PIONS and NUCLEI

- In Honour of the PION*eers -*

Wolfram Weise
Technische Universität München

Foundations of Pion-Nuclear Physics

- **Pion-nucleus optical potential**
- **Pionic atoms**
- **Pion propagation** in a **nuclear medium**
- **Ericson-Ericson-Lorentz-Lorenz effect**
- **Pion absorption**

ANNALS OF PHYSICS: 36, 323–362 (1966)

Optical Properties of Low-Energy Pions in Nuclei

M. ERICSON

Institut de Physique Nucléaire, Lyon, France

AND

T. E. O. ERICSON

CERN, Geneva, Switzerland

A simple nonlocal potential for low-energy pions in finite nuclei is calculated from the amplitudes for πN scattering and for π production in NN collisions. The potential includes absorption and has no free parameters. The appropriate multiple scattering equations are derived in the coordinate representation with nuclear pair correlations included. Owing to the large mass of the scatterers the pion field behaves nearly classically. It is shown that short-range pair correlations are important in the multiple scattering owing to the dominant dipole component in the πN scattering. To a good approximation this produces a Lorentz-Lorenz effect analogous to the one occurring in the scattering of electromagnetic waves in dense media. The contributions of Fermi motion to the potential are shown to be small. The isospin part of the potential is derived and is shown to have a tensor component in addition to the ordinary vector one. The former gives rise to direct double charge exchange of pions; its strength becomes important for high momentum pions. The potential is further found to have a term which gives a small but possibly observable hyperfine coupling.

A comparison is made between predictions of the potential and experimental data on level shifts and widths for π mesic atoms. Satisfactory agreement is found within experimental uncertainties which is quantitative evidence for nuclear pair-absorption of pions. There is also some indication of short range anticorrelations between nucleons.

Pion-Nuclear Many-Body Problems

- **Nuclear PCAC**
- **Spin-isospin (axial) polarizabilty**
- **Delta-isobar in nuclei**
- **Renormalization** of the **axial vector coupling in nuclei**

ANNALS OF PHYSICS 102, 273–322 (1976)

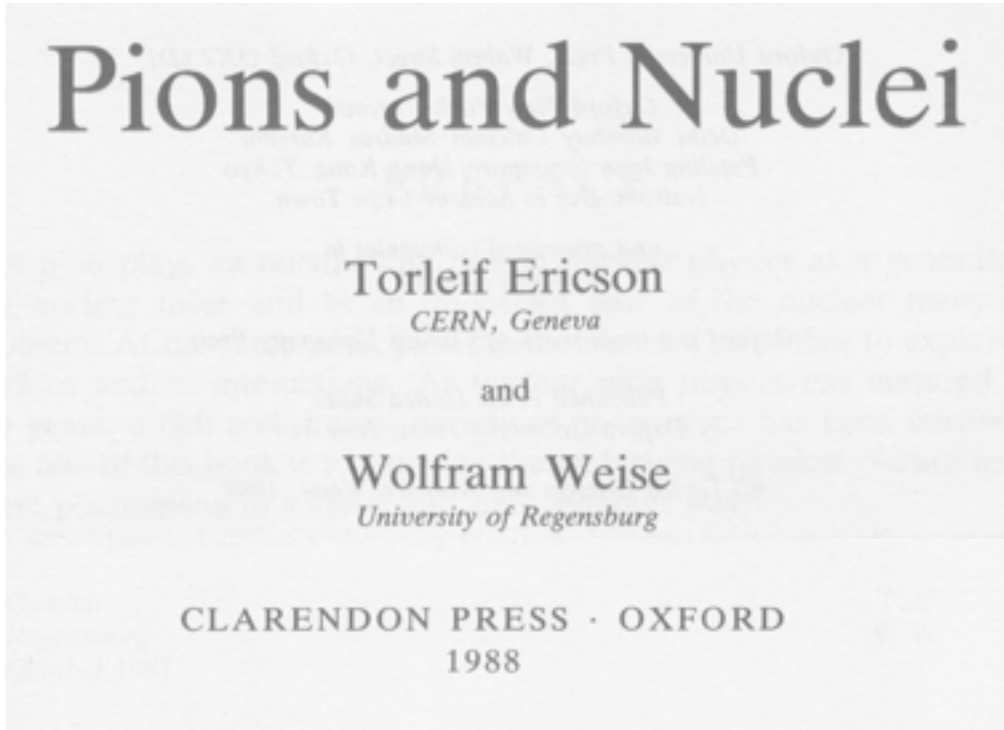
Axial Polarizability and Weak Currents in Nuclei

J. Delorme, M. Ericson*, A. Figureau, and C. Thévenet

Institut de Physique Nucléaire, Université Claude Bernard Lyon-I and IN2P3, 43 Bd du 11 novembre 1918, 69621 Villeurbanne, France

Received May 6, 1976

The effect of the isobaric excitations on the weak axial coupling constants in nuclei is studied through P.C.A.C. We first establish the Klein–Gordon equation for the virtual pion field in the nucleus; it takes into account pion rescattering. The influence of isobar excitation is contained in the axial polarizability coefficient which is linked to the *p*-wave π–*N* scattering volume. The derivation of this equation stresses its analogies with electromagnetism. We give then a basic relation between the axial current and the pionic field. It incorporates the effects of the isobars in the axial polarizability, which leads naturally to an electromagnetic analog. We show that this relation leads in heavy nuclei to a quenching of the axial coupling constant by the Lorentz–Lorenz factor, which may originate from the short range or the Pauli correlations, depending on the range of the π–*N* forces. Hence this quenching may have a different origin than the existence of short-range correlations and may arise from a Pauli blocking effect. On the other hand, the pseudoscalar coupling constant is found to be strongly suppressed. In finite nuclei, these basic quenchings can be masked by surface effects, the general features of which are studied with the help of a solvable model. This model is further used to obtain the asymptotic pion field which is linked to the effective pion–nucleus coupling constant and can be determined experimentally through π-nucleus dispersion relations. We find that this quantity is quenched, in agreement with recent experimental data.


