Are giant nuclei in supernova matter stable with respect to deconfinement?

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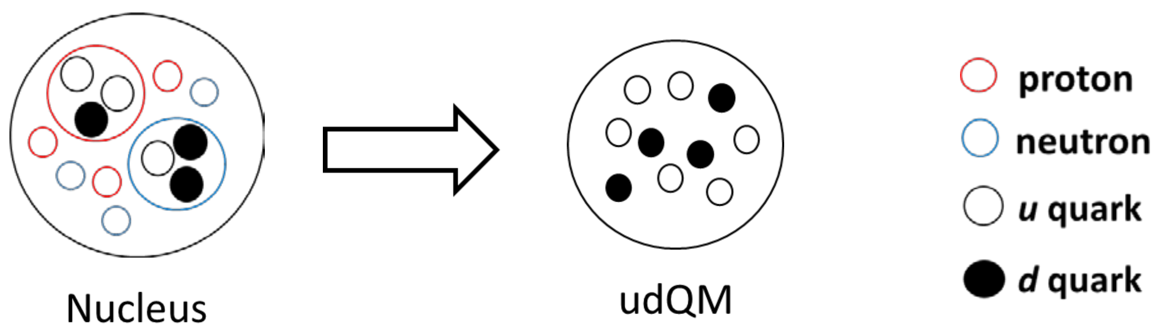
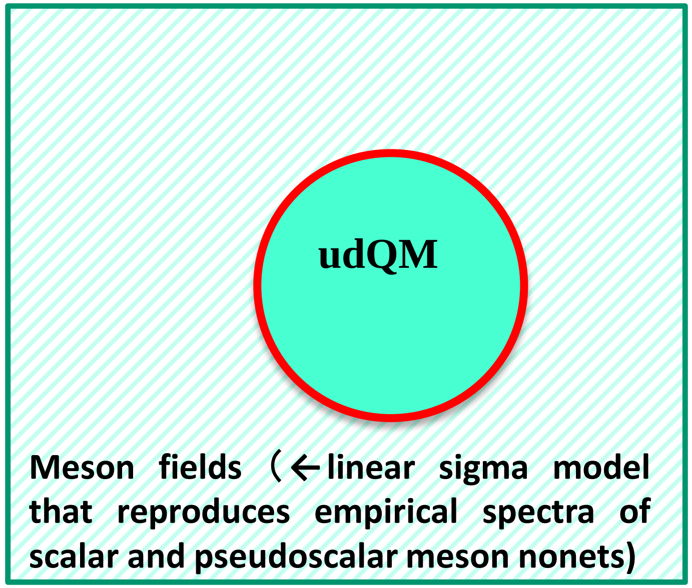
We consider whether or not nuclei in supernova cores with mass number far exceeding superheavy nuclei are stable against two-flavor quark matter.



From a nucleus to udQM via deconfinement

Stability of ud quark matter(udQM)



ud quark matter is predicted to be more stable than uds quark matter!

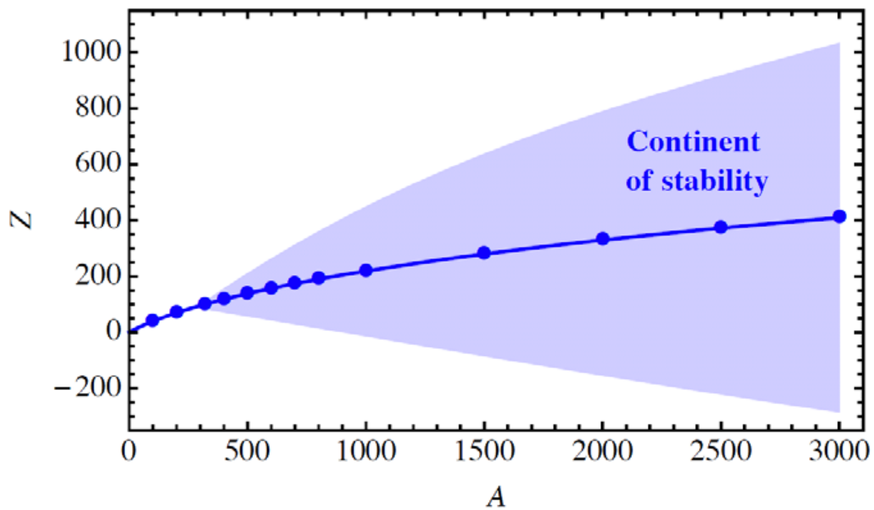


FIG. 3: The electric charge of *ud*QM: full result (blue dots) and the bulk approximation (blue line).

