Andreas Schmitt

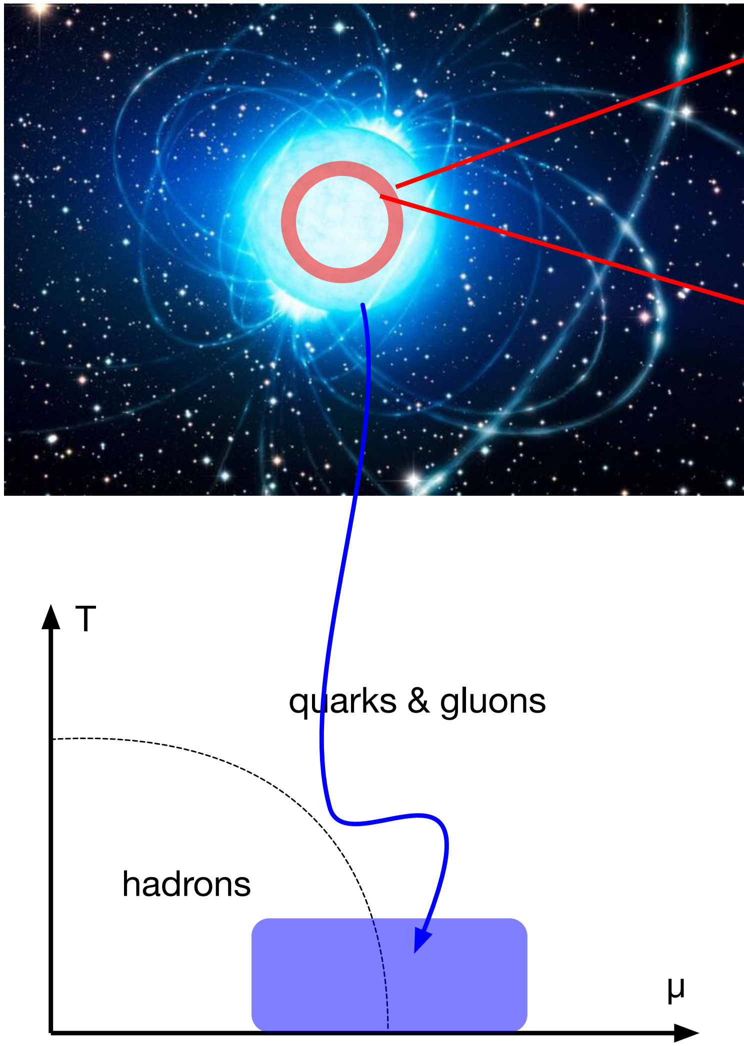
Mathematical Sciences and STAG Research Centre
University of Southampton
Southampton SO17 1BJ, United Kingdom

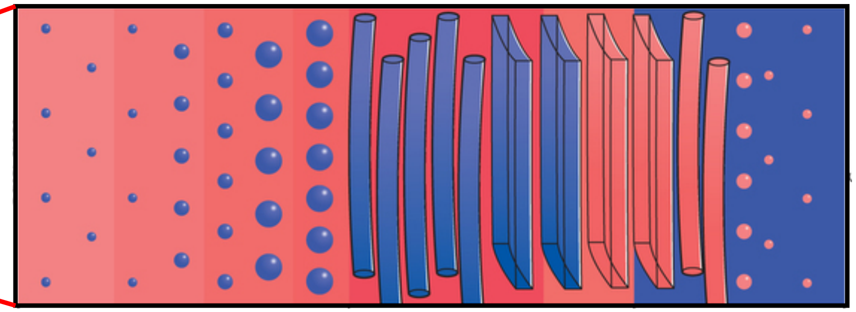
Strange quark matter from a baryonic approach

E. S. Fraga, M. Hippert, A. Schmitt, PRD 99, 014046 (2019)
A. Schmitt, PRD 101, 074007 (2020)
E. S. Fraga, R. da Mata, S. Pitsinigkos, A. Schmitt, in preparation

- main idea:
  quark-hadron phase transition (chiral transition)
  in cold, dense matter within a single model (based on nucleons)
- compute pasta phases consistently
- include hyperons to create "strange quark matter"

Quark-hadron transition





quark-hadron pasta layer?

- at what critical μ?
  is that μ reached in neutron stars?
- order of transition?
  crossover?
- properties in the vicinity?
  inhomogeneous phases?
- observable effects for neutron stars?
  for mergers?

Quark-hadron transition

no qualitative difference between hadronic and quark matter:

order parameter	Polyakov loop (confinement)	chiral condensate
spontaneously breaks	$\mathbb{Z}_{N_c}$	$SU(N_f) \times SU(N_f)$
symmetry exact for	pure Yang-Mills ($m_q = \infty$)	chiral limit ($m_q = 0$)

additional transitions due to Cooper pairing (ignored here)

T. Schäfer, F. Wilczek, PRD 60, 074014 (1999)

M. G. Alford, A. Schmitt, K. Rajagopal, T. Schäfer, RMP 80, 1455 (2008)

A. Cherman, S. Sen, L. G. Yaffe, PRD 100, 034015 (2019)

- first-principle calculations: difficult (strongly coupled regime)
- model descriptions: usually two models patched together
- our approach: single model with baryonic degrees of freedom and chiral phase transition

