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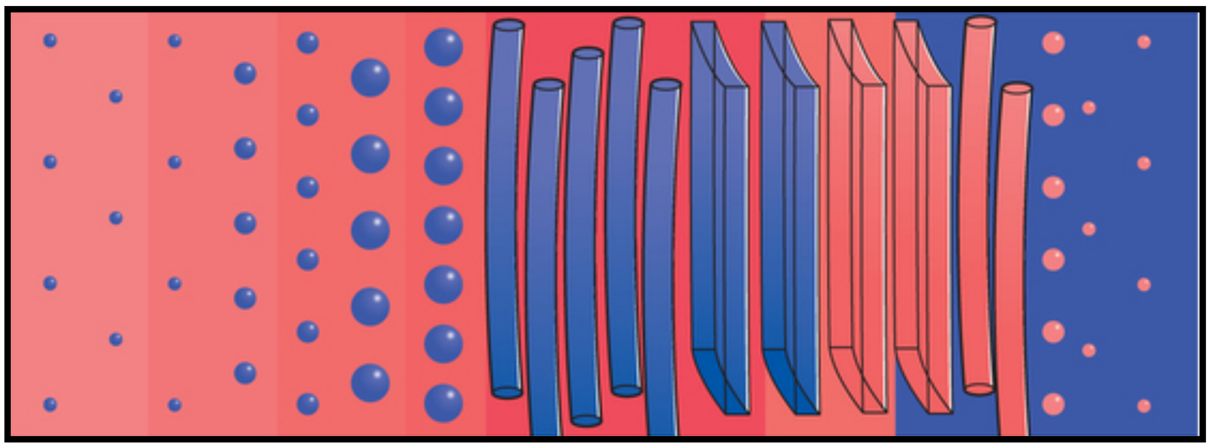
Quark-hadron mixed phases in neutron star interiors

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

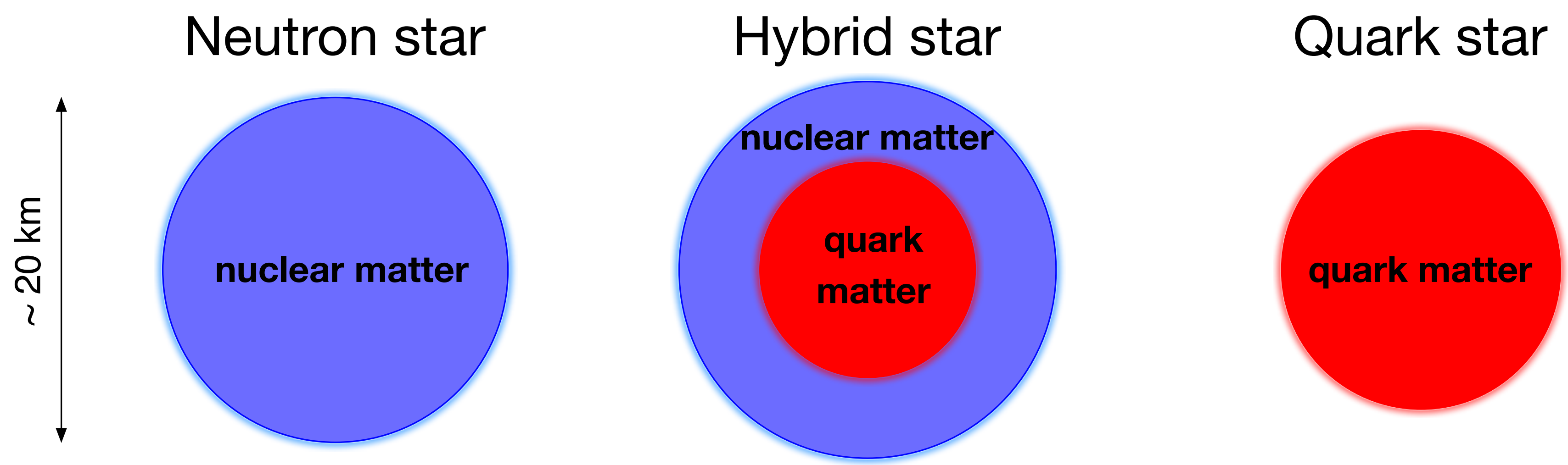
A. Pfaff, Project Report (2019)