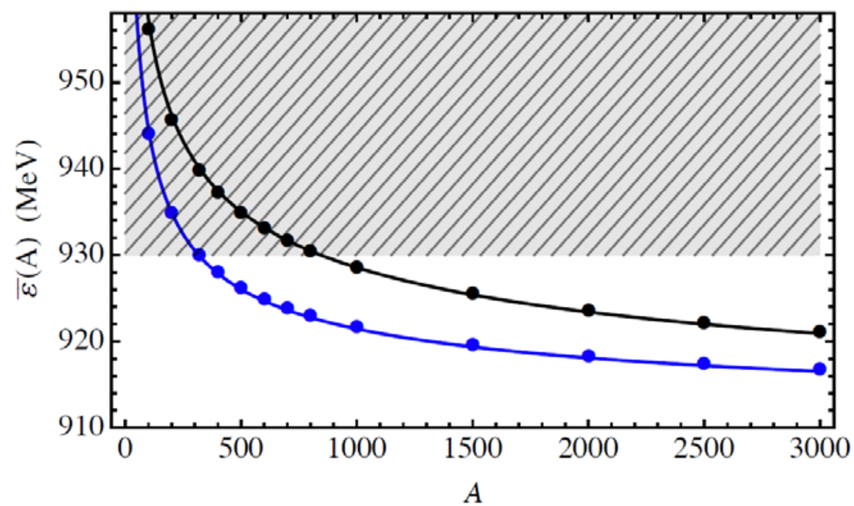


FIG. 4: The minimal energy per baryon $\bar{\varepsilon}(A)$ for *ud*QM (lower), compared to the charge neutral configuration (upper).

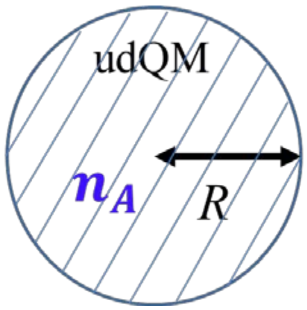
Ref. Holdom, Ren, & Zhang, PRL **120** (2018) 222001.

Mass formula

A typical udQM mass formula (per baryon) [1]:

$$\varepsilon_0(A,Z) = 3\bar{p}_F \frac{n_u^{4/3} + n_d^{4/3}}{(3n_A)^{4/3}} + \frac{4\pi\Sigma R^2}{A} + \frac{3Z^2e^2}{5AR}$$

Bulk Surface Coulomb



Averaged Fermi momentum:

$\bar{p}_F = (3\pi^2 n_A)^{1/3}$

Baryon density:

$n_A = \frac{1}{3}(n_u + n_d) = 0.23\ \mathrm{fm}^{-3}$

Surface tension:

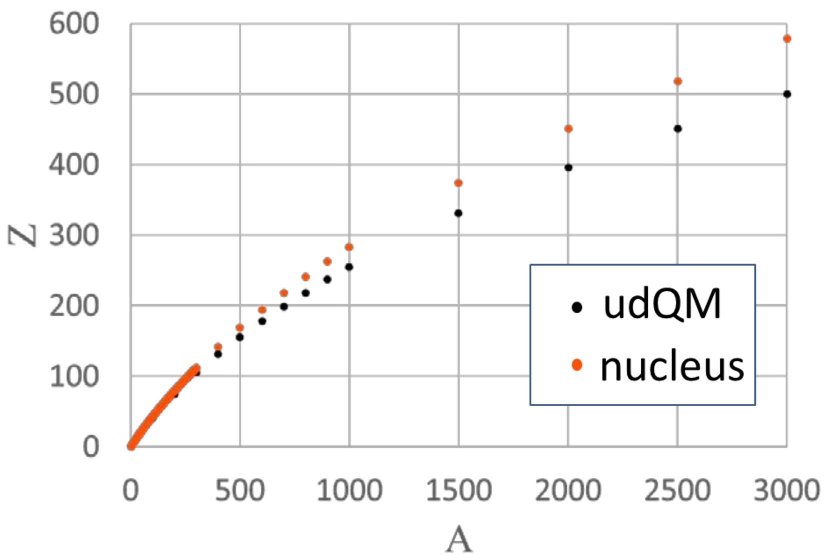
$\Sigma = 19.4\ \mathrm{MeV}\cdot\mathrm{fm}^{-2}$

