Phases of **Strongly Interacting Matter**

Wolfram Weise

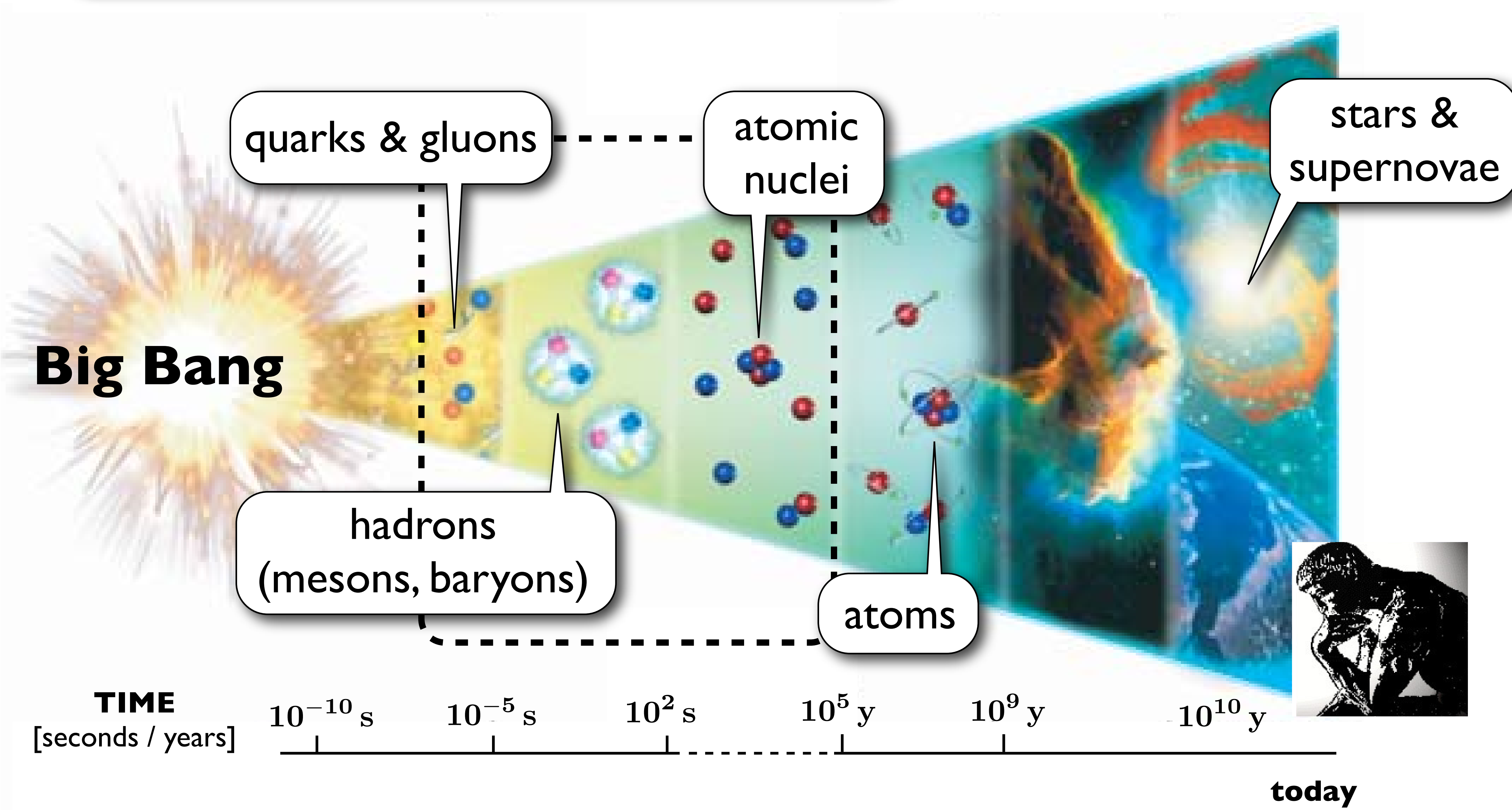
ECT* Trento and **T**echnische **U**niversität **M**ünchen

- **Emergence** of **Structures** (Hadrons, Nuclei, Neutron Stars) in **Quantum Chromodynamics** (**QCD**)
  - **Symmetries**, **Scales** & **Symmetry Breaking Patterns**
- **QCD Phase Diagram**
  - **Confinement** / **Deconfinement** Transition
  - **Chiral Symmetry** and QCD Interface with **Nuclear Physics**
  - **New Constraints** from **Neutron Stars**

in memoriam

Professor Alfredo Molinari (1936-2014)

from **Quarks** and **Gluons**
to **Nuclei** and **Neutron Stars**



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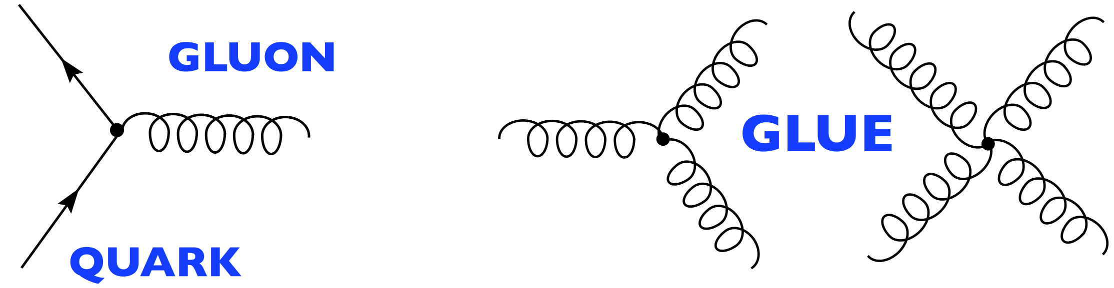
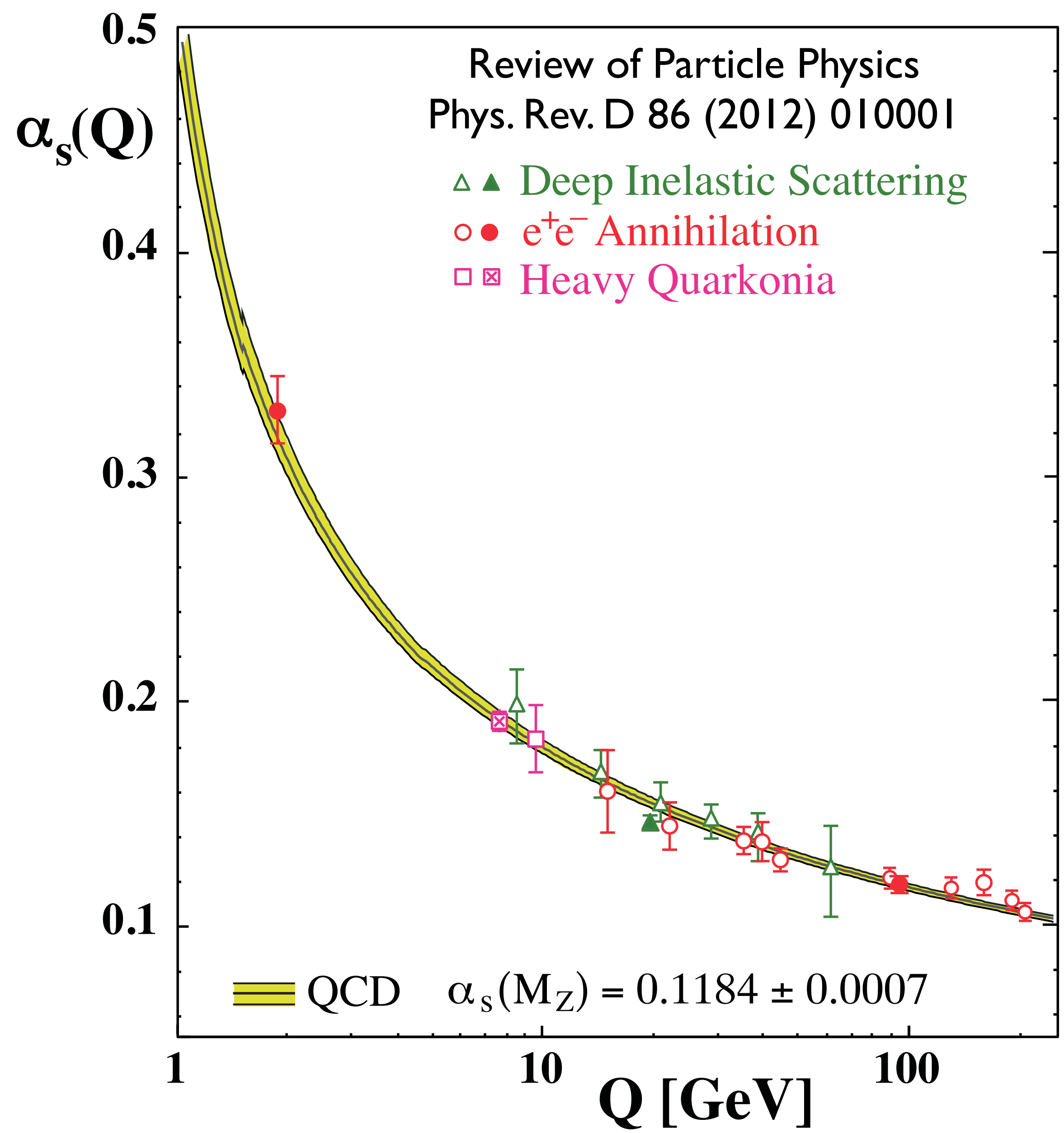
Framework:

QUANTUM CHROMO DYNAMICS

$$\mathcal{L}_{\mathbf{QCD}} = \bar{\psi}\left(i\gamma_{\mu}\mathcal{D}^{\mu} - \mathbf{m}\right)\psi - \frac{1}{4}\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}$$



Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	**0.003**	2/3
d down	**0.005**	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	174	2/3
b bottom	4.3	−1/3



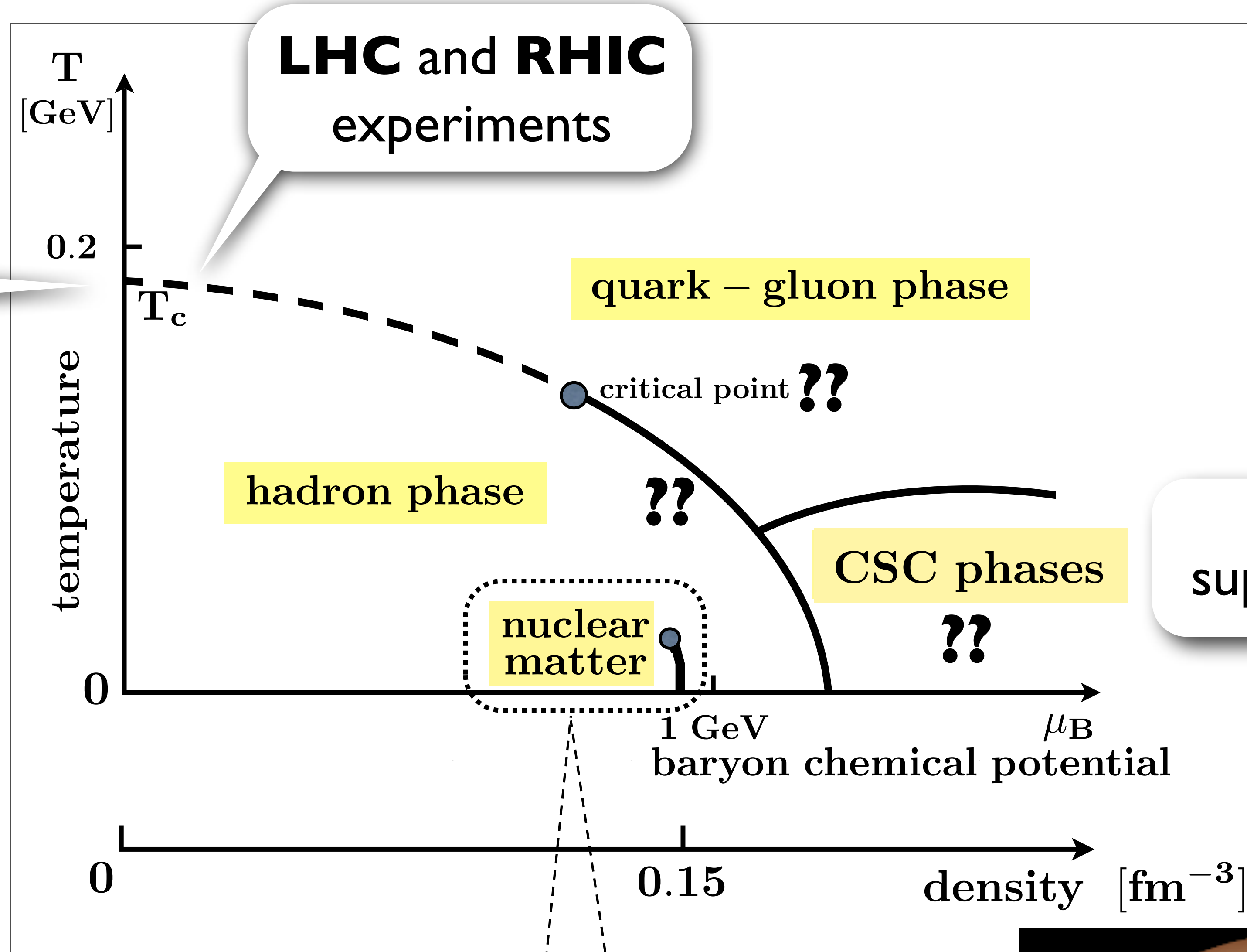
1. Introductory preview :

