Phases of Strongly Interacting Matter

- From Quarks to Nuclei and Neutron Stars -

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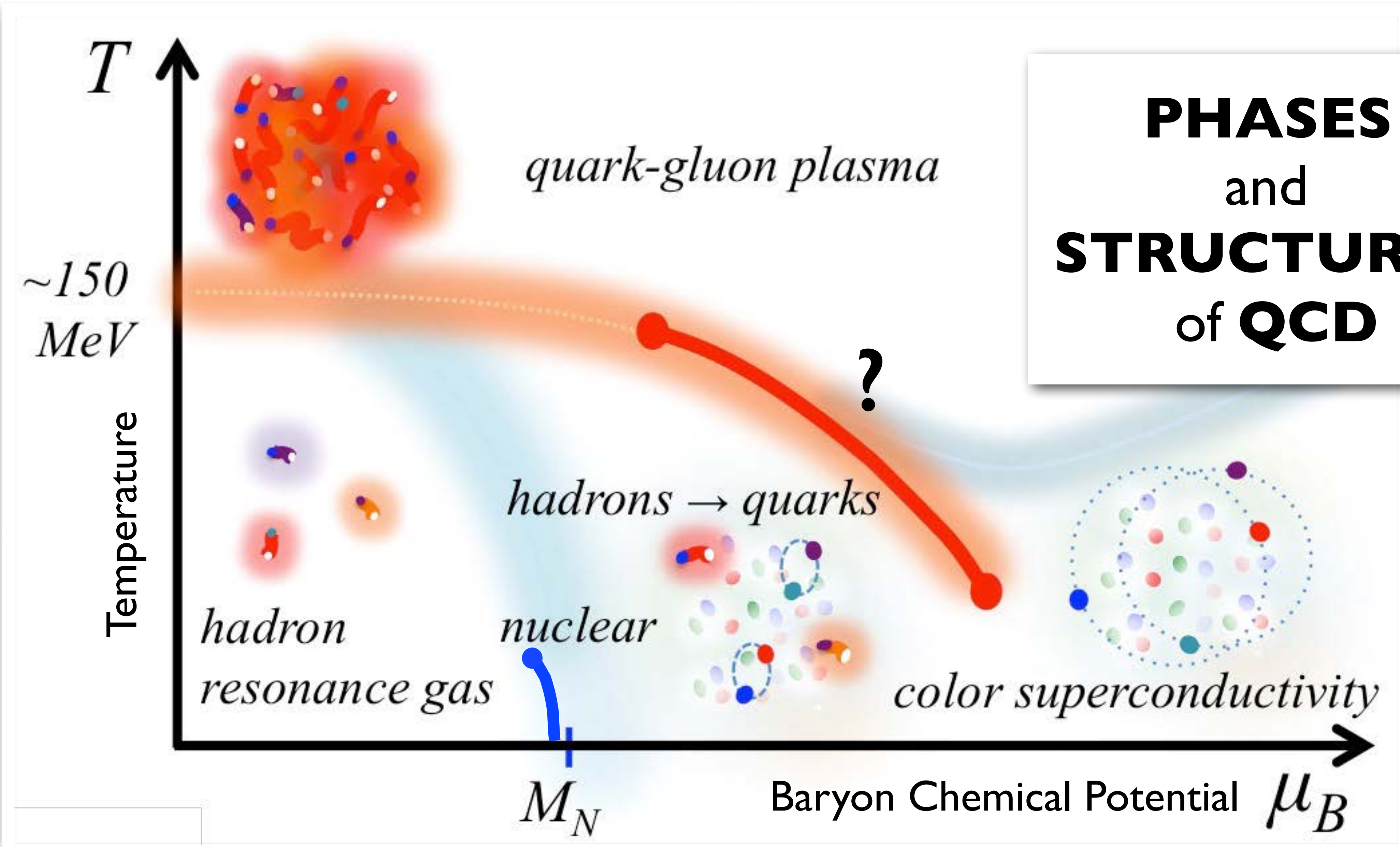
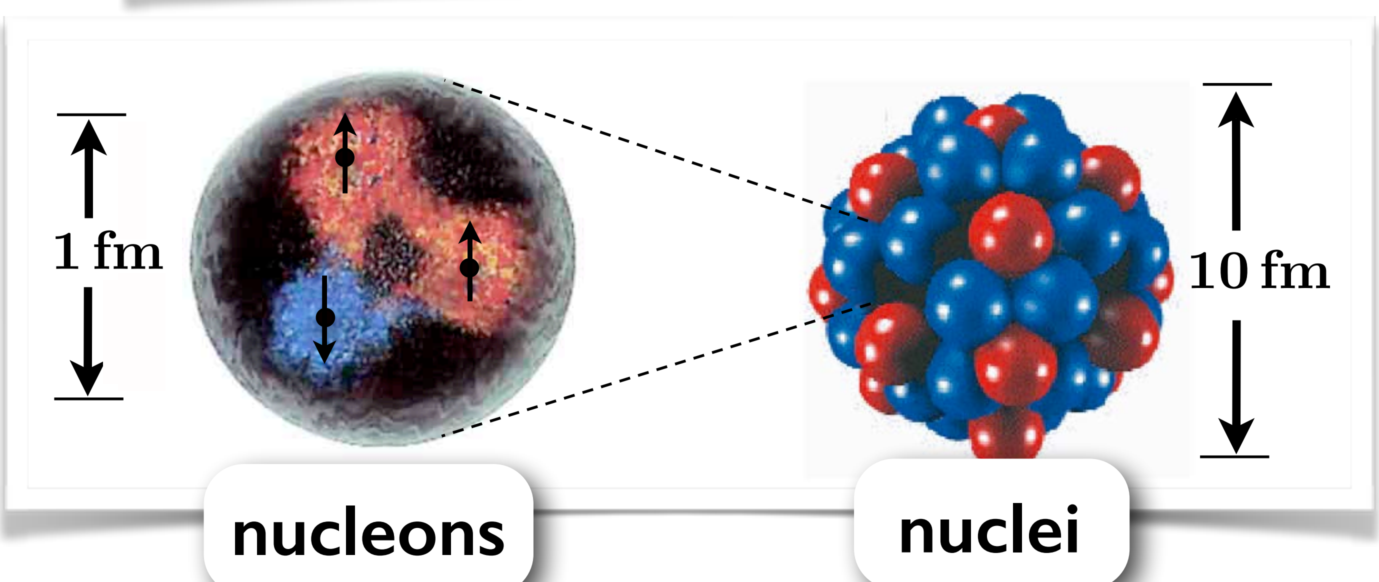
- QCD symmetries and scales
  - From massless quarks to massive nucleons
  - Chiral symmetry and interface with nuclear physics
- QCD phase diagram
  - High temperature: confinement / deconfinement transition
  - Moderate temperatures and densities: nuclear thermodynamics
  - High baryon density: constraints from massive neutron stars

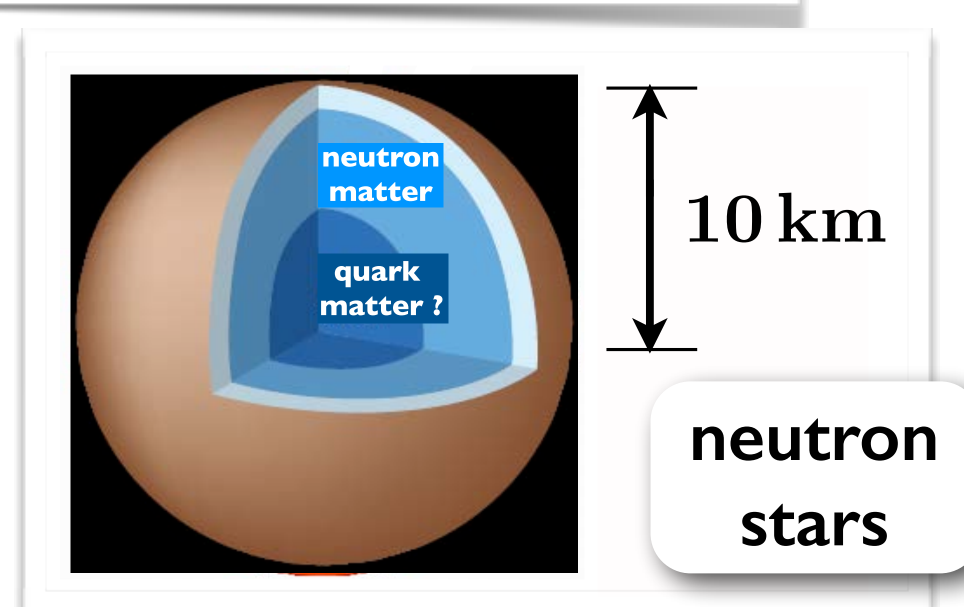
PHASES and STRUCTURES of QCD



from:
G. Baym,
T. Hatsuda,
et al.

Rept. Prog. Phys. 81 (2018) 056902





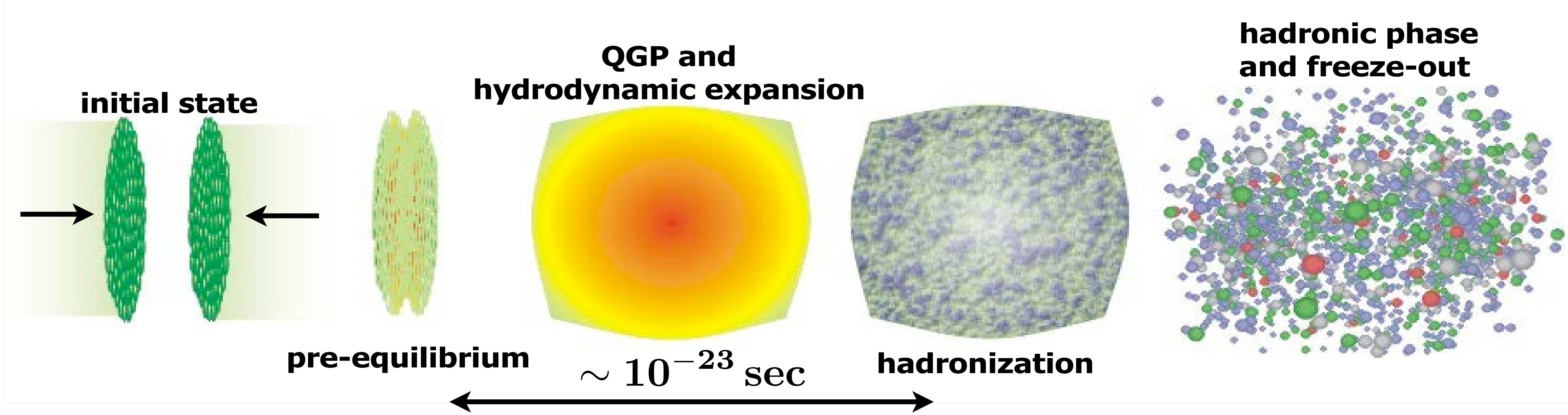
1.

Preview :

What do we know about the PHASES of QCD ?

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

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

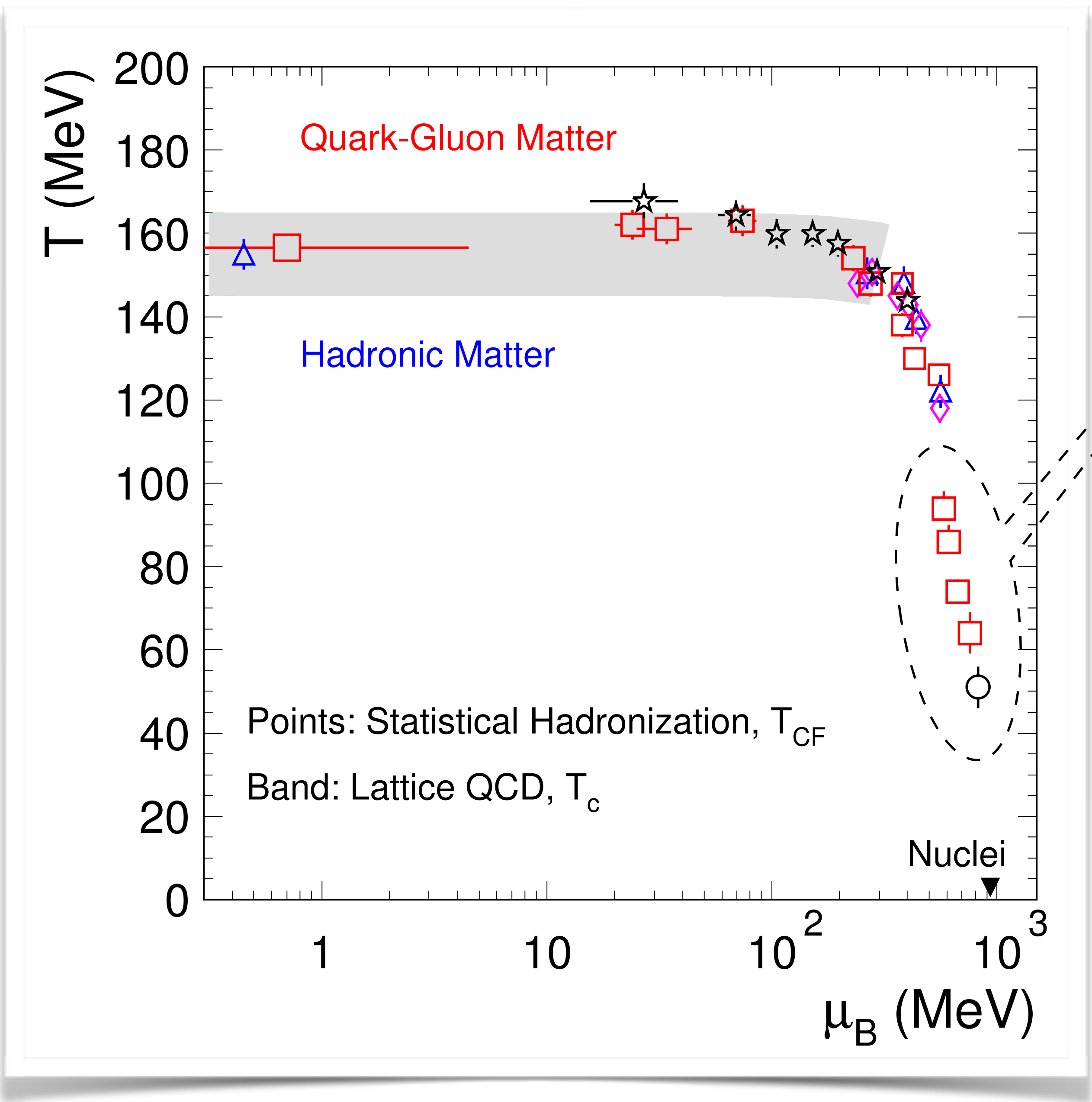


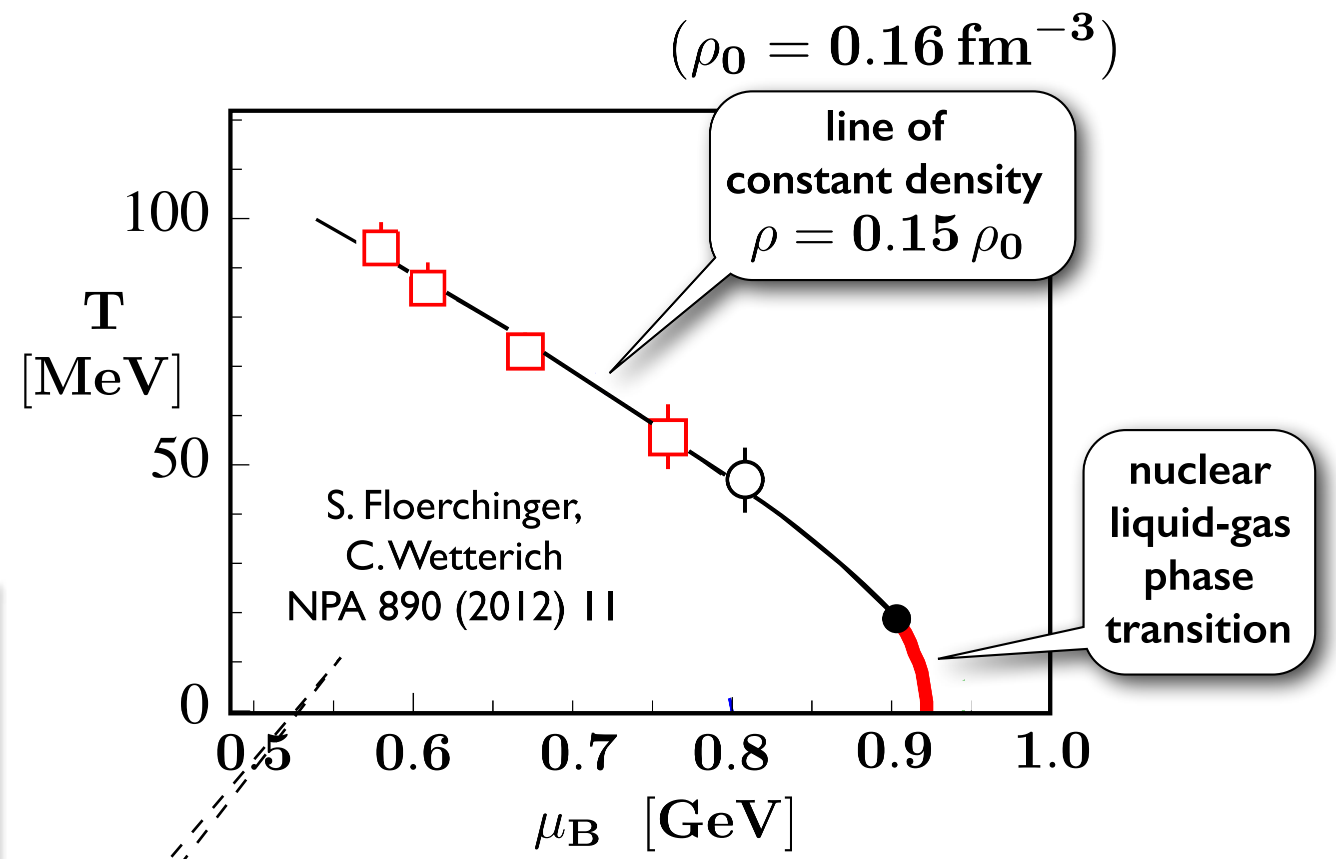
- Analysis of **RHIC** and **LHC** data:

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

CHEMICAL FREEZE-OUT

A. Andronic, P. Braun-Munzinger, K. Redlich. J. Stachel
Nature 561 (2018) 321





- **Freeze-out temperature**
  $$T_{CF} = 156 \pm 2 \text{ MeV}$$
  at $\mu_B \simeq 0$

- **Low-temperature freeze-out trajectory : NOT a first-order phase transition line**

Strategies PART II: **Lattice QCD**

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

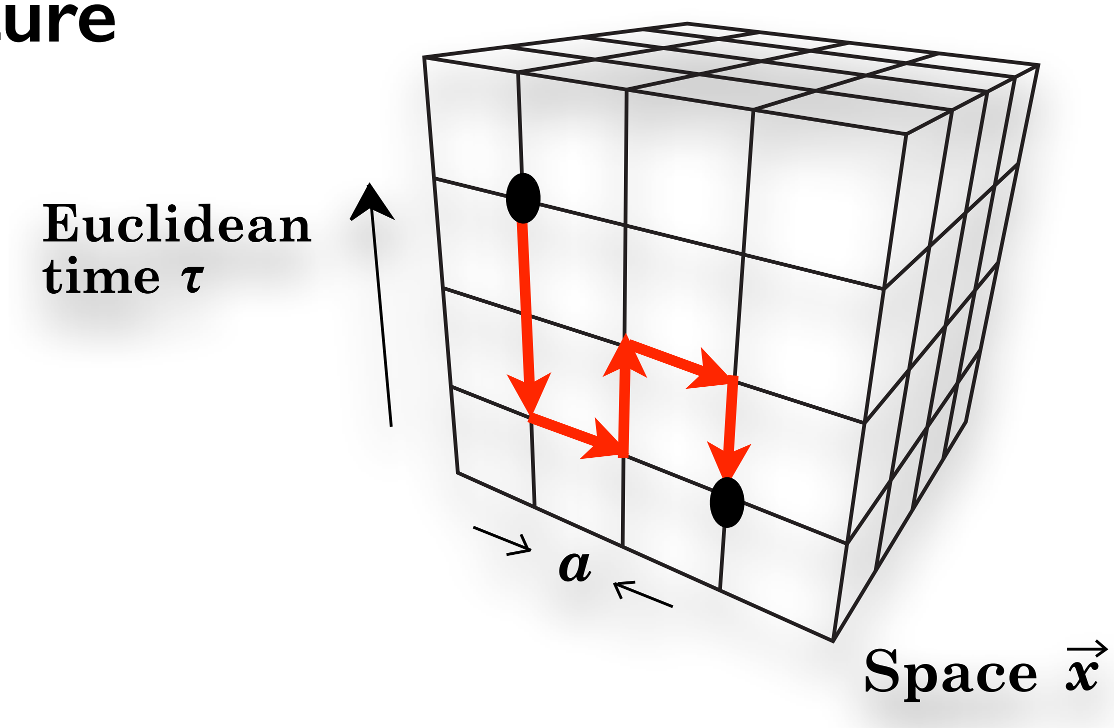
- Large-scale computer simulations on
  EUCLIDEAN SPACE-TIME Lattices

