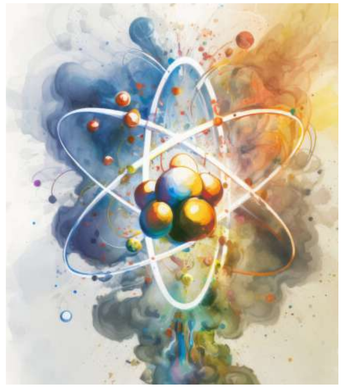


SIZE and DISTANCE SCALES in NUCLEONS and in DENSE BARYONIC MATTER

Wolfram Weise
Technische Universität München
PHYSIK DEPARTMENT

- **Sizes of the Nucleon**
  - Nucleon form factors: electric, axial and gravitational
  - Valence quark core and quark-antiquark cloud: a two-scales picture
- **Dense Matter in Neutron Stars: Equation of State and Related**
  - Bayesian inference results and empirical constraints
  - Distance scales and scenarios for neutron star core matter

J. Subatomic Part. Cosmol. 6 (2026) 100499

Part One

Sizes of the Nucleon

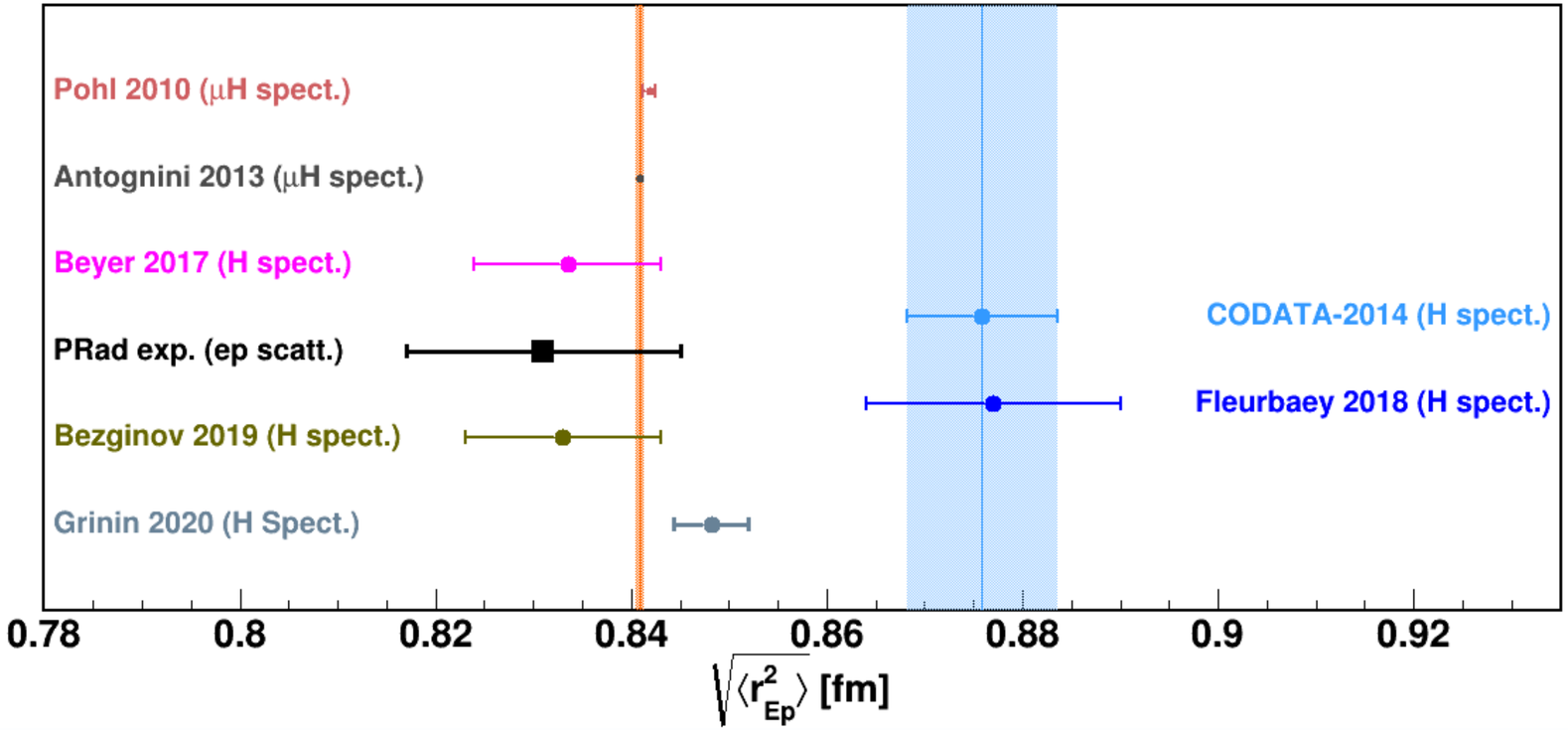
- **Different probing fields see different radii**
- **Two scales :**

  compact valence quark core and

  soft mesonic (quark-antiquark) surface

Reminder : Proton Charge Radius

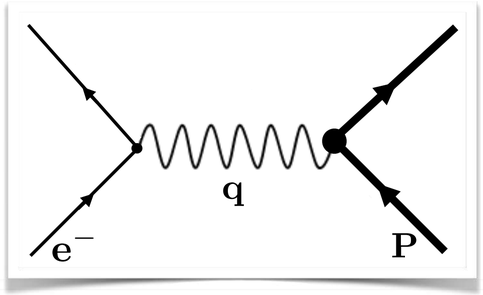
- **Sources of information :**
  muonic hydrogen and ordinary hydrogen spectroscopy, electron scattering



H. Gao, M.Vanderhaeghen
Rev. Mod. Phys.
94 (2022) 015002

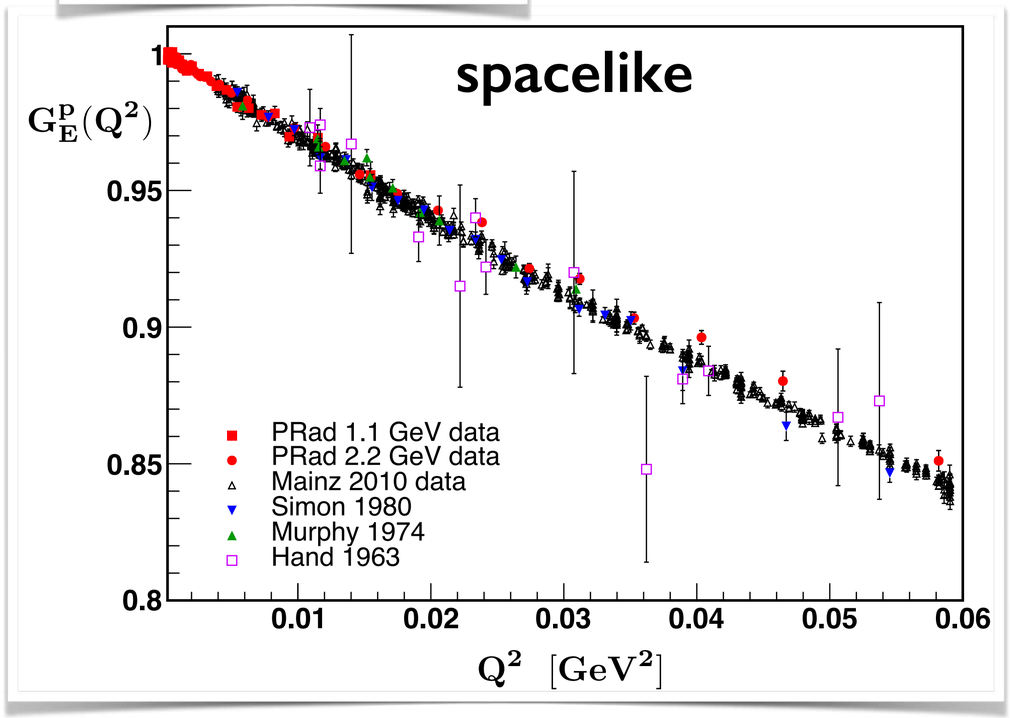
- **Highest precision reached with muonic hydrogen Lamb shift analysis**

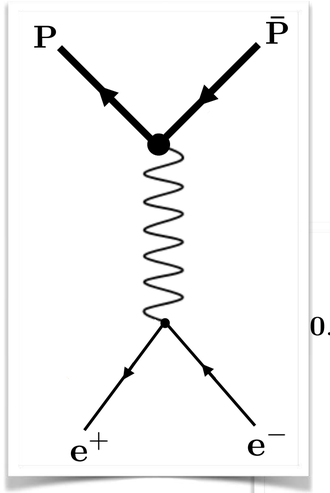
Electromagnetic Form Factors

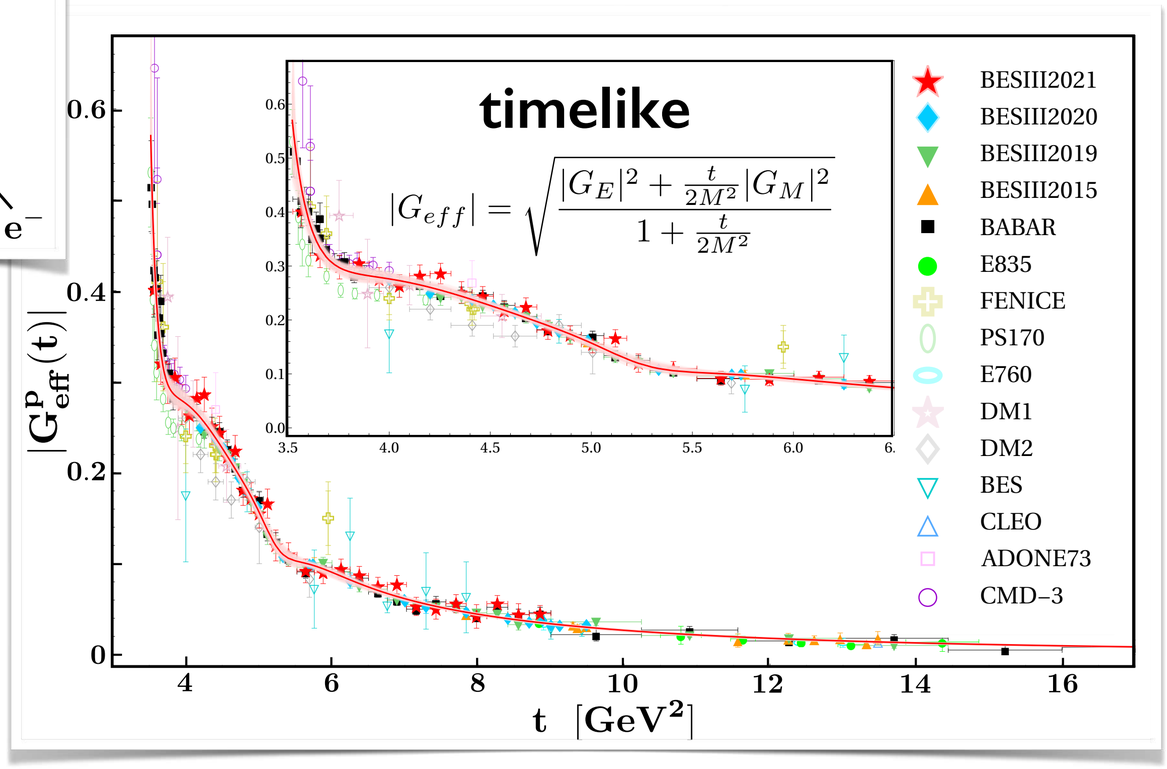


$$t = q^2 = -Q^2$$

Data type	range of $\lvert t\rvert$ [GeV^2]	# of data
$\sigma(E,\theta)$, PRad	$0.000215 - 0.058$	71
$\sigma(E,\theta)$, MAMI	$0.00384 - 0.977$	1422
$\mu_p G_E^p/G_M^p$, JLab	$1.18 - 8.49$	16
G_E^n, world	$0.14 - 1.47$	25
G_M^n, world	$0.071 - 10.0$	23
$\lvert G_{\text{eff}}^p\rvert$, world	$3.52 - 20.25$	153
$\lvert G_{\text{eff}}^n\rvert$, world	$3.53 - 9.49$	27
$\lvert G_E/G_M\rvert$, BaBar	$3.52 - 9.0$	6
$d\sigma/d\Omega$, BESIII	$1.88 - 1.95$	10







