A unified description for strange quark matter objects

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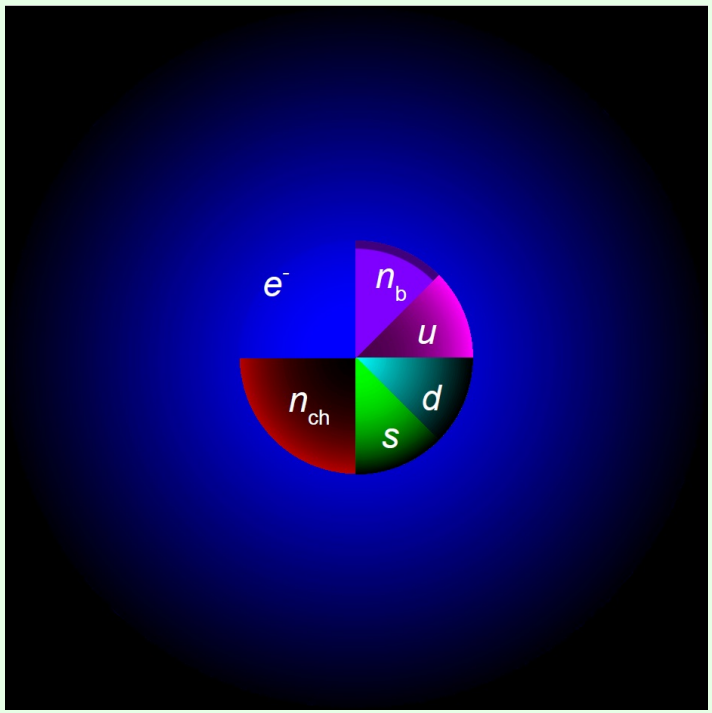
Zhejiang University

Collaborators: Peng Guang-Xiong, Zhao En-Guang, Zhou Shan-Gui



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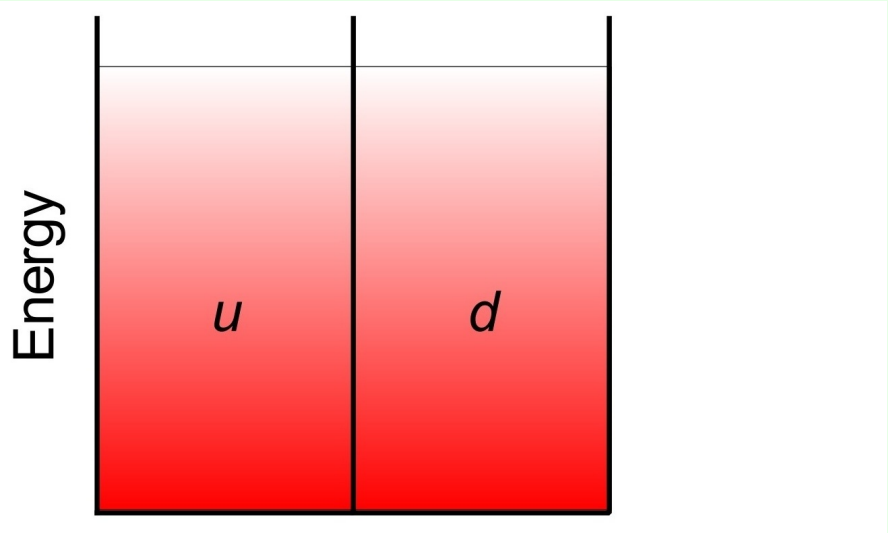

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- Witten reported on the stability of SQM consisting of approximately equal numbers of u, d and s quarks, suggesting that SQM could indeed be stable even at zero external pressure [Witten1984_PRD30-272].

If Witten-Bodmer hypothesis is true, there exists stable lumps of SQM with the baryon number $A \approx 2 \sim 10^{57}$:

Strangelets ($A \lesssim 10^7$)

Comparing with nuclei, strangelets have: lower charge-to-mass ratio; larger mass; smaller radius; spherical shape; ...

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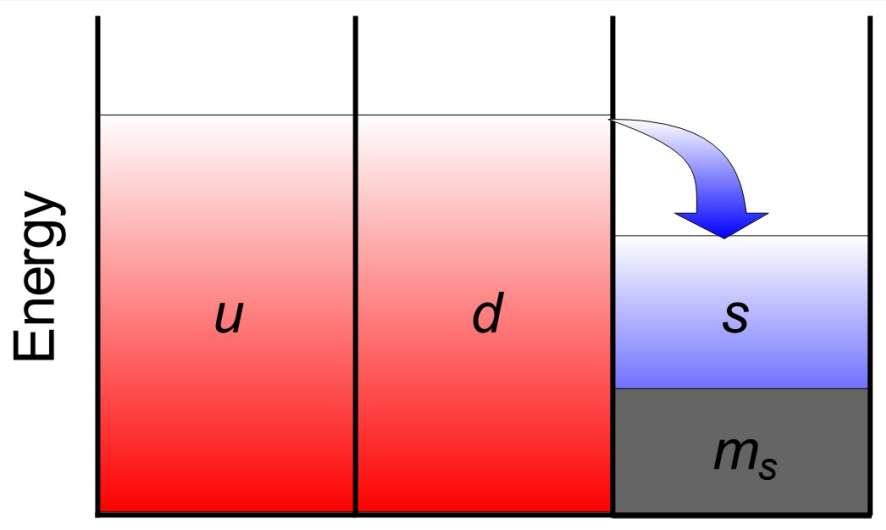

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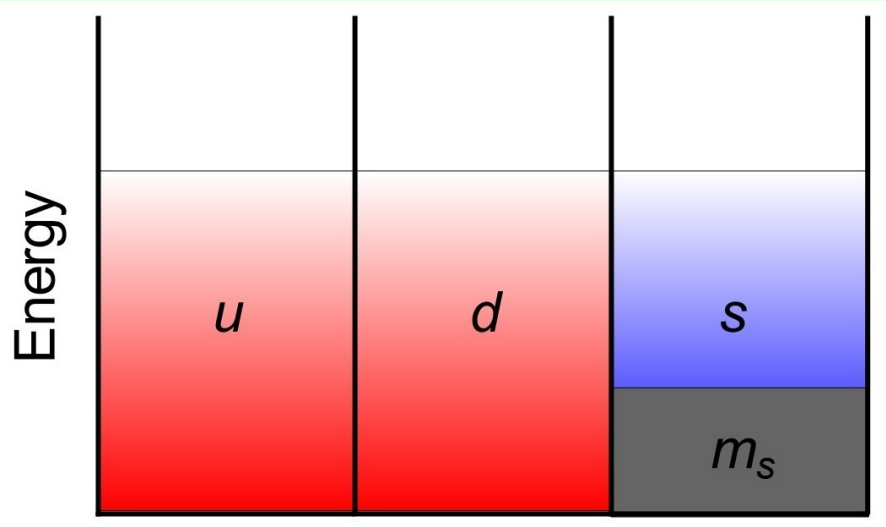

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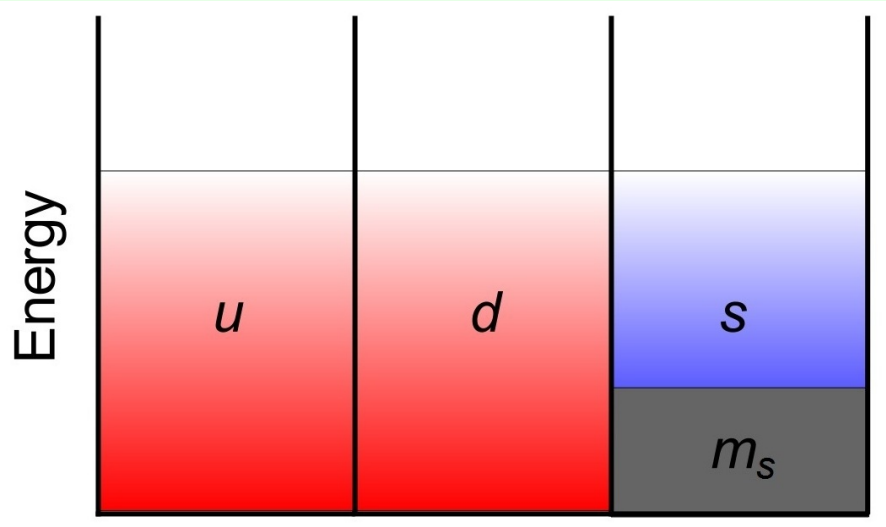

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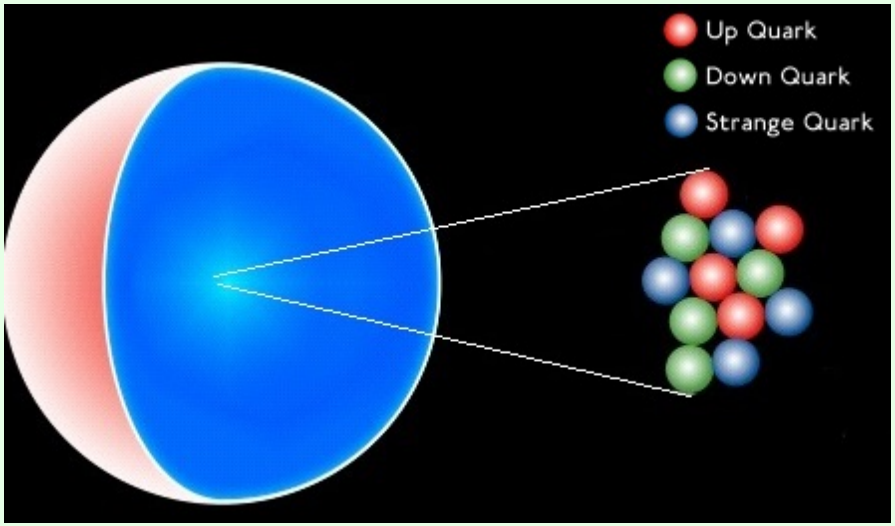

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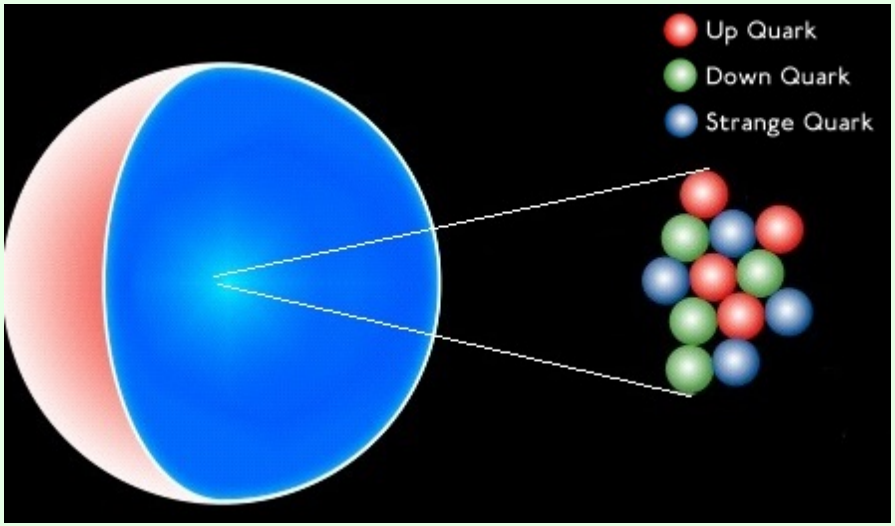

