Evidence for pulsars metamorphism and their possible connection to black holes and dark matter in cosmology

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ABSTRACT

Pulsars and neutron stars are generally more massive than the Sun, whereas black holes have unlimited mass-spectrum, though the mass-gap between 2 - 5\(M_\odot\), which applies for both classes, is evident and remains puzzling.

Based on the solution of the TOV equation modified to include a universal scalar field \(\phi\) at the background of supranuclear densities, we claim that pulsars must be born with embryonic super-baryons (SBs), that form through the merger of individual neutrons at their centers. The cores of SBs are made of purely incompressible superconducting gluon-quark superfluids (henceforth SuSu-fluids). Such quantum fluids have a uniform supranuclear density and governed by the critical EOSs for baryonic matter \(P_b = \mathcal{E}_b\) and for \(\phi\)–induced dark energy \(P_\phi = -\mathcal{E}_\phi\).

The incompressibility here ensures that particles communicate on the shortest possible timescale, superfluidity and superconductivity enforce SBs to spin-down promptly as dictated by the Onsager-Feynman equation, whereas their lowest energy state grants SBs lifetimes that are comparable to those of protons. The extraordinary long lifetimes suggests that conglomeration of SuSu-objects would evolve over several big bang events to possibly form dark matter halos that embed the galaxies in the observable universe.

Having pulsars been converted into SuSu-objects, which is predicted to last for one Gyr or even shorter, then they become extraordinary compact and turn invisible. It turns out that recent observations on the quantum, stellar and cosmological scales remarkably support the present scenario.

Keywords: Relativity: general, black hole physics — neutron stars — gluon-quark fluids, low temperature physics, superfluidity — QCD — dark energy — dark matter

1 SUPERFLUIDITY IN PULSARS

Pulsars and NSs are considered to be made of superfluids governed by triangular lattice of quantized vortices as prescribed by the Onsager-Feynman equation: \(\oint \mathbf{v} \cdot d\mathbf{l} = \frac{2\pi \hbar N}{m}\). \(\mathbf{v}, d\mathbf{l}, \hbar, m\) here denote the velocity field, the vector of line-element, the reduced Planck constant and the mass of the superfluid particle pair, respectively.
Accordingly, Crab pulsar should have approximately $N_n = 8.6 \times 10^{17}$ neutron and $N_p \approx 10^{30}$ proton-vortices (Fig. 1). Let the evolution of the number density of vortex lines, $n_v$, obeys the following advection-diffusion equation:

$$\frac{\partial n_v}{\partial t} + \nabla \cdot n_v \mathbf{u}_f = \nu_t \Delta n_v,$$

(1)

where $t$, $\mathbf{u}_f$, $\nu_t$ denote the transport velocity at the cylindrical radius $r = r_f$ and dissipative coefficient in the local frame of reference, respectively. When $\nu_t = 0$, then the radial component of $\mathbf{u}_f$ in cylindrical coordinates reads:

$$u_f^{\text{max}} \approx - (\Omega/\Omega^\ast) r > 0.$$ 

In the case of the Crab; this would imply that approximately $10^6$ neutron vortices must be expelled/annihilated each second, and therefore the object should switch off after $10^6$ or $10^{13}$ yr, depending on the underlying mechanism of heat transport (see [Baym 1995] [Link 2012] and the references therein). However both scenarios are contrary to observation, as numerous NSs has been found, which are older than $10^6$ yrs, though none of them is older than $10^9$ yrs. On the other hand, recent numerical calculations of superfluids reveal generation of large amplitude Kelvin waves that turn superfluids turbulent (see [Baranghi 2008] [Baggaley & Laurie 2014] [Dix & Zieve 2014] and the references therein). It is therefore unlikely that trillions of Kilometer-long neutron and protons-vortices inside pulsars and NSs would behave differently. In this case, $u_f$ should be replaced by a mean turbulent velocity $< u_f >^\ast$ with $u_f^{\text{max}}$ being an upper limit.

