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# Hydrodynamics of the dark superfluid: I. genesis of fundamental particles.

Marco Fedi

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**Abstract** Here we consider the existence of an ubiquitous dark superfluid which fills the universe corresponding to dark energy ( $\sim 70\%$  of the universe mass-energy, also expressed in the cosmological constant) and dark matter. As in other superfluids, quantum vortices would originate, whose geometry can describe the spin of fundamental particles, suggesting the validity of a quantum hydrodynamic approach to particle physics. This seething dark superfluid would also justify the continuous formation and annihilation of virtual particles and antiparticles in quantum vacuum as vortex-antivortex pairs, letting us reinterpret quantum vacuum as hydrodynamic spontaneous fluctuations of this dark superfluid. In this case, it would be correct to say that dark energy (or rather the dark superfluid) does not interact with our baryon world unless it is hydrodynamically perturbed, in which case it could even correspond to the particles of the Standard Model. Antimatter and its absence in the universe, as well as particle decay may also have place in a superfluid model, completing the picture, while fundamental forces exerted by particles, such as gravity or electromagnetism, have their hydrodynamic equivalents in the Bernoulli force which may cause attraction or repulsion between quantum vortices. As regards the repulsive force attributed to dark energy in cosmology, it would depend on the internal pressure of the dark superfluid, represented by its energy density, while the cosmic microwave background at  $\sim 2.72\text{K}$  would be its superfluidity temperature, consistent with those of other superfluids as  $^4\text{He}$ .

**Keywords** superfluid vacuum · dark energy · dark matter · particle physics · spin

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## 1 Introduction: a superfluid universe?

K.Huang has dedicated a book [11] to the possibility that our universe possess superfluid features. Here we want to continue the theoretical investigation, also taking into account recent experiments and observations and in this first paper concerning the hydrodynamics of the dark superfluid we focus on fundamental particles described as topological defects (quantum vortices) in this dark medium. Data from the ESA Planck Space Observatory say that dark energy constitutes 69.1% of the universe mass-energy. The only detectable effect currently attributed to dark energy is its repulsive force, which opposes gravity and causes a supposed (we propose a different, superfluid cosmological model [2]) accelerated expansion of the universe. Since it is otherwise undetectable and its density does not affect the motion of the celestial bodies, it is believed that it does not interact with ordinary matter. On the contrary, we speculate that it may be a fundamental superfluid, whose internal pressure opposes gravity [2, 7] — indeed the energy of vacuum per unit volume, whose value<sup>1</sup> is currently believed to be  $\sim 6 \cdot 10^{-9}\text{J}/\text{m}^3$  from WMAP measurements, has units of pressure — and whose hydrodynamic perturbation may even correspond to the known massive fundamental particles, as quantized vortices, a picture thanks to which we can also understand quantum vacuum and the infinite pairs of virtual particles and antiparticles which continuously form and annihilate in it, probably as vortex-antivortex pairs, as indeed observed in other superfluids and in polariton condensates [42, 43], also at room temperature [19]. Quantum vacuum or here the cosmic and ubiquitous dark superfluid<sup>2</sup> (DS), would

<sup>1</sup> resorting to the upper value of the cosmological constant, otherwise a much higher value according to quantum electrodynamics. See also [2] Sect. 2 for the problem of vacuum energy density.

<sup>2</sup> we believe that here the term *dark energy* may be confusing as it does not underline its mass density and hypothesized superfluidity. The

be a cosmic Bose-Einstein condensate (BEC) [1, 7, 4–6, 8–12] of dark energy’s quanta, we call them dark superfluid quanta (DSQ). An analogy with the granular, quantized spacetime of Loop Quantum Gravity [13, 14] shall be reported, in which the superfluidity of the spin network should not be excluded. The existence of a false vacuum with non-zero energy content is definitively accepted and proven in a lot of physical phenomena as the Lamb shift, the Casimir effect, the Unruh effect, the anomalous magnetic moment, vacuum birefringence [35] etc. All these phenomena could be rooted in the ubiquitous DS. Its quantum granular, foamy nature seems to have been confirmed by G. Amelino-Camelia in a recent statistical analysis on the observation of neutrinos and photons using to data from the IceCube and the Fermi GLAST [44]. Let us reflect on vacuum fluctuations

$$\Delta E \Delta t \geq \hbar. \quad (1)$$

The circulation in a quantized vortex,  $\oint_C \mathbf{v} \cdot d\mathbf{l} = nh/m$ , multiplied by mass becomes the Bohr-Sommerfeld quantization condition, expressing mass circulation in a quantized vortex