Weizsäcker-Bethe (WB) mass formula:

$$E_0 = NM_n + ZM_p - a_v A + a_s A^{2/3}\left[1 - b_s\left(1 - \frac{2Z}{A}\right)^2\right] + a_I\left(1 - \frac{2Z}{A}\right)^2 A + a_c\frac{Z^2}{A^{1/3}}$$

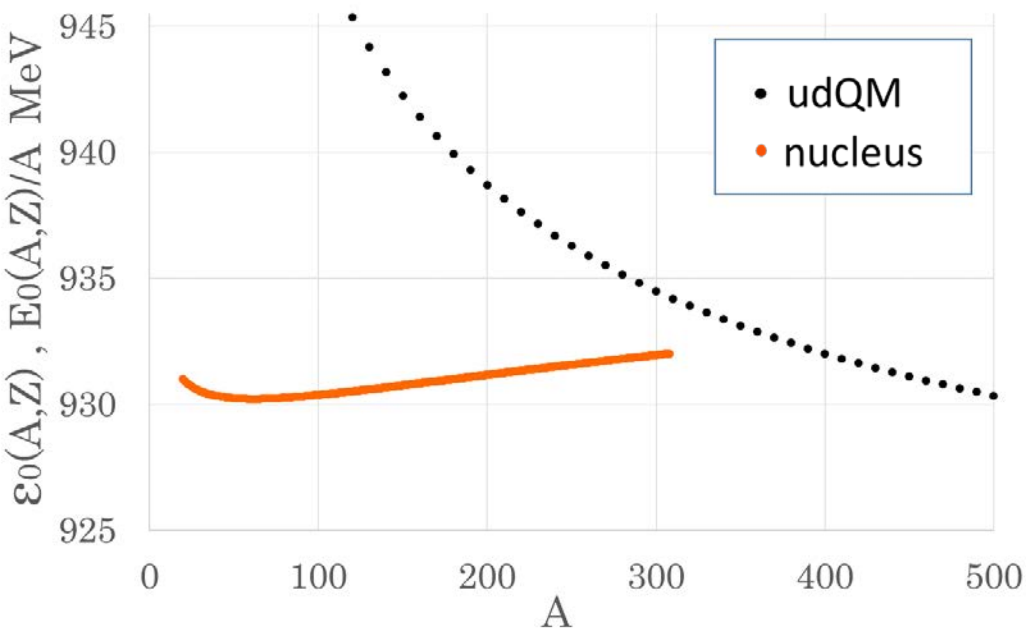
[1] B. Holdom, J. Ren, and C. Zhang, PRL 120, 222001 (2018).

β stability line and mass in vacuum



β stability line

Both lines are close to each other.
This is because the symmetry energy coefficient is of the same order.



Mass on the β stability line

Nuclei are more stable than udQM up to a superheavy regime.

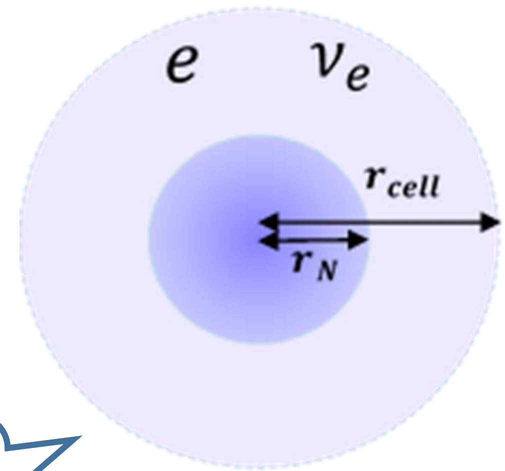
udQM is possibly more stable for even larger mass as encountered in supernova cores, thanks to the large surface tension.