What do we know about the **PHASES** of **QCD ?**

PHASES and STRUCTURES of QCD

LHC and RHIC experiments

LATTICE QCD

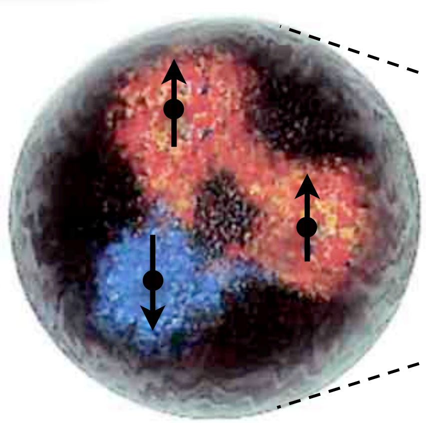


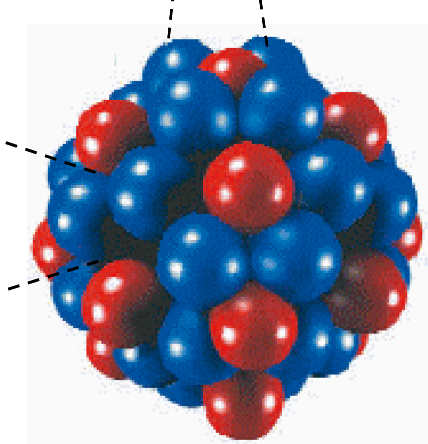
color superconducting

nucleons & nuclei

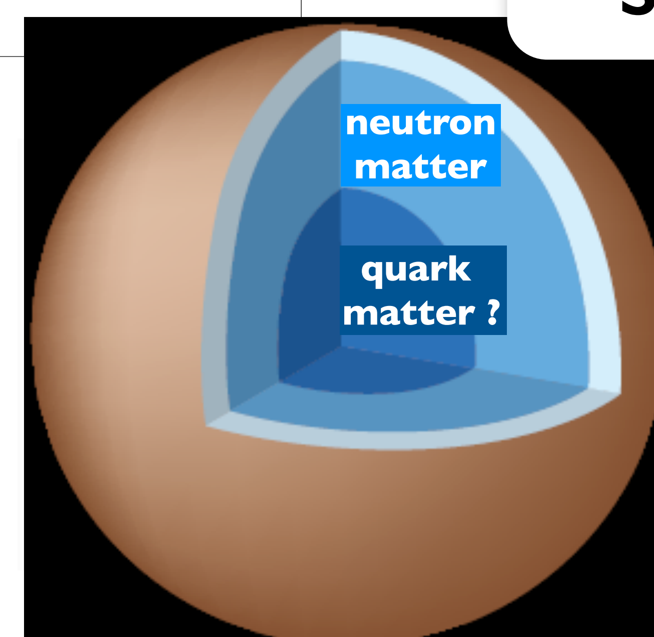
neutron stars

1 fm



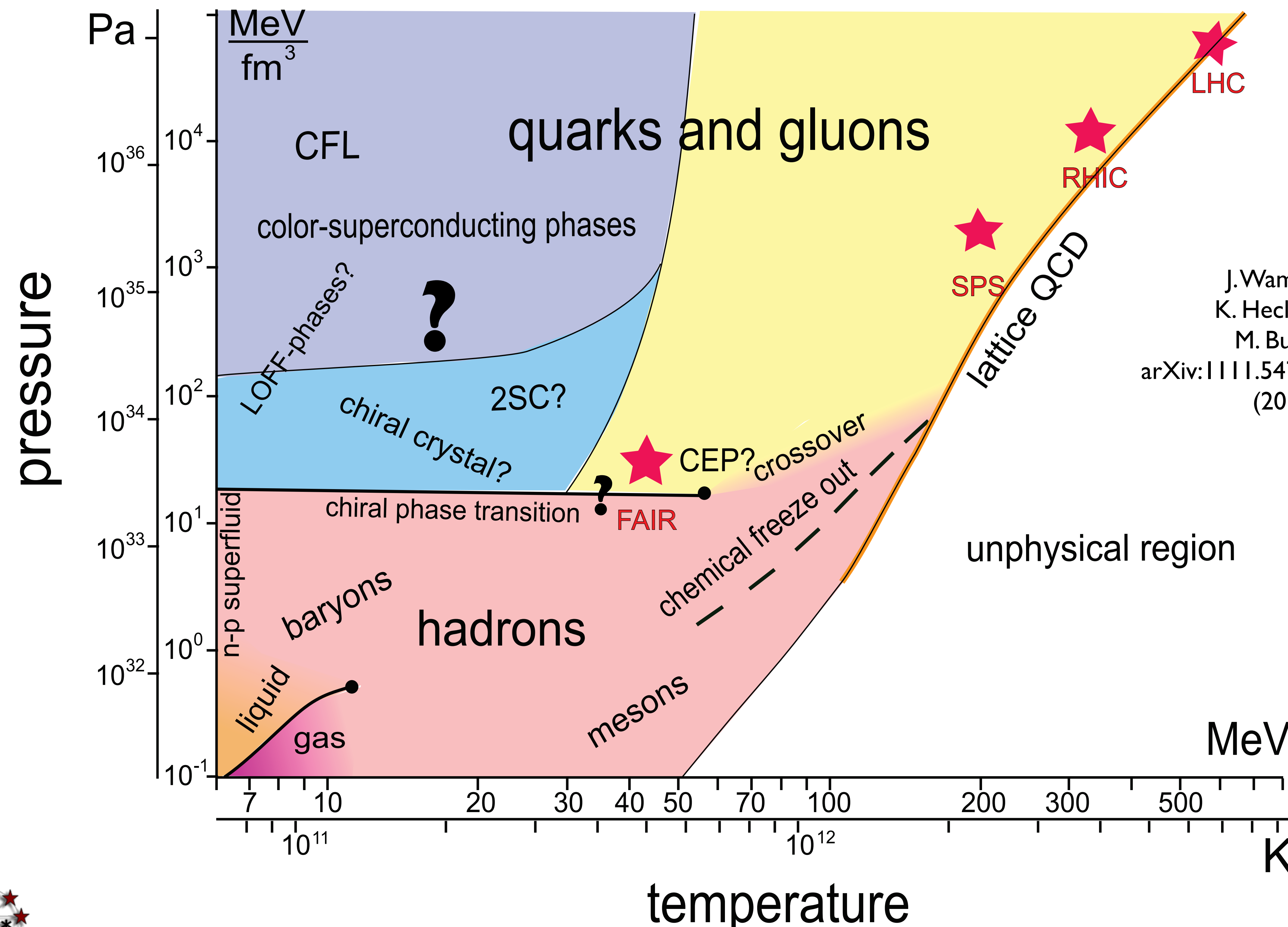


10 fm



10 km

PHASES and STRUCTURES of QCD
- facts and visions -



J. Wambach,
K. Heckmann,
M. Buballa
arXiv:1111.5475v2 [hep-ph]
(2012)

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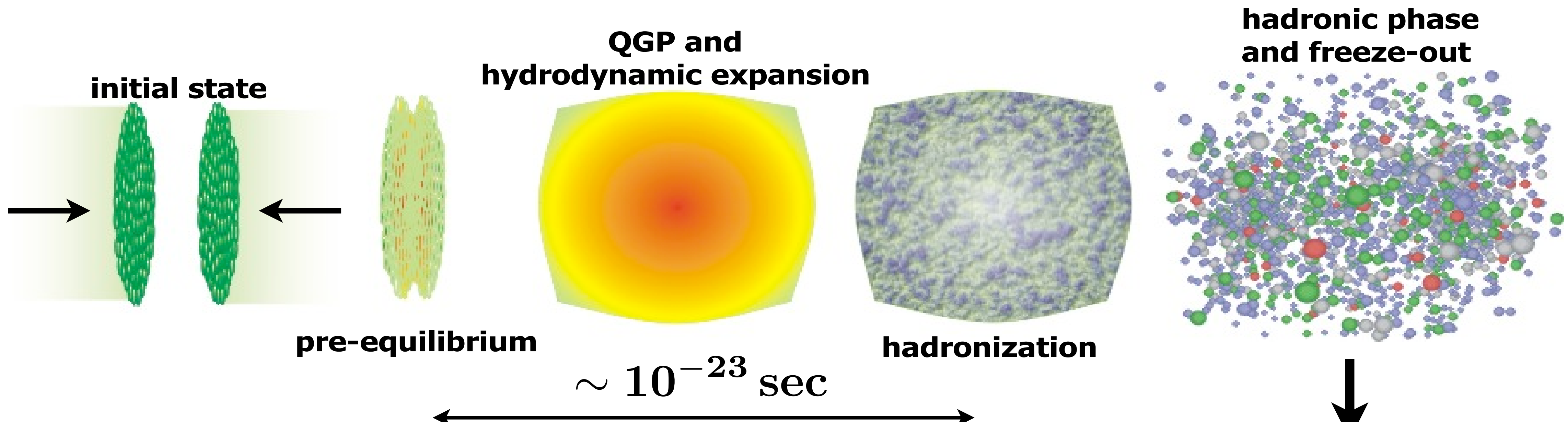
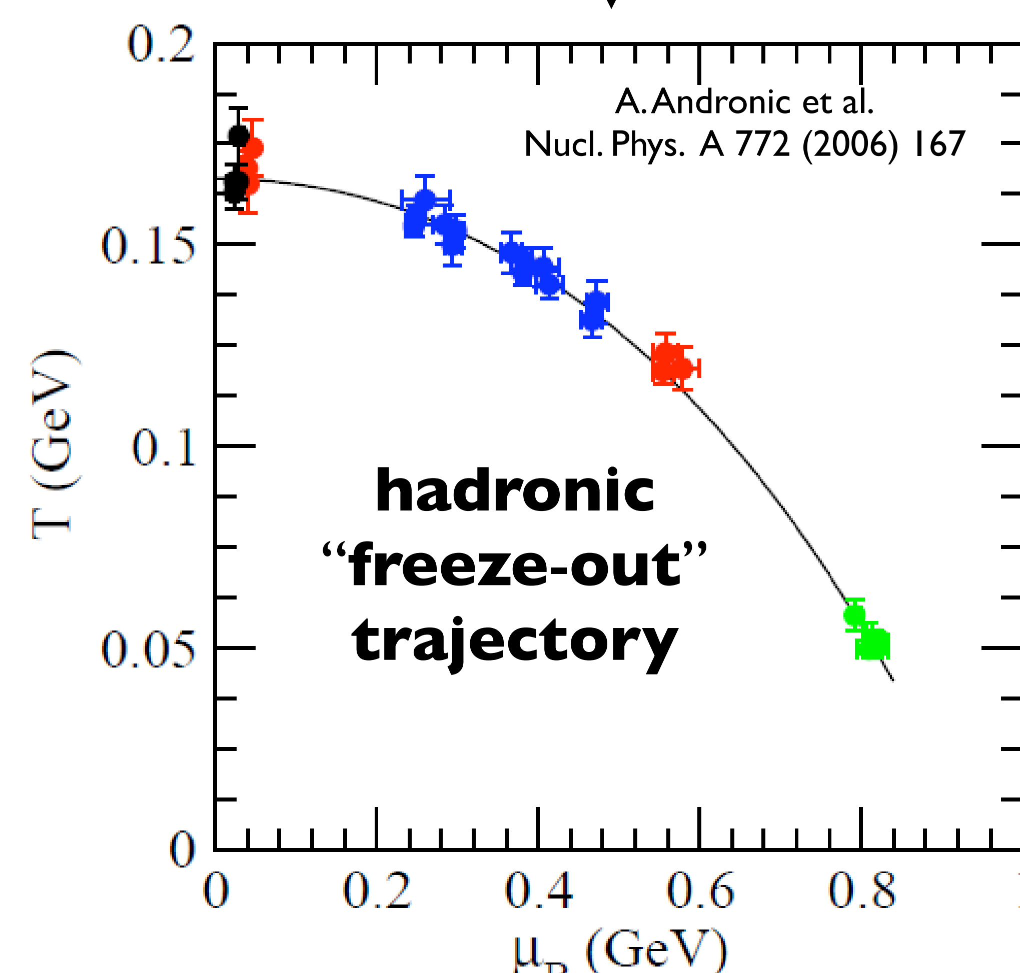
Strategies PART I: **Heavy-Ion Physics**

- **High Energy Nuclear Collisions** @ CERN/SPS, **RHIC**, **LHC**



- Analysis of **RHIC** and **LHC** data:

  - Initial temperatures 300 - 500 MeV
  - **Fast equilibration**
  - **Strongly correlated quark-gluon matter**



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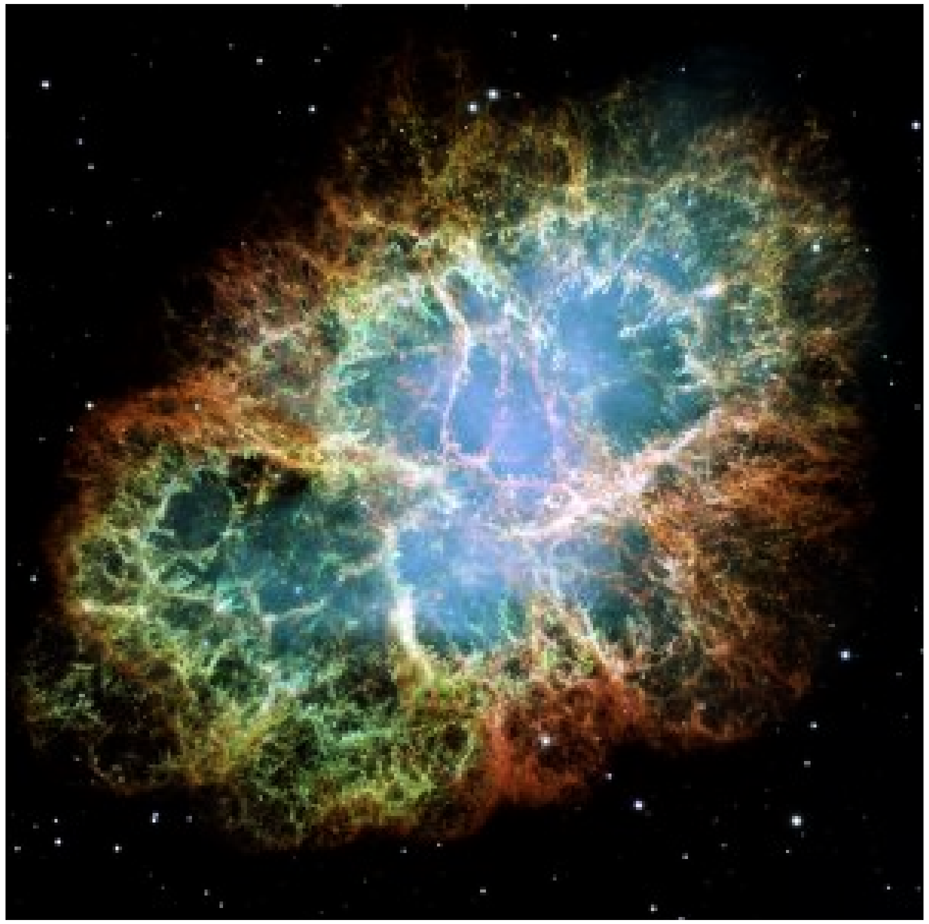
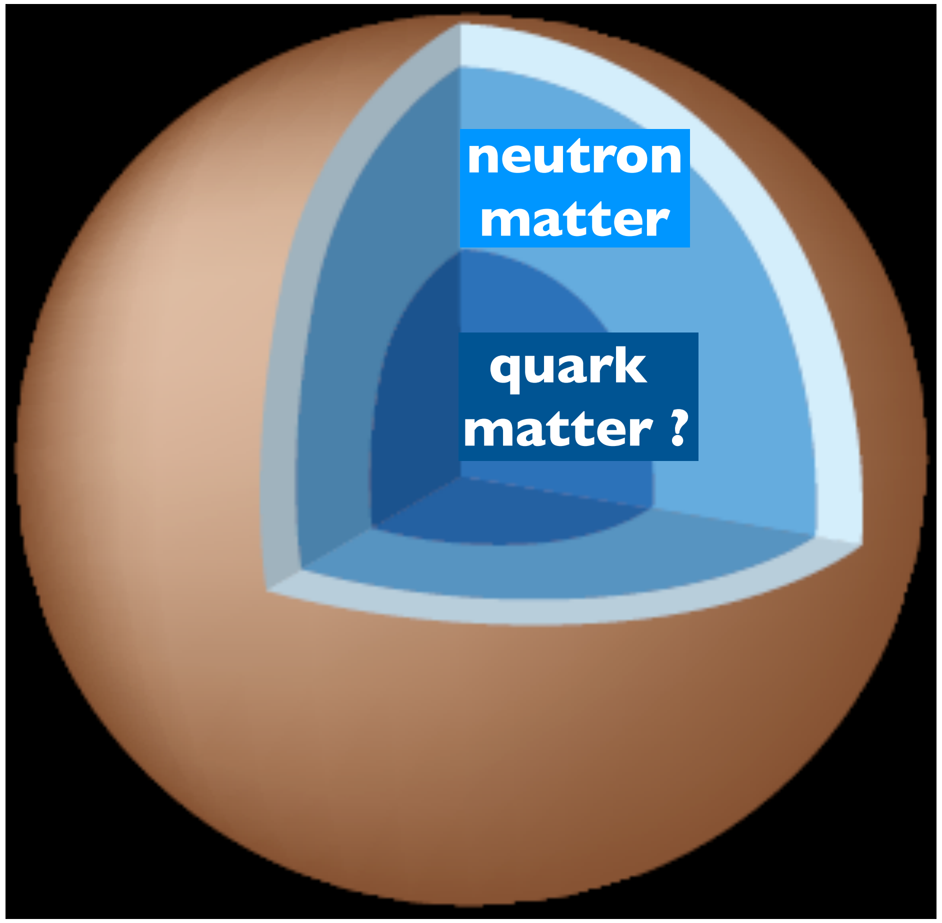
Strategies PART II: **Astrophysical Observations**

- Constraints on **Equation of State** of baryonic matter at **HIGH DENSITY** and **LOW TEMPERATURE**





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

Strategies PART III: **Lattice QCD**

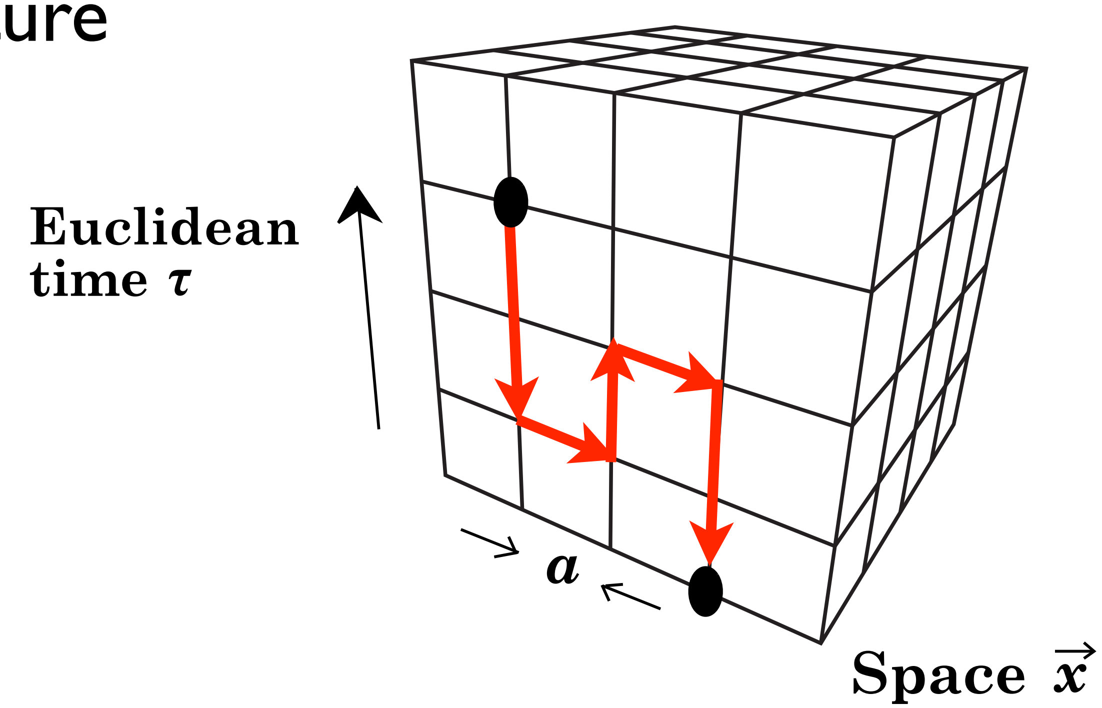
$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}\left(i\gamma_\mu \mathcal{D}^\mu - \mathbf{m}\right)\psi - \frac{1}{4}\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}$$

- Large-scale computer simulations on **EUCLIDEAN SPACE-TIME** Lattices
- Euclidean time ≙ inverse temperature

$$\tau = \mathbf{1/T}$$

quarks on lattice sites

gluon fields on links



- **QCD THERMODYNAMICS**

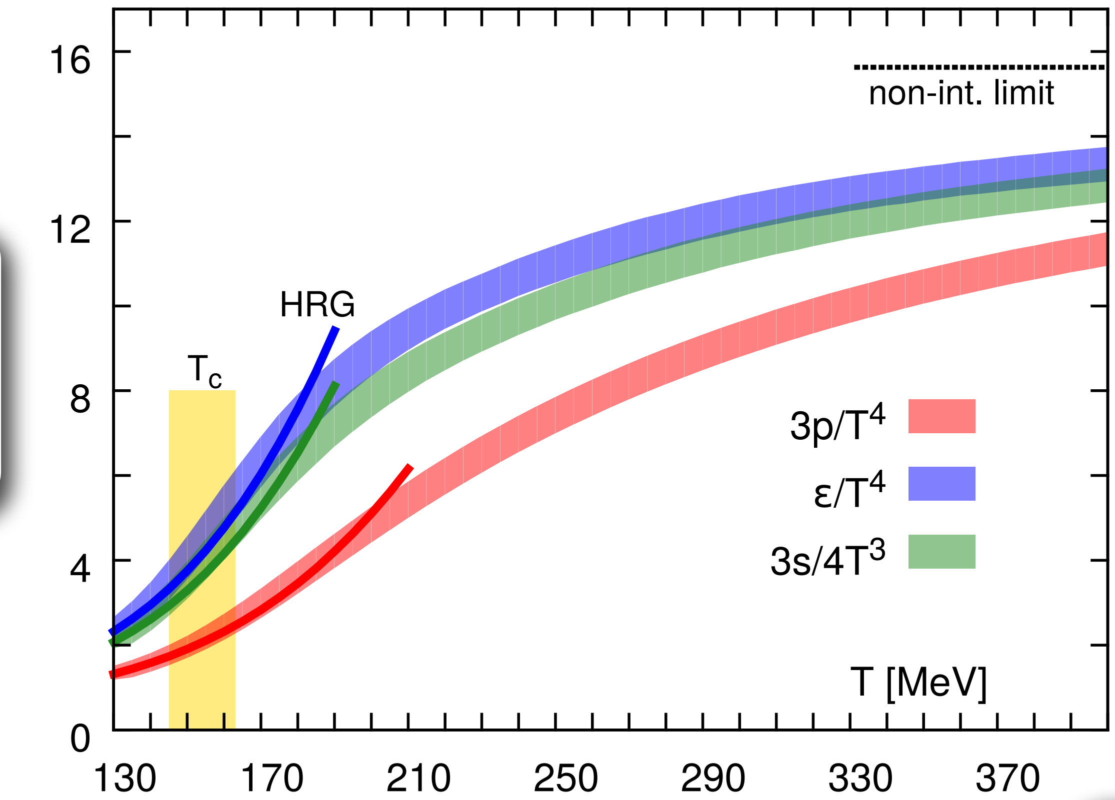
Partition function

$$\mathcal{Z} = \int [\mathrm{d}\mathcal{U}\,\mathrm{d}\psi\,\mathrm{d}\bar{\psi}]\,\mathrm{e}^{-\mathcal{S}_{\mathbf{G}}(\mathcal{U}) - \mathcal{S}_{\mathbf{q}}(\psi,\bar{\psi},\mathcal{U})}$$

► Non-perturbative "condensed matter physics" of QCD

QCD THERMODYNAMICS on the LATTICE

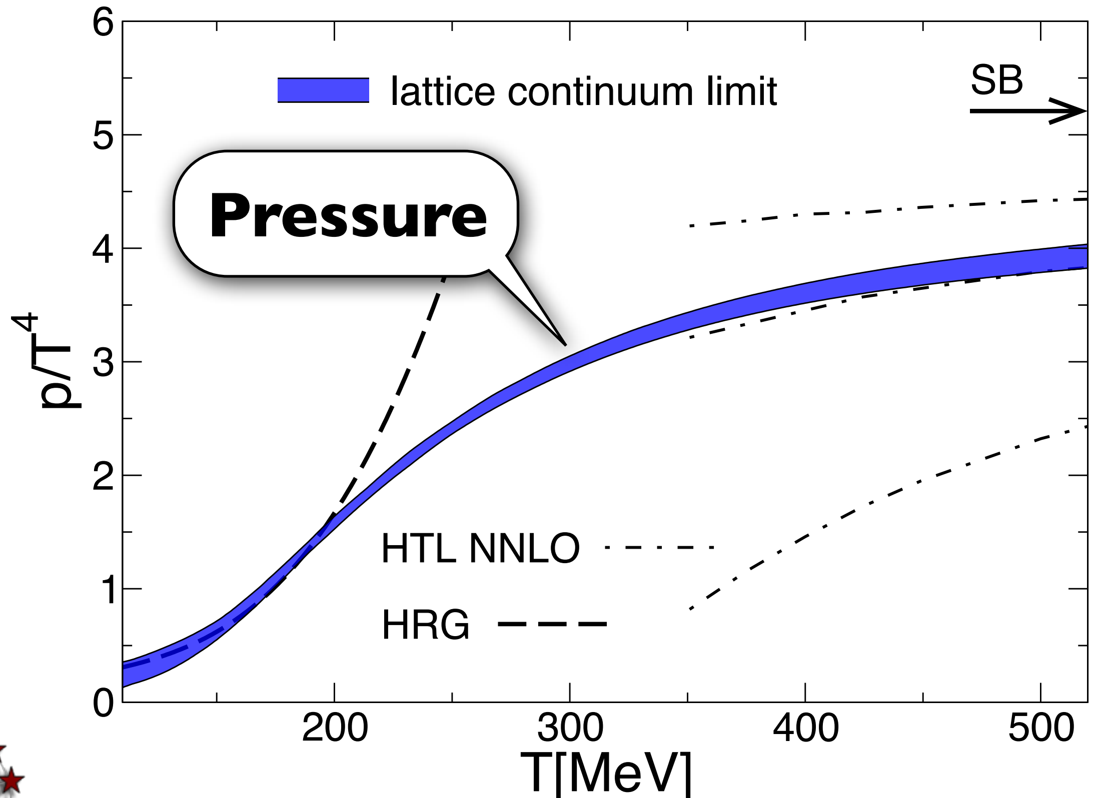
crossover transition
(not a phase transition)

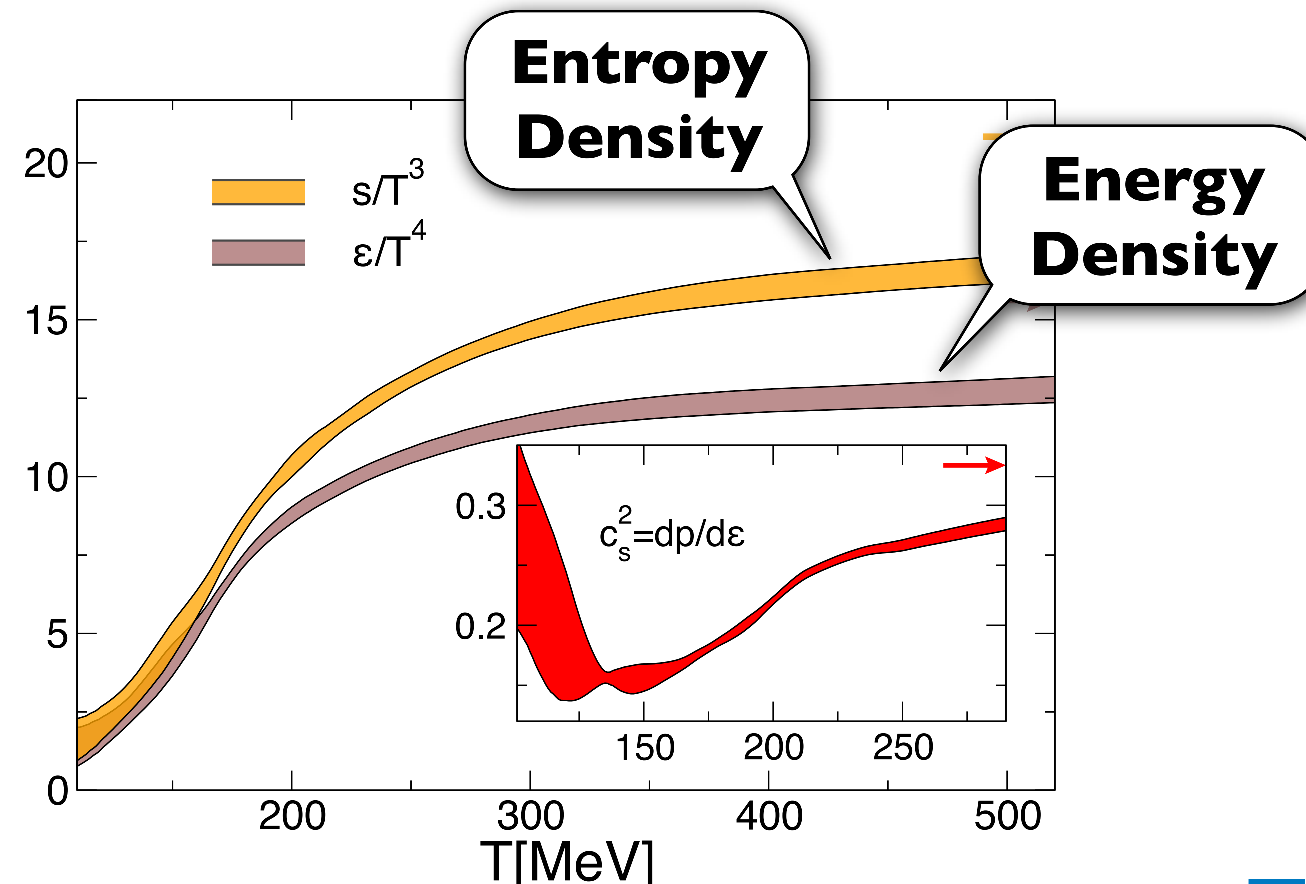


A. Bazanov et al. (HotQCD collab.)
arXiv:1407.6387 [hep-lat]
(2014)

transition temperature
$T_c \simeq 150 - 160\,\mathrm{MeV}$

S. Borsanyi et al.
Phys. Lett. B 738 (2014) 187





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2.

