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# Neutron star versus neutral star: On the 90th anniversary of Landau's publication in astrophysics

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**Abstract**

In the late age of developing quantum mechanics, Lev Landau made great efforts to understand the nature of matter, even stellar matter, by applying the quantum theory. Ninety years ago, he published his idea of "neutron" star, which burst upon him during his visit over Europe in the previous year. The key point that motivated Landau to write the paper is to make a state with lower energy for "gigantic nucleus", avoiding extremely high kinematic energy of electron due to the new Fermi–Dirac statistics at that time. Landau had no alternative but to neutralize by "combining a proton and an electron" before the discovery of neutron. However, our understanding of the nature has fundamentally improved today, and another way (strangeonization) could also embody neutralization and thus a low-energy state that Landau had in mind, which could further make unprecedented opportunities in this multi-messenger era of astronomy. Strangeon matter in "old" physics may impact dramatically today's physics, from compact stars initiated by Landau, to cosmic rays and dark matter. In this essay, we are making briefly the origin and development of neutron star concept to reform radically, to remember Landau's substantial contribution to astrophysics and to recall those peculiar memories.

**KEYWORDS**

dense matter, elementary particles, neutron star, pulsar

## 1 | INTRODUCTION

The Mandela effect[1] is miraculous in psychology and media studies, which could be the result of wrong combination of memory fragments under memory reconstruction. Unfortunately, it affects also tremendously the historical memory of the neutron star concept, as will be explained briefly here. *Researchers* are encouraged to think seriously and independently to read the literature, drawing a lesson from the mix-up memory, especially during this information age.

　　Yes, it should be recommended for one to focus on real things rather than only on fashions in the mainstream, since the latter could be strongly coupled with media transportation. Nonetheless, there are some fundamental differences between natural sciences and social actions: the laws of nature are objective, never minding the social emotions! In this sense, the publication of Landau's idea about neutron stars could also be an excellent example for *educational* meaning.

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[1]Interestingly, a similar effect has already been included in a Chinese idiom, "to circulate erroneous reports by someone wrongly informed" (yǐ é chuán é) in as early as the southern Song dynasty, to be very popular in the social contacts nowadays.

Let us make an effort in this aspect. In order to clarify the fact and its implications, the sciences relevant to the publication by Landau (1932) on stars, including the past and future, would be reformed from the bottom in this contribution, on the 90th anniversary of Landau's presenting his original idea.

## 2 | THE MAGNIFICENT ERA: PHYSICS FROM MACROSCOPIC TO MICROSCOPIC, AND EVENTUALLY TO THE QUANTUM

The developments of social civilization are driven by the curiosity of human beings. What is the nature of our material world (e.g., the rock shown in Figure 1)? Why does it exist?

The basic unit of normal matter was speculated even in the pre-Socratic period of the Ancient era (the basic stuff was hypothesized to be indestructible[2] "atoms" by Democritus, $\sim 460BC-370BC$), but it was a belief that symmetry, which is well-defined in mathematics, should play a key role in understanding the material structure, such as the Platonic solids (i.e., the five regular convex polyhedrons).

The above philosophical thinking became gradually related to practical sciences of understanding the thermal phenomenon more than two thousand years later ($\sim 1700AD - 1900AD$), resulting in the first industrial revolution. Thermodynamics focuses on the thermal properties of matter from a macro perspective, while statistical physics studies the global behavior of a huge number of particles in molecular models. Both approaches reach the same end from different directions. Many forerunners offered wisdom for understanding atom matter (e.g., Figure 1), especially the realist among the main figures, Ludwig Edward Boltzmann (1844 − 1906), who "stands as a link between two other great theoretical physicists: James Clerk Maxwell in the 19th century and Albert Einstein in the 20th" (Cercignani & Penrose 2006). This is a pretty big step to explore the fundamental units of nature, leading us into a scientific world from atoms to subatoms.

