INSTITUTE for NUCLEAR THEORY

Symmetry in Subatomic Physics: In Memory of Ernest Henley

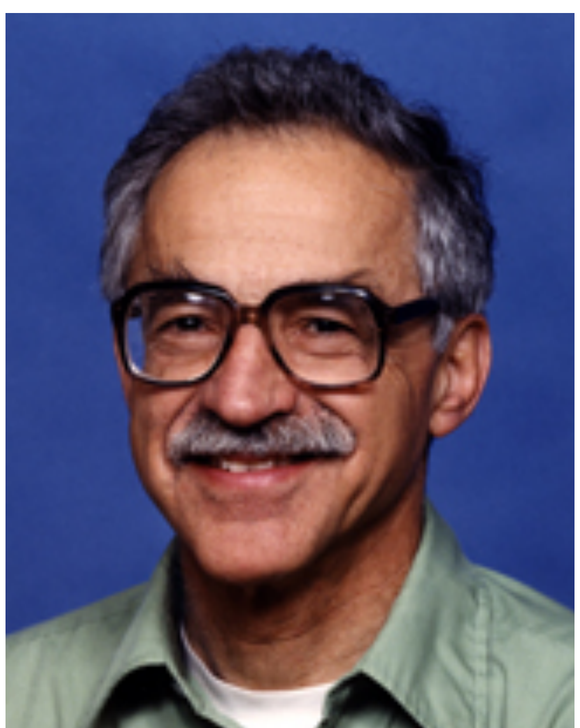
10 September 2018

From SYMMETRIES of QCD to NUCLEI and NEUTRON STARS

Wolfram Weise

Technische Universität München

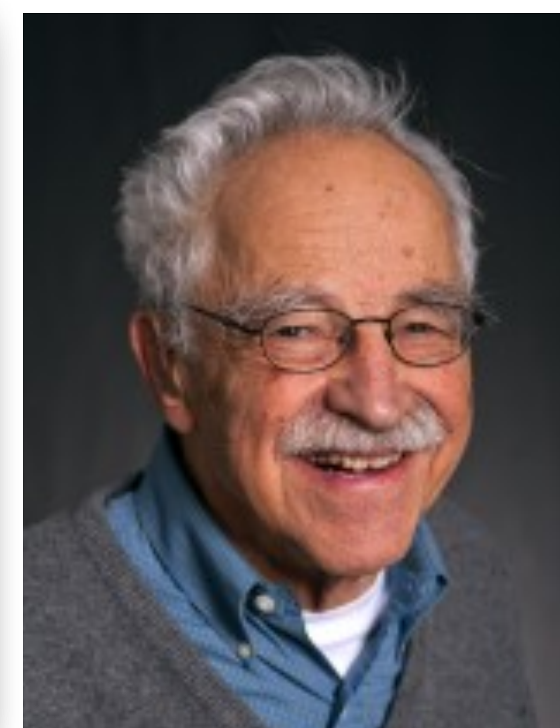
PHYSIK DEPARTMENT

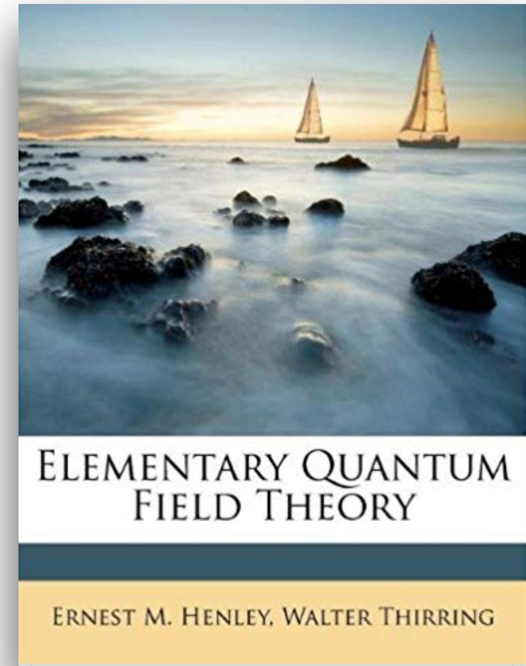


dedicated in memory of

Professor Ernest M. Henley

(1924-2017)

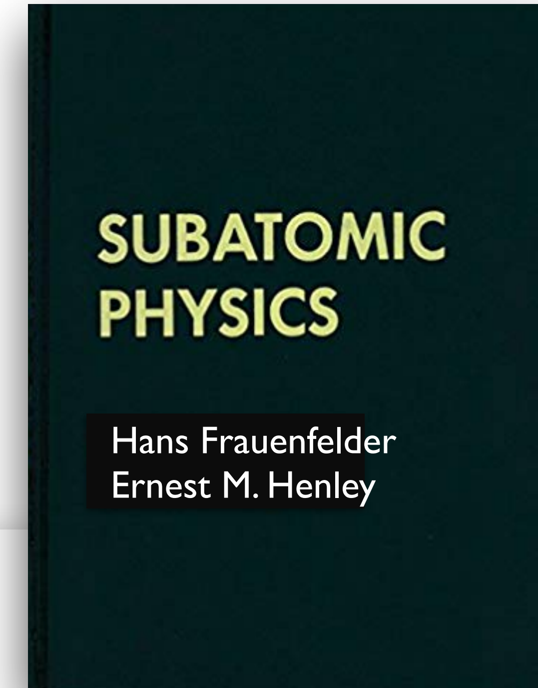




Physics Letters B
Volume 255, Issue 4, 21 February 1991, Pages 498-502

Singlet fraction in $\bar{p}p \to \bar{\Lambda}\Lambda$

M.A. Alberg[a,b], E.M. Henley[c], W. Weise[c,d]



Physics Letters B 502 (2001) 99

Coordinate Space Distributions of Antiquark Flavor Asymmetries in the Proton *)

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European Physical Journal A47 (2011) 140

Spin structure of the nucleon: QCD evolution, lattice results and models

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The QUESTION :

Are there guiding principles leading from

QCD SYMMETRIES

to strongly interacting **COMPLEX SYSTEMS**

such as

NUCLEI and **DENSE BARYONIC MATTER**

?

SYMMETRIES, SYMMETRY BREAKING PATTERNS and SCALES in QCD

- (almost) **massless u- and d-quarks :** CHIRAL SYMMETRY

$$\mathbf{SU}(2)_R \times \mathbf{SU}(2)_L$$

- Low energy : **spontaneous chiral symmetry breaking**
- **PIONS** as (almost) massless **Nambu-Goldstone bosons**

- **Symmetry breaking scale :**

$$\Lambda_\chi = 4\pi\, \mathrm{f}_\pi \sim 1\,\mathrm{GeV}$$

- **Pion decay constant :**

$\mathrm{f}_\pi^{(0)} \simeq 86\,\mathrm{MeV}$ (chiral limit) $\mathrm{f}_\pi = 92.2\,\mathrm{MeV}$ (empirical)

SYMMETRIES, SYMMETRY BREAKING PATTERNS and SCALES in QCD (contd.)

SCALE INVARIANCE and TRACE ANOMALY

- QCD with massless quarks - no dimensional parameter
- Invariance under scale transformations :

$$\psi(x) \to \lambda^{\frac{3}{2}} \psi(\lambda x) \qquad\qquad A^a_\mu(x) \to \lambda A^a_\mu(\lambda x)$$

- Trace of energy-momentum tensor $\Theta_{\mu\nu}$ vanishes classically …
- … but - QCD as a QFT introduces renormalisation scale, and so :

$$\Theta^\mu_\mu = \frac{\beta(g)}{g}\,\mathbf{Tr}[G_{\mu\nu}G^{\mu\nu}] \qquad \textbf{(trace anomaly)}$$

SYMMETRIES, SYMMETRY BREAKING PATTERNS and SCALES in QCD (contd.)

MASS of the NUCLEON and TRACE ANOMALY

- From massless quarks to massive nucleon :

$$\mathbf{M_N^{(0)}} = \langle N \,|(\beta/g)\mathbf{Tr}[G_{\mu\nu}G^{\mu\nu}]|\, N\rangle = \frac{9}{4}\langle N|\frac{\alpha_s}{\pi}(\mathbf{E^2}-\mathbf{B^2})|N\rangle$$

- Physical nucleon mass : $\mathbf{M_N} = \mathbf{M_N^{(0)}} + \sigma_\mathbf{N} = \mathbf{0.94\,GeV}$

- Sigma term : $\sigma_\mathbf{N} = \frac{1}{2}(m_u + m_d)\langle N \left|\bar{u}u + \bar{d}d\right| N\rangle$

- Recent values :

$\sigma_\mathbf{N} \simeq 50 - 60\ \mathrm{MeV}$ (from pion-nucleon scattering analysis)