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

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

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**

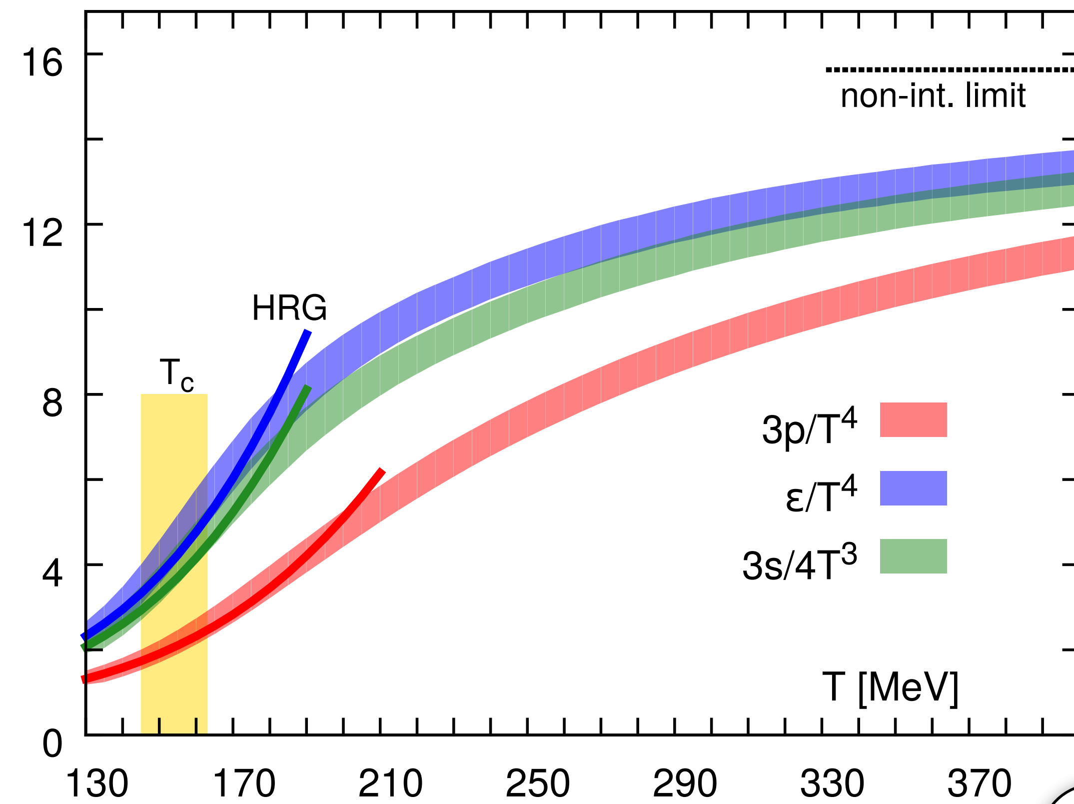
QCD THERMODYNAMICS on the LATTICE

baryon chemical potential

$$\mu_B = 0$$

crossover

(not a phase transition)

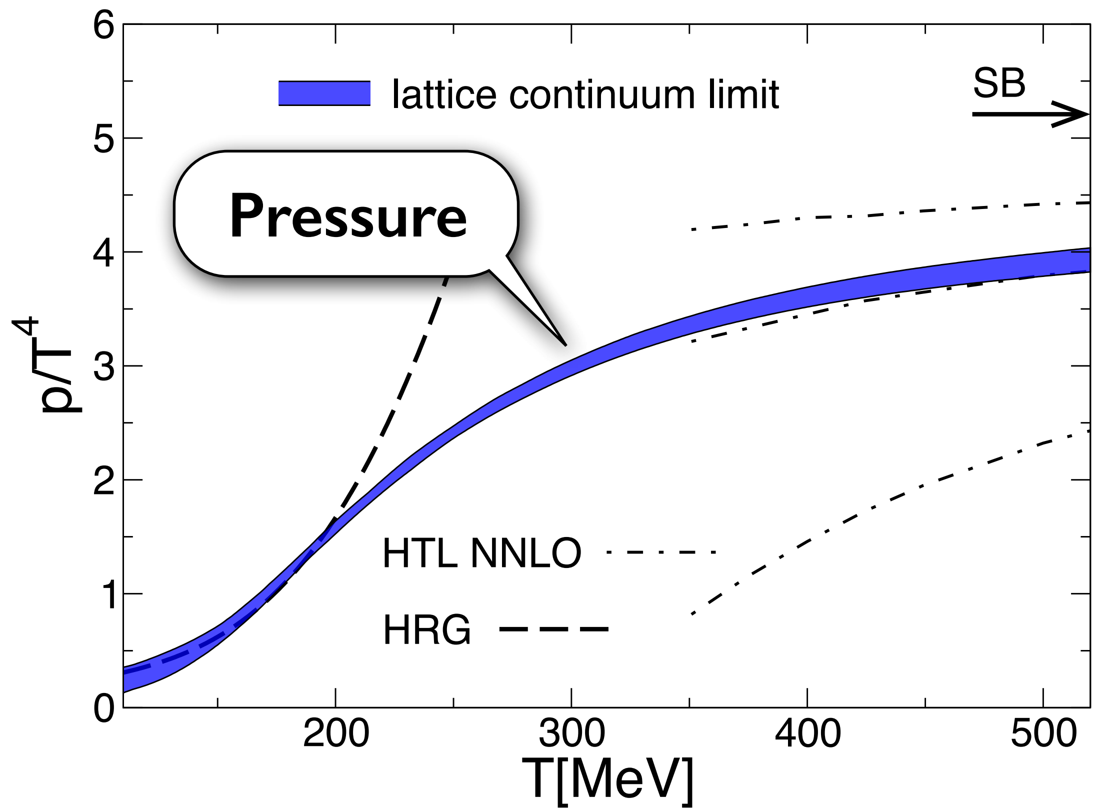


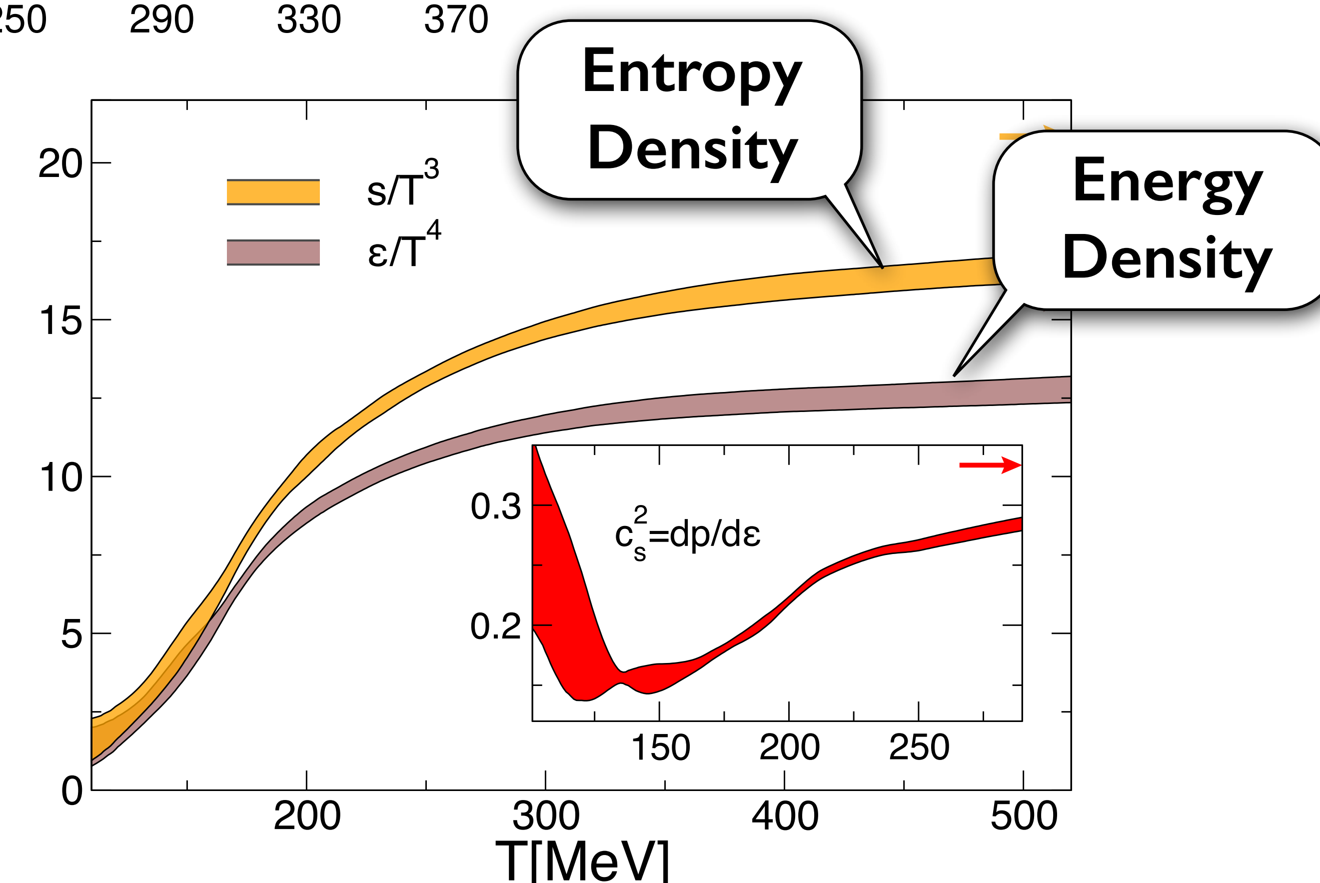
A. Bazavov et al. (HotQCD collab.)
Phys. Rev. D90 (2014) 094503

transition temperature

$$T_c \simeq 154 \pm 9 \text{ MeV}$$

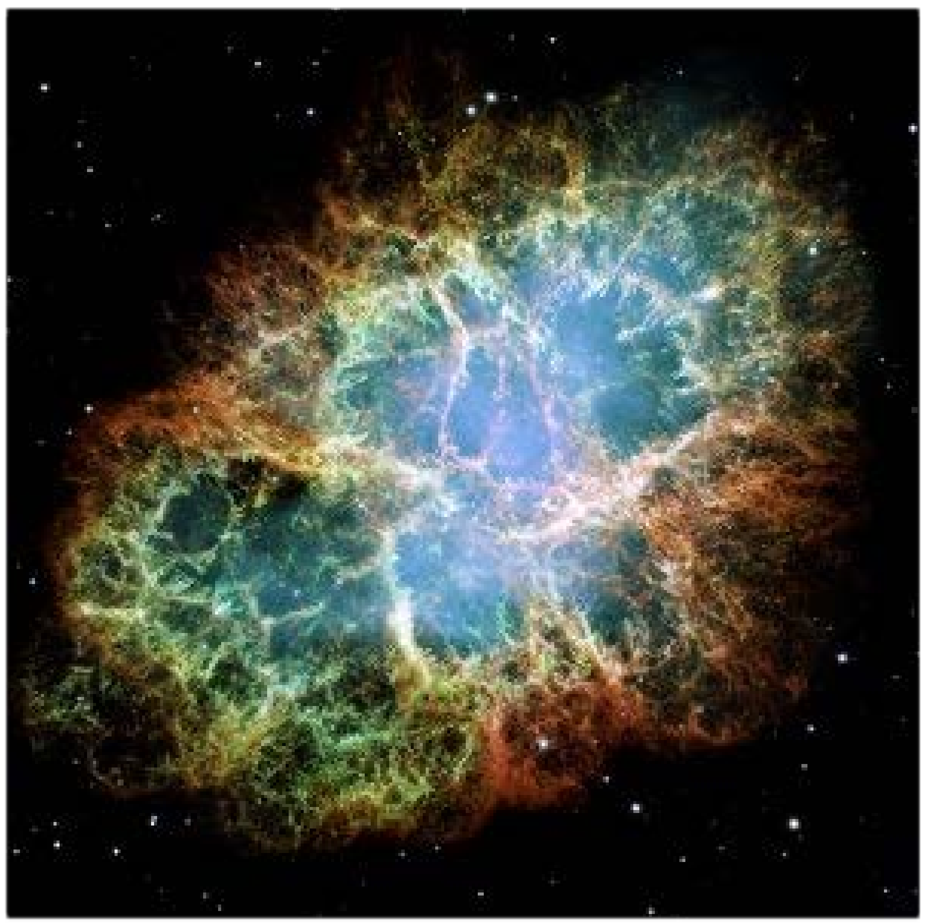
S. Borsanyi et al.
Phys. Lett. B 738 (2014) 187

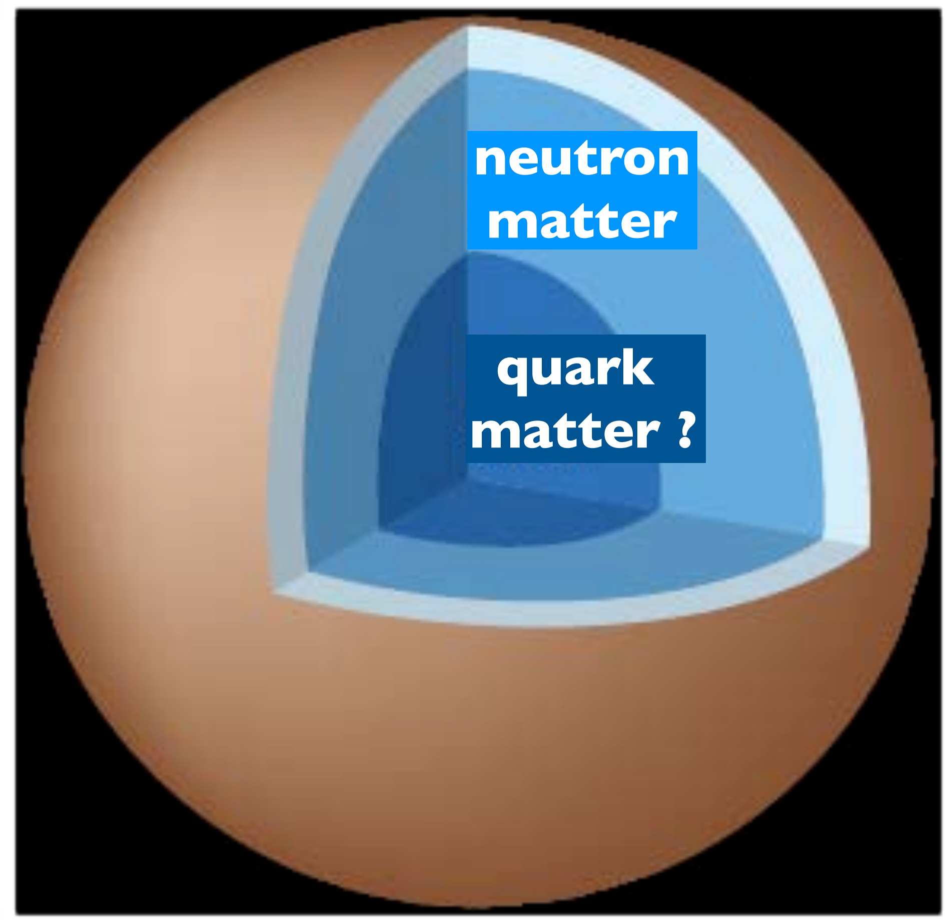




Strategies PART III: **Astrophysical Observations**

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

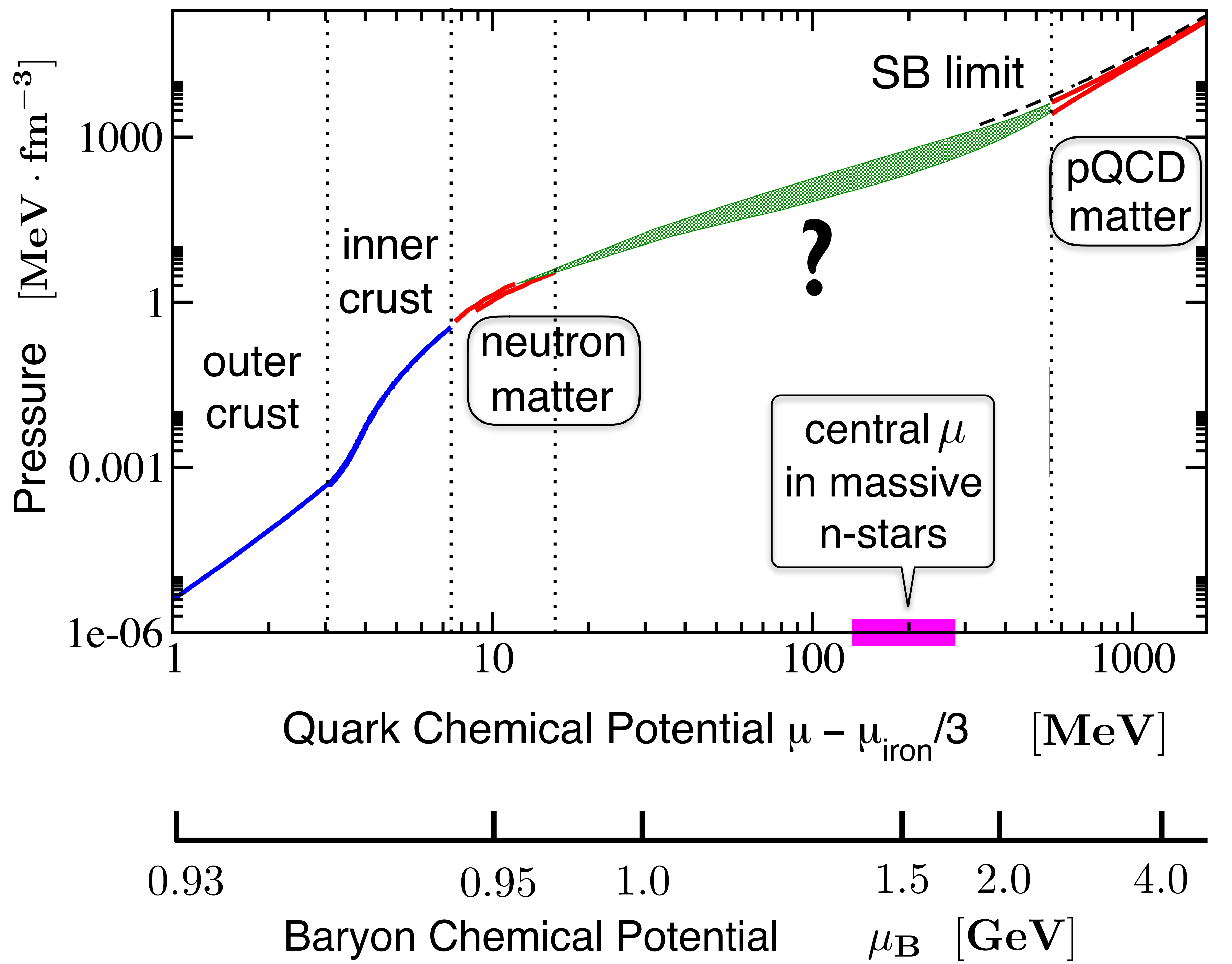




- from **Supernovae** to **Neutron Stars**

… and **neutron star merger GW's (LIGO & Virgo)**

EQUATION of STATE
NEUTRON STARS and beyond



A. Kurkela,
E.S. Fraga,
J. Schaffner-Bielich,
A. Vuorinen

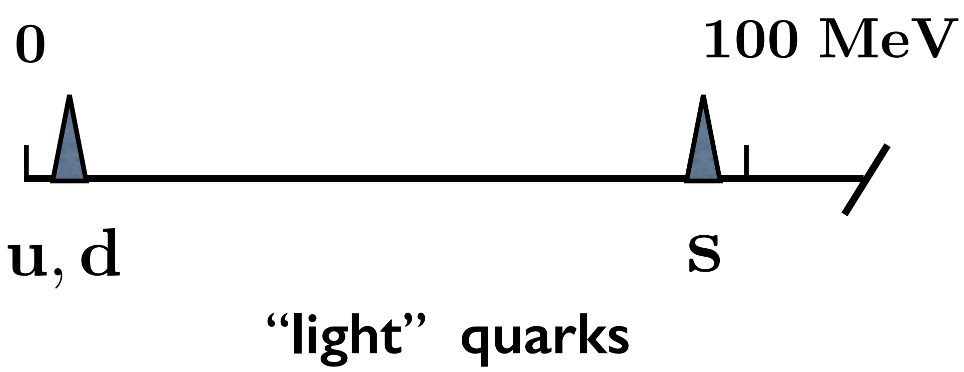
Astroph. J.
789 (2014) 127

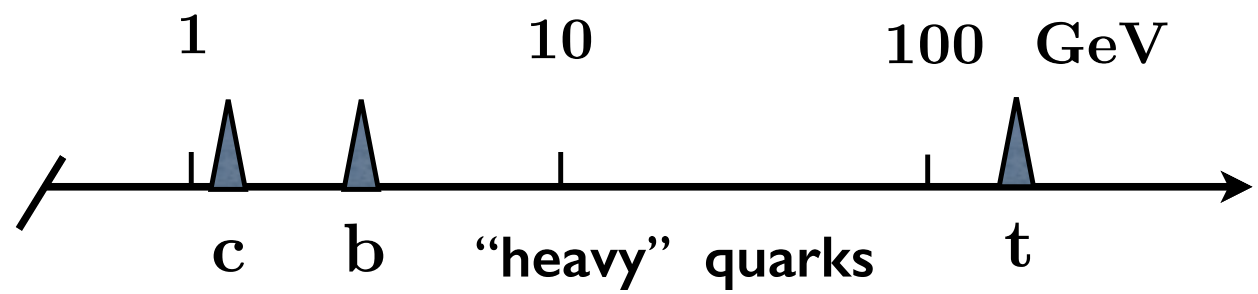
2.

