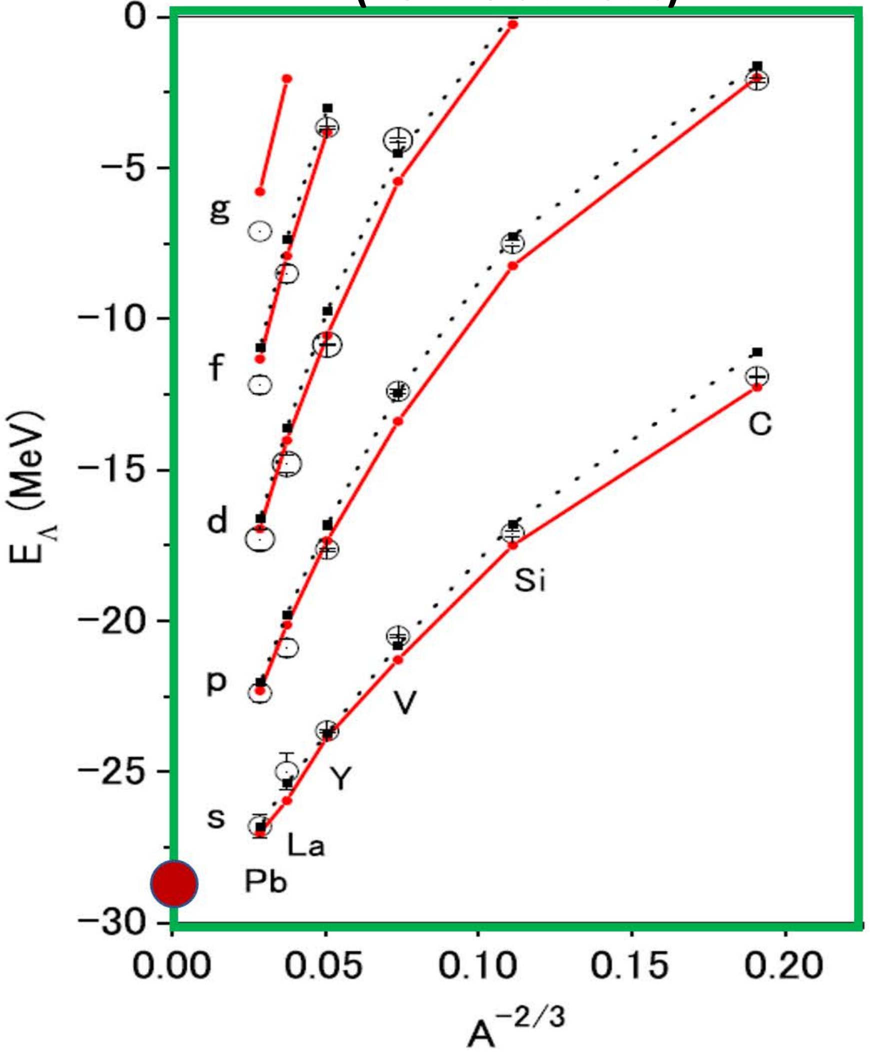
Giessen DBHF
(covariant)

ESC08+MPP
(non-relativistic)

Nuclear Matter
S_Λ = 28…30 MeV



Keil, Hofmann, H.L., Phys.Rev.C 61 (2000) 064309

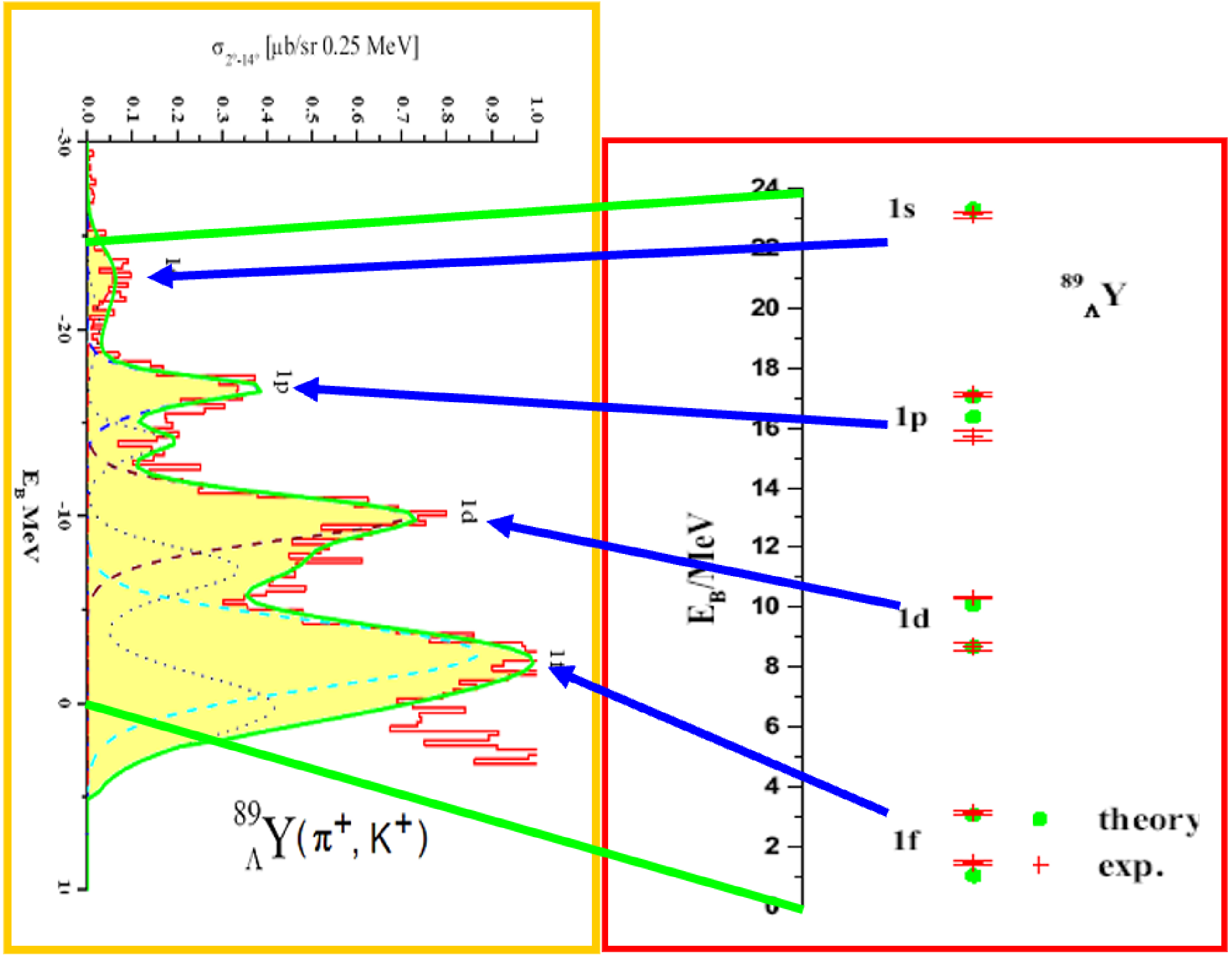


Yamamoto et al., Phys. Rev. C 90 (2014) 045805

Covariant EDF
GI-DBHF/DDRH Vertex Functionals

G-matrix Folding Approach
YNN by Multi-Pomeron Forces +TBA

GI-DBHF Spectrum of ^{89}Y



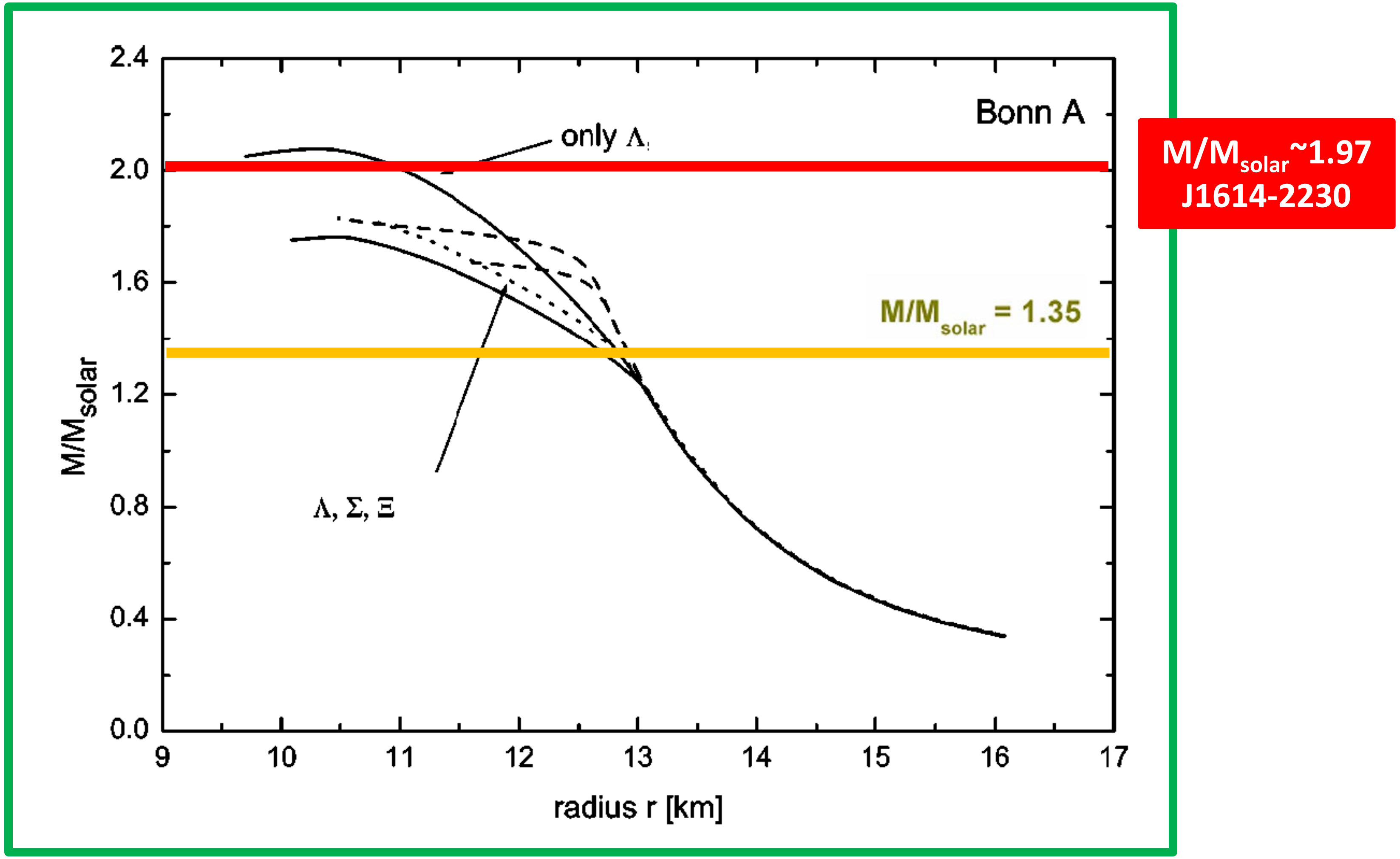
- $^{89}Y = \Lambda + {}^{88}Y(4-, g.s.)$
- Λ–Core Interactions
- Covariant Tensor Interaction

