58th International Winter Meeting on Nuclear Physics
Bormio, 21 January 2020

HYPERON-NUCLEAR INTERACTIONS and STRANGENESS in NEUTRON STARS

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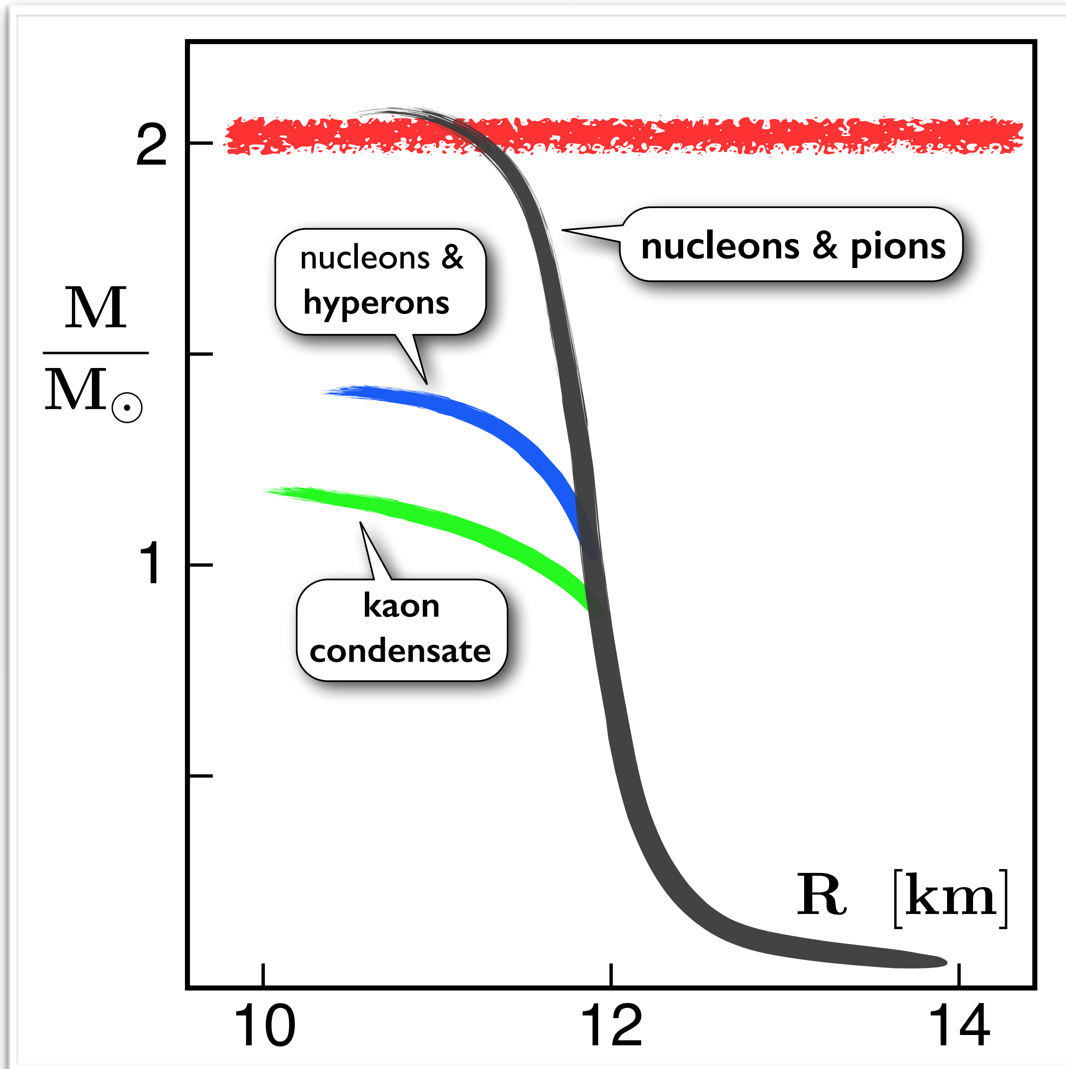
- Brief overview: neutron star equation-of-state
  - Constraints from $2\,\mathrm{M}_\odot$ stars and mergers (GW signals)
  - Neutron star matter as a (relativistic) Fermi Liquid
- Strangeness and baryonic matter
  - Hyperon-nuclear interactions and three-body forces
  - "Hyperon puzzle" in neutron stars

Key Issue:

Role of **STRANGENESS** (Kaons/Antikaons, Hyperons) in **DENSE BARYONIC MATTER** (Neutron Stars)

- Several **heavy neutron stars** observed with masses around $\mathrm{M} \simeq 2\ \mathrm{M}_\odot$



- **Hyperon puzzle (strangeness puzzle) in neutron star matter:**

Appearance of **hyperons** (or **kaon condensate**)

⇓

neutron star equation-of-state far too soft !

- **Basic requirements:**

⇨ **Many-body theory of dense baryonic matter**

⇨ **Theory of hadronic interactions including strangeness**

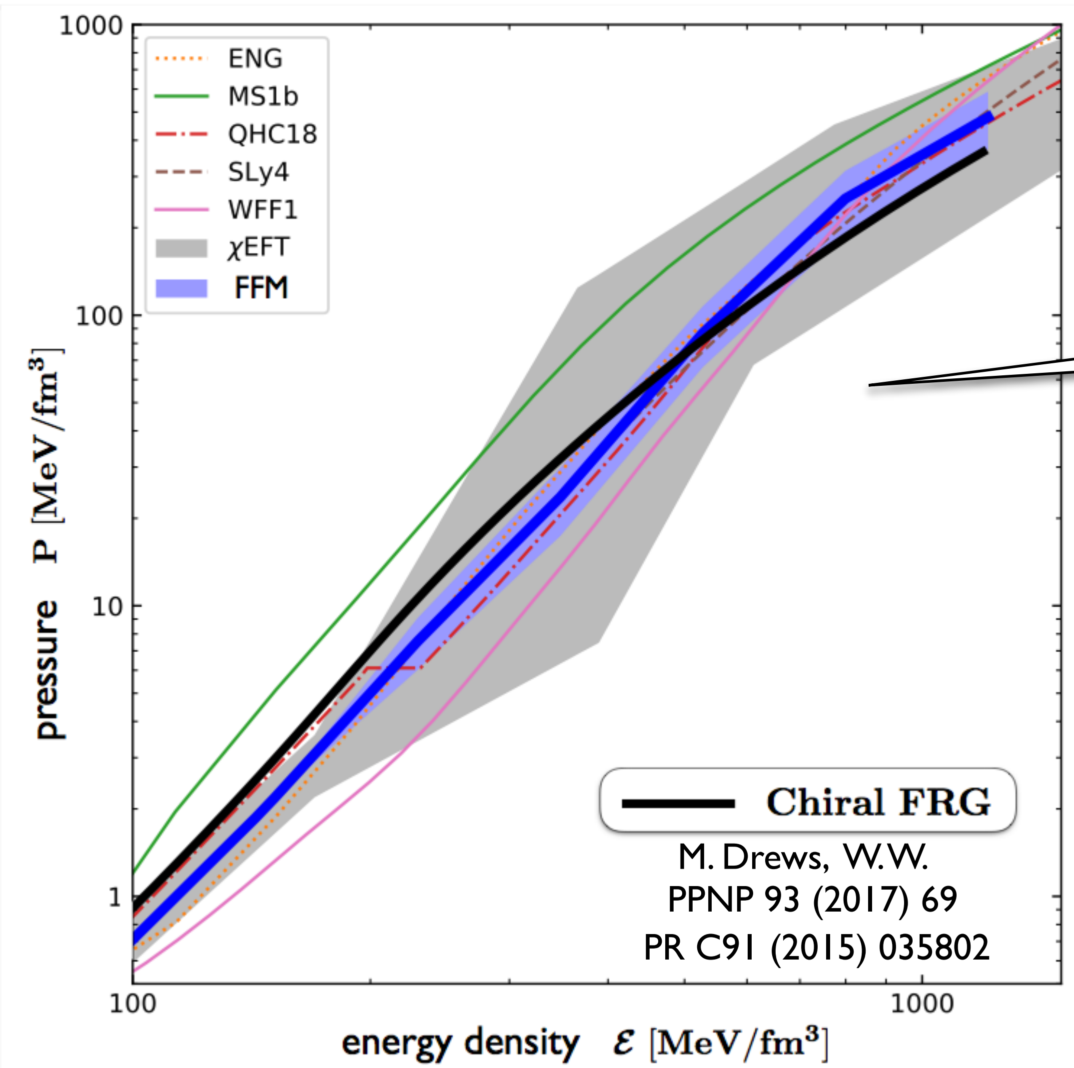
Part I.

Status of Neutron Star Equation-of-State

- **Stiffness constraint:**
  EoS must support massive $(\sim 2\,\mathrm{M}_\odot)$ neutron stars
- **Compatibility with GW neutron star merger signals (tidal deformability)**
- **Microscopic EoS and Landau Fermi-Liquid theory**

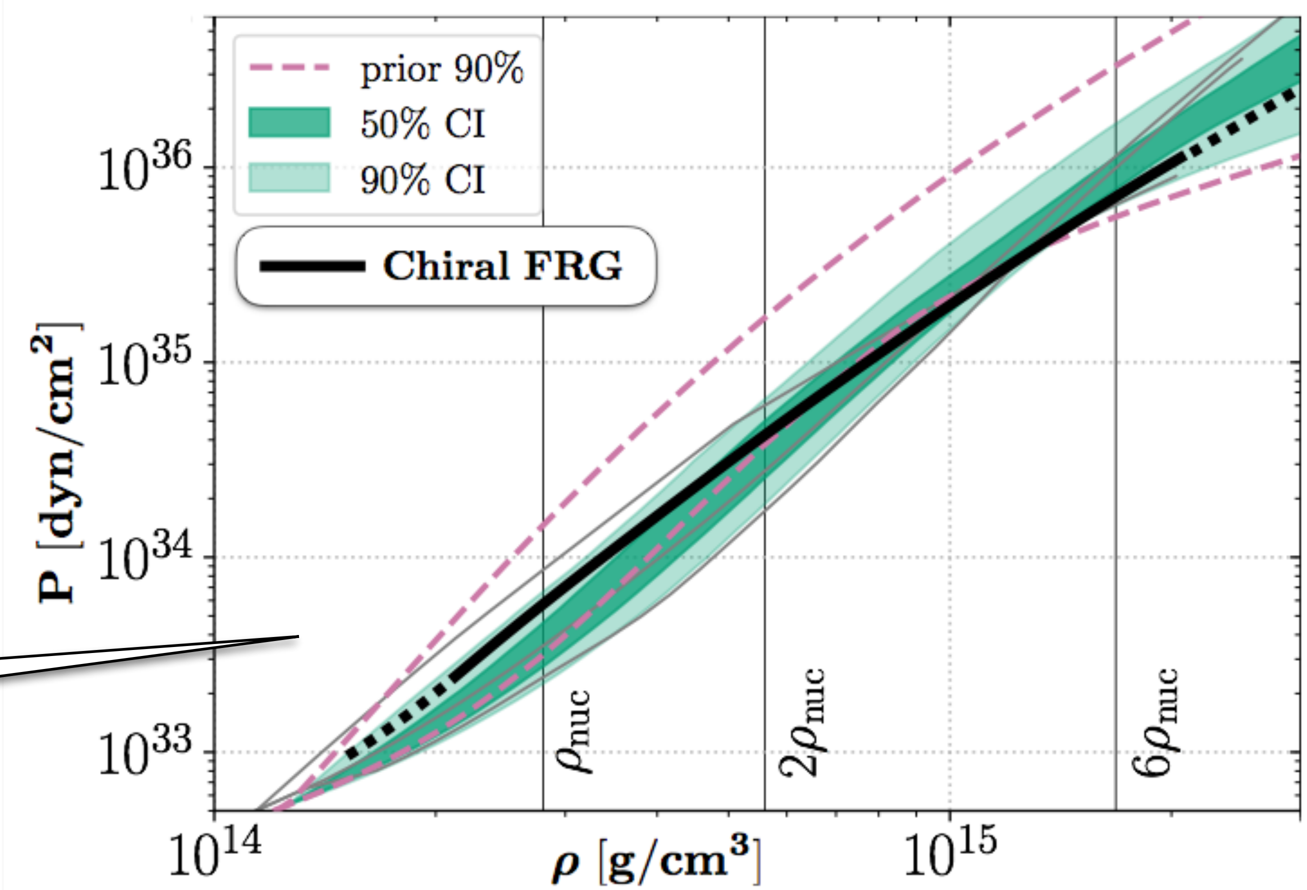
NEUTRON STAR MATTER   Equation of State

- Comparisons: EoS reconstructions from neutron star data and a microscopic equation-of-state



utilising machine learning (neural network) methods

Y. Fujimoto, K. Fukushima, K. Murase
arXiv: 1903.03400



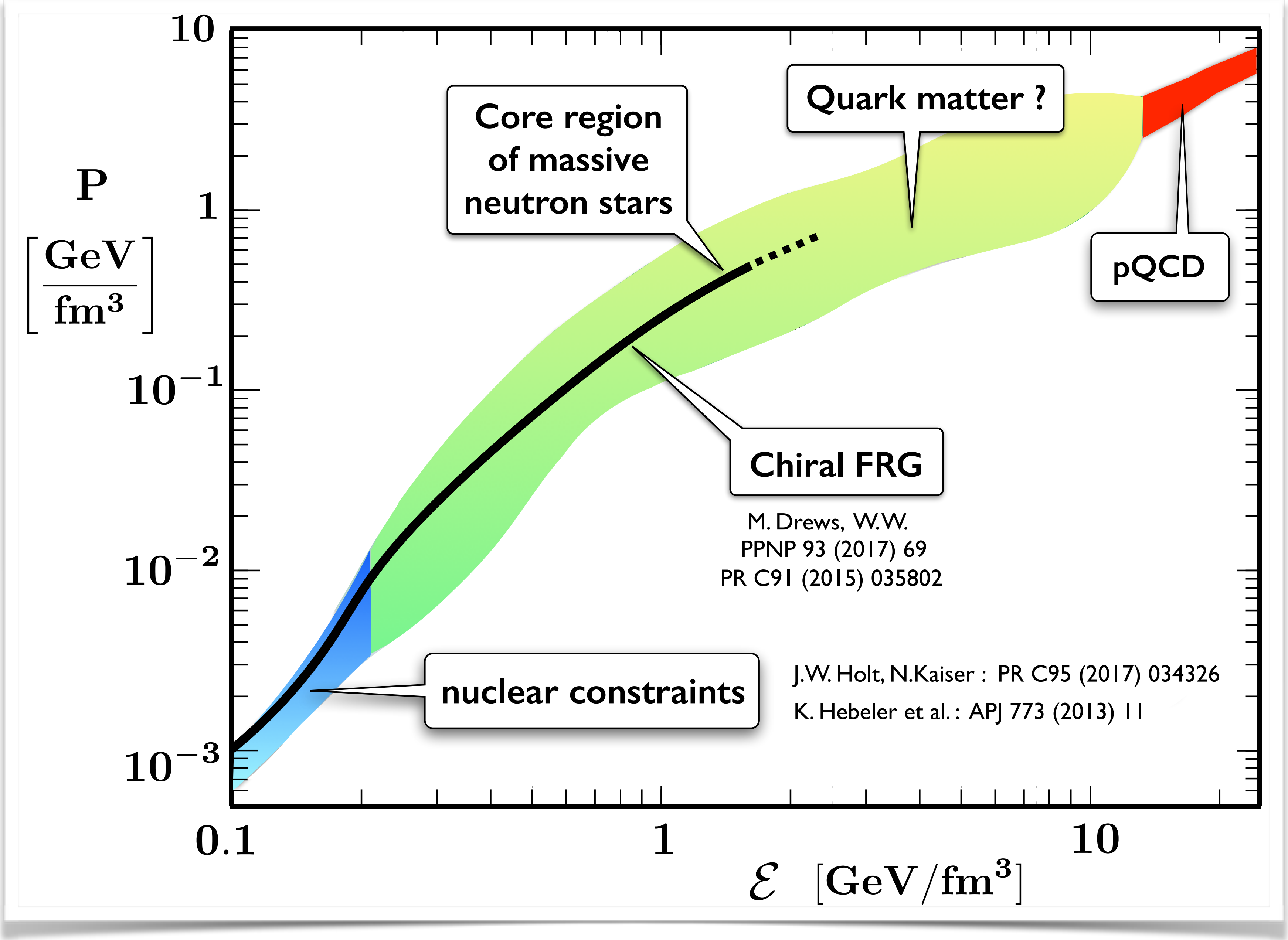
utilising GW 170817 data analysis

LIGO & Virgo,   B.P. Abbot et al.
Phys. Rev. Lett. 121 (2018) 161101

NEUTRON STAR MATTER Equation of State

- incl. $M_{max} \simeq 2\,M_\odot$ + **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 : Nucl. Phys. A982 (2019) 36