QCD Symmetries, Symmetry Breaking Patterns and Scales

Hierarchy of QUARK MASSES in QCD

- Separation of Scales -





$$m_u = 2.2 \pm 0.5 \text{ MeV}$$

$$m_d = 4.7 \pm 0.5 \text{ MeV}$$

$$m_s = 95^{+9}_{-3} \text{ MeV}$$

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

PDG 2018

CHIRAL EFFECTIVE FIELD THEORY
of **pions & nucleons**

- **Idealised QCD**
  $m_{u,d} \rightarrow 0$
- **Scale Invariance**
  and
  Trace Anomaly
  from **massless quarks** to **massive nucleons**
- **Chiral Symmetry**
  spontaneously broken at low energy

CHIRAL SYMMETRY

- (almost) **massless u- and d-quarks :**

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

  - Low energy : **spontaneous chiral symmetry breaking**
  - **PIONS** as (almost) massless **Nambu-Goldstone bosons**

- **Symmetry breaking scale :**

$$\mathbf{\Lambda}_\chi = 4\pi\, \mathbf{f}_\pi \sim \mathbf{1\,GeV}$$

  - **Pion decay constant :**

$\mathbf{f}_\pi^{(0)} \simeq \mathbf{86\,MeV}$ (chiral limit) $\qquad$ $\mathbf{f}_\pi \simeq \mathbf{92\,MeV}$ (empirical)

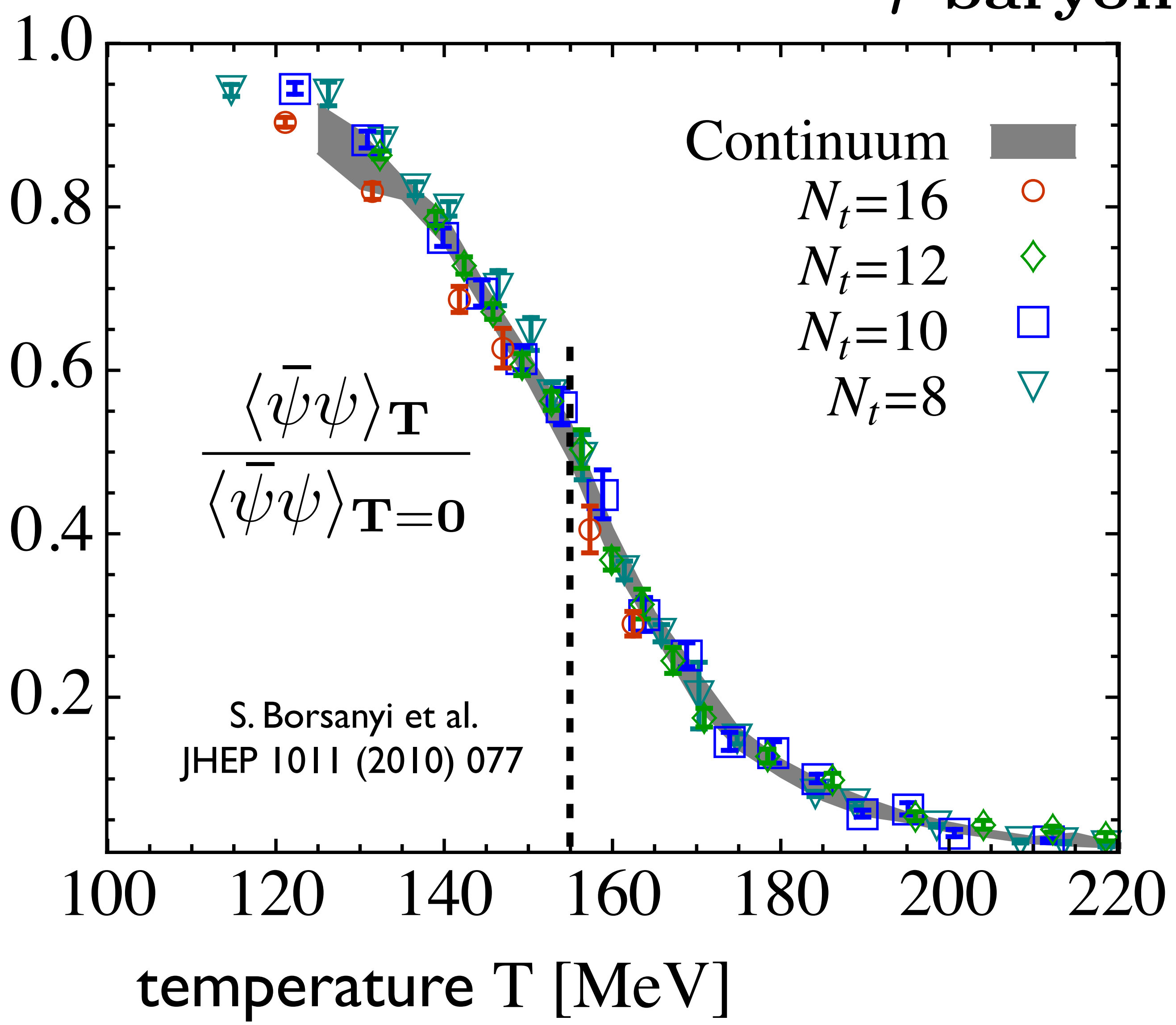
- **Order parameter $\mathbf{f}_\pi$:**

  - **Chiral (quark) condensate and sigma field**

$$\mathbf{f}_\pi^2 = -\frac{\mathbf{m_u} + \mathbf{m_d}}{\mathbf{2\,m}_\pi^2}\langle \bar{\mathbf{q}}\mathbf{q}\rangle = \langle\sigma\rangle^2$$

LATTICE QCD THERMODYNAMICS: CHIRAL and DECONFINEMENT TRANSITIONS

$$\mu_{\mathbf{baryon}} = 0$$



Quark Condensate

Order Parameter
of
spontaneously broken
Chiral Symmetry

Crossover
transition temperature

$$\mathrm{T_c} \simeq 155\,\mathrm{MeV}$$

CHIRAL and **DECONFINEMENT**
crossover transitions appear to be closely **connected**

SCALE INVARIANCE, TRACE ANOMALY and MASS of the NUCLEON

- QCD with massless quarks : no dimensional parameter
  - Invariance under scale transformations $\mathbf{x} \to \lambda \mathbf{x}$
  - Trace of energy-momentum tensor $\Theta_{\mu\nu}$ vanishes classically …
- … but - QCD as a QFT introduces renormalisation scale, and so :

$$\Theta^\mu_\mu \propto \mathbf{Tr}\left[G_{\mu\nu}G^{\mu\nu}\right]$$ (**TRACE ANOMALY**)

- From **MASSLESS QUARKS** to **MASSIVE NUCLEONS** :

$$\mathbf{M_N^{(0)}} = \langle N|\Theta^\mu_\mu|N\rangle = \frac{9}{4}\langle N\left|\frac{\alpha_s}{\pi}(\mathbf{E^2} - \mathbf{B^2})\right|N\rangle \simeq \mathbf{0.89\,GeV}$$

  - Physical nucleon mass : $\mathbf{M_N} = \mathbf{M_N^{(0)}} + \sigma_\mathbf{N} = \mathbf{0.94\,GeV}$
  - Sigma term : $\sigma_\mathbf{N} = \frac{1}{2}(m_u + m_d)\langle N\left|\bar{u}u + \bar{d}d\right|N\rangle$

NUCLEON MASS
- two aspects of symmetry breaking in QCD -

$$\propto \langle \mathbf{N} | \mathbf{Tr} \, [\mathbf{G}_{\mu\nu} \mathbf{G}^{\mu\nu}] | \mathbf{N} \rangle$$

TRACE ANOMALY

Gluon dynamics

$$\mathbf{M_N}$$

$$= g \, \mathbf{f}_\pi \equiv g \, \langle \sigma \rangle \quad \left(g = \frac{g_{\pi N}}{g_A} \right)$$

Spontaneously broken

CHIRAL SYMMETRY

Goldberger - Treiman Relation

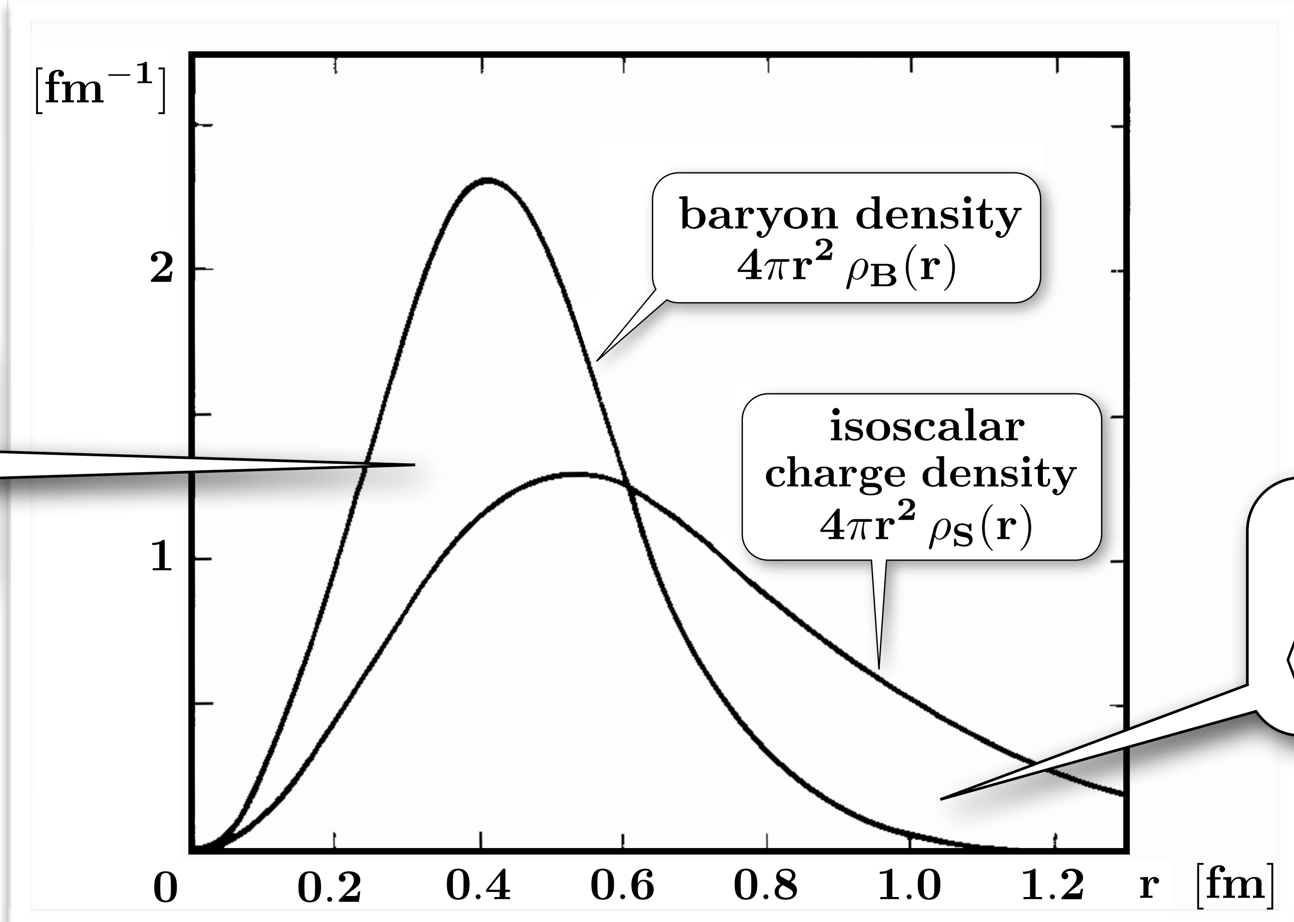
Reminder about **SIZES** :
CHIRAL SOLITON MODEL of the **NUCLEON**

Spontaneously broken chiral symmetry + localisation (confinement)

- **NUCLEON : compact valence quark core + mesonic cloud**

baryonic core

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



mesonic cloud

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

N. Kaiser,
U.-G. Meißner, W.W.

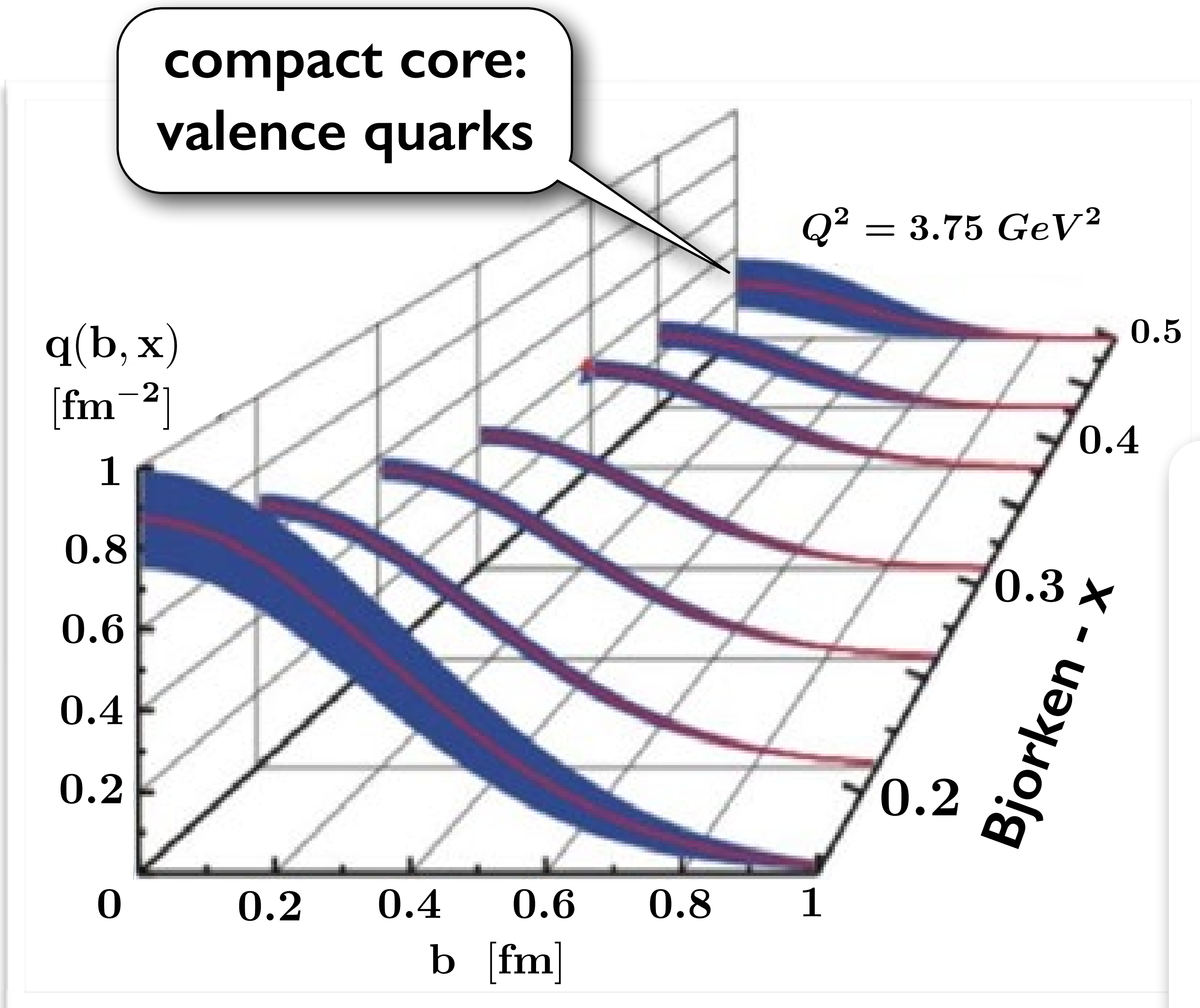
Nucl. Phys.
A466 (1987) 685

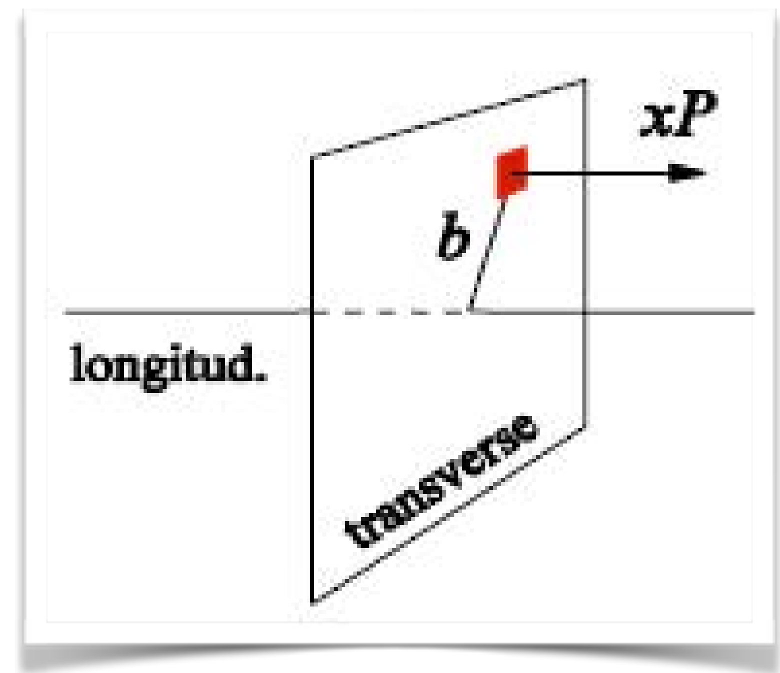
- Significant difference of scales between
compact baryonic core and (multi-)**pion cloud**