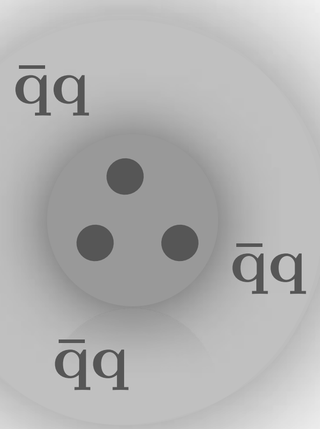
- **High-precision fits to form factor data at both spacelike and timelike q^2**

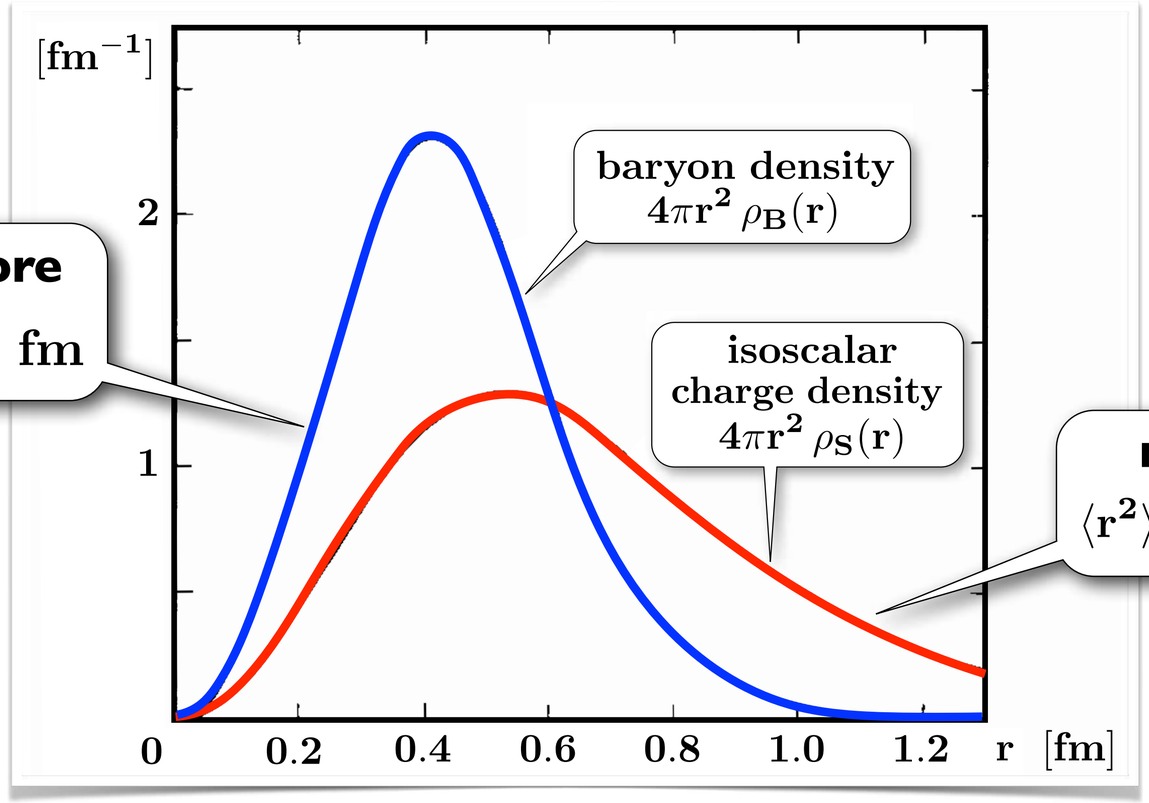
Y.H. Lin, H.-W. Hammer, U.-G. Meißner : PRL 128 (2022) 052002

History: **Baryon Number** and **Charge Distributions** 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





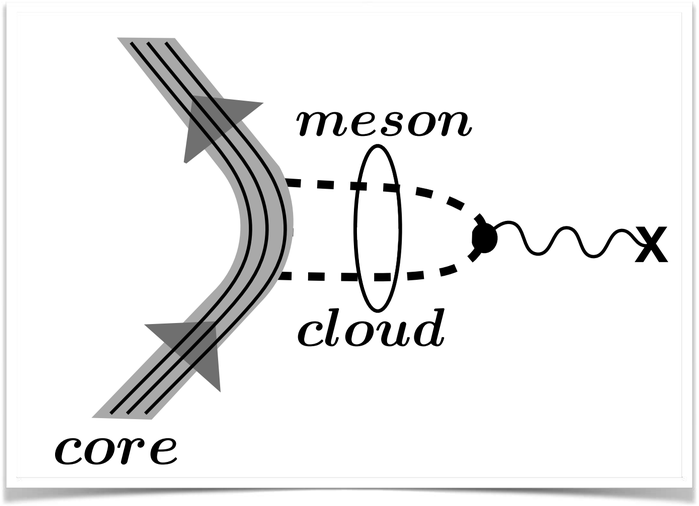
N. Kaiser,
U.-G. Meißner,
W.W.
Nucl. Phys. A466 (1987) 685

- **Separation of scales**

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

FORM FACTORS of the NUCLEON

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



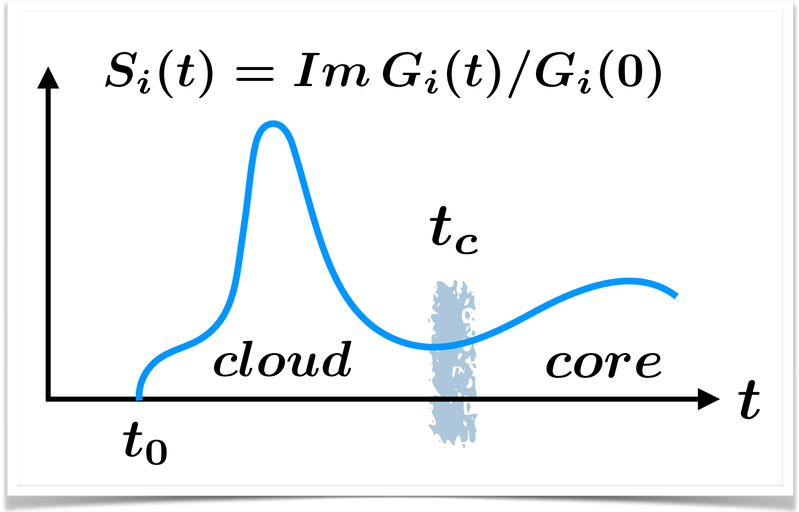
- **Delineation of**

valence quark (qqq) **CORE**

and

mesonic (multi $\bar{q}q$) **CLOUD**

$$t_c \simeq 1\,\mathrm{GeV}^2$$



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

- **Detailed spectral analysis of accurately determined empirical form factors**

N. Kaiser, W.W. : Phys. Rev. C110 (2024) 015202

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

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

Empirical : $\langle r_p^2\rangle^{1/2} = 0.840 \pm 0.004\,\text{fm}$

$\langle r_n^2\rangle = -0.105 \pm 0.006\,\text{fm}^2$

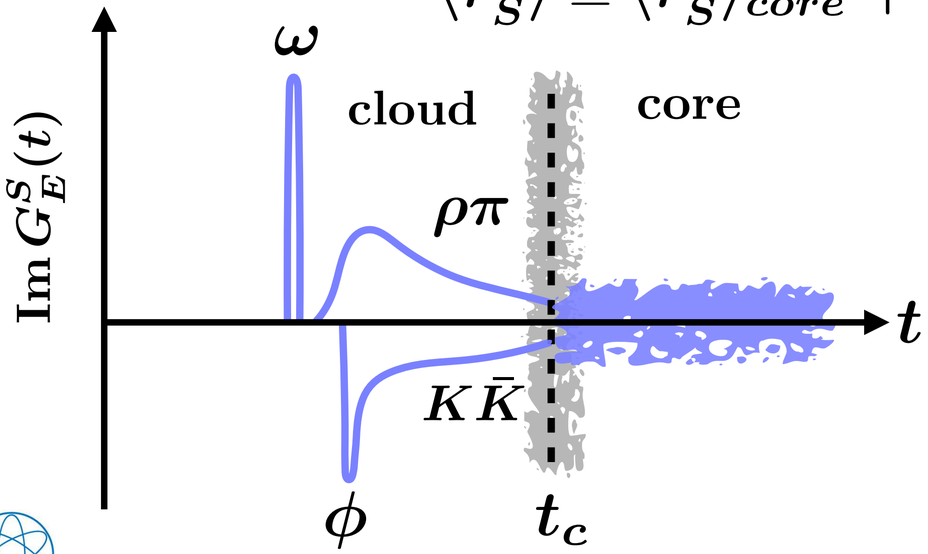
$\langle r_S^2\rangle^{1/2} = 0.78 \pm 0.01\,\text{fm}$

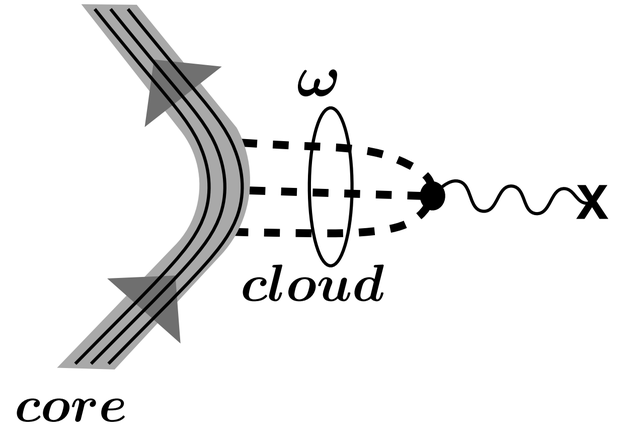
Y.H. Lin, H.-W. Hammer, U.-G. Meißner PRL 128 (2022) 052002

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

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

$$\langle r_S^2\rangle \simeq \langle r_S^2\rangle_{core} + \frac{6}{m_\omega^2} \quad \rightarrow \quad \langle r_S^2\rangle_{core}^{1/2} \simeq 0.48\,\text{fm}$$





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

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

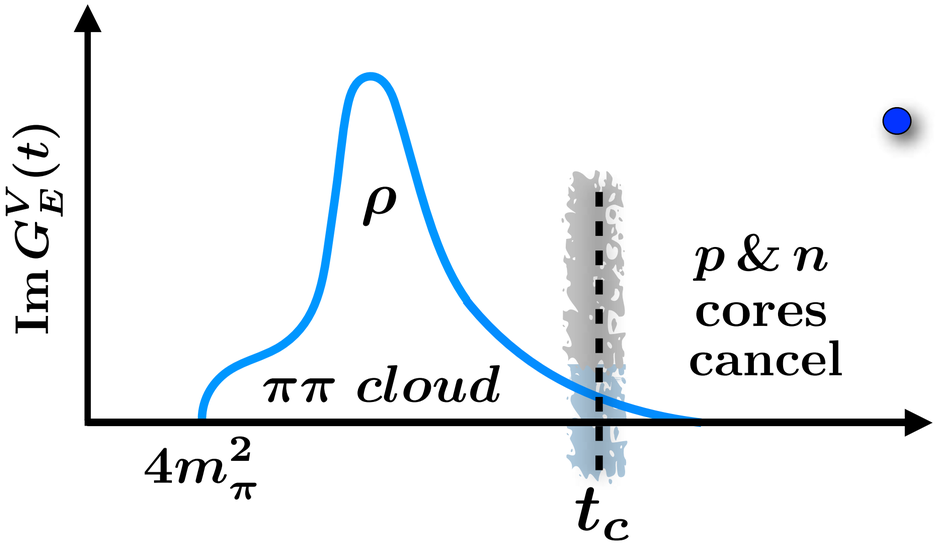
N. Kaiser, W.W. Phys. Rev. C110 (2024) 015202

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

- **Isovector electric form factor** $G_E^V(q^2) = \frac{1}{2}\left[G_E^p(q^2) - G_E^n(q^2)\right] \qquad \langle r_V^2 \rangle = \langle r_p^2 \rangle - \langle r_n^2 \rangle$

