Quarkyonic Matter: From Neutron Stars to Normal Nuclei

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ANL Physics Division Seminar

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Thanks to:

V. Koch, L. McLerran, G. Miller, T. Moss, R. Poberezhniuk, H. Stoecker

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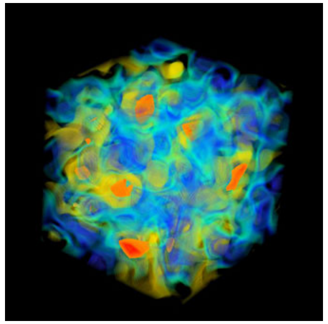
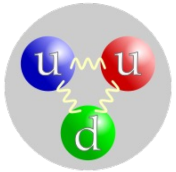
Strongly interacting matter

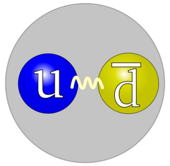
- Theory of strong interactions: *Quantum Chromodynamics* (QCD)

$$\mathcal{L} = \sum_{q=u,d,s,\dots} \bar{q}\left[i\gamma^{\mu}(\partial_{\mu} - igA^{a}_{\mu}\lambda_{a}) - m_{q}\right] q - \frac{1}{4} G^{a}_{\mu\nu} G^{\mu\nu}_{a}$$



- Basic degrees of freedom: quarks and gluons that carry color charge
- At smaller energies confined into baryons (qqq) and mesons $(q\bar{q})$



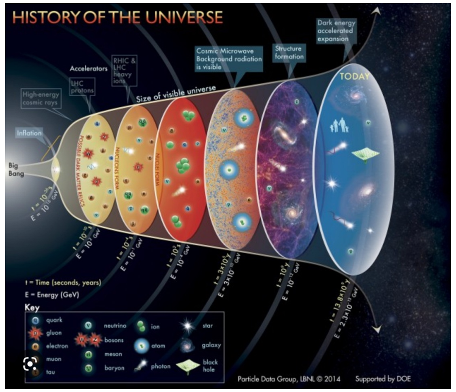


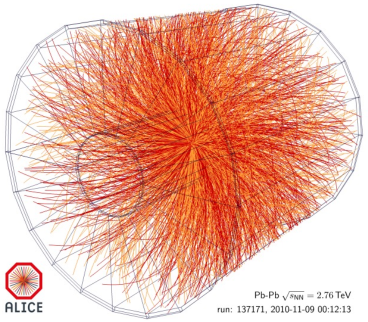
Scales

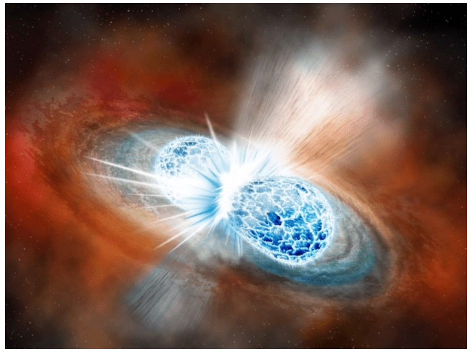
- Length: 1 femtometer $= 10^{-15}$ m
- Temperature: 100 MeV$/k_B = 10^{12}$ K

Where is it relevant?

- Early Universe
- Laboratory: heavy-ion collisions
- Astrophysics: Neutron star (mergers)



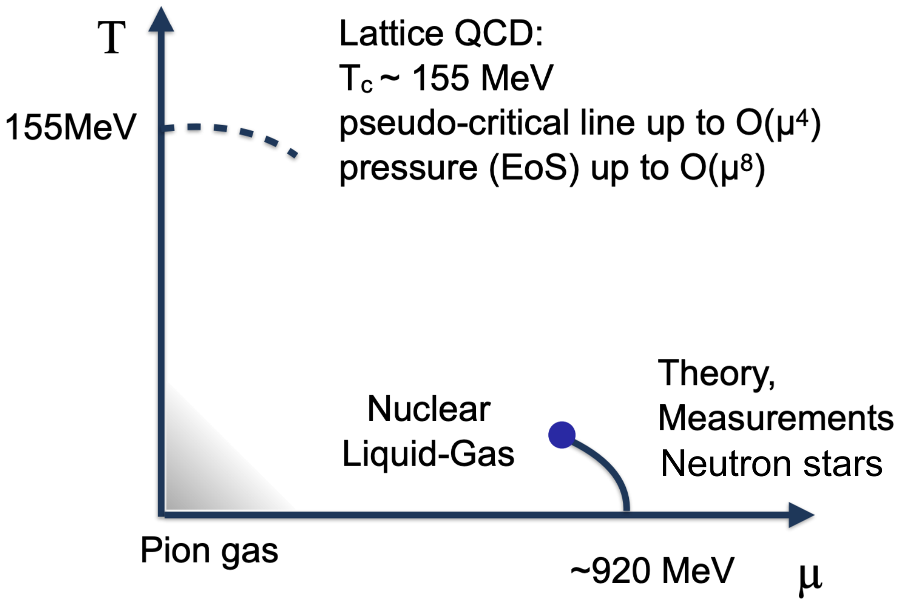




(c) NASA

QCD under extreme conditions

What we know



Lattice QCD:
$T_c \sim 155$ MeV
pseudo-critical line up to $O(\mu^4)$
pressure (EoS) up to $O(\mu^8)$

Figure courtesy of V. Koch

What we hope to know

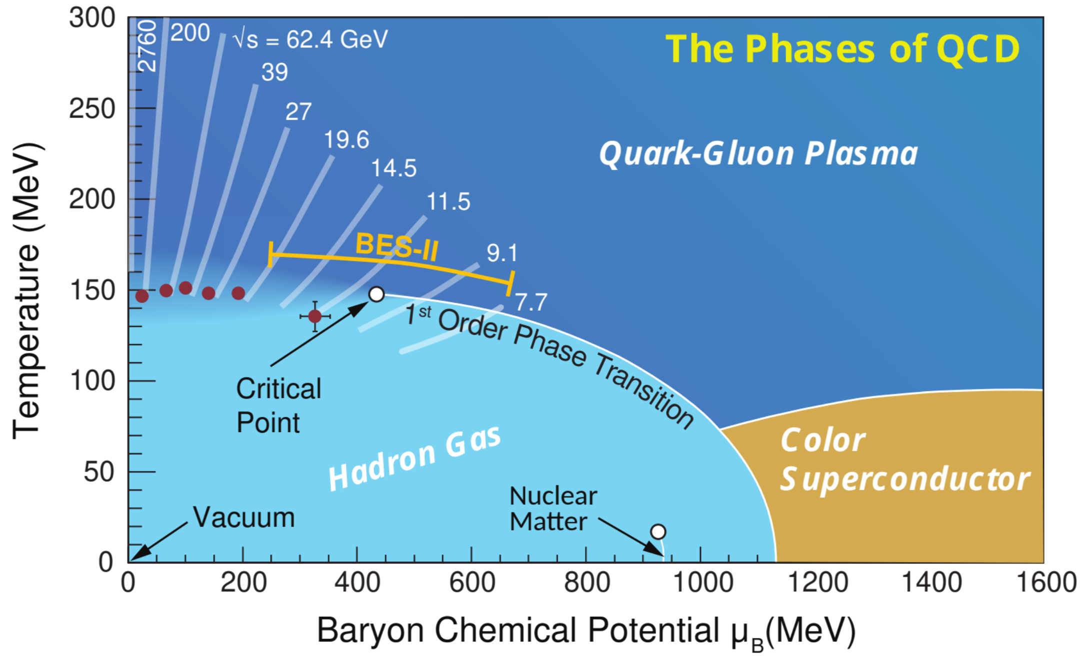


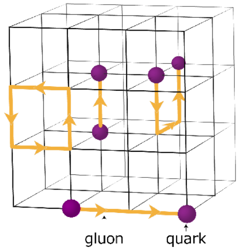
Figure from Bzdak et al., Phys. Rept. '20 & 2015 US Nuclear Long Range Plan

- Dilute hadron gas at low T & μ_B due to confinement, quark-gluon plasma high T & μ_B
- Nuclear liquid-gas transition in cold and dense matter, lots of other phases conjectured
- Chiral crossover at $\mu_B = 0$ which may turn into a *first-order phase transition* at finite μ_B

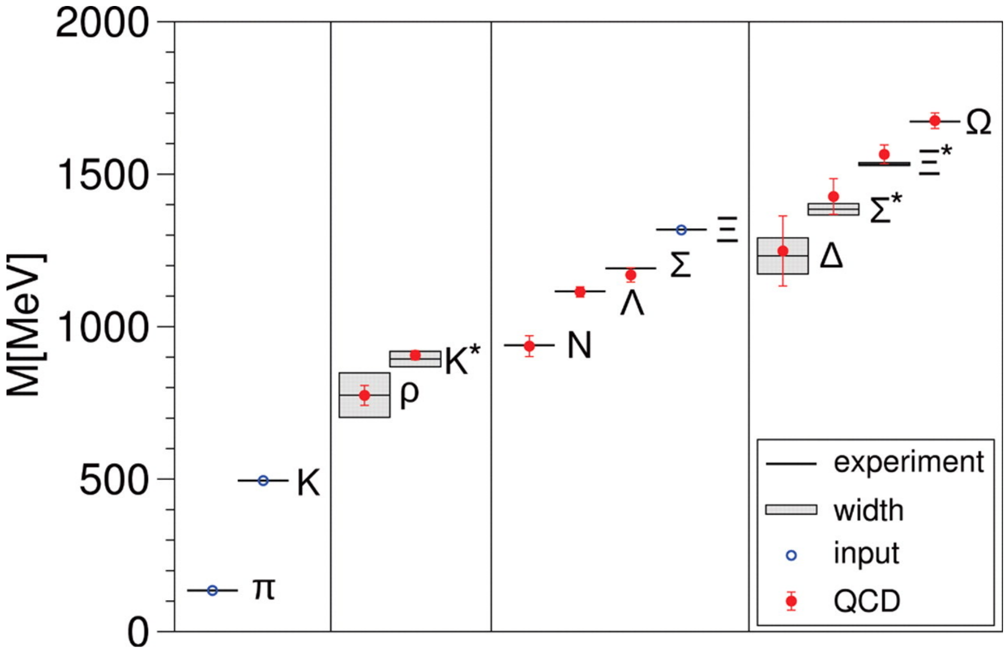
Key question: *What is the nature of hadron-quark transition and/or coexistence?*

Non-perturbative methods

First-principle tool: **Lattice QCD**



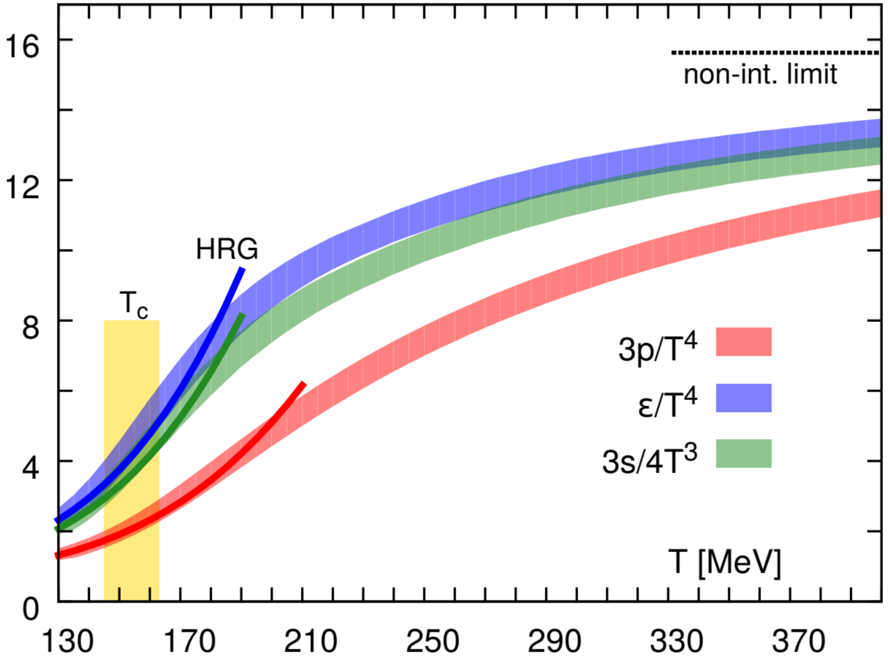
Ab-initio calculation of hadron masses



BMW Collaboration, Science 322, 1224 (2008)

Remarkable agreement of QCD with the experiment

QCD EoS at zero baryon density



Analytic crossover at vanishing net baryon density at $T_{pc} \approx 155$ MeV

QCD transition at finite μ_B

Finite baryon densities inaccessible with lattice QCD due to the sign problem

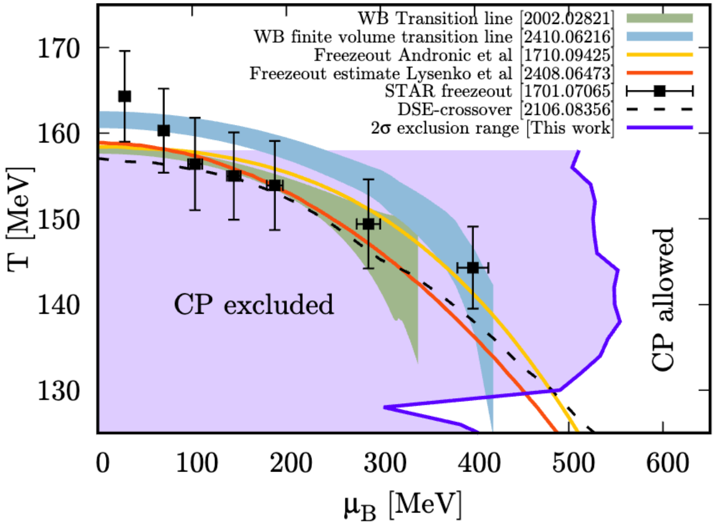


Figure from S. Borsanyi et al., PRD 112, L111505 (2025)

