1. INTRODUCTION

It is impossible to review all the fundamental works of Landau Institute, which made important contribution to physics in general. Here I will discuss only a part of these works, only those which directly influence my own work during 50 years (1968-2018). Khalatnikov created the unique Institute, where practically all important areas of theoretical physics have been represented, opening broad possibilities for collaboration. The multidisciplinary environment of the Landau Institute was the main element of inspiration.

2. KHALATNIKOV LECTURES AND EMERGENT RELATIVITY IN SUPERFLUIDS

The Khalatnikov lectures on superfluid $^4$He for students in Kapitza Institute led me to strange connection between superfluid hydrodynamics and special and general relativity (probably in 1967). The relativistic character of the flow of superfluid $^4$He is manifested at low temperature, where the normal component is represented by "relativistic" excitations with linear spectrum – phonons. The Eq.(3.13) in the Khalatnikov book [1] shows the free energy of phonons in the presence of the counterflow $w = v_n - v_s$ (the flow of normal component of the liquid with respect to the superfluid component):

$$F_{ph}(T, w) = \frac{F_{ph}(T)}{1 - w^2/c^2} \sim \left( \frac{T}{\sqrt{1 - w^2/c^2}} \right)^4,$$

with $F_{ph}(T) \propto T^4$. This equation recalls the Tolman law in general relativity, $T(r) = T/\sqrt{g_{00}(r)}$, which may suggest (and indeed suggested for me) the idea that the vacuum is superfluid; the matter is represented by excitations; the gravitational field is the result of the flow of the vacuum with superfluid velocity $v_s^2/2 = GM/r$ (in full thermodynamic equilibrium one has $v_n = 0$, while $v_s$ may depend on coordinates, and $g_{00}(r) = 1 - w^2/c^2 = 1 - v_s^2(r)/c^2$); and GR is some extension of the Landau-Khalatnikov two-fluid hydrodynamics. My attempt to share this crazy idea with Sharvin, who governed the student seminar at the Kapitza Institute, was not successful. I got the response that GR is a very beautiful theory, and it should not be spoiled by unjustified models. Now I fully agree with his absolutely correct response.
However, later on the papers by Unruh on black hole analogs in moving liquids appeared [2, 3]. The effective metric experienced by sound waves in liquids (or correspondingly phonons in superfluids) became known as the acoustic metric, and the flow of the liquid with the acoustic horizon as the river model of black holes [4]. In GR, the flow metric with acoustic horizon corresponds to the Painlevé-Gullstrand (PG) metric [5], see Fig. 1. Following this stream with Ted Jacobson, we considered the Painlevé-Gullstrand metric, which emerges for the fermionic excitations in superfluid $^3$He – the Bogoliubov-Nambu quasiparticles – and discussed the possibility to create the analogs of black hole and white hole horizons using moving textures, solitons [6].

The PG metric is useful for consideration of the processes inside and across the horizon, see Ref. [7] for the analog black hole and Ref. [8] for the real black hole.

The acoustic metric allows us to simulate many different spacetimes. I remember the talk by Polyakov in 1981, where he mentioned that the Minkowski signature in GR may emerge from the Euclidean one in a kind of the symmetry breaking phase transition. The effective Minkowski-to-Euclidean signature change can be probed in particular using acoustic metric for Nambu-Goldstone mode in the Bose-Einstein condensate of magnons [9, 10].

In 2003, many different analogies between the condensed matter on one side and relativistic quantum fields and gravity on the other side have been collected in the book [11]. In the fermionic Weyl and Dirac materials, emergent gravity is formulated in terms of tetrad fields (see also the recent papers [12, 13]), instead of the metric gravity emerging in bosonic condensed matter systems. Moreover, in Weyl materials, gravity emerges together with all the ingredients of the relativistic quantum field theories (relativistic spin, chiral fermions, gauge fields, $\Gamma$-matrices, etc.), see also Sec. 16.

### 3. IORDANSKII AND MACROSCOPIC QUANTUM TUNNELING

In Landau Institute my supervisor was Iordanskii – the author of thermal nucleation of vortices [14] and, together with Finkelstein, of quantum formation of nucleation centers in a metastable crystal [15, 16]. Iordanskii suggested to me the problem of quantum nucleation of vortices in superfluids. This resulted in the paper on vortex nucleation in moving superfluids by quantum tunneling [17].

