3-flavor extension of the excluded volume model for the hard-core repulsion

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Outline

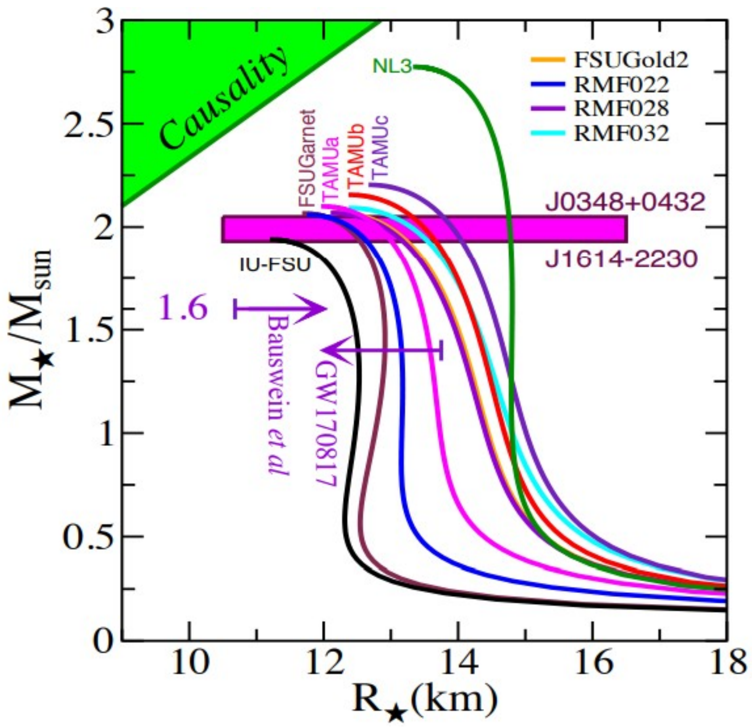
- Motivation;
- Quarkyonic matter;
- Excluded Volume Model;
- Some Numerical Results;
- Final Remarks

Motivation

- Observation and analysis of GW170817: Important clues to understand cold and dense matter.

- 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 inscrease rapidly and can be greater then its conformal value $c_s^2 \geq 1/3$.



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

Motivation

$R_{1.4} \leq 13.5$ km inferred by tidal deformability observed in neutron star inspiral with 90% credence, and subsequent analyses suggests even more compact neutron stars: Need for not too hard EoS for intermediate density.

- Inclusion of some other particle?
- Repulsive nuclear interaction is enough?
- Phase transition to quark matter?

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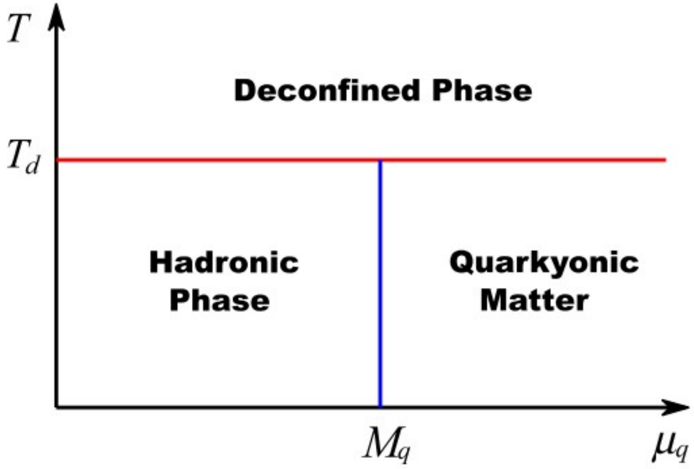
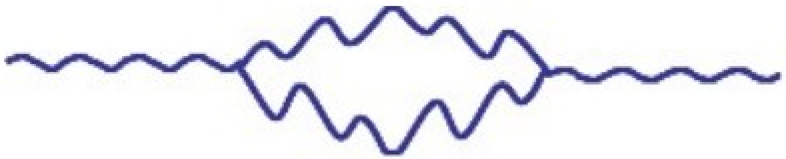
Another candidate: Quarkyonic matter

Quarkyonic Matter



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



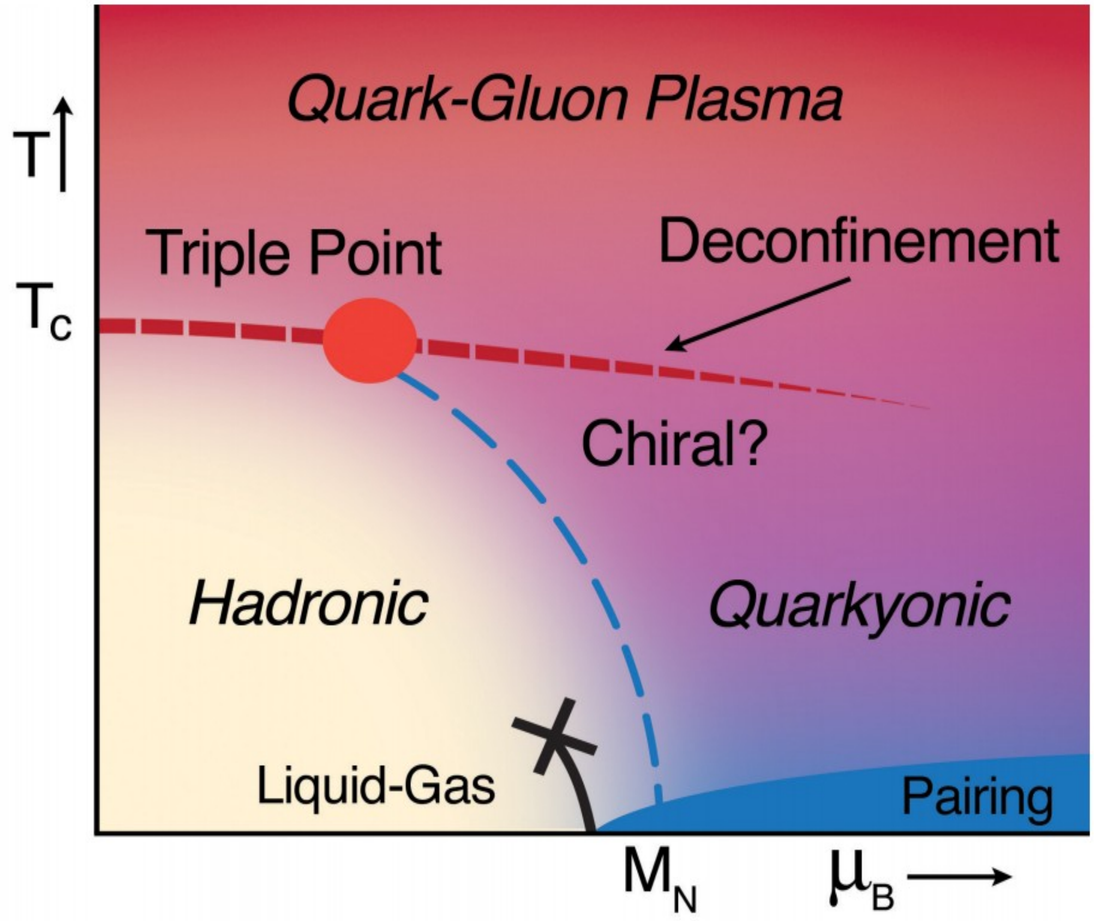
Gluon loop

Quark loop

- $g^2 N_c T^2 \sim T^2$;
- Dynamics not affected by quarks;
- Debye screening at large distances.