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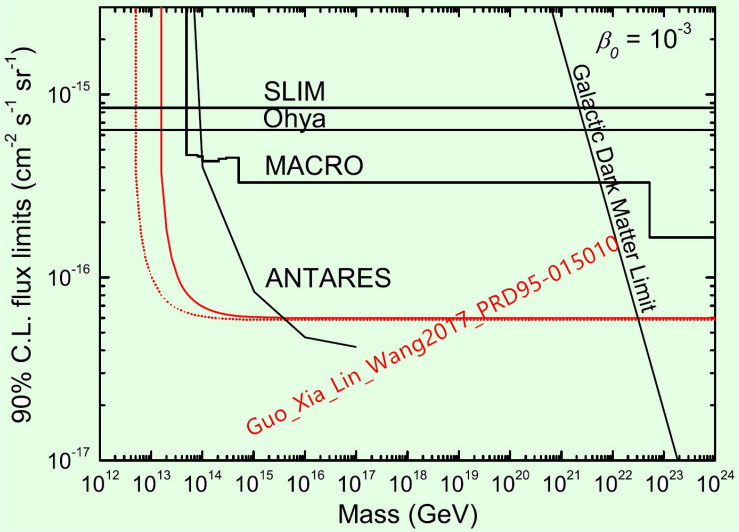

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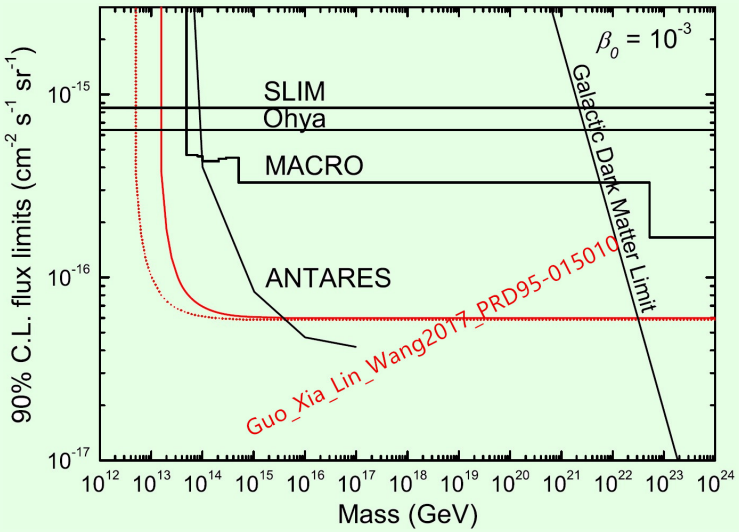

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The UDS model

The gravity and electrostatic interaction are considered on the macroscopic scale while the strong and weak interactions are incorporated locally.

The metric for a spherically symmetric object:

$$\mathrm{d}s^2 = \mathrm{e}^{\nu}\mathrm{d}t^2 - \mathrm{e}^{\lambda}\mathrm{d}r^2 - r^2(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\phi^2), \tag{1}$$

with $\mathrm{e}^{-\lambda} = 1 - \frac{2G}{r}M_{\mathrm{t}}(r)$ and $\frac{\mathrm{d}\nu}{\mathrm{d}r} = \frac{2G\mathrm{e}^{\lambda}}{r^2}\left[4\pi r^3\left(P - \frac{\alpha Q^2}{8\pi r^4}\right) + M_{\mathrm{t}}\right]$.
The particle number: $N_i(r) = \int_0^r 4\pi n_i(r)\mathrm{e}^{\lambda/2}r^2\mathrm{d}r$; The total charge: $Q(r) \equiv \sum_i q_i N_i(r)$; The total mass: $M_{\mathrm{t}}(r) = \int_0^r 4\pi r^2\left(E + \frac{\alpha Q^2}{8\pi r^4}\right)\mathrm{d}r$.

Distribution functions [Xia_Peng_Zhao_Zhou2016_SciBull61-172]

By minimizing the mass $M = M_{\mathrm{t}}(\infty)$ with respect to the particle distribution $N_i(r)$ at fixed $N_i(\infty)$, we obtain the constancy of the generalized chemical potential

$$\bar{\mu}_i = \mu_i(r)\mathrm{e}^{\nu(r)/2} + q_i\varphi(r) = \text{constant} \tag{2}$$

with $\frac{\mathrm{d}\varphi}{\mathrm{d}r} = -\frac{\alpha Q}{r^2}\mathrm{e}^{(\lambda+\nu)/2}$ (Klein1949_RMP21-531, Olson_Bailyn1975_PRD12-3030, Kodama_Yamada1972_PTP47-444).

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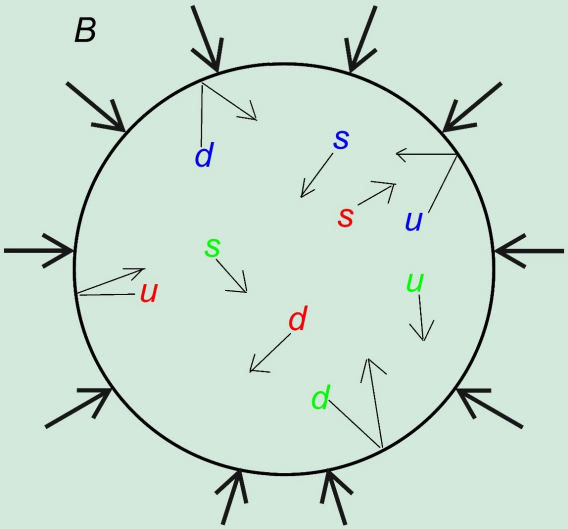
The UDS model: Local properties

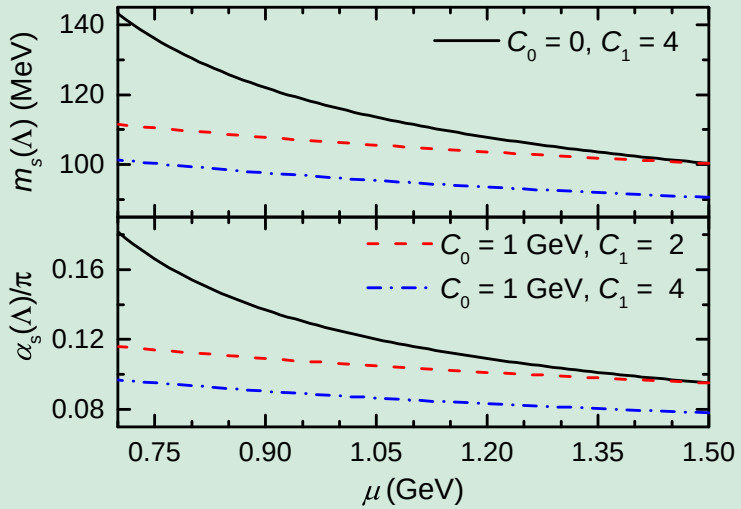
Strong interaction

The thermodynamic potential density at zero temperature:

Bag Model: $\Omega = -\sum_i \omega_i^0 + B$ [Xia_Peng_Zhao_Zhou2016_PRD93-085025].



Perturbation Model: $\Omega = \sum_i^{N_f} \left(\omega_i^0 + \omega_i^1 \alpha_s\right) + \omega_e^0 + B$ [Xia_Zhou2017_NPB916-669].



Renormalization scale: $\bar{\Lambda} = C_0 + \frac{C_1}{N_f} \sum_i \mu_i$

Other thermodynamic quantities: $n_i = -\left.\frac{\partial \Omega}{\partial \mu_i}\right|_{\mu_{j\neq i}}$, $E = \Omega + \sum_i \mu_i n_i$, and $P = -\Omega$.

Weak interaction

Weak reactions: $d, s \leftrightarrow u + e + \bar{\nu}_e$, $s + u \leftrightarrow u + d$, ...

The weak equilibrium is reached: $\mu_u + \mu_e = \mu_d = \mu_s$.

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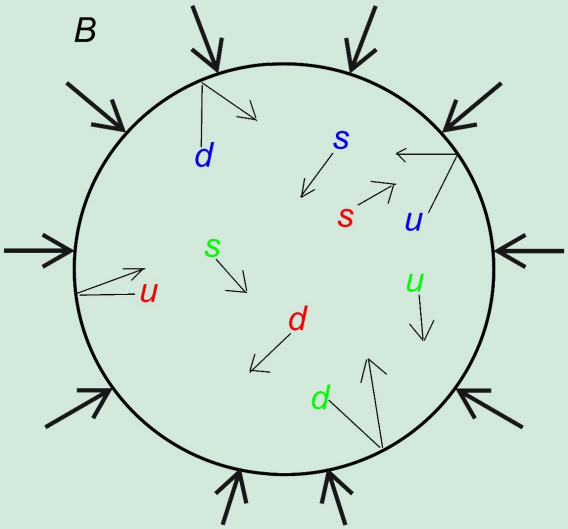

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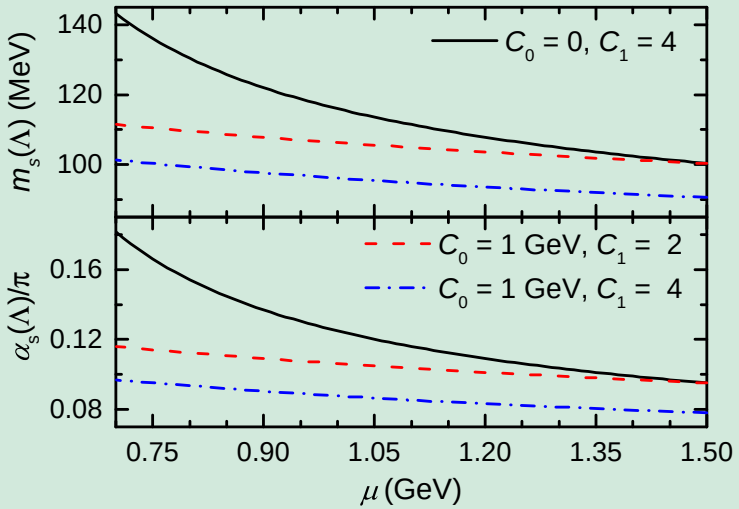

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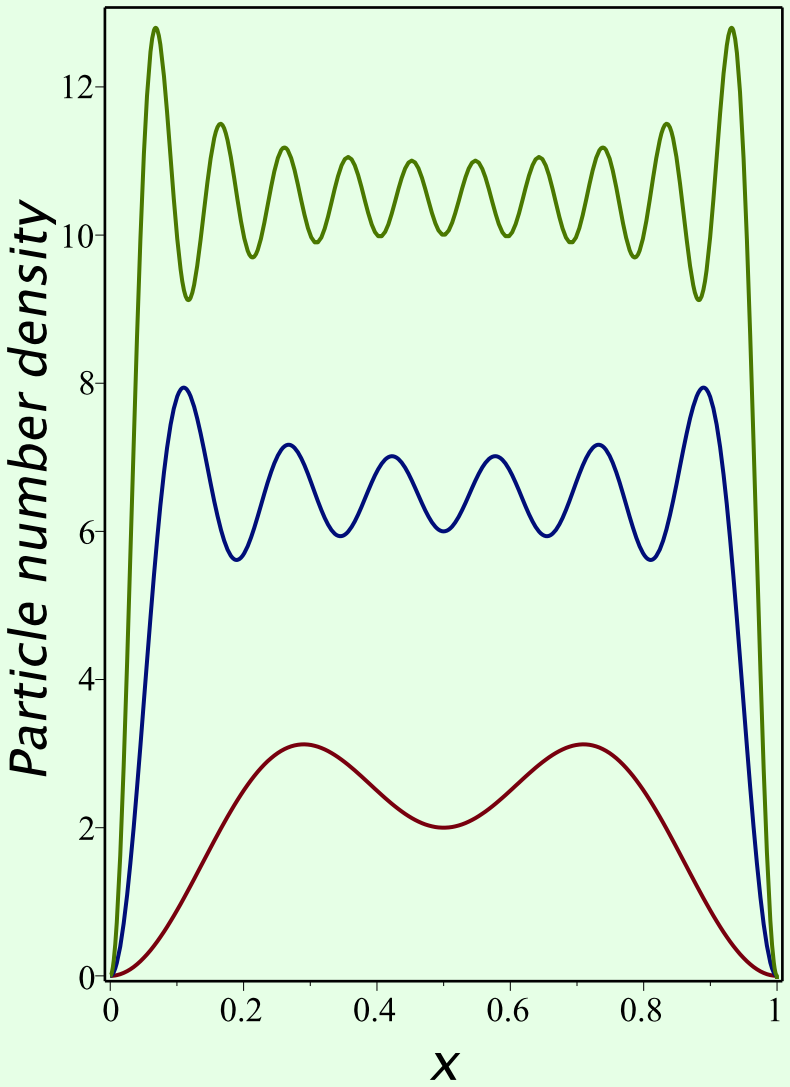

MRE method [Berger_Jaffe1987_PRC35-213, Madsen1994_PRD50-3328, . . .]

