Is there a hidden connection between massive neutron stars and dark matter in cosmology?

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ABSTRACT

Astronomical observations reveal a gap in the mass spectrum of relativistic objects: neither black holes nor neutron stars with 2 - 5 solar masses have ever been observed.

In this article I proceed in presenting the scenario which discloses a possible hidden connection between massive neutron stars (MANSs), dark matter and dark energy in cosmology. Accordingly, when the curved spacetime embedding MANSs compresses the nuclear matter to beyond a critical supranuclear density \( n_{cr} \), mesons, generally transmitting the residual nuclear forces between neutrons, could gain energy by frequently interacting with a scalar field \( \phi \) at the background. When the effective energy of mesons becomes comparable to the bag energy enclosing the quarks, the neutrons merge together and form a super-baryon (SB), whose interior is made of incompressible gluon-quark superfluid. It turns out that the process has a runaway-character: it enables the super-baryon to grow in mass and volume from inside-to-outside to finally metamorphose the entire object into a completely invisible dark gluon-quark object, practically indistinguishable from isolated stellar black holes. The inability of these objects to merge with other objects whilst agglomerating in clusters makes them excellent candidates both for black holes and for dark matter halos in cosmology.

Keywords: Relativity: general, black hole physics — neutron stars — superfluidity — QCD — dark energy — dark matter

1 INTRODUCTION: COSMOLOGY OF MASSIVE NEUTRON STARS?

Unlike luminous stars, whose energies are generated through nuclear fusion, neutron stars emit the rest energy stored in their interiors from old evolutionary epochs. As in the case of luminous normal stars, the total energy emitted by neutron stars is proportional to the their masses, implying therefore that massive neutron stars must be short-living objects also.

Similar to the natural selection scenario of primates, most massive astrophysical objects must have disappeared relatively quickly, but only solar-like objects are able to shine for billion of years and to be observable until the present universe: thanks to the parameters characterizing our universe.

Just for illustration: a ten solar masses star has a lifetime 1000 shorter than that of the Sun. On the other hand, cosmological simulations reveal that the first stars must have been 100 to 10000 solar masses and that they should have formed from primordial clouds made solely of hydrogen (Bromm & Larson 2004). In the absence of heavy elements, it is believed that these massive stars must have collapsed directly into stellar black holes, but whose masses have been growing continuously through accretion of matter from their surroundings and/or through repeated mergers with other objects to become the monstrous black holes that reside the centers of almost all observable galaxies. However, an evolutionary track in which the first stars, or

\[
N_{\text{merg}} \approx 10^3
\]

\[
N_{\text{max}} \approx 10 \times N_{\text{merg}}
\]

\[
N_{\text{obs}} \approx 10^{-5} N_{\text{max}}
\]

\[
N_{\text{dark}} < 10^{-5} N_{\text{max}}
\]

Figure 1. NSs and pulsars emit their radiation mainly in the X-ray and radio bands. Among the several billions of stars of the Milky Way, only several thousands NSs and pulsars and about several hundreds stellar black holes have been observed so far. These numbers are about one million times smaller than those expected from theoretical and statistical considerations.
at least a part of them, may have collapsed to form pulsars and/or neutron stars statistically cannot be excluded. Moreover, if the parameters characterizing our universe indeed do not allow matter-density to grow indefinitely (Nassif et al. 2016), then the abundance of massive neutron stars at that epoch must have been rich. Under these circumstances, the first generation of NSs must have emitted their energies long time ago to become invisible and disappear from our today observational windows. Indeed, the following list of arguments are only a few in favor of this scenario:

- Relativistic compact objects with $2 \, M_{\odot} < M < 6 M_{\odot}$ practically do not exist
- The number of relativistic compact objects so far found to populate the Milky Way is approximately one-million time smaller than expected from theoretical and statistical considerations (Fig. 1, Witten 1984)
- The mass range of black holes is practically unlimited with neither lower nor upper bounds are known, whereas NSs enjoy an unusually narrow mass range.
- Isolated neutron stars that are older than one Gyr haven’t been observed yet.
- Modelling the internal structure of NSs requires their central densities to be far beyond the nuclear density: an unknown density regime in which most EOSs become physically inconsistent (Camenzind 2007, Hempel et al. 2011).
- All EOSs break down when nuclear fluid becomes weakly compressible.
- The glitch phenomena observed in NSs and pulsars indicate that NS-cores are governed by superfluids (Fig. 2, Shapiro & Teukolsky 1983, Espinoza 2011).

As a consequence, we expect isolated massive NSs to metamorphose into dark objects, whose interior are made of incompressible gluon-quark superfluids and to subsequently disappear from our observation windows.

## 2 NORMAL DISSIPATIVE FLUIDS VERSUS SUPERFLUIDS

Normal matter is usually made of self-interacting particles, non-ideal and dissipative medium. The illustrate exemplify these concepts, consider the flowing water in a river. Particles at the surface communicate with the motionless ones at the ground, generating thereby a velocity profile that varies with the depth, i.e. normal to the direction of motion. If we were to replace the water by honey, the profile of depth-depending velocity would change dramatically. The same applies for other materials, as each material has its own chemical and physical properties that determine the way particles communicate with each other. The collective effect is called friction, which mathematically represented by anisotropic stress-tensor. The components normal to the direction of motions is called tension with the dynamical viscosity serves as a coefficient, inside which the chemical properties are encapsulated.

The effect of viscosity is generally to speed up and/or slow down the motions of particles in different portions of the domain toward enforcing a uniform motion. But if the flow is subject to external (non-conservative) forces and the viscosity is sufficiently small, then the motion of the particles become random, where the entropy of the system saturates. Such a fluid flow is said to be dissipative and therefore irreversible.

It turns out that when the temperature of the fluid falls below a certain critical value, the effect of viscosity diminishes. In this case, the fluid enters the so-called superfluid phase, where quantum mechanical effects start to emerge on global scales, for example, climbing up the walls of the container or forming discrete number of vortices that rotate coherently with each other.

In such fluids the De Broglie wavelengths $\lambda_{DB}$, surpasses the mean free path characterizing the collisions between particles, and then each particle starts to coordinate its motion with its neighbours to finally clothe their quantum state: an extraordinary phenomenon in which micro-quantum states start showing up on the macroscopic scales (Fig. 3).

In terrestrial fluids superfluidity phases start to show up when the temperature of the fluid becomes approximately one-hundred times smaller than the corresponding Fermi-temperature. In the cores of neutron stars however, although the temperature is of order one hundred million degrees, nuclear fluids are still about ten thousand times lower than the corresponding Fermi-temperature, implying therefore that NS-cores most likely are in quantum superfluid phase.

### 2.1 Astrophysics of weakly compressible and incompressible fluid flows

In an ever expanding universe the ultimate phase of nuclear fluids inside the cores of isolated NSs should have vanishing entropy inviscid and incompressible. In the early evolutionary phases of NSs, their cores should be threaded by...
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The rate and form of interactions between particles depend strongly on the temperature. According to quantum dynamics, each particle is associated with the De Broglie thermal wavelength, \( \lambda_{DB} \), which is inversely proportional to the temperature. It turns out that at sufficiently low temperature, when \( \lambda_{DB} \) becomes larger than the mean free path between particles, then they start sharing their quantum properties with their neighbors.

Vortex lines, where the rotational energy is stored. In this case, Kelvin waves in combination with buoyancy effects are expected to be the dominant transporter of energy from their interiors into the surrounding media. In fact, computer simulations of rotating superfluids reveal that the enclosed vortices are not static, but oscillate and intersect with each other to finally turn the configuration turbulent (Fig. 4, Baranghai 2008; Baggaley & Laurie 2014). Based on these observations, we don’t expect the 10-kilometer long vortex lines threading the cores of NSs and pulsars to behave differently. As a consequence, turbulent motion of vortex lines in superfluids generally enhances dissipation of rotational energy to subsequently lower their energy state.

