

Phases of Strongly Interacting Matter

- From **Quarks** to **Nuclei** and **Neutron Stars** -



Wolfram Weise

ECT* Trento & Technische Universität München



Emergence of structures in QCD

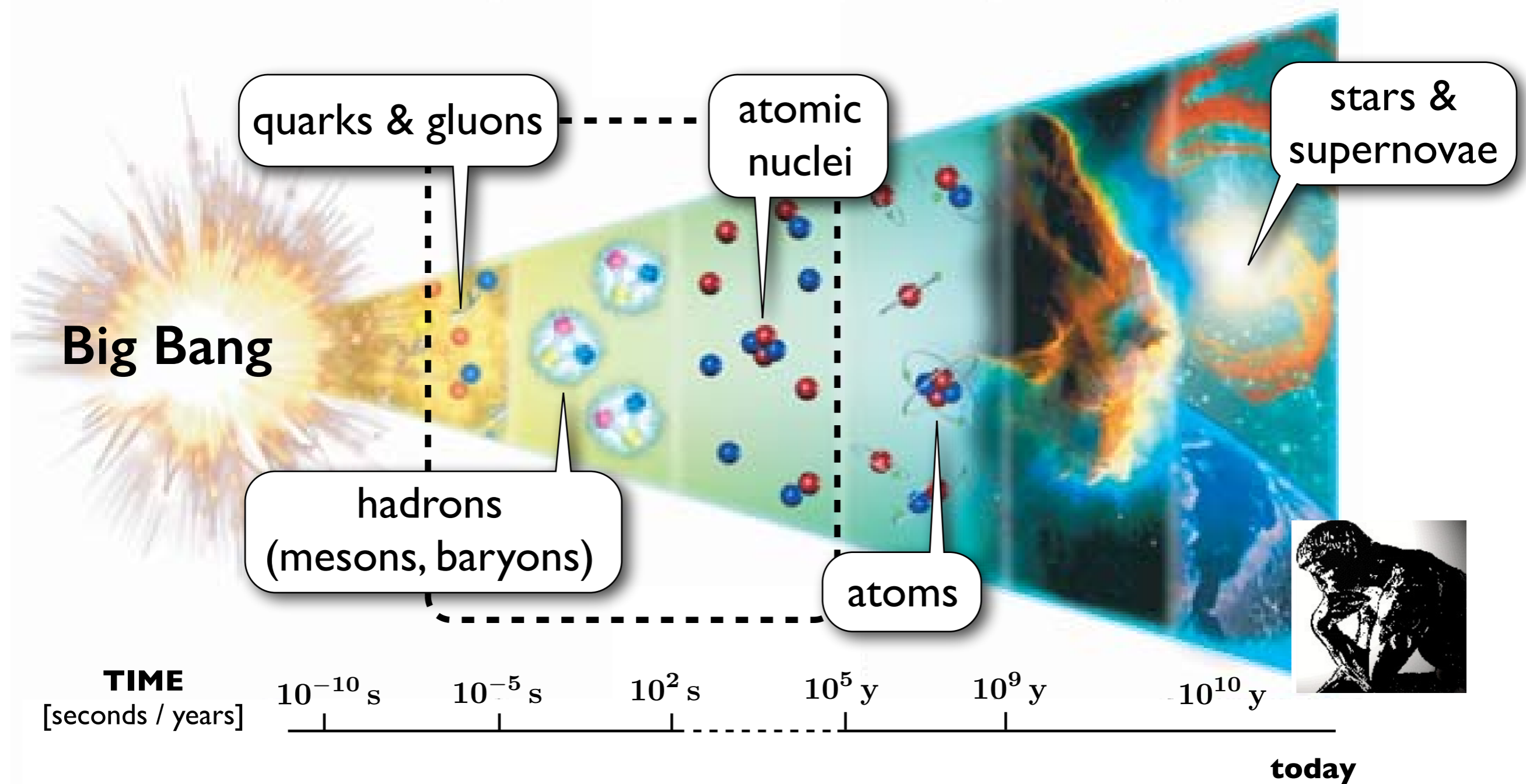
- From quarks to nuclei and dense baryonic matter
- Chiral symmetry and interface with nuclear physics



QCD phase diagram

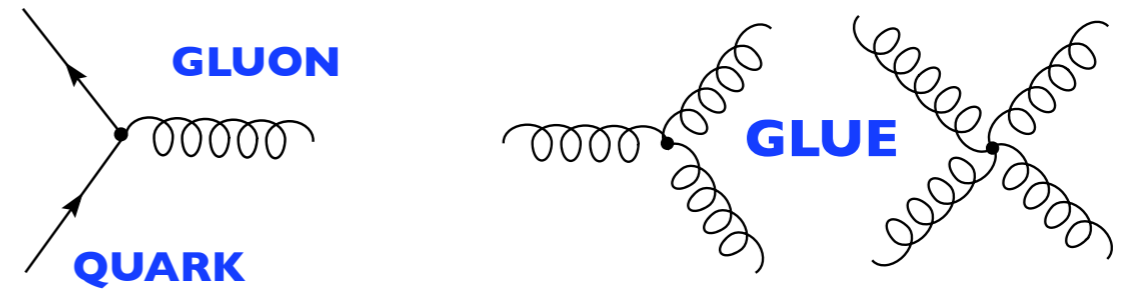
- High temperature: confinement / deconfinement transition
- Moderate temperatures and densities:
Nuclear thermodynamics
- High density: new constraints from neutron stars

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



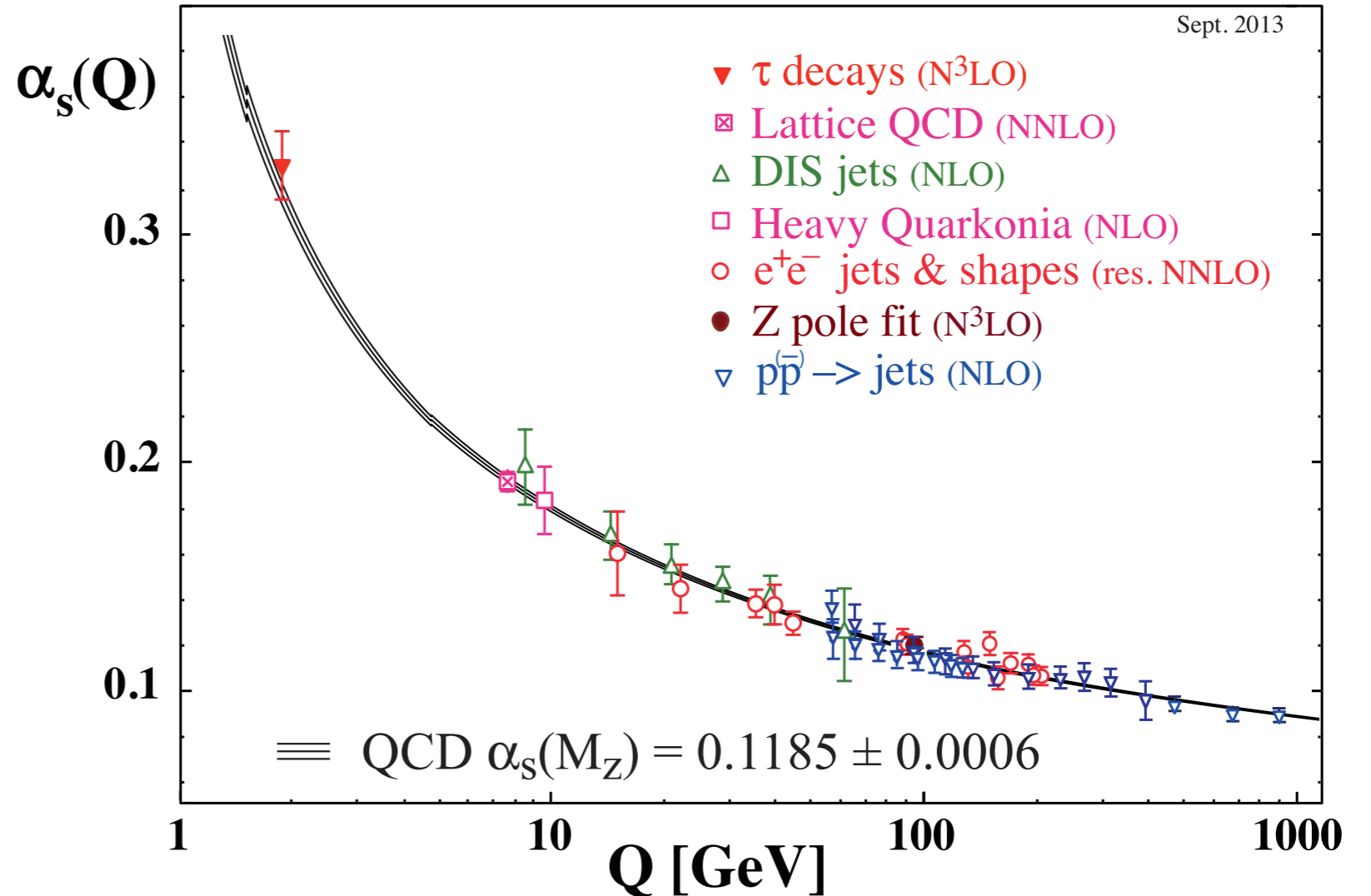
Framework:
**QUANTUM
 CHROMO
 DYNAMICS**

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



Particle Data Group:
 Chin. Phys. C38 (2014) 090001

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	175	2/3
b bottom	4.2	-1/3



1. Introductory preview :

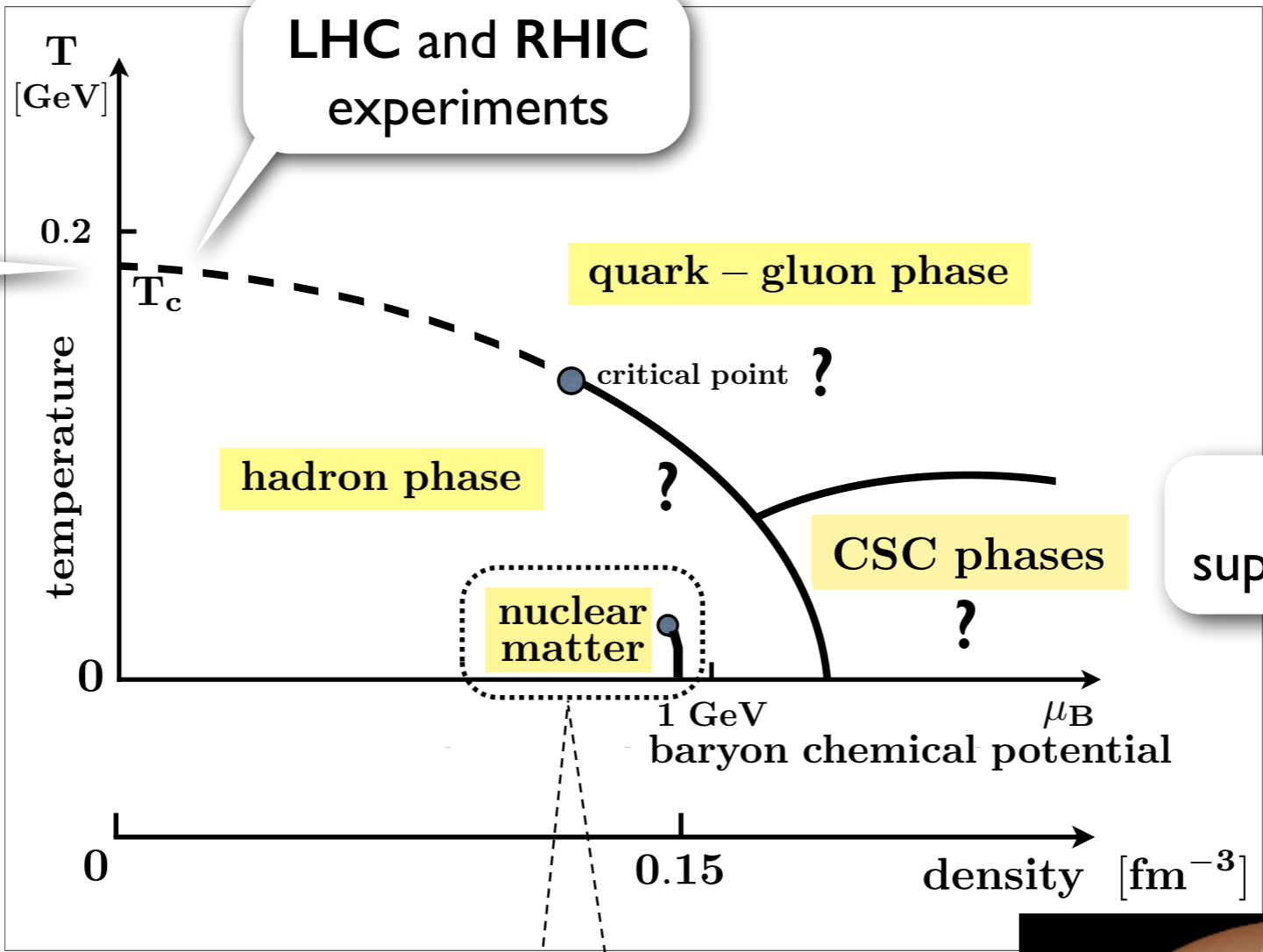
**What do we know
about the
PHASES of QCD ?**



PHASES and STRUCTURES of QCD

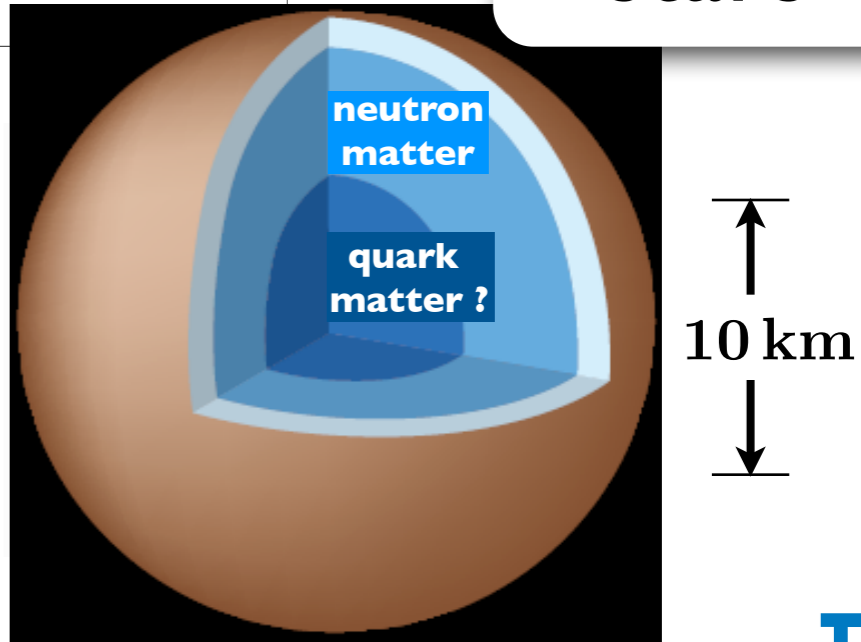
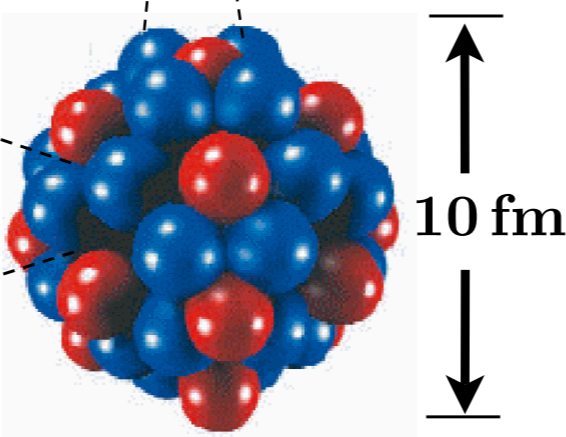
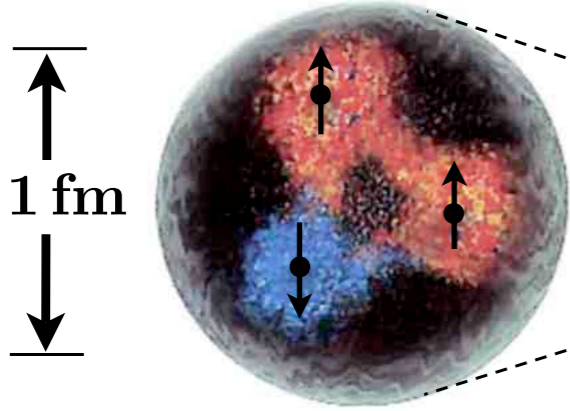
LATTICE QCD

