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Interface effects of strange quark matter

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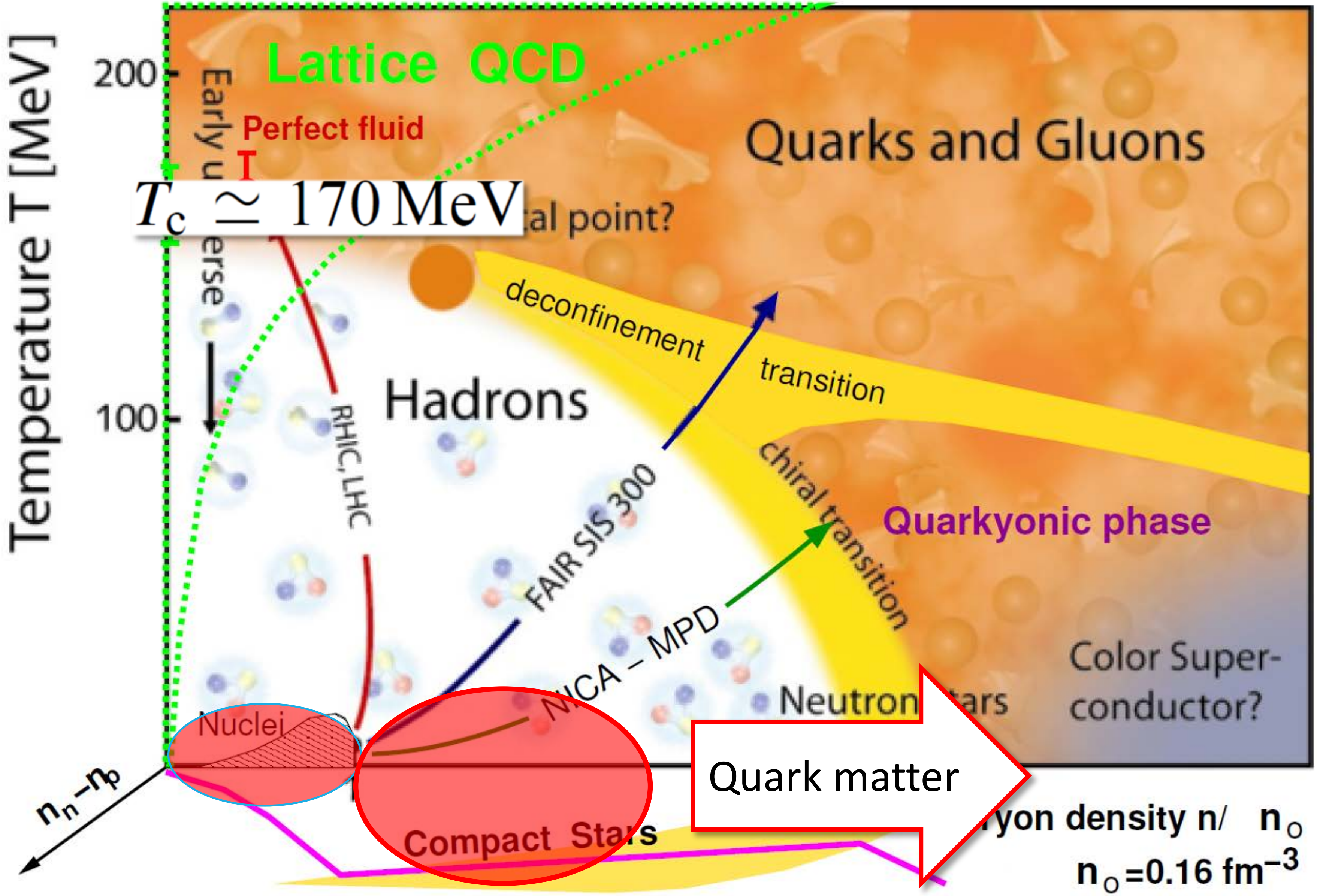
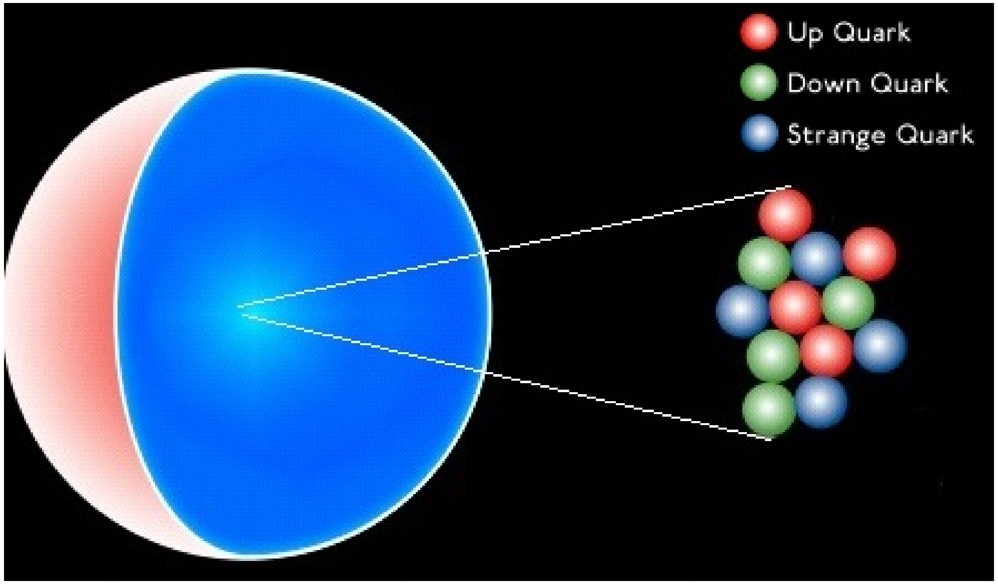
QCD Phase Diagram [McLerran2009_NPB195-275]



Strange quark matter (SQM)



Witten-Bodmer hypothesis

- Bodmer first suggested a low energy nuclear state called "collapsed nuclei" [Bodmer1971_PRD4-1601];
- 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 ≈ 2~10^{57}:

Strangelets (A<10^7)

