HYPERON - NUCLEAR INTERACTIONS and DENSE BARYONIC MATTER

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PHYSIK DEPARTMENT

- Equation of State of dense baryonic matter : Chiral EFT and constraints from massive neutron stars
- Hyperon - nucleon interactions from Chiral SU(3) Effective Field Theory
- Hyperon-NN three-body forces and hyperon-nuclear single particle potential
- "Hyperon puzzle" and emerging repulsions : suppression of hyperons in neutron star matter

Part 1.

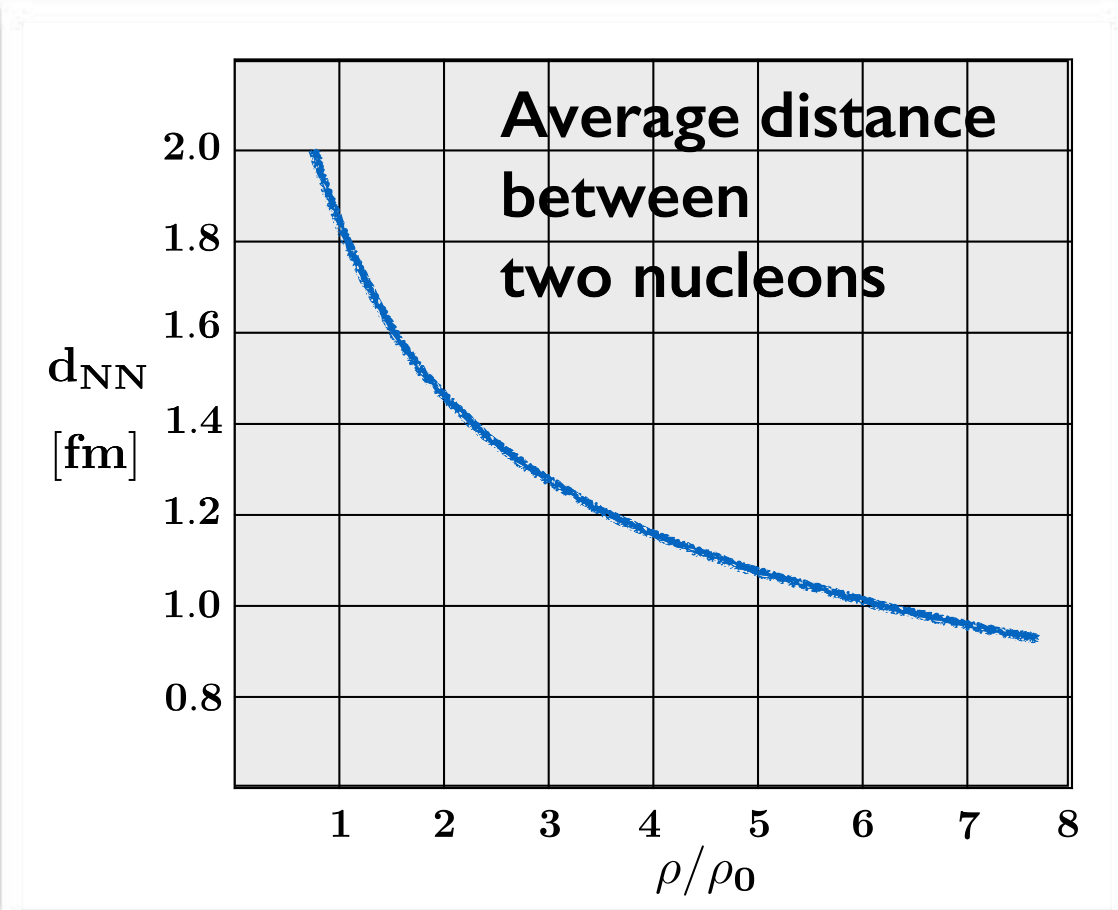
Brief overview:
Chiral EFT + FRG and
Dense Baryonic Matter

- Pions and Nucleons as "active" degrees as freedom in a Nuclear Fermi Sea

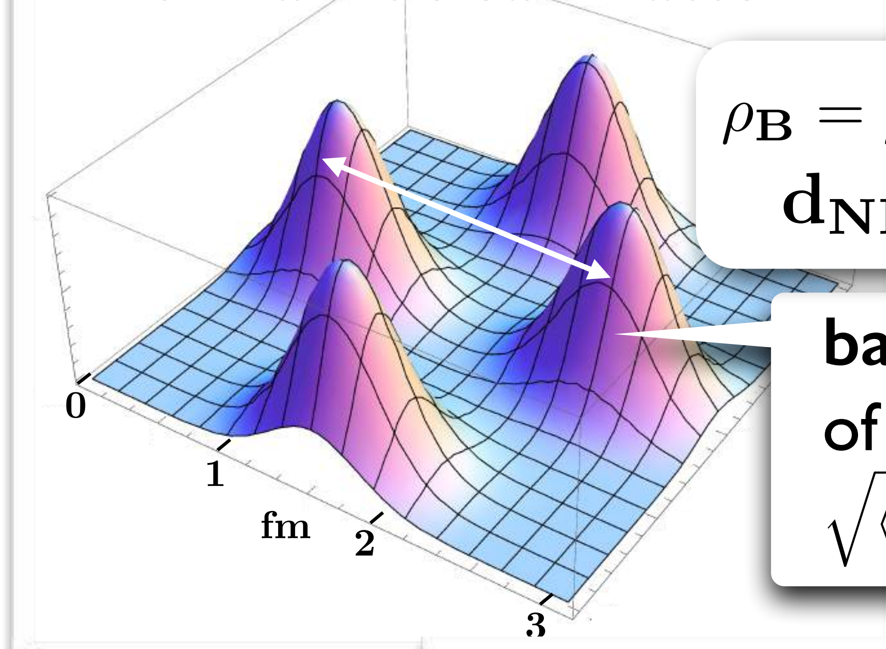
- Perturbative methods:
  Chiral Effective Field Theory
  and
  Nuclear Many-Body Problem
  (baryon densities $\rho \lesssim 2\,\rho_0$)

- Non-perturbative methods:
  Chiral Nucleon-Meson Field Theory
  and
  Functional Renormalisation Group
  (towards higher densities : $\rho \sim 5\,\rho_0$)

Densities and Distance Scales in Baryonic Matter



normal nuclear matter



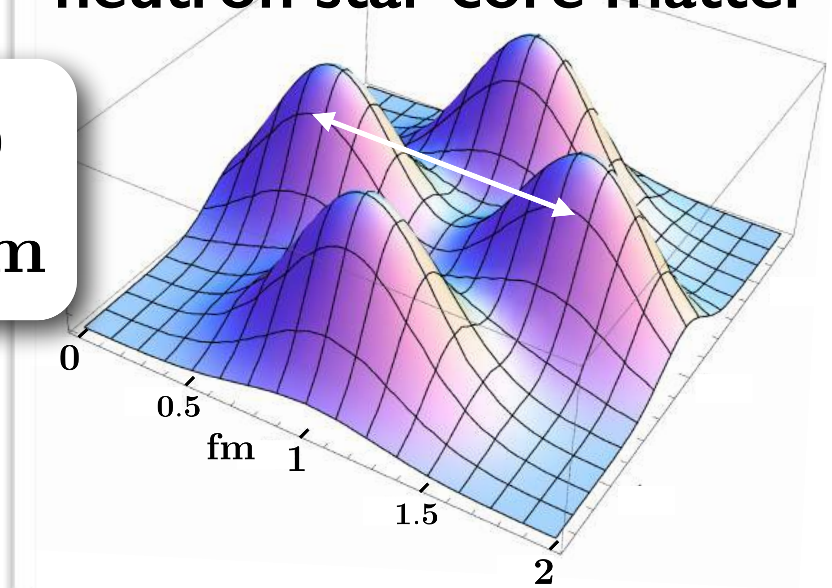
$\rho_B = \rho_0 = 0.16\ \mathrm{fm}^{-3}$

$d_{NN} \simeq 1.8\ \mathrm{fm}$

baryonic core of the nucleon

$\sqrt{\langle r_B^2 \rangle} \simeq 1/2\ \mathrm{fm}$

neutron star core matter



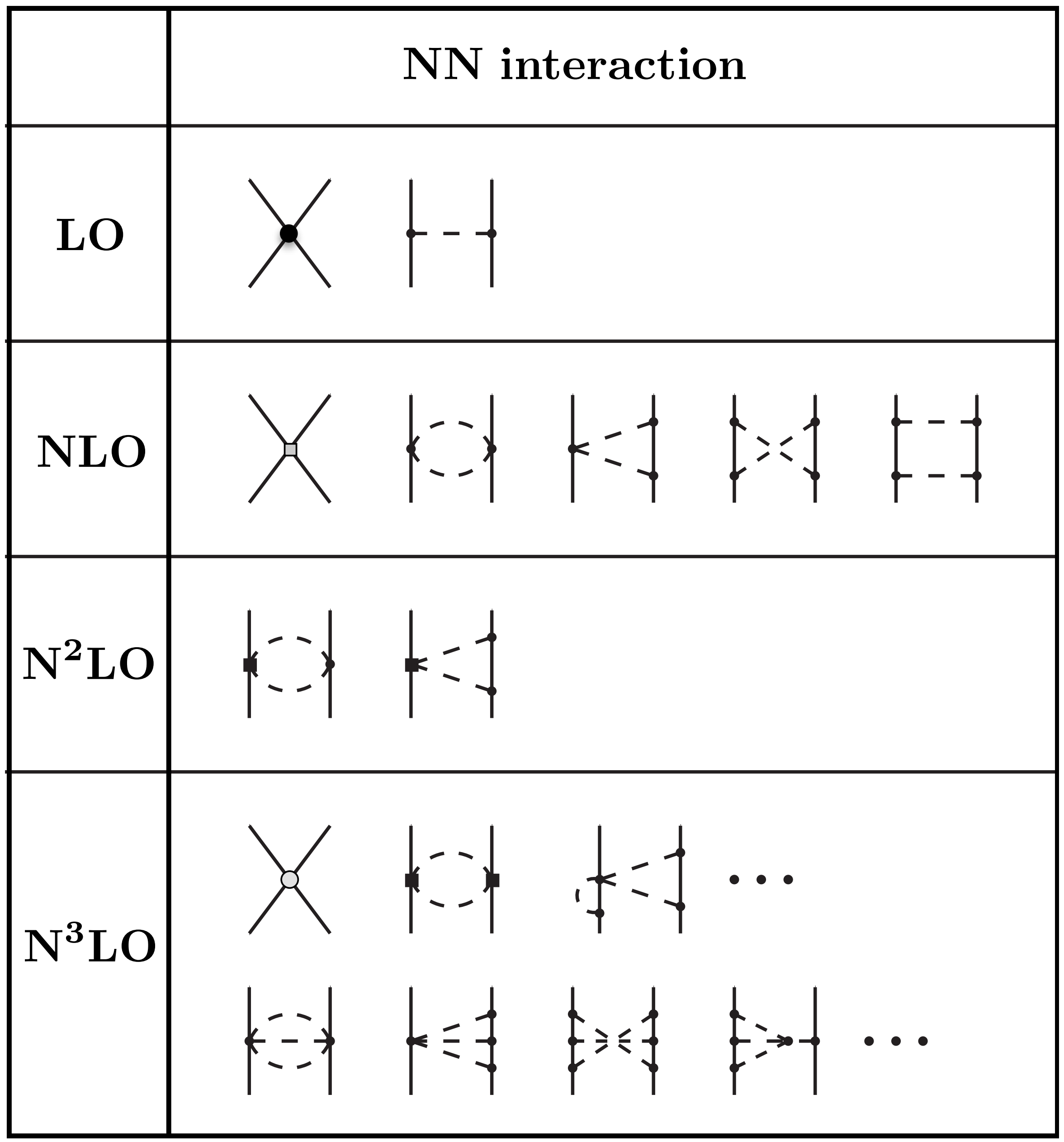
$\rho_B \sim 5\,\rho_0$

$d_{NN} \sim 1\ \mathrm{fm}$

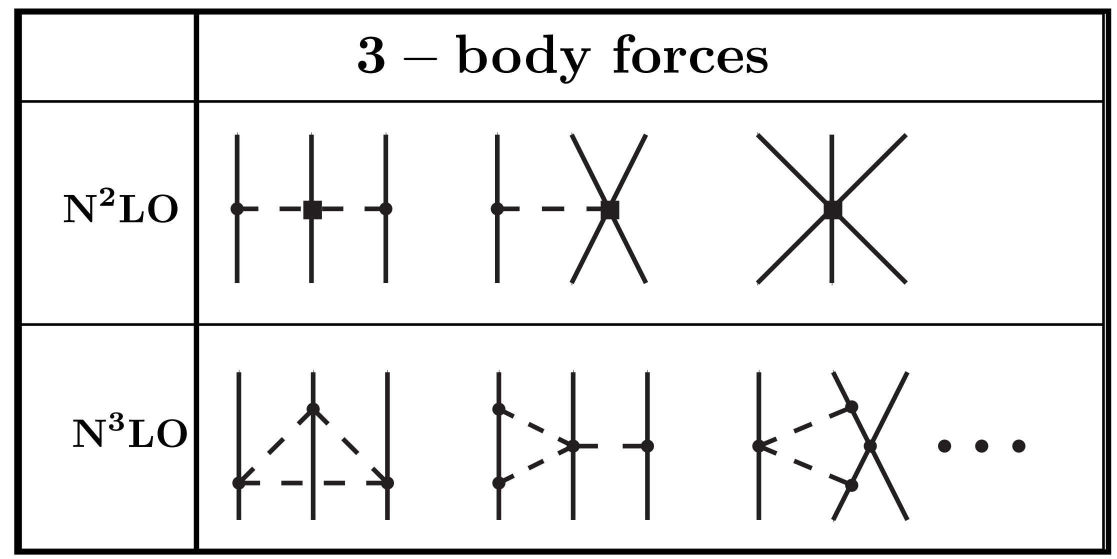
- (Multi-)pion fields in space between baryonic sources (ChEFT)
- Quark cores of nucleons overlap (percolate) at baryon densities $\rho_B > 5\,\rho_0$

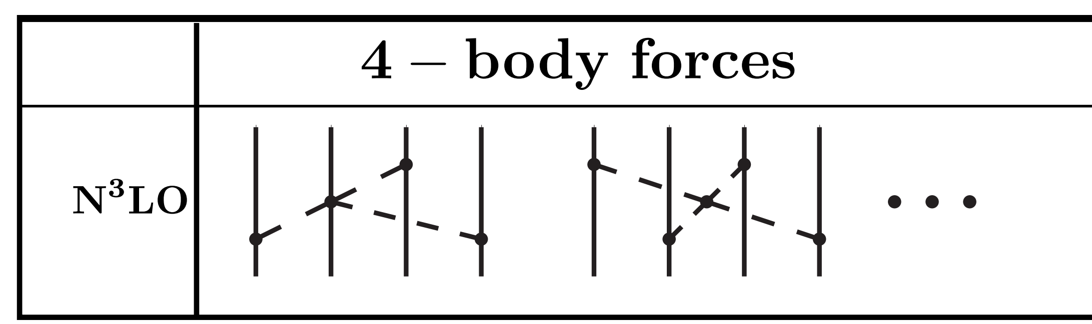
NUCLEON-NUCLEON INTERACTION from CHIRAL EFFECTIVE FIELD THEORY

Weinberg   Bedaque & van Kolck   Bernard, Epelbaum, Kaiser, Meißner ; . . .



