Chiral Symmetry in **Strongly Interacting Matter**

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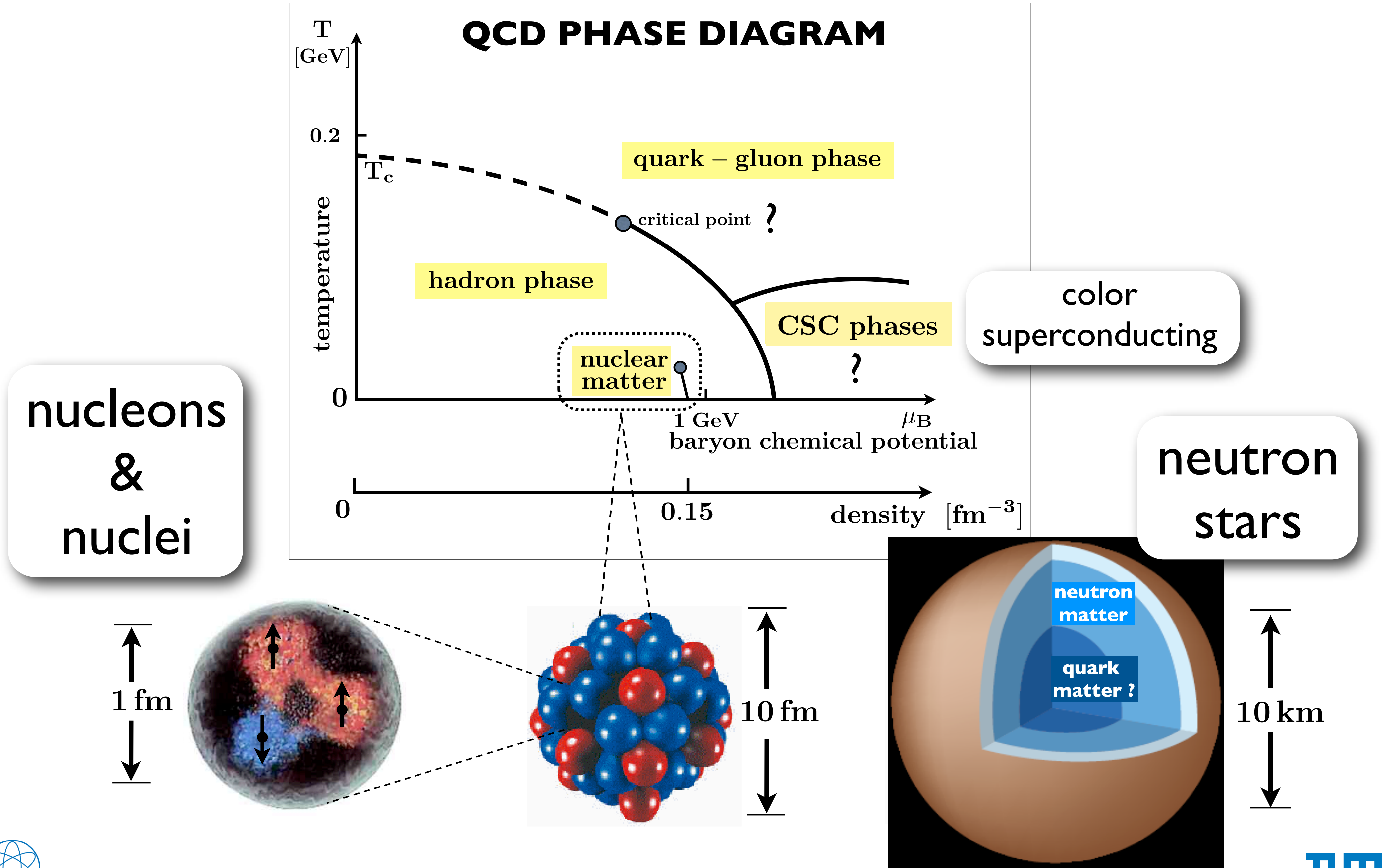
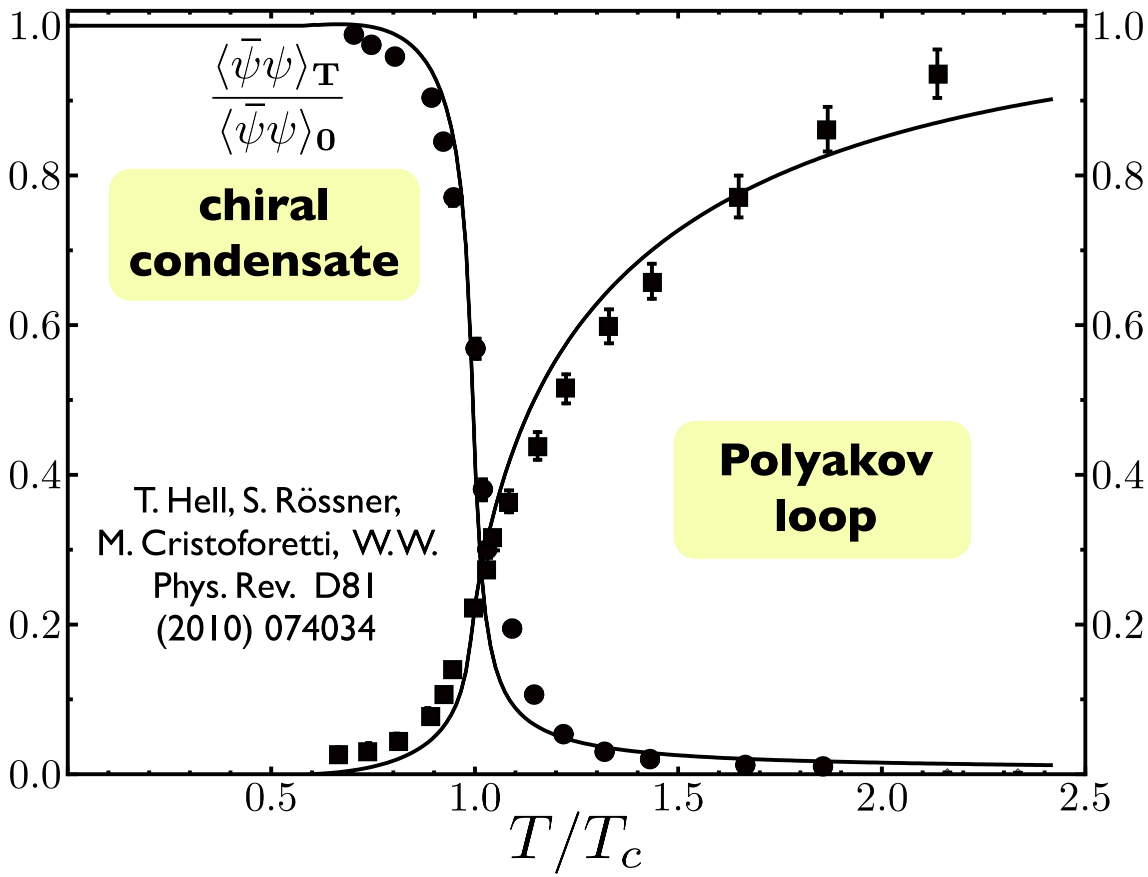
- Spontaneously Broken Chiral Symmetry and
  Nuclear Chiral (Thermo-)Dynamics
- QCD interface with Nuclear Physics:
  Chiral Effective Field Theory
- Nuclear Equation of State
  in the context of the QCD Phase Diagram
- Density and Temperature Dependence of the Chiral Condensate
- Astrophysical Constraints from Neutron Stars in Binaries

1 Prelude: PHASES and STRUCTURES of QCD



Phases and Symmetry Breaking Pattern

QCD Thermodynamics at zero baryon chemical potential



Lattice QCD
(2+1 flavours)

M. Cheng et al.
Phys. Rev. D77 (2008) 014511

Quasiparticle Model

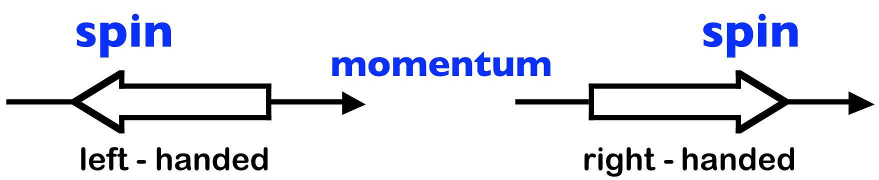
Chiral Quarks + Polyakov Loop (**PNJL** Model)

S. Rössner, C. Ratti, W.W.
Phys. Rev. D 75 (2007) 034007

- **Spontaneously broken CHIRAL SYMMETRY**
  at low temperature $\mathbf{T < T_c \simeq 0.2\ GeV}$

2 Low-Energy QCD : CHIRAL SYMMETRY

- **QCD** with (almost) **MASSLESS u-** and **d-QUARKS** ($N_f = 2$)



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

$$\psi = (\mathbf{u}, \mathbf{d})$$

pseudoscalar isovector

$$\pi^a \leftrightarrow \bar{\psi}\,\gamma_5\,\mathbf{t}^a\,\psi$$

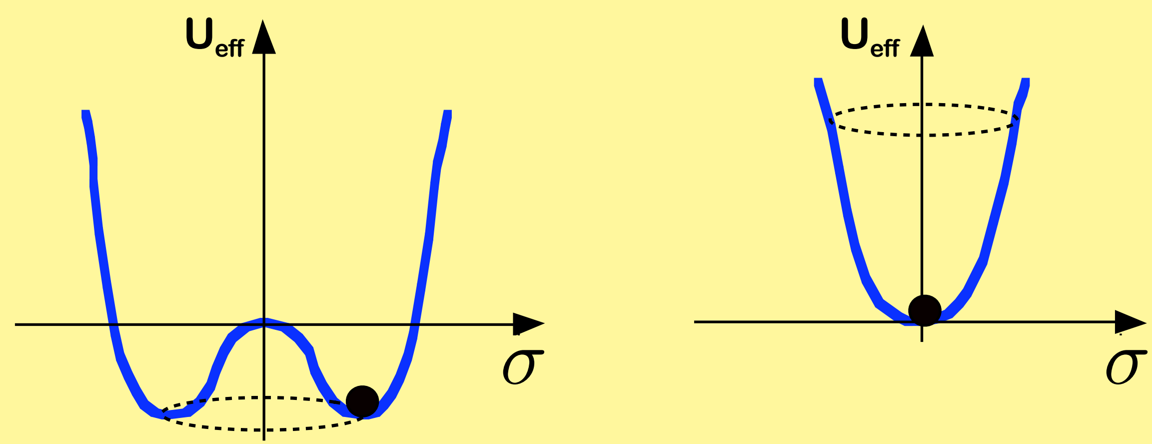
PION

scalar isoscalar

$$\sigma \leftrightarrow \bar{\psi}\,\psi$$

- **SPONTANEOUS SYMMETRY BREAKING**
(Nambu - Goldstone)

Low T | High T



- **CHIRAL** (QUARK) **CONDENSATE**

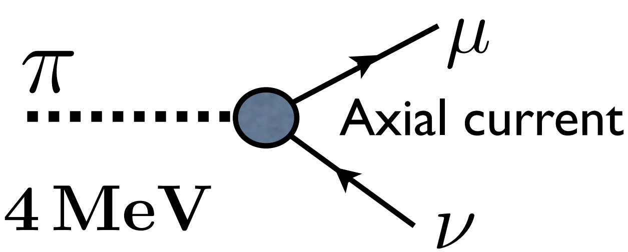
$$\langle \bar{\mathrm{q}}\mathrm{q} \rangle \neq 0 \qquad\qquad \langle \bar{\mathrm{q}}\mathrm{q} \rangle = 0$$

Low-Temperature Limit:

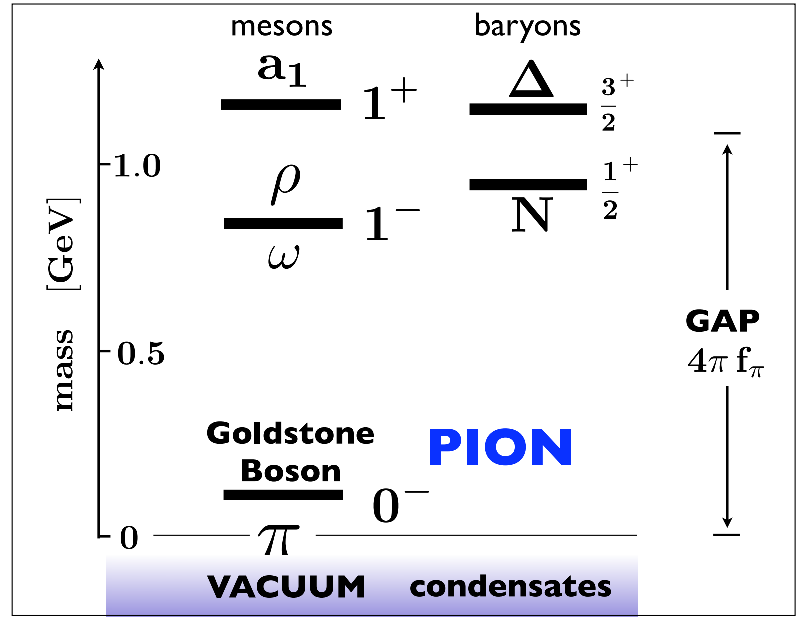
Spontaneously Broken CHIRAL SYMMETRY

- **NAMBU - GOLDSTONE BOSON**:
  PION

- **ORDER PARAMETER**:
  PION DECAY CONSTANT



$$\mathrm{f}_\pi = 92.4\,\mathrm{MeV}$$



- **P**artially **C**onserved **A**xial **C**urrent: $\mathbf{m}_\pi^2\,\mathbf{f}_\pi^2 = -\mathbf{m_q}\,\langle\bar{\psi}\psi\rangle + \mathcal{O}(m_q^2)$

- **Low-energy / low temperature** limit of **QCD** is realized as a **Chiral Effective Field Theory** of (weakly interacting) **Nambu-Goldstone Bosons (PIONS)**

CHIRAL EFFECTIVE FIELD THEORY

Gasser & Leutwyler   Weinberg   Ecker   . . . many others

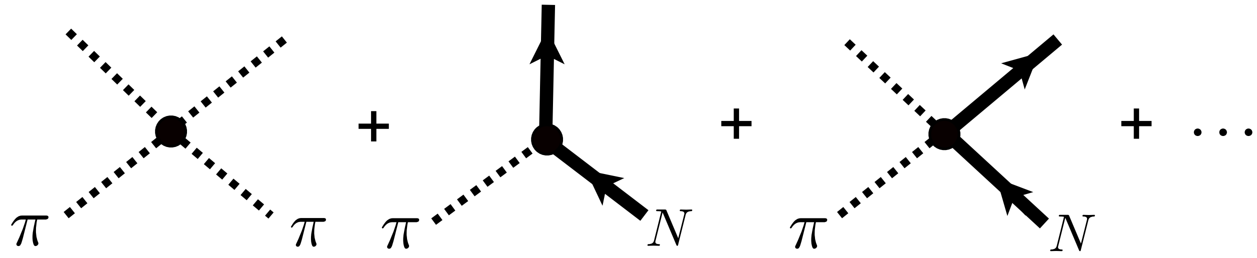
- **LOW-ENERGY QCD**: **E**ffective **F**ield **T**heory of **weakly** interacting **Nambu-Goldstone Bosons** (PIONS) representing QCD at scales $Q << 4\pi f_\pi \sim 1\,GeV$

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**

Low-Energy Expansion: **CHIRAL PERTURBATION THEORY**

- **small parameter**:

$$\frac{Q}{4\pi f_\pi} \qquad \frac{\textbf{energy} \,/\, \textbf{momentum} \,/\, \text{pion mass}}{1\,\text{GeV}}$$

- successfully applied to:

→ **PION-PION** scattering

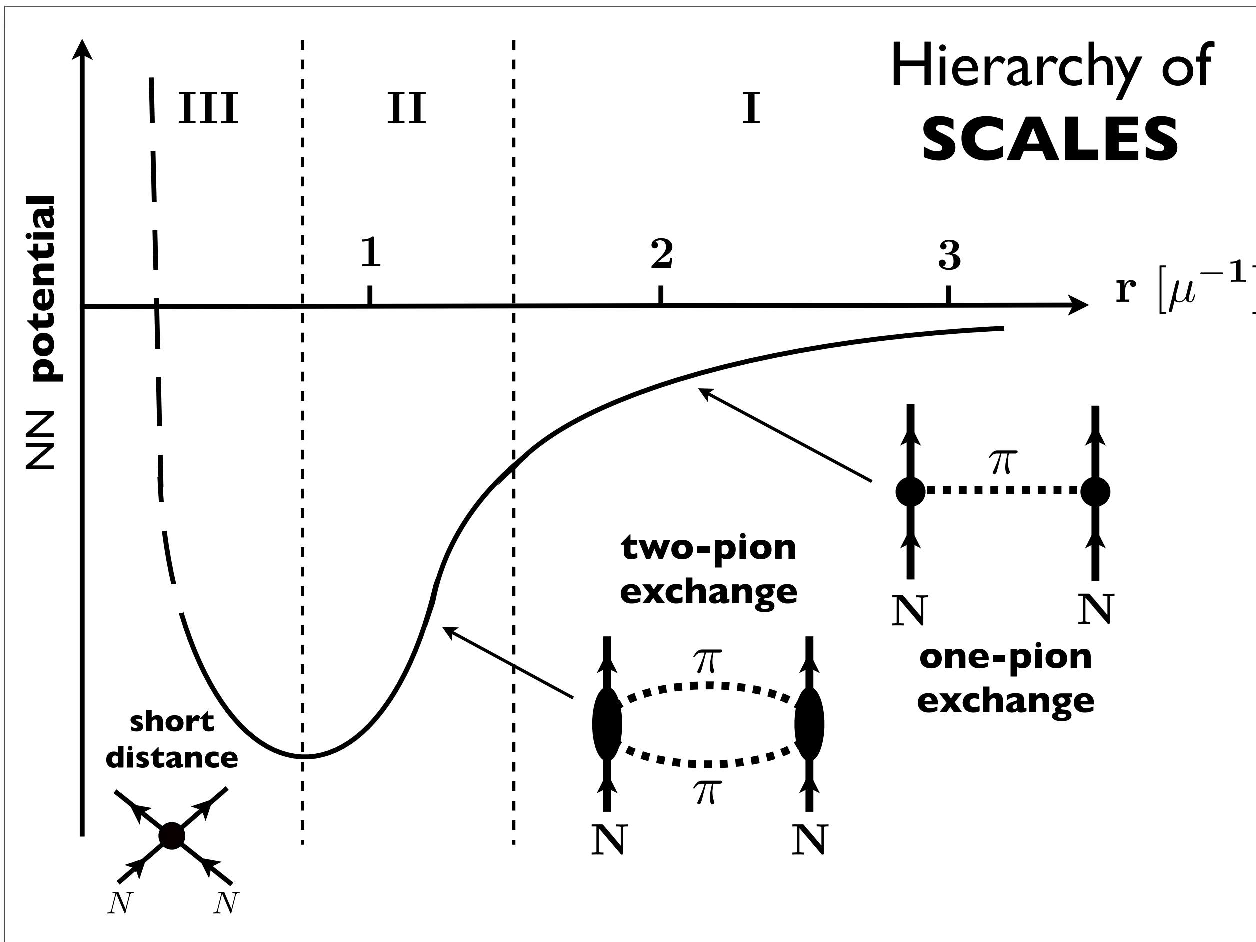
→ **PION-NUCLEON** scattering

→ **PION photoproduction** and COMPTON scattering on the NUCLEON

→ long range **NUCLEON-NUCLEON** interaction

→ **NUCLEAR MATTER** and **NUCLEI**

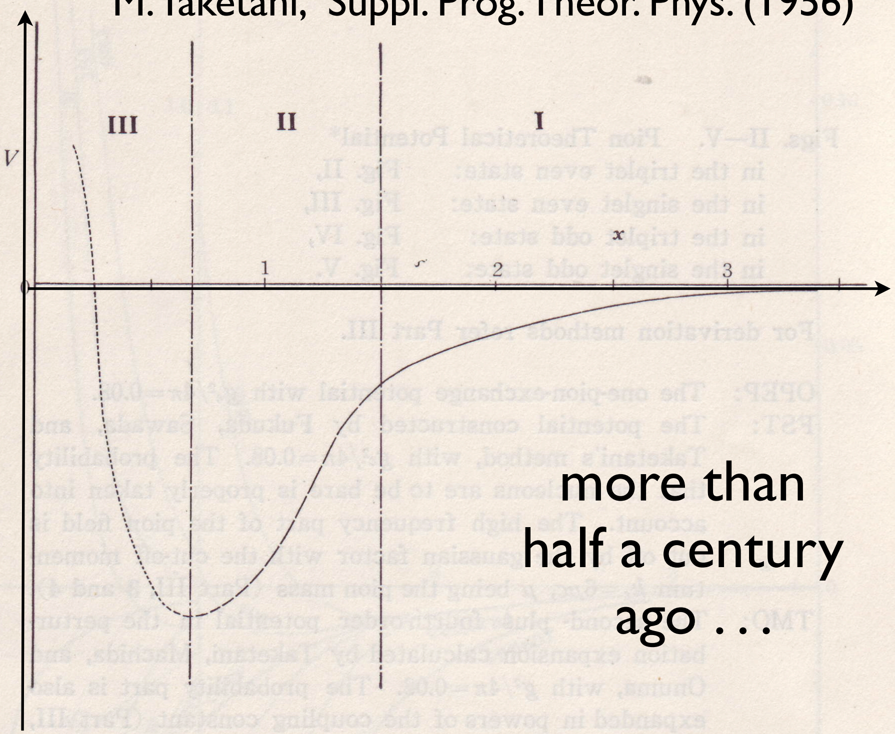
3
Nuclear Forces from CHIRAL EFT



Nucleon-Nucleon Interaction

M. Taketani, S. Nakamura, M. Sasaki
Prog. Theor. Phys. **6** (1951) 581

M. Taketani, Suppl. Prog. Theor. Phys. (1956)



more than half a century ago . . .

