Momentum shell and rapid stiffening in Quarkyonic matter from explicit duality

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Based on: Y. Fujimoto, T. Kojo, L. D. McLerran, arXiv:2306.04304 [nucl-th].

Quarkyonic duality

Collins,Perry (1974)

Contrary to the common belief of free deconfied quarks at high μ…

Large-*Nc* QCD implies:

McLerran,Pisarski (2007)

Duality between quark matter and baryonic matter

$r_{\rm Debye}^{-1} \sim \frac{1}{N_c}\lambda_{\text{'t Hooft}}\,\mu^2$ … Never screened when $N_c \to \infty$ $(\lambda_{\text{'t Hooft}} = g^2 N_c)$

Real QCD ($N_c = 3$):

Confinement when $r_{\rm Debye} > r_{\rm conf} \sim \Lambda_{\rm QCD}^{-1}$

→ Quarkyonic regime: $\Lambda_{\rm QCD} \ll \mu \ll \sqrt{N_c}\Lambda_{\rm QCD}$

…Quark Fermi sea formed but confined (baryonic)

Theory with an explicit Quarkyonic duality

Kojo (2021); Fujimoto,Kojo,McLerran (2023)

Momentum distributions of baryons and quarks:

$$0 \le f_{\rm B}(k) \le 1\,, \quad 0 \le f_{\rm Q}(q) \le 1$$

Fermi gas model w/ an explicit duality:

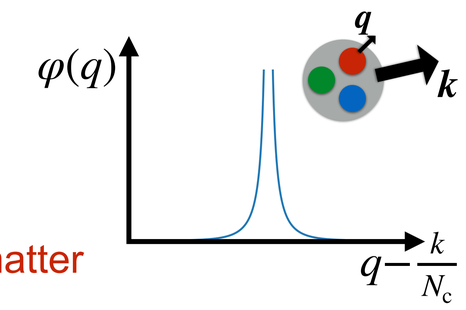
$$\varepsilon = \int_{\boldsymbol{k}} \sqrt{k^2 + M_{\rm N}^2}\, f_{\rm B}(k) = \int_{\boldsymbol{q}} E_{\rm Q}(q) f_{\rm Q}(q)$$

$$n_{\rm B} = \int_{\boldsymbol{k}} f_{\rm B}(k) = \int_{\boldsymbol{q}} f_{\rm Q}(q)$$

Duality relation from quark model:

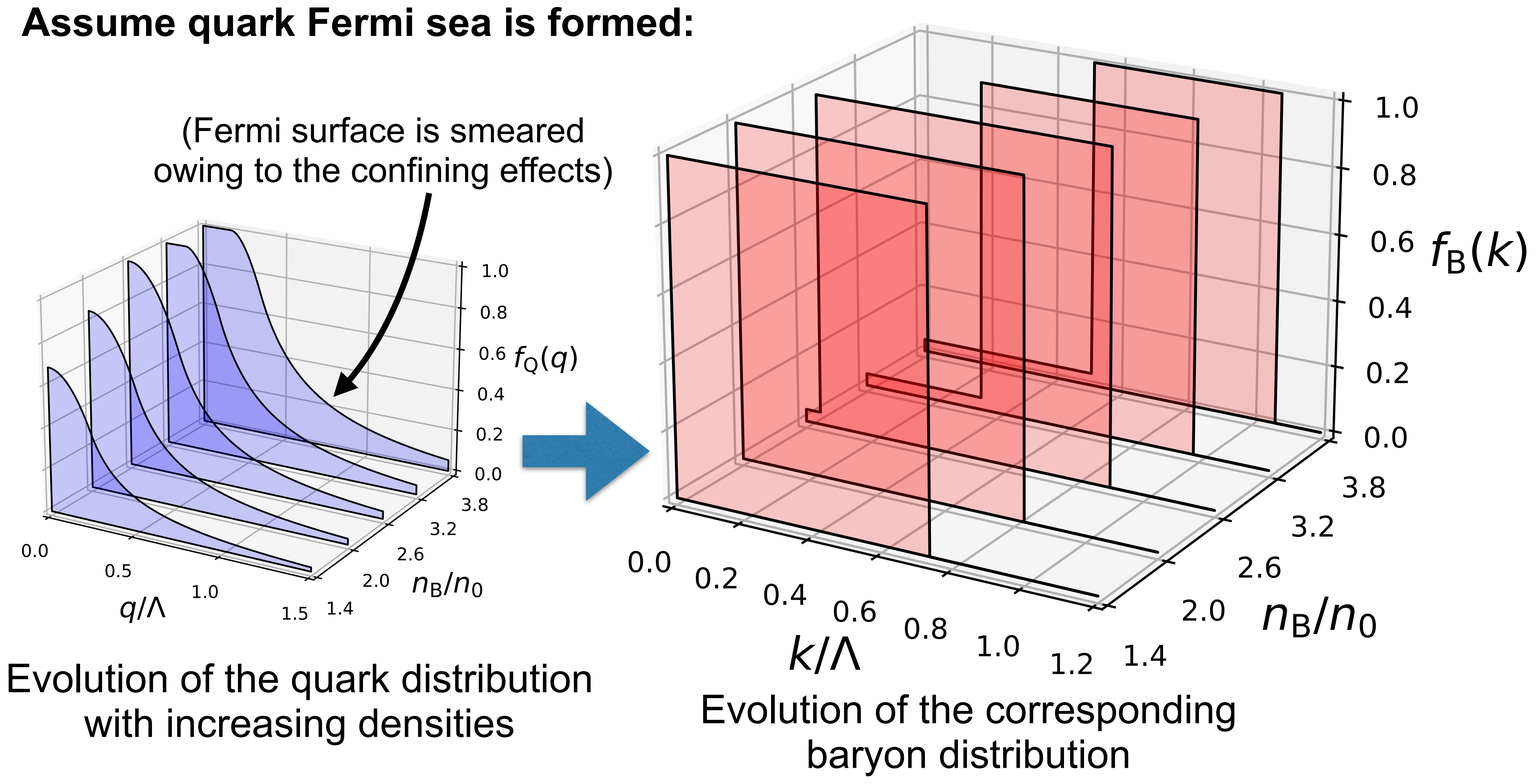
$$f_{\rm Q}(q) = \int_{\boldsymbol{k}} \varphi\left(\boldsymbol{q} - \frac{\boldsymbol{k}}{N_c}\right) f_{\rm B}(k)$$