- Systematically organized hierarchy in powers of $\frac{Q}{\Lambda}$
  (Q: momentum, energy, pion mass)



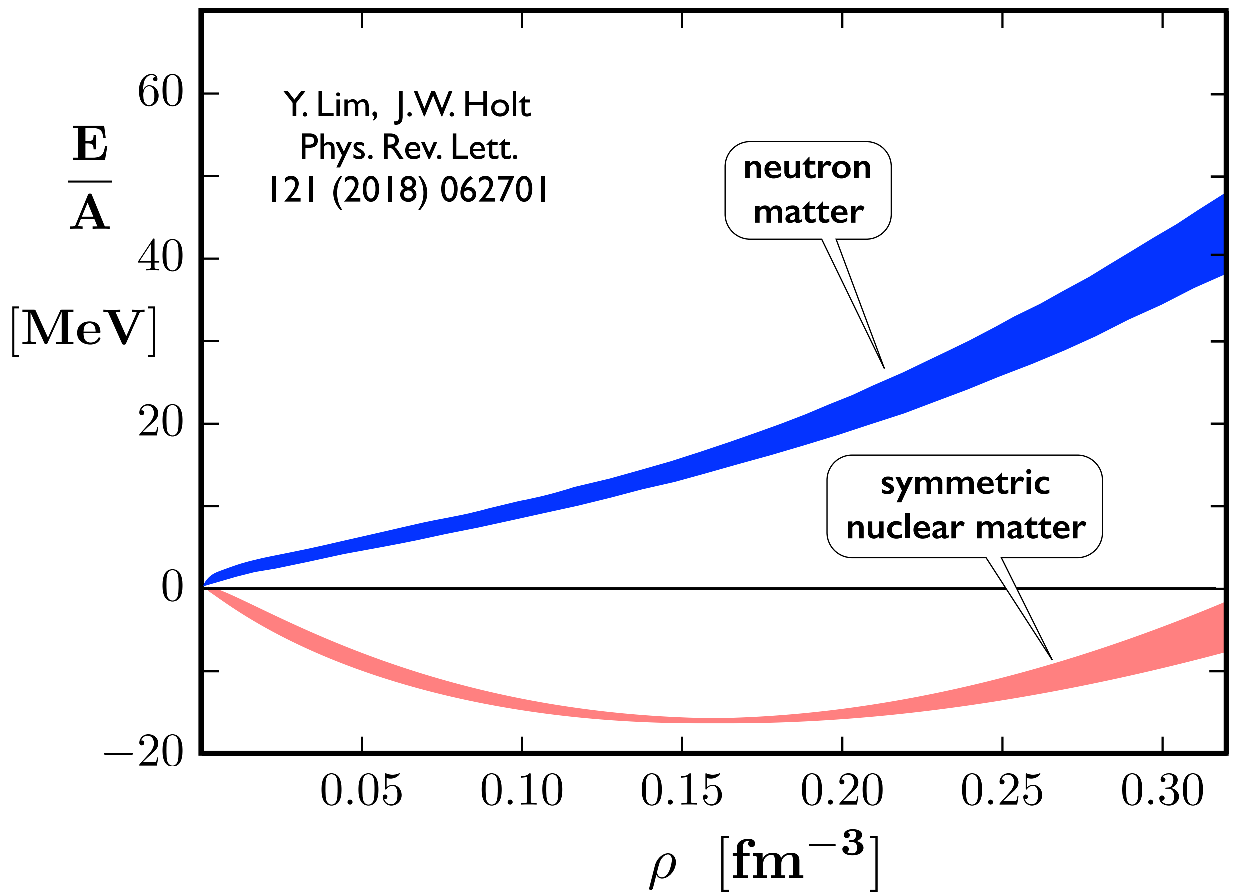


- NN interaction state-of-the-art: N^4LO plus convergence tests at N^5LO

NEUTRON and NUCLEAR MATTER from CHIRAL EFT

- N3LO chiral NN interactions + N2LO 3-body forces
- Many-body perturbation theory (3rd order)

J.W. Holt, N. Kaiser
Phys. Rev. C95 (2017) 034326



Perturbative Chiral EFT :

applicable up to baryon densities

$$\rho \sim 2\,\rho_0$$

- **Agreement with advanced many-body calculations**
  (e.g. Quantum Monte Carlo computations - S. Gandolfi et al.: EPJ A50 (2014) 10)

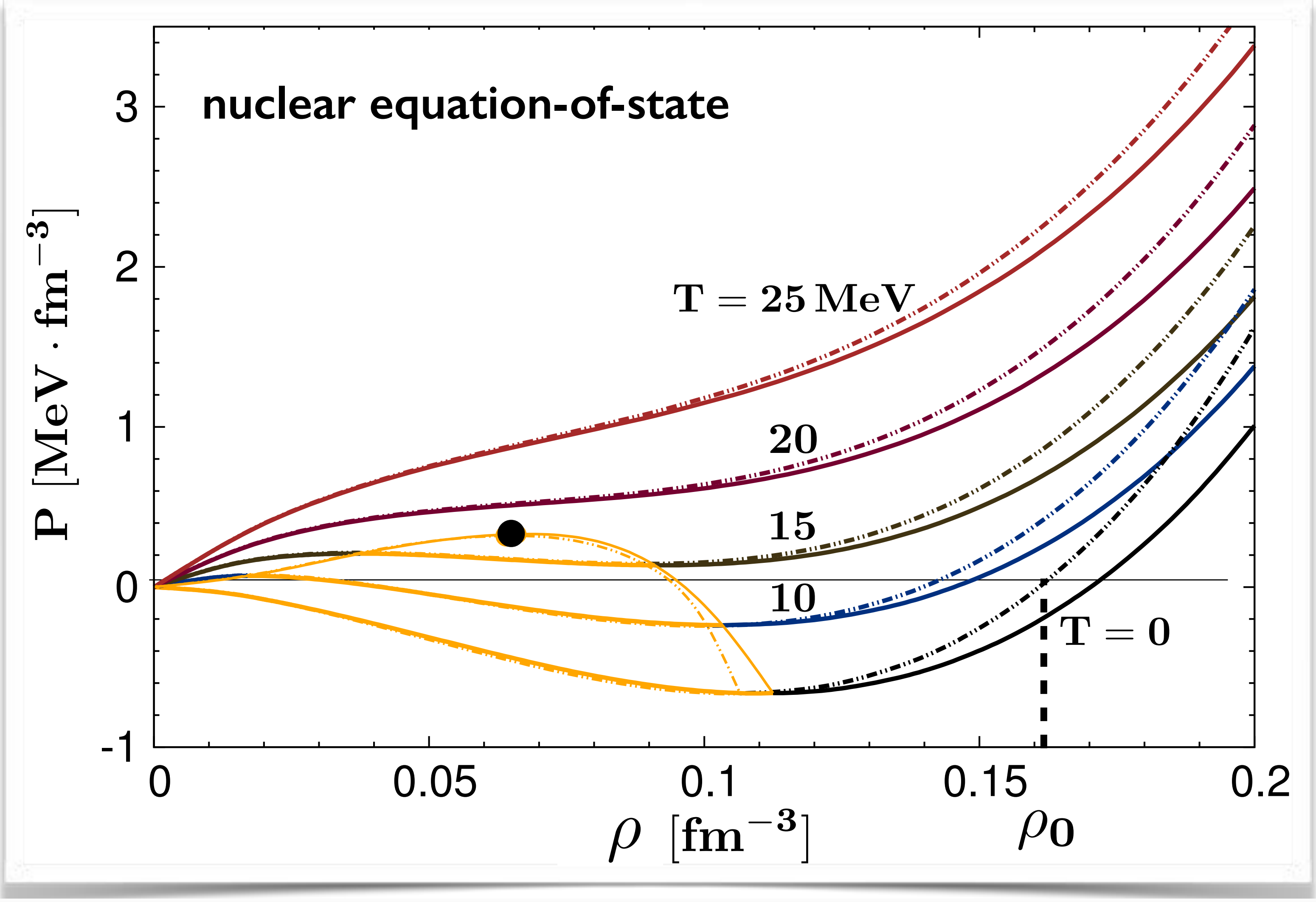
C. Wellenhofer, J.W. Holt, N. Kaiser, W.W.: Phys. Rev. C89 (2014) 064009, C92 (2015) 015801

- **Further recent developments: N4LO** F. Sammarruca et al.: arXiv:1807.06640

NUCLEAR THERMODYNAMICS from CHIRAL EFT

- Symmetric nuclear matter : 1st order **liquid-gas phase transition**
- N3LO chiral NN interactions + N2LO 3-body forces

C. Wellenhofer, J.W. Holt, N. Kaiser, W.W. Phys. Rev. C89 (2014) 064009 C92 (2015) 015801



Critical temperature of liquid-gas first-order transition :

$T_c = 17.4$ MeV

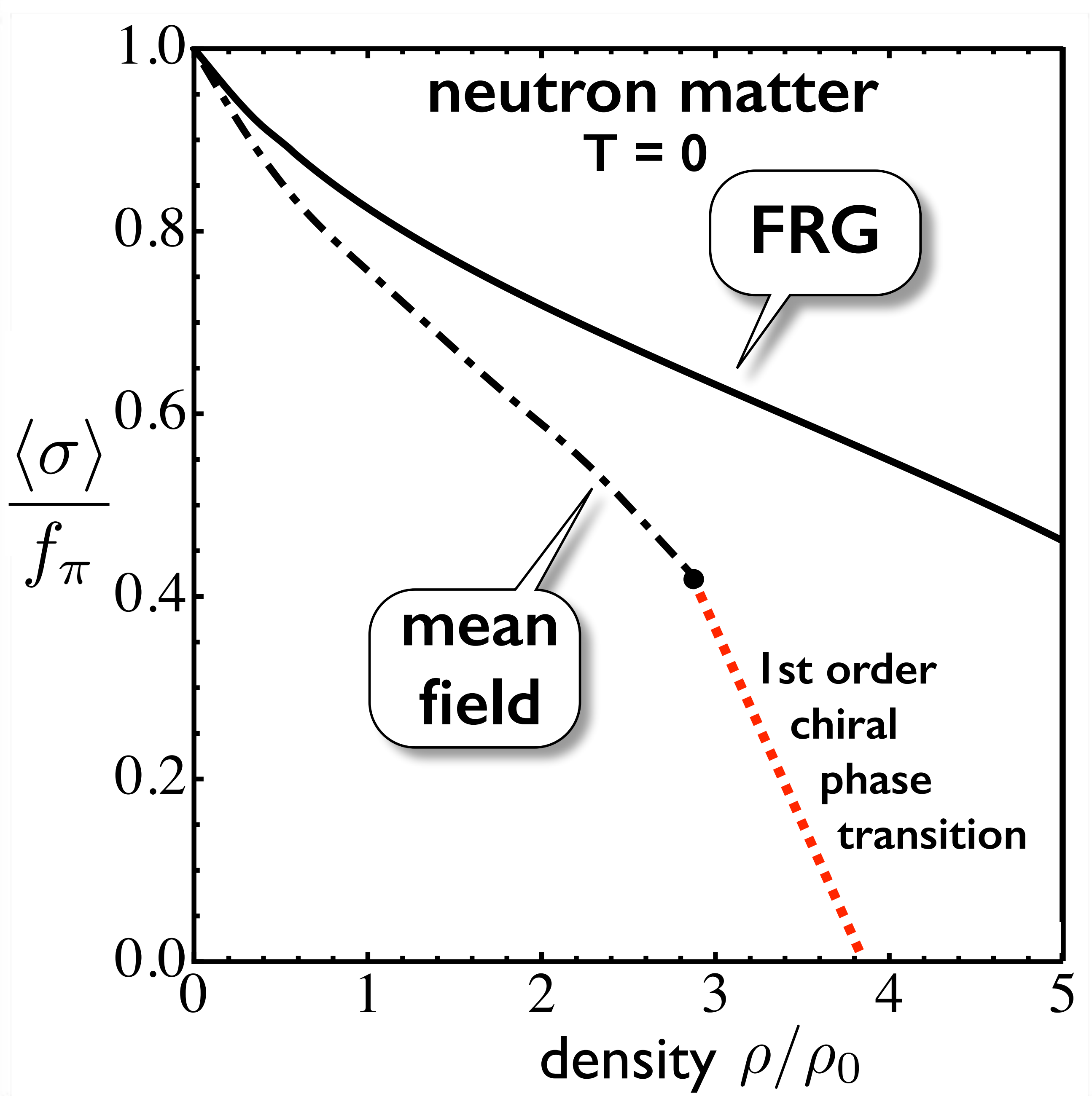
► **Empirical position of liquid-gas critical point :** J. B. Elliot et al. : Phys. Rev. C87 (2013) 054622

$\mathrm{T_c} = 17.9 \pm 0.4$ MeV $\mathrm{P_c} = 0.31 \pm 0.07\ \mathrm{MeV \cdot fm^{-3}}$ $\rho_c = 0.06 \pm 0.01\ \mathrm{fm^{-3}}$

CHIRAL ORDER PARAMETER in NEUTRON MATTER

- **Chiral Nucleon-Meson Field Theory** and **F**unctional **R**enormalization **G**roup

M. Drews, W.W. Phys. Rev. C91 (2015) 035802 Prog. Part. Nucl. Phys. 93 (2017) 69



- **Chiral order parameter :**

sigma field

↕

in-medium pion decay constant

$$\langle\sigma\rangle_\rho = f_\pi^*(\rho)$$

Important role of **fluctuations** beyond mean-field approximation:

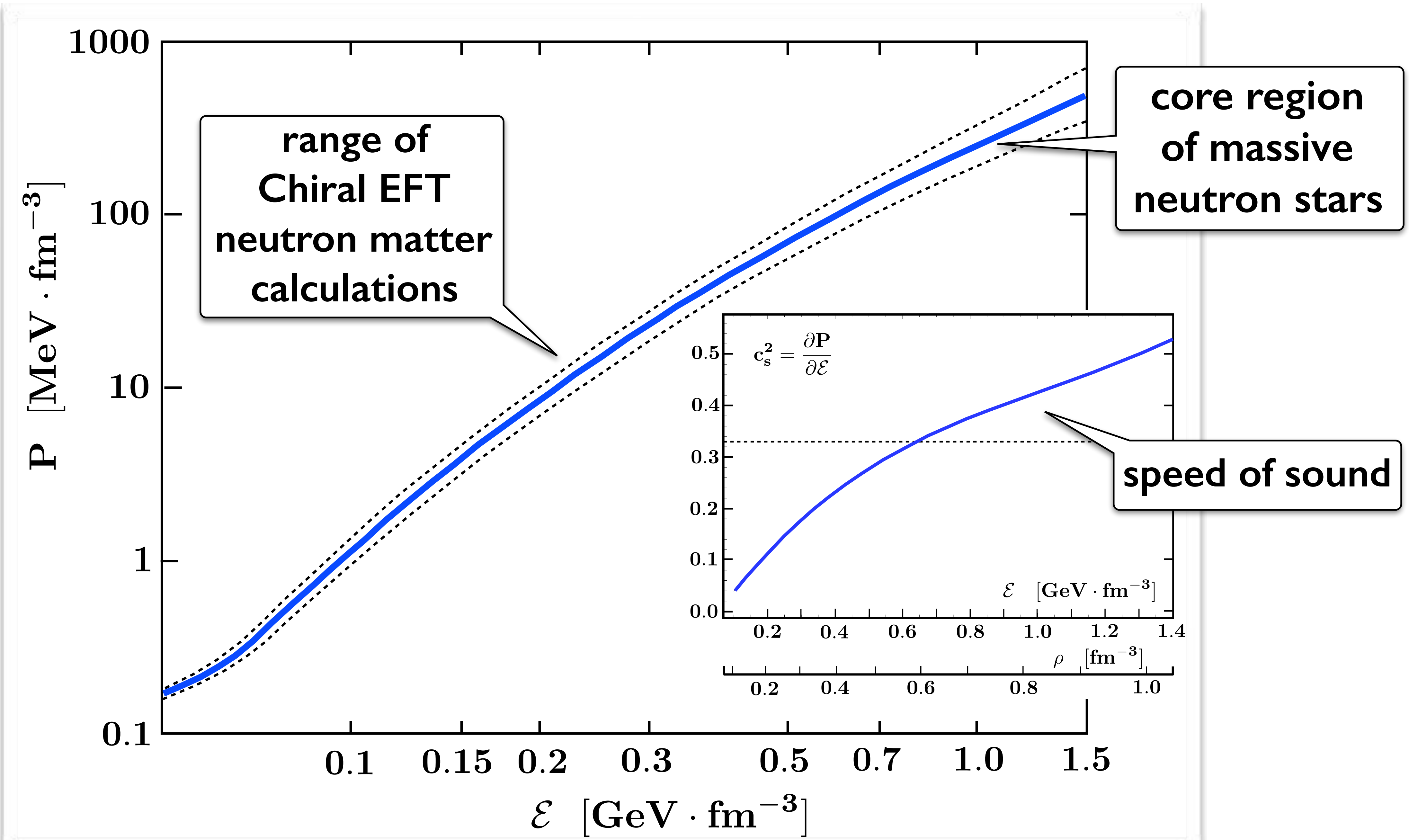
pionic & **nucleon-hole** excitations
many-body correlations
Pauli effects

DISAPPEARANCE
of first-order
chiral phase transition

NEUTRON STAR MATTER
Equation of State

- Chiral Nucleon-Meson Field Theory
- **FRG** calculations with inclusion of beta equilibrium

M. Drews, W.W. Phys. Rev. C91(2015) 035802 Prog. Part. Nucl. Phys. 93 (2017) 69

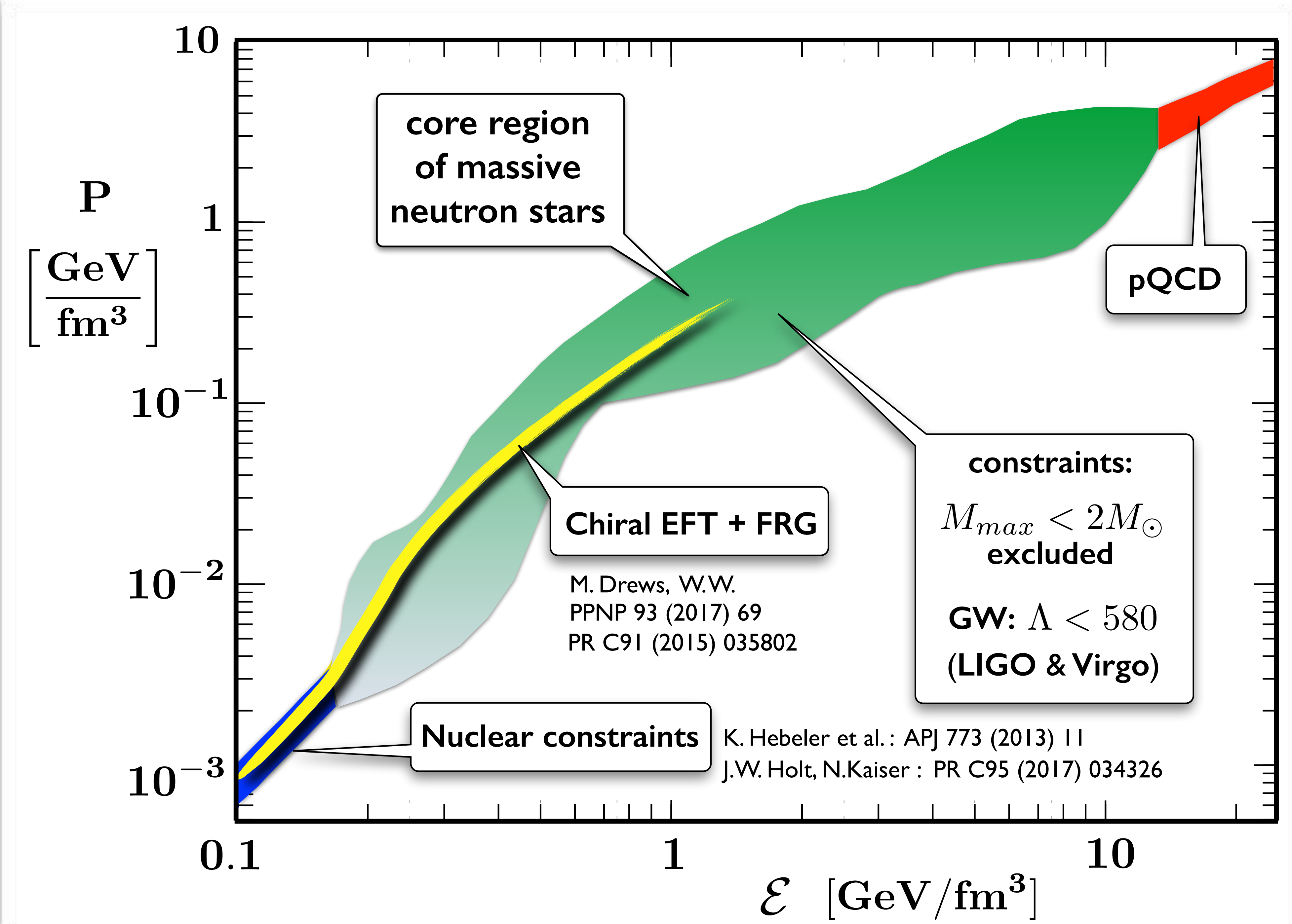


NEUTRON STAR MATTER Equation of State

- incl. updated **GW constraints** and extrapolation to **pQCD limit**

A. Kurkela et al. : Astroph. J. 789 (2014) 127 A. Annala et al. : PRL 120 (2018) 172703

A. Vuorinen : arXiv:1807.04480



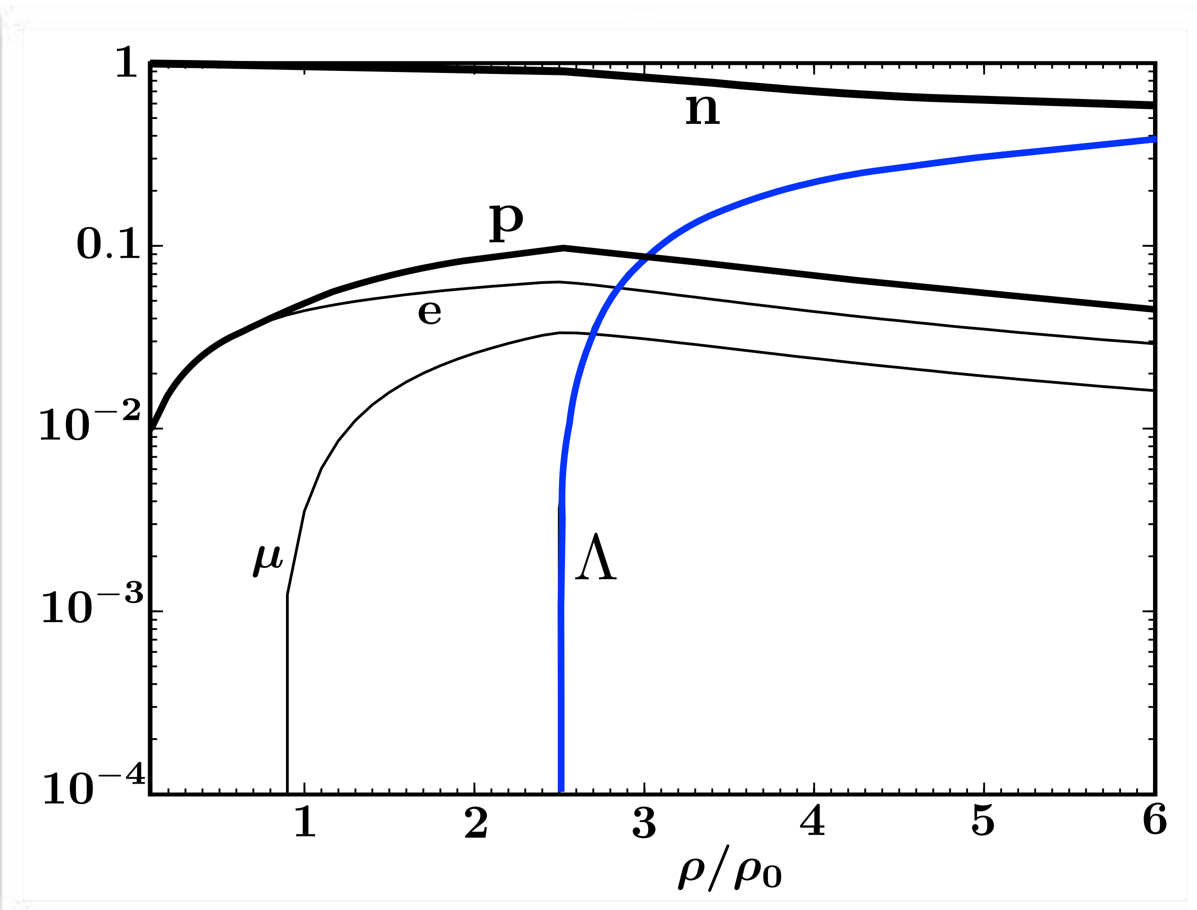
Part 2.

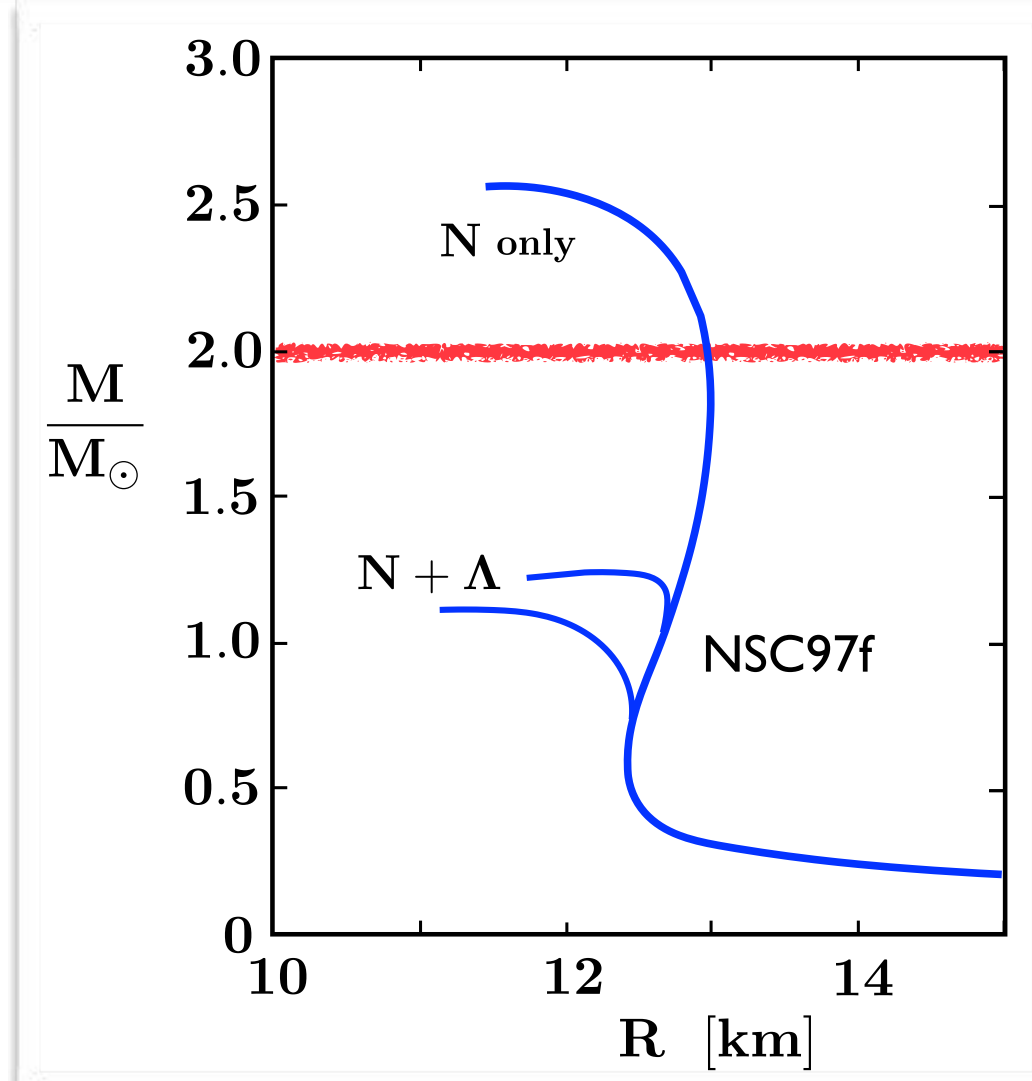
The Hyperon Puzzle:
Strangeness in Neutron Stars ?