Keil, Hofmann, H.L., Phys.Rev.C 61 (2000) 064309

Data: Hotchi et al., Phys. Rev. C64 (2001) 044302

Neutron Stars in GI-DBHF Theory

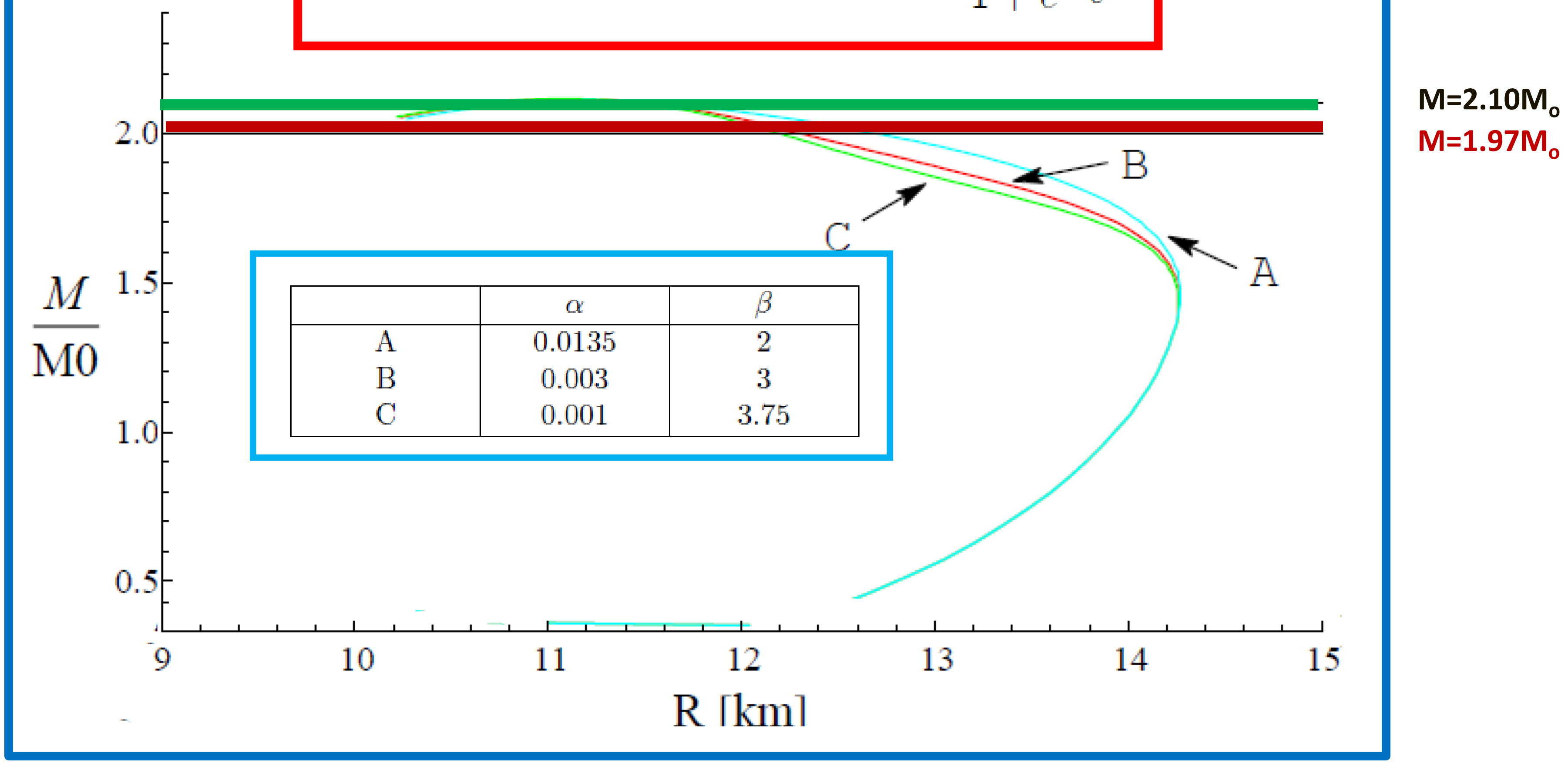
Neutron Stars in GI-DBHF Theory



Frank Hofmann, C. M. Keil, and H. Lenske, Phys. Rev. C 64, 025804 (2001)

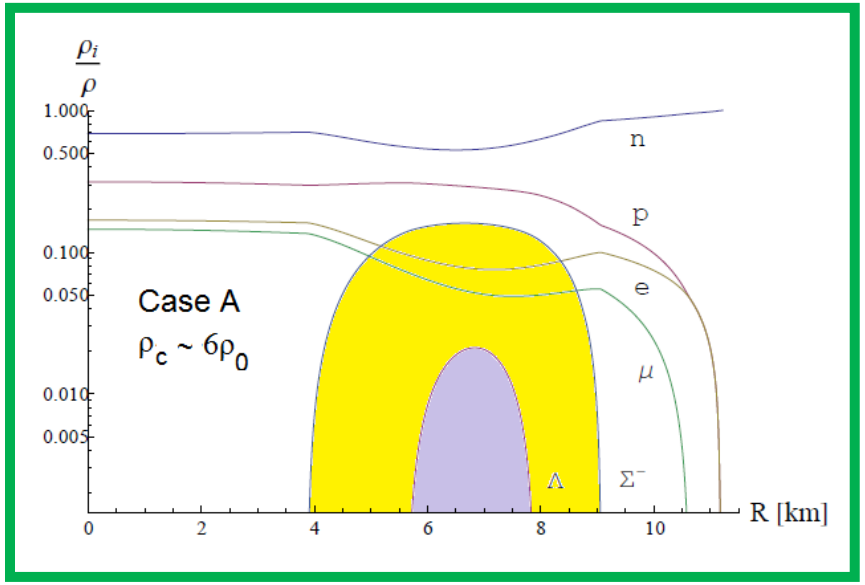
Exploring the Mass-Radius Relation with Hyperon Vector Repulsion

$$g^*_\omega = g_\omega\ (1+\alpha\ (1-f)\ (\frac{\rho}{\rho_0})^\beta)\ ;\ f = \frac{1}{1+e^{\frac{\rho-\rho_h}{c}}}$$

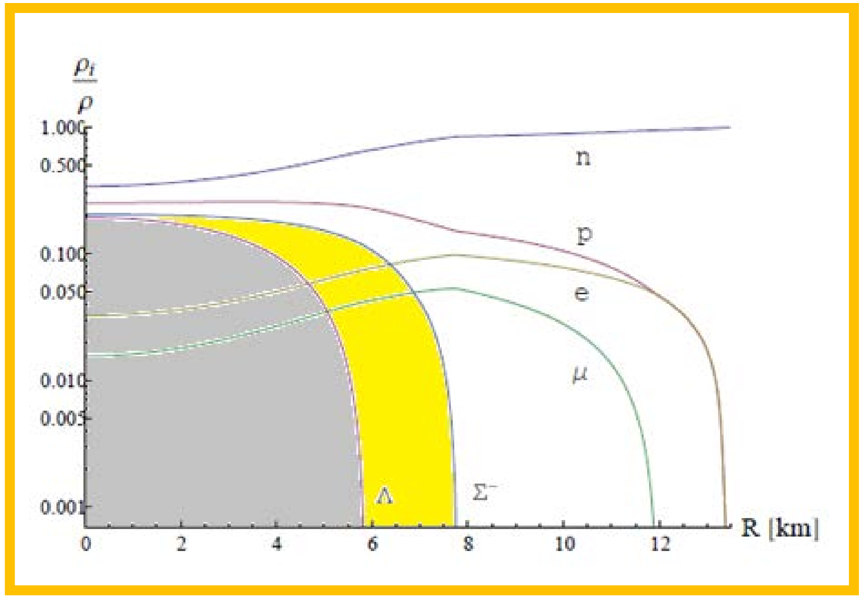


	α	β
A	0.0135	2
B	0.003	3
C	0.001	3.75

• *J. Wilhelm, H.L, EPJ Web Conf.* 107 (2016) 10001

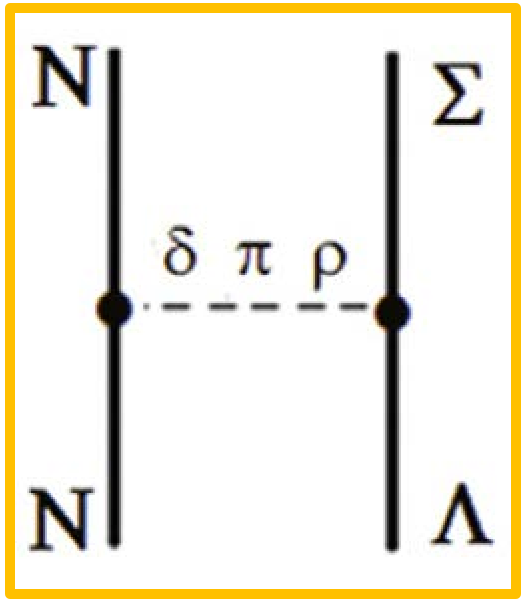


Vector-Repulsion scenario:
Hyperon shell in a neutron star

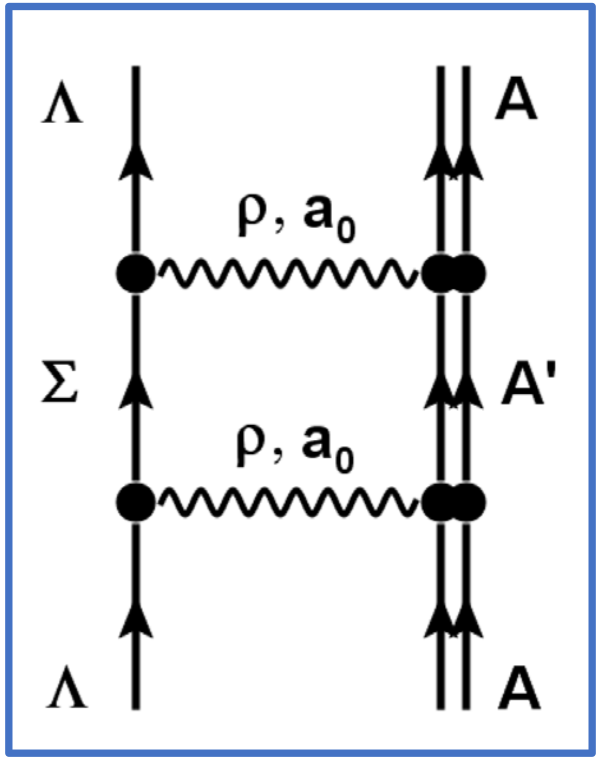


Standard Scenario:
Hyperon core in a neutron star

Λ-Σ Mixing by the Isovector Interactions

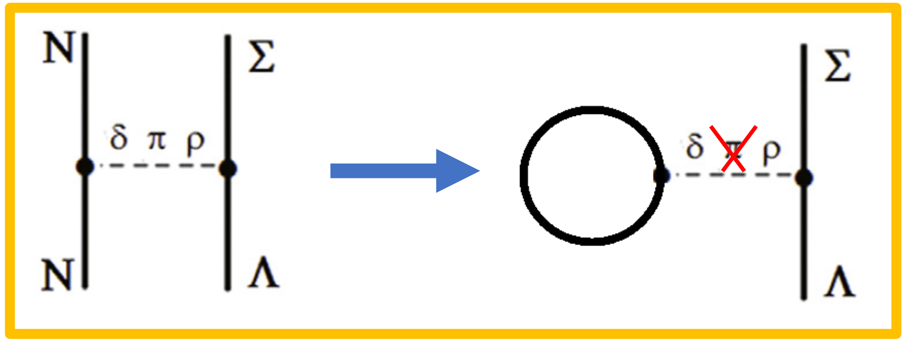


Induced Hyperon Self-Energies in Nuclear Matter by Isovector Interactions



$$L = -g_{\Lambda\Sigma s}\overline{\Psi}_{\Sigma}\vec{\tau}\Psi_{\Lambda}\bullet\vec{\phi} + g_{\Lambda\Sigma v}\overline{\Psi}_{\Sigma}\vec{\tau}\gamma_{\mu}\Psi_{\Lambda}\bullet\vec{V}^{\mu}$$

