Quarkyonic or Baryquark matter?

On the dynamical generation of momentum space shell structure

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Based on V. Koch, VV, arXiv:2211.14674

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QCD phase diagram

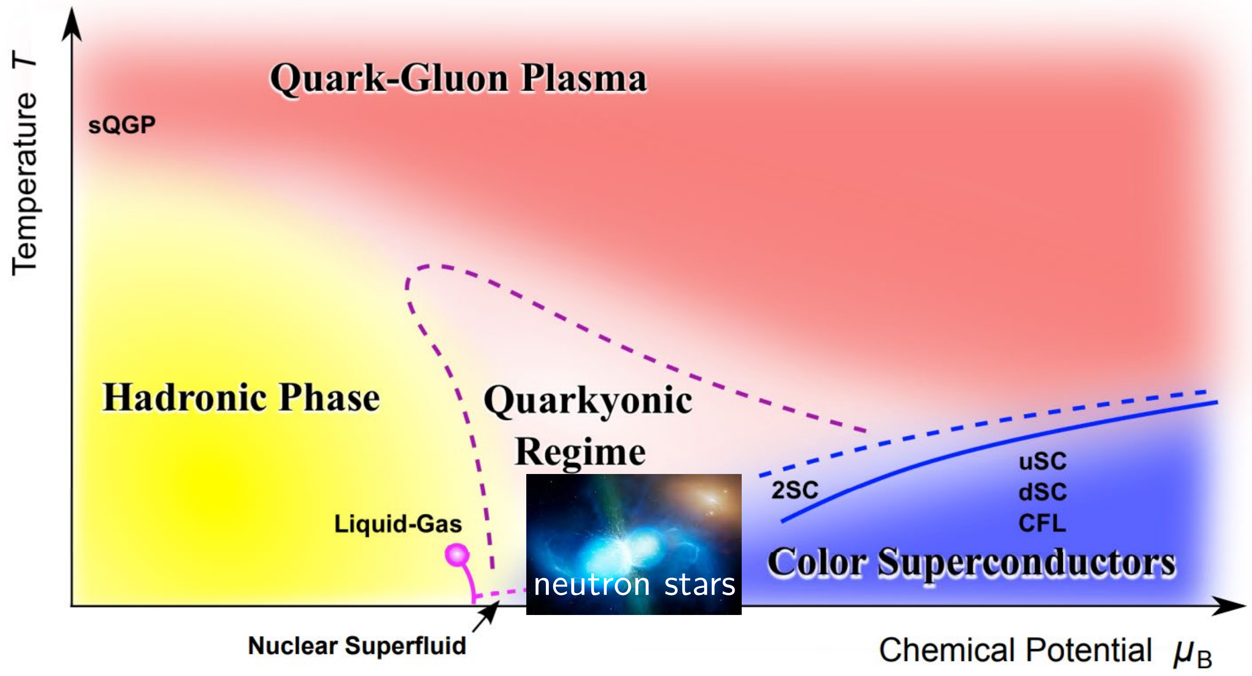
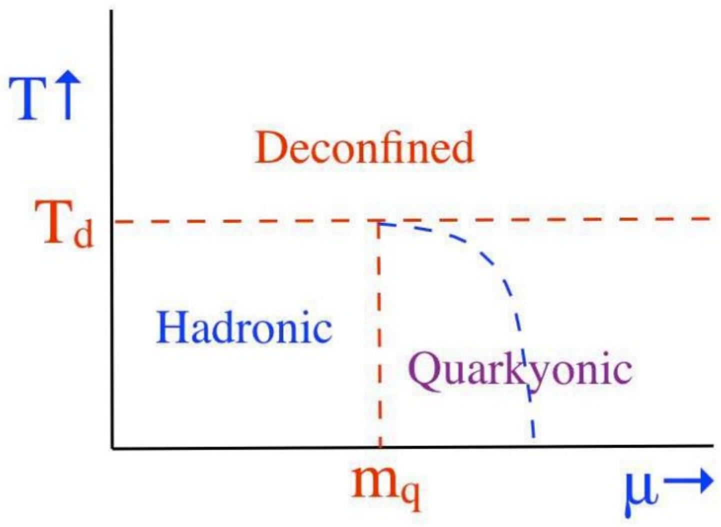


