ECT* Workshop “The physics of strongly interacting matter: neutron stars, cold atomic gases and related systems”
Trento, 25 April 2024

CONTRAINTS on PHASE TRANSITIONS in NEUTRON STAR MATTER and RELATED TOPICS

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PHYSIK DEPARTMENT

- Dense Matter in Neutron Stars: Speed of Sound and Equation of State
  - Observational constraints from heavy neutron stars and binary mergers
  - Bayesian inference results and constraints on phase transitions
- Phenomenology and Models for Dense Baryonic Matter
  - Low-energy nucleon structure and a two-scales scenario
  - Hadron-quark continuity and crossover
  - Chiral symmetry restoration : from first-order phase transition to crossover
  - Dense baryonic matter as a (relativistic) Fermi liquid

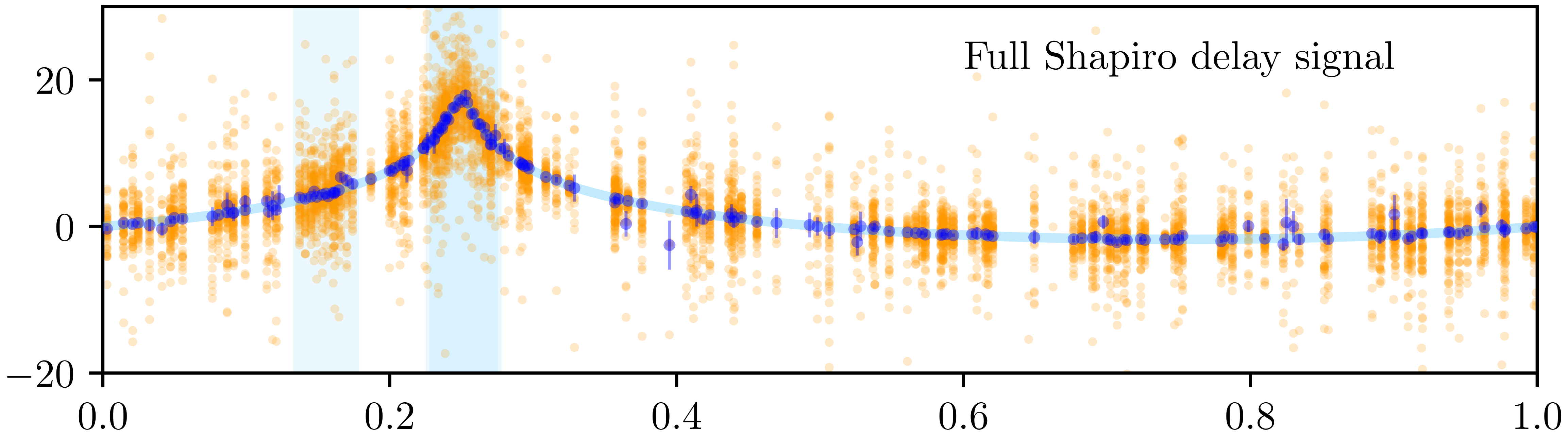
Part One

Equation-of-State of Dense Baryonic Matter :

Empirical Constraints from Neutron Stars

NEUTRON STARS : DATA

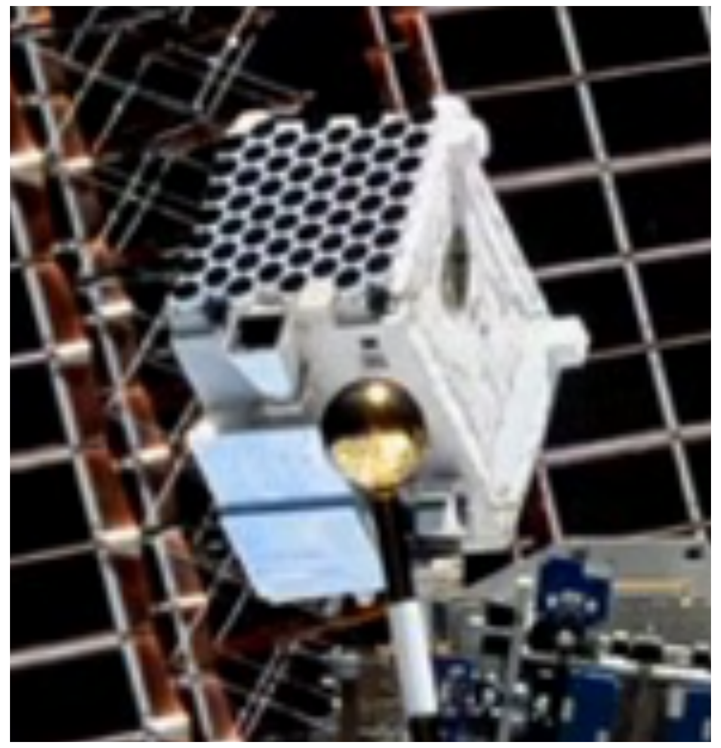
- Database for **inference of Equation-of-State** and other properties of neutron stars



- **Neutron star masses**

  Shapiro delay measurements
  (Green Bank Telescope)

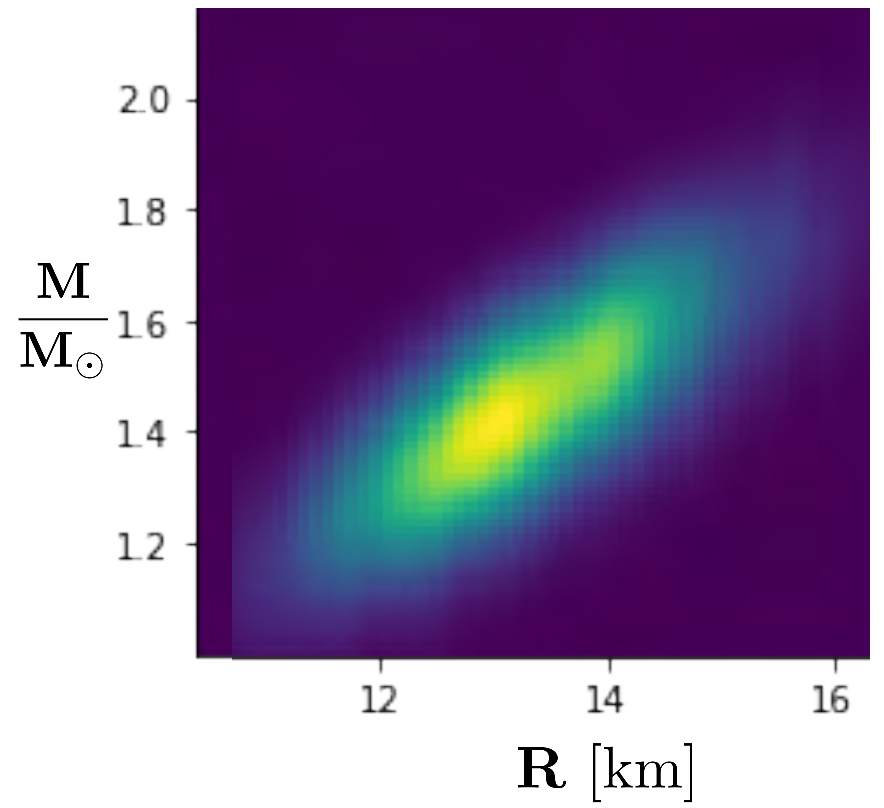
  Radio observations
  (Effelsberg)

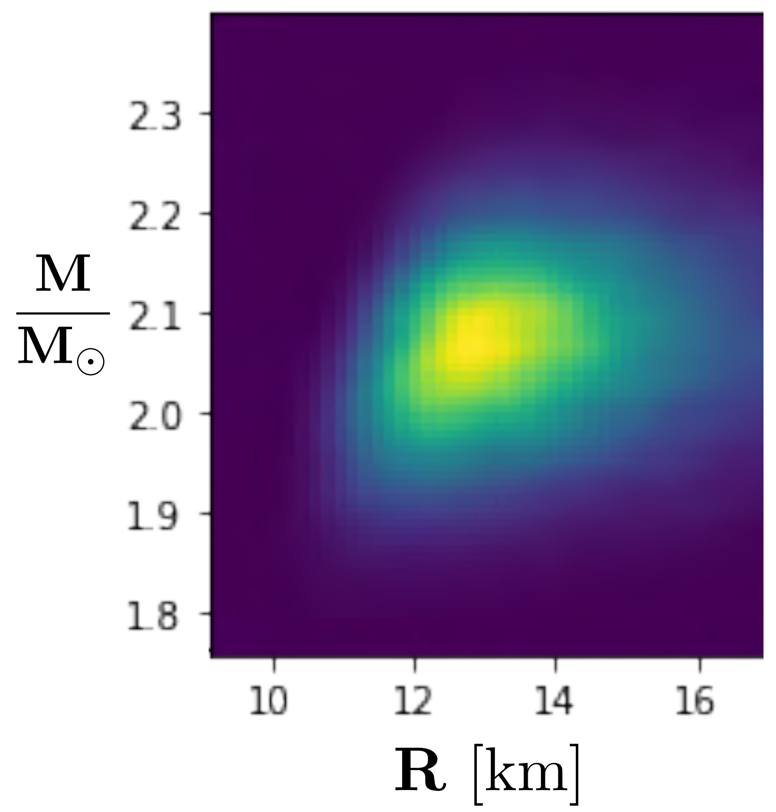


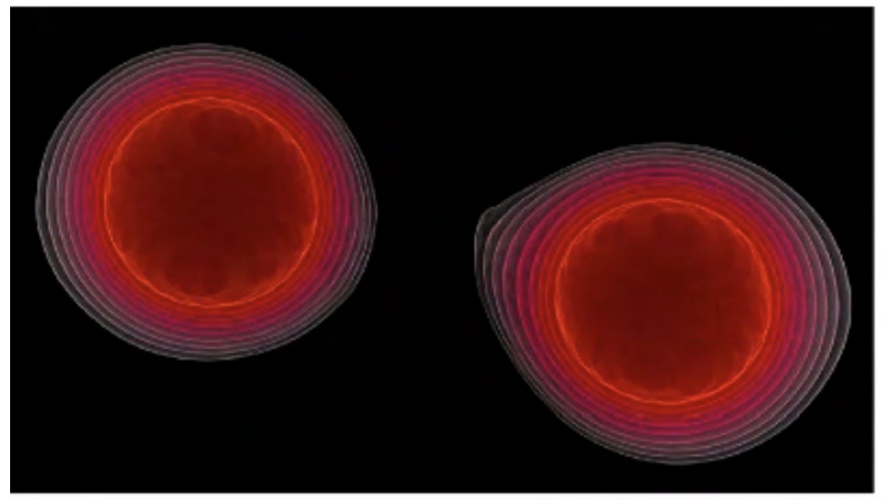
- **Masses and radii**

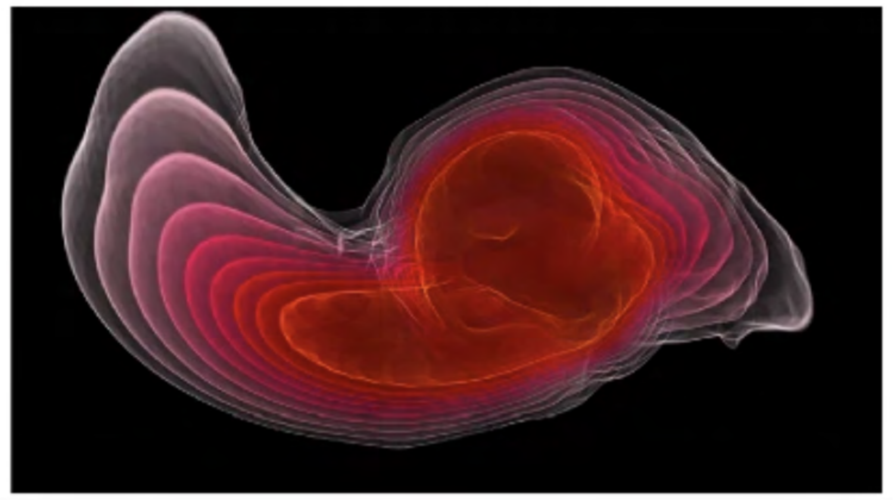
  X rays from hot spots on the surface of rotating neutron stars

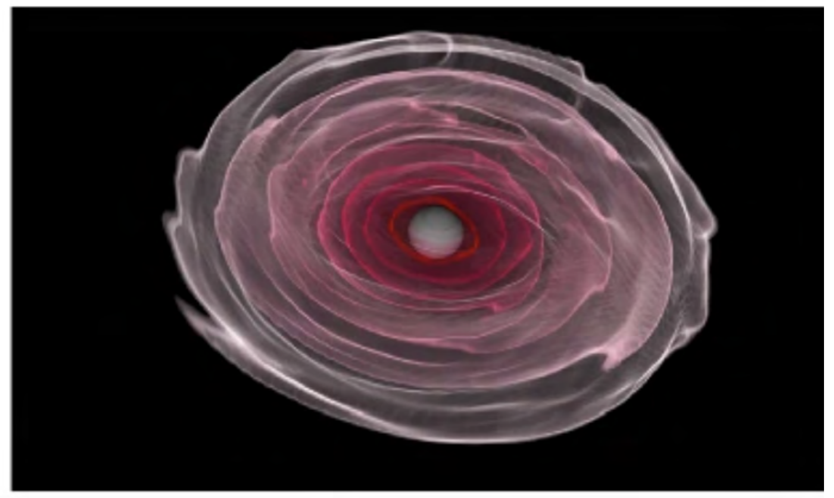
  (NICER Telescope @ ISS)











- **Tidal deformabilities**

  Gravitational wave signals of neutron star mergers

  (LIGO and Virgo Collab.)

NEUTRON STARS : DATA

- **Masses of $2\,M_\odot$ stars**
  (Shapiro delay & radio observations)

PSR J0348+0432

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

J. Antoniadis et al. : Science 340 (2013) 1233232

PSR J1614-2230

$$M = 1.908 \pm 0.016\ M_\odot$$

Z. Arzoumanian et al. , Astrophys. J. Suppl. 235 (2018) 37

PSR J0740+6620

$$M = 2.08 \pm 0.07\ M_\odot$$

E. Fonseca et al. , Astrophys. J. Lett. 915 (2021) L12

- **Masses and Radii** (NICER)

PSR J0030+0451

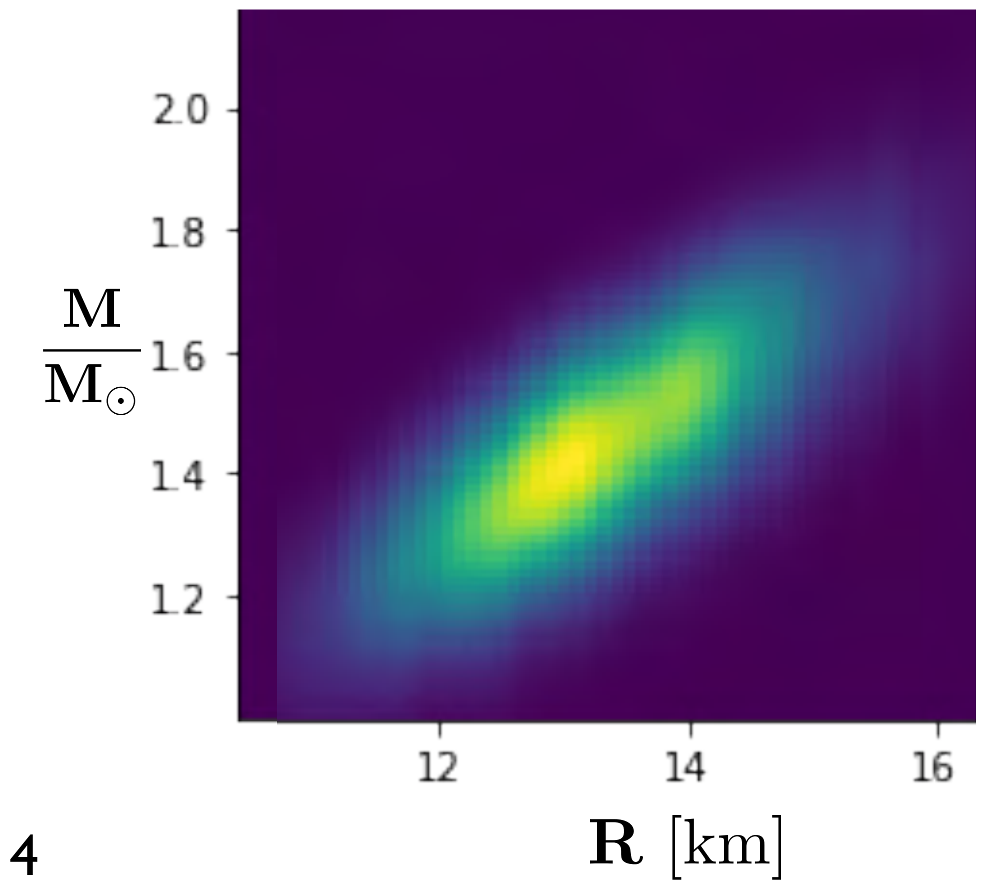
$$M = 1.34 \pm 0.16\,M_\odot \qquad R = 12.71^{+1.14}_{-1.19}\ \mathrm{km}$$

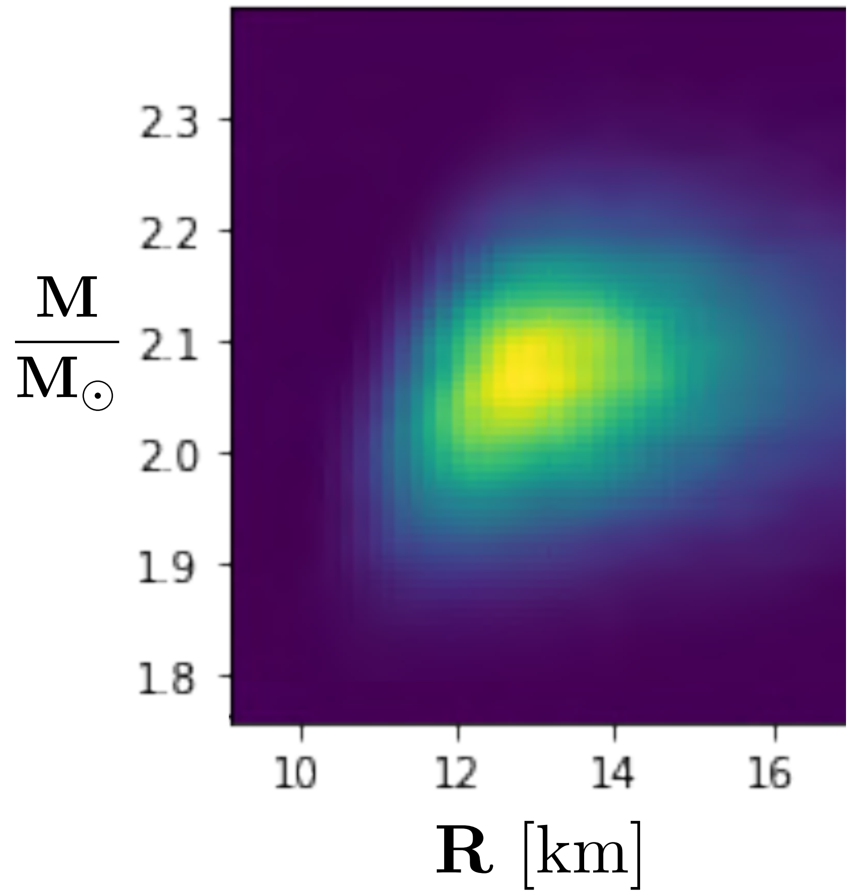
T.E. Riley et al. (NICER), Astroph. J. Lett. 887 (2019) L21

PSR J0740+6620

$$M = 2.07 \pm 0.07\,M_\odot \qquad R = 12.39^{+1.30}_{-0.98}\ \mathrm{km}$$

T.E. Riley et al. (NICER + XMM Newton), Astroph. J. Lett. 918 (2021) L27





NEUTRON STARS : DATA (contd.)