nucleons & nuclei



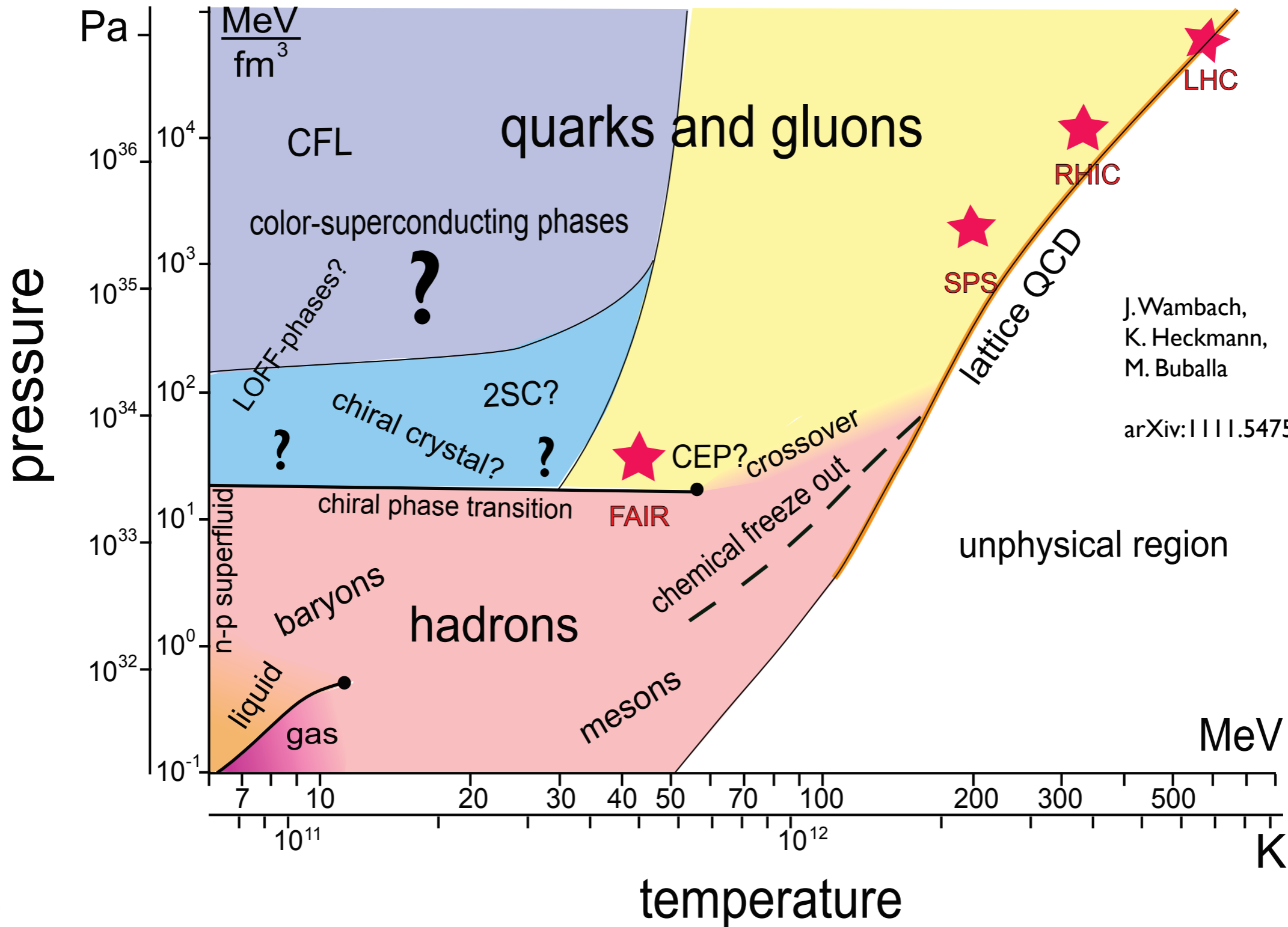
color superconducting

neutron stars



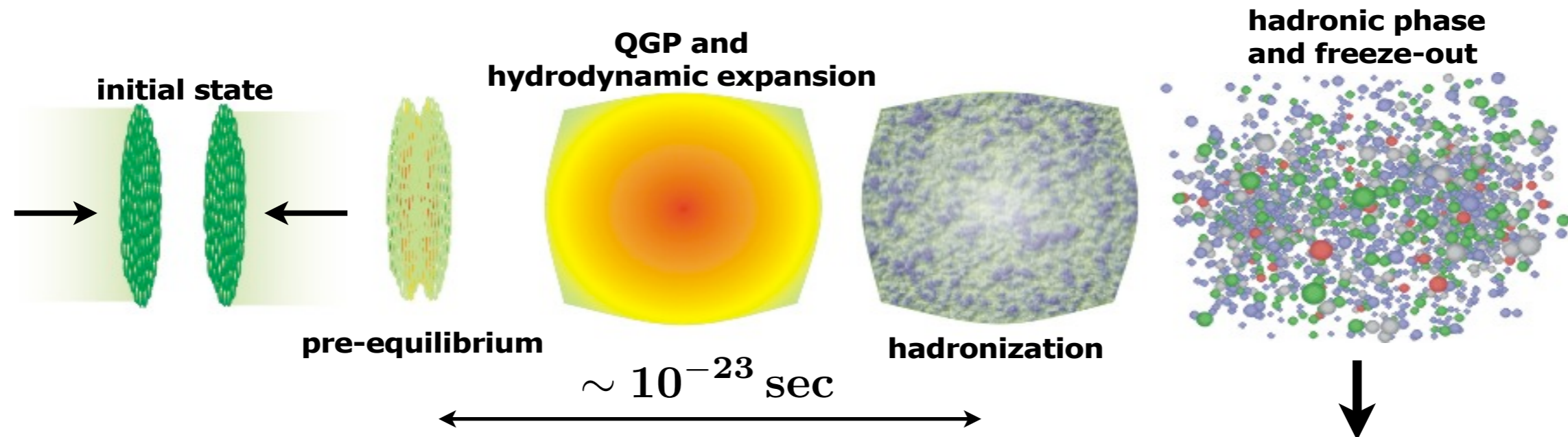
PHASES and STRUCTURES of QCD

- facts and visions -



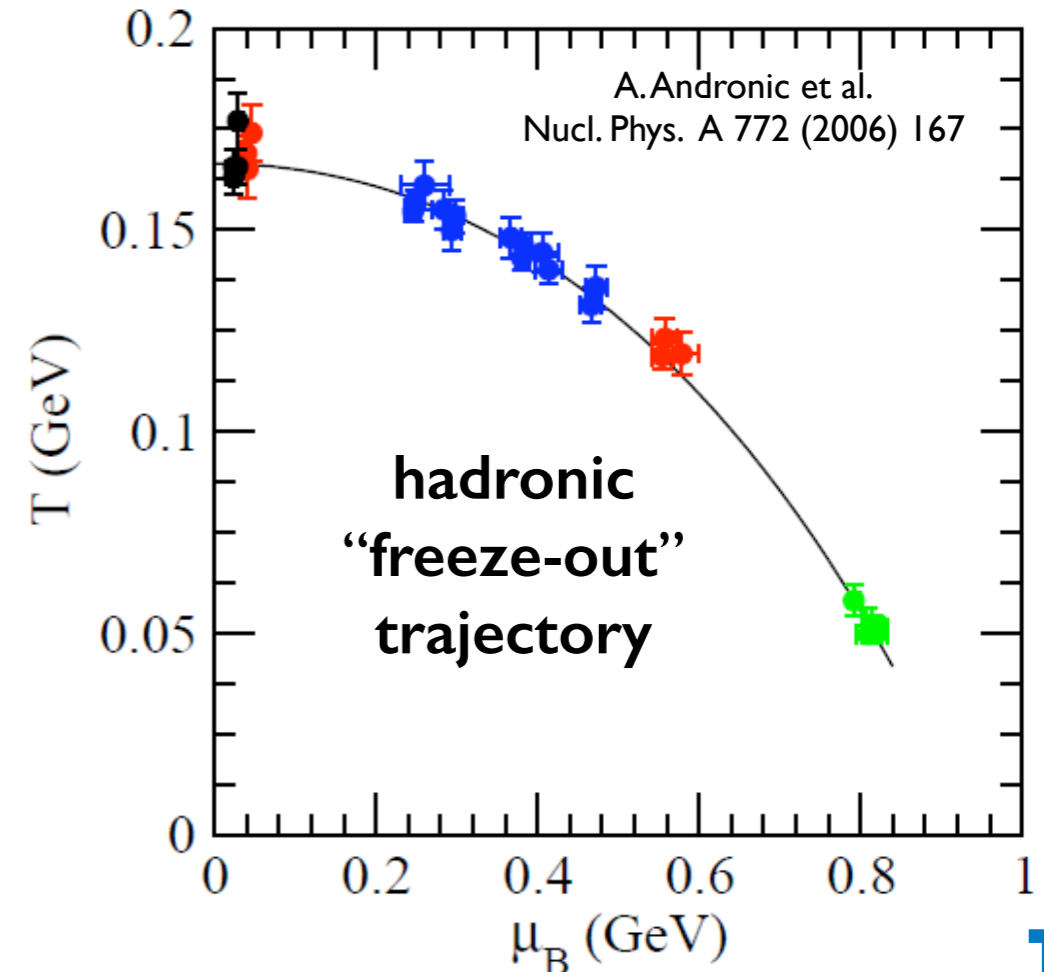
Strategies PART I: **Heavy-Ion Physics**

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



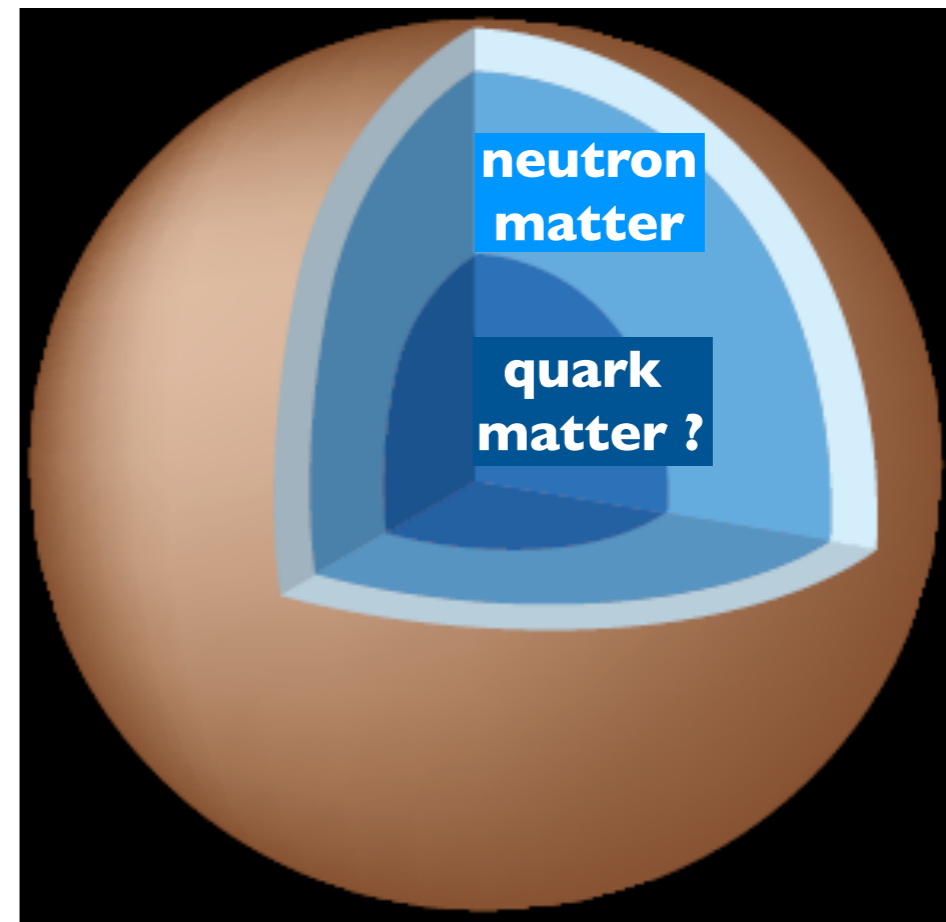
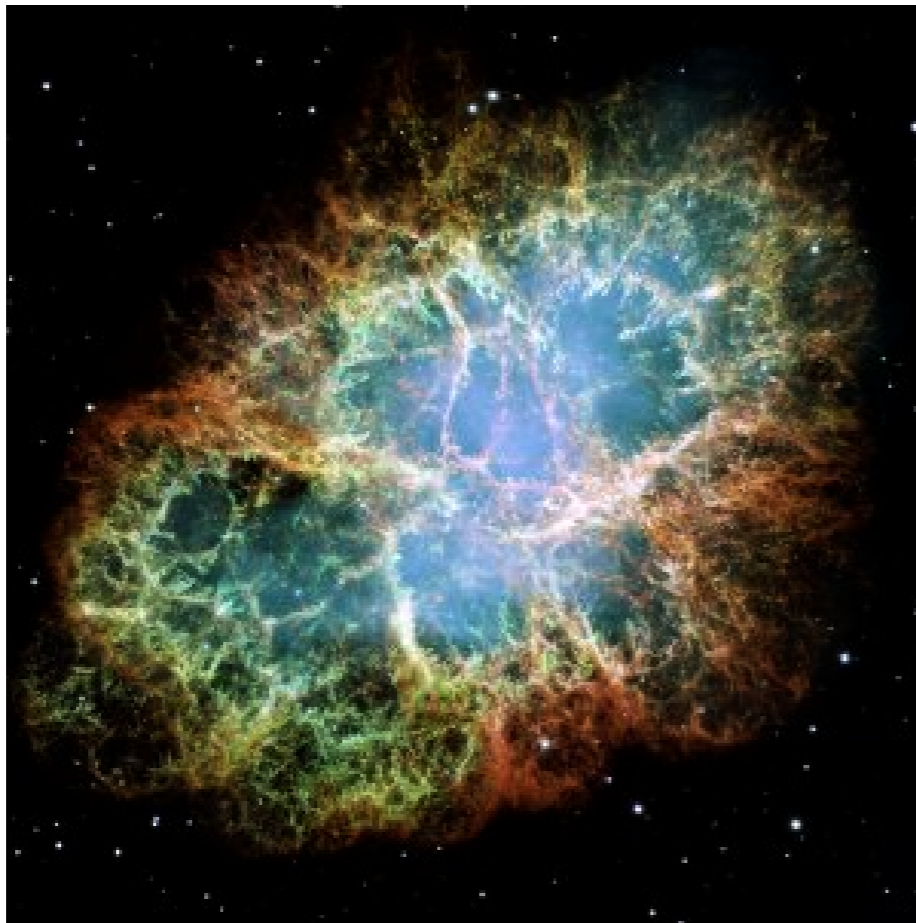
● **Analysis of RHIC and LHC data:**

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



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**

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

- Large-scale computer simulations on

EUCLIDEAN SPACE-TIME Lattices

- Euclidean time $\hat{=}$ inverse temperature

$$\tau = 1/T$$

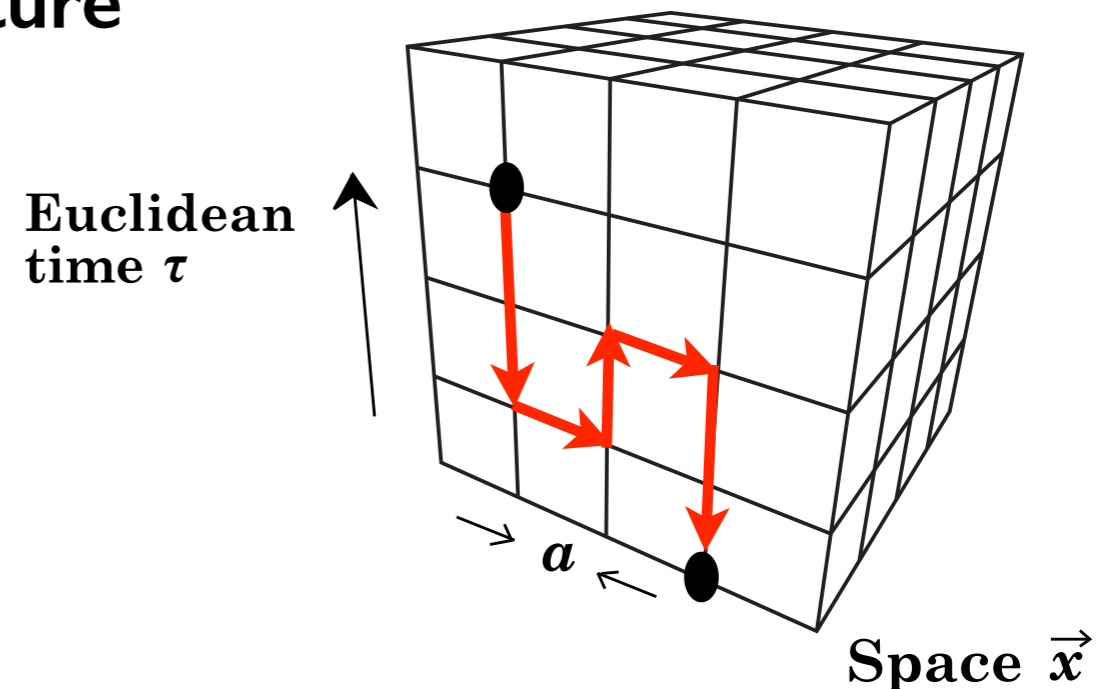
quarks on lattice sites

gluon fields on links

- **QCD THERMODYNAMICS**

Partition function

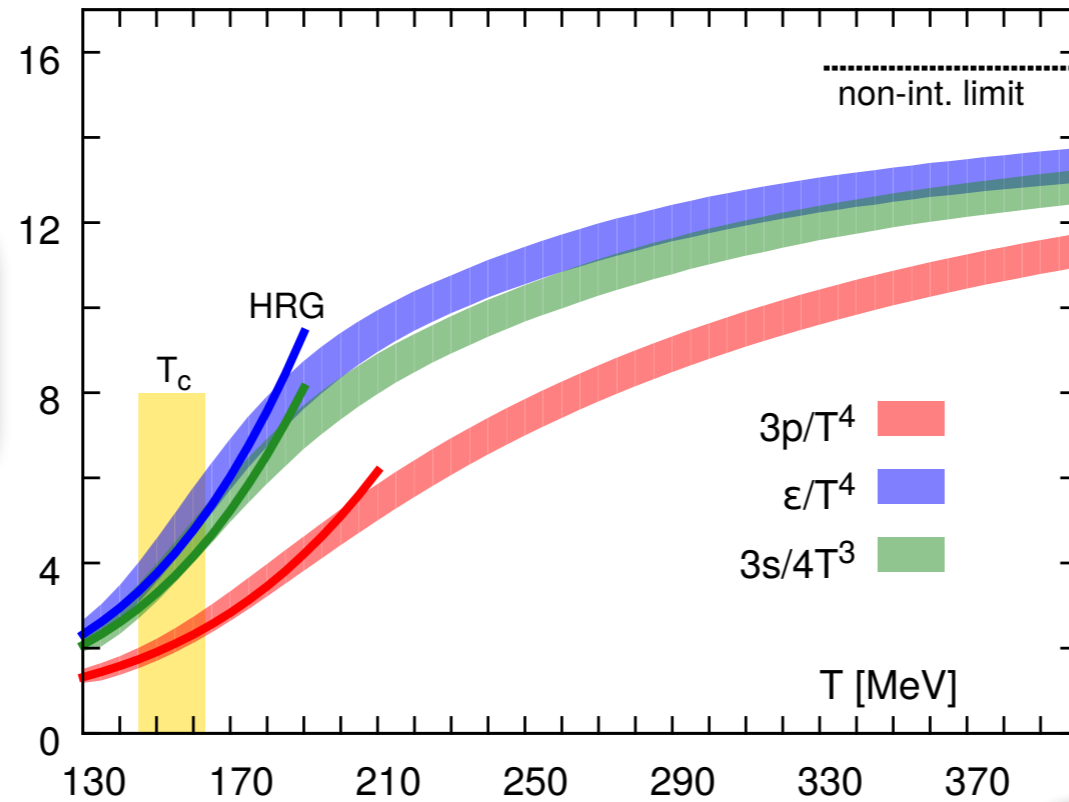
$$\mathcal{Z} = \int [d\mathcal{U} d\psi d\bar{\psi}] e^{-S_{\text{G}}(\mathcal{U}) - S_{\text{q}}(\psi, \bar{\psi}, \mathcal{U})}$$



- ▶ Non-perturbative “condensed matter physics” of QCD

QCD THERMODYNAMICS on the LATTICE

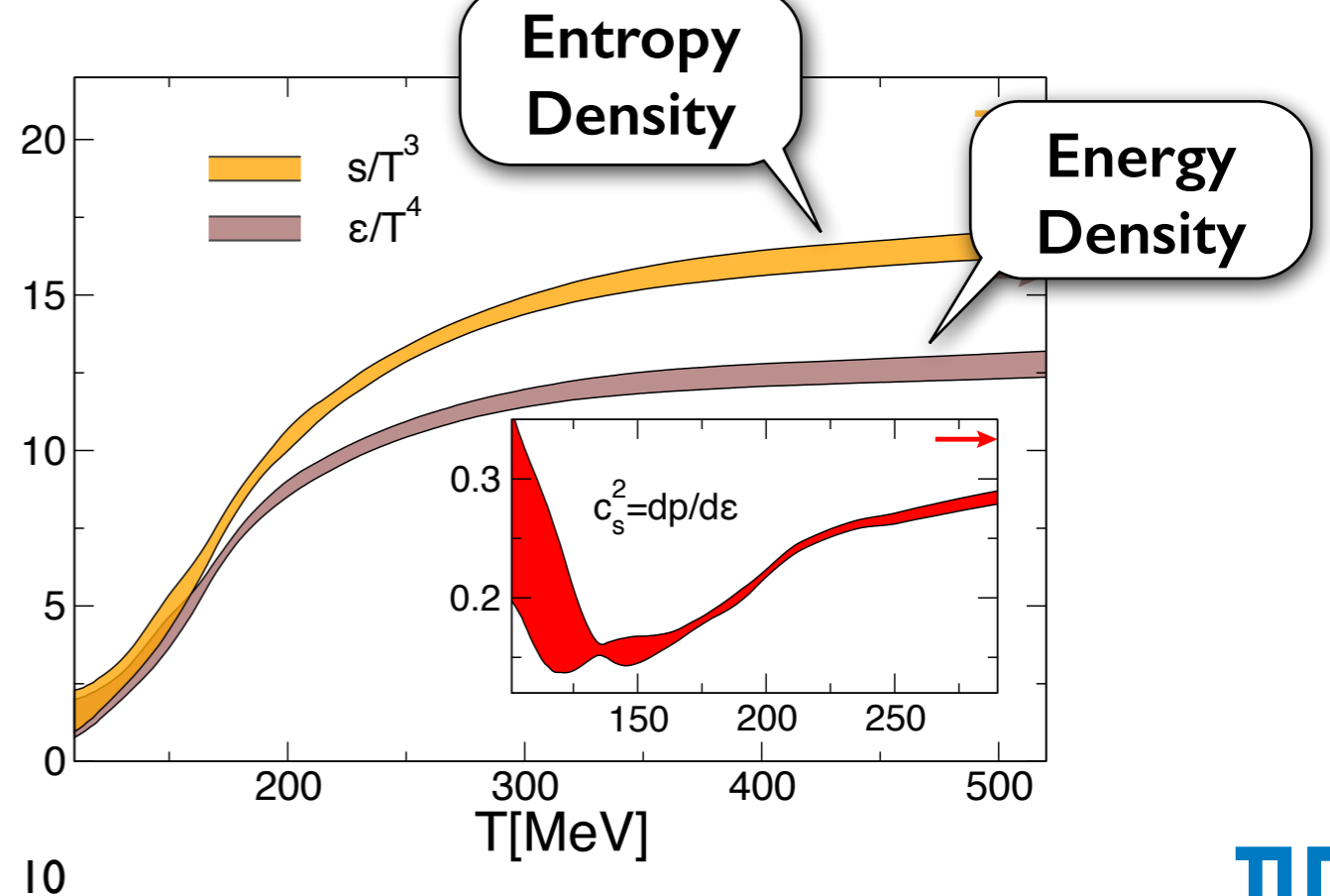
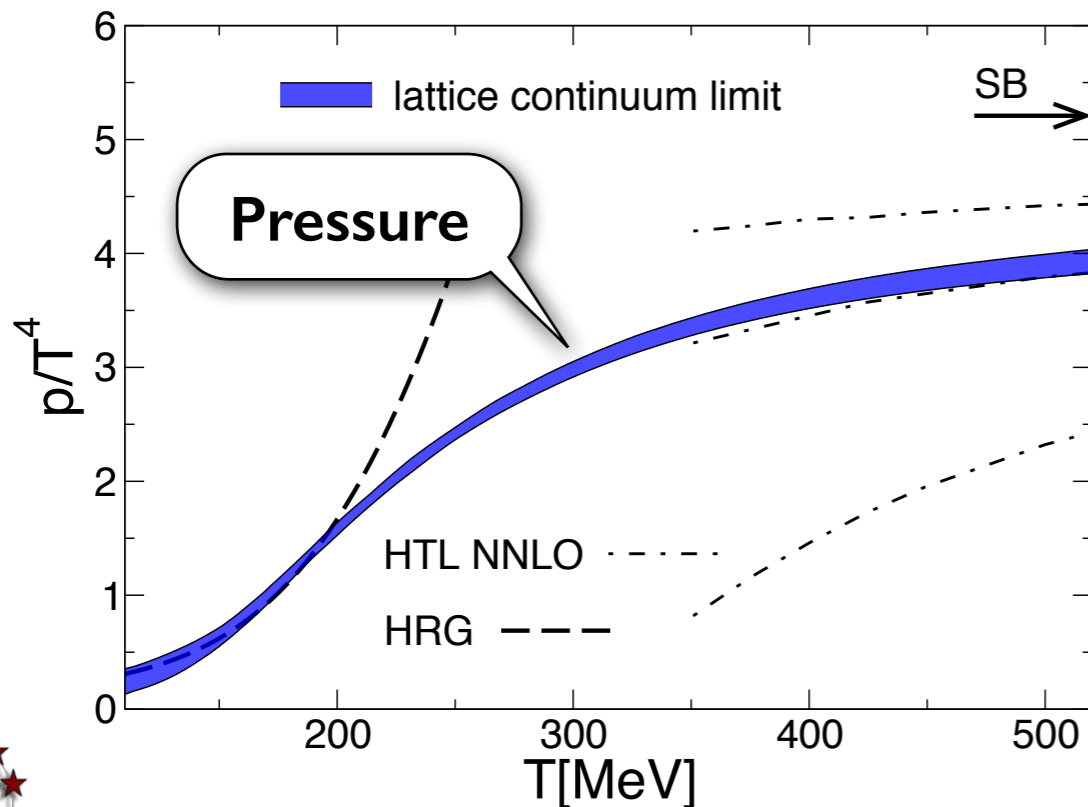
crossover
(not a phase transition)