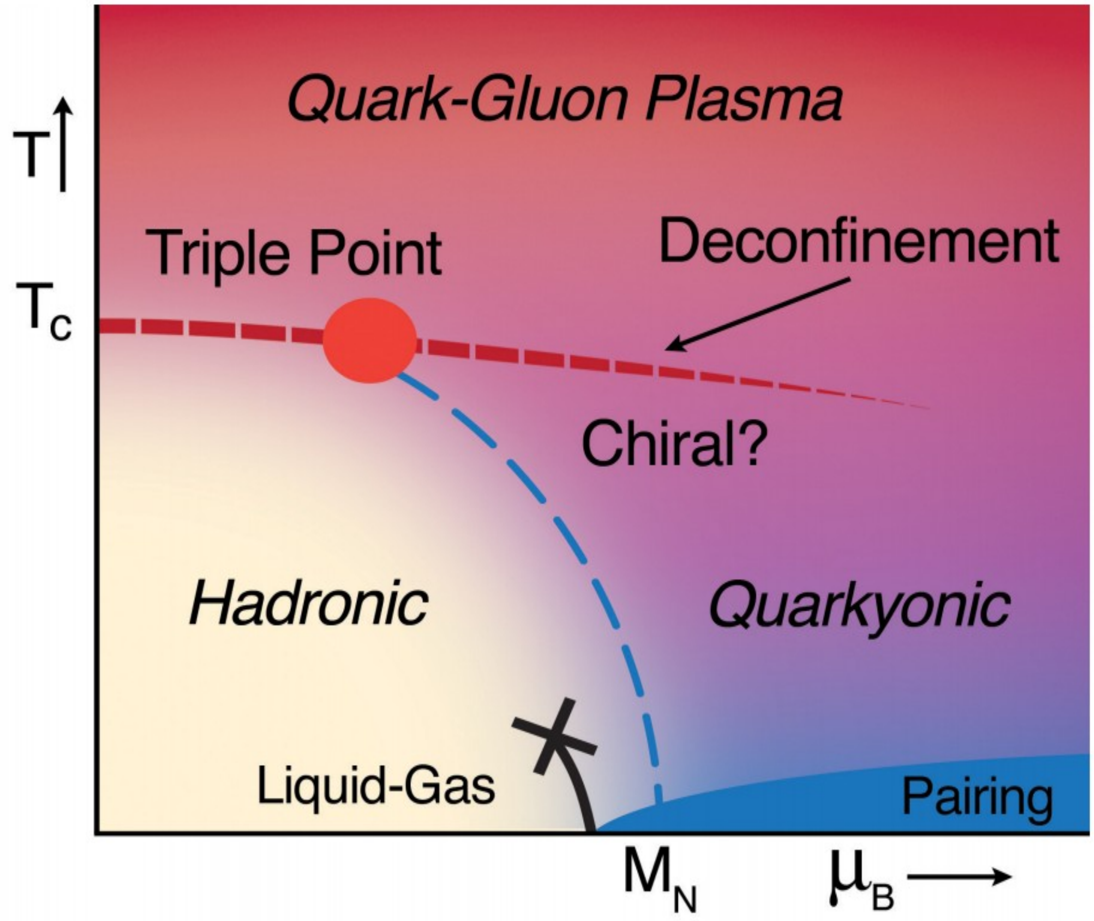
- $\sim \mu_Q{}^2 g^2 \Rightarrow$ Supressed by $1/N_c$ at large N_c.
- High density limit: $\mu_Q \gg \Lambda_{QCD}$, so quarks are important when $\mu_Q \sim N_c^{1/2} \Lambda_{QCD}$.
- Debye screen mass $m_D \simeq g\,\mu_Q$

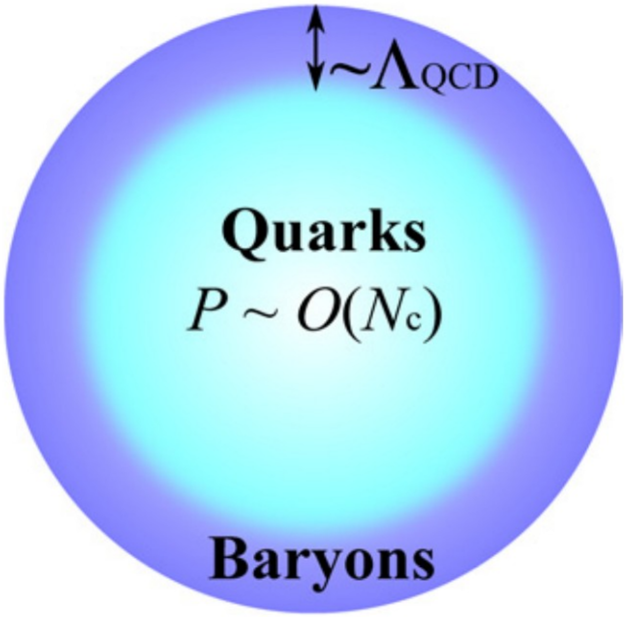
Quarkyonic Matter



- Different phase in confined world, appear when $\mu_q > M_q$ and n_B becomes nonzero.
- Pressure changes suddenly from $O(N_c^{\,0}) \rightarrow O(N_c)$.
- Weakly interacting quark system or baryonic system?

Quarkyonic Matter





Quarkyonic Matter

Nuclear ➡ Quarkyonic

(at few times ρ_0)

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

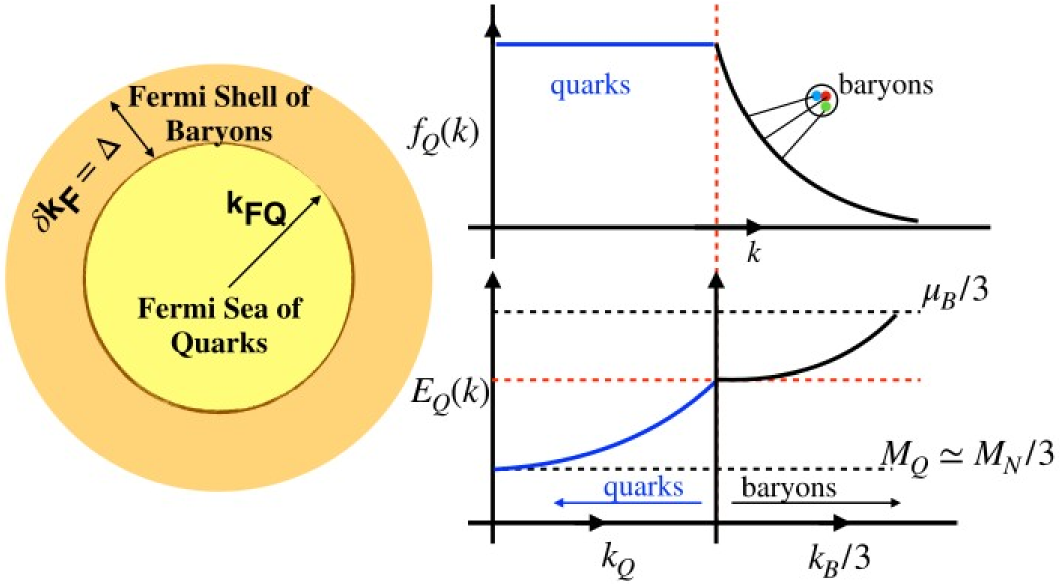
For $\Lambda_{\rm QCD} \lesssim k_F^B \leq N_c \Lambda_{\rm QCD}$: Quarks starts to take low phase space, and a shell-like structure is formed.

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 Matter

- Alternative that could take into account the hardness of EoS at low densities and its softness when the density increases.



Quarks and nucleons are quasiparticles: At low T quark states near Fermi surface are confined in the baryon-like states.