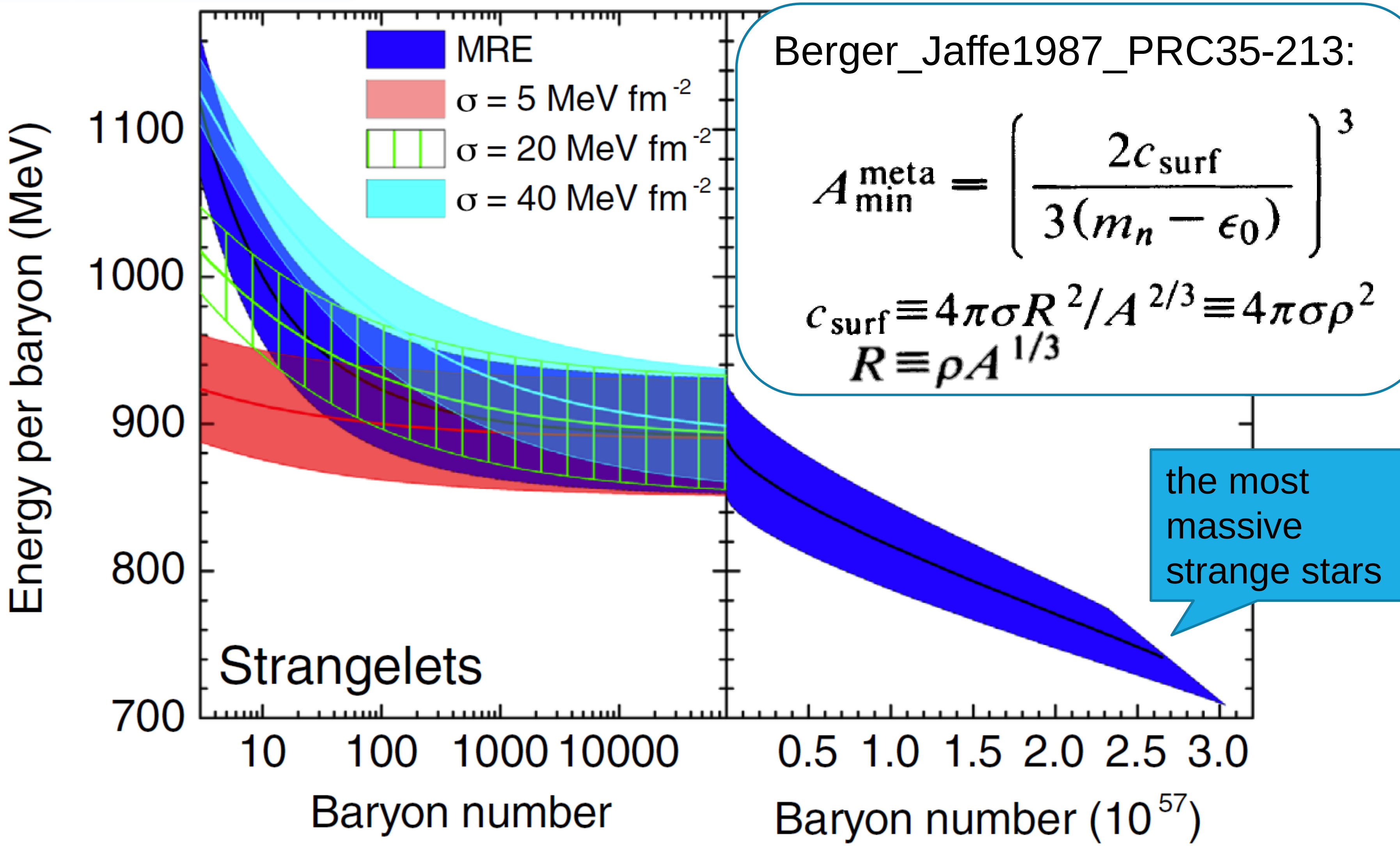
Comparing with nuclei, strangelets have: lower charge-to-mass ratio; larger mass; smaller radius; spherical shape; ...

Nuclearites [Rujula_Glashow1984_ Nature312-734]; **Meteorlike Compact Ultradense Objects (CUDO)** [Rafelski_Labun_Birrell2013_PRL110-111102]; ...

Strange stars (A ≈ 10^{57})

Comparing with traditional neutron stars, strange stars have: no crust; different mass-radius relations; smaller radii; higher rotational frequencies; ...

Energy per baryon



Berger_Jaffe1987_PRC35-213:

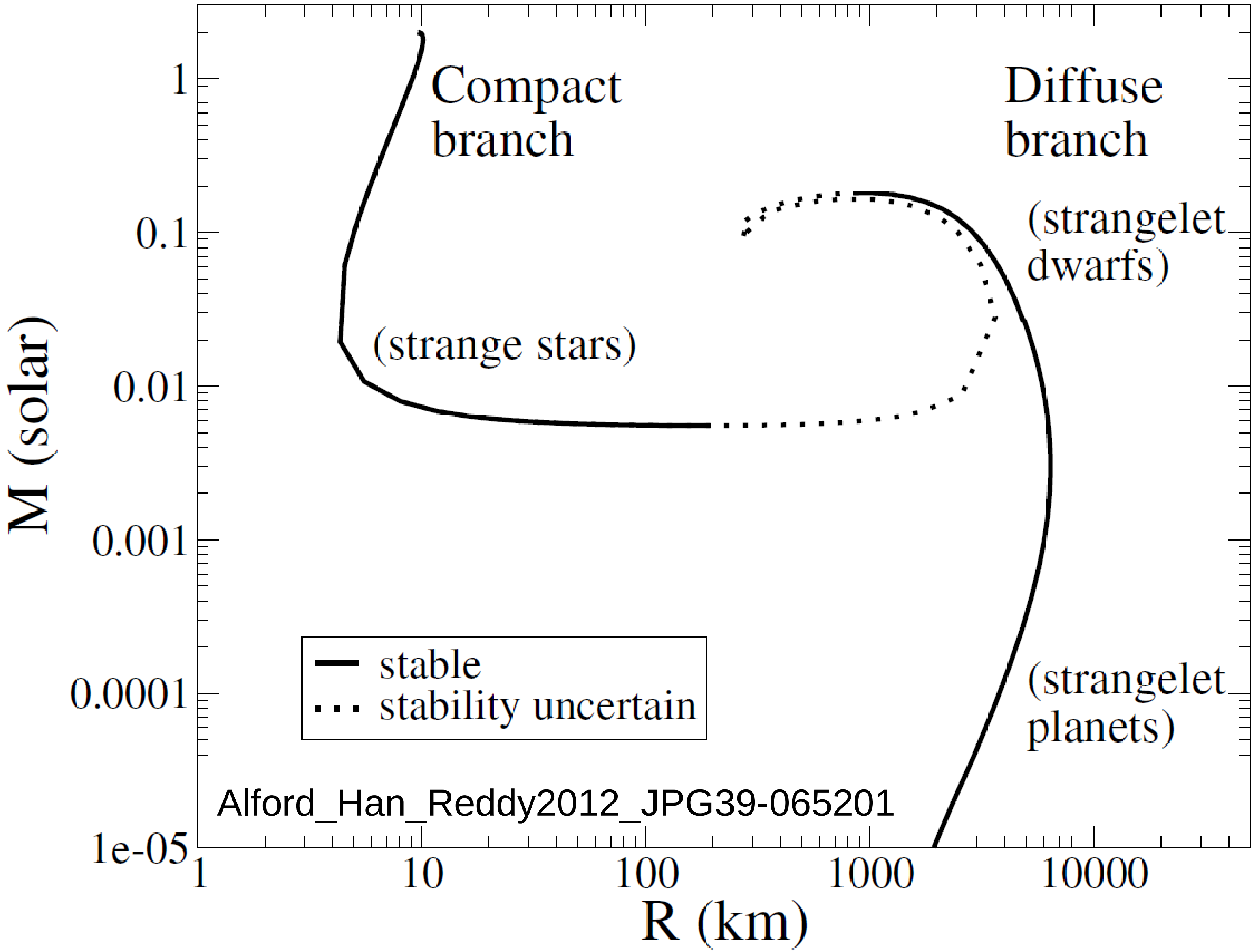
$$A_{\rm min}^{\rm meta} = \left(\frac{2c_{\rm surf}}{3(m_n - \epsilon_0)} \right)^3$$

$$c_{\rm surf} \equiv 4\pi\sigma R^2/A^{2/3} \equiv 4\pi\sigma\rho^2$$

$$R \equiv \rho A^{1/3}$$

The shaded region correspond to the results obtained with $B^{1/4} = 152 \pm 7$ MeV. [Xia_Peng_Zhao_Zhou2016_PRD93-085025]

