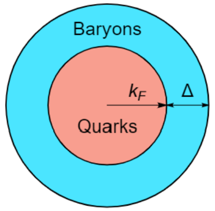

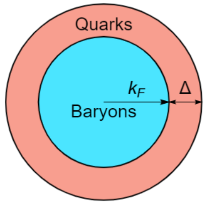

Quarkyonic or Baryquark matter?

On the dynamical generation of momentum space shell structure

Volodymyr Vovchenko (University of Houston)

Nuclear Theory Seminar at Iowa State University

May 11, 2022

Based on
V. Koch, VV, arXiv:2211.14674, Phys. Lett. B 841, 137942 (2023)
R. Poberezhnyuk, VV, in preparation

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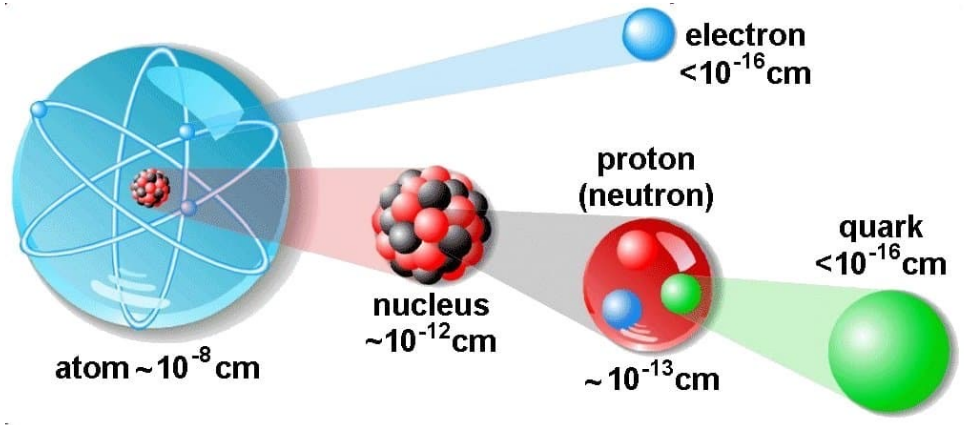
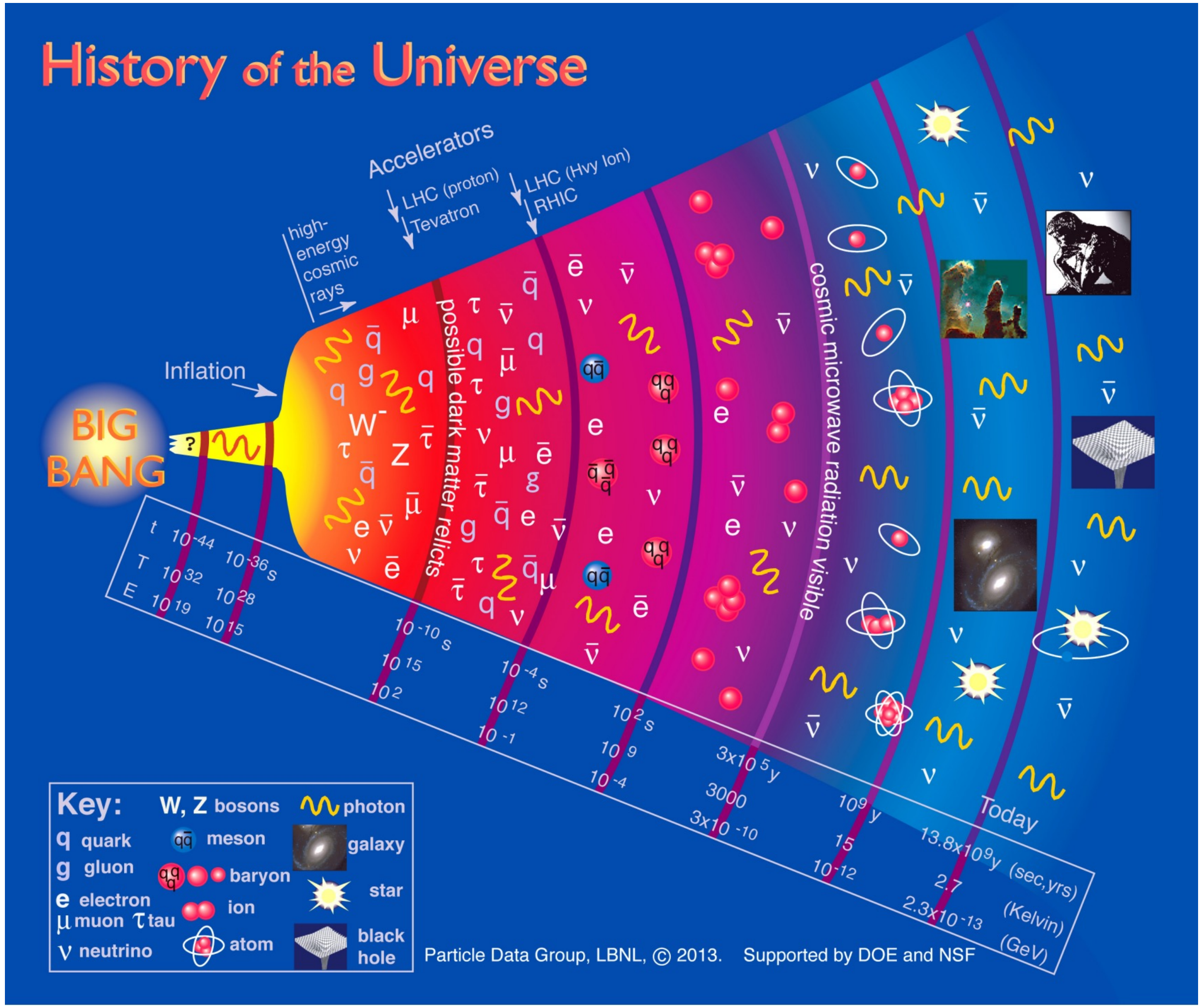
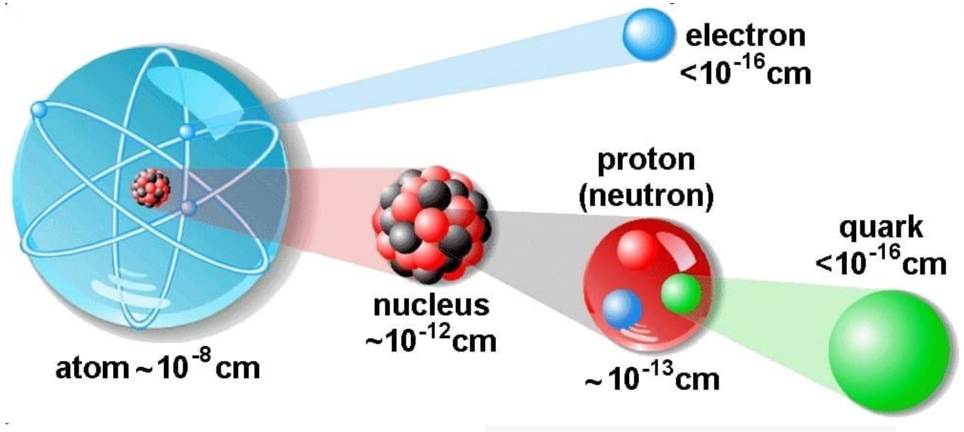
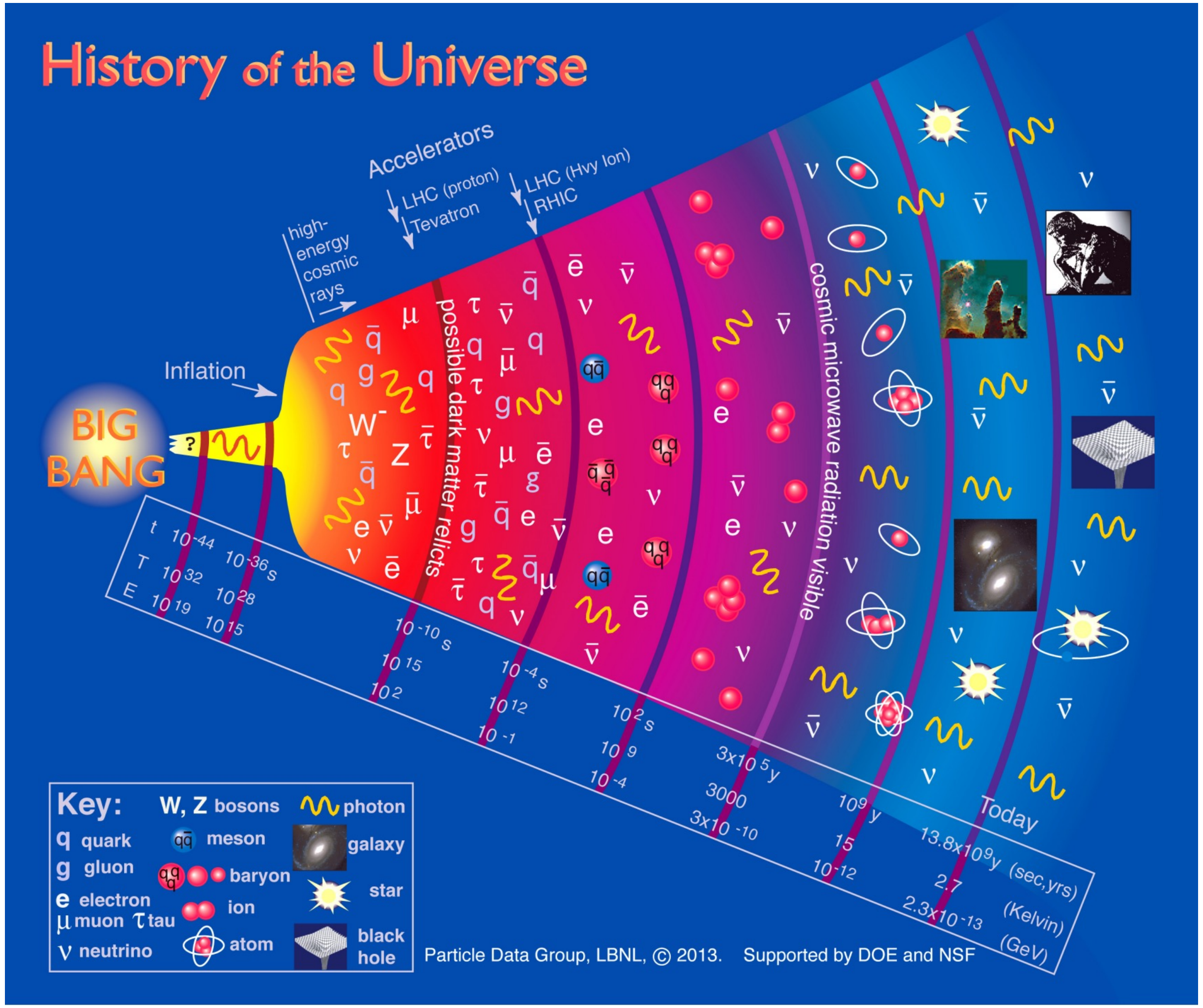
Structure of matter