The average effects due to quark depletion are treated with a modification to the density of states, i.e.,

$$\frac{\mathrm{d}N_i^{\mathrm{surf}}}{\mathrm{d}p_i} = -\frac{g_i R^2 p_i}{\pi}\arctan\left(\frac{m_i}{p_i}\right) + \frac{2g_i R}{3\pi}\left[1 - \frac{3p_i}{2m_i}\arctan\left(\frac{m_i}{p_i}\right)\right]$$

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$$\bar{E}_i^{\mathrm{surf}} = \int_0^{\nu_i(R)} \sqrt{p_i^2 + m_i^2}\,\frac{\mathrm{d}N_i^{\mathrm{surf}}}{\mathrm{d}p_i}\,dp_i$$

and pressure

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Note: Adopting a constant surface tension does not predicts reasonable properties for SQM objects! [Xia_Peng_Zhao_Zhou2016_PRD93-085025]

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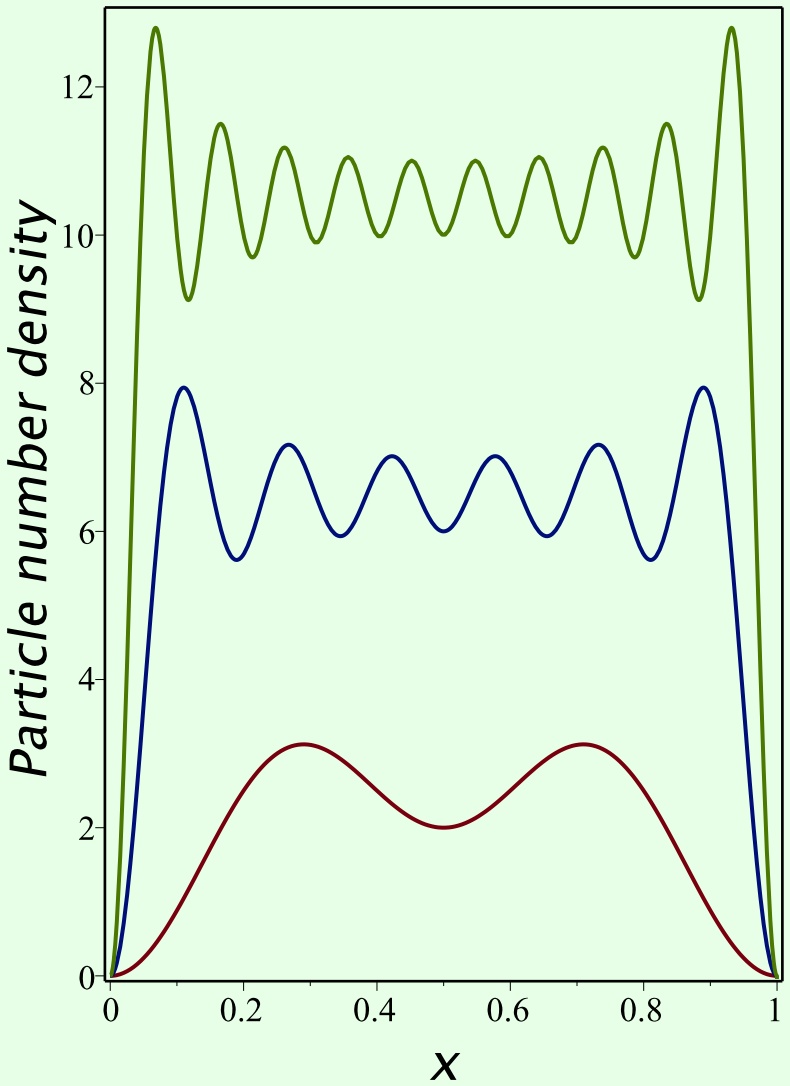

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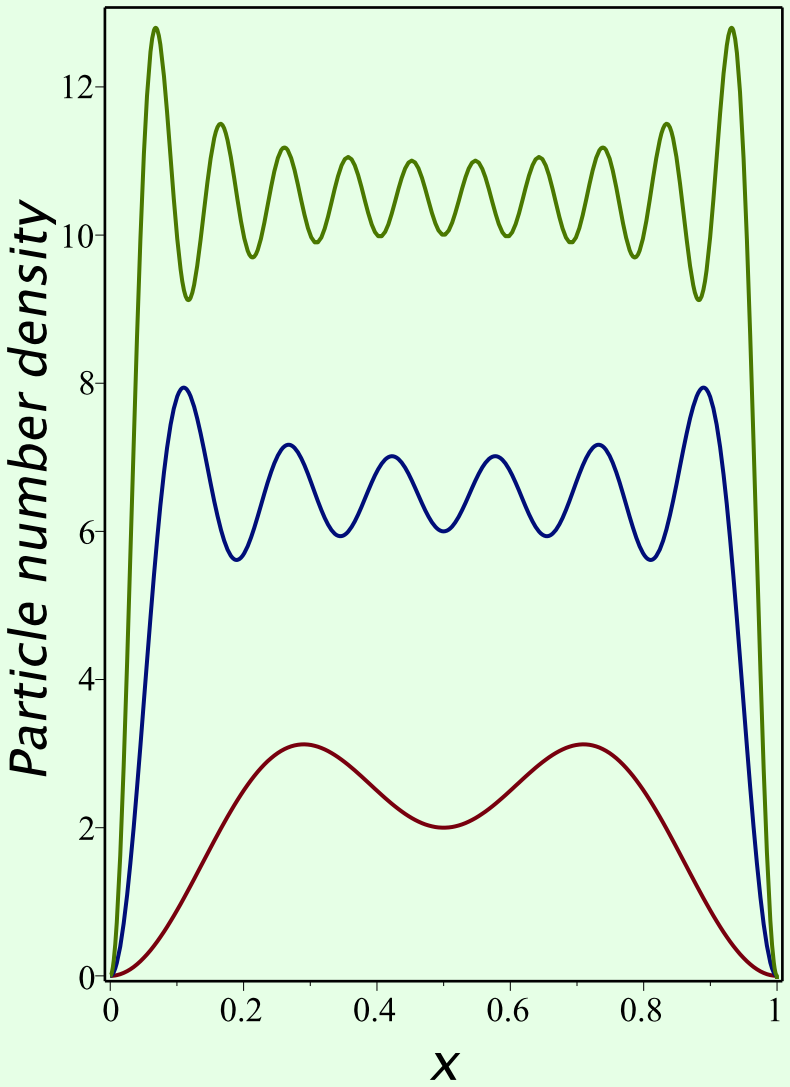

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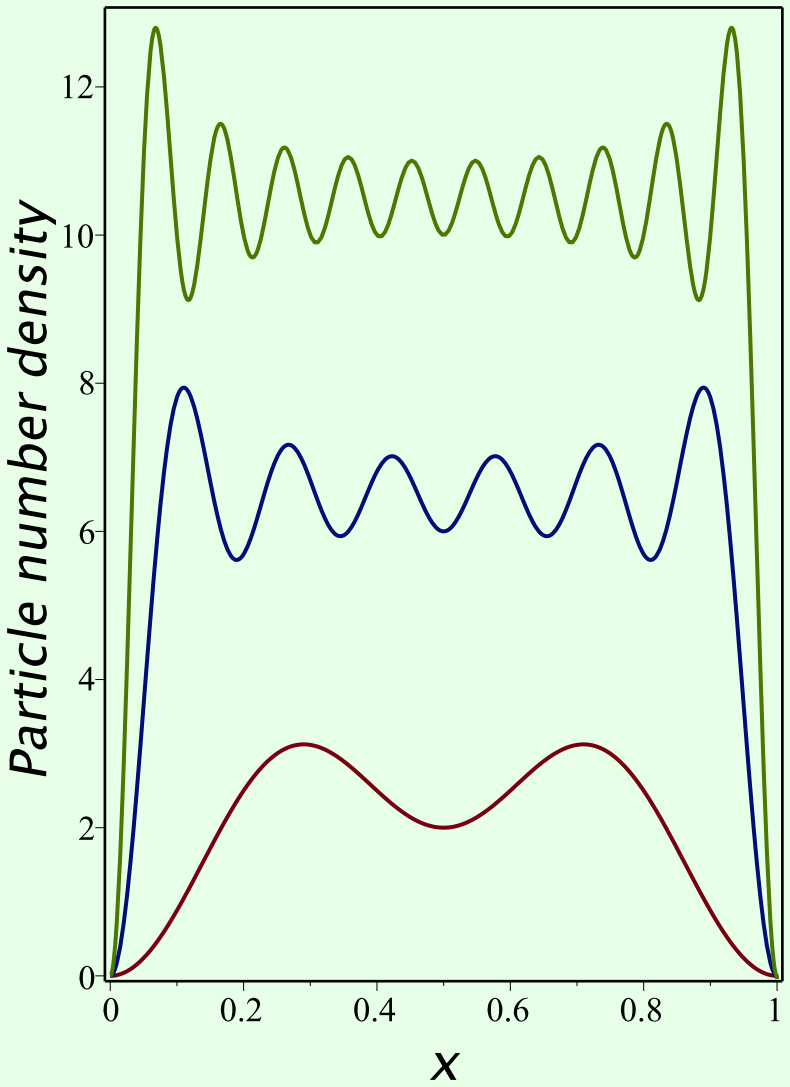


MRE method [Berger_Jaffe1987_PRC35-213, Madsen1994_PRD50-3328, . . .]