Extrapolations from $\mu_B = 0$:

- Crossover at $T_{pc} \approx 155$ MeV maintained until at least $\mu_B < 450$ MeV
  - No conclusive evidence for critical point
  - Consistent with RHIC-BES measurements of proton number fluctuations

Opposite limit: zero temperature, T = 0 ($\mu_B/T \to \infty$)

- No thermal excitations (resonances less relevant)
- Accessible in neutron stars
- Perturbative QCD: high densities only, $n_B > 40 n_0$

QCD transition at zero temperature and neutron stars

- QCD matter at zero temperature is present in interior of neutron stars
- Its pressure balances the gravitational pull

QCD EoS

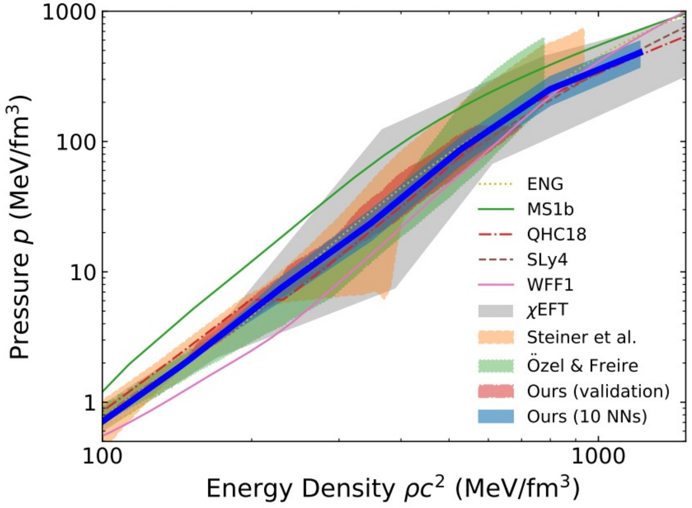
$$P = P(\rho)$$

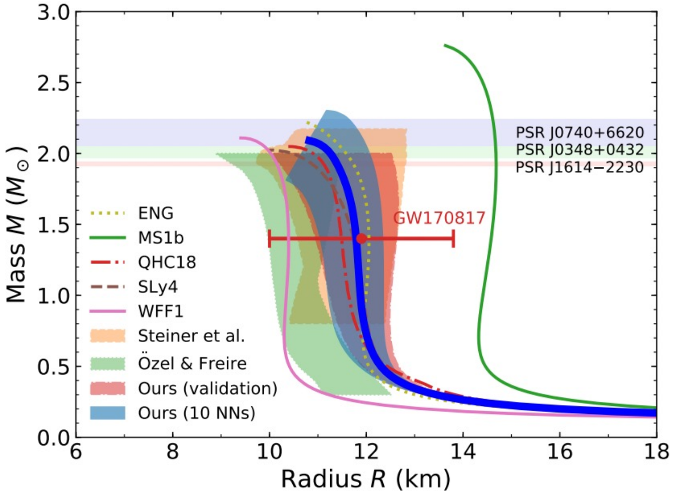
Tolman-Oppenheimer-Volkoff equation

$$\frac{dP}{dr} = -\frac{Gm}{r^2}\rho\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi r^3 P}{mc^2}\right)\left(1-\frac{2Gm}{rc^2}\right)^{-1}$$

NS mass-radius curve

$$M = M(R)$$





Figures from Fujimoto, Fukushima, Phys. Rev. D (2020)

+ multi-messenger constraints (neutron star mergers, nuclear physics, heavy-ion coll.)

QCD EoS in the cold and dense regime from neutron stars

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Speed of sound: $c_s^2 = \frac{n_B}{\mu_B}\frac{d\mu_B}{dn_B}$

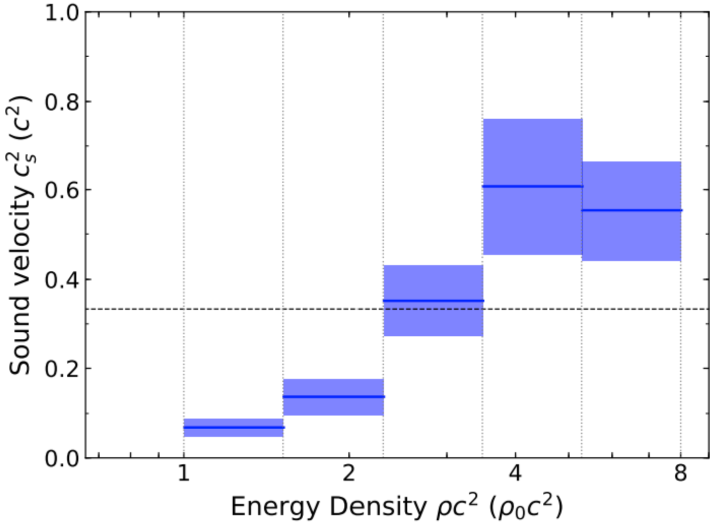
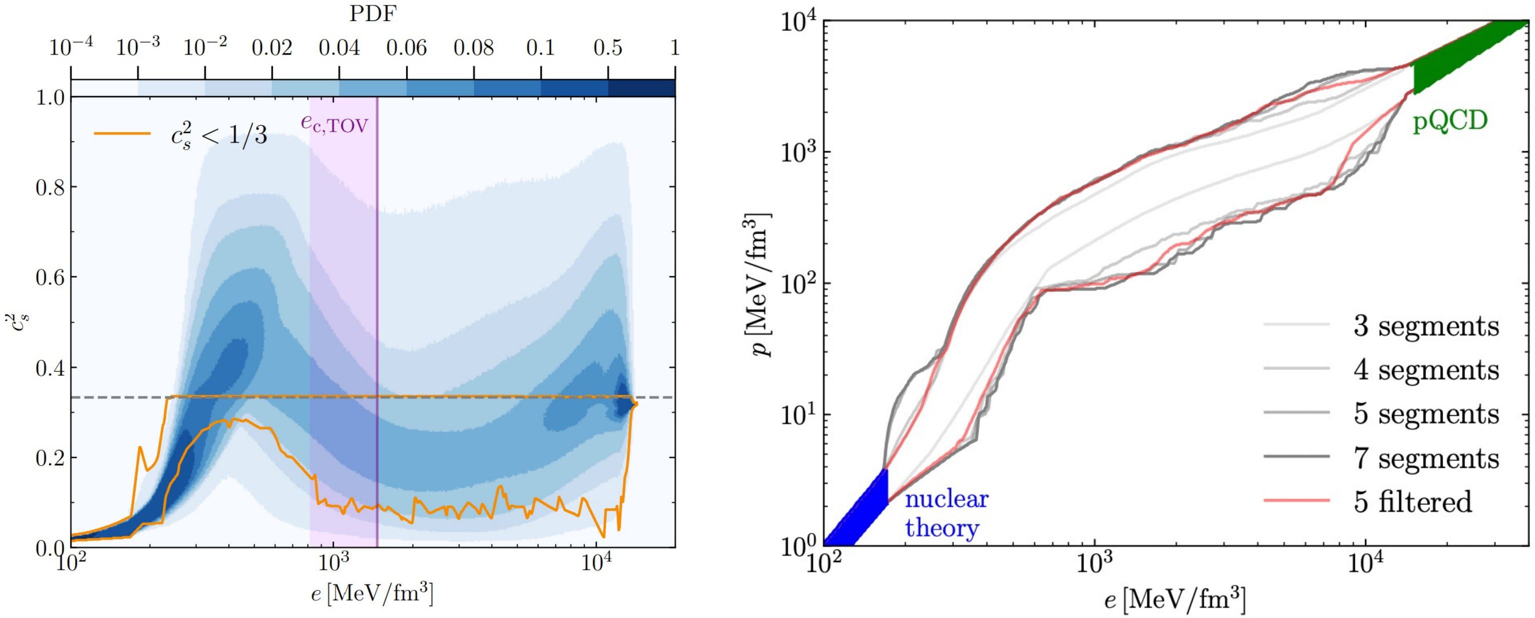


Figure from Fujimoto, Fukushima, Phys. Rev. D (2020)

Pressure



Figures from Altiparmak, Ecker, Rezzolla, ApJL (2022)

Many constraints from neutron star observations indicate a strong rise of c_s^2 beyond the conformal limit

Tews, Carlson, Gandolfi, Reddy, ApJ 860 (2018) 149;
Fujimoto, Fukushima, PRD 101 (2020) 054016;
Tang, Norohna-Hostler, Yunes, PRL 125 (2020) 261104;
Altiparmak, Ecker, Rezzolla, ApJL 939 (2022) L34;
...

QCD the cold and dense regime and quarkyonic matter

Neutron-star matter EoS based on astrophysical observations:

- Consistent with nuclear physics at low densities (neutrons)
- Perturbative QCD at high densities (quarks)
- Does not elucidate the state of matter in-between

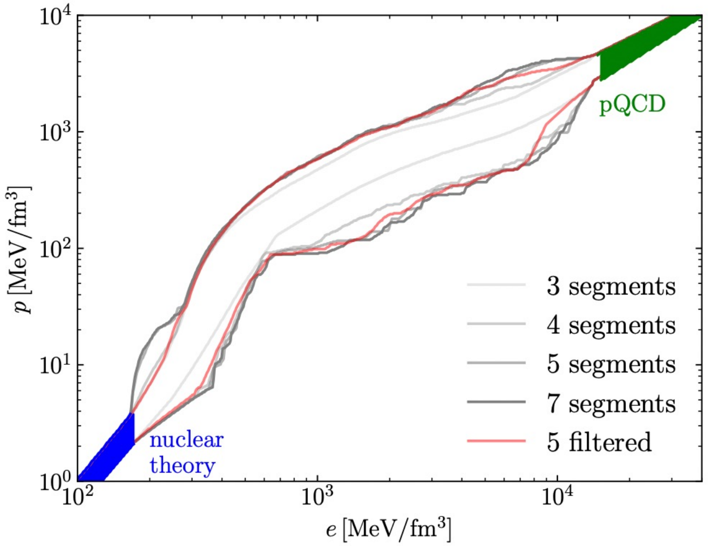


Figure from Altiparmak, Ecker, Rezzolla, ApJL (2022)

QCD the cold and dense regime and quarkyonic matter

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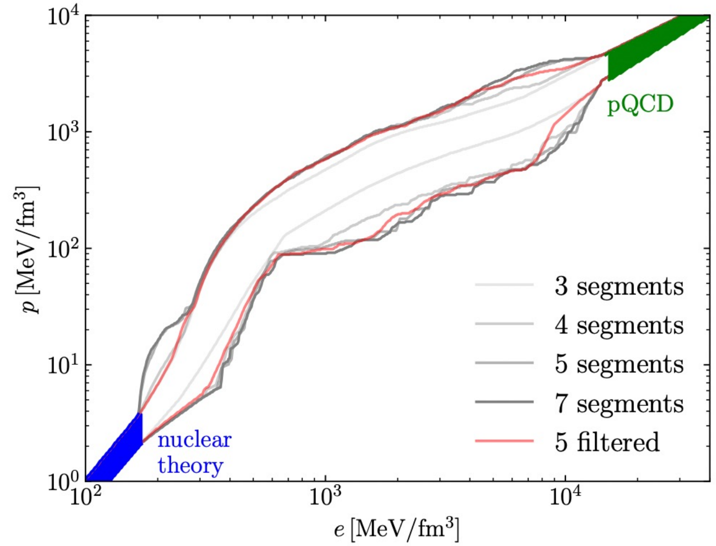


Figure from Altiparmak, Ecker, Rezzolla, ApJL (2022)

Quarkyonic matter?

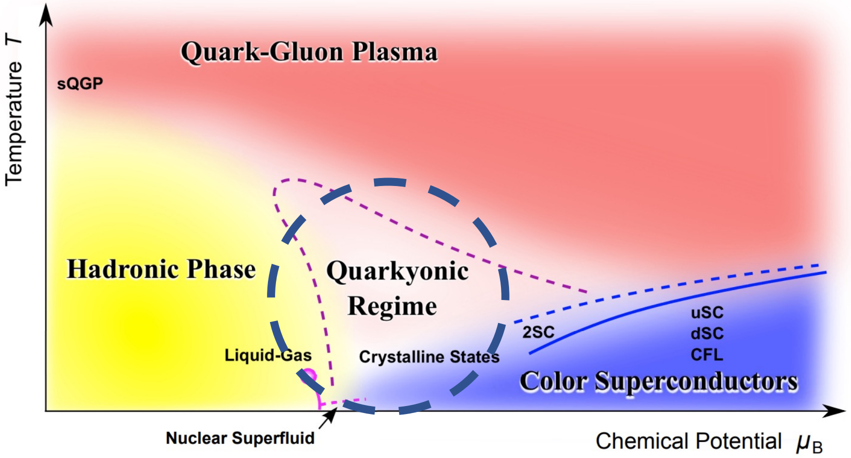
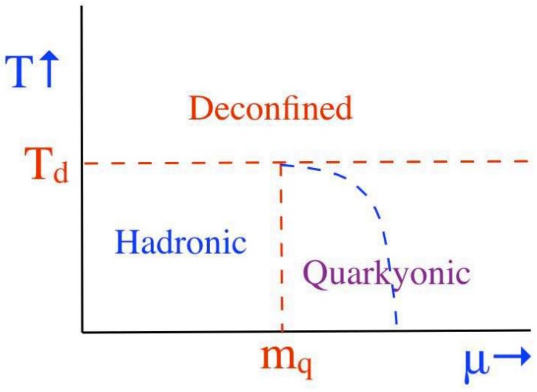


Figure adapted from Fukushima, Sasaki, PPNP '13

Large N_c



McLerran, Pisarski, NPA '07

Enter **Quarkyonic matter:** baryon-quark coexistence, baryonic excitations around the Fermi surface

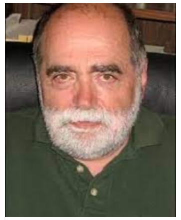
McLerran, Pisarski, NPA 796, 83 (2007)