Figure adapted from Fukushima, Sasaki, PPNP '13

Large N_c



McLerran, Pisarski, NPA '07

- Low $\rho_{B,}$ meson-dominated, (crossover) transition to QGP at ~const T~160 MeV
- Large ρ_B, baryon-dominated, transition to quarkyonic(?) matter at ~const $\rho_B \sim$ several ρ_0
- **Quarkyonic matter:** baryon-quark coexistence, baryonic excitations around the Fermi surface

McLerran, Pisarski, NPA 796, 83 (2007)

QCD EoS in the cold and dense regime from neutron stars

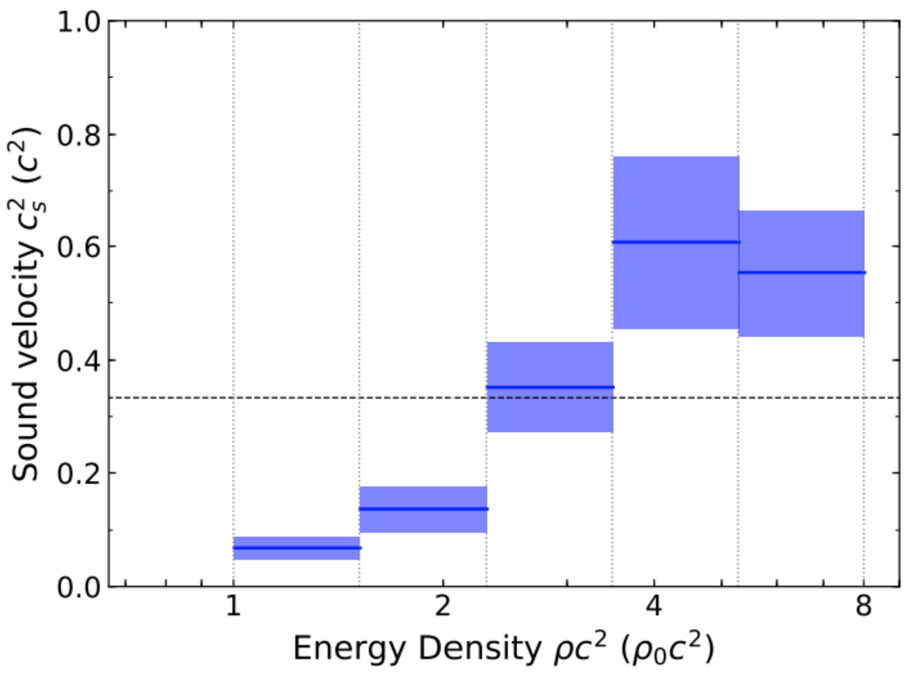


Figure from Fujimoto, Fukushima, Phys. Rev. D (2020)

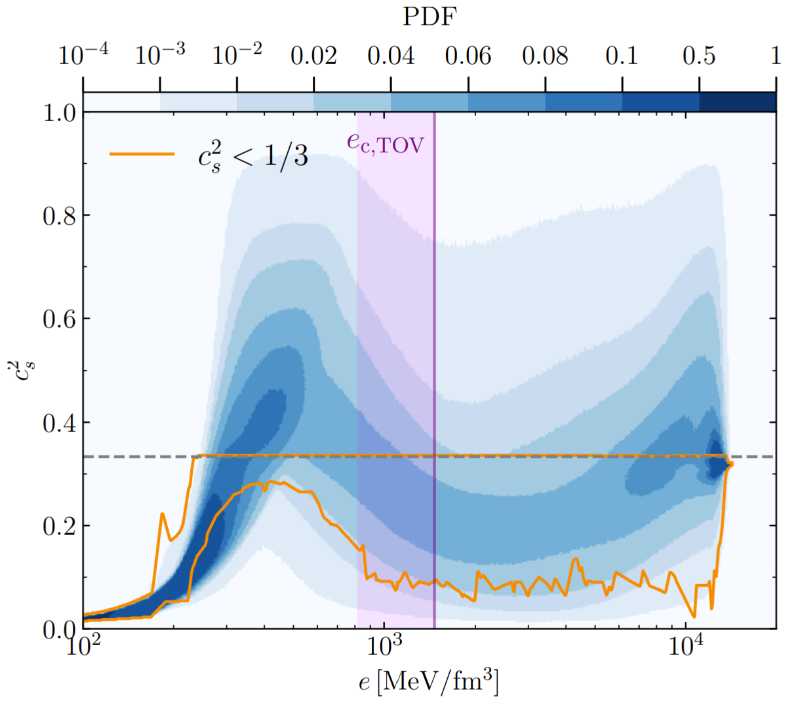


Figure from Altiparmak, Ecker, Rezzolla, ApJL (2022)

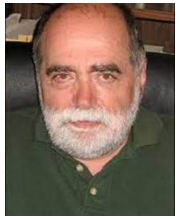
Many constraints from neutron star observations indicate a strong rise of c_s^2 beyond the conformal limit

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;
...