Structure of matter





Strongly interacting matter

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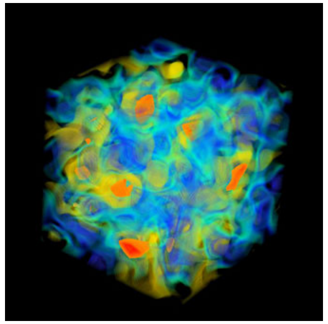
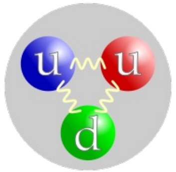
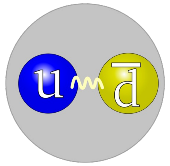
- Theory of strong interactions: *Quantum Chromodynamics* (QCD)

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



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



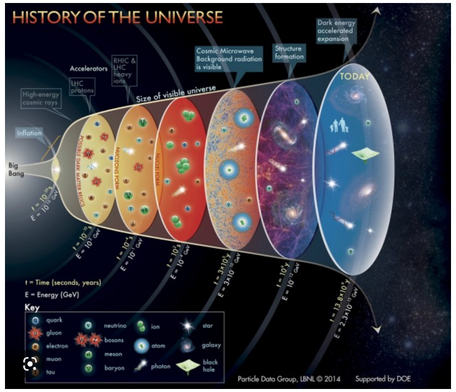


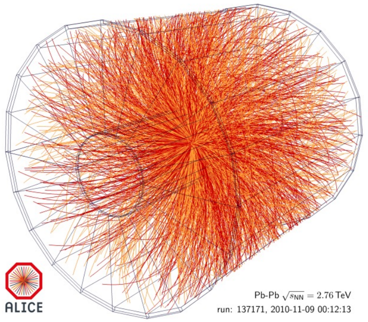
Scales

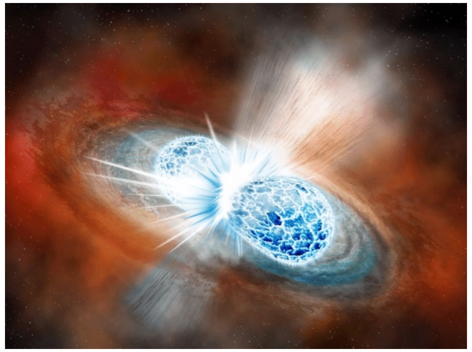
- Length: 1 femtometer $= 10^{-15}$ m
- Temperature: 100 MeV$/k_B = 10^{12}$ K

Where is it relevant?

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



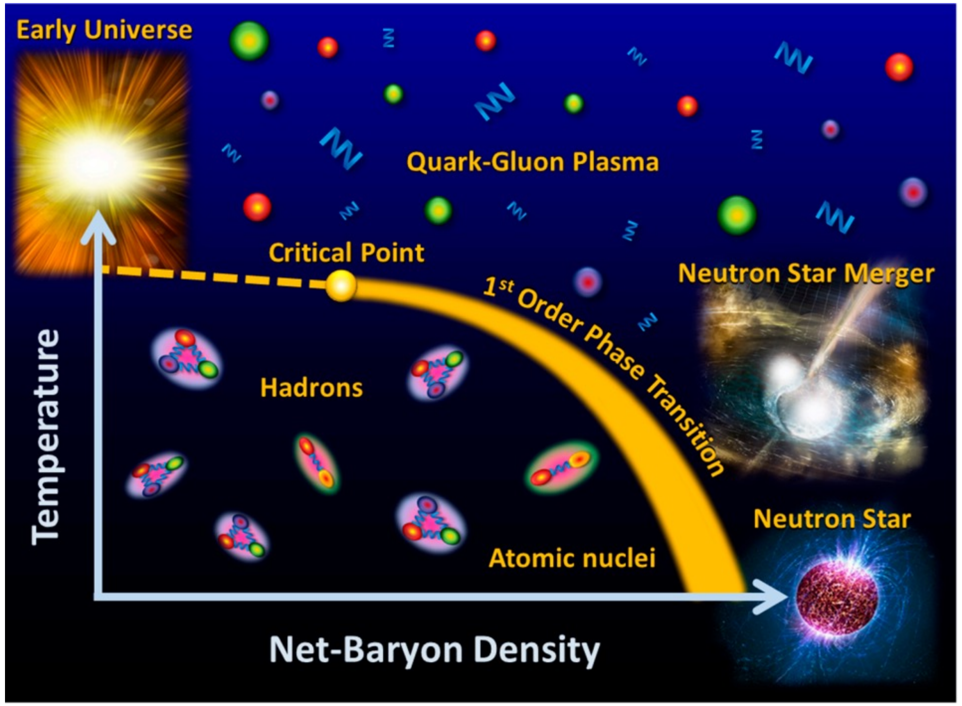




(c) NASA

QCD matter under extreme conditions

Regulate temperature (heating) and/or baryon density (compression) → QCD phase diagram