Phenomenological, but unified, approach

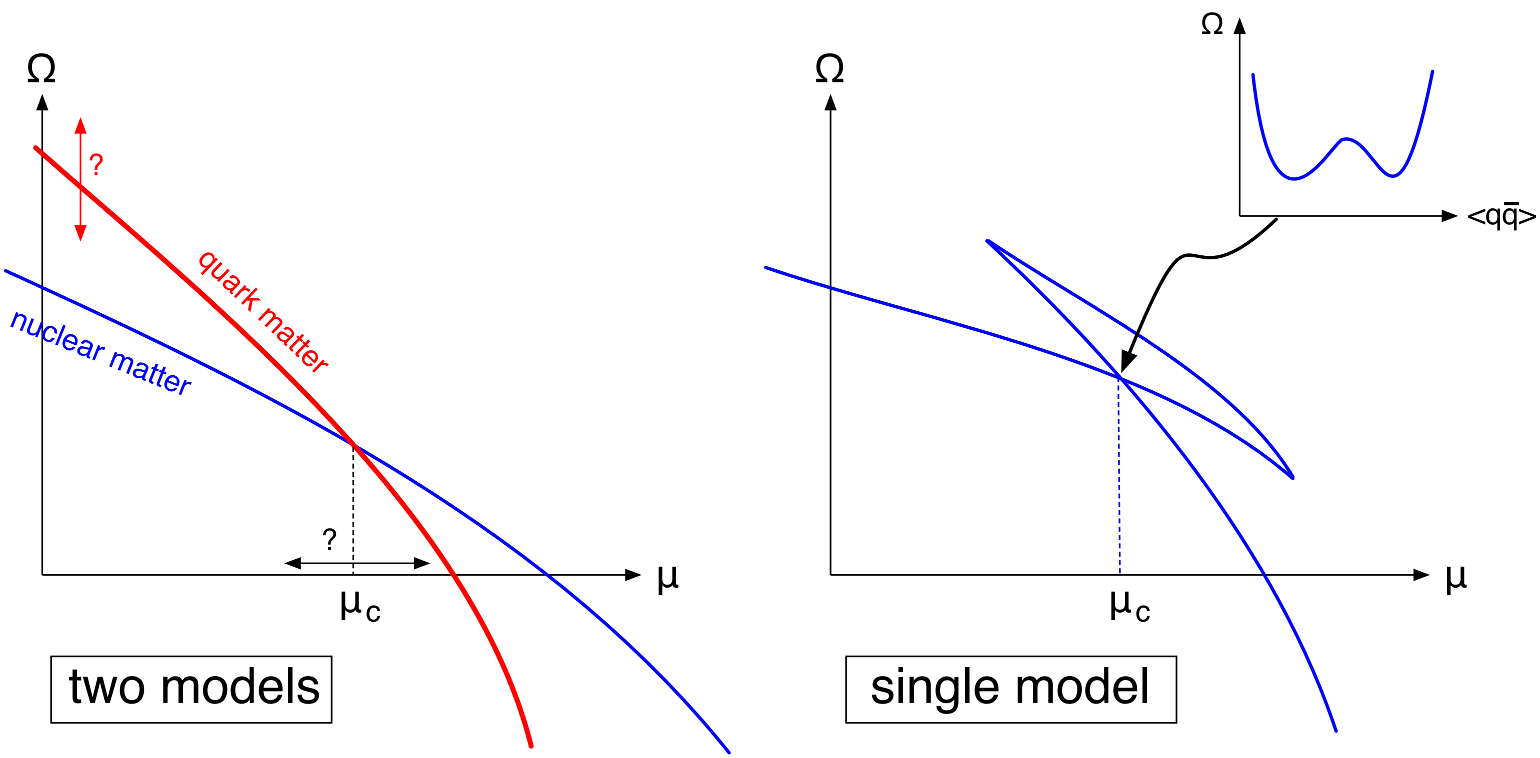
- our approach: single model with baryonic degrees of freedom and chiral phase transition

  see also K. Bitaghsir Fadafan, F. Kazemian, and A. Schmitt, JHEP 03, 183 (2019)

  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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- our approach: single model with baryonic degrees of freedom and chiral phase transition

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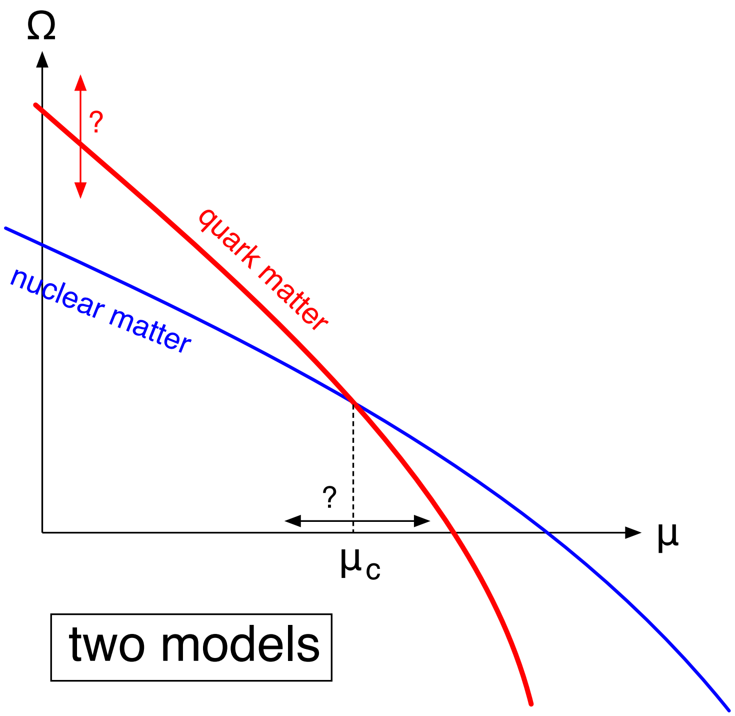