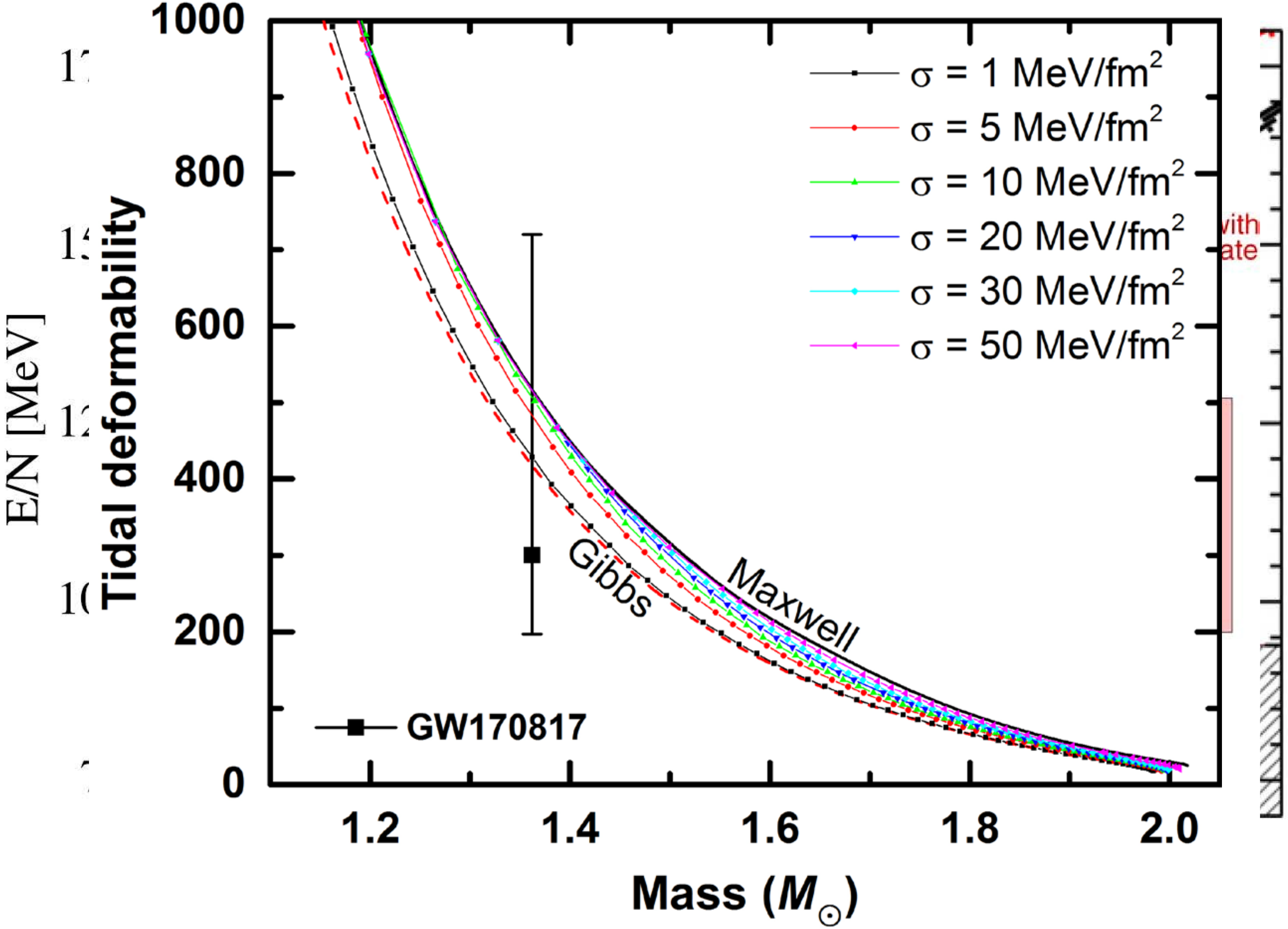
Energy excess per baryon



Th 7 MeV.

[Xi

Unstable SQM



Estimations of surface tension

Lattice QCD: Huang, Potvin, Rebbi, Sanielevici, Alves, Brower, de Forcrand, Lucini, Vettorazzo, et al.

For vanishing chemical potentials!

Effective models:

Linear sigma model [Palhares_Fraga2010_PRD82-125018, Pinto_Koch_Randrup2012_PRC86-025203, Kroff_Fraga2015_PRD91-025017], Nambu-Jona-Lasinio (NJL) model [Garcia_Pinto2013_PRC88-025207, Ke_Liu2014_PRD89-074041], three-flavor Polyakov-quark-meson model [Mintz_Stiele_Ramos_Schaffner-Bielich2013_PRD87-036004], and Dyson-Schwinger equation approach [Gao_Liu2016_PRD94-094030]

$$\sigma = 5\sim30\ \mathrm{MeV/fm^2}$$

Quasiparticle mode [Wen_Li_Liang_Peng2010_PRC82-025809]

$$\sigma = 30\sim70\ \mathrm{MeV/fm^2}$$

NJL model adopting the MRE method [Lugones_Grunfeld_Ajmi2013_PRC88-045803]

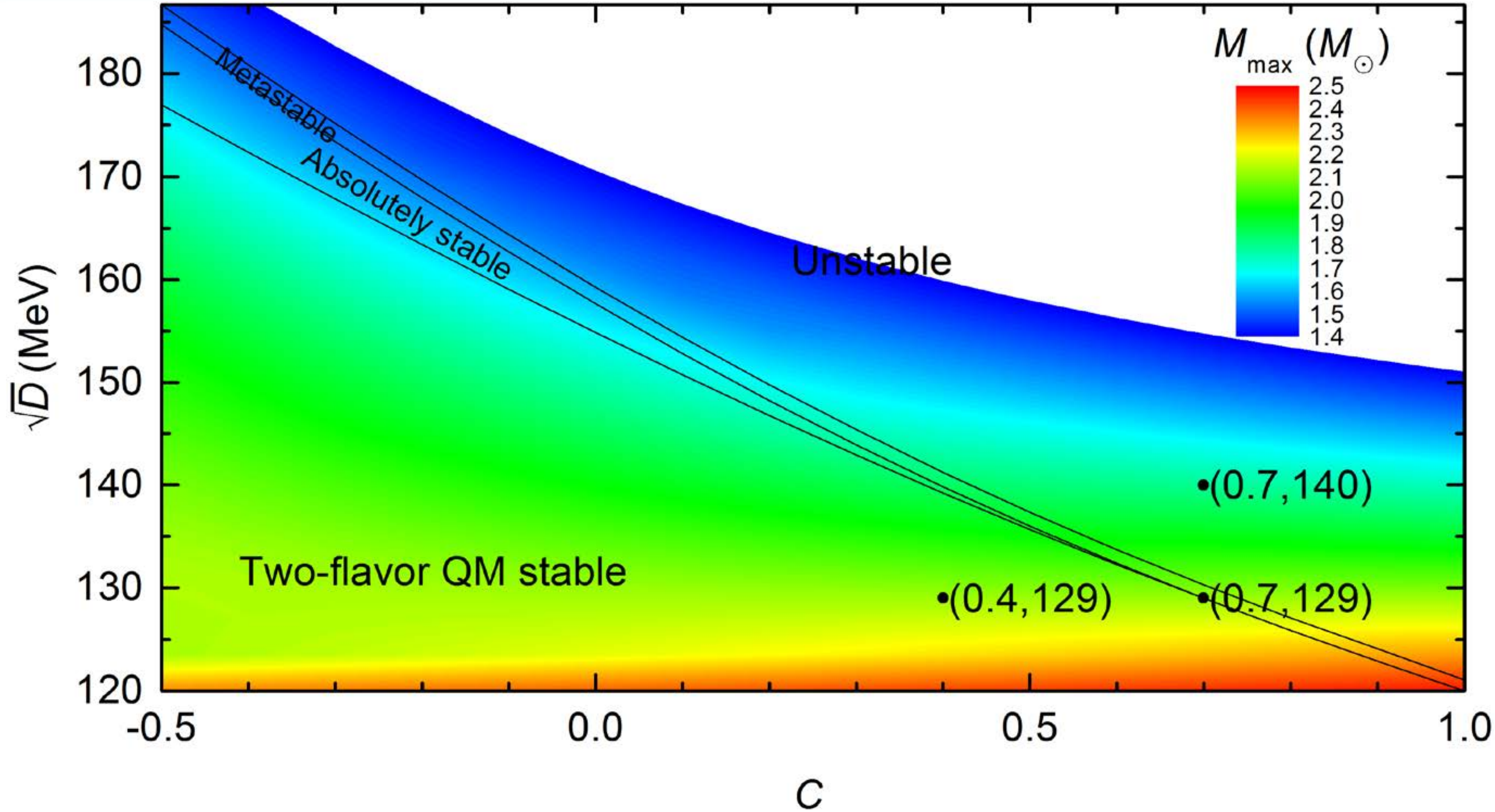
$$\sigma = 145\sim165\ \mathrm{MeV/fm^2}$$