Pions and Nuclei

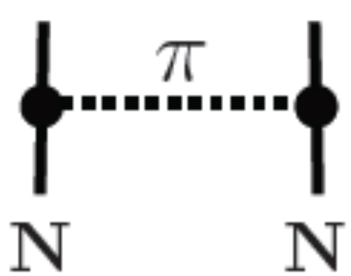
Torleif Ericson
CERN, Geneva

and

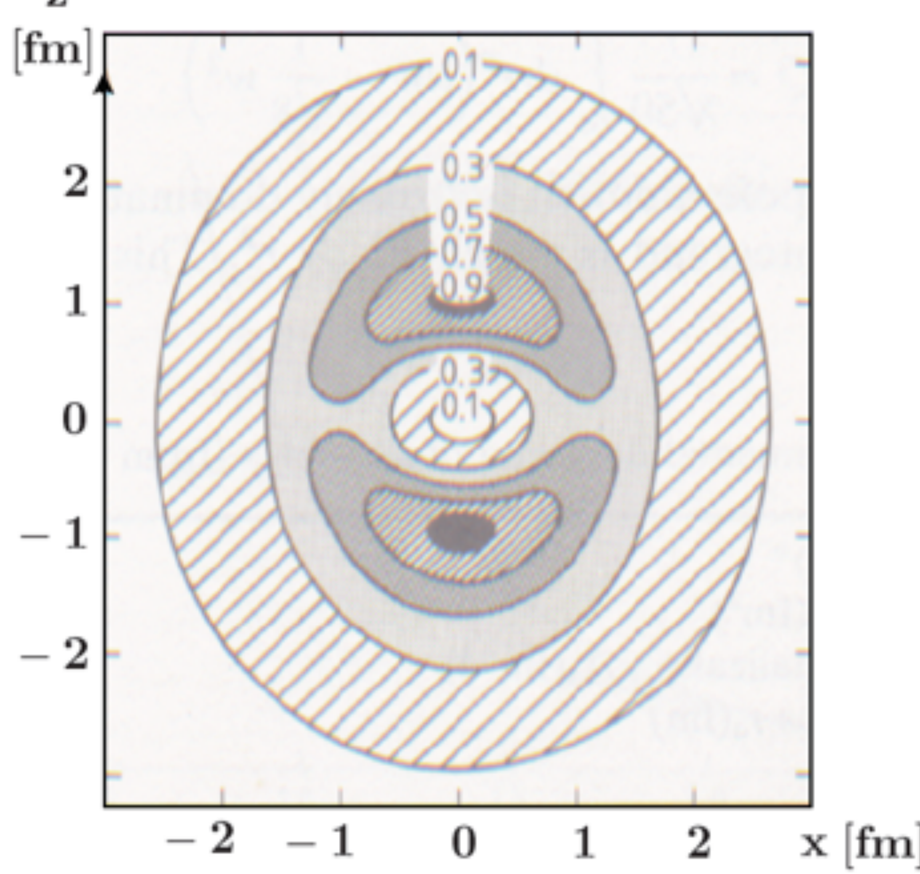
Wolfram Weise
University of Regensburg

CLARENDON PRESS · OXFORD
1988

Prominent role of
PION-EXCHANGE TENSOR FORCE
in nuclear physics



deuteron density contours

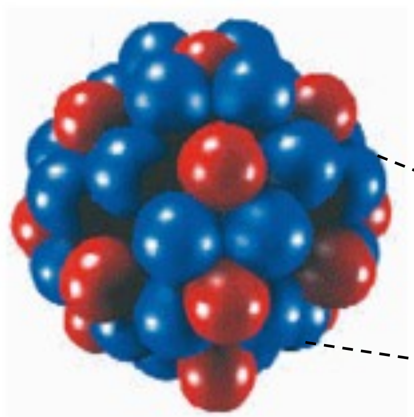


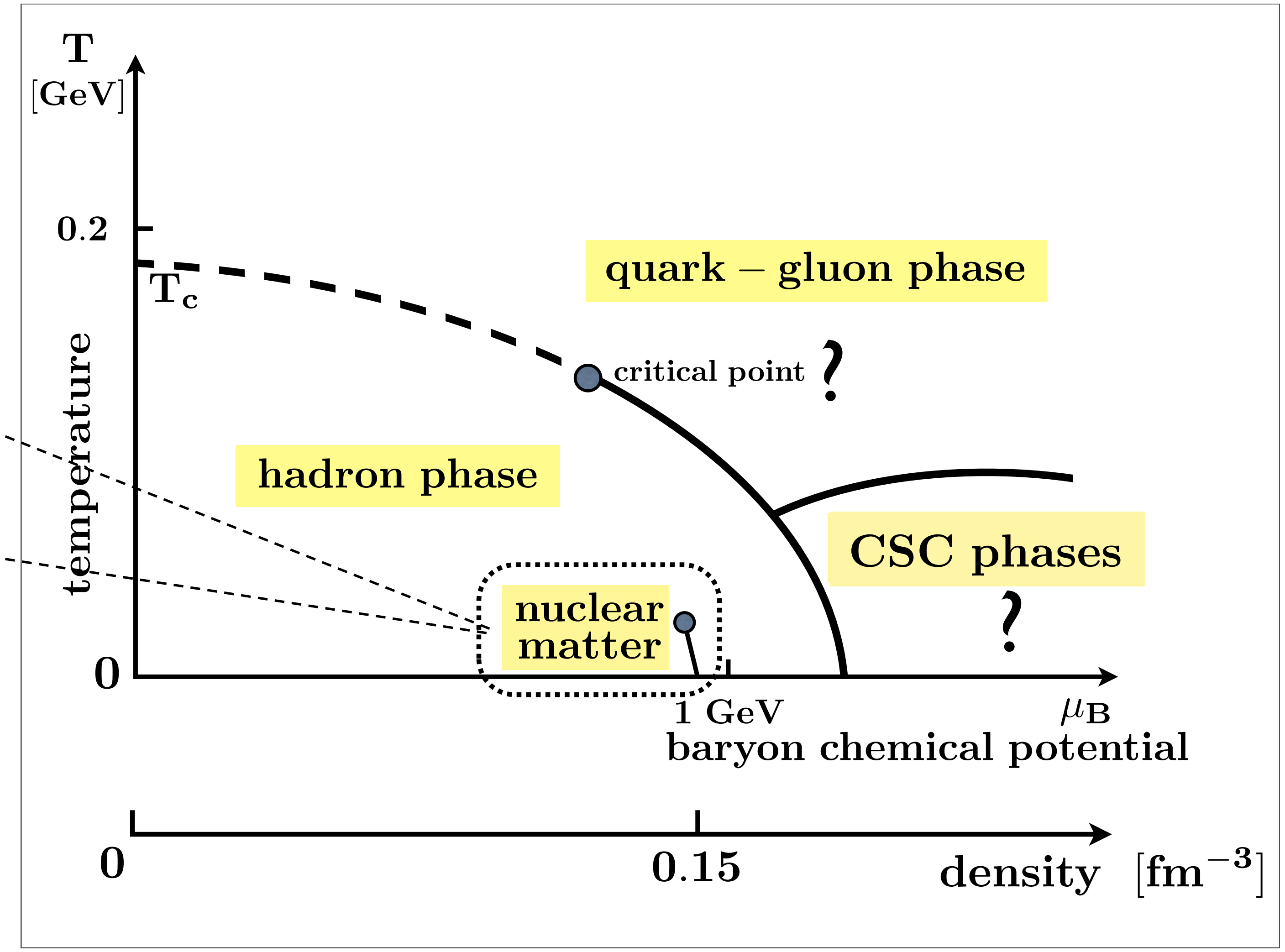
- **deuteron properties** largely determined by **one-pion exchange**

T. E.O. Ericson, M. Rosa-Clot (1985)

NUCLEAR MATTER and QCD PHASES

nuclei





Scales in **nuclear matter**:

- momentum scale: **Fermi momentum** $k_F \simeq 1.4\ \mathrm{fm}^{-1} \sim 2m_\pi$
- NN distance: $d_{NN} \simeq 1.8\ \mathrm{fm} \simeq 1.3\ m_\pi^{-1}$
- energy per nucleon: $E/A \simeq -16\ \mathrm{MeV}$
- compression modulus: $K = (260 \pm 30)\ \mathrm{MeV} \sim 2m_\pi$

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

- **CONFINEMENT** of quarks and gluons in hadrons

- Spontaneously broken **CHIRAL SYMMETRY**

- **LOW-ENERGY QCD**:
  Effective **F**ield **T**heory of **weakly** interacting
  Nambu-Goldstone Bosons (PIONS)
  representing QCD at (energy and momentum) scales
  $$\mathrm{Q} << 4\pi\, \mathrm{f}_\pi \sim 1\,\mathrm{GeV}$$

Weinberg Gasser & Leutwyler

CHIRAL EFFECTIVE FIELD THEORY

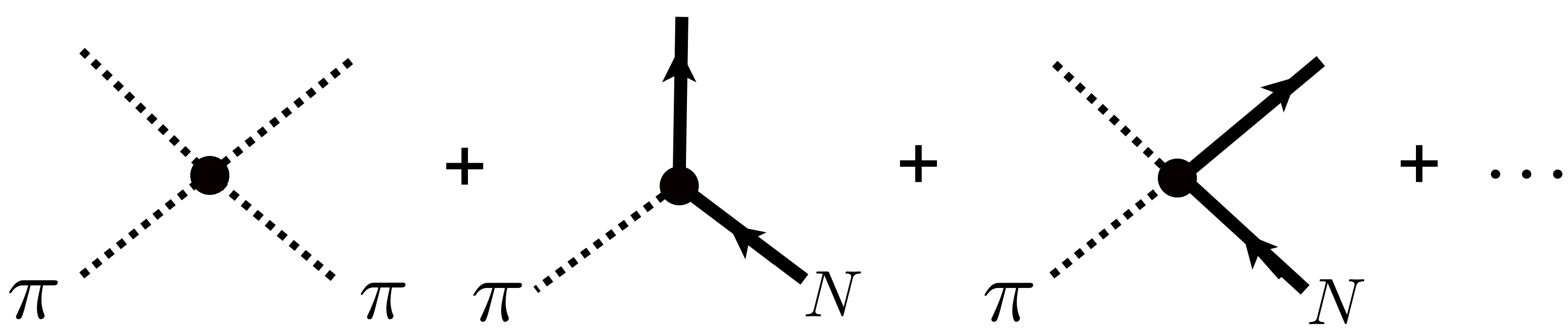
- Systematic framework at interface of QCD and Nuclear Physics

