NUCLEAR CHIRAL THERMODYNAMICS
and PHASES of QCD

Wolfram Weise
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- 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**

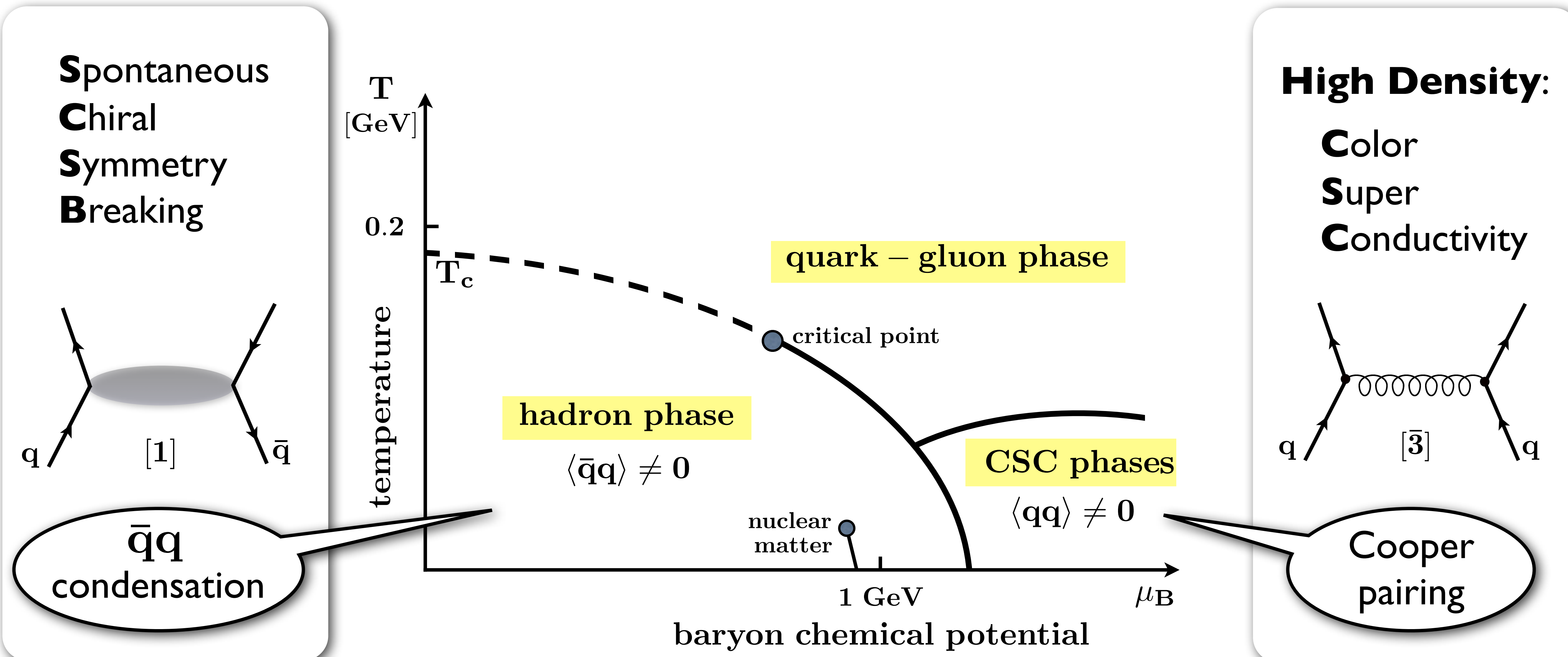
Part I: Prelude

QCD PHASE DIAGRAM

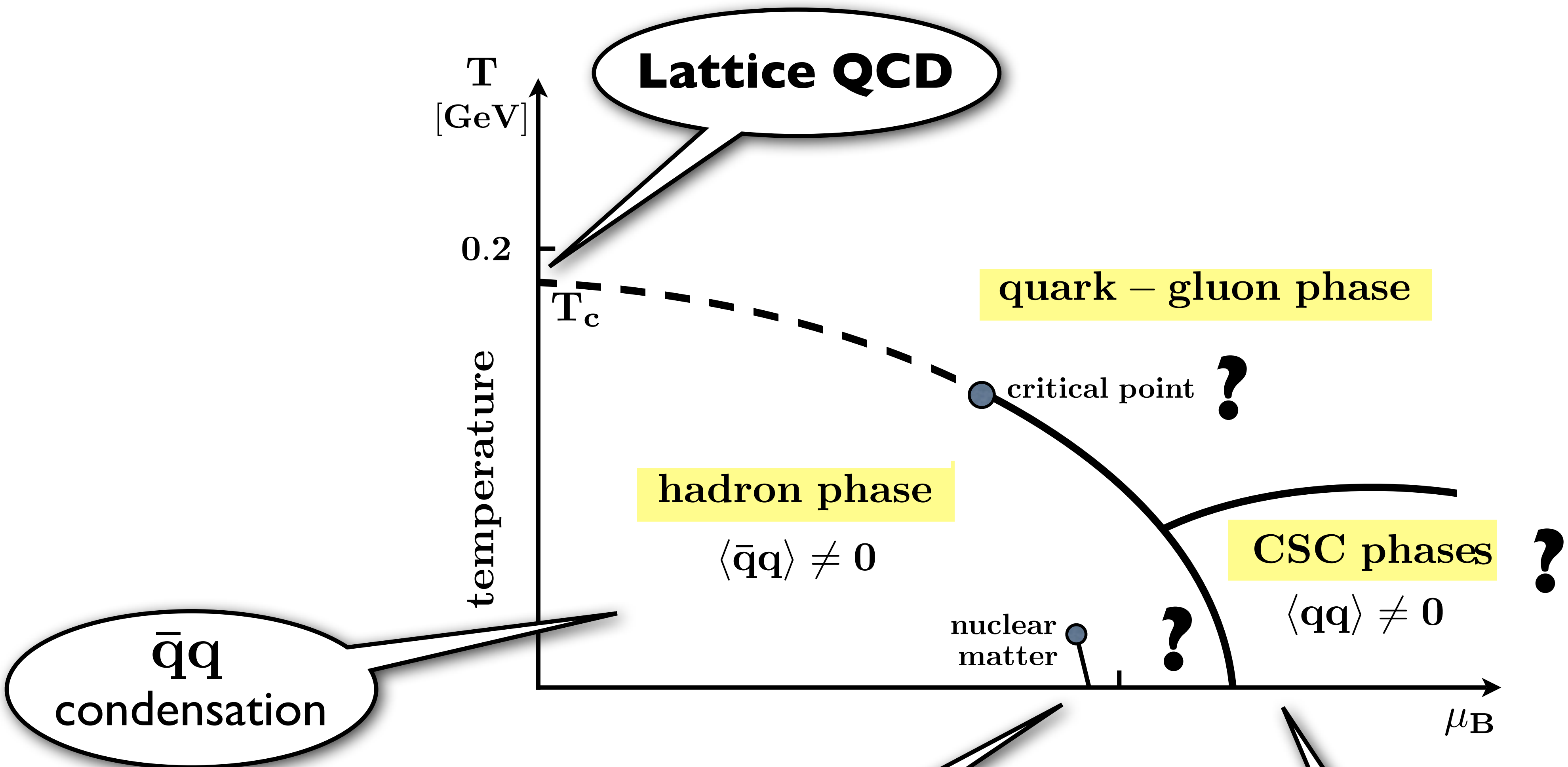
Visions & Facts

QCD PHASE DIAGRAM

(theorists' vision)



QCD PHASE DIAGRAM



Constraints
from
Nuclear Physics

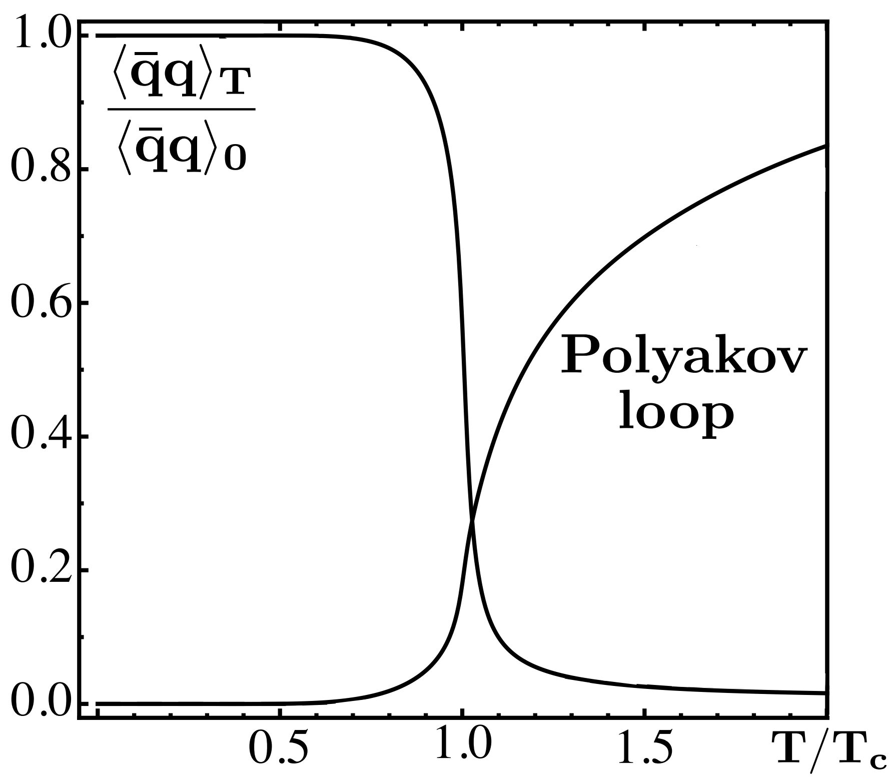
New constraints
from
Neutron Stars

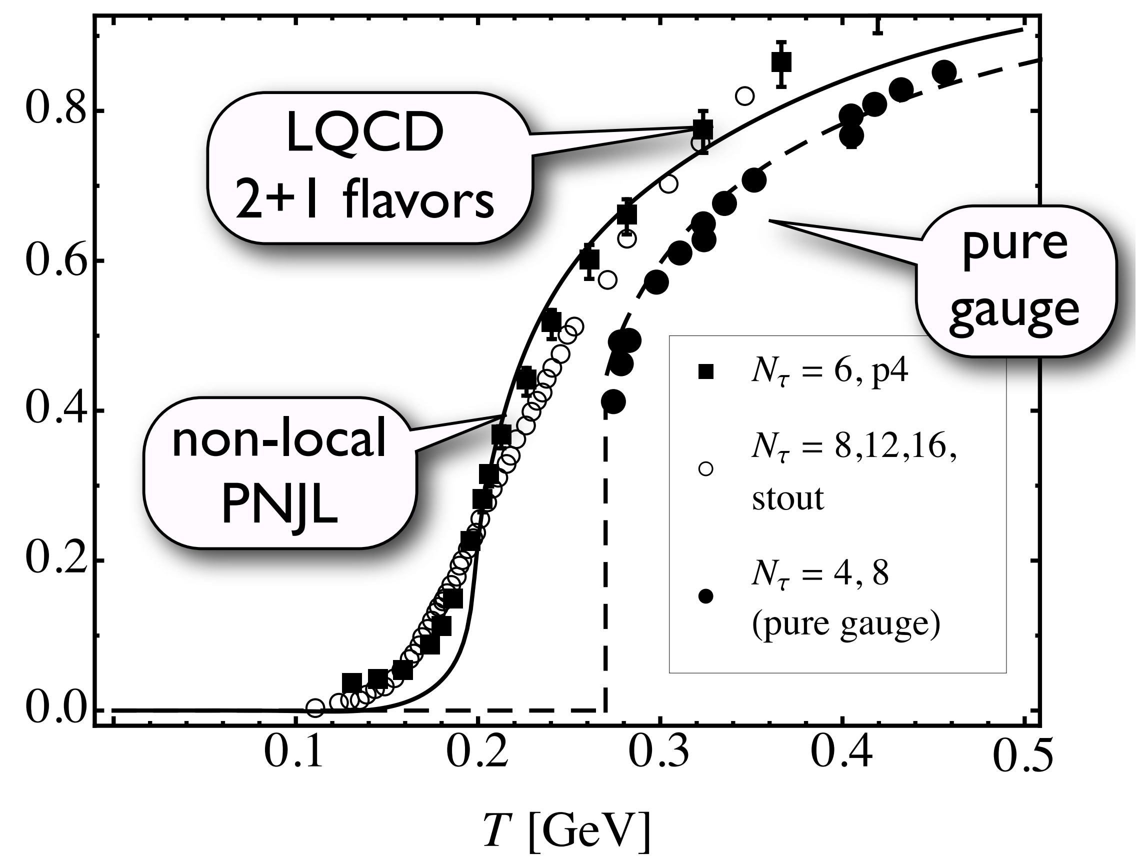
MODELING the QCD PHASE DIAGRAM

- 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)

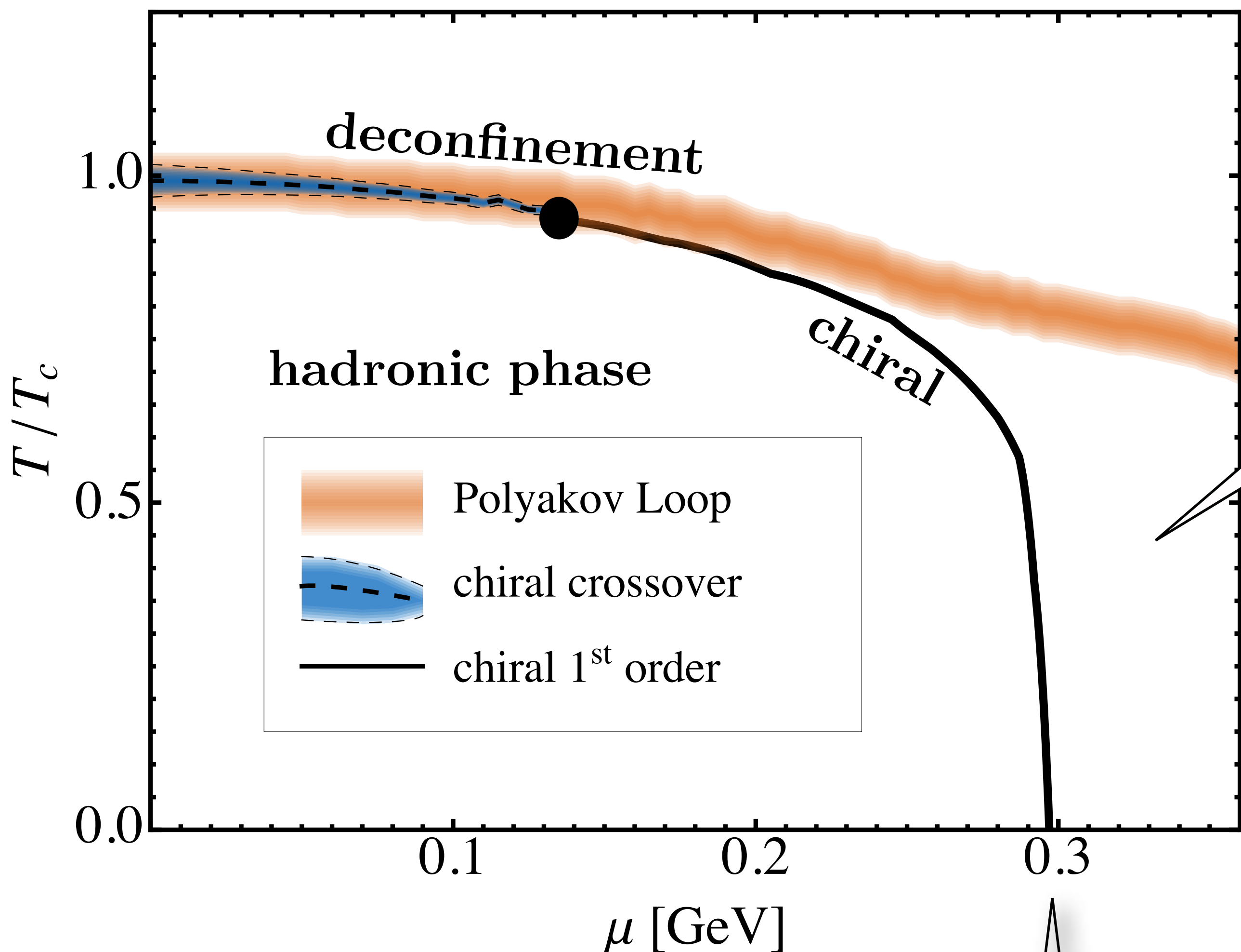




T. Hell, S. Rössner, M. Cristoforetti, W.W. : Phys. Rev. D81 (2010) 074034
T. Hell, K. Kashiwa, W.W. : Phys. Rev. D83 (2011) 114008