McLerran and Reddy, PRL 122,122701 (2019)

Excluded Volume Model

- Need of repulsive interaction to support hard EoS at high density regime.
- Considering a hard core repulsion: Scale can be measured by the effective size of the baryon.
- Protons + Neutrons + Hyperons in an excluded volume $v_0 = 1/n_0$:

$$\varepsilon_N = \left(1 - \frac{n_{\tilde{B}}}{n_0}\right) \sum_{i=p,n,\Lambda} \int_0^{K_F^i} \frac{dk k^2}{\pi^2} \sqrt{k^2 + m_i^2} + \varepsilon_e$$

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Electron

Excluded volume model: $K_F^i = \left(3\pi^2 \frac{n_i}{1 - n_{\tilde{B}}/n_0}\right)^{1/3}$

3 Flavor Excluded Volume Model

- Provides a hard-soft EoS in the case of single flavor‡ when considering shell structure.

- Generalization for 3 flavor and inclusion of β-equilibrium and electromagnetic charge neutrality: Possibility of making EoS softer.

$$n_N^{ex} = \sum_{i=p,n,\Lambda} \frac{n_N}{1 - n_{\tilde{B}}/n_0} = 2\int_0^{K_F^i} \frac{dkk^2}{2\pi^2}$$

$$n_N = n_p + n_n + n_\Lambda; \qquad n_{\tilde{B}} = n_p + n_n + (1+\alpha)n_\Lambda; \qquad \mu_i = \frac{\partial \varepsilon}{\partial n_i}$$

‡K. S. J., L. M. and S. S., arXiv:1908.04799 [nucl-th]

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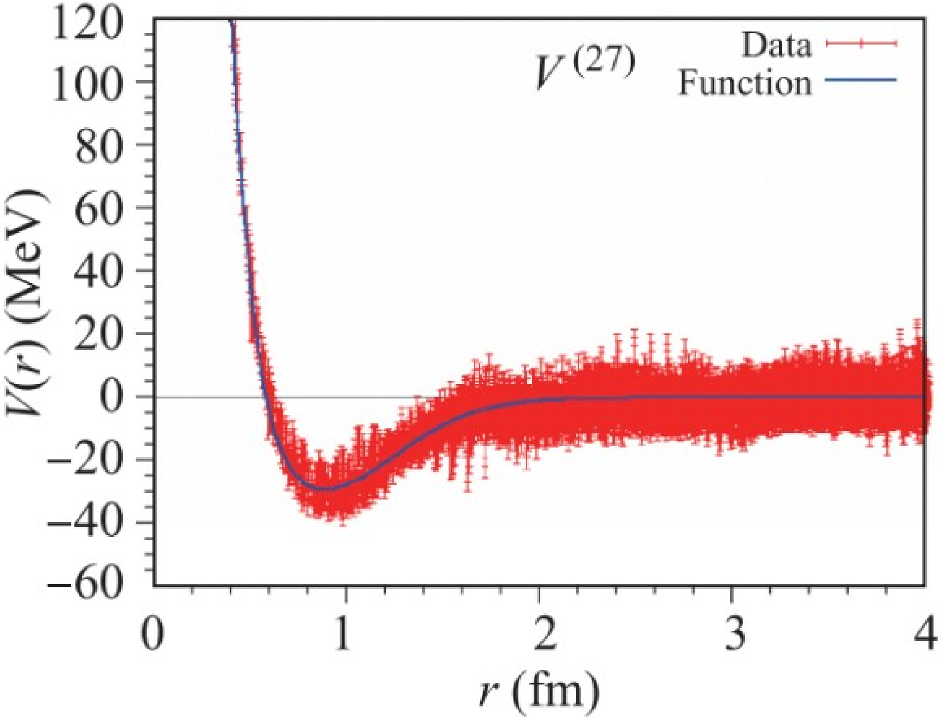
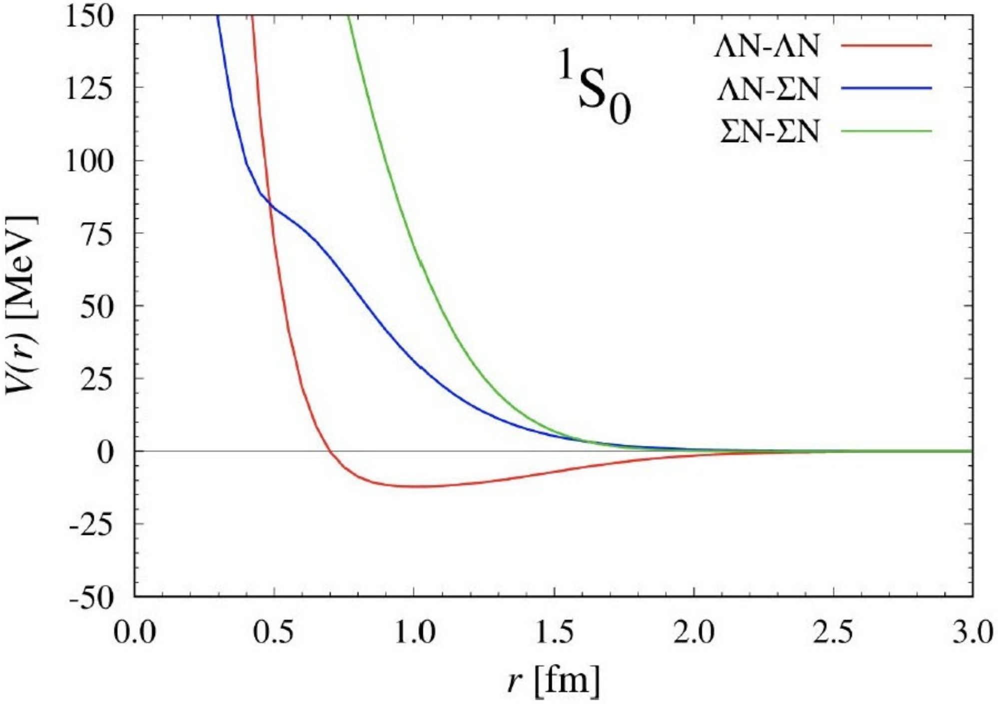
Strength of Λ repulsion

‡K. S. J., L. M. and S. S., arXiv:1908.04799 [nucl-th]

T. Hatsuda, Front. Phys. 13(6), 132105 (2018)



T. Hatsuda, private communication



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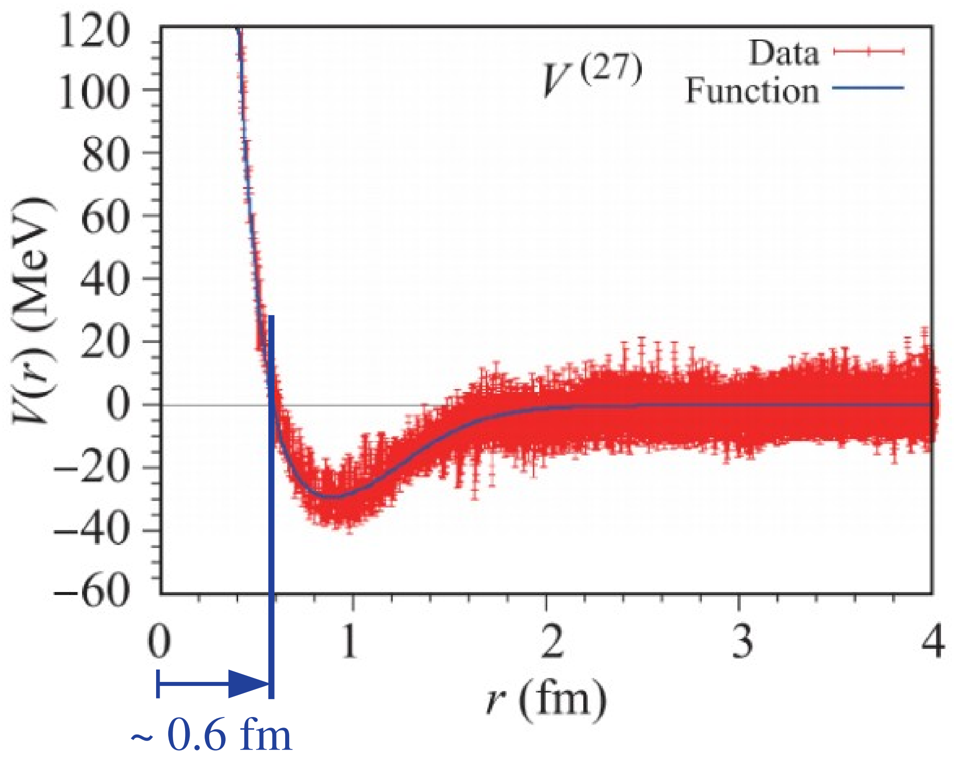