In supernova matter

In the Wigner-Seitz approximation:

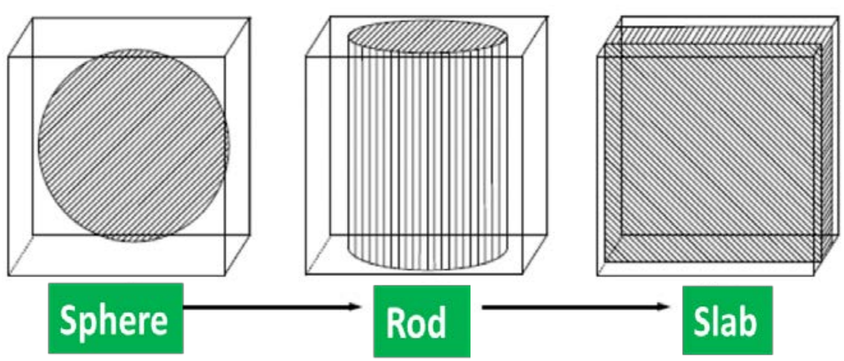
Coulomb term in the WB formula modified by electrons by a factor of

$$f(u) = 1 - \frac{3}{2}u^{1/3} + \frac{1}{2}u$$



A sphere in which a nucleus is embedded in a uniform neutralizing background of electrons.

Wigner-Seitz cell [2]



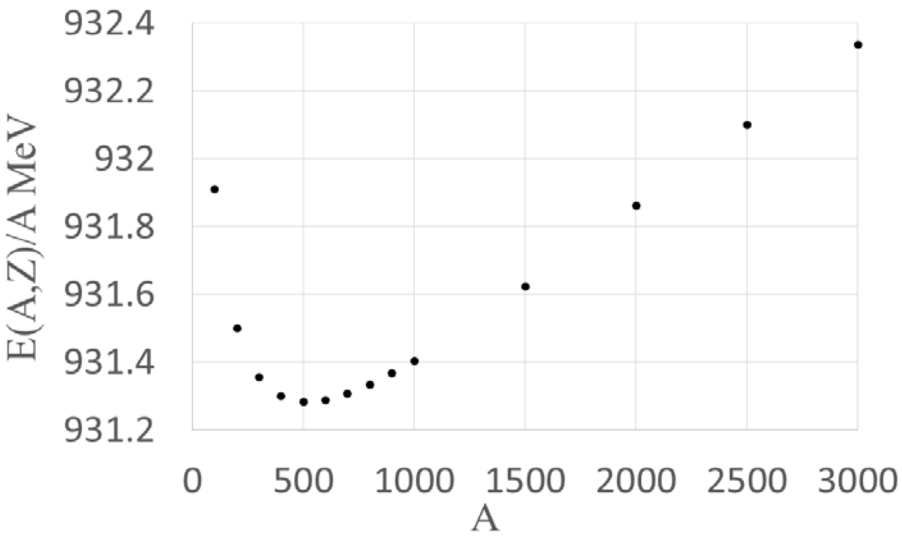
Changes in nuclear shape

Volume fraction: $u = \left(\frac{r_N}{r_{\text{cell}}}\right)^3$

Shape of nuclei in supernova matter changes from sphere to rod around $\boldsymbol{u = 0.2}$.

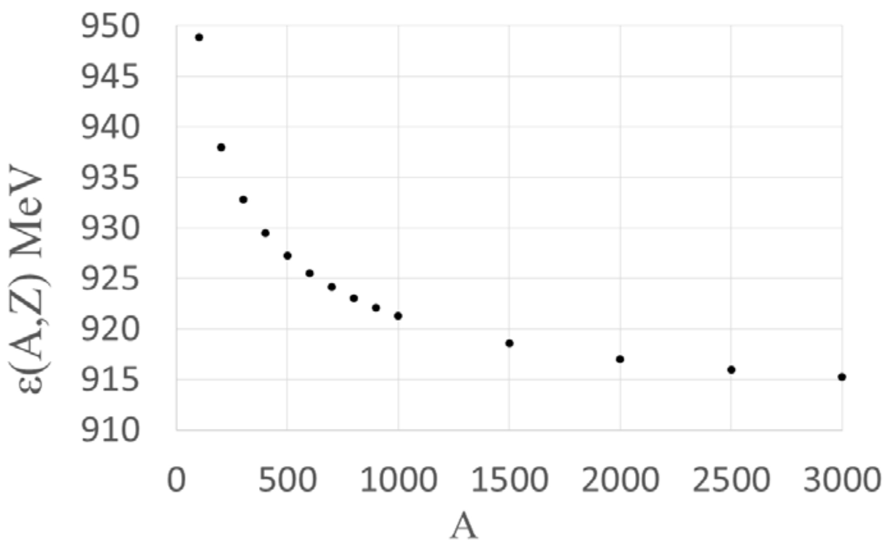
[2] Y. Naito, bachelor thesis (Kochi University, 2008).