- 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**

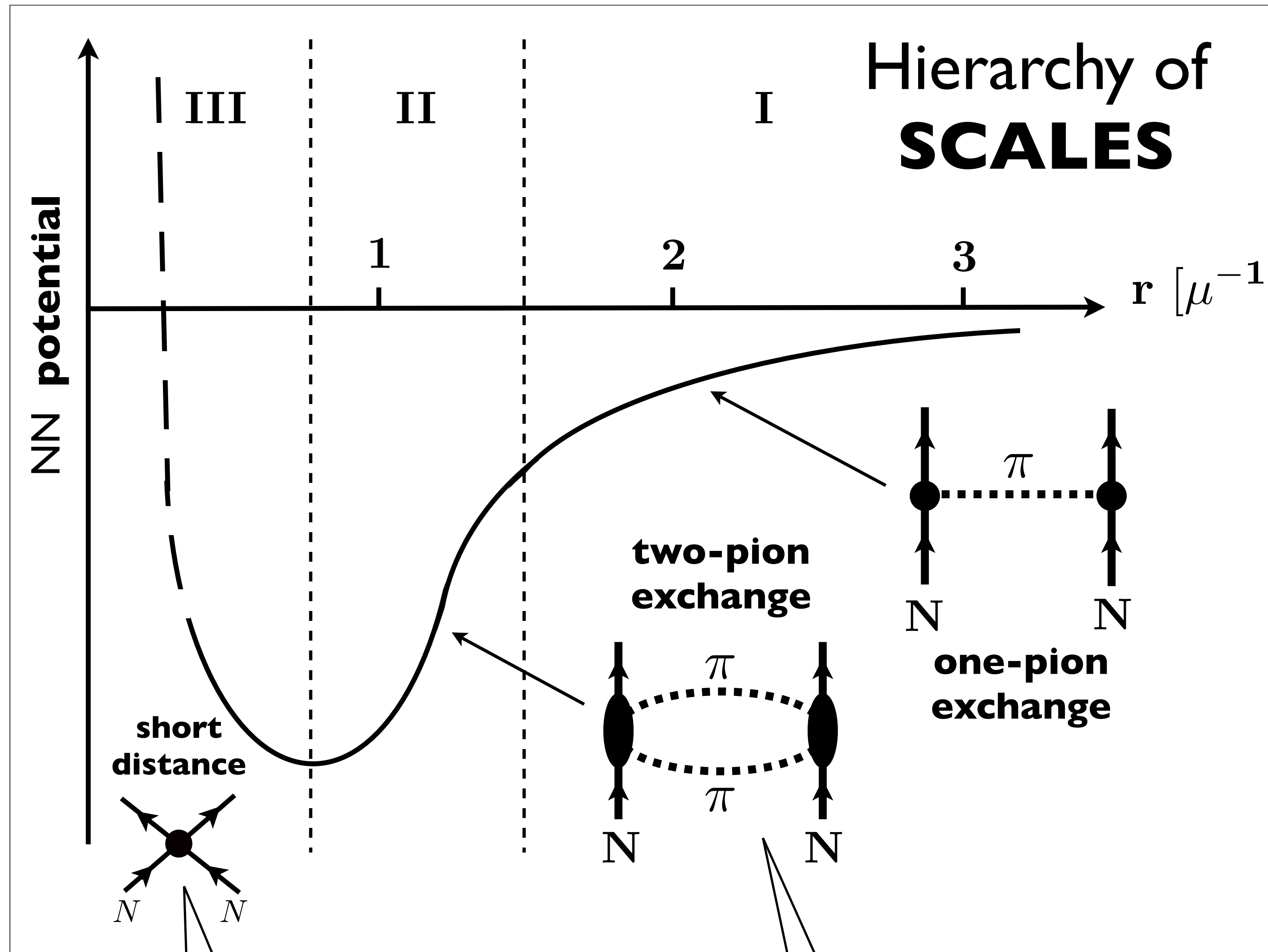


short distance dynamics: **contact terms**

Nuclear Forces

- recent developments -

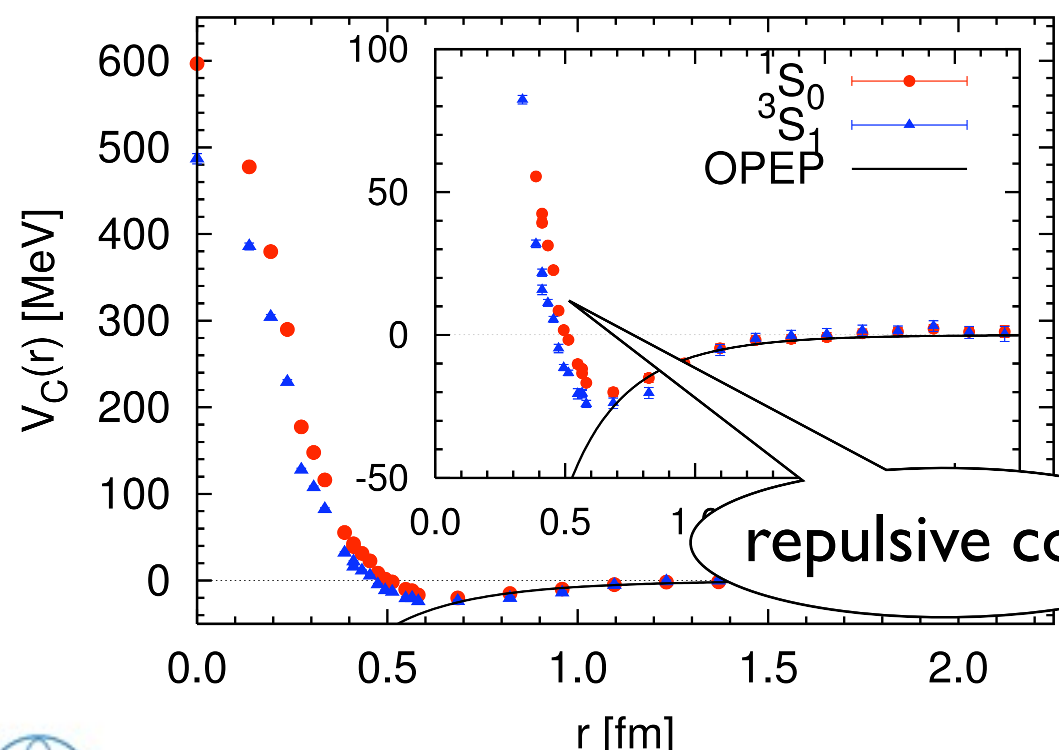
Early history: M. Taketani et al. (1951)



contemporary approach:

Chiral Effective Field Theory
+
Lattice QCD

N. Ishii, S. Aoki, T. Hatsuda: PRL (2007)



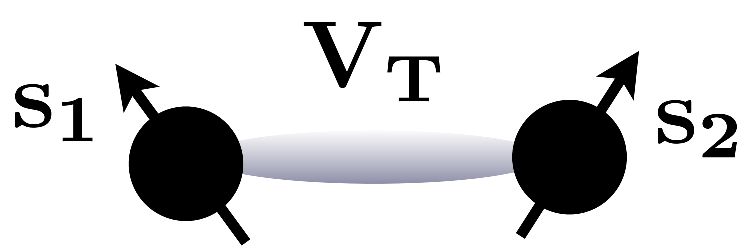
repulsive core

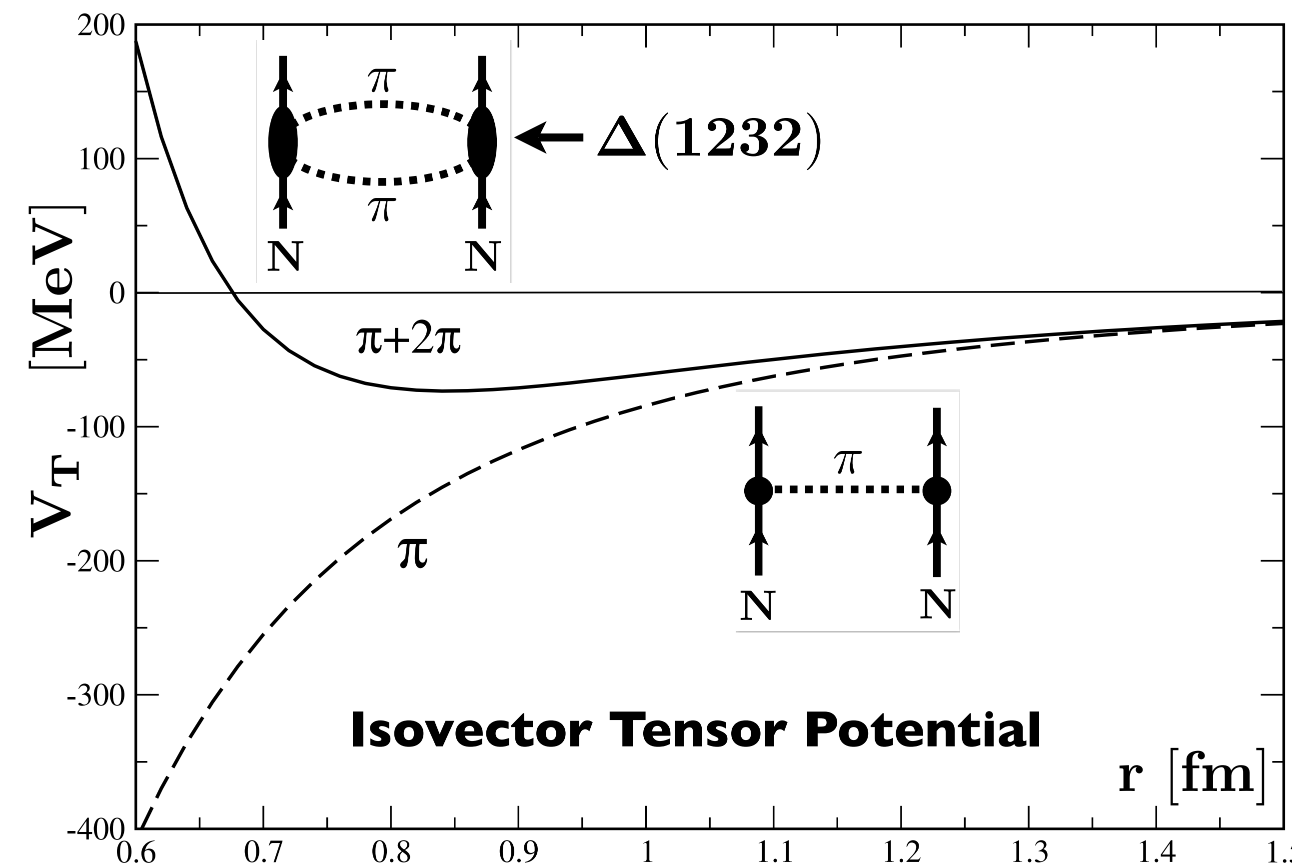
contact terms

explicit treatment of
two-pion exchange

Important pieces of the
CHIRAL NUCLEON-NUCLEON INTERACTION

- **ISOVECTOR TENSOR FORCE**



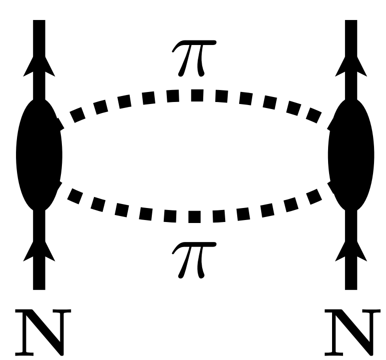


N. Kaiser, S. Gerstendörfer, W.W.: Nucl. Phys. A 637 (1998) 395

- note: **no** ρ meson

- **CENTRAL ATTRACTION** from **TWO-PION EXCHANGE**

  - $\Delta(1232)$



  - note: **no** σ boson

Van der WAALS - like force:

$$\mathbf{V_c(r)} \propto -\frac{\exp[-2\mathbf{m_\pi r}]}{\mathbf{r^6}}\mathbf{P(m_\pi r)}$$

