NUCLEAR CHIRAL THERMODYNAMICS and PHASES of QCD

Wolfram Weise
Technische Universität München

- Prelude: **QCD Phase Diagram** (Concepts, Models, Problems)
- Main Theme: **Nuclear Chiral Thermodynamics**
  - QCD interface with nuclear physics: **Chiral Effective Field Theory**
  - **Nuclear Equation of State** and QCD phase diagram
  - Density and temperature dependence of the **Chiral (Quark) Condensate**
- Outlook: New constraints from **Neutron Stars**

Part I: Prelude

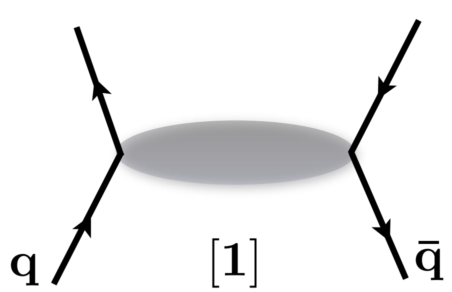
QCD PHASE DIAGRAM

Visions & Facts

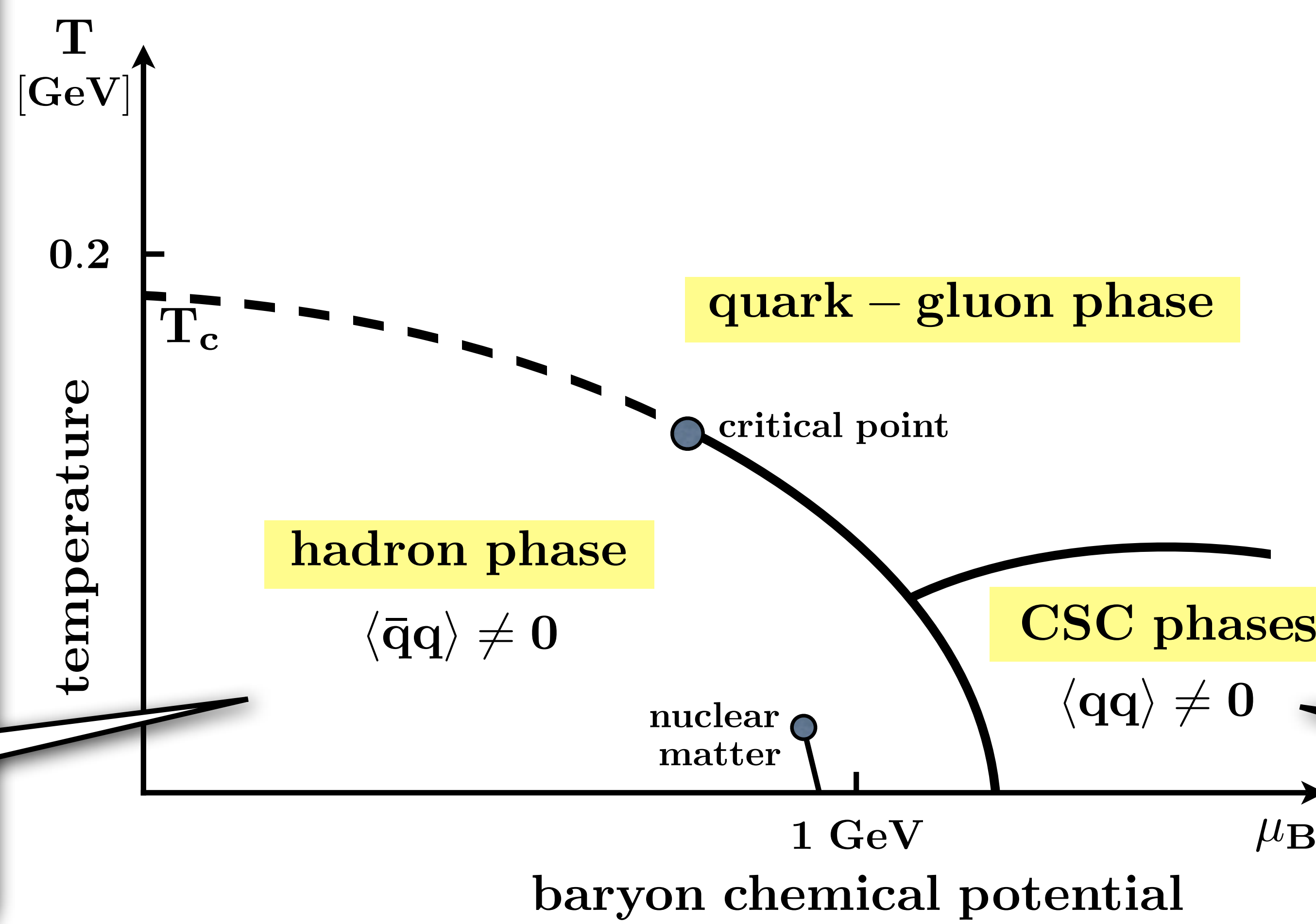
QCD PHASE DIAGRAM

(theorists' vision)

Spontaneous
Chiral
Symmetry
Breaking

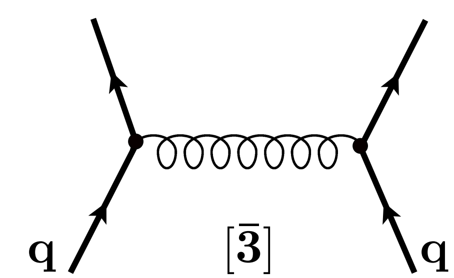


$\bar{q}q$
condensation



High Density:

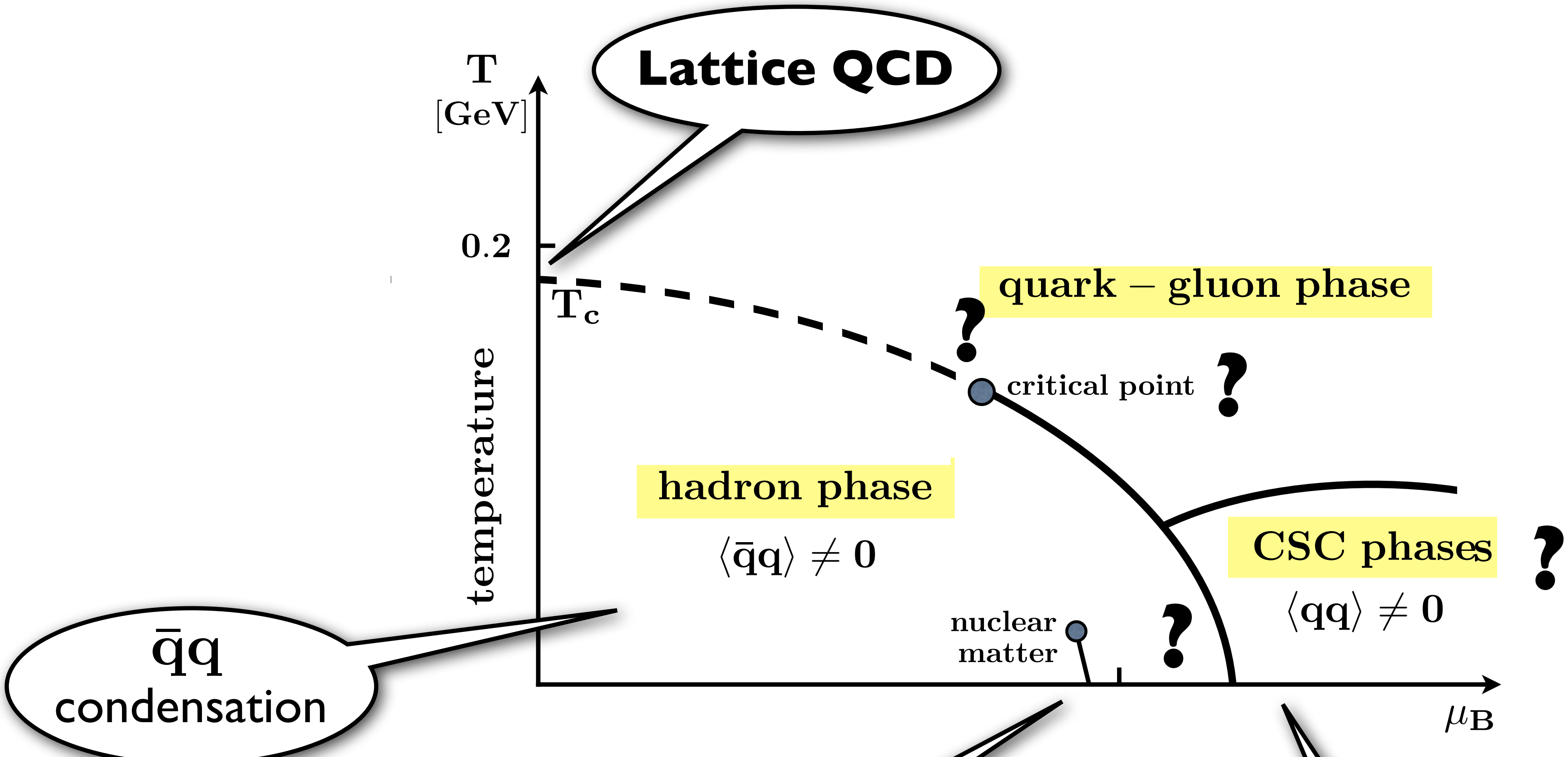
Color
Super
Conductivity



Cooper
pairing

QCD PHASE DIAGRAM

(reality ? facts ?)



Constraints from **Nuclear Physics**

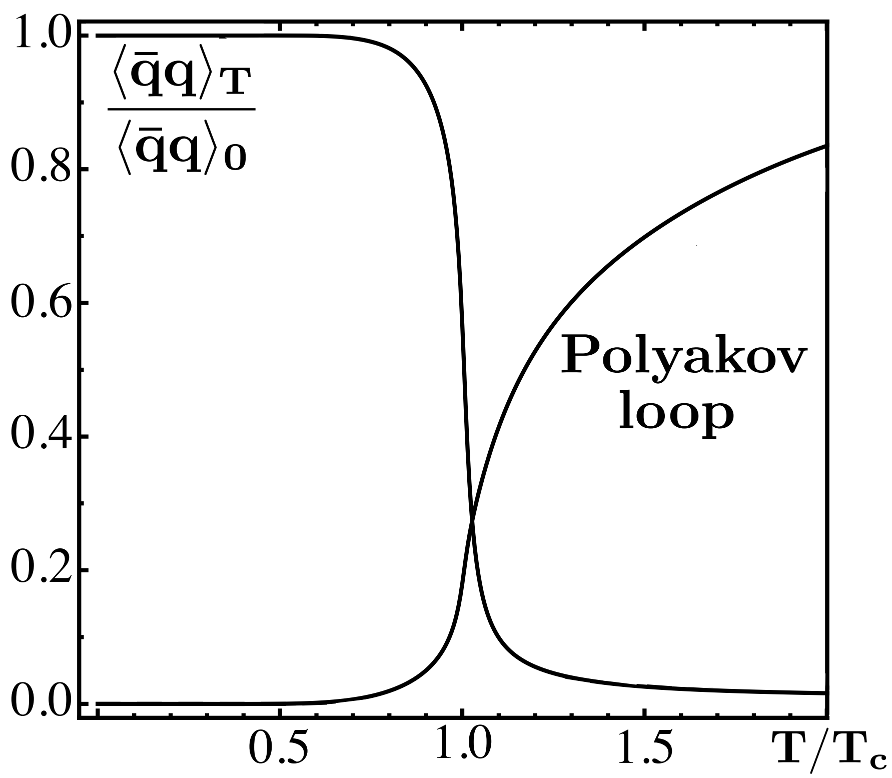
New constraints from **Neutron Stars**

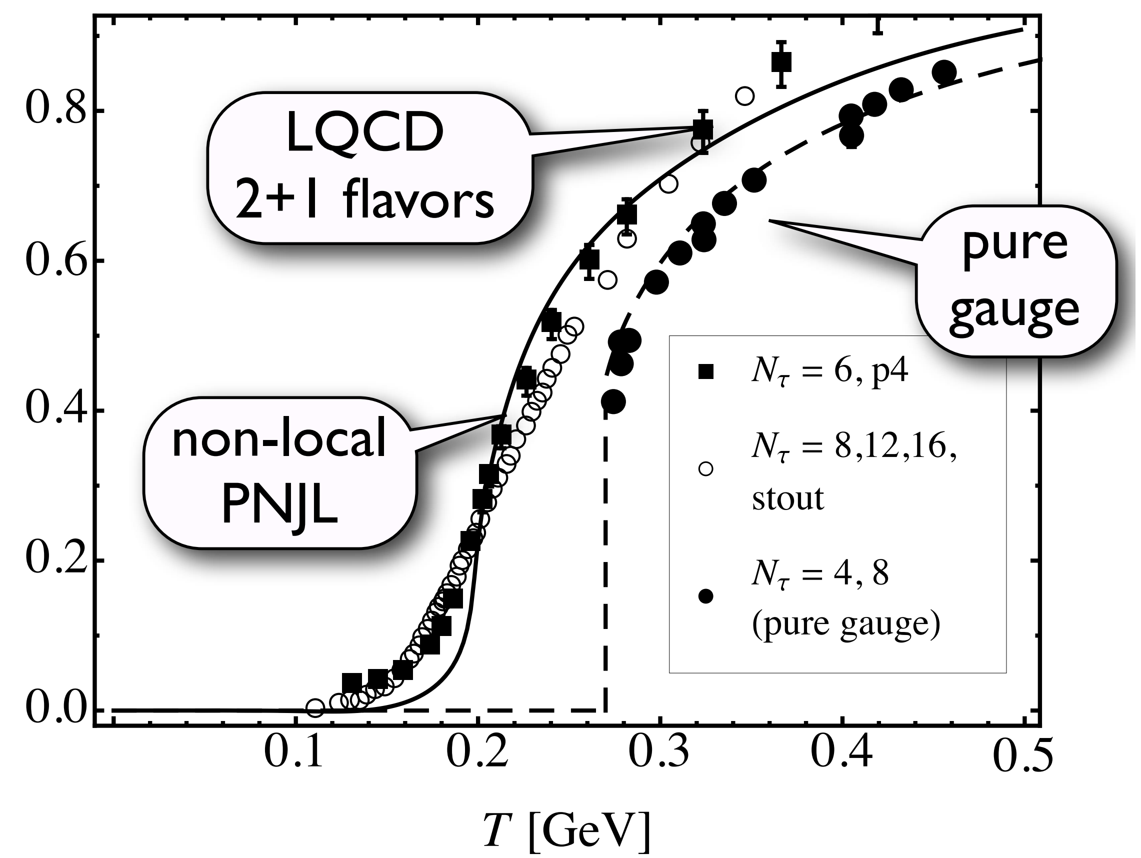
MODELING the QCD PHASE DIAGRAM

- Guiding principle:
  QCD **symmetries** and symmetry **breaking** patterns

Spontaneously broken **chiral** symmetry $SU(N_f)_R \times SU(N_f)_L$ → non-local **PNJL** model ← Centre $Z(3)$ of $SU(3)_c$ gauge group