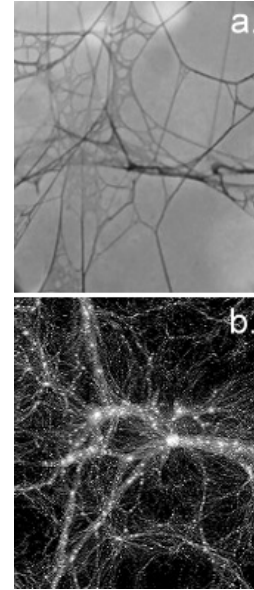
$$\oint_C \mathbf{p} \cdot d\mathbf{x} = nh. \quad (2)$$

For  $n = 1$ , Eq. (2) tells us that the quantum of action,  $h$ , actually refers to a complete turn along a circular path, performed by a quantum whose momentum is  $p$ . In (1)  $2\pi$  ( $\hbar = h/2\pi$ ) also refers to a complete turn and we can interpret vacuum fluctuations as the circulation of DSQ in quantized vortices during a time  $\Delta t$  (1), before vortex-antivortex annihilation occurs.

Quantum vortices are known to manifest in superfluids, as in superfluid  $^4\text{He}$  [10, 15], so this interpretation of quantum fluctuations is a first clue to think of quantum vacuum as a superfluid. Furthermore, fermions spin- $1/2$  may be described in hydrodynamic terms as the circulation of DSQ in a torus vortex (see Sect. 3). Thus, if vacuum fluctuations are superfluid vortices, where is the underlying superfluid in which they arise?

Also according to Huang [11], the possible answers are either the Higgs field or dark energy, both observed as “dark” scalar fields. Being the Higgs boson the fundamental excitation of the Higgs field, it is probably a vortex itself, so we opt for dark energy, as a cosmic fundamental scalar field with superfluid features. After all, we know it constitutes  $\sim 69\%$  of the mass-energy of the universe, also expressed in the cosmological constant,  $\Lambda = k\rho_0$ , of Einstein field equation, where  $\rho_0$  ( $T^{00}$ , as regards the stress-energy tensor) indicates the density of dark energy. Along with dark matter, which can be interpreted as a quantum hydrodynamic manifestation of dark energy itself [5, 12] and whose existence is evident in the dark halos of spiral galaxies which the flat

definition *dark superfluid* also helps to understand dark matter as a hydrodynamic manifestation of superfluid vacuum, as we argue (Fig.1).



**Fig. 1** Left: (a) Metal atoms trapped in superfluid helium vortices highlight a structure of vortex filaments [31]; (b) galactic filaments of dark matter which baryon matter aggregates on forming stars and galaxies [45]. Here the relationship between dark energy and dark matter is the same existing between superfluid helium and the vortex filaments which manifest in it, i.e. we suppose dark matter is a hydrodynamic manifestation of dark energy [5, 12].

profiles of orbital velocities are believed to be due to, we arrive at  $\sim 95\%$ . Thus, we are probably facing a superfluid universe [11, 12].

The temperature of the cosmic microwaves background radiation (CMB),  $\sim 2.72$  K, would be in reasonable agreement with the temperature of other superfluids such as  $^4\text{He}$ . Fig. 1 shows dark matter distribution in the universe in analogy with the structure of a vortex web arising in a familiar superfluid ( $^4\text{He}$ ). Within this analogy all the space among the filaments is occupied by liquid helium in (a) and by the DS in (b). Moreover in (a) the filaments are made visible using metallic atoms which adhere to the vortices, while in (b) baryon matter (dust, gases) adhere to the vortices of dark matter making them visible in a similar way. Indeed we do not directly observe dark matter but its “pilot-action” on baryon matter’s dynamics.