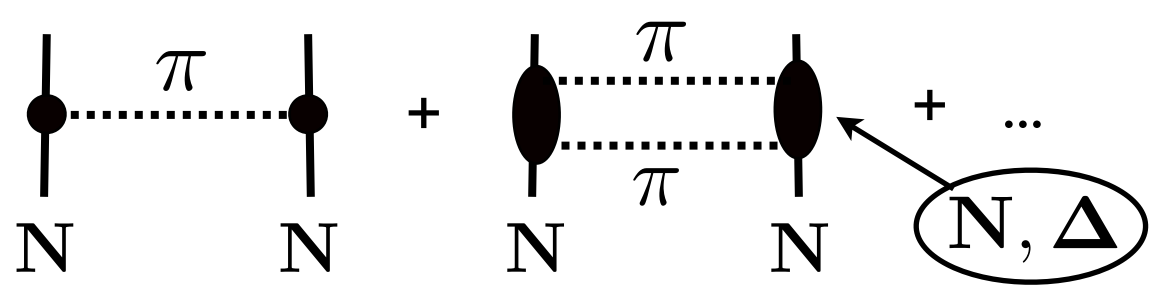
... at intermediate and long distance

CHIRAL DYNAMICS and the **NUCLEAR MANY-BODY PROBLEM**

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

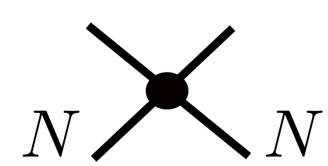
- **Small scales:** $k_F \sim 2\,m_\pi \sim M_\Delta - M_N << 4\pi\, f_\pi$
- **PIONS** (and **DELTA** isobars) as **explicit** degrees of freedom
- **IN-MEDIUM CHIRAL PERTURBATION THEORY**

pion exchange processes in presence of filled **Fermi sea**



in-medium

2nd order **TENSOR** force + nucleon's **SPIN-ISOSPIN** polarizability

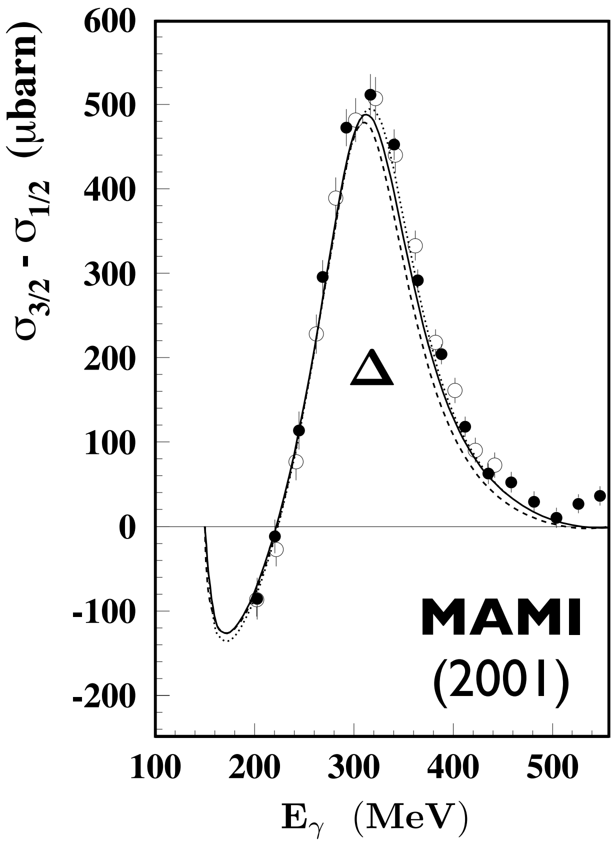
short-distance dynamics: 

contact interactions

► **Ericsonian concepts** at work, now implemented in ChPT

Explicit $\Delta(1230)$ DEGREES of FREEDOM

- **Large spin-isospin polarizabilty** of the Nucleon



◀ example: polarized Compton scattering

$$\beta_\Delta = \frac{g_A^2}{f_\pi^2 (M_\Delta - M_N)} \sim 5\,\mathrm{fm}^3$$

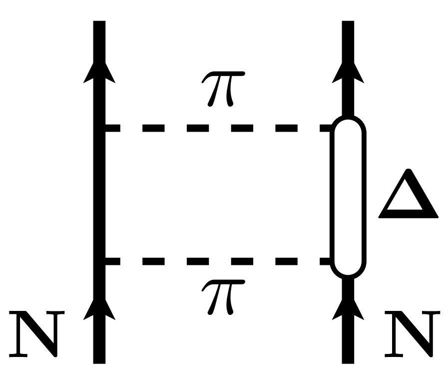
$$M_\Delta - M_N \simeq 2\ m_\pi << 4\pi\, f_\pi$$

(small scale)

- **Pionic Van der Waals** - type intermediate range central potential

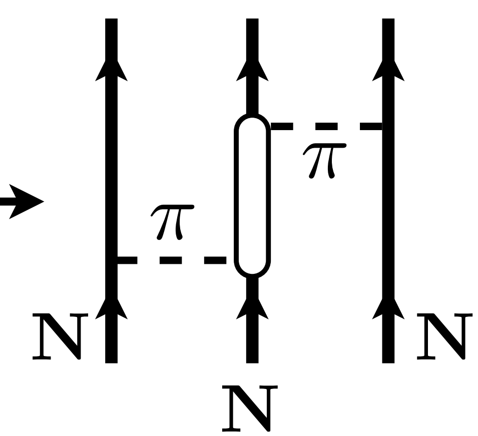
N. Kaiser, S. Gerstendörfer, W.W., NPA637 (1998) 395

N. Kaiser, S. Fritsch, W.W., NPA750 (2005) 259



$$V_c(r) = -\frac{9\,g_A^2}{32\pi^2 f_\pi^2}\,\beta_\Delta\,\frac{e^{-2m_\pi r}}{r^6}\,P(m_\pi r)$$

⟷



strong 3-body interaction

J. Fujita, H. Miyazawa (1957)

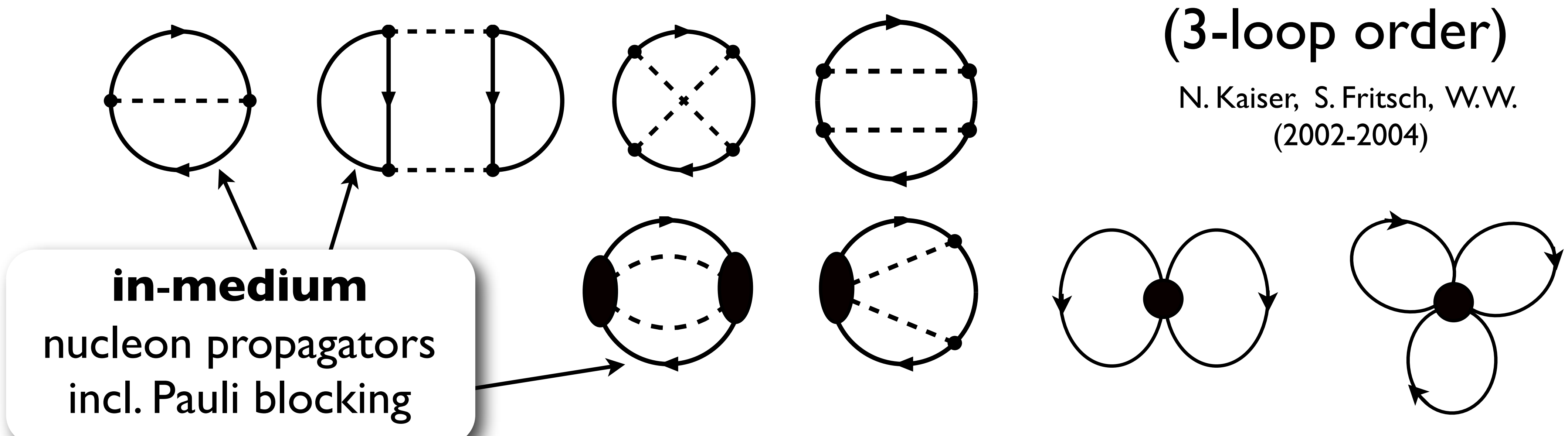
Pieper, Pandharipande, Wiringa, Carlson (2001)