Quarkyonic matter and neutron stars

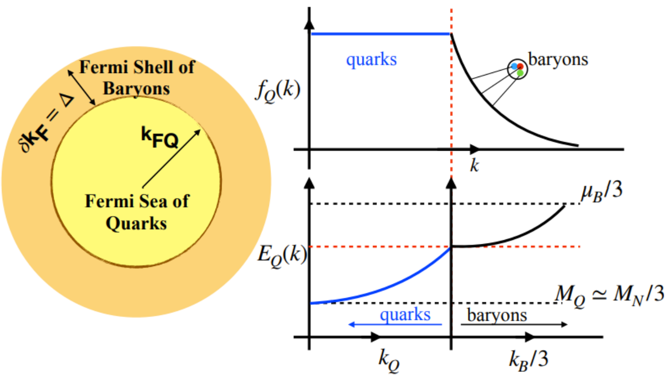
First(?) practical realization of quarkyonic matter (T=0)

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



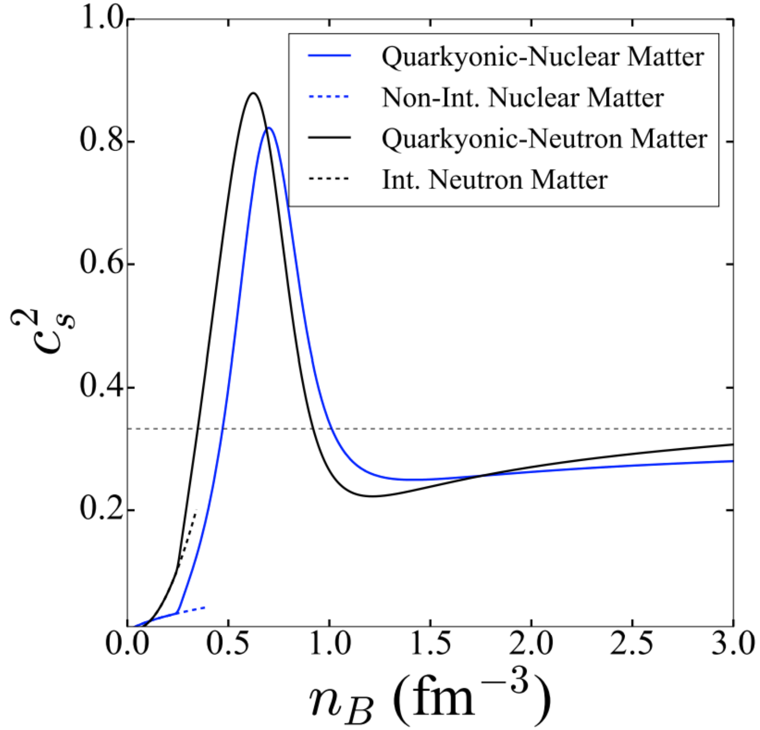
Mixture of “confined” quarks (baryons) and deconfined quarks with Pauli principle*

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



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

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



*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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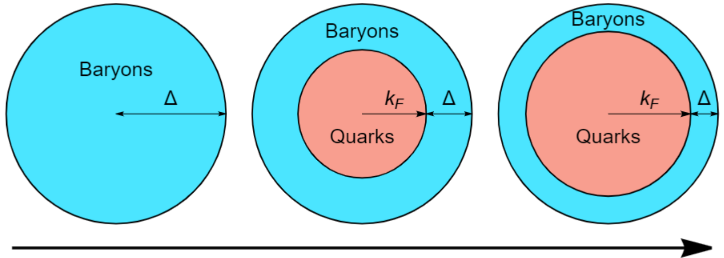
AN EXCLUDED VOLUME THEORY OF NUCLEAR INTERACTIONS

