

LAMBDA-NUCLEAR THREE-BODY FORCES and **HYPERONS in NEUTRON STARS**



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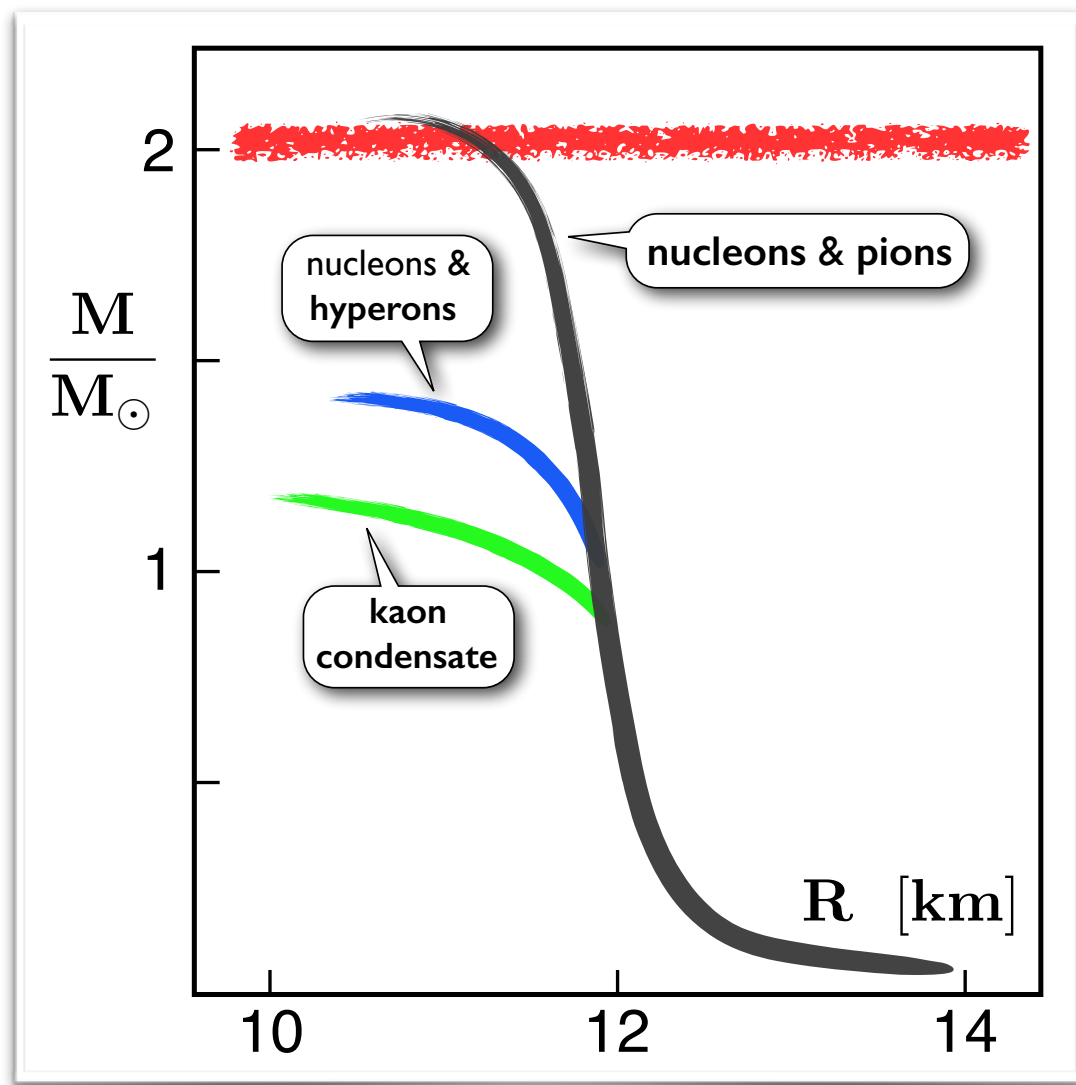
- ★ **Brief overview: neutron star equation-of-state**
 - Constraints from $2 M_{\odot}$ stars and mergers (GW signals)
 - Neutron star matter as a (relativistic) Fermi Liquid

- ★ **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 $M \simeq 2 M_{\odot}$



- 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 (guided by QCD symmetries)

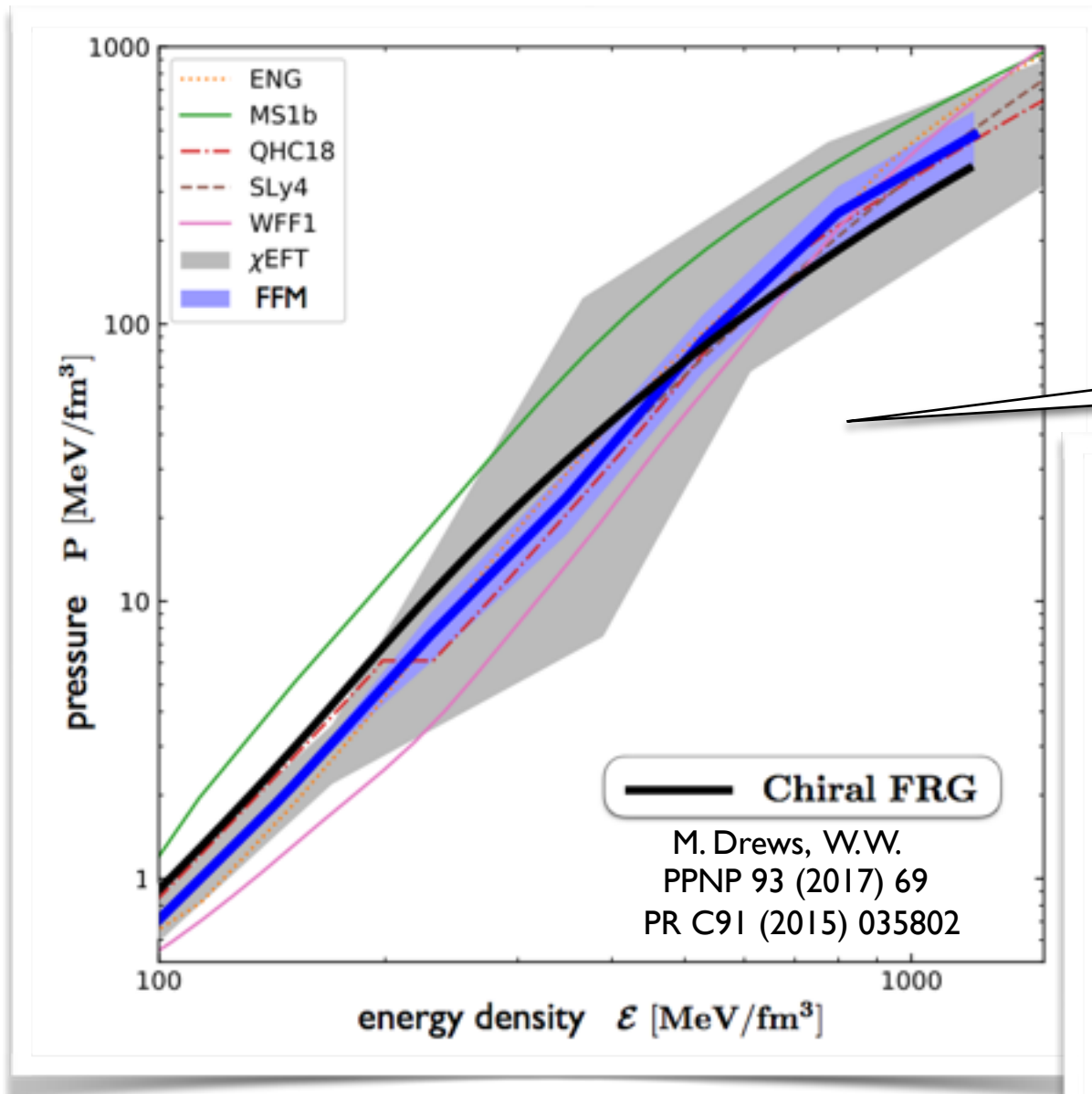
Part I.

Status of Neutron Star Equation-of-State

- **Stiffness constraint:**
EoS must support massive ($2.17 M_{\odot}$) neutron star
- **Compatibility with GW neutron star merger signals**
(tidal deformability)
- **Microscopic EoS and Landau Fermi-Liquid theory**