The average effects due to quark depletion are treated with a modification to the density of states, i.e.,

$$\frac{\mathrm{d}N_i^{\mathrm{surf}}}{\mathrm{d}p_i} = -\frac{g_i R^2 p_i}{\pi}\arctan\left(\frac{m_i}{p_i}\right) + \frac{2g_i R}{3\pi}\left[1 - \frac{3p_i}{2m_i}\arctan\left(\frac{m_i}{p_i}\right)\right]$$

with the contributions to the total energy

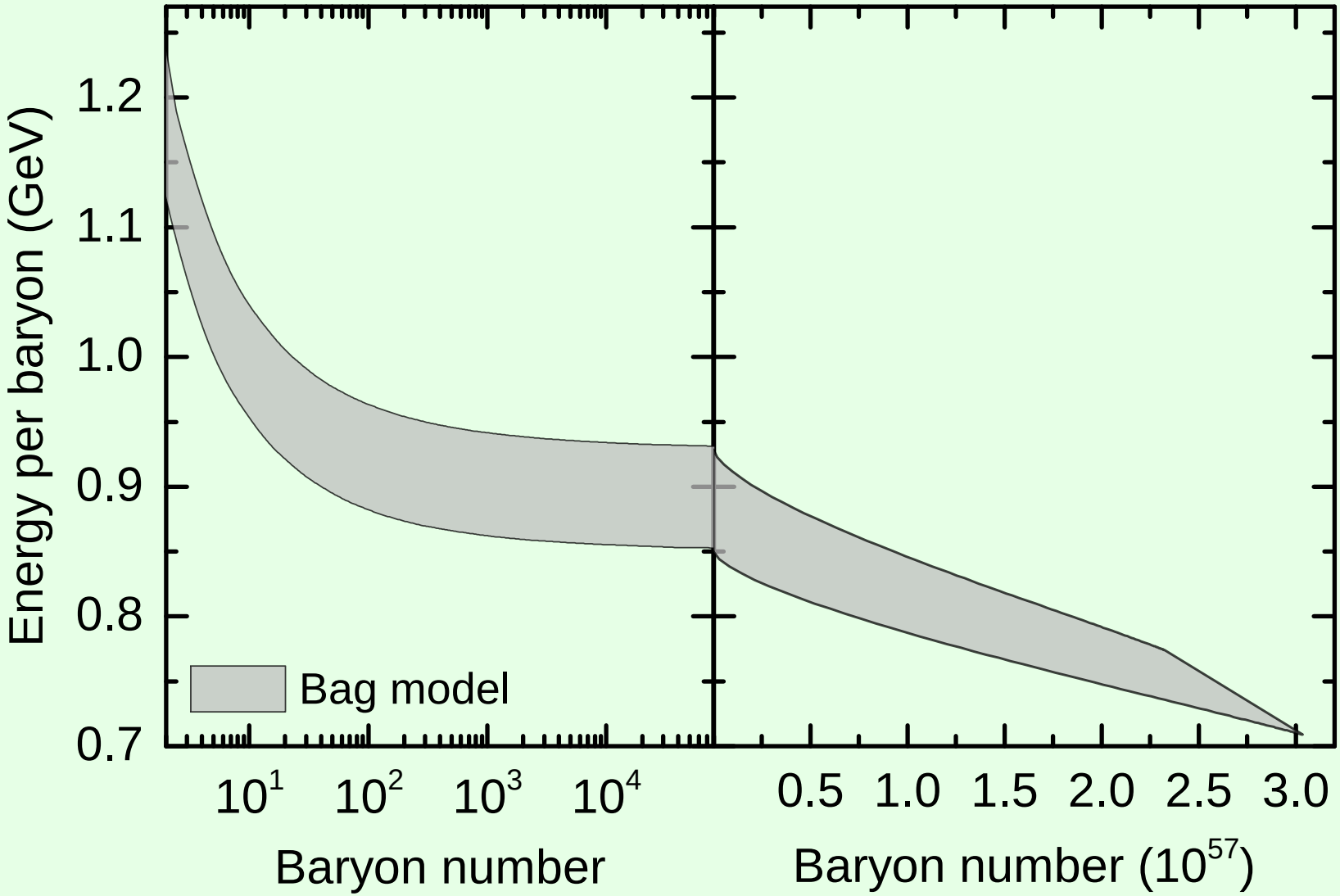
$$\bar{E}_i^{\mathrm{surf}} = \int_0^{\nu_i(R)} \sqrt{p_i^2 + m_i^2}\,\frac{\mathrm{d}N_i^{\mathrm{surf}}}{\mathrm{d}p_i}\,dp_i$$

and pressure

$$P^{\mathrm{surf}} = -\sum_i \left.\frac{\mathrm{d}\bar{E}_i^{\mathrm{surf}}}{\mathrm{d}V}\right|_{N_i^{\mathrm{surf}}}.$$

Note: Adopting a constant surface tension does not predicts reasonable properties for SQM objects! [Xia_Peng_Zhao_Zhou2016_PRD93-085025]

Energy per baryon



The shaded region correspond to the results obtained with $B^{1/4} = 152 \pm 7$ MeV.

The minimum energy per baryon is marked with open circles, corresponding to the most massive strange stars.

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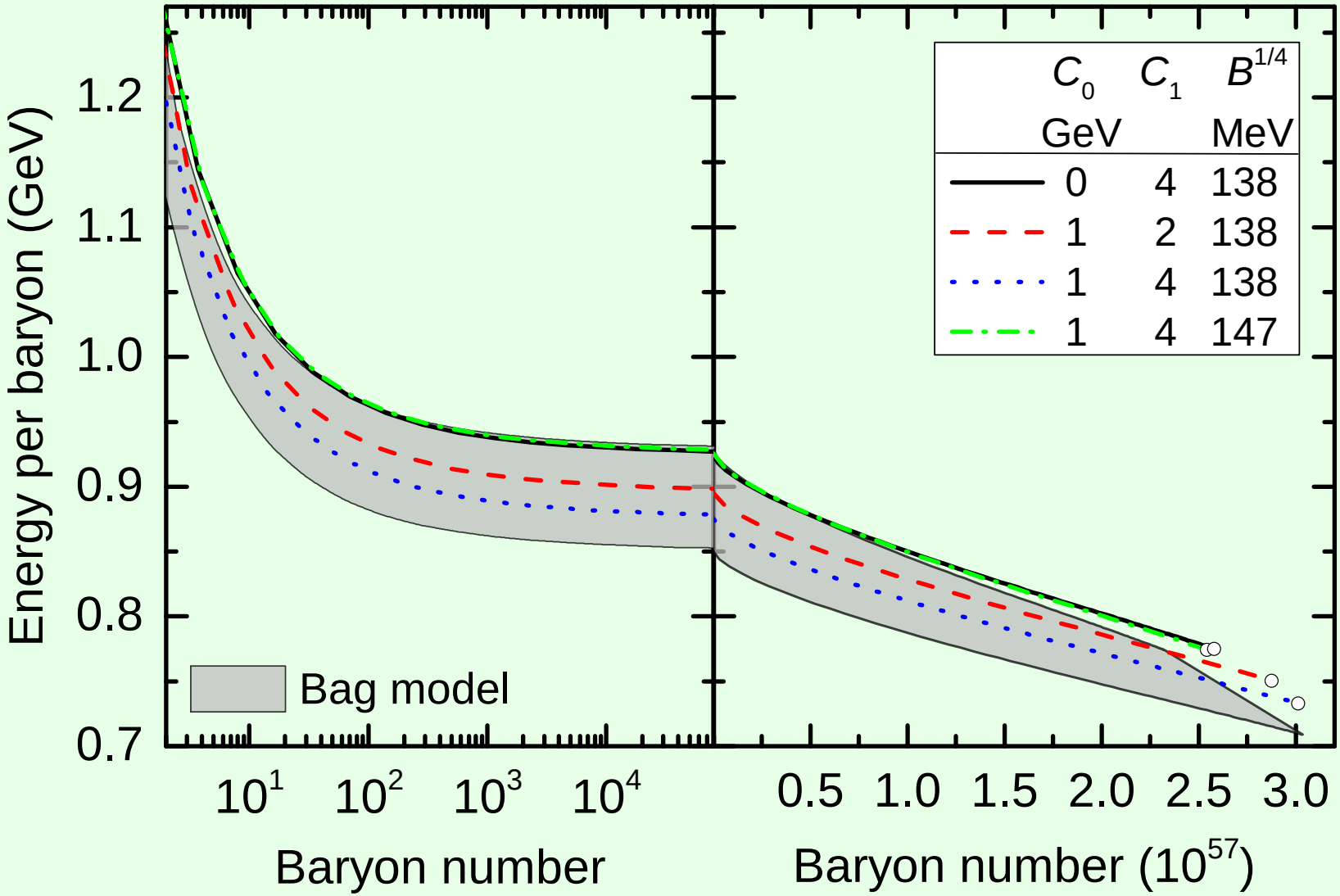

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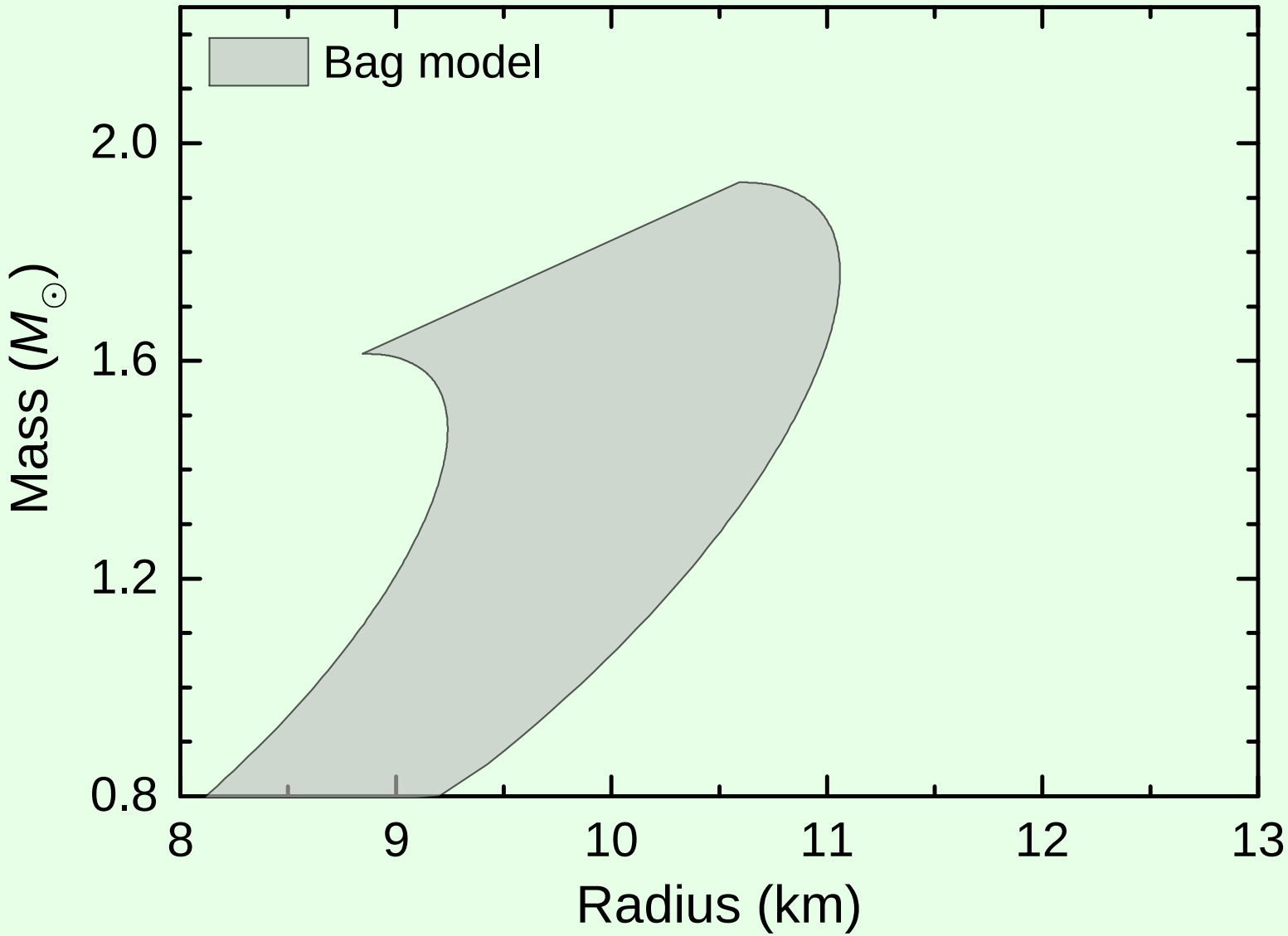
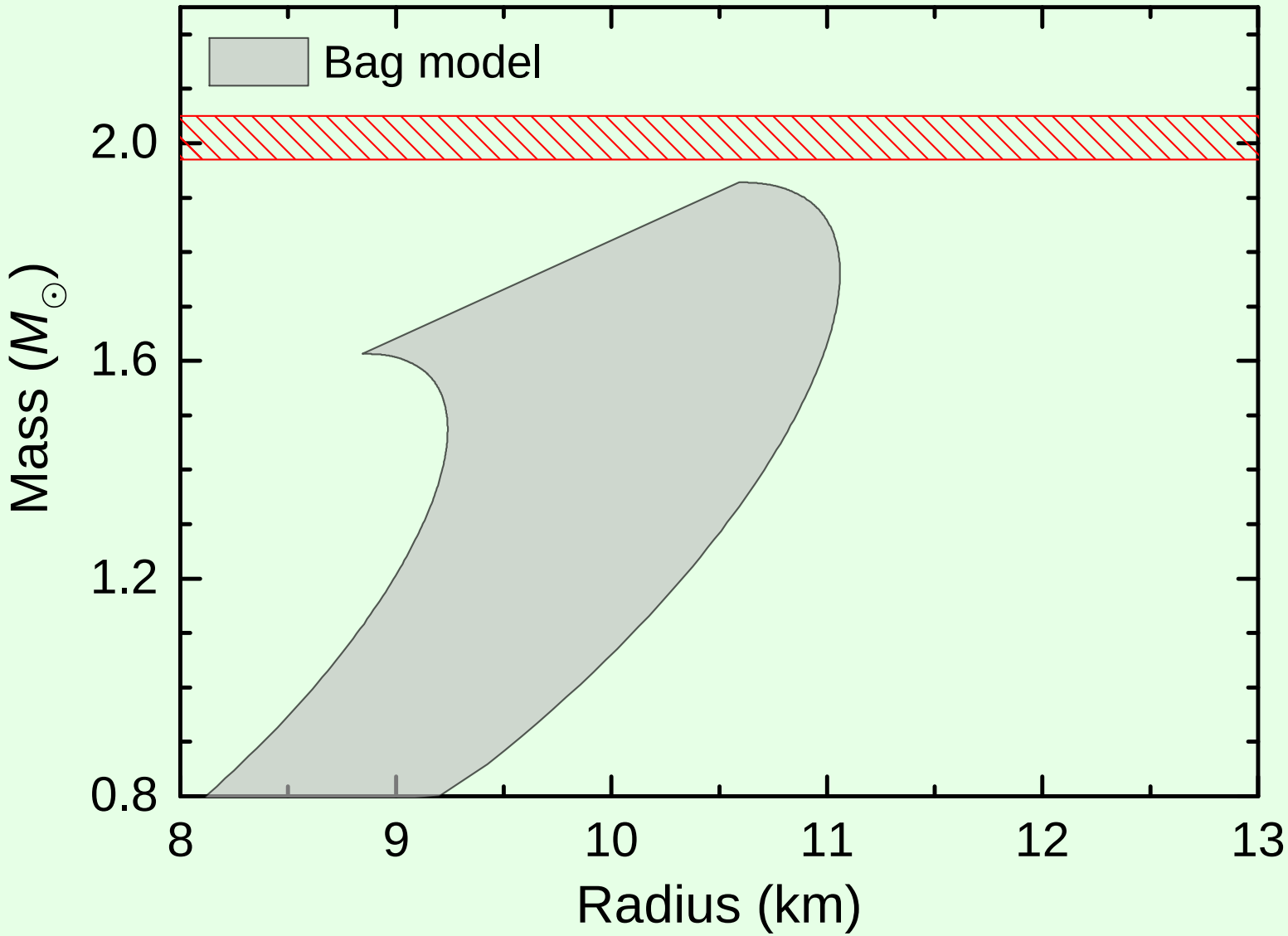
Masses and radii of strange stars