As the number of vortex lines decreases with time due to emission of magnetic dipole radiation and therefore the separation between them increases non-linearly, it is reasonable to associate a time-dependent turbulent length scale $\ell_t(t)$, which covers the two limiting cases: $\ell_t(t = 0) = \ell_0 \approx 10^{-3}$ cm and $\ell_t(t = \infty) = \ell_\infty = R_s$. This yields the geometrical mean $< \ell_t > = \sqrt{\ell_0 \ell_\infty} \approx O(10)$ cm. Putting terms together and using $\nu_{\text{tur}} = \nu_t$ to describe the effective turbulent viscosity, we obtain an upper limit for the global diffusion time scale: $\tau_{\text{diff}} = R_s^2 / \nu_{\text{tur}} = O(10^9)$ yr. Similarly, a comparable time scale for the Ohmic diffusion in this turbulent medium can be constructed as well. This is in line with observations, which reveal that most isolated luminous NSs known are younger than $10^9$ yr (see [Espinoza et al. 2011] and the references therein). On the other hand, as stable degenerate NSs require the density gradient to be negative, then the very central region would be the first to be evacuated from vortex lines and all other removable energies that do not contribute significantly to the pressure. Let $r_f$ be the radius of the central region. The star cools and loses energy, $r_f$ would creep outwards with an average velocity: $\dot{r}_f \sim R_s / \tau_{\text{diff}} \approx 10^{-10}$ cm/s. As I show in the next sections, the nuclear matter inside $r_f$ would undergo a transition from compressible dissipative neutron fluid into an incompressible gluon-quark superfluid phase; the lowest possible energy state. Once $r_f = R_s - \epsilon$ ($\epsilon \ll 1$), then the object turns invisible.

In analogy with normal massive luminous stars, we expect massive NSs to also switch-off earlier than their less massive counterparts. The reason is that most models of EoSs for NSs predict a correlation of $M_{NS} \propto \alpha_s$, where $\alpha_s(\approx R_s / \lambda_c^\ast)$ denotes the compact-

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**Figure 1.** A magnetized pulsar is born with an embryonic rigid-body rotating super-baryon (SB) at its center, which is made of incompressible gluon-quark superfluid. By interacting with the ambient medium, the SB expels certain number of vortex lines that are absorbed by the surrounding dissipative medium, thereby causing to promptly spin up: the exact quantum signatures of the glitches observed in pulsars and young neutron star systems.

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1 The rotational energy associated with the outward-transported vortex lines from the central regions are turbulently re-distributed in the outer shells and should not necessary suffer of a complete annihilation.
ness parameter, $R_c$, $R_S$ are star and the corresponding Schwarzschild radii (Haensel et al. 2007). In the extremal case however, when $\alpha_s = 1$, it is reasonable to expect that there will be no turbulence to dissipate. In this case the expression of for the global turbulent diffusion time scale should be modified as follows:

$$\tau_{\text{diff}} = \frac{R_S}{\nu_{\text{tur}}} \rightarrow (R_S - R_c)^2/\nu_{\text{tur}}.$$  

In terms of NS-parameters, the turbulent viscosity reads: $\nu_{\text{tur}} = R_NS^2(\hat{\Omega}/\Omega)\sqrt{\ell_0/R_NS}$. Putting terms together, we obtain $\tau_{\text{diff}} = (1-\alpha_s)/\sqrt{(R_NS/\ell_0)(\Omega/\hat{\Omega})}$. For a Vela-type pulsar with $\alpha_s \approx 2/3$, the effect of compactness would shorten $\tau_{\text{diff}}$ by almost one order of magnitude.

2 THE INCOMPRESSIBILITY OF SUPRANUCLEAR DENSE FLUIDS

Modeling the internal structure of cold NSs while constraining their masses and radii to observations, would require their central densities to inevitably be much higher than the nuclear density $-\rho_0$: a density regime in which all EOSs become rather uncertain and mostly acausal (see Hampel & Fischer 2012 and the references therein). On the other hand, at very high densities, almost all EOSs converge to the stiffest EOS: $P_{\text{local}} = E$ (Camenzind 2007), where fluids become purely incompressible.

The corresponding chemical potential here reads:

$$\mu = \frac{\partial \mathcal{E}_b}{\partial n} = P_{\text{local}} + \mathcal{E}_b = 2\mathcal{E}_b/n,$$

whose solution is:

$$\mathcal{E}_b = a_\infty \, n^2.$$

Particles obeying this EOS communicate with the speed of light. This implies that the number density must be upper-bounded by $n_{\text{tur}}$, beyond which local thermodynamical quantities become constants, specifically $\mu = \mathcal{E}_\phi = P_{\text{local}} = \text{const}$. In this case calculating the degenerate pressure from the local quantities becomes invalid as it yields a vanishing local pressure ($P_{\text{local}} = n^2 \frac{\partial}{\partial n} (\mathcal{E}_b/n) = 0$).