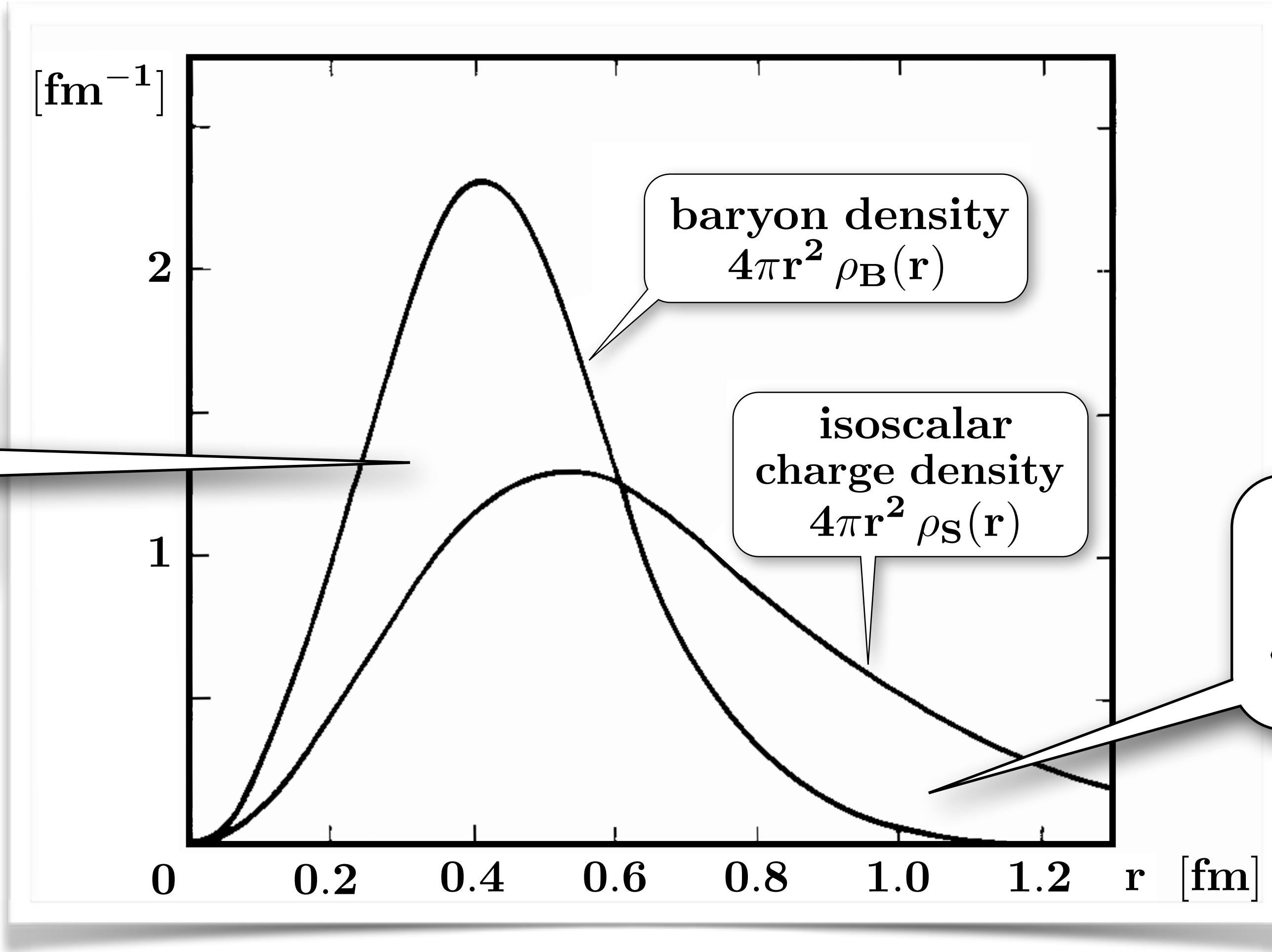
$\sigma_\mathbf{N} \simeq 40\ \mathrm{MeV}$ (from Lattice QCD)

Binding energy per nucleon in nuclear matter : $\mathrm{E}/A = 16\,\mathrm{MeV}$

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

Spontaneously broken chiral symmetry + localisation (confinement)

- **NUCLEON : compact valence quark core + mesonic cloud**



baryonic core

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

mesonic cloud

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

N. Kaiser,
U.-G. Meißner, W.W.

Nucl. Phys.
A466 (1987) 685

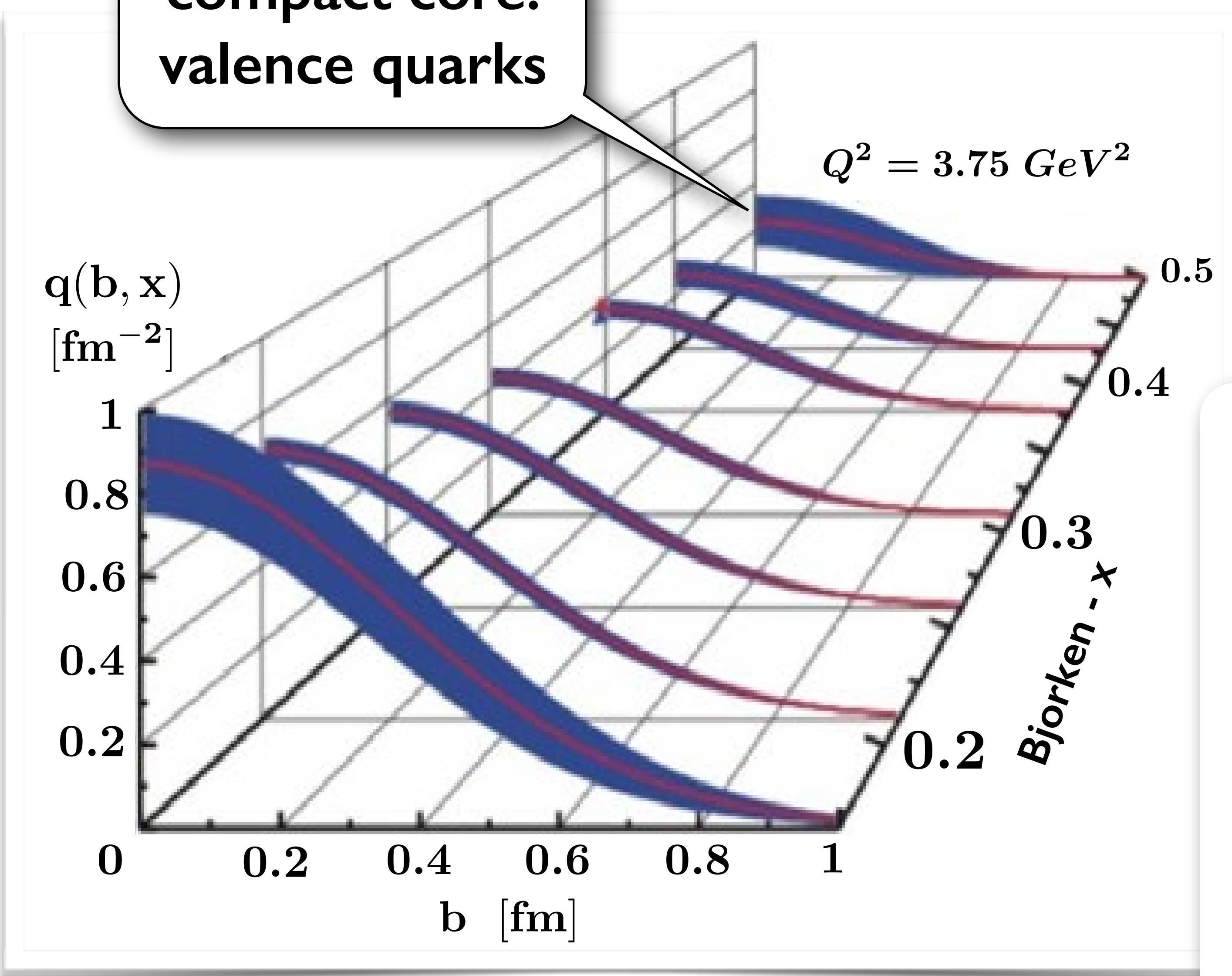
- **Difference of scales between**
  compact baryonic core and (multi-)**pion cloud**

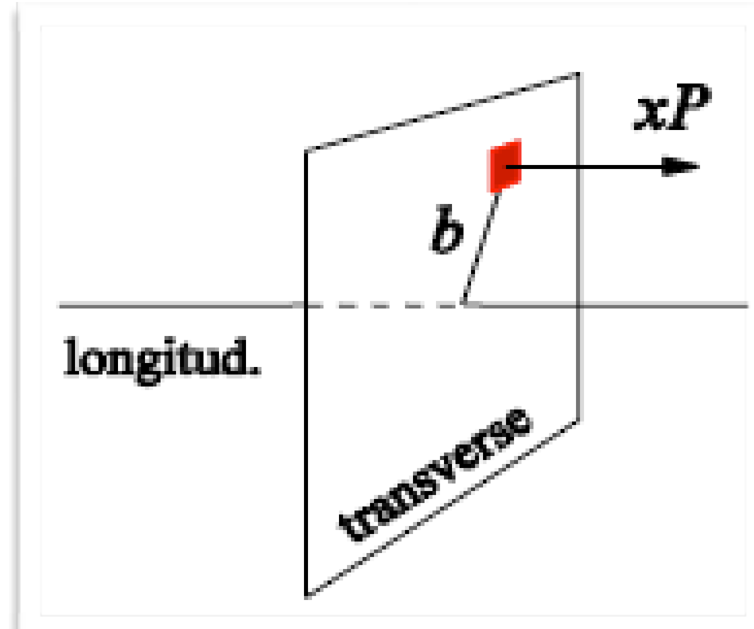
Transverse distributions of **quarks** in the **proton**