A. Bazavov et al. (HotQCD collab.)
Phys. Rev. D90 (2014) 094503

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

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

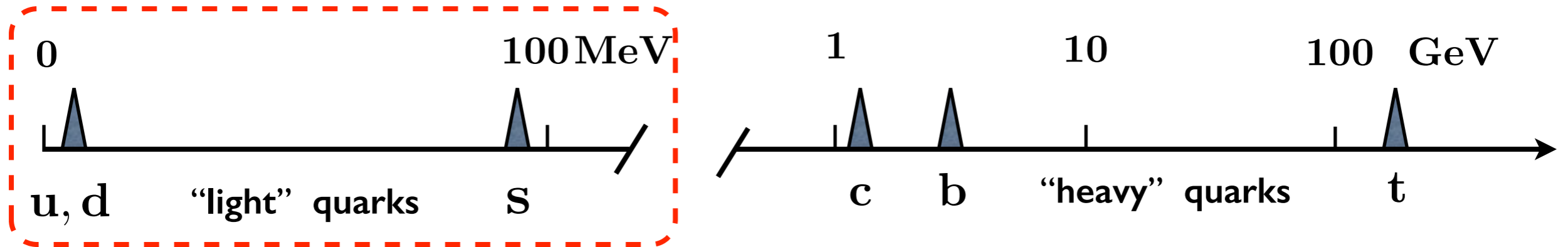


2.

The **Hadronic** Phase:
Low-Energy QCD
and
Spontaneously Broken
Chiral Symmetry



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



$$m_u = 2.3 \pm 0.7 \text{ MeV}$$

$$m_u/m_d \sim 0.4 - 0.6$$

$$m_s = 95 \pm 5 \text{ MeV}$$

$$(\mu \simeq 2 \text{ GeV})$$

PDG 2014

- **LOW-ENERGY QCD: CHIRAL EFFECTIVE FIELD THEORY**
- **expansion in m_q and in powers of low momentum**

$$m_c = 1.28 \pm 0.03 \text{ GeV}$$

$$m_b = 4.18 \pm 0.03 \text{ GeV}$$

$$m_t = 173.2 \pm 1.2 \text{ GeV}$$

- **Non-Relativistic QCD: HEAVY QUARK EFFECTIVE THEORY**
- **expansion in powers of $1/m_Q$**

Low-Energy QCD : CHIRAL SYMMETRY

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



$$SU(2)_R \times SU(2)_L$$

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

- Realizations of CHIRAL SYMMETRY:

pseudoscalar
isovector

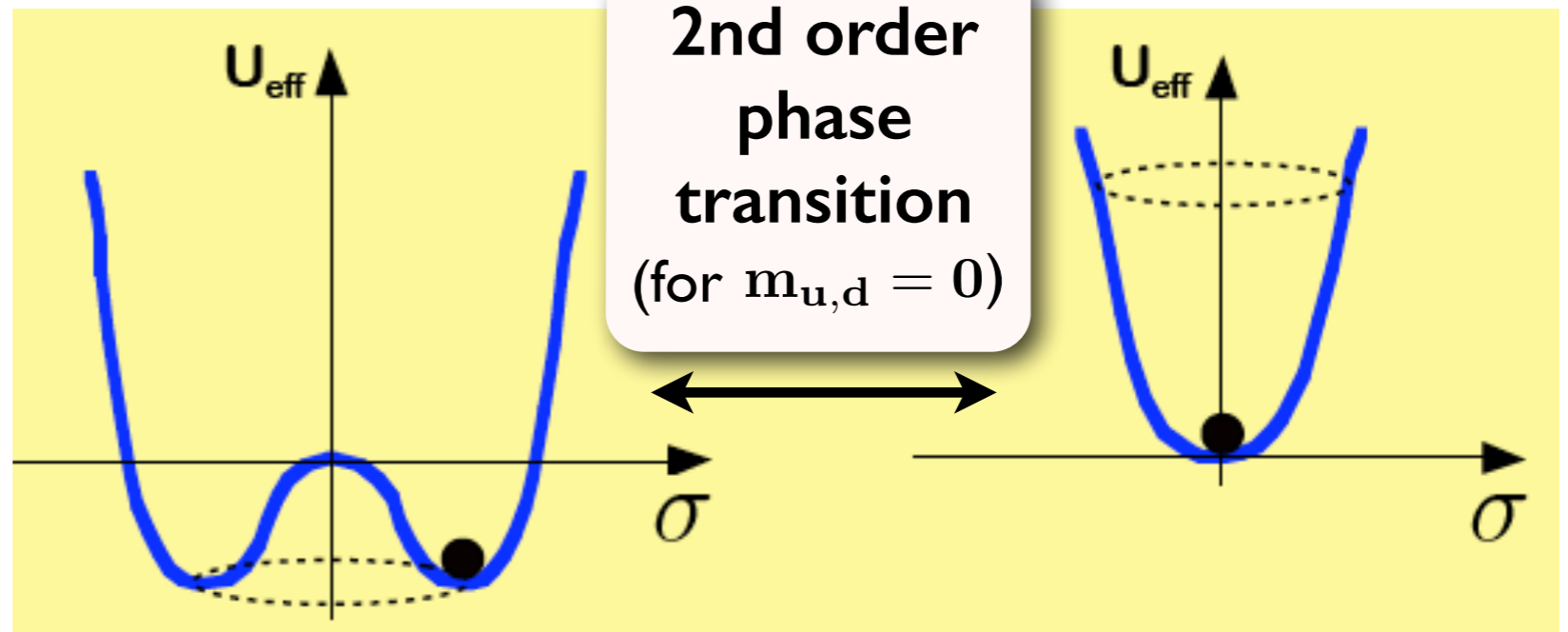
$$\pi^a \leftrightarrow \bar{\psi} i\gamma_5 \tau^a \psi$$

scalar
isoscalar

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

invariant:

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



Nambu-Goldstone

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

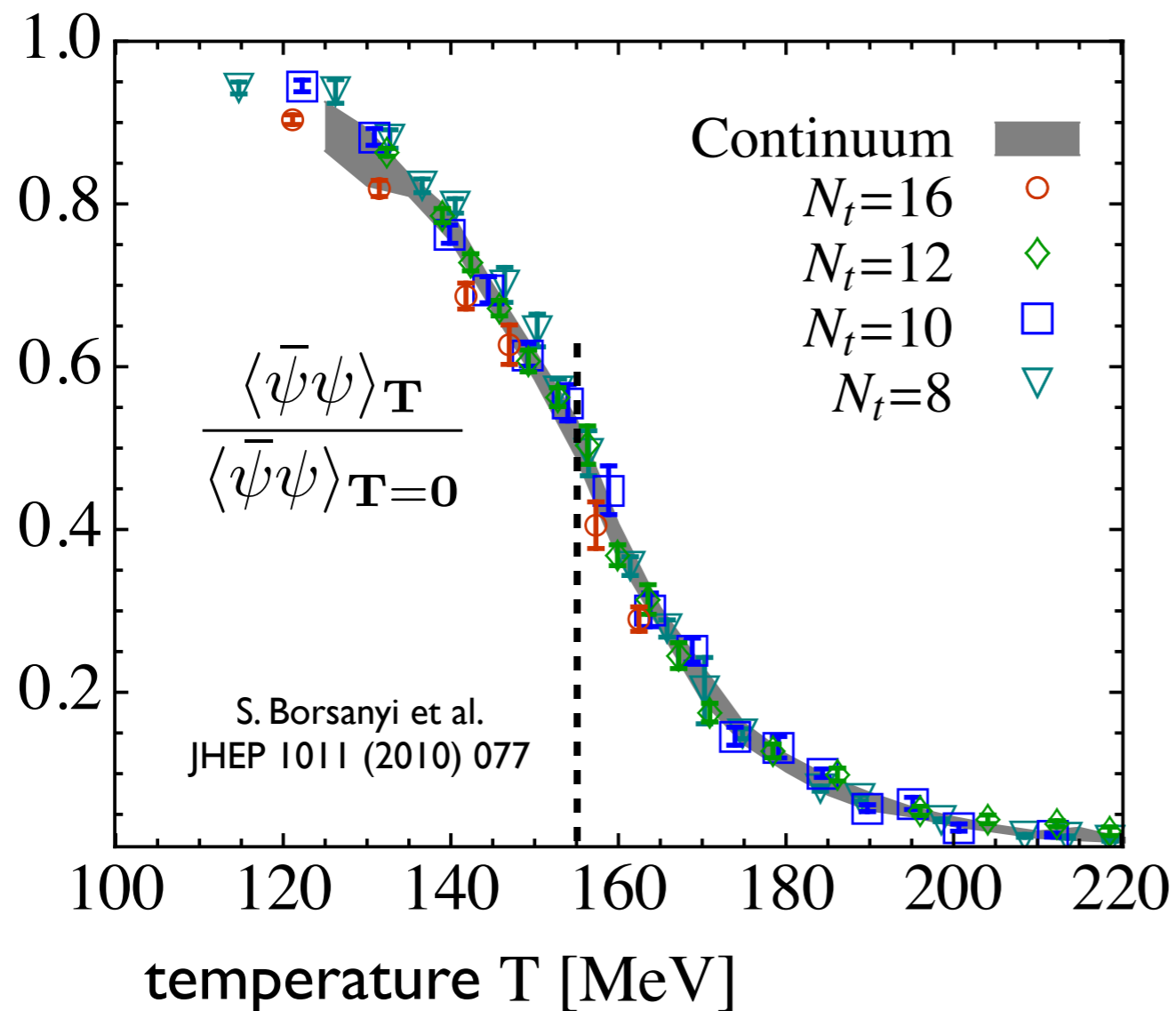
at low energy /
low temperature

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

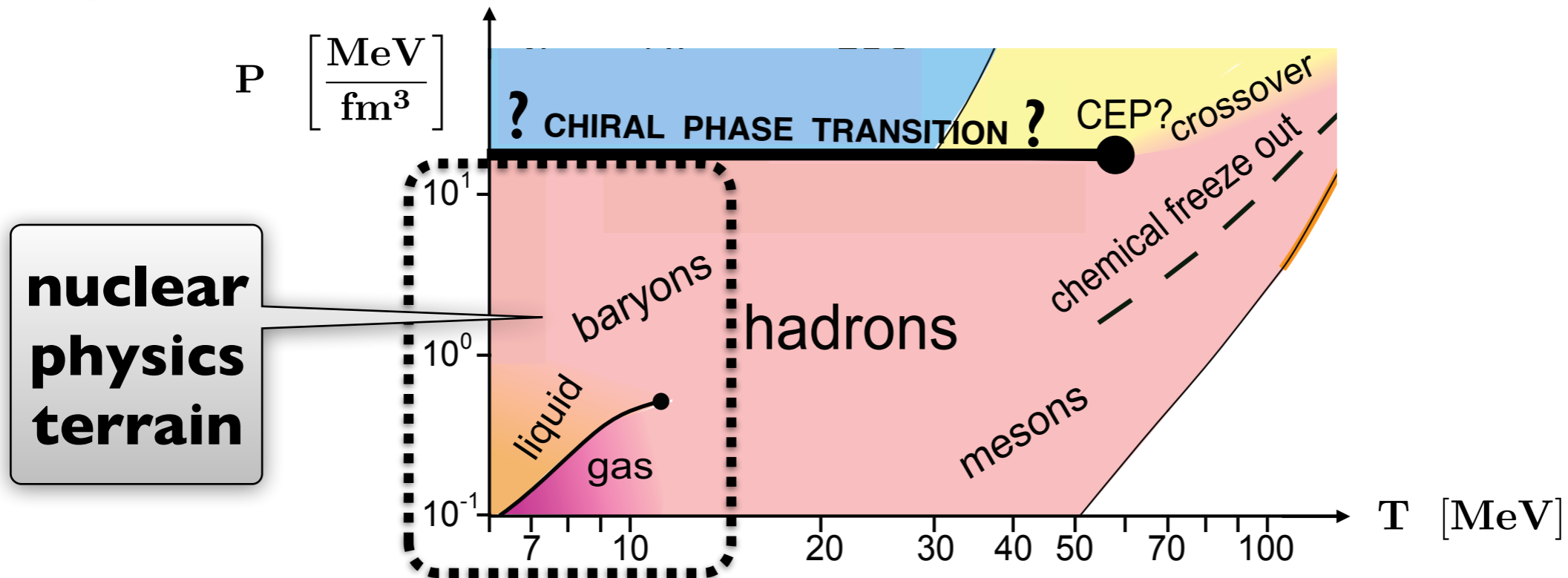
crossover
transition temperature
 $T_c \simeq 155 \text{ MeV}$

chiral and deconfinement
crossover transitions appear to be closely connected

CHIRAL SYMMETRY RESTORATION

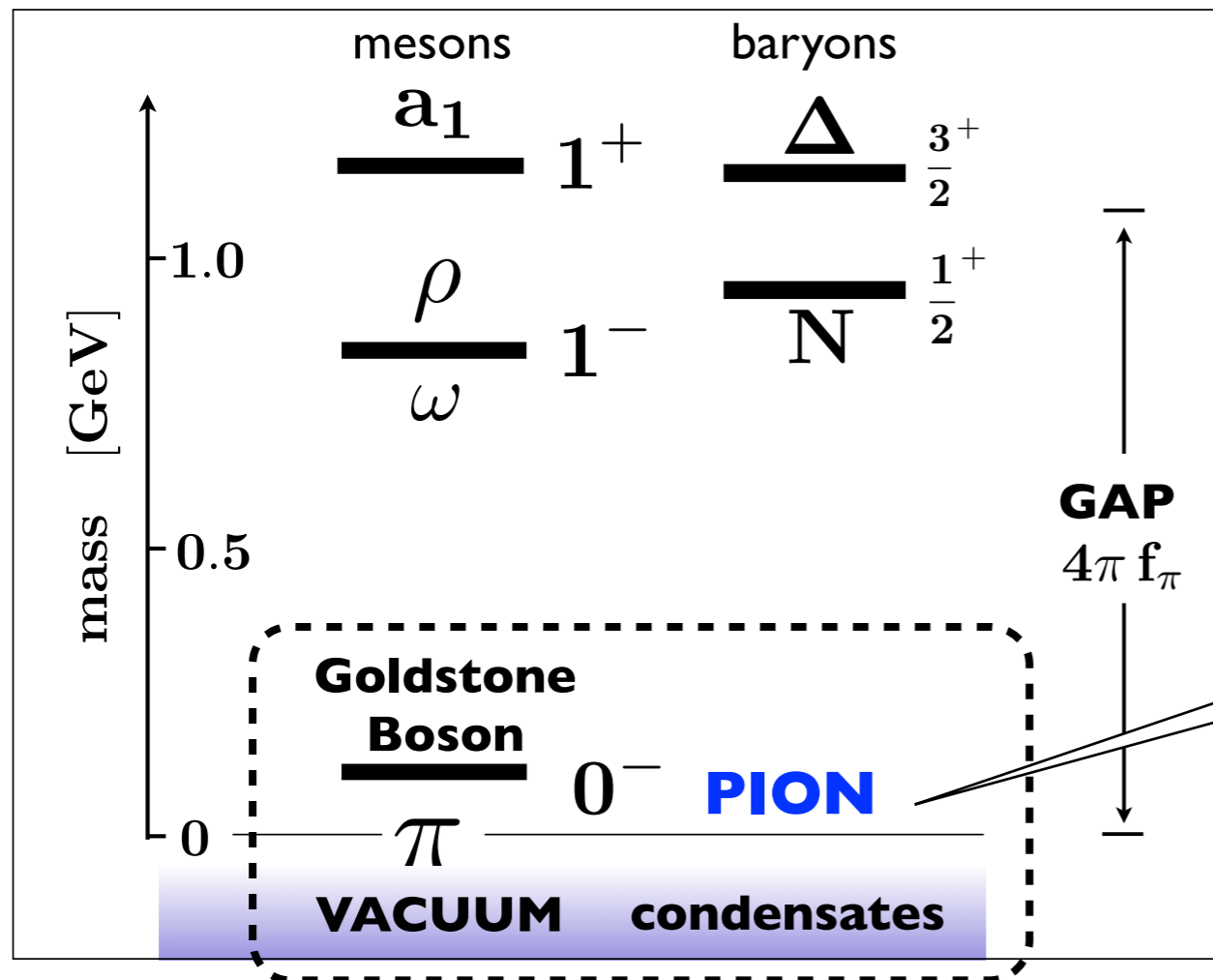
from **Nambu-Goldstone** to
Wigner-Weyl Realisation of **Chiral Symmetry**

- **PHASE TRANSITION** or smooth **CROSSOVER** ?



- **Chiral first-order phase transition** and **critical point** ?
... based on quark models which do **not** respect **nuclear physics** constraints
- Needed: systematic approach to **nuclear thermodynamics**

Spontaneously Broken CHIRAL SYMMETRY



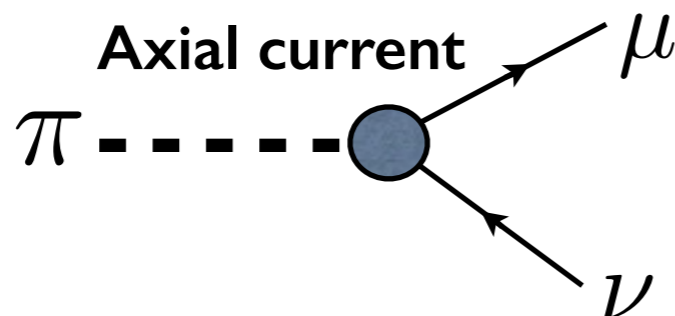
Triplet
of
NAMBU - GOLDSTONE BOSONS:

$$\pi^+, \pi^0, \pi^-$$

Characteristic Symmetry Breaking SCALE:

$$4\pi f_\pi \sim 1 \text{ GeV}$$

- PION DECAY CONSTANT**



$$f_\pi = 92.2 \pm 0.2 \text{ MeV}$$

QCD and the ORIGIN of MASS

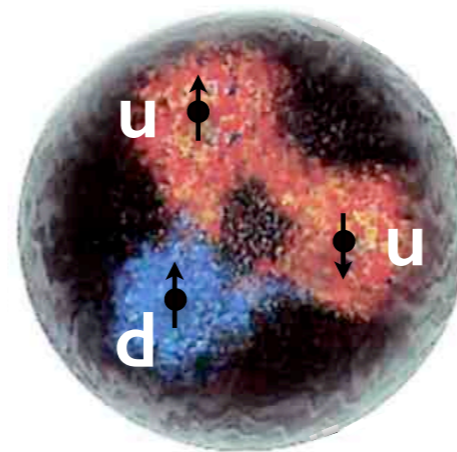
- HOW does the PROTON get its mass ? (NOT from Higgs !!)