- Recent news: msec pulsar J0740+6620 with $M = (2.14 \pm 0.10)\,M_\odot$

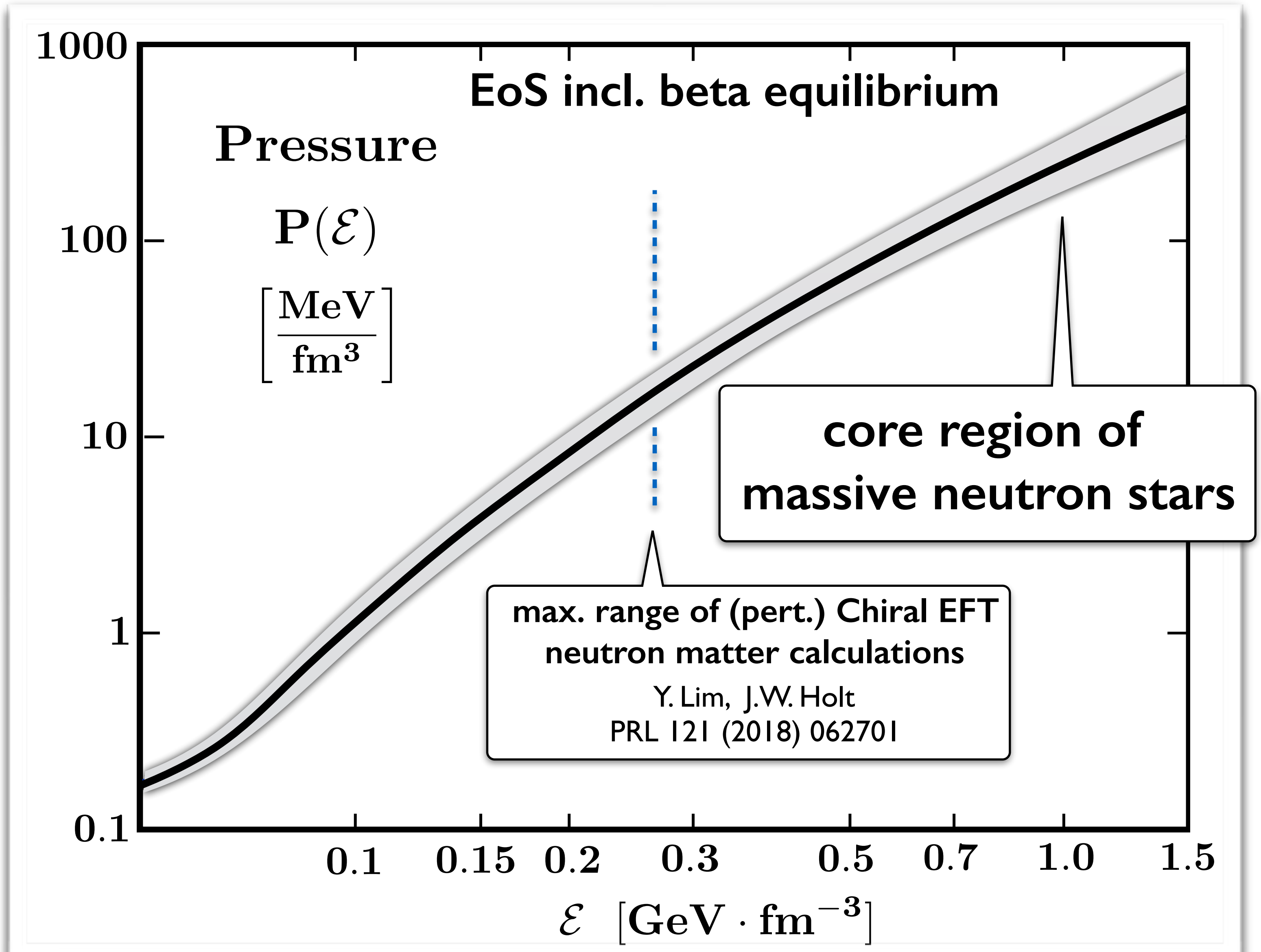
H.T. Cromartie et al. : Nat. Astron. 4 (2019) 72 ; arXiv:1904.06759 [astro-ph.HE]

NEUTRON STAR MATTER : Chiral FRG Equation of State

- Chiral Nucleon-Meson Field Theory & **F**unctional **R**enormalisation **G**roup

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

- **Consistent with** (perturbative) **ChEFT at low densities**
- **Reproduces nuclear matter properties** (incl. liquid-gas phase transition, …)

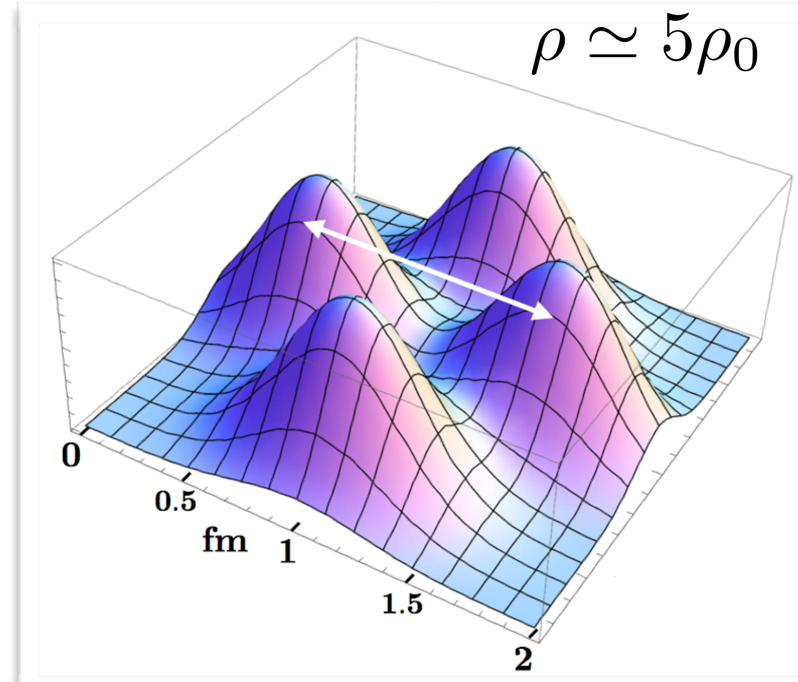


Non-perturbative
FRG calculations :

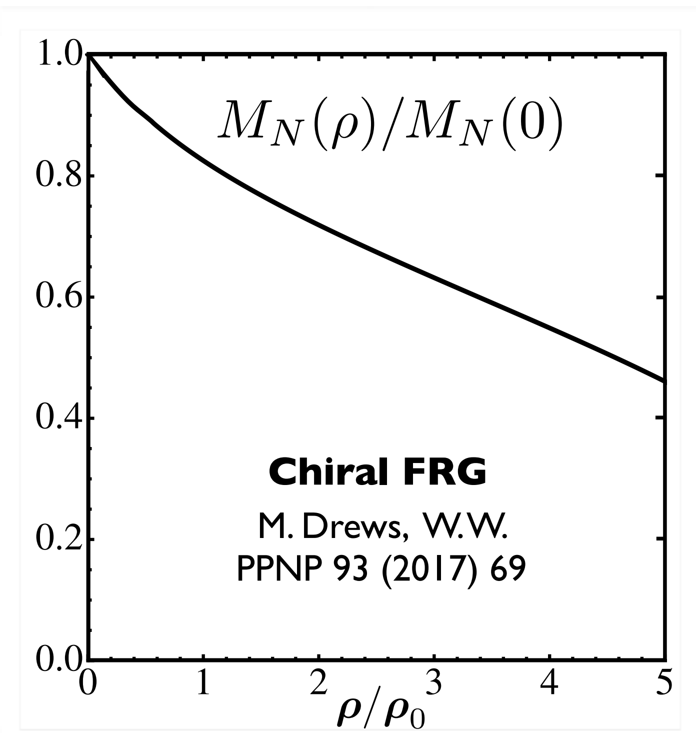
- **multi-pion exchange** processes
- **nucleon-hole** excitations
- **multi-nucleon** correlations
- **NO chiral phase transition**

DENSE BARYONIC MATTER in NEUTRON STARS as a RELAVISTIC FERMI LIQUID

B. Friman, W.W.   Rhys. Rev. C100 (2019) 065807



- **Neutron Star Matter : Fermi liquid**
  dominantly **neutrons** + ca. 5 % protons
- **Quasiparticles:**
  nucleons "dressed" by their **strong interactions**
  … and imbedded in **multi-pion field**
- **Neutrons** as **relativistic quasiparticles**
  Fermi momentum in neutron star core region :



$$p_F = (3\pi^2 \rho)^{1/3} \sim \mathbf{0.5 - 0.6\,GeV/c} \gtrsim M_N(\rho)$$

- **Landau effective mass**

$$m^*(\rho) = \sqrt{p_F^2 + M_N^2(\rho)}$$

- **Chemical potential**

$$\mu = \frac{\partial \mathcal{E}}{\partial \rho} = M_0 + \left(1 + \rho \frac{\partial}{\partial \rho}\right) \frac{E(\rho)}{A} = m^*(\rho) + U(\rho)$$

repulsive many-body correlations

Relativistic Landau Fermi-Liquid Theory (contd.)

- **Quasiparticle interaction** expanded in **Legendre series**
  Coefficients: **Landau Fermi-liquid parameters**

- **Leading Landau parameters (T=0) :**

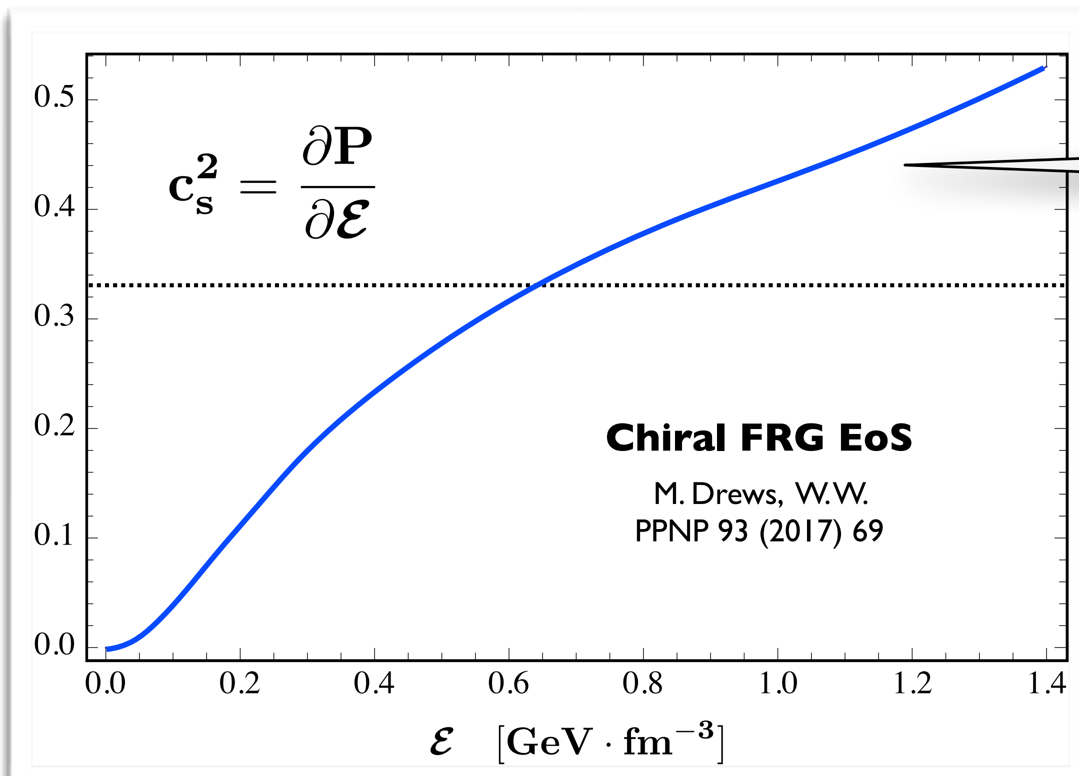
incompressibility

Landau effective mass

$$1 + F_0(\rho) = \frac{p_F\, m^*(\rho)}{\pi^2}\,\frac{\partial^2 \mathcal{E}(\rho)}{\partial \rho^2} = \frac{m^*(\rho)}{3p_F^2}\,\mathcal{K}(\rho) \qquad 1 + \frac{F_1(\rho)}{3} = \frac{m^*(\rho)}{\mu}$$

- **Speed of sound**

$$c_s^2 = \frac{1}{3}\left(\frac{p_F}{\mu}\right)^2 \frac{1 + F_0}{1 + \frac{1}{3}F_1}$$



strongly repulsive correlations

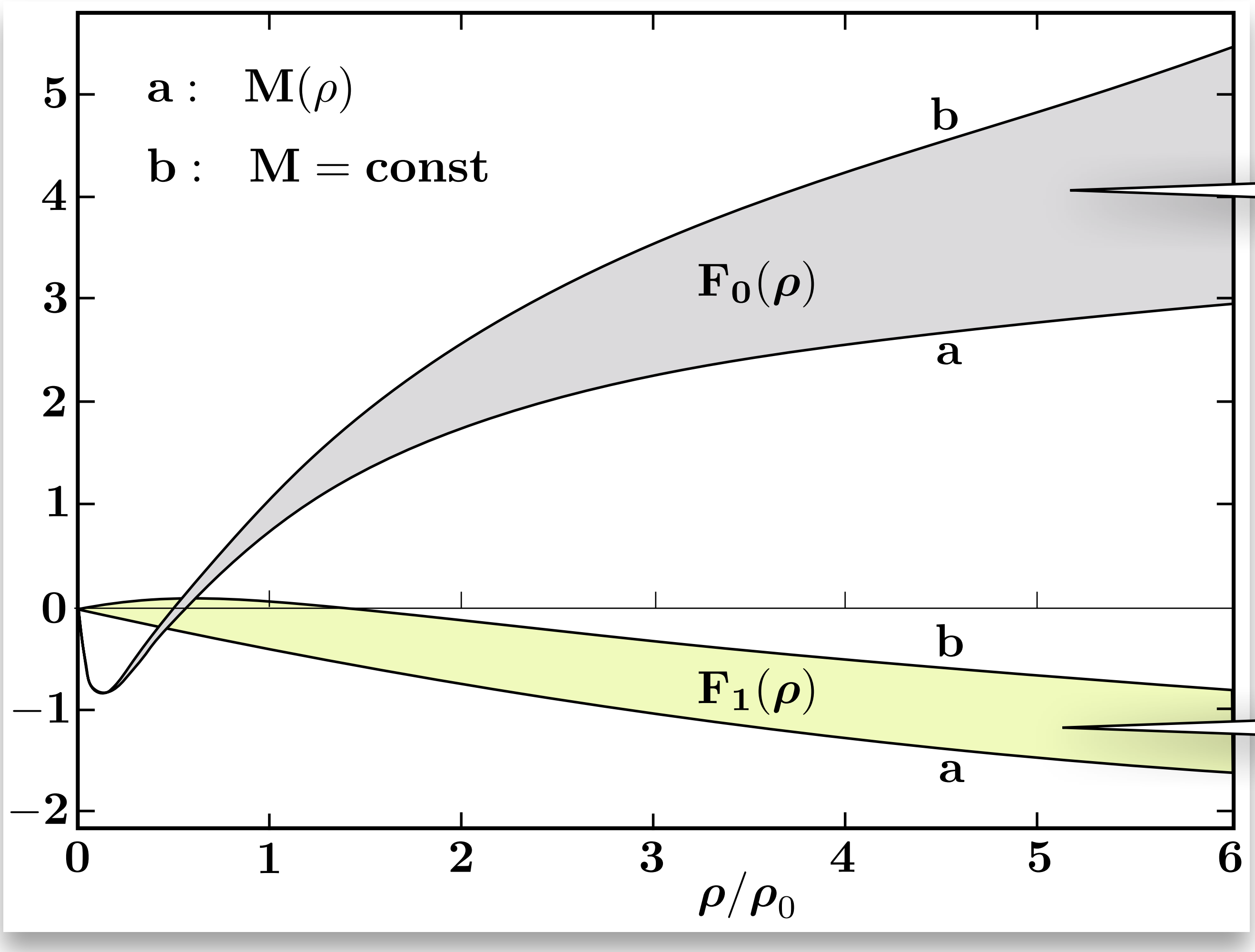
$$c_s > \frac{1}{\sqrt{3}}$$

B. Friman, W.W. Rhys. Rev. C100 (2019) 065807

LANDAU FERMI-LIQUID PARAMETERS

- **Deduced from neutron star matter EoS calculated using Chiral Nucleon-Meson Field Theory & Functional Renormalisation Group**

neutron star matter
:
strongly correlated Fermi liquid
...
but not "extreme" !



strongly repulsive many-body correlations

decreasing effective Fermion mass

B. Friman, W.W. Phys. Rev. C100 (2019) 065807

- **Low densities $\rho \lesssim \rho_0$:** good agreement with (perturbative) **ChEFT results**

J.W. Holt, N.Kaiser, W.W. : Phys. Rev. C87 (2013) 014338

LANDAU FERMI-LIQUID PARAMETERS (contd.)