IN-MEDIUM CHIRAL PERTURBATION THEORY

- **Loop expansion** in Chiral Perturbation Theory $\longleftrightarrow$
  Systematic expansion of **ENERGY DENSITY** $\mathcal{E}(\mathbf{k_F})$ in
  powers of **Fermi momentum** [modulo functions $\mathbf{f_n}(\mathbf{k_F}/\mathbf{m}_\pi)$]

- **Finite nuclei** $\longleftrightarrow$ energy **density functional**
  many quantitatively successful applications throughout the nuclear chart

- Nuclear **thermodynamics**: compute **free energy density**

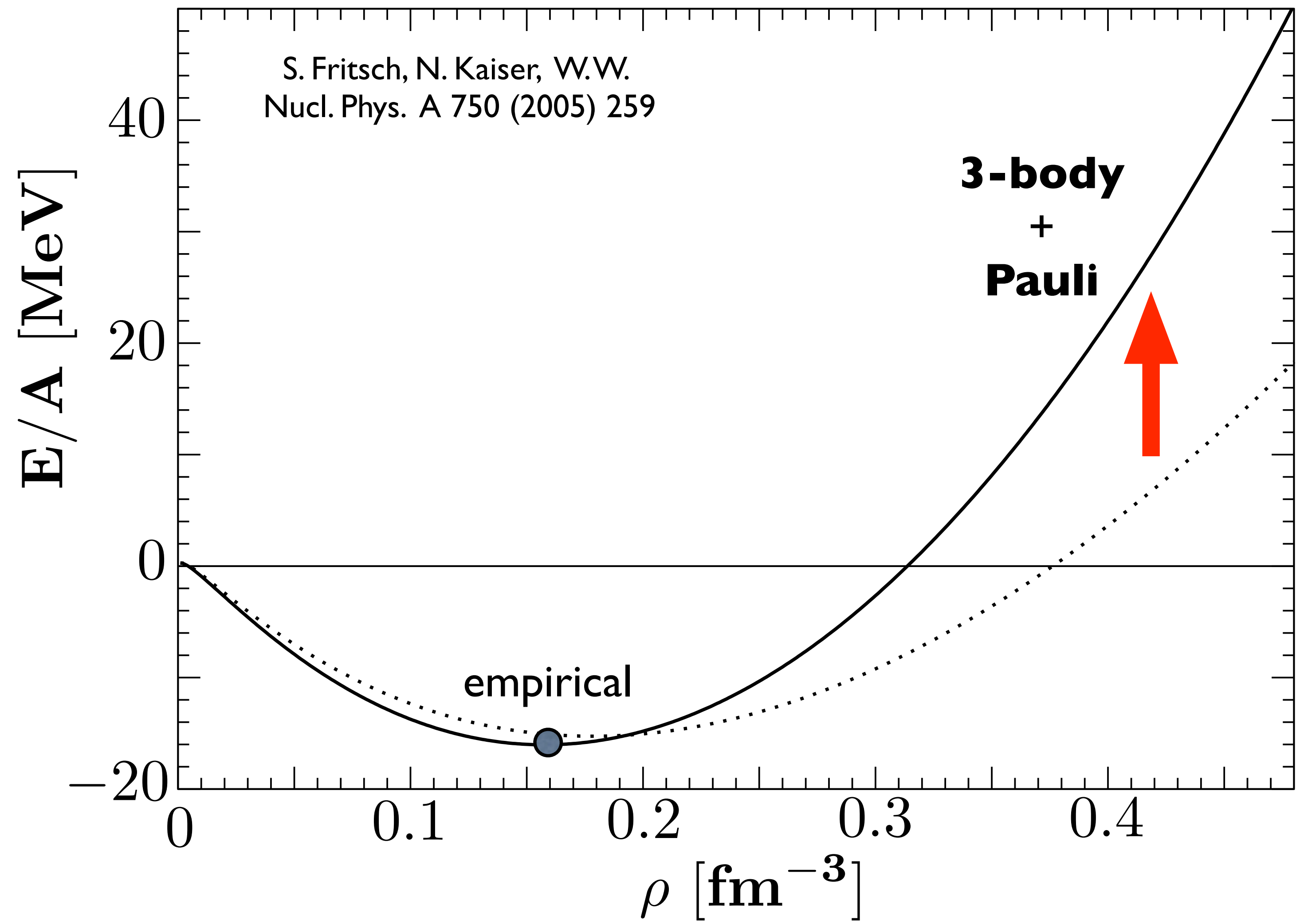


(3-loop order)

N. Kaiser, S. Fritsch, W.W.
(2002-2004)

NUCLEAR MATTER

- **In-medium ChPT**
  3-loop $(\pi, \mathrm{N}, \Delta)$
- **Input** parameter:
  single contact term
- basically:
  analytic calculation



- **Output**:
  - Binding & saturation

$$\mathbf{E_0/A = -16\,MeV} \;,\; \rho_0 = \mathbf{0.16\,fm^{-3}} \;,\; \mathbf{K = 290\,MeV}$$

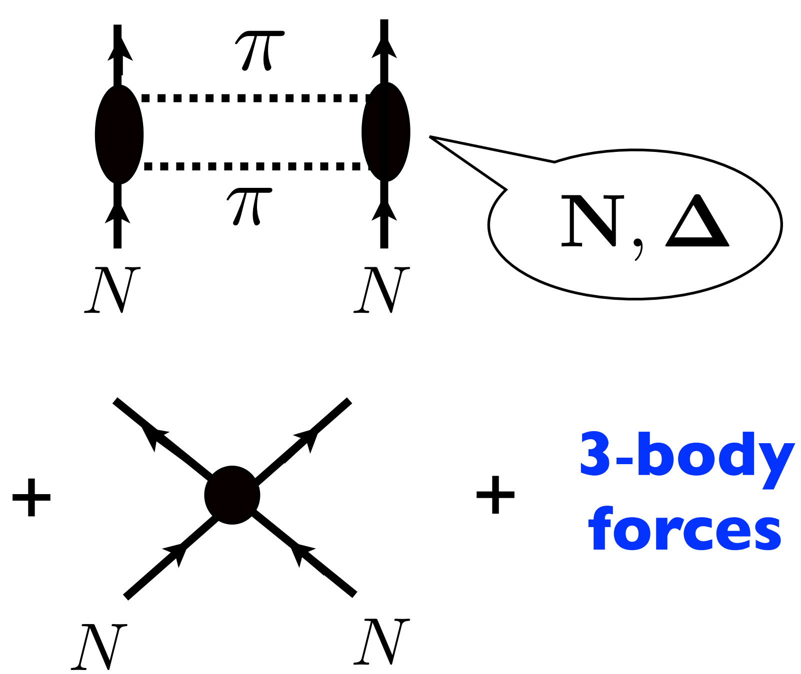
  - Realistic (complex, momentum dependent) single-particle potential
    ... satisfying Hugenholtz - van Hove and Luttinger theorems (!)
  - Asymmetry energy $\mathbf{A(k_F^0) = 34\,MeV}$
  - Landau parameters

