Quark Nuggets

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Working in progress + 2306.17160

What is a quark nugget?

PHYSICAL REVIEW D VOLUME 4, NUMBER 6 15 SEPTEMBER 1971

Collapsed Nuclei*

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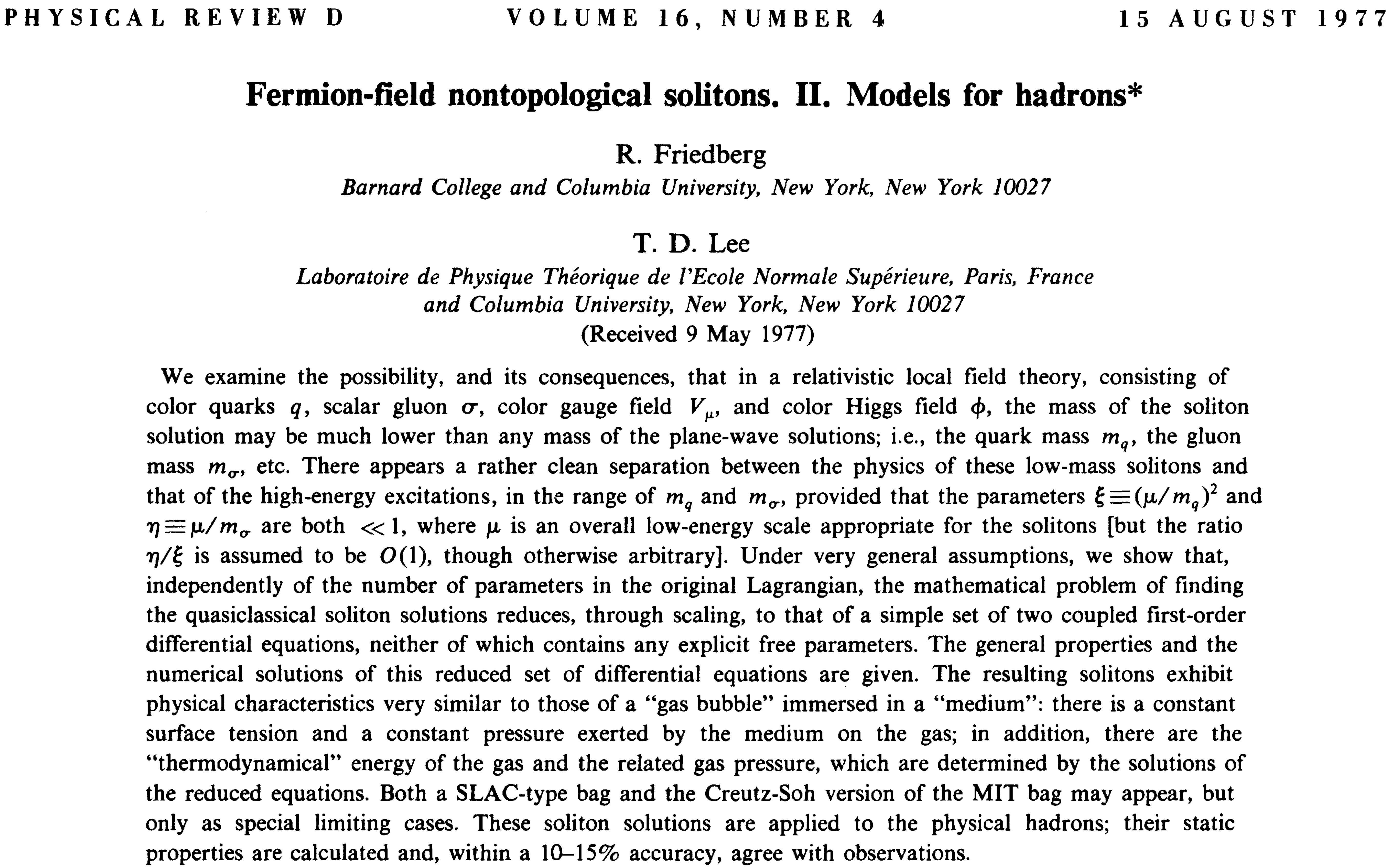
(Received 29 March 1971)

We discuss the observational consistency, possible properties, and detection of collapsed nuclei C_A. These may be considered as elementary particles with mass number $A>1$ and of much smaller radius than ordinary nuclei N_A. The existence of C_A of (perhaps much) lower energy than N_A is observationally consistent if N_A are very long-lived isomers against collapse because of a "saturation" barrier between C_A and N_A. Barrier-penetrability estimates show that sufficiently long lifetimes $\gtrsim 10^{31}$ sec are plausible for $A \gtrsim 16-40$. The properties of C_A are discussed using composite baryon and quark models; small charges and hypercharges and, especially, neutral C_A are possible. C_A can be effectively a source or sink of baryons. Some astrophysical implications are briefly discussed, in particular the possible large scale presence of C_A and the possibility that accelerated collapse in massive objects may be a source of energy comparable to the rest mass.



PHYSICAL REVIEW D VOLUME 16, NUMBER 4 15 AUGUST 1977

Fermion-field nontopological solitons. II. Models for hadrons*

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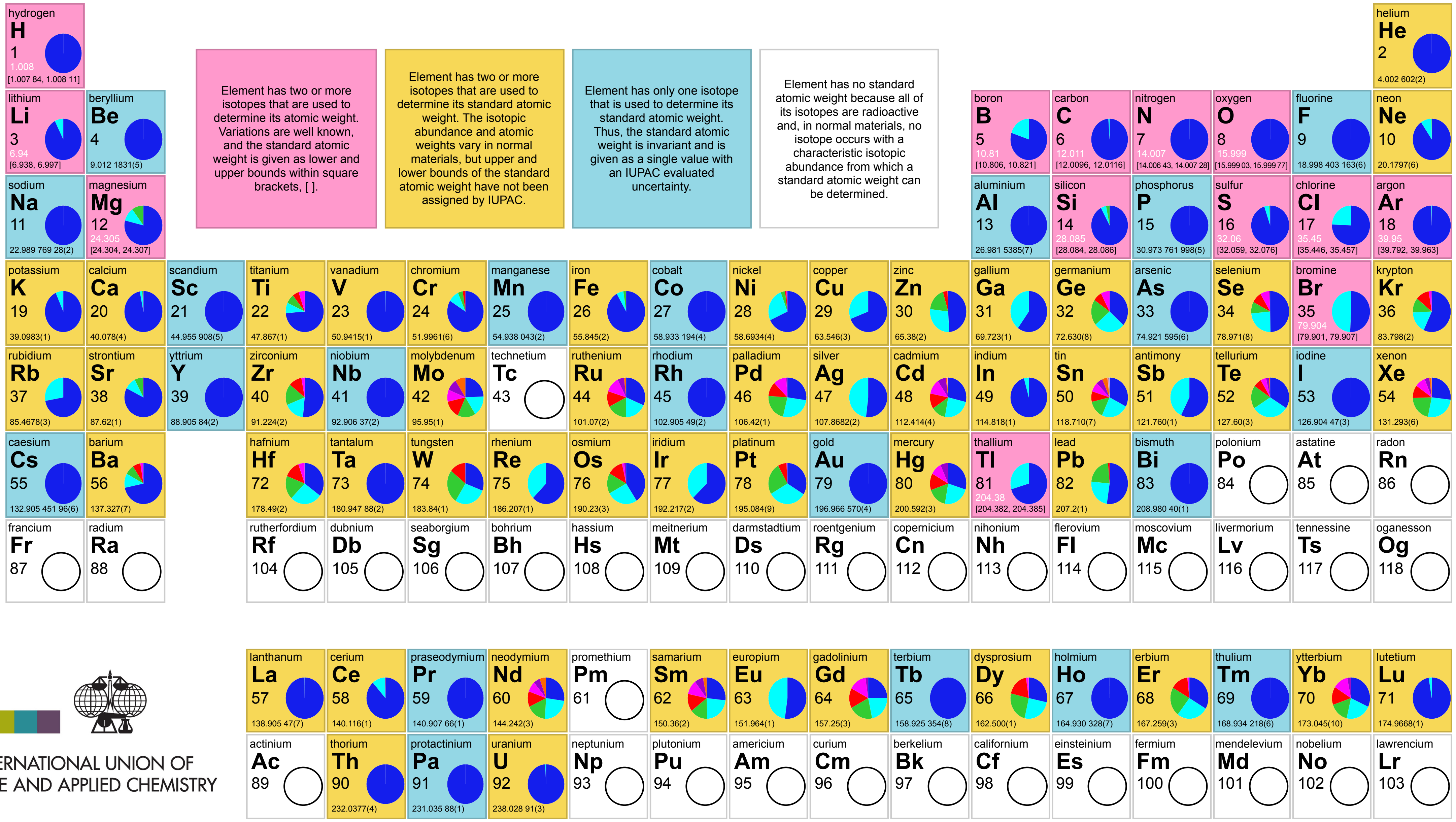
(Received 9 May 1977)

We examine the possibility, and its consequences, that in a relativistic local field theory, consisting of color quarks q, scalar gluon σ, color gauge field V_μ, and color Higgs field ϕ, the mass of the soliton solution may be much lower than any mass of the plane-wave solutions; i.e., the quark mass m_q, the gluon mass m_σ, etc. There appears a rather clean separation between the physics of these low-mass solitons and that of the high-energy excitations, in the range of m_q and m_σ, provided that the parameters $\xi \equiv (\mu/m_q)^2$ and $\eta \equiv \mu/m_\sigma$ are both $\ll 1$, where μ is an overall low-energy scale appropriate for the solitons [but the ratio η/ξ is assumed to be $O(1)$, though otherwise arbitrary]. Under very general assumptions, we show that, independently of the number of parameters in the original Lagrangian, the mathematical problem of finding the quasiclassical soliton solutions reduces, through scaling, to that of a simple set of two coupled first-order differential equations, neither of which contains any explicit free parameters. The general properties and the numerical solutions of this reduced set of differential equations are given. The resulting solitons exhibit physical characteristics very similar to those of a "gas bubble" immersed in a "medium": there is a constant surface tension and a constant pressure exerted by the medium on the gas; in addition, there are the "thermodynamical" energy of the gas and the related gas pressure, which are determined by the solutions of the reduced equations. Both a SLAC-type bag and the Creutz-Soh version of the MIT bag may appear, but only as special limiting cases. These soliton solutions are applied to the physical hadrons; their static properties are calculated and, within a 10–15% accuracy, agree with observations.

IUPAC Periodic Table of the Elements and Isotopes



Element has two or more isotopes that are used to determine its atomic weight. Variations are well known, and the standard atomic weight is given as lower and upper bounds within square brackets, [ ].

Element has two or more isotopes that are used to determine its standard atomic weight. The isotopic abundance and atomic weights vary in normal materials, but upper and lower bounds of the standard atomic weight have not been assigned by IUPAC.

Element has only one isotope that is used to determine its standard atomic weight. Thus, the standard atomic weight is invariant and is given as a single value with an IUPAC evaluated uncertainty.

Element has no standard atomic weight because all of its isotopes are radioactive and, in normal materials, no isotope occurs with a characteristic isotopic abundance from which a standard atomic weight can be determined.

hydrogen **H** 1 1.008 [1.007 84, 1.008 11]																	helium **He** 2 4.002 602(2)
lithium **Li** 3 6.94 [6.938, 6.997]	beryllium **Be** 4 9.012 1831(5)											boron **B** 5 10.81 [10.806, 10.821]	carbon **C** 6 12.011 [12.0096, 12.0116]	nitrogen **N** 7 14.007 [14.006 43, 14.007 28]	oxygen **O** 8 15.999 [15.999 03, 15.999 77]	fluorine **F** 9 18.998 403 163(6)	neon **Ne** 10 20.1797(6)
sodium **Na** 11 22.989 769 28(2)	magnesium **Mg** 12 24.305 [24.304, 24.307]											aluminium **Al** 13 26.981 5385(7)	silicon **Si** 14 28.085 [28.084, 28.086]	phosphorus **P** 15 30.973 761 998(5)	sulfur **S** 16 32.06 [32.059, 32.076]	chlorine **Cl** 17 35.45 [35.446, 35.457]	argon **Ar** 18 39.95 [39.792, 39.963]
potassium **K** 19 39.0983(1)	calcium **Ca** 20 40.078(4)	scandium **Sc** 21 44.955 908(5)	titanium **Ti** 22 47.867(1)	vanadium **V** 23 50.9415(1)	chromium **Cr** 24 51.9961(6)	manganese **Mn** 25 54.938 043(2)	iron **Fe** 26 55.845(2)	cobalt **Co** 27 58.933 194(4)	nickel **Ni** 28 58.6934(4)	copper **Cu** 29 63.546(3)	zinc **Zn** 30 65.38(2)	gallium **Ga** 31 69.723(1)	germanium **Ge** 32 72.630(8)	arsenic **As** 33 74.921 595(6)	selenium **Se** 34 78.971(8)	bromine **Br** 35 79.904 [79.901, 79.907]	krypton **Kr** 36 83.798(2)
rubidium **Rb** 37 85.4678(3)	strontium **Sr** 38 87.62(1)	yttrium **Y** 39 88.905 84(2)	zirconium **Zr** 40 91.224(2)	niobium **Nb** 41 92.906 37(2)	molybdenum **Mo** 42 95.95(1)	technetium **Tc** 43	ruthenium **Ru** 44 101.07(2)	rhodium **Rh** 45 102.905 49(2)	palladium **Pd** 46 106.42(1)	silver **Ag** 47 107.8682(2)	cadmium **Cd** 48 112.414(4)	indium **In** 49 114.818(1)	tin **Sn** 50 118.710(7)	antimony **Sb** 51 121.760(1)	tellurium **Te** 52 127.60(3)	iodine **I** 53 126.904 47(3)	xenon **Xe** 54 131.293(6)
caesium **Cs** 55 132.905 451 96(6)	barium **Ba** 56 137.327(7)		hafnium **Hf** 72 178.49(2)	tantalum **Ta** 73 180.947 88(2)	tungsten **W** 74 183.84(1)	rhenium **Re** 75 186.207(1)	osmium **Os** 76 190.23(3)	iridium **Ir** 77 192.217(2)	platinum **Pt** 78 195.084(9)	gold **Au** 79 196.966 570(4)	mercury **Hg** 80 200.592(3)	thallium **Tl** 81 204.38 [204.382, 204.385]	lead **Pb** 82 207.2(1)	bismuth **Bi** 83 208.980 40(1)	polonium **Po** 84	astatine **At** 85	radon **Rn** 86
francium **Fr** 87	radium **Ra** 88		rutherfordium **Rf** 104	dubnium **Db** 105	seaborgium **Sg** 106	bohrium **Bh** 107	hassium **Hs** 108	meitnerium **Mt** 109	darmstadtium **Ds** 110	roentgenium **Rg** 111	copernicium **Cn** 112	nihonium **Nh** 113	flerovium **Fl** 114	moscovium **Mc** 115	livermorium **Lv** 116	tennessine **Ts** 117	oganesson **Og** 118
			lanthanum **La** 57 138.905 47(7)	cerium **Ce** 58 140.116(1)	praseodymium **Pr** 59 140.907 66(1)	neodymium **Nd** 60 144.242(3)	promethium **Pm** 61	samarium **Sm** 62 150.36(2)	europium **Eu** 63 151.964(1)	gadolinium **Gd** 64 157.25(3)	terbium **Tb** 65 158.925 354(8)	dysprosium **Dy** 66 162.500(1)	holmium **Ho** 67 164.930 328(7)	erbium **Er** 68 167.259(3)	thulium **Tm** 69 168.934 218(6)	ytterbium **Yb** 70 173.045(10)	lutetium **Lu** 71 174.9668(1)
			actinium **Ac** 89	thorium **Th** 90 232.0377(4)	protactinium **Pa** 91 231.035 88(1)	uranium **U** 92 238.028 91(3)	neptunium **Np** 93	plutonium **Pu** 94	americium **Am** 95	curium **Cm** 96	berkelium **Bk** 97	californium **Cf** 98	einsteinium **Es** 99	fermium **Fm** 100	mendelevium **Md** 101	nobelium **No** 102	lawrencium **Lr** 103

INTERNATIONAL UNION OF
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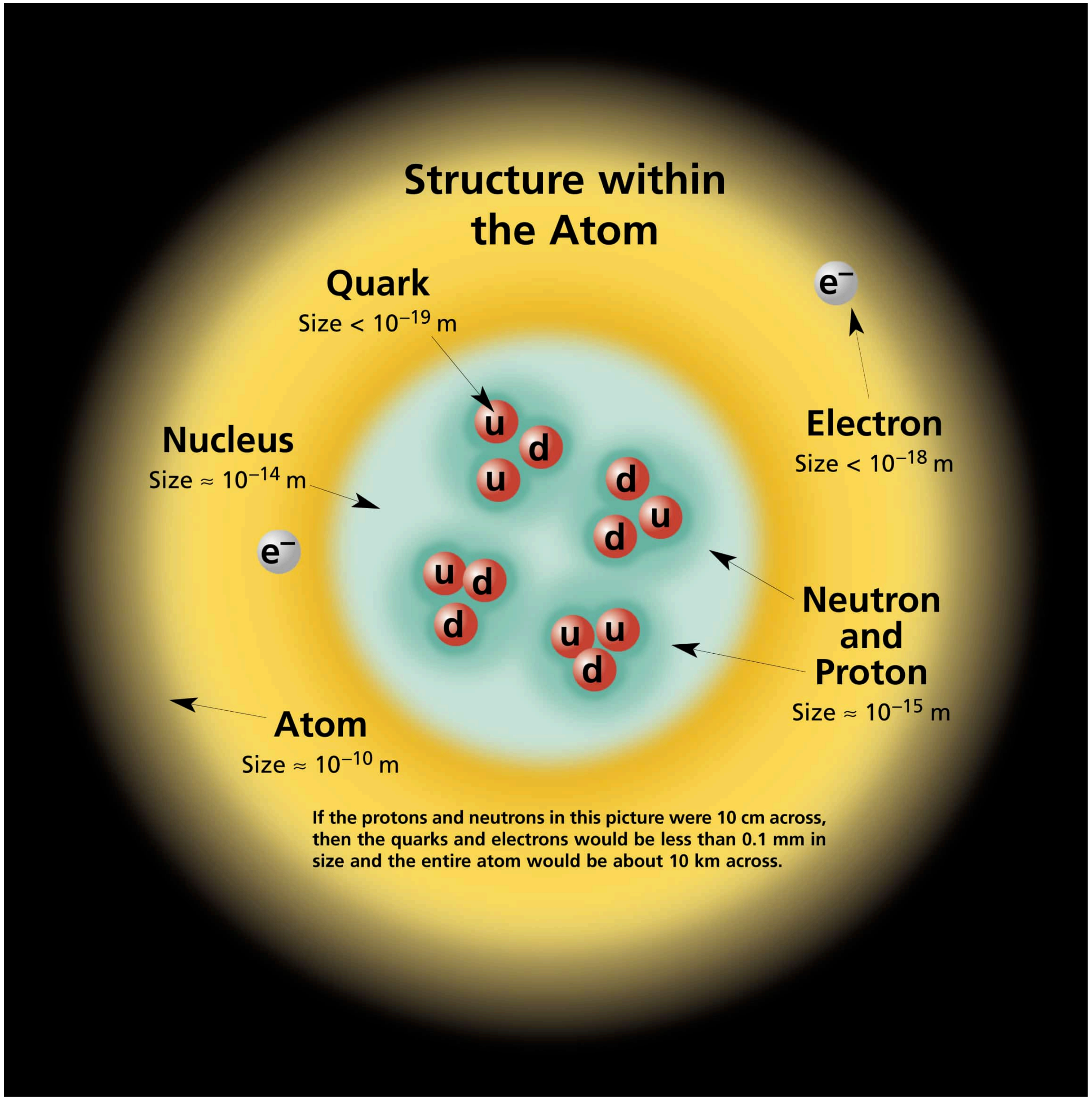
Standard atomic weights are the best estimates by IUPAC of atomic weights that are found in normal materials, which are terrestrial materials that are reasonably possible sources for elements and their compounds in commerce, industry, or science. They are determined using all stable isotopes and selected radioactive isotopes (having relatively long half-lives and characteristic terrestrial isotopic compositions). Isotopes are considered stable (non-radioactive) if evidence for radioactive decay has not been detected experimentally.

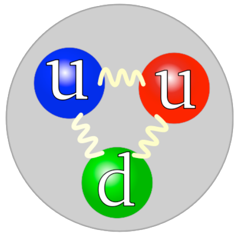
For the interactive version see **ISOTOPESMATTER.COM**



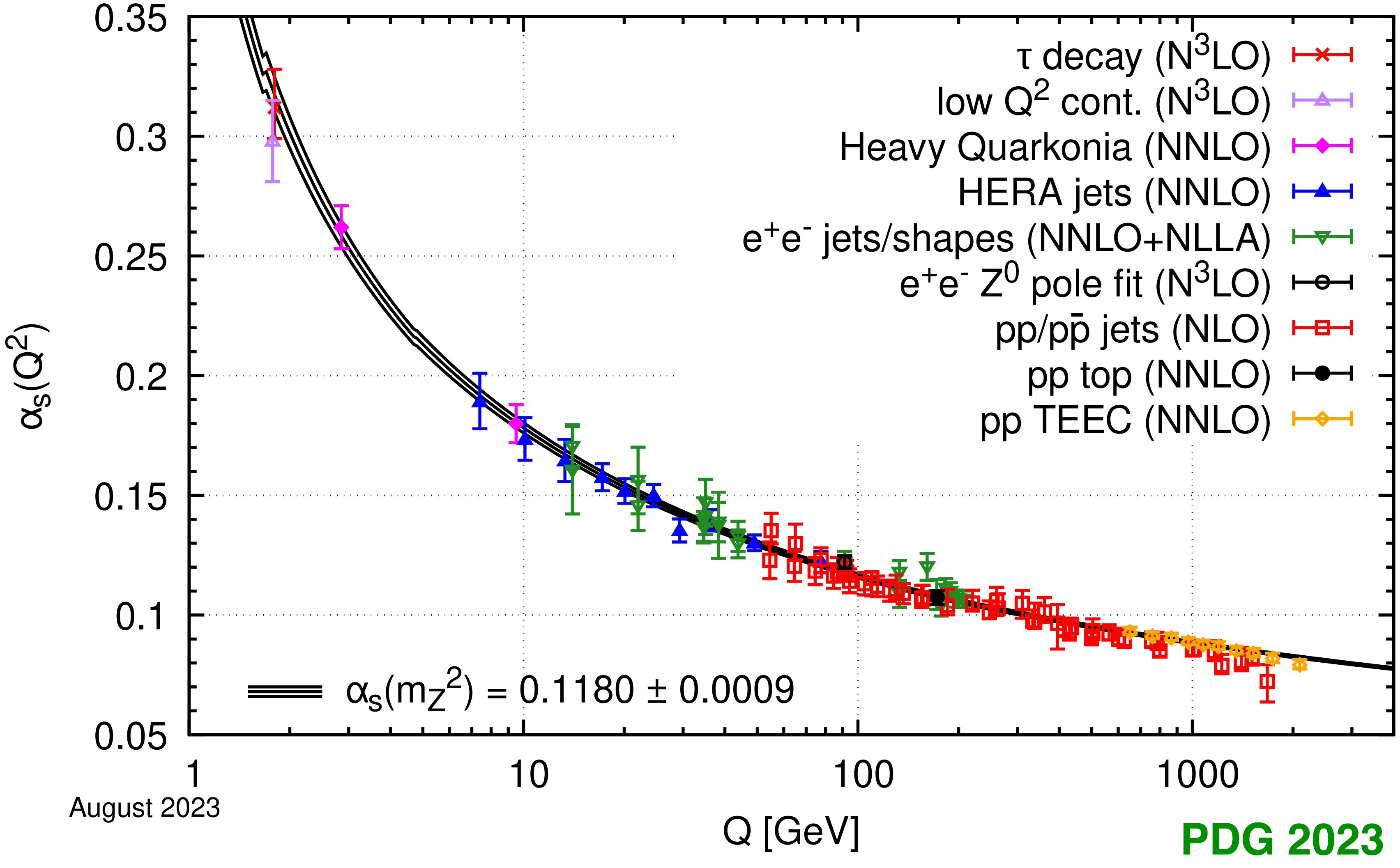
Structure within the Atom

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Quantum Chromodynamics (QCD)



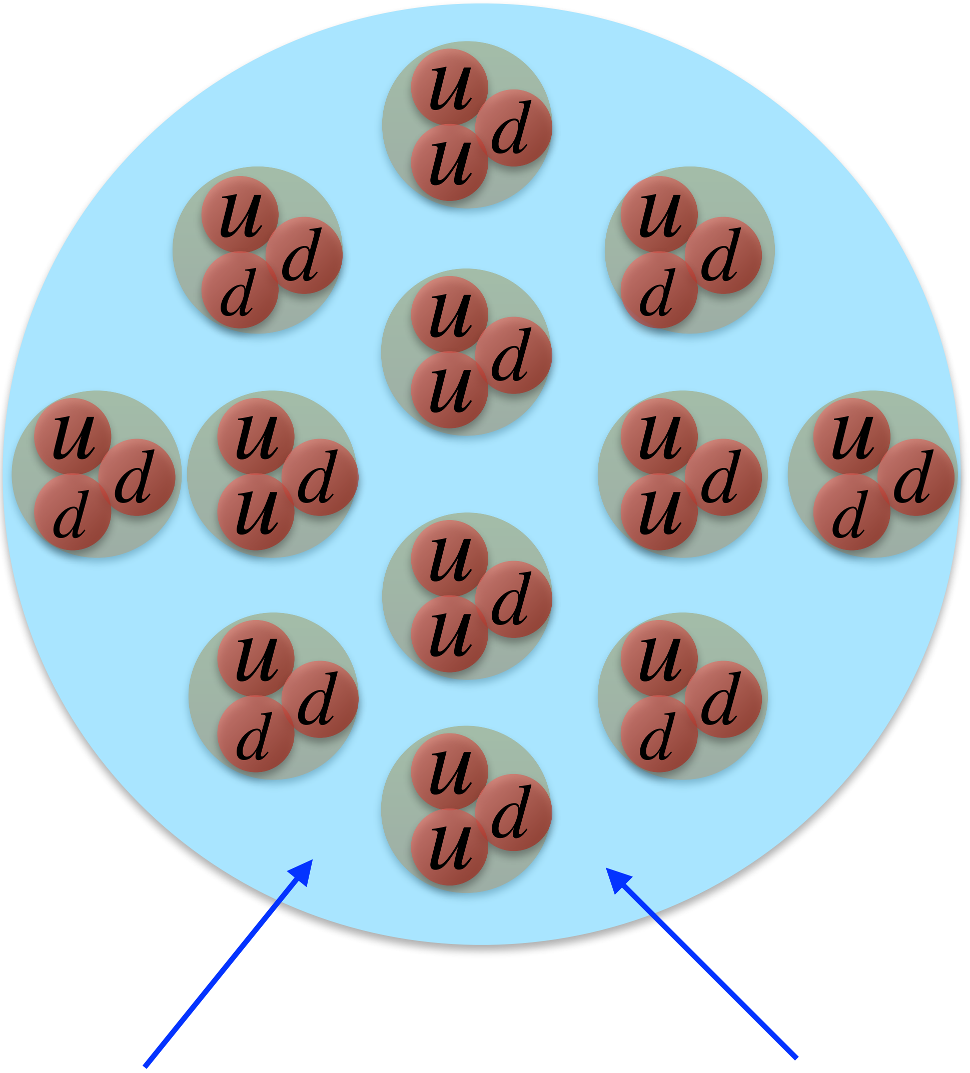
$$\mathscr{L}_{\rm QCD} = \sum_q \overline{\psi}_q (i\, D_\mu\, \gamma^\mu - m_q)\psi_q - \frac{1}{4}\, G^a_{\mu\nu} G^{a\,\mu\nu}$$



vacuum: $\langle \overline{\psi}_q \psi_q \rangle \sim \Lambda^3_{\rm QCD}$ $\langle G^a_{\mu\nu} G^{a\,\mu\nu} \rangle \sim \Lambda^4_{\rm QCD}$