- **Chiral SU(3) Effective Field Theory**
  and
  Hyperon-Nuclear Interactions
- **Two- and Three-Body Forces**

NEUTRON STAR MATTER including HYPERONS

H. Djapo, B.-J. Schaefer, J. Wambach
Phys. Rev. C81 (2010) 035803





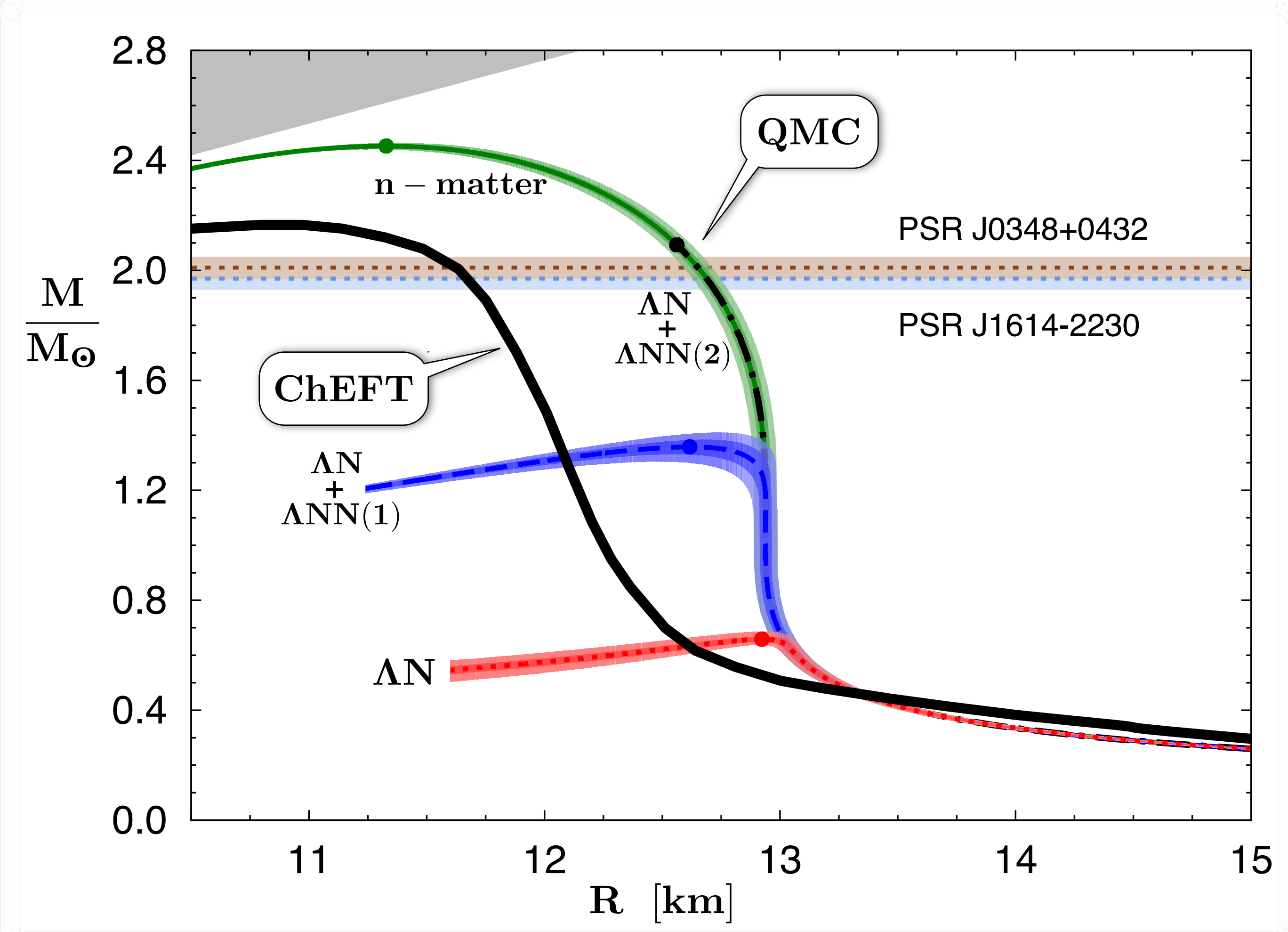
- Adding hyperons ⟶ Equation of State far too soft
"Hyperon Puzzle"

NEUTRON STAR MATTER including HYPERONS

Quantum Monte Carlo **calculations** using phenomenological hyperon-nucleon and hyperon-NN **three-body** interactions constrained by **hypernuclei**

ChEFT calculations "conventional" n-star matter

T. Hell, W.W.
PRC90 (2014) 045801



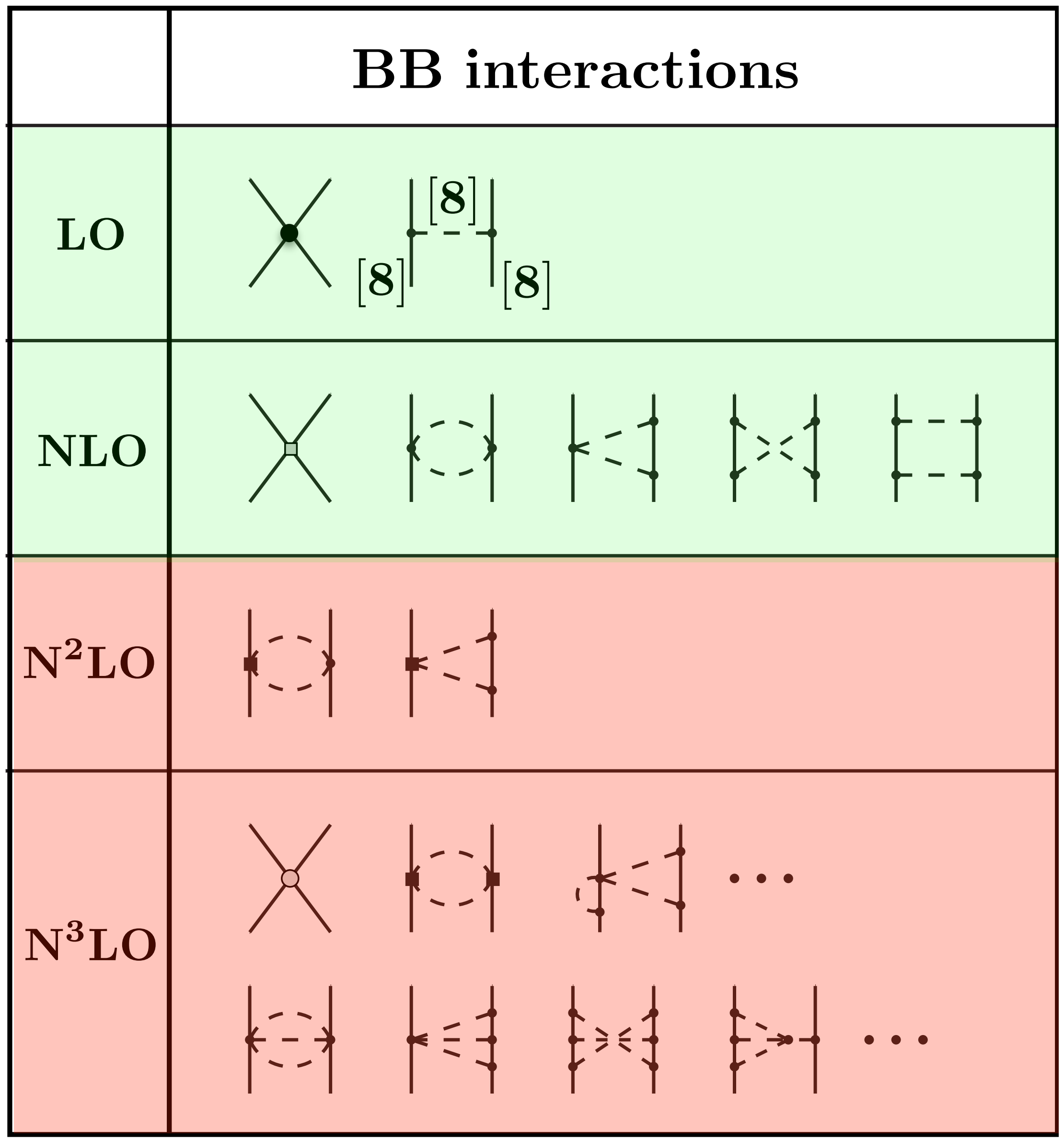
QMC computations (hyper-neutron matter):

D. Lonardoni,
A. Lovato,
S. Gandolfi,
F. Pederiva

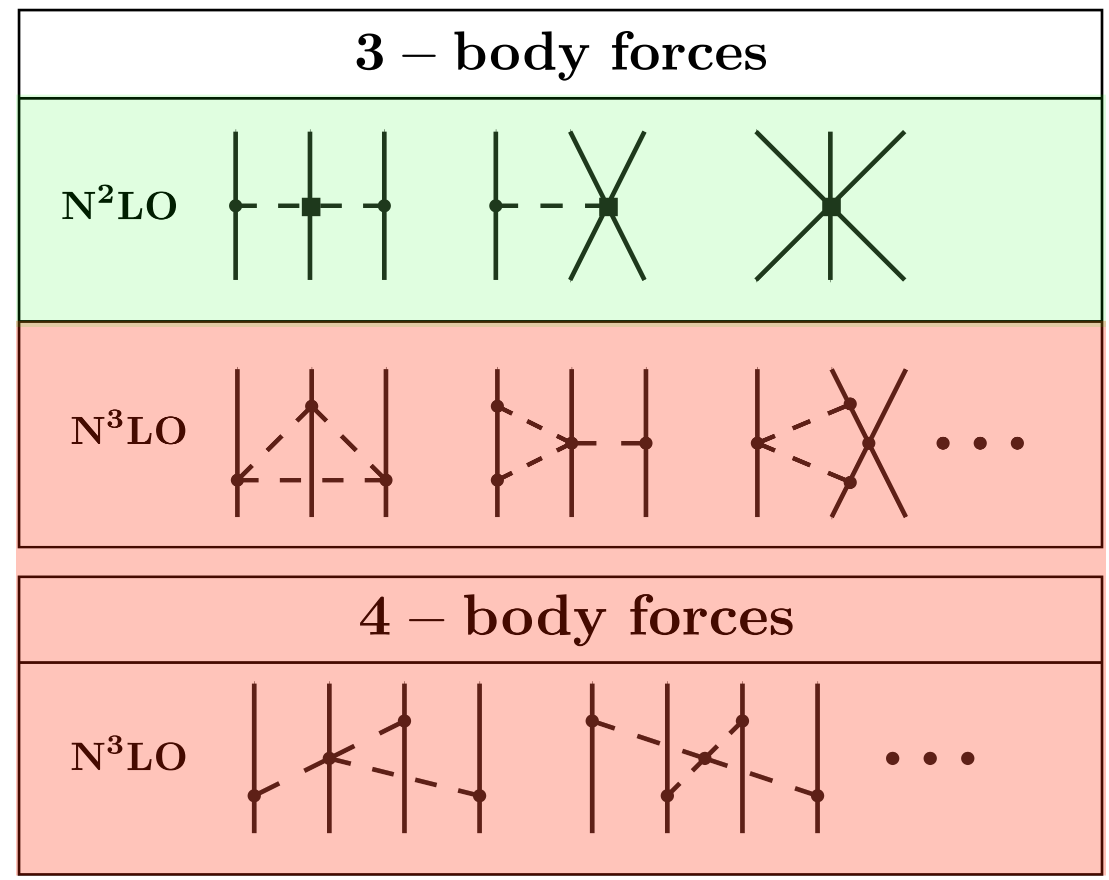
Phys. Rev. Lett.
114 (2015) 092301

Inclusion of **hyperons**: EoS **too soft** to support 2-solar-mass n-stars unless: **strong repulsion** in **YN** and **YNN** … interactions

BARYON-BARYON INTERACTIONS from CHIRAL SU(3) EFFECTIVE FIELD THEORY



- Systematically organized hierarchy in powers of $\frac{Q}{\Lambda}$
  (Q: momentum, energy, pion mass)



- **NN interaction :** has reached $\mathrm{N^4LO}$ level
- **YN interaction :** so far very limited empirical data base
  ⟶ **restriction** to NLO plus **YNN three-body forces**

Chiral SU(3) Effective Field Theory and Hyperon-Nucleon Interactions

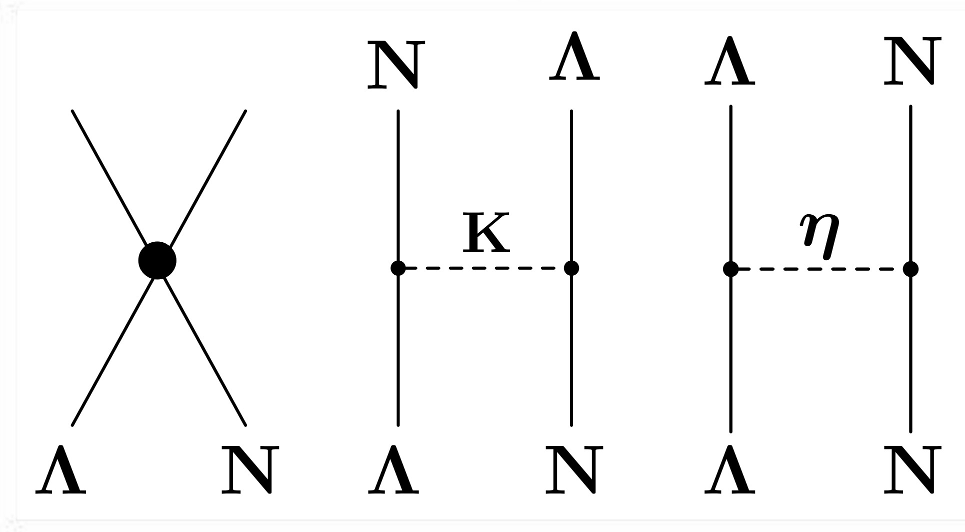
J. Haidenbauer, S. Petschauer, N. Kaiser, U.-G. Meißner, A. Nogga, W.W.: Nucl. Phys. A 915 (2013) 24

Example:

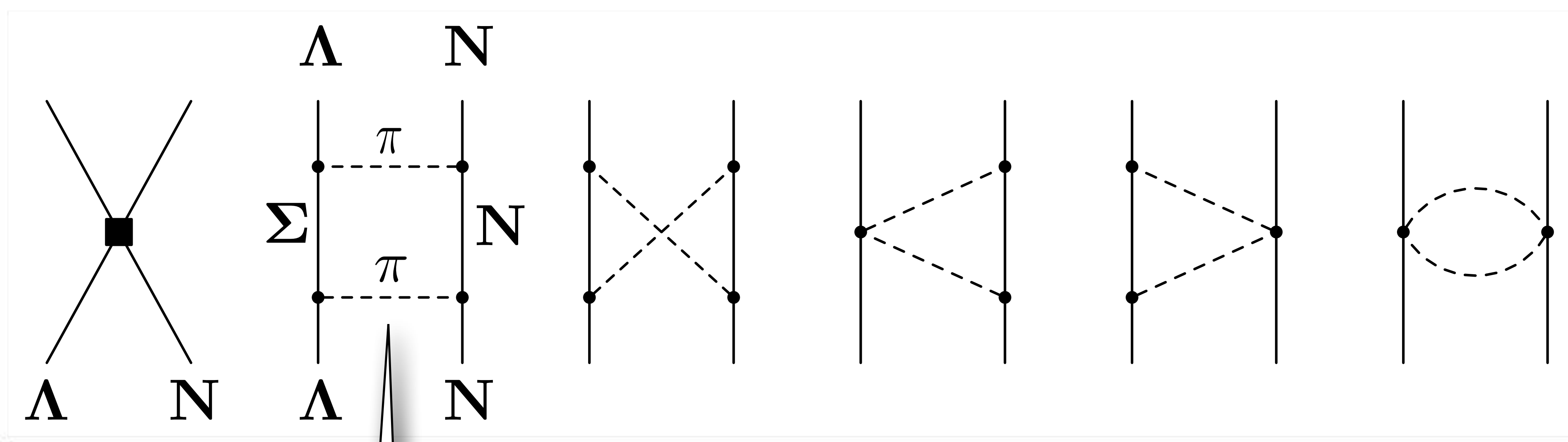
Λ N

interaction

- **Leading order (LO)**

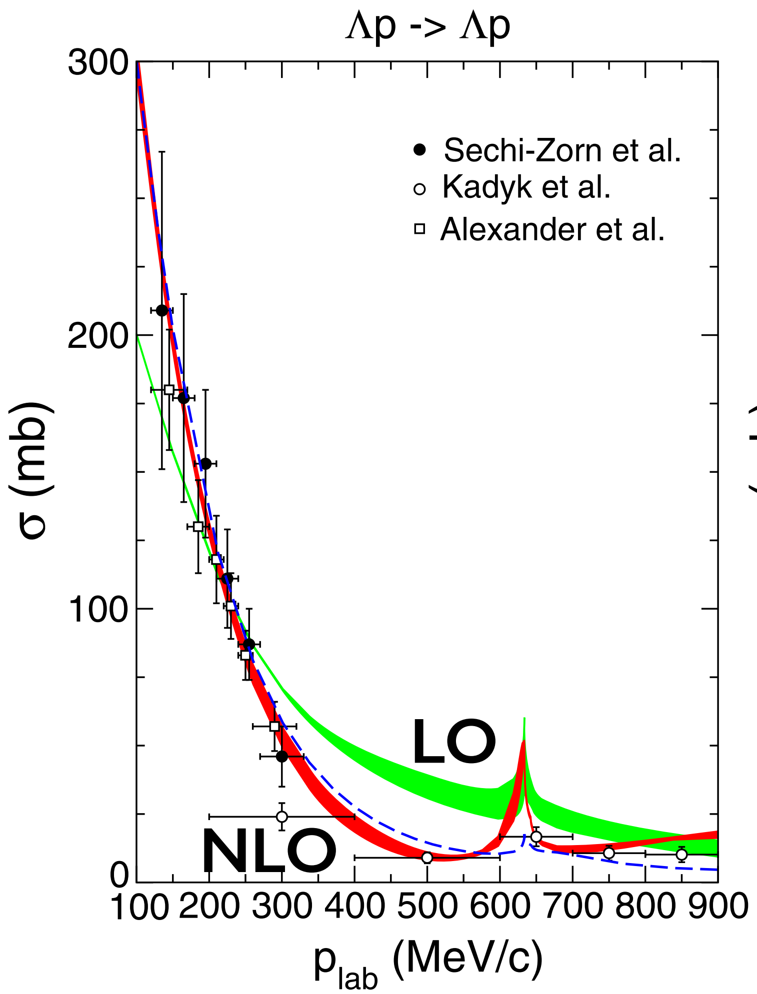


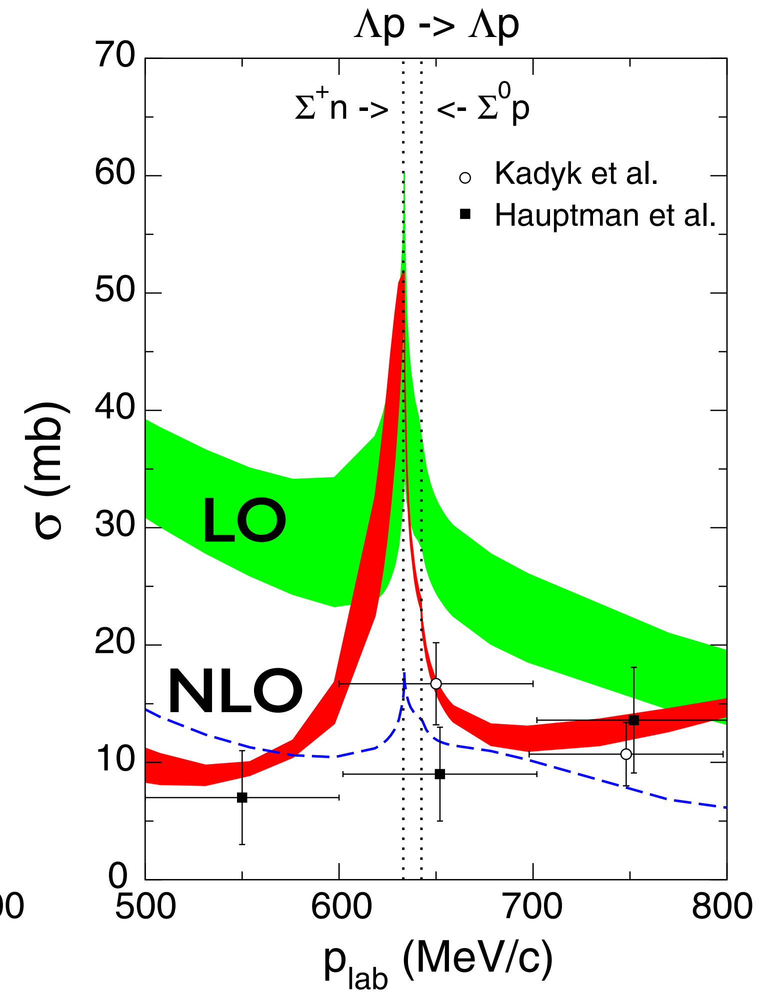
- **Next-to-leading order (NLO)**



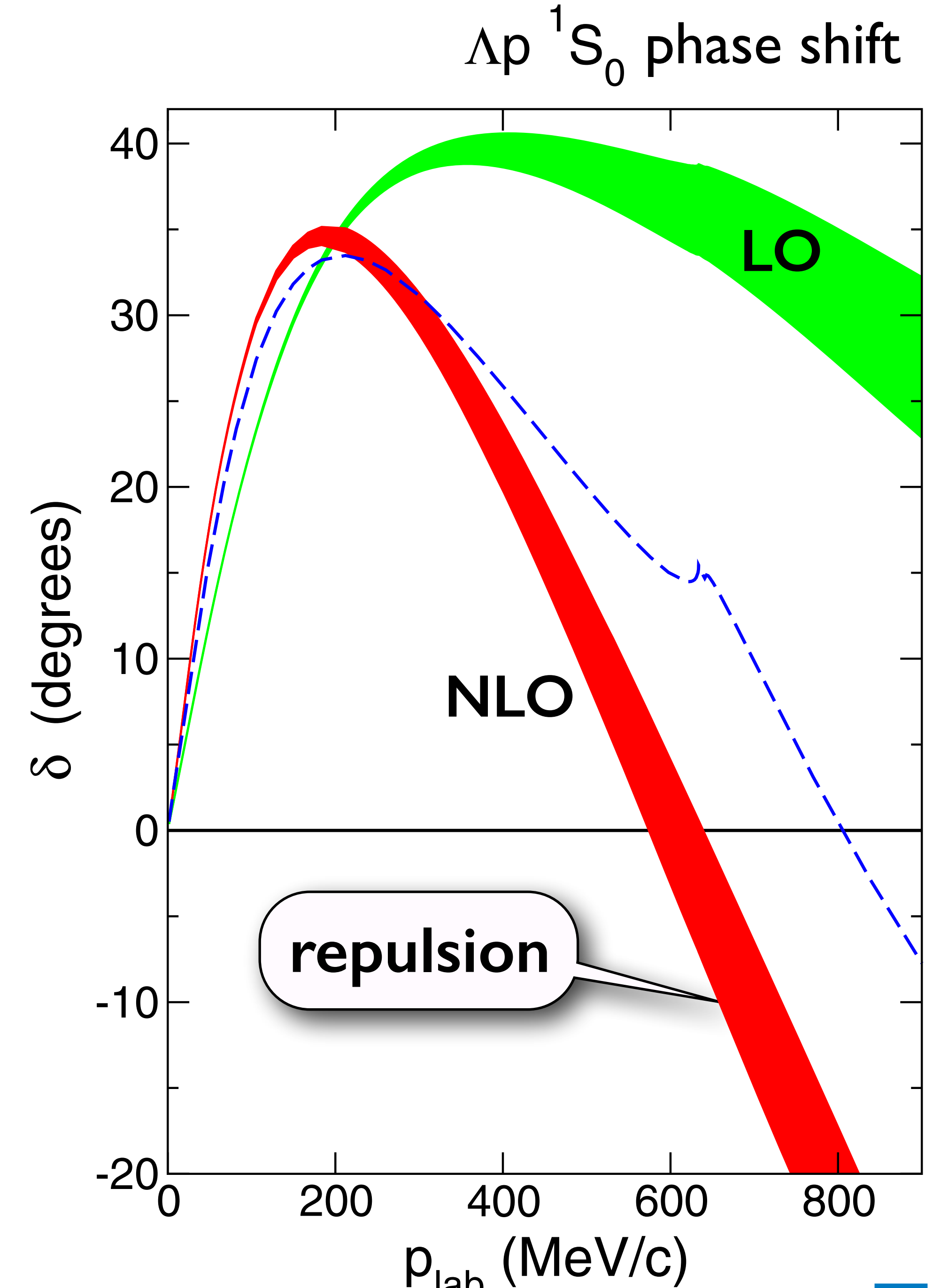
2nd order tensor force

Hyperon - Nucleon Interaction
from Chiral SU(3) EFT





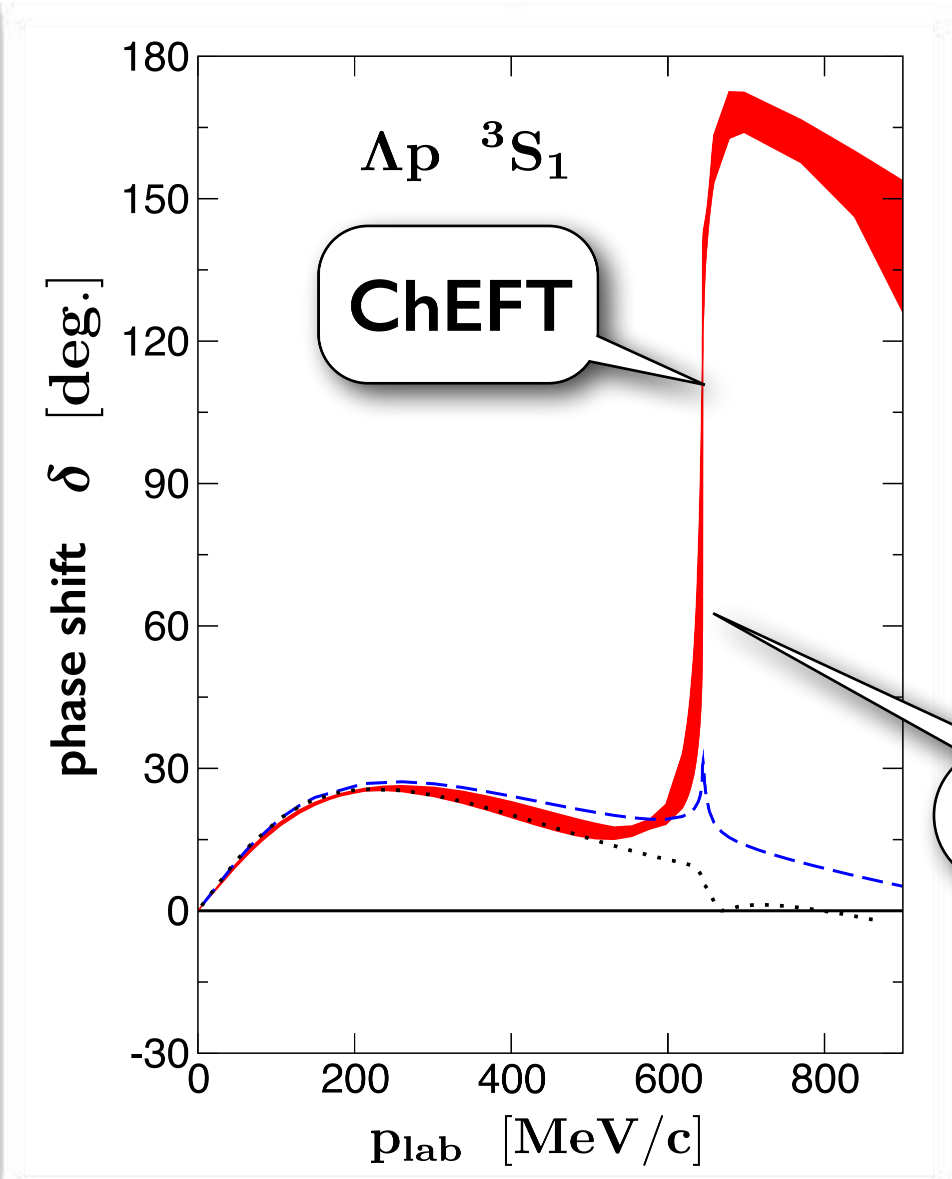
J. Haidenbauer, S. Petschauer, N. Kaiser, U.-G. Meißner, A. Nogga, W.W.
Nucl. Phys. A 915 (2013) 24

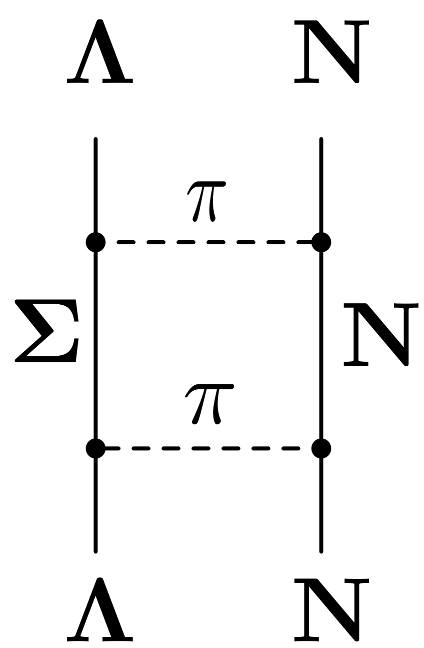


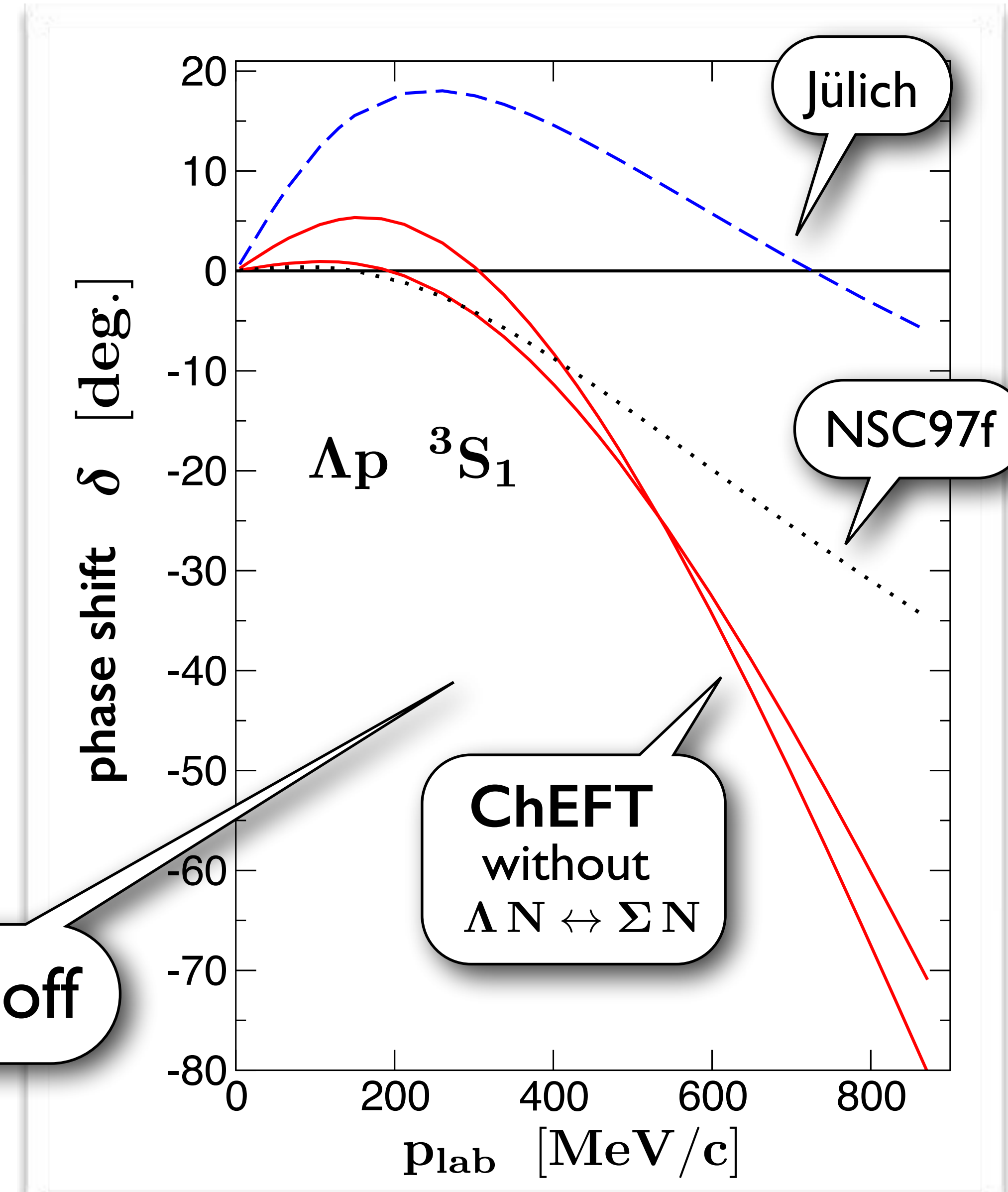
- **moderate attraction** at **low momenta**
  → relevant for **hypernuclei**
- **strong repulsion** at **higher momenta**
  → relevant for **dense baryonic matter**

Hyperon - Nucleon Interaction (contd.)