Ahh … What is the nature of atom? In fact, atoms are *destructible* since J. J.Thomson addressed that the so-called "cathode rays" leaving from atoms are actually negatively charged but extremely light units (i.e., electrons) in 1897. The other part of atom is believed to be positive, massive, and small nucleus after Ernest Rutherford explained the



A rock containing copper (Malachite). Normal atom matter at pressure free is condensed by the electromagnetic (or simply electric) force, while the strangeon matter, to be explained in §6, is by the fundamental strong interaction. Multiscale forms can exist for both kinds of condensed matter, the electric and the strong ones

large angle scattering of the Geiger–Marsden experiment in 1911. However, such a "nucleus+electron(s)" atom cannot be stable at all in classical electrodynamics, though Niels Bohr assumed that an atom should not collapse by introducing a quantum angular momentum (i.e., Bohr's distinct energy states) in 1913, that calls for a new era of completely different mechanics.

It is now well known that the revolution of quantum mechanics unveiled the facts of atom. Beginning with the study of black-body radiation, especially Planck's formulas of spectrum in 1900 (it is worth noting that Boltzmann's ideas were central to Planck's analysis), we know that light is particle-like, each one with energy (Einstein in 1905) and momentum (Compton in 1923), though it is wave-like in classical electromagnetism. This peculiar wave-particle duality of light was extended for all the other "particles", particularly the electron, by de Broglie in 1924. Eventually, *quantum mechanics* (the matrix mechanics by Heisenberg in 1925 and the wave mechanics by Schrödinger in 1926) was established, which reproduces quantitatively the eigen energies of the ground state and the excited ones, providing essentially a solid foundation for Bohr's distinct energy states.

However, why do not all the electrons in a stable atom go to the ground quantum state? Physicists cannot understand until a "new" statistics (i.e., the third one) was discovered.

## 3 | THE "NEW" STATISTICS AND ITS IMPLICATIONS

By the end of the 19th century and at the beginning of the 20th, Maxwell–Boltzmann (MB) statistics, successful

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[2]Oppositely, substances in our daily life are thought to be destructible in ancient China, as was recorded in Tianxia Pian by Zhuang Zi ($\sim 369BC-286BC$): "*Taking a stick of wood with finite extent, one cuts half each day; it is expected to last for an infinitely long time*".

in explaining the thermodynamics of gas and sometimes of liquid and solid, was believed without doubt until Einstein received a letter from Bose in 1924, about revisiting the puzzling black-body radiation. Today, we know that Bose–Einstein (BE) statistics is for a quantum system of identical particles (i.e., Bosons) whose states are exchangeable. Certainly, the thermal system of photons is a typical example.

The third statistics was established soon after Pauli proposed his exclusion principle for electrons in 1925, explaining the periodic law of chemical elements. This statistical property of electron, differing from that of photon, was noted[3] independently by Fermi and Dirac in 1926, marking the birth of the new statistics, that is, the Fermi–Dirac (FD) one.

FD statistics is powerful in understanding the nature, and the first three examples are listed as follows.

1. To solve a problem in the "Heaven" by Fowler (1926): What's nature of white dwarfs with extremely high compactness compared with normal main-sequence stars? In FD statistics, cold electron gas in a white dwarf, even at zero temperature, could still contribute significant pressure, while the pressure in main-sequence stars is only of MB statistics. In fact, at low temperature limit, the pressure of FD statistics is surprisingly larger than that of traditional MB statistics, because the kinematic energy of dense electrons is remarkably high, as illustrated by the Heisenberg relation $\Delta x \cdot \Delta p \sim \hbar$, with $\Delta x$ the separation between electrons, $\Delta p$ the order of momentum and $\hbar$ the Planck constant.

2. To solve a problem on the "Earth" by Sommerfeld (1927): Why is the specific heat of electrons in metal negligible? Although the Drude–Lorentz model (1900–1909) based on MB statistics may explain the electrical and thermal conductivities of metal, only a small part of electrons near the Fermi surface, $\sim kT/E_f$, would contribute to the heat capacity in FD statistics, with $k$ as the Boltzmann constant, $T$ is the temperature, and $E_f$ is the Fermi energy of electron, which is much larger than $kT$ at room temperature. The reason for this is also that the kinematic energy of an electron in comparably cold and dense matter is remarkably high. This was testing the capability of quantum theory on problems beyond atoms, but the point of extremely high energy in cold and dense electron gas is meaningful again!

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[3] It is also said that Pascual Jordan (1902–1980) was the first one who proposed the new statistics in 1925 (Schucking 1999). This sad story happened due to Max Born's negligence. Jordan referred to his own brainchild as "the Pauli statistics".