Induced Λ-Σ Mixing by Isovector Interactions



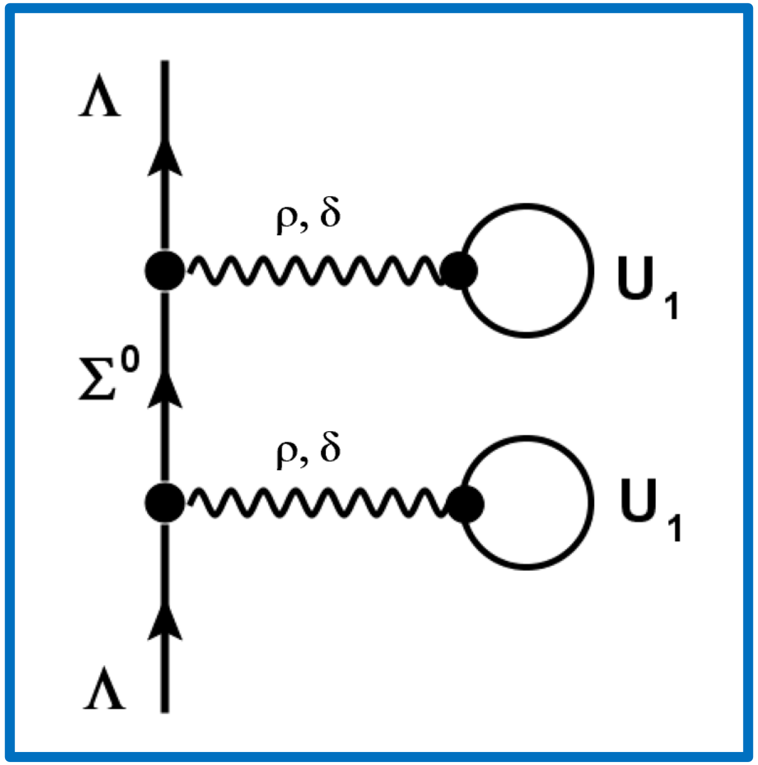
$$U_\tau^{YY'} \approx g_{YY'\tau} g_{NN\tau} \langle A | F_\tau \tau_N | A \rangle \langle Y | \tau_Y | Y' \rangle \approx \frac{g_{YY'\tau}}{g_{NN\tau}} (N-Z) U_1^{(A)} \langle Y | \tau_Y | Y' \rangle$$

Mean-Field Induced Mixing

$$U_1^{\Lambda\Sigma}(\rho_B) = U_\delta^{(NN)}(\rho_B)\left(\frac{g_{\Lambda\Sigma\delta}}{g_{NN\delta}}\right) + U_\rho^{(NN)}(\rho_B)\left(\frac{g_{\Lambda\Sigma\rho}}{g_{NN\rho}}\right)$$

$$\begin{pmatrix} H_{\Lambda A} - E & U_{\Lambda\Sigma} \\ U_{\Lambda\Sigma}^\dagger & H_{\Lambda A} + m_{\Sigma\Lambda} - E \end{pmatrix} \begin{pmatrix} \left[\phi_\Lambda \otimes |A\rangle\right]_{I_A N_A} \\ \left[\phi_\Sigma \otimes |A\rangle\right]_{I_A N_A} \end{pmatrix} = 0$$

Second Order Λ Self-Energy from Λ-Σ^0 Mixing by Nuclear Isovector Mean-Field

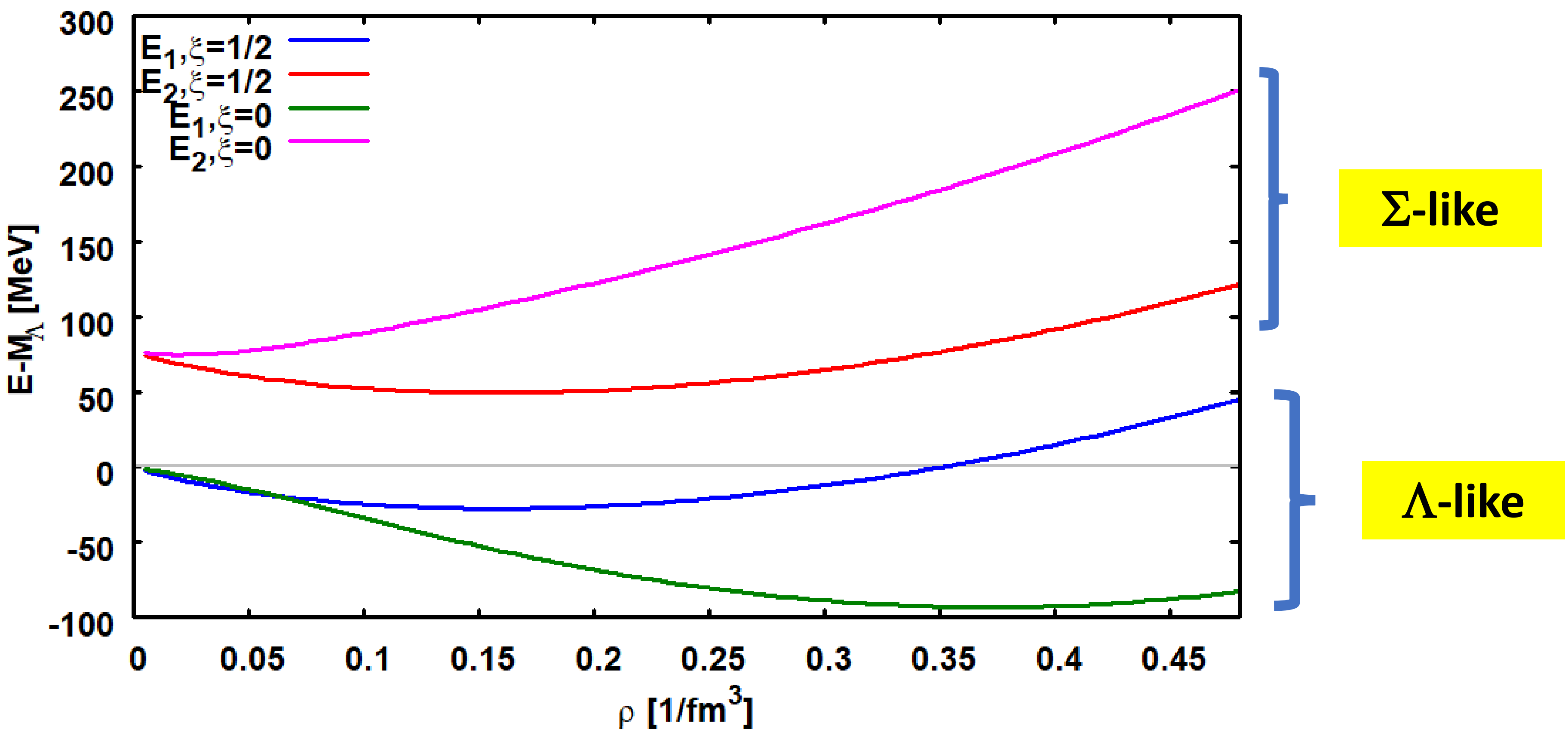


$$\sim \frac{(N-Z)^2}{M_\Sigma^* - M_\Lambda^*}\langle V_\tau\rangle^2 \approx 2...3(N-Z)^2$$

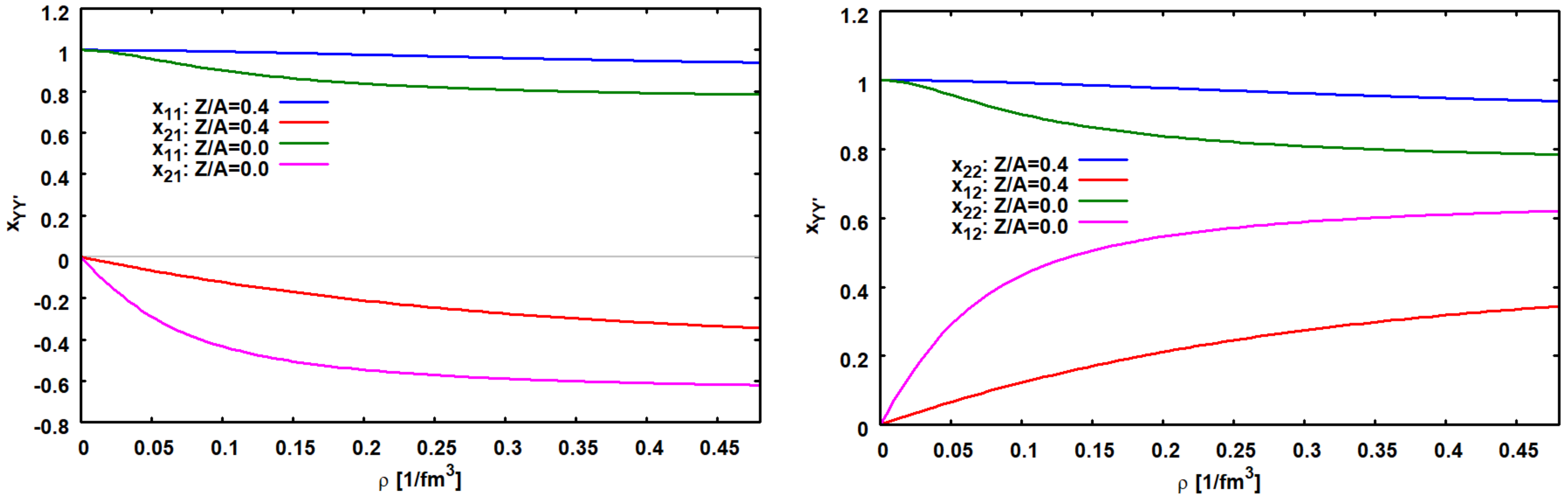
$$U_\Lambda^{(2)}(\rho_B,\omega) = U_1^{\Lambda\Sigma}(\rho_B)G_\Sigma(\omega)U_1^{\Sigma\Lambda}(\rho_B)\langle\Lambda|\tau_0|\Sigma^0\rangle^2$$

$$U_1^{\Lambda\Sigma}(\rho_B) = U_\delta^{(NN)}(\rho_B)\left(\frac{g_{\Lambda\Sigma\delta}}{g_{NN\delta}}\right) + U_\rho^{(NN)}(\rho_B)\left(\frac{g_{\Lambda\Sigma\rho}}{g_{NN\rho}}\right)$$