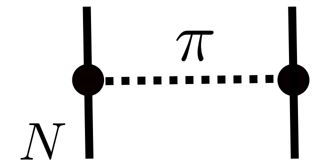
Fig. I. Three Regions of Nuclear Potential.*

Region I. *Classical region*, $r \lesssim 1.5\kappa^{-1}$, ($\kappa^{-1}$ is the pion Compton wave length) where the one-pion-exchange potential dominates and the quantitative behavior of the potential has been established.

Region II. *Dynamical region*, $0.7\kappa^{-1} \lesssim r \lesssim 1.5\kappa^{-1}$, where the two-pion-exchange potential competes with and exceeds the one-pion-exchange potential. The recoil effect is also appreciable in this region. The qualitative behavior, however, has been clarified.

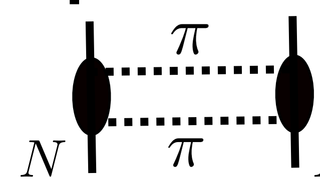
Region III. *Phenomenological region*, $r \lesssim 0.7\kappa^{-1}$, where exist so many complicated effects, e.g., the relativistic effect, the isobar effect, the effect of new particles, etc., that at present we may have no means but some phenomenological treatment to fit with experiments.

region I
long distance:
one-pion exchange



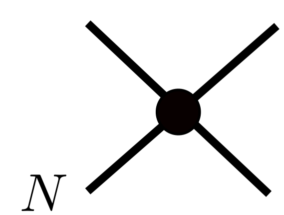
H. Yukawa (1935)

region II
intermediate distance:
two-pion exchange



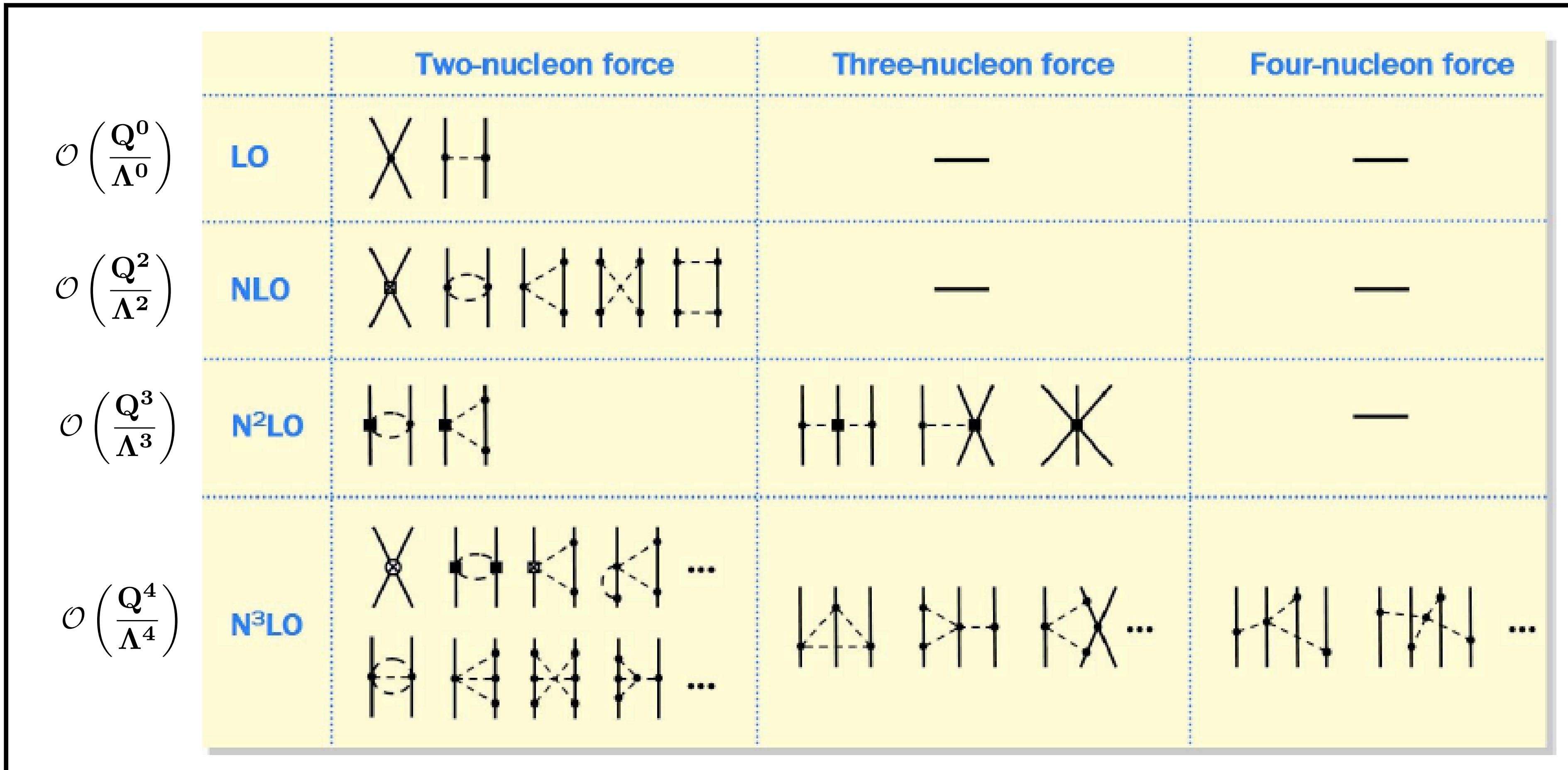
H. Miyazawa et al. (1957)

region III
short distance: unresolved



NUCLEAR INTERACTIONS from CHIRAL EFFECTIVE FIELD THEORY

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



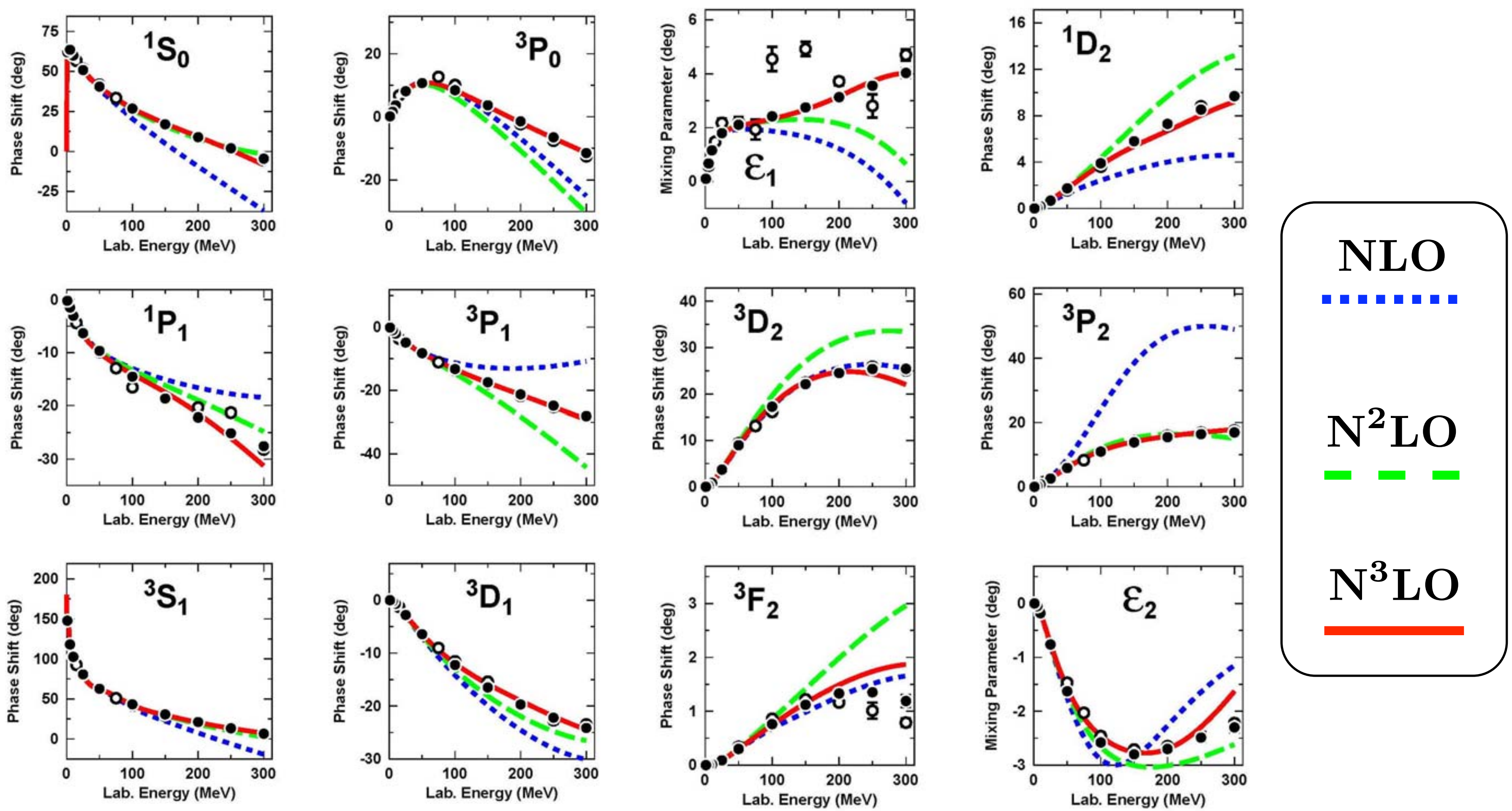
- **Systematically organized HIERARCHY**

NN Scattering Phase Shifts

from **CHIRAL EFFECTIVE FIELD THEORY**

Entem, Machleidt, Phys. Rev. C68 (2003) 041001

Epelbaum, Glöckle, Meißner, Nucl. Phys. A747 (2005) 362



- quantitatively accurate at same level of precision as best phenomenological potentials

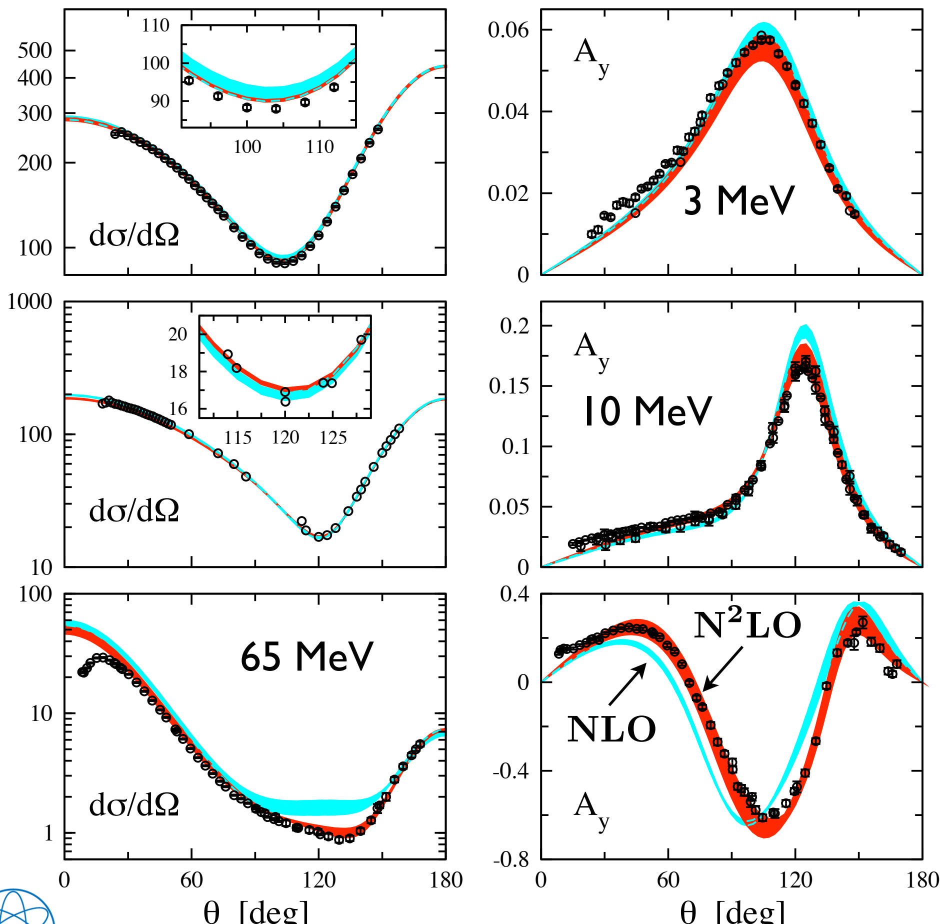
CHIRAL EFFECTIVE FIELD THEORY
at work in nuclear few-body systems

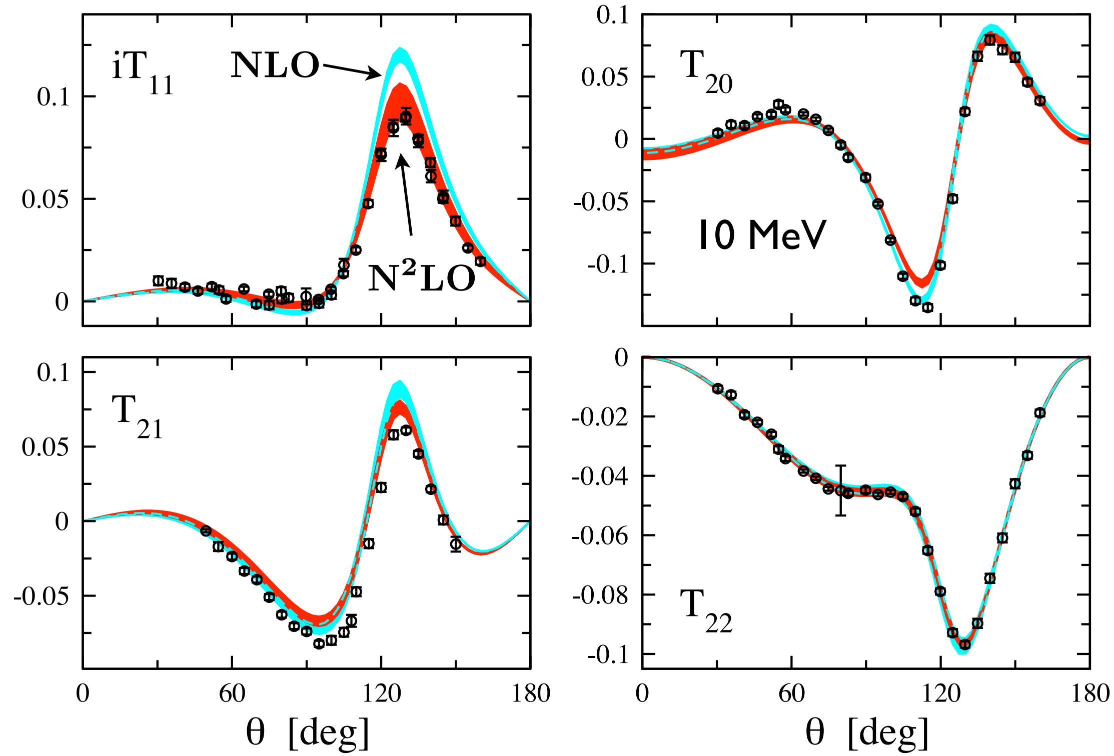
- example: elastic **nd** scattering

differential cross sections [mb/sr]

vector analyzing powers

tensor analyzing powers

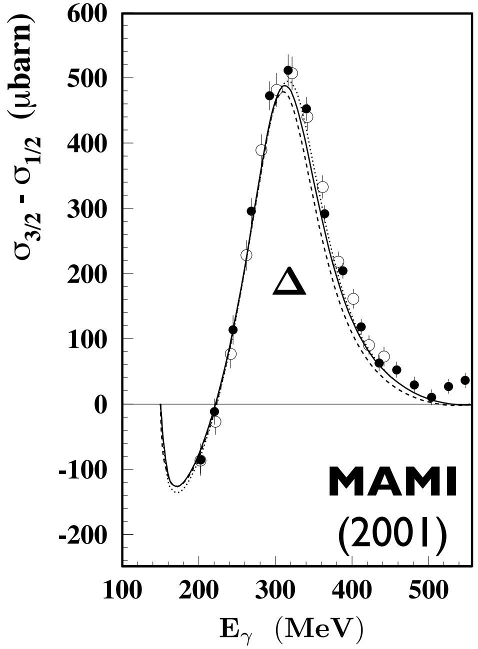




E. Epelbaum: Prog. Part. Nucl. Phys. 57 (2006) 654

Explicit $\Delta(1230)$ DEGREES of FREEDOM

- Large **spin-isospin polarizability** of the nucleon



- example: polarized Compton scattering

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

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

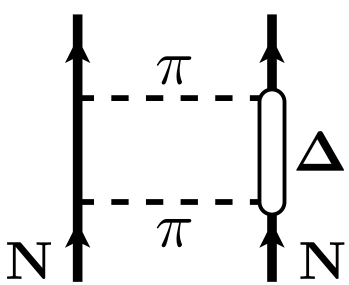
(small scale)