3. To make an effort of understanding magnetism, to be so familiar with a phenomenon but also a test of FD statistics. The early history of quantum theory of solids, especially of metals was well summarized by Hoddeson et al. (1987). Pauli (1927), for the first time, attempted to explain paramagnetism with FD statistics, but the others experimentally observed (e.g., diamagnetism, magnetoresistance, the Hall effect) were still puzzling. As one of the visiting fellows, Landau joined Pauli's group in 1929, and away from the group, he published his solution of the full quantum-mechanical problem of electrons orbiting in a magnetic field, explaining diamagnetism (Landau 1930). This research was related to Landau's trip to Europe, which will be discussed in the next section.

## 4 | LEV LANDAU AND HIS SCIENTIFIC TRIP OVER EUROPE

The west side of Europe is a vital source of modern sciences, which was certainly attracting young students with a strong spirit of inquiry about the nature. Although international exchanges become more and more convenient, there are still two major ways of reaching the center of science even today. Two archetypes of the successful Asian-born youngsters of genius, during the later period of developing quantum theory in 1930s, are presented next.

One is for Subrahmanyan Chandrasekhar (1910–1995), born in India (Saikia & Trimble 2011) as a part of the British Commonwealth (about 6000 kilometers away from the center of science). As one of the undergraduates at Presidency college, Chandra listened to the speech lectured by Sommerfeld in the autumn of 1928 and discussed afterward about FD statistics, leading him to publish the first and undergraduate research (Chandrasekhar 1929) on Compton scattering of moving electrons, which obey FD statistics (communicated by R. H. Fowler), to supplement Dirac's work on Compton scattering of moving electrons with Maxwellian distribution in hot stellar atmosphere (Dirac 1925).

On his two-and-a-half week journey from India to Cambridge in July 1930, Chandra recognized that his supervisor's calculation (Fowler 1926) was based on non-relativistic energy momentum relation, but the degenerate electrons could be relativistic in massive white dwarfs. Chandra submitted this research titled "The maximum mass of ideal white dwarfs" ($M_{max} = 0.91M_\odot$, applying the theory of polytropic gas spheres) to ApJ on 12 November 1930, published in the following July (Chandrasekhar 1931), known as the "Chandrasekhar limit" in textbooks. Chandra was very productive in

astrophysics, from hydrodynamics, magnetohydrodynamics, to general relativity and black hole.

The other is for Lev Landau (1908–1968), born in Baku of Azerbaijan (Lifshitz 1969), one of the former Soviet Union republics (about 4000 kilometers away from the center of science). Landau started to travel abroad in October 1929, initially supported by the People's Commissariat of Education, worked in Denmark, Great Britain, and Switzerland, and returned to Leningrad Physicotechnical Institute in March 1931. Besides the theory of the diamagnetism of an electron gas, Landau was thinking of the relativistic electrons in white dwarfs during his third time of visit to Bohr's group in Copenhagen when his Soviet stipend had run out but Bohr helped obtain a Rockefeller Fellowship, which allowed Landau to prolong his stay. During this time from February to March in 1931, Landau, Bohr, and Rosenfeld discussed a paper written by Landau but not published, nonetheless, Landau submitted the manuscript in January 1932 and published it in February (Landau 1932), the same month when the discovery of the neutron was announced (Yakovlev et al. 2013).

The key point of Landau (1932) is also relevant to the highly kinematic energy of dense electron gas, as sampled in §3 on FD statistics. Can any physical mechanism cancel the kinematic energy of electrons (typically $\hbar c/\Delta x \sim$ 300 MeV if electrons keeps there) to form a stable state with lower energy? Landau provided a way to do this, by combining "protons and electrons in atomic nuclei very close together", and he "expect that this must occur when the density of matter becomes so great that atomic nuclei come in close contact, forming one gigantic nucleus". However, he did not define *gigantic nucleus*: where is the boundary of baryon number, $A_c$, between normal microscopic and gigantic nuclei? Certainly a nucleus with stellar mass (baryon number $A \sim 10^{57}$) is gigantic since the corresponding number $A < 300$ for atomic nuclei of chemical elements, but the critical number $A_c$ could be somewhere between numbers differing $\sim 55$ orders of magnitude!