For color-flavor locked SQM, dimensional analysis suggests: [Alford_Rajagopal_Reddy_Wilczek2001_PRD64-074017]

$$\sigma \approx 300\ \mathrm{MeV/fm^2}$$

For magnetized SQM, σ has a different value in the parallel and transverse directions with respect to the magnetic field [Lugones_Grunfeld2017_PRC95-015804]

Equivparticle model



(Wen_Zhong_Peng_Shen_Ning2005_PRC72-015204)

5. The one-gluon-exchange interaction was further included by Chen *et al.*: $m_{\rm I} = \frac{D}{n^{1/3}} - Cn^{1/3}$; (Chen_Gao_Peng2012_CPC36-947)

6. The quark matter symmetry energy was considered by Chu and Chen: $m_{\rm I} = \frac{D}{n^{1/3}} - \tau_i \delta D_I n^{\alpha} e^{-\beta n}$; (Chu_Chen2014_ApJ780-135)

$D \simeq \frac{3(2/\pi) \sigma_0 \rho^*}{-\sum_q \langle q\bar{q} \rangle_0}$

$C = C_1 \sqrt{\frac{2}{3}} \alpha$

$C_{\rm max} = (3\pi^2/N_{\rm f})^{1/3}$

Strangelets in MFA

For spherically symmetric strangelets, the Dirac spinor of quarks is

$$\psi_{n\kappa m}(\boldsymbol{r}) = \frac{1}{r}\begin{pmatrix} iG_{n\kappa}(r) \\ F_{n\kappa}(r)\boldsymbol{\sigma}\cdot\hat{\boldsymbol{r}} \end{pmatrix} Y^{l}_{jm}(\theta,\phi)$$

radial wave functions

spinor spherical harmonics

$$\kappa = (-1)^{j+l+1/2}(j+1/2)$$

Dirac equation

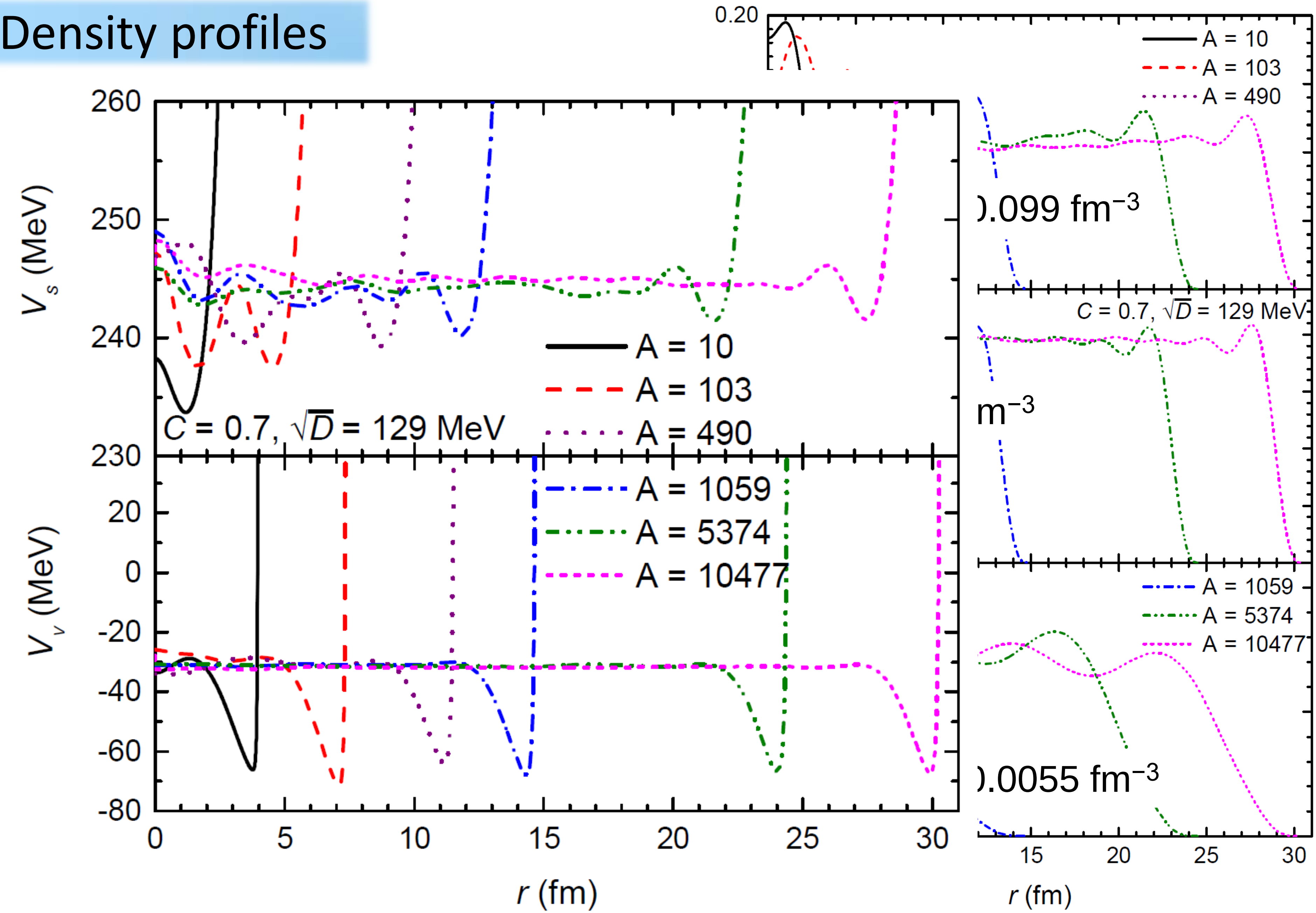
$$\begin{pmatrix} V_i + V_S & -\frac{\mathrm{d}}{\mathrm{d}r} + \frac{\kappa}{r} \\ \frac{\mathrm{d}}{\mathrm{d}r} + \frac{\kappa}{r} & V_i - V_S - 2m_{i0} \end{pmatrix} \begin{pmatrix} G_{n\kappa} \\ F_{n\kappa} \end{pmatrix} = \varepsilon_{n\kappa} \begin{pmatrix} G_{n\kappa} \\ F_{n\kappa} \end{pmatrix}$$