$$Z = \mathrm{Tr}(e^{-(\hat{H}-\mu\hat{N})/T})$$

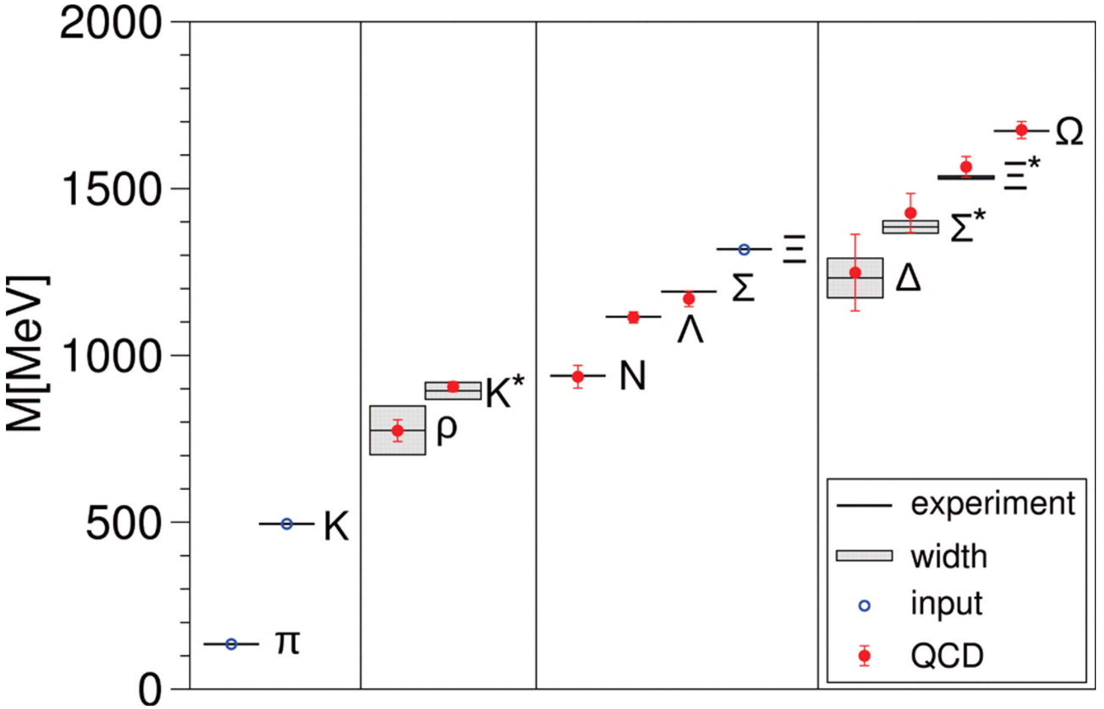
Figure from P. Senger, N. Herrman, Nucl. Phys. News

- Hadrons at low densities (confinement), quarks at high densities (asymptotic freedom)
- What is the nature of hadron-quark transition and/or coexistence?
  - The question is inherently non-perturbative

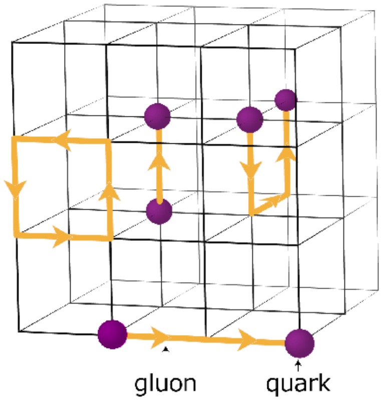
Non-perturbative methods

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 transition at $\mu_B = 0$ from lattice QCD

$$Z = \mathrm{Tr}(e^{-(\hat{H}-\mu\hat{N})/T}) = \int DU \det M[U,\mu]\, e^{-S_{YM}}$$

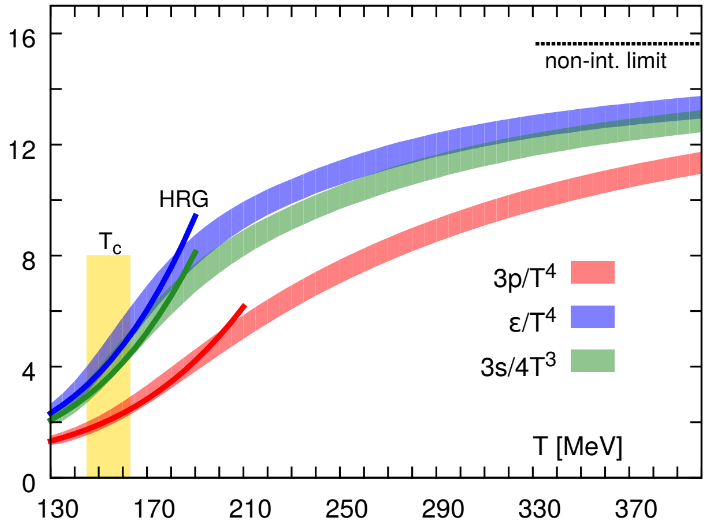


Figure from HotQCD coll., PRD '14

lattice QCD

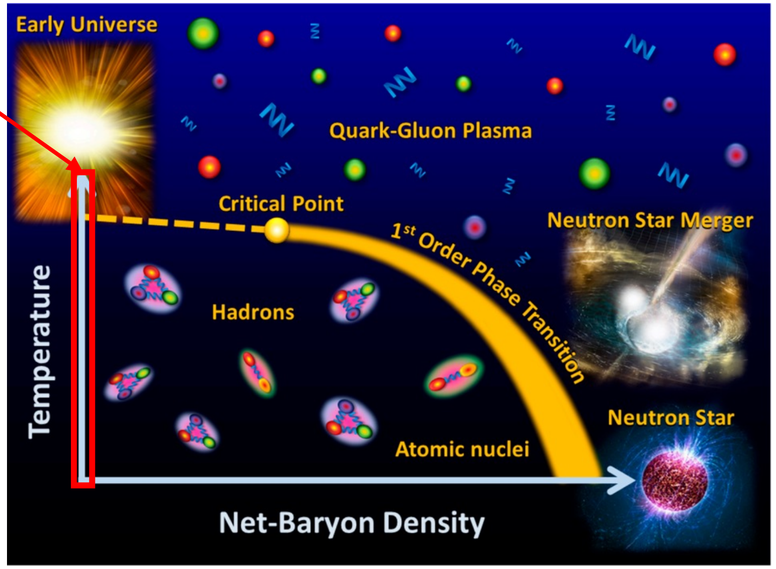


Figure from P. Senger, N. Herrman, Nucl. Phys. News

- Analytic crossover at vanishing net baryon density at $k_B T_{pc} \approx 155$ MeV – a first-principle result [Y. Aoki et al., Nature 443, 675 (2006)]
- Smooth connection between hadrons and quarks – **quark-hadron duality?**
  - On the hadronic size realized by adding resonances (HRG model) and eigenvolumes
  - Quark side – (hard-thermal loop) perturbation theory

[M. Albright, J. Kapusta, C. Young, Phys. Rev. C 90, 024915 (2014)]

QCD transition at finite μ_B

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

Extrapolations from $\mu_B = 0$:

- Crossover at $T_{pc} \approx 155$ MeV maintained till $\frac{\mu_B}{T} < 2 - 3$
  - No evidence for critical point
  - Consistent with heavy-ion data on proton number fluctuations

lattice QCD

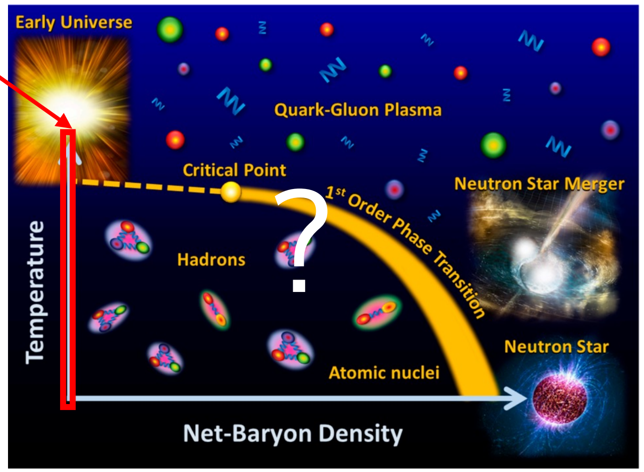


Figure from P. Senger, N. Herrman, Nucl. Phys. News

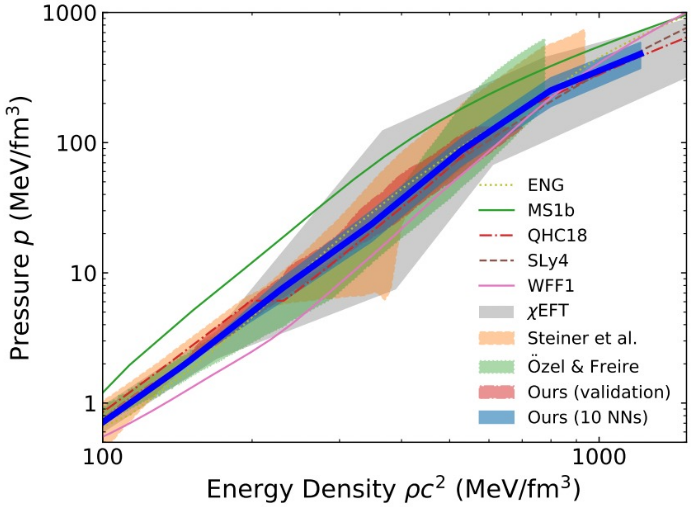
Ultimate limit: zero temperature, T = 0 ($\mu_B/T \to \infty$)