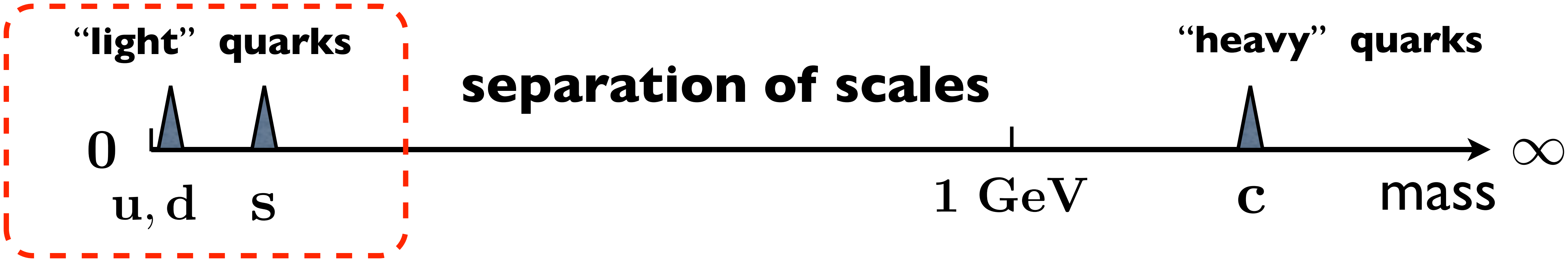
The **Hadronic** Phase:
Low-Energy QCD

and

Spontaneously Broken

Chiral Symmetry

Hierarchy of **QUARK MASSES** in **QCD**



$$\mathrm{m_u} \simeq 2 - 3\ \mathrm{MeV}$$
$$\mathrm{m_u/m_d} \sim 0.4 - 0.6$$
$$\mathrm{m_s} = 95 \pm 5\ \mathrm{MeV}$$
$$(\mu \simeq 2\ \mathrm{GeV})$$

PDG Phys. Rev. D 86 (2012)

- **LOW-ENERGY QCD: CHIRAL EFFECTIVE FIELD THEORY**
- **expansion in $\mathrm{m_q}$ and in powers of low momentum**

$$\mathrm{m_c} \simeq 1.25\ \mathrm{GeV}$$
$$m_b \simeq 4.2\ GeV$$
$$m_t \simeq 174\ GeV$$

- **N**on-**R**elativistic **QCD**: **HEAVY QUARK EFFECTIVE THEORY**
- **expansion in powers of $1/\mathrm{m_Q}$**

Low-Energy QCD : CHIRAL SYMMETRY

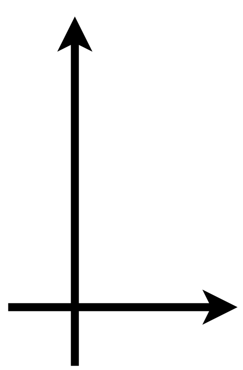
- **QCD** with (almost) **MASSLESS u-** and **d-QUARKS**

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

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

pseudoscalar
isovector

$$\pi^a \leftrightarrow \bar{\psi}\, i\gamma_5\, \tau^a \psi$$



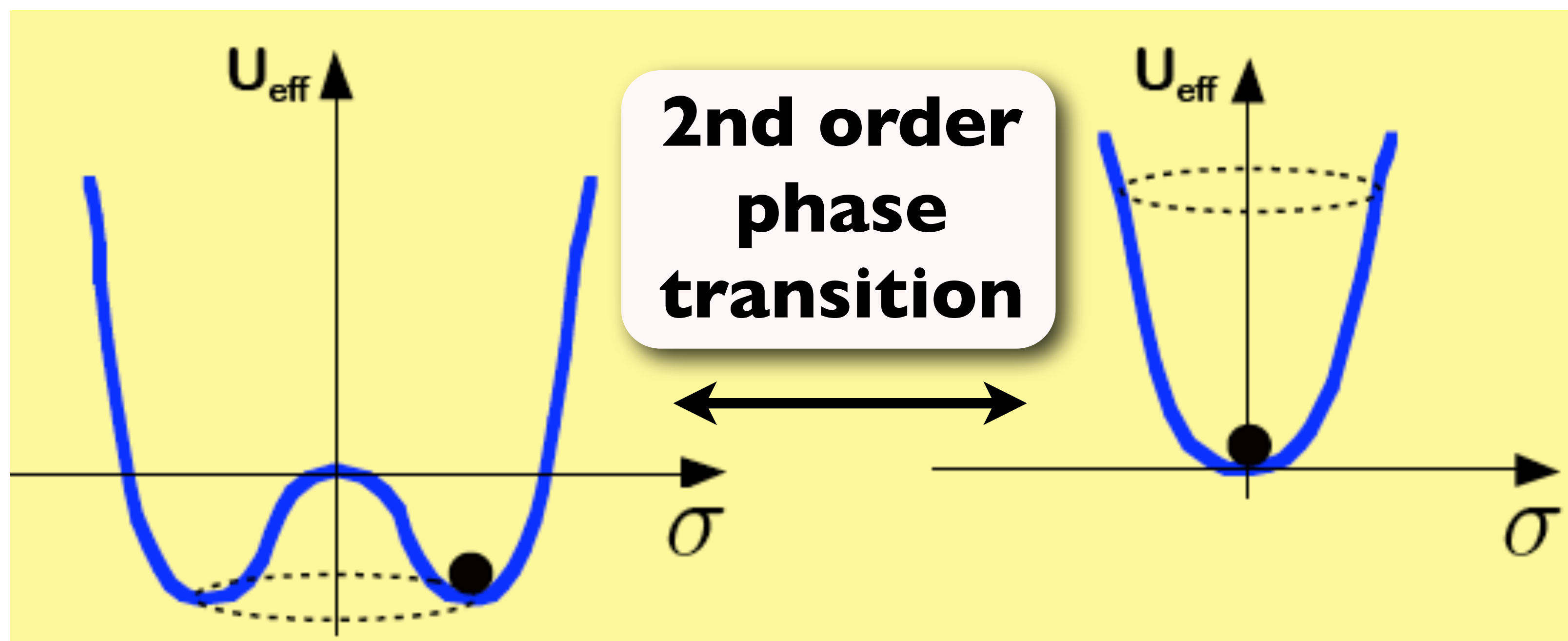
scalar
isoscalar

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

invariant:

$$\sigma^2 + \pi^2 = \mathbf{f}^2$$

- **Realizations** of **CHIRAL SYMMETRY**:



Nambu-Goldstone

$$\langle \bar{\psi}\psi \rangle \neq 0$$

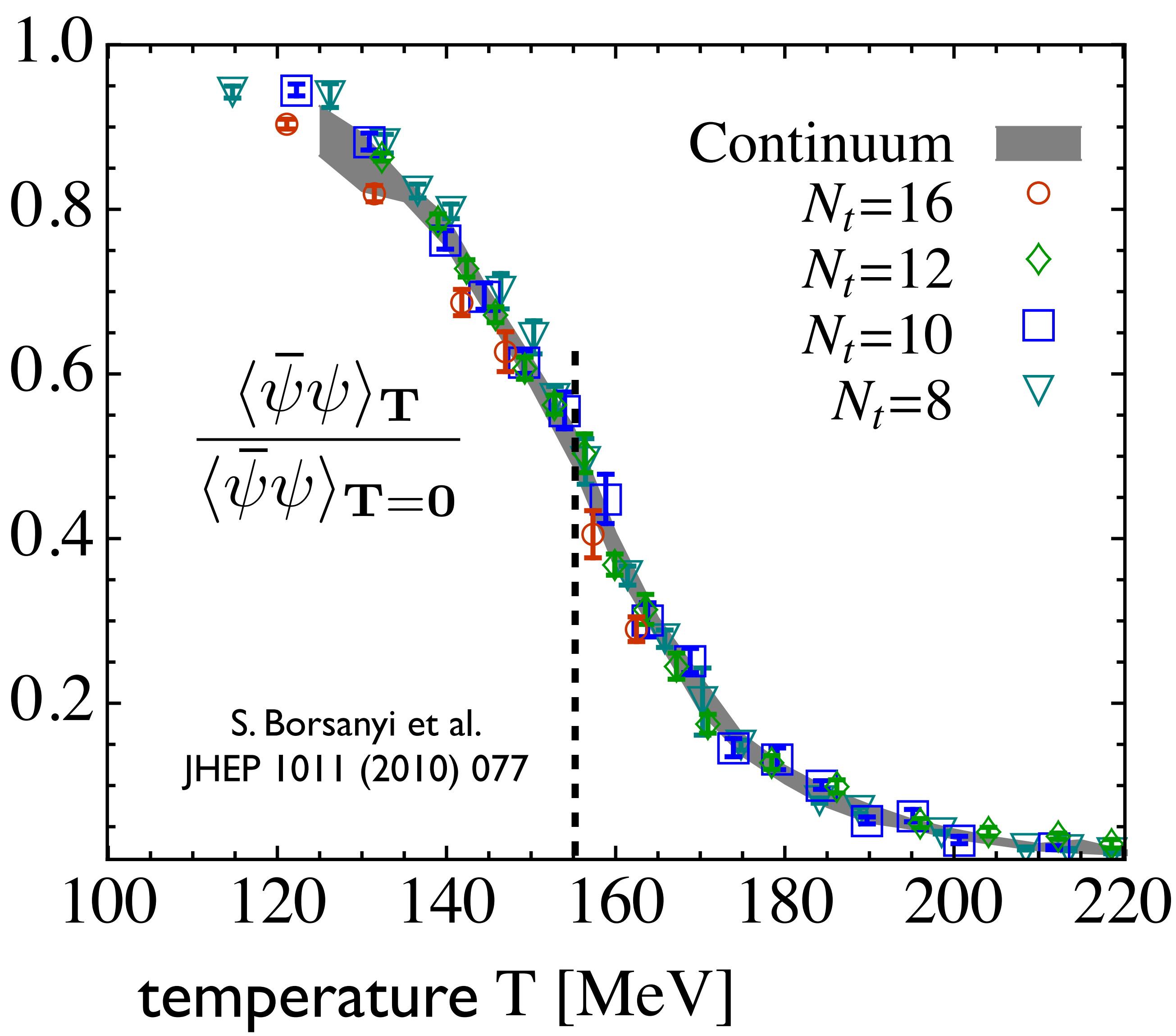
at low energy / low temperature

Wigner-Weyl

$$\langle \bar{\psi}\psi \rangle = 0$$

at high energy / high temperature

LATTICE QCD THERMODYNAMICS: CHIRAL and DECONFINEMENT TRANSITIONS



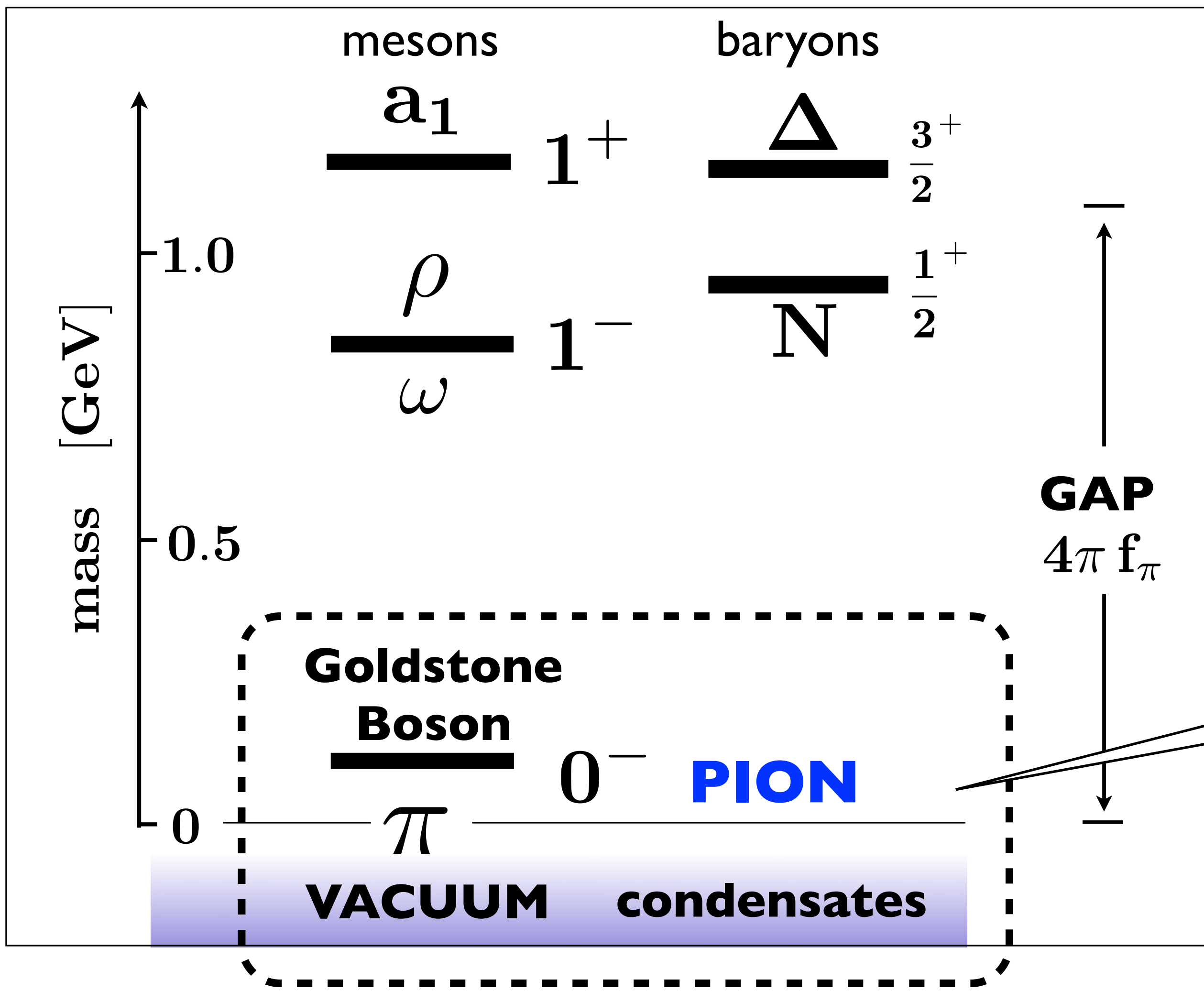
Quark Condensate

Order Parameter
of
spontaneously broken
Chiral Symmetry

crossover
transition temperature
$T_c \simeq 155\,\mathrm{MeV}$

chiral and **deconfinement**
crossover transitions appear to be closely **connected**

Spontaneously Broken CHIRAL SYMMETRY

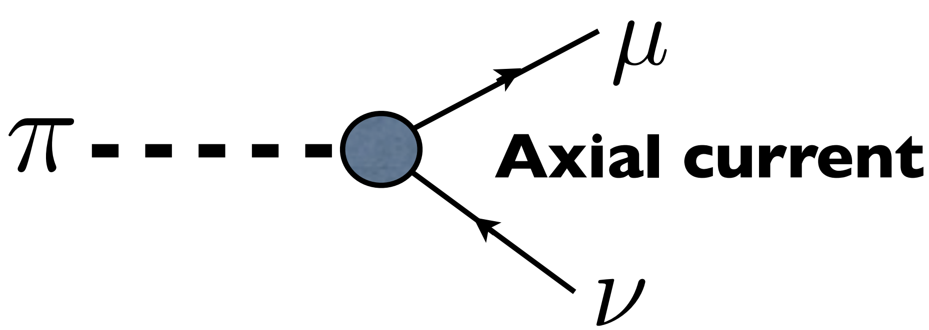


Triplet
of
NAMBU - GOLDSTONE BOSONS:
$\pi^+,\ \pi^0,\ \pi^-$

Characteristic Symmetry Breaking SCALE:

$$4\pi\, f_\pi \sim 1\ \mathrm{GeV}$$

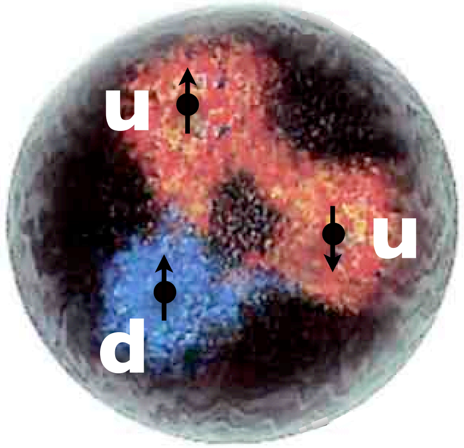
- **PION DECAY CONSTANT**



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

QCD and the ORIGIN of MASS

HOW does the PROTON get its mass ? (NOT from Higgs !!)



