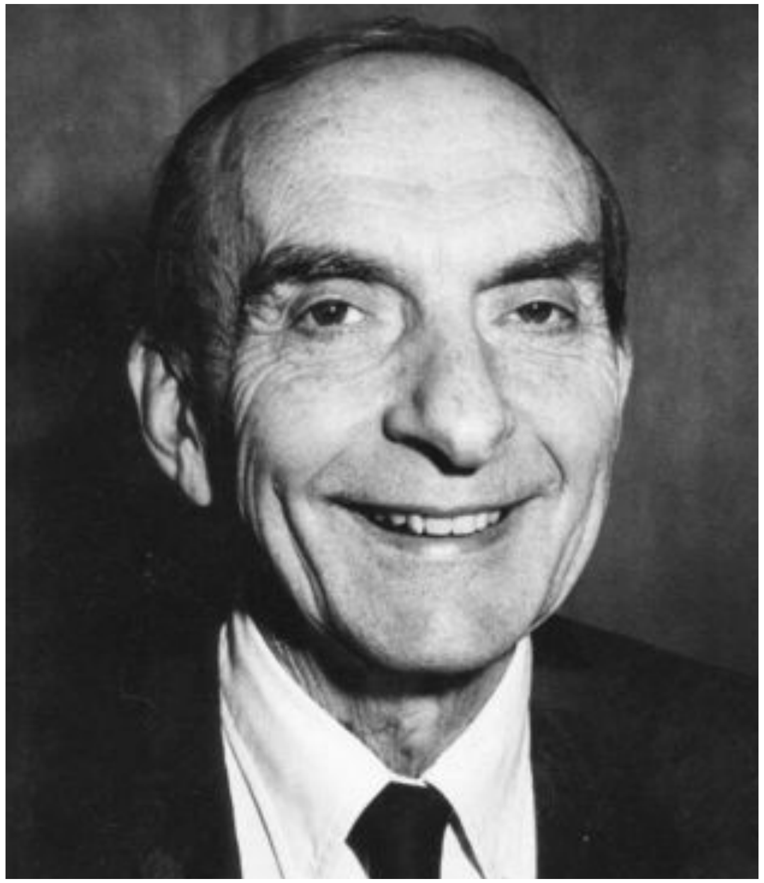


Dedicated to Gerry with deep gratitude

Gerald E. Brown
1926 - 2013

Nuclear Chiral Dynamics and **Thermodynamics**

Wolfram Weise

European Centre for Theoretical Studies
in Nuclear Physics and Related Areas, Trento

and

Technische Universität München

Memories of the Seventies ...

PHYSICS LETTERS B 48 (1974) 297

CORRELATION EFFECTS IN PION CONDENSATES

W. WEISE‡ and G.E. BROWN‡‡

Department of Physics, SUNY, Stony Brook, New York 11790, USA

Received 10 January 1974

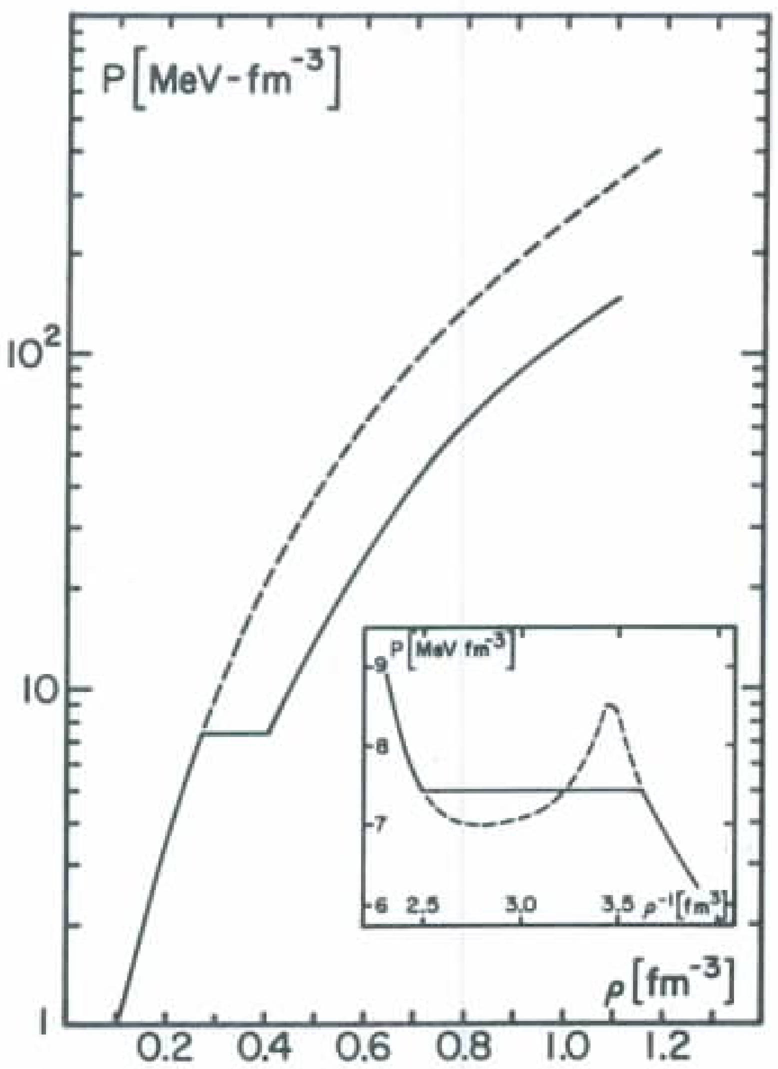
PHYSICS LETTERS B 58 (1975) 300

EQUATION OF STATE FOR NEUTRON MATTER IN THE PRESENCE OF A PION CONDENSATE

W. WEISE* and G.E. BROWN**

Department of Physics, State University of New York, Stony Brook, N.Y. 11794, USA

Received 19 June 1975



PHYSICS REPORTS (Section C of Physics Letters) 27, No. 1 (1976) 1–34.

PION CONDENSATES

G. E. BROWN*

NORDITA and *Physics Department, State University of New York, Stony Brook, New York, U.S.A.*

and

W. WEISE**

Physics Department, State University of New York, Stony Brook, New York, U.S.A.

Received December 1975

PHYSICS REPORTS (Section C of Physics Letters) 22, No. 6 (1975) 279–337

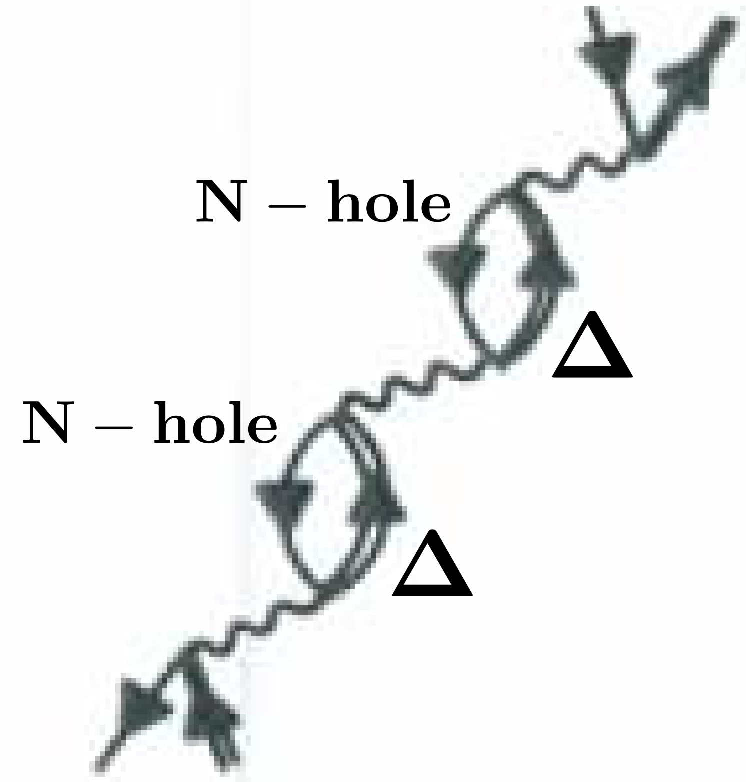
PION SCATTERING AND ISOBARS IN NUCLEI

G.E. BROWN*
Nordita, Copenhagen
and Institute for Theoretical Physics, State University of New York, Stony Brook, N.Y.

and

W. WEISE‡
Physics Department,
State University of New York, Stony Brook, N.Y.

Received August 1975

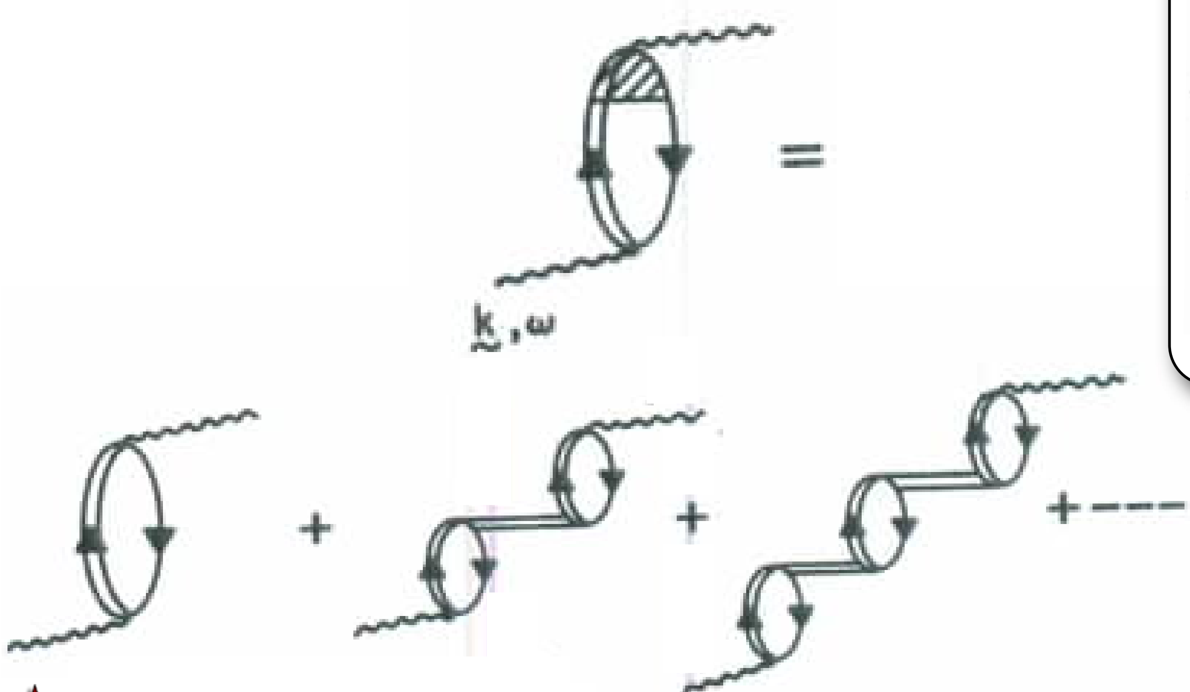


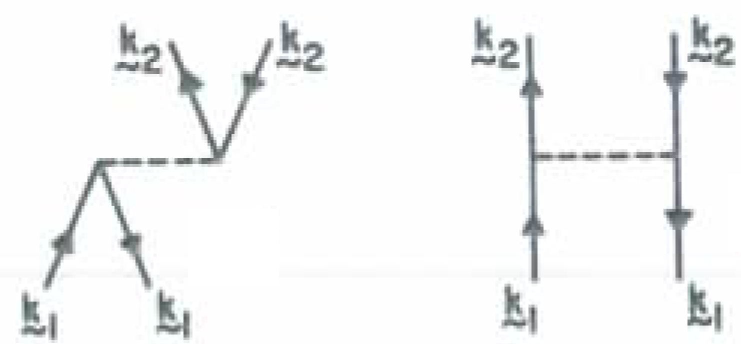
Nuclear Physics **A286** (1977) 191–210

CALCULATION OF SPIN-DEPENDENT PARAMETERS IN THE LANDAU-MIGDAL THEORY OF NUCLEI †

G. E. BROWN, S.-O. BÄCKMAN ††, E. OSET ††† and W. WEISE ‡
Department of Physics, State University of New York, Stony Brook, New York 11794

Received 1 December 1976





Technische Universität München

... and of the Eighties

Nuclear Physics A454 (1986) 669–690

PHENOMENOLOGICAL DELINEATION OF THE QUARK–GLUON STRUCTURE FROM NUCLEON ELECTROMAGNETIC FORM FACTORS*

G.E. BROWN, MANNQUE RHO[1] and W. WEISE[2]

Department of Physics, State University of New York at Stony Brook, Stony Brook, NY 11794, USA

Received 4 November 1985

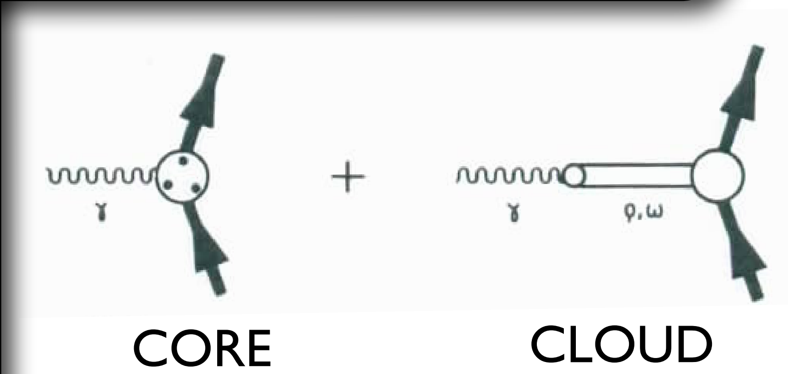
Z. Phys. A – Atomic Nuclei 331, 139–149 (1988)

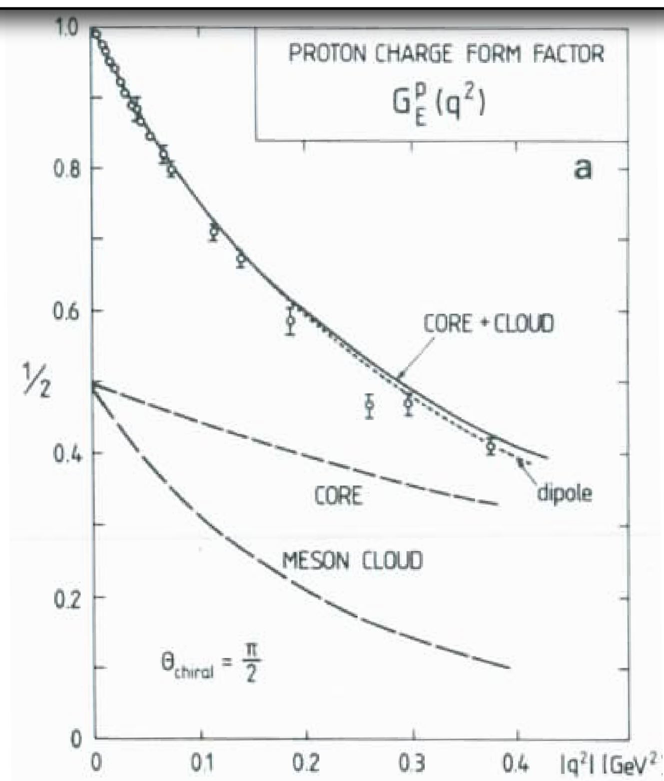
Phenomenological Sizes of Confinement Regions in Baryons*

G.E. Brown[1], S. Klimt[2], M. Rho[3], and W. Weise[2]

[1] Department of Physics, State University of New York, Stony Brook, USA
[2] Institut für Theoretische Physik, Universität Regensburg, Federal Republic of Germany
[3] Service de Physique Théorique, CEN Saclay, France

Received February 12, 1988





PHYSICAL REVIEW LETTERS 60 (1988) 2723

K^+-Nucleus Scattering and the "Swelling" of Nucleons in Nuclei

G. E. Brown
State University of New York, Stony Brook, New York 11794

C. B. Dover
Brookhaven National Laboratory, Upton, New York 11973

P. B. Siegel
California State Polytechnic University, Pomona, California 91768

and

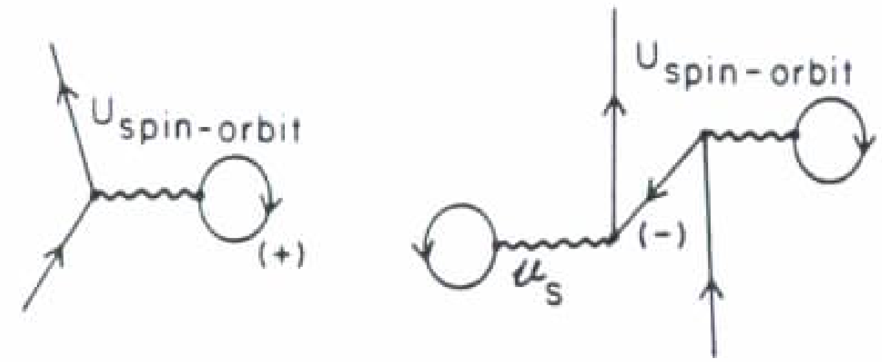
W. Weise
Institut für Theoretische Physik, Universität Regensburg, D-8400 Regensburg, Federal Republic of Germany
(Received 15 January 1988)

Comments Nucl. Part. Phys.
1987, Vol. 17, No. 1, pp. 39–62

Relativistic Effects in Nuclear Physics

G. E. BROWN and W. WEISE*
Department of Physics,
State University of New York at Stony Brook,
Stony Brook, New York 11794

G. BAYM† and J. SPETH**
Los Alamos National Laboratory,
Los Alamos, New Mexico 87545

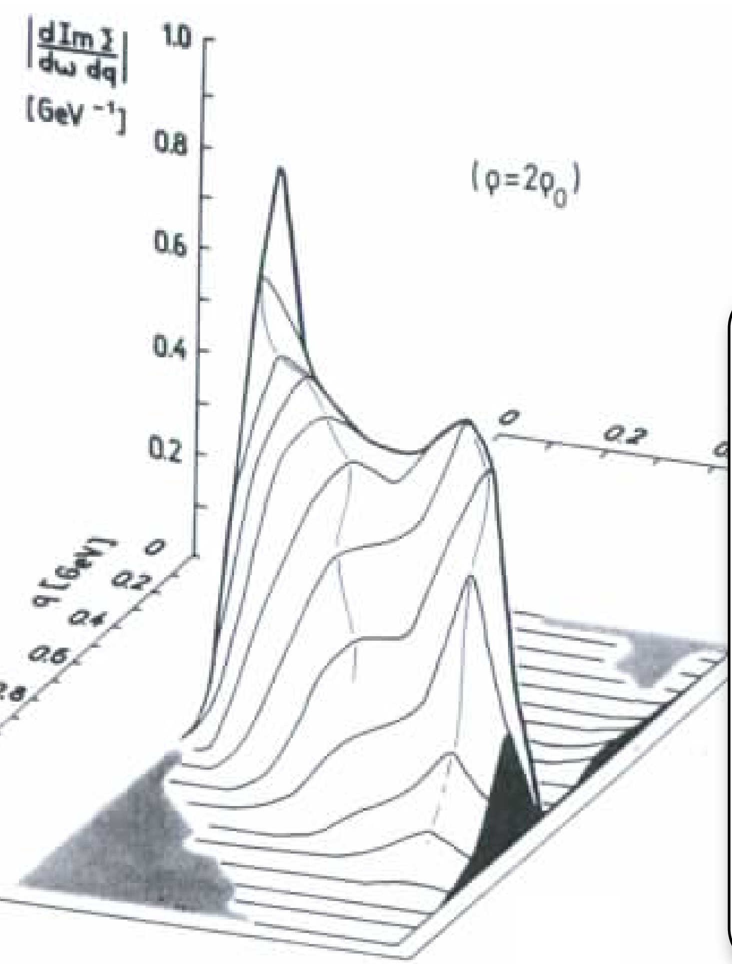


PHYSICS LETTERS B 200 (1988) 37

LOOP CORRECTIONS AND OTHER MANY-BODY EFFECTS IN RELATIVISTIC FIELD THEORIES ☆

T.L. AINSWORTH, G.E. BROWN, M. PRAKASH and W. WEISE [1,2]
Physics Department, SUNY at Stony Brook, Stony Brook, NY 11794, USA

Received 2 February 1987



Nuclear Physics **A505** (1989) 823–834

PRODUCTION OF PIONIC MODES IN RELATIVISTIC HEAVY-ION COLLISIONS*

G.E. BROWN
Department of Physics, State University of New York, Stony Brook, NY 11794, USA

E. OSET[1], M. VICENTE VACAS[2] and W. WEISE[3]
Institute of Theoretical Physics, University of Regensburg, D-8400 Regensburg, Fed. Rep. Germany

Received 28 March 1989

NUCLEAR CHIRAL DYNAMICS
and
THERMODYNAMICS

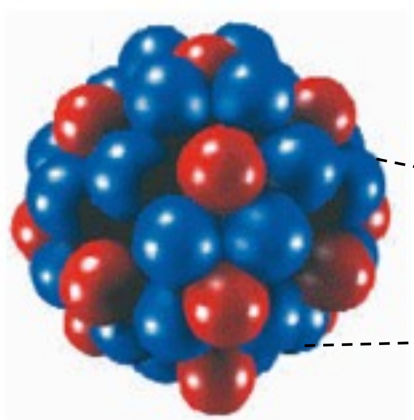
Jeremy W. Holt, N. Kaiser, W. Weise

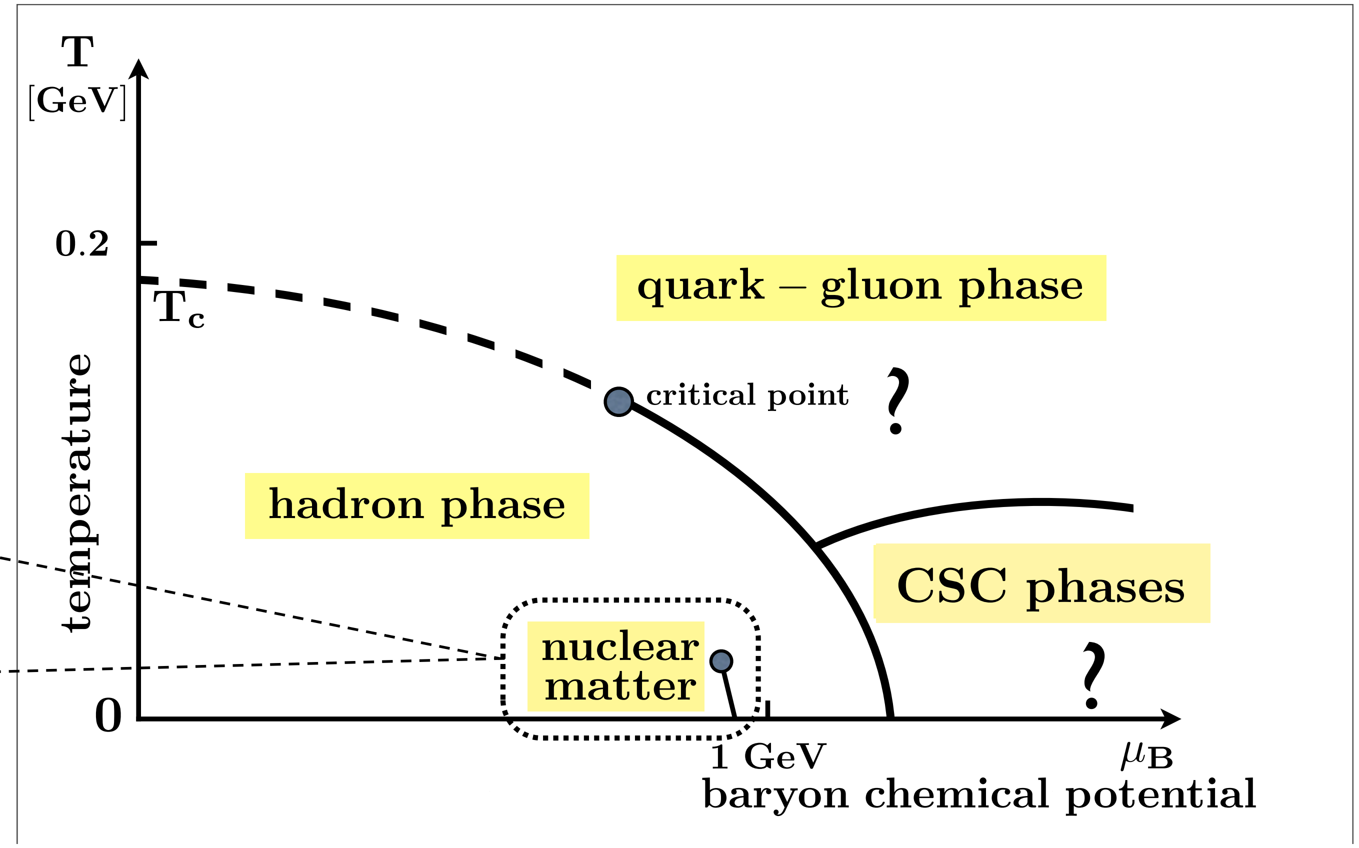
[1]Physics Department, University of Washington, Seattle, WA 98195-1550, USA
[2]Physik-Department, Technische Universität München, D-85747 Garching, Germany
[3]ECT*, Villa Tambosi, I-38123 Villazzano (Trento), Italy

Progress Part. Nucl. Phys. **73** (2013) 35

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: $K = (260 \pm 30)\ \mathrm{MeV} \sim 2m_\pi$

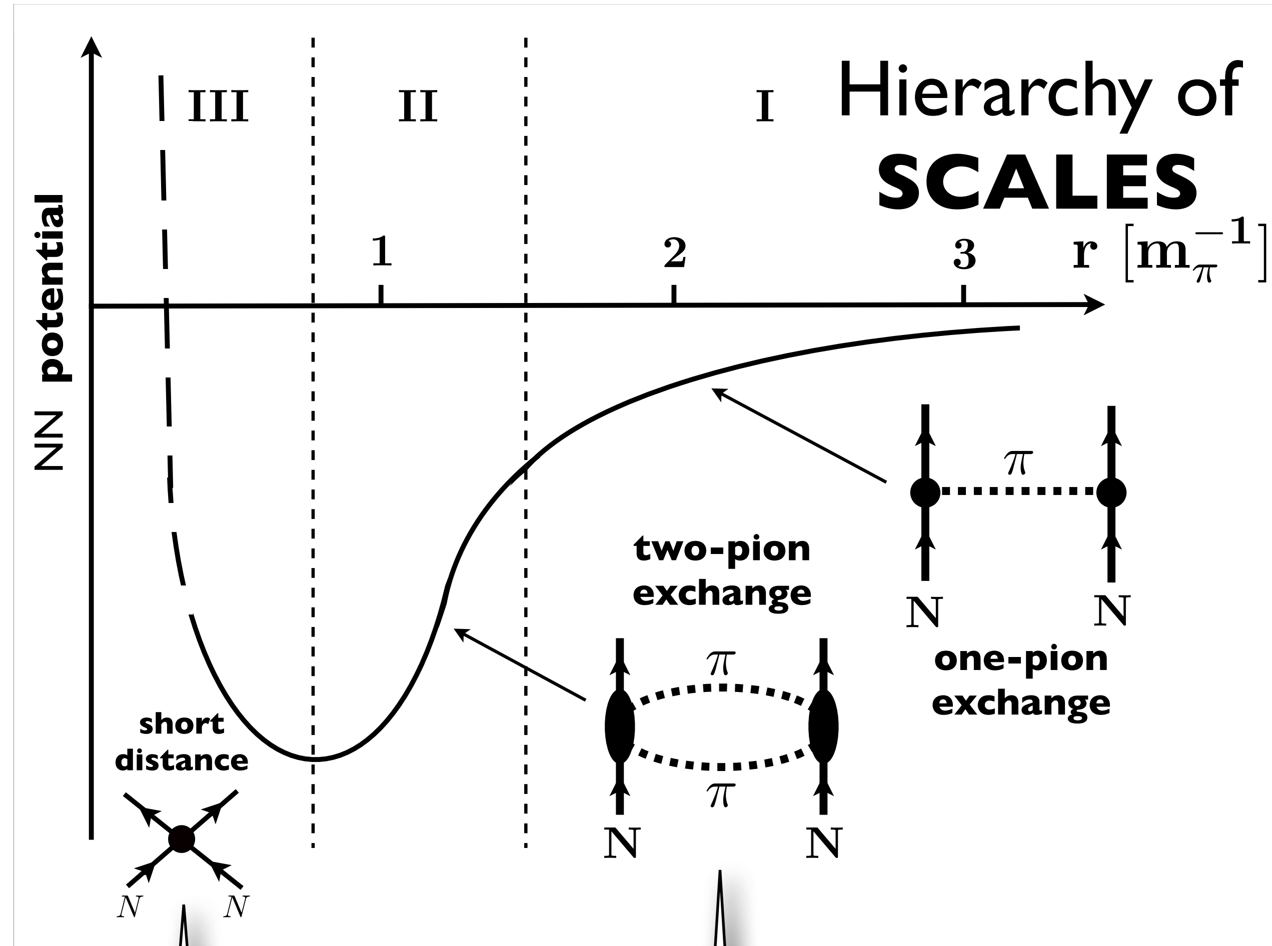
Nuclear Forces

G.E. Brown & A.D. Jackson
The Nucleon-Nucleon Interaction

contemporary approaches:

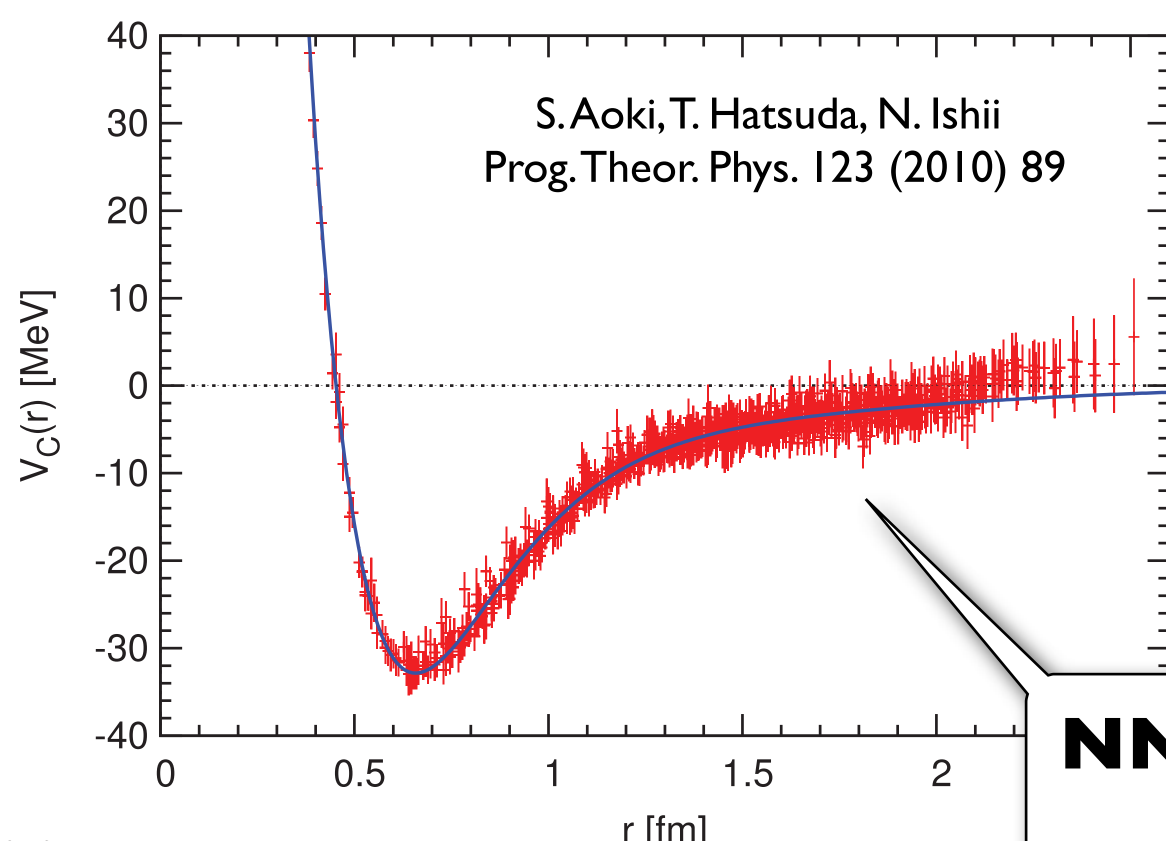
Chiral Effective Field Theory
+
Lattice QCD

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



contact terms

explicit treatment of **two-pion exchange**



NN Central Potential
from Lattice QCD

CHIRAL EFFECTIVE FIELD THEORY

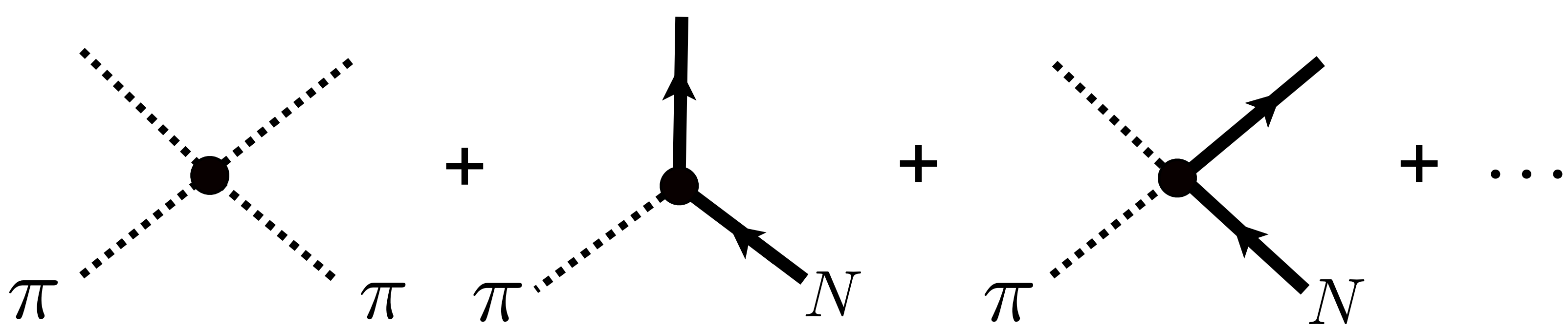
- Systematic framework at interface of QCD and Nuclear Physics

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

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

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

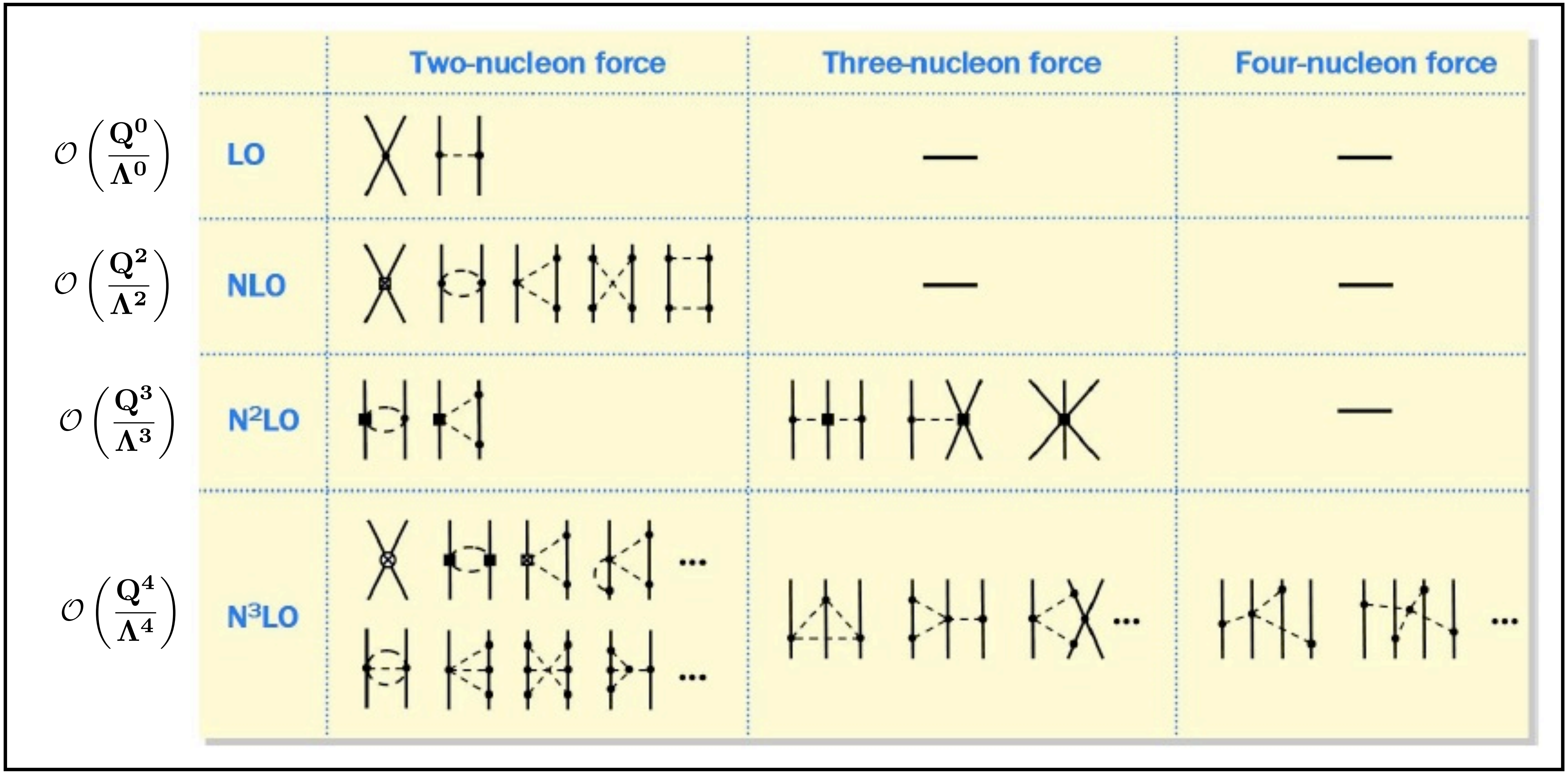
- Construction of Effective Lagrangian: **Symmetries**



short distance dynamics: **contact terms**

NUCLEAR INTERACTIONS from CHIRAL EFFECTIVE FIELD THEORY

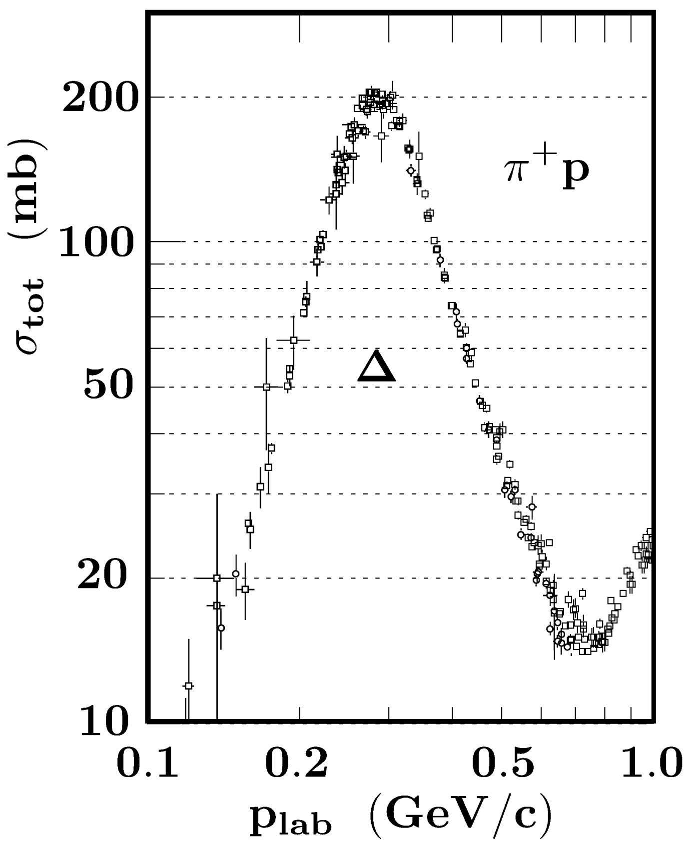
Weinberg   Bedaque & van Kolck   Bernard, Epelbaum, Kaiser, Meißner; ...



- **Systematically organized HIERARCHY**

Explicit $\Delta(1230)$ DEGREES of FREEDOM

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

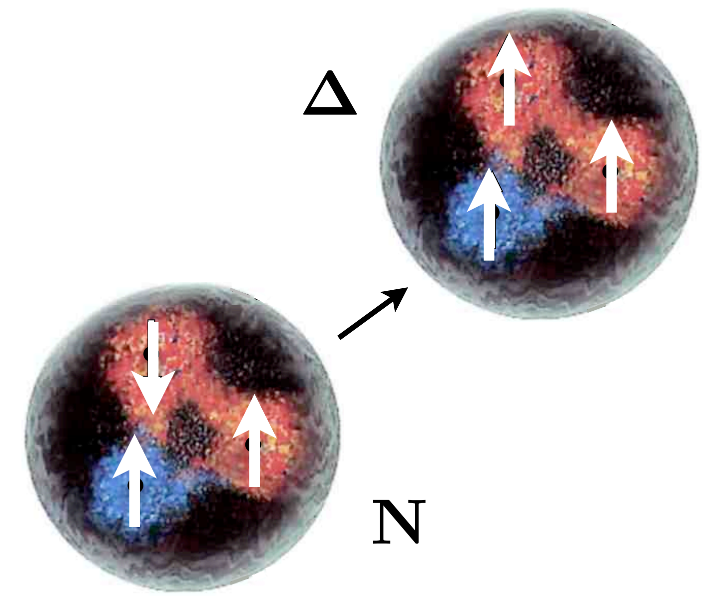


◀ dominance of $\Delta(1230)$ in pion-nucleon scattering

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

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

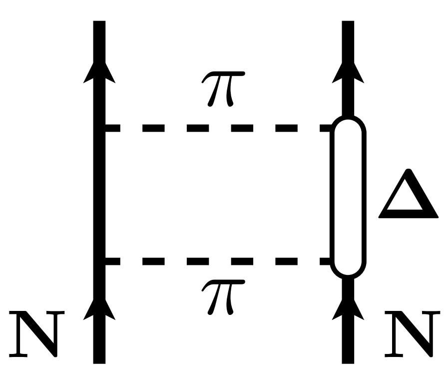
(small scale)



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

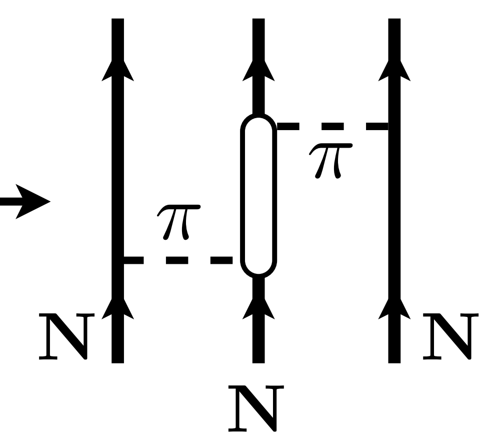
N. Kaiser, S. Gerstendörfer, W.W., NPA637 (1998) 395

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



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

⟷

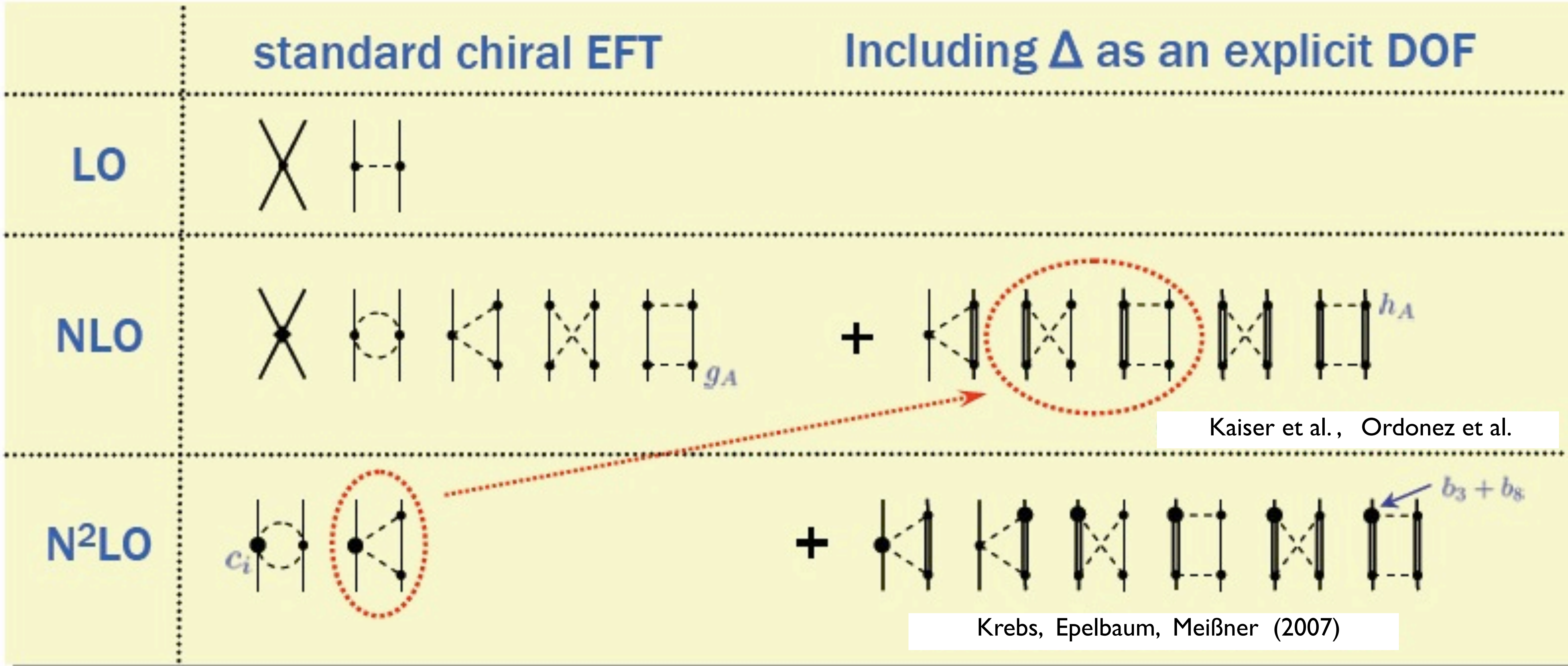


strong 3-body interaction

J. Fujita, H. Miyazawa (1957)

Pieper, Pandharipande, Wiringa, Carlson (2001)

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

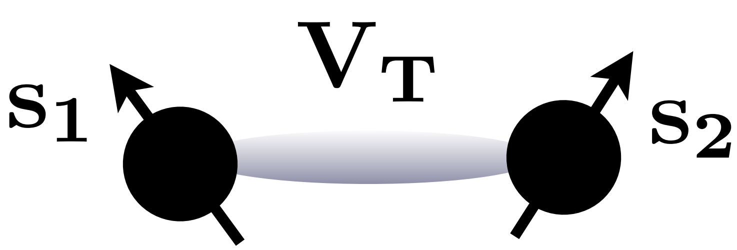


- **Important physics** of $\Delta(1230)$ promoted to **NLO**
- **Improved** convergence

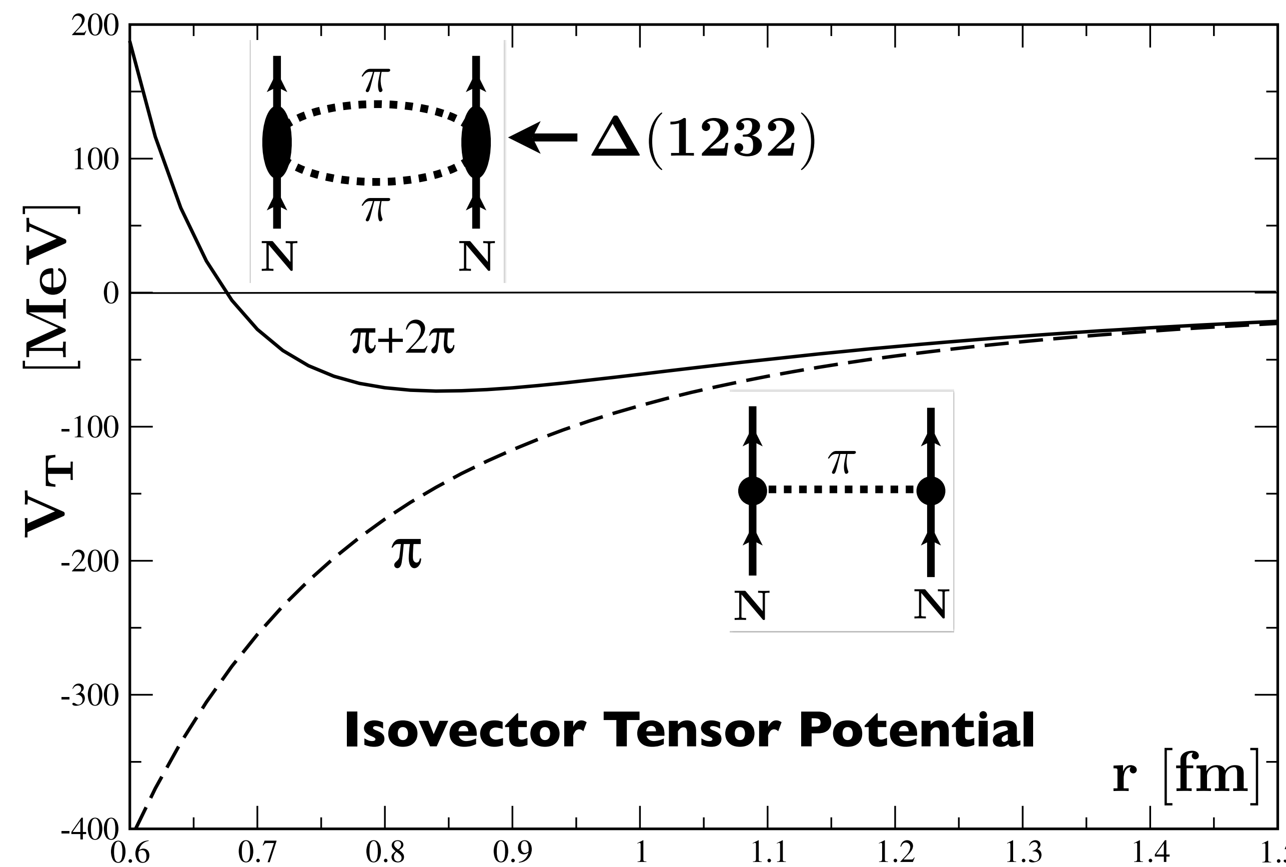
Important pieces of the

CHIRAL NUCLEON-NUCLEON INTERACTION

- **ISOVECTOR TENSOR FORCE**

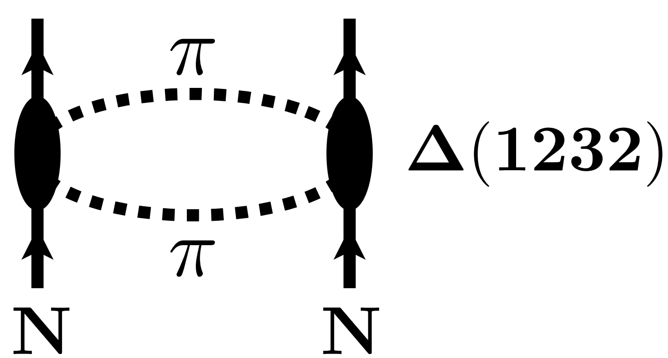


- note: **no** ρ meson



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

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



- note: **no** 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

IN-MEDIUM CHIRAL PERTURBATION THEORY

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

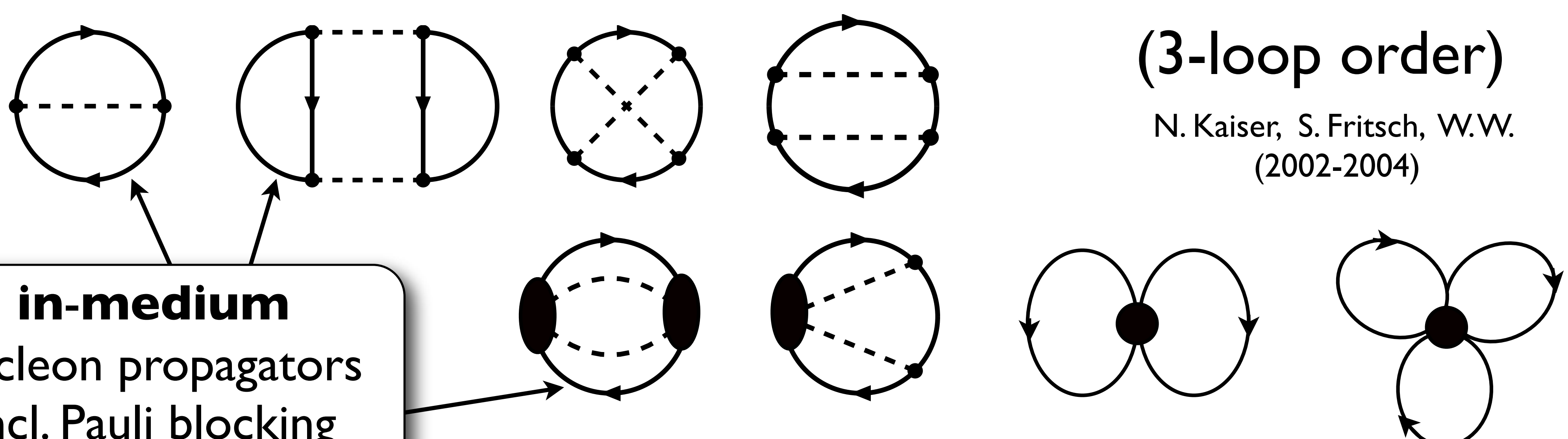
- **Loop expansion** of (**I**n-**M**edium) **Ch**iral **P**erturbation **T**heory

  ↕

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

  (works for $k_F << 4\pi\, f_\pi \sim 1\,\mathrm{GeV}$)

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



(3-loop order)

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

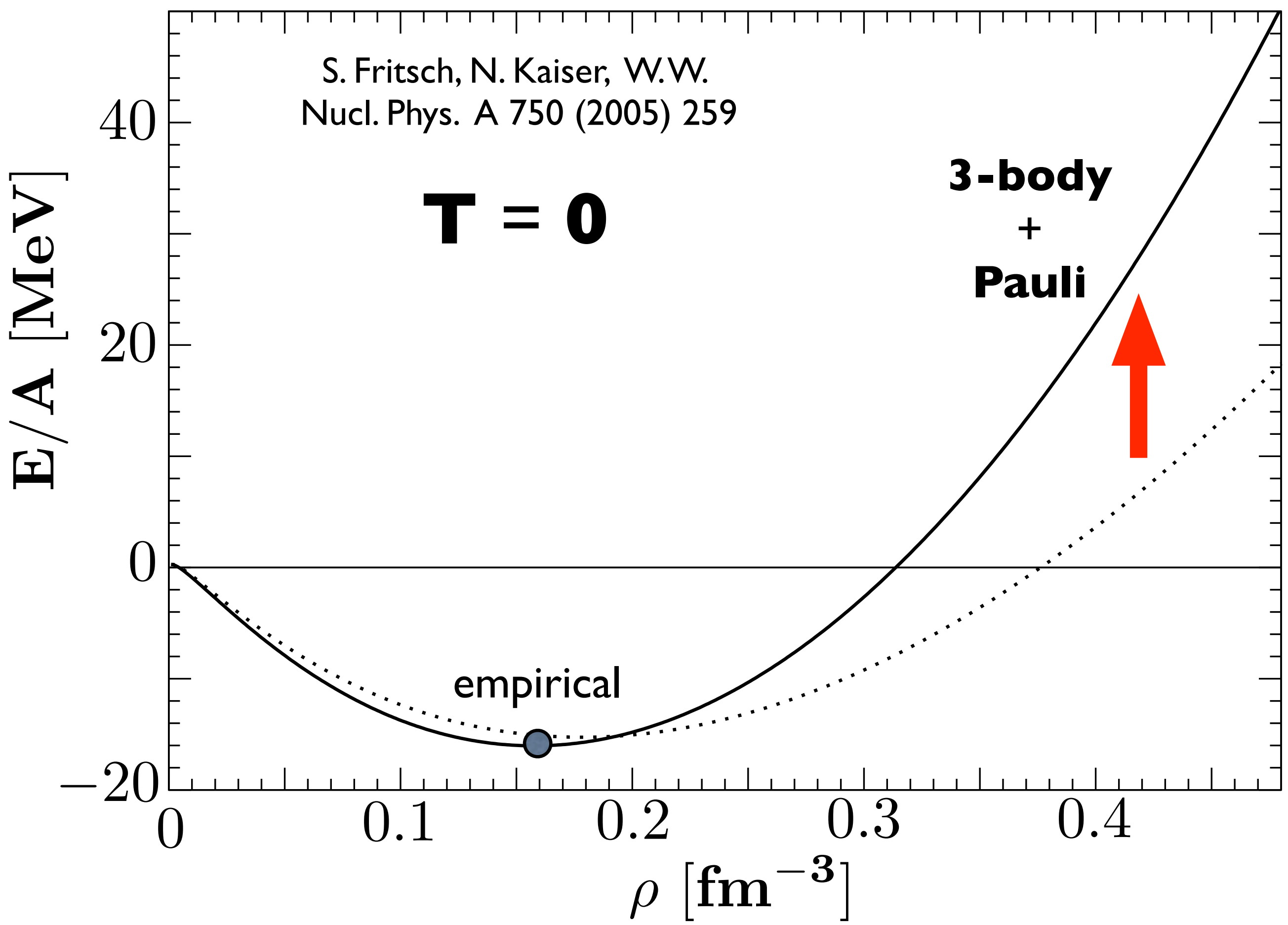
in-medium
nucleon propagators
incl. Pauli blocking

NUCLEAR MATTER

- **In-medium ChPT**
  3-loop (π, N, Δ)

- **Input** parameters:
  two contact terms

- basically:
  analytic calculation



- **Output**:
  - Binding & saturation
    $$\mathbf{E_0/A = -16\,MeV\ ,\ \rho_0 = 0.16\,fm^{-3}\ ,\ K = 290\,MeV}$$
  - Realistic (complex, momentum dependent) single-particle potential
  - Asymmetry energy: $\mathbf{A(k_F^0) = 34\,MeV}$
  - Fermi Liquid Theory:
    Quasiparticle interaction and Landau parameters

J.W. Holt, N. Kaiser, W.W.
Nucl. Phys. A 870 (2011) 1,
Nucl. Phys. A 876 (2012) 61,
Phys. Rev. C 87 (2013) 014338

ECT*

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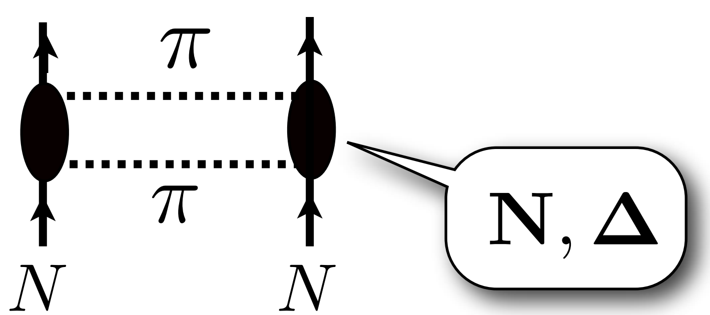
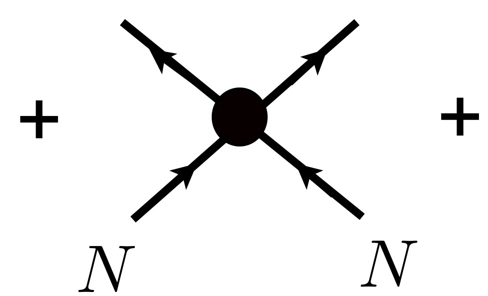
NUCLEAR THERMODYNAMICS

NUCLEAR
CHIRAL (PION) DYNAMICS

BINDING & SATURATION:

Van der Waals + Pauli

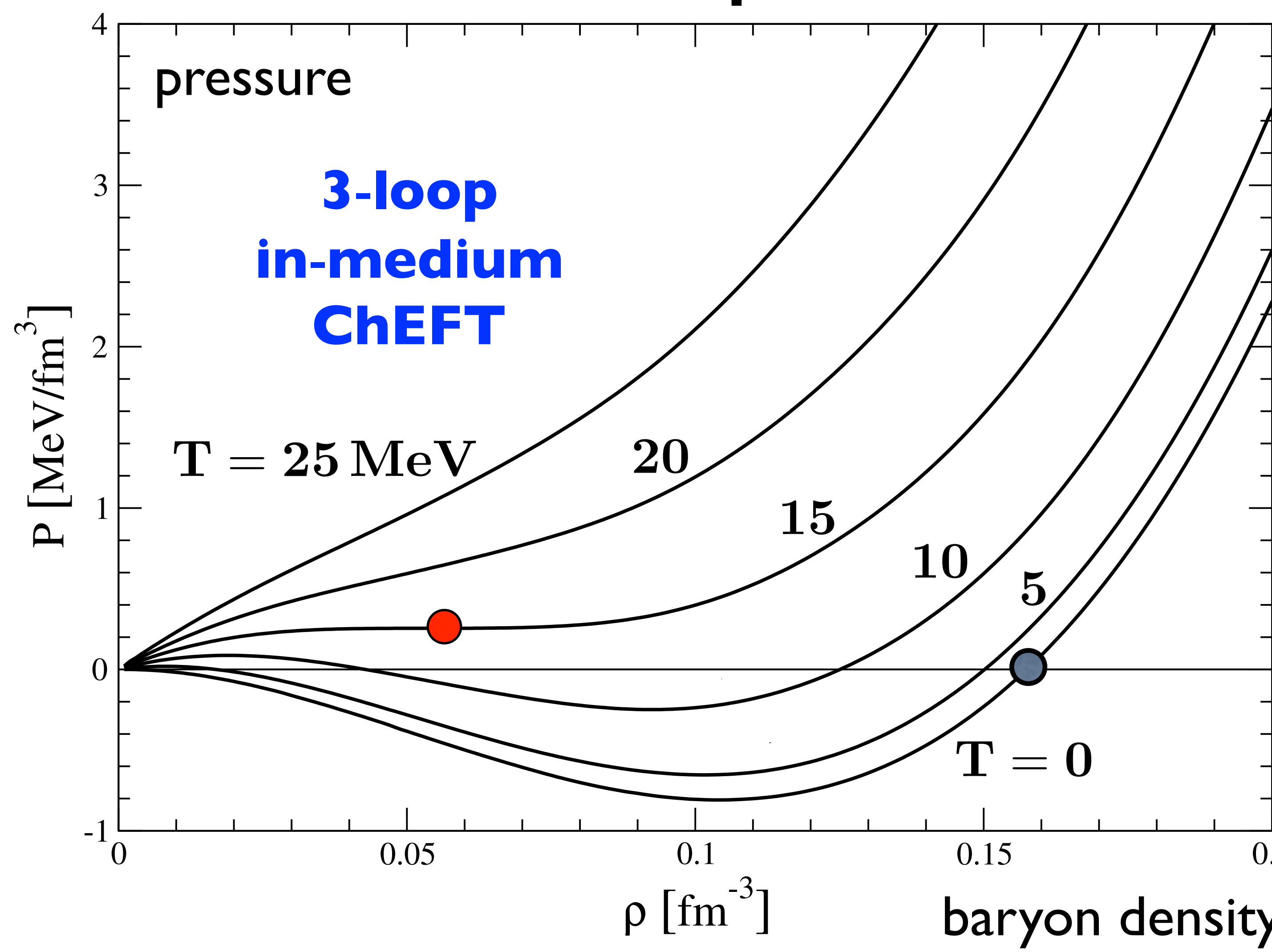




3-body forces

contact terms

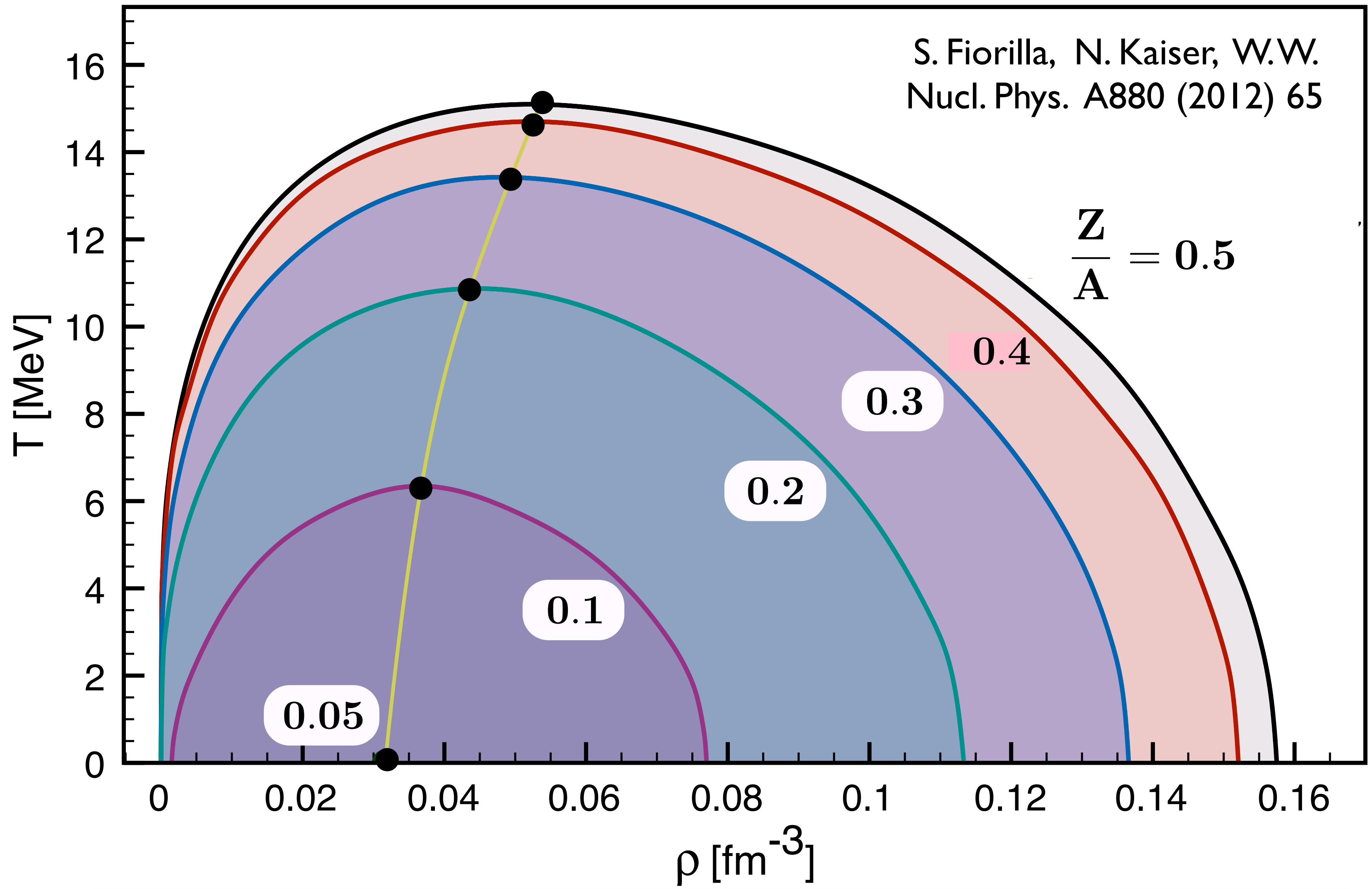
nuclear matter: equation of state



Liquid - Gas Transition at
Critical Temperature T_c = 15 MeV
(empirical: T_c = 16 - 18 MeV)

PHASE DIAGRAM of NUCLEAR MATTER

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

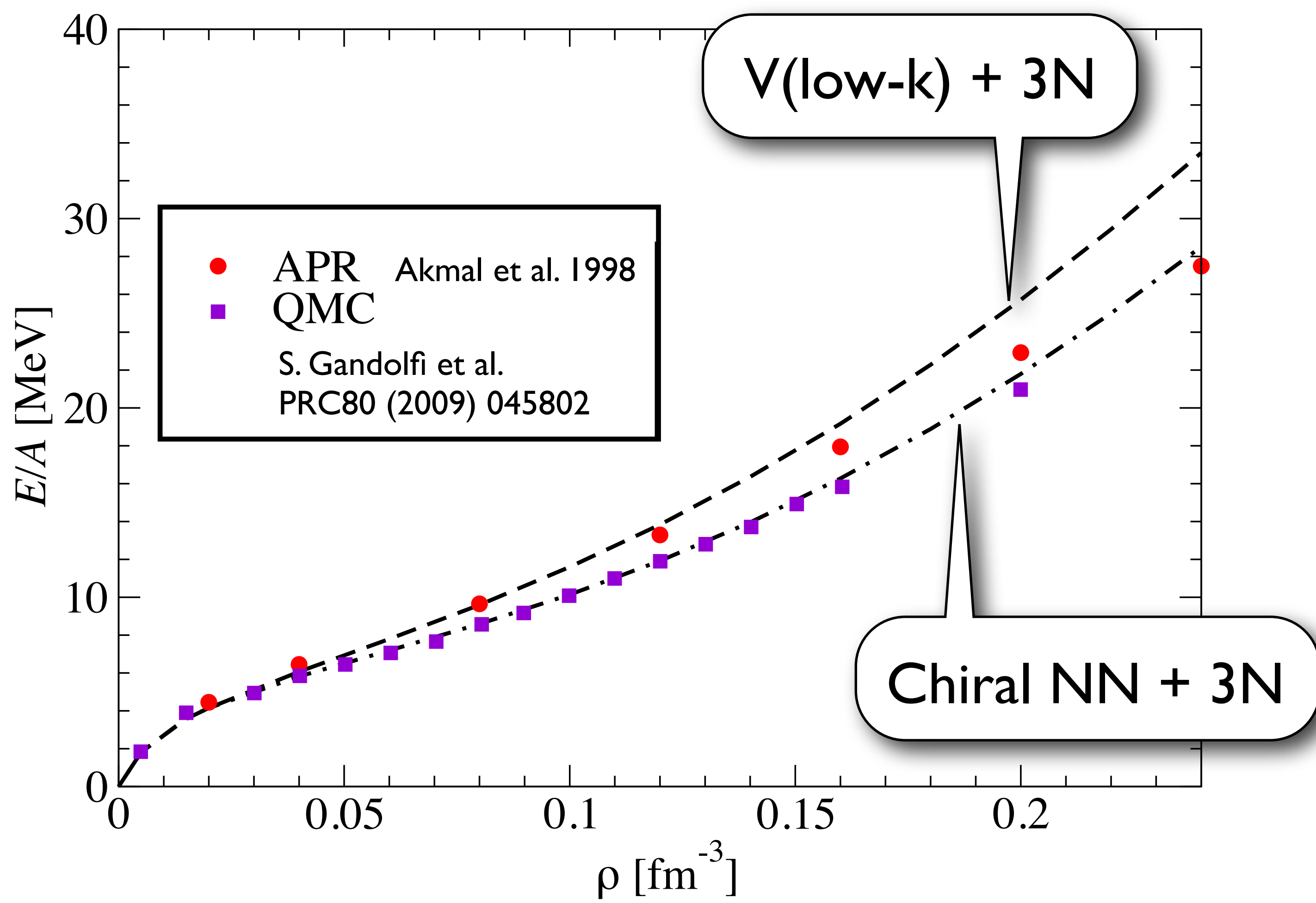


. . . determined almost completely by
isospin dependent (one- and two-) **pion** exchange dynamics

NEUTRON MATTER

(T = 0)

- In-medium chiral effective field theory (3-loop) with resummation of short distance contact terms (large nn scattering length, $a_s = 19\ \mathrm{fm}$)



- Neutron matter behaves almost (but not quite) like a unitary Fermi gas
- Bertsch parameter

$$\xi = \frac{\bar{E}}{E_{\mathrm{Fermi\,gas}}} \simeq 0.5$$

J.W. Holt, N. Kaiser, W.W.
Phys. Rev. C 87 (2013) 014338

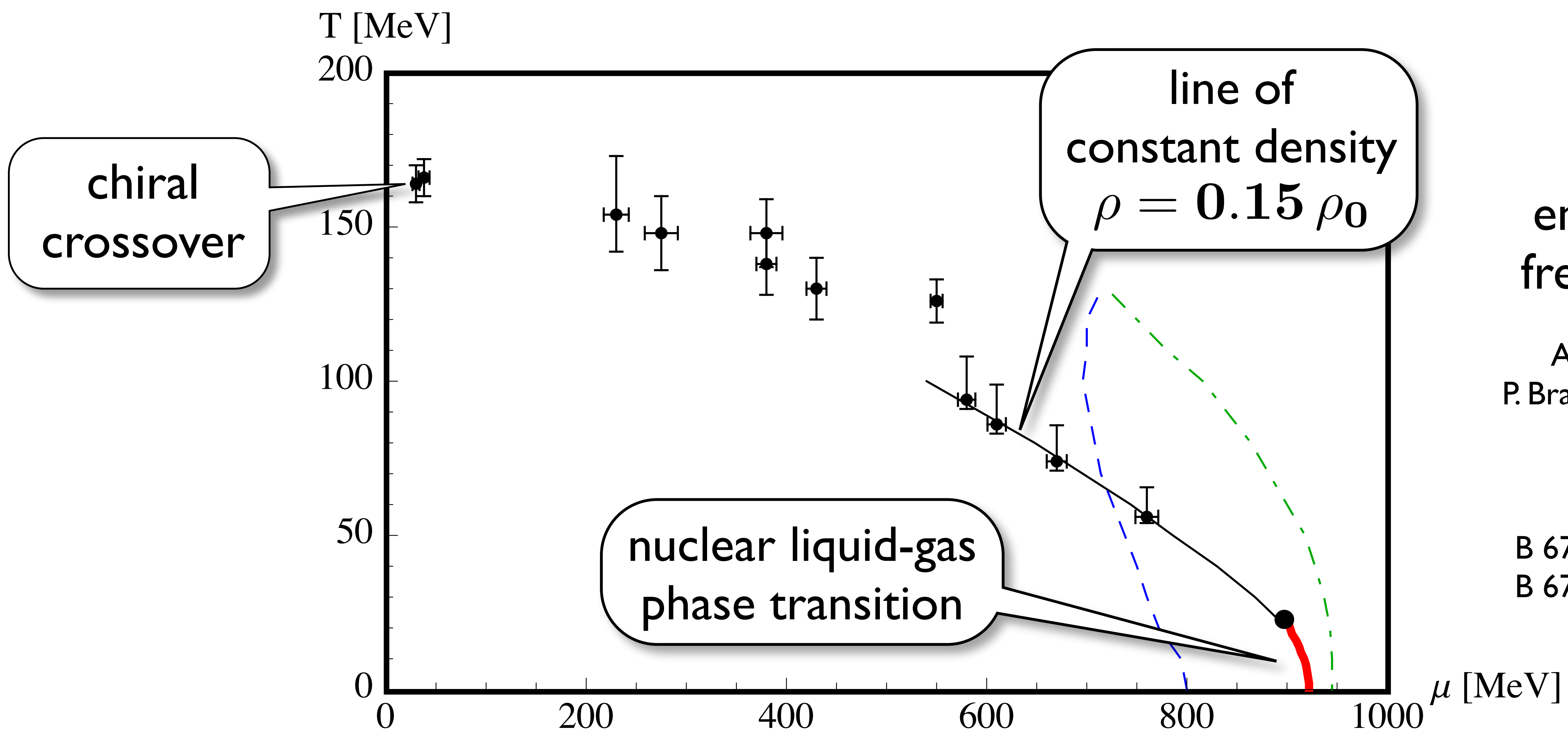
- perfect agreement with sophisticated many-body calculations

(e.g. Quantum Monte Carlo computations (P. Armani et al., arXiv:1110.0993))

CHEMICAL FREEZE-OUT

- **Chiral nucleon - meson model**

S. Floerchinger, Ch. Wetterich : Nucl. Phys. A 890-891 (2012) 11



empirical freeze-out:

A. Andronic,
P. Braun-Munzinger,
J. Stachel

Phys. Lett.
B 673 (2009) 142
B 678 (2009) 516

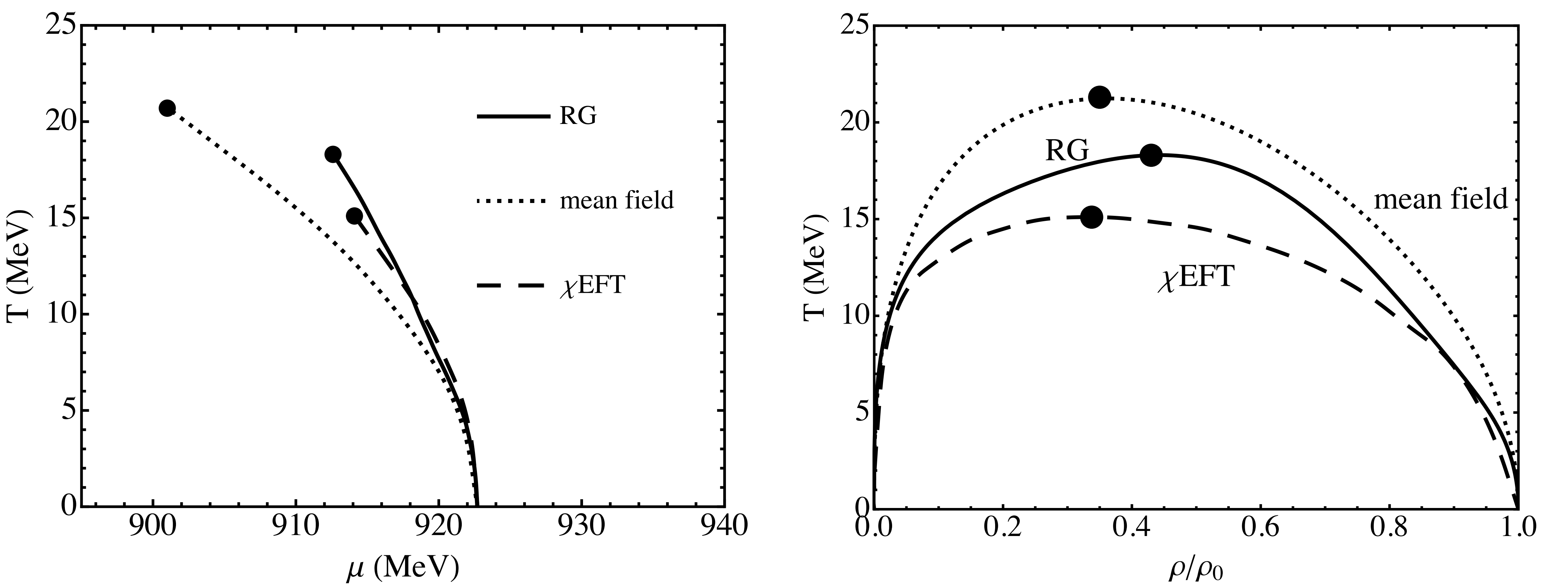
- **Chemical freeze-out** in **baryonic matter** at T < 100 MeV is **not** associated with **chiral** phase transition or rapid crossover

Chiral nucleon - meson model beyond mean-field
- Renormalization Group strategies -

M. Drews, T. Hell, B. Klein, W.W.
arXiv:1307.6973; Phys. Rev. D (2013), in print

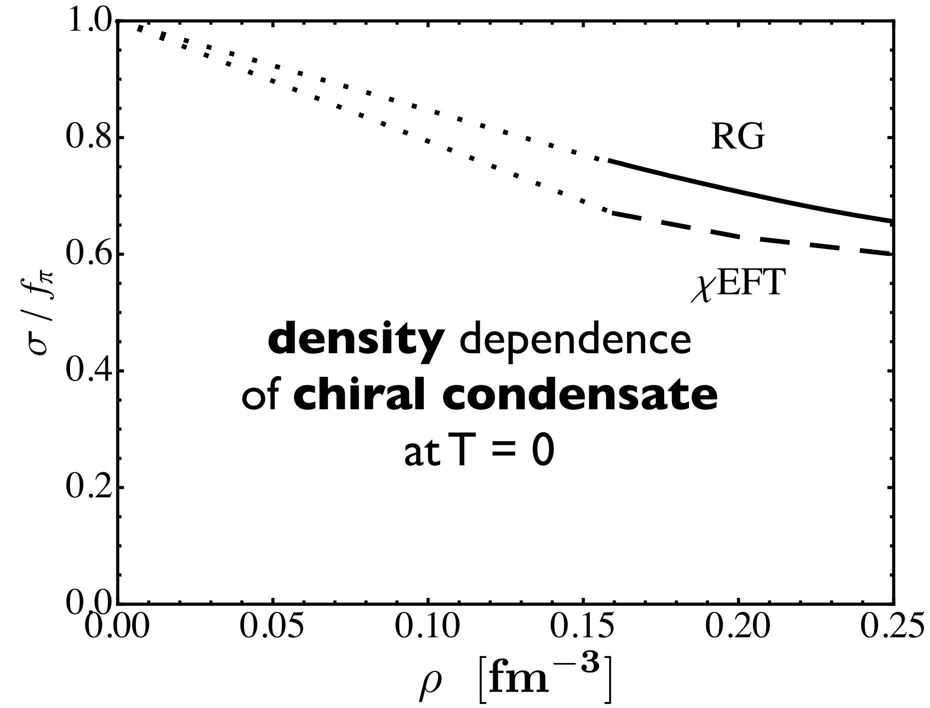
- Incorporate fluctuations using Wetterich's RG flow equations
- One-loop meson contributions included non-perturbatively (all orders)
- Comparison with in-medium chiral EFT (3-loop)

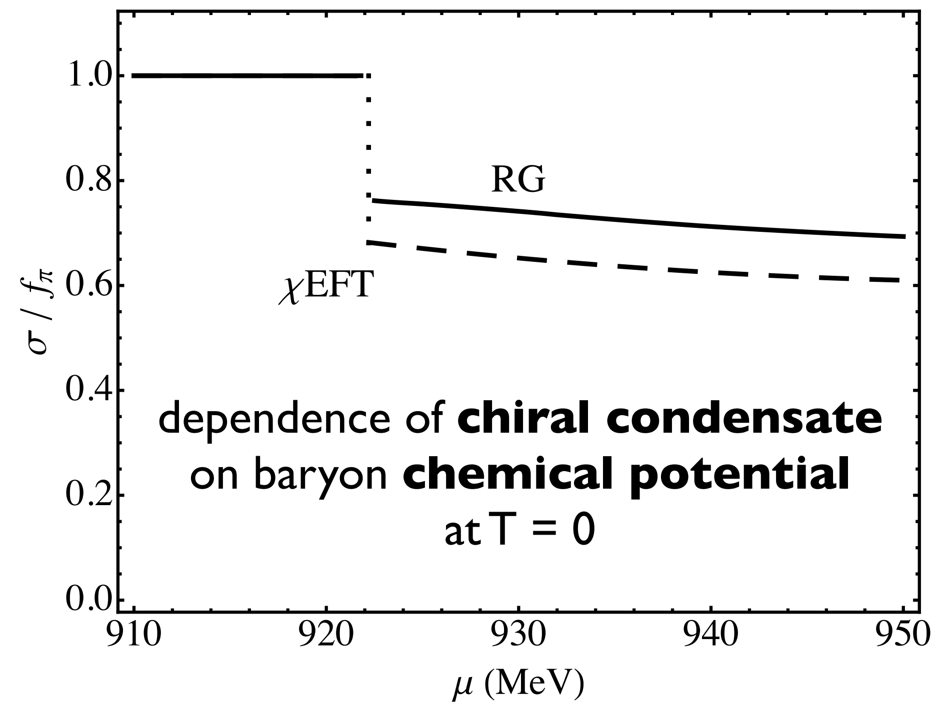
S. Fiorilla, N. Kaiser, W.W.
Nucl. Phys. A880 (2012) 65

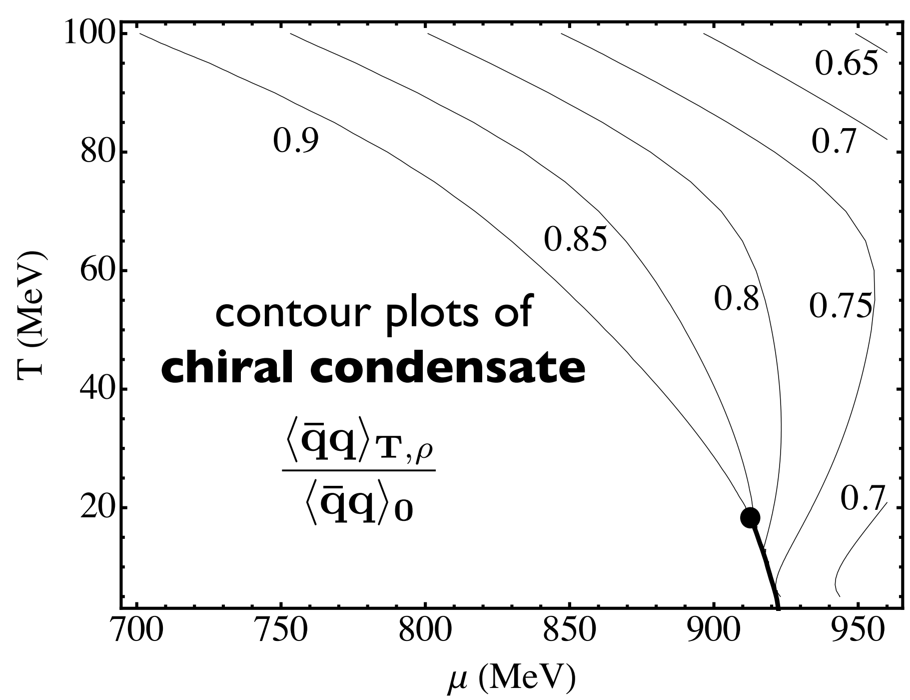


CHIRAL CONDENSATE
in nuclear matter

- Comparison of chiral effective field theory and model RG results







- Remarkable consistency between RG and chiral effective field theory results

- **No** tendency towards **chiral** phase transition for baryon chemical potentials $\mu \lesssim 1\ \mathbf{GeV}$ and temperatures $\mathbf{T} \lesssim \mathbf{100\ MeV}$

M. Drews, T. Hell, B. Klein, W.W.
arXiv:1307.6973; Phys. Rev. D (2013), to appear

ECT*

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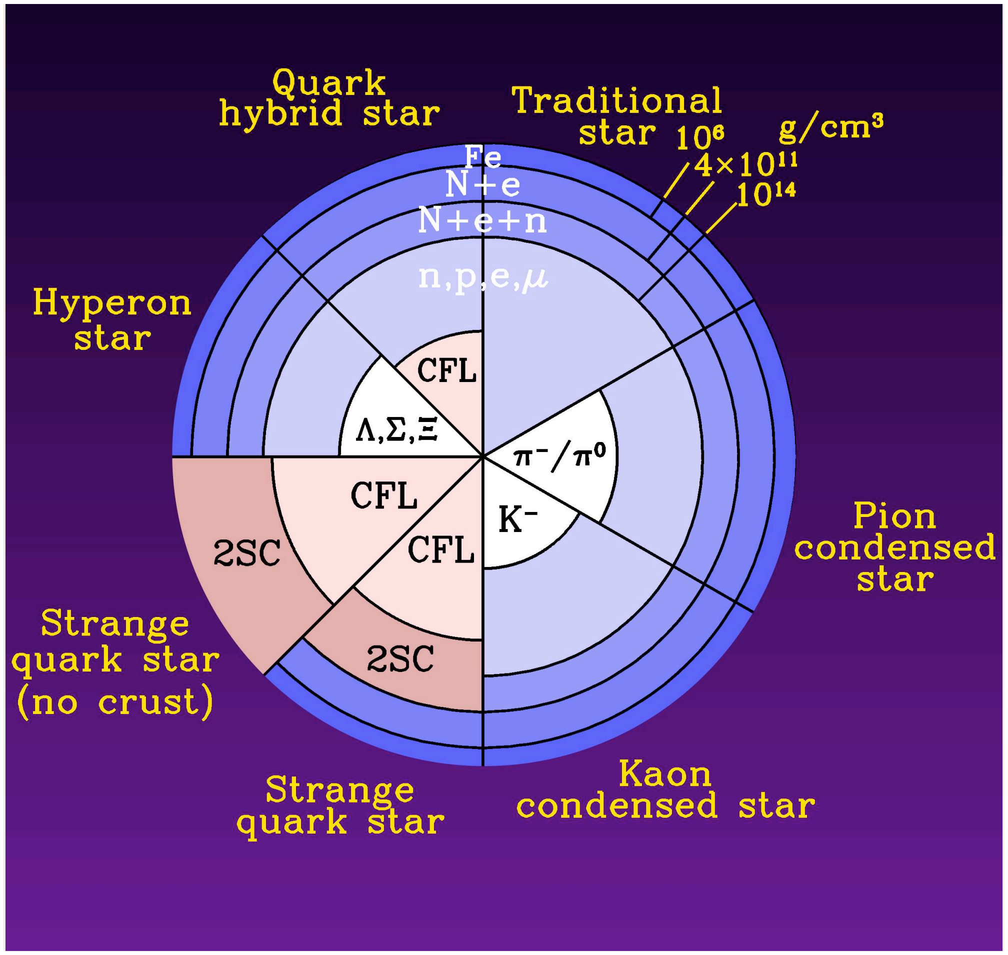
NEUTRON STARS and the EQUATION OF STATE of DENSE BARYONIC MATTER

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

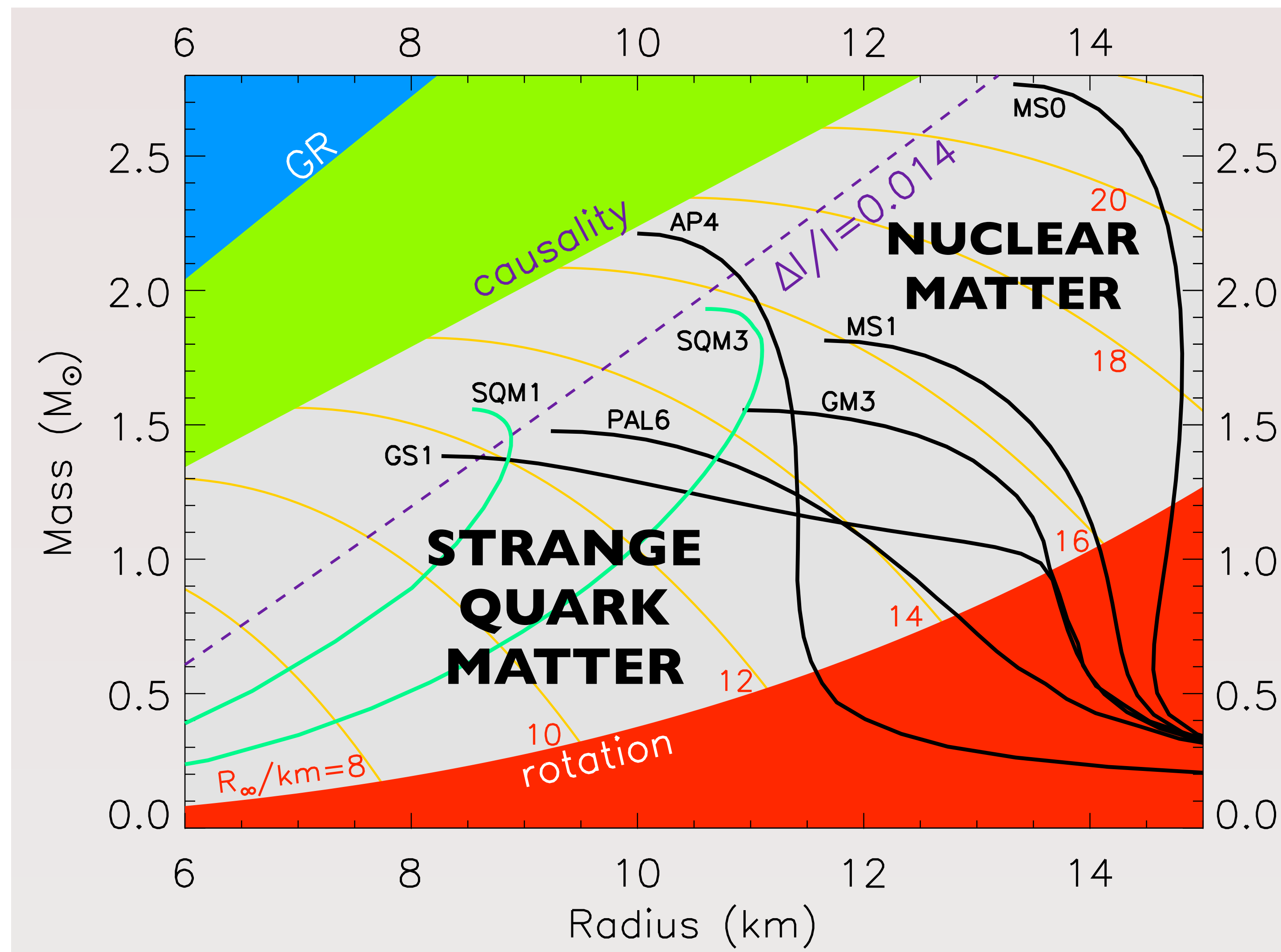


- **Neutron Star Scenarios**
- **T**olman-**O**ppenheimer-**V**olkov equations

$$\frac{dP}{dr} = -\frac{G}{c^2}\frac{(M + 4\pi P r^3)(\mathcal{E} + P)}{r(r - GM/c^2)}$$

$$\frac{dM}{dr} = 4\pi r^2 \frac{\mathcal{E}}{c^2}$$

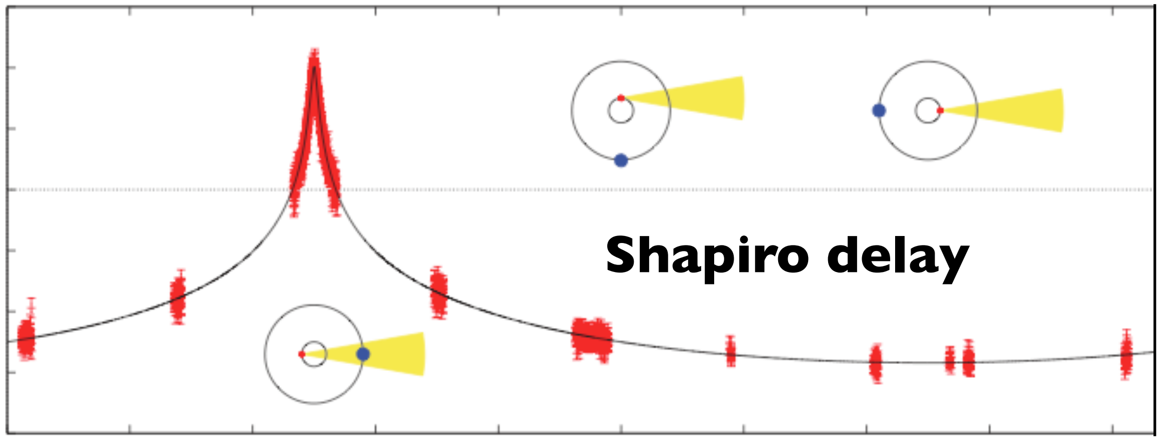
- **Mass-Radius Relation**

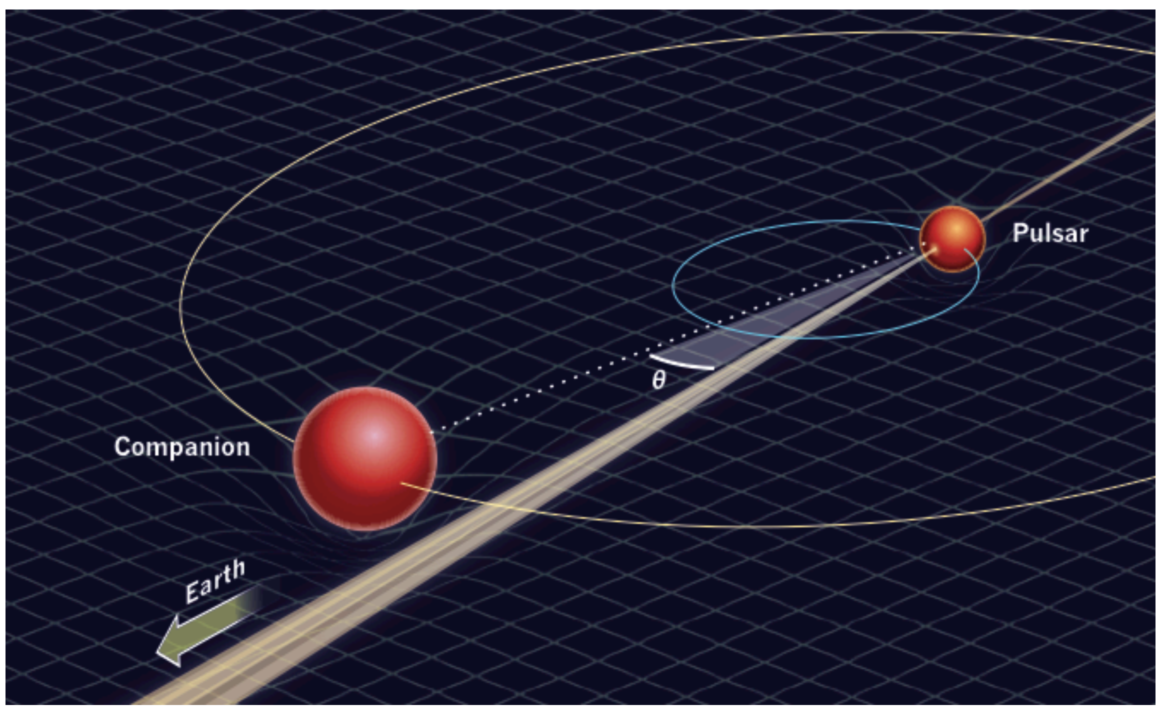


Technische Universität München

New constraints from NEUTRON STARS

P. Demorest et al.
Nature **467** (2010) 1081

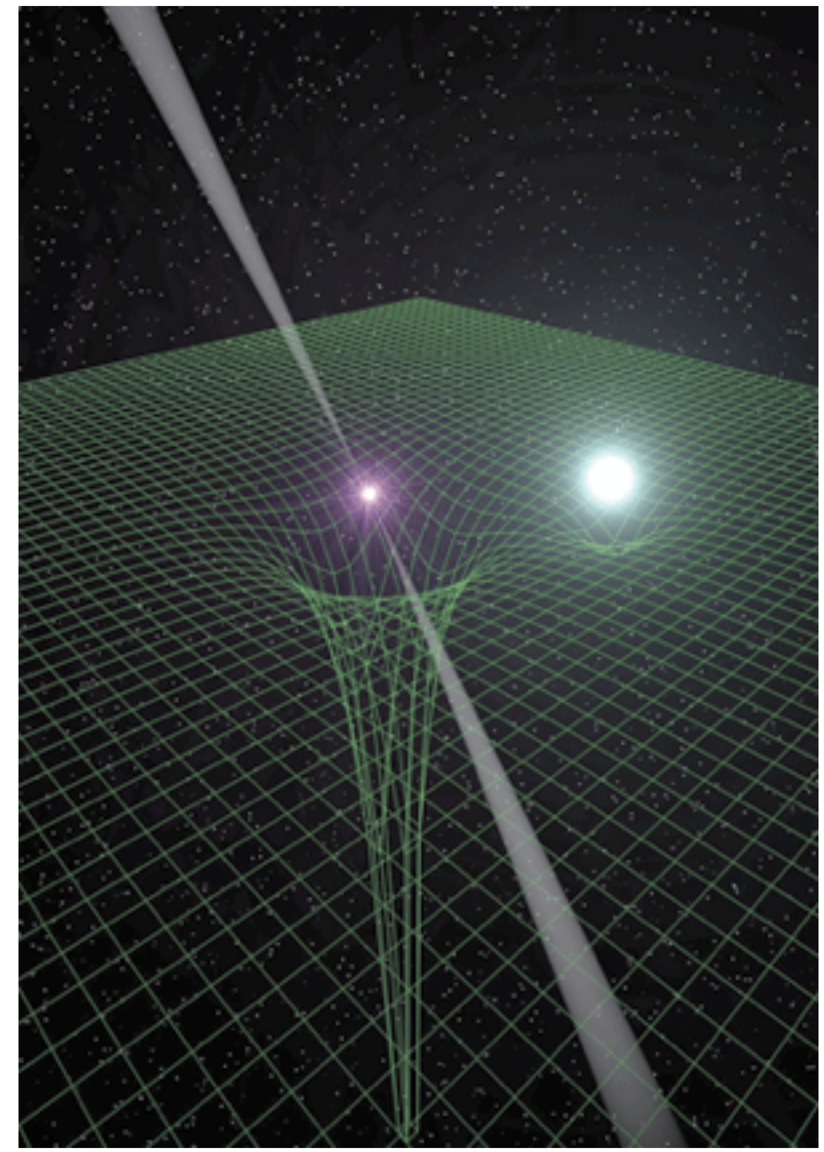




PSR J1614-2230

$$M = 1.97 \pm 0.04 \ M_\odot$$

J. Antoniadis et al.
Science **340** (2013) 6131



PSR J0348+0432

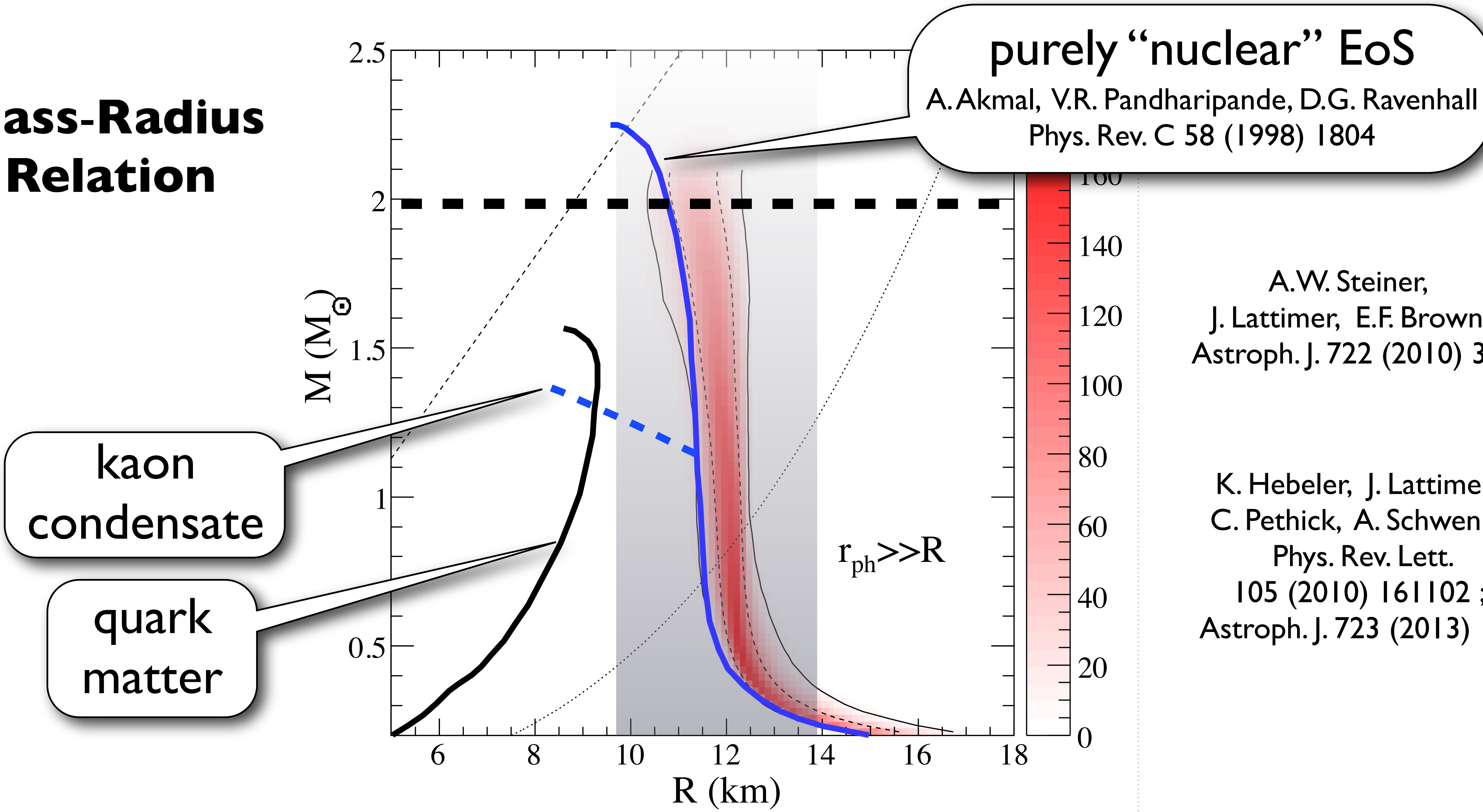
$$M = 2.01 \pm 0.04 \ M_\odot$$

News from NEUTRON STARS

- Constraints from **neutron star observables**

F. Özil, D. Psaltis: Phys. Rev. D80 (2009) 103003
F. Özil, G. Baym, T. Güver: Phys. Rev. D82 (2010)101301

Mass-Radius Relation



A.W. Steiner,
J. Lattimer, E.F. Brown
Astroph. J. 722 (2010) 33

K. Hebeler, J. Lattimer,
C. Pethick, A. Schwenk:
Phys. Rev. Lett.
105 (2010) 161102 ;
Astroph. J. 723 (2013) 11

- "**Exotic**" equations of state ruled out ?

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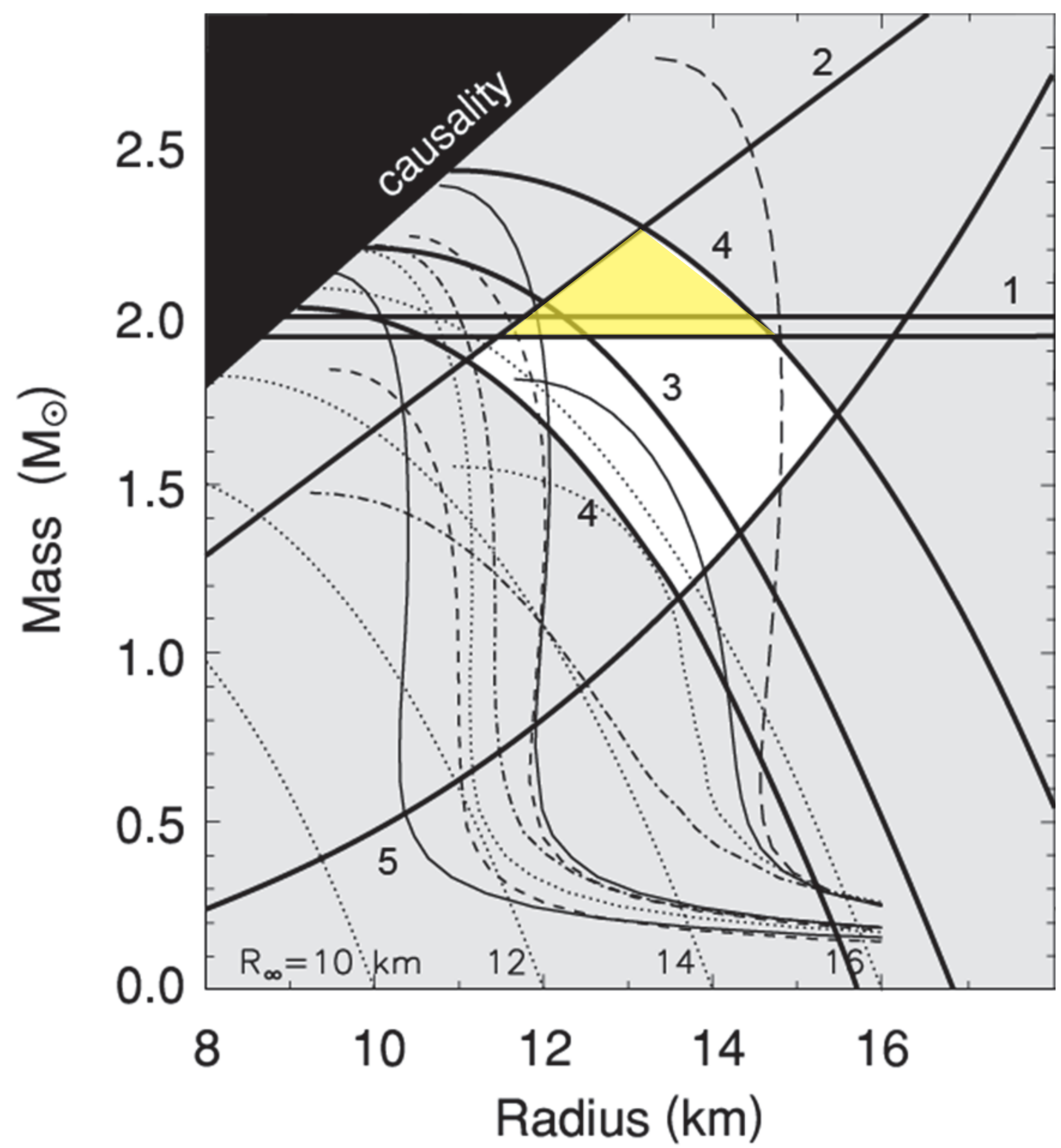
NEUTRON STARS: MASS and RADIUS constraints



J. E. Trümper
Prog. Part. Nucl. Phys.
66 (2011) 674

very **stiff**
Equation **of** **S**tate
required !

1 Largest mass J1614 - 2230
(Demorest et al. 2010)

2 Maximum gravity XTE 1814 – 338
(Bhattacharyya et al. 2005)

3 Minimum radius RXJ1856 - 3754
(Trümper et al. 2004)

4 Radius, 90% confidence limits LMXB 47 Tuc
(Heinke et al. 2006)

5 Largest spin frequency J1748 – 2446
(Hessels et al. 2006)

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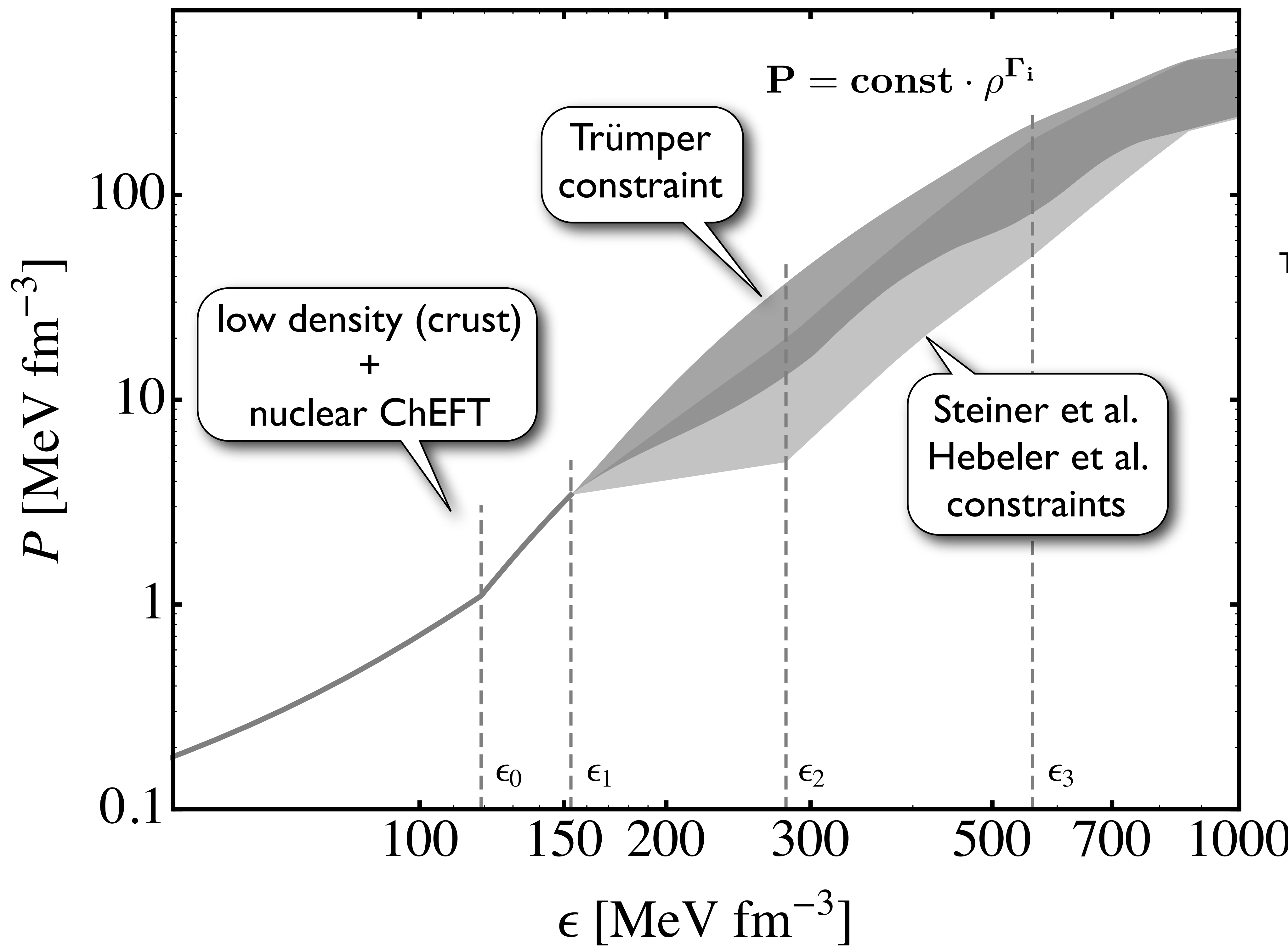
NEUTRON STAR MATTER

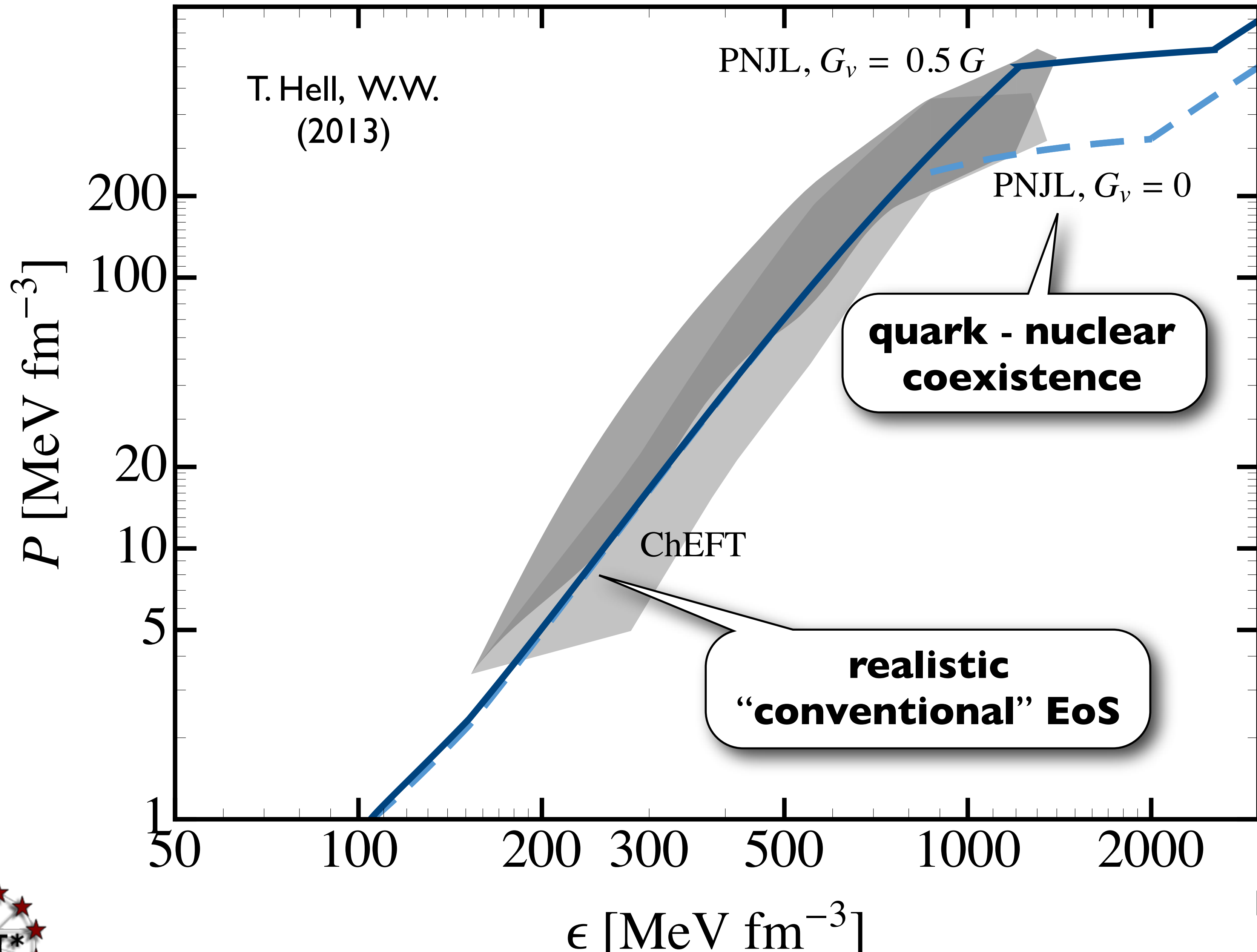
Equation of State (contd.)



T. Hell, B. Röttgers, W.W.
arXiv:1307.4582

NEUTRON STAR MATTER
Equation of State

- In-medium **C**hiral **E**ffective **F**ield **T**heory up to 3 loops
  (reproducing thermodynamics of normal nuclear matter)
- **3-flavor PNJL** model at high densities (incl. **strange** quarks)



- beta equilibrium
  $\mathbf{n} \leftrightarrow \mathbf{p} + e, \mu$
- charge conservation
- coexistence region:
  Gibbs conditions
- **quark-nuclear** coexistence occurs (if at all) at baryon densities
  $\rho > \mathbf{5}\ \rho_0$

see also:
K. Masuda, T. Hatsuda, T. Takatsuka
PTEP (2013) 7, 073D01

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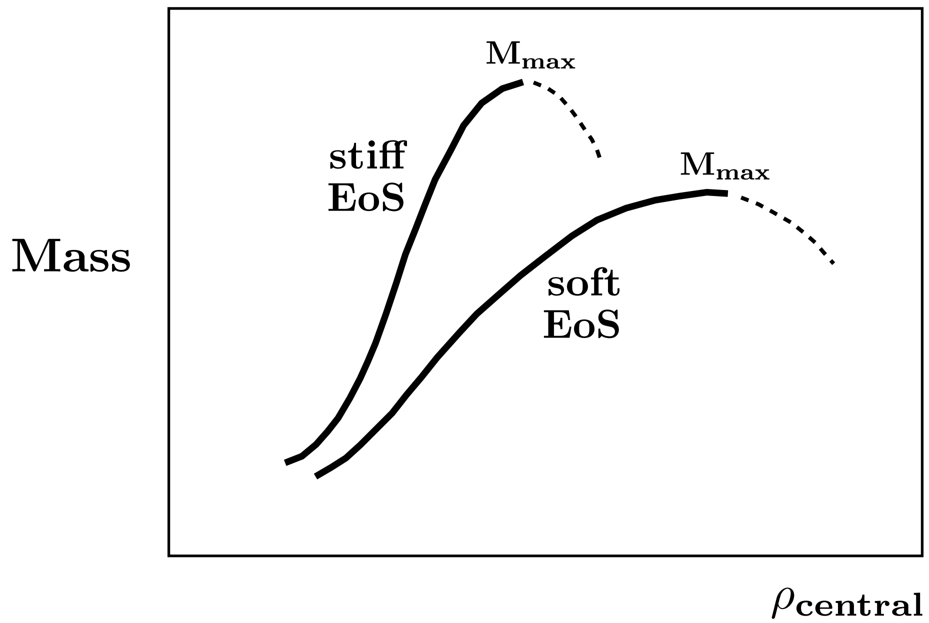
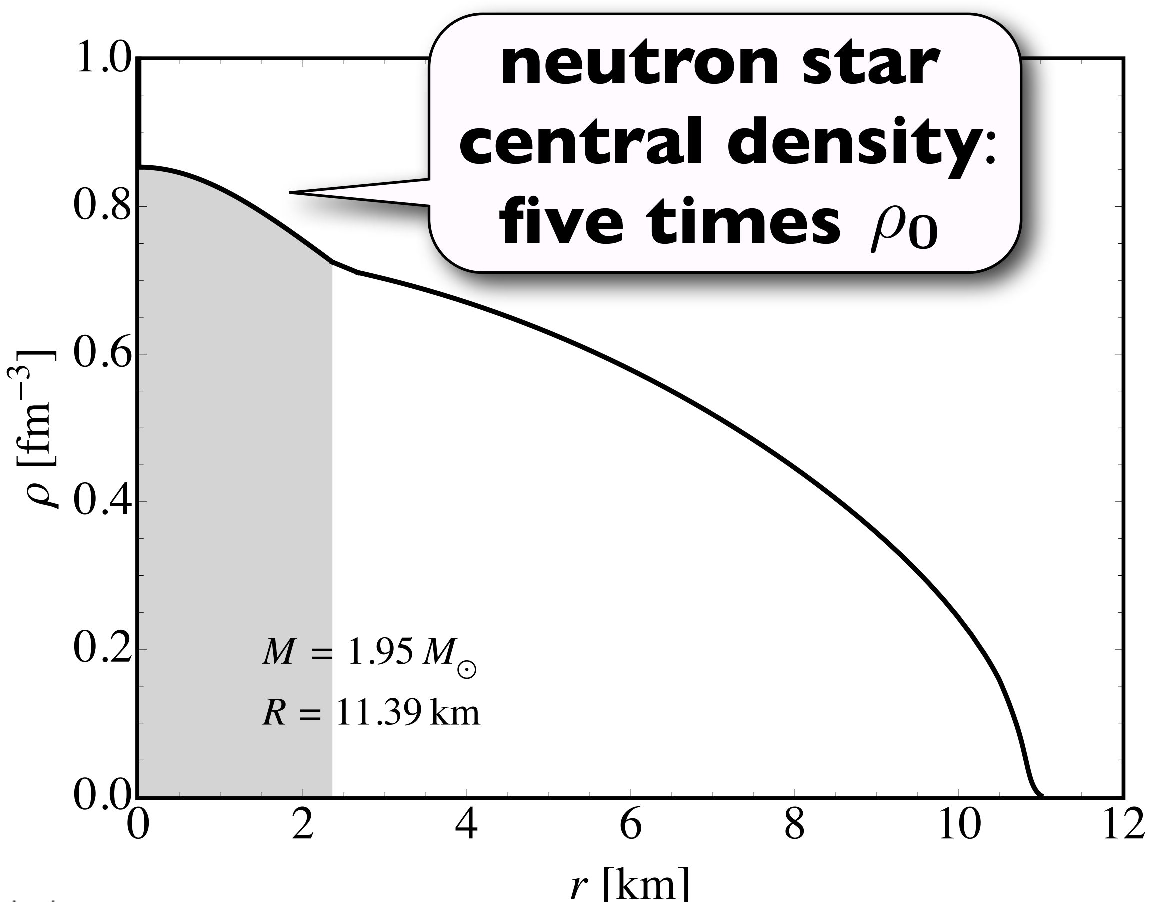
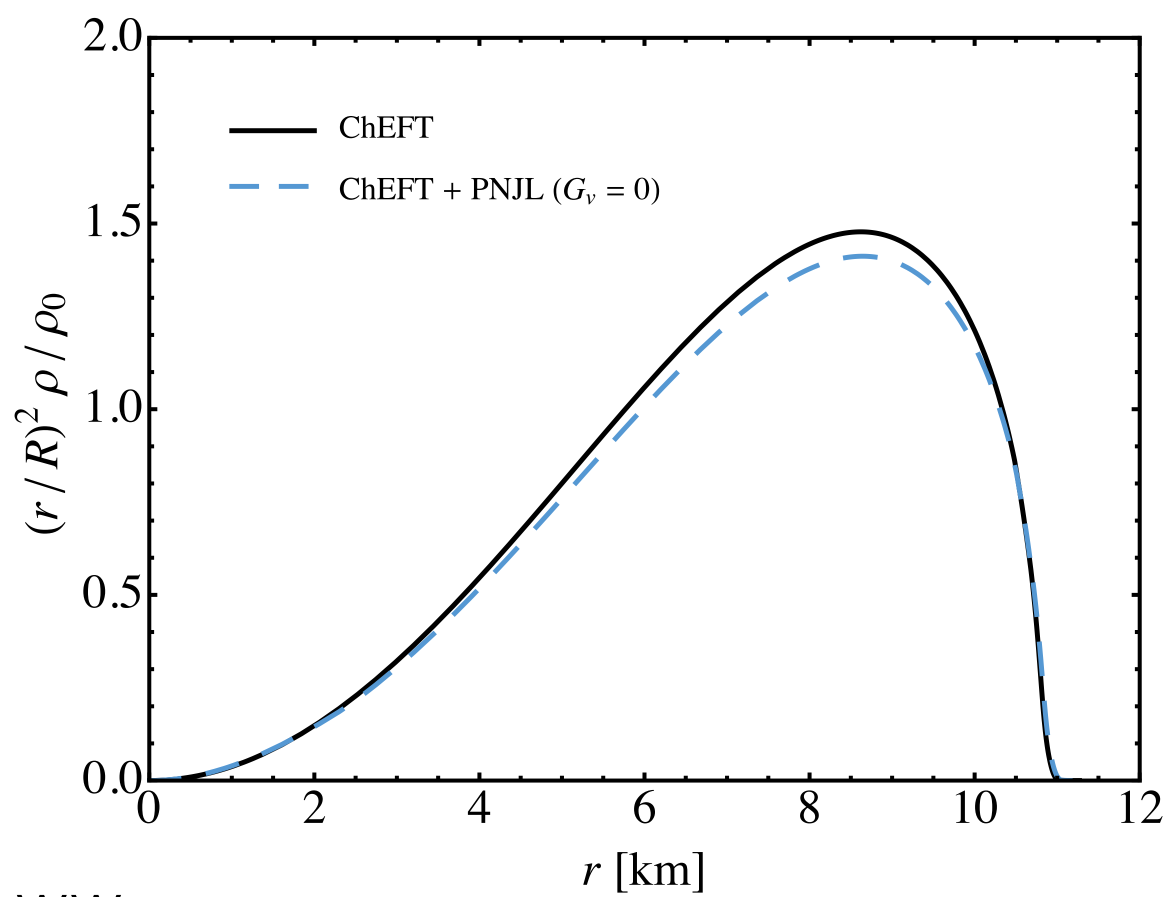
NEUTRON STAR MATTER
Density Profiles



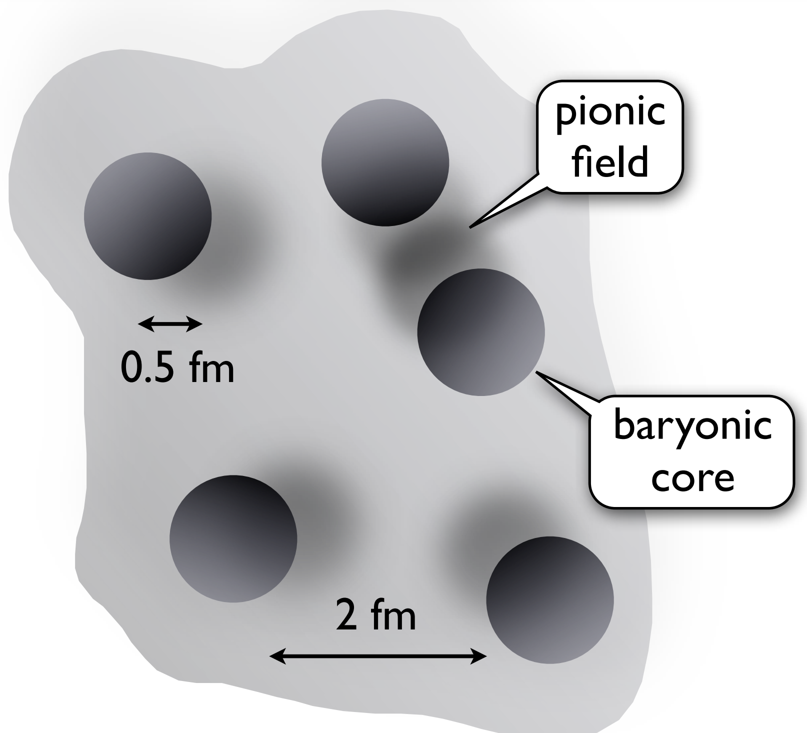
- stiff EoS
  → larger maximum mass
  → lower central density
- $$\mathbf{M(R)} = \frac{4\pi}{c^2}\int_0^R dr\, r^2\, \mathcal{E}(r)$$
  → relevant quantity: $r^2\rho(r)$





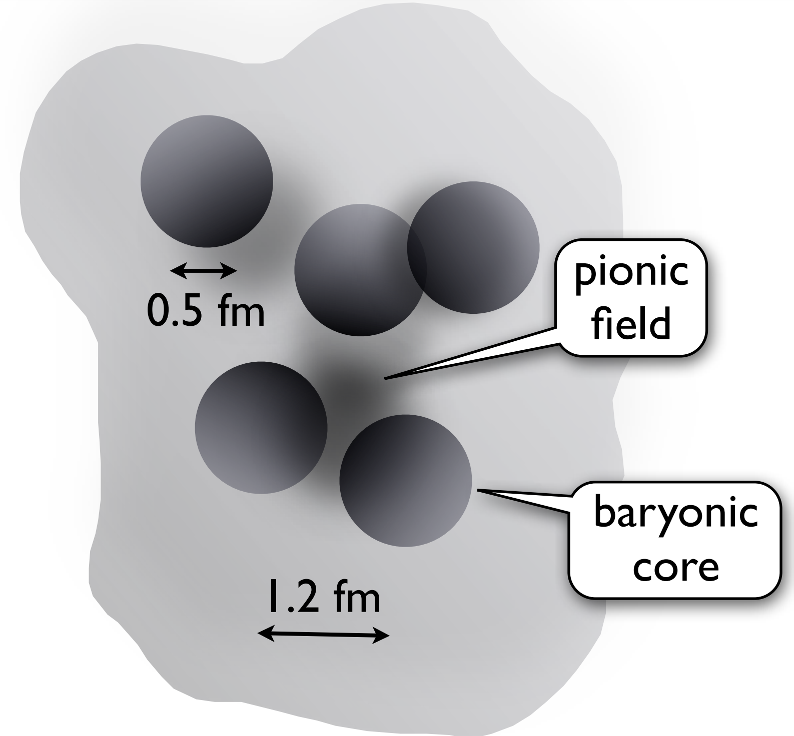
T. Hell, W.W. (2013)

Densities and Scales in Compressed Baryonic Matter



$\rho_B = 0.15\ \mathrm{fm}^{-3}$

normal nuclear matter: **dilute**

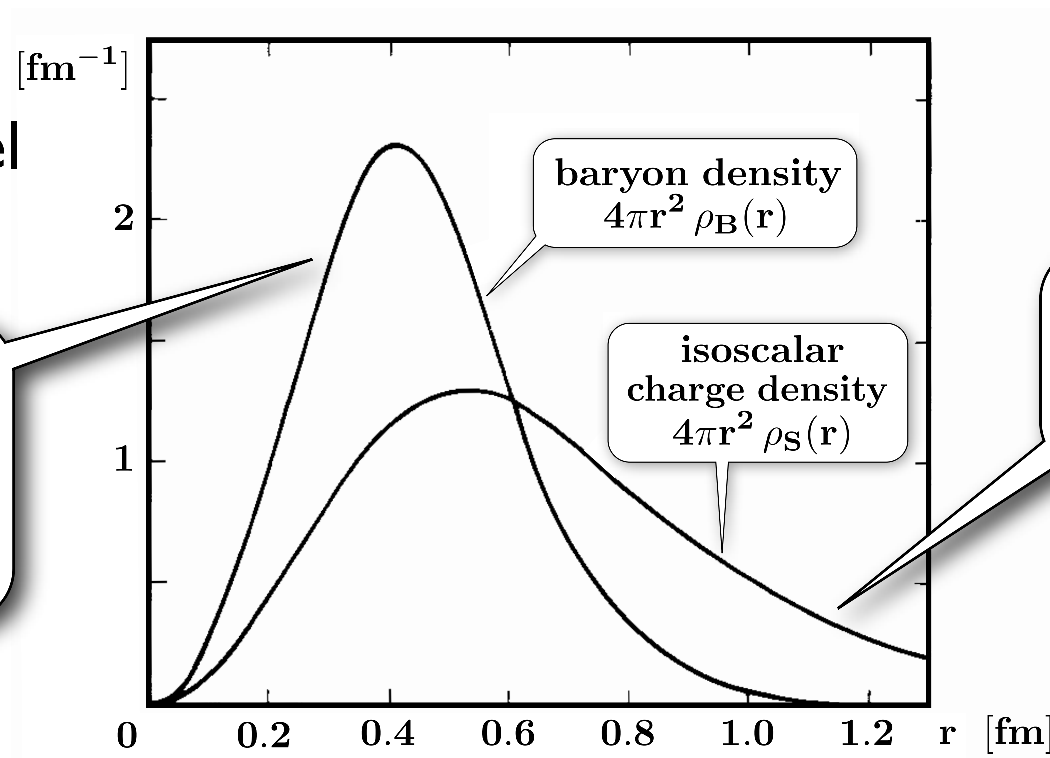


$\rho_B = 0.6\ \mathrm{fm}^{-3}$

neutron star core matter:
compressed but **not superdense**

remember the Brown-Rho Chiral Bag

- recall:
  chiral (soliton) model of the **nucleon**



N. Kaiser, U.-G. Meißner, W.W. Weise
Nucl. Phys. A 466 (1987) 685

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

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

. . . treated properly in chiral EFT