Even if the fluid were weakly-compressible only, $\nabla P_{\text{local}}$ would be too smooth to hold the object against its own self-gravity. This becomes even blatant at the center, where the gradient of the pressure vanishes to meet the regularity condition. The usual adopted strategy to escape this pressure-deficiency is to enforce an unfounded inward-increase of $\mathcal{E}_b$ as $r \to 0$, resulting therefore in unreasonably large central densities.

Alternatively, one could argue that the strong gravitational field would enforce fusing of neutrons at the center of NSs and form a sea of gluon-quark fluid. However, a phase transition from normal nuclear matter into a gluon-quark plasma (GQP) under classical conditions was found to be unlikely (Baym & Chin 1976; Chapline & Nauenberg 1977). The GQPs in these studies were assumed to be locally conformal, compressible and governed by a non-local and constant bag pressure.

However, the situation may differ if there is a mechanism at the background of supranuclear densities, that among others, is capable of injecting energy into the system. This in turn would effectively increase the mass of the object, steepen the curvature of the embedding spacetime and compress the nuclear fluid up to the saturation level, beyond which it becomes purely incompressible. The underlying conjecture here is that compression would mainly affect the distance between individual neutrons, $\ell_q$, rather than the distance, $\ell_s$, between the quarks enclosed in individual neutrons.

In fact there are at least two observational facts that in favor of this argument:

(i) Massless gluons mediate the strong force between quarks with the speed of light, whereas global compression of the central fluid-core proceeds almost in a quasi-stationary manner. Hence, as the quark contribution to baryon mass is negligibly small, compressibility of the gluon-quark plasma would violate the causality principle.

(ii) The quark potential $V_q$ inside baryons increases with the radius to attains maximum at the boundaries - $r_b$.

Quark confinement however requires that $V_q(r_b) \approx 0.94$ GeV. In this case the effective/reactive velocity at the boundary would read: $< V > = \Delta v/\Delta t = \Delta x \Delta E/h \approx c$, where we set $\Delta x = 10^{-13}$ cm. Consequently, the reaction time of GQPs inside neutrons to whatsoever external compressional effects is of order $10^{-23}$ sec: the shortest possible time scale in the entire system.

Moreover, recalling that the lifetime of neutrons in free space is extremely short compared to that of protons, then compression of GQPs inside neutrons most likely would provoke a runaway decay into protons and would give rise to neutrino-dominated electromagnetic eruptions. However, such events can be safely ruled out by observations.

(iii) Recent RHIC and LHC experiments have revealed that the matter resulting from smashed protons behaves like fluids, whose constituents move collectively and relatively slowly. These observations are in line with the basic properties of incompressible fluids rather than randomly moving particles in plasmas. Moreover, the coupling constant in QCD is inversely proportional to the density: $\alpha_s \approx 1/\rho$. Hence matter with $\rho > \rho_0$ and $T = 0$ yields automatically $\alpha_s \ll 1$. This means that the interaction strength is at low-
Figure 2. The analytical solution of the TOV equation \( (P_{\text{ana}}) \), assuming the fluid to be incompressible (i.e., the internal energy density \( E_{\text{in}} = \text{const.} \)) for a compactness parameter \( \alpha_s \) near the critical value \( 8/9 \). Obviously, the solution diverges as the center is approached, where the matter becomes ultrabaric. The second profile \( (P_{\text{num}}) \) corresponds to a numerical integration of the TOV equation using \( E_{\text{in}} = \text{const.} \) and assuming \( P(r = 0) = E_{\text{in}} \).

est and therefore the quarks must be moving freely, practically unaffected by whatsoever external forces.

Consequently, as GQPs inside neutrons are incompressible, we expect nuclear fluid inside SBs to be indifferent. This implies that, when the distance between neutrons becomes critically small, e.g., \( \ell_n / \ell_q = \mathcal{O}(1) \), then the pions, \( \pi^0 \), the carriers of the residual strong force between neutrons, become sufficiently energetic and overcome the repulsive barrier, where they go through a "gluonization" process, which subsequently enables them to mediate the strong force between quarks inside SBs efficiently (Fig. 3).

Unlike EOSs in compressible normal plasmas, classical EOSs in incompressible superfluids are non-local. In the latter case, constructing a communicator that merely depends on local exchange of information generally would not be sufficient 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 classical incompressible fluids \( (E = \text{const.}) \). In this case, the pressure depends, not only on the global compactness of the object, but it becomes even acausal whenever the global compactness is enhanced (see Fig. 2).