Ordinary Nucleus

$^{A}_{Z}N$

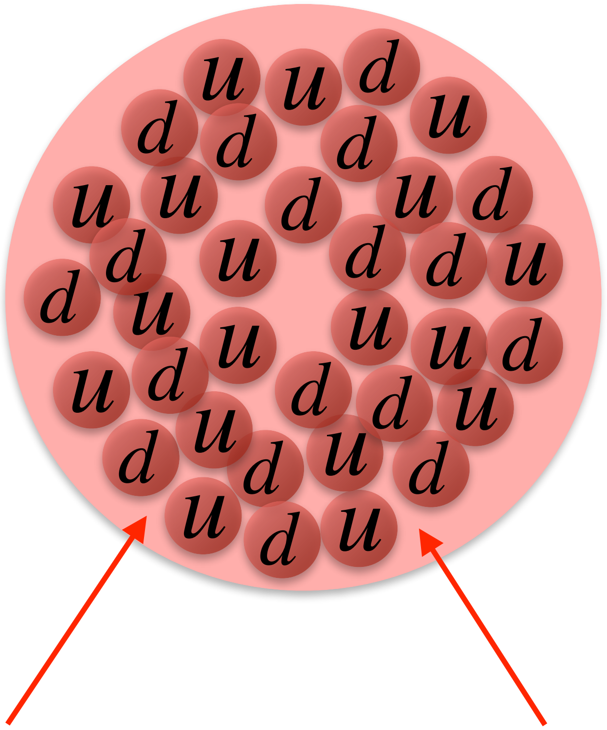


$\langle \overline{\psi}_q \psi_q \rangle \sim \Lambda^3_{\rm QCD}$

$\langle G^a_{\mu\nu} G^{a\,\mu\nu} \rangle \sim \Lambda^4_{\rm QCD}$

Quark Nugget

$^{A}_{Z}Q$

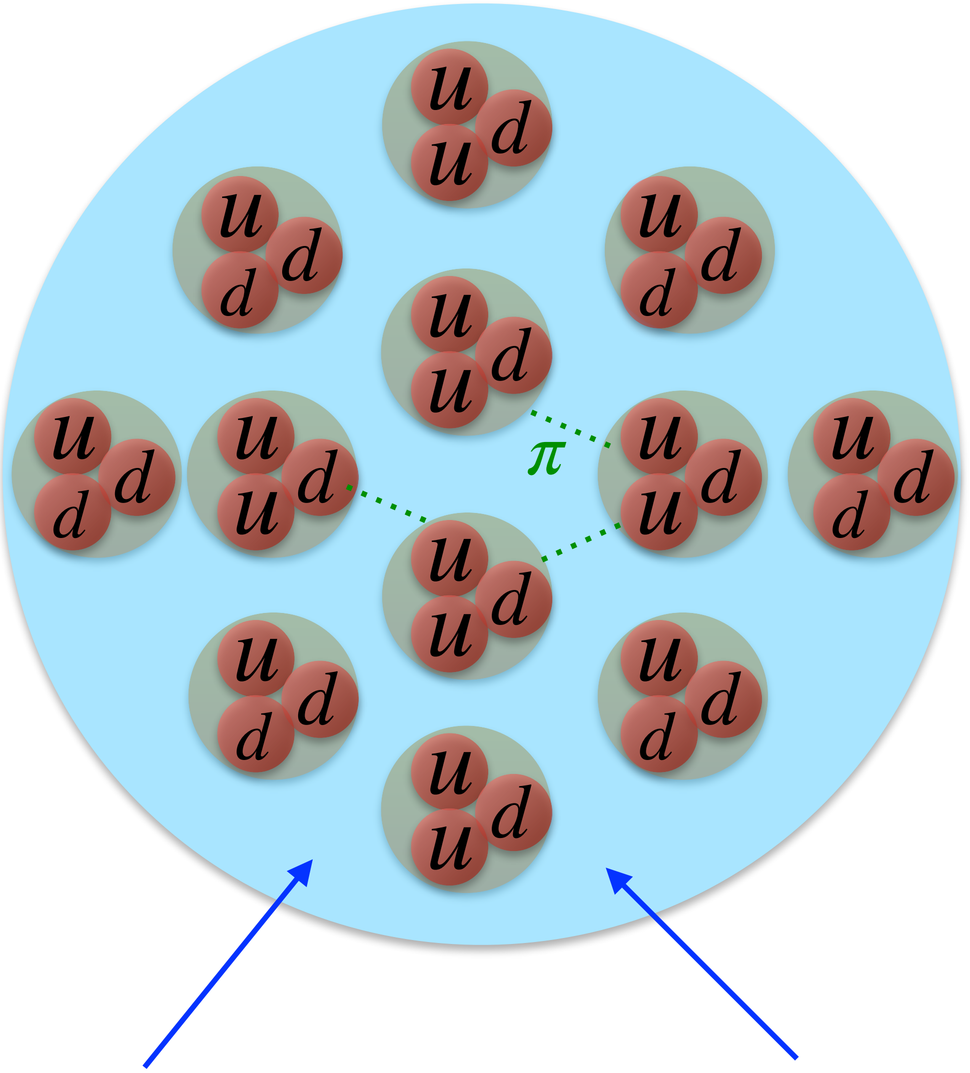


$\langle \overline{\psi}_q \psi_q \rangle = 0$

$\langle G^a_{\mu\nu} G^{a\,\mu\nu} \rangle = 0$

Ordinary Nucleus

$^{A}_{Z}N$



$\langle \overline{\psi}_q \psi_q \rangle \sim \Lambda^3_{\rm QCD}$ $\langle G^a_{\mu\nu} G^{a\,\mu\nu} \rangle \sim \Lambda^4_{\rm QCD}$

Quark Nugget

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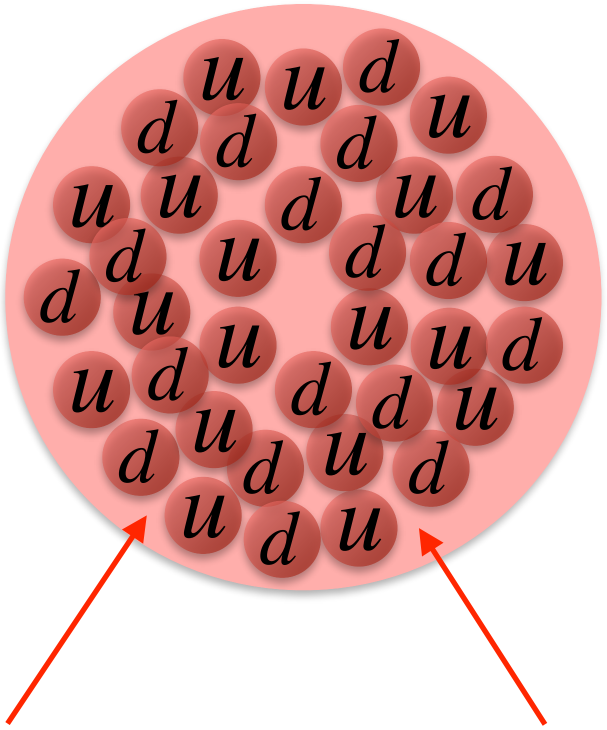

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Ordinary Nucleus

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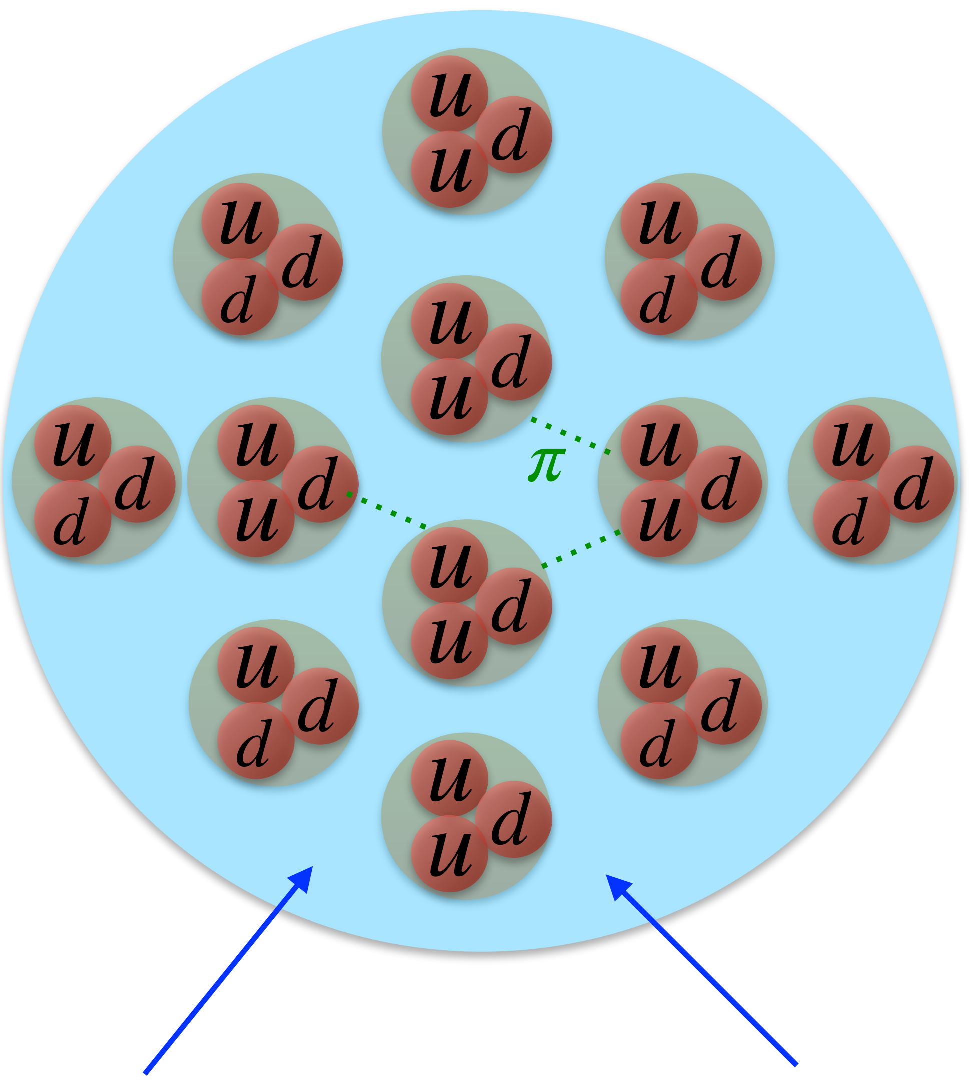

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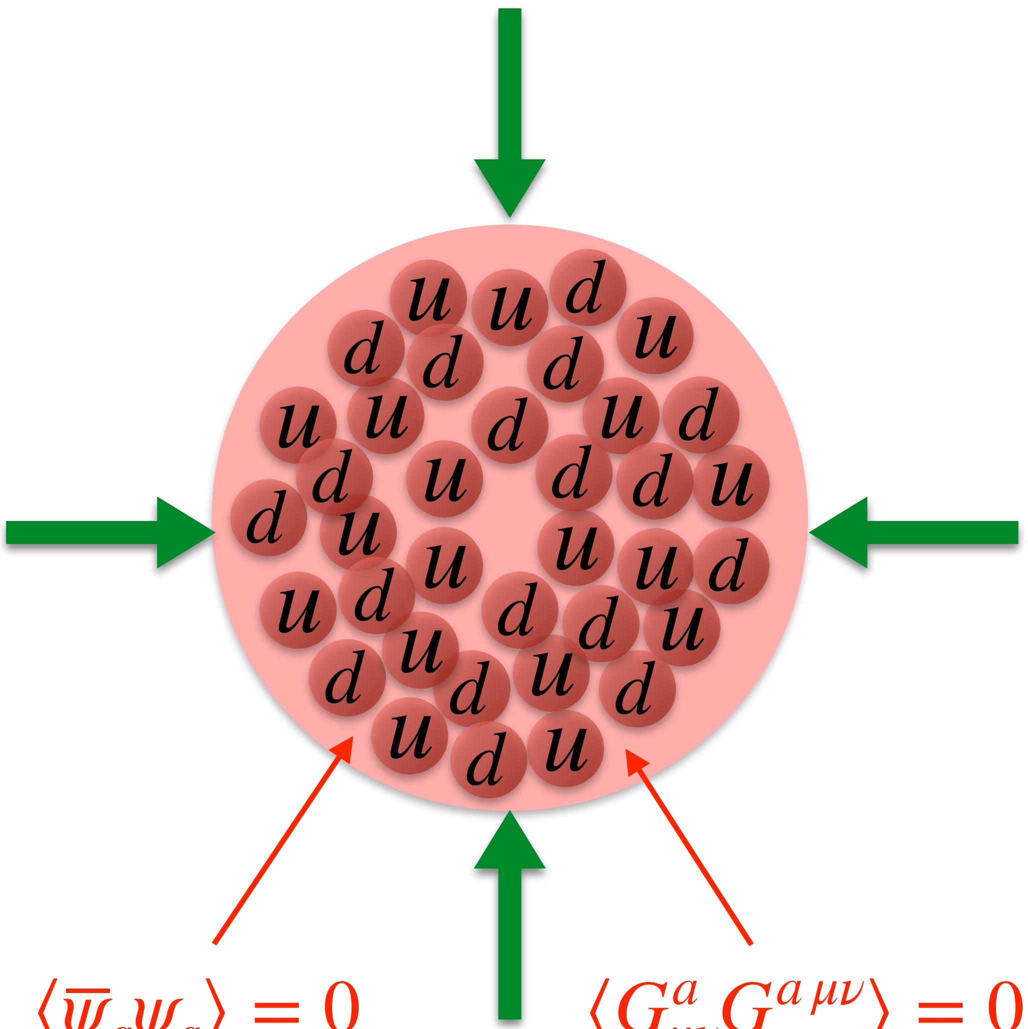
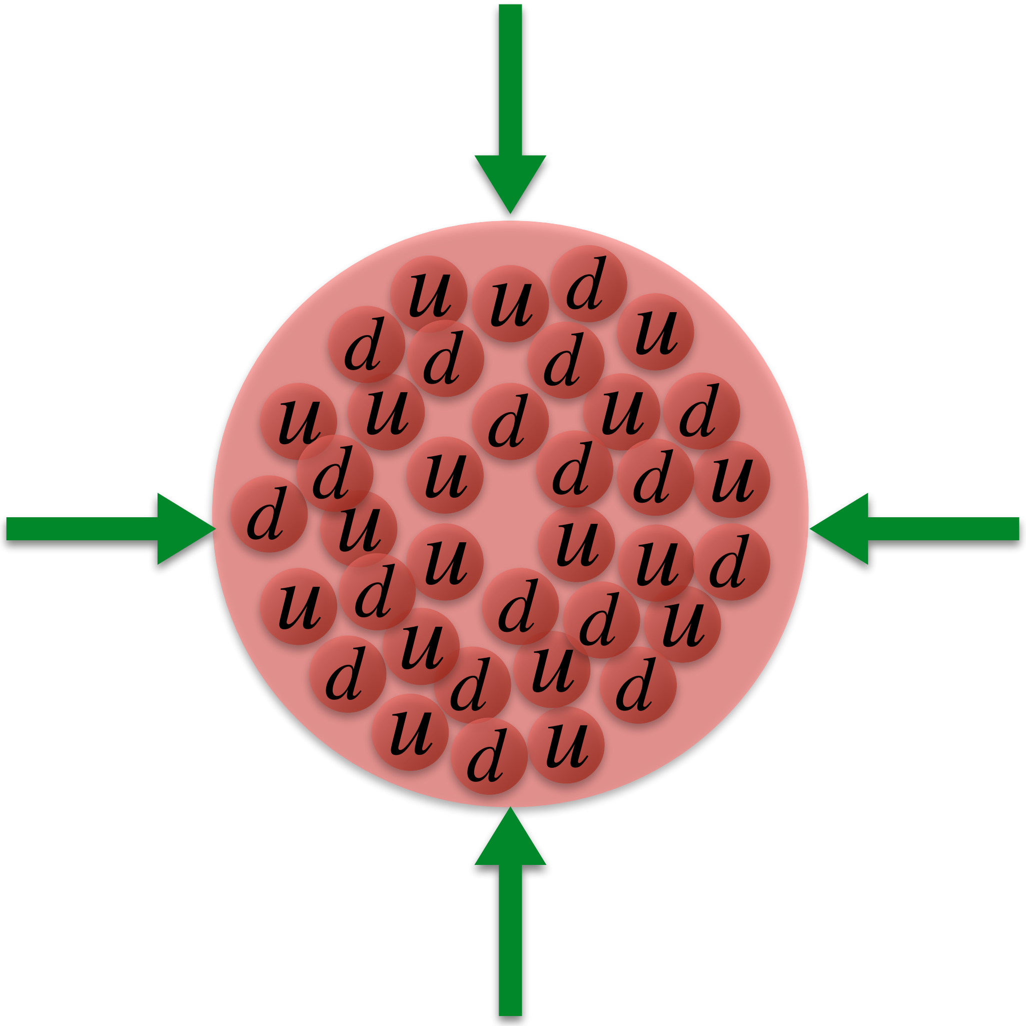


$\langle \overline{\psi}_q \psi_q \rangle = 0$

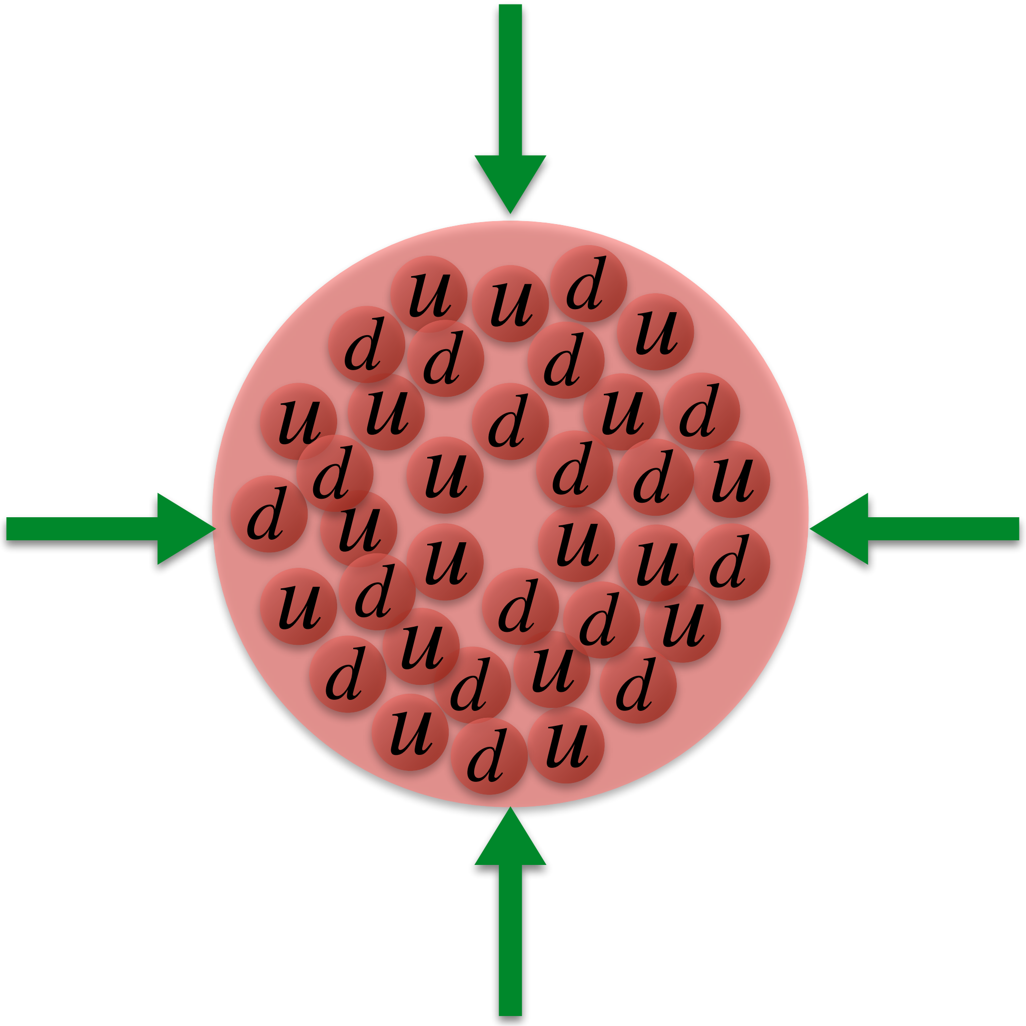
$\langle G^a_{\mu\nu} G^{a\,\mu\nu} \rangle = 0$

Degenerate Fermi gas



vacuum pressure
($B \sim \Lambda_{\mathrm{QCD}}^4$)

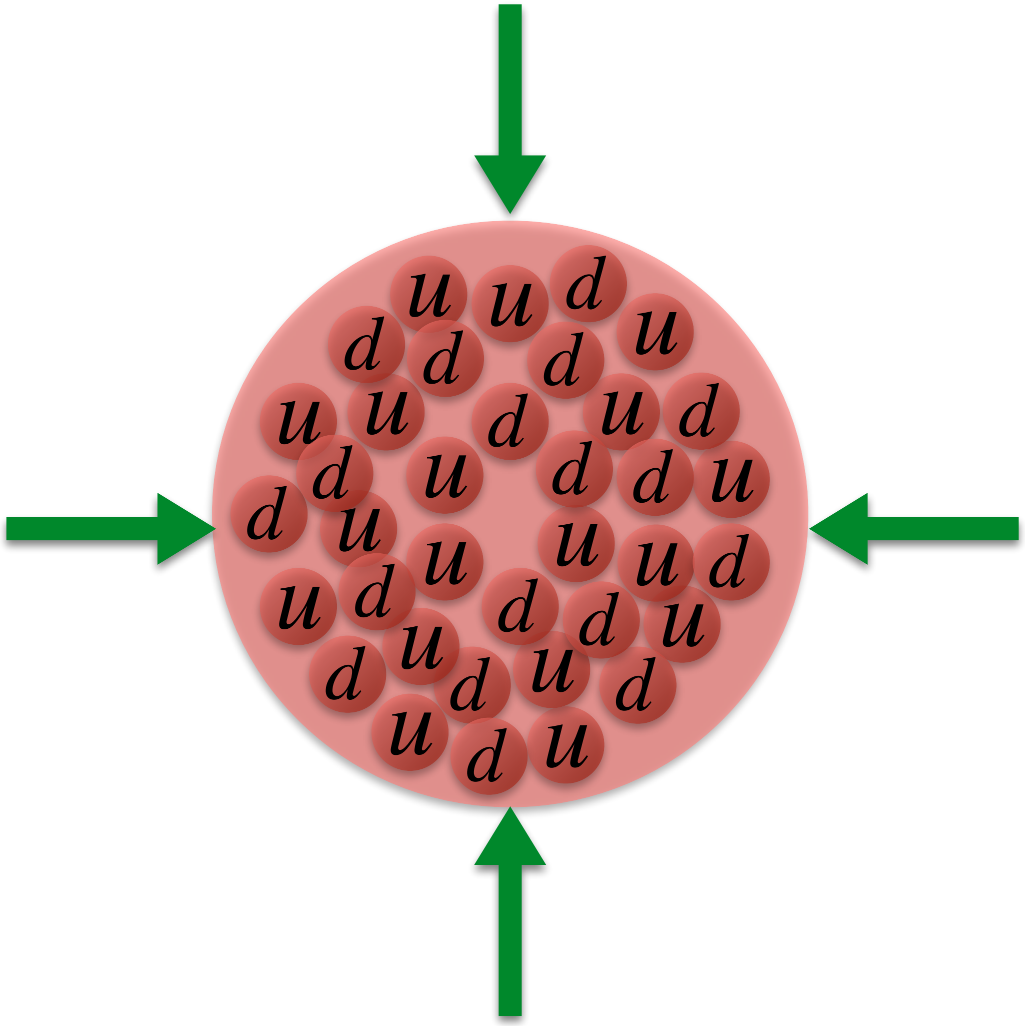
Degenerate Fermi gas



$n \propto p_F^3$

vacuum pressure
$(B \sim \Lambda_{\rm QCD}^4)$

Degenerate Fermi gas

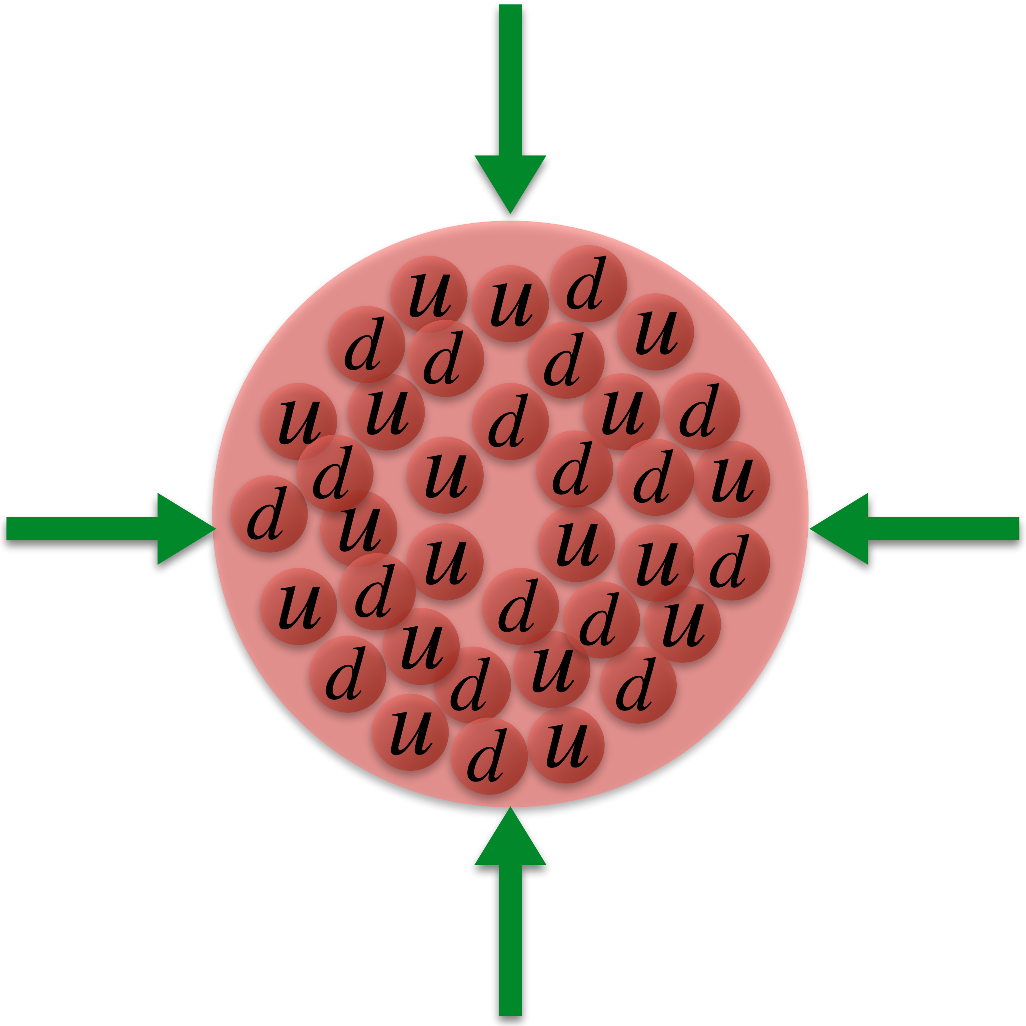


$$n \propto p_F^3$$
$$A \propto R^3 \, n$$

vacuum pressure
($B \sim \Lambda_{\rm QCD}^4$)