The equation of state of cosmology for a single-fluid model can be referred to superfluid dark energy, where  $P_d$  and  $\rho_d$  are respectively pressure and density of dark energy [37]

$$w = \frac{P_d}{\rho_d} \quad (3)$$

Treating the universe as a fluid medium is therefore already a standard praxis in cosmology. The analogy showed in Fig. 1 let us also suppose that the universe was (or still is) spinning (we confirm that in the superfluid cosmological model [2]). But to be precise, it would be the DS filling the uni-

verse that would be spinning. Indeed, we know that rotatory motion produces vortex structures in laboratory superfluids. The observed asymmetry in spiral galaxies chirality [32] suggests the rotation of the cosmic superfluid, and this fact would also explain the left-handed bias in the world of fundamental particles and of life molecules [20]. Lathrop [11, 28] has hypothesized the genesis of spiral galaxies from giant vortices on which matter particles accrete and gravitate, up to creating a black hole at the center of most galaxies. Moreover, if particles have formed as quantized vortices in the spinning DS, this would also be the reason for the non-detection of antimatter in the universe (vortex-particles have arisen either left- or right-handed) and would be a further clue for a superfluid origin of fundamental particles. Indeed, about baryon asymmetry, the decay of B mesons is predicted to favor the production of matter over antimatter but not enough to explain the huge preponderance of matter in the present universe. Other tests at LHCb [36] have investigated the CP symmetry violation in baryons that seem to follow different decay paths, however stronger data are necessary and the observed phenomenon may be too rare in nature. This would testify that the CMB radiation is not the echo of the primordial matter-antimatter annihilation but the intrinsic average temperature of the DS in the cosmos.

We understand that such a superfluid approach has also important cosmological implications, which are discussed in detail in [2] and that suggest a new superfluid cosmological model, where the still unsolved criticalities of the current standard model, from cosmic inflation to accelerated expansion, do not appear.

## 2 Fundamental particles as quantized vortices in the dark superfluid.

Quantum vortices form in superfluids, as in  $^4\text{He}$  [10, 11, 15] and in other quantum fluids. Recent experiments with polariton condensates [46] have highlighted a particle-like behavior of quantum vortices as far as several aspects of particle physics are concerned, e.g. attraction, repulsion [53], annihilation as vortex-antivortex. By considering quantum vacuum as a superfluid [1, 3, 6, 10, 11, 34], Sbitnev applies quantum considerations to Navier Stokes equations to describe vortex objects (vortex balls) which, unlike Hill's spherical vortices, show intersected streamlines and seem to satisfactorily reproduce fermions' spin by varying their orientation at each revolution. In a later stage the author agreed [30] with the torus-shaped vortex model of fermions reproducing the spin-1/2 (Sect. 3), previously presented also in [34]. Also Volovik [9, 10] discusses the possible topology of quantum vacuum and the appearance of vortices. Huang affirms that quantum turbulence (chaotic vorticity; vortex tangle sustained by vortex reconnection) in the early universe was able to create all the matter in the universe [11], saving the

Big Bang theory. The author has indeed not come to develop a completely superfluid picture of cosmology and relativity, which on the contrary we believe in [2, 40, 39].

Vortices in superfluids behave as gaps in the medium where superfluidity breaks down and their structure, due to the healing length (Fig. 2), would suggest the non-necessity of renormalization, since no ultraviolet divergence occurs in this case, unlike in the picture of particles as adimensional points, where a *classical radius* has to be artificially assigned. The healing length can be defined as

$$\xi \equiv \sqrt{\frac{V}{8\pi a N}} \quad (4)$$

where  $V$  is the volume of the system where the vortex arises,  $a$  the scattering length of DSQ and  $N$  a normalized number of quanta in the volume.

By considering the DS as a BEC [1], we can start to describe its behavior from the Gross-Pitaevskii equation (GPE) [16]