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

$m_u \simeq 3 \text{ MeV}$

$m_d \simeq 5 \text{ MeV}$

$3 + 3 + 5 \neq 938 \text{ !}$

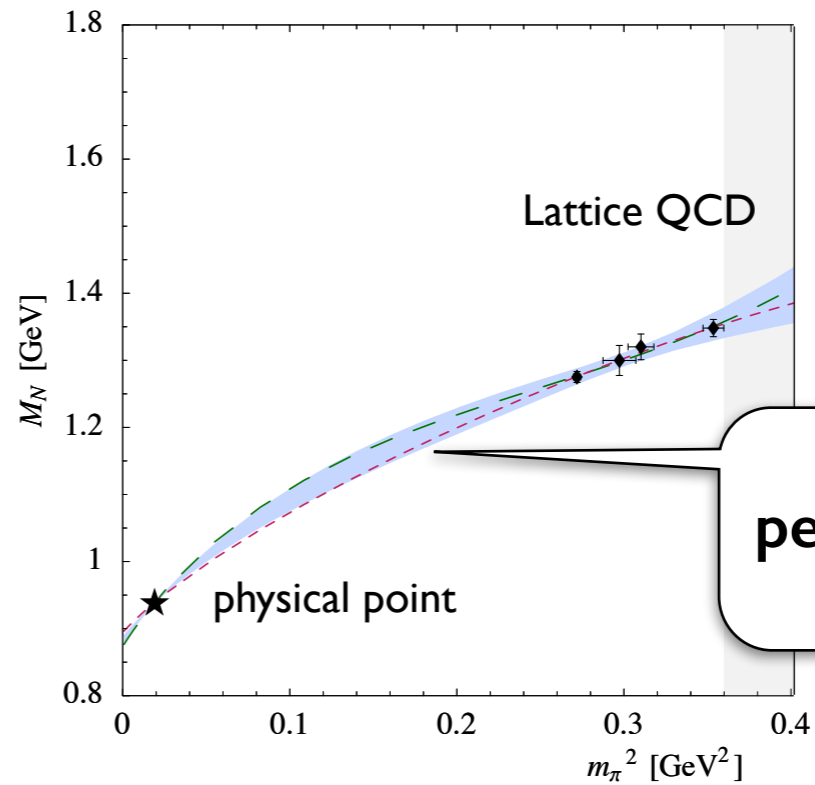


... mostly
GLUONIC
field energy
 $M = E/c^2$

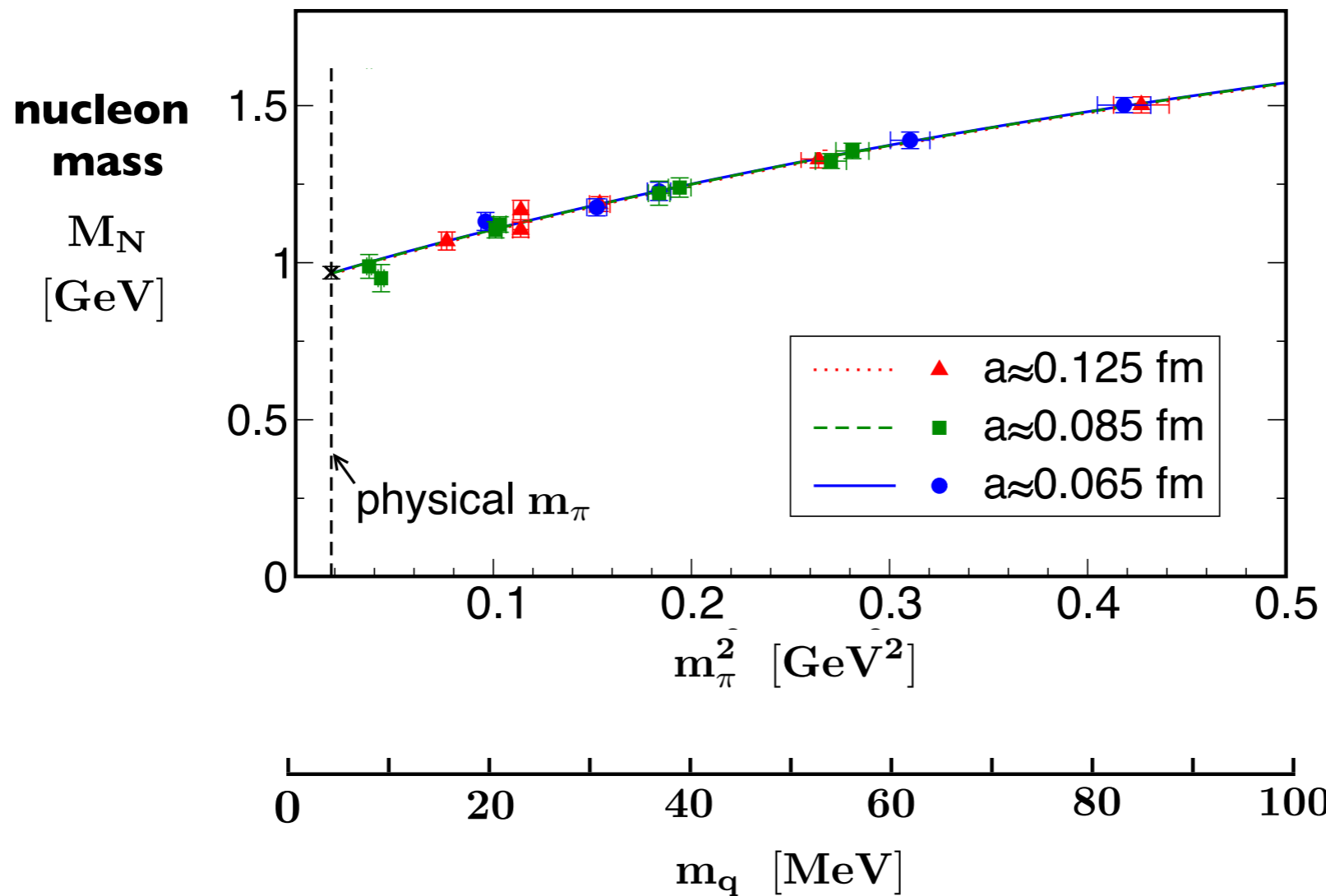
Trace anomaly:

$$M_N \sim \langle N | \text{Tr}[G_{\mu\nu} G^{\mu\nu}] | N \rangle + \sum_i m_i \langle N | \bar{q}q | N \rangle$$

Nucleon Mass from Lattice QCD



M. Procura et al.
Phys. Rev.
D73 (2006) 114510



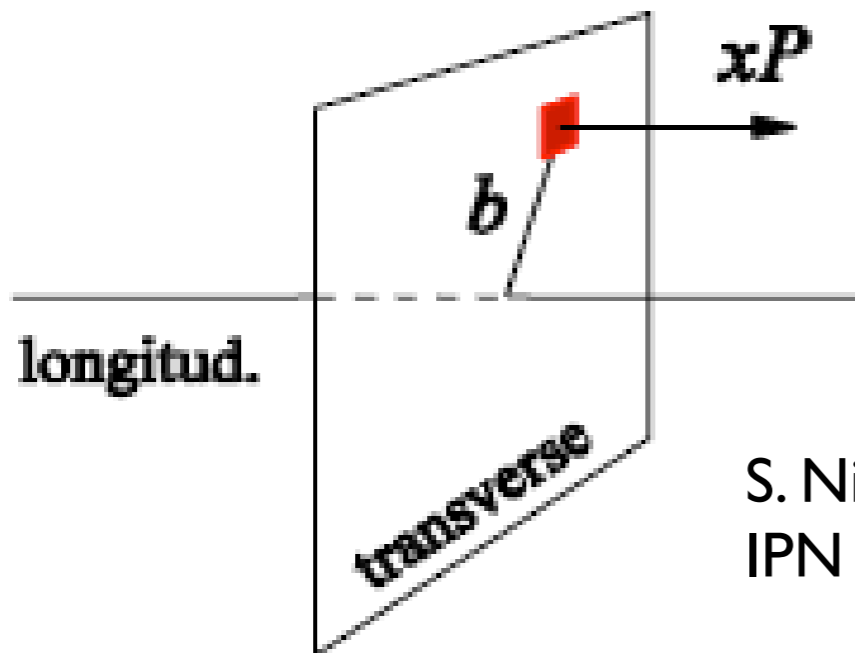
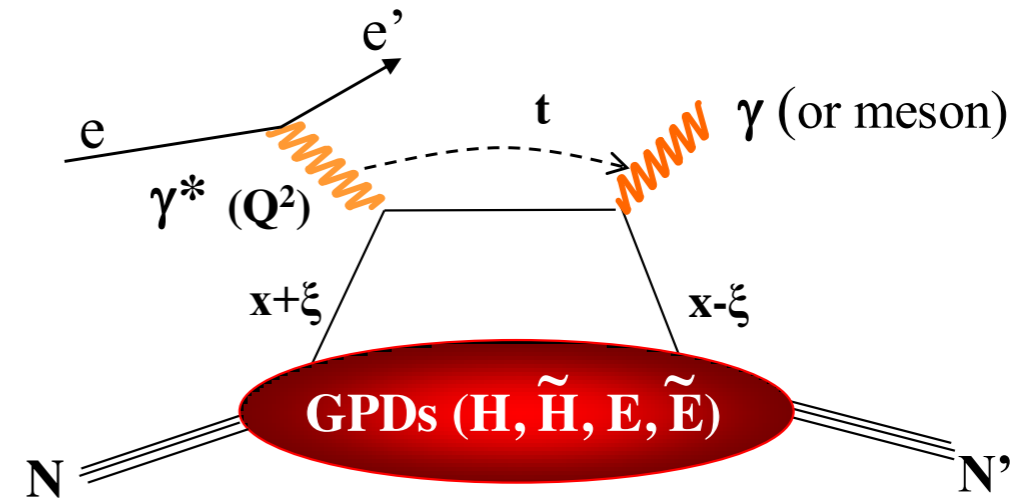
Budapest-Marseille-
Wuppertal
Collaboration
Science 322 (2008) 1224

pion mass
squared

quark mass

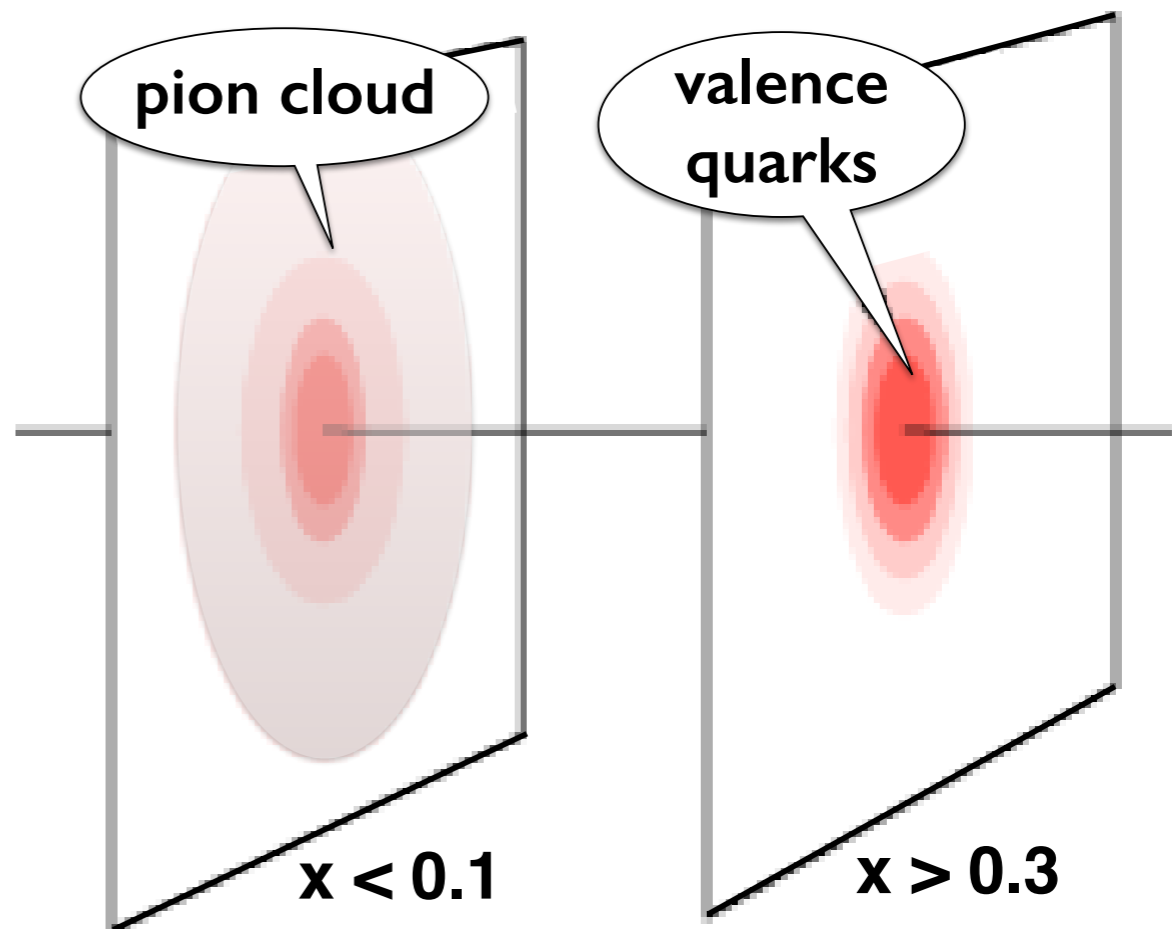
Valence quark core and pion cloud of the nucleon towards experimental verification ?

- Generalized Parton Distributions (GPD's)
- Deeply Virtual Compton Scattering (DVCS @ JLab)



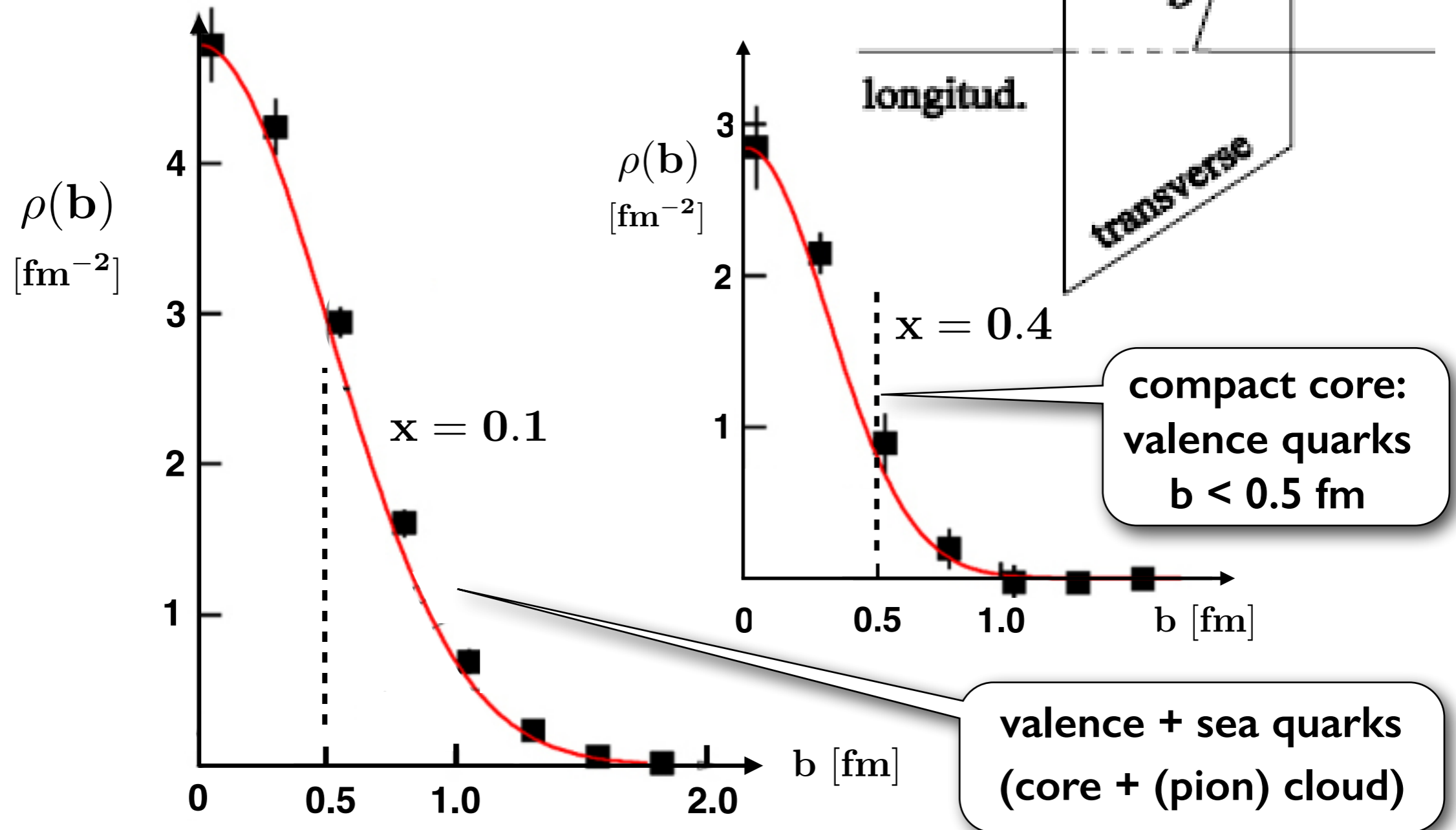
S. Niccolai
IPN Orsay

$$q(x, b_{\perp}) = \int_0^{\infty} \frac{d^2 \Delta_{\perp}}{(2\pi)^2} e^{i\Delta_{\perp} b_{\perp}} H(x, 0, -\Delta_{\perp}^2)$$



Transverse distributions of quarks in the proton

M. Guidal, H. Moutarde, M. Vanderhaeghen
Rep. Prog. Phys. 76 (2013) 066202



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

$$Q \ll 4\pi f_\pi \sim 1 \text{ GeV}$$

CHIRAL EFFECTIVE FIELD THEORY

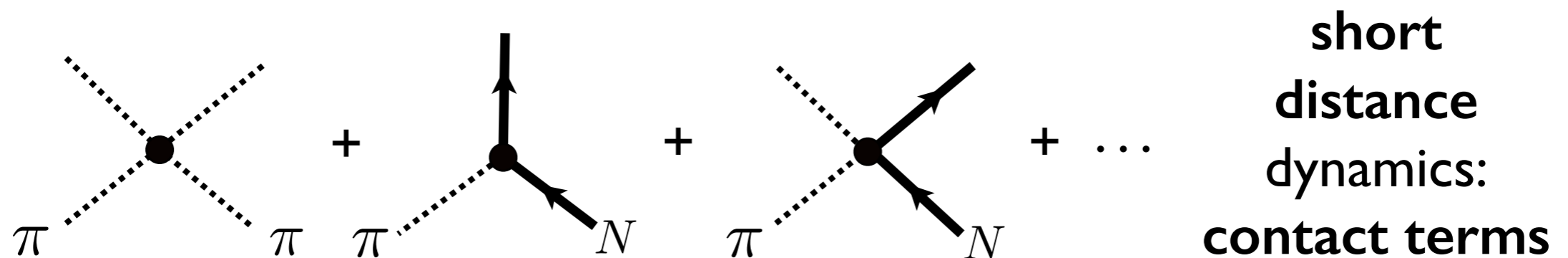
- Systematic framework at interface of QCD and Nuclear Physics