Deeply Virtual Compton Scattering @ JLab

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

compact core:
valence quarks



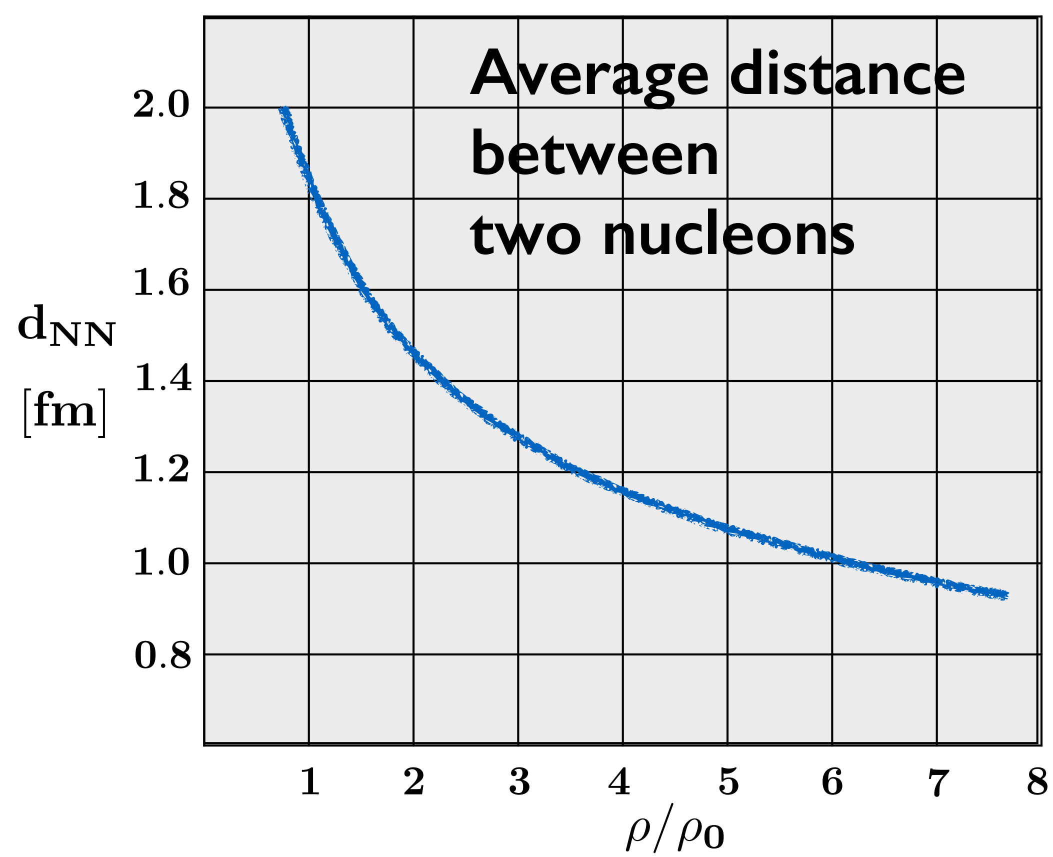


$$\langle b^2 \rangle \simeq 0.16\,\mathrm{fm}^2 \cdot \ln(1/x)$$

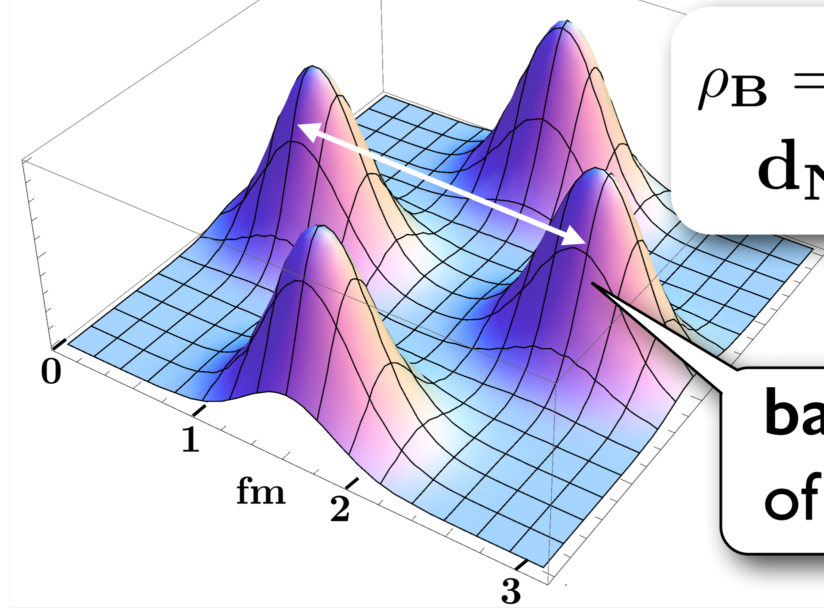
- **Valence quark region:**
  $0.3 < x < 0.5$
- **Core size:**

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

Densities and Distance Scales in Baryonic Matter



normal nuclear matter

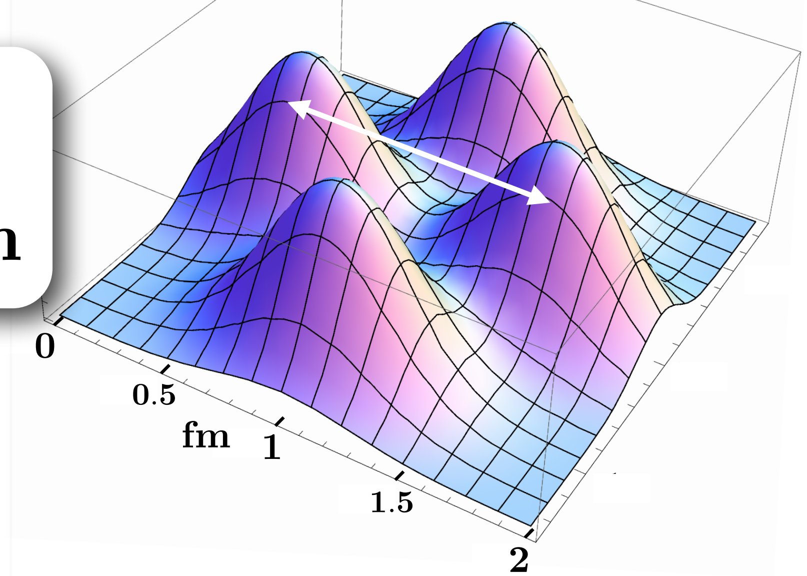


$\rho_B = \rho_0 = 0.16\ \text{fm}^{-3}$

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

baryonic core of the nucleon

neutron star core matter



$\rho_B \sim 5\,\rho_0$

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

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

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

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

↓

LOW-ENERGY QCD

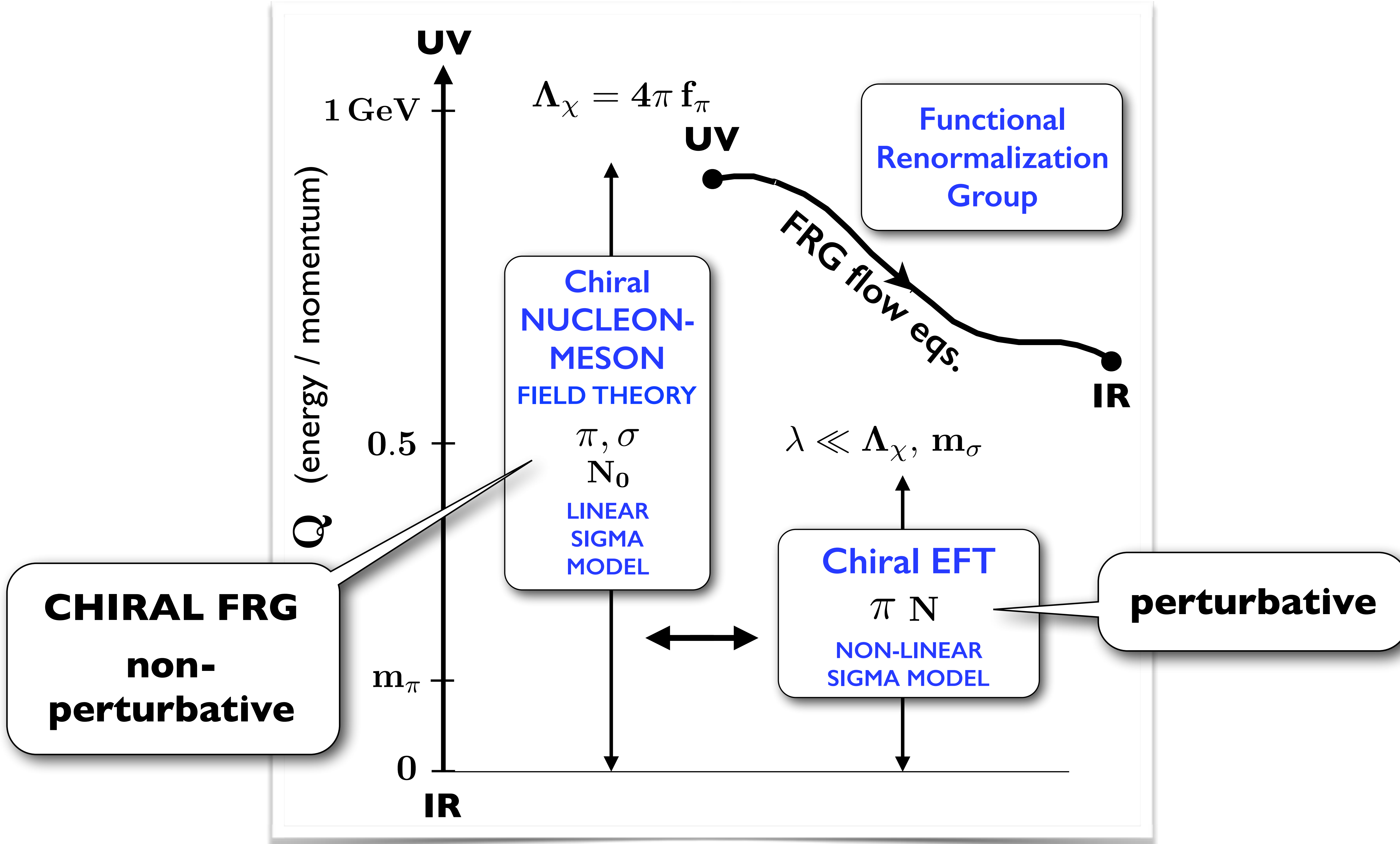
At (energy and momentum) scales $\mathrm{Q} < 4\pi\,\mathrm{f}_\pi \sim 1\,\mathrm{GeV}$

is realised as an

Effective Field Theory

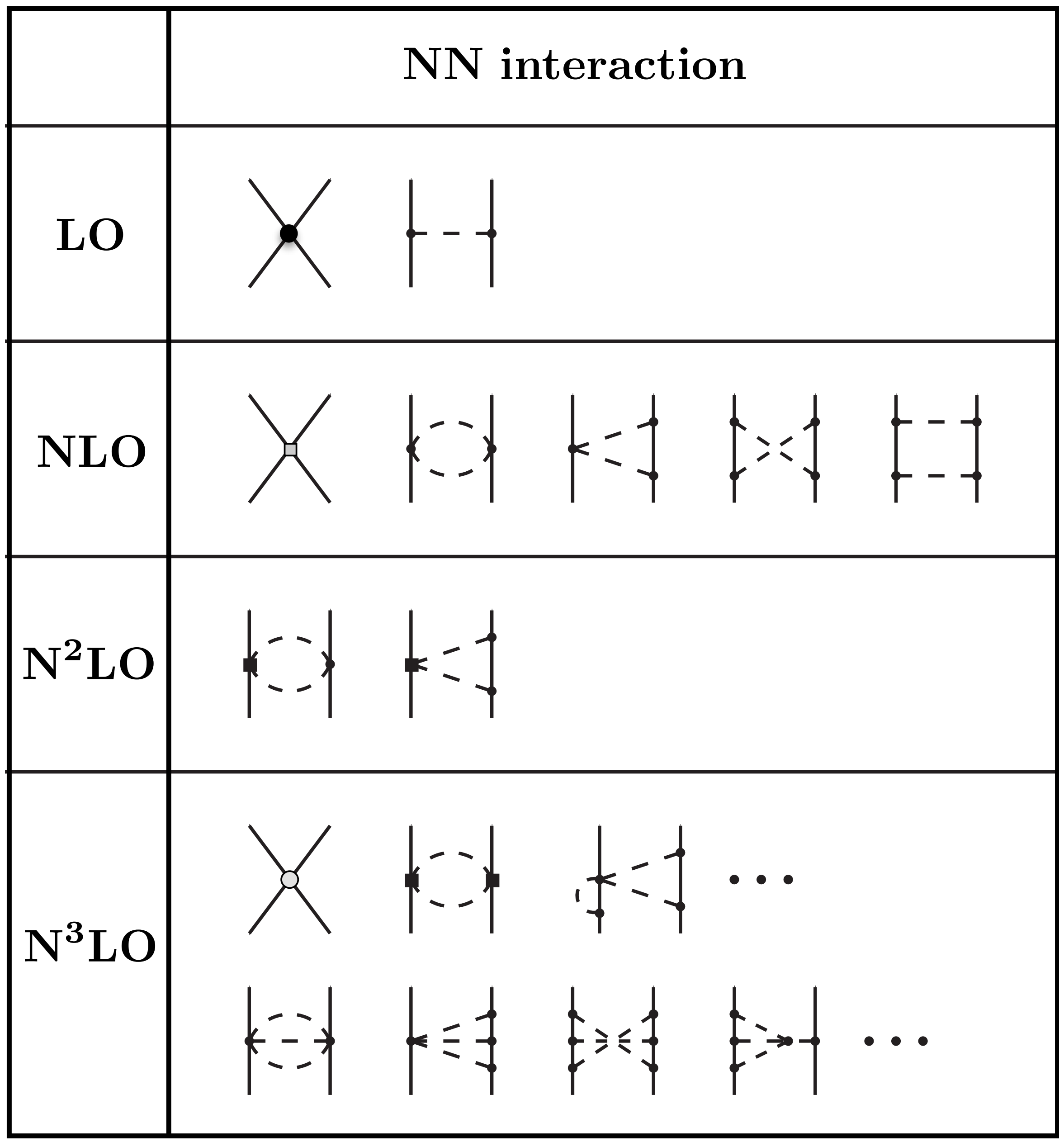
of Nambu-Goldstone Bosons (PIONS) coupled to
NUCLEONS as (heavy) Fermion sources