- Triplet-S channel and $\Lambda N \leftrightarrow \Sigma N$ **coupling** (2nd order **tensor force**)







- In-medium (Pauli) **suppression of** $\Lambda N \leftrightarrow \Sigma N$ **coupling : increasing repulsion with rising density**

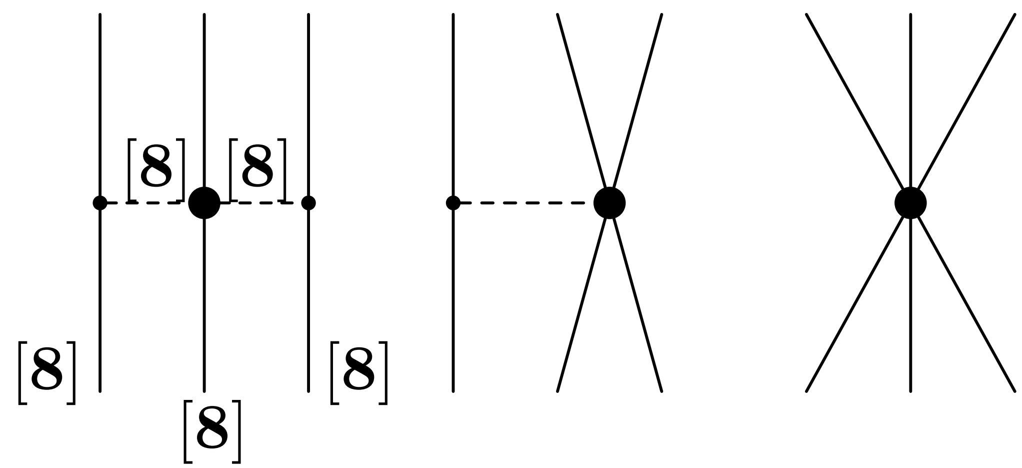
HYPERON - NUCLEON - NUCLEON THREE-BODY FORCES from CHIRAL SU(3) EFT

S. Petschauer et al. Phys. Rev. C93 (2016) 014001

- **Chiral SU(3) Effective Field Theory:**
  interacting pseudoscalar meson & baryon octets + contact terms

3-baryon sector:

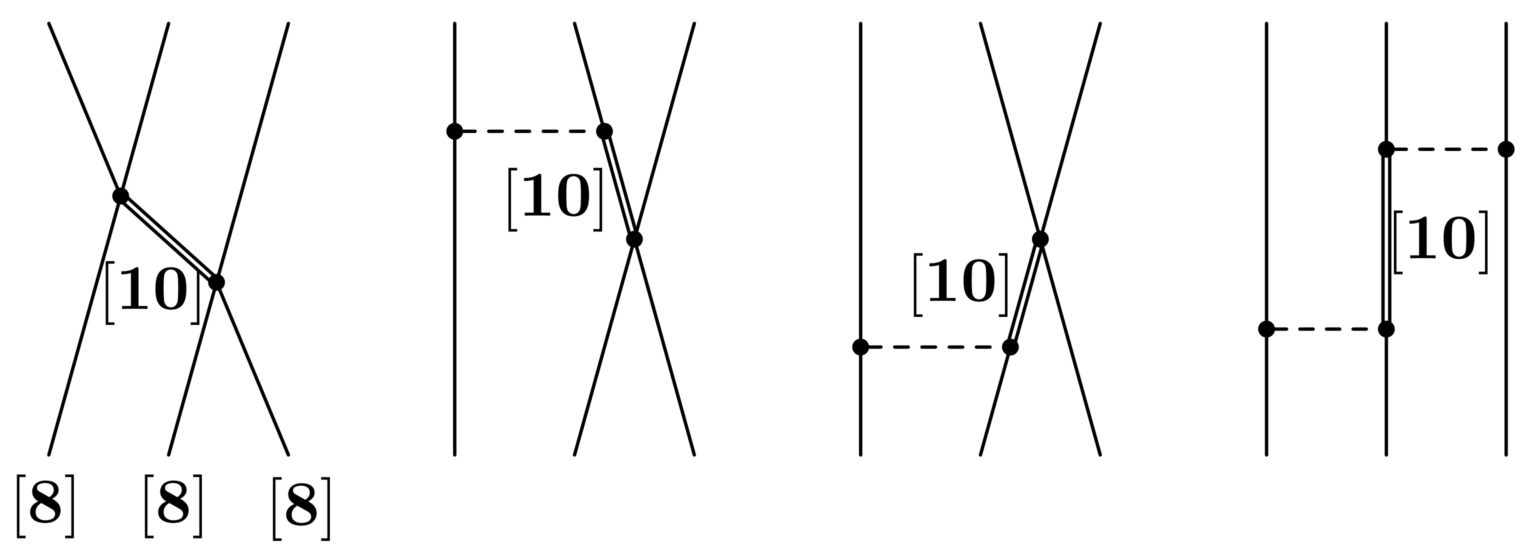
NNLO:



- Chiral SU(3) Effective Field Theory with **explicit decuplet baryons**:

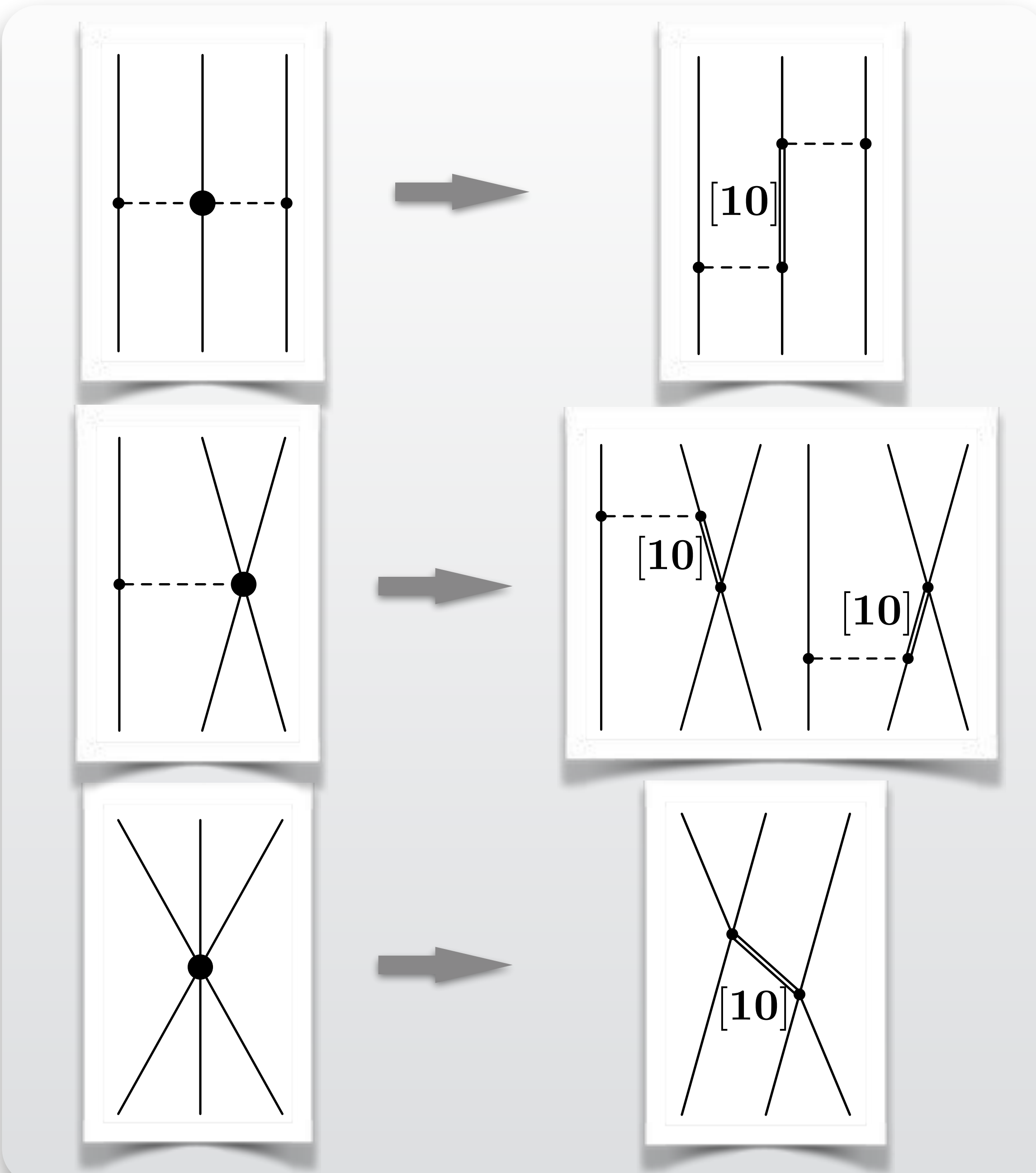
explicit treatment of **baryon decuplet** :

promotion to **NLO**

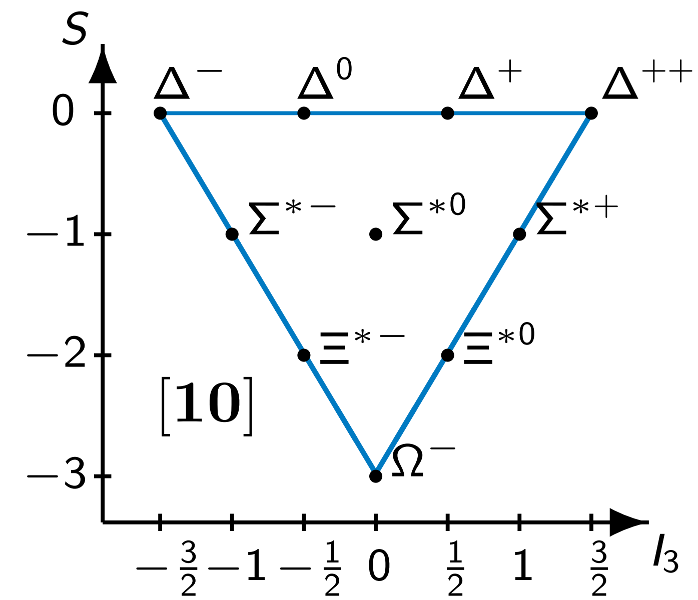


Decuplet Dominance
in YNN three-body forces

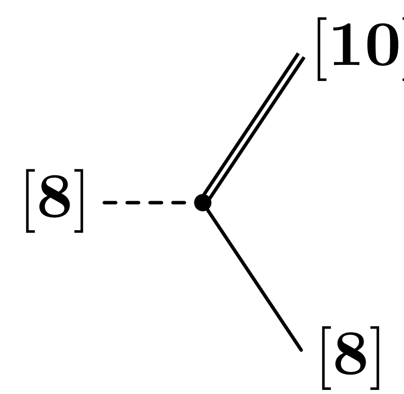
- Estimates of **YNN** 3-body interactions assuming dominant **decuplet** (Σ^*, Δ) intermediate states



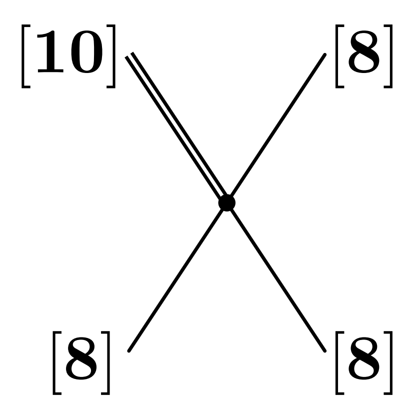
promotion from **NNLO** to **NLO**



- … much reduced set of parameters - **Basic vertices :**



One constant
$(C = \frac{3}{4} g_A \approx 1 \text{ from } \Delta \to N\pi)$

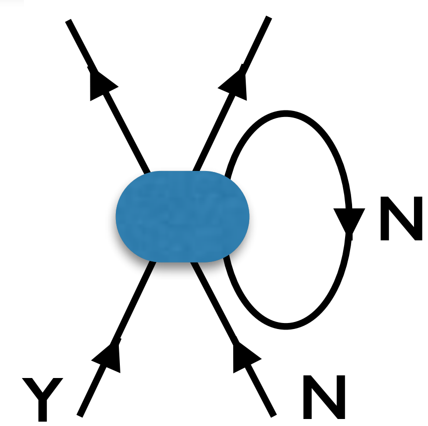


Pauli-forbidden in NN sector

Two constants
$(\mathbf{H_1},\ \mathbf{H_2})$
(Typical magnitude $|\mathbf{H_i}| \sim \mathbf{f_\pi^{-2}}$)

Density-dependent EFFECTIVE HYPERON - NUCLEON INTERACTION from CHIRAL THREE-BARYON FORCES

S. Petschauer, J. Haidenbauer, N. Kaiser, U.-G. Meißner, W.W. Nucl. Phys. A957 (2017) 347



$$V_{12}^{\textbf{eff}} = \sum_B \mathrm{tr}_{\sigma_3} \int_{|\vec{k}| \leq k_f^B} \frac{\mathrm{d}^3 k}{(2\pi)^3} V_{123}$$