- **Very massive** and **fast rotating galactic neutron star**

PSR J0952-0607

$$\mathrm{M} = 2.35 \pm 0.17\ \mathrm{M}_\odot$$

R.W. Romano et al. : Astroph. J. Lett. 935 (2022) L17

(Keck Observatory)

→ equivalent non-rotating mass after rotational correction : $\mathrm{M} = 2.3 \pm 0.2\ \mathrm{M}_\odot$

- **Tidal deformabilities** from binary neutron star mergers (gravitational wave signals)

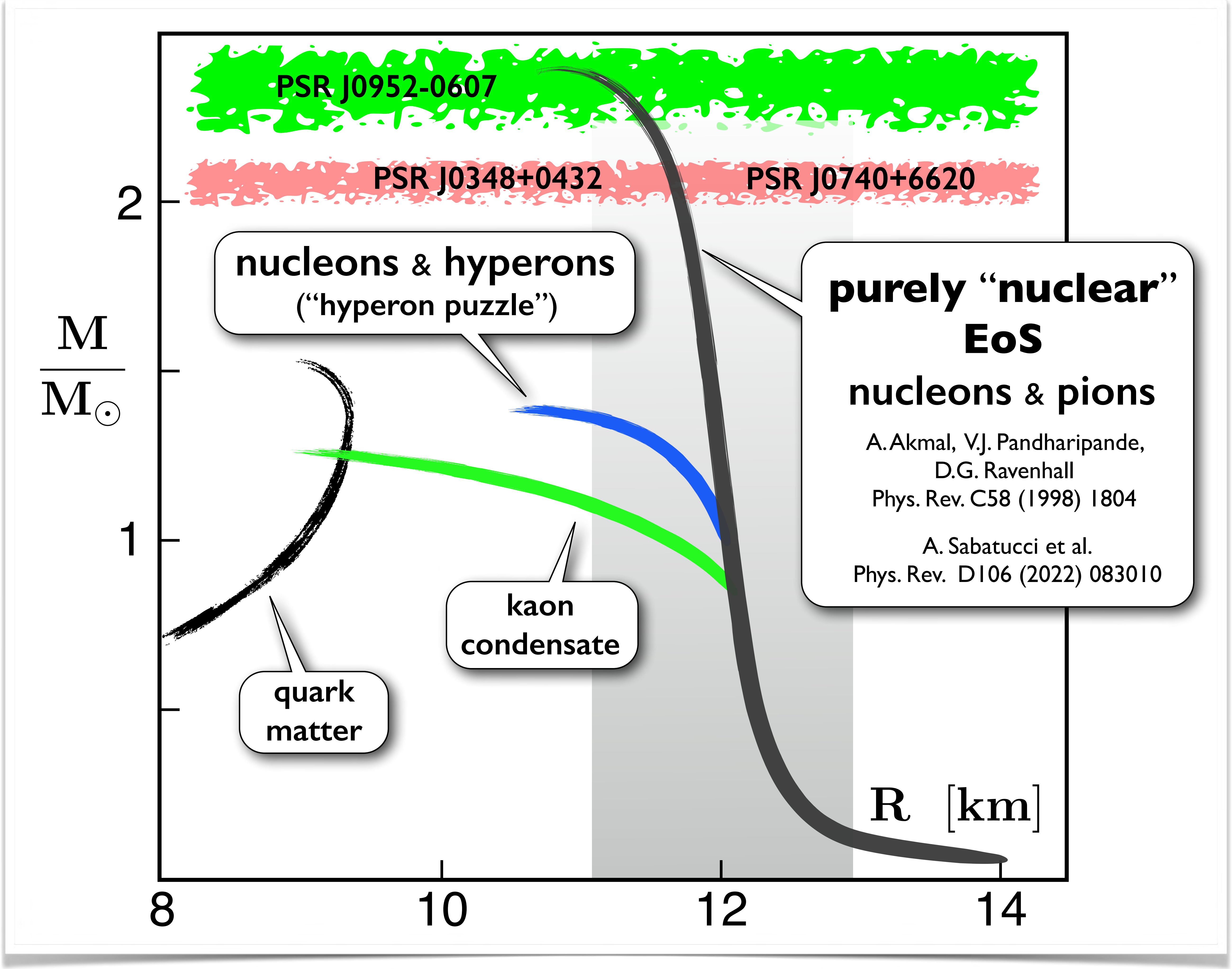
$$\tilde{\Lambda} = \frac{16}{13}\frac{(M_1 + 12\,M_2)M_1^4\Lambda_1}{(M_1+M_2)^5} + (1 \leftrightarrow 2)$$

GW170817 $\Lambda_{1.4} = 190^{+390}_{-120}$

B.P. Abbot et al. : Phys. Rev. Lett. 121 (2018) 161101

CONSTRAINTS on EQUATION of STATE $P(\varepsilon)$

- from observations of massive neutron stars



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

$$\frac{dP(r)}{dr} = \frac{G\,[\varepsilon(r) + P(r)]\,\left[m(r) + 4\pi r^3 P(r)\right]}{r\,[r - 2\,G\,m(r)]}$$

$$\frac{dm(r)}{dr} = 4\pi r^2 \varepsilon(r)$$

$$M = m(R) = 4\pi \int_0^R dr\, r^2 \varepsilon(r)$$

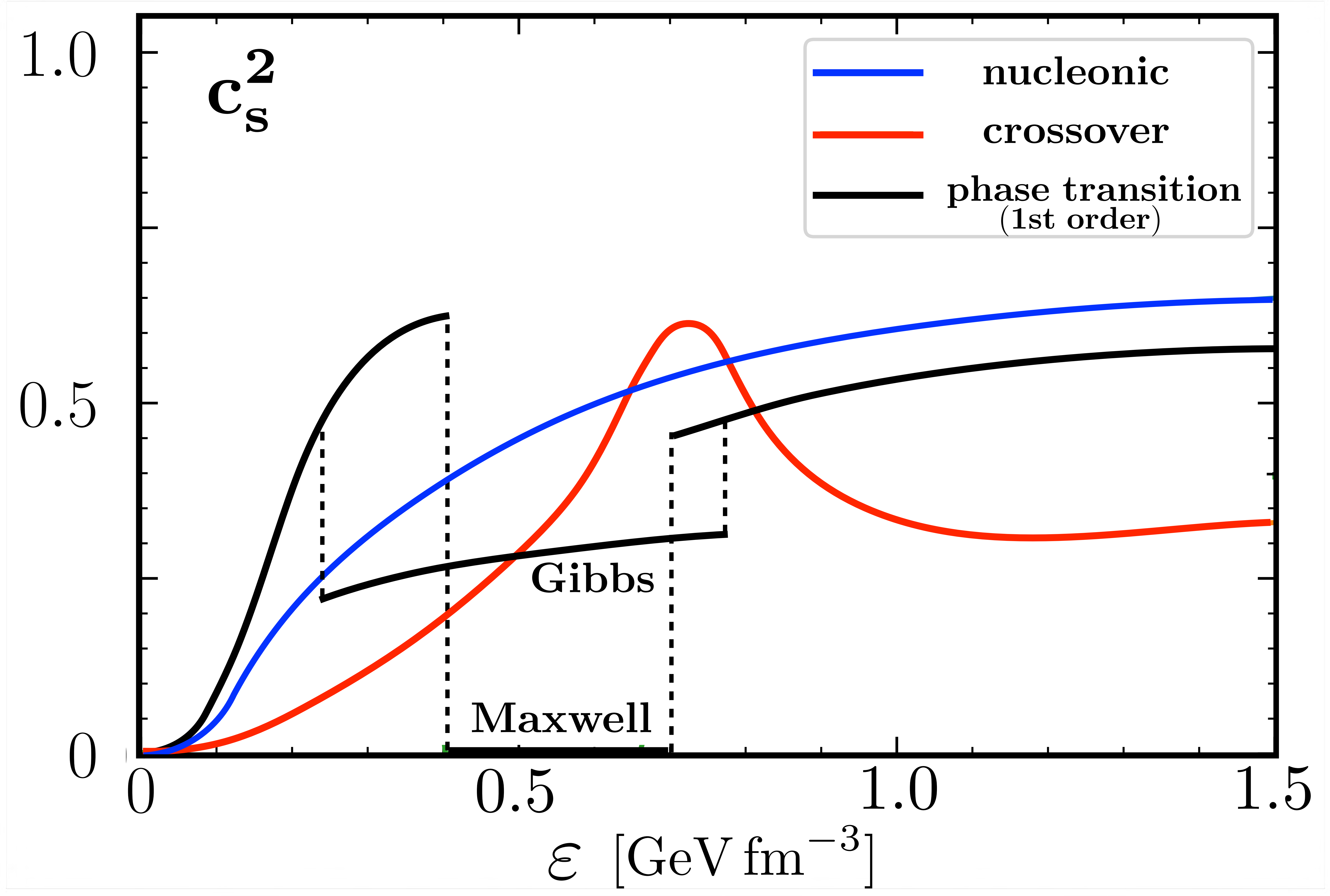
- **Stiff equation-of-state $P(\varepsilon)$ required**
- **Simplest forms of exotic matter** (kaon condensate, quark matter, ...) **ruled out**

SOUND VELOCITY and EQUATION of STATE

- Key quantity : **Speed of Sound**

$$c_s^2(\varepsilon) = \frac{\partial P(\varepsilon)}{\partial \varepsilon}$$

displays
characteristic signature
of
phase transition
or
crossover

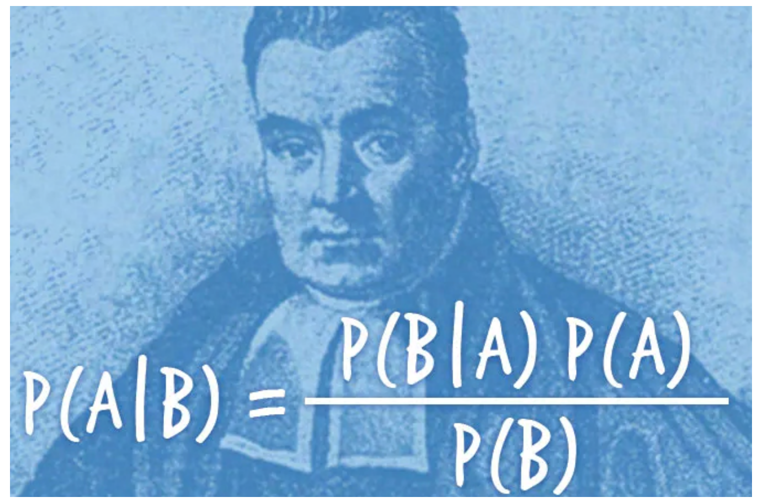


energy density

- **E**quation **of S**tate :

$$P(\varepsilon) = \int_0^\varepsilon d\varepsilon' \, c_s^2(\varepsilon')$$

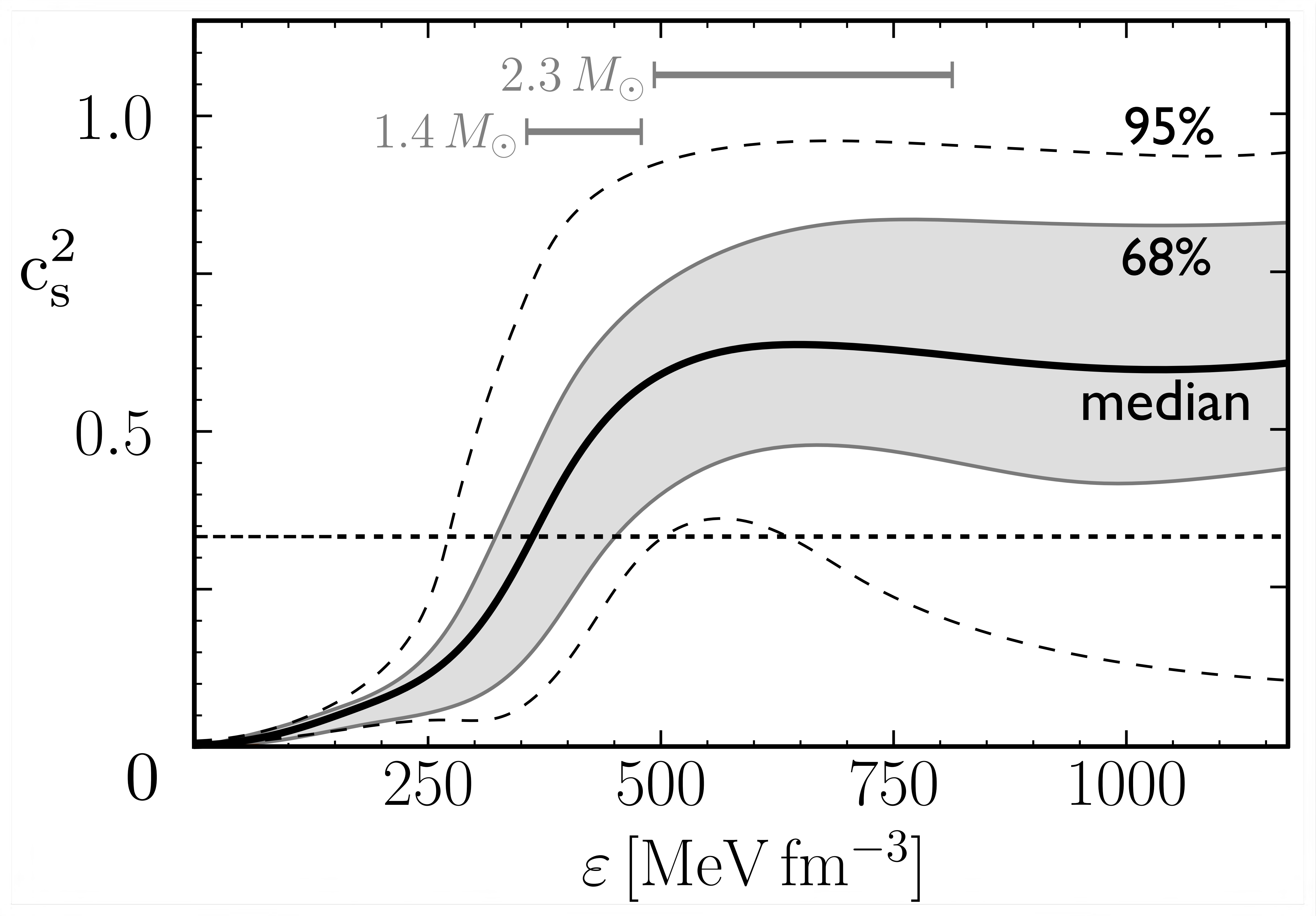
NEUTRON STAR MATTER : EQUATION of STATE

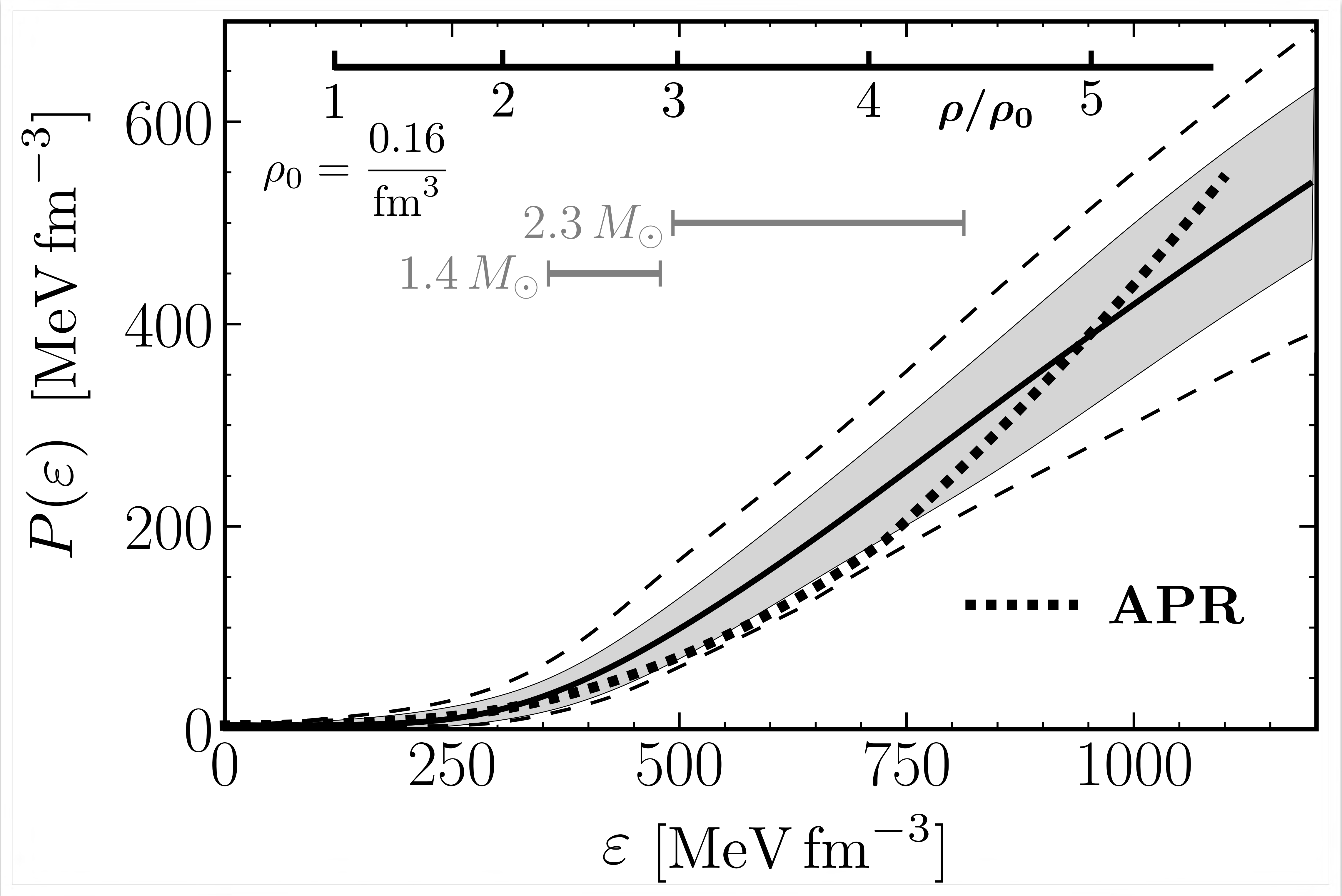


- Bayesian inference of **sound speed** and **EoS**

PSR masses, NICER & GW data, low-density constraints (ChEFT), asymptotic constraints (pQCD)

L. Brandes, W.W. , N. Kaiser : Phys. Rev. D 107 (2023) 014011 ; Phys. Rev. D 108 (2023) 094014 - L. Brandes, W.W. : Symmetry 16 (2024) 111

