# Hyperons in nuclear matter with YN and YNN interactions of ChEFT

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- Use of NN interactions parametrized by ChEFT is now standard for ab initio calculations of nuclear structures.
  - Low-energy effective theory of spontaneously broken chiral symmetry of QCD.
  - 3NFs are introduced systematically and consistently with 2NFs.
- Progress also in strangeness sector; at present NLO.
  - Experimental data of elementary processes is insufficient.
- It is important to carry out hyper nuclear physics on the basis of YN and YNN interactions of ChEFT.
  - Role of YNN interactions. (3NFs are decisively important in nuclear physics.)
  - Reason of the existence or non-existence of hyperons in neutron star matter.
    - Negative information from recent observation of $2m_{\odot}$ neutron stars.
- Investigate properties of present NLO YN and YNN interactions developed by Bonn-Jülich-München group, by calculating hyperon properties in nuclear matter.

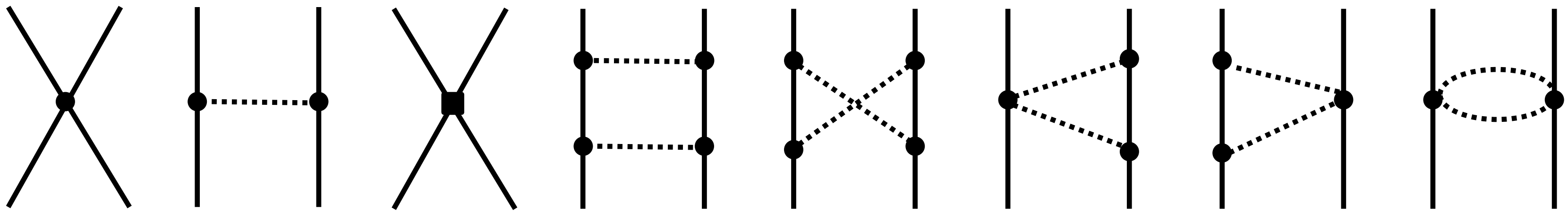
# Nuclear physics on the basis of ChEFT

- 3NF is introduced systematically and consistently with 2NF
  - Previous 3NF is largely phenomenological.
  - 3NFs in ChEFT consist of the components determined by the parameters in 2NFs and the new contact terms.
- Basic properties of nuclei are reproduced by adjusting two parameters ($c_D$ and $c_E$) without relying on much phenomenology.
  - Few-body systems and saturation properties (saturation curve)
  - Strength of one-body spin-orbit field essential for nuclear shell structure
  - Enhancement of tensor force (explain the neutron drip-limit of O isotopes)
- ChEFT NN and 3NF are standard for use in ab initio studies of nuclear structures:（ CCM, no-core shell model, Monte-Carlo, …）
  - In place of modern NN potentials such as AV18, CD-Bonn, Nijmegen
- Studies in strangeness sector are in progress (Bonn-Jülich-München group)

# Baryon-baryon interactions in chiral effective field theory

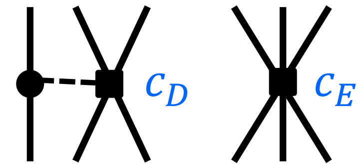
- Starting from general Lagrangian written in terms nucleons and pions which satisfies chiral symmetry (of QCD), and expanding it with respect to momentum (power counting) （low energy effective theory）
- Construction of NN potential（elimination of pions by unitary-transformation or calculation of Feynman diagrams）
  - Coupling constants are determined by $\pi\pi, \pi N, and\ NN$ scattering data and few nucleon systems.
    - E. Epelbaum, H.-W. Hammer and U.-G. Meißner, Rev. Mod. Phys.81 1773 (2009)
    - R. Machleid and D.R. Entem, Phys. Rep. 503,1 (2011)
- Actual scattering and bound states cannot be treated in perturbation:
  ➡ Lippmann-Schwinger or Schroedinger eq.
- Renormalization in Feynman diagrams and reguralization in L-S equation
  - LS eq. の regulator function $f(\Lambda) = \exp\left(-(p'^4 + p^4)/\Lambda^4\right)$

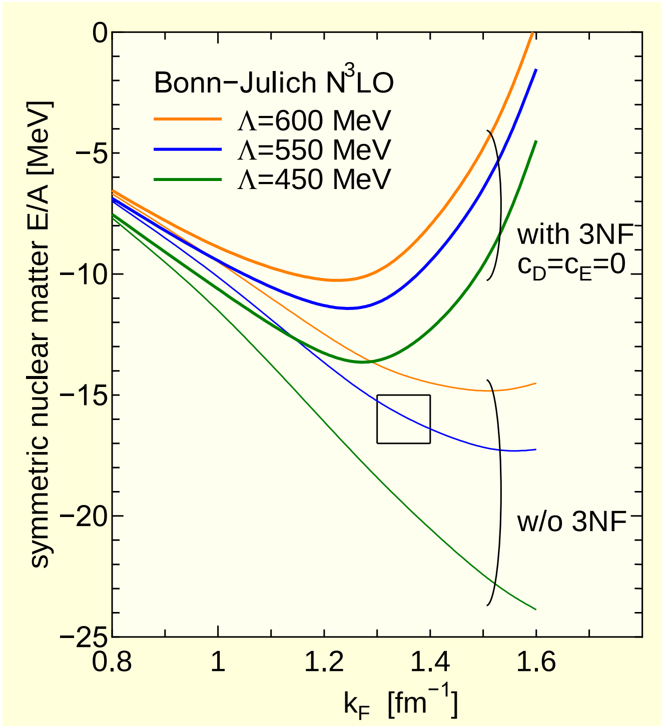
    cutoff scale $\Lambda = 400\ - 600$ MeV
- NLO diagrams（$\pi$, $K$, and $\eta$ exchanges in SU(3)）

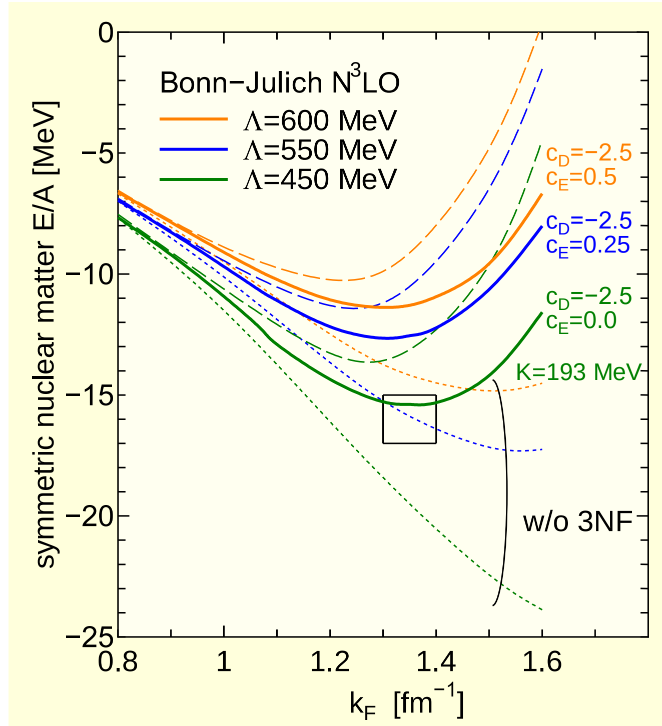


# LOBT calculations with NN+"3NF" of ChEFT

- Calculated saturation curves with 3 choices of cutoff $\Lambda$.
  - Results of $c_D = 0$ and $c_E = 0$.
  - Pauli effects are sizable.
- Tune $c_D$ and $c_E$.

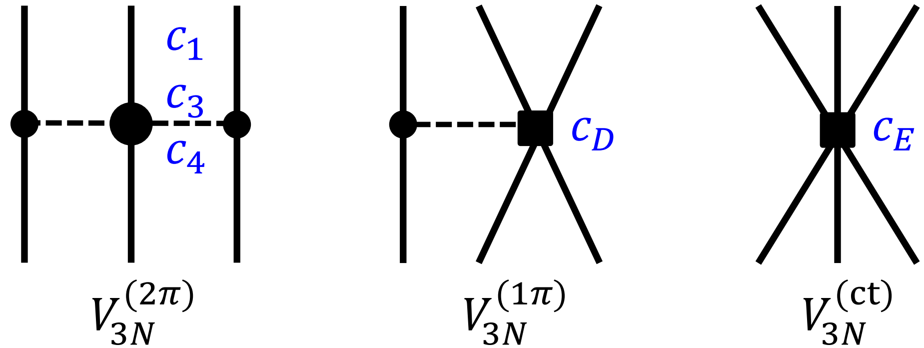



It is not easy to explain nuclear matter properties with parameters fitted in few-body systems. There are attempts to readjust parameters to fit simultaneously finite nuclei and nuclear matter at the NNLO level [$\mathrm{NNLO_{sat}}$, Ekström et al., Phys.Rev. C91 (2015) 051301.].

# NNLO 3NFs in Ch-EFT




$$V_{3N}^{(2\pi)} = \sum_{i \neq j \neq k} \frac{g_A^2}{8 f_\pi^4} \frac{(\boldsymbol{\sigma}_i \cdot \boldsymbol{q}_i)(\boldsymbol{\sigma}_j \cdot \boldsymbol{q}_j)}{(\boldsymbol{q}_i^2 + m_\pi^2)(\boldsymbol{q}_j^2 + m_\pi^2)} F_{ijk}^{\alpha\beta} \tau_i^\alpha \tau_j^\beta$$

$$F_{ijk}^{\alpha\beta} = \delta^{\alpha\beta}\left[-4 c_1 m_\pi^2 + 2 c_3 \boldsymbol{q}_i \cdot \boldsymbol{q}_j\right] + c_4 \epsilon^{\alpha\beta\gamma} \tau_k^\gamma \boldsymbol{\sigma}_k \cdot (\boldsymbol{q}_i \times \boldsymbol{q}_j)$$

$$V_{3N}^{(1\pi)} = -\sum_{i \neq j \neq k} \frac{g_A c_D}{8 f_\pi^4 \Lambda_\chi} \frac{\boldsymbol{\sigma}_j \cdot \boldsymbol{q}_j}{(\boldsymbol{q}_j^2 + m_\pi^2)} \boldsymbol{\sigma}_i \cdot \boldsymbol{q}_j \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j$$

$$V_{3N}^{(\mathrm{ct})} = \sum_{i \neq j \neq k} \frac{c_E}{2 f_\pi^4 \Lambda_\chi} \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j$$

$\boldsymbol{q}_i = \boldsymbol{p}_i - \boldsymbol{p}_i, \Lambda_\chi = 700$ MeV

$c_1 = -0.81\ \mathrm{GeV}^{-1}, c_3 = -3.4\ \mathrm{GeV}^{-1}$, and $c_4 = 3.4\ \mathrm{GeV}^{-1}$ are fixed in NN sector. $c_D$ and $c_E$ are to be determined in many-body systems.