The "neutron star" concept superficially anticipated by Landau is not surprising, though before the discovery of neutron. Before the establishment of quantum mechanics, it is a general idea that neutral doublet (combination of an electron and a proton, thus to differentiate cementing electrons from planetary ones in an atom) may exist in an atomic nucleus (e.g., Harkins 1920; Rutherford 1920), postulating "novel properties": to move freely through matter and to be difficult to detect. This specific feature of weak interaction resembles that of dark matter with indirect evidence by gravity. Harkins (1921) renamed doublet "neutron", which was discovered by Chadwick (1932). Today, neutron imaging is very useful in material science and engineering, as well as in biology (Anderson et al. 2009).

Even before the work by Chandrasekhar (1931), Edmund C. Stoner (1899–1968), known for his work on the origin and nature of magnetism, had also noted a limiting mass of white dwarfs ($M_{\max} \sim M_\odot$) in the uniform density approximation (Stoner 1930), considering that the total energy of kinetic electrons and stellar gravity should be minimum. Landau (1932) recalculated the mass limit of white dwarfs ($M_{\max} = 1.5 M_\odot$) too, which could be expressed in terms of fundamental constants. Let us consider a self-gravitational star with mass $M$ and radius $R$, consisting of basic unit with mass $m_0$ and total number $N$. With the overall energy, $E \simeq N \cdot \left( \hbar c N^{1/3} - G m_0^2 N \right) / R$, one has then the mass limit $M_{\max} \sim N_{\max} \cdot m_0 \simeq M_p^3/m_0^2$, with the Planck mass $M_p = \sqrt{\hbar c/G} = 1.2 \times 10^{19}$ GeV, otherwise $R = 0$ if $N > N_{\max}$. Estimating the scale of each unit to be the Compton wavelength $\lambda_0 \sim \hbar / (m_0 c)$, we have thus the typical radius $R \simeq \lambda_0 \cdot N_{\max}^{1/3}$. For $m_0 \sim 1$ GeV, we have characteristic magnitudes for compact stars: $N_{\max} \sim 10^{57}$ and $M_{\max} \sim M_\odot$. It is evident that both quantum physics and special/general relativity should participate in this study, as was indicated by the physical constants of $\hbar$, $c$ and $G$.

Landau's idea develops then, especially after the discovery of pulsars, and becomes very elaborate models of normal neutron stars in the mainstream. But there is still a fundamental misunderstanding about the origin of the idea. Rosenfeld told an anecdote in 1974 that Landau improvised the concept of neutron stars in a discussion with Bohr and Rosenfeld just after the news of the discovery of the neutron reached Copenhagen in February 1932, which is noted in the famous textbook by Shapiro and Teukolsky (1983). This false memory of Rosenfeld, presented in a talk 43 years later, matters seriously in the academic society, which is another example caused by the Mandela effect.

## 5 | LANDAU'S FAITH: NEUTRON STAR OR NEUTRAL STAR?

As discussed above, Landau's mind was actually to make a neutral star when density becomes so large that atomic nuclei come in close contact. It is worth noting, however, that the mass of Landau's gigantic nucleus (Landau 1932) should not always be $> M_\odot$, but probably $\ll M_\odot$, that is, maybe $A_c \ll 10^{57}$. Landau noticed that a white dwarf with mass $> M_{\max}$ cannot be stable against collapsing to a gigantic nucleus, but low-mass such a nucleus, surrounded by normal ions and electrons, could still be possible if the laws of quantum mechanics (and thus FD statistics) are violated. Many authors did then follow along the line of Landau (Landau 1932; Landau 1938), to model neutron stars tested by astronomical observations, setting

chemical equilibrium between phases in a star, since afterwards Landau published a special paper focused again on this topic, trying to solve the problem of stellar energy (Landau 1938).

We have to say that only neutronization can achieve Landau's goal of neutralization during the era when proton and neutron are supposed to be fundamental particles. But a dangerous law, unknown at Landau's time, lurks in this option: the nuclear *symmetry energy*! Although neutronization can remove energetic electrons, an extremely high asymmetry of the resultant isospin will contribute significant symmetry energy. Meanwhile, due to the large asymmetry of isospin, dense electron gas would be necessary to suppress the $\beta$-decay of neutron to proton, which requires normal matter of stellar crust to meet the standard of such an electron density.

