

When a man is old, he must do more than when he was young . Johann Wolfgang Goethe

What is the Evidence for Dense Quarkyonic Matter

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with

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Quarkyonic Matter is High Baryon Density Matter that simultaneously exhibits properties of a confined system and a deconfined system

At large N_c , the Debye screening length goes like

$$\lambda_{Debye} = \sqrt{N_c}/E_F$$

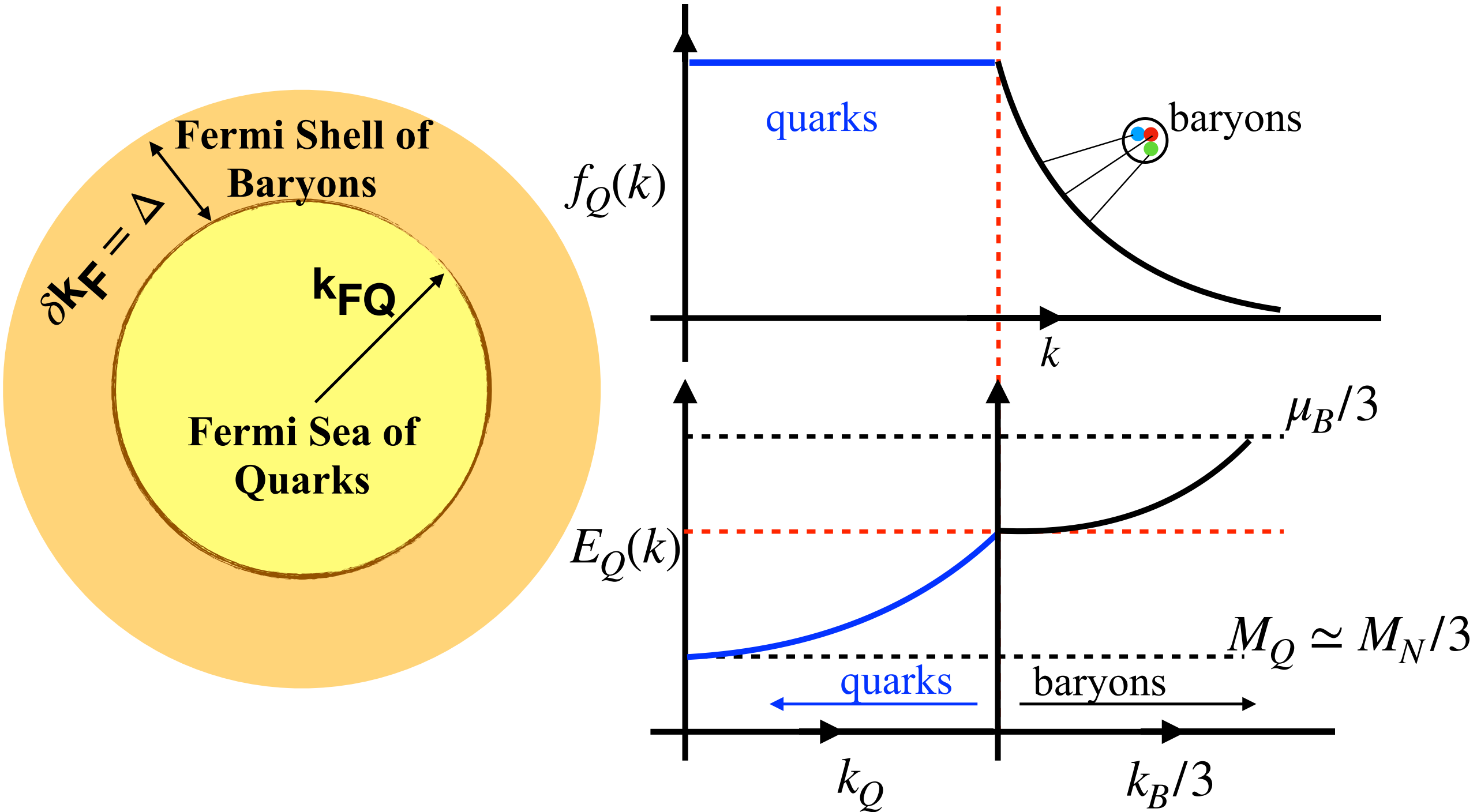
So that

$$\lambda_{Debye} < \Lambda_{QCD} \Rightarrow E_F > \sqrt{N_c}\Lambda_{QCD}$$

Typical interactions inside the Fermi sea are weak, but at the Fermi surface interactions can be sensitive to the infrared, and are confined

Quarkyonic matter is relativistic and the transition to quarkyonic matter can generate sound velocities with an excess