Degenerate Fermi gas

$$n \propto p_F^3$$
$$A \propto R^3\, n$$
$$p_F \propto A^{1/3}\, R^{-1}$$



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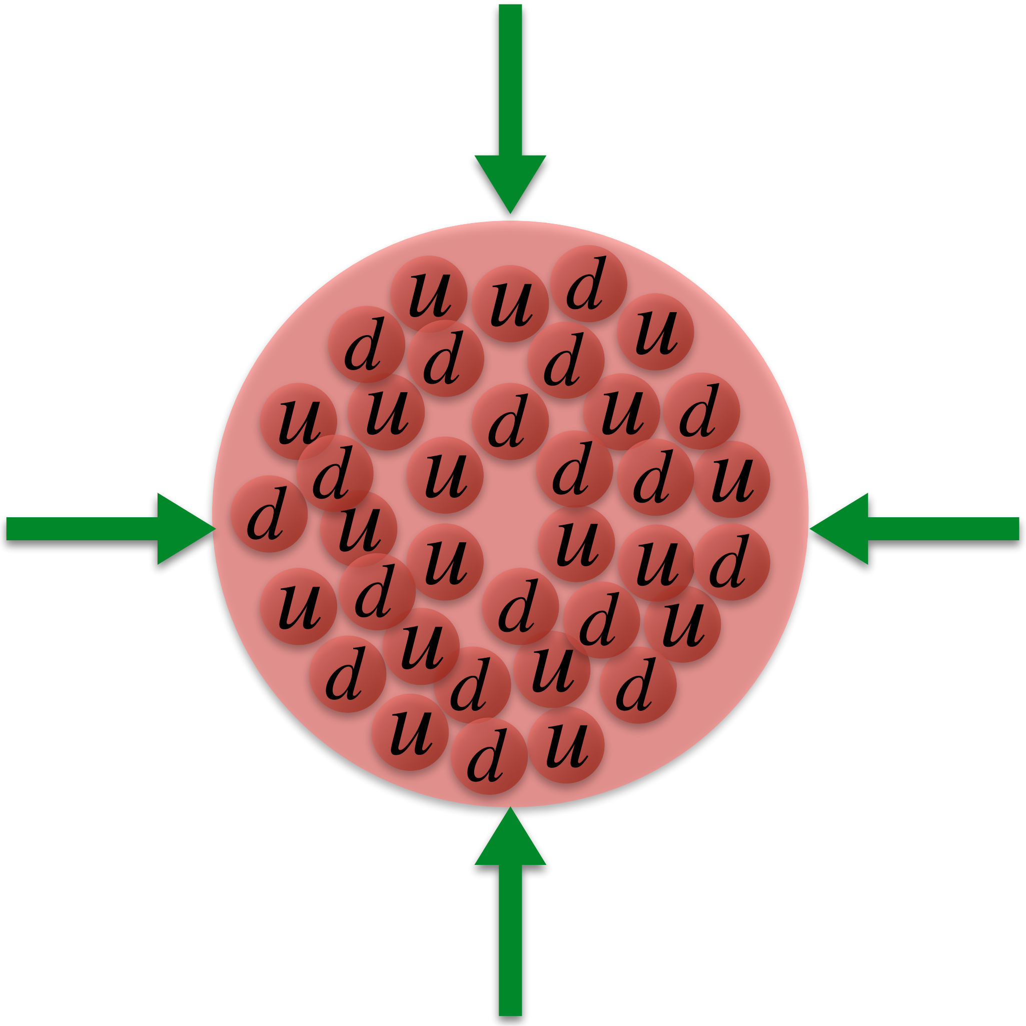

vacuum pressure
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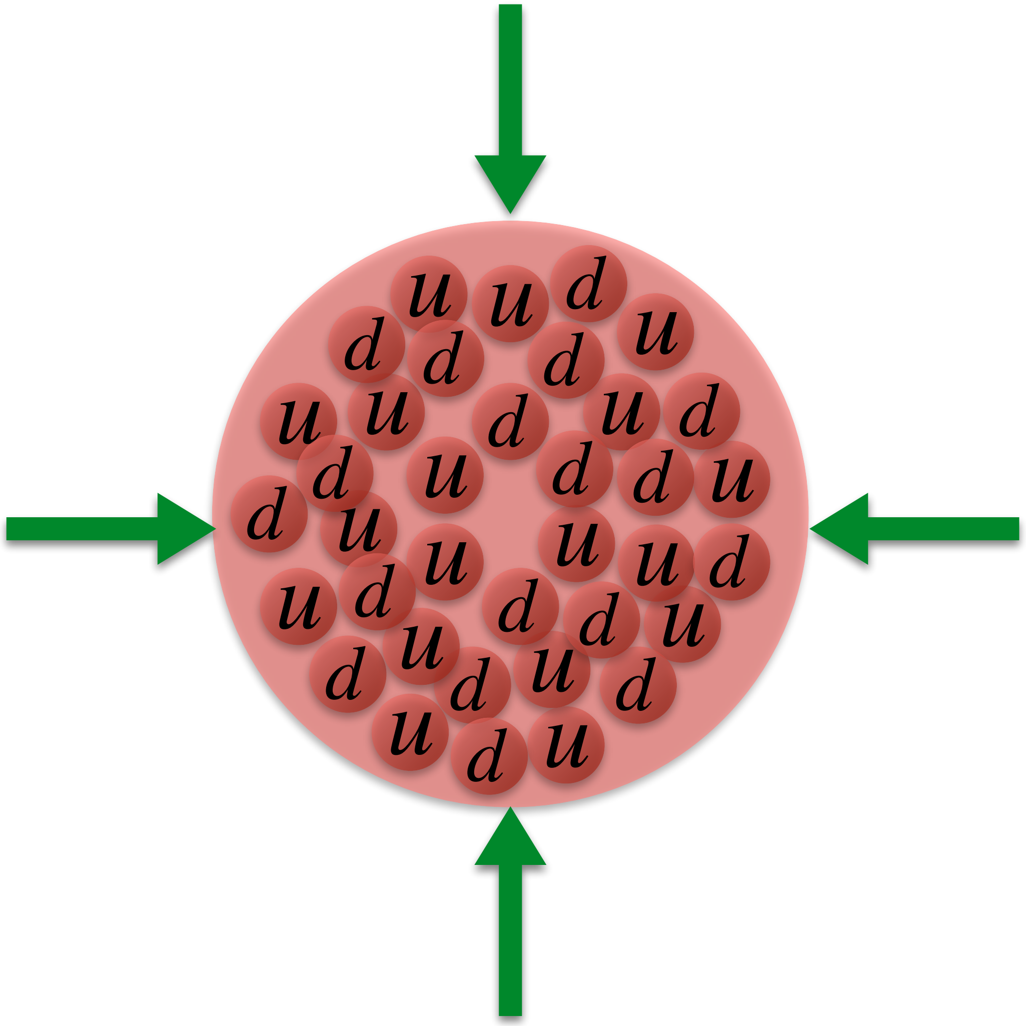
$$n \propto p_F^3$$
$$A \propto R^3\, n$$
$$p_F \propto A^{1/3}\, R^{-1}$$

$$E_{\rm kin} \propto R^3\, p_F^4 \; \propto A^{4/3}\, R^{-1}$$

Degenerate Fermi gas



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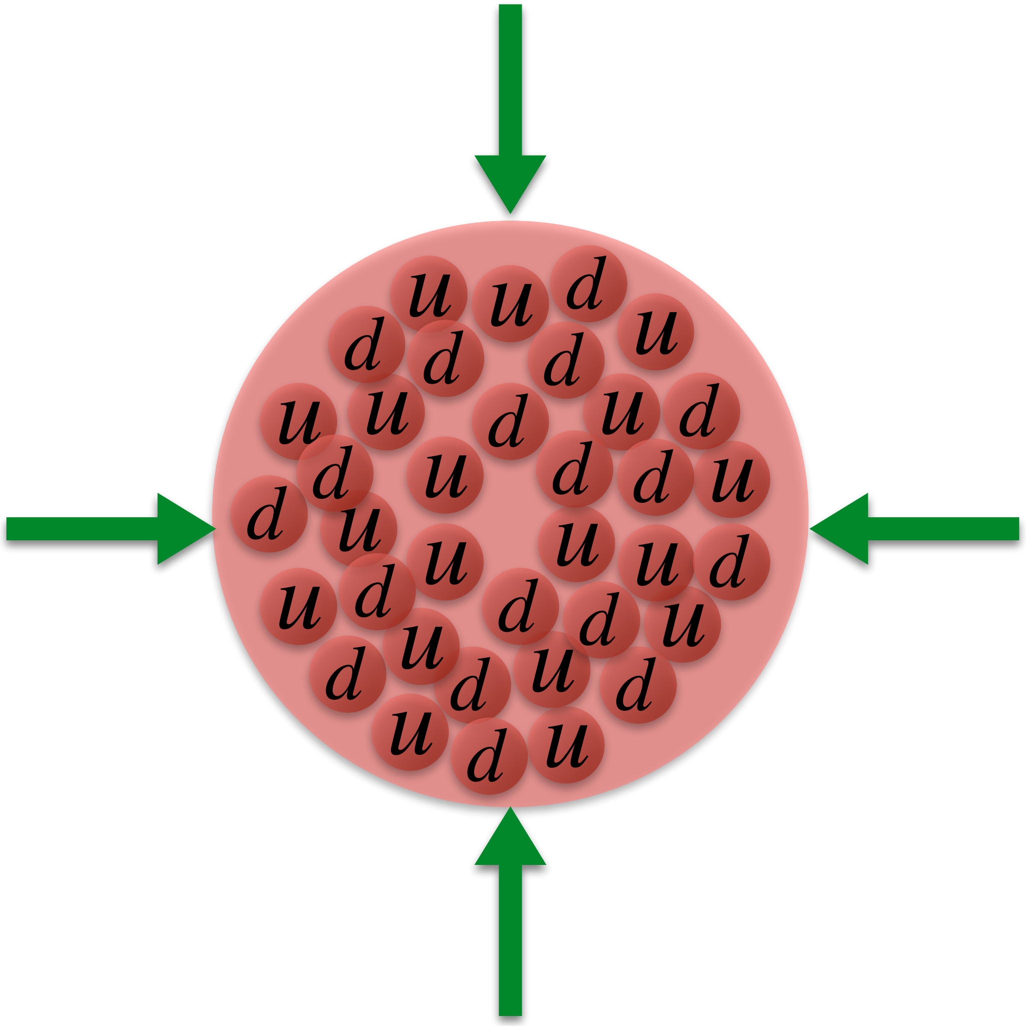
Degenerate Fermi gas



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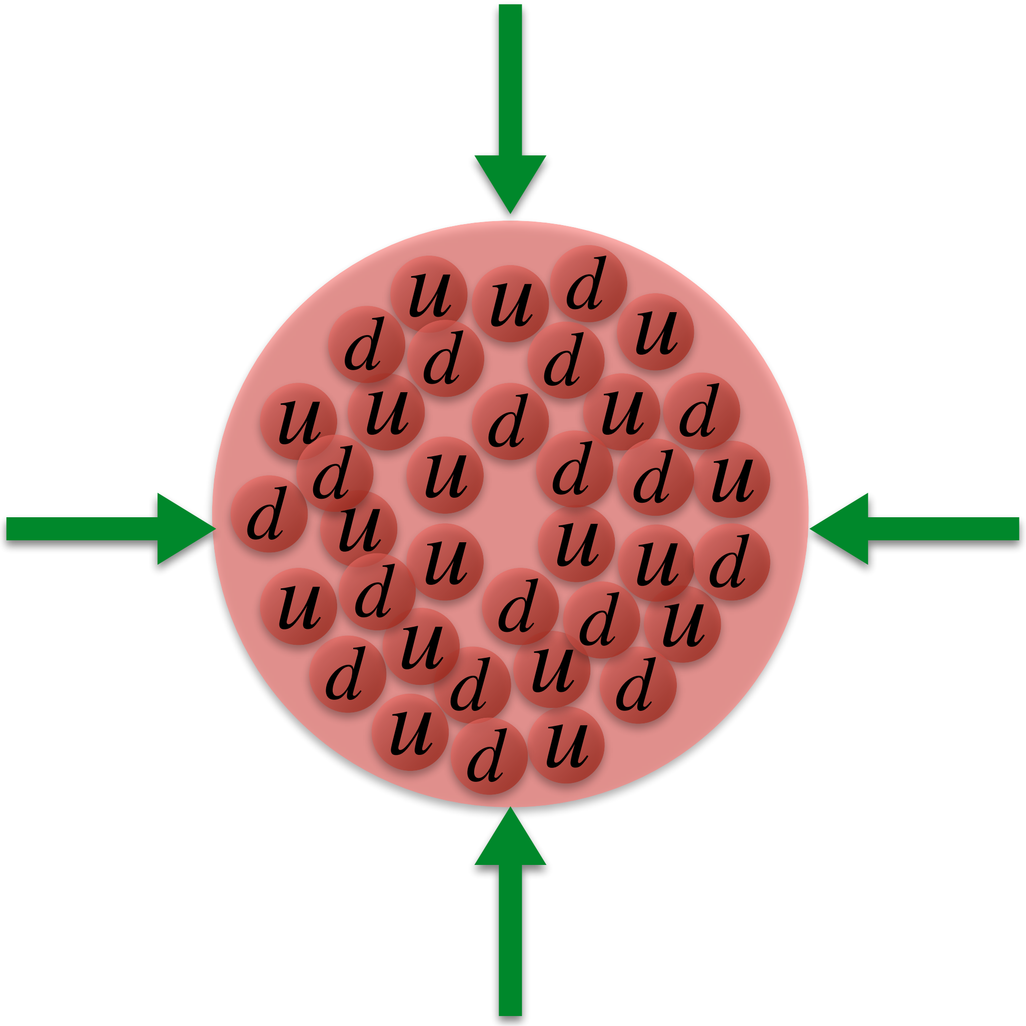
$$E_{\rm kin} \propto R^3\, p_F^4 \propto A^{4/3}\, R^{-1} \qquad E_{\rm vac} \propto R^3\, B \qquad E_{\rm tot} = E_{\rm kin} + E_{\rm vac}$$

Degenerate Fermi gas



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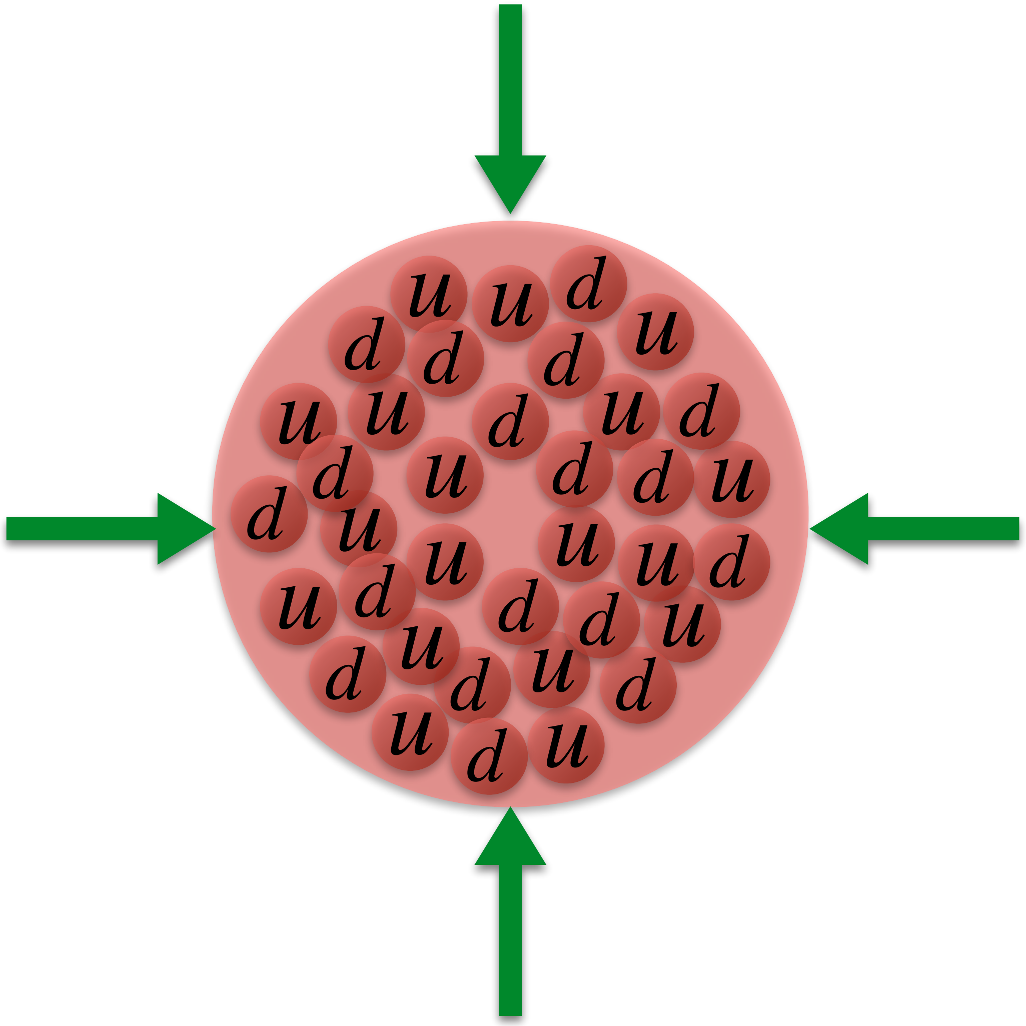
$R_{\rm min} \propto B^{-1/4}\, A^{1/3}$

Degenerate Fermi gas



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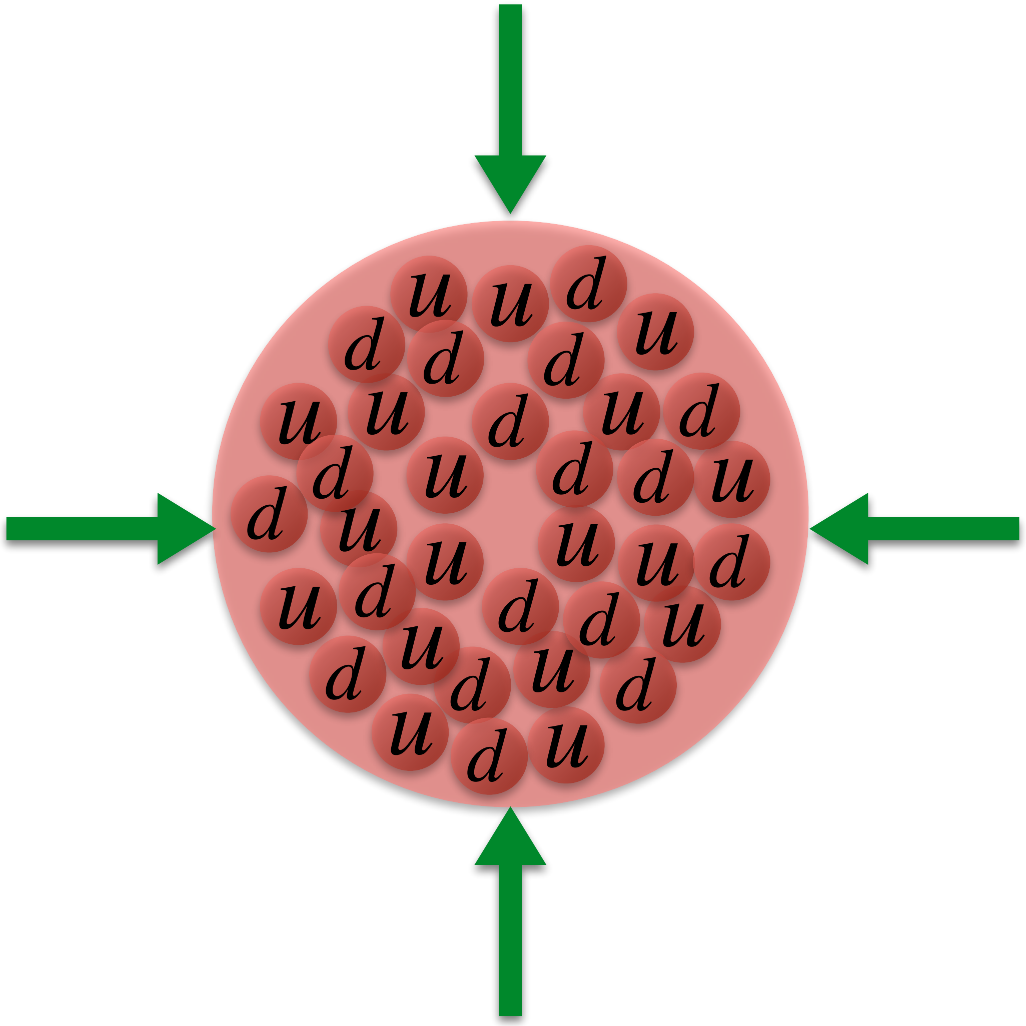
$$R_{\rm min} \propto B^{-1/4} A^{1/3} \qquad E_{\rm tot,min}/A = 3 \times 2^{1/4} \pi^{1/2} (2/n_f)^{1/4} B^{1/4}$$

Degenerate Fermi gas



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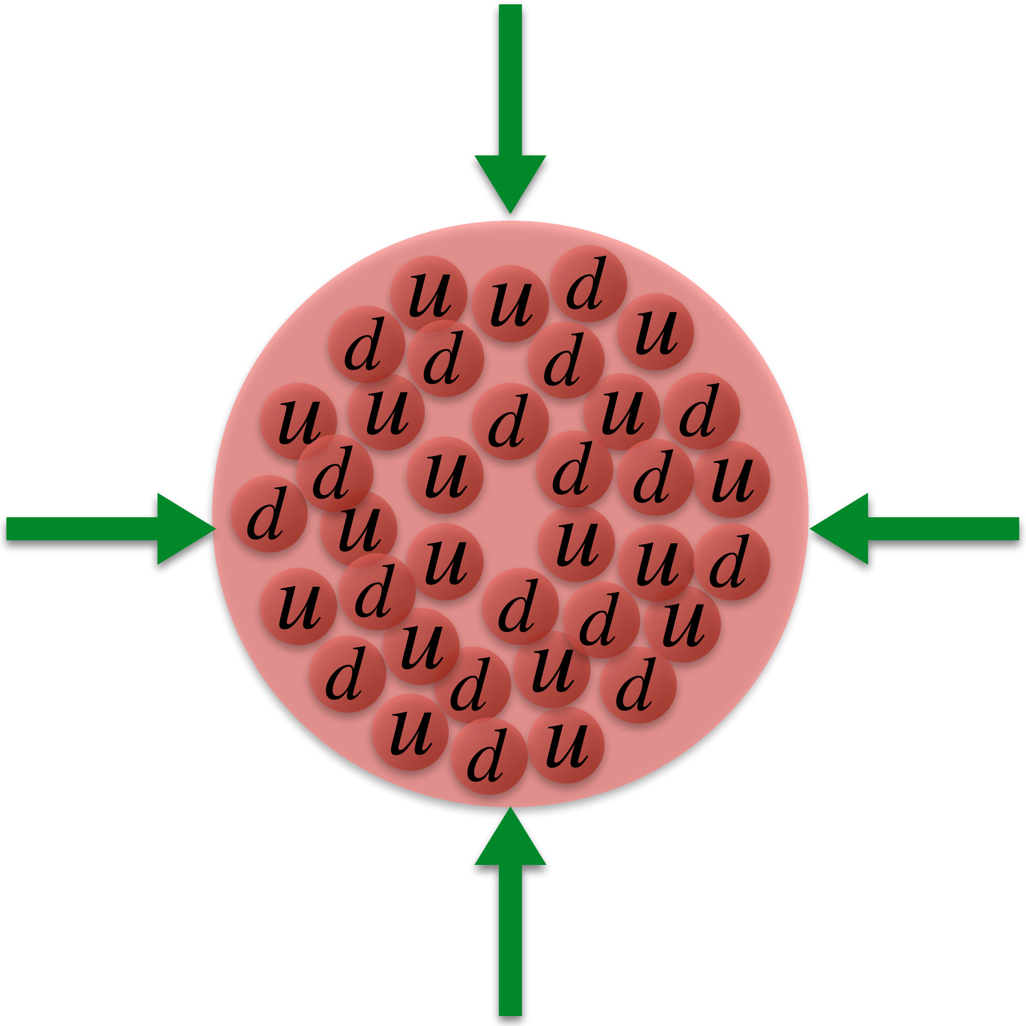
$$= 917\,\text{MeV}\,(B^{1/4}/145\,\text{MeV})$$