Eigenvalues in Nuclear Matter

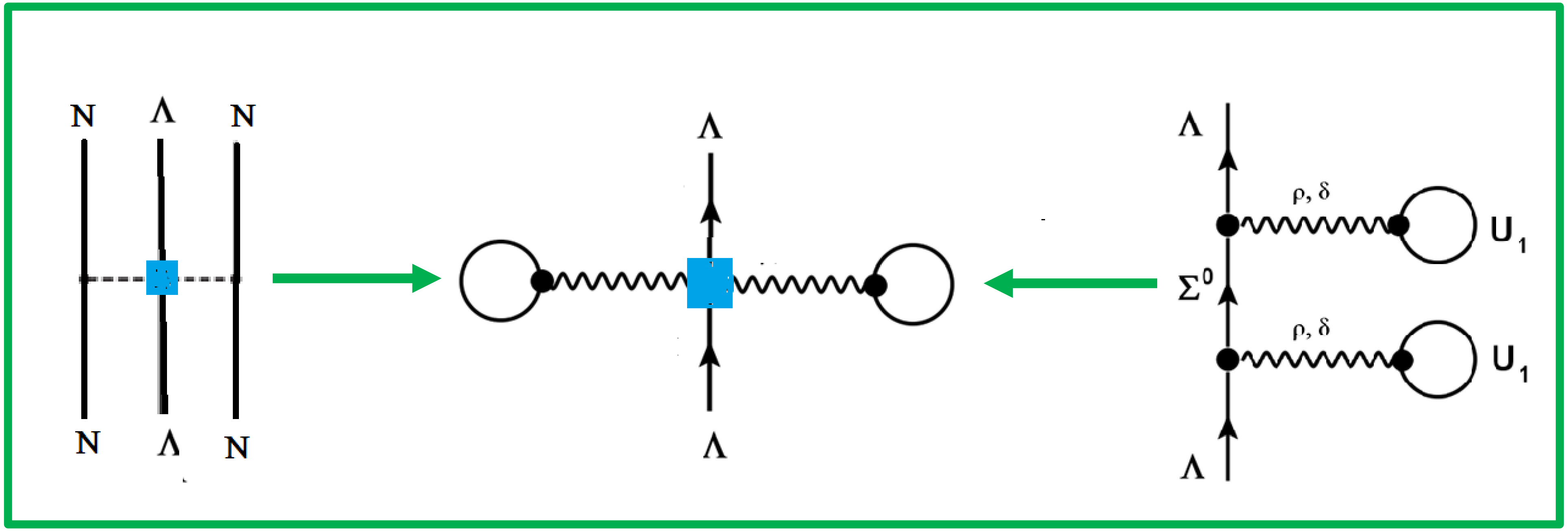


Configuration Amplitudes



$$\begin{pmatrix} h_{\Lambda A} - E & U_{\Lambda\Sigma} \\ U^{\dagger}_{\Lambda\Sigma} & h_{\Sigma A} + m_{\Sigma\Lambda} - E \end{pmatrix} \begin{pmatrix} \varphi_{(\Lambda\Lambda),(\Sigma\Lambda)} \\ \varphi_{(\Lambda\Sigma),(\Sigma\Sigma)} \end{pmatrix} = 0$$

Effective YNN 3-Body Interaction

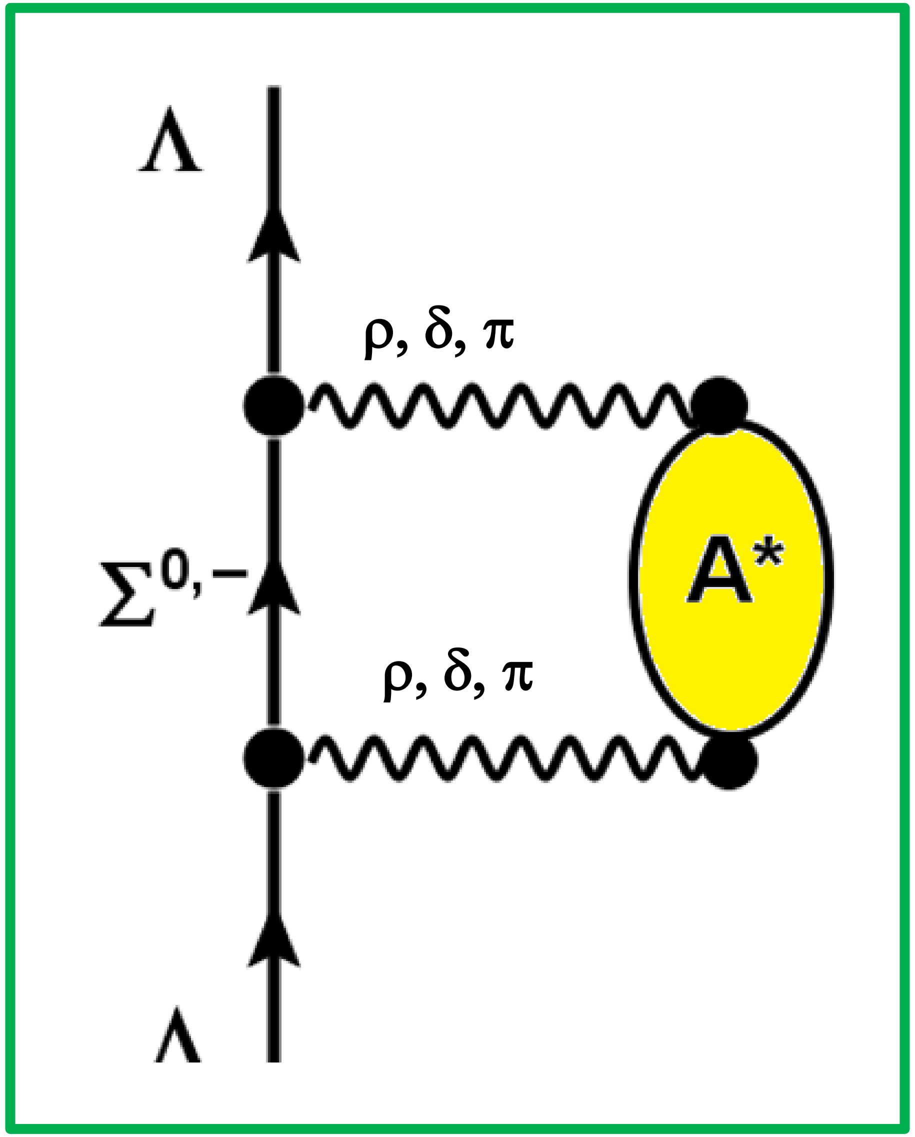


N²LO χEFT

contracted over Fermi-Sea

Isovector Mixing

Induced Λ Dynamical Polarization Self-Energy by Isovector Λ-Σ Mixing



Fermi- and Gamov-Teller Modes

Remarks on „Three-Nucleon“ Interactions

3-Nucleon Interactions

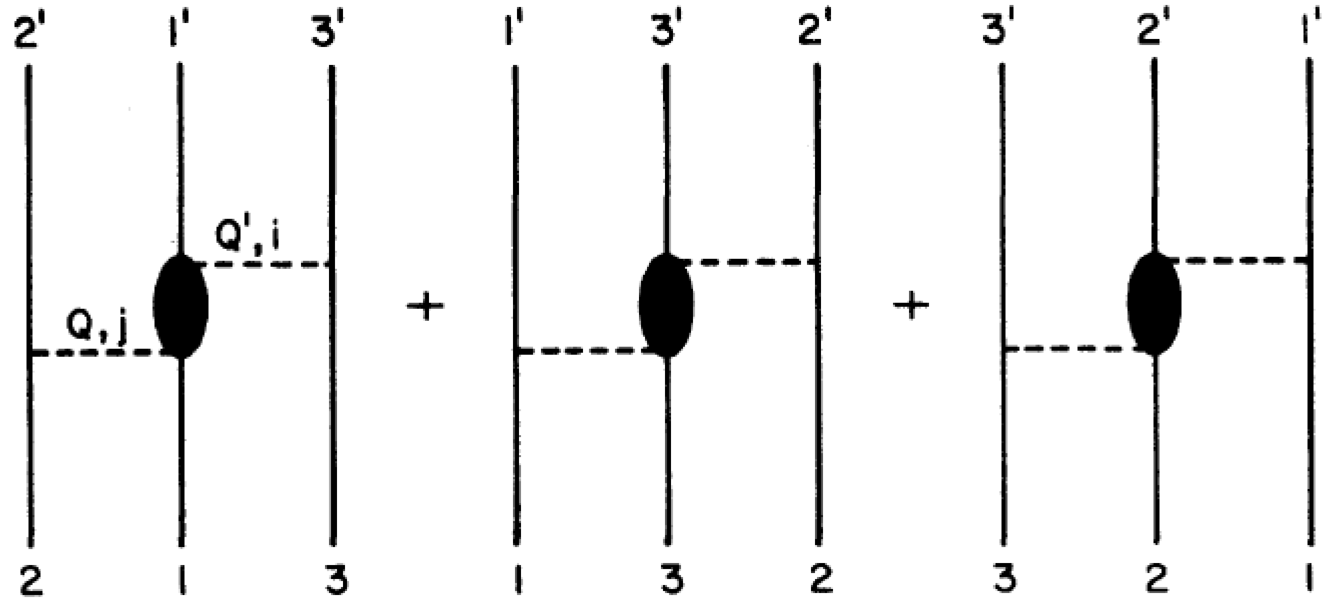
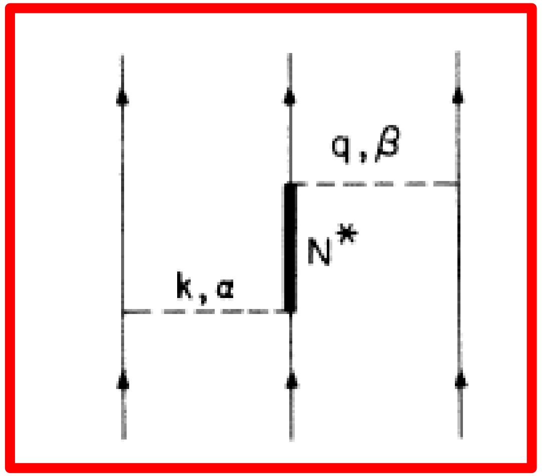


FIG. 1. The Feynman diagrams for the two-pion exchange three-nucleon potential. The shaded oval represents anything except a forward propagating nucleon state.

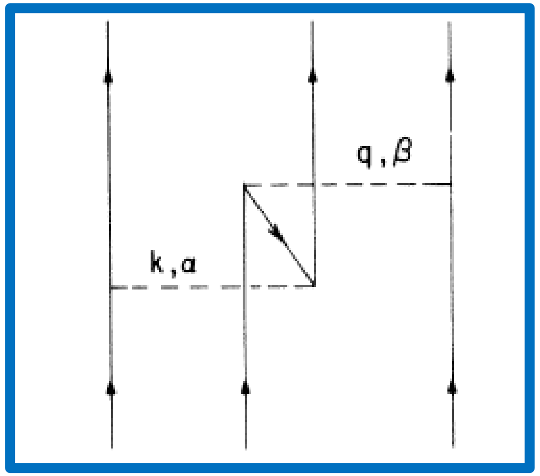
From: Coon and Glöckle, PRC 23 (1981) 1790

Origin of 2-(pion)-Meson Exchange 3-Nucleon Interactions
…or the meaning of „anything“



One nucleon scattered into a resonance state

+



Three-body force arising from a virtual nucleon-antinucleon pair.