NEUTRON STAR MATTER Equation of State

- Comparisons with EoS reconstructions from neutron star data

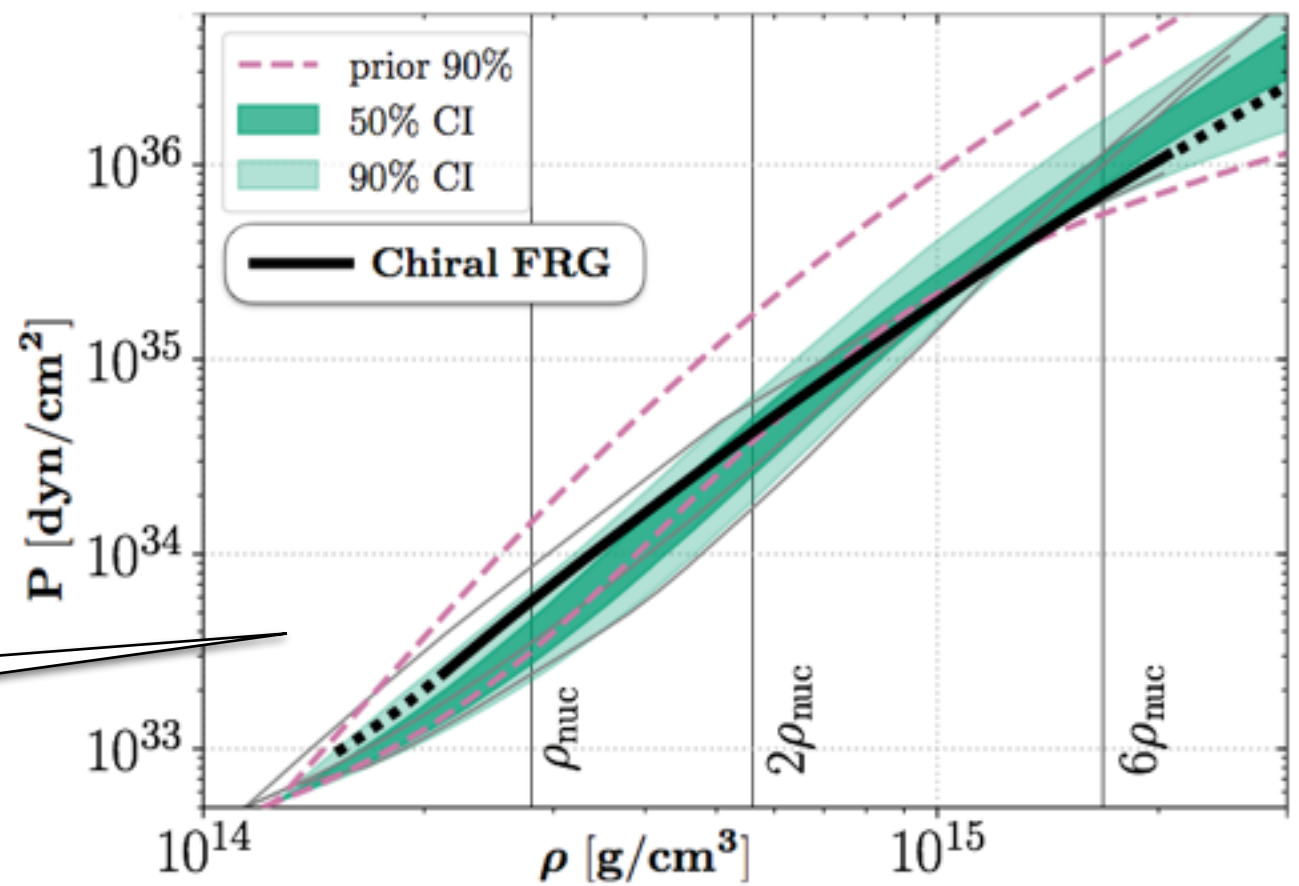


utilising machine learning
(neural network) methods

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

utilising GW 170817 data analysis

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



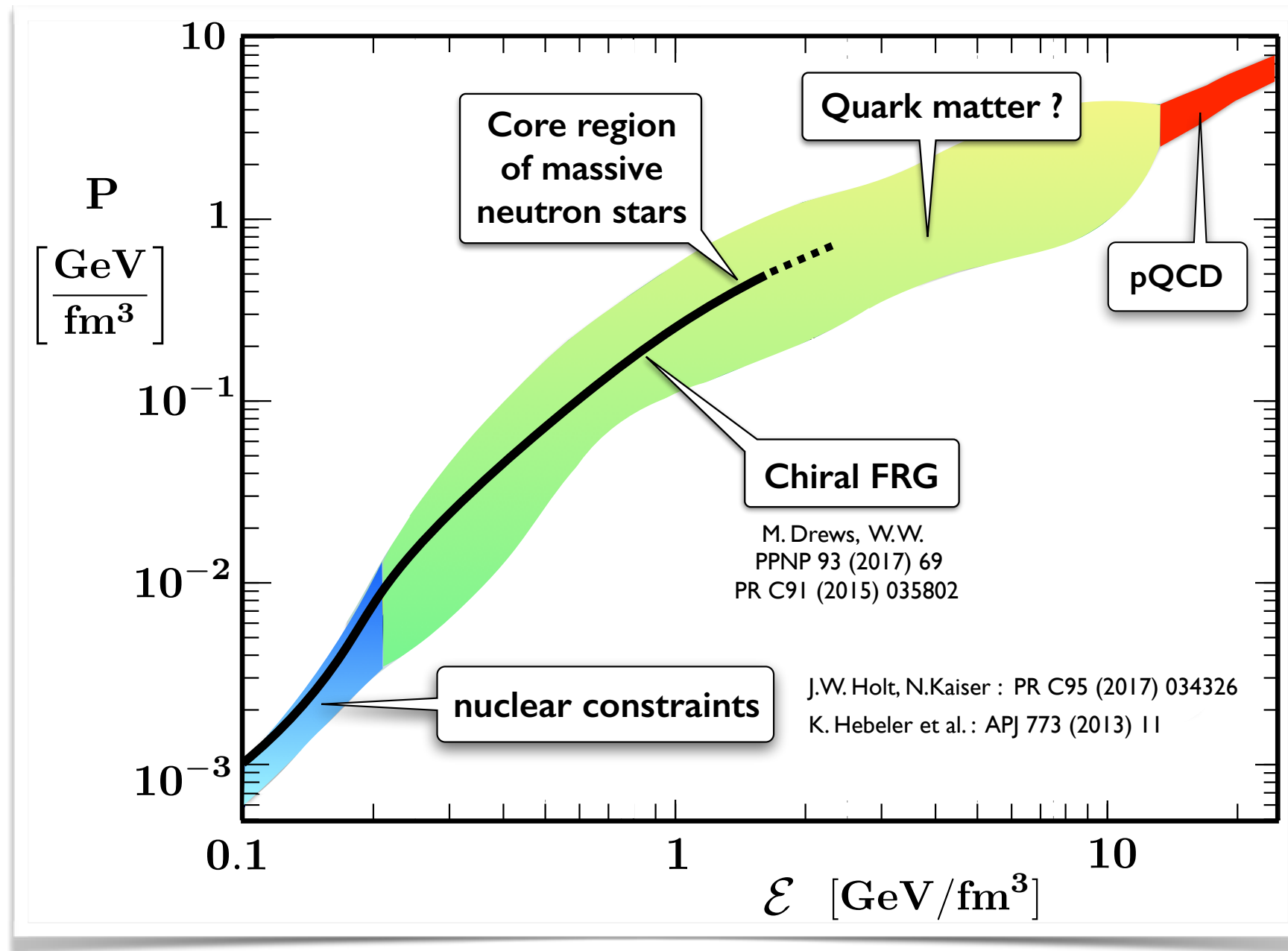
NEUTRON STAR MATTER Equation of State

- incl. $M_{max} \gtrsim 2 M_{\odot}$ + 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 $M = (2.17 \pm 0.11) M_{\odot}$

H.T. Cromartie et al. arXiv:1904.06759 [astro-ph.HE]

NEUTRON STAR MATTER : Chiral FRG Equation of State

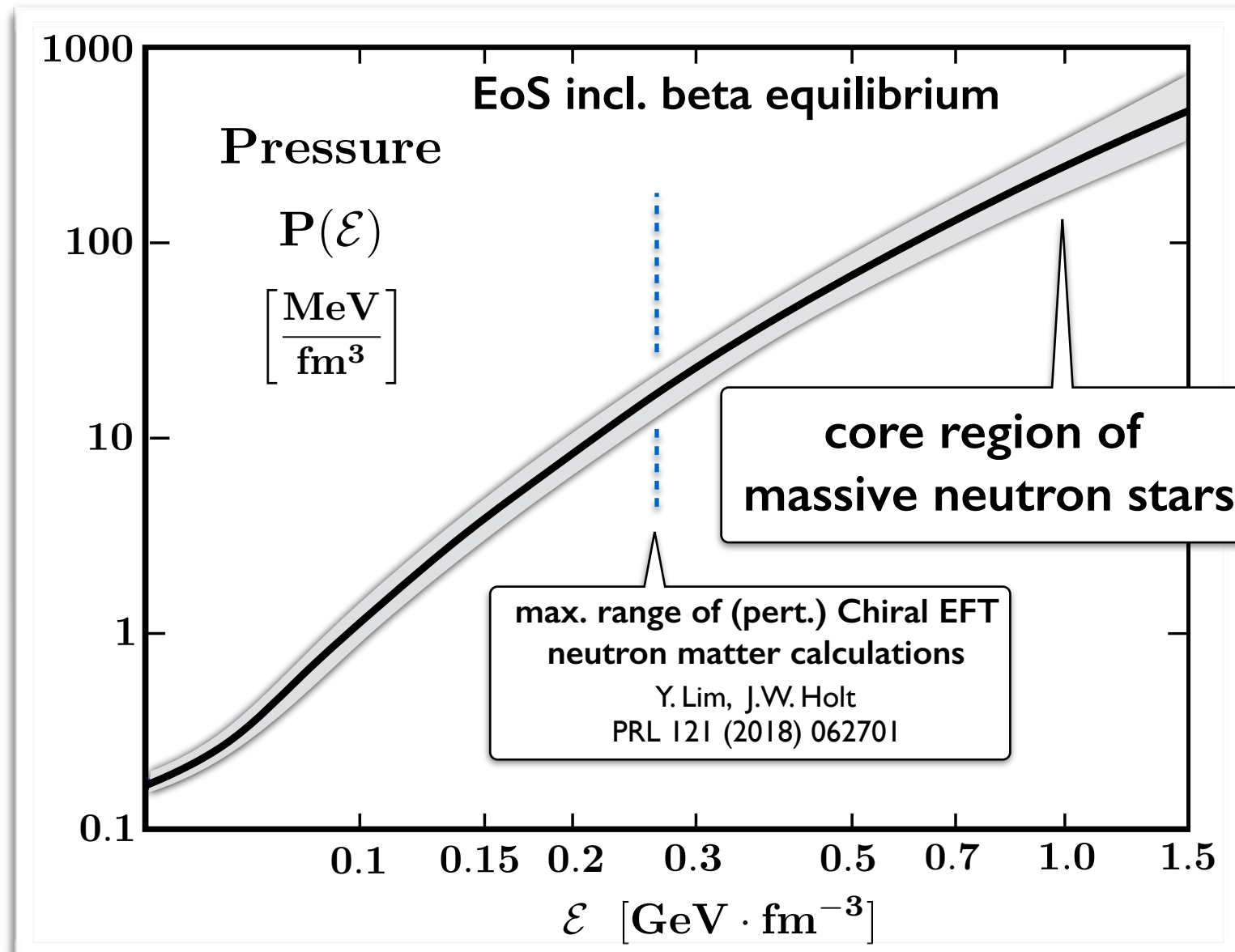
- Chiral Nucleon-Meson Field Theory & Functional Renormalisation Group

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, ...)



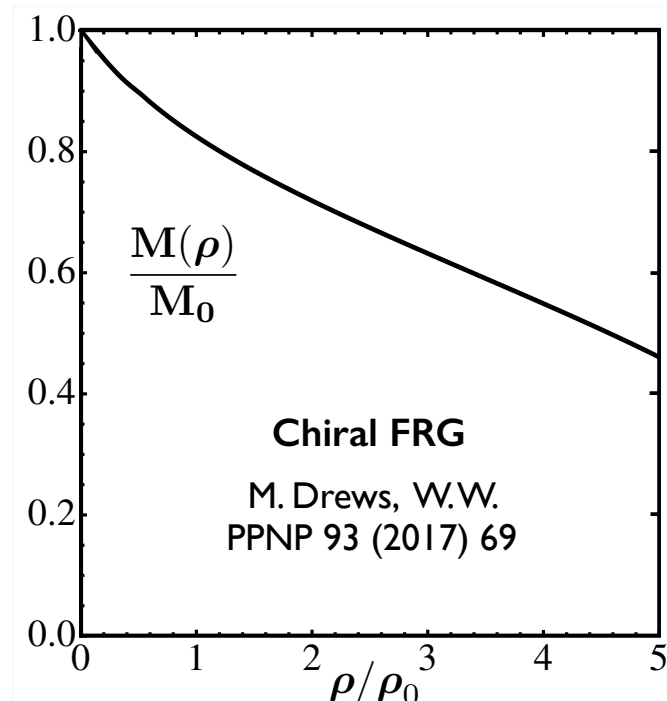
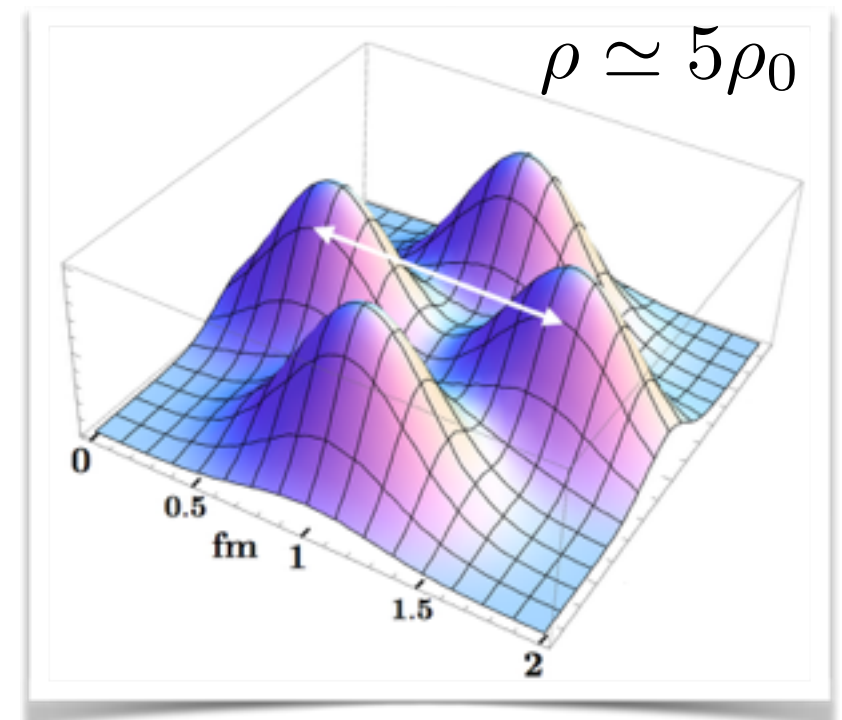
Non-perturbative FRG calculations :

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

DENSE BARYONIC MATTER in NEUTRON STARS as a RELATIVISTIC FERMILY LIQUID

B. Friman, W.W. arXiv: 1908.09722 [nucl-th]

- **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 :



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

- **Landau effective mass** $m^* = \sqrt{p_F^2 + M^2(\rho)}$

- **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 Fermi-Liquid Theory (contd.)

