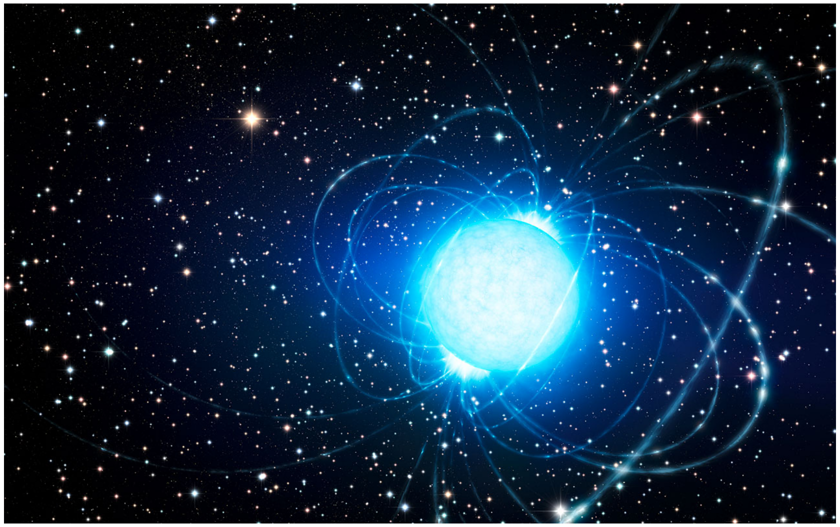
Andreas Schmitt

Institut für Theoretische Physik
Technische Universität Wien
1040 Vienna, Austria

Magnetic catalysis in nuclear matter

A. Haber, F. Preis and A. Schmitt, arXiv:1409.0425 [nucl-th]

- magnetic catalysis (in QCD)
- models used here and how they account for magnetic catalysis
- onset of nuclear matter in a magnetic field

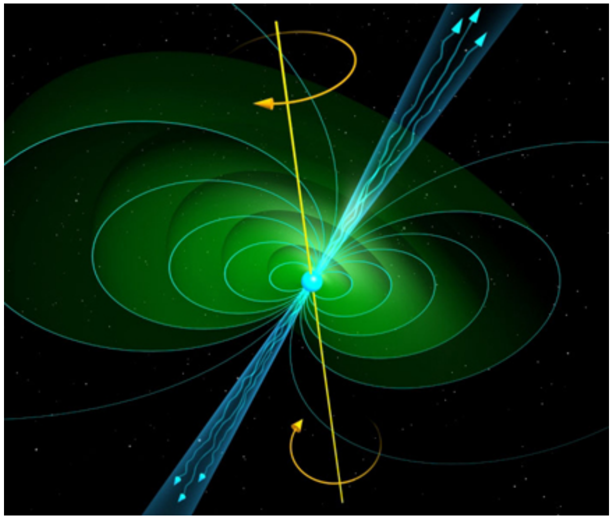


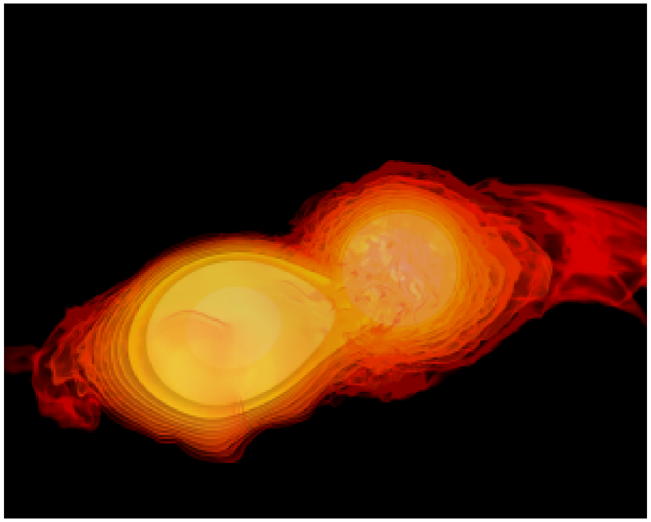
Artist's impression of a magnetar (www.eso.org)

• Strong magnetic fields in compact stars

- on surface of magnetars: $B \lesssim 10^{15}\,\mathrm{G}$
  Duncan, Thompson, Astrophys.J. 392, L9 (1992)
- in the core, $B \sim 10^{18-20}\,\mathrm{G}$?
  Lai, Shapiro, Astrophys.J. 383, 745 (1991)
  E. J. Ferrer *et al.*, PRC 82, 065802 (2010)