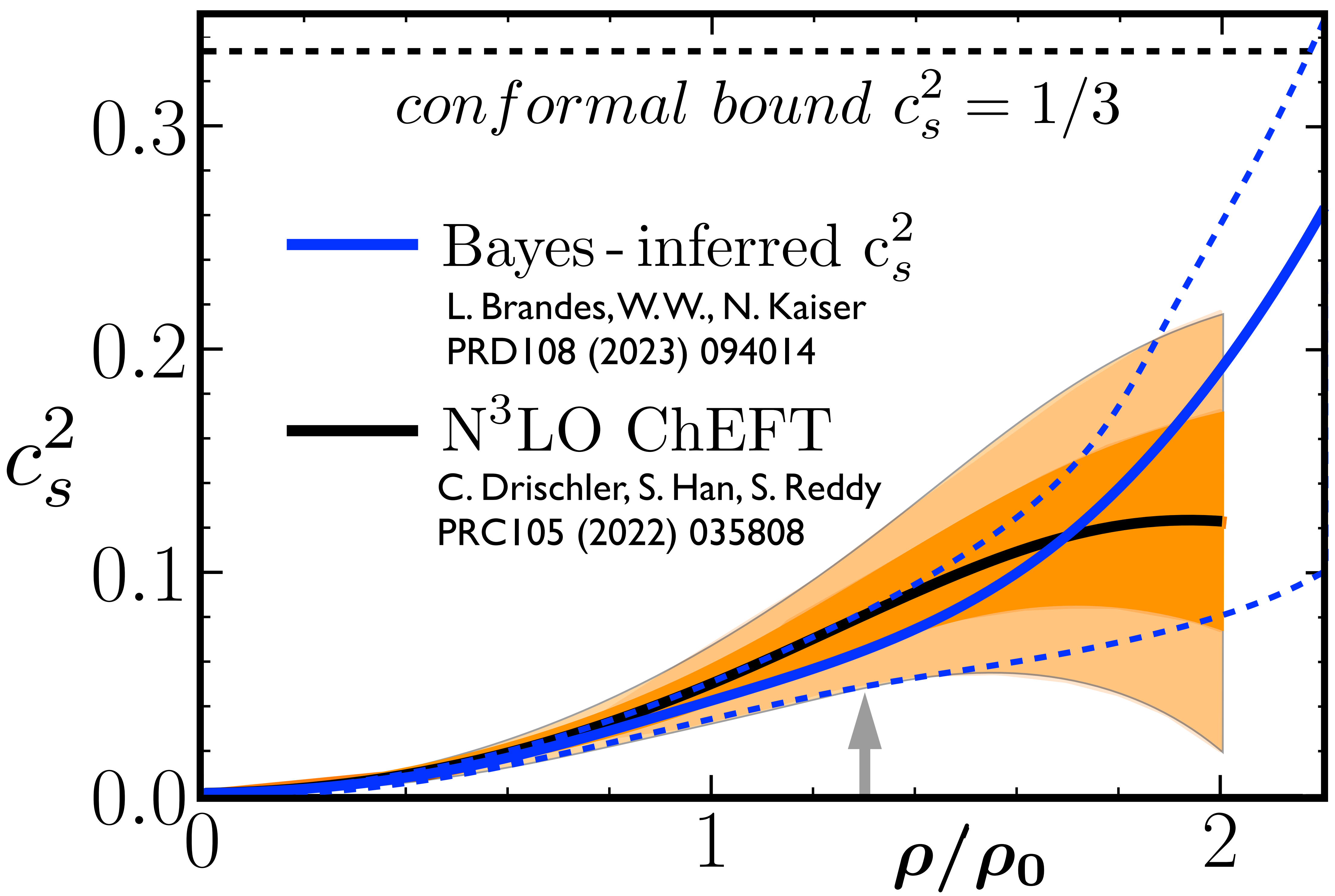




- Squared **speed of sound** exceeds conformal bound $c_s^2 = 1/3$ at baryon densities $\boldsymbol{\rho > 3\rho_0}$
  - **Strongly repulsive correlations** in dense baryonic matter

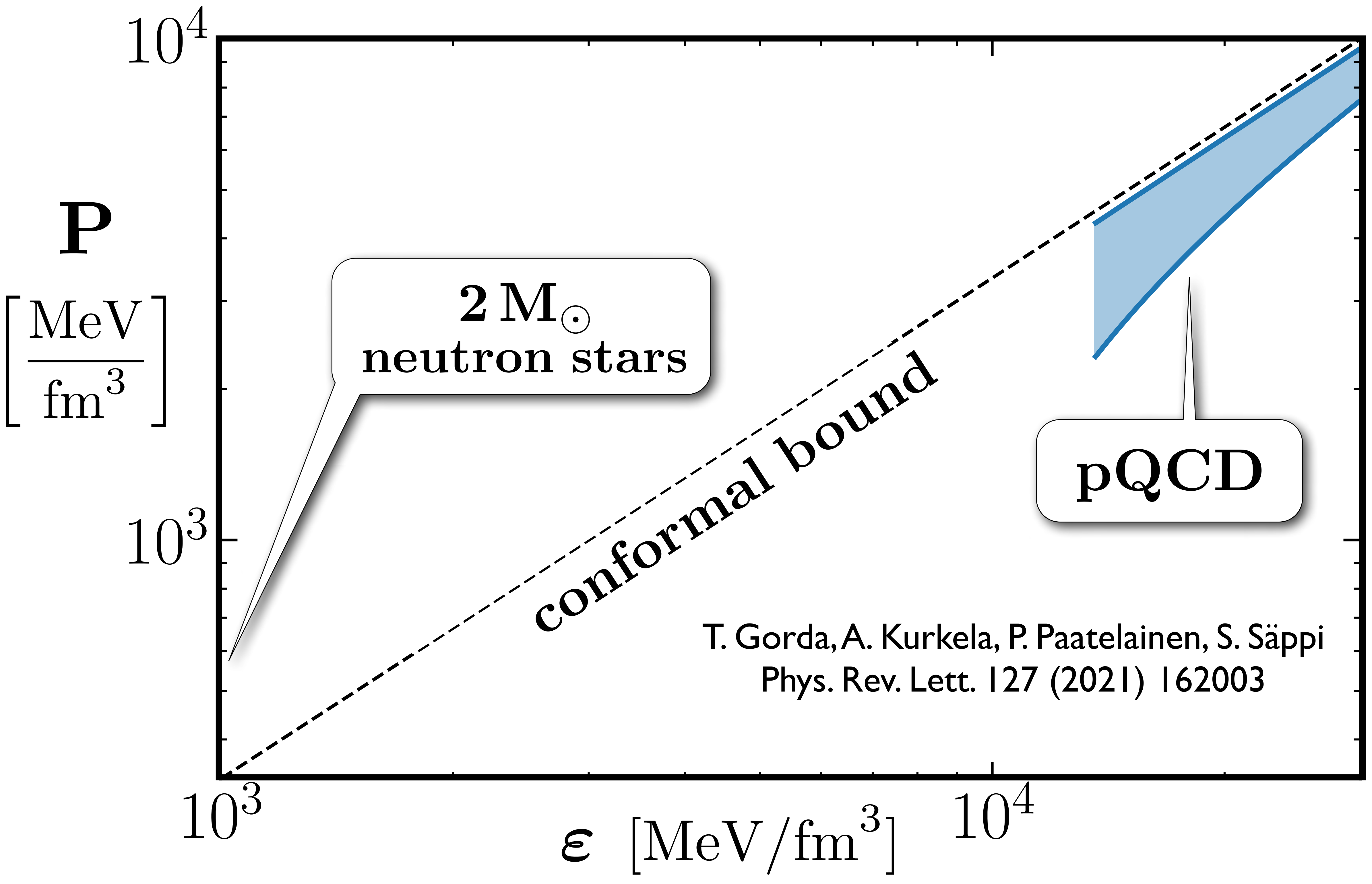
EQUATION of STATE and SOUND VELOCITY
- boundary conditions -

- Low densities : Chiral EFT @ $\rho \lesssim 2\,\rho_0$



- Employ ChEFT constraint at $\rho = 1.3\,\rho_0$ in Bayes inference as **Likelihood, NOT Prior**

- Extremely high densities : $\rho \gg \rho_c(2M_\odot)$

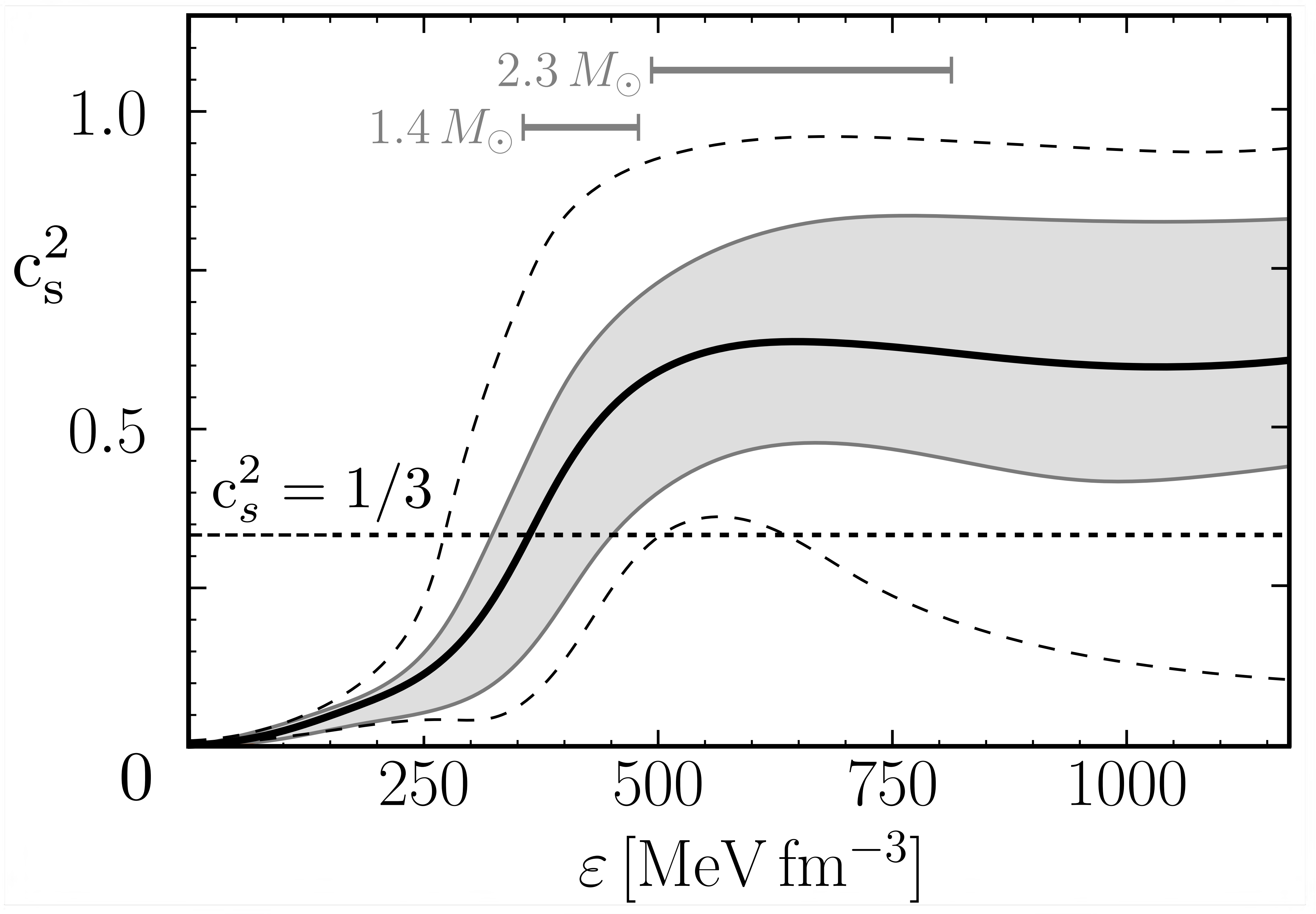


- **Conformal bound** $c_s^2 = \frac{1}{3}$ reached asymptotically

Comment : **SPEED of SOUND** exceeding **CONFORMAL BOUND**

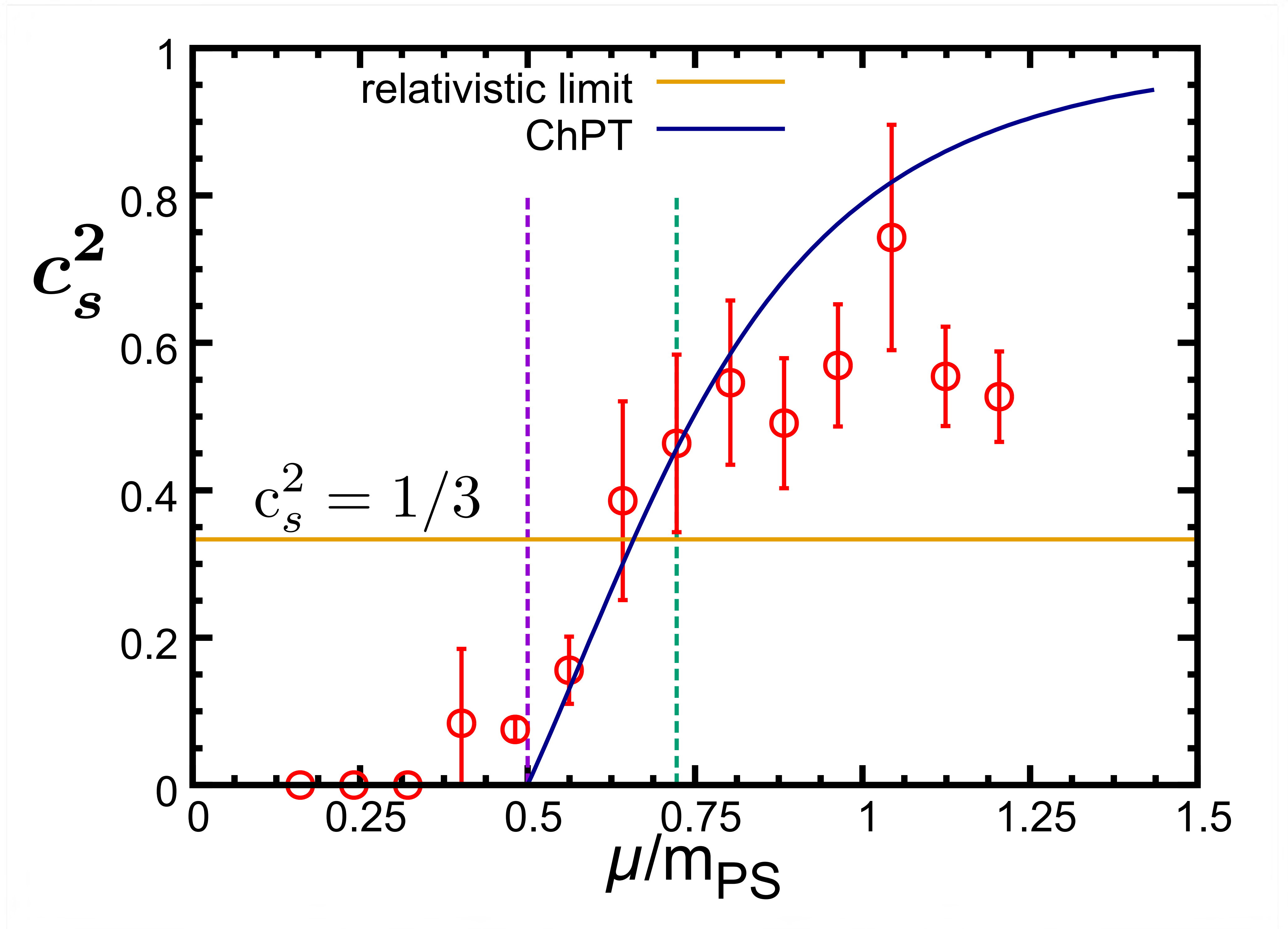
- Bayesian inference of **sound speed** in neutron star matter

L. Brandes, W.W., N. Kaiser : Phys. Rev. D 108 (2023) 094014



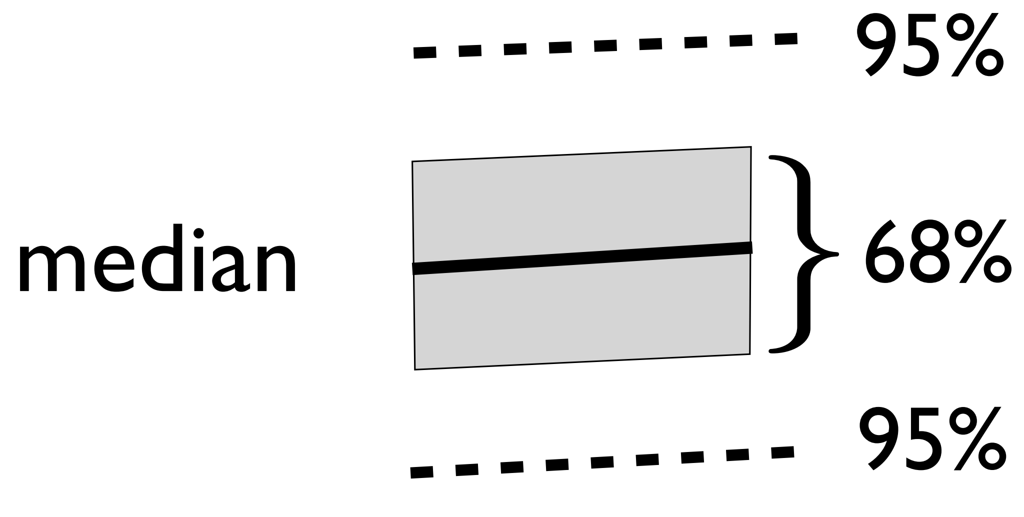
- Sound speed as function of baryon chemical potential in $N_c = 2$ LQCD

E. Itou, K. Iida : PTEP2022, 11 (2022) 111B01



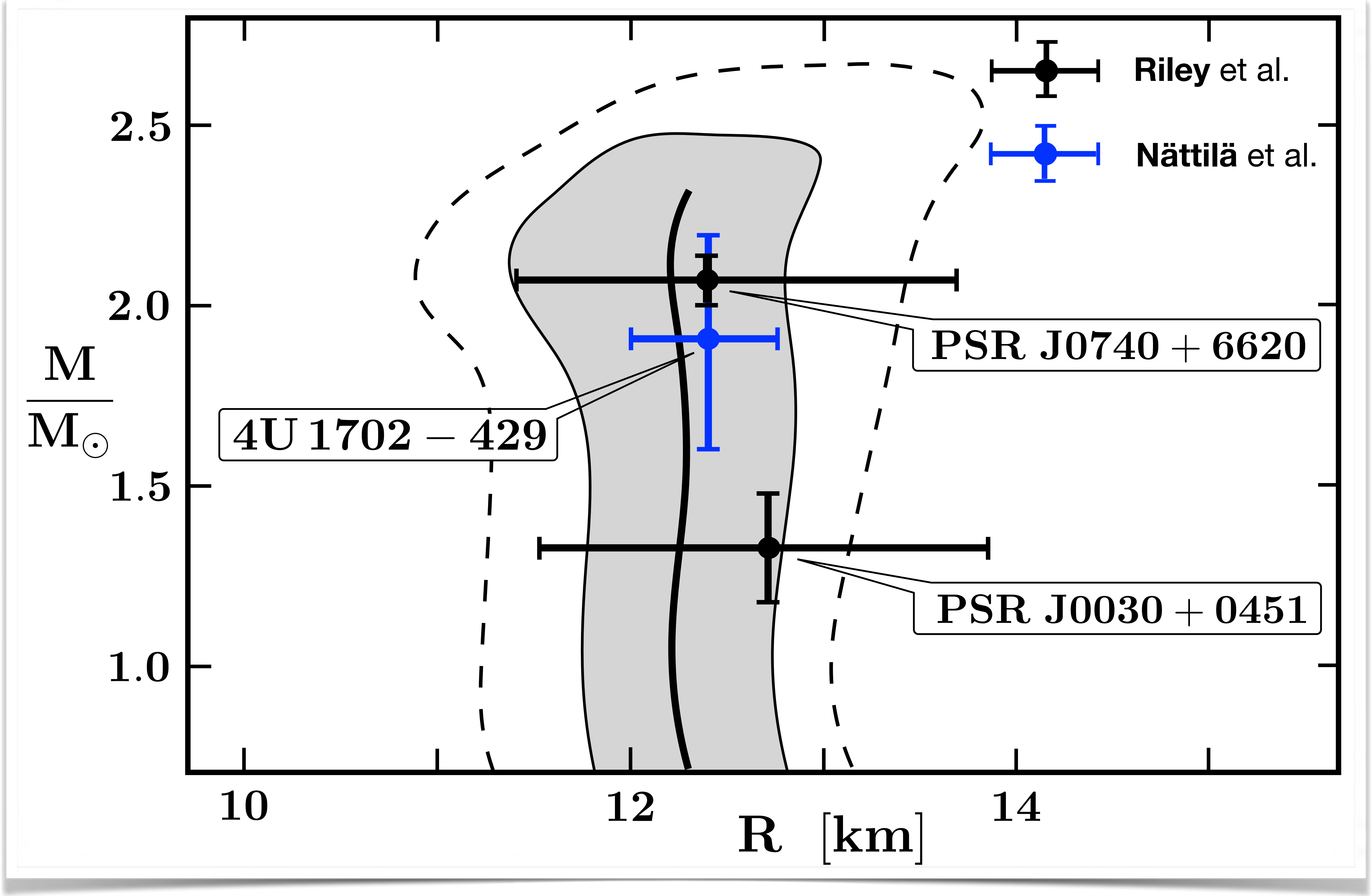
- Squared **speed of sound** exceeds conformal bound $c_s^2 = 1/3$ at baryon densities $\rho > 3\rho_0$
- Similar results in recent Bayesian inference using even larger data base : H. Koehn et al. : arXiv:2402.04172