Theoretical FRAMEWORKS and METHODS

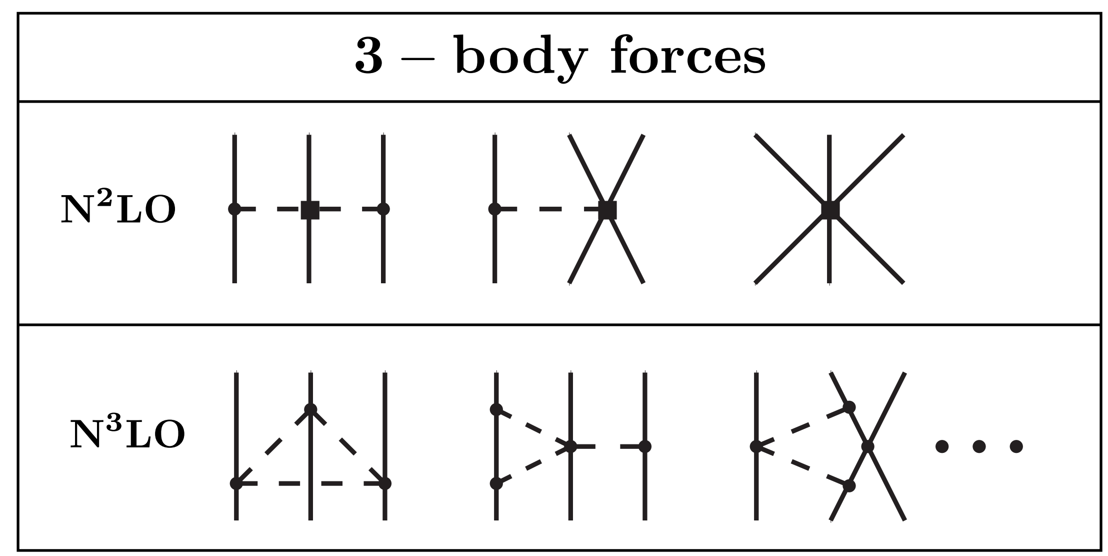


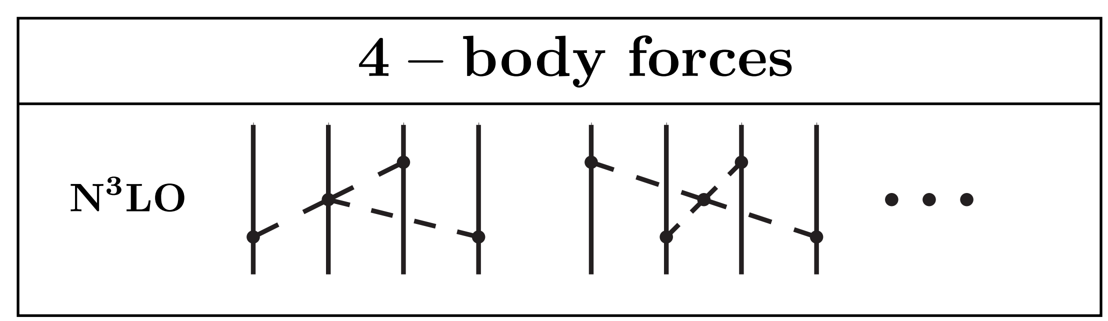
NUCLEON-NUCLEON INTERACTION from CHIRAL EFFECTIVE FIELD THEORY

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



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



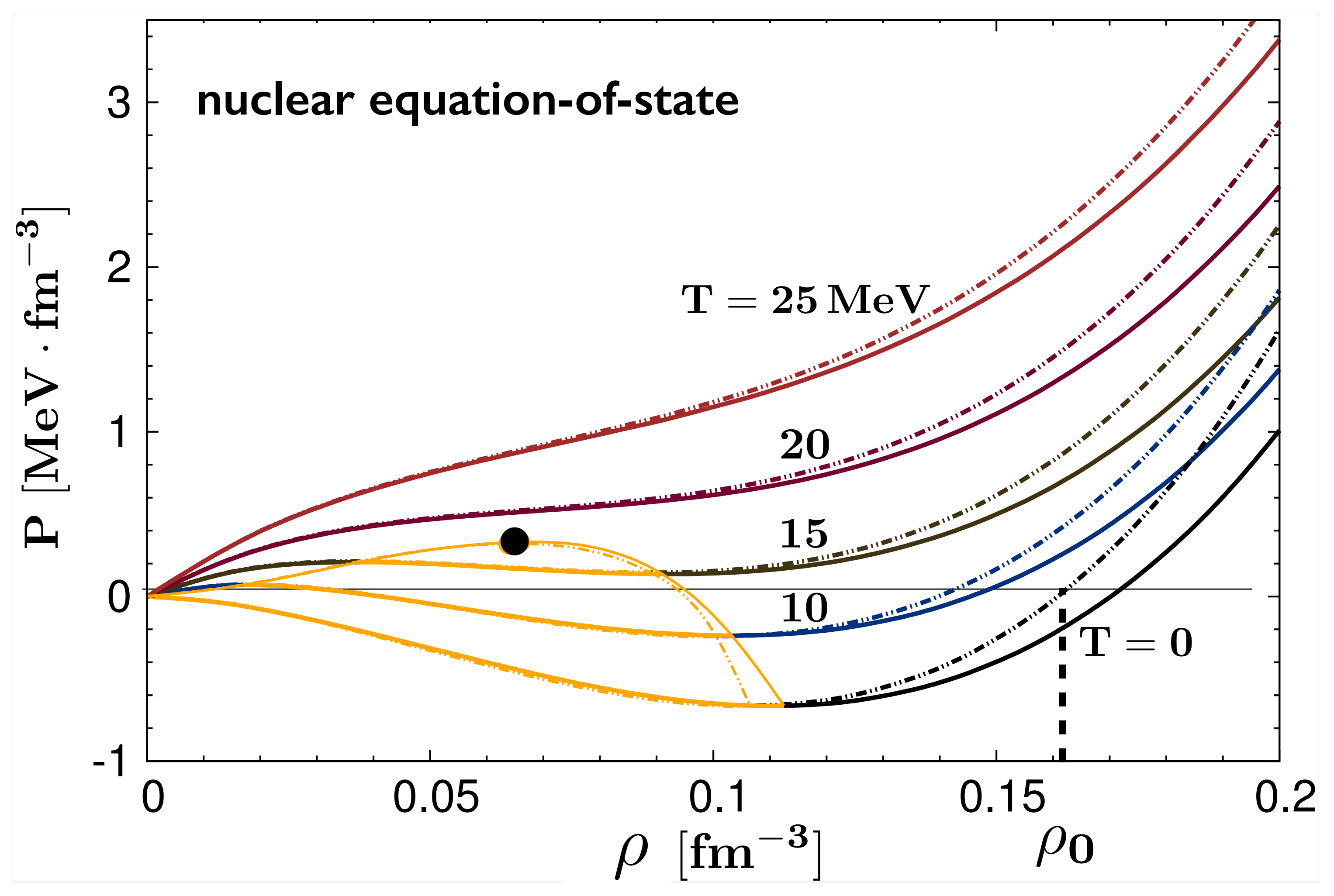


- NN interaction state-of-the-art: N^4LO plus convergence tests at N^5LO

NUCLEAR 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 :