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

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

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

- Construction of Effective Lagrangian: **Symmetries**

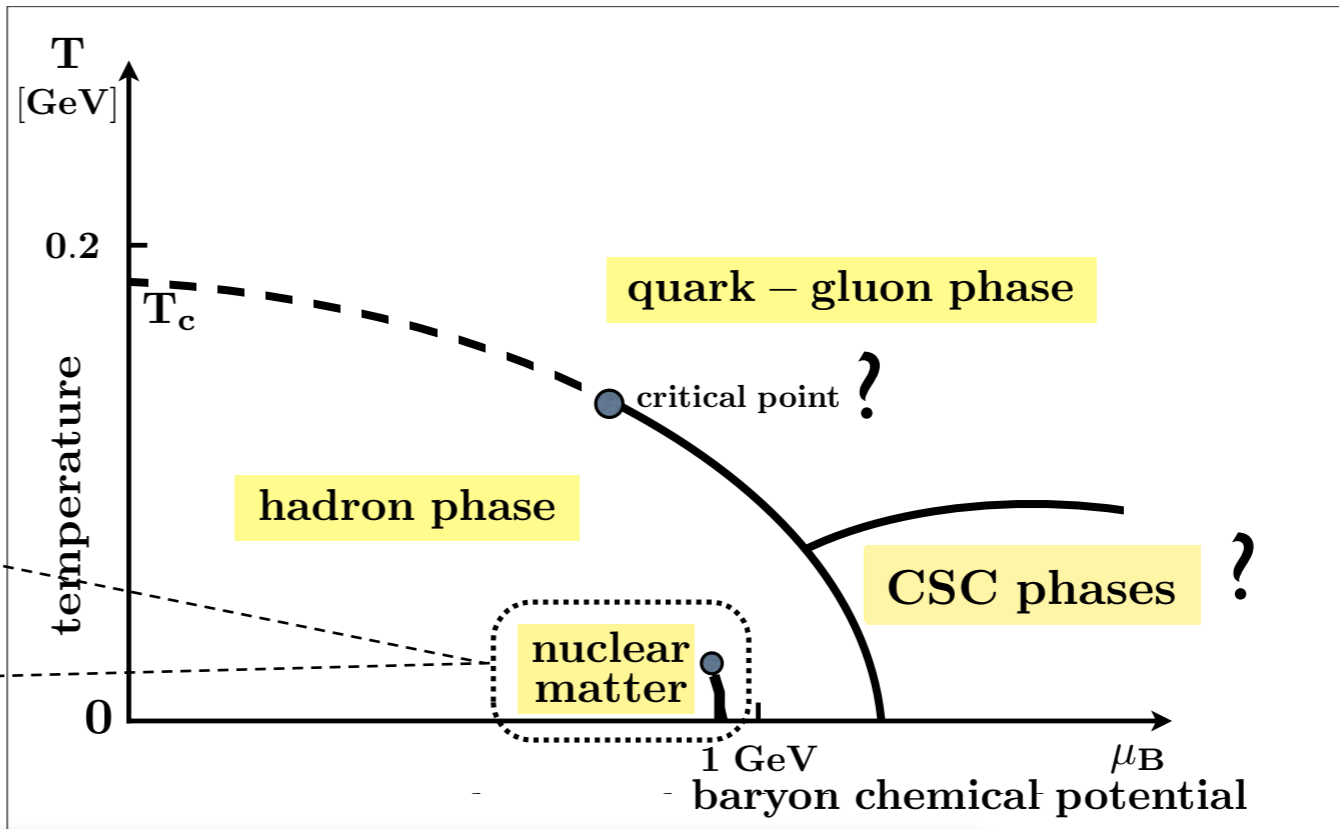
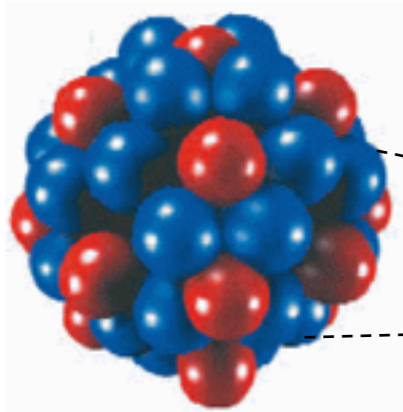


3. NUCLEAR CHIRAL THERMODYNAMICS



NUCLEAR MATTER and QCD PHASES

nuclei



Scales in $N = Z$ nuclear matter:

- momentum scale:
Fermi momentum $k_F \simeq 1.4 \text{ fm}^{-1} \sim 2m_\pi$
- 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: $K = (260 \pm 30) \text{ MeV} \sim 2m_\pi$

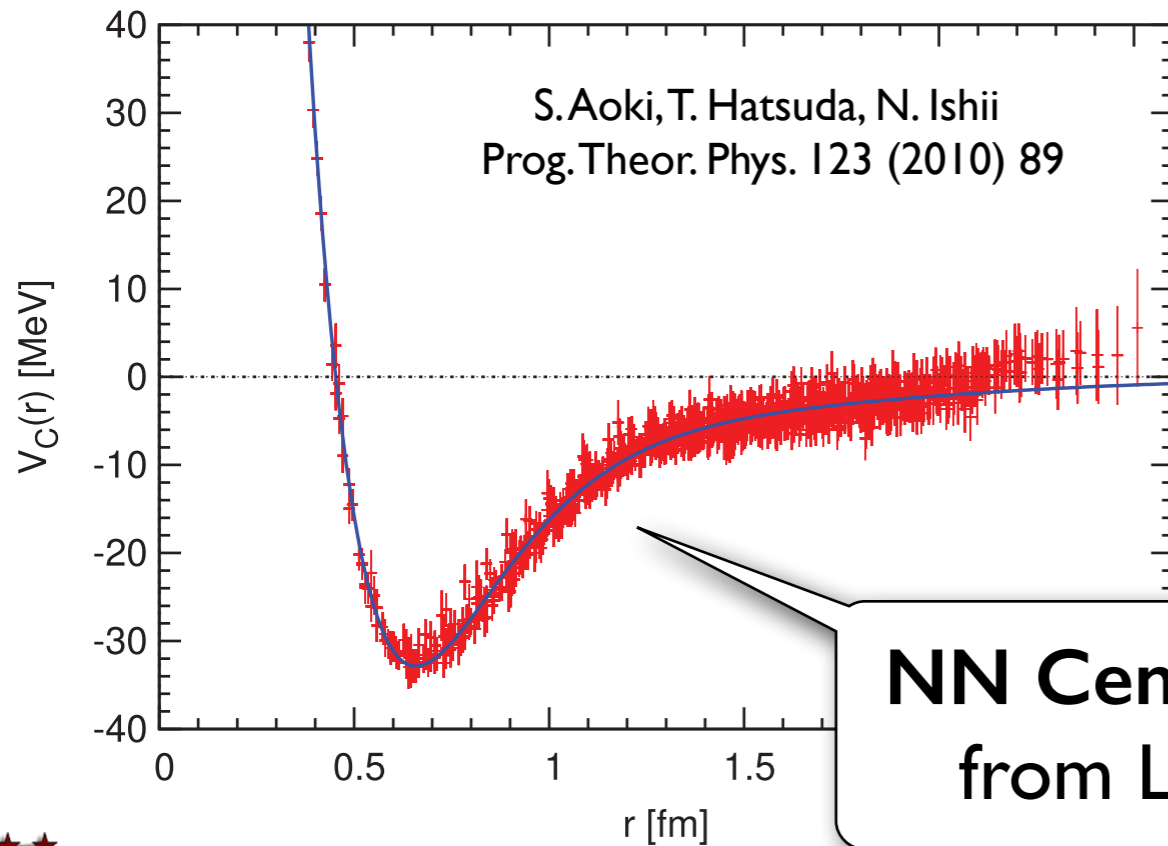
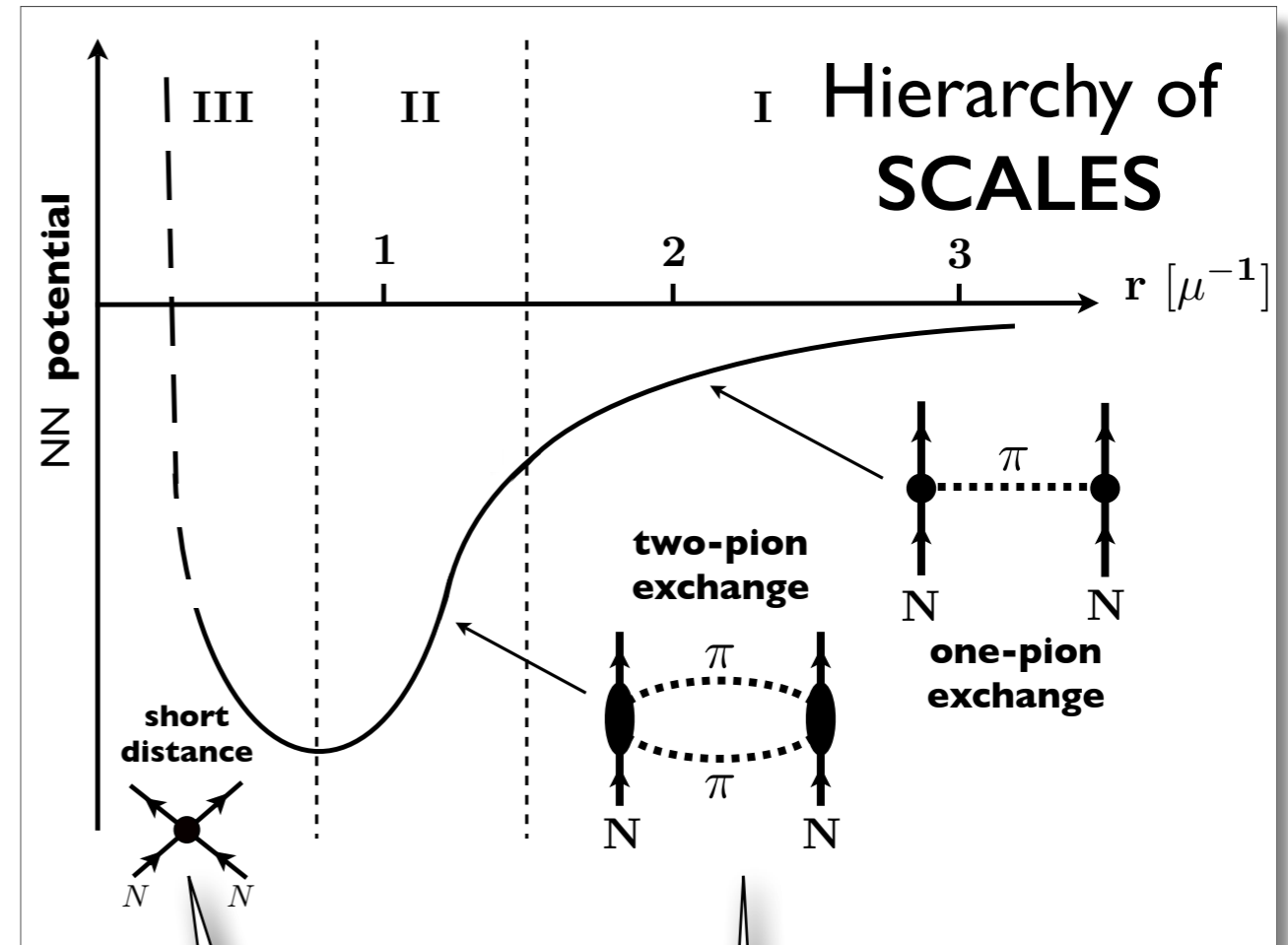
Nuclear Forces

- recent developments -

contemporary approaches:

**Chiral Effective
Field Theory
&
Lattice QCD**

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



contact terms

**NN Central Potential
from Lattice QCD**

**explicit
treatment of
two-pion exchange**



NUCLEAR INTERACTIONS from CHIRAL EFFECTIVE FIELD THEORY

Weinberg

Bedaque & van Kolck

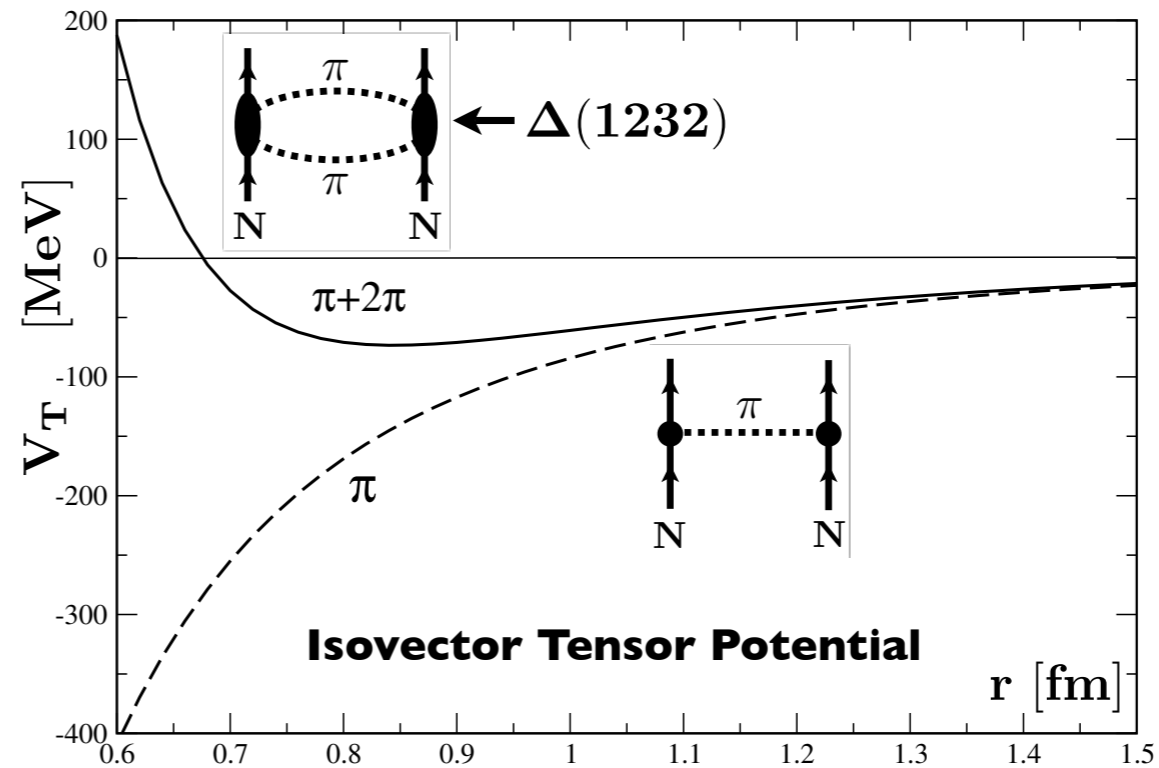
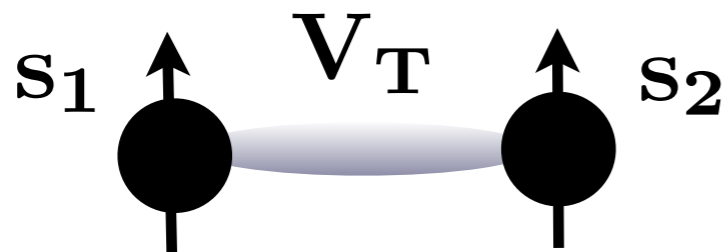
Bernard, Epelbaum, Kaiser, Meißner; ...

		Two-nucleon force	Three-nucleon force	Four-nucleon force
$\mathcal{O}\left(\frac{Q^0}{\Lambda^0}\right)$	LO		—	—
$\mathcal{O}\left(\frac{Q^2}{\Lambda^2}\right)$	NLO		—	—
$\mathcal{O}\left(\frac{Q^3}{\Lambda^3}\right)$	N ² LO			—
$\mathcal{O}\left(\frac{Q^4}{\Lambda^4}\right)$	N ³ LO			

- Systematically organized HIERARCHY

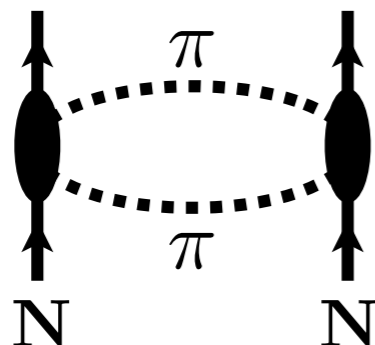
Important pieces of the CHIRAL NUCLEON-NUCLEON INTERACTION

● 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

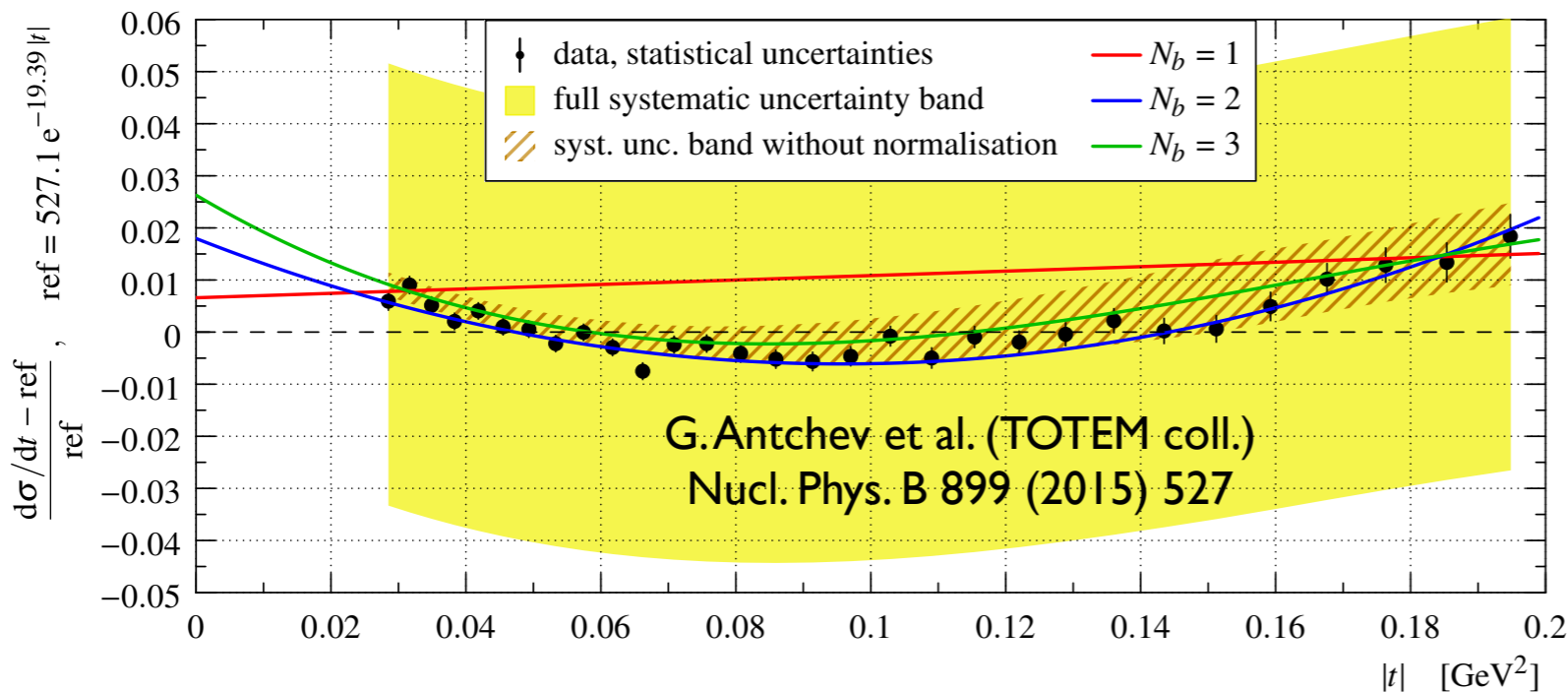
Important : Explicit treatment of two-pion exchange dynamics



● **Short digression:**

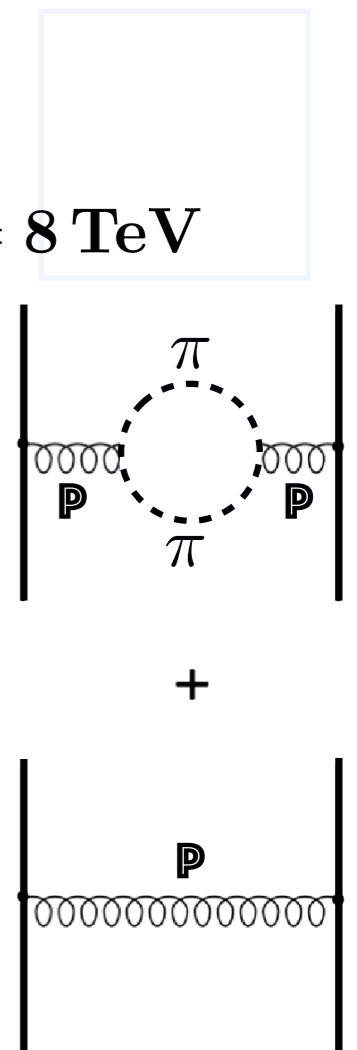
“Discovery” of two-pion exchange at LHC: elastic pp scattering at $\sqrt{s} = 8 \text{ TeV}$

deviation from standard exponential behaviour $\frac{d\sigma}{dt} \propto e^{bt}$