- **Comparison with atomic liquid helium-3 in its normal phase at low temperature (3 K)**

- **Interaction** between **He-3 atoms:**
  attractive **van der Waals** potential plus strongly **repulsive short-range core**

- **Landau parameters** of **liquid helium-3** at pressures P = (0 - 30) bar:

$$\mathbf{F_0(^3He) \sim 10 - 70} \qquad \mathbf{F_1(^3He) \sim 5 - 13}$$

… **much larger** by order of magnitude than
Landau parameters of **neutron star matter** !!

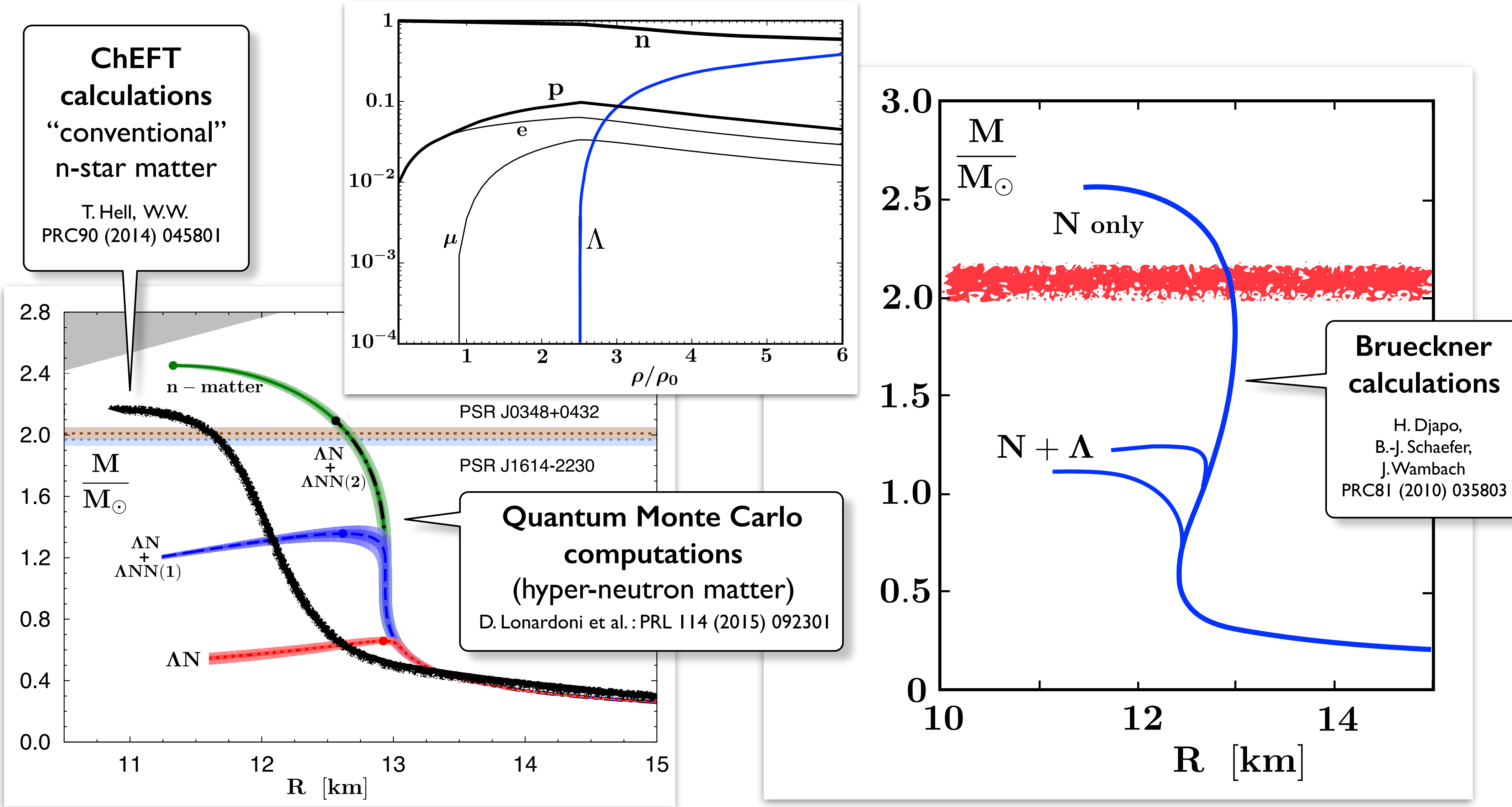
- Intermediate conclusion :
  Neutron star matter at central densities
  is a **strongly correlated Fermi system**
  … but not as extreme as one might have thought !

Part II.

Hyperon-Nuclear Interactions
and
Strangeness in Dense Matter

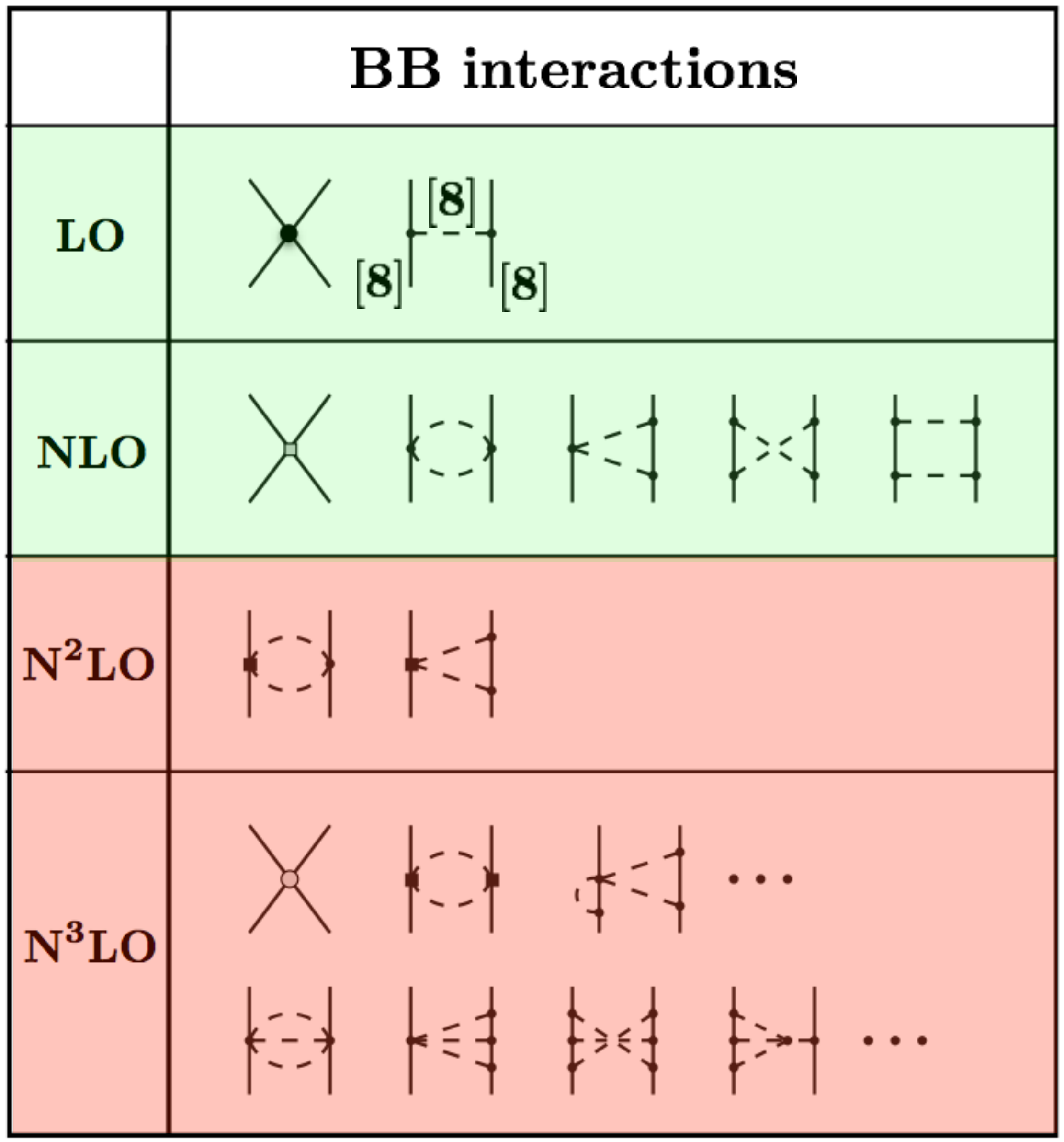
- **Chiral SU(3) Effective Field Theory of Hyperon-Nucleon Interactions**
- **Hyperon-NN Three-Body Forces**
- **“Hyperon Puzzle” in Neutron Stars ?**

NEUTRON STAR MATTER including HYPERONS



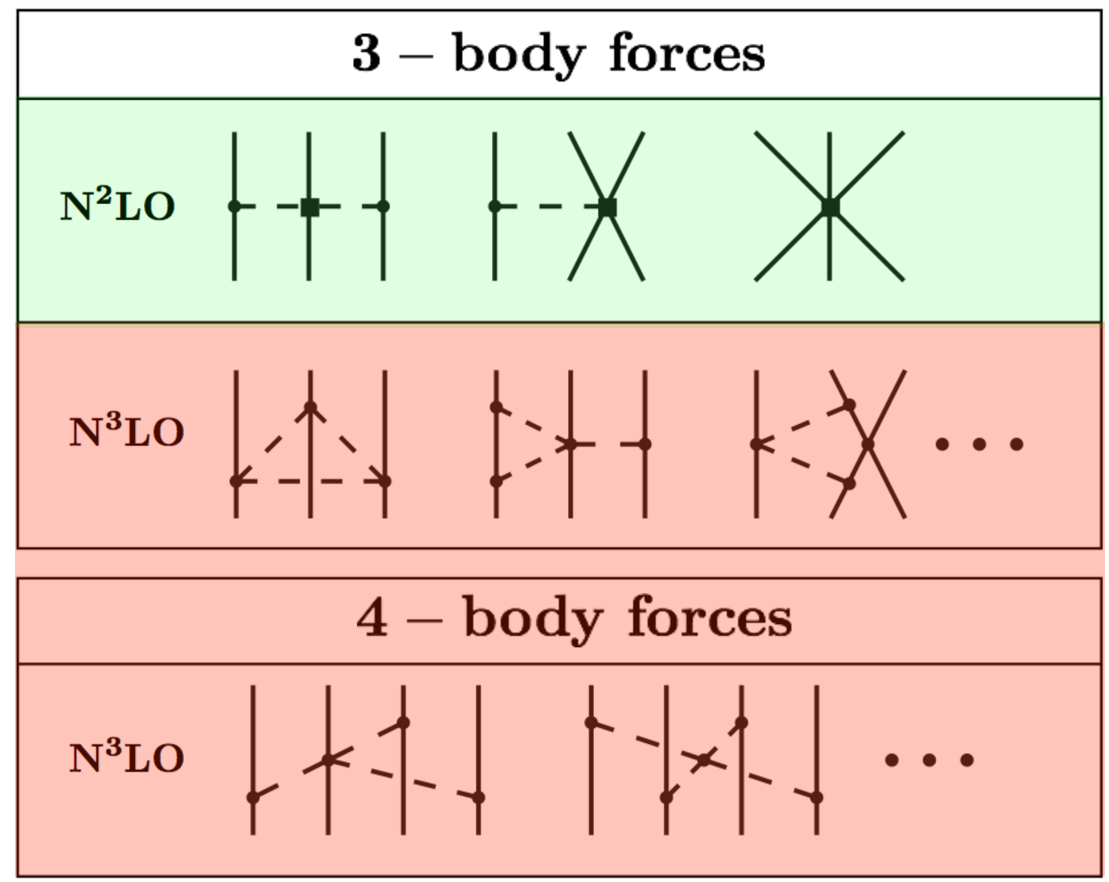
Inclusion of **hyperons**: EoS **too soft** to support 2-solar-mass n-stars unless: **strong repulsion** in **YN** and/or **YNN** … interactions

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



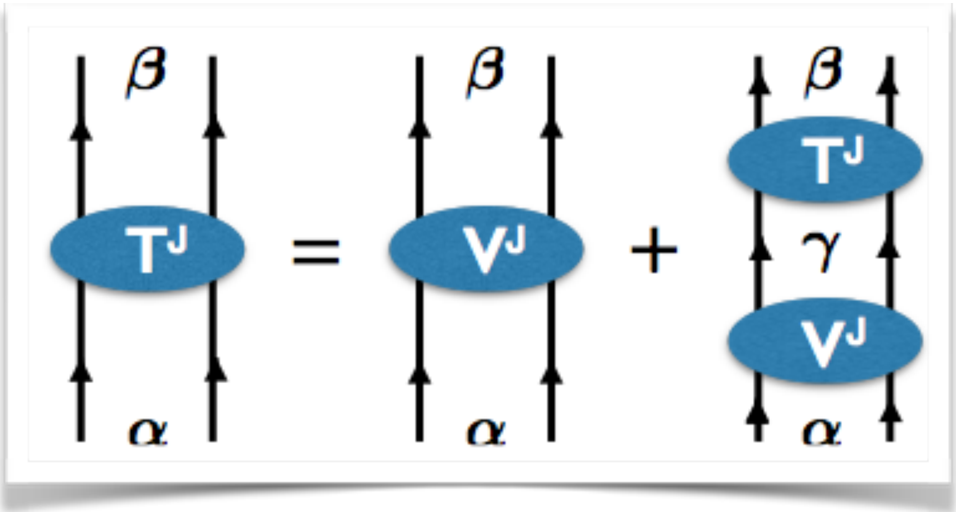
- **Systematically organized hierarchy in powers of Q/Λ**

(Q: momentum, energy, pion mass)



- **NN interaction :** has reached N^4LO level
- **YN interaction :** still very limited empirical data base
  ⟶ **restriction to** NLO plus **YNN three-body forces**

Coupled-Channels Lippmann-Schwinger Equation

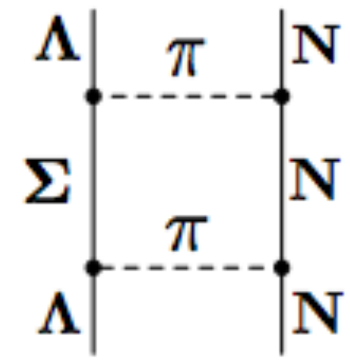


example ΛN scattering

inclusion of

ΛN ↔ ΣN

coupled channels



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

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

- Input **V** from chiral SU(3) EFT baryon-baryon interaction at NLO
- Momentum of intermediate channels γ determined by :

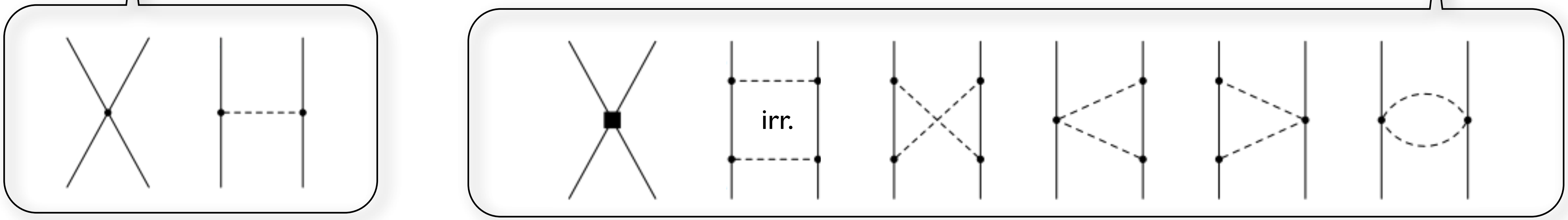
$$\sqrt{s} = \sqrt{M_{\gamma,1}^2 + p_\gamma^2} + \sqrt{M_{\gamma,2}^2 + p_\gamma^2}$$

