Chiral EFT approach to **Nuclear Many-Body Systems**

- with implications for **Neutron Stars** -

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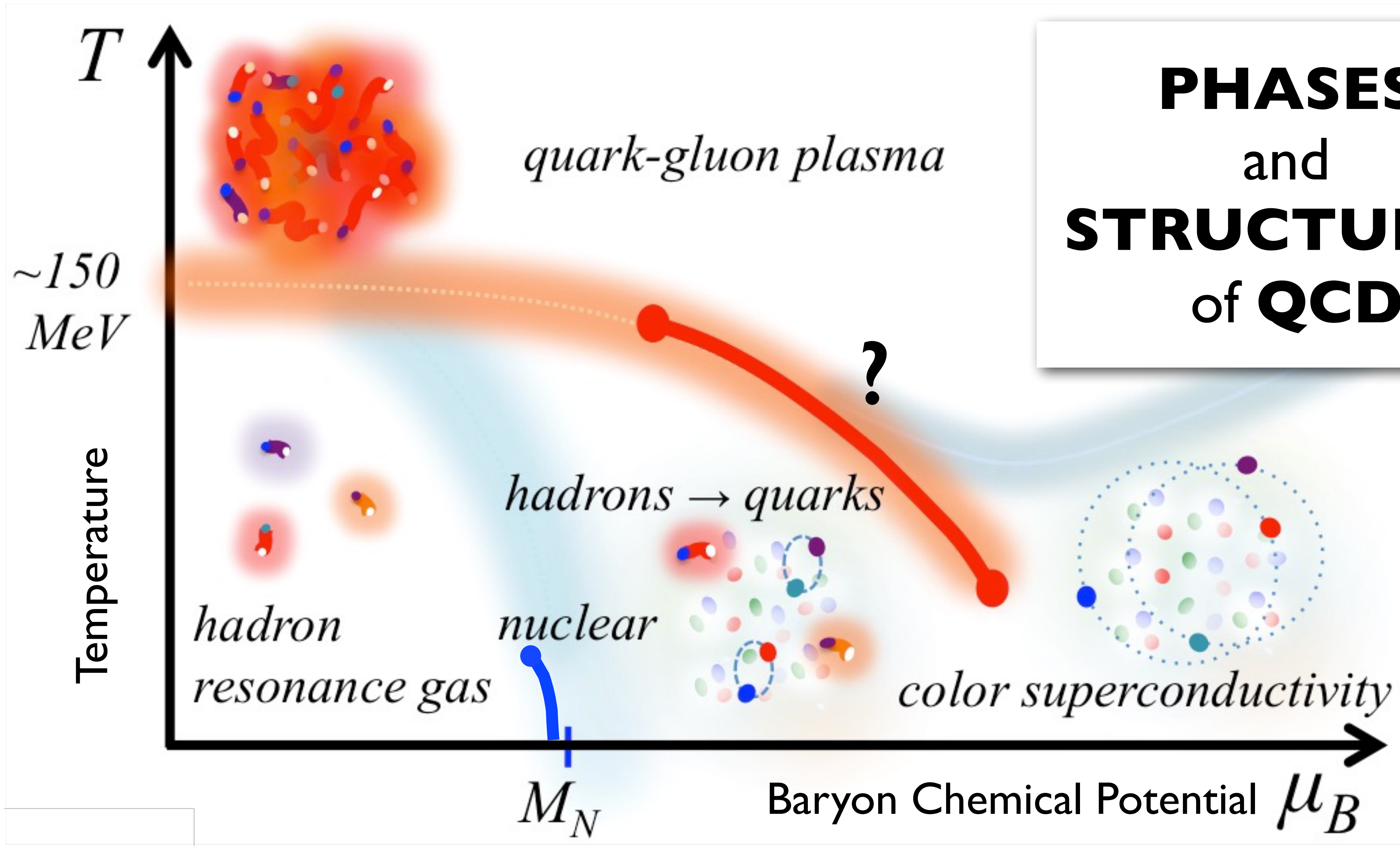
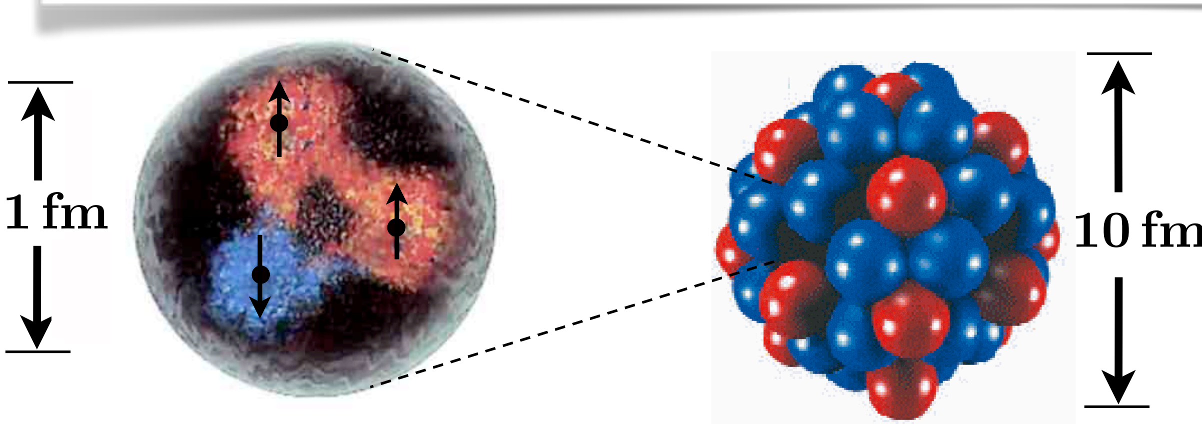
- Introductory reminder of relevant scales
- From nuclear to dense baryonic matter
  - Nuclear chiral thermodynamics
  - In-medium chiral EFT and renormalisation group methods
  - Compressed baryonic matter and massive neutron stars
- Chiral SU(3) EFT: strangeness and baryonic matter
  - Hyperon puzzle in neutron stars ?

PHASES and **STRUCTURES** of **QCD**

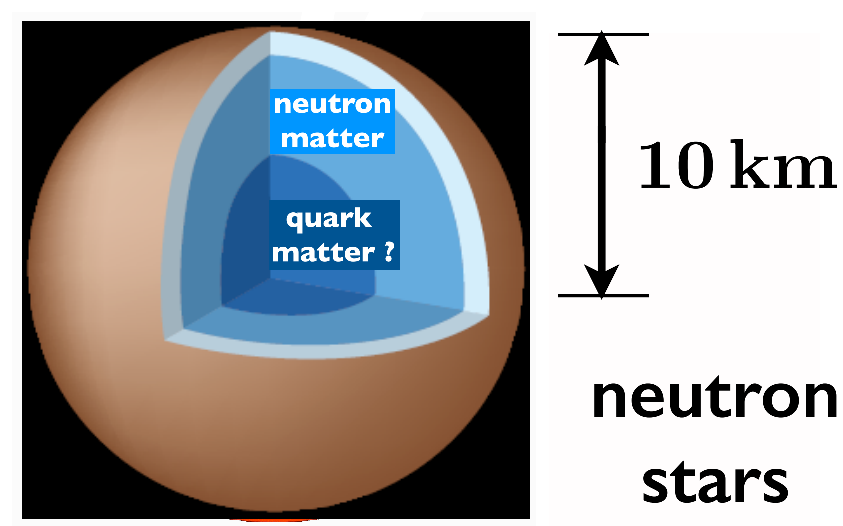


from:
G. Baym,
T. Hatsuda,
et al.

arXiv:1707.04966



nucleons **nuclei**



neutron stars

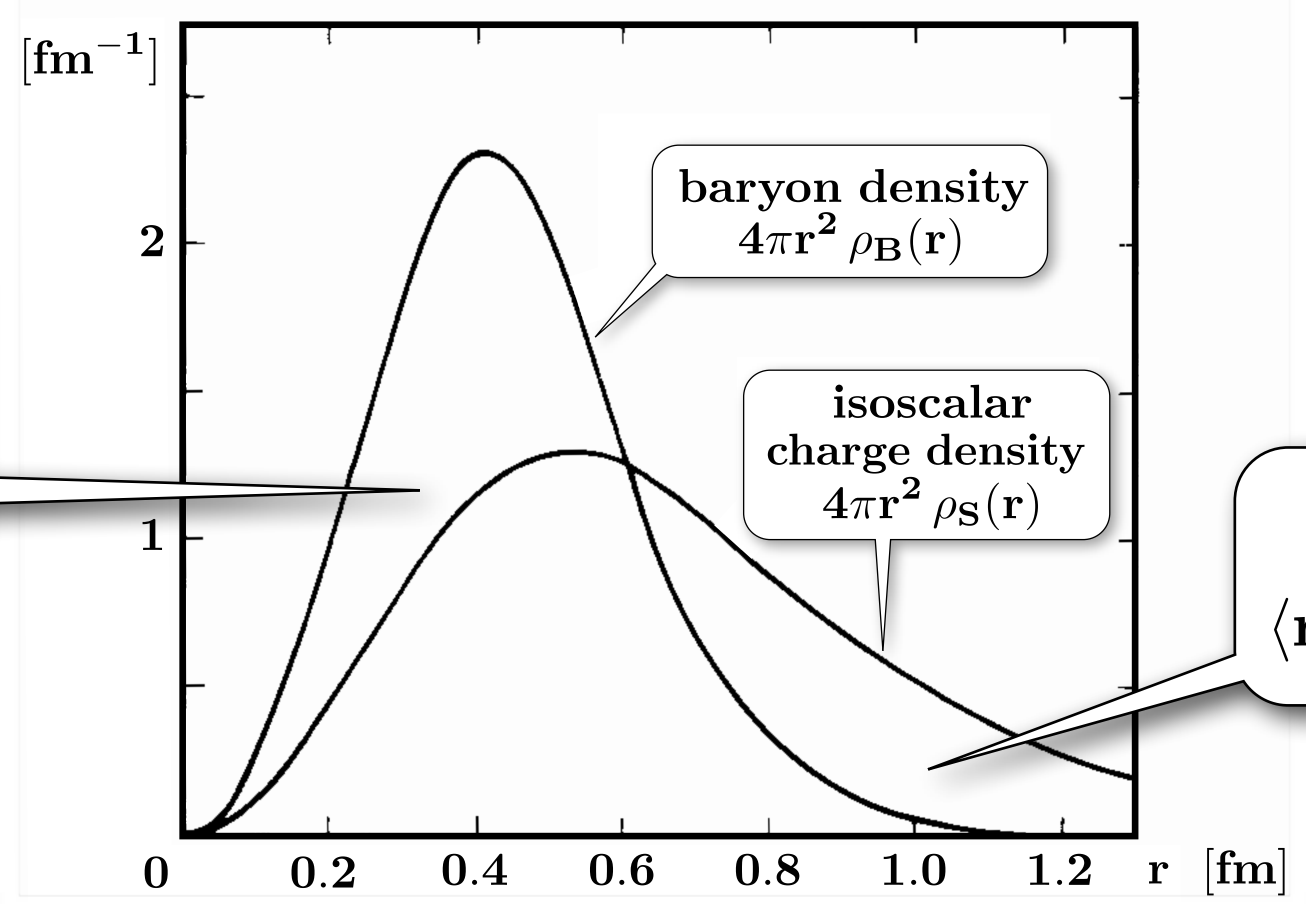
1.

Introductory Notes about Scales

- **Nucleon structure and its low energy realisation: valence quark core and $q\bar{q}$ (mesonic) cloud**
- **Distance scales in dense baryonic matter**
- **Repulsive NN core from Lattice QCD**

Historical Reminder:
CHIRAL SOLITON MODEL of the **NUCLEON**

- **… based on non-linear sigma model + 4th order term**
- **Compact valence quark core + meson cloud**



compact
baryonic core
$\langle r^2\rangle_B^{1/2} \simeq 0.5$ fm

mesonic cloud
$\langle r^2\rangle_{E,\text{isoscalar}}^{1/2} \simeq 0.8$ fm

N. Kaiser,
U.-G. Meißner, W.W.

Nucl. Phys.
A466 (1987) 685

- Necessary condition for **Chiral EFT** approach to nuclear systems :

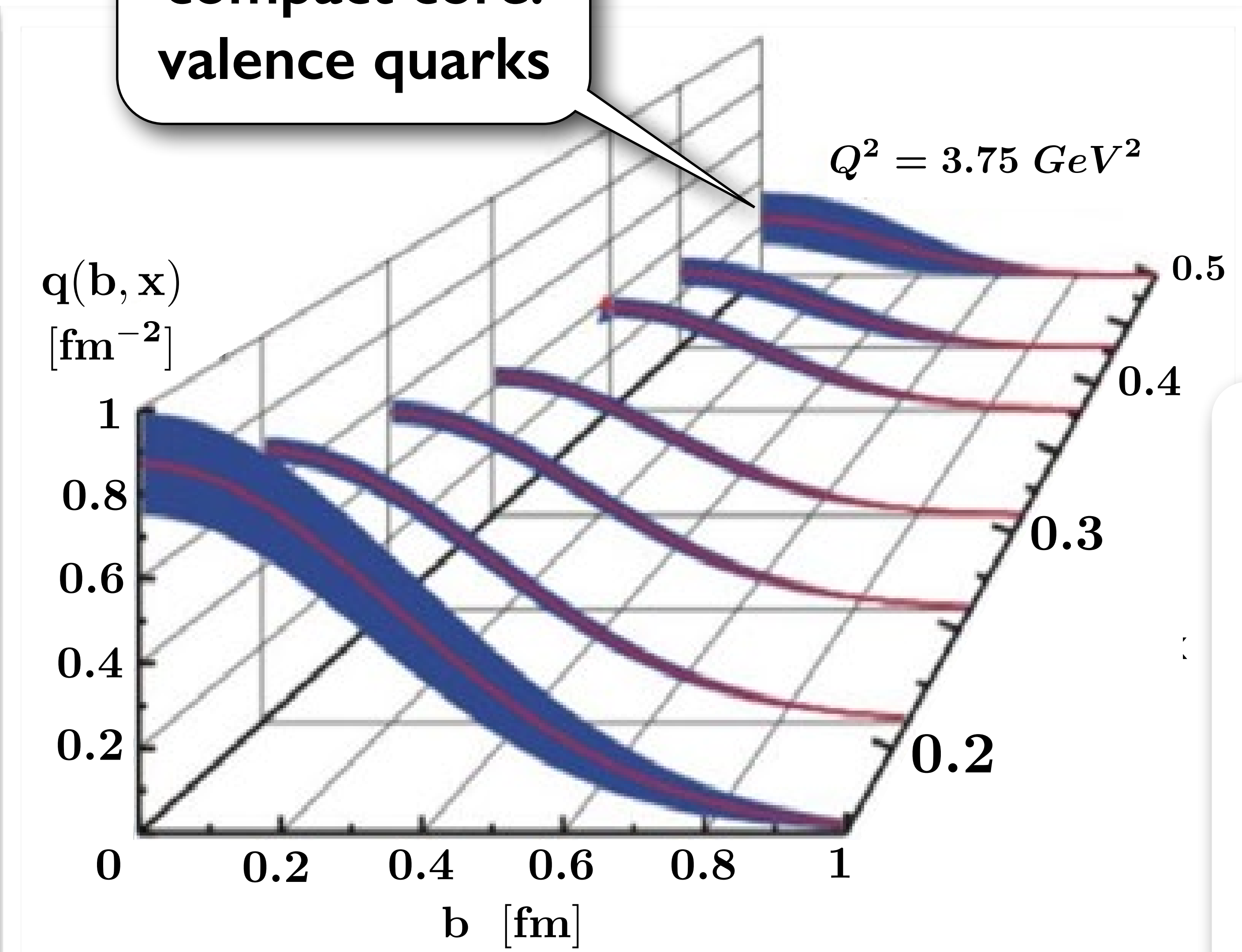
Separation of scales between compact baryonic core and (multi-)pion cloud