  $\rightarrow$ B-corrections to equation of state?
  $(\Lambda^2_{\mathrm{QCD}} \sim 10^{18}\,\mathrm{G})$





Merger simulation (astro.uni-frankfurt.de)

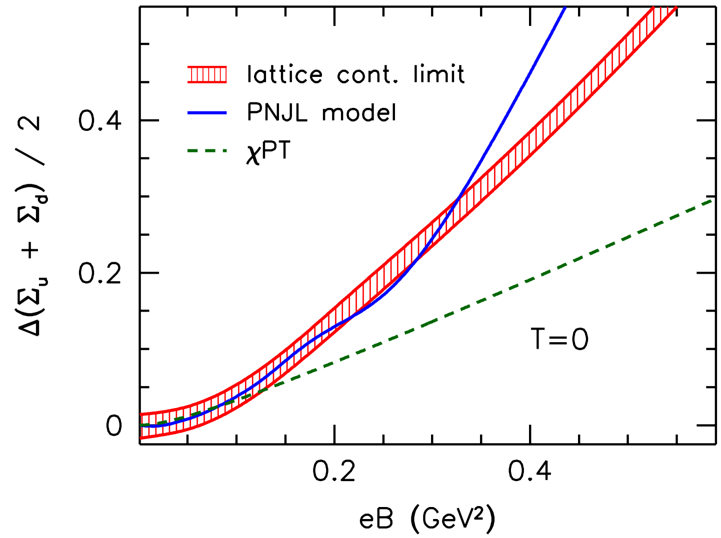
- compact star mergers: gravitational waves sensitive to equation of state
  J. S. Read *et al.*, PRD 88, 044042 (2013)
- magnetorotational instability in merger process
  D. M. Siegel *et al.*, PRD 87, 121302 (2013)

- **Chiral magnetic catalysis at weak coupling**

Magnetic catalysis	**BCS superconductor**
chiral condensate $\langle\bar{\psi}\psi\rangle$	Cooper pair condensate $\langle\psi\psi\rangle$
$M \propto \sqrt{eB}\, e^{-\text{const.}/G\nu_0}$ (ν_0: d.o.s. at $E=0$ surface)	$\Delta \propto \mu\, e^{-\text{const.}/G\nu_F}$ (ν_F: d.o.s. at $E=\mu$ Fermi surface)
effectively (1+1)-dimensional in lowest Landau level (LLL) because of magn. field	pairing dynamics effectively (1+1)-dimensional because of Fermi surface