PHASE DIAGRAM

Non-local 3-flavor PNJL model calculation

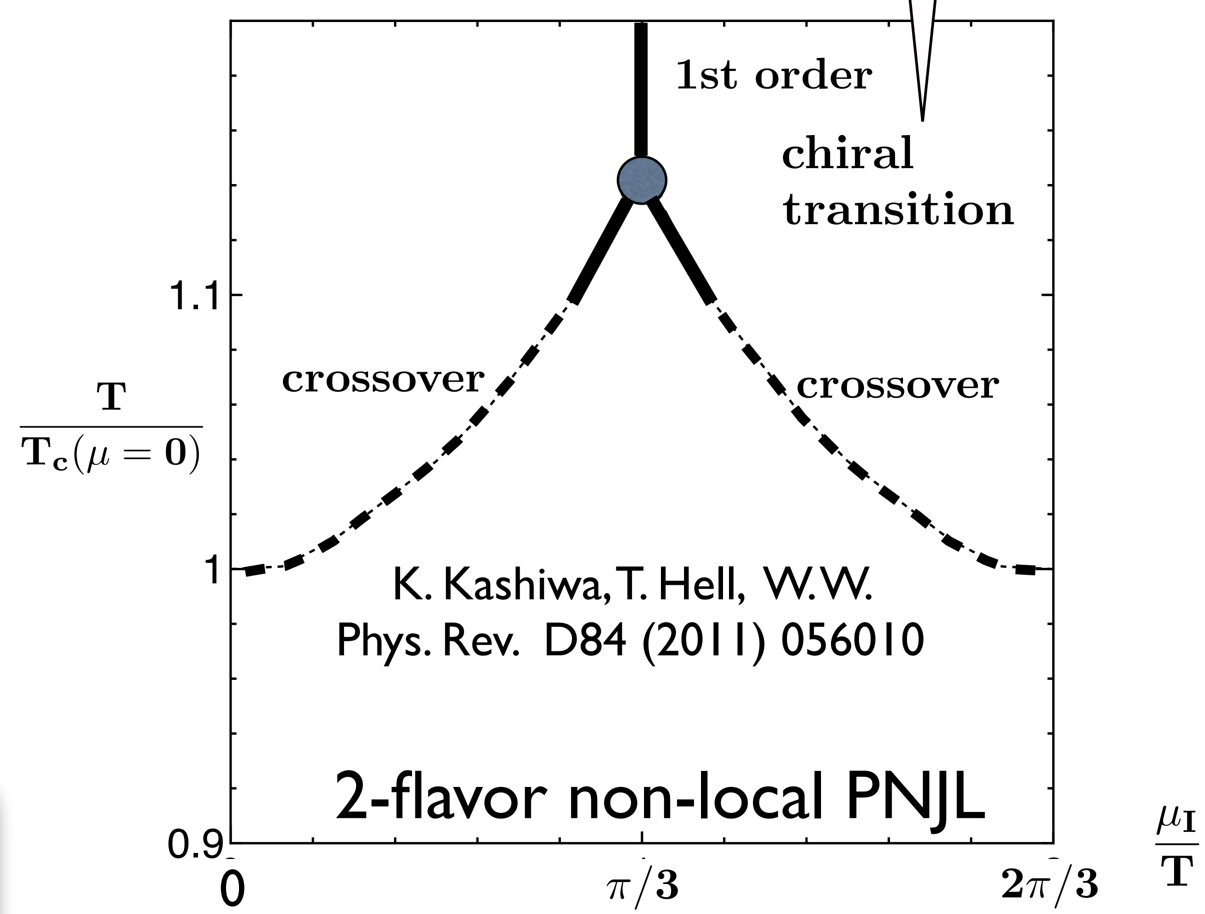


T. Hell, K. Kashiwa, W.W. :
Phys. Rev. D83 (2011) 114008

quarkyonic ?
L. McLerran, R. Pisarski

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

chiral 1st order transition line ?



imaginary chemical potential

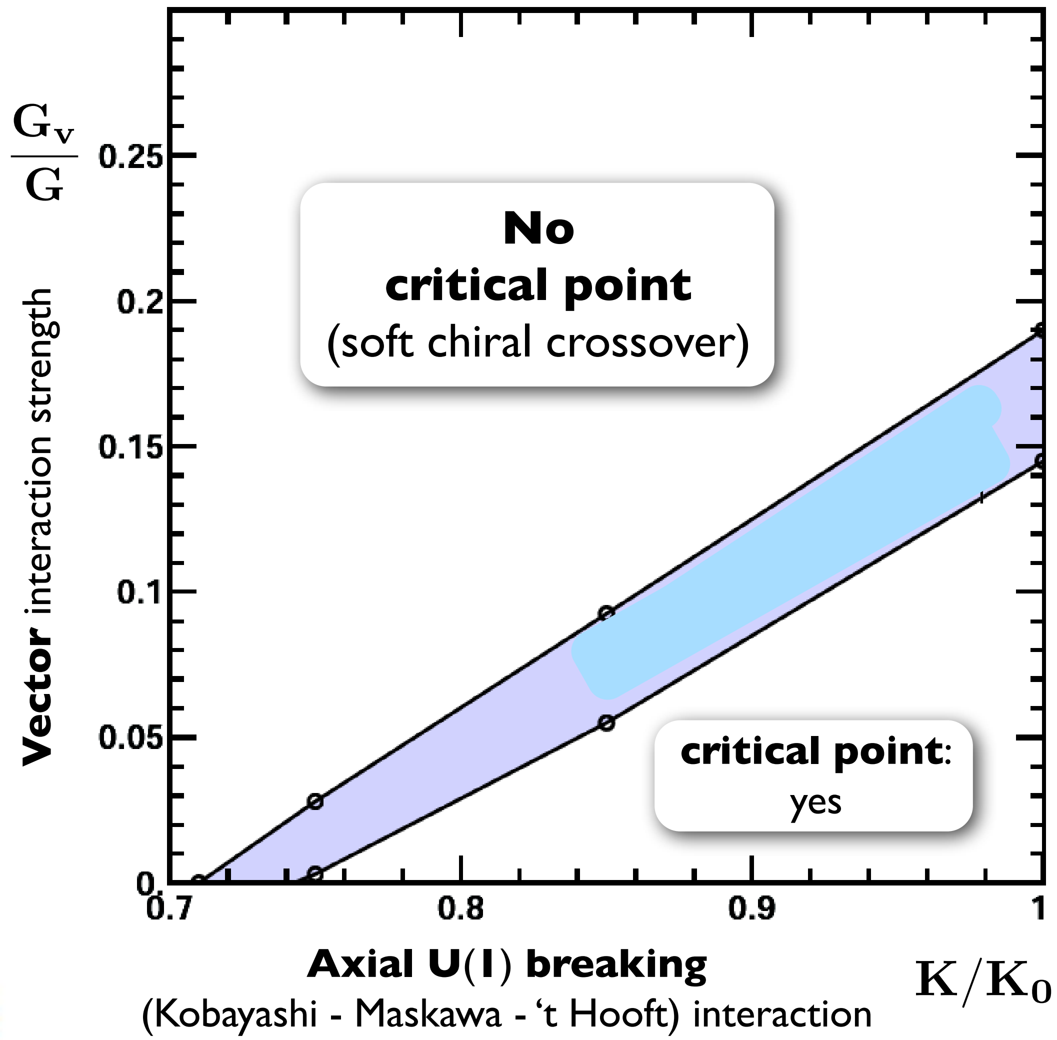
- Does the **first-order line** really extend down to **low** temperatures **?**

PHASE DIAGRAM (contd.)

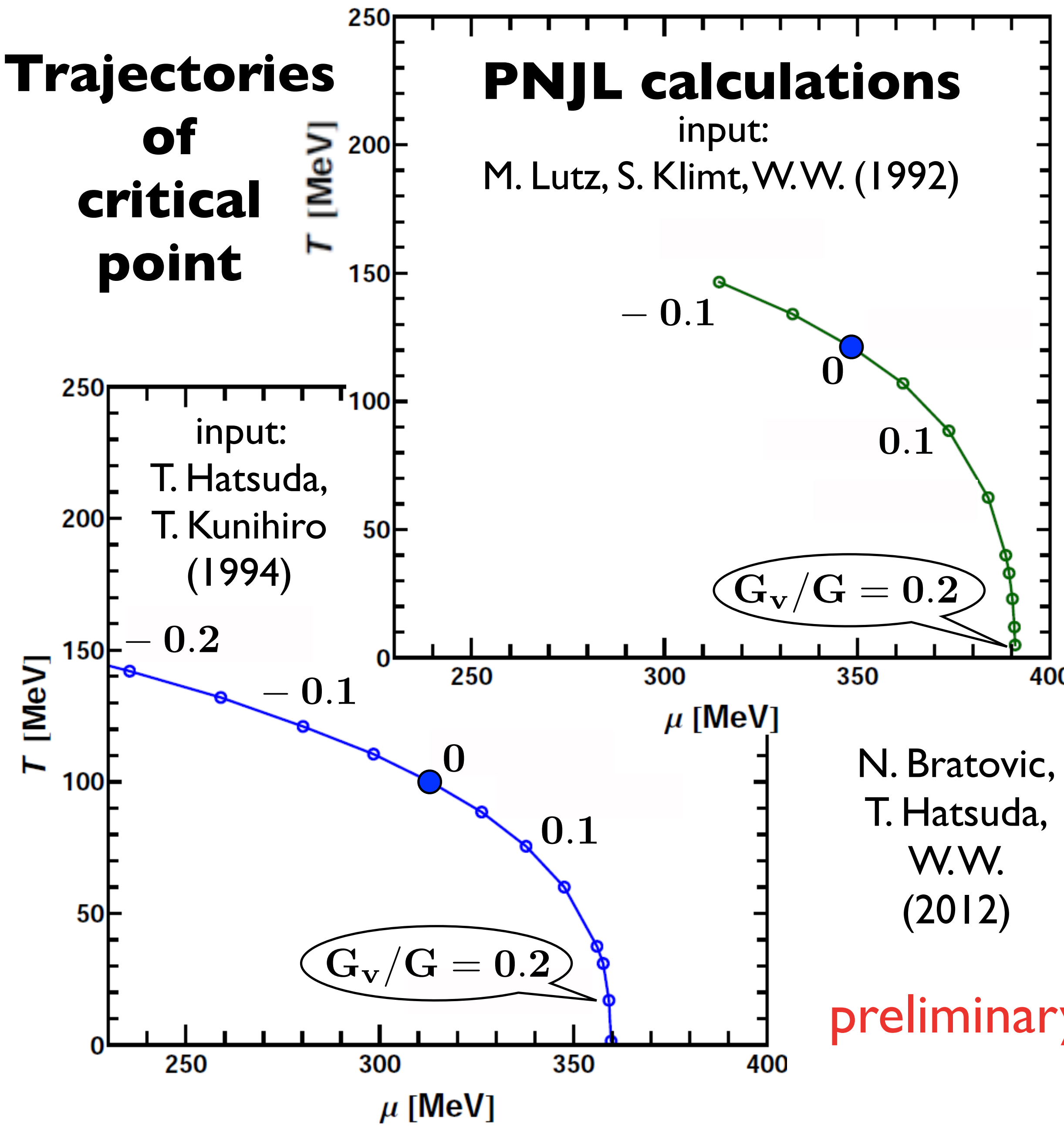
- PNJL analysis of Lattice QCD phase diagram at **imaginary** chemical potential suggests significant isoscalar **vector** term in the effective quark-quark interaction

$$\delta\mathcal{L}_V = -G_V\,(\bar\psi\gamma_\mu\psi)(\bar\psi\gamma^\mu\psi)$$

- Existence and location of critical point: extremely sensitive to
  a) Strength of vector interaction
  b) Axial U(1) breaking interaction



Trajectories of critical point



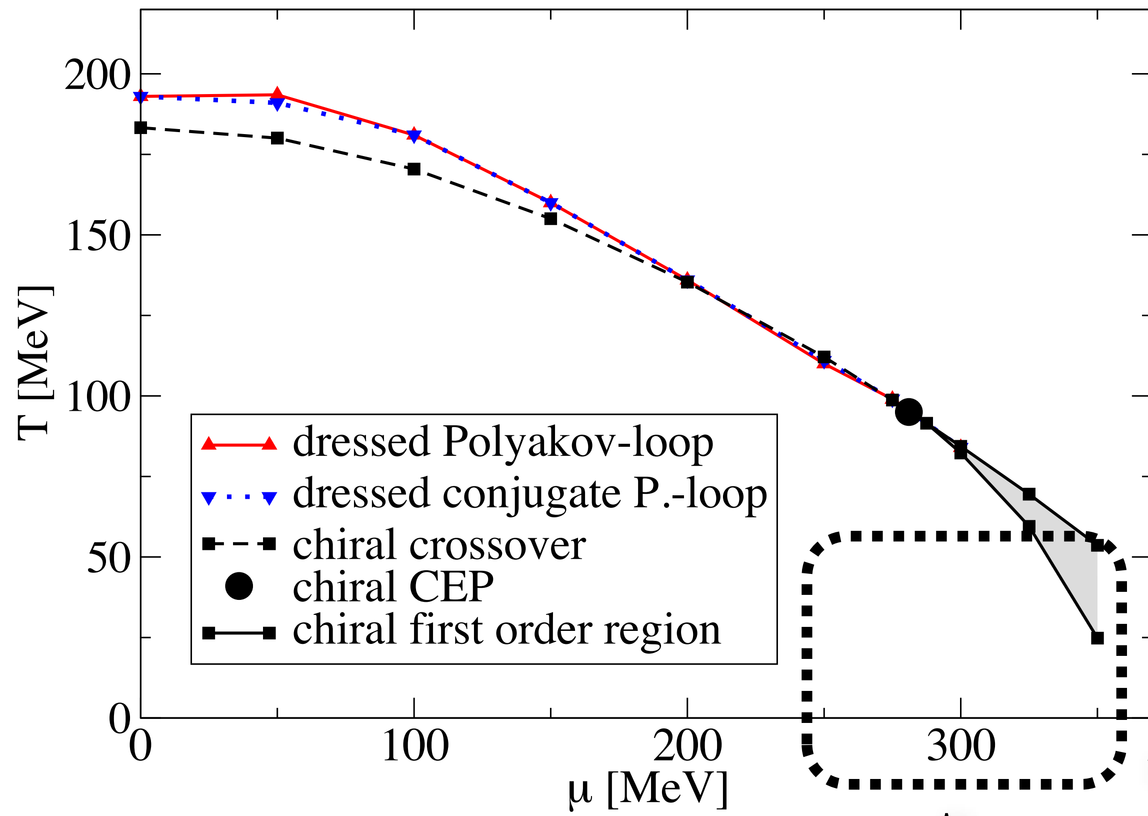
N. Bratovic, T. Hatsuda, W.W. (2012)

preliminary

PHASE DIAGRAM (contd.)