Degenerate Fermi gas



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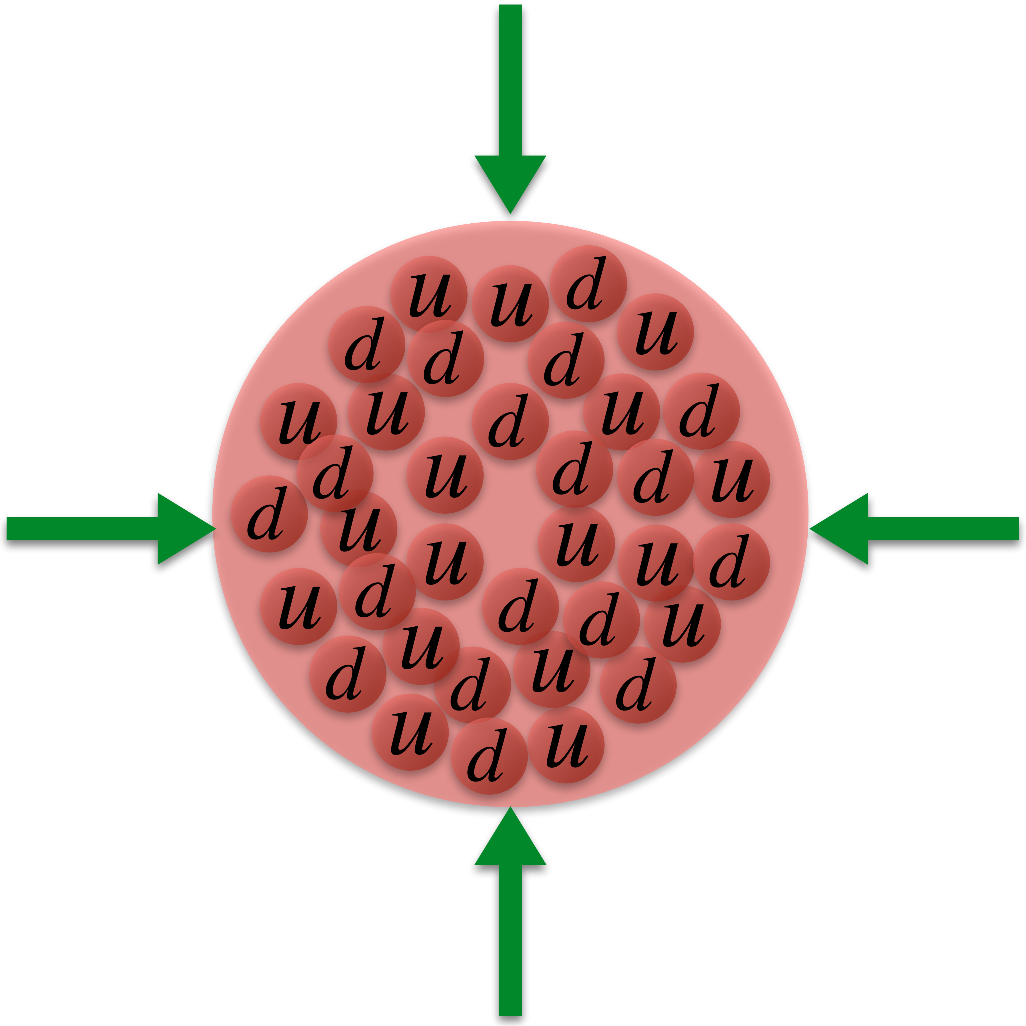
"Ground state of QCD"

Degenerate Fermi gas



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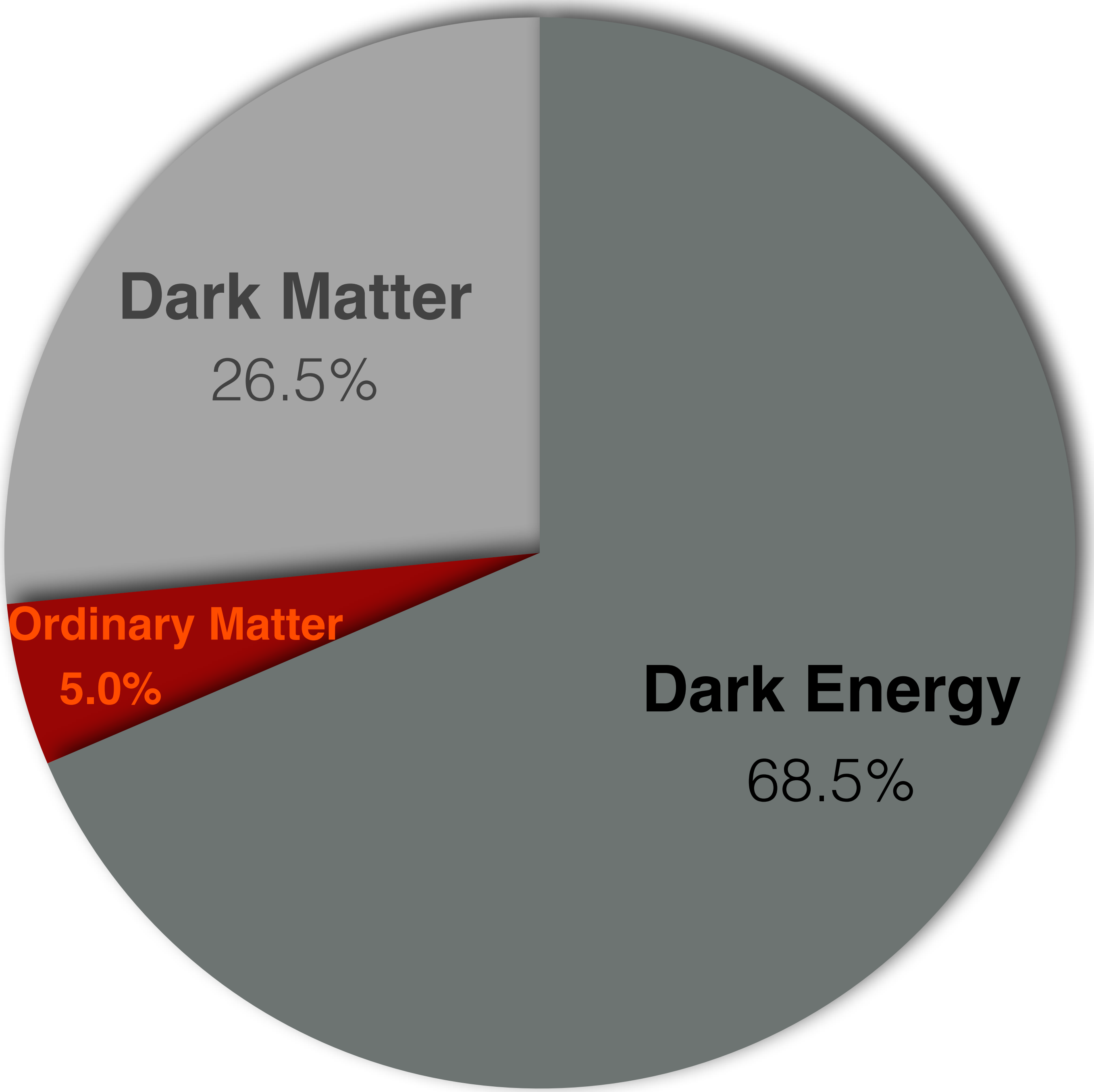
"Ground state of QCD"

Bodmer (1971'), Witten(1984')

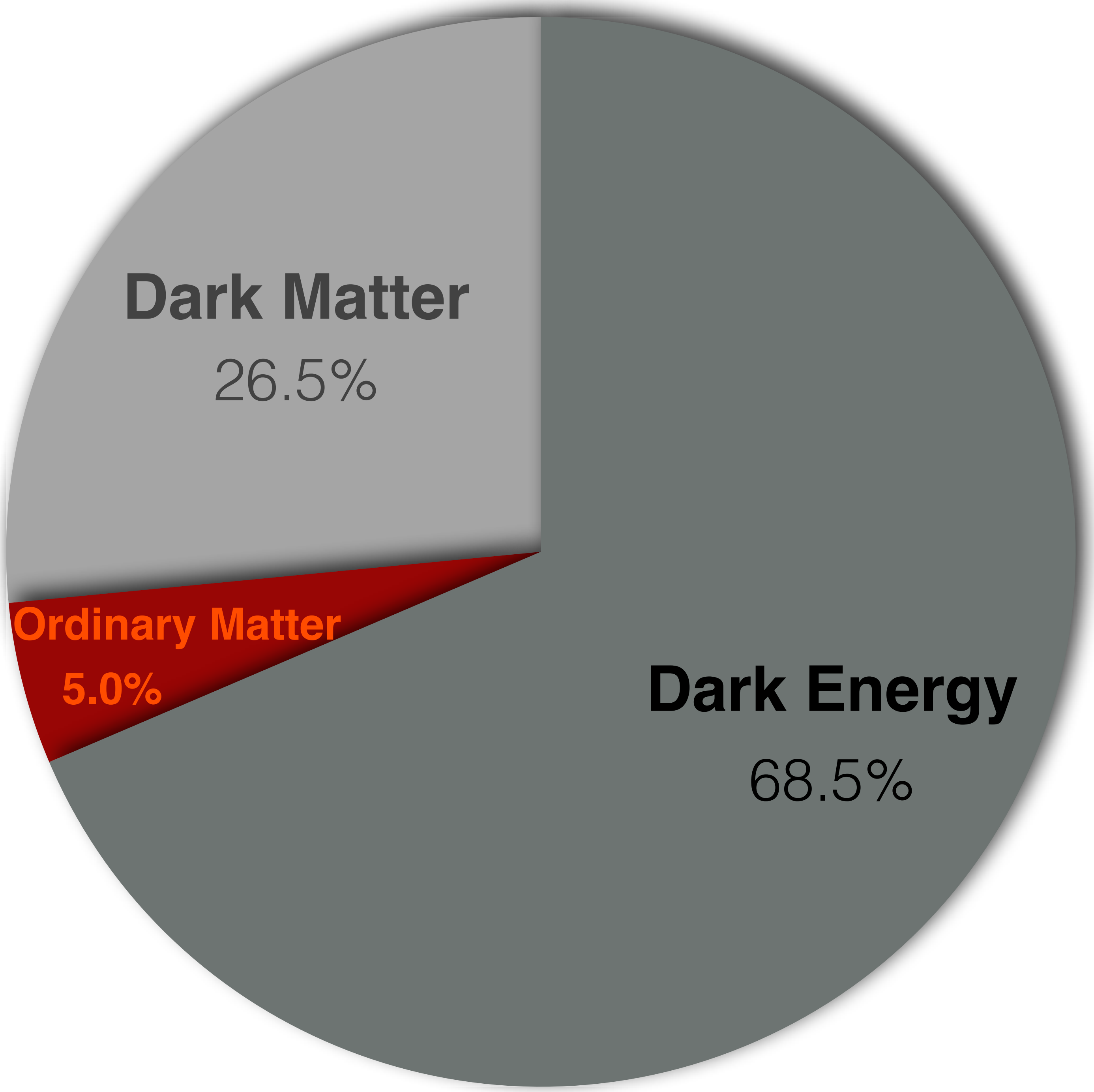
Why do we care?

Dark world



from PLANCK, 1807.06209

Quark nuggets for dark matter



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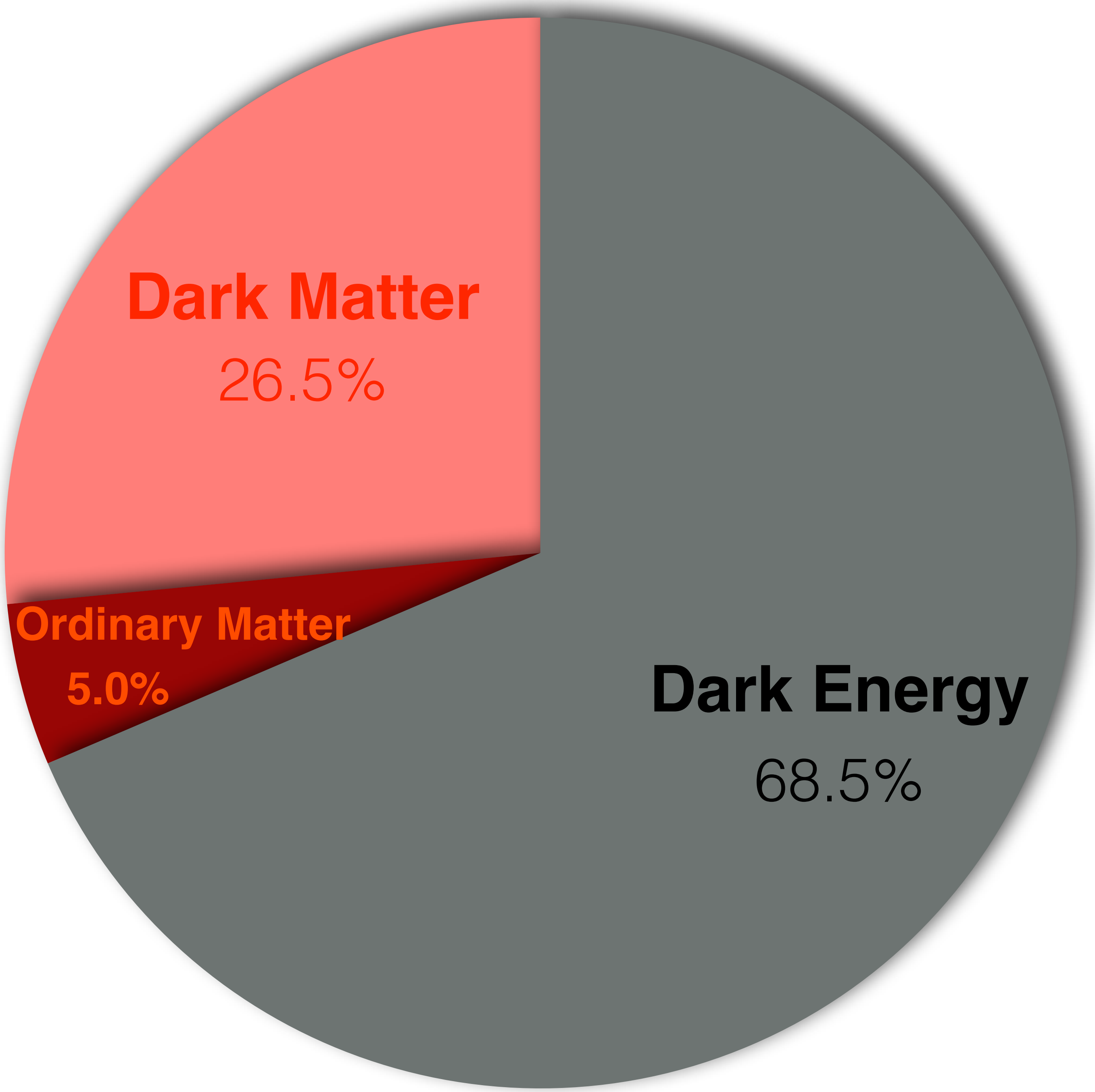
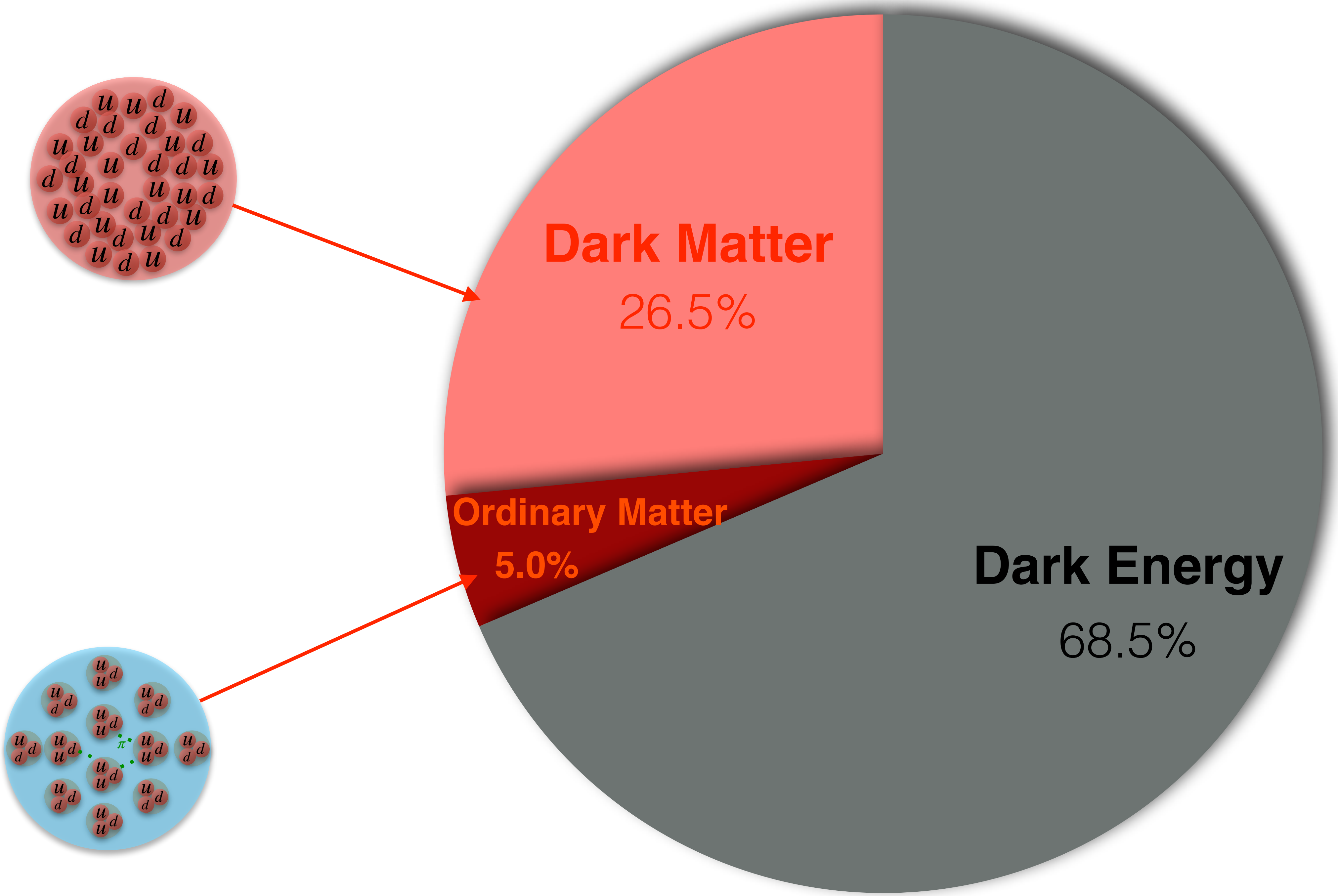


Quark nuggets for dark matter

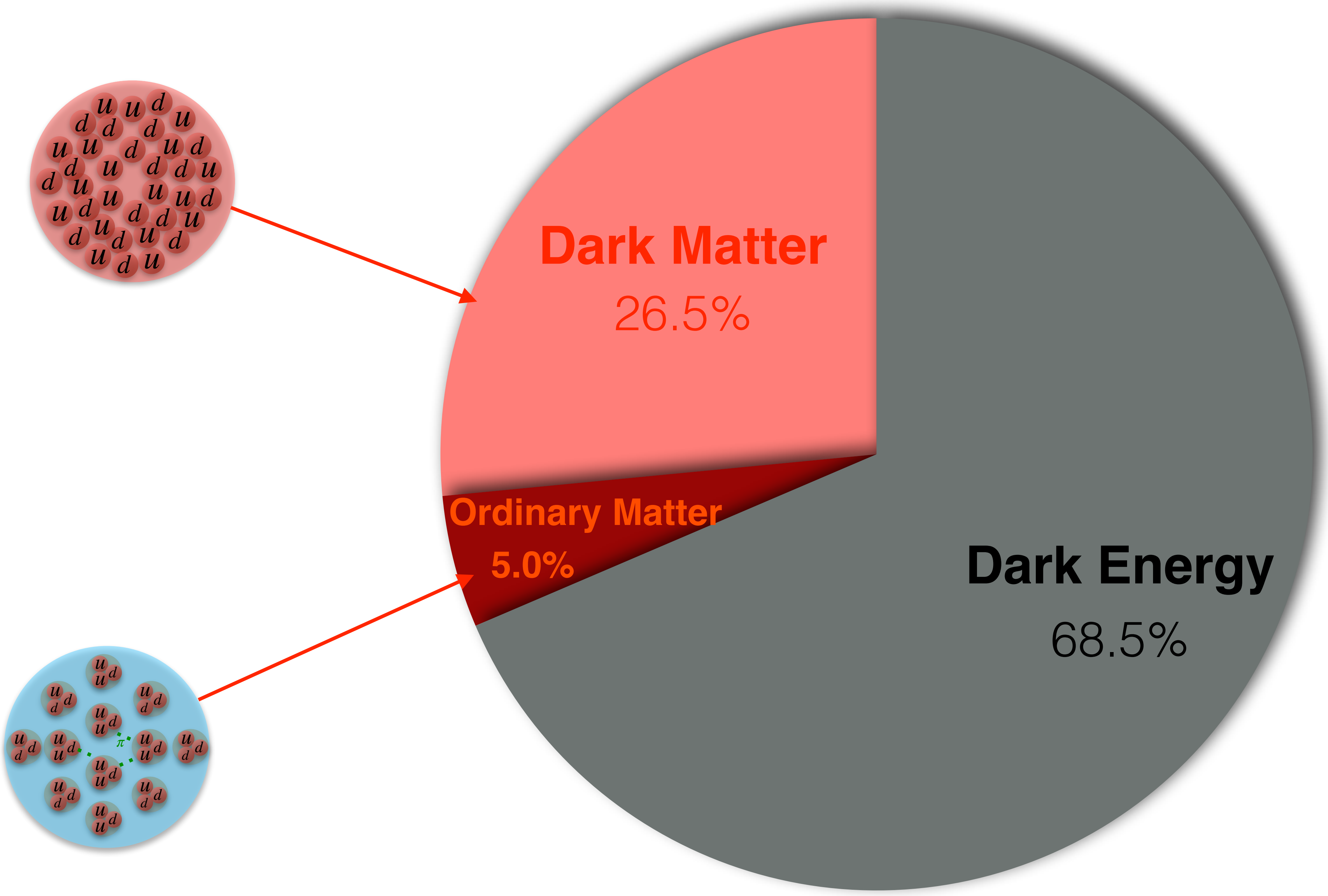


Dark Matter
26.5%

Ordinary Matter
5.0%

Dark Energy
68.5%

Quark nuggets for dark matter



- ❖ **Explain dark matter using states in the Standard Model**

Properties

Degenerate Fermi gas model

- **A phenomenological linear sigma model plus constituent quark model**

$$\mathscr{L} \supset \mathrm{Tr}(\partial_\mu \Sigma^\dagger \partial^\mu \Sigma) - V(\Sigma, \Sigma^\dagger) - g \left(\bar{\psi} \Sigma \psi + \text{h.c.}\right)$$

$$\Sigma = \frac{1}{2} \begin{pmatrix} \sigma_n & 0 & 0 \\ 0 & \sigma_n & 0 \\ 0 & 0 & \sqrt{2}\,\sigma_s \end{pmatrix}$$

- **In the normal chiral-symmetry-breaking vacuum**

$$v_n \equiv \langle \sigma_n \rangle = 92\,\text{MeV} \qquad v_s \equiv \langle \sigma_s \rangle = 91\,\text{MeV}$$

$$m_p \approx 3\, g\, v_n \approx 940\,\text{MeV}$$

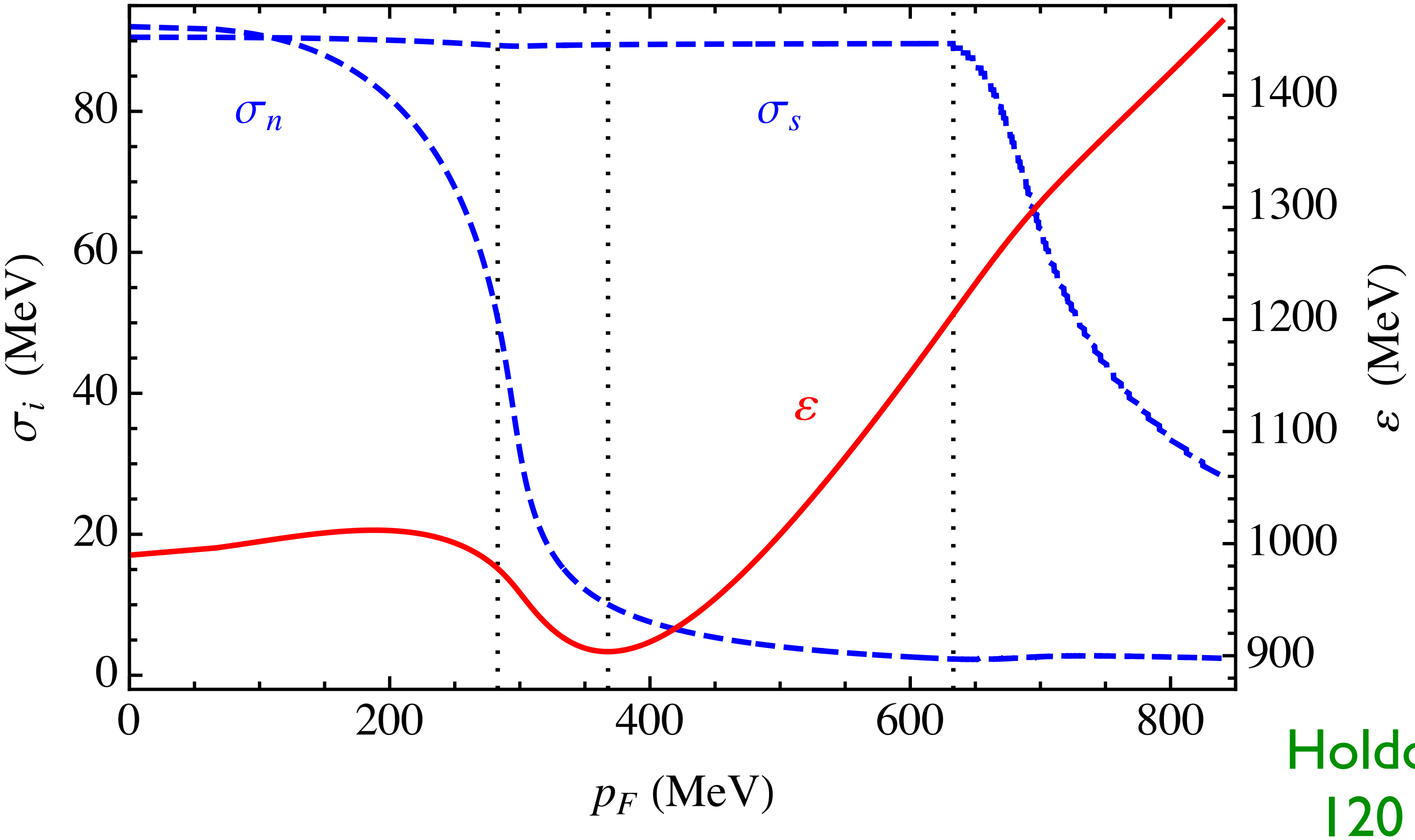
Degenerate Fermi gas model

- **Finite-density of quarks modifies the EOMS of scalars**

T. D. Lee et. al

$$\nabla^2\sigma_n = \frac{\partial V}{\partial \sigma_n} + g\sum_{i=u,d}\langle\bar{\psi}_i\psi_i\rangle \qquad \nabla^2\sigma_s = \frac{\partial V}{\partial \sigma_s} + \sqrt{2}g\langle\bar{\psi}_s\psi_s\rangle$$

$$\epsilon = \epsilon_\sigma + \epsilon_\psi + \epsilon_Z \qquad \langle\bar{\psi}_i\psi_i\rangle = \frac{2\,N_c}{(2\pi)^3}\int_0^{p_{Fi}} d^3p\,\frac{m_i(\sigma)}{\sqrt{p^2+m_i^2(\sigma)}}$$