A. Schmitt, work in progress

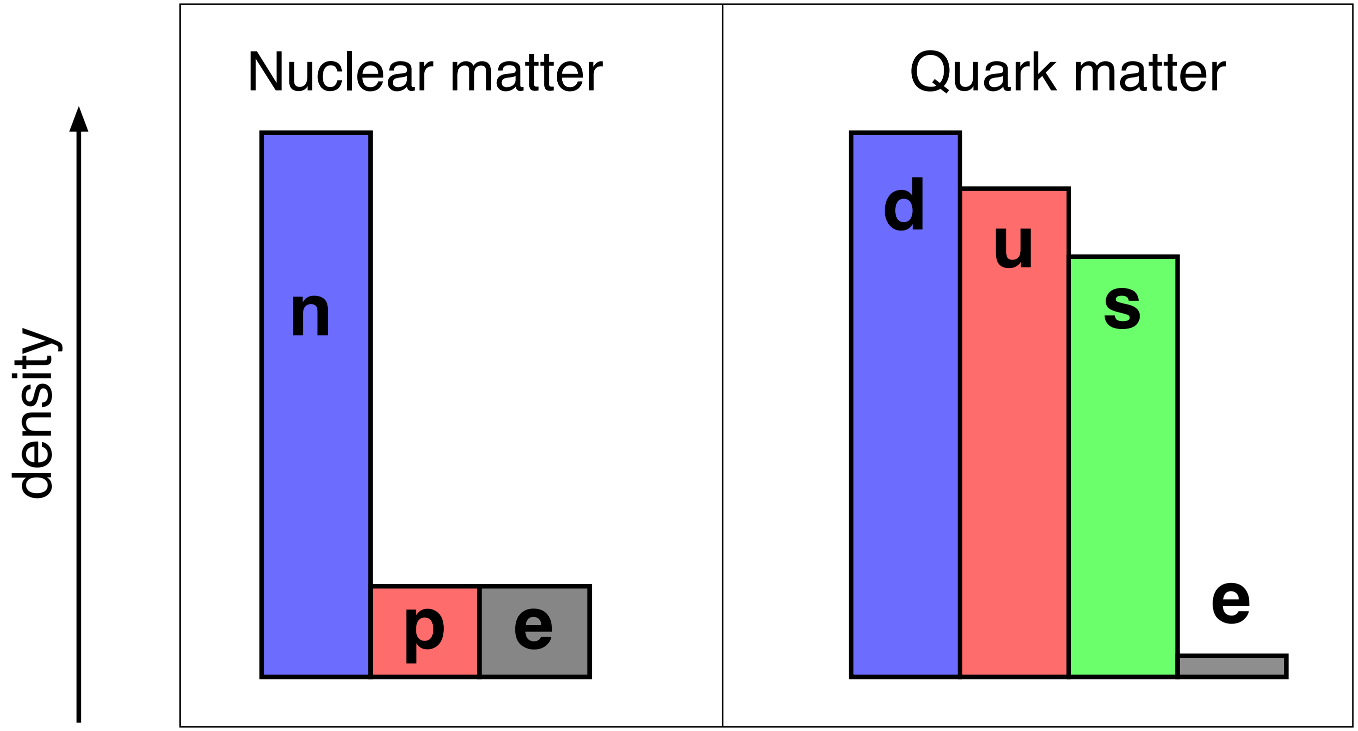


taken (and modified) from W.G. Newton, Nature Physics 9, 396 (2013)