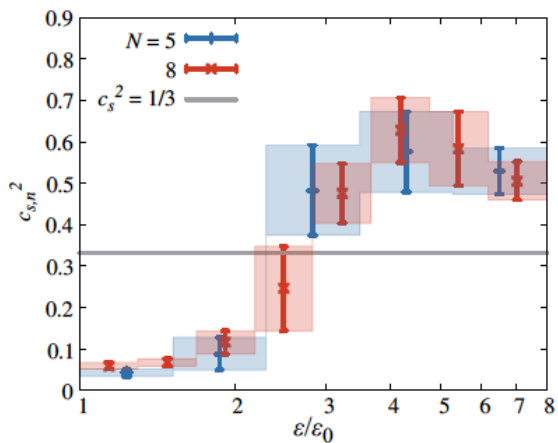
$$v_s^2 \geq 1/3$$



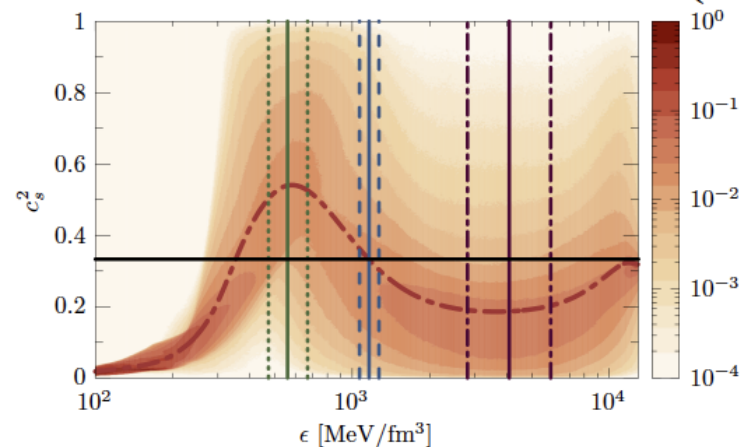
Neutron Star Eos

(Extracted from observed from mass, radii and deformability)

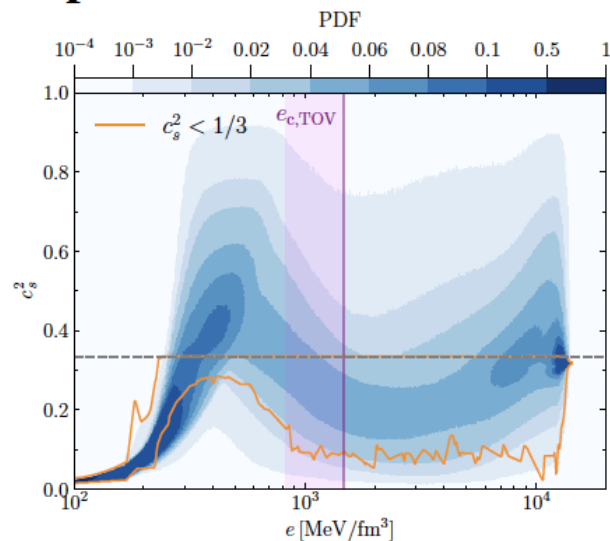
Fujimoto-Fukushima-Kamata-Murase (2018-2024)



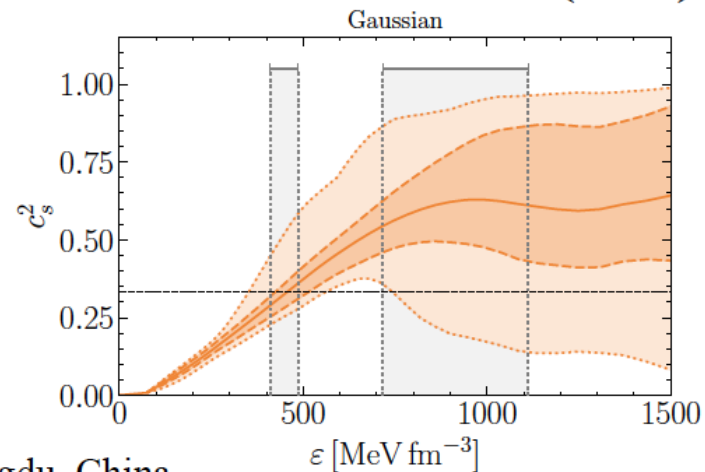
Marczenko-McLerran-Redlich-Sasaki (2022)



Altiparmak-Ecker-Rezzolla (2022)



Brandes-Weise-Kaiser (2022)



From talk of K.
Fukushima

If quark degrees of freedom become important, should be approaching scale invariance (massless-ness)