magnetic catalysis
= chiral condensate enhanced by magnetic field

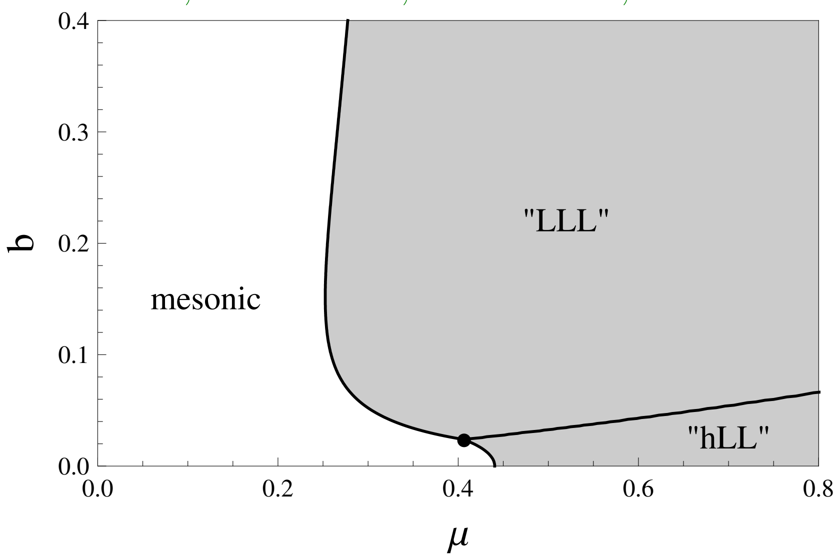
• Magnetic catalysis in QCD

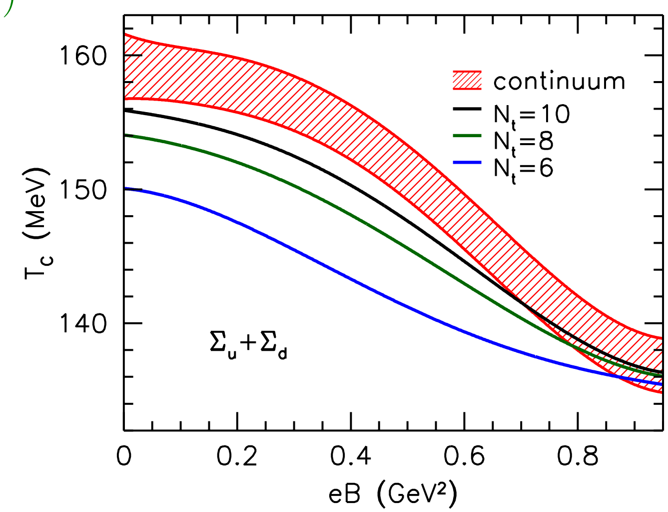


- chiral condensate increases monotonically at $T = 0$
  G. S. Bali *et al.*, PRD 86, 071502 (2012)

- "inverse magnetic catalysis" at finite μ (models) or T (QCD)

F. Preis, A. Rebhan, A. Schmitt, JHEP 1103, 033 (2011)





G. S. Bali *et al.*, JHEP 1202, 044 (2012)

• Models used here for nuclear matter

- Walecka model J.D. Walecka, Annals Phys. 83, 491 (1974)
  include magnetic field: A. Broderick, M. Prakash, J.M. Lattimer, Astrophys. J. 537, 351 (2000)
- extended linear sigma model (eLSM)
  S. Gallas, F. Giacosa, G. Pagliara, Nucl. Phys. A872, 13 (2011)
  "mirror assignment": C.E. DeTar and T. Kunihiro, PRD 39, 2805 (1989)

	Walecka	eLSM
(isospin-symmetric) nucleons	$N = n, p$	$N, N^* \rightarrow N(1535)$
interactions	meson exchange (Yukawa): $g_\sigma \bar{\psi}\sigma\psi$ etc.	
meson fields	$\omega, \sigma \rightarrow f_0(500)$	$\omega, (\sigma, \chi) \rightarrow (f_0(500), f_0(1370))$
chiral symmetry	always broken	dynamically broken by $\bar{\sigma}$
parameters	fitted to saturation properties ($B = 0$)	
magnetic field	$\bar{\psi} i\gamma^\mu(\partial_\mu + iQA_\mu)\psi$ with $Q = \mathrm{diag}(0, e)$, $A_\mu = (0, yB, 0, 0)$	

• Dirac sea contribution (page 1/2)

- renormalized vacuum terms:

$$\Omega = (\text{tree-level potential}) + \underbrace{\frac{B^2}{2} + \Omega_{N,\text{sea}}} + (\text{matter part})$$

$$\Omega_{N,\text{sea}}(B=0) + \frac{B_r^2}{2} - \frac{|q_r B_r|^2}{2\pi^2}\left[\frac{x^2}{4}(3-2\ln x) + \frac{x}{2}\left(\ln\frac{x}{2\pi} - 1\right) + \psi^{(-2)}(x)\right] \qquad x \equiv \frac{M^2}{2|q_r B_r|}$$

- literature: all sea terms omitted ("no-sea approximation")

A. Broderick, M. Prakash, J.M. Lattimer, Astrophys. J. 537, 351 (2000)

A. Broderick, M. Prakash, J.M. Lattimer, PLB 531, 167 (2002)

A. Rabhi, P.K. Panda, C. Providência, PRC 84 (2011)

F. Preis, A. Rebhan, A. Schmitt, JPG 39, 054006 (2012)

J. Dong, W. Zuo, J. Gu, PRD 87 103010 (2013)

M. Sinha, B. Mukhopadhyay, A. Sedrakian, NPA 898, 43 (2013)

R.C.R. de Lima, S.S. Avancini, C. Providência, PRC 88, 035804 (2013)