This is similar to the case when solving the incompressible Navier-Stokes equations, where an additional Laplacian for describing the spatial variation of a non-local scalar field is constructed to generate a pseudo-pressure (; actually a Lagrangian multiplier), which, again, does not respect causality (Hujeirat & Thielemann 2009).

3 THE ONSET OF SUPERFLUIDITY

In the presence of magnetic torque and in the absence of energy generation at the center of pulsars, all types of energies, including magnetic, rotational and rest of thermal energies must diffuse outwards. This energy loss enforces the degenerate core to cool down to \( T = 0 \) and to increase its density. In this case the corresponding de Broglie wave length, \( \lambda_{\text{De}} \propto 1/T \), which coincides with the radius of the core, increases and the enclosed particles start occupying the same quantum state, hence entering the superfluid phase with vanishing entropy: \( (S = k_b ln(\Omega) = 0) \). In fact this is the lowest energy state possible in the system, which is termed here \( L - \text{State} \).

Indeed, recent RHIC and LHC-experiments reveal that GQPs inside smashed protons, which are generally at much higher energy states than the states considered here, were found to be nearly perfect with even smaller viscosity over entropy ratio (Shuryak 2017).

Consequently, we predict the interiors of SBs, which result from fusion of individual neutrons in the \( L - \text{State} \), to be in a purely superfluid and superconducting phase.

The injected dark energy by \( \phi \) may affect the central nuclear fluid in two way: it first strengthens the curvature of the embedding spacetime, enhancing
compression of the central fluid, and secondly, it provokes the "gluonization" procedure:

$$\Delta E_g + \Delta E_G + \pi^0 \rightarrow \Delta E_{g \phi}^{SB},$$

(3)

where $\Delta E_g, \Delta E_G, \pi^0, \Delta E_{g \phi}^{SB}$ denote the local energy enhancement by $\phi$ and "$G$" (gravitational force), the pion energy and the resulting excess of energy gained by the SB, respectively. This reaction is assumed to proceed directly and silently without destroying the superfluidity character of GQ-fluid inside SBs.

On the other hand, the rotational torque of the dissipative ambient medium exerted on the SBs would enforce them co-rotate uniformly. However, SBs are quantum identities and therefore must obey the laws of quantum mechanics. This means that their dimensions and energies can accept discrete values only. It turns out that SBs evolve in a discrete manner as prescribed by Onsager-Feynmann equation in superfluids. SBs here must eject a certain number of vortex lines in order to increase their dimensions [Hujeirat 2017]. Following this scenario, the internal structure of pulsars and UCOs looks as follow:

(a) Pulsars are born with SB-embryos at their centers, which are made of an incompressible superconducting gluon-quark superfluid,

(b) a dissipative neutron fluid that surrounds the SB, and

(c) a geometrically thin boundary layer in-between (BL), where the residual of the strong nuclear force becomes dominant over the viscous forces. The viscosity of the neutron fluid here decreases strongly inwards and vanishes at the boundary of the SB. The BL here is practically the zone, where the neutron fluid is prepared to match the physical conditions governing GQ-fluids inside SBs prior to their merger with other neutrons. It turns out that these merger events are identical to the sudden glitch phenomena observed in pulsars and young neutron star systems [Hujeirat 2017]. Accordingly, once the rotational frequency of the ambient medium falls below a certain critical frequency $\Omega_c$, the SB then undergo a sudden spin-down to the next quantum-allowable frequency, thereby expelling a certain number of vortices, which are then absorbed by the ambient medium and causes the observed spin-up of crusts of pulsars (see Fig. 4). However, the excess of rotational energy is then viscously-redistributed into the entire ambient dissipative medium: a process that may last for weeks or even months.

Indeed, very recent observations appear to confirm our scenario. [Eya et al. 2017] found that the mean fractional moment of inertia in the glitching pulsars correlates weakly with the pulsar spin, implying therefore that glitches are provoked by a central core of different physical properties. Also [Serim et al. 2017] discovered for the first time that the short X-ray outburst 25 days prior to the glitch in the accretion-powered pulsar SXP 1062 did not alter the spin-down of the source, which indicates that glitches are triggered by the core of the NS rather than by the outer shells.

4 CROSSOVER PHASE TRANSITION

For $\rho > \rho_0$, short-range interactions between particles mediated by the exchange of vector mesons most likely would enhance the convergence of the EOSs towards $P \rightarrow \mathcal{E}_b \sim n_b^2$ (see Haensel et al. 2007; Camenzind 2007, and the references therein). The chemical potential here: $\mu \equiv (\mathcal{E}_b + p)/n_b$ increases linearly with the number density $n_b$. Matter with $d\mu/dn > 0$ is classified here as H-State and depicted in red-color in Fig. (5).

