Introductory Comments on High Density and Quarkyonic Matter

The concept of quarkyonic matter comes from the large N_c limit

In this limit the interaction strength is

$$\frac{g^2 N_c}{4\pi} \sim \alpha$$

and is finite in the limit

$$N_c \to \infty$$

In this limit gluon loops are important and quark loops are not because there are ~ N^2 gluons but only N quarks. So at finite density and zero temperature, quarks will not Debye screen the potential. Matter is always confined. This is true until

$$\mu^2_{Quark} \sim N_c \Lambda^2_{QCD} \qquad \text{or} \qquad \mu_{Baryon} \sim \sqrt{N_c}\; M_{proton}$$

If matter is confined and chiral symmetry is broken, then baryons have a mass

$$M_B \sim N_c \Lambda_{QCD}$$

So that for temperatures less than or of the order of the QCD scale there are no baryons

$$e^{(\mu_B - M_B)/T} \sim e^{-N_c}$$

When the baryon chemical potential exceeds the baryon mass there can be baryons, but matter remains in the confined phase. This can be true until the baryon chemical potential is parametrically large compared to the baryon mass where we would ordinarily expect de-confined matter

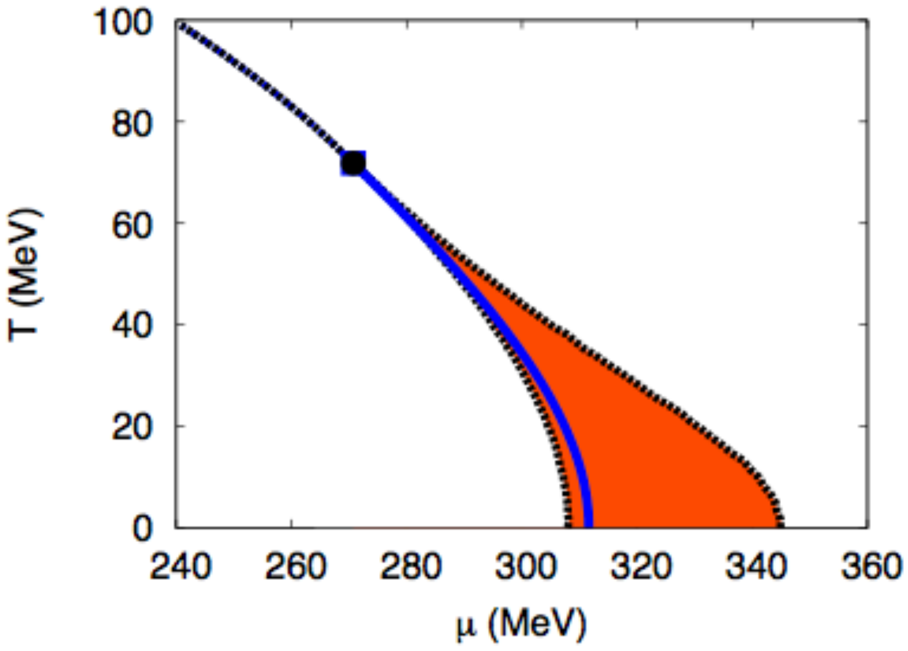
This new matter which has a densities large compared to natural QCD scales has properties of both quark matter and baryonic matter and is therefore named quarkyonic matter

When typical quark energy scales are large compared to QCD scales, typical scatterings will be at a hard scale and therefore the quarks can be treated perturbatively. Quarks deep inside the Fermi sea scatter as such, and we can think of matter deep inside the Fermi sea as an almost free gas of quarks.

On the Fermi surface, quarks can scatter at small angles so long distance effects are important. The Fermi surface is intrinsically non-perturbative. Thermal excitations such as quark particle hole excitations and glouns, and quark baryonic degrees of freedom near the Fermi surface are confined mesons, glueballs and baryons

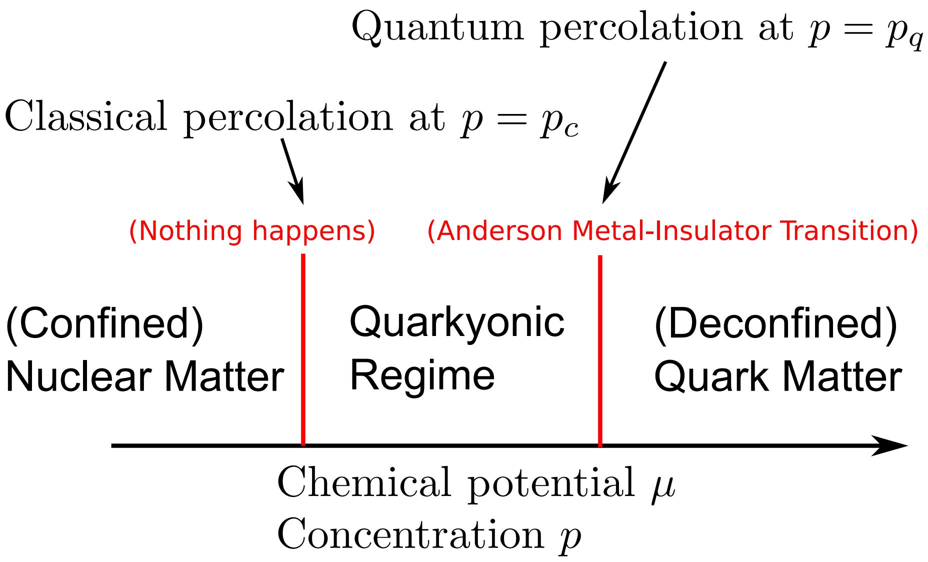
As we raise the temperature at low baryon number density, one reaches a confinement transition. At large N, and finite baryon number density not parametrically large compared to the QCD scale the confinement transition is unaffected by the baryon density. It is a line at fixed temperature.

What happens with chiral symmetry?
If matter is confined, one expects that chiral symmetry is broekn. Even if densities are large compared to QCD scales.
Chiral symmetry breaking can take place near the Fermi surface
If one tries to condense a particle hole excitations at finite density, these a particle and hole near the Fermi surface have an energy that is twice the Fermi energy. Therefore the mesons of such a condensate carry finite momentum.
This means that such a condensate will not be rotationally and translationally invariant.
This is a rich area for study, and there are many issue unresolved.
(See talks by Carignano, Chao, Fukushima, He and Hidaka
In particular are the mean field conclusions modified by quantum fluctuations)



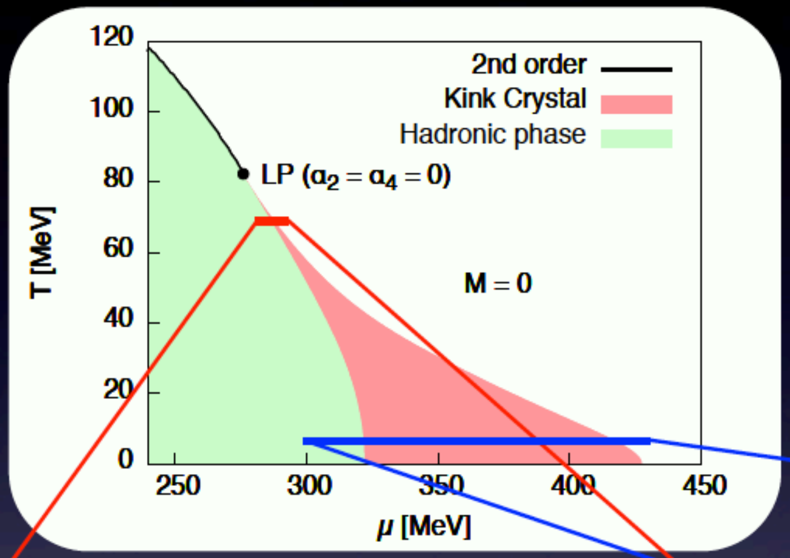
- Allow for 1D modulations like $M(z) = \Delta\sqrt{\nu}\,\mathrm{sn}(\Delta z|\nu)$
- First order transition line covered by inhomogeneous phase
- All phase transitions are 2nd order
- Critical point $\rightarrow$ Lifschitz point

Carignano

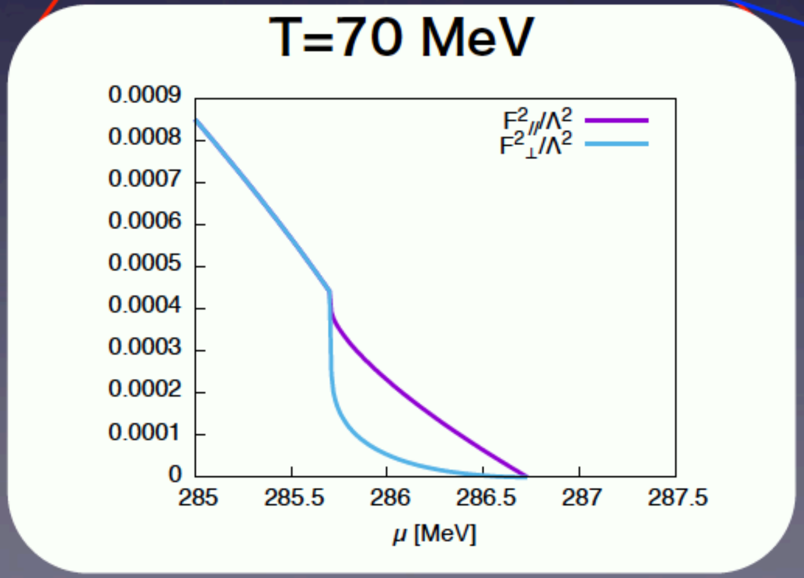


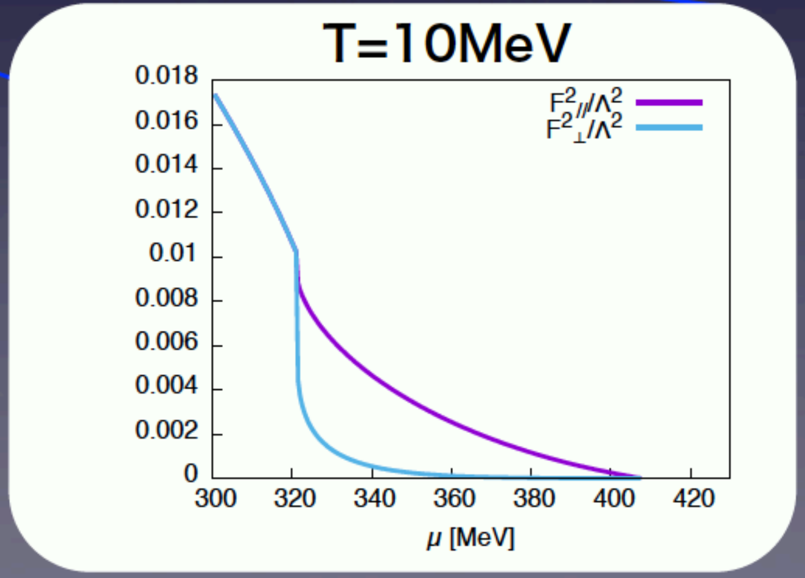
Fukushima

Elastic free energy for pion



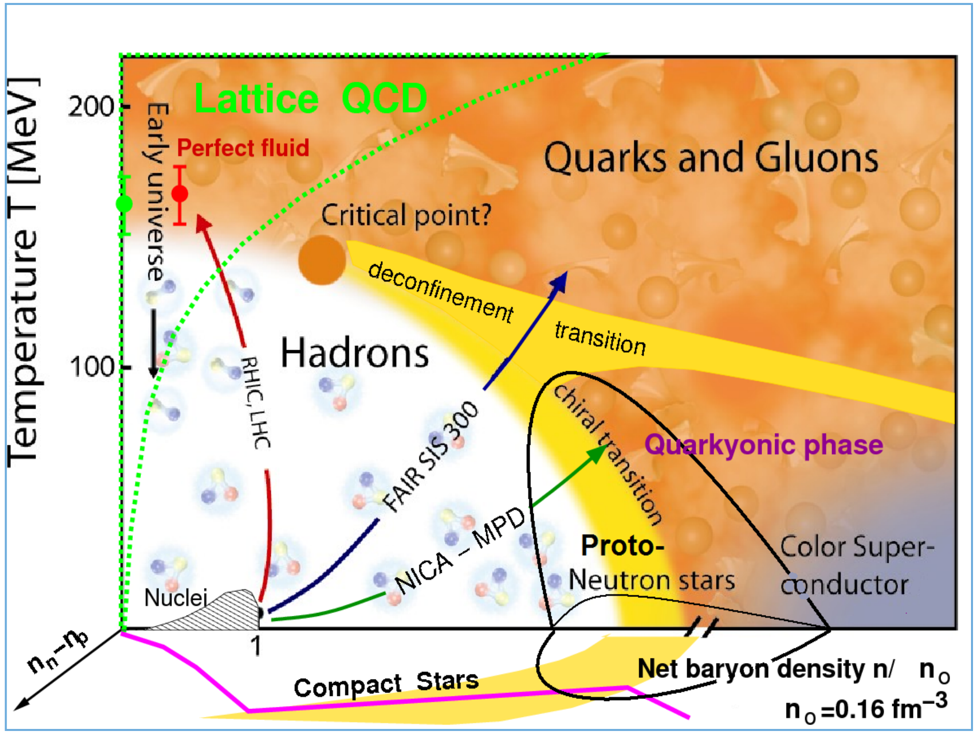
$$\Omega_{\rm el} = \frac{F_z^2}{2}(\partial_z \pi^a)^2 + \frac{F_\perp^2}{2}(\nabla_\perp \pi^a)^2 + \cdots$$





Anisotropic dispersion relation for pions but first order transitions disappears?

Hidaka



“Inhomogeneous Phases”

A region surrounded by lines of phase transitions where there is a chiral symmetry breaking in non-translational and rotational invariant mode

“Triple point”

Where the quark gluon plasma, quarkyonic matter and confined mesonic matter coexist

“Critical End Point”

Where first order phase transition end, assuming there is a region with first order phase transitions

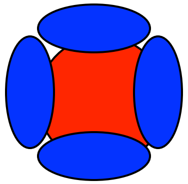
Color Superconductivity:

At very high density and low temperature, should be colored Cooper pairs analogous to Cooper pairs of ordinary matter.

How does one understand chiral symmetry breaking at high baryon density?

Various !+1 dimensional models:
(Tsvelik)

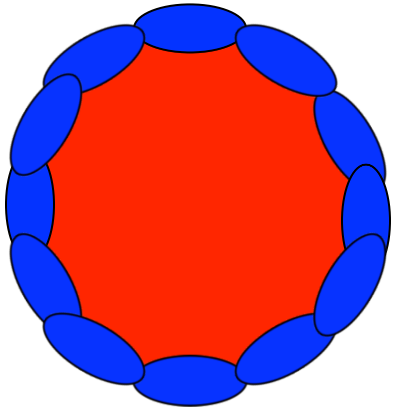
Mean Fields Models in 2+1 Dimensions:
Kojo, Tsvelik, Pisarski, Hidaka, Mclerran



An effective low energy theory near the Fermis surface, with a cutoff scale associated with how deep into the Fermi surface one measures. Generalization to the lattice with renormalization group techniques?

$$\mu_Q \sim \Lambda_{QCD}$$

Patching the Fermi surface:



N-fold discrete symmetry cannot in general be mapped into a regular periodic structure. Quasi crystals are "almost" periodic lattices.

Phase structure can be rich and complex with different strutures important as the density increases.

$$\mu_Q \sim \sqrt{N_c}\Lambda_{QCD}$$

Another way to understand the gross features of the phase diagram of QCD:

Numbers of degrees of freedom

Quark gluon plasma ~ N^2 for gluons
Confined matter ~ 1
Quarkyonic matter ~ N for quarks

Quarkyonic transition should be in a narrow range of baryon chemical potential

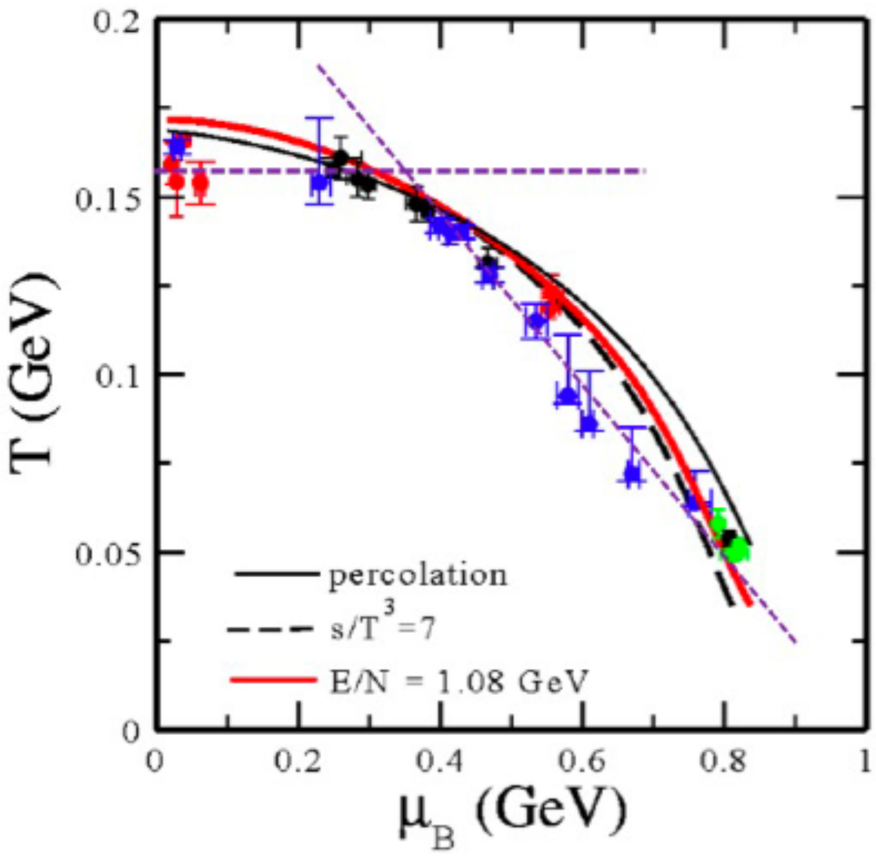
$$k_f \sim \Lambda_{QCD}$$

$$k_f^2/2M \sim 1/N_c$$

$$\delta\mu_Q \sim 1/N_c^2$$

Phase boundary:
Deconfinement;
T – constant
Quarkyonic

$$\mu_B/T \sim constant$$



A. Andronic, D. Blaschke, P. Braun-Munzinger, J. Cleymans, K. Fukushima, L.D. McLerran, H. Oeschler, R.D. Pisarski, K. Redlich, C. Sasaki, H. Satz, J. Stachel,

Reinhard Stock, Francesco Becattini, Thorsten Kollegger, Michael Mitrovski, Tim Schuster

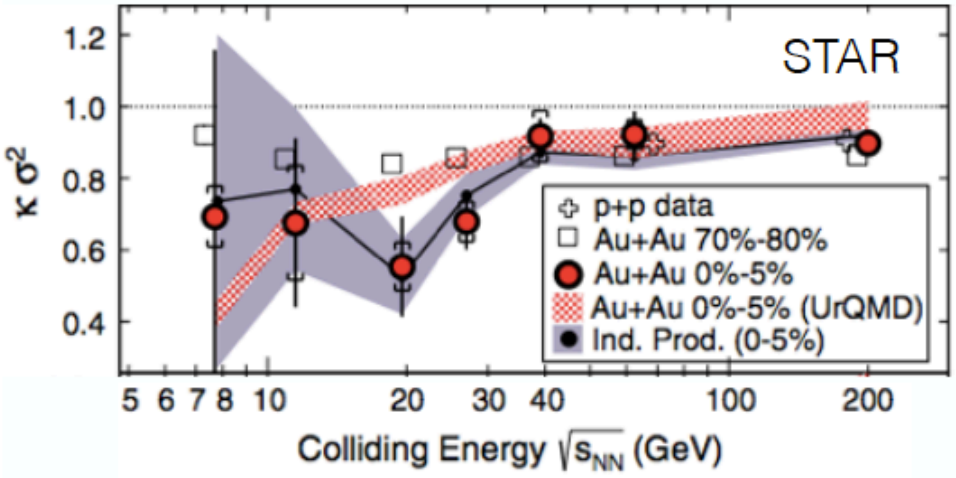
Measured abundances fall on curve with fixed baryon chemical potential and temperature at each energy: suggests a phase transition with a rapid change in energy density

High density low T points deviate from expectations of deconfinement transition

Decoupling curve more or less what one expects.

What can we learn from experiment:
Braun Munzinger

Cumulants of proton number fluctuations



$$(\kappa\sigma^2)_B = \frac{\chi^B_{4,\mu}}{\chi^B_{2,\mu}} = \frac{\chi^B_4}{\chi^B_2}\left[1 + \left(\frac{\chi^B_6}{\chi^B_4} - \frac{\chi^B_4}{\chi^B_2}\right)\left(\frac{\mu_B}{T}\right)^2 + \cdots\right]$$

In the O(4) universality class:

$$\chi^B_6 < 0\,, \qquad T \sim T_c$$

Heng-Tong Deng: Perhaps measured fluctuations are related to lattice computations? Beam energy scan?

OR

These may have little to do with the phase boundary, or might be related to universal behaviour in the expansion dynamics (Mukherjee, Venugopalan, Yin)

In heavy ion collisions and neutron stars, there are strong magnetic fields

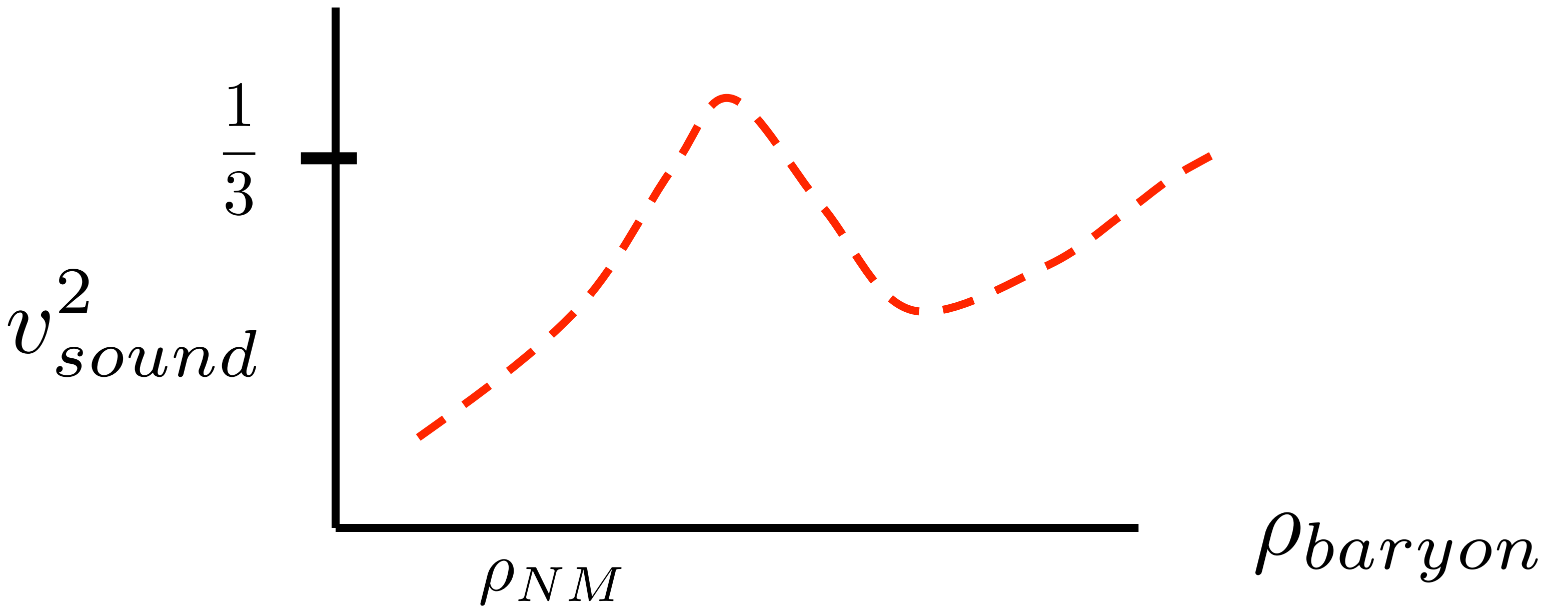
How do magnetic fields affect the phase structure and phenomena such as deconfinement and chiral symmetry breaking? Are there new condensates and new phenomena?
Ferrer, de Incerra, Hattori

How do do an honest description of matter in magnetic fields, with vorticity and possibly novel topological effects?
Yamamoto

How does this affect transport in supernova explosions
Yamamoto

Neutron Stars

Observed maximum mass of neutron start requires a maximum in the speed of sound at a few times nuclear matter density. The sound velocity squared at this maximum is close to 1/3 . The equation of state need to stiffen up to support the star



Such a maximum occurs in computations where quark matter is continuously mapped to nuclear matter/ (Kojo)
Is this a possible signature for a transition to quark degrees of freedom?

Speculative questions?

The large N_c limit:
Even N_c: Baryons are bosons
Odd N_c baryons are fermions
Is there a duality between Bose condensations and a Fermi sea
at large N_c

In the standard way of counting the large N_c limit in the chiral limit, pions are massless but have interaction strength of order N_c. In fact, nuclear matter is bound by an energy of order the nucleon mass, and nuclear matter is a giant crystal. In nature the binding energy of nuclear matter is of order $1/N_c$.
Also long and intermediate range nuclear forces are not strong in nature due to mysterious cancellations?

Are we counting correctly?
Are we missing a crucial ingredient
Kojo, Pisarski, Hidaka, McLerran