N* = Δ_{33}(1232) → Fujita-Miyazawa TNI

J. Fujita and H. Miyazawa, Prog. Theor. Phys. **17**, 360 (1957).

Non-relativistically suppressed
but strong in covariant approaches

Conclusion by the mid-1990ies
from the Fujita-Miyazawa (FM) and the Tucson-Melbourne TNI

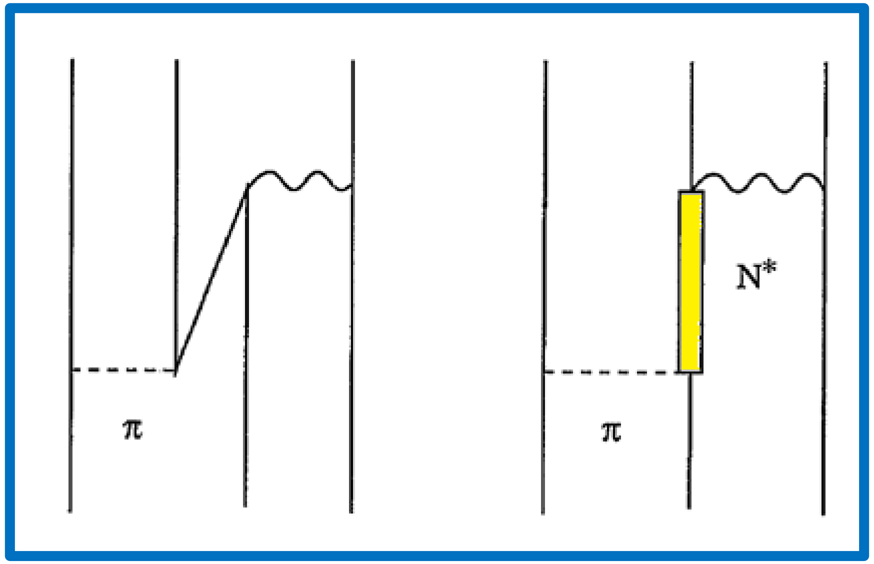
- **Overbinding of ^3H and ^3He by a few hundred keV**
- **Overbinding of the α-particle by 2-4 MeV**
- **Missing spin-independent 3-nucleon repulsion**
- **→ Urbana model: FM-attraction and phenomenological 3-body repulsion**

  (Pandharipande, Wiringa…)

Repulsive short-range three-nucleon interaction

S. A. Coon, M. T. Peña, and D. O. Riska

(PRC 52 (1995) 2925)

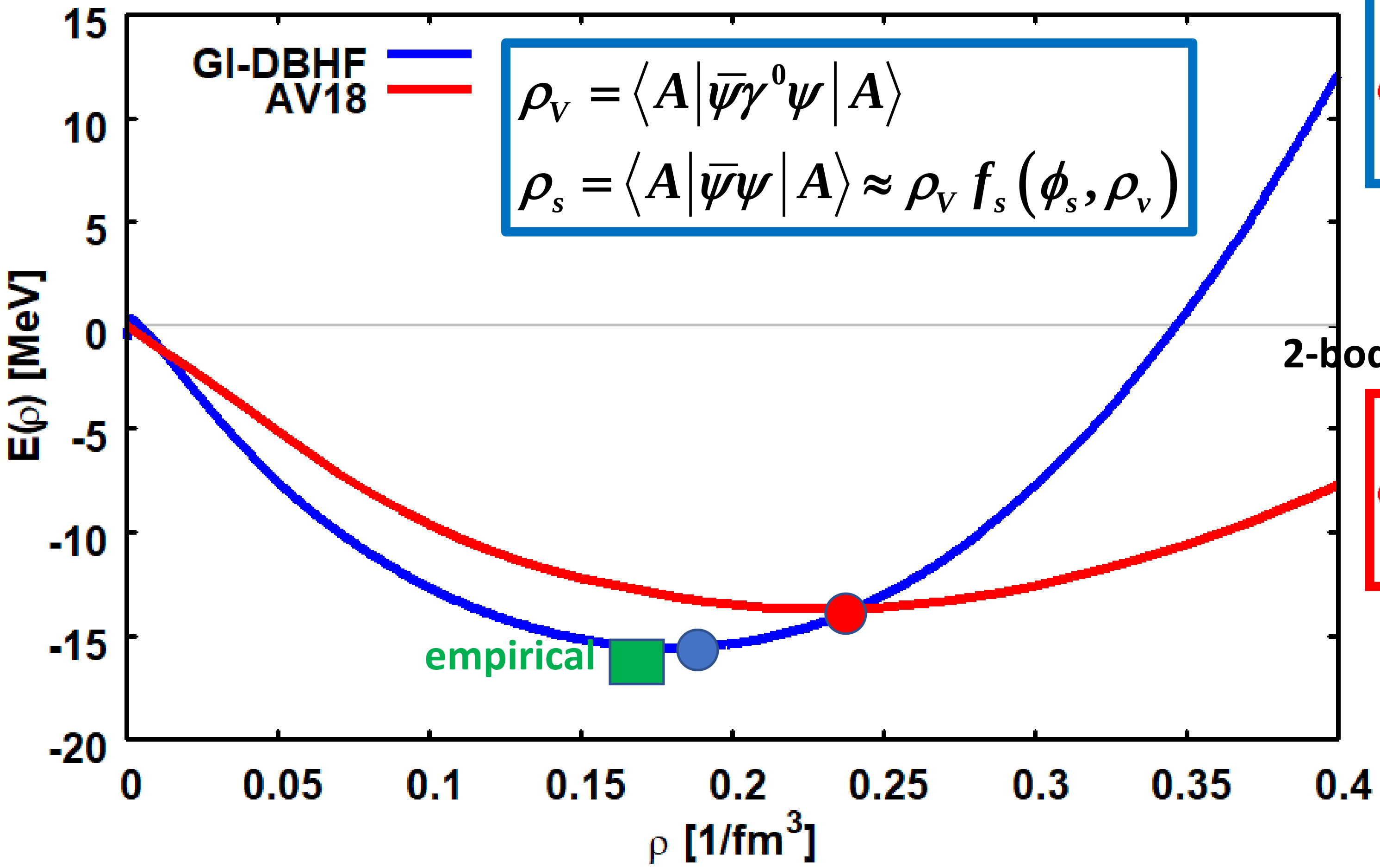


= scalar (σ,a_0) and vector mesons (ω,ρ)

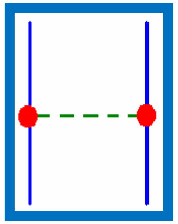
= pions

= Δ_{33}(1232) and N_{11}(1440) „Roper“

Covariant vs. Non-Relativistic Nucleonic EoS

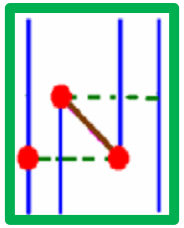


2-body covariant



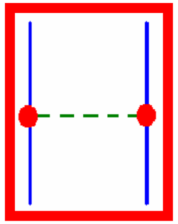
+

included

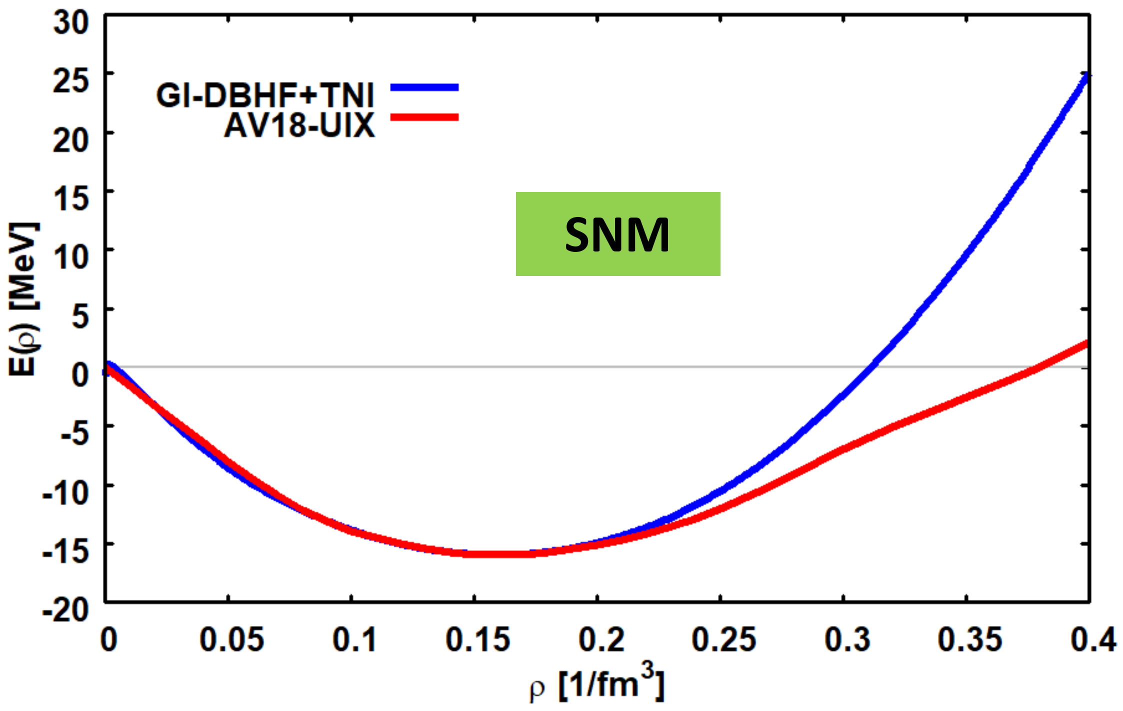


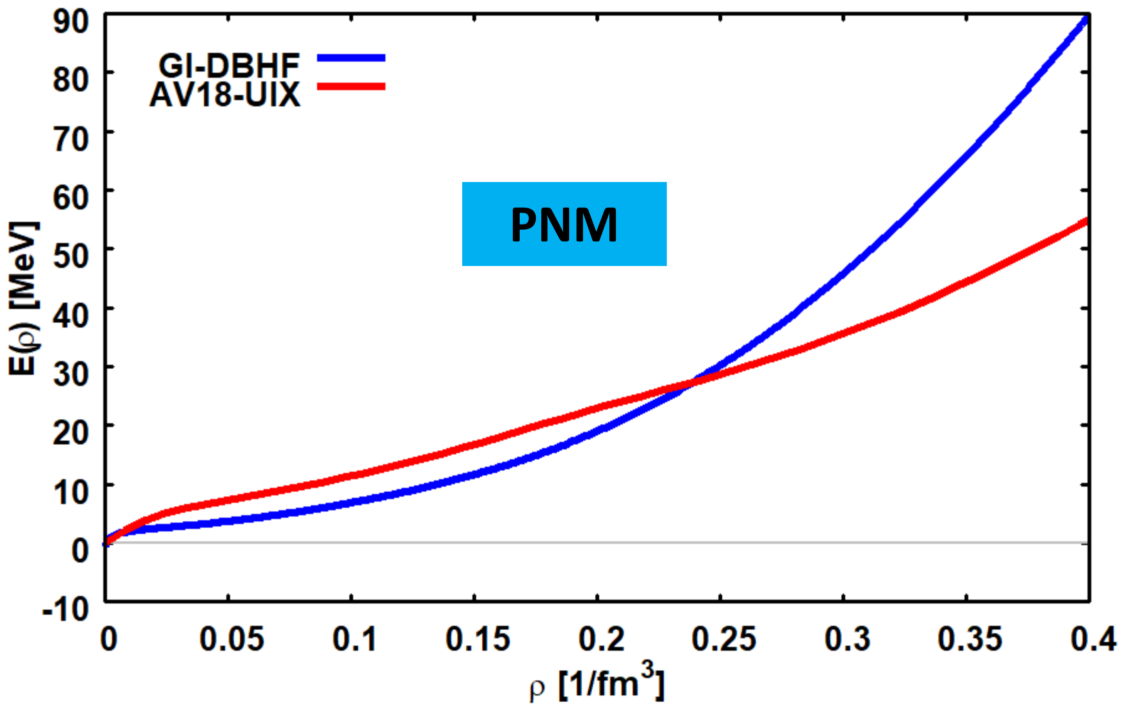
??