Still, we have still to determine whether nuclear fluids inside the very central regions of NSs are compressible or incompressible (see Hujeirat & Thielemann 2009 and the references therin). I should note that if the fluids inside the cores of these objects were compressible and stratified, then energy may be still extracted via acoustic waves from their interior into the crust or the surrounding media, thereby weakening the compressibility of the fluid even more. In fact such an energy extraction process is considered to be the underlying heating mechanism of the solar corona (Bingham et al. 2010).

In the case of NSs, I argue that incompressibility is an inevitable phase of matter once the number density becomes larger than the nuclear one. Among the reasonable arguments that favor this phase are the following:

(i) The spatial variation of the coefficient \( g_{rr} \) of the Schwarzschild metric on the length scales of atomic nuclei is roughly \( (dg_{rr}/dl) \ll 10^{-19} \) implying therefore that gravity-induced stratification is unmeasurably small.

(ii) The effective potential of the gluon-field inside individual baryons is predicted to increases with radius as \( r^{3/2} \). Thus the gluon-quark effective force inside hadrons opposes compression by gravity.

(iii) Most EOSs used for modeling the very central regions of NS-cores display sound velocities that do not respect causality. However, fluids with \( V_s = O(c) \) cannot be compressed anymore. In fact recent numerical simulations of classical incompressible Navier-Stokes fluid-like flows reveal a blatant inconsistency in the capturing flow configurations,
whenever the employed EOSs are set to depend on the local properties of the fluid only \cite{Bethe1990, SAE Air 2004}. In this case communicators that merely depend on local exchange of information are insufficient for efficiently coupling different/remote parts of the fluid in a physically consistent manner. A relevant example is the solution of the TOV-equation for the incompressible case, where the internal energy density, $\varepsilon$ is set to be constant. The pressure here turns out to depend on the global compactness of the object, but it becomes even acausal when the global compactness of the object is enhanced \cite{Glendenning 2007}. Thus, using a local description of the pressure for simulating weakly compressible or incompressible fluids is physically inconsistent.

(iv) Beyond the nuclear density, most sophisticated EOSs tend to converge to the limiting EOS: $P_l = \varepsilon$ (Fig. 5), where $P_l, \varepsilon$ denote the local pressure and the energy density, respectively. However, such fluids cannot accept compressibility anymore as otherwise the causality condition would be violated. In this case the nuclear fluid must obey the EOS: $\varepsilon = a n^2$, where $n$ is the number density. When taking the regularity condition of the pressure at the center of the object into account, i.e., $\nabla P |_{r=0} = 0$, one finds that there is a maximum critical number density $n_{cr}$, at which both the Gibbs function as well as its derivative vanish. In a previous work \cite{Hujeirat 2016}, it was shown that $n_{cr} = 3 n_0$, where $n_0$ is the nuclear density. For $n \geq n_{cr}$ the nuclear fluid becomes purely incompressible. Such fluids are expected to form, when all other forms of energies, e.g. kinetic ($E_{Kin}$), magnetic ($E_{mag}$) and thermal ($E_{th}$) energies have been evacuated out of the very central region of NSs. One may think of these energies as perturbations superimposed on a zero entropy state at the background.

The classical form of the first law of thermodynamics: $dE = Tds - pdV$ is not valid for incompressible nuclear fluids as both $dE$ and $dV$ are unrelated and therefore the local pressure $P_l$ cannot be calculated from $dE/dV$.