NUCLEAR THERMODYNAMICS

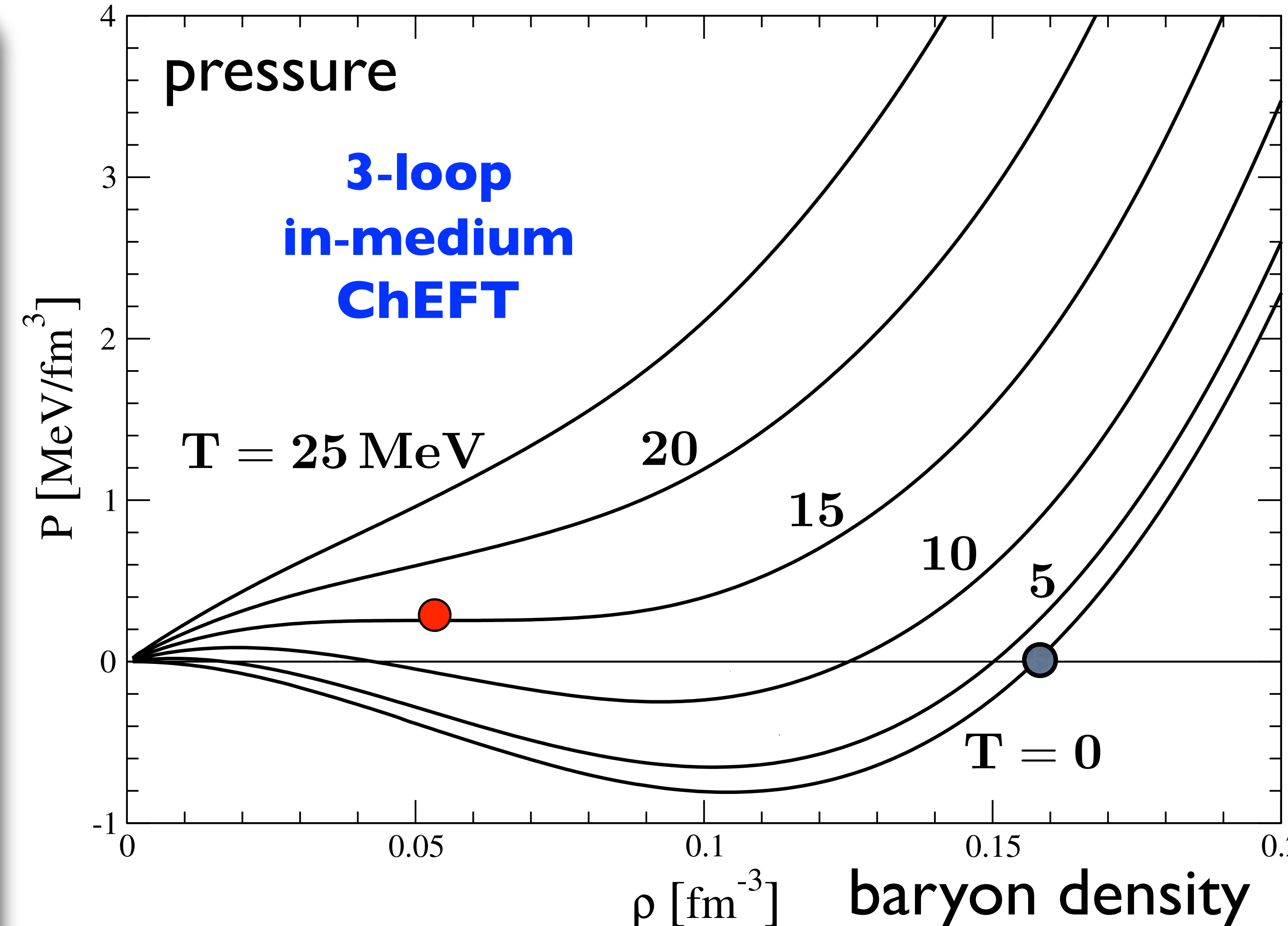
NUCLEAR CHIRAL (PION) DYNAMICS

BINDING & SATURATION:

Van der Waals + Pauli



nuclear matter: equation of state



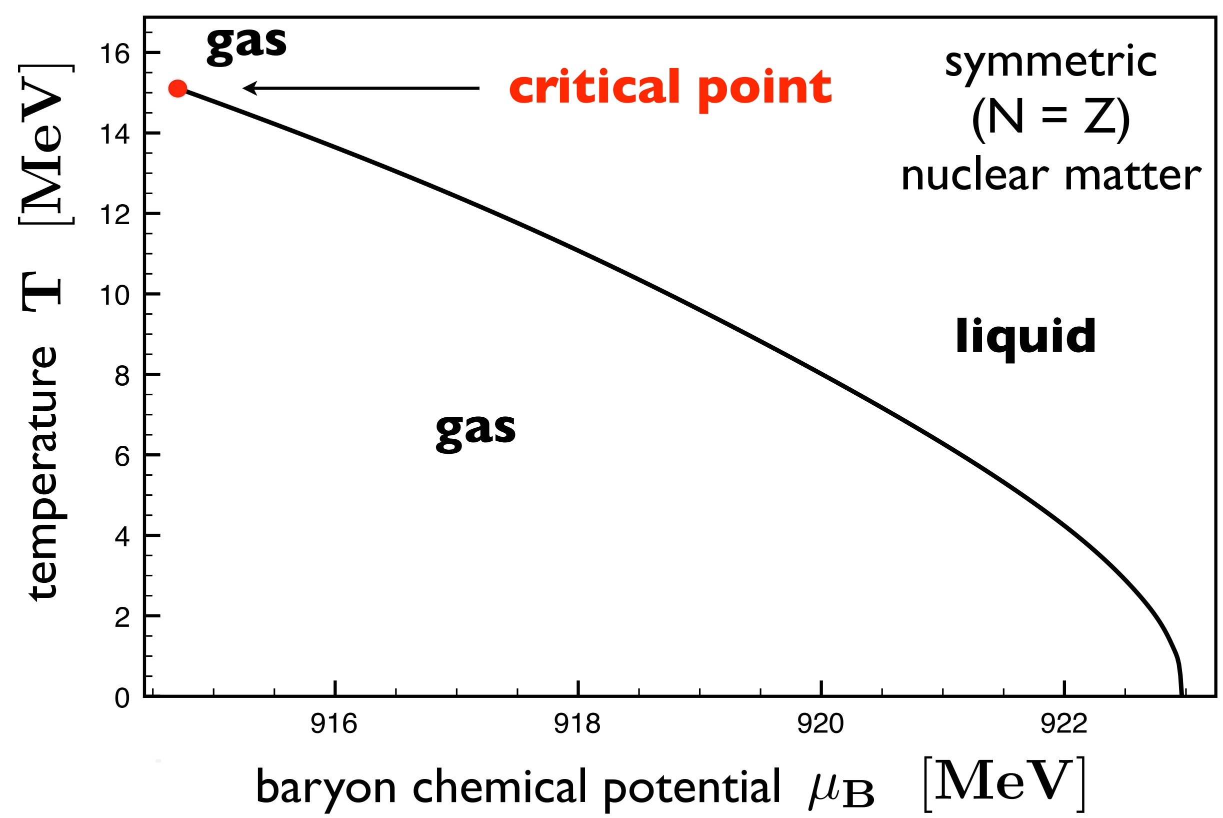
Liquid - Gas Transition at

Critical Temperature T_c = 15 MeV

(empirical: T_c = 16 - 18 MeV)

S. Fritsch, N. Kaiser, W.W.: Nucl. Phys. A 750 (2005) 259

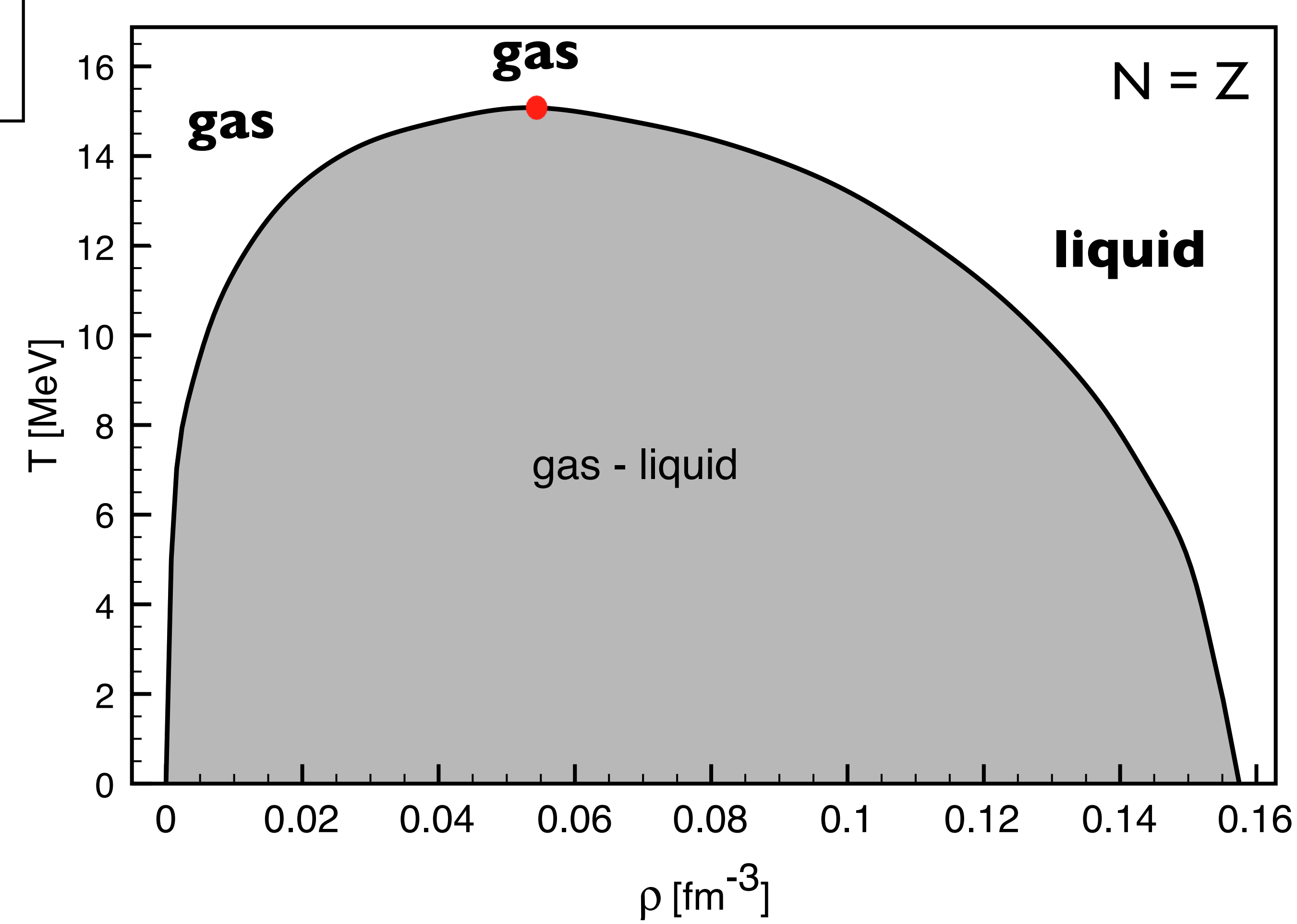
PHASE DIAGRAM of NUCLEAR MATTER



- In-medium
  chiral effective field theory
  (3-loop in the free energy density)