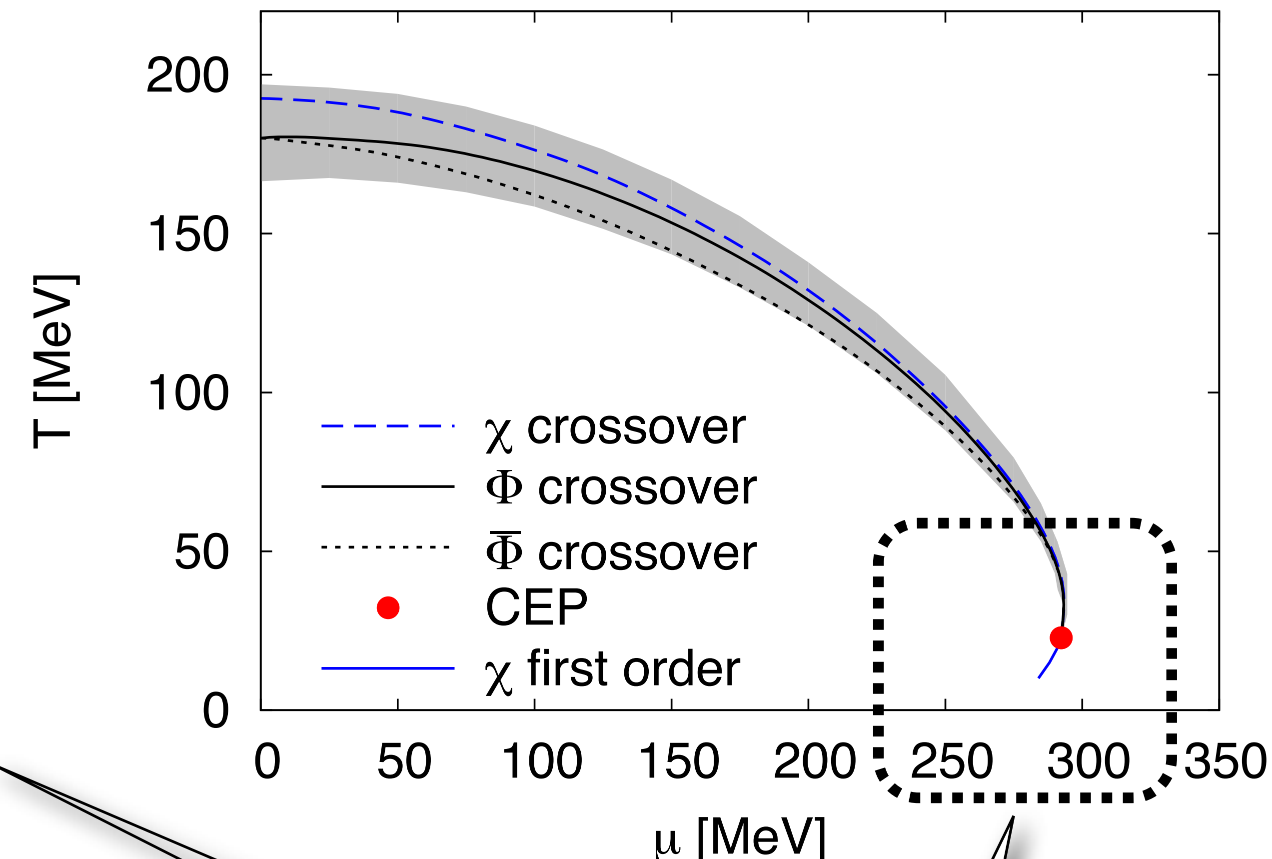
Dyson - Schwinger QCD

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



Polyakov - Quark-Meson model

T. K. Herbst, J. Pawlowski, 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 !

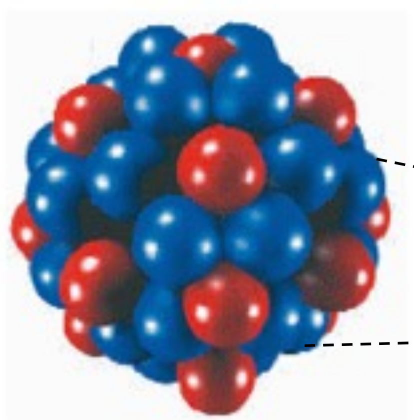
- Quarks are **not** the **relevant active quasiparticles** at low temperatures and at baryon chemical potentials $\mu_B \lesssim 1$ GeV

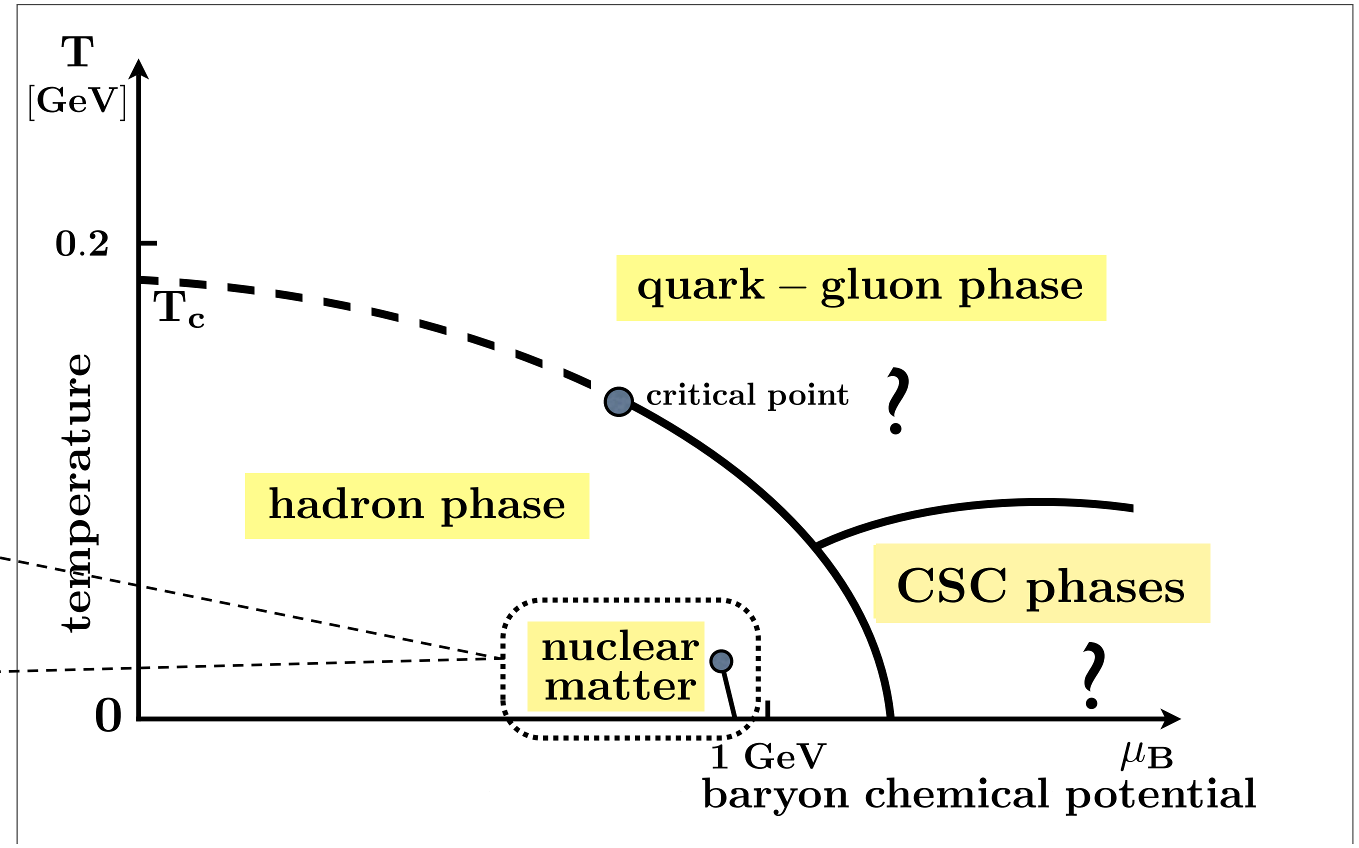
Part II:

NUCLEAR CHIRAL THERMODYNAMICS

NUCLEAR MATTER and QCD PHASES

nuclei





Scales in nuclear matter:

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

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

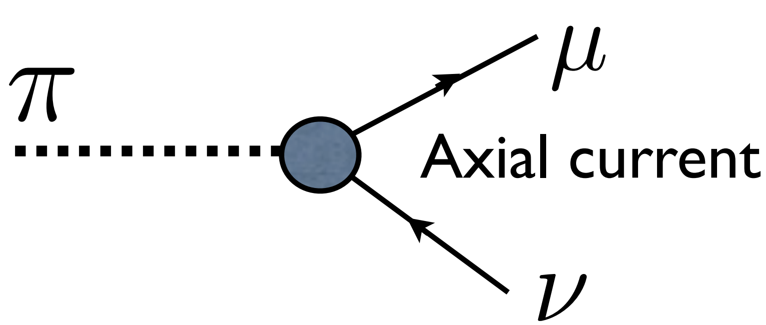
- **CONFINEMENT** of quarks and gluons in hadrons
- Spontaneously broken **CHIRAL SYMMETRY**

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

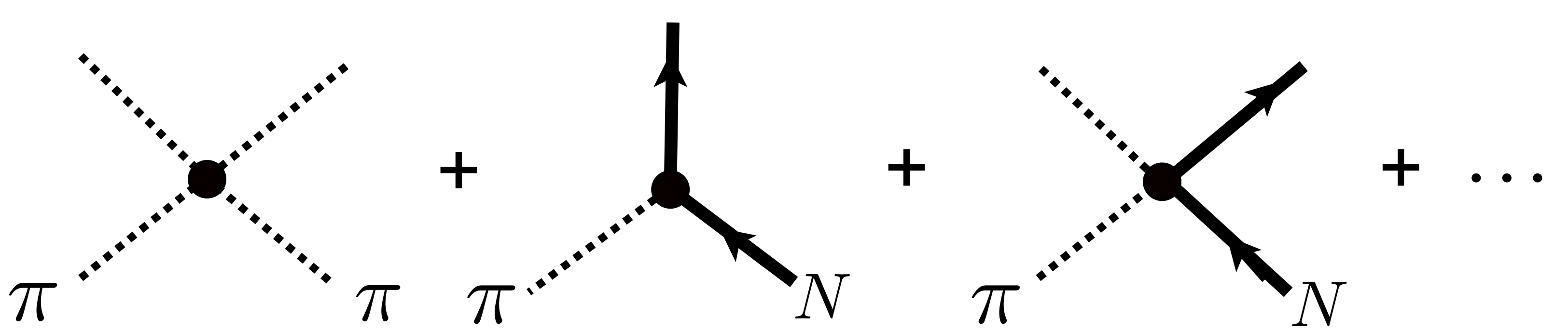
- Systematic framework at interface of QCD and Nuclear Physics

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

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

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

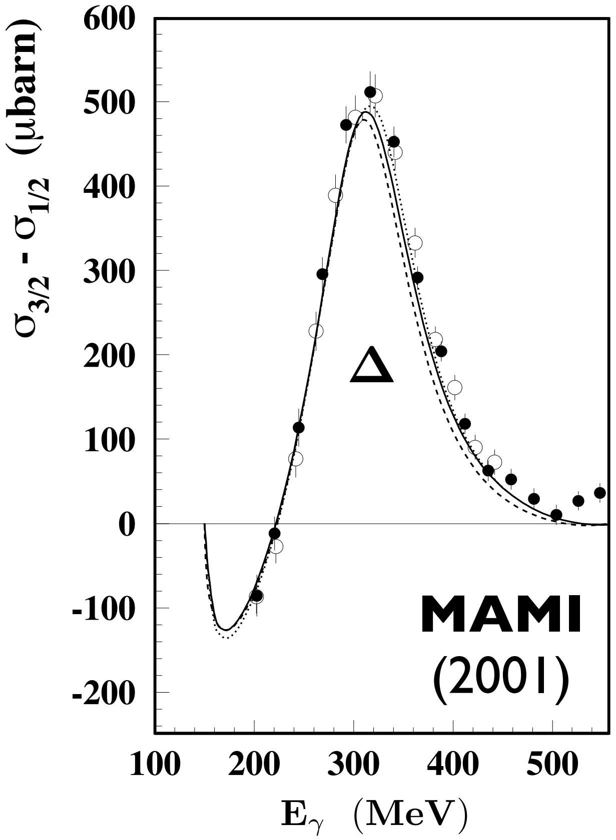
- Construction of Effective Lagrangian: **Symmetries**



short distance dynamics: **contact terms**

Explicit $\Delta(1230)$ DEGREES of FREEDOM

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

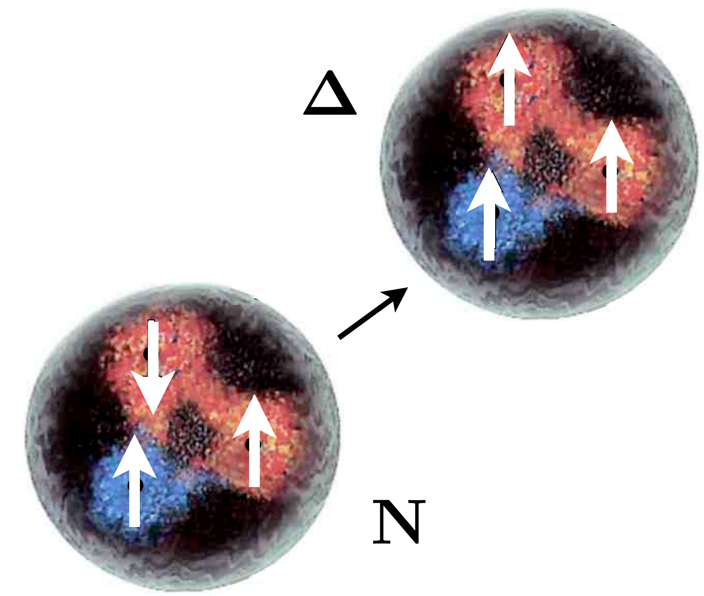


◀ example: polarized Compton scattering

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

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

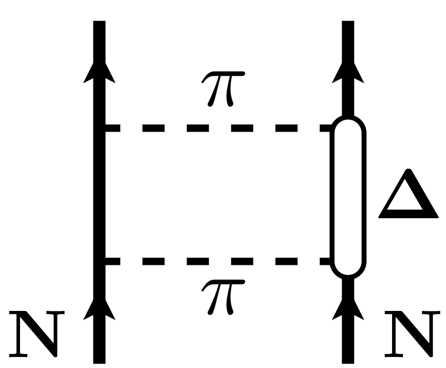
(small scale)