In fact the imposed regularity condition on the pressure at $r=0$ manifests the incompressibility character of the fluid and therefore the break down of formula $dE/dV = -P_l = -n^2 \frac{\partial}{\partial n}(\varepsilon/n)$. Moreover, assuming the matter at the center to obey the EOS: $P = \varepsilon$, then the TOV equation can be integrated to yield: $\varepsilon(r) e^{\nu(r)} = const.$, where $\nu$ stands for the gravitational potential. However, nuclear matter obeying $P = \varepsilon$, cannot be compressed and therefore $\nu$ must be constant, which means a vanishing gravitation-induced stratification. Nevertheless, most NS-models rely on using a non-vanishing density-gradient even at the vicinity of $r = 0$. In order to have a NS of a reasonable mass, the central density must be much beyond the nuclear density: a density regime which is experimentally untestable and where our theoretical knowledge is severely limited (Fig. 5). Consequently, the existence of a non-local pressure in an environment, where the fluid is weakly compressible, such as in the vicinity of the center of NSs is necessary in order to escape their collapse into black holes.

In fact, it appears that nuclear fluids with $n_{cr} \geq 3 n_0$, having a constant internal energy density and $E_{Kin} = E_{th} = E_{mag} = 0$ should be incompressible gluon-quark superfluids (see Hujeirat 2016 and the refer-

![Figure 5](image.png)

**Figure 5.** According to numerical and theoretical studies, the bulk of matter in NSs must have densities beyond the nuclear one, though the physical properties of matter in this density regime are poorly understood. Nevertheless, in this supranuclear density regime most EOSs appear to converge towards the stiffest possible EOS: $P = \varepsilon = a_0 n^2$. Fluids governed by such a critical EOS become purely incompressible.

![Figure 6](image.png)

**Figure 6.** When two neutrons are brought together to merge, the employed force should be equal or even larger than the energy required for their creation. The employed effective energy is then absorbed and used to form new communication channels between quarks, thereby enhancing the effective mass of the newly formed super-baryon. This is in line with experimental data which revealed that the effective energy of the short-living pentaquarks correlates almost linearly with the number of communication channels, through which the strong force is communicated.
3 BUT WHAT MAKES DEQOS DISAPPEAR FROM OUR OBSERVATIONAL WINDOWS AND HOW CAN THEY STILL ESCAPE COLLAPSE INTO BHS?

The brief answer is that when the number density of zero-temperature quantum fluids surpasses the critical density \( n \geq n_{cr} \), the sub-nuclear particles, such as mesons and gluons, start interacting with the scalar field more frequently, thereby enhancing their effective mass and enabling individual baryons to merge together to form a super-baryon. The potential governing its interior increases with radius, giving rise to a non-local negative pressure that opposes compression. Consequently, the compactness of the object is significantly enhanced and therefore the object sinks deeply into the embedding curved spacetime to finally disappear from all direct observational windows.

What is the underlying physical mechanism for generating "dark energy" in NSs?

The contribution of quarks to the baryon mass is approximately 2%, whereas the energy required to deconfine them is roughly equal or even larger than the energy needed for the creation of the whole baryon, which is roughly equal to 0.94 GeV. However, as gluons are virtual particles that are generated by vacuum fluctuations that popping into existence and disappearing, then the symmetry between creation and annihilation must be perfectly tuned, as otherwise protons would not survive a lifetime of the order \( 10^{10} \) years.

When the first baryons at \( r=0 \) merge with its neighbors and form a new super-baryon, the number of communication channels increases with radius, giving rise to a non-local negative pressure that opposes compression. Consequently, the compactness of the object is significantly enhanced and therefore the object sinks deeply into the embedding curved spacetime to finally disappear from all direct observational windows.

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As the nuclear fluid in the very central region of NSs has density beyond the nuclear one, the only degree of freedom left, where exotic energy could be still created would be through merging baryons and generating new communication channels between the quarks. This however requires enhancing compression by external forces, e.g. enhancing the curvature of the embedding spacetime (Fig. 12). Similar to the recently explored pentaquarks, new communication channels must be generated between the quarks to ensure stability of the internal structure of the newly born super-baryon. The energy required for constructing the channels comes mainly from quark-antiquark interactions with the field, which we term here as dark energy.