Quarkyonic matter and neutron stars

Quasiparticle model: First(?) practical realization of quarkyonic matter (T=0)

[McLerran, Reddy, PRL 122, 122701 (2019)]

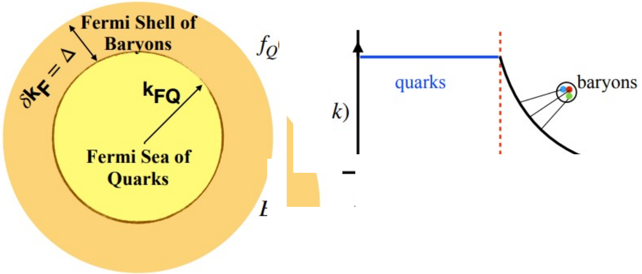
SEATTLE SUPERSONICS



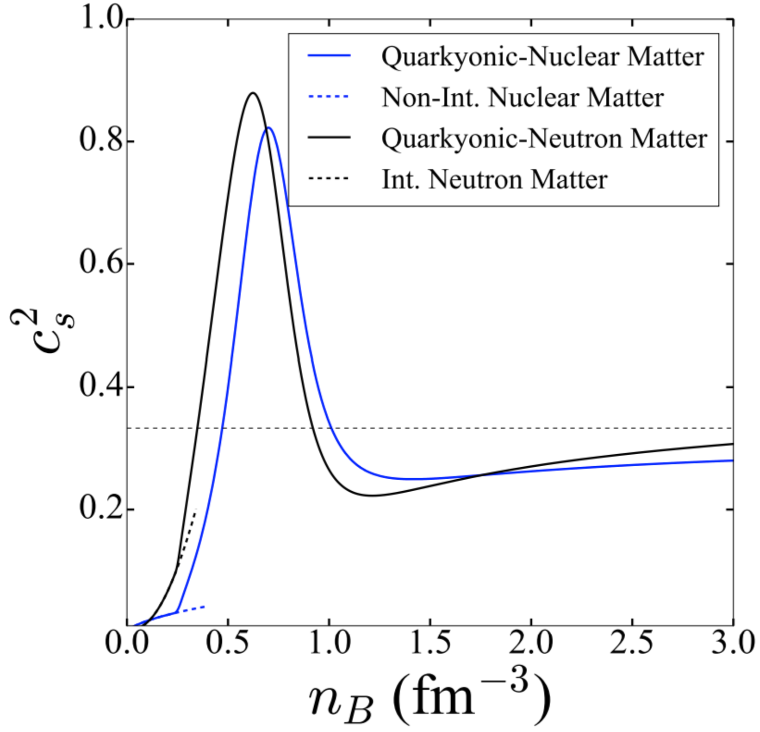
Mixture of "confined" quarks (baryons) and deconfined quarks with Pauli principle*

Enforce *momentum space shell structure* (baryonic Fermi surface) and its (parametric) density evolution

$$\Delta = \frac{\Lambda^3}{k_{\rm FB}^2} + \kappa\frac{\Lambda}{N_c^2} \qquad m_N = N_c m_Q$$



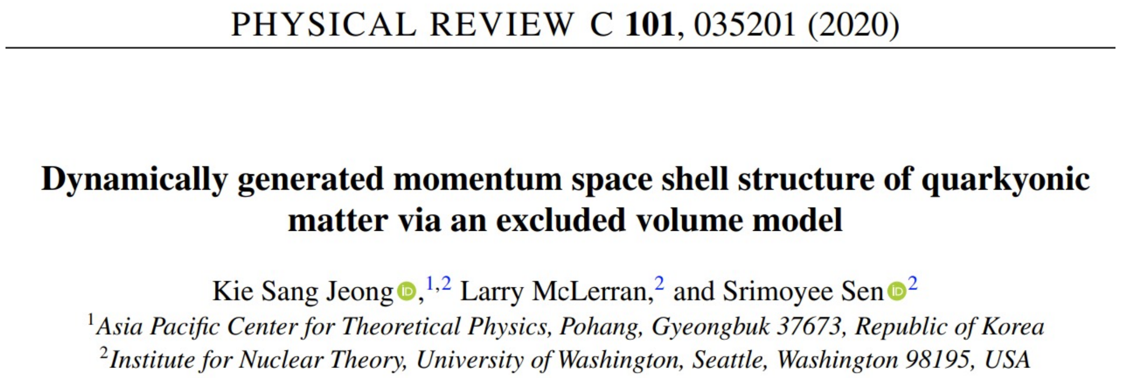
$$\varepsilon(n_B) = 4\int_{N_c k_{\rm FQ}}^{k_{\rm FB}} \frac{d^3k}{(2\pi)^3}\sqrt{k^2+M_n^2}\,,$$
$$+\,2\times N_c\int_0^{k_{\rm FQ}} \frac{d^3k}{(2\pi)^3}\sqrt{k^2+M_q^2}$$



Hallmark feature: Sound velocity peak

*Due to coinciding spin-isospin degeneracies, baryon and quark states cannot overlap

Dynamical generation of momentum space shell structure



PHYSICAL REVIEW C **101**, 035201 (2020)

Dynamically generated momentum space shell structure of quarkyonic matter via an excluded volume model

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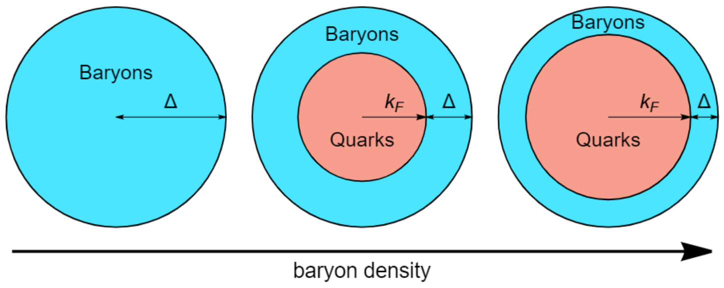
[2]*Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195, USA*

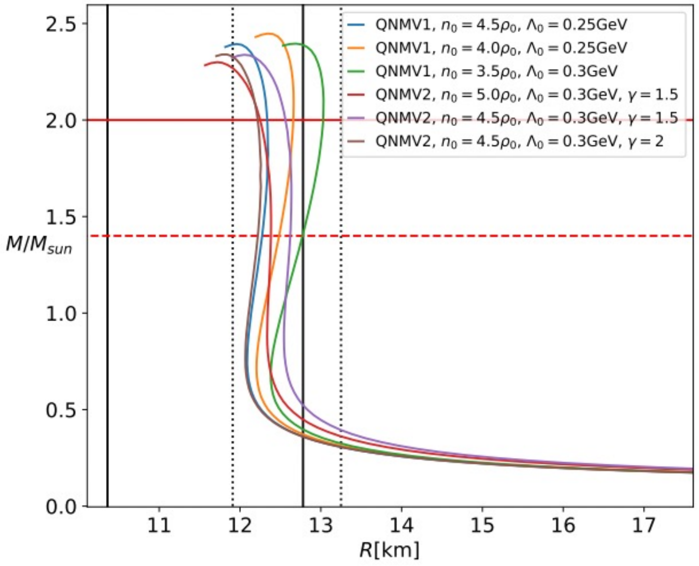


AN EXCLUDED VOLUME THEORY OF NUCLEAR INTERACTIONS

$$n_{ex}^N = \frac{n_N^N}{1 - n_N^N/n_0}$$

Minimize energy density at fixed n_B to find k_F and Δ

$$\tilde{\epsilon} = 4\left(1 - \frac{n_N^N}{n_0}\right)\int_{k_F}^{k_F+\Delta}\frac{d^3k}{(2\pi)^3}\left((N_c m_Q)^2 + k^2\right)^{\frac{1}{2}} + \frac{2Nc}{\pi^2}\int_0^{k_F/N_c} dkk\,(\Lambda^2 + k^2)^{\frac{1}{2}}\,(m_Q^2 + k^2)^{\frac{1}{2}}$$



Requires infrared regulator to avoid superluminal speed of sound

Works reasonably well for neutron stars, extendable to strange quarks

D. Duarte, S. Hernandez-Ortiz, K. Jeong, PRC 102 (2020) 025203; PRC 102 (2020) 065202
S. Sen, L. Sivertsen, ApJ 915, 109 (2021)

Quarkyonic matter and nuclear matter

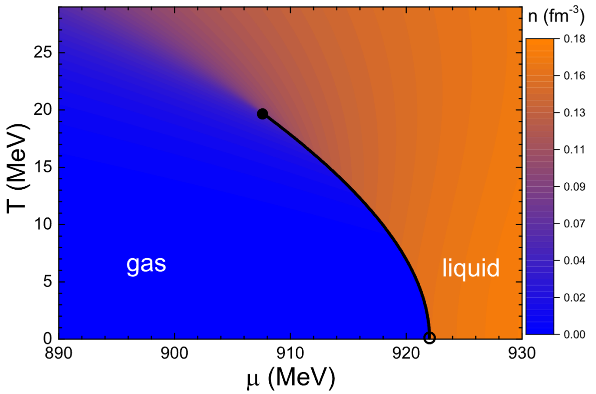
Quantum van der Waals model:

excluded-volume (repulsion) + mean-field (attraction)

yields a simple model describing nuclear liquid-gas transition

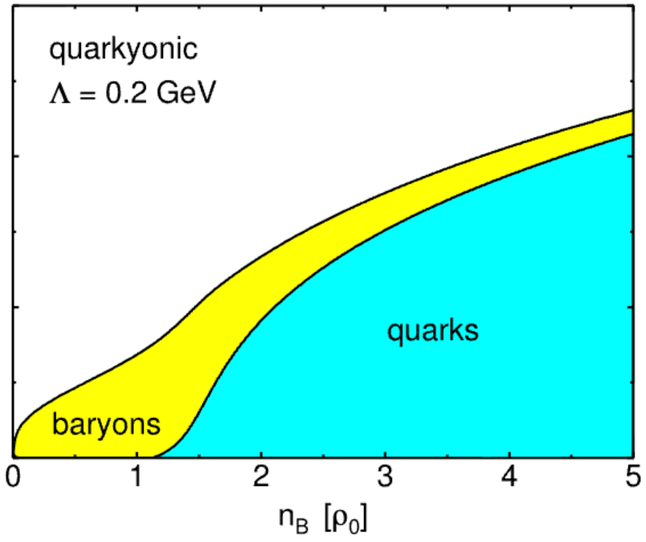
$$n_N = f(n_N)\, n_N^{\mathrm{id}}(k_F), \qquad f_{\mathrm{vdW}}(n_N) = 1 - b n_N$$

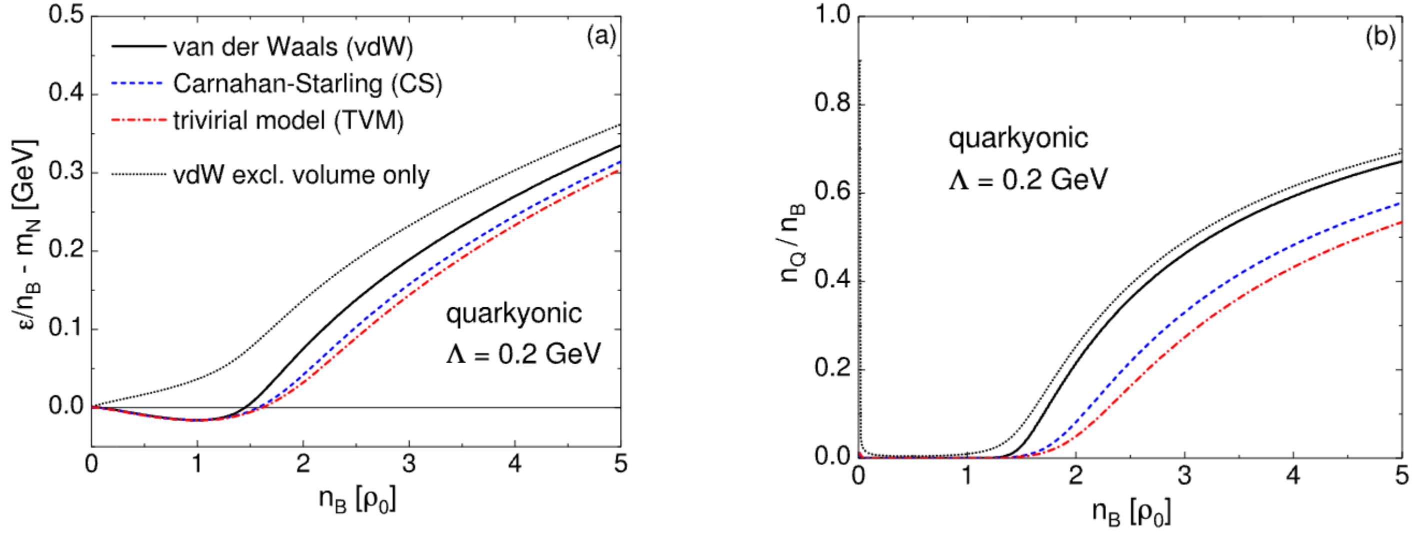
$$\varepsilon_N = f(n_N)\, \varepsilon_N^{\mathrm{id}}(k_F) + n_N\, u(n_N), \qquad u(n_N) = -a n_N$$



[VV, Anchishkin, Gorenstein, PRC 91, 064314 (2015)]

Implementing momentum shell structure *predicts* the onset of quarkyonic matter at 1.5-2n$_0$