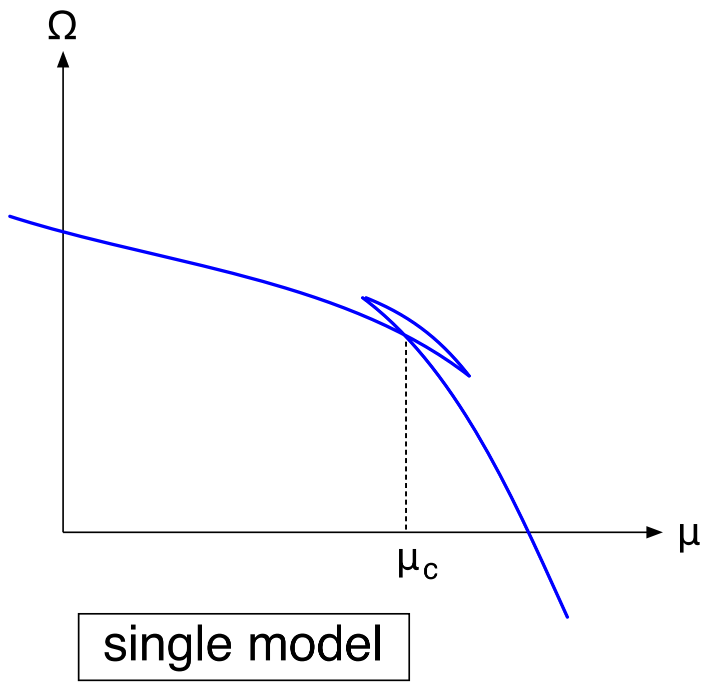

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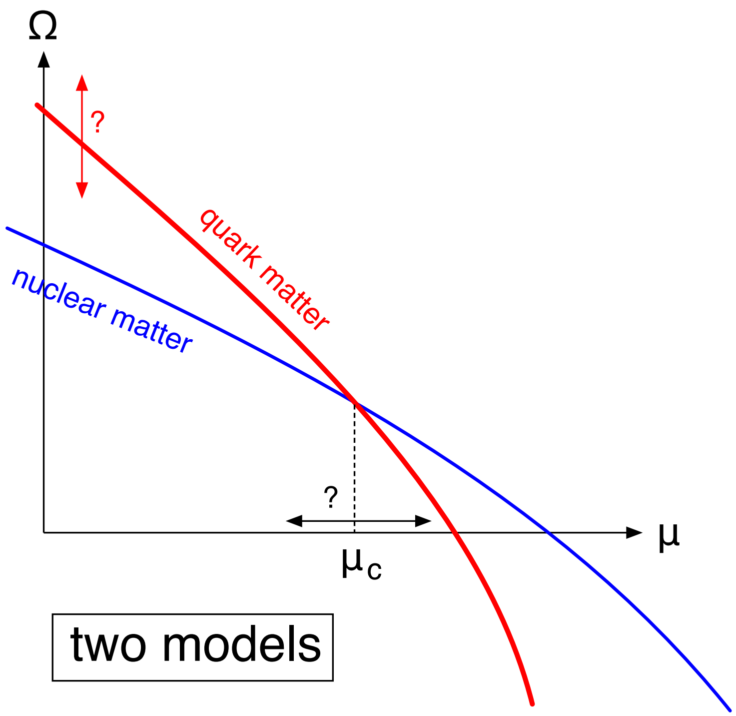
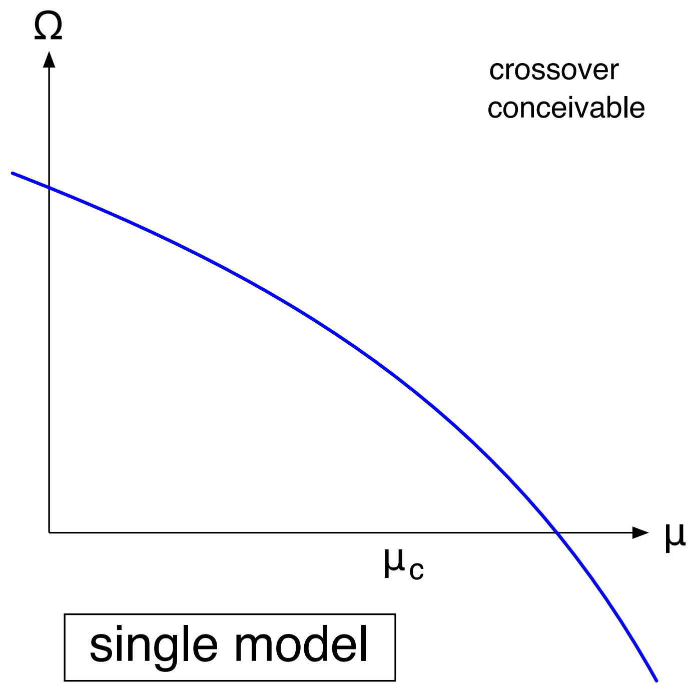




Nucleon-meson model

M. Drews and W. Weise, PRC 91, 035802 (2015)

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

Nucleonic degrees of freedom (+ leptons) without explicit mass terms

$$\mathcal{L} = \sum_{i=n,p} \bar{\psi}_i (i\gamma^\mu \partial_\mu + \gamma^0 \mu_i)\psi_i + \frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma - U(\sigma) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{4}\rho^0_{\mu\nu}\rho_0^{\mu\nu} + \frac{m_\omega^2}{2}\omega_\mu\omega^\mu + \frac{m_\rho^2}{2}\rho^0_\mu\rho_0^\mu$$
$$- \sum_{i=n,p} \bar{\psi}_i (g_{i\sigma}\sigma + g_{i\omega}\gamma^\mu \omega_\mu + g_{i\rho}\gamma^\mu \rho^0_\mu)\psi_i - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Approximations: mean field, no sea, zero temperature, Thomas-Fermi

$$\nabla^2 \langle\sigma\rangle = \frac{\partial U}{\partial\langle\sigma\rangle} + g_\sigma n_s$$
$$\nabla^2 \langle\omega\rangle = m_v^2 \langle\omega\rangle - g_\omega n_B$$
$$\nabla^2 \langle\rho\rangle = m_v^2 \langle\rho\rangle - g_\rho n_I$$
$$\frac{\nabla^2 \mu_e}{e^2} = -n_p + n_e + n_\mu$$