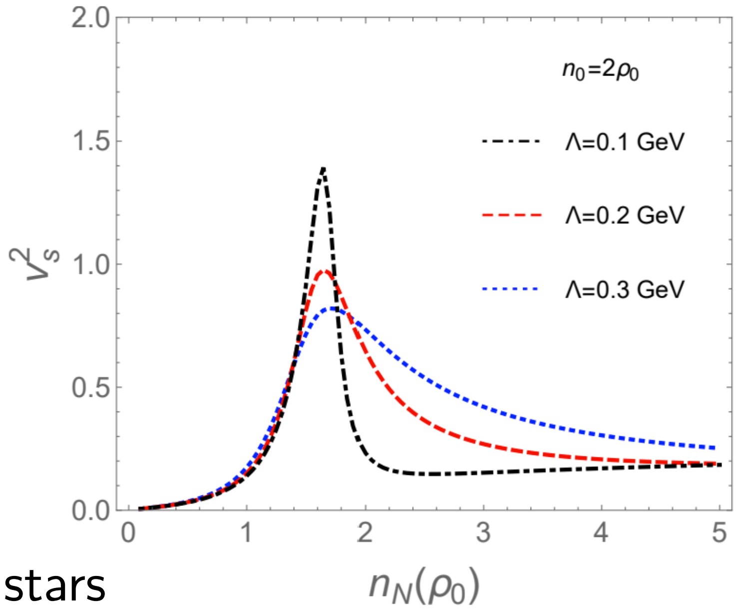
$$n^N_{ex} = \frac{n^N_N}{1 - n^N_N/n_0}$$



Minimize energy density at fixed n_B to find k_F and Δ

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

Requires infrared regulator to avoid superluminal speed of sound



Extendable to strange quarks, works reasonably well for neutron stars

Duarte, Hernandez-Ortiz, Jeong, PRC 102 (2020) 025203; PRC 102 (2020) 065202

Dynamical generation of momentum space shell structure

The excluded volume mechanism applied to baryon-quark mixture

- Helps to explain how quarks appear with baryon density
  - When baryon cores start to overlap, it becomes energetically unfavorable to have nucleons only

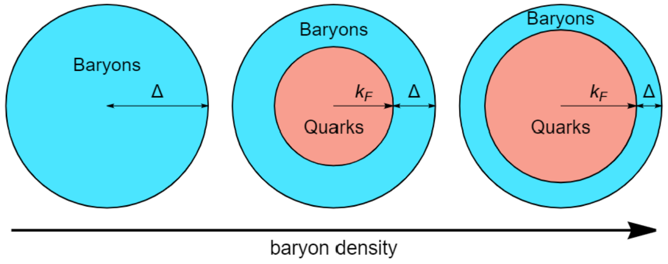
- Does not explain why quarks are in the Fermi sea and baryons are on the Fermi surface
- Requires infrared regulator

Key question: Is quarkyonic matter momentum shell structure the energetically preferred state of dense QCD matter? Will it emerge in a true dynamical mechanism (e.g. transport simulations)?