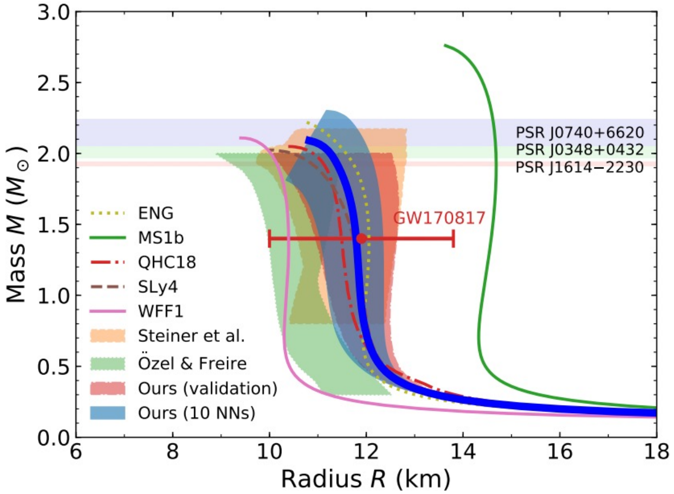
- No thermal excitations (resonances less relevant)
- Pauli blocking between "deconfined" and confined (baryons) quarks
- Accessible in neutron stars
- Perturbative QCD: high densities only, $n_B > 40 n_0$

QCD transition at zero temperature and neutron stars

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

QCD EoS	**Tolman-Oppenheimer-Volkoff equation**	**NS mass-radius curve**
$P = P(\rho)$	$\frac{dP}{dr} = -\frac{Gm}{r^2}\rho\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi r^3 P}{mc^2}\right)\left(1-\frac{2Gm}{rc^2}\right)^{-1}$	$M = M(R)$





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

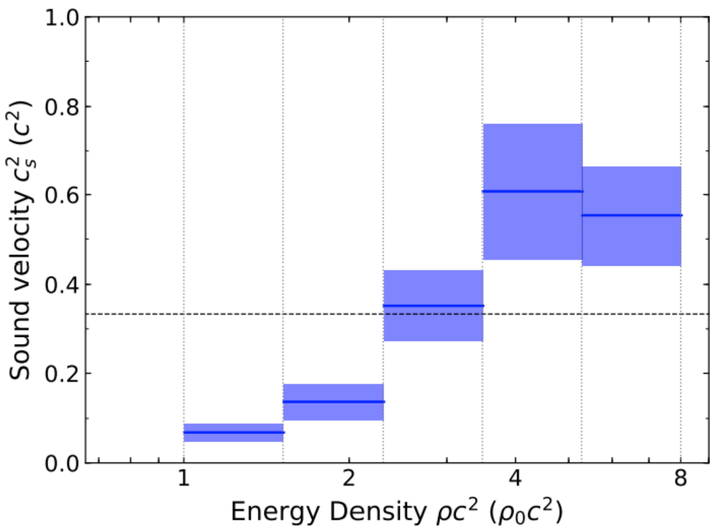
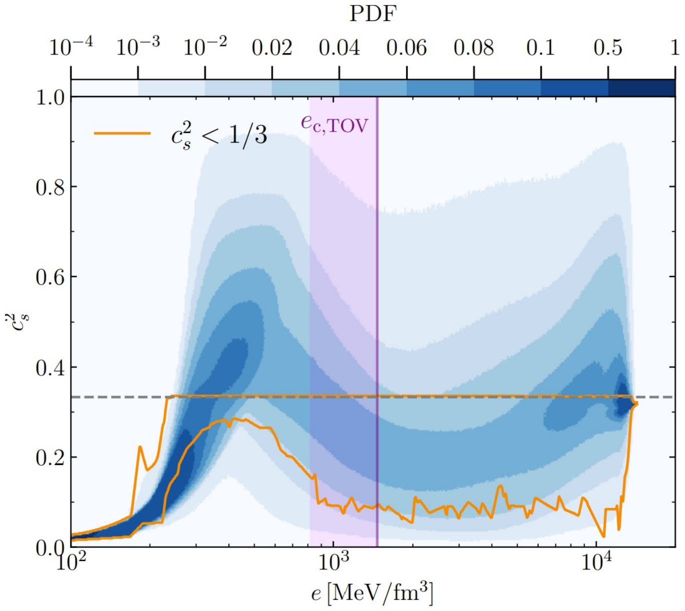
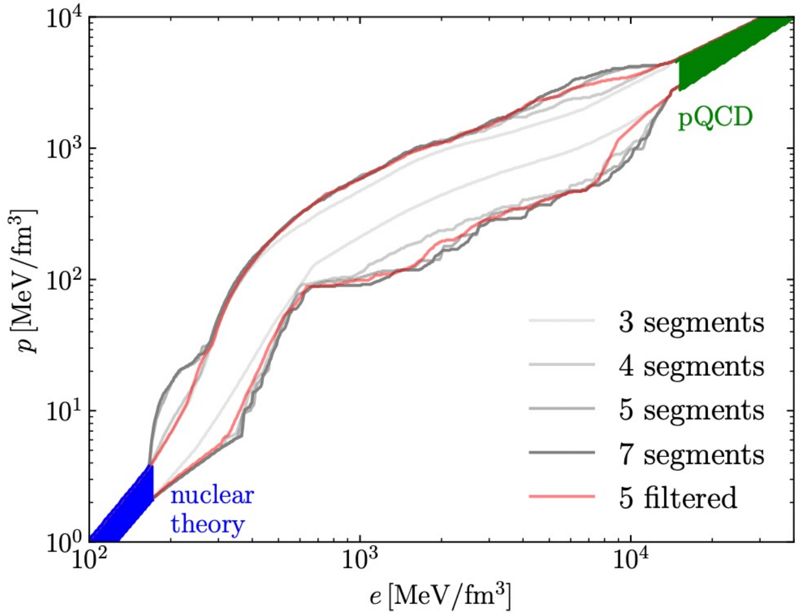


Figure from Fujimoto, Fukushima, Phys. Rev. D (2020)



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

We have 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

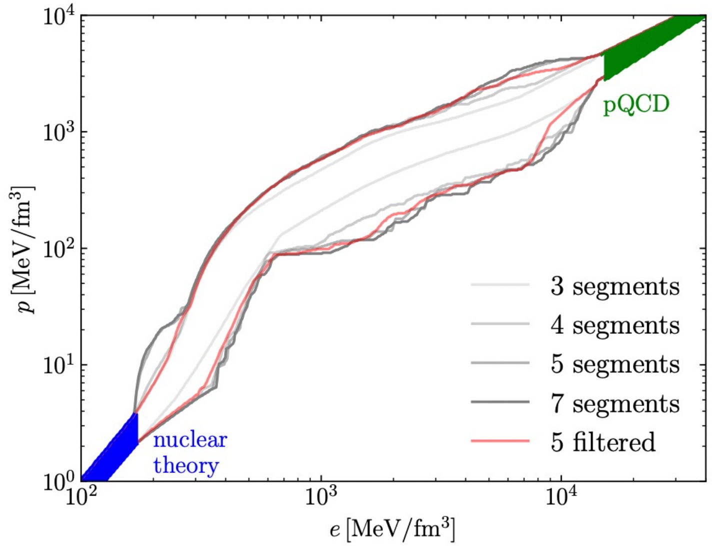


Figure from Altiparmak, Ecker, Rezzolla, ApJL (2022)

QCD the cold and dense regime and quarkyonic matter

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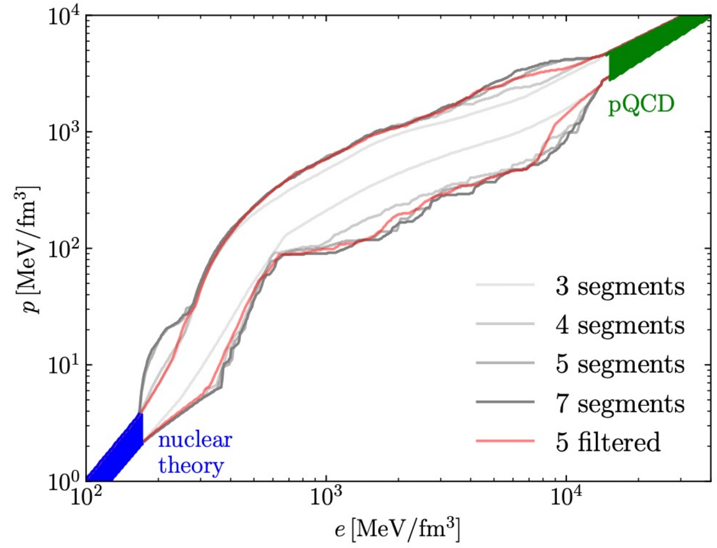


Figure from Altiparmak, Ecker, Rezzolla, ApJL (2022)

Quarkyonic matter?