Mean field scalar and vector potentials

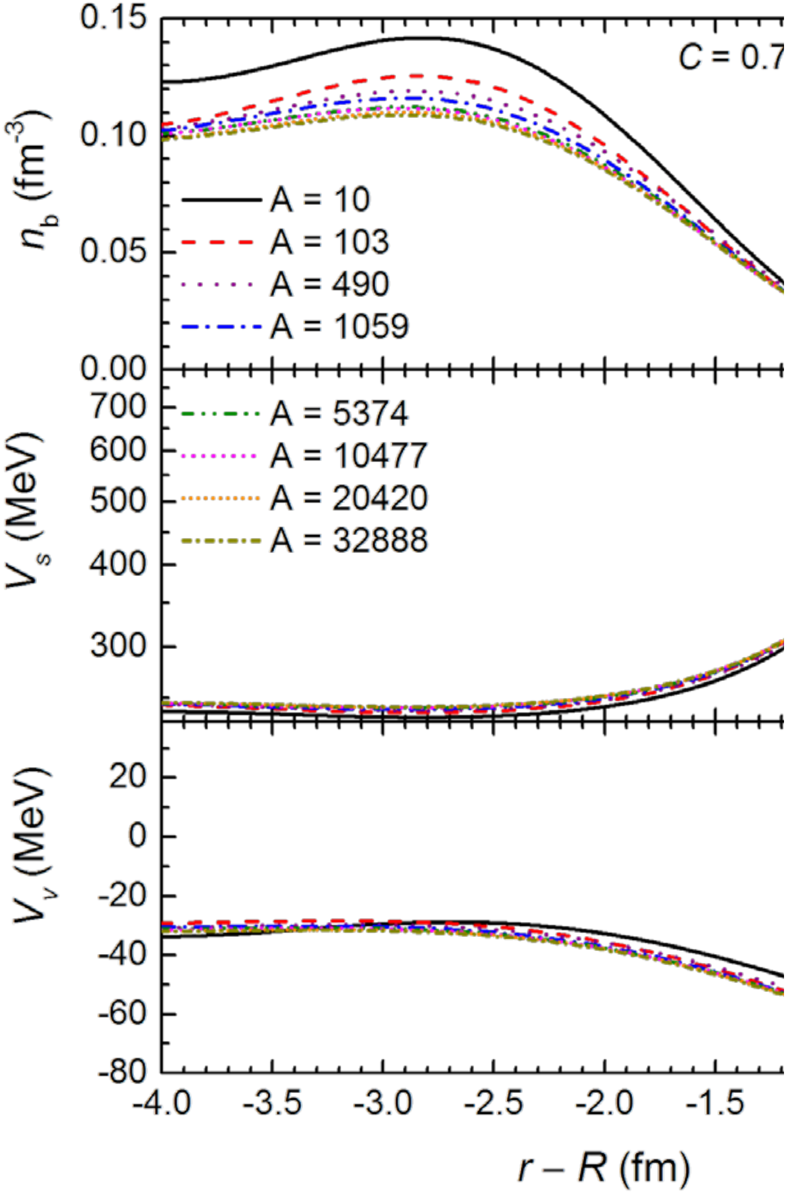
$$V_S = m_{\mathrm{I}}(n_{\mathrm{b}}),$$

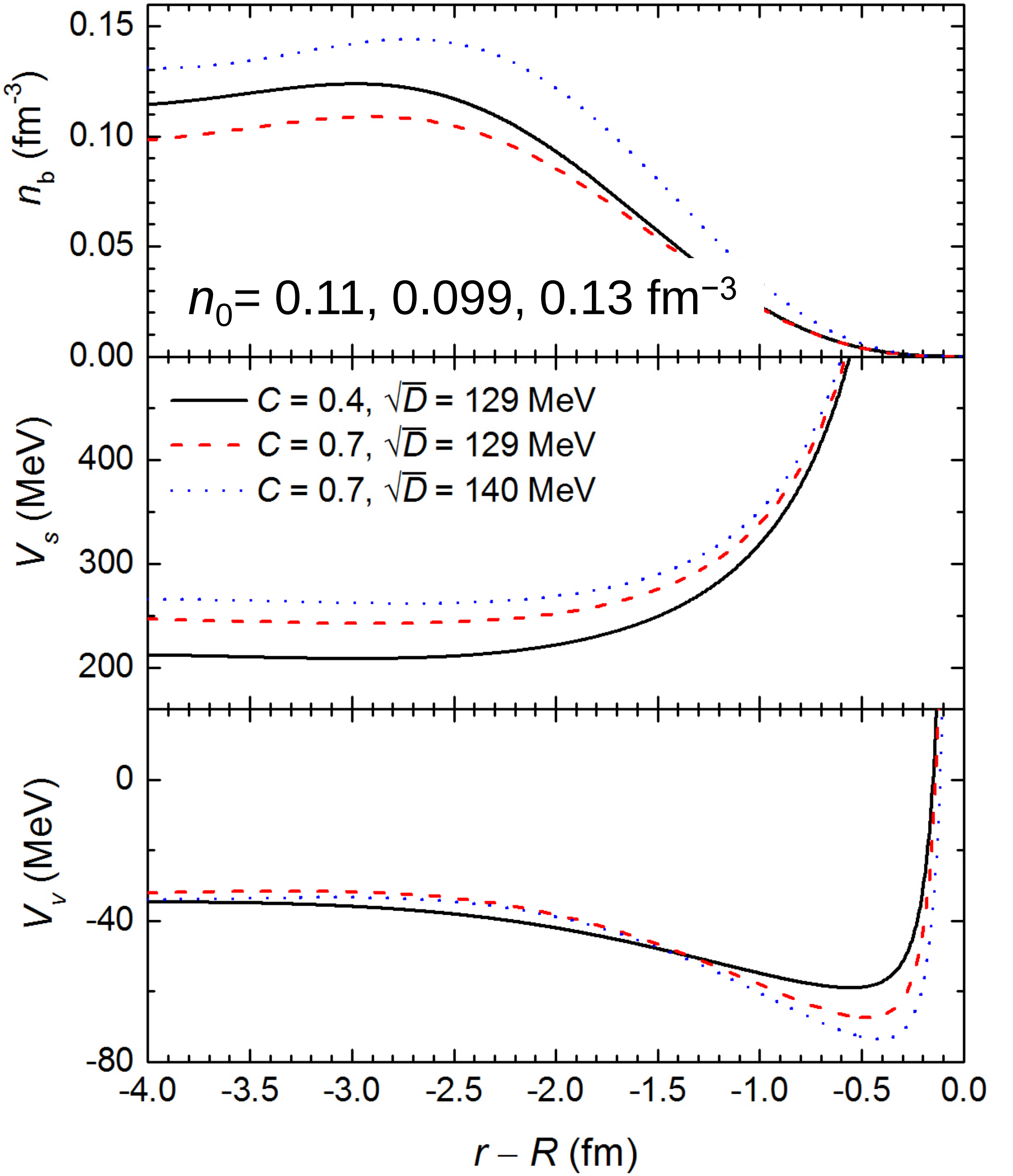
$$V_i = \frac{1}{3}\frac{\mathrm{d}m_{\mathrm{I}}}{\mathrm{d}n_{\mathrm{b}}}\sum_{i=u,d,s} n_i^{\mathrm{s}} + eq_i A_0.$$