The strange stars obtained with bag model do not reach $2M_\odot$ (PSR J0348+0432).

The masses and radii of strange stars increase with C_0 and C_1 but decrease with B.

Masses and radii of strange stars



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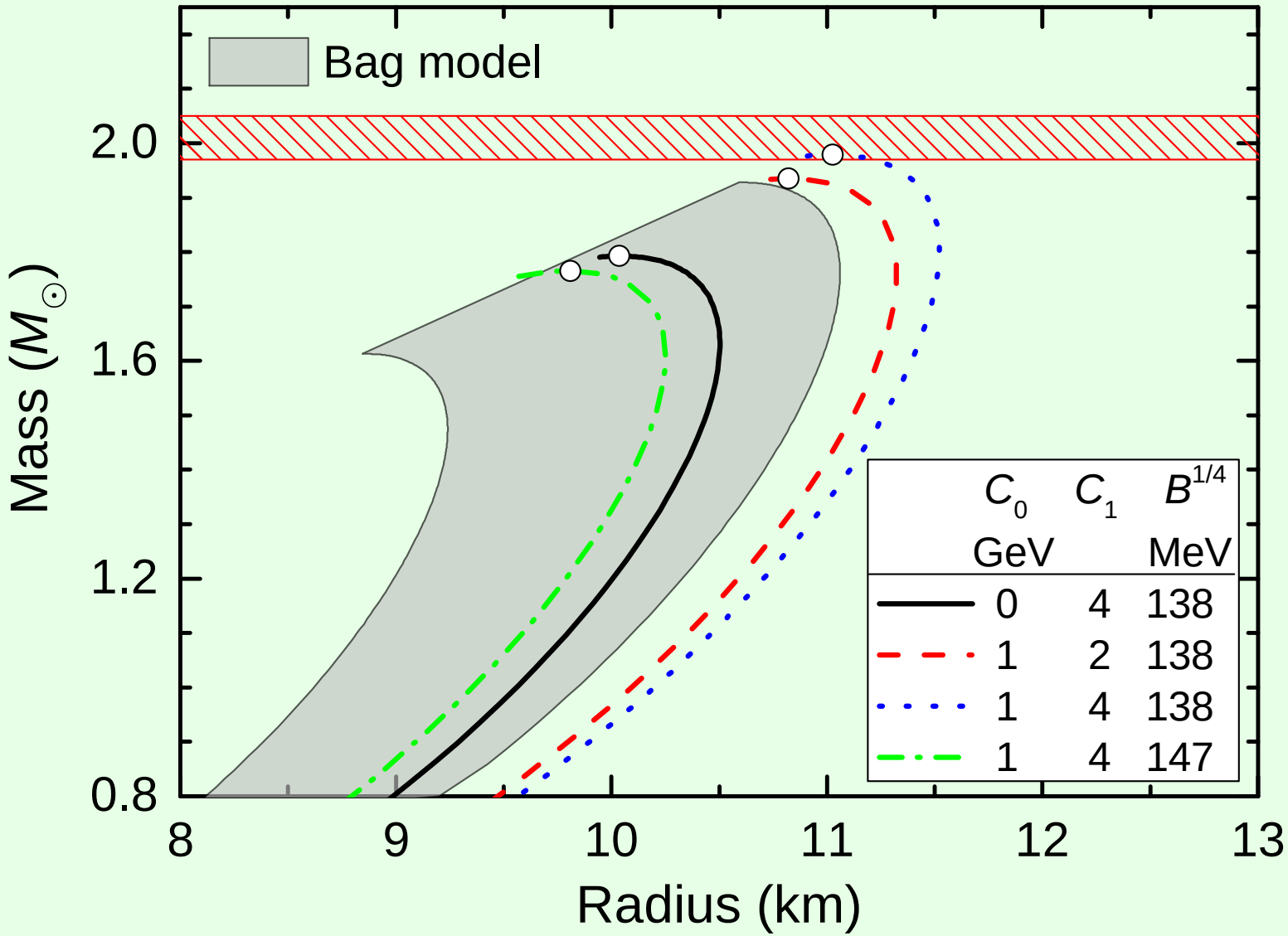

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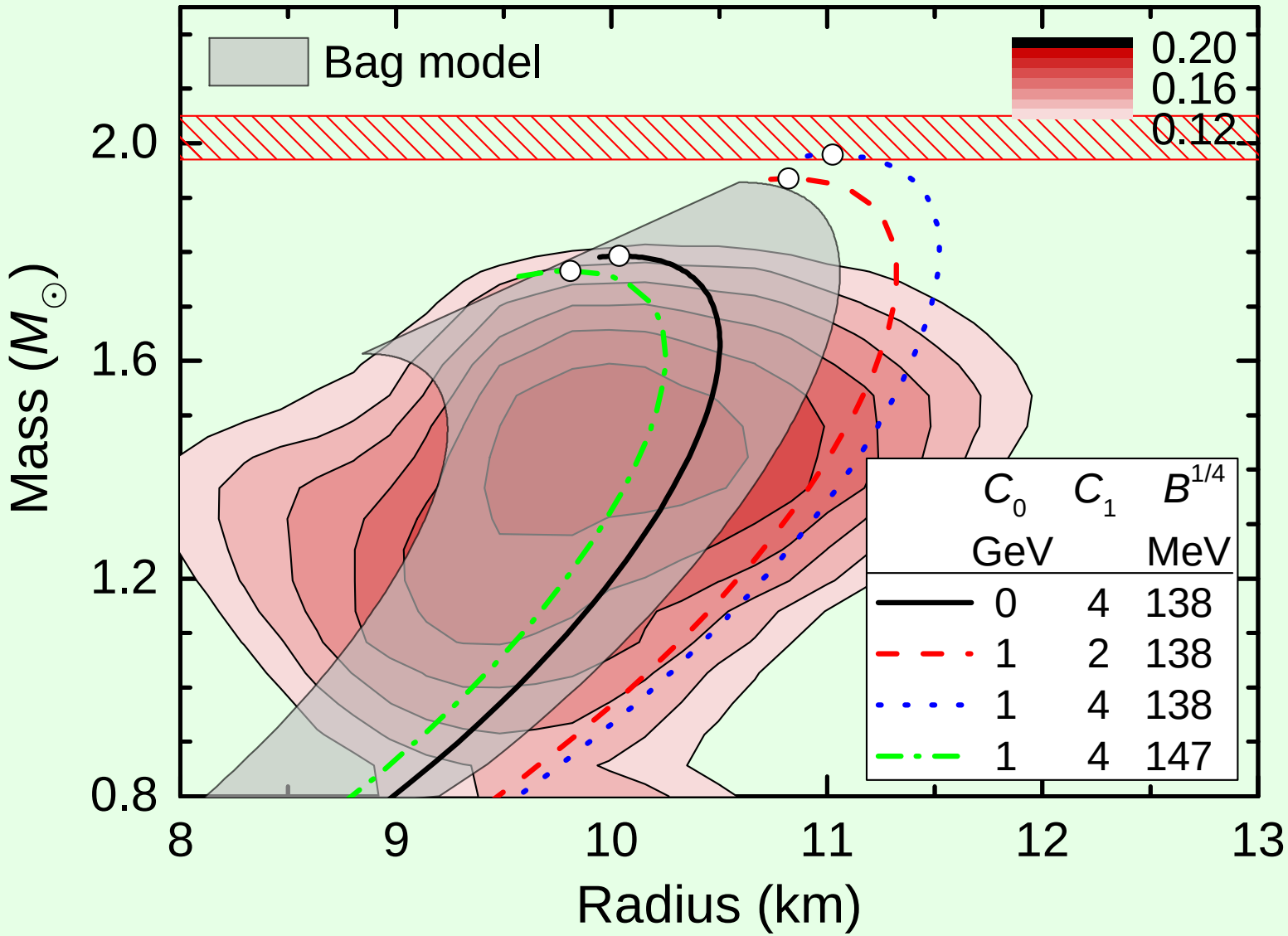