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the concerned super-baryon is spherically symmetric and composed of incompressible fluids \((P, dN/dV = \text{const.})\), we obtain that \(n \cdot dT = \alpha_\Phi r^2\) and therefore the dark energy density would have the form:

\[
\mathcal{E}_\Phi = \alpha_\Phi r^2 + \beta_\Phi.
\] (2)

\(\alpha_\Phi, \beta_\Phi\) are constants. In fact this is similar to the static quark-antiquark potential inside individual baryons, which can be described as a superposition of Coulomb-like term, i.e. \((\text{const.}/r)\) and a term, whose action increases with radius.

As the concerned quantum fluid is incompressible, in hydrostatic equilibrium and in a superfluid phase, the scalar field, which is the source of dark energy, can be safely considered as a spatially and temporally constant. This implies that the EOS of dark energy is necessary for boosting the energy of the concerned quantum fluid to merge together without violating the incompressibility character of the fluid? One could envisage an instantaneous crossover phase transition in which the compressible nuclear fluid consisting of individual baryons and having chemical potential \(\mu \sim n\) turns into incompressible gluon-quark-superfluid with \(\mu \sim \text{const.}\) (Fig. 8). Here the injection of dark energy plays the role of a catalyst, i.e. the instantaneous change of the EOS must run as follows:

\[
\mathcal{E} = a_0 n^2 \frac{\text{dark energy}}{\text{vol}} \to \mathcal{E} = a_{qf} \times n,
\] (3)

where \(a, a_{qf}\) are constant coefficients. Note that the injection of dark energy is necessary for boosting the energy of mesons and to subsequently convert them into gluons needed for forming the new flux tubes between the quarks inside the super-baryon.

In order to insure that the dark energy goes to solely enable a smooth crossover phase transition, we require that there must be a critical number density \(n_{cr}\), where the Gibbs function vanishes. The combined energy density (i.e., the density of internal energy of baryons and that of dark energy \(\mathcal{E}_\Phi\)) per particle should be larger than or equal to the energy required to de-confine the quarks inside individual baryons:

\[
f(n) = \frac{\mathcal{E}_\Phi + \mathcal{E}_\mathcal{E}}{n} - 0.939 \text{ GeV} \geq 0.
\] (4)

Using the scalings \([p] = 10^{15}\text{g/cm}^3\) \((\approx 0.597/\text{fm}^3)\), chemical potential (energy per particle) \([\mu] = 1\text{GeV}\), we then obtain \([a_0] = 1.674 \text{ GeV/fm}^3\) and \([a_\phi] = 5.97 \times 10^{-39} \text{ GeV/fm}^3\) and \([b_\phi] = 0.597 \text{ GeV/fm}^3\). In this case the Gibbs function in non-dimensional units reads:

\[
f(n) = a_0 n + \frac{b_\phi}{n} - 0.939.
\] (5)

The function \(f(n)\) may have several minima, depending on the values of \(a_0\) and \(b_\phi\). However, for a crossover phase transition to occur, both \(f(n)\) and \(\partial f(n)/\partial n\) must vanish, which occurs at \(n = 0.81\) for the most reasonable values: \(a_0 = 1\) and \(b_\phi = 0.37\) (Fig. 9).

Thus the potential of vacuum energy at \(r=0\) is \(V_0 = b_\phi\), and therefore there is a non-local pressure \(P_{NL} = -\mathcal{E}_\Phi = -V_\phi = -b_\phi\). For determining the value of \(a_\phi\), we need to study the ultimate global structure of the object.