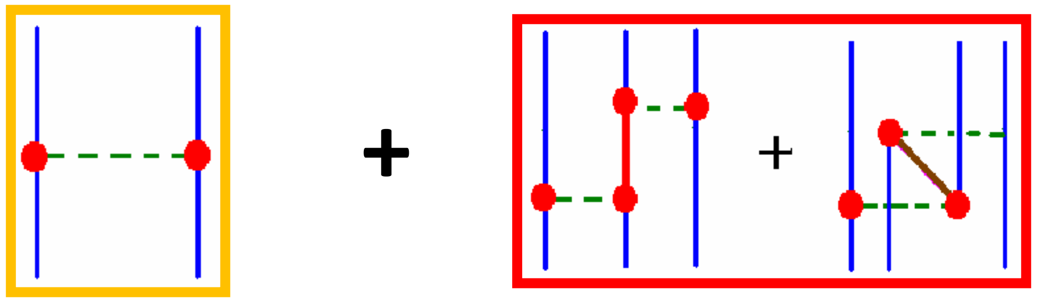
2-body non-relat.



…supplemented by TNI







Summary

- **Covariant formulation of BB-interactions**
- **In-medium interaction by DBHF theory: GI-DHBF**
- **SU(3) relations connecting NN, NY, and YY interactions**
- **Hypermatter and hypernuclei**
- **Different views on three-nucleon interactions, their origins and their interpretation**

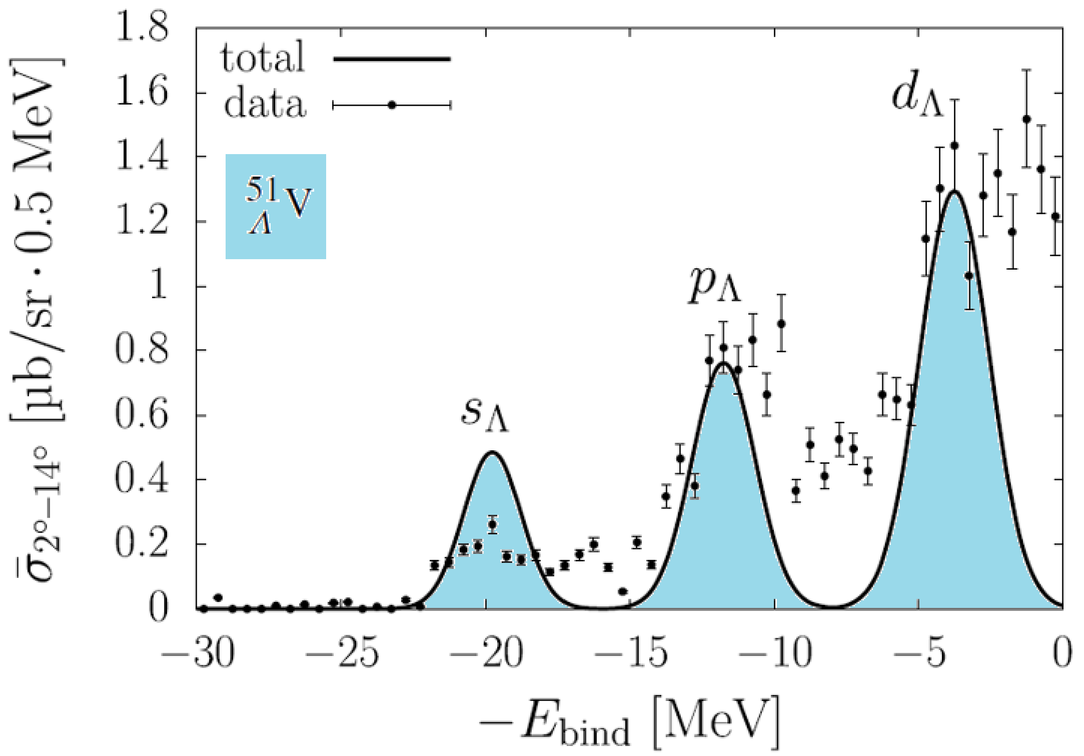
Recent reviews:

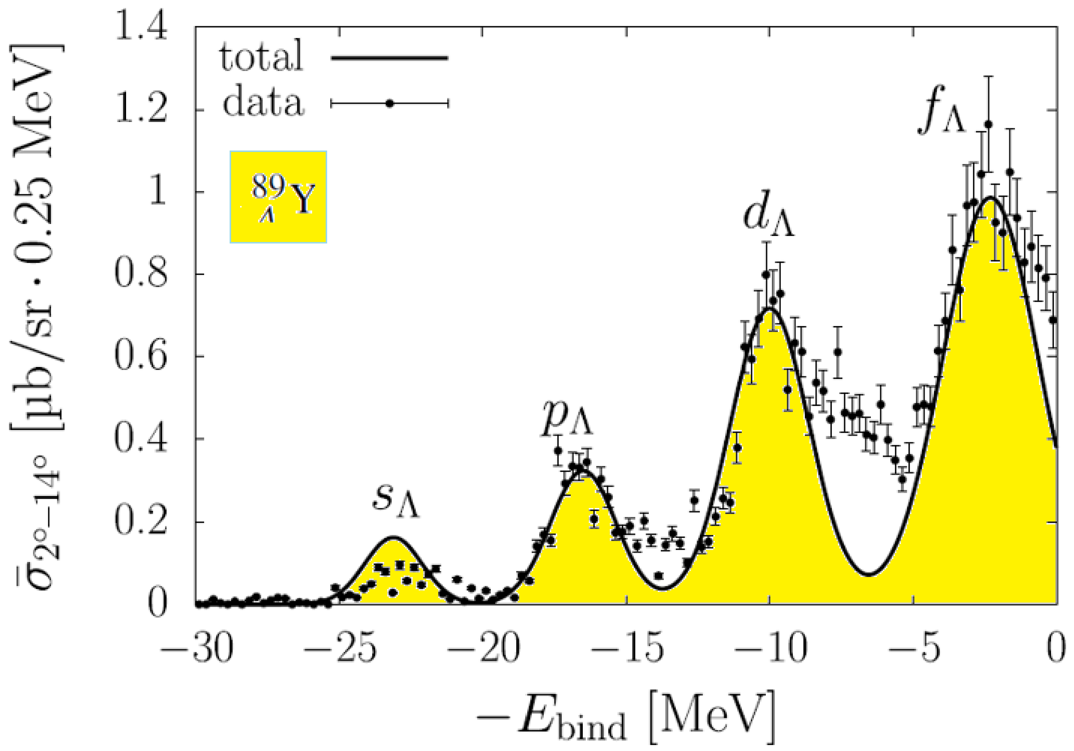
H.L., M. Dhar, Lect.Notes Phys. **948 (2018) 161**

H.L., M. Dhar, Th. Gaitanos, Xu Cao, Prog.Part.Nucl.Phys. **98 (2018) 119**

Hypernuclear Production
using
(π^+,K^+) Reactions

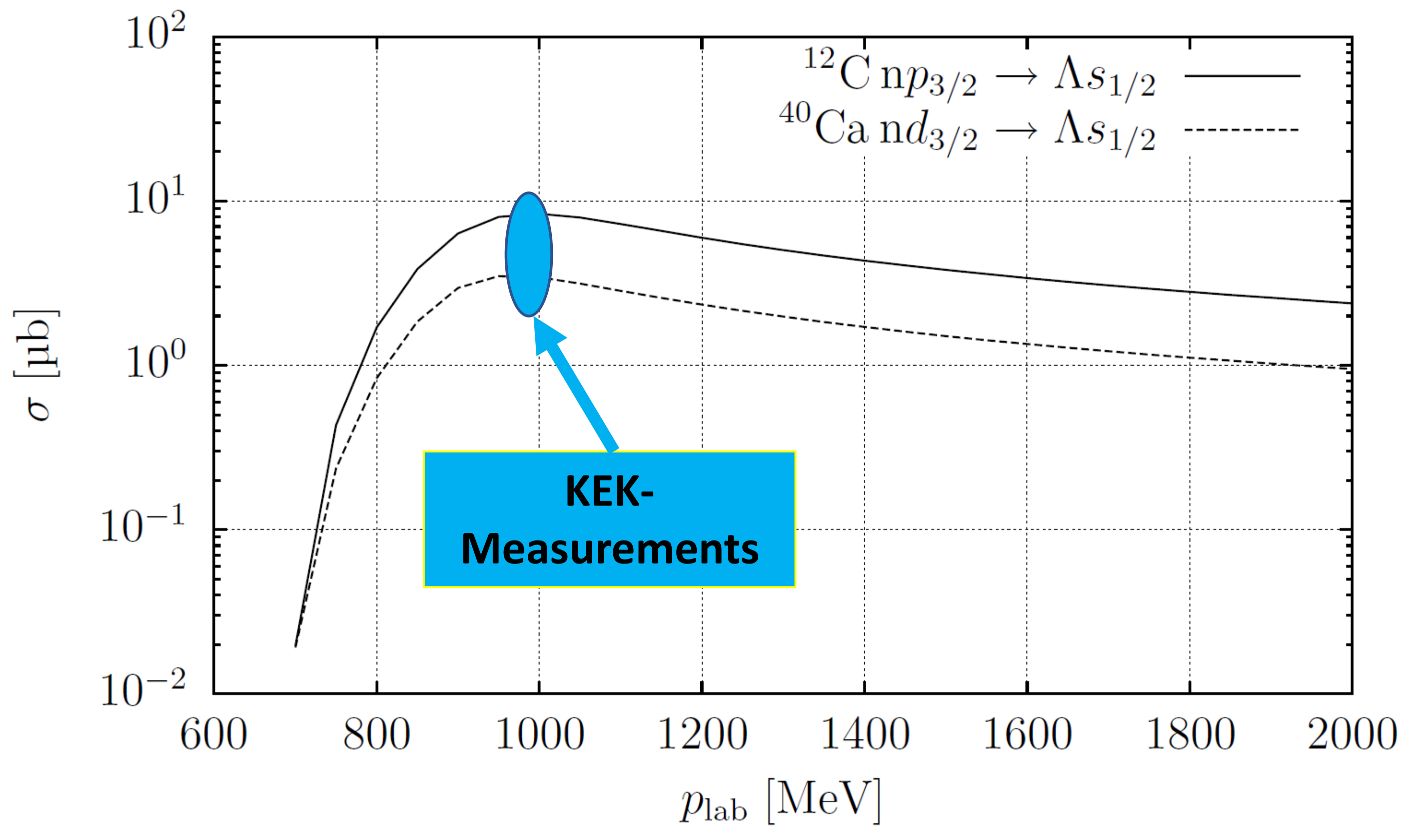
Hypernuclear Production in the (π^+,K^+)-Reaction at p_{Lab}=1.05 GeV