Possible variants of neutron stars

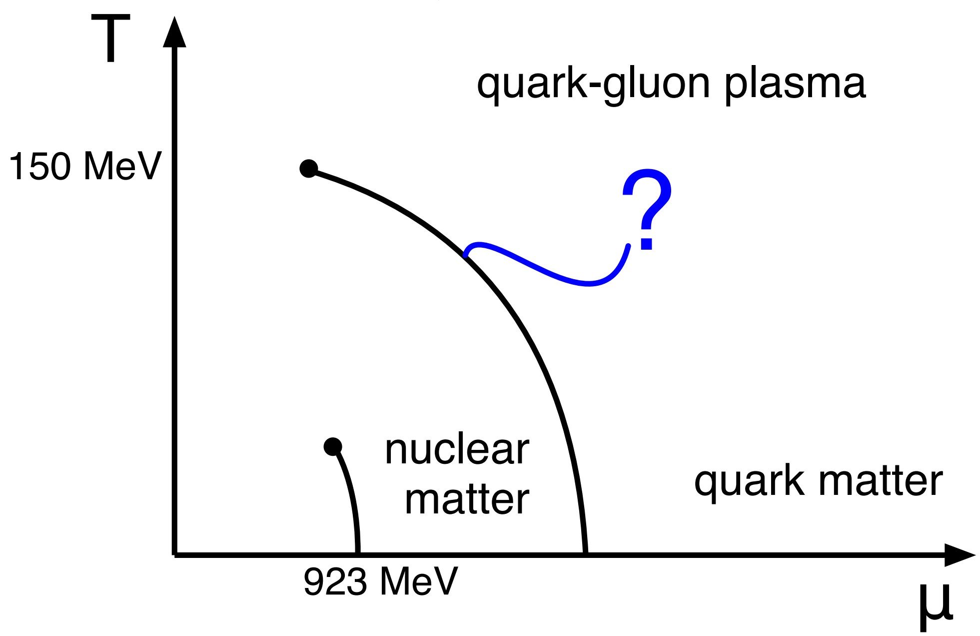


Schematically: nuclear and quark matter



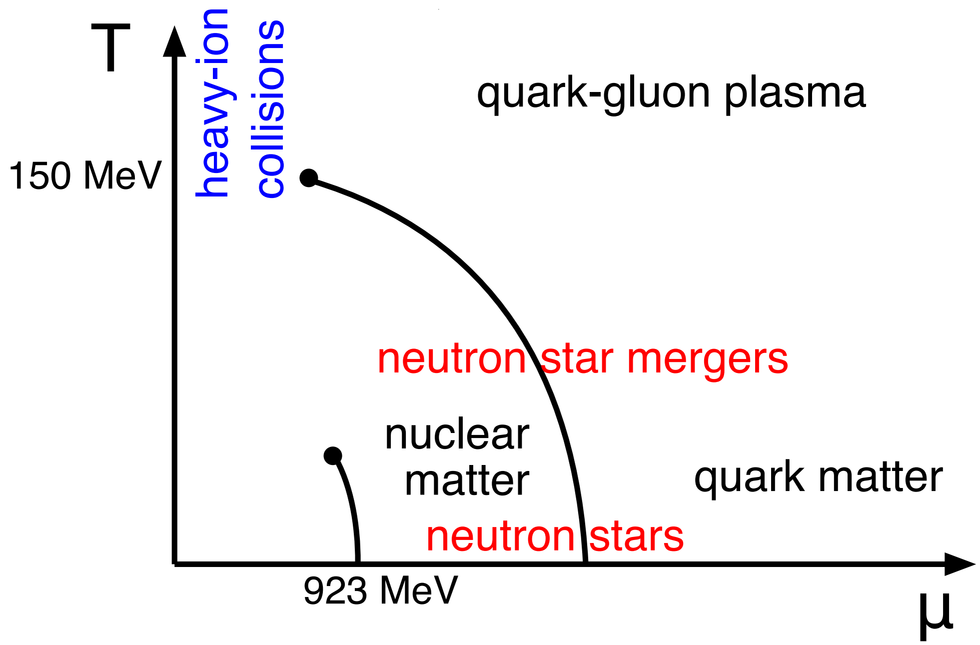
(plus hyperons, muons, ...)

Theoretical background: QCD phase diagram



- deconfinement transition at $\mu = 0$ known to be smooth ("crossover")
- nature and location of deconfinement transition at large μ is unknown

Theoretical background: QCD phase diagram



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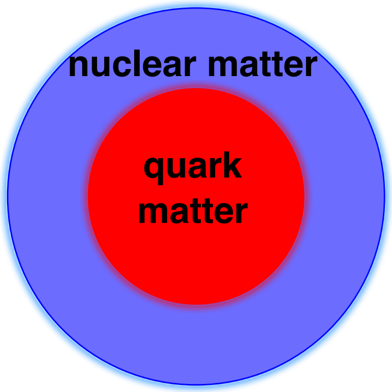
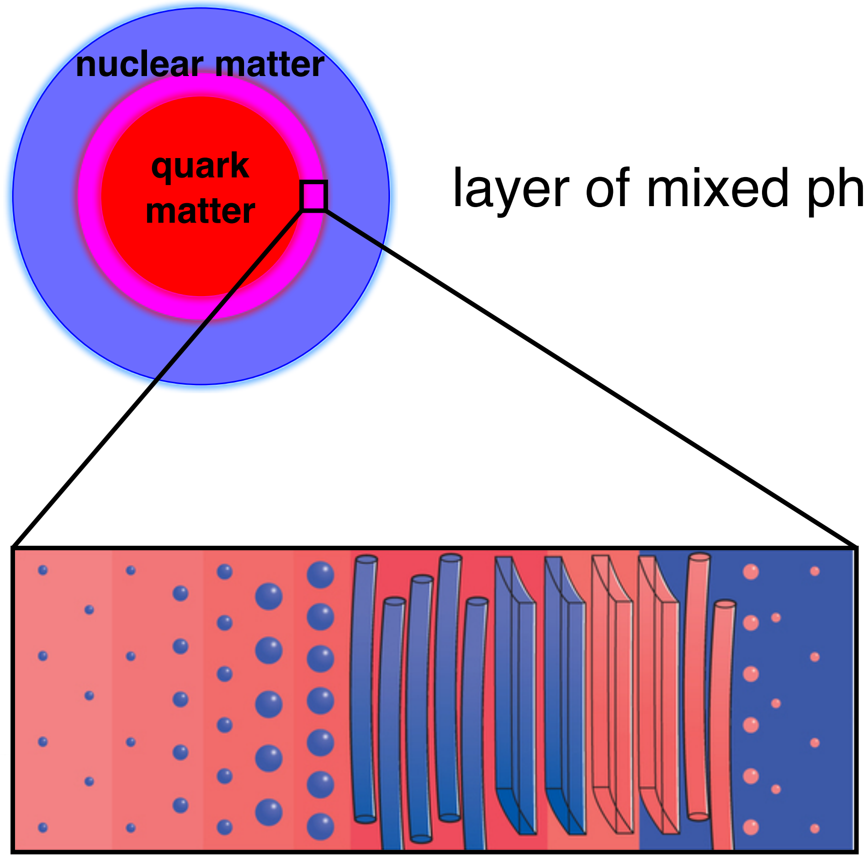
If transition is first order ...