The main difference from other types of macroscopic quantum tunneling is that the role of the canonically conjugate quantum variables is played by the $z$ and $r$ coordinates of the vortex ring. This provides the volume law for the vortex instanton: the action contains the topological term $S_{\text{top}} = 2\pi \hbar n V_L = 2\pi \hbar N_L$, where $n$ is the particle density; $V_L$ is the volume inside the surface swept by vortex line between its nucleation and annihilation; and $N_L$ is the number of atoms inside this volume, see Sec. 26.4.3 in the book [11]. For other linear topological defects and for fundamental strings the area law is applied [18].

The further development of this macroscopic quantum tunneling in superconductors can be found in the review paper [19], where most authors are from Landau Institute: Feigel’man, Geshkenbein and Larkin.

### 4. KHALATNIKOV, SUPERFLUID $^3$HE, PARADOX OF ANGULAR MOMENTUM AND CHIRAL ANOMALY

It is not surprising that the epoch of superfluid $^3$He in Landau Institute has been initiated by Khalatnikov. My participation in this programme started with collaboration with Khalatnikov and Mineev on the extension of the Landau-Khalatnikov hydrodynamics of superfluid $^4$He to the dynamics of mixture of Bose and Fermi superfluids [20]. The most interesting topic there was the Andreev-Bashkin effect, when the superfluid current of one component depends also on the superfluid velocity of the other component [21]. The seminal paper by Andreev and Bashkin [21] had been published just in the previous issue of JETP, which demonstrated the traditionally close connection between the Landau and Kapitza Institutes.

The first attempts to extend the Landau-Khalatnikov hydrodynamics to the hydrodynamics of the chiral superfluid $^3$He-A immediately showed some strange paradox related to the intrinsic angular momentum of the liquid with Cooper pairing into the $p + ip$ state [22, 23]. The calculated magnitude of the dynamical angular momentum was by factor $(\Delta_0/E_F)^2$ smaller than the expected angular momentum of the stationary state, $L_z = \hbar N/2$, which corresponds to $\hbar$ for each of $N/2$ Cooper pairs, where $N$ is the number of atoms. With $\Delta_0$ being the gap amplitude in the fermionic quasiparticle spectrum and $E_F$ the Fermi energy, this factor is very small, $(\Delta_0/E_F)^2 \sim 10^{-5}$.
Only about ten years later some understanding was achieved [24, 25] that the source of the angular momentum paradox and of the other related paradoxes in the $^3$He-A dynamics was the analog of the chiral anomaly in RQFT, see Eq.(7). The chiral anomaly is realized in the quantum vacuum with Weyl fermions, and the topologically protected Weyl fermions emerge in the chiral superfluid $^3$He-A [11]. The Khalatnikov-Lebedev hydrodynamics of chiral superfluid $^3$He [26] has to be modified to include the chiral anomaly effects.

The effect of chiral anomaly has been experimentally verified in dynamics of skyrmions in $^3$He-A [27], see Sec. 21. See also the recent discussion on the connection of chiral anomaly to the angular momentum paradox in chiral superfluids and superconductors [28, 29].

5. POLYAKOV MONOPOLE AND VORTEX WITH FREE END

Polyakov gave a talk at Landau Institute seminar in Chernogolovka on the hedgehog-monopole, which later got the name ‘t Hooft-Polyakov monopole [30, 31]. Inspired by this talk, we with Mineev suggested the analog of magnetic monopole in $^3$He-A [32] (the same suggestion was made by Blaha [33]). As distinct from the ‘t Hooft-Polyakov monopole, this monopole terminates the linear defects – vortices and strings. It can terminate either singular doubly quantized vortex with $N = 2$ in Fig. 2 (top), which we called the vortex with free end; or two singly quantized vortices with $N = 1$ in Fig. 2 (middle); or four half-quantum vortices with $N = 1/2$ in Fig. 2 (bottom). In electroweak theory such monopole terminating the electroweak string is known as the Nambu monopole [34].

The condensed matter analog of magnetic monopole, which terminates the string, has been observed in cold gases [35].