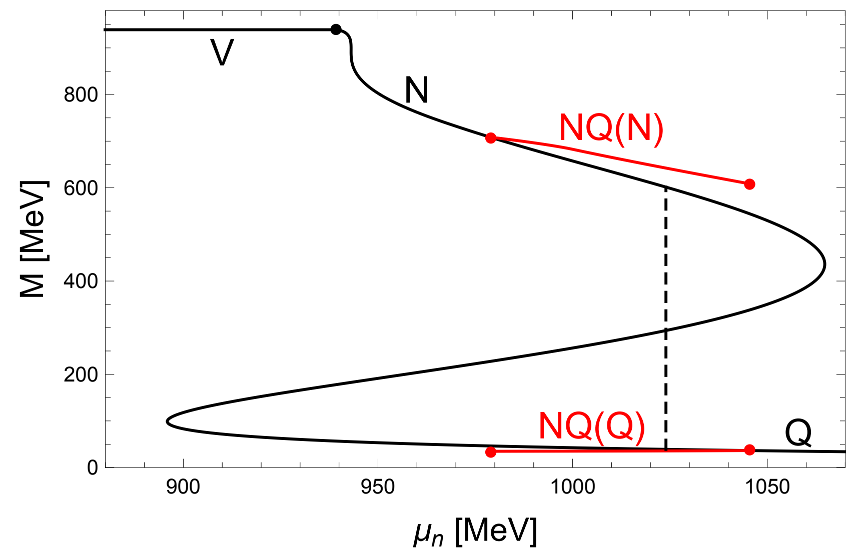
- Euler-Lagrange equations for meson condensates and electric potential (Poisson equation)
- electroweak equilibrium

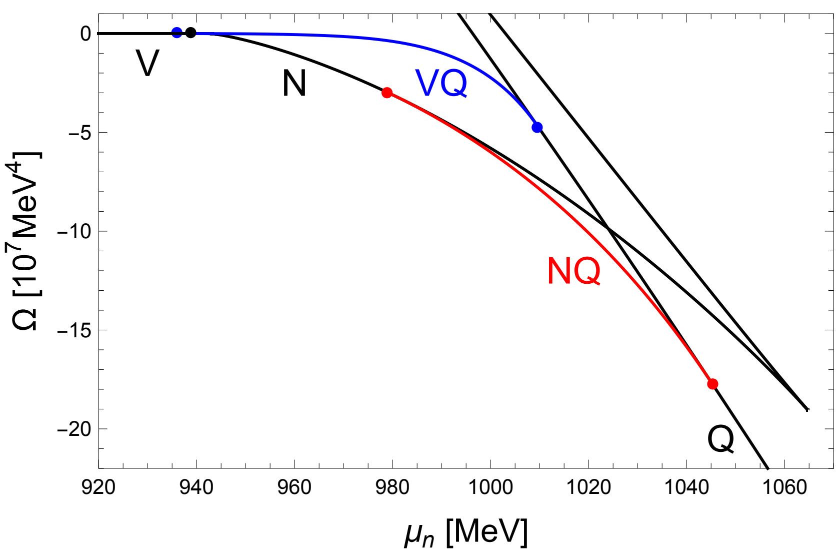
$$\mu_p + \mu_e = \mu_n\,, \quad \mu_\mu = \mu_e$$

Parameters chosen to reproduce nuclear matter properties at saturation

Homogeneous solutions and mixed phases without surface and Coulomb costs

V vacuum (lepton gas)
N nuclear matter
Q chirally restored phase
("quark matter")

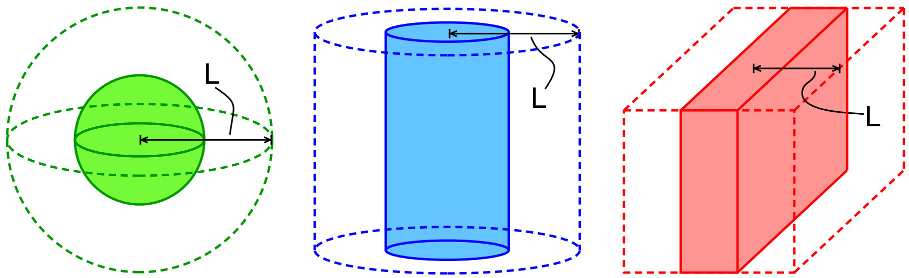




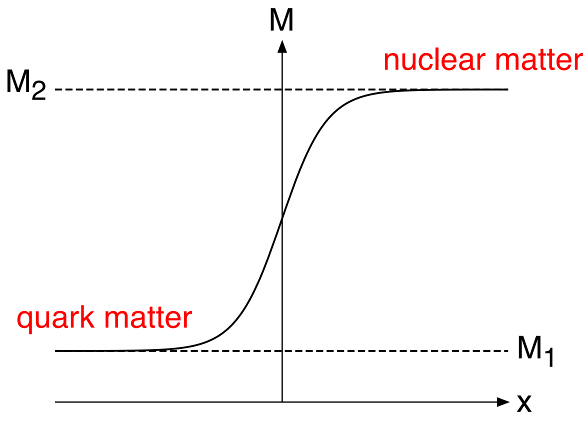
NQ quark-hadron mixed phase
VQ quark-vacuum mixed phase
(crust of quark star)