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \psi + g\psi |\psi|^2 - \psi \mu_0 \quad (5)$$

where  $\psi$  is the condensate wave function, with  $m$  as the mass of a quantum,  $\mu_0$  the chemical potential and  $g = 4\pi a \hbar^2/m$  a low-energy parameter, where  $a$  refers to the scattering length between quanta. In the phase representation  $\psi = \sqrt{\rho} e^{i\phi}$ ,  $\rho$  is the density of the superfluid. From (5) we can write the hydrodynamic equations, i.e. the continuity equation and the analogue of the Euler equation

$$\frac{\partial \rho_d}{\partial t} + \nabla \cdot (\rho_d \mathbf{v}_S) = 0 \quad (6)$$

$$m \left( \frac{\partial \rho_d}{\partial t} + \mathbf{v}_S \cdot \nabla \right) \mathbf{v}_S = \nabla \left( \mu_0 - g\rho_d + \frac{\hbar^2}{2m} \frac{\nabla^2 \sqrt{\rho_d}}{\sqrt{\rho_d}} \right) \quad (7)$$

where  $\mathbf{v}_S = \frac{\hbar}{m} \nabla \phi$  is the superfluid velocity and

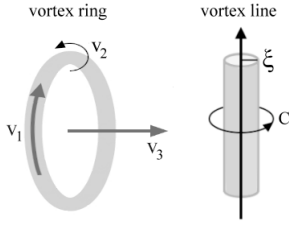
$$\frac{\hbar^2}{2m} \frac{\nabla^2 \sqrt{\rho_d}}{\sqrt{\rho_d}} \quad (8)$$

represents the quantum potential. Since the condensate must be a continuous function in space, its phase has continuous modulo  $2\pi$ . We define then the quantized circulation ( $\Gamma$ ) through the line integral

$$\oint_C d\mathbf{x} \cdot \mathbf{v}_S = \frac{2\pi\hbar}{m} n \equiv \Gamma \quad (n = 0, \pm 1, \pm 2, \dots) \quad (9)$$

in which  $C$  is a close loop in space that must encircle a vortex line where  $\psi = 0$  and the superfluid density vanishes. According to Helmholtz's second theorem, the vortex line, if it does not end on a boundary must form a closed loop and it will indeed form a vortex ring.

As said above, the problem of ultraviolet divergence and of the radius of the fundamental particles is solved in this



**Fig. 2** On the right a vortex ring, actually a torus, where  $v_1$  is the toroidal velocity,  $v_2$  the poloidal velocity and  $v_3$  the translational velocity of the ring. On the right a vortex line with healing length  $\xi$ , actually a vortex tube

approach by the fact that we do not deal with adimensional point-particles, as believed in the current theoretical framework, but with toroidal superfluid vortices of DSQ, with radius  $R = 2\xi$ , being  $\xi$  the healing length of the vortex. Here the velocities  $v_1$  and  $v_2$  (Fig. 2) of DSQ in the vortex may correspond to the spin- $1/2$  of fermions, as discussed below.

### 3 Spin as vortex geometry.

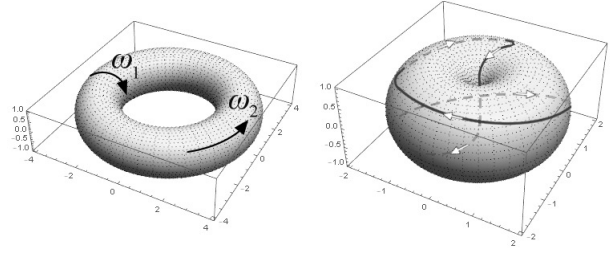
We now show how the flow of quanta in a torus vortex can satisfactorily represents the spin- $1/2$ , as well as any other spin of the Standard Model. According to Salvatore Esposito [24], who cites Recami and Salesi [25], we think that the quantum potential of a particle

$$Q = -\frac{1}{2}mv^2_S - \frac{1}{2}\nabla \cdot \mathbf{v}_S \quad (10)$$

totally arises from its internal motion  $\mathbf{v}_S \times \mathbf{s}$ , where

$$\mathbf{v}_S = \frac{1}{2m}\rho^{-1}\nabla\rho = \frac{1}{2m}\frac{\nabla R^2}{R^2}, \quad (11)$$

putting  $\hbar = 1$  and being  $\mathbf{s}$  is the direction of spin. By looking at a particle's spin as internal motion, the link with the concept of vortex-particle is quite immediate. Vorticity has however to explain the specific spin of any particle. As far as the most appropriate vortex geometry to hydrodynamically explain spin is concerned, let us consider a torus-shaped vortex (Fig. 3), [34]. Also Villois, Krstulovic *et al.* analyze vortex tubes evolving into vortex tori in superfluids [38] and demonstrate the emergence of non-trivial topology. This geometry seems to well account for the spin of fundamental particles. In the case a quantum of DS flowing in the torus vortex needed the same time the vortex needs to complete two turns in the toroidal direction to return in the same position after having completed one turn in the poloidal direction, then the vortex would have spin- $1/2$  (fermion), i.e. the system returns in the same state after a toroidal rotation of  $720^\circ$ , after each quantum forming the vortex has moved along a Möbius-strip path (Fig. 3 on the right). It is interesting to notice that such a two-components spin can explain