Quarkyonic vs baryquark matter

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

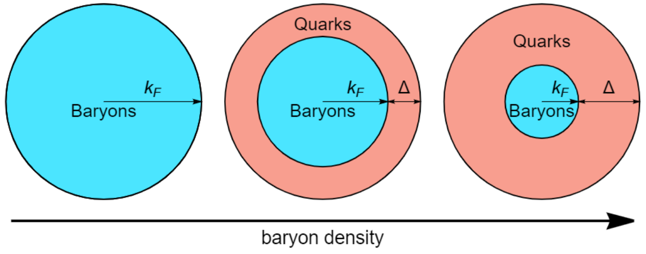
Quarkyonic



$$n_B = n_N + n_Q$$

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

Baryquark



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

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

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

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

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

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

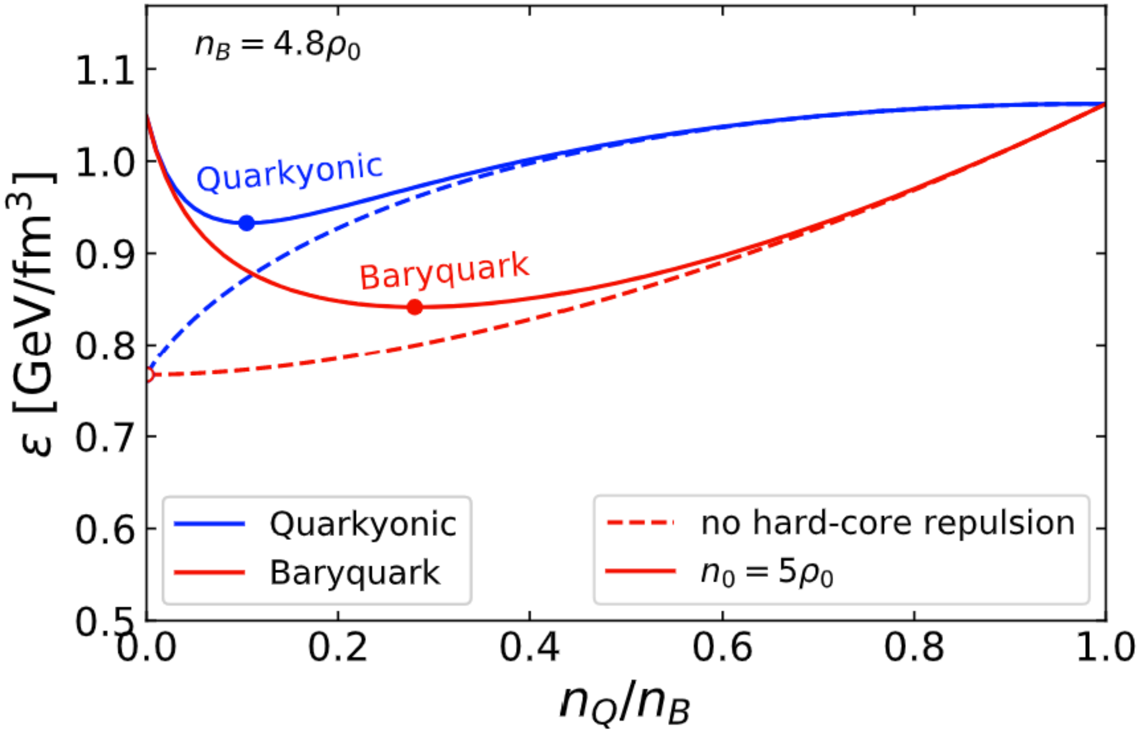
$$\varepsilon_Q = \frac{2N_c}{\pi^2} \int_{k_F/N_c}^{(k_F+\Delta)/N_c} dk\, k^2 \sqrt{m_Q^2 + k^2}$$

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

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

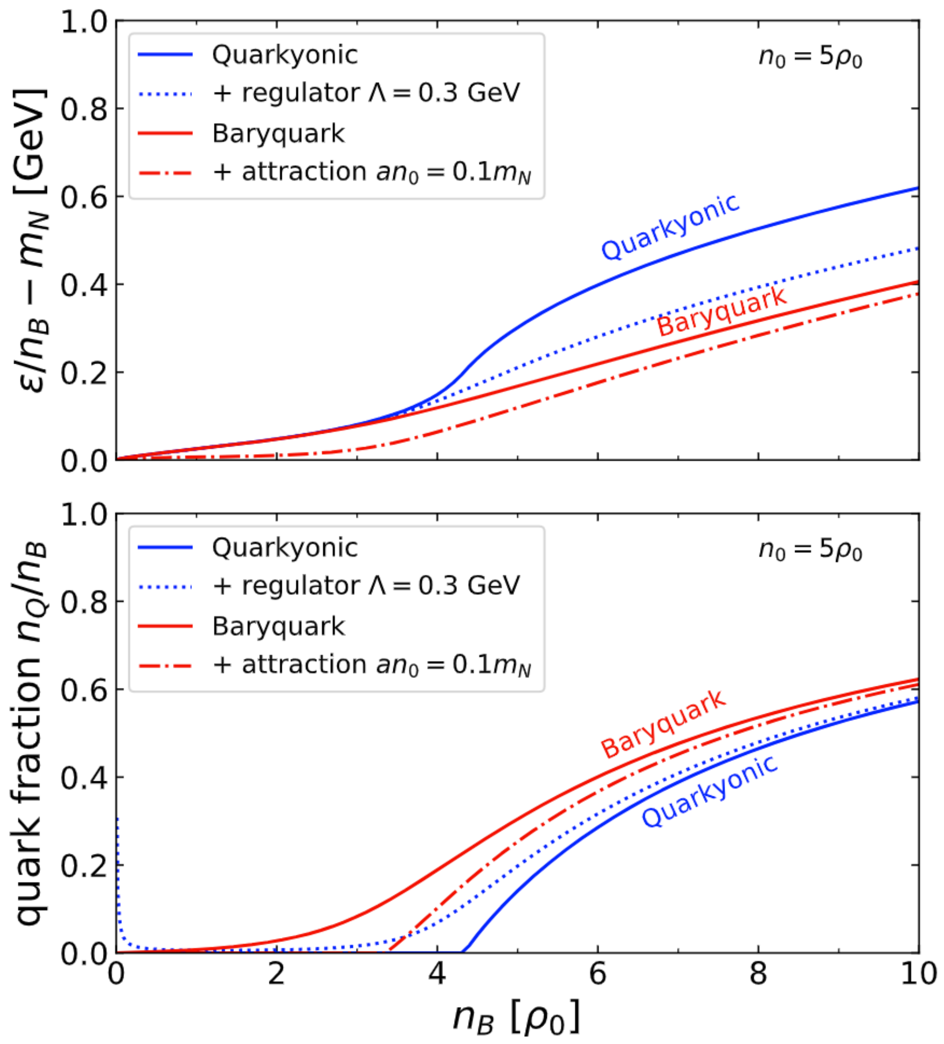
Quarkyonic vs baryquark matter: energy minimization