- **chiral** and **deconfinement crossover** transitions (3 flavor PNJL model)

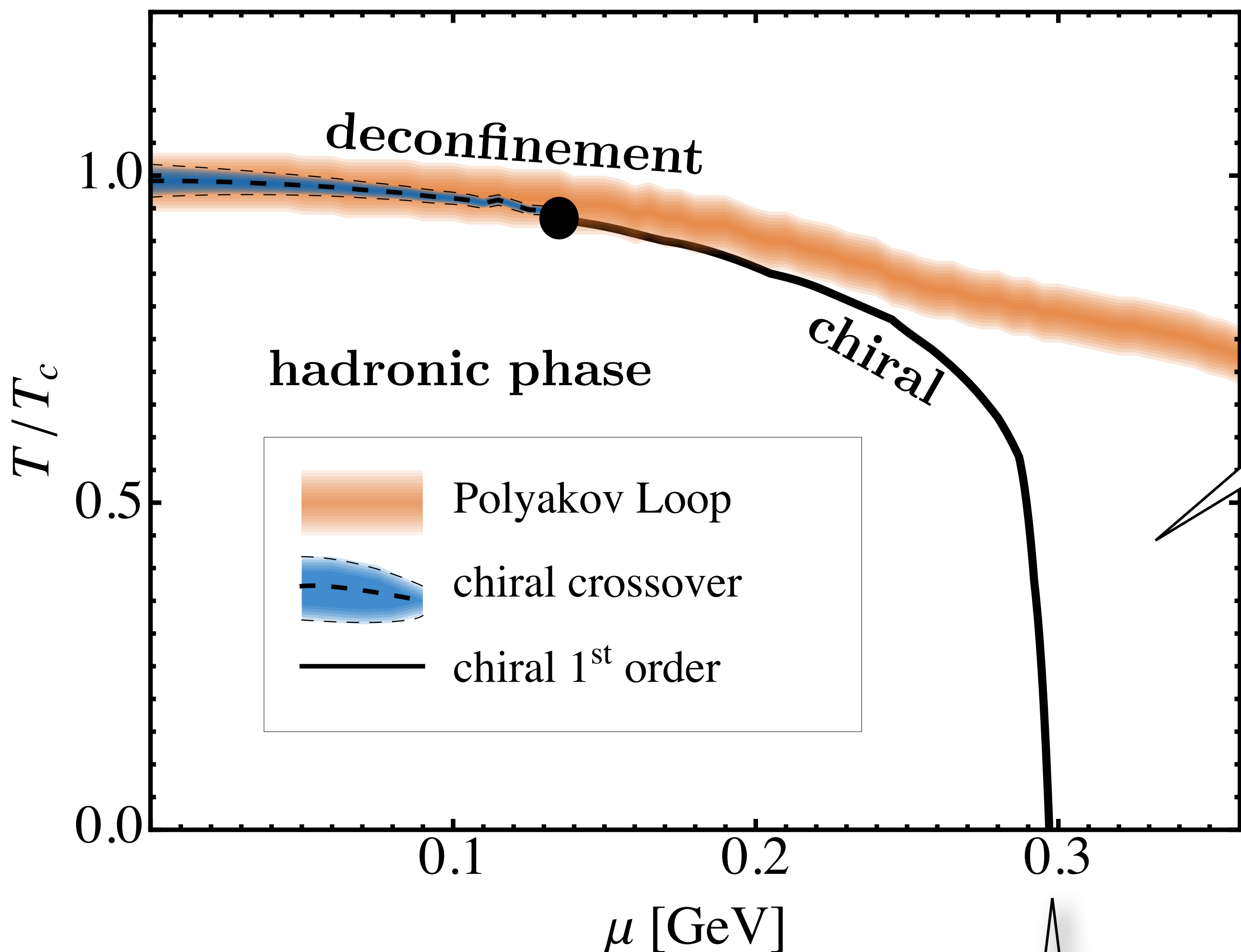




T. Hell, S. Rössner, M. Cristoforetti, W.W.: Phys. Rev. D81 (2010) 074034
T. Hell, K. Kashiwa, W.W.: Phys. Rev. D83 (2011) 114008

PHASE DIAGRAM

Non-local 3-flavor PNJL model calculation

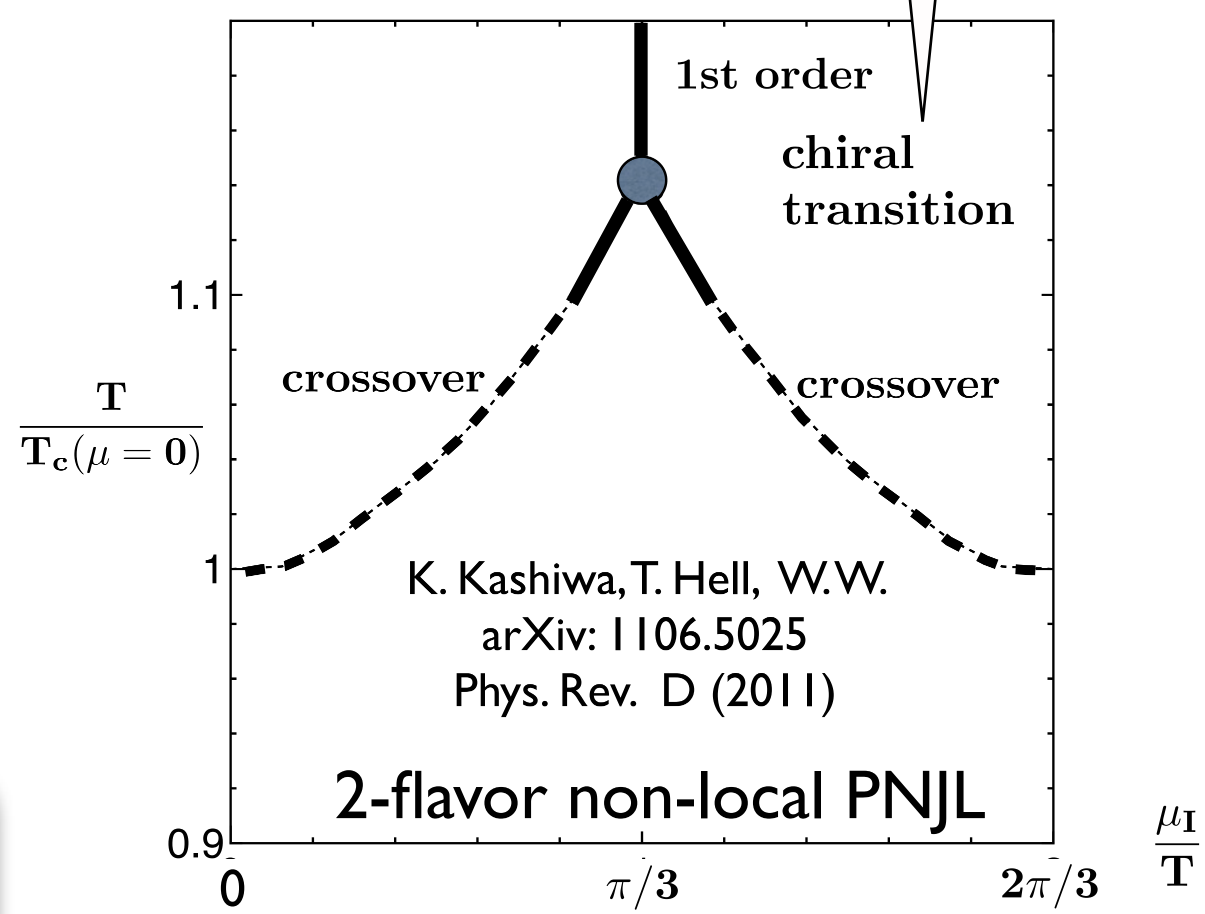


T. Hell, K. Kashiwa, W.W. :
Phys. Rev. D83 (2011) 114008

quarkyonic ?
L. McLerran, R. Pisarski

accessible by
Lattice QCD
P. de Forcrand, O. Philipsen

chiral 1st order transition line ?



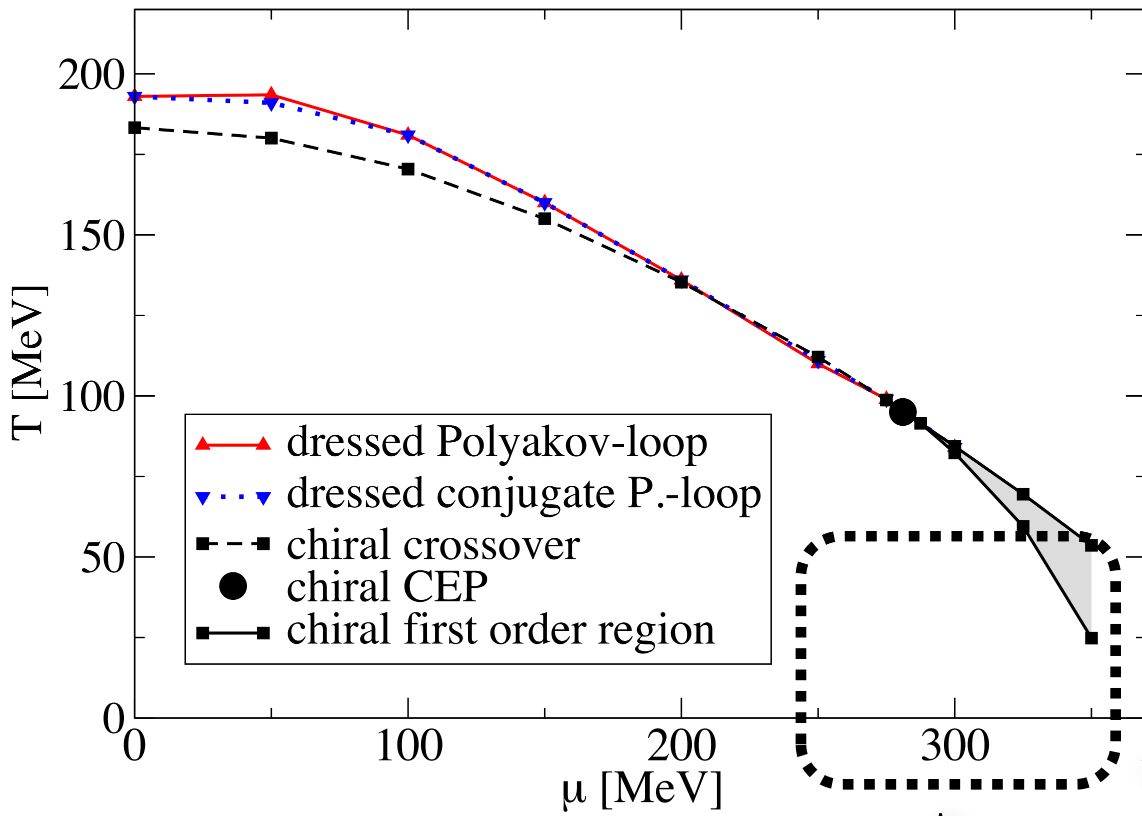
imaginary chemical potential

- Does the **first-order line** really extend down to **low** temperatures **?**

PHASE DIAGRAM (contd.)

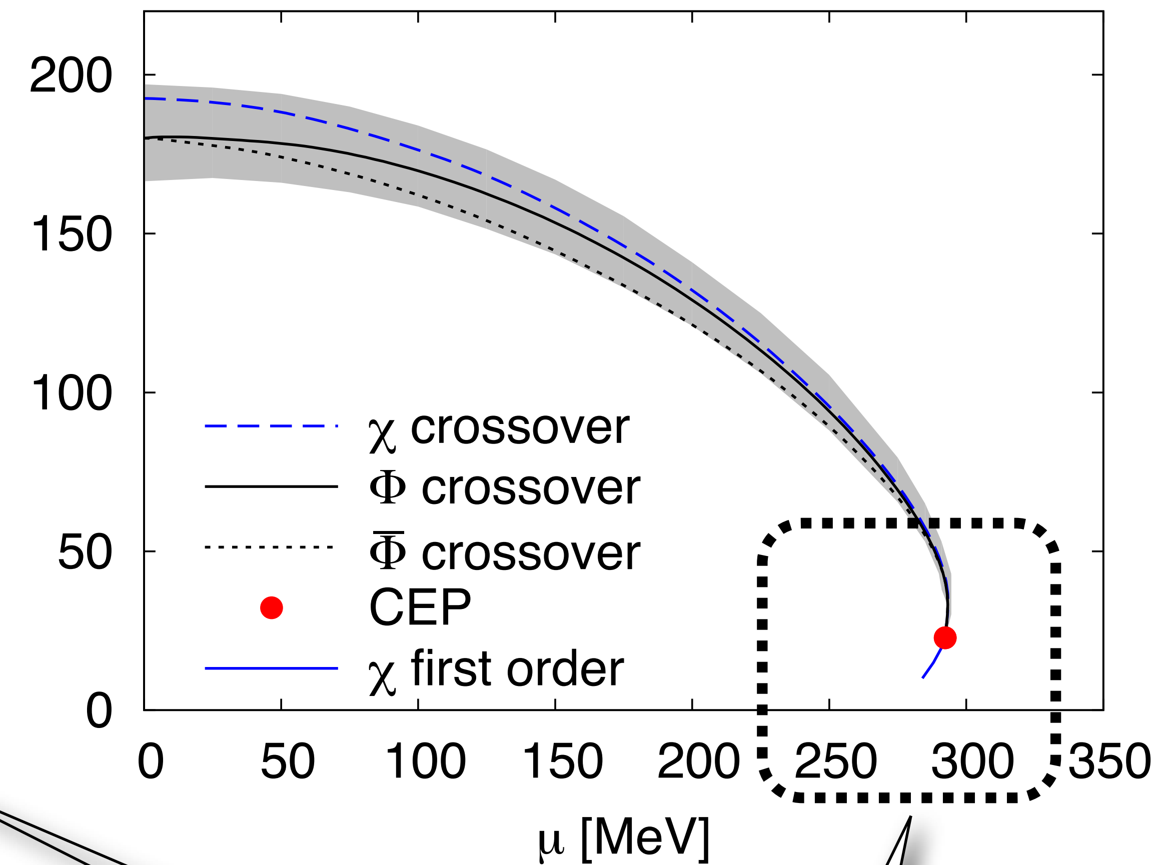
Dyson - Schwinger QCD

C.S. Fischer, J. Luecker, J.A. Mueller: PLB 702 (2011) 438



Polyakov - Quark-Meson model

T. K. Herbst, J. Pawloski, B.-J. Schäfer: PRL 106 (2011) 58



baryon densities

$$\rho_B = \frac{1}{3}\left(\frac{\partial P}{\partial \mu}\right)_T$$

in the range

$$0.1 - 0.2 \text{ fm}^{-3}$$

nuclear terrain !