Correlations between incompressibility and onset of quarks

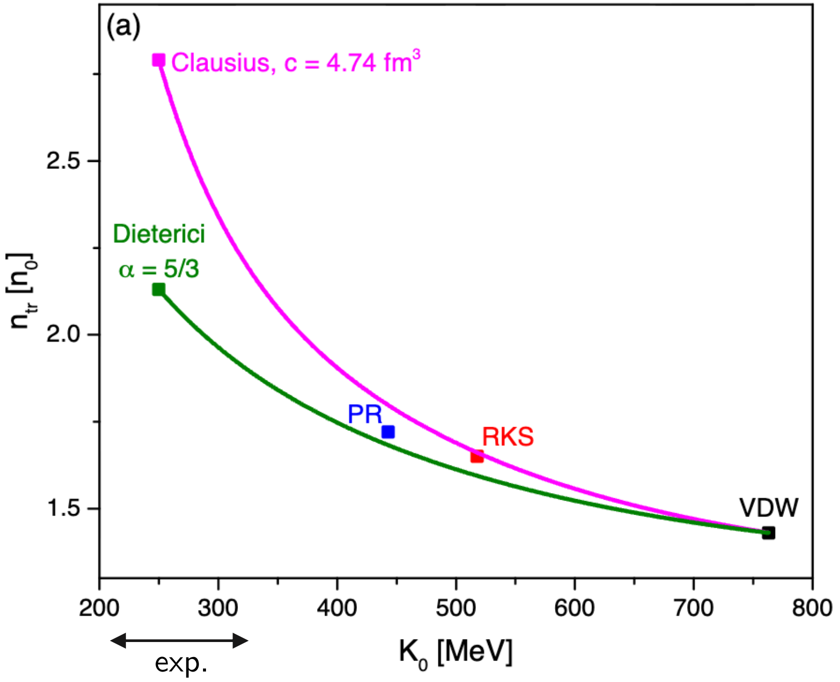
Bare quantum van der Waals model overshoots nuclear incompressibility

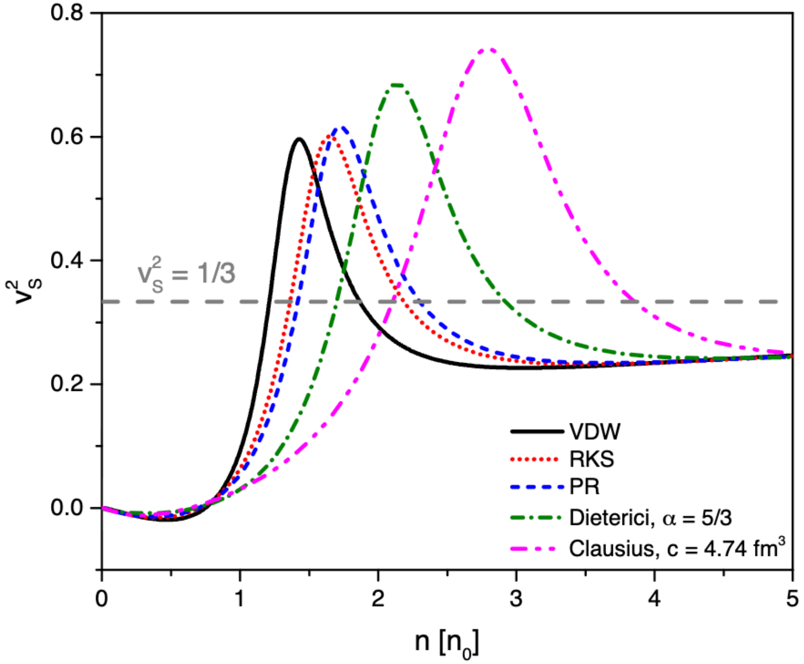
Consider variations of the QvdW model by employing non-linear mean fields

$$u_{\rm VDW}(n) = -an \,, \quad u_{\rm RKS}(n) = -\frac{a}{b}\,\ln(1+bn)\,,$$

$$u_{\rm PR}(n) = -\frac{a}{2\sqrt{2}b}\,\ln\frac{1+bn+\sqrt{2}bn}{1+bn-\sqrt{2}bn}\,,$$

$$u_{\rm C}(n) = -\frac{an}{1+cn}\,, \quad u_{\rm D}(n) = -\,a\frac{n^{\alpha-1}}{\alpha-1}\,.$$



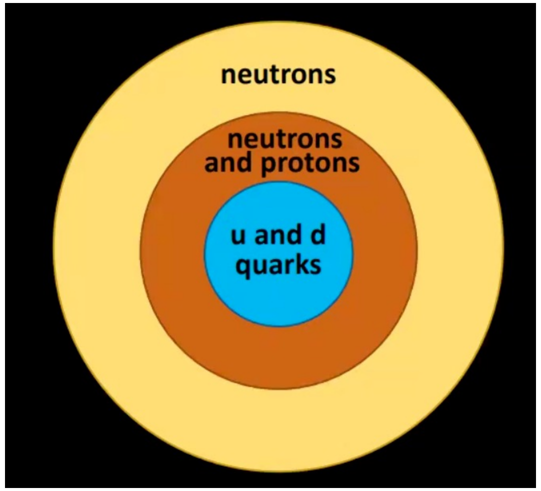


Lysenko, Gorenstein, Moss, Poberezhniuk, VV, PRC 111, 035204 (2025)

- lower incompressibility → onset of quarks at higher densities (n_{tr} = 2-2.7n_0)

Quarkyonic matter at non-zero isospin asymmetry

Asymmetric nuclear matter: proton (charge) fraction 0<y<1 $y = \frac{\rho_Q}{\rho_B}$



Nuclear phase: mixture of protons and neutrons

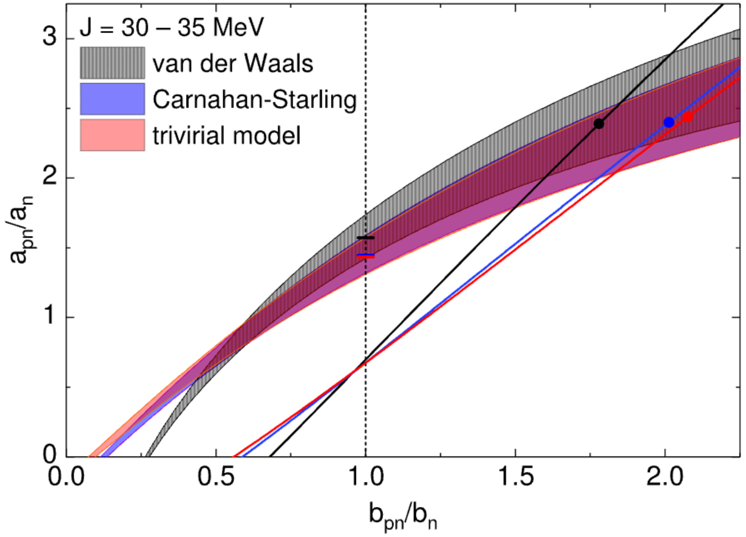
- Isospin-like (a_p, b_p) and isospin-unlike (a_{pn}, b_{pn}) int. parameters
- y = ½: symmetric matter for $a = (a_n + ap_n)/2$ and $b = (b_n + bp_n)/2$
- Mode 1: $b_n = b_{pn}$; a_n and a_{pn} from $J = 32$ MeV
- Mode 2: $b_n \neq b_{pn}$; constraints from $J = 32$ MeV and L = 59 MeV

Quark phase: mixture of *u* and *d* quarks

Quarkyonic regime

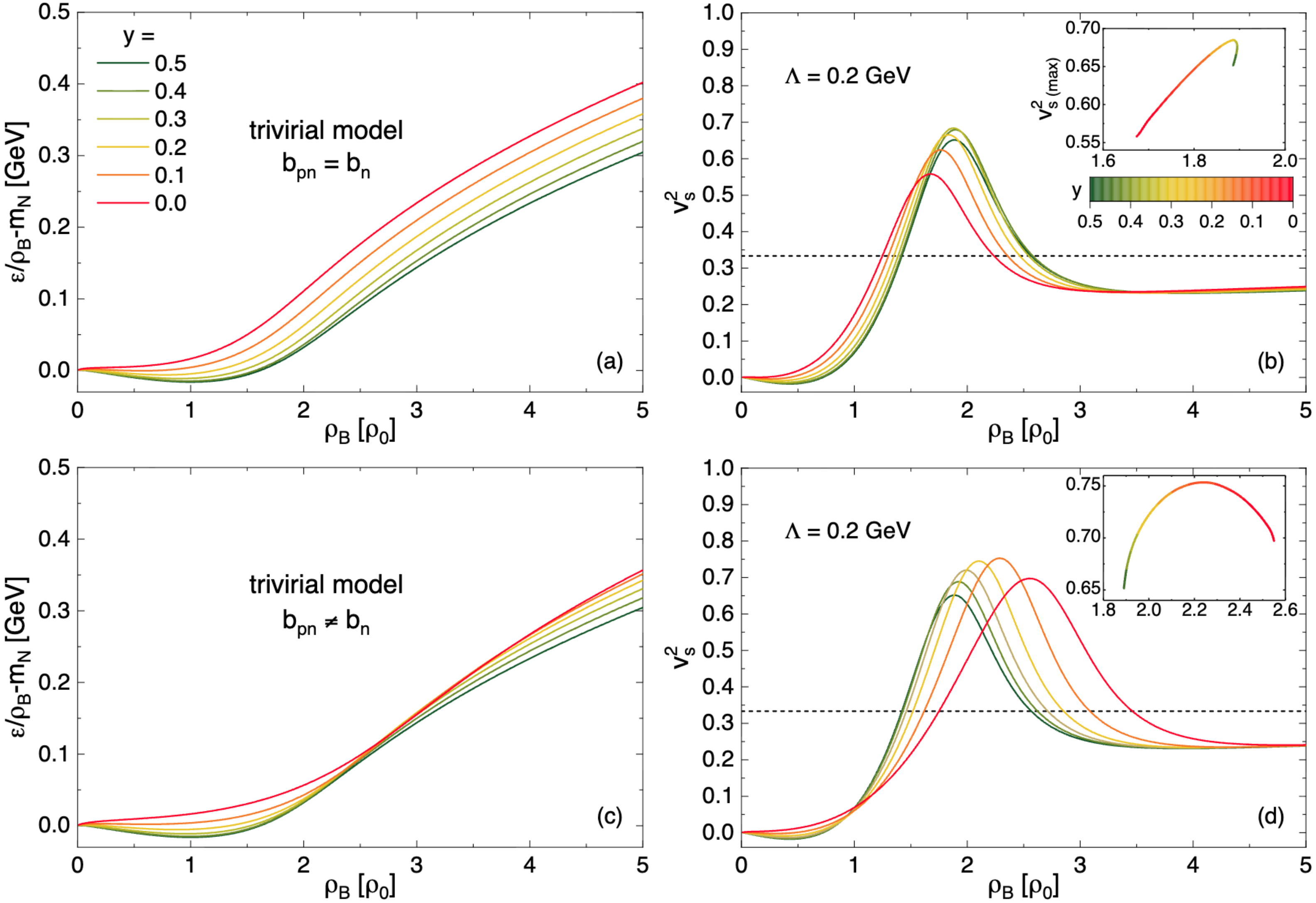
- *u* and *d* quarks share the same Fermi surface (quark-hadron duality)
- charge fraction enforced both in the nucleon and quark sector

$$y = \frac{\rho_Q}{\rho_B} = \frac{n_p}{n_p + n_n} = \frac{\frac{2}{3}n_u - \frac{1}{3}n_d}{\frac{1}{3}n_u + \frac{1}{3}n_d}$$



Moss, Poberezhniuk, VV, PRC 111, 025803 (2025)

Quarkyonic matter at non-zero isospin asymmetry



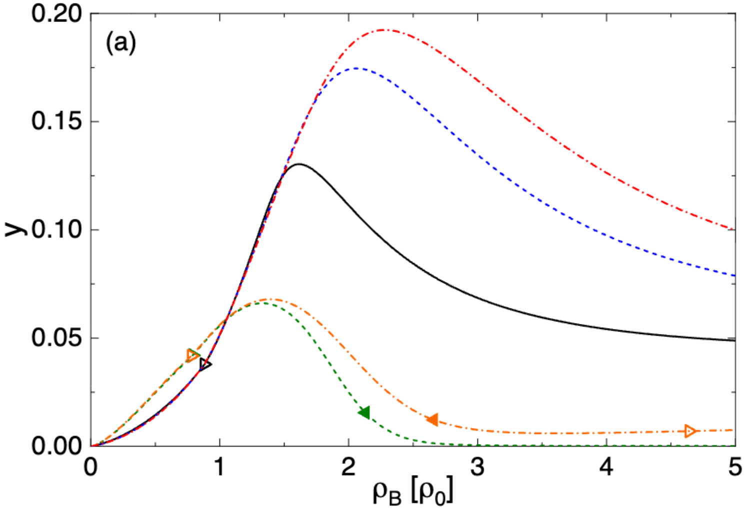
Moss, Poberezhniuk, VV, PRC 111, 025803 (2025)