Transverse distributions of quarks in the proton

Deeply Virtual Compton Scattering @ JLab

R. Dupré, M. Guidal, M. Vanderhaeghen
Phys. Rev. D95 (2017) 011501





$$\langle b^2 \rangle \simeq 0.16\,\mathrm{fm}^2 \cdot \ln(1/x_B)$$

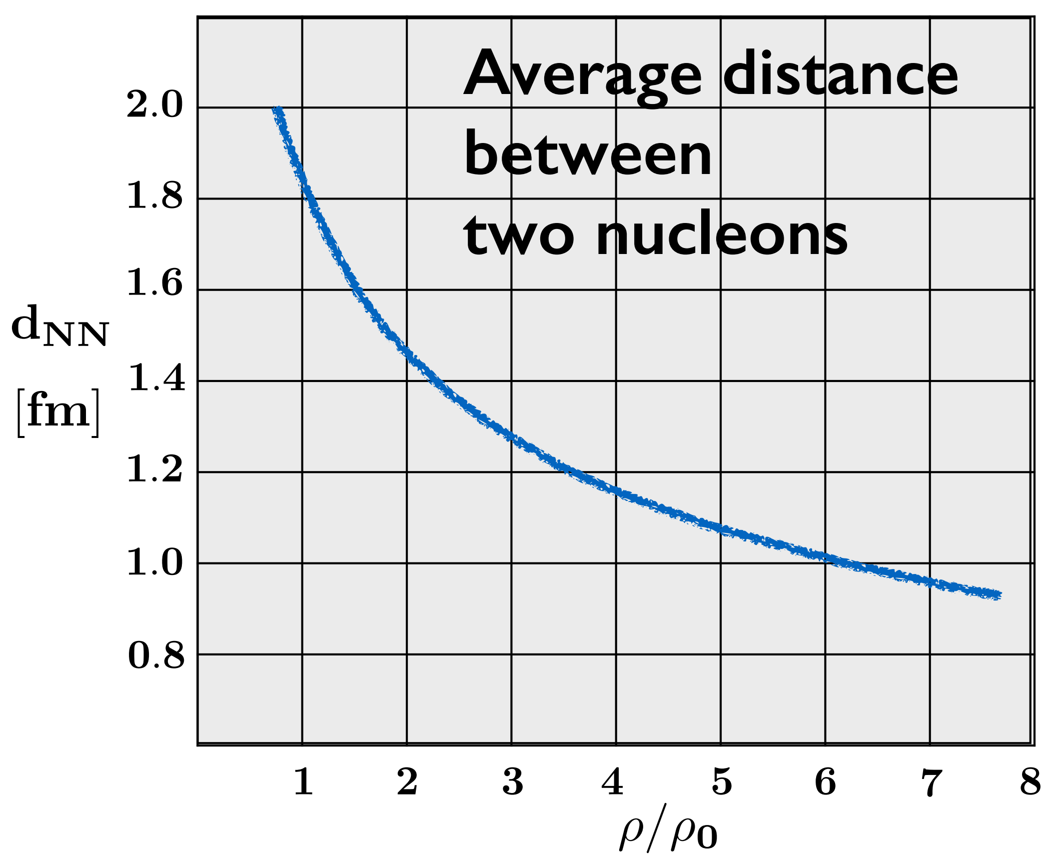
- **Valence quark region:**

$$\frac{1}{3} < x_B < \frac{1}{2}$$

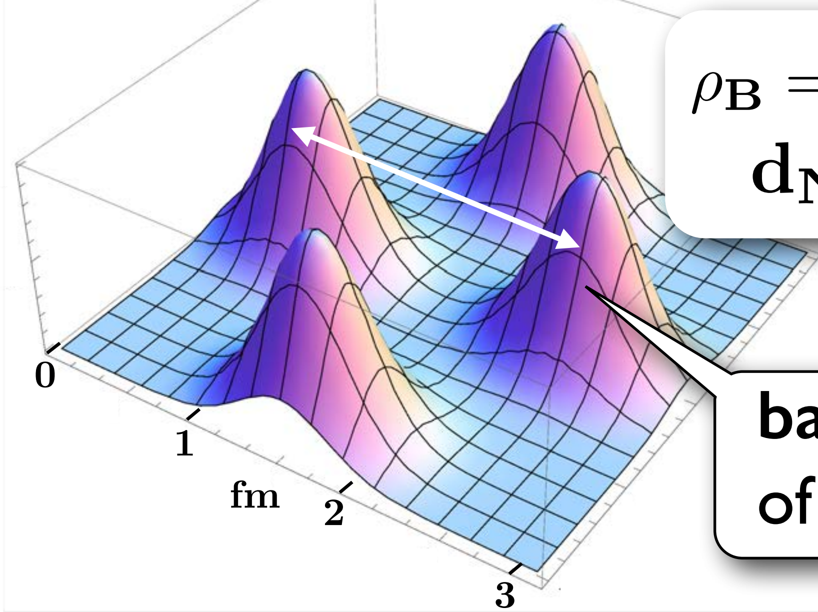
- **Core size:**

$$R_{core} = \sqrt{\frac{3}{2}\langle b^2 \rangle} \sim 0.4 - 0.5\ \mathrm{fm}$$

Densities and **Distance Scales** in **Baryonic Matter**



normal nuclear matter



$\rho_B = \rho_0 = 0.16\ \mathrm{fm}^{-3}$

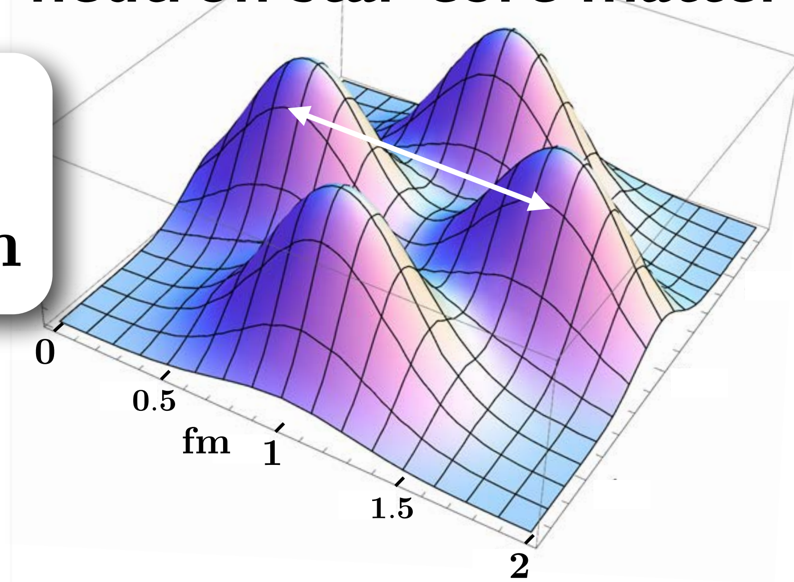
$d_{NN} \simeq 1.8\ \mathrm{fm}$

baryonic core of the nucleon

neutron star core matter

$\rho_B \sim 5\,\rho_0$

$d_{NN} \sim 1\ \mathrm{fm}$



- (Multi-)pion fields in space between baryonic sources (ChEFT)
- Quark cores of nucleons overlap (percolate) at baryon densities $\rho_B > 5\,\rho_0$

NUCLEAR FORCES from LATTICE QCD

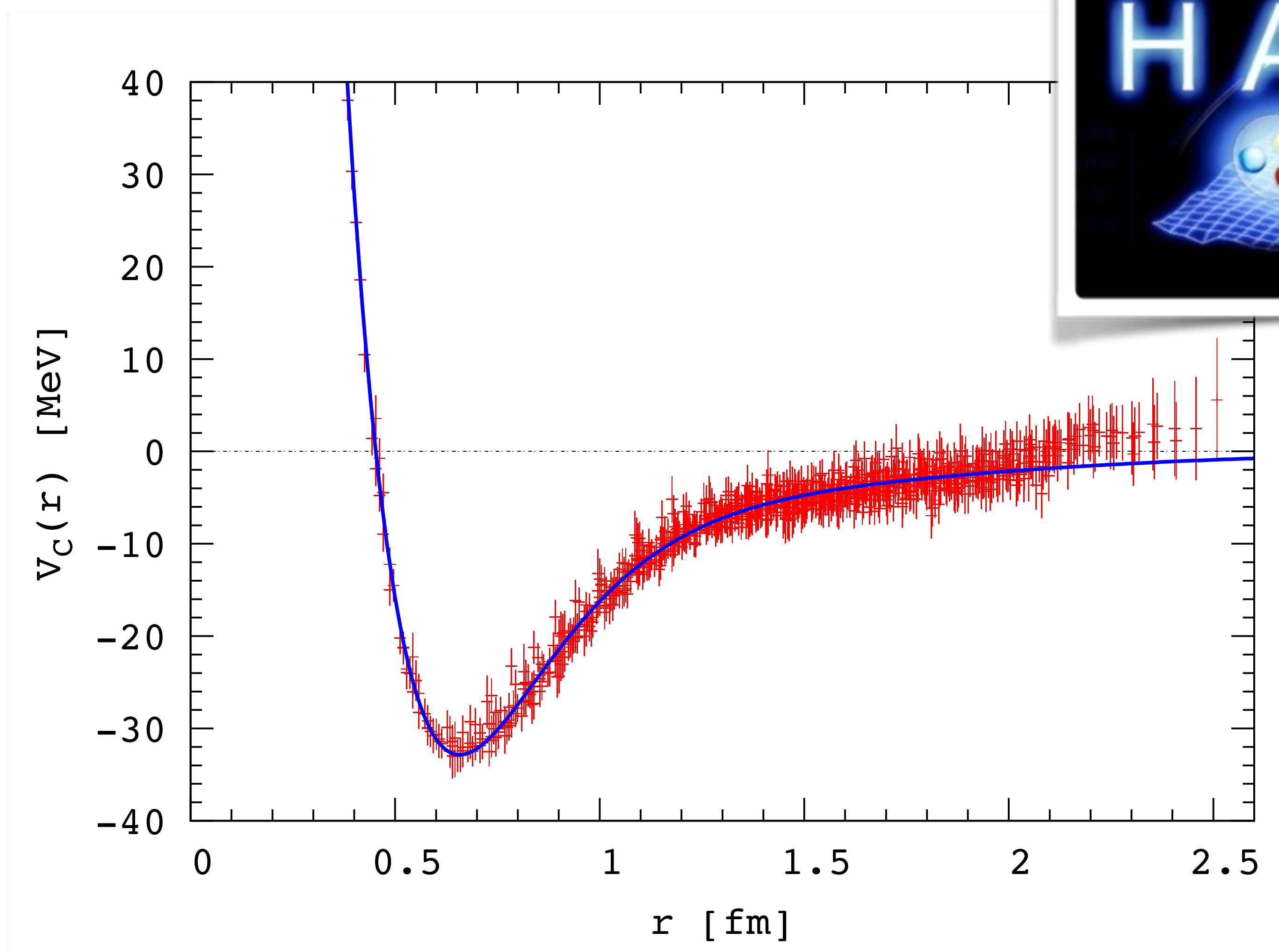
NN Central Potential (S = 0, I = 1)
deduced from LQCD two-nucleon (6-quark) correlation function

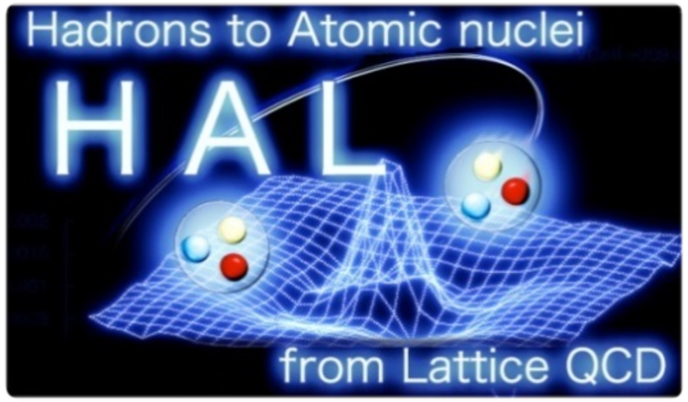
previously:
unphysically large u- and d-quark masses

...but :
stable 0.5 Fermi
repulsive core

S. Aoki, T. Hatsuda, N. Ishii
Prog. Theor. Phys. 123 (2010) 89

S. Aoki
Eur. Phys. J. A49 (2013) 81





now:

towards **physical quark masses**

Technische Universität München

3.

Chiral Effective Field Theory
and related approaches to the
Nuclear Many-Body Problem

PIONS and NUCLEI
in the context of LOW-ENERGY QCD

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

↓

LOW-ENERGY QCD

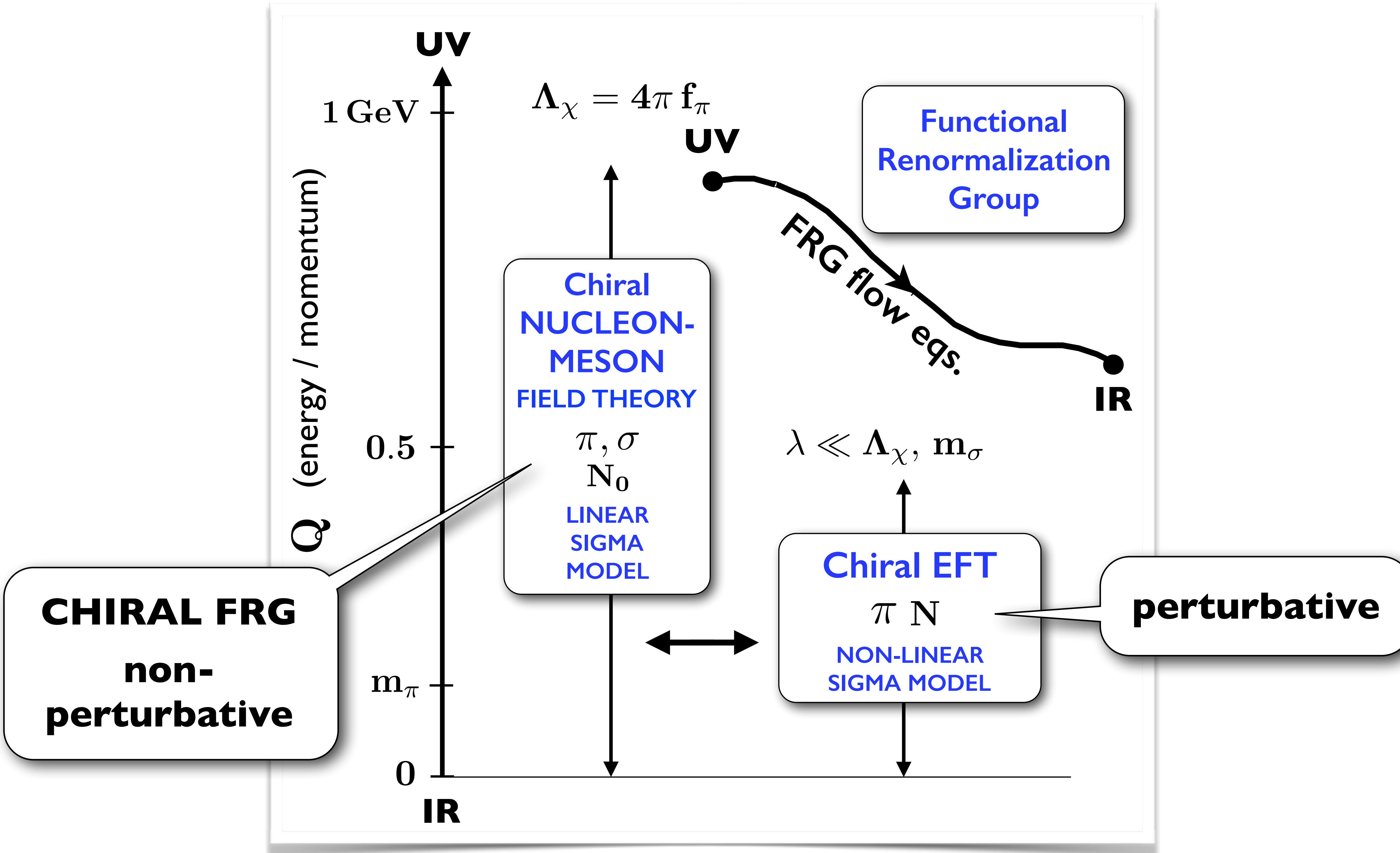
At (energy and momentum) scales $\mathrm{Q} < 4\pi\,\mathrm{f}_\pi \sim 1\,\mathrm{GeV}$