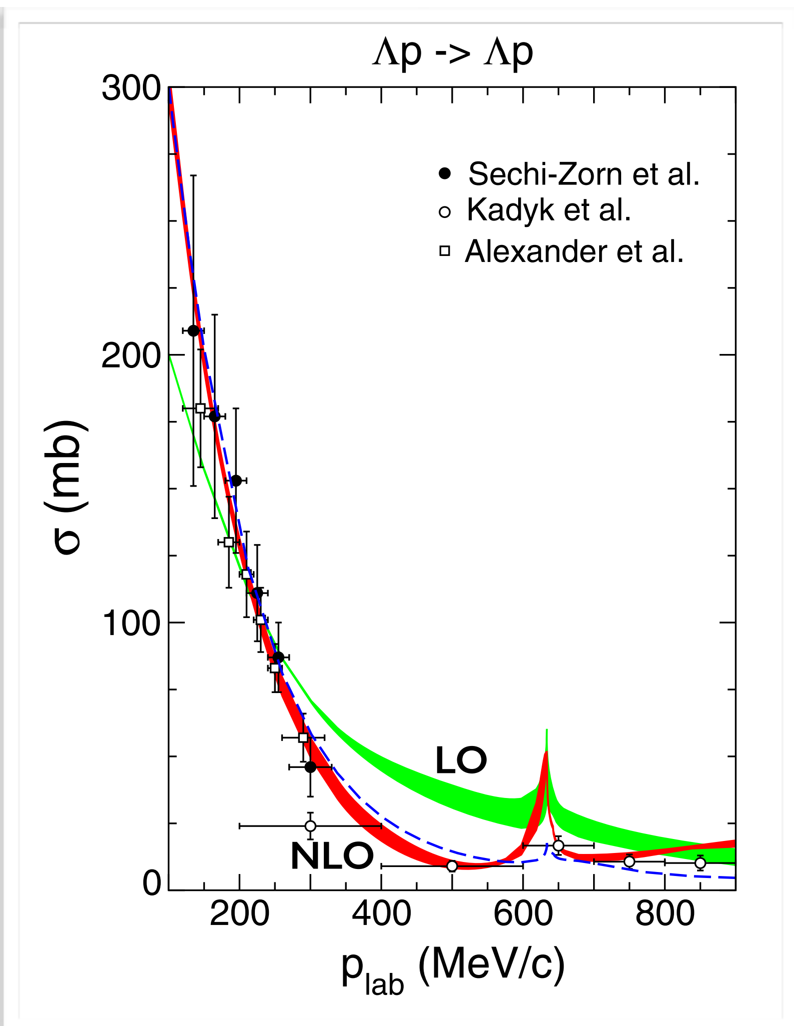
- Momentum space cutoff: 0.5 - 0.6 GeV

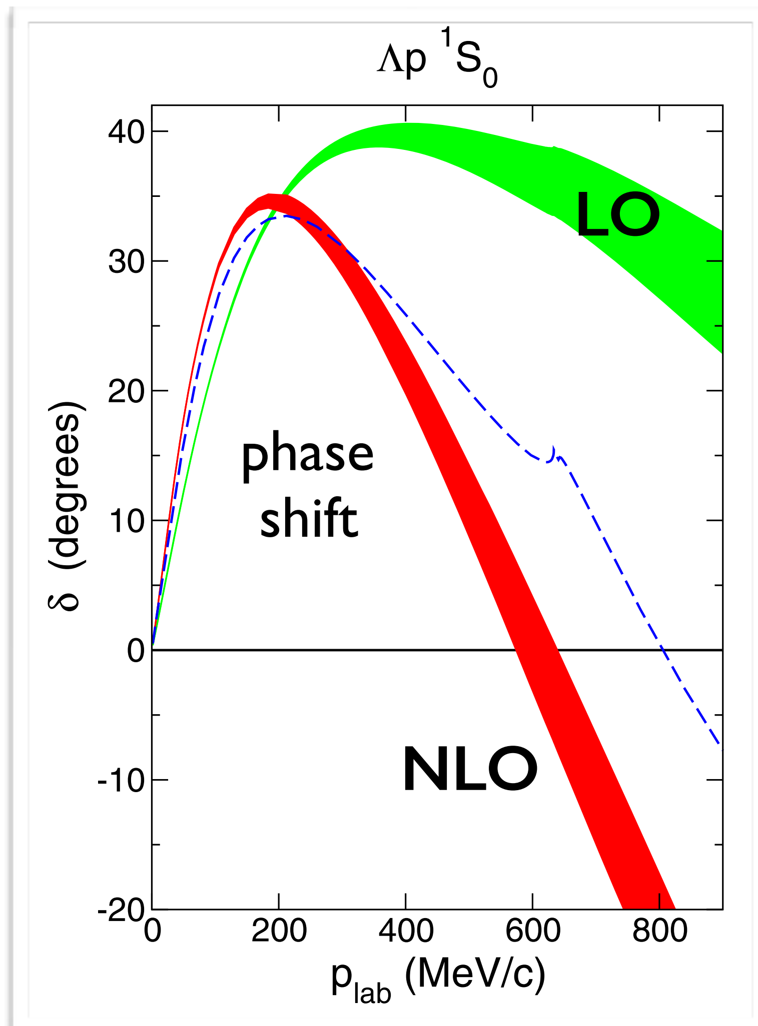
Hyperon - Nucleon Interaction
from CHIRAL SU(3) Effective Field Theory

LO

NLO







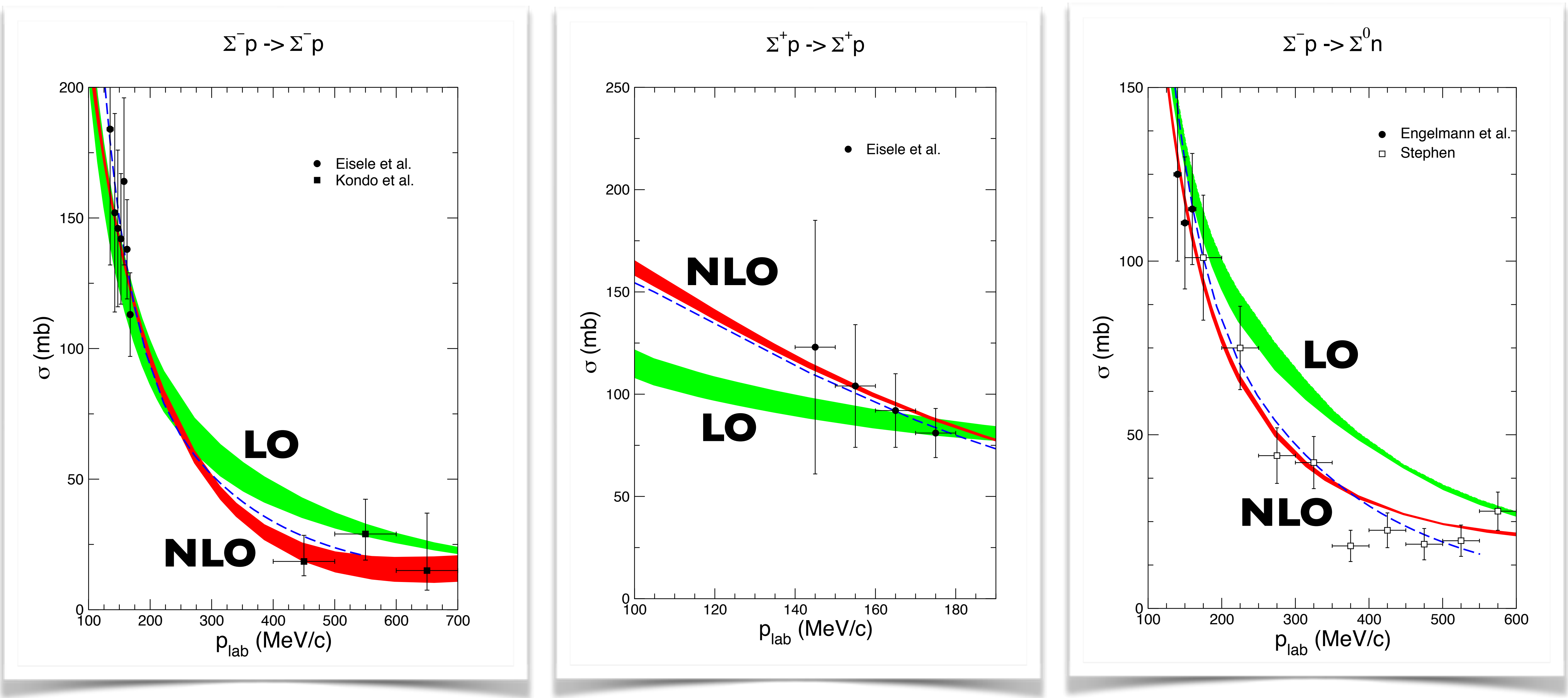
- **moderate attraction** at low momenta
  - ➞ relevant for **hypernuclei**
- **increasing repulsion** at higher momenta
  - ➞ relevant for **dense baryonic matter**

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

Hyperon - Nucleon Interaction (contd.)

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

- ΣN elastic and charge exchange scattering



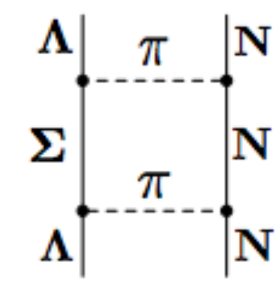
- Quest for much improved hyperon-nucleon scattering data base !

Hyperon - Nucleon Interaction : recent update

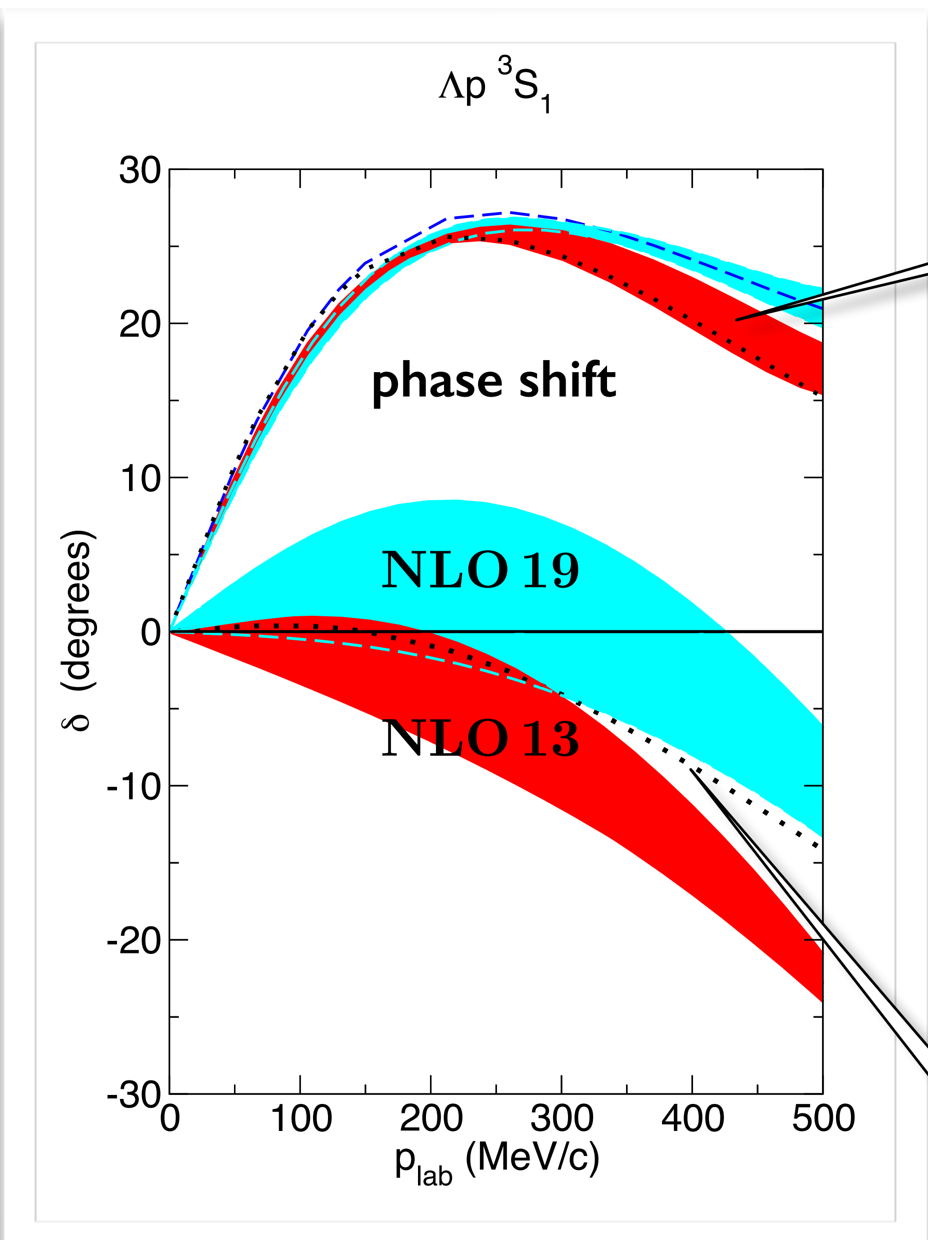
J. Haidenbauer, U.-G. Meißner, A. Nogga arXiv:1906.11681 [nucl-th]

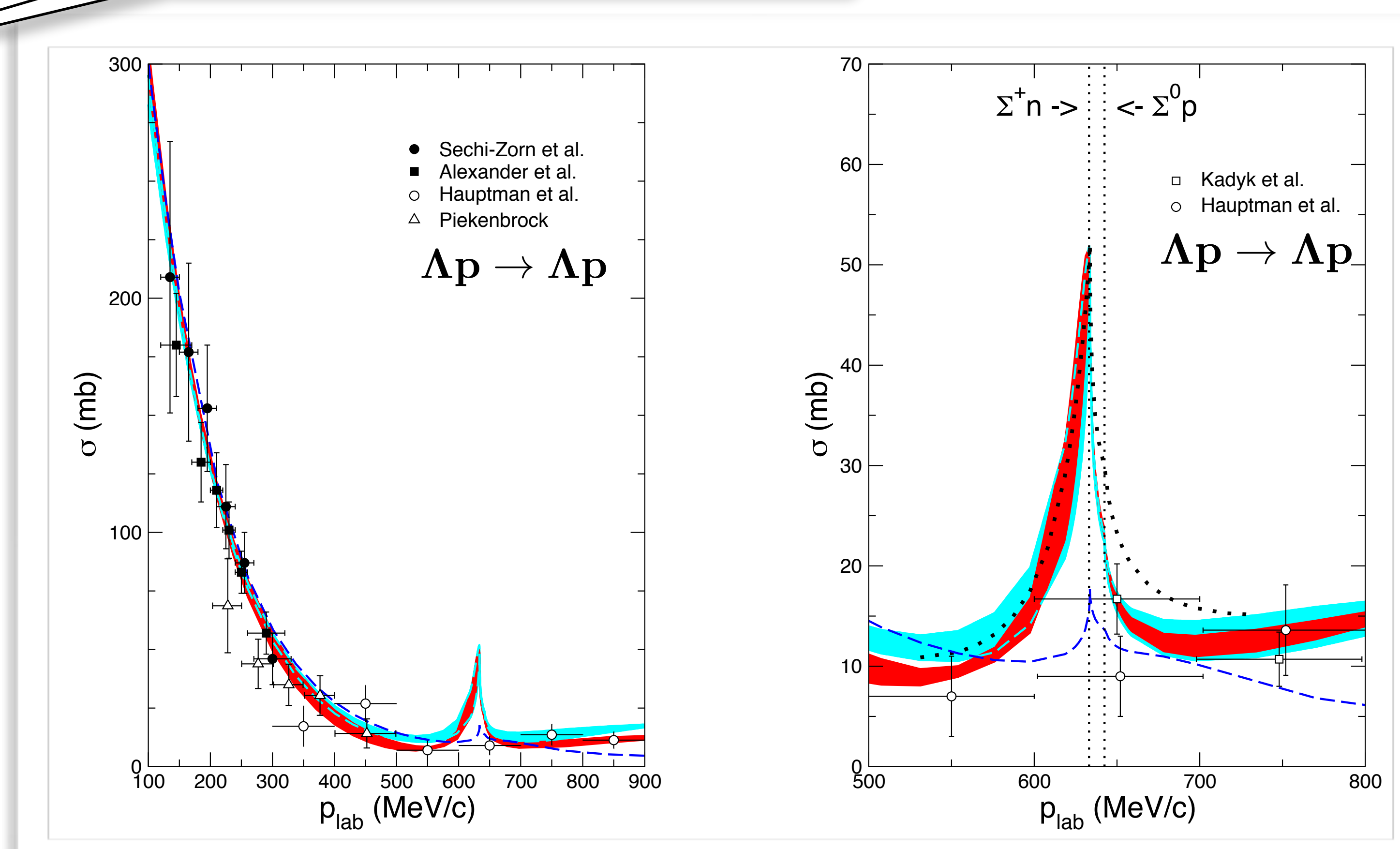
- Reduced no. of independent contact terms at NLO by imposing symmetries connecting NN and YN S-waves