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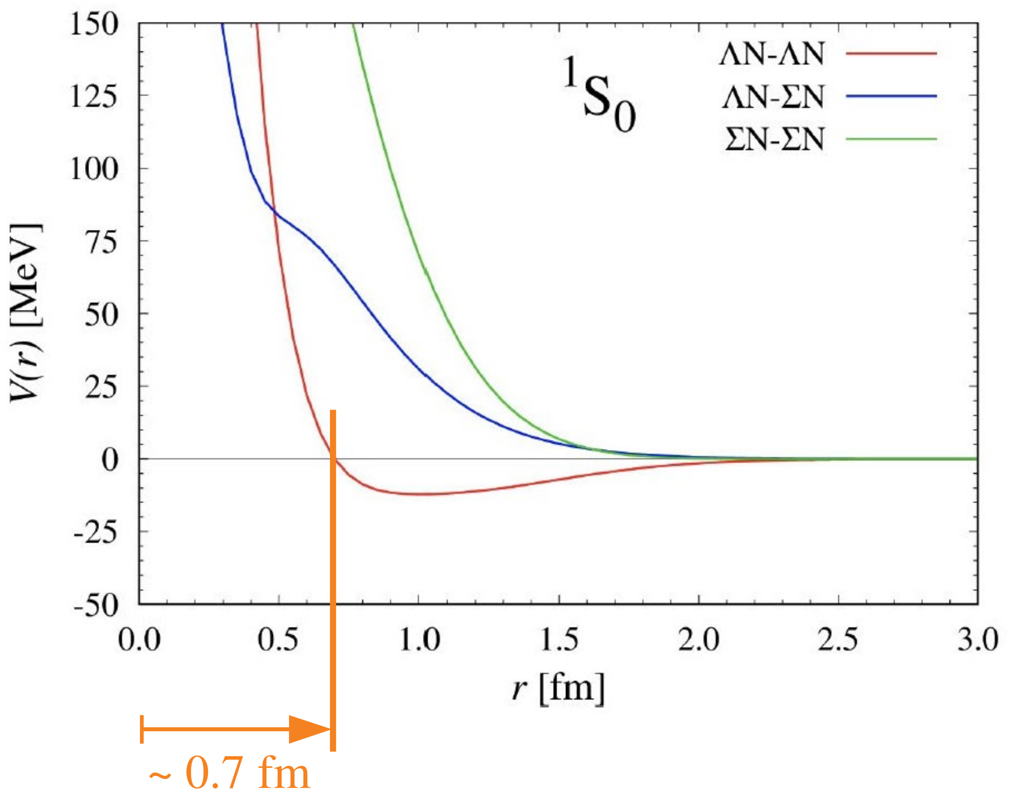
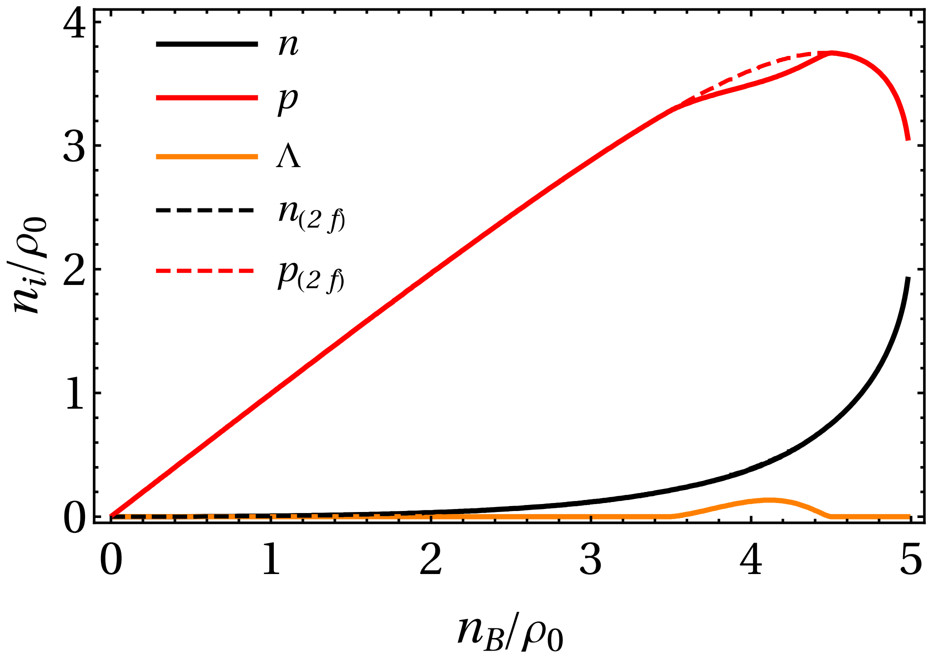


$$n_{\tilde{B}} = n_p + n_n + (1+\alpha)n_\Lambda$$

3 Flavor Excluded Volume Model: Nucleons only

$\alpha = 0.2$ case



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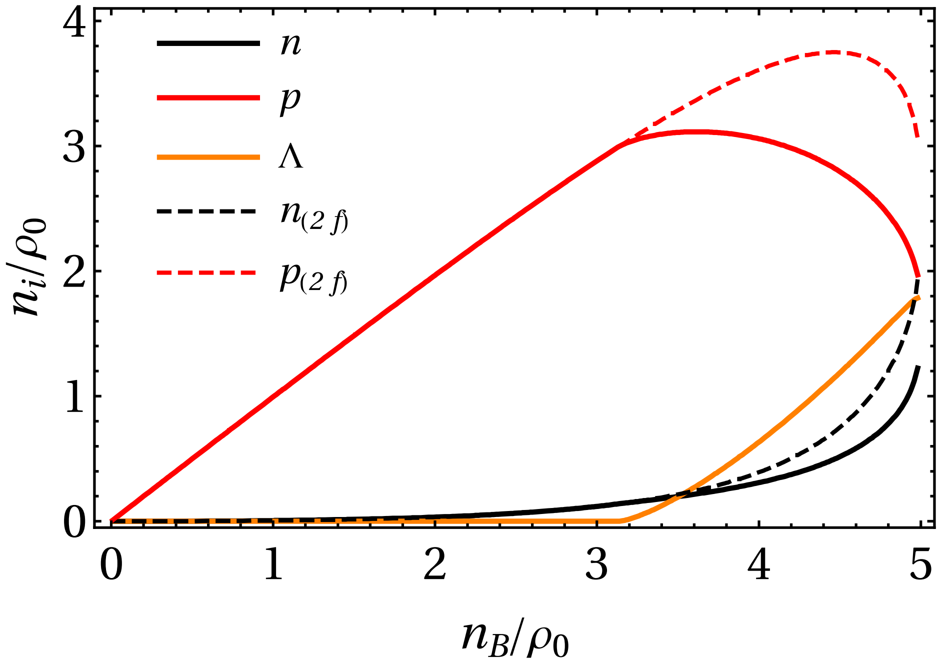

$\mu_n = \mu_p + \mu_e$ and $\mu_\Lambda = \mu_n$

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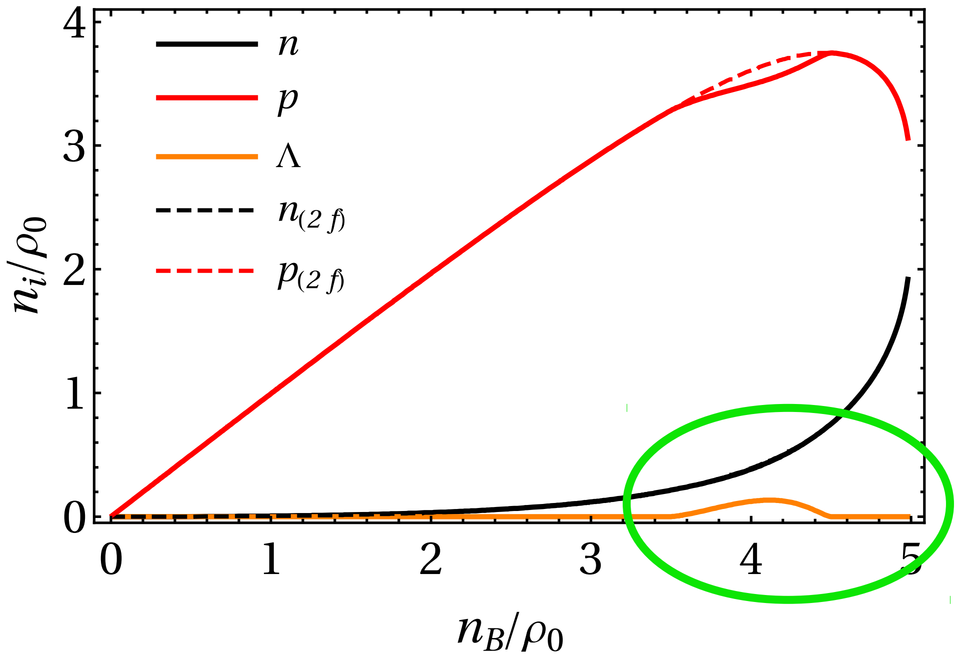

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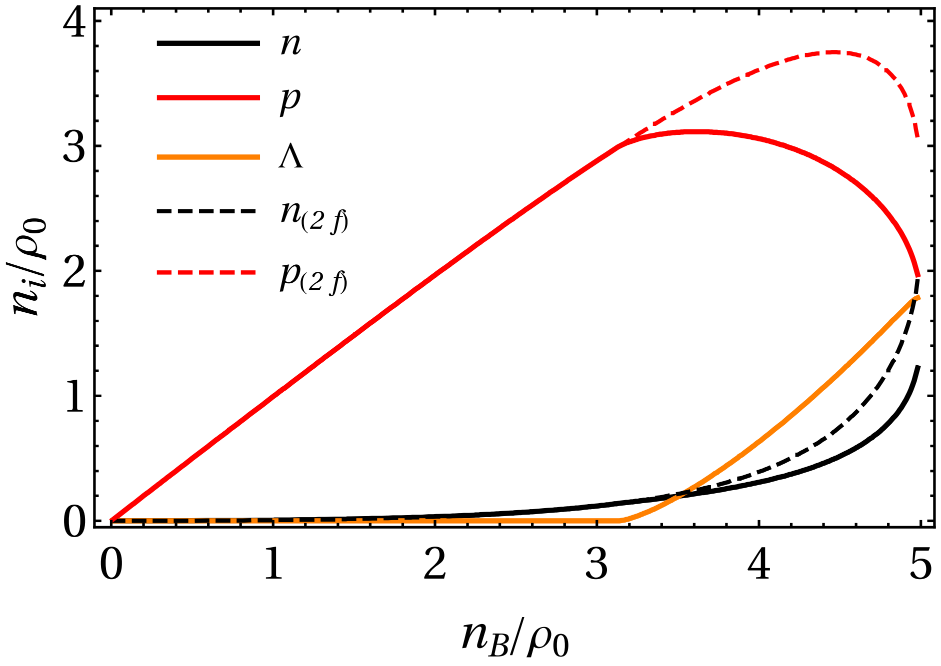

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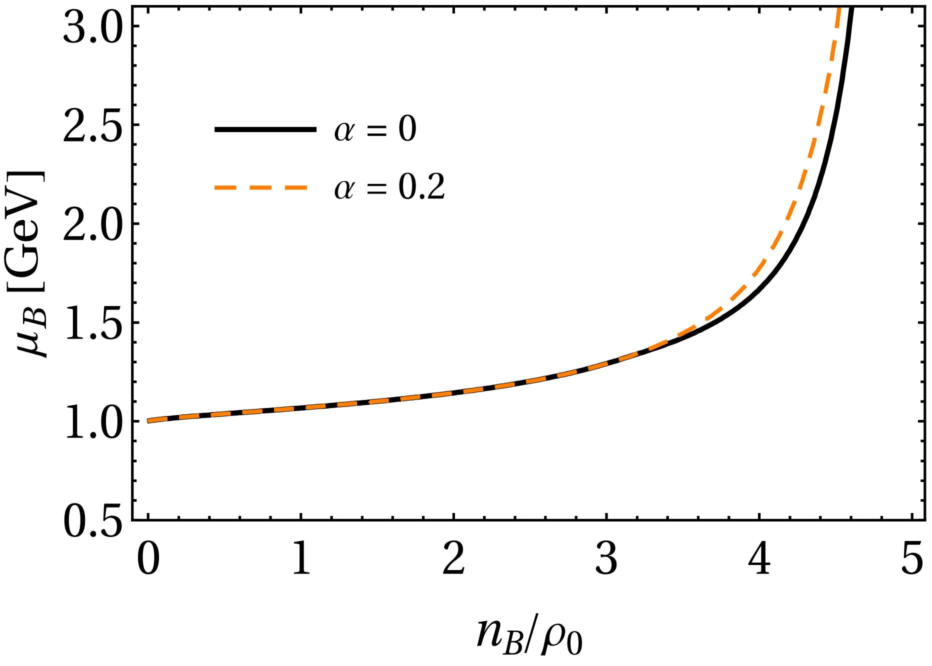
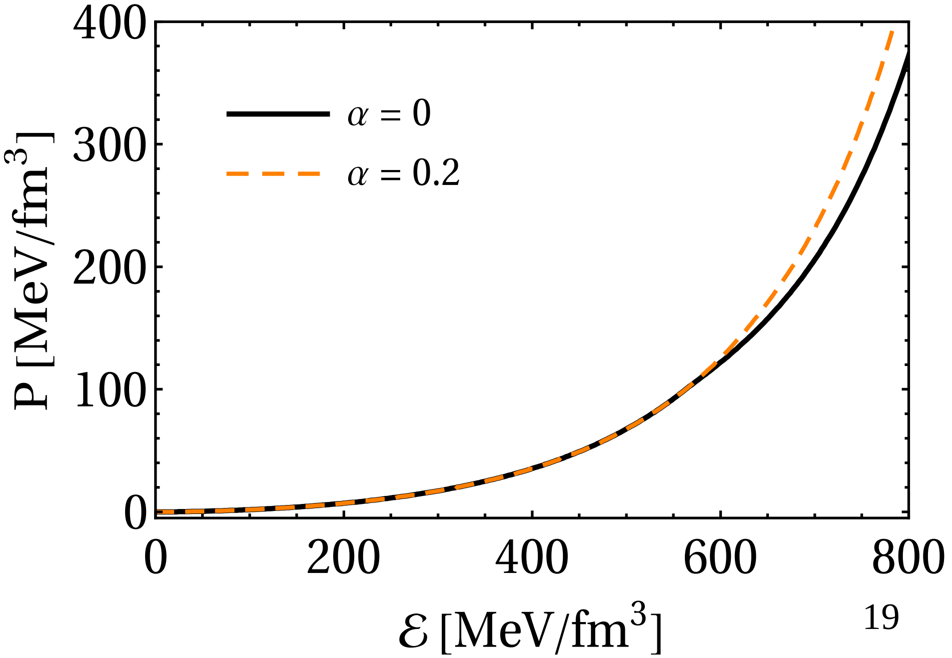
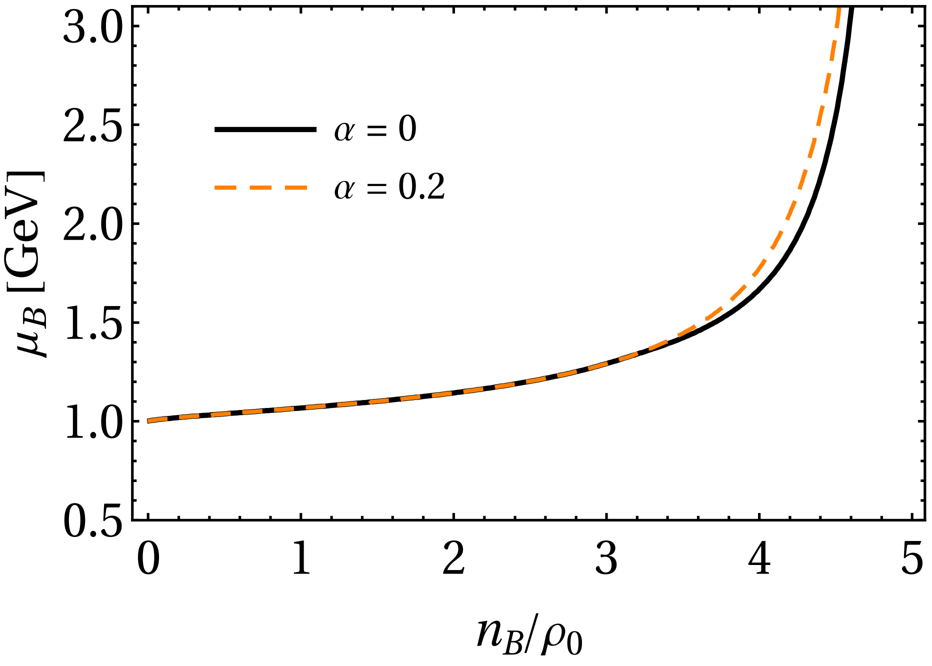


$$\mu_B = \sum_{f=p,n,\Lambda,e} \mu_f \frac{\partial n_f}{\partial n_B}$$

→ Very soft EoS for low densities;

→ Generate singular sound velocity





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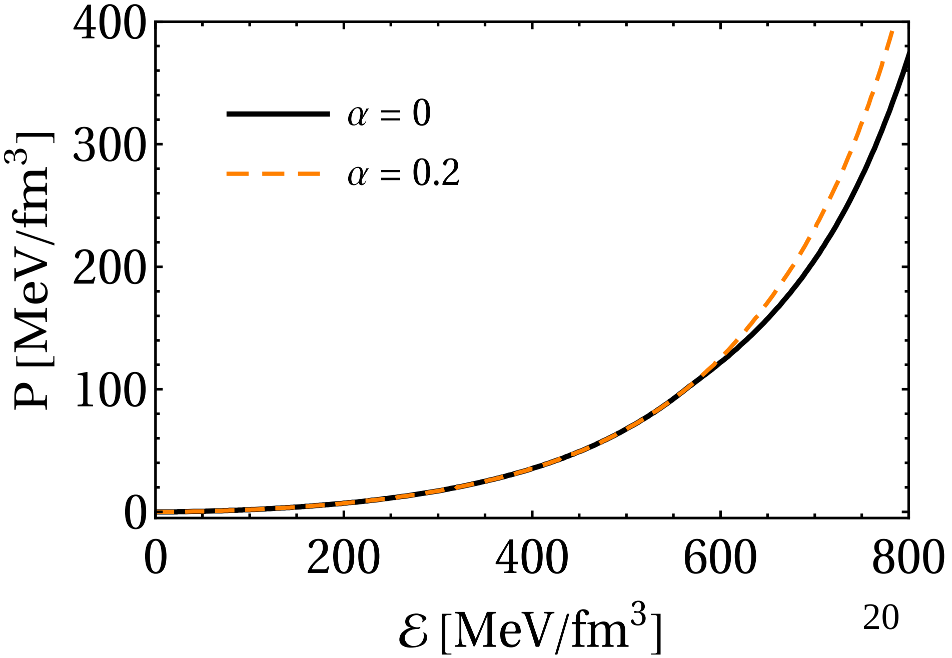
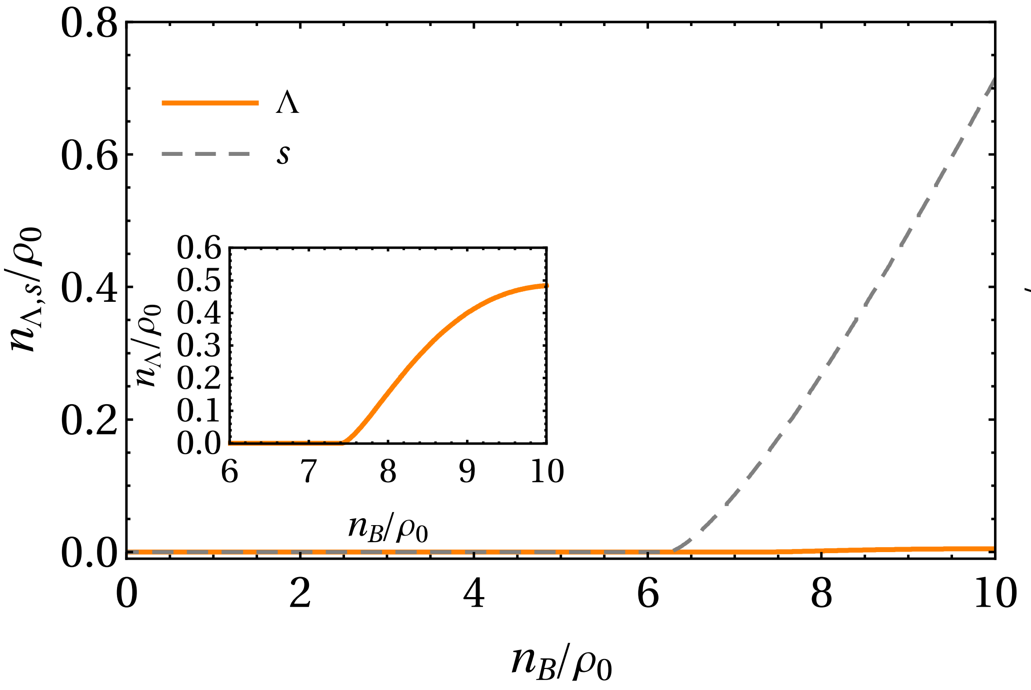
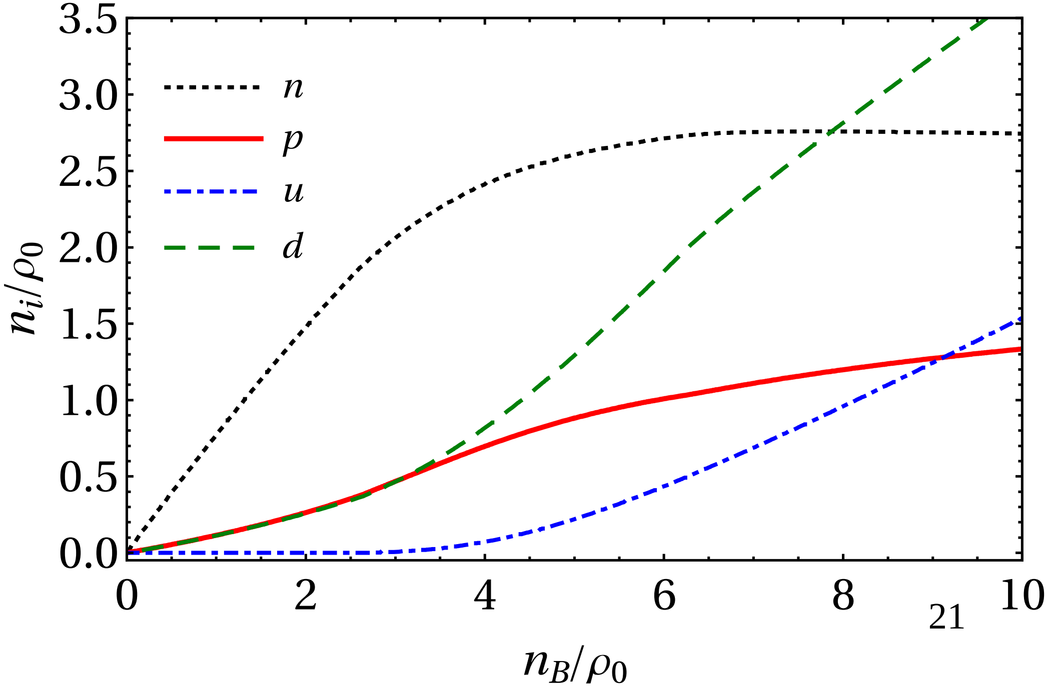


Mean Field Mixture: $n_B = n_Q + n_N$ in each point

Protons + Neutrons + Hyperons in an excluded volume + *u, d, s* quarks.

$$\varepsilon_{\rm mix} = \left(1 - \frac{n_{\tilde{B}}}{n_0}\right) \sum_{i=p,n,\Lambda} \int_0^{K_F^i} \frac{dk k^2}{\pi^2} \sqrt{k^2 + m_i^2} + \varepsilon_e + \sum_{j=u,d,s} \int_0^{k_F^{Q_j}} \frac{dk k^2}{\pi^2} \sqrt{k^2 + m_j^2}$$





$$n_Q = 2\sum_{j=u,d,s}\int_0^{k_F^{Q_j}} \frac{dk k^2}{2\pi^2}$$

- **Electromagnetic charge neutrality**

$$n_e = n_p + 2n_{\tilde{u}} - n_{\tilde{d}} - n_{\tilde{s}}$$

- **Beta equilibrium conditions**

$$\mu_n = \mu_p + \mu_e$$

$$\mu_{\tilde{d}} = \mu_{\tilde{u}} + 3\mu_e$$

- **Existence of Λ hyperon**

$$\mu_\Lambda = \mu_n$$

- **Existence of s quark**

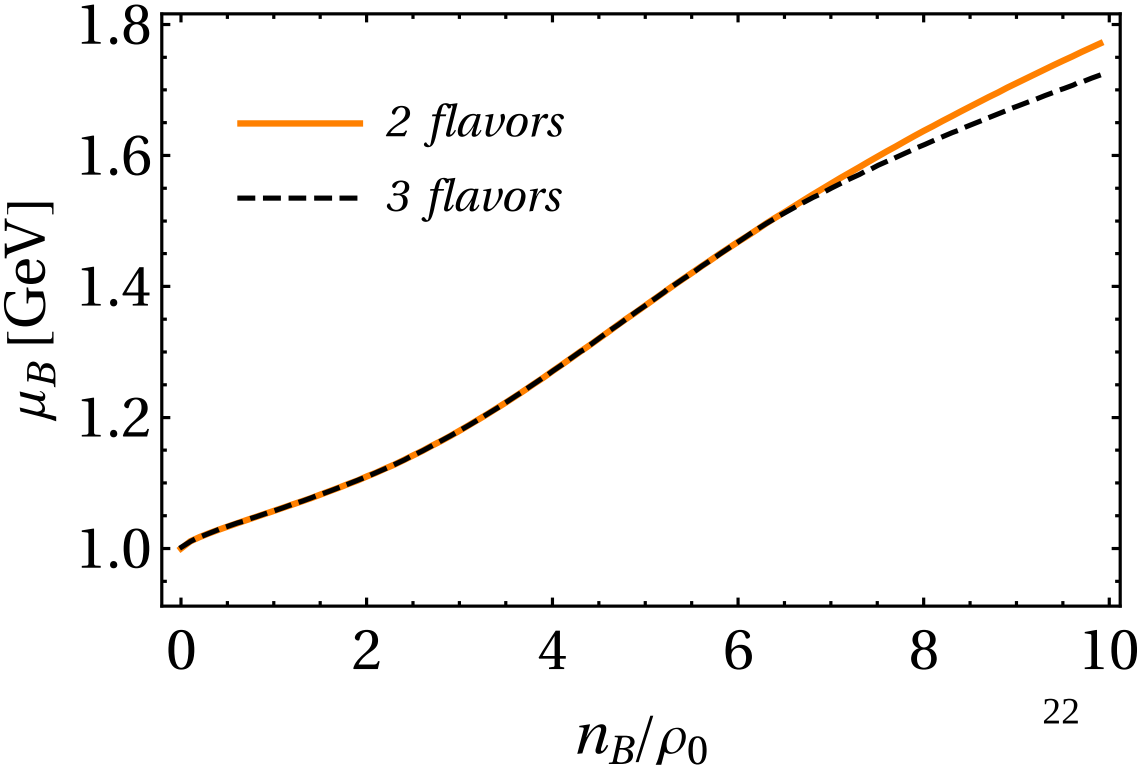
$$\mu_{\tilde{s}} = \mu_{\tilde{d}}$$

Condition for the minimum of energy density:

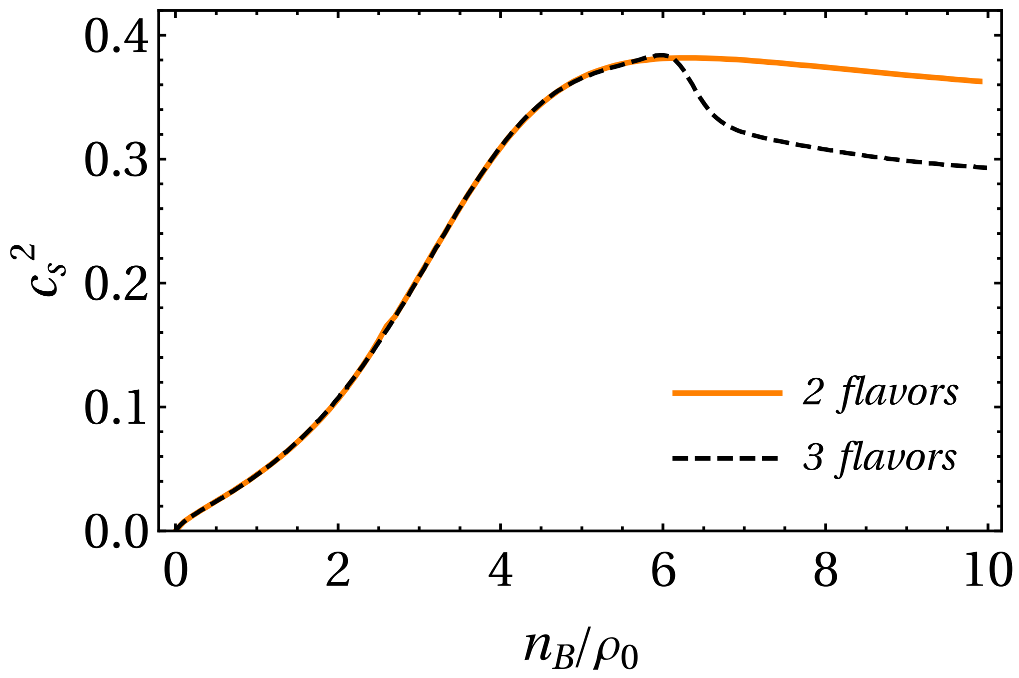
$$dn_B = dn_n + dn_Q = 0$$

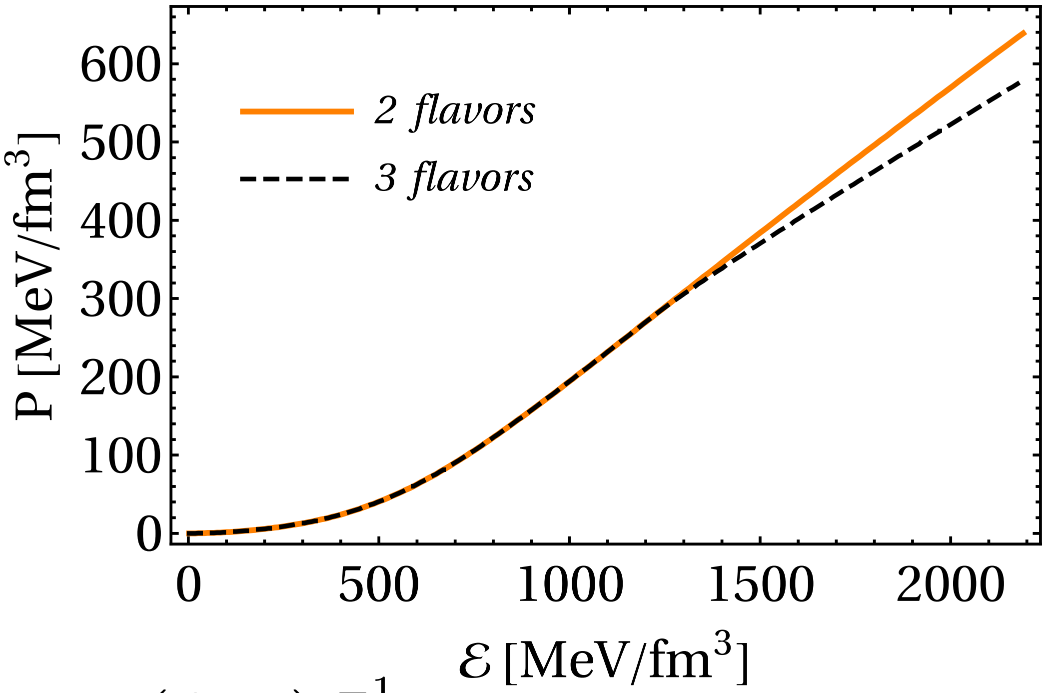
from which we obtain

$$\mu_n = N_c \mu_{\tilde{d}} - \mu_e$$



Hard-Soft EoS





$$c_s^2 = \frac{\partial P}{\partial \varepsilon_{\rm mix}} = \frac{n_B}{\mu_B}\left(\frac{\partial n_B}{\partial \mu_B}\right)^{-1}$$

Final Remarks

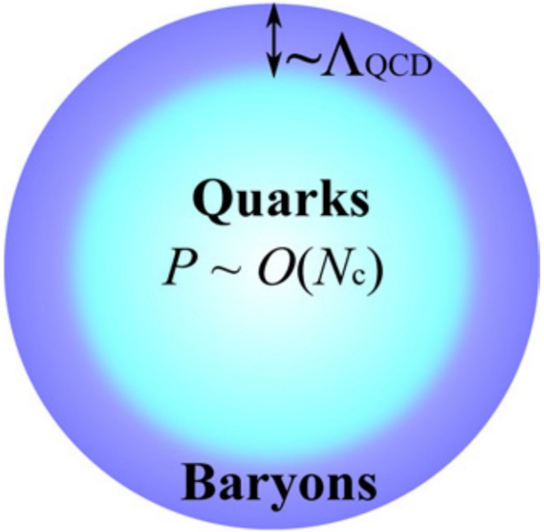
- We study the baryon-quark mixture with three flavor particles in β equilibrium and considering electromagnetic charge neutrality.

- The mean field mixture generates a hard-soft EoS, and in the high density limit the 3-flavor EoS is softer.

- Next step: More realistic model, including the baryon-like shell structure that correctly describes quarkyonic matter (in progress).

$$\varepsilon_N = \left(1 - \frac{n_{\tilde{B}}}{n_0}\right) \sum_{i=p,n,\Lambda} \int_{K_F^i}^{K_F^i+\Delta_i} \frac{dk k^2}{\pi^2} \sqrt{k^2 + m_i^2} + \sum_{j=u,d,s} \int_0^{k_F^{Q_j}} \frac{dk k^2}{\pi^2} \sqrt{k^2 + m_j^2}$$

Thanks to Larry McLerran for all the useful discussions during the development of this work.



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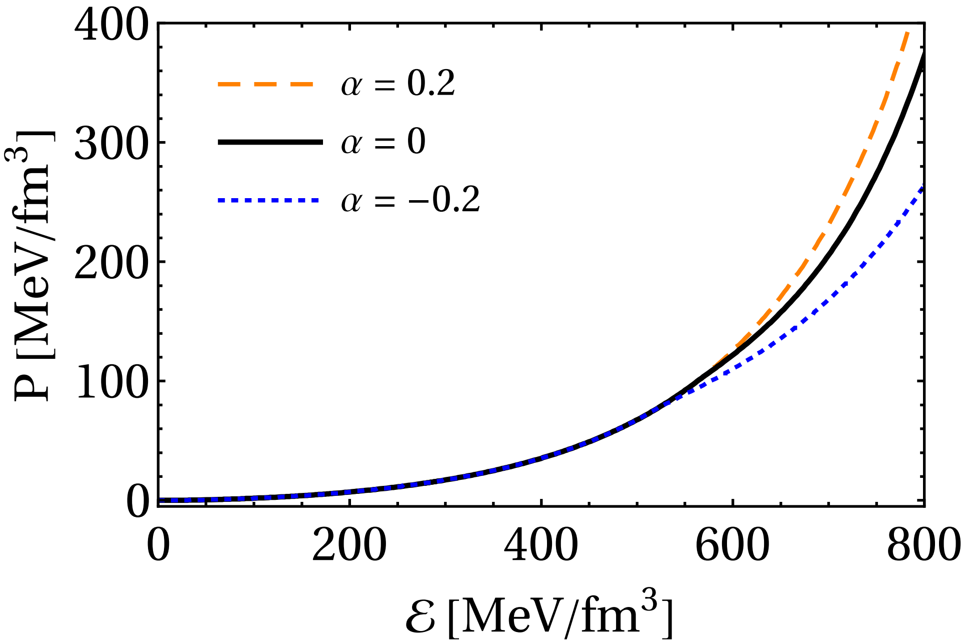
Thanks for your attention!

Only Nucleons



Mean Field mixture