**Fig. 3** Vortex torus. The ratio of the toroidal angular velocity to the poloidal one may determine the spin of a particle. Each quantum of DS forming the torus vortex flows along a Möbius-strip trajectory. Given the ratio  $1/2$  of the poloidal angular velocity to the toroidal angular velocity, each quantum returns in its starting position after a  $720^\circ$  rotation of the particle. These characteristics are typical of fermions spin- $1/2$

in mechanical terms any other type of spin as the ratio of toroidal to poloidal rotations. Defining  $\omega_1, \omega_2$  as the angular velocities for the respectively cited directions, the spin angular momentum ( $S$ ) would be determined by the ratio  $\omega_1/\omega_2 = (n\pi/dt)/(2\pi/dt)$ , after the cancellations

$$\frac{\omega_1}{\omega_2} = \frac{n}{2} = S. \quad (12)$$

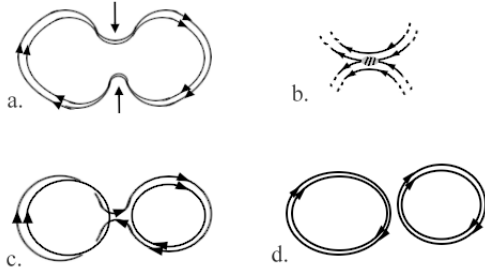
One rotation in the poloidal direction each two in the toroidal direction corresponds to spin- $1/2$ . The case of spin-0 may be determined by further evolution of the horn torus into a spheroidal vortex or correspond to simple, rotating clumps of DSQ. A particular case is the photon, treated by us as a quasi-particle (a special phonon through the DS, see [39], and from this assumption we obtain a simple and effective equation for the whole data set of cosmological redshift [2]). The parametric equation defining the position of a quantum in the torus-vortex after a time  $dt$  can be expressed as follows

$$\begin{cases} x = (r + \xi \cos(\omega_1 dt + \phi_0)) \cos(\omega_2 dt + \theta_0) \\ y = (r + \xi \cos(\omega_1 dt + \phi_0)) \sin(\omega_2 dt + \theta_0) \\ z = \xi \sin(\omega_1 dt + \phi_0) \end{cases} \quad (13)$$

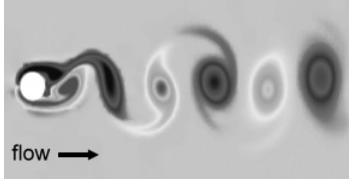
where  $r \geq 2\xi$  is the distance between the center of the tube

and that of the torus,  $\xi$  is the healing length (4),  $\omega_1 = d\phi/dt$ ,  $\omega_2 = d\theta/dt$  and  $\phi_0$  and  $\theta_0$  are the phases having arbitrary values between  $0$  and  $2\pi$ .

The toroidal shape of fundamental particles, which let them appear as subatomic quantized rings, let us also think of the theorized loops in Loop Quantum Gravity [13, 14]. Here however on a higher scale to describe particles but it is not excluded at the moment that also our DSQ may have loop-like geometry. At the same time, we could also notice a certain analogy between a vortex line and a string.



**Fig. 4** Vortex reconnection according to Feynman, as a by us suggested mechanism to explain particle decay. In grey (b) a region where vorticity cancels during reconnection.



**Fig. 5** A computer simulation of a Kármán vortex street. Clumps of DSQ (dark matter?) or other disturbances along a flow in the dark superfluid might be responsible for the joined appearance of particles and antiparticles as vortex-antivortex pairs in the DS.