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

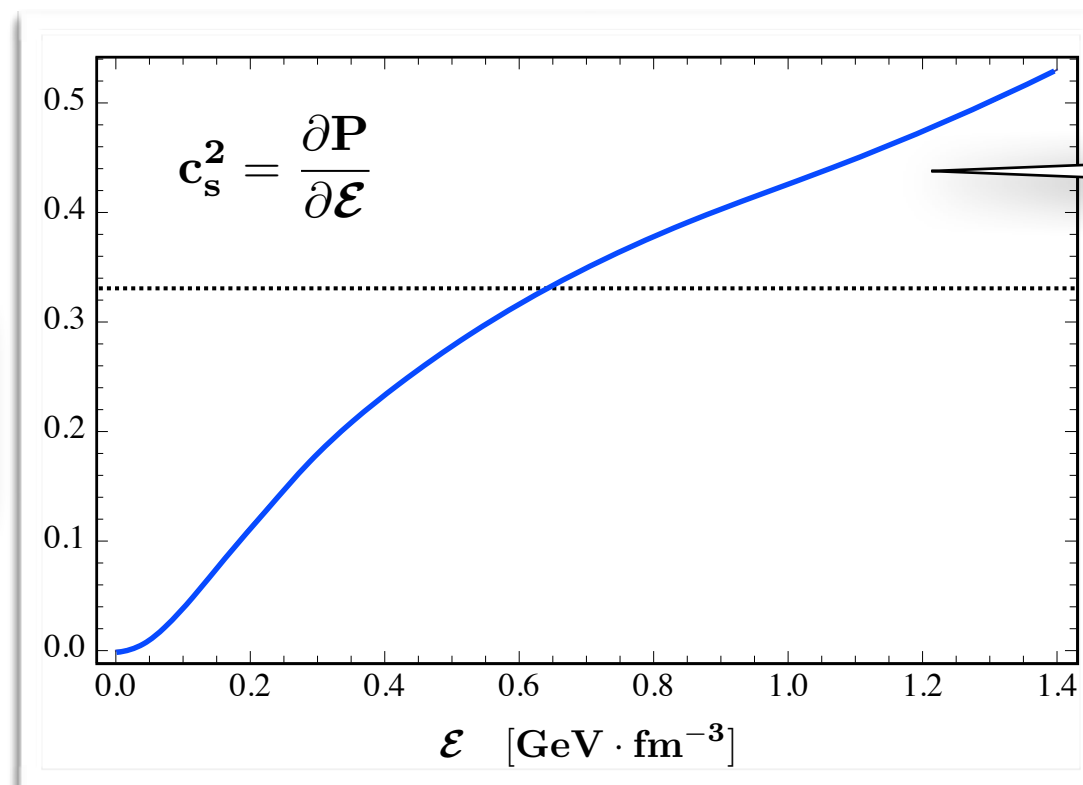
Landau
effective mass

- Leading Landau parameters (T=0) : incompressibility

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

- Speed of sound

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



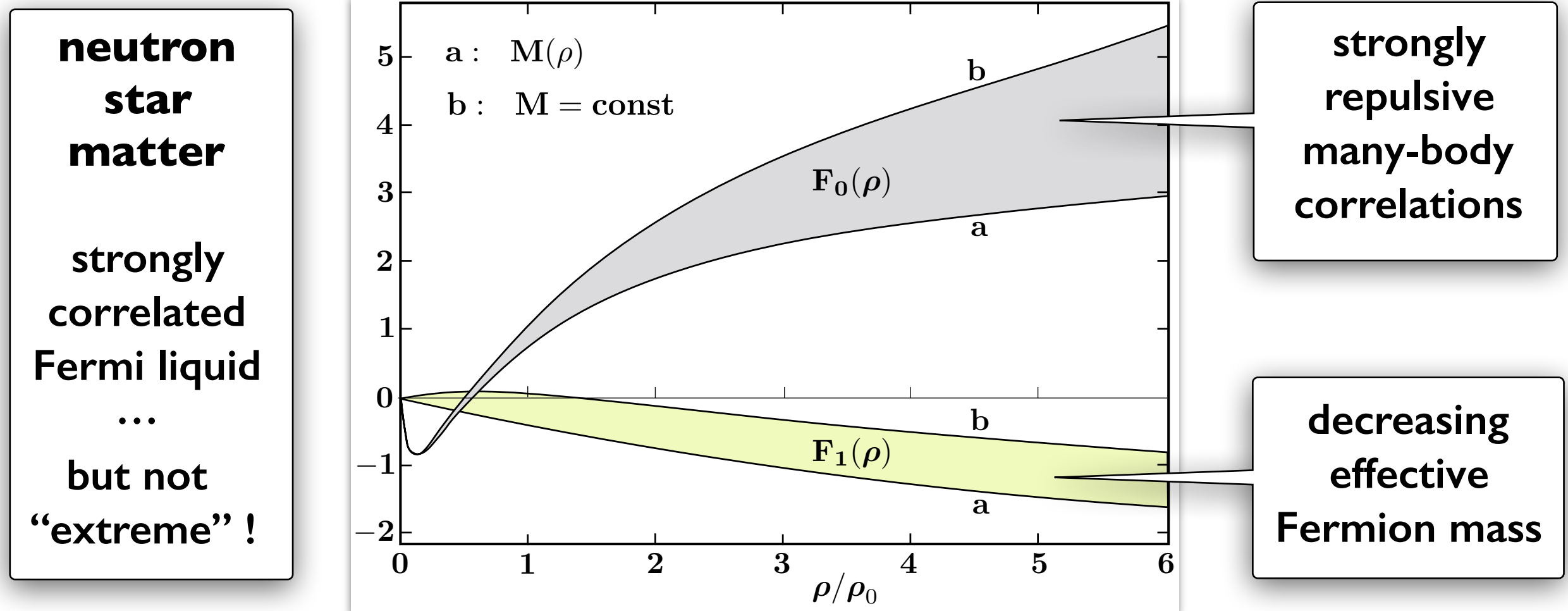
strongly
repulsive
correlations
drive
 $c_s > \frac{1}{\sqrt{3}}$

B. Friman, W.W. arXiv:1908.09722



LANDAU FERMI-LIQUID PARAMETERS

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



B. Friman, W.W. arXiv: 1908.09722

- 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 FERM-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:

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

... **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 !



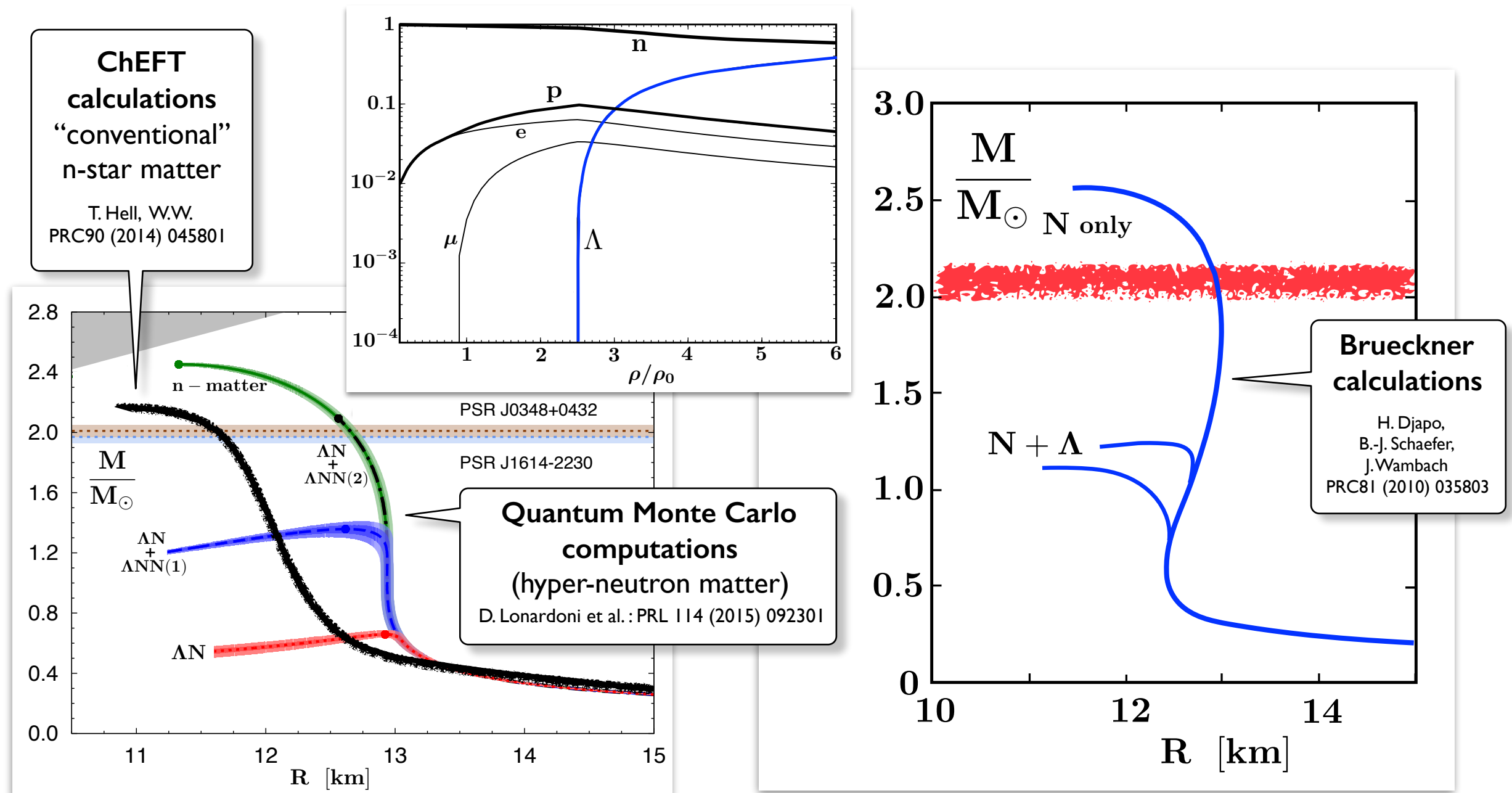
Part II.

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

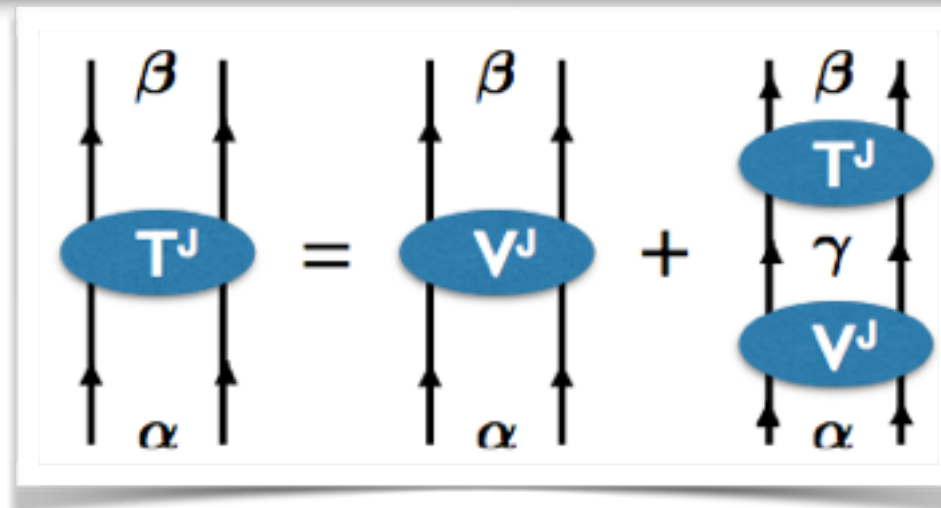
	BB interactions
LO	
NLO	
N ² LO	
N ³ LO	

- Systematically organized hierarchy in powers of Q/Λ
(Q : momentum, energy, pion mass)

3 – body forces	
N ² LO	
N ³ LO	
4 – body forces	
N ³ LO	

- NN interaction : has reached **N⁴LO** level
- YN interaction : so far very limited empirical data base
→ restriction to **NLO** plus **YNN** three-body forces

Coupled-Channels Lippmann-Schwinger Equation



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

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

- Input $\mathbf{V}$ from chiral SU(3) EFT baryon-baryon interaction at NLO
- Momentum of intermediate channels γ determined by :

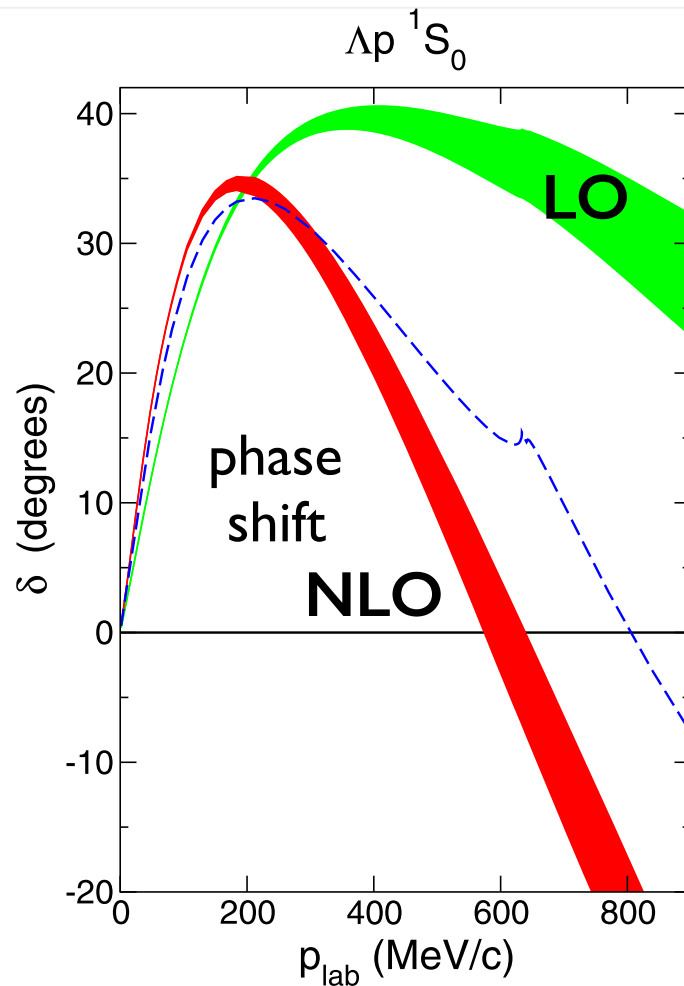
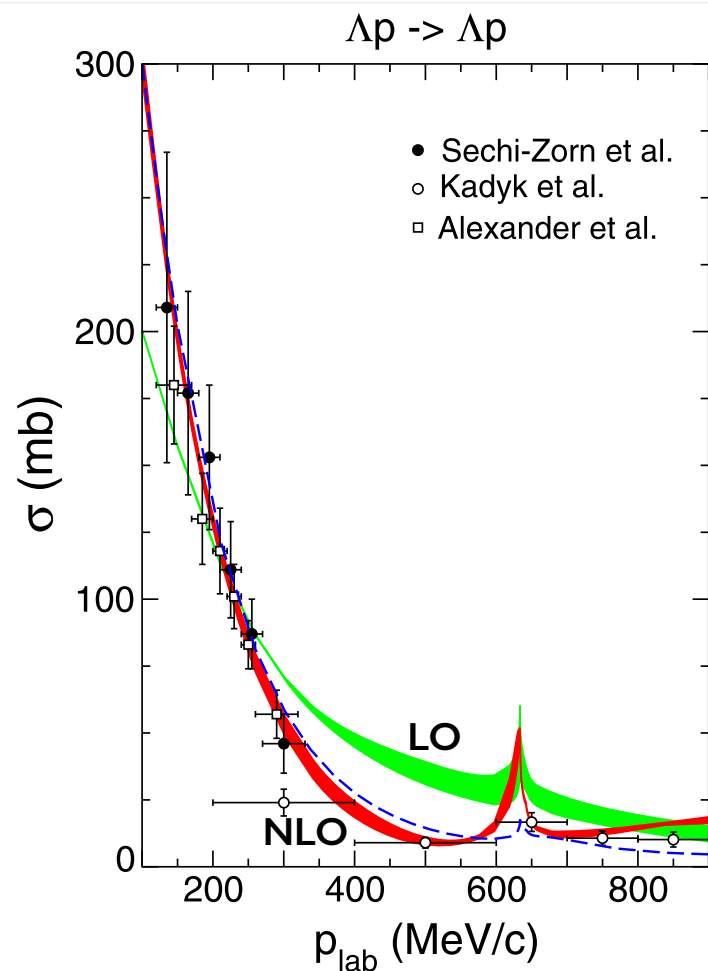
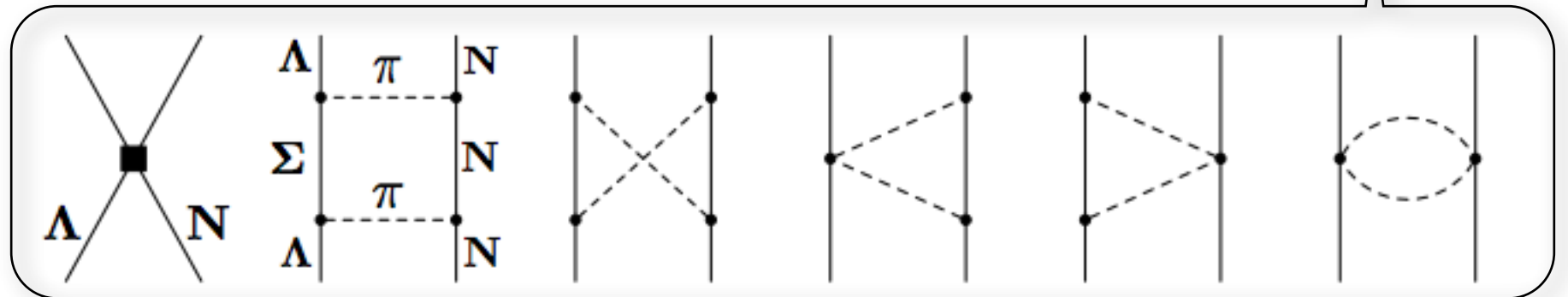
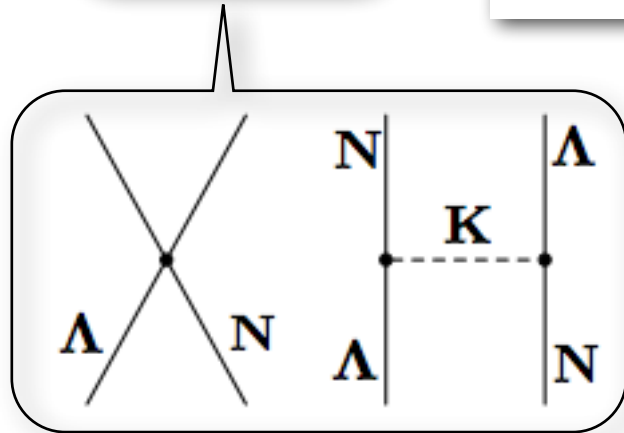
$$\sqrt{s} = \sqrt{M_{\gamma,1}^2 + p_{\gamma}^2} + \sqrt{M_{\gamma,2}^2 + p_{\gamma}^2}$$