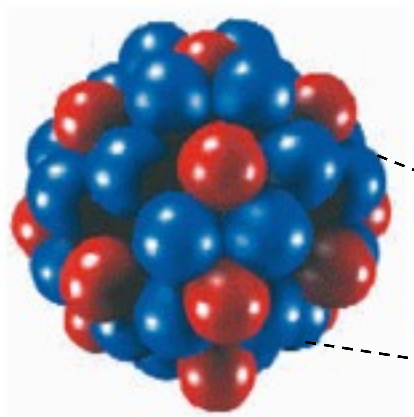
- Quarks are **not** the **relevant active quasiparticles** at low temperatures and baryon chemical potentials

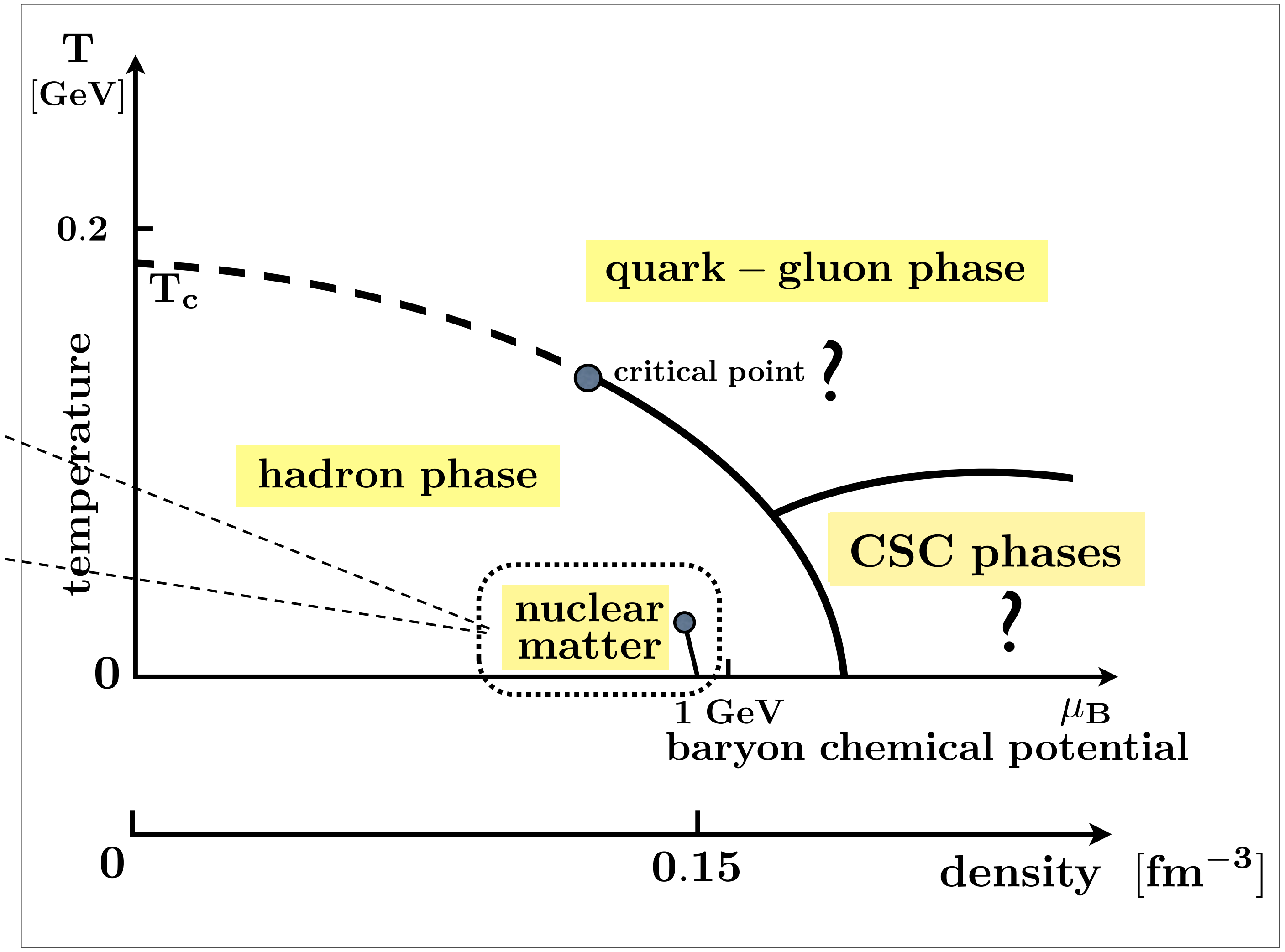
Part II:

NUCLEAR CHIRAL THERMODYNAMICS

NUCLEAR MATTER and QCD PHASES

nuclei





Scales in **nuclear matter**:

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

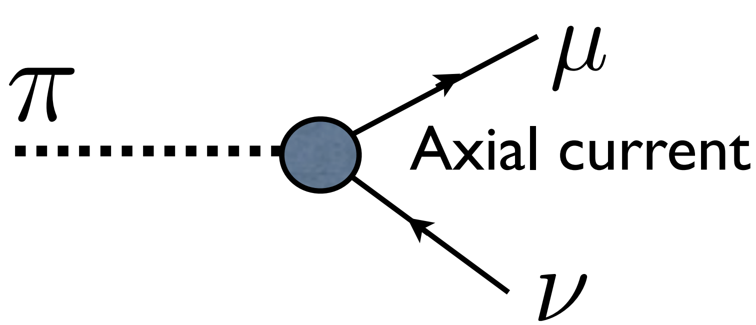
PIONS and **NUCLEI** in the context of **LOW-ENERGY QCD**

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

LOW-ENERGY / 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

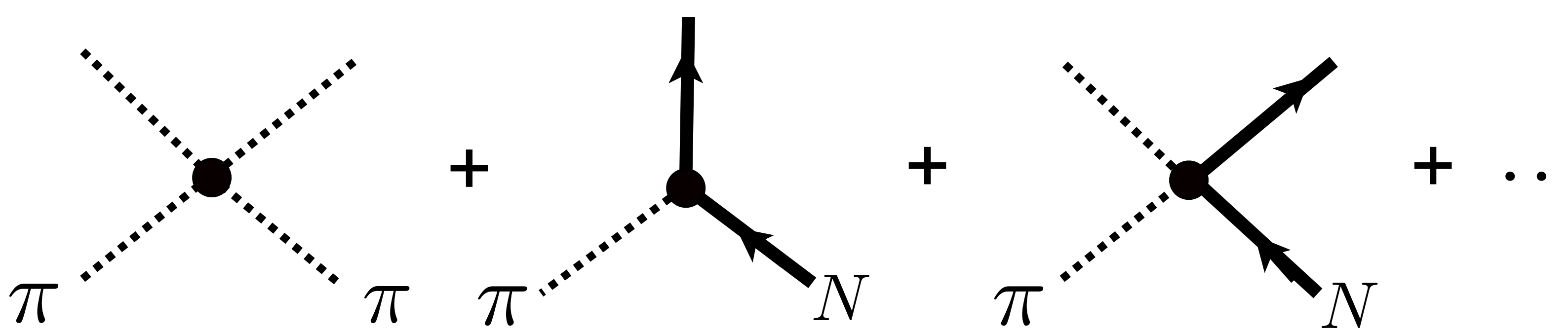
- Systematic framework at interface of QCD and Nuclear Physics

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

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

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

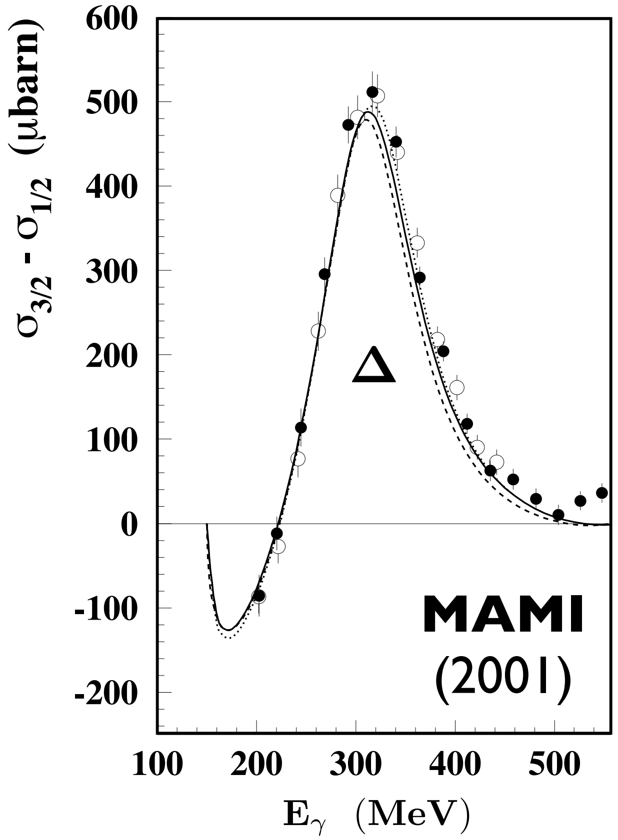
- Construction of Effective Lagrangian: **Symmetries**



short distance dynamics: **contact terms**

Explicit $\Delta(1230)$ DEGREES of FREEDOM

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

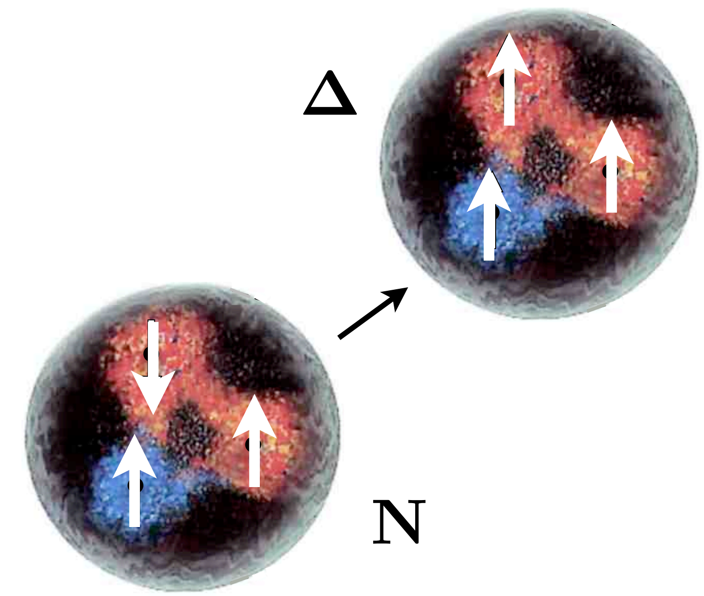


example: polarized Compton scattering

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

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

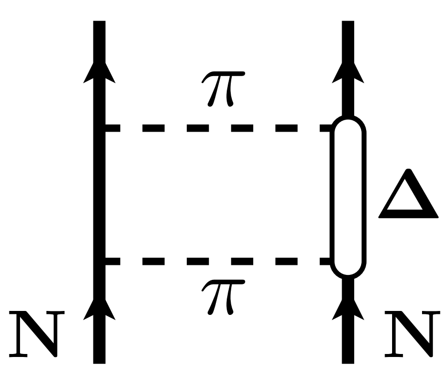
(small scale)



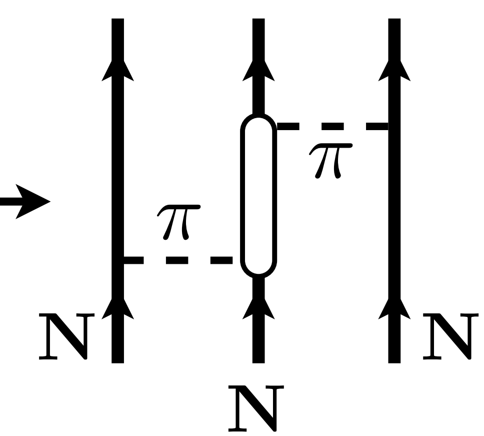
- **Pionic Van der Waals** - type intermediate range central potential

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

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



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



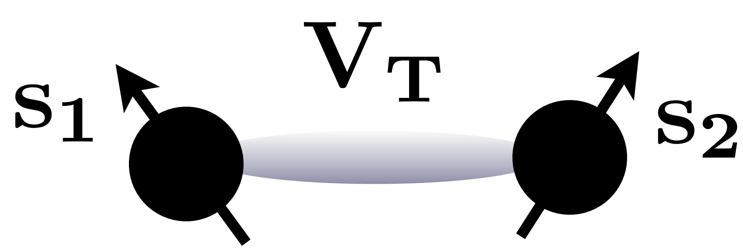
strong 3-body interaction

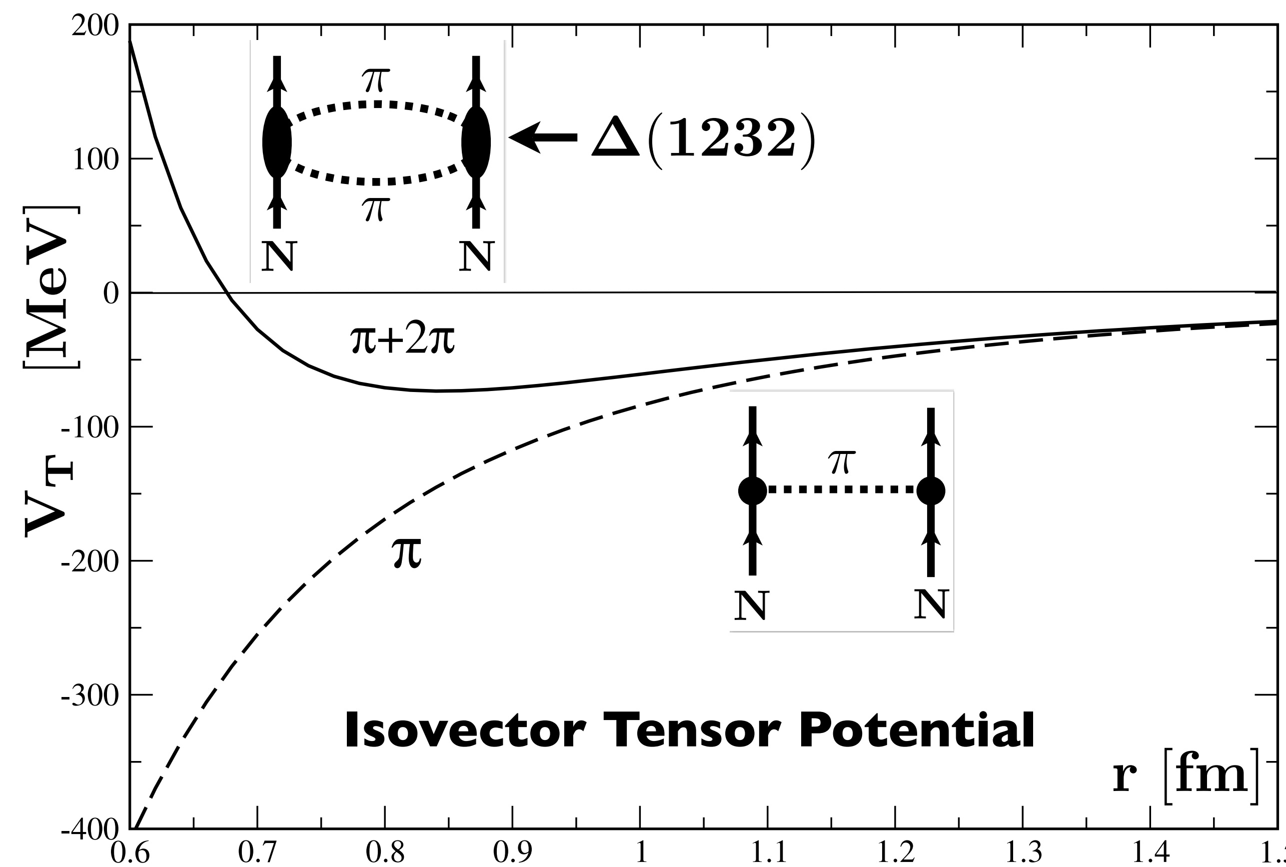
J. Fujita, H. Miyazawa (1957)