Quarkyonic matter and neutron stars

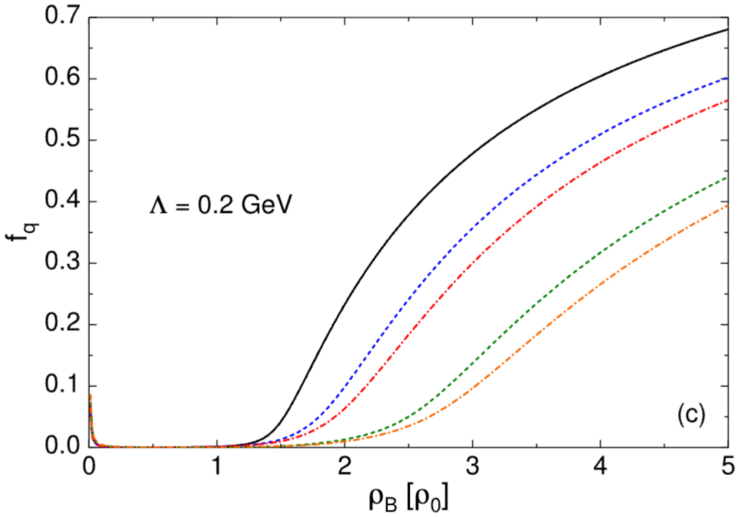
Neutron-star matter: add leptons and enforce beta-equilibrium conditions

$$\rho_e(k_F^e) + \rho_\mu(k_F^\mu) = \rho_Q(y, \rho_B)$$

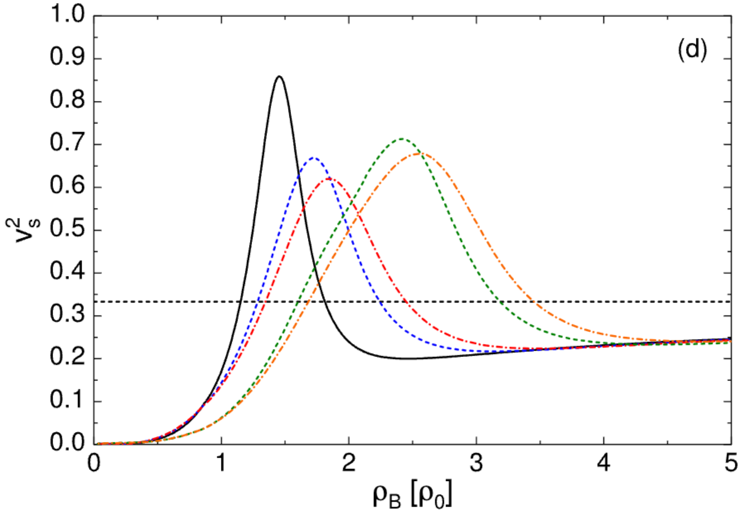
isospin asymmetry



quark fraction

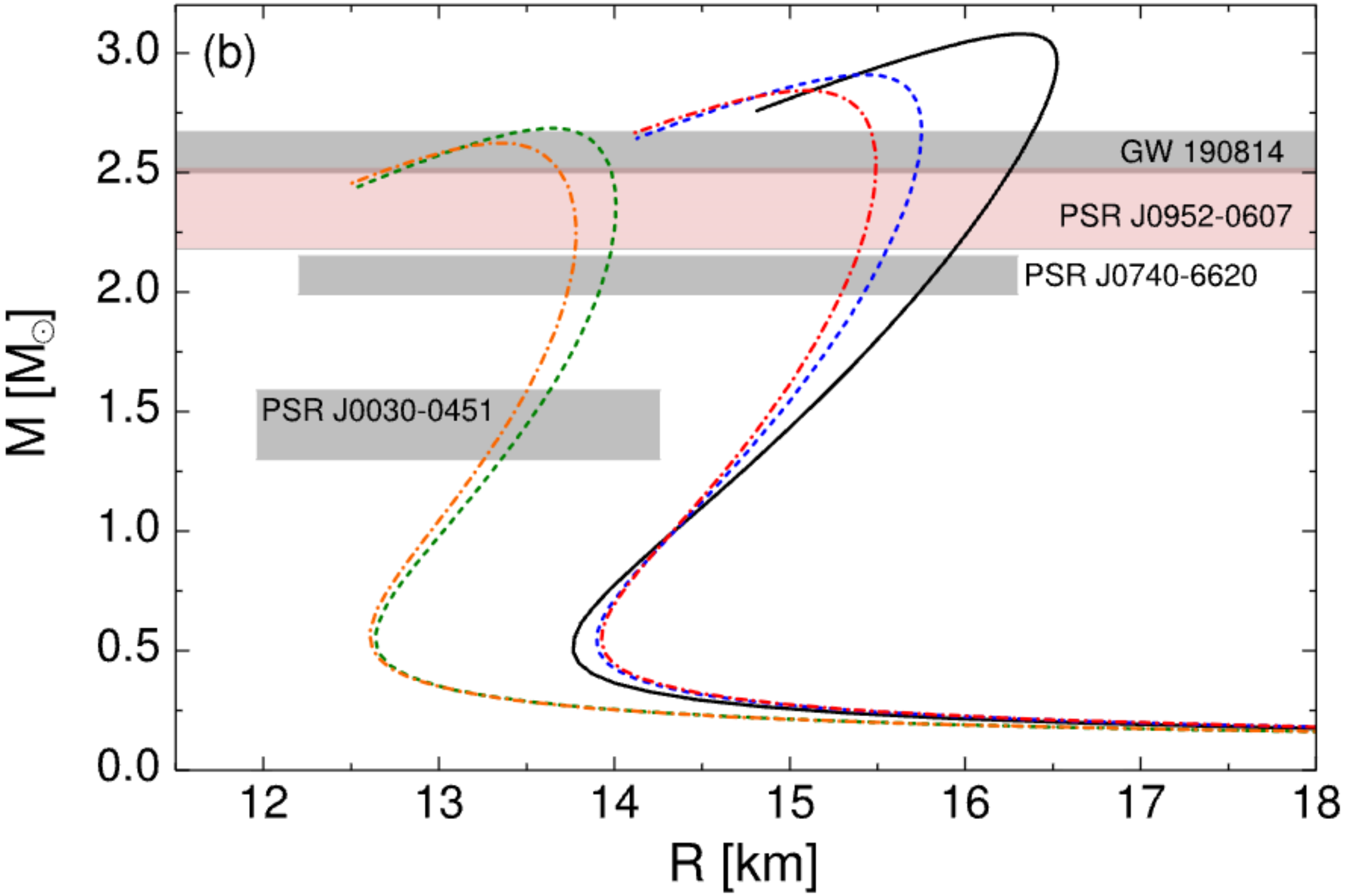


sound velocity



Moss, Poberezhniuk, VV, PRC 111, 025803 (2025)

Quarkyonic matter and neutron stars



Quarkyonic matter supports heavy neutron stars

Moss, Poberezhniuk, VV, PRC 111, 025803 (2025)

Quarkyonic or baryquark matter?

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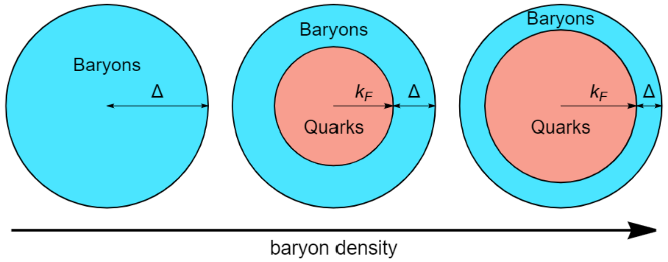
Consider opposite scenarios for the realization of Pauli exclusion principle in baryon-quark mixture

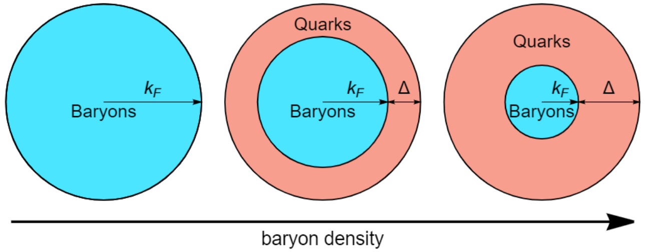
Quarkyonic



$$n_B = n_N + n_Q$$

$$\varepsilon = \varepsilon_N + \varepsilon_Q$$

Baryquark



$$n_Q = \frac{2}{\pi^2}\int_0^{k_F/N_c} dk\, k^2 = \frac{2\,k_F^3}{3\pi\, N_c^3}$$

$$n_N = f_{\rm ev}\int_{k_F}^{k_F+\Delta} dk\, k^2 = f_{\rm ev}\frac{2[(k_F+\Delta)^3 - k_F^3]}{3\pi^2}$$

$$\varepsilon_Q = \frac{2N_c}{\pi^2}\int_0^{k_F/N_c} dk\, k^2\sqrt{m_Q^2+k^2},$$

$$\varepsilon_N = f_{\rm ev}\frac{2}{\pi^2}\int_{k_F}^{k_F+\Delta} dk\, k^2\sqrt{m_N^2+k^2}.$$

$$n_Q = \frac{2}{\pi^2}\int_{k_F/N_c}^{(k_F+\Delta)/N_c} dk\, k^2 = \frac{2\left[(k_F+\Delta)^3 - k_F^3\right]}{3\pi\, N_c^3}$$

$$n_N = f_{\rm ev}\frac{2}{\pi^2}\int_0^{k_F} dk\, k^2 = f_{\rm ev}\frac{2\,k_F^3}{3\pi}.$$

$$\varepsilon_Q = \frac{2N_c}{\pi^2}\int_{k_F/N_c}^{(k_F+\Delta)/N_c} dk\, k^2\sqrt{m_Q^2+k^2}$$

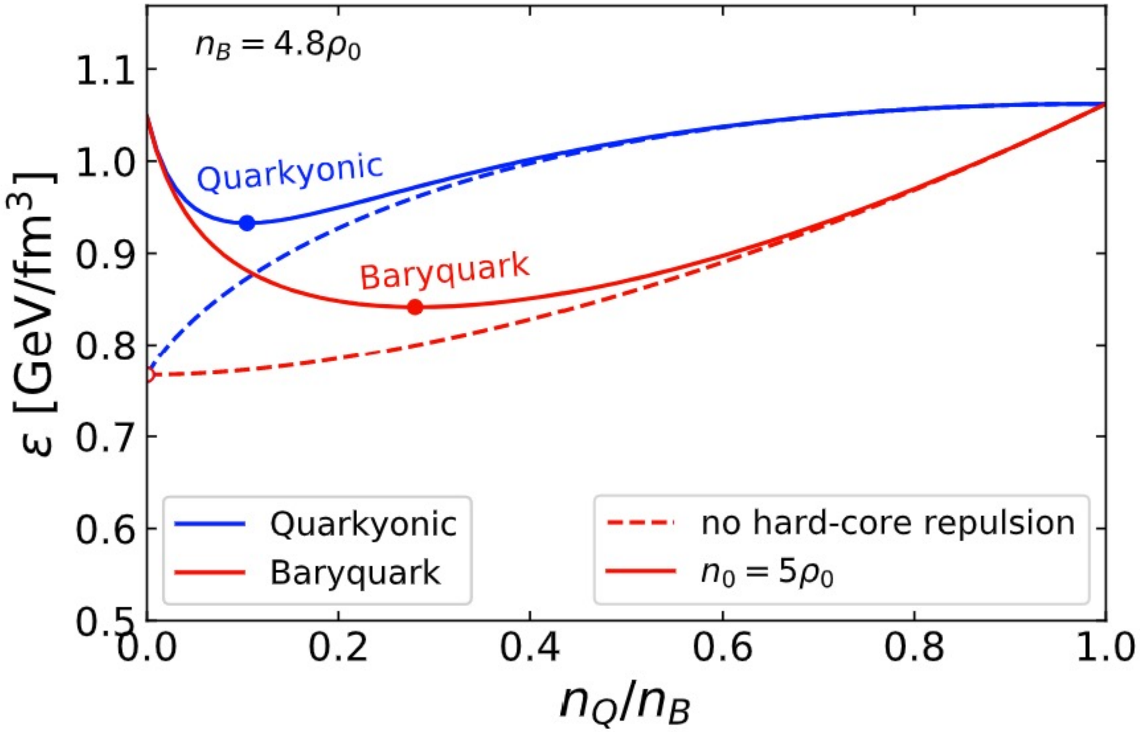
$$\varepsilon_N = f_{\rm ev}\frac{2}{\pi^2}\int_0^{k_F} dk\, k^2\sqrt{m_N^2+k^2}.$$

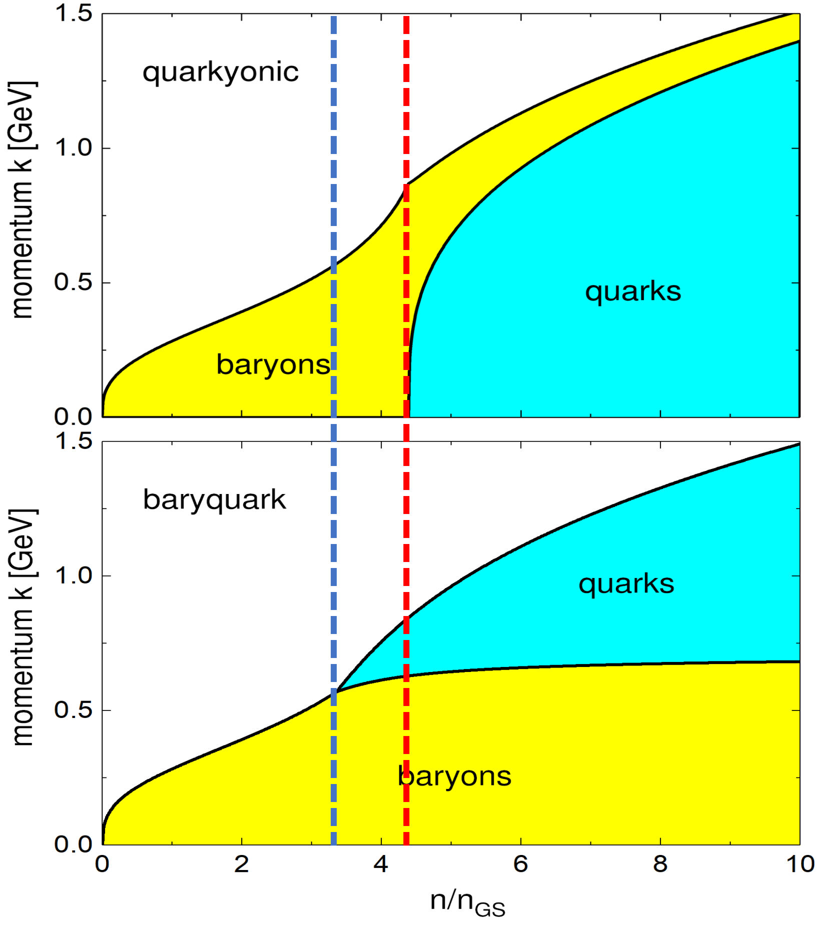
$$f_{\rm ev} = (1 - n_N/n_0)$$

V. Koch, VV, Phys. Lett. B 841, 137942 (2023)

Quarkyonic vs baryquark matter: energy minimization

At each baryon density n_B minimize energy density wrt to quark fraction n_Q/n_B





- Baryquark scenario is preferred in quasiparticle picture
  - Adding quarks to the surface is energetically favorable
- Resulting equation of state is similar: driven by the appearance of quarks