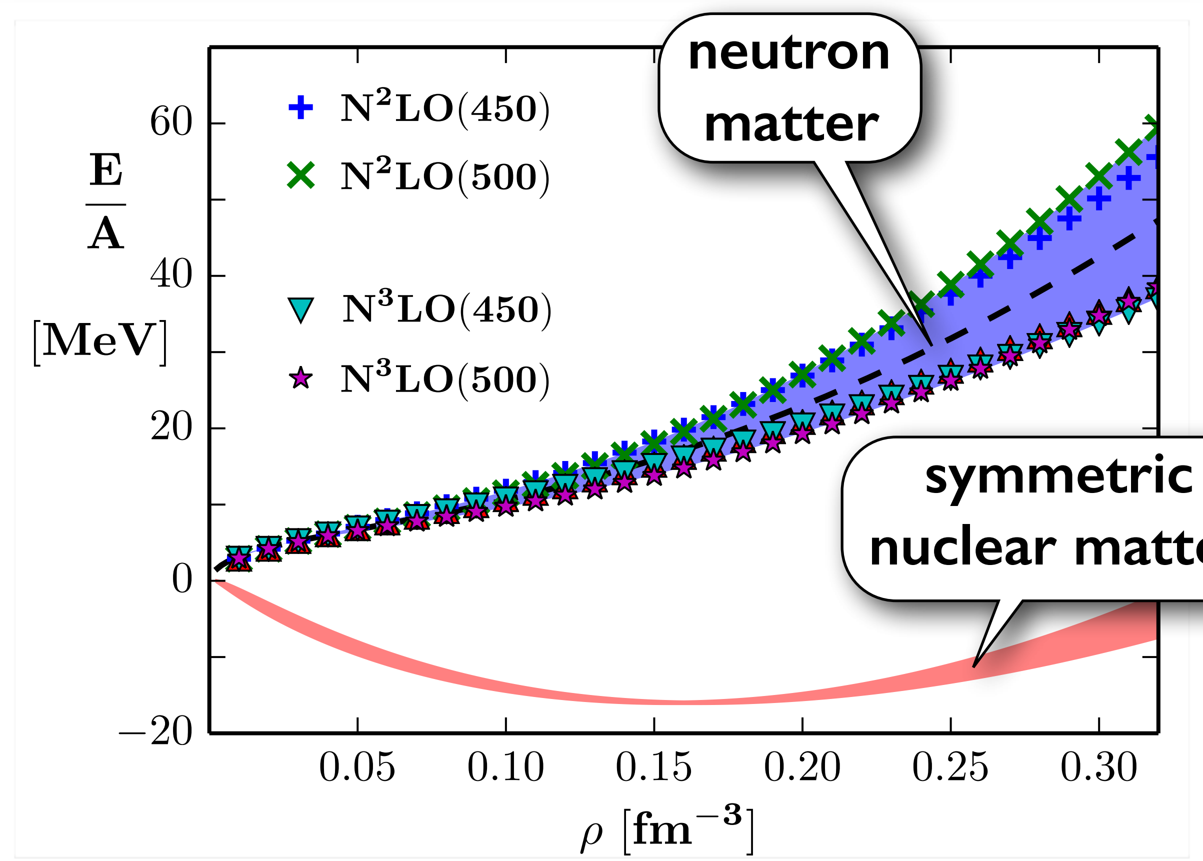
$$T_c = 17.4 \text{ MeV}$$

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

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

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



Y. Lim, J.W. Holt
Phys. Rev. Lett. 121 (2018) 062701

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)

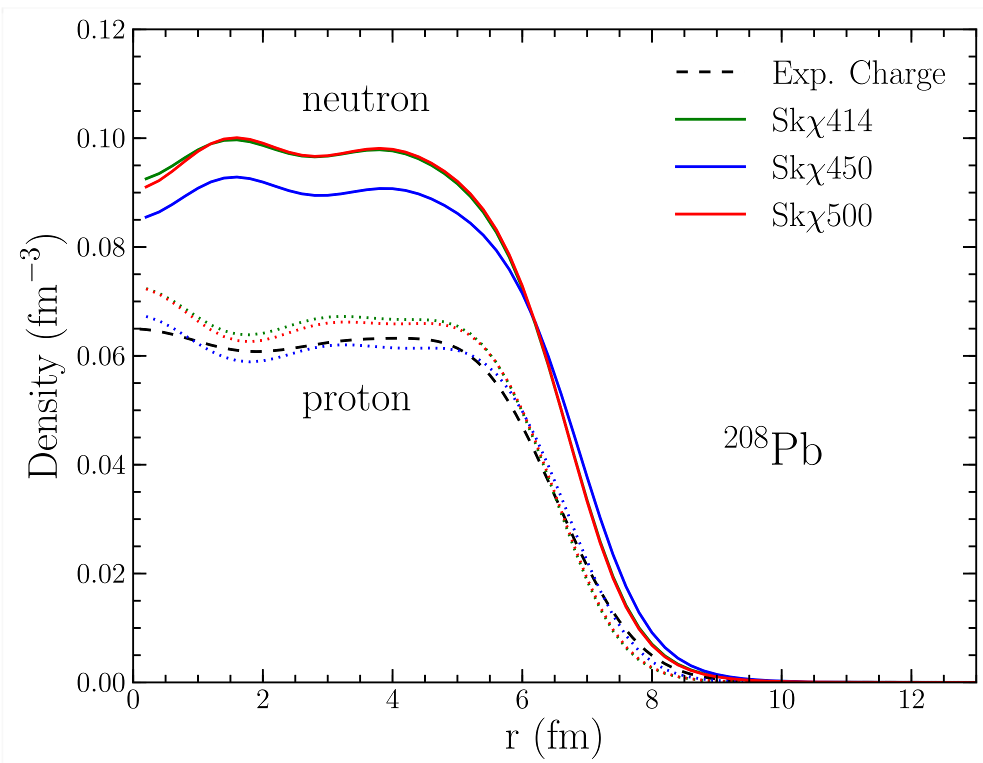
C. Wellenhofer, J.W. Holt, N. Kaiser, W.W.: Phys. Rev. C89 (2014) 064009, C92 (2015) 015801

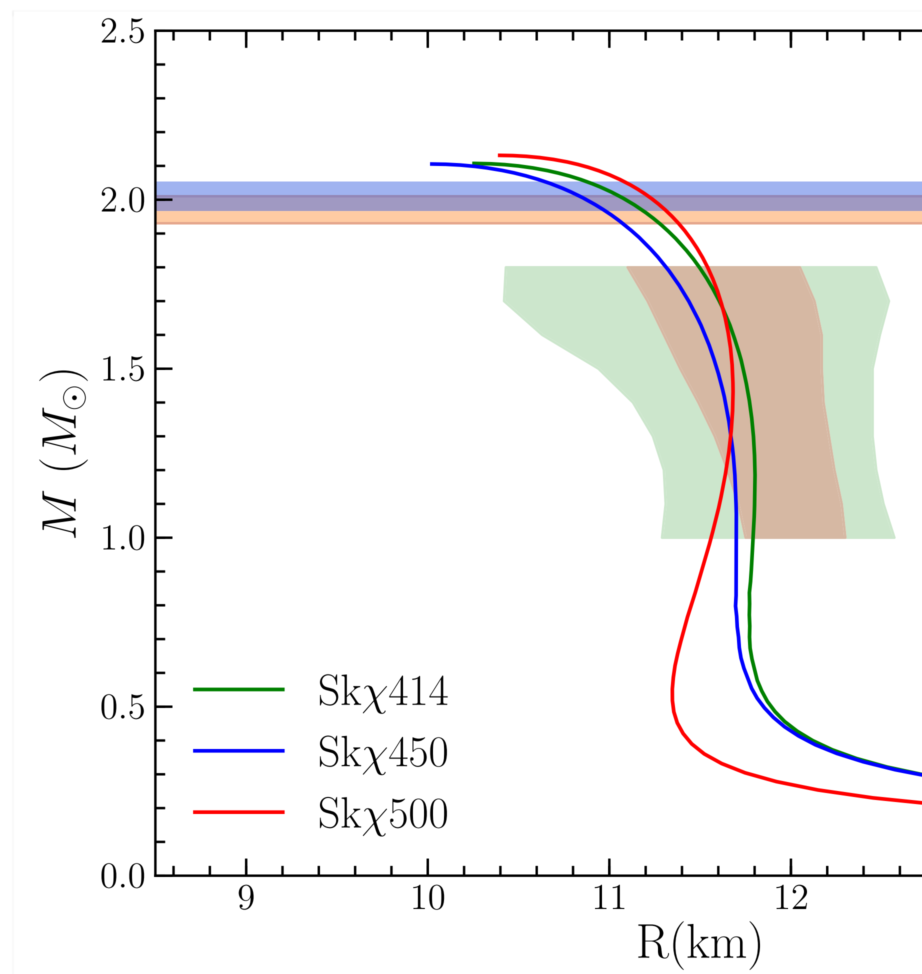
- **Further recent developments: N4LO** F. Sammarruca et al.: arXiv:1807.06640