is realised as an

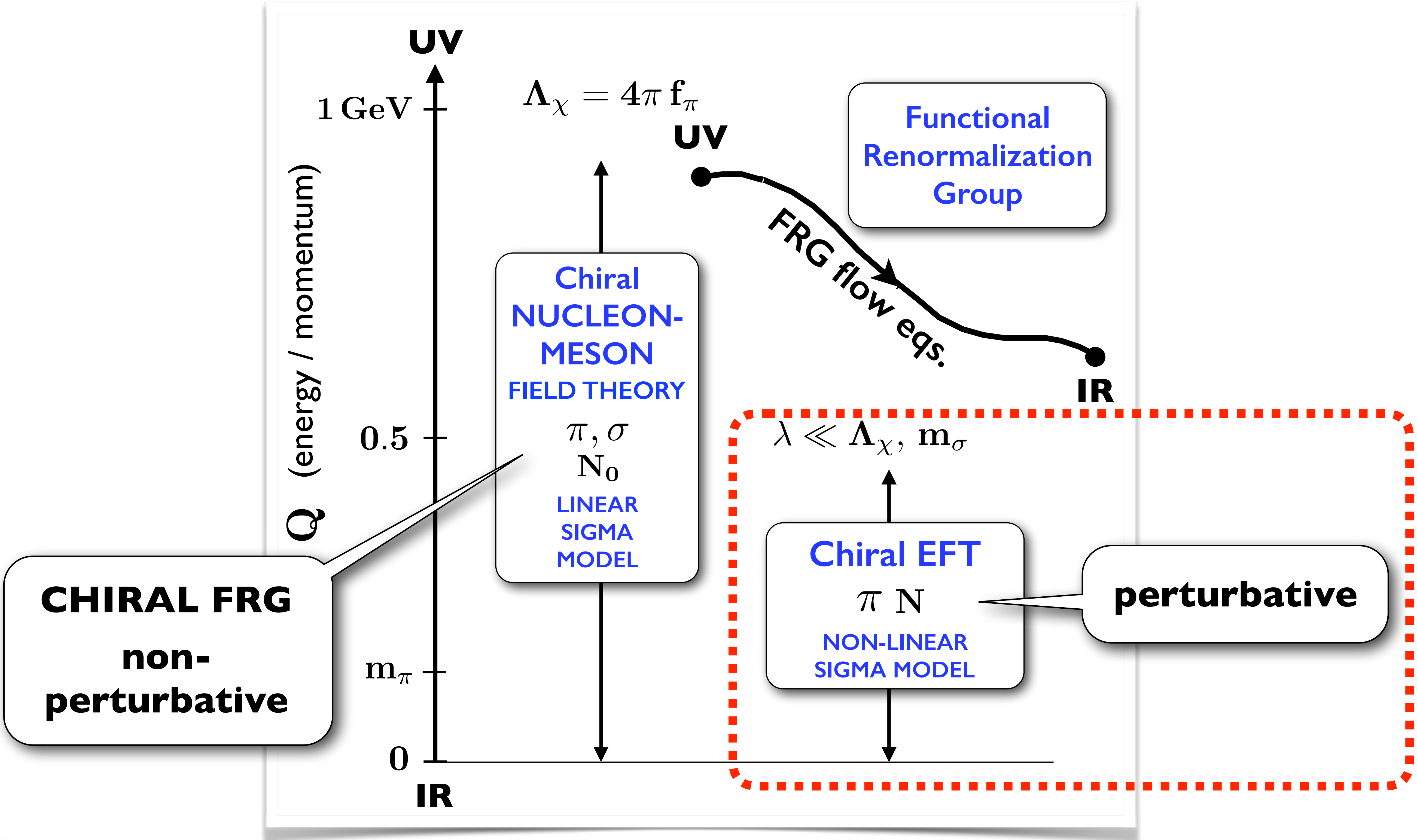
Effective Field Theory

of Nambu-Goldstone Bosons (PIONS) coupled to
NUCLEONS as (heavy) Fermion sources

Theoretical FRAMEWORKS and METHODS

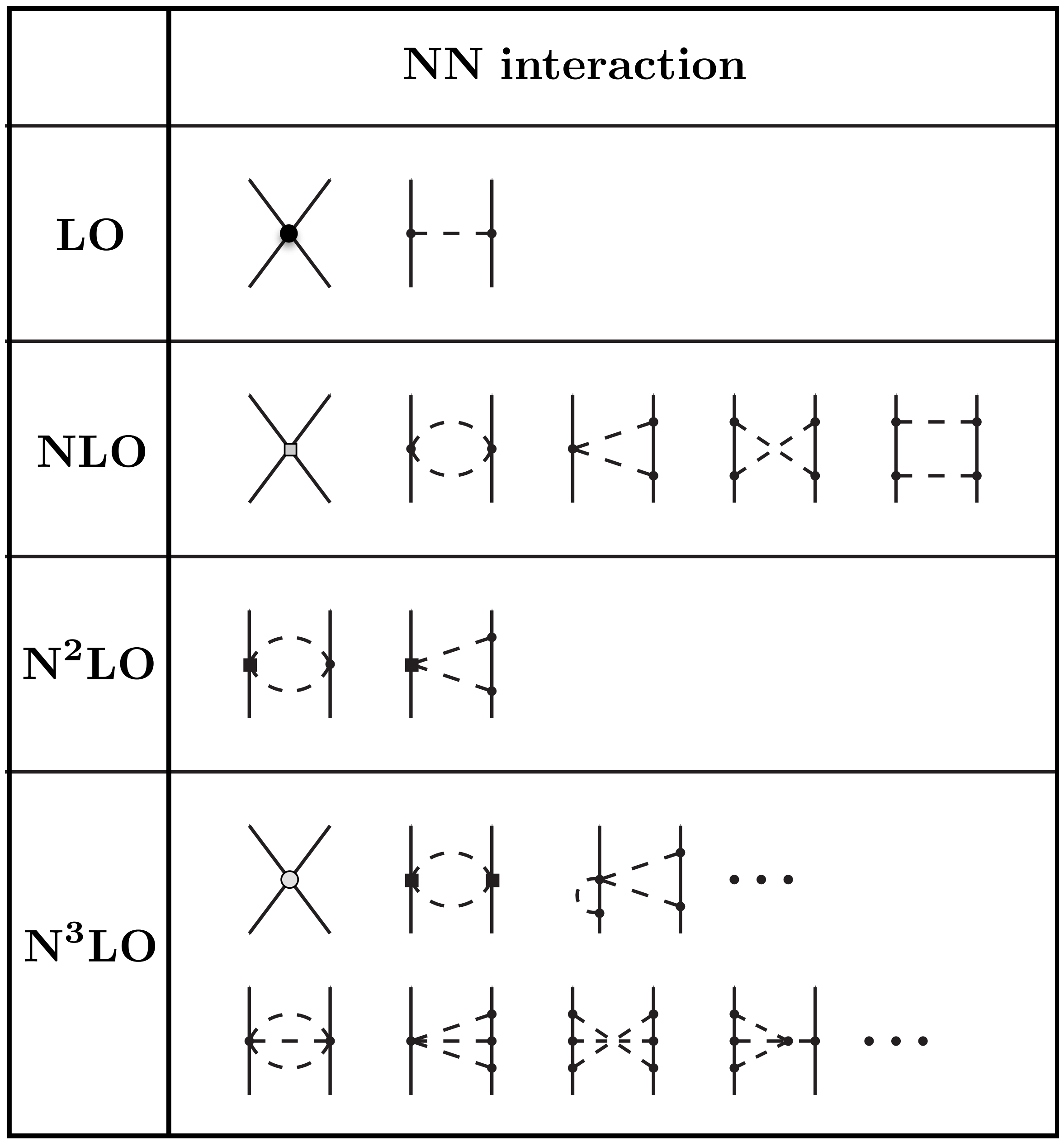


Theoretical FRAMEWORKS and METHODS

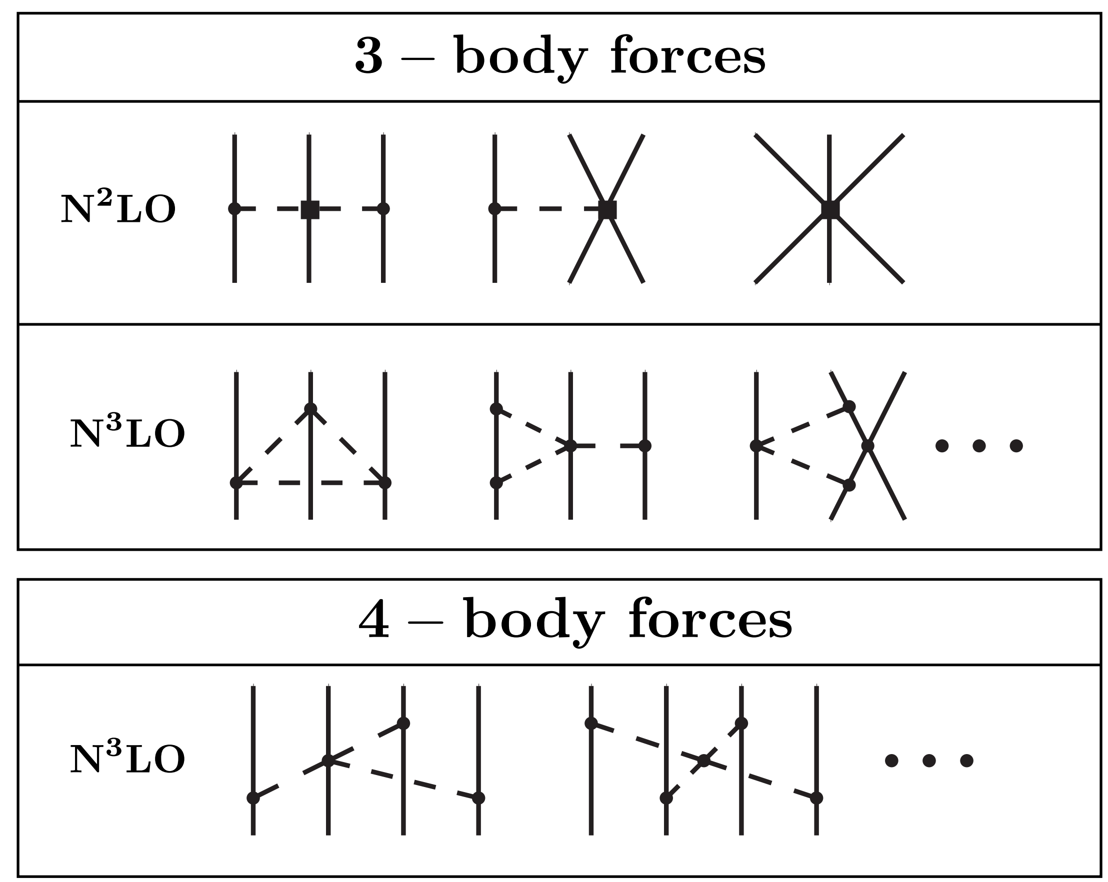


NUCLEON-NUCLEON INTERACTION from CHIRAL EFFECTIVE FIELD THEORY

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



- Systematically organized hierarchy in powers of $\frac{Q}{\Lambda}$
  (Q: momentum, energy, pion mass)

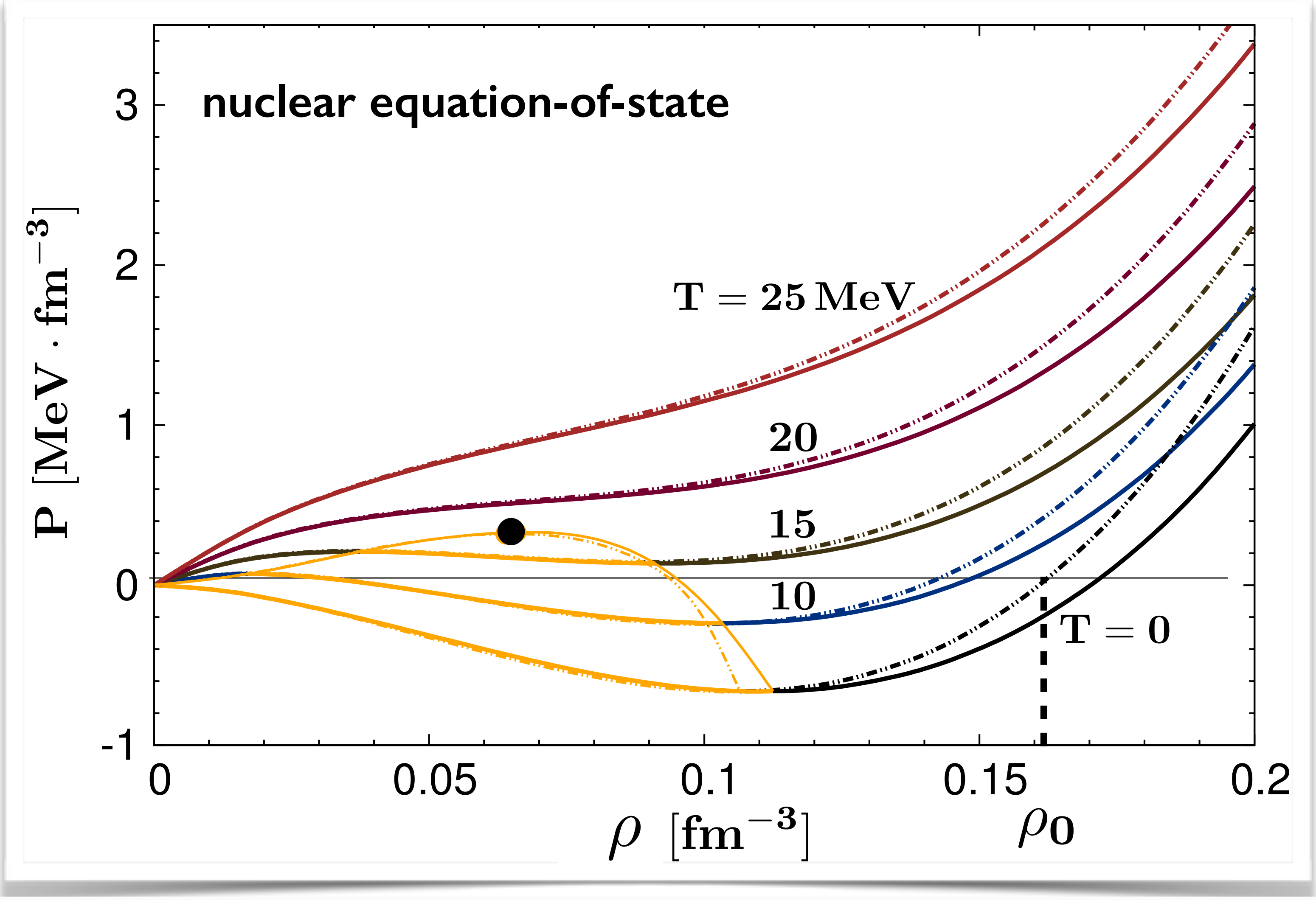


- NN interaction state-of-the-art: N^4LO plus convergence tests at N^5LO

NUCLEAR THERMODYNAMICS from CHIRAL EFT

- Symmetric nuclear matter : 1st order **liquid-gas phase transition**
- N3LO chiral NN interactions + N2LO 3-body forces

C. Wellenhofer, J.W. Holt, N. Kaiser, W.W. Phys. Rev. C89 (2014) 064009 C92 (2015) 015801



Critical temperature of liquid-gas first-order transition :

$$T_c = 17.4 \text{ MeV}$$

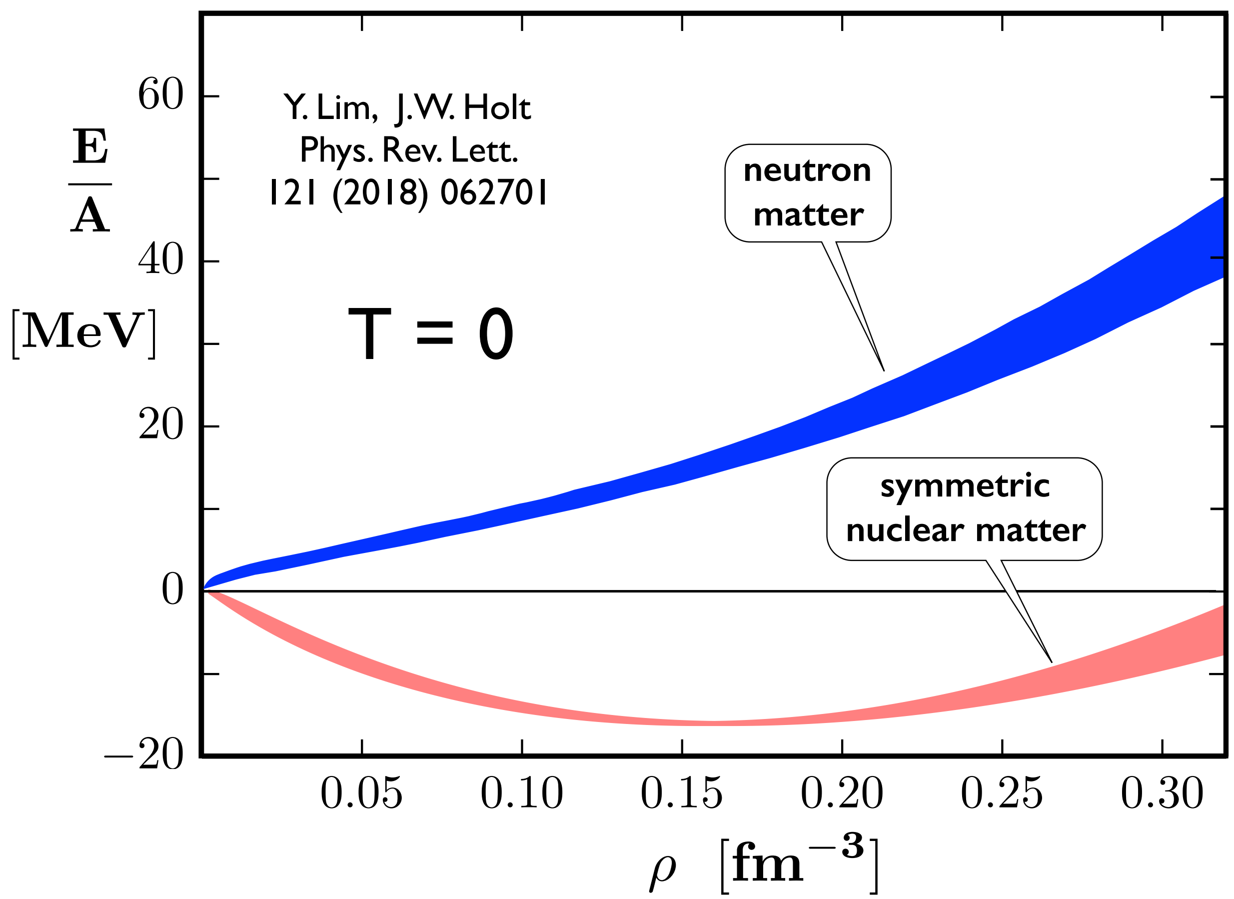
► **Empirical position of liquid-gas critical point :** J. B. Elliot et al. : Phys. Rev. C87 (2013) 054622

$$T_c = 17.9 \pm 0.4 \text{ MeV} \quad P_c = 0.31 \pm 0.07 \text{ MeV} \cdot \text{fm}^{-3} \quad \rho_c = 0.06 \pm 0.01 \text{ fm}^{-3}$$

NEUTRON and NUCLEAR MATTER from CHIRAL EFT

- N3LO chiral NN interactions + N2LO 3-body forces
- Many-body perturbation theory (3rd order)

J.W. Holt, N. Kaiser
Phys. Rev. C95 (2017) 034326



Perturbative Chiral EFT :

applicable up to baryon densities

$\rho \sim 2\,\rho_0$

- **Agreement with advanced many-body calculations**
  (e.g. Quantum Monte Carlo computations - S. Gandolfi et al.: EPJ A50 (2014) 10)

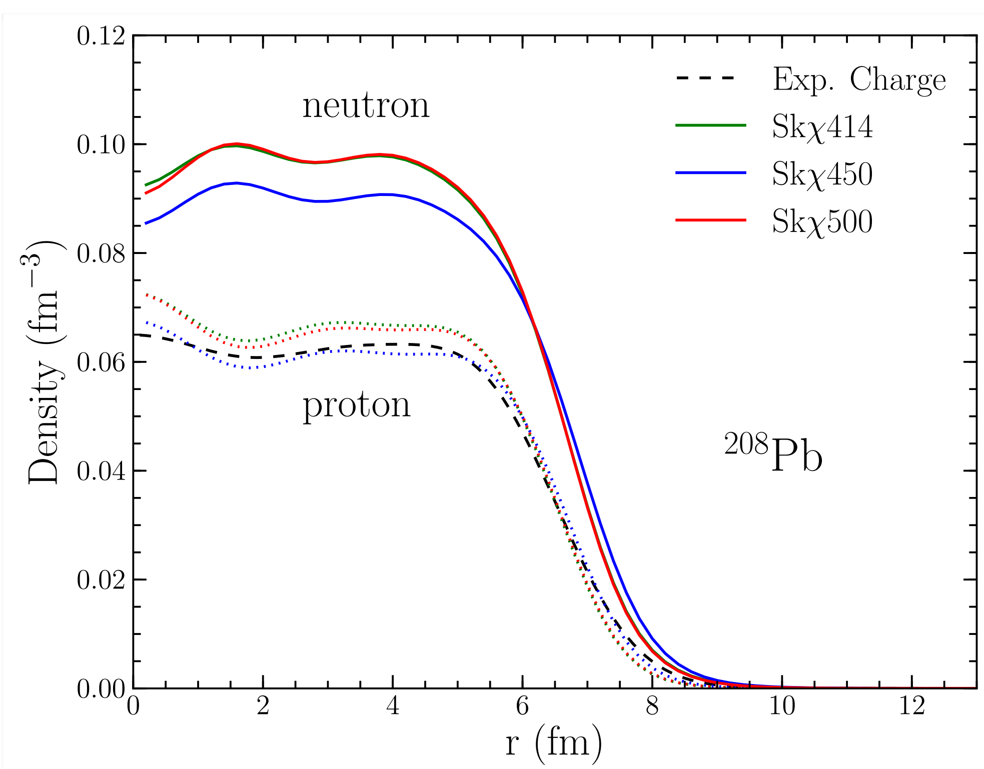
C. Wellenhofer, J.W. Holt, N. Kaiser, W.W.: Phys. Rev. C89 (2014) 064009, C92 (2015) 015801

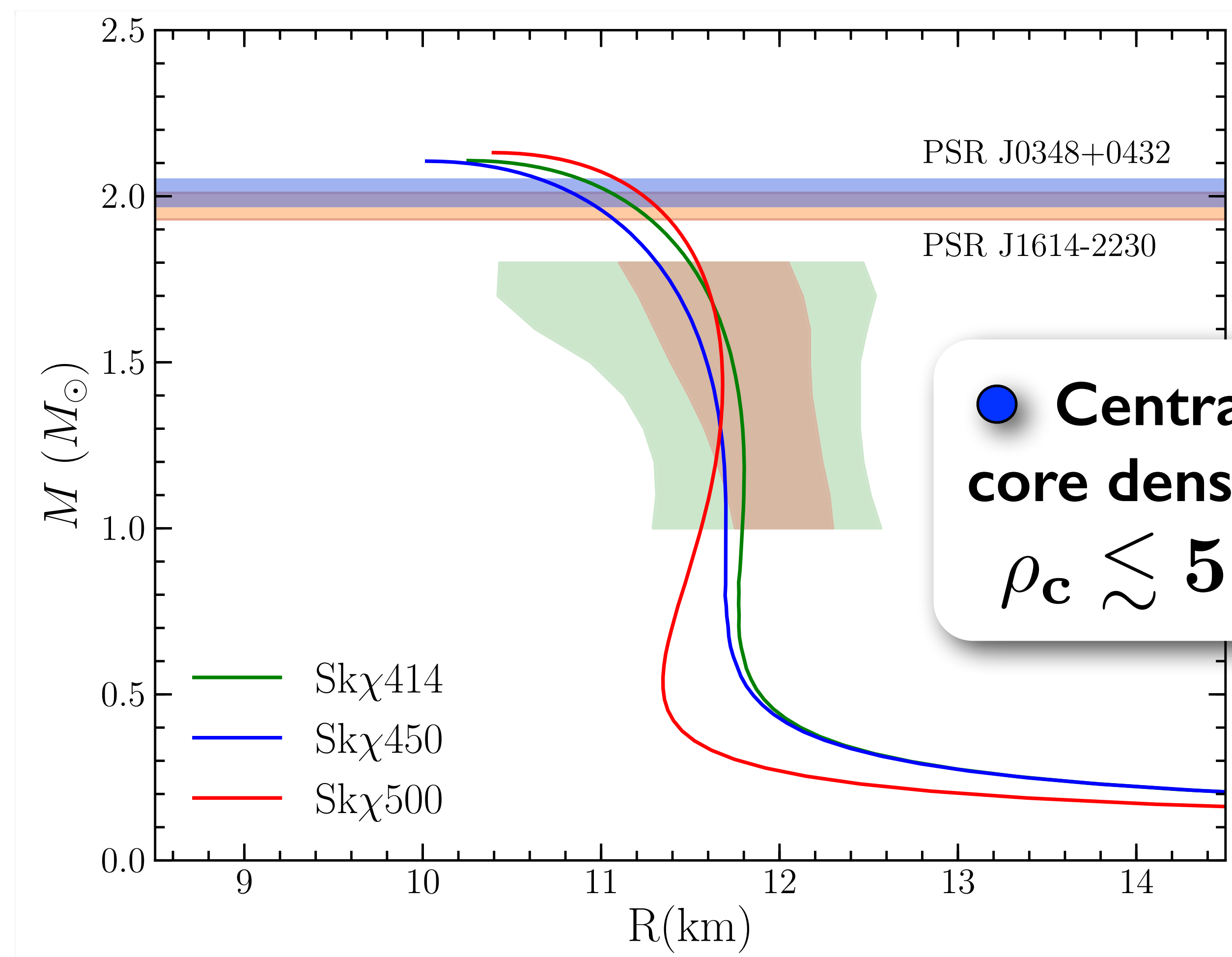
- **Further recent developments: N4LO** F. Sammarruca et al.: arXiv:1807.06640

NEUTRON STAR MATTER

- **Energy Density Functional (Skyrme-Hartree-Fock)** deduced from
  Chiral Effective Field Theory
  N3LO two-body interactions, N2LO three-body forces
  density dependence consistent with ChEFT expansion in powers of Fermi momenta
  Y. Lim, J.W. Holt Phys. Rev. C95 (2017) 065805