Should the neutronization be the only way to neutralize in a gigantic nucleus? Certainly, alternative way to neutralize is possible in the standard model of particle physics. Due to the strong coupling of $\alpha_s \sim 1$, quarks are bound inside a system (e.g., a nucleon) with a scale of $\leq 1$ fm, and the typical energy is then $E_{scale} \sim \hbar c / \Delta x \simeq 0.5$ GeV, with $\Delta x$ the separation between quarks. This means that, in the first step, we may ignore heavy flavors of quarks (c,t,b) and could take advantage of a triangle diagram (Figure 2) for the light flavors of quarks (u,d,s). Normal atomic nuclei are around point "A". Landau's way ends at point "n", while the other way could be from "A" to "s". Both ways described above are of neutralization, in response to the original intention of Landau (1932). At the quark level, the net results of neutronization ($\{3u/2, 3d/2\} \rightarrow \{udd\}$) and strangeonization ($\{3u/2, 3d/2\} \rightarrow \{uds\}$) are respectively $\{u + e \rightarrow d + \nu_e\}$, $\{u + e \rightarrow s + \nu_e, u + d \rightarrow s + u\}$, in the regime of non-perturbative QCD.

Light-quark flavor symmetry is restored at point "s", but the building units could be either quarks (e.g., Witten 1984) or strangeons (Lai & Xu 2017; Xu 2003). The former is based on the perturbative strong interaction between quarks, while the latter is on the nonperturbative. It is well known that the nature of an atomic nucleus, as microscopic strong matter, is determined by nonperturbative QCD (quantum chromodynamics), and one may simply argue that a gigantic nucleus at pressure free could also be the similar. In this sense, a strangeon is an analogy of a nucleon, but only changing the number of valence-quark flavors from 2 to 3, that is, 2-flavored nucleon while 3-flavored strangeon.

In a word, atomic nuclei are 2-flavored, but a gigantic nucleus could be 3-flavored. Where is the boundary? One should be embarrassed for answering the question about $A_c$, which is essentially determined by both the weak and strong interactions, especially the latter in nonperturbative regime. Frankly speaking, one should
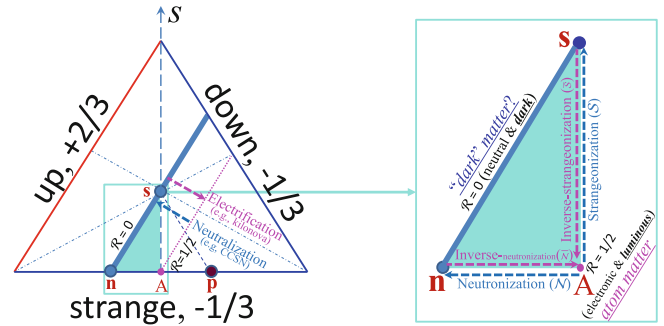


**FIGURE 2** An updated triangle of light-quark flavors (Xu 2020). The points inside the triangle define the states with certain quark number densities of three flavors ($\{n_u, n_d, n_s\}$ for up, down, and strange quarks), measured by the heights of one point to one of the triangle edges. Axis $S$ denotes strangeness, with perfect isospin symmetry. Normal nuclei are around point "A", conventional neutron stars are in point "n", extremely unstable proton stars are in point "p", and strange stars (both strange quark star and strangeon star) in point "s" in the center of the triangle with $n_u = n_d = n_s$. The charge-mass-ratio of quarks at point "A" is $\mathcal{R} \simeq 1/2$, but $\mathcal{R} = 0$ on the line of "ns"; the former is "electronic" and "luminous", while the latter could hardly be detected because of neutrality and would take a "dark" role as matter. The zoomed $\Delta$snA shown in the right indicates that supernovae explosions (from point "A" to a point in line "ns") realize neutronization ($\mathcal{N}$) or strangeonization ($\mathcal{S}$), and kilonovae realize inverse-neutronization ($\overline{\mathcal{N}}$, from point "n" back to point "A") or inverse-strangeonization ($\overline{\mathcal{S}}$, "s → A")

ask Landau for $A_c$ since he proposed "gigantic nucleus" 90 years ago, if he could still be healthy today and if one does not care about Landau's possible feeling of awkwardness. Nonetheless, from the weak side, an electron becomes relativistic if localized in the Compton wavelength $\hbar / (m_e c) \sim 10^3$ fm, one may have $A_c \sim 10^9$. From the strong side, one could have $A_c \geq 10^3$ in a liquid drop model (the Coulomb energy could be larger than the mass difference between strange and up/down quarks if $A \geq 10^3$). We may then estimate a value of $A_c$ between $10^3$ and $10^9$.