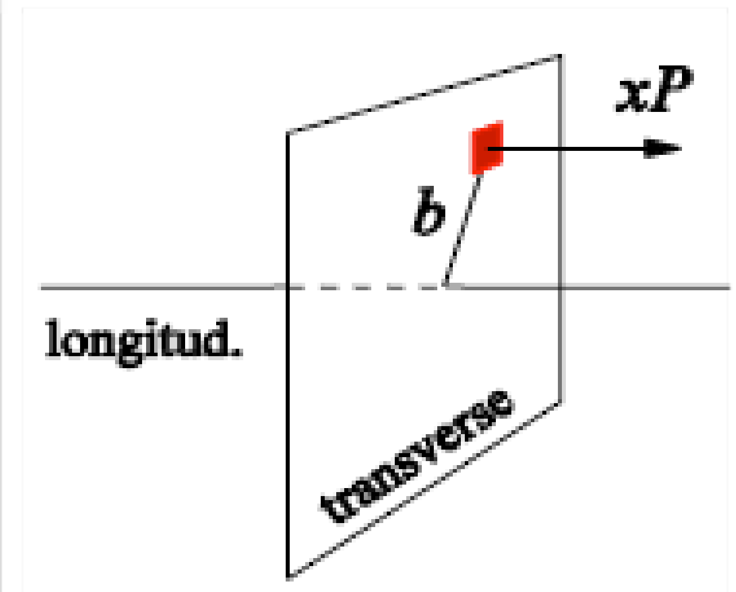
Transverse distributions of quarks in the proton

Deeply Virtual Compton Scattering @ JLab

R. Dupré, M. Guidal, M. Vanderhaeghen
Phys. Rev. D95 (2017) 011501

compact core:
valence quarks



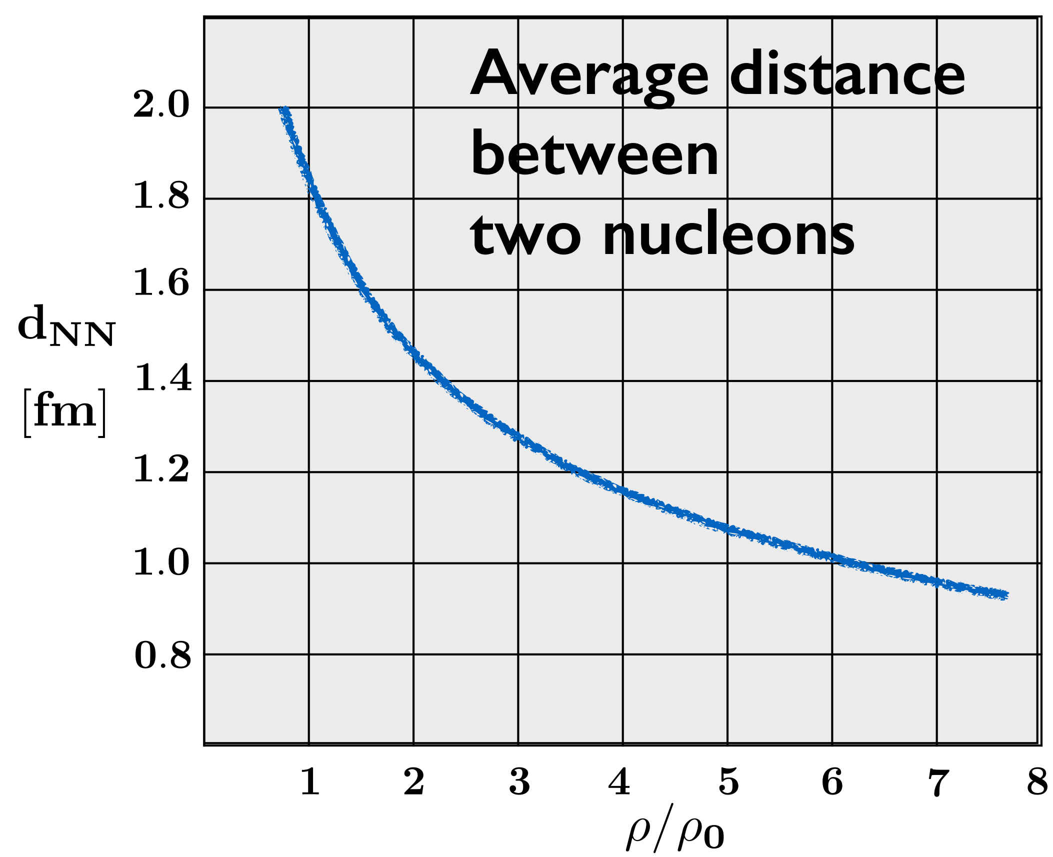


$$\langle b^2 \rangle \simeq 0.16\,\mathrm{fm}^2 \cdot \ln(1/x)$$

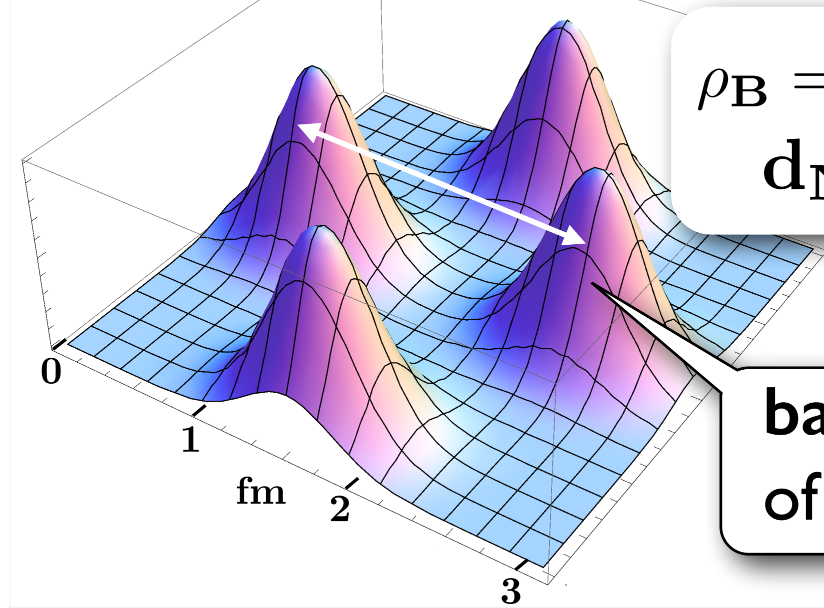
- Valence quark region:
  $0.3 < x < 0.5$
- Core size:

$$R_{core} = \sqrt{\frac{3}{2}\langle b^2 \rangle} \sim 0.4 - 0.5\ \mathrm{fm}$$

Densities and Distance Scales in Baryonic Matter



normal nuclear matter

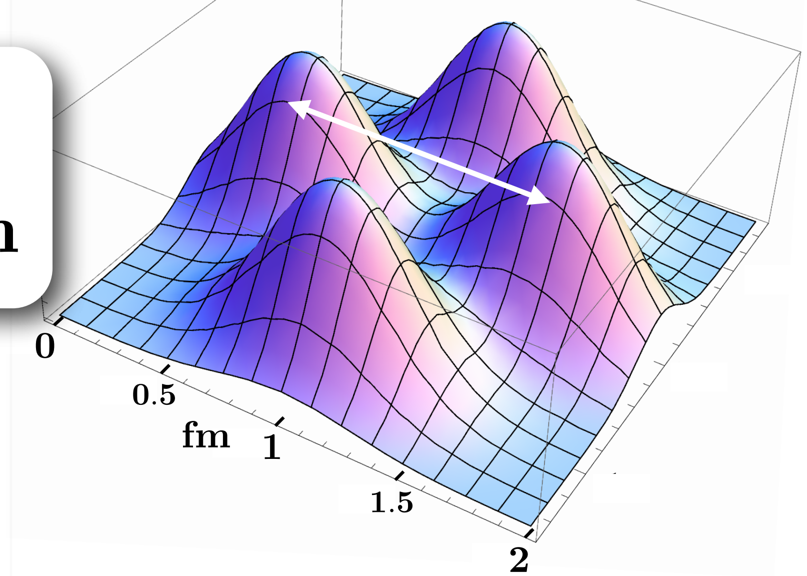


$\rho_B = \rho_0 = 0.16\ \mathrm{fm}^{-3}$

$d_{NN} \simeq 1.8$ fm

baryonic core of the nucleon

neutron star core matter



$\rho_B \sim 5\,\rho_0$

$d_{NN} \sim 1$ fm

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

NUCLEAR FORCES from LATTICE QCD

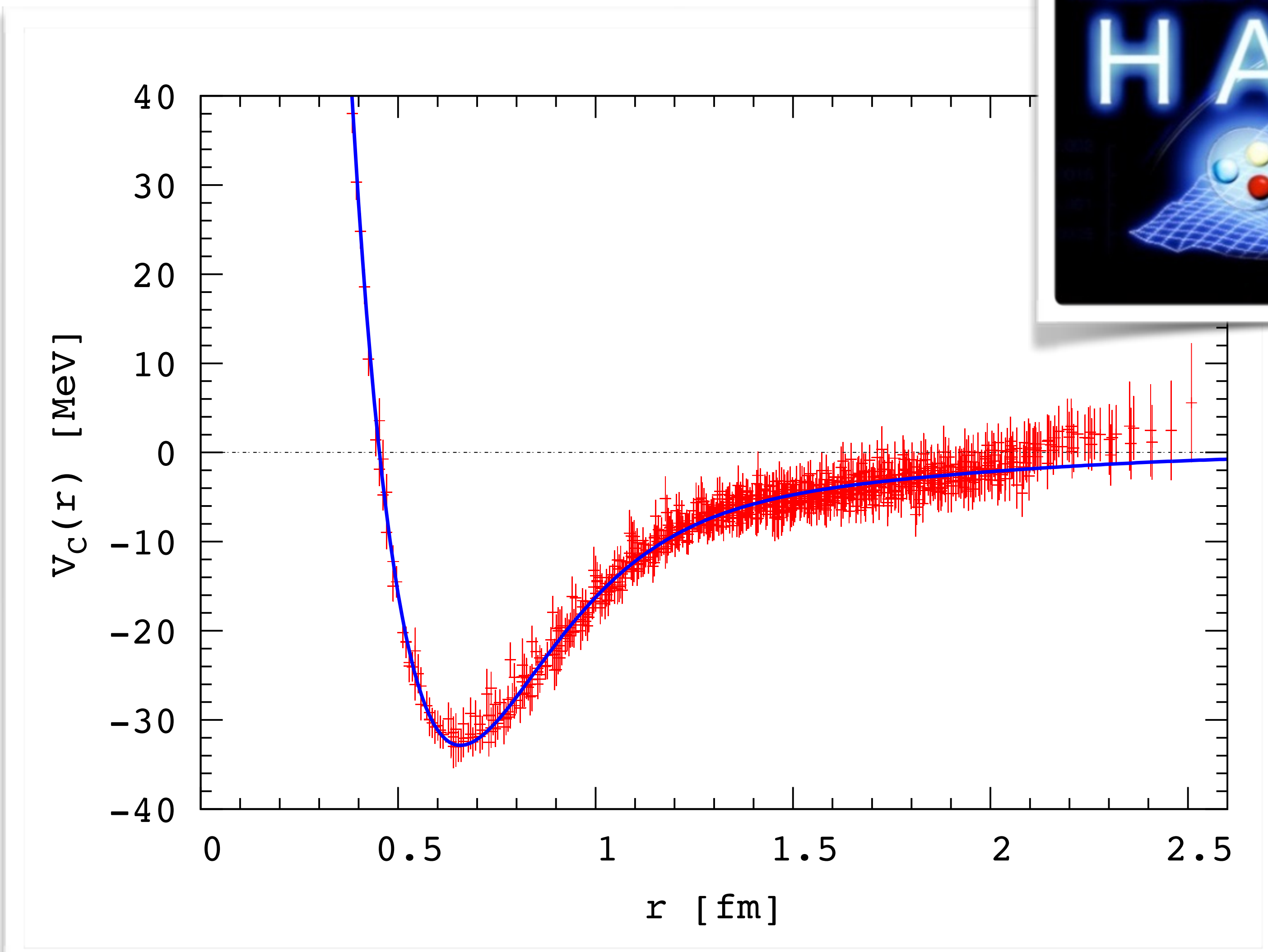
NN Central Potential (S = 0, I = 1)
deduced from LQCD two-nucleon (6-quark) correlation function

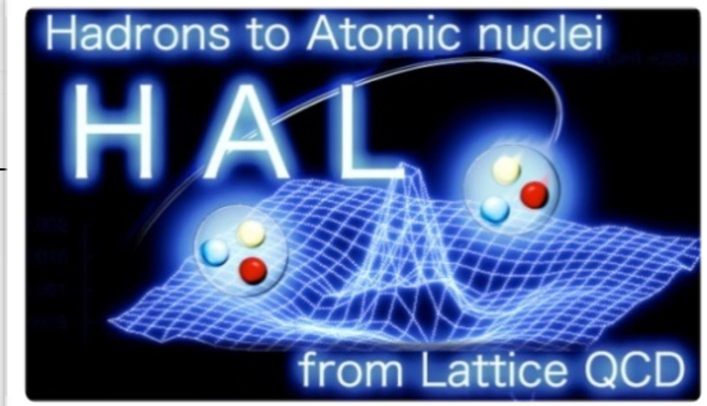
previously:
unphysically large
u- and d-quark
masses, but :

stable **0.5 Fermi**
repulsive core

S. Aoki, T. Hatsuda, N. Ishii
Prog. Theor. Phys. 123 (2010) 89

S. Aoki
Eur. Phys. J. A49 (2013) 81





now:

towards physical quark masses

2.

Chiral Effective Field Theory and related approaches to Nuclear Many-Body Problems

- **Chiral Nuclear Forces**
- **In-medium Chiral Perturbation Theory**
- **Non-perturbative methods :**
  Energy Density Functional
  Functional Renormalization Group

PIONS and **NUCLEI** in the context of **LOW-ENERGY QCD**

- **CONFINEMENT** of quarks and gluons in hadrons
- Spontaneously broken **CHIRAL SYMMETRY**

LOW-ENERGY QCD

at (energy and momentum) scales

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

is realised as an

Effective **F**ield **T**heory of

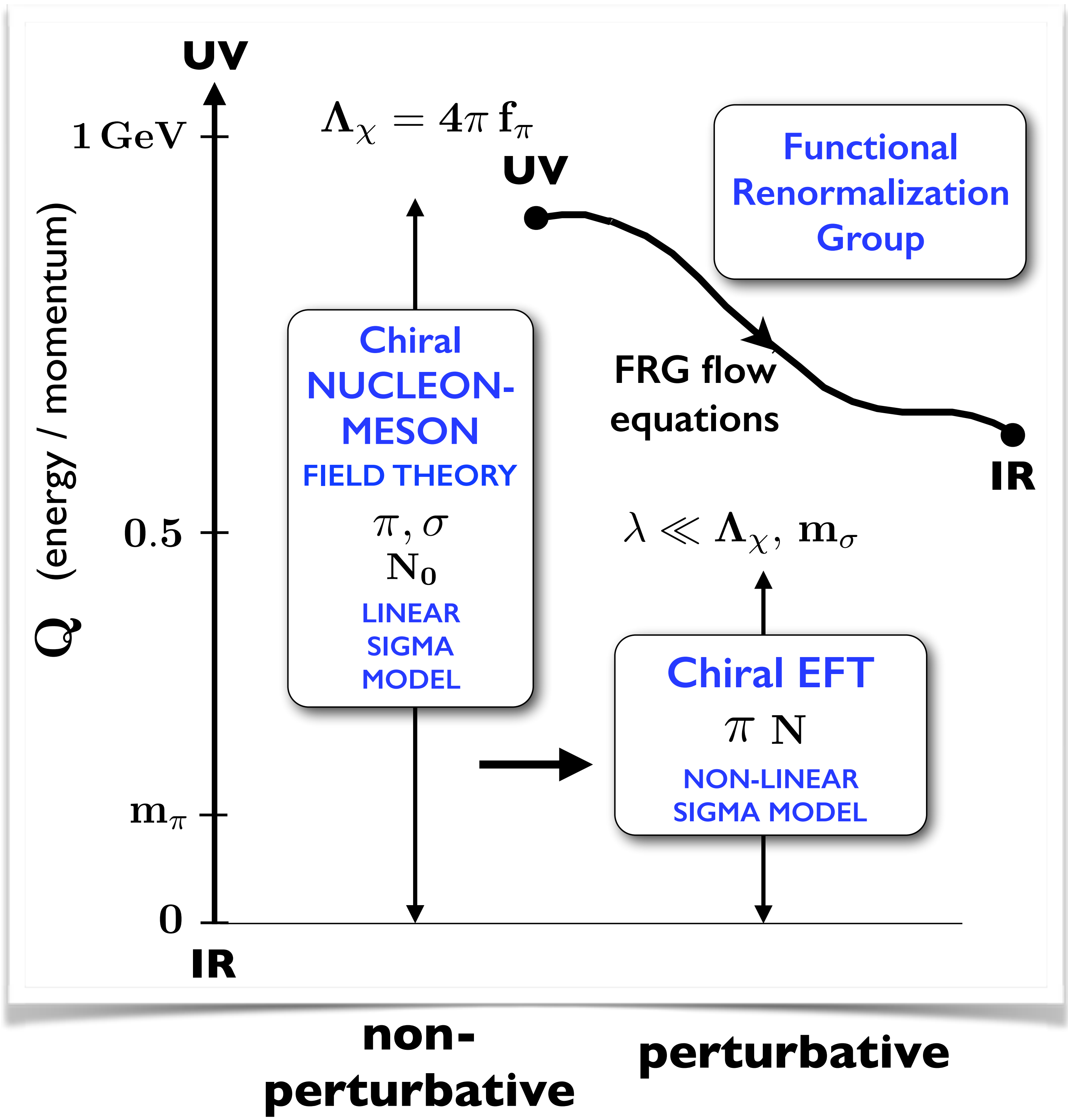
Nambu-Goldstone Bosons (PIONS)

