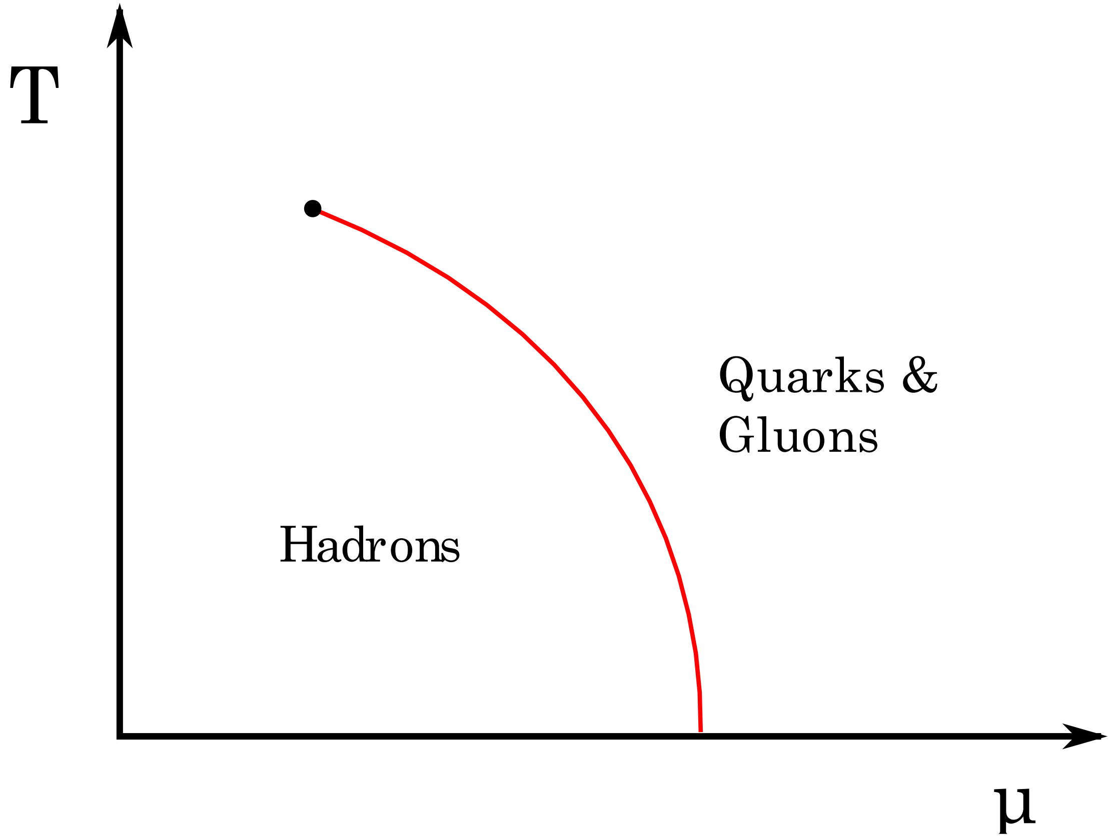
Strange quark matter from a baryonic approach

Savvas Pitsinigkos

18th international conference "QCD in extreme conditions", Trondheim, July 2022

E. S. Fraga, R. da Mata, S. Pitsinigkos, A. Schmitt, (2206.09219)

Cold and dense matter



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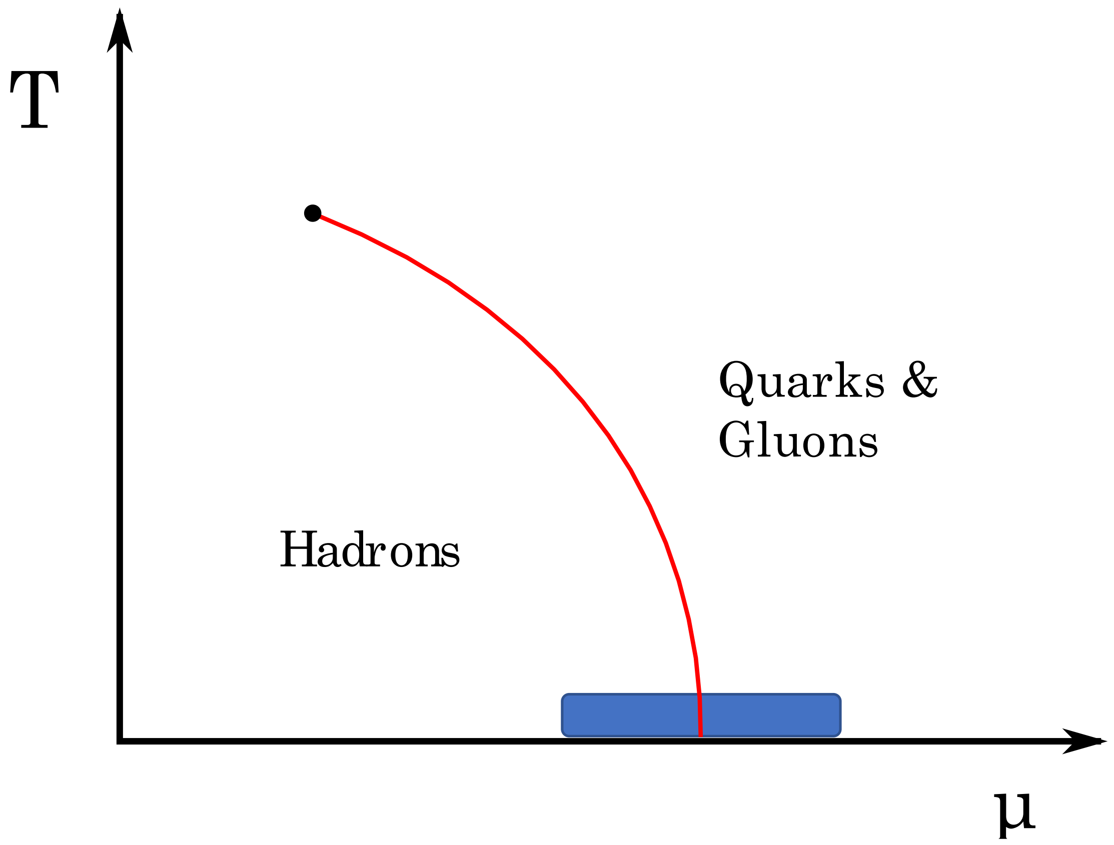

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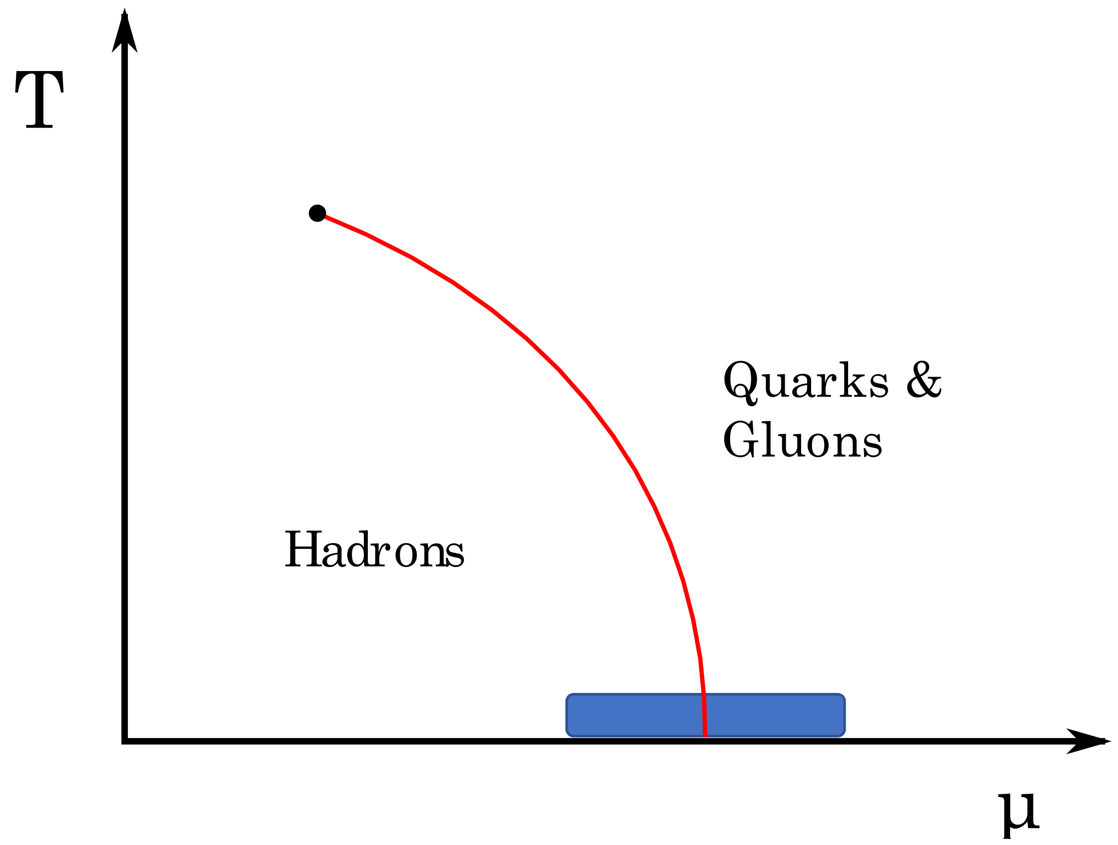

- What is the critical μ for the phase transition?
- What is the order of the phase transition?
- Can we find inhomogeneous phases in the vicinity?
- What happens in neutron stars?

Two options

Use one model for each phase, then stitch models together.

Build a single model that describes both phases.

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T. Ishii, M. Järvinen, and G. Nijs, JHEP 07, 003 (2019)
M. Marczenko, D. Blaschke, K. Redlich, and C. Sasaki, Astron. Astrophys. 643, A82 (2020)
V. Dexheimer, R. O. Gomes, T. Klähn, S. Han, and M. Salinas, PRC 103, 025808 (2021)