We note that the radius of the super-baryon behaves like a transition front that propagates outwards through the ultra-weakly compressible nuclear fluid of the NS, leaving the matter behind its front in an incompressible gluon-quark-superfluid phase. When the front reaches the surface of the entire object, which is expected to occur on the scale of \(O(10^8)\) yrs, then the object becomes a DEQO and disappears from our observational windows, as its radius would be indistinguishable from the corresponding event horizon. Equivalently, we require the following equation to be fulfilled:

\[
R_{\phi} = R_S = \frac{2G_s^4(M_{NS} + M_\phi)}{c^2},
\] (6)

where \(R_{\phi}, R_S, M_{NS}\) and \(M_\phi\) denote the radius of the object, Schwarzschild radius, Mass of the original NS and the mass-enhancement due to dark energy, respectively. As the number density inside the DEQO is constant and equal to \(3 \times n_0\) and as the vacuum energy density obey the relation
Figure 9. \( E = a_0 n^2 \) corresponds to the limiting EOS in the supranuclear density regime, where baryons may merge together to form super-baryons. The injection of dark energy goes mainly to create communication channels connecting the quarks. The global effect of the injected dark energy takes the form of a non-local negative pressure that apposes compression by the embedding spacetime. When analyzing the Gibbs function, we find that it attains zero-minimum at roughly three times the nuclear density, i.e. \( n_{cr} \approx 3 n_0 \). Note that for a crossover phase transition to occur, both the Gibbs function and its derivative must vanish.

Figure 10. The matter density inside DEQOs correspond to the limiting EOS in the supranuclear density regime, where baryons may merge together to form super-baryons. The injection of dark energy goes mainly to create communication channels connecting the quarks. The global effect of the injected dark energy takes the form of a non-local negative pressure that apposes compression by the embedding spacetime. When analyzing the Gibbs function, we find that it attains zero-minimum at roughly three times the nuclear density, i.e. \( n_{cr} \approx 3 n_0 \). Note that for a crossover phase transition to occur, both the Gibbs function and its derivative must vanish.

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Figure 11. The ultimate total mass of the object relative to its original baryonic mass versus the black energy coefficient \( \alpha_\phi \) is shown for different values of the bag energy \( \beta_\phi \) and manual enhanced weight \( \gamma_\phi \) of \( \alpha_\phi \). According to QCD, the value of \( \beta_\phi \) should lay around 0.221 GeV, which is equivalent to 0.37 in the here-used non-dimensional units. The value: \( \alpha_\phi = 490 \) gives rise to an object whose radius coincides with the corresponding event horizon of the object. This value of \( \alpha_\phi \) is crucial for the dynamical stability of the object, as other low or high values would eventually lead to its self-collapse into a BH.

\[ E_\phi = \alpha_\phi r^2 + \beta_\phi, \] then:

\[ M_{NS} = 4 \pi \int_0^{R_{NS}} E_\phi r^2 \, dr = \frac{4 \pi}{3} \rho_{cr} R_{NS}^3 \]

\[ M_\phi = 4 \pi \int_0^{R_\phi} E_\phi r^2 \, dr = \frac{4 \pi}{3} \alpha_\phi R^3 + \frac{4 \pi}{3} \beta_\phi R^3. \] (7)

Let us nondimensionlize Eq. (6) using the following scaling values: \( [R] = 10^6 \text{cm}, [\beta_\phi] = [\rho] = 10^{15} \text{g/cc}, [\alpha_\phi] = [\rho/R^2], [\mathcal{M}] = [\mathcal{M}] = \frac{4 \pi}{3} [\rho] [R]^3 = 2.1 M_\odot \). We then obtain the following equivalent form to Eq. (6):

\[ \frac{M_\phi}{M_{NS}} = \frac{3}{5} \left( \frac{R_\phi^2}{\rho_{cr}} \right) \alpha_\phi + \frac{\beta_\phi}{\rho_{cr}}. \] (8)

The term \( \alpha_\phi r^2 \) in Eq. (2) is the source of the non-local vacuum pressure, which yields the incompressibility character of the gluon-quark superfluid in self-gravitating systems.