Theoretical FRAMEWORKS and METHODS

Chiral Effective Field Theory

and

Functional Renormalization Group



CHIRAL EFFECTIVE FIELD THEORY

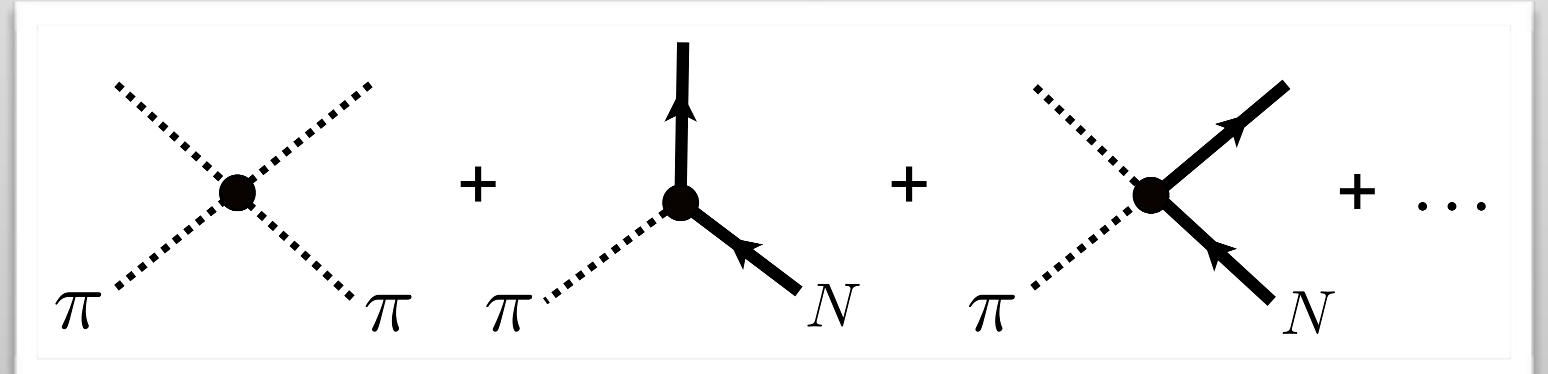
Interface of QCD and Nuclear Physics

- Interacting systems of
  PIONS (light / fast) and **NUCLEONS** (heavy / slow):

$$\mathcal{L}_{eff} = \mathcal{L}_\pi(U, \partial U) + \mathcal{L}_N(\Psi_N, U, \ldots)$$

$$U(x) = exp[i\tau_a \pi_a(x)/f_\pi]$$

- Construction of Effective Lagrangian: **Symmetries**

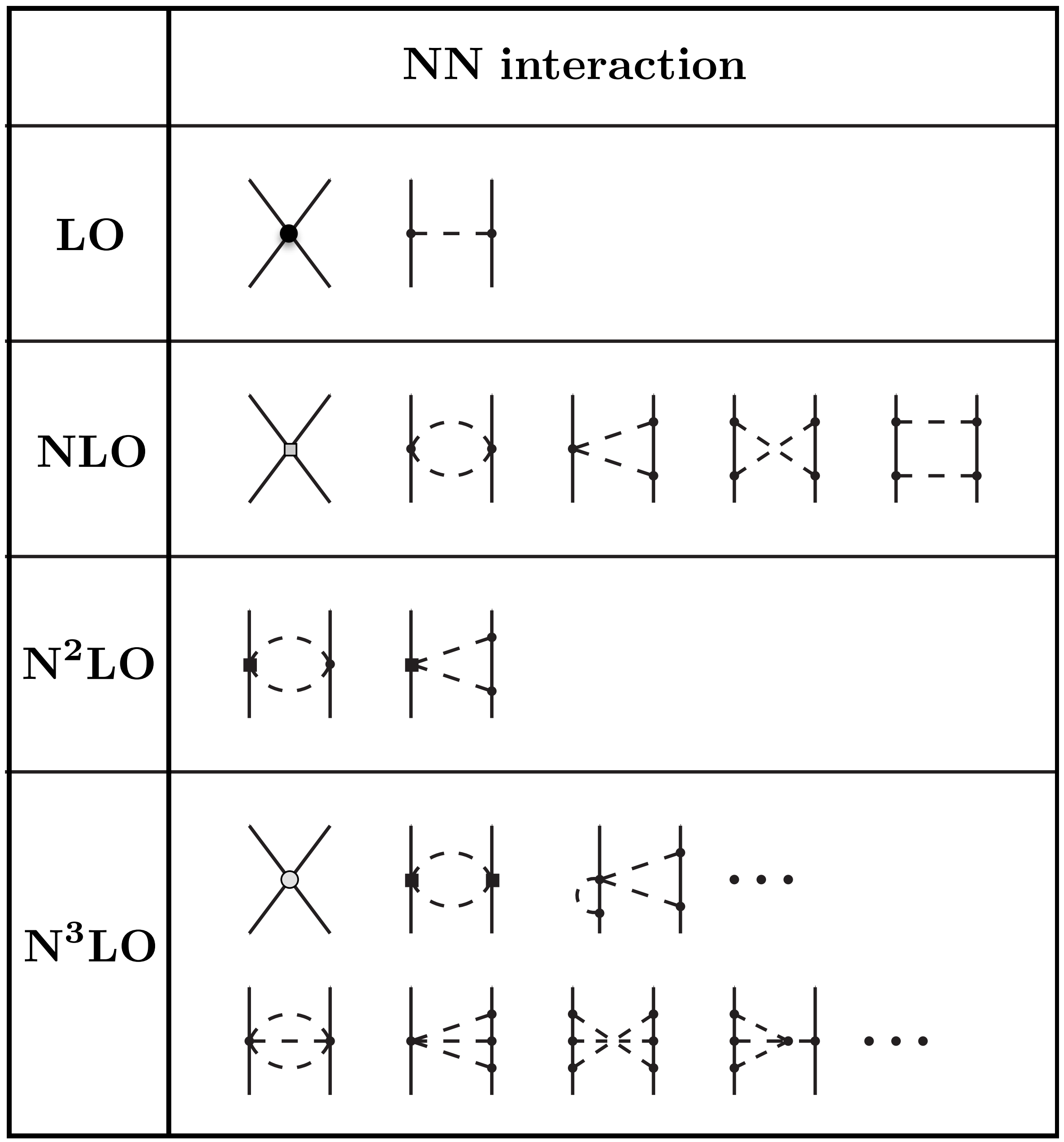


short distance dynamics: **contact terms**

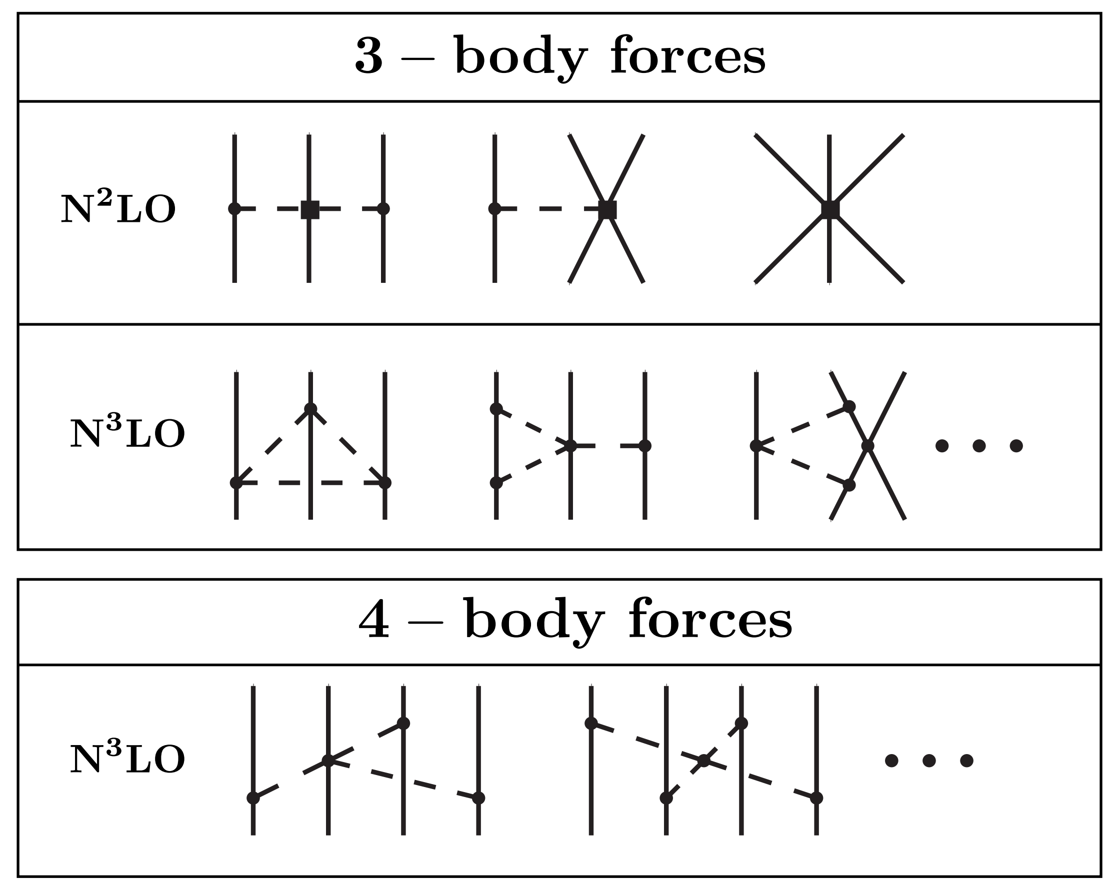
- **Nambu-Goldstone Pions** : derivative couplings $\propto \partial^\mu \pi(x)$

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

Nuclear Many-Body Problem
IN-MEDIUM CHIRAL PERTURBATION THEORY

- **Small scales:** energy, momentum, $m_\pi,\ k_F << 4\pi f_\pi \sim 1\,\mathrm{GeV}$

- "Medium insertion" in the nucleon propagators:

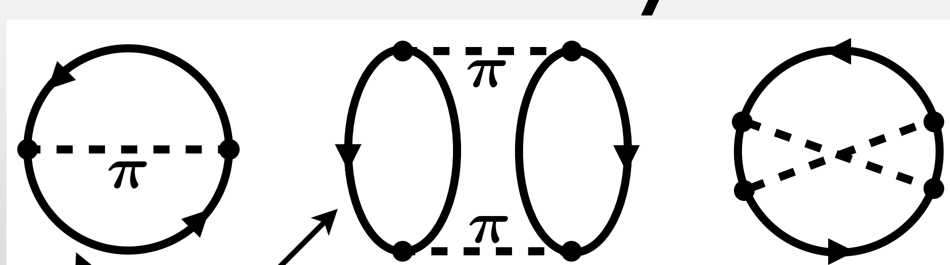
$$(\gamma_\mu p^\mu + M_N)\left[\frac{i}{p^2 - M_N^2 + i\varepsilon} - 2\pi\,\delta(p^2 - M_N^2)\,\theta(p^0)\,\theta(k_F - |\vec{p}|)\right]$$

Loop expansion of (In-Medium) Chiral Perturbation Theory
$\longleftrightarrow$ Expansion of **ENERGY DENSITY** $\mathcal{E}(k_F)$ in
powers of Fermi momentum [modulo functions $f_n(k_F/m_\pi)$]

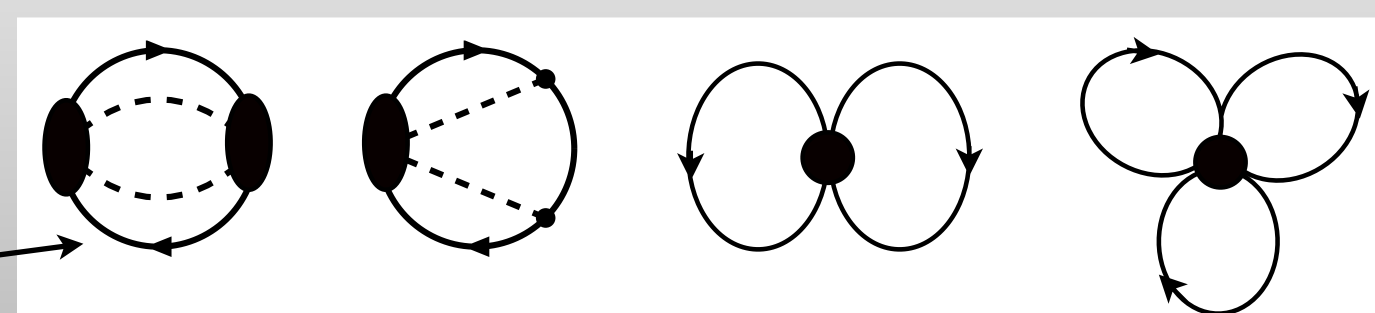
Nuclear thermodynamics: free energy density

(3-loop order)

N. Kaiser, S. Fritsch, W.W.
(2002-2005)



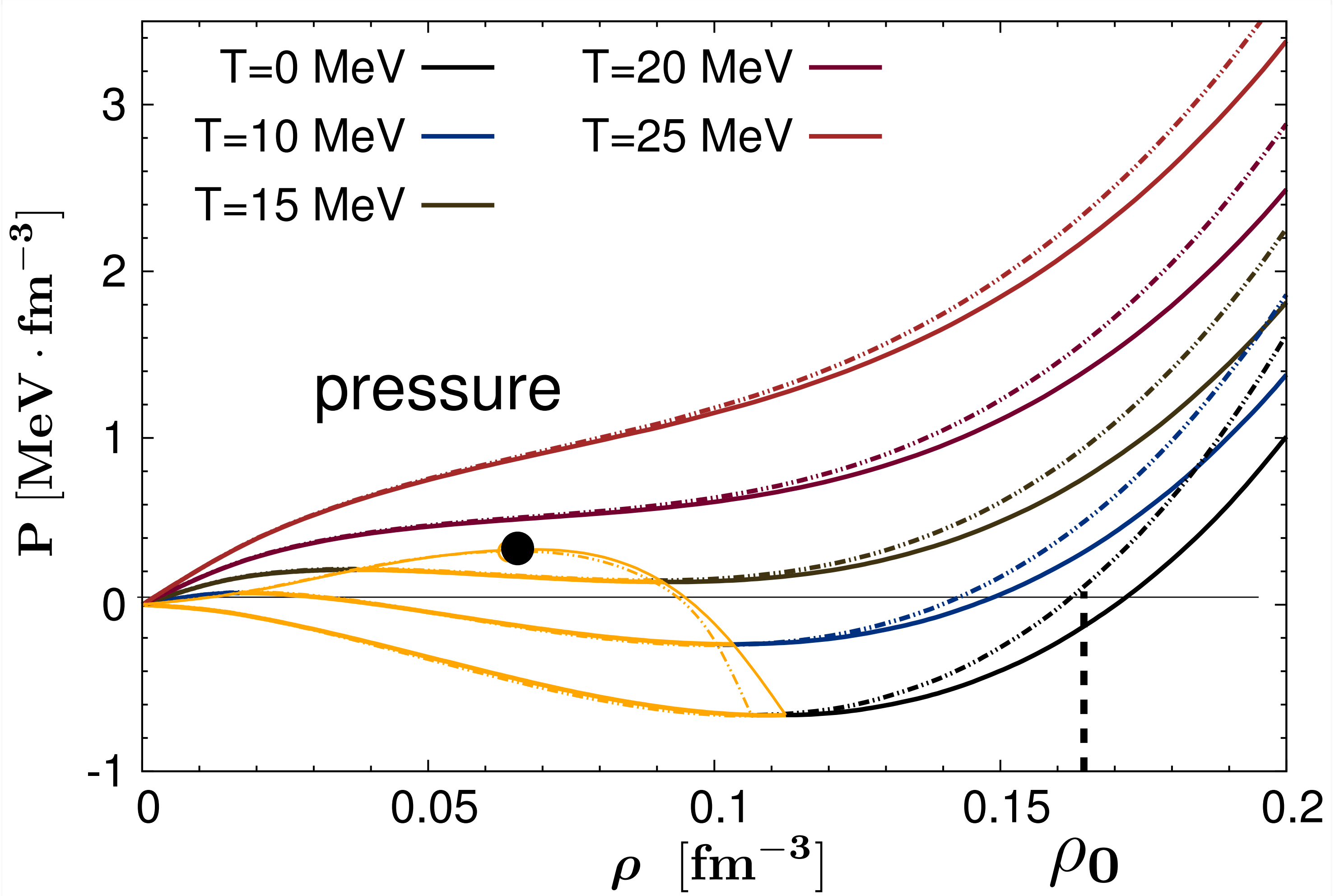
in-medium
nucleon propagators
incl. **Pauli blocking**