S. Fritsch, N. Kaiser, W.W.: NPA 750 (2005) 259

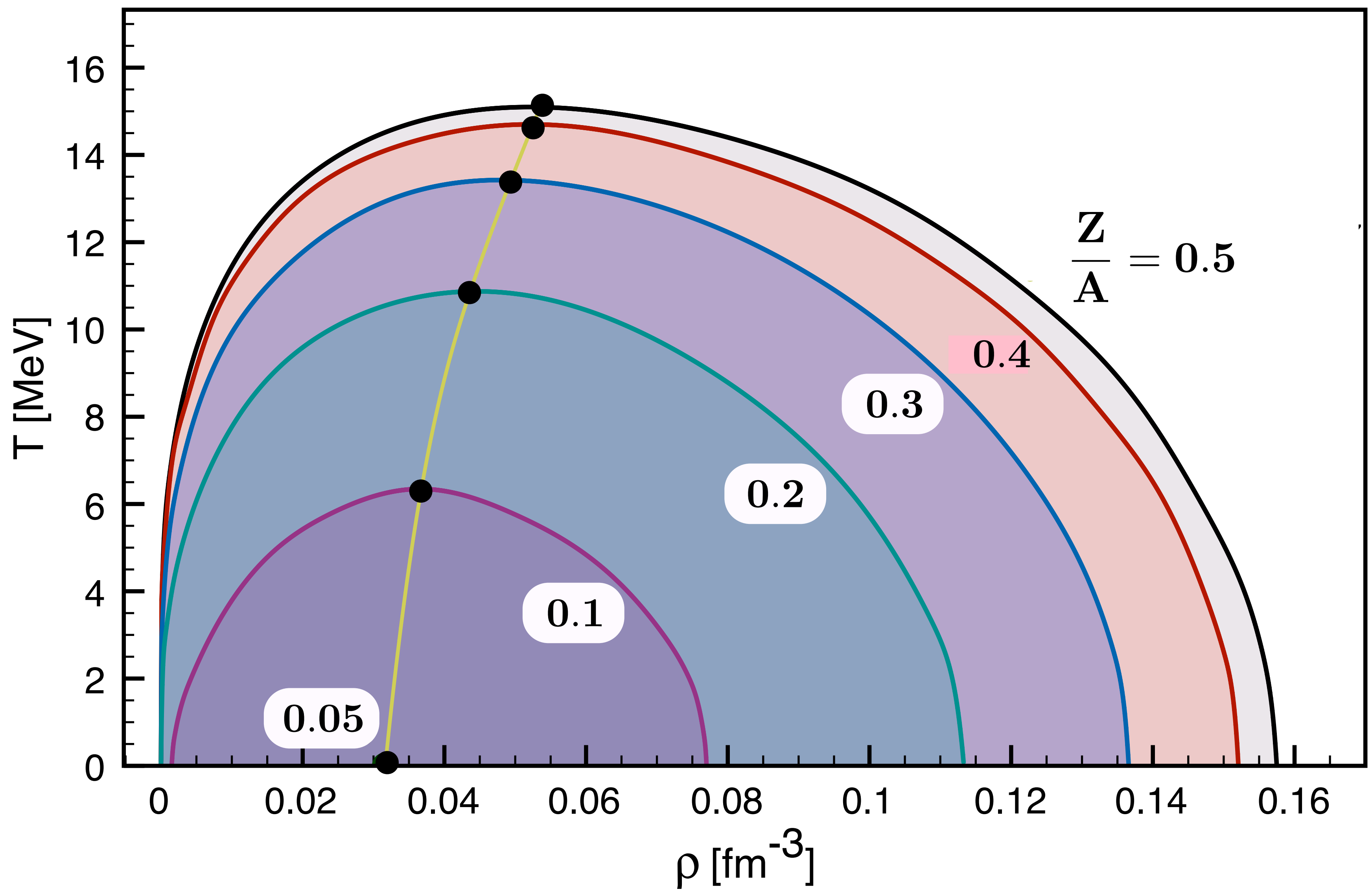
S. Fiorilla, N. Kaiser, W.W. (2010)



- Pion-nucleon dynamics
  incl. delta isobars
- Short-distance
  NN contact terms
- Three-body forces

PHASE DIAGRAM of NUCLEAR MATTER

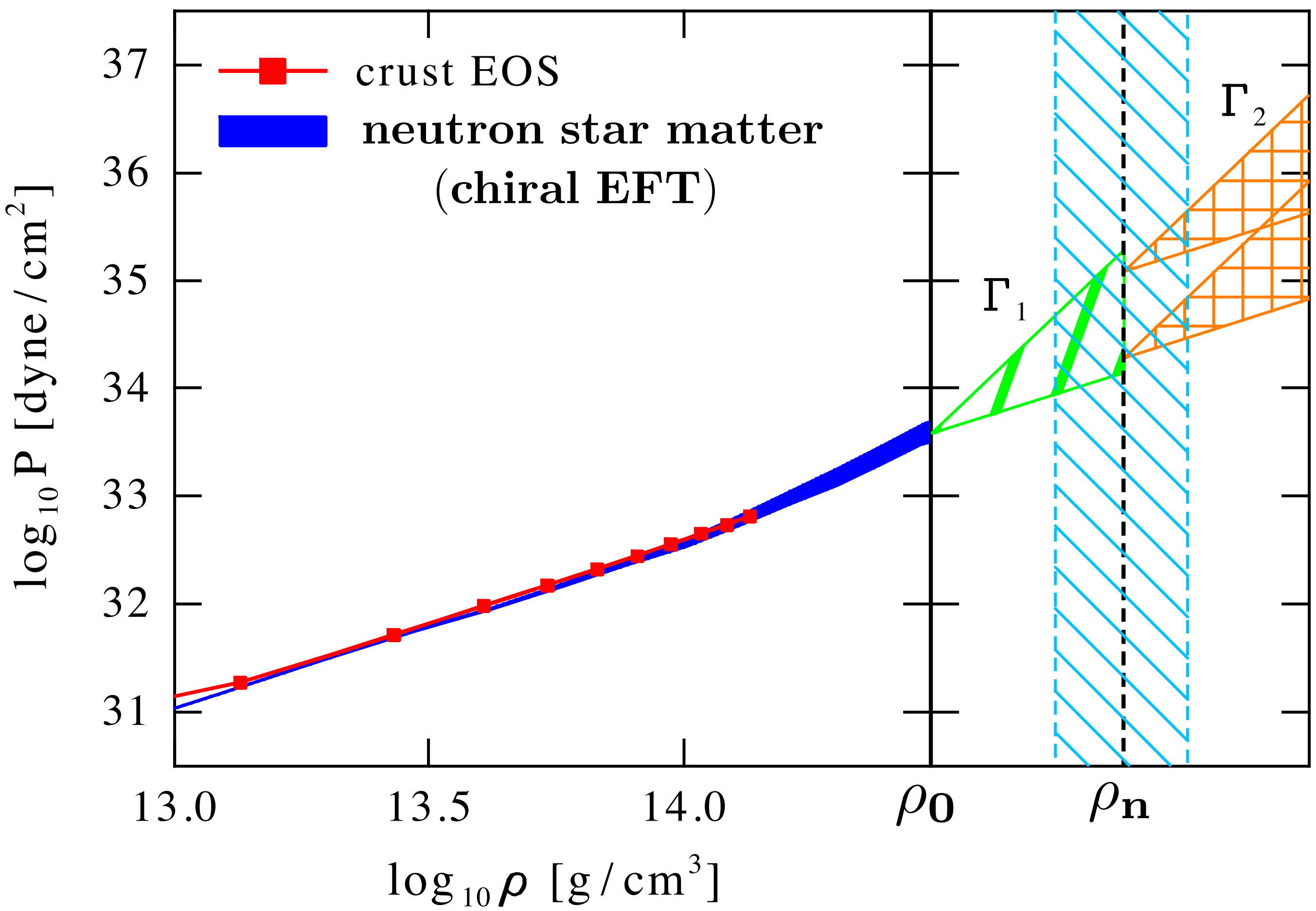
- Trajectory of **CRITICAL POINT** for **asymmetric matter** as function of proton fraction Z/A