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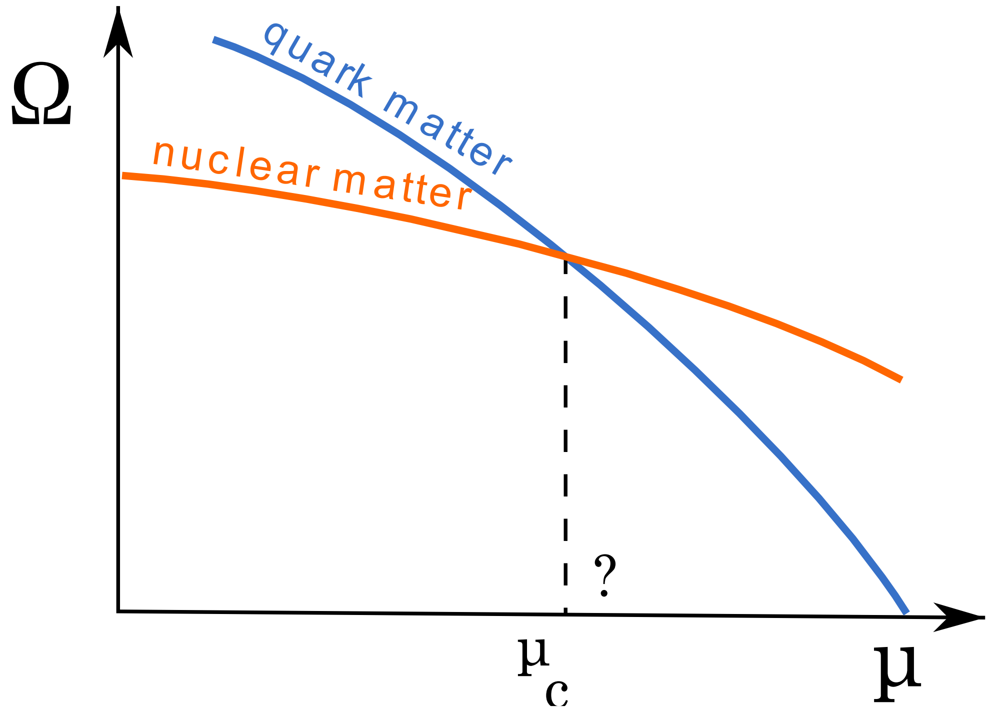
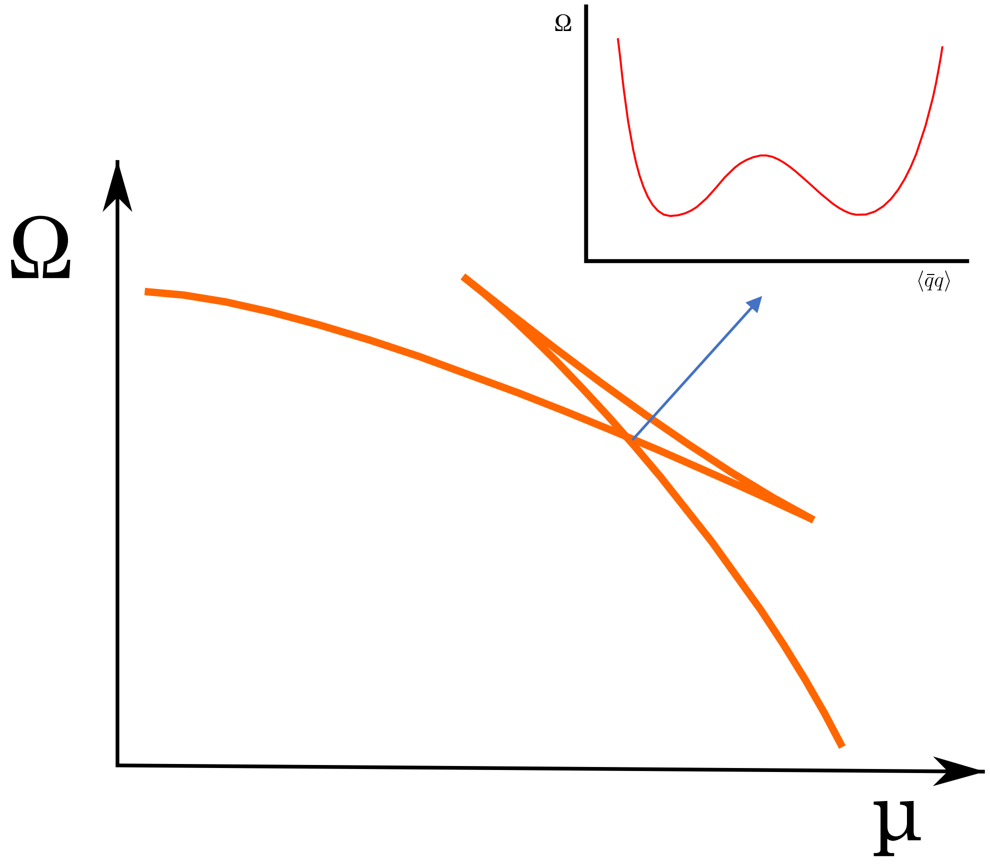
Build a baryon-meson model with spontaneous chiral symmetry restoration at high densities. Use chirally restored phase to describe quark matter.

No quark degrees of freedom!

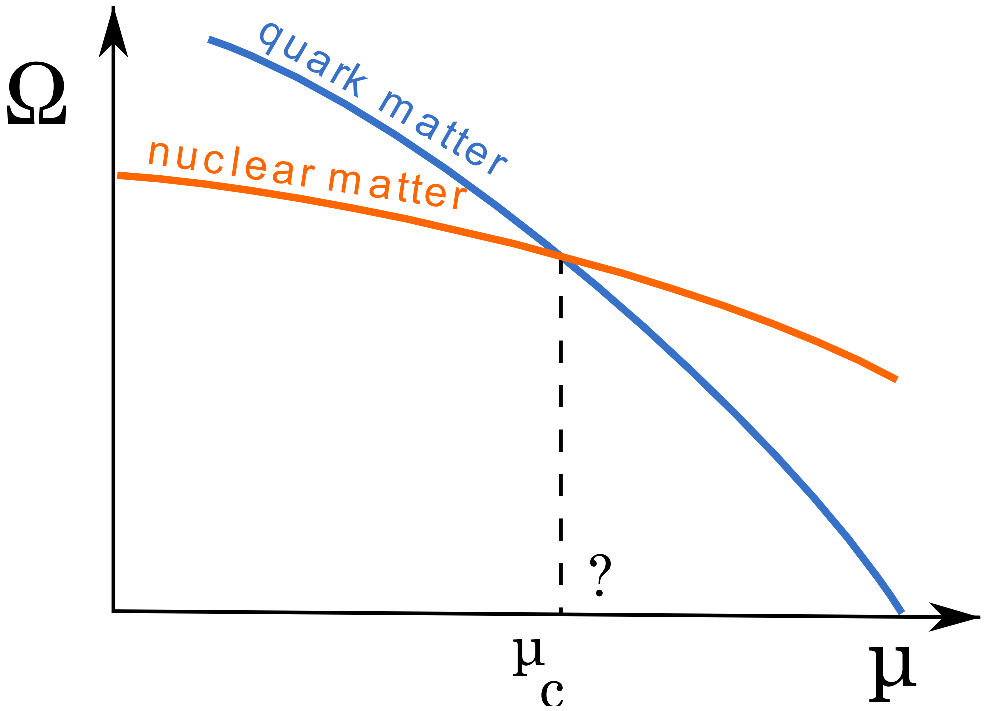
Two models vs single model

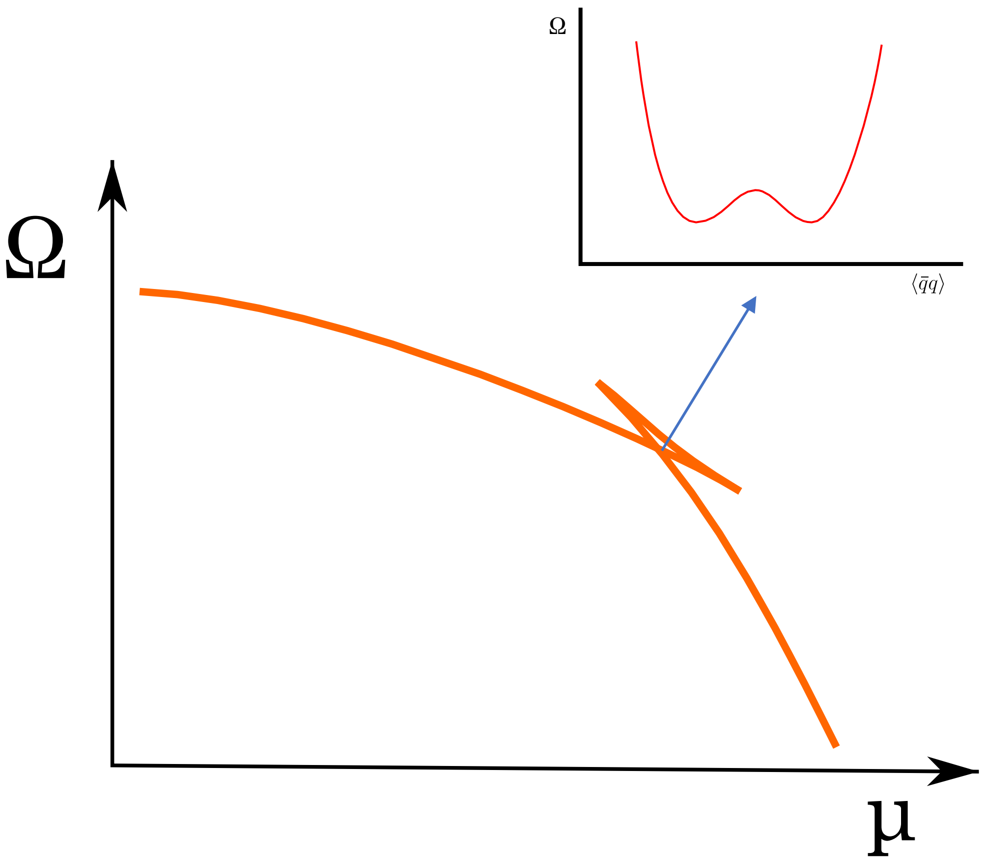




Critical chemical potential μ_c is calculated dynamically.