#### 4 Particles decay and antimatter hydrodynamically explained?

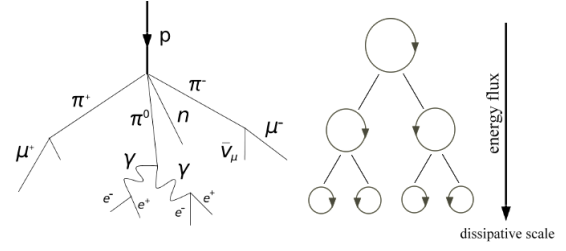
There are at least other two interesting facts about the possibility that fundamental particles be superfluid vortices. First, the phenomenon of vortex reconnection as suggested by Feynman [17], which could explain the decay of a particle into other ones (Fig.4).

In Fig. 4(a) a vortex ring undergoes reconnection when it shrinks to a critical distance, which is estimated by Schwarz [18] to be

$$\delta \approx 2R \ln \frac{R}{c_0 R_0} \quad (14)$$

where  $c_0$  and  $R_0$  are constants. The reconnection process has been experimentally observed by Bewley, Paoletti *et al.* [29] and numerically analyzed using the GPE by Koplik and Levine [21] and by Kivotides, Barengi, Samuels [22].

Another hydrodynamic phenomenon useful to describe the world of fundamental particles is the Kármán vortex street (Fig. 5) [23]. The presence of an obstacle situated in a flow produces a series of vortex-antivortex pairs, whose various appearance depends on the value of the Reynolds number (15). In our superfluid analogy with particle physics, this phenomenon could account for particle-antiparticle simultaneous formation, appearing as a possible hydrodynamic phenomenon involved in parity symmetry, when it occurs in the DS. Moreover, conflicting vorticity would explain the phenomenon of matter-antimatter annihilation, in which vortices and antivortices would decompose into D-SQ producing phonons which propagate through the dark



**Fig. 6** A particle shower (left) compared to a Richardson energy cascade (right) in a superfluid, for wave number  $k < 2\pi/\ell$ , sustained by vortex reconnection, here simplified to a few eddies.

superfluid and these might correspond to photons [39]. Attention to vortex-antivortex dynamics has been paid by several authors [47–53]. The passage from laminar to turbulent flow in the vortex street phenomenon is predicted using the Reynolds number

$$Re_L = UL \frac{\rho_0}{\mu_0} \quad (15)$$

where  $U$  is the free stream flow speed,  $L$  a characteristic length parameter of the obstacle or of the channel,  $\rho_0$  the fluid density and  $\mu_0$  the dynamic viscosity of the stream, which also in superfluids is never exactly zero. Within the understanding of particle decay as vortex reconnection, Fig. 6 shows an analogy between the particle shower induced by a cosmic ray (a proton, in this case) and a Richardson cascade, which in a superfluid and for wave number  $k < 2\pi/\ell$ , may be sustained by vortex reconnection. For  $k > 2\pi/\ell$  the process gives way to a Kelvin-wave cascade, which ends with phonon emission (see also [39]). As regards antimatter, it is eventually worth remembering that the rotation of the cosmic superfluid in a given direction would produce single-handed particles, helping to explain the cause of the observed baryon asymmetry [2].

#### 5 Attractive and repulsive forces

An intrinsic peculiarity of fundamental particles is that of exerting and undergoing fundamental forces (gravitational, electromagnetic, weak and strong interactions). Also these forces therefore need to be hydrodynamically explained within the superfluid picture of quantum particles that we want to sketch. In this case fundamental forces might however become hydrodynamic *apparent* forces. Our attention is focused on the Bernoulli force observed in quantum vortices, able to determine attractive or repulsive forces between vortices, as investigated by Pshenichnyuk [53]. The author describes attractive and repulsive interactions only for vortices arising in a two-component fluid, described as a superfluid with a small quantity of a *doping* substance, e.g. metallic atoms in superfluid  $^4\text{He}$ . In our case the analogy is strong, by considering a two-component DS due to dark energy and to

a smaller amount of dark matter, which, as in Fig. 1b, would adhere to the vortices. The force, due to Bernoulli pressure, can change its sign being attractive or repulsive according to the respective chirality of two interacting vortices. The force is given as