including $\Lambda N \leftrightarrow \Sigma N$ coupling



blue : NLO 19
red : NLO 13



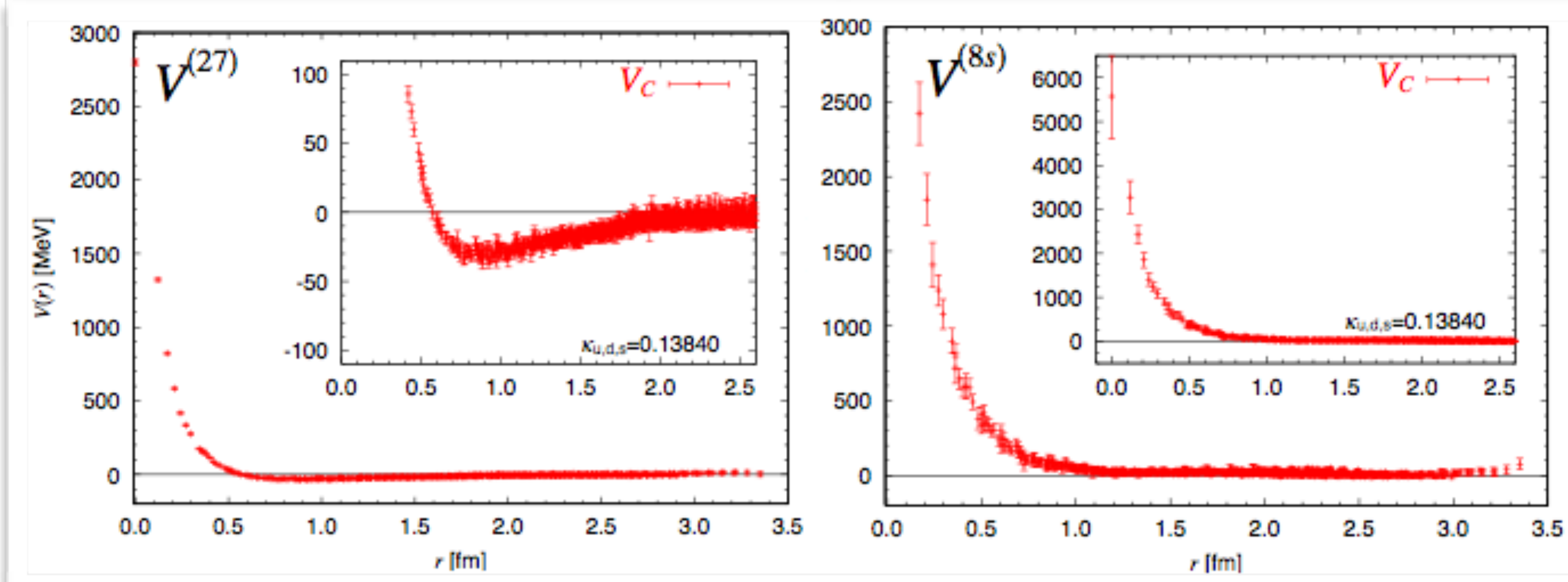


without $\Lambda N \leftrightarrow \Sigma N$ coupling

Hyperon - Nucleon Interactions from **Lattice QCD**

Hadrons to Atomic nuclei HAL from Lattice QCD

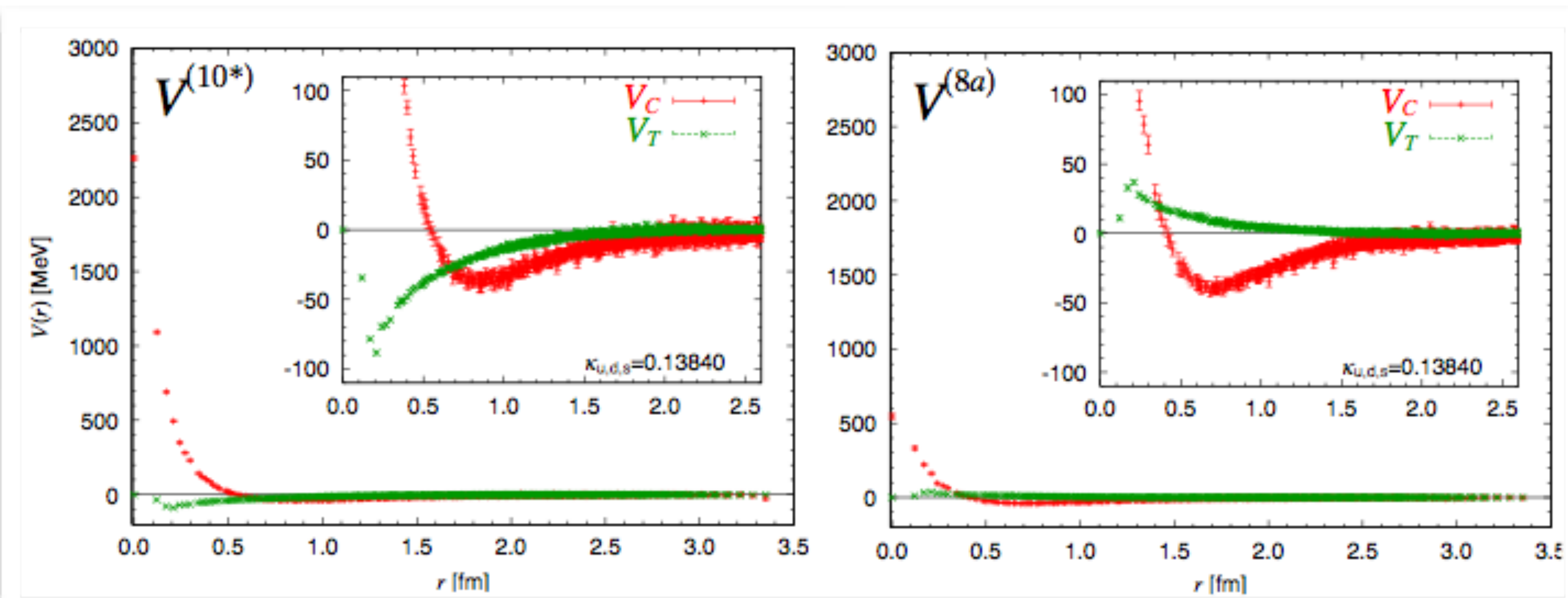
$$\mathbf{\Lambda N(^1S_0) = \frac{9}{10}[27] + \frac{1}{10}[8_s]}$$



$$\mathbf{m_{ps} = 0.47\,GeV}$$

T. Inoue et al.
PTP 124 (2010) 591
Nucl. Phys. A881 (2012) 28

$$\mathbf{\Lambda N(^3S_1) = \frac{1}{2}[10^*] + \frac{1}{2}[8_a]}$$



Short-range repulsive core in all channels

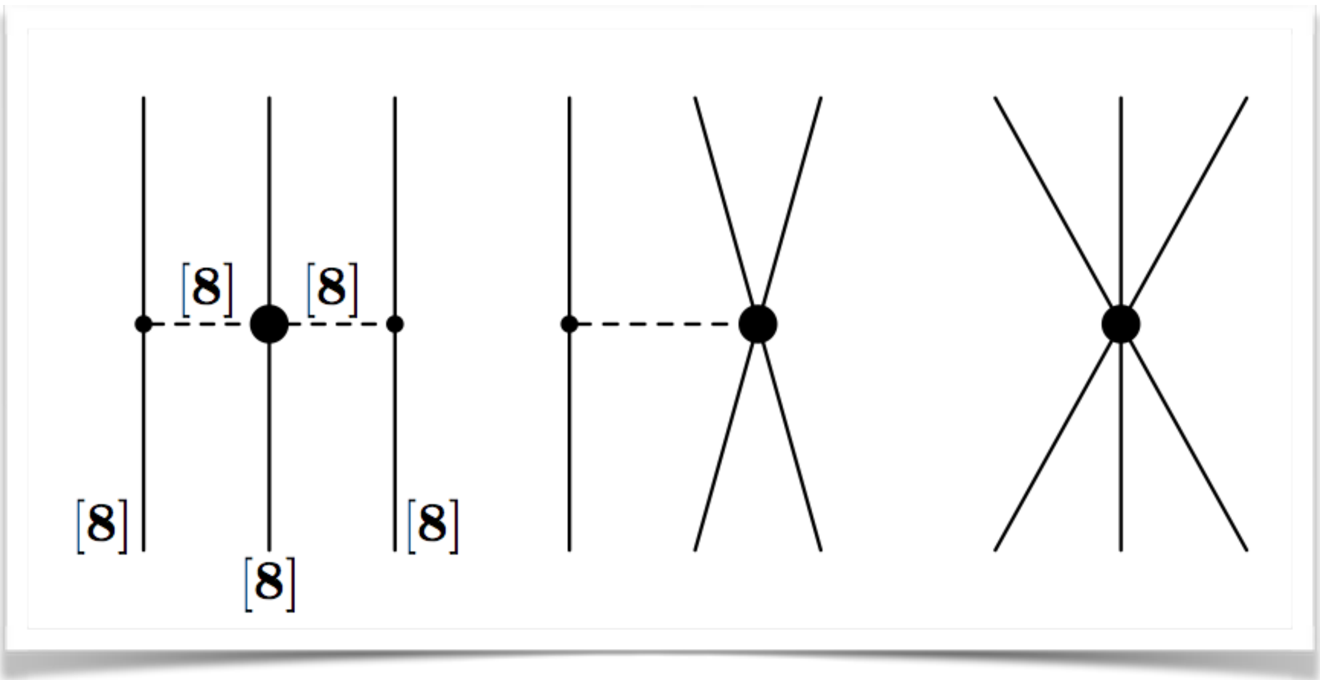
. . . towards physical quark masses

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

S. Petschauer, N. Kaiser, J. Haidenbauer, U.-G. Meißner, W.W. Phys. Rev. C93 (2016) 014001

- **Chiral** $\mathbf{SU(3)_L \times SU(3)_R}$ **Effective Field Theory:**
  interacting pseudoscalar meson & baryon octets + contact terms

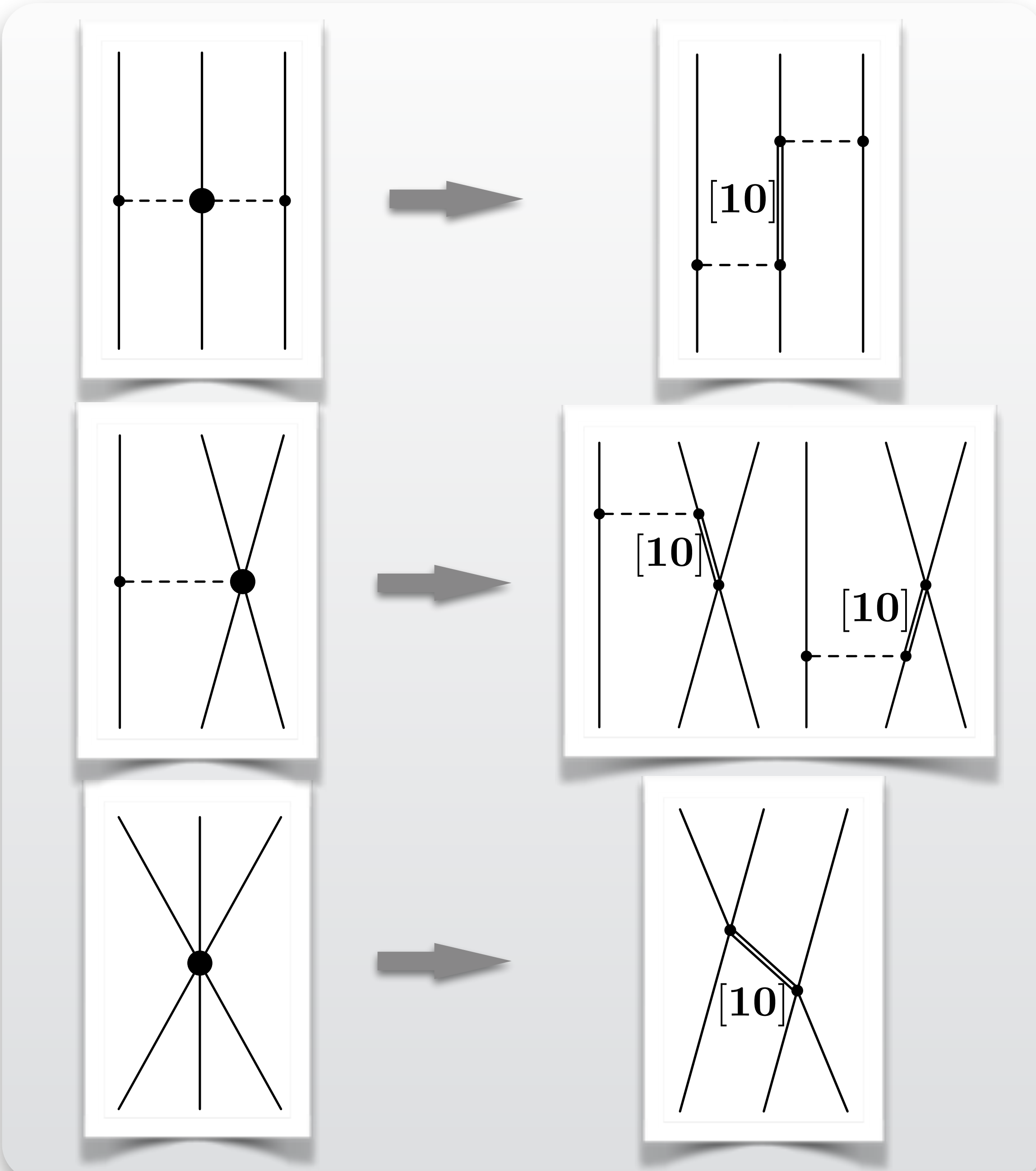
3-baryon sector at **NNLO**



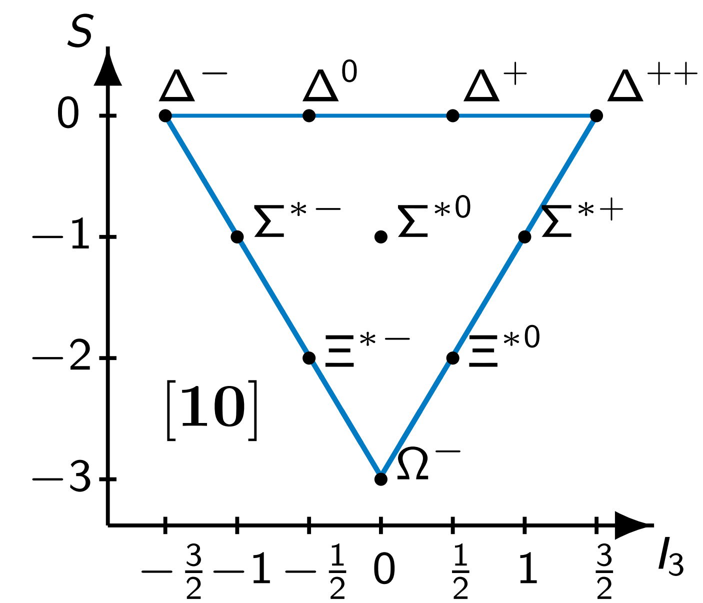
- **SU(3) symmetry** used to restrict no. of independent parameters
- Further reduction through **decuplet dominance**

Decuplet Dominance
in YNN three-body forces

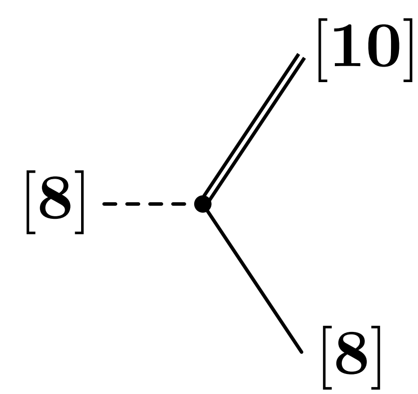
- Estimates of **YNN** 3-body interactions assuming dominant **decuplet** (Σ^*, Δ) intermediate states