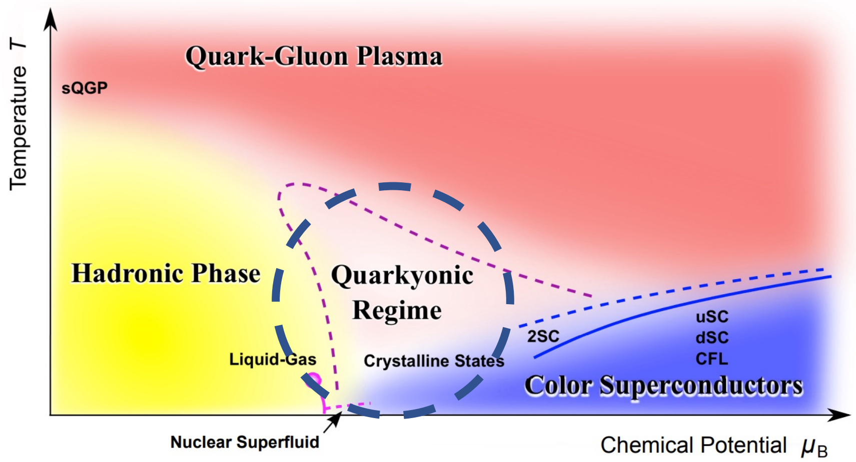
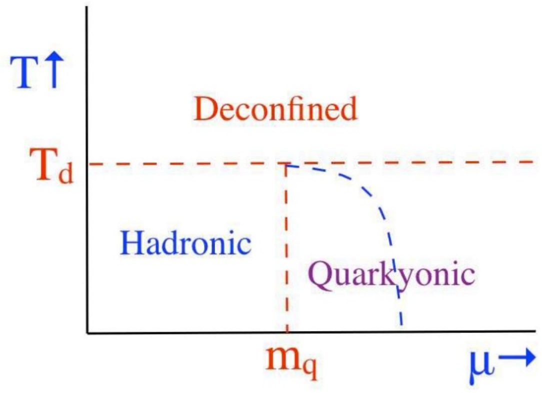


Figure adapted from Fukushima, Sasaki, PPNP '13

Large N_c



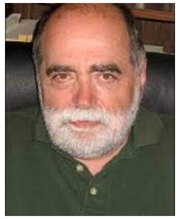
McLerran, Pisarski, NPA '07

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

McLerran, Pisarski, NPA 796, 83 (2007)

Quarkyonic matter and neutron stars

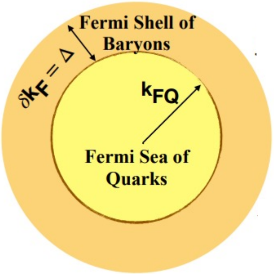
First(?) practical realization of quarkyonic matter (T=0)
[McLerran, Reddy, PRL 122, 122701 (2019)]

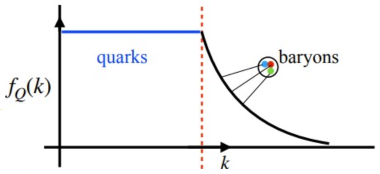


Mixture of "confined" quarks (baryons) and deconfined quarks with Pauli principle*

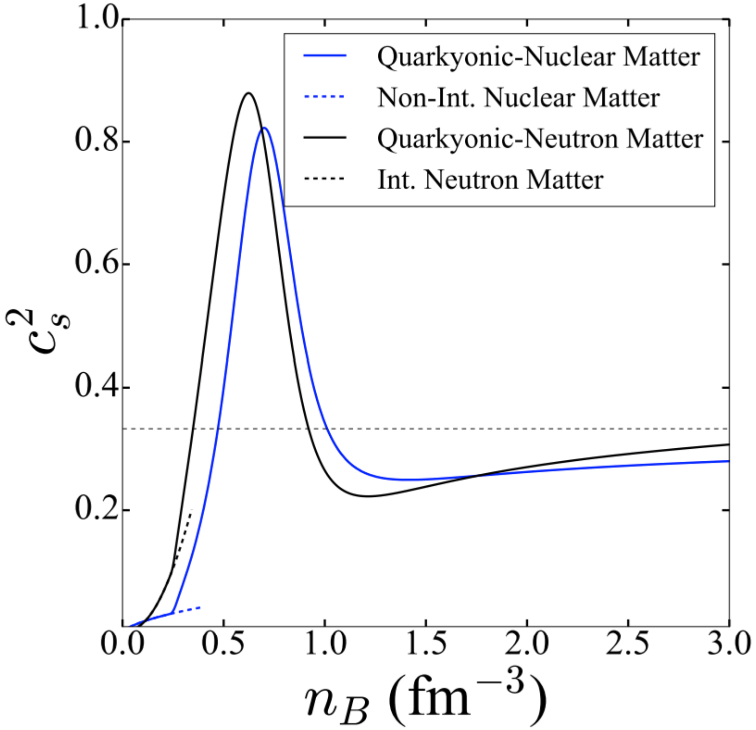
Enforce *momentum space shell structure* (baryonic Fermi surface) and its density evolution

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





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



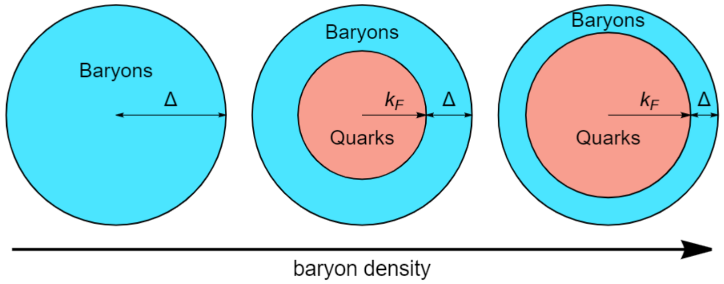
*Due to coinciding spin-isospin degeneracies, baryon and quark states cannot overlap

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

Kie Sang Jeong,[1,2] Larry McLerran,[2] and Srimoyee Sen[2]
[1] *Asia Pacific Center for Theoretical Physics, Pohang, Gyeongbuk 37673, Republic of Korea*
[2] *Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195, USA*