NEUTRON STAR PROPERTIES

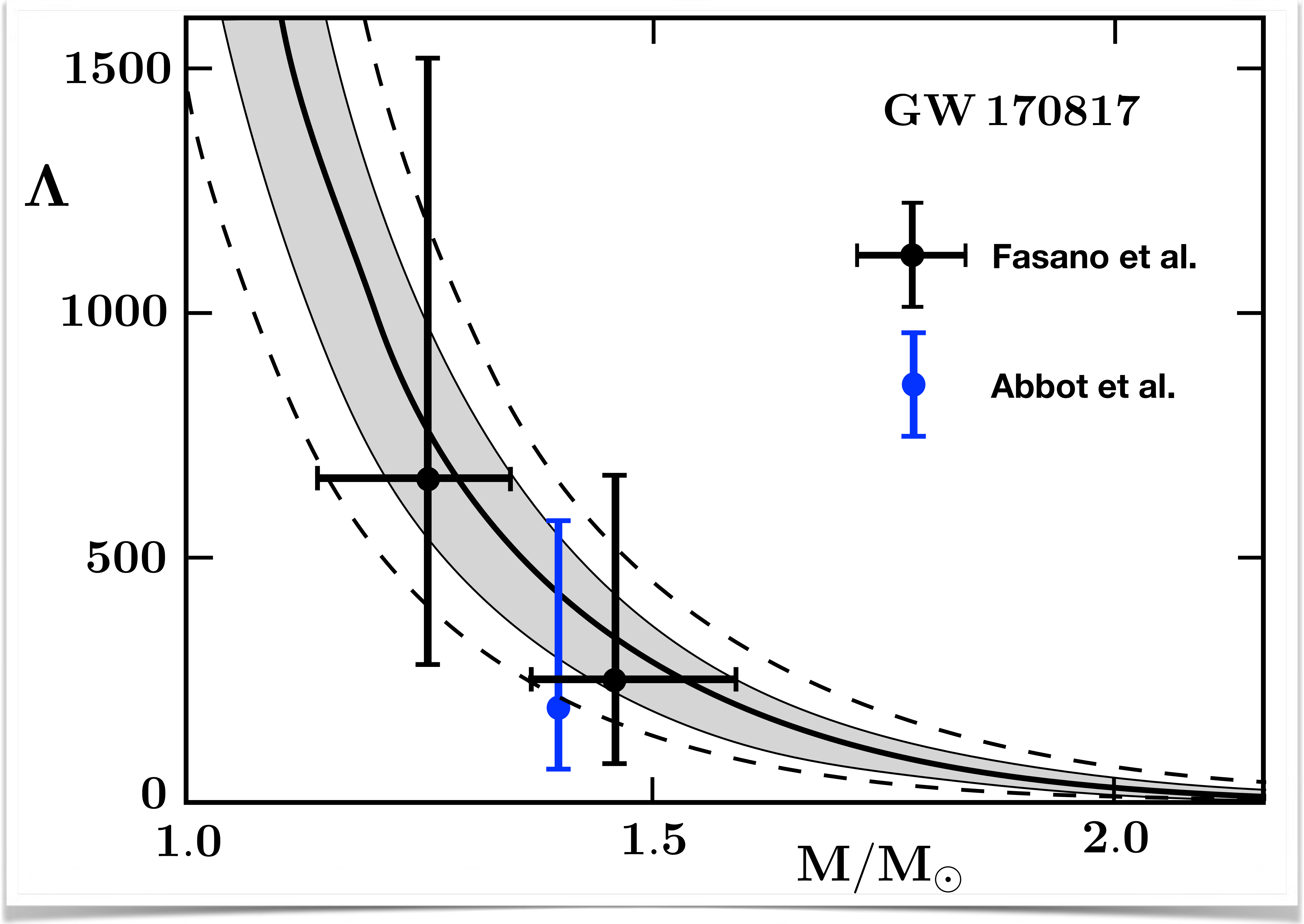


- **Bayesian inference posterior bands** (68% and 95% c.l)

- **Mass - Radius relation (TOV)**



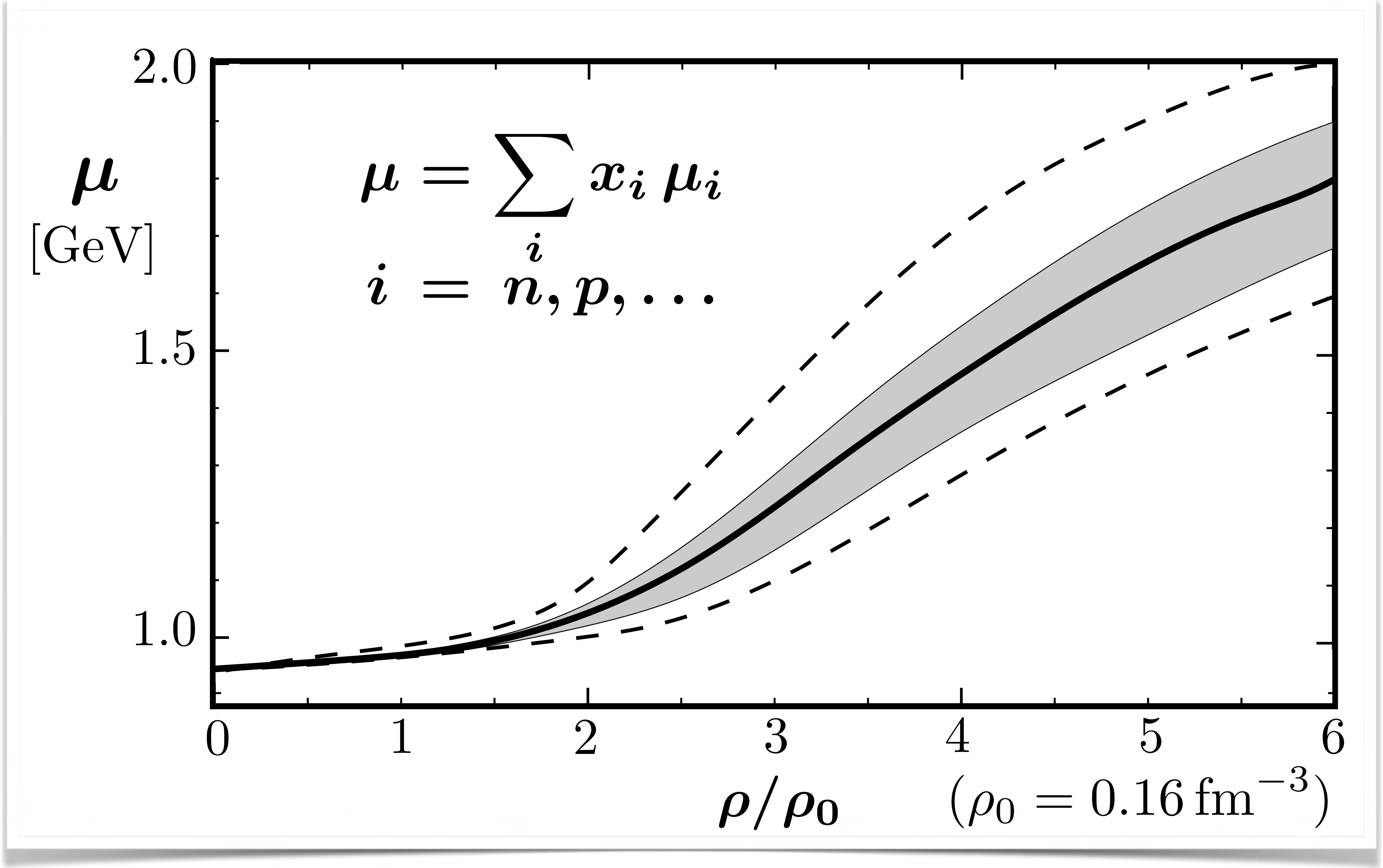
- **Tidal deformability**



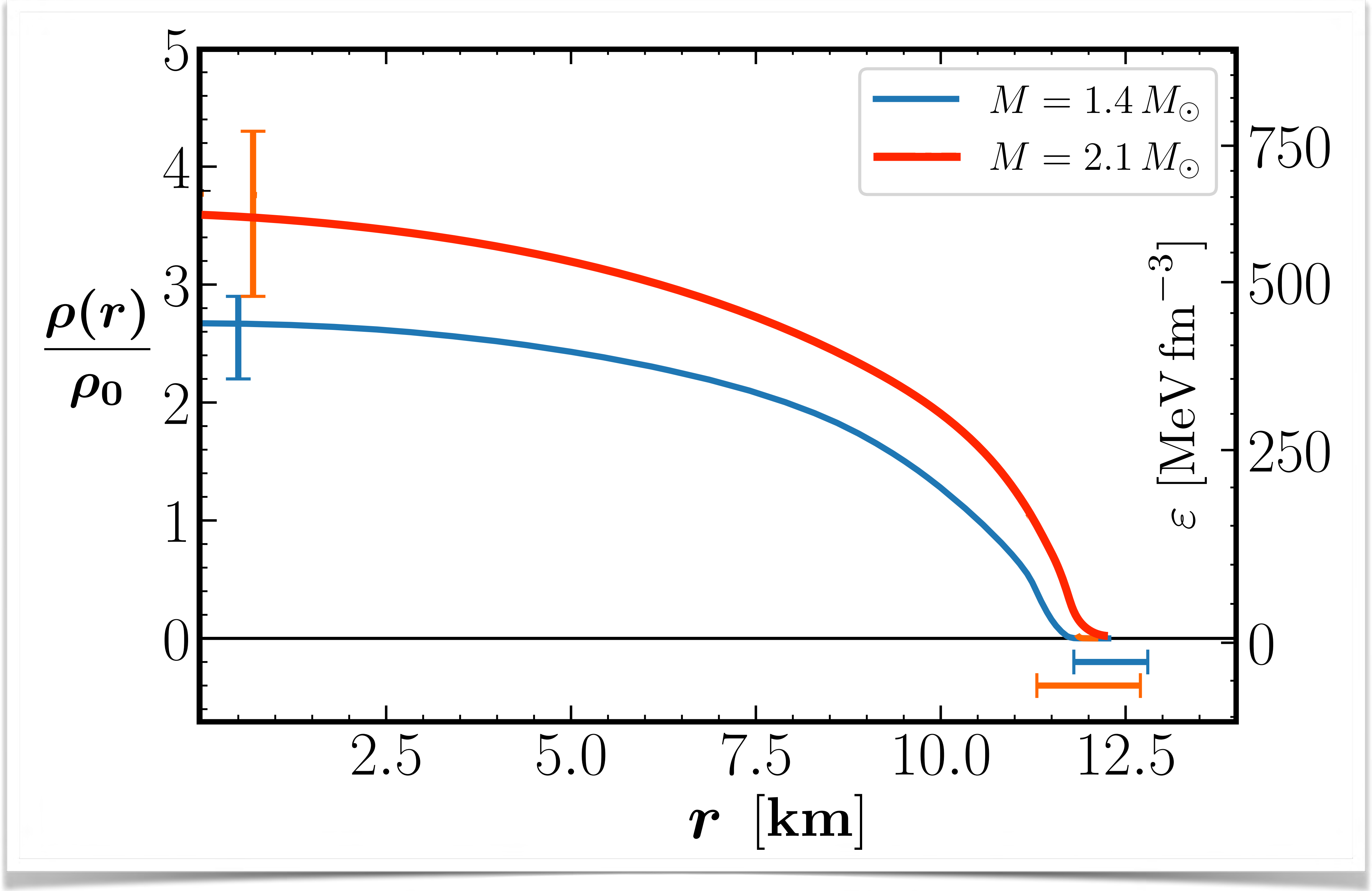
L. Brandes, W. W., N. Kaiser : Phys. Rev. D 107 (2023) 014011 ; Phys. Rev. D 108 (2023) 094014

NEUTRON STAR PROPERTIES (contd.)

- Baryon chemical potential



- Density profiles of neutron stars



L. Brandes, W. W., N. Kaiser : Phys. Rev. D 107 (2023) 014011 ; Phys. Rev. D 108 (2023) 094014.

- **Stiff equation of state** → **central core densities in neutron stars are NOT extreme :**

$$\rho_c(1.4\,M_\odot) = 2.6^{+0.3}_{-0.4}\,\rho_0 \qquad \rho_c(2.1\,M_\odot) = 3.6 \pm 0.7\,\rho_0 \qquad \rho_c(2.3\,M_\odot) = 3.8 \pm 0.8\,\rho_0$$

(68% c.l.)

Constraints on
FIRST-ORDER PHASE TRANSITION in NEUTRON STAR MATTER

- **Bayes factor analysis :**

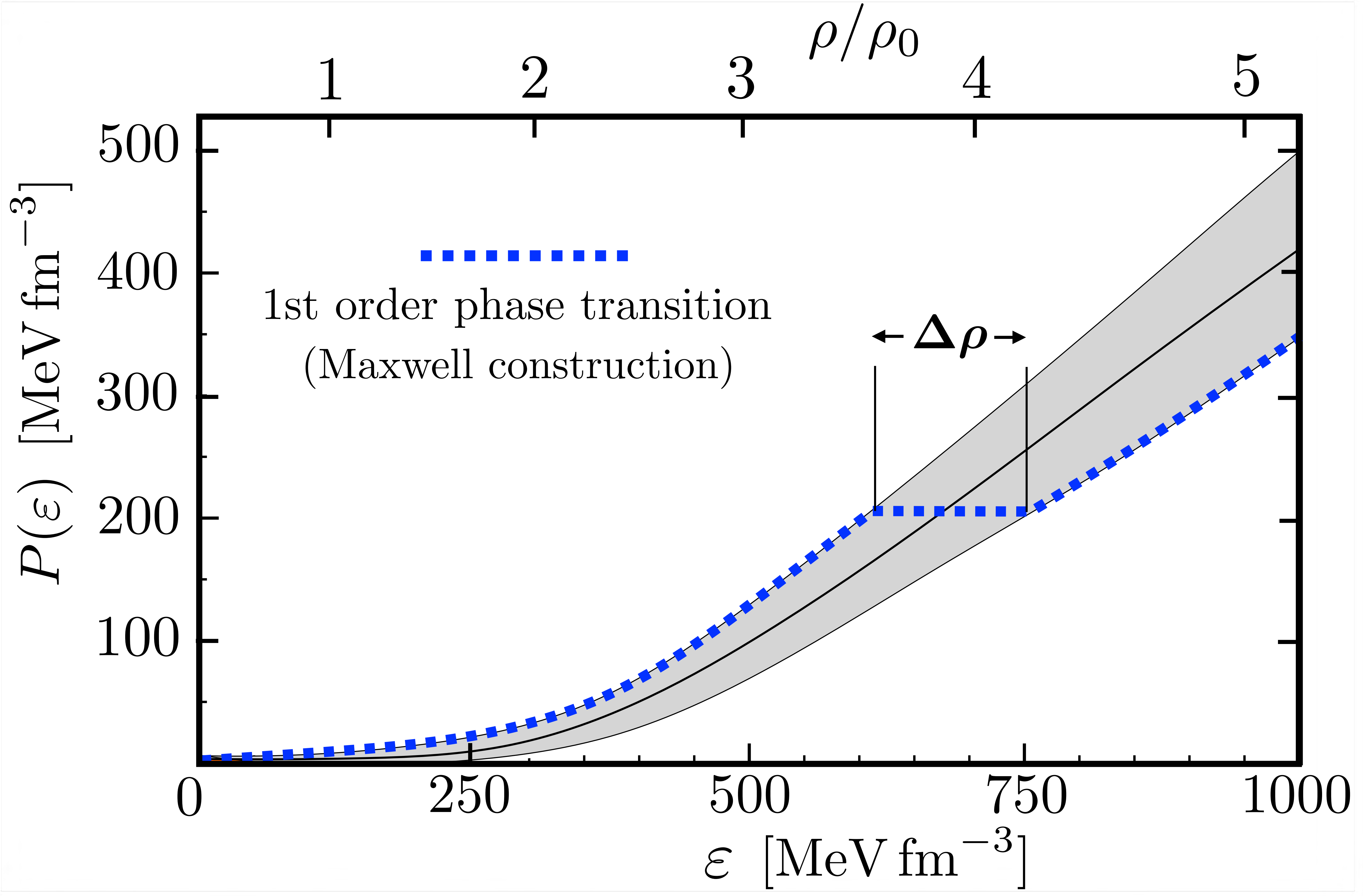
  → Extreme evidence for sound velocities $c_s > 0.5$ in cores of all neutron stars with

  $$1.4 \leq M/M_\odot \leq 2.3$$

- **Evidence against strong 1st order phase transition :**

  → Maximum possible extension of phase coexistence domain

  $$\Delta\rho/\rho \lesssim 0.2 \quad \text{(68\% c.l.)}$$



L. Brandes, W.W., N. Kaiser : Phys. Rev. D 108 (2023) 094014 - L. Brandes, W.W. : Symmetry 16 (2024) 111

→ **For comparison :**
Maxwell construction for nuclear liquid-gas phase transition $(\Delta\rho/\rho > 1)$

INTERMEDIATE SUMMARY

- **Bayesian inference analysis**
  now including heavy $(\mathrm{M} = 2.35 \pm 0.17\,\mathrm{M}_\odot)$ galactic neutron star
  - → even **stiffer equation of state** required
  - → almost **constant neutron star radii** $(\mathrm{R} \simeq 12 \pm 1\ \mathrm{km})$ for all masses

- **Extreme evidence** for sound velocities $\mathrm{c_s} > 1/\sqrt{3}$ in neutron star cores
  - → **strongly repulsive correlations** at work

- **Evidence** against **strong 1st order phase transition** in neutron star cores
  - → **not** excluded: **baryonic** matter or **hadron-quark** continuous crossover

- **No extreme central core densities** even in the heaviest neutron stars:

  $$\rho \lesssim 4.5\,\rho_0 \text{ for } M \leq 2.3\,M_\odot \quad \text{(68\% c.l.)}$$

  - → average baryon-baryon distance in the core: $\mathrm{d} \gtrsim 1\,\mathrm{fm}$