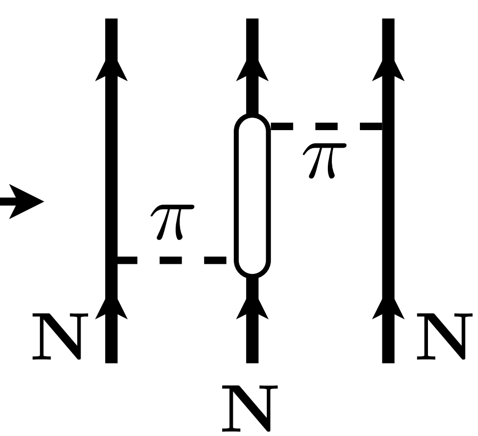
- **Pionic Van der Waals** - type intermediate range central potential

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

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



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



strong 3-body interaction

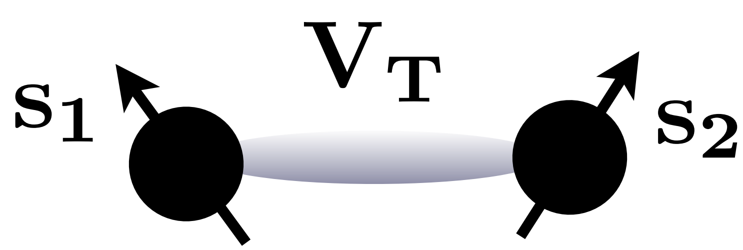
J. Fujita, H. Miyazawa (1957)

Pieper, Pandharipande, Wiringa, Carlson (2001)

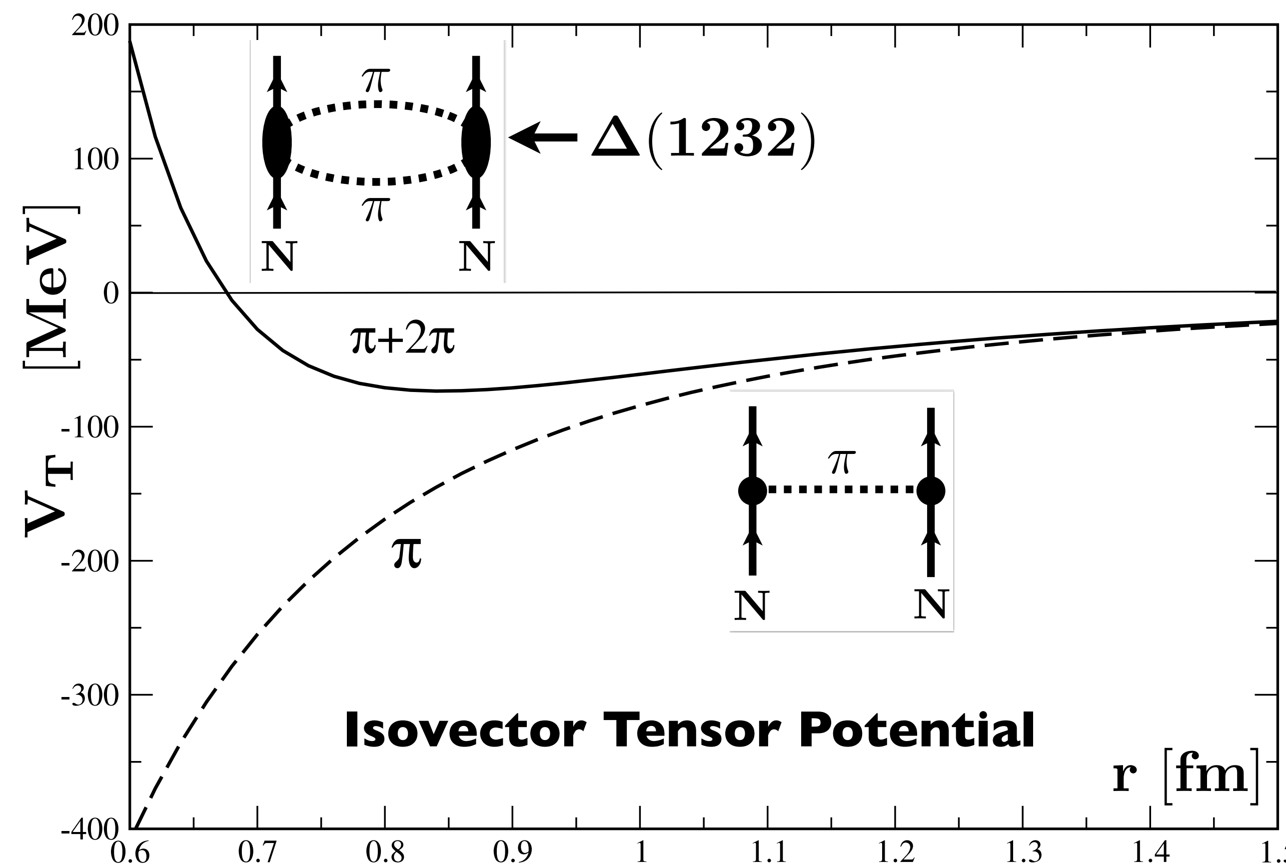
Important pieces of the

CHIRAL NUCLEON-NUCLEON INTERACTION

- **ISOVECTOR TENSOR FORCE**

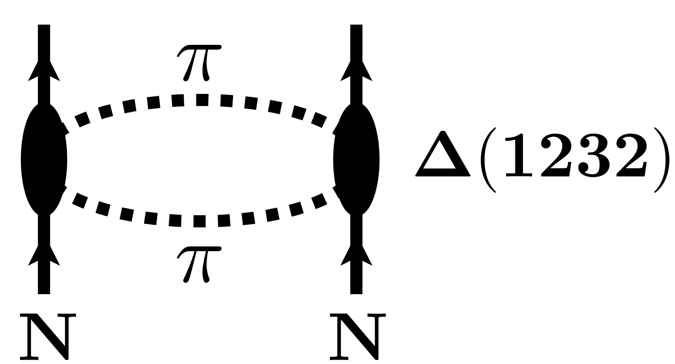


- note: **no** ρ meson



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

- **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

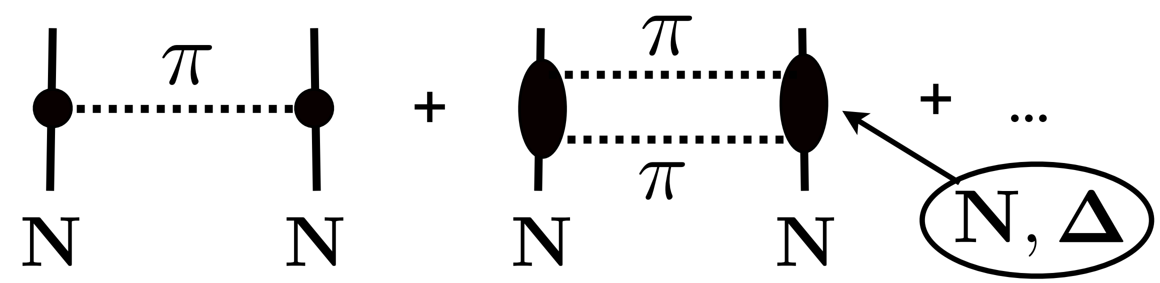
- note: **no** σ boson

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**

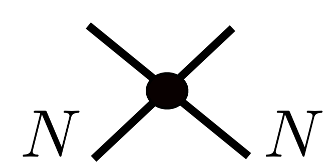
pion exchange processes in presence of filled **Fermi sea**



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

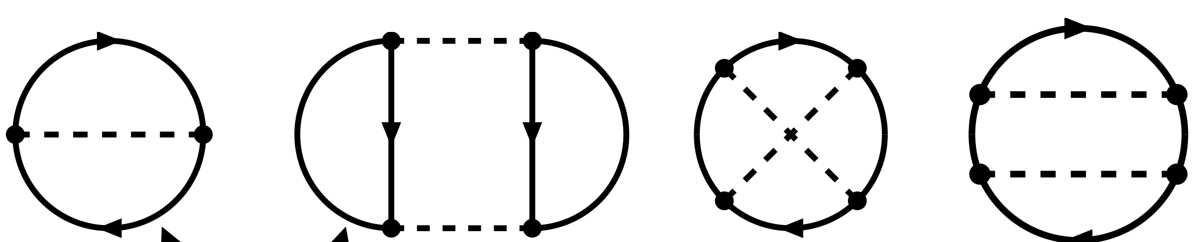
- **Finite nuclei** $\longleftrightarrow$ energy **density functional**

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

  many quantitatively successful applications throughout the nuclear chart

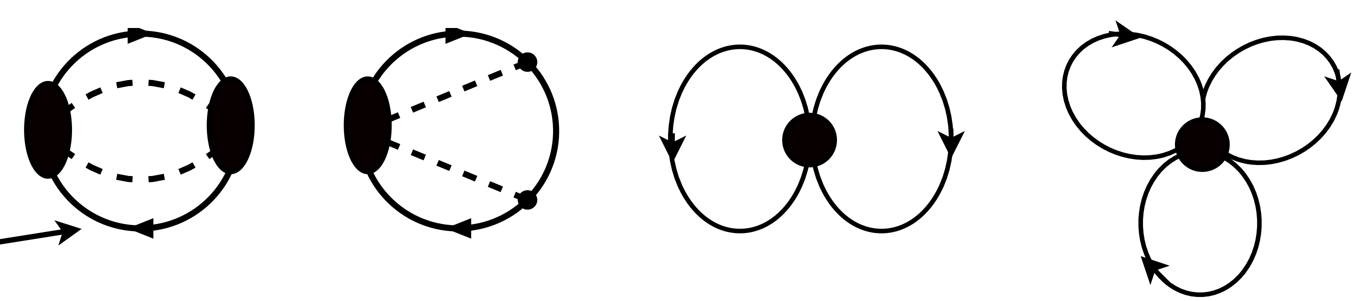
  e.g. P. Finelli et al.: Nucl. Phys. A 770 (2007) 1

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



(3-loop order)

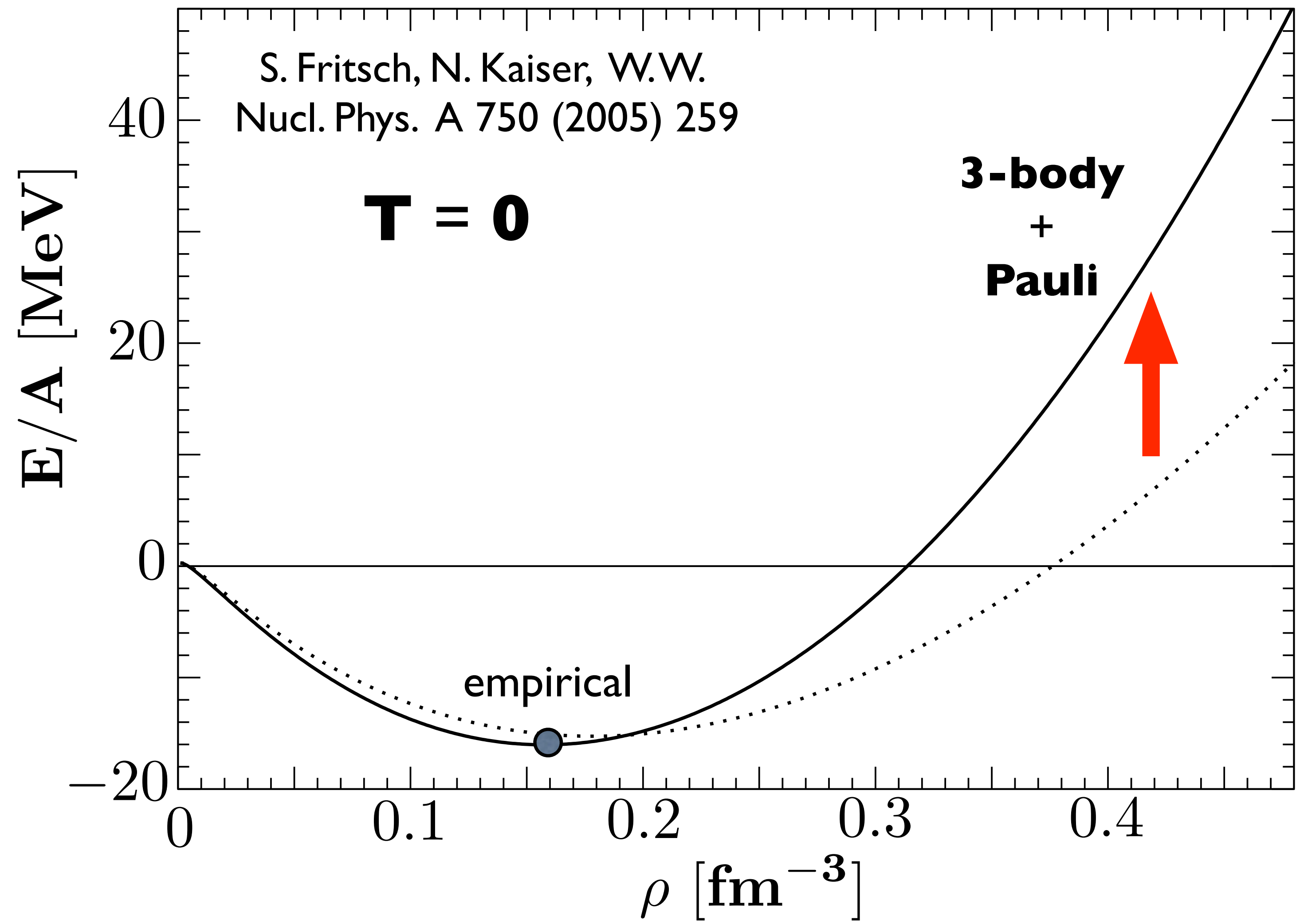
N. Kaiser, S. Fritsch, W.W. (2002-2004)



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

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

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

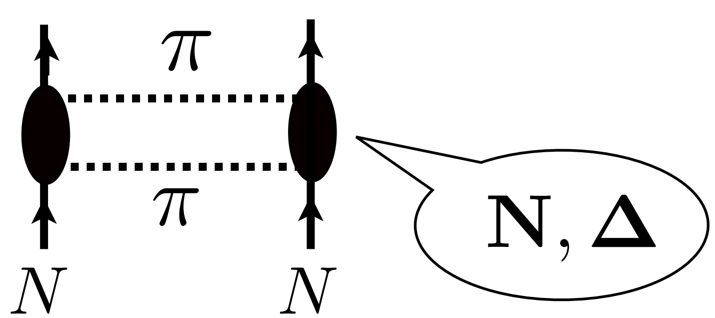
J.W. Holt, N. Kaiser, W.W.
Nucl. Phys. A 870 (2011) 1,
arXiv: 1111.1924 [nucl-th]
(NPA (2012), in print)