Density profiles

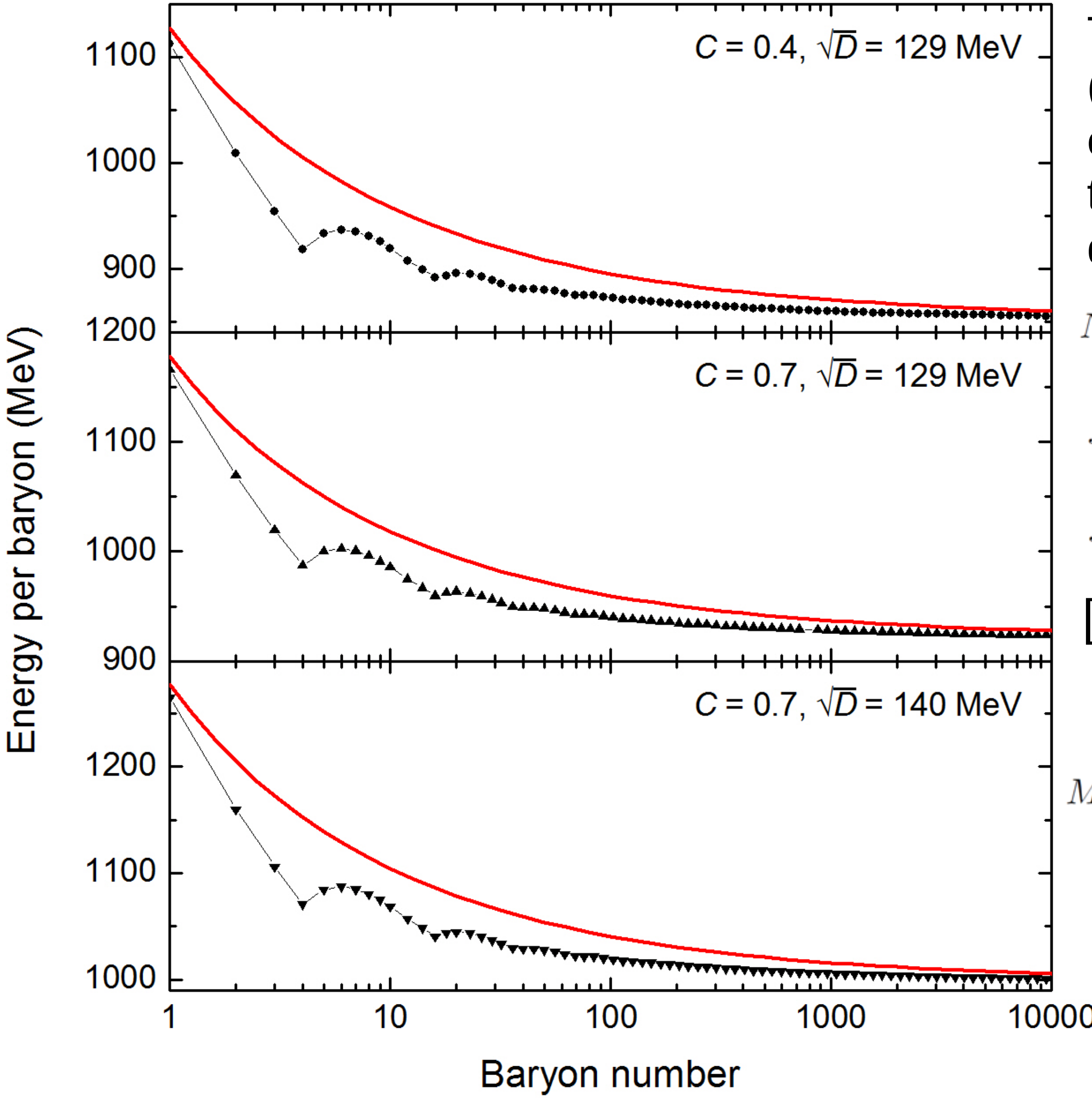


Surface structures





Energy per baryon



The multiple reflection expansion (MRE) method: The average effects due to quark depletion are treated with a modification to the density of states, i.e.,

$$N_i'(p) = 6\left[\frac{p^2 v}{2\pi^2} + f_s\left(\frac{p}{m_i}\right) ps + f_c\left(\frac{p}{m_i}\right) c\right],$$

$$f_s(x) = -\frac{\eta_s}{4\pi^2}\arctan\left(\frac{1}{x}\right),$$

$$f_c(x) = \frac{\eta_c}{12\pi^2}\left[1 - \frac{3}{2}x\arctan\left(\frac{1}{x}\right)\right].$$

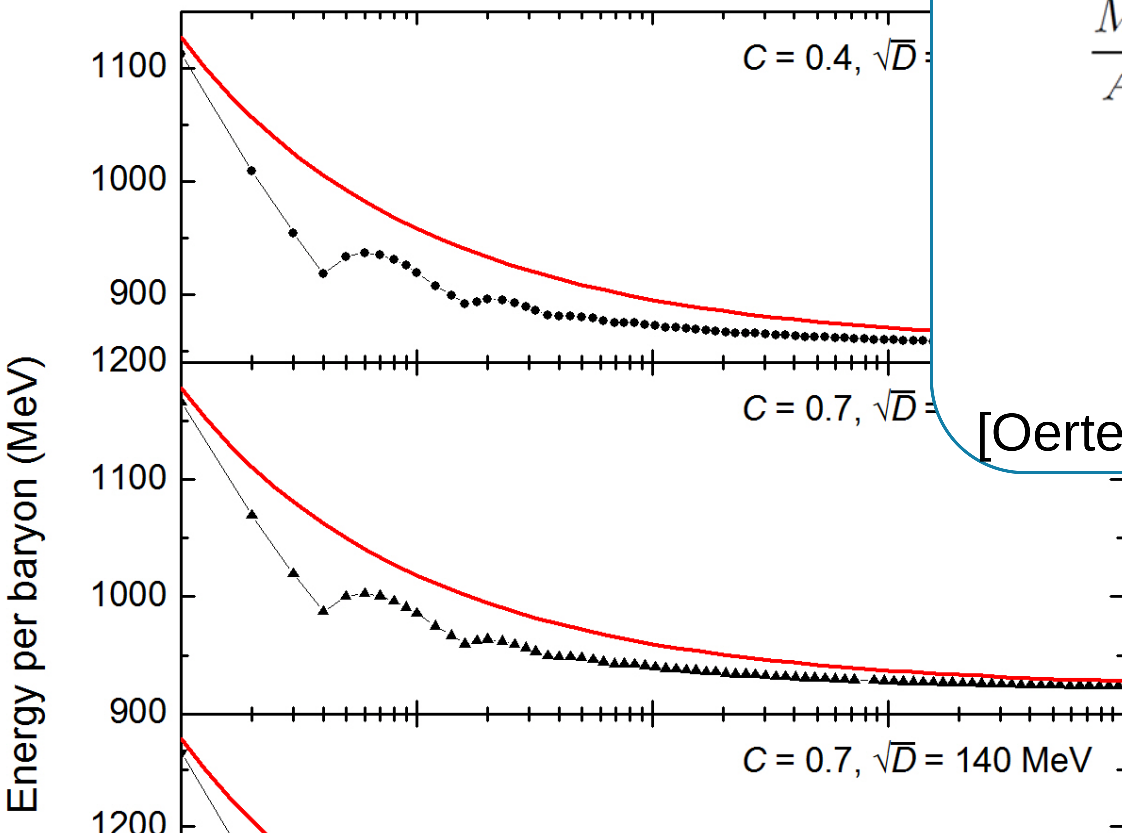
[Madsen1994_PRD50-3328, ...]

$$N_i = \int_0^{\nu_i} N_i'(p)\mathrm{d}p$$

$$M = \sum_{i=u,d,s}\int_0^{\nu_i}\sqrt{p^2 + m_i(n_\mathrm{b})^2}N_i'(p)\mathrm{d}p + M_\mathrm{ch}$$

Red solid: $\eta_s = 1$, $\eta_c = 1$.