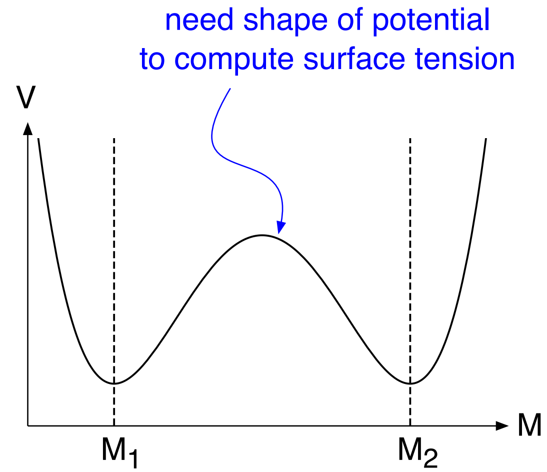
Mixed phases in the Wigner-Seitz approximation

- 3 geometries
  (bubbles, rods, slabs)



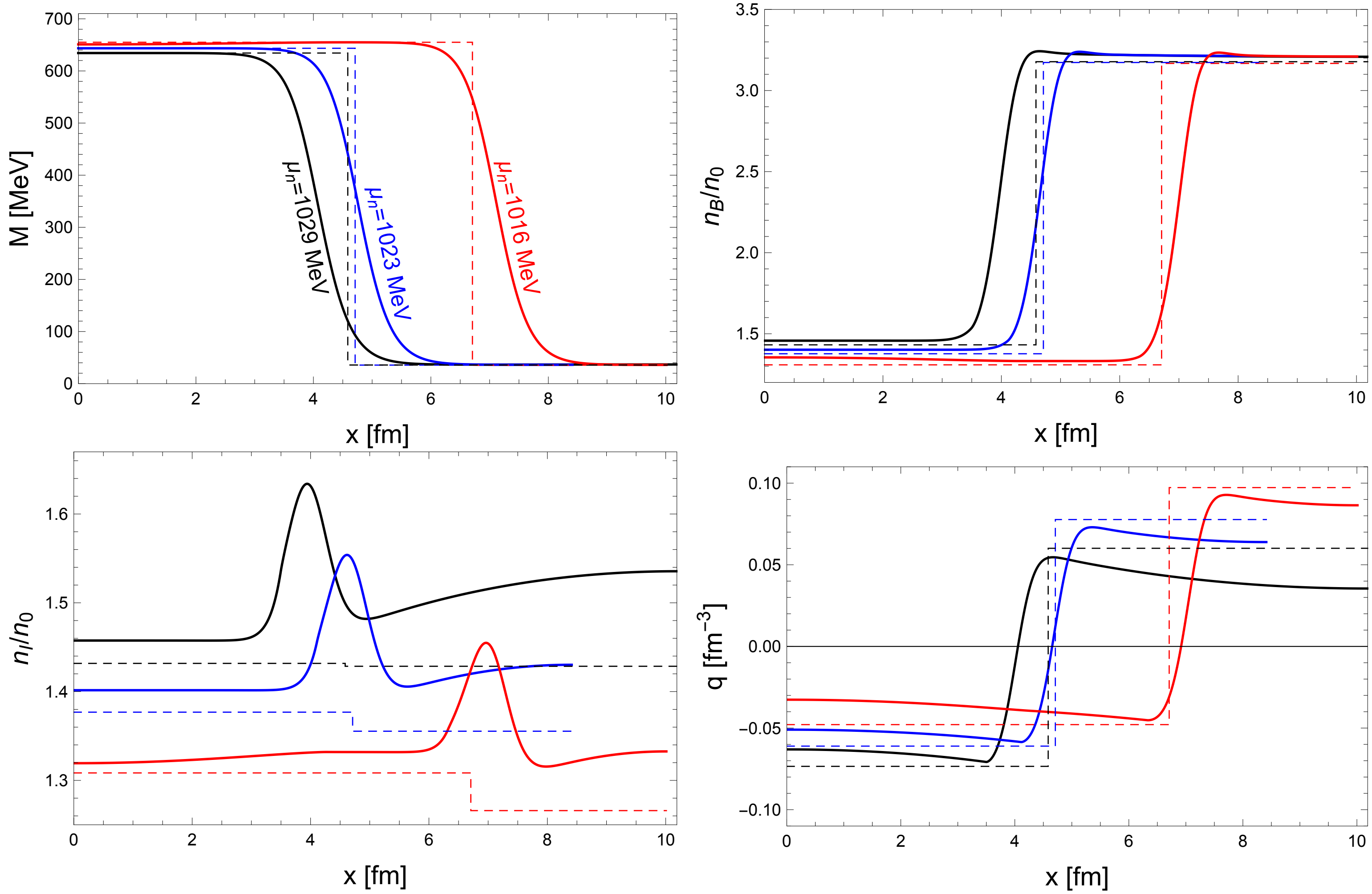
- approximate Wigner-Seitz cell by same geometry
- solve interface profiles numerically and determine size of unit cell L dynamically
  (competition Coulomb energy vs. surface tension)
  vacuum/nuclear interface: T. Maruyama, *et al.*, PRC 72, 015802 (2005)





Interface profiles at preferred cell size (slabs)