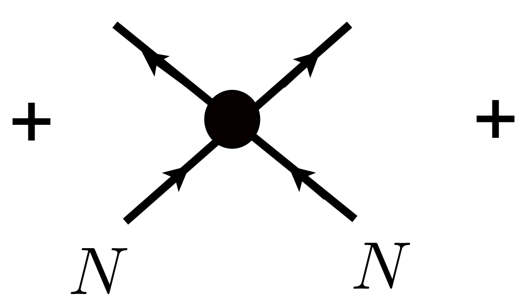
NUCLEAR THERMODYNAMICS

NUCLEAR
CHIRAL (PION) **DYNAMICS**

BINDING & SATURATION:

Van der Waals + Pauli

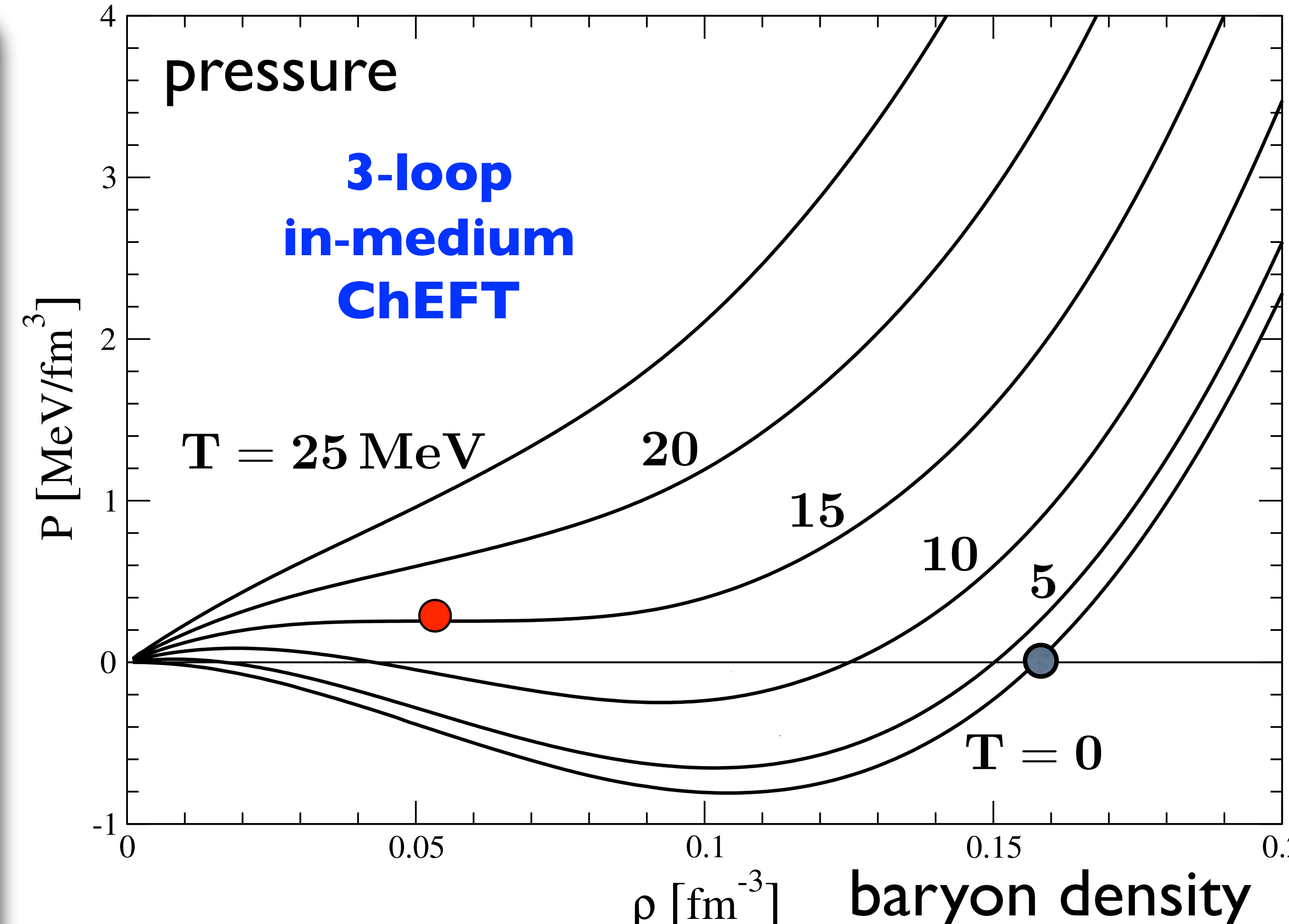




3-body forces

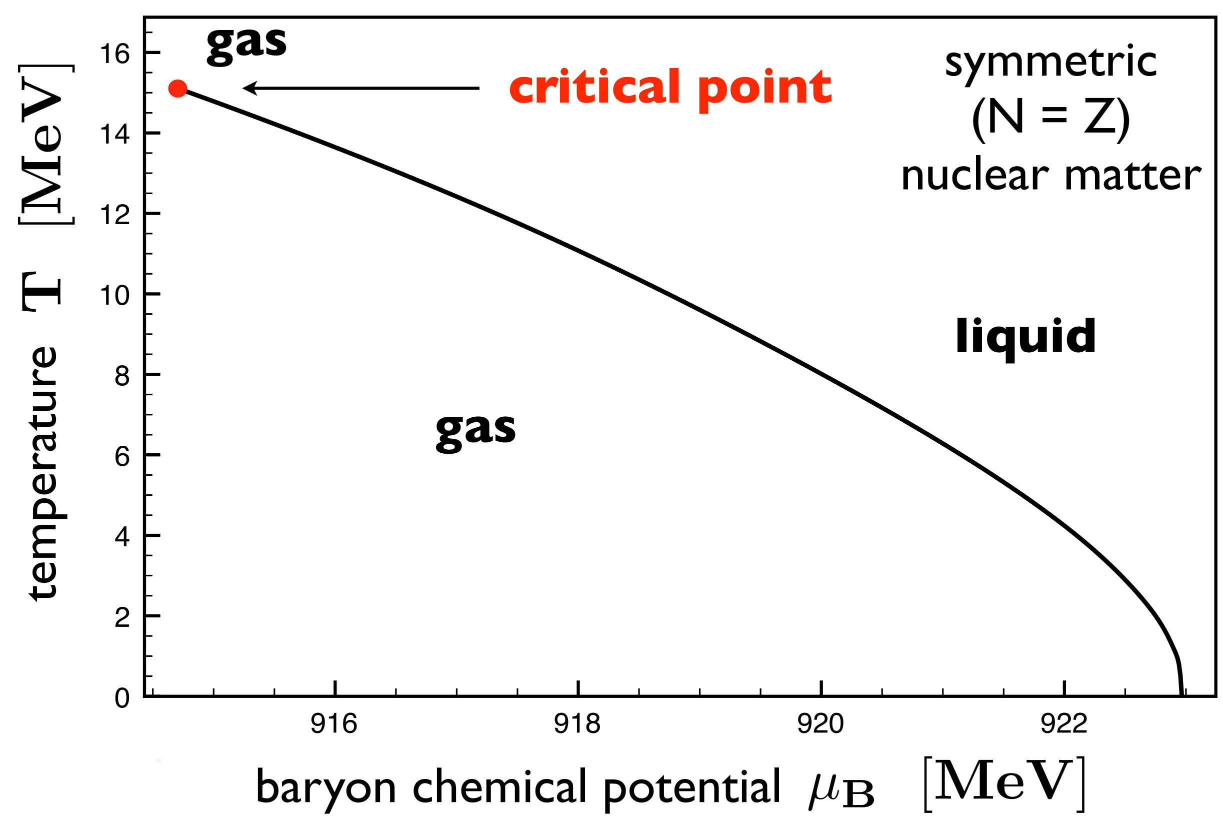
contact terms

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

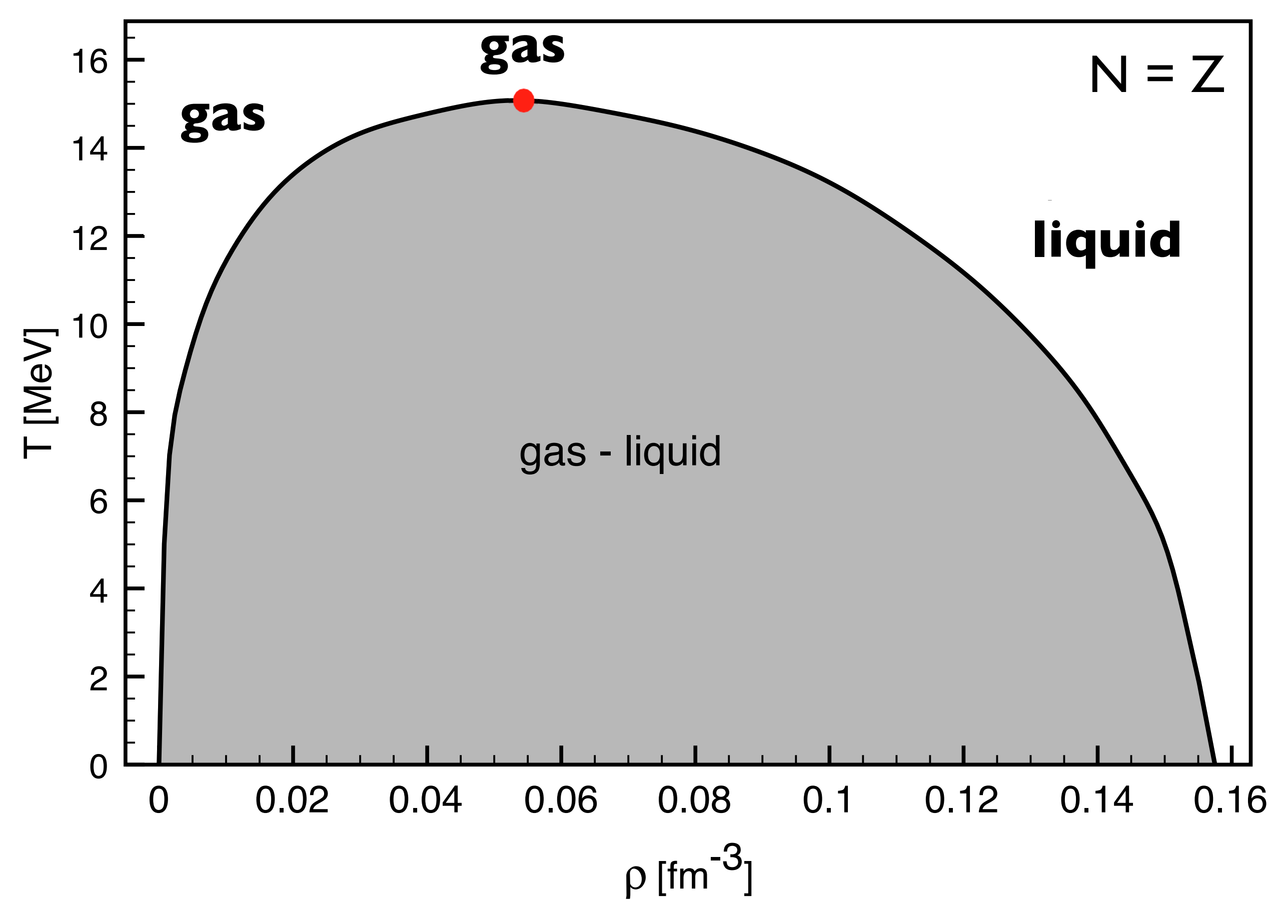


- In-medium
  chiral effective field theory
  (3-loop calculation of free energy density)

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

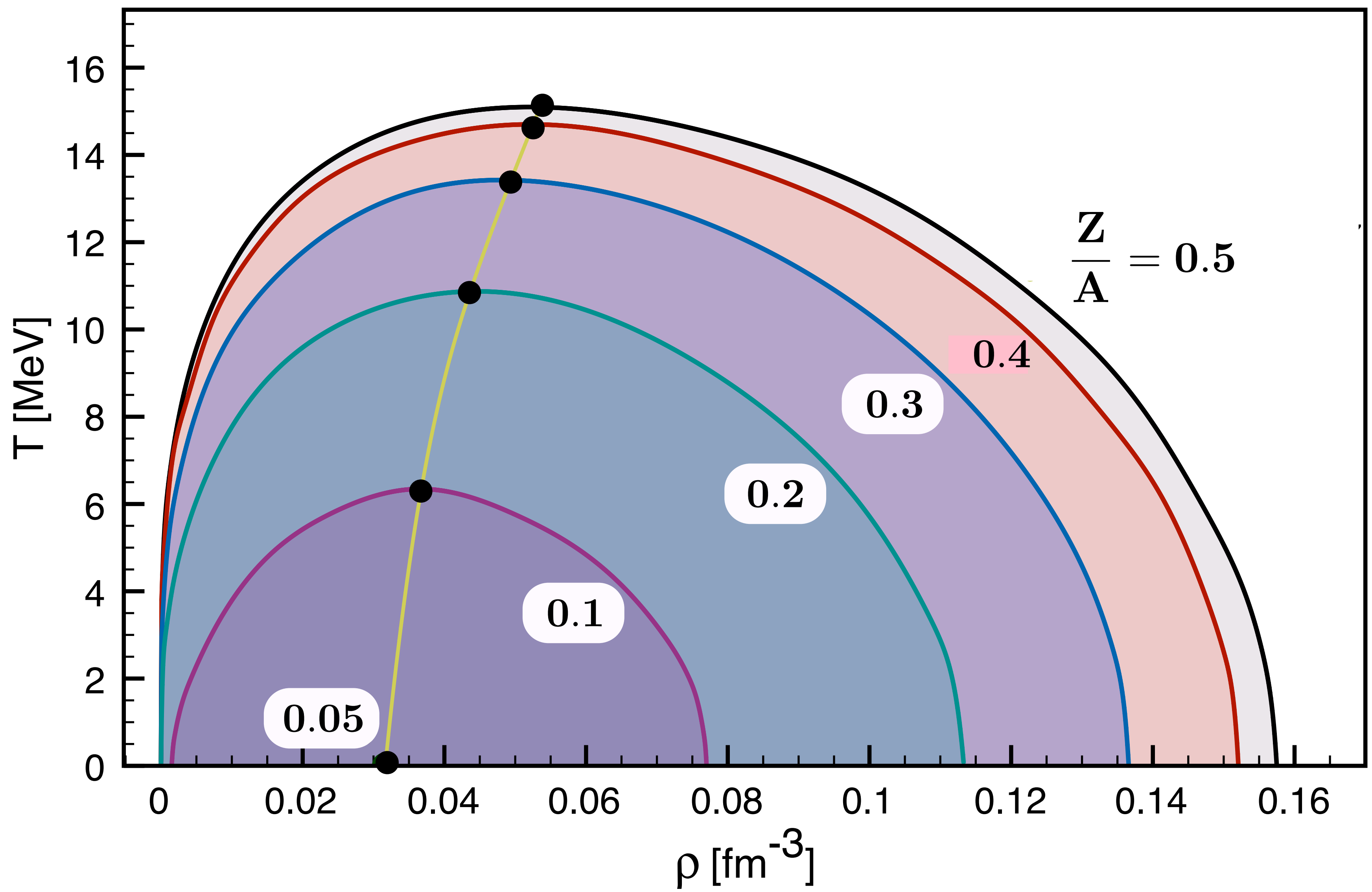
S. Fiorilla, N. Kaiser, W.W.
arXiv:1111.3688 [nucl-th], Nucl. Phys. A (2012), in print