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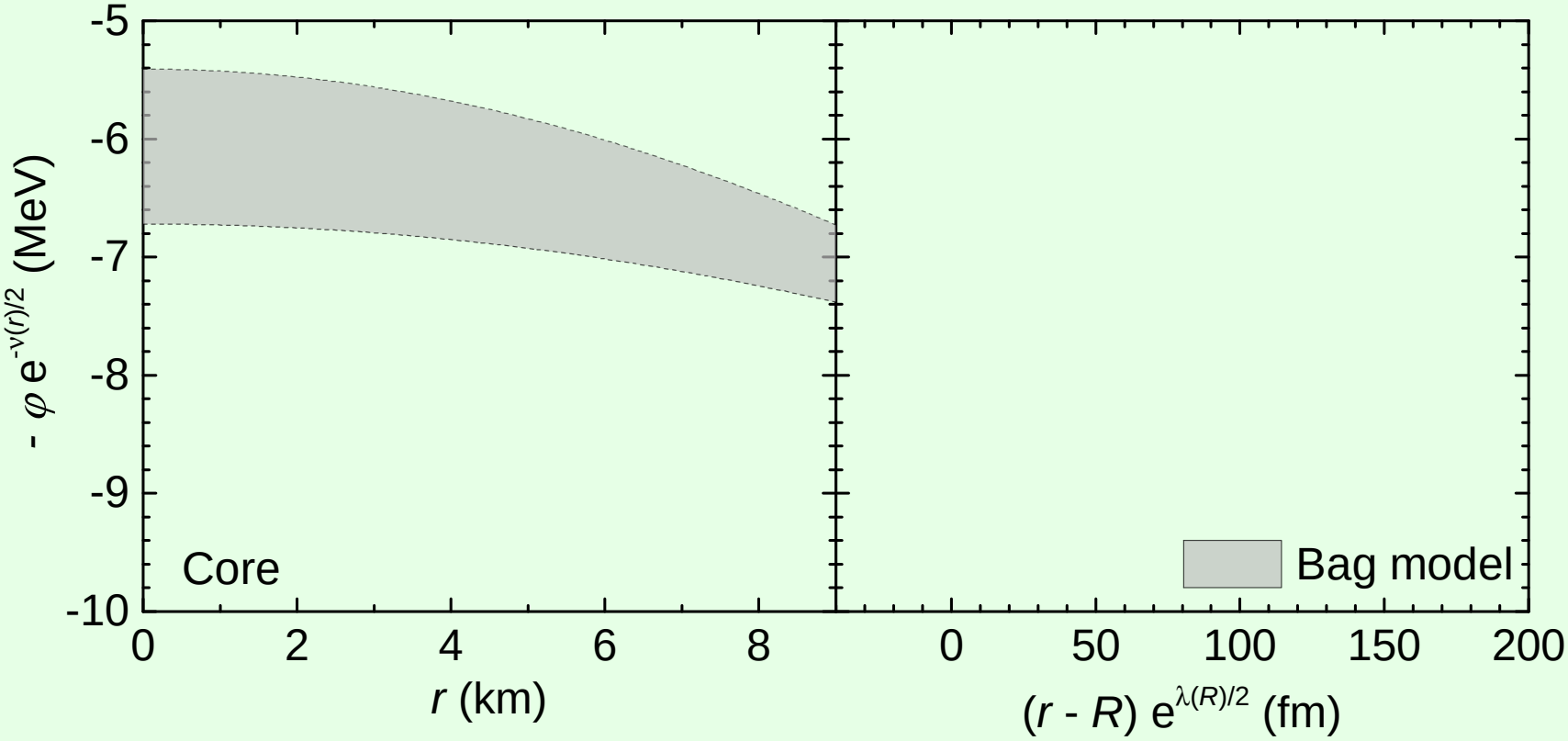
Electric potential ($R = 9$ km)



At $r \leq R$, $\varphi(r) = \varphi_{\rm S}(r) + \varphi_{\rm G}(r) + \varphi_0$ with $n_{\rm ch}(\varphi_0, \nu_0) = 0$,

$\varphi_{\rm S} = \frac{c_1}{r}\left[\mathrm{e}^{(r-R)/\bar{\lambda}_{\rm D}} - \mathrm{e}^{-(r+R)/\bar{\lambda}_{\rm D}}\right]$, and

$\varphi'_{\rm G}(r) = 4\pi\alpha \mathrm{e}^{\nu(r)/2}\lambda_{\rm D}(r)^2 \left.\frac{\partial n_{\rm ch}}{\partial \nu}\right|_{\varphi} \nu'(r)$.

At $r > R$, $\bar{\varphi}'' + 2\bar{\varphi}'/r - 4\pi\alpha n_{\rm e}\mathrm{e}^{\lambda} = 0$ with $\bar{\varphi} \equiv \varphi \mathrm{e}^{-\nu/2}$.

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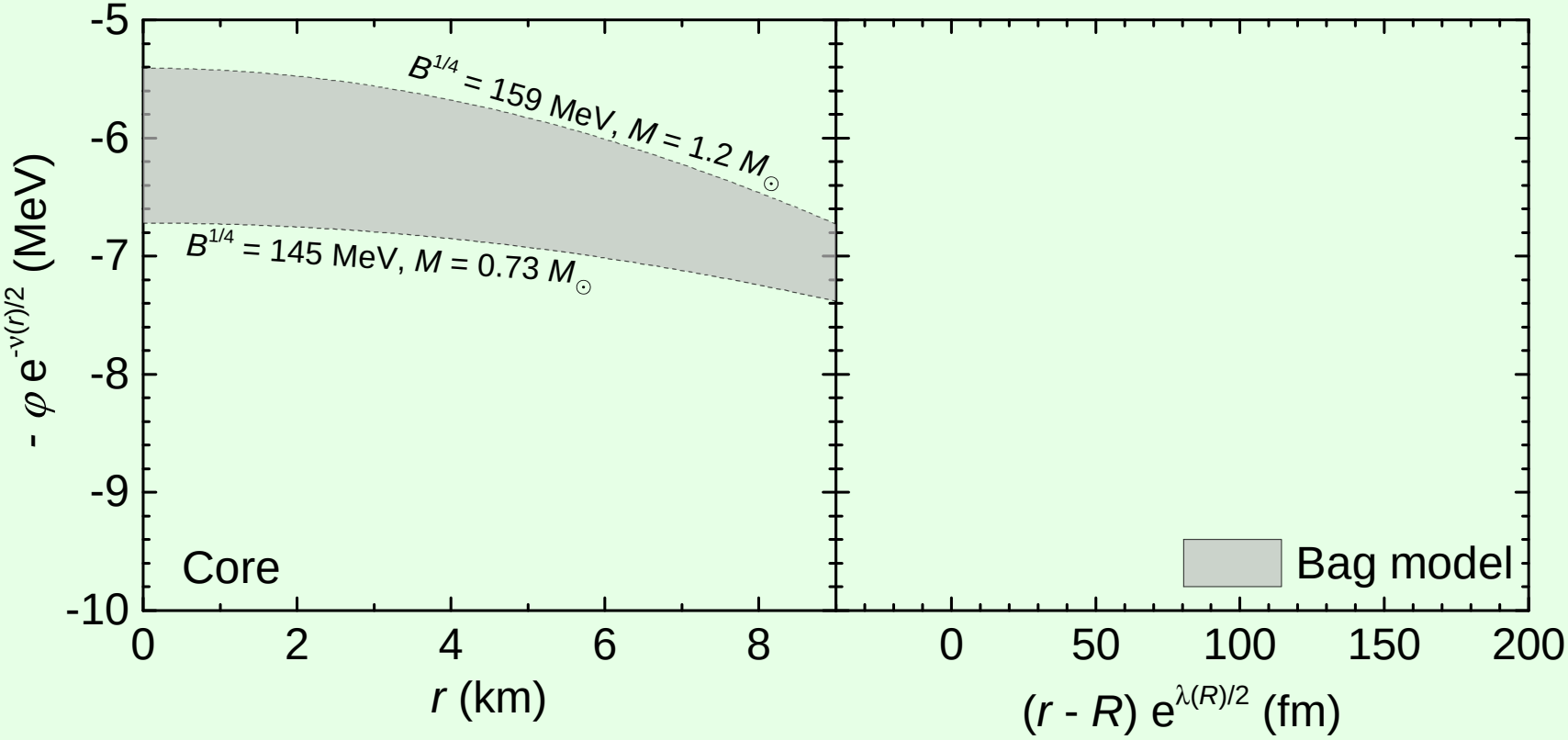

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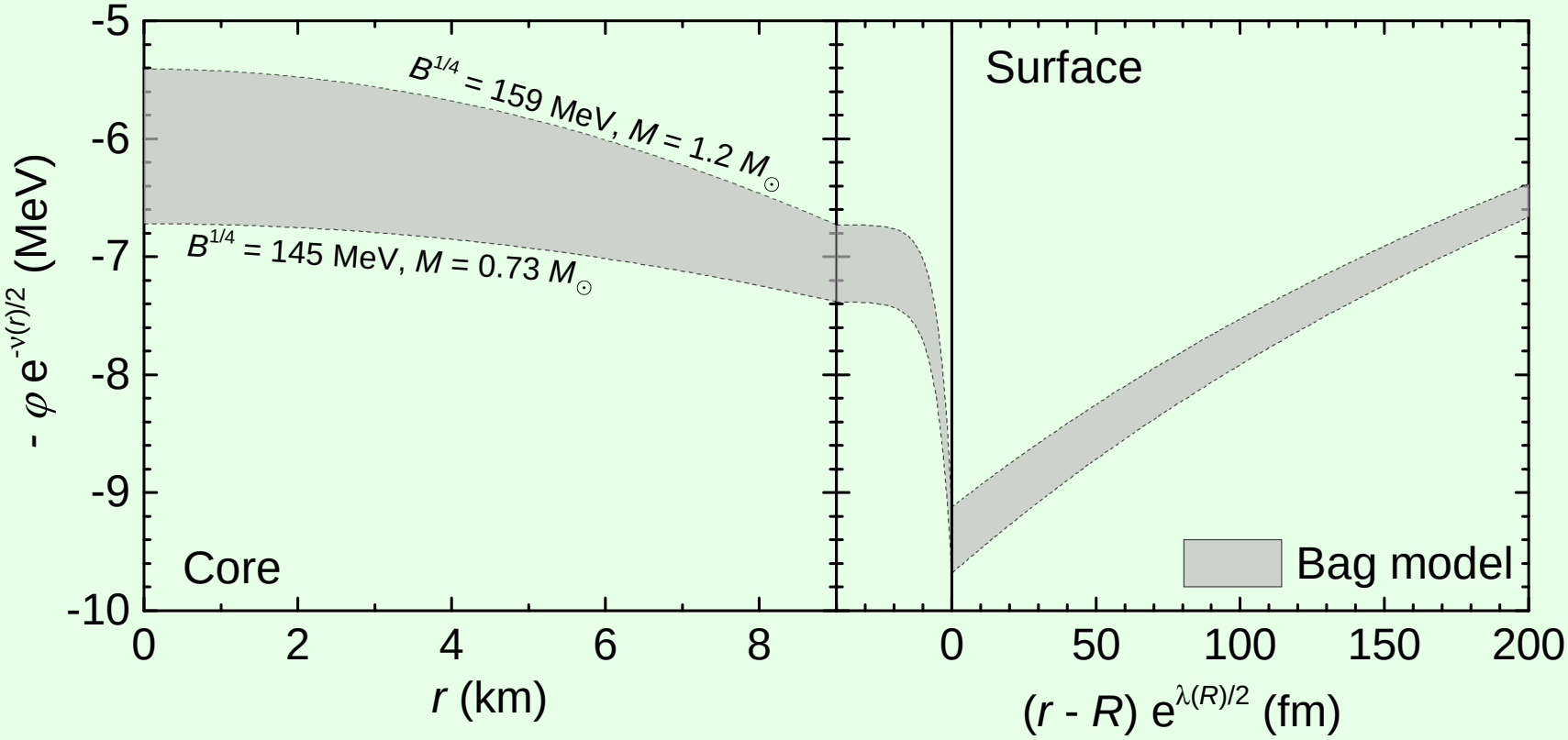