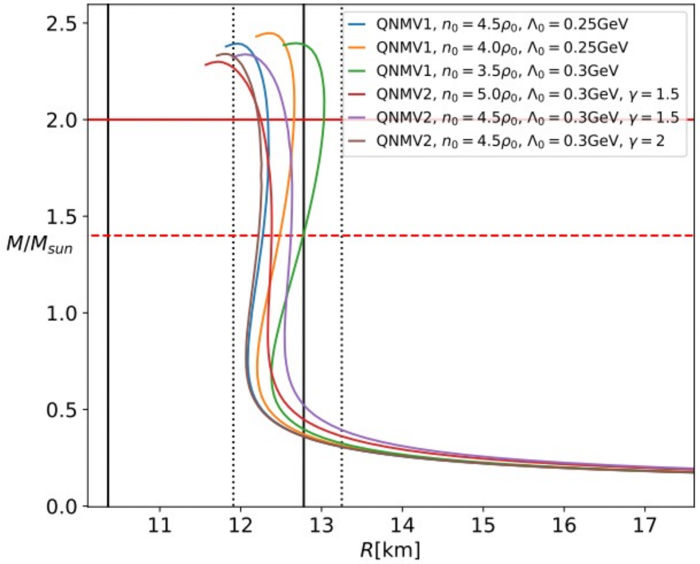


AN EXCLUDED VOLUME THEORY OF NUCLEAR INTERACTIONS

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

Minimize energy density at fixed n_B to find k_F and Δ

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



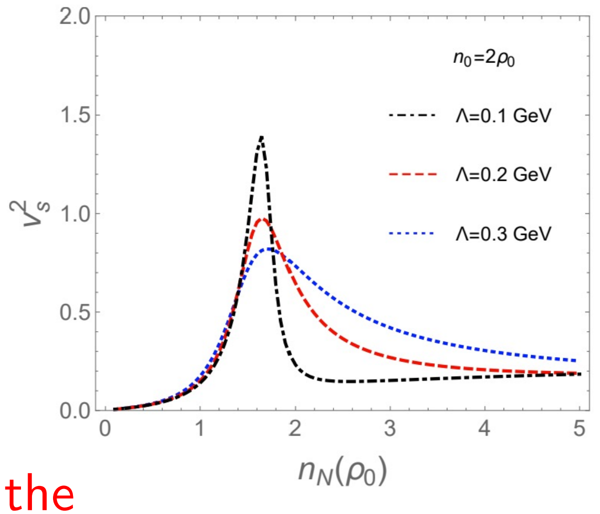
Requires infrared regulator to avoid superluminal speed of sound

Works reasonably well for neutron stars, extendable to strange quarks

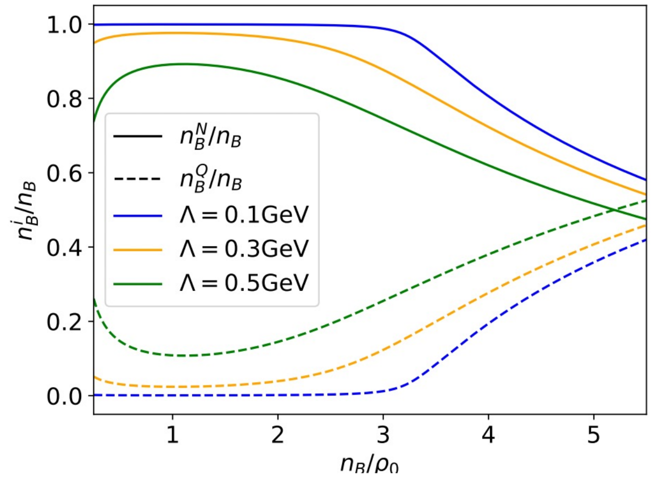
D. Duarte, S. Hernandez-Ortiz, K. Jeong, PRC 102 (2020) 025203; PRC 102 (2020) 065202
S. Sen, L. Sivertsen, ApJ 915, 109 (2021)

Issues

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
  - Hard to constrain its value independently
  - Quarks appear at low densities



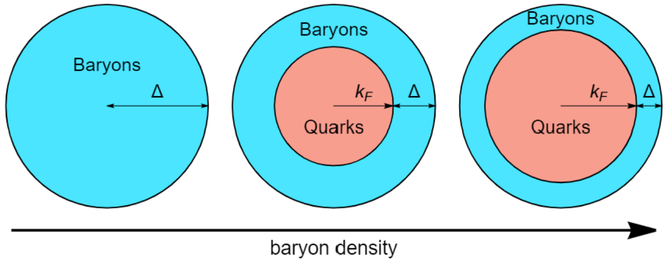
addressed in S. Sen, L. Sivertsen, ApJ 915, 109 (2021)

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

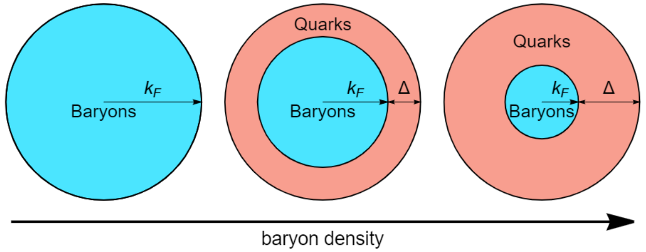
Quarkyonic



$$n_B = n_N + n_Q$$

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

Baryquark



Quarkyonic:

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

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

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

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

Baryquark:

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

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

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

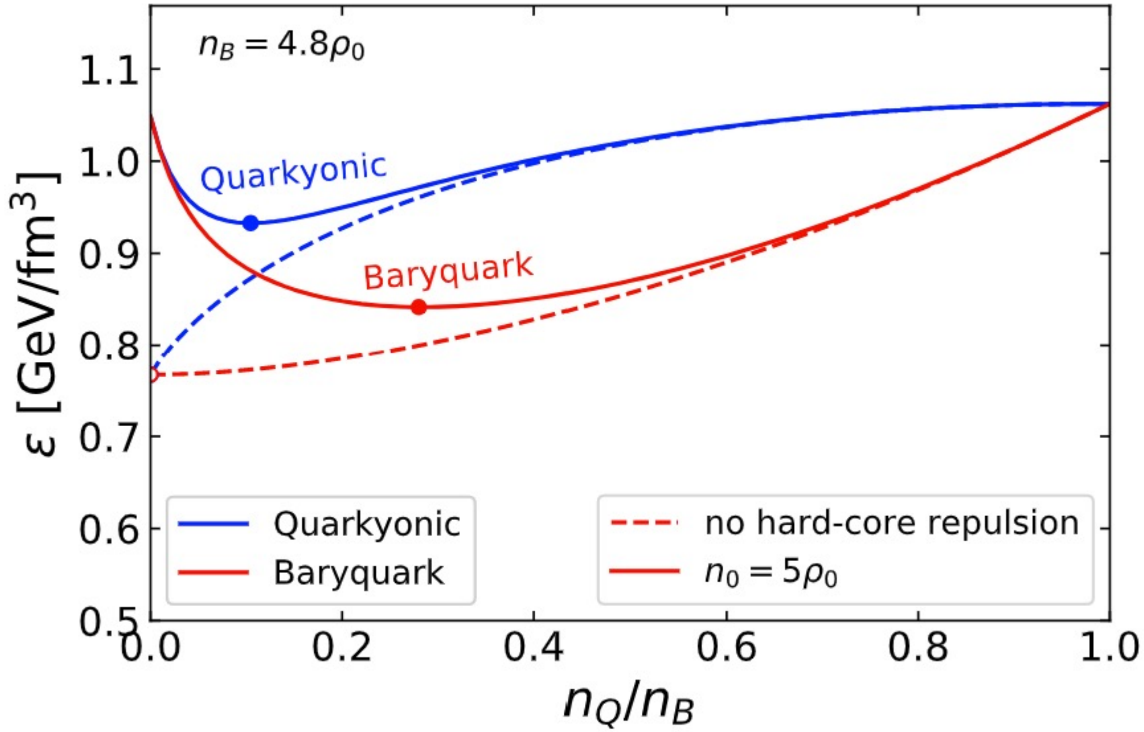
$$\varepsilon_N = f_{\rm ev}\frac{2}{\pi^2}\int_0^{k_F} dk\, k^2\sqrt{m_N^2+k^2}.$$