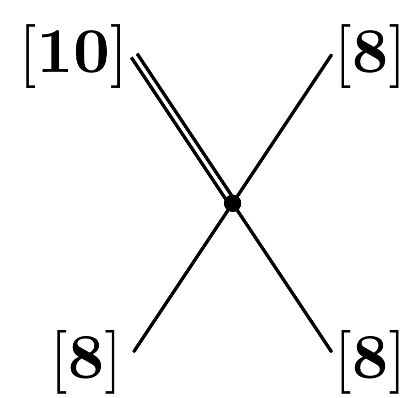
promotion from **NNLO** to **NLO**



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



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

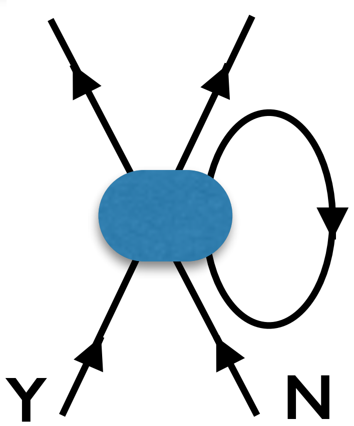


Pauli-forbidden
in NN sector

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



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

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

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

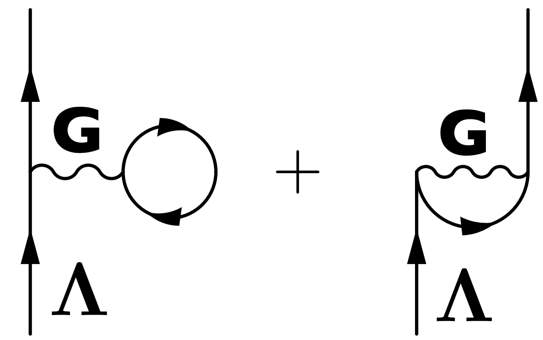
$$V_{\Lambda n}^{\text{eff},\pi} = \frac{C H\, g_A}{9 f^2 \Delta} [\rho_n + 2\rho_p] + \mathcal{G}(k_F^p, k_F^n; p, q)$$ **+/-**

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

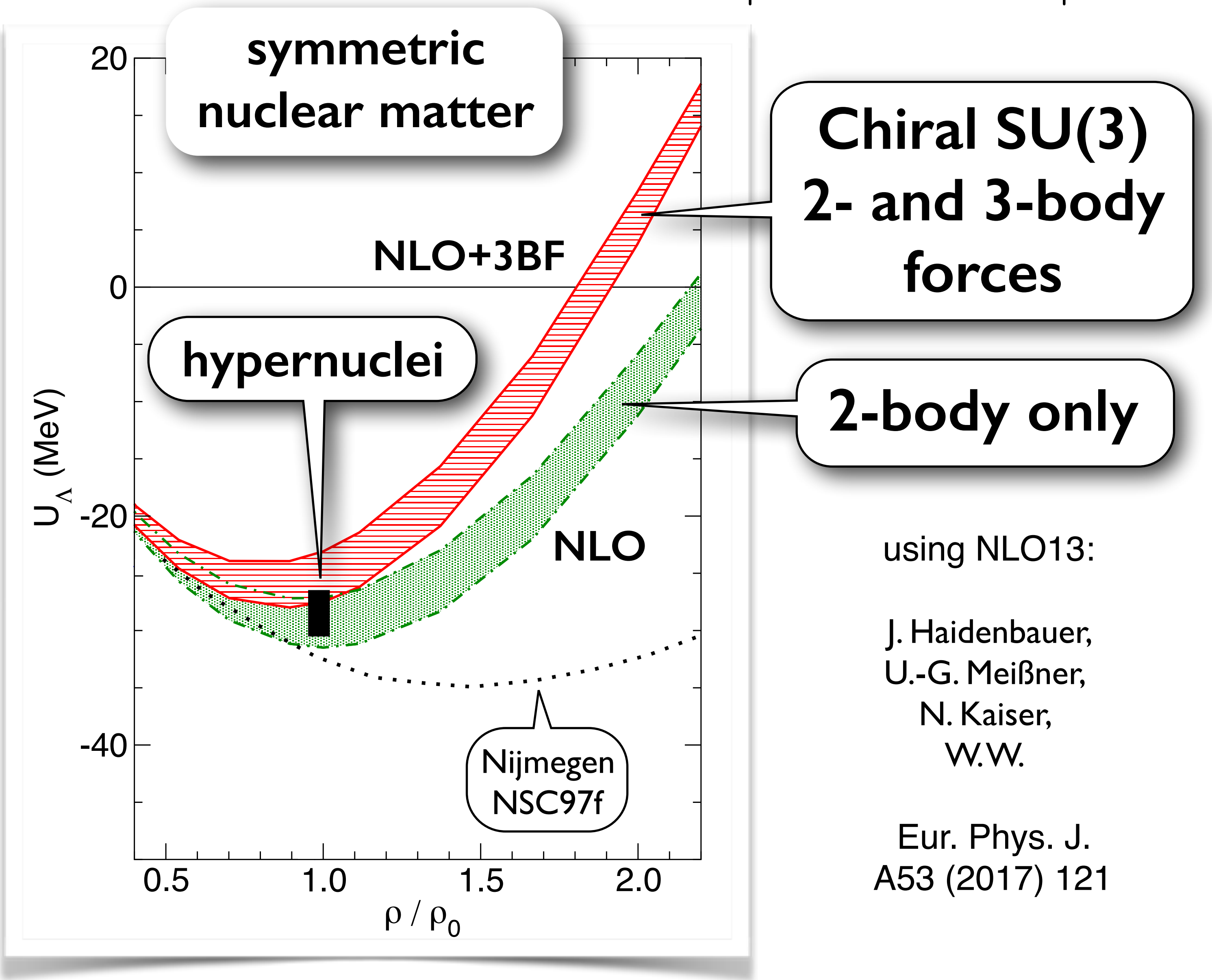
- **Decuplet-octet mass difference** $\Delta = M_{[10]} - M_{[8]} = 270\, MeV$
- **Coupling parameters :** $C = \frac{3}{4} g_A \simeq 1 \quad -\frac{1}{f^2} \lesssim H \lesssim +\frac{1}{f^2}$ (dim. arguments natural size)

Density dependence of Λ single-particle potential

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



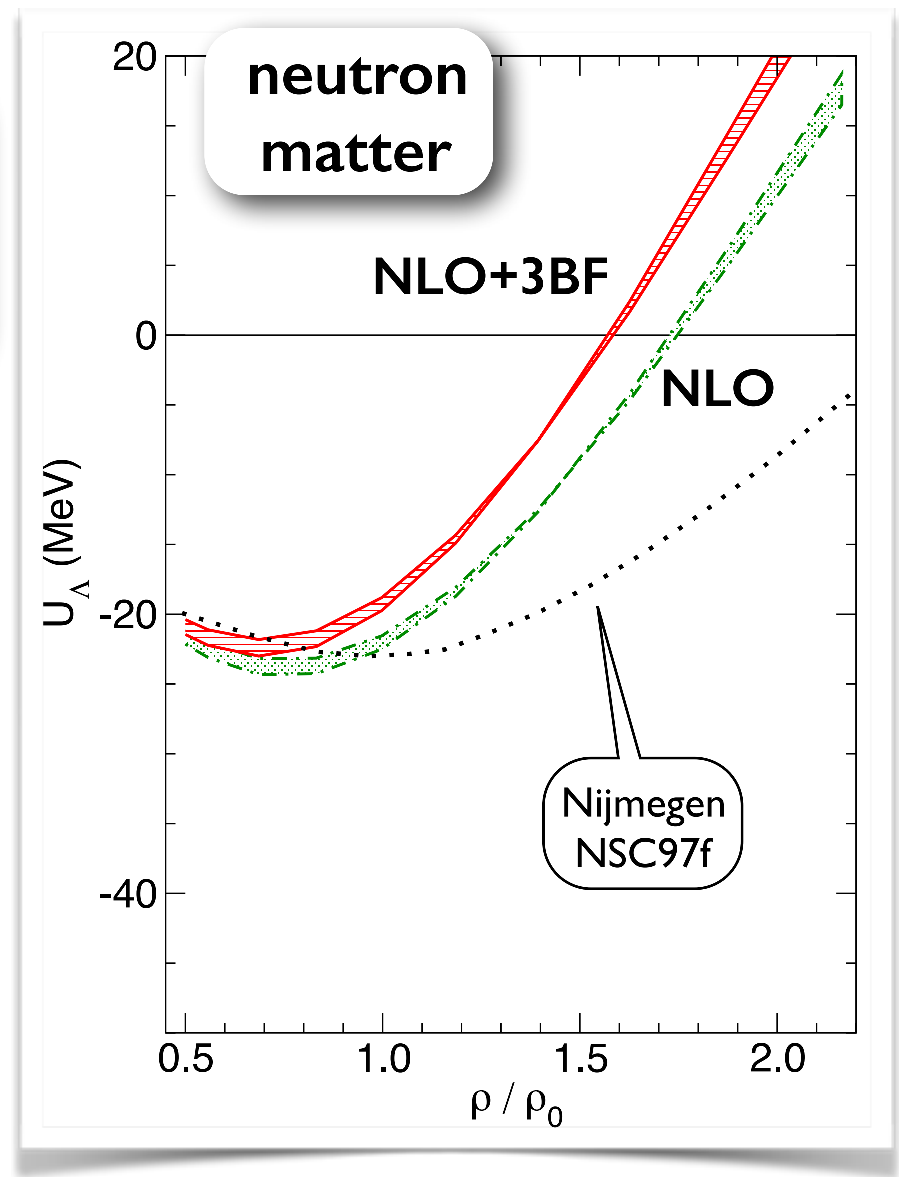
$$\mathbf{G}(\omega) = \mathbf{V} + \mathbf{V}\,\frac{\mathbf{Q}}{\mathbf{e}(\omega) + \mathbf{i}\epsilon}\,\mathbf{G}(\omega)$$



using NLO13:

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

Eur. Phys. J. A53 (2017) 121



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

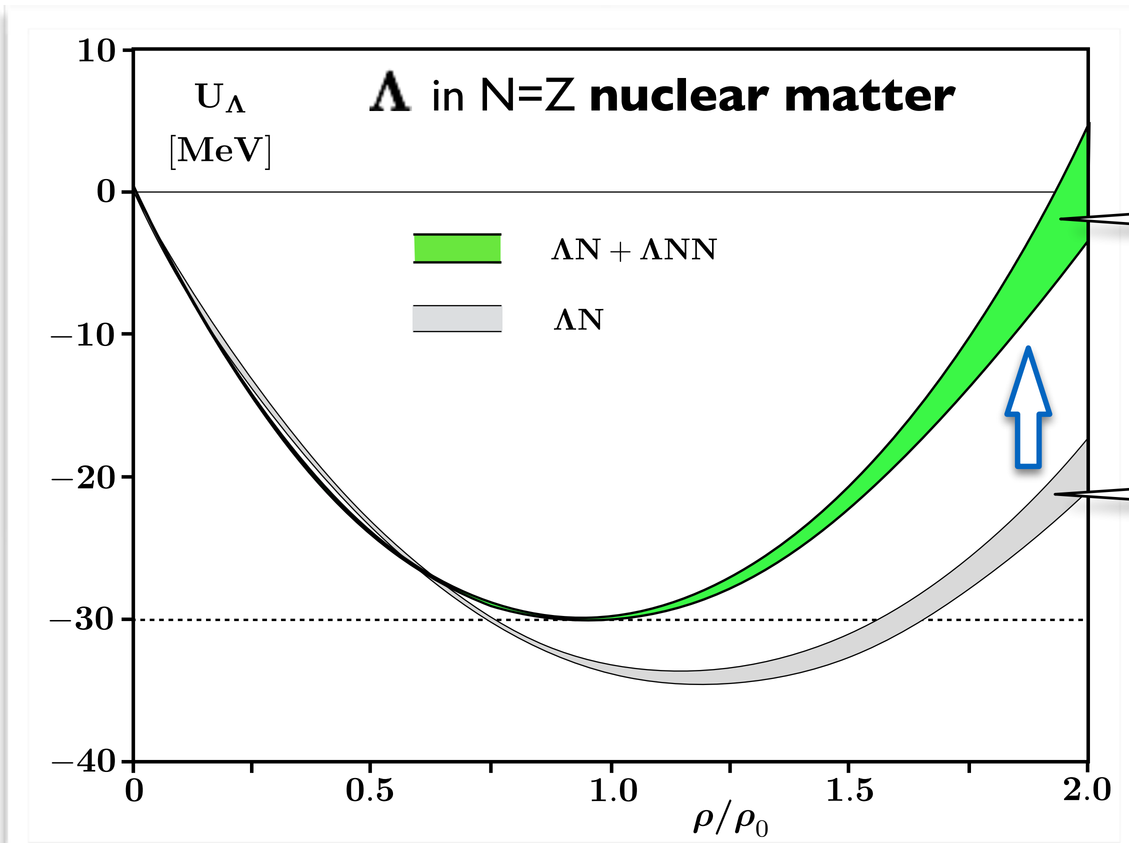
Density dependence of Λ single particle potential (contd.)

- Further extended Brueckner - Bethe - Goldstone calculations

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

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

Strong additional repulsion from YNN three-body forces



2+3-body
$-H_1 \in [2.2, 2.5]\ f_\pi^{-2}$
$H_2 \in [0, 1.2]\ f_\pi^{-2}$

2-body only

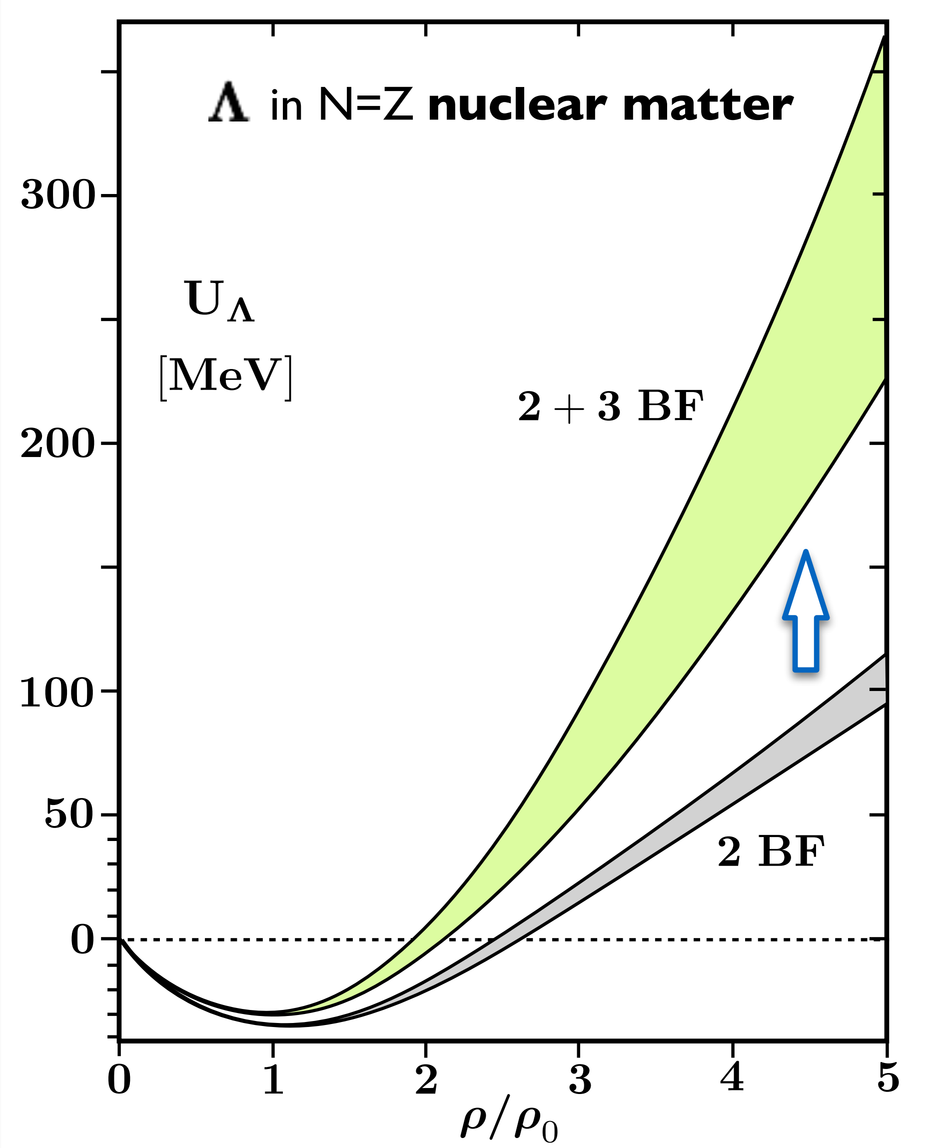
D. Gerstung, N. Kaiser, W.W. (2019)