- Momentum space cutoff: 0.5 - 0.6 GeV

LO

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

NLO

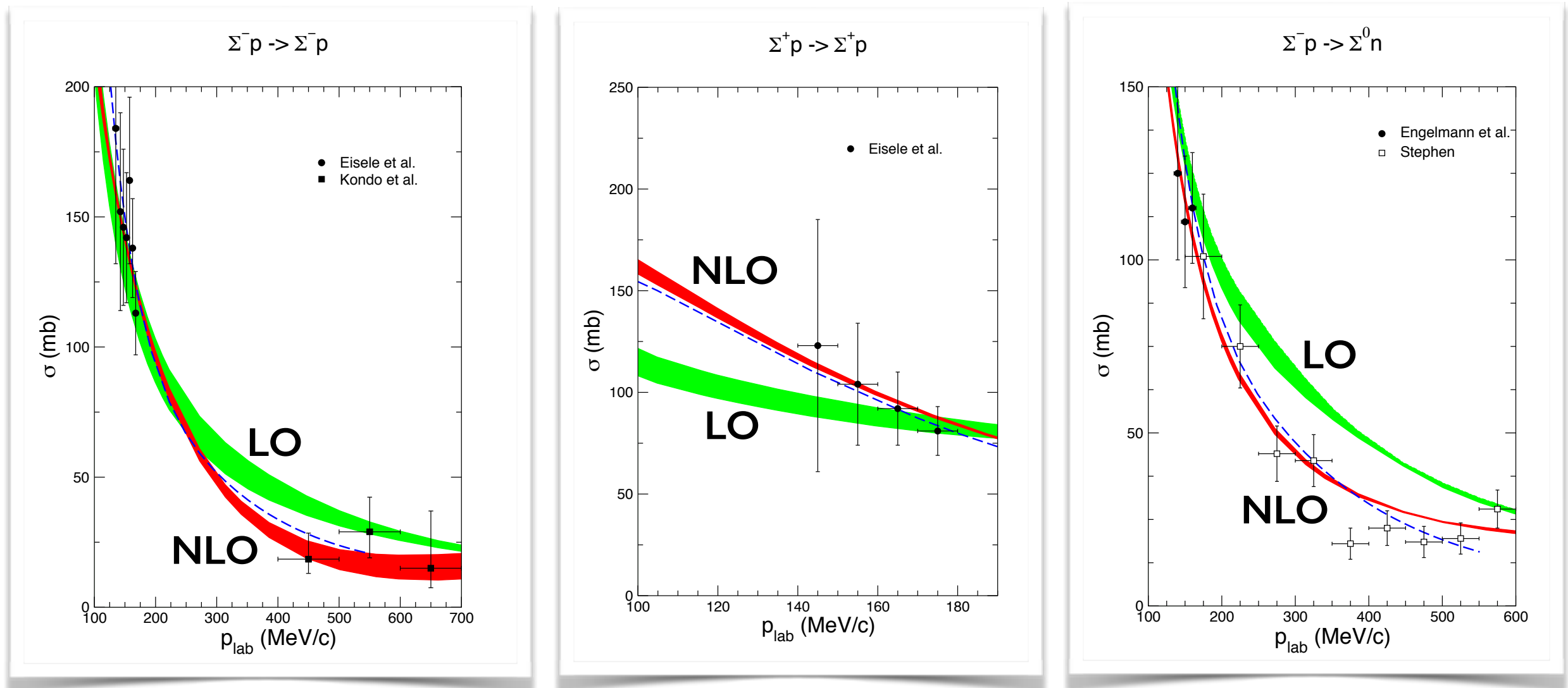


- moderate attraction at low momenta
→ relevant for hypernuclei
- increasing repulsion at higher momenta
→ relevant for dense baryonic matter

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 !
(... looking forward to J-PARC E40)

Hyperon - Nucleon Interaction : recent update

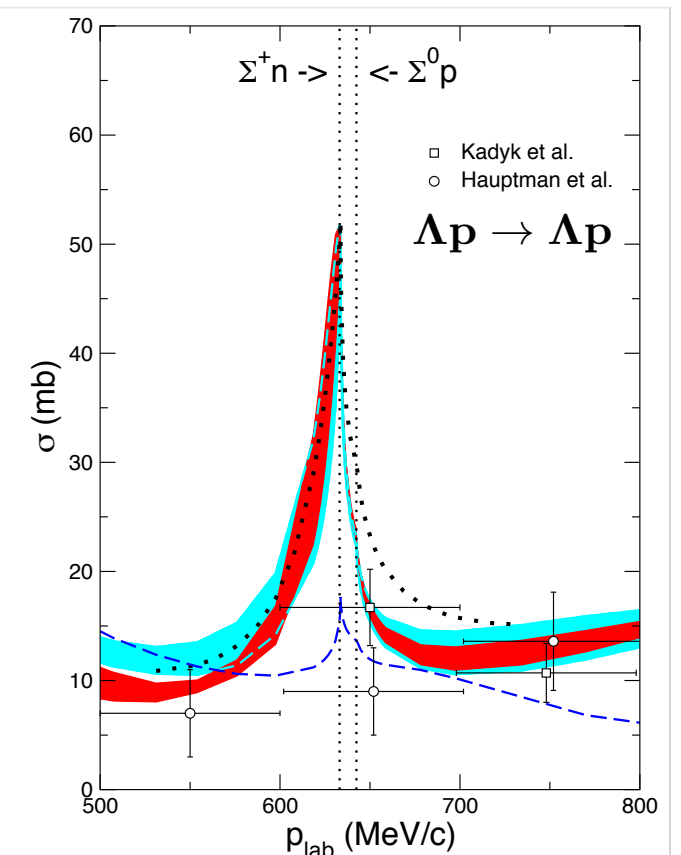
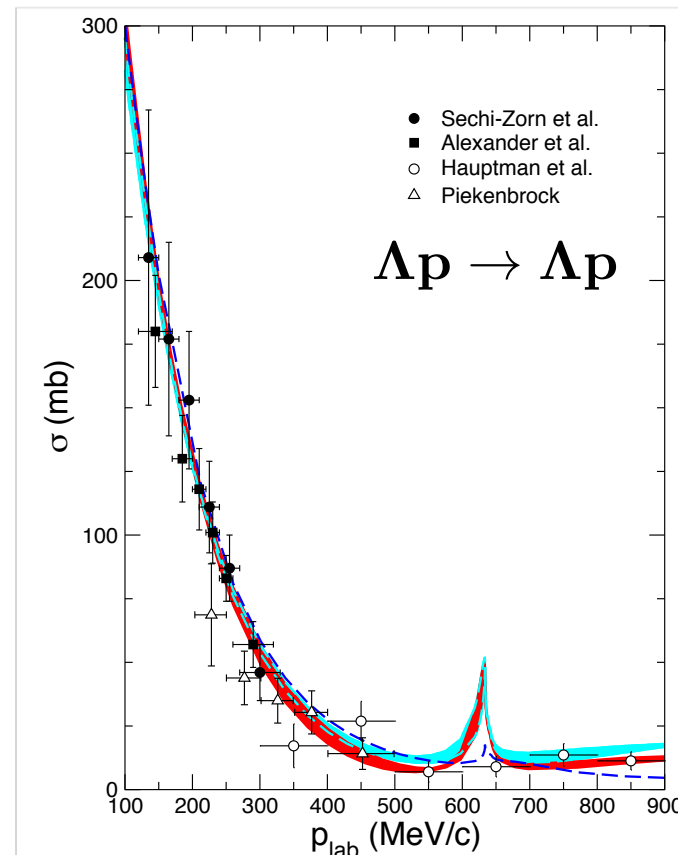
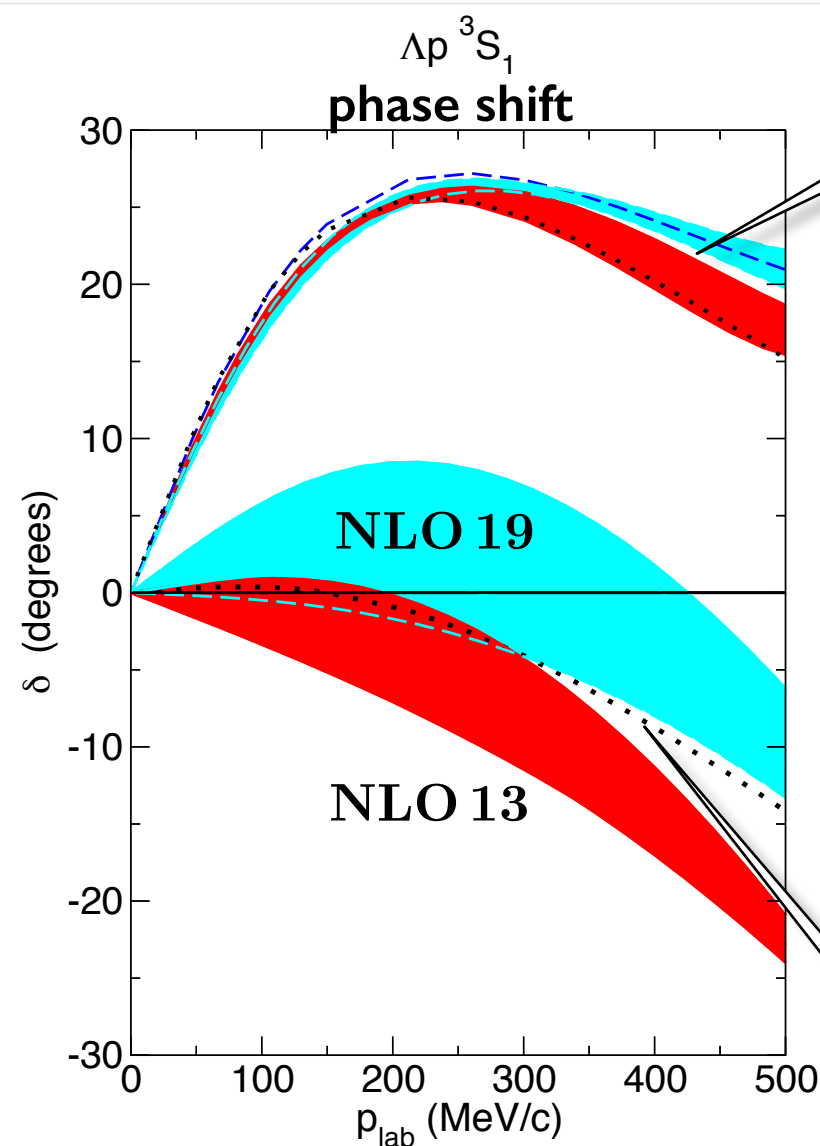
J. Haidenbauer, U.-G. Meißner, A. Nogga arXiv:1906.11681 [nucl-th]