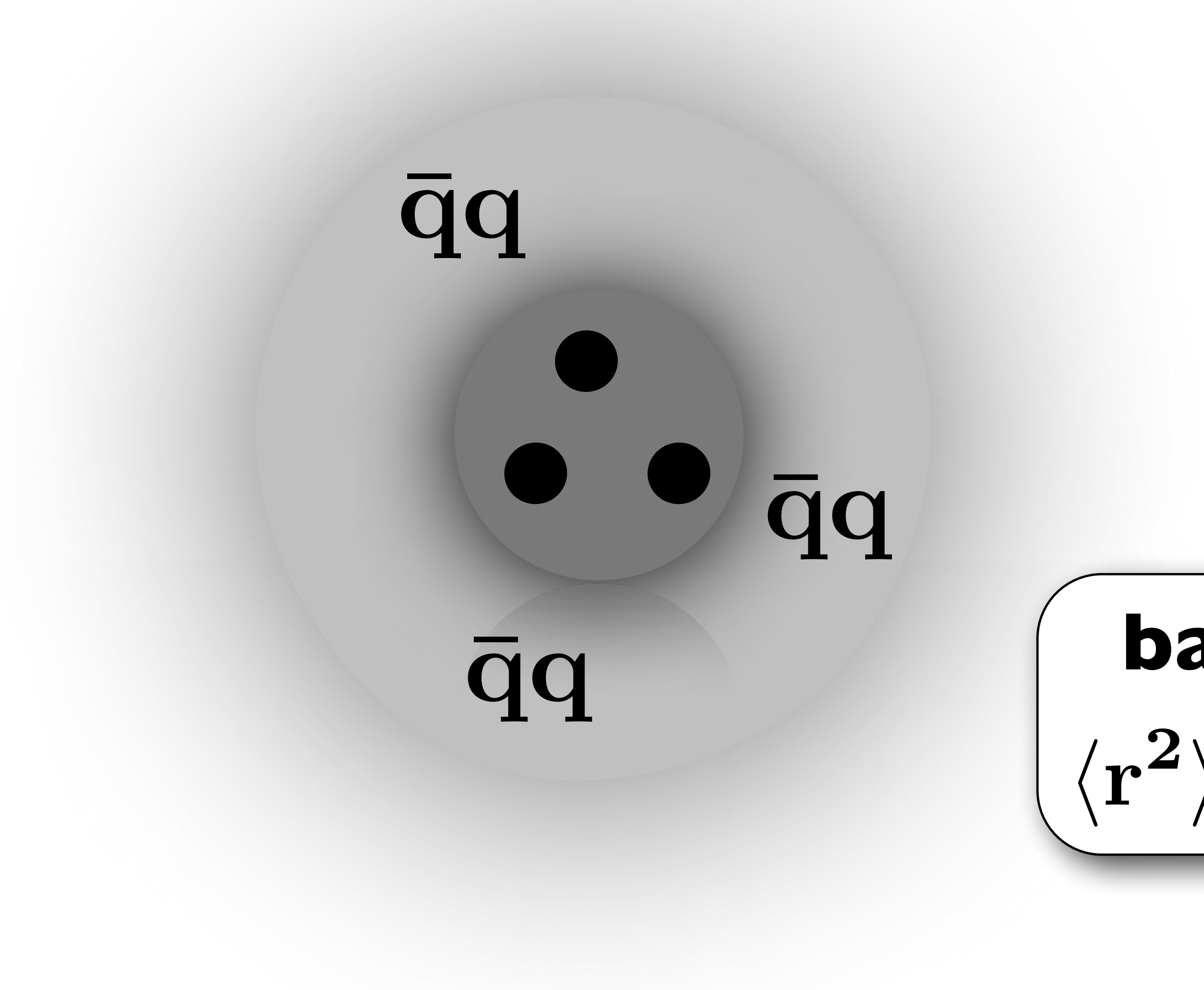
Part Two

Phenomenology, Models and Possible Dense Matter Scenarios

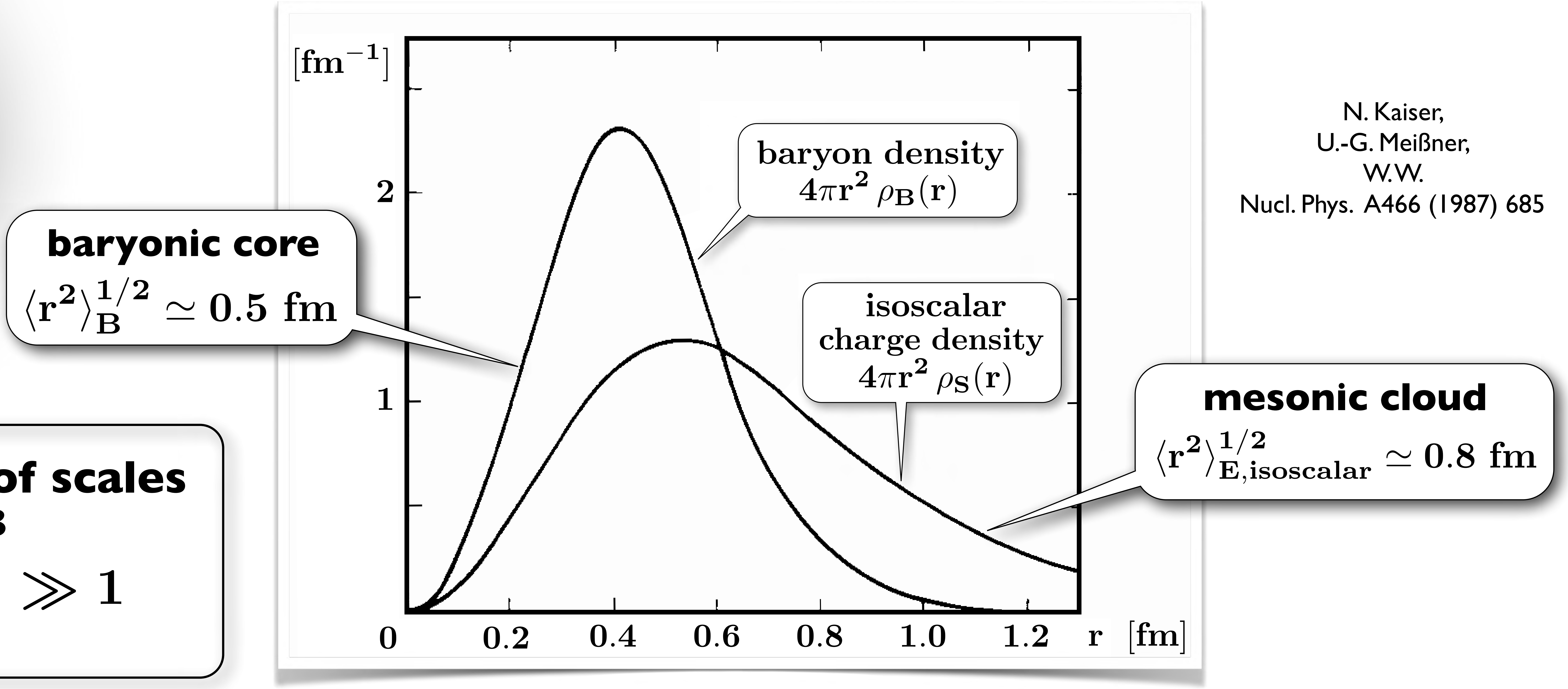
Historical reminder: **SIZES** of the **NUCLEON**

Low-energy QCD: **spontaneously broken chiral symmetry + localisation (confinement)**

- **NUCLEON** : **compact valence quark core + mesonic** (multi $\bar{q}q$) **cloud**



- Example: Chiral Soliton Model of the Nucleon



N. Kaiser,
U.-G. Meißner,
W.W.
Nucl. Phys. A466 (1987) 685

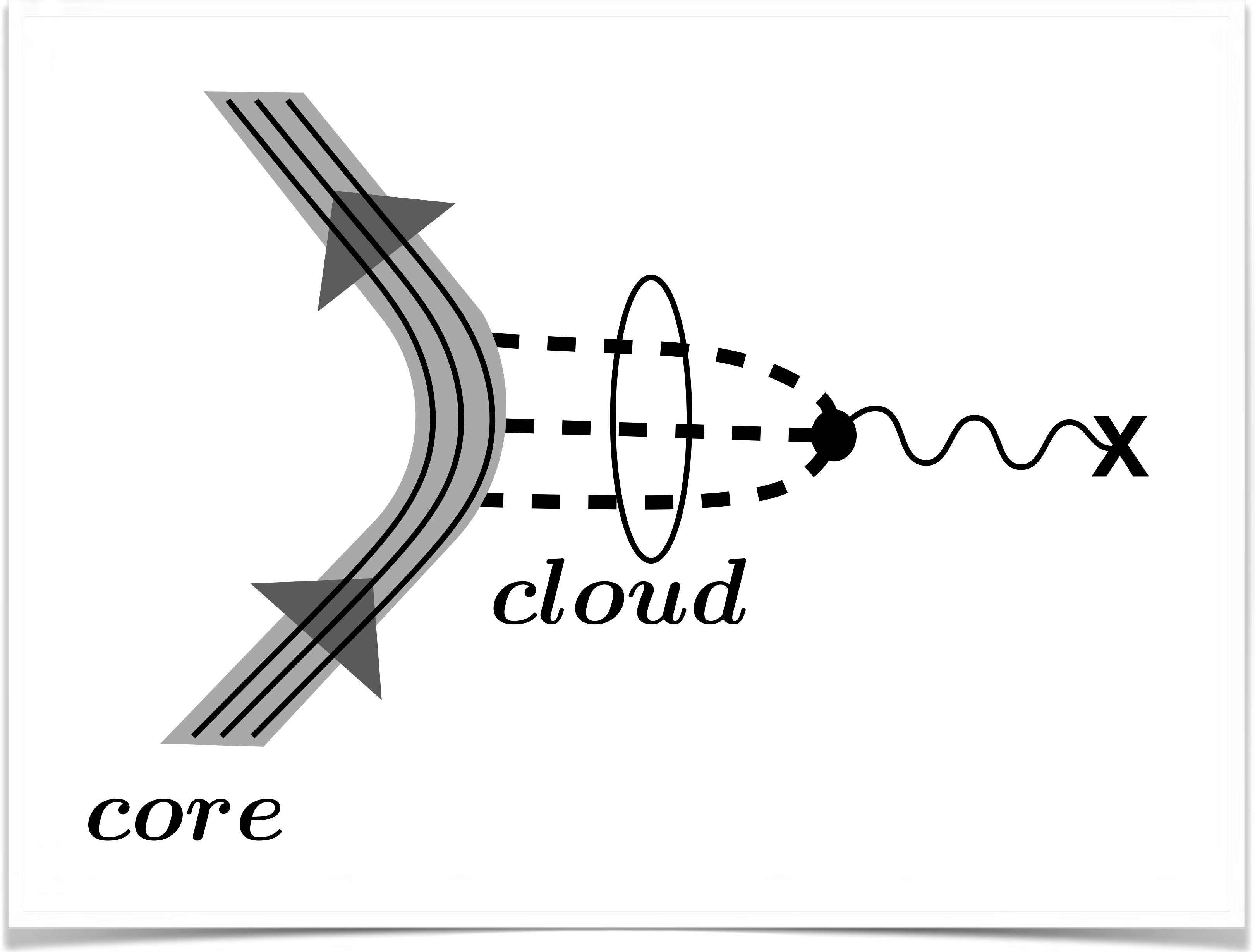
- **Separation of scales**

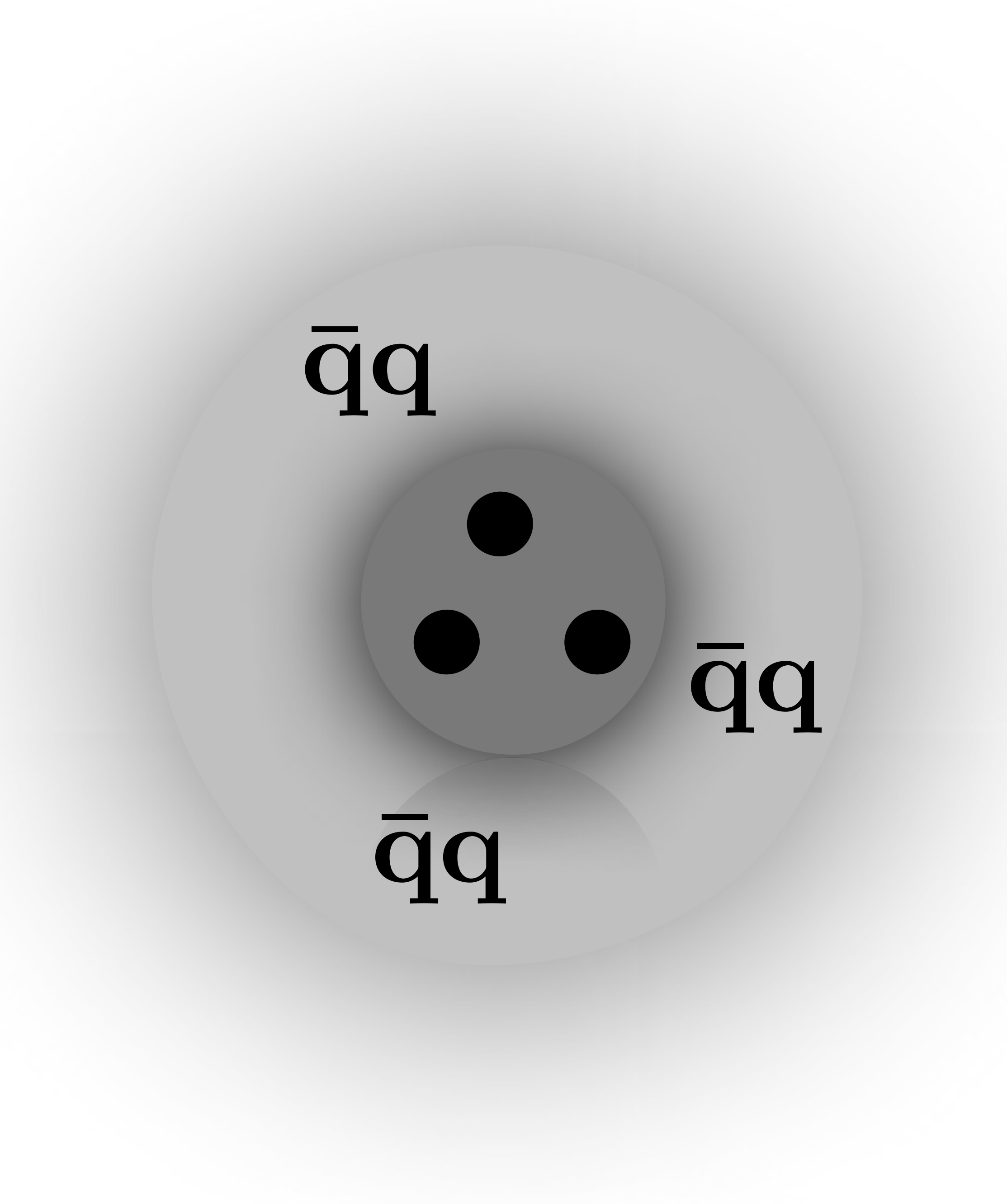
$$\left(\frac{R_{cloud}}{R_{core}}\right)^3 \gg 1$$

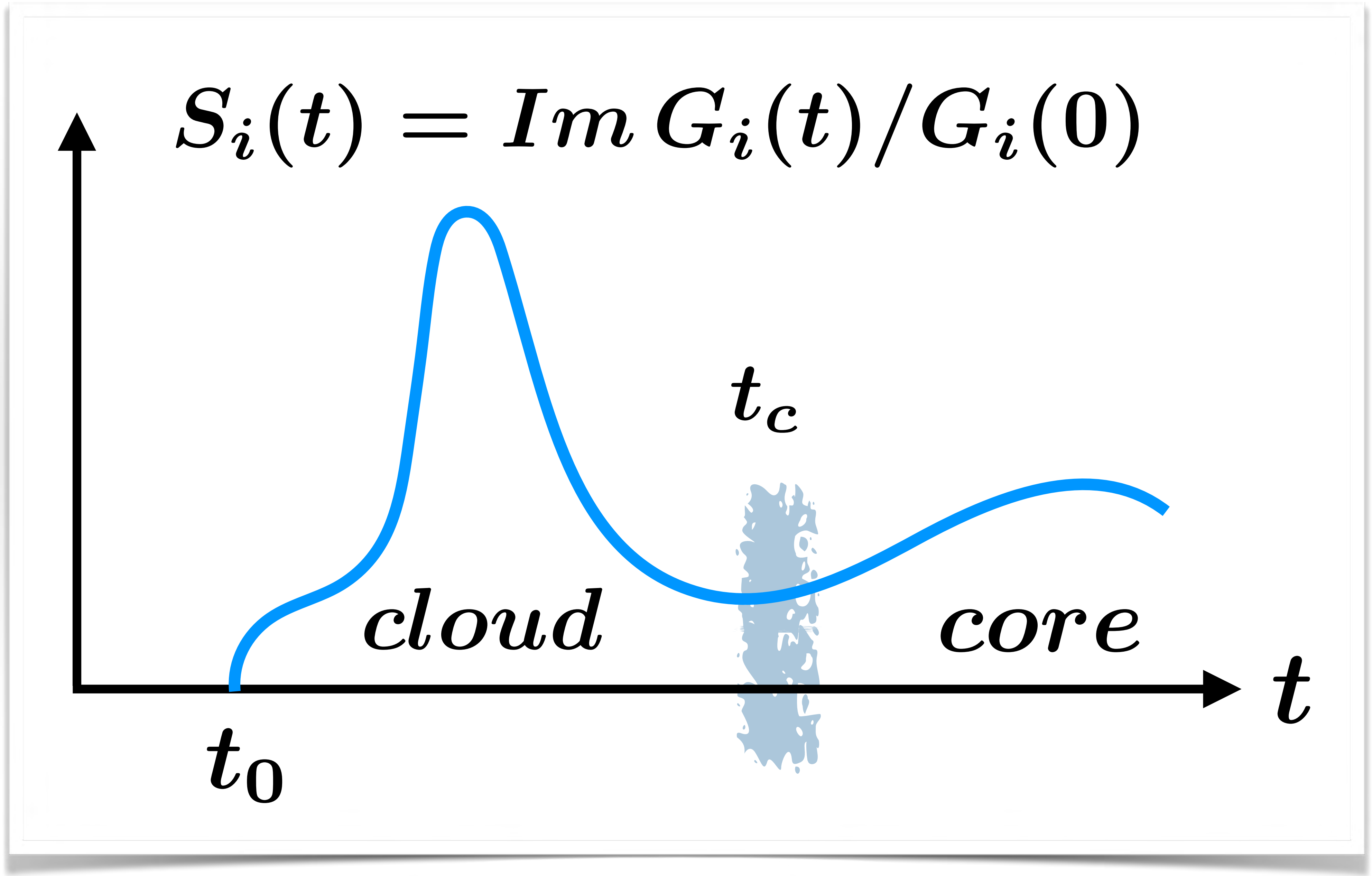
Technische Universität München

FORM FACTORS of the NUCLEON

$$G_i(q^2) = G_i(0) + \frac{q^2}{\pi}\int_{t_0}^{\infty} dt \frac{Im\, G_i(t)}{t(t-q^2-i\epsilon)} \qquad \langle r_i^2 \rangle = \frac{6}{G_i(0)} \frac{dG_i(q^2)}{dq^2}\Big|_{q^2=0} = \frac{6}{\pi}\int_{t_0}^{\infty} \frac{dt}{t^2} S_i(t)$$







$$\langle r_i^2 \rangle = \langle r_i^2 \rangle_{cloud} + \langle r_i^2 \rangle_{core} = \frac{6}{\pi}\left[\int_{t_0}^{t_c} \frac{dt}{t^2} S_i(t) + \int_{t_c}^{\infty} \frac{dt}{t^2} S_i(t)\right]$$

Example 1: **ISOSCALAR ELECTRIC FORM FACTOR** of the **NUCLEON**

- **Isoscalar electric form factor** $G_E^S(q^2) = \frac{1}{2}\left[G_E^p(q^2) + G_E^n(q^2)\right]$ $\quad \langle r_S^2 \rangle = \langle r_p^2 \rangle + \langle r_n^2 \rangle$