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

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

Quarkyonic vs baryquark matter: energy minimization

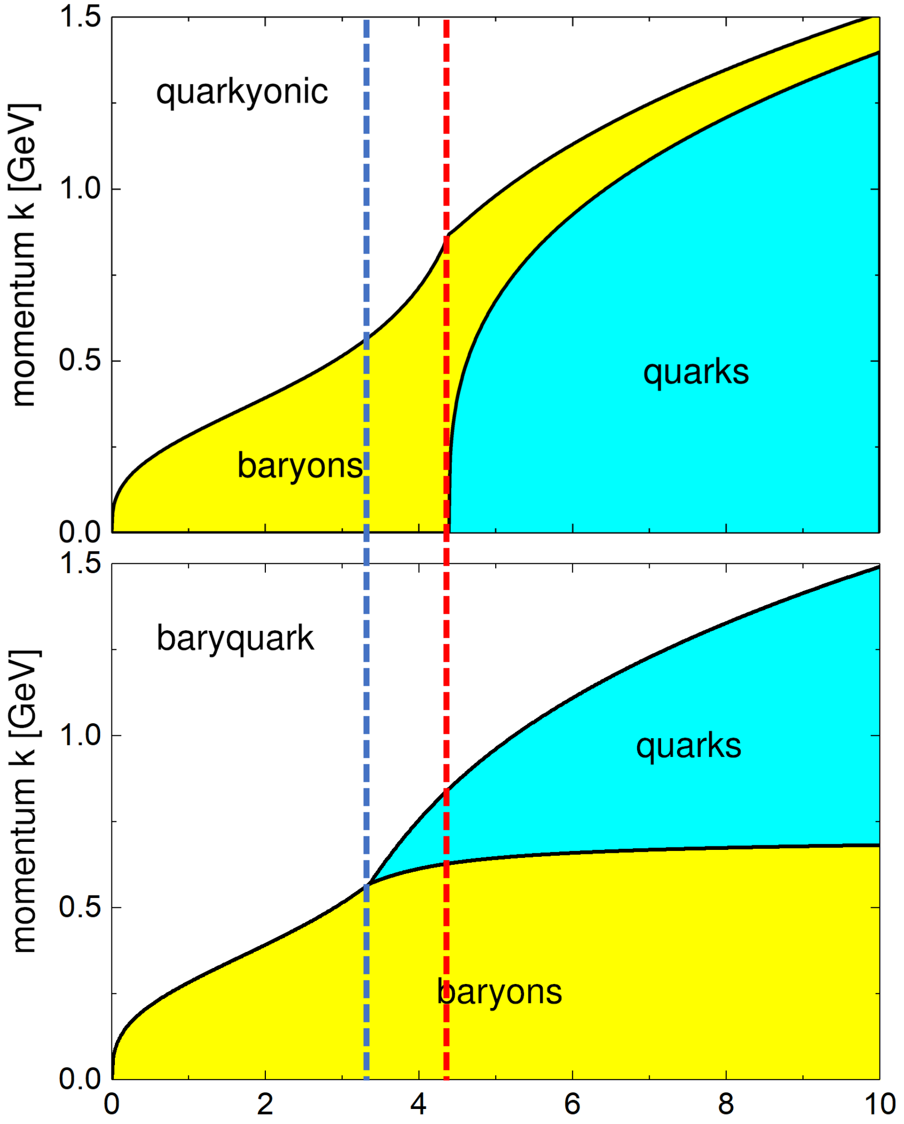
At each baryon density n_B minimize energy density wrt to quark fraction n_Q/n_B



- 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

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

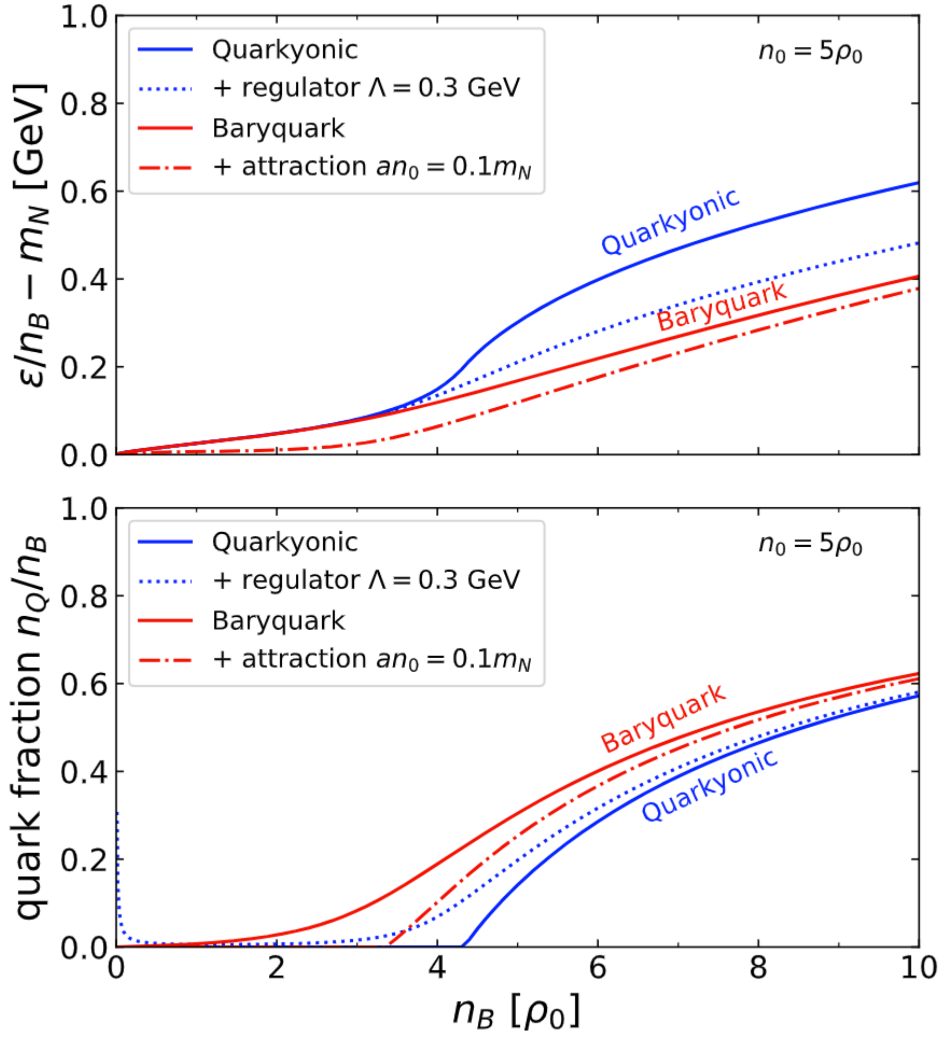
Quarkyonic vs baryquark matter: momentum shell structure



NB: quark momenta scaled by N_c n/n_{GS} Figure courtesy of R. Poberezhnyuk

- Non-zero quark fraction emerges at a certain density as a result of energy minimization
  - Both scenarios give the same EoS (pure nucleon matter) before the quark onset
  - Appearance of quarks in baryquark matter is earlier and smoother

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

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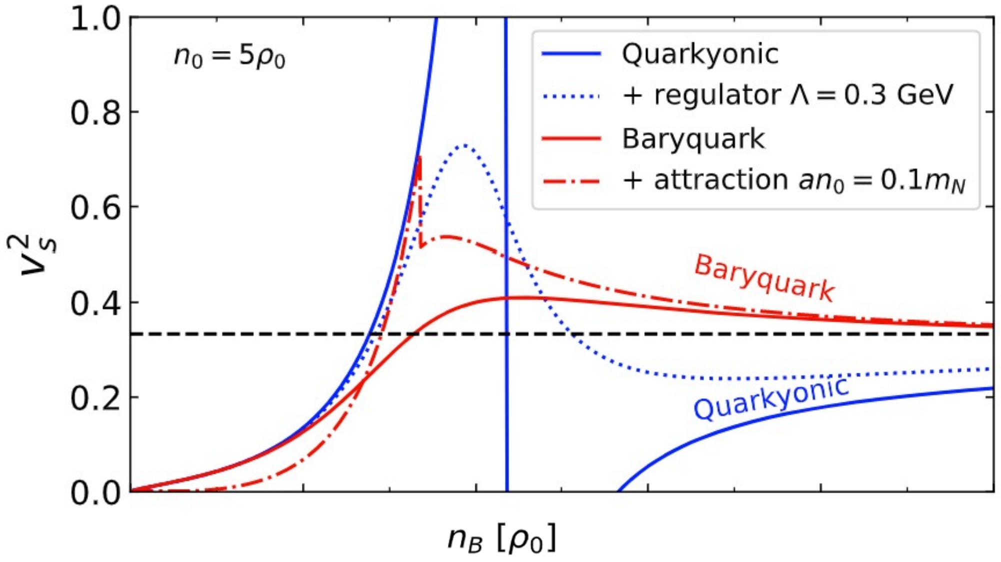
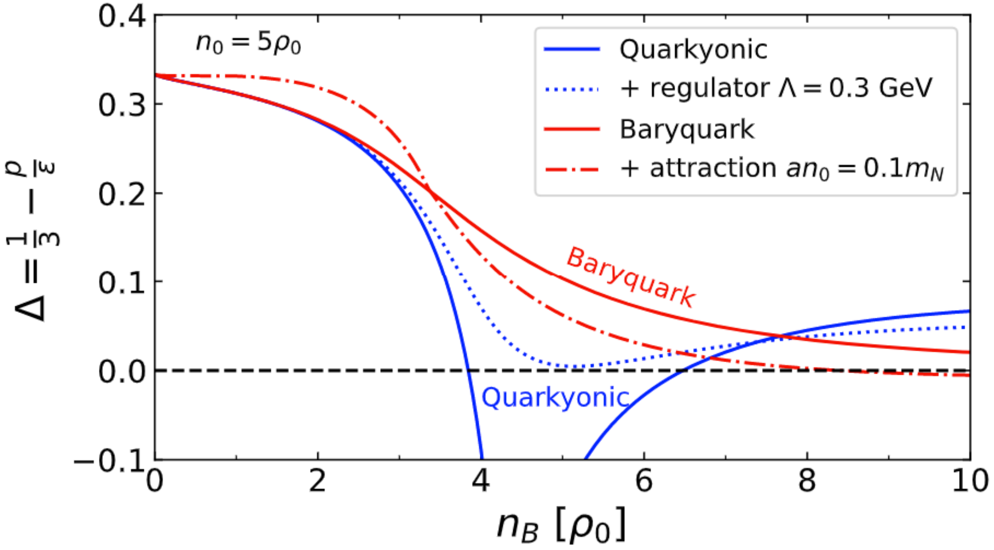