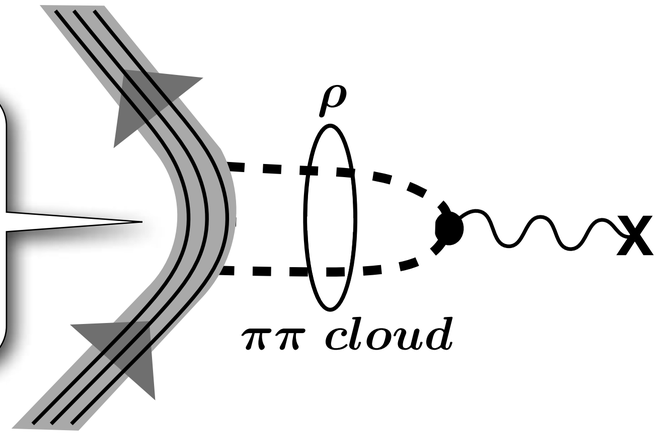
  Empirical : $\langle r_V^2 \rangle^{1/2} = 0.90 \pm 0.01\ \mathrm{fm}$ Y.H. Lin, H.-W. Hammer, U.-G. Meißner PRL 128 (2022) 052002

Test case : in the limit of exact isospin symmetry, contributions from proton and neutron valence quark cores **CANCEL**



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

$[uud]_{core}$ — $[udd]_{core}$



$|\langle r_V^2 \rangle_{core}| \simeq 0.02\ \mathrm{fm}^2$ … almost vanishing

- **Isovector charge radius** almost entirely determined by **two-pion cloud** (ρ meson + prominent low-mass tail extending down to $\pi\pi$ threshold)

N. Kaiser, W.W. Phys. Rev. C110 (2024) 015202

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

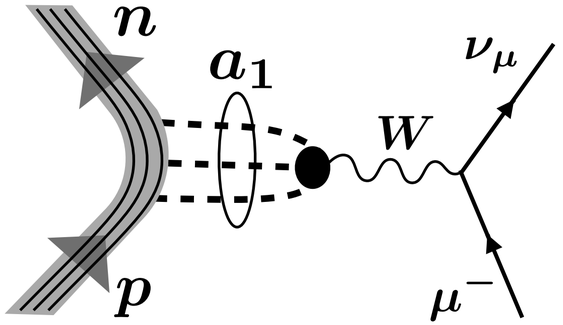
- **Axial form factor** $G_A(q^2) = g_A \left[1 + \frac{1}{6} \langle r_A^2 \rangle q^2 + \dots \right]$

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

Empirical :

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

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



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

(from μp capture and
νd scattering analysis)

Axial radius significantly smaller than proton charge radius $\left(\langle r_p^2 \rangle = 0.71 \pm 0.01 \,\text{fm}^2 \right)$

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

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

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

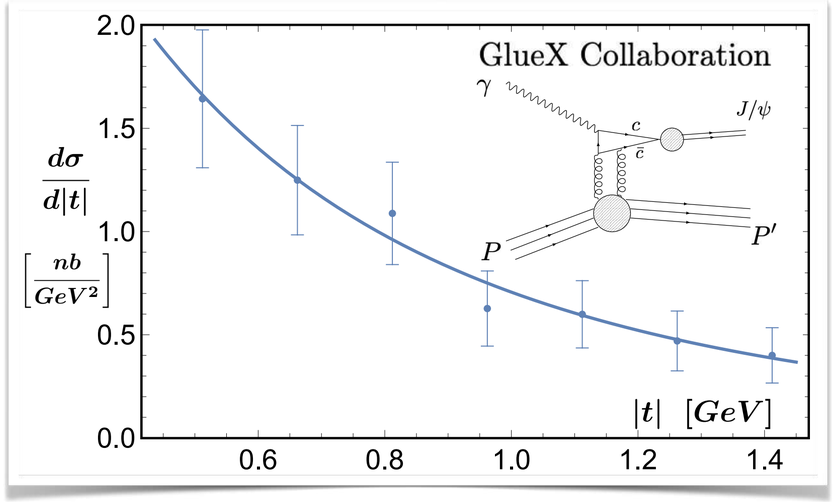
N. Kaiser, W.W.
Phys. Rev. C110 (2024) 015202

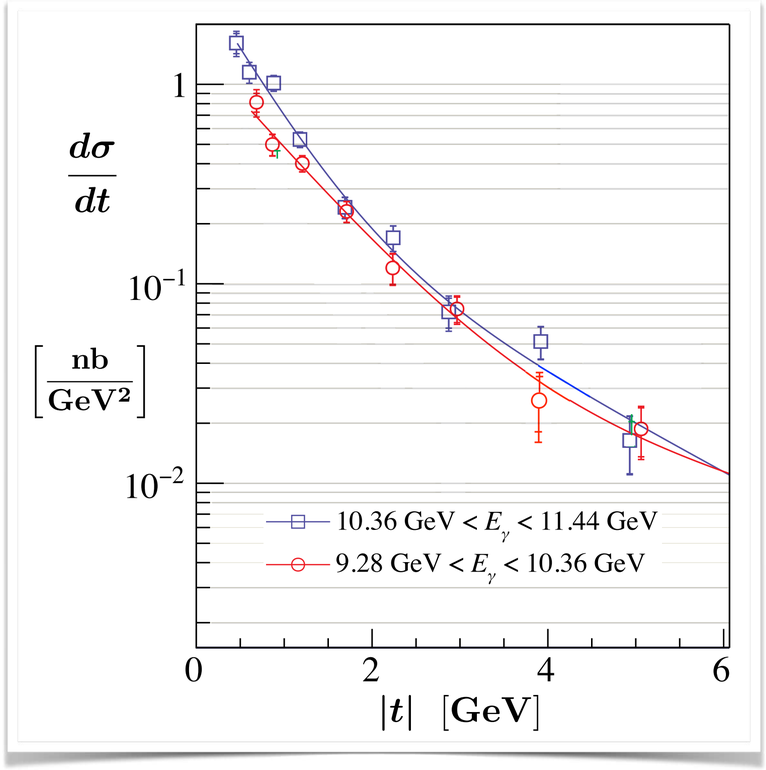
[based on **a)** ; correspondingly larger uncertainty when using **b)**]

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

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

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





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

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

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

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

- **Empirical mass radius**

$$\langle r^2_m\rangle^{1/2} = (0.55 \pm 0.03)\,\text{fm}$$

$$\langle r^2_m\rangle^{1/2} = (0.53 \pm 0.04)\,\text{fm}$$

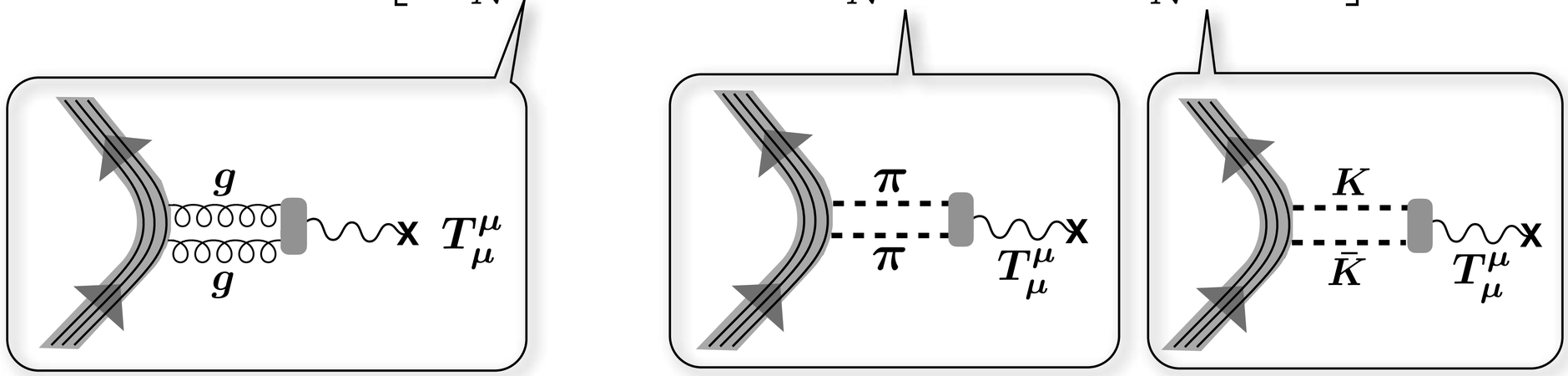
D. Kharzeev : Phys. Rev. D104 (2021) 054015

GlueX Update: S. Adhikari et al. : Phys. Rev. C108 (2023) 025201

Example IV: **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

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

use: $\sigma_N = 56 \, \text{MeV}$

πN Hoferichter et al. (2023)

π *atoms* Friedman, Gal (2019)

$$\langle r_m^2 \rangle_{core}^{1/2} = 0.51 \pm 0.05 \, \text{fm}$$

N. Kaiser, W.W.
Phys. Rev. C110 (2024) 015202

W.W.: J. Subatomic Part. Cosm. 6 (2026) 100499

NUCLEON RADII : SUMMARY

form factor		J^π (cloud)	empirical rms radii
• isoscalar electric	$G_E^S(q^2)$	1^-	$\langle r_S^2\rangle^{1/2} = 0.78 \pm 0.01\,\mathrm{fm}$ Y.H. Lin, H.-W. Hammer, U.-G. Meißner PRL 128 (2022) 052002
• isovector electric	$G_E^V(q^2)$	1^-	$\langle r_V^2\rangle^{1/2} = 0.90 \pm 0.01\,\mathrm{fm}$
• isovector axial	$G_A(q^2)$	1^+	$\langle r_A^2\rangle^{1/2} = 0.67 \pm 0.01\,\mathrm{fm}$ $(\langle r_A^2\rangle^{1/2} = 0.68 \pm 0.11\,\mathrm{fm})$ R.J. Hill et al. : Rep. Prog. Phys. 81 (2018) 096301
• mass	$G_m(q^2) = \langle p'\|T_\mu^\mu\|p\rangle$	0^+	$\langle r_m^2\rangle^{1/2} = 0.55 \pm 0.03\,\mathrm{fm}$ D. Kharzeev : Phys. Rev. D104 (2021) 054015 $\langle r_m^2\rangle^{1/2} = 0.53 \pm 0.04\,\mathrm{fm}$ S. Adhikari et al. : Phys. Rev. C108 (2023) 025201

extracted core radii

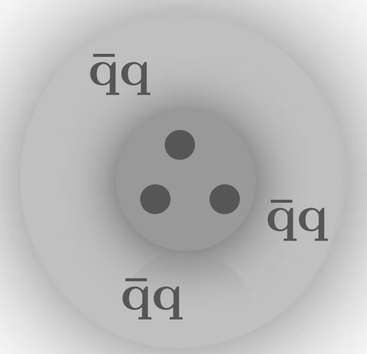
N. Kaiser, W.W. : Phys. Rev. C110 (2024) 015202

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

$$\langle r_V^2\rangle_{core} \simeq 0\,(\pm 0.02)\,\mathrm{fm}^2\ !!$$

$$\langle r_A^2\rangle_{core}^{1/2} = 0.53 \pm 0.02\,\mathrm{fm} \quad (0.5 \pm 0.2)$$

$$\langle r_m^2\rangle_{core}^{1/2} = 0.51 \pm 0.05\,\mathrm{fm}$$



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

$$\langle r_S^2 \rangle_{core}^{1/2} \simeq \langle r_A^2 \rangle_{core}^{1/2} \simeq \langle r_m^2 \rangle_{core}^{1/2} \equiv R_{core} \simeq \frac{1}{2}\ \mathrm{fm}$$

$R_{core} \sim \frac{1}{2}\ \mathrm{fm}$ $\quad R_{cloud} \sim 1\ \mathrm{fm}$ $\quad$ • **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** $f_\pi^*(n_B)$
- **Hard baryonic core** governed by **gluon dynamics**
  expected to remain approximately **stable** with increasing baryon density up until
  hard compact cores begin to touch and overlap

(Example: extended NJL model calculation : $R_{core}(n_B = 5n_0)/R_{core}(n_B = 0) \simeq 1.1$)