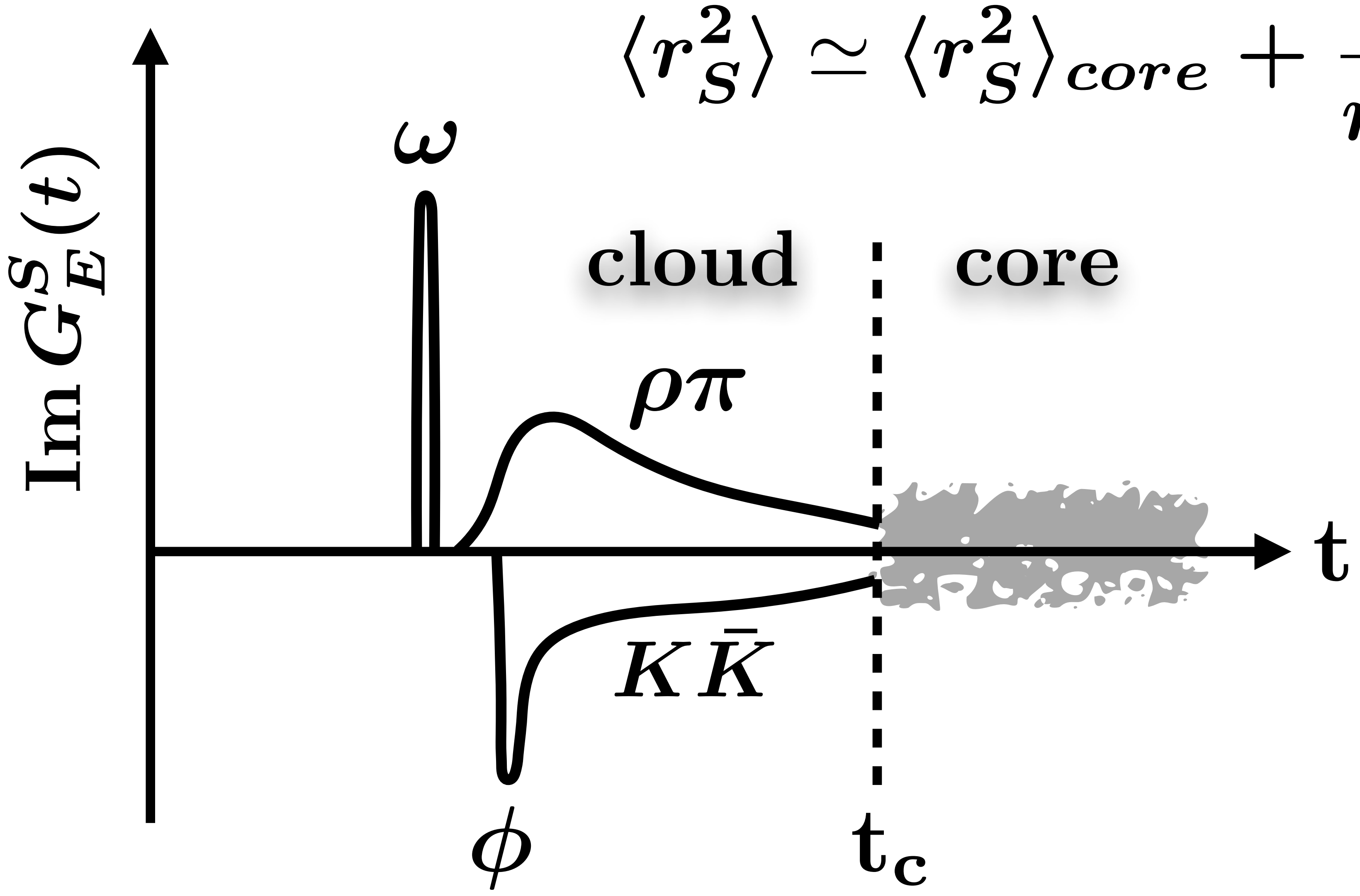
Empirical : $\langle r_p^2 \rangle^{1/2} = 0.840 \pm 0.004\,\mathrm{fm}$ $\quad \langle r_n^2 \rangle = -0.105 \pm 0.006\,\mathrm{fm}^2$ $\quad \langle r_S^2 \rangle^{1/2} = 0.775 \pm 0.011\,\mathrm{fm}$

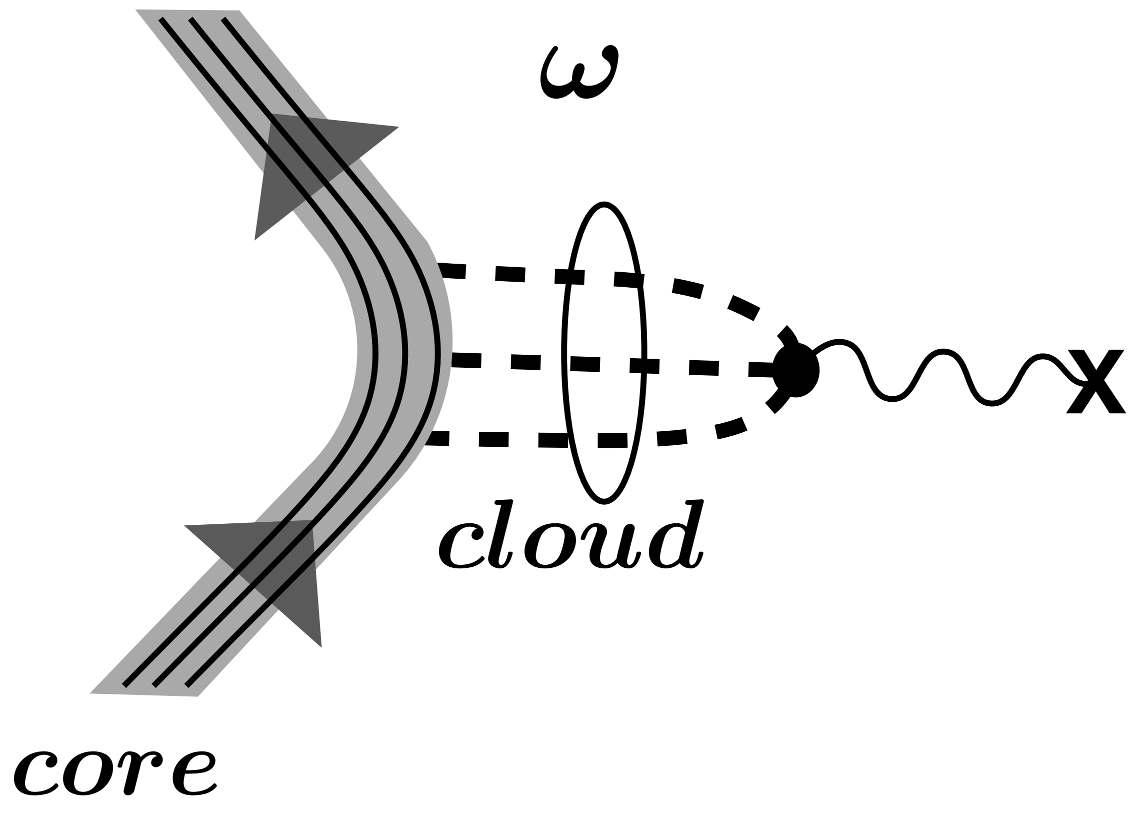
Y.H. Lin, H.-W. Hammer, U.-G. Meißner PRL 128 (2022) 052002

… based on **precision fits** to form factors at both **spacelike and timelike** q^2

- **Simplest Vector Dominance Model:** "cloud" dominated by ω meson

$$\langle r_S^2 \rangle \simeq \langle r_S^2 \rangle_{core} + \frac{6}{m_\omega^2} \quad \rightarrow \quad \langle r_S^2 \rangle_{core}^{1/2} \simeq 0.47\,\mathrm{fm}$$





- **Detailed analysis using best-fit spectral functions :**

$$\langle r_S^2 \rangle_{core}^{1/2} \equiv \langle r_B^2 \rangle^{1/2} = 0.50 \pm 0.01\,\mathrm{fm}$$

N. Kaiser, W.W. (2024) arXiv:2404.11292

Example II: **ISOVECTOR AXIAL FORM FACTOR** of the **NUCLEON**

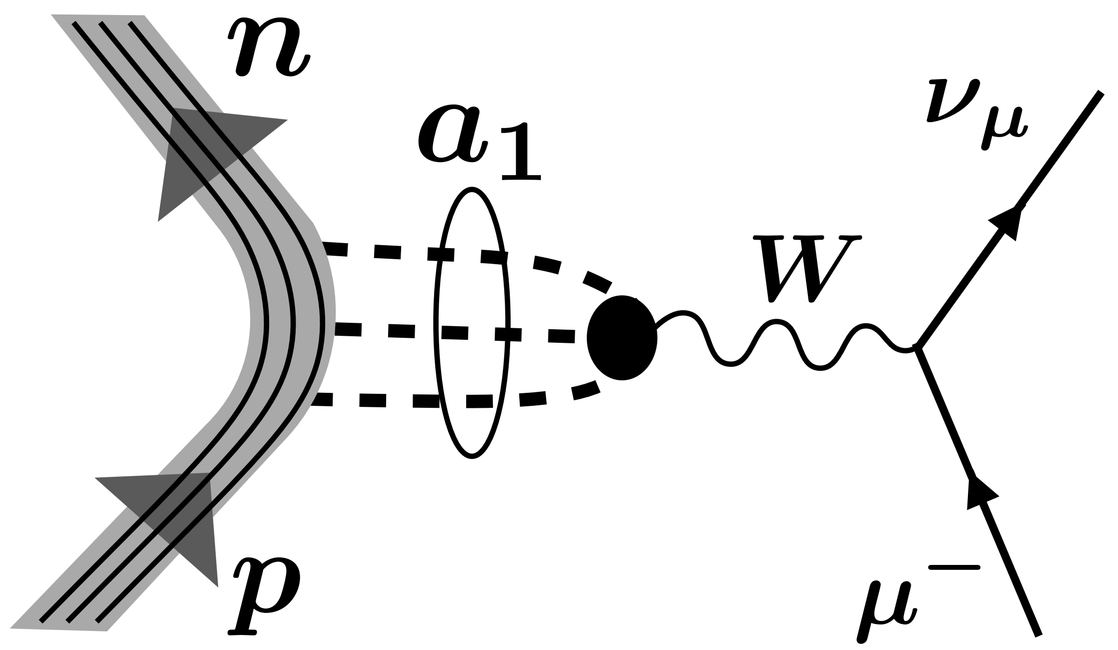
- **Axial form factor** $$G_A(q^2) = g_A \left[1 + \frac{1}{6} \langle r_A^2 \rangle q^2 + \dots \right]$$

R.J. Hill, P. Kammel, W.C. Marciano, A. Sirlin
Rep. Prog. Phys. 81 (2018) 096301

Empirical :

$$\langle r_A^2 \rangle = 0.46 \pm 0.16 \text{ fm}^2$$

(from μp capture and νd scattering analysis)



$$\langle r_A^2 \rangle = 0.454 \pm 0.013 \text{ fm}^2$$

(from νd scattering and $e\,p \to e\,n\pi^+$ dipole fits)

- **Detailed analysis using three-pion spectrum dominated by broad a_1 meson :**

$$\langle r_A^2 \rangle = \langle r_A^2 \rangle_{core} + \frac{6}{m_a^2}(1 + \delta_a) \qquad \delta_a = -\frac{m_a^3}{\pi} \int_{9m_\pi^2}^{t_{max}} dt \frac{\Gamma_a(t)}{t^2(t - m_a^2)}$$

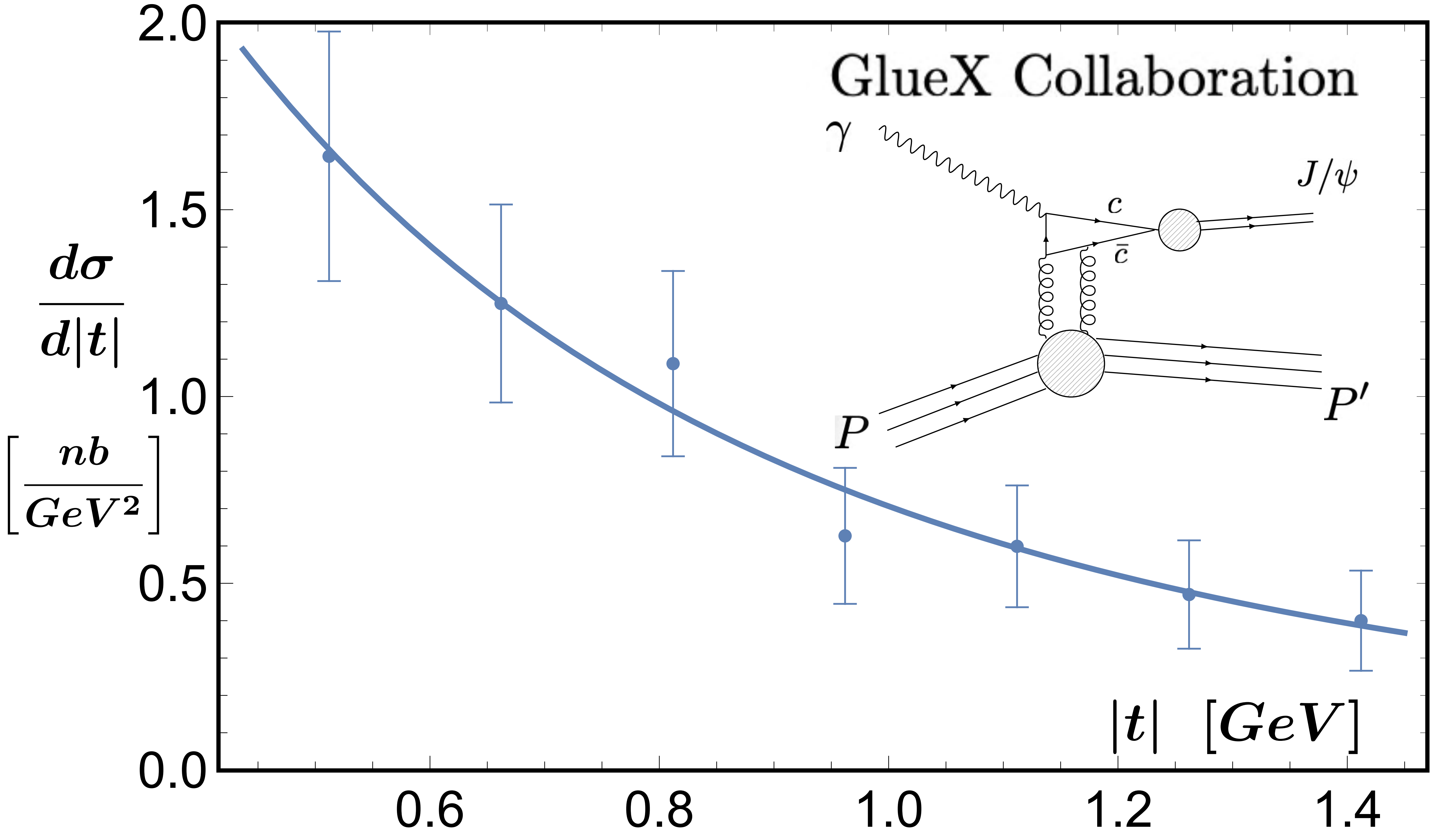
→ $$\langle r_A^2 \rangle_{core}^{1/2} = 0.53 \pm 0.02 \text{ fm}$$

N. Kaiser, W.W. (2024)
arXiv:2404.11292

Example III: **MASS RADIUS of the NUCLEON**

- Mass (“gravitational”) form factor
- Trace of QCD energy-momentum tensor

$$G_m(q^2) \sim \langle P'|T^\mu_\mu|P\rangle = \langle P'|\frac{\beta}{2g}G^{\mu\nu}_a G^a_{\mu\nu} + m_q(\bar{u}u + \bar{d}d) + m_s\bar{s}s|P\rangle$$



$$G_m(0) = M_N \simeq 0.94\,\mathrm{GeV}$$

$$M_N = M_0 + \sigma_N + \sigma_s$$

$$(M_0 \gtrsim 0.9\,M_N)$$

$$\langle r_m^2\rangle = \frac{6}{M_N}\frac{dG_m(q^2)}{dq^2}\Big|_{q^2=0}$$

- Empirical mass radius

$$\langle r_m^2\rangle^{1/2} = (0.55 \pm 0.03)\,\mathrm{fm}$$

D. Kharzeev : Phys. Rev. D104 (2021) 054015

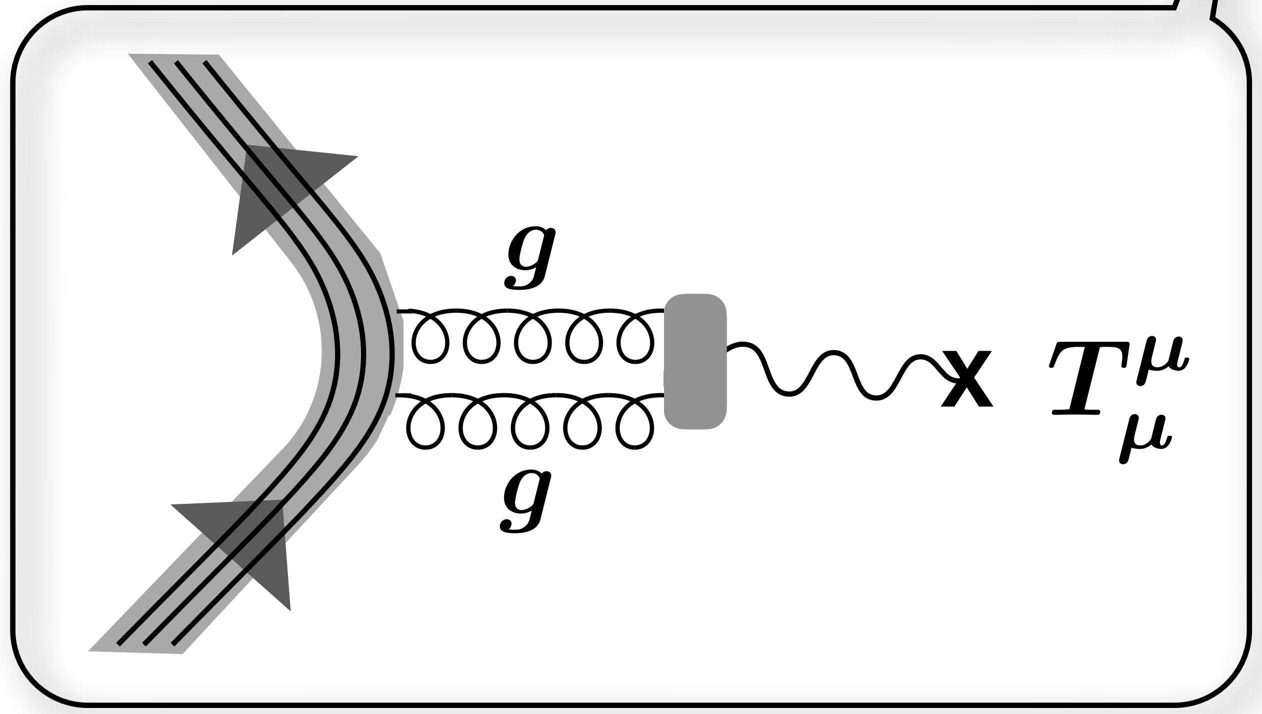
- Effects of open-charm coupled channels ?