A. Schmitt, PRD 101, 074007 (2020)

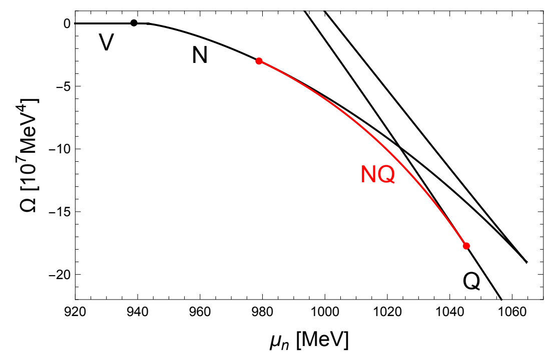


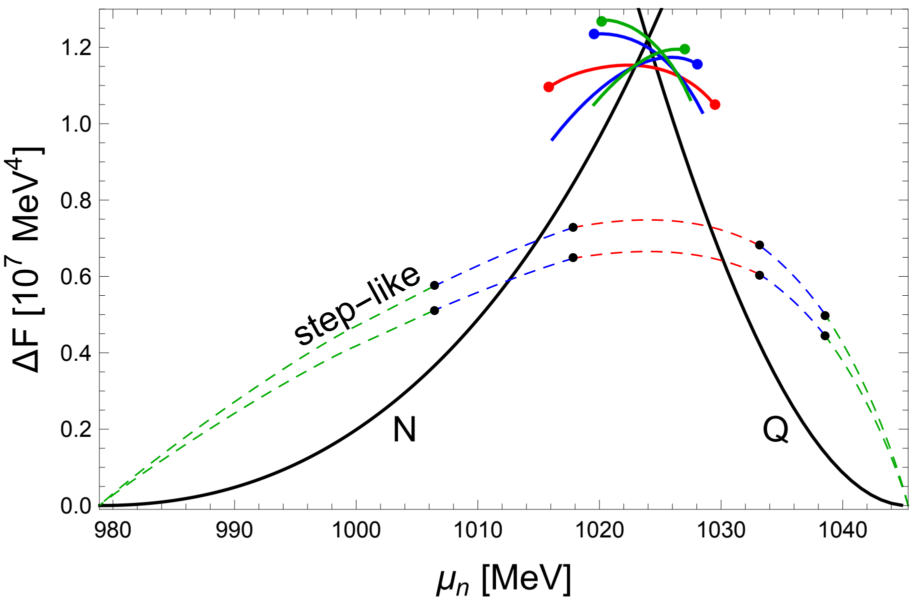
surface tension, charge screening, Coulomb energy emerge dynamically

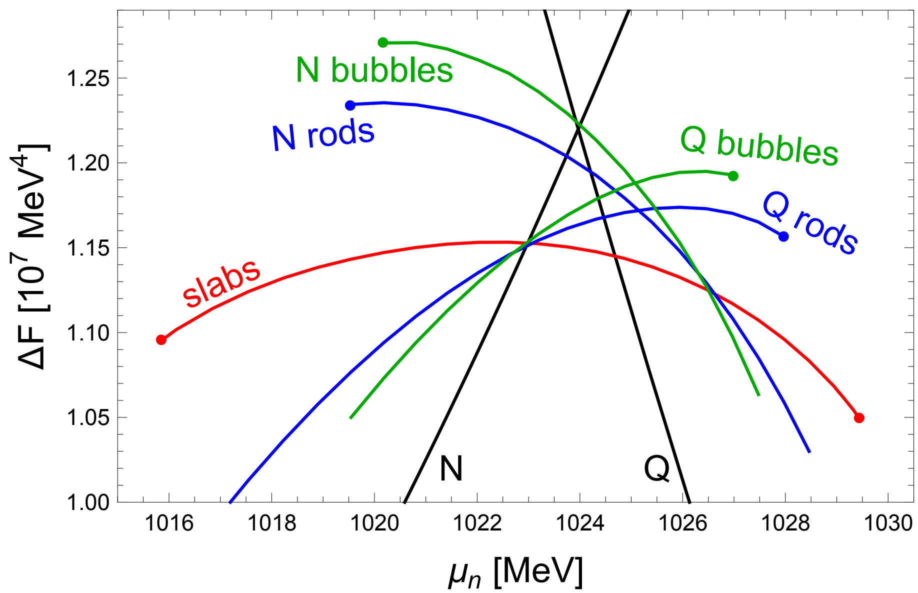
charge screening at vacuum/quark interface: M. G. Alford, K. Rajagopal, S. Reddy and A. W. Steiner, PRD 73, 114016 (2006)

Free energy comparison of pasta structures

A. Schmitt, PRD 101, 074007 (2020)







- mixed phases are less favored compared to step-like approximation
- density dependent surface tension $\Sigma \simeq (5.2 - 6.2)\,\mathrm{MeV/fm^2}$
  similar to (slightly smaller than) isospin-symmetric matter
  same model: E. S. Fraga, M. Hippert and A. Schmitt, PRD 99, 014046 (2019)
  quark-meson model: L. F. Palhares and E. S. Fraga, PRD 82, 125018 (2010)