… IdylliQ (Ideal dual Quarkyonic) matter



Result: Formation of the baryon shell

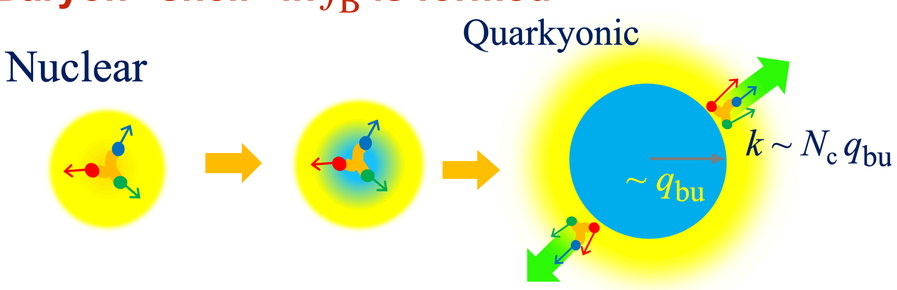
Assume quark Fermi sea is formed:



Evolution of the quark distribution with increasing densities

Evolution of the corresponding baryon distribution

- Baryon has N_c^3 times larger phase space compared to quarks
  → Pauli exclusion of quarks, $f_{\rm Q} \le 1$, leads to a partial occupation in the corresponding $f_{\rm B}$
- Pauli exclusion in $f_{\rm Q}$ leads to an effective repulsion between baryons
- **Baryon "shell" in $f_{\rm B}$ is formed**



Previously proposed:

Baryon shell sitting on top of the quark Fermi sea

McLerran,Pisarski (2007)

From a duality principle:

Baryon shell is formed at large momentum k on top of the low-k part of $f_{\rm B}(k)$, where the quark nature ($f_{\rm Q} \le 1$) is reflected

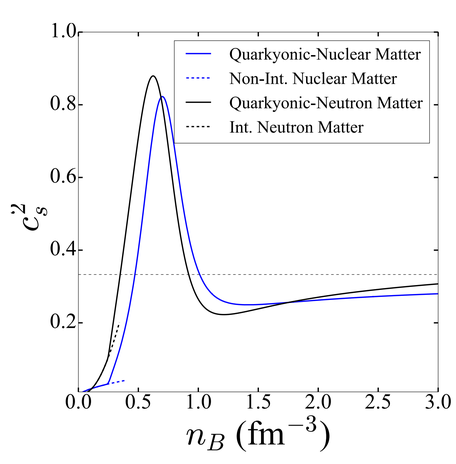
Discussion: Rapid stiffening in sound speed

Observational signature of Quarkyonic matter: large peak in sound speed McLerran,Reddy (2018)

A partial occupation of available baryon phase space indeed leads to the **large sound speed**

$$v_s^2 = \frac{n_{\rm B}}{\mu_{\rm B} dn_{\rm B}/d\mu_{\rm B}} \to \frac{\delta\mu_{\rm B}}{\mu_{\rm B}} \sim v_s^2 \frac{\delta n_{\rm B}}{n_{\rm B}}$$

For underoccupied baryons, the change in density is small and the change in Fermi energy is large



Summary

- Formulation of *IdylliQ* matter: ideal Quarkyonic matter with an explicit duality with an effective repulsion due to the Pauli exclusion
- Previously proposed Fermi shell structure of Quarkyonic matter naturally arises in the baryon distribution from a duality principle
- Observable signature of Quarkyonic matter is a rapid rise in the sound speed: underoccupied baryonic states naturally leads to a peak