Localization (**confinement**) of quarks in the nucleon ➔ spontaneous (dynamical) **breaking** of **Chiral Symmetry**

$$\mathrm{u + u + d = proton}$$

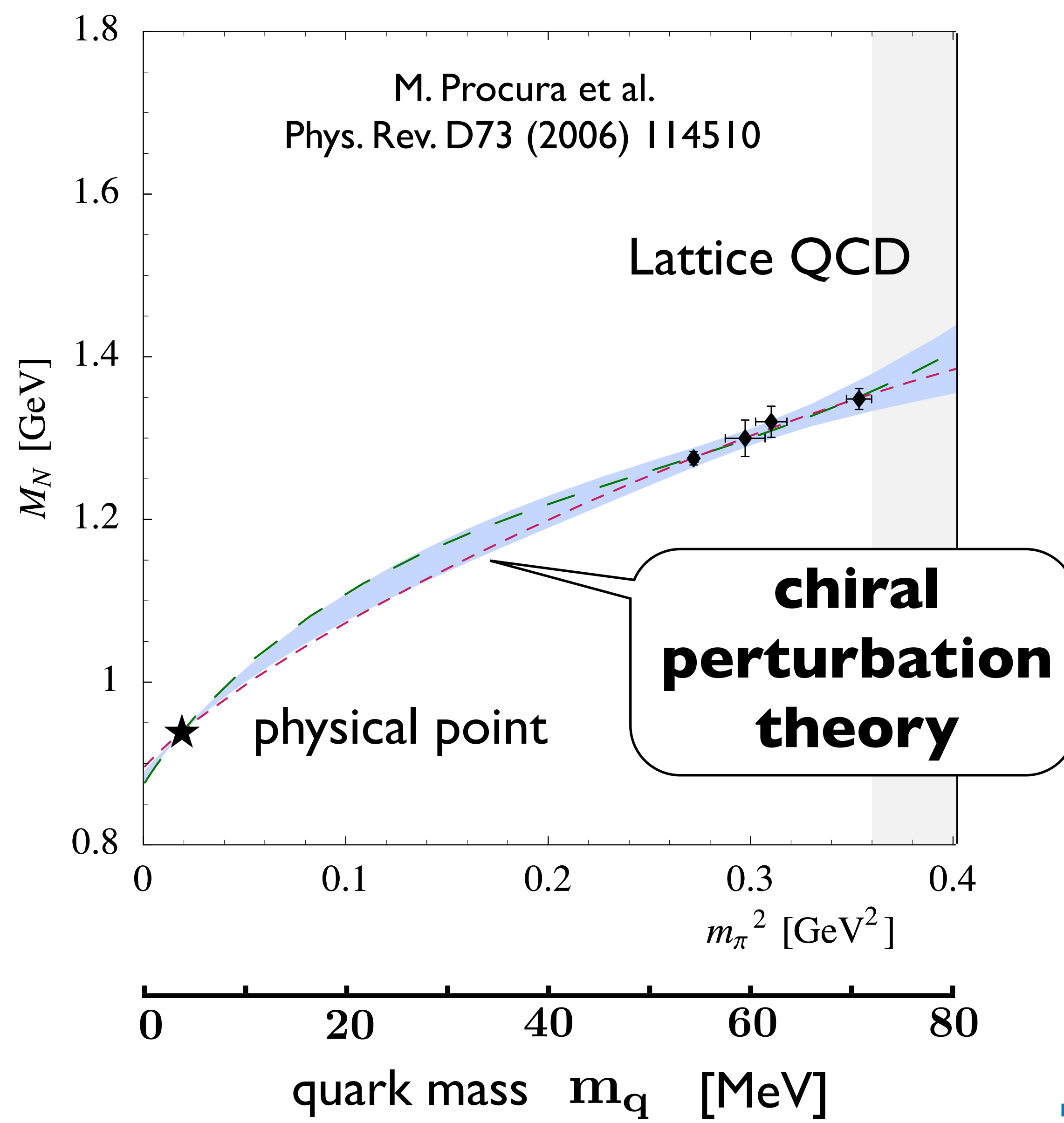
$$\mathrm{m_u \simeq 3\ MeV} \quad \mathrm{m_d \simeq 5\ MeV}$$

$$3 + 3 + 5 \neq 938 \quad !\,?$$

answer:

mostly **GLUON Dynamics**

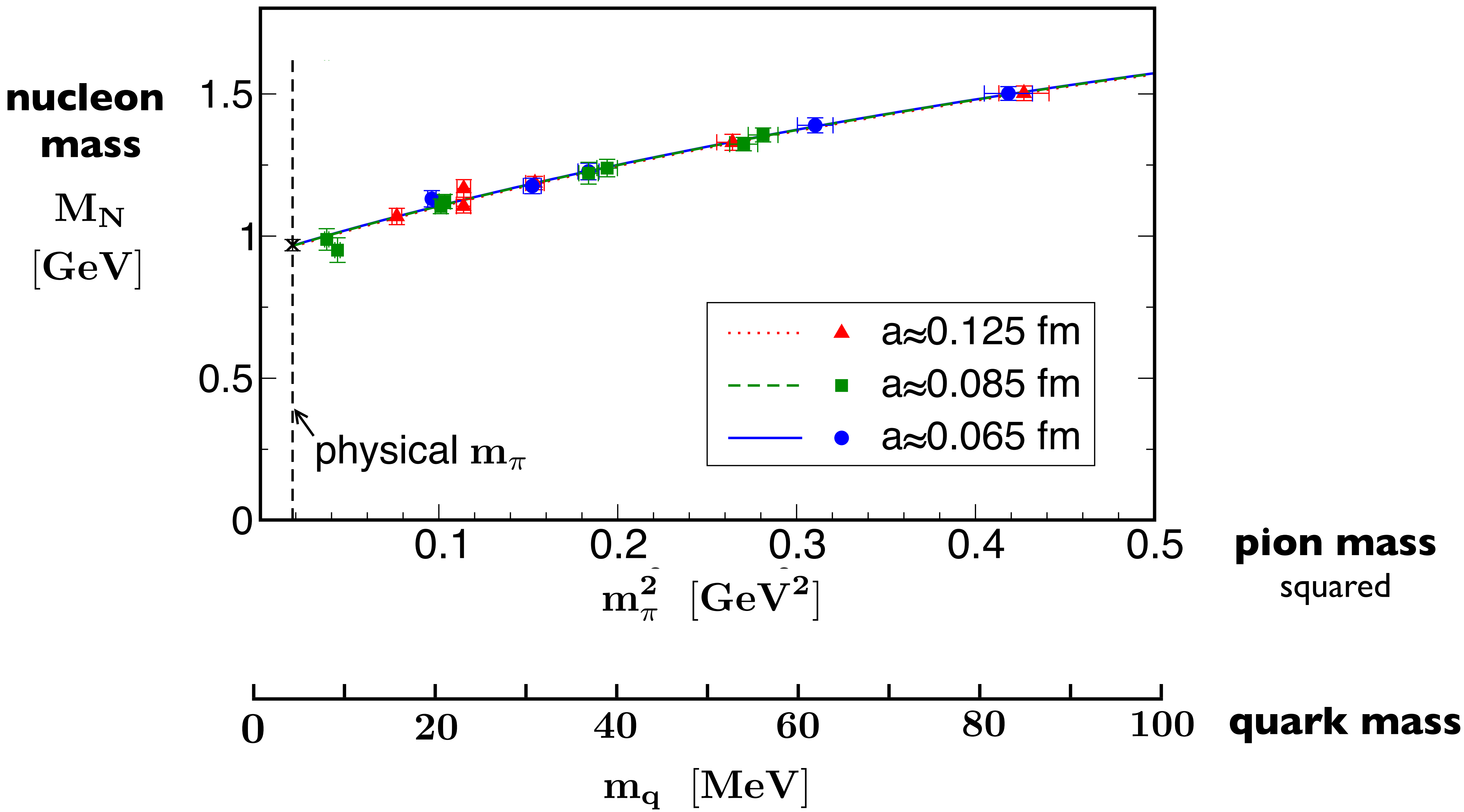
$$E = m\,c^2$$



Nucleon Mass from Lattice QCD

Budapest-Marseille-Wuppertal Collaboration

Science 322 (2008) 1224



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

- **CONFINEMENT** of quarks and gluons in hadrons
- Spontaneously broken **CHIRAL SYMMETRY**
- **LOW-ENERGY QCD**:
  Effective **F**ield **T**heory of **weakly** interacting
  Nambu-Goldstone Bosons (PIONS)
  representing QCD at (energy and momentum) scales

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

CHIRAL EFFECTIVE FIELD THEORY

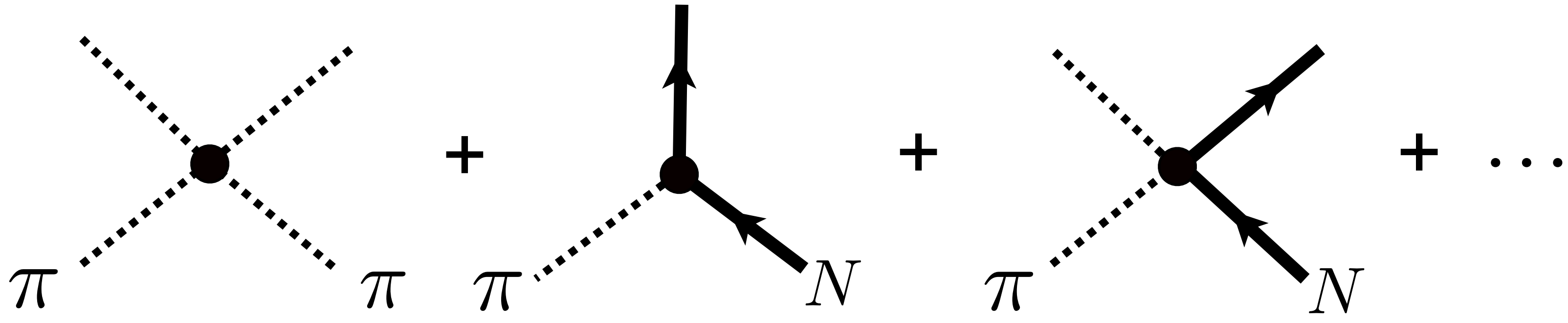
- Systematic framework at interface of QCD and Nuclear Physics

- 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**



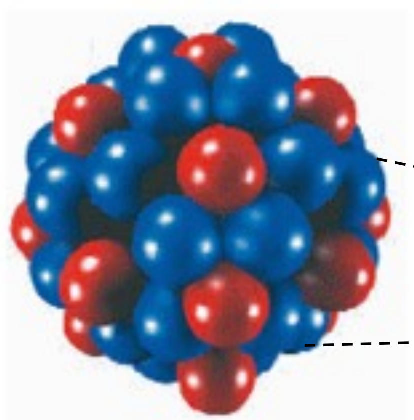
short distance dynamics: **contact terms**

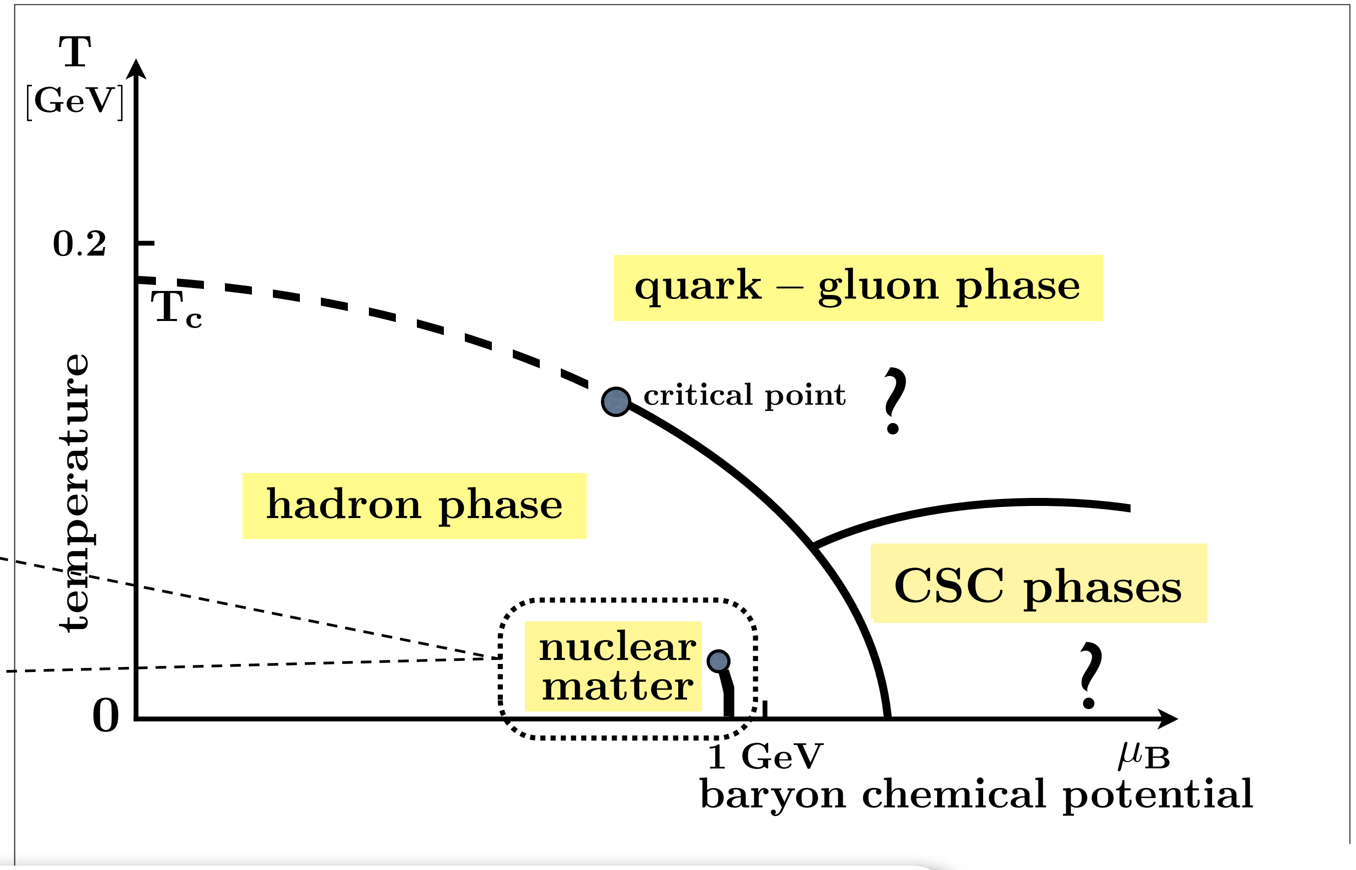
3.

NUCLEAR CHIRAL THERMODYNAMICS

NUCLEAR MATTER and QCD PHASES

nuclei





Scales in N = Z **nuclear matter**:

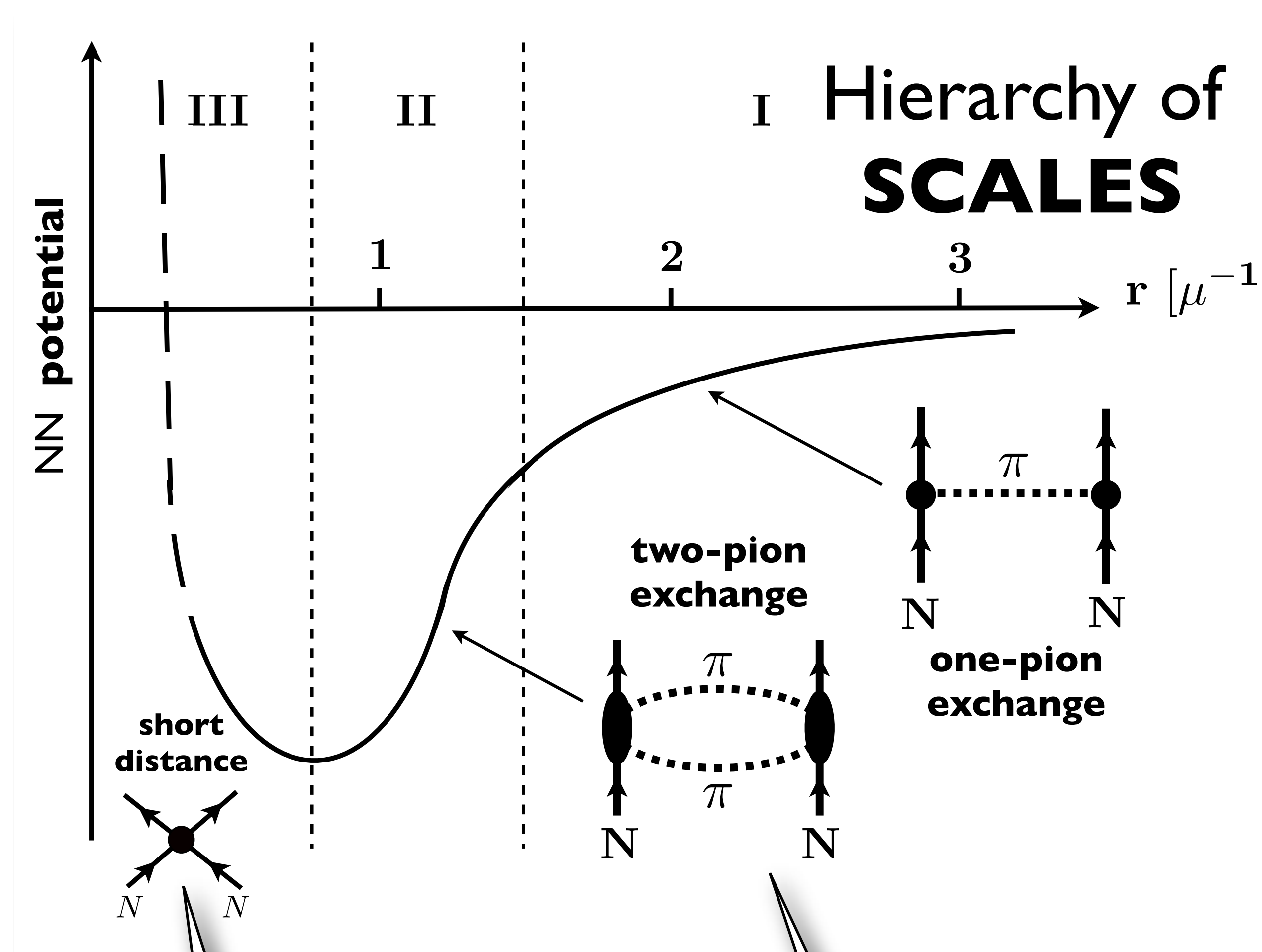
- momentum scale:
  Fermi momentum $k_F \simeq 1.4\ \mathrm{fm}^{-1} \sim 2m_\pi$
- NN distance: $d_{NN} \simeq 1.8\ \mathrm{fm} \simeq 1.3\ m_\pi^{-1}$
- energy per nucleon: $E/A \simeq -16\ \mathrm{MeV}$
- compression modulus: $K = (260 \pm 30)\ \mathrm{MeV} \sim 2m_\pi$

Nuclear Forces
- recent developments -

contemporary approach:

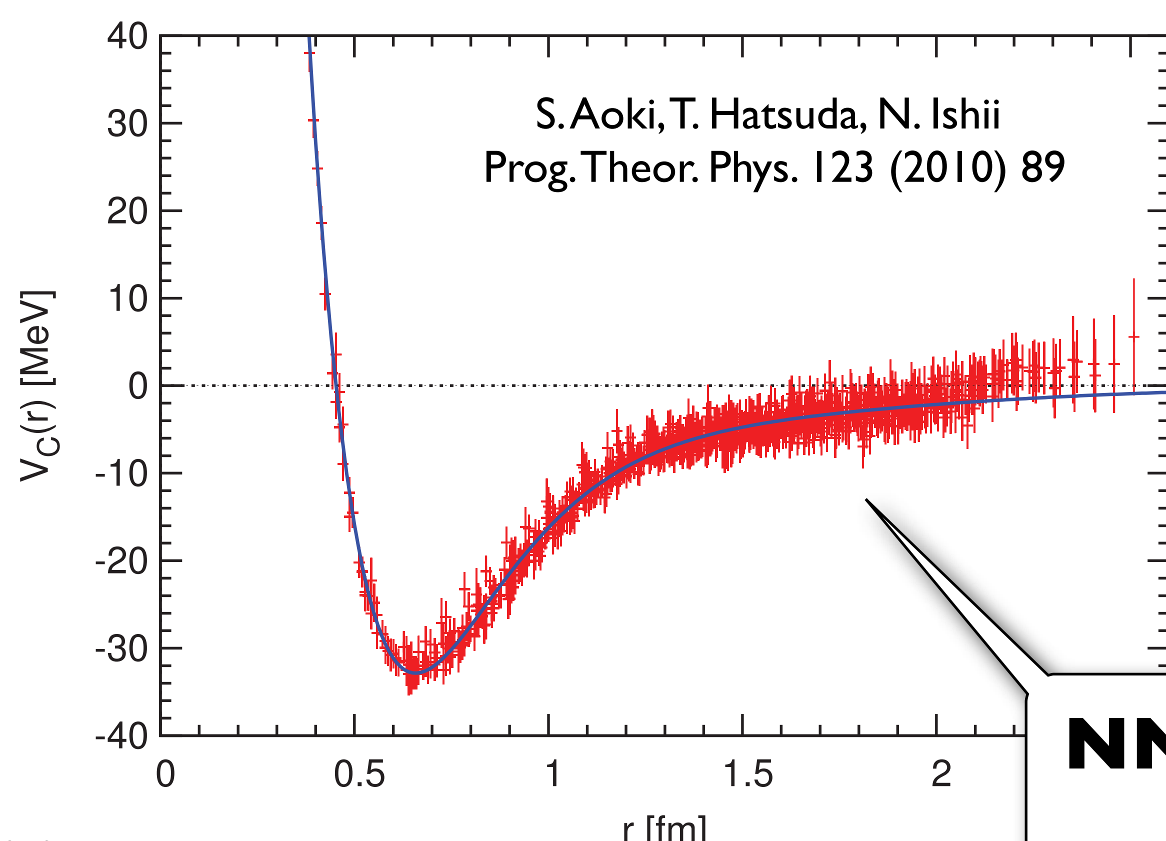
Chiral Effective Field Theory
+
Lattice QCD