- successfully reproduces properties of **finite nuclei** …

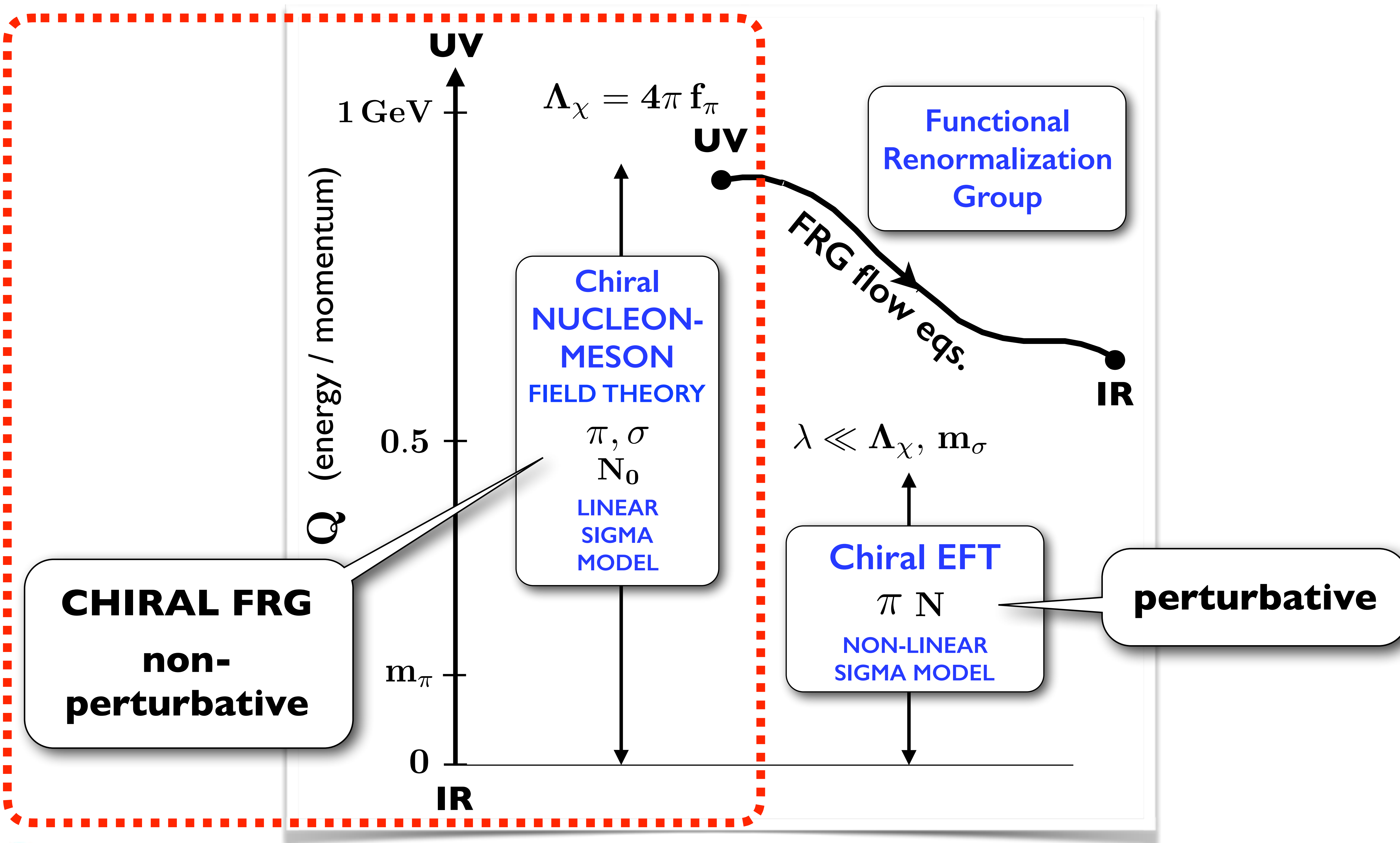




- **Central core densities** $\rho_c \lesssim 5\,\rho_0$

… and **neutron star crust** together with $2\,M_\odot$ **constraint**

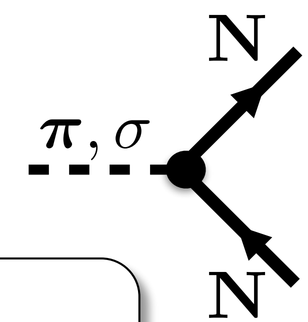
Theoretical FRAMEWORKS and METHODS



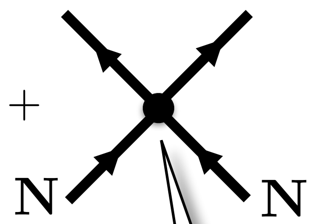
Mesons, Nucleons, Nuclear Matter
and
Functional Renormalization Group

- **Chiral nucleon - meson Lagrangian**

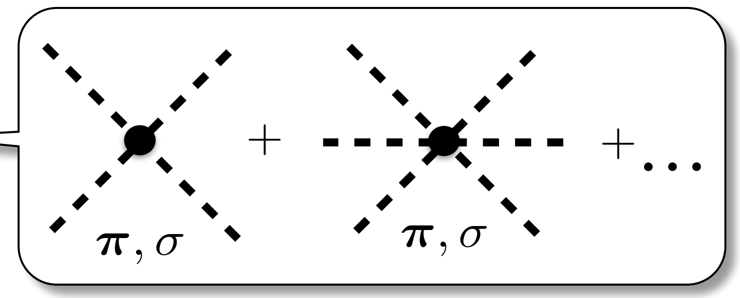
$$\mathcal{L} = \bar{\mathrm{N}}\, i\gamma_\mu \partial^\mu \mathrm{N} + \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma + \partial_\mu\boldsymbol{\pi}\cdot\partial^\mu\boldsymbol{\pi}\right) + $$



$+$



$- \mathcal{U}(\boldsymbol{\pi}, \sigma)$



isoscalar & isovector current-current interactions

- **Nambu-Goldstone boson** π and "**heavy**" σ

- **Potential** $\mathcal{U}(\sigma, \boldsymbol{\pi})$ **: polynomial** in $\chi = \boldsymbol{\pi}^2 + \sigma^2$ constructed to reproduce **vacuum physics** and **equilibrium nuclear matter**

- **Pionic fluctuations**, **nucleonic particle-hole excitations** and **many-body correlations** treated **non-perturbatively** using **FRG**

Review: M. Drews, W.W. : Prog. Part. Nucl. Phys. 91 (2017) 347

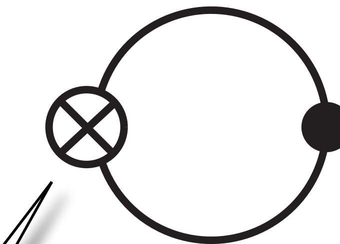
Renormalization Group strategies

k-dependent action

full propagator

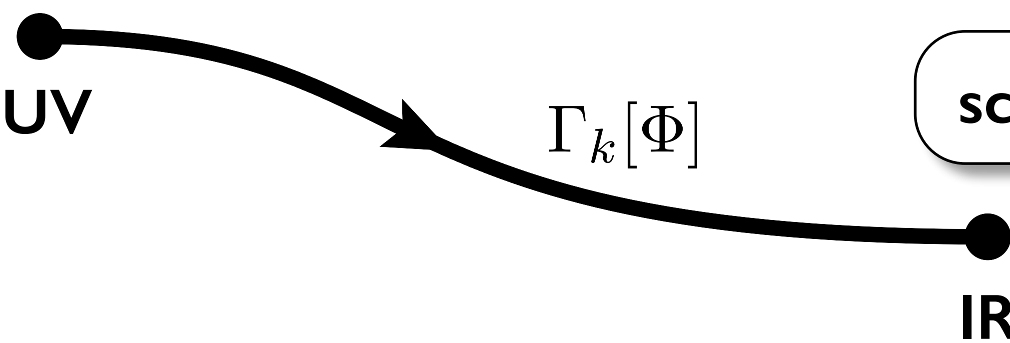
Wetterich's FRG flow equations

$$k\,\frac{\partial \Gamma_k[\Phi]}{\partial k} = \frac{1}{2}\mathrm{Tr}\left[k\frac{\partial R_k}{\partial k}\cdot\left(\Gamma_k^{(2)}[\Phi]+R_k\right)^{-1}\right] =$$



scale regulator R_k

$\Gamma_{k=\Lambda}[\Phi] = S$

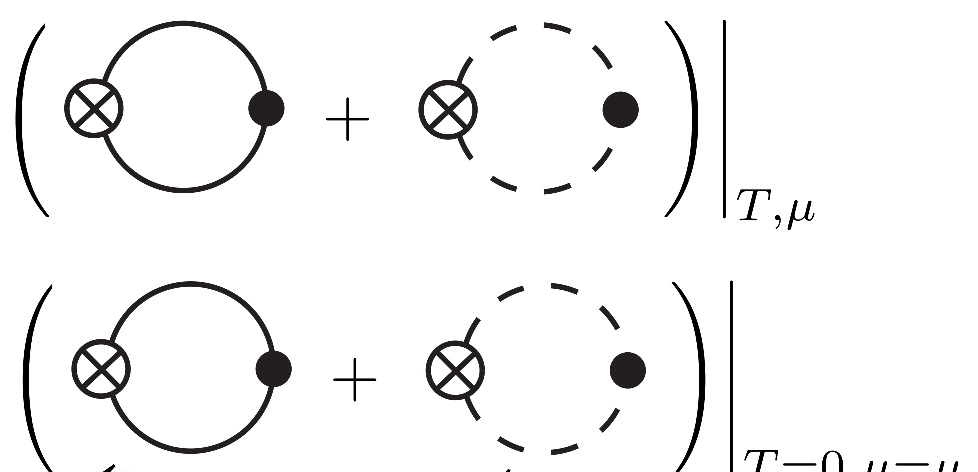


$\Gamma_{k=0}[\Phi] = \Gamma[\Phi]$

C. Wetterich:
Phys. Lett. B 301 (1993) 90

- **Thermodynamics:**

$k\,\partial_k\bar{\Gamma}_k(T,\mu) =$



nucleons

pions

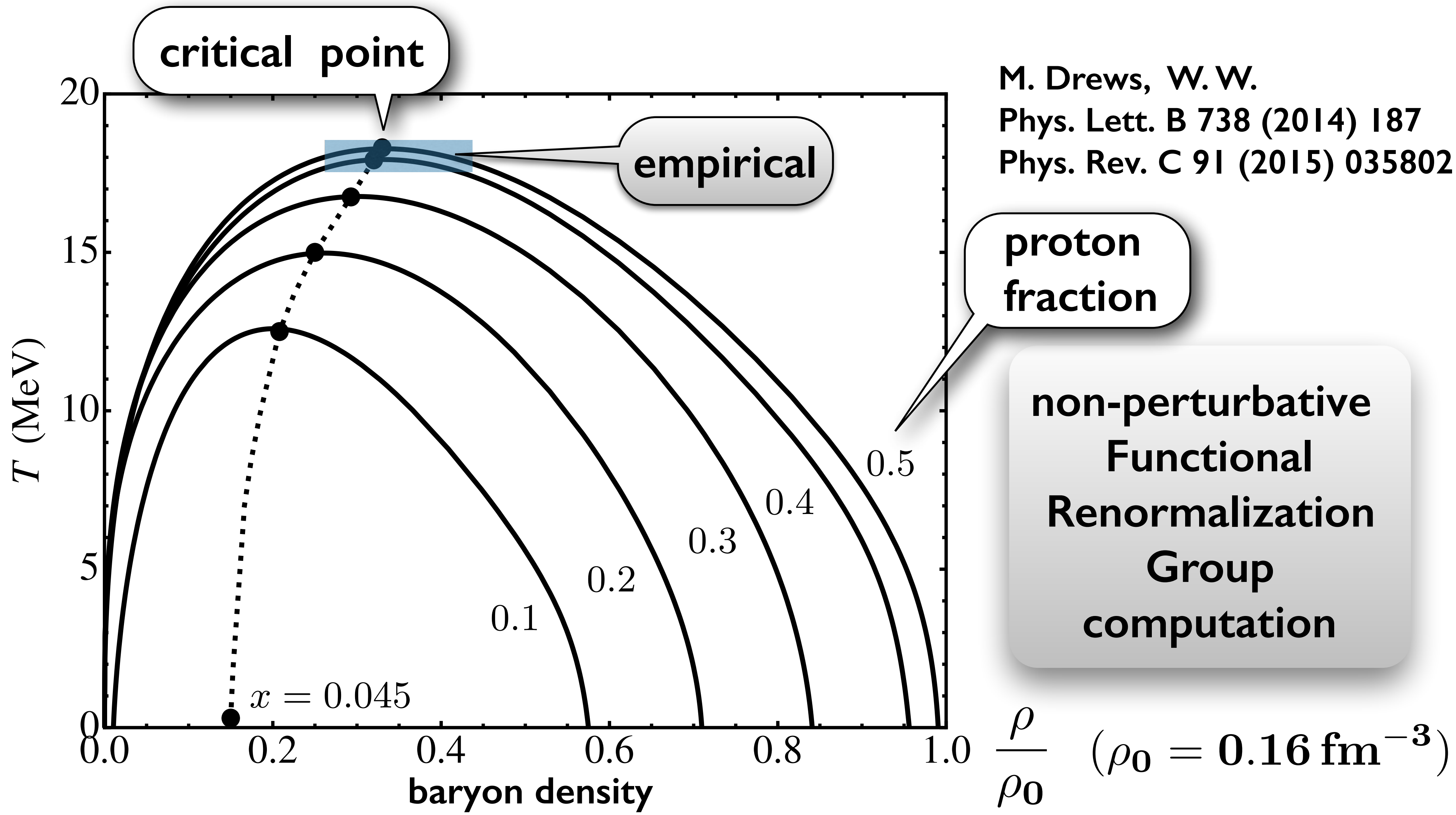
Non-perturbative treatment of :

- **multi-pion exchange** processes
- **nucleon-hole** excitations
- **multi-nucleon** correlations

PHASE DIAGRAM of NUCLEAR MATTER

- Trajectory of CRITICAL POINT of Liquid - Gas transition for asymmetric matter as function of proton fraction Z / A

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

non-perturbative Functional Renormalization Group computation

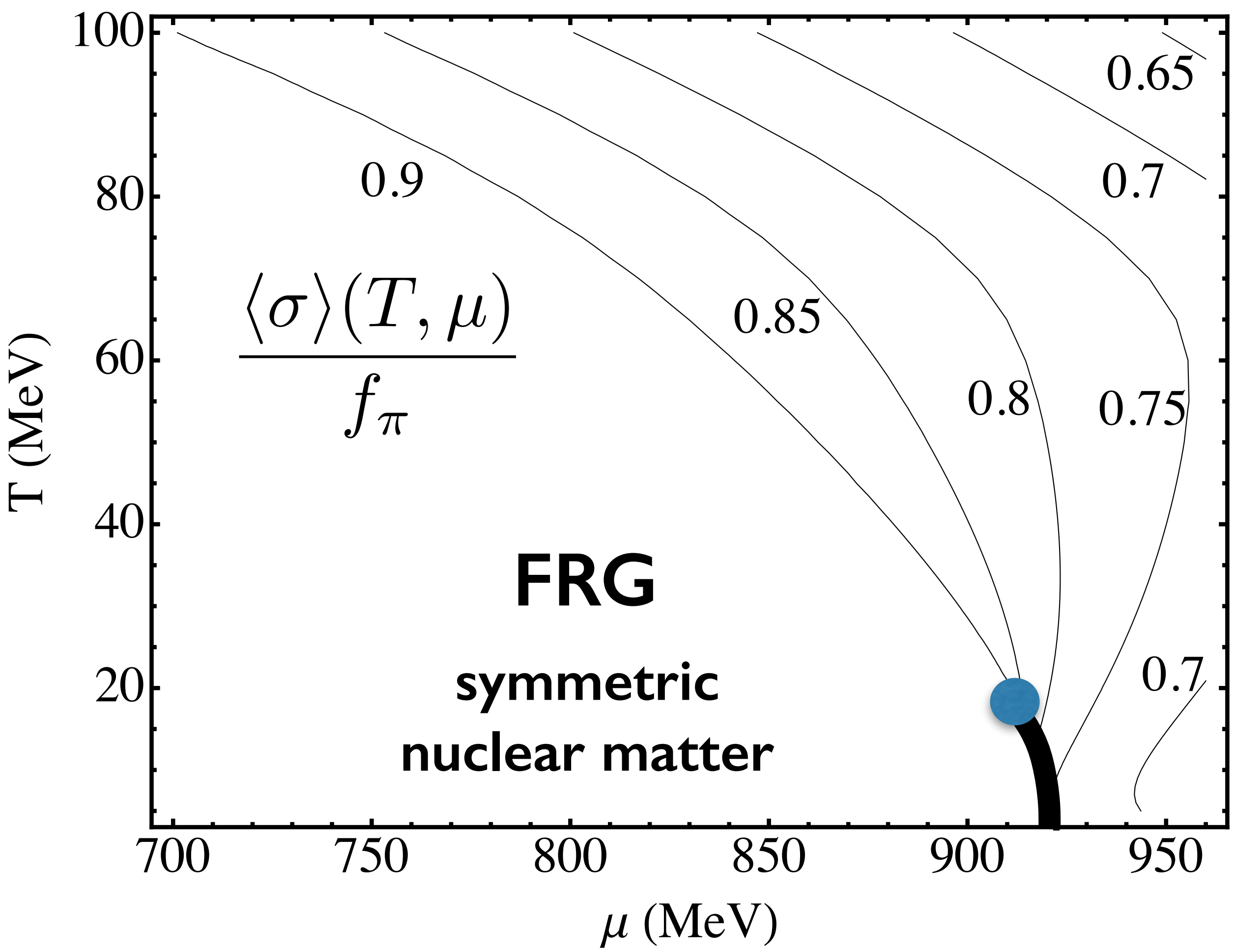
Governed by isospin dependent (two-)pion exchange dynamics

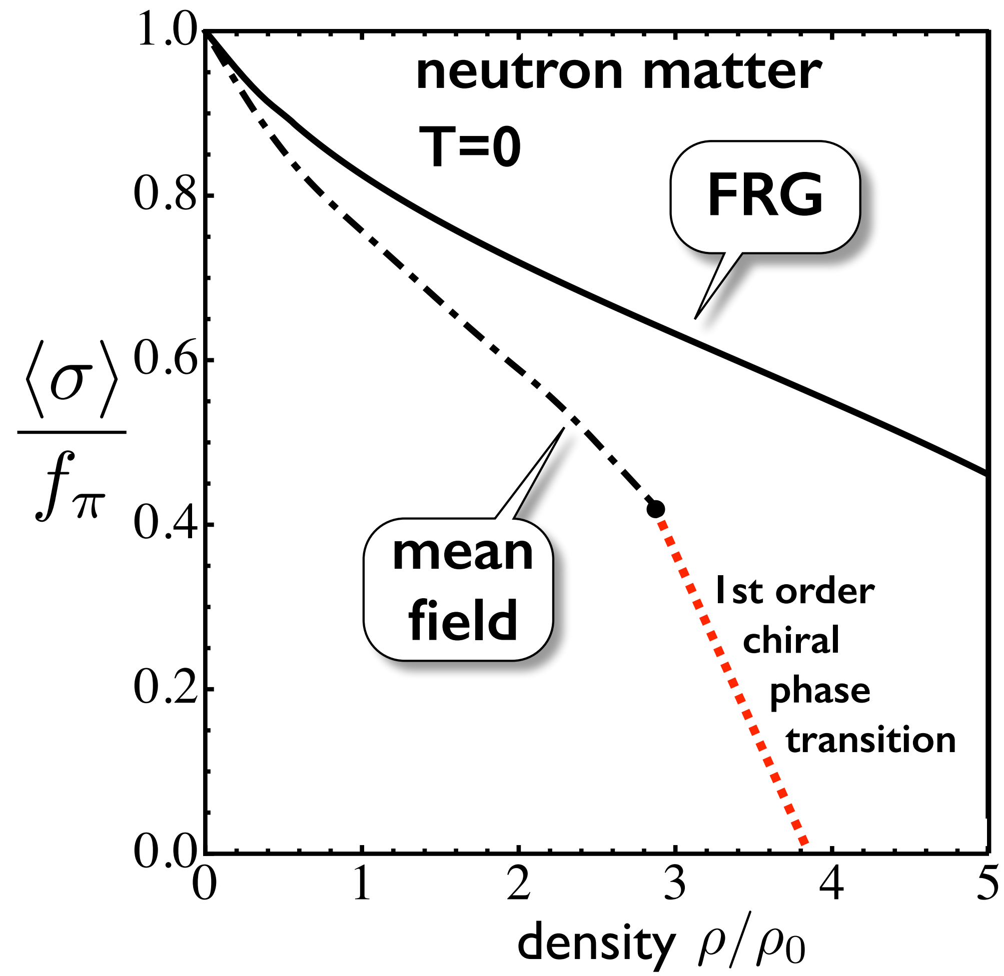
CHIRAL ORDER PARAMETER in NUCLEAR and NEUTRON MATTER

- **Chiral Nucleon-Meson field theory** and **F**unctional **R**enormalization **G**roup