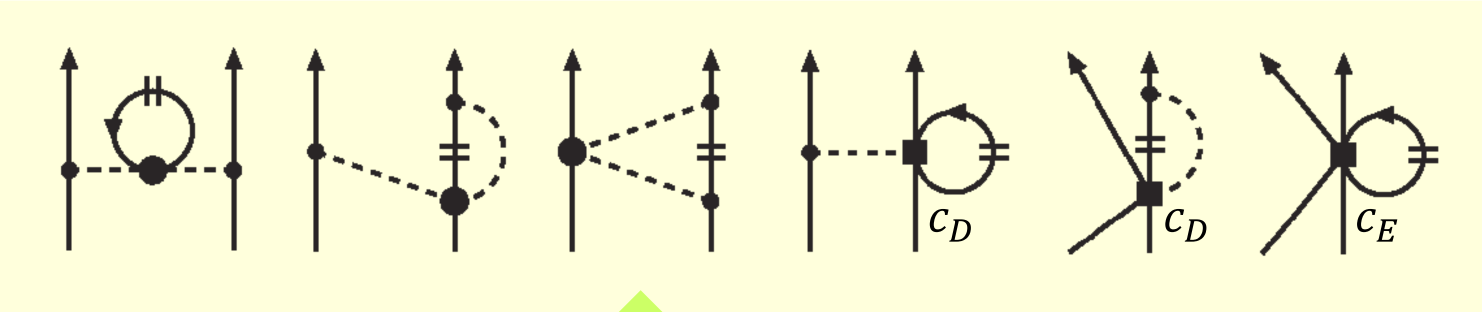
# Reduction of 3NF $v_{123}$ to density dependent NN $v_{12(3)}$

Normal-ordered 2NF from 3NF with respect to nuclear matter:

$$\langle ab|v_{12(3)}|cd\rangle_A \equiv \sum_h \langle abh|v_{123}|cdh\rangle_A$$

Diagrammatical representation by Holt et al.

[J.W. Holt, N. Kaiser, and W. Weise, Phys. Rev. C81, 024002 (2010)]




- Contributions from the two left diagrams tend to cancel.

- This diagram partly corresponds to the Pauli blocking of the isobar Δ excitation in a conventional picture.

- Expand them into partial waves, add them to NN and carry out G matrix calculation.

➢ (*) A factor of $\frac{1}{3}$ is necessary for the calculation of energy at the HF level.

# Effective two-body interaction and partial wave expansion

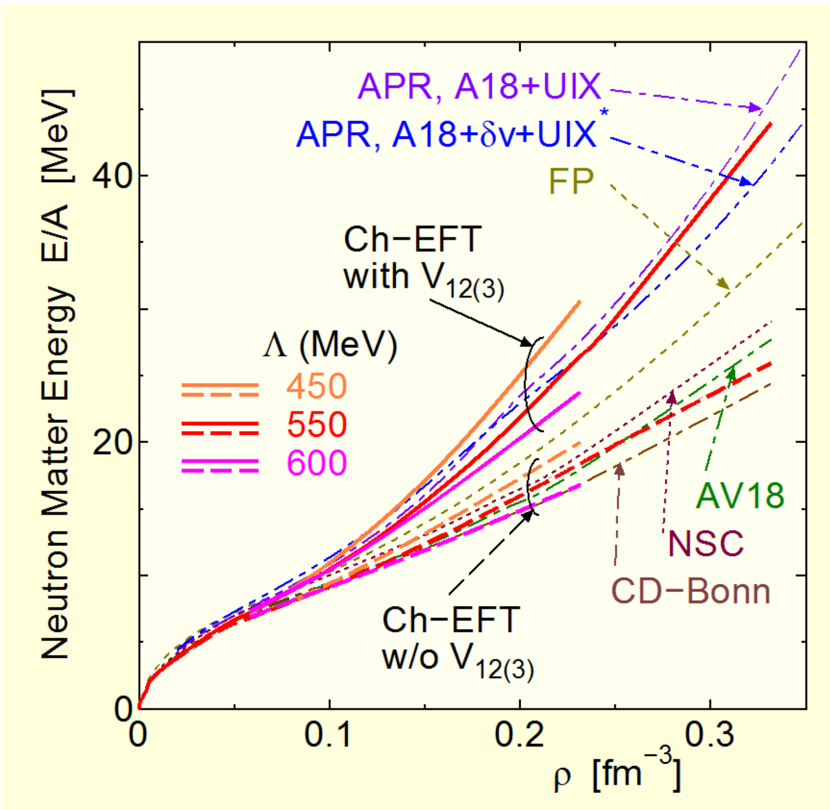
- Integrating over the third nucleon in nuclear matter ($|\boldsymbol{k}_3| \leq k_F, \sigma_3, \tau_3$).
Example: $c_1$ term of the Ch-EFT NNLO 3NF.

$$\left\langle \boldsymbol{k}'\sigma_1'\tau_1', -\boldsymbol{k}'\sigma_2'\tau_2' \middle| V_{12(3)}^{c_1} \middle| \boldsymbol{k}\sigma_1\tau_1, -\boldsymbol{k}\sigma_2\tau_2 \right\rangle$$
$$= -\frac{c_1 g_A^2 m_\pi^2}{f_\pi^4} \sum_{\boldsymbol{k}_3,\sigma_3,\tau_3} \langle \boldsymbol{k}'\,\sigma_1'\tau_1', -\boldsymbol{k}'\,\sigma_2'\tau_2', \boldsymbol{k}_3\sigma_3\tau_3 | \left\{ \frac{(\boldsymbol{\sigma}_1\cdot\boldsymbol{q}_1)(\boldsymbol{\sigma}_2\cdot\boldsymbol{q}_2)}{(\boldsymbol{q}_1^2+m_\pi^2)(\boldsymbol{q}_2^2+m_\pi^2)}(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2) \right.$$
$$\left. + \frac{(\boldsymbol{\sigma}_1\cdot\boldsymbol{q}_1)(\boldsymbol{\sigma}_3\cdot\boldsymbol{q}_3)}{(\boldsymbol{q}_1^2+m_\pi^2)(\boldsymbol{q}_2^2+m_\pi^2)}(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_3) + \frac{(\boldsymbol{\sigma}_2\cdot\boldsymbol{q}_2)(\boldsymbol{\sigma}_3\cdot\boldsymbol{q}_3)}{(\boldsymbol{q}_2^2+m_\pi^2)(\boldsymbol{q}_3^2+m_\pi^2)}(\boldsymbol{\tau}_2\cdot\boldsymbol{\tau}_3) \right\}$$
$$|[\boldsymbol{k}\,\sigma_1\tau_1, -\boldsymbol{k}\,\sigma_2\tau_2]_a, \boldsymbol{k}_3\sigma_3\tau_3 + [-\boldsymbol{k}\,\sigma_2\tau_2]_a, \boldsymbol{k}_3\sigma_3\tau_3, [\boldsymbol{k}\,\sigma_1\tau_1]_a + \boldsymbol{k}_3\sigma_3\tau_3, [\boldsymbol{k}\,\sigma_1\tau_1, -\boldsymbol{k}\,\sigma_2\tau_2]_a\rangle$$

  - Spin and isospin summations
    → two-body central, spin-orbit, and tensor components
  - $\boldsymbol{k}_3$-integration for general case of $k' \neq k$
  - expand the result into partial waves
  - Then, form factor in the form of $\exp\left\{-\left(\frac{k'}{\Lambda}\right)^6 - \left(\frac{k}{\Lambda}\right)^6\right\}$ is multiplied

# Neutron matter

- EoS of neutron matter: basic to theoretical studies of neutron star.
  - EoS of APR, including phenomenological 3NFs, has been standard.
    - Necessity of the repulsive contributions from 3NF.

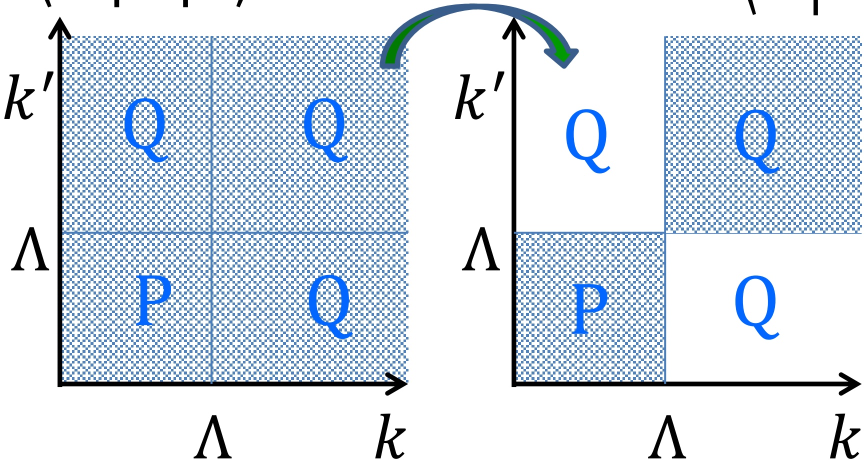


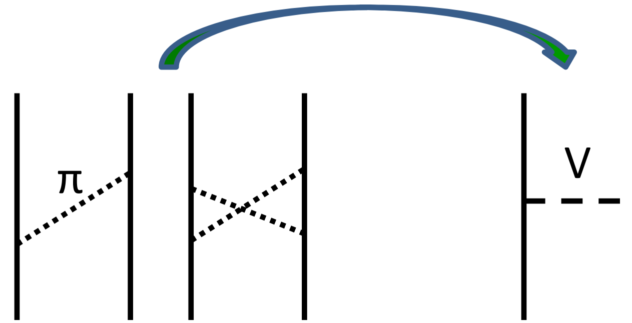

- Dependence on different two-body NN interactions is small, because of the absence of tensor effects in the $^3E$ state.
- The contribution of ChEFT 3NFs (no $c_D$ and $c_E$ terms) is similar to the standard phenomenological one by APR.
  - ChEFT is not applicable to the high-density region of $\rho > 2\rho_0$.