Recalling that numerical and theoretical studies of the internal structure of NSs predict a compactness parameter \( \alpha_s(\equiv R_s/R_{NS}) \gtrsim 1/2 \), which, in combination with the requirement that the object should turn invisible at the end of its cosmological life time, we conclude that its final total mass \( M_{tot} \leq 2 \times M_{NS} \). As it is shown in Fig. (11), and displayed as blue dashed line, \( \alpha_\phi = 490 \) appears to safely fulfill these constrains.

To summarize the parameter determination procedure:

(i) Let the isolated NS has the mass \( M_{NS} \).
(ii) The baryonic fluid at the verge of phase transition obeys the EOS \( E_b = a_0 n^2 \), whereas the EOS of the gluon-quark superfluid is \( E_b = \text{const.} \) and \( E_\phi = \alpha_\phi r^2 + \beta_\phi \) for the dark energy.
(iii) From the minimization requirement of the Gibbs function we obtained the coefficient $\alpha_0$ and $\beta_0$, where the latter was set to equalize the bag constant in terms of the MIT-description of quarks in QCD. Here we use $B^{1/4} = 220 \text{ MeV}$, which is equivalent to 0.37 in the here-used non-dimensional units.

(iv) The coefficient $\alpha_0$ has been determined by requiring that the radius of the original NS coincides with the corresponding Schwarzschild radius after its metamorphosis into a DEQO.

5 HOW COULD DEQOS BE CONNECTED TO DARK MATTER AND DARK ENERGY IN COSMOLOGY?

Baryon matter in QCD is made of gluon-quark plasmas (Bethke 2007). The quarks themselves however make merely 2% of the baryon mass, whereas the remaining 98% are from the field and other related sources. Hence the flux tubes governed by gluons are the ones that grant neutrons most of their effective masses. Indeed, this is in line with experimental data from the LHC during the years 2009-12, which reveals that pentaquarks have been detected in the range between 4.38 - 4.45 GeV (LHCb Collaboration 2015, Roca et al. 2015). Obviously they are more massive as the sum of just two individual baryons. The increase of effective mass appears to correlate with the number of communications channels of the gluons connecting the quarks. Here, instead of just 12 in two distinct baryons, there are 30 channels in hexaquarks, i.e. 15 bonds. Assuming the energy stored in each bond connecting two arbitrary quarks to be $(0.938/3) \text{ GeV/channel} = \text{const}$, then a super-baryon consisting of hexaquarks would have roughly the energy: $15 \times (0.938/3) \text{ GeV/channel} \approx 4.6 \text{ GeV}$, which is only slightly higher than the value revealed from pentaquark. However, due to the strong confinement effect, quarks and gluons exist exclusively inside baryons and never in free space.

In the here-presented model, the density of matter at the very central region of massive NSs is beyond the nuclear density, and therefore mergers of baryons to form super-baryons cannot be excluded. As more baryons are dissolved and join the super-baryon, its volume and mass will increase to finally reach the surface of the entire object on the cosmological time scale.

Similar to gluon-quark plasmas inside individual baryons, the ocean of the incompressible gluon-quark superfluid inside the object would be shielded from the outside world by a repulsive quantum membrane, whose strength is proportional to the number of the enclosed quarks (Fig. 12). We conjecture that this membrane, which would be located at the horizon, would be sufficiently strong to prohibit quantum tunnelling of particles both from inside and outside the wall, except for gravitons. If this is indeed the case, then there must be a length scales $\Lambda_{rm}$, so that when the separation length, $d$, between two arbitrary DEQOs is comparable to $\Lambda_{rm}$, the objects would experience repulsive forces similar to those operating between individual baryons in atomic nuclei.

Hydrodynamically, the generation of the dark energy inside the cores of massive NSs can be modelled by introducing a scalar field, which, together with the baryonic energy, may be used to solve the TOV-equation inside these general relativistic objects (Hujeirat 2016).

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Is there a hidden connection between massive neutron stars and dark matter in cosmology?

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