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

blue : NLO 19

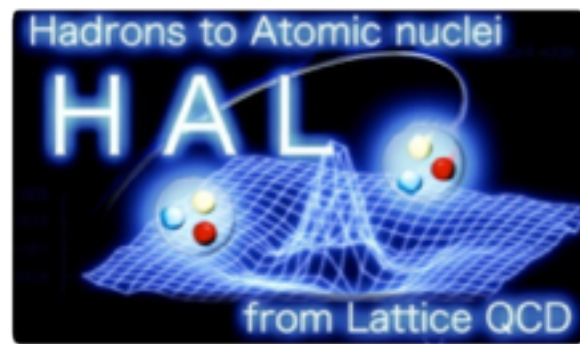
red : NLO 13

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



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

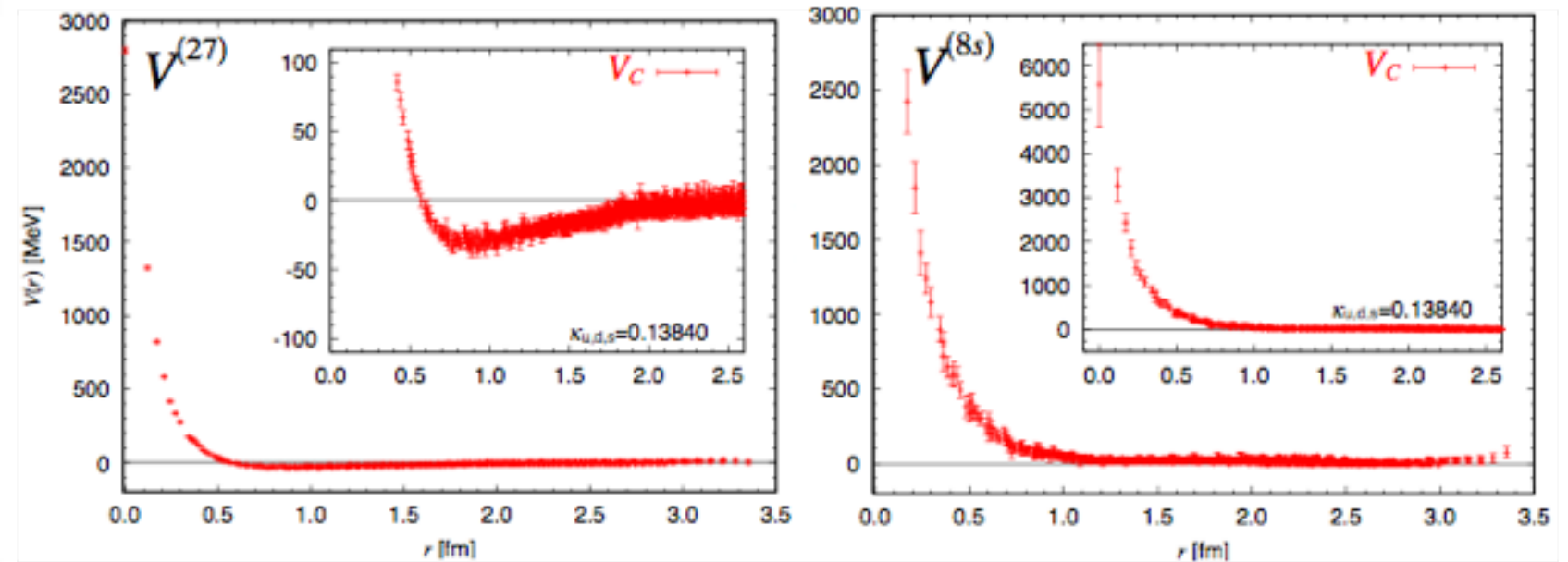
Hyperon - Nucleon Interactions from Lattice QCD



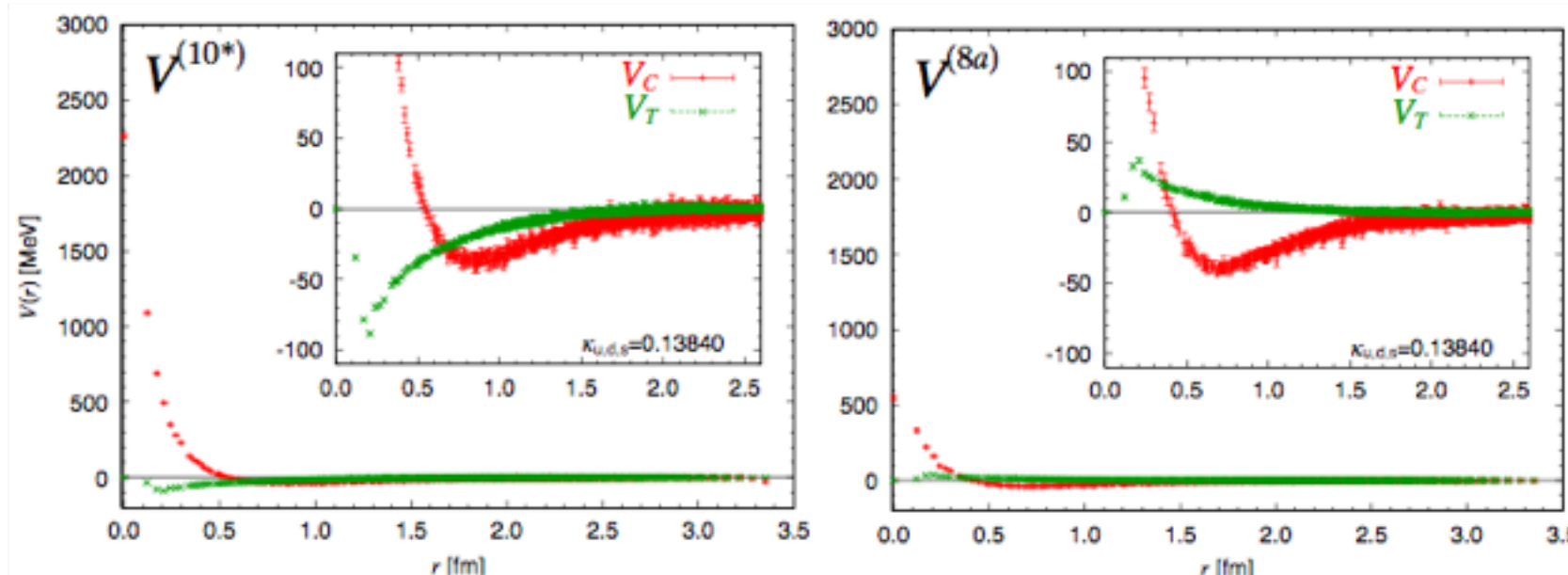
$$m_{ps} = 0.47 \text{ GeV}$$

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

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



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



Short-range
repulsive core
in all channels

... towards
physical
quark masses

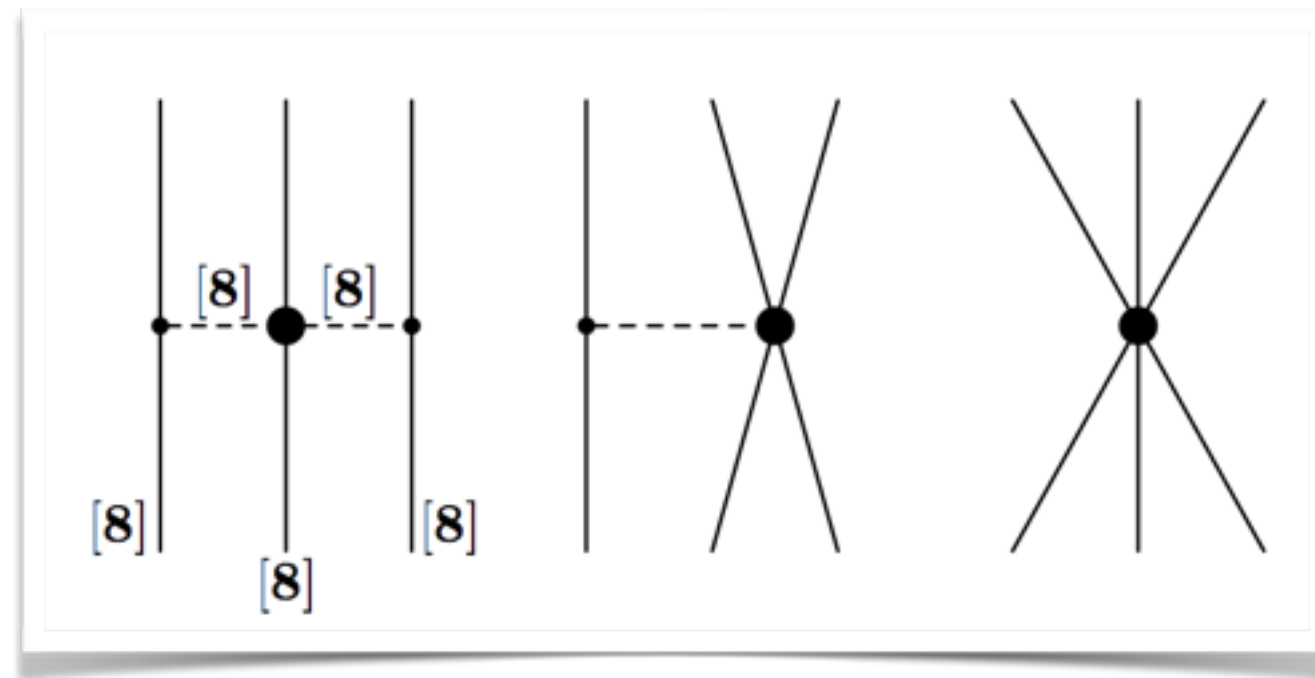
HYPERON - NUCLEON - NUCLEON THREE-BODY FORCES from CHIRAL SU(3) EFT