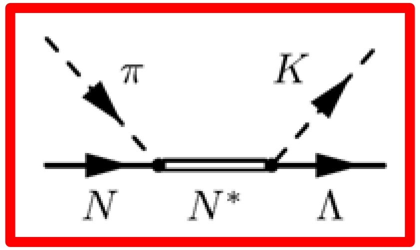
- *Bender, Shyam, H.L., Nucl.Phys.A* 839 (2010) 51
- Data: Hotchi et al., PHYS. REV. C64:044302 (2001)

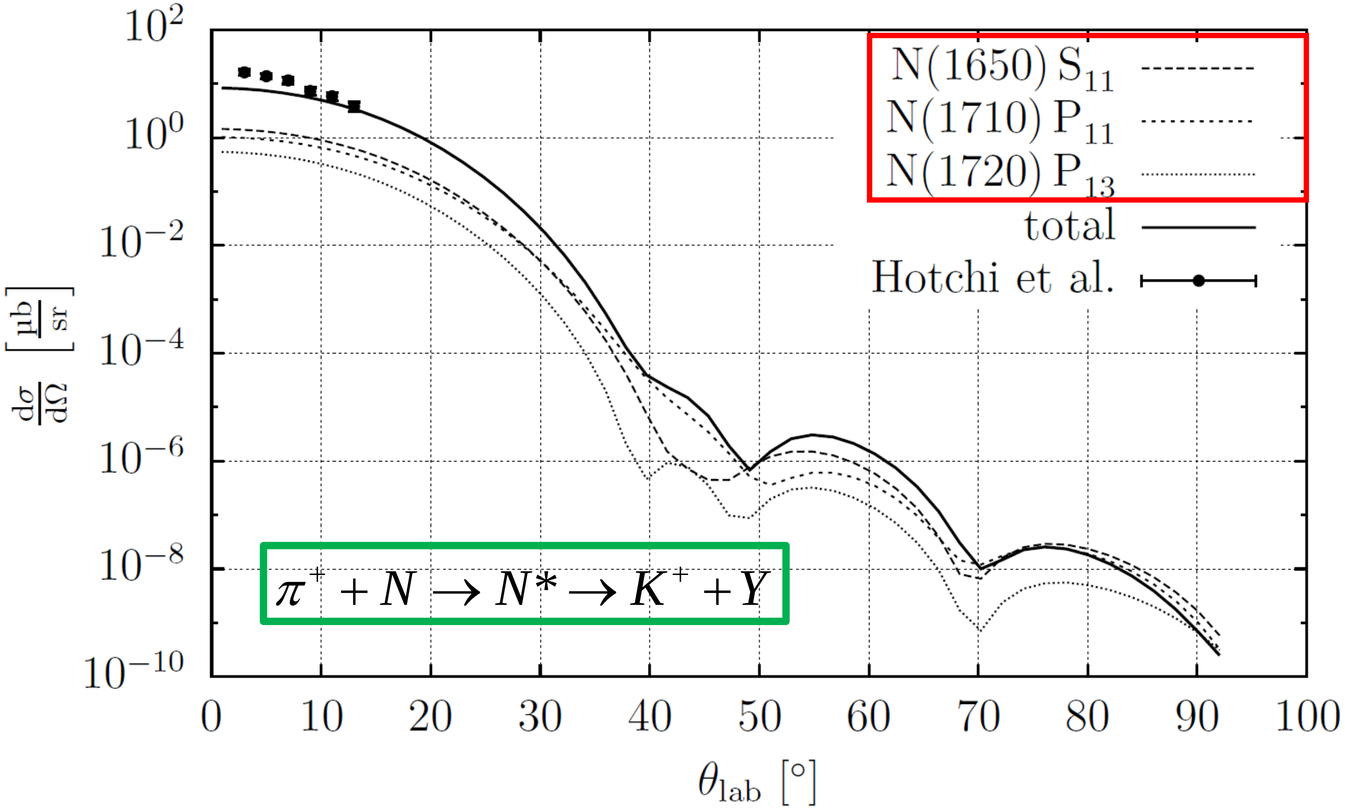
Total (π^+,K^+) on ^{12}C and ^{40}Ca



The total cross sections for $\pi^+ + {}^{12}\mathrm{C} \rightarrow \mathrm{K}^+ + {}^{12}_{\Lambda}\mathrm{C}$ (solid line) and $\pi^+ + {}^{40}\mathrm{Ca} \rightarrow \mathrm{K}^+ + {}^{40}_{\Lambda}\mathrm{Ca}$ (dashed line)

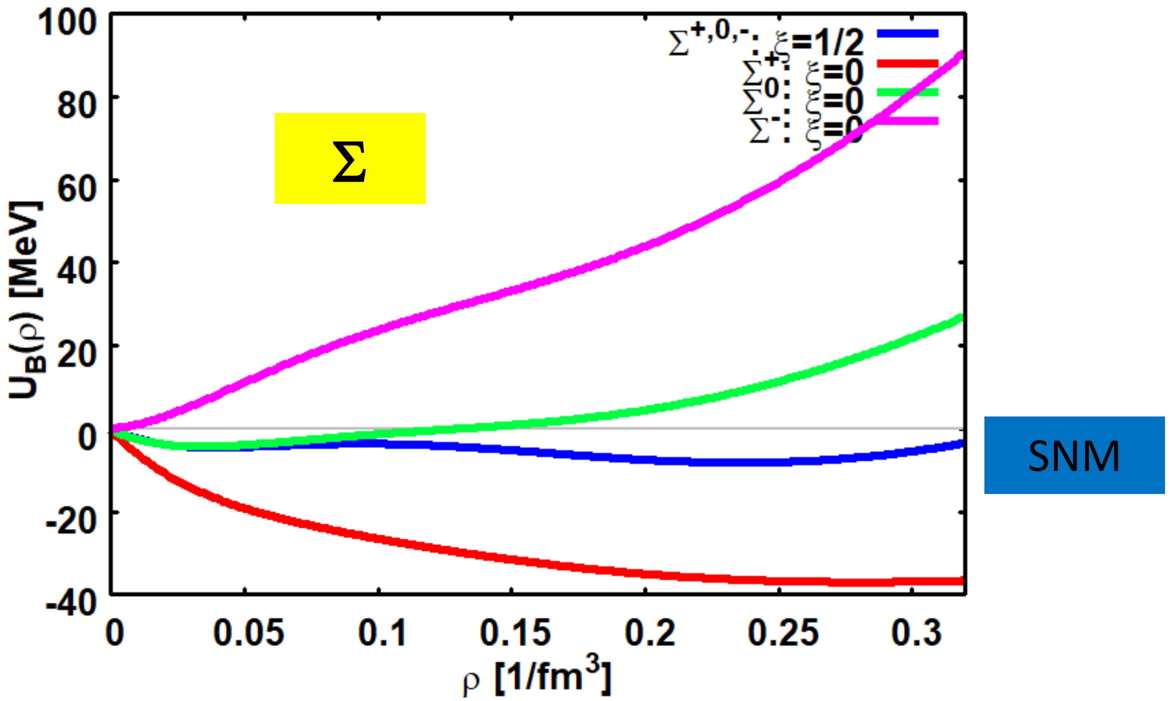
Reaction Mechanism of $A(\pi^+,K^+)_\Lambda A$ Reaction:
Where do the Kaons come from?