# 6 | NEUTRON VERSUS STRANGEON

Although both neutron and strangeon are neutral, two differences between them are worth noting.

1. *Flavor Symmetry*. Adopting a phenomenological approach, nuclear physicists introduce a symmetry energy representing the symmetry between the proton and neutron of a stable nucleus, which is essentially the balance of two flavors of quarks (u,d), but the underlying physics is yet to be well understood. For
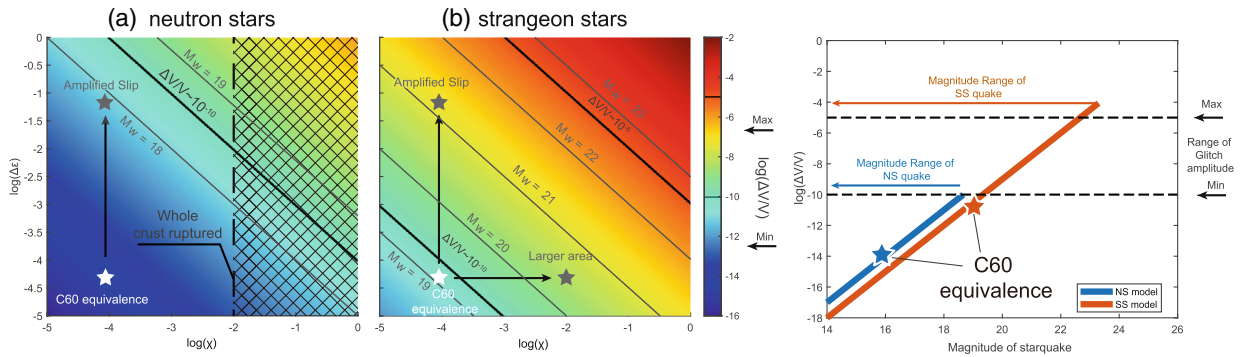
**FIGURE 3** A comparison between starquakes in conventional neutron stars (panel "a", NS) and in strangeon stars (panel "b", SS), showing dependence of glitch magnitude ($\log (\Delta \nu / \nu)$) on the starquake strain drop ($\varepsilon$) and moment ratio ($\chi$). The maximum and minimum glitch magnitude ($10^{-10} \sim 10^{-5}$) are bounded by black lines. The line of $10^{-5}$ is not given in NS model for it is over the theoretical maximum. The shadow in panel "a" mark the area that $\chi$ is not allowed in neutron stars. A scaled earthquake of the largest observed one (i.e., C60: 1960 Chile earthquake) is marked as white stars in both figures as references, respectively. Gray lines are isolines of starquake magnitude with corresponding $\Delta \varepsilon$ and $\chi$. Panel "c" shows the comparison between NS and SS models. The range of observation glitch amplitude is shown as horizontal dot lines. C60 in the two models is respectively marked as the blue and orange stars. These calculations presented by Lu et al. (2022) show that the observed glitch amplitude can be explained by the starquakes in the strangeon star model, though the required scaled starquake magnitude is much larger than that occurred on the Earth

**2**-flavored nuclei, it is impossible to satisfy both the neutralization and the flavor symmetry, but simply a straightforward task for **3**-flavored nuclei.[4] It seems natural if Nature loves a principle of flavor maximization (Miao et al. 2022; Xu 2018). This difference carries profound implications: **2**-flavored strong matter in bulk cannot be too less-massive to be stable against decaying into atomic nuclei (the minimum mass of a conventional neutron star could be $\sim 0.1 M_\odot$), while the baryon number of stable strangeon matter could be as low as $10^{10}$ (the so-called strangeon nugget).