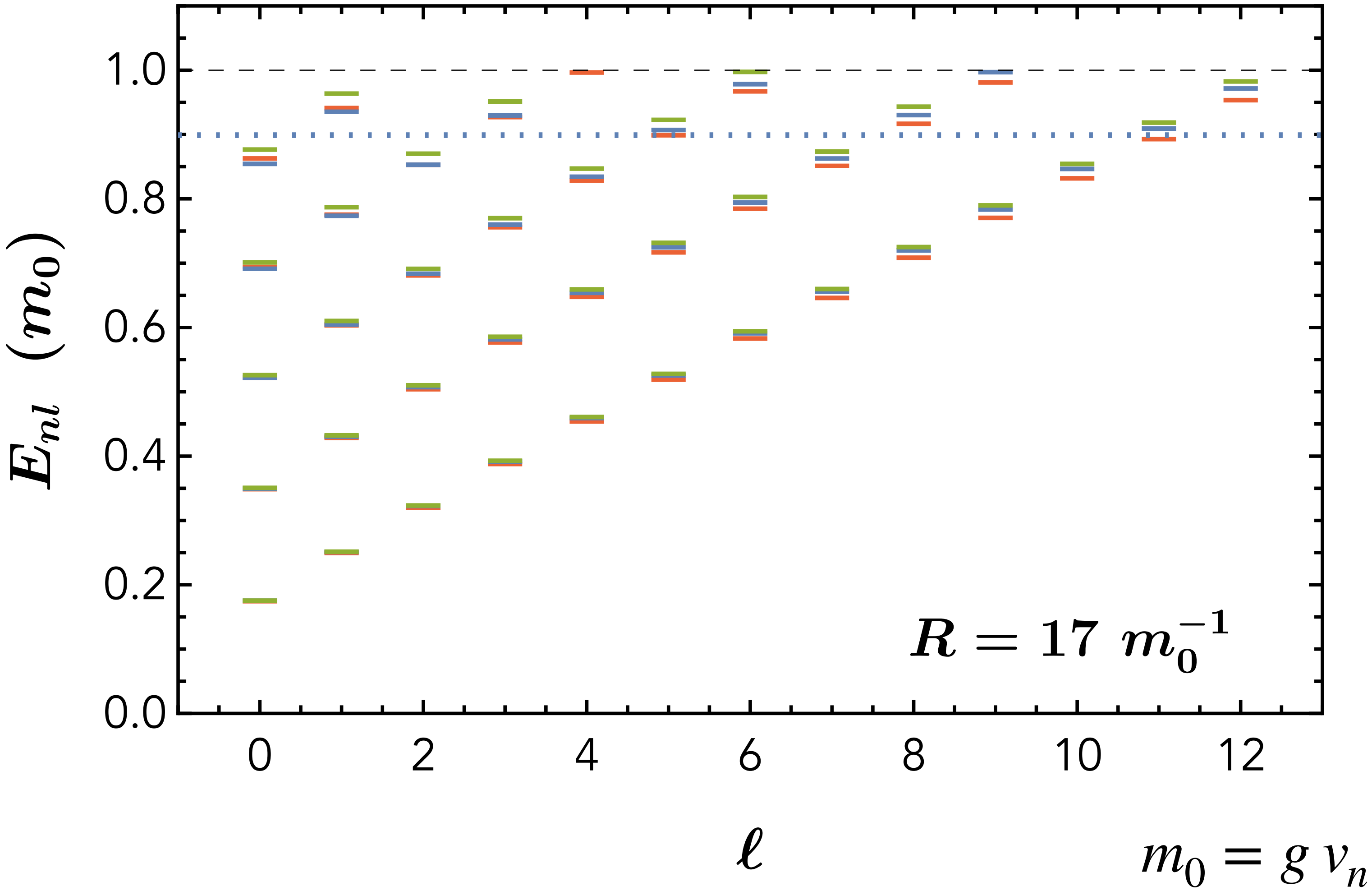
Holdom, Ren, Zhang, PRL 120 (2018) 22, 222001

Friedberg-Lee shell model

- **Obtain the actual energy levels of quarks**
- **Assuming a step-function profile for the sigma field**

$$(i\gamma^\mu \partial_\mu - m_q(r))\psi(t, \mathbf{r}) = \mathbf{0}$$

$$\frac{E_{nl} j_{l+1}(E_{nl}R)}{j_l(E_{nl}R)} = \sqrt{m_0^2 - E_{nl}^2}\,\frac{K_{l+3/2}(\sqrt{m_0^2 - E_{nl}^2}R)}{K_{l+1/2}(\sqrt{m_0^2 - E_{nl}^2}R)}\,,$$

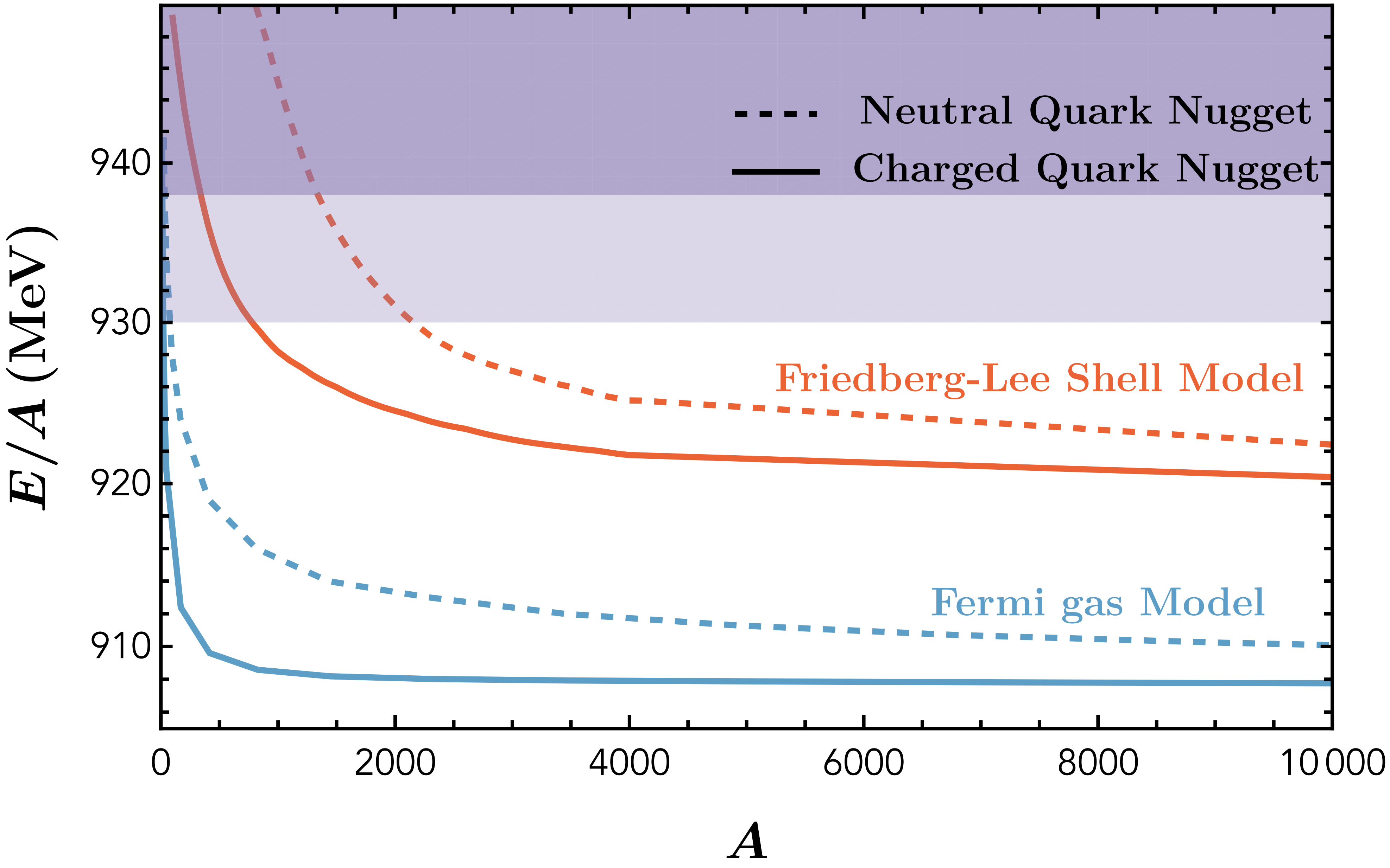


$m_0 = g\, v_n = 326.6$ MeV

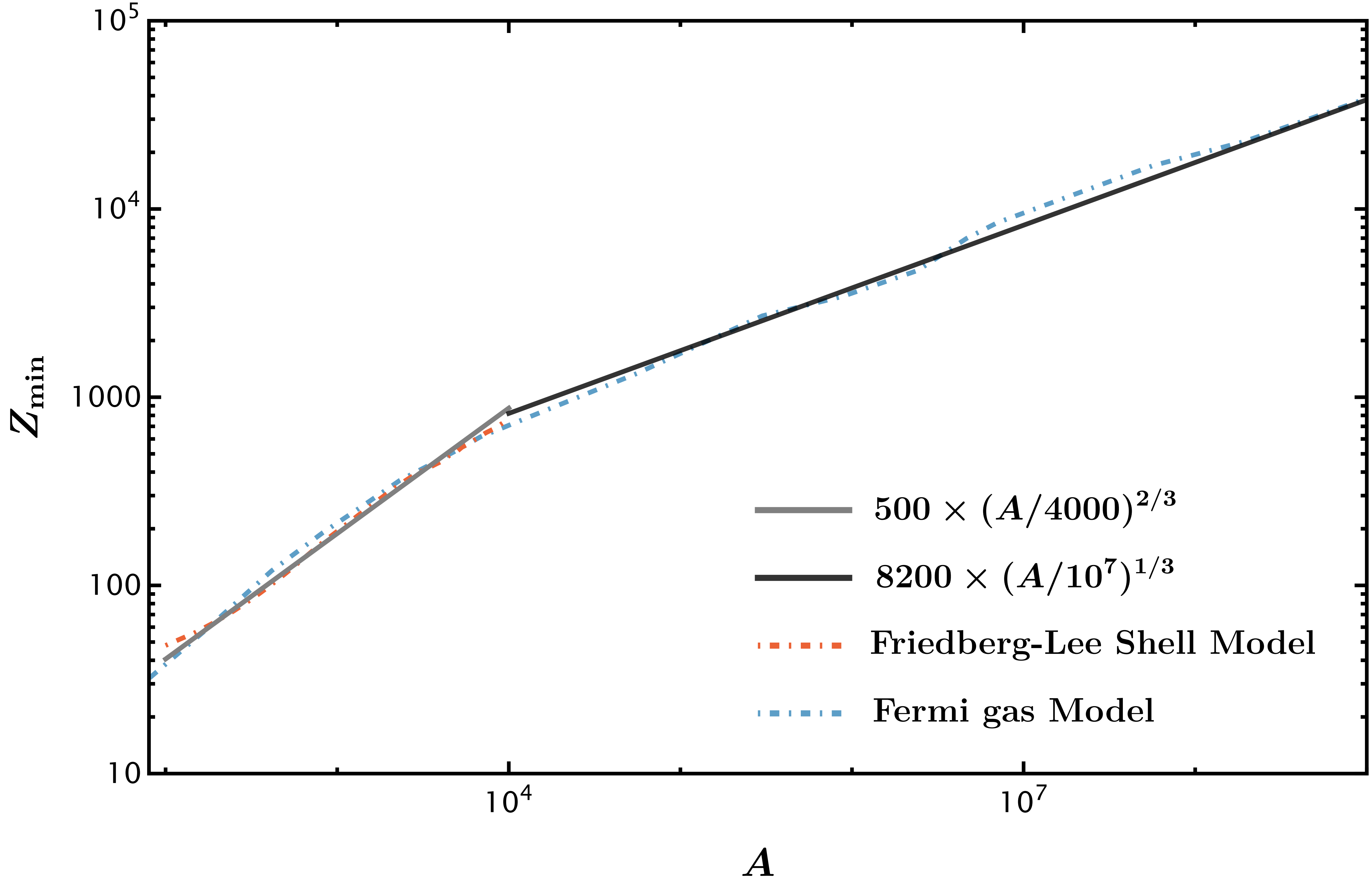
Energy of quark nuggets

- **Add electrons to neutralize the total electric charge**

$$\epsilon_e = \int_0^{p_{F,e}} \frac{2}{(2\pi)^3} d^3p \sqrt{p^2 + m_e^2}$$

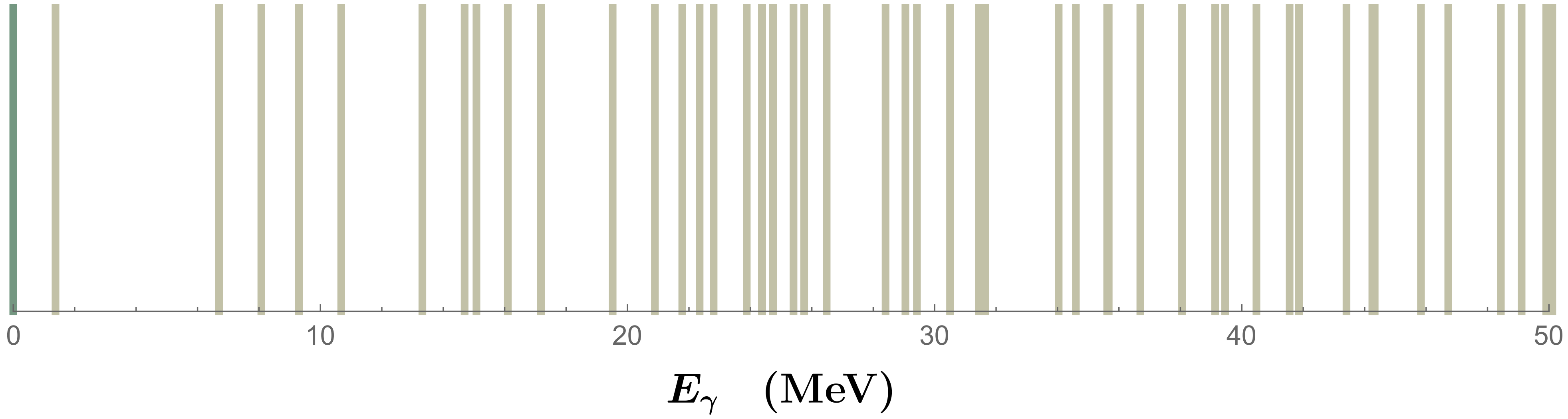


Charge over mass

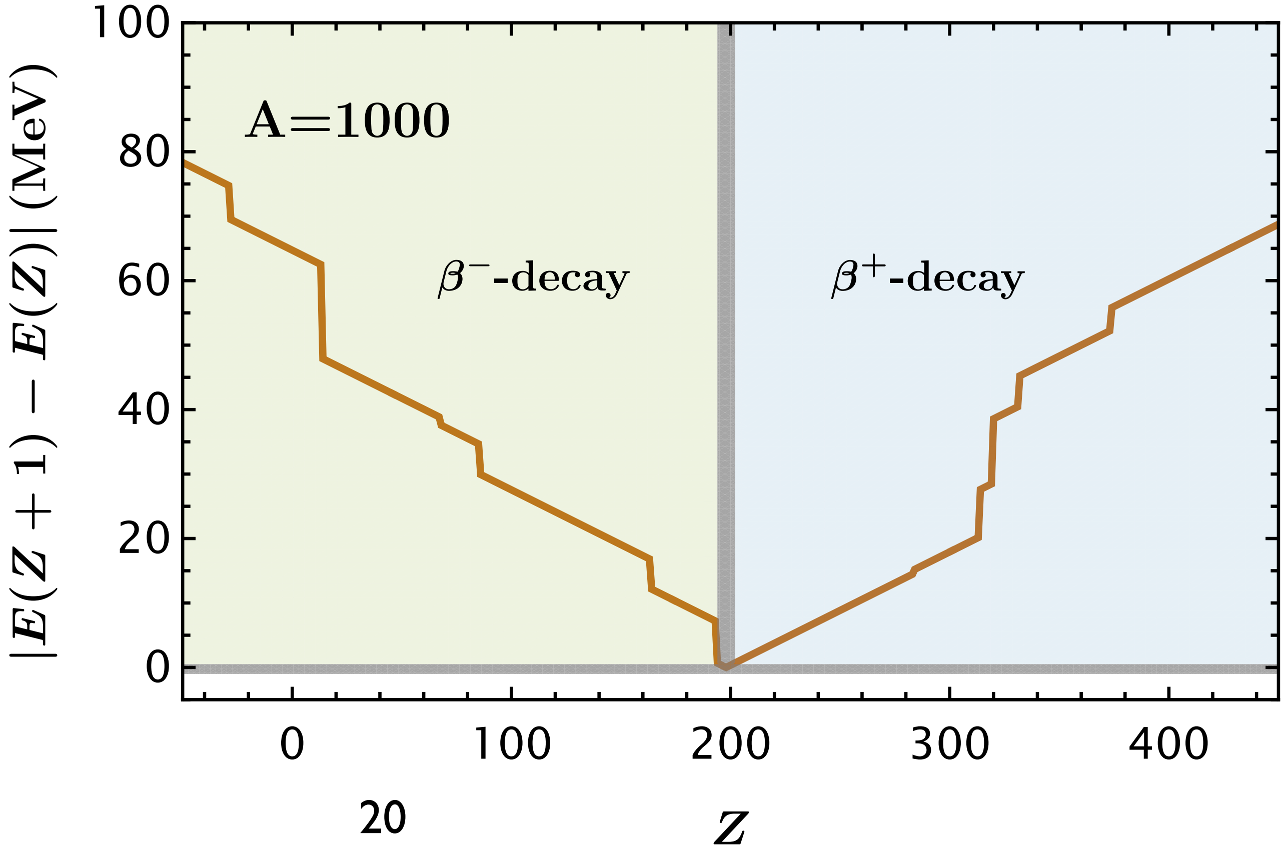


Radioactivity of quark nugget

- **Gamma-decay**



- **Beta-decay**



More precise solutions

- **Solving the coupled scalar and fermion EOM's**

$$(i\gamma^\mu\partial_\mu - m_q(r))\psi(t,\mathbf{r}) = \mathbf{0}$$

$$\psi_{nljm}(\boldsymbol{r}) = \begin{pmatrix} i\, f_{nlj}(r)\, \mathcal{Y}_{ljm}(\hat{\boldsymbol{r}}) \\ g_{nlj}(r)\, \vec{\sigma}\cdot\hat{\boldsymbol{r}}\mathcal{Y}_{ljm}(\hat{\boldsymbol{r}}) \end{pmatrix} = \begin{pmatrix} i\, \frac{a_{nlj}(r)}{r}\, \mathcal{Y}_{ljm}(\hat{\boldsymbol{r}}) \\ \frac{b_{nlj}(r)}{r}\, \vec{\sigma}\cdot\hat{\boldsymbol{r}}\mathcal{Y}_{ljm}(\hat{\boldsymbol{r}}) \end{pmatrix}$$

$$\frac{da_{nlj}}{dr} = \frac{\kappa_{lj}}{r}a_{nlj}(r) + [m_q(r) + E]\, b_{nlj}(r)$$

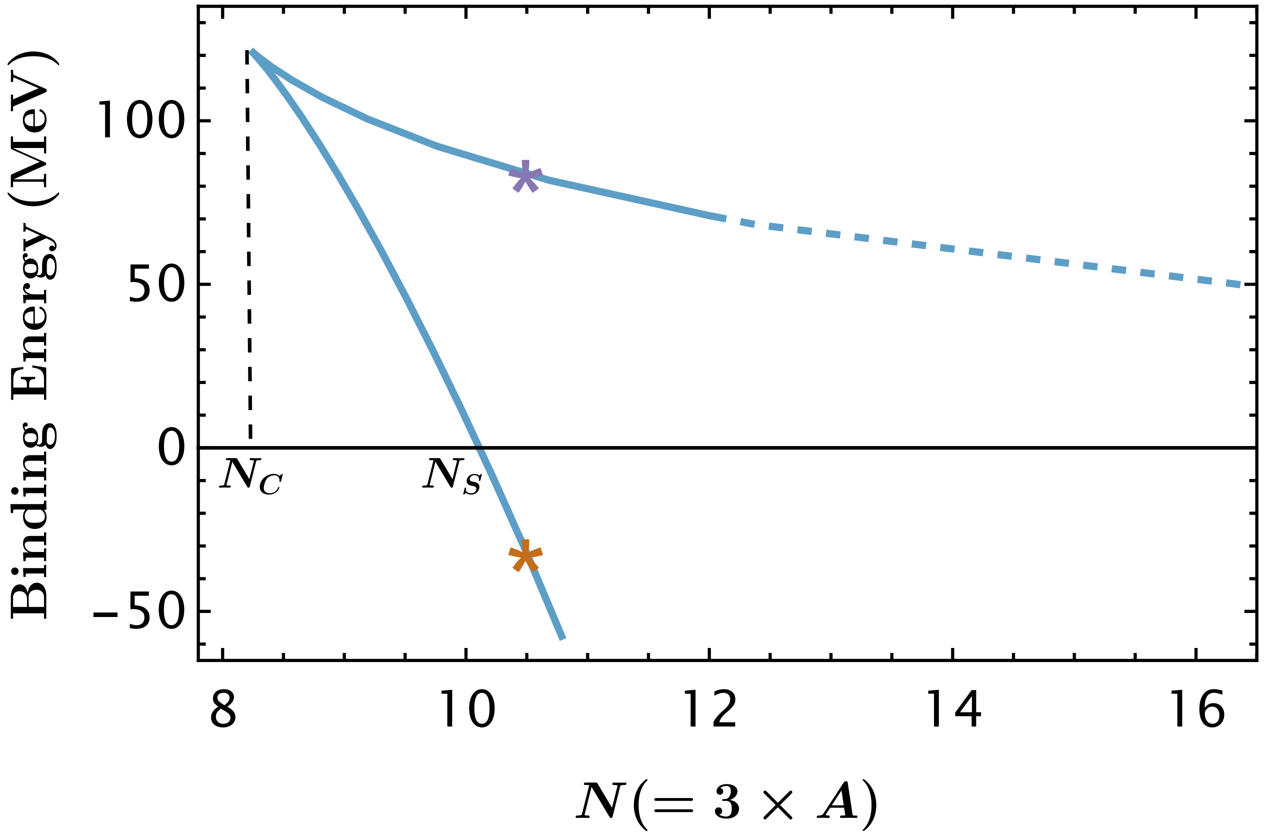
$$\kappa_{lj} = \frac{1}{2} \pm (l + \frac{1}{2})$$

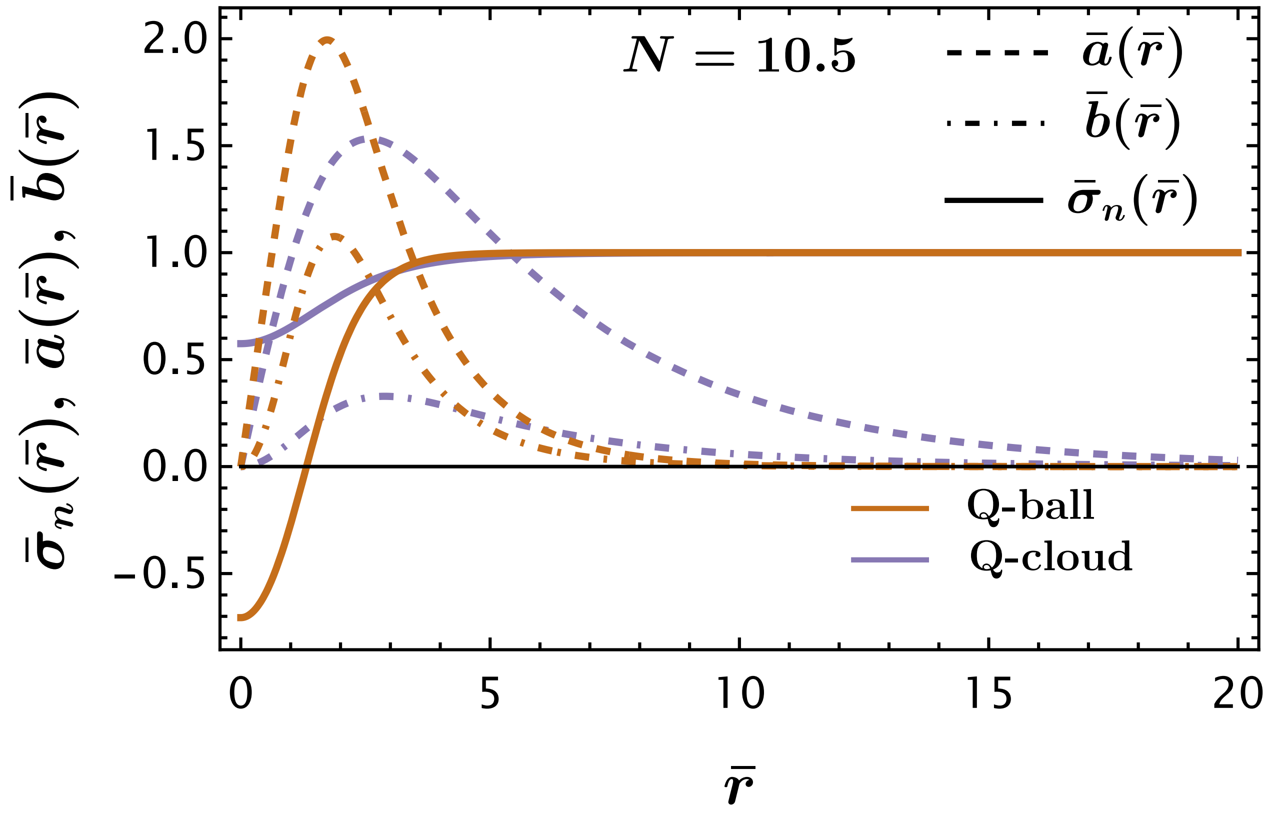
$$\frac{db_{nlj}}{dr} = [m_q(r) - E]\, a_{nlj}(r) - \frac{\kappa_{lj}}{r}b_{nlj}(r)$$

$$\frac{d\sigma}{dr^2} + \frac{2}{r}\,\frac{d\sigma}{dr} = \frac{dV}{d\sigma} + g\, N_c\, \frac{1}{r^2}(a_{nlj}^2 - b_{nlj}^2)$$

$$a_{nlj}(\infty) = 0, \quad b_{nlj}(0) = 0, \quad \sigma(\infty) = v_n \quad d\sigma/dr(r = 0) = 0$$

Q_c vs Q_s





$$\tau \approx (g\, v_n)^{-1}\, e^{\#\,(N-N_c)} \qquad \text{for} \qquad N_c < N < N_s$$

- **Some light quark nuggets could be metastable and eventually evaporate to ordinary nucleons**

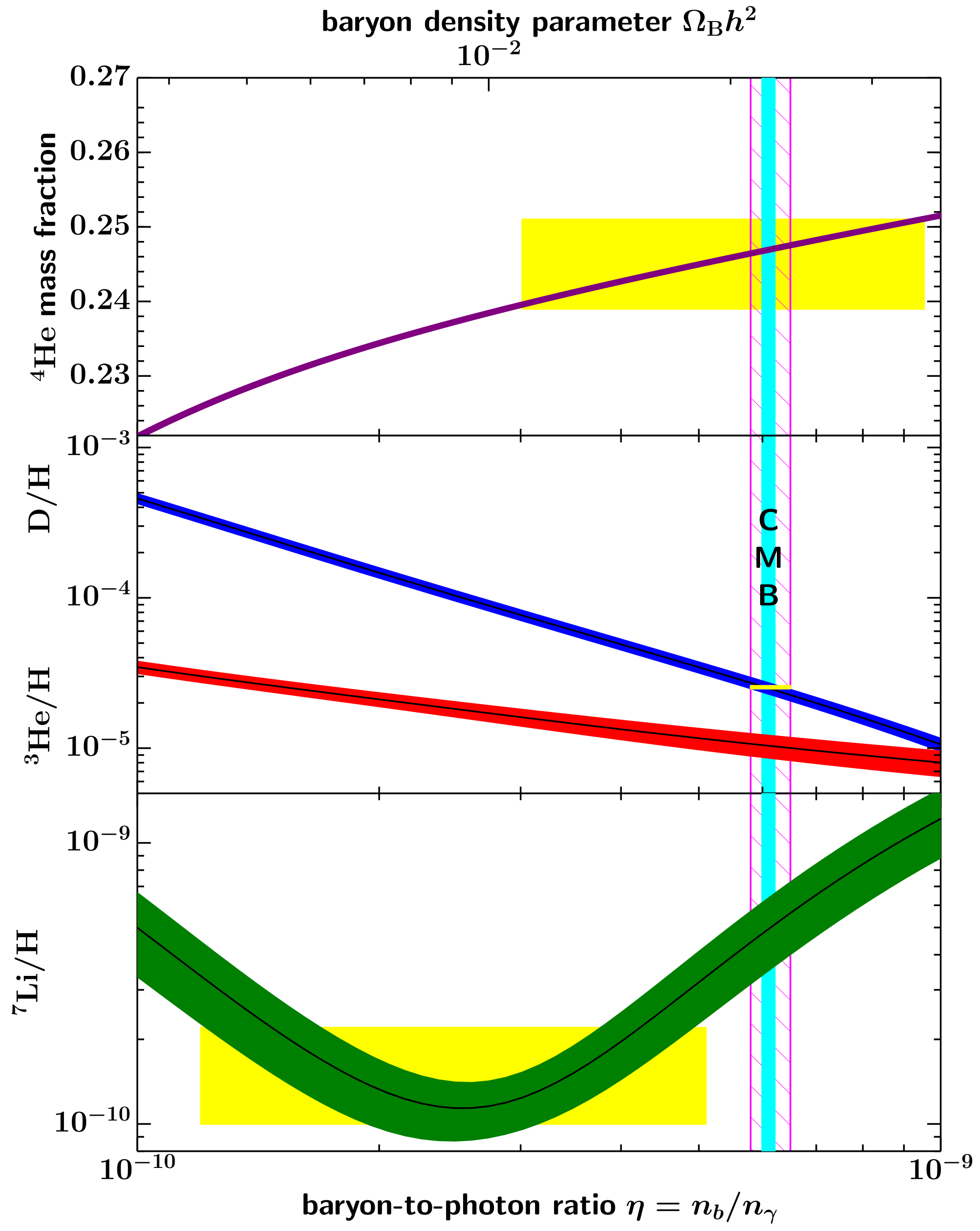
Levkov, Nugget, Popescu, 1711.05279

Son, Stephanov, Yee, 2112.03318

How to form it?