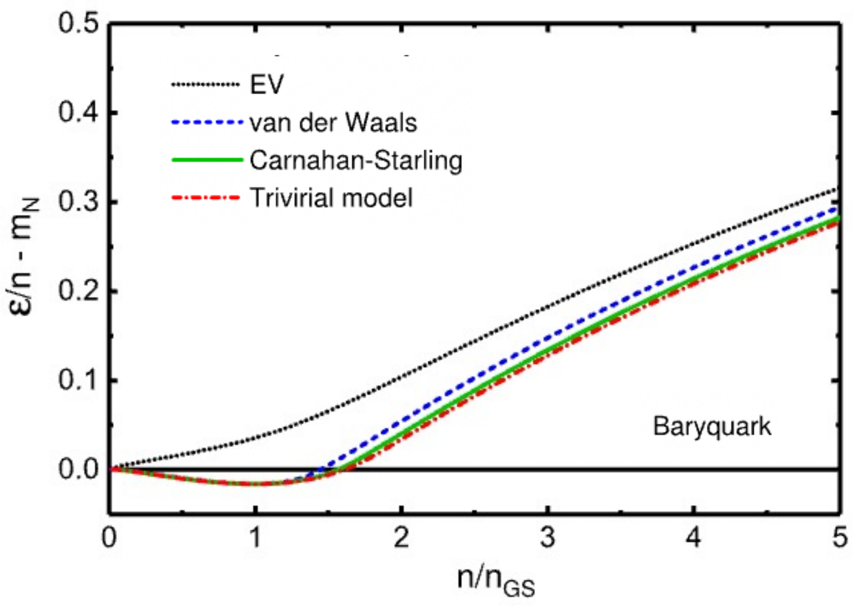


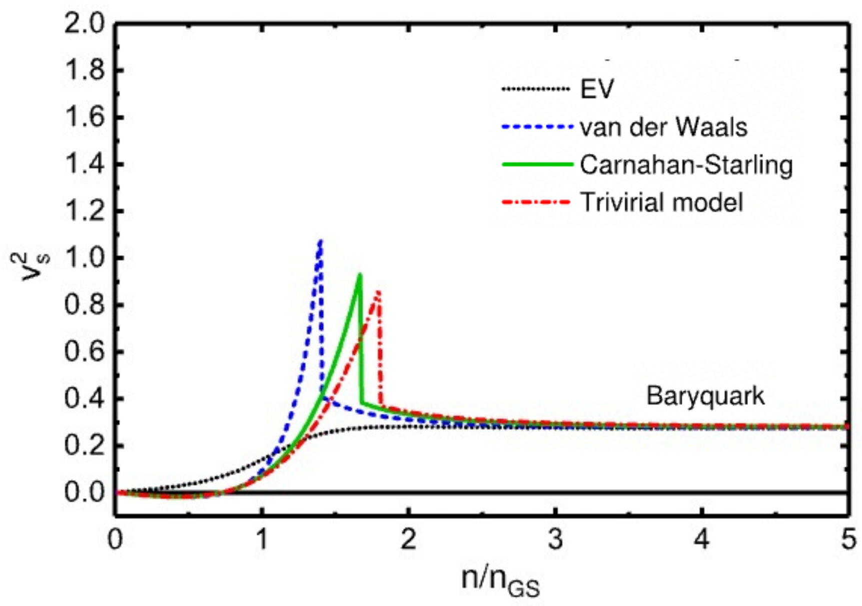
- In quarkyonic matter need to introduce regulator to obtain physically acceptance speed of sound
- In baryquark matter the behavior is acceptable without the need to introduce regulators
- The speed of sound exceeds the conformal limit ($c_s^2 = 1/3$) in all cases
- Trace anomaly: exceeding the conformal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

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

Outlook: Realistic low-density equation of state

Achieved by matching with quantum real gas model
- Generalized excluded-volume model
- Attractive mean-field





R. Poberezhnyuk, VV, to appear

Outlook: Neutron-star baryquark matter

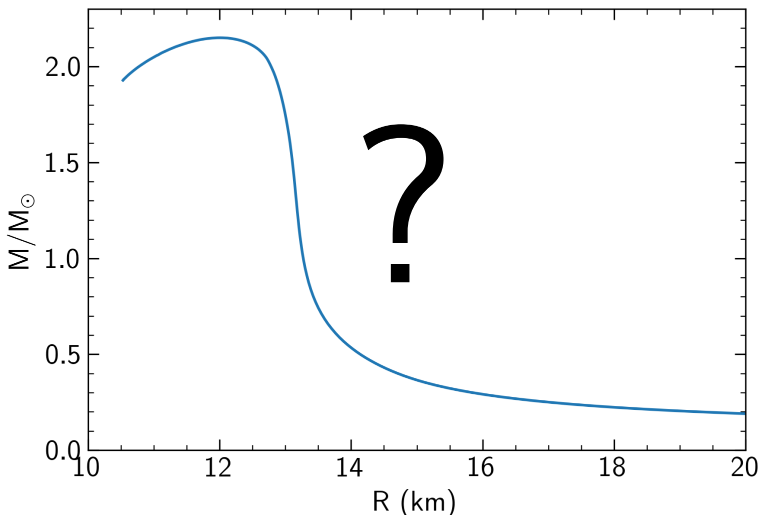
Isospin-symmetric matter:

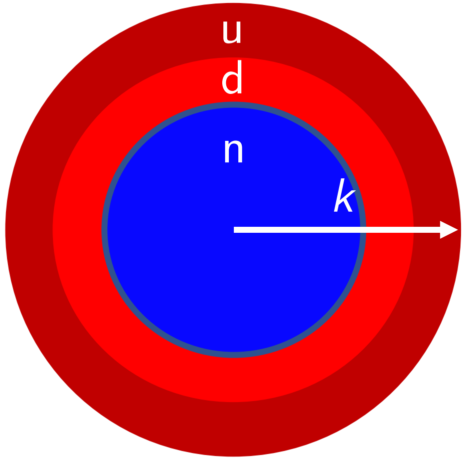
- same # of protons (uud) and neutrons (udd)
- Fermi surfaces of u & d quarks coincide

Pure neutron matter:

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

Mass-radius relation





Summary

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- Quark-hadron coexistence at $T = 0$ implies a mixed phase in the momentum space
- Equation of state of baryon-quark mixture with Pauli principle and baryonic hard-core
  - Disfavors quarkyonic matter (baryonic Fermi surface) compared to baryquark (quark Fermi surface)
  - Qualitatively similar resulting EoS but baryquark does not require infrared regulator
- Existing quarkyonic matter descriptions require modifications if this picture is to be preserved
  - Momentum-dependence nuclear interactions?
  - Abandon the quasiparticle picture? (too naïve)
  - A judicious regulator?
- Outlook: [R. Poberezhnyuk, VV, to appear]
  - Match to realistic low-density EoS
  - Variations on Pauli exclusion principle and quark-hadron duality implementations
  - Isospin asymmetry and neutron stars

Thanks for your attention!