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 :

$T_c = 17.4\ \mathrm{MeV}$

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

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

ISOSPIN-ASYMMETRIC MATTER and SYMMETRY ENERGY

- **Energy per particle :** $E(\rho,\eta) = E(\rho,\eta=0) + S(\rho)\,\eta^2 + \ldots \qquad \eta = \frac{\rho_n - \rho_p}{\rho}$
- **Symmetry energy :**

$$S(\rho) = E_n(\rho) - E(\rho)$$

neutron matter ($E_n(\rho)$)

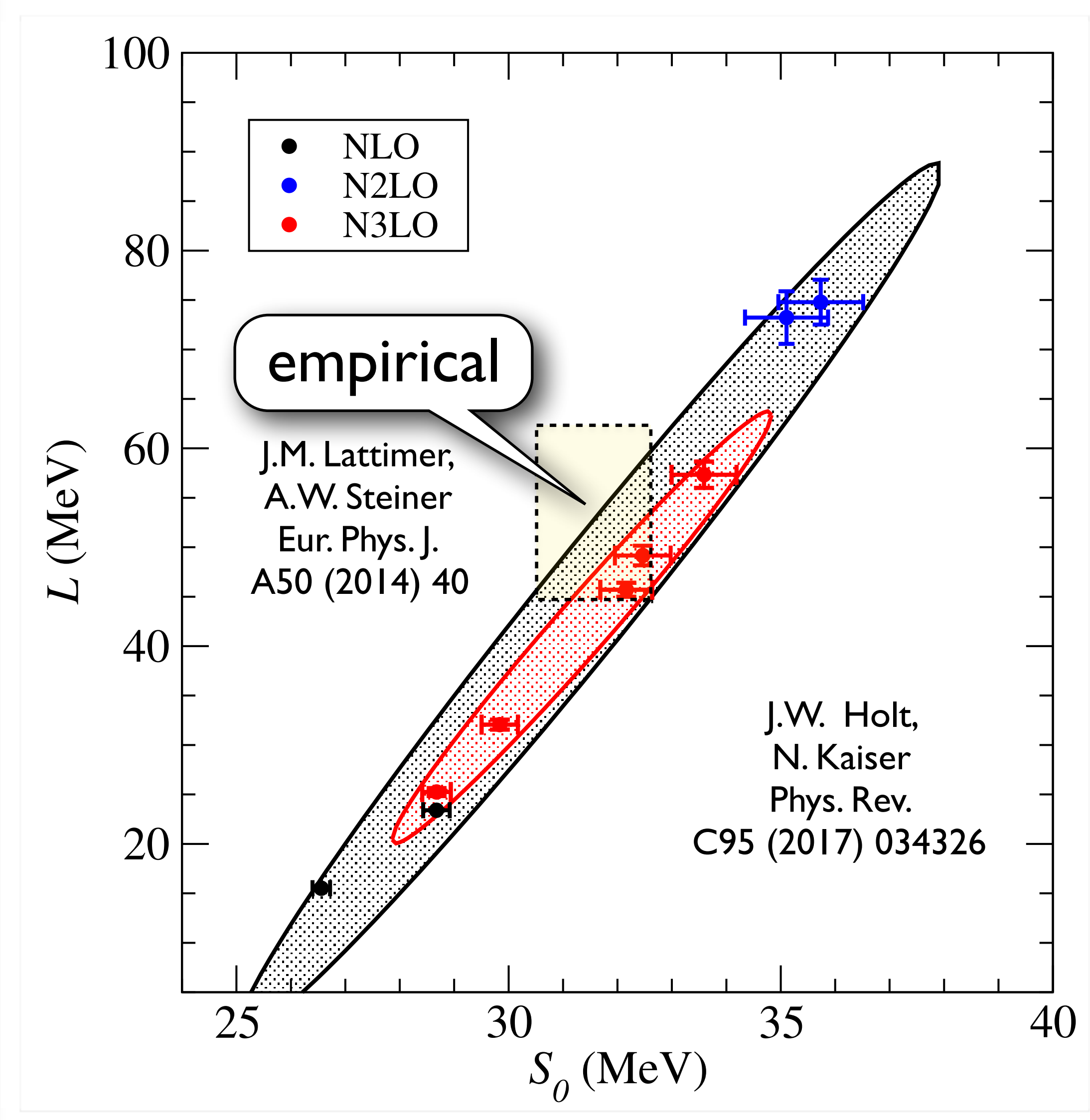
symmetric nuclear matter ($E(\rho)$)

$$S_0 \equiv S(\rho = \rho_0)$$

$$L = 3\rho \frac{\partial S(\rho)}{\partial \rho}\Big|_{\rho_0}$$

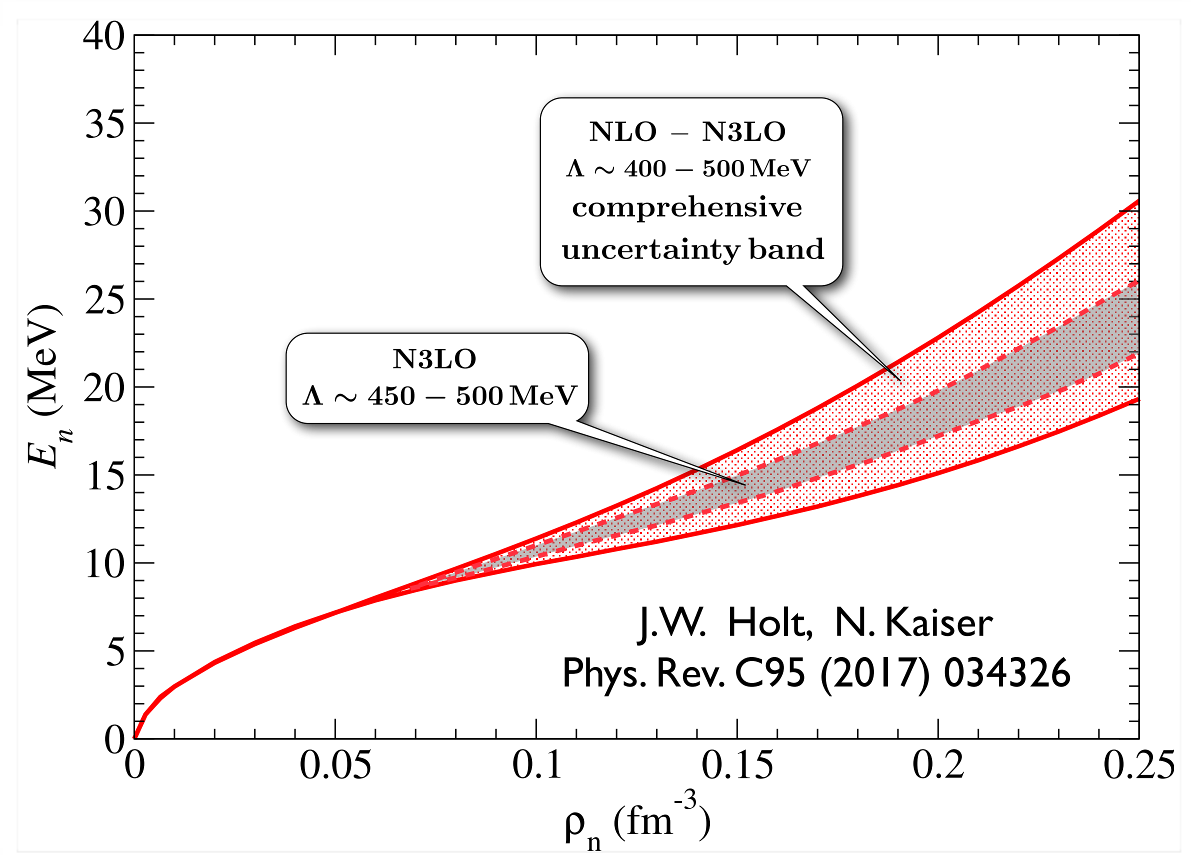
- **Key quantities for neutron-rich nuclei and astrophysics**

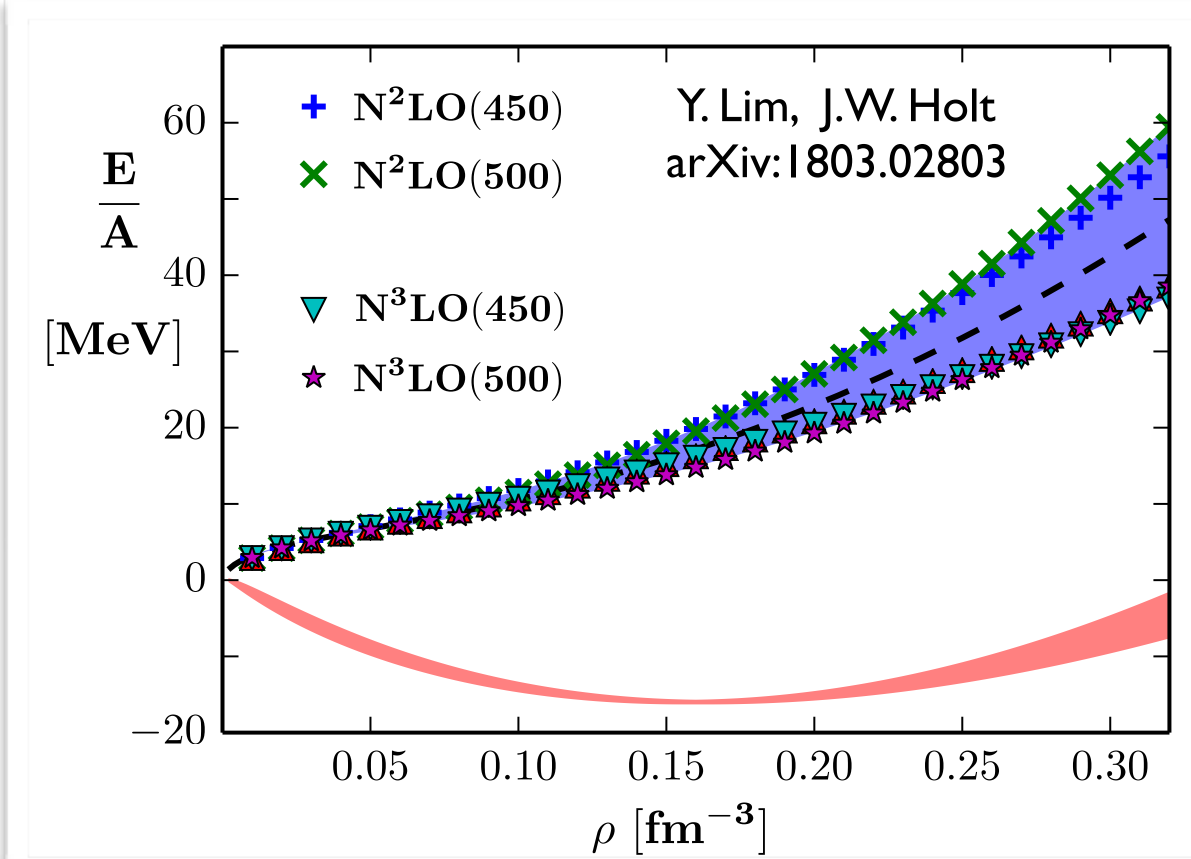
N3LO chiral NN interactions
+ N2LO 3-body forces