- Constrained by hypernuclear physics : $U_\Lambda(\rho=\rho_0) \simeq -30\,\mathrm{MeV}$

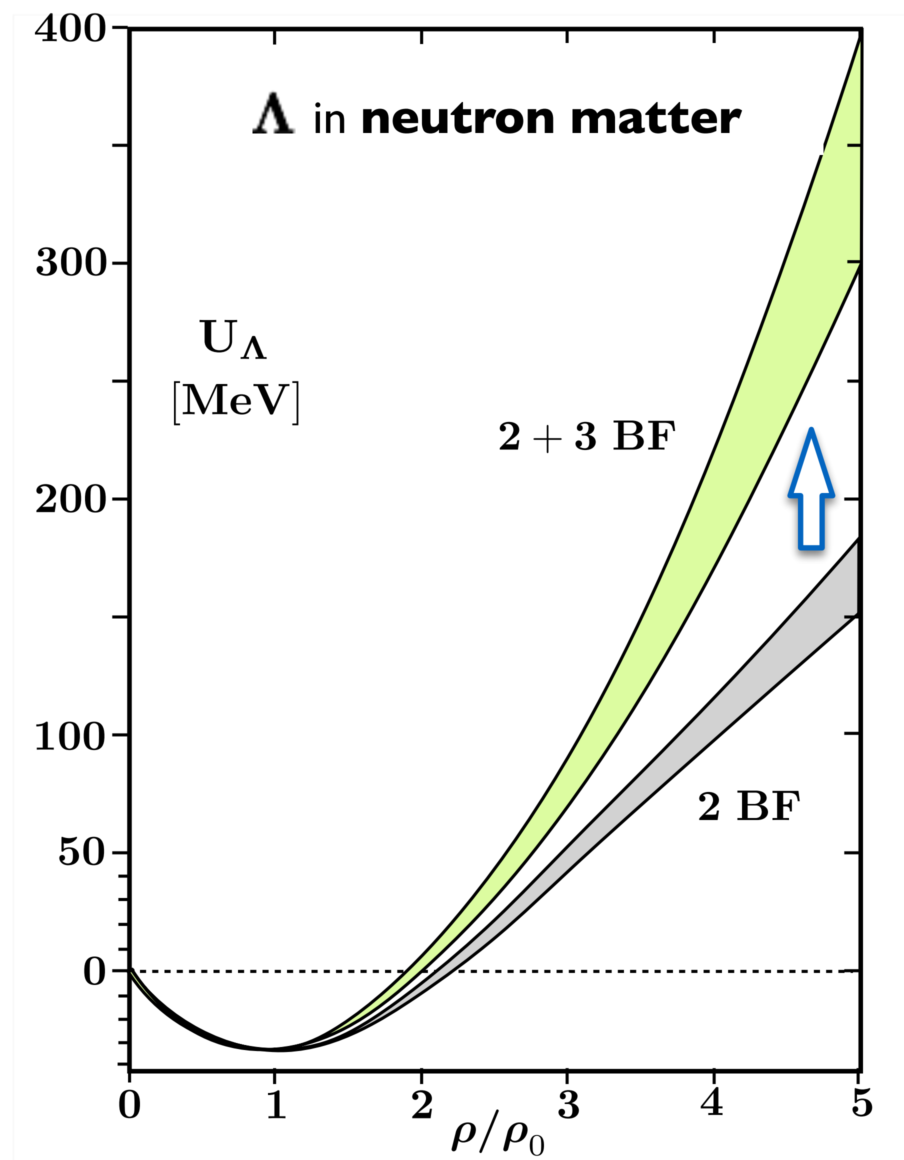
A. Gal, E. Hungerford, D. Milner
Rev. Mod. Phys. 88 (2016) 035004

Density dependence of Λ single-particle potential (contd.)

- **Extrapolations to high baryon densities**
- **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**



Strong additional repulsion from YNN three-body forces



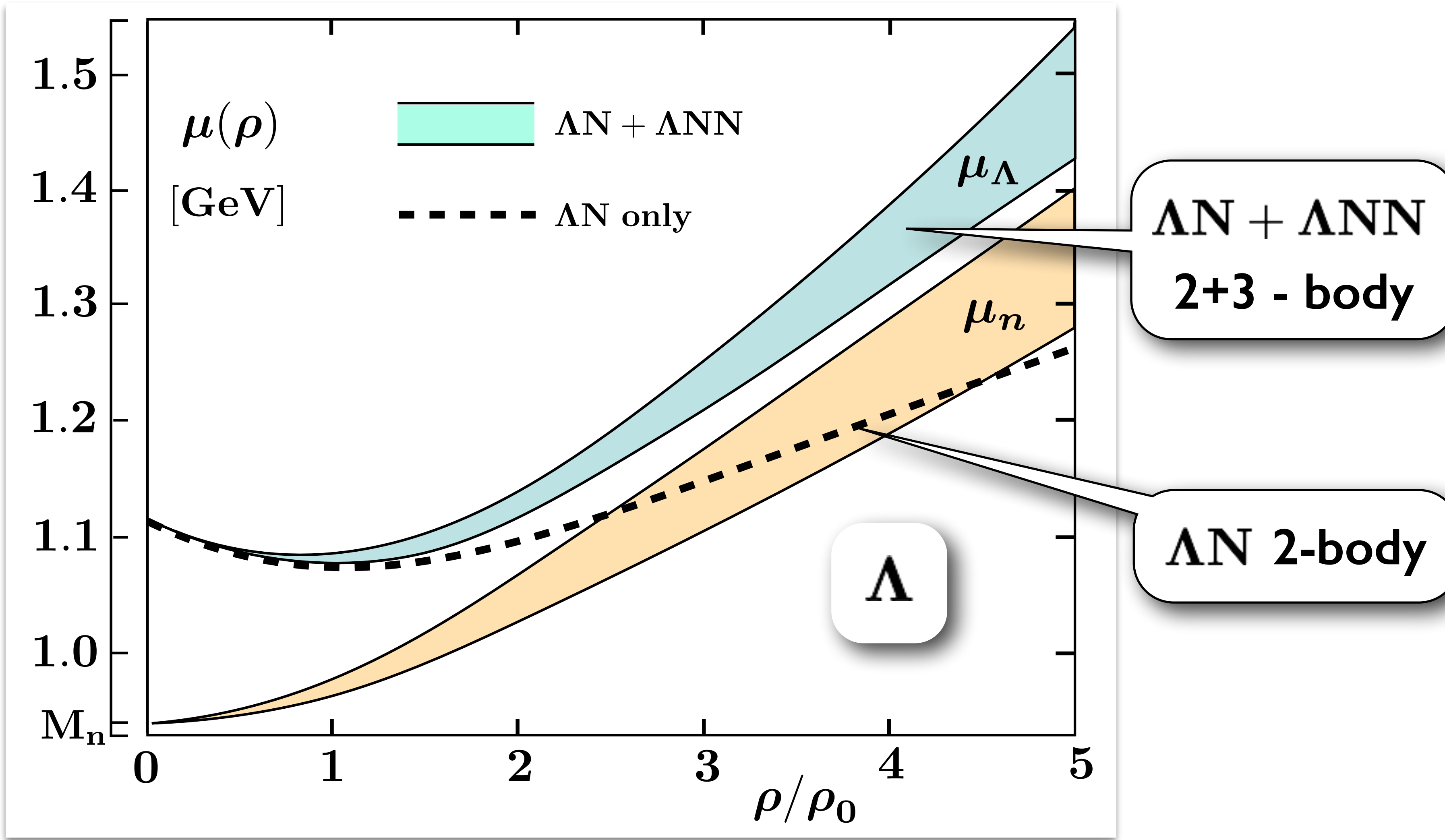
D. Gerstung, N. Kaiser, W.W. (2019 / 2020)

Λ Hyperons in Neutron Stars ?

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

  Equality of **chemical potentials** $\mu_\Lambda = \mu_n$

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



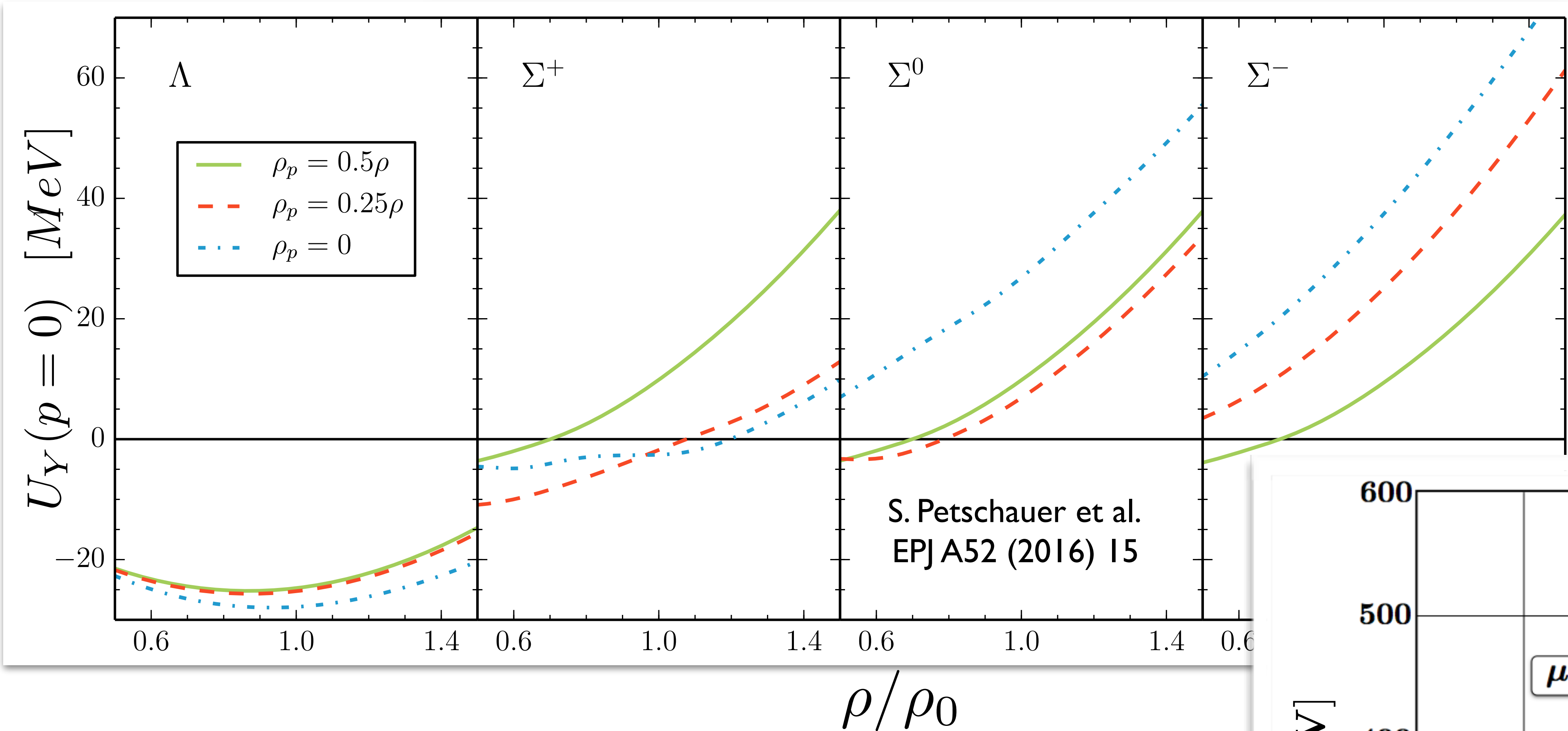
- **Hyperon chemical potential** in **neutron matter** from **Chiral SU(3) EFT** interactions

  D. Gerstung, N. Kaiser, W.W. (2019 / 2020)

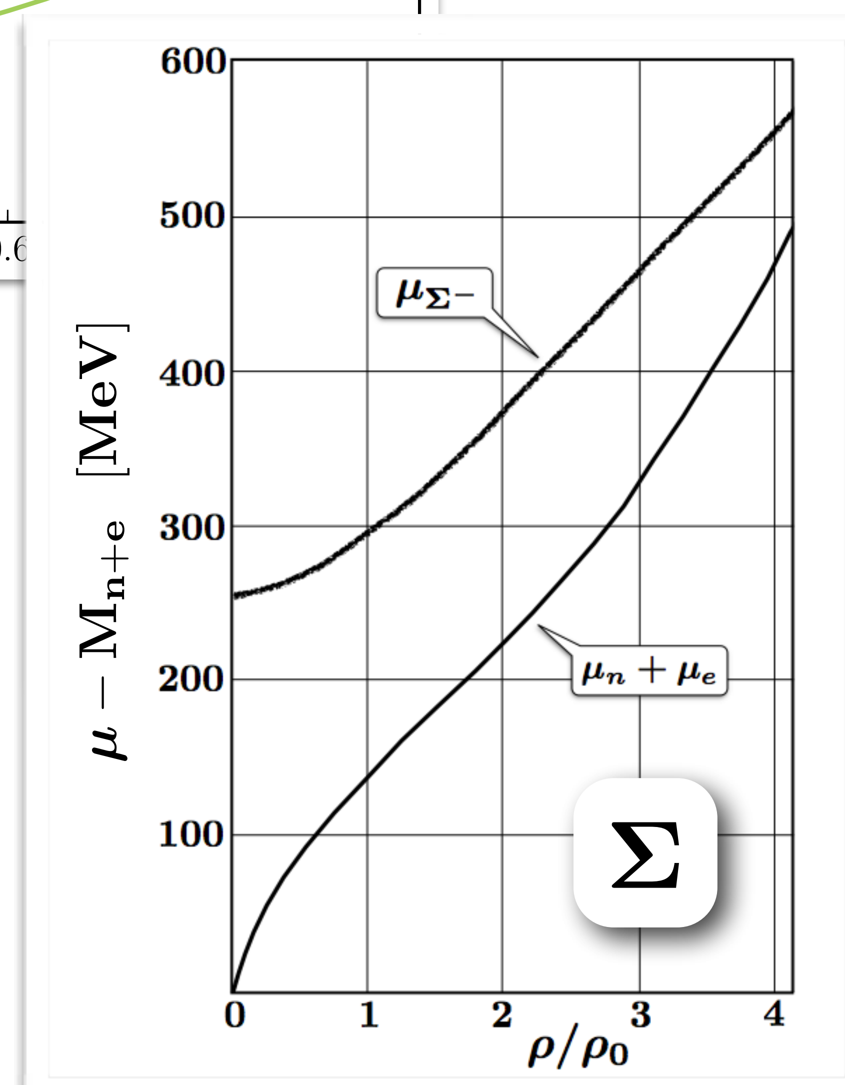
- **Neutron chemical potential** in **neutron star matter** from **Chiral EFT + FRG** equation-of-state

  M. Drews, W.W. PPNP 93 (2017) 69

Σ Hyperons in Neutron Stars ?