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** …

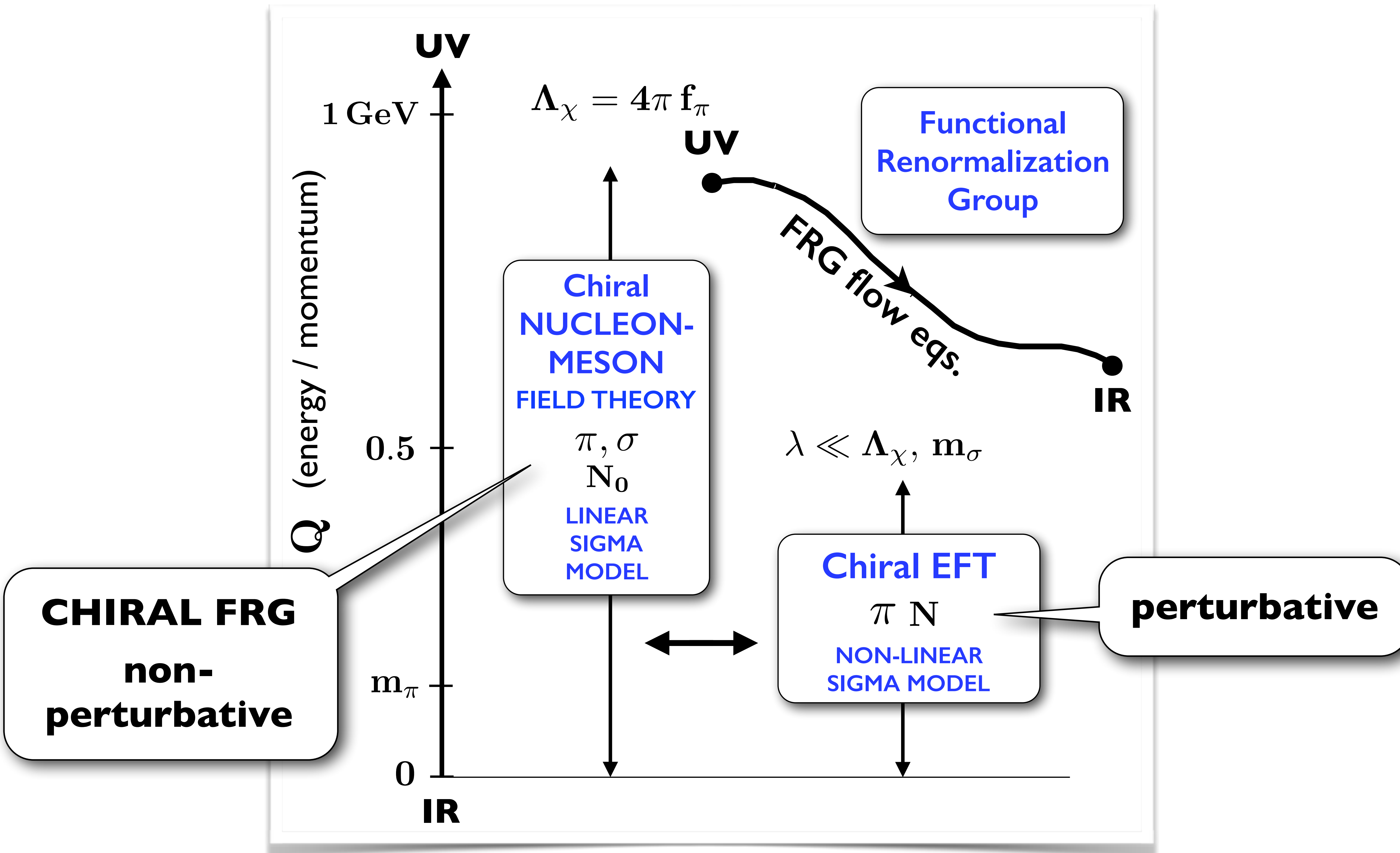




- **Central core densities** $\rho_c \lesssim 5\,\rho_0$

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

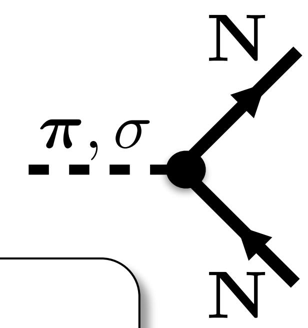
Theoretical FRAMEWORKS and METHODS



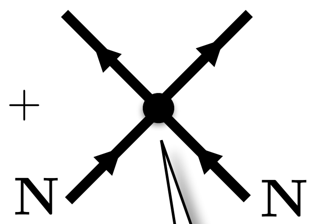
Mesons, Nucleons, Nuclear Matter
and
Functional Renormalization Group

- **Chiral nucleon - meson Lagrangian**

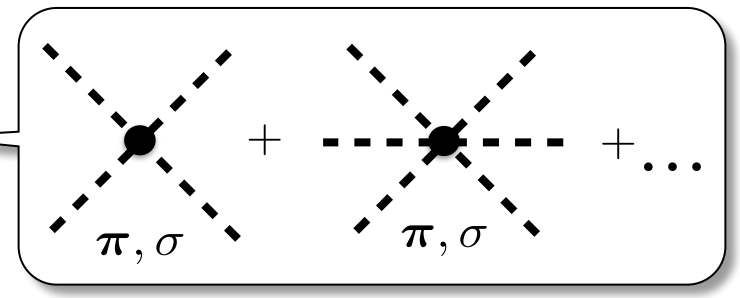
$$\mathcal{L} = \bar{\mathrm{N}}\, i\gamma_\mu \partial^\mu \mathrm{N} + \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma + \partial_\mu\boldsymbol{\pi}\cdot\partial^\mu\boldsymbol{\pi}\right) +$$



$+$



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



isoscalar & isovector current-current interactions

- **Nambu-Goldstone boson** $\boldsymbol{\pi}$ 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**

- **Pionic fluctuations, nucleonic particle-hole** excitations and **many-body correlations** treated **non-perturbatively** using **FRG**

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

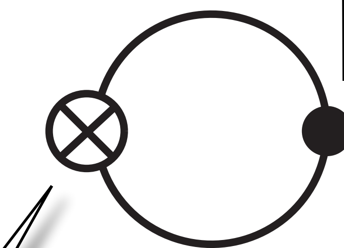
Renormalization Group strategies

k-dependent action

full propagator

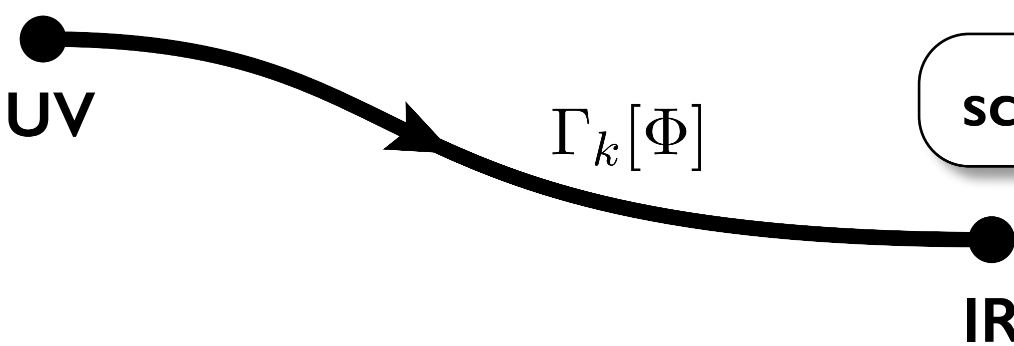
Wetterich's FRG flow equations

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



scale regulator R_k

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

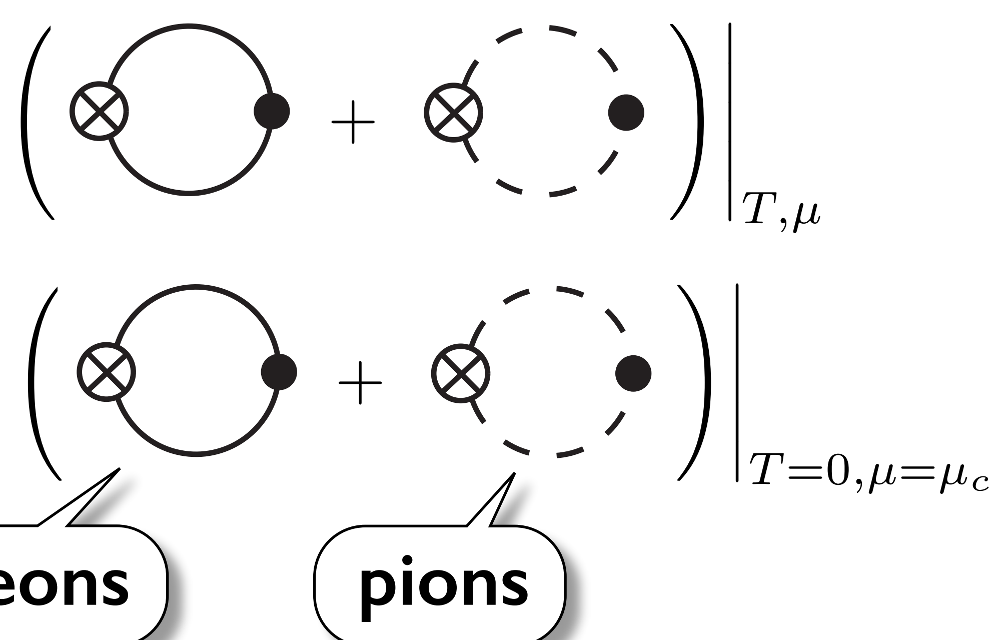


$\Gamma_{k=0}[\Phi] = \Gamma[\Phi]$

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

- **Thermodynamics:**

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



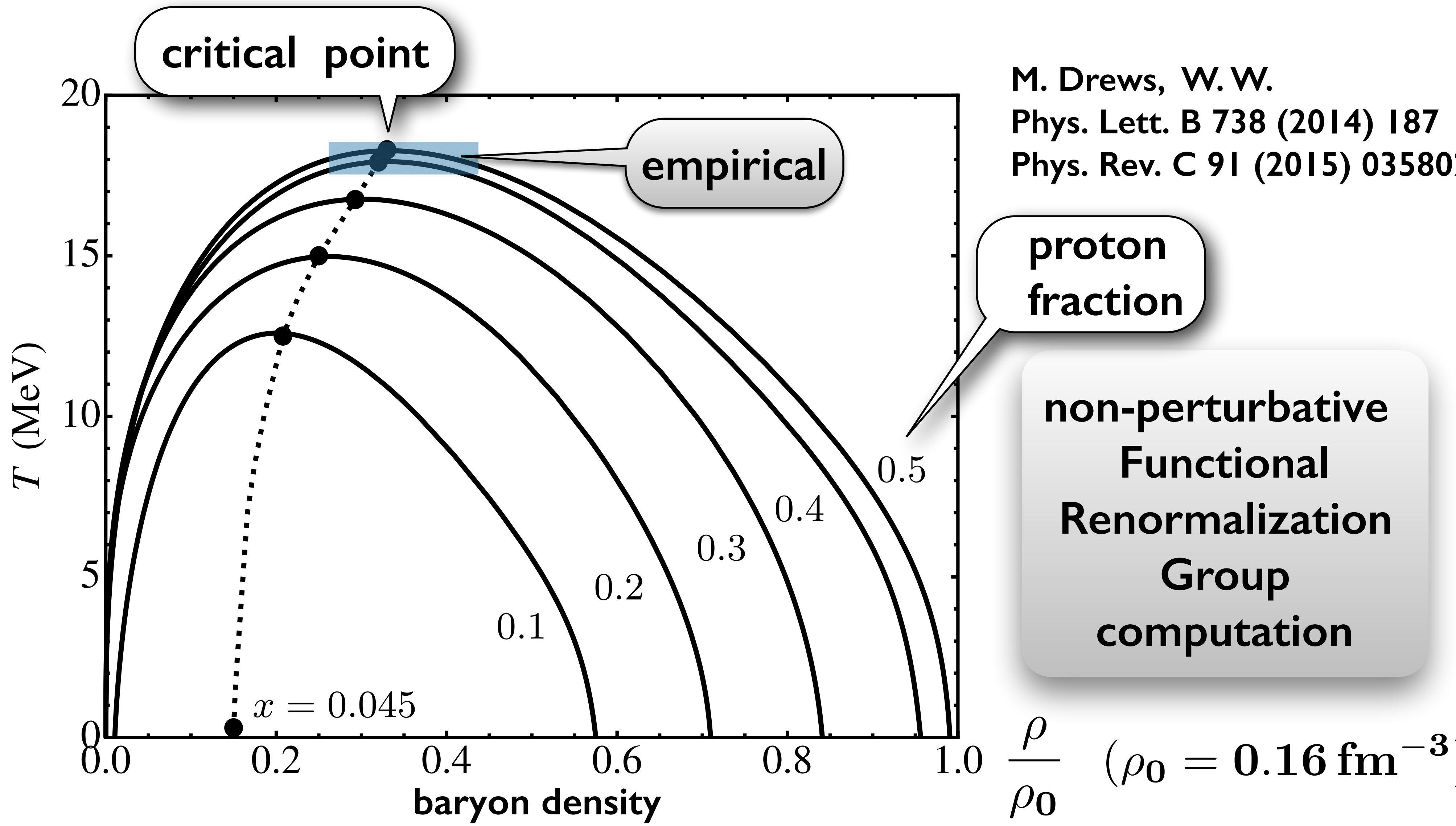
Non-perturbative treatment of :