6. FERROMAGNETIC HEDGEHOG AS MAGNETIC MONOPOLE IN SYNTHETIC FIELD

The monopole-hedgehog topic started by Polyakov and also some vague ideas on the possible emergence of gauge fields had the following development. It appeared that in ferromagnets, the Berry phase gives rise to a synthetic electromagnetic field [36]:

$$ F_{ik} = \partial_i A_k - \partial_k A_i = -\frac{1}{2} \mathbf{m} \cdot (\partial_i \mathbf{m} \times \partial_k \mathbf{m}), $$

(2)

Fig. 2. Magnetic monopole in chiral superconductor – the analog of the Nambu monopole. (Top): monopole, which terminates the doubly quantized vortex, $N = 2$. (Middle): the same monopole terminates two vortices with $N = 1$. (Bottom): nexus – monopole with four half-quantum ($N = 1/2$) vortices – the Alice strings in Fig. 4. Red arrows show direction of magnetic flux, which is brought to the monopole by vortices, and then radially propagates from the monopole. The blue arrows is the field of the orbital vector $l$, which forms the hedgehog.
The hedgehog in ferromagnets in Fig. 3 (left) appeared to be the monopole in the Berry phase magnetic field \( B \) \([36]\). This somewhat reminds the Polyakov hedgehog in the Higgs field, which at the same time represents the magnetic monopole. However, as distinct from Weyl material scenario of the emergent gauge field, in this Berry phase scenario the full analogy with the electromagnetic field is missing.

7. NOVIKOV, TOPOLOGY, ALICE STRING, BEREZINKII

During his seminar talk at the Landau Institute on the hedgehog-monopole, Polyakov mentioned that mathematicians claim that the hedgehog cannot be destroyed for topological reasons. This led to the intensive study of topology in physics and discussions with the members of the Novikov group in Landau Institute (Bogoyavlensky, Grinevich, and others). Also the Anisimov-Dzyaloshinskii paper on disclinations appeared \([39]\), where the variety of structures in liquid crystals was discussed. With Mineev we wanted to understand how and why these and other structures including our vortex with free end (the analog of Nambu monopole) were topologically stable or not.

This led us to the homotopy group classification of topological structures \([40, 41]\). Among these structures, some unexpected exotic topological objects were suggested, such as the half-quantum vortex in \( ^3 \)He-A \([40]\). In RQFT, the analog of the half-quantum vortex is the Alice string in Fig. 4 discussed by Schwarz \([42]\), who collaborated with Belavin and Polyakov in the instanton problem \([43]\). Experimentally the half-quantum vortices were observed only 40 years later, first in the time-reversal symmetric polar phase of \( ^3 \)He \([44]\), and finally in the chiral \( ^3 \)He-A \([45]\). Moreover, it was found that they survive the phase transition to \( ^3 \)He-B, where the half-quantum vortex is topologically unstable: it becomes the termination line of the nontopological domain wall - the analog of Kibble cosmic wall \([46]\).

Vortices in \( ^3 \)He-A are described by the \( Z_4 \) homotopy group, which means that \[ 1/2 + 1/2 + 1/2 + 1/2 = 1 + 1 = 2 = 0, \]
Fig. 5. In $^3$He-B, Alice string (the half-quantum vortex) becomes the termination line of non-topological domain wall – the Kibble wall [45]. There are two roads to antispacetime: the safe route around the Alice string (along the contour $C_1$) or dangerous route along $C_2$ across the Kibble wall [47].

thus 4 half-quantum vortices can terminate at the monopole in Fig. 2. Also, in systems such as liquid crystals, the topological defects – disclinations – may obey even the non-Abelian homotopy groups. All this caused the interest from Berezinzkii to the possibility of the extension of the BKT transition [48, 49] to the more general symmetry breaking patterns, but unfortunately he passed away in 1980.

Novikov himself also participated in the $^3$He business. In particular, he resolved the paradox related to the number of the Nambu-Goldstone (NG) modes in $^3$He-A: in the weak coupling limit there are 9 NG modes, but only 8 broken symmetry generators [50]. Novikov formulated the new counting rule [51]: the number of NG modes coincides with the dimension of the tangent space. The mismatch between the total number of NG bosons and the number of broken symmetry generators equals the number of extra flat directions in the Higgs potential.

8. NOVIKOV, TOPOLOGY, SKYRMIONS

The next our step in the classification of topological structures in condensed matter was triggered again by the Landau Institute environment: the Belavin-Polyakov topological object in 2D Heisenberg ferromagnets [52], dynamical solitons discussed by the Zakharov group [53], and discussions with members of the Novikov group (Golo and Monastyrsky [54]). All this led us to classification of the continuous structures in terms of relative homotopy groups [55].

These structures include in particular the analogs of the 3D skyrmions: the particle-like solitons described by the $\pi_3$ homotopy group [56] (which got the name Shankar monopole [57]). The isolated 3D skyrmions have been observed in cold gases [58]. In superfluid $^3$He, it is still difficult to stabilize the isolated skyrmions, but the $\pi_3$ objects at the crossing of 1D and 2D topological solitons have been created experimentally [59], see the topological analysis of these combined objects by Makhlin and Misirpashaev [60].