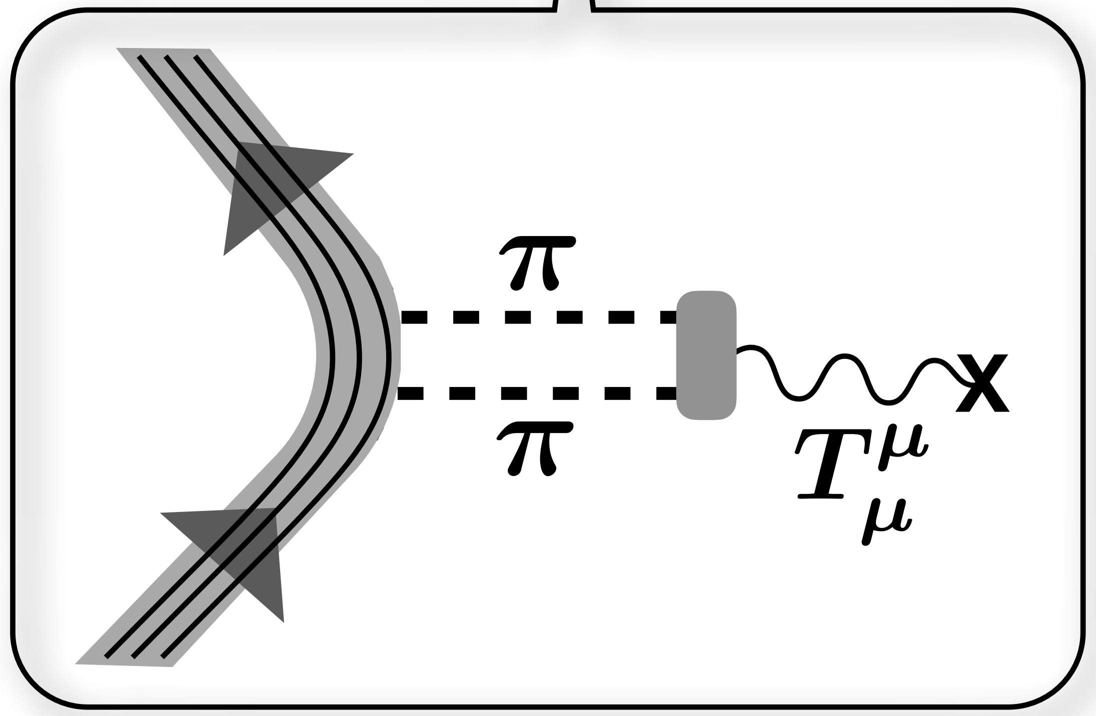
Meng-Lin Du *et al.* : Eur. Phys. J. C80 (2020) 1053

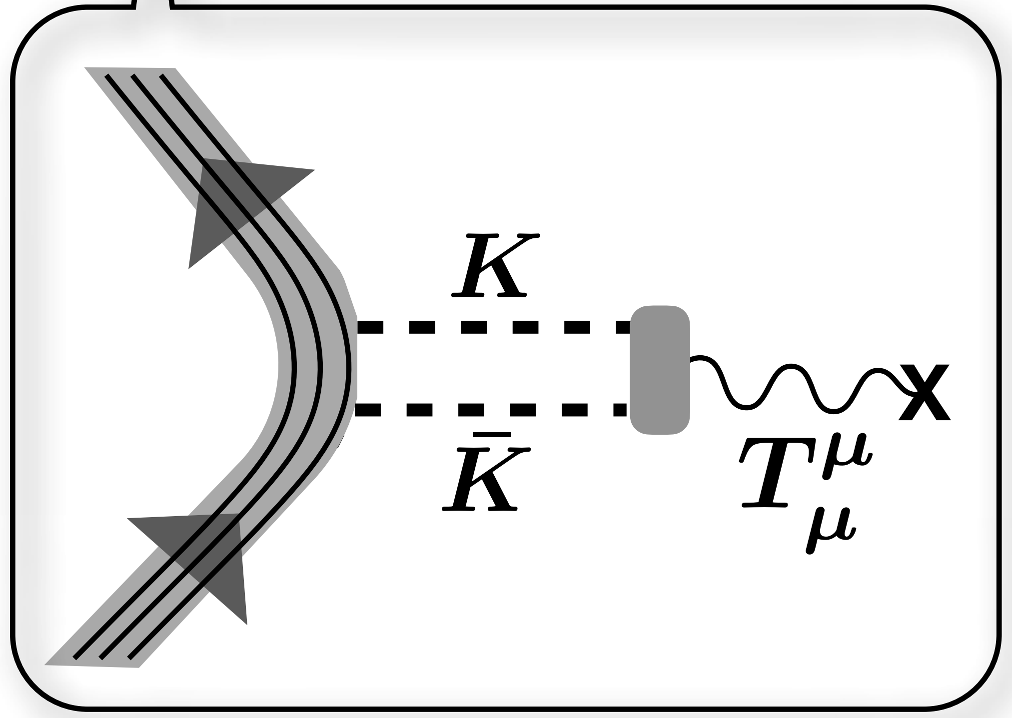
Example III: MASS RADIUS of the NUCLEON (contd.)

- Core (gluon) dominance plus small corrections from sigma terms

$$\langle r_m^2 \rangle = \left[\frac{M_0}{M_N} \langle r_m^2 \rangle_{core} + \frac{\sigma_N}{M_N} \langle r_{\pi\pi}^2 \rangle + \frac{\sigma_s}{M_N} \langle r_{K\bar{K}}^2 \rangle \right]$$







- Estimates of sigma terms and associated radii from Lattice QCD and ChPT

$\sigma_N \simeq 40 - 60$ MeV , $\sigma_s \simeq 30$ MeV $\qquad \langle r_{\pi\pi}^2 \rangle^{1/2} \simeq 1.3$ fm , $\langle r_{K\bar{K}}^2 \rangle \sim (m_\pi / m_K)^2 \langle r_{\pi\pi}^2 \rangle$

→ $$\langle r_m^2 \rangle_{core} = 0.48 \pm 0.05 \text{ fm}$$

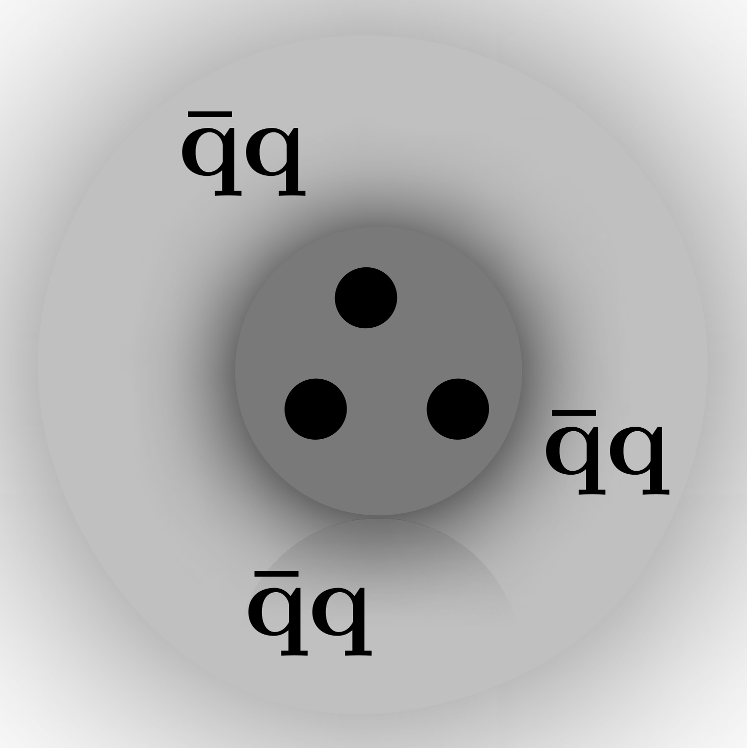
N. Kaiser, W.W. (2024)
arXiv:2404.11292

TWO-SCALES Picture of the NUCLEON : implications for DENSE BARYONIC MATTER

$$\langle r_S^2\rangle_{core}^{1/2} \simeq \langle r_A^2\rangle_{core}^{1/2} \simeq \langle r_m^2\rangle_{core}^{1/2} \equiv R_{core} = 0.50 \pm 0.02\ \text{fm}$$

$$R_{core} \sim \frac{1}{2}\ \text{fm}$$

$$R_{cloud} \sim 1\ \text{fm}$$



- **Separation of scales**

$$\left(\frac{R_{cloud}}{R_{core}}\right)^3 \gg 1$$

- **Soft mesonic (multi-pion) cloud**

  expected to expand with increasing baryon density along with decreasing **in-medium pion decay constant** $f_\pi^*(\rho)$

- **Hard baryonic core** governed by **gluon dynamics**

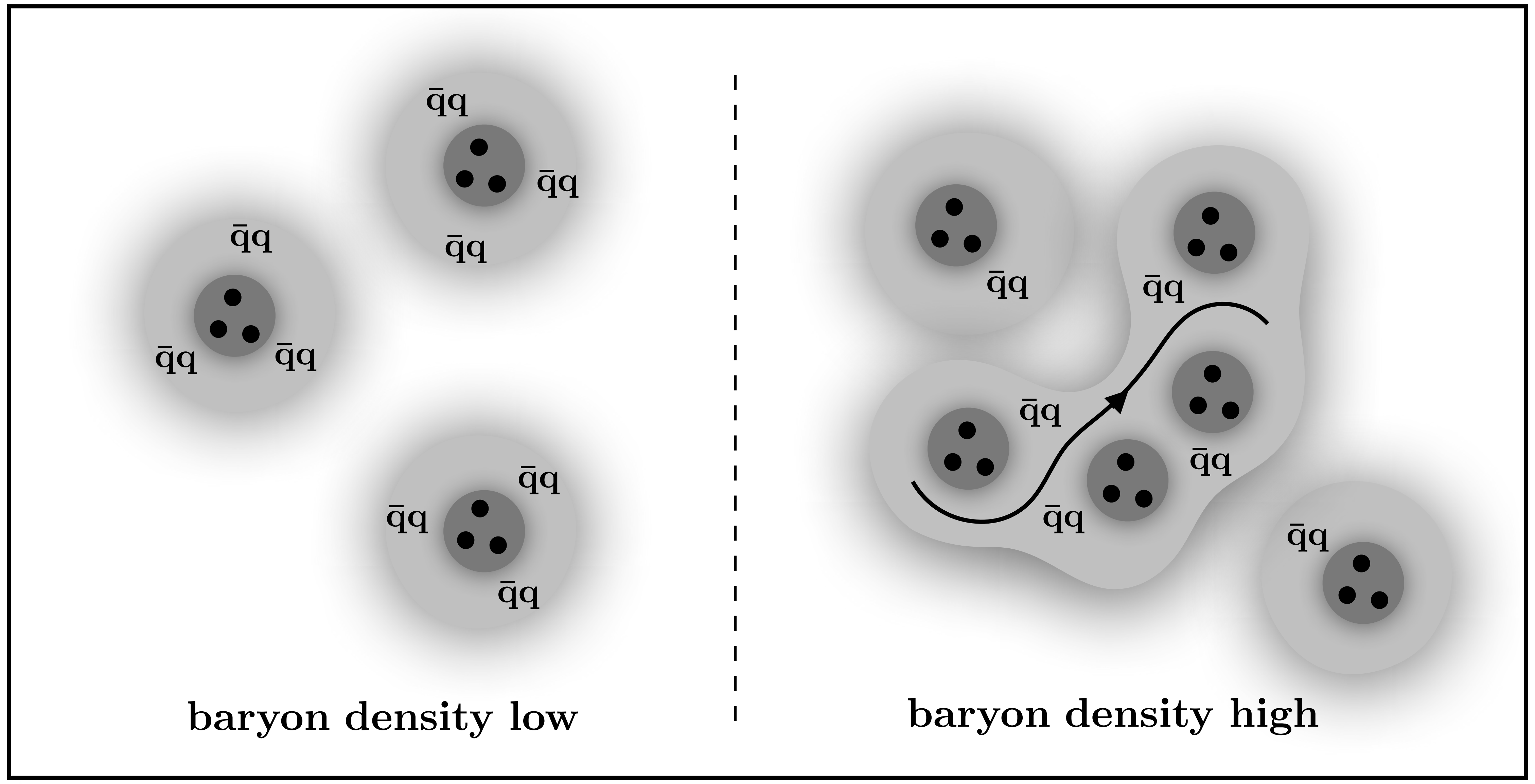
  expected to remain stable with increasing baryon density up until hard compact cores begin to touch and overlap

TWO-SCALES Scenario for DENSE BARYONIC MATTER

- Baryon densities

  $\rho \sim \rho_0 = 0.16\,\mathrm{fm}^{-3}$

  tails of mesonic clouds overlap :
  two-body exchange forces
  between nucleons



- $\rho \gtrsim 2 - 3\,\rho_0$

  Soft $\bar{q}q$ clouds delocalize:
  percolation → many-body forces
  baryonic cores still separated, but subject to increasingly strong repulsive Pauli effects

K. Fukushima, T. Kojo, W.W.
Phys. Rev. D 102 (2020) 096017

- $\rho > 5\,\rho_0$ (beyond central densities of neutron stars)

  compact nucleon cores begin to touch and overlap at distances $d \lesssim 1\,\mathrm{fm}$
  (but still have to overcome repulsive NN hard core)

Key words: **hadron-quark continuity** and **crossover**

y-scaling in electron-nucleus scattering → strongly correlated **NUCLEONS**
at short distances corresponding to densities as high as $\rho \sim 5\,\rho_0$

Particles **2023**, *1*, 1–11

arXiv:2306.01367

Testing the Paradigm of Nuclear Many-Body Theory

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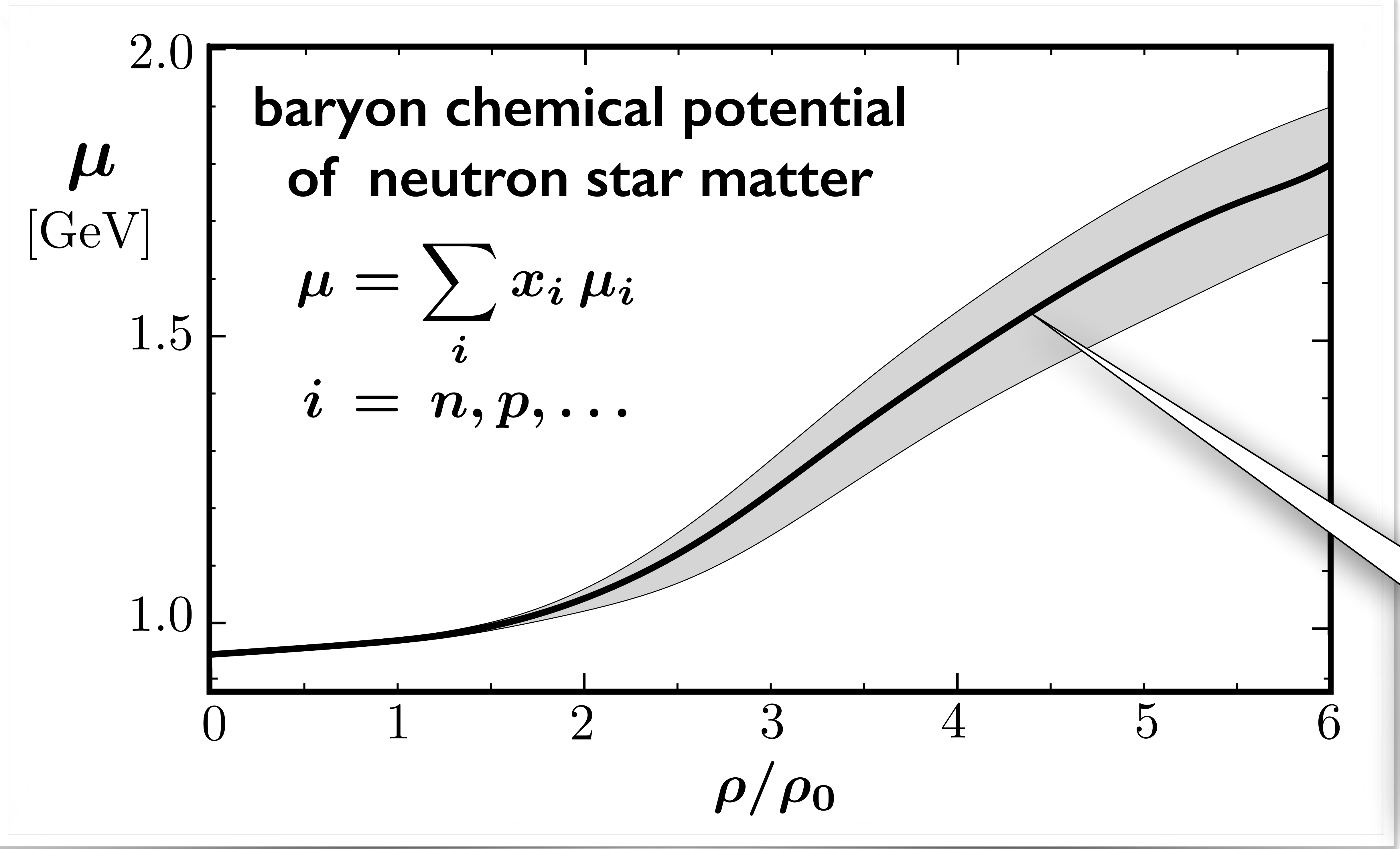
Abstract: Nuclear many-body theory is based on the tenet that nuclear systems can be accurately described as collections of point-like particles. This picture, while providing a remarkably accurate explanation of a wealth of measured properties of atomic nuclei, is bound to break down in the high-density regime, in which degrees of freedom other than protons and neutrons are expected to come into play. Valuable information on the validity of the description of dense nuclear matter in terms of nucleons, needed to firmly establish its limit of applicability, can be obtained from electron–nucleus scattering data at large momentum transfer and low energy transfer. The emergence of *y*-scaling in this kinematic region, unambiguously showing that the beam particles couple to high-momentum nucleons belonging to strongly correlated pairs, indicates that at densities as large as five times nuclear density—typical of the neutron star interior—nuclear matter largely behaves as a collection of nucleons.