- 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)

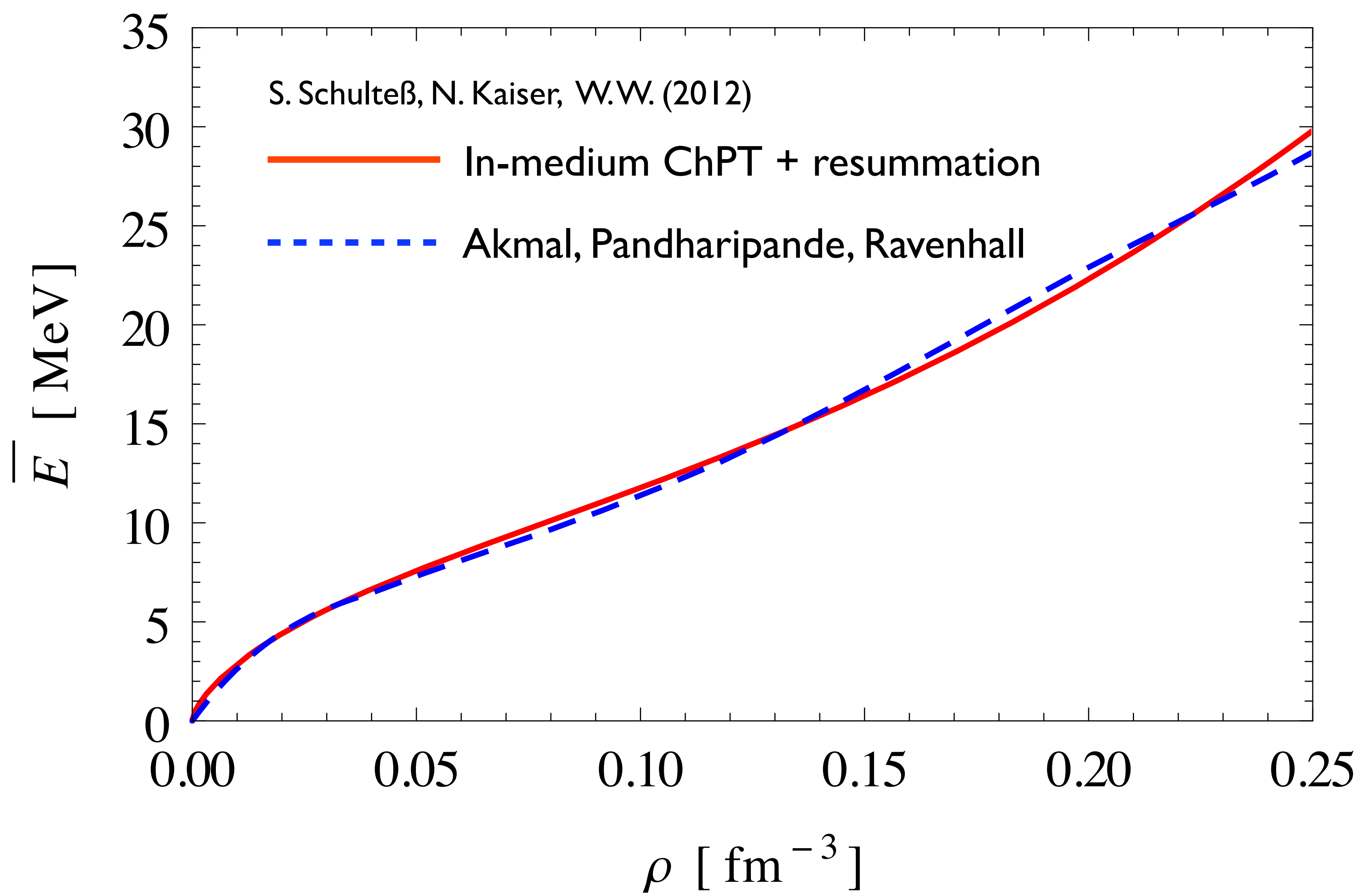
. . . determined almost entirely by

isospin dependent (one- and two-) **pion** exchange dynamics

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

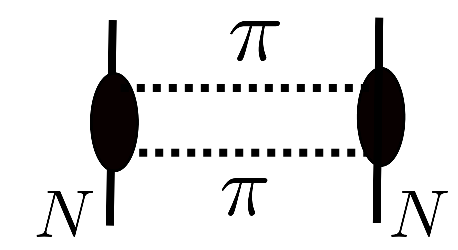
CHIRAL CONDENSATE at finite BARYON DENSITY

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

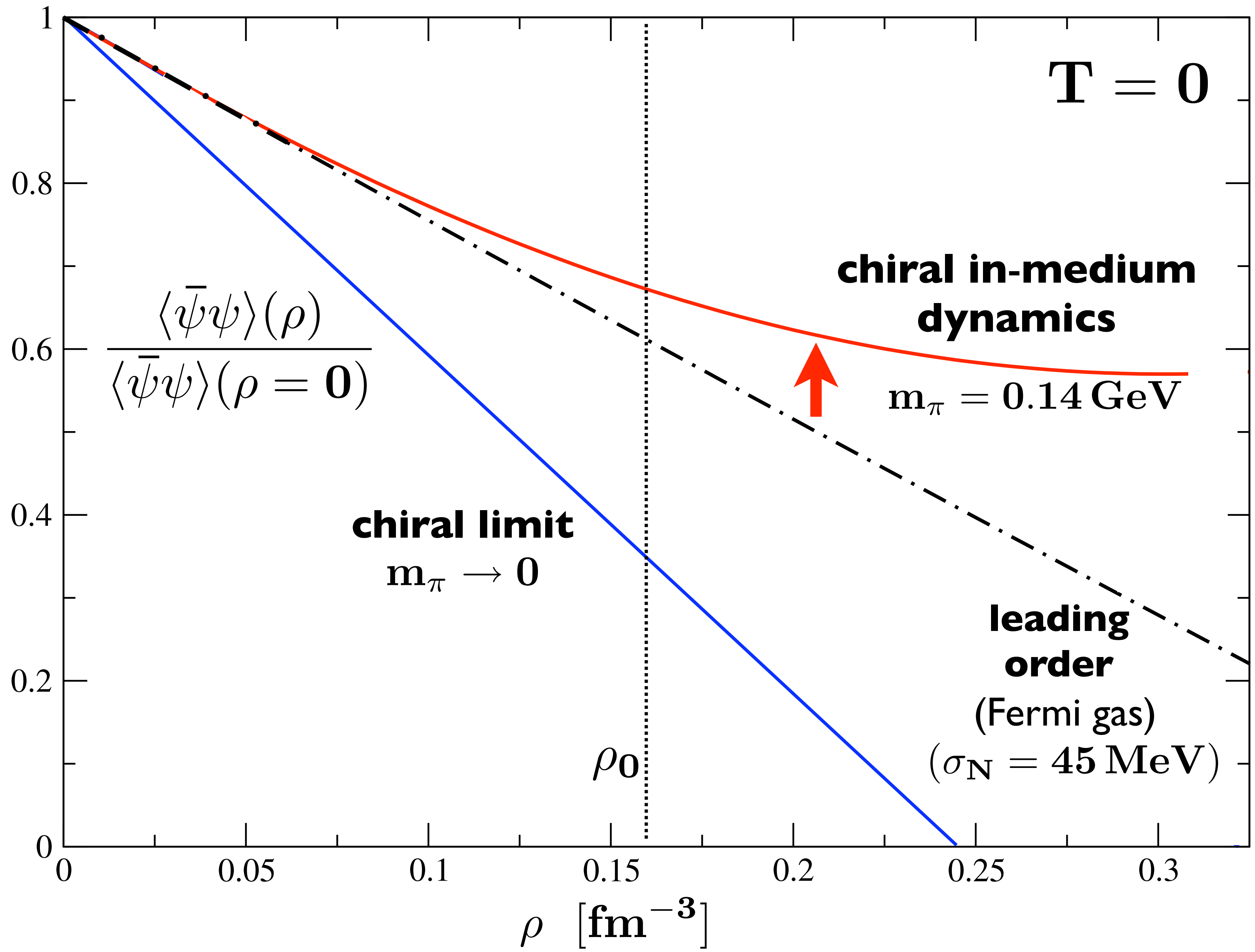
CHIRAL CONDENSATE: DENSITY DEPENDENCE

- **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 $m_q \sim 5\,\mathrm{MeV}$

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

CHIRAL CONDENSATE:
DENSITY and TEMPERATURE DEPENDENCE

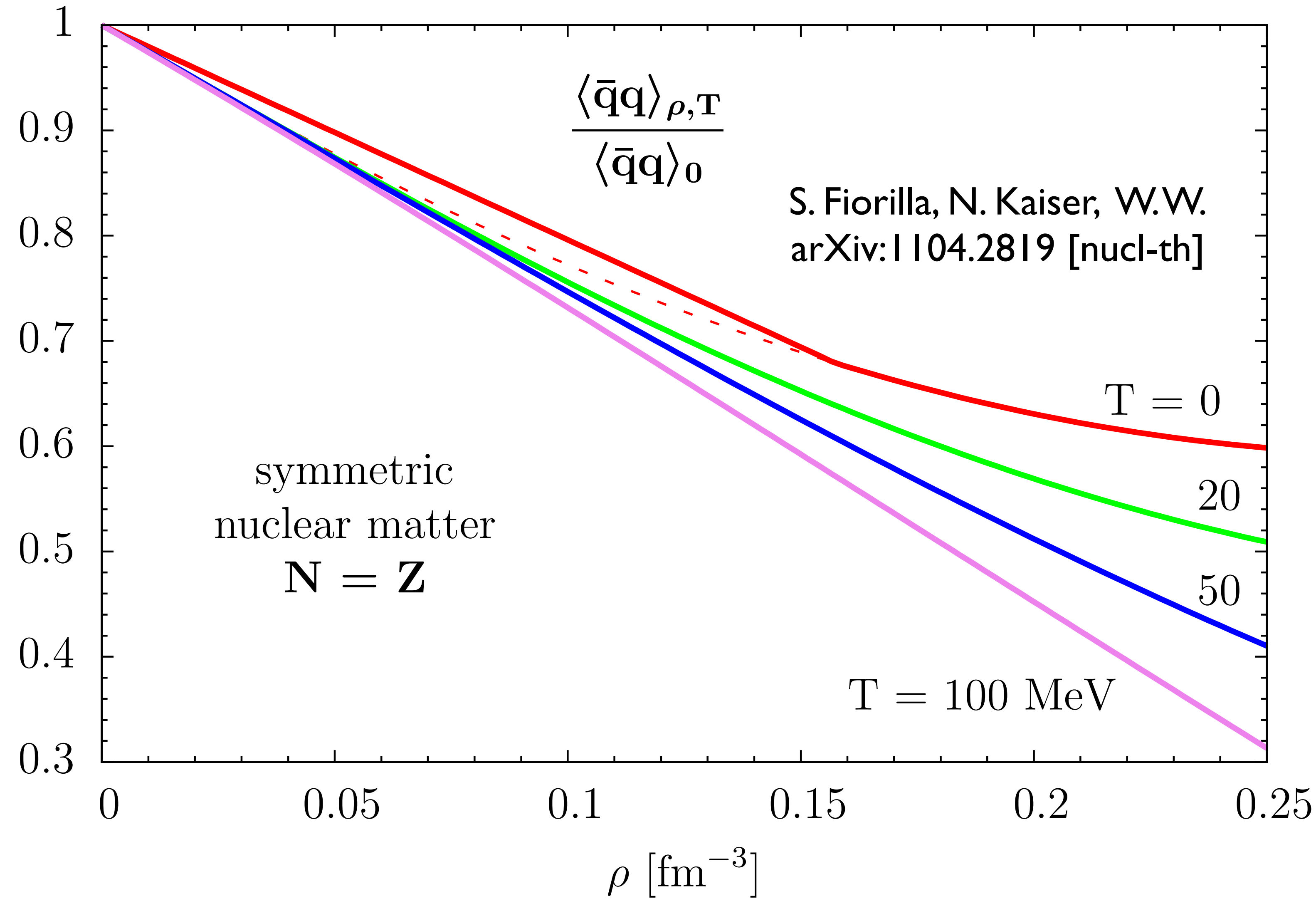
- Free energy density $\mathcal{F}(\mathbf{m_q}; \rho, \mathbf{T})$

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

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

(NLO 3-loop)

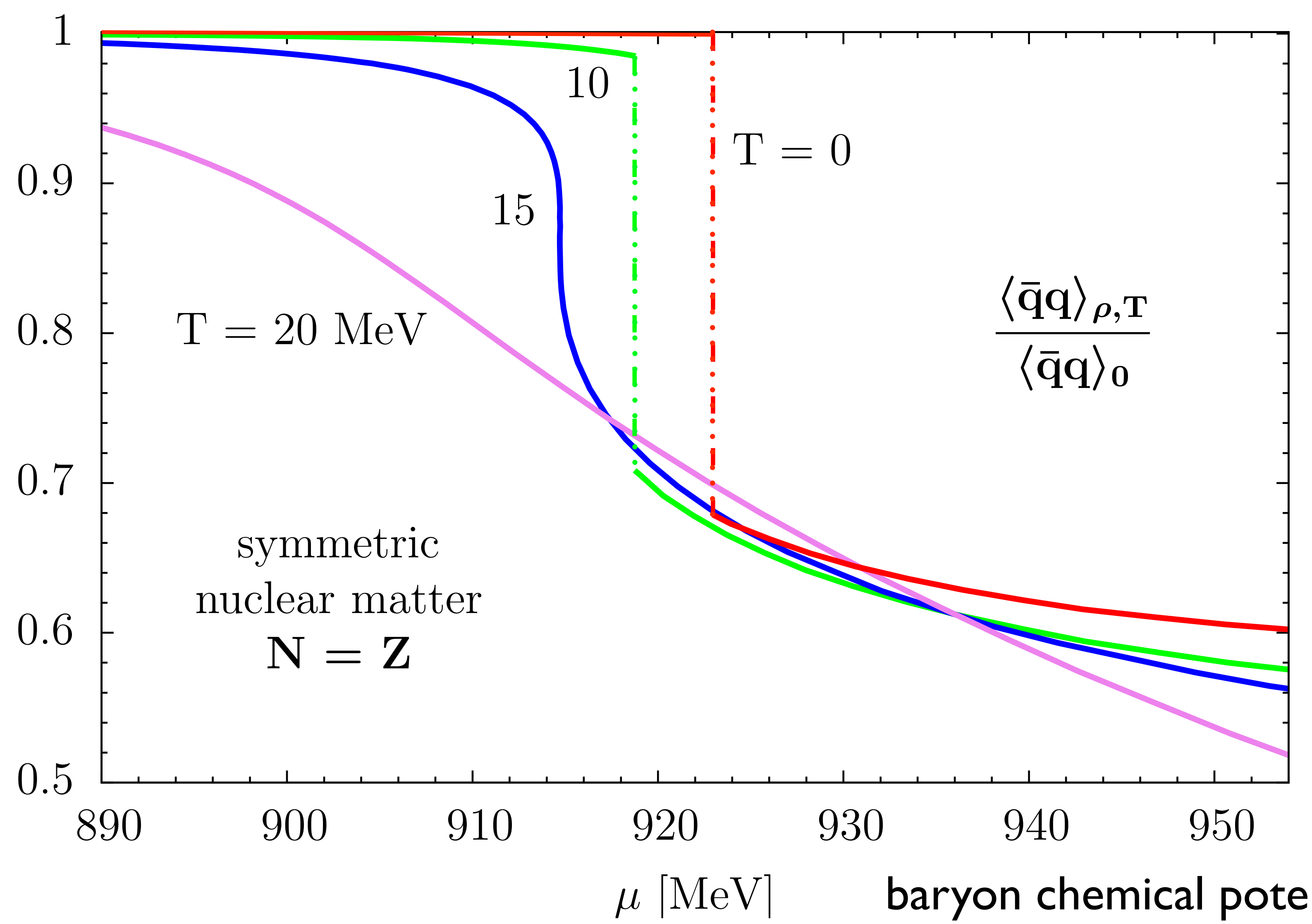
constrained by **realistic nuclear equation of state**