One measure of this is the trace of the energy momentum tensor, which is zero for a scale invariant system:

$$\Delta = \frac{1}{3} - \frac{P}{\epsilon}$$

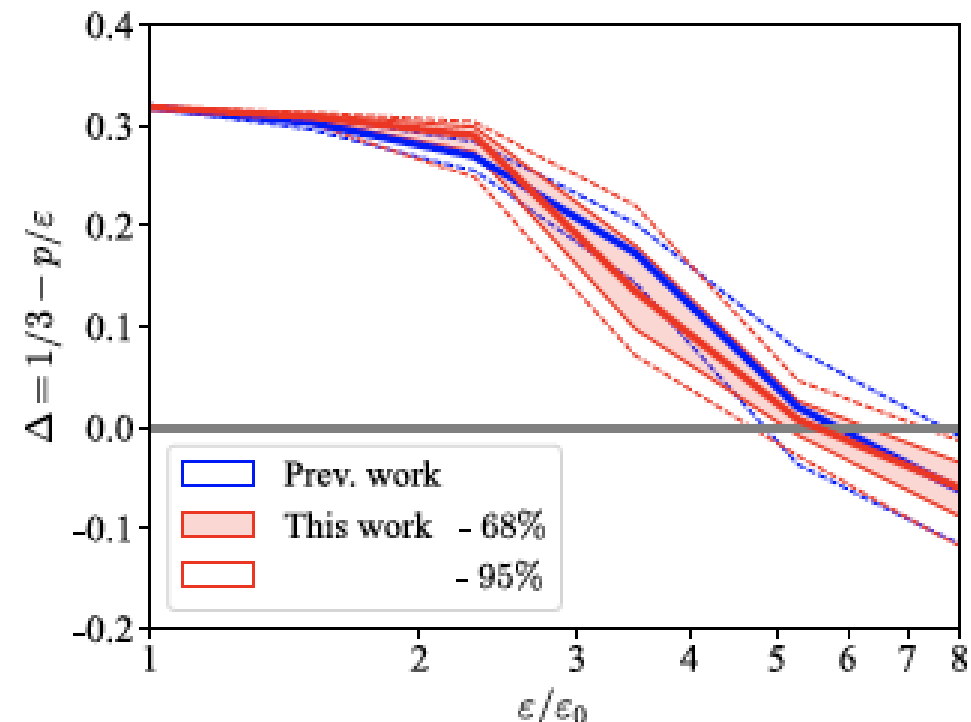
Fujimoto, Fukushima, McLerran, Praszalowicz

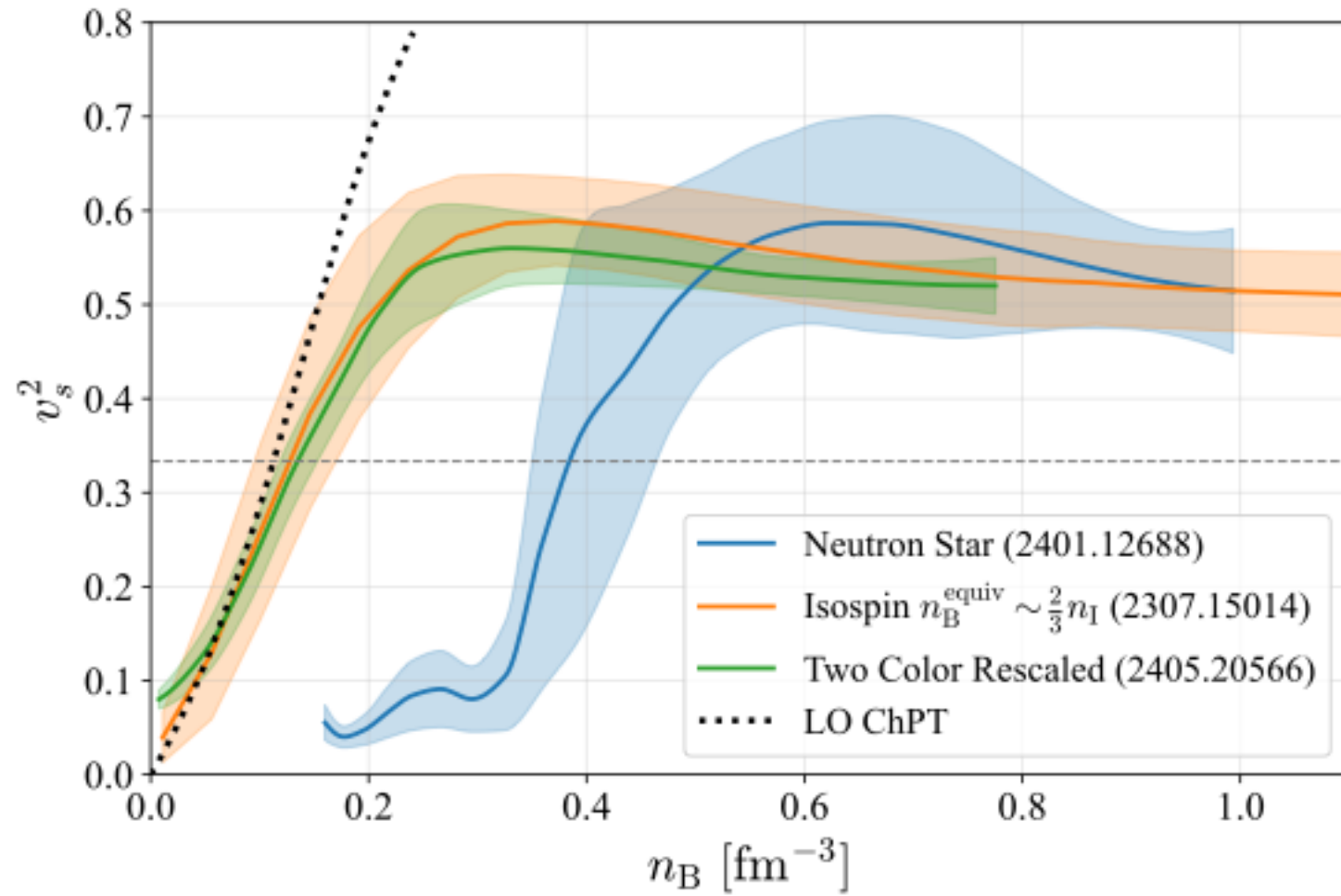
$$v_s^2 = \frac{dP}{d\epsilon} = v_{s,deriv}^2 + v_{s,non-deriv}^2$$