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

Phys. Rev. C93 (2016) 014001

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

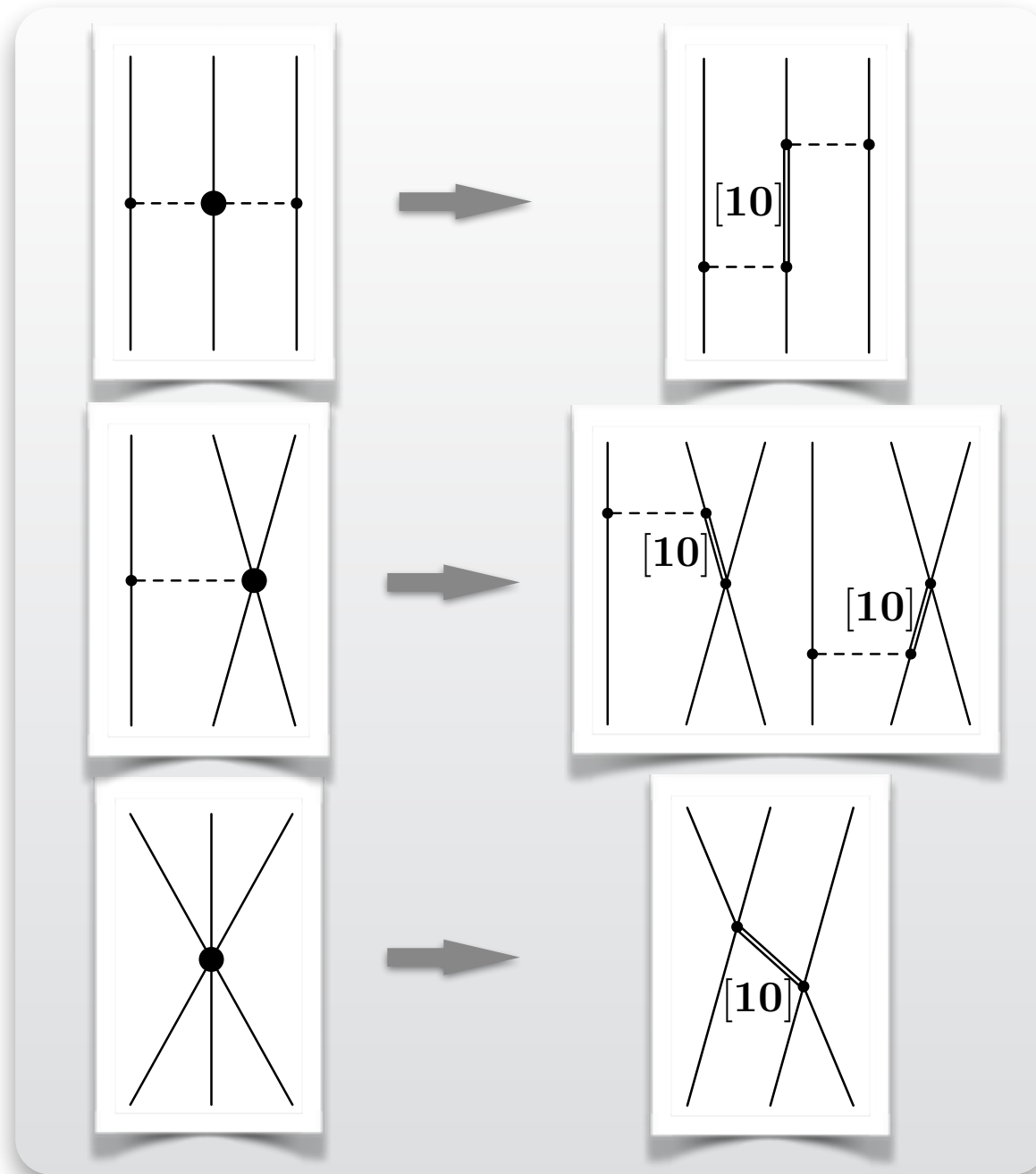
3-baryon
sector at
NNLO



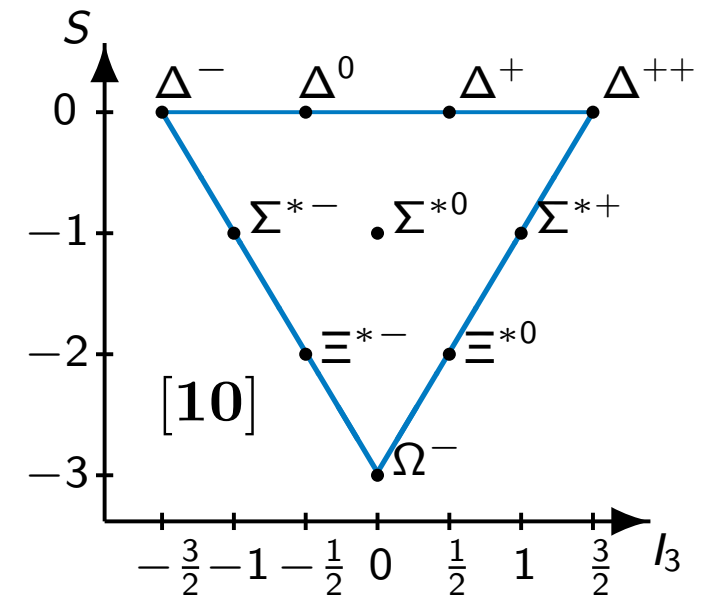
- $SU(3)$ symmetry used to restrict no. of independent parameters
- Further reduction through decuplet dominance

Decuplet Dominance in YNN three-body forces

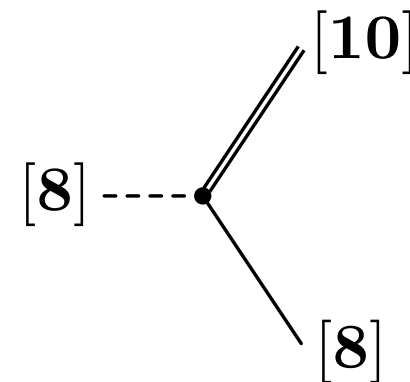
- Estimates of YNN 3-body interactions assuming dominant decuplet (Σ^* , Δ) intermediate states



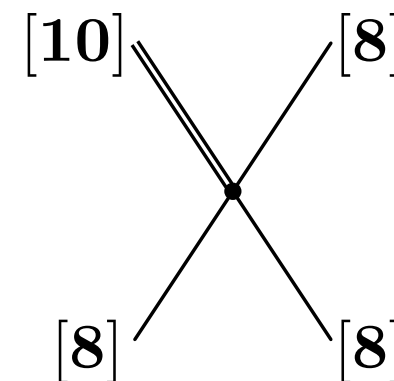
promotion from **NNLO** to **NLO**



- ... 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

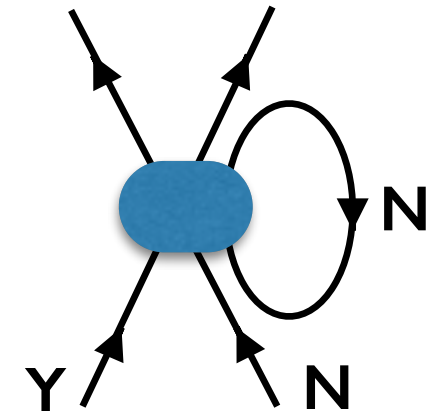
Two constants
(H_1, H_2)
(Typical magnitude $|H_i| \sim f_\pi^{-2}$)

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

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



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

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

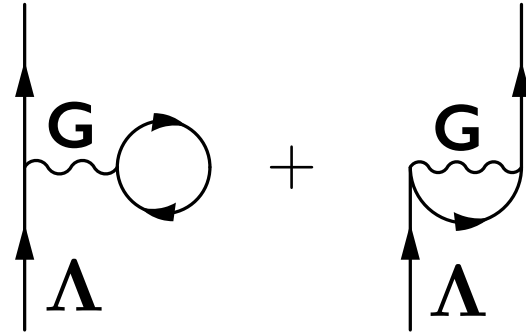
$$V_{\Lambda n}^{\text{eff}, \pi} = \frac{CH g_A}{9f^2 \Delta} [\rho_n + 2\rho_p] + \mathcal{G}(k_F^p, k_F^n; p, q) \quad +/\text{-}$$

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

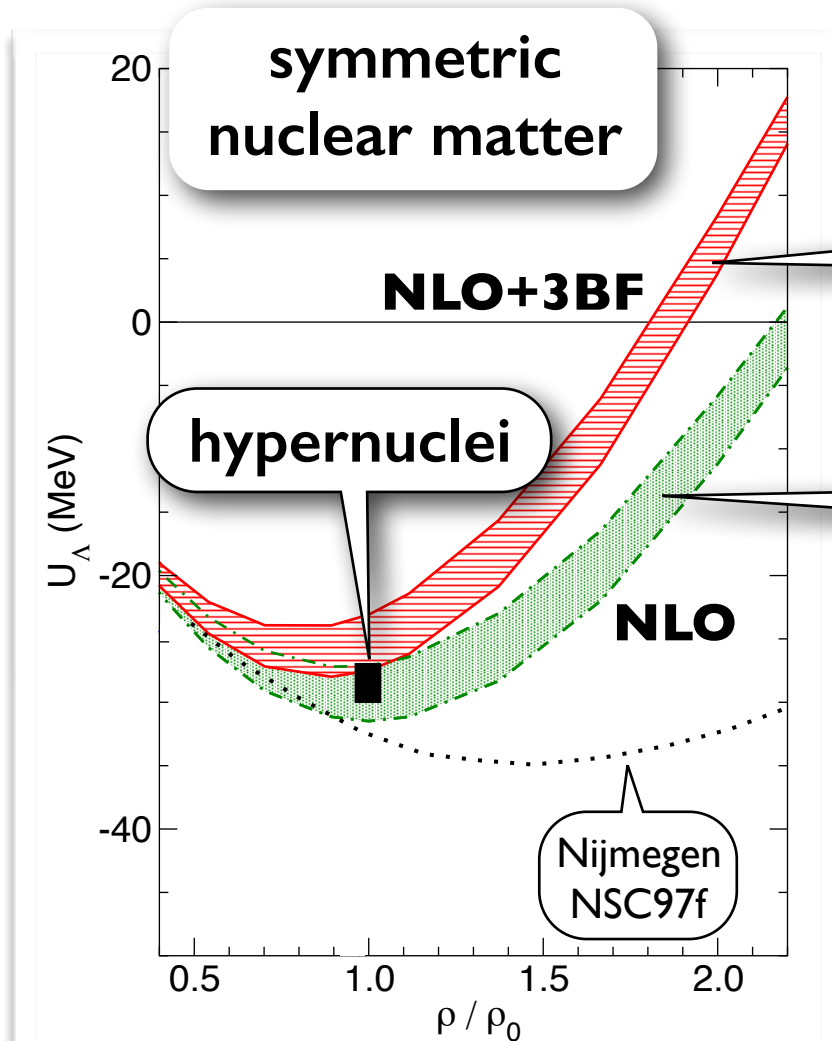
- Decuplet-octet mass difference $\Delta = M_{[10]} - M_{[8]} = 270 \text{ MeV}$
- Coupling parameters : $C = \frac{3}{4}g_A \simeq 1 \quad -\frac{1}{f^2} \lesssim H \lesssim +\frac{1}{f^2}$ (dim. arguments natural size)

Density dependence of Λ single particle potential

- Brueckner calculations using chiral SU(3) interactions



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



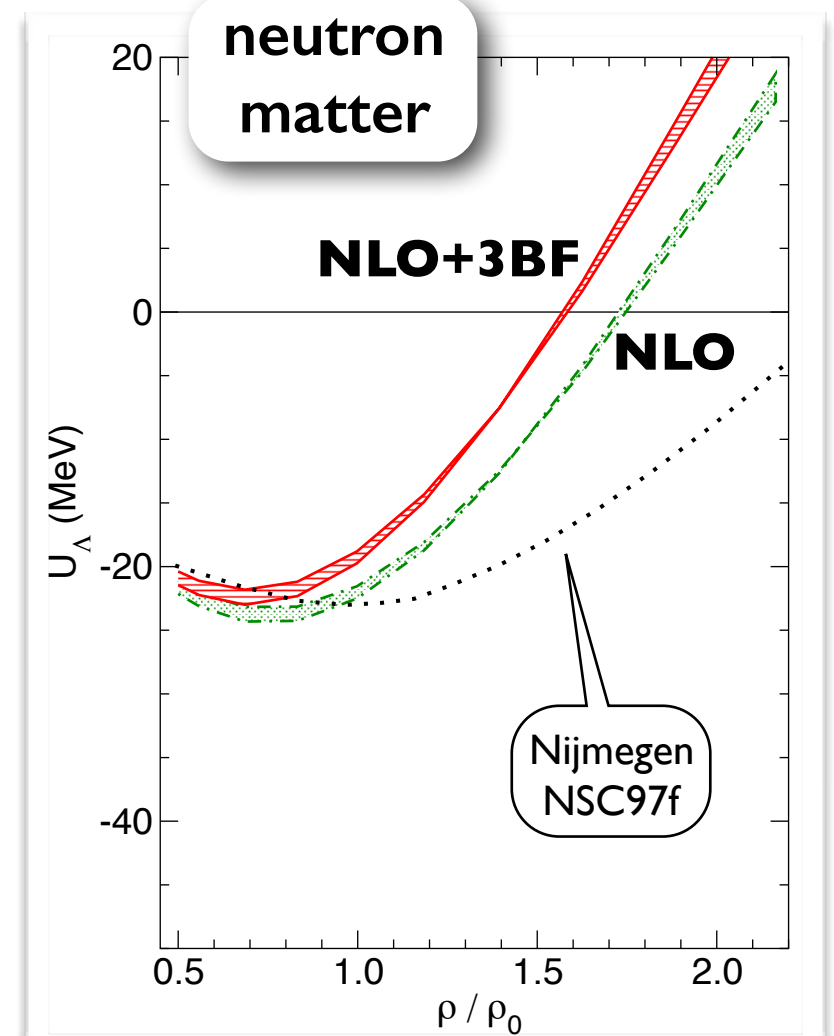
Chiral SU(3)
2- and 3-body
forces

2-body only

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” ?
- see also: finite hypernuclei using **NLO13** and **NLO19**

J. Haidenbauer, I. Vidaña
arXiv : 1910.02695

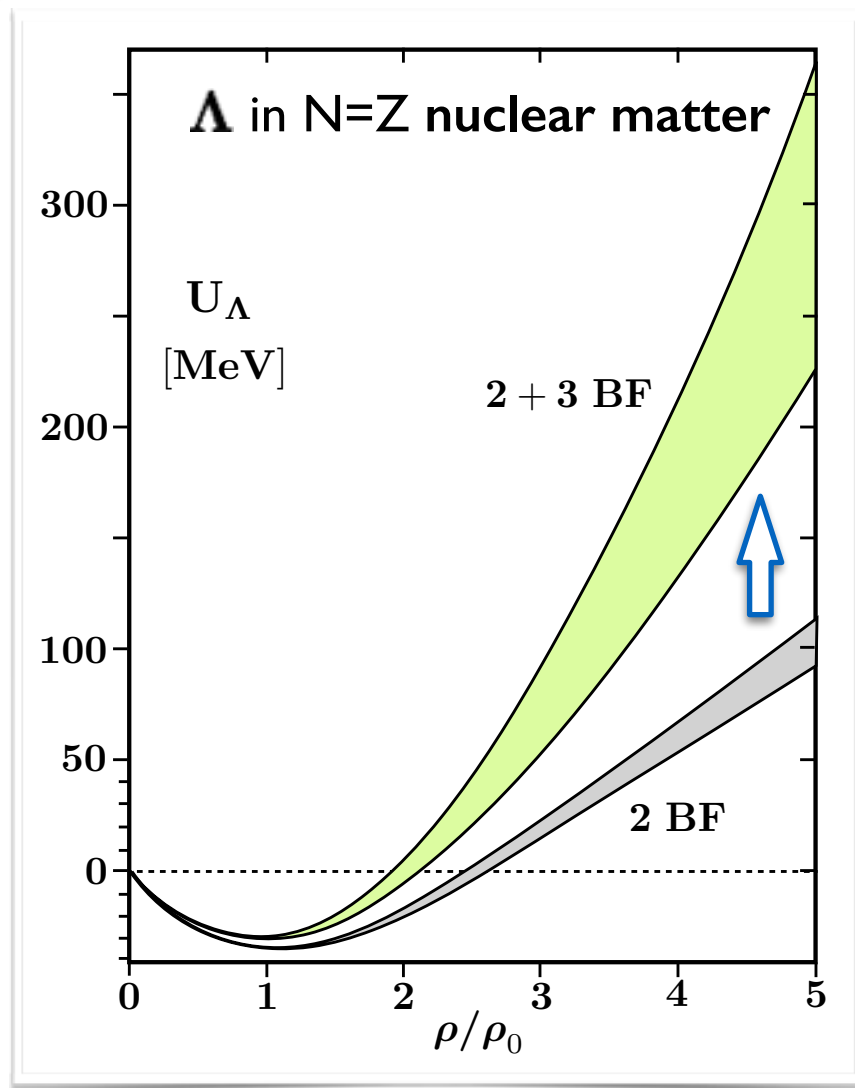
Density dependence of Λ single particle potential (contd.)