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

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

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

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

Outlook:

New Constraints
from
NEUTRON STARS

doi:10.1038/nature09466

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

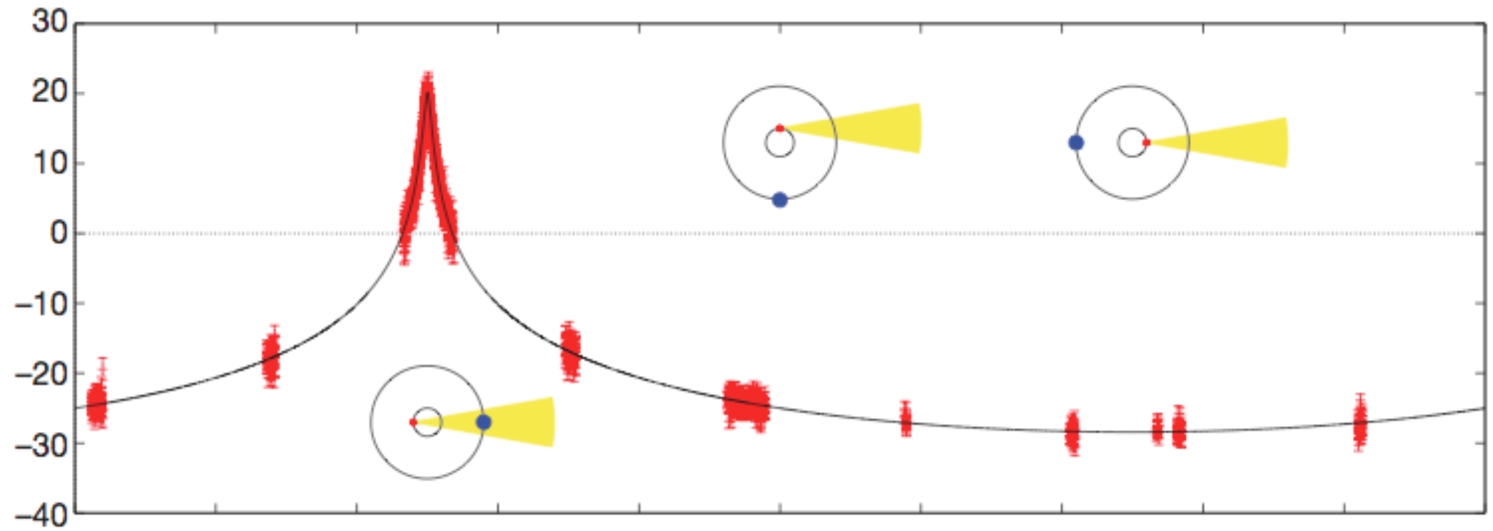
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