or



layer of mixed phases

sharp interface (~ fm)
jump in density

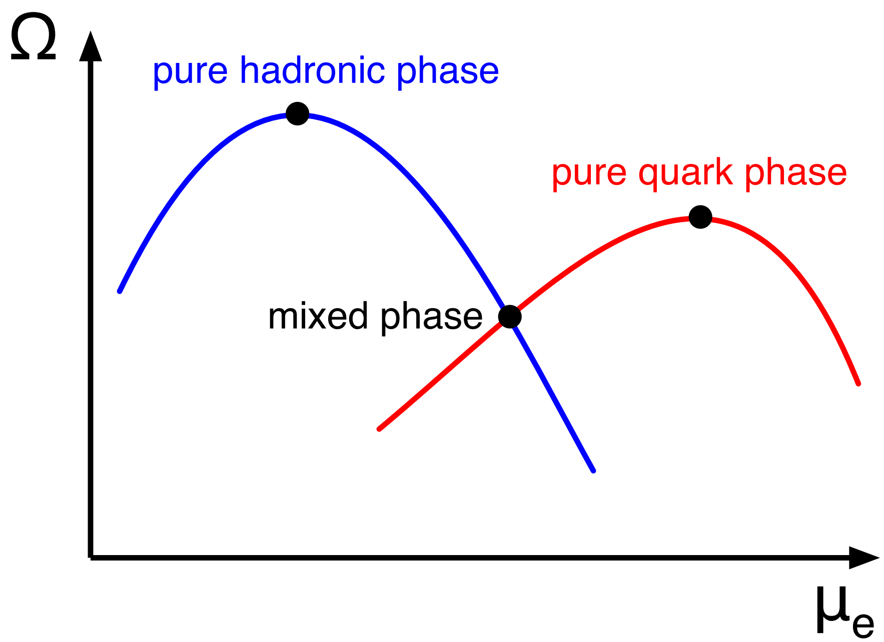
General argument for mixed phases

- pure phases: locally neutral

$$n_p - n_e = 0 \qquad \frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s - n_e = 0$$

- mixed phase: globally neutral

$$\frac{\partial\Omega}{\partial\mu_e} = q$$



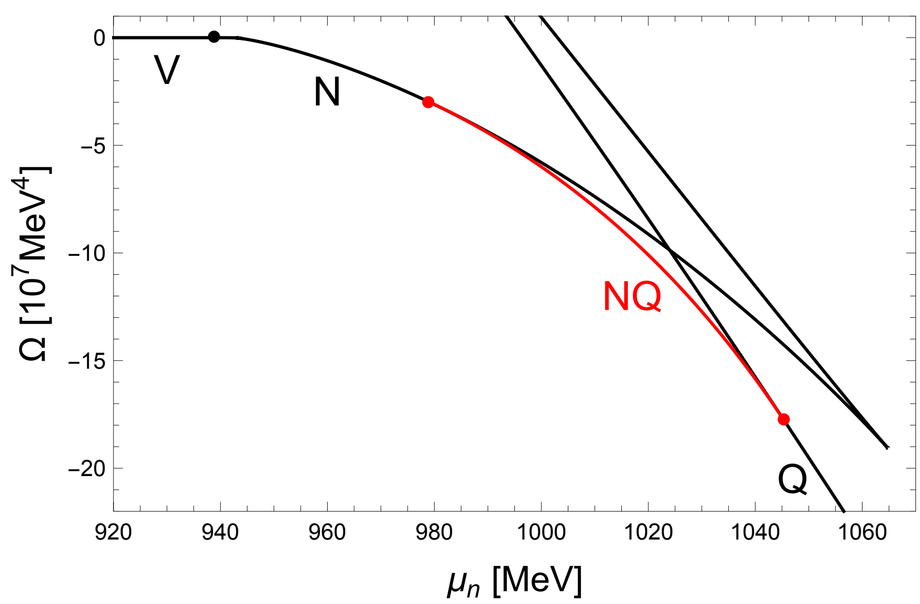
Mixed phases in a model calculation

Nucleon-meson Lagrangian:

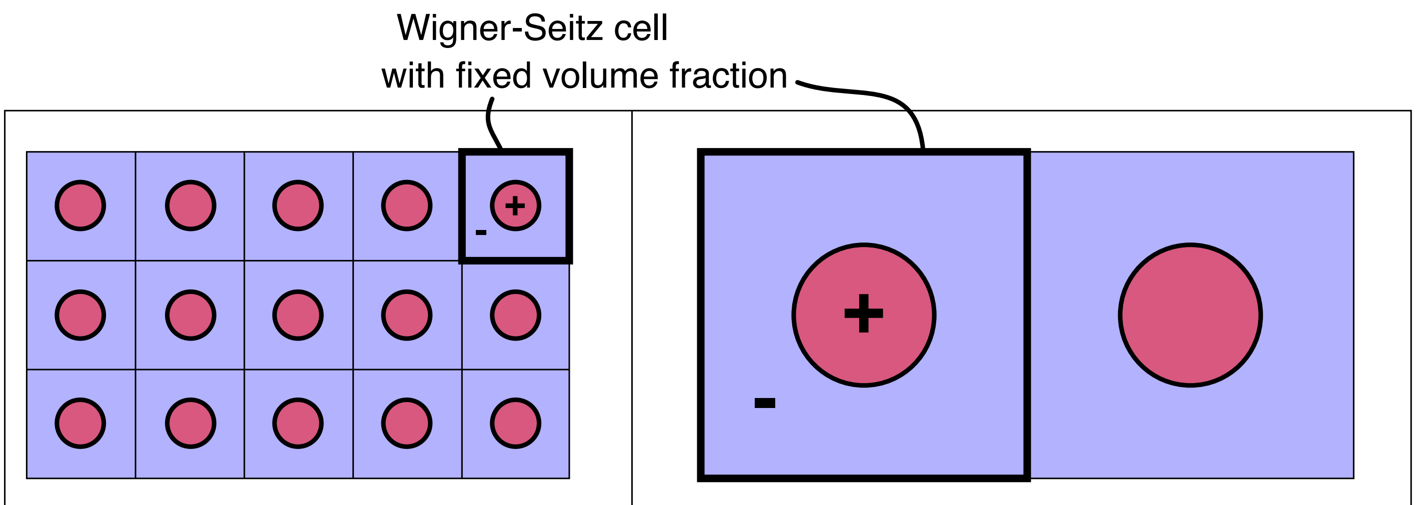
$$\mathcal{L} = \bar{\psi}(i\gamma_\mu\partial^\mu + \gamma^0\hat{\mu})\psi + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{1}{4}\mathrm{Tr}[\partial_\mu\pi\partial^\mu\pi] - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{8}\mathrm{Tr}[\rho_{\mu\nu}\rho^{\mu\nu}]$$

$$+\frac{1}{2}m_v^2\left(\omega_\mu\omega^\mu + \frac{1}{2}\mathrm{Tr}[\rho_\mu\rho^\mu]\right) - \mathcal{U}(\sigma,\pi) - \bar{\psi}\Big[g_\sigma(\sigma + i\gamma^5\pi) + \gamma_\mu(g_\omega\omega^\mu + g_\rho\rho^\mu)\Big]\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Nucleon-Quark (NQ) mixed phase constructed without surface and Coulomb energy costs:



Coulomb and surface energies (page 1/2)



surface energy	LARGE	SMALL
Coulomb energy	SMALL	LARGE

→ For given geometry (e.g., bubbles) and given volume fraction, need to find size of Wigner-Seitz cell with minimal energy

[approximate Wigner-Seitz cell for bubbles by a sphere]

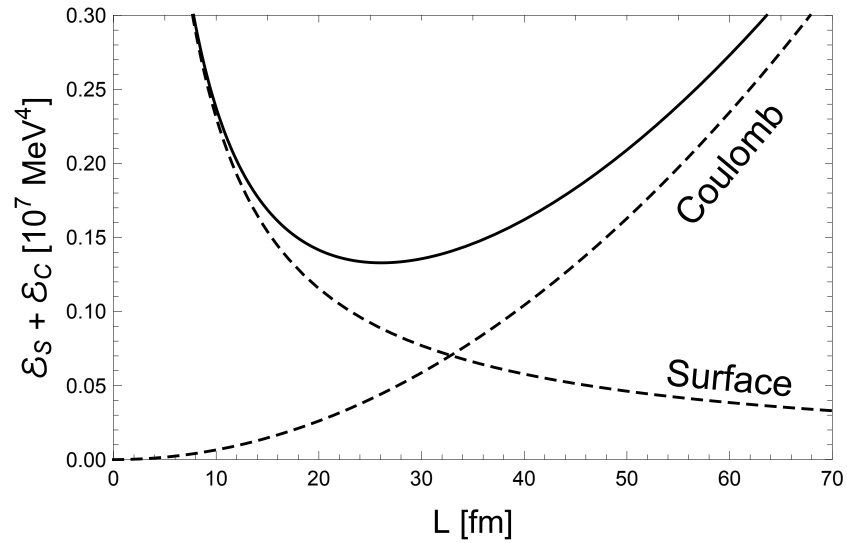
Coulomb and surface energies (page 2/2)