Pieper, Pandharipande, Wiringa, Carlson (2001)

Important pieces of the
CHIRAL NUCLEON-NUCLEON INTERACTION

- **ISOVECTOR TENSOR FORCE**

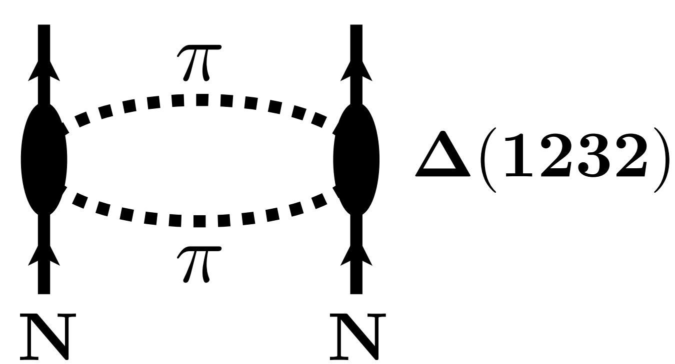




N. Kaiser, S. Gerstendörfer, W.W.: Nucl. Phys. A 637 (1998) 395

- 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

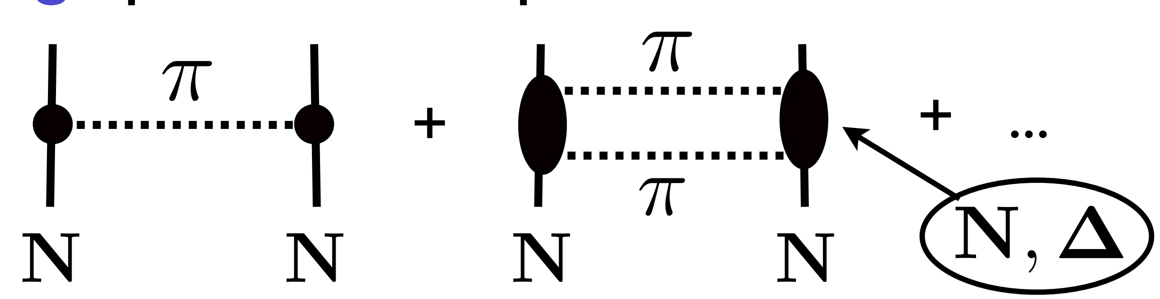
N. Kaiser, S. Fritsch, W.W. (2002 - 2005)

- **Small scales:** $\mathbf{k_F \sim 2\, m_\pi \sim M_\Delta - M_N << 4\pi\, f_\pi}$

- **PIONS** (and **DELTA** isobars) as **explicit degrees of freedom**

- **IN-MEDIUM CHIRAL PERTURBATION THEORY**

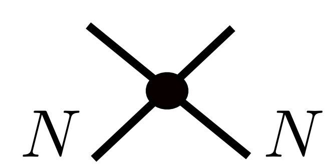
pion exchange processes in presence of filled **Fermi sea**



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

  ↕

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

- **Finite nuclei** ⟷ energy **density functional**

  J.W. Holt, N. Kaiser, W.W. ; arXiv:1107.5966 [nucl-th]

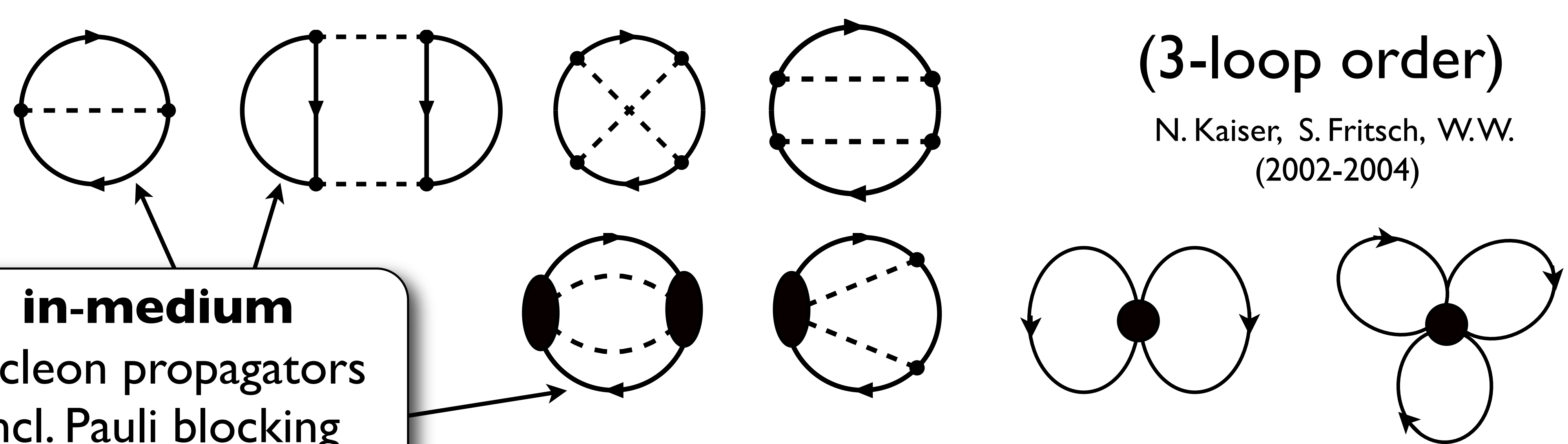
  many quantitatively successful applications throughout the nuclear chart

  e.g. P. Finelli et al.: Nucl. Phys. A 770 (2007) 1

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

  (3-loop order)

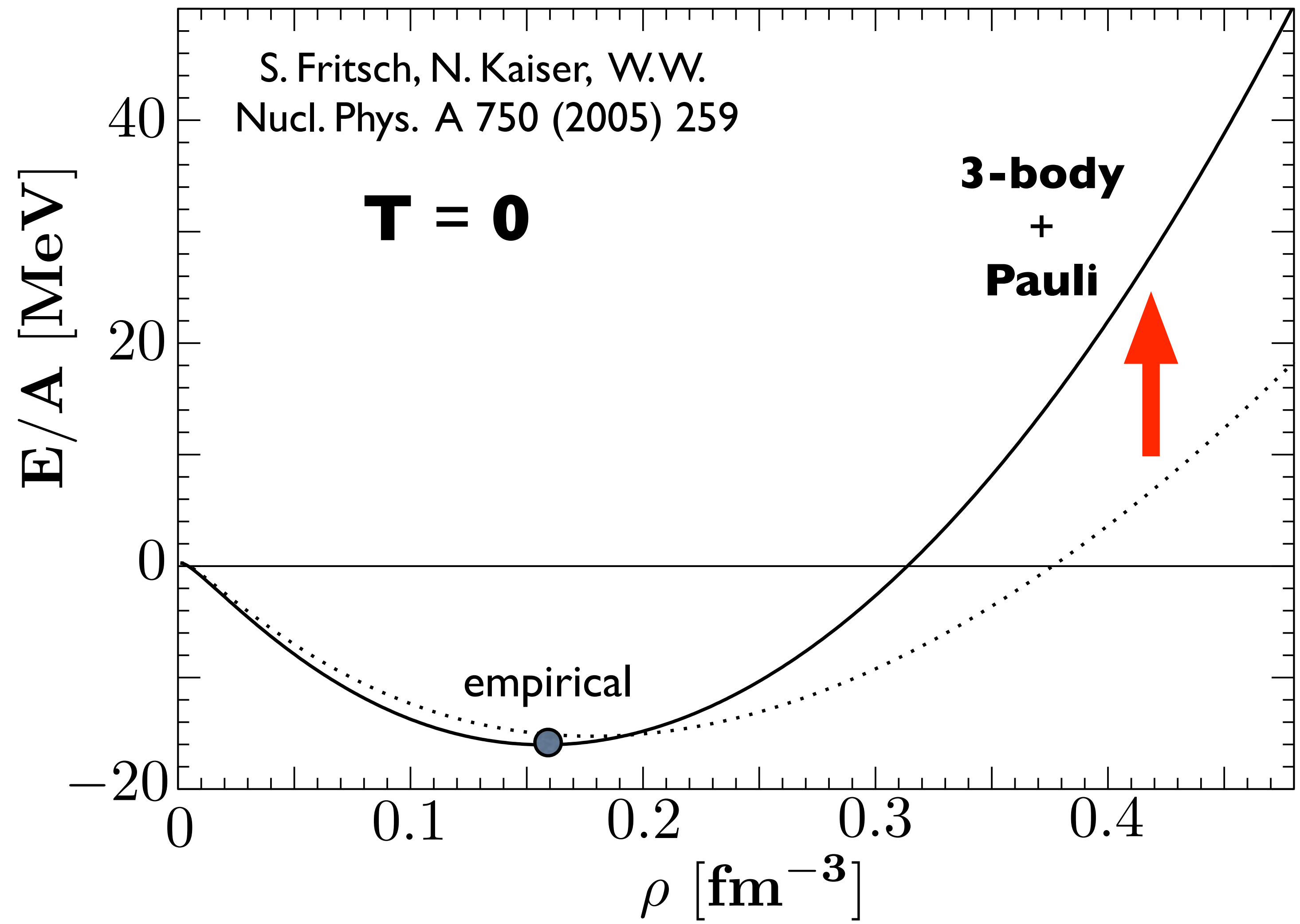
  N. Kaiser, S. Fritsch, W.W. (2002-2004)



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

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

- 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

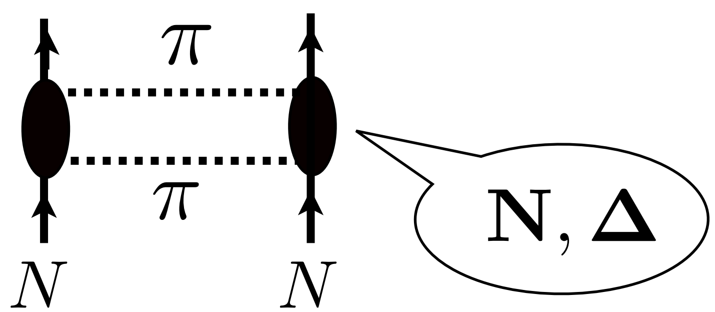
J.W. Holt, N. Kaiser, W.W.
arXiv: 1106.5702 [nucl.-th], NPA (2011)

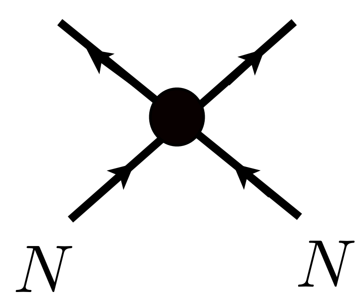
NUCLEAR THERMODYNAMICS

NUCLEAR
CHIRAL (PION) **DYNAMICS**

BINDING & SATURATION:

Van der Waals + Pauli

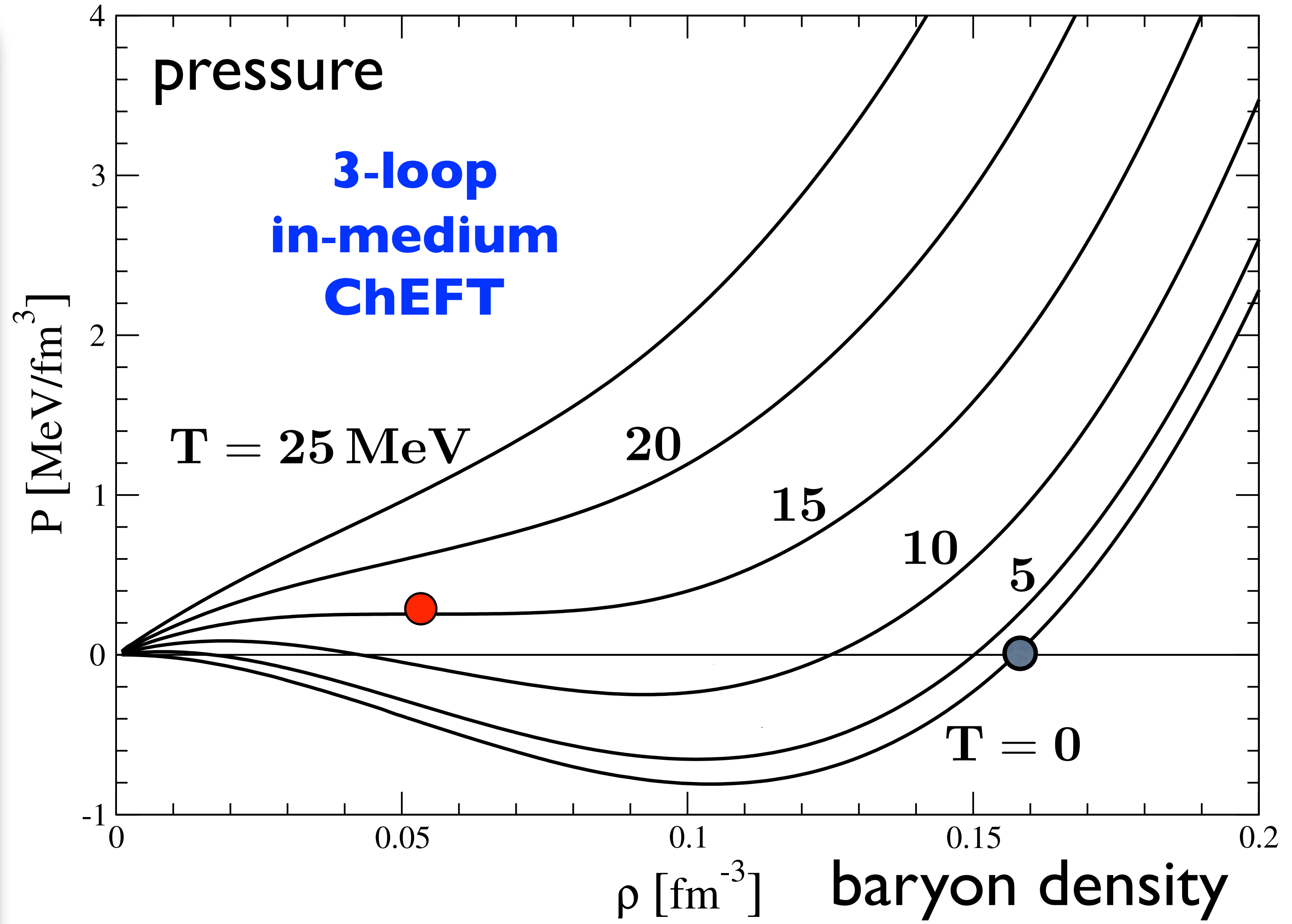


+ 

+ **3-body forces**

contact terms

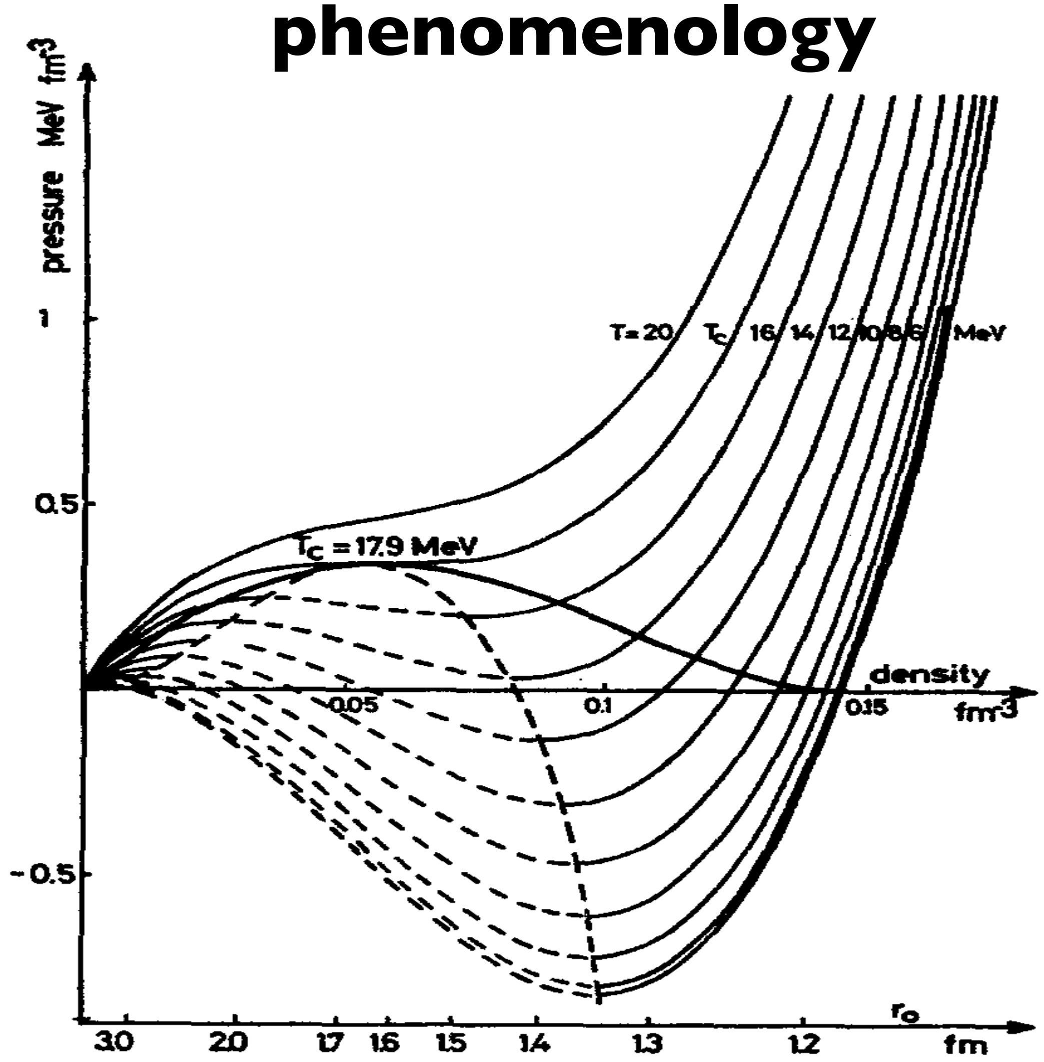
nuclear matter: equation of state



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

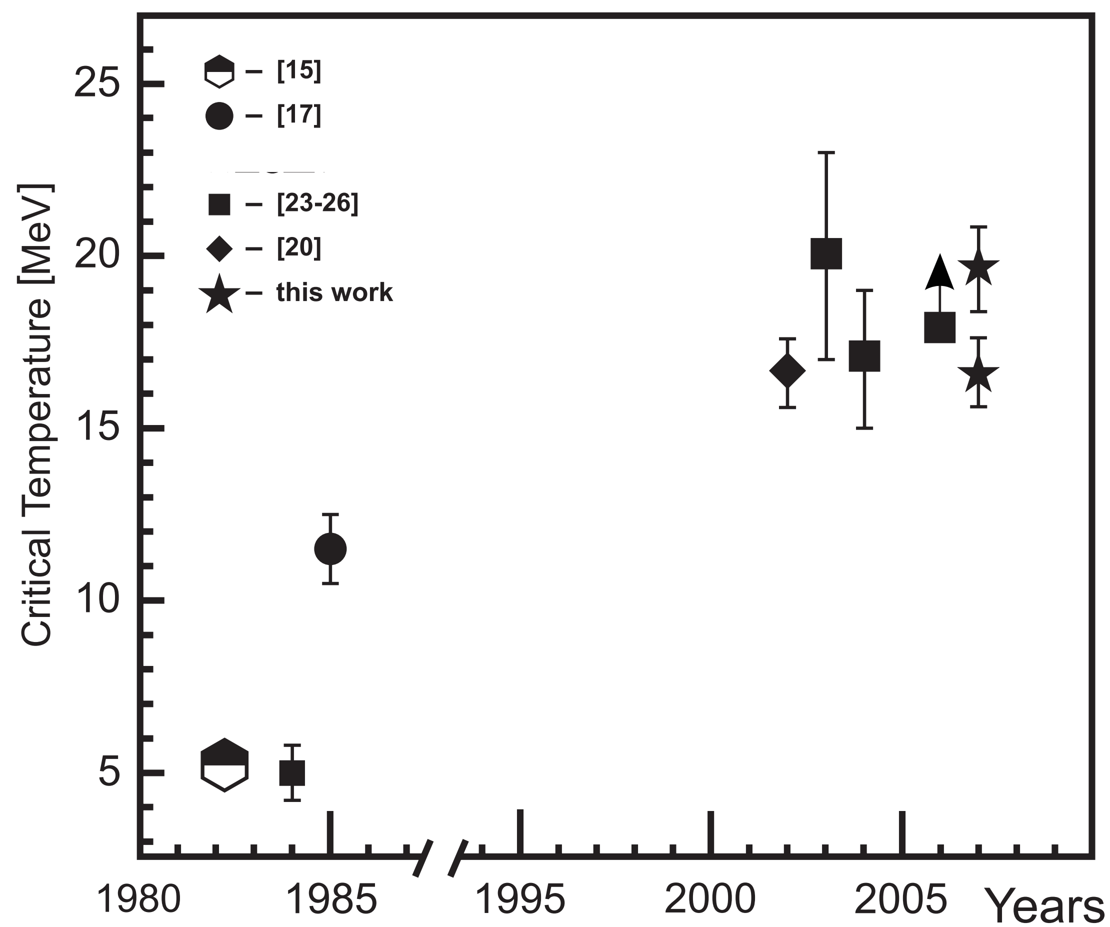
NUCLEAR THERMODYNAMICS

Skyrme phenomenology



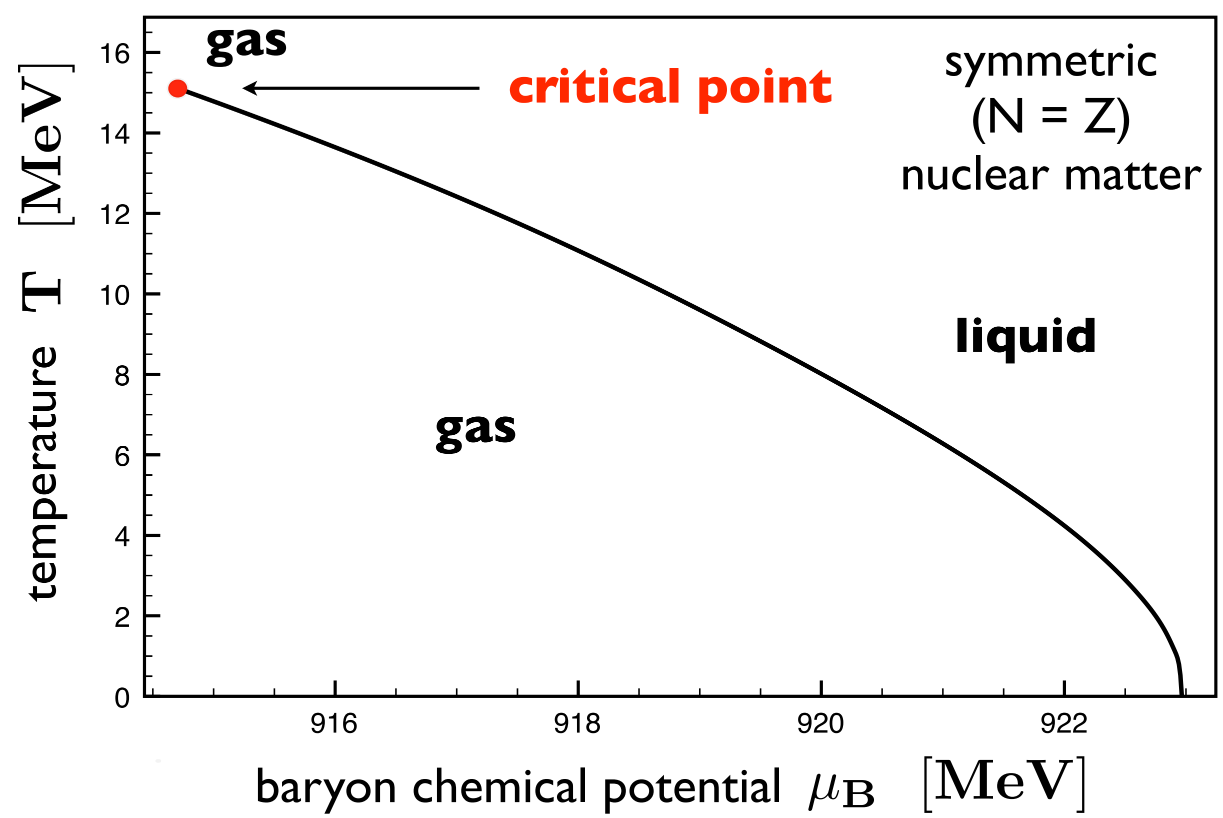
G. Sauer, H. Chandra, U. Mosel
Nucl. Phys. A 264 (1976) 221