- 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

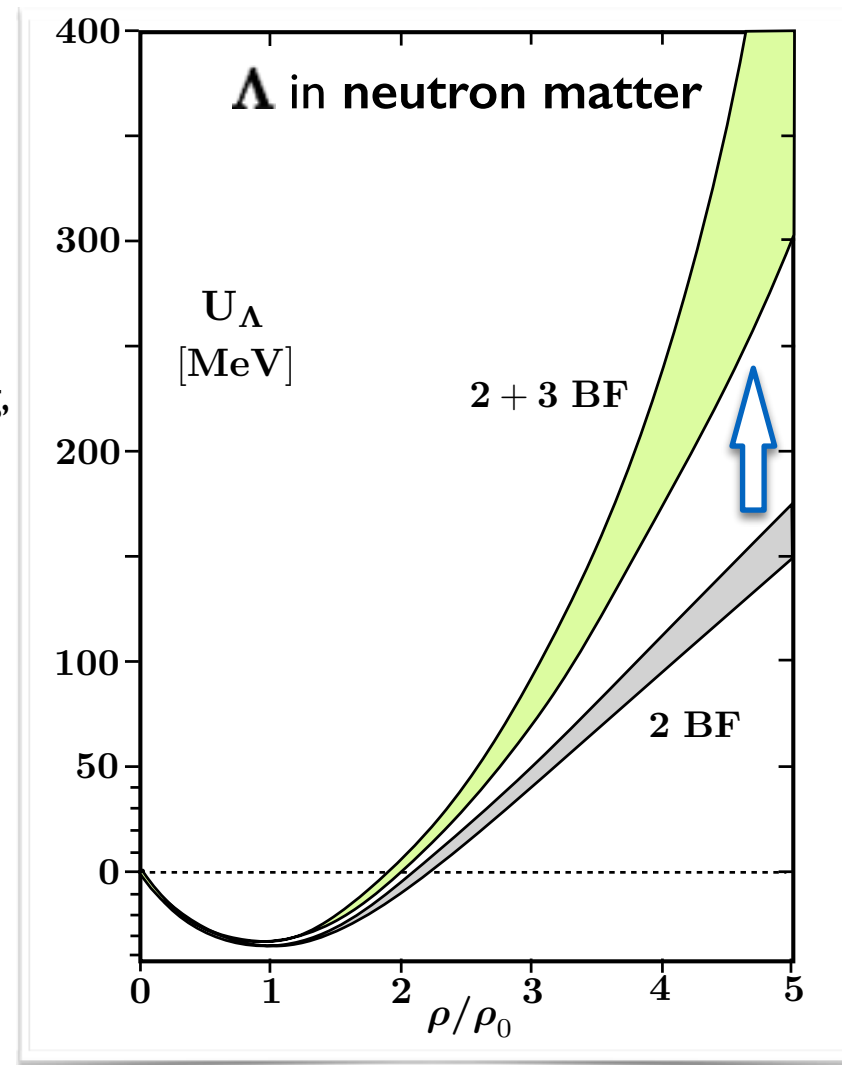
$$\mathbf{G}_{\alpha\beta}(\omega; \rho) = \mathbf{V}_{\alpha\beta}(\rho) + \mathbf{V}_{\alpha\gamma}(\rho) \frac{\mathbf{Q}}{\mathbf{e}(\omega) + i\epsilon} \mathbf{G}_{\gamma\beta}(\omega; \rho)$$

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

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



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



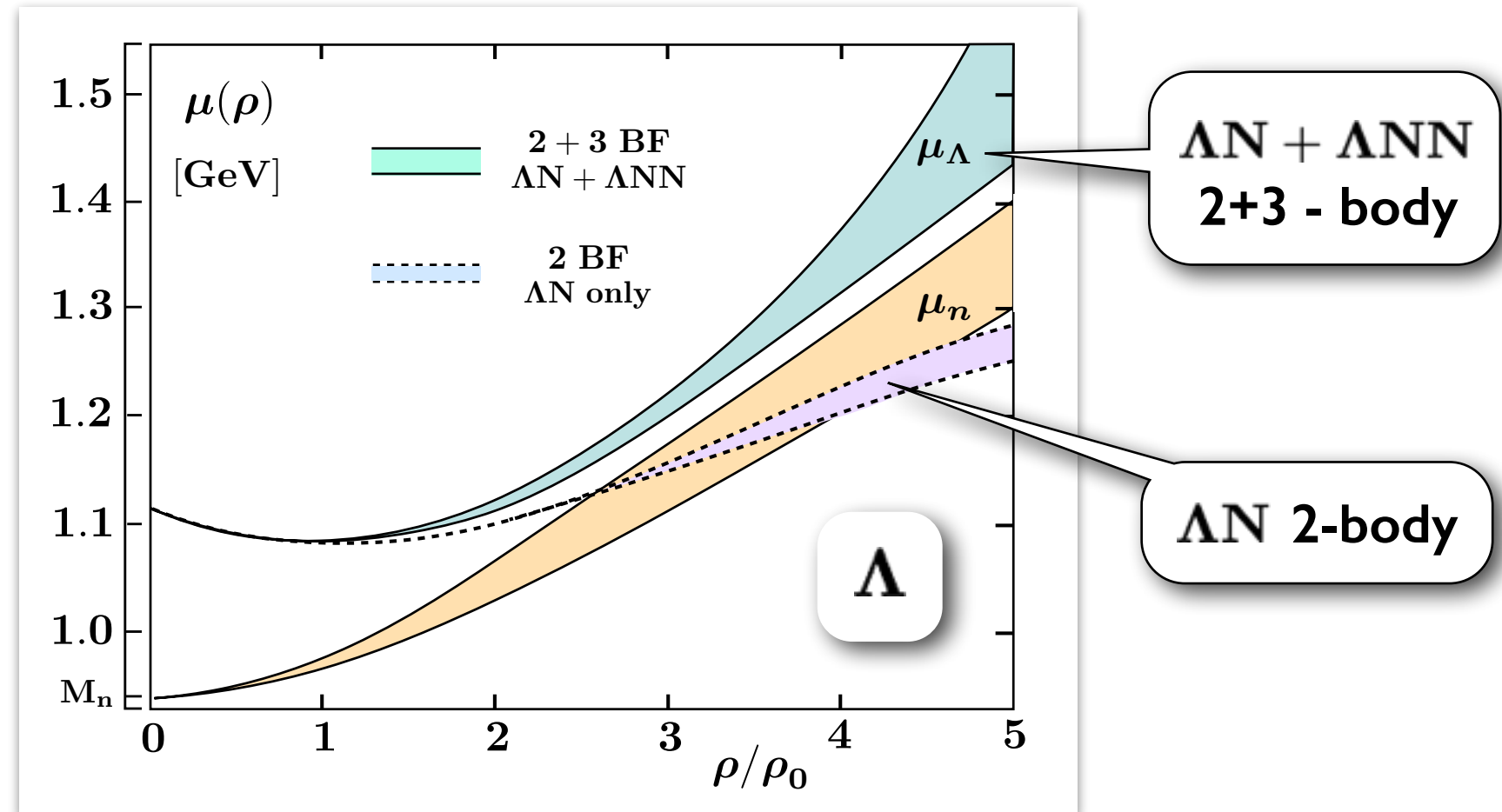
**Strong
additional
repulsion
from YNN
three-body
forces**

- Range of 3-body-force parameters: $-H_1 = (2.2 - 2.5) f_{\pi}^{-2}$ $H_2 = (0 - 1.2) f_{\pi}^{-2}$

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

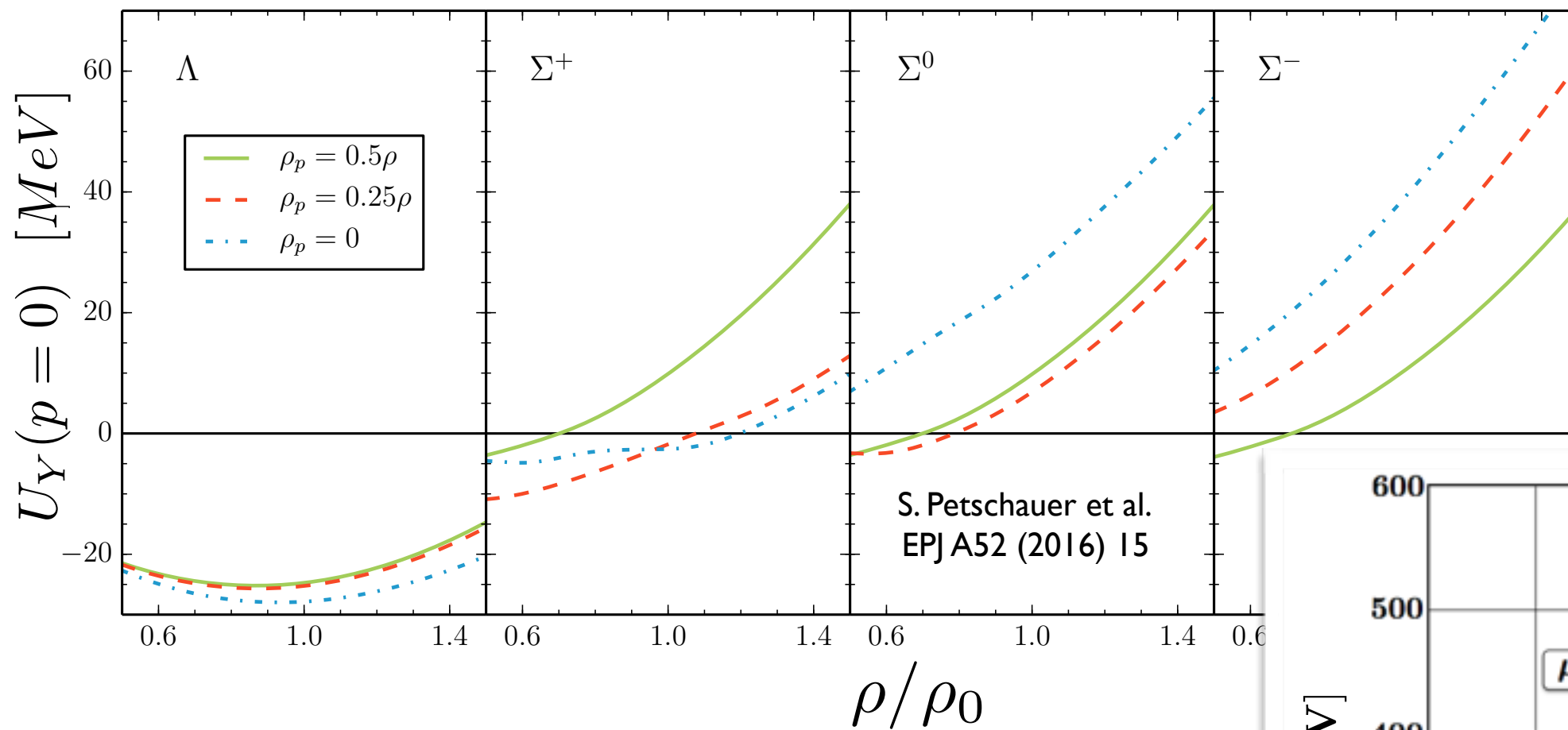
D. Gerstung, N. Kaiser, W.W. 2019

- neutron chemical potential
in neutron star matter from
Chiral FRG EoS

(symmetry energy range 30-34 MeV)

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

Σ Hyperons in Neutron Stars ?