$$\mathbf{F}_b = \int_S K(\mathbf{r}) \mathbf{n}(\mathbf{r}) dS \quad (16)$$

where  $K(\mathbf{r}) = \rho v^2/2$  hydrodynamically expresses the density of kinetic energy (which dominates on the vortex surface, while the density of the superfluid drops to zero within the healing distance) and  $\mathbf{n}(\mathbf{r})$  is a unit vector normal to the cylindrical surface  $S$  over which the integral is calculated. Bernoulli force arises in a superfluid as superposition of the vortices' velocity fields obeying a  $1/r$  function. Points where the fields reinforce each other and points where their interaction makes them weaker, generate a Bernoulli effect, as schematically shown in [53]. Interesting are the analogies with gravity and electromagnetism, in the latter when opposite-sign particles attract each other or repel when possessing the same kind of charge. In this case we have *topological* charges but the question arises whether also charges in electromagnetism could be hydrodynamically described in a DS, currently called quantum vacuum which, as known, is responsible for the existence of the fields. The lines of a gravitational or magnetic field would in this case correspond to those of the velocity field in the superfluid. The proximity to the concept of pilot-wave by de Broglie and Bohm make us reflect further.

## 6 Entropy from two different points of view.

The formation of a vortex in the DS is a loss of order in the scalar field (a topological defect), while, from our point of view, something with a higher order parameter emerges, acquires a structure. Our order is the disorder of the cosmic superfluid and vice versa. We can say that

$$S_{universe} = S_{ds} + S_{struct.} = const. \quad (17)$$

i.e. the entropy of the universe is constant, since that of the DS and the entropy of all hydrodynamically structured objects ( $S_{struct.}$ ) in the universe (from particles to galaxies) are inversely proportional. In other words, when we apply a wave function to the DS, to describe a particle, its entropy increases. The wave function acts on the local density of the superfluid, determining a modification in the configuration space [33], following the logarithmic function

$$S_Q = \frac{1}{2} \ln \rho_d. \quad (18)$$

as quantum entropy and describing the degree of order/chaos of the DS. Agreement with Sbitnev [26,27] is expressed

about the fact that the quantum entropy which describes the configuration space order degree produced by the density of the particles associated with the wave function, is the source of the quantum potential. In other words, the hydrodynamics of the DS, the rupture of its spatial homogeneity, determines its entropy degree and the quantum potential, which in turn acts as a pilot-wave, by virtue of space modifications due to density and kinetics of the DS. Sbitnev shows that by introducing the quantum Hamilton-Jacobi equation (in the momentum  $p$  representation)

$$\frac{\partial S_p}{\partial t} + \frac{p^2}{2m} + \frac{k}{2} \left( \frac{\partial S_p}{\partial p} \right)^2 - \frac{k}{2R_p} \left( \frac{\partial^2 R_p}{\partial p^2} \right) = 0 \quad (19)$$

the quantum potential for a one-body system can be expressed as follows

$$Q = -\frac{\hbar^2}{2m} (\nabla S_Q)^2 + \frac{\hbar^2}{2m} (\nabla^2 S_Q) \quad (20)$$

and the related Bohm's quantum Hamilton-Jacobi equation associated with the wave function  $\psi(\mathbf{x}, t)$  reads

$$\frac{|\nabla S|^2}{2m} - \frac{\hbar^2}{2m} (\nabla S_Q)^2 + V + \frac{\hbar^2}{2m} (\nabla^2 S_Q) = -\frac{\partial S}{\partial t}, \quad (21)$$

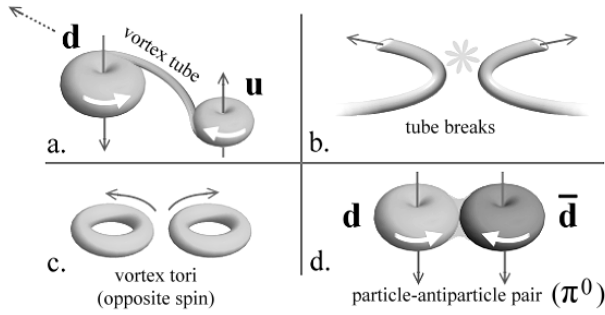
where  $-\frac{\hbar^2}{2m} (\nabla S_Q)^2$  represents the quantum correction of the kinetic energy  $\frac{|\nabla S|^2}{2m}$ , while  $\frac{\hbar^2}{2m} (\nabla^2 S_Q)$  of the potential energy  $V$ . Thus, quantum entropy  $S_Q$  (18) may determine the quantum correctors of a particle's quantum potential. Finally by equating to quantum potential as spin from Eq. (10) we have