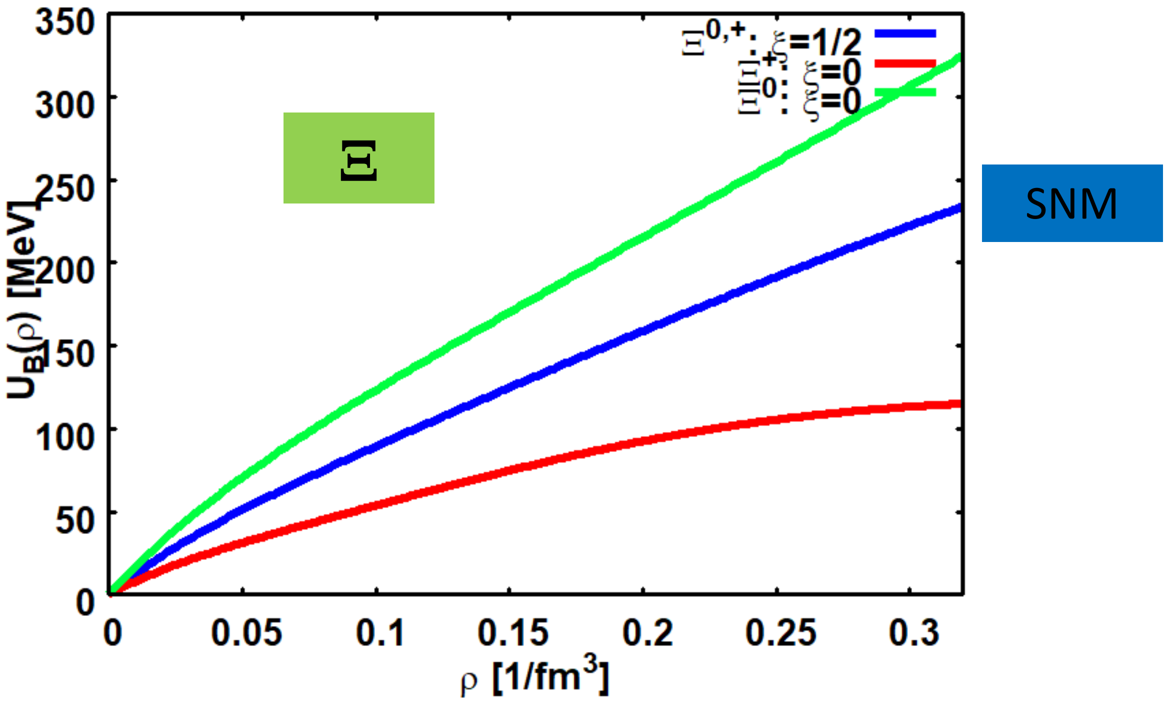




Backups

Probing SU(3) Flavor Symmetry:
Covariant Σ and Ξ Self-Energies in Nuclear Matter

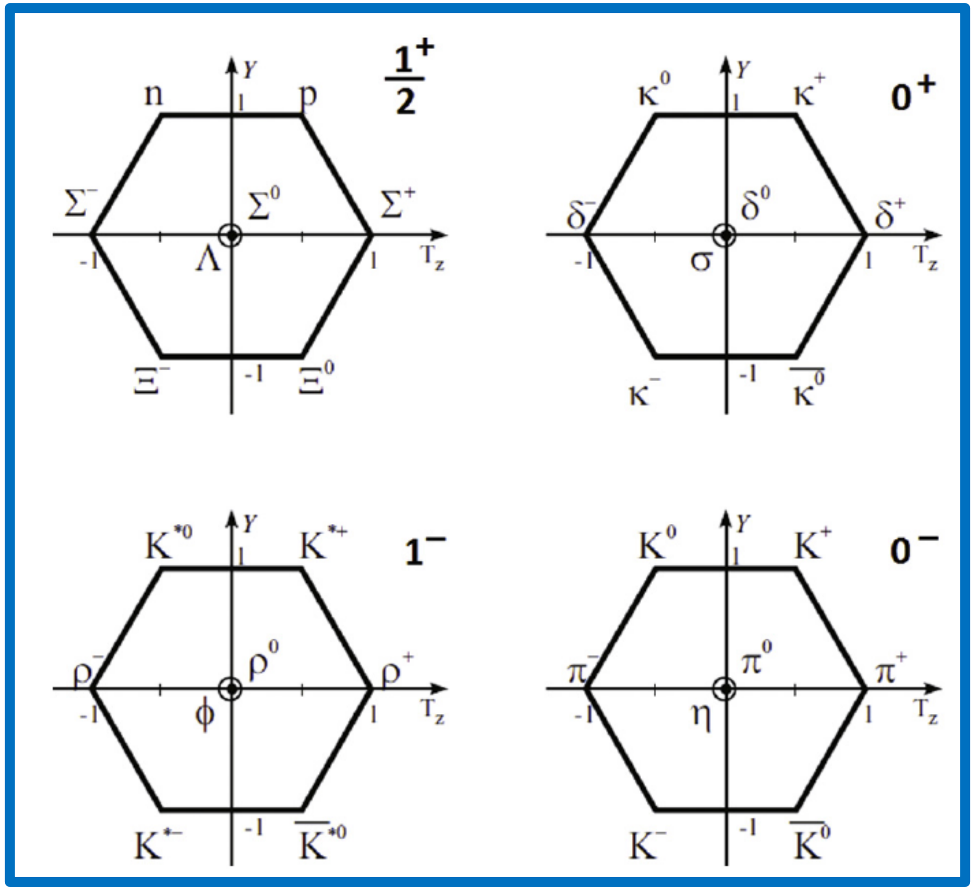




- **SU(3) „extrapolation" is insufficient (?)**
- **Mixing interactions are important**
- **Induced many-body interactions are important**

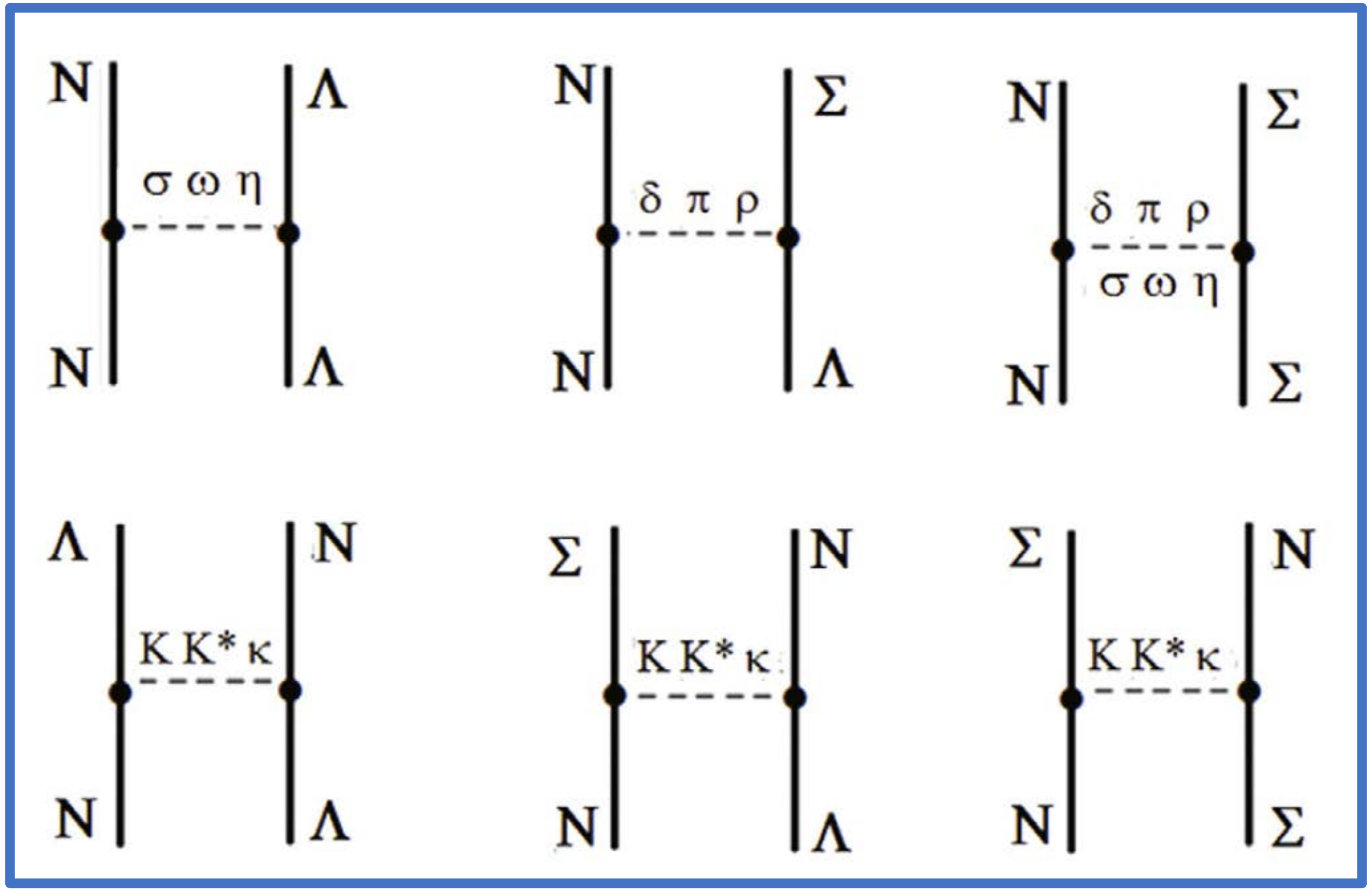
SU(3) Aspects of BB-Interactions

Baryon and Meson $SU_f(3)$-Multiplets



$$\mathcal{L} = \mathcal{L}_{\mathcal{B}} + \mathcal{L}_{\mathcal{M}} + \mathcal{L}_{int}$$

Meson-Exchange Octet-Interactions for *S*=-1 Baryon-Baryon States



SU(3) Relations for BBM-Octet Coupling Constants

$$g_D = \{g_D^{PS}, g_D^{V}, g_D^{S}\} \qquad g_F = \{g_F^{PS}, g_F^{V}, g_F^{S}\}$$

$$g_{NNa} = g_D + g_F, \qquad g_{\Lambda N\tilde{K}} = -\sqrt{\frac{1}{3}}(g_D + 2g_F), \qquad g_{NNf} = \frac{1}{\sqrt{3}}(3g_F - g_D),$$

$$g_{\Sigma\Sigma a} = 2g_F, \qquad g_{\Xi\Lambda\tilde{K}} = \frac{1}{\sqrt{3}}(3g_F - g_D), \qquad g_{\Lambda\Lambda f} = -\frac{2}{\sqrt{3}}g_D,$$

$$g_{\Lambda\Sigma a} = \frac{2}{\sqrt{3}}g_D, \qquad g_{\Sigma N\tilde{K}} = (g_D - g_F), \qquad g_{\Sigma\Sigma f} = \frac{2}{\sqrt{3}}g_D,$$

$$g_{\Xi\Xi a} = -(g_D - g_F), \qquad g_{\Xi\Sigma\tilde{K}} = -(g_D + g_F), \qquad g_{\Xi\Xi f} = -\frac{1}{\sqrt{3}}(3g_F + g_D)$$

$$a \in \{\pi, \rho, \delta\} \qquad \tilde{K} \in \{K, K^*, \kappa\} \qquad f \in \{\eta, \omega, \sigma\}$$

NN-Interactions and the fundamental SU(3) Octet Coupling Constants

$$g_{NN\pi} = g_D^{(ps)} + g_F^{(ps)} \quad ; \quad g_{NN\eta} = \frac{1}{\sqrt{3}}\left(-g_D^{(ps)} + 3g_F^{(ps)}\right)$$

$$\rightarrow \quad g_D^{(ps)} = \frac{1}{4}\left(3g_{NN\pi} - \sqrt{3}g_{NN\eta}\right) \quad ; \quad g_F^{(ps)} = \frac{1}{4}\left(g_{NN\pi} + \sqrt{3}g_{NN\eta}\right)$$

and accordingly for the scalar and vector couplings, also including octet-singlet mixing

...but caution: there is symmetry breaking!

SU(3) Relations for Singlet Coupling Constants

$$g_{NNf'} = g_{\Lambda\Lambda f'} = g_{\Sigma\Sigma f'} = g_{\Xi\Xi f'} = g_S$$

$$f' \in \{\eta_1, \phi_1, \sigma_1\}$$

Singlet-Octet Mixing:

$$\{\eta_1, \phi_1, f_1\} \rightarrow \{\eta'(958), \phi(1020), f_0(980)\}$$

$$\{\eta_8, \omega_8, \sigma_8\} \rightarrow \{\eta(548), \omega(782), f_0(500)\}$$

In-medium T matrix for nuclear matter with three-body forces: Binding energy and single-particle properties

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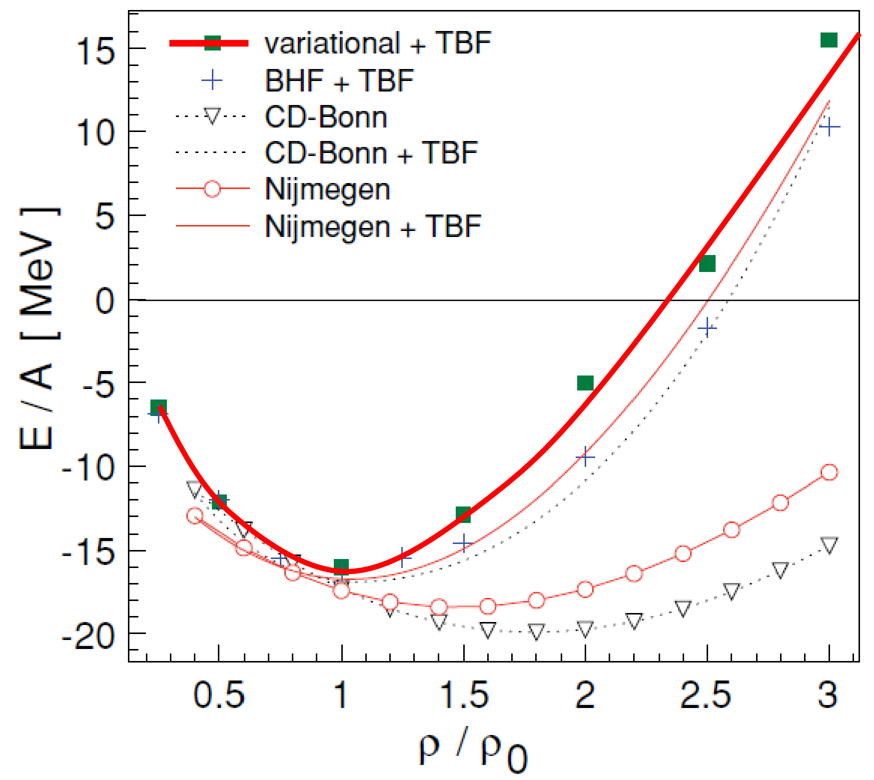

$$T = V + VGQ_FT$$

with

$$V = V^{2body} + V^{3body}$$

EoS with In-Medium T-Matrix