V.A. Khoze, A.D. Martin,
M.G. Ryskin
J. Phys. G 42 (2015) 025003

L. Jenkovszky, A. Lengyel
Acta Phys. Pol.
B 46 (2015) 863



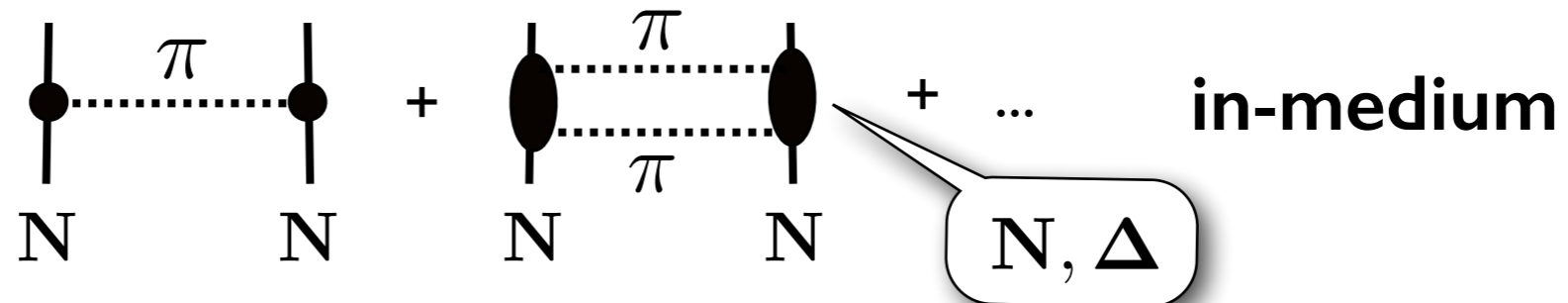
CHIRAL DYNAMICS and the NUCLEAR MANY-BODY PROBLEM

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

- **Small scales:** energy, momentum, $m_\pi, k_F \ll 4\pi f_\pi \sim 1 \text{ GeV}$
- **PIONS** and **NUCLEONS** as explicit degrees of freedom

IN-MEDIUM CHIRAL PERTURBATION THEORY

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



short-distance dynamics:  **contact interactions**

IN-MEDIUM CHIRAL PERTURBATION THEORY

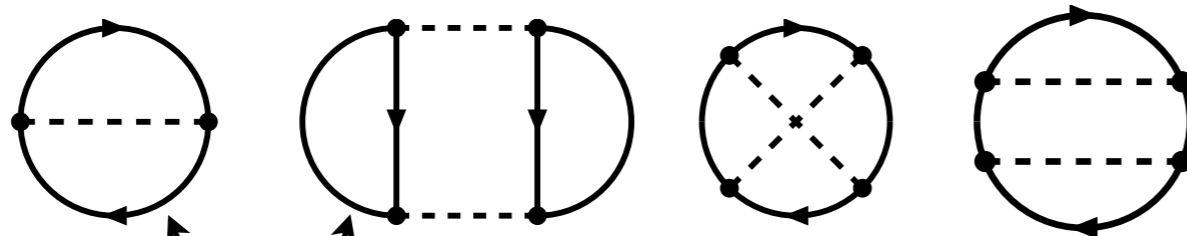
- Loop expansion of (In-Medium) Chiral Perturbation Theory



Systematic expansion of **ENERGY DENSITY** $\mathcal{E}(k_F)$
in powers of Fermi momentum

(convergent for $k_F \ll 4\pi f_\pi \sim 1 \text{ GeV}$)

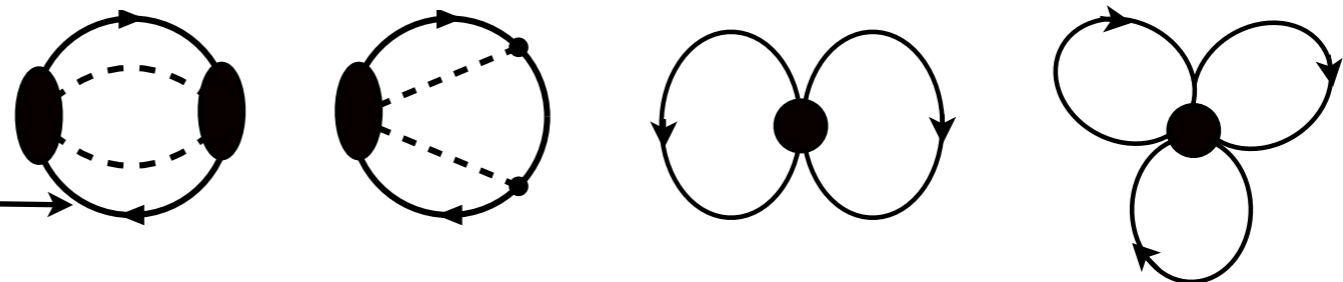
- Nuclear thermodynamics: compute free energy density



(3-loop order)

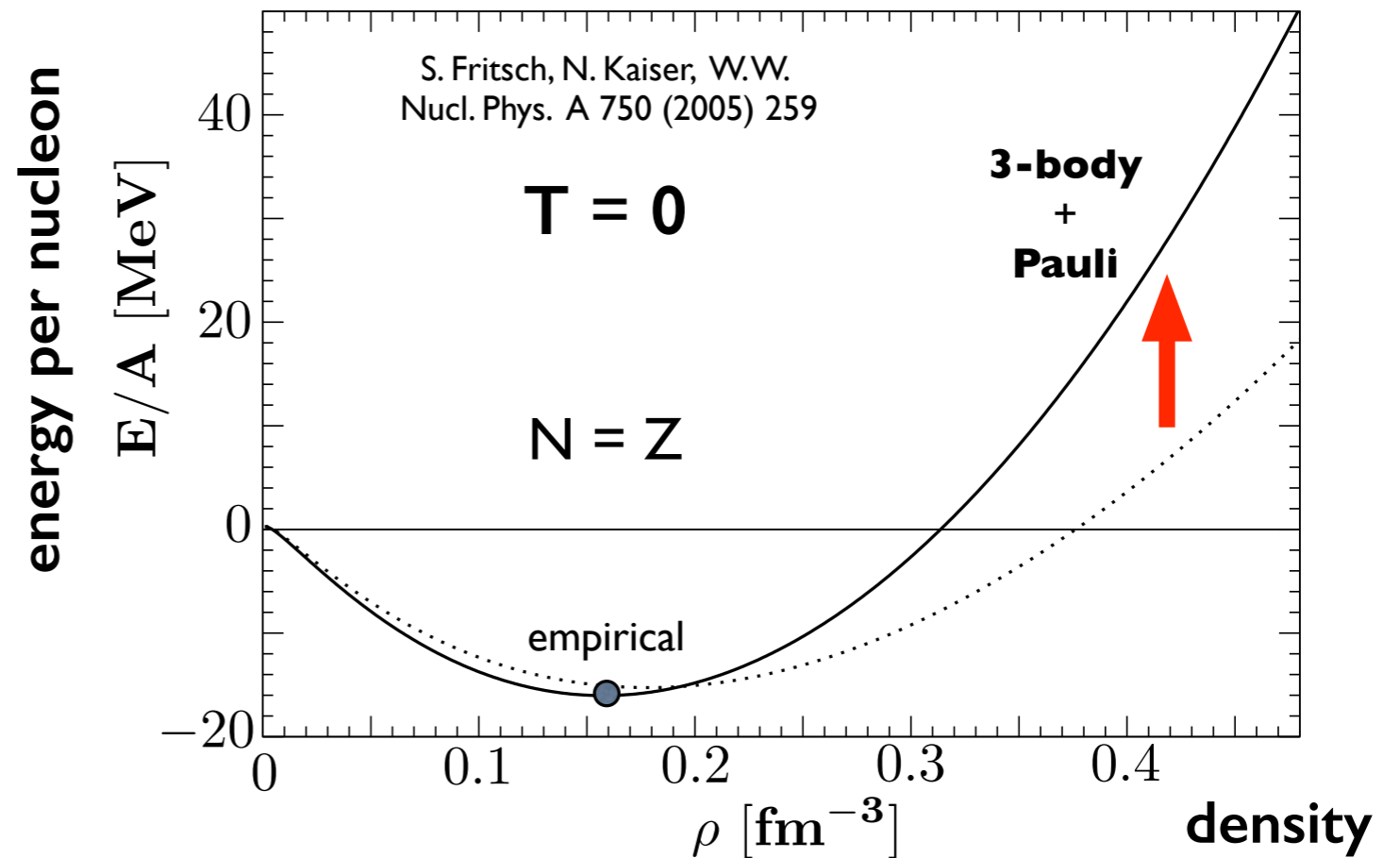
N. Kaiser, S. Fritsch, W.W.
(2002-2005)

in-medium
incl. Pauli blocking



NUCLEAR MATTER

- In-medium ChEFT
3-loop (π, \mathbf{N}, Δ)
- Input parameters:
few contact terms
- basically:
analytic calculation
- Output:



▶ **Binding & saturation**

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

▶ **Asymmetry energy: $A(k_F^0) = 34 \text{ MeV}$**

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

▶ **Finite nuclei: Density Functional methods**

C. Wellenhofer, J.W. Holt,
N. Kaiser, W.W.

▶ **Fermi Liquid Theory:**

Quasiparticle interaction and Landau parameters

Phys. Rev. C 89 (2014) 064009

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

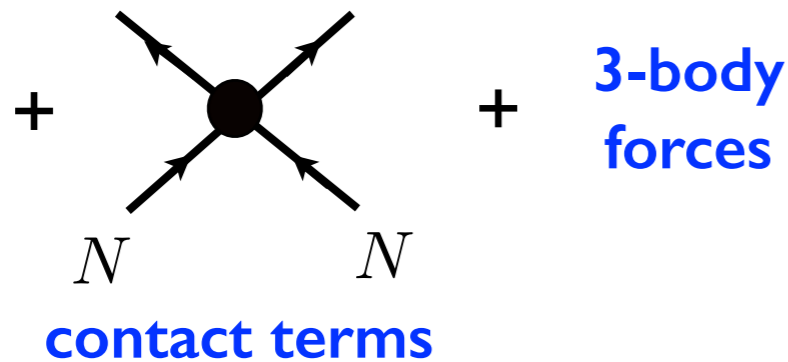
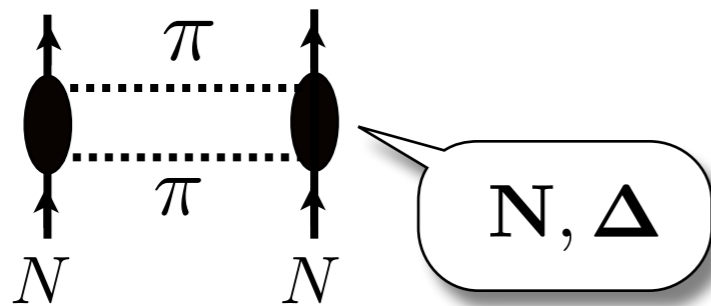
J.W. Holt, M. Rho, W.W.: Physics Reports (2015), in print

NUCLEAR THERMODYNAMICS

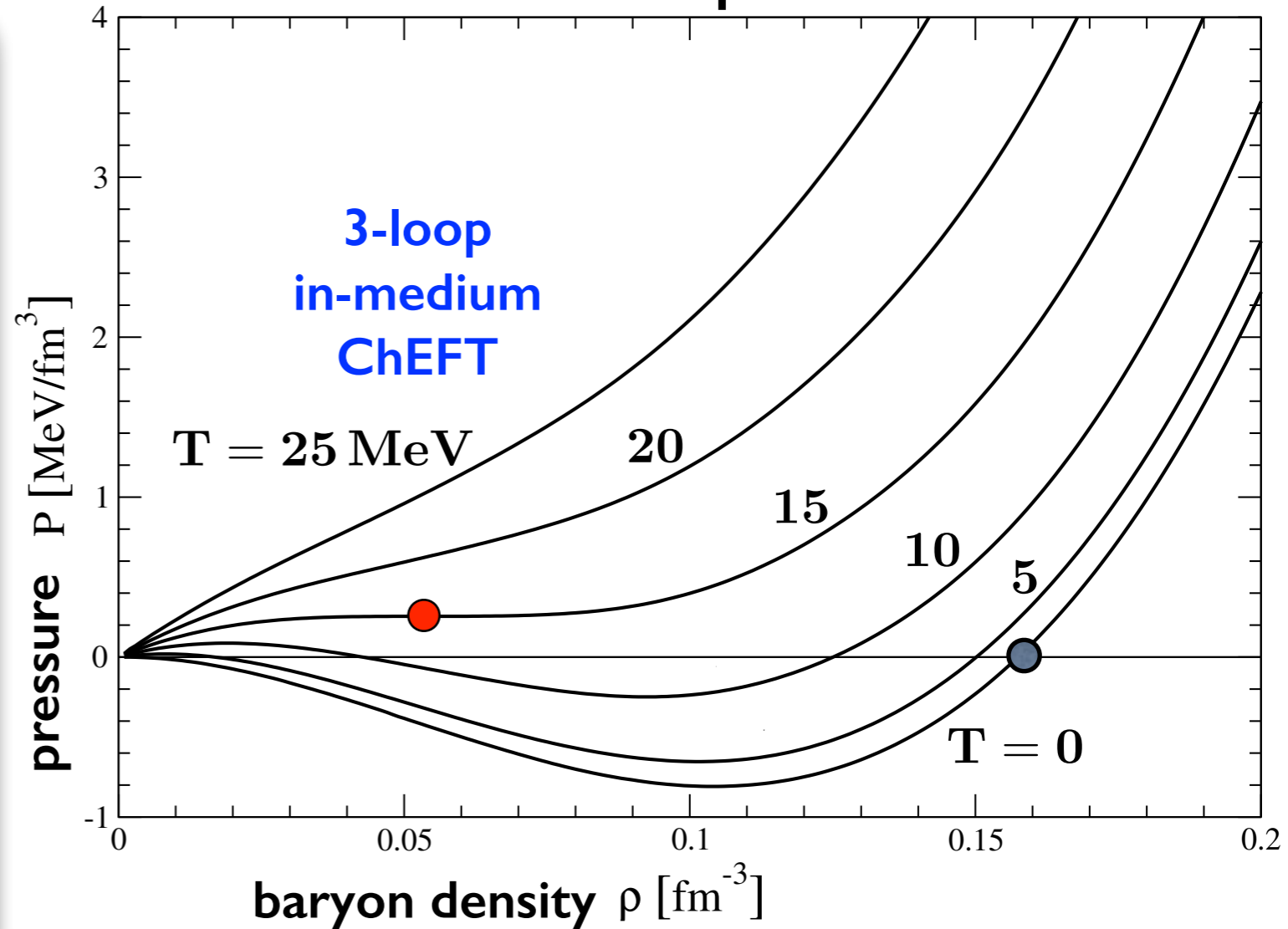
NUCLEAR CHIRAL (PION) DYNAMICS

BINDING & SATURATION:

Van der Waals + Pauli



nuclear matter: equation of state

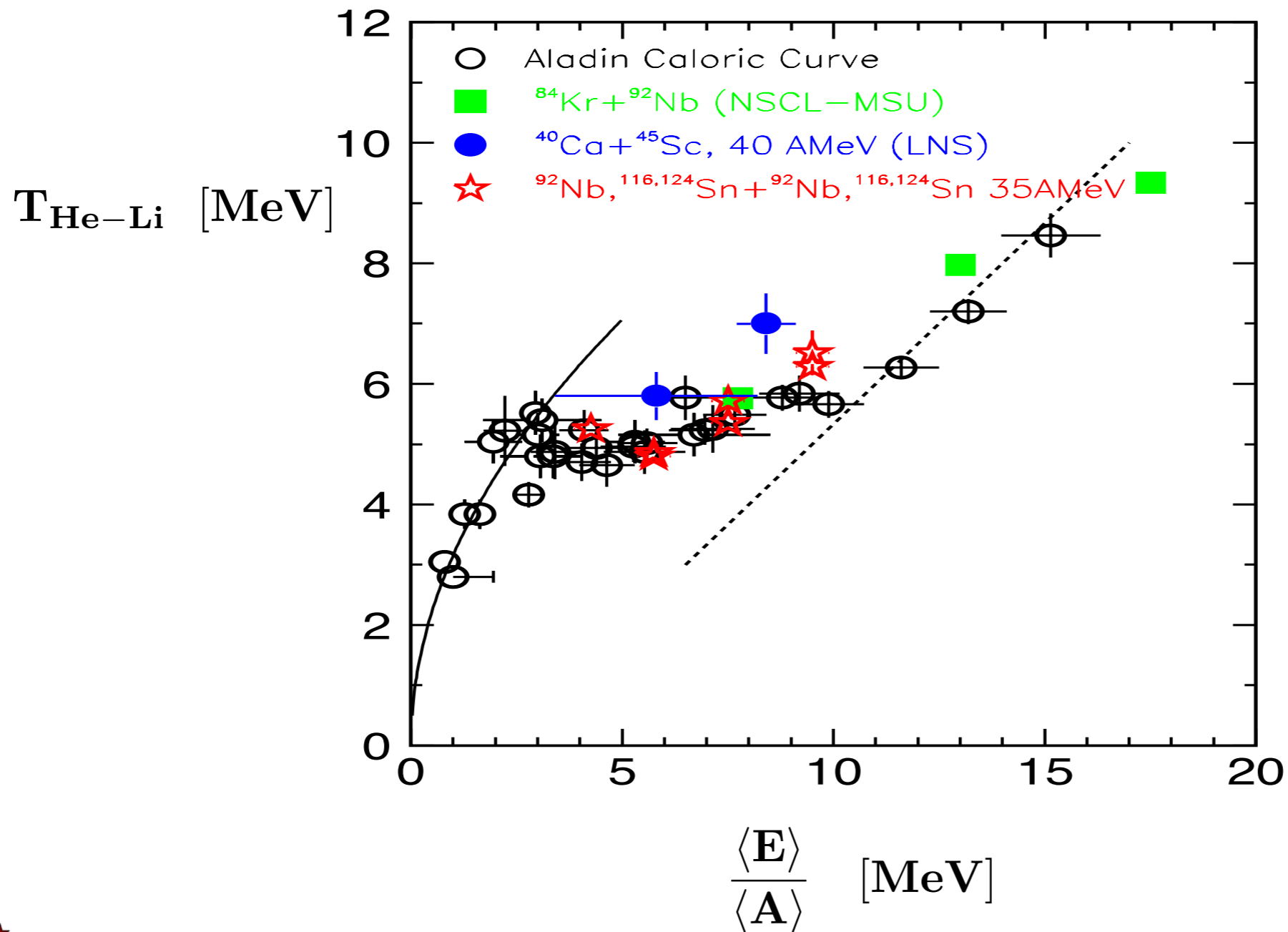


Liquid - Gas first-order phase transition
 Critical Temperature $T_c = 15 \text{ MeV}$
 (empirical: $T_c = 16 - 18 \text{ MeV}$)