V. Koch, VV, Phys. Lett. B 841, 137942 (2023)

Resolution: IdylliQ model with explicit duality

Explicit duality: describe baryon density either in terms baryon or quarks

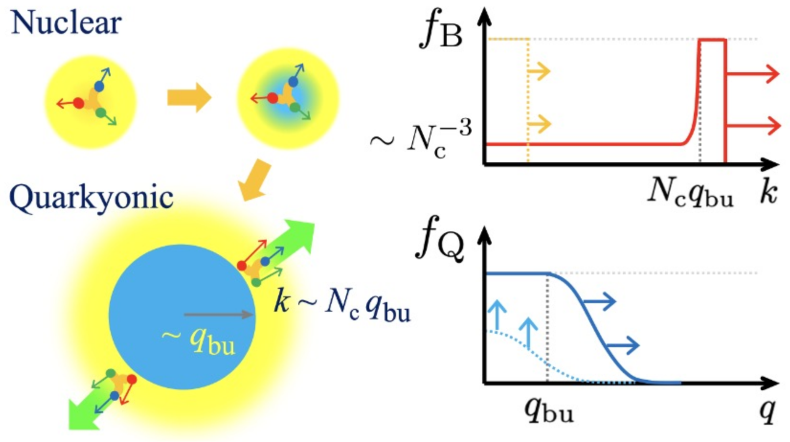
$$n_{\mathrm{B}} = 4\int_k f_{\mathrm{B}}(k) = 4\int_q f_{\mathrm{Q}}(q)$$

Quark momentum distribution inside a nucleon with momentum k: $\phi_N(q - \frac{k}{N_c})$

Quark occupation number $$f_Q(p) = \int \frac{d^3k}{(2\pi)^3}\varphi(|p - k/N_c|)f_N(k)$$

Pauli principle: $f_Q(q) \leq 1$

Quark substructure of the nucleon leads to the emergence of quarkyonic distribution once $\mathrm{f_Q}(0) = 1$

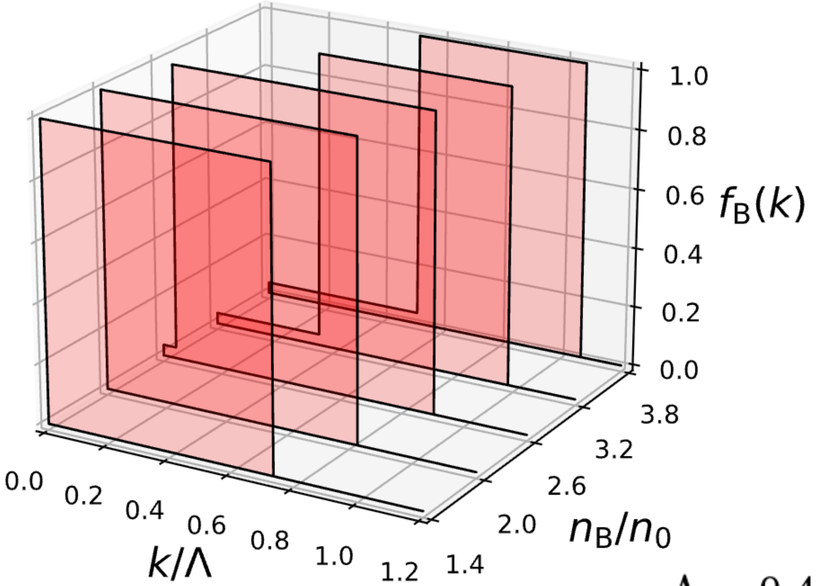


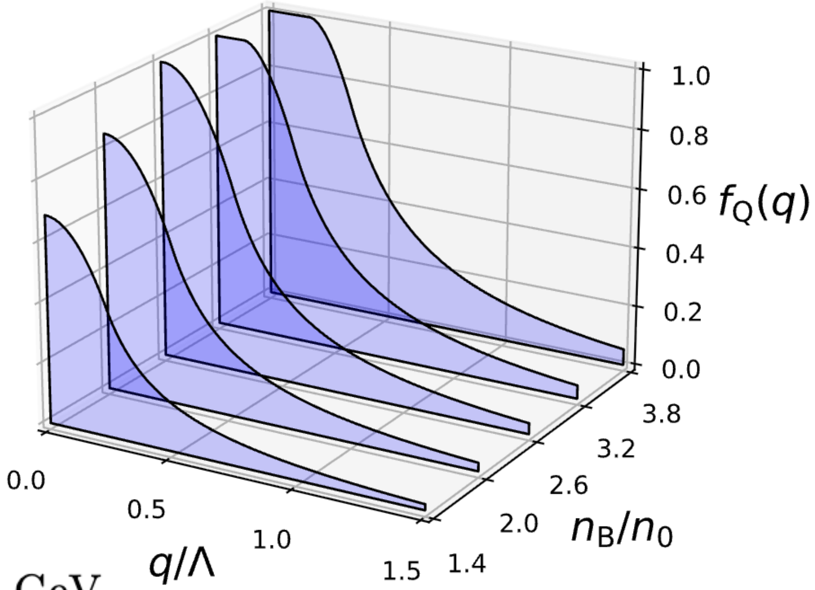
Fujimoto, Kojo, McLerran, Phys. Rev. Lett. 132, 112701 (2024)

Quarkyonic vs baryquark matter: momentum shell structure

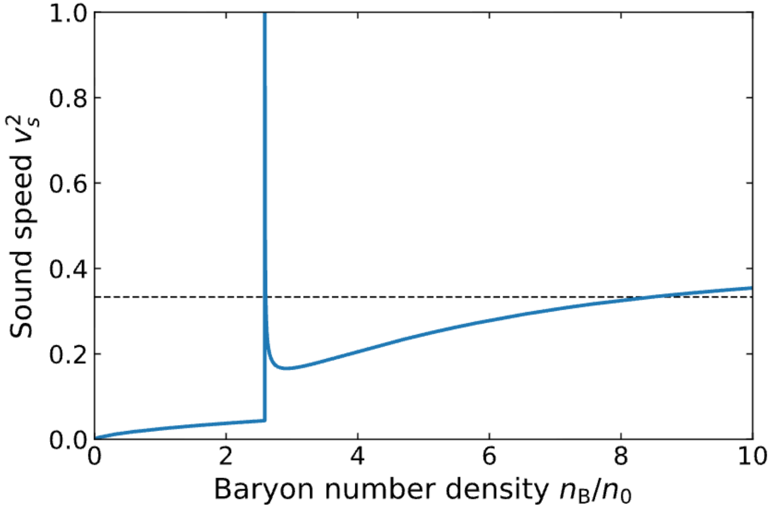
Thermodynamics: minimize energy density subject to constraint $f_Q(q) \leq 1$

Exactly solvable for Yukawa-type kernel $$\varphi_{3\mathrm{d}}(\boldsymbol{q}) = \frac{2\pi^2}{\Lambda^3}\frac{e^{-q/\Lambda}}{q/\Lambda}$$





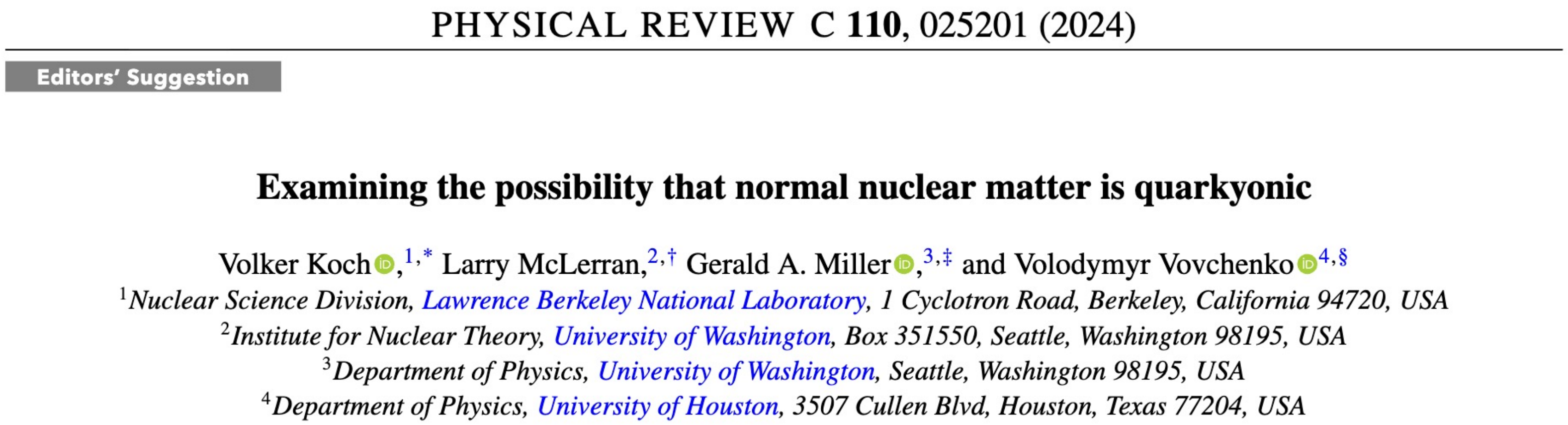
$\Lambda = 0.4$ GeV



$$f_p(k) = f_n(k) = \frac{1}{N_c^3}\Theta(k_{\mathrm{bu}} - k) + \Theta(k_{\mathrm{sh}} - k)\Theta(k - k_{\mathrm{bu}})$$

Fujimoto, Kojo, McLerran, Phys. Rev. Lett. 132, 112701 (2024)

Might normal nuclear matter be quarkyonic?


PHYSICAL REVIEW C **110**, 025201 (2024)

Editors' Suggestion

Examining the possibility that normal nuclear matter is quarkyonic

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Consider quark momentum saturation condition in the IdylliQ picture $1 = f_Q(0) = \int_{k<k_F^{\mathrm{crit}}} \frac{d^3k}{(2\pi)^3} \varphi(k/N_c) f_N(k)$

with Gaussian kernel $\varphi_{\mathrm{gauss}}(p) = 8\pi^{3/2} R^3 e^{-p^2R^2}$

Estimates: critical Fermi momentum for quark saturation k^F_{crit} is comparable to the nuclear Fermi gas momentum $k^F_{NM} \approx 265$ MeV for a reasonable choice of $\mathrm{r_{rms}}$.

For RMS = 1 fm: $f_Q(q=0) = 1$ for $\rho_{crit} = 1.1\rho_0$, for RMS = 0.8 fm: $\rho_{crit} = 2.2\rho_0$

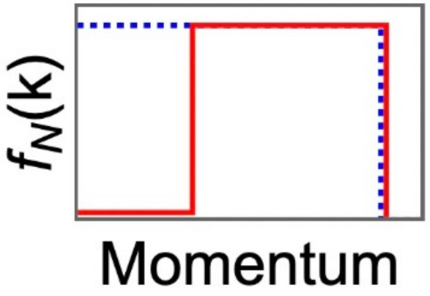
Koch, McLerran, Miller, VV, Phys. Rev. C 110, 025201 (2024)

Calculations using realistic quark transverse momentum distributions (TMDs) suggest $\rho_{crit} = 0.17 \pm 0.04\ \mathrm{fm}^3$

McLerran, Miller, Phys. Rev. C 110, 045203 (2024)

IdylliQ Sigma Model

Adopt baryon occupation numbers predicted by the IdylliQ model



symmetric matter $$f_p(k) = f_n(k) = \frac{1}{N_c^3}\Theta(k_{\rm bu} - k) + \Theta(k_{\rm sh} - k)\Theta(k - k_{\rm bu})$$

pure neutron matter $$f_p(k) = 0, \qquad f_n(k) = \frac{3}{2}\,\frac{1}{N_c^3}\Theta(k_{\rm bu} - k) + \Theta(k_{\rm sh} - k)\Theta(k - k_{\rm bu})$$

$$n_B = \frac{\gamma_s}{2\pi^2}\int dk\, k^2\,[f_p(k) + f_n(k)],$$

Energy density includes mean field, and sigma and pion exchange contributions

$$\varepsilon(n_B) = \varepsilon_K + \varepsilon_{\rm MF} + \varepsilon_{\rm exch}^{\sigma} + \varepsilon_{\rm exch}^{\pi}$$

$$\varepsilon_K = \frac{\gamma_s}{2\pi^2}\int dk\, k^2\sqrt{k^2 + m_N^2}\,[f_p(k) + f_n(k)],$$