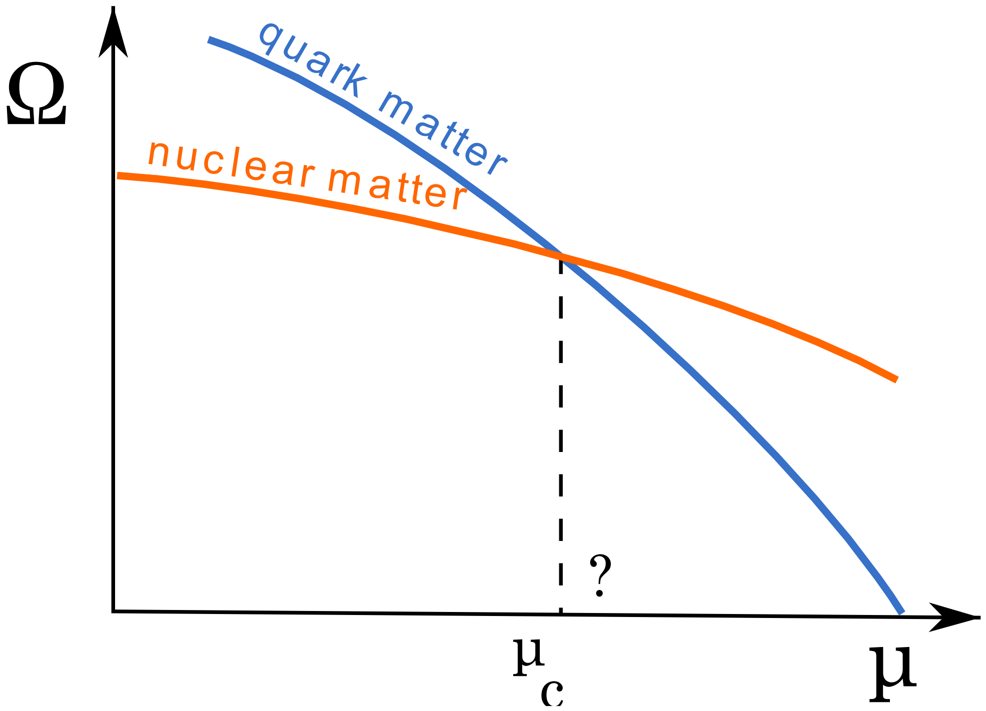
Two models vs single model

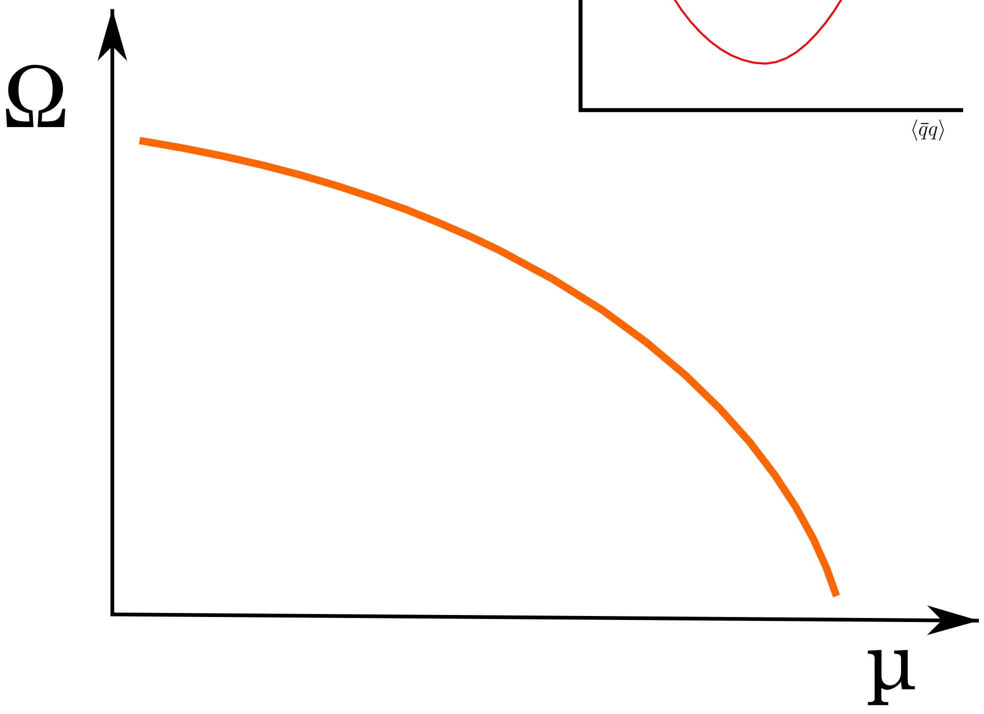


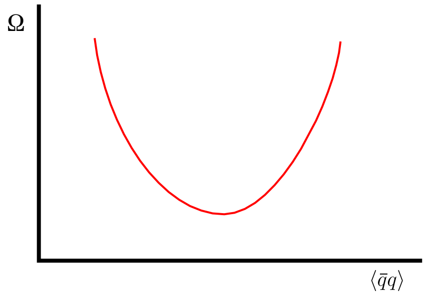


Spinodal region size varies.

Two models vs single model



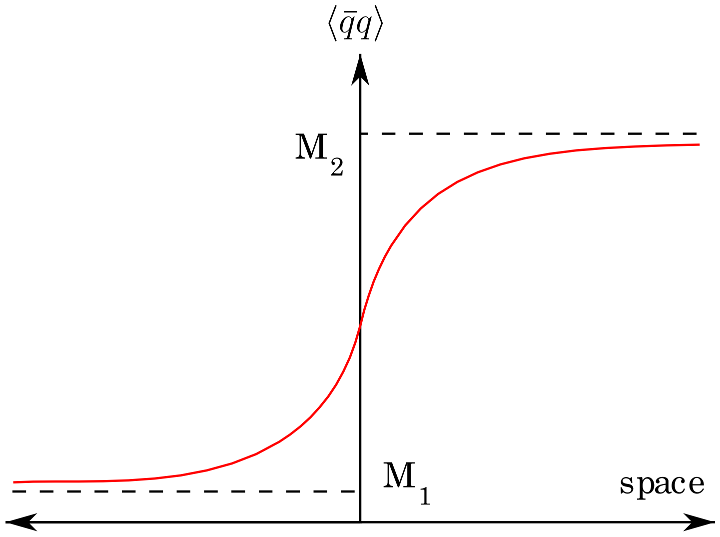




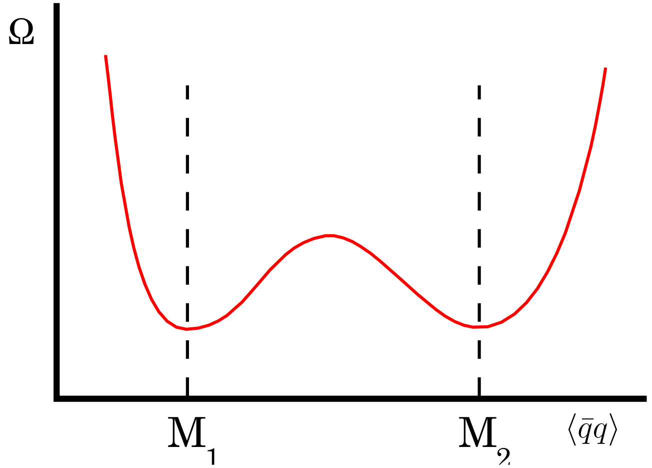
Crossover is also an option.

Inhomogeneous phases

Surface tension E. S. Fraga, M. Hippert, A. Schmitt, PRD 99, 014046 (2019)



Relevant for bubble nucleation rate and wall dynamics



Intermediate potential necessary

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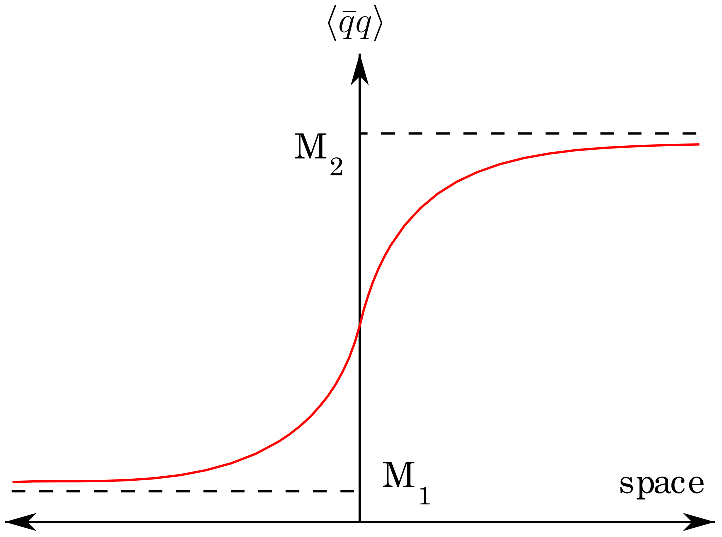

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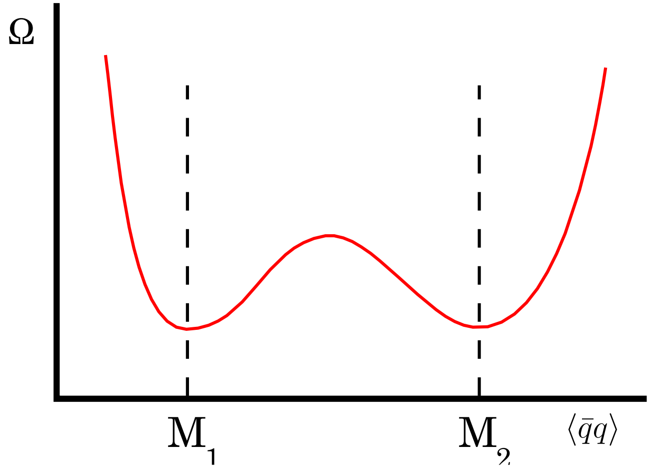


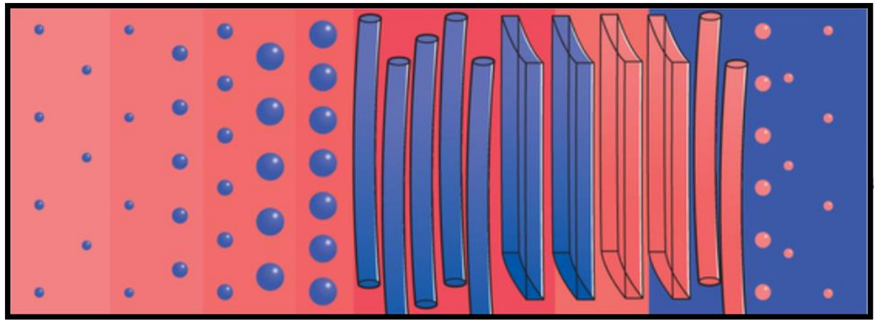
Pasta phases

A. Schmitt, PRD 101, 074007 (2020)

Global charge neutrality

+ Coulomb effects
+ Surface tension

Consistently calculate pasta phase free energy.



The model

M. Drews and W. Weise, Phys. Rev. C91, 035802 (2015)
A. Schmitt, PRD 101, 074007 (2020)

+ hyperons

$$\mathcal{L} = \sum_i \bar{\psi}_i \left(i\gamma^\mu \partial_\mu + \gamma^0 \mu_i \right) \psi_i + \frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma - U(\sigma) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} - \frac{1}{4}\rho^0_{\mu\nu}\rho^{\mu\nu}_0 + \frac{m_\omega^2}{2}\omega_\mu \omega^\mu$$

$$+ \frac{m_\phi^2}{2}\phi_\mu \phi^\mu + \frac{m_\rho^2}{2}\rho^0_\mu \rho^\mu_0 + \frac{d}{4}\left(\omega_\mu \omega^\mu + \rho^0_\mu \rho^\mu_0 + \phi_\mu \phi^\mu \right)^2 - \sum_i \bar{\psi}_i \left(g_{i\sigma}\sigma + g_{i\omega}\gamma^\mu \omega_\mu + g_{i\rho}\gamma^\mu \rho^0_\mu + g_{i\phi}\gamma^\mu \phi_\mu \right) \psi_i$$

$$i = n,\, p,\, \Sigma^0,\, \Sigma^-,\, \Sigma^+,\, \Lambda,\, \Xi^0,\, \Xi^-$$

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Free parameters ↔ properties of *symmetric nuclear matter at saturation*:

- Binding energy: $E_B = -16.3\ \mathrm{MeV}$
- Density: $n_0 = 0.15\ \mathrm{fm}^{-3}$
- Incompressibility: $K \approx (200 - 300)\ \mathrm{MeV}$
- Symmetry energy: $S \approx (30 - 34)\ \mathrm{MeV}$
- Slope of symmetry energy: $L \approx (40 - 140)\ \mathrm{MeV}$ (PREX), Phys. Rev. Lett. 126, 172502 (2021)
- Effective nucleon mass: $M_0 \approx (0.7 - 0.8) m_N$

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Hyperon potentials $U_Y^{(N)}$?

We will explore the (M_0, L) subspace systematically.