  M. Drews, W.W. Phys. Rev. C91 (2015) 035802 Prog. Part. Nucl. Phys. 93 (2017) 69

- **Chiral order parameter :**
  Sigma field ⟷ in-medium pion decay constant $\langle\sigma\rangle_{T,\mu} = f_\pi^*(T,\mu)$





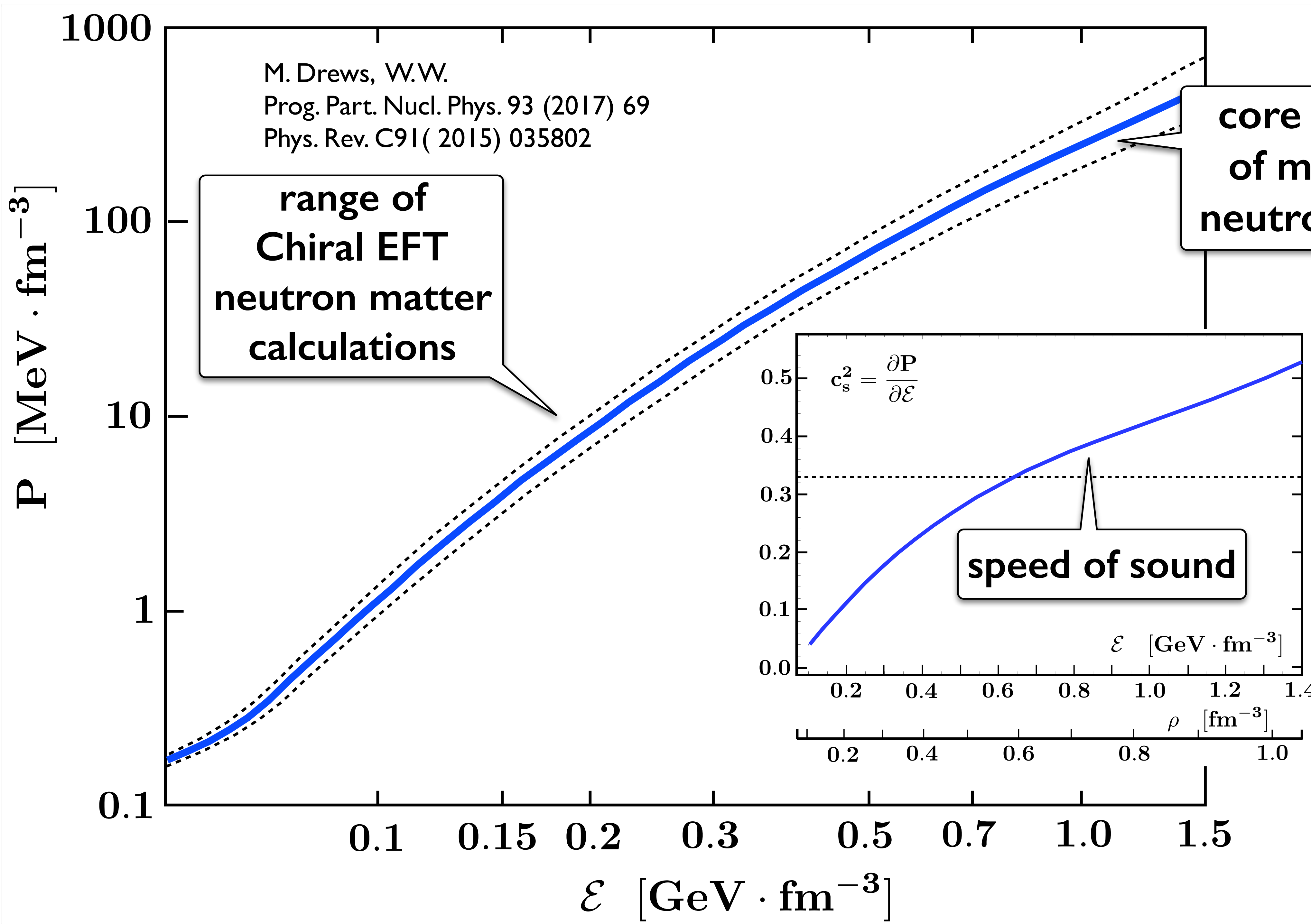
Important role of **fluctuations** (**pionic** and **nucleon-hole**) beyond mean-field appr. :

DISAPPEARANCE of first-order chiral phase transition

NEUTRON STAR MATTER Equation of State

from Chiral Nucleon-Meson Field Theory

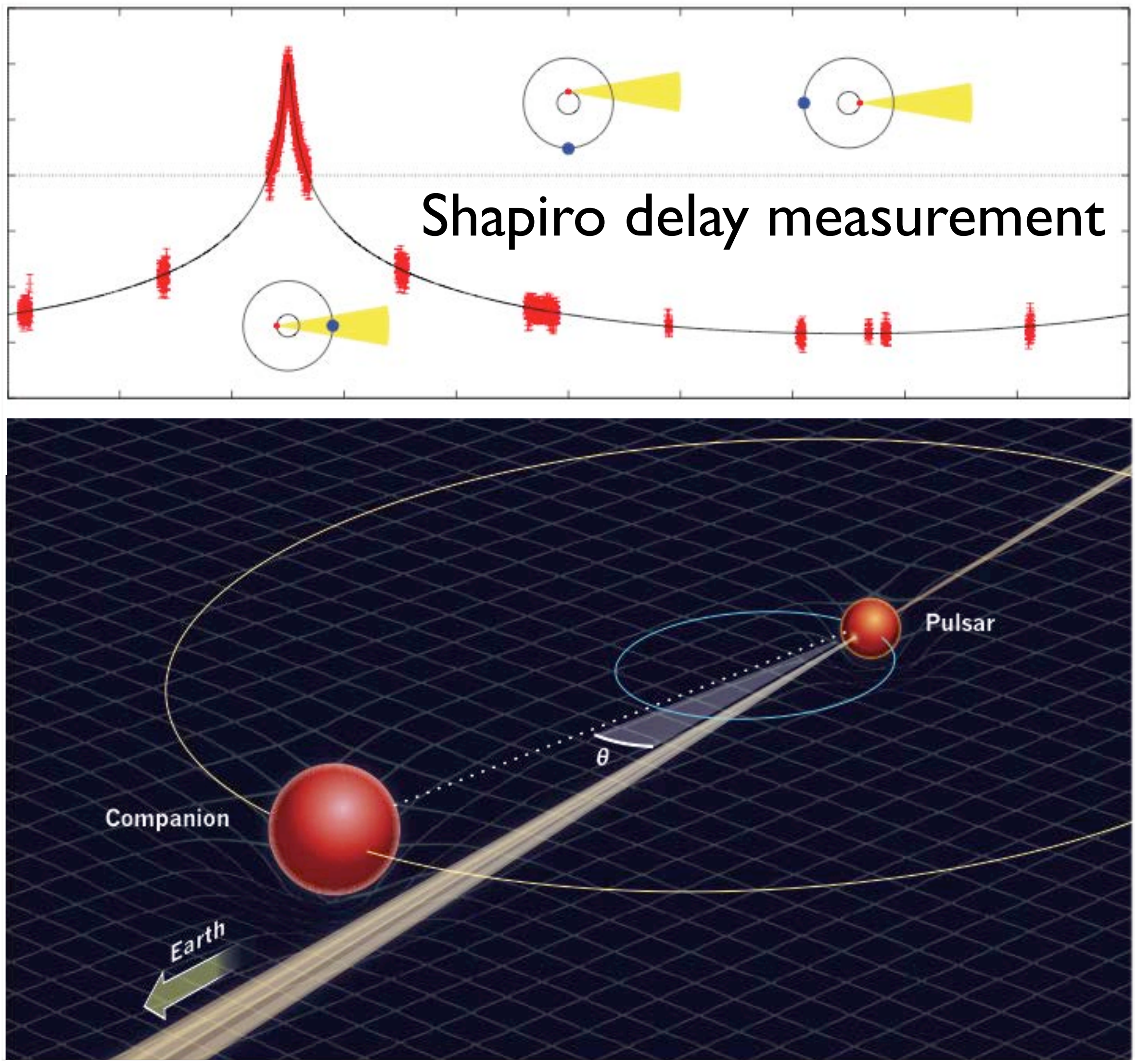
- **FRG** calculations with inclusion of beta equilibrium



4.
Constraints from NEUTRON STARS

MASSIVE NEUTRON STARS

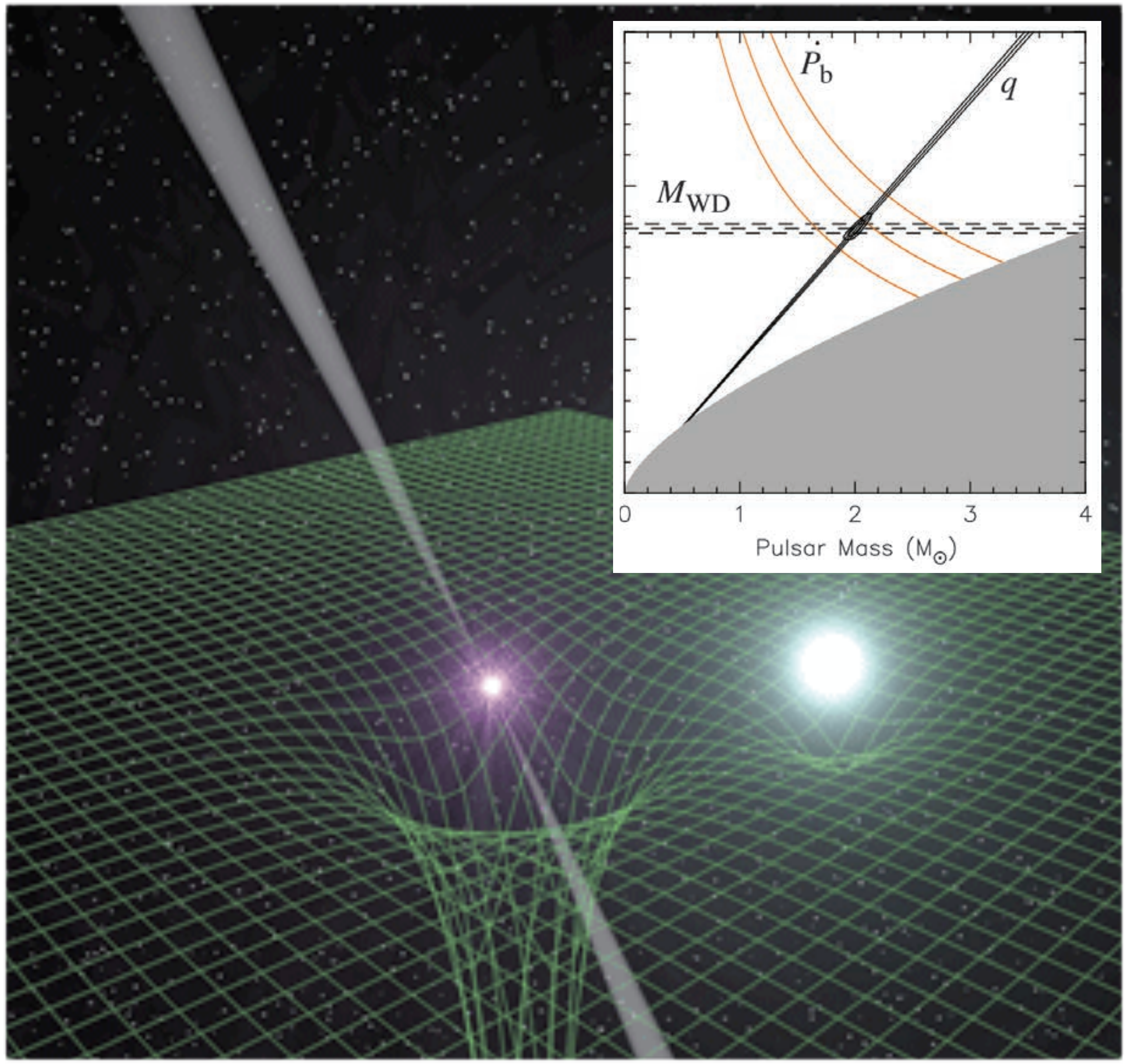
P.B. Demorest et al.
Nature 467 (2010) 1081



PSR J1614+2230

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

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

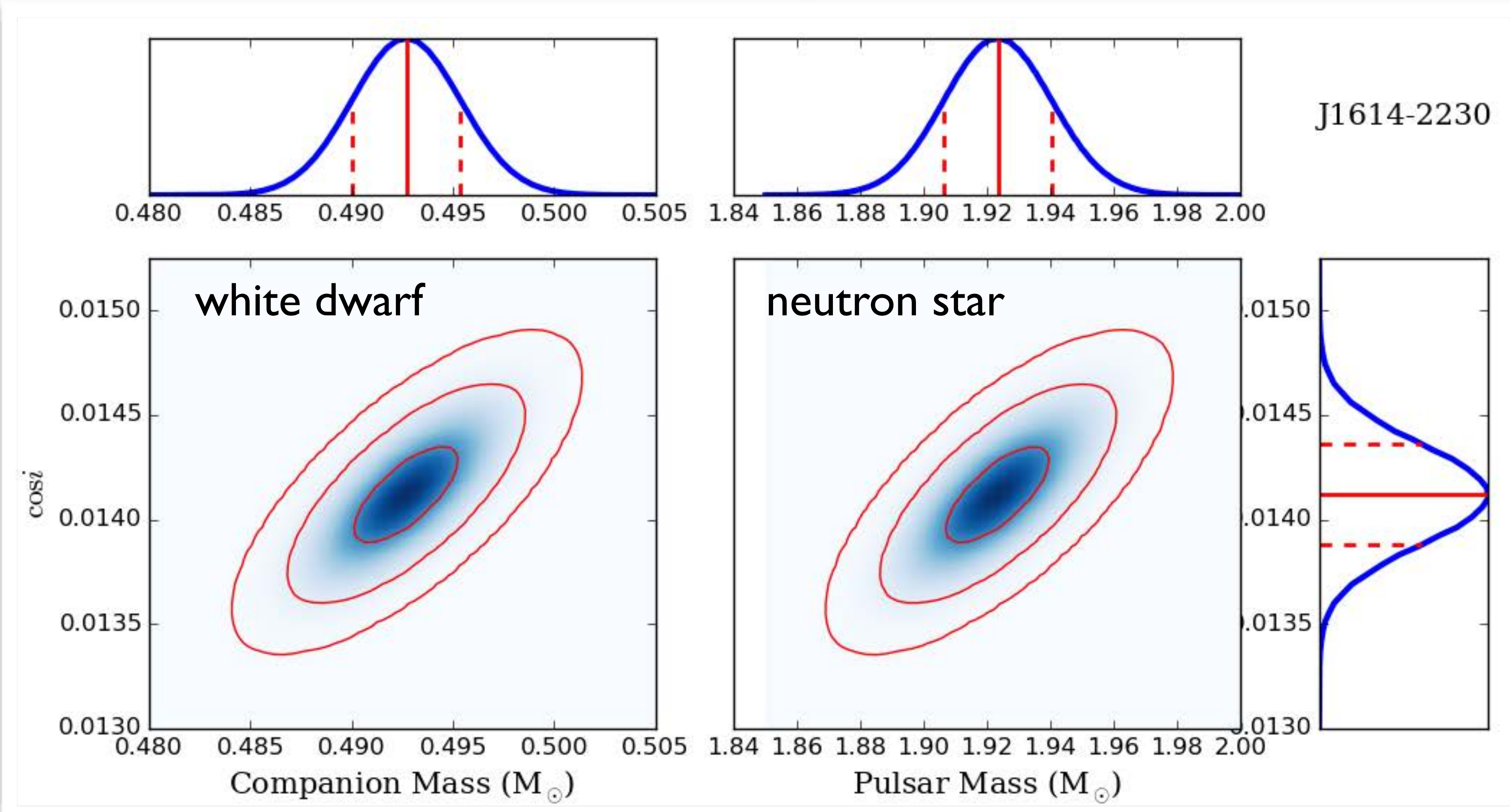


PSR J0348+0432

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

Technische Universität München

Updated mass determination of J1614-2230



$$\mathbf{M = 1.928 \pm 0.017\ M_\odot}$$

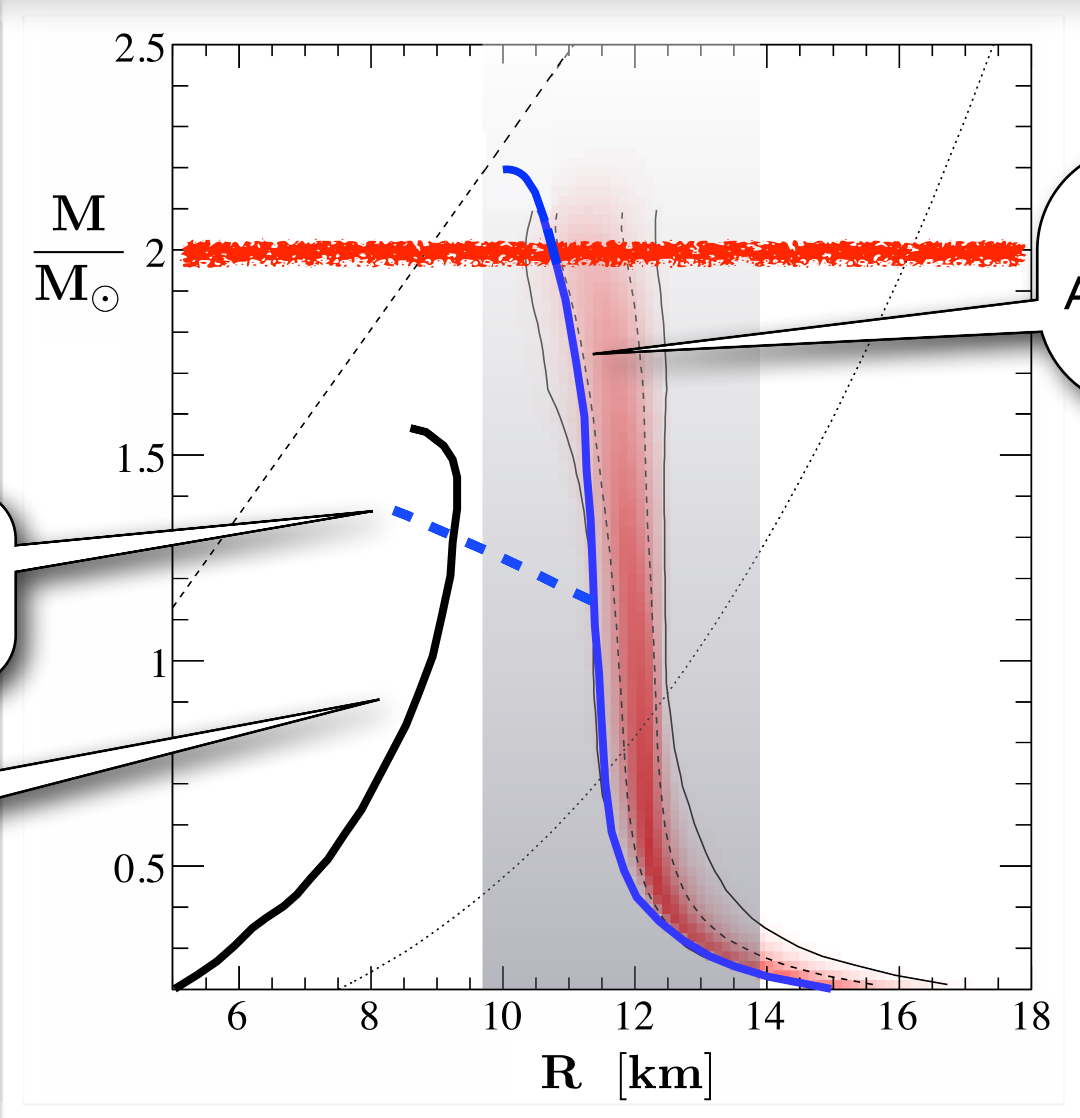
E. Fonseca et al., Astrophys. J. 832 (2016) 167