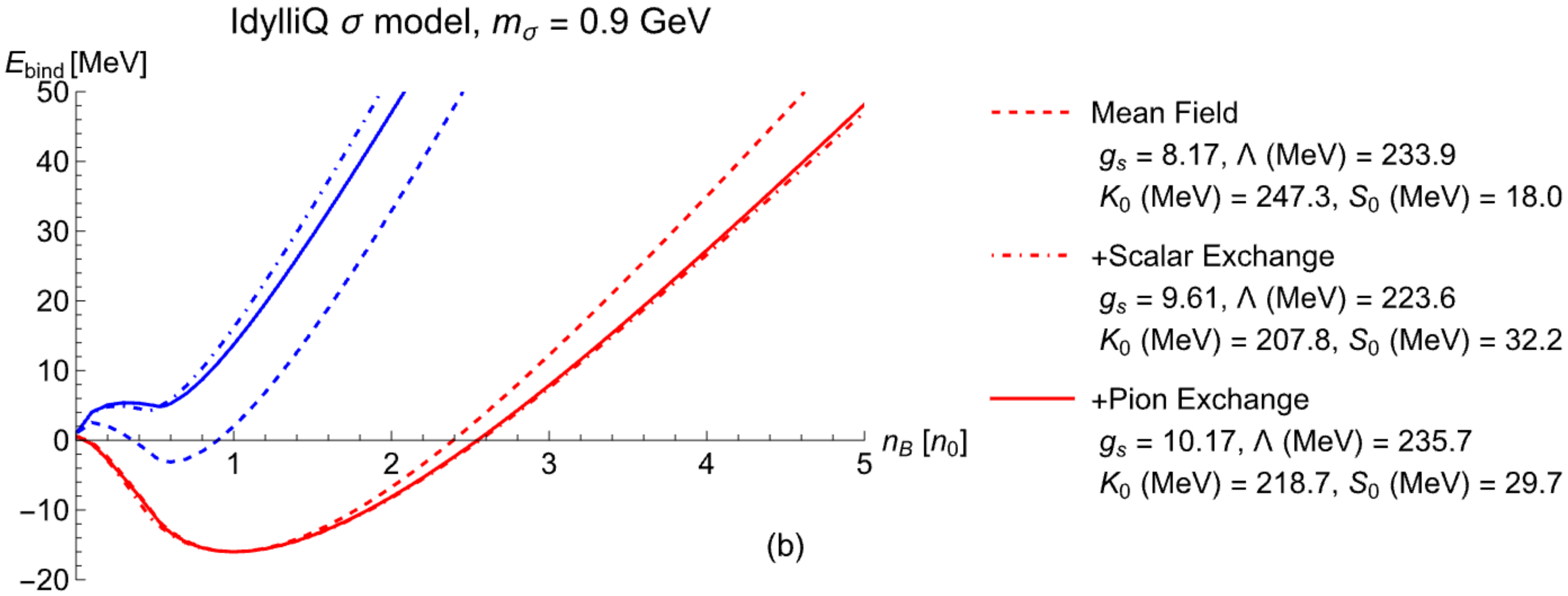
$$n_s = \frac{\gamma_s}{2\pi^2}\int dk\, k^2\,\frac{m_N}{\sqrt{k^2 + m_N^2}}\,[f_p(k) + f_n(k)].$$

$$\varepsilon_{\rm MF} = -\frac{g_s^2}{2m_\sigma^2}n_s^2,$$

Contrast to the Walecka model: vector (ω) repulsion replaced by quark Pauli principle

Koch, McLerran, Miller, VV, Phys. Rev. C 110, 025201 (2024)

IdylliQ Sigma Model: Equation of state

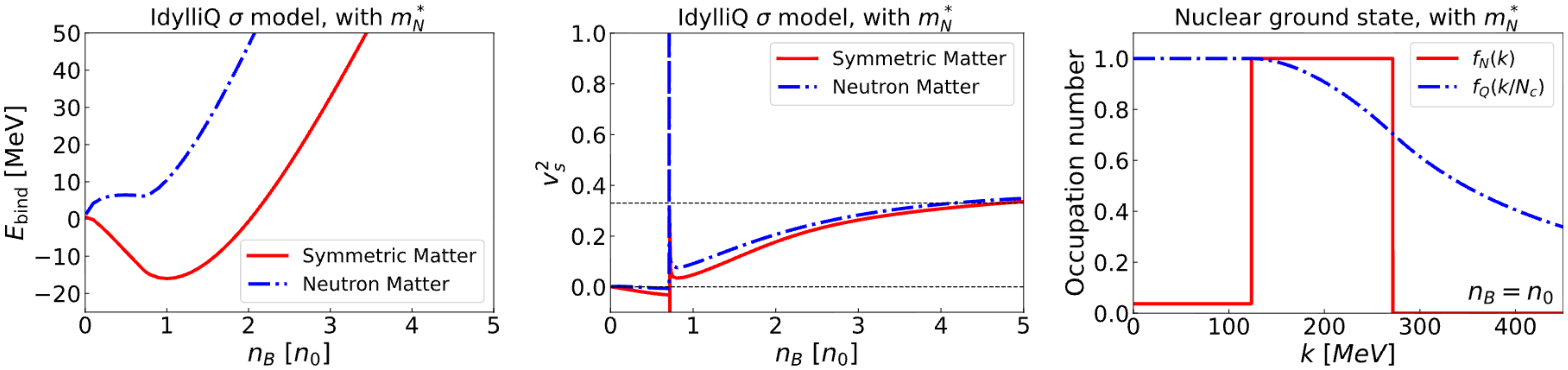


Repulsion needed to describe saturation generated entirely by the quark Pauli principle

Reasonable *predicted* values of incompressibility and symmetry energy

Koch, McLerran, Miller, VV, Phys. Rev. C 110, 025201 (2024)

IdylliQ Sigma Model



Koch, McLerran, Miller, VV, Phys. Rev. C 110, 025201 (2024)

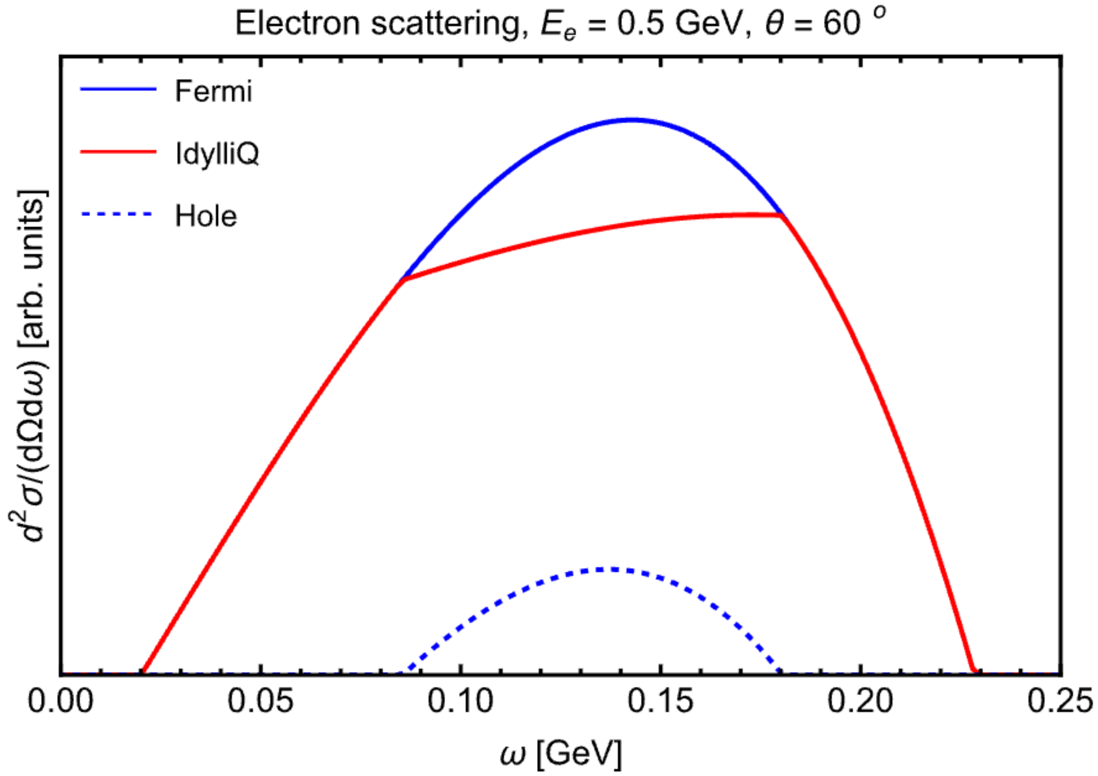
Extensions to strangeness: quark Pauli principle may delay the appearance of hyperons and resolve the hyperon puzzle

Fujimoto, Kojo, McLerran, arXiv:2410.22758

Quasielastic electron scattering

Quasielastic (e, e′) electron scattering from nuclei provides information about nucleon momentum distributions

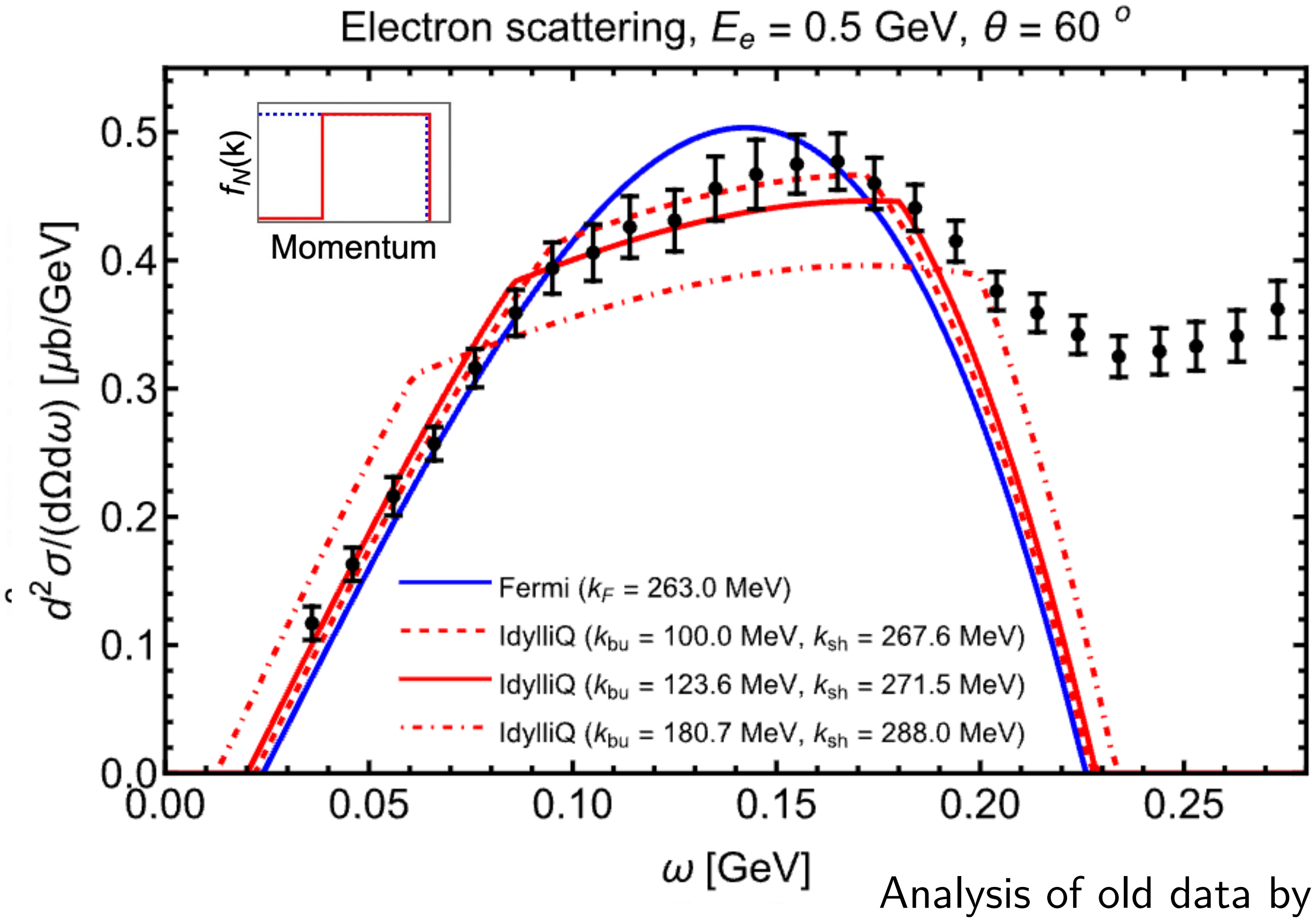
Quarkyonic scenario: Recalculate with nucleon distributions containing the hole at $k < k_{bu}$



Depletion of low-nucleon momenta modifies the shape of the scattering peak

Koch, McLerran, Miller, VV, Phys. Rev. C 110, 025201 (2024)

Quasielastic electron scattering: comparing to data

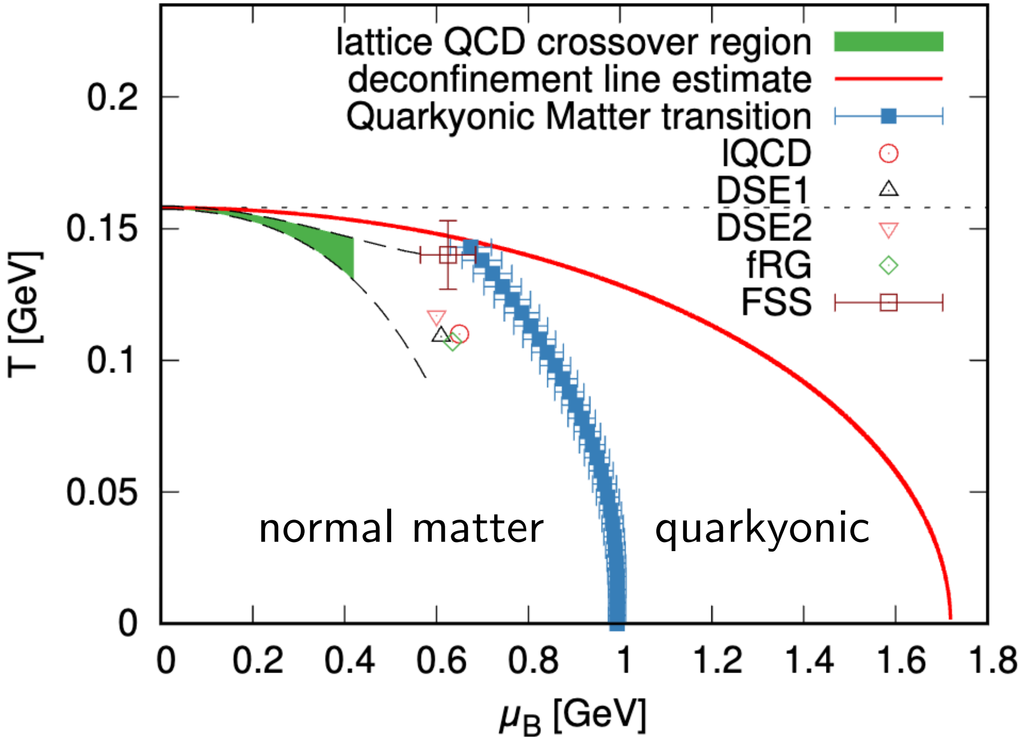


Analysis of old data by Day et al., PRC (1989)