The model

We minimize Ω with respect to the condensates:

Approximations:

- Mean field approximation
- Zero temperature limit
- No sea approximation
- Equilibrium phases description

$$-\frac{\partial U}{\partial \sigma} = \sum_i g_{i\sigma} n_{\mathrm{sc},i}$$

$$m_\omega \, \omega + d\, \omega \left(\omega^2 + \rho^2 + \phi^2\right) = \sum_i g_{i\omega} n_i$$

$$m_\rho \, \rho + d\, \rho \left(\omega^2 + \rho^2 + \phi^2\right) = \sum_i g_{i\rho} n_i$$

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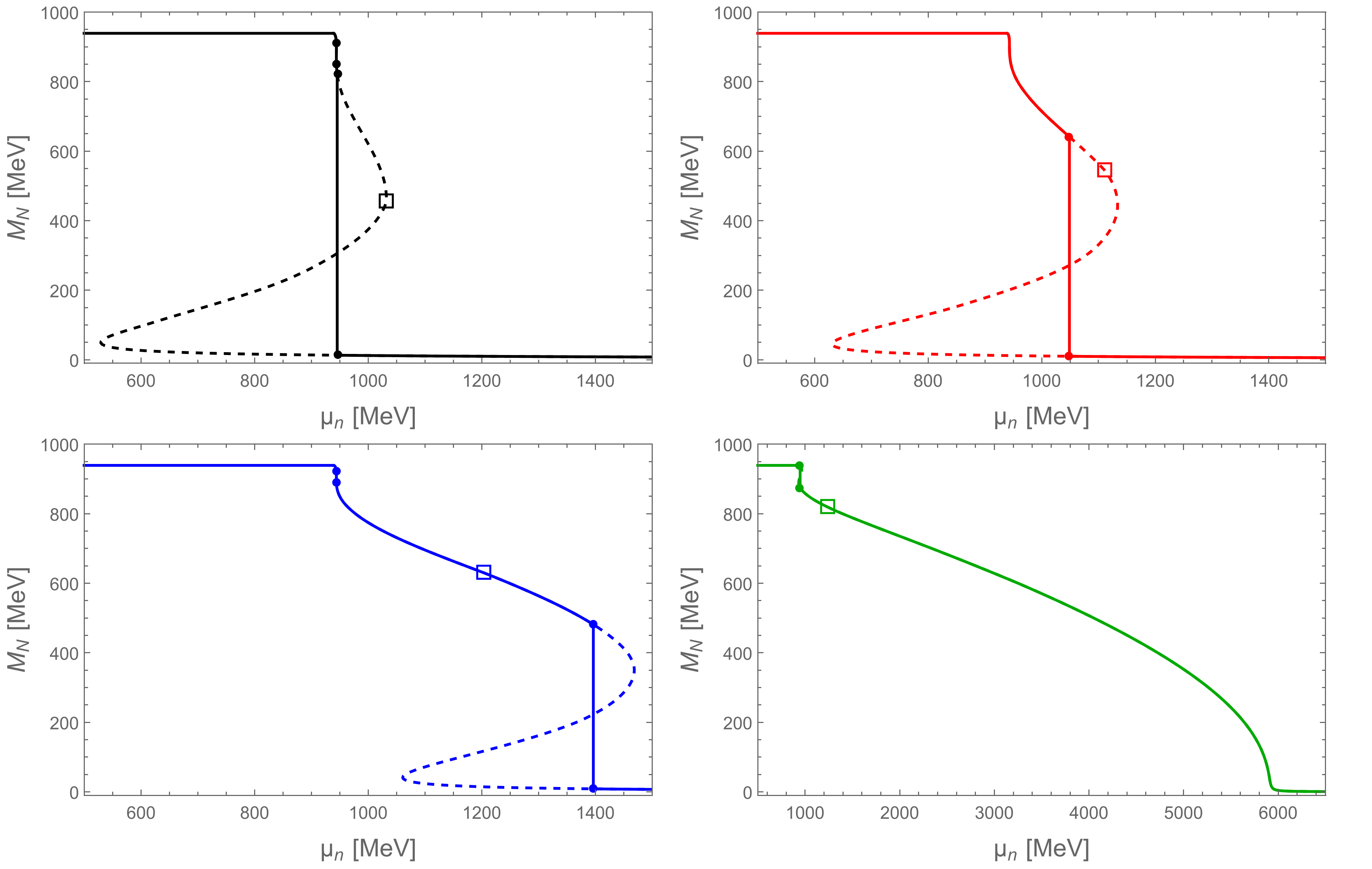
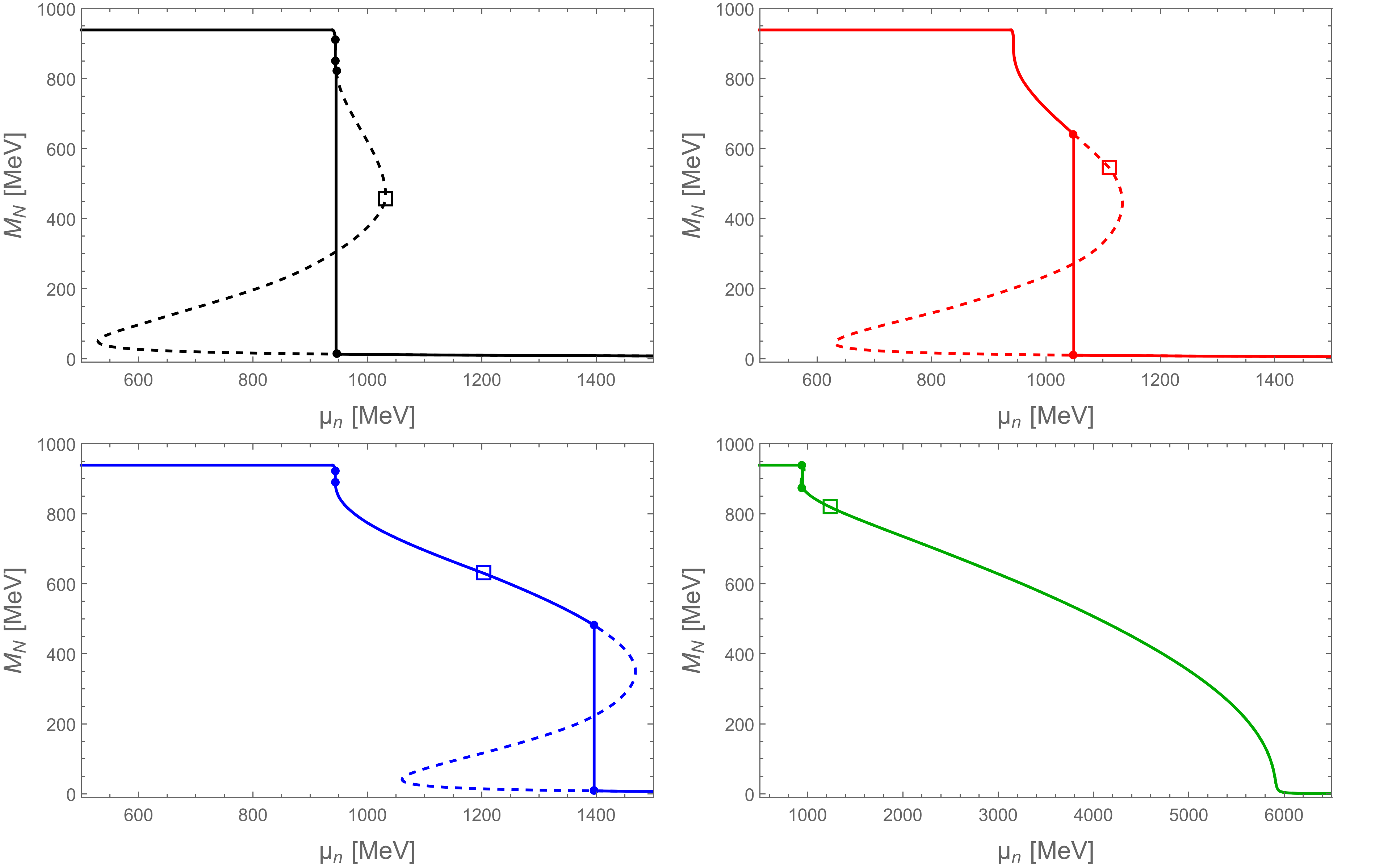
Beta equilibrium and charge neutrality are imposed leaving one independent chemical potential.



$$m_N \propto \langle \bar{q}q \rangle$$



Qualitatively different scenarios for the onset of strangeness.

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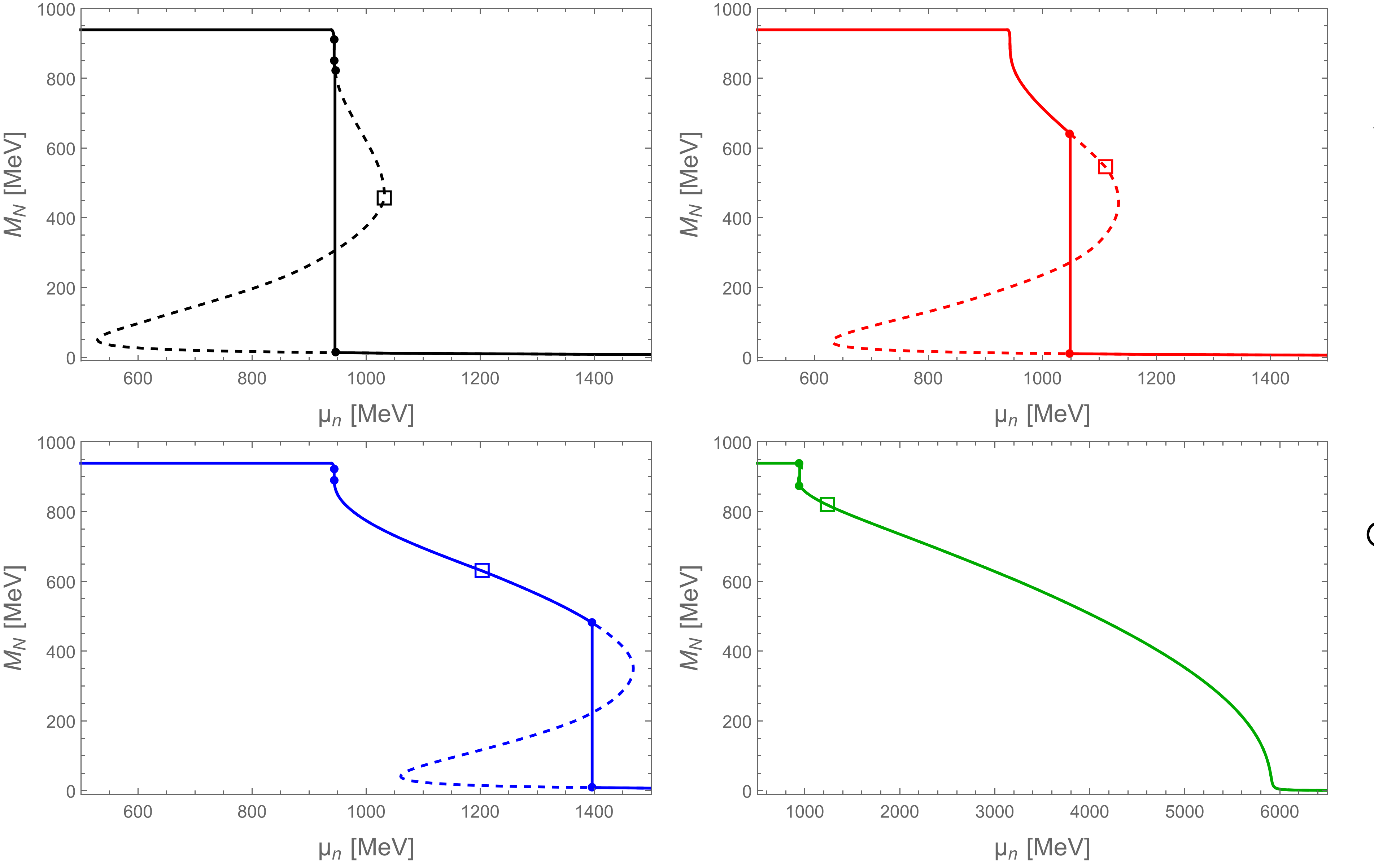

Qualitatively different scenarios for the onset of strangeness.