2. *Mass and Wavepacket Size*. It might be fine to represent an atomic nucleus as a liquid drop since the quantum wavepackets of identical nucleons could overlap. However, the quantum wavelength of massive strangeon is comparably short, and one may attribute the properties of strangeon matter to classical physics. Unless during its formation at high temperature, strangeon matter could be in a solid state as the thermal kinematic energy would be much lower than the interaction potential (a few, MeVs) between strangeons. The free energy, elastic and gravitational, of solid strangeon stars could power extraordinary astrophysical bursts, from the so-called magnetars (Xu et al. 2006), to fast radio bursts (Wang et al. 2022), and even $\gamma -$ ray burst (Xu & Liang 2009). Further, the nonrelativity of strangeons results in a stiffer equation of state than that of nucleon matter

(Lai & Xu 2009), a simple key to solving the hyperon puzzle.

Is strangeon matter just hyperon matter? No hyperon matter has been conjectured yet, but strangeon differs from hyperon in two facts at least. *a*, The baryon number of hyperon is $B = 1$, whereas strangeon is baryon-like but not a real baryon, whose number could be $B > 1$, at least $B = 2$ (dibaryon) and maybe $B = 6$ (quark alpha, $Q_\alpha$). *b*, The interaction between two $\Lambda$-particles could be attractive, with binding energy of a few MeVs (Green et al. 2021) or higher according to lattice QCD simulations. Certainly, an attractive interaction in-between could not support against gravity.

Let us go back to Figure 1. The mass spectrum of normal electric matter is continuous, from molecules (a few atom-units), to dusts (much smaller than the Avogadro constant), planets ($\sim 10^{52}$), and stars ($\sim 10^{57}$). However, there could be a gap (around $\sim A_c$) in the mass distribution of strong matter: nucleon matter exists for baryon number $A < A_c$, while strangeon matter for $A_c < A < A_{max}$.

Quakes are natural on the solid Earth, and thus on solid strangeon stars too. Similar to electric matter inside the solid Earth, the geometrical symmetry of strangeons in solid matter could also not be simple and perfect, and a quasicrystal structure is possible too. An amorphous (glass-like) structure of solid strangeon matter could even form if the cooling is so quick that phase equilibrium can hardly be achieved during liquid–solid transition. Anyway, a quake as a result of slip should occur along the direction on a fault plane (Lu et al. 2022), as commonly observed on the Earth, with simulated results illustrated in Figure 3. Besides strangeon stars, strangeon nuggets

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[4]The isospin is 1/2 for nucleon, but could be defined as 0 for strangeon.

formed through a crossover QCD phase transition in the early Universe before the big bang nucleosynthesis has also been demonstrated, indicating a strangeon dark matter candidate without introducing particles beyond the standard model (Wu et al. 2022).

## 7 | SUMMARY AND OUTLOOKS

This note is my second one in memory of Landau's original idea on neutron star, with the first one published around 10 years ago (Xu 2011). Following Landau's approach more than 90 years ago, we are explaining a novel kind of matter at pressure free, the strong matter by strangeons rather than by nucleon, as an analogy of the normal atom matter, is illustrated in Figure 1, for example. Today, the nature of pulsar-like stars is focused in both physics and astrophysics, hopefully to be the first big problem solved in this multi-messenger era of astronomy. A detailed study in microphysics may eventually reveal the critical number, $A_c$. Although the number cannot yet be computed from the first principles at present, it does not mean that nature will not adopt this idea and refuse to use it.

In fact, a strangeon is a kind of multi-quark state, which is hotly discussed in high-energy physics, both theoretical and experimental. It is surely welcome to investigate the formation of strangeon with either lattice QCD or effective field theory, which would be conducive to quantitatively describing the state equation of supranuclear matter. Although one cannot rule out other possibilities, for example, that multi-quark states and free quarks could coexist (Burikham et al. 2009), the energy scale of strong matter at pressure free should not be fine-tuned. Therefore, a consistent state of chemical composition would be reasonable, but the baryon numbers, $A$, of strangeons from the surface to the center may increase slightly nevertheless.

Looking back at the journey to understand the nature of our material world, we could be trying to know strong matter in an opposite direction to that of electric matter. The study of electric matter in Figure 1 shows eventually the micro-units and their quantum nature, but we are reproducing the world of strong matter with the standard model (QCD and the electroweak theory). Certainly, the reproduced material world should be tested by multi-messenger observations.

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