Energy per baryon



Liquid-drop type formula:

$$\frac{M}{A} = \frac{E_0}{n_0} + \frac{\alpha_S}{A^{1/3}} + \frac{\alpha_C}{A^{2/3}}$$

$$\sigma = \alpha_S \left(\frac{n_0^2}{36\pi}\right)^{1/3},$$

$$\lambda = \alpha_C \left(\frac{n_0}{384\pi^2}\right)^{1/3}.$$

[Oertel_Urban2008_PRD77-074015]

$$f_c(x) = \frac{\eta_c}{12\pi^2}\left[1 - \frac{3}{2}x \arctan\left(\frac{1}{x}\right)\right].$$

[Madsen1994_PRD50-3328, ...]

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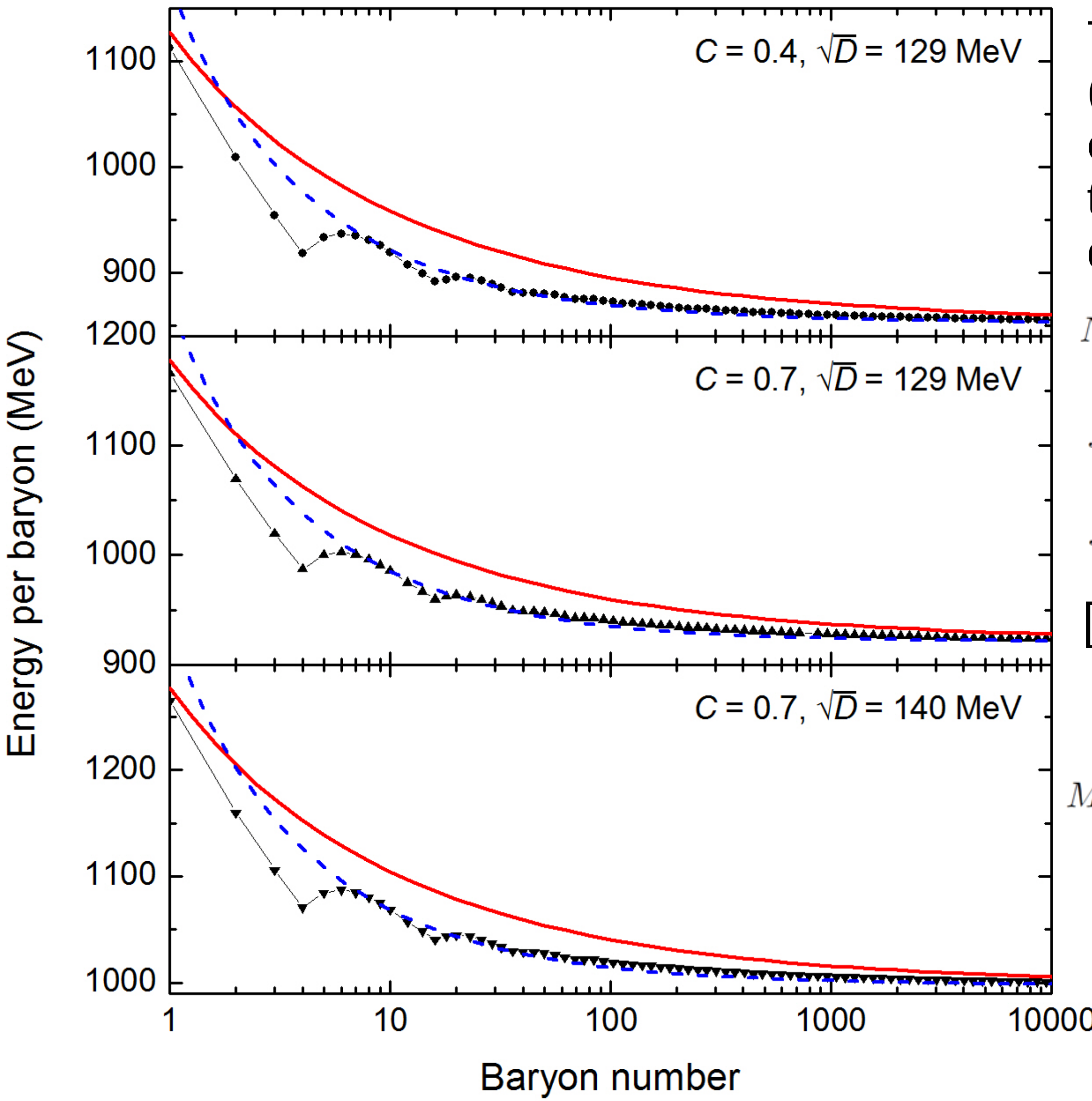
Parameters		Bulk properties			MFA				MRE method				
C	$\sqrt{D}$ MeV	n_0 fm^{-3}	E_0/n_0 MeV	f_S	α_S MeV	α_C MeV	σ MeV/fm^2	λ MeV/fm	α_S MeV	α_C MeV	σ MeV/fm^2	λ MeV/fm	$\sigma^{\mathrm{MFA}}/\sigma^{\mathrm{MRE}}$
0.4	129	0.11	850.91	0.20	56	177	2.7	5.49	190.5	86.1	9.247	2.67	0.29
0.7	129	0.099	918.94	0.056	54	172	2.4	5.12	173.5	85.7	7.681	2.54	0.31
0.7	140	0.13	995.77	0.14	61	185	3.3	6.03	191.1	90.9	10.18	2.96	0.32