Multifragmentation and fission analysis



V.A. Karnaukhov et al. :
Phys. Atom. Nucl. 71 (2008) 2067

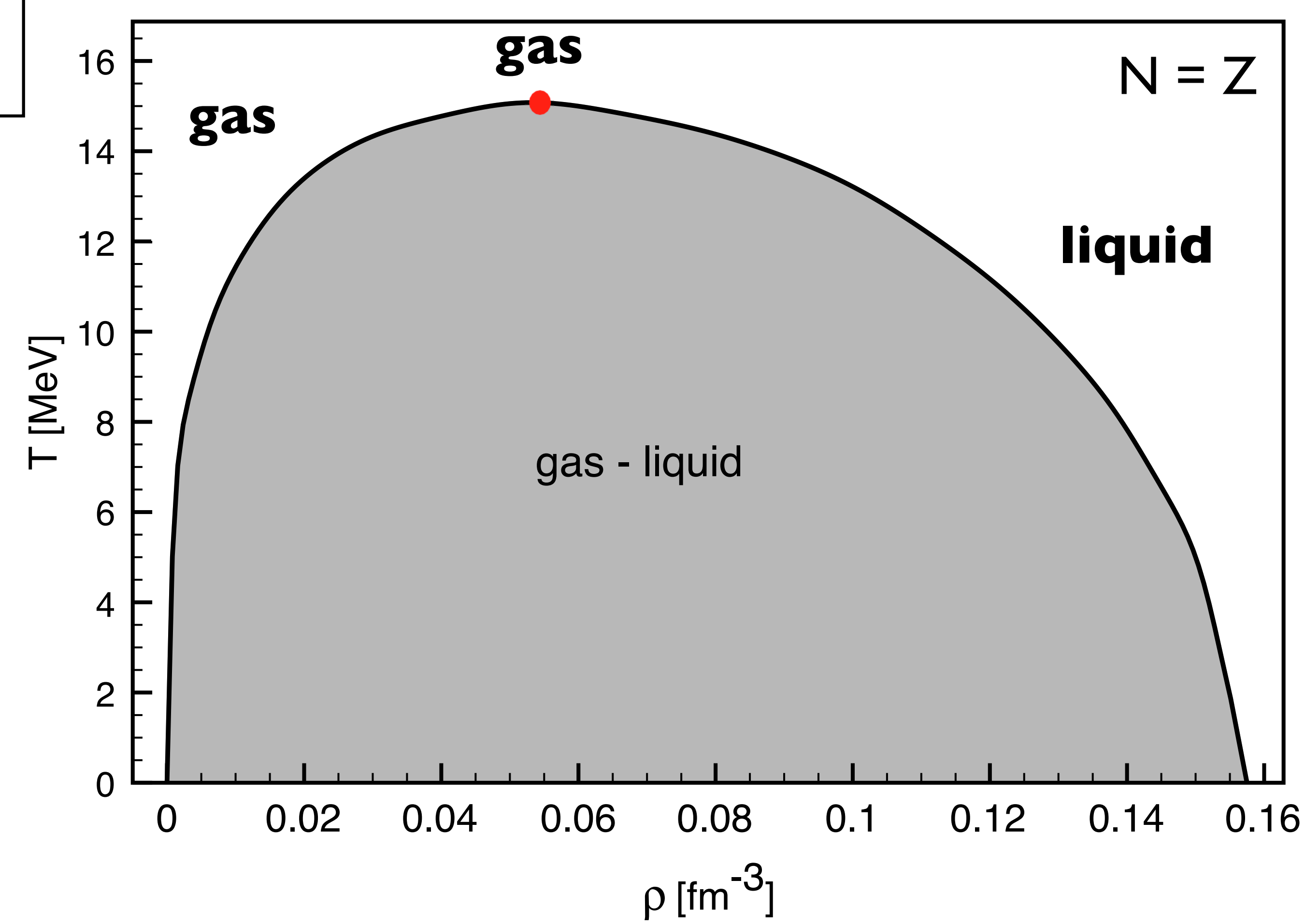
PHASE DIAGRAM of NUCLEAR MATTER



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

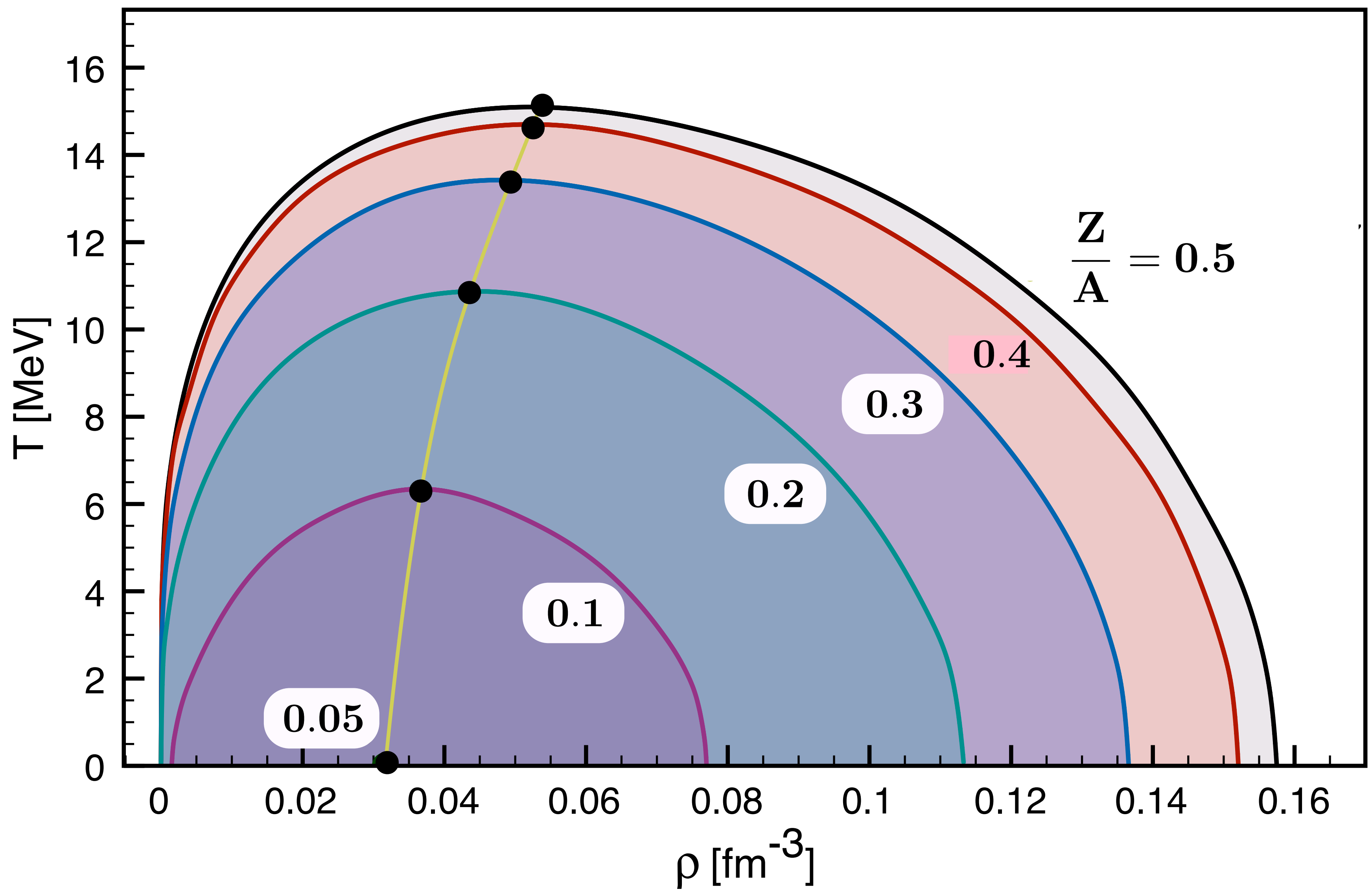
S. Fritsch, N. Kaiser, W.W.: NPA 750 (2005) 259
S. Fiorilla, N. Kaiser, W.W. (2011)

- 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. (2011)

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

CHIRAL CONDENSATE at finite **BARYON DENSITY**

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

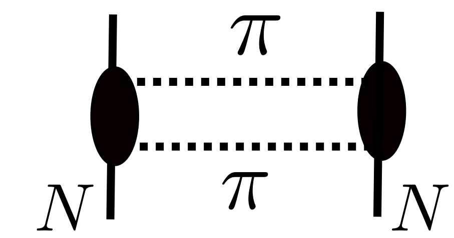
  Order parameter of spontaneously broken chiral symmetry in QCD

- 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



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

(free) Fermi gas of nucleons

nuclear interactions (dependence on pion mass)

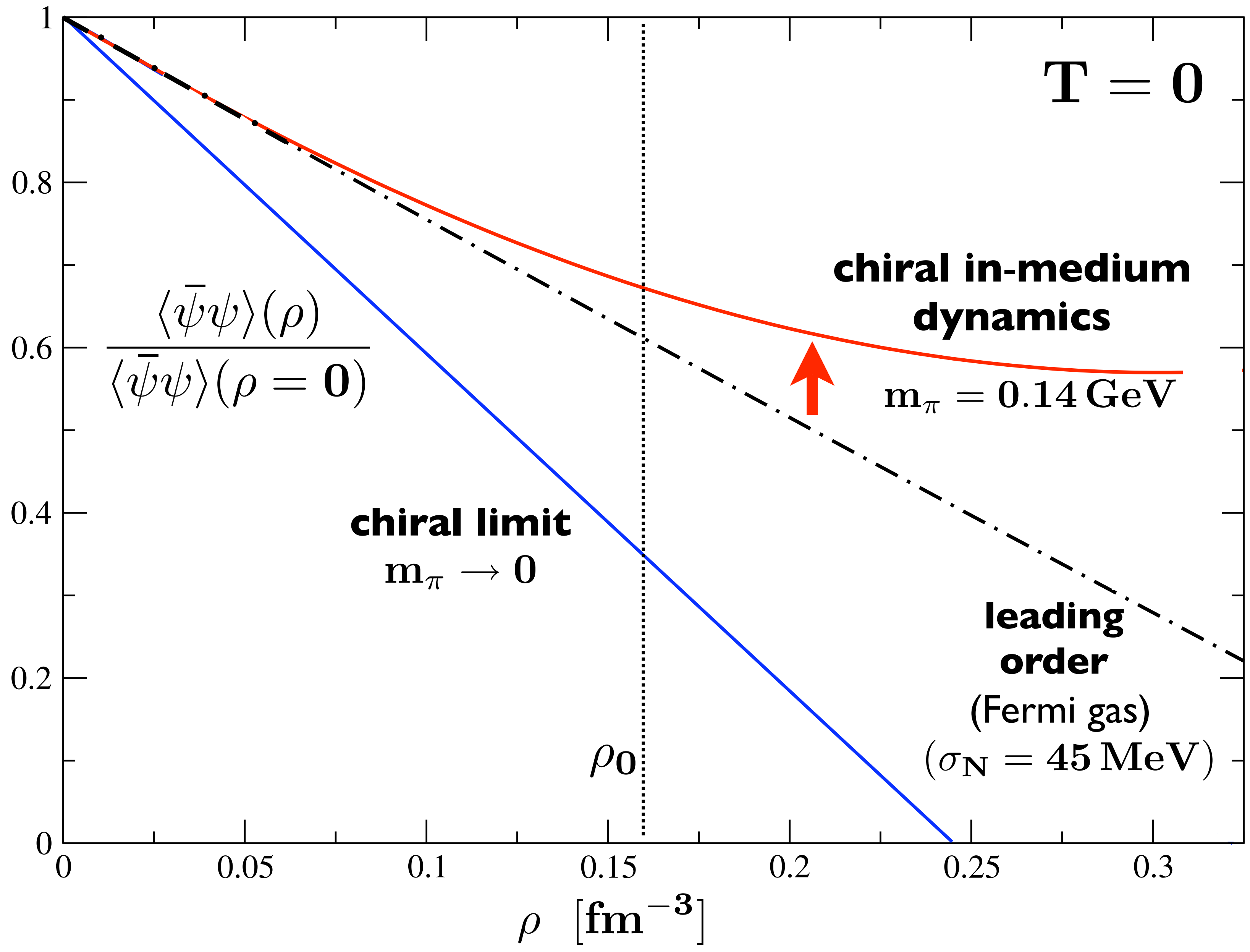
CHIRAL CONDENSATE: DENSITY DEPENDENCE

- **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

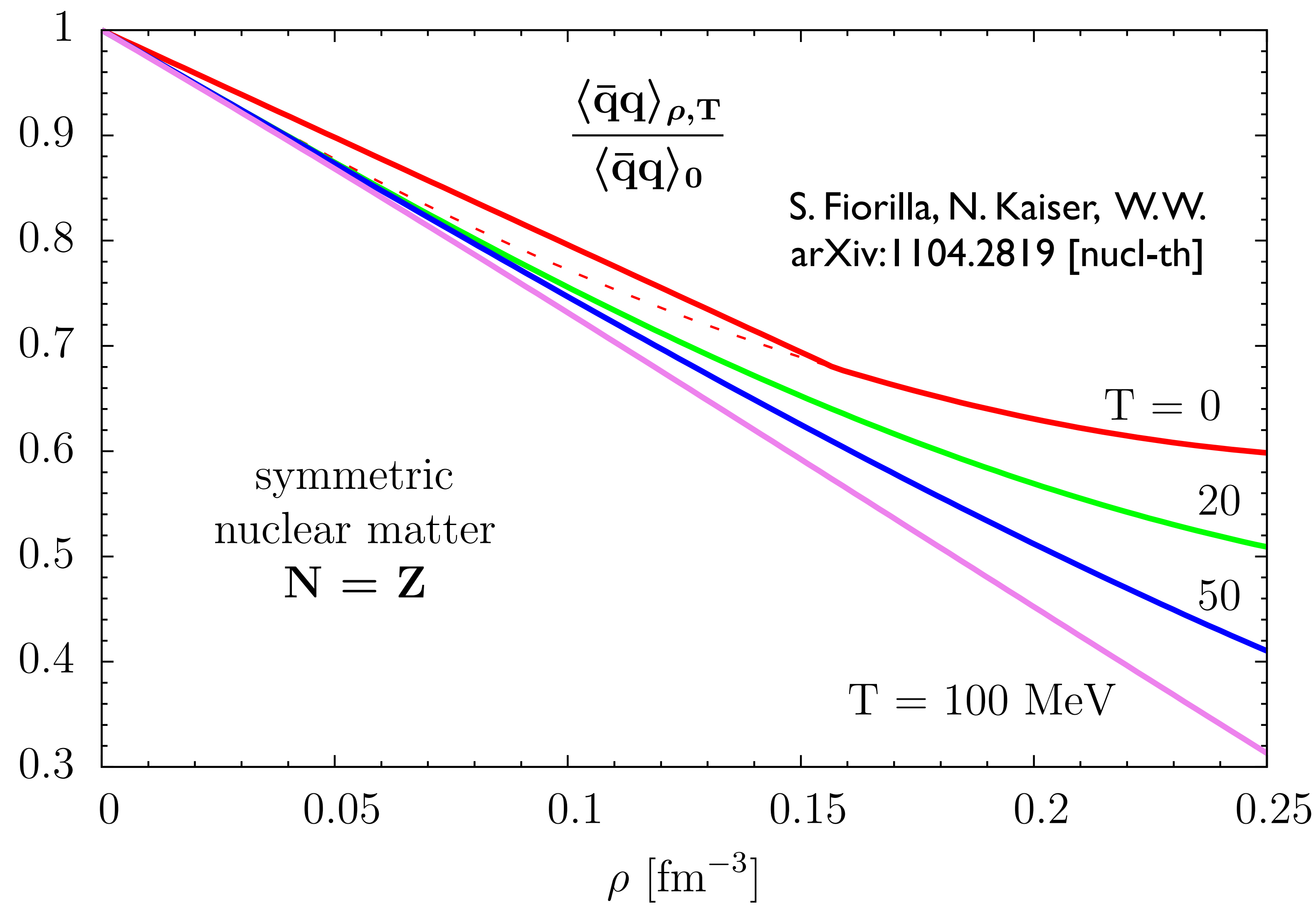
- Free energy density $\mathcal{F}(\mathbf{m_q};\rho,\mathbf{T})$

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

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

(NLO 3-loop)