- Example: **Λ-neutron** density-dependent effective interaction in a nuclear medium (protons + neutrons)

$$V_{\Lambda n}^{\textbf{eff},\pi\pi} = \frac{C^2 g_A^2}{2 f^4\, \Delta} [\rho_n + 2\rho_p] + \mathcal{F}(k_F^p, k_F^n; p, q) \qquad \textbf{repulsive}$$

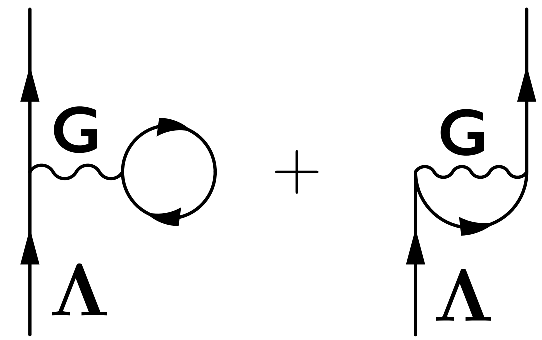
$$V_{\Lambda n}^{\textbf{eff},\pi} = \frac{C H\, g_A}{9 f^2\, \Delta} [\rho_n + 2\rho_p] + \mathcal{G}(k_F^p, k_F^n; p, q) \qquad \textbf{+/-}$$

$$V_{\Lambda n}^{\textbf{eff},ct} = \frac{H^2}{18\Delta} [\rho_n + 2\rho_p] \qquad (H = H_1 + 3H_2) \qquad \textbf{repulsive}$$

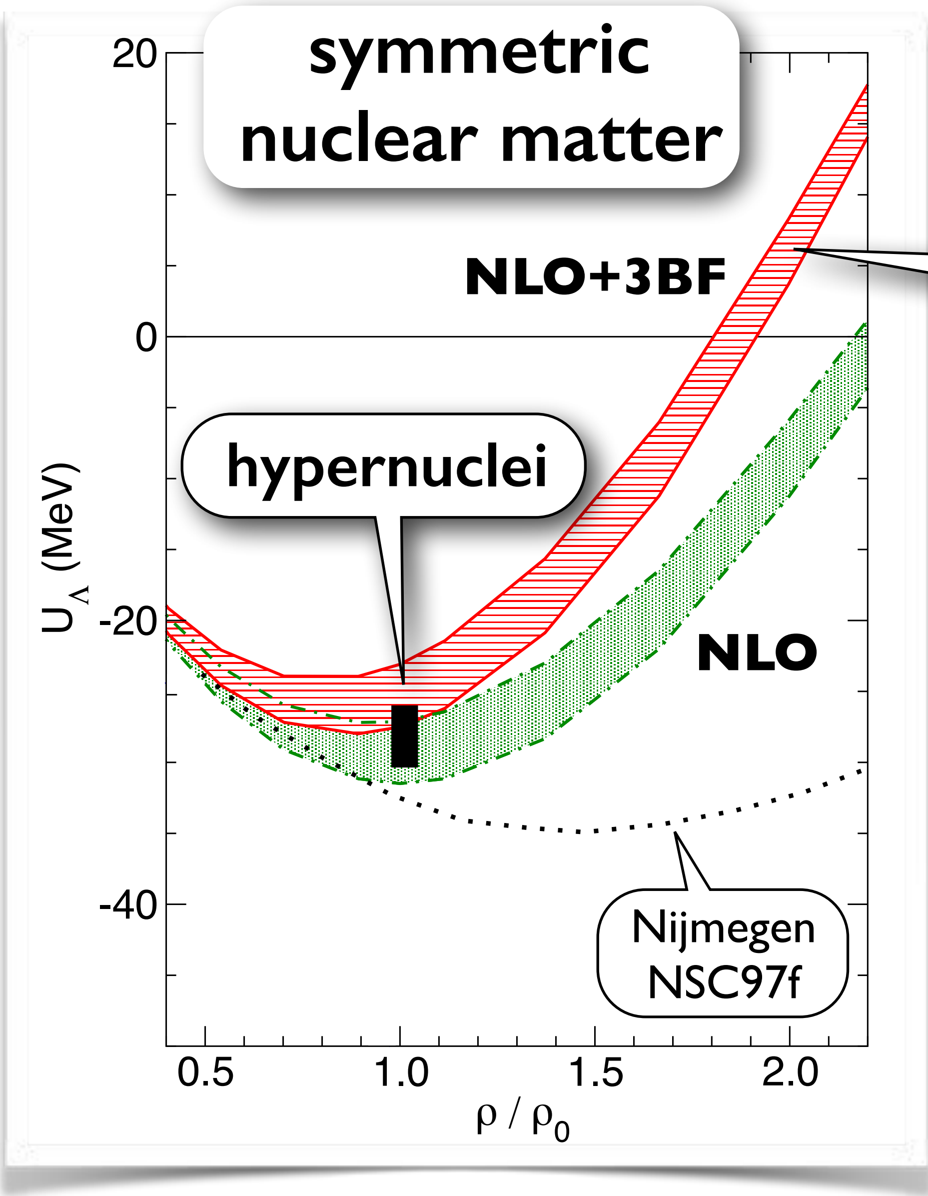
- **Decuplet-octet mass difference** $\Delta = M_{[10]} - M_{[8]} = 270\, MeV$
- **Coupling parameters :** $C = \frac{3}{4} g_A \simeq 1 \qquad -\frac{1}{f^2} \lesssim H \lesssim +\frac{1}{f^2}$ (dim. arguments natural size)

Density dependence of Λ single particle potential

- **Brueckner calculations**
  using
  chiral SU(3) interactions



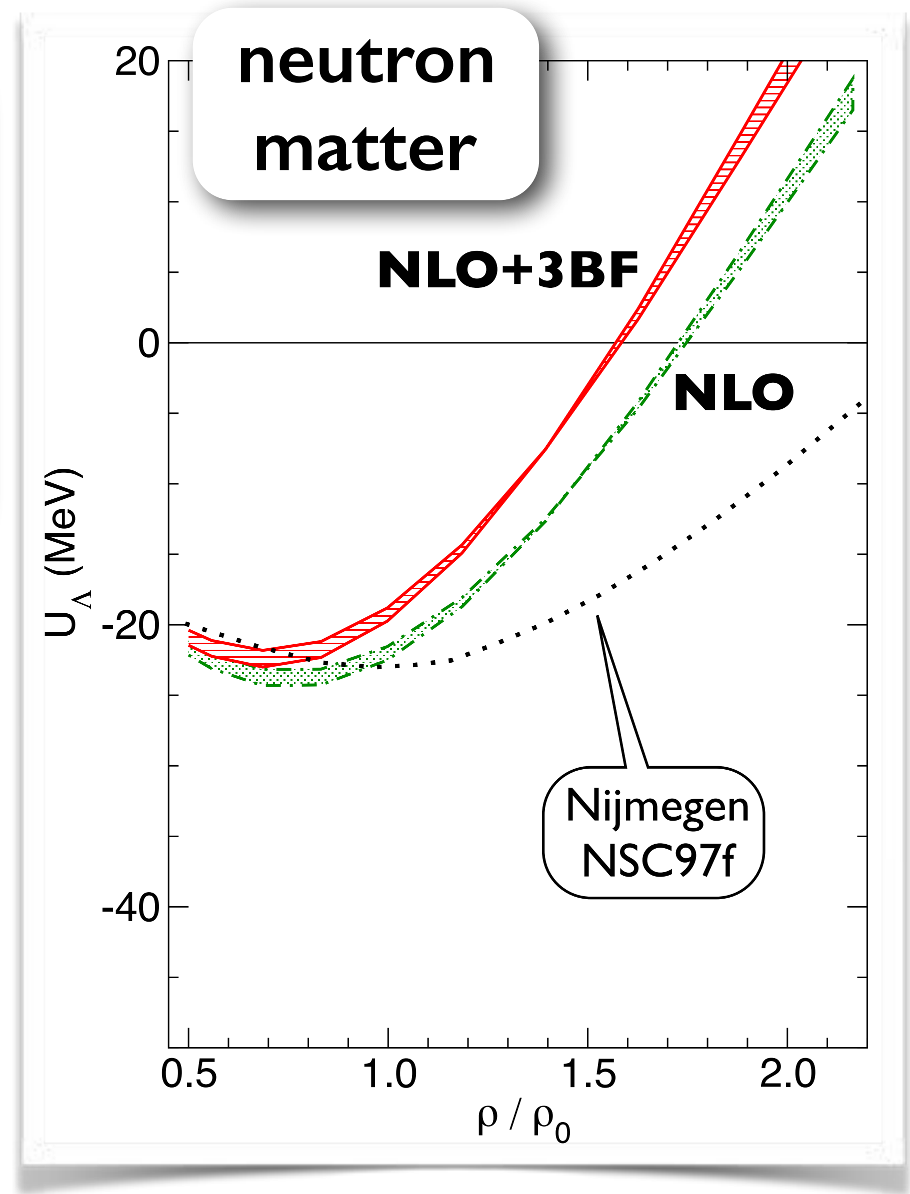
$$\mathbf{G}(\omega) = \mathbf{V} + \mathbf{V}\,\frac{\mathbf{Q}}{\mathbf{e}(\omega) + \mathbf{i}\epsilon}\,\mathbf{G}(\omega)$$



Chiral SU(3) 2- and 3-body forces $\left(H = -\frac{1}{f^2}\right)$

J. Haidenbauer, U.-G. Meißner, N. Kaiser, W.W.

Eur. Phys. J. A53 (2017) 121

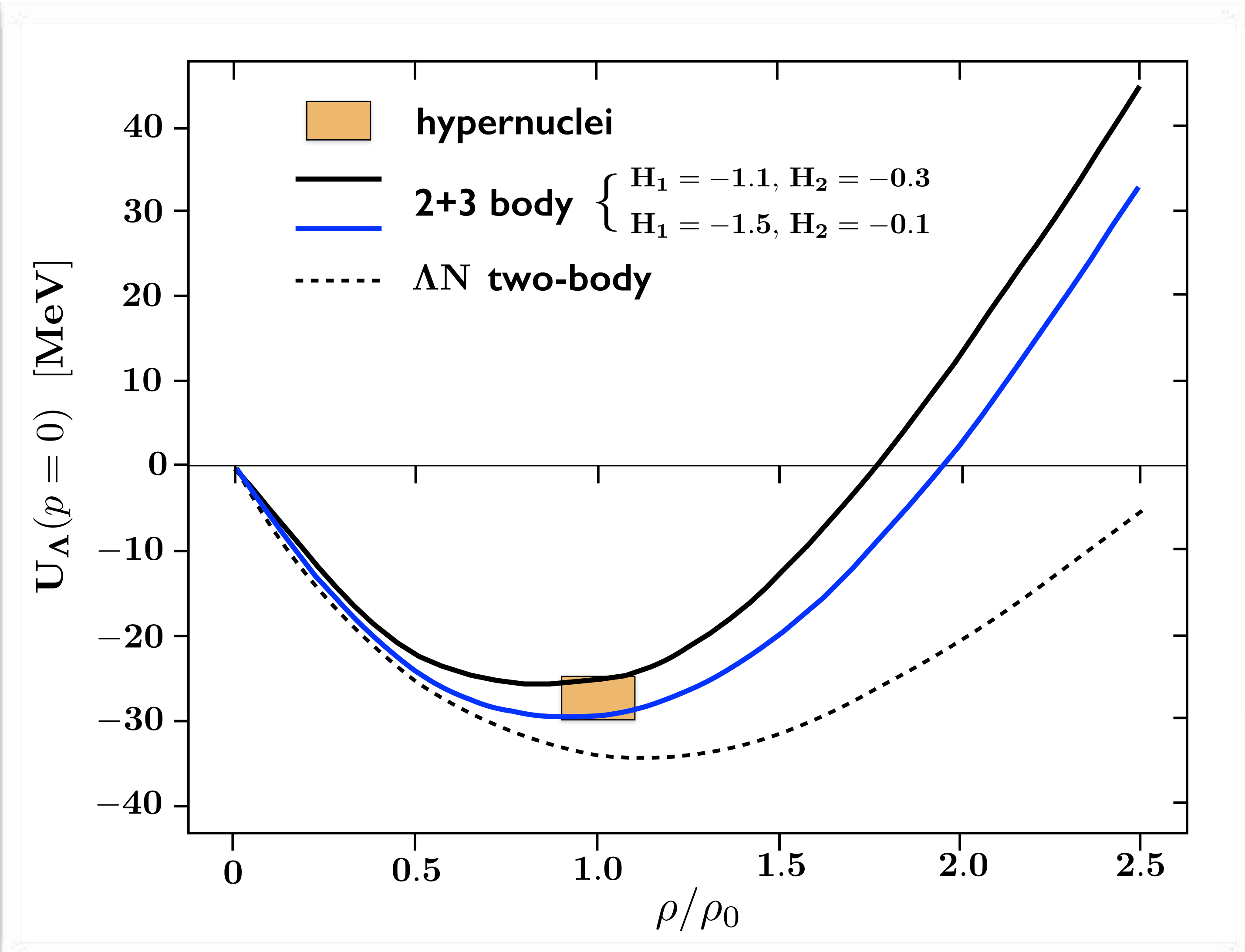


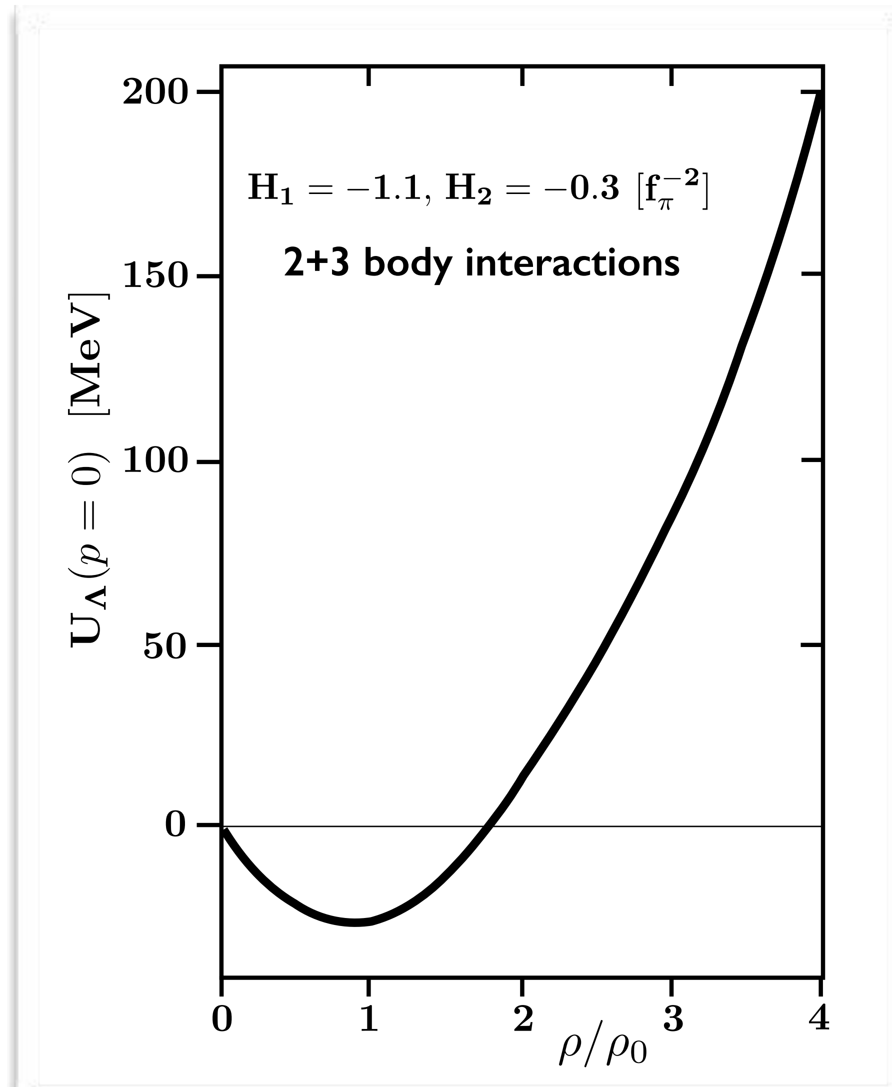
- **… towards a possible solution of the "hyperon puzzle" ?**

Density dependence of Λ single particle potential (contd.)