NEUTRON and NUCLEAR MATTER from CHIRAL EFT

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





- 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

NEUTRON STAR MATTER

- **Energy density functional (Skyrme-Hartree-Fock)** deduced from

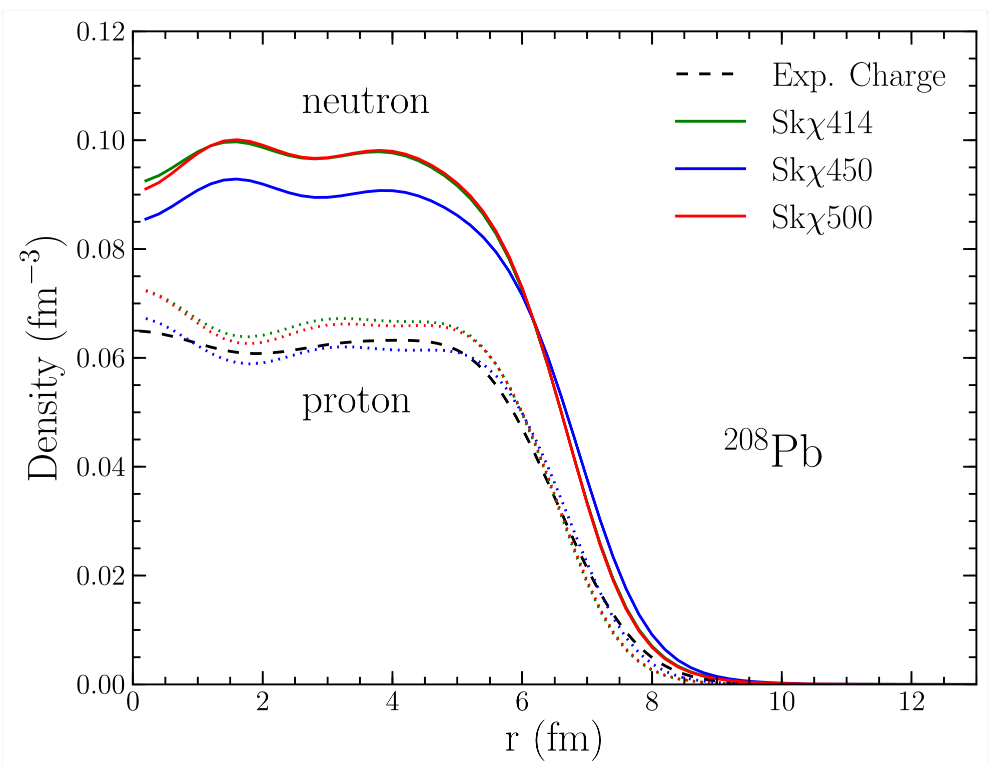
Chiral Effective Field Theory

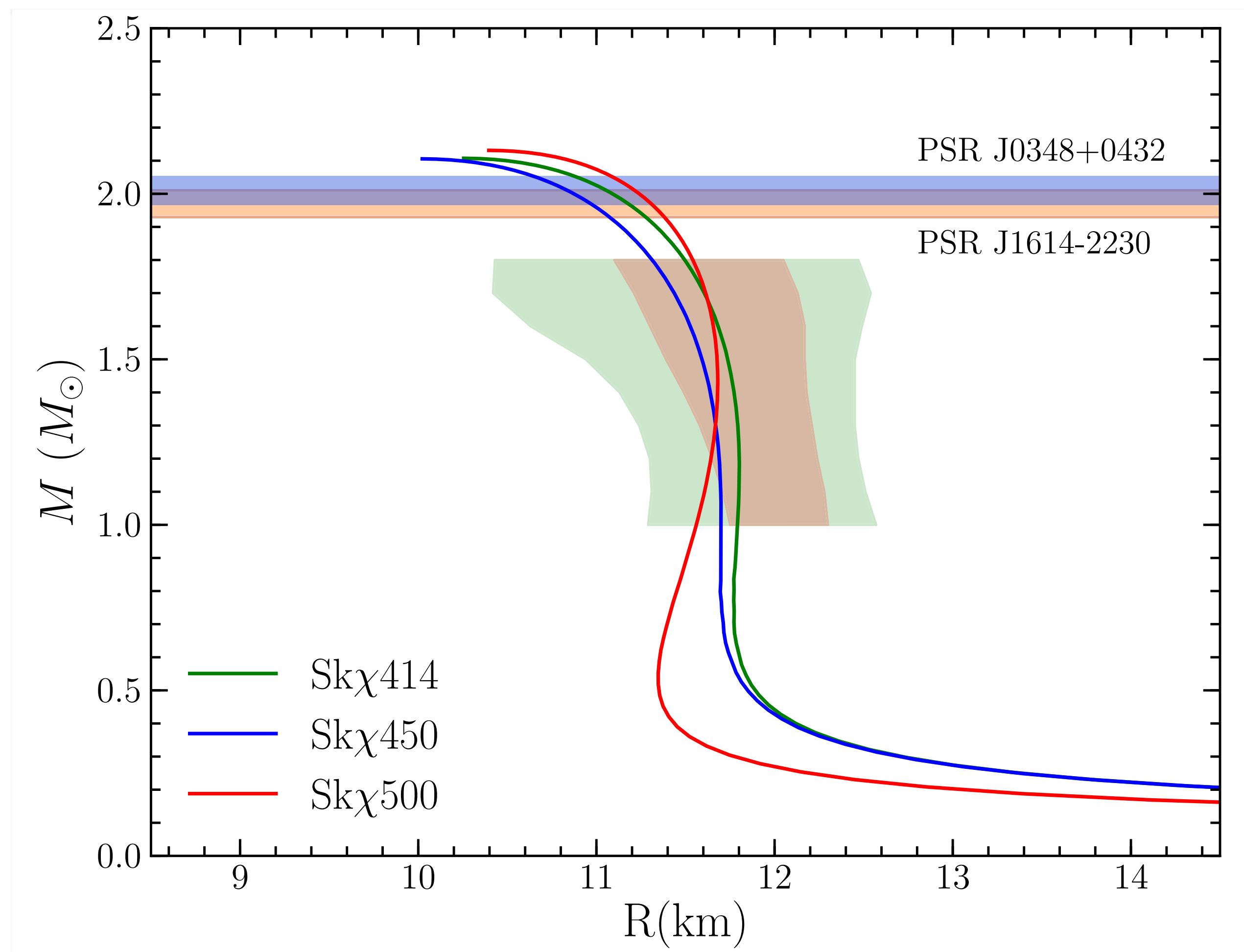
N3LO two-body interactions, N2LO three-body forces

density dependence consistent with ChEFT expansion in powers of Fermi momenta

Y. Lim, J.W. Holt Phys. Rev. C95 (2017) 065805

- successfully reproduces properties of finite nuclei …



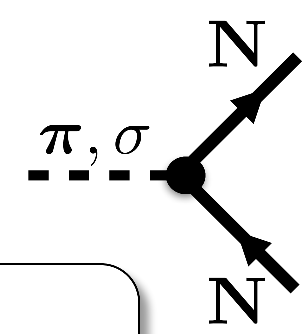


… and neutron star crust together with $2\,M_\odot$ constraint

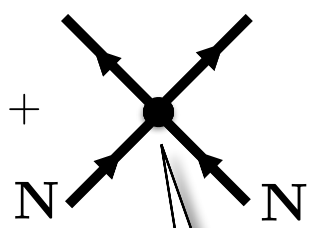
Mesons, Nucleons, Nuclear Matter
and
Functional Renormalization Group

- **Chiral nucleon - meson Lagrangian**

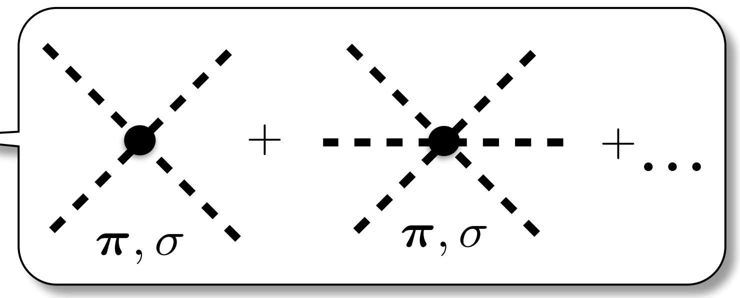
$$\mathcal{L} = \bar{\mathrm{N}}\, i\gamma_\mu \partial^\mu \mathrm{N} + \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma + \partial_\mu\boldsymbol{\pi}\cdot\partial^\mu\boldsymbol{\pi}\right) +$$



$+$



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



isoscalar & isovector current-current interactions

- **Nambu-Goldstone boson** π and "**heavy**" σ
- **Potential** $\mathcal{U}(\sigma, \boldsymbol{\pi})$ constructed to reproduce vacuum physics and nuclear matter at equilibrium
- **Pionic fluctuations** and **nucleonic particle-hole** excitations treated **non-perturbatively** using **FRG**

M. Drews, T. Hell, B. Klein, W.W. Phys. Rev. D88 (2013) 096011
M. Drews, W.W. Phys. Lett. B738 (2014) 187 Phys. Rev. C91 (2015) 035802
Review: M. Drews, W.W. Prog. Part. Nucl. Phys. 91 (2017) 347

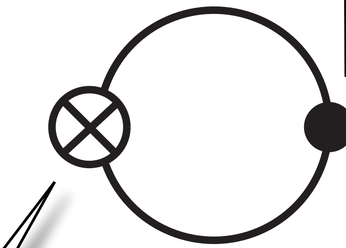
Renormalization Group strategies

Wetterich's FRG flow equations

k-dependent action

full propagator

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



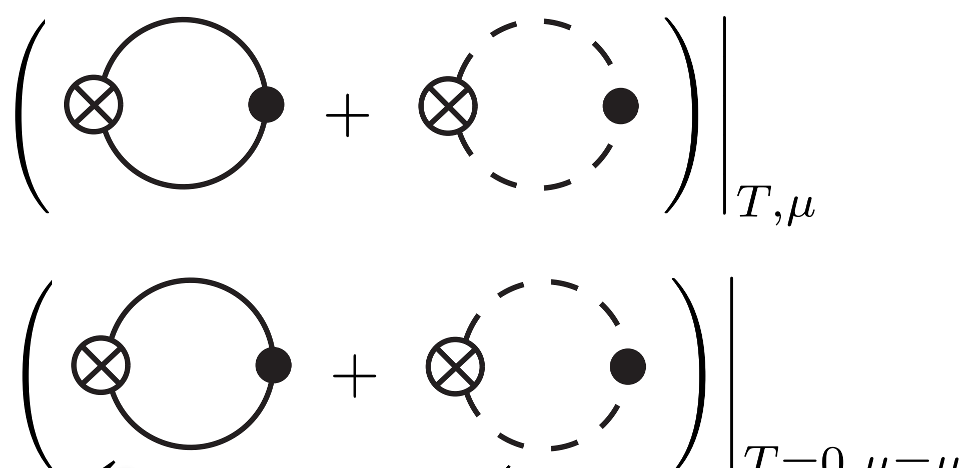
scale regulator R_k

$\Gamma_{k=\Lambda}[\Phi] = S$ → $\Gamma_k[\Phi]$ → $\Gamma_{k=0}[\Phi] = \Gamma[\Phi]$

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

- **Thermodynamics:**

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



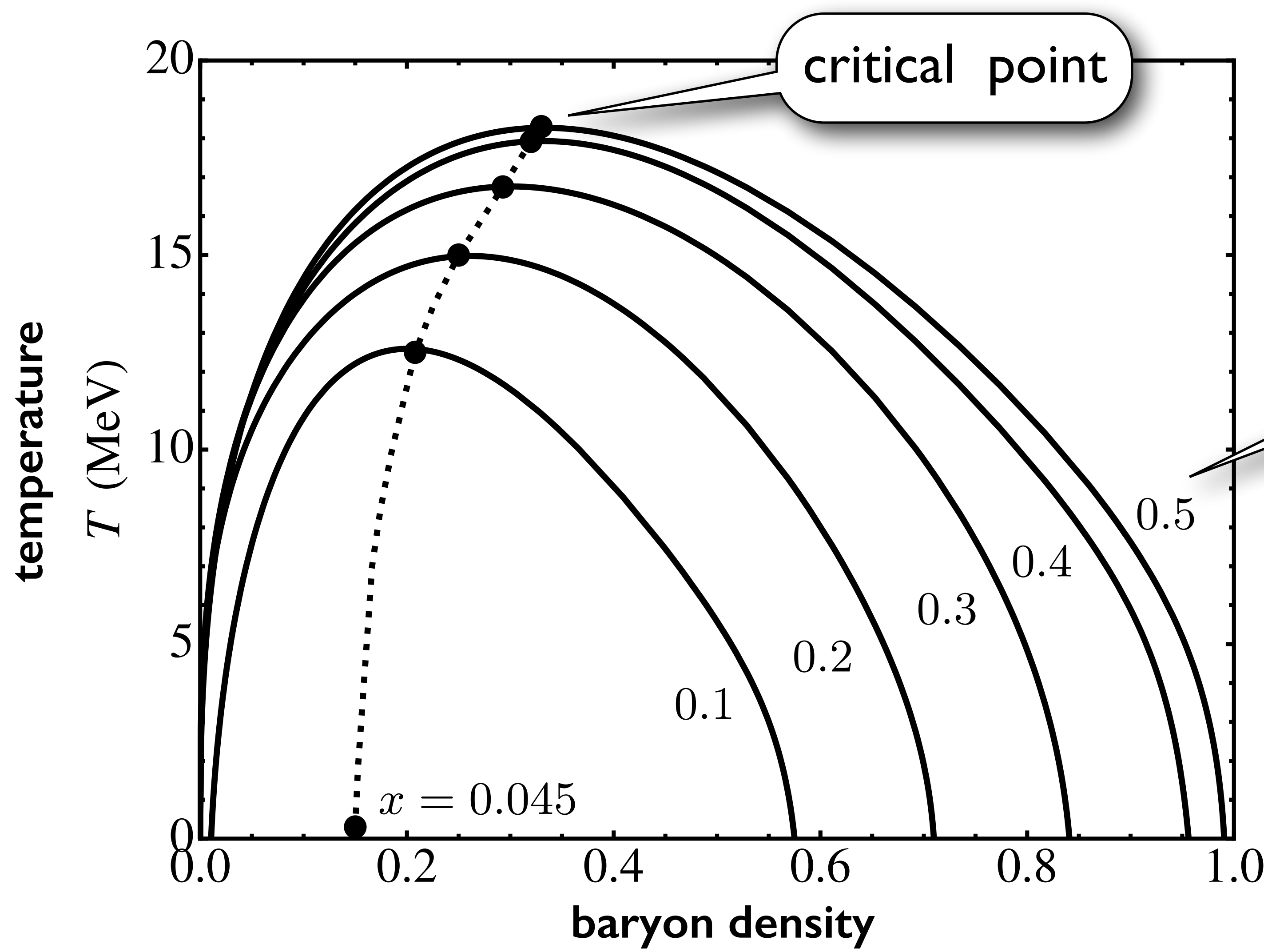
Non-perturbative treatment of :

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

PHASE DIAGRAM of NUCLEAR MATTER

- Trajectory of **CRITICAL POINT of Liquid - Gas transition** for **asymmetric matter** as function of proton fraction Z / A

S. Fiorilla, N. Kaiser, W.W. Nucl. Phys. A 880 (2012) 65



M. Drews, T. Hell, B. Klein, W.W. Phys. Rev. D 88 (2013) 096011

M. Drews, W.W. Phys. Lett. B 738 (2014) 187 Phys. Rev. C 91 (2015) 035802

. . . including **non-perturbative** effects **(Functional Renormalization Group)**

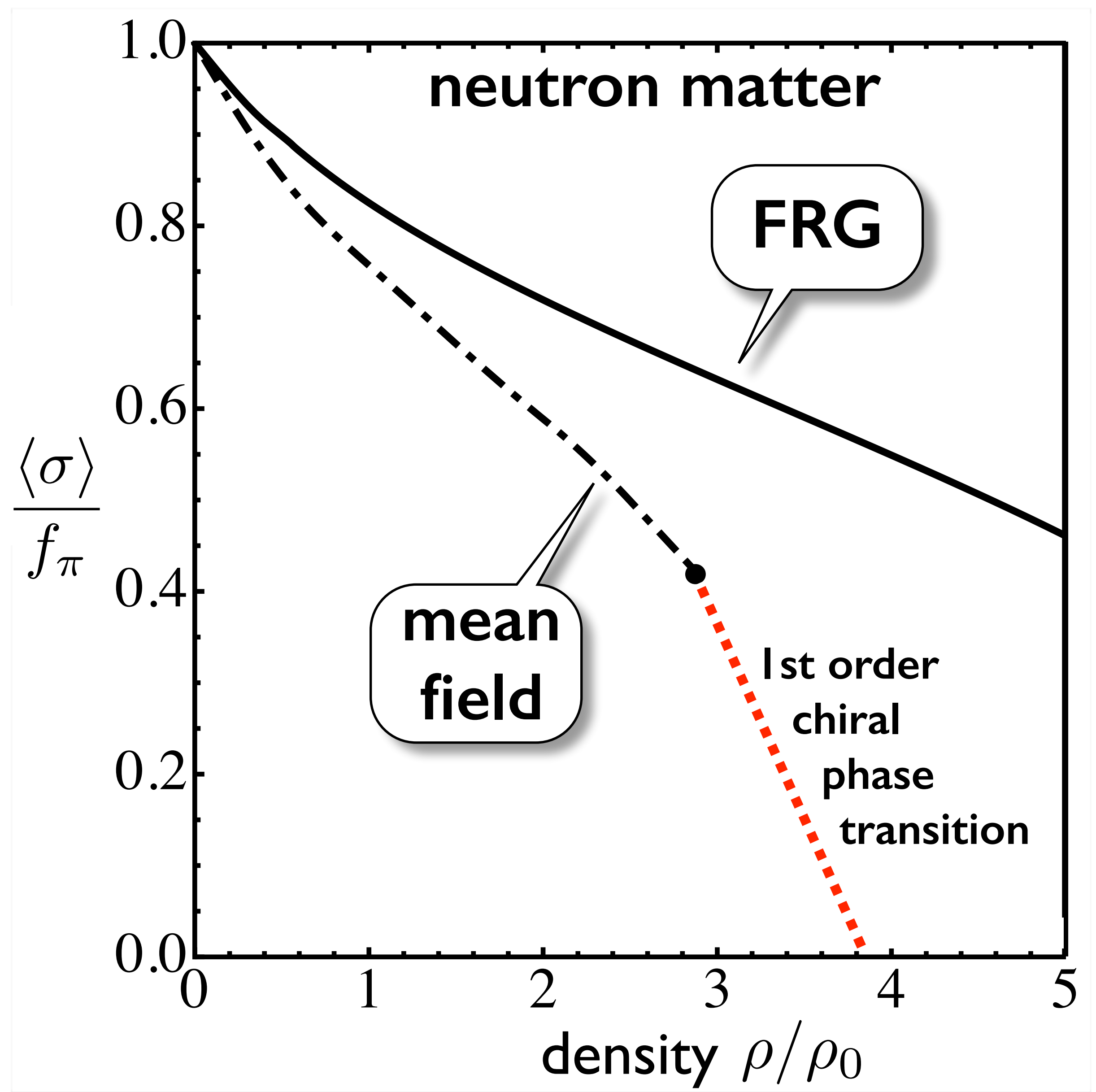
$$\frac{\rho}{\rho_0} \quad (\rho_0 = \mathbf{0.16\,fm^{-3}})$$