- **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

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

non-perturbative Functional Renormalization Group computation

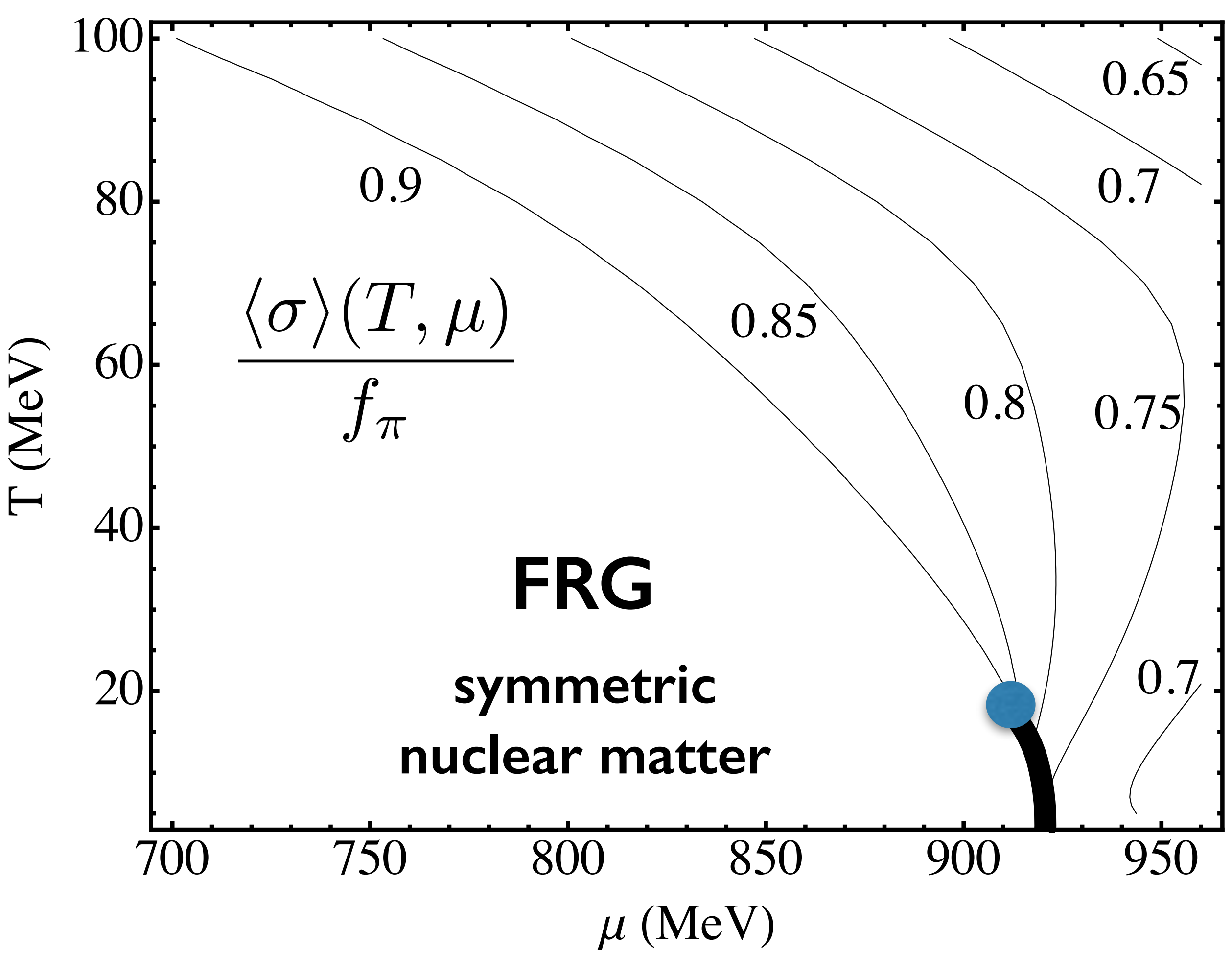
Governed by isospin dependent (two-)pion exchange dynamics

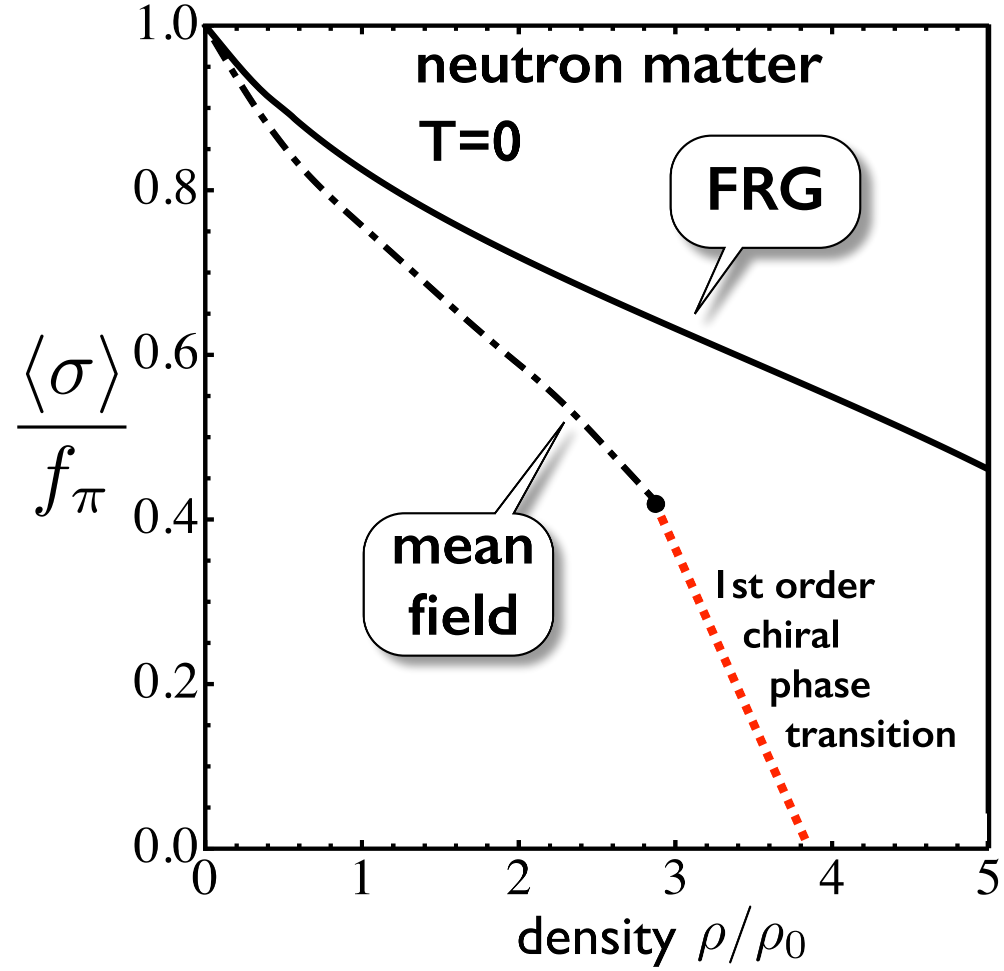
CHIRAL ORDER PARAMETER in NUCLEAR and NEUTRON MATTER

- **Chiral Nucleon-Meson field theory and Functional Renormalization Group**

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 $\langle\sigma\rangle_{T,\mu} = f_\pi^*(T,\mu)$



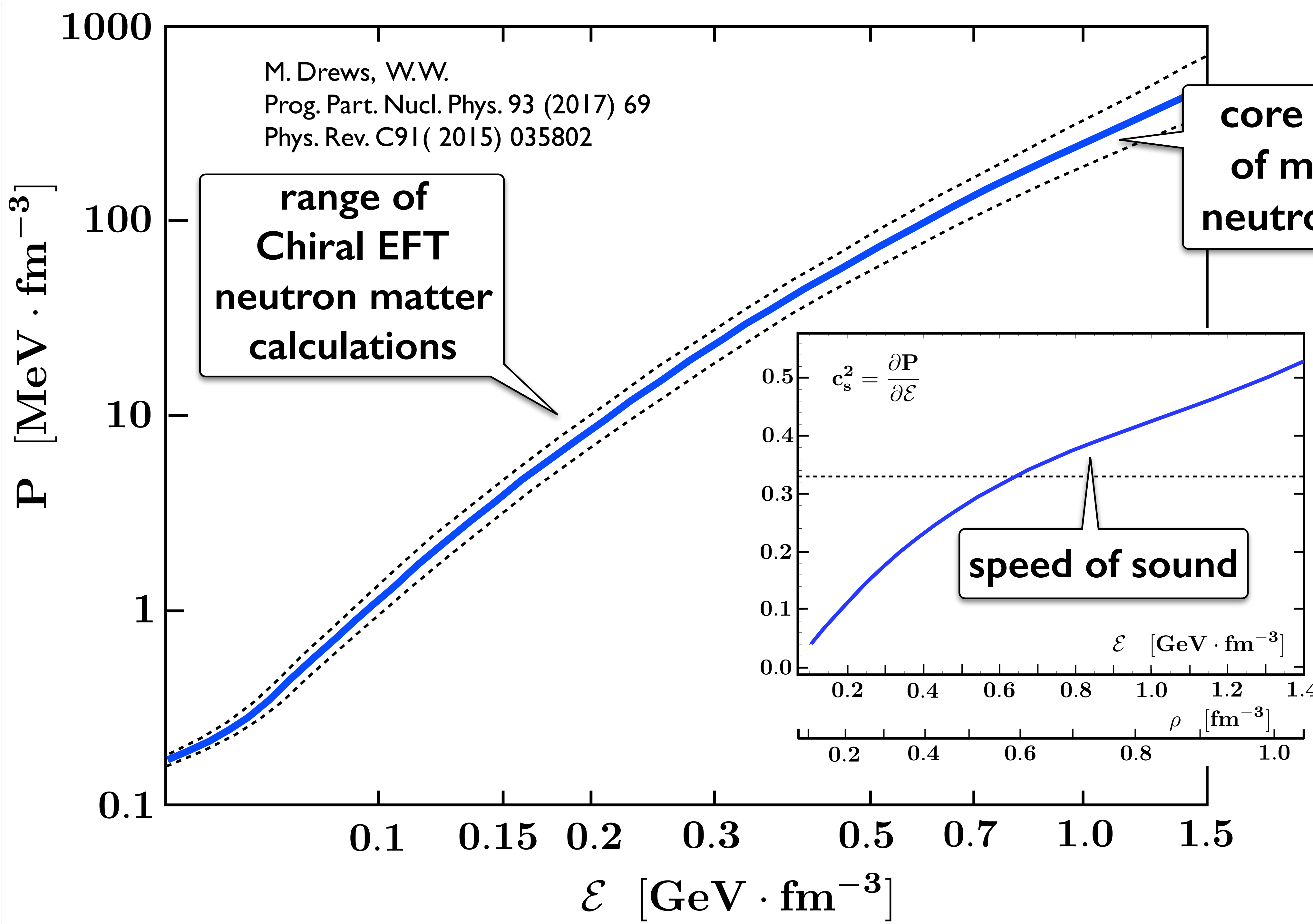


Important role of **fluctuations** (pionic and nucleon-hole) beyond mean-field appr. :