NUCLEAR LIQUID-GAS TRANSITION

from multi-fragmentation measurements in heavy-ion collisions



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

P. Chomaz
Nucl. Phys. A 685 (2001) 274

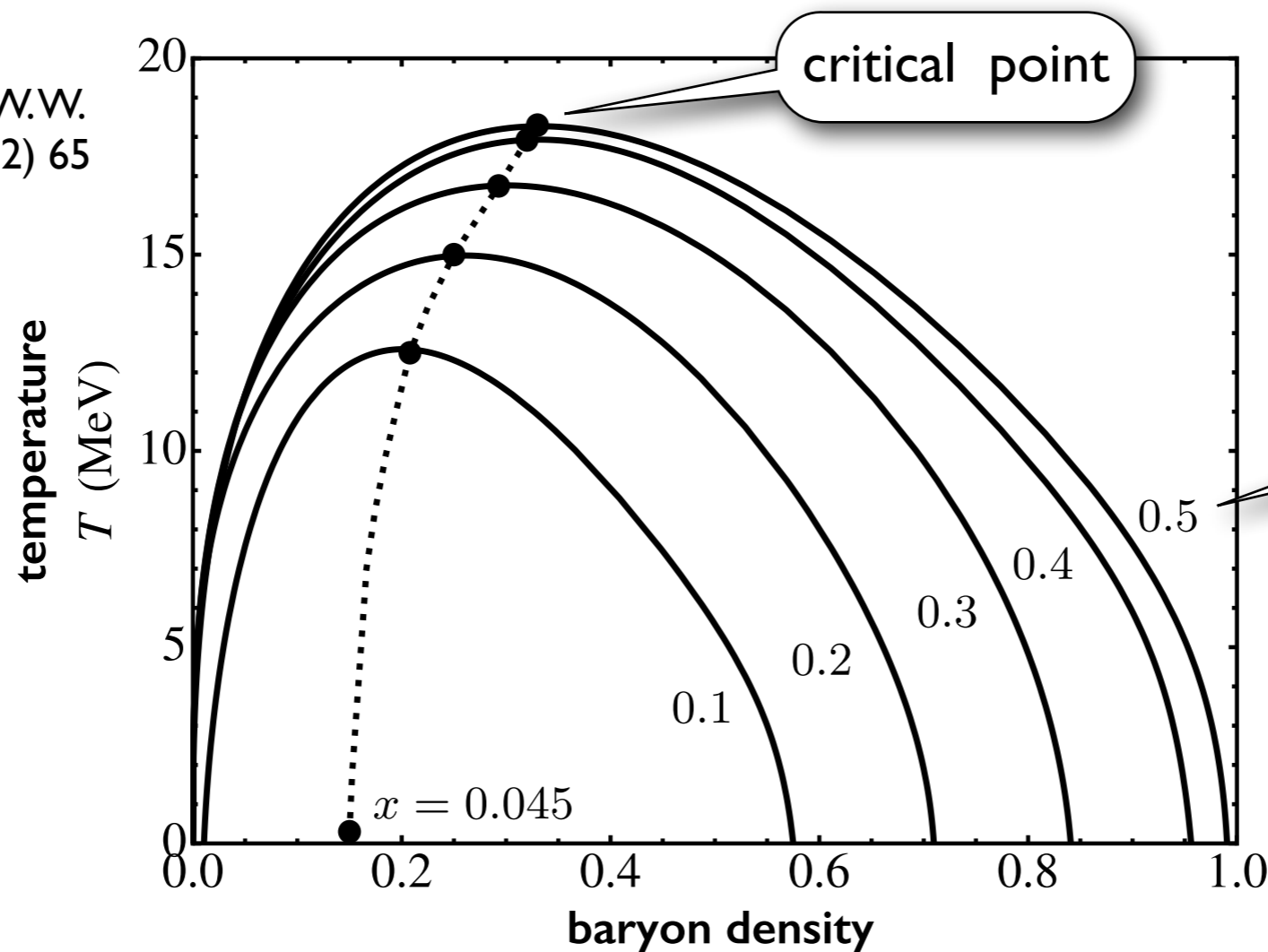
M. D'Agostino et al.
Nucl. Phys. A 749 (2005) 55



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



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

M. Drews, W.W.
Phys. Lett. B 738 (2014) 187
Phys. Rev. C 91 (2015) 035802

... including
non-perturbative effects
(Renormalization Group)

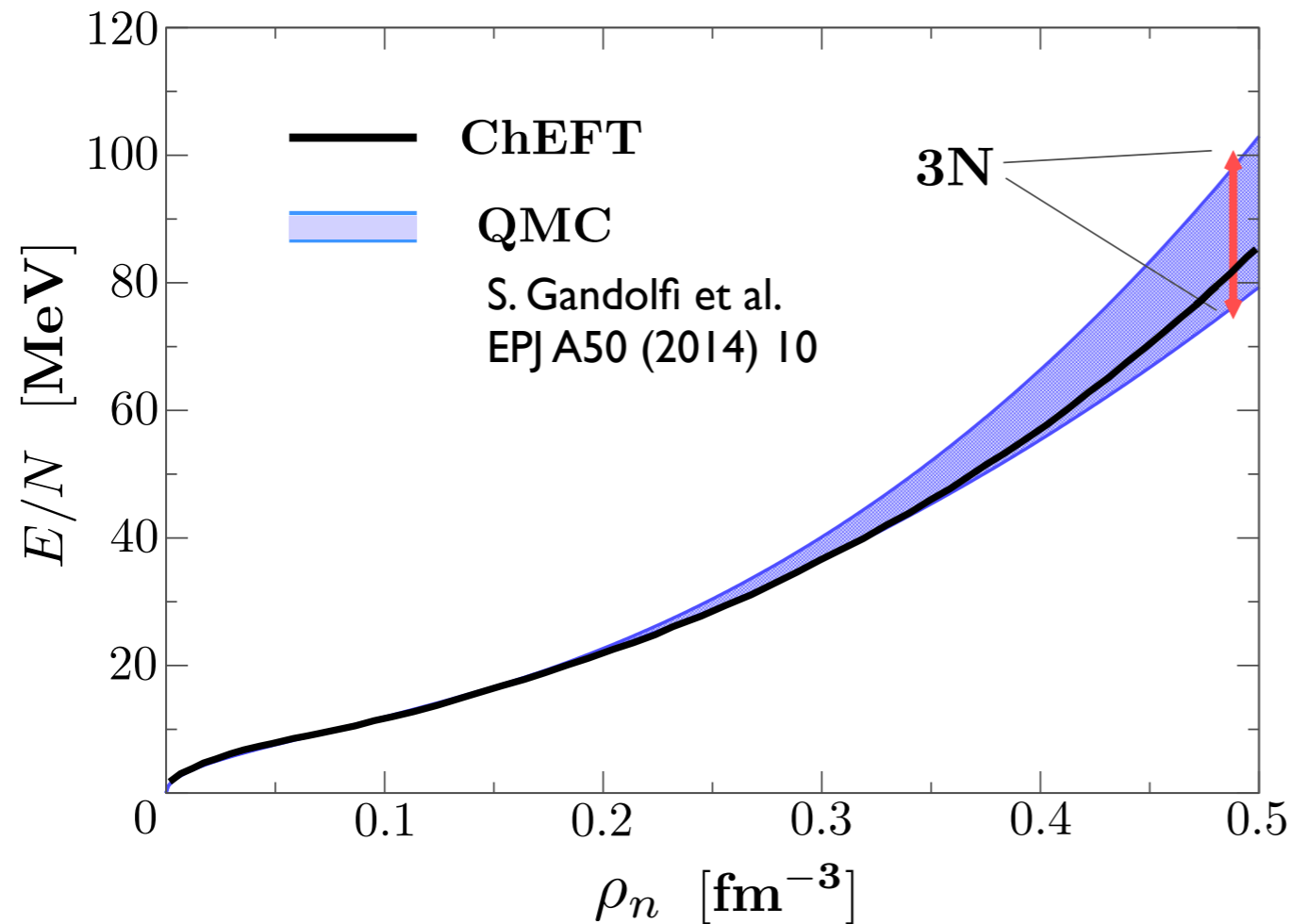
$\frac{\rho}{\rho_0}$ ($\rho_0 = 0.15 \text{ fm}^{-3}$)

... 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, $a_s = 19$ fm)



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

- Bertsch parameter

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

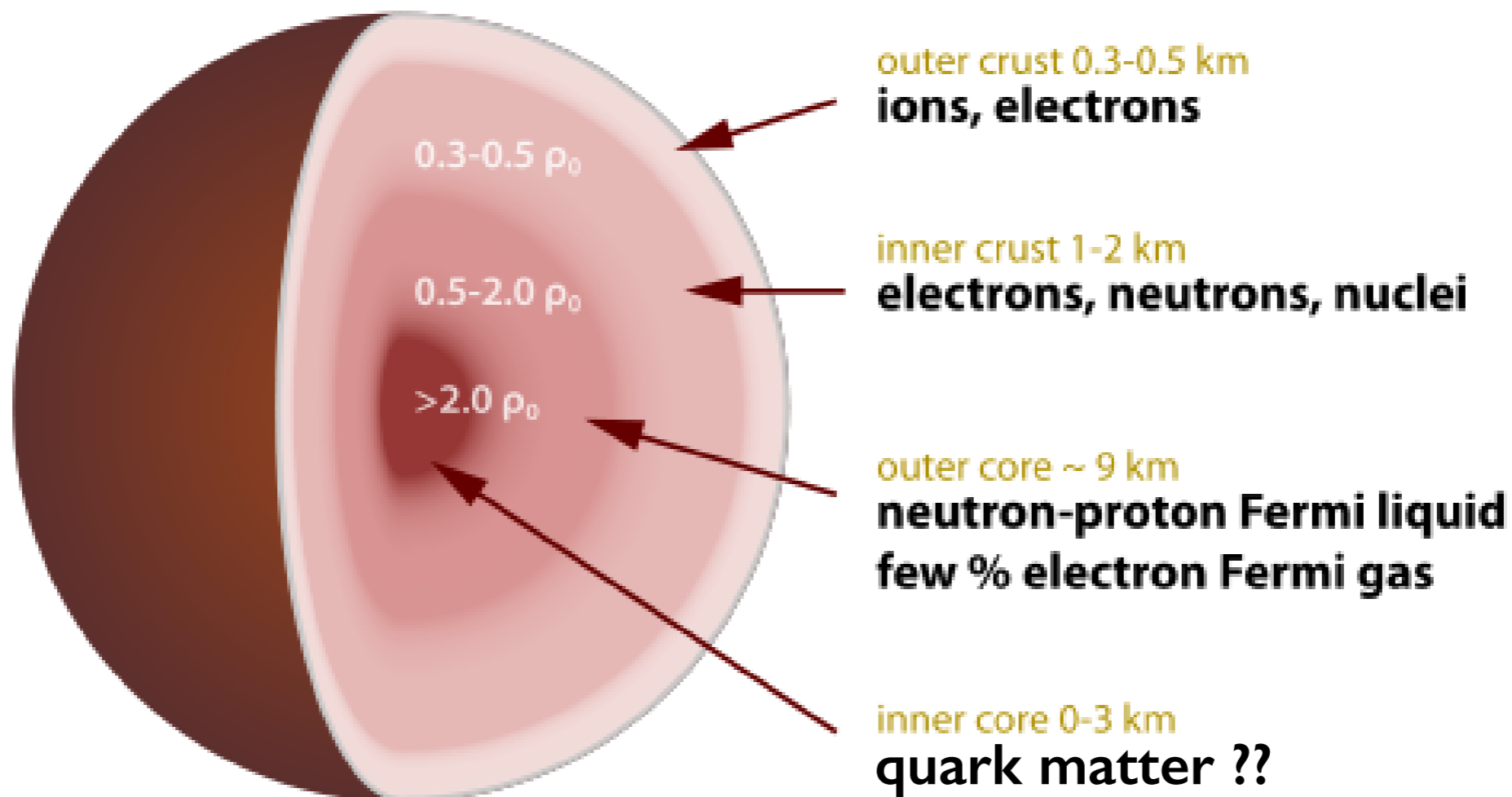
J.W. Holt, N. Kaiser, W.W.
Phys. Rev. C 87 (2013) 014338

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

- agreement with advanced many-body calculations (e.g. recent Quantum Monte Carlo computations)



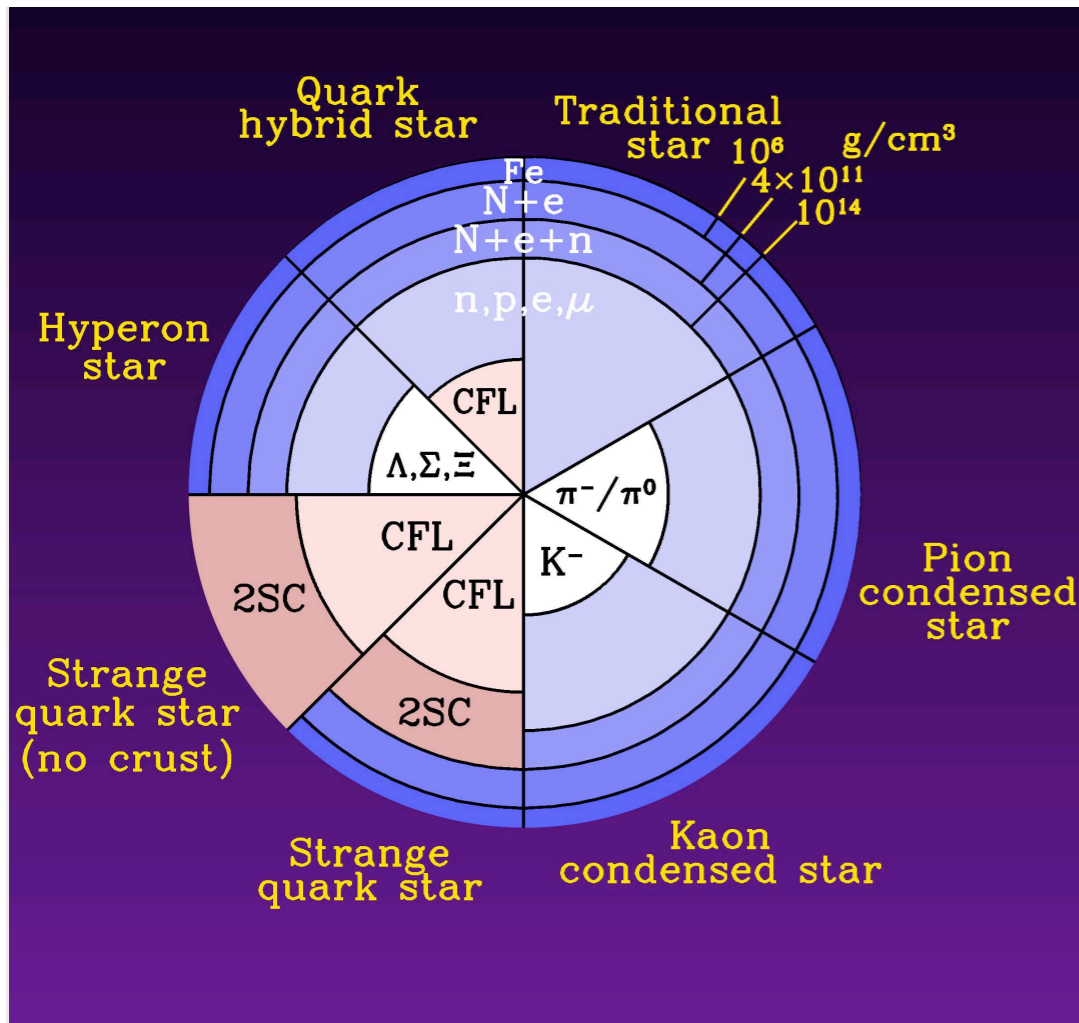
4. Outlooks: **New Constraints** from **NEUTRON STARS**



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

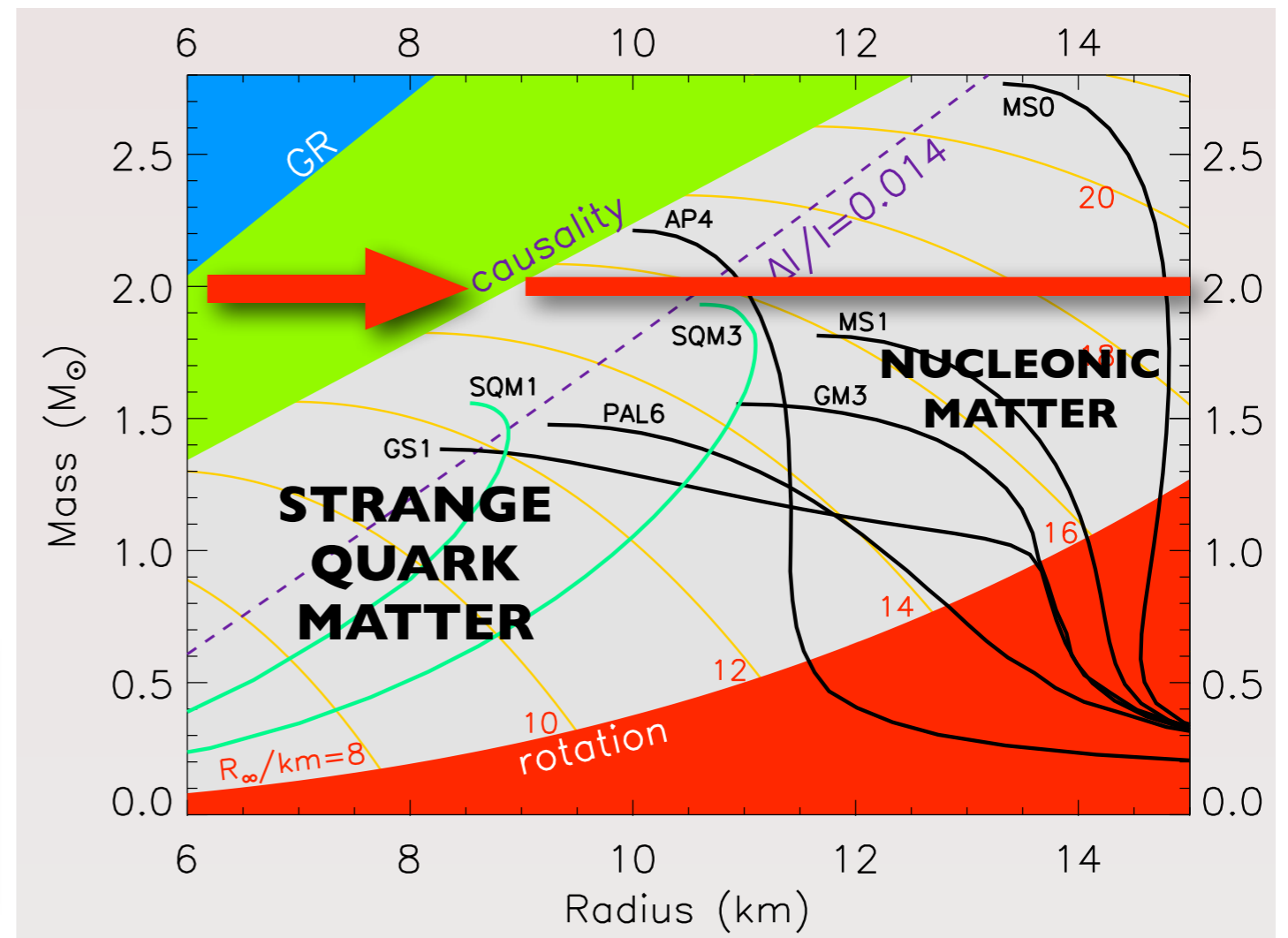
● Mass-Radius Relation



Neutron Star Scenarios Tolman-Oppenheimer-Volkov Equations

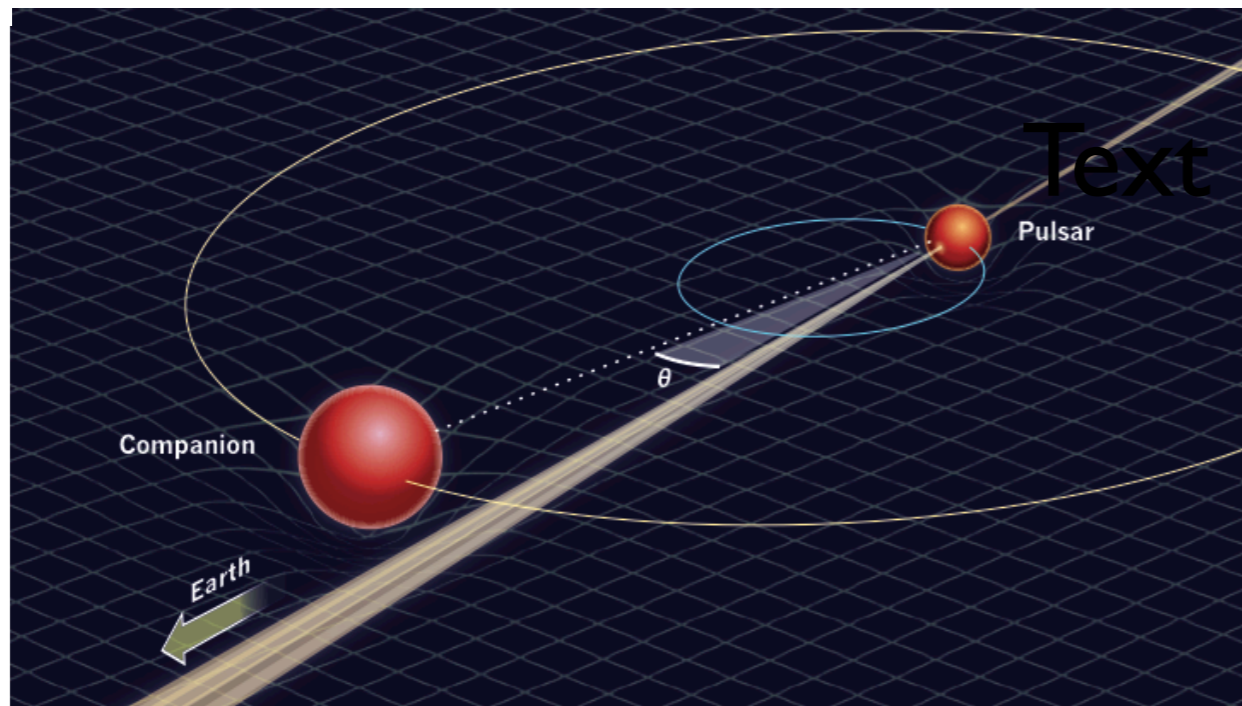
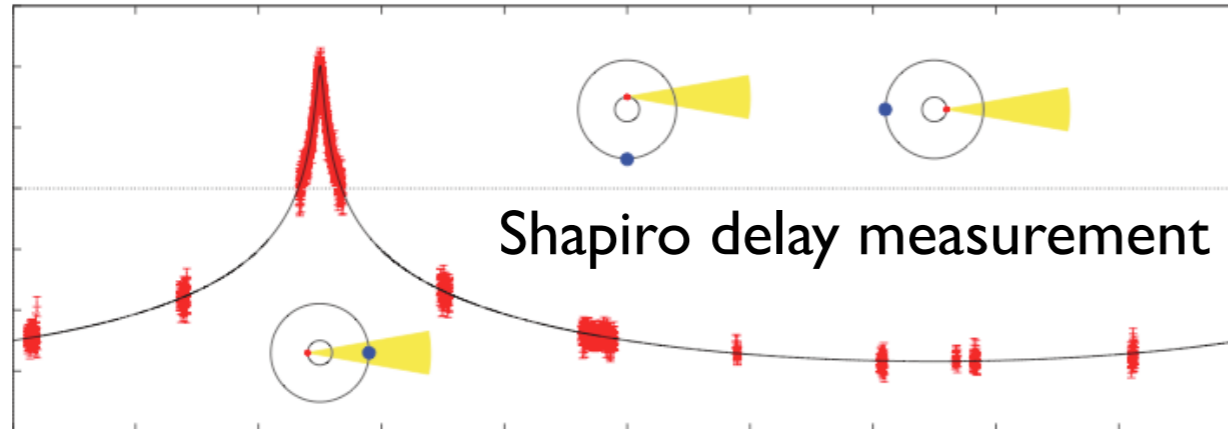
$$\frac{dP}{dr} = -\frac{G}{c^2} \frac{(M + 4\pi Pr^3)(\mathcal{E} + P)}{r(r - GM/c^2)}$$