Origin for ordinary nuclei

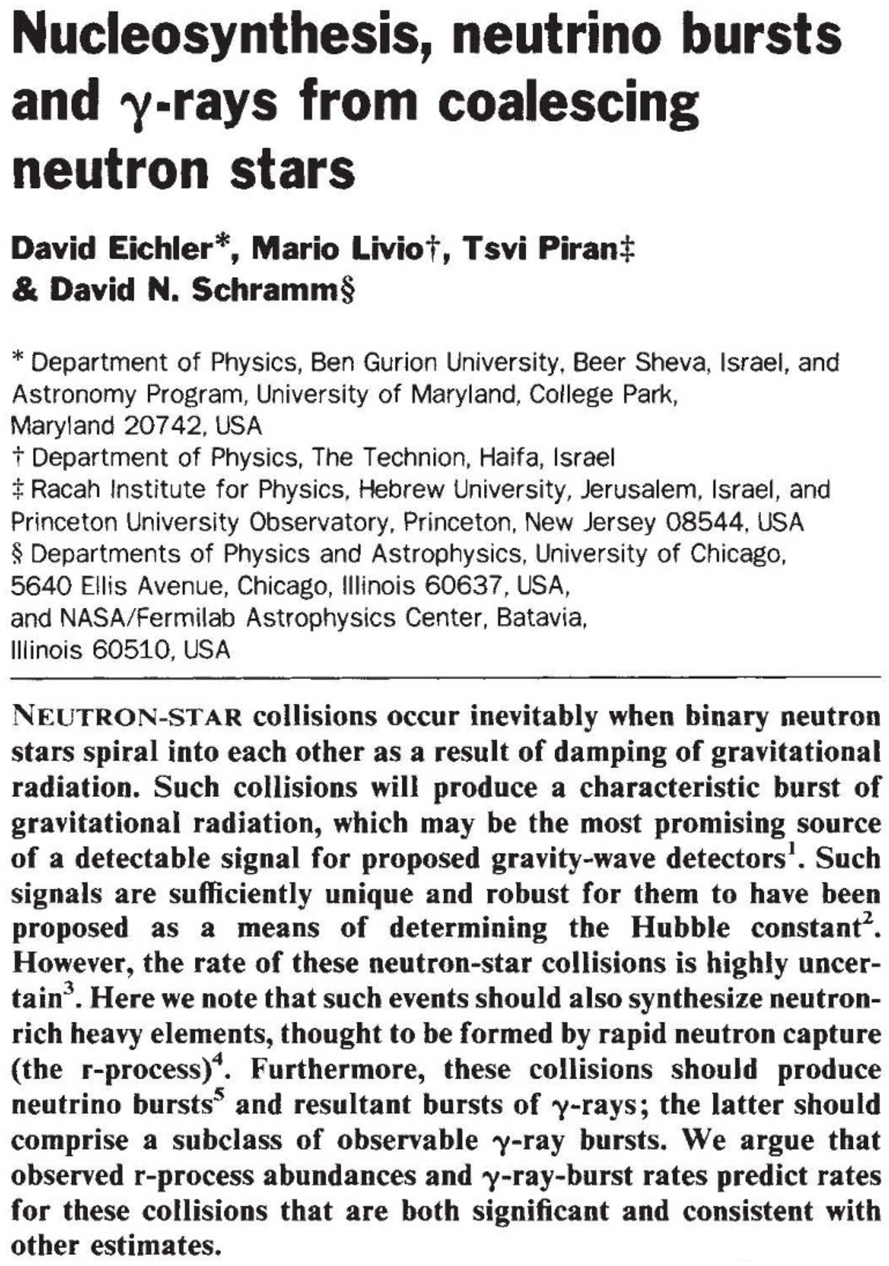
- **Baryon anti-baryon asymmetry (unknown)**
- **Light elements from nucleosynthesis**



PDG 2022

Origin for ordinary nuclei

- **Heavy elements from nucleosynthesis of neutron star mergers**



Nucleosynthesis, neutrino bursts and γ-rays from coalescing neutron stars

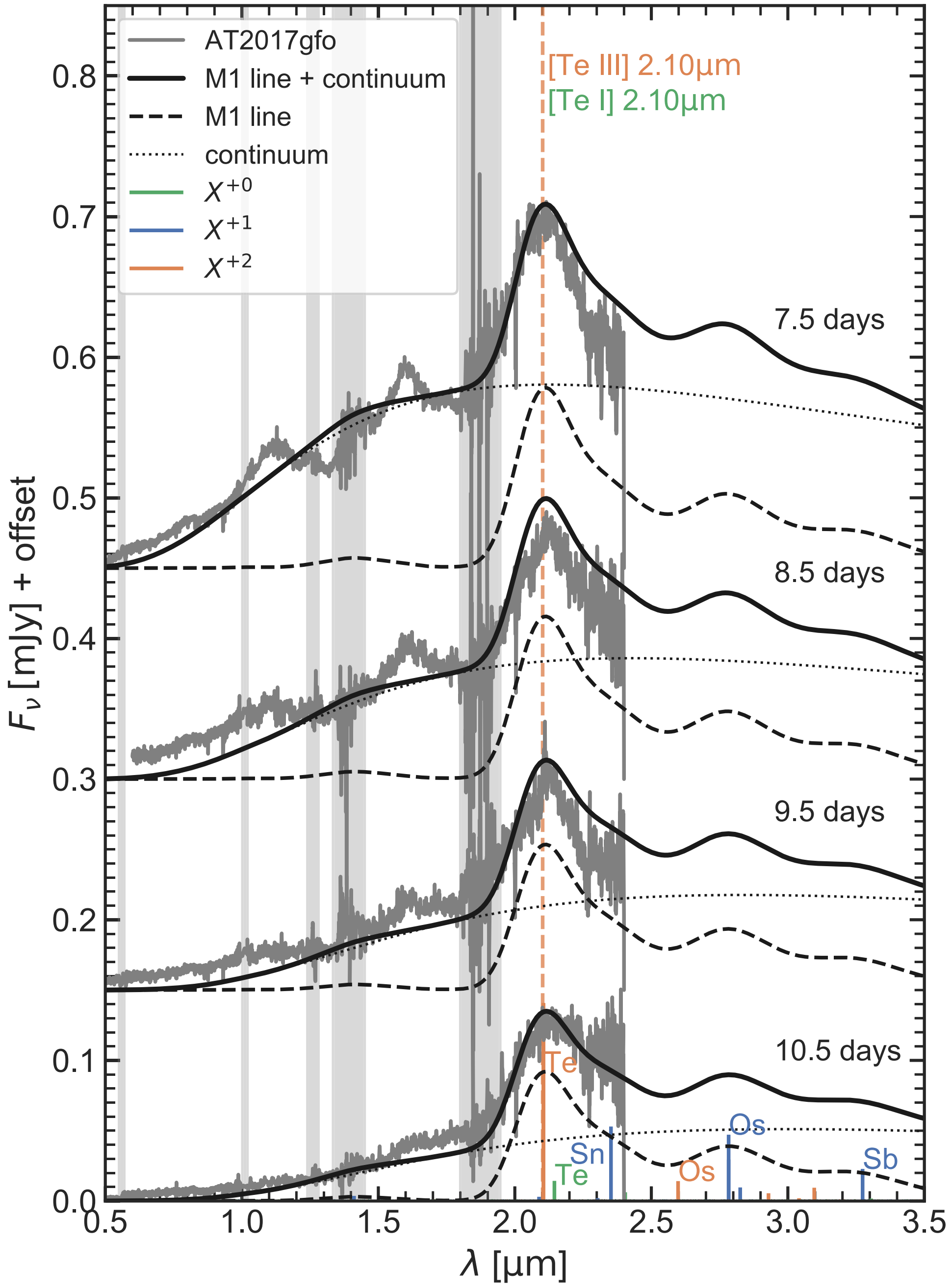
David Eichler*, Mario Livio†, Tsvi Piran‡ & David N. Schramm§

* Department of Physics, Ben Gurion University, Beer Sheva, Israel, and Astronomy Program, University of Maryland, College Park, Maryland 20742, USA
† Department of Physics, The Technion, Haifa, Israel
‡ Racah Institute for Physics, Hebrew University, Jerusalem, Israel, and Princeton University Observatory, Princeton, New Jersey 08544, USA
§ Departments of Physics and Astrophysics, University of Chicago, 5640 Ellis Avenue, Chicago, Illinois 60637, USA, and NASA/Fermilab Astrophysics Center, Batavia, Illinois 60510, USA

NEUTRON-STAR collisions occur inevitably when binary neutron stars spiral into each other as a result of damping of gravitational radiation. Such collisions will produce a characteristic burst of gravitational radiation, which may be the most promising source of a detectable signal for proposed gravity-wave detectors[1]. Such signals are sufficiently unique and robust for them to have been proposed as a means of determining the Hubble constant[2]. However, the rate of these neutron-star collisions is highly uncertain[3]. Here we note that such events should also synthesize neutron-rich heavy elements, thought to be formed by rapid neutron capture (the r-process)[4]. Furthermore, these collisions should produce neutrino bursts[5] and resultant bursts of γ-rays; the latter should comprise a subclass of observable γ-ray bursts. We argue that observed r-process abundances and γ-ray-burst rates predict rates for these collisions that are both significant and consistent with other estimates.

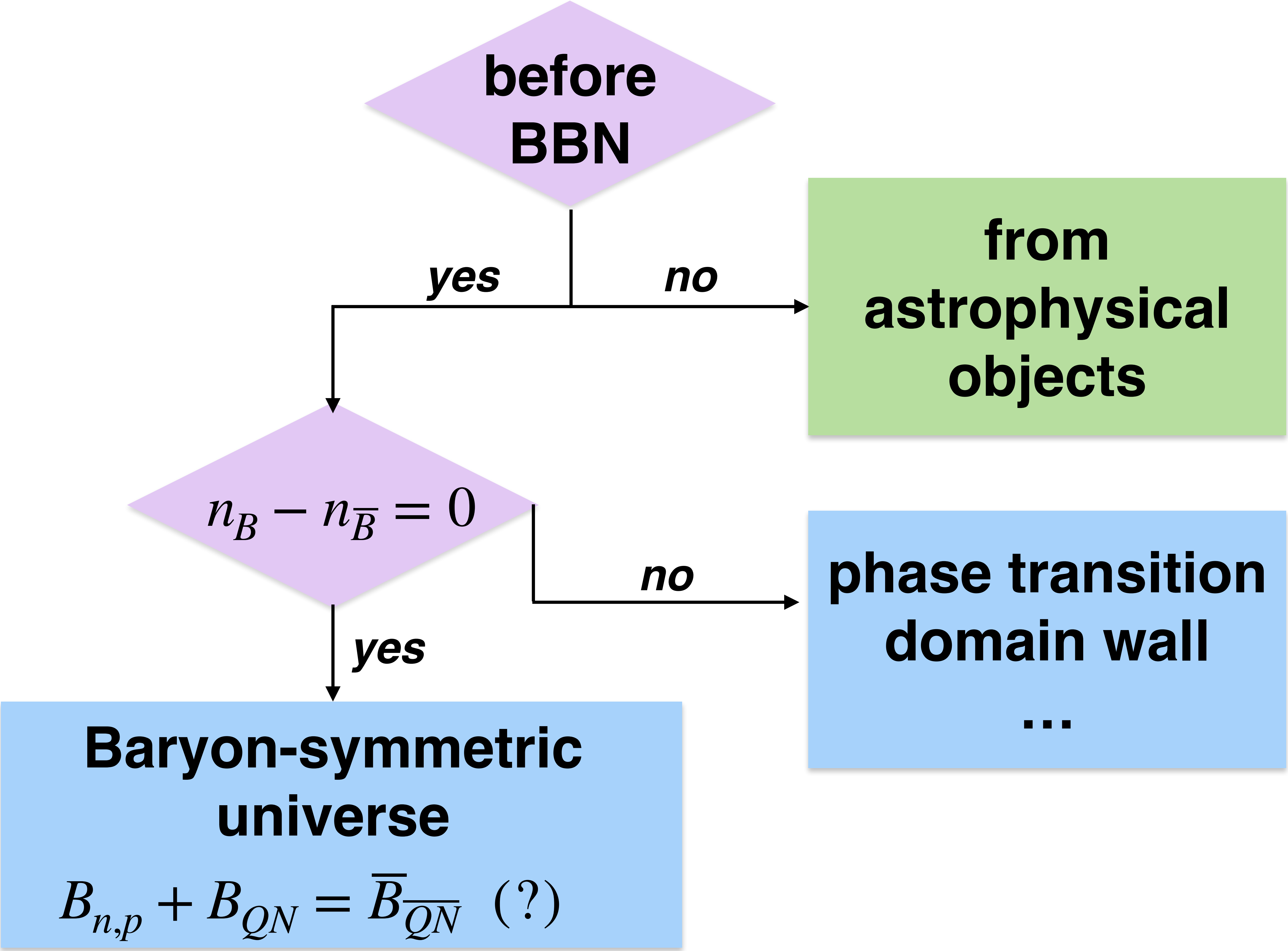
Nature, Vol 340, 126 (1989)

GW170817



Hotokezaka, MNRAS, 526, L155-L159 (2023)

Formation of quark nuggets



before BBN

yes

no

from astrophysical objects

$n_B - n_{\overline{B}} = 0$

no

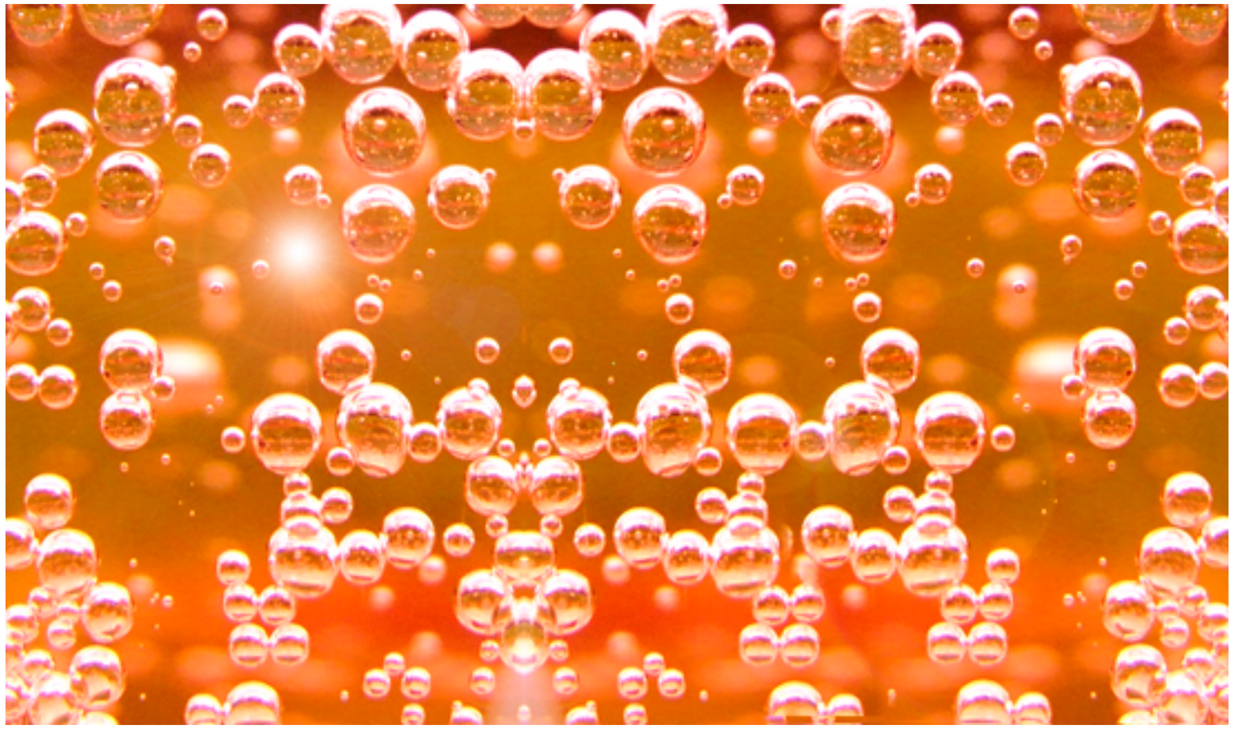
phase transition
domain wall
...

yes

Baryon-symmetric universe

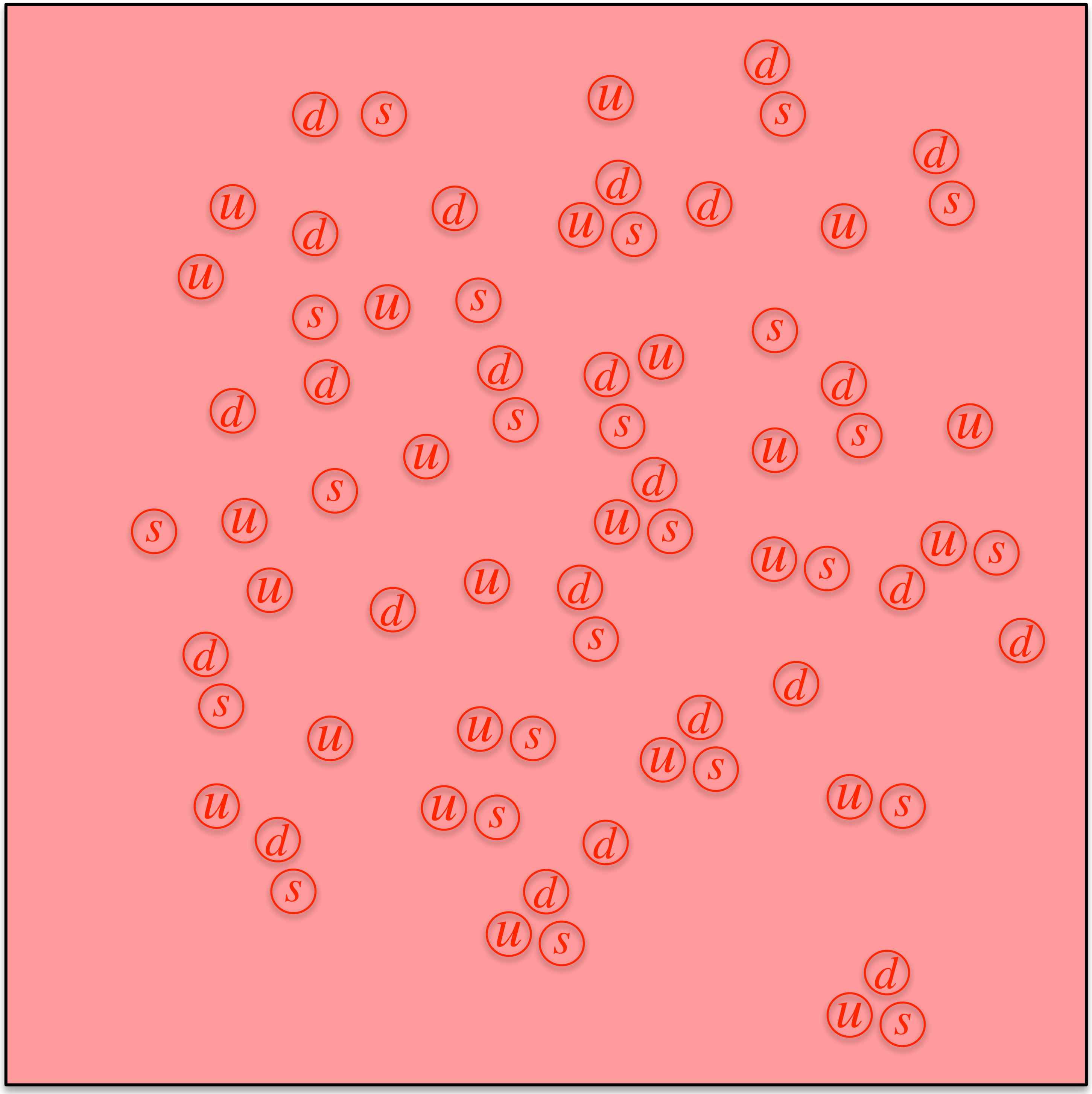
$B_{n,p} + B_{QN} = \overline{B}_{\overline{QN}} \quad (?)$