W. Bentz, I.C. Cloet : Symmetry 17 (2025) 505

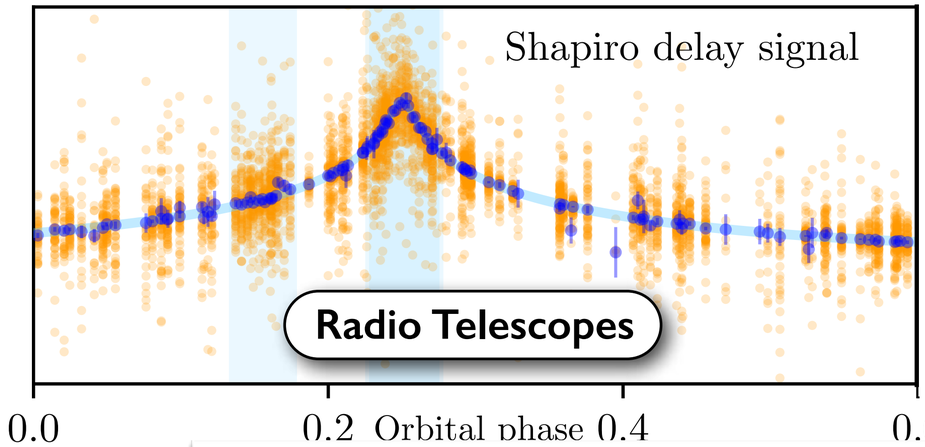
Part Two

Dense Baryonic Matter

- **Constraints on the EoS of dense baryonic matter from neutron star observations**
- **Distance scales and possible scenarios**

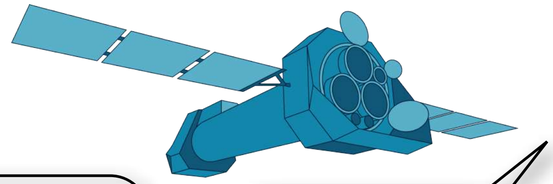


NEUTRON STARS : DATA

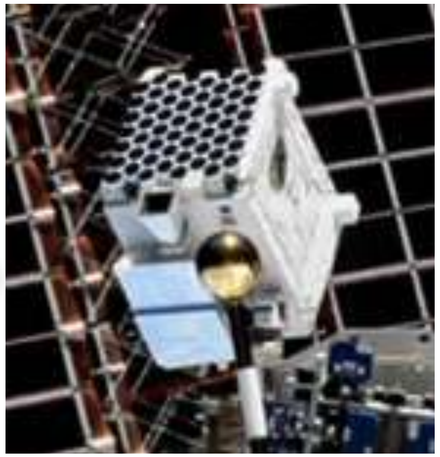




Keck Observatory



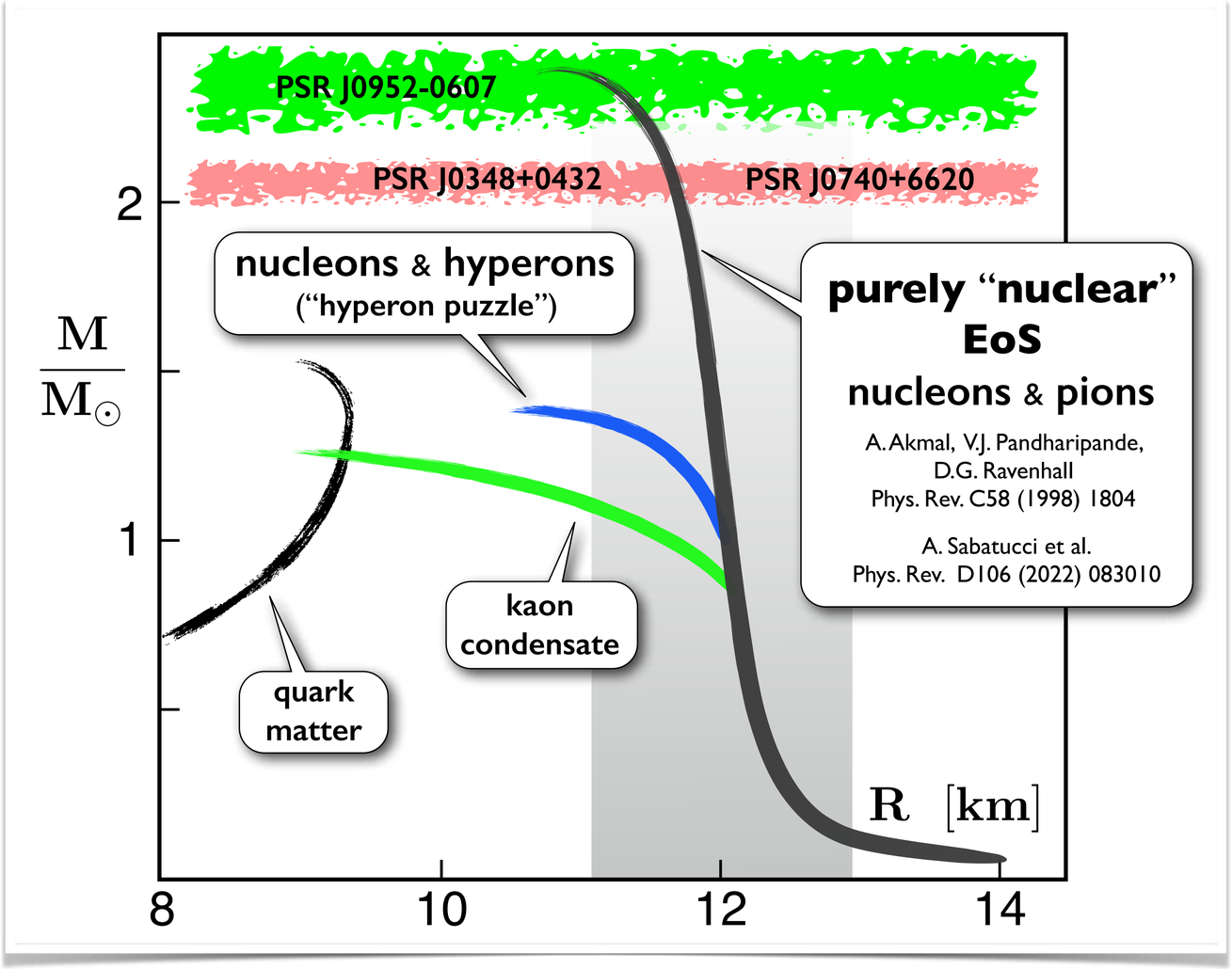
NICER + XMM Newton



PSR	Mass $M/M_\odot$	Radius R [km]	Ref.
J0348+0432	1.806 ± 0.037	–	A. Saffer *et al.*, Astrophys. J. Lett. **983** (2025) L20
J1614-2230	1.937 ± 0.014	$\left(10.06^{+1.25}_{-0.87}\right)$	G. Agazie *et al.*, Astrophys. J. Lett. **951** (2023) L9 (L. Mauviard *et al.*, arXiv:2609.00172)
J0952-0607	2.32 ± 0.11	–	R.W. Romani *et al.*, Astrophys. J. **993** (2025) 173.
J0740+6620	2.073 ± 0.069	$12.76^{+1.49}_{-1.02}$	A.J. Dittmann *et al.*, Astrophys. J. **974**, (2024) 295
J0030+0451	$1.43^{+0.20}_{-0.17}$	$12.68^{+1.31}_{-1.04}$	Y. Kini *et al.*, Astrophys. J. **1005** (2026) 201.
J0614-3329	$1.44^{+0.06}_{-0.07}$	$10.29^{+1.01}_{-0.86}$	L. Mauviard *et al.*, Astrophys. J. **995** (2025) 60
J0437-4715	1.418 ± 0.044	13.45 ± 1.65	M.C. Miller *et al.*, Astrophys. J. Lett. **1000** (2026) L48

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

- from observations of massive neutron stars



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

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

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

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

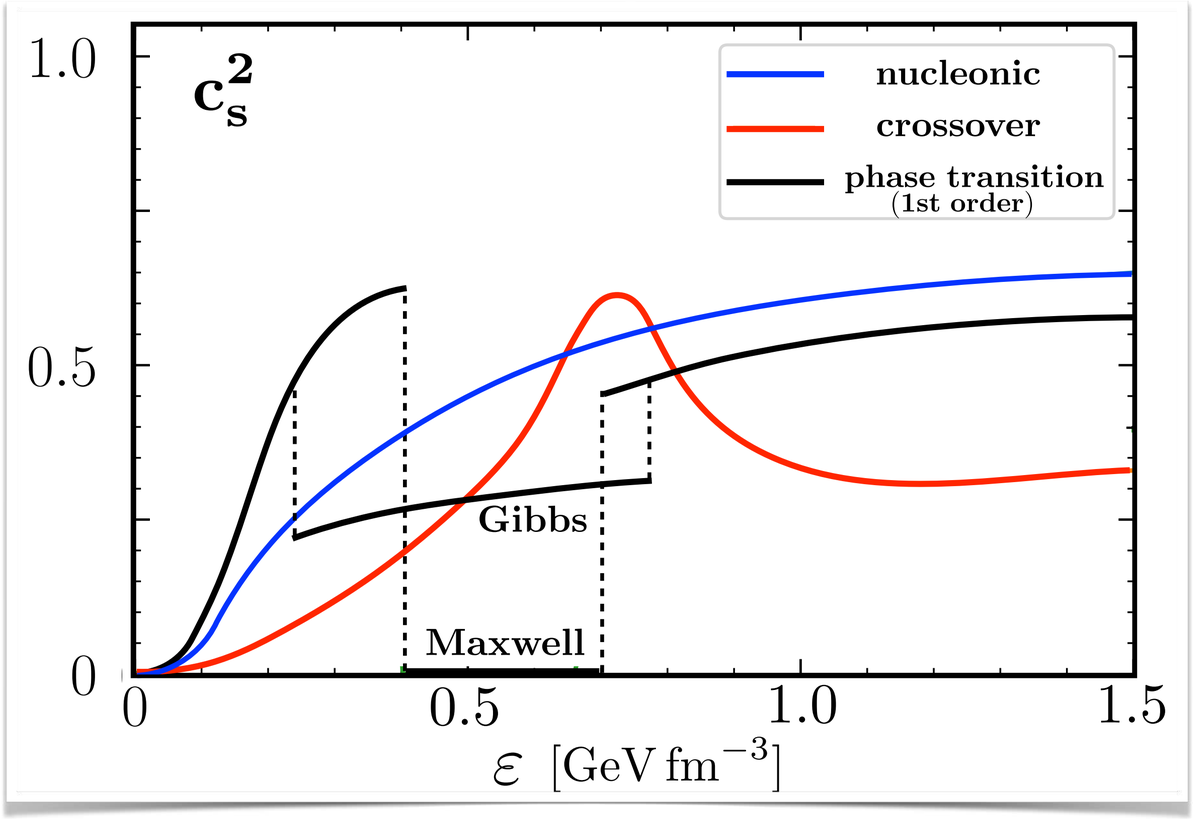
- **Stiff equation-of-state $P(\varepsilon)$ required**
- **Simplest forms of exotic matter** (kaon condensate, quark matter, …) **ruled out**

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**



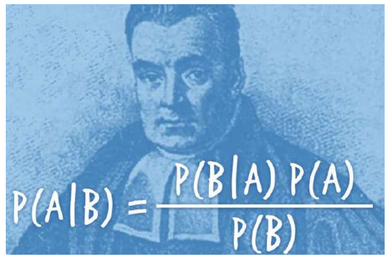
- Equation of State :

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

- Gibbs - Duhem equation (T=0)

$$P + \varepsilon = \mu_B\, n_B = \sum_i \mu_i\, n_i$$

- Baryon density $n_B = \partial P / \partial \mu_B$
- Baryon chemical potential $\mu_B = \partial \varepsilon / \partial n_B$



INFERENCE of SOUND SPEED and RELATED PROPERTIES of NEUTRON STARS

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

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

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

$$P(\theta|\mathcal{D}) \propto P(\mathcal{D}|\theta)\, P(\theta)$$

→ Choose general **Prior** $P(\theta)$ → Compute **Posterior** $P(\theta|\mathcal{D})$ from **Likelihood** $P(\mathcal{D}|\theta)$