. . . determined almost completely by **isospin** dependent (one- and **two-**) **pion** exchange dynamics

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 and **nucleon-hole)**

beyond mean-field approximation:

DISAPPEARANCE of

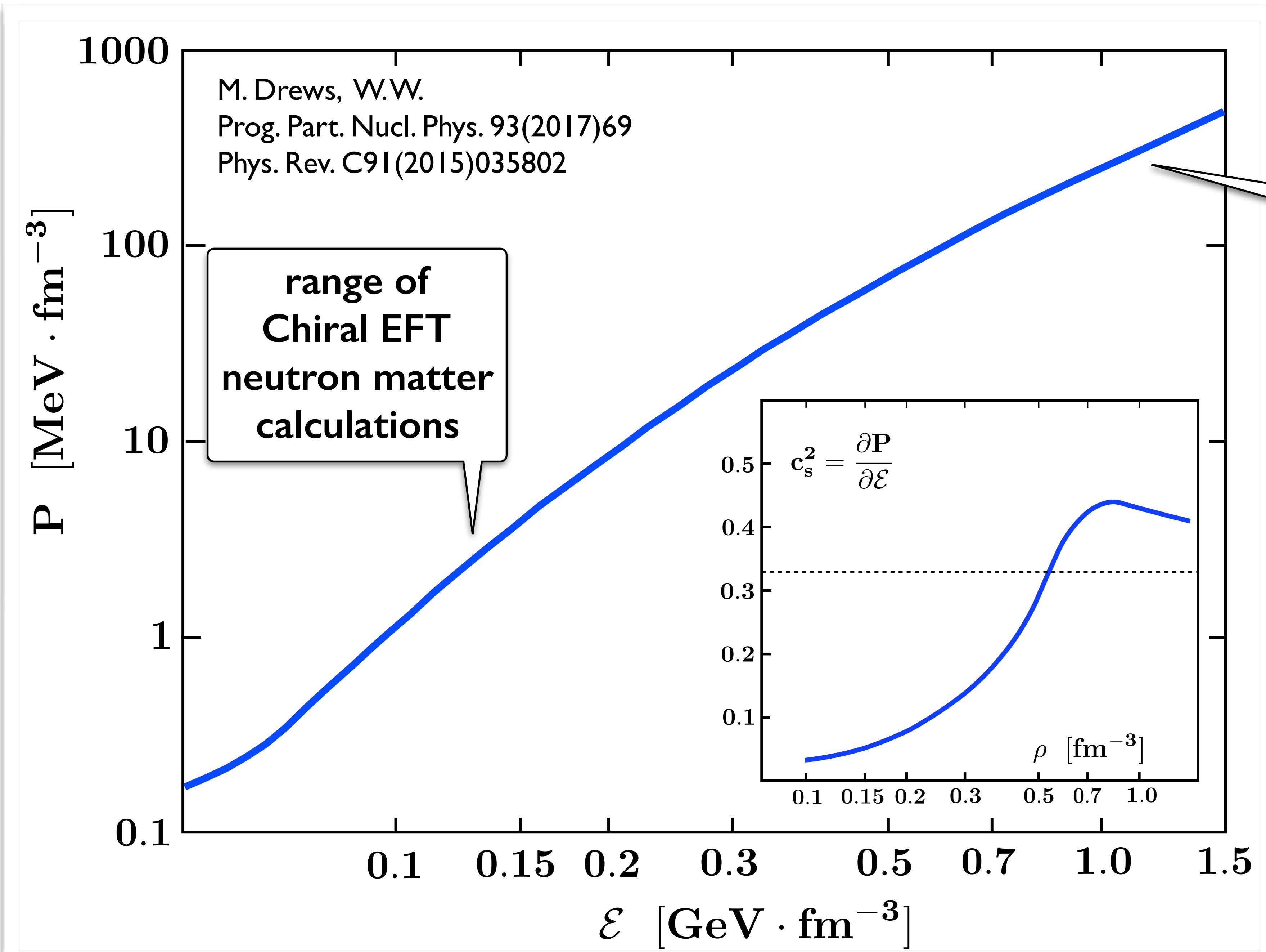
first-order

chiral phase transition

NEUTRON STAR MATTER
Equation of State

- **Chiral FRG calculations** with inclusion of beta equilibrium

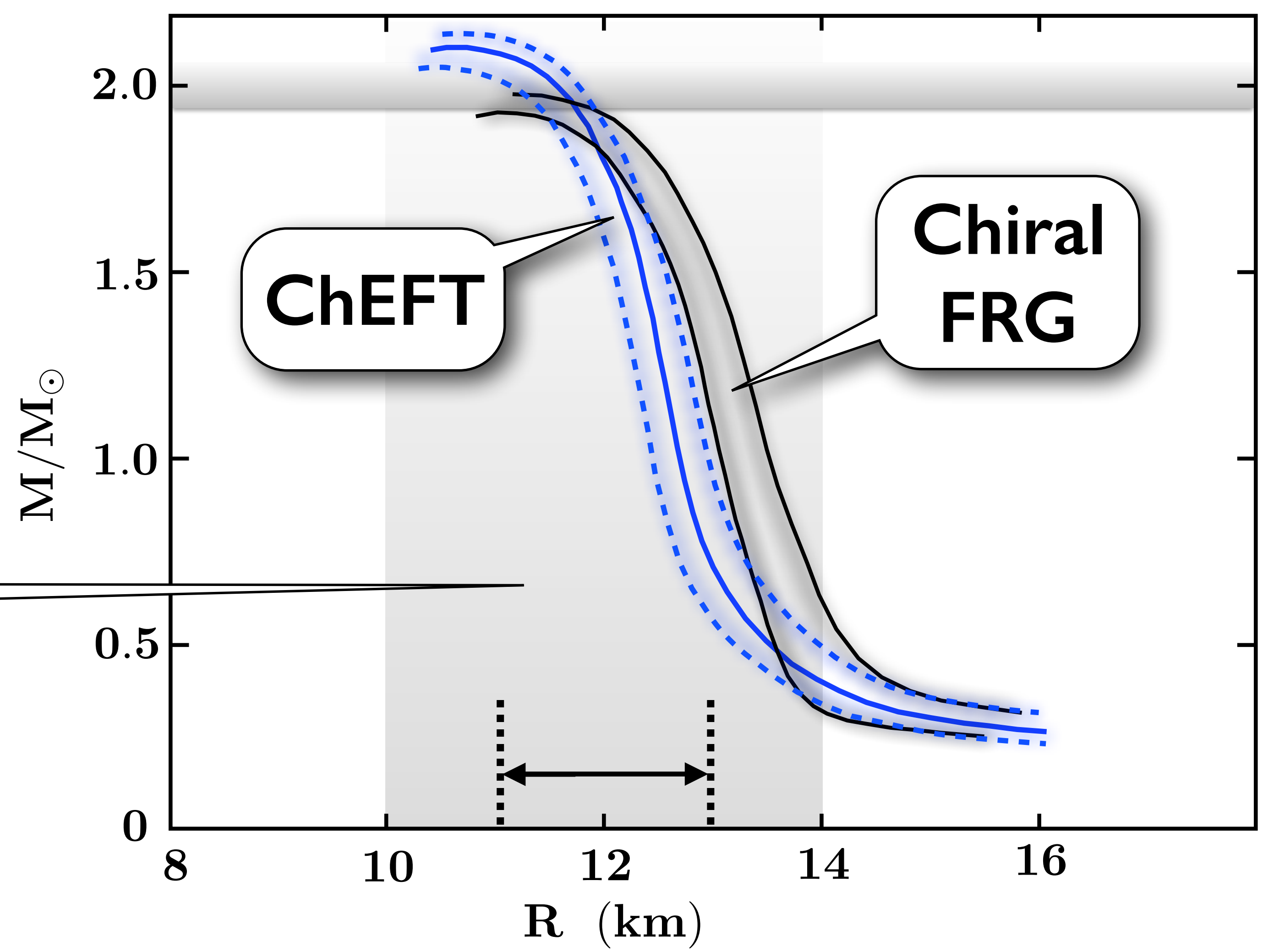
M. Drews, W.W. Phys. Rev. C91 (2015) 035802 Prog. Part. Nucl. Phys. 93 (2017) 69



NEUTRON STAR MATTER from Chiral EFT and FRG

- Symmetry energy range: 30 - 35 MeV
- Crust: SLy EoS

T. Hell, W.W.
Phys. Rev.
C90 (2014) 045801



Radius window

A.W. Steiner,
J.M. Lattimer, E.F. Brown
EPJ A52 (2016) 18

M. Drews, W.W.

Phys. Rev.
C91 (2015) 035802

Prog. Part. Nucl. Phys.
93 (2017) 69

- **Central core density**

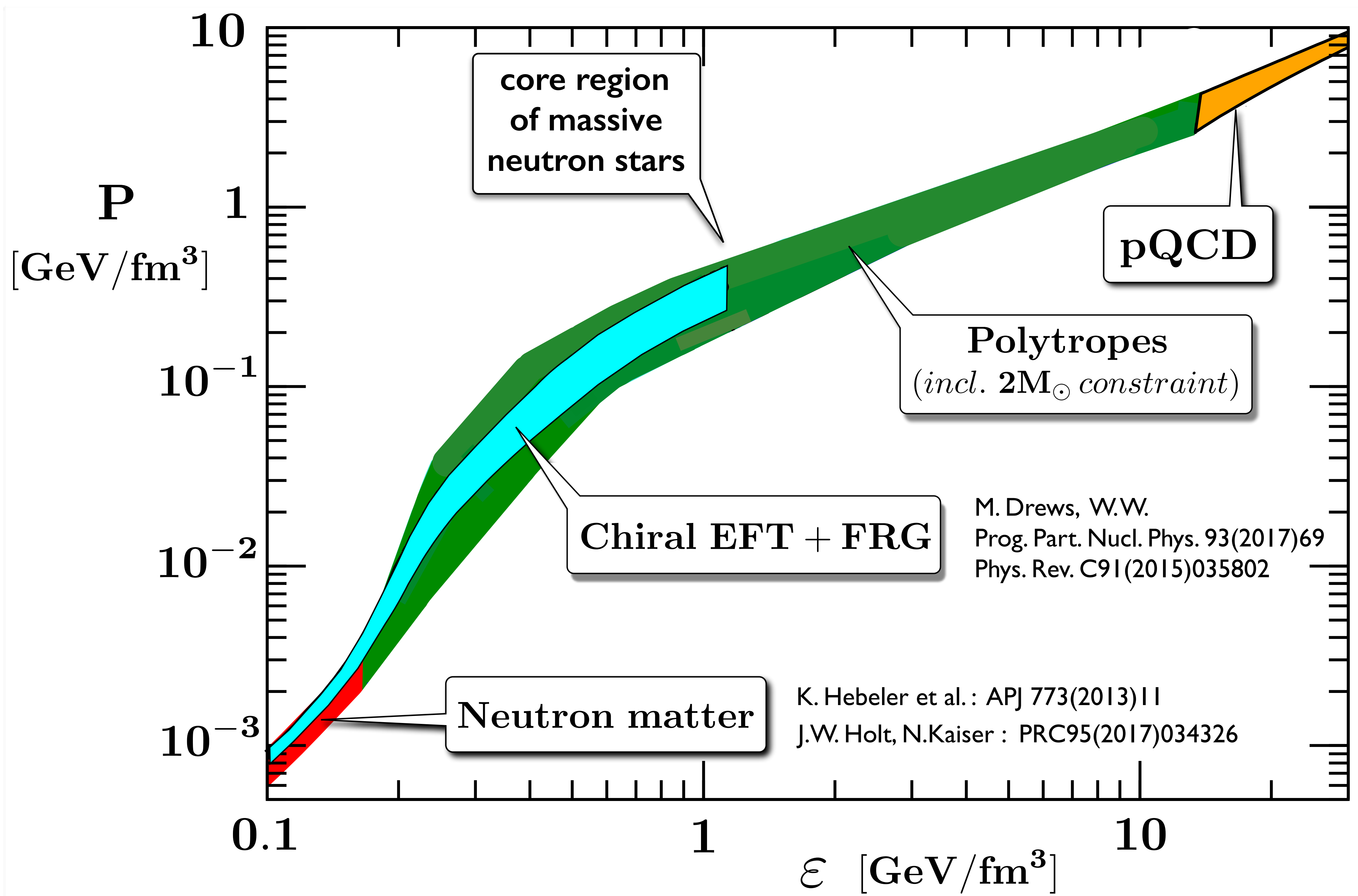
$\rho_c \lesssim 5\,\rho_0$

- **Chiral many-body dynamics using "conventional" (pion & nucleon) degrees of freedom is consistent with neutron star constraints**

NEUTRON STAR MATTER
Equation of State

… and extrapolation to PQCD limit

A. Kurkela et al. : Astroph. J. 789 (2014) 127



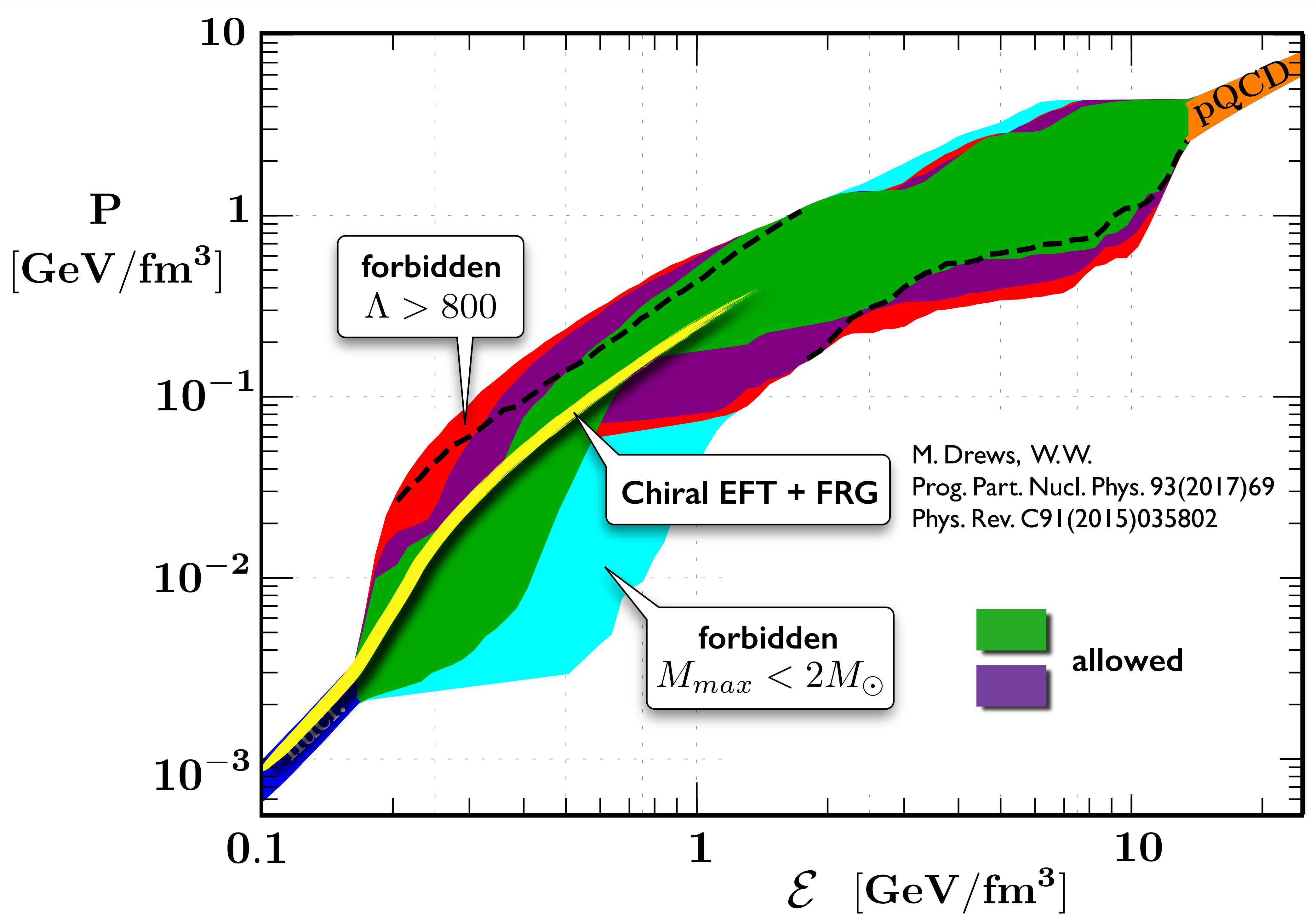
M. Drews, W.W.
Prog. Part. Nucl. Phys. 93(2017)69
Phys. Rev. C91(2015)035802

K. Hebeler et al. : APJ 773(2013)11
J.W. Holt, N.Kaiser : PRC95(2017)034326

NEUTRON STAR MATTER
Equation of State

... now including GW constraints

E. Annala, T. Gorda, A. Kurkela, A.Vuorinen
Phys. Rev. Lett. 120 (2018) 172703



3.