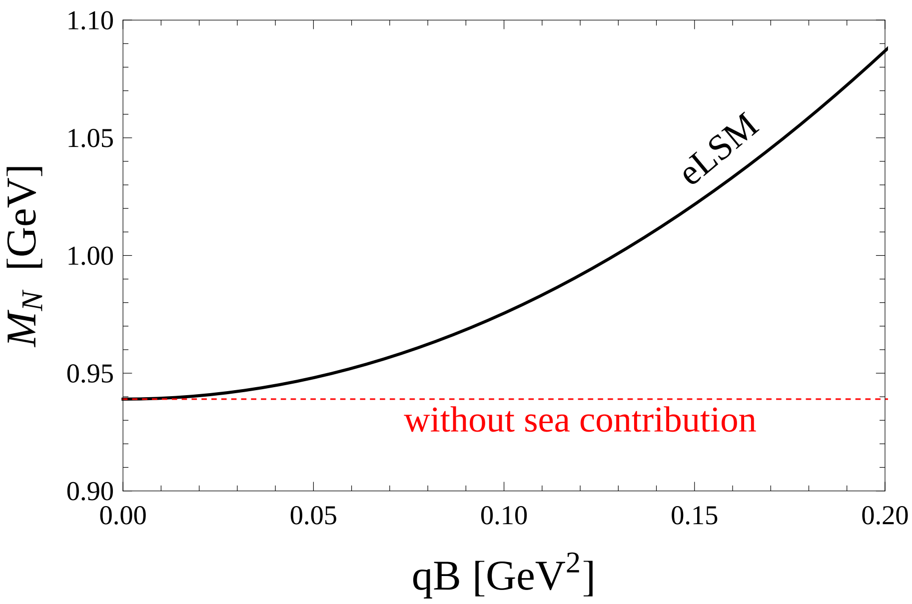
R. Casali, L.B. Castro, D.P. Menezes, PRC 89, 015805 (2014)

- in quark models usually taken into account (NJL, bag model, ...)

• Dirac sea contribution (page 2/2)

- keep B-dependent sea contribution!
- $\Omega_{N,\mathrm{sea}}(B=0)$ negligible
- calculation: minimize free energy w.r.t. meson condensates in mean-field approximation

Vacuum mass of the nucleons ($\mu < M_N$):

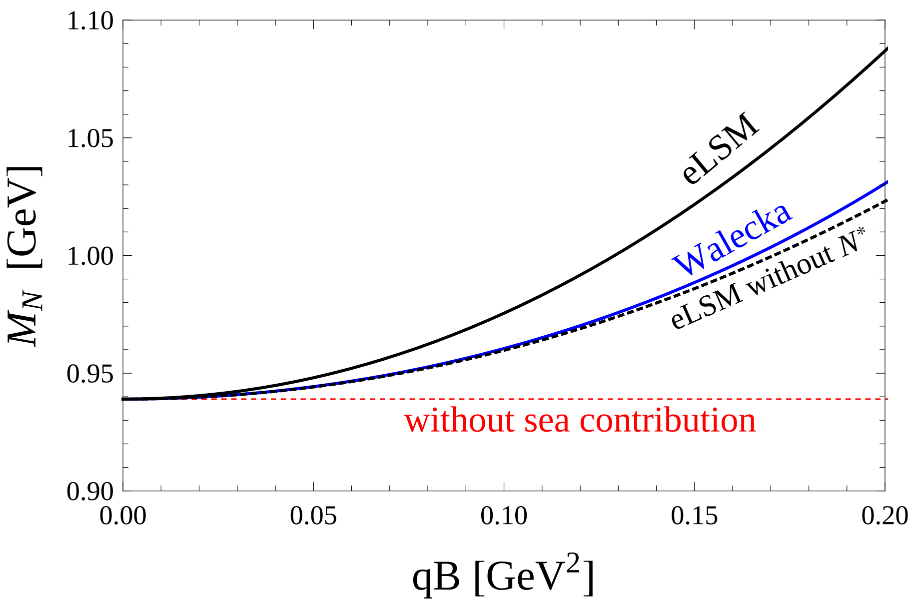


$[eB = 0.2\,\mathrm{GeV}^2 \rightarrow B \simeq 3.4 \times 10^{19}\,\mathrm{G}]$

• Dirac sea contribution (page 2/2)

- keep B-dependent sea contribution!
- $\Omega_{N,\text{sea}}(B=0)$ negligible
- calculation: minimize free energy w.r.t. meson condensates in mean-field approximation