9. KOPNIN AND VORTEX SKYRMION LATTICE

As distinct form 3D skyrmions, the 2D skyrmions are typical in the Helsinki experiments with the chiral $^3$He-A in a rotating cryostat. In superfluid $^3$He-A, the vorticity can be continuous (nonsingular) and can form a periodic texture in the rotating vessel – the 2D skyrmion lattice, which we discussed with Kopnin [61], see Fig. 5. This paper opened the collaboration with Kopnin. The 2D skyrmions have been later identified in NMR experiments [62]. Subsequently, the change of the topological charge of skyrmion was observed in ultrasound experiments [63]. Sweeping the magnetic field, we could see the first order topological transition between different configurations. In small fields, the skyrmion has nontrivial charges both in the orbital and in the spin vector fields, $N_l = 1$ and $N_d = 1$. In high field, the skyrmion loses one of the winding numbers, $N_l = 1$ and $N_d = 0$.

The similar skyrmion lattice has been suggested by Kopnin for anisotropic superconductivity, in which the symmetry breaking pattern is $(SU(2) \times U(1)_N)/Z_2 \to U(1)_{S_z - N/2}$ [64].

10. BEKAREVICH-KHALATNIKOV THEORY OF ROTATING SUPERFLUID

Fig. 6 demonstrates the skyrmion lattice in rotating cryostat in the presence of the interface between $^3$He-A and $^3$He-B [65]. Experimentally one can produce different pattern of rotating superfluids. In particular, one of the superfluids, the A-phase, contains the equilibrium number of vortices, while another one, the B-phase, is vortex-free, see Fig. 6 (bottom). In this case the vortices bend and form the vortex sheet. To describe this bending we used the hydrodynamic equations derived by Bekarevich and Khalatnikov [66].
11. INTERFACE INSTABILITY: KORSHUNOV, KUZNETSOV, LUSHNIKOV

The arrangement in Fig. 6 allowed us to study experimentally the analog of the Kelvin-Helmholtz instability in superfluids [67]. At some critical velocity of rotation the interface becomes unstable towards formation of ripplons at the interface [68]. Originally the Kelvin-Helmholtz (KH) instability in superfluids was studied by Korshunov [69, 70]. Instead of the conventional KH instability of the interface between two fluids, Korshunov considered rather unusual case: using the Landau-Khalatnikov two-fluid model he studied the instability of the surface of the liquid under counterflow of the superfluid and normal components of the same liquid. It happens that arrangement in the Fig. 6 is very similar to the Korshunov case. On one side of the interface, the vortex-full A-phase rotates together with the container, \( <v_{A} > = v_{nA} = \Omega \times r \). On the other side of the interface, in the vortex-free B-phase, only the normal component rotates with container, while its superfluid velocity is at rest: \( v_{sB} = 0, v_{nB} = \Omega \times r \). That is why the instability occurs due to the counterflow on the B-phase side, \( w_{B} = v_{nB} - v_{sB} \).

The nonlinear stage of the KH instability has been considered by Kuznetsov and Lushnikov [71, 72]. In our experiments, the development of the interface instability leads to penetration of the A-phase skyrmions through the interface to the B-phase, where they are finally transformed to the singular vortices. Fig. 7 demonstrates the possible scenario of this transformation. However, the complete analysis of the this process is still missing.

12. VORTEX CREATION IN A MICRO BIG-BANG, KOPNIN, KAMENSKY, MANAKOV

Another nonlinear out-of-equilibrium phenomenon studied experimentally in superfluid \(^3\)He had its origine in the interplay of high-energy physics and cosmology. This is the nucleation of topological defects during the phase transition in expanding universe [73], which got the name Kibble-Zurek mechanism of defect formation. In \(^3\)He-B, the Big-Bang event was simulated by neutron irradiation, which caused nuclear reaction and heating of the bubble of about 100 \( \mu m \) size above the transition temperature [74], see Fig. 8. Then the cooling of the bubble back through the second order phase transition to the broken symmetry state resulted in the creation of a vortex sheet.
Fig. 8. Development of the Kelvin-Helmholtz type of instability at the interface between the vortex-full chiral superfluid $^3$He-A and vortex-free non-chiral $^3$He-B in rotating cryostat in Fig. 6. The instability leads to creation of vortices in $^3$He-B. The possible scenario: the droplet of the A-phase with vorticity concentrated in the skyrmions penetrates the AB interface, where vorticity transforms to the singular vortices. The NMR experiments show that the number of the B-phase vortices formed after instability is consistent with the wavelength of the critical ripplon.