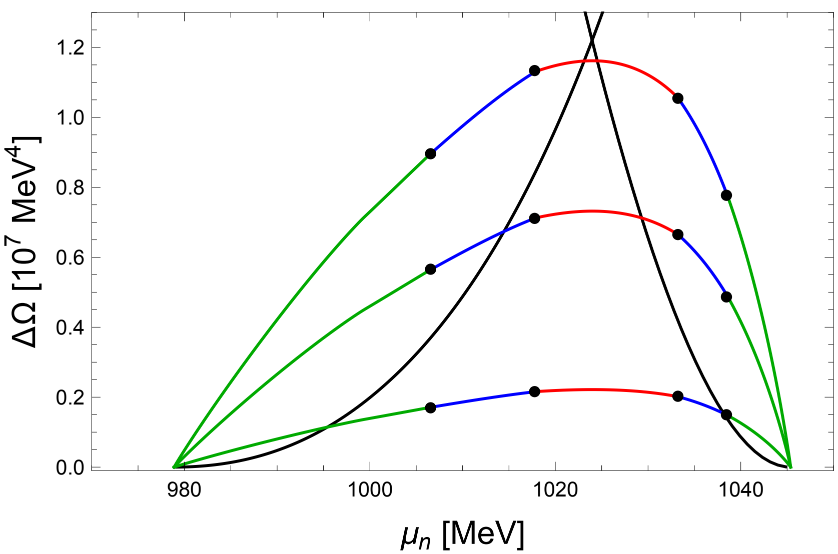
Approximation for step-like profile

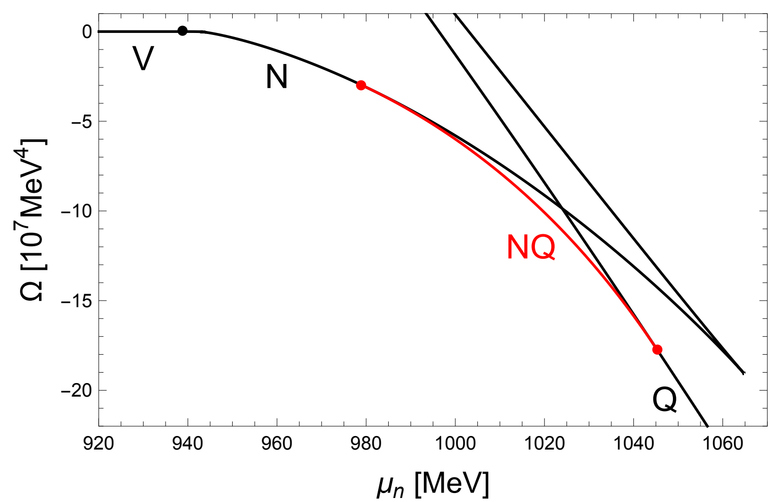
$$\mathcal{E}_S \propto \frac{\Sigma}{L} \qquad \mathcal{E}_C \propto L^2$$

L width of Wigner-Seitz cell

Σ surface tension

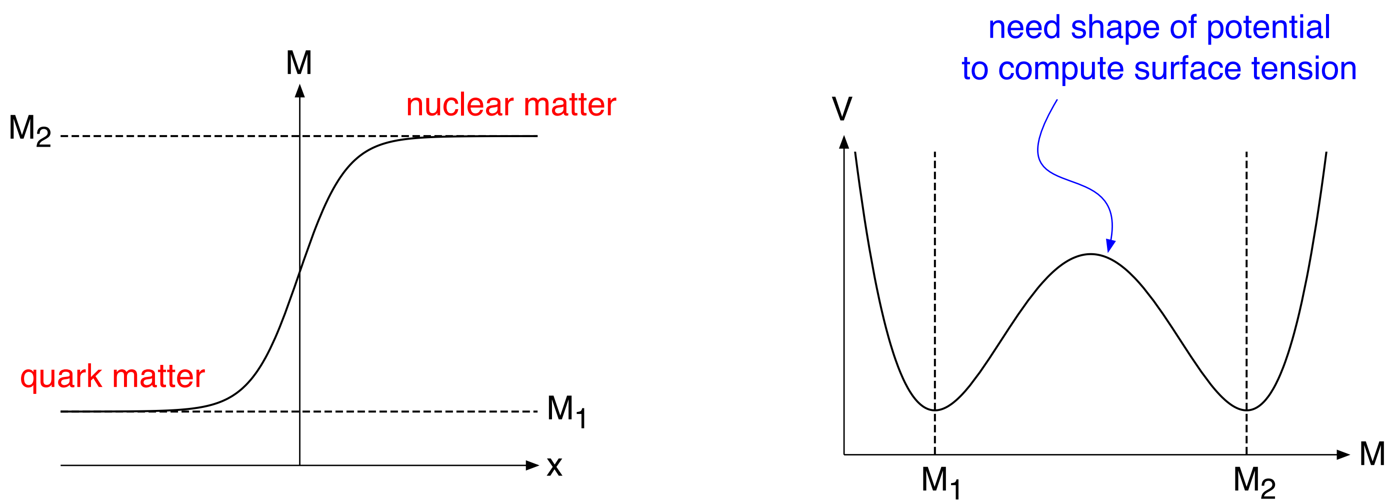






Bubbles, rods, slabs for $\Sigma = 1, 6, 12\,\mathrm{MeV/fm}^2$

Microscopic calculation of surface tension



→ need quark and nuclear matter from single theory/model

- from QCD: too difficult at large μ
- from phenomenological models

  quark-meson model L. F. Palhares and E. S. Fraga, PRD 82, 125018 (2010)