→ Quantify **Evidences** for hypotheses H_1 vs. H_2 in terms of **Bayes factors** $\mathcal{B}_{H_2}^{H_1} = \frac{P(\mathcal{D}|H_1)}{P(\mathcal{D}|H_2)}$

- Important : **Posterior** must be driven by **DATA** , not by choice of Prior

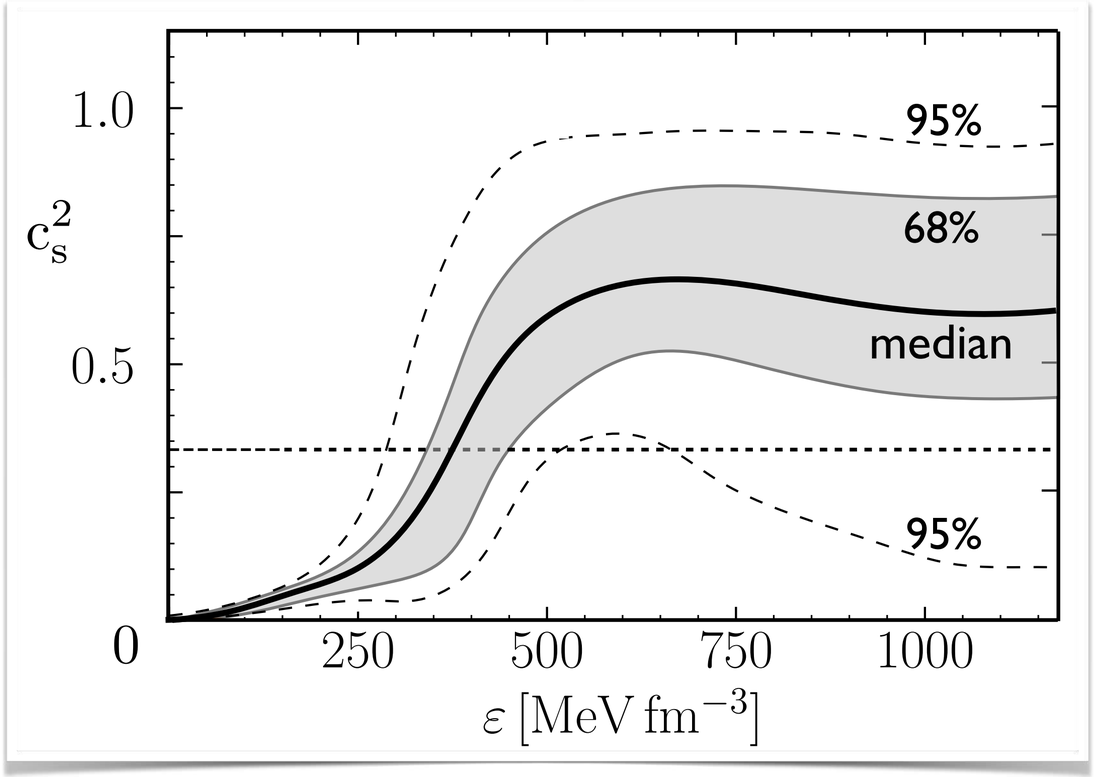


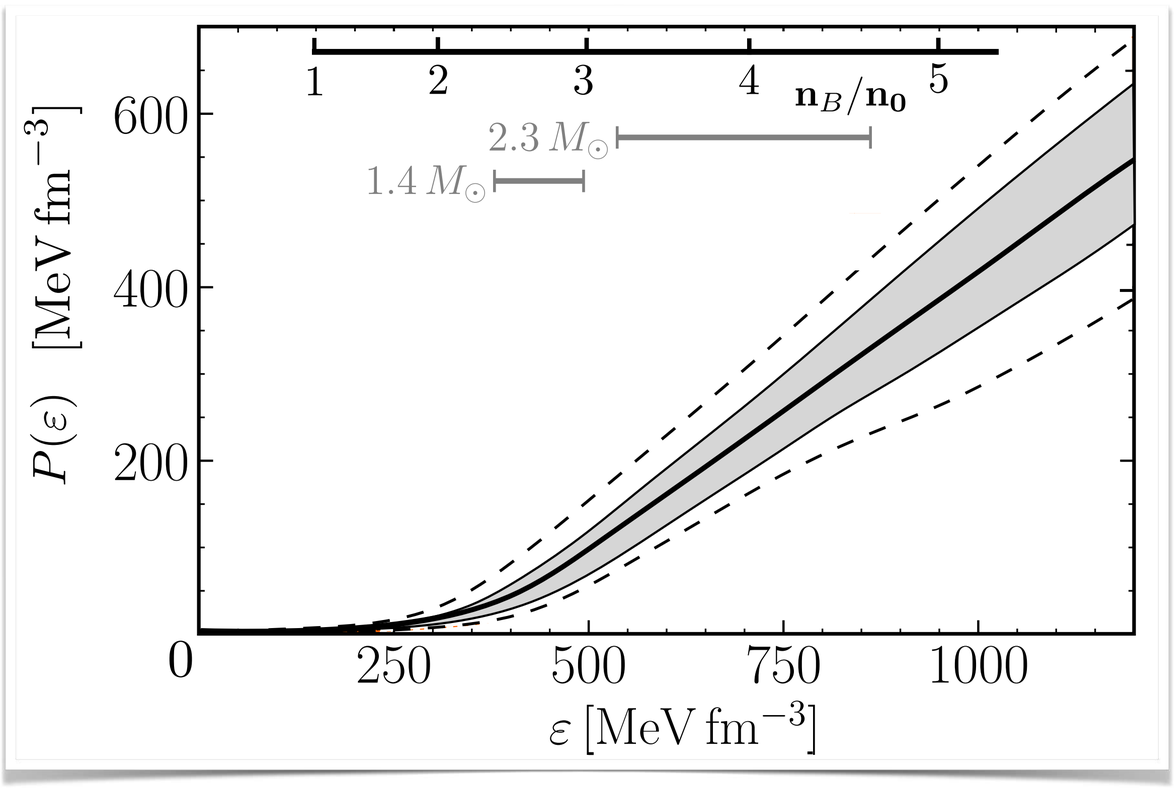
NEUTRON STAR MATTER : EQUATION of STATE

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

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

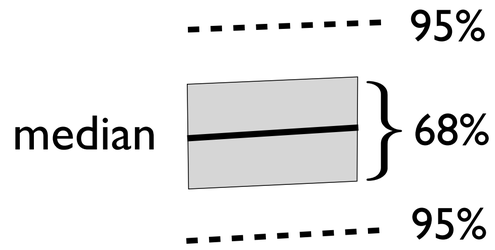
L. Brandes, W.W., N. Kaiser : Phys. Rev. D 107 (2023) 014011 ; Phys. Rev. D 108 (2023) 094014
L. Brandes, W.W.: Symmetry 16 (2024) 111 ; Phys. Rev. D 111 (2025) 034005





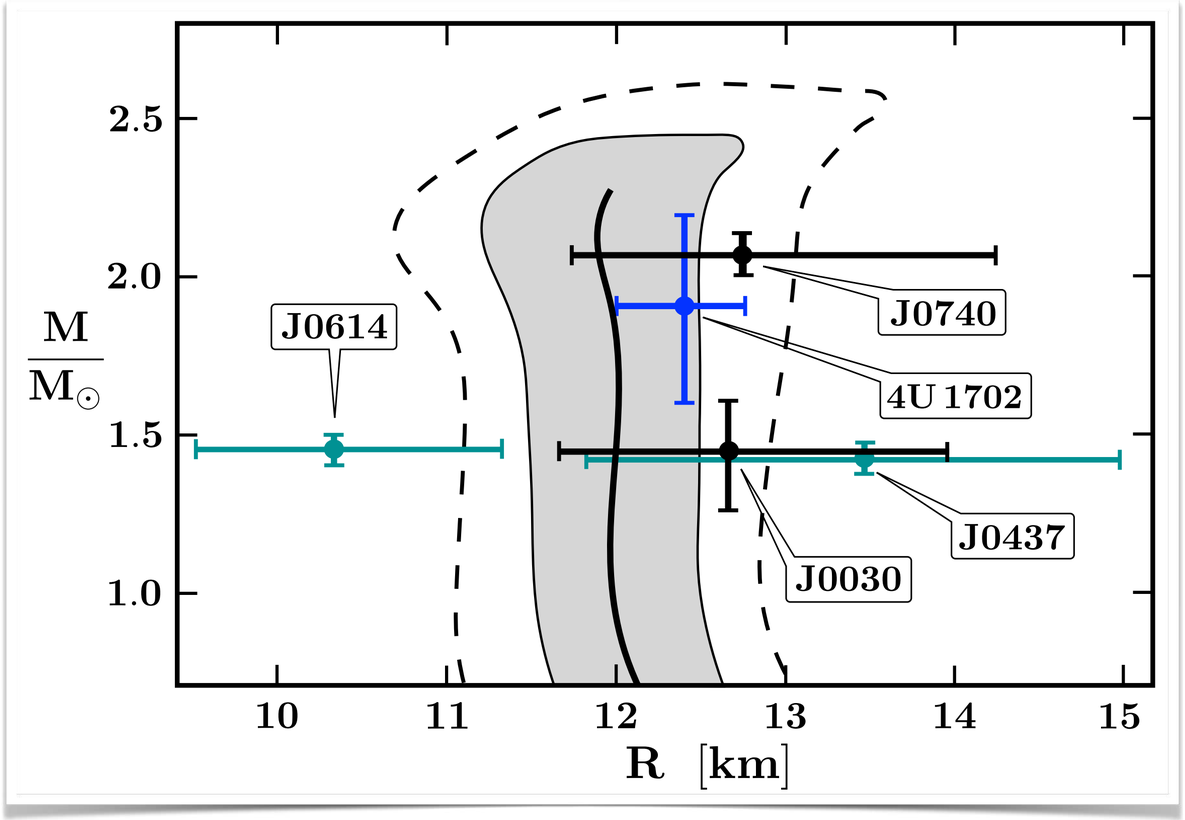
- **Speed of sound** exceeds conformal bound $c_s = 1/\sqrt{3}$ at baryon densities $n_B > 2 - 3\, n_0$
  - **Strongly repulsive correlations** in dense baryonic matter

NEUTRON STAR PROPERTIES

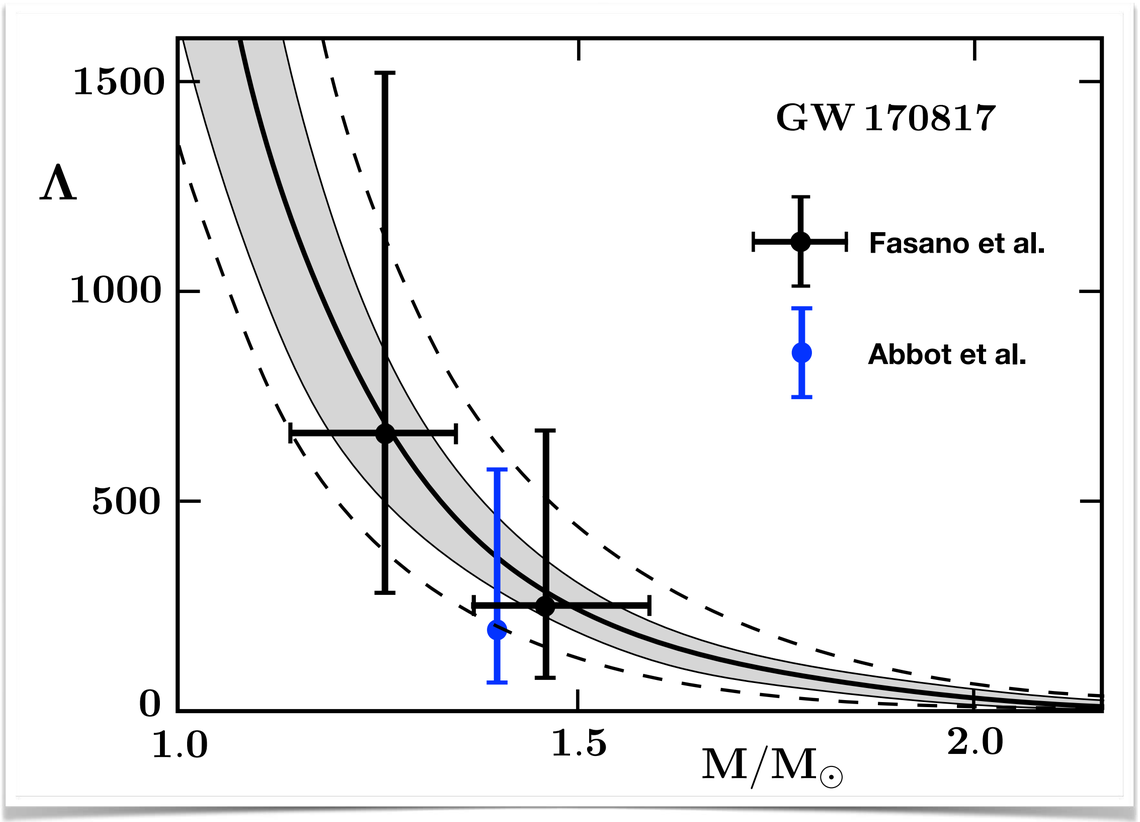


- **Bayesian inference posterior bands** (68% and 95% c.l)