Order of increasing M_0

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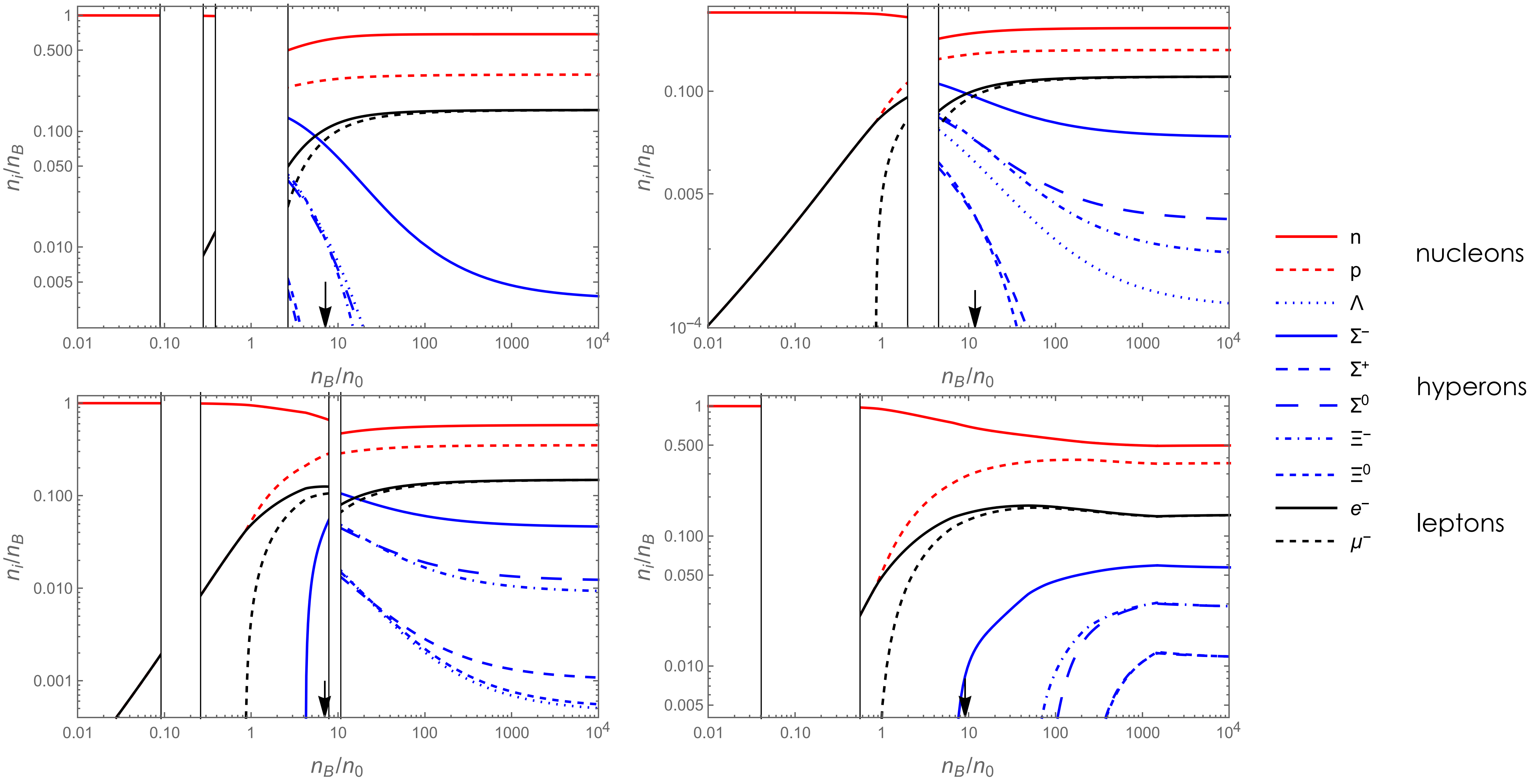
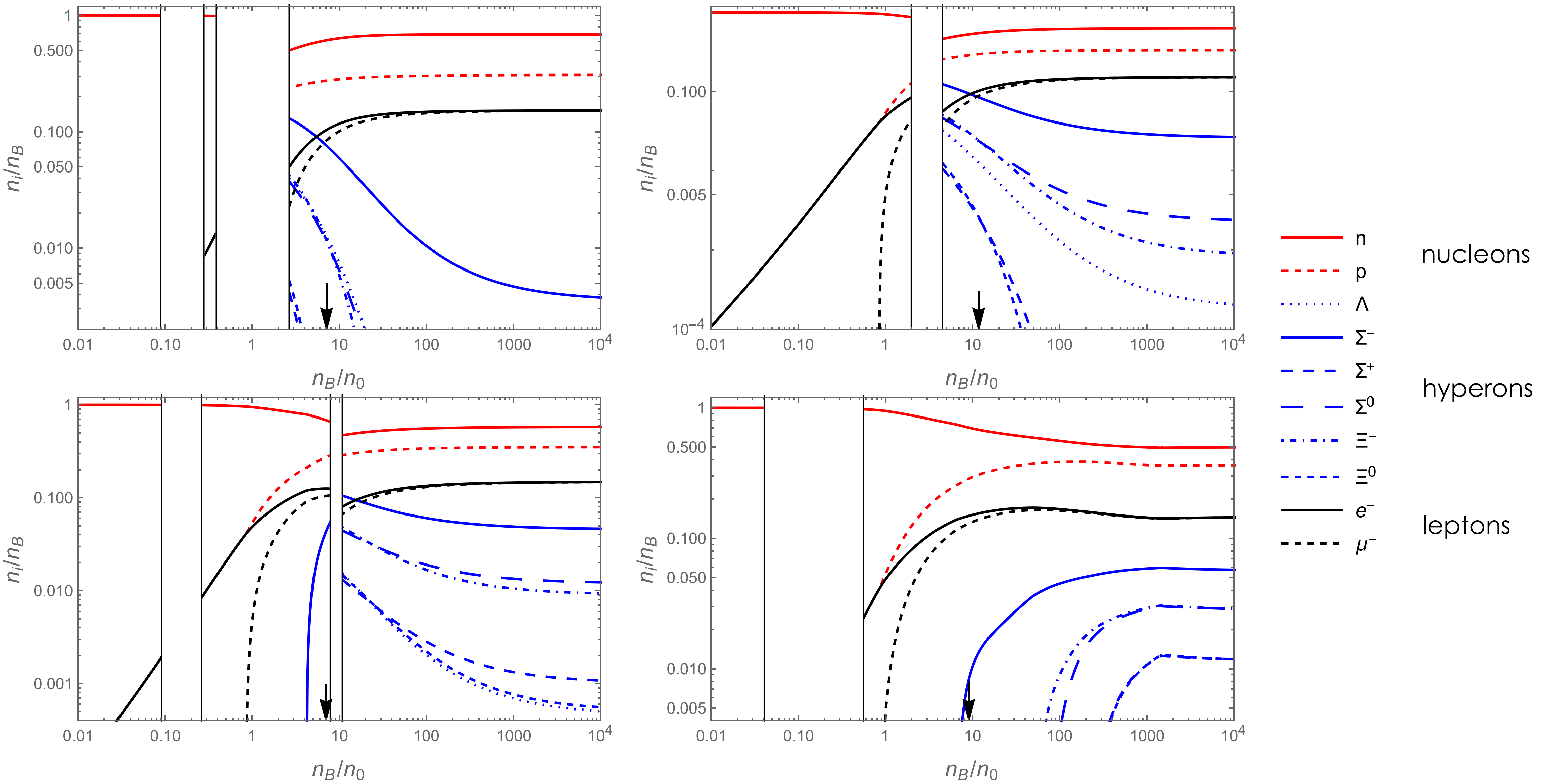
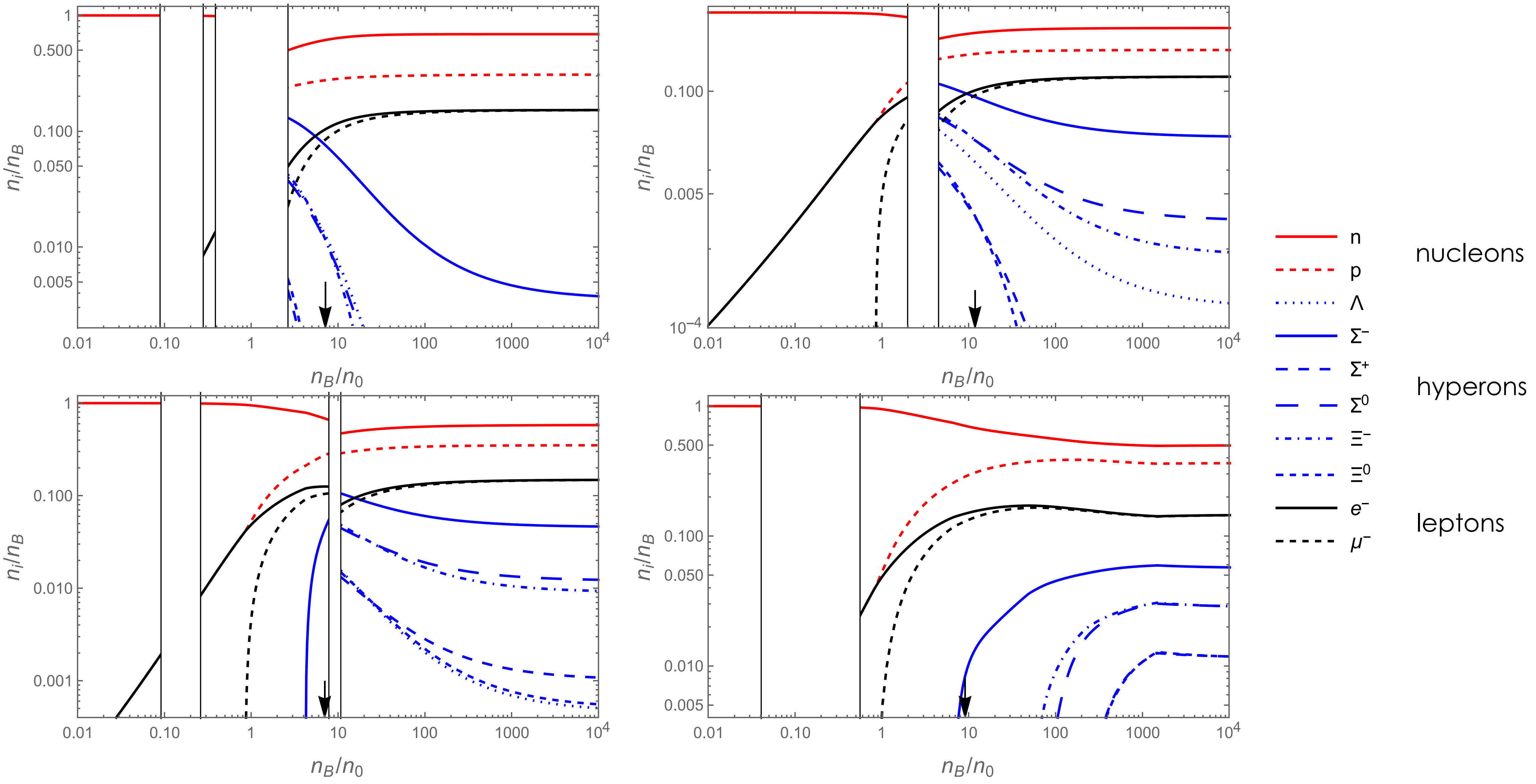


