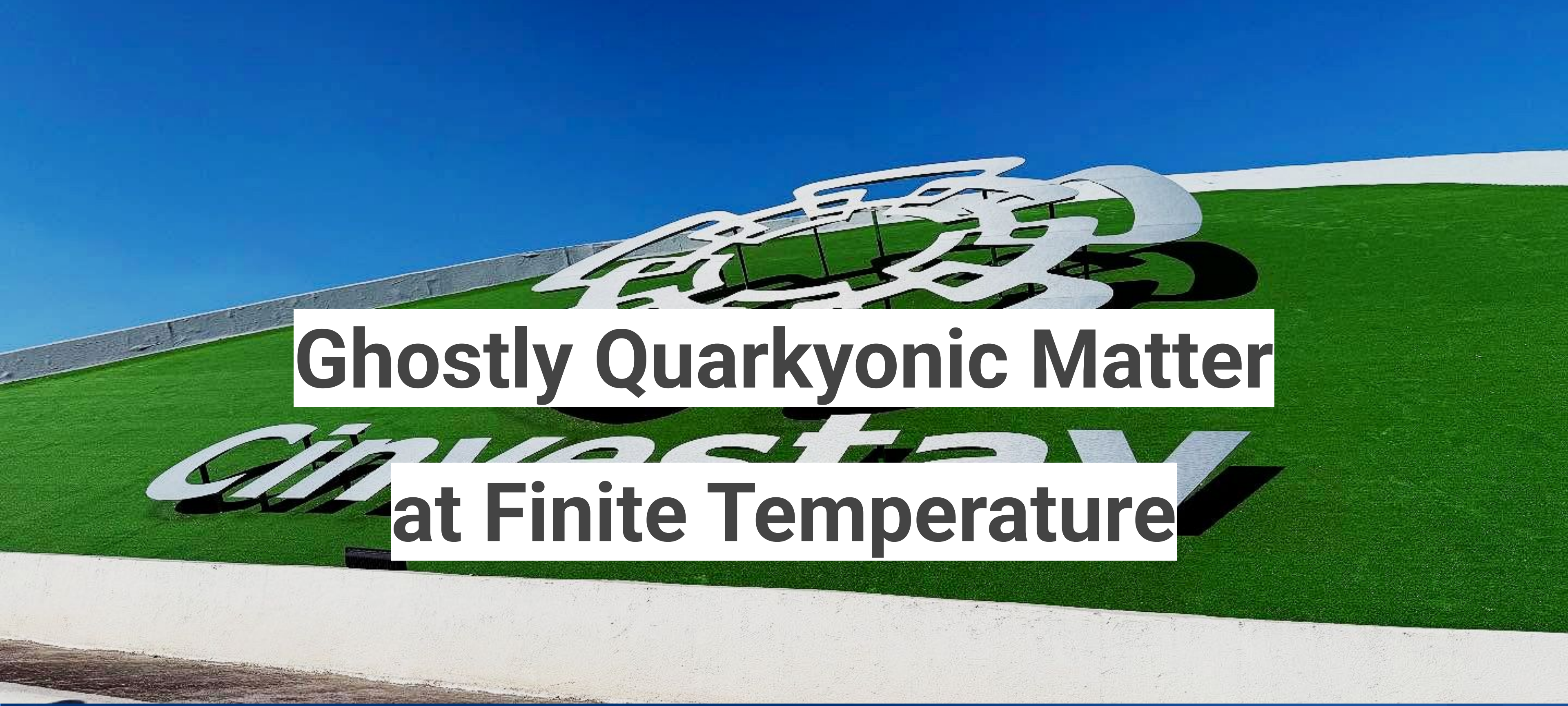
Ghostly Quarkyonic Matter at Finite Temperature



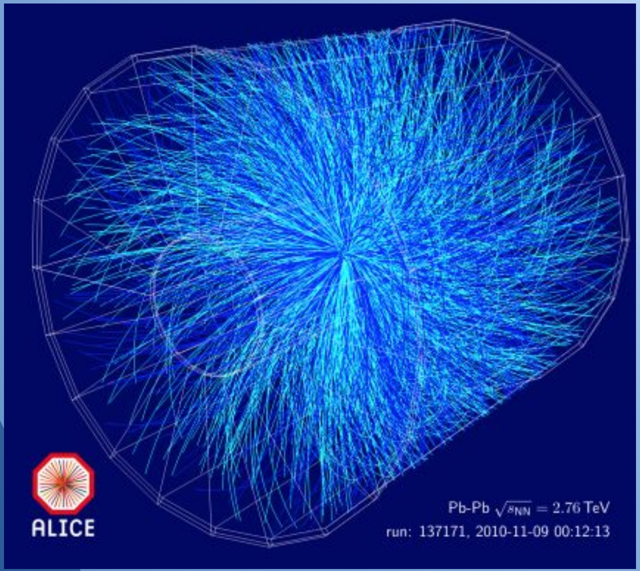
Saúl Hernández-Ortiz

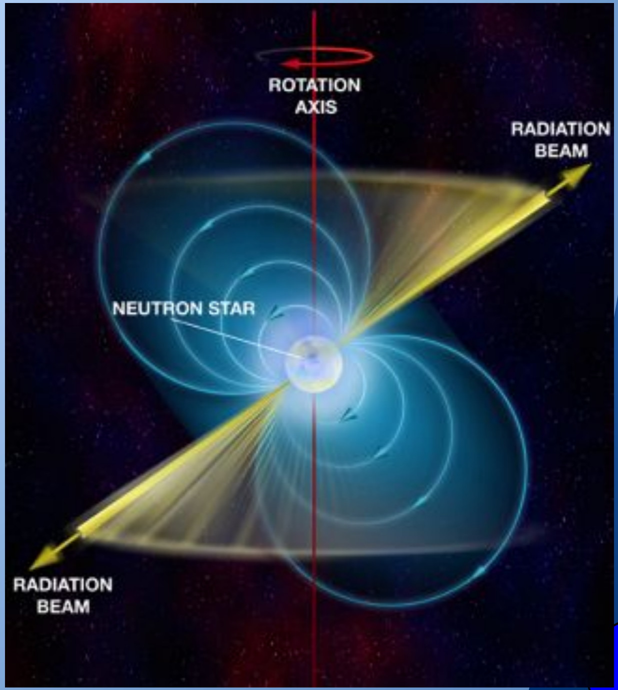
Outline

- Motivation
- Quarkyonic Matter
- Introducing ghost field
- Finite Temperature
- Final Remarks

Motivation

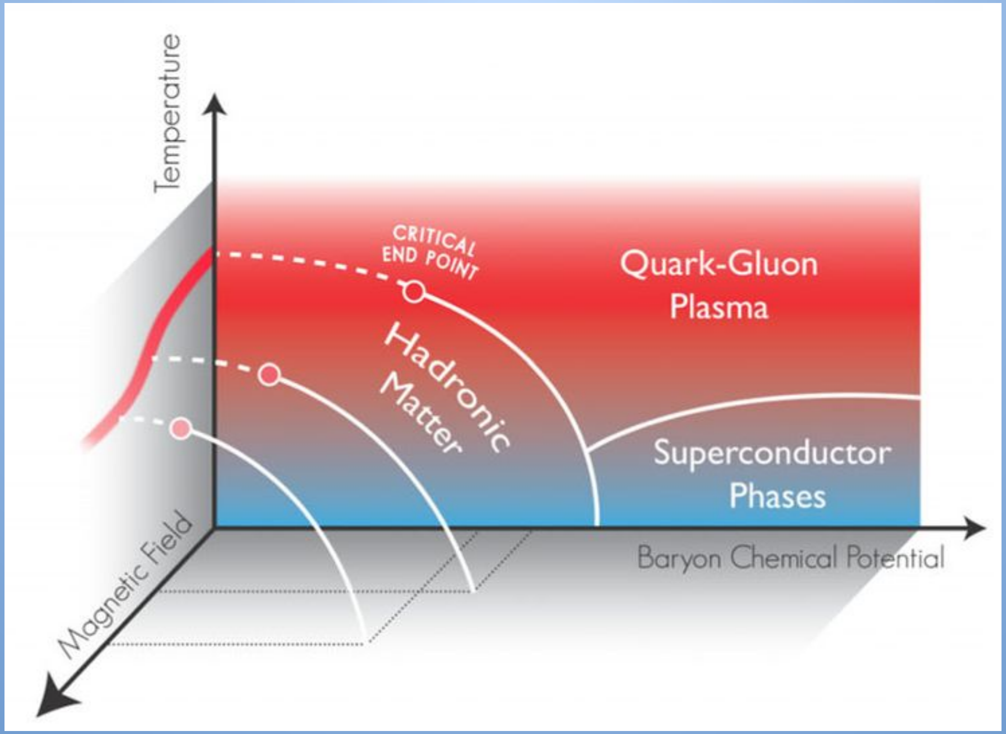
- QCD under extreme conditions (temperature, finite density and magnetic fields) plays an important role in understanding the transitions that took place in the early universe.





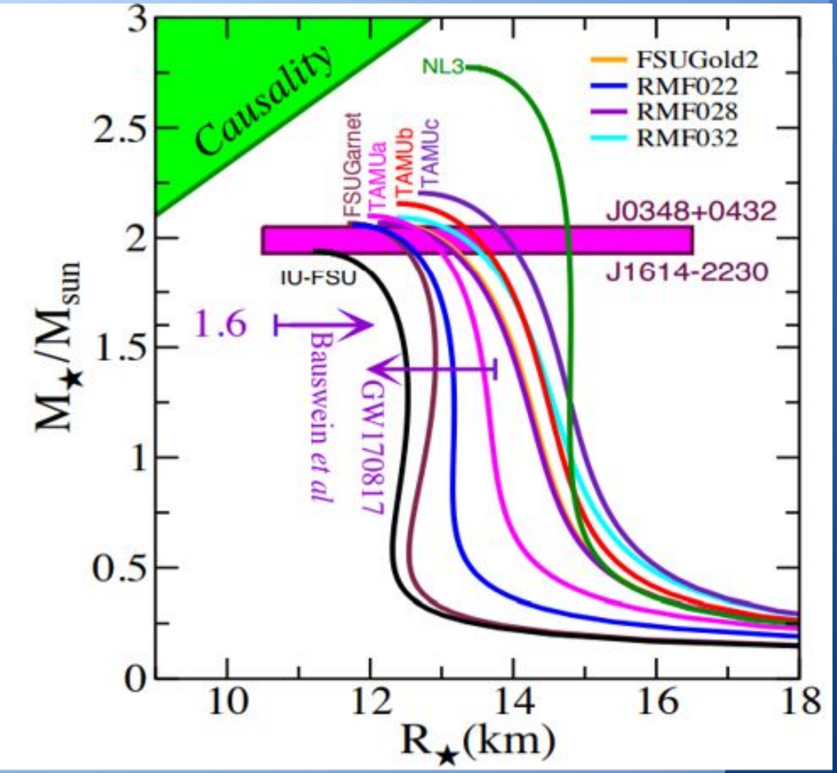
Motivation

- One way to illustrate the different phases of strongly interacting matter we seek to study is by means of the phase diagram



Motivation

- Observation and analysis of GW170817: Important clues to understand cold and dense matter.
- The structure of a neutron star (NS) is determined by the Tolman-Oppenheimer-Volkoff Equation (TOV).

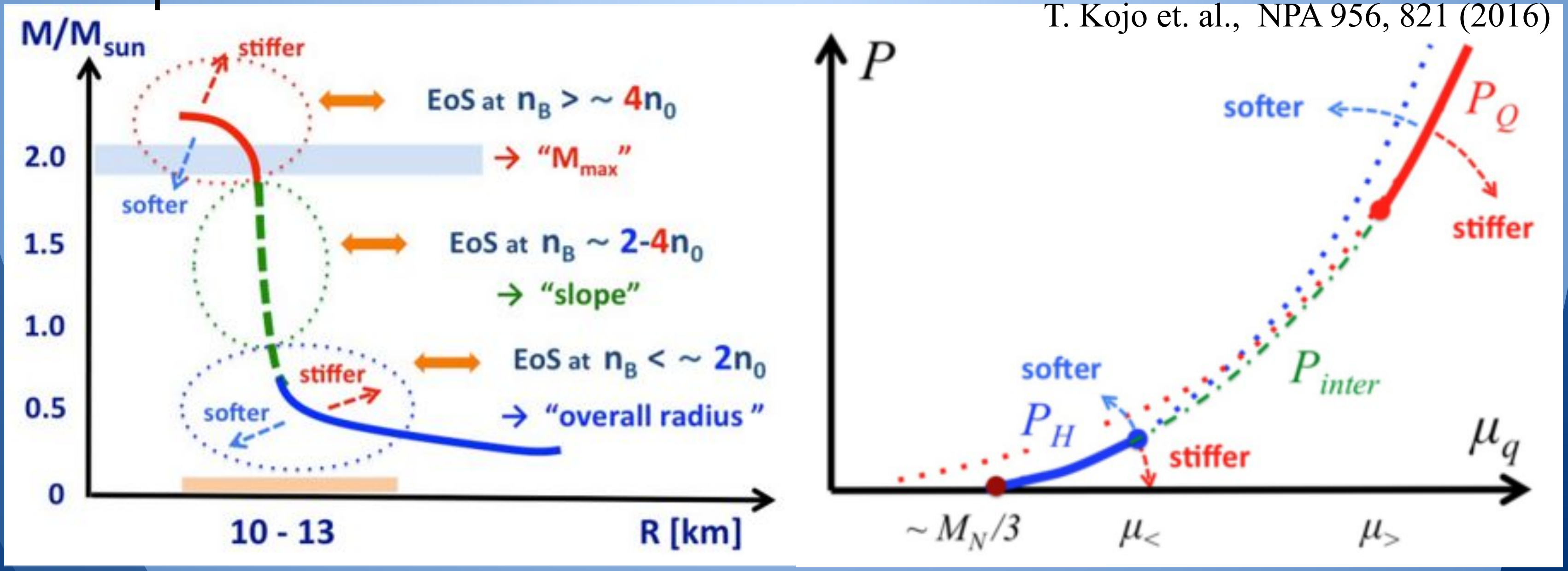


F. J. Fattoyev et. al, PRL 120, 172702 (2018)

Motivation

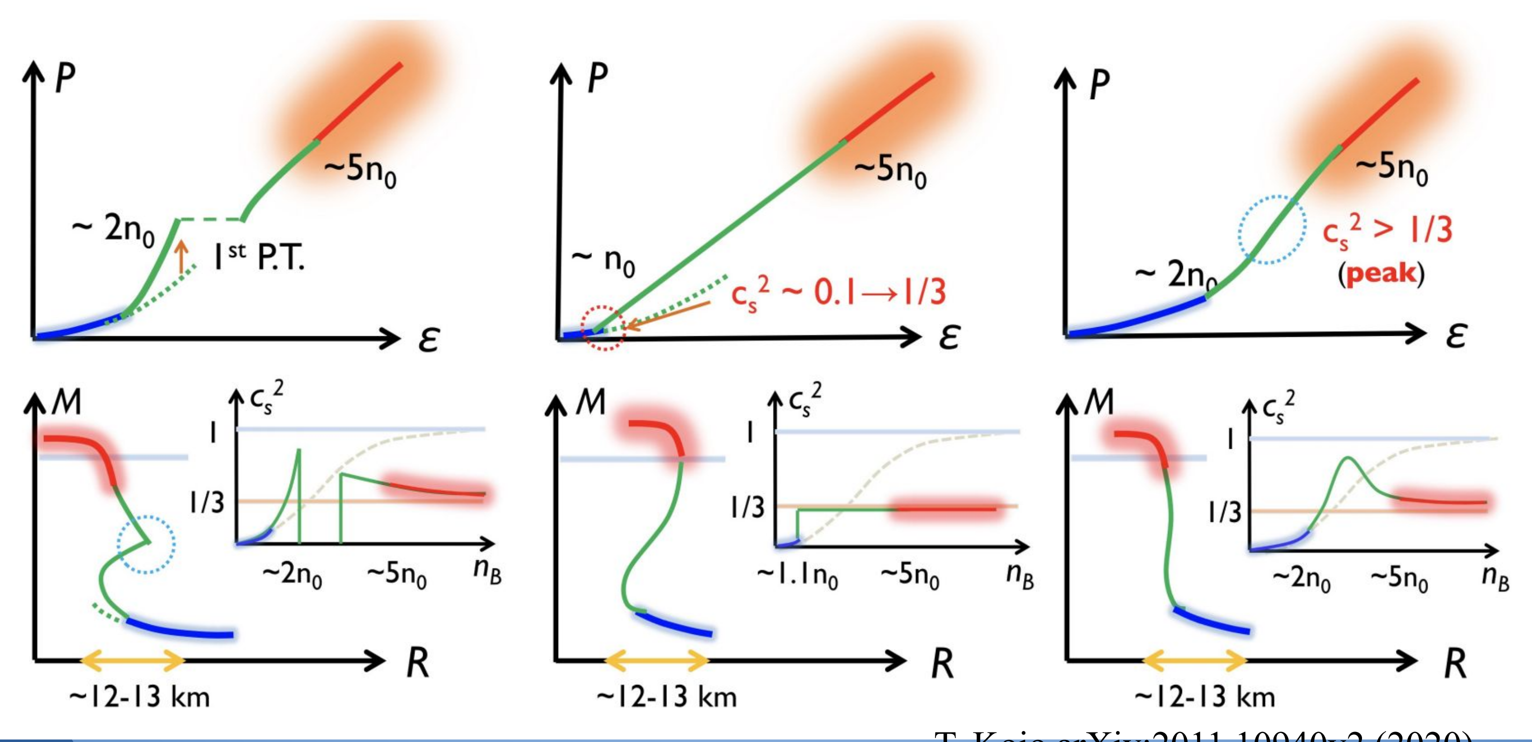
- Description of Equation of State (EoS) of dense QCD matter:
  - Around saturation density: Nuclear experiments.
  - Very high density limit: Asymptotic freedom allows perturbative calculation.

T. Kojo et. al., NPA 956, 821 (2016)



Motivation

- TOV and EoS can give some insight about the transition quark-nucleon matter.



T. Kojo arXiv:2011.10940v2 (2020)

Motivation

- The square of the speed of sound is usually defined as

$$c_\chi^2 = \left(\frac{\partial p}{\partial \epsilon}\right)_\chi$$

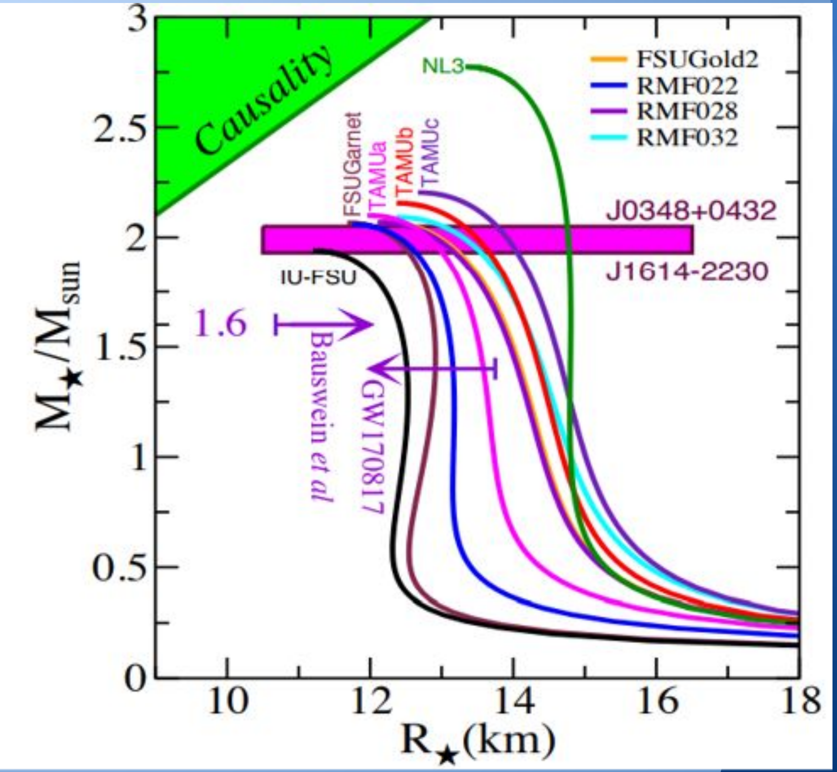
where χ denotes the parameter fixed in the calculation of the speed of sound.

- According to the properties on the propagation medium, it may be more useful to keep one quantity fixed rather than another.

Motivation

- EoS should be hard enough to support $2M_\odot$ and soft enough to satisfy $R_{1.4} \leq 13.5$ km.

- This is also reflected in sound velocity, that should increase rapidly and can be greater then its conformal value $c_s^2 \geq 1/3$.



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Any suggestions?

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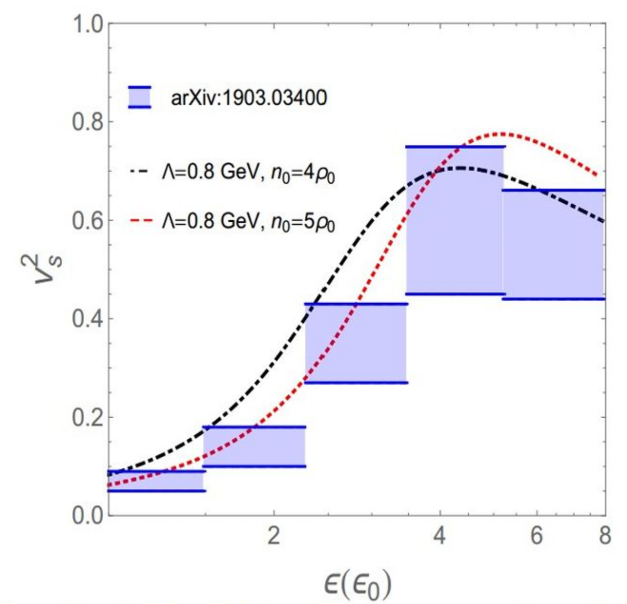
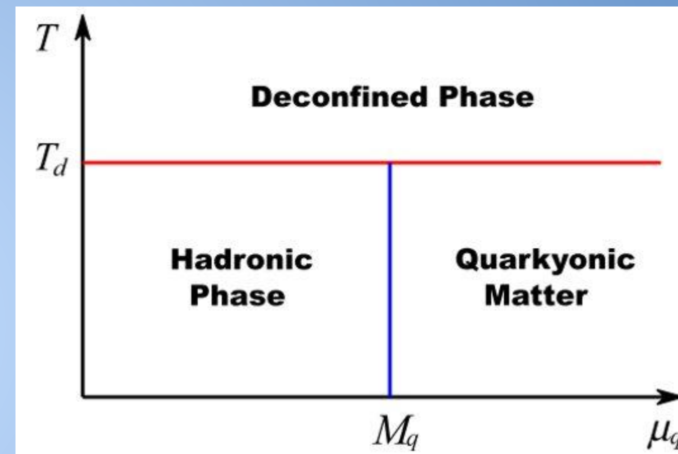
Any suggestions?

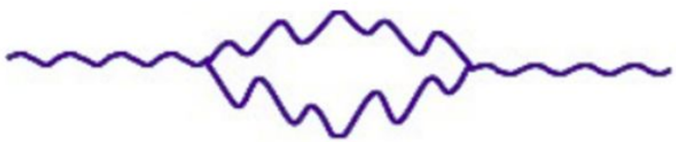


Sound velocity obtained from an equation of state extracted from neutron stars properties using deep neural network.
K.S. Jeong, L. McLerran, S. Sen, Phys. Rev. C 101 035201 (2020)

Quarkyonic Matter

Phase of dense matter, argued from large Nc approximation and model computations.





Gluon loop

→$g^2N_cT^2 \sim T^{2};$

→Dynamics not affected by quarks;

→Debye screening at large distances.

Quark loop

→$\sim \mu_Q^2 g^2 \Rightarrow$ Supressed by $1/N_c$ at large N_c.

→High density limit: $\mu_Q \gg \Lambda_{QCD}$, so quarks are important when $\mu_Q \sim N_c^{1/2}\Lambda_{QCD.}$

→Debye screen mass $m_D \simeq g\,\mu_Q$

Quarkyonic Matter

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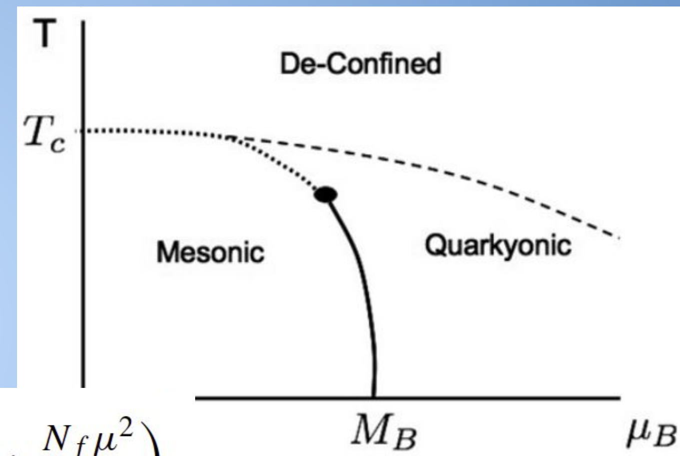
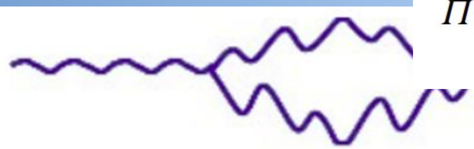


$$\Pi^{\mu\mu}(0) = g^2\left(\left(N_c + \frac{N_f}{2}\right)\frac{T^2}{3} + \frac{N_f\mu^2}{2\pi^2}\right).$$



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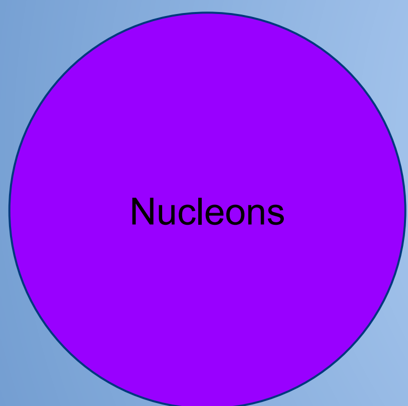
Quarkyonic Matter

Nuclear → Quarkyonic

(at few times ρ_0)



- For $k_F^B < \Lambda_{\mathrm{QCD}}$: Quarks confined in nucleons.

Quarkyonic Matter

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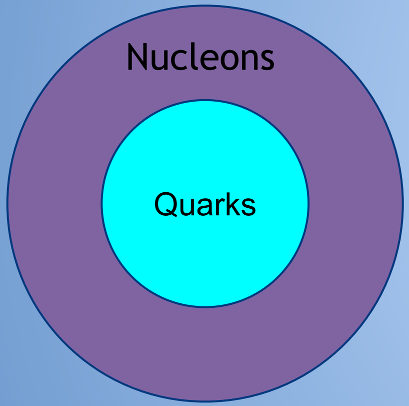

- For $k_F^B < \Lambda_{\mathrm{QCD}}$: Quarks confined in nucleons.
- For $\Lambda_{\mathrm{QCD}} \leq k_F^B \leq N_c \Lambda_{\mathrm{QCD}}$: Quarks starts to take low phase space, and a shell-like structure is formed.

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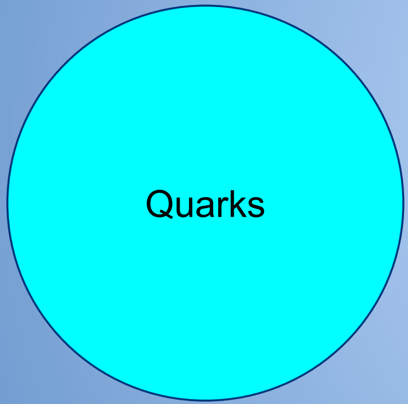


- For $k_F^B < \Lambda_{\rm QCD}$: Quarks confined in nucleons.
- For $\Lambda_{\rm QCD} \leq k_F^B \leq N_c \Lambda_{\rm QCD}$: Quarks starts to take low phase space, and a shell-like structure is formed.
- For $k_F^B \simeq N_c^{3/2} \Lambda_{\rm QCD}$: Confinement disappears.

- Total baryon density has smooth behavior and chemical potential for confined states enhance suddenly, then pressure suddenly increases. *This is not an usual phase transition!*

Quarkyonic Field Theory

- Field theory of quarkyonic matter: nucleonic and quark degrees of freedom in the same description: How to deal with??
  - Nucleons are composed by quarks: since inside the Fermi sea the lower momentum states are occupied by quarks, the nucleons cannot propagate in the region of momentum.
  - In addition to quarkyonic matter, such EFT should reduce to a theory of nucleons and mesons at low densities, and evolve to quarks at high density and temperature.

Quarkyonic Field Theory

- Field theory of quarkyonic matter: nucleonic and quark degrees of freedom in the same

Solution: Inclusion of a negative metric ghost field, that fill precisely the same state as the quarks, and cancel away the degrees of freedom of unconstrained nucleons.

region of momentum.

  - In addition to quarkyonic matter, such EFT should reduce to a theory of nucleons and mesons at low densities, and evolve to quarks at high density and temperature.

Quarkyonic Field Theory

- Nucleons can be thought of as an ensemble of quarks: If there is a quark Fermi sea with a chemical potential μQ in the low momentum states, the quarks composing the nucleon cannot occupy the same states.

$$\rho^G = \frac{1}{1+e^{\beta(N_C E_Q - \mu_G)}} - \frac{1}{1+e^{\beta(N_C E_Q + \mu_G)}}$$

Density of the states in which nucleons cannot exist: Region of quark Fermi sea up to $\mu_G = N_c \mu_Q$.

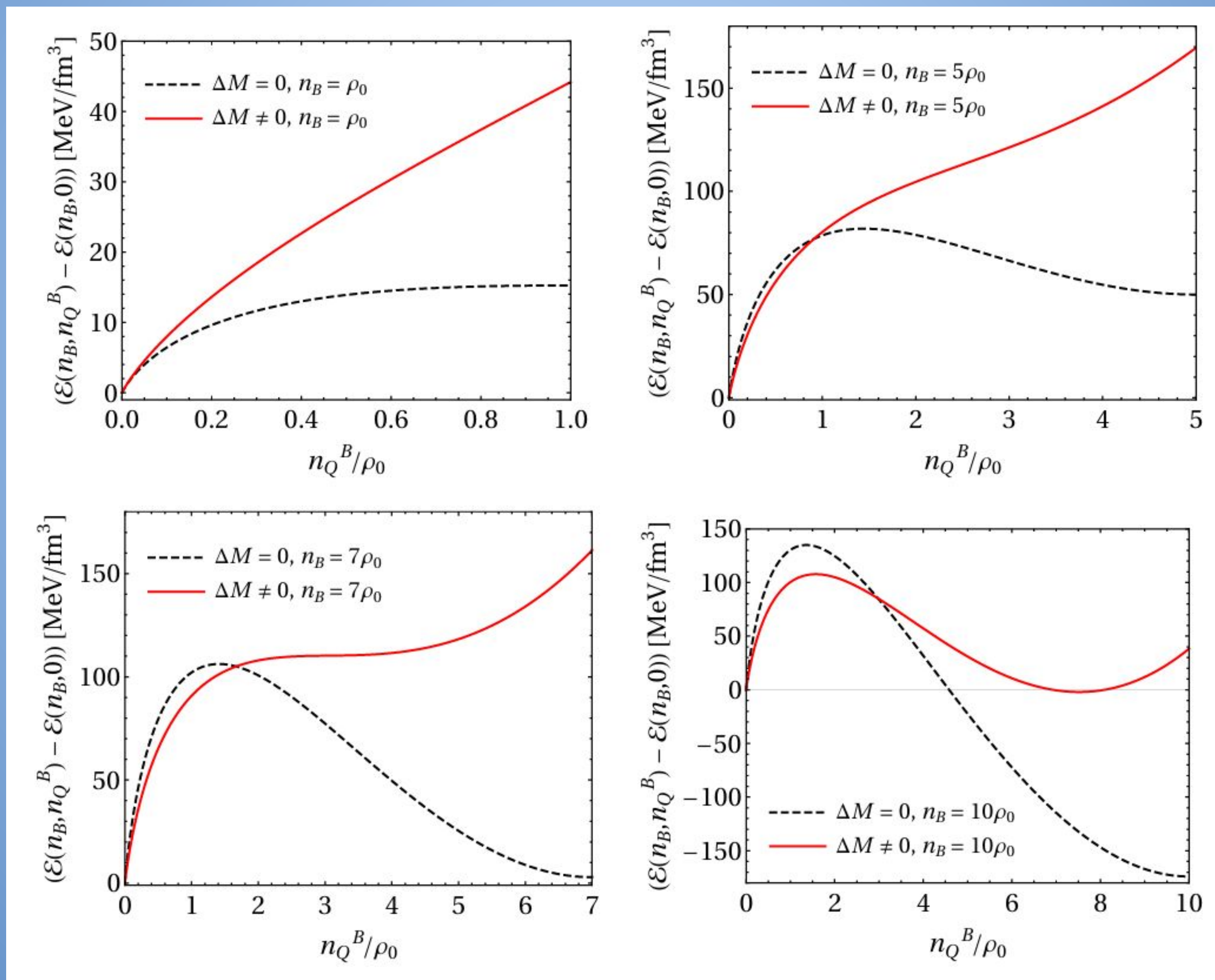
$$\rho^Q = \frac{1}{1+e^{\beta(E_Q - \mu_Q)}} - \frac{1}{1+e^{\beta(E_Q + \mu_Q)}}$$

Density of quarks in a noninteracting gas of quarks and nucleons;

$$\rho^N_{\text{const.}} = \rho^n = \frac{1}{1+e^{\beta(E_N - \mu_N)}} - \frac{1}{1+e^{\beta(E_N - \mu_G)}}$$

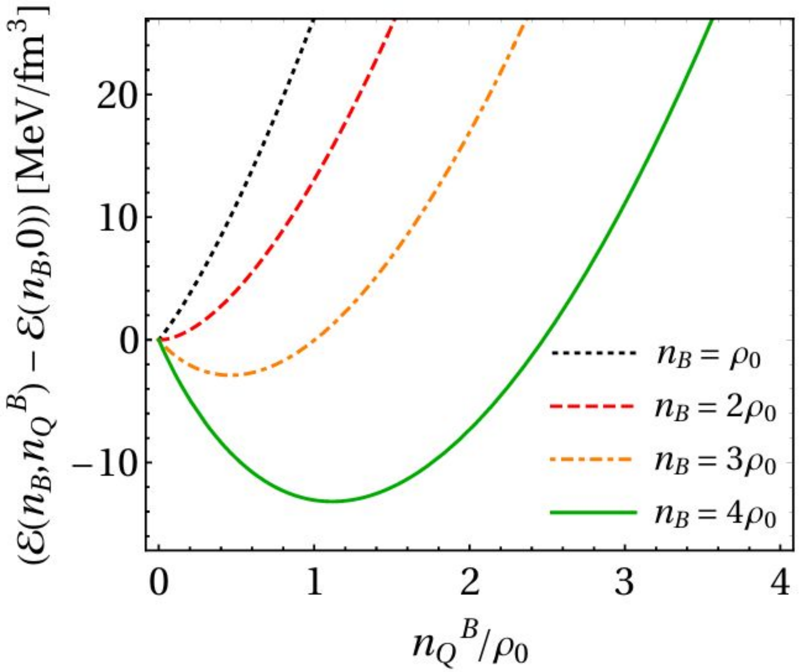
Density of nucleons constrained to not propagate in the quark Fermi sea:

Quarkyonic Field Theory

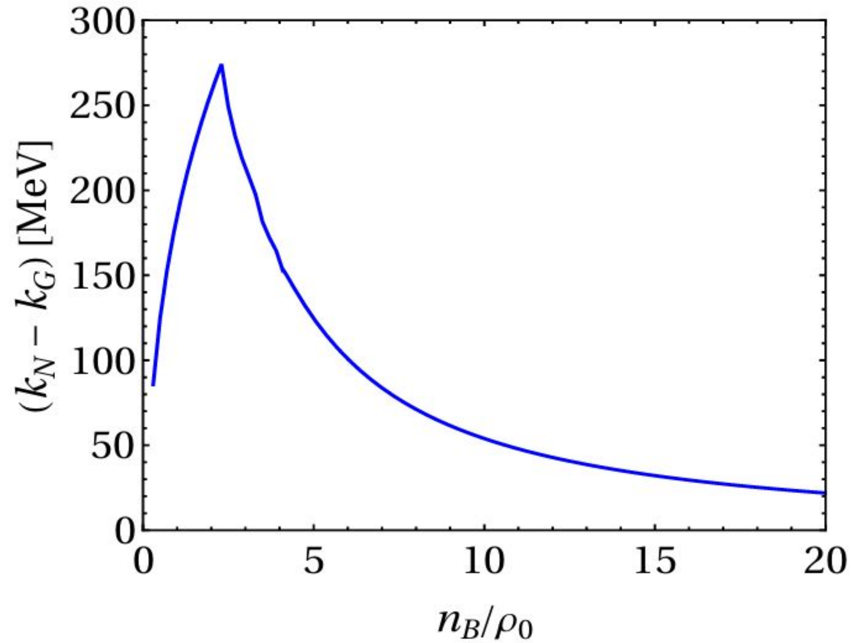


Dyana Duarte, K.S. Jeong, S. Hernandez-Ortiz, L.McLerran, PRC 107, 065201 (2023).

Quarkyonic Field Theory



Continuous transition at $T = 0$.



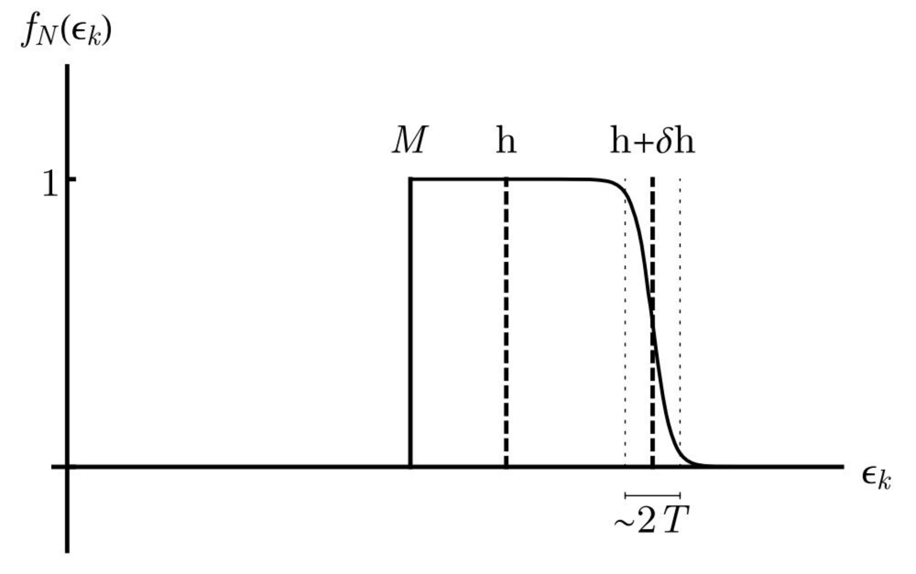
Shell thickness

Dyana Duarte, K.S. Jeong, S. Hernandez-Ortiz,L.McLerran, PRC 107, 065201 (2023).

Finite temperature case

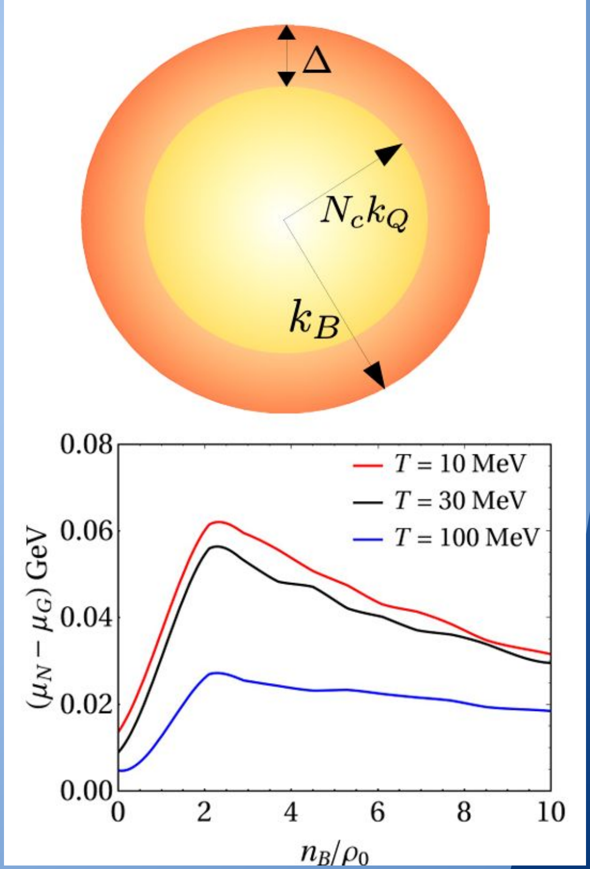
- To implement finite temperature we are trying to do it in the simplest way by softening the boundary of the shell and replacing the step function by fermi-distribution, with,

$$g(\epsilon, \mu) = \frac{1}{e^{\frac{\epsilon-\mu}{T}} + 1}$$



Quarkyonic Field Theory

- Why EFT+ghost is naturally suited for finite temperature?



- Thermal excitations must preserve the constrained phase space.
- The cancellation mechanism naturally suppresses unphysical low-momentum baryonic states.
- Thermal effects can then be incorporated consistently without modifying the underlying shell structure.

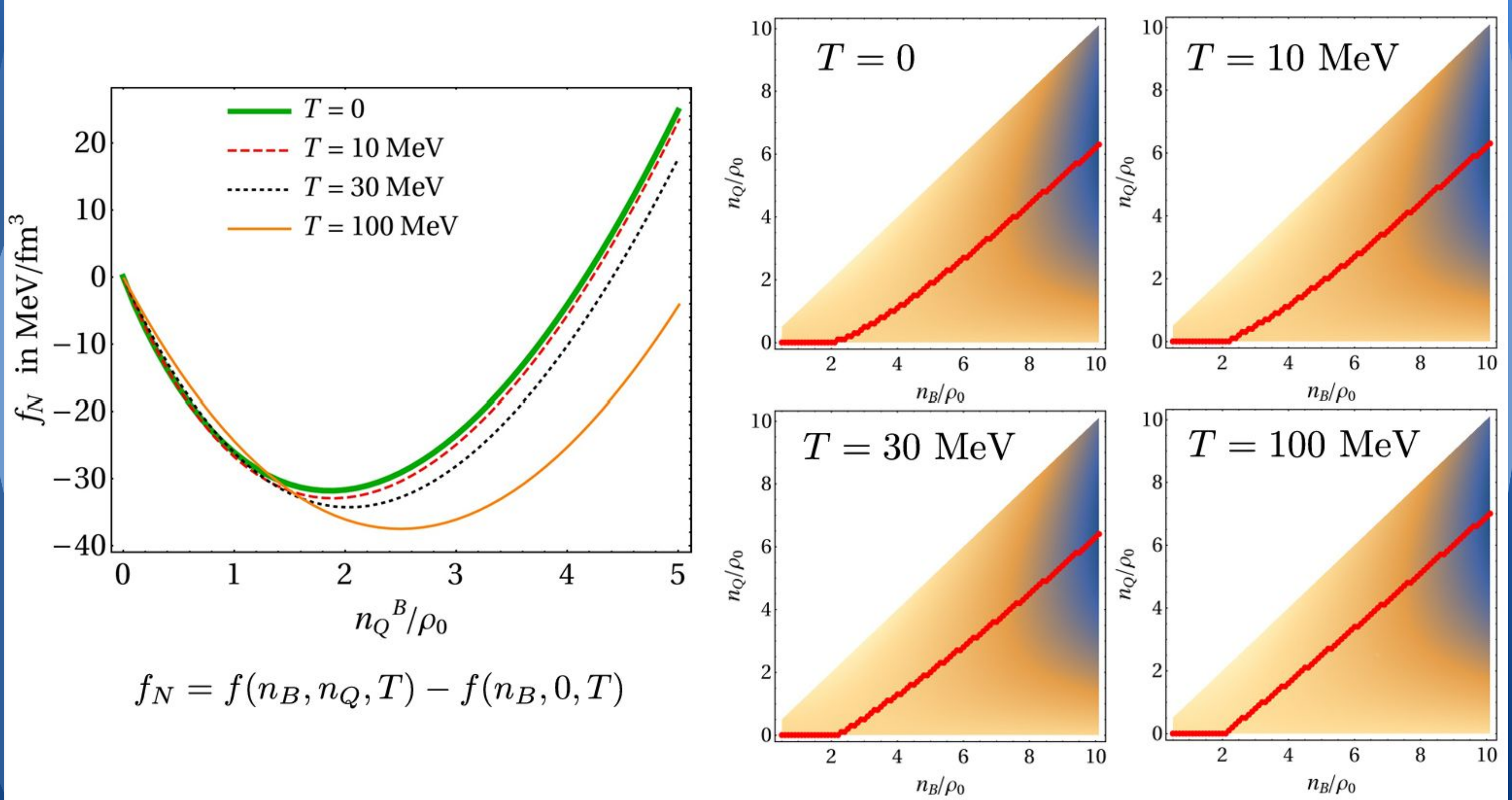
Quarkyonic Field Theory

- What should we expect at finite temperature?

- Thermal broadening of the shell
- Enhanced quark population
- Smooth crossover behavior
- Competition between confinement and thermal excitations

$$\mu_Q^B = N_c \left[\left(M_Q + n_Q^B \frac{a}{M_Q^2} + a \frac{T^2}{M_Q} \right) \Theta(r - n_Q^B) + \left(\kappa (n_Q^B)^{\frac{1}{3}} - \frac{\pi^2}{12} \frac{T^2}{\kappa (n_Q^B)^{1/3}} \right) \Theta(n_Q^B - r) \right]$$

Preliminary Results



$$f_N = f(n_B, n_Q, T) - f(n_B, 0, T)$$

Conclusions

- Quarkyonic matter provides a natural framework for intermediate-density QCD.
- Current GW data do not exclude quarkyonic scenarios. Therefore, extending quarkyonic matter to finite temperature is astrophysically relevant.
- Finite T effects favor the quark population, but have small effects on the onset of quark Fermi sea.

THANKS FOR WATCHING!