Include strangeness

E. S. Fraga, R. da Mata, S. Pitsinigkos, A. Schmitt, in preparation

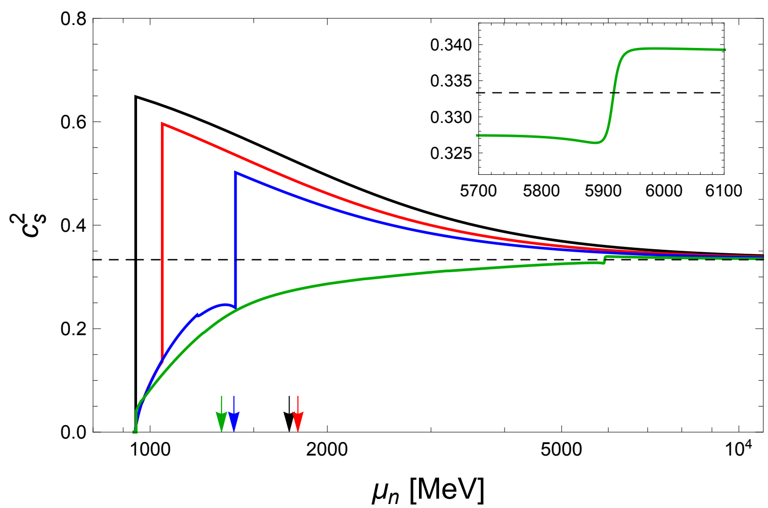
- so far: no strangeness, no negative charge carriers

  → include hyperons to create "strange quark matter", $i = n, p, \Sigma^0, \Sigma^-, \Sigma^+, \Lambda, \Xi^0, \Xi^-$

$$\mathcal{L} = \sum_i \bar{\psi}_i(i\gamma^\mu\partial_\mu + \gamma^0\mu_i)\psi_i + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - U(\sigma) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} - \frac{1}{4}\rho^0_{\mu\nu}\rho_0^{\mu\nu} + \frac{m_\omega^2}{2}\omega_\mu\omega^\mu$$
$$+\frac{m_\phi^2}{2}\phi_\mu\phi^\mu + \frac{m_\rho^2}{2}\rho^0_\mu\rho_0^\mu + \frac{d}{4}(\omega_\mu\omega^\mu + \rho^0_\mu\rho_0^\mu + \phi_\mu\phi^\mu)^2 - \sum_i \bar{\psi}_i(g_{i\sigma}\sigma + g_{i\omega}\gamma^\mu\omega_\mu + g_{i\rho}\gamma^\mu\rho^0_\mu + g_{i\phi}\gamma^\mu\phi_\mu)\psi_i$$

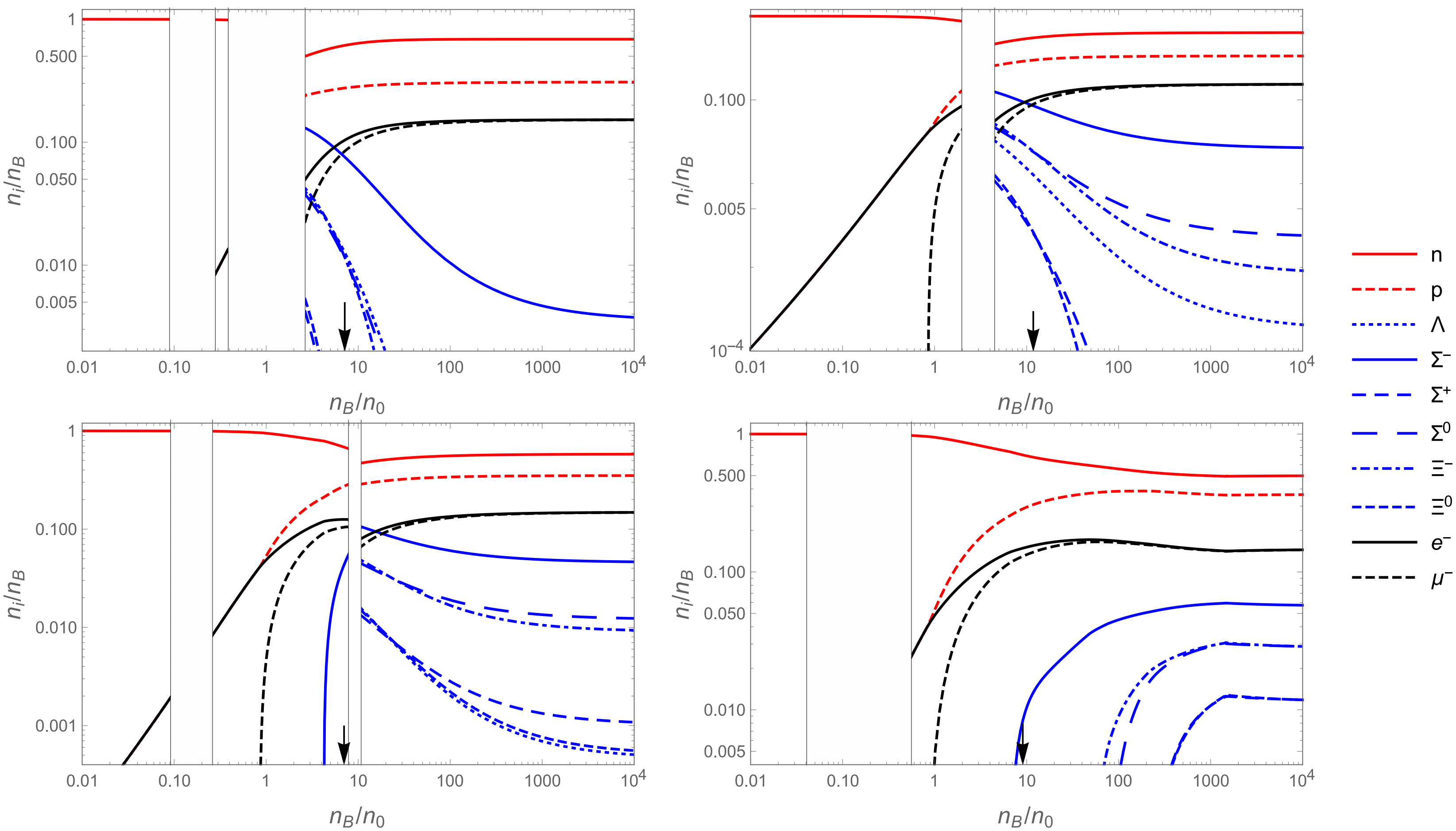
- use chiral symmetry + nuclear matter properties + hyperon potentials to fix parameters V. Dexheimer, S. Schramm, Astrophys. J. 683, 943 (2008)
  S. Weissenborn *et al.*, NPA 881, 62 (2012)
  V. B. Thapa *et al.*, Particles 3, 660 (2020)