The explanation of the observed vortex creation in the frame of the Kibble-Zurek scenario looks reasonable. Moreover, it is supported by the correct power-law dependence of the number of the created vortices on the velocity of the superfluid. Nevertheless the modifications and extensions of the Kibble-Zurek scenario were necessary in order to take into consideration the inhomogeneity of the process. In particular, the effect of propagation of the transition front was considered in our paper with Kibble [75] and in papers by Kopnin and coauthors [76, 77]. But the original idea that vortices can be created by the propagating front of the second order phase transition belongs to Kamensky and Manakov [78].

The Poyakov [79] and the Belavin-Polyakov-Schwartz-Tyupkin (BPST) [43] instantons inspired the study of the instanton structures in condensed matter. The $1 + 1$ instanton lattice [80] in Fig. 9 served for explanations of the oscillations observed in the counterflow experiments in chiral superfluid $^3$He-A [81]. This $1 + 1$ lattice in the $z, t$ plane is
the counterpart of the $2 + 0$ skyrmion lattice in Fig. 5, where $z$ is the coordinate along the counterflow. Similar $1 + 1$ instanton structure, but in terms of of the $(z,t)$ counterparts of Abrikosov vortex lattice, is discussed for superconductors by Ivlev and Kopnin [82].

14. DZHALOSHINSKII, SPIN GLASSES AND GENERAL HYDRODYNAMICS

The natural objects for studies of the topologically stable structures are magnetic materials, where the main expert in Landau Institute was Dzyaloshinskii – the author of Dzyaloshinskii-Moriya interaction [83,84]. The common interest in topological defects in magnetic materials led to our collaboration. We considered frustrations in spin glasses introduced by Villain [85] and suggested that on the macroscopic hydrodynamic level, the frustrations can be described in terms of the topological defects – disclinations, which destroy the long range magnetic order [86]. The continuous distribution of disclinations and their dynamics can be described using the effective gauge fields: the $U(1)$ gauge field in XY spin glasses, and $SU(2)$ gauge field in the Heisenberg spin glasses. This provides another scenario for emergent gauge fields in addition to the Berry phase scenario in ferromagnets and Weyl point scenario in $^3$He-A and in Weyl semimetals.

The hydrodynamics of systems with distributed defects was then extended to superfluids with vortices, and crystals with dislocations and disclinations [87,88]. The relevant gauge fields which describe the distributed dislocations and disclinations are correspondingly the torsion and Riemann curvature in the formalism of general relativity, see also [89].

All this can be useful for the description of different types of spin and orbital glasses, observed in the superfluid phases of $^3$He in aerogel [90], see also Sec.20.

15. ABRIKOSOV-BENESLAVSKII-HERRING MONOPOLE

The Polyakov hedgehog-monopole-instanton saga had one more important development, now extended to momentum space. The momentum-space counterpart of the Berry phase magnetic monopole is shown in Fig. 3 (right). This Figure shows the topological signature of the $2 \times 2$ Hamiltonian describing the Weyl fermions [91]. The spin (or pseudospin in Weyl materials) forms the hedgehog in momentum space, representing the Berry phase monopole in momentum space. The stability of this hedgehog is also supported by topology, but now it is the topology in momentum space. The topological description of the band contact points can be found in the paper by Novikov [92]. Topological stability of the Weyl point provides the emergence of the relativistic Weyl fermions in the vicinity of the hedgehog even in condensed matter nonrelativistic vacuum such as in superfluid $^3$He-A. Together with the chiral Weyl fermions, also gravity in terms of the tetrad fields and relativistic quantum gauge fields emerge in this superfluid. In other words, the whole Universe (or actually its caricature) can be found in a droplet of $^3$He [11].

Unfortunately at that time I was unaware on another, the essentially older, Universe created by Abrikosov, who together with Beneslavskii considered the relativistic Weyl fermions in semimetals [93–95]. But in 1998, after the Abrikosov-70 workshop in Argonne, I got from Abrikosov the reference to his papers. Then I realized that as a student I visited his seminar talk in Chernogolovka in 1970, where he discussed the "relativistic" conical spectrum of electrons in semimetals. Though later I forgot about that seminar, it was somehow deep in my subconscious mind. The Berry phase hedgehog-monopole in momentum space could be called Abrikosov-Beneslavskii-Herring (ABH) monopole.

The topological invariant which describes the Weyl node can be also written in terms of the Green’s function important in the case of strong interaction, