CHIRAL THERMODYNAMICS: from NUCLEAR MATTER to NEUTRON STARS

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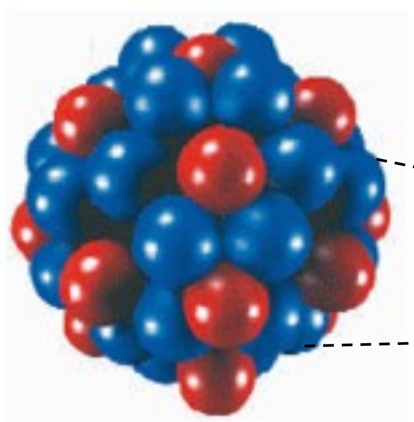
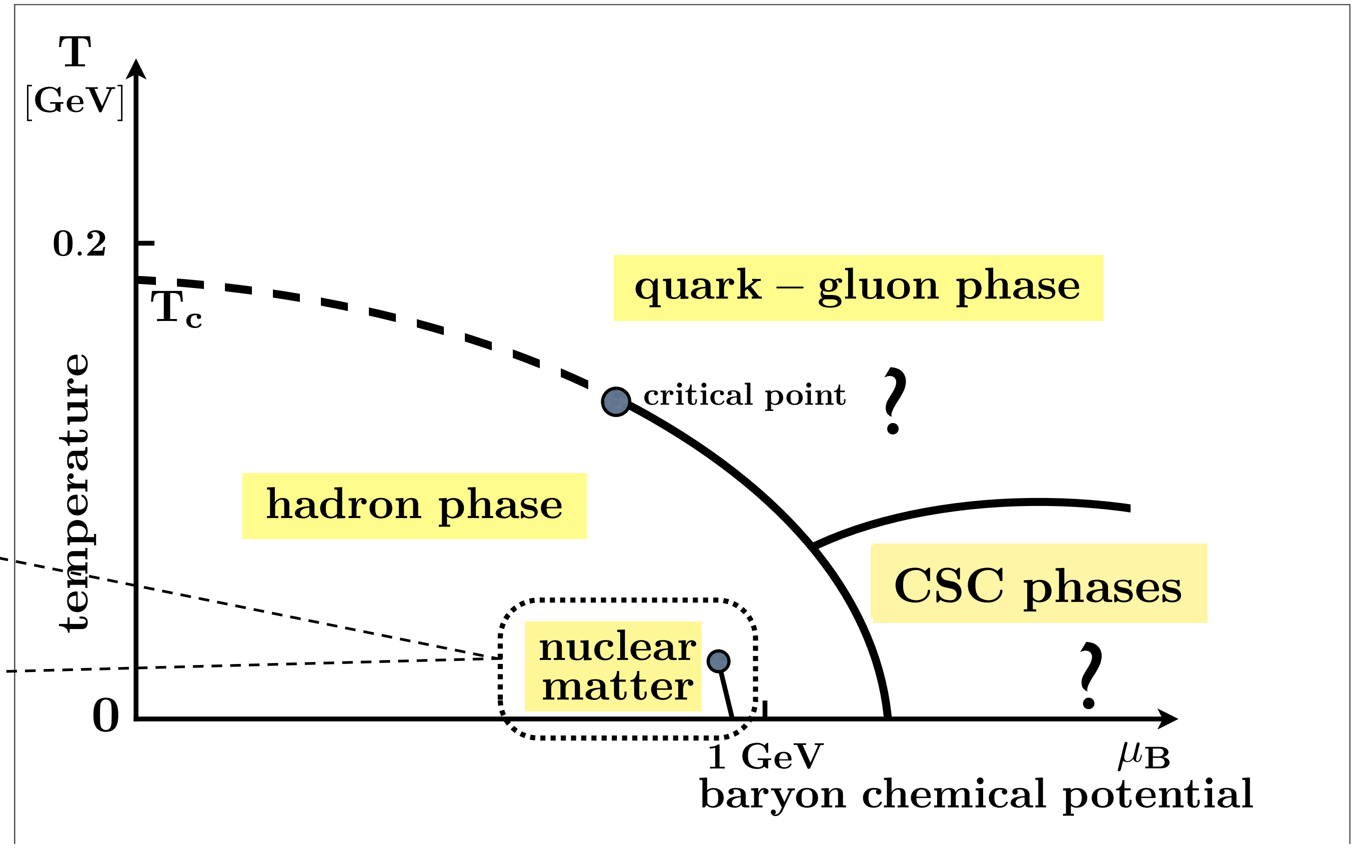
Technische Universität München

- QCD interface with nuclear physics:
  in-medium **Chiral Effective Field Theory**
- **Nuclear Equation of State**:
  liquid-gas phase transition and its N/Z evolution
- Density and temperature dependence of the
  Chiral (Quark) Condensate
- **Equation of State** of dense and cold matter:
  new constraints from **Neutron Stars**

NUCLEAR MATTER and QCD PHASES

nuclei

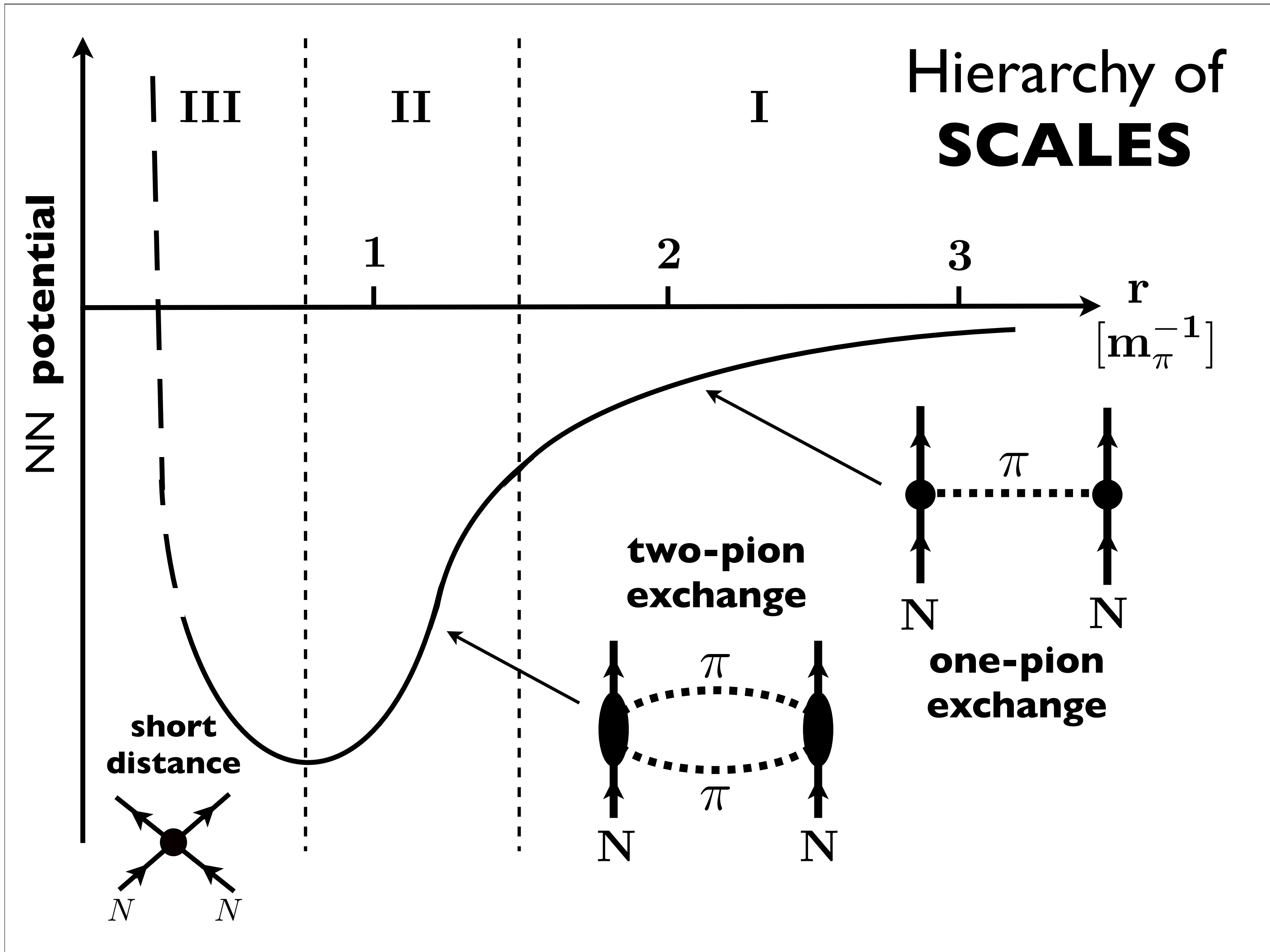




Scales in **nuclear matter**:

- 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
- Contemporary Developments -



Early history:

M. Taketani,
S. Nakamura,
M. Sasaki
(1951)

Today's approach:

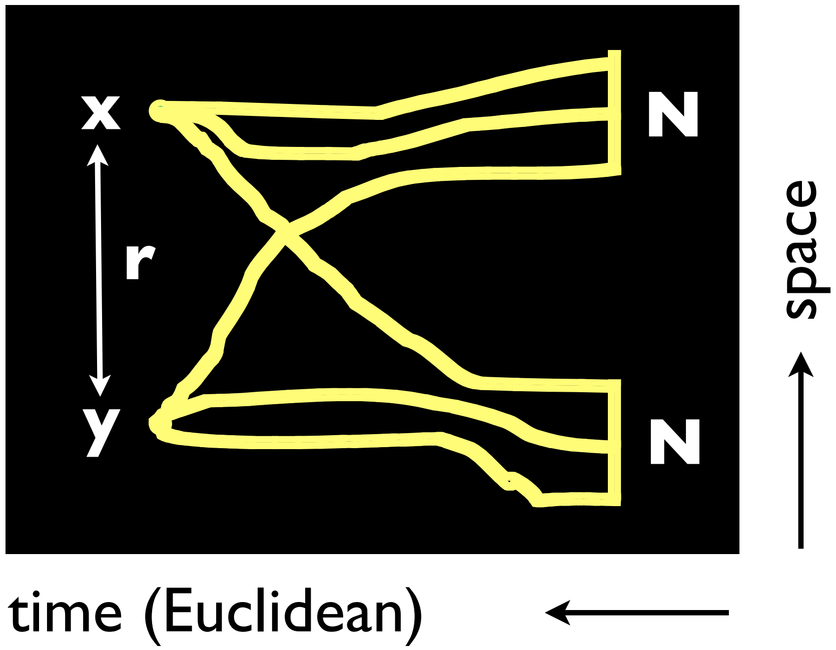
Chiral Effective Field Theory + Lattice QCD

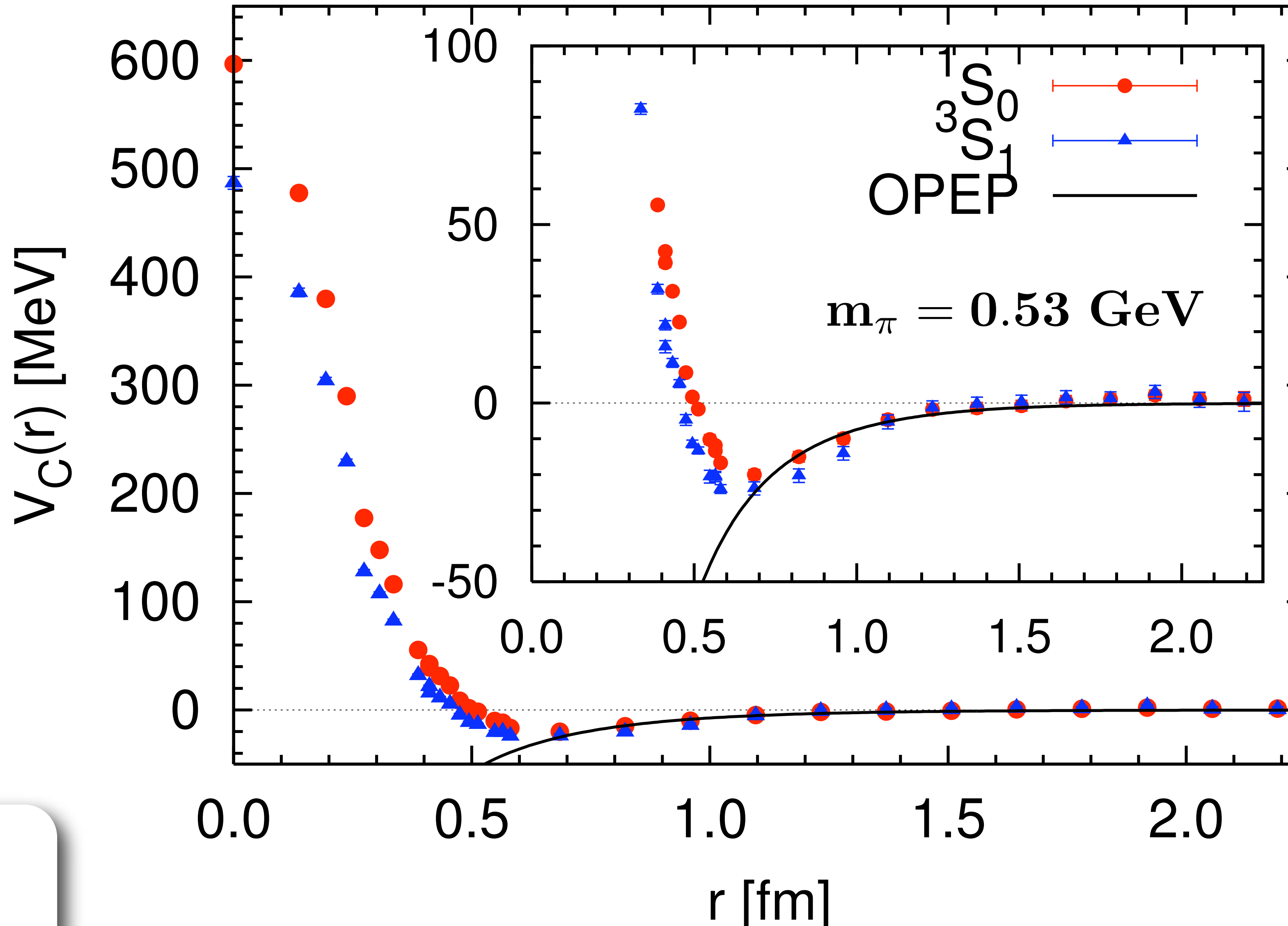
Short distance: NN POTENTIAL from LATTICE QCD

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

K. Murano, N. Ishii, S. Aoki, T. Hatsuda: Prog. Theor. Phys. 125 (2011) 1225

$\phi(\mathbf{r})$





still: mostly quenched QCD

"large" quark/pion masses

- Reconstruct potential from wave function:

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

- **Repulsive core** from Lattice QCD

Chiral Effective Field Theory
and the
Nuclear Many-Body Problem

PIONS and NUCLEI in the context of LOW-ENERGY QCD

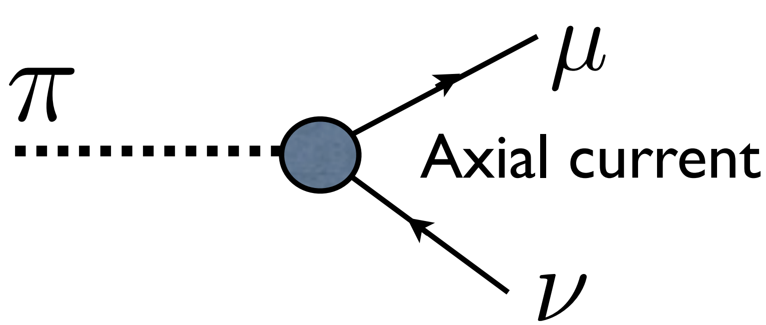
- **CONFINEMENT** of quarks and gluons in hadrons
- Spontaneously broken **CHIRAL SYMMETRY**

LOW-ENERGY / LOW-TEMPERATURE QCD:

Effective **F**ield **T**heory of **weakly** interacting **Nambu-Goldstone Bosons (PIONS)**

representing QCD at (energy and momentum) scales

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



$$\mathbf{f_\pi = 92.4\,MeV}$$

spontaneous symmetry breaking

$$\mathbf{m_\pi^2\, f_\pi^2} = -\mathbf{m_q}\, \langle \bar{\psi}\psi \rangle + \mathcal{O}(m_q^2)$$

explicit symmetry breaking

CHIRAL EFFECTIVE FIELD THEORY

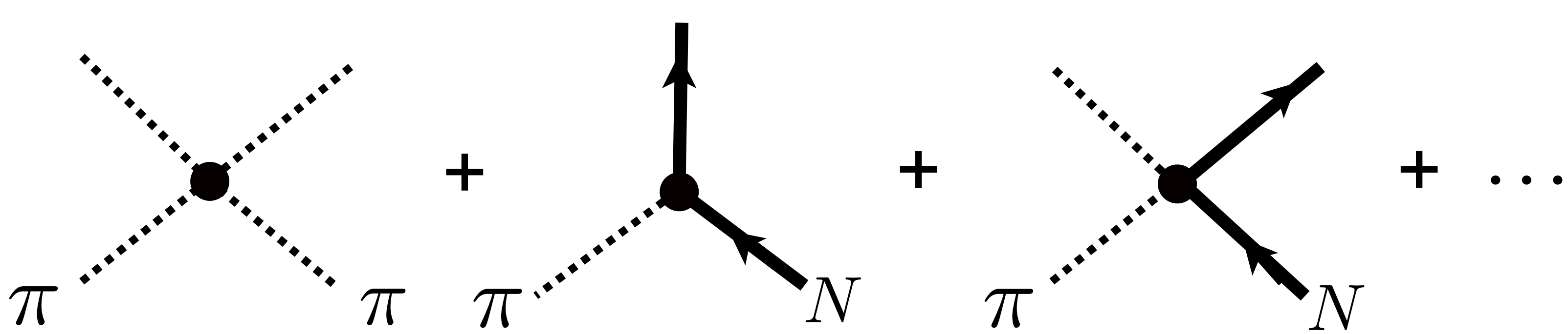
- Systematic framework at interface of QCD and Nuclear Physics

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

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

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

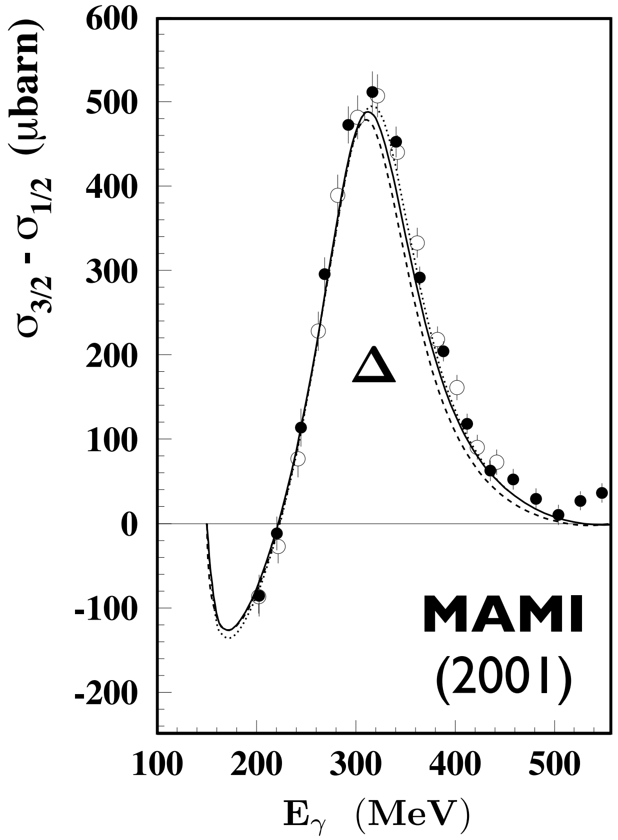
- Construction of Effective Lagrangian: **Symmetries**



short distance dynamics: **contact terms**

Explicit $\Delta(1230)$ DEGREES of FREEDOM

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

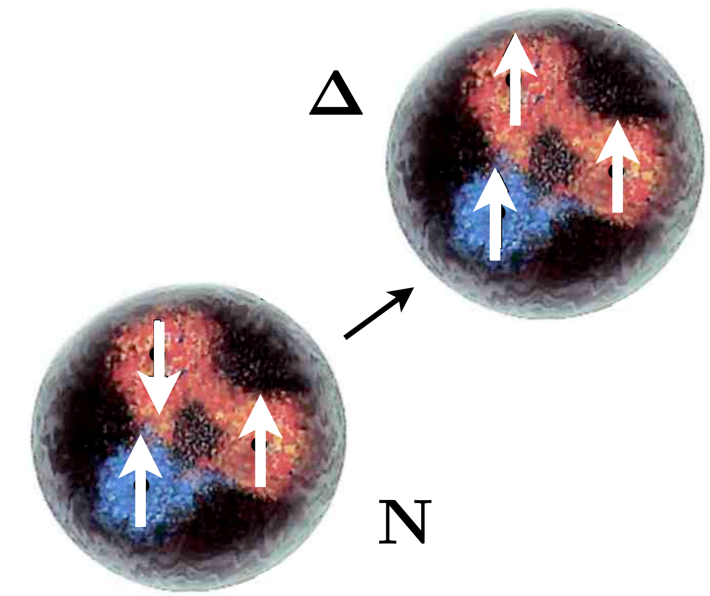


◀ example: polarized Compton scattering

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

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

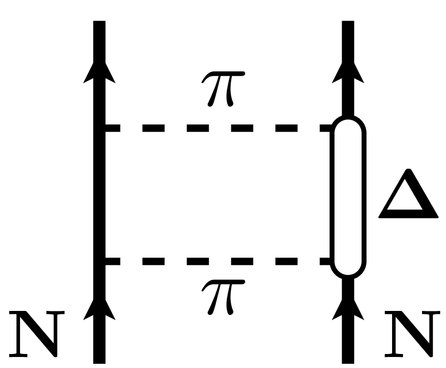
(small scale)



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

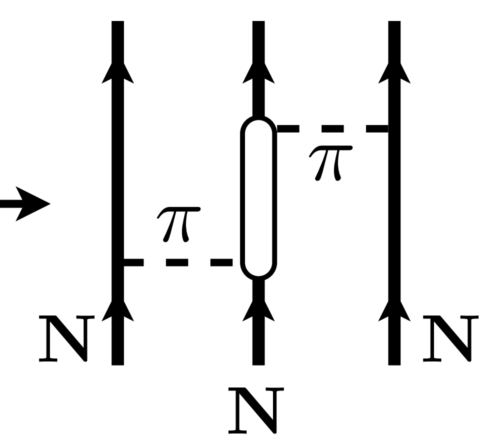
N. Kaiser, S. Gerstendörfer, W.W., NPA637 (1998) 395

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



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

⟷

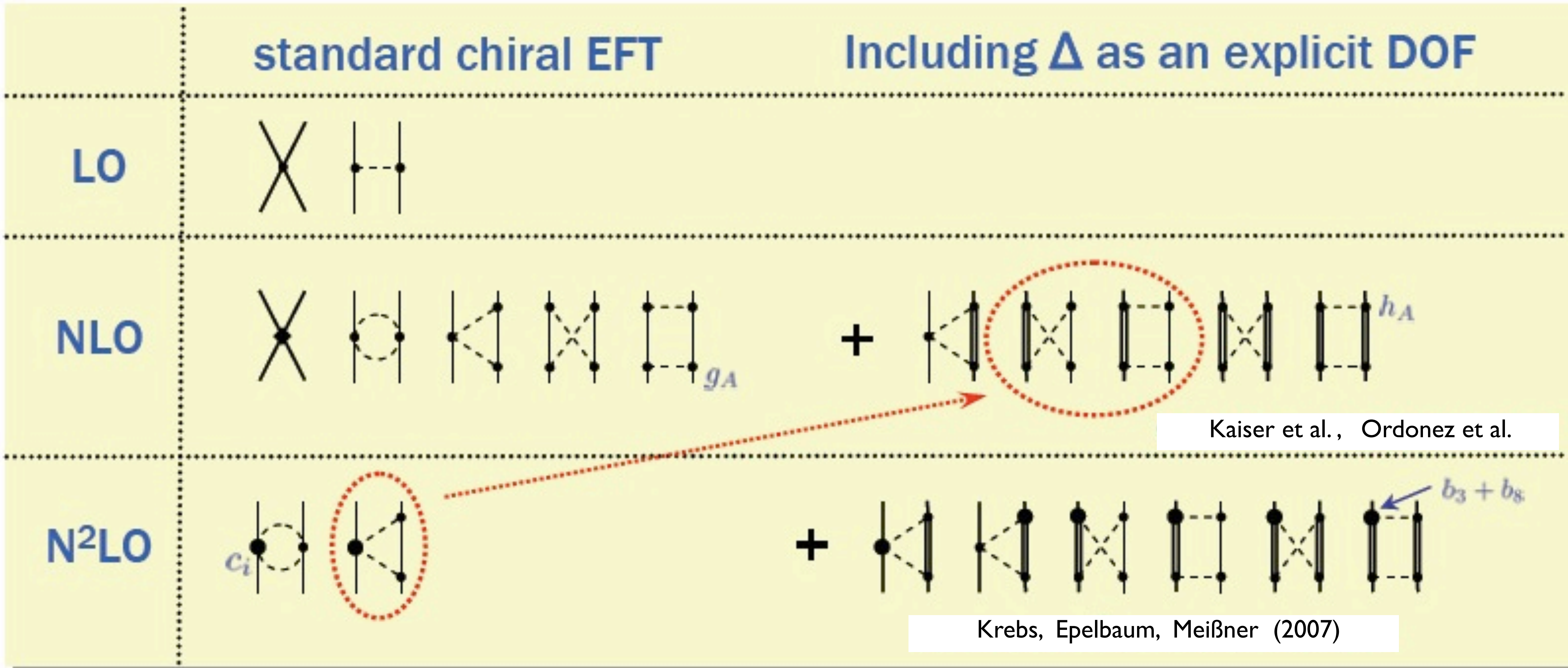


strong 3-body interaction

J. Fujita, H. Miyazawa (1957)

Pieper, Pandharipande, Wiringa, Carlson (2001)

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



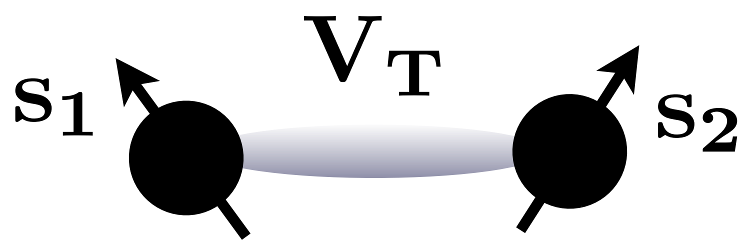
(with thanks to Evgeny Epelbaum)

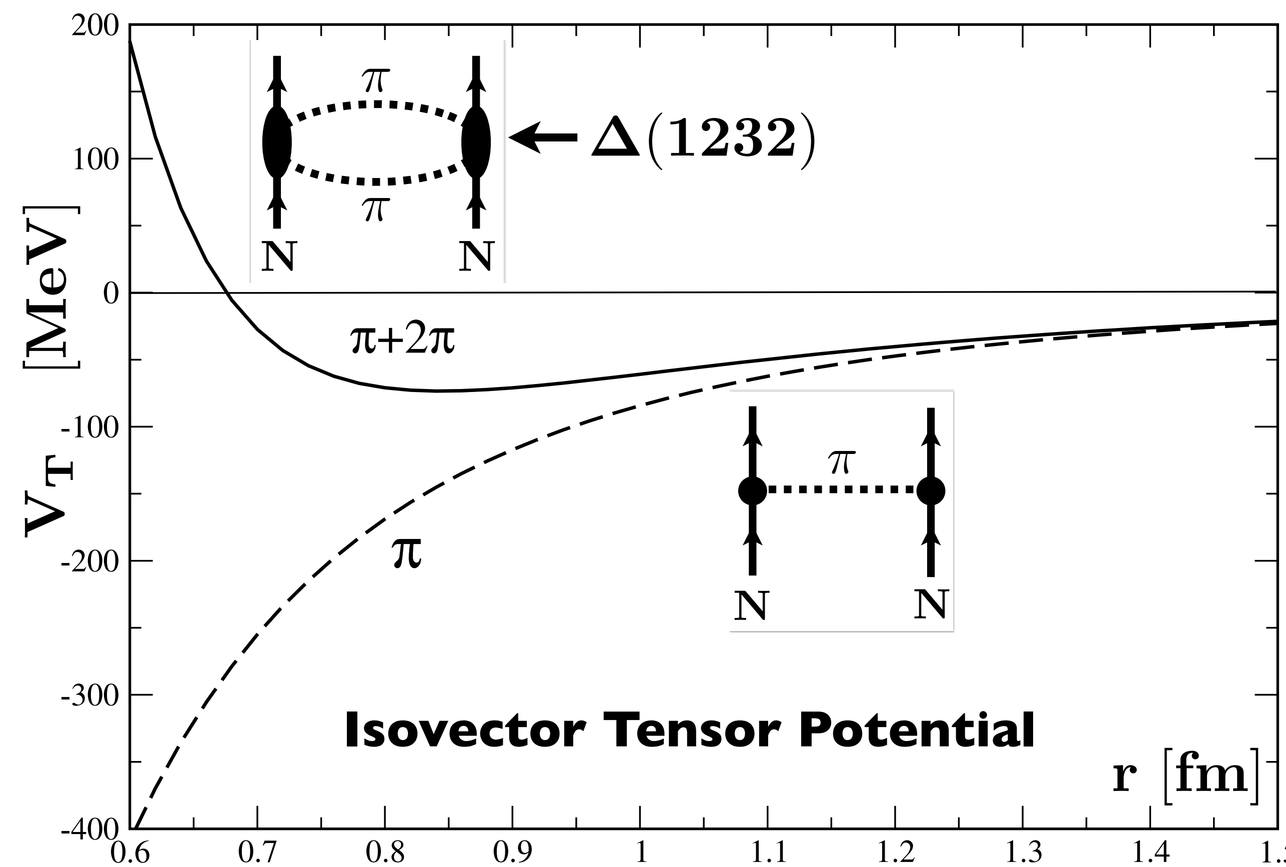
- **Important physics** of $\Delta(1230)$ promoted to **NLO**
- **Improved** convergence

Important pieces of the

CHIRAL NUCLEON-NUCLEON INTERACTION

- **ISOVECTOR TENSOR FORCE**

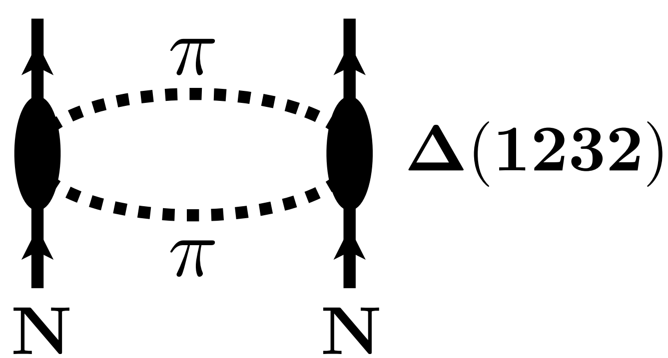




N. Kaiser, S. Gerstendörfer, W.W.: Nucl. Phys. A 637 (1998) 395

- note: **no** ρ meson

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



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

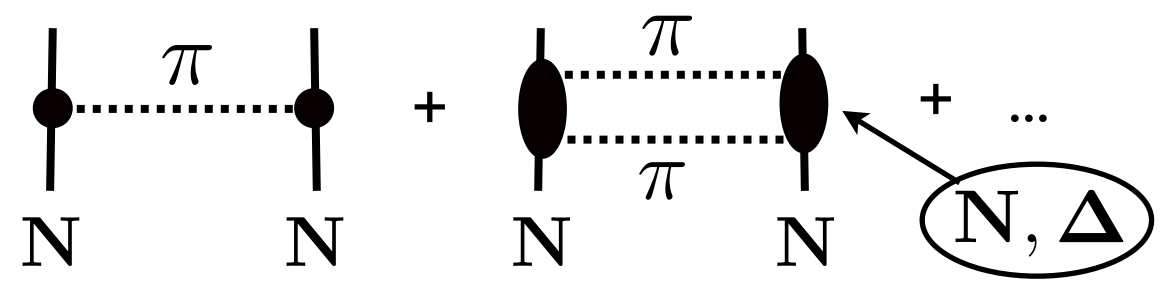
- note: **no** σ boson

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**

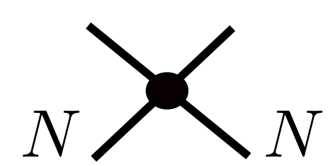
pion exchange processes in presence of filled **Fermi sea**



in-medium

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

short-distance dynamics:



contact interactions (incl. **resummations**)

IN-MEDIUM CHIRAL PERTURBATION THEORY

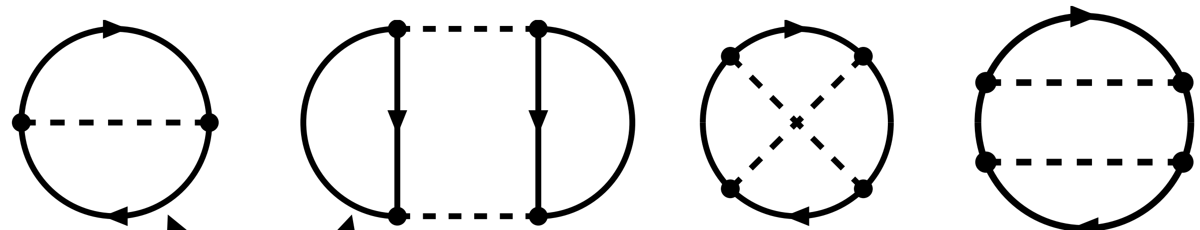
- **Loop expansion** of (**I**n-**M**edium) **Ch**iral **P**erturbation **T**heory

  $\updownarrow$

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

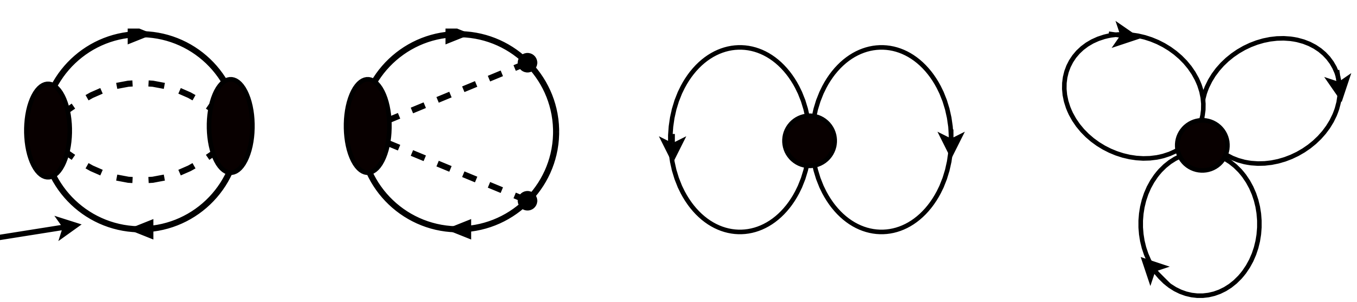
  (works for $\mathbf{k_F << 4\pi\, f_\pi \sim 1\, GeV}$)

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



(3-loop order)

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



in-medium
nucleon propagators
incl. Pauli blocking

FINITE NUCLEI

- . . . including the **nuclear surface** :

  Energy **Density Functional**

  J.W. Holt, N. Kaiser, W.W. : Eur. Phys. J. A 47 (2011) 128

- many quantitatively successful applications throughout the nuclear chart e.g. P. Finelli et al.: Nucl. Phys. A 770 (2007) 1

  - **binding energies** and **charge radii**
  - **pairing** and **ground state deformations**

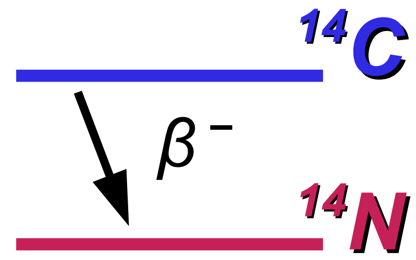
- systematics through **isotopic chains** governed by

  isospin dependent forces
  from **chiral pion dynamics**

… further 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

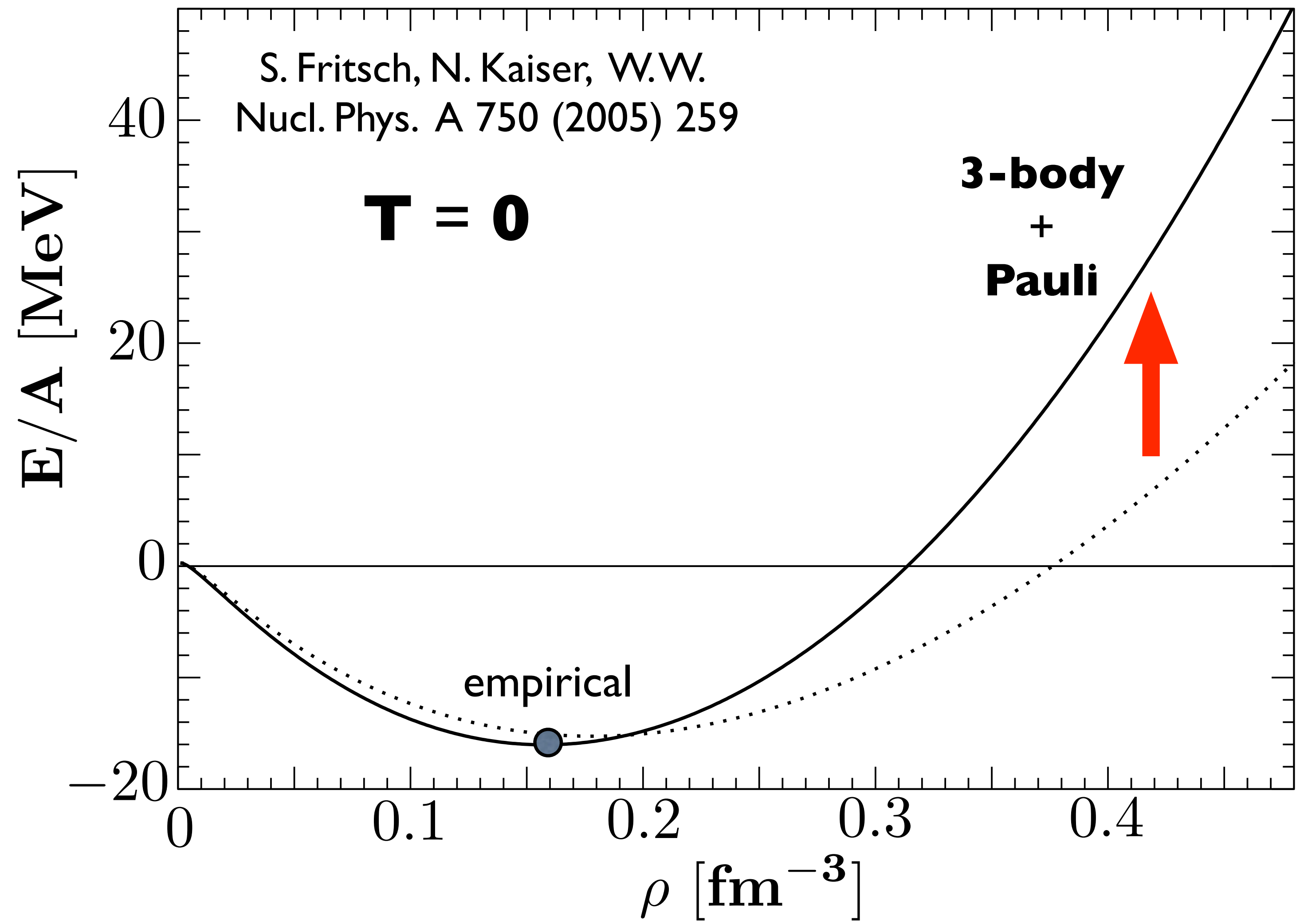
NUCLEAR MATTER

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

- **Input** parameters:
  two contact terms

- 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 $A(k_F^0) = 34\,\mathrm{MeV}$

  - Quasiparticle interaction and Landau parameters

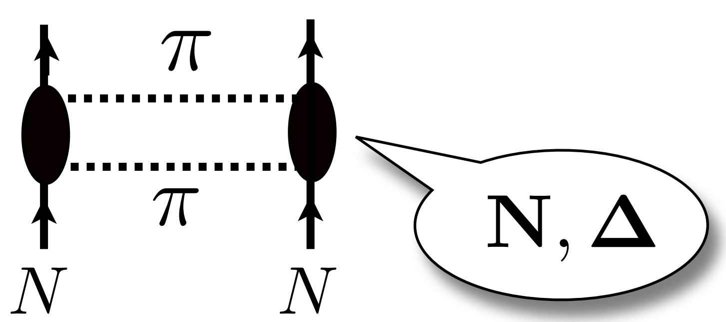
J.W. Holt, N. Kaiser, W.W.
Nucl. Phys. A 870 (2011) 1,
Nucl. Phys. A 876 (2012) 61

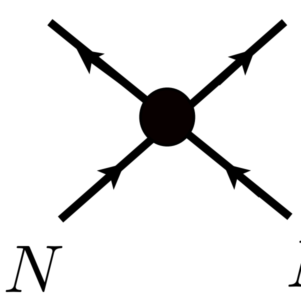
NUCLEAR THERMODYNAMICS

NUCLEAR
CHIRAL (PION) **DYNAMICS**

BINDING & SATURATION:

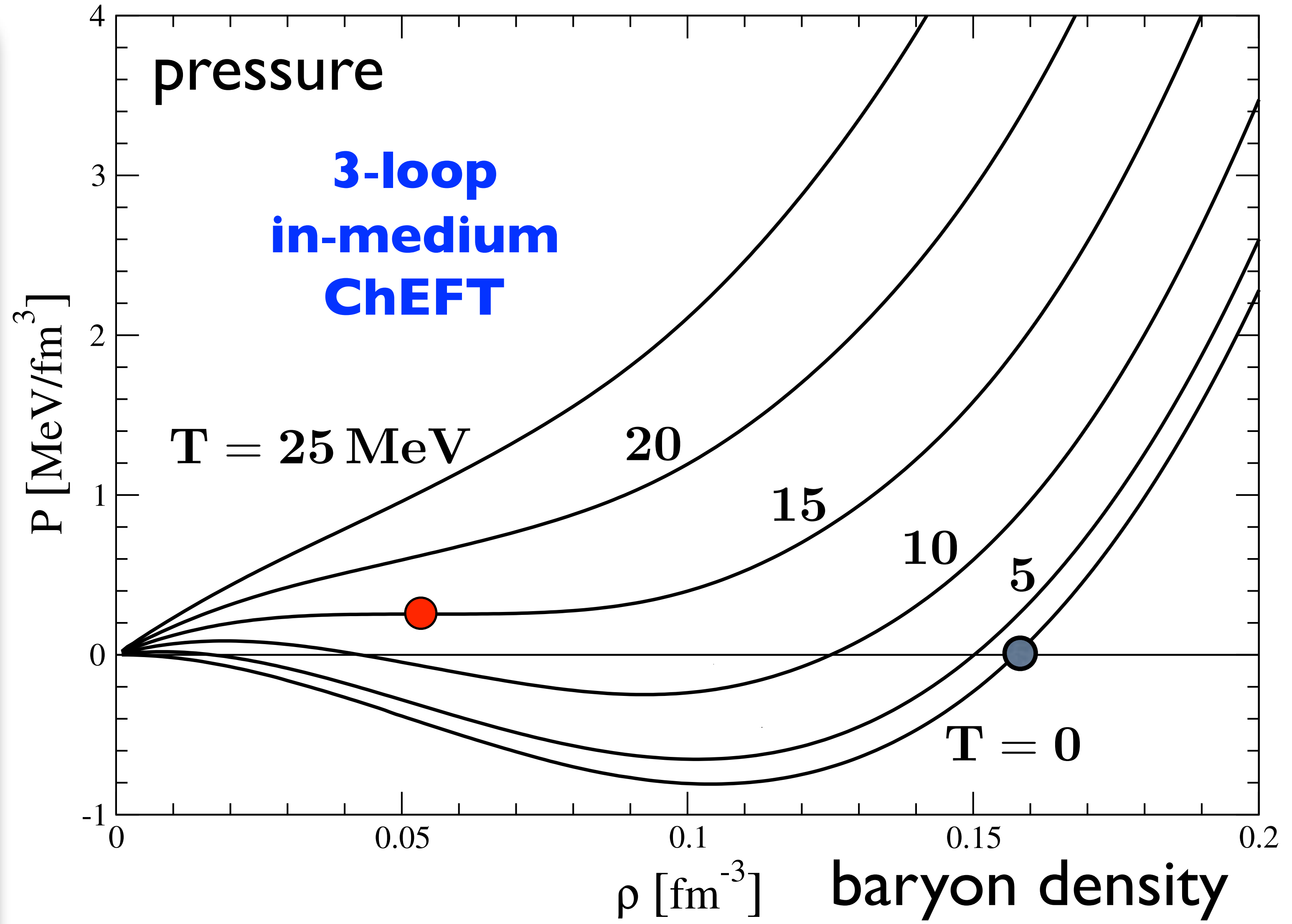
Van der Waals + Pauli



\+  + **3-body forces**

contact terms

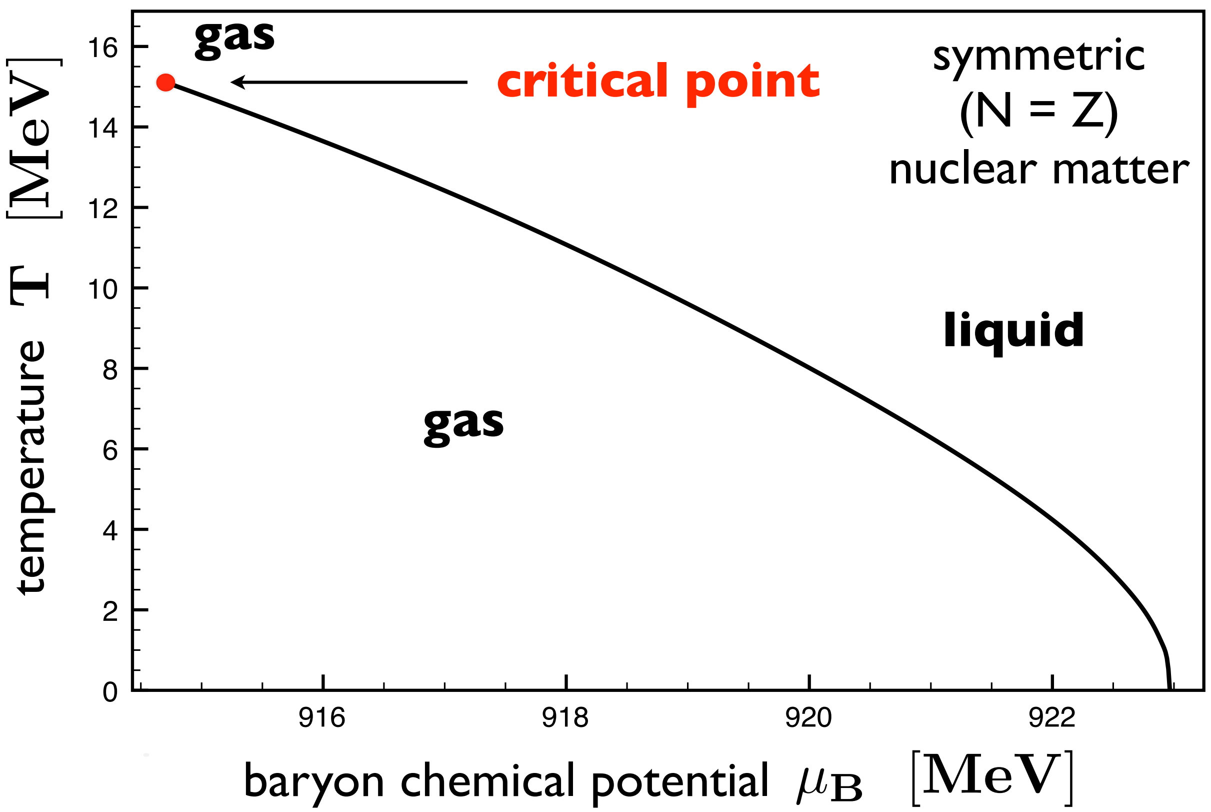
nuclear matter: equation of state



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

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

PHASE DIAGRAM of NUCLEAR MATTER

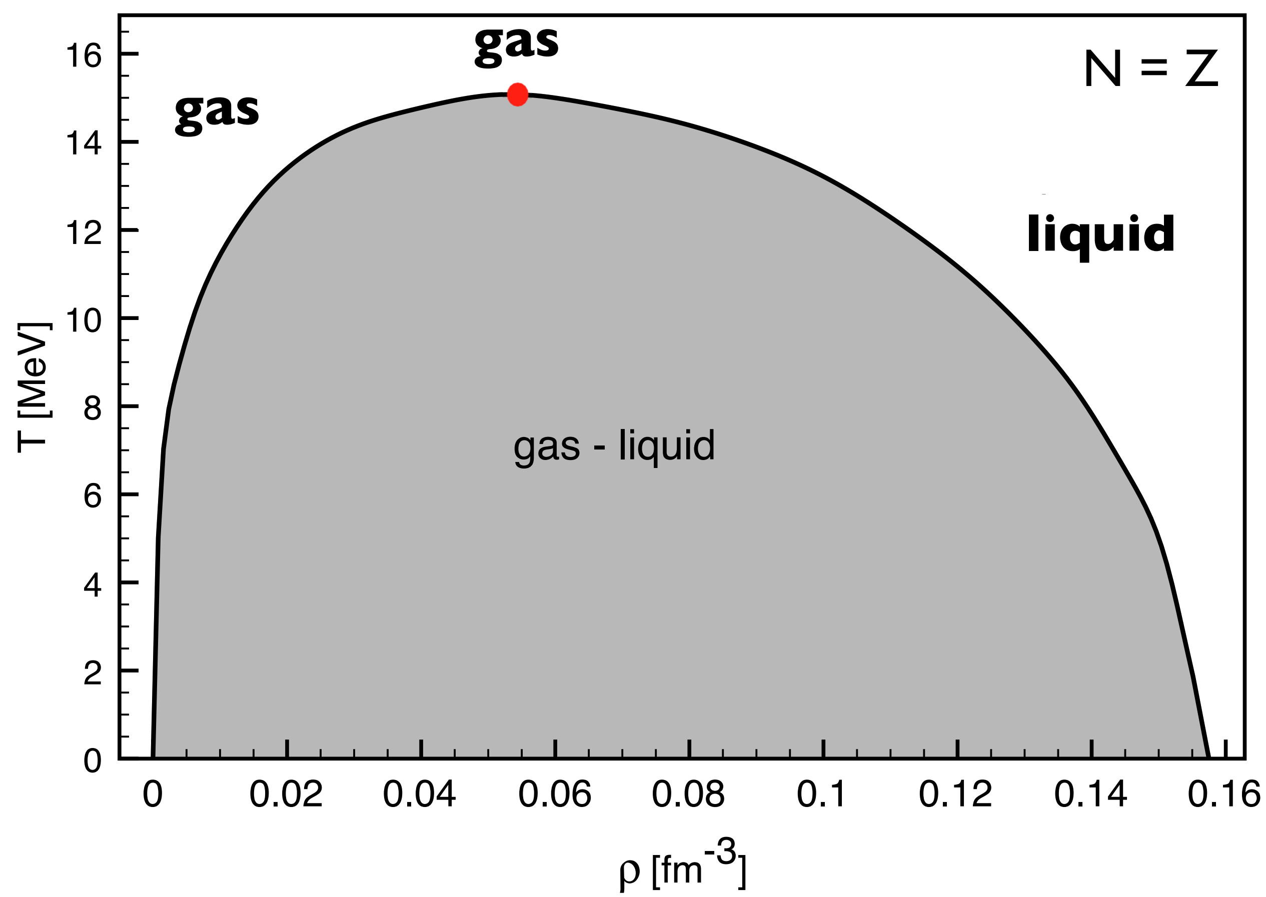


- Pion-nucleon dynamics incl. delta isobars
- Short-distance NN contact terms
- Three-body forces

- In-medium **chiral effective field theory** (3-loop calculation of free energy density)

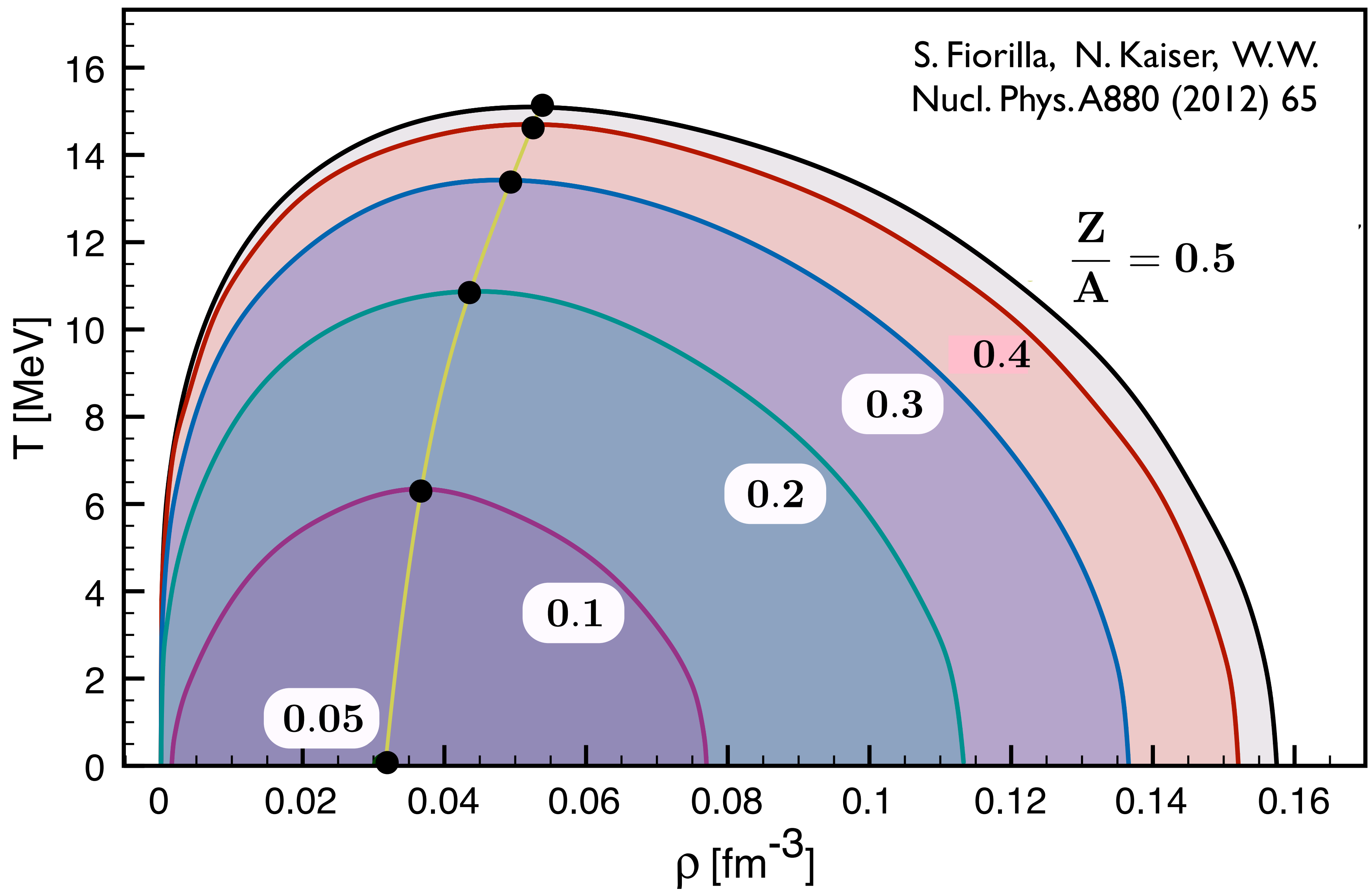
S. Fritsch, N. Kaiser, W.W.
Nucl. Phys. A 750 (2005) 259

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



PHASE DIAGRAM of NUCLEAR MATTER

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

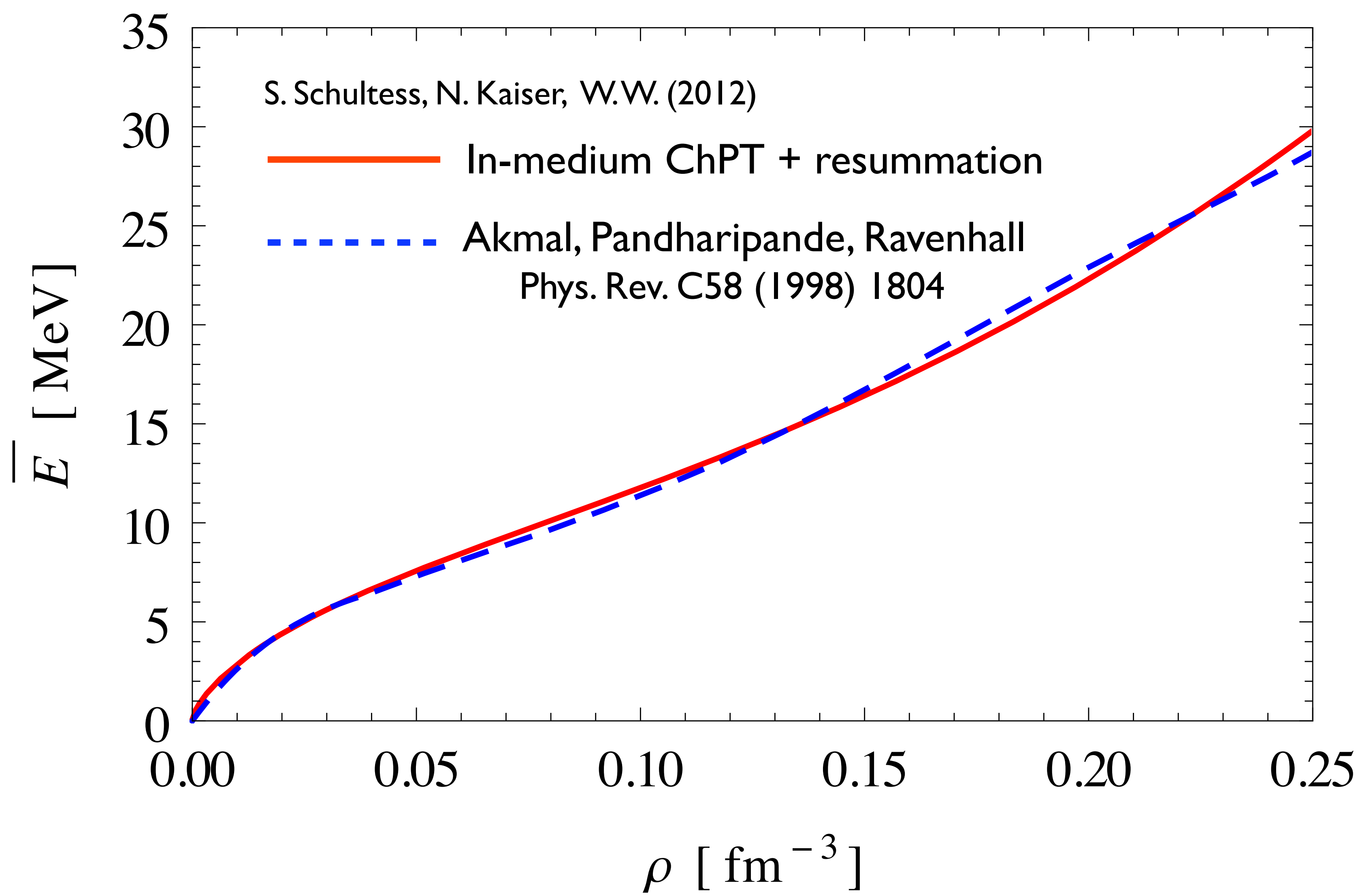


. . . determined almost entirely by
isospin dependent (one- and two-) **pion** exchange dynamics

NEUTRON MATTER

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

N. Kaiser, Nucl. Phys. A 860 (2011) 370



- perfect agreement with sophisticated many-body calculations
  (e.g. VCS (Urbana) or QMC methods (P. Armani et al., arXiv:1110.0993))

. . . short digression:

Nuclear Thermodynamics

and the

Chiral Condensate

CHIRAL CONDENSATE at finite BARYON DENSITY

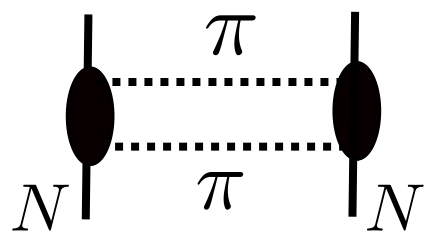
- Chiral (quark) condensate $\langle\bar{q}q\rangle$: $\qquad m_\pi^2 f_\pi^2 = -2\, m_q \langle\bar{q}q\rangle$

  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)

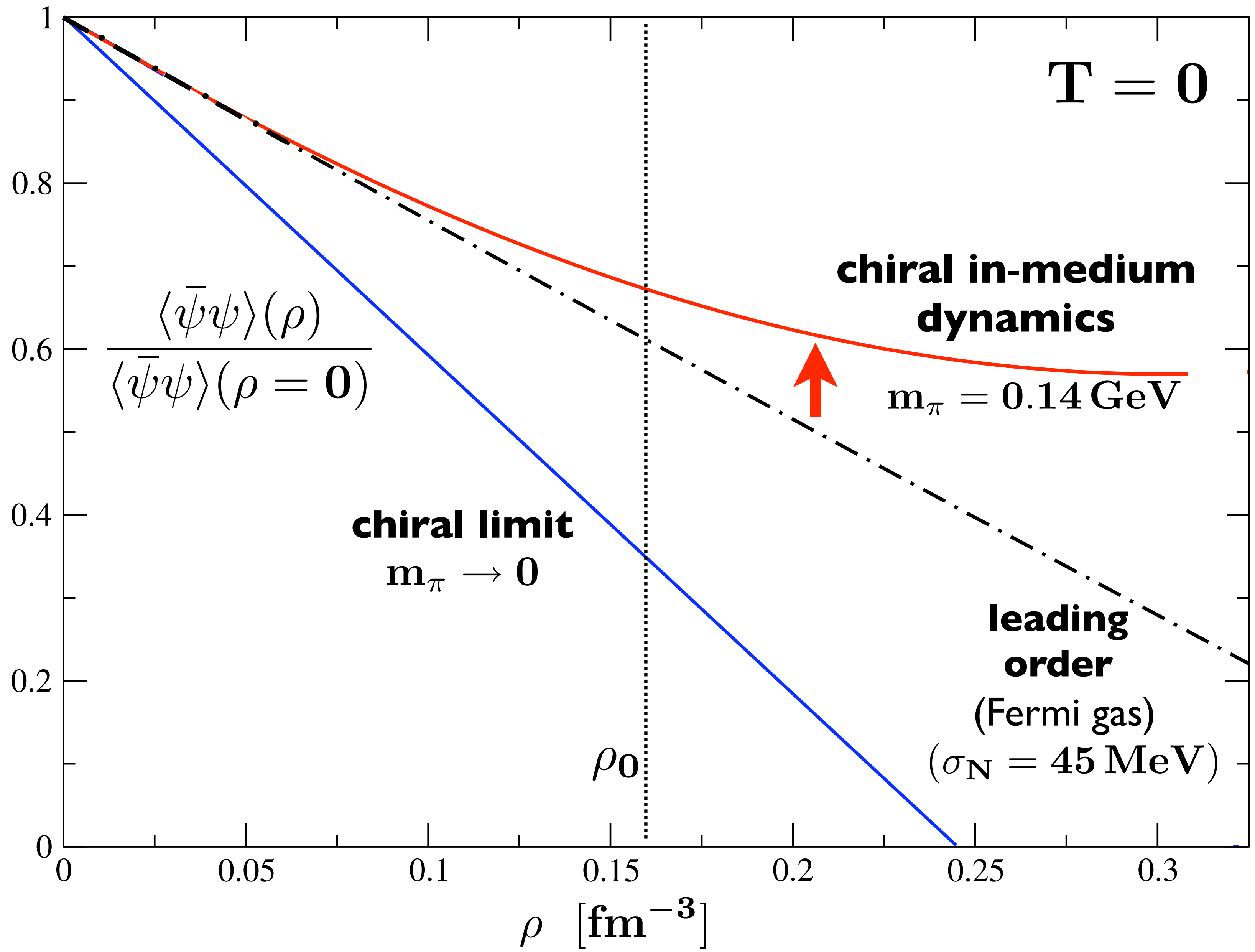
CHIRAL CONDENSATE: DENSITY DEPENDENCE

- **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 $m_q = 0$ and physical quark mass $m_q \sim 5\,MeV$

- **Nuclear Physics** would be **very different** in the **chiral limit** !

CHIRAL CONDENSATE:
DENSITY and TEMPERATURE DEPENDENCE

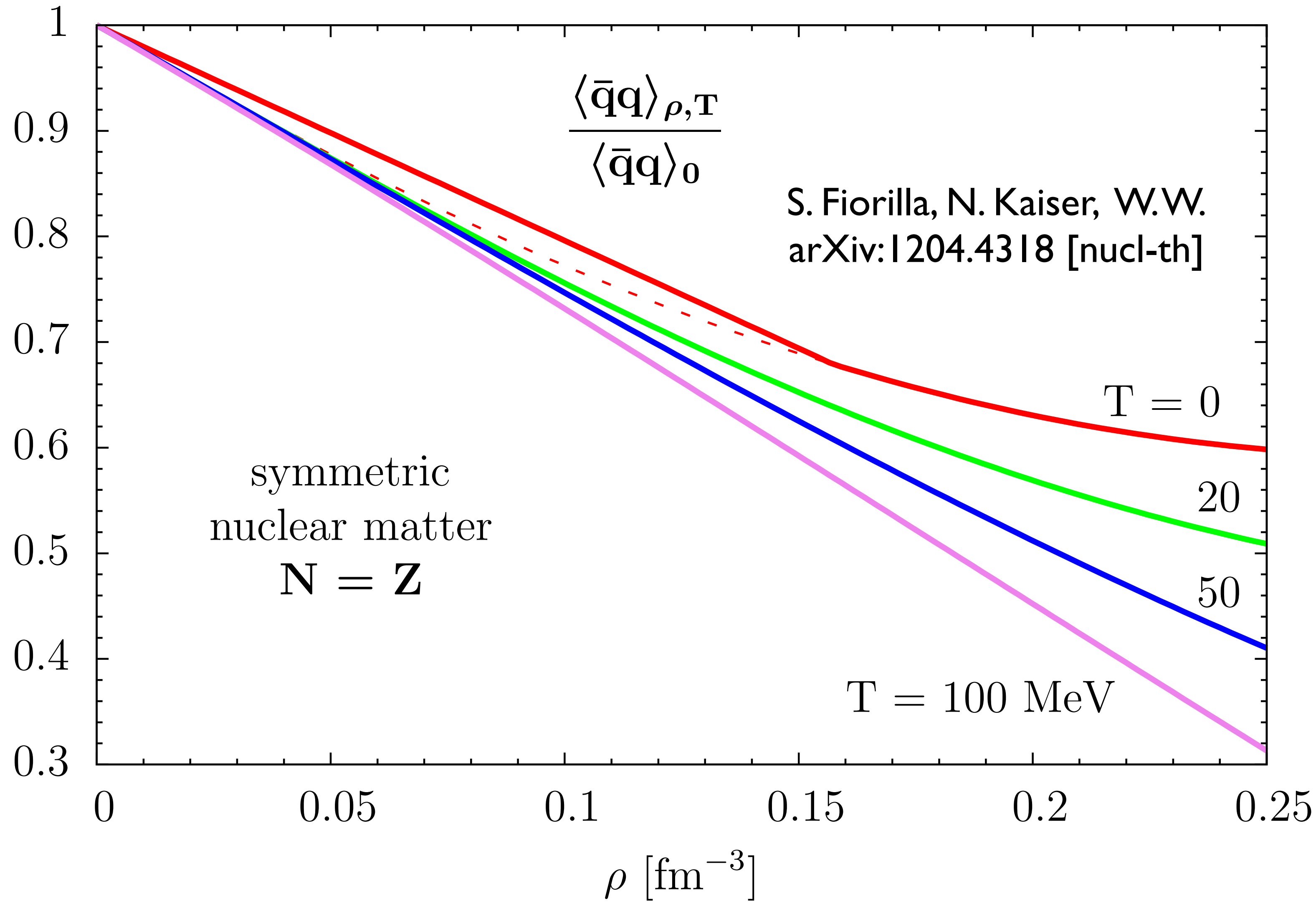
- Free energy density $\mathcal{F}(\mathbf{m_q}; \rho, \mathbf{T})$

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

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

  (NLO 3-loop)

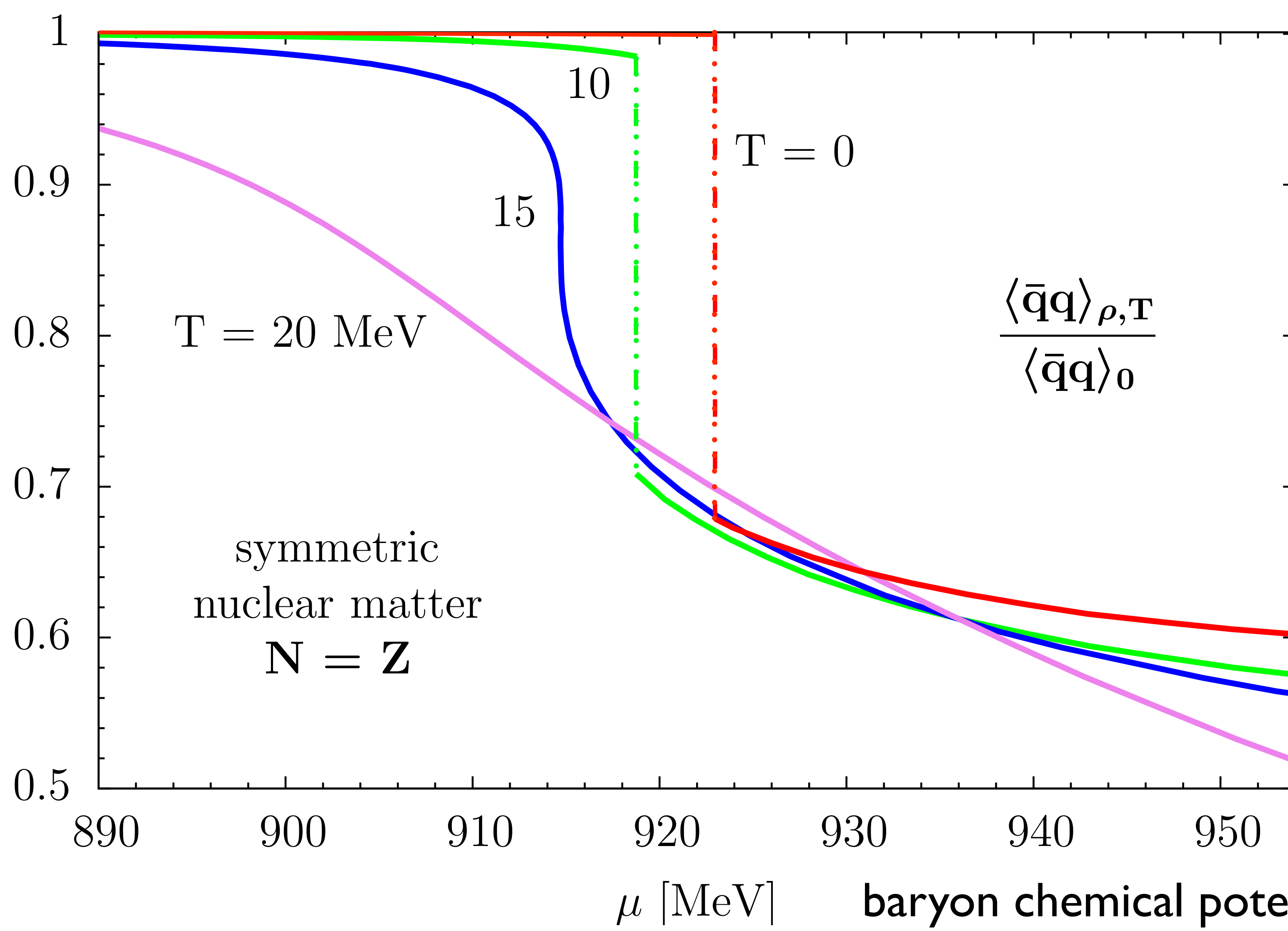
  constrained by **realistic nuclear equation of state**



- **No indication** of first order **chiral phase transition** for

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

CHIRAL CONDENSATE:
Dependence on
TEMPERATURE and BARYON CHEMICAL POTENTIAL



baryon chemical potential

S. Fiorilla,
N. Kaiser,
W.W.
arXiv:1204.4318
[nucl-th]

- **liquid-gas** phase transition leaves its signature also in chiral condensate
- but: **no** tendency toward **chiral first order transition** in the range

$$\mu_B \lesssim 1\ \mathrm{GeV}$$

Outlooks:

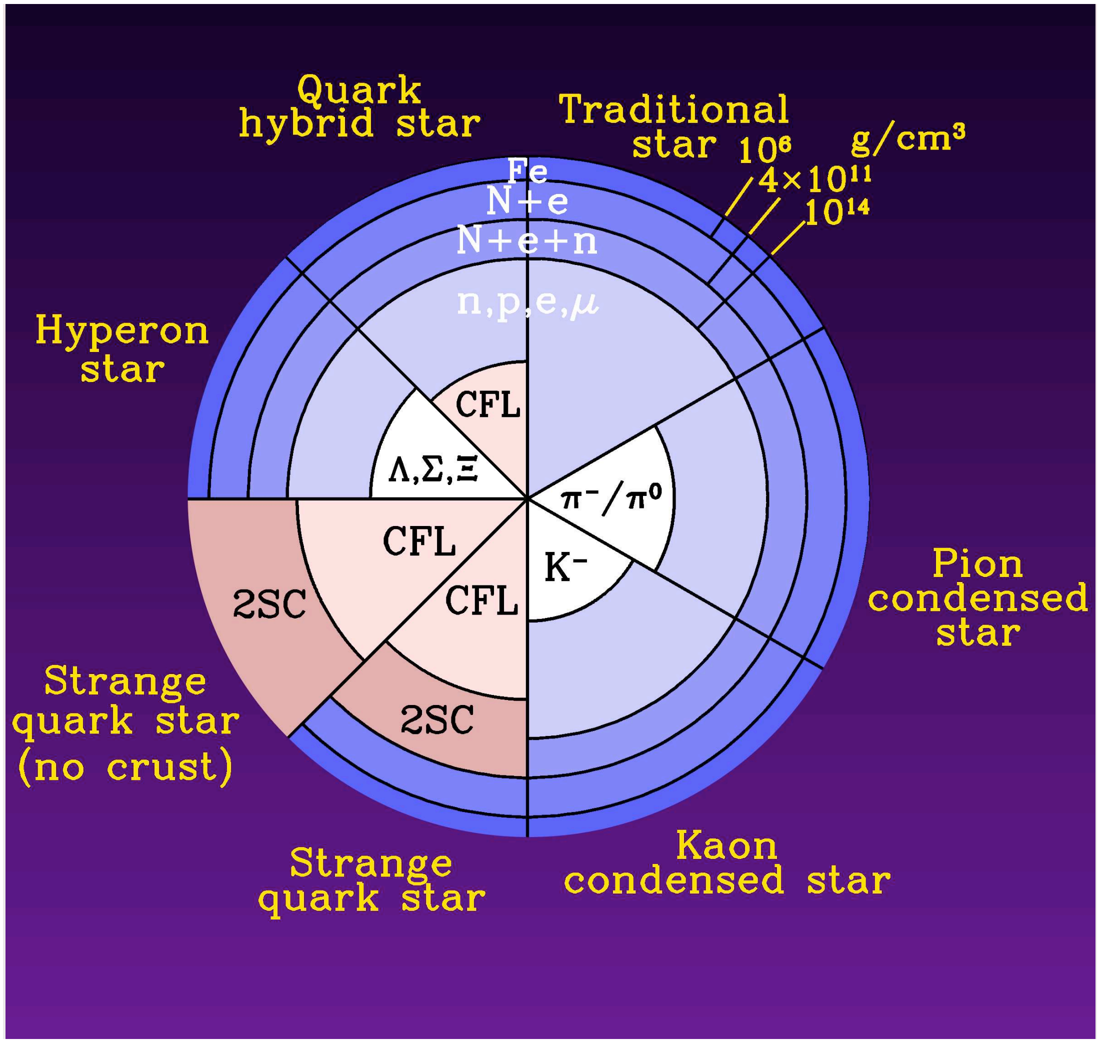
New Constraints

from

NEUTRON STARS

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



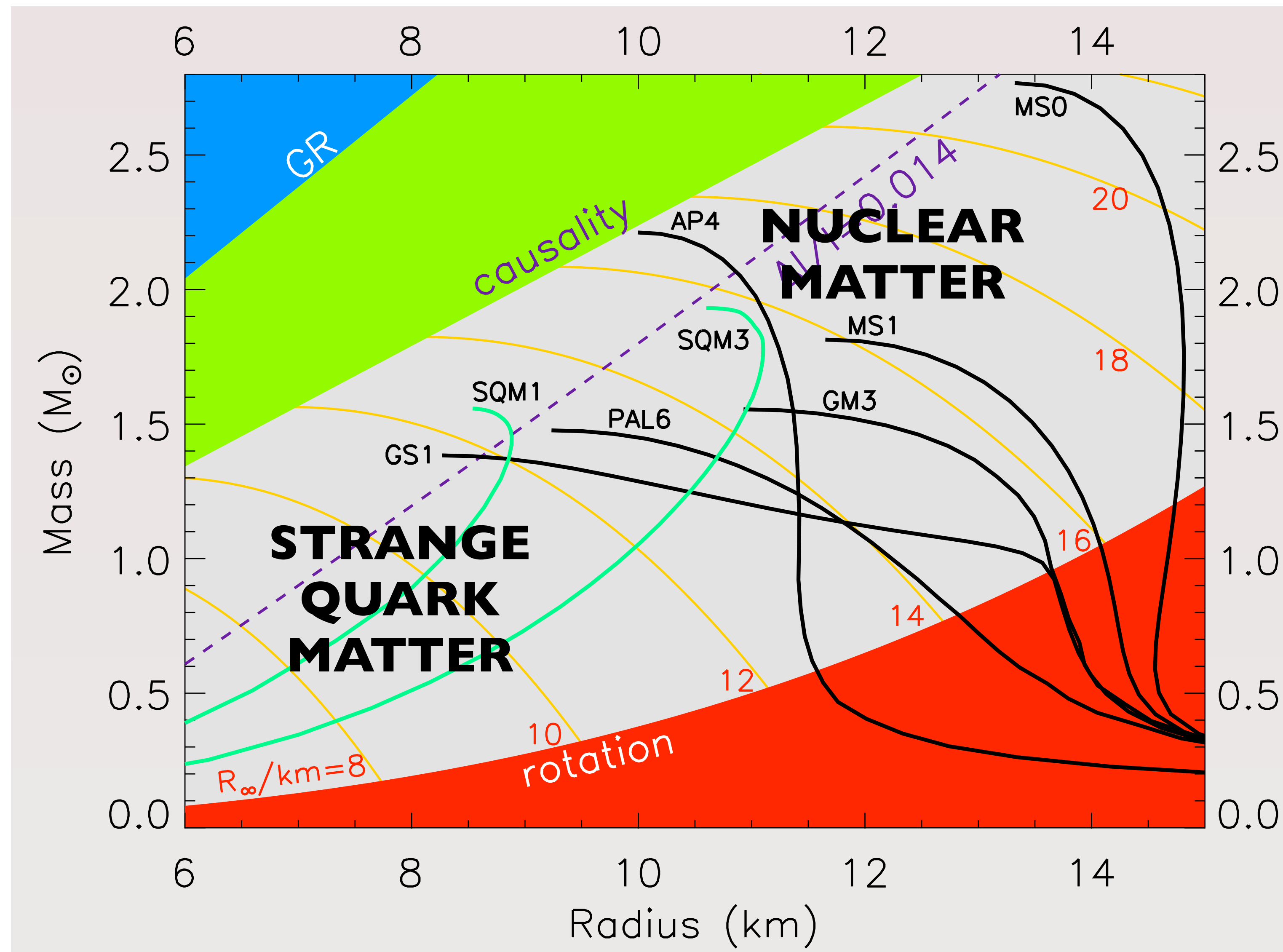
- **Neutron Star Scenarios**

- **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**



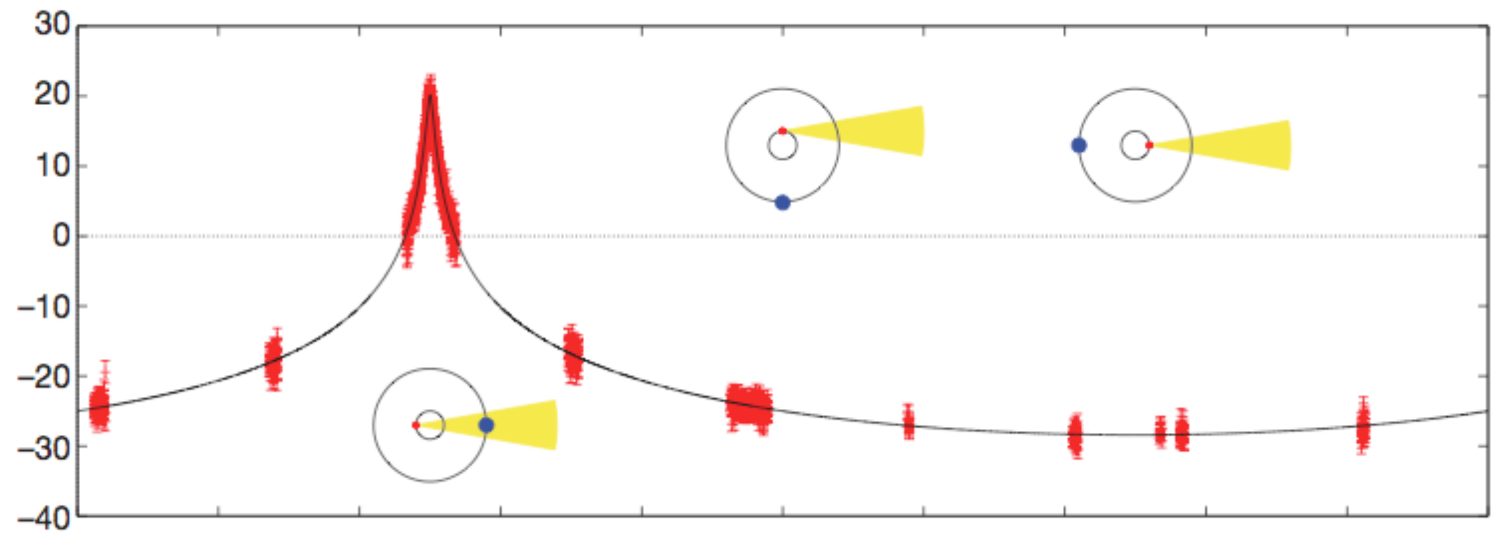
doi:10.1038/nature09466

A two-solar-mass neutron star measured using Shapiro delay

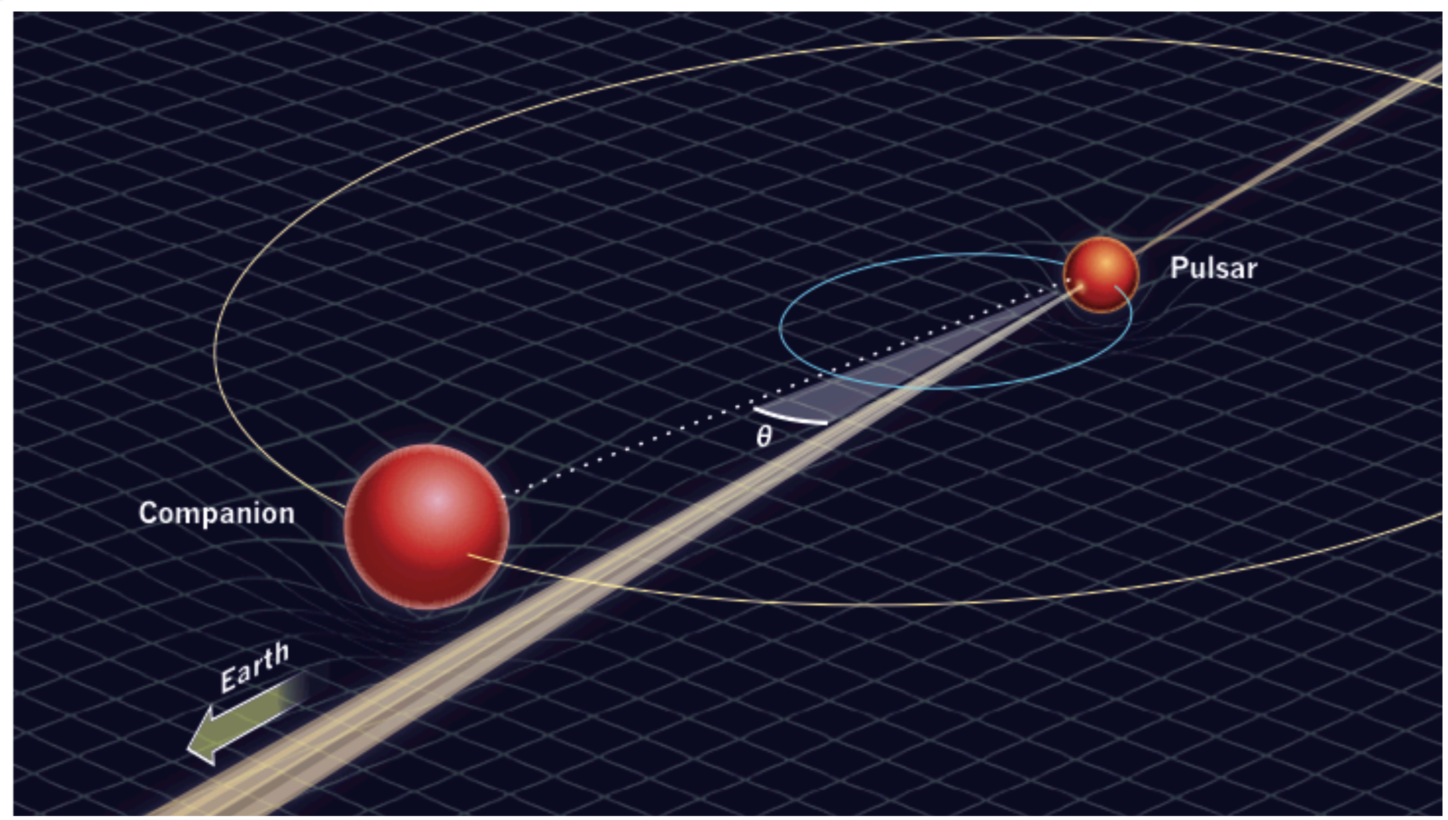
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

Nature, Oct. 28, 2010

direct measurement of neutron star mass from increase in travel time near companion



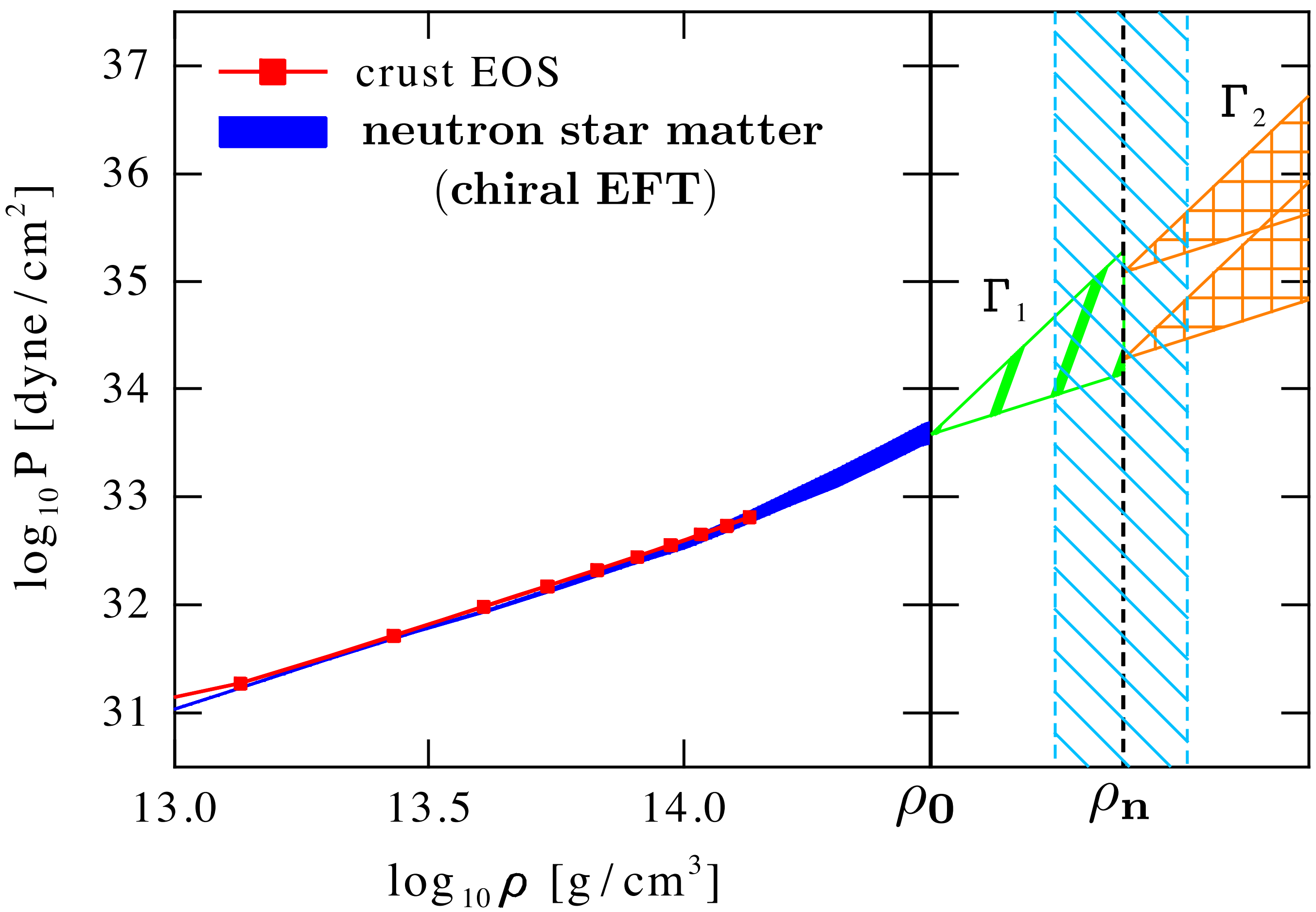
J1614-2230
most edge-on binary pulsar known (89.17°)
+ massive white dwarf companion (0.5 M_{sun})



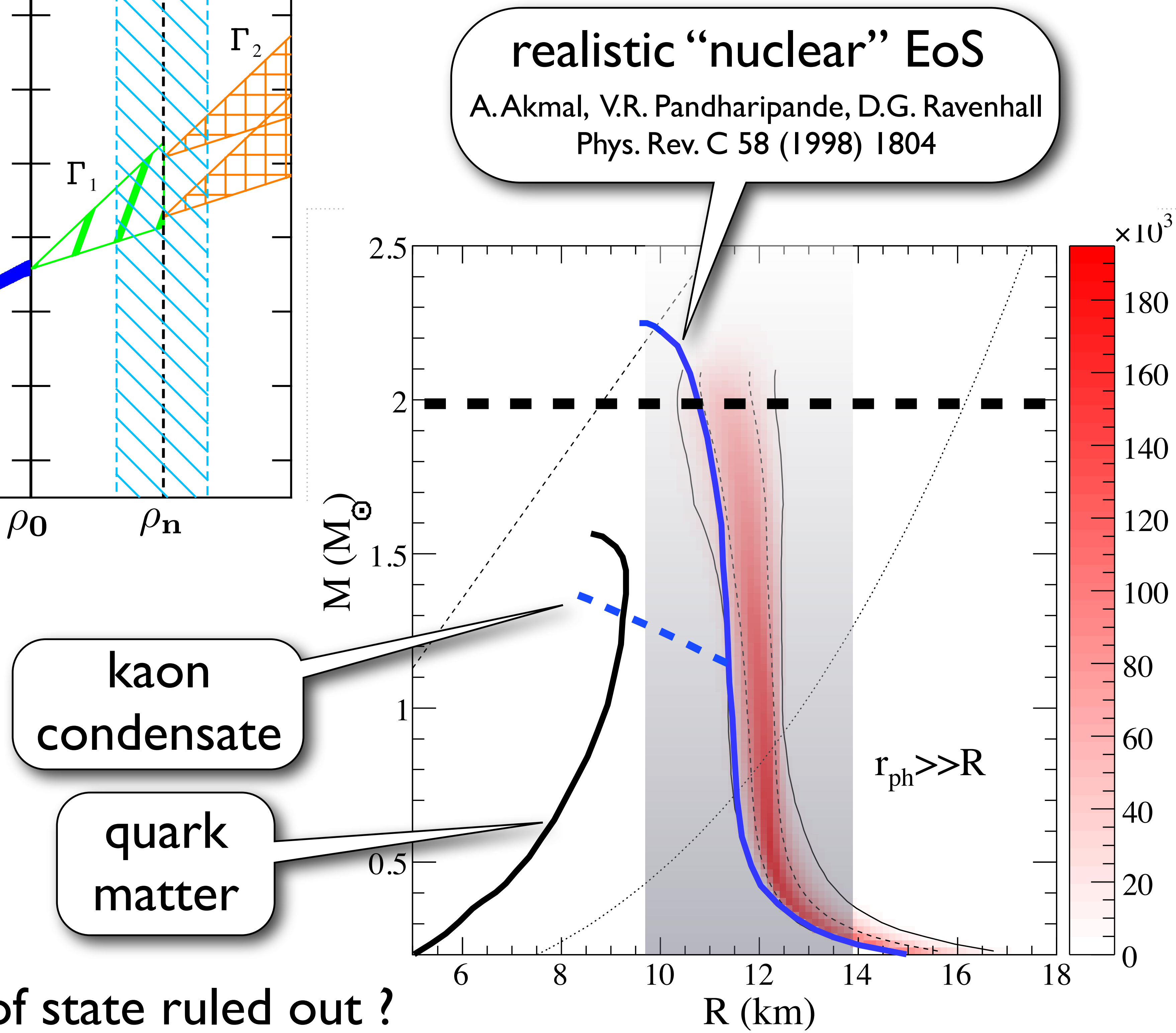
heaviest neutron star with 1.97±0.04 M_{sun}

News from NEUTRON STARS

K. Hebeler, J. Lattimer, C. Pethick, A. Schwenk
PRL 105 (2010) 161102

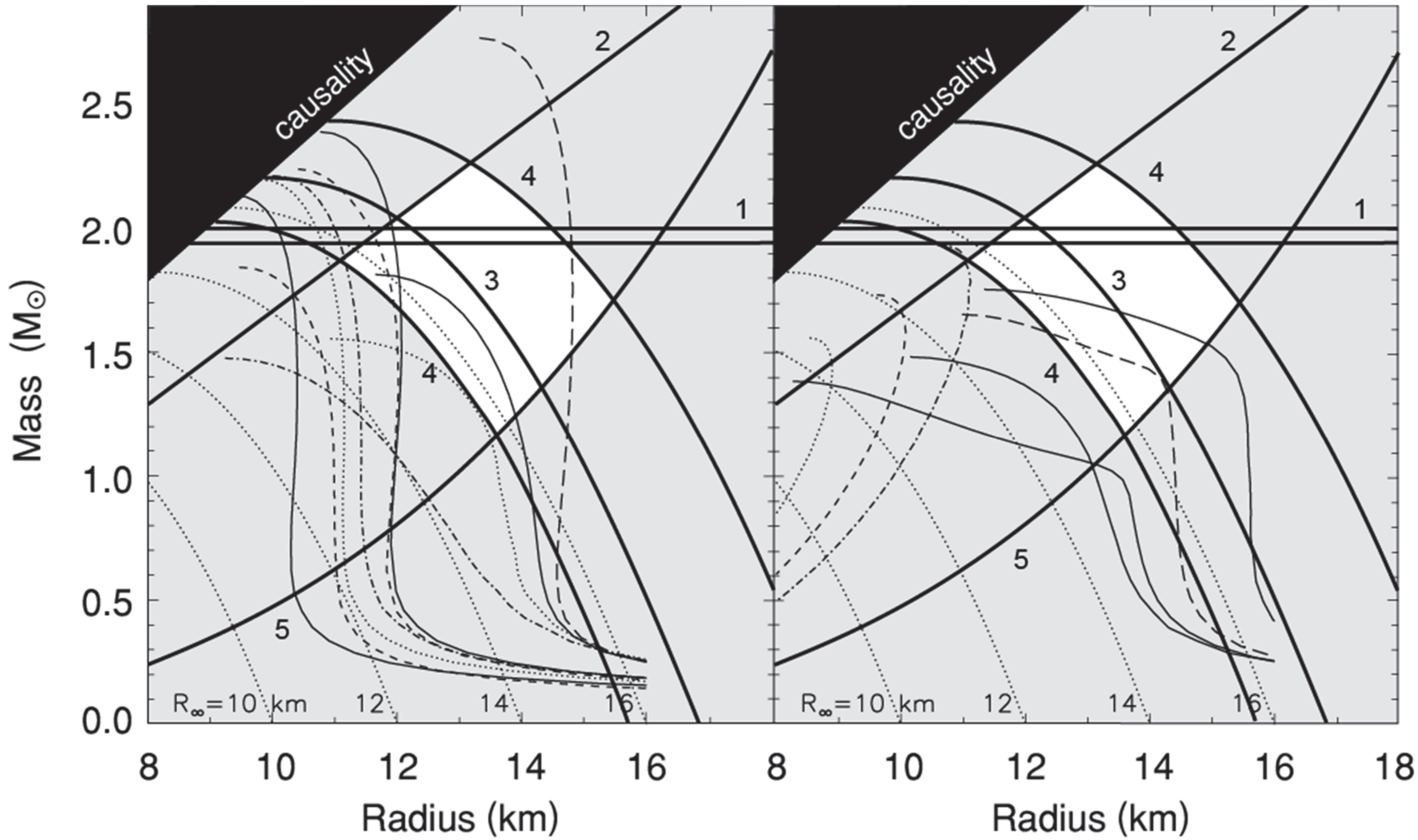


A.W. Steiner, J. Lattimer, E.F. Brown
Astroph. J. 722 (2010) 33



- New constraints from **EFT** and **neutron star observables**
- "**Exotic**" equations of state ruled out ?

NEUTRON STARS: MASS and RADIUS constraints



from:
J. Trümper

Irsee
Symposium
2012

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

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

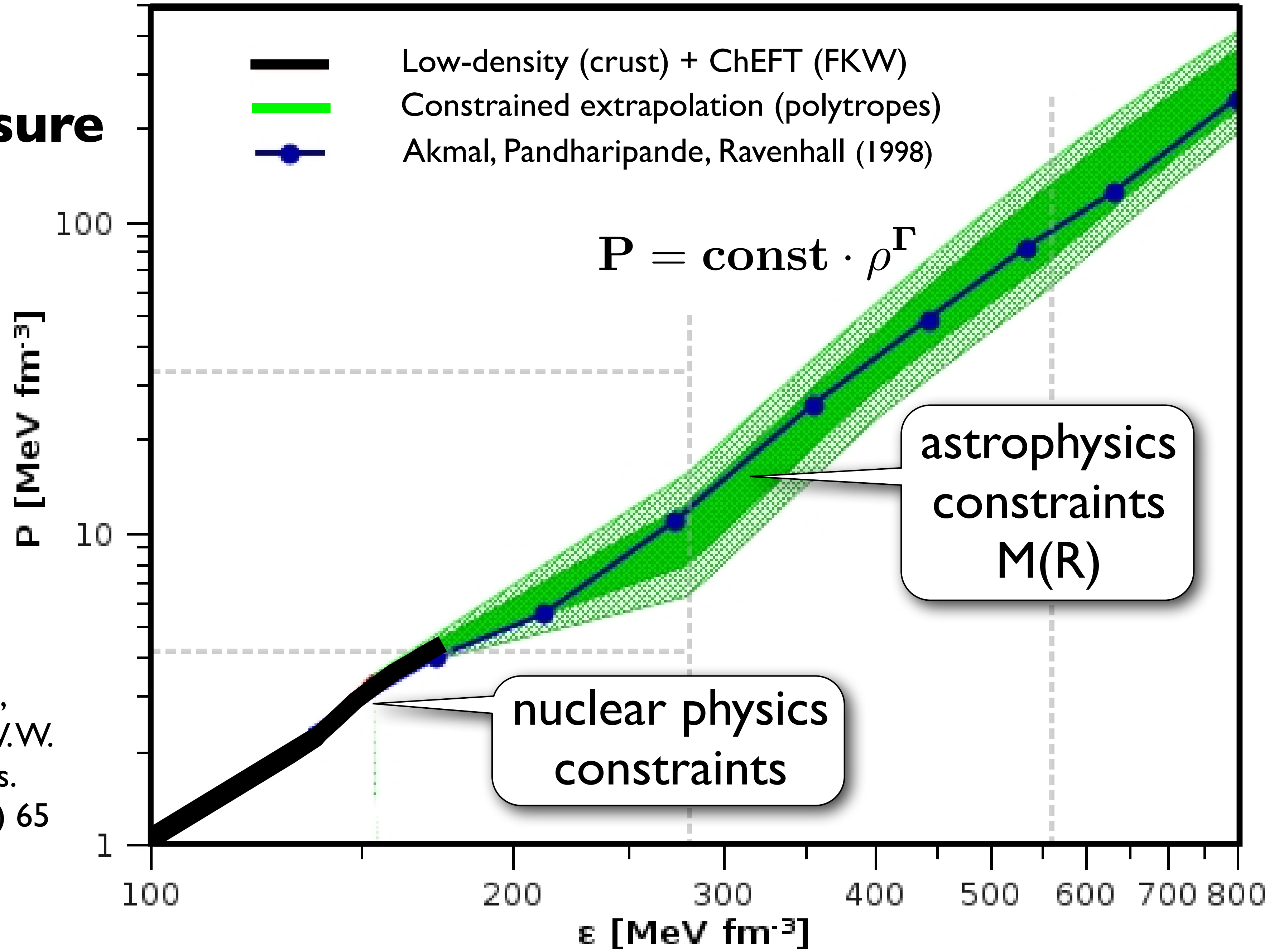
3 Minimum radius RXJ1856 - 3754
(Trümper et al. 2004)

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

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

NEUTRON STAR MATTER
Equation of State

pressure



energy density

B. Röttgers, W.W. (2011)

Prog. Part. Nucl. Phys. 67 (2012) 299

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

- Including new neutron star constraints plus **C**hiral **E**ffective **F**ield **T**heory at lower density

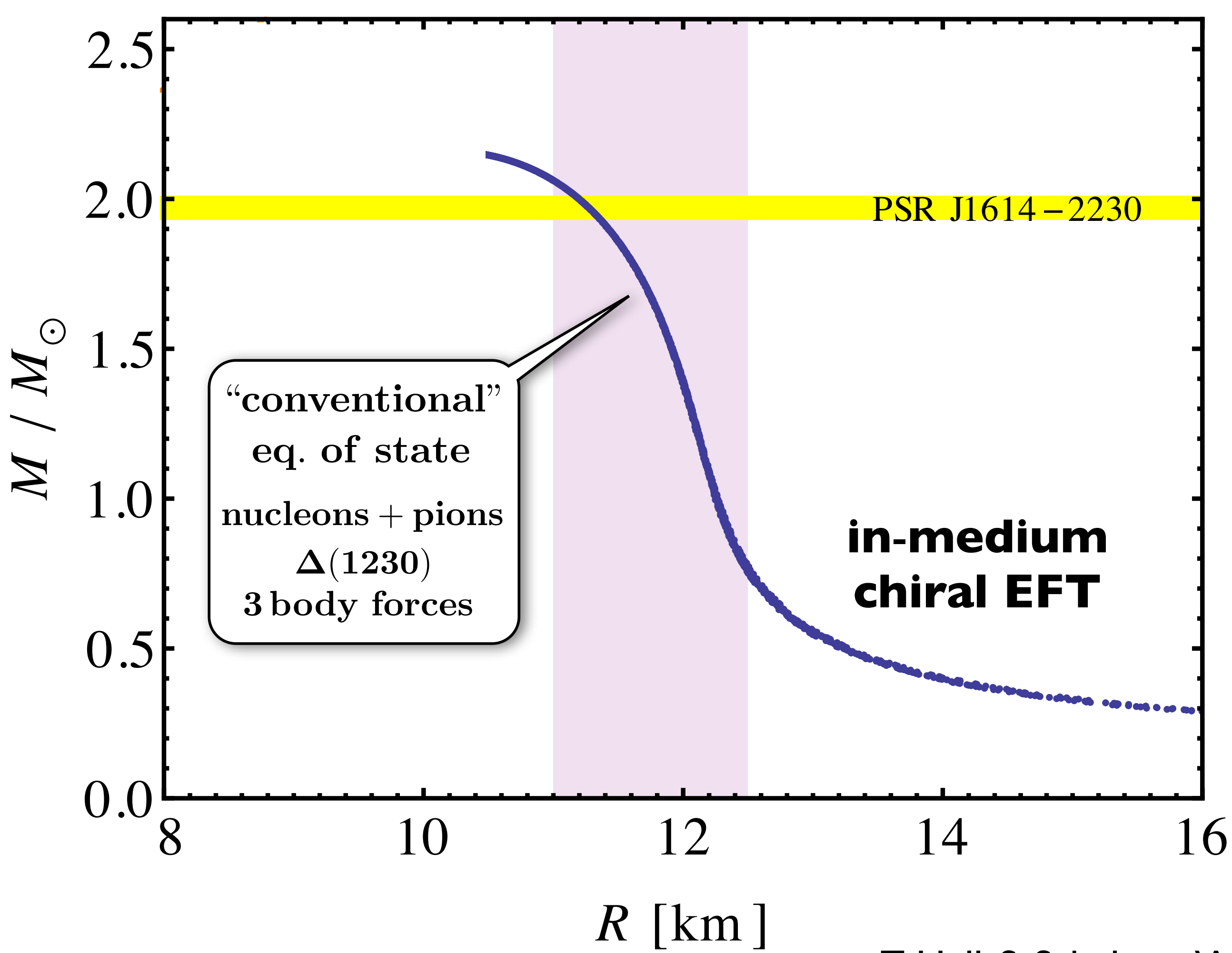
NEUTRON STAR MATTER

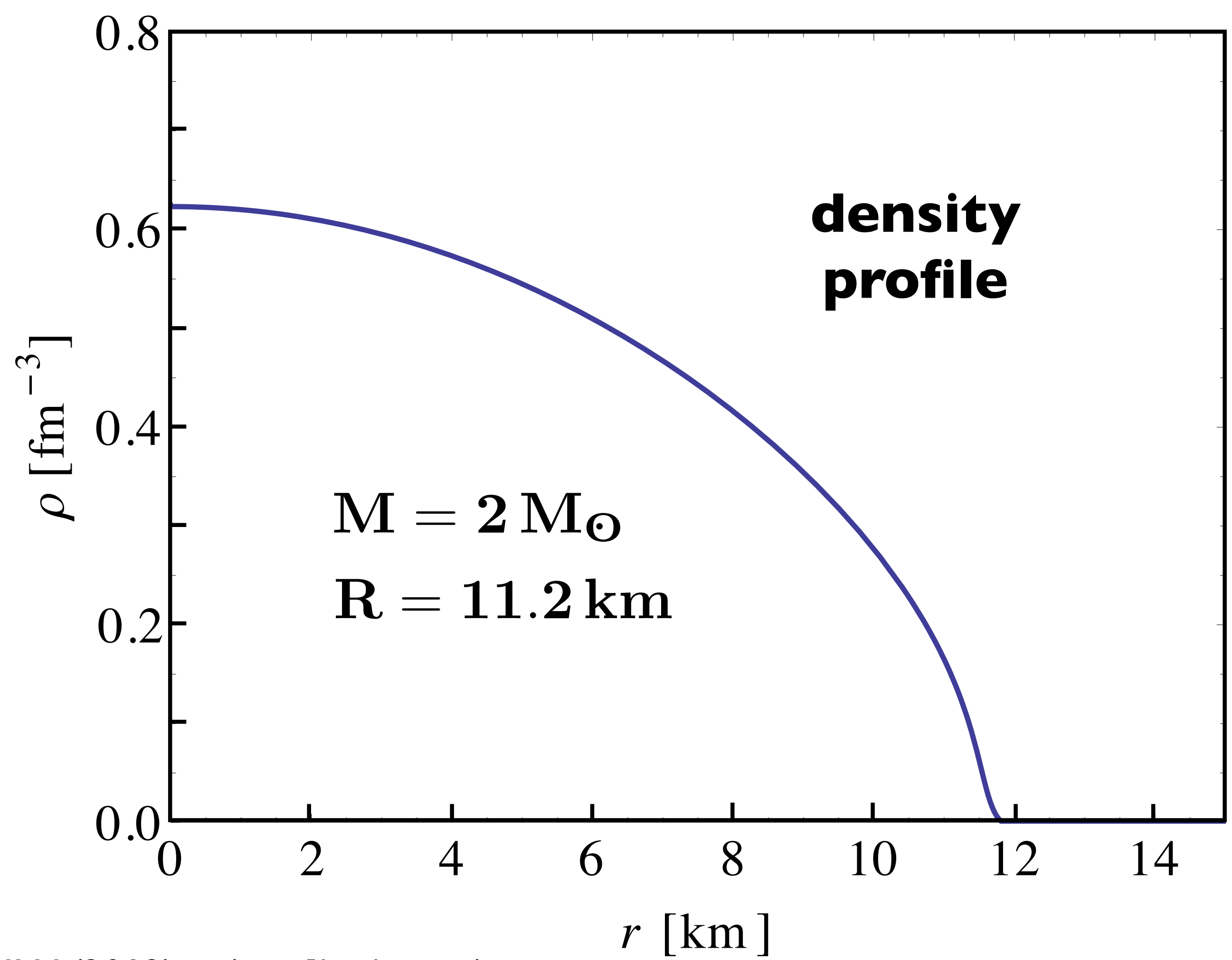
Mass - Radius relation

- **Option** I:
  Conventional hadronic (**baryonic** + **mesonic**) degrees of freedom

- In-medium **C**hiral **E**ffective **F**ield **T**heory up to 3 loops (reproducing thermodynamics of normal nuclear matter) including beta equilibrium condition $\mathbf{n} \leftrightarrow \mathbf{p} + e, \mu$

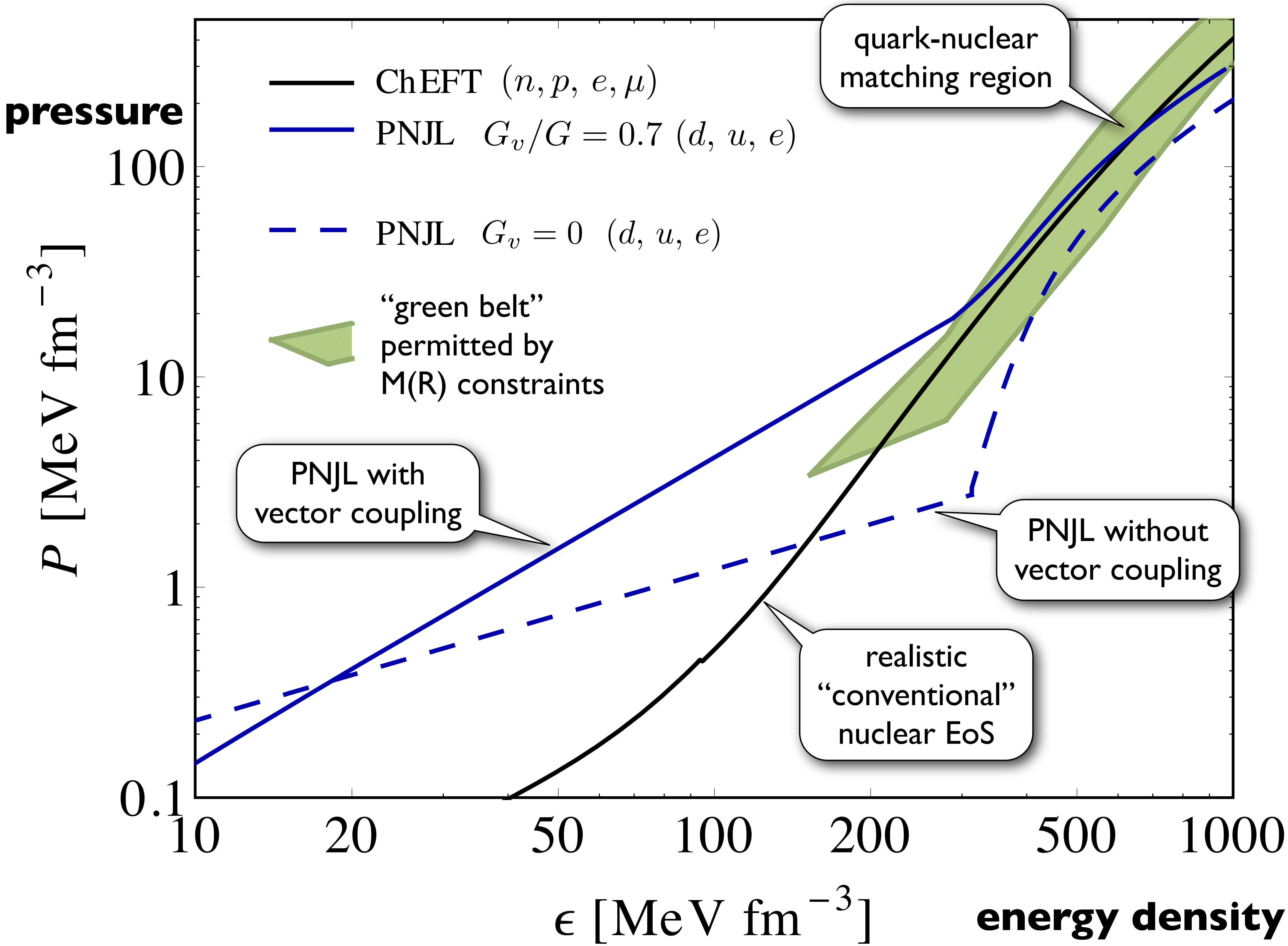
S. Fiorilla, N. Kaiser, W.W. Nucl. Phys. A 880 (2012) 65





T. Hell, S. Schultess, W.W. (2012) - (**preliminary**)

NEUTRON STAR Equation of State

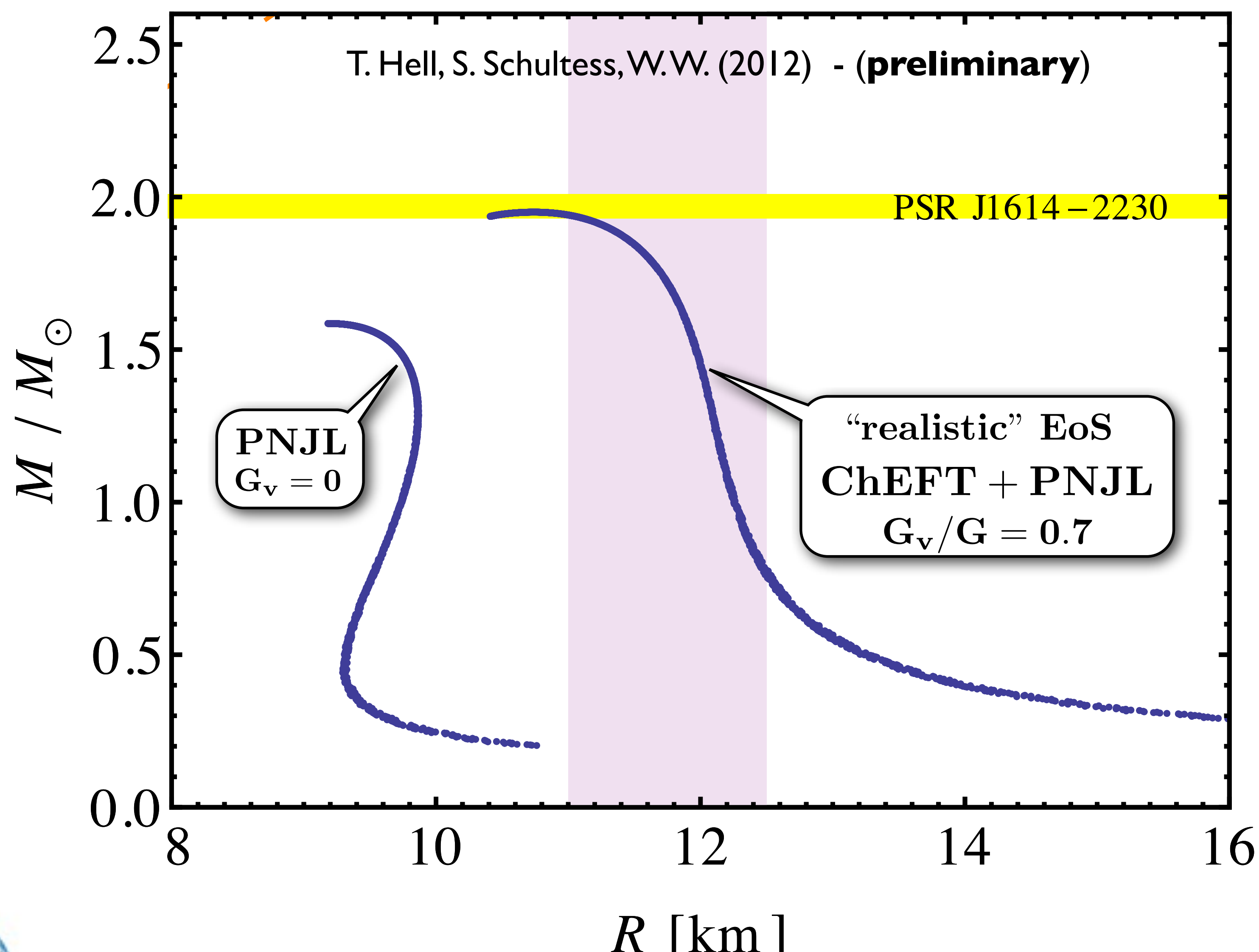


NEUTRON STAR MATTER

Mass - Radius relation (contd.)

- **Option** II:
  Polyakov - **N**ambu - **J**ona-**L**asinio (**PNJL**) model
  (u-,d- and s-**quarks** as **quasiparticles** with dynamically generated constituent masses)

- ... features **first order chiral phase transition**
  ... produces **too soft** equation of state for neutron matter $\longrightarrow$ does **not** work !



- **Option** III:
  Conventional hadronic EoS (**ChEFT**) matched at

$$\rho \sim 4\,\rho_0$$

  to **PNJL** EoS incl. **vector coupling**

- soft **crossover** between **hadronic** and **quark** phases

SUMMARY

- **Nuclear thermodynamics** based on in-medium **C**hiral **E**ffective **F**ield **T**heory valid for $\mathbf{k_F} < 4\pi\, \mathbf{f}_\pi \sim 1\,\mathbf{GeV}$
  - Proper treatment of in-medium **two-pion exchange** and **three-body forces**
  - Fermi liquid ↔ interacting Fermi gas (1st order transition)
  - **Realistic** equations of state for **nuclear** and **neutron matter**
  - **No** indication of first order **chiral** transition in the density and temperature range $\rho \lesssim \mathbf{2}\,\rho_\mathbf{0}\,,\ \mathbf{T} \lesssim \mathbf{100\,MeV}$
  - **Convergence** issues: **four-body** correlations **?**

- **New dense** & **cold matter** constraints from **neutron stars**:
  - **Mass-radius** relation; observation of two-solar-mass neutron star
  - **Stiff EoS required**; "non-exotic" equation of state works best !

The End

thanks to :

Nino Bratovic
Thomas Hell

Matthias Drews
Jeremy Holt
Sebastian Schulteß

Salvatore Fiorilla
Norbert Kaiser

arXiv:1202.1671 [nucl-th]

Chemical freeze-out in heavy ion collisions at large baryon densities

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We argue that the chemical freeze-out in heavy ion collisions at high baryon density is not associated to a phase transition or rapid crossover. We employ the linear nucleon-meson model with parameters fixed by the zero-temperature properties of nuclear matter close to the liquid-gas quantum phase transition. For the parameter region of interest this yields a reliable picture of the thermodynamic and chiral properties at non-zero temperature. The chemical freeze-out observed in low-energy experiments occurs when baryon densities fall below a critical value of about 15 percent of nuclear density. This region in the phase diagram is far away from any phase transition or rapid crossover.

$$\begin{aligned}\mathcal{L} = {} & \bar\psi_a \, i\gamma^\nu(\partial_\nu - i\,g\,\omega_\nu - i\,\mu\,\delta_{0\nu})\,\psi_a \\ & + \sqrt{2}\,h\left[\bar\psi_a\left(\tfrac{1+\gamma_5}{2}\right)\phi_{ab}\psi_b + \bar\psi_a\left(\tfrac{1-\gamma_5}{2}\right)(\phi^\dagger)_{ab}\psi_b\right] \\ & + \tfrac{1}{2}\phi^*_{ab}(-\partial_\mu\partial^\mu)\phi_{ab} + U_{\text{mic}}(\rho,\sigma) \\ & + \frac{1}{4}(\partial_\mu\omega_\nu - \partial_\nu\omega_\mu)(\partial^\mu\omega^\nu - \partial^\nu\omega^\mu) + \frac{1}{2}m_\omega^2\,\omega_\mu\omega^\mu\end{aligned}$$

$$\phi_{ab} = \begin{pmatrix} \frac{1}{\sqrt{2}}(\sigma + i\pi^0) & i\pi^- \\ i\pi^+ & \frac{1}{\sqrt{2}}(\sigma - i\pi^0)\end{pmatrix}$$

$$U_{\text{mic}}(\rho,\sigma) = \bar U(\rho) - m_\pi^2 f_\pi \sigma$$

$$\rho = \tfrac{1}{2}(\sigma^2 + \boldsymbol{\pi}^2)$$

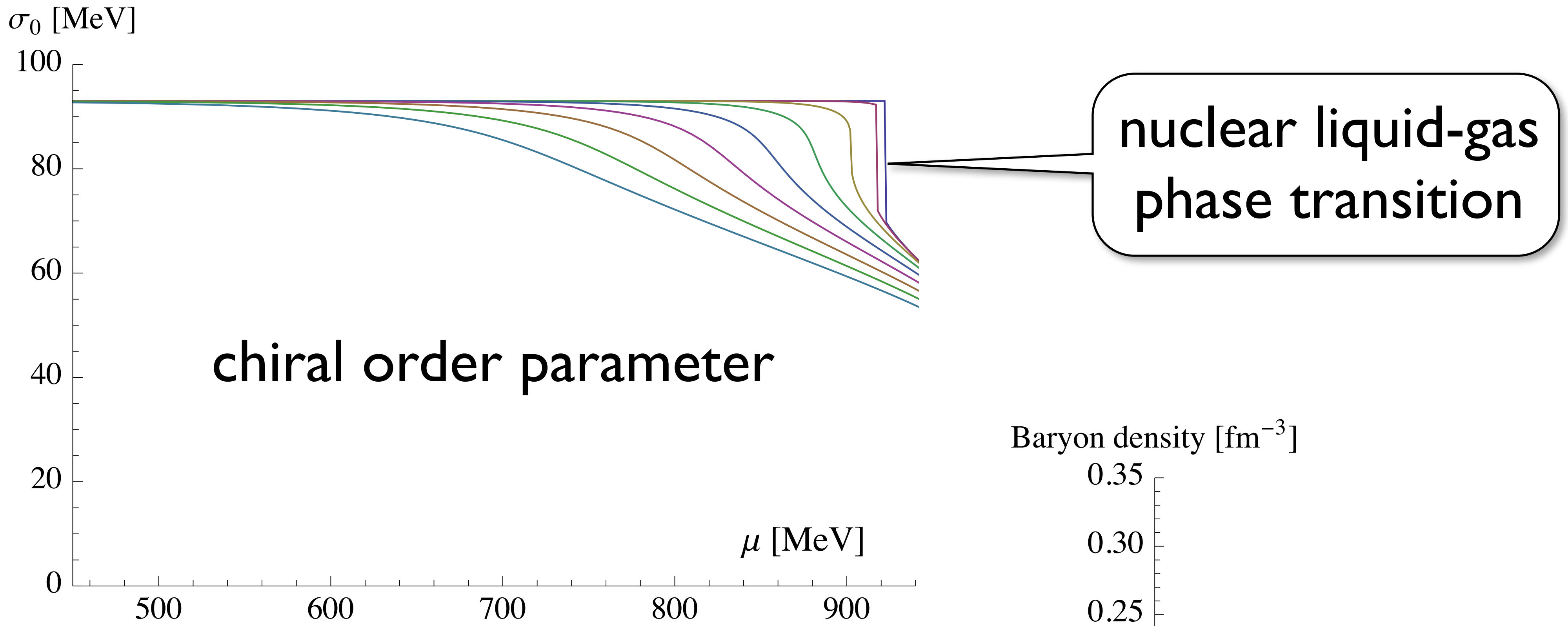

FIG. 6: Chiral order parameter σ_0 as a function of the chemical potential for $T = 0$ (uppermost curve), $T = 10$ MeV, $T = 20$ MeV, $T = 30$ MeV, $T = 40$ MeV, $T = 50$ MeV, $T = 60$ MeV, $T = 70$ MeV and $T = 80$ MeV (lowermost curve).

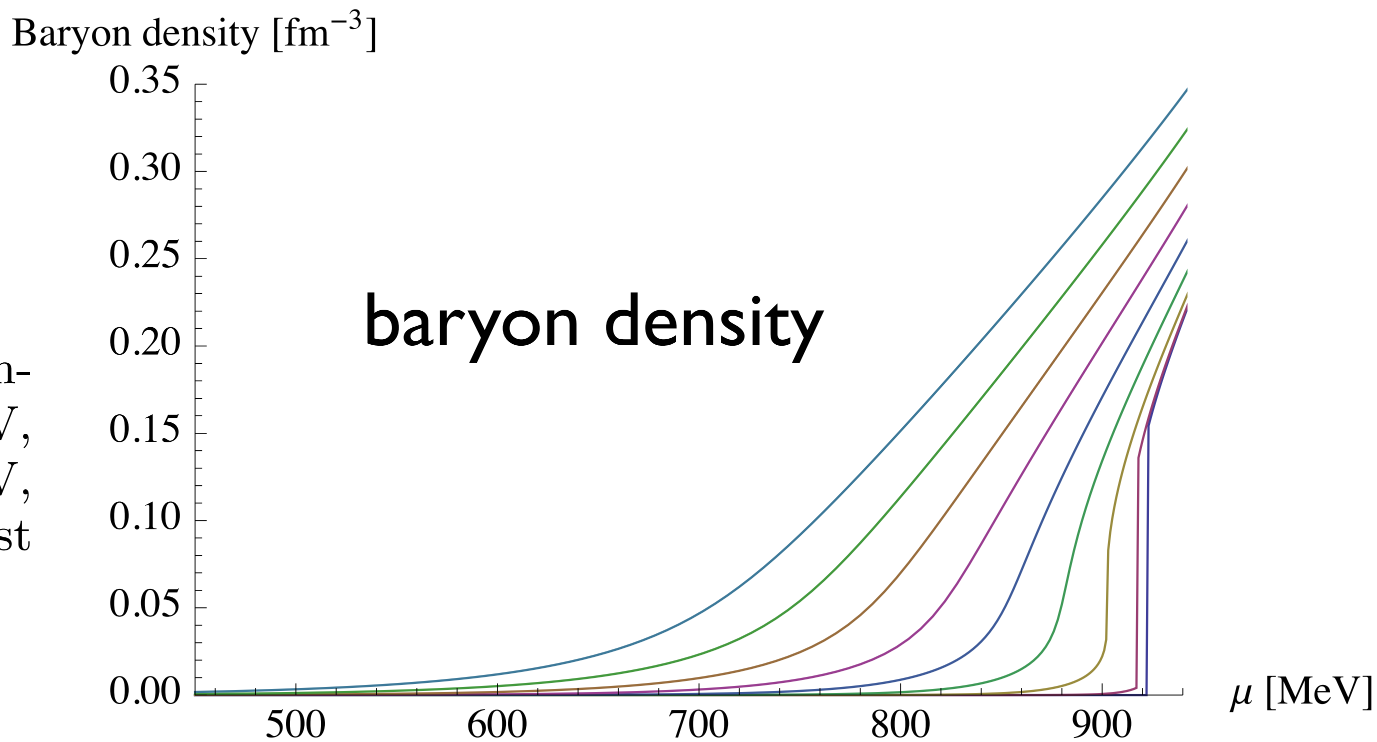

FIG. 7: Baryon number density as a function of the chemical potential for $T = 0$ (lowermost curve), $T = 10$ MeV, $T = 20$ MeV, $T = 30$ MeV, $T = 40$ MeV, $T = 50$ MeV, $T = 60$ MeV, $T = 70$ MeV and $T = 80$ MeV (uppermost curve).

CHEMICAL FREEZE-OUT