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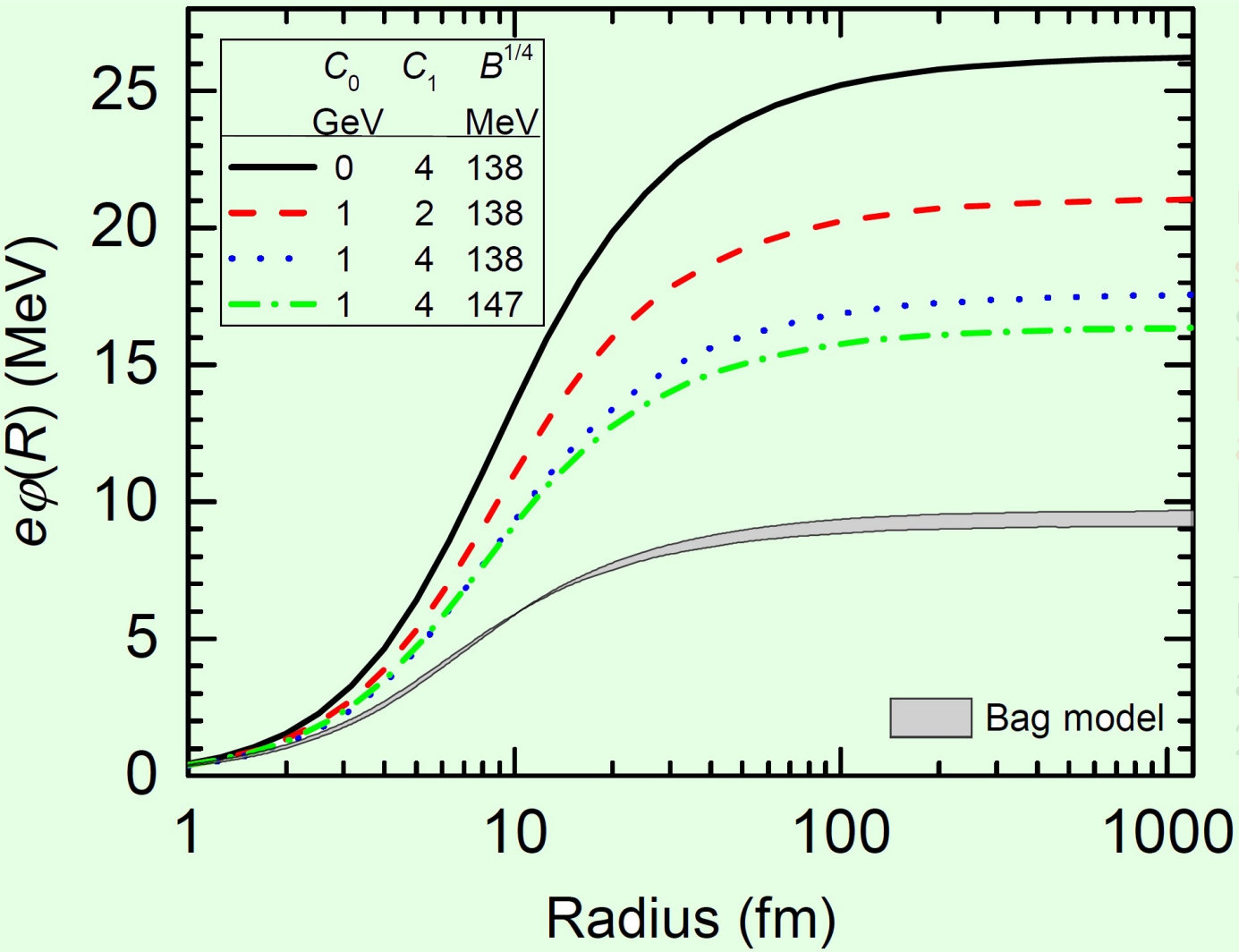

Experimental search for SQM via heavy-ion activation [Farhi_Jaffe1985_PRD32-2452, Isaac et al.1998_PRL81-2416].

Coulomb barrier for finite nuclei: $E_C = \alpha Z/R_e$ ($R_e = r_e A^{1/3} + R_p$ with $r_e = 1.62$ fm and $R_p = 1.443$ fm [Vaz_Alexander1974_PRC10-464]).

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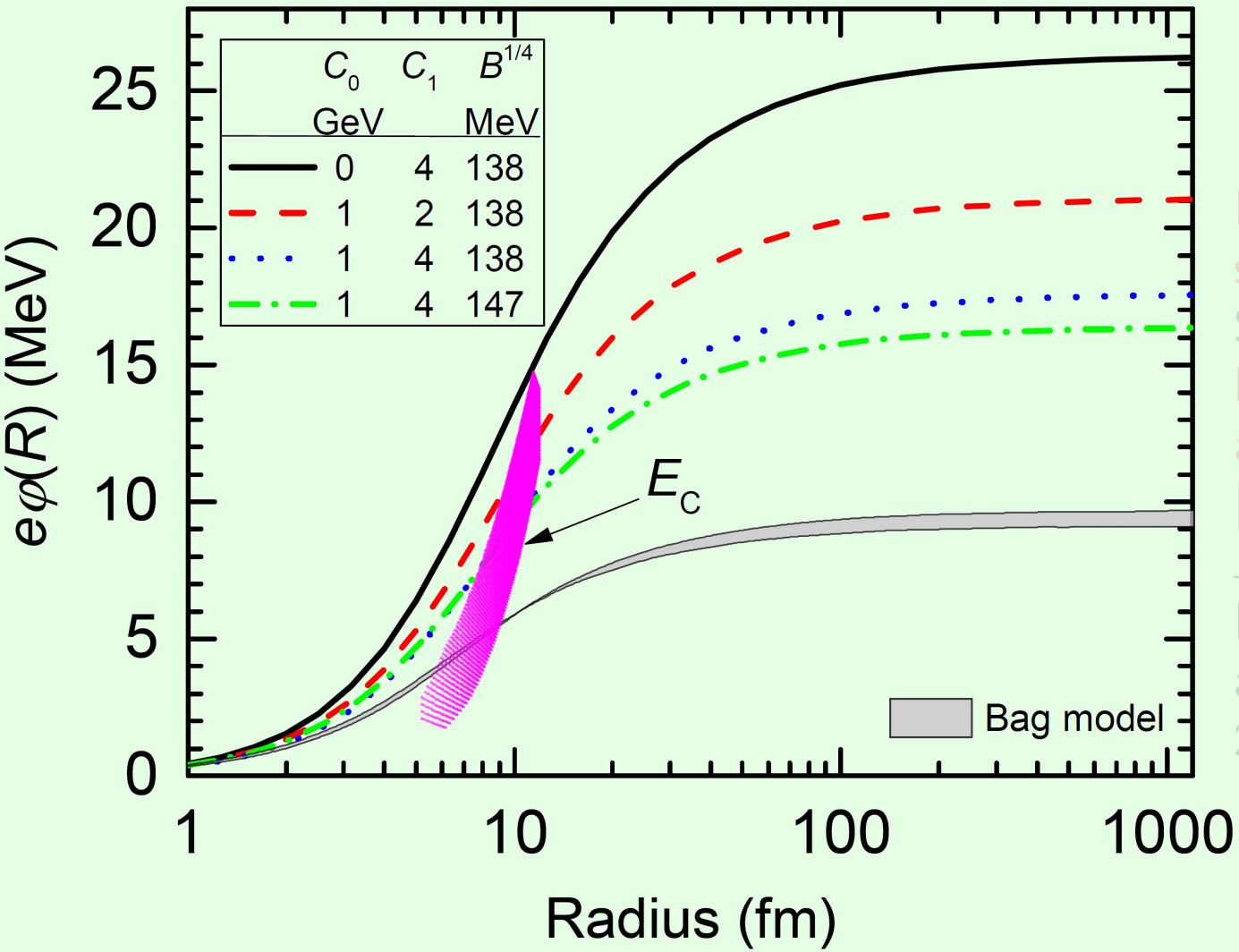

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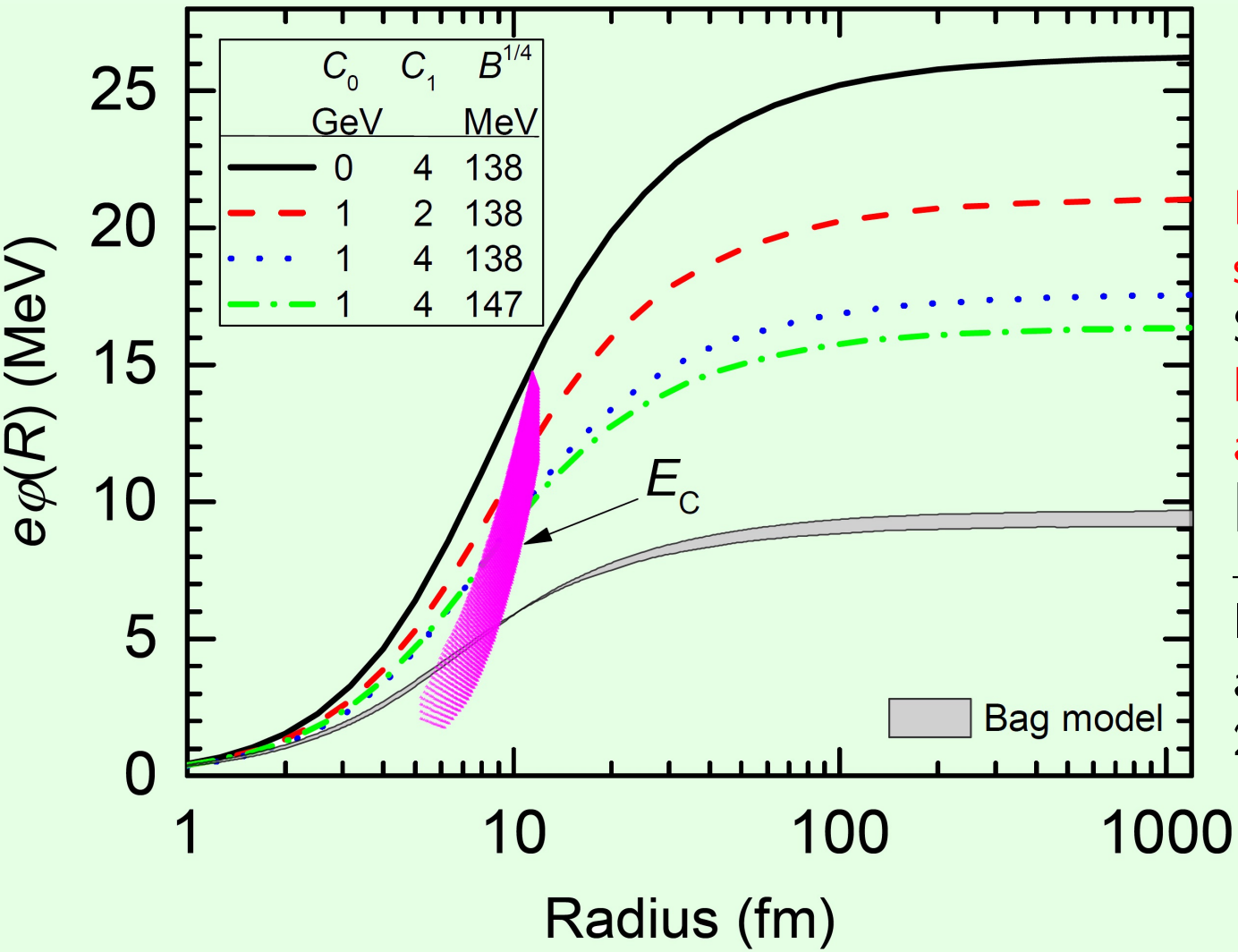