- quartic meson coupling $d > 0$ ensures $c_s^2 = \frac{1}{3}$ asymptotically



Particle fractions

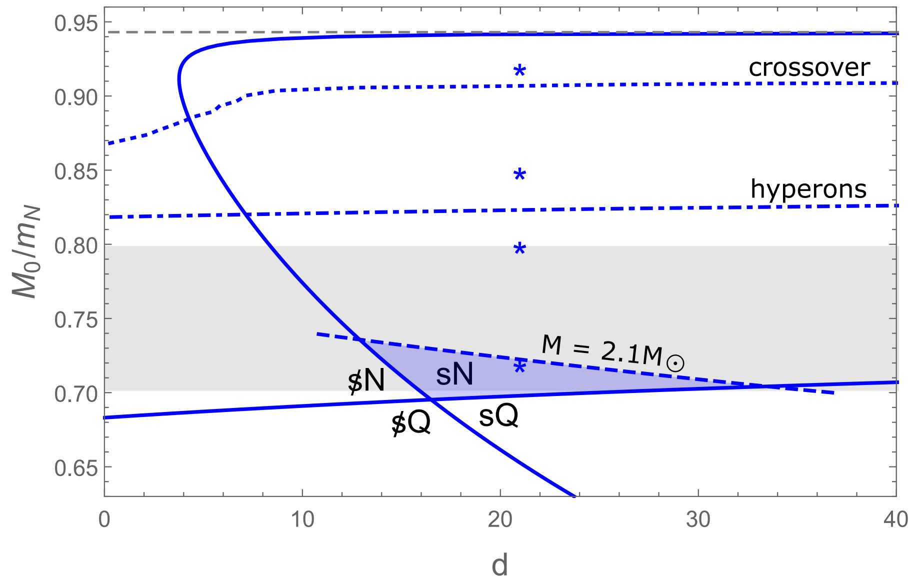
- vary effective nucleon mass at saturation M_0 within (and beyond) empirical range

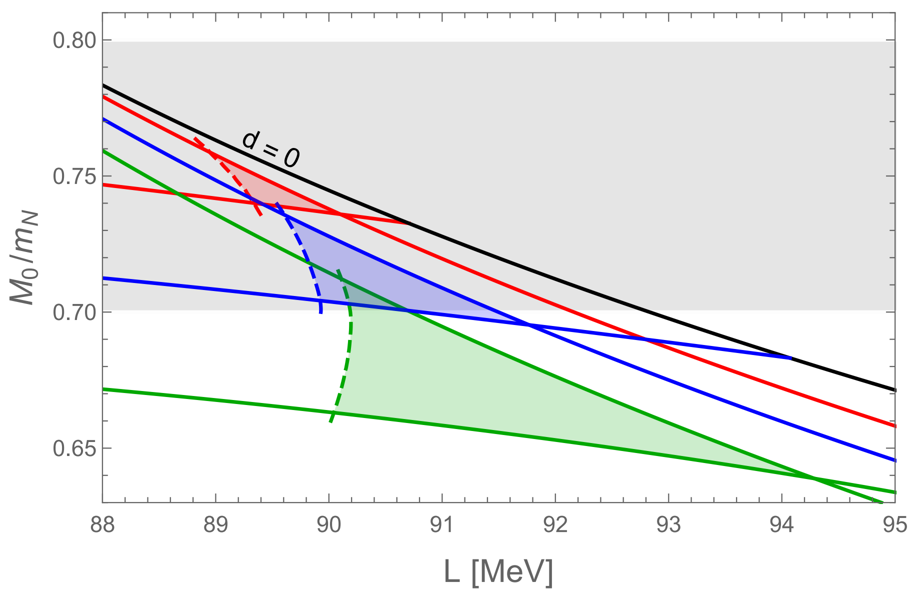


- parameters chosen such that strangeness survives asymptotically
  – although no flavor symmetry

Identify realistic parameter region

- neutron stars $M > 2.1\, M_\odot$
- asymptotic strangeness (s)
- nuclear matter stable at zero pressure (N)





- vary hyperon potentials
- prediction for slope of symmetry energy $L \simeq (88 - 92)$ MeV

Summary

- nucleon-meson model can be employed to study properties of high-density chiral phase transition ("quark-hadron transition") (complementary to e.g. Nambu-Jona-Lasinio model)

- mixed phase less favored in fully consistent calculation compared to widely used step-like approximation

- model strange quark matter by introducing hyperonic degrees of freedom (even if actual hyperons are dynamically disfavored)

Outlook

- improve model (e.g., include scalar $\langle s\bar{s}\rangle$ condensate)

- nonzero temperatures $\rightarrow$ neutron star mergers

- include Cooper pairing (on both sides)

- include quarkyonic phase?

- re-compute interfaces/surface tension including strangeness
  E. S. Fraga, R. da Mata, S. Pitsinigkos, A. Schmitt, work in progress

- study chiral density wave and its competition with mixed phase
  E. S. Fraga, R. da Mata, S. Pitsinigkos, A. Schmitt, work in progress