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



- Without excluded volume, the pure nucleon phase is always preferred
  - Already in this limit evident that adding quarks to the surface is energetically favorable
- With hard-core repulsion minimum may be at finite $n_Q/n_{B,}$ baryquark has a deeper minimum

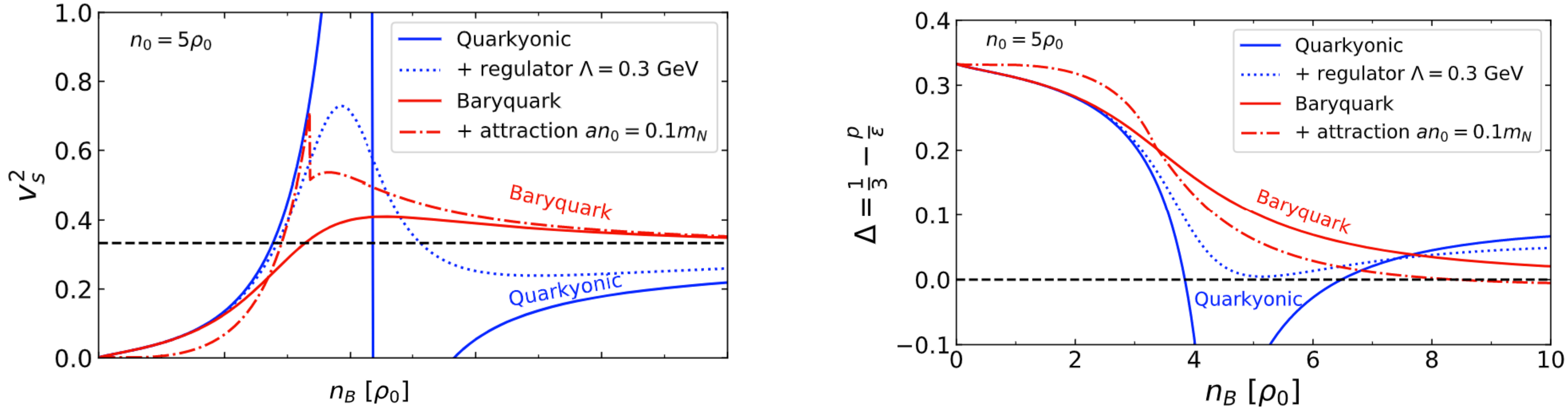
Quarkyonic vs baryquark matter: equation of state



- Non-zero quark fraction emerges at a certain density as a result of energy minimization
  - For most parameter setups the quark onset corresponds to a 2^{nd}-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

Quarkyonic vs baryquark matter: 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 in all cases
- Trace anomaly: exceeding the conformal limit is less obvious

Summary

- Equation of state of baryon-quark mixture with Pauli principle and baryonic hard-core
  - Disfavors quarkyonic matter momentum shell structure (baryonic Fermi surface) compared to baryquark matter (quark Fermi surface)
  - Qualitative behavior of the EoS is sensitive to the appearance of quarks but less so to their momentum space structure
- Existing quarkyonic matter descriptions will require modifications if this picture is to be preserved, e.g.
  - Momentum-dependence nuclear interactions
  - Abandon the quasiparticle picture (too naïve)
- Outlook:
  - Match to realistic low-density EoS [R. Poberezhnyuk, VV, in progress]
  - Isospin asymmetry and neutron stars

Thanks for your attention!