CONSTRAINTS on EQUATION of STATE

- Tolman - Oppenheimer - Volkov Equations

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

Mass-Radius Relation



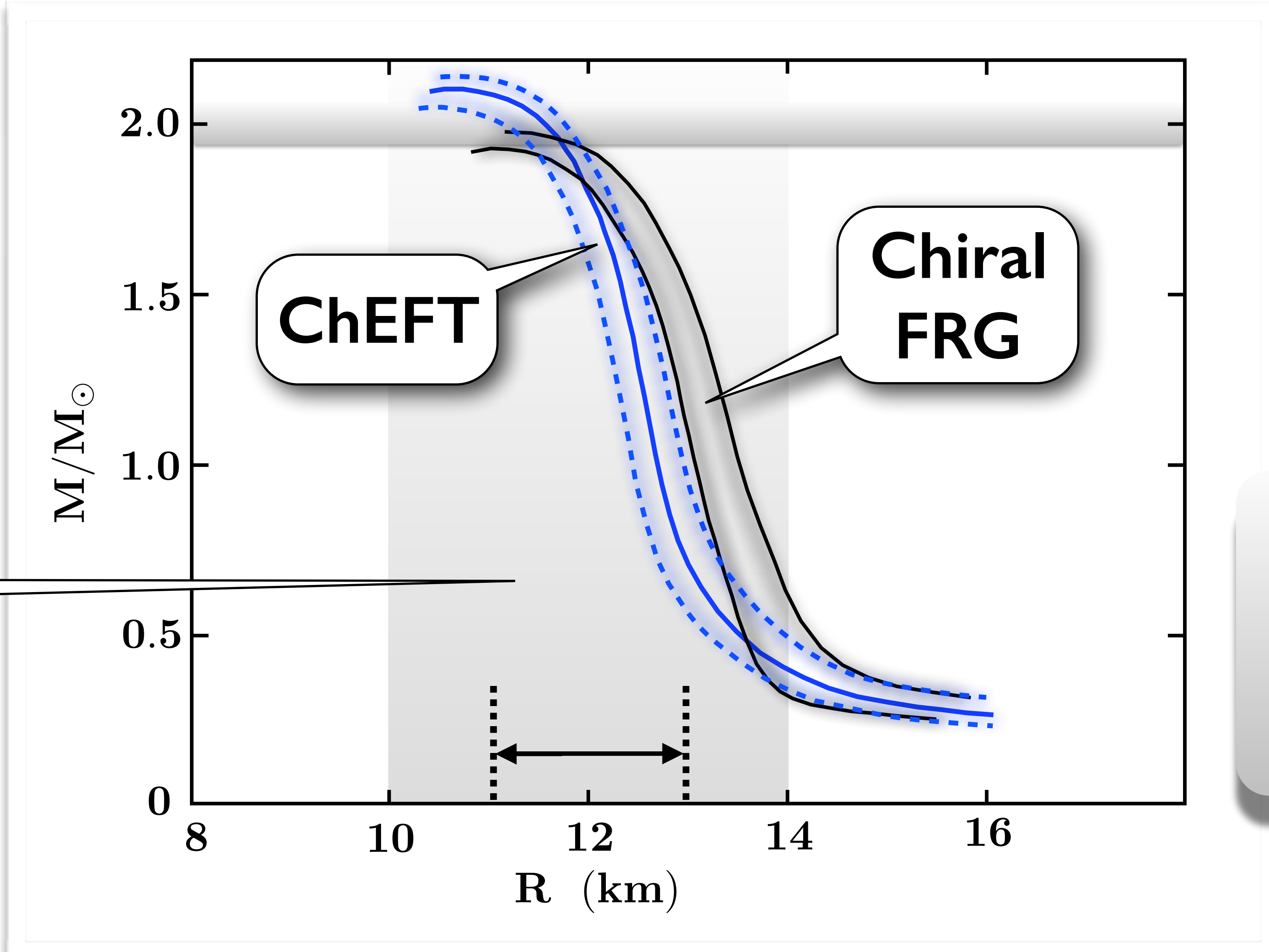
K. Hebeler,
J. Lattimer,
Ch. Pethick,
A. Schwenk:
Phys. Rev. Lett.
105 (2010) 161102

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

- Stiff equation of state required !

NEUTRON STAR MATTER from Chiral EFT and FRG

- **Symmetry energy range: 30 - 35 MeV**
- **Crust: SLy EoS**



M. Drews, W.W.

Phys. Rev. C91 (2015) 035802

Prog. Part. Nucl. Phys. 93 (2017) 69

T. Hell, W.W. Phys. Rev. C90 (2014) 045801

A.W. Steiner, J.M. Lattimer, E.F. Brown EPJ A52 (2016) 18

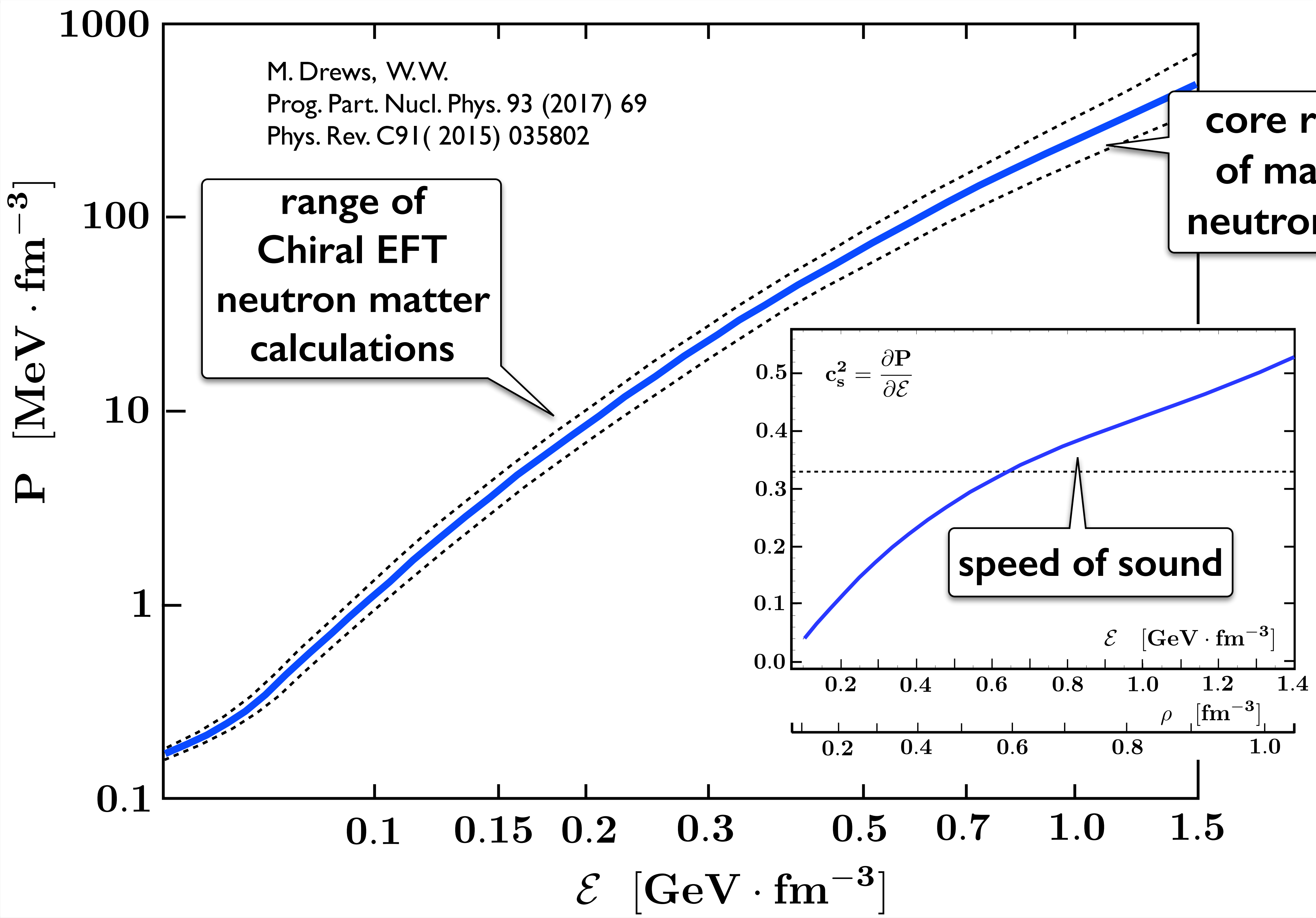
- **Central core density**

$$\rho_c \lesssim 5\,\rho_0$$

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

NEUTRON STAR MATTER
Equation of State

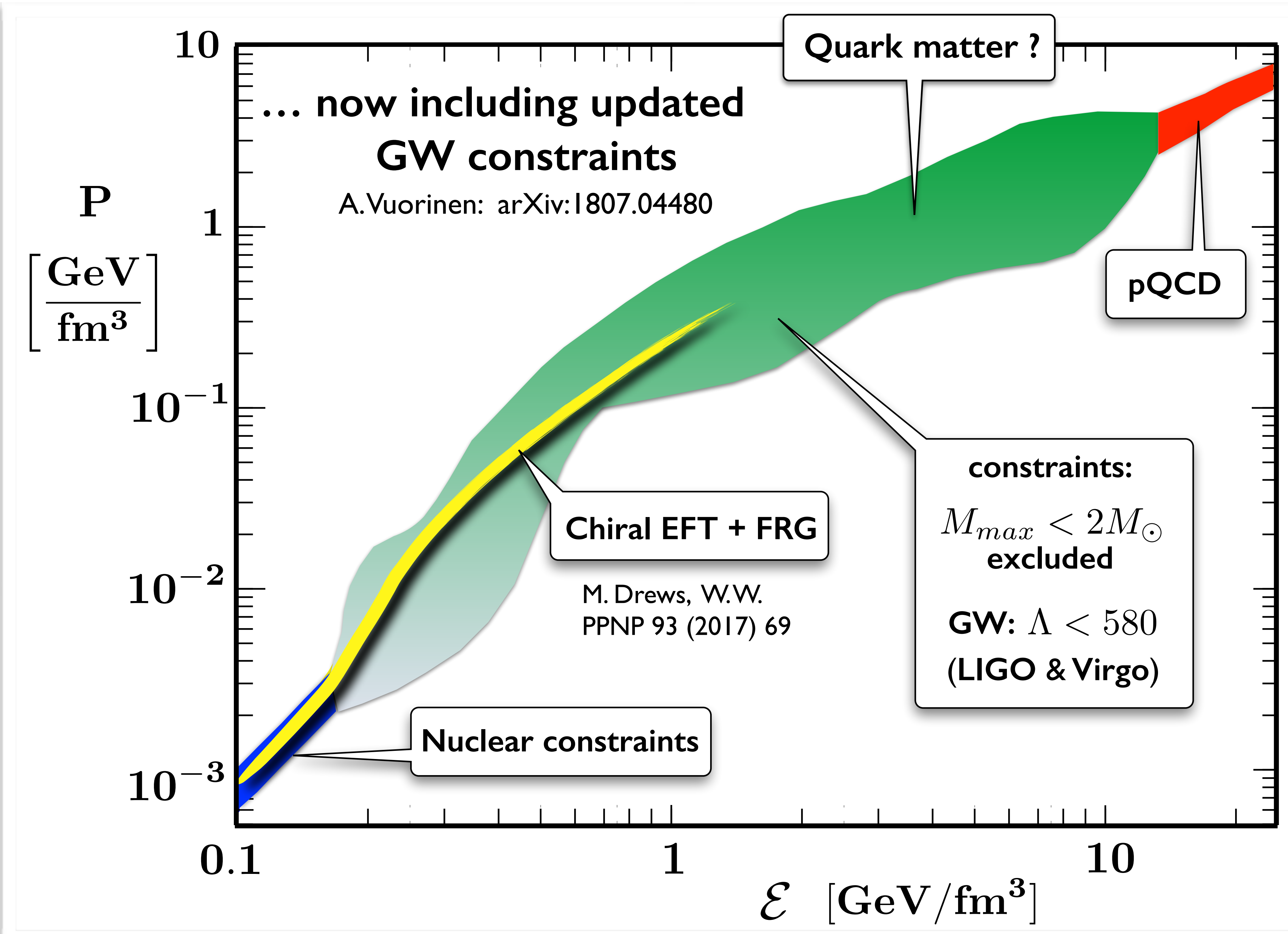
- Chiral **FRG** calculations with inclusion of beta equilibrium



NEUTRON STAR MATTER
Equation of State

A. Kurkela et al. : Astroph. J. 789 (2014) 127

A. Annala et al. : PRL 120 (2018) 172703



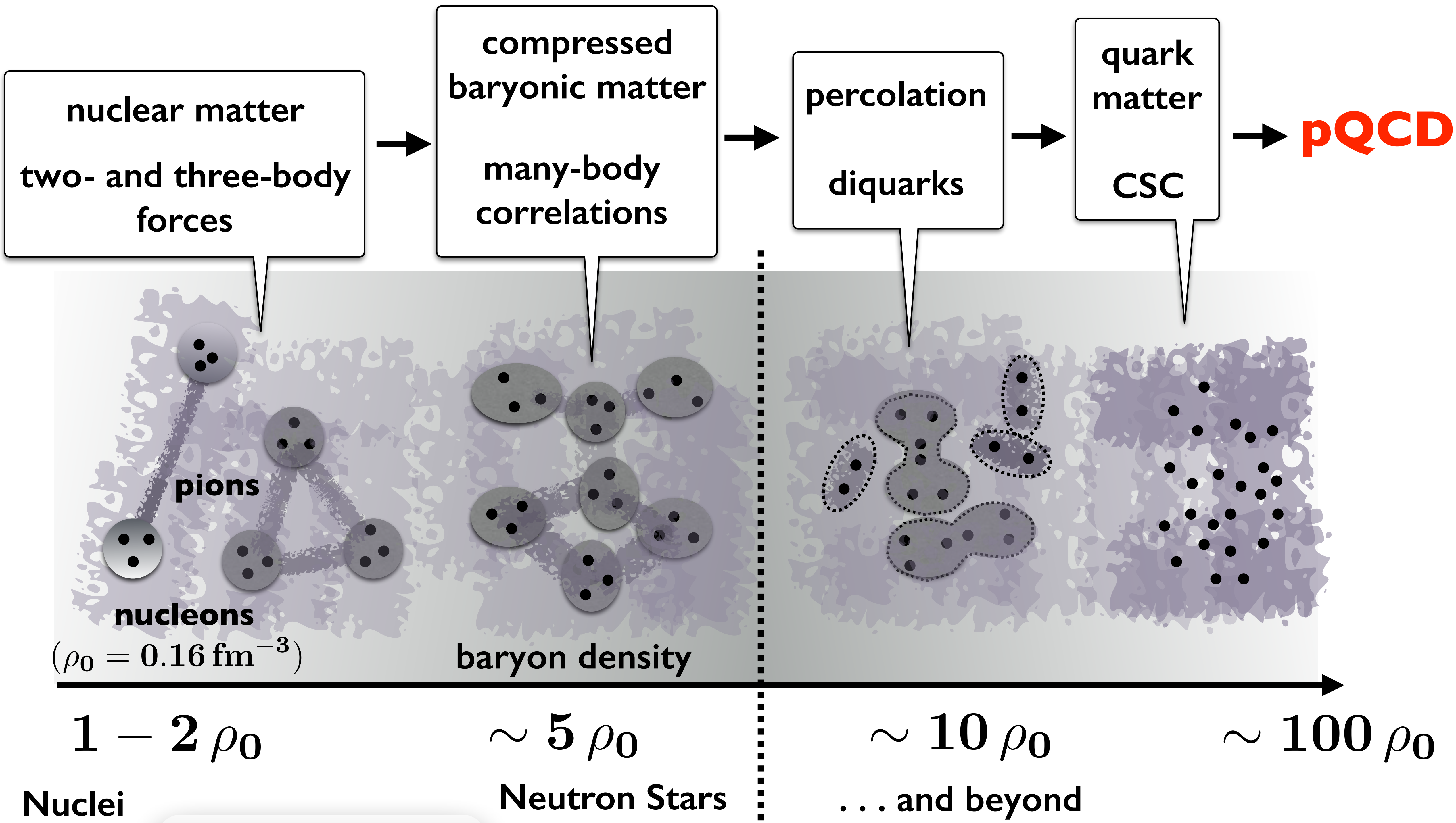
SUMMARY

- Systematic framework at the interface of QCD (with light quarks) and physics of hadrons, nuclei and nuclear forces :

Chiral Effective Field Theory
combined with
Functional Renormalization Group

- ChEFT + many-body perturbation theory works for $\rho \lesssim 2\,\rho_0$
- ChEFT + (non-perturbative) FRG may work at even higher densities
  - **No** chiral phase transition in n-matter up to at least $\rho > 5\,\rho_0$
  - "Conventional" (non-exotic) EoS consistent with constraints from neutron stars ($\mathrm{M}_{max} \simeq 2\,\mathrm{M}_\odot$, tidal deformability from GW)
  - Strangeness in the neutron star core ? Hyperon puzzle ? New developments: hyperon-nuclear interactions from Chiral SU(3) Effective Field Theory

PICTORIAL SUMMARY : COLD BARYONIC MATTER



FERMI LIQUID

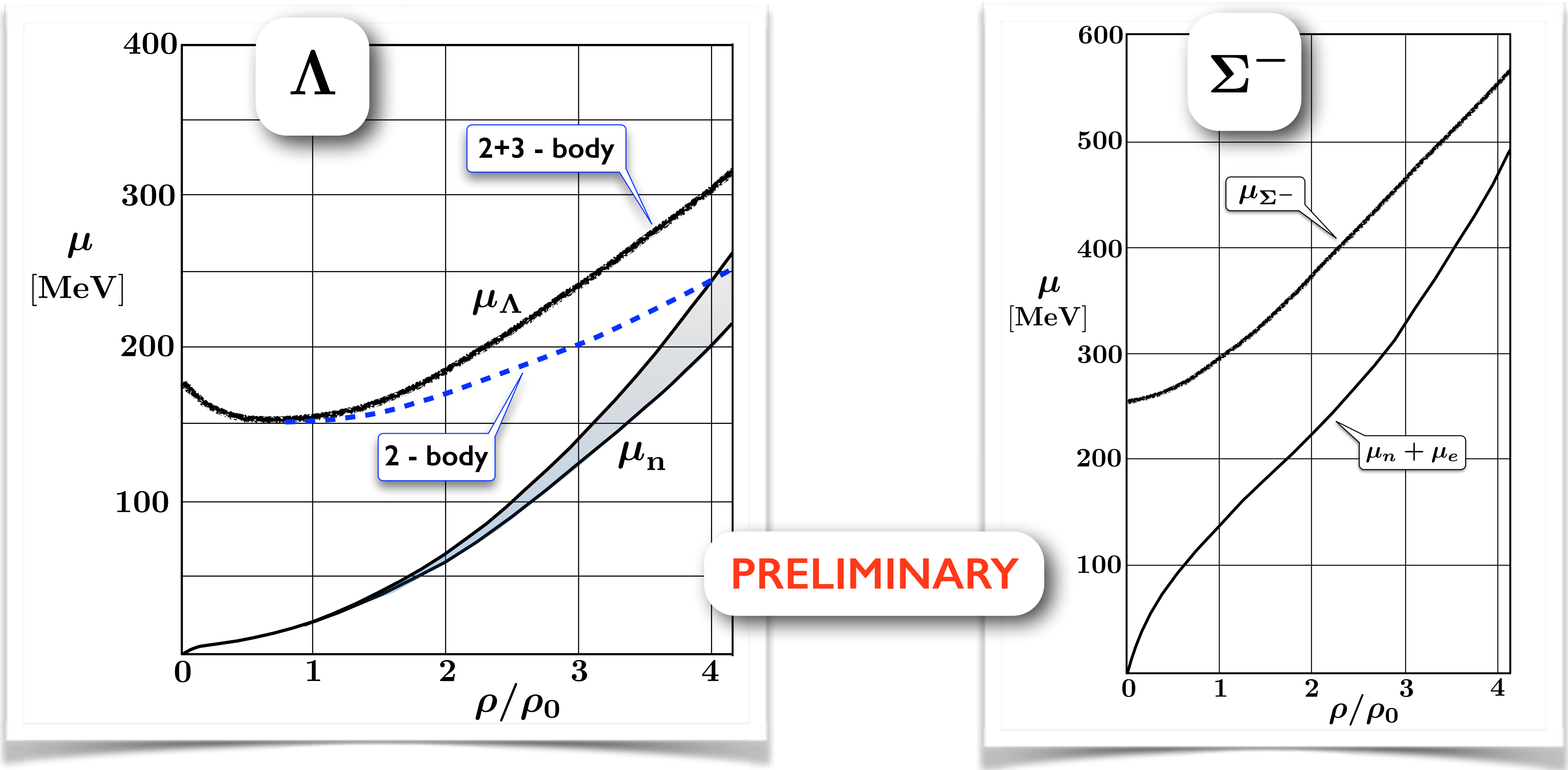
hadron - quark continuity ?

Outlook: **Hyperons in Neutron Stars ?**

- Onset conditions for appearance of **hyperons in neutron stars :**

Equalities for **chemical potentials** $\mu_i = \frac{\partial \mathcal{E}}{\partial \rho_i}$

$$\mu_\Lambda = \mu_n \qquad \mu_{\Sigma^-} = \mu_n + \mu_e = 2\,\mu_n - \mu_p$$



- Extrapolations using **hyperon single particle potentials** in **neutron matter** from **Chiral SU(3) EFT** interactions

- Extensive and more detailed calculations in progress (D. Gerstung, N. Kaiser, W.W.)