Outlook:
Strangeness in Neutron Stars ?

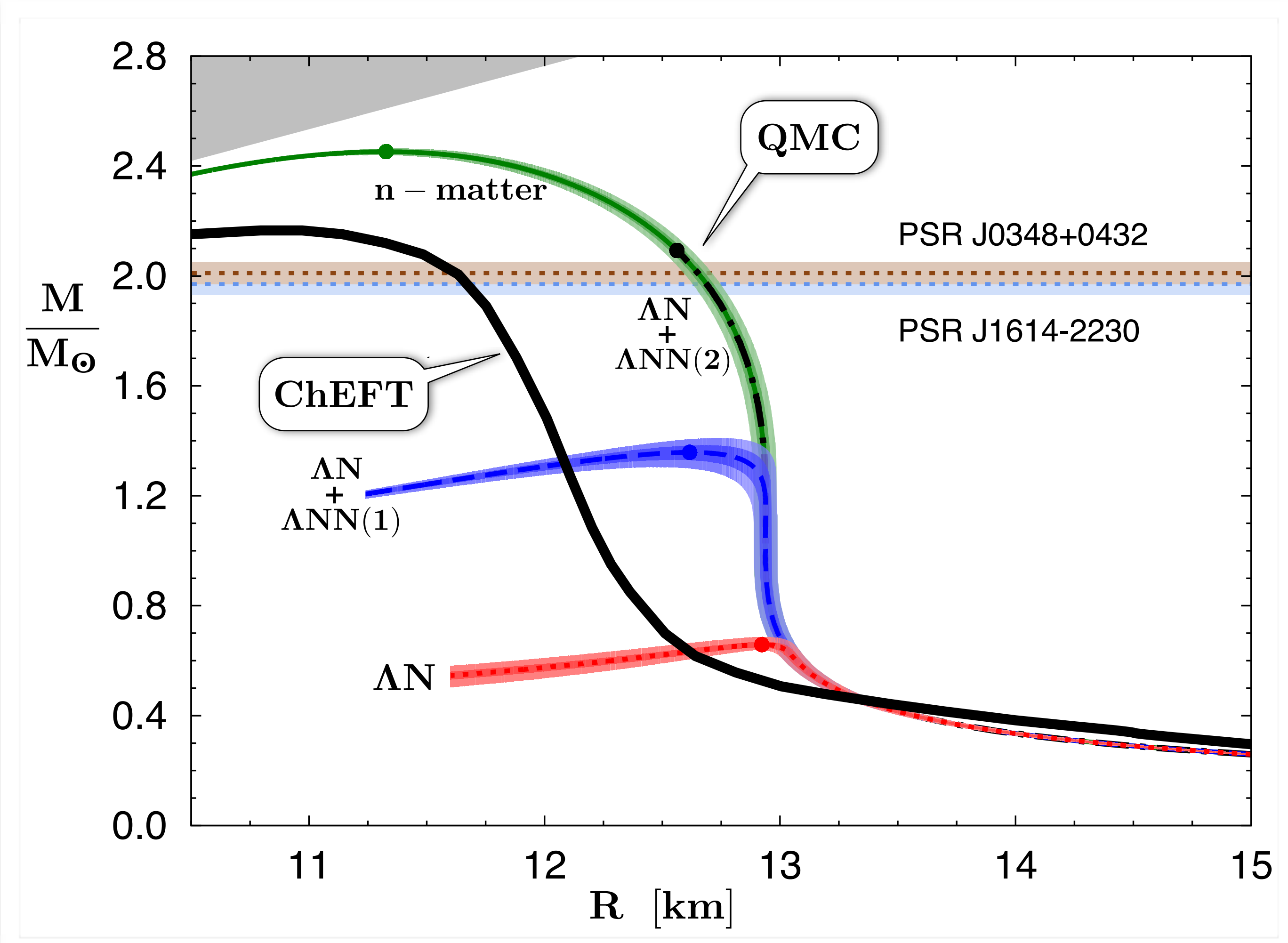
- **The Hyperon Puzzle**
- **Chiral SU(3) Effective Field Theory**
- **Hyperon - Nuclear Interactions**

NEUTRON STAR MATTER including HYPERONS

Quantum **M**onte 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):

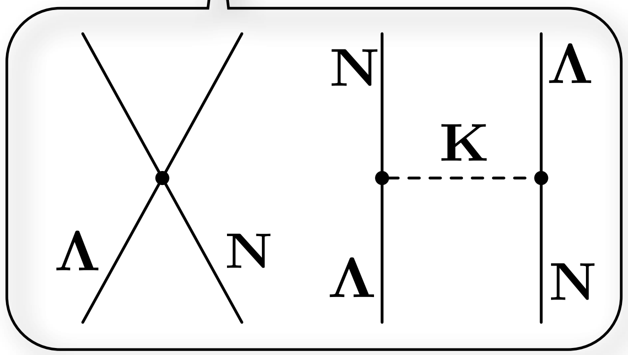
D. Lonardoni,
A. Lovato,
S. Gandolfi,
F. Pederiva

Phys. Rev. Lett.
114 (2015) 092301

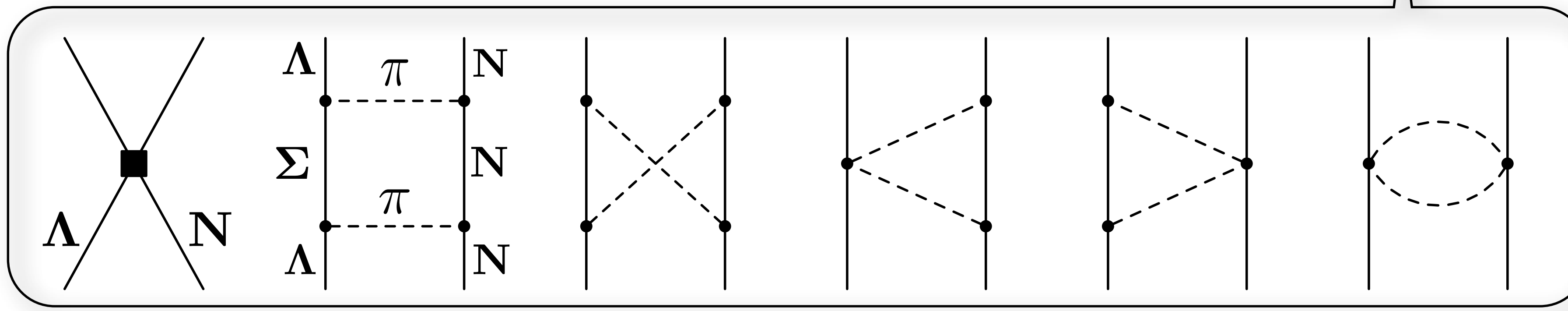
Inclusion of **hyperons**: EoS **too soft** to support 2-solar-mass n-stars
unless: **strong repulsion** in **YN** and **YNN** … interactions

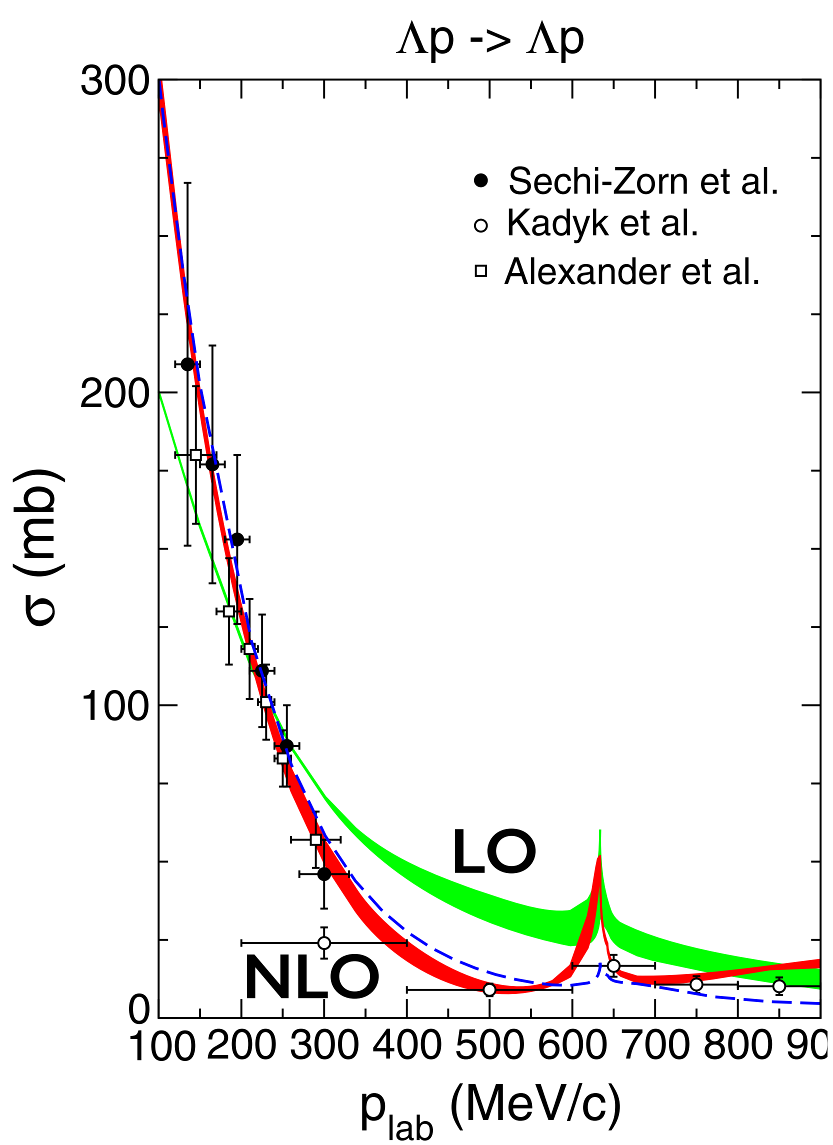
Hyperon - Nucleon Interaction
from **CHIRAL SU(3) Effective Field Theory**

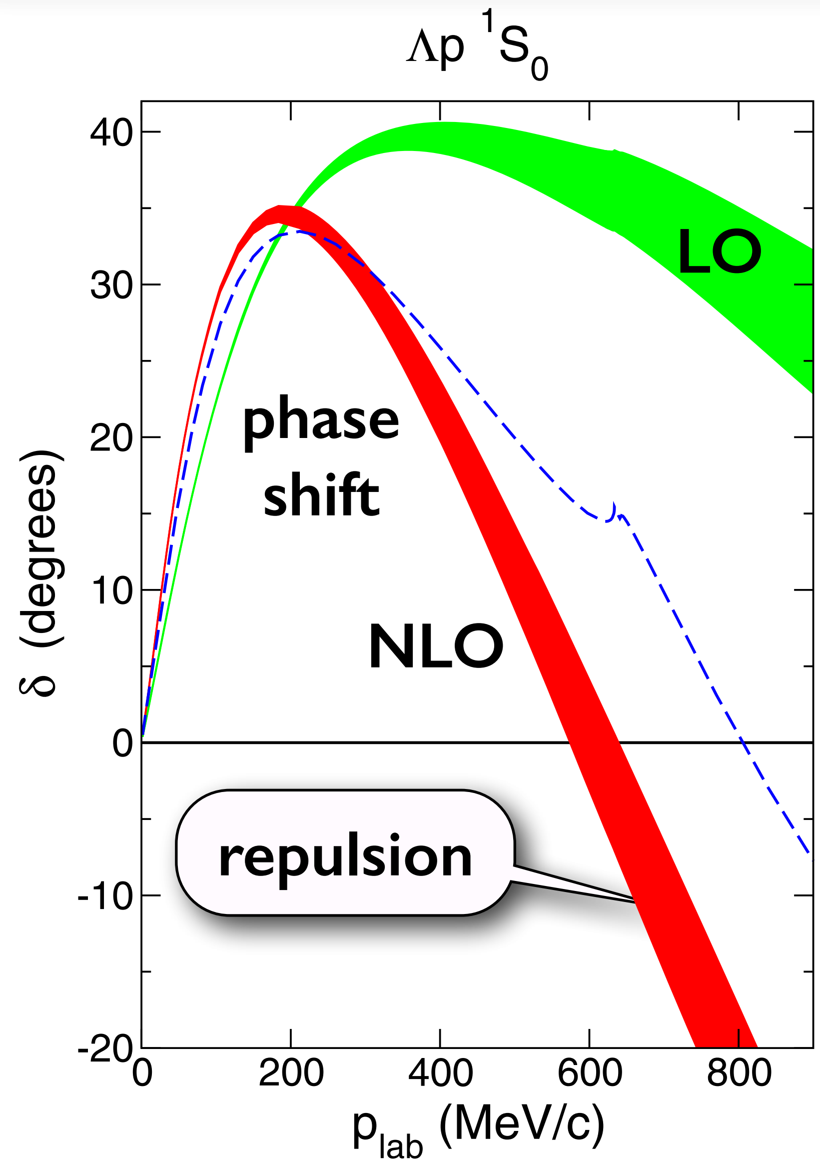
LO



NLO







- **moderate attraction** at low momenta
  → relevant for **hypernuclei**
- **strong 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

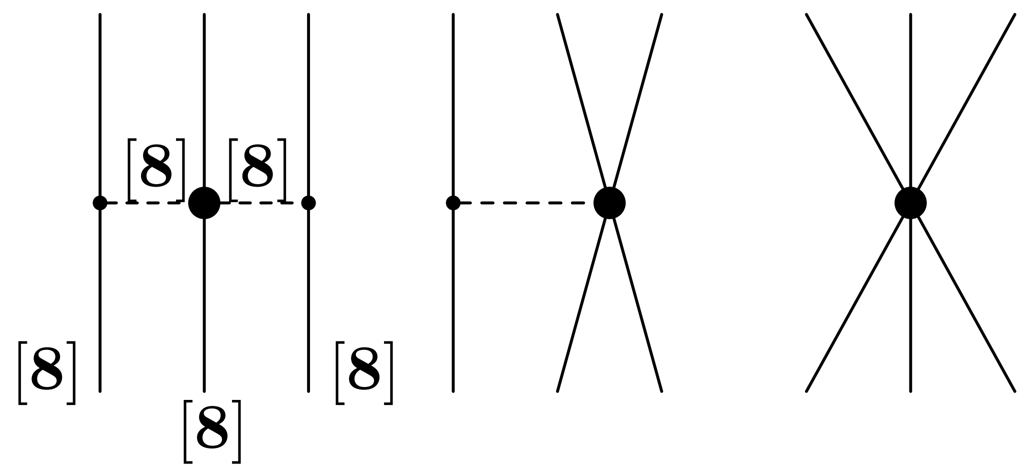
HYPERON - NUCLEON - NUCLEON THREE-BODY FORCES from CHIRAL SU(3) EFT

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:

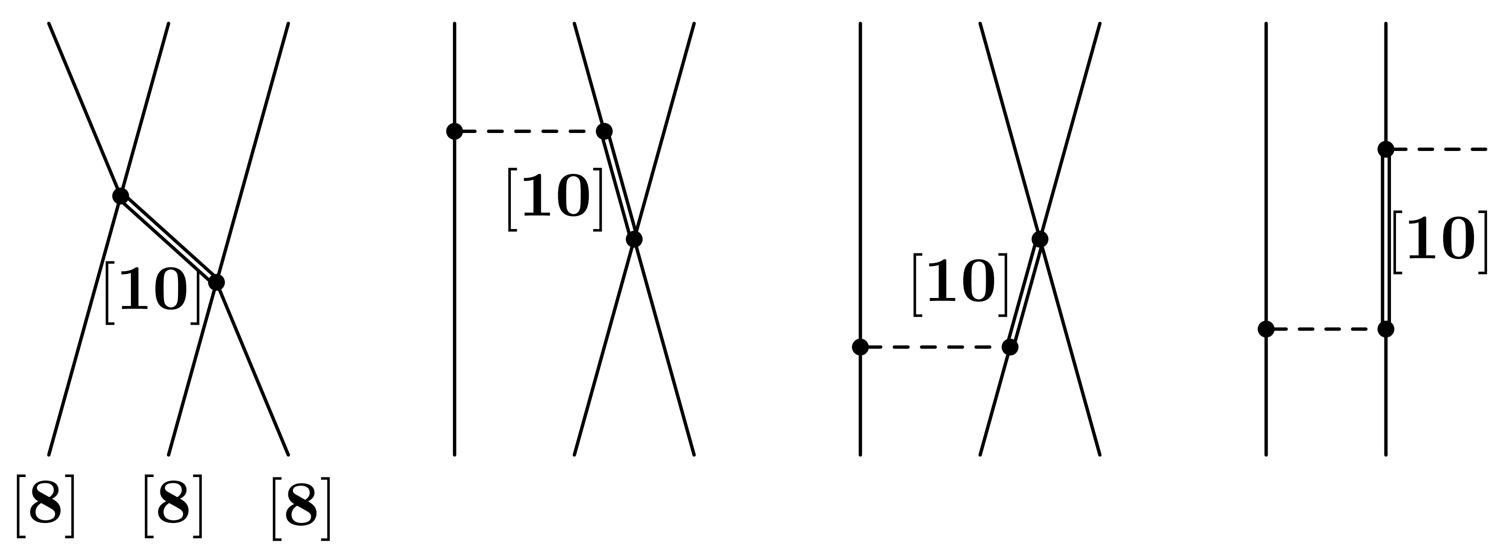
NNLO:



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

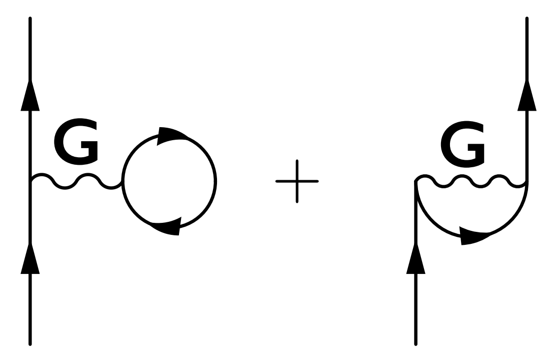
explicit treatment of **baryon decuplet** :

promotion to **NLO**

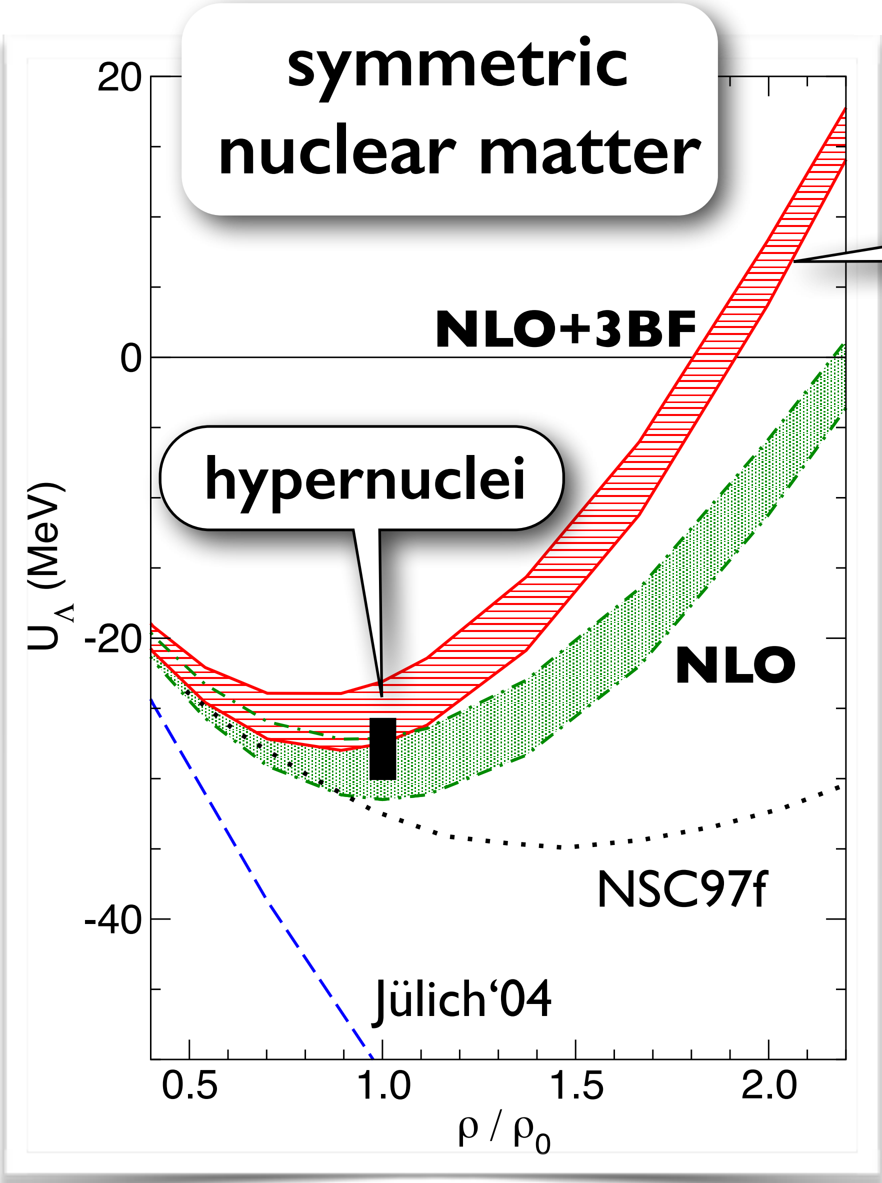


Density dependence of Λ single particle potential

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



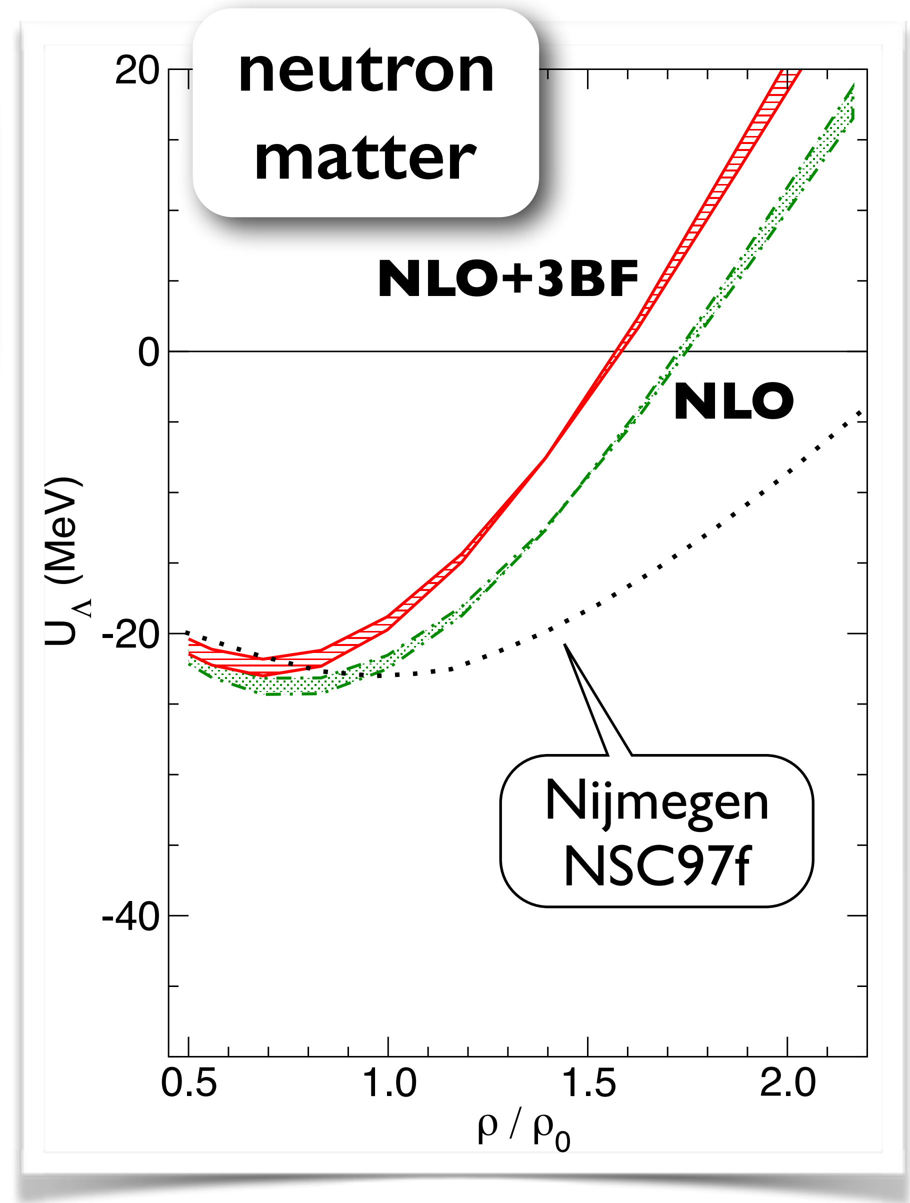
$$\mathbf{G}(\omega) = \mathbf{V} + \mathbf{V}\,\frac{\mathbf{Q}}{\mathbf{e}(\omega) + \mathbf{i}\epsilon}\,\mathbf{G}(\omega)$$



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

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

Eur. Phys. J.
A53 (2017) 121



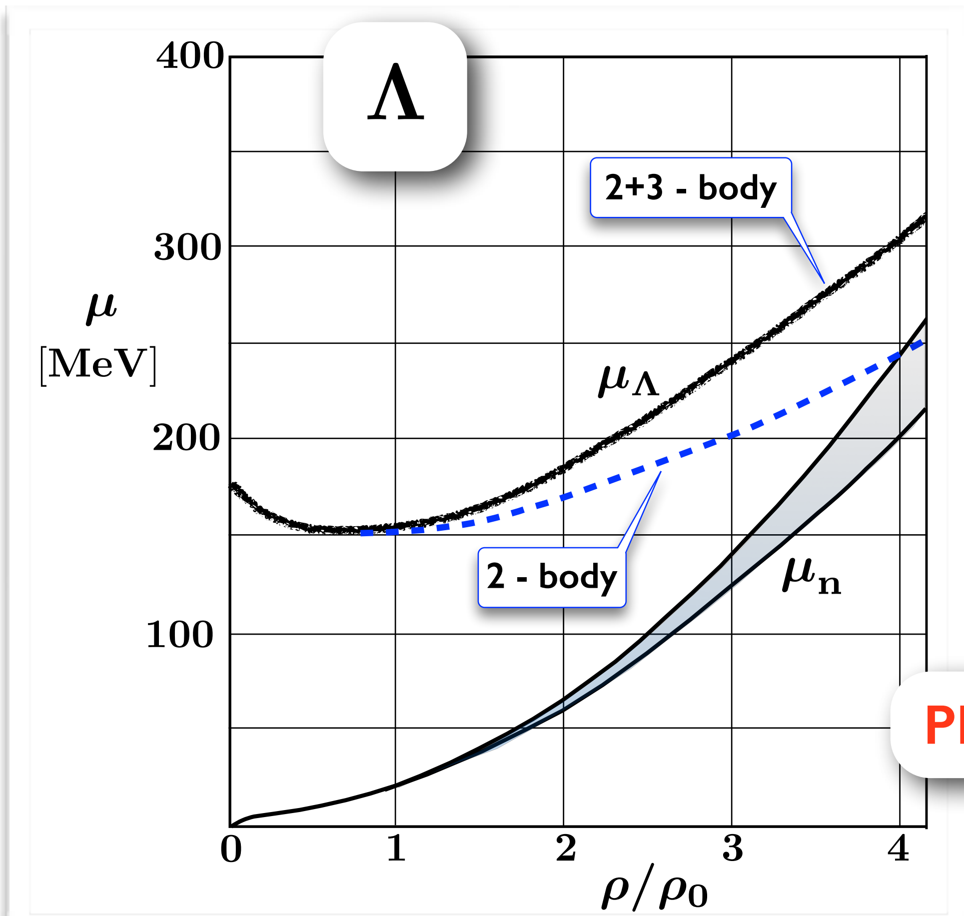
- **… towards a possible solution of the "hyperon puzzle" ?**

Hyperons in Neutron Stars ?

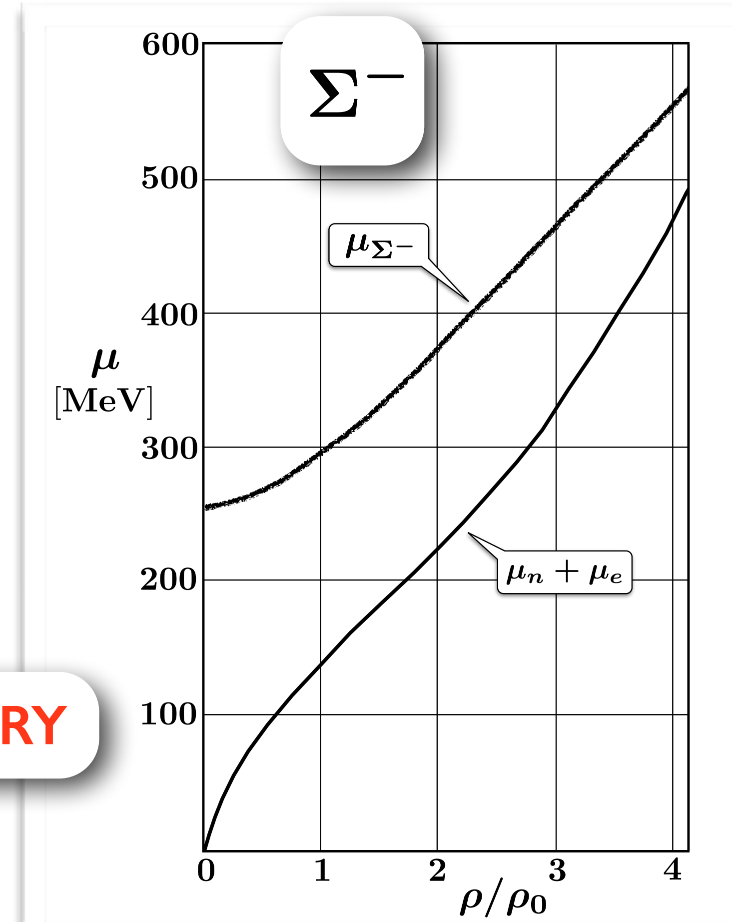
- Onset conditions for appearance of **hyperons in neutron stars :**

Equalities for **chemical potentials** $\mu_i = \frac{\partial \mathcal{E}}{\partial \rho_i}$

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



PRELIMINARY



- Extrapolations using **hyperon single particle potentials** in **neutron matter** from **Chiral SU(3) EFT** interactions

- Extensive and more detailed calculations in progress (D. Gerstung, N. Kaiser, W.W.)

SUMMARY

- Systematic framework at the interface of **QCD** (with light quarks) and physics of **hadrons, nuclei** and **nuclear forces** :

Chiral Effective Field Theory
combined with
Functional Renormalization Group

- **ChEFT + many-body perturbation theory** works for $\rho \lesssim 2\,\rho_0$
- **ChEFT + (non-perturbative) FRG** may work for **higher densities**
  - **No chiral phase transition** in n-matter up to at least $\rho > 5\,\rho_0$
  - "**Conventional**" (non-exotic) **EoS** consistent with constraints from **neutron stars** ($\mathrm{M}_{max} \simeq 2\,\mathrm{M}_\odot$, tidal deformability from GW)
  - **Strangeness** in the **neutron star core** ?
    New developments: hyperon-nuclear interactions from
    Chiral SU(3) Effective Field Theory