Energy per baryon



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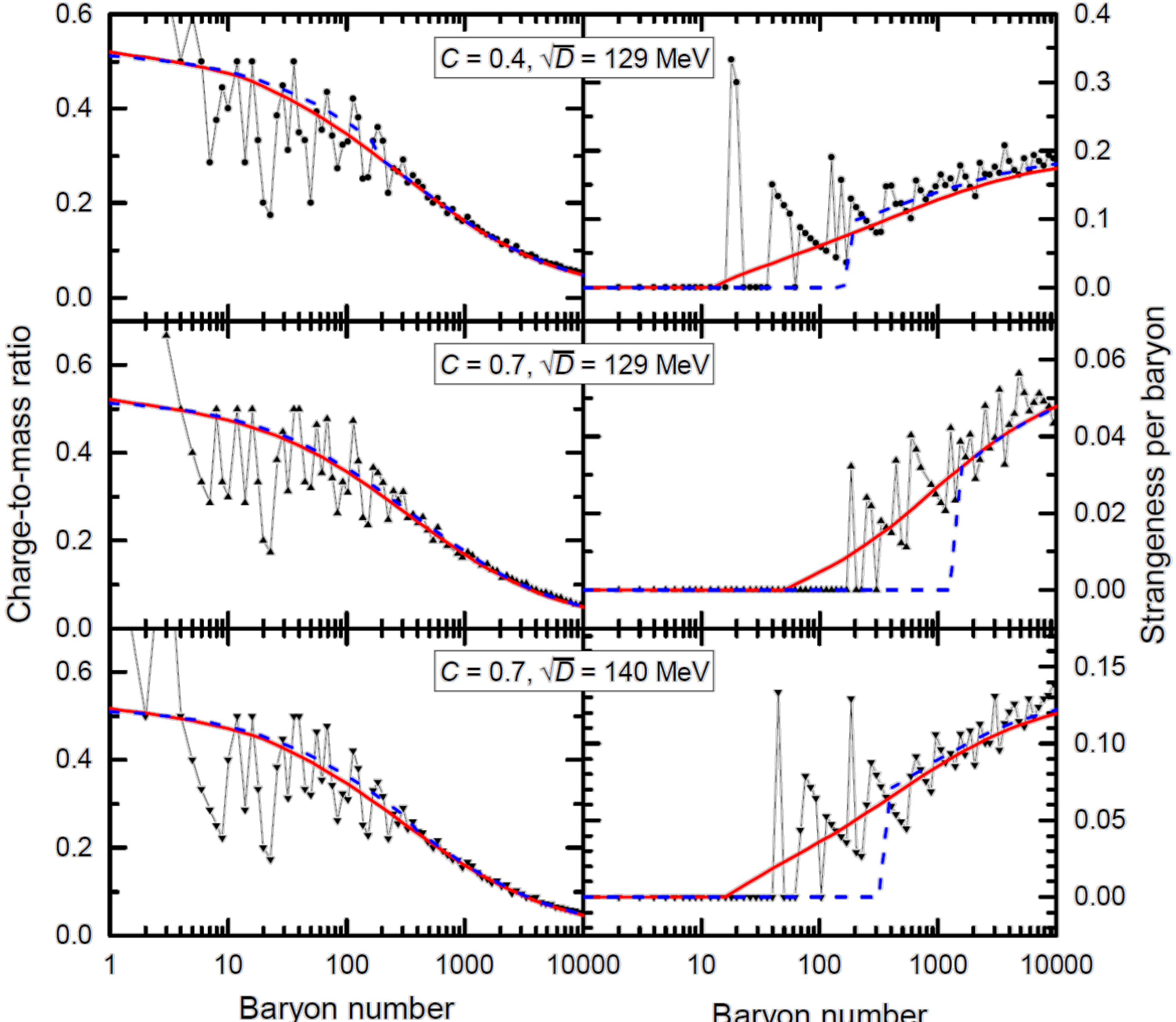
$$M = \sum_{i=u,d,s}\int_0^{\nu_i}\sqrt{p^2 + m_i(n_\mathrm{b})^2}N_i'(p)\mathrm{d}p + M_{\mathrm{ch}}$$

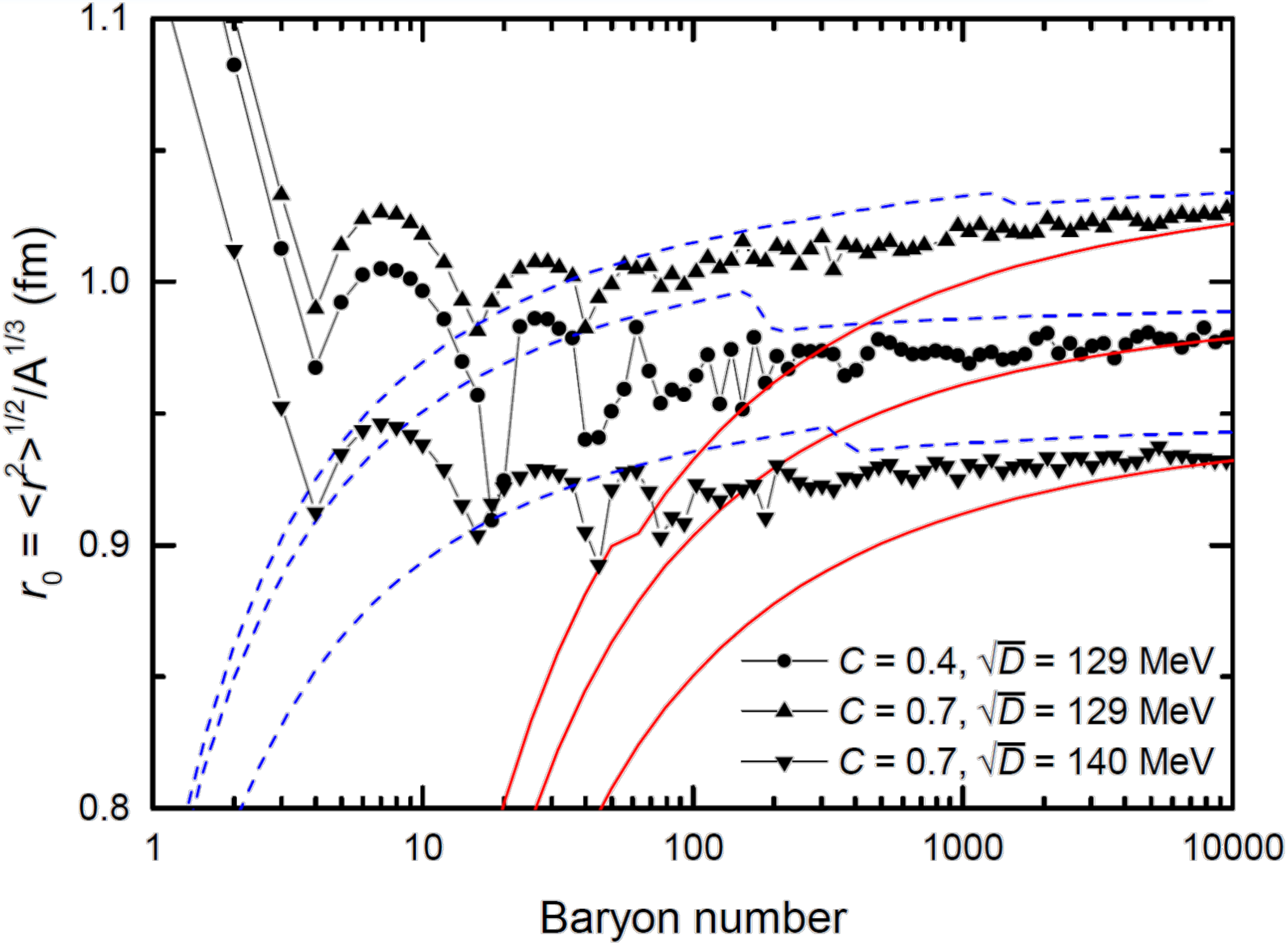
Red solid: $\eta_s = 1$, $\eta_c = 1$.

Blue dashed: $\eta_s = 0.3$, $\eta_c = 0.1$.

Charge-to-mass ratio and Strangeness per baryon



Ratio of root-mean-square radius to baryon number



Summary

Based on an equivparticle model, we study the interface effects in strangelets adopting mean-field approximation (MFA). It is found that

① the surface tension and curvature term of strange quark matter (SQM) become larger for larger confinement strength and smaller perturbative strength;

② if SQM is absolutely stable and a strange star can reach 2 solar mass, the surface tension is ~2.4 MeV/fm^2;

③ the MRE method overestimates the surface tension and underestimates the curvature term, which can be fixed be introducing proper damping factors; . . .

Thank you!!!

The single-particle levels for u-quarks