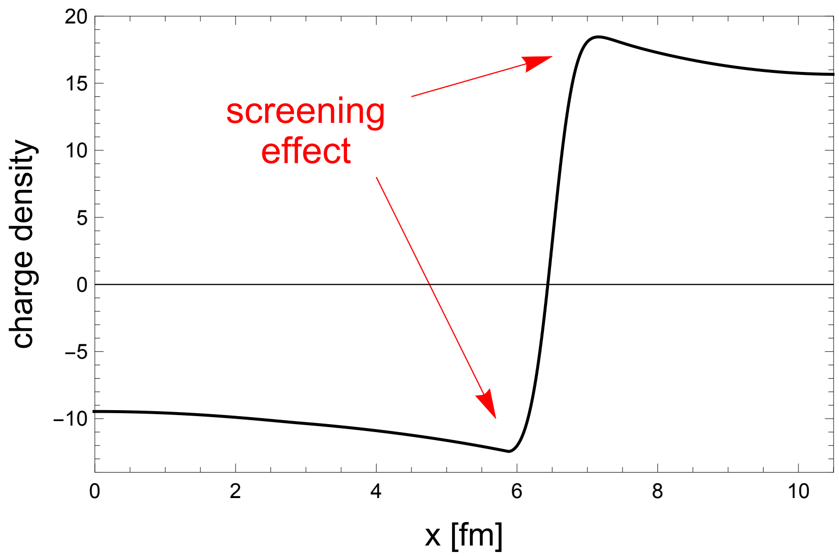
  nucleon-meson model E. S. Fraga, M. Hippert and A. Schmitt, PRD 99, 014046 (2019)

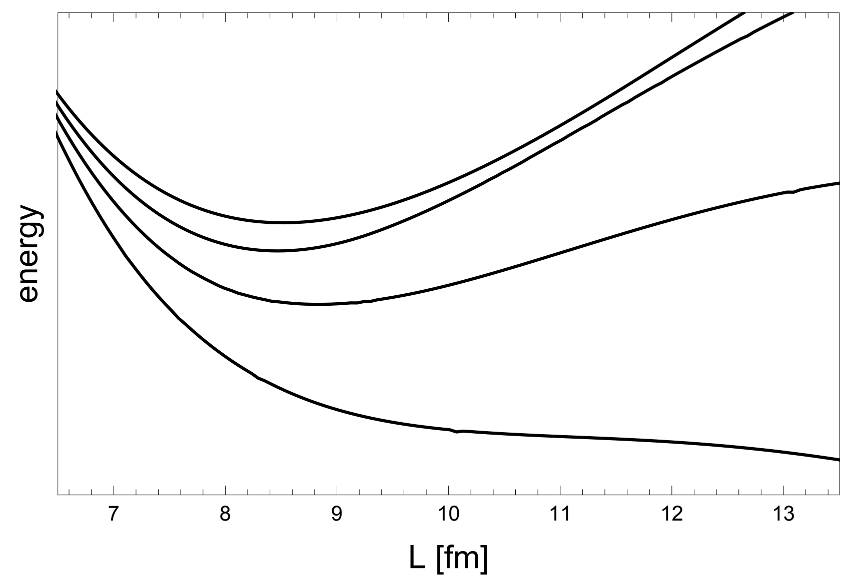
  → $\Sigma \sim (1 - 20)\,\mathrm{MeV/fm}^2$ (neglecting neutrality)

Microscopic calculation of Wigner-Seitz profile (page 1/2)

A. Schmitt, work in progress

compute interfaces consistently from equations of motion, including Poisson equation for electric potential