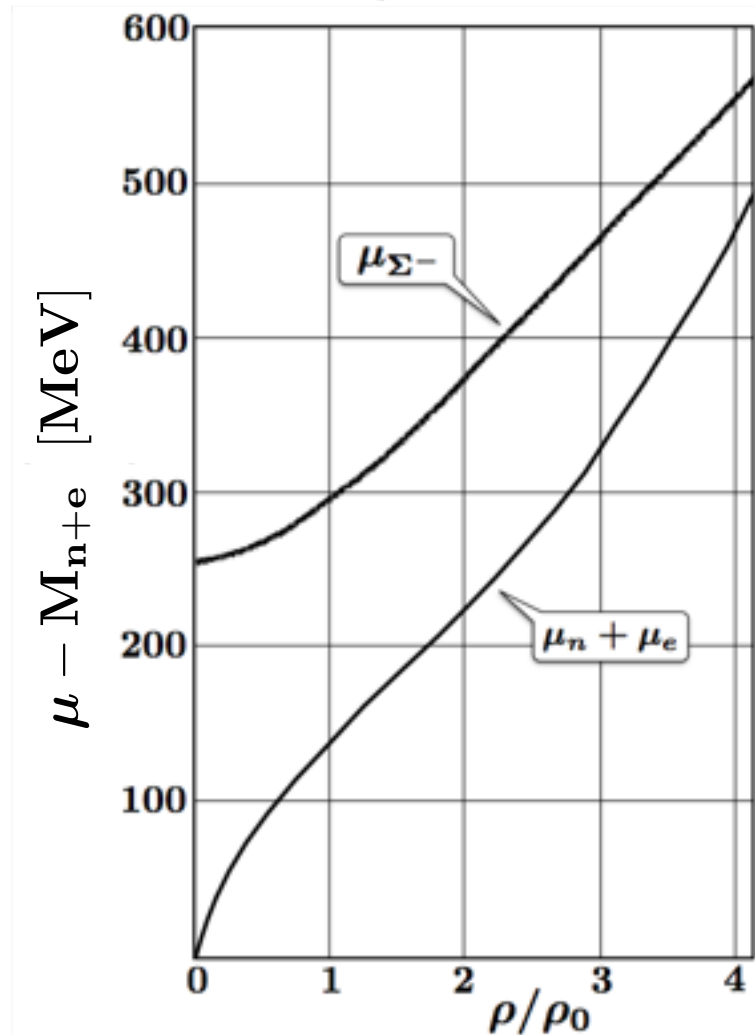


- Hyperon potentials from Chiral SU(3) EFT interactions

- 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

- ▶ $M_{max} \simeq 2.2 M_{\odot}$, $R \sim 10 - 12 \text{ km}$ ($R_{1.4 M_{\odot}} = 11.0^{+0.9}_{-0.6} \text{ km}$) 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 !!

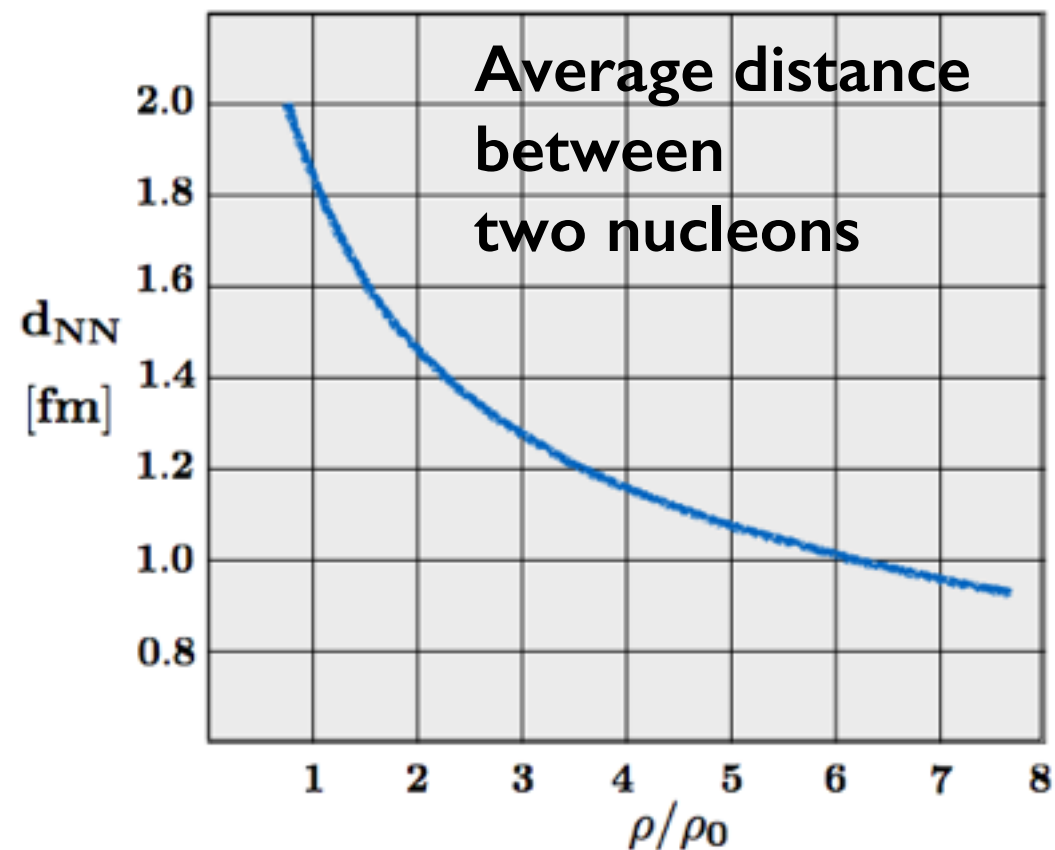


Appendix

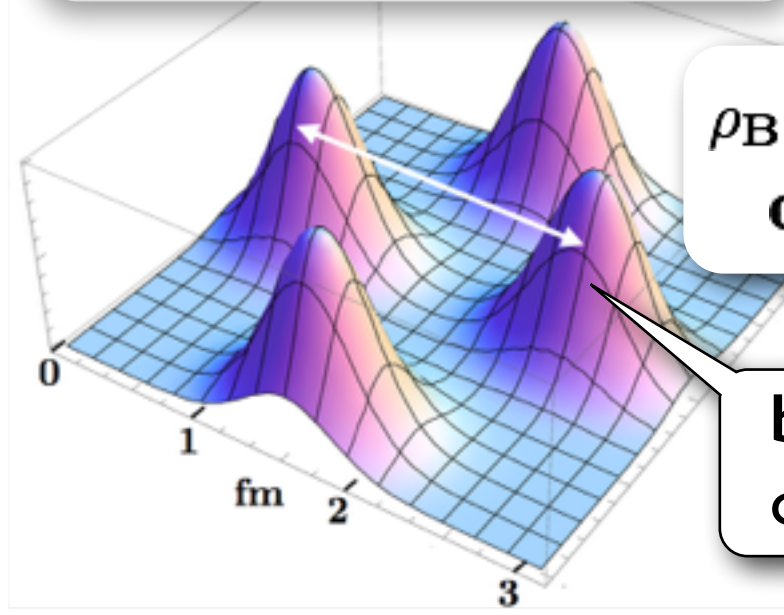
Supplementary Materials

*Chiral Nucleon-Meson Field Theory
and
Functional Renormalisation Group*

Densities and Distance Scales in Baryonic Matter



normal nuclear matter



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

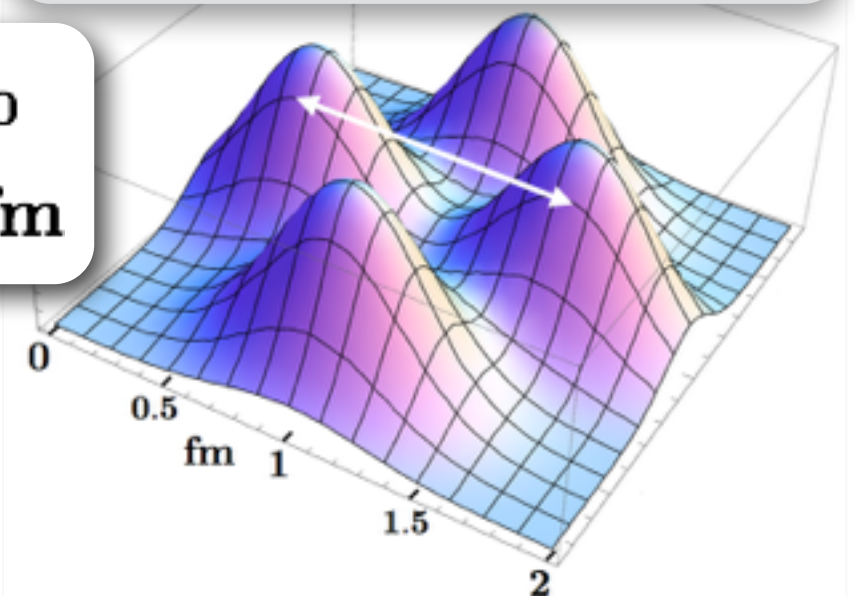
$$d_{NN} \simeq 1.8 \text{ fm}$$

baryonic core of the nucleon

neutron star core matter

$$\rho_B \sim 5 \rho_0$$

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



- (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

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

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

- Nambu-Goldstone boson π and “heavy” σ
- Potential $\mathcal{U}(\sigma, \pi)$: polynomial in $\chi = \pi^2 + \sigma^2$ 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

Wetterich's FRG flow equations

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

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

UV

$\Gamma_k[\Phi]$

scale regulator R_k

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

IR

full
propagator

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

● Thermodynamics:

$$k \partial_k \bar{\Gamma}_k(T, \mu) = \left(\text{diagram 1} + \text{diagram 2} \right) \Big|_{T, \mu} - \left(\text{diagram 3} + \text{diagram 4} \right) \Big|_{T=0, \mu_0}$$

nucleons pions

Non-perturbative treatment of :

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

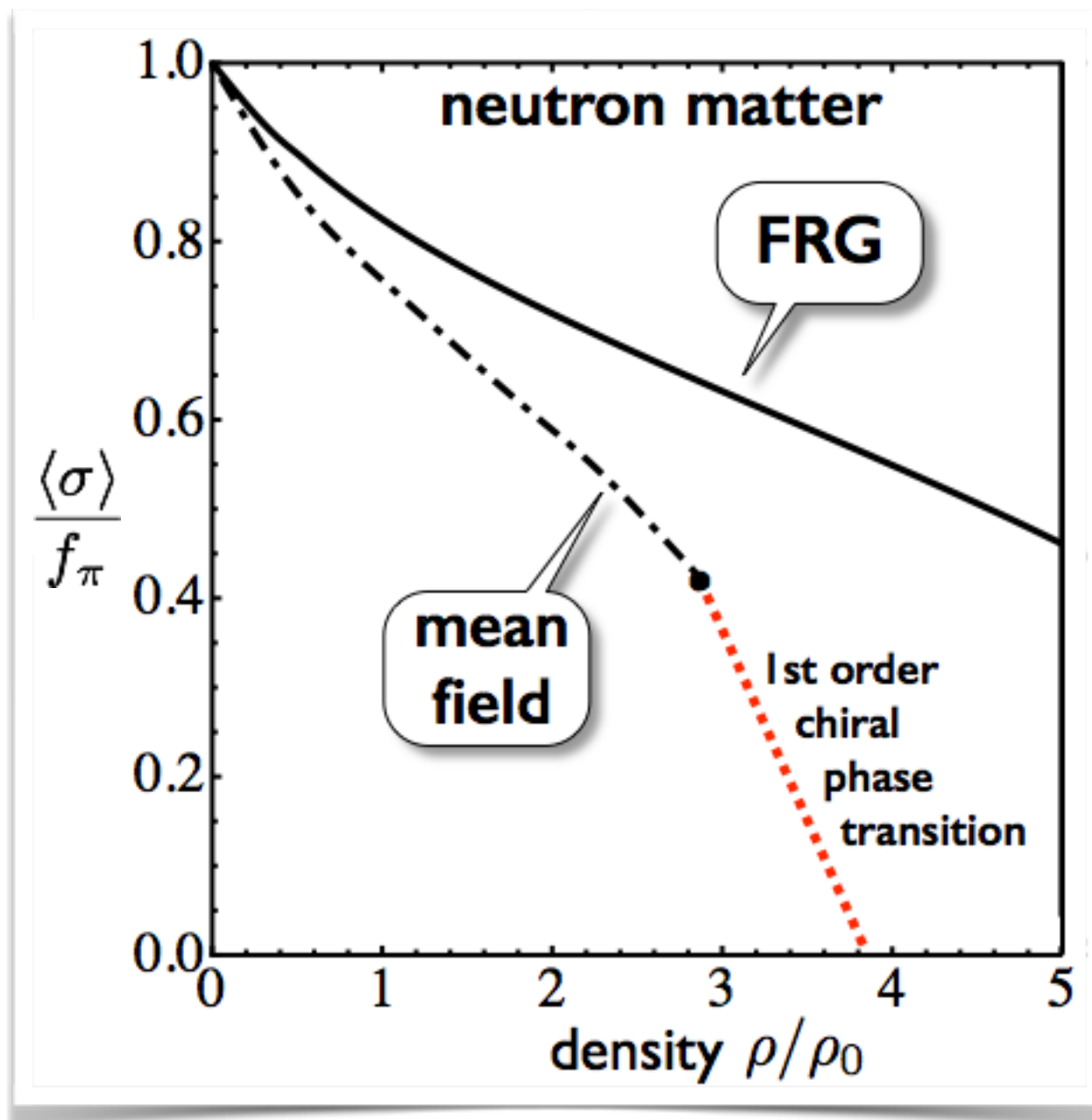
CHIRAL ORDER PARAMETER in NEUTRON MATTER

- 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 $\updownarrow$ 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**