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



- **Tidal deformability**



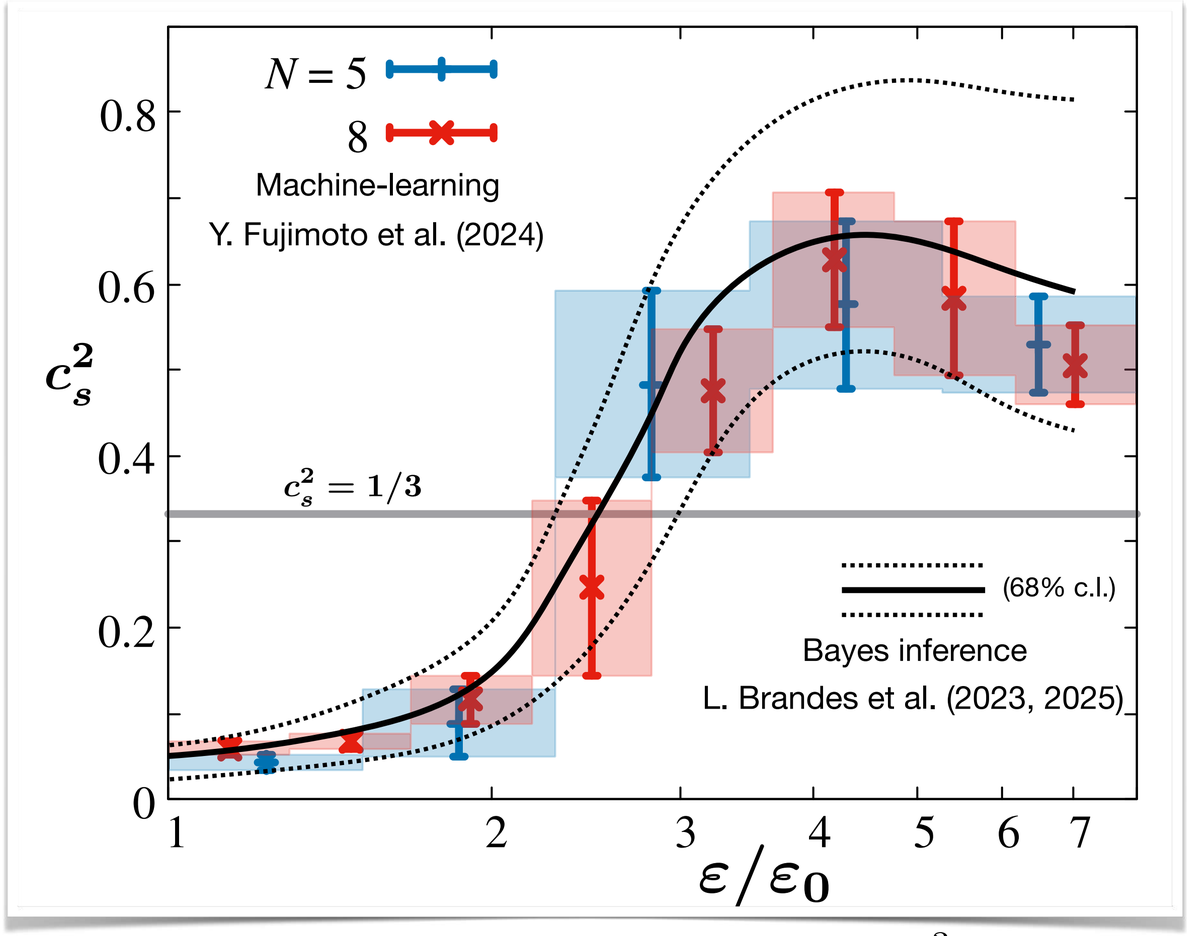
L. Brandes, W. W., N. Kaiser : Phys. Rev. D 107 (2023) 014011 ; Phys. Rev. D 108 (2023) 094014

L. Brandes, W. W. : Phys. Rev. D 111 (2025) 034005

NEUTRON STAR MATTER : SPEED of SOUND

- **Machine-learning inference of sound speed and EoS**

Y. Fujimoto, K. Fukushima, S. Kamata, K. Murase : Phys. Rev. D 110 (2024) 034035



$$\varepsilon_0 = M_N n_0 = 0.15\,\mathrm{GeV/fm}^3$$

- **Consistency**

  between **machine-learning** (neural networks) and **Bayes inference** approaches

- **Note:**
  Support from **empirical data base** for inference procedures is limited to $\varepsilon \lesssim 6\,\varepsilon_0$

EQUATION of STATE from NICER

- **EoS inferred from latest NICER data including re-analysed J0437-4715**

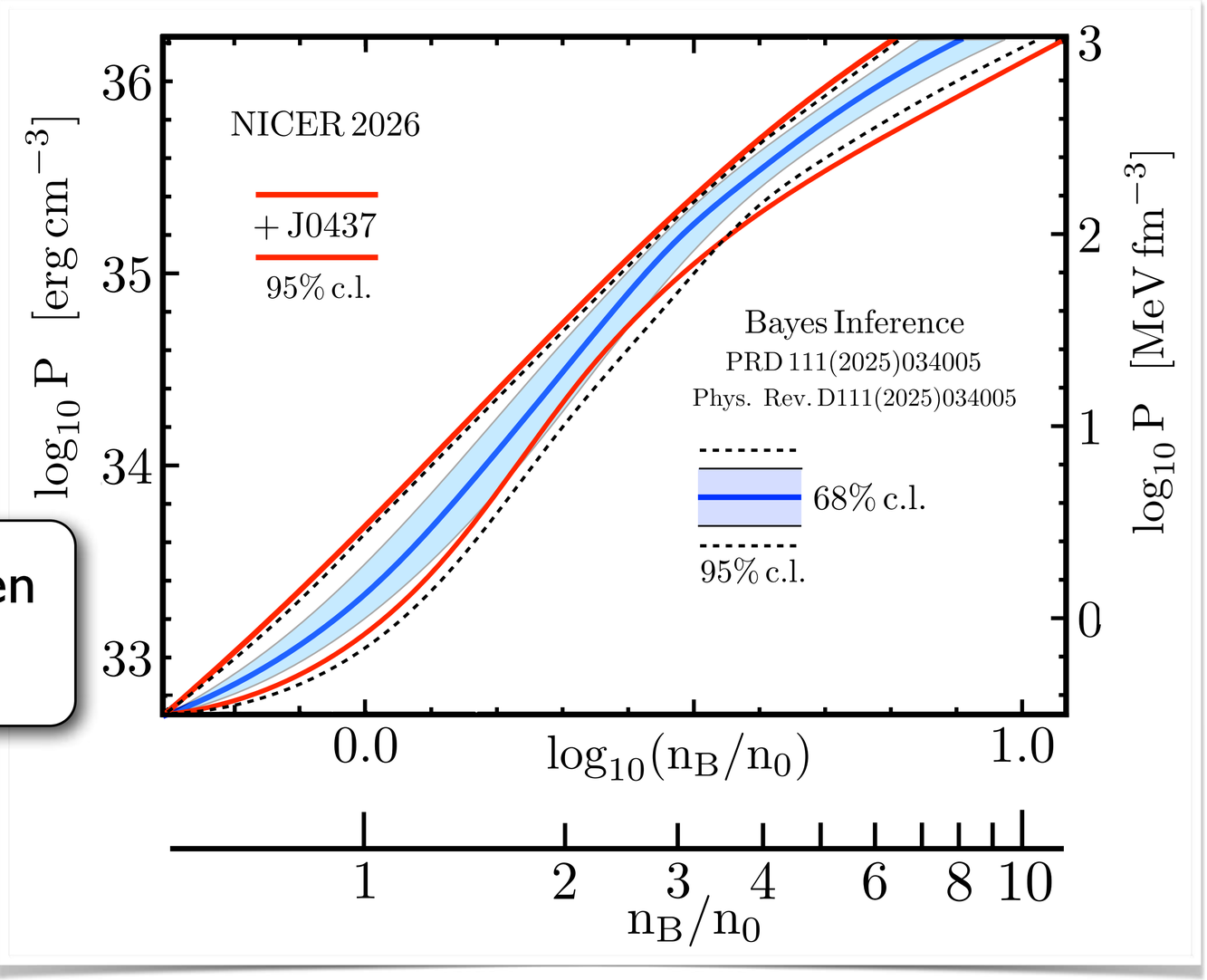
  M.C. Miller, A.J. Dittmann, et al. : Astroph. J. Lett. 1000 (2026) L48

  - Comparison with previous **Bayes inference** results

    L. Brandes, W.W. : Phys. Rev. D 111 (2025) 034005

→ Successful **consistency check** between two completely independent analyses

Note again :
Support from empirical data base is limited to baryon dentities $n_B \lesssim 5\, n_0$



NEUTRON STAR PROPERTIES (contd.)

- **Baryon chemical potential**

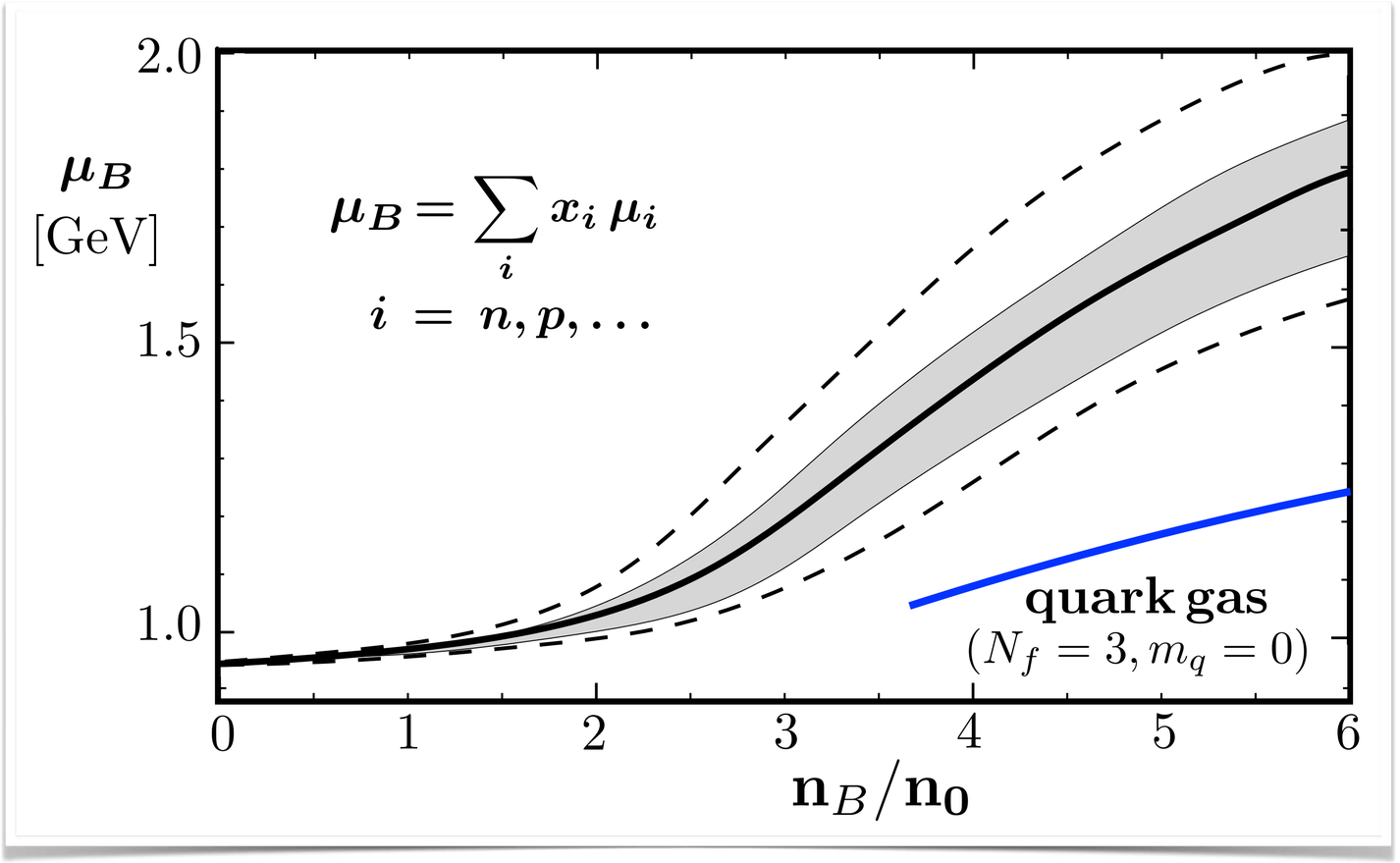
$$\mu_B = \frac{\partial \varepsilon}{\partial n_B} = \frac{P + \varepsilon}{n_B}$$