DENSE BARYONIC MATTER in NEUTRON STARS as a RELAVISTIC FERMI LIQUID

B. Friman, W.W. : Rhys. Rev. C100 (2019) 065807 L. Brandes, W.W. : Symmetry 16 (2024) 111

- **Neutron Star Matter : Fermi liquid** / dominantly neutrons + ca. 5 % protons
- **Baryonic Quasiparticles** :
  baryons "dressed" by their **strong interactions** and imbedded in **mesonic (multi-pion) field**



- **Landau effective mass**

$$m_L^*(\rho) = \sqrt{p_F^2 + m^2(\rho)}$$

- **Baryon chemical potential**

$$\mu(\rho) = m_L^*(\rho) + \mathcal{U}(\rho)$$

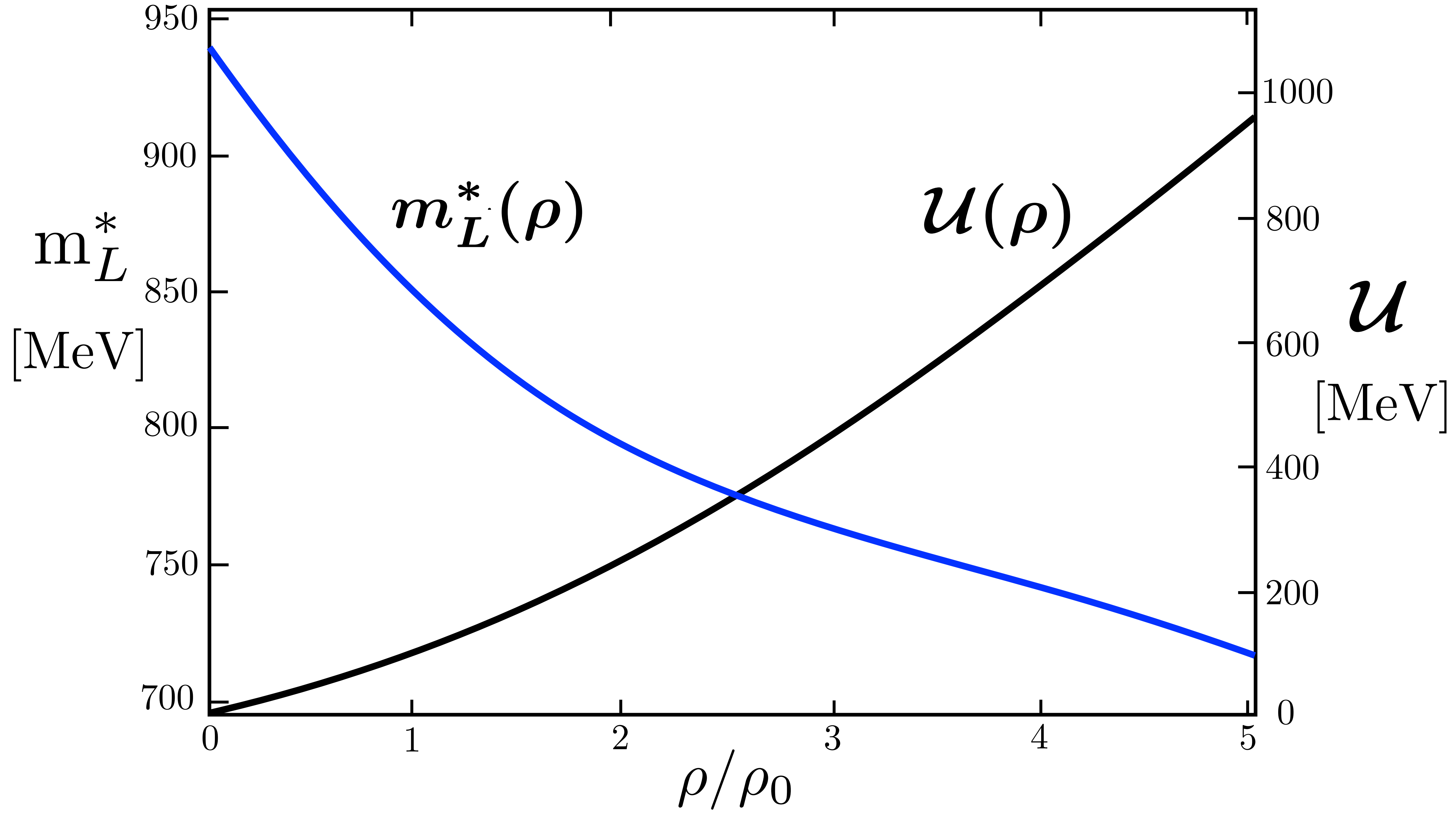
take median of $\mu(\rho)$ from Bayesian-inferred neutron star EoS

quasiparticle potential

QUASIPARTICLE POTENTIAL and FERMI-LIQUID PARAMETERS

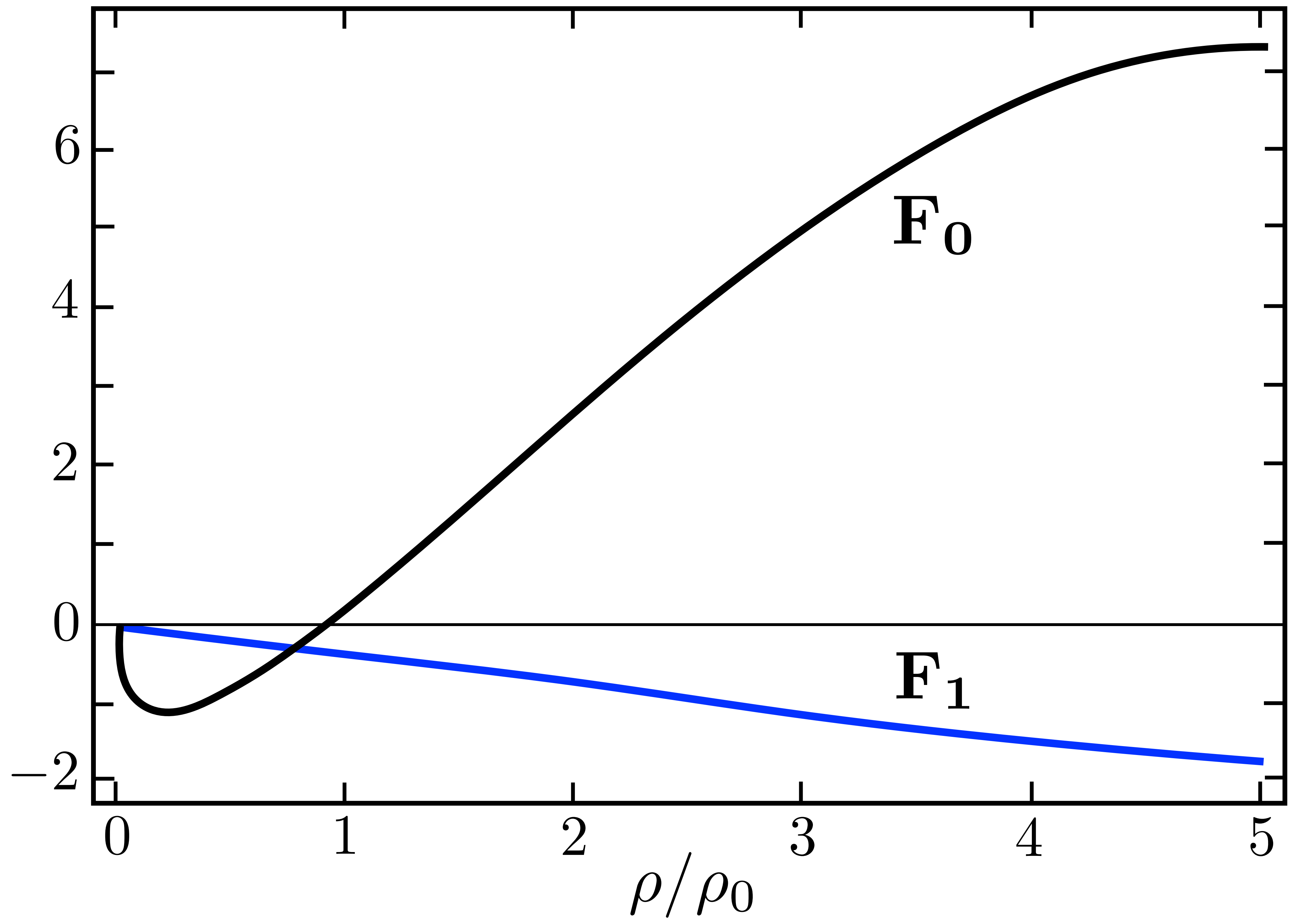
- $m_L^*(\rho)$ from **chiral nucleon-meson field theory** & Functional Renormalisation Group
- Quasiparticle effective potential

$$\mathcal{U}(\rho) = \sum_n u_n \left(\frac{\rho}{\rho_0}\right)^n$$



- Landau Fermi-Liquid parameters

$$F_0 = \frac{m_L^* p_F}{\pi^2}\frac{\partial\mu}{\partial\rho} - 1 \qquad F_1 = -\frac{3\,\mathcal{U}}{\mu}$$



➡ **Strongly repulsive correlations** including **many-body forces** with $n \geq 2$

CONCLUSIONS

Constraints on phase transitions in neutron star matter

- **very stiff equation of state** implied by Bayesian inference results
- **strong first-order transition** unlikely in neutron star cores
- **central baryon densities** in neutron stars : $\rho < 5\,\rho_0$
- **chiral phase transition** shifted to **crossover** beyond $\rho > 6\,\rho_0$

Scenarios for cold dense matter in the core of neutron stars

- **hadron-quark** continuity
  two-scales scenario: soft-surface delocalisation (percolation)
  followed by hard-core deconfinement at densities well above ρ_c
- neutron-dominated **baryonic** matter
  e.g. relativistic **Fermi liquid** featuring strongly repulsive
  many-body forces between **baryonic quasiparticles**

Supplementary Materials

INFERENCE of SOUND SPEED and RELATED PROPERTIES of NEUTRON STARS

- Introduce **general parametrization of sound velocity** by segment-wise representation :

$$c_s^2(\varepsilon, \theta) = \frac{(\varepsilon_{i+1} - \varepsilon) c_{s,i}^2 + (\varepsilon - \varepsilon_i) c_{s,i+1}^2}{\varepsilon_{i+1} - \varepsilon_i} \quad , \quad \text{parameter set} \quad \theta = (c_{s,i}^2, \varepsilon_i) \ (i = 1, \ldots, N)$$

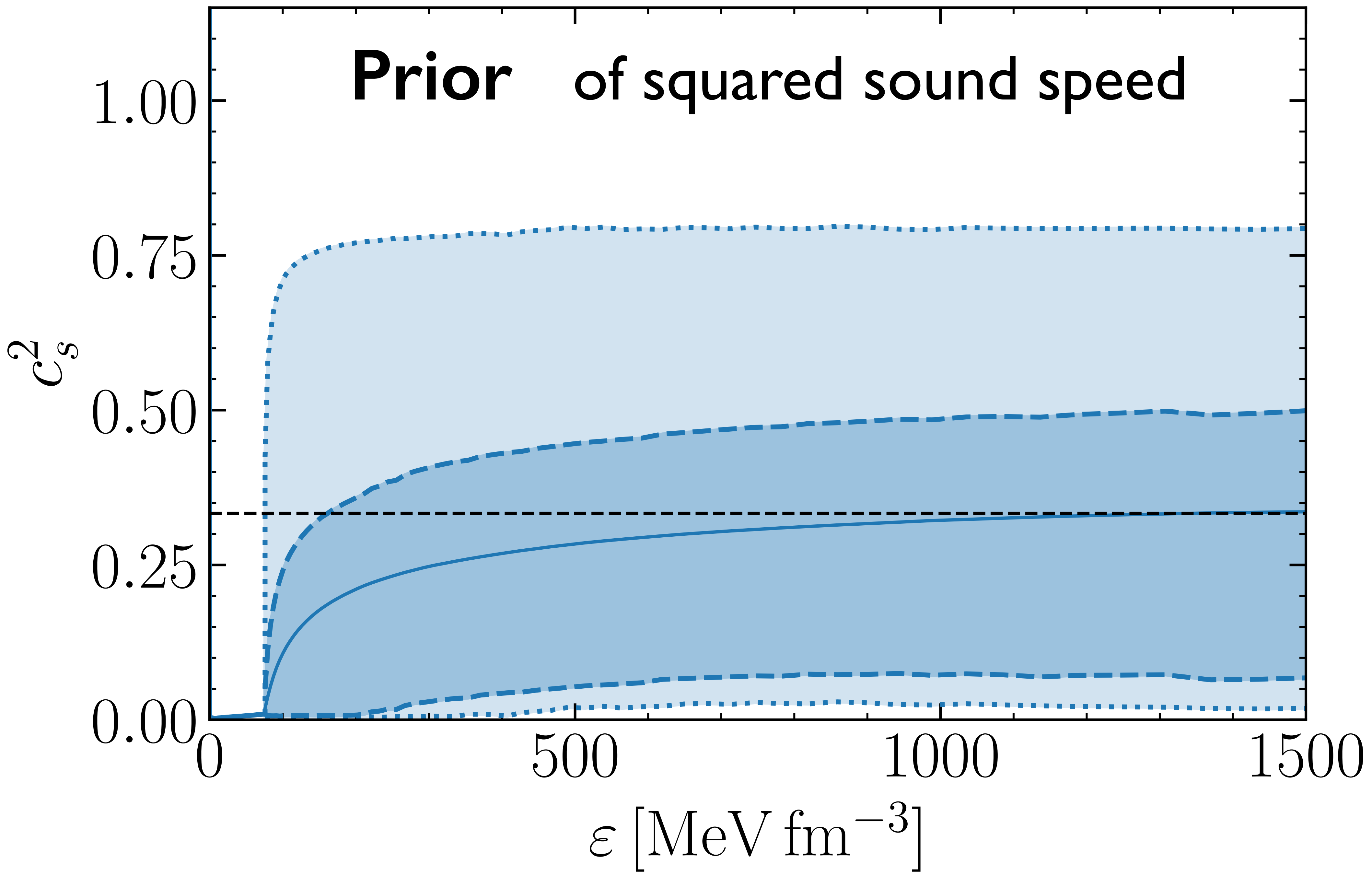
- Constrain parameters θ by **Bayesian inference** using **nuclear** and **astrophysical data** $\mathscr{D}$:

$$\Pr(\theta|\mathscr{D}) \propto \Pr(\mathscr{D}|\theta) \Pr(\theta)$$

→ Choose **Prior** $\Pr(\theta)$

→ Compute **Posterior** $\Pr(\theta|\mathscr{D})$ from **Likelihood** $\Pr(\mathscr{D}|\theta)$

→ Quantify **Evidences** for hypotheses H_0 vs. H_1 in terms of **Bayes factors** $\mathscr{B}^{H_1}_{H_0} = \frac{\Pr(\mathscr{D}|H_1)}{\Pr(\mathscr{D}|H_0)}$



- Median, 95% and 68% credible intervals for neutron star properties :

radius R tidal deformability Λ

central density n_c energy density ε_c

central pressure P_c

L. Brandes, W.W., N. Kaiser : Phys. Rev. D 108 (2023) 094014

		Previous + BW	
		95%	68%
$2.3M_\odot$	n_c/n_0	$3.8^{+1.6}_{-1.3}$	$^{+0.7}_{-0.8}$
	ε_c [MeV fm^{-3}]	673^{+363}_{-268}	$^{+140}_{-180}$
	P_c [MeV fm^{-3}]	237^{+226}_{-134}	$^{+69}_{-104}$
	R [km]	12.3 ± 1.2	$^{+0.7}_{-0.6}$
	Λ	14^{+17}_{-10}	$^{+4}_{-9}$

		Previous		Previous + BW	
		95%	68%	95%	68%
$1.4M_\odot$	n_c/n_0	$2.8^{+0.8}_{-0.7}$	± 0.4	2.6 ± 0.7	$^{+0.3}_{-0.4}$
	ε_c [MeV fm^{-3}]	451^{+133}_{-123}	$^{+62}_{-71}$	423^{+118}_{-116}	$^{+56}_{-67}$
	P_c [MeV fm^{-3}]	64^{+30}_{-23}	$^{+12}_{-16}$	60^{+28}_{-20}	$^{+11}_{-14}$
	R [km]	$12.2^{+0.9}_{-1.0}$	± 0.5	$12.3^{+0.8}_{-1.0}$	± 0.5
	Λ	396^{+226}_{-197}	$^{+107}_{-127}$	421^{+236}_{-200}	$^{+114}_{-124}$
$2.1M_\odot$	n_c/n_0	$4.1^{+1.9}_{-1.5}$	$^{+0.8}_{-0.9}$	$3.6^{+1.6}_{-1.3}$	± 0.7
	ε_c [MeV fm^{-3}]	716^{+416}_{-326}	$^{+162}_{-213}$	628^{+357}_{-251}	$^{+149}_{-146}$
	P_c [MeV fm^{-3}]	225^{+239}_{-134}	$^{+62}_{-110}$	186^{+184}_{-104}	$^{+52}_{-80}$
	R [km]	11.9 ± 1.3	± 0.7	$12.1^{+1.3}_{-1.2}$	$^{+0.6}_{-0.8}$
	Λ	21^{+30}_{-15}	$^{+9}_{-13}$	26^{+30}_{-20}	$^{+10}_{-14}$

Similar conclusions as in our Bayesian inference analysis reached in recent work :

arXiv:2402.04172 [astro-ph.HE]

An overview of existing and new nuclear and astrophysical constraints on the equation of state of neutron-rich dense matter

Hauke Koehn,[1,*] Henrik Rose,[1] Peter T. H. Pang,[2,3] Rahul Somasundaram,[4] Brendan T. Reed,[5,6,7] Ingo Tews,[5] Adrian Abac,[8,1] Oleg Komoltsev,[9] Nina Kunert,[1] Aleksi Kurkela,[9] Michael W. Coughlin,[10] Brian F. Healy,[10] and Tim Dietrich[1,8]

PHYSICAL REVIEW C **109**, 035801 (2024)

Symmetry energy and neutron star properties constrained by chiral effective field theory calculations

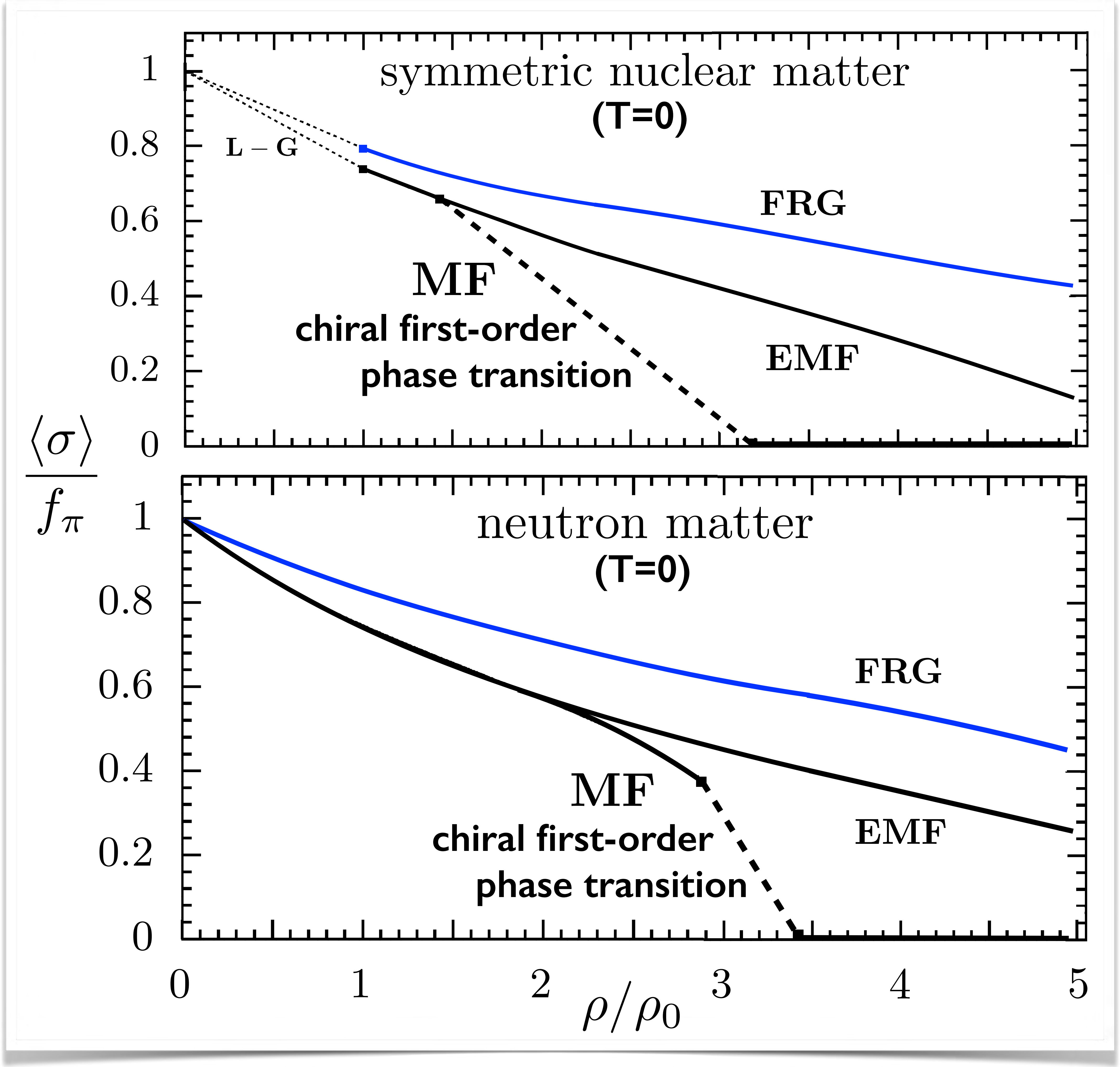
Yeunhwan Lim[1,*] and Achim Schwenk[2,3,4,†]

CHIRAL PHASE TRANSITION in DENSE BARYONIC MATTER ?

- Studies in chiral nucleon-meson field theory

M. Drews, W.W.: Prog. Part. Nucl. Phys. 93 (2017) 69 — L. Brandes, N. Kaiser, W.W.: Eur. Phys. J. A57 (2021) 243

- **Mean-field** approximation **(MF)** :
  chiral first-order phase transition
  at baryon densities $\rho \sim 2 - 3\,\rho_0$
- **Vacuum fluctuations** (EMF) :
  shift chiral transition to **high density**
  → **smooth crossover**
- **Functional Renormalisation Group** (FRG) :
  non-perturbative loop corrections
  involving **pions** & **nucleon-hole** excitations
  → further reinforcement of **stabilising effects**



Chiral crossover transition at $\rho > 6\,\rho_0$
far beyond core densities in neutron stars