However In the absence of energy generation, degenerate matter cannot hold a correlation of the type $\mu \sim n_b$ indefinitely and it must terminate at a certain critical density $n_{c,r}$. This agrees with the two facts: (i) central densities in NSs, $\rho_c$, increase with their masses and (ii) $\rho_c$ must be upper-bounded by $\rho_c \lesssim 12.5 \times \rho_0$ in order to fit the observed mass function (see Latimer 2011 and the references therein).

On the other hand, in an ever expanding universe, the eternal-state of matter should be the one at which the internal energy attains a global minimum in spacetime (zero-temperature, zero-entropy and where Gibbs energy per baryon is lowest, i.e. in the L-State). Taking into account that $\mu(r) e^{\mathcal{V}(r)} \equiv const.$ inside massive NSs together with the a posteriori results $e^\mathcal{V} \ll 1$ (see Fig. 9), we conclude that $\mu \sim \mathcal{E}_b/n_b = const.$ Under these conditions the gradient of the local pressure $P_{local}$ vanishes and a non-local pressure $P_{NL}$

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is necessary to avoid self-collapse of the object into a BH.

The slope of the chemical potential $d\mu/dn$ between the H and L-states in the n-space could attain positive, negative or even discontinuous values. However the case with $d\mu/dn > 0$ should be excluded, as it implies that the eternal state of matter would be more energetic than the H-State, which is a contradiction by construction. Similarly, the case $d\mu/dn < 0$ is forbidden as it would violate energy conservation ($dP/dn < 0 \Leftrightarrow$ adding more particles yields a smaller pressure). Moreover, let us re-write the TOV equation in terms of $\mu$:

$$\frac{d\mu}{dr} = -\frac{G}{c^2 r^2} \left(\frac{dE_b}{d\mu}\right) \frac{d\mu}{dn} \left(\frac{m + 4\pi^3 P}{1 - r_s/r}\right).$$  \hspace{1cm} (4)

Obviously, as $\mu > 0$, a negative $d\mu/\mu$ would destabilize the hydrostatic equilibrium, unless external sources are included, e.g. bag energy and/or external fields.

Therefore, although a first order phase transition may not be completely excluded, a crossover phase transition into an incompressible superfluid phase with $\mu = \mu(n = n_{cr}) = const.$ would be more likely. Here, $\mu$ and $P$ on both sides of the transition front are equal and, with the help of an external field, both $(\mathcal{E}_{tot}/n)^+$ and $(\mathcal{E}_{tot}/n)^-$ across the front can be made continuous (Fig. 2).

In the present study, the crossover phase transition corresponds to "silent" mergers of baryons forming SBs. Inside SBs, the fluids have $\mu = n = const.$ and $T = 0$ and therefore vanishing entropy. To overcome the repulsive barrier between individual neutrons and provoke their merger, external forces are required. In the present study, we assume that, in addition to compression by self-gravity, there is a universal scalar field, $\phi$, at the background of supranuclear dense matter, which provide the energy required for forming an eternal stable GQ-cloud inside SBs. In this case, the dark energy potential associated with $\phi$ should have similar effects as the generalized quark-potentials inside individual neutrons, namely:

$$V_{\phi} = a_{\phi} r^\gamma + b_{\phi} + \frac{c_{EM}^E}{r},$$ \hspace{1cm} (5)

where $a_{\phi}, b_{\phi}, c_{EM}^E$ are constant coefficients (see Sugiuchi & Suganuma 2015 and the references therein). Without loss of generality, we may set $c_{EM}^E = 0$ and $\gamma = 2$. As the scalar field is universal, its special and temporal variations are assumed to vanish. Therefore,

2 Classically incompressible fluids with $\mathcal{E} = const.$ have negative local pressure. Therefore an acausal non-local pressure is usually used for stabilizing the fluid configurations modelled by the incompressible Navier-Stokes equations.
The superscripts "0" and "φ" refer to the canonical energy scale at which momentum transfer between quarks saturates, i.e., \( b_0 = 0.221 \) GeV. The fluid in the post transition phase is governed by the EOS: \( P^0 = P_L = E^0 = \rho \epsilon c^2 = const. \)

For a given central density, the solution procedure adopted here is based on integrating the TOV-equations for the pressure, enclosed mass and for the pseudo-gravitational potential from inside-to-outside, using either the first order Euler or the fourth order Runge-Kutta integration methods.

For verification purposes the TOV equation has been solved using a polytropic EOS as well as for incompressible case (\( \mathcal{E}_b = const. \)), and using both integration methods (Fig. 7).

Similarly, in Figures (8) and (9)/top we show the profiles of the negative pressure, the enclosed effective mass (i.e. the energy due to baryon and energy enhancement by the scalar field \( \phi \)) and the inverse of the metric coefficient \( g_{rr} \) for different values of the dark energy coefficient \( a_0 \) (see Eq. 4).

Obviously, assuming the object to have \( a_S = 1/2 \) initially, its final compactness must then increase with increasing \( a_0 \), i.e. with increasing the rate of dark energy injection. Using the limiting values \( a_0 = 0.78 \) and \( b_0 = 0.22 \), the scalar field is capable of injecting the energy required to deeply sink the object into spacetime and turn it invisible, where \( a_0^c = 1 - \epsilon \), hence attaining its maximum possible value. Note that \( \epsilon \) must be extremely small, but still finite in order to prevent the collapse of the object into a BH.

These values of \( a_0^c \) and \( b_0 \) yield a final effective mass that is twice as the initial baryonic mass.

Once the object has completely metamorphosed into a stellar-size SB and its compactness attained the critical limit \( a_S^c \), then the spatial variation of the metric coefficient \( g_{rr} \) across its surface becomes nearly singular (Fig. 9), which implies that all sorts of surface radiation will be extraordinary redshifted, hence the object becomes observationally indifferent from its BH-counterpart. On the other hand, the metric coef-
efficient $g_{1\ell}$, which is a monotonic function of the gravitational potential, appears to be fairly flat inside the object, but it undergoes a dramatic change across the surface to finally attains its weak-field values outside the object.

In addition, we have solved the TOV equation using two different EOSs: an EOS that corresponds to an incompressible GQ-superfluid inside a gradually growing SB together with a polytropic EOS for the ambient medium at different evolutionary epochs (Fig. 10). While the scalar field here is set to inject energy into the SB and therefore increasing its effective mass, the surrounding medium appears to stably and comfortably adjust to the new condition of the SB.

In Fig. 11 we display the Mass of fully-developed SuSu-objects and their progenitors versus $\rho_{cr}$ superimposed on the locations of NSs as reported by Lattimer [2011]. Most remarkable here is that Hulse-Taylor type pulsars are able to form SBs at their centers at much lower central density than usually required for a phase transition into quark fluids, whilst still end up twice as massive as their initial mass (Fig. 11).

### 6 SUMMARY & DISCUSSIONS

The here-presented model is motivated by the following issues:

- Why neither NSs nor BHs have ever been observed in the mass-range 2 - 5 $M_\odot$.
- Most sophisticated EOS used to model the internal structure of NSs are based on central densities that are far beyond the nuclear density: an unknown density regime with great uncertainty.
- What is the origin of glitches observed in pulsars and young neutron stars and wether these carry information that may disclose the internal structure of their cores?
- Could massive NSs end as maximally compact dark objects, i.e. as BH-candidates?
- How does the state of matter in pulsars and NSs evolve on the cosmological time scale and whether they have hidden connection to dark matter and dark energy in cosmology?

In this respect a scenario has been presented, which can be summarized as follows:

(i) Pulsars are born with embryos at their centers (here termed super-baryons -SBs). The interiors of SBs are made of GQ-superfluids and governed by the EOS $P = \mathcal{E} = \alpha_{\infty} n^2$: a purely incompressible fluid state. As a consequence, there is a universal maximum density $\rho_{n}^{\text{uni}}(= \mathcal{O}(\rho_{cr}))$, where the momentum transfer between quarks saturates, the coupling constant $\alpha_{\text{asy}m}$ attains its universal minimum, where quarks are moving freely.

Recalling that the spatial variation of the coefficient $g_{\phi}$ of the Schwarzschild metric on the nuclear length scales is negligibly small ($dg_{\phi}/dl \ll 10^{-10}$), the GQ-superfields may not accept stratification by gravitational fields.

(ii) In the presence of a universal scalar field $\phi$ at the background of supranuclear densities, the injected dark energy by $\phi$ is capable of provoking a phase transition from compressible dissipative neutron fluids into incompressible GQ-superfluids. The effect of both the gravitational and scalar fields is to mainly enhance and convert the residual strong force between nucleons into a strong force that holds quarks together. This action is termed here as a "gluonization" procedure, which is equivalent to energy injection into the system, thereby maximally enhancing the effective mass of the object and turns it invisible. It turns out that using an interaction potential of the type $V_\phi = a_\phi r^2 + b_\phi$ appear to be most appropriate for maximizing the compactness of the object without significantly changing its dimensions (Fig. 5).

(iii) In a recent study, I have shown that the glitch phenomena observed to associate the evolution of pulsars and NSs are in perfect-agreement with the formation scenario of embryonic SBs at their centers.

(iv) Once the entire object has metamorphosed into a stellar-size SB, the spacetime in its interior would be fairly flat, but become exceedingly curved across its surface (Fig. 5). Hence SBs are practically trapped in spacetime, extraordinarily redshifted and therefore completely invisible.

(v) According to the here-presented scenario, all visible pulsars and NSs must contain SBs. The gravitational significance of these SBs depends strongly on their evolutionary phase and in particular on their ages and initial compactness. Accordingly, pulsars and young NSs should be less massive than old ones, and the very old NSs should turn invisible by now. To quantify the mass-enhancement by $\phi$, let $M_\phi$ be the mass of the NS at its birth and $M_b$ being the mass enhancement due to $\phi$. Requiring $R_\phi > R_b$, then the following inequality holds:

$$1 + \alpha_{DE} \leq \left(\frac{3 \rho_{cr}}{32\pi}\right)^{1/3} \frac{c^2}{GM_b^{2/3}},$$

or equivalently,

$$1 \leq \frac{E_{\text{tot}}}{E_b} \leq 2.06 \frac{P_{15}^{1/3}}{M_{14.4}^{2/3}}.$$
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interacting with \( \phi \), they become more massive and more compact to finally reach \( R_\star = R_S + \epsilon \) at the end of their luminous phase \( (\epsilon \ll 1) \), which would last for approximately \( 10^9 \) yr or even less, depending on their initial compactness Fig. 4 and Fig. 7).

Similar to atomic nuclei, I conjecture that the enormous surface stress confining the sea of GQ-superfluid inside stellar-size SBs render their surfaces impenetrable by external low energy particles, hence maintaining the eternal stability and invisibility of SuSu-objects. This implies that the core of a fully-developed SB would be shielded by a protecting repulsive barrier. However, due to the deep gravitational wells of SBs, such incidents would be practically observable, though they are ruled out by observations completely. Even if there were no repulsive barriers, we expect SBs to still be stable against mass-enhancement from external sources. Let a certain amount of baryonic matter, \( \delta M_b \), be added to the object via accretion from external sources. Then the relative increase of \( R_\star \) compared to \( R_S \) scales as:

\[
\frac{\delta R_\star}{R_S} \approx \frac{\rho_{\text{new}}}{\rho_{\text{cr}}},
\]

where \( \rho_{\text{new}} \) is the average density of the newly settled matter. Unless \( \rho_{\text{new}} \geq \rho_{\text{cr}} \), which is forbidden under normal astrophysical conditions, the SuSu-object would react stably. However, in the case of super-Eddington accretion or merger, the newly settled matter must first decelerate, compressed and subsequently becomes virially hot, giving rise therefore to \( \rho_{\text{new}} \ll \rho_{\text{cr}} \). On the other hand, such events would lower the confinement stress at the surface and would turn the quantum jump of the energy density at \( R_\star \), which falls abruptly from approximately \( E \approx 10^{36} \) erg/cc at \( R_\star \) down to zero outside it, into an extraordinary steep pressure gradient in the continuum. While such actions would smooth the strong curvature of spacetime across \( R_\star \), they would enable SuSu-objects to eject quark matter into space with ultra-relativistic speeds, which is forbidden. Nonetheless, even if this would occur instantly, then the corresponding time scale \( \tau_d \) would be of order \( \Lambda_j/c \), where \( \Lambda_j \) is the jump width in centimeters. Relating \( \Lambda_j \) to the average spacing between two arbitrary particles \( (\sim n^{-1/3}) \), this yields \( \tau_d \approx 10^{-24} \) s, which is many orders of magnitude shorter than any known thermal relaxation time scale between arbitrary luminous particles.

Although electromagnetic activities and jets have never been observed in dark matter halos, they are typical events for systems containing black holes. Recalling that supermassive GBECs are dynamically unstable (Hujeirat 2012), our results here address the following two possibilities:

- The passivity of DM to electromagnetic radiation may indicate that the collective effect of the repulsive forces of a cluster of SuSu-objects is repulsive on smaller length scales and attractive on the larger ones. Hence approaching luminous matter will be forced to deviate from face-to-face collisions with the cluster of SuSu-objects, though n-body and SPH-numerical calculations are needed here to verify this argument.

- If the onset of \( \phi \)-baryon interaction indeed occurs at \( n_{\text{cr}} \), then the majority of the first generation of stars must have collapsed into UCOs and subsequently became SuSu-objects, rather than collapsing into stellar BHs with \( M \leq 5 \times M_\odot \). These objects are expected to conglomerate into dark matter halos over several big bang events and to embed the galaxies in the observable universe. This conclusion is in line with recent observations of NASA’s Spitzer Space Telescope, which reveal the existence of primordial galaxies, such as GN-z11, whose age might be even bigger than that of our universe (7).

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For test purposes the profiles of the pressure and enclosed mass of a NS that have been obtained by solving the TOV equation, using a polytropic EOS ($P = K \rho^\gamma$). In the lower figure the numerical errors for two different numerical integration methods are shown: the first order Euler and the fourth order Runge-Kutta methods using $10^4$ grid points compared to a reference solution that has been obtained using $10^7$ grid points. While the accuracy of Runge-Kutta method is highly superior over Eulers, the effect of errors on the solutions presented here can be safely neglected.

**Figure 8.** The radial distributions of the baryonic pressure ($P_{\text{bar}}$) and negative pressure ($P_\phi$) inside an incompressible GQ-superfluid core (left). The enclosed mass of the baryonic matter and the gradual mass-enhancement due to dark energy is shown for different values of $a_\phi$ (right).
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Figure 9. In the top panel we show the radial distributions of the metric coefficients $g_{rr}$ and $g_{tt}$ inside a normal NS ($P_L = K\rho^n$ and $P^\phi = 0$) and inside a SuSu-object ($P_{local} = const.$ and $P^\phi = -V^\phi$). Obviously, normal models of NSs have larger radii and considerably less compact than their SuSu-counterparts, which can be inferred from the very limited spacial variations of $g_{rr}$ and $g_{tt}$. In the lower panel, the compactness of a typical SuSu-object, expressed in terms of $-1/g_{rr}$ is shown for different values of $a^\phi$. The object turns invisible if $V^\phi$ is calculated with $a^\phi = 0.78$ and $b^\phi = 0.22$.

Figure 10. The profiles of the total energy density $E_{tot}$, the pressure $P^\phi$ induced by $\phi$ and the combined pressure $P_{tot}$ versus radius are shown for different evolutionary epochs $\tau_1 < \tau_2 < \tau_3$. Inside $r_f$: $P_L = 0$ and $P^\phi = -V^\phi$, whereas outside $r_f$: $P_L = K\rho^n$ and $P^\phi = 0$. In each epoch, the object has an SB-core overlayed by a shell of normal compressible matter obeying a polytropic EOS. Obviously, the object appears to stably and comfortably adjust itself to the mass-redistribution inside $r_f$, where the matter is in incompressible GQ-superfluid state.
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Figure 11. Upper mass limit of SuSu-objects versus critical density $n_{cr}$ (in units of $n_0$) is shown. The $\phi$–baryon interaction is set to occur at $n_{cr}$, which in turn provokes the phase transition into the incompressible GQ-superfluid state. The most probable mass-regime for SuSu-objects is marked here in blue colour. Accordingly, the progenitor of a SuSu-object with $3.36 M_\odot$ should be a pulsar/NS of $1.68 M_\odot$, provided it has an initial compactness $\alpha_S = 1/(1 + \alpha_{DE}) = 1/2$ and $n_{cr} = 3n_0$. Similarly, a Hulse-Taylor type pulsar would end as an SuSu-object of $2.91 M_\odot$, if its initial compactness was $\alpha_S = 1/2$ and if $n_{cr} = 4n_0$. On the other hand, moderate and massive NSs with initial compactness $\alpha_S \geq 2/3$, i.e., $\alpha_{DE} \leq 1/3$, need less dark energy to become invisible SuSu-objects, though an unreasonably high $n_{cr}$ is required for triggering $\phi$–matter interaction. NSs falling in this category are to be compared with the colored small cycles and triangles, which show the approximate locations of various NS-models as depicted in Fig. (4) of Lattimer & Prakash (2011).

Figure 12. A schematic description of an invisible SuSu-object trapped in spacetime and surrounded by a repulsive barrier that protects/confines the enclosed sea of GQ-superfluid. The spacetime inside SuSu-objects is fairly flat, but extraordinary curved and nearly singular across their surfaces.
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