- **Stiff equation of state**

  ↓

  strongly repulsive correlations at work between baryons / quarks

- **Quark gas ruled out at densities $n_B \lesssim 6\, n_0$**



L. Brandes, W. W., N. Kaiser : Phys. Rev. D 108 (2023) 094014
L. Brandes, W. W. : Phys. Rev. D 111 (2025) 034005

QCD TRACE ANOMALY and CONFORMALITY in NEUTRON STARS

Y. Fujimoto, K. Fukushima, L.D. McLerran, M. Praszalowicz : Phys. Rev. Lett. 129 (2022) 252702

- **Trace of energy-momentum tensor :** $T^\mu_\mu = \Theta = \frac{\beta}{2g} G^a_{\mu\nu} G^{\mu\nu}_a + (1+\gamma_m) \sum_f m_f \, \bar{q}_f q_f$

$$\langle \Theta \rangle_{T,\mu_B} = \varepsilon - 3P$$

- **Trace anomaly measure**

$$\Delta \equiv \frac{\langle \Theta \rangle_{T,\mu_B}}{3\varepsilon} = \frac{1}{3} - \frac{P}{\varepsilon}$$

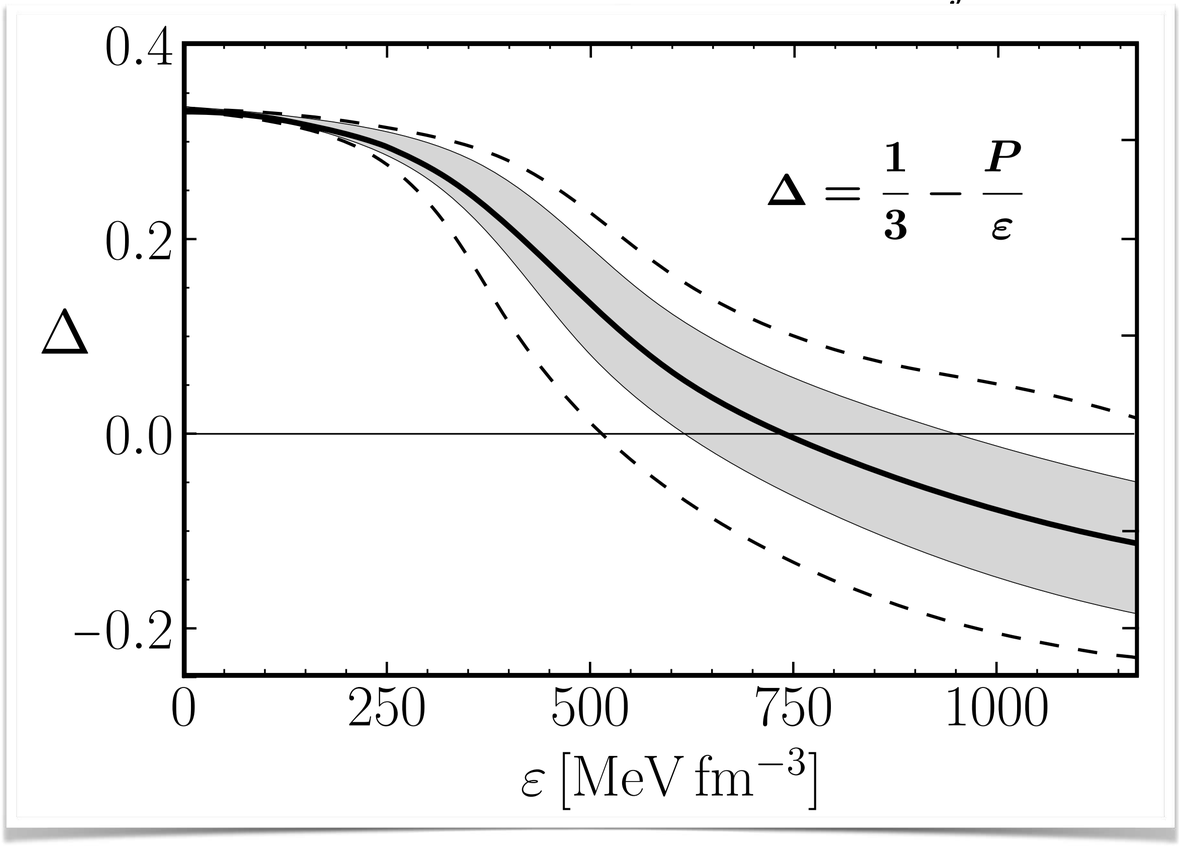
- **Conformal limit :** $\Delta \to 0$

- **Bayes factor analysis:**

  Strong evidence for

  $\Delta < 0 \quad (P > \varepsilon/3)$

  at densities $n_B \simeq 4 - 6\, n_0$



L. Brandes, W.W., N. Kaiser : Phys. Rev. D 108 (2023) 094014
L. Brandes, W.W. : Phys. Rev. D 111 (2025) 034005

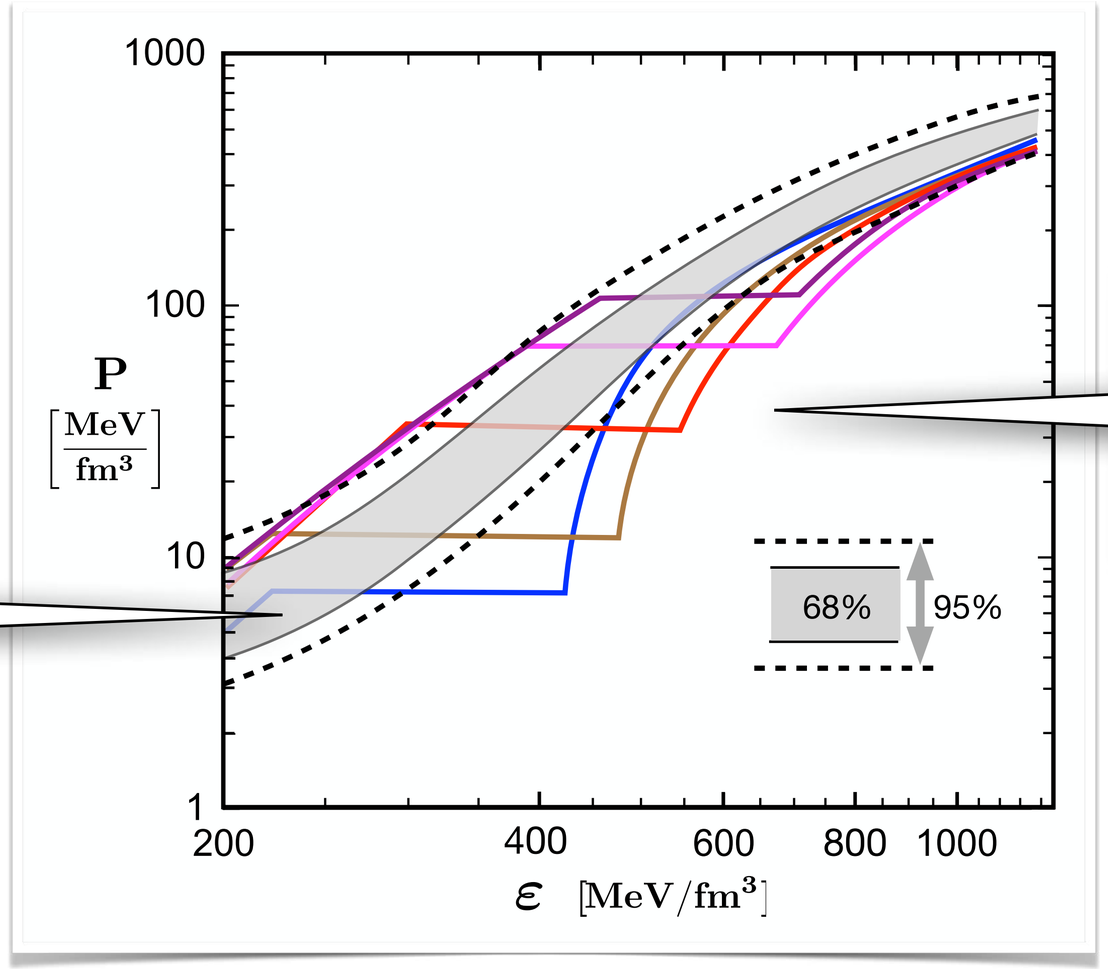
Constraints on **FIRST-ORDER PHASE TRANSITIONS** in **NEUTRON STAR MATTER**

- **Restrictions at work:**

  Narrowing down the likelihoods for exotics (twins, hybrids)

empirically constrained band (Bayes inference)

L. Brandes, W. W.
Phys. Rev. D 111 (2025) 034005



various scenarios involving first-order phase transitions

J.J. Li, A. Sedrakian, M. Alford
Astrophys. J. 967 (2024) 116

NEUTRON STAR PROPERTIES (contd.)