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



contact terms

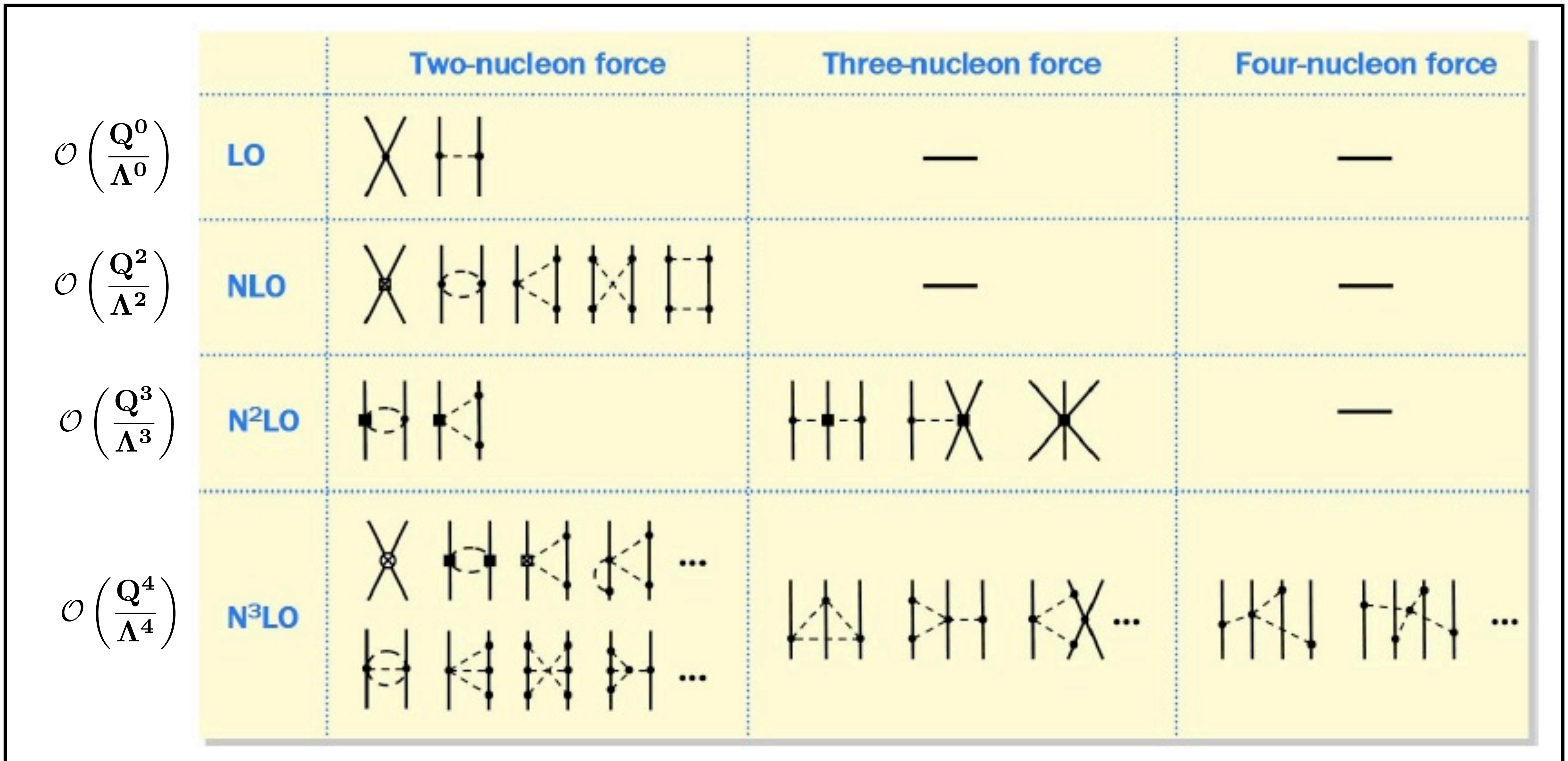
explicit treatment of **two-pion exchange**



NN Central Potential
from Lattice QCD

NUCLEAR INTERACTIONS from CHIRAL EFFECTIVE FIELD THEORY

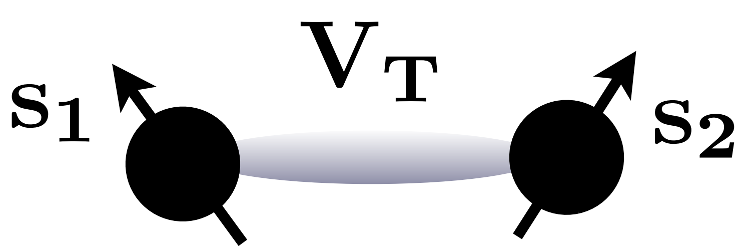
Weinberg Bedaque & van Kolck Bernard, Epelbaum, Kaiser, Meißner; ...

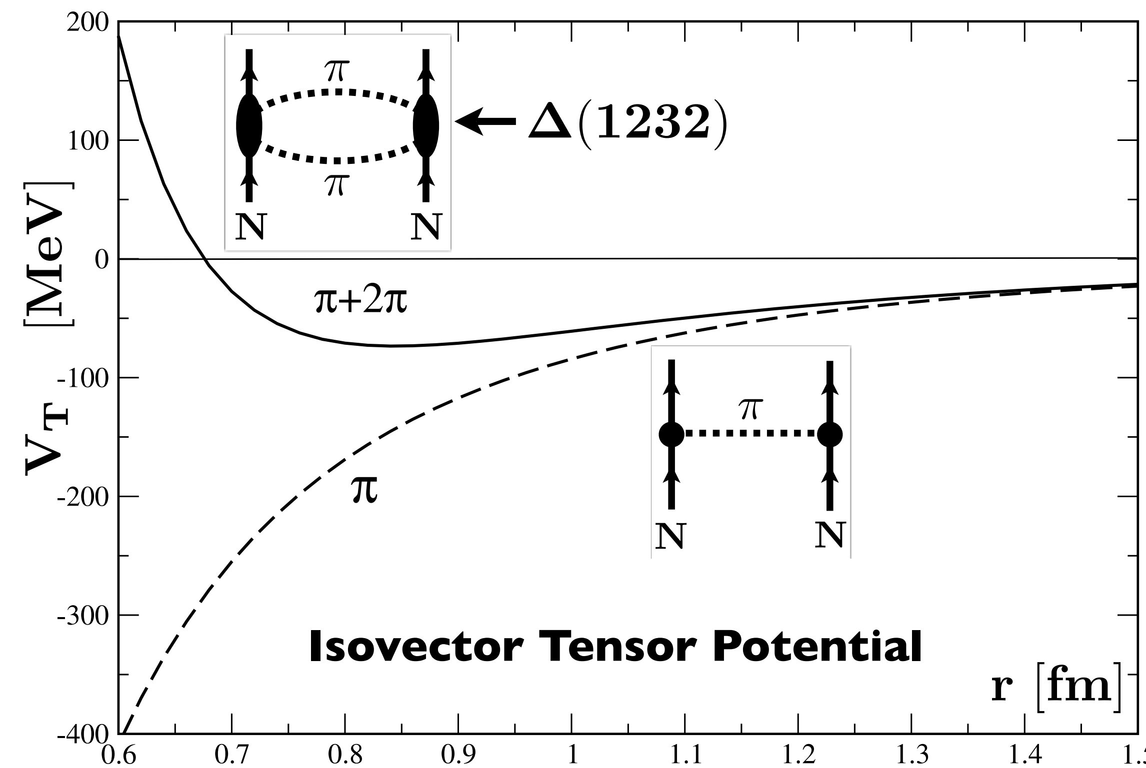


- **Systematically organized HIERARCHY**

Important pieces of the
CHIRAL NUCLEON-NUCLEON INTERACTION

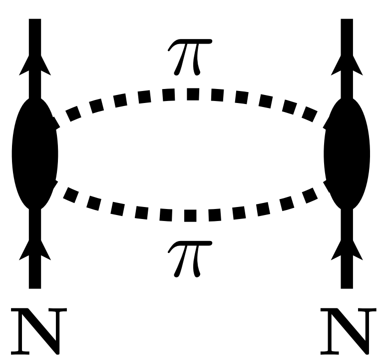
- **TENSOR FORCE**





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

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



Van der WAALS - like force

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

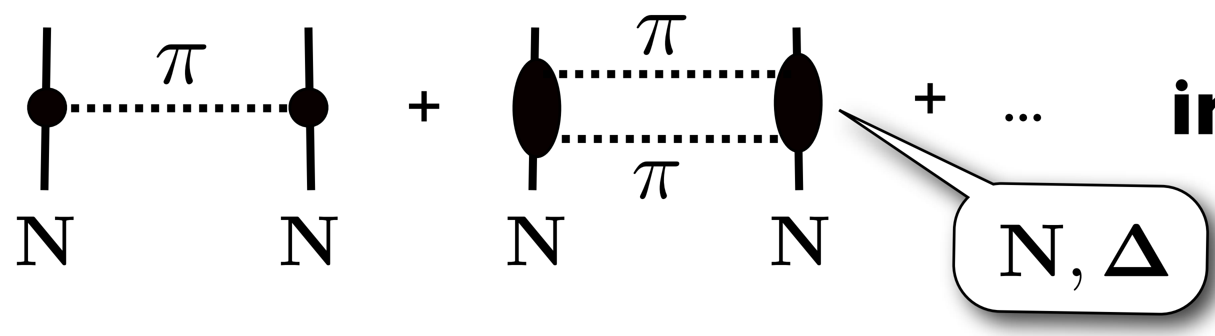
... at intermediate and long distance

CHIRAL DYNAMICS and the NUCLEAR MANY-BODY PROBLEM

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

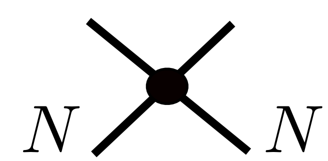
- **Small scales**: energy, momentum, $\mathbf{m}_\pi\,,\;\; \mathbf{k_F} << 4\pi \mathbf{f}_\pi \sim 1\,\mathrm{GeV}$
- **PIONS** and **NUCLEONS** as **explicit degrees of freedom**
- **IN-MEDIUM CHIRAL PERTURBATION THEORY**

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



in-medium

short-distance dynamics:



contact interactions

IN-MEDIUM CHIRAL PERTURBATION THEORY

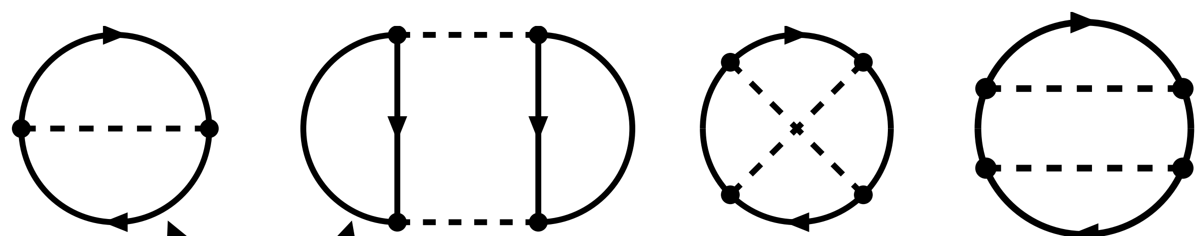
- **Loop expansion** of (**I**n-**M**edium) **Ch**iral **P**erturbation **T**heory

  ↕

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

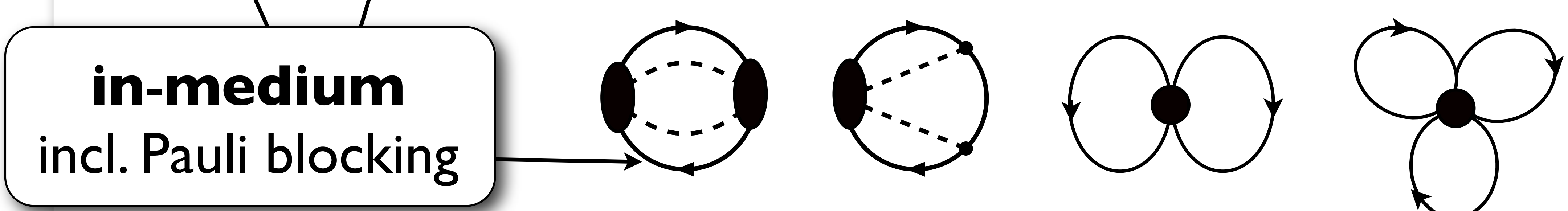
  (works for $\mathbf{k_F << 4\pi\, f_\pi \sim 1\, GeV}$)

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



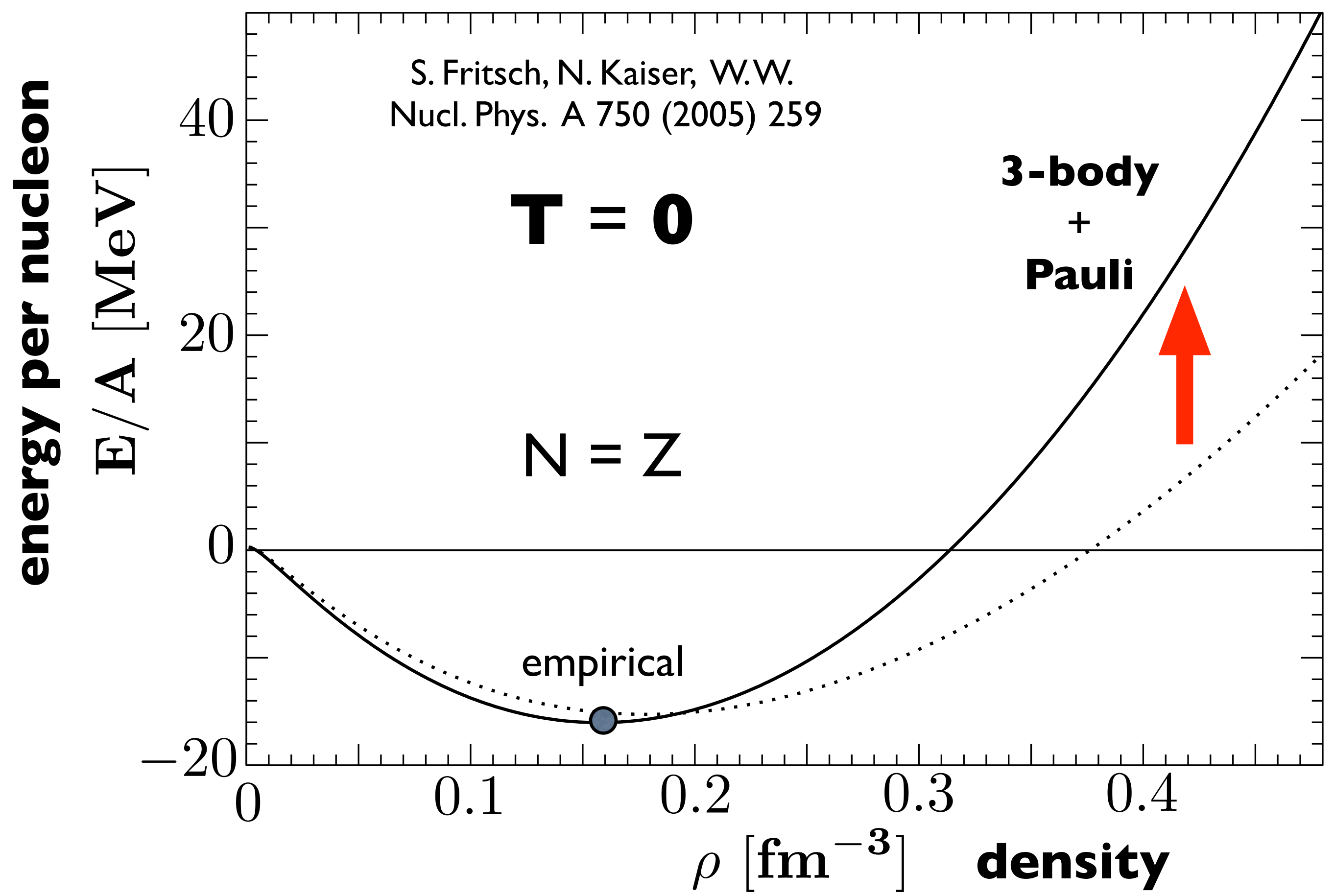
(3-loop order)

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



NUCLEAR MATTER

- **In-medium ChEFT**
  3-loop $(\pi, \mathrm{N}, \boldsymbol{\Delta})$
- **Input** parameters:
  few contact terms
- basically:
  analytic calculation
- **Output**:



- Binding & saturation
  $$\mathbf{E_0/A = -16\,MeV} \;,\; \boldsymbol{\rho_0} \mathbf{= 0.16\,fm^{-3}} \;,\; \mathbf{K = 290\,MeV}$$
- Asymmetry energy: $\mathbf{A(k_F^0) = 34\,MeV}$

J.W. Holt, N. Kaiser, W.W.
(2011-2013)

- Finite nuclei: Density Functional methods

C. Wellenhofer, J.W. Holt, N. Kaiser, W.W.
Phys. Rev. C 89 (2014) 064009

- Fermi Liquid Theory:
  Quasiparticle interaction and Landau parameters

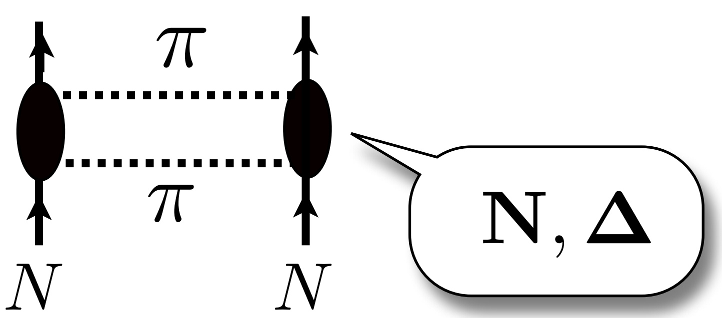
Recent review: J.W. Holt, N. Kaiser, W.W.: Prog. Part. Nucl. Phys. 73 (2013) 35

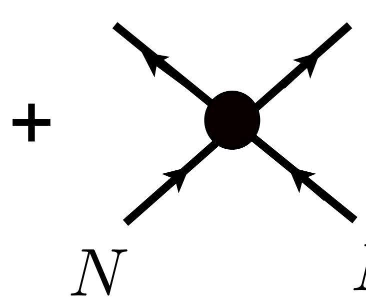
NUCLEAR THERMODYNAMICS

NUCLEAR
CHIRAL (PION) **DYNAMICS**

BINDING & SATURATION:

Van der Waals + Pauli

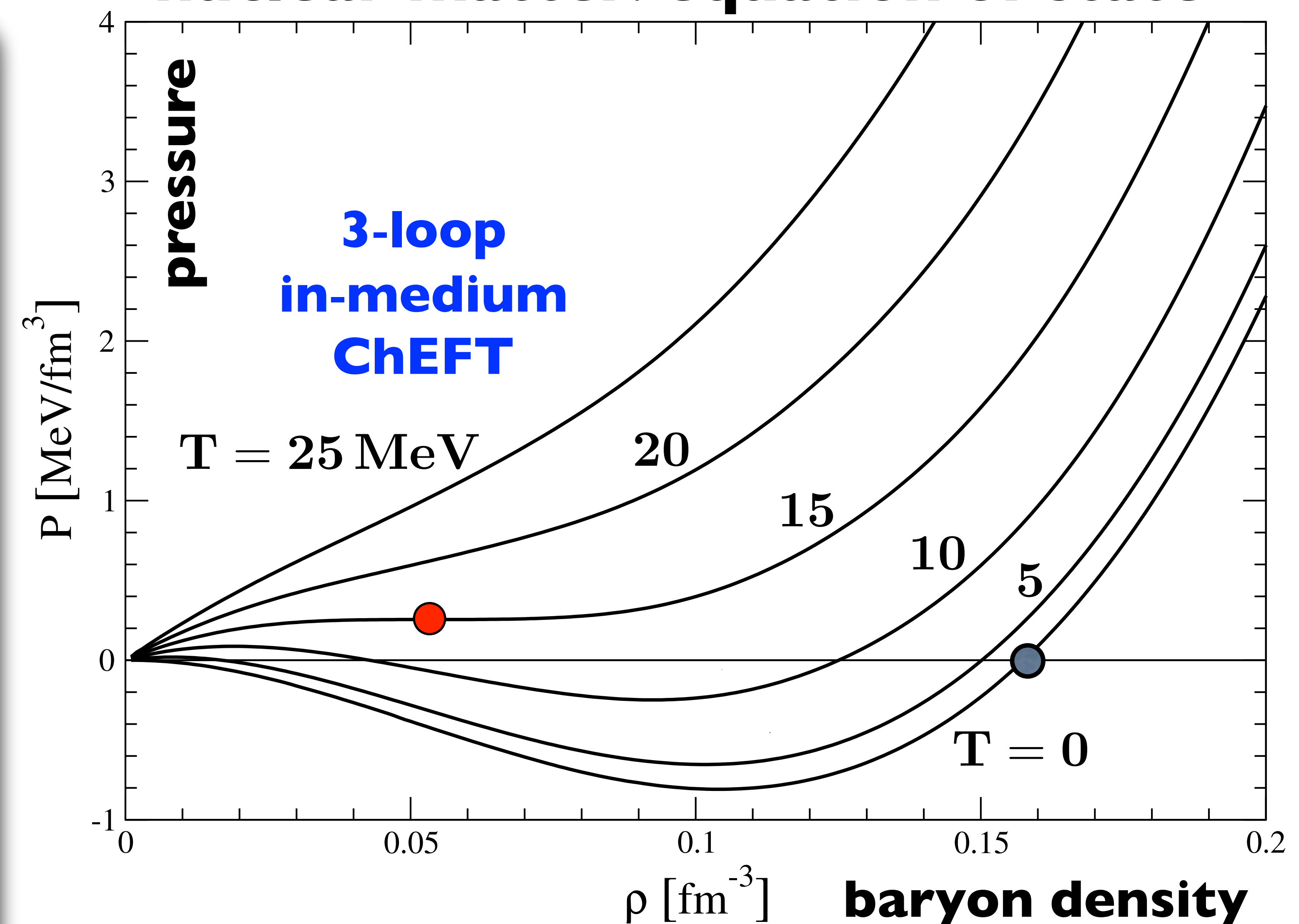




contact terms

+ **3-body forces**

nuclear matter: equation of state



Liquid - Gas 1st order phase transition
Critical Temperature T_c = 15 MeV
(empirical: T_c = 16 - 18 MeV)