- **Chiral NN** (N3LO) + **YN** (NLO) **interactions** + **NNN & YNN 3-body** forces
- **Coupled-channels G-matrix including explicit $\Lambda NN \leftrightarrow \Sigma NN$ three-body interactions**

$$\mathbf{G}_{\alpha\beta}(\omega;\rho) = \mathbf{V}_{\alpha\beta}(\rho) + \mathbf{V}_{\alpha\gamma}(\rho)\frac{\mathbf{Q}}{\mathbf{e}(\omega)+\mathbf{i}\epsilon}\mathbf{G}_{\gamma\beta}(\omega;\rho)$$





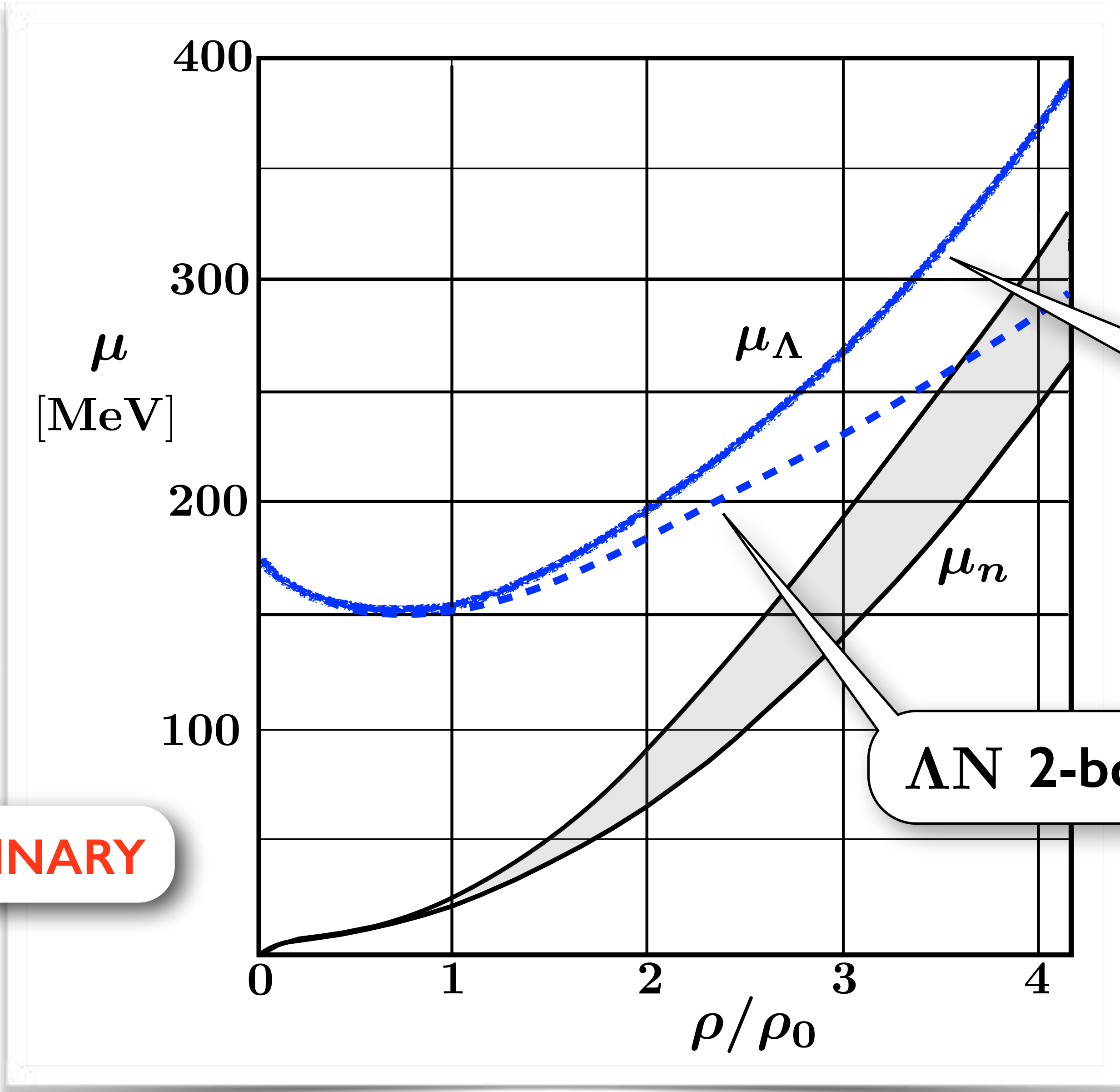
D. Gerstung, N. Kaiser, W.W. (2018)

Hyperons in Neutron Stars ?

- Onset condition for appearance of Λ **hyperons in neutron stars :**

chemical potentials

$$\mu_i = \frac{\partial \mathcal{E}}{\partial \rho_i}$$



$$\mu_\Lambda = \mu_n$$

PRELIMINARY

- Extrapolations using Λ **single particle potential** in **neutron (star) matter** from **Chiral SU(3) EFT** interactions
- Further calculations in progress

(D. Gerstung, N. Kaiser, W.W. 2018)

SUMMARY

- **Constraints on dense baryon matter equation-of-state from neutron stars :**
  - **Stiff EoS** required **!**
  - **“Non-exotic” EoS (nuclear chiral dynamics + FRG)** seems to work
  - **No first-order chiral phase transition** in sight
  - **Hyperon puzzle:** naively adding hyperons implies **far too soft EoS**

- **Progress in constructing hyperon-nuclear interactions from Chiral SU(3) Effective Field Theory**
  - **YN two-body interactions** at **NLO**
  - **Importance of** $\Lambda\,\mathrm{N} \leftrightarrow \Sigma\,\mathrm{N}$ (2nd order pion exchange tensor force)
  - **YNN three-body forces** (incl. $\Lambda\mathrm{NN} \leftrightarrow \Sigma\mathrm{NN}$ coupled channels)

- **Single particle potential of a** Λ in **nuclear** and **neutron matter**
  - **Moderately attractive** at low density (**hypernuclei**)
  - **Strongly repulsive** at high density (**2+3 - body interactions**)

    . . . possible solution of “**hyperon puzzle**” in **neutron stars** ?

Appendix :
some details
Baryon-Baryon Interactions
from Chiral SU(3) EFT

Chiral $\mathbf{SU(3)_L \times SU(3)_R}$ Effective Field Theory

- Realization of **Low-Energy QCD** for energies / momenta

$$\mathbf{Q < 4\pi\, f \sim 1\, GeV}$$

- based on SU(3) **Non-Linear Sigma Model** plus (heavy) **baryons**

Pseudoscalar meson octet

$\mathbf{SU(3)_L \times SU(3)_R}$

Nambu-Goldstone bosons

$$P = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta}{\sqrt{6}} \end{pmatrix}$$

coupled to **baryon octet**

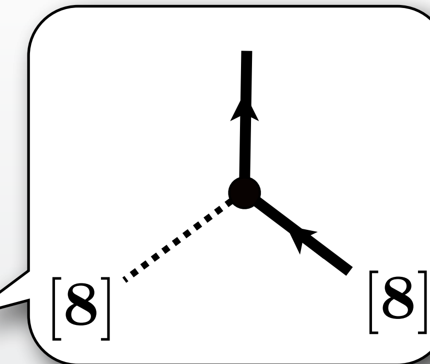
$$B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ -\Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}$$

Chiral $\mathbf{SU(3)_L \times SU(3)_R}$ Effective Field Theory

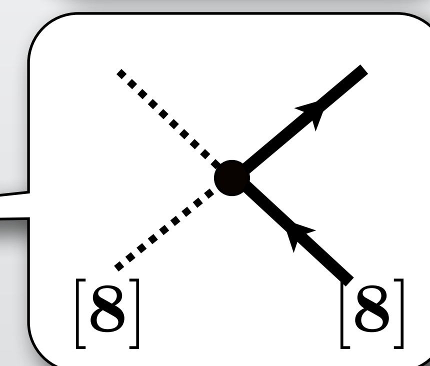
- **Interaction Lagrangian:** expand in powers of meson fields P(x)

$$\mathcal{L}_{int} = \mathcal{L}_1 + \mathcal{L}_2 + \ldots + \text{ mass terms}$$

$$\mathcal{L}_1 = -\frac{\sqrt{2}}{2f}\,\mathrm{tr}\big(D\bar{B}\gamma^\mu\gamma_5\{\partial_\mu P, B\} + F\bar{B}\gamma^\mu\gamma_5[\partial_\mu P, B]\big)$$

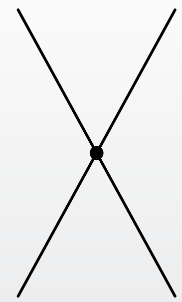


$$\mathcal{L}_2 = \frac{1}{4f^2}\,\mathrm{tr}\big(\mathrm{i}\bar{B}\gamma^\mu[[P, \partial_\mu P], B]\big)$$

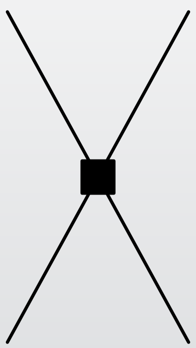


- **Input** : $F = 0.46 \quad D = 0.81$ $(g_A = F + D = 1.27)$ $\quad f = 0.09\,GeV$
- **Physical** meson and baryon masses (SU(3) breaking)

Hyperon - Nucleon Interaction
Contact Terms



$$V^{(0)}_{BB\to BB} = C_S + C_T \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$



$$V^{(2)}_{BB\to BB} = C_1 \mathbf{q}^2 + C_2 \mathbf{k}^2 + \left(C_3 \mathbf{q}^2 + C_4 \mathbf{k}^2\right)\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + \frac{\mathrm{i}}{2} C_5 (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)\cdot(\mathbf{q}\times\mathbf{k})$$
$$+ C_6 (\mathbf{q}\cdot\boldsymbol{\sigma}_1)(\mathbf{q}\cdot\boldsymbol{\sigma}_2) + C_7 (\mathbf{k}\cdot\boldsymbol{\sigma}_1)(\mathbf{k}\cdot\boldsymbol{\sigma}_2) + \frac{\mathrm{i}}{2} C_8 (\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_2)\cdot(\mathbf{q}\times\mathbf{k})$$

- **SU(3) symmetry** reduces number of independent constants

$$\mathbf{8}\otimes\mathbf{8} = \mathbf{27}\oplus\mathbf{8_s}\oplus\mathbf{1}\oplus\mathbf{10}\oplus\mathbf{10}^*\oplus\mathbf{8_a}$$

S	Channel	I	$V_{^1S_0,\,^3P_0,\,^3P_1,\,^3P_2}$	$V_{^3S_1,\,^3S_1\text{-}^3D_1,\,^1P_1}$
0	$NN\to NN$	0	–	C^{10^*}
	$NN\to NN$	1	C^{27}	–
-1	$\Lambda N\to\Lambda N$	$\frac{1}{2}$	$\frac{1}{10}\left(9C^{27}+C^{8_s}\right)$	$\frac{1}{2}\left(C^{8_a}+C^{10^*}\right)$
	$\Lambda N\to\Sigma N$	$\frac{1}{2}$	$\frac{3}{10}\left(-C^{27}+C^{8_s}\right)$	$\frac{1}{2}\left(-C^{8_a}+C^{10^*}\right)$
	$\Sigma N\to\Sigma N$	$\frac{1}{2}$	$\frac{1}{10}\left(C^{27}+9C^{8_s}\right)$	$\frac{1}{2}\left(C^{8_a}+C^{10^*}\right)$
	$\Sigma N\to\Sigma N$	$\frac{3}{2}$	C^{27}	C^{10}

S. Petschauer,
N. Kaiser

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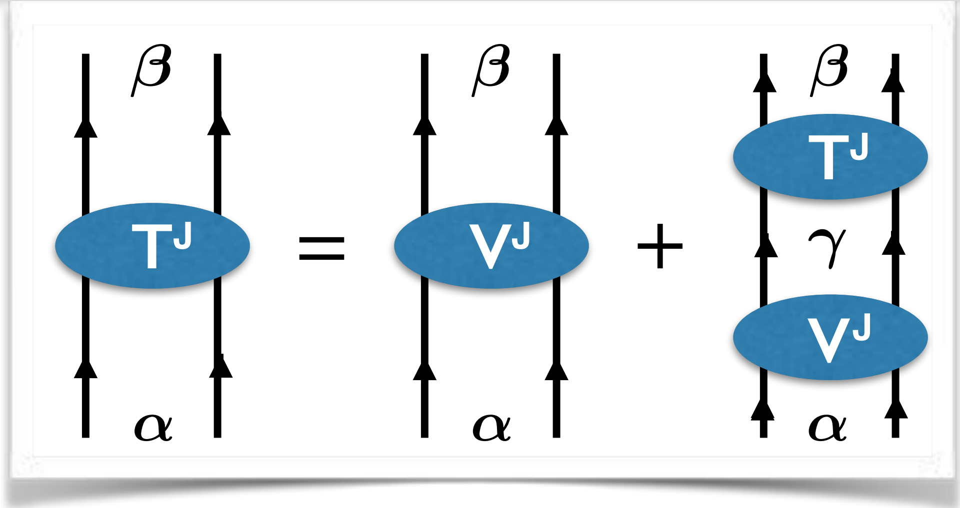
A 916 (2013) 1-29

Coupled-Channels Lippmann-Schwinger Equation



- Partial waves (LS)J , baryon-baryon channels α, β

$$\mathbf{T}^{J}_{\beta\alpha}(p_f, p_i; \sqrt{s}) = \mathbf{V}^{J}_{\beta\alpha}(p_f, p_i) + \sum_{\gamma} \int_0^\infty \frac{dp\, p^2}{(2\pi)^3} \mathbf{V}^{J}_{\beta\gamma}(p_f, p) \frac{2\mu_\gamma}{p_\gamma^2 - p^2 + i\varepsilon} \mathbf{T}^{J}_{\gamma\alpha}(p, p_i; \sqrt{s})$$

- On-shell momentum of intermediate channel γ determined by :

$$\sqrt{s} = \sqrt{M^2_{\gamma,1} + p^2_\gamma} + \sqrt{M^2_{\gamma,2} + p^2_\gamma}$$

- Relativistic kinematics relating lab. and c.m. momenta
- Momentum space cutoffs: 0.5 - 0.6 GeV