Analysis at higher energies hindered by final-state effects

Koch, McLerran, Miller, VV, Phys. Rev. C 110, 025201 (2024)

Outlook: Quarkyonic matter in the QCD phase diagram



Bluhm, Fujimoto, McLerran, Nahrgang, Phys. Rev. C 111, 044914 (2025)

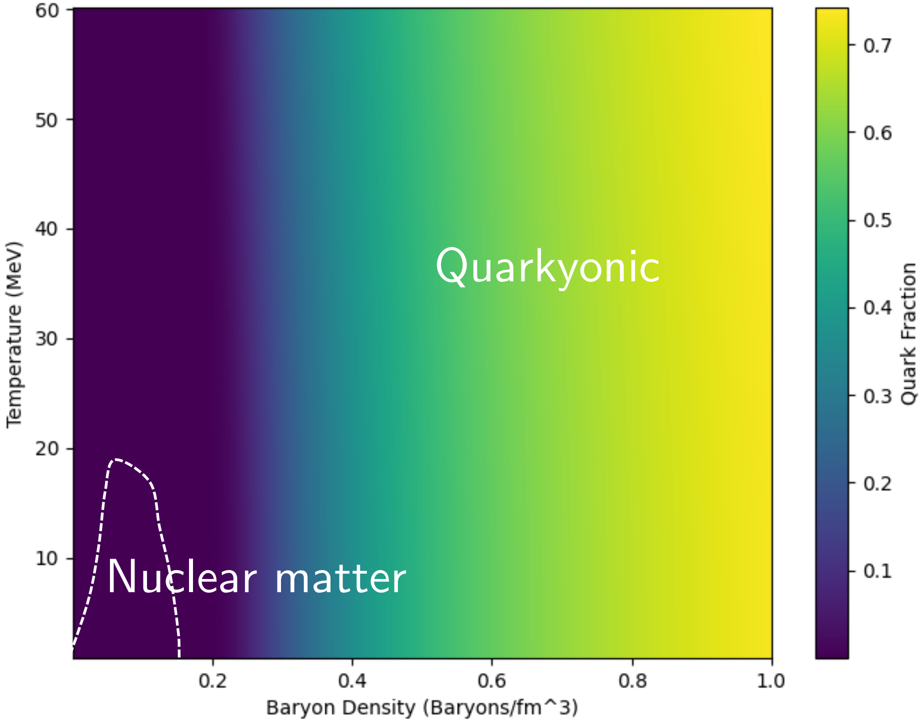
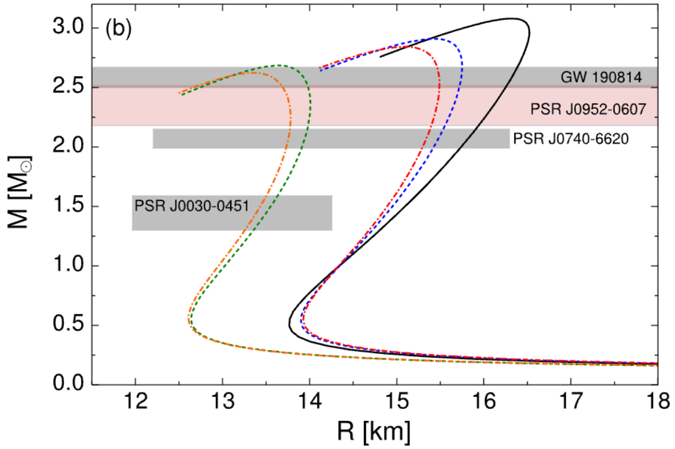
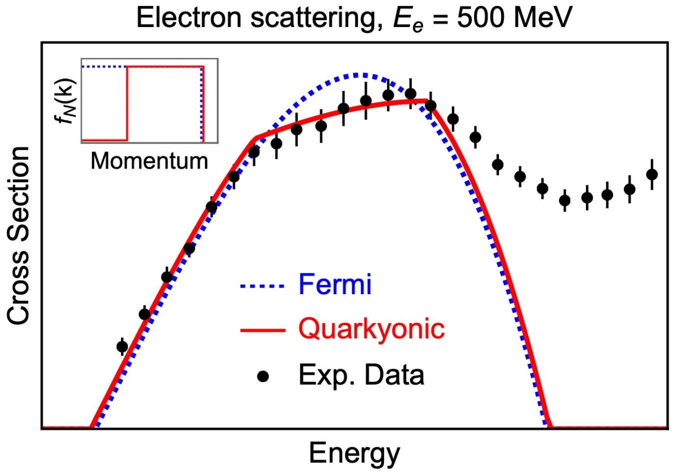


Figure courtesy of T. Moss (UH)

Summary

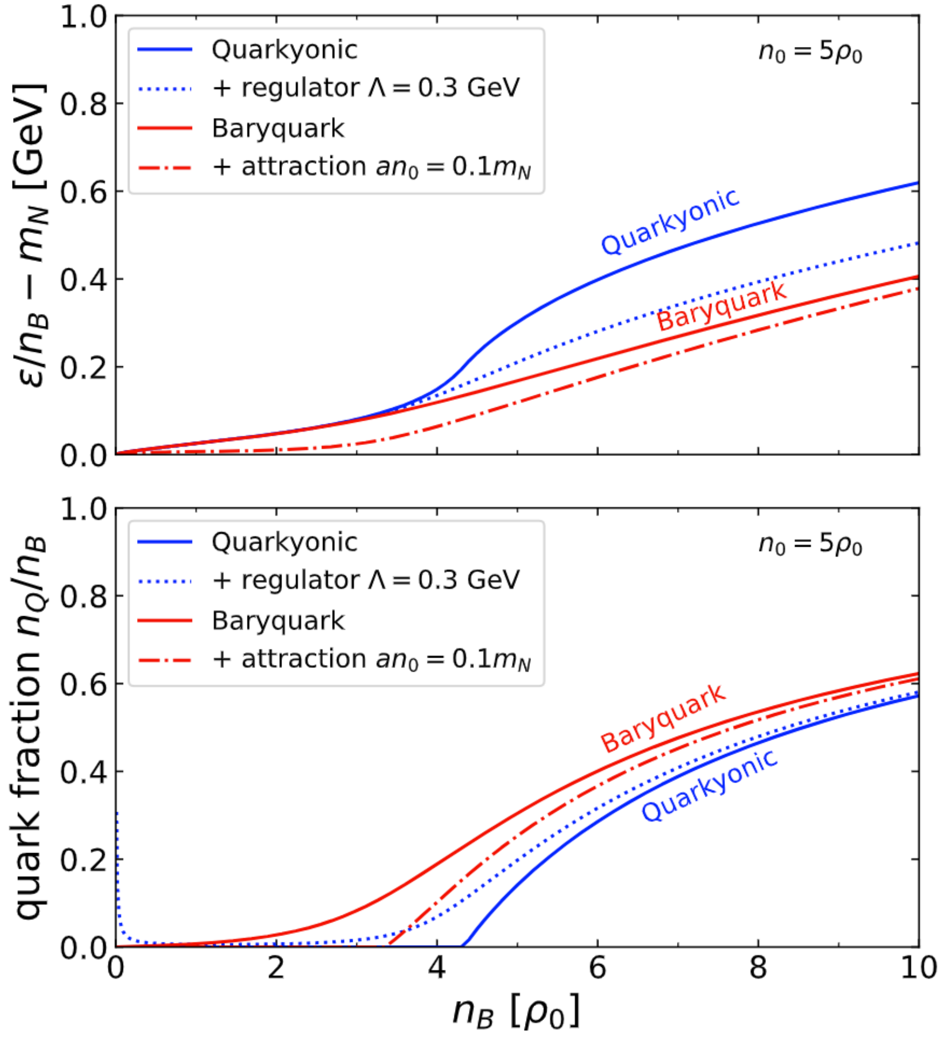
- Two approaches to quarkyonic matter
- Quasiparticle picture: quark-nucleon mixed phase of in momentum space
  - Repulsive interactions lead to emergence of quarkyonic matter at increased density
  - Matching to low-density nuclear matter predicts the transition at 2-2.5n_0
  - Leads to peak in the sound velocity and heavy neutron stars (up to 2.6M_{solar})
- Quarkyonic matter in normal nuclear matter from quark-hadron duality
  - Quark Pauli principle leads to effective repulsion
  - Including sigma and pion interactions leads to realistic nuclear matter
  - Hole in nuclear Fermi sea in nuclear ground state?
- Outlook:
  - Signatures of low-momentum baryon depletion in heavy nuclei
  - Finite-temperature extension and application to heavy-ion collisions and neutron-star mergers





Thanks for your attention!

Quarkyonic vs baryquark matter: equation of state



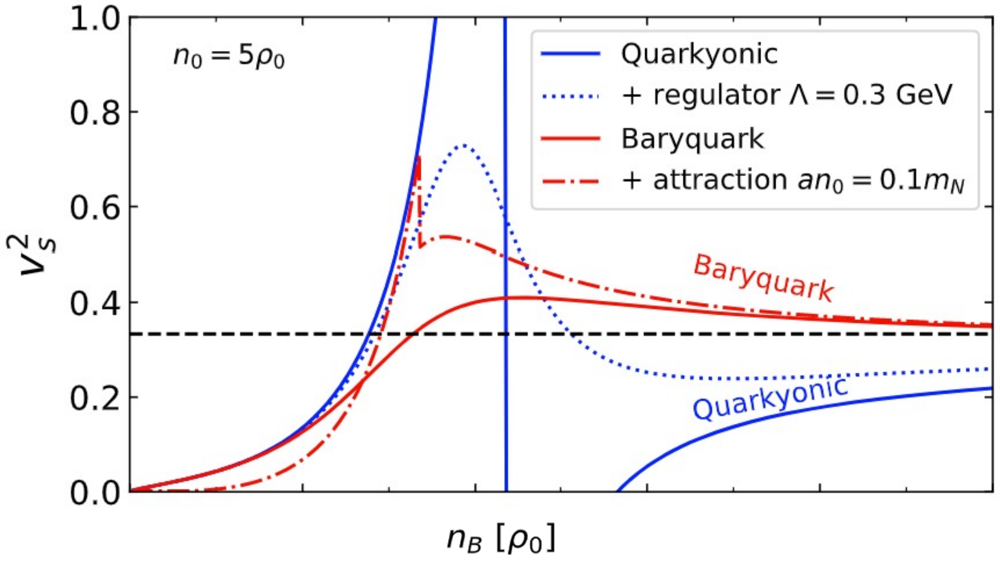
- For most parameter setups the quark onset corresponds to a 2nd-order phase transition

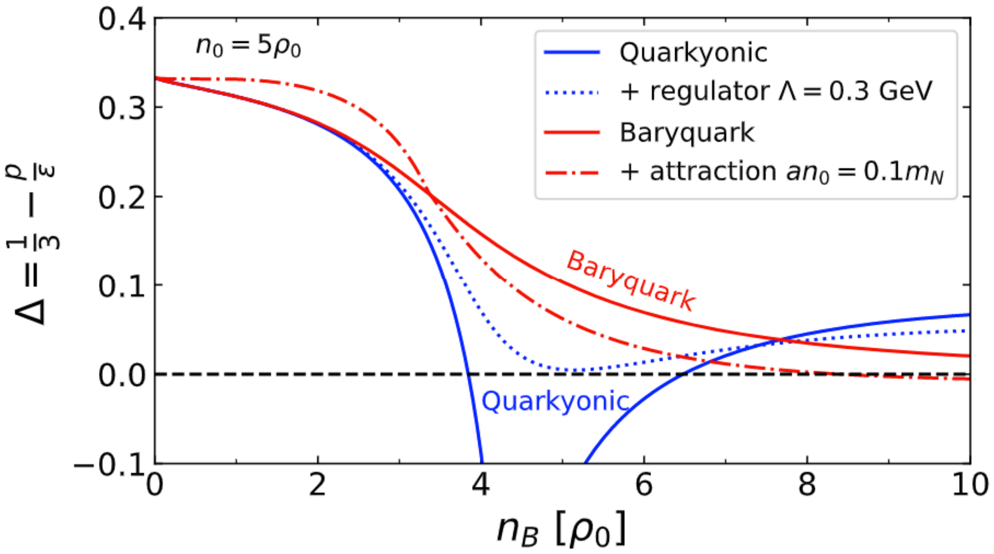
- "Early" appearance of quarks
  - In baryquark matter likely an artifact of missing nucleon attraction, $\varepsilon_N \to \varepsilon_N - a n_N^2$
  - In quarkyonic matter appears due to infrared regulator

- Infrared regulator does not make quarkyonic energetically favored over baryquark

V. Koch, VV, Phys. Lett. B 841, 137942 (2023)

Quarkyonic vs baryquark: speed of sound, conformality





- In quarkyonic matter need to introduce regulator to obtain physically acceptance speed of sound
- In baryquark matter the behavior is acceptable without the need to introduce regulators
- The speed of sound exceeds the conformal limit ($c_s^2 = 1/3$) in all cases
- Trace anomaly: exceeding the conformal limit ($\varepsilon = 3p$) is less obvious

V. Koch, VV, Phys. Lett. B 841, 137942 (2023)

Outlook: Neutron-star baryquark matter

Isospin-symmetric matter:

- same # of protons (uud) and neutrons (udd)
- Fermi surfaces of u & d quarks coincide

Pure neutron matter:

- Neutrons (udd) only → nud-matter
- charge neutrality ($n_u = 2n_d$)
- different Fermi surfaces for u & d quarks

Mass-radius relation