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

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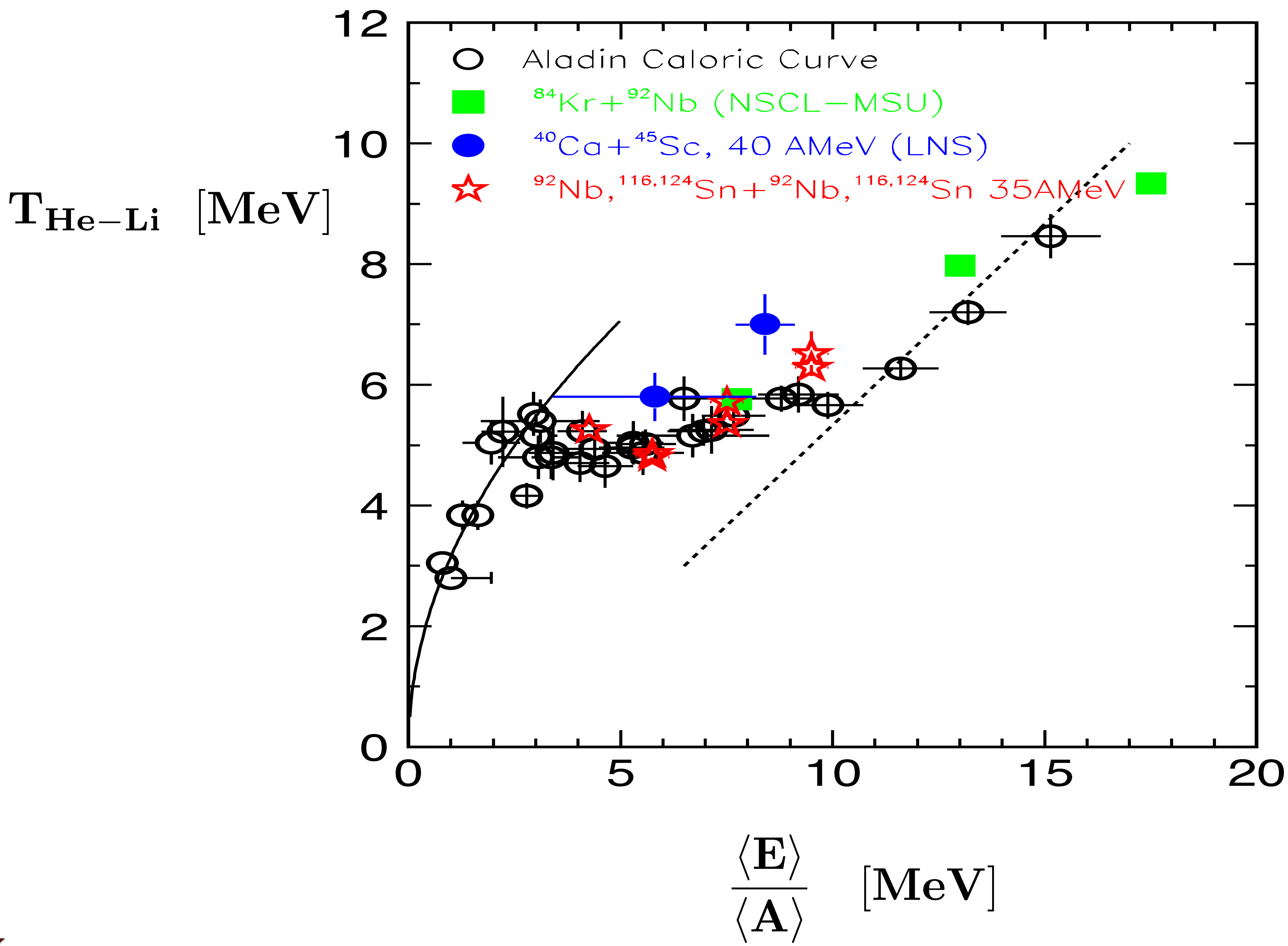
NUCLEAR LIQUID-GAS TRANSITION

from multifragmentation measurements in heavy-ion collisions



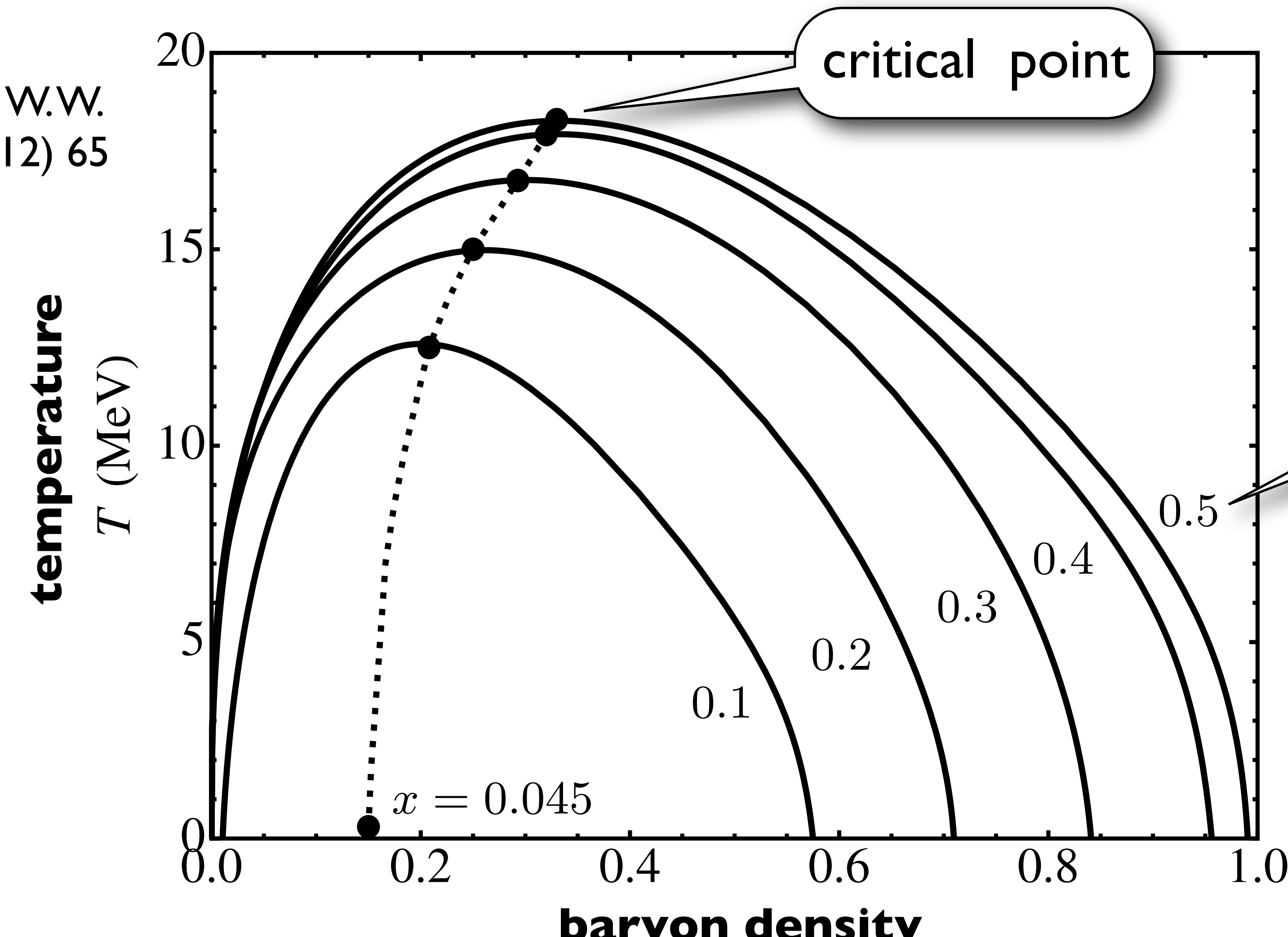
J. Pochodzalla et al.
Phys. Rev. Lett. 75 (1995) 1040

M. D'Agostino et al.
Nucl. Phys. A 749 (2005) 55

PHASE DIAGRAM of NUCLEAR MATTER

- Trajectory of **CRITICAL POINT** for **asymmetric matter** as function of proton fraction Z / A (A = Z + N)

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



$\frac{\rho}{\rho_0}$ $(\rho_0 = \mathbf{0.15\,fm^{-3}})$

M. Drews, T. Hell, B. Klein, W.W.
Phys. Rev. D 88 (2013) 096011

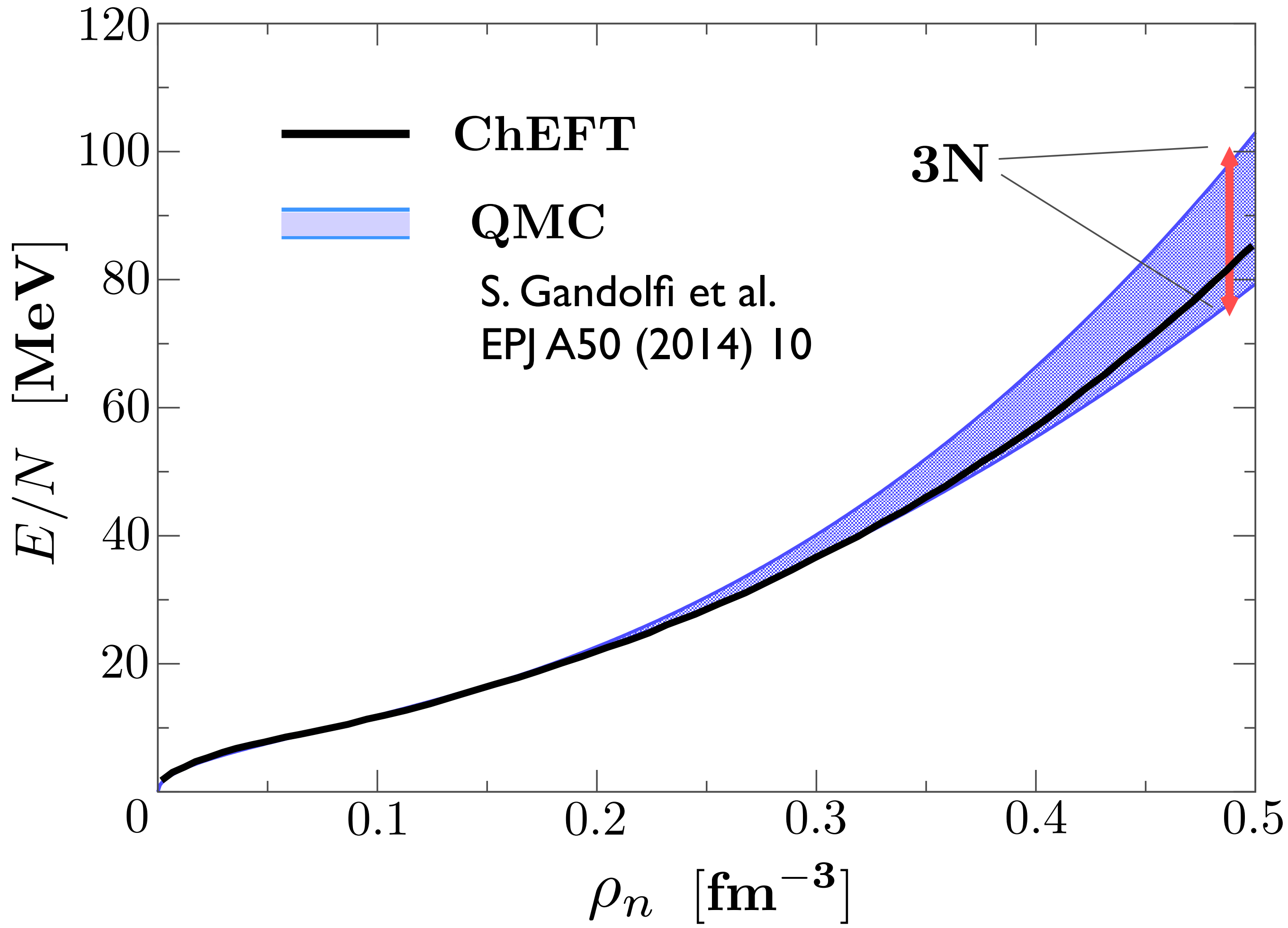
M. Drews, W.W.
Phys. Lett. B 738 (2014) 187

. . . including non-perturbative effects (**R**enormalization **G**roup)

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

COLD NEUTRON MATTER

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



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

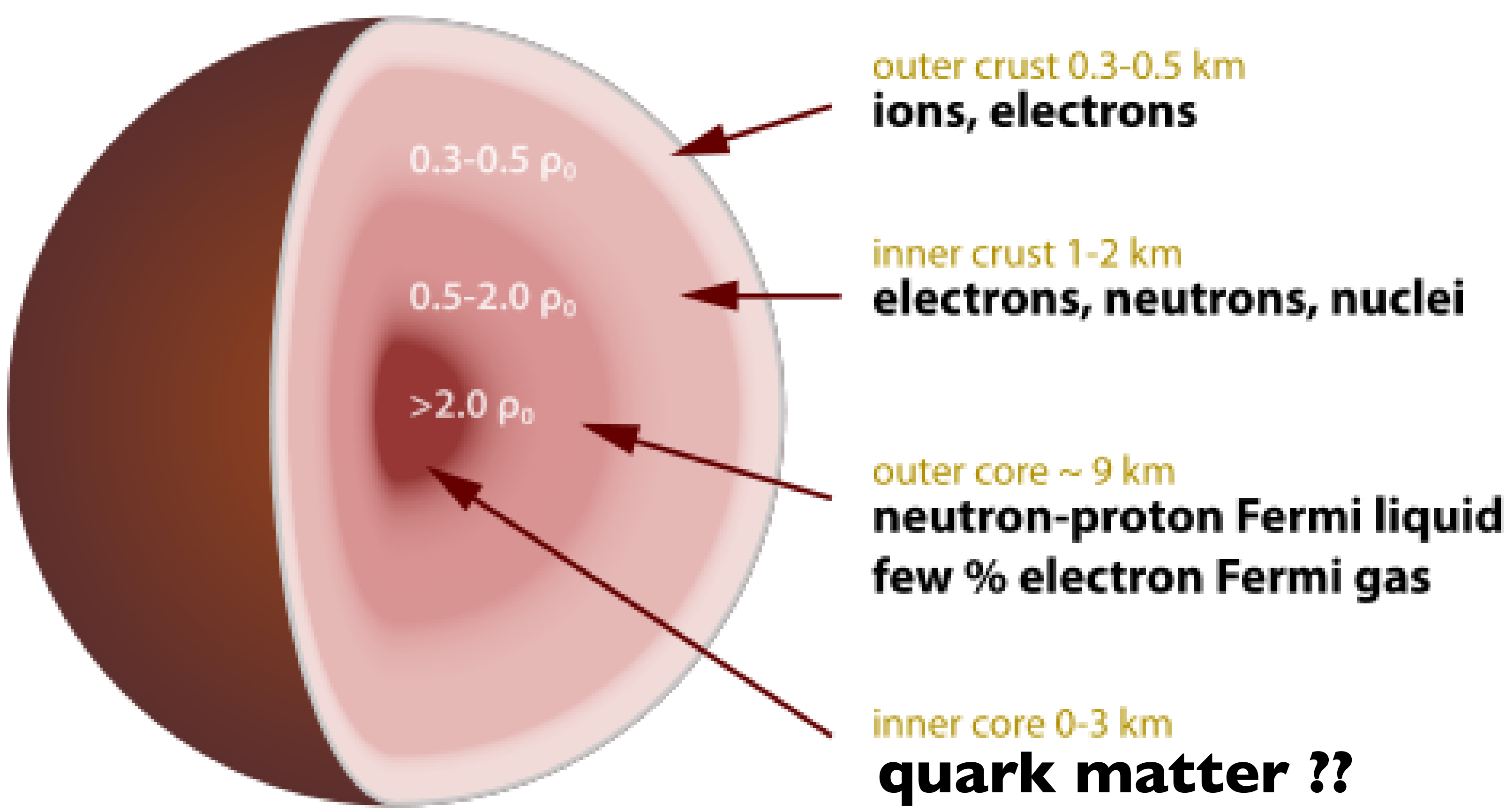
$$\xi = \frac{\bar{\mathbf{E}}}{\mathbf{E_{Fermi\,gas}}} \simeq \mathbf{0.5}$$

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

- agreement with sophisticated many-body calculations

(e.g. recent **Q**uantum **M**onte **C**arlo computations)

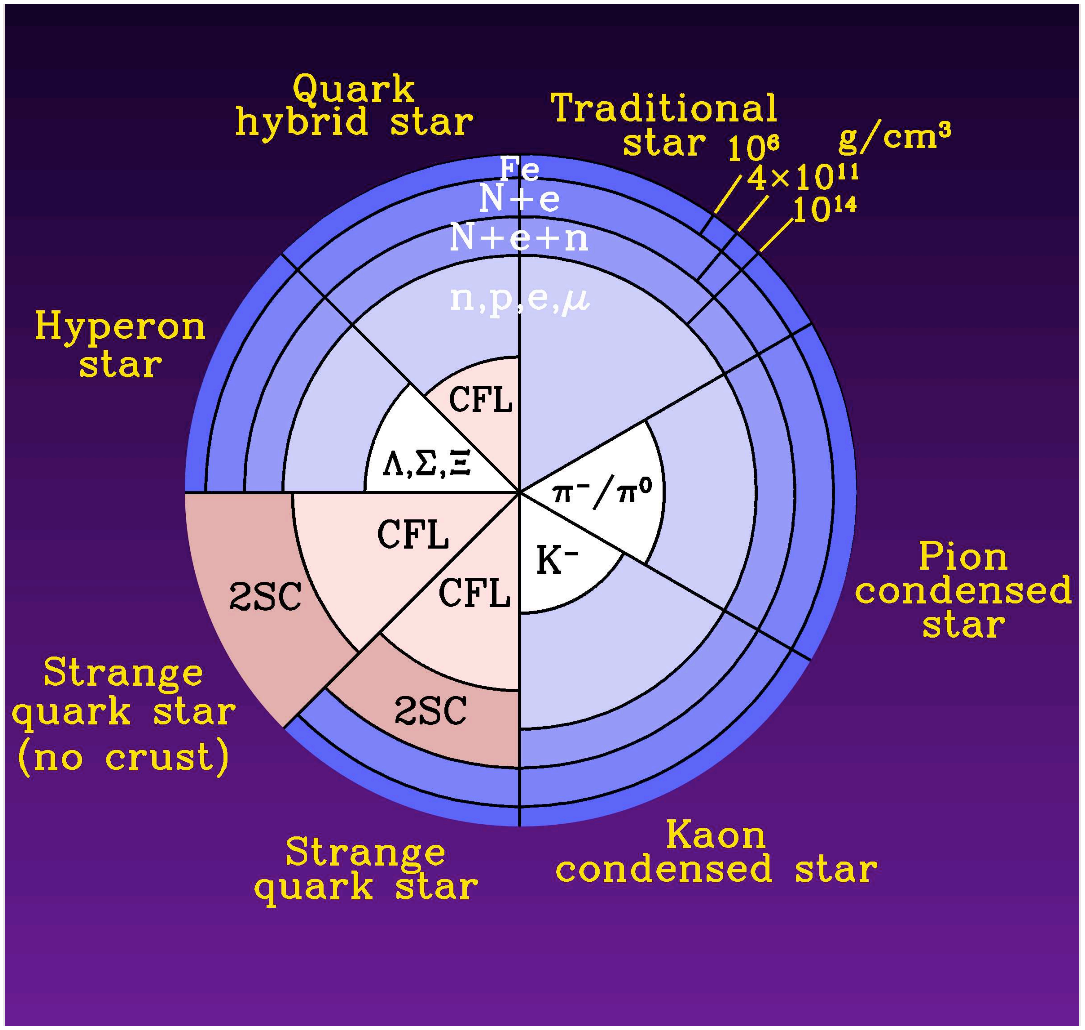
4. Outlooks:
New Constraints from NEUTRON STARS