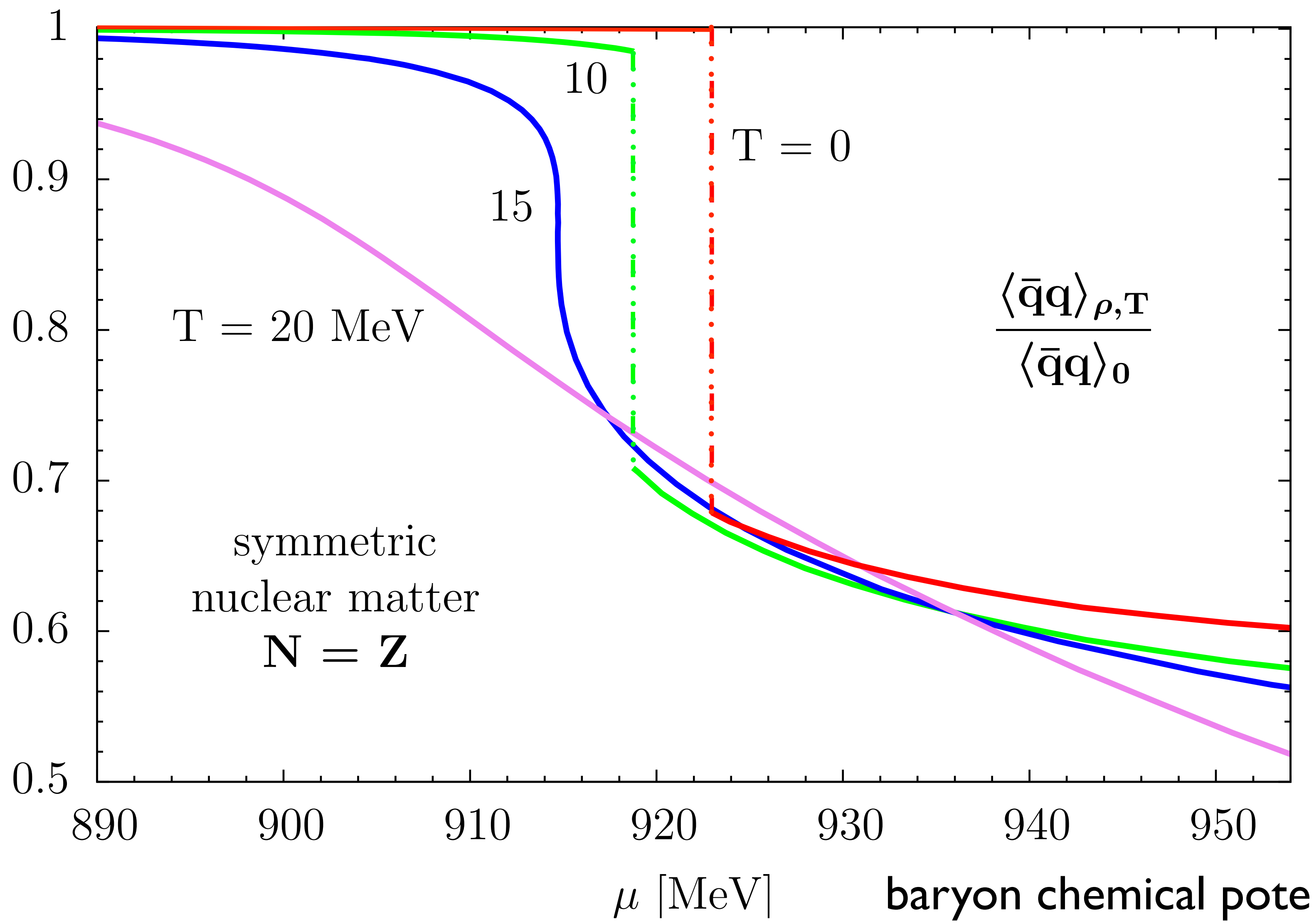
constrained by **realistic nuclear equation of state**



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

$$\rho \lesssim \mathbf{2}\,\rho_0\,, \quad \mathbf{T} \lesssim \mathbf{100\,MeV}$$

CHIRAL CONDENSATE:
Dependence on TEMPERATURE and BARYON CHEMICAL POTENTIAL



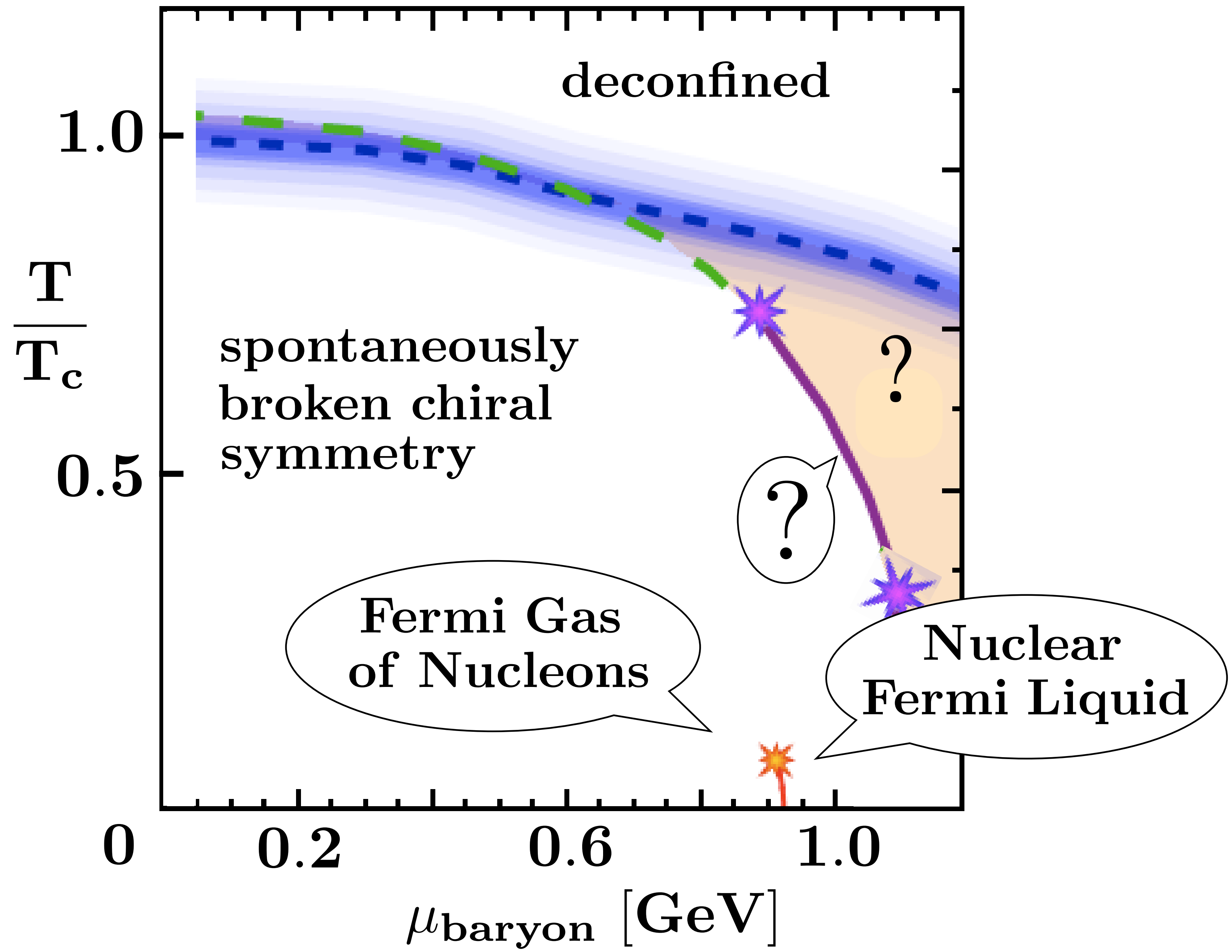
baryon chemical potential

S. Fiorilla, N. Kaiser, W.W. (2011)

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

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

Summary: PHASE DIAGRAM with NUCLEAR PHYSICS CONSTRAINTS



from nuclear **chiral thermodynamics** :

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

$$\rho \lesssim 2\,\rho_0$$

$$T \lesssim 100\,\text{MeV}$$

S. Fiorilla, N. Kaiser, W.W.
arXiv:1104.2819 [nucl-th]

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

Outlook:

New Constraints
from
NEUTRON STARS

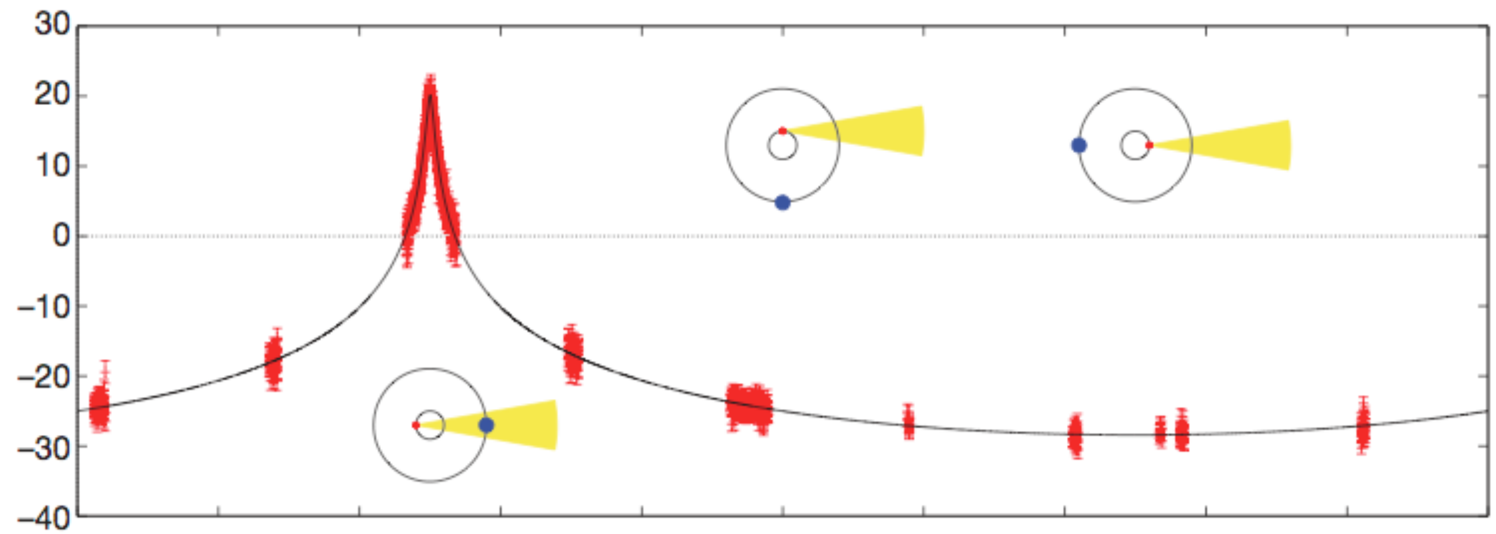
doi:10.1038/nature09466

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

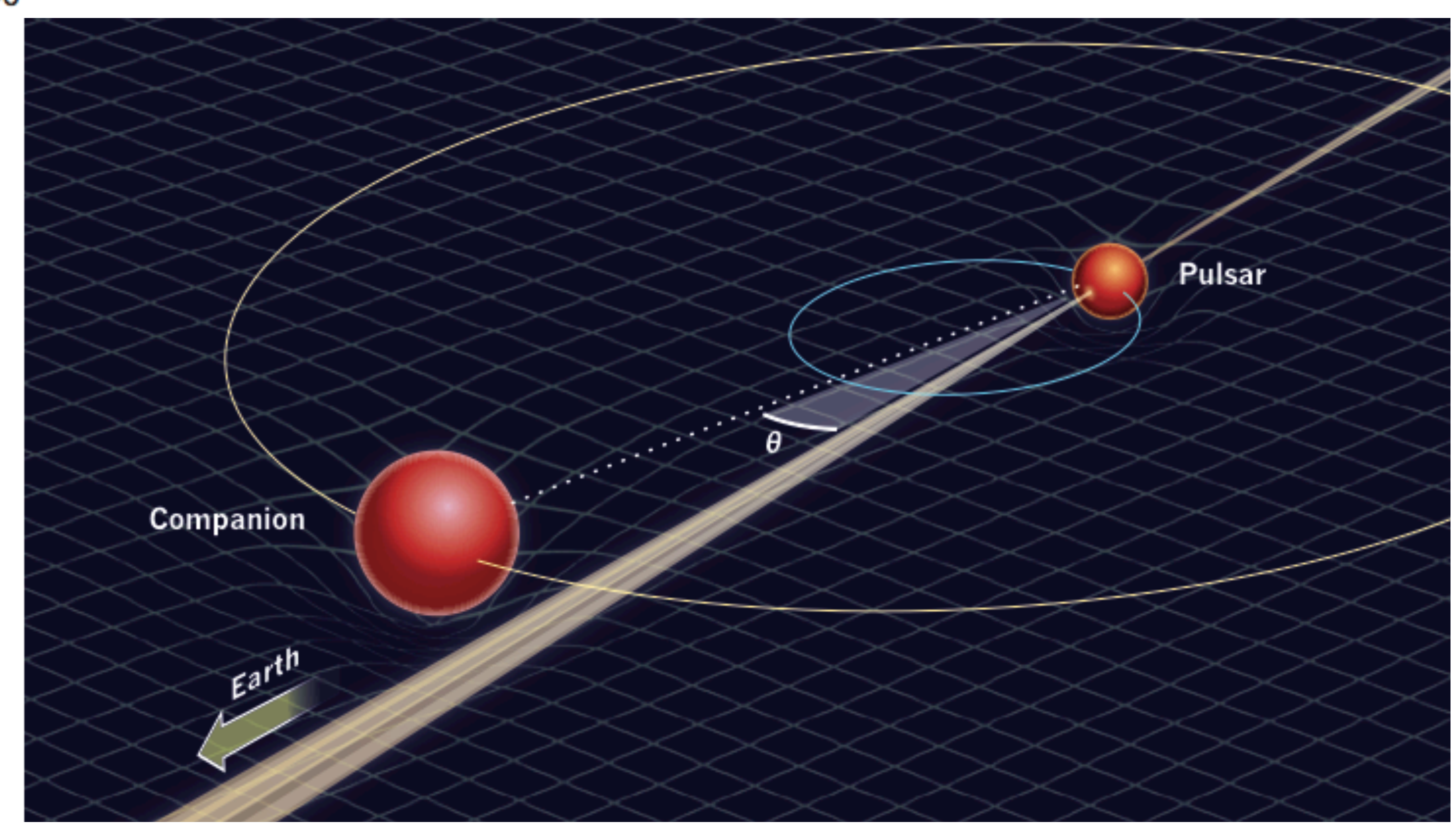
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

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})