DISAPPEARANCE of first-order chiral phase transition

NEUTRON STAR MATTER
Equation of State

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

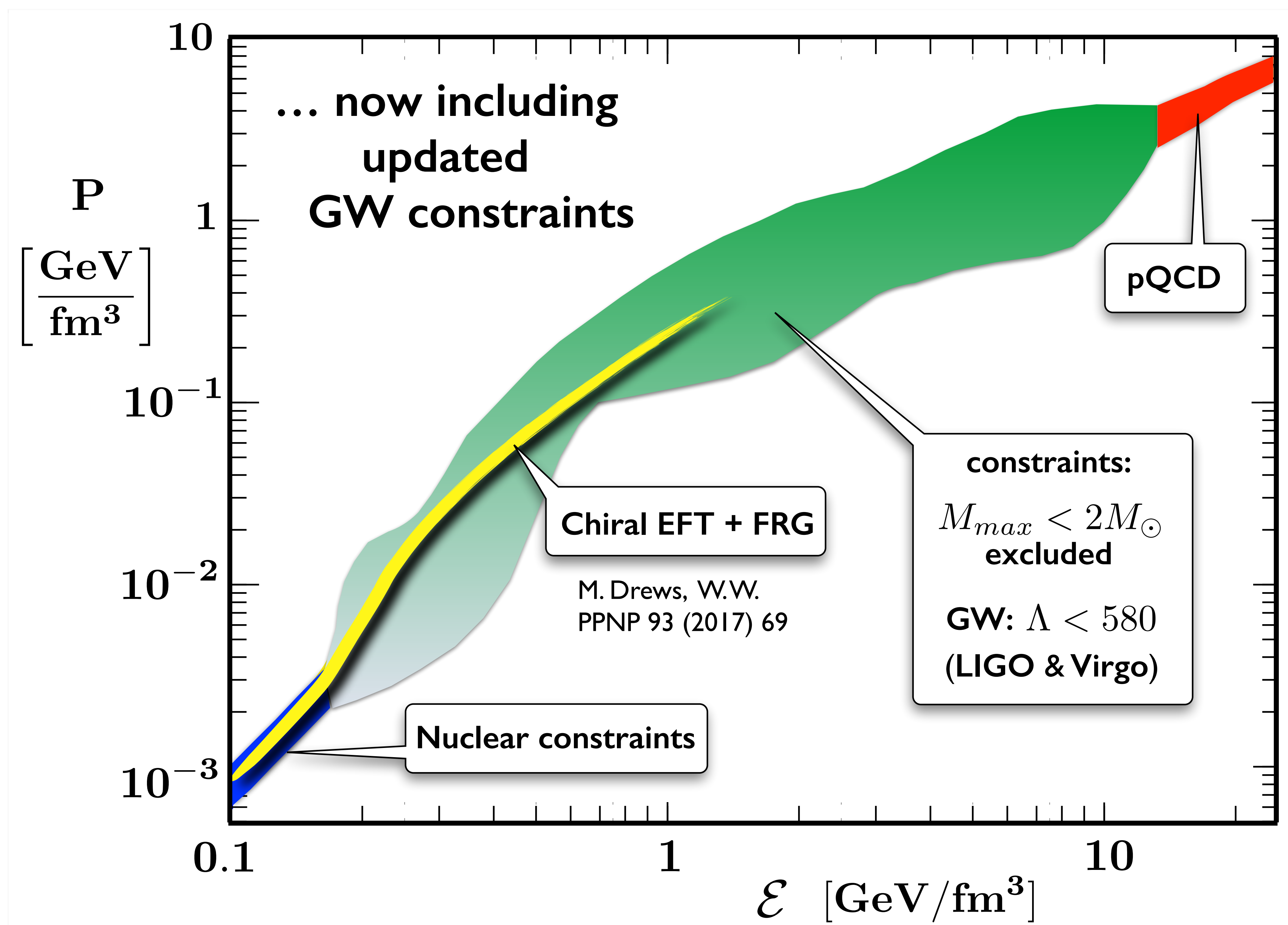


NEUTRON STAR MATTER
Equation of State

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

A. Annala et al. : PRL 120 (2018) 172703

A. Vuorinen : arXiv:1807.04480



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

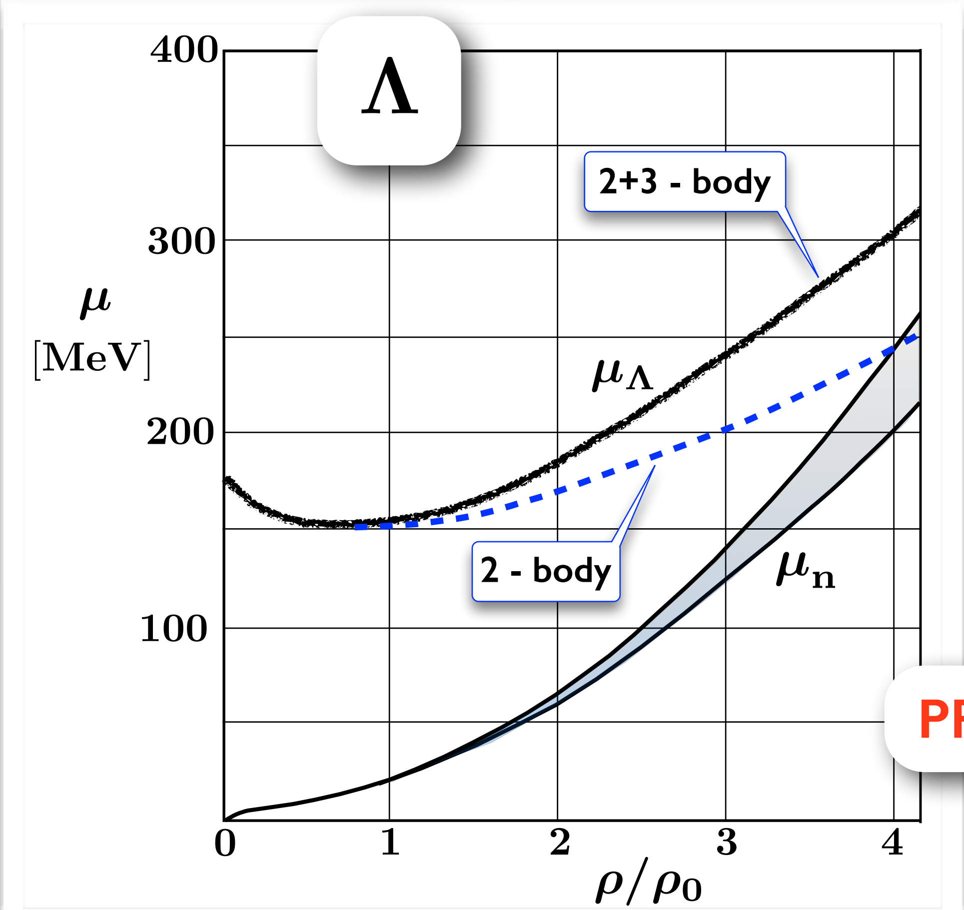
- ChEFT + many-body perturbation theory works for $\rho \lesssim 2\,\rho_0$
- ChEFT + (non-perturbative) FRG may work for higher densities
  - **No** chiral phase transition in n-matter up to at least $\rho > 5\,\rho_0$
  - "Conventional" (non-exotic) EoS consistent with constraints from neutron stars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

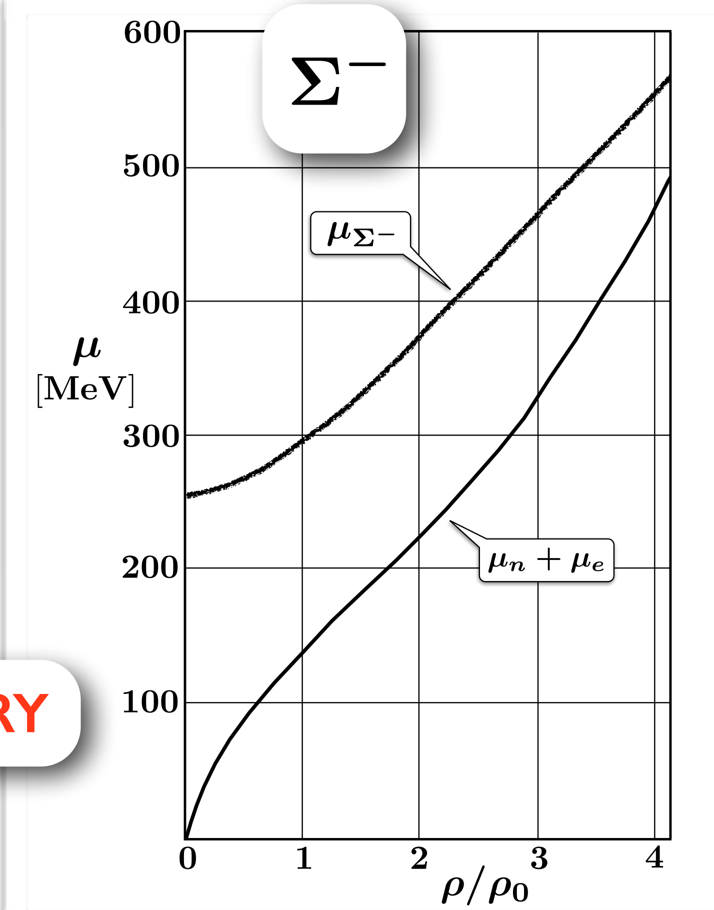
Hyperons in Neutron Stars ?

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

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

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





- 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.)

with gratitude to Ernest

for decades of

inspiring exchanges

and exciting discussions