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

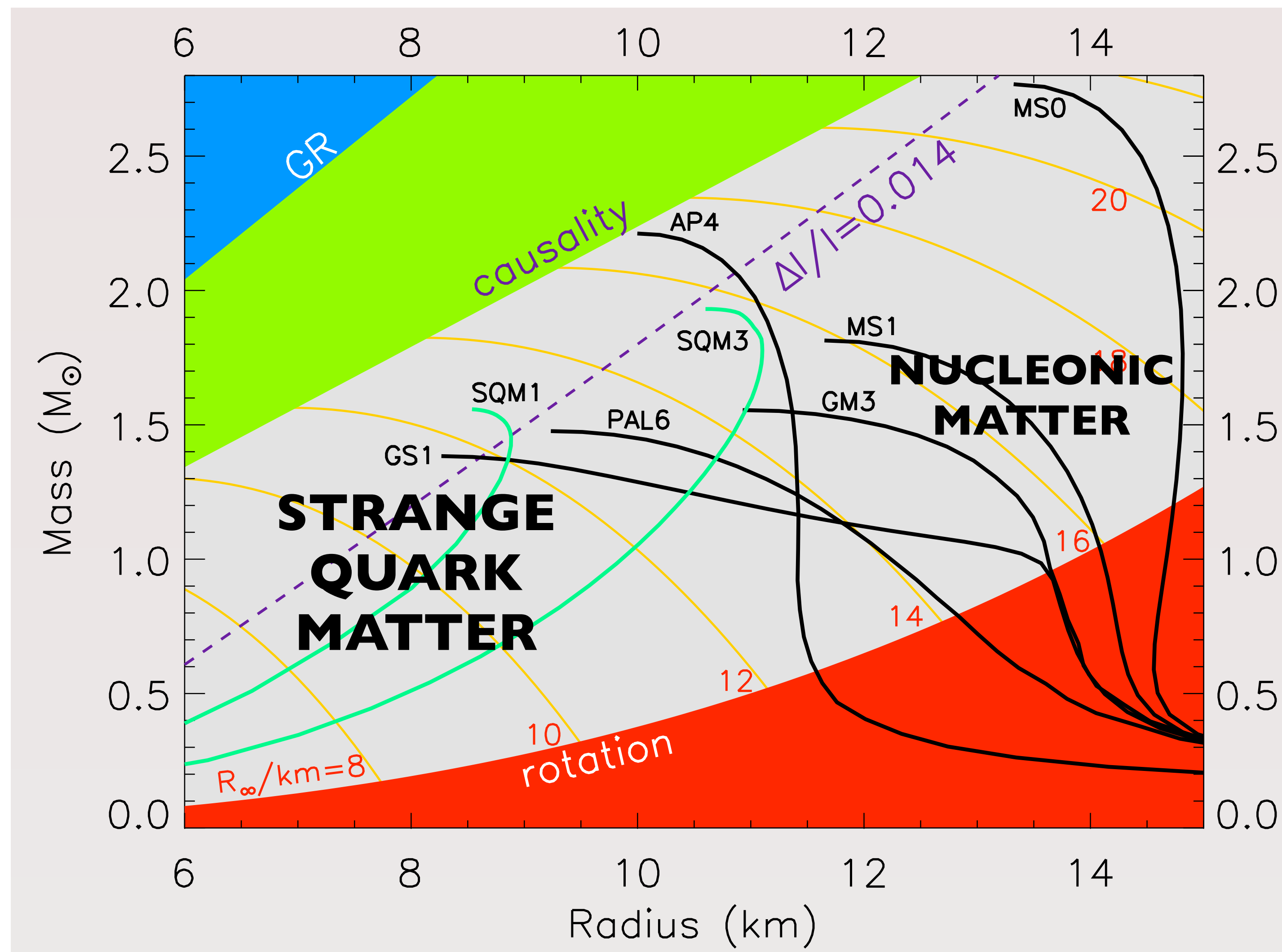


Tolman-**O**ppenheimer-**V**olkov Equations

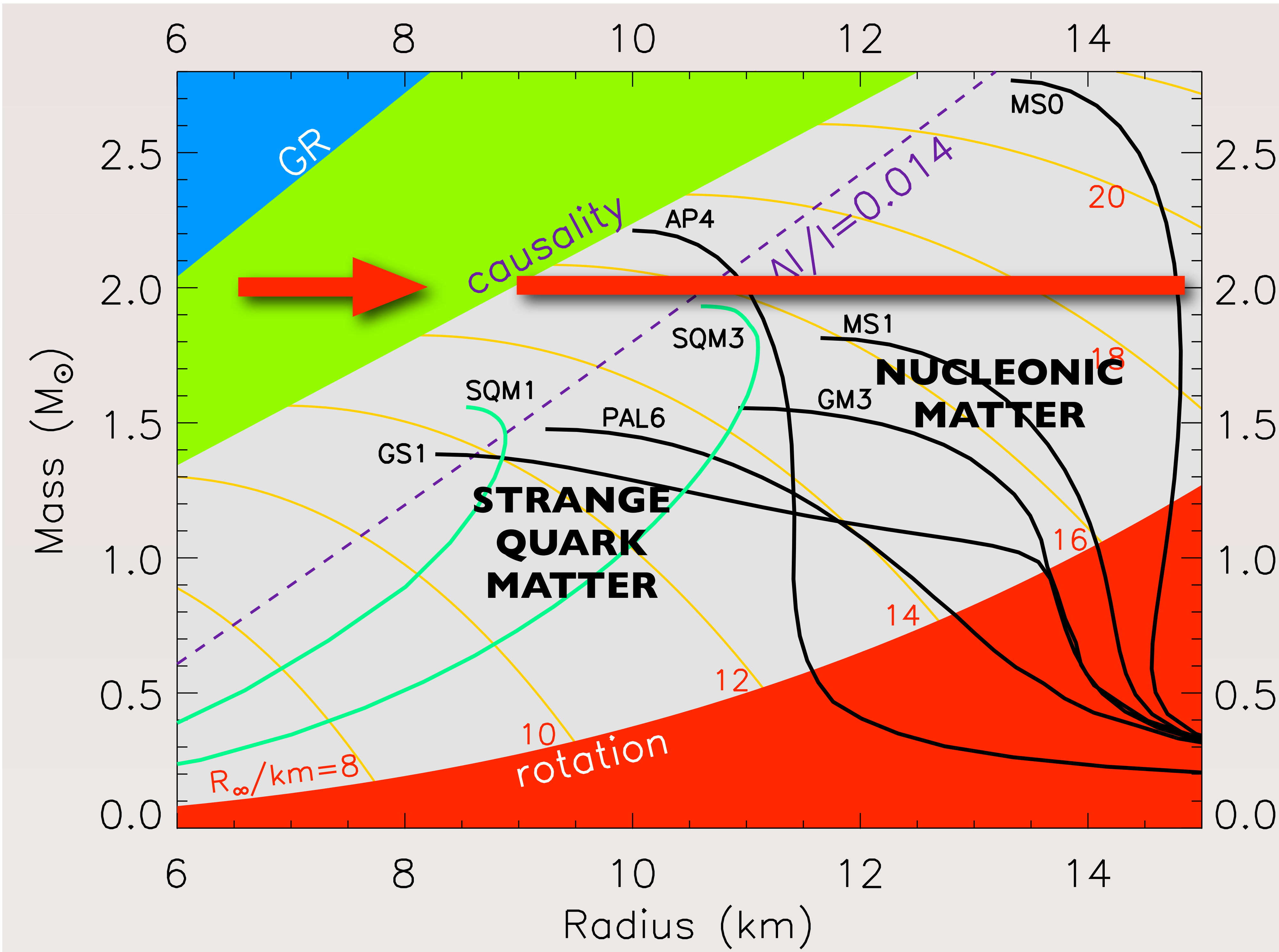
$$\frac{dP}{dr} = -\frac{G}{c^2}\frac{(M+4\pi P r^3)(\mathcal{E}+P)}{r(r-GM/c^2)}$$

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

- **Mass-Radius Relation**

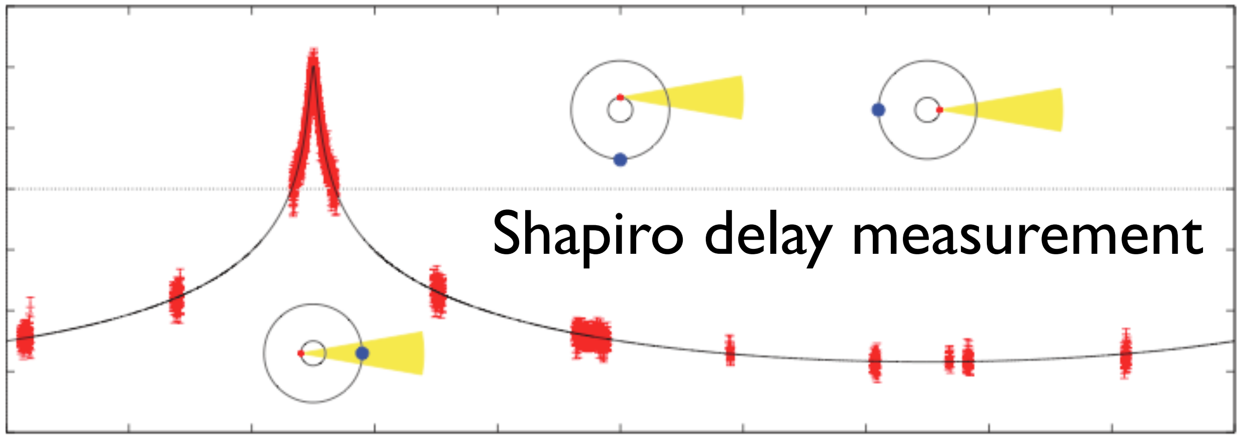


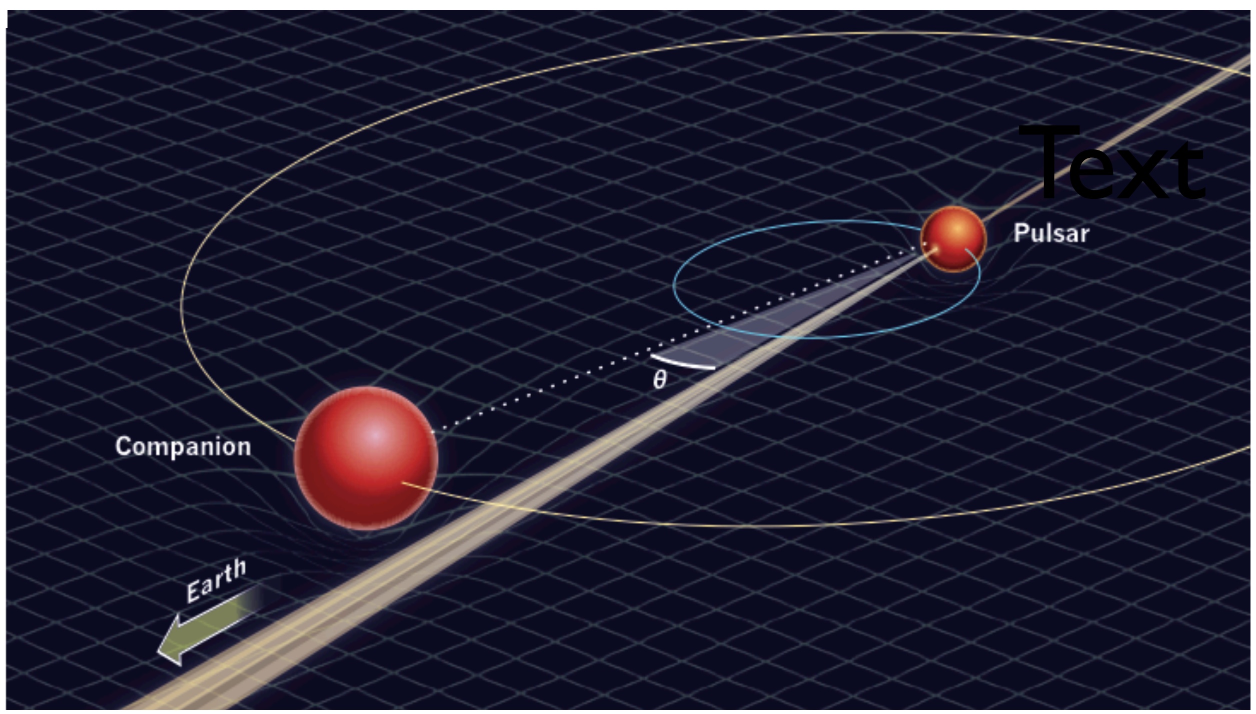
New constraints
from **2-solar-mass NEUTRON STARS**