APR: Akmal, Pandharipande, and Ravenhall, PRC58, 1804 (1998)

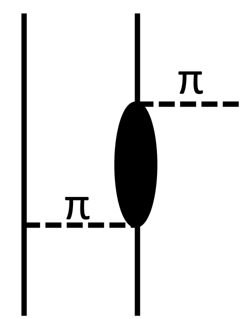
# Instantaneous NN potential

$\langle k'|H|k\rangle$ $\quad \widetilde{H} = e^{-S_{12}} H e^{S_{12}}$ $\quad \langle k'|\widetilde{H}|k\rangle$



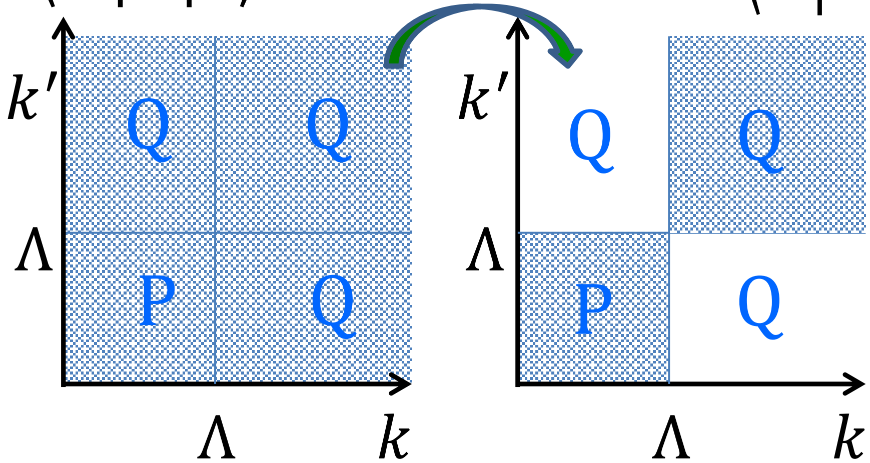




- To construct instantaneous interaction between two nucleons, meson degrees of freedom is eliminated by some unitary transformation. [Okubo, PTP64 (1958)]
- The unitary tf. $e^{S_{12}}$ should satisfy a decoupling condition $\langle Q|\widetilde{H}|P\rangle = \langle P|\widetilde{H}|Q\rangle = 0$ in two-body space.
- (Induced) Many-body forces appear in many-nucleon space. Typical example: Fujita-Miyazawa type.



# Equivalent interaction in restricted (low-mom.) space

$\langle k'|H|k\rangle$ $\quad \widetilde{H} = e^{-S_{12}} H e^{S_{12}}$ $\quad \langle k'|\widetilde{H}|k\rangle$



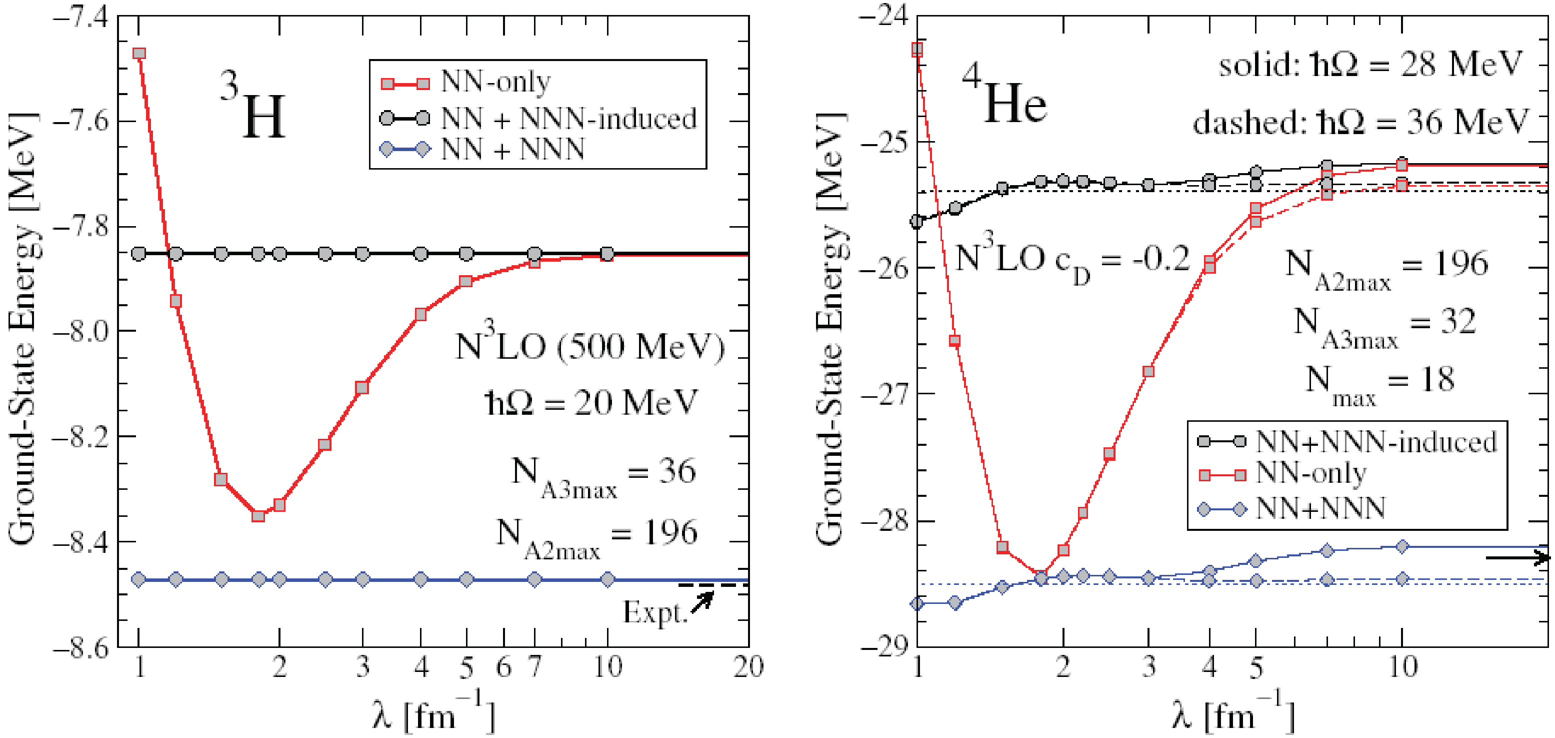

- Apply some unitary transformation $e^{S_{12}}$ to $H$ to obtain an equivalent Hamiltonian $\widetilde{H}$ in a restricted (P) space

  [Suzuki and Lee, PTP64 (1980)]

- The unitary tf. $e^{S_{12}}$ should satisfy a decoupling condition $\langle Q|\widetilde{H}|P\rangle = \langle P|\widetilde{H}|Q\rangle = 0$ in two-body space (block diagonal).
  - Singular high-momentum components are eliminated.
- Eigenvalues, namely on-shell properties, in the restricted (P) space do not change.
  - Off-shell properties naturally change.
- Induced many-body forces appear in many-body space.

# Example of induced 3NF in SRG method

- Red curve: calculation with low-momentum interaction by SRG method
- When induced 3NF is included, the exact energy is recovered (black curve).
  - $\lambda$ represents the scale of low-momentum space.
  - To reproduce experimental values, genuine 3NF is needed (attractive).




E.D. Jurgenson, P. Navratil, and R.J. Furnstahl, Phys. Rev. C83, 034301 (2011)
"Evolving nuclear many-body forces with the similarity renormalization group"

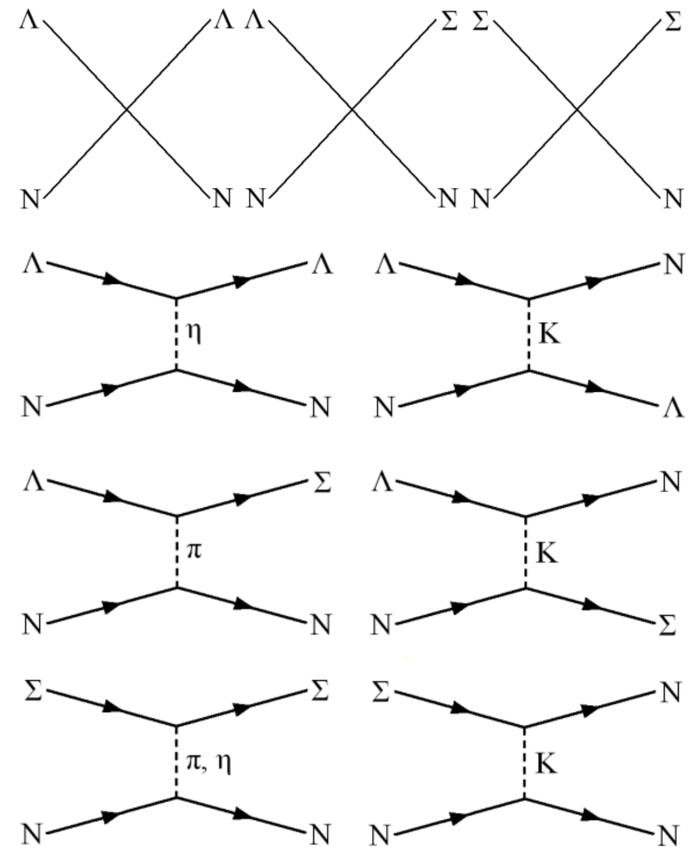
# Summary of effects of 3NF in chiral effective field theory

- Phenomenological adjustment is minimal.
- 3NFs have to be expected as induced effective interaction when other degrees of freedom than nucleons are eliminated in many-nucleon space.
- The repulsive contribution is essential, at least semi-quantitatively, to explain basic saturation properties.
- In addition:
  - Enhancement of spin-orbit strength of the nuclear mean field.
  - Enhancement of tensor component: due to the suppression of the reduction of the tensor force from NNLO 2-π exchange.
    - E.g., the neutron drip limit is reproduced in oxygen isotopes.
- Subjects to be studied: 3BF contributions in the strangeness sector; hyper nuclei and neutron star matter.

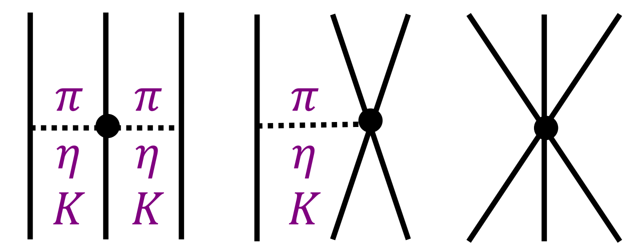
# Strangeness sector: YN and YNN interaction in ChEFT

- Parametrization by Bonn-Jülich-München
- Lowest order:
  - Polinder, Haidenbauer, and Meißner, Nucl. Phys. A779, 244 (2006)
    - Parameters: $f_{NN\pi} = \frac{2f_\pi}{g_A}$ and $\alpha = \frac{F}{F+D}$, also five low-energy constants:

$$C^{\Lambda\Lambda}_{1S0}, C^{\Lambda\Lambda}_{3S1}, C^{\Sigma\Sigma}_{1S0}, C^{\Sigma\Sigma}_{3S1}, C^{\Lambda\Sigma}_{3S1}$$




- Next-to-Leading order
  - Haidenbauer, Petschauer, Kaiser, Meißner, Nogga, and Weise, Nucl. Phys. A915, 24 (2013)
- Leading three-baryon forces
  - Petschauer, Kaiser, Haidenbauer, Meißner, and Weise, Phys. Rev. C93, 014001 (2016)



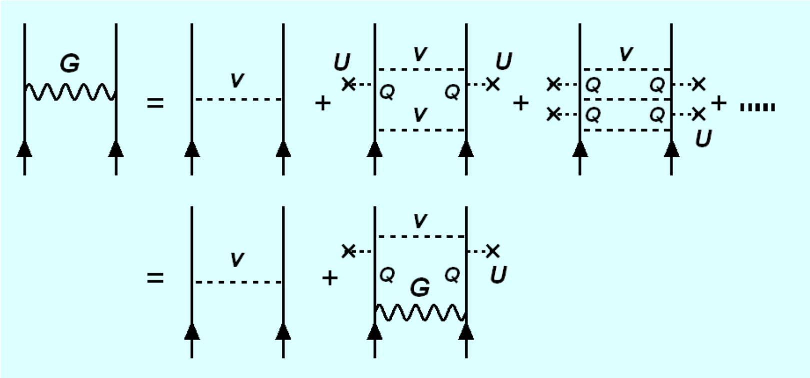

  - Estimation of $1\pi$ and contact LEC: decouplet dominance

# Hyperon s.p. potentials in nuclear matter

- First, hyperon ($\Lambda, \Sigma$ and $\Xi$) single-particle potentials are calculated in nuclear matter using Ch-NLO YN interactions only.
  - cutoff scale of 400~600 MeV is still hard to treat the interaction by HF method.

➡ Standard lowest-order Brueckner method to take care of high momentum part with the continuous choice for intermediate spectra.

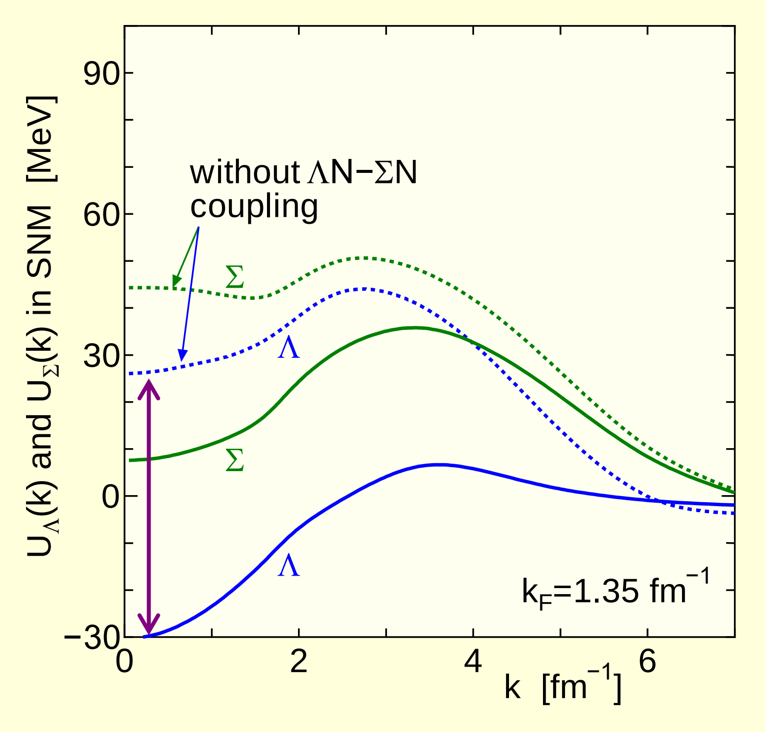
$$G = v + v \frac{Q}{\omega - (t_1 + U_1 + t_2 + U_2)} G$$



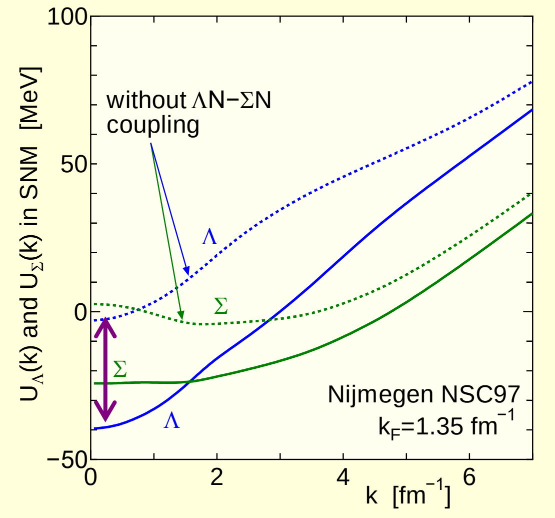

- Salient features, in comparison with other previous YN interactions.
  - Strong ΛN-ΣN coupling, which generates ΛN attraction
    - Charge symmetry breaking in few-body systems may be accounted for.
  - Λ s.p. potential does not become deeper at high densities.

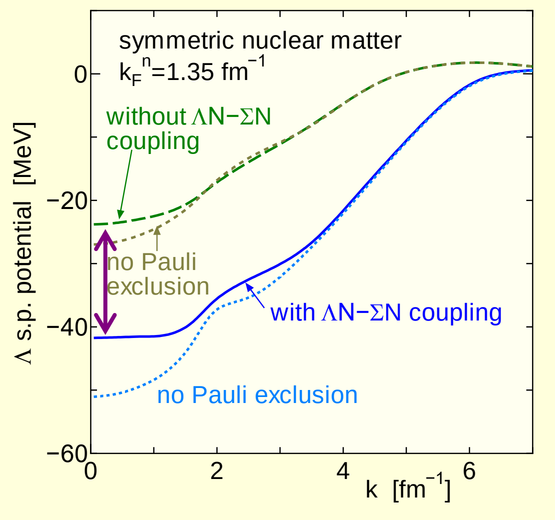
# Λ and  Σ s.p. potentials from G-matrices in symmetric nuclear matter

- The ΛN attraction (experimentally, s.p. potential depth is around 30 MeV) comes from ΛN -ΣN coupling through tensor force.
- The coupling effect is large in ChNLO potential.



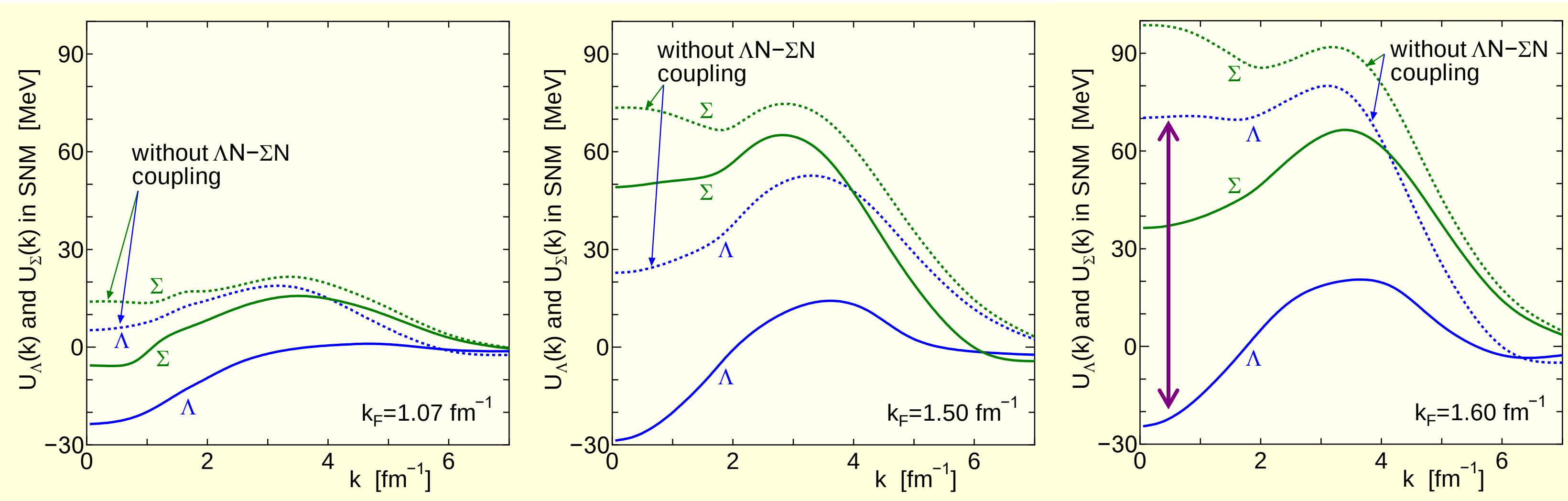

Cf: Results of Nijmegen and quak model (fss2) potentials



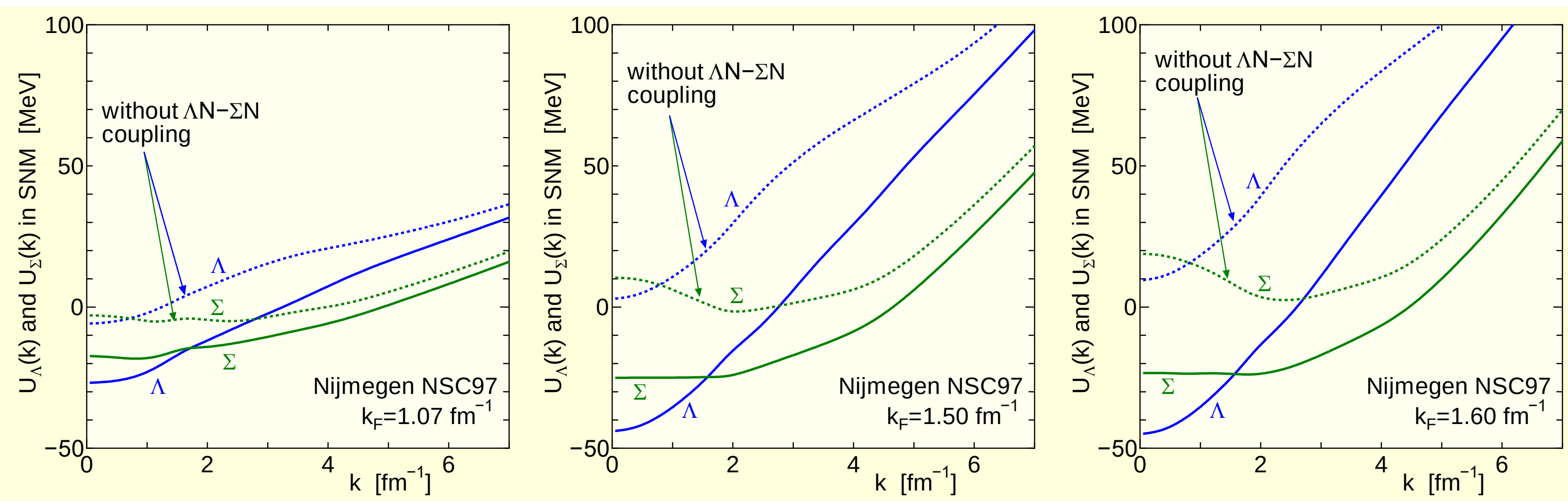



# Calculations at other densities of $k_F = 1.07, 1.50$ and $1{,}60\ \mathrm{fm}^{-1}$

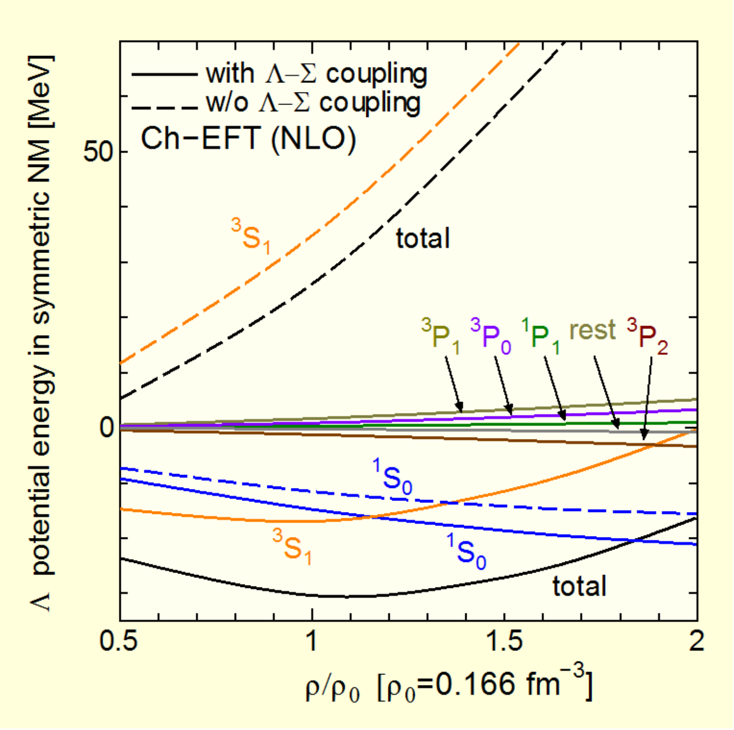
- NLO ChEFT The Λ potential stays shallow at higher densities.




- Nijmegen

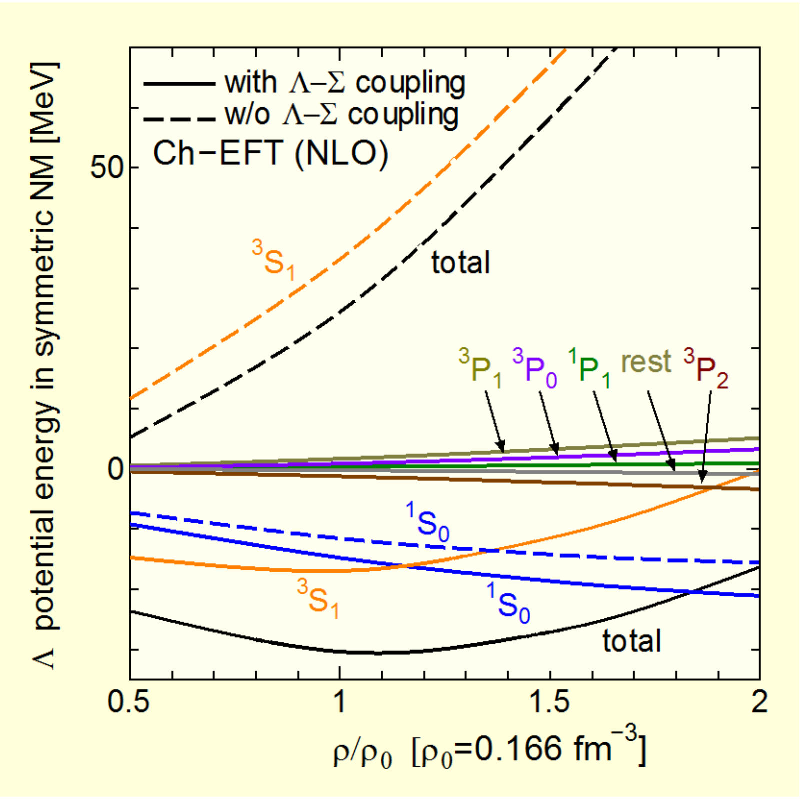


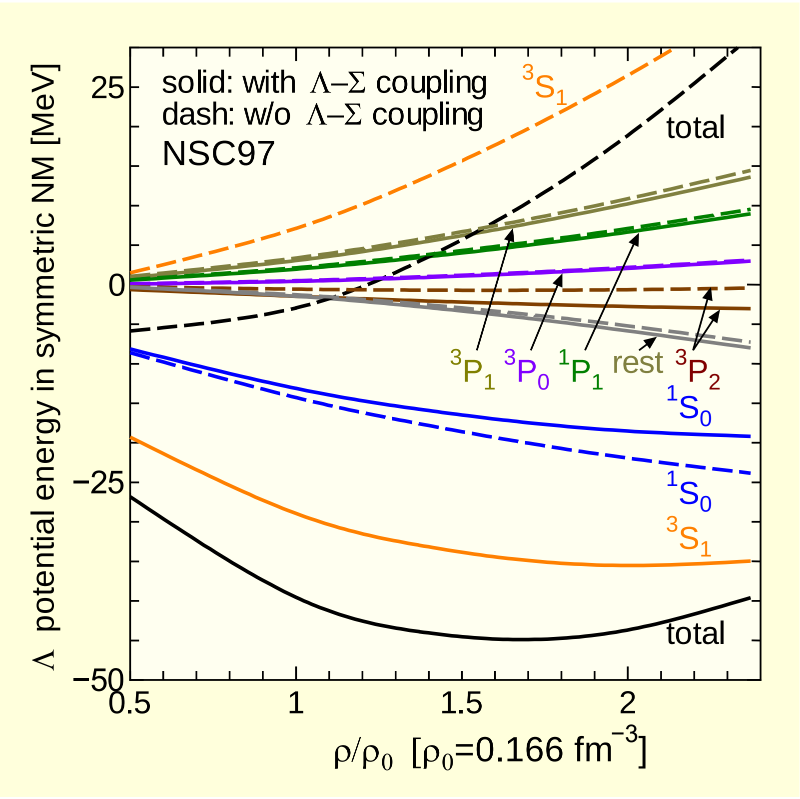
# Density-dependence of the potential of the Λ hyperon at rest




- Shallowness of the potential of the Λ hyperon at rest is due to behavior of the $^3S_1$ contribution.
- Qualitatively same results with those of Haidenbauer, Meißner, Keiser, and Weise [arXiv:1612.03758, EPJA in print].

# Comparison with the results from Nijmegen 97f potential

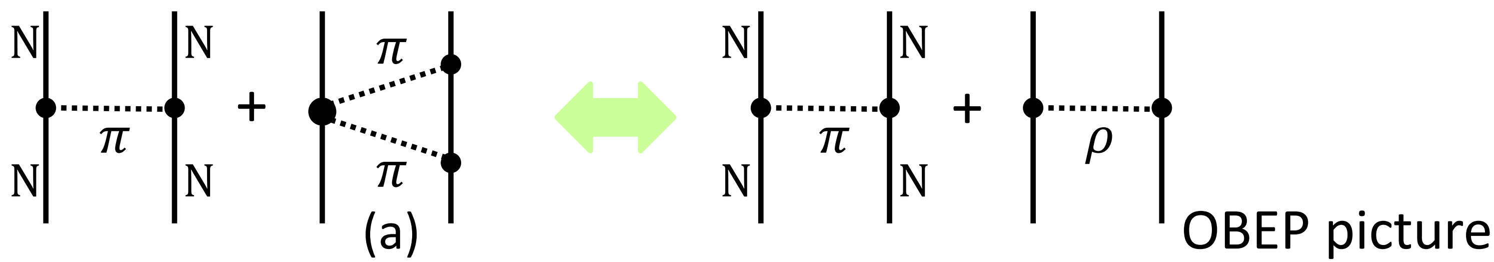


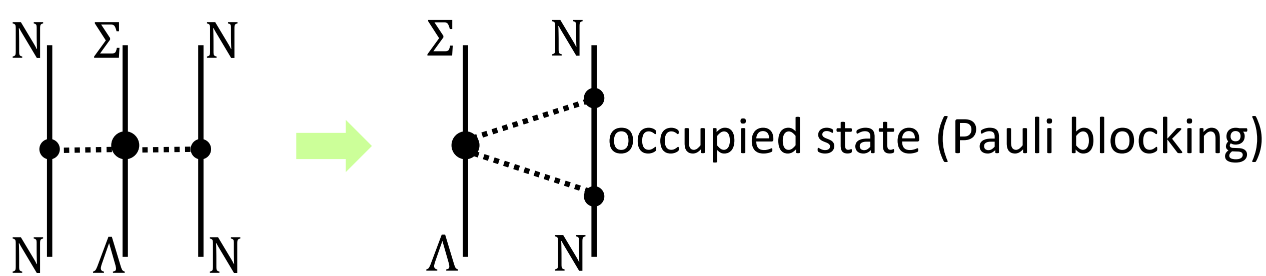

- Qualitative resemblance between ChEFT and NSC97F.
  - Note that NSC97f predicts attractive Σ potential; inconsistent with experimental data.

# comment

- The tensor component from one-pion exchange process in the ΛN-ΣN coupling at the NLO may be overestimated.
  - In the NN case, it is known that 2$\pi$ exchange NNLO diagram (a) reduces the strong one-pion exchange tensor force, which corresponds to the role of the $\rho$ meson in the OBEP picture.

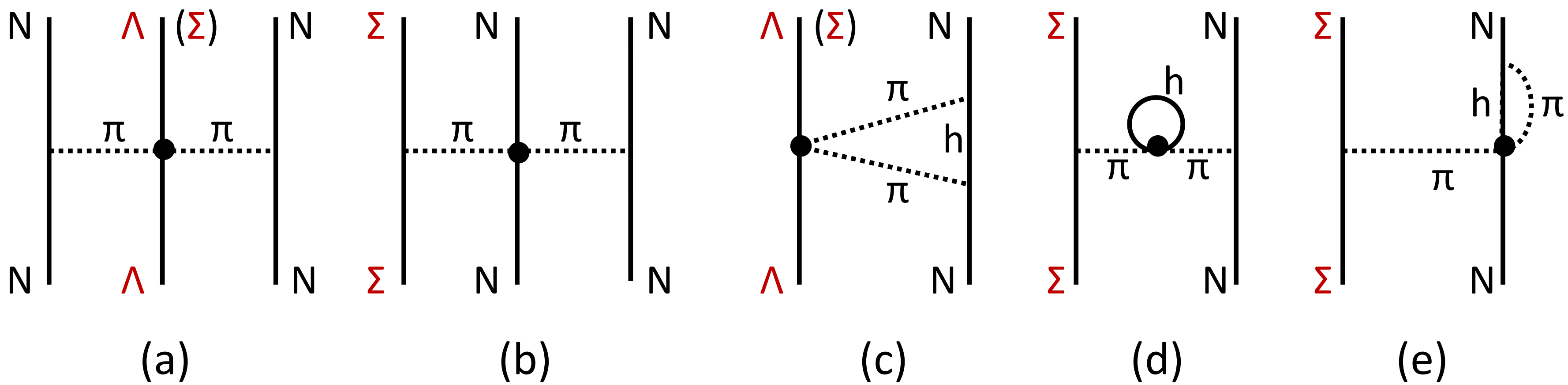



- This is related to the later observation that the effect of ΛNN- ΣNN 3BF coupling enhances the tensor component.



# Inclusion of YNN interactions

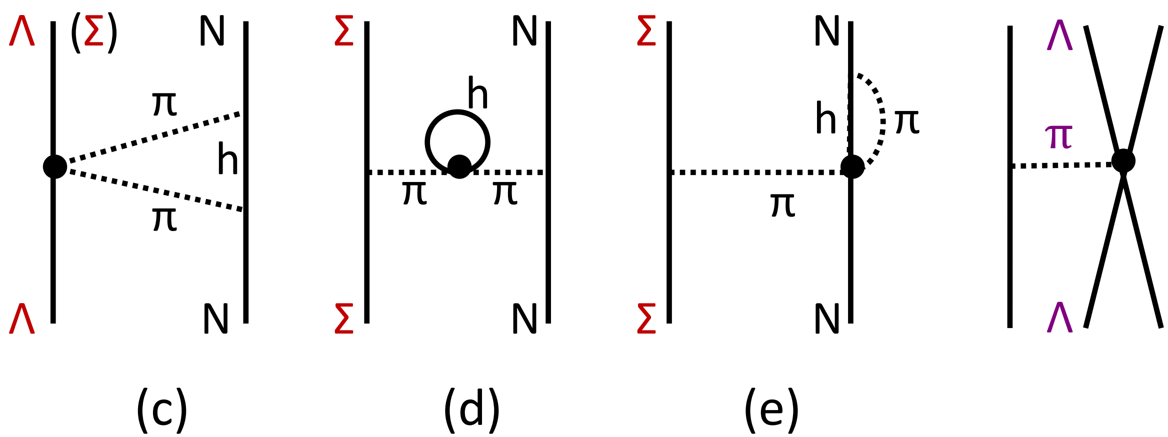
- Next, introducing normal-ordering for YNN force in the 2BF level, LOBT calculations are carried out.
  - Petschauer et al., “Leading three-baryon force from SU(3) chiral effective filed theory”, Phys. Rev. C93, 014001 (2016)




- YNN 3BF(a) is reduced to density-dependent 2BF(c) in nuclear matter (normal-ordering). Solve G-matrix equations, with 2BF + DD 2BF, to obtain Λ s.p. potential.

# Effects of YNN interactions in ChEFT

- Pauli blocking type contribution (c) suppresses the attraction in free space, namely the repulsive contribution. The suppression becomes become larger at higher density, like in the NNN case.



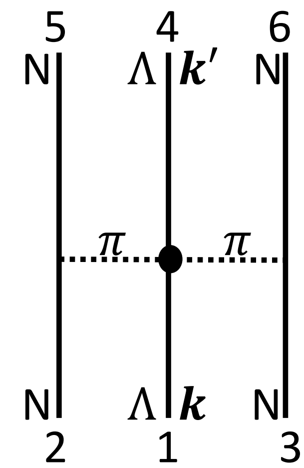

- Contributions of 1$\pi$exchange 3BF can be attractive contribution, depending the sign of the coupling constant.
- Effects from ΛNN-ΣNN coupling can be attractive by the enhancement of the tensor component.

# Contributions of 2-pion exchange ΛNN interaction

- $2\pi$ exchange ΛNN 3-body interaction $V_{\Lambda NN}^{TPE}$

$$\frac{g_A^2}{3f_0^2}(\boldsymbol{\tau}_2\cdot\boldsymbol{\tau}_3)\frac{(\boldsymbol{\sigma}_3\cdot\boldsymbol{q}_{63})(\boldsymbol{\sigma}_2\cdot\boldsymbol{q}_{52})}{(\boldsymbol{q}_{63}^2+m_\pi^2)(\boldsymbol{q}_{52}^2+m_\pi^2)}\{-Am_\pi^2+B\boldsymbol{q}_{63}\cdot\boldsymbol{q}_{52}\}$$

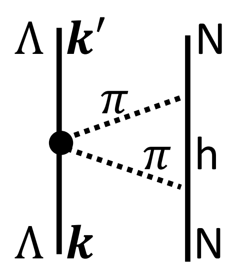
Estimation by Petschauer： $A=0,\ B=-3.0\ \mathrm{GeV}^{-1}$



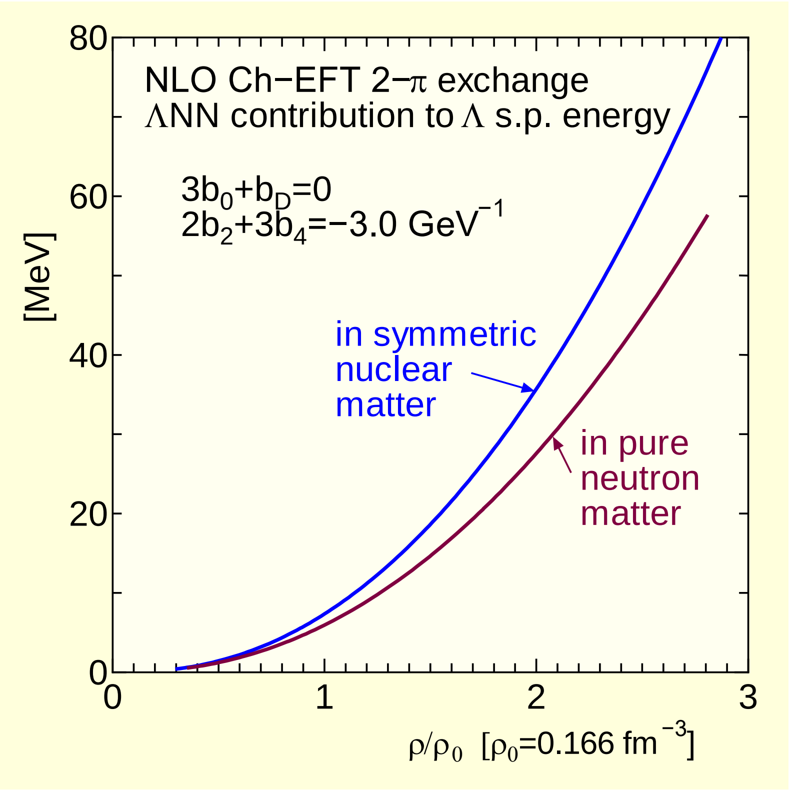

- Normal-ordered 2-body int. in symmetric nuclear matter

$$\langle \boldsymbol{k}'\sigma_\Lambda{}', -\boldsymbol{k}'\sigma'\tau' | V_{\Lambda N(N)} | \boldsymbol{k}\sigma_\Lambda, -\boldsymbol{k}\sigma\tau\rangle$$
$$\equiv \frac{1}{2}\sum_{\boldsymbol{k}_h,\sigma_h,\tau_h}\langle \boldsymbol{k}'\sigma_\Lambda', -\boldsymbol{k}'\sigma'\tau', \boldsymbol{k}_h,\sigma_h,\tau_h | V_{\Lambda NN} | \boldsymbol{k}\sigma_\Lambda, -\boldsymbol{k}\sigma\tau, \boldsymbol{k}_h,\sigma_h,\tau_h\rangle_A$$

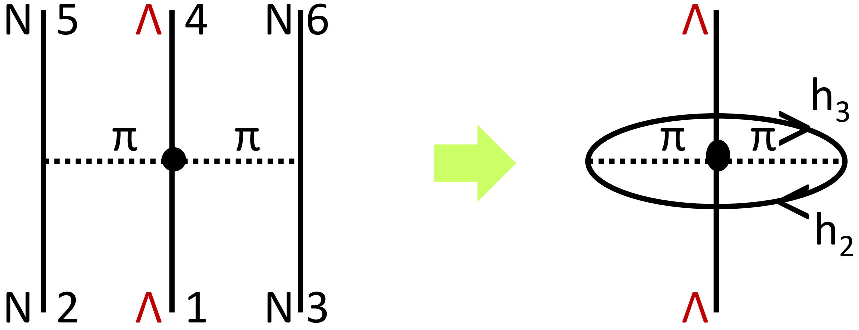
  - Density-dependent central, LS, ALS 成分
  - No tensor component
  - Additional statistical factor $\frac{1}{2}$
  - Repulsive character of Pauli blocking type
  - Partial waves expansion ➡ G-matrix calculation



# HF contribution of 2$\pi$ exchange $\Lambda$NN force to $\Lambda$ potential



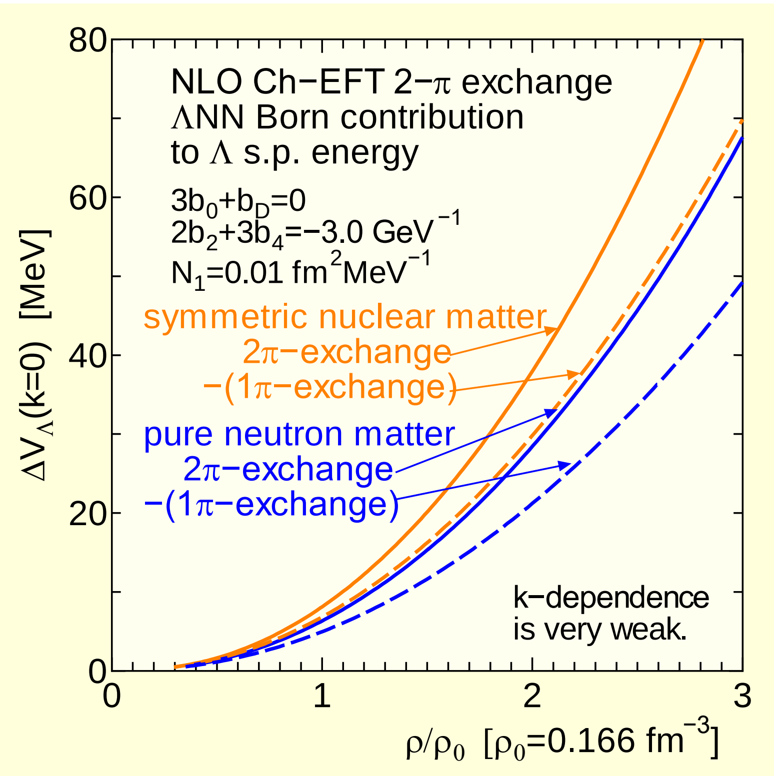

$$V_{\Lambda NN}^{TPE} = \frac{g_A^2}{3f_0^4}(\boldsymbol{\tau_2}\cdot\boldsymbol{\tau}_3)\frac{(\boldsymbol{\sigma_3}\cdot\boldsymbol{q}_{63})(\boldsymbol{\sigma_2}\cdot\boldsymbol{q}_{52})}{(\boldsymbol{q}_{63}^2+m_\pi^2)(\boldsymbol{q}_{63}^2+m_\pi^2)}$$
$$\times\{-(3b_0+b_D)m_\pi^2+(2b_2+3b_4)\boldsymbol{q}_{63}\cdot\boldsymbol{q}_{52}\}$$



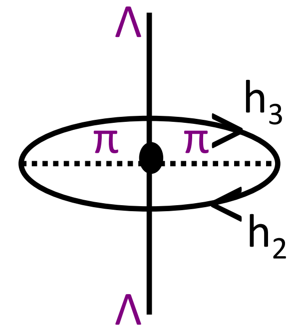

$$\Delta U_\Lambda(\boldsymbol{k}_\Lambda) = \frac{1}{2}\sum_{2,3}\langle \boldsymbol{k}_\Lambda\boldsymbol{k}_2\boldsymbol{k}_3|V_{\Lambda NN}^{TPE}|\boldsymbol{k}_\Lambda\boldsymbol{k}_2\boldsymbol{k}_3\rangle_A$$
$$= \frac{g_A^2}{3f_0^4}\frac{1}{(2\pi)^6}\int_0^{k_F} q^2\,dq\,\frac{64\pi^2}{3}(k_F-q)^2$$
$$\times(2k_F+q)\frac{4q^2}{(4q^2+m_\pi^2)^2}$$
$$\times\{-(3b_0+b_D)m_\pi^2+(2b_2+3b_4)q^2\}$$

- ChEFT may not be relevant to $\rho > 2\rho_0$.
- Contributions from contact terms have also to be considered.

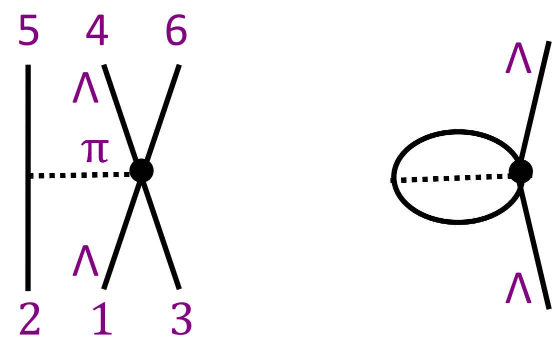
# HF contribution of $2\pi$ and $1\pi$ exchange ΛNN forces to Λ potential



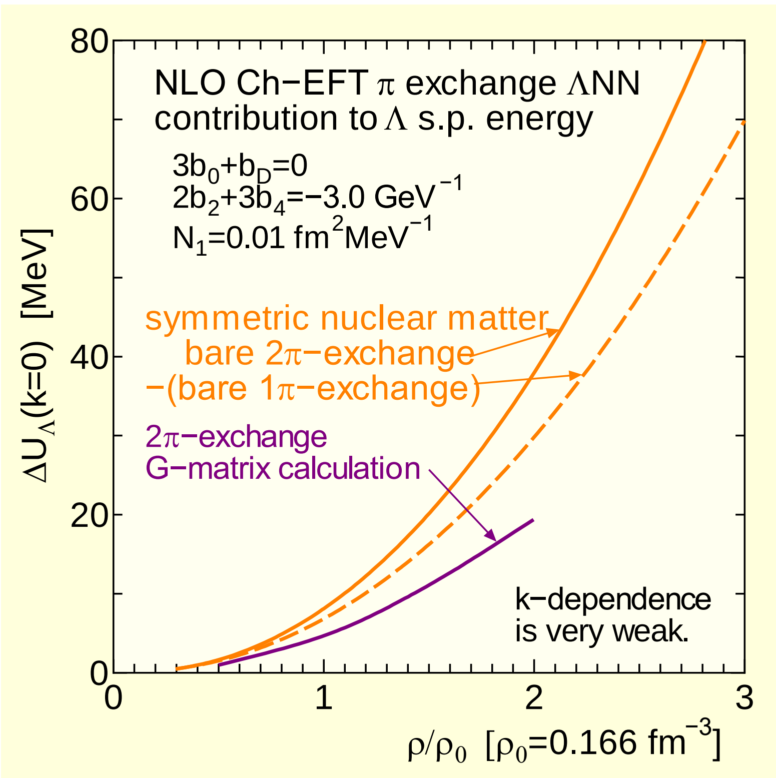

$$V^{TPE}_{\Lambda NN} = \frac{g_A^2}{3f_0^4}(\boldsymbol{\tau_2}\cdot\boldsymbol{\tau}_3)\frac{(\boldsymbol{\sigma_3}\cdot\boldsymbol{q}_{63})(\boldsymbol{\sigma_2}\cdot\boldsymbol{q}_{52})}{(\boldsymbol{q}_{63}^2+m_\pi^2)(\boldsymbol{q}_{63}^2+m_\pi^2)}$$
$$\times\{-(3b_0+b_D)m_\pi^2+(2b_2+3b_4)\boldsymbol{q}_{63}\cdot\boldsymbol{q}_{52}\}$$



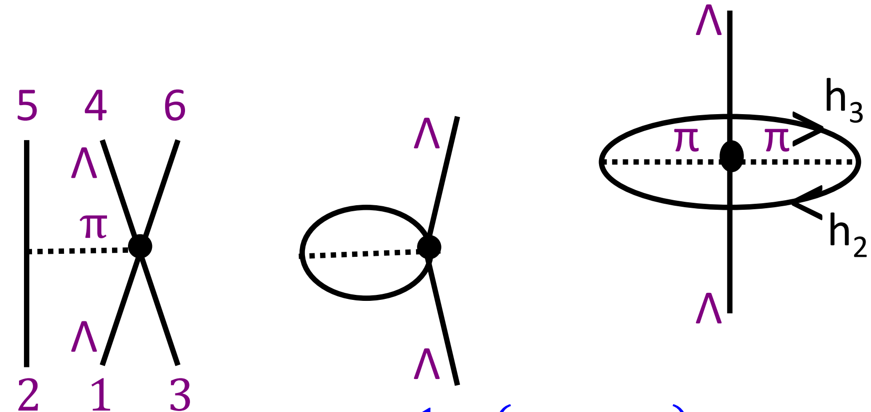

$$V^{\Lambda NN}_{OPE} = \frac{1}{2f_0^4}\frac{(\boldsymbol{\sigma_2}\cdot\boldsymbol{q_{52}})}{(\boldsymbol{q}_{52}^2+m_\pi^2)}$$
$$\times\{N_1\boldsymbol{\sigma_3}\cdot\boldsymbol{q_{52}}+N_2 i(\boldsymbol{\sigma_1}\times\boldsymbol{\sigma_3})\cdot\boldsymbol{q}_{52}\}$$



# Contributions of 2$\pi$ exchange ΛNN force in G-matrix calculations



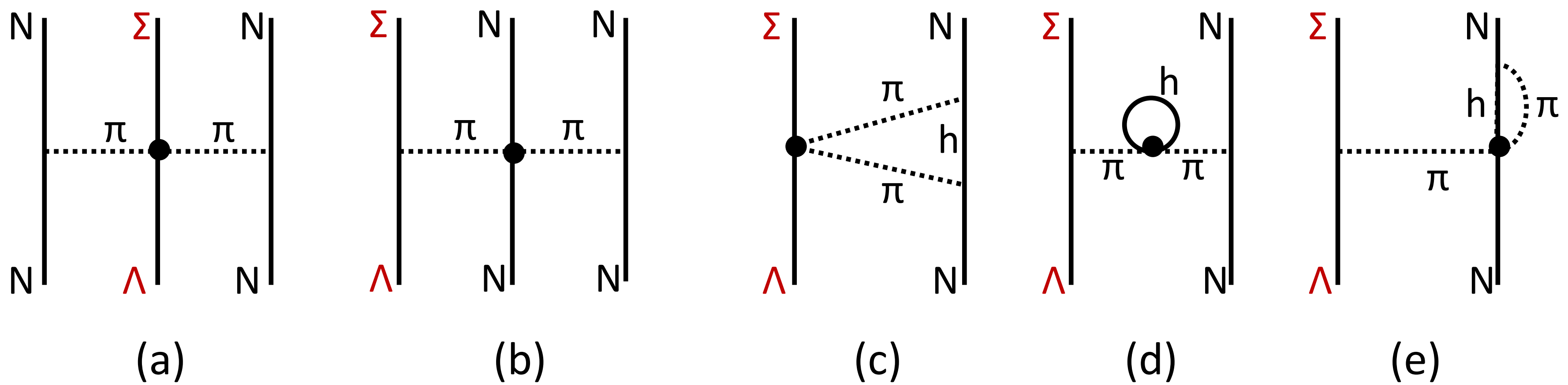

$$V_{TPE}^{\Lambda NN} = \frac{g_A^2}{3f_0^4}(\boldsymbol{\tau}_2\cdot\boldsymbol{\tau}_3)\frac{(\boldsymbol{\sigma}_3\cdot\boldsymbol{q}_{63})(\boldsymbol{\sigma}_2\cdot\boldsymbol{q}_{52})}{(\boldsymbol{q}_{63}^2+m_\pi^2)(\boldsymbol{q}_{63}^2+m_\pi^2)}$$
$$\times\{-(3b_0+b_D)m_\pi^2+(2b_2+3b_4)\boldsymbol{q}_{63}\cdot\boldsymbol{q}_{52}\}$$




$$V_{OPE}^{\Lambda NN} = \frac{1}{2f_0^4}\frac{(\boldsymbol{\sigma}_2\cdot\boldsymbol{q}_{52})}{(\boldsymbol{q}_{52}^2+m_\pi^2)}$$
$$\times\{N_1\boldsymbol{\sigma}_3\cdot\boldsymbol{q}_{52}+N_2 i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_3)\cdot\boldsymbol{q}_{52}\}$$

- Absolute values of the are reduced by the correlation from the G-matrix equation.
- Contributions below the normal density are not large, though depending on the sign of the 1-pion exchange contact term.
- Effects of the ΛNN-ΣNN coupling are to be included.

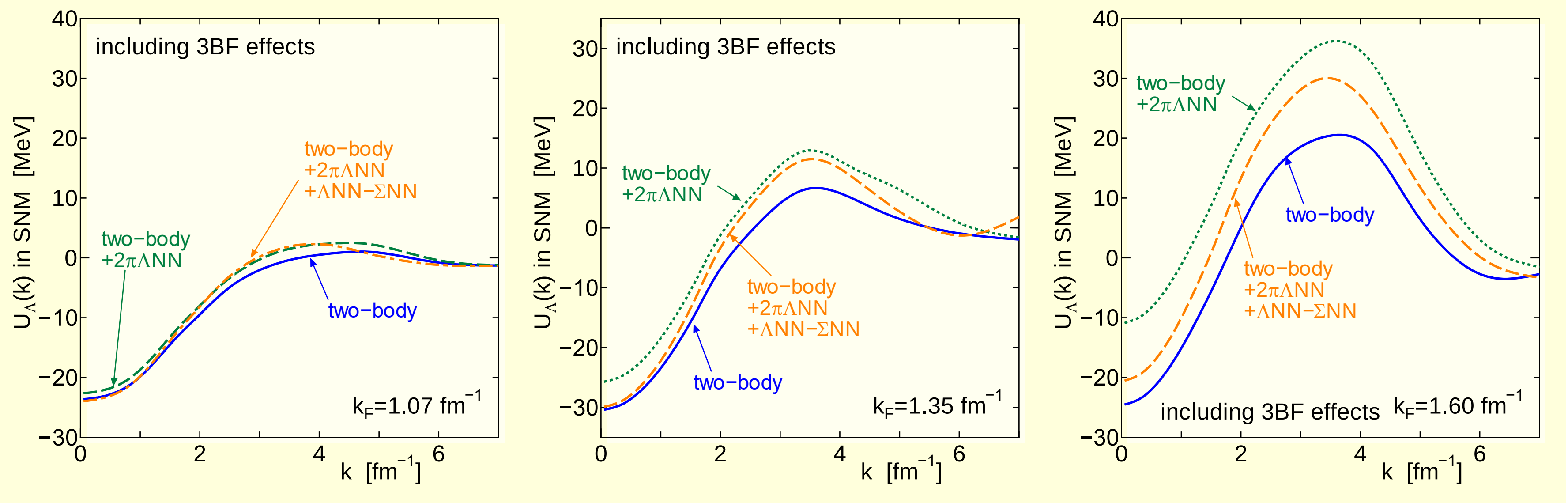
# Normal-ordered 2body force from ΛNN- ΣNN coupling interaction




- Again, normal-ordered 2NF is introduced.
- As in the case of 3NFs
  - Contributions of (d) and (e) diagrams cancel each other.
  - The diagram (c) enhances the tensor component.

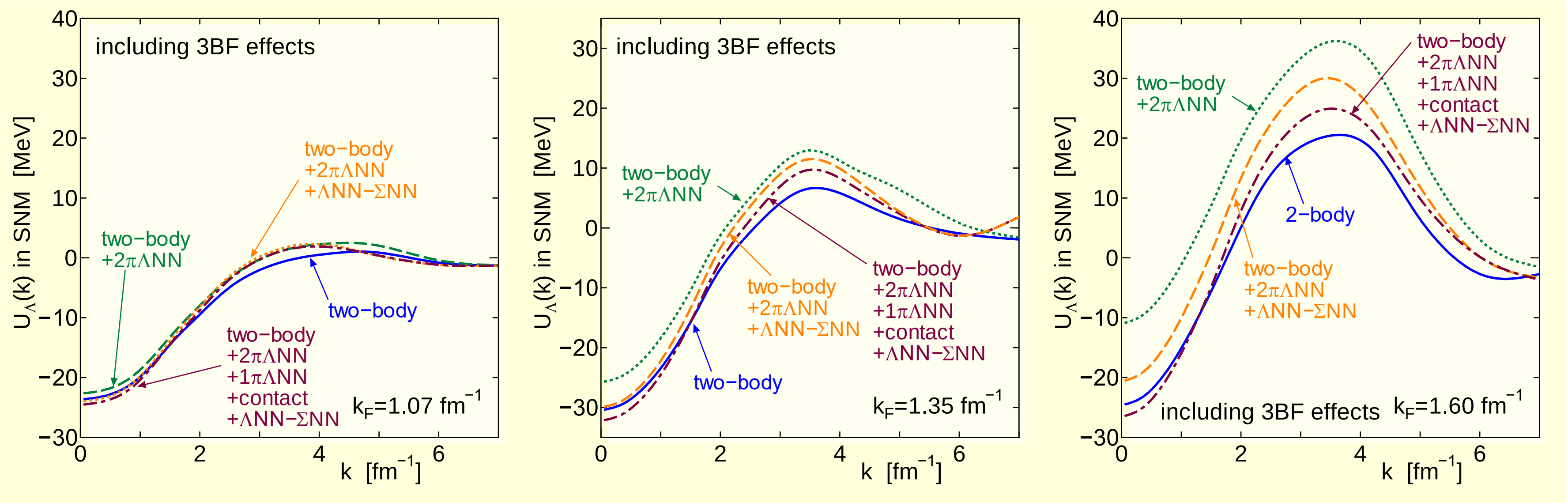
# Λ s.p. potential in symmetric nuclear matter including 3BFs

- $k_F = 1.07, 1.35$ and $1{,}60$ fm$^{-1}$ ( $\rho = \frac{1}{2}\rho_0$, $\rho_0$, and $1.66\rho_0$, respectively)
  - 2π-exchange ΛNN interaction
  - 2π-exchange ΛNN- ΣNN interaction



# Λ s.p. potential in symmetric nuclear matter including 3BFs

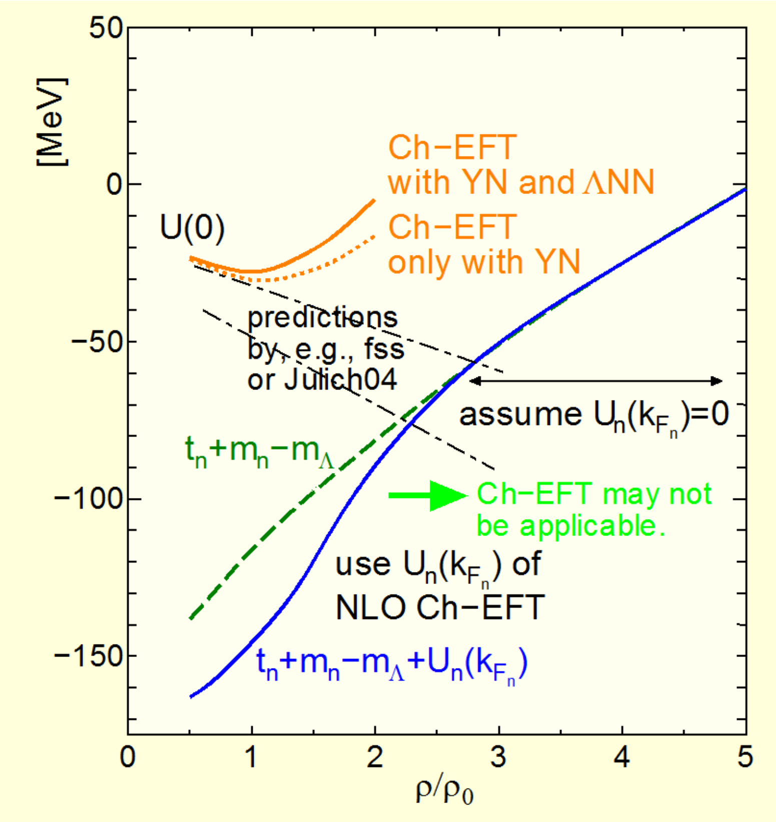
- $k_F = 1.07, 1.35$ and $1,60\ \mathrm{fm}^{-1}$ ( $\rho = \frac{1}{2}\rho_0$, $\rho_0$, and $1.66\rho_0$, respectively)
  - 2π-exchange ΛNN interaction
  - 2π-exchange ΛNN- ΣNN interaction
  - Contact + attractive 1π-exchange ΛNN interaction



# Possibility to resolve hyperon puzzle

- A naive condition for the $\Lambda$ hyperon to appear in pure neutron matter.

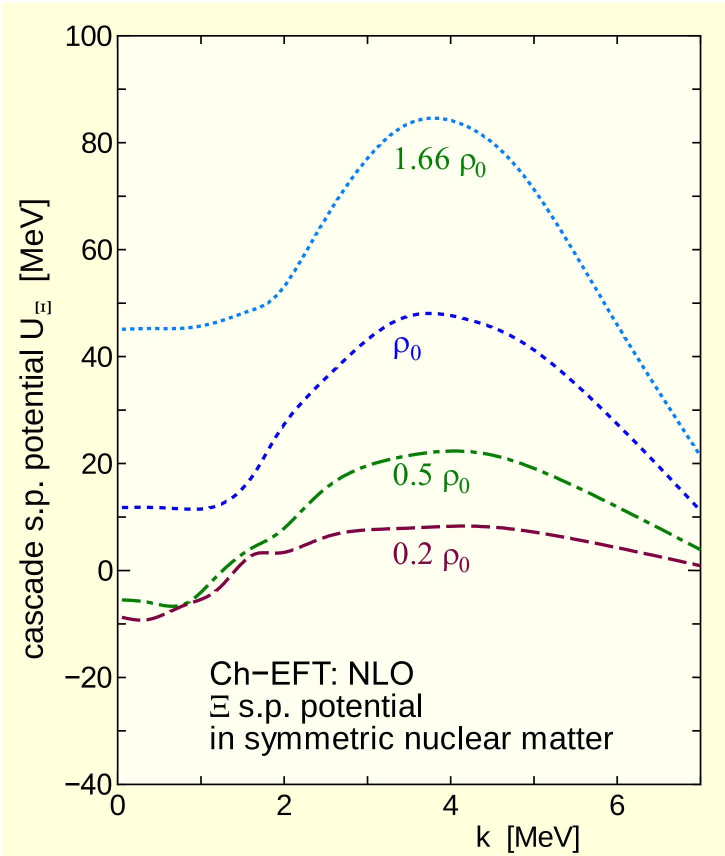
$$U_\Lambda(0) < \frac{\hbar^2}{2m_n} {k_{F_n}}^2 + m_n - m_\Lambda + U_n(k_{F_n})$$




- $\Lambda$ s.p. potential predicted by NLO YN potential does not become deep at high densities.
  - $U_\Lambda(0) > -30$ MeV
  - The attractive effect from $\Lambda$NN-$\Sigma$NN coupling does not change this feature qualitatively.
- $U_\Lambda(0)$ is always above $\frac{\hbar^2}{2m_n} \times {k_{F_n}}^2 + m_n - m_\Lambda + U_n(k_{F_n})$; namely, $\Lambda$ hyperon does not appear in the high density medium.

（Note：Actual calculations in neutron matter are in progress.）

# Ξ s.p. potential in symmetric nuclear matter




- Coupling constants in $S = -2$ sector are largely uncertain.
  - Constraint from the non-existence of H and bound ΞN state.
- Various baryon-channel coupling (ΞN-ΛΛ-ΣΣ (T=0), ΞN-ΛΣ-ΣΣ (T=1)) state and density dependences
- Ξ-nucleus potential from ChEFT NLO interaction may be attractive but shallow at the surface region.
- Recent experimental data suggest some weakly bound Ξ-nucleus states.
  - Kiso event: $\Xi^-$-$^{14}$N (Nakazawa et al.)
  - $^{12}$C($K^-$,$K^+$)X spectra at 1.8 GeV/c (Nagae et al.), which showed some strength below the threshold, though not conclusive until the future experiment.
- Effects from 3BFs should be included.

# Summary

- General remarks for 3-body interaction
- LOBT G-matrix calculations to obtain hyperon single-particle potentials in (symmetric) nuclear matter, using Ch-EFT NLO interactions in the strangeness sector developed by the Bonn-Jülich-München group.
  - Strong ΛN-ΣN coupling
  - Λ s.p. potential does not become deeper at higher densities.
    - Λ is energetically unfavorable in high density matter. Does hyperon puzzle dissolve?
  - Contributions of 3BF do not change the situation.
  - ΛNN 3BF gives repulsive contribution, while the effect from ΛNN- ΣNN is attractive.
- Subjects to be studied in the future
  - NNLO
  - New experiments to reduce uncertainties of coupling constants and low energy constants.
  - Consideration of diagrams including $K$ and $\eta$ exchanges.
  - Explicit (ab initio) calculations of finite hypernuclei.