$$Q = -\frac{\hbar^2}{2m} (\nabla S_Q)^2 + \frac{\hbar^2}{2m} (\nabla^2 S_Q) = -\frac{1}{2} m \mathbf{v}^2_s - \frac{1}{2} \nabla \cdot \mathbf{v}_s \quad (22)$$

which relates the entropy of the DS to the internal motion of a particle (circulation of DSQ  $\Leftrightarrow$  spin. See Sect. 3).

## 7 Implications for quantum chromodynamics.

Describing fermions as superfluid vortices is in our opinion also useful for a better understanding of quantum chromodynamics. The strong interaction can be in fact described as an exchange of gluons seen as DSQ passing from a vortex to another. This continuous exchange of DSQ is interpreted as the action of gluons and would account for the fact that most of the mass-energy of bound quarks is in the form of force-field energy and for the fact that "color" continuously and circularly migrates from a quark to another. Thus, also the gluon flow would be nothing but a hydrodynamic manifestation of the DS. In Fig. 7 we try to depict the so-called residual strong interaction, as the exchange of DSQ between close vortices. A vortex tube between two quarks (d and u) arises which, once broken, results in two vortex tori (see also Fig. 3) that correspond to a quark-antiquark



**Fig. 7** residual strong interaction (in proton-neutron bond). In a neutron, the quark down is separated from the quark up and a vortex tube appears. When the tube breaks it generates two vortex rings, which evolve as a couple of down/antidown quarks (in mutual spin  $\Rightarrow$  no annihilation), forming a neutral pion that will complete the process of residual strong interaction. Here the vortex tube is a consequence of the already present exchange of DSQ between the two quarks (d, u) having mutual spins.

pair (a neutral pion,  $\pi^0$ ), belonging to the representations  $3$  and  $\bar{3}$  of color SU(3), which in our case are interpreted as a vortex-antivortex pair, within a self-sustainable process.

## Conclusion

The discussed theoretical framework seems to be strong enough to suggest to proceed with the approach of a superfluid universe, where dark energy and dark matter can be considered and described from a renewed point of view as components of a cosmic, dark superfluid at the temperature of the cosmic microwave background, whose fundamental scalar field has  $0_+$  viscosity. One of the geometries that we know can emerge from such a medium is a torus-shaped vortex, which seems to satisfactorily reproduce the spin of fermions. Vortex-antivortex pairs could account for particle-antiparticle formation and so for antimatter, whose annihilation with matter would be due to conflicting vorticity (conflicting spins) during vortex-antivortex interactions as indeed observed in standard superfluids. During annihilation the vortices break up into their fundamental constituents (DSQ in our case) also emitting phonons. In vortex-antivortex annihilation occurring in the DS, phonons would be detected as photons [39]. A possible primordial spinning universe, or a still spinning dark superfluid, in which particles have arisen as same-handed quantized vortices, would account for the single-handed bias of the universe from particles to spiral galaxies and for the non-detection, so far, of antimatter in the universe, perhaps representing a solution to baryon asymmetry. For this reason the CMB might not be the echo of the primordial matter-antimatter annihilation but the zero-point thermal noise of a lively DS. Its heartbeat. The vortex web arising in more familiar superfluids is interestingly comparable to the observed cosmic filaments of

dark matter, letting us speculate that dark matter be nothing but macroscopic vortices taking shape in dark energy (Fig. 1). This agrees with Lathrop's hypothesis [11, 28] on galaxy formation and would justify dark matter galactic halos. The superfluid picture of particle physics has went on along our investigation. The phenomenon of vortex reconnection may in our opinion account for particle decay, while gluons exchange in the strong interaction can be observed as a flow of DSQ. We therefore believe that it is worth to theoretically and experimentally deepen the superfluid approach to fundamental particles, by continuing the investigations on quantum fluids, to obtain a complete quantum hydrodynamic theory of atomic and subatomic physics, as well as to better understand our universe, its genesis, evolution and destiny [2]. Indeed, an effective superfluid approach cannot be conceived without conjoining cosmos and microcosm.

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