New constraints from NEUTRON STARS

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

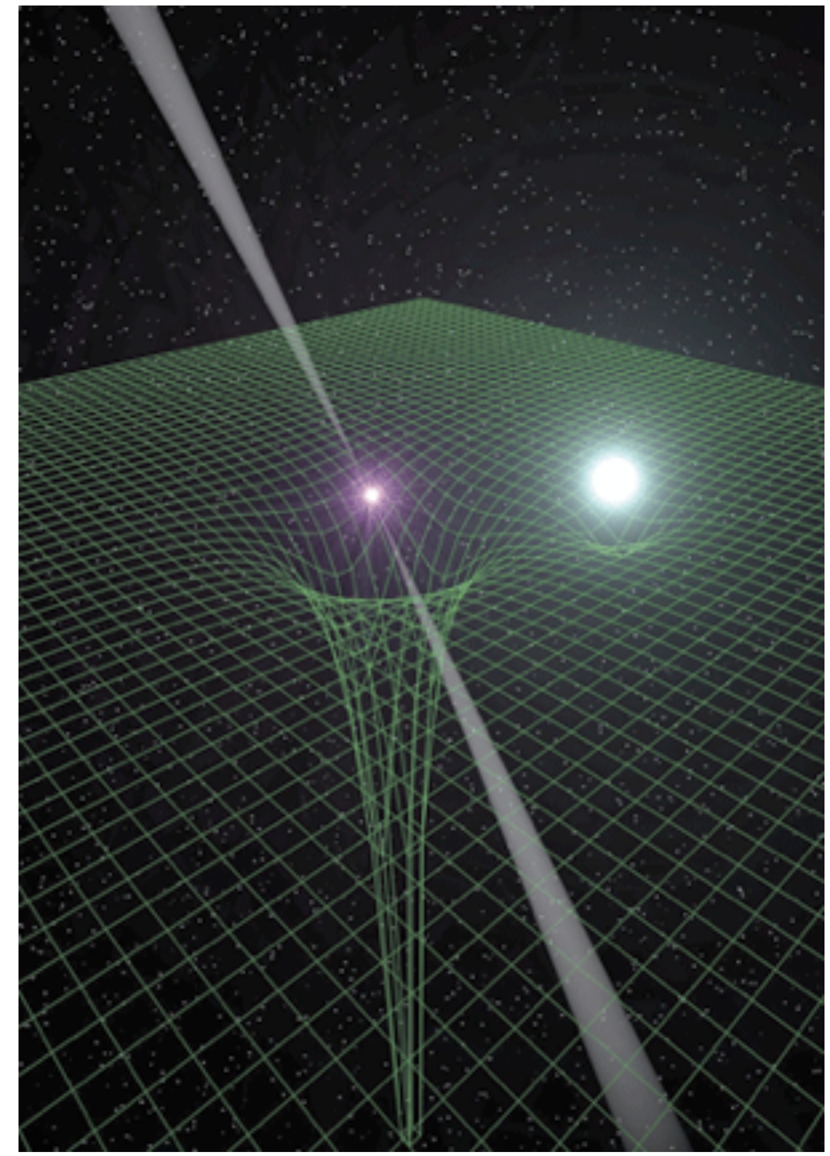




PSR J1614+2230

$$\mathrm{M} = 1.97 \pm 0.04\ \mathrm{M}_\odot$$

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



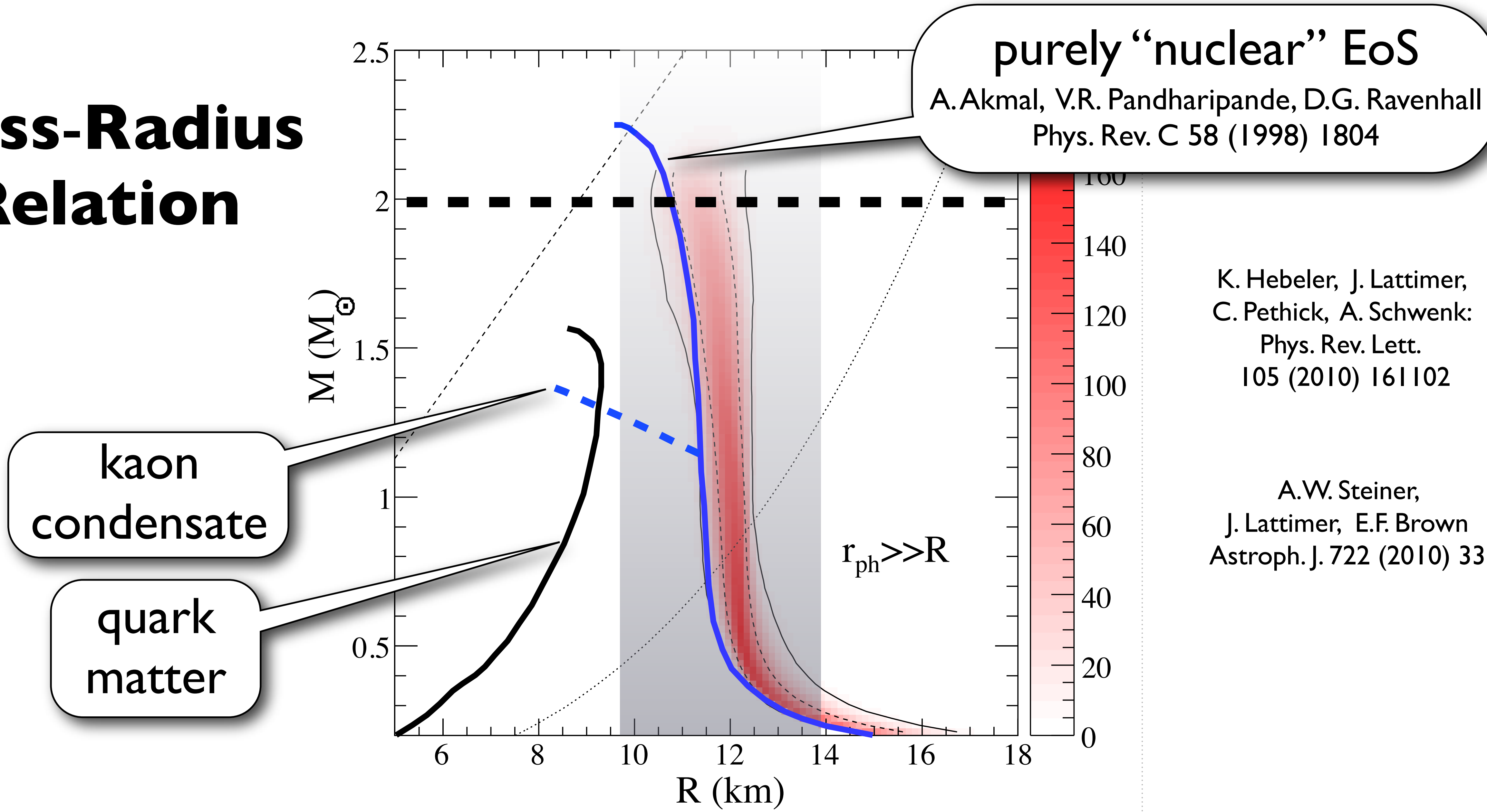
PSR J0348+0432

$$\mathrm{M} = 2.01 \pm 0.04\ \mathrm{M}_\odot$$

News from **NEUTRON STARS**

- Constraints from **neutron star observables**

Mass-Radius Relation

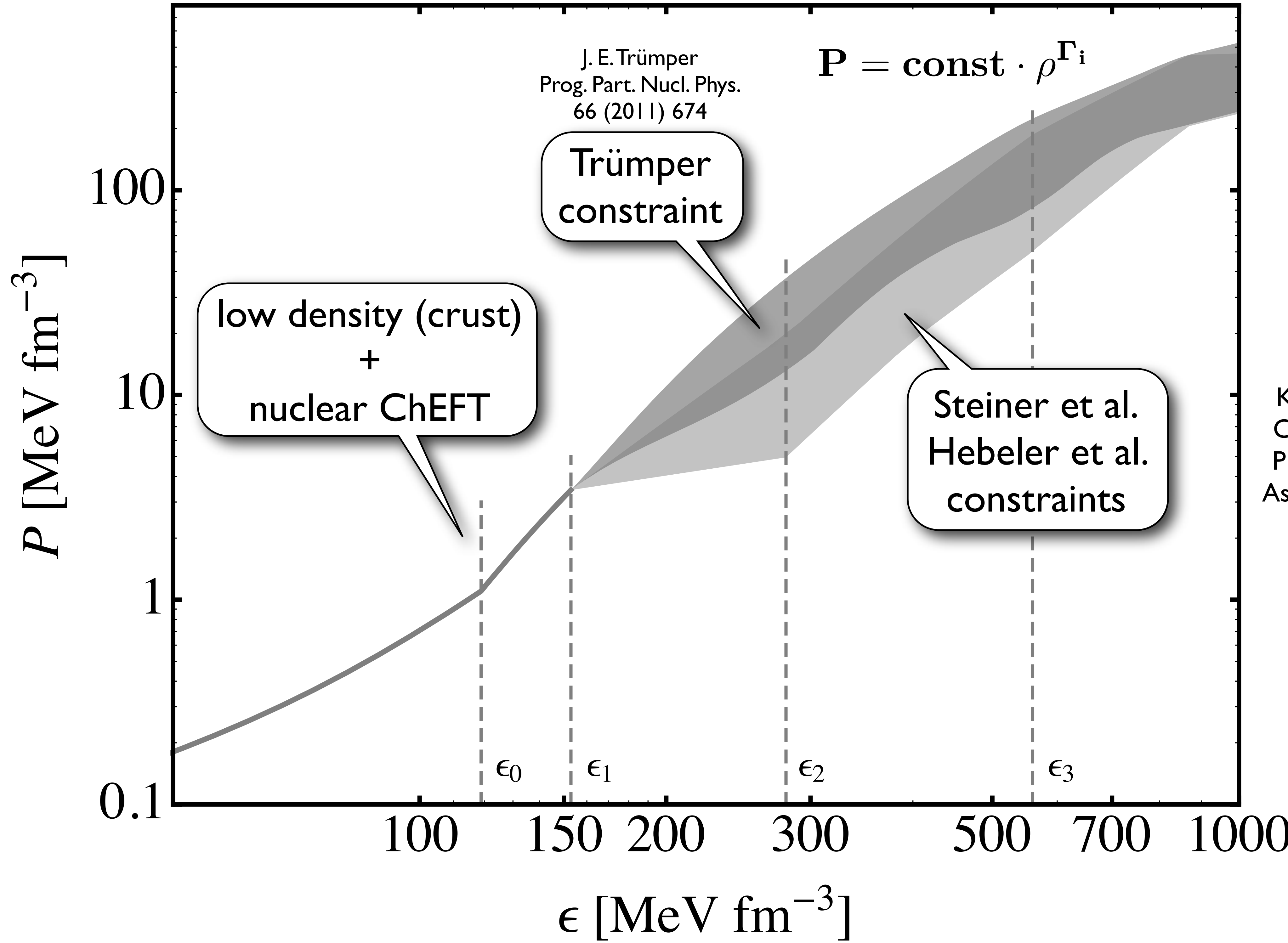


K. Hebeler, J. Lattimer, C. Pethick, A. Schwenk: Phys. Rev. Lett. 105 (2010) 161102

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

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

NEUTRON STAR MATTER

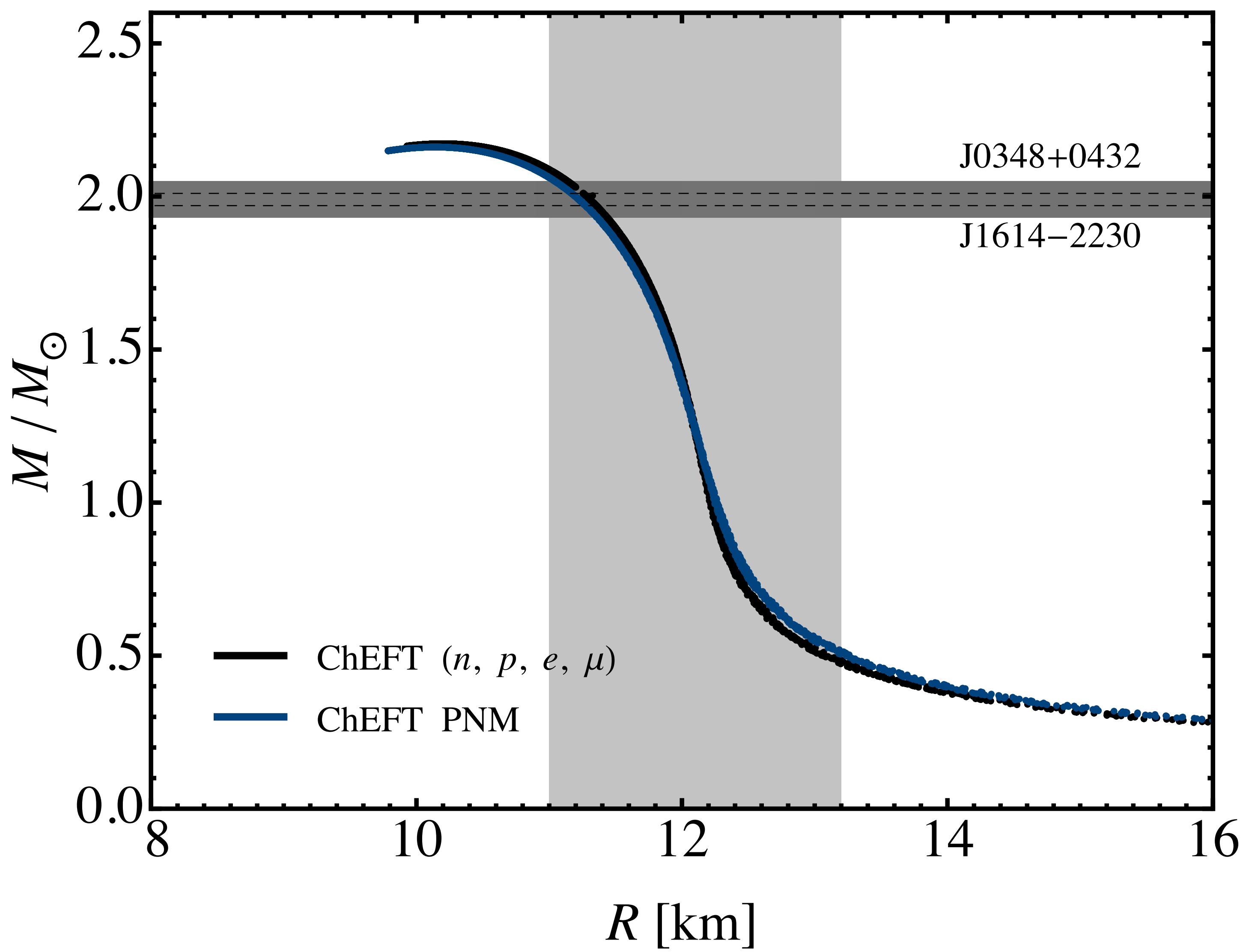


Th. Hell, W.W.
arXiv:1402.4098
Phys. Rev. C (2014)

K. Hebeler, J. Lattimer,
C. Pethick, A. Schwenk
PRL 105 (2010) 161102
Astroph. J. 773 (2013) 11

NEUTRON STAR MATTER
Mass - Radius Relation

- In-medium **C**hiral **E**ffective **F**ield **T**heory
  Active degrees of freedom: nucleons, pions
  Chiral two- and three-body interactions

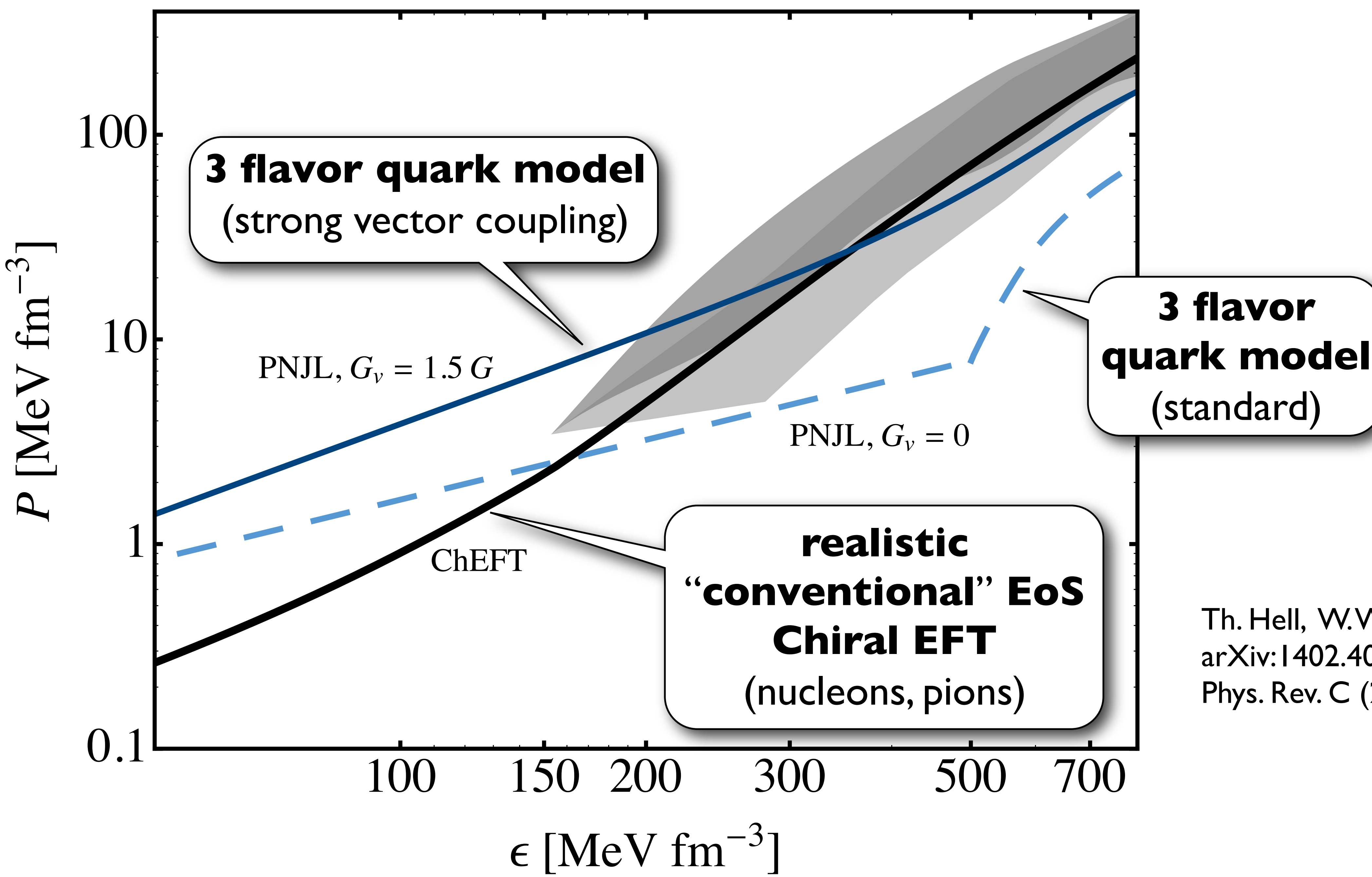


Th. Hell, W.W.
arXiv:1402.4098
Phys. Rev. C (2014)

NEUTRON STAR Equation of State

conventional nuclear vs. **quark** degrees of freedom

Chiral **E**ffective **F**ield **T**heory vs. **P**olyakov - **N**ambu - **J**ona-**L**asinio model



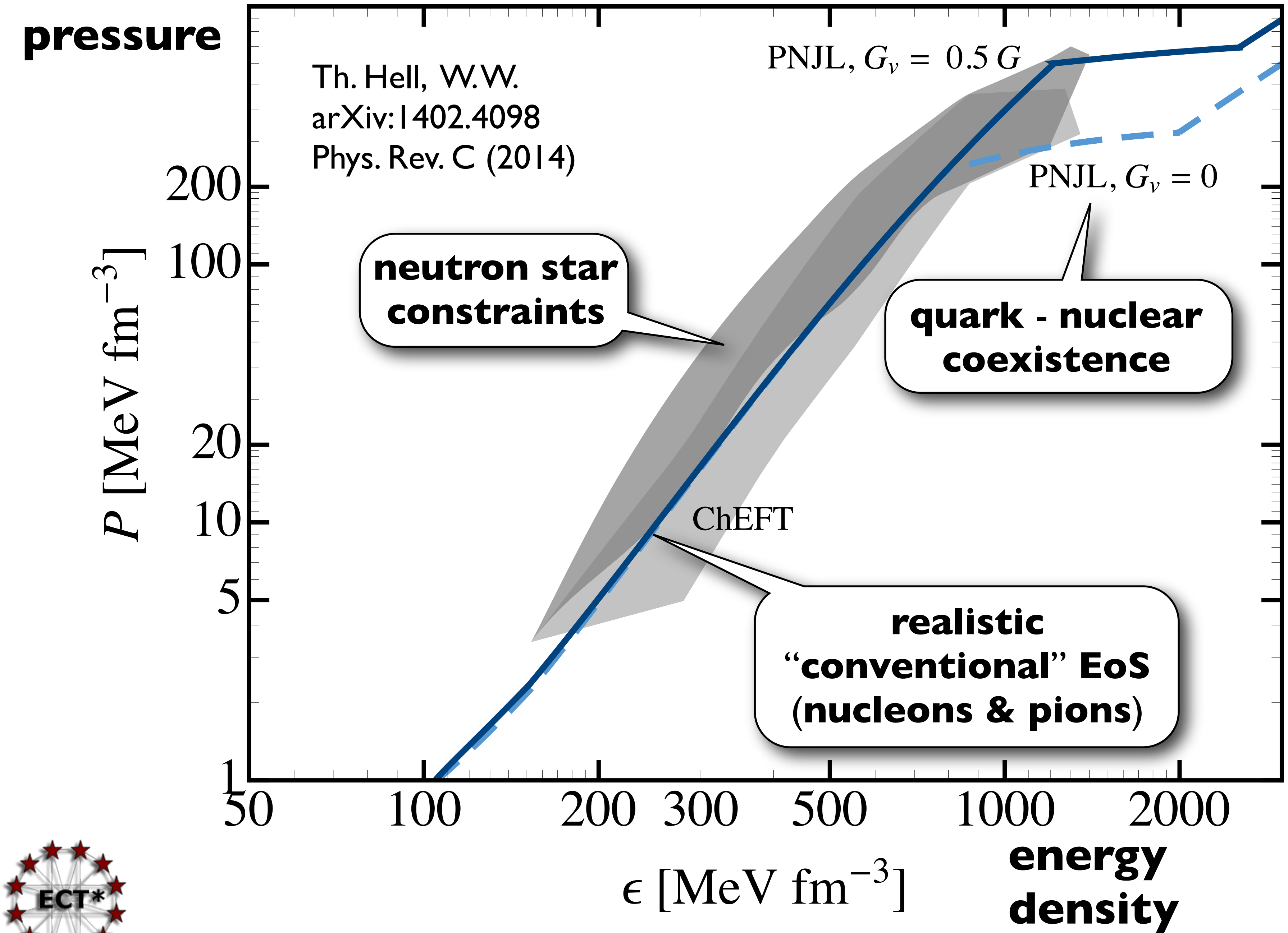
Th. Hell, W.W.
arXiv:1402.4098
Phys. Rev. C (2014)

ECT*

Technische Universität München

NEUTRON STAR MATTER
Equation of State

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

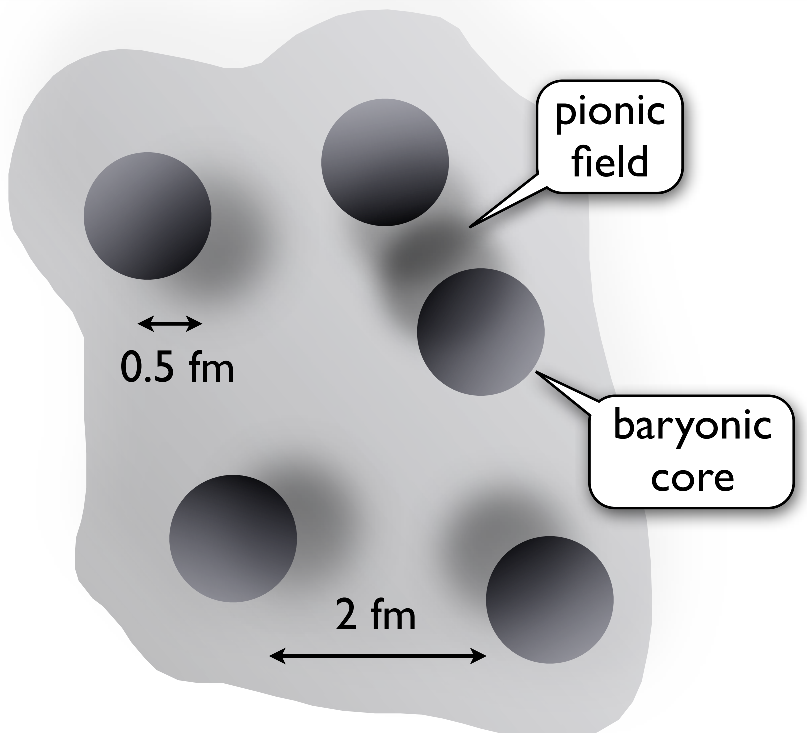


- beta equilibrium
  $\mathbf{n} \leftrightarrow \mathbf{p} + e, \mu$
- charge conservation
- coexistence region:
  Gibbs conditions

- **quark-nuclear** coexistence occurs (if at all) at baryon densities
  $\rho > \mathbf{5}\ \rho_0$

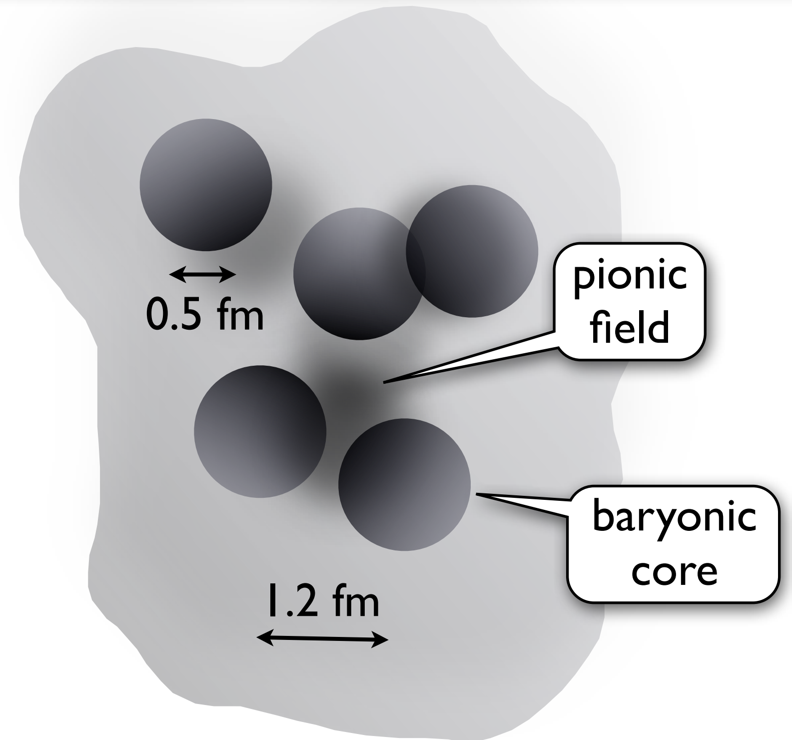
see also:
K. Masuda, T. Hatsuda, T. Takatsuka
PTEP (2013) 7, 073D01

Densities and Scales in Compressed Baryonic Matter



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

normal nuclear matter: dilute

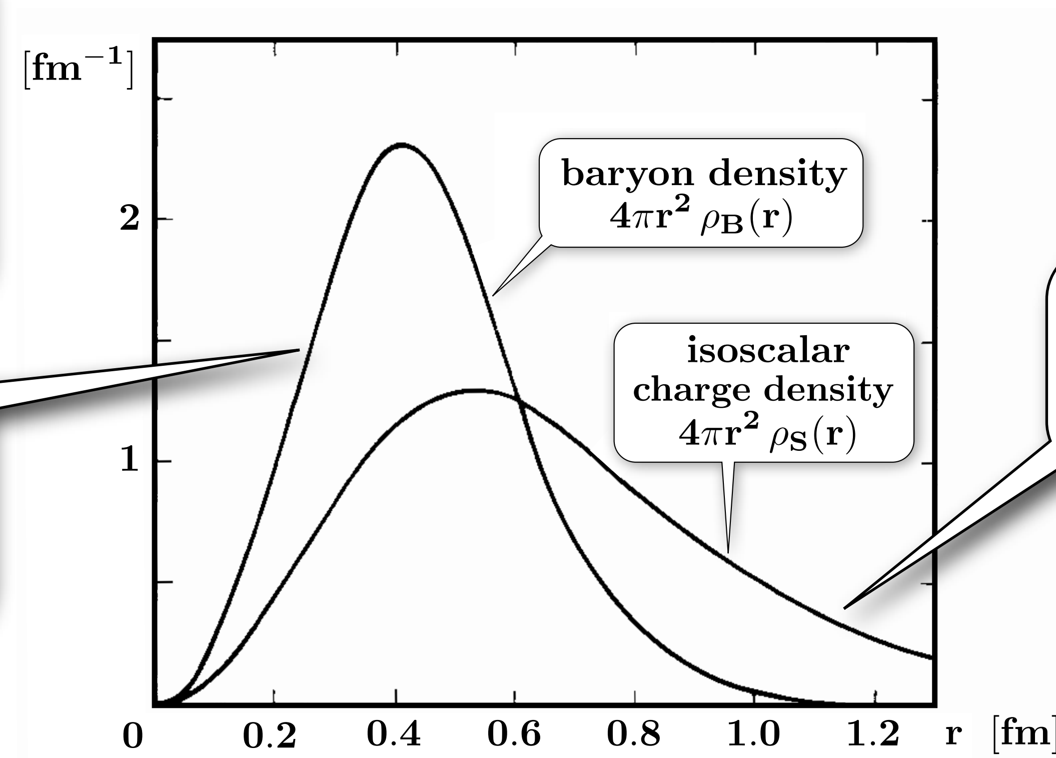


$\rho_B = 0.6\ \mathrm{fm}^{-3}$

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

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

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



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

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

. . . treated properly
in chiral EFT

CONCLUSIONS

- Systematic approach at the interface of **QCD** and the physics of **hadrons**, **nuclei** and **nuclear forces** :

  Chiral Effective Field Theory

- New constraints from **neutron stars** for the **equation-of-state** of **dense** & **cold baryonic matter** :

  - Mass - radius relation: **stiff equation of state** required ! **No** ultrahigh densities ($\varrho_{\mathrm{core}} \lesssim 5\,\varrho_0$)

  - "**Conventional**" (non-exotic) **EoS works** remarkably well (nuclear effective field theory + advanced many-body methods)

- "The constraints strongly suggest that the compact objects . . . are really **neutron stars** and not . . . quark stars." (J.Trümper)

The End

thanks to

Nino Bratovic	Matthias Drews	Salvatore Fiorilla
Thomas Hell	Jeremy Holt	Norbert Kaiser
Robert Lang	Sebastian Schultess	Corbinian Wellenhofer