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



New constraints from NEUTRON STARS

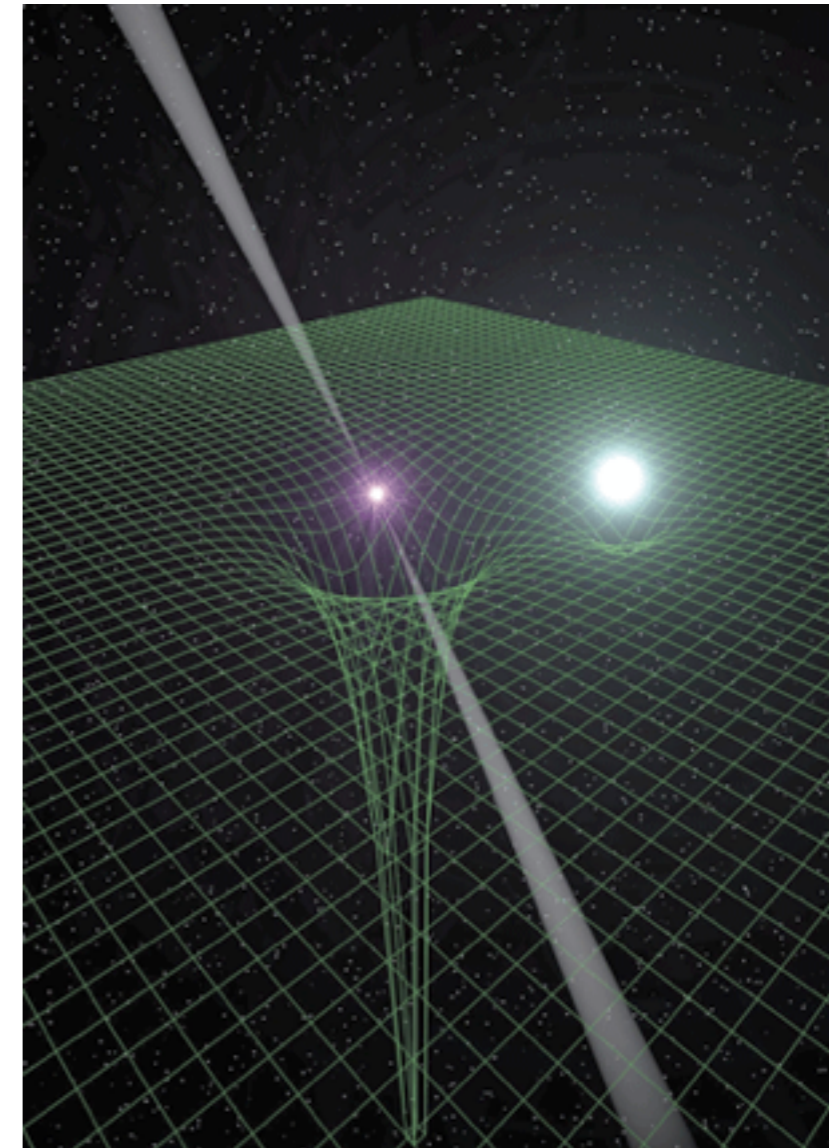
P.B. Demorest et al.
Nature 467 (2010) 1081



PSR J1614+2230

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

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



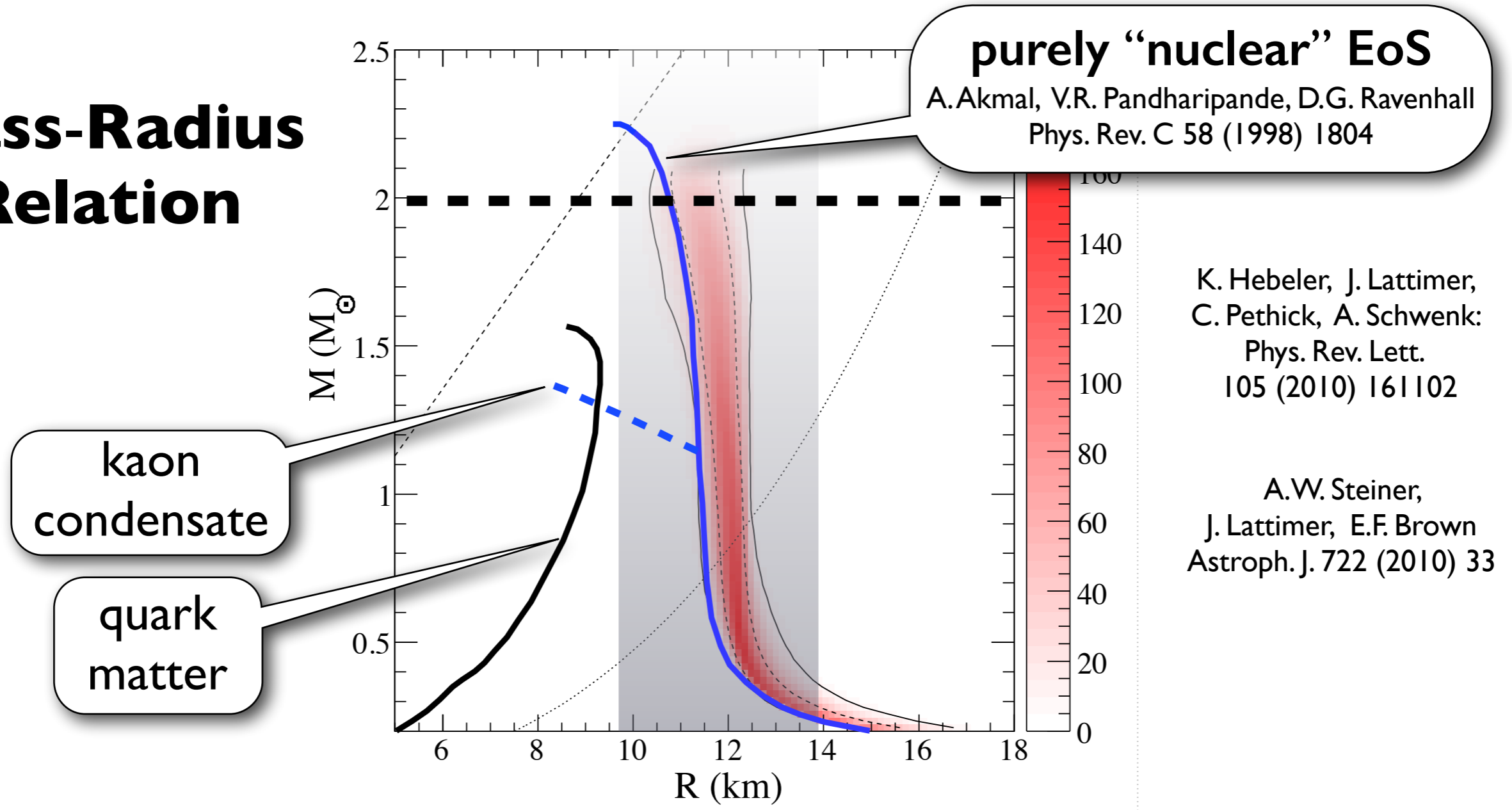
PSR J0348+0432

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

News from **NEUTRON STARS**

- Constraints from neutron star observables

Mass-Radius Relation

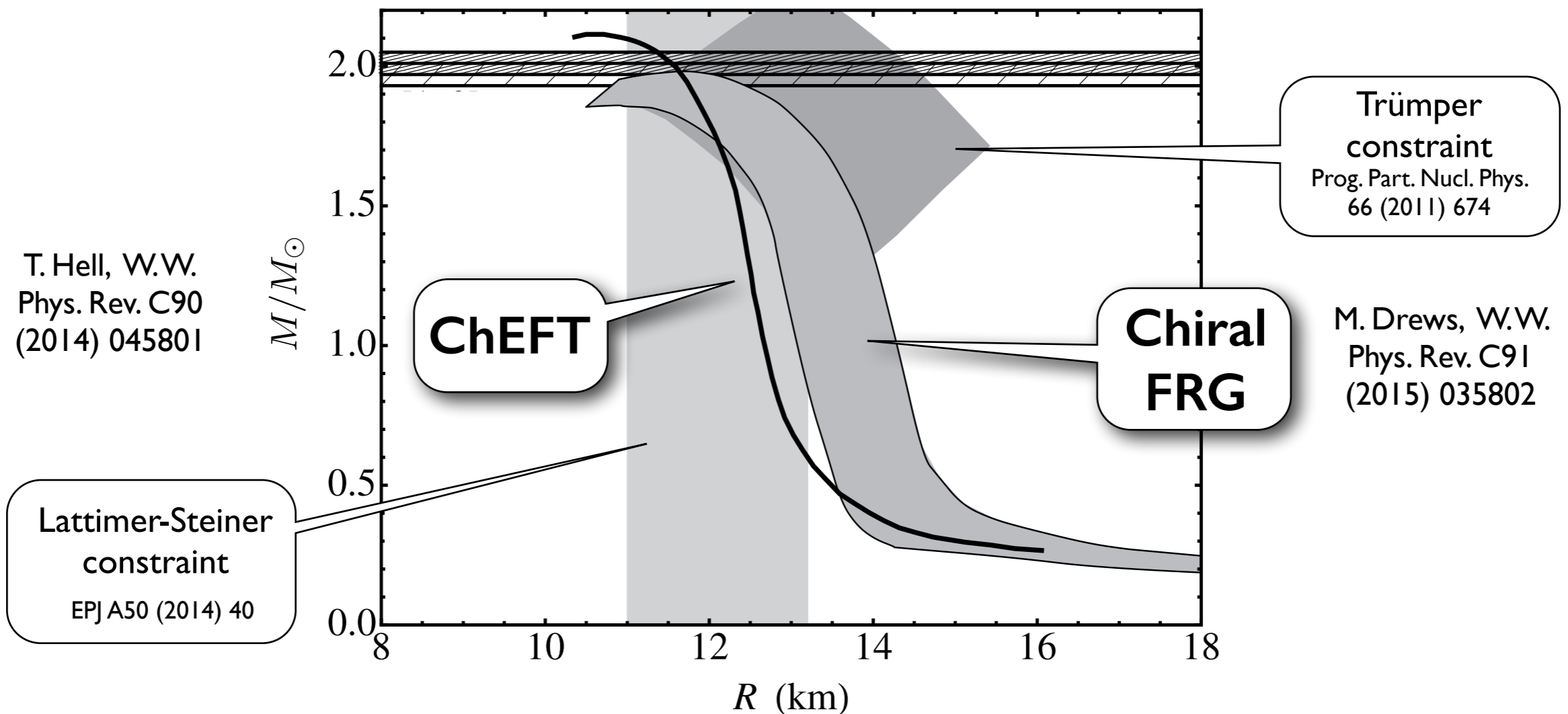


- “Exotic” equations of state ruled out ?

NEUTRON STAR MATTER

from **Chiral Effective Field Theory** and **Functional Renormalization Group**

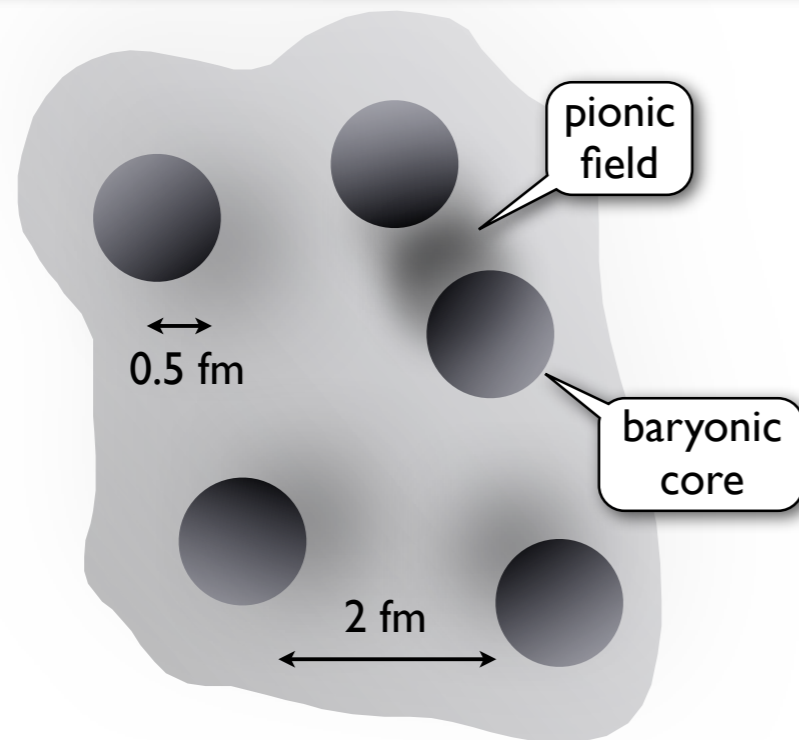
- Neutron matter plus proton admixture (beta equilibrium)
- Symmetry energy range: 30 - 37 MeV



- Chiral many-body dynamics using “conventional” (pion & nucleon) degrees of freedom is consistent with neutron star constraints

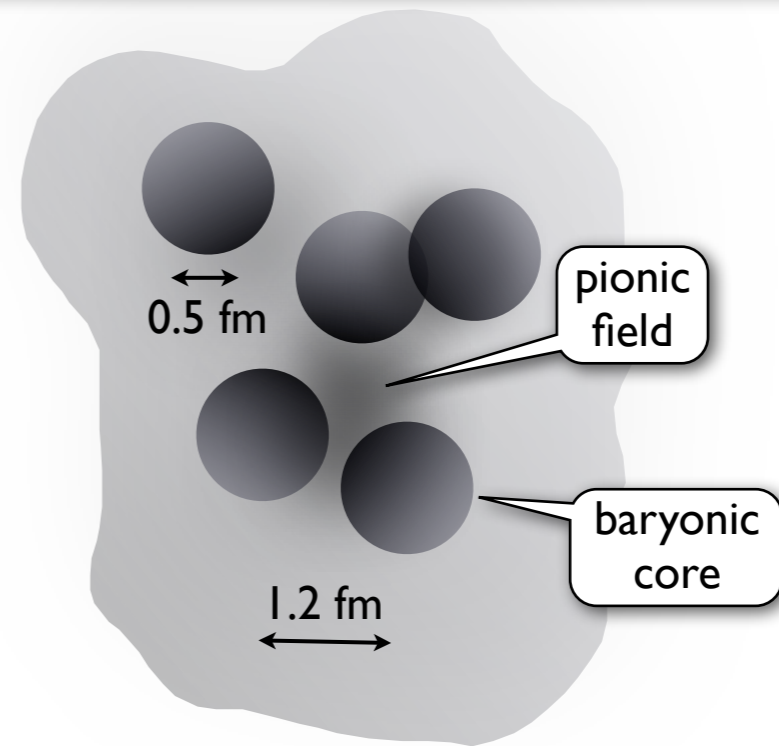


Densities and Scales in Compressed Baryonic Matter



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

normal nuclear matter: dilute

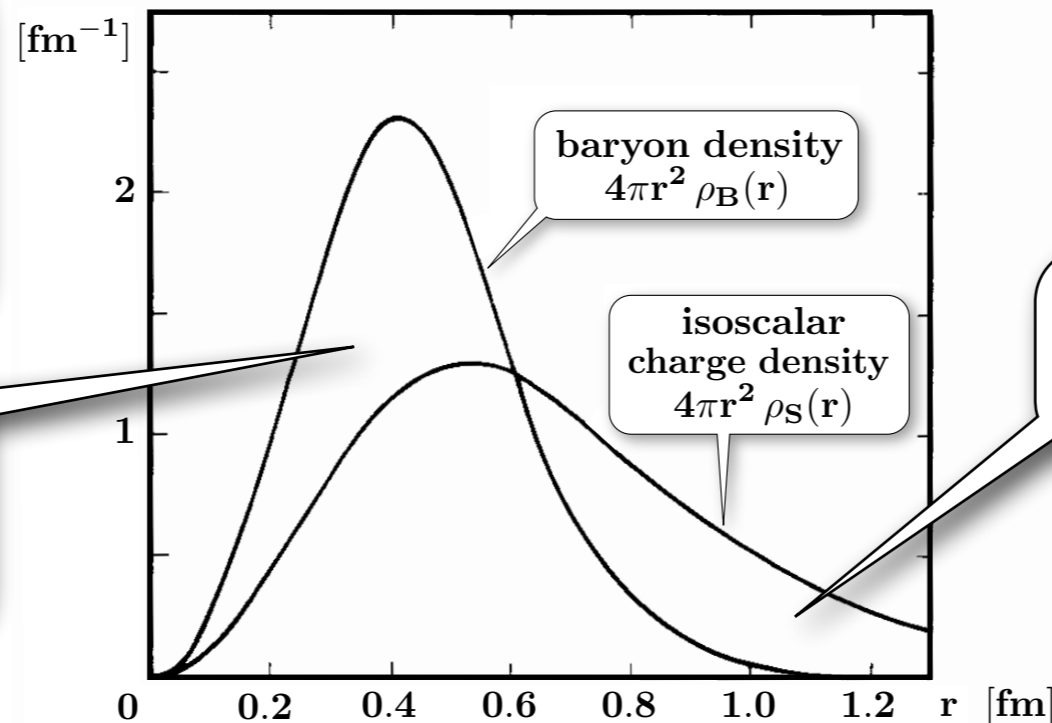


$$\rho_B = 0.6 \text{ fm}^{-3}$$

neutron star core matter:
compressed but not superdense

● chiral (soliton) model of the nucleon

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



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

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

... treated properly in chiral EFT

CONCLUSIONS

- Systematic approach at the interface of QCD (with light quarks) 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 ($\rho_{\text{core}} \lesssim 5 \rho_0$)
 - ▶ “**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

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Robert Lang

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