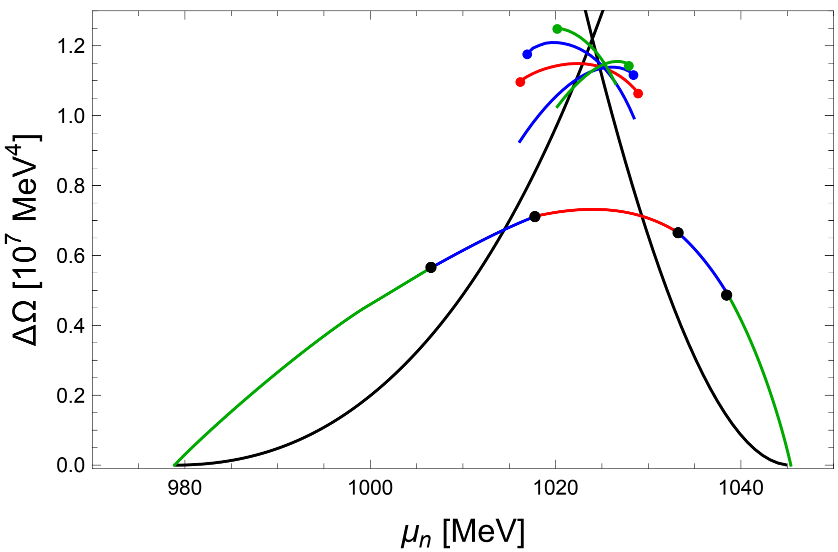


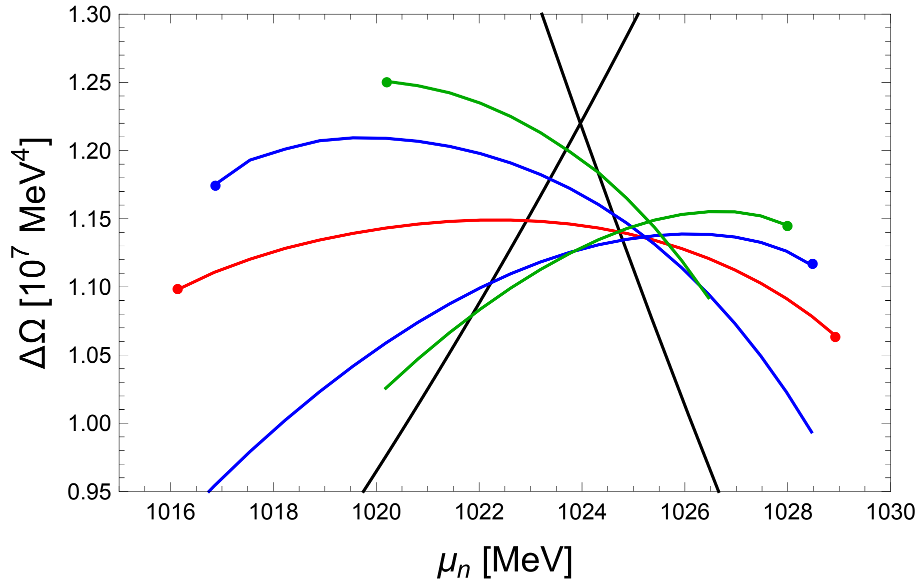
electric charge accumulates at interface → reduced Coulomb cost

Microscopic calculation of Wigner-Seitz profile (page 2/2)

A. Schmitt, work in progress

Full calculation compared to step-like approximation with $\Sigma = 6\,\mathrm{MeV/fm}^2$

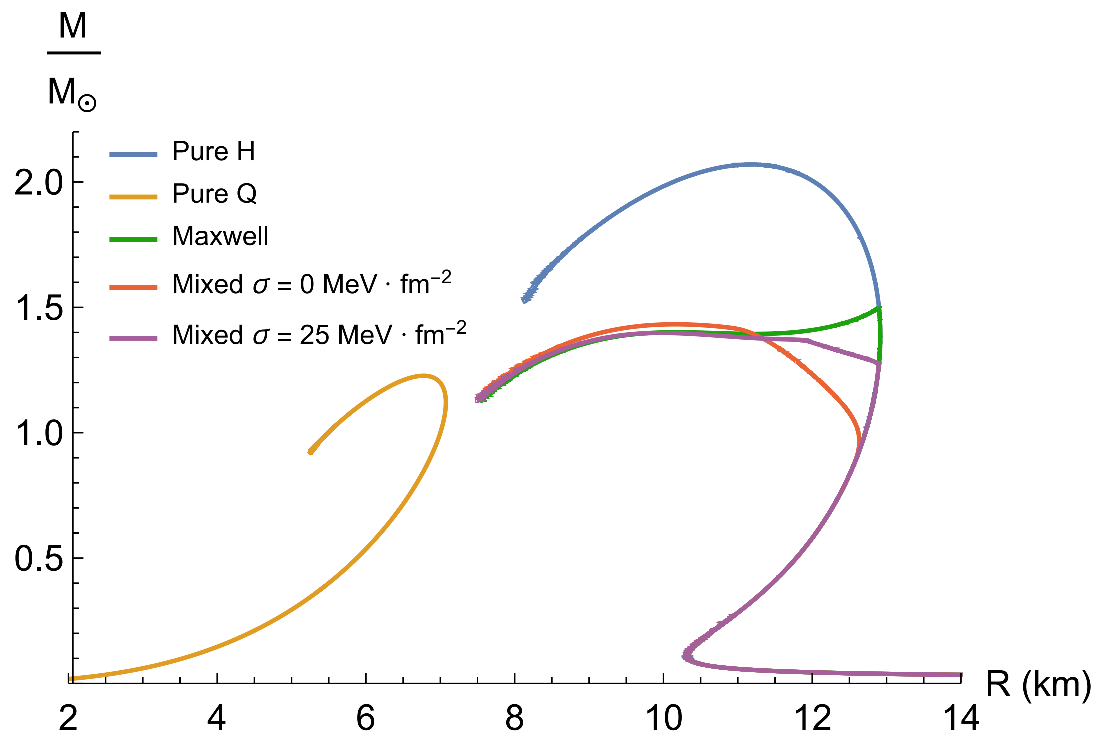




→ mixed phases (quark bubbles and quark rods) exist in small density regime (for the chosen set of model parameters)

Mass-radius relation with mixed phase

A. Pfaff, Project Report (2019)



- existence of quark matter core reduces maximum mass (depends strongly on model, here "bag model")
- mixed phases stabilize hybrid star (here step-like approximation is used)

Summary

- location and nature of quark-hadron phase transition at large baryon densities is unknown
- observable properties of neutron stars (mass, radius, ...) are sensitive to properties of the transition
- "quark-hadron pasta" appears if the transition is first order and Coulomb + surface energy is sufficiently small
- calculation of mixed phase profiles requires unified treatment of quark and hadron matter (which, even on the level of phenomenological models, is very challenging)

Open questions

- progress in high-density QCD from first principles?
- improved unified models?
  holographic approach: K. Bitaghsir Fadafan, F. Kazemian, A. Schmitt, JHEP 1903, 183 (2019)
  N. Kovensky and A. Schmitt, work in progress
- how does "quark-hadron pasta" affect transport properties?
- mixed phases during neutron star merger?
  $\rightarrow$ need nonzero-temperature calculation
- phase transition during supernova:
  nucleation time from surface tension
- how does a magnetic field and/or Cooper pairing
  affect mixed phases?