$$v_{s,deriv}^2 = -\epsilon \frac{d\Delta}{d\epsilon}$$

$$v_{s,non-deriv}^2 = \frac{1}{3} - \Delta$$

The derivative term generates the peak in the sound velocity





Comparisons of lattice computations of finite density matter for two color QCD, for three colors at finite isospin density and neutron star results

How does one understand the onset of quarkyonic matter:

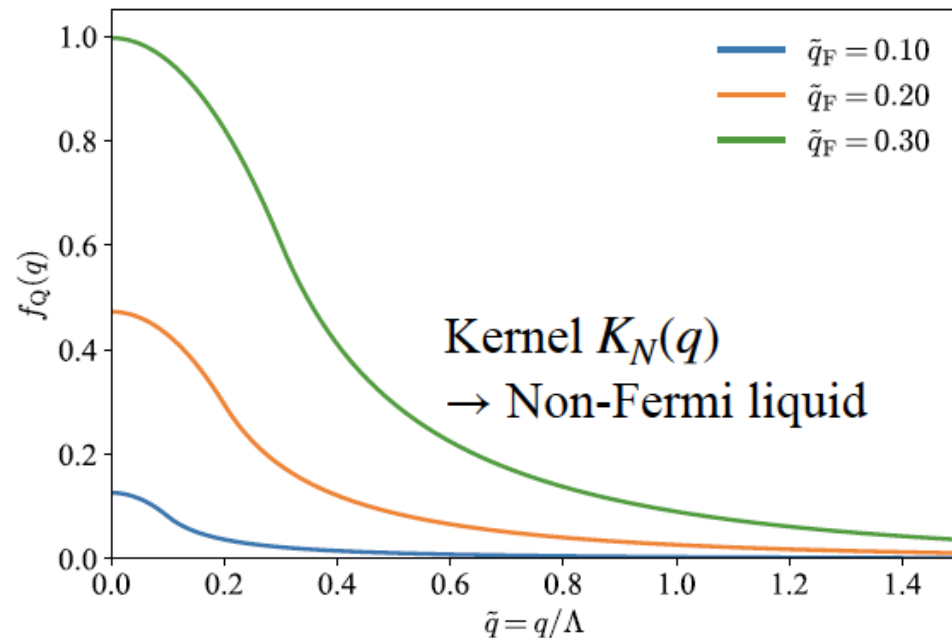
Kojo

$$f_Q(q) = \int \frac{d^3k}{(2\pi)^3} K_N(q - k/N_c) f_B(k)$$

$K_N(q)$ is the probability to find a quark of momentum q in the nucleon

f are phase space distributions for quarks and nucleons: $n = g \int \frac{d^3p}{(2\pi)^3} f$

If we take a Fermi-Dirac distribution: $f_B(k) = \theta(\mu_B - k)$



Increasing baryon chemical potential results in increasing occupation of quarks at $q = 0$: but the occupation density cannot be larger than 1

At some density the Fermi-Dirac distribution for nucleons must be strongly modified

This is Kojo Filling Criteria KFC

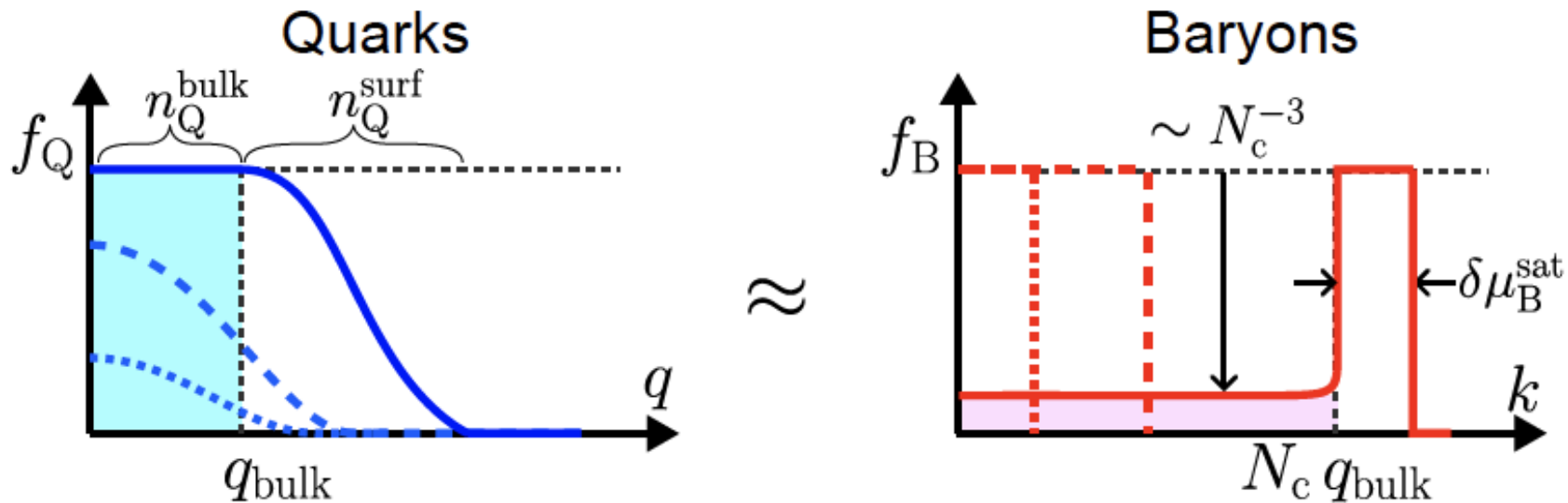
For reasonable probability distribution this occurs close to nuclear matter density
Quarkyonic Saturation

At very high density, the width of the baryon number distribution becomes large compared to the width of the quark probability distribution

$$f_Q(k) = 1 \sim N_c^3 f_B(N_c q) \Rightarrow f_B(N_c q) = \frac{1}{N_c^3}$$

This works for an ideal gas of nucleons where for a particular probability distribution, the theory may be solved exactly: Idylliq Model

Fujimoto, Kojo, McLerran

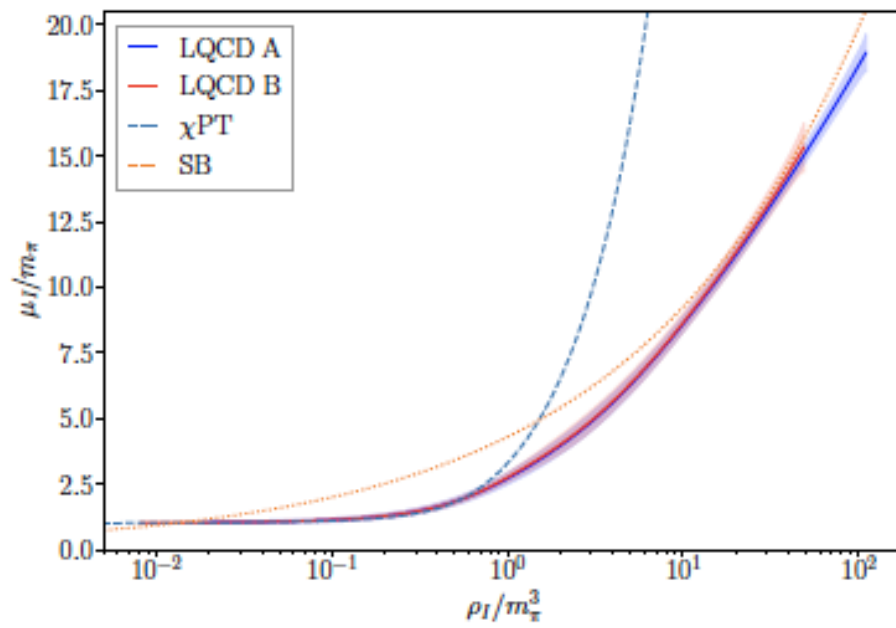
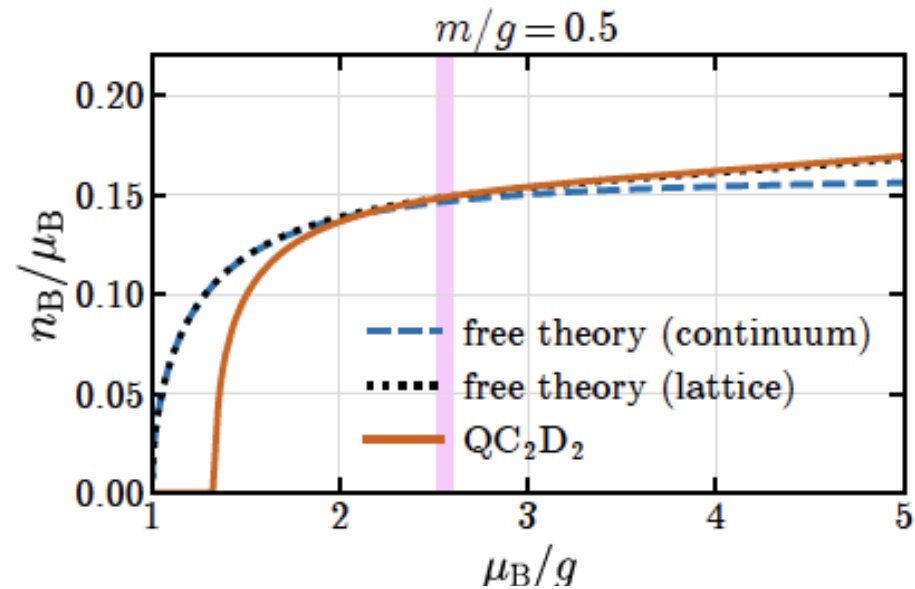


$$v_s^2 = \frac{n_B}{\mu_B dn_B / d\mu_B}$$

Increases and can have maximum at transition

Can we see this in QCD like systems:

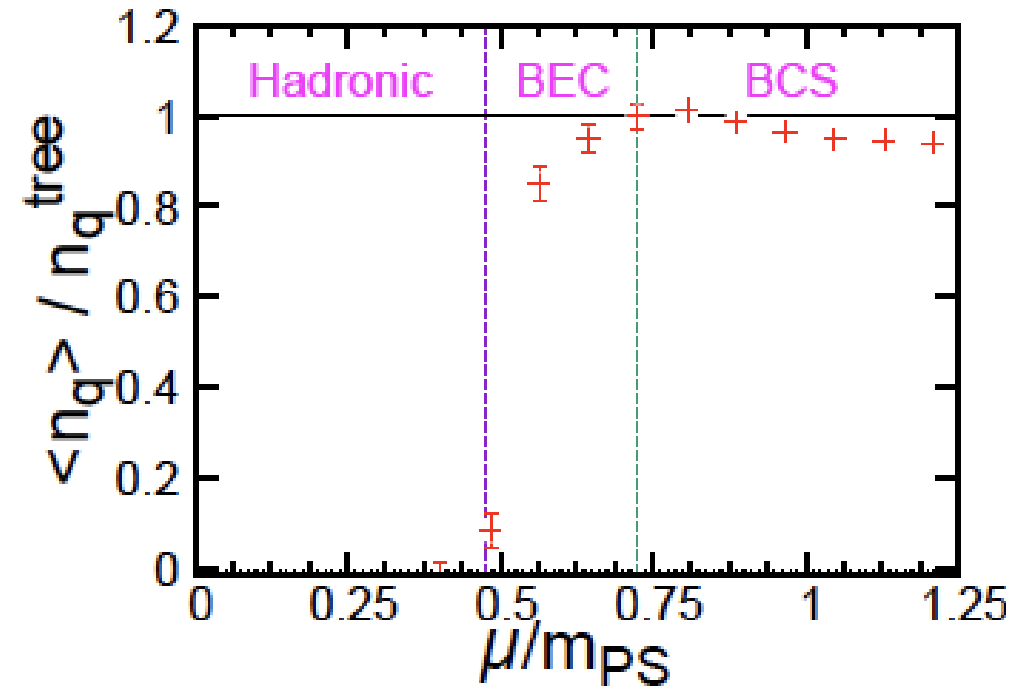
2-D 2 color QCD Fujikura-Hidaka



4 D 3 Color
Isospin
Density

Detmold et.
Al.

4 D 2 color QCD Itou



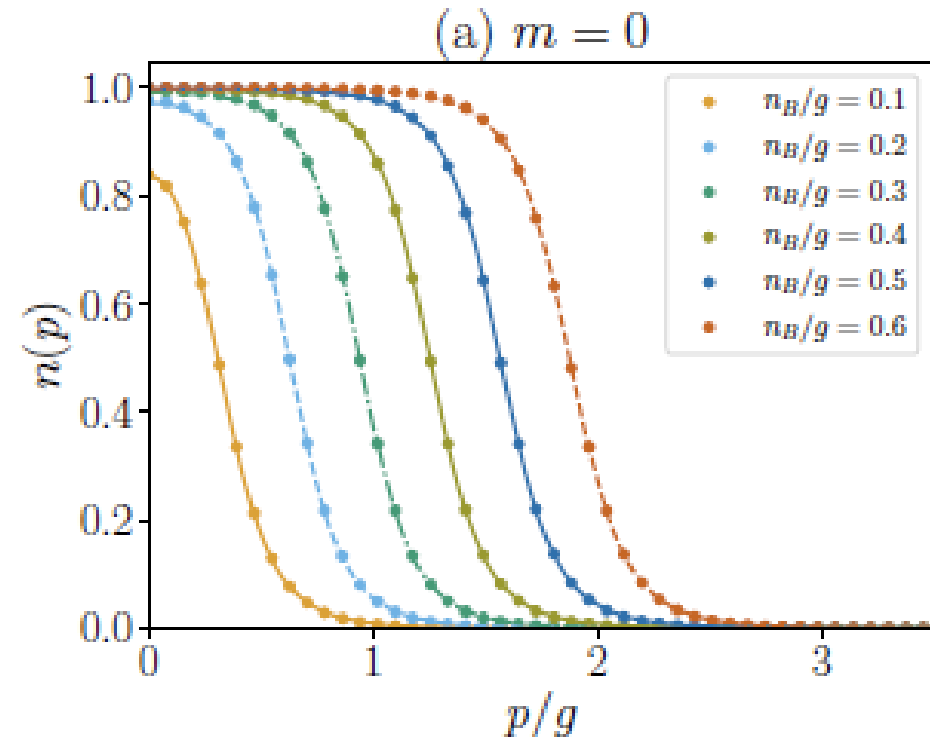
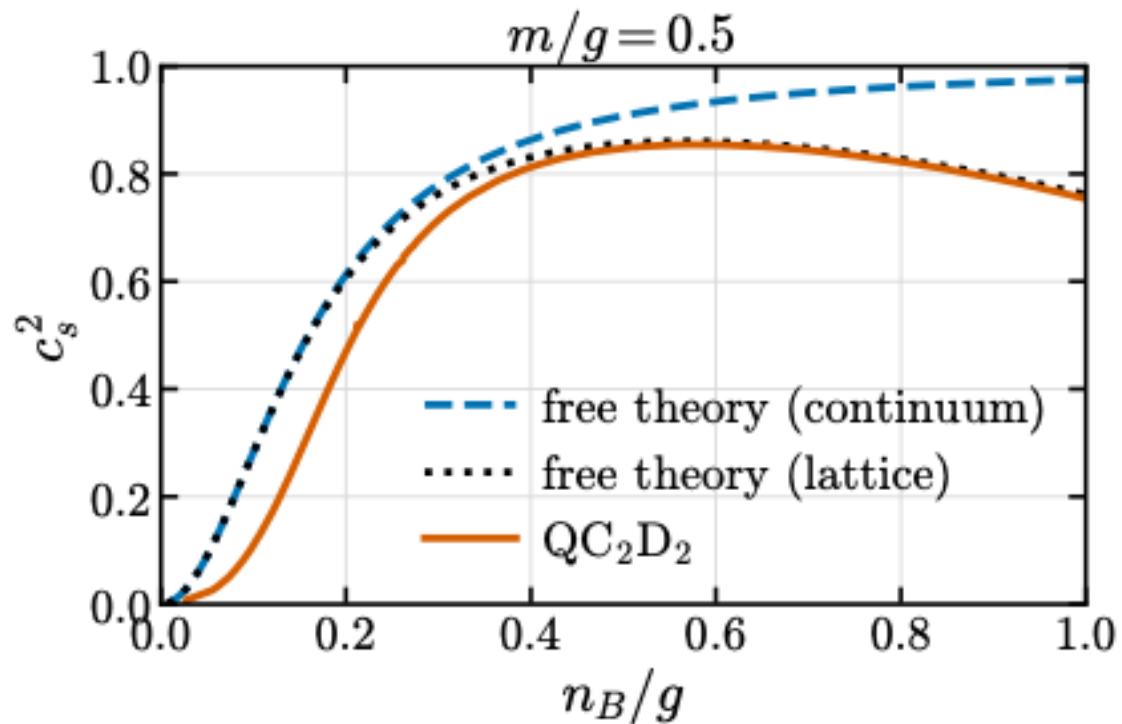
All go rapidly to Stephen-Boltzman
limits for quark densities:

But in first two case there is
compelling data and arguments
that the systems are confined

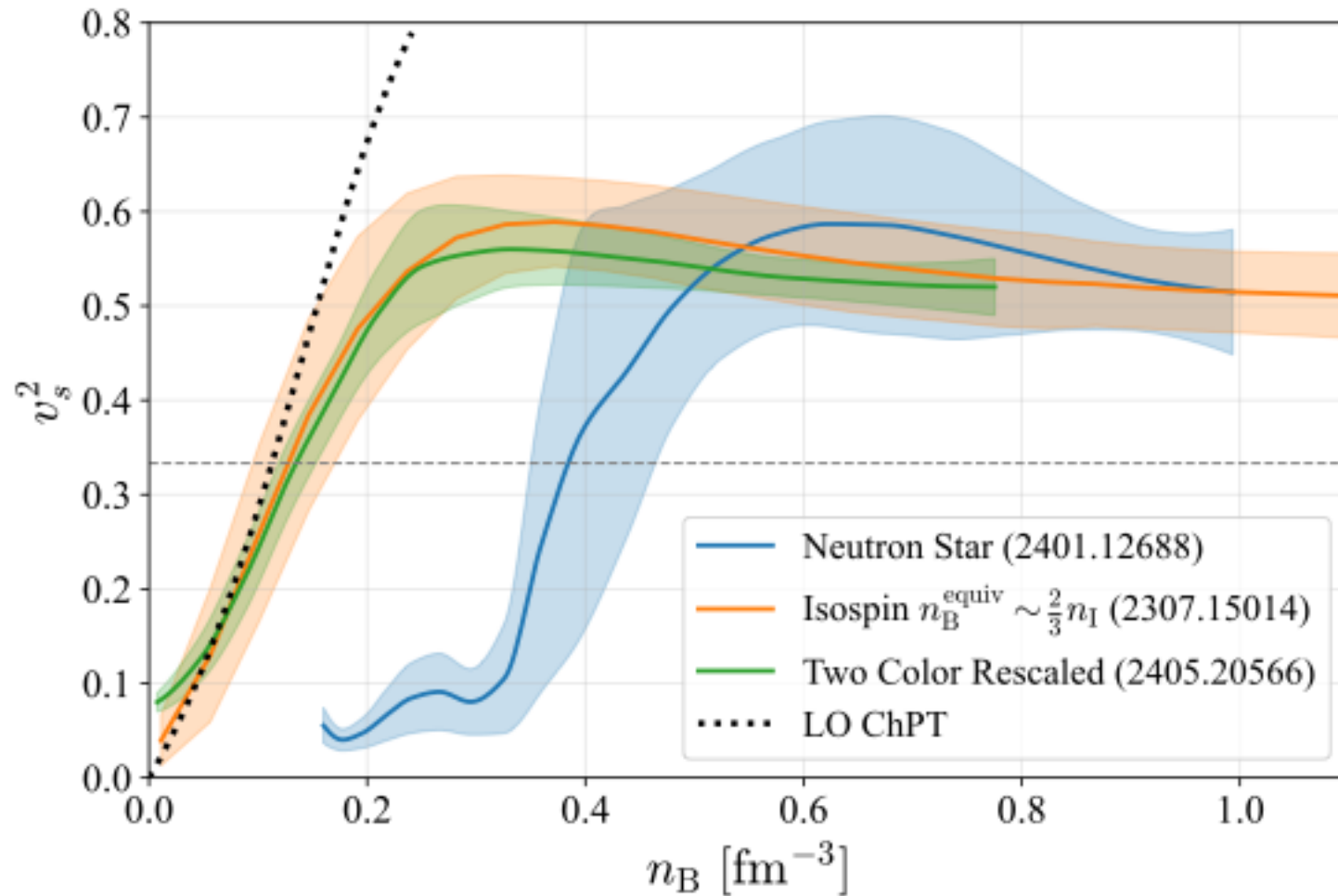
In 1+1 dimension, density barely effects Debye mass and theory is confined for all densities

$$M_D^2 \sim \frac{g^2}{N_c} \ln(\mu/g)$$

Kojo scenario sets in at very low density



There is no condensation in 1+1 d computation, and it can be generalized, to general N_c , with increasing computational difficulty as N_c increases



Lattice computations appear to support the Quarkyonic Hypothesis

In spite of system being strongly interacting, and confined, the phase space density of quarks saturates and tends to Steffan-Boltzman values. This transition generate large sound velocities. For theories with condensation, the rise in sound velocity is driven by condensates.

The saturation of sound velocity seems to correspond to formation of Quarkyonic matter.

Need Wilson loop information for isospin density theories.

Need information on quark phase space densities for 3+1 d theories

Quarkyonic Matter provides a simple and natural explanation of the hard equations of state required to describe neutron stars.