Formation from 1’st order phase transition



Witten, ’1984

T > Tc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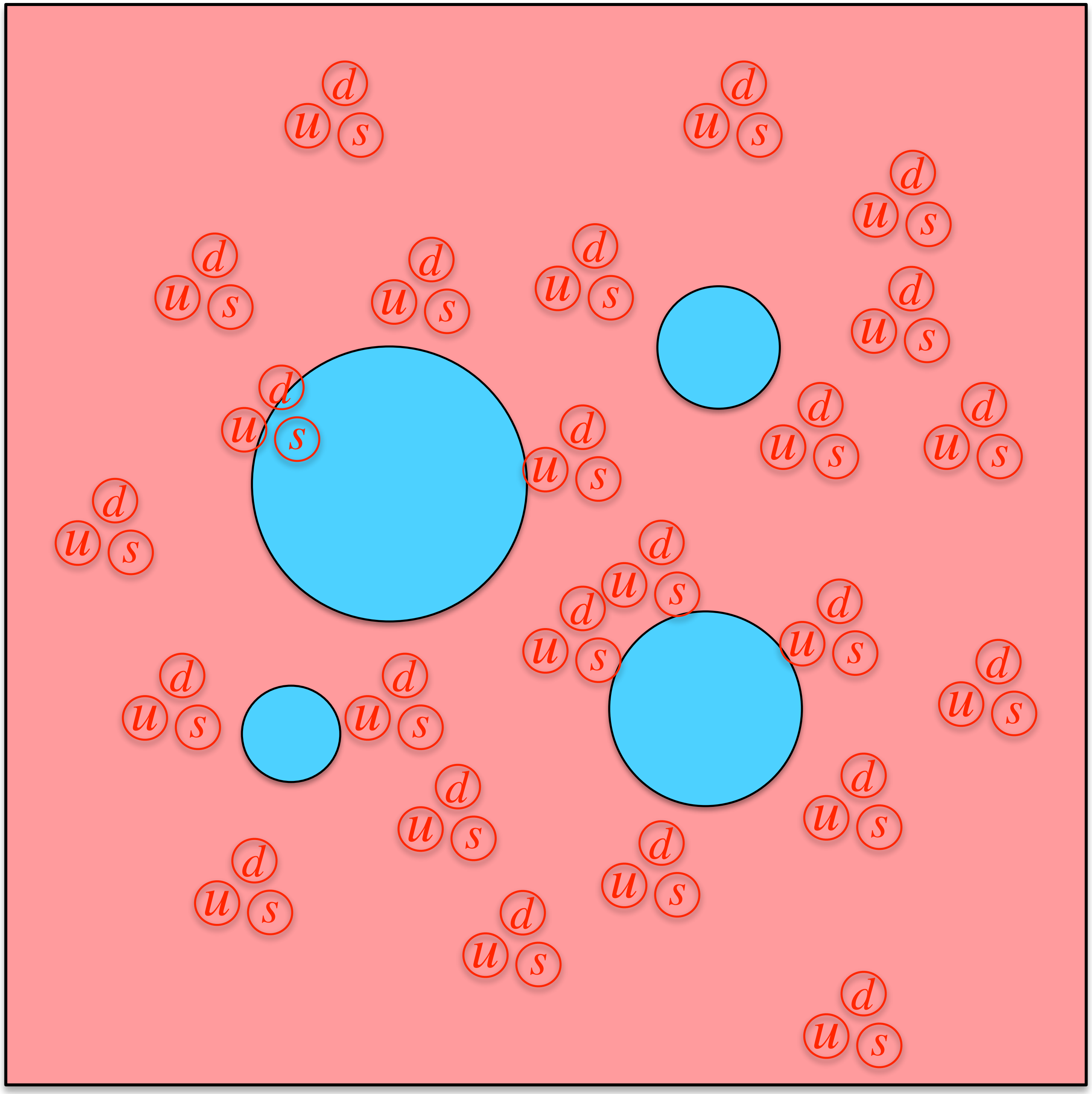
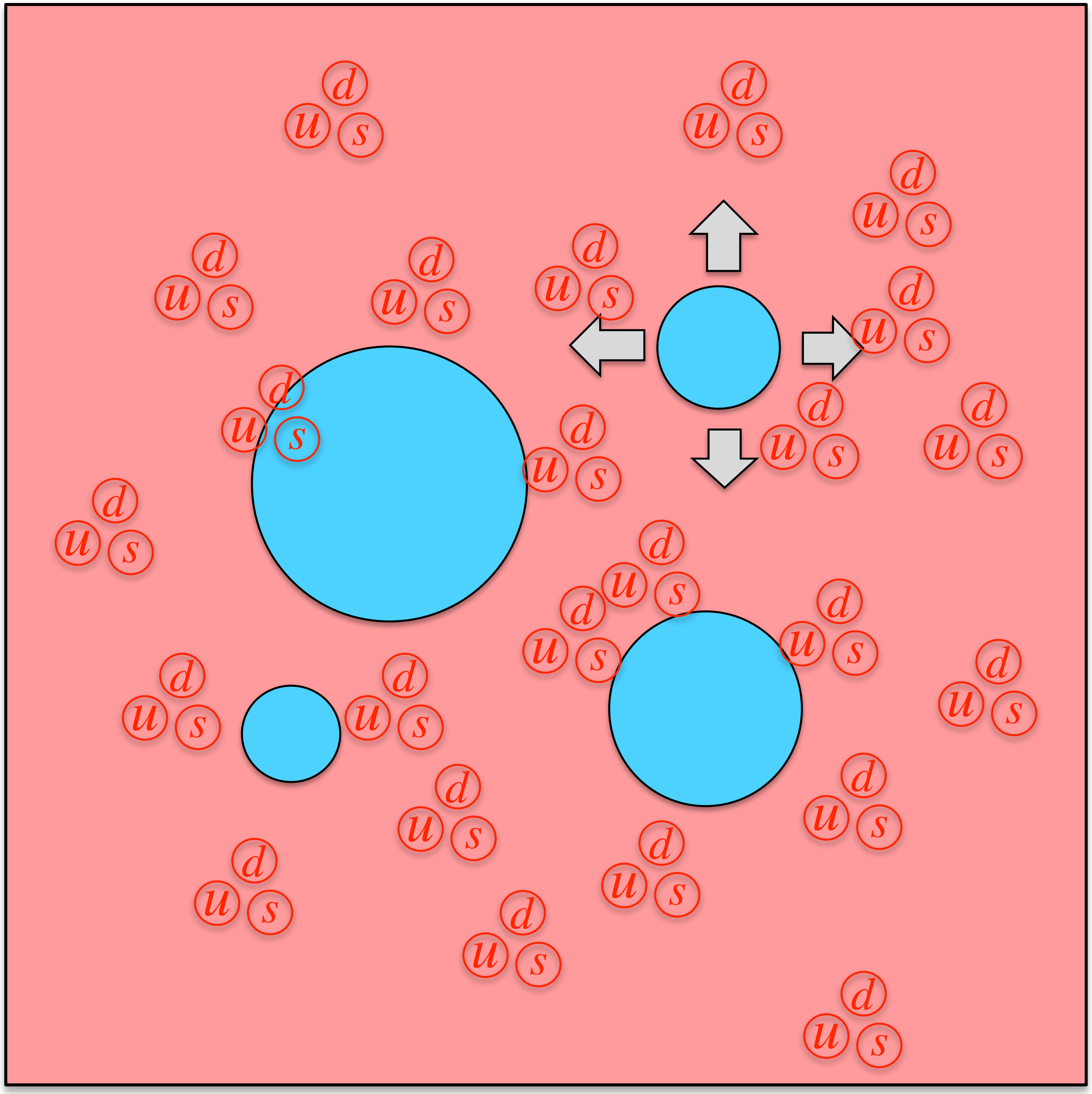
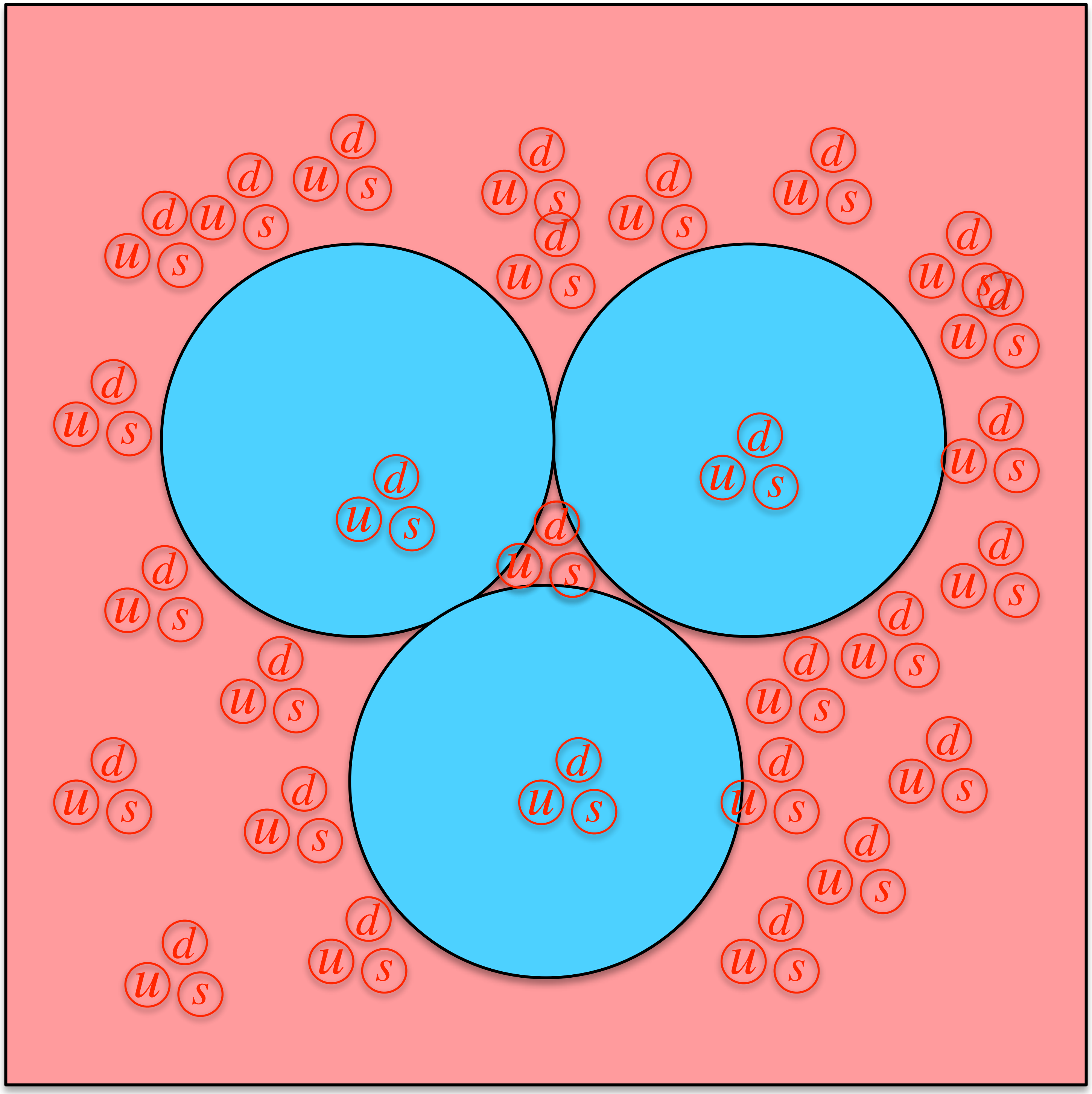
T ~ Tc



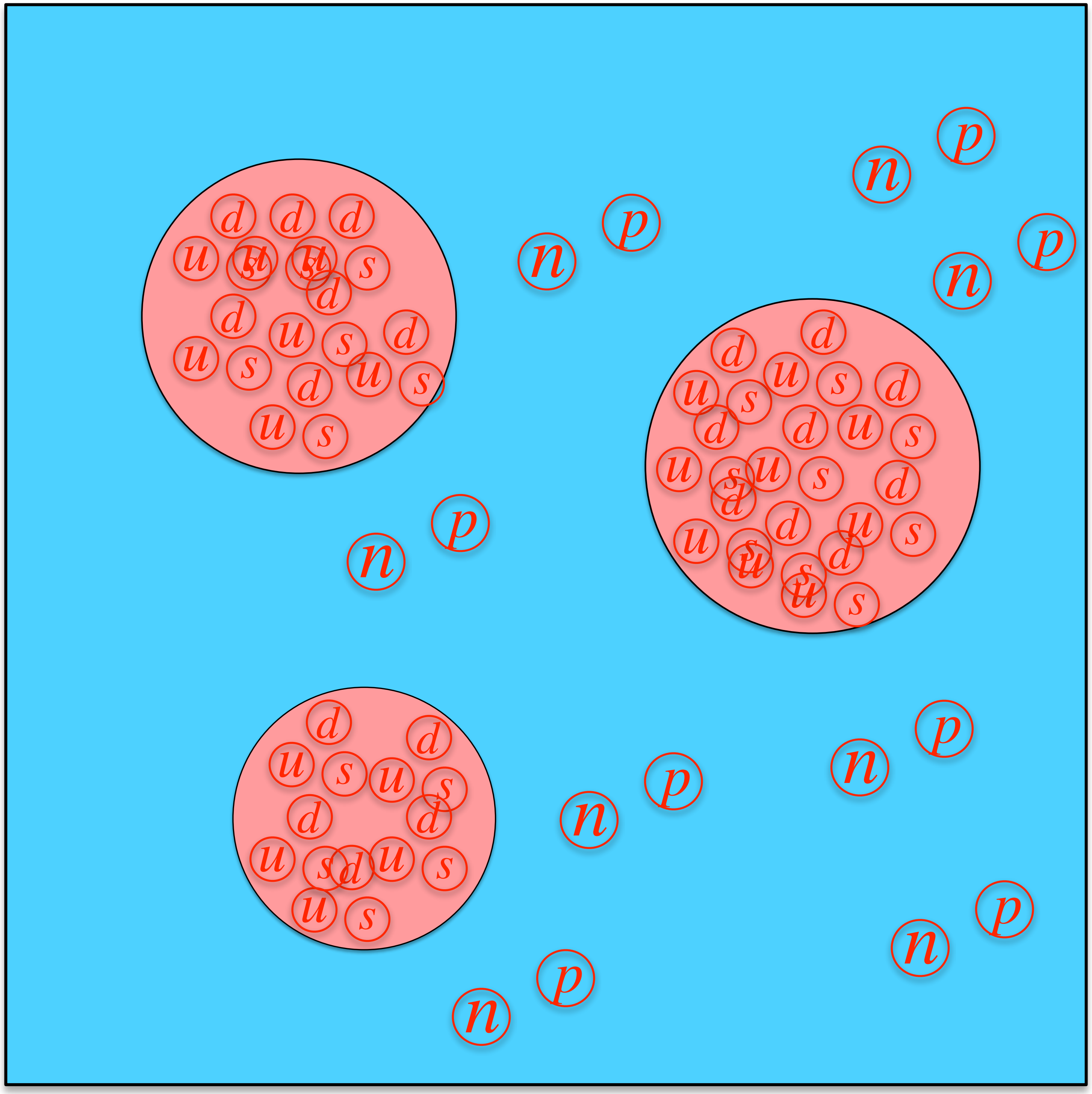
T ~ Tc



Hadron bubbles grow



Isolated quark nuggets



Properties of quark nuggets

- **The mass of the quark nugget is**

$$M_{\mathrm{QN}} \sim 10^{14}\,\mathrm{g}$$

- **The radius of the quark nugget is**

$$R_{\mathrm{QN}} \sim 1\,\mathrm{cm}$$

Properties of quark nuggets

- **The mass of the quark nugget is**

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Properties of quark nuggets

- The mass of the quark nugget is

$$M_{\rm QN} \sim 10^{14}\,\mathrm{g}$$

- The radius of the quark nugget is

$$R_{\rm QN} \sim 1\,\mathrm{cm}$$

- The energy density of the QM is similar to a Neutron Star, except with a much smaller radius

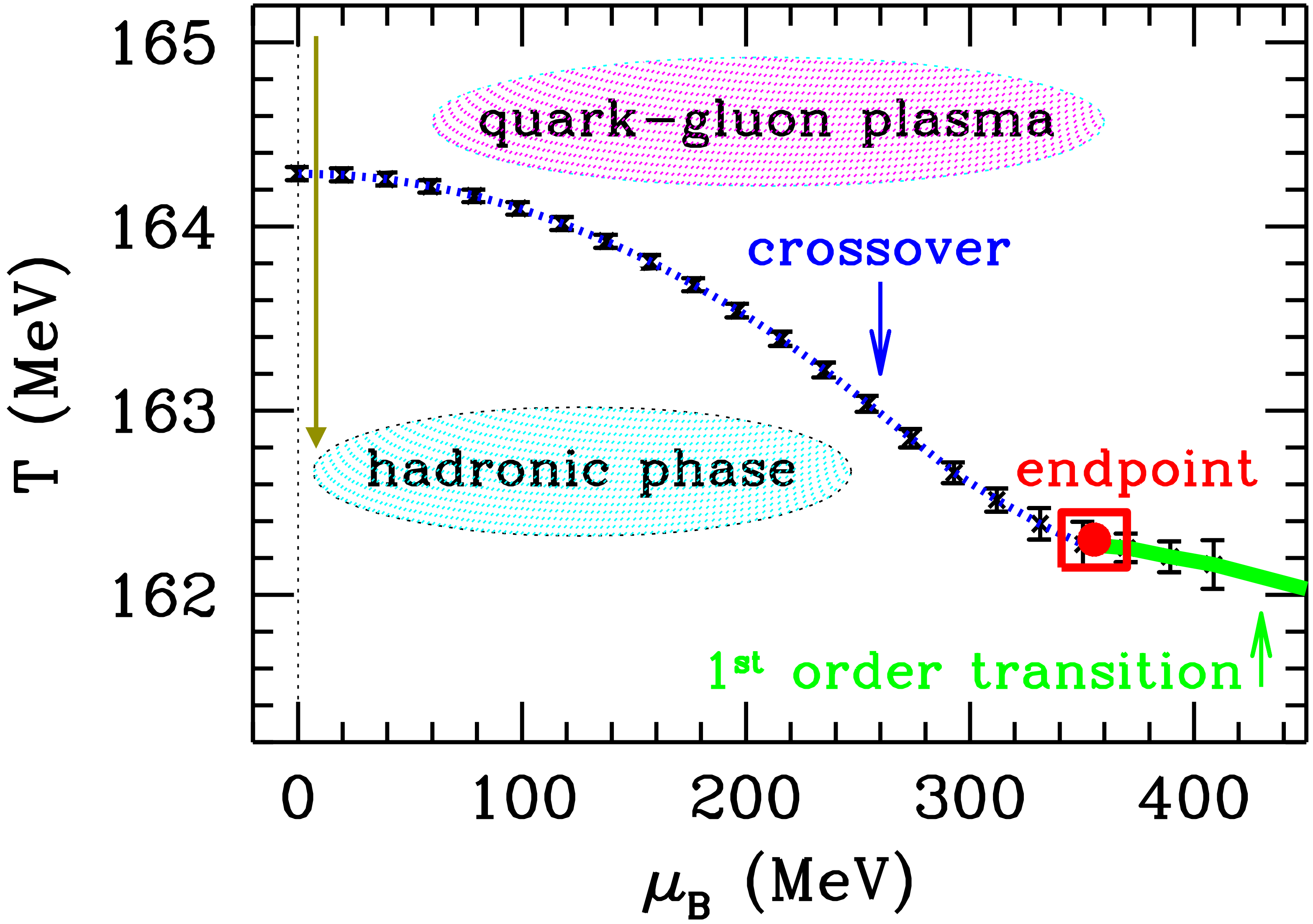
“micro Neutron Star”

- One example of Macroscopic Dark Matter

QCD phase transition

- **Crossover in the minimal Standard Model of Particle Physics with the normal early universe history**

Fodor and Katz, '2004



How to have QCD 1’st-order PT?

- Making the strange quark lighter during the transition time (FOPT for 3 massless quarks)

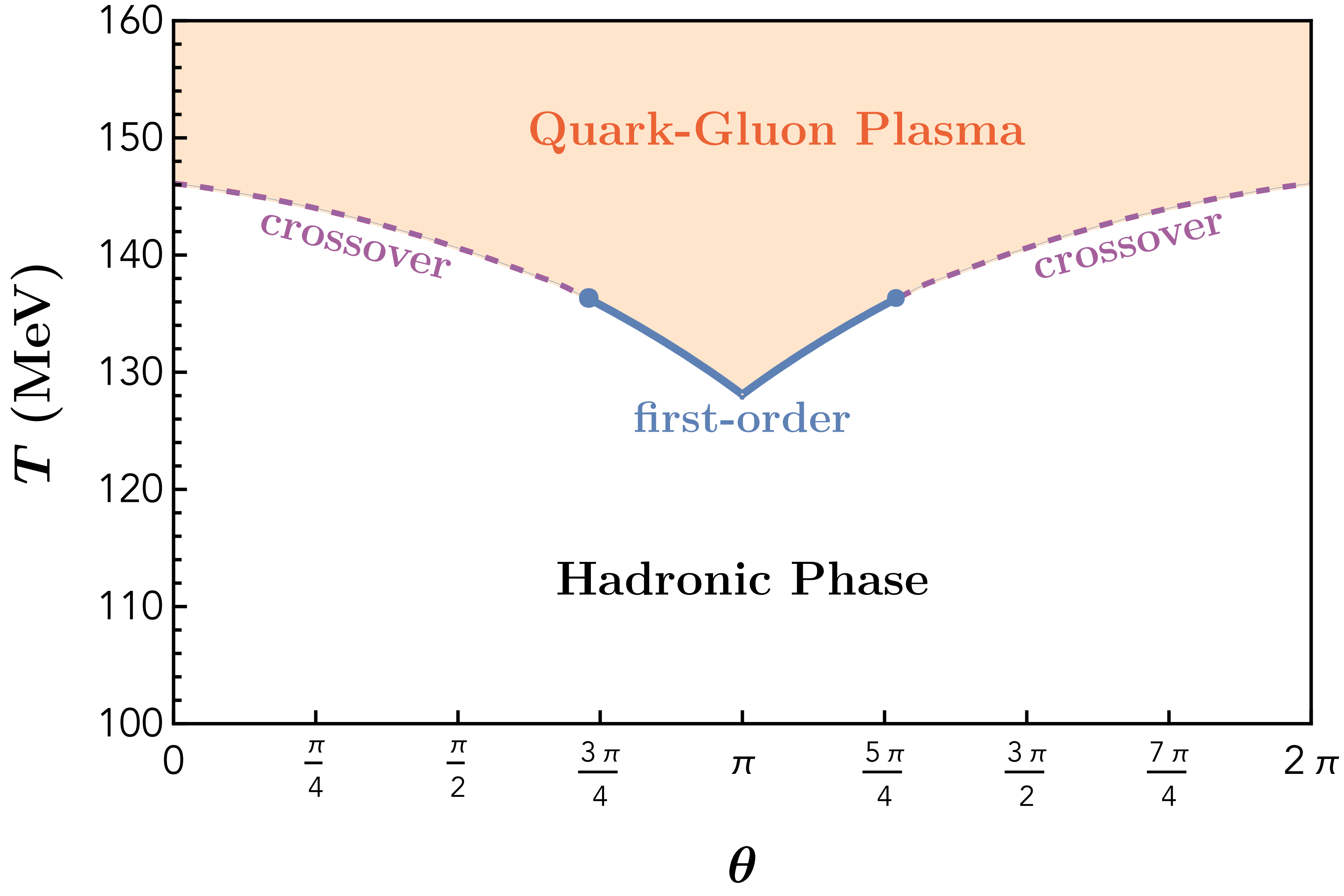
  For instance, using Froggatt-Nielsen fields to dynamically control quark masses (suffers fine-tuning and flavor constraints)

- Supercool the electroweak phase transition to be below the QCD scale (requires a non-trivial flat potential)

- Existing a large lepton number chemical potential (suffers from BBN and CMB constraints)

QCD phase transition with $\theta \neq 0$

$$\mathscr{L} \supset -\frac{1}{32\pi^2} G^{\mu\nu} \widetilde{G}_{\mu\nu} \theta$$

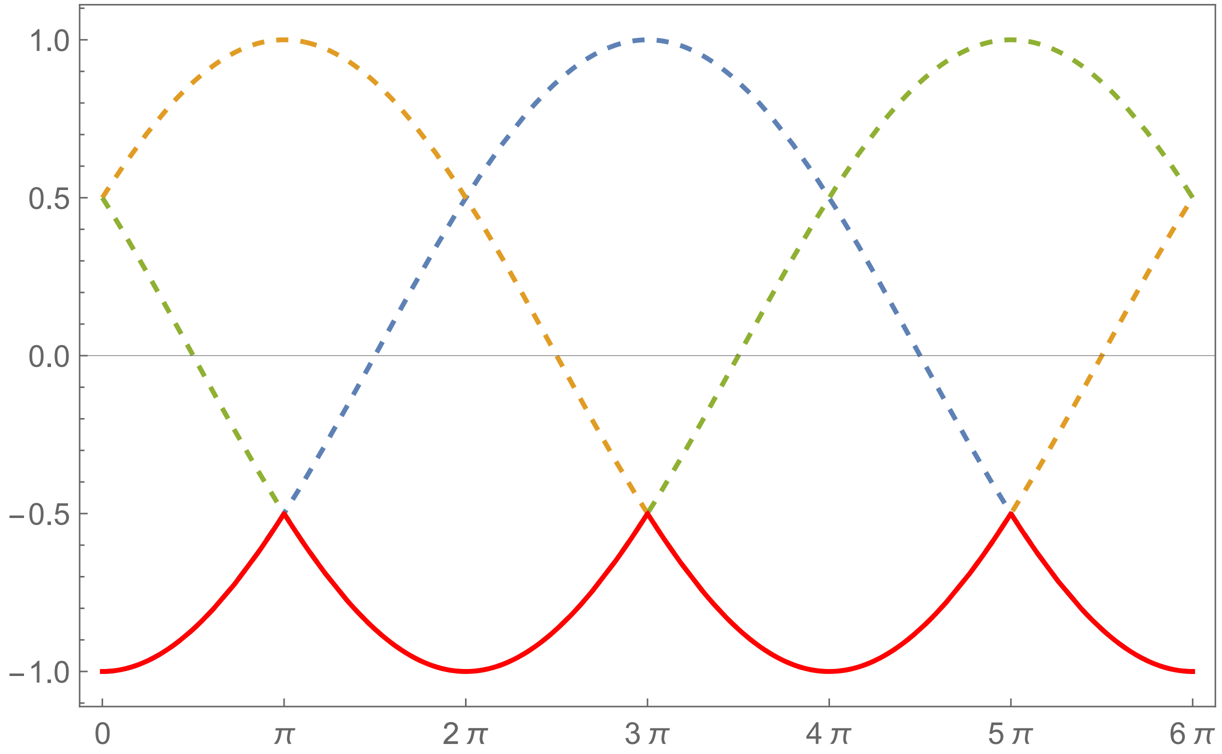


YB, Chen, Korwar, JHEP 12 (2023) 194

QCD with $\theta = \pi$

- In large N_c, the periodicity in θ and continuity of the vacuum energy function suggests a multibranched function

$$V(\theta) = -N_c^2\,\Lambda^4\,\mathrm{min}_k\left[\cos\left(\frac{\theta + 2\pi k}{N_c}\right)\right], \quad k = 0, \cdots, N_c - 1$$



Dashen '1971; Witten '1980;
Gaiotto, Kapustin, Komargodski, Seiberg, '2017

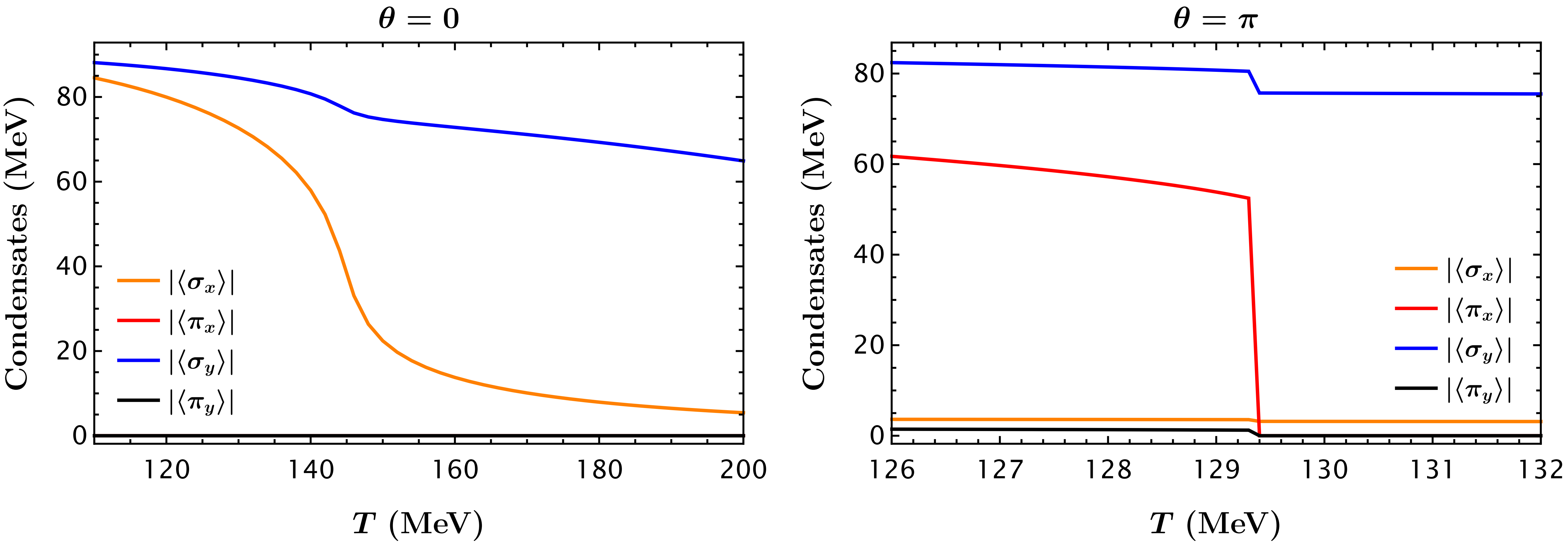
Phenomenological LSMq

$$V(\Phi) = \mu^2 \mathrm{Tr}\left(\Phi^\dagger \Phi\right) + \lambda_1 \left[\mathrm{Tr}\left(\Phi^\dagger\Phi\right)\right]^2 + \lambda_2 \mathrm{Tr}\left[\left(\Phi^\dagger\Phi\right)^2\right]$$

$$-\frac{\kappa}{2}\left[e^{-i\theta}\det(\Phi) + e^{i\theta}\det\left(\Phi^\dagger\right)\right] - \mathrm{Tr}\left[H\left(\Phi + \Phi^\dagger\right)\right]$$

Pisarski, hep-ph/9601316

$$\Phi = T_a\left(\sigma_a + i\pi_a\right) \qquad H = T_a h_a \qquad \mathscr{L}_{\text{Yukawa}} \supset \bar{q}\left[-g T_a\left(\sigma_a + i\gamma^5\pi_a\right)\right] q$$



QCD PT inside domains

- **The early universe could have different domains with different effective θ angle**

0	π	0	π	0
π	0	π	0	π
0	π	0	π	0
π	0	π	0	π

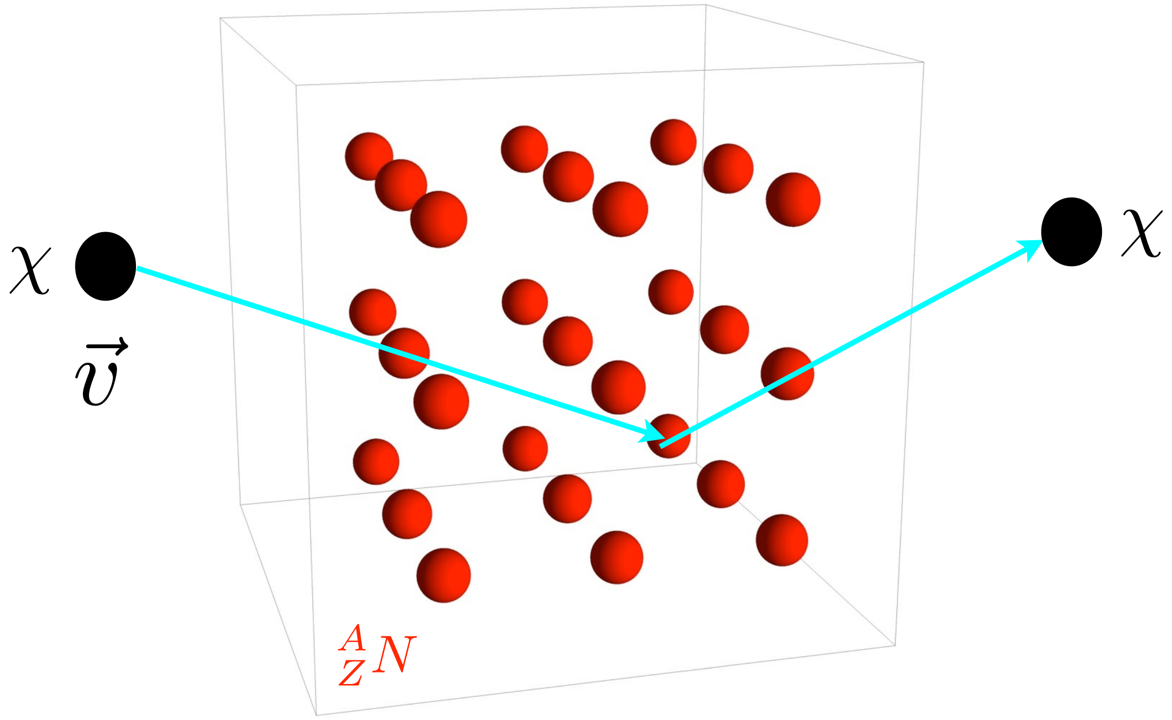
- **One half of the domains could have FOPT for QCD**

YB, Chen, Korwar, 2306.17160

How to find it?