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

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

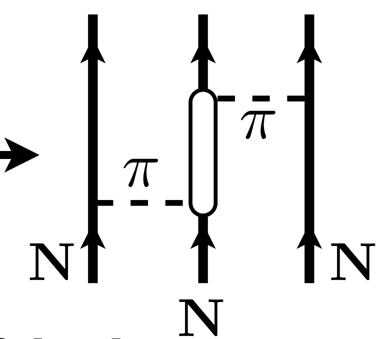
N. Kaiser, S. Fritsch, W.W., NPA750 (2005) 259

C. Ordonez, L. Ray, U. van Kolck, PRL 72 (1994) 1982



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

↔

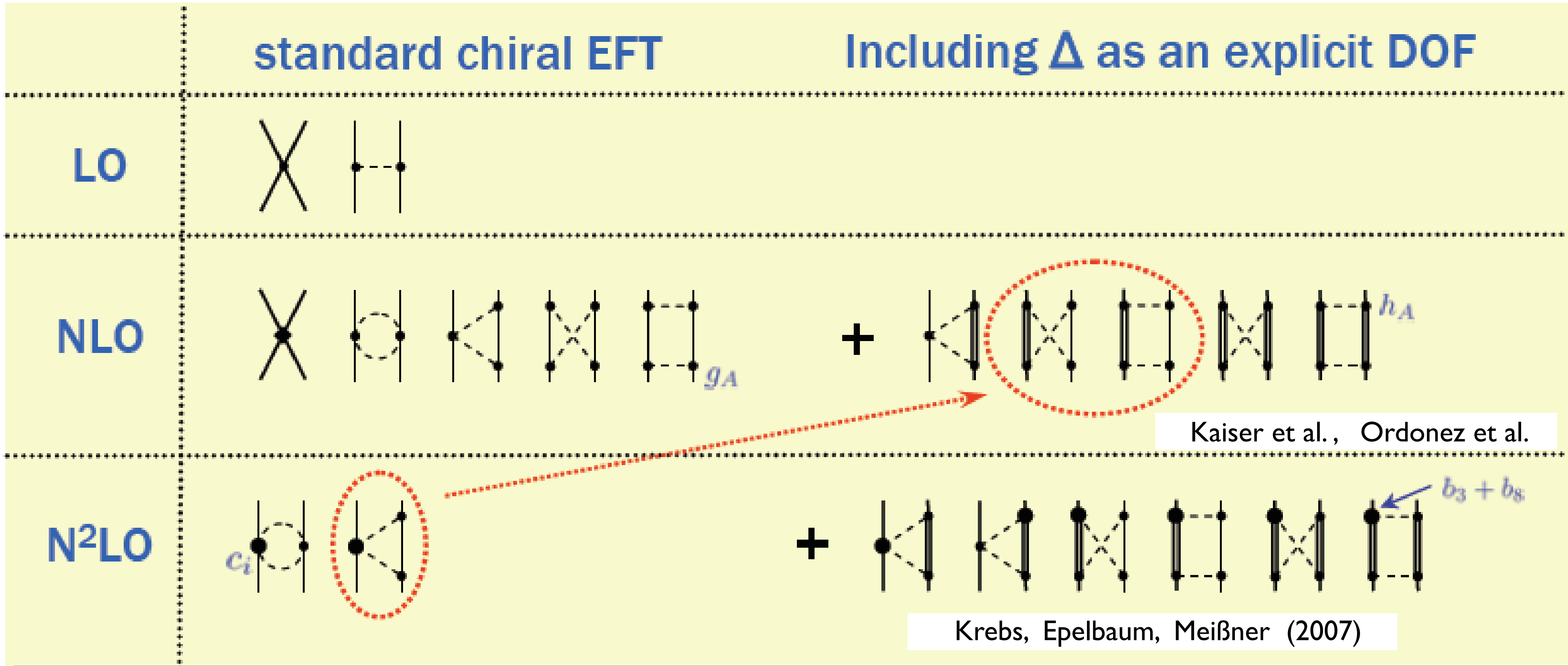


strong 3-body interaction

J. Fujita, H. Miyazawa; Prog. Theor. Phys. 17 (1957) 360

Pieper, Pandharipande, Wiringa, Carlson, PRC64 (2001) 014001

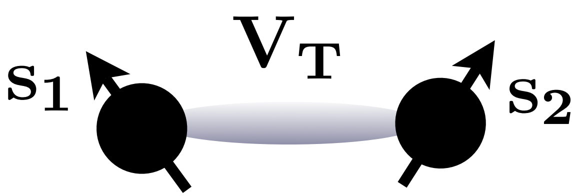
Explicit $\Delta(1230)$ DEGREES of FREEDOM (contd.)



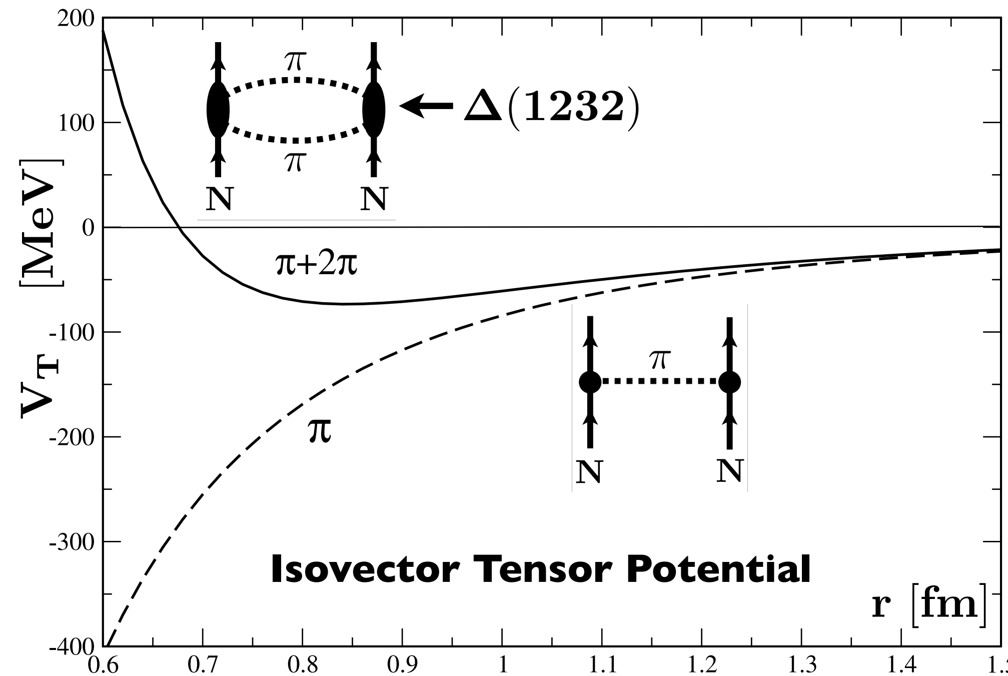
- **Important physics** of $\Delta(1230)$ promoted to **NLO**
- **Improved** convergence

Important pieces of the
CHIRAL NUCLEON-NUCLEON INTERACTION

- **ISOVECTOR TENSOR FORCE**

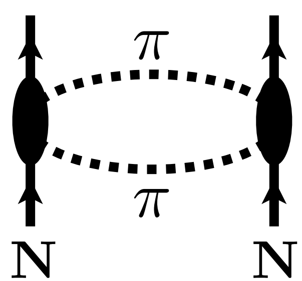


- note: **no** ρ meson



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

- **CENTRAL ATTRACTION** from **TWO-PION EXCHANGE**
  - $\Delta(1232)$



  - note: **no** fictitious σ boson

Van der WAALS - like force:

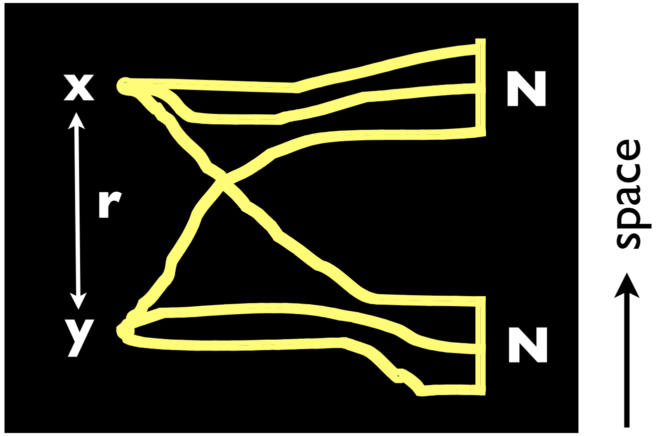
$$V_c(r) \propto -\frac{\exp[-2m_\pi r]}{r^6} P(m_\pi r)$$

... at intermediate and long distance

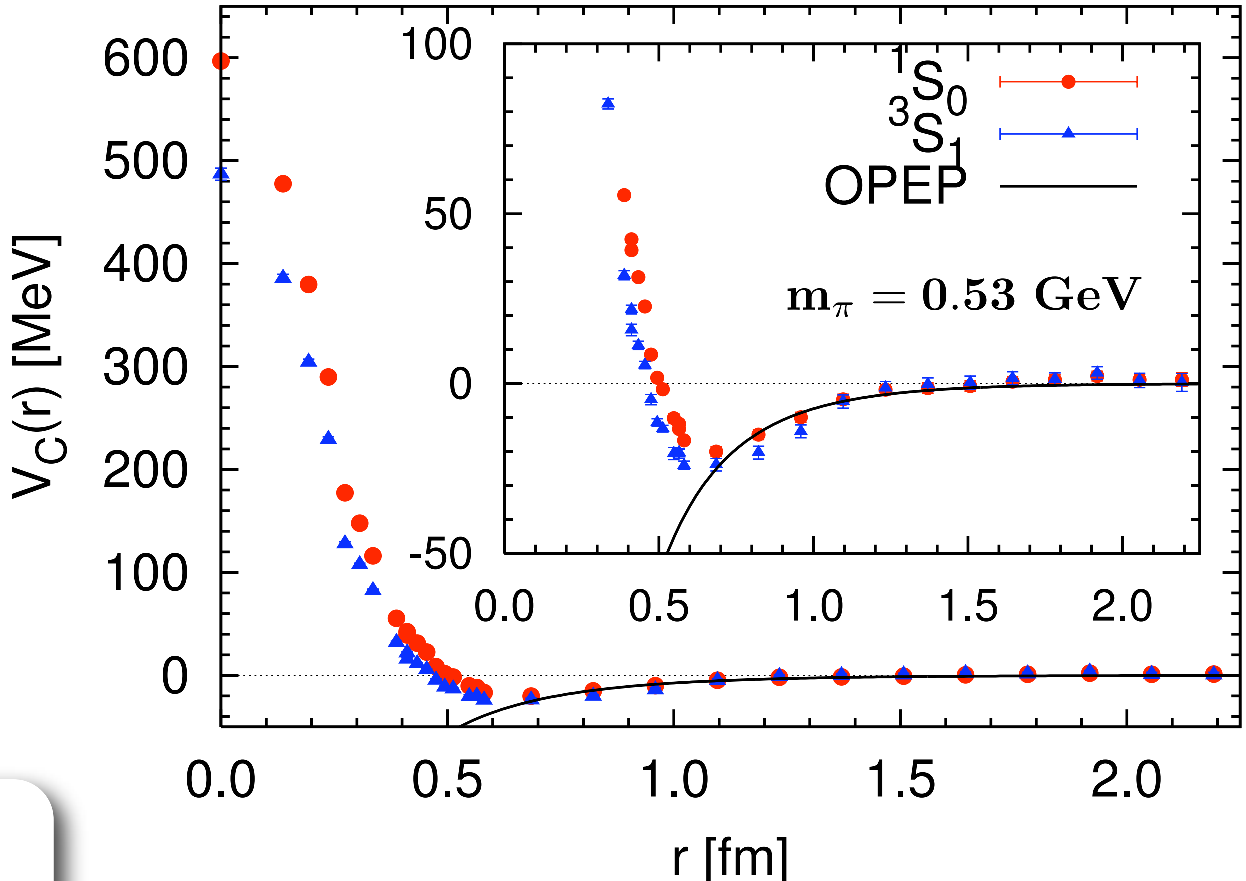
Short distance: NN POTENTIAL from LATTICE QCD

N. Ishii, S. Aoki, T. Hatsuda: Phys. Rev. Lett. 99 (2007) 022001

$\phi(\mathbf{r})$



time (Euclidean)



quenched QCD
"large" quark/pion masses

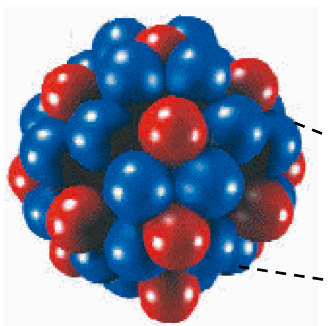
- Reconstruct potential from wave function:

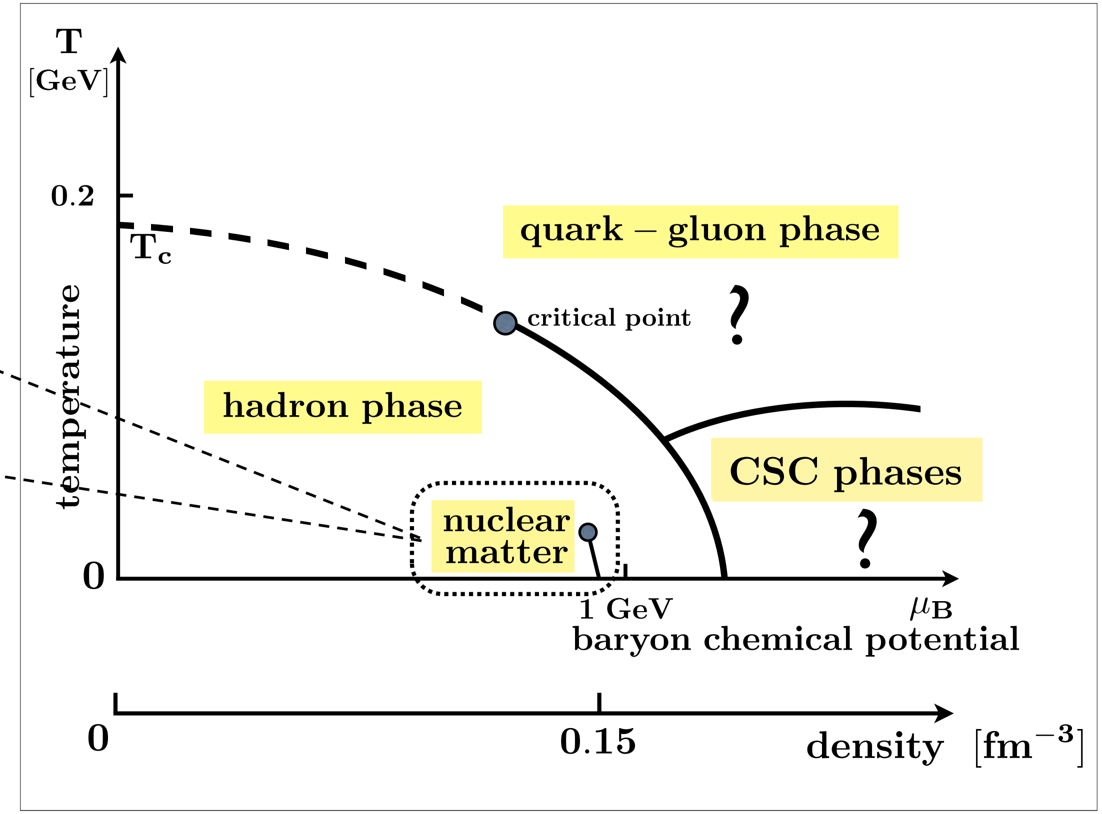
$$V_C(\mathbf{r}) = \mathbf{E} + \frac{\nabla^2\phi(\mathbf{r})}{2\mu\ \phi(\mathbf{r})}$$

- **Repulsive core** from Lattice QCD

4 NUCLEAR MATTER and QCD PHASES

nuclei





Scales in **nuclear matter**:

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

CHIRAL DYNAMICS and the NUCLEAR MANY-BODY PROBLEM

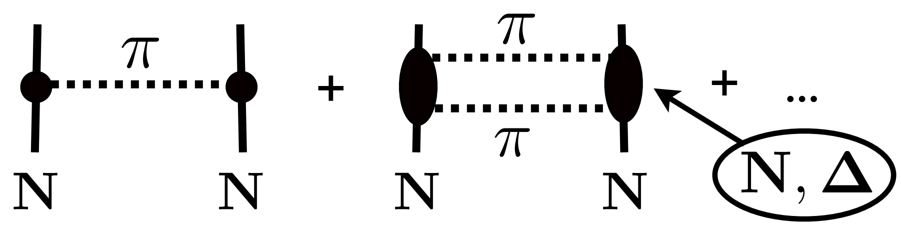
N. Kaiser, S. Fritsch, W.W. (2002 - 2005)

- **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

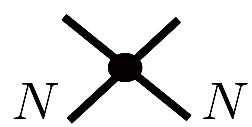
- **IN-MEDIUM CHIRAL PERTURBATION THEORY**

→ 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

IN-MEDIUM CHIRAL PERTURBATION THEORY

- In-medium **nucleon propagator**:

$$\frac{\mathbf{i}}{\gamma \cdot \mathbf{p} - \mathbf{M_N} + \mathbf{i}\epsilon} - \mathbf{2}\pi(\gamma \cdot \mathbf{p} + \mathbf{M_N})\delta(\mathbf{p^2} - \mathbf{M_N^2})\theta(\mathbf{p_0})\theta(\mathbf{k_F} - |\vec{\mathbf{p}}\,|)$$

- **Loop expansion** in ChPT $\longleftrightarrow$

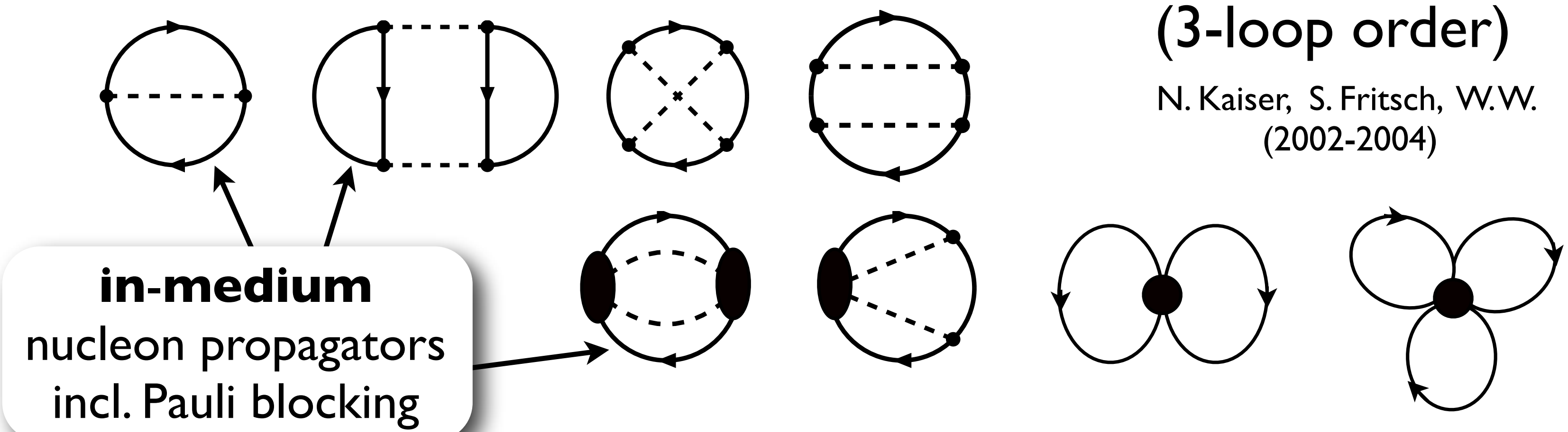
  Systematic expansion of **ENERGY DENSITY** $\mathcal{E}(\mathbf{k_F})$ in **powers** of **Fermi momentum** [modulo functions $\mathbf{f_n}(\mathbf{k_F}/\mathbf{m_\pi})$]

- **Finite nuclei** $\longleftrightarrow$ energy **density functional**

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

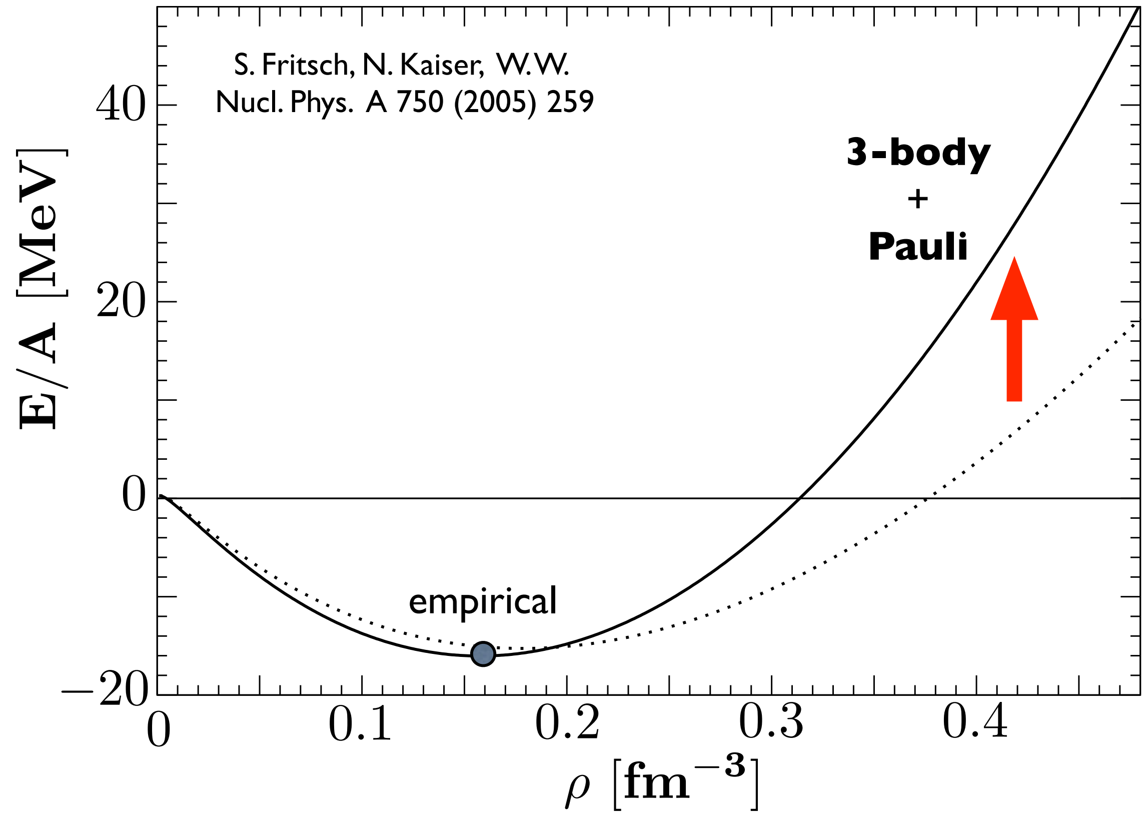
(3-loop order)

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



NUCLEAR MATTER

- **In-medium ChPT**
  3-loop (π, N, Δ)
- **Input** parameter:
  single contact term
- basically:
  analytic calculation



- **Output**:
  - Binding & saturation

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

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

NUCLEAR THERMODYNAMICS

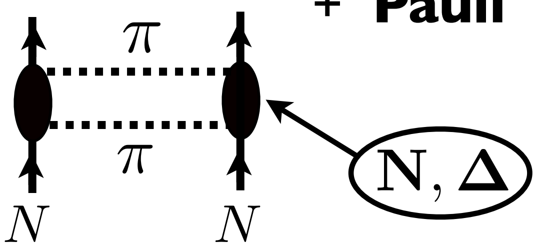
NUCLEAR CHIRAL (PION) DYNAMICS

BINDING & SATURATION:

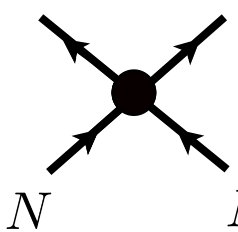
Yukawa

+ Van der Waals

+ Pauli



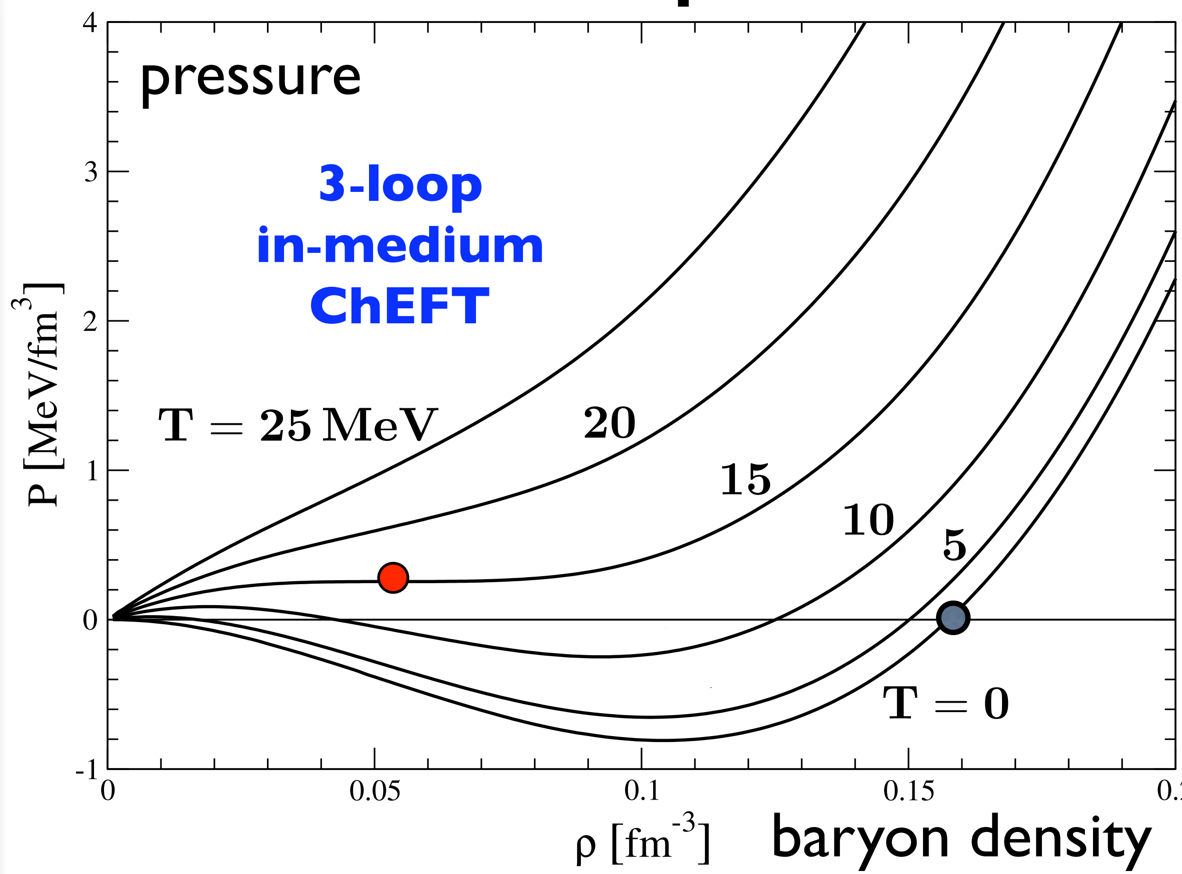
$$\mathbf{V(r)} \sim -\frac{\mathbf{e^{-2m_\pi r}}}{\mathbf{r^6}}\mathbf{P(m_\pi r)}$$

+ 

+ 3-body forces

contact terms

nuclear matter: equation of state



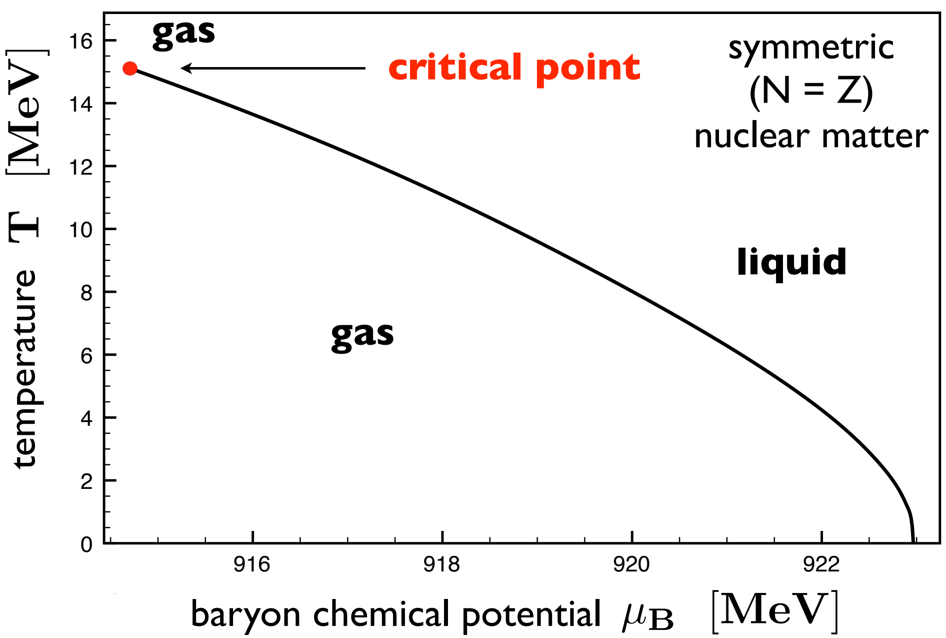
Liquid - Gas Transition at

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

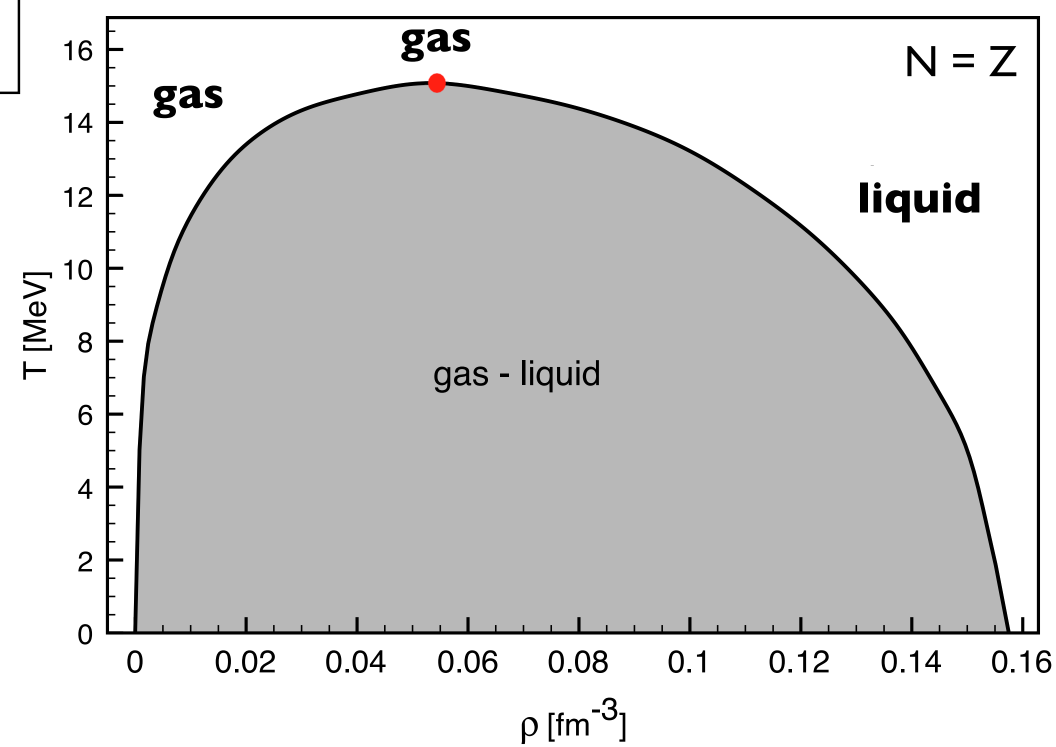


- In-medium
  chiral effective field theory
  (3-loop in the free energy density)

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

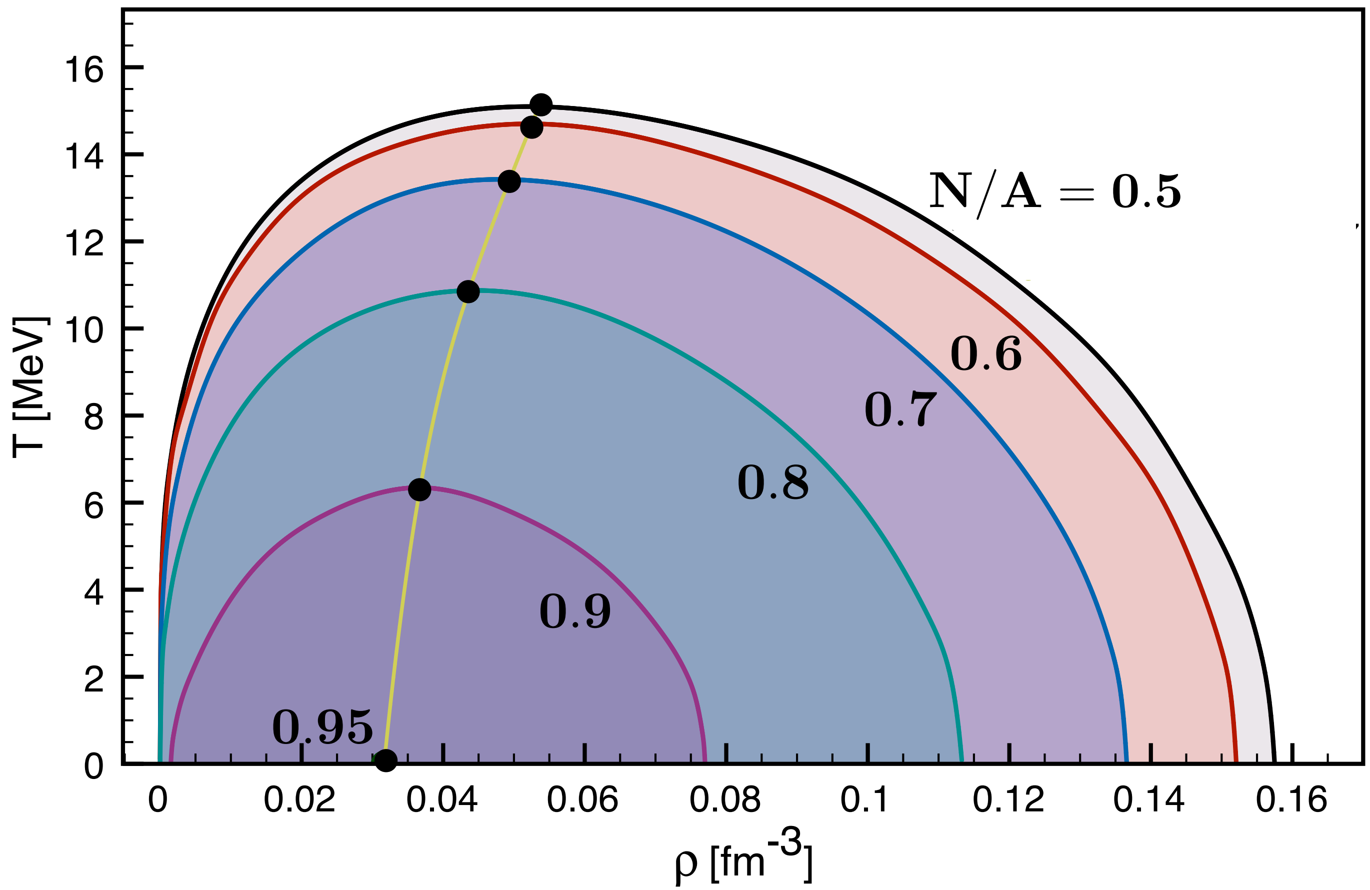
S. Fiorilla, N. Kaiser, W.W. (2010)

- 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**



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

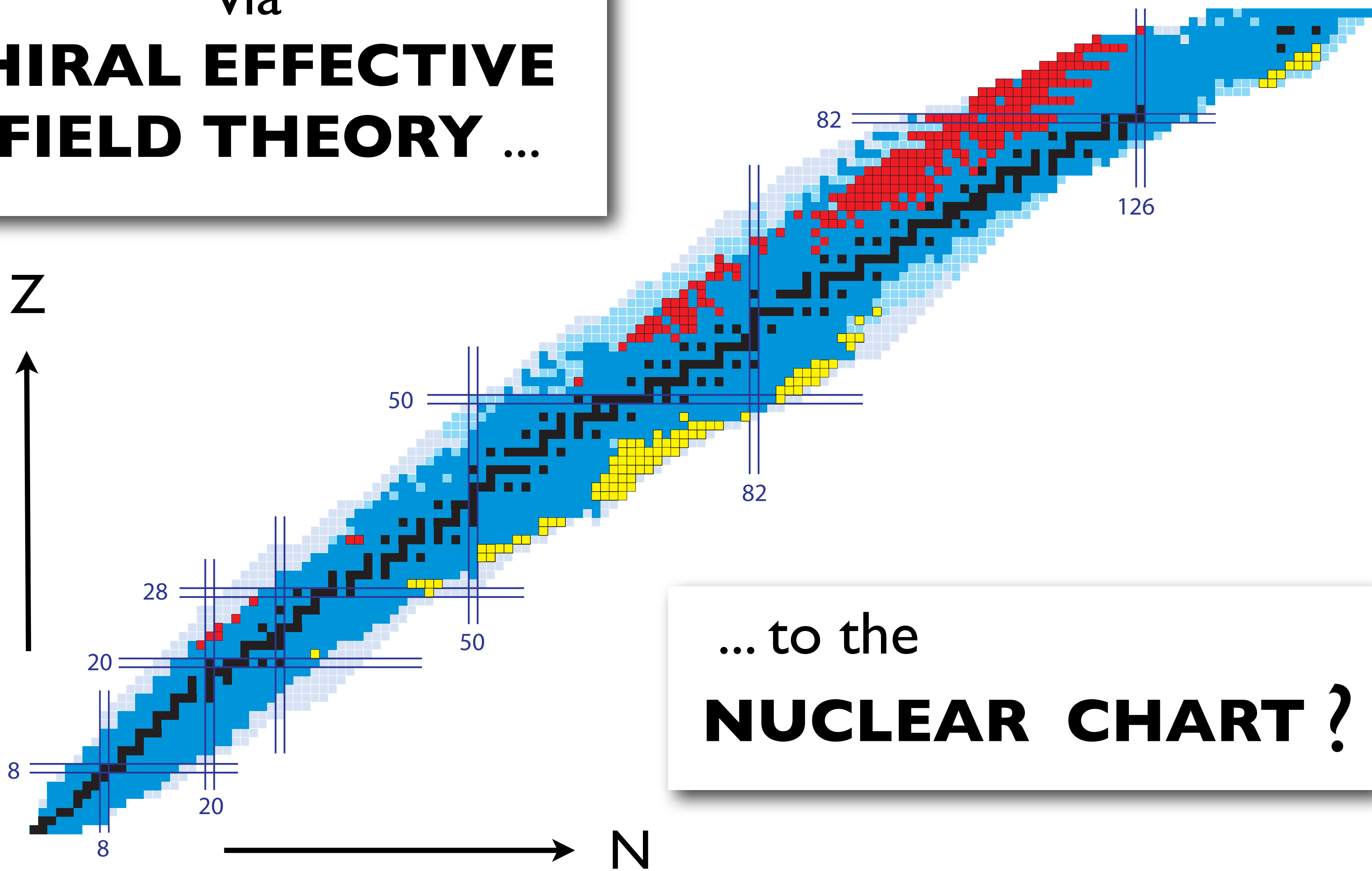
...determined almost entirely by **isospin** dependent **pion** exchange dynamics

5

... from **QCD**

via

CHIRAL EFFECTIVE FIELD THEORY ...

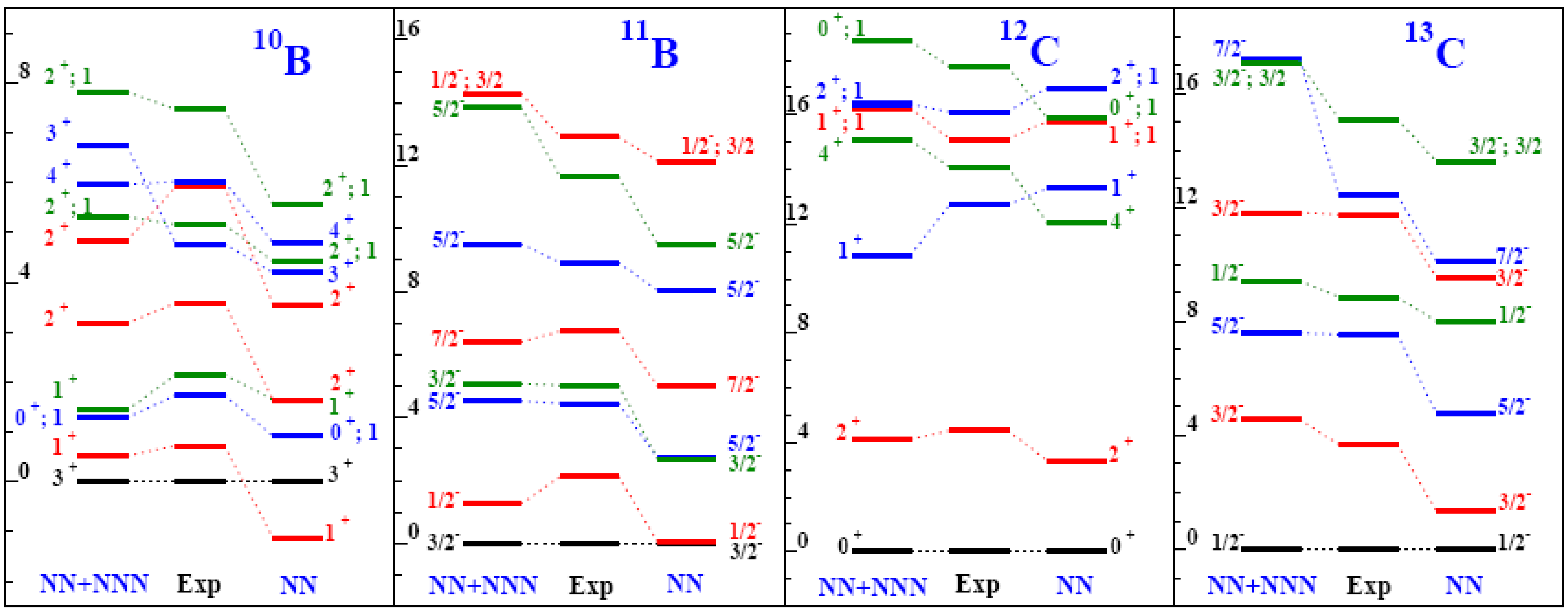


... to the **NUCLEAR CHART ?**

NUCLEAR MANY-BODY CALCULATIONS

- ... using NN and NNN interactions from Chiral Effective Field Theory

No-Core-Shell-Model results for ^{10}B, ^{11}B, ^{12}C and ^{13}C @ N^{2}LO



Navratil et al., PRL 99 (2007) 042501

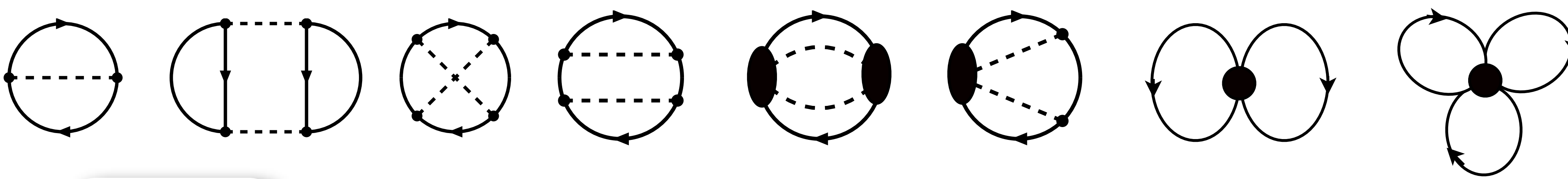
- systematic improvements with inclusion of 3-body interactions

DENSITY FUNCTIONAL STRATEGIES

... constrained by (chiral) **symmetry breaking pattern** of **Low-Energy QCD**

$$\mathbf{E}[\rho] = \mathbf{E_{kin}} + \int \mathbf{d^3x}\,[\mathcal{E}^{(\mathbf{0})}(\rho) + \mathcal{E}_{\mathbf{exc}}(\rho)] + \mathbf{E_{coul}}$$

$\rho \rightarrow \rho(\mathbf{x})$ ↳ Kohn - Sham equations



- $\mathcal{E}_{\mathbf{exc}}(\rho):$ from in-medium **C**hiral **P**erturbation **T**heory ("**Pionic fluctuations**")
- $\mathcal{E}^{(\mathbf{0})}(\rho):$ Hartree mean field(s) from **contact terms**

(equiv. to) ⟷ strong **SCALAR** and **VECTOR** mean fields

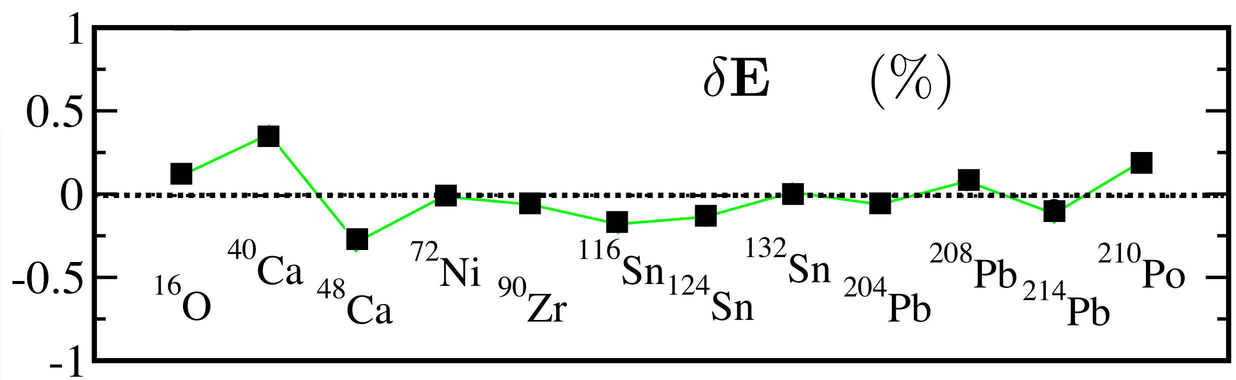
⟷ leading order IN-MEDIUM changes of **QCD CONDENSATES**

Examples (part I)

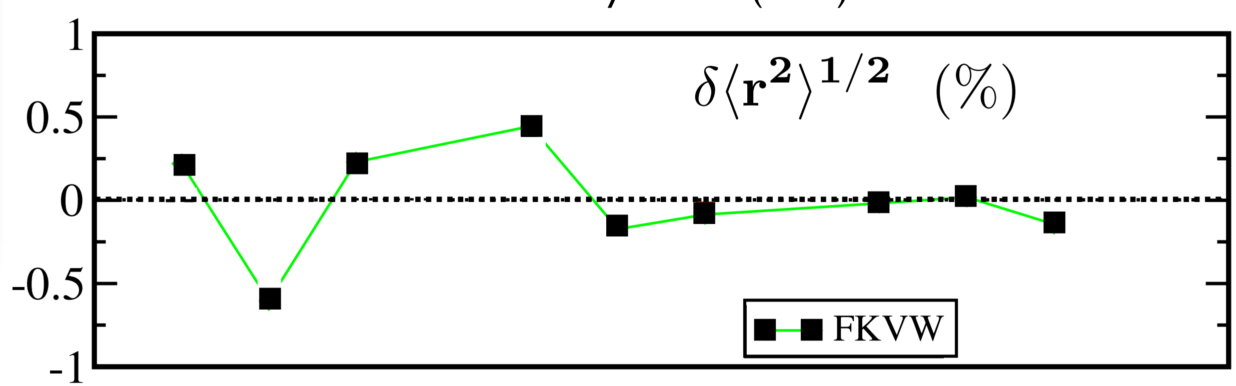
- Strategy :
  - Calculate physics at **long** and **intermediate** distances using nuclear **chiral effective field theory**
  - Fix **short** distance constants (contact interactions) e.g. in Pb region
  - Predict **systematics** for all other nuclei

deviations (in %) between calculated and measured **binding energies** per nucleon ...

... and **charge radii**

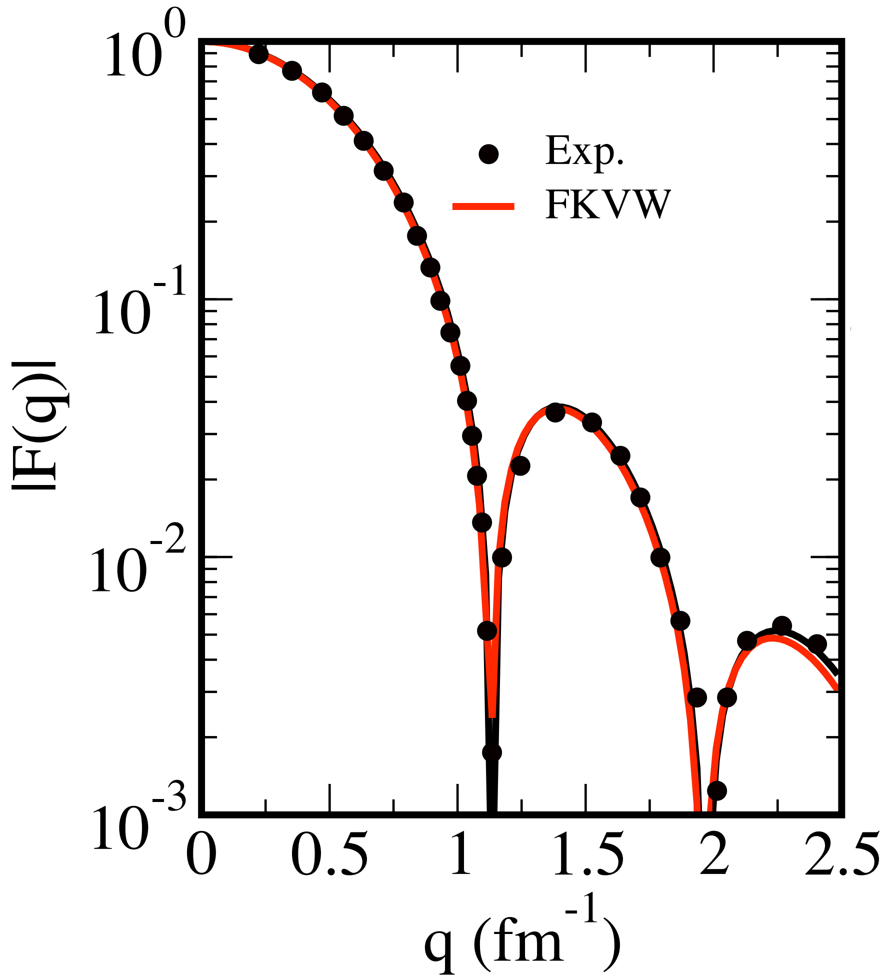


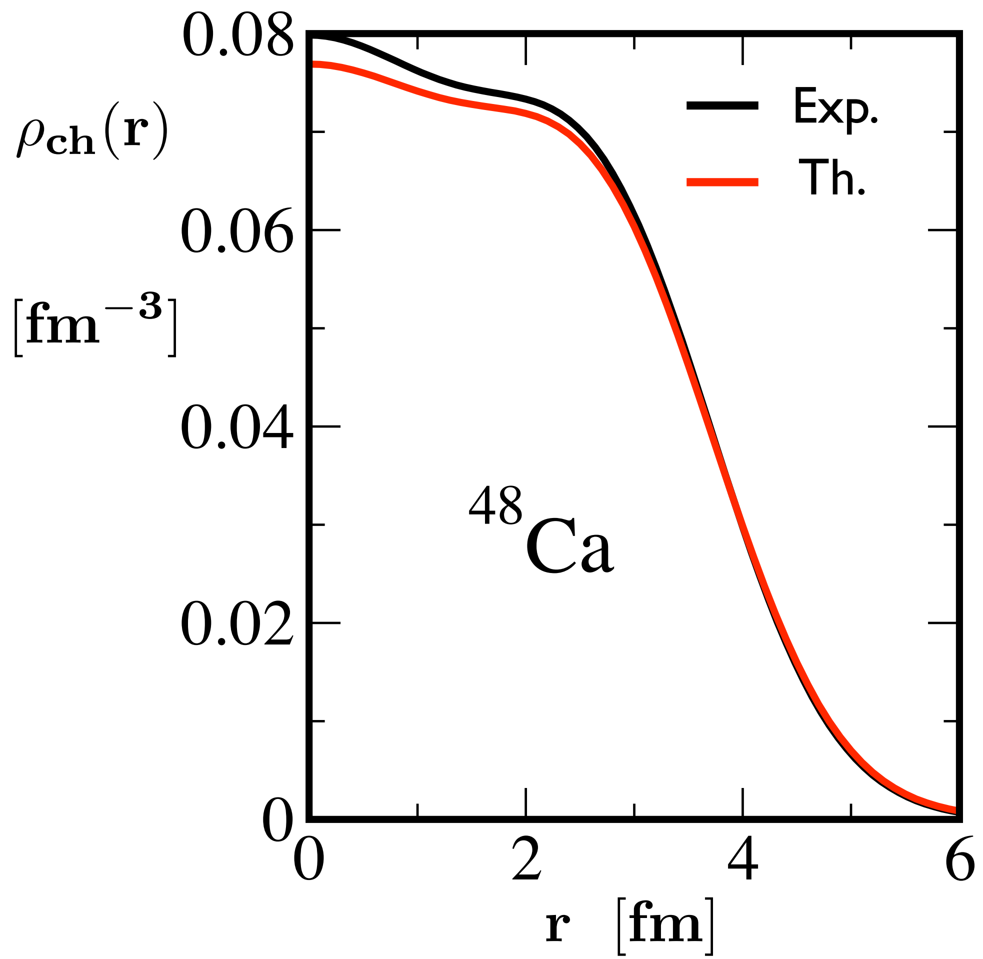
P. Finelli, N. Kaiser, D.Vretenar, W.W. :
Nucl. Phys. A770 (2006) 1



Examples (part II)

charge density of ^{48}Ca



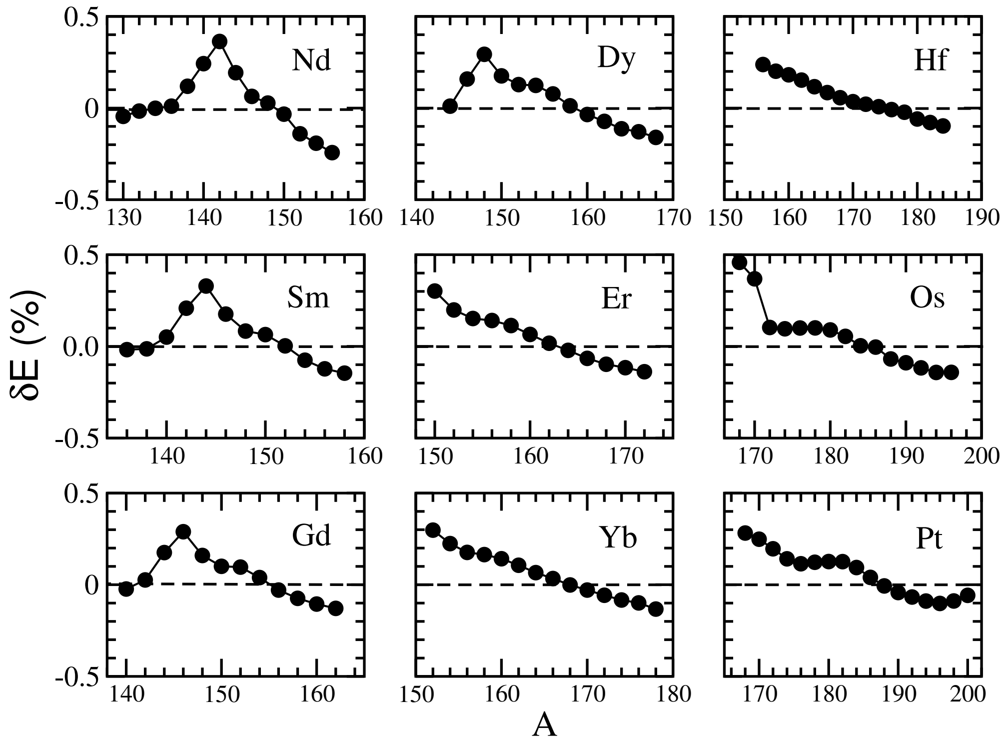


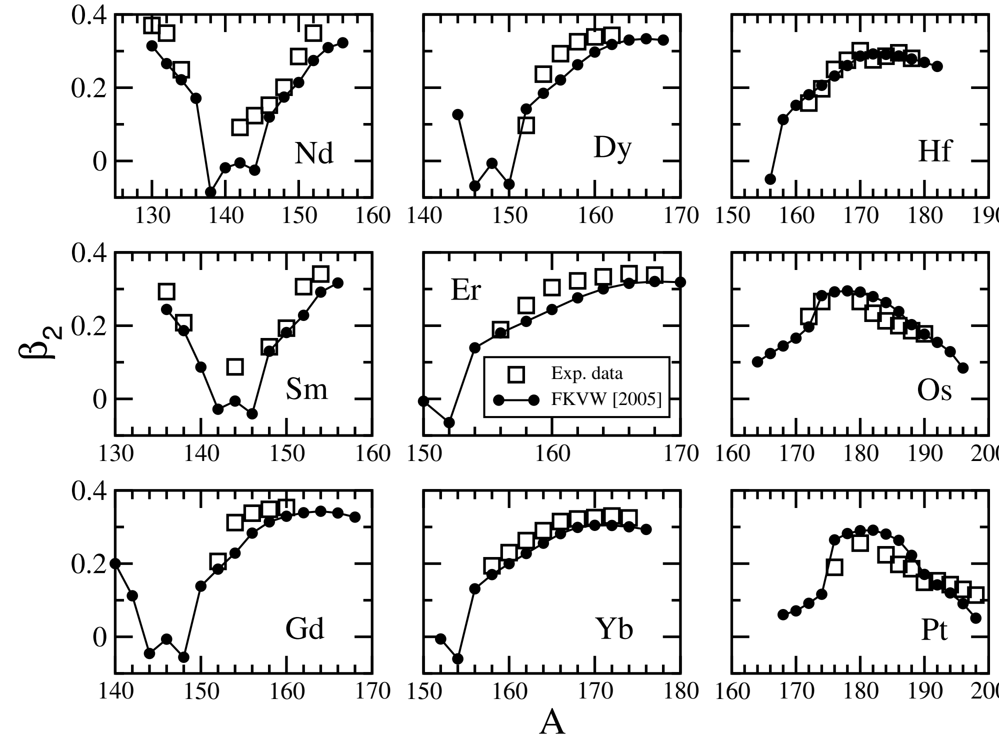
P. Finelli, N. Kaiser, D. Vretenar, W.W.: Nucl. Phys. A735 (2004) 449, A770 (2006) 1

Examples (part III): **DEFORMED NUCLEI**

deviations (in %) between
calculated and measured binding energies

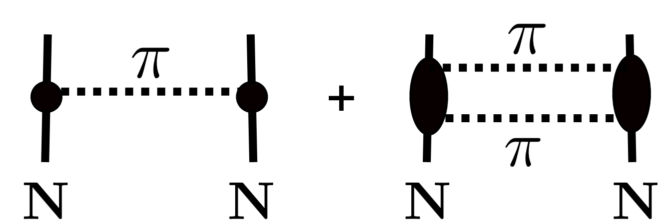
Ground state deformations





P. Finelli et al., Nucl. Phys. A770 (2006) 1

Systematics through **isotopic chains**
governed by
isospin dependent forces
from **chiral pion dynamics**

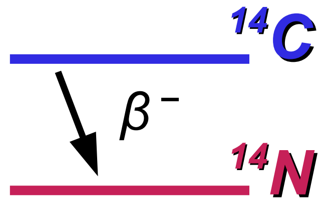


TENSOR force

… more applications

- **Gamow-Teller beta decays**

interesting case:



anomalously long lifetime (5739 y) enables radiocarbon dating

Theoretically **not** understood on the basis of **two-nucleon** interactions only

▶ Solution: **chiral effective interaction** including **three-body force**

J.W. Holt, N. Kaiser, W.W.: Phys. Rev. C79 (2009) 054331, Phys. Rev. C81 (2010) 024002

- **Spin-orbit interactions**

▶ Role of **2nd order tensor force** from **pion exchange** and **three-body interactions**

N. Kaiser: Phys. Rev. C68 (2003) 054001; N. Kaiser and W.W.: Nucl. Phys. A804 (2008) 60

- **In-medium Chiral SU**(3) **dynamics** and **hypernuclei**

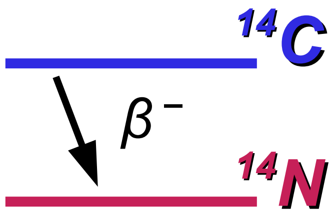
▶ **Weak Λ-nuclear spin-orbit coupling**

N. Kaiser, W.W.: Phys. Rev. C71 (2005) 015203

P. Finelli, N. Kaiser, D.Vretenar, W.W.: Phys. Lett. B658 (2007) 90; Nucl. Phys. A831 (2009) 163

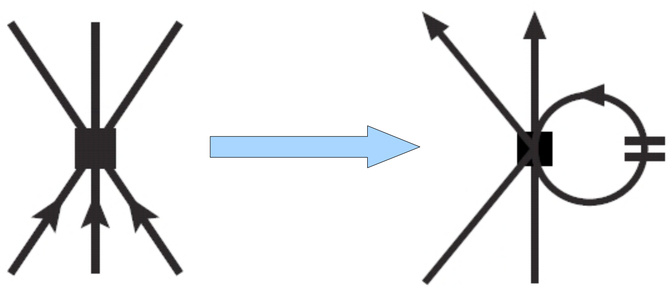
Anomalously long beta decay lifetime of $^{14}\mathrm{C}$

- Early history: B. Janovici, I. Talmi : Phys. Rev. 95 (1954) 289 (Role of **tensor force**)



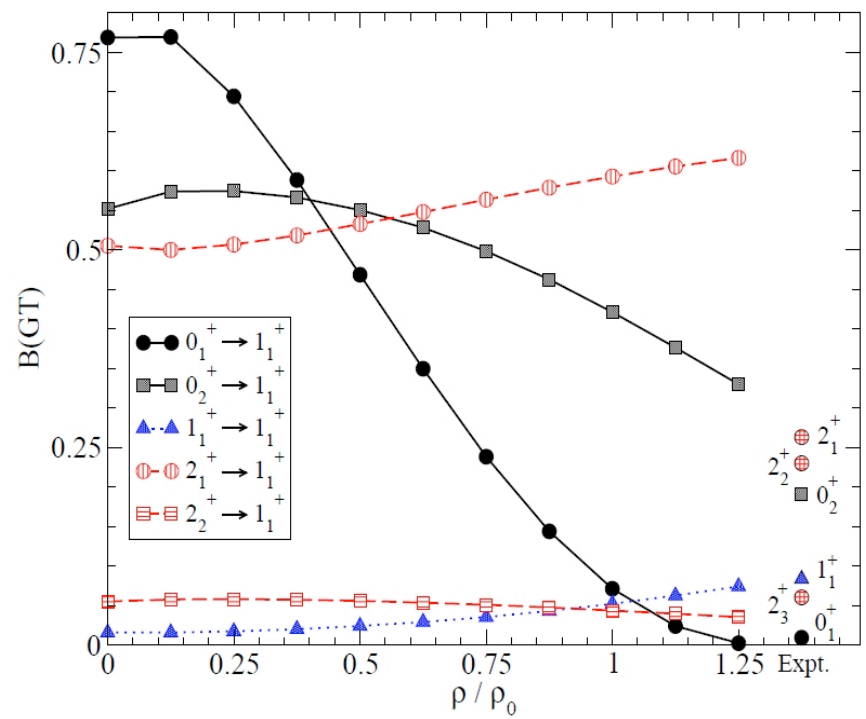
- *Known lifetime of 5730 years enables radiocarbon dating*
- *But theoretical description using realistic nucleon-nucleon interactions overestimates the GT strength*

Idea: Derive a density-dependent two-nucleon force from the leading-order chiral three-nucleon force



$$T_{1/2} = \frac{1}{f(Z,E_0)} \frac{2\pi^3\hbar^7 \ln 2}{m_e^5 c^4 G_V^2} \frac{1}{g_A^{*\,2} |M_{GT}|^2}$$

$$\mathrm{Expt:} \quad B(GT) \simeq |M_{GT}|^2 \simeq 10^{-6}$$



- *Large suppression of GT strength at ρ_0 due to chiral 3NF!*

J.W. Holt, N. Kaiser, W.W. : Phys. Rev. C79 (2009) 054331, Phys. Rev. C81 (2010) 024002

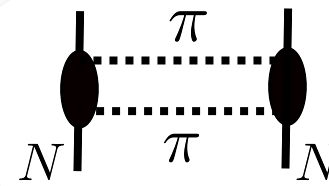
6 CHIRAL CONDENSATE at finite DENSITY

$$(\mathbf{T = 0})$$

- 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



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

(free) Fermi gas of nucleons

nuclear interactions (dependence on pion mass)

CHIRAL CONDENSATE: DENSITY DEPENDENCE

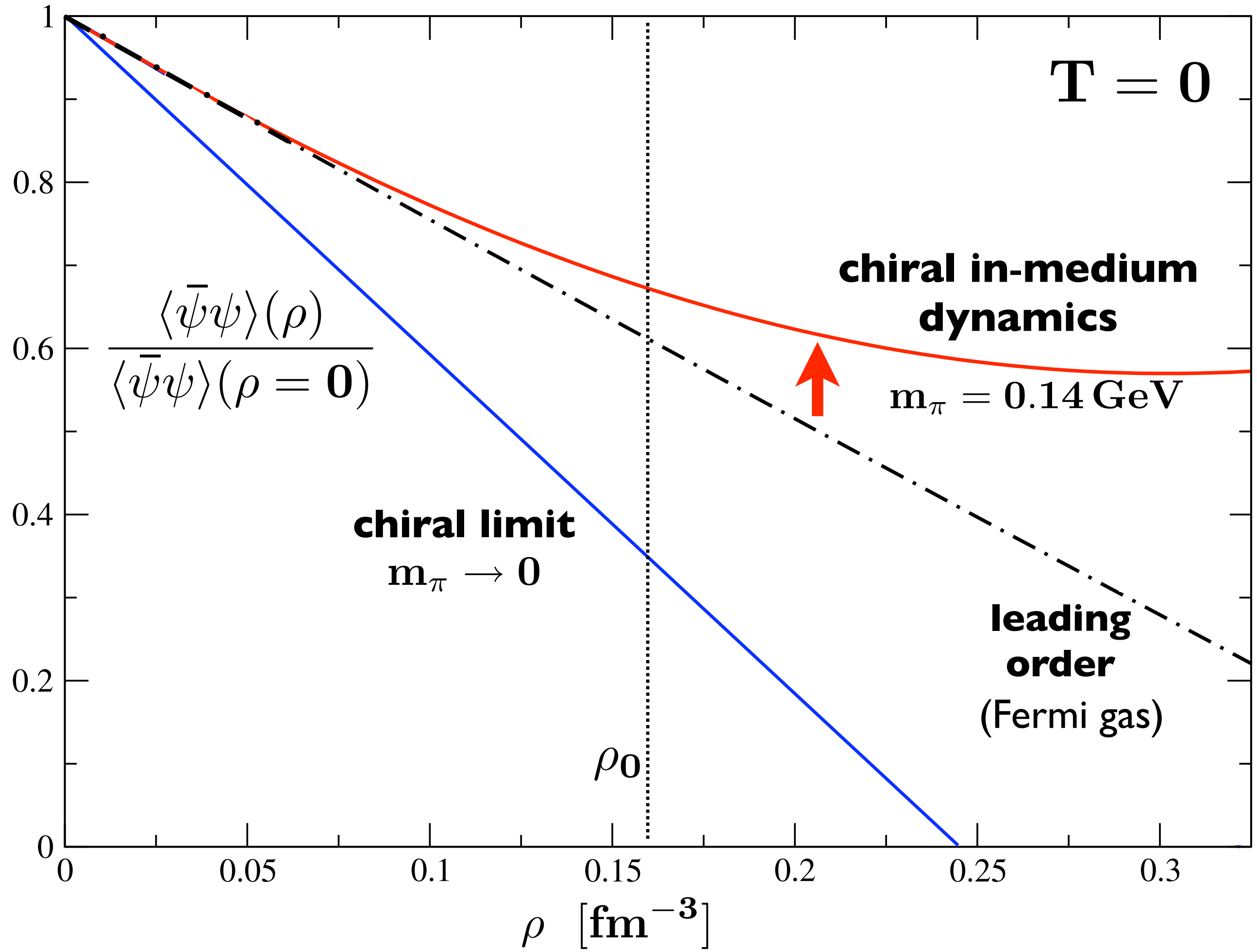
Symmetric Nuclear Matter

- **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 $m_q = 0$ and physical quark mass $m_q \sim 5\,\mathrm{MeV}$
- **Nuclear Physics** would be **very different** in the **chiral limit** !

CHIRAL CONDENSATE:
DENSITY and TEMPERATURE DEPENDENCE

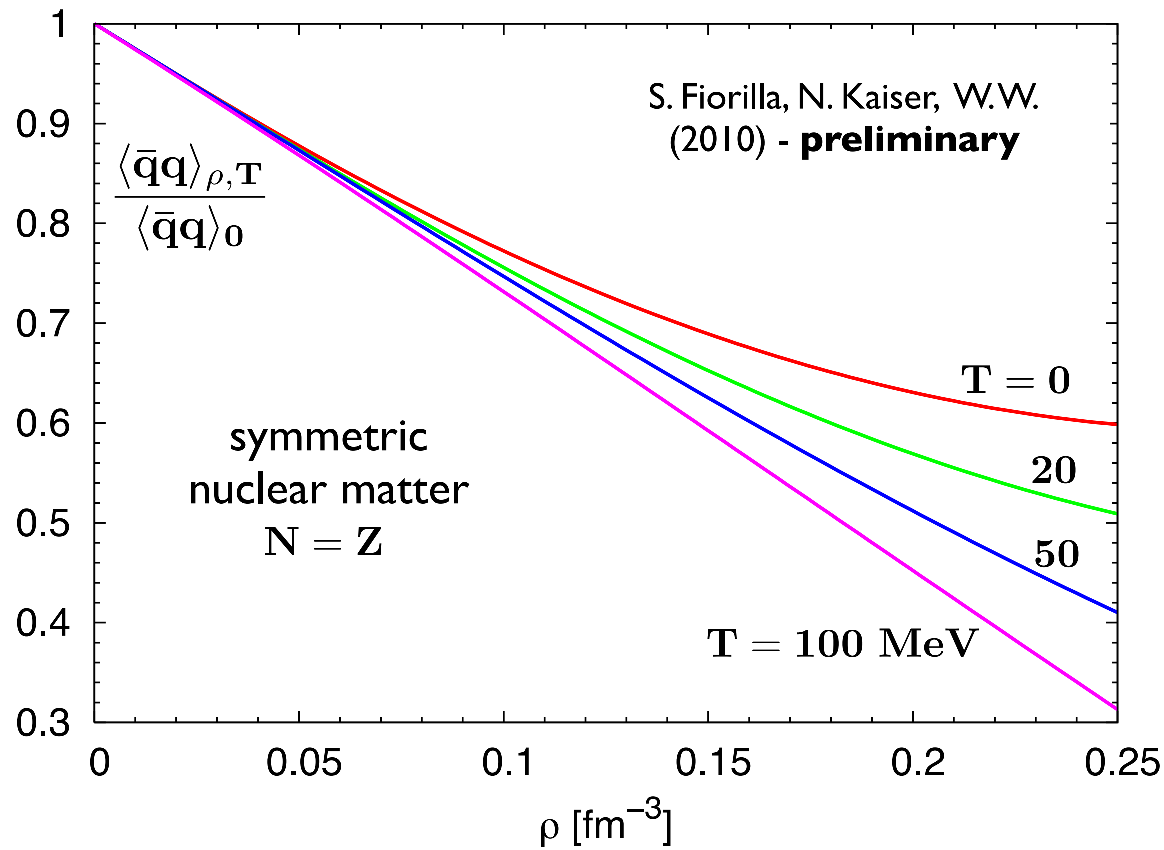
- Free energy density $\mathcal{F}(\mathbf{m_q}; \rho, \mathbf{T})$

$$\langle \boldsymbol{\Psi} | \bar{\mathbf{q}}\mathbf{q} | \boldsymbol{\Psi} \rangle_{\rho,\mathbf{T}} = \frac{\partial \mathcal{F}(\mathbf{m_q}; \rho, \mathbf{T})}{\partial \mathbf{m_q}}$$

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

(NLO 3-loop)

constrained by **realistic nuclear equation of state**

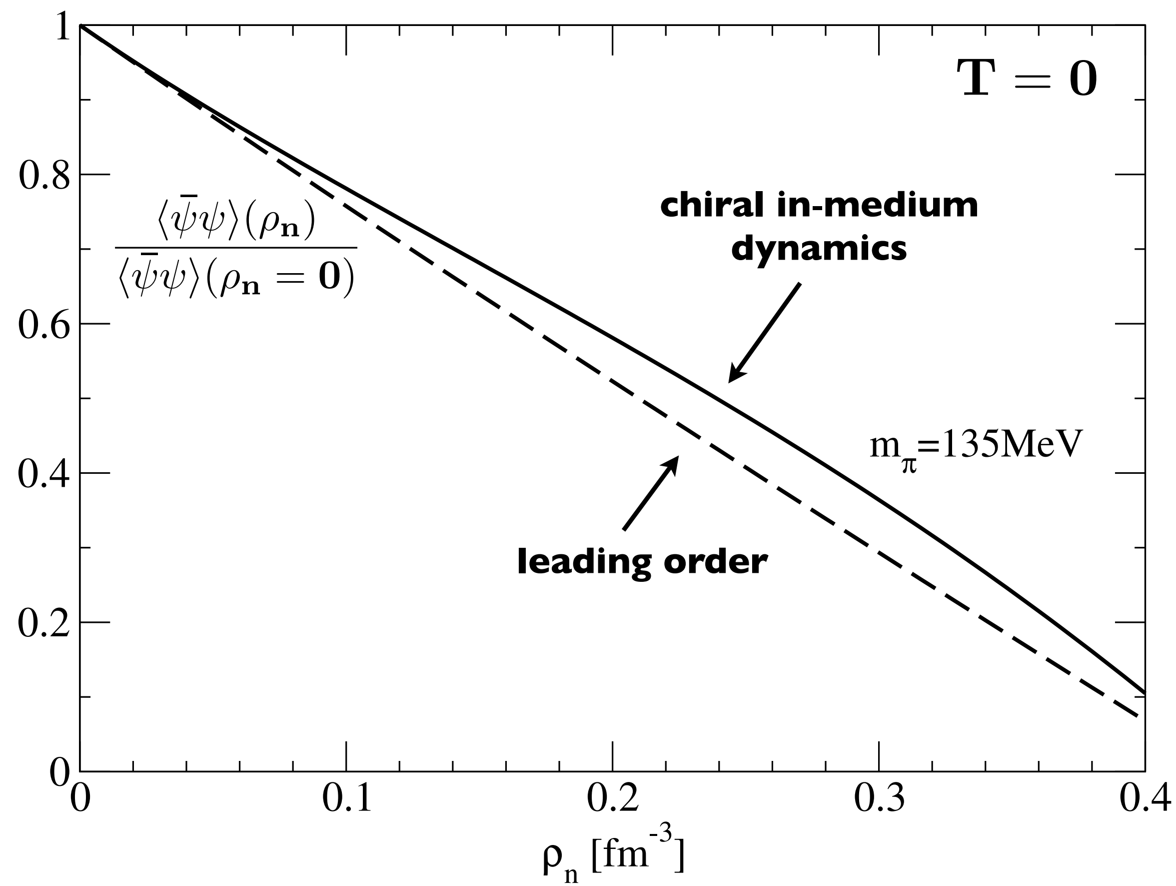


- **No indication** of first order **chiral phase transition** in the range

$$\rho \leq \mathbf{2}\rho_{\mathbf{0}}, \quad \mathbf{T} \leq \mathbf{100\ MeV}$$

CHIRAL CONDENSATE: DENSITY DEPENDENCE

Neutron Matter



N. Kaiser, W.W.
Phys. Lett. B671 (2009) 25

neutron star territory

- Qualitative difference between **nuclear** and **neutron** matter
- Chiral limit: logarithmic singularity as $m_\pi \to 0$
- Important: realistic treatment of **two-body** and **three-body correlations** in extrapolations to high-density matter

Modelling the **QCD PHASE DIAGRAM**

POLYAKOV LOOP dynamics ⟷ **Confinement**

Synthesis

Fukushima (2004)
Ratti, Thaler, Weise (2005)

PNJL MODEL

NAMBU & JONA-LASINIO model ⟷ Spontaneous **Chiral Symmetry** Breaking

Nambu, Jona-Lasinio (1961)

- **Action :**

Fermion (quark) effective **Hamiltonian**

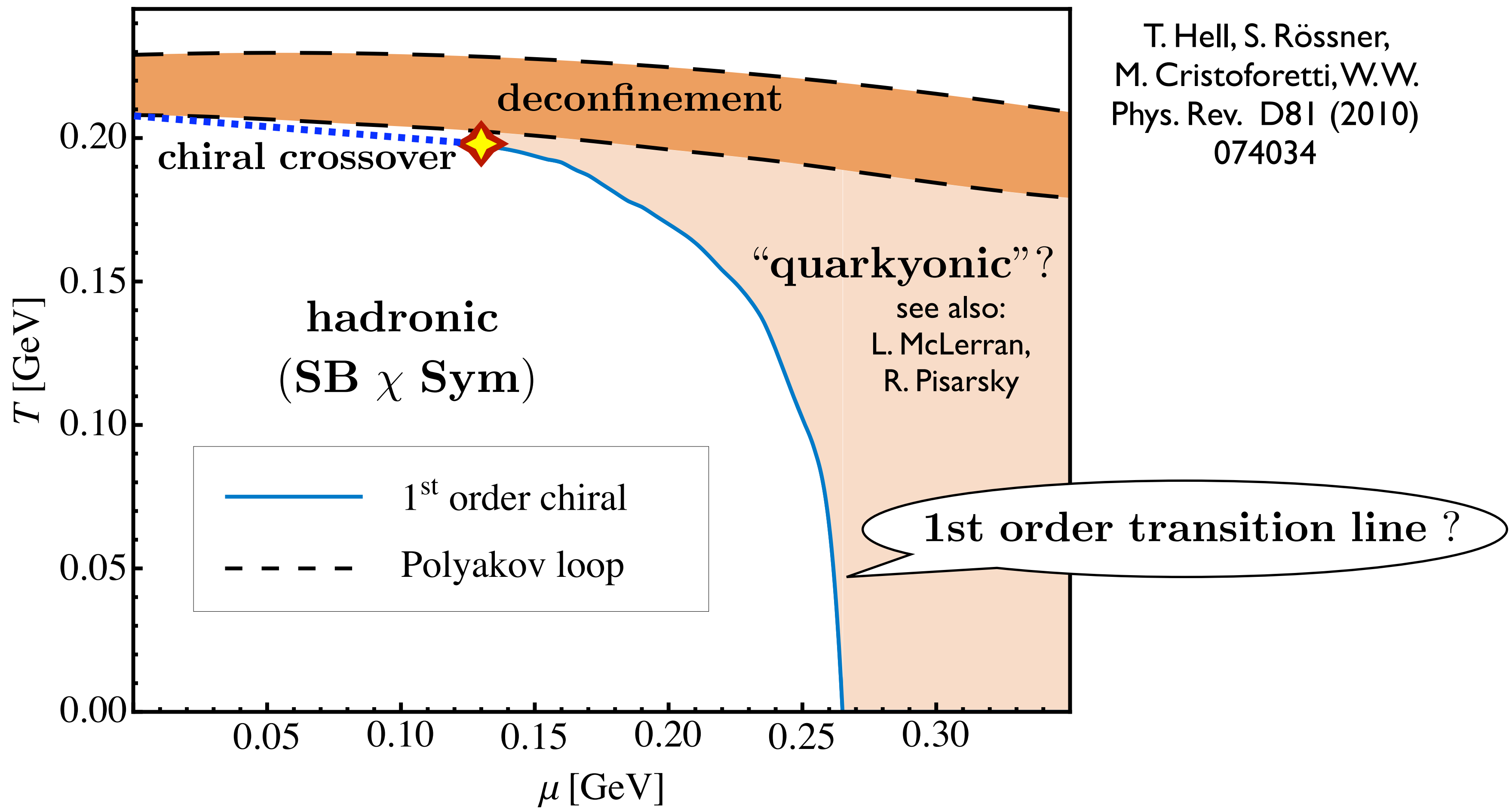
Polyakov loop effective **potential**

$$\mathcal{S}(\psi,\psi^\dagger,\phi) = \int_0^{\beta=1/T} d\tau \int_V d^3x \left[\psi^\dagger\partial_\tau\psi + \mathcal{H}(\psi,\psi^\dagger,\phi)\right] - \frac{V}{T}\,\mathcal{U}(\phi,T)$$

- identify leading **collective degrees of freedom** ($\rightarrow$ **order parameters**)
- **quarks** as **quasiparticles** with dynamically generated masses

PHASE DIAGRAM (contd.)

Non-local **3-flavour PNJL** model calculation

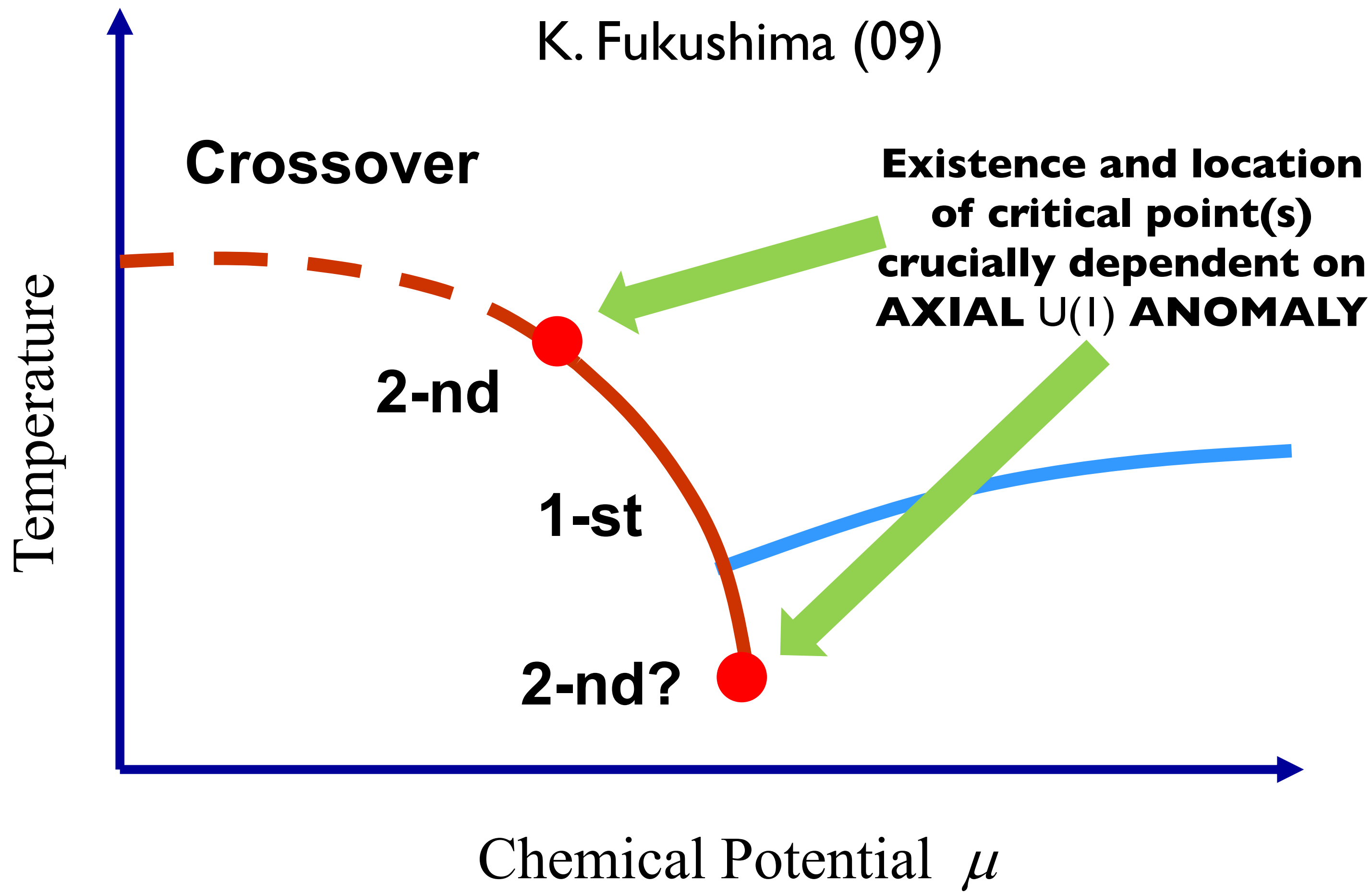


T. Hell, S. Rössner,
M. Cristoforetti, W. W.
Phys. Rev. D81 (2010)
074034

- "**wrong**" degrees of freedom
  at low temperature, non-zero **baryon** density **?**

PHASE DIAGRAM (contd.)

- Issues: ⇨ **Critical Point**(s)
  ⇨ Diquarks and **C**olor **S**uper **C**onducting **Phases**

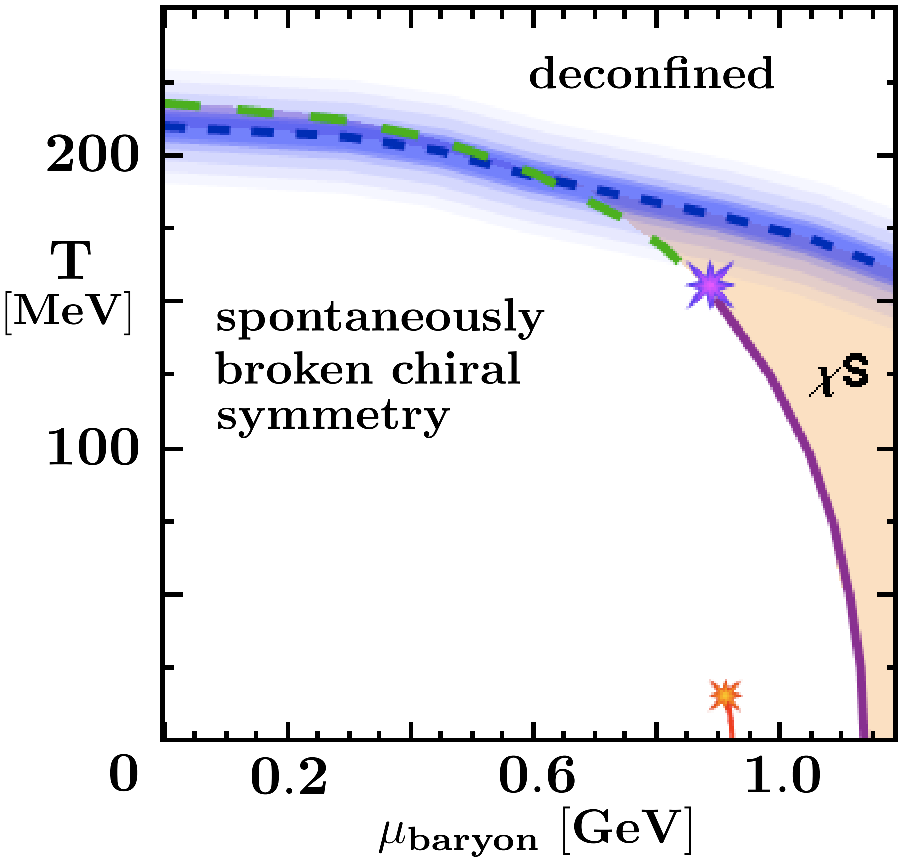


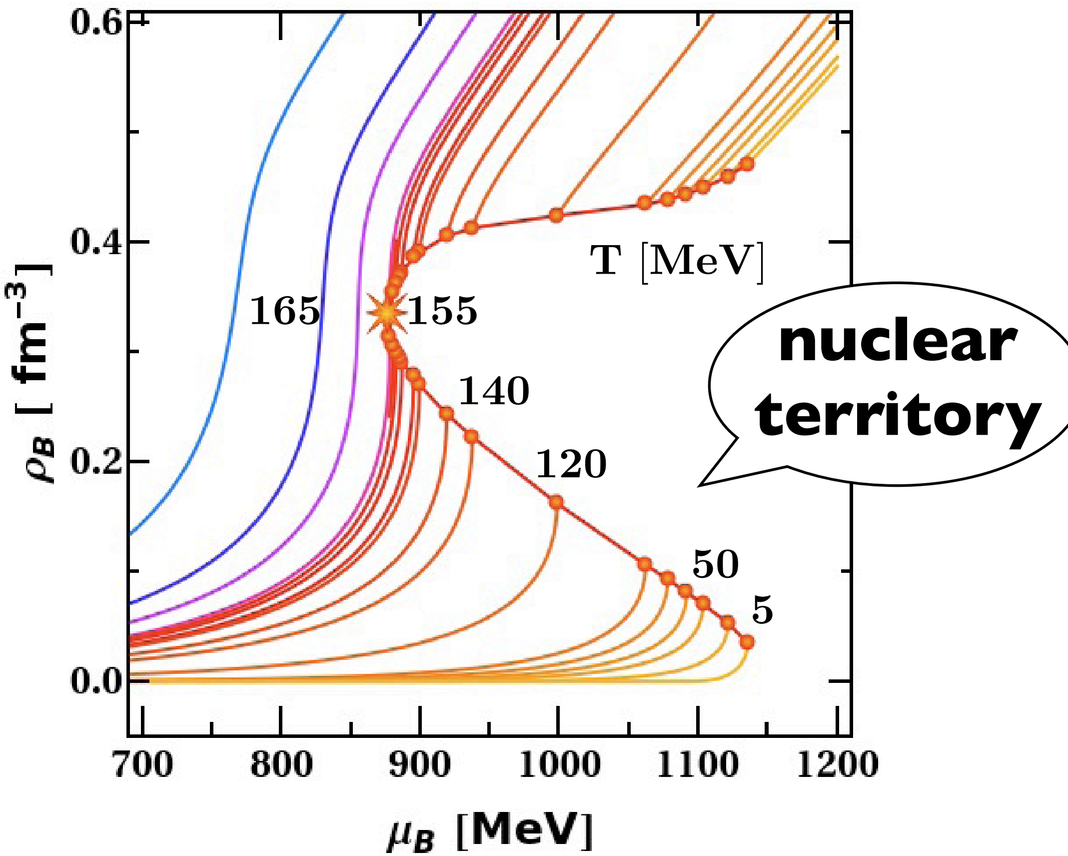
M. Tachibana, N. Yamamoto, T. Hatsuda, G. Baym (2006-09)

PHASE DIAGRAM (contd.)

PNJL model calculations

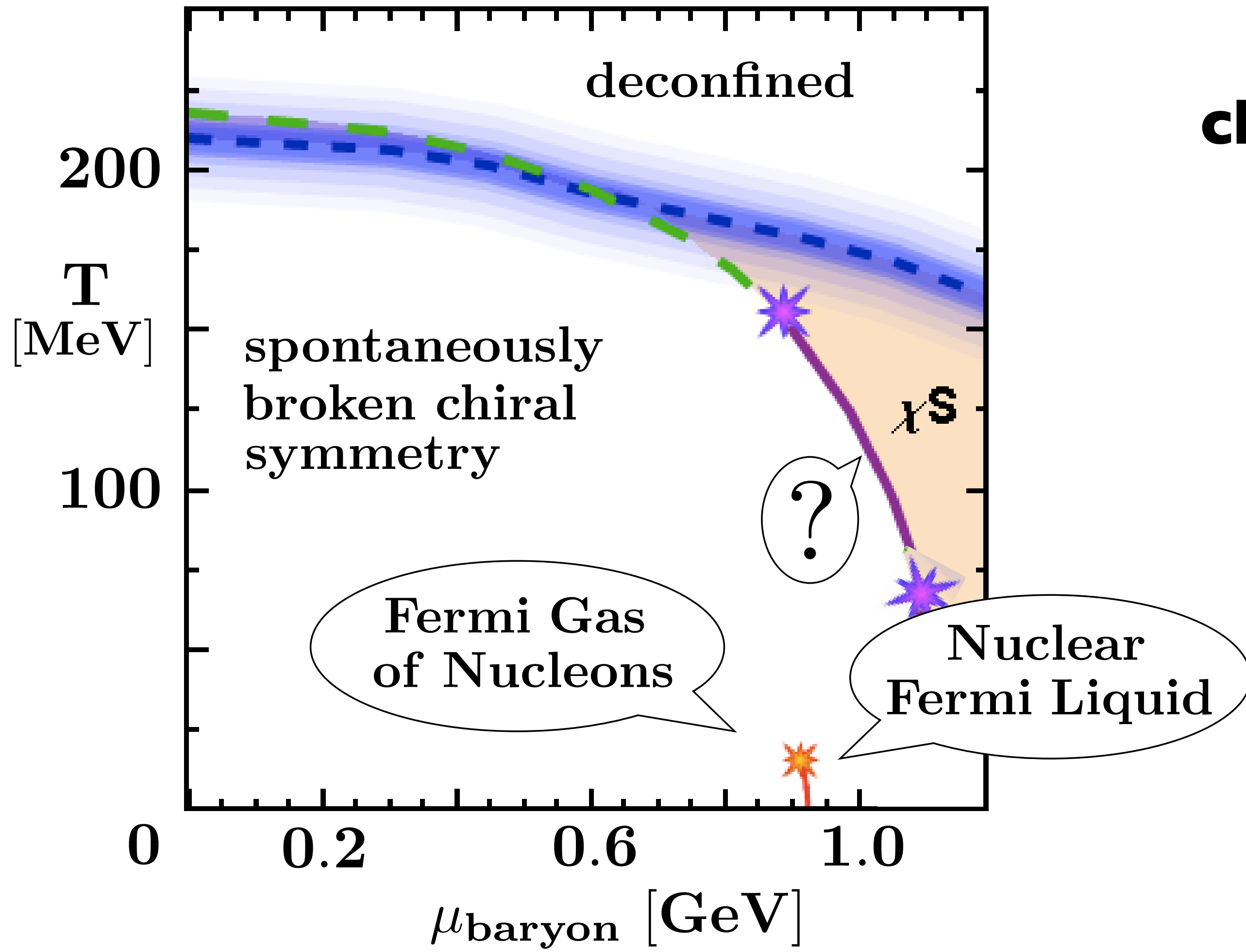
N. Bratovich, T. Hell, W.W. (2010)





- Quarks **cannot** be the relevant **active quasiparticles** at low temperatures and baryon chemical potentials $\mu_B \sim 1$ GeV

PHASE DIAGRAM (contd.)