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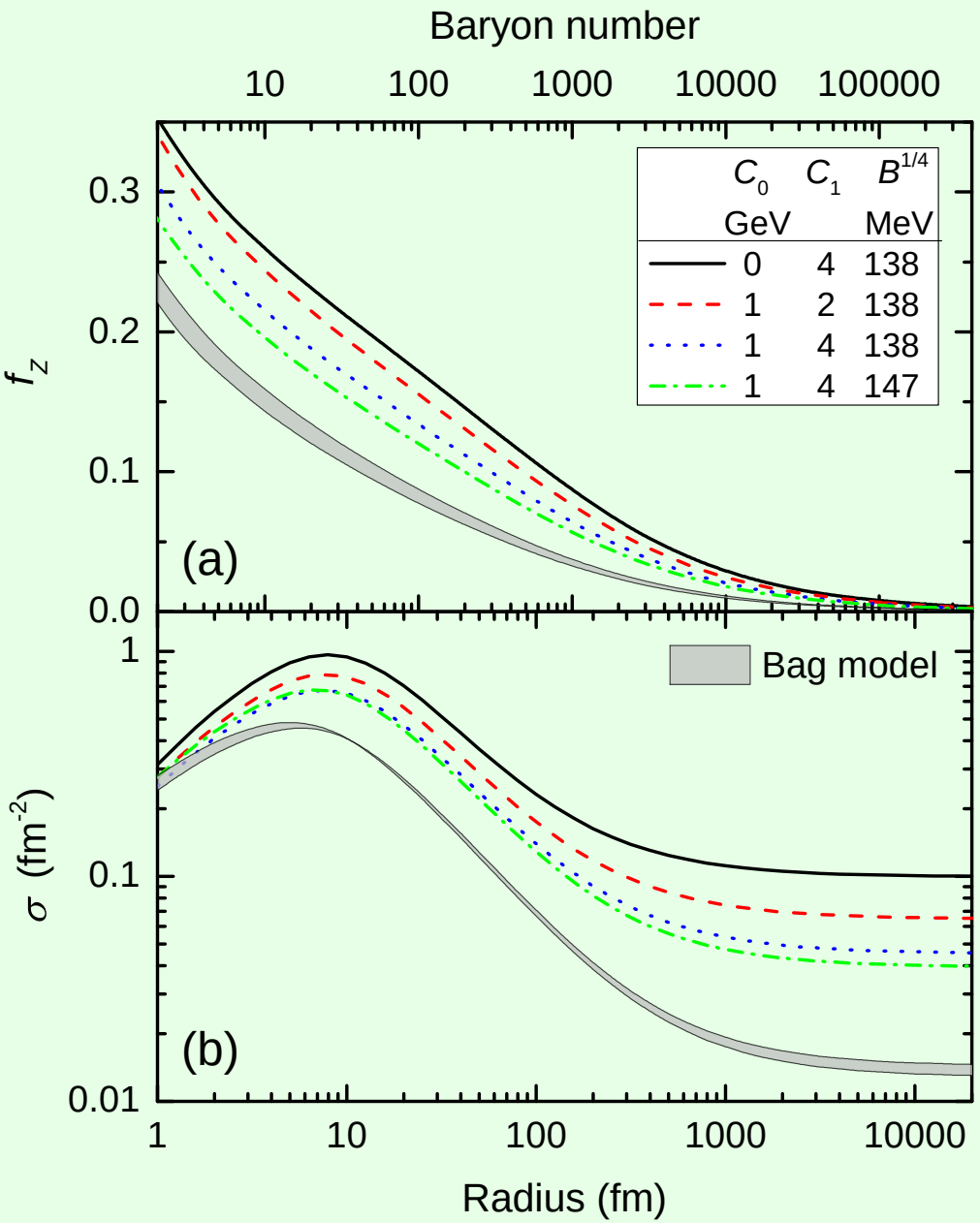
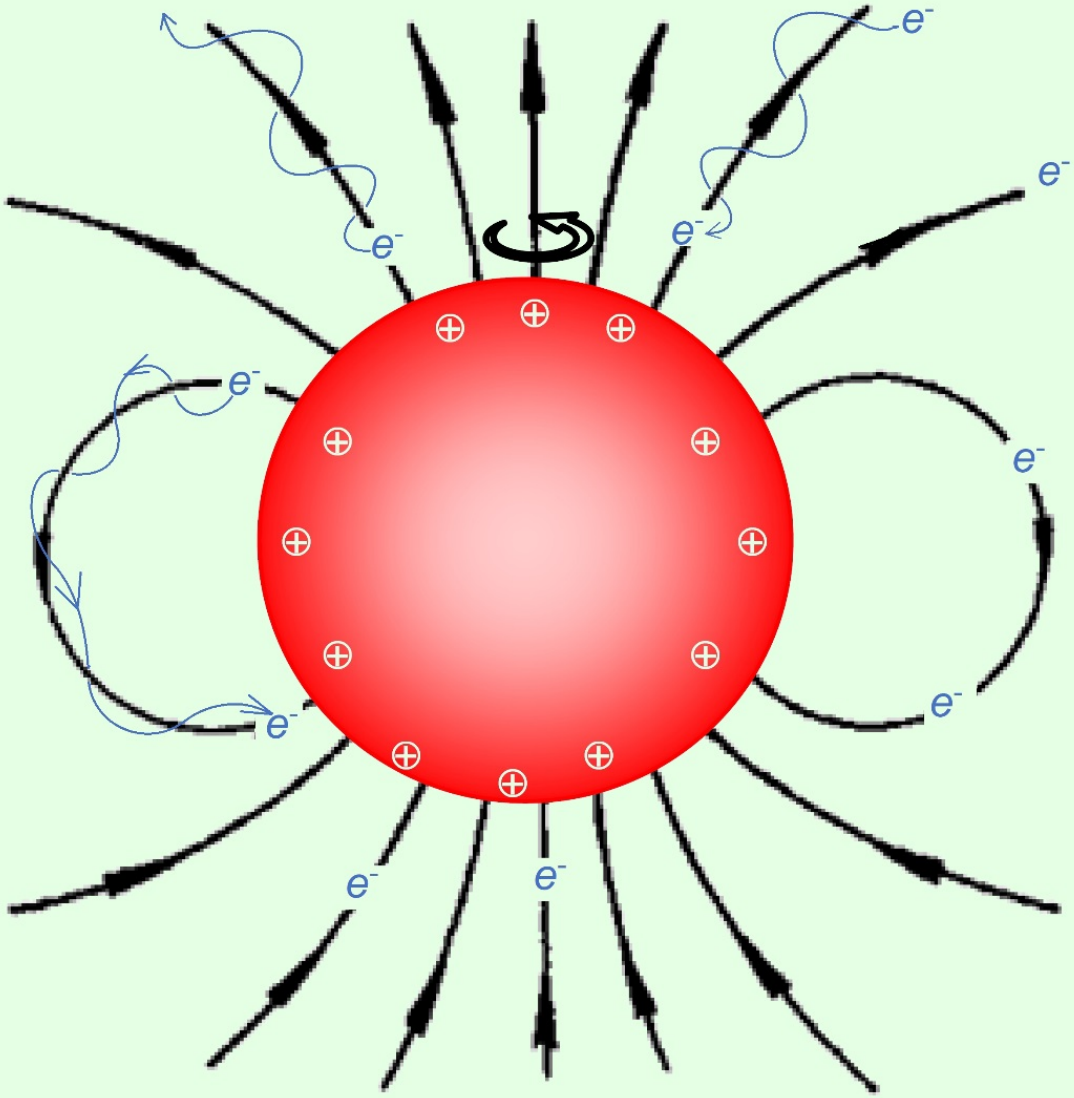
Charge properties



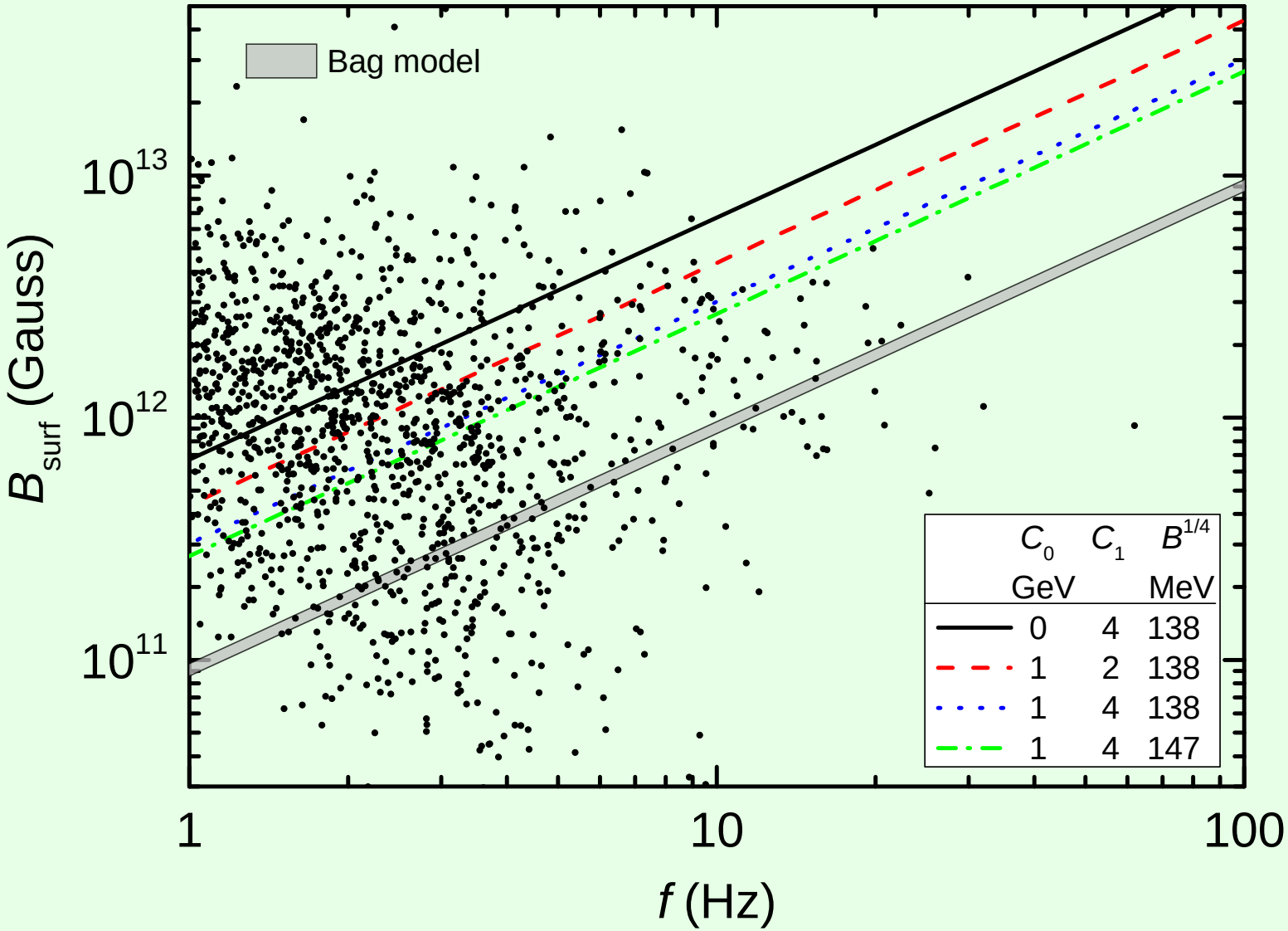
- The charge-to-mass ratio of the SQM core of strangelets;
- The surface charge density σ of the SQM core for strangelets.

The magnetic field of a rotating strange star



The magnetic field formed at the pole area on the surface of a rotating SQM core [Negreiros et al.2010_PRD82-103010]: $B_{\rm surf} = \frac{1}{3} u_0 \sigma R f$.

The magnetic field of a rotating strange star



The binary pulsars are excluded since their magnetic fields may be dampened by mass accretion (Bhattacharya_van den Heuvel1991_PR203-1).

Summary

Based on the UDS model, we investigated the properties of SQM objects. There exist nonzero charge inside an SQM object, i.e., the charge located on the quark-vacuum interface due to the separation of electrons from SQM and the gravity induced charge throughout the object. Aside from the increase of masses and radii of strange stars, due to the effects of perturbative interactions,

1. the electric field becames stronger and extends deeper into the core;
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Thank You!!!