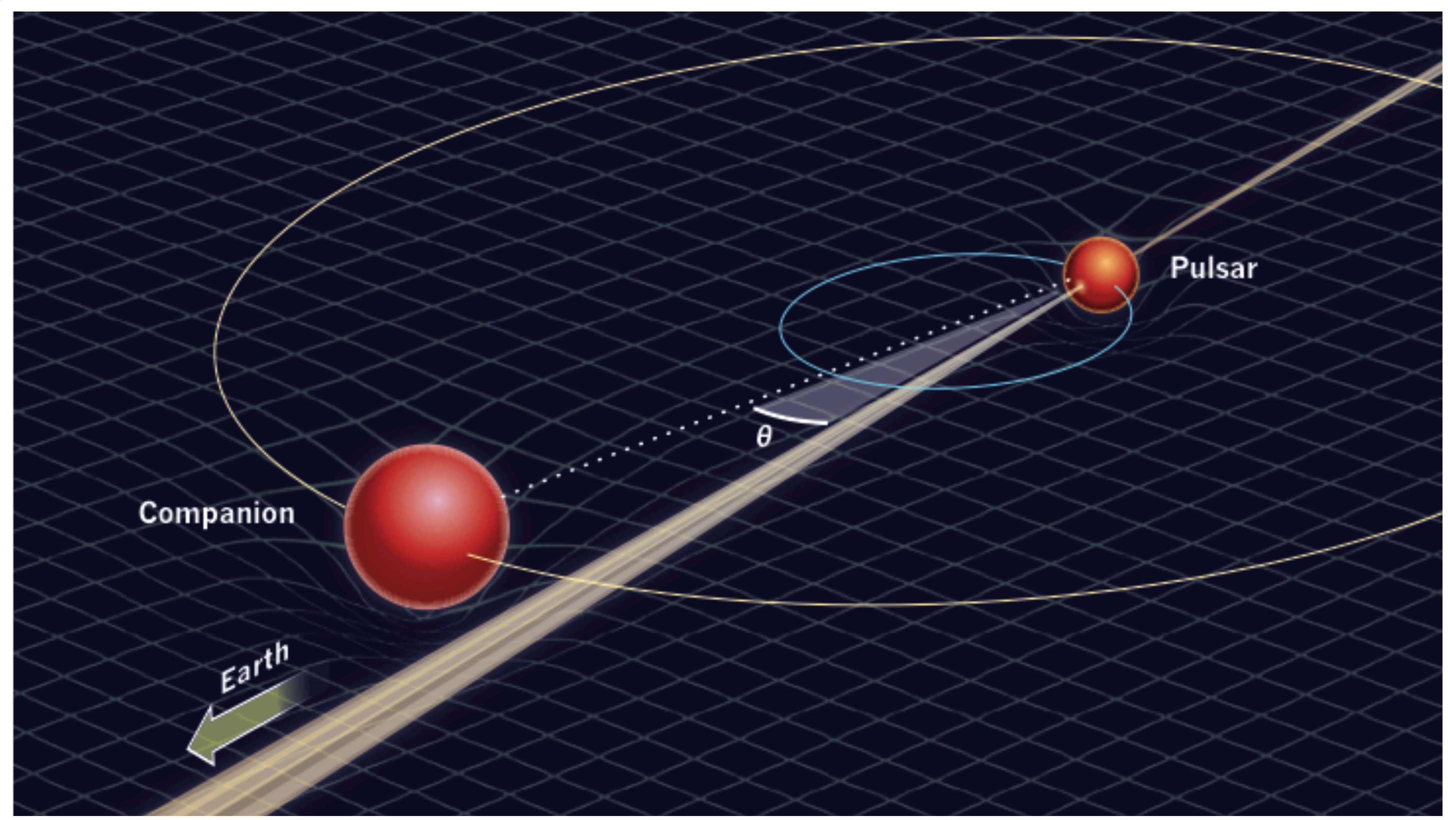
Nature, Oct. 28, 2010

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}

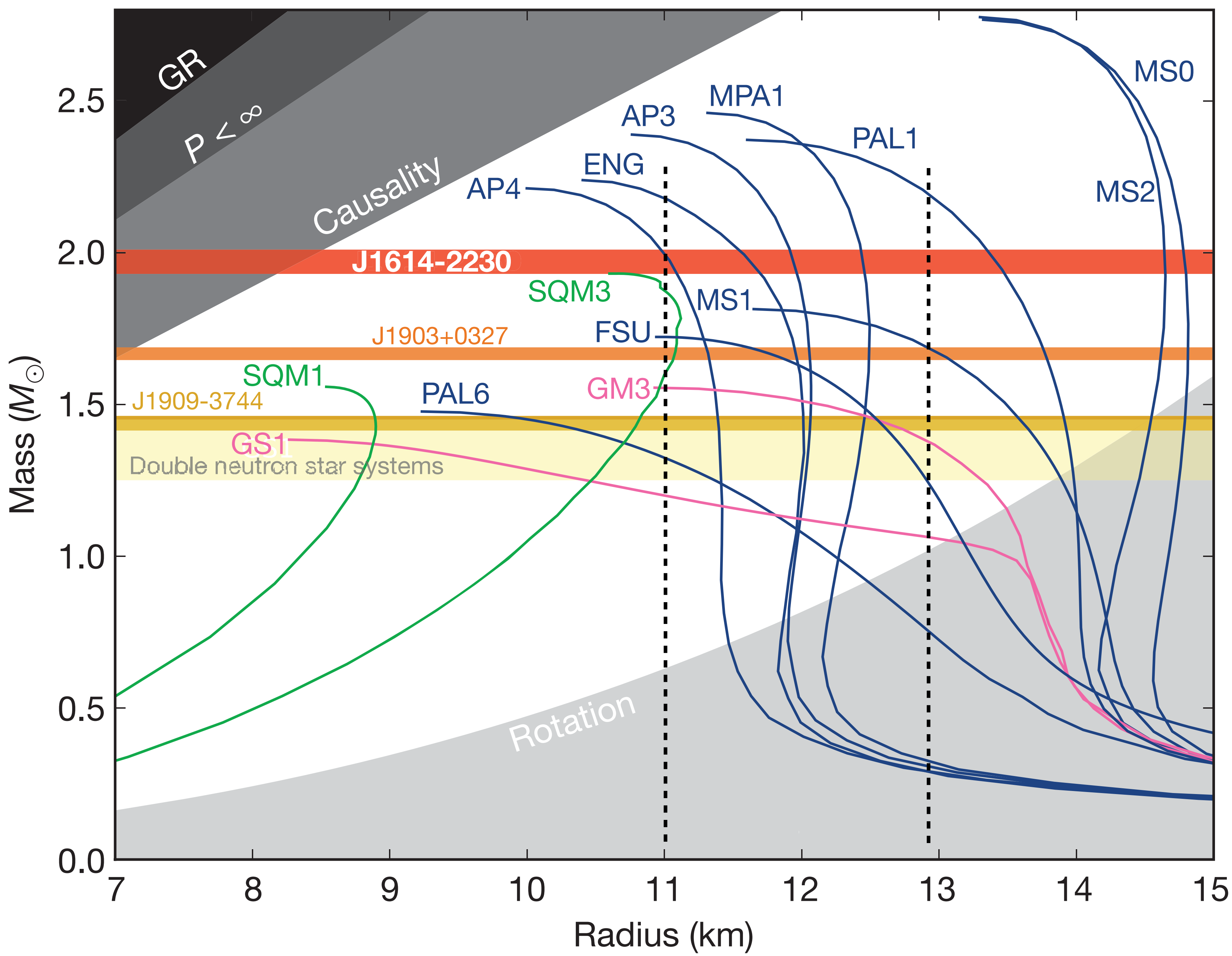




TWO-SOLAR-MASS NEUTRON STAR

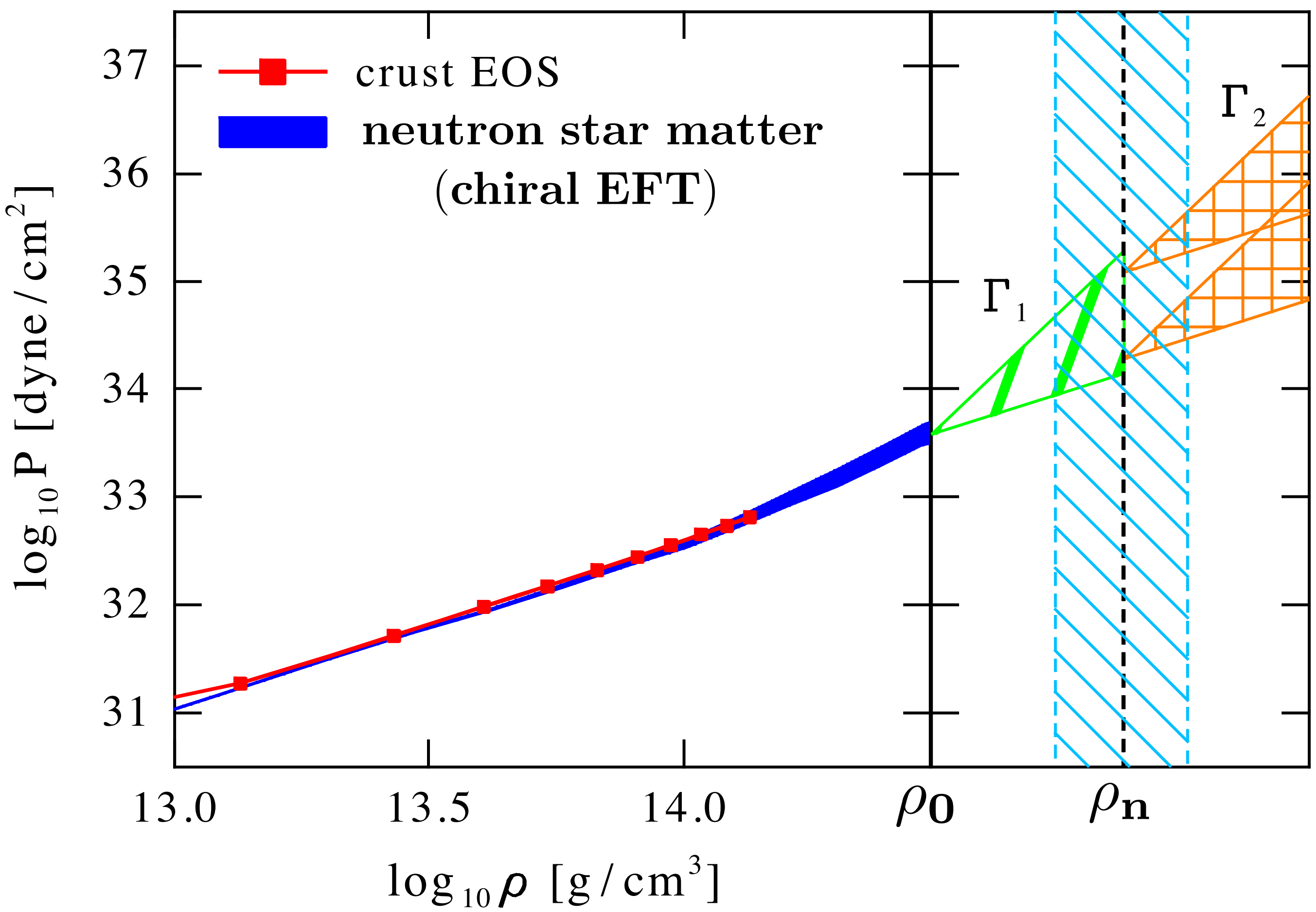
. . . observed using Shapiro delay

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



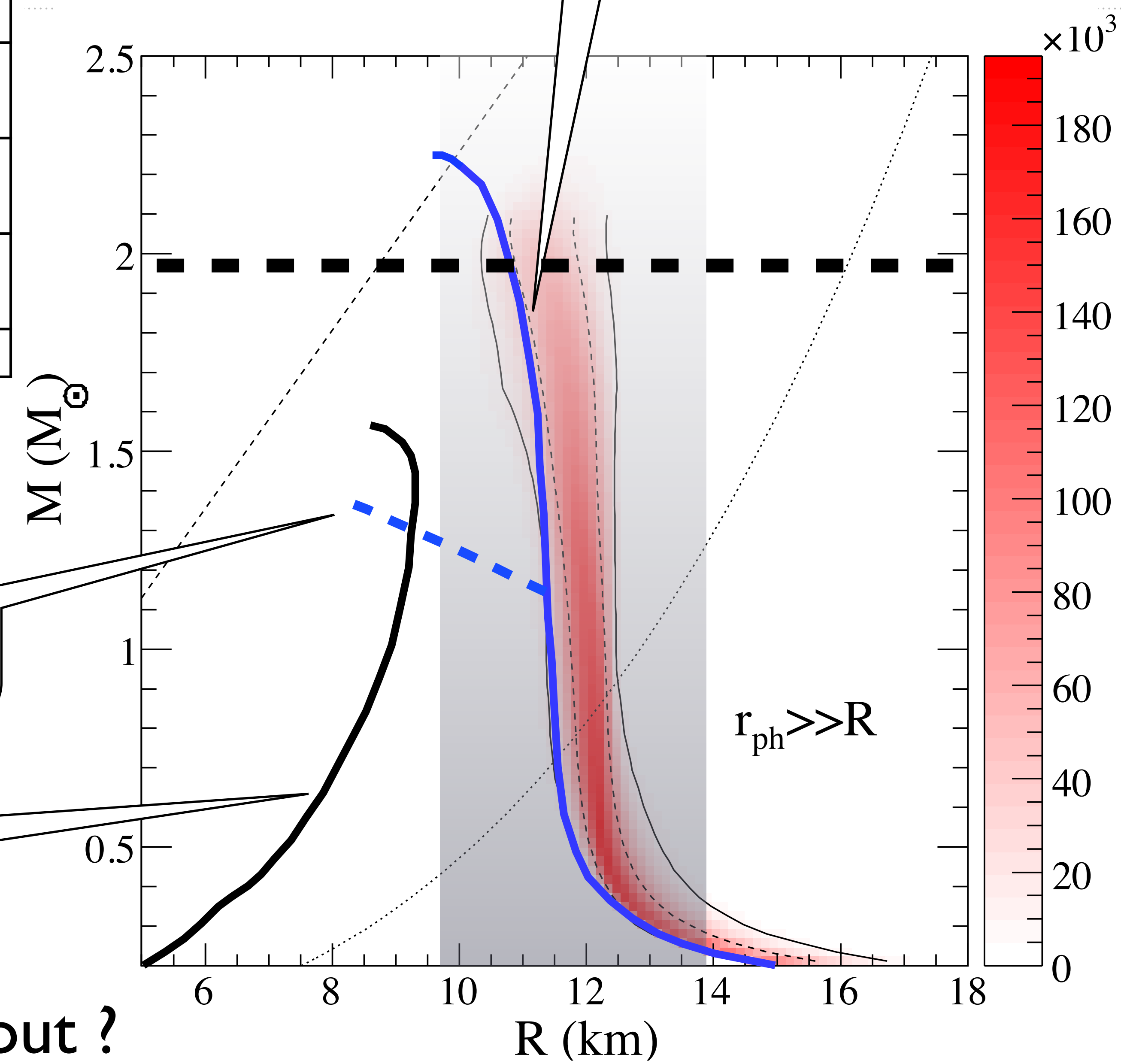
News from NEUTRON STARS

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

realistic "nuclear" EoS (Illinois)

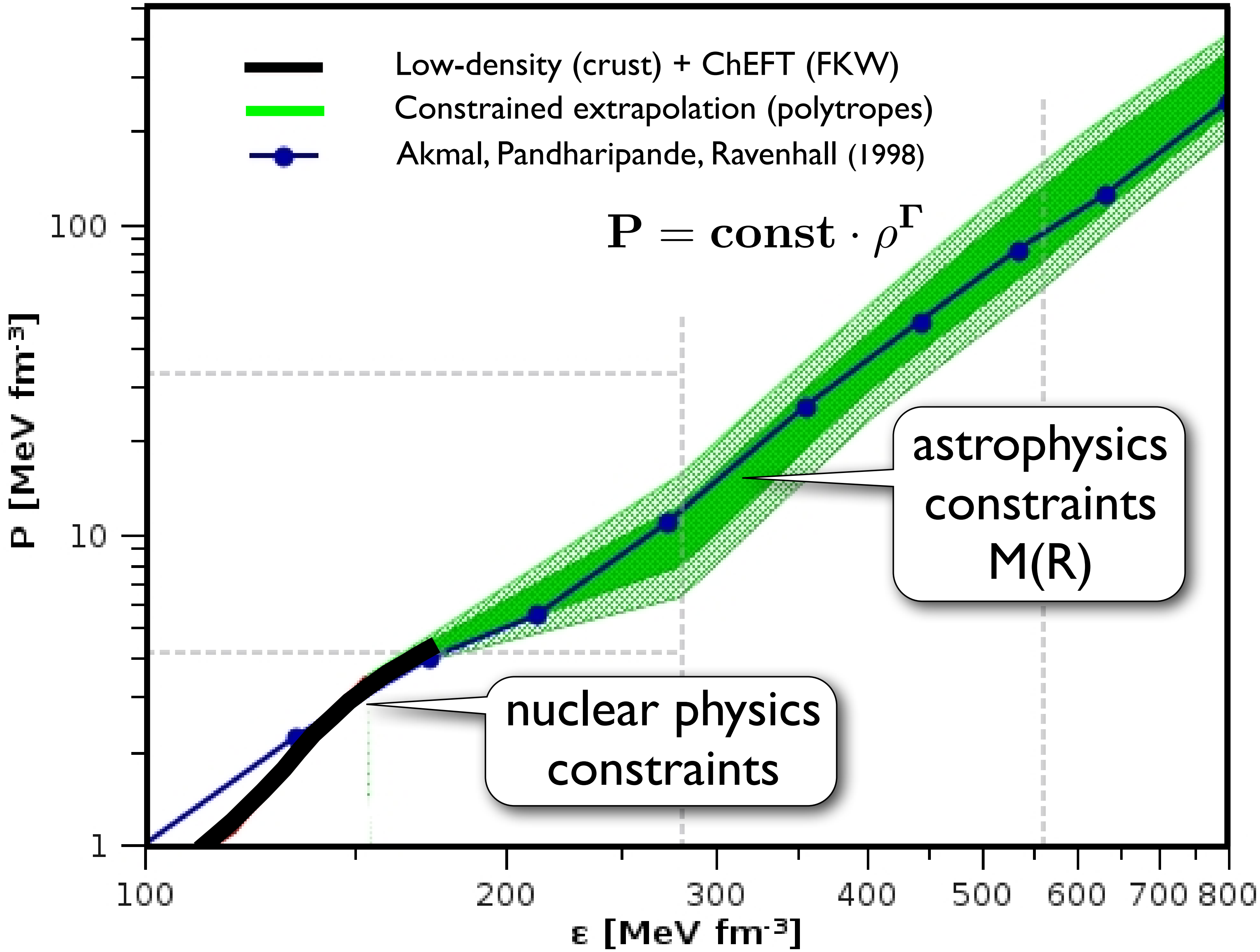


kaon condensate

quark matter

- 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 $\leftrightarrow$ 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

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Salvatore Fiorilla
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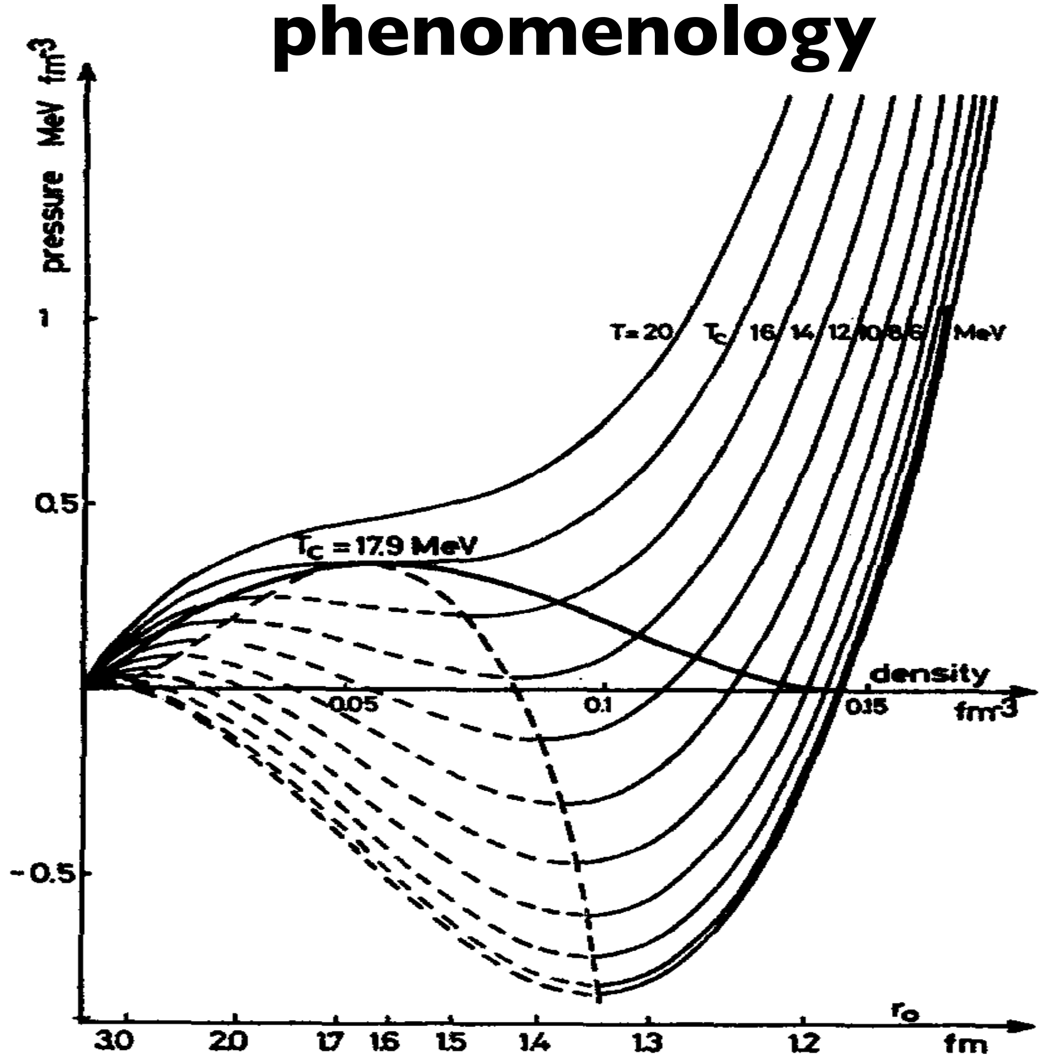
Jeremy Holt
Norbert Kaiser
Kouji Kashiwa

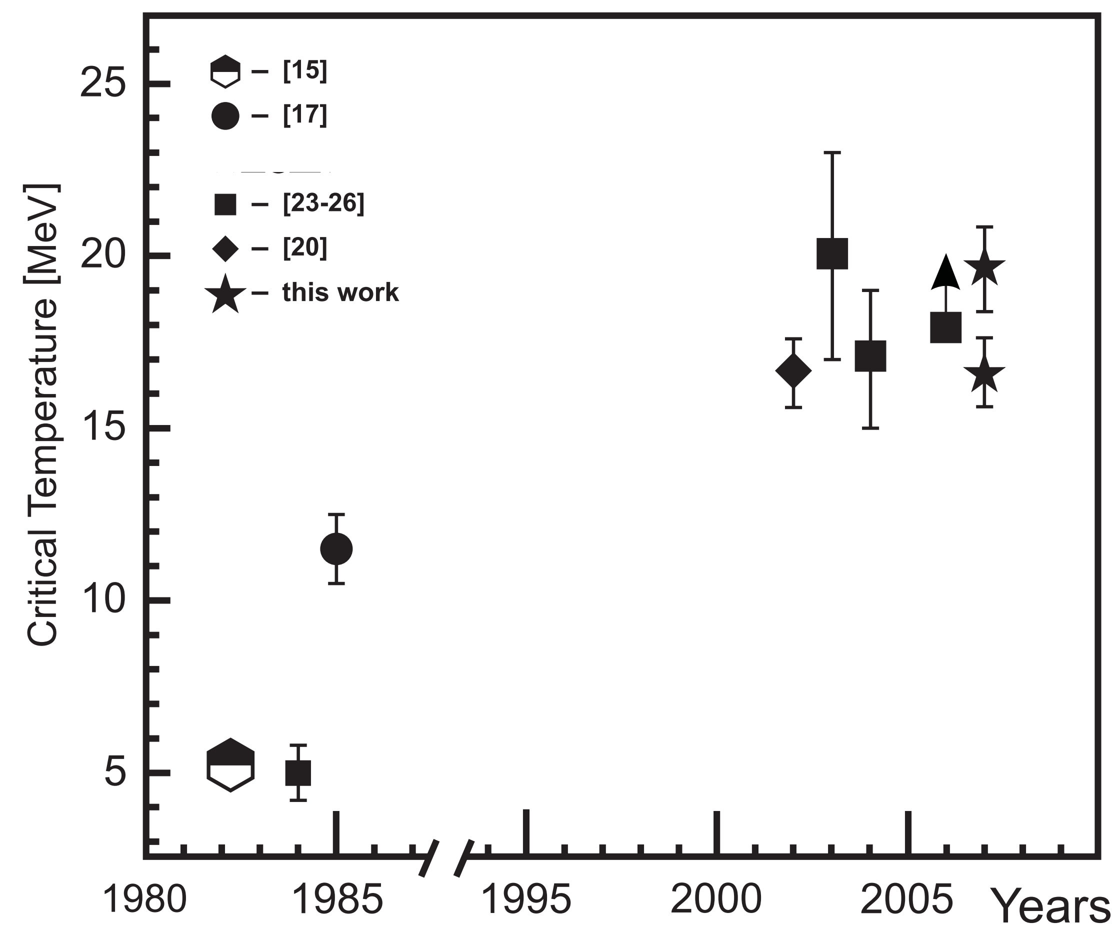
NUCLEAR THERMODYNAMICS

Skyrme phenomenology



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

Multifragmentation and fission analysis



V.A. Karnaukhov et al. :
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