- from **nuclear chiral thermodynamics**:

corridor of **spontaneously broken chiral symmetry** extends at least up to:

$$\rho \leq 2\rho_0$$

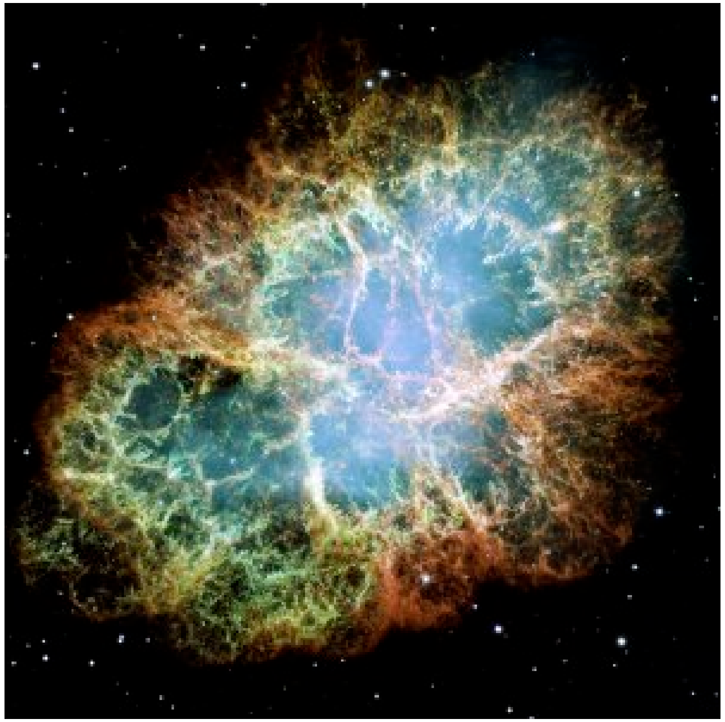
$$T \leq 100 \text{ MeV}$$

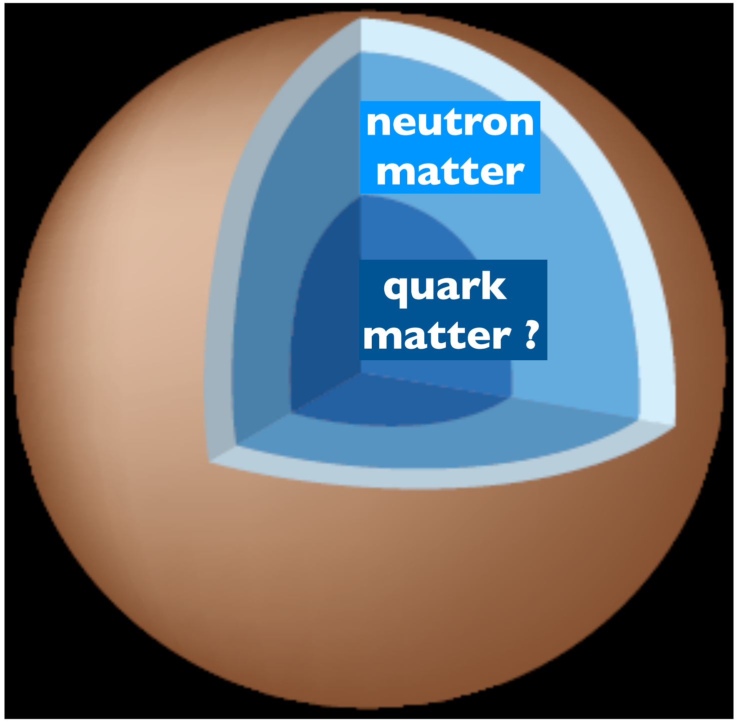
S. Fiorilla, N. Kaiser, W.W. (2010) - preliminary

- Major challenge: design **QCD phase diagram** in accordance with known realistic **constraints** from **hadronic** and **nuclear** physics

8 Constraints from Astrophysical Observations

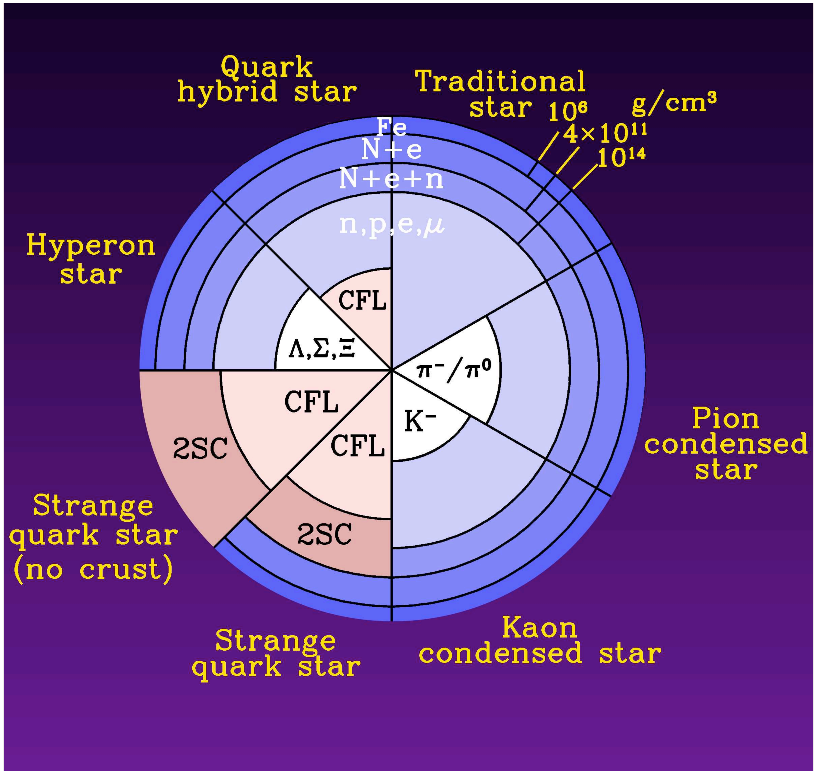
- Constraints on **Equation of State** at **HIGH DENSITY**
  (2 - 10 times the density of normal nuclear matter)





- from **Supernovae** to **Neutron Stars**

NEUTRON STARS and the EQUATION OF STATE of DENSE BARYONIC MATTER



- **Neutron Star Scenarios**

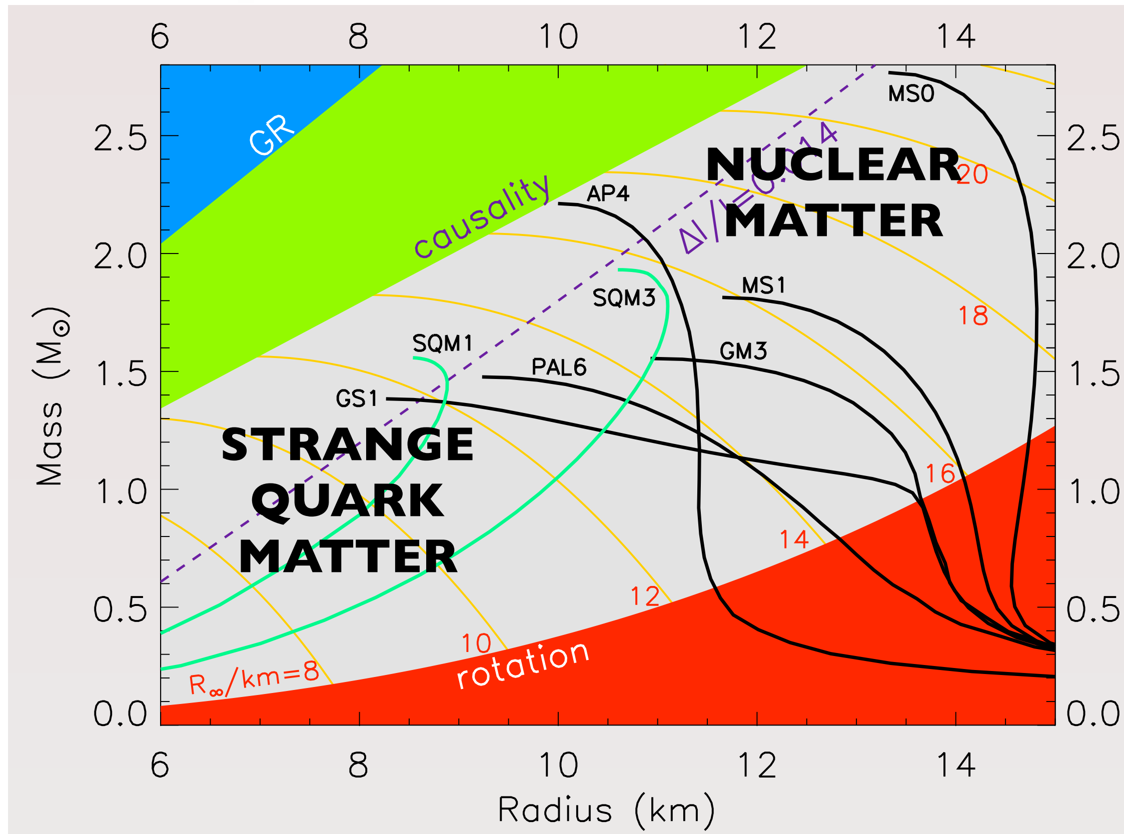
- **T**olman-**O**ppenheimer-**V**olkov equations

$$\frac{dp}{dr} = -\frac{G}{c^2}\frac{(m+4\pi p r^3)(\epsilon+p)}{r(r-2Gm/c^2)}$$

$$\frac{dm}{dr} = 4\pi\frac{\epsilon}{c^2}r^2$$

J. Lattimer, M. Prakash: Astrophys. J. 550 (2001) 426
Phys. Reports 442 (2007) 109

- **Mass-Radius Relation**



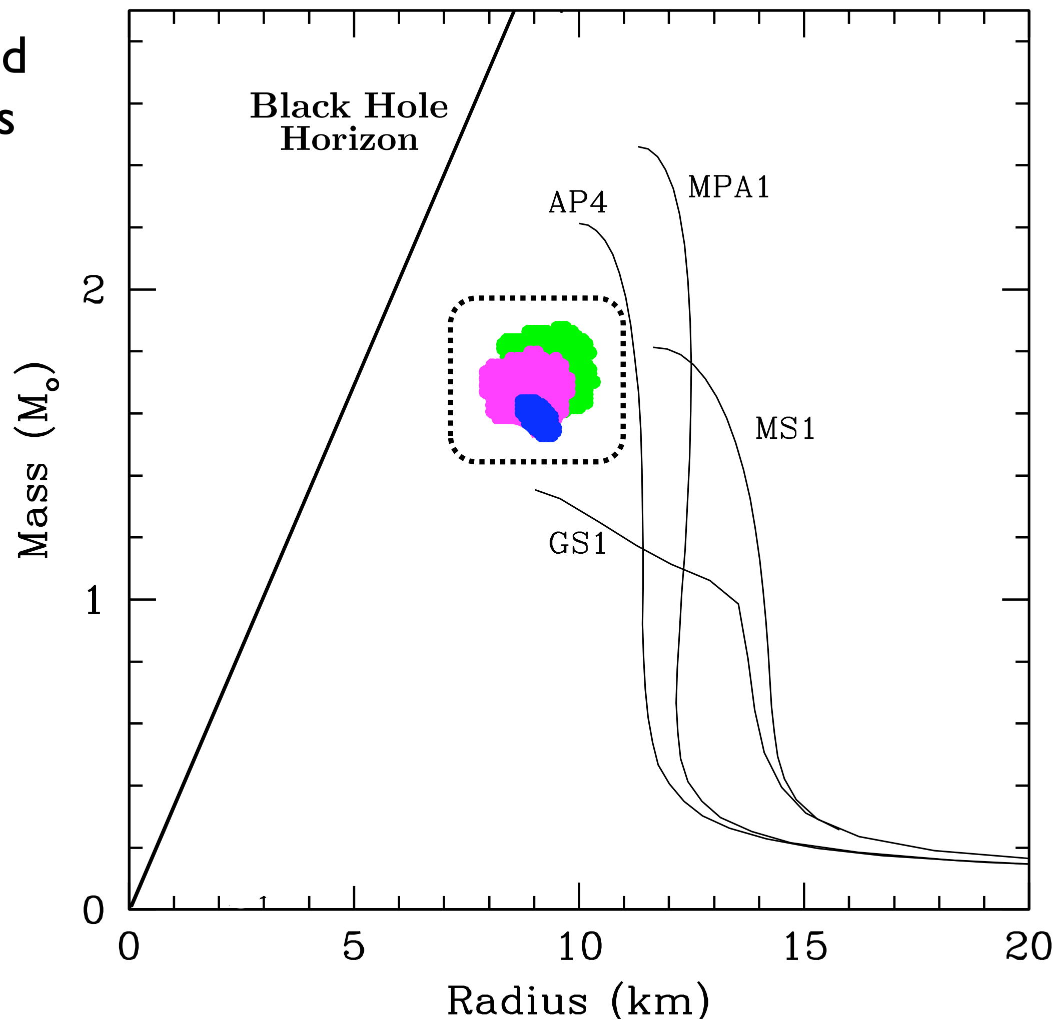
Technische Universität München

Oulook: New Constraints from NEUTRON STARS in BINARIES

. . . using additional information from observables such as apparent surface and flux during cooling phase of burst

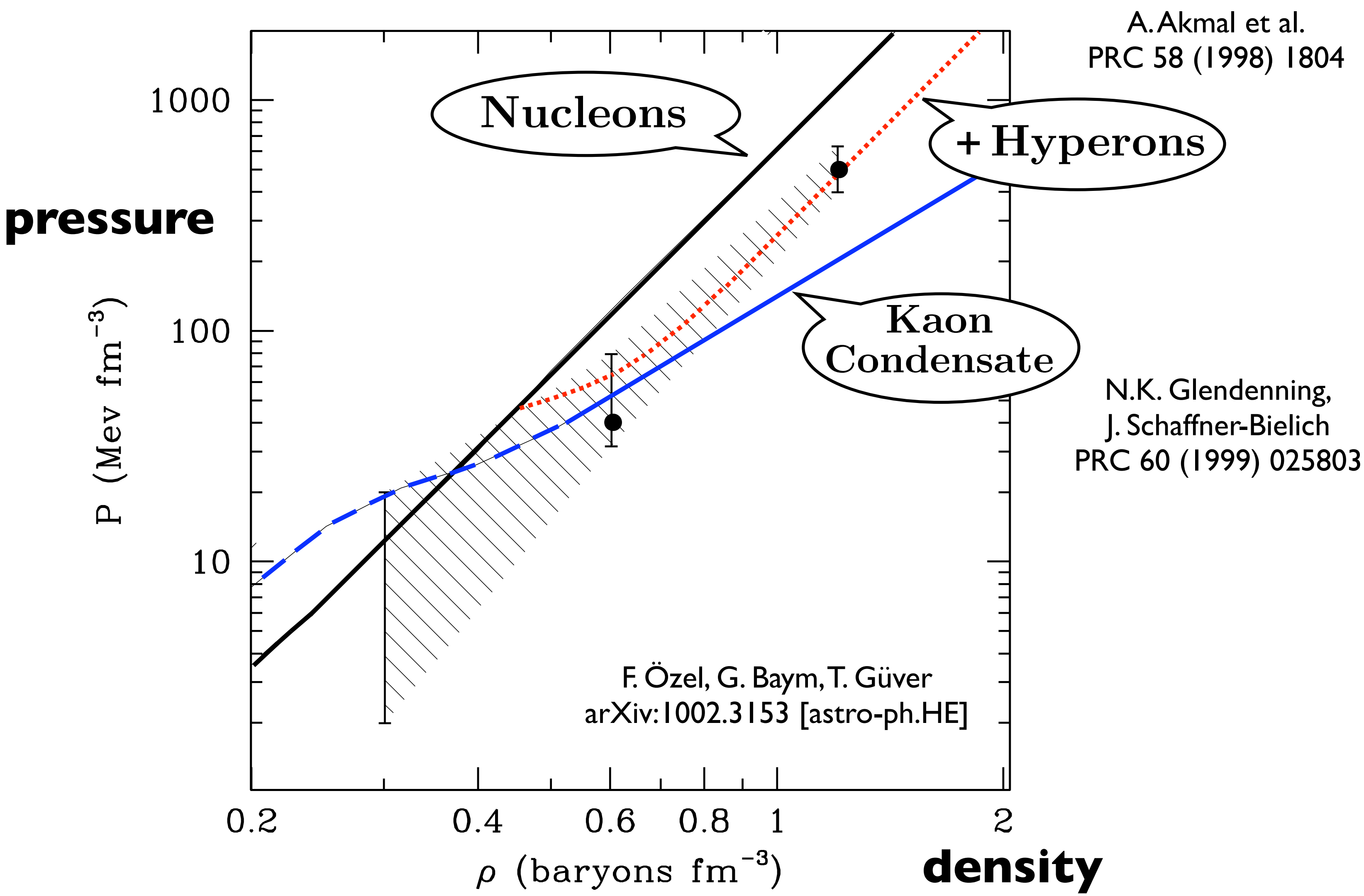
techniques now applied to three neutron stars in binaries

4U 1608-248
EXO 1745-248
4U 1820-30



F. Özel, G. Baym, T. Güver
arXiv:1002.3153
[astro-ph.HE]

Implications for the EQUATION of STATE



- **Nucleons + Hyperons** more likely than **Kaon Condensate** or **Quark Matter**

Summary and **Conclusions**

- **Interface** of **Low-Energy QCD** and **Nuclear Physics**:
  Nuclear **Chiral** (Thermo-) **Dynamics** really works !

- Importance of **Two-Pion Exchange in-medium** processes in combination with Pauli principle

- **Three-Nucleon Forces** are natural part of nuclear chiral dynamics
  $\longrightarrow$ important stabilizer of nuclear matter at higher density

- Magnitude of **Chiral Condensate** remains non-zero in the range

$$\rho \leq 2\rho_0, \quad \mathrm{T} \leq 100 \ \mathrm{MeV}$$

  $\longrightarrow$ corridor of **Spontaneous Chiral Symmetry Breaking** persists along baryon density axis

thanks to:

Nino Bratovic, Marco Cristoforetti, Paolo Finelli, Salvatore Fiorilla
Thomas Hell, Jeremy Holt, Norbert Kaiser, Bertram Klein