Direct Detection

- **A suppressed flux for a heavy quark nugget as dark matter**

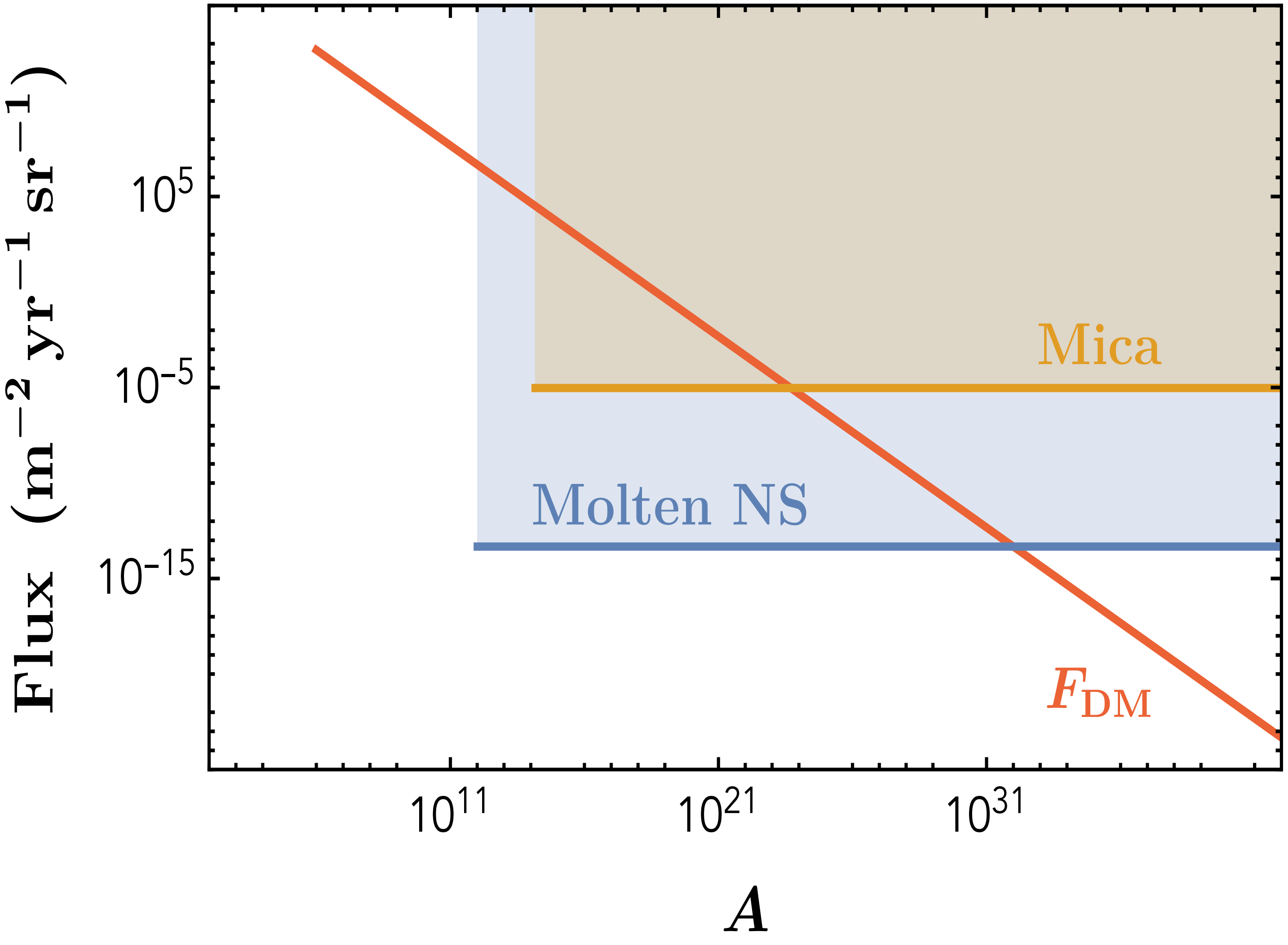


$$1 \sim \frac{\rho_{\rm DM}}{m_{\rm DM}}\, v_{\rm DM}\, A_{\rm det}\, t_{\rm exp} \sim \frac{1\,\mathrm{g}}{m_{\rm DM}}\, \frac{A_{\rm det}}{(100\,\mathrm{m})^2}\, \frac{t_{\rm exp}}{10\,\mathrm{yr}}$$

Detectors with large $A_{\rm det}\, t_{\rm exp}$

De Rujula, Glashow, Nature, 312, 734, (1984)

Madsen, PRL, 61, 2909 (1988)



Detectors with large $A_{\rm det}\, t_{\rm exp}$

De Rujula, Glashow, Nature, 312, 734, (1984)

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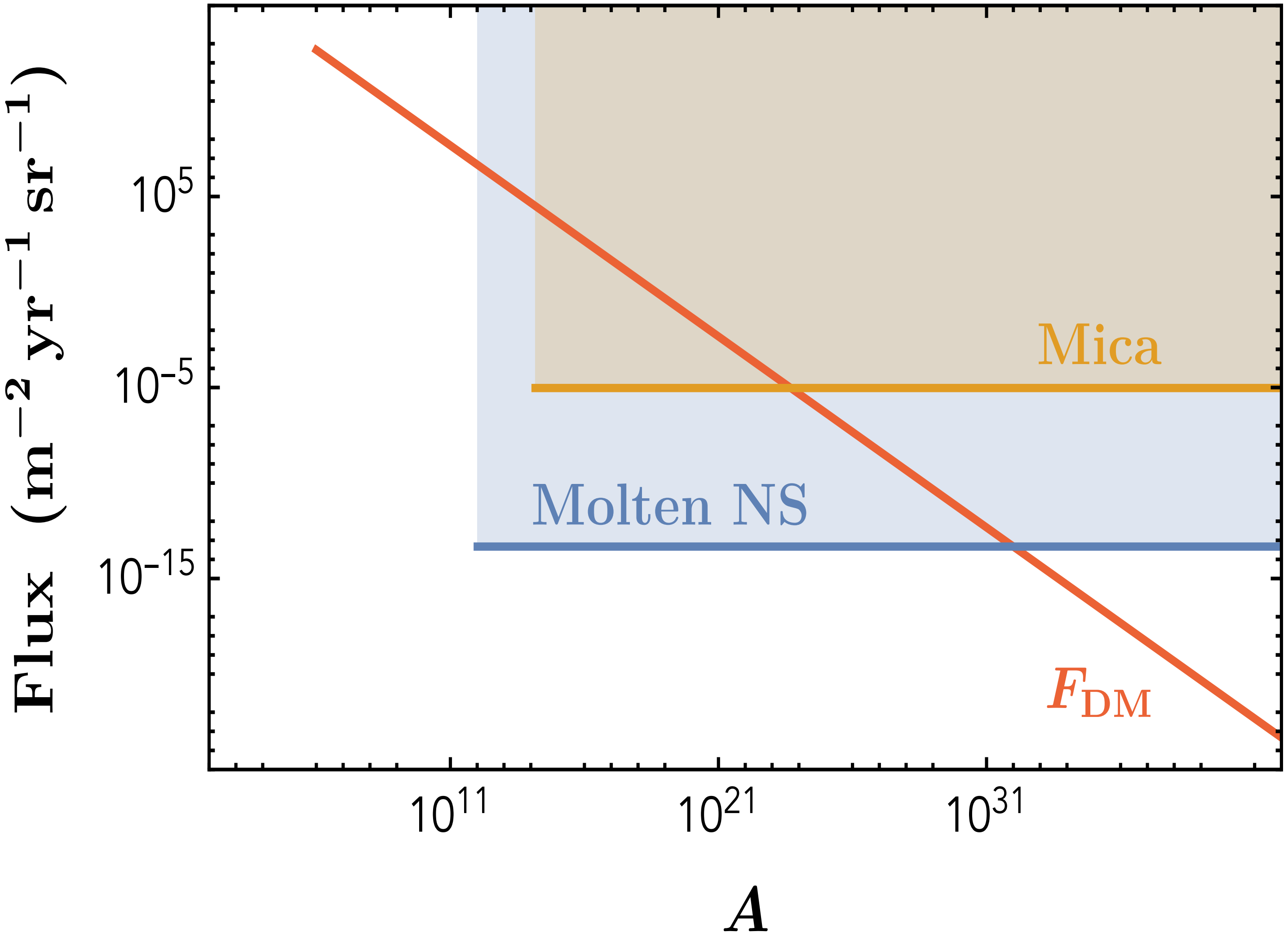
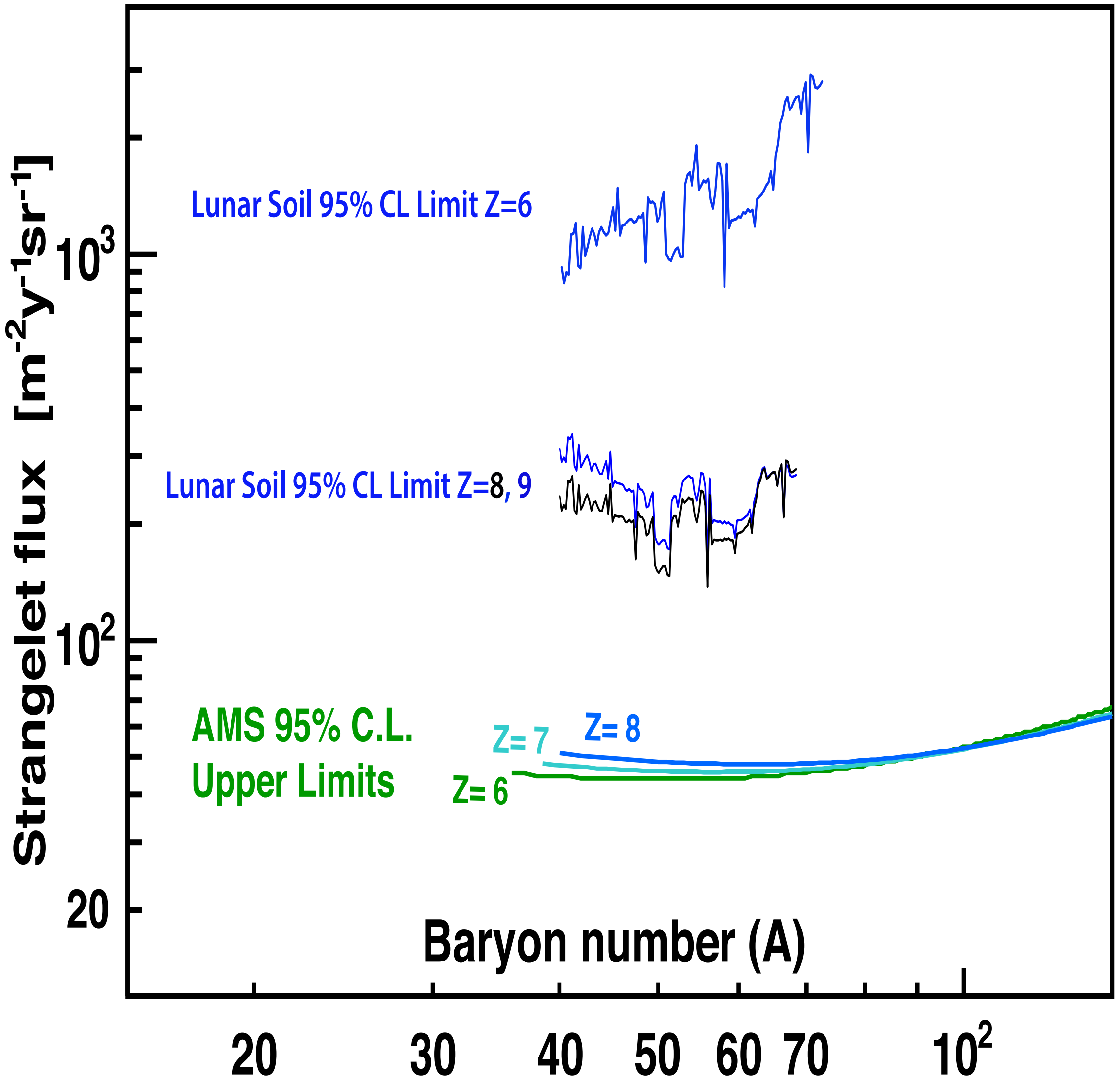
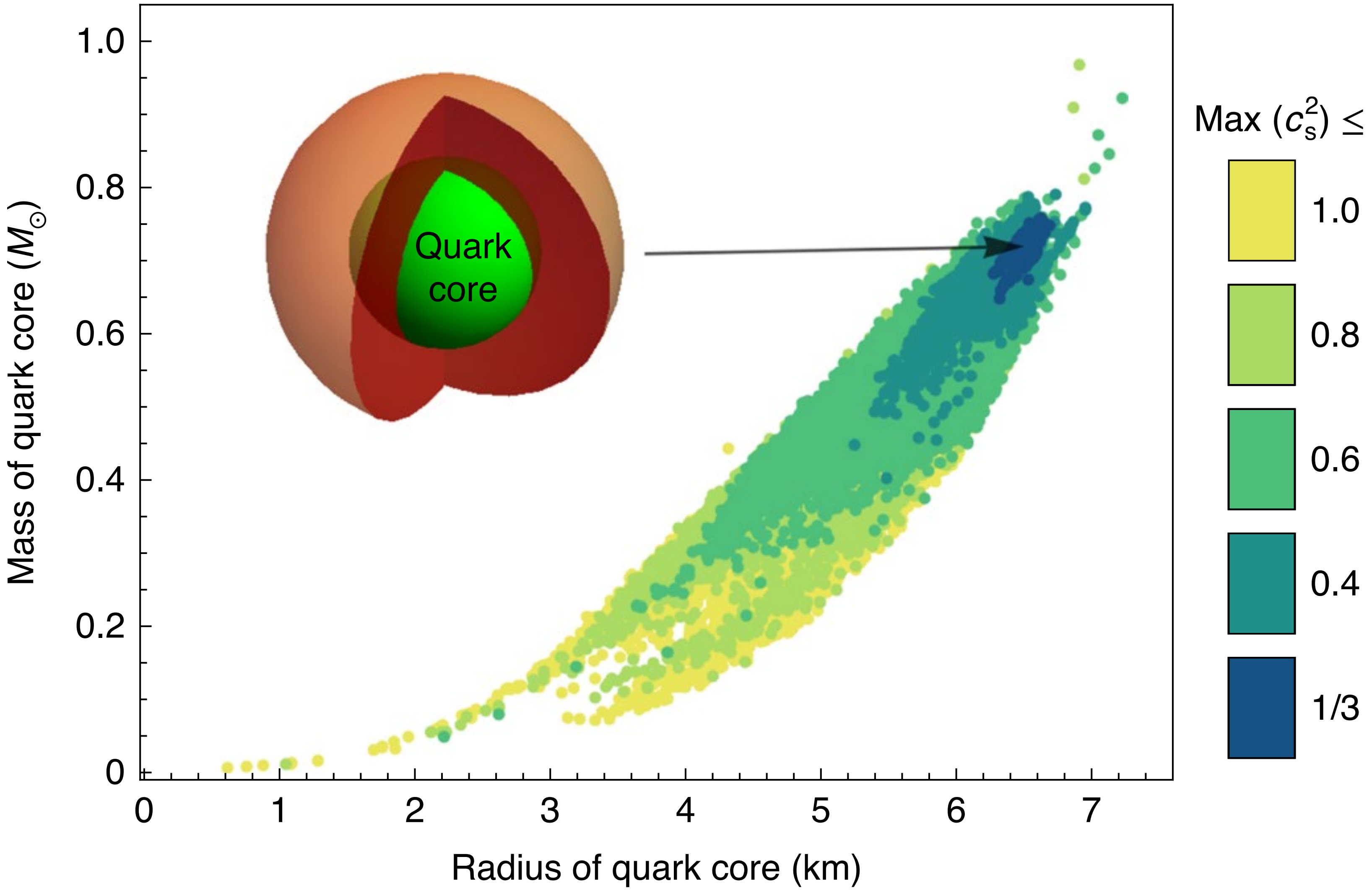


AMS, Phys. Reports, 894 (2021) 1



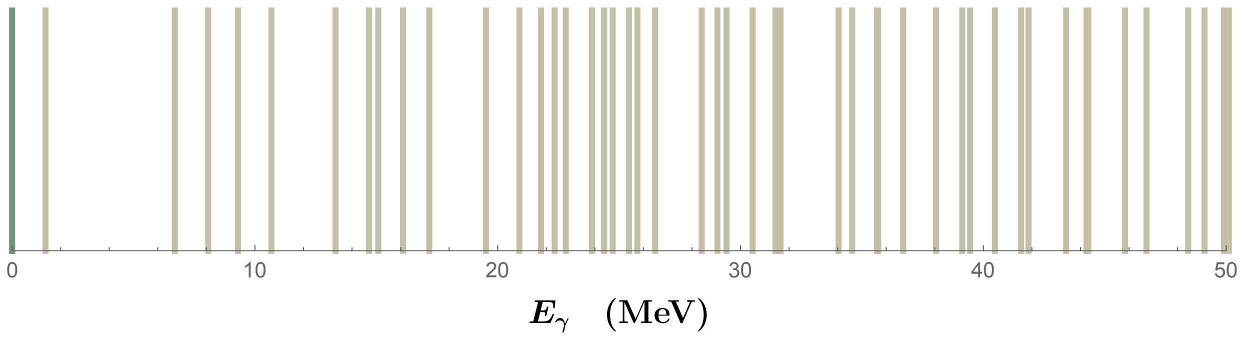
New opportunities:
Quark nuggets from NS mergers

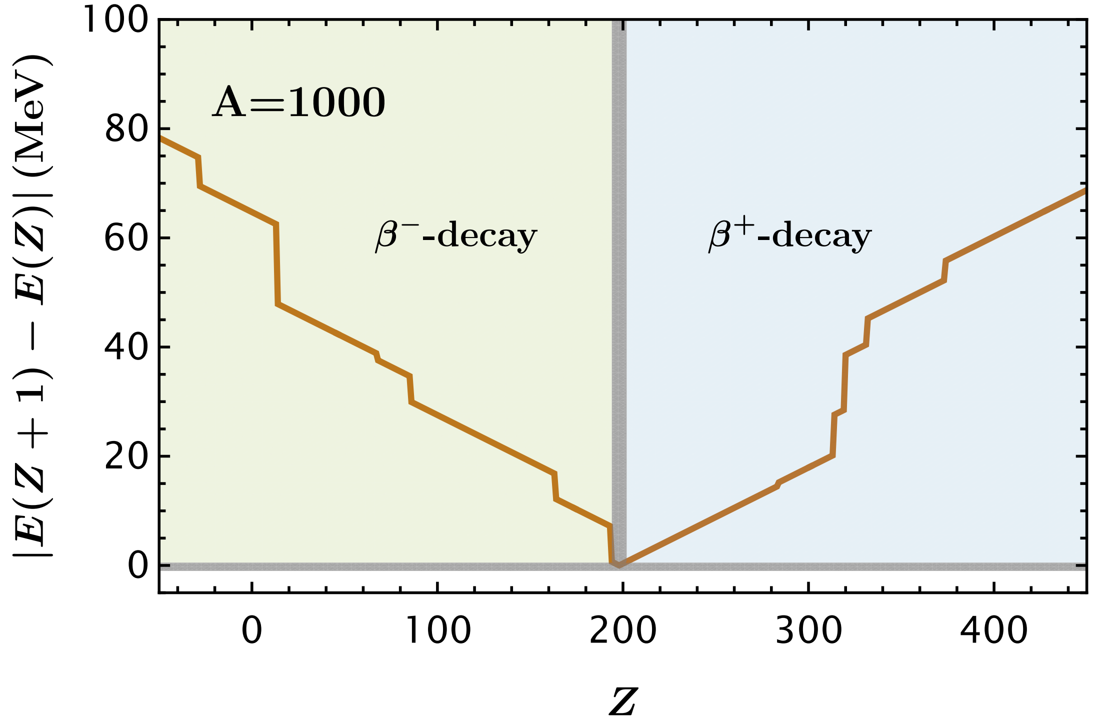
Annala et. al, Nature Physics, 907, vol 16 (2020)

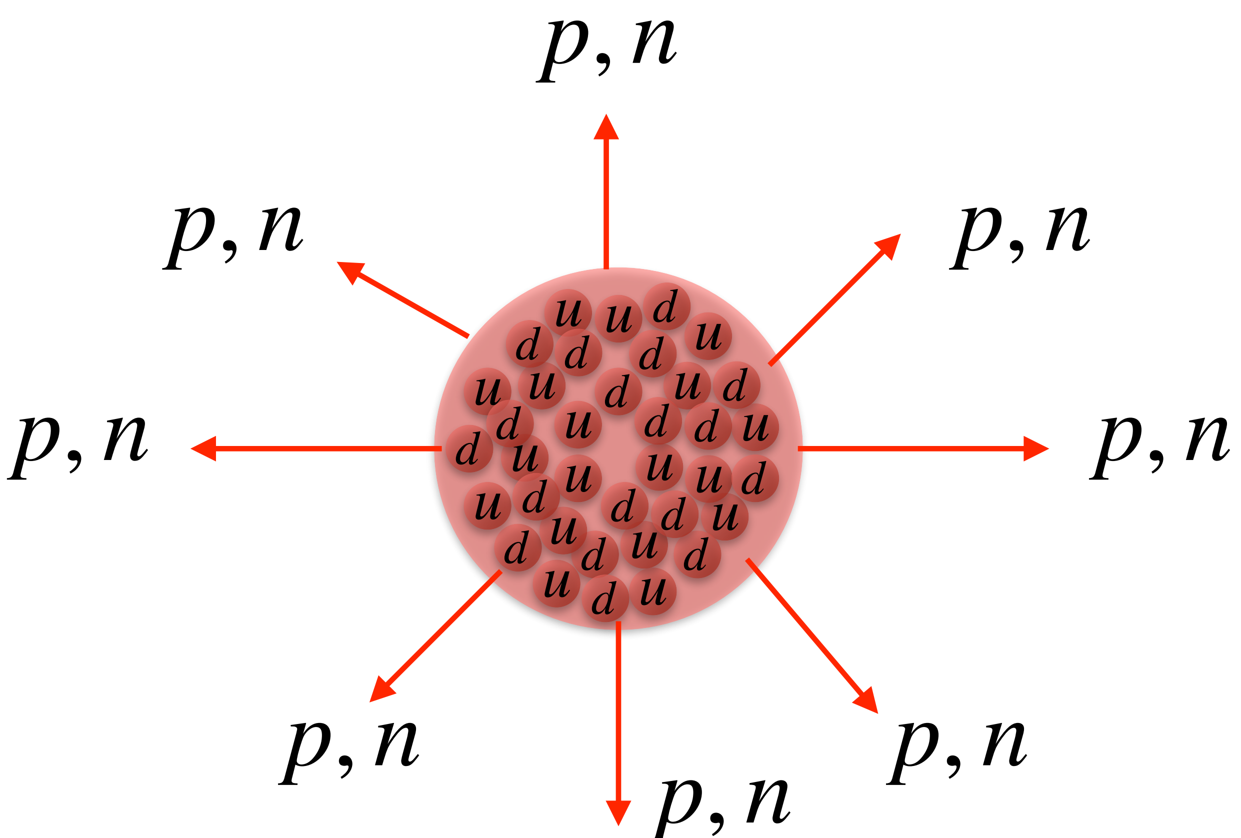


- **How can we know that quark nuggets are produced there?**

Radioactivity of quark nuggets







To be understood

- **Distribution function in A for the generated quark nuggets**

- **Any unique features for the electromagnetic signatures from the radioactivity of "hot" quark nuggets?**
- **Can we distinguish them in the busy environment of neutron star merger events?**
- **Can we "measure" the vacuum pressure parameter using neutron star properties?**

Conclusions

- “Exotic elements” or quark nuggets could exist in the QCD sector of the Standard Model.
- The quark nugget could be a dark matter candidate, with additional BSM physics that can modify the QCD phase transition.
- Neutron star mergers could produce quark nuggets on site. One may use the radioactivity properties of quark nuggets to observe them.

Thanks!