In supernova matter



Nuclear mass

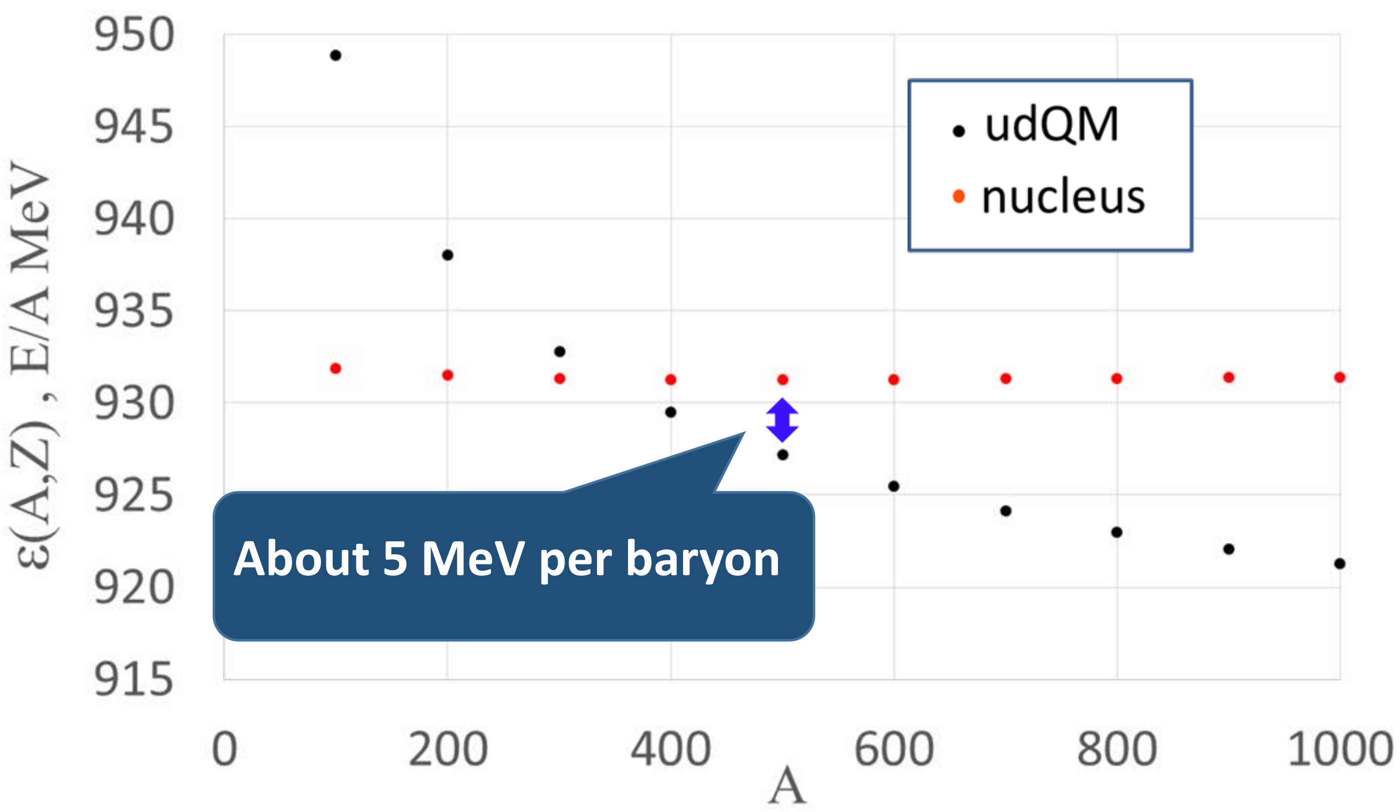
Most stable around $A \sim 500$
(minimum E/A = 931.28 MeV)



Deconfined udQM mass

Energy per baryon of udQM of the same *A* and *Z* in supernova matter; the Coulomb term is modified by electrons of the same density.

Comparison of nuclear mass and deconfined udQM mass



Astrophysical implications

- As a result of deleptonization and cooling, the neutron star might have a crust of which the deepest region is composed of udQM.
- Electron screening might play a role in determining the optimal *A* of the nucleus and udQM in supernova matter.
- We will reconstruct the mass formulas by including the effect of electron screening.