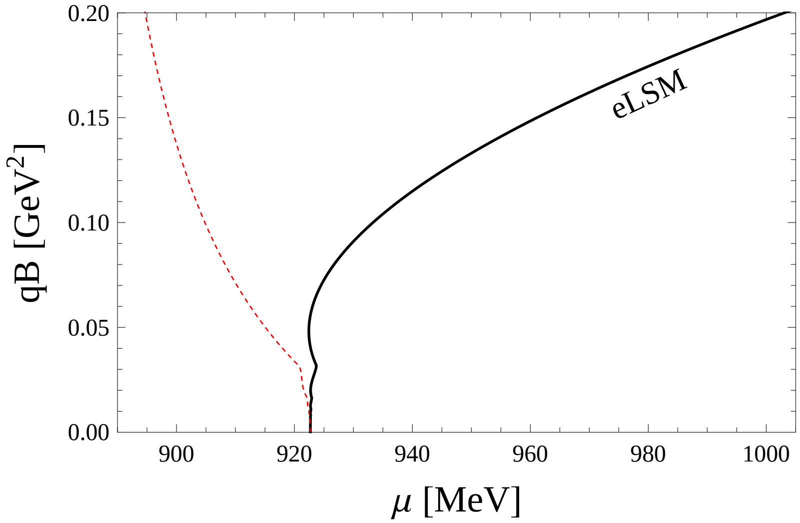
Vacuum mass of the nucleons ($\mu < M_N$):

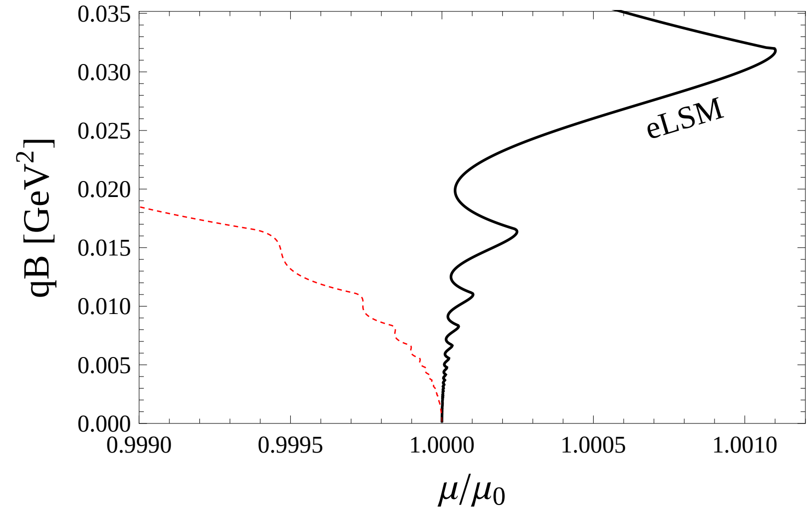


$[eB = 0.2\,\text{GeV}^2 \rightarrow B \simeq 3.4 \times 10^{19}\,\text{G}]$

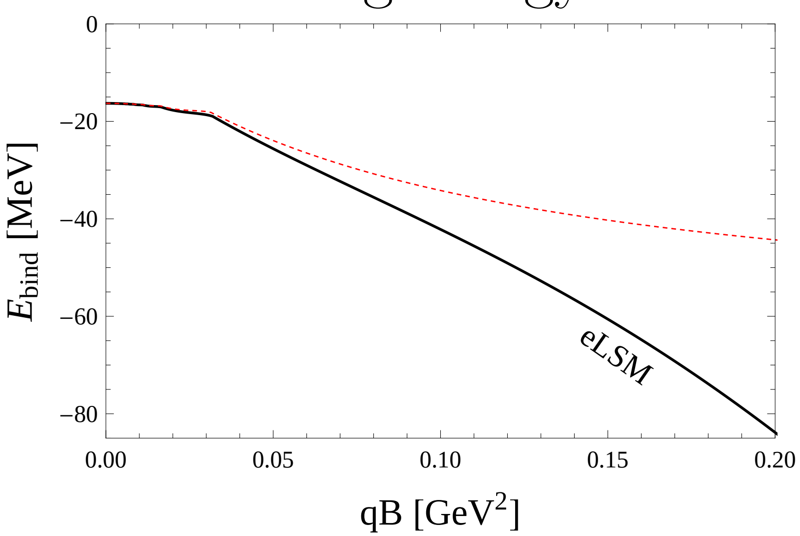
• Onset of nuclear matter

critical chemical potential:

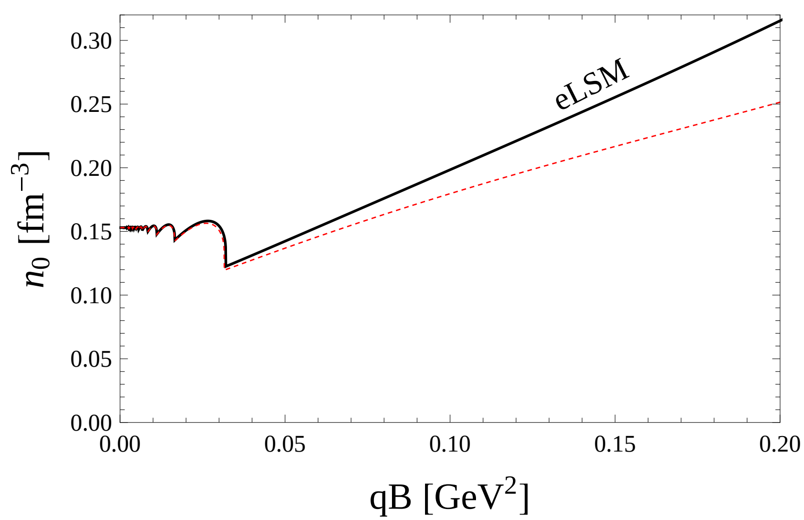




binding energy:

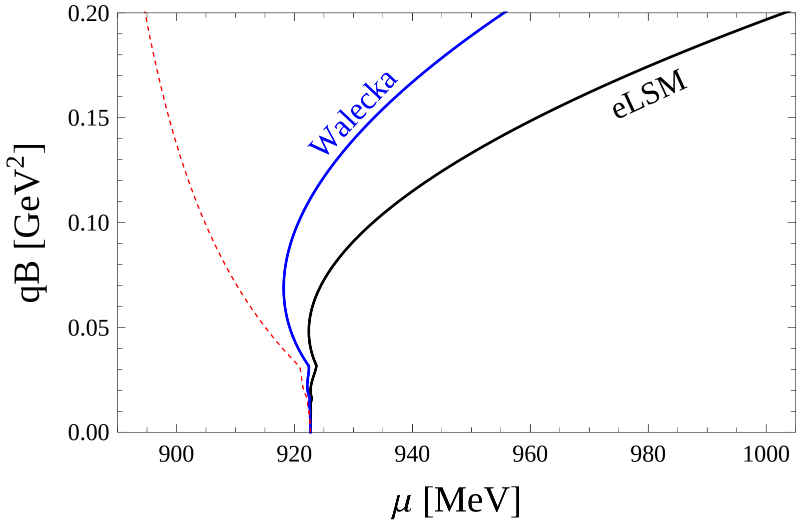


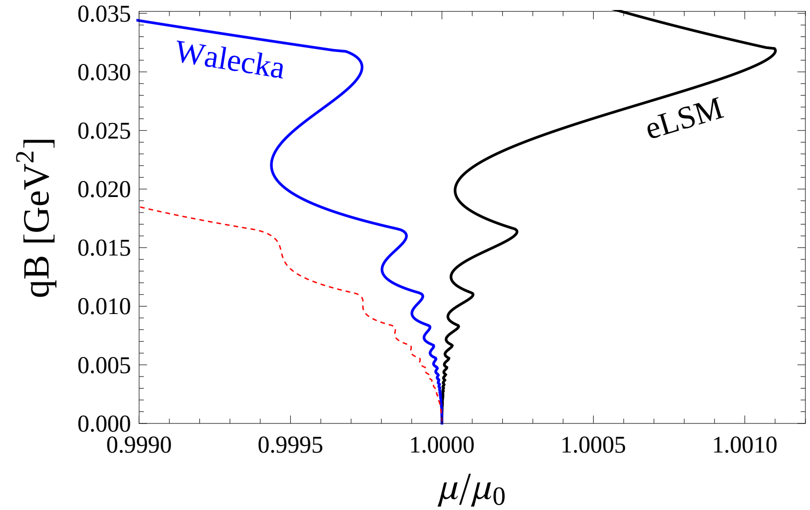
saturation density:



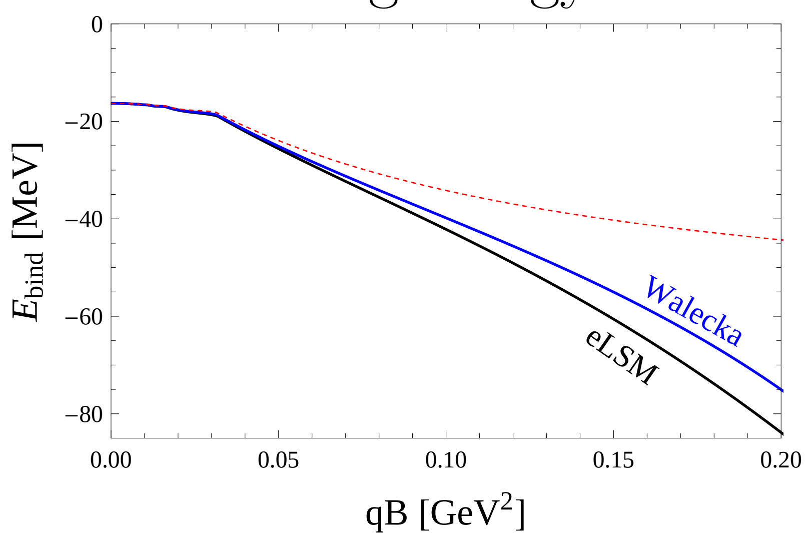
• Onset of nuclear matter

critical chemical potential:

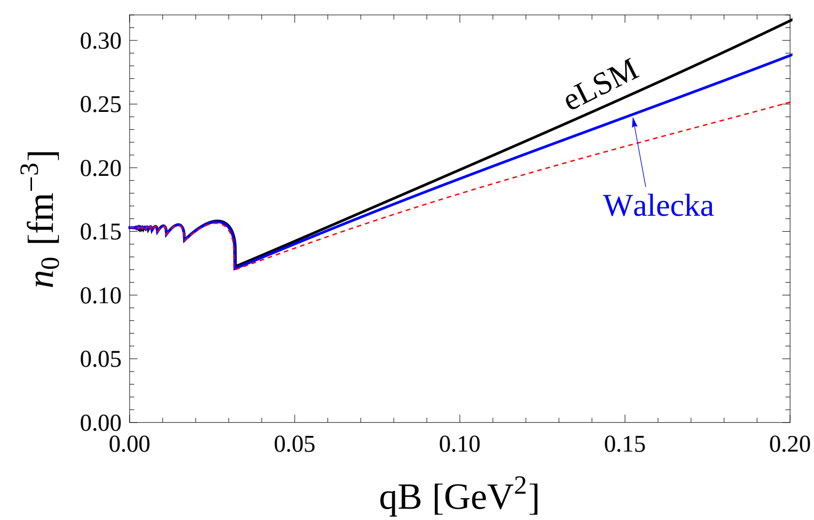




binding energy:



saturation density:



• Discussion (QCD vs. models used here)

- magnetic catalysis (zero temperature) → quarks get heavier
- vacuum nucleon mass: quark mass + interaction effects
  - models: point-like nucleons → nucleons get heavier
    - ∗ see however: Andreichikov, Kerbikov, Orlovsky, Simonov, PRD 89, 074033 (2014)
    - ∗ improve models by including anomalous magnetic moments
    - ∗ compute magnetized nucleon mass on the lattice?
- nuclear matter onset: vacuum nucleon mass + binding energy
  - models: both effects included → non-trivial onset curve

• Outlook

- more realistic nuclear matter: include
  - anomalous magnetic moment (renormalization?)
  - isospin-breaking forces
  - neutrality & β-equilibrium (maybe not needed for mergers)
  - more (charged) hadrons (pions, rho, hyperons)

- effect of magnetic catalysis on equation of state
  and masses/radii of compact stars?

- phase diagram with onset *and* chiral phase transition
  comparison to holographic results F. Preis, A. Rebhan, A. Schmitt, JPG 39, 054006 (2012)

- allow for anisotropic chiral condensate
  "chiral density wave": A. Heinz, F. Giacosa and D. H. Rischke, arXiv:1312.3244 [nucl-th].