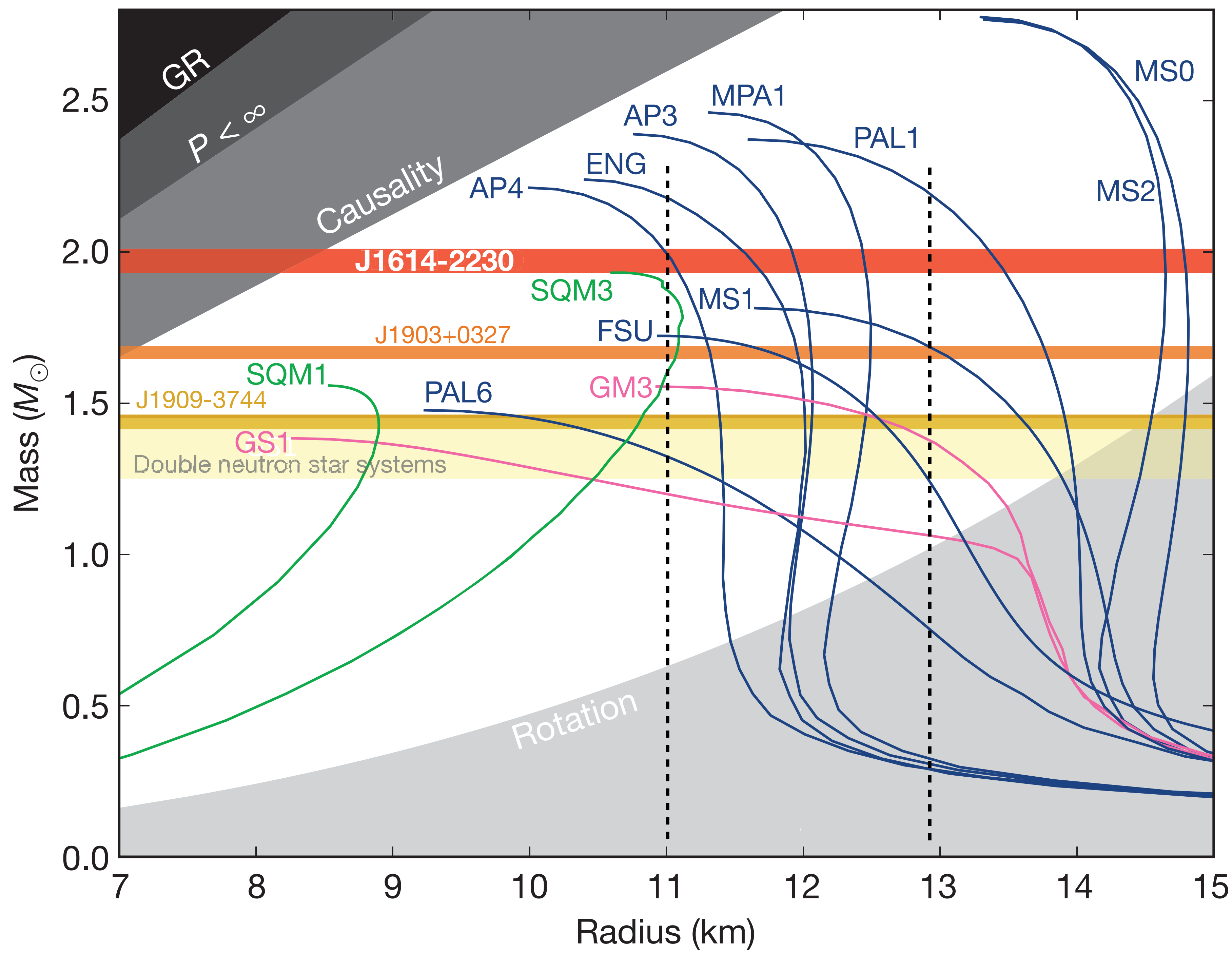


heaviest neutron star with 1.97±0.04 M_{sun}

TWO-SOLAR-MASS NEUTRON STAR

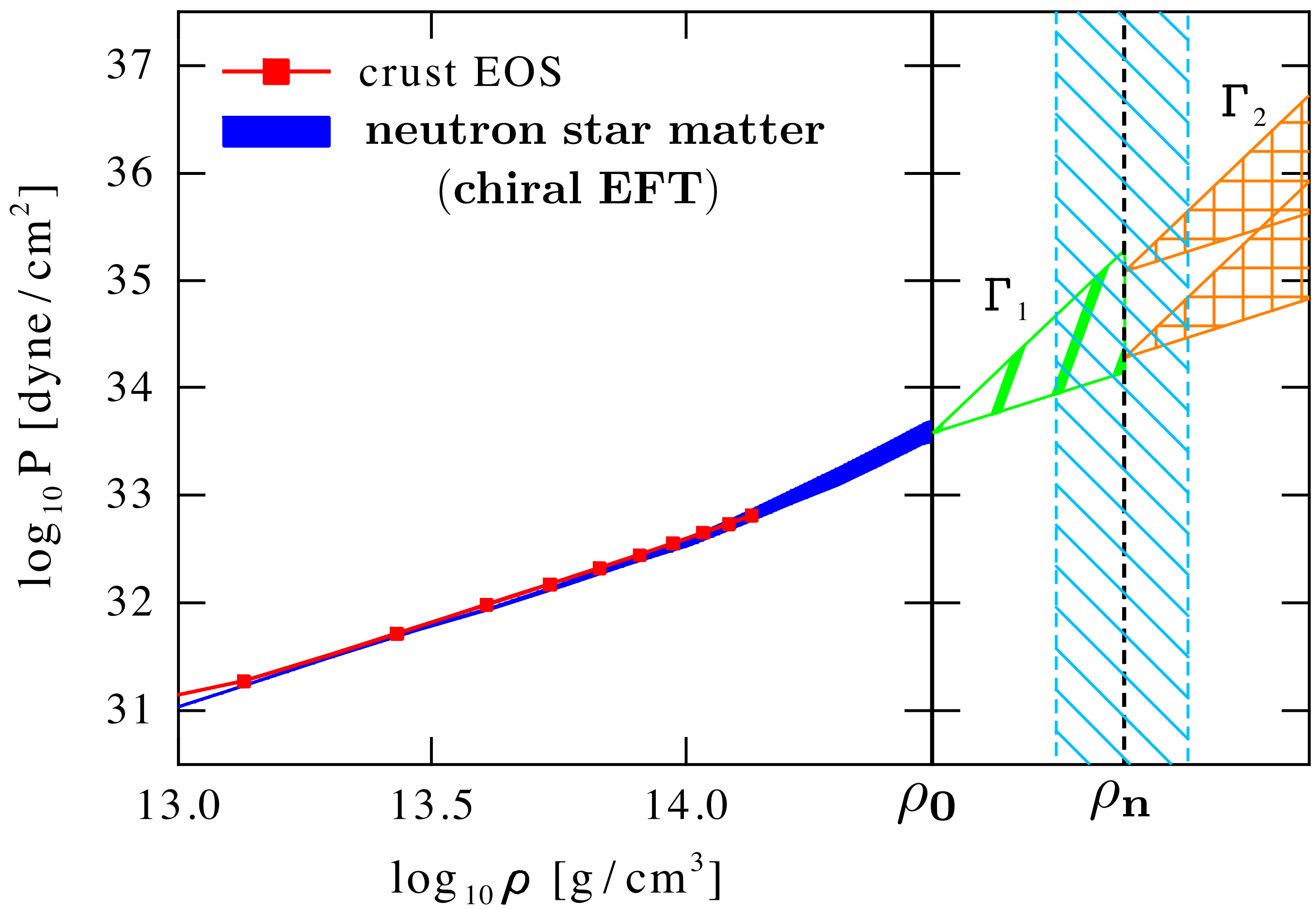
. . . measured using Shapiro delay

P.B. Demorest et al., Nature 467 (2010) 1081

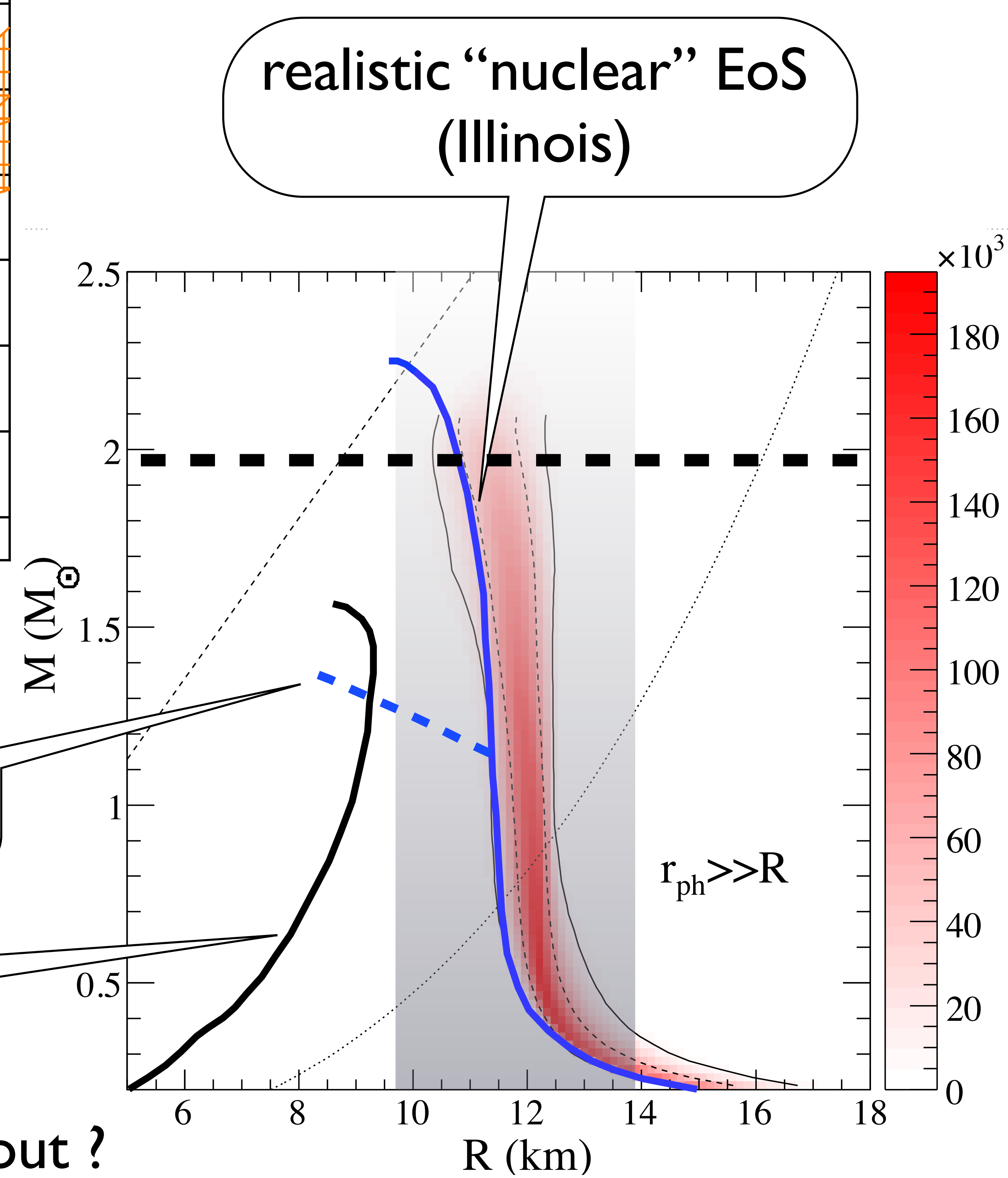


News from NEUTRON STARS

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



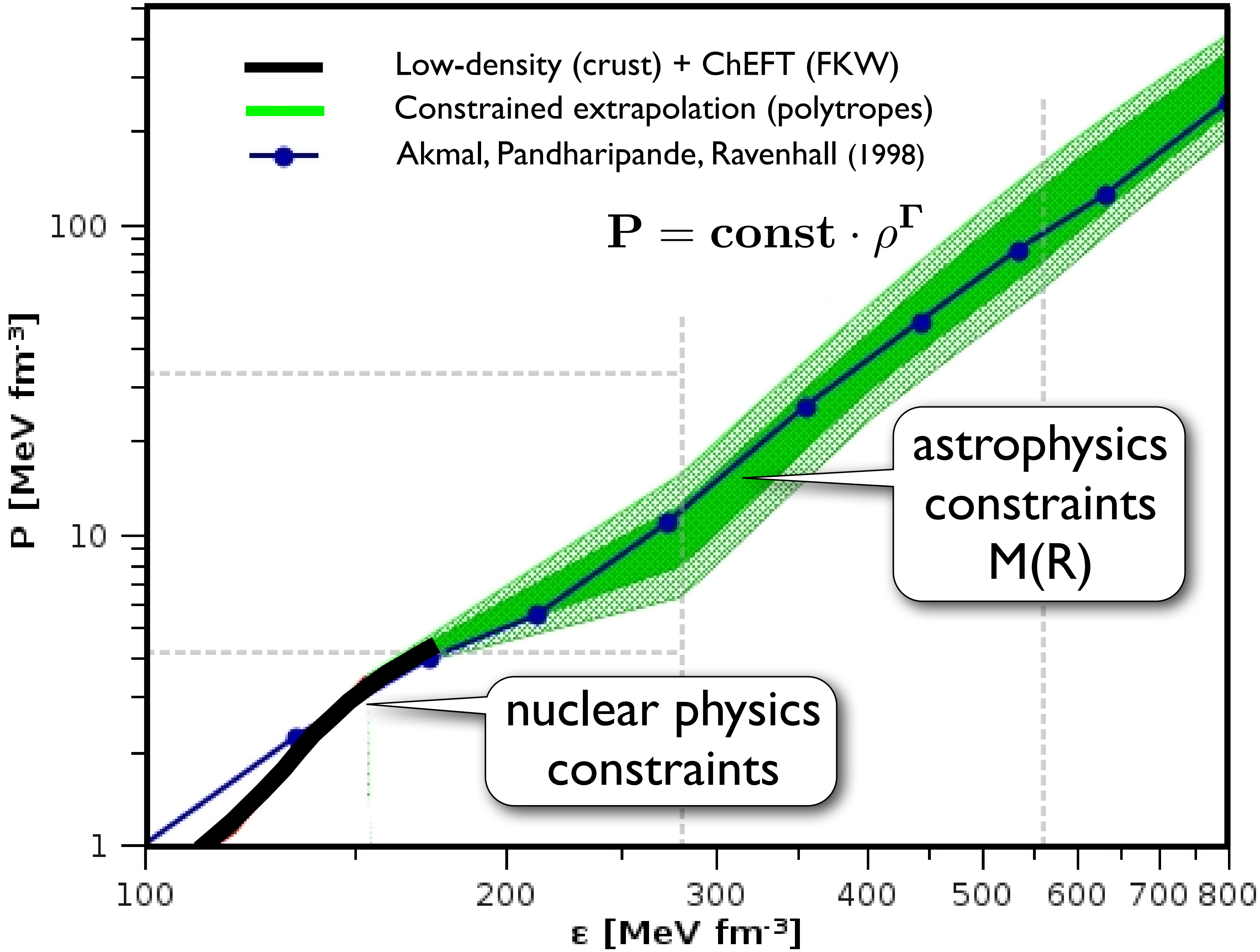
A.W. Steiner, J. Lattimer, E.F. Brown
Astroph. J. 722 (2010) 33



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

NEUTRON STAR MATTER

Equation of State



Bernhard Röttgers, W.W. (2011)

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

SUMMARY

- Exploration of **QCD phase diagram**:
  progress concerning basic symmetry breaking patterns
  - Lattice QCD (restricted to small quark chemical potentials)
  - Models (PNJL, PQM) (but: nuclear physics constraints missing)
  - Dyson-Schwinger QCD (-- same problem --)

- **Nuclear thermodynamics** based on
  In-medium **C**hiral **E**ffective **F**ield **T**heory

  Fermi liquid ↔ interacting Fermi gas (1st order transition)
  - **No** indication of first order **chiral** transition in the range

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

  - Major challenge: design **QCD phase diagram** that is consistent with established hadronic and nuclear physics

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

The End

thanks to :

Nino Bratovic
Jeremy Holt

Salvatore Fiorilla
Norbert Kaiser

Thomas Hell
Kouji Kashiwa