- **Density profiles of neutron stars**
  using inferred median of $P(\varepsilon)$

- **Central core densities**

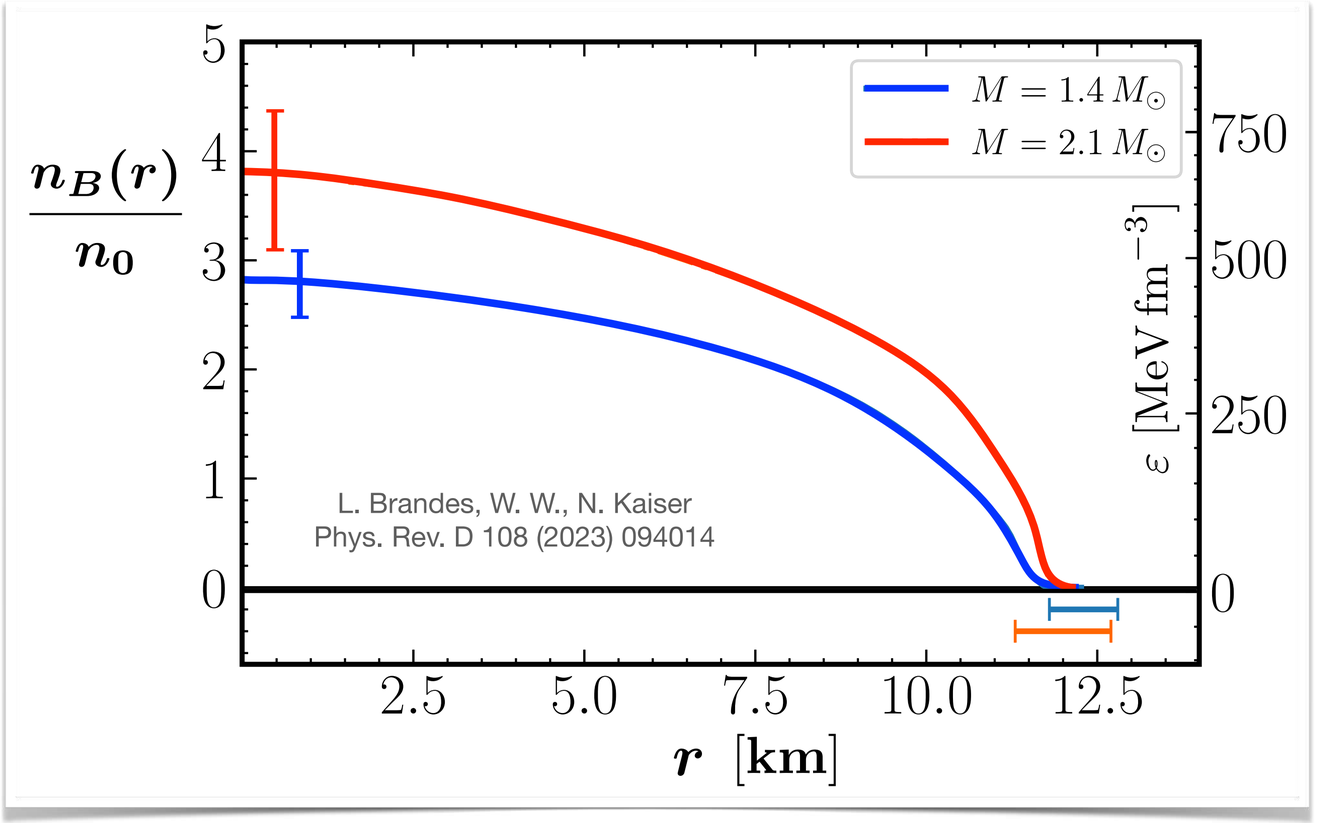
$$n_c = n_B(r = 0)$$

in neutron stars are NOT extreme

- **Average distance between baryons :**

$$d \gtrsim 1\,\mathrm{fm}$$

even for the heaviest neutron stars



$$n_c(1.4\,M_\odot) = 2.8 \pm 0.3\,n_0 \qquad n_c(2.1\,M_\odot) = 3.8^{+0.6}_{-0.7}\,n_0 \qquad n_c(2.3\,M_\odot) = 4.0^{+0.6}_{-0.9}\,n_0$$

(68% c.l. — including new NICER data and "black widow" PSR J0952-0607)

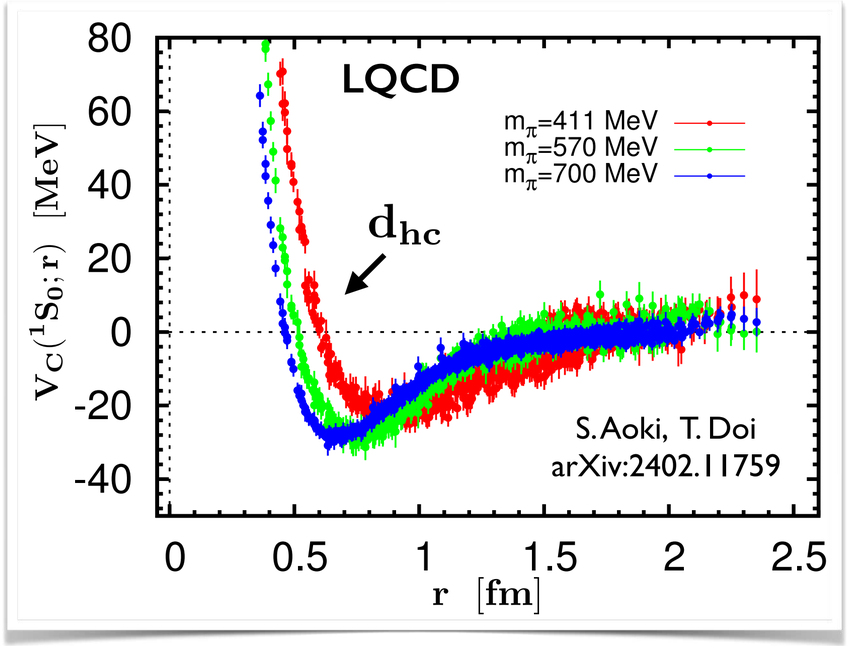
L. Brandes, W. W. : Phys. Rev. D 111 (2025) 034005

BARYONIC MATTER

- **Example:**
  hexagonal lattice arrangement

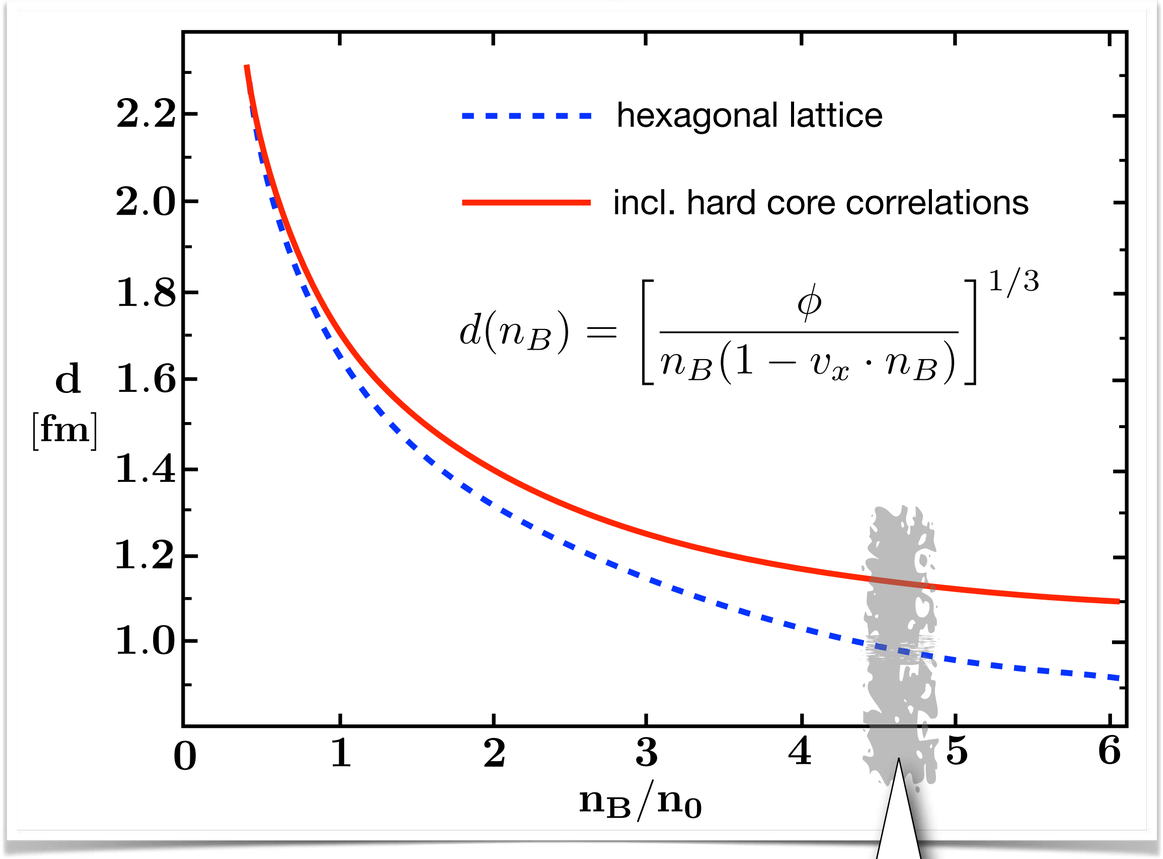
  packing fraction $\phi = \dfrac{\pi}{3\sqrt{2}} = 0.74$

- **Repulsive short-range correlations**



→ **Excluded volume** $v_x = \dfrac{2\pi}{3} d_{hc}^3$

- **Average distance between baryons**



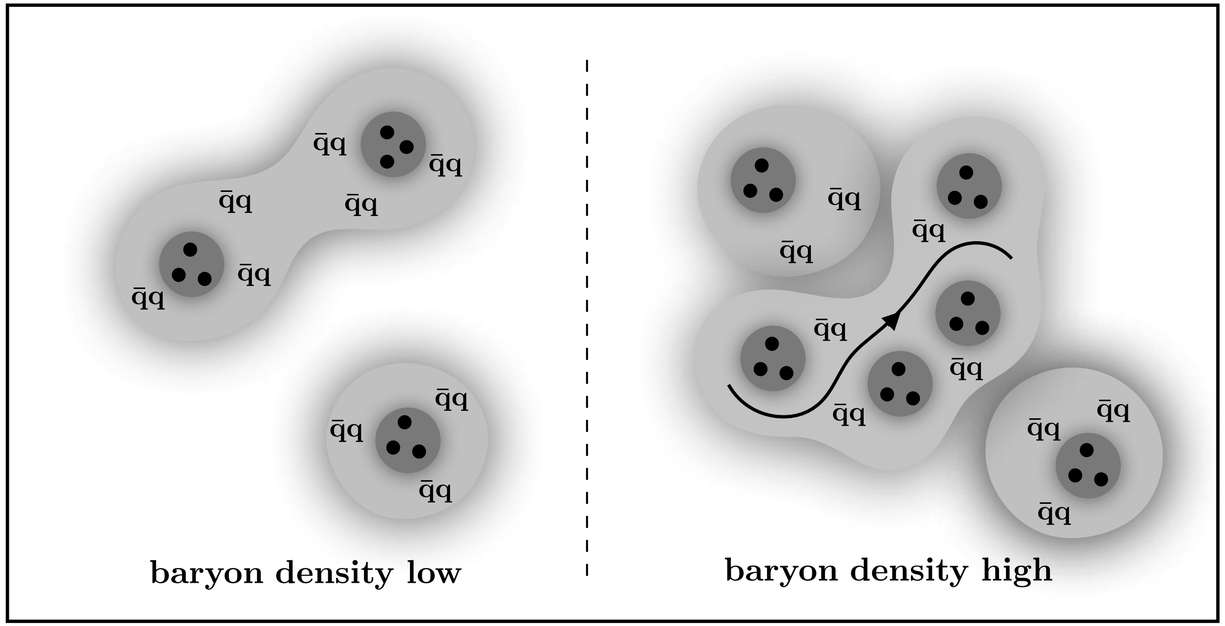
max. range of central densities in neutron star cores

BARYONIC MATTER and a TWO-SCALES SCENARIO

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

$$R_{core} \simeq 0.5\,\mathrm{fm} \qquad \left(\frac{R_{cloud}}{R_{core}}\right)^3 \gg 1$$

N. Kaiser, W.W. : Phys. Rev. C110 (2024) 015202



- $n_B \sim n_0 = 0.16\,\mathrm{fm}^{-3}$

  Tails of mesonic clouds overlap : two-body boson exchange forces between baryons

- $n_B \gtrsim 2 - 3\,n_0$

  Soft $\bar{q}q$ clouds delocalize : **percolation** ➔ many-body forces

  baryonic cores still separated, but subject to increasingly strong repulsive Pauli effects

- $n_B > 5\,n_0$ (beyond central densities of neutron stars)

  K. Fukushima, T. Kojo, W.W. Phys. Rev. D102 (2020) 096017

  Compact baryonic valence quark cores begin to touch and overlap at distances $d < 1\,\mathrm{fm}$ (but still have to overcome repulsive hard core)

SUMMARY

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

- **Central core densities not extreme** even in the heaviest neutron stars:

  $n_B < 5\ n_0$ for $M \leq 2.3\, M_\odot$ (68% c.l.)

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

- **Evidence** against **strong first-order phase transition in neutron star cores**

- **Two-scales** picture of the **nucleon** and its **evolution** in **cold dense matter**
  - → question : meaning of **(de)confinement**
  - → physics of nucleon core (baryon no. & mass) distributions