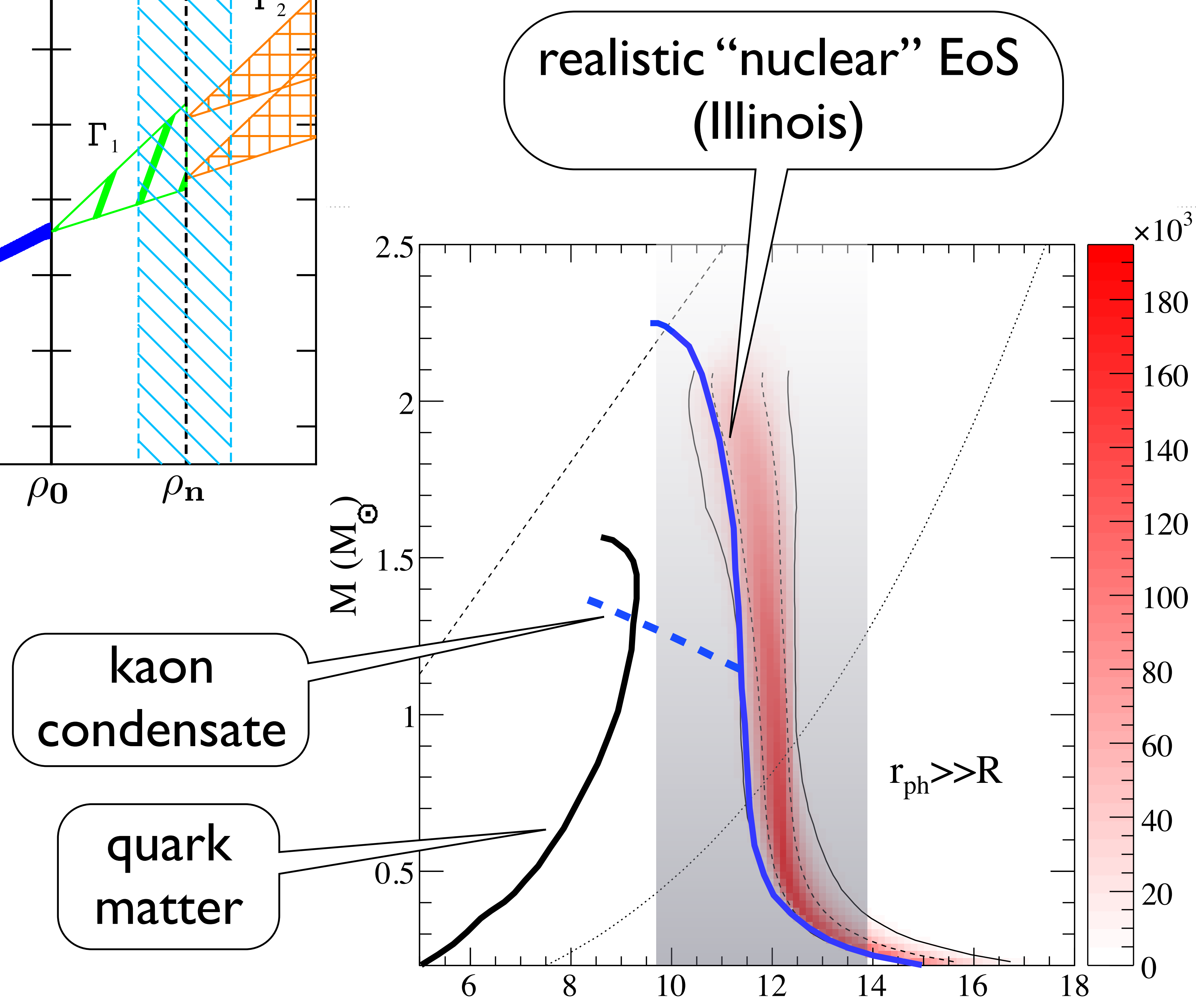
S. Fiorilla, N. Kaiser, W.W. (2010)

. . . determined almost entirely by **isospin** dependent **pion** exchange dynamics

DENSE MATTER and NEUTRON STARS



K. Hebeler, J. Lattimer, C. Pethick, A. Schwenk (2010)



A.W. Steiner, J. Lattimer, E.F. Brown (2010)

- New constraints from EFT and neutron star observables

CHIRAL CONDENSATE at finite BARYON DENSITY

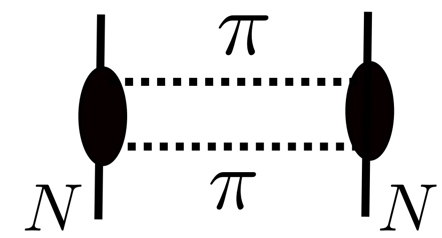
- Chiral (quark) condensate $\langle \bar{q}q \rangle$:
  Order parameter of spontaneously broken chiral symmetry in QCD

- Hellmann - Feynman theorem: $\langle \Psi | \bar{q}q | \Psi \rangle = \langle \Psi | \frac{\partial \mathcal{H}_{QCD}}{\partial m_q} | \Psi \rangle = \frac{\partial \mathcal{E}(m_q;\rho)}{\partial m_q}$

sigma term

$$m_q \frac{\partial M_N}{\partial m_q}$$

in-medium chiral effective field theory



$$\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle_0} = 1 - \frac{\rho}{f_\pi^2}\left[\frac{\sigma_N}{m_\pi^2}\left(1 - \frac{3\,p_F^2}{10\,M_N^2} + \ldots\right) + \frac{\partial}{\partial m_\pi^2}\left(\frac{E_{int}(p_F)}{A}\right)\right]$$

(free) Fermi gas of nucleons

nuclear interactions (dependence on pion mass)

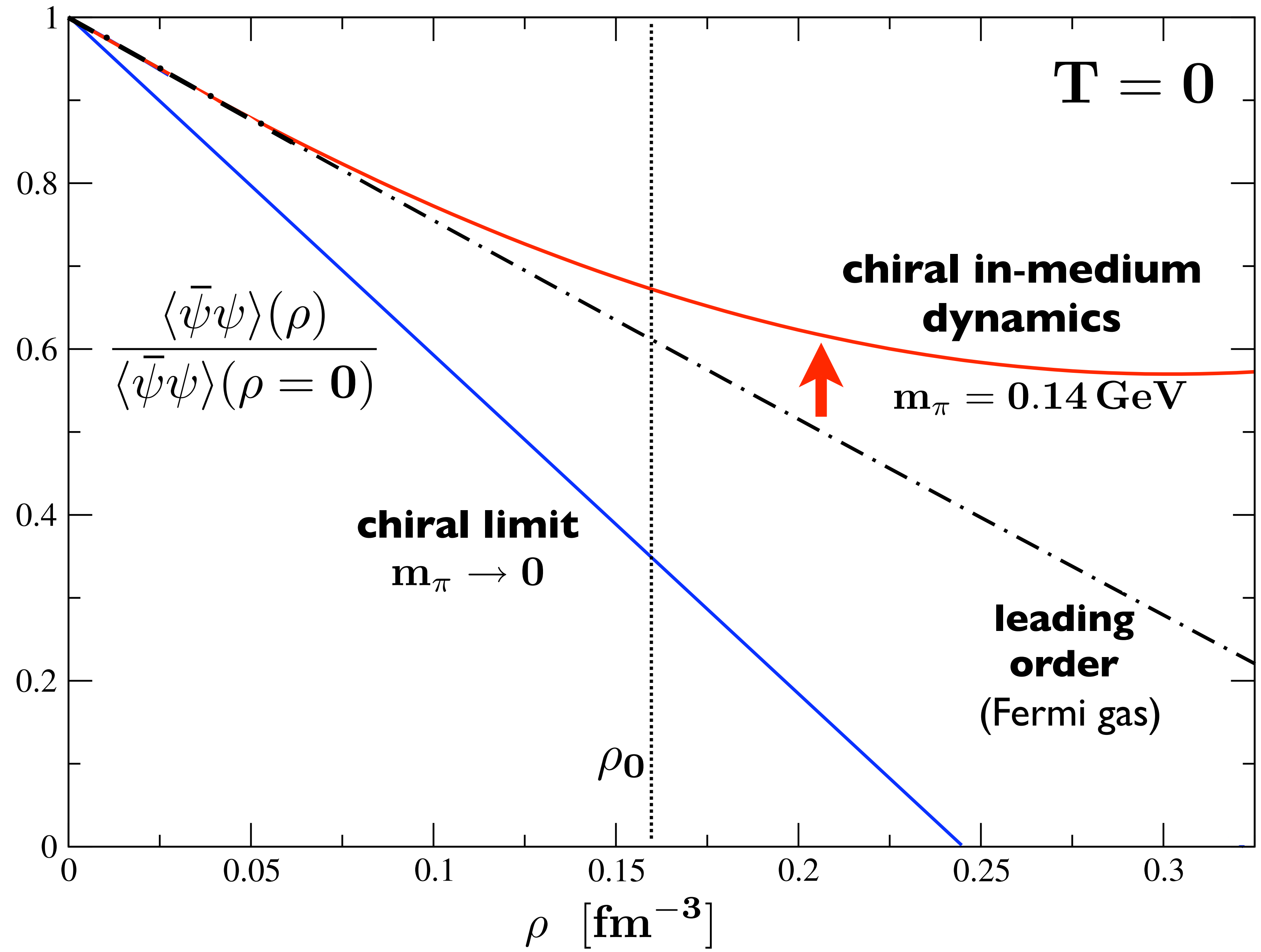
CHIRAL CONDENSATE: DENSITY DEPENDENCE

- **In-medium Chiral Effective Field Theory**

  (NLO 3-loop)

  constrained by **realistic nuclear equation of state**

  N. Kaiser, Ph. de Homont, W.W. Phys. Rev. C 77 (2008) 025204



- Substantial **change** of **symmetry breaking scenario** between chiral limit $\mathbf{m_q = 0}$ and physical quark mass $\mathbf{m_q \sim 5\,MeV}$
- **Nuclear Physics** would be **very different** in the **chiral limit** !

a long road together

… thank you, Magda & Torleif