- Hyperon potentials from **Chiral SU(3) EFT** interactions



- Σ-nuclear potentials are **repulsive**
- Condition for appearance of Σ^- in neutron star matter :

$$\mu_{\Sigma^-} = \mu_n + \mu_e = 2\mu_n - \mu_p$$

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

SUMMARY & OUTLOOK

- **Neutron star matter:**
  EoS constrained by increasing amounts of observational data
  - $\mathbf{M}_{max} \simeq \mathbf{2\,M_\odot}$, $\mathbf{R} \sim \mathbf{11 - 13\,km}$ $\quad (R_{1.4\,M_\odot} = 11.0^{+0.9}_{-0.6}\,km)$ C.D. Capano et al., arXiv:1908.10352
  - **Tidal deformability from GW signals of binary n-star merger**

- **ChEFT,** (non-perturbative) **FRG and Fermi-Liquid Theory**
  - **Conventional EoS consistent with "stiffness" constraints**
  - **No chiral phase transition in n-matter up to at least** $\rho > 5\,\rho_0$
  - **New keywords: continuity of quark and hadron matter ? Superfluidity…**

  Rept. Prog. Phys. 81 (2018) 056902 arXiv:1903.08963 arXiv: 1908.09360

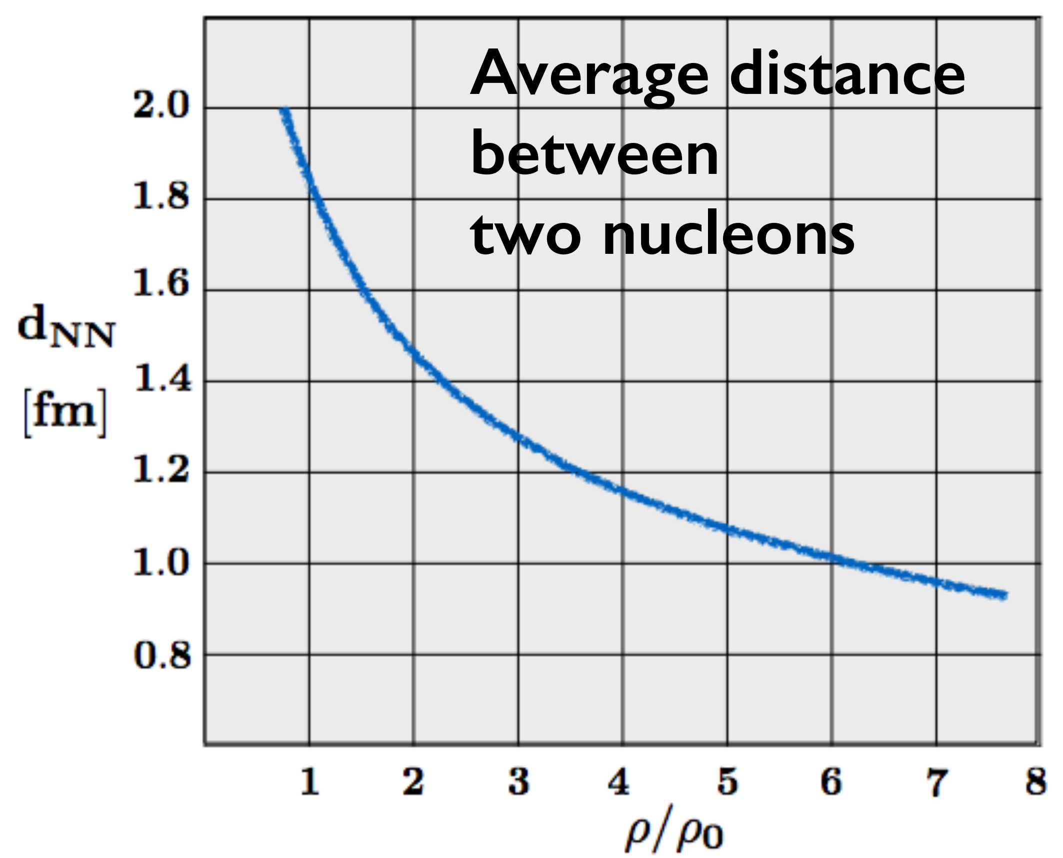
- **Strangeness in the core of neutron stars ?**
  - **Hyperon-nuclear interactions from Chiral SU(3) EFT**
  - **Repulsive YNN three-body forces are capable of resolving hyperon puzzle**
  - **But: quest for much improved hyperon-nucleon/nuclear data base !!**

Appendix

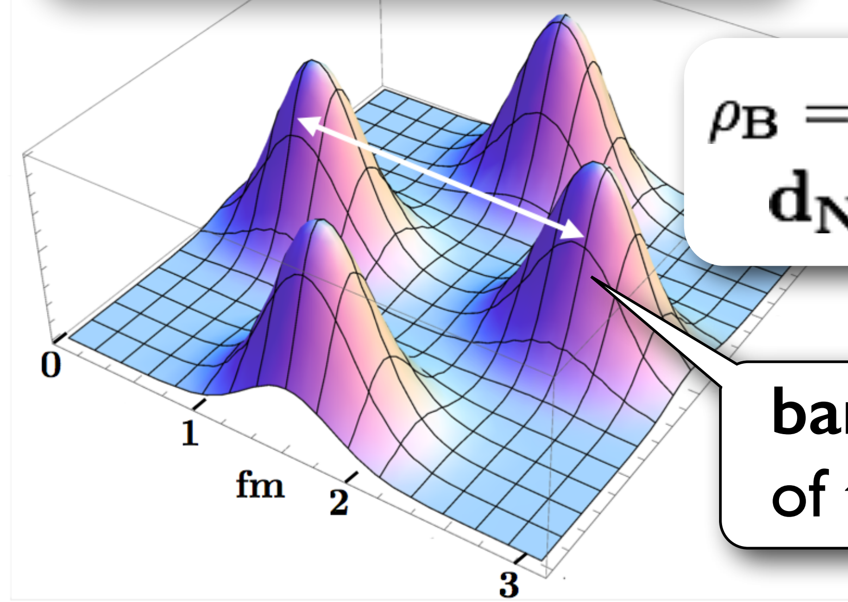
Supplementary Materials

Chiral Nucleon-Meson Field Theory
and
Functional Renormalisation Group

Densities and Distance Scales in Baryonic Matter



normal nuclear matter



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

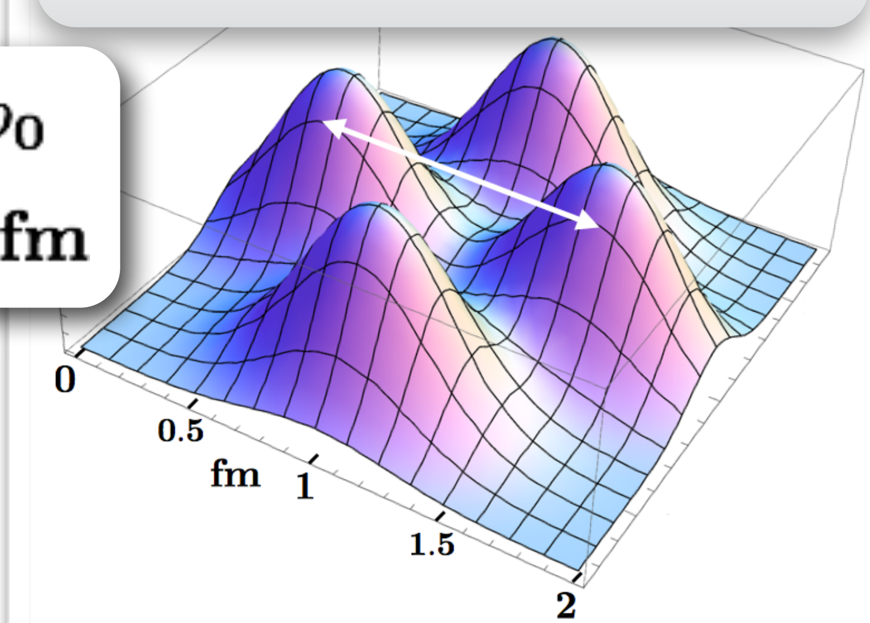
$d_{NN} \simeq 1.8\ \mathrm{fm}$

baryonic core of the nucleon

neutron star core matter

$\rho_B \sim 5\,\rho_0$

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



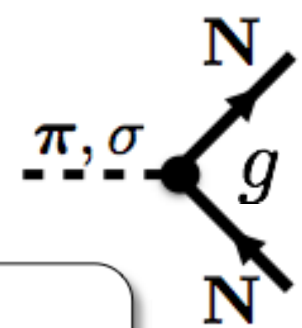
- (Multi-)pionic field in the space between baryonic core sources
- Quark cores of nucleons overlap (percolate) at baryon densities

$$\rho_B > 5\,\rho_0$$

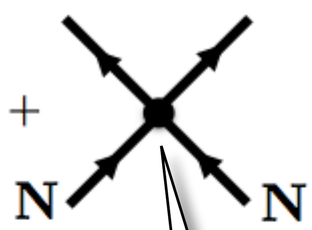
Mesons, Nucleons, Dense Baryonic Matter
and
Functional Renormalisation Group

- **Chiral nucleon - meson Lagrangian**

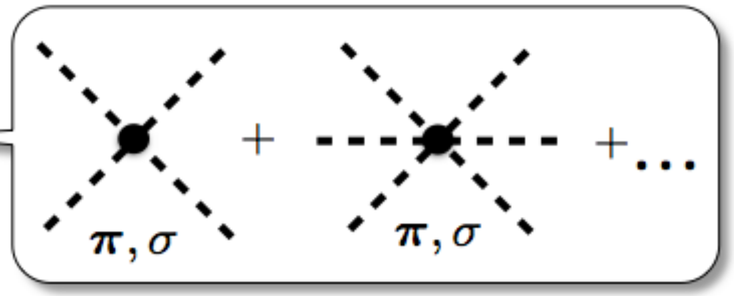
$$\mathcal{L} = \bar{\mathbf{N}}\, i\gamma_\mu \partial^\mu \mathbf{N} + \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma + \partial_\mu\boldsymbol{\pi}\cdot\partial^\mu\boldsymbol{\pi}\right) +$$



$+$



$- \mathcal{U}(\boldsymbol{\pi}, \sigma)$



isoscalar & isovector current-current interactions
mediated by heavy vector fields

- **Nambu-Goldstone boson** $\boldsymbol{\pi}$ and "**heavy**" σ

- **Potential** $\mathcal{U}(\sigma, \boldsymbol{\pi})$ **: polynomial** in $\chi = \boldsymbol{\pi}^2 + \sigma^2$ constructed to reproduce **vacuum physics** and **equilibrium nuclear matter**

- **Symmetry-breaking mass term + $\chi^2 \log \chi$ term**

Review: M. Drews, W.W. : Prog. Part. Nucl. Phys. 91 (2017) 347

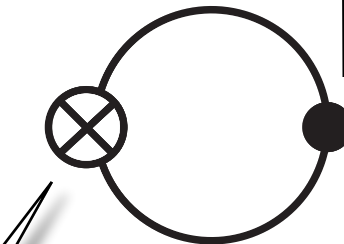
Renormalisation Group strategies

k-dependent action

full propagator

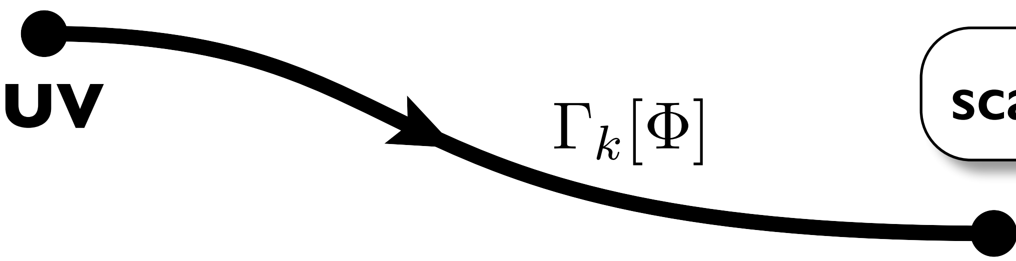
Wetterich's FRG flow equations

$$k\,\frac{\partial \Gamma_k[\Phi]}{\partial k} = \frac{1}{2}\mathrm{Tr}\left[k\frac{\partial R_k}{\partial k}\cdot\left(\Gamma_k^{(2)}[\Phi]+R_k\right)^{-1}\right] =$$



scale regulator R_k

$\Gamma_{k=\Lambda}[\Phi] = S$

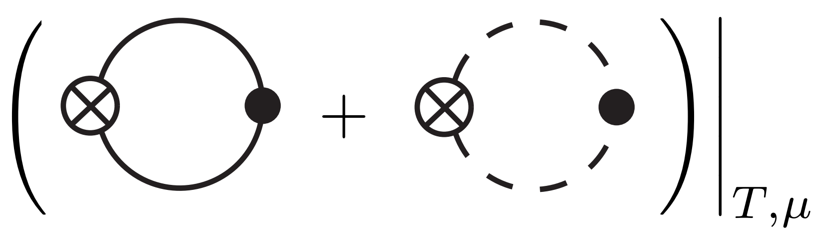


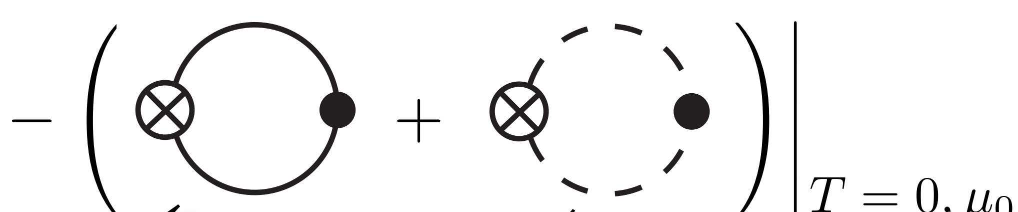
$\Gamma_{k=0}[\Phi] = \Gamma[\Phi]$

C. Wetterich:
Phys. Lett. B 301 (1993) 90

- **Thermodynamics:**

$$k\,\partial_k \bar{\Gamma}_k(T,\mu) =$$





nucleons

pions

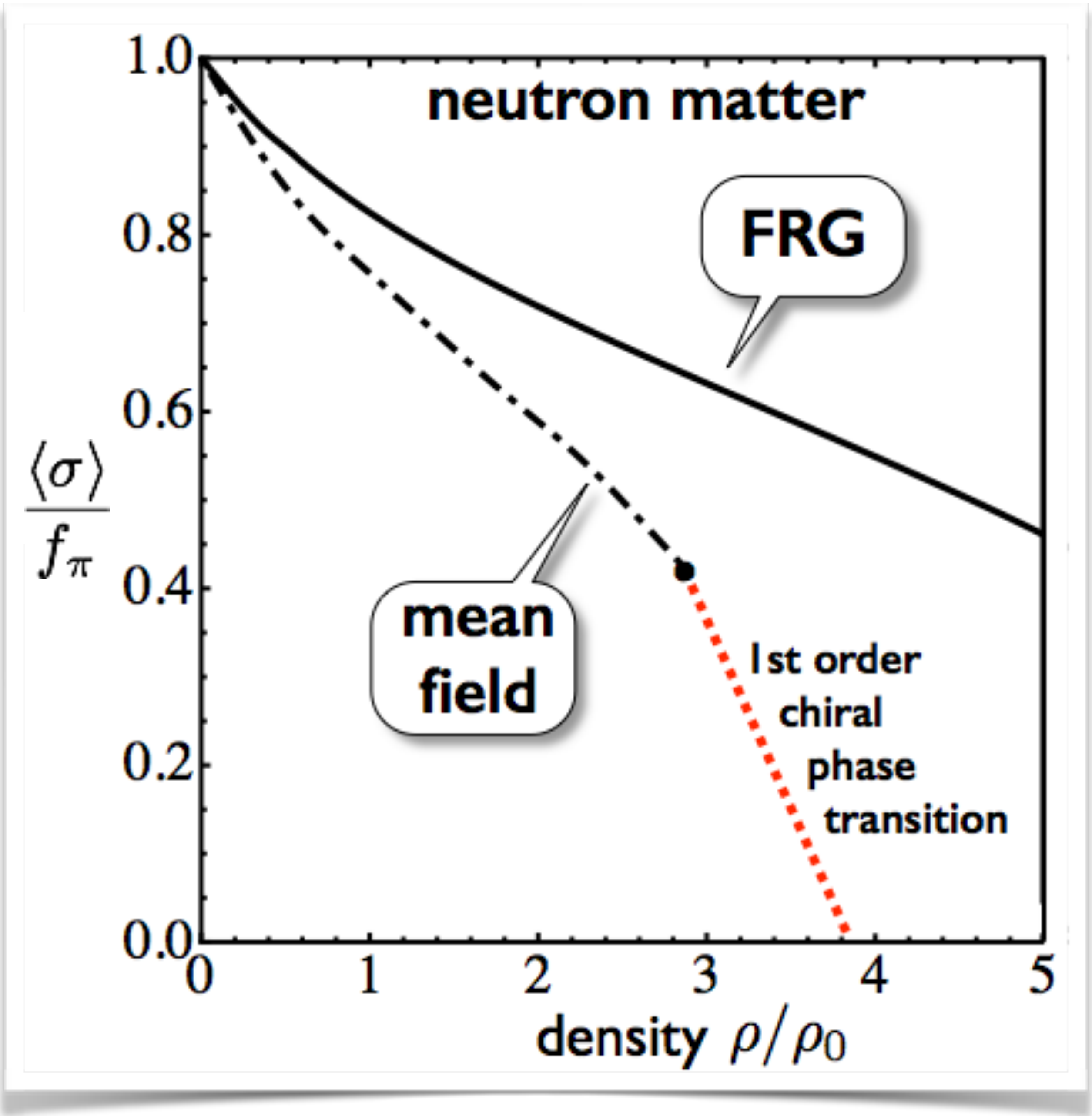
Non-perturbative treatment of :

- multi-pion exchange processes
- nucleon-hole excitations
- multi-nucleon correlations

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**

(pionic, nucleon-hole, many-body correlations)

beyond mean-field approximation:

NO first-order chiral phase transition in the n-star density range