n_i/n_B
n_B/n_0
n
p
Λ
Σ⁻
Σ⁺
Σ⁰
Ξ⁻
Ξ⁰
e⁻
μ⁻
nucleons
hyperons
leptons

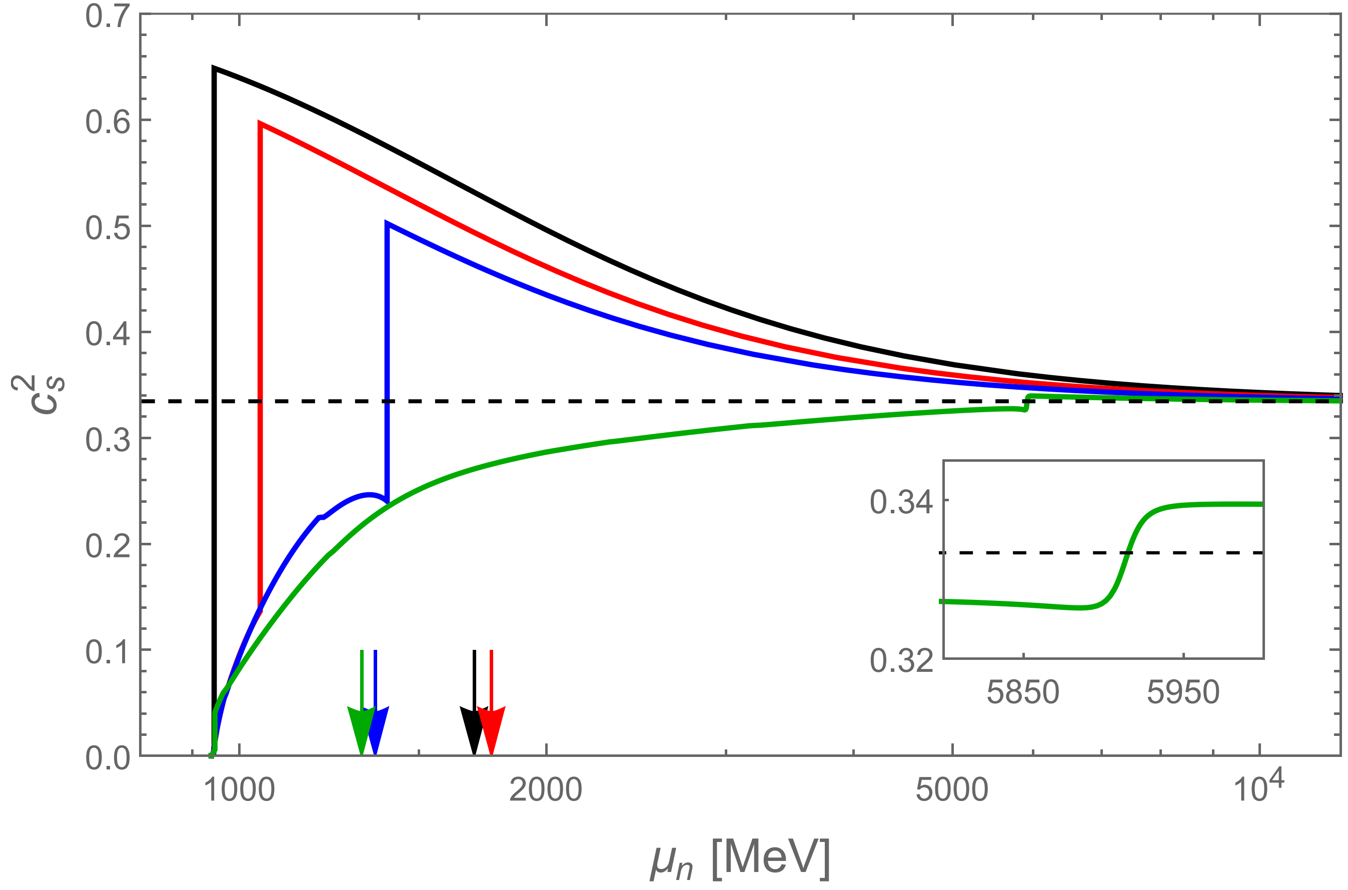


Strangeness survives asymptotically

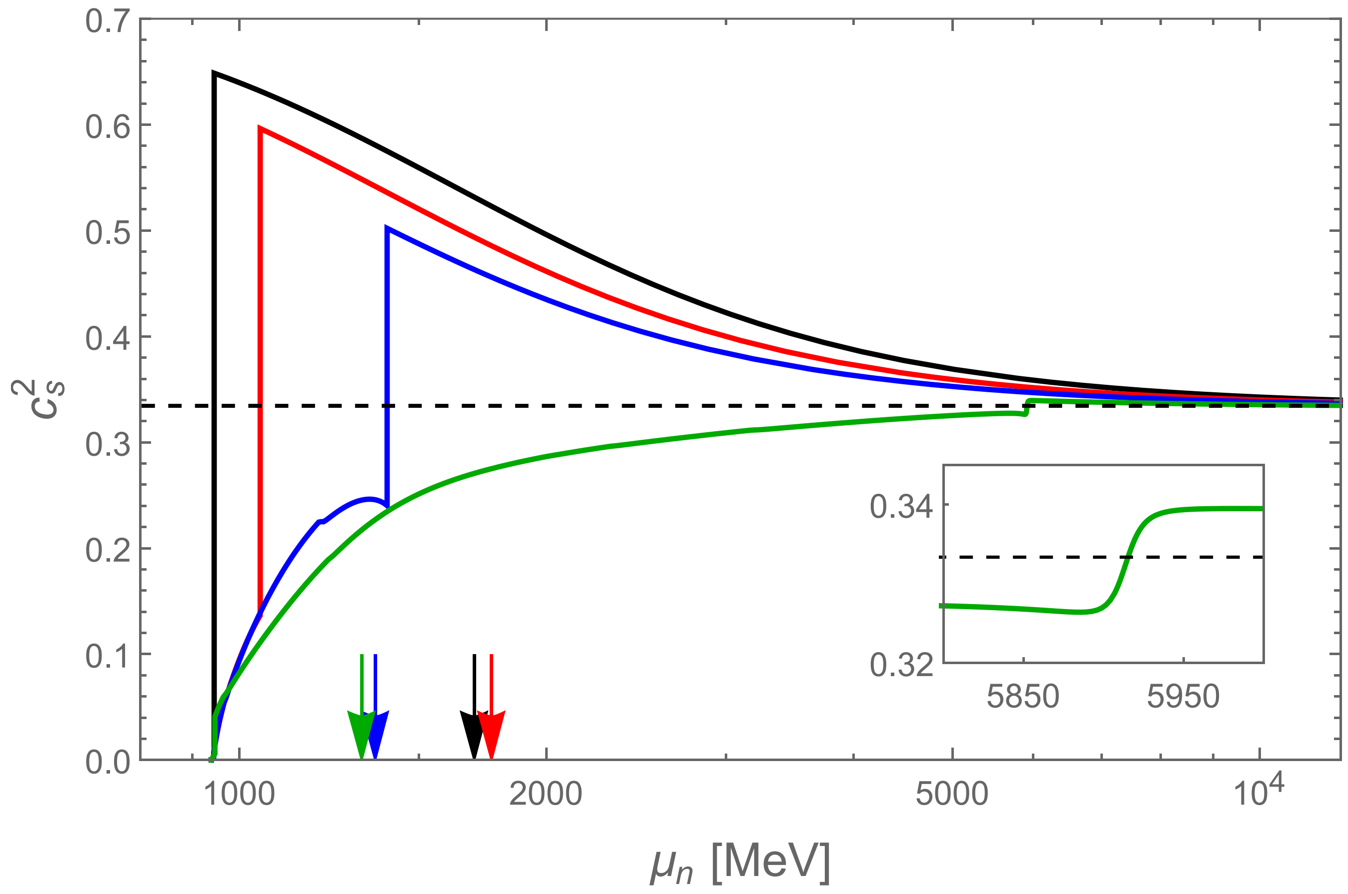


Strangeness survives asymptotically

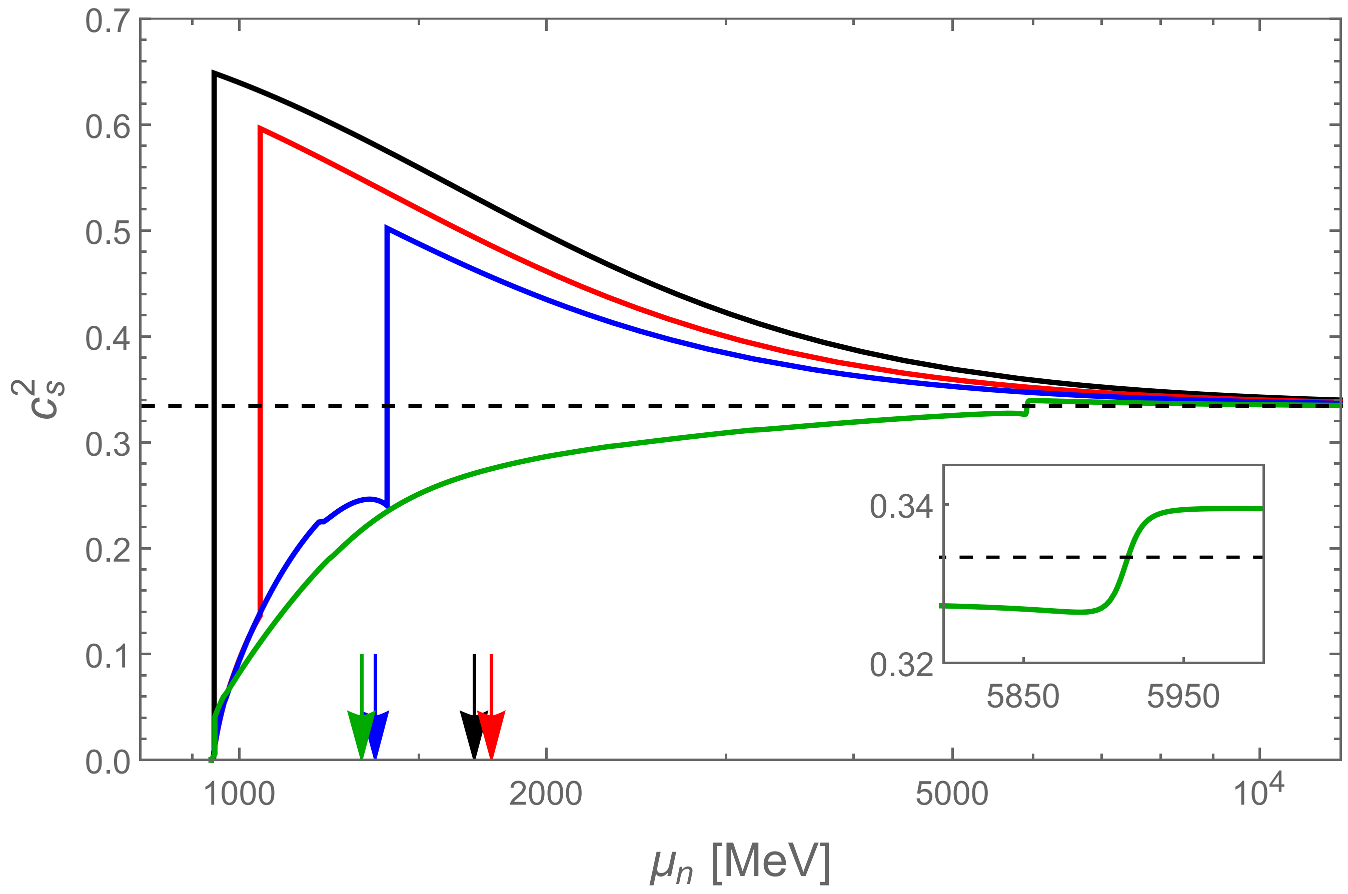
Strangeness fraction does not asymptote to $^1/_3$



0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
c_s^2
1000
2000
5000
10^4
μ_n [MeV]
0.34
0.32
5850
5950



- The conformal limit of $c_s^2 \to 1/3$ is reproduced.
- The speed of sound jumps to high values after the chiral phase transition (also seen in Y. Fujimoto and K. Fukushima, Phys. Rev. D 105, 014025 (2022))
- Heavy compact stars are made of mostly chirally symmetric matter.



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Now turn to systematically constraining the parameter space

Systematic constraints

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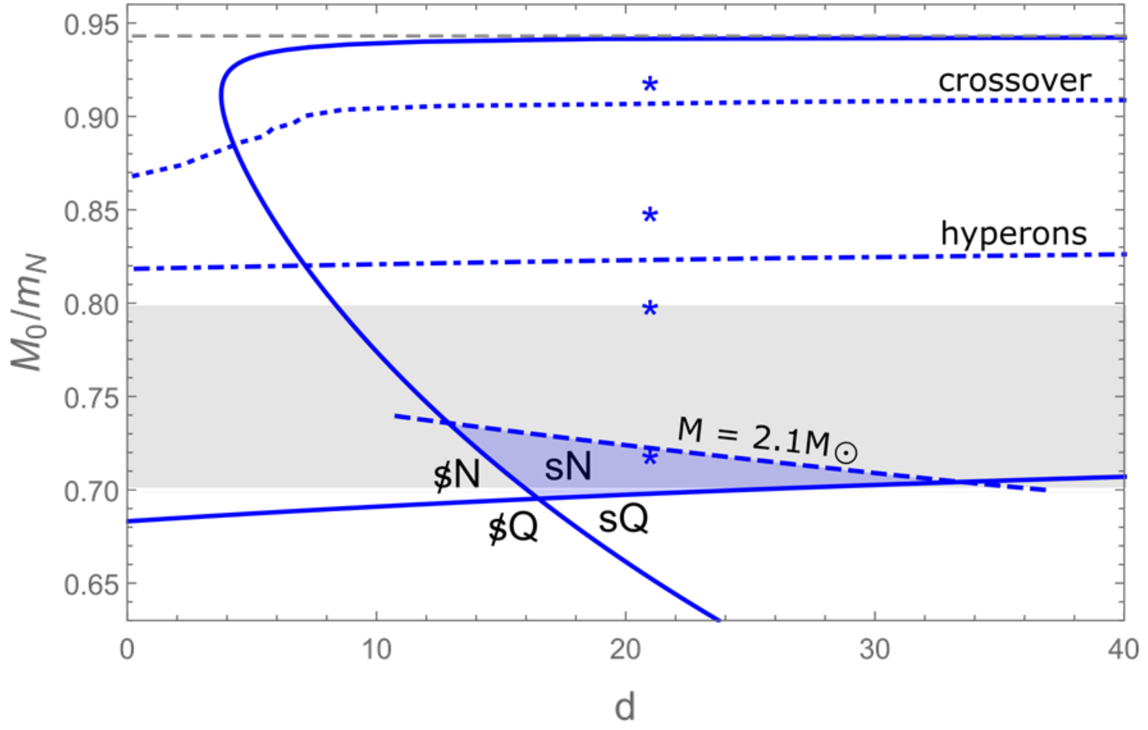
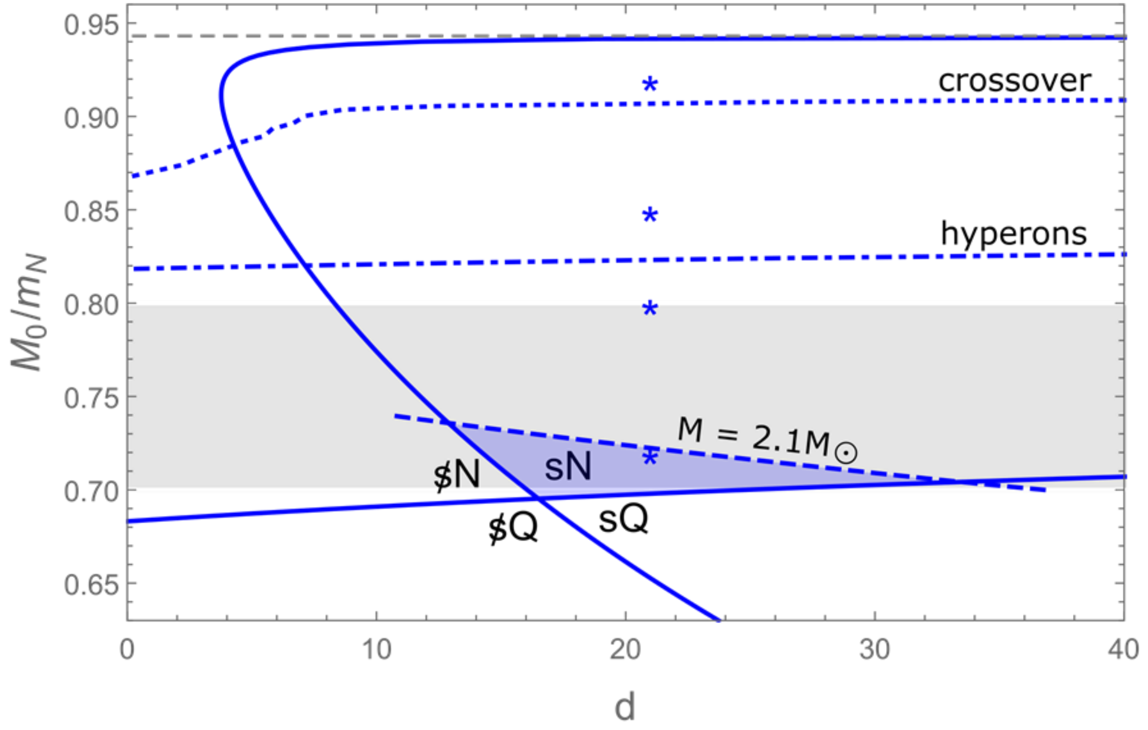
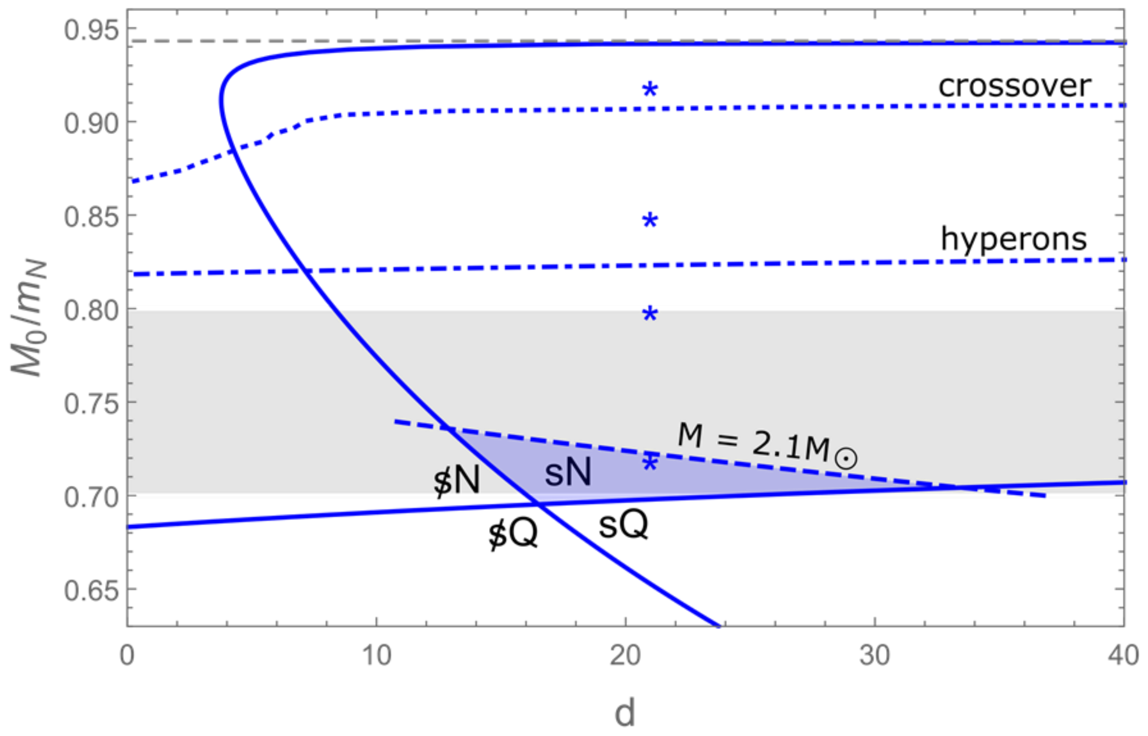
3) Sufficiently heavy stars can be constructed.
   Observational constraint.



crossover
hyperons
M = 2.1M☉
$\not{s}$N
sN
$\not{s}$Q
sQ
0.95
0.90
0.85
0.80
0.75
0.70
0.65
M_0/m_N
0
10
20
30
40
d



- The crossover scenario is disfavored.
- Hyperons do not appear in stars.
- Heavy stars require an early chiral phase transition



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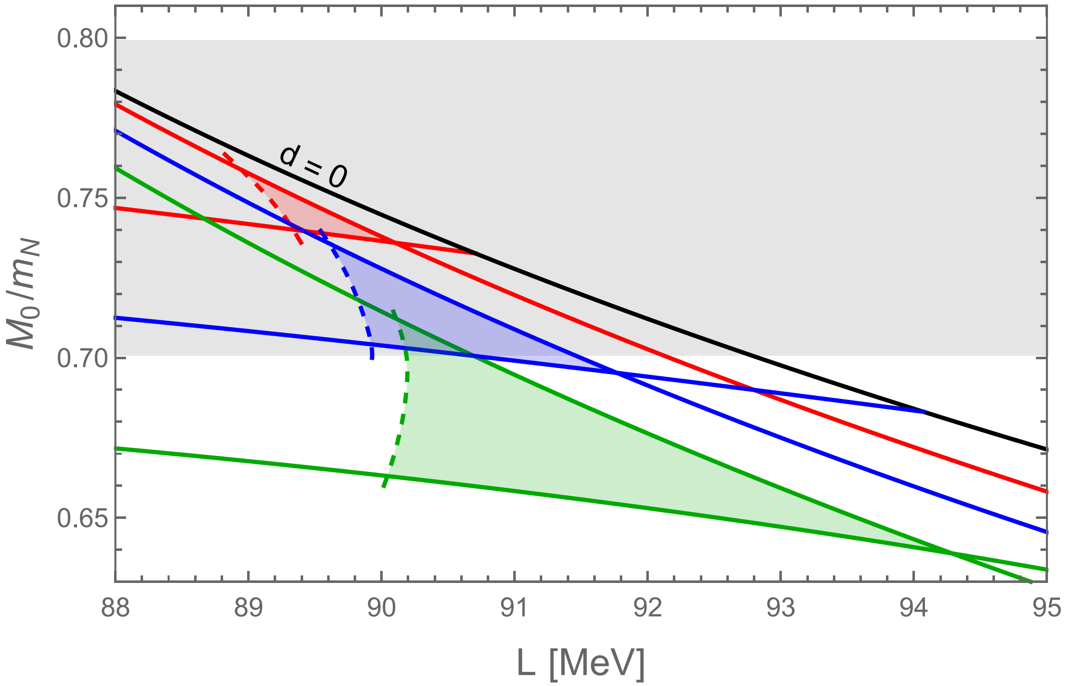

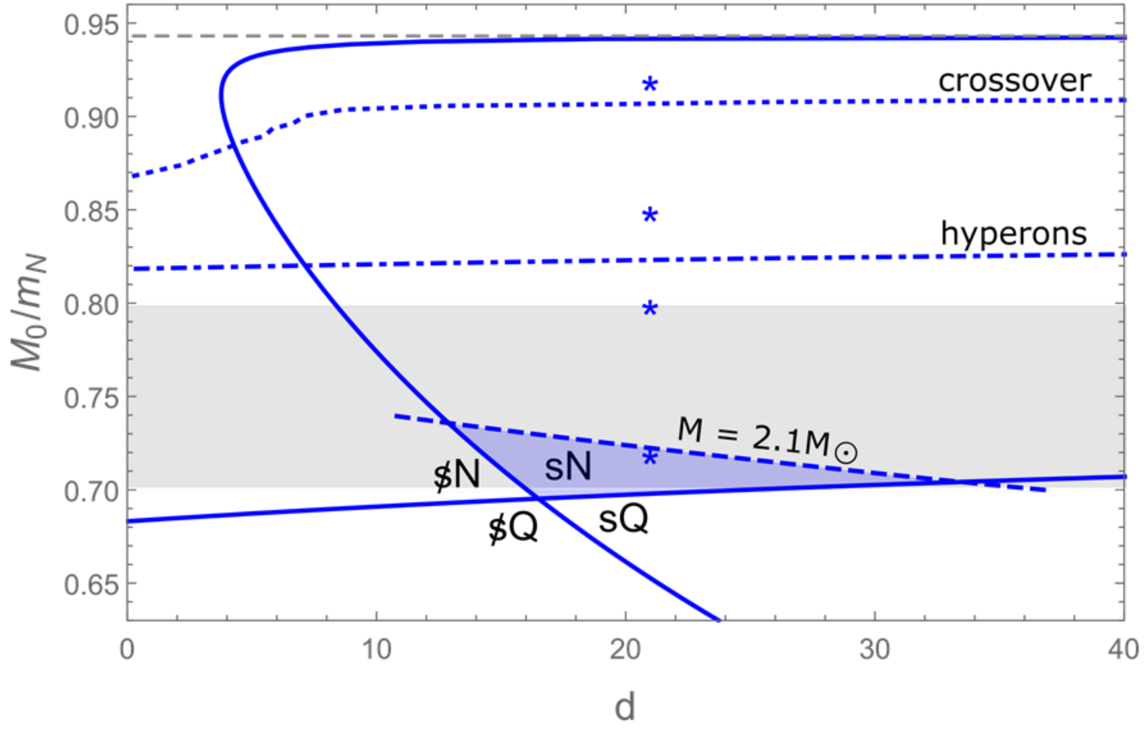

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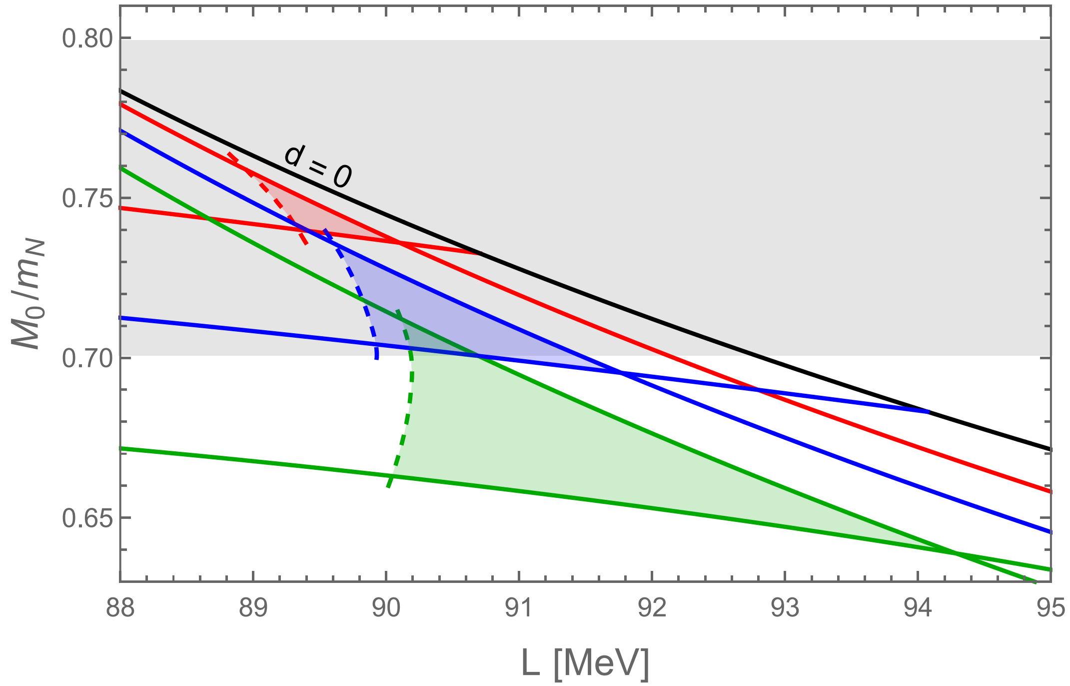


- The slope parameter is significantly constrained: $L \approx (88 - 92)$ MeV.
- The hyperon potential depths U_Y^N do not significantly change the slope parameter L acceptable range.

Summary

- We built a phenomenological model that describes a chirally broken and a chirally restored phase, with strangeness.
- Interpreting the latter as "quark matter", we explored the quark-hadron transition.
- The quark-hadron crossover scenario is disfavored.
- An early chiral phase transition prevents hyperons from appearing in heavy stars, suggesting a resolution to the hyperon puzzle.
- The slope parameter of the symmetry energy is significantly constrained:

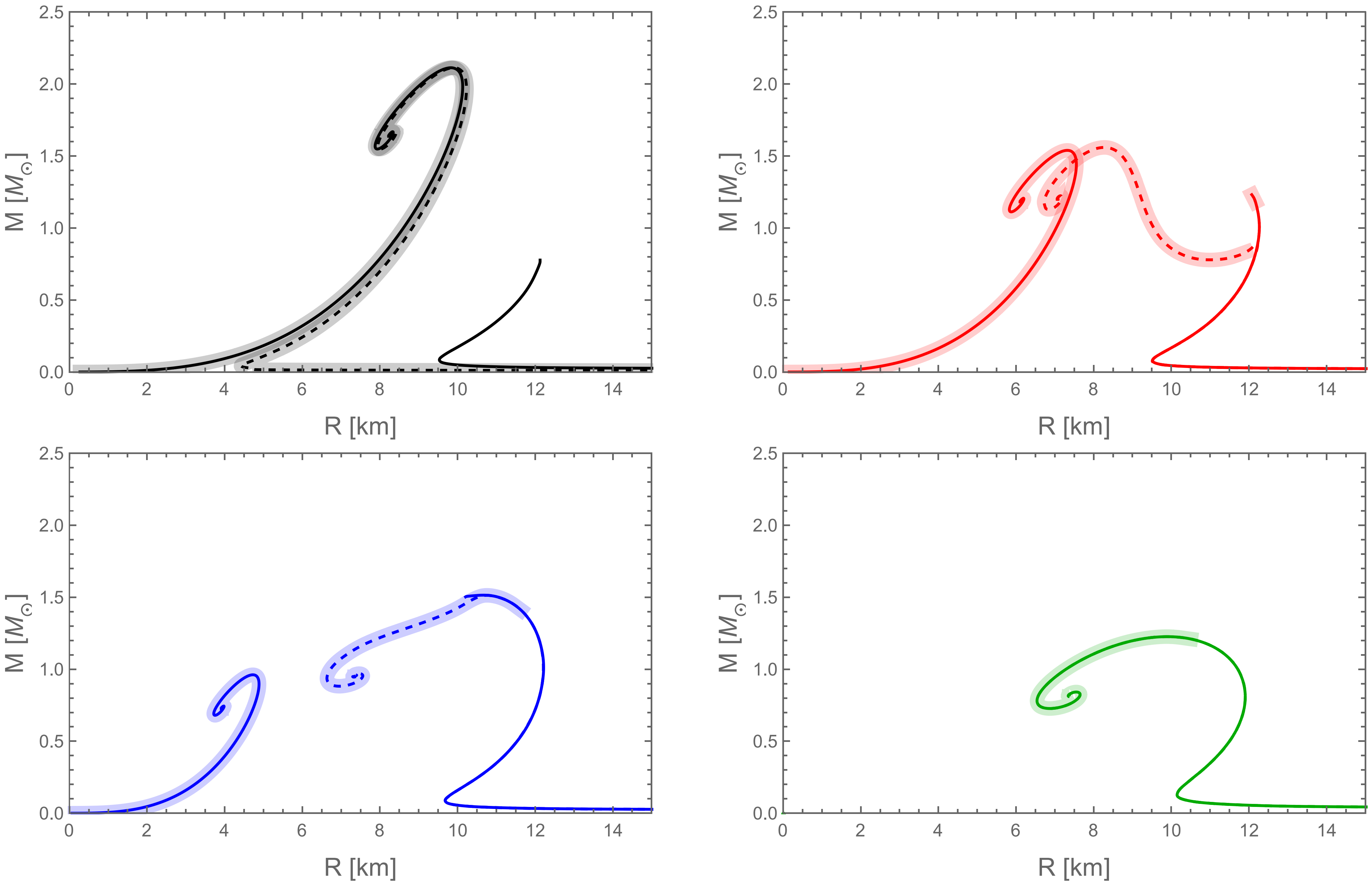
$$L \approx (88 - 92)\ \mathrm{MeV}$$

Outlook

- Compute the surface tension.
- Chiral density wave and interplay with pasta phases.
- Inclusion of the strange condensate $\langle \bar{s}s \rangle$.
- Include pairing (both sides).
- Extend to finite temperature (mergers).
- Go beyond mean field.

Thank you !

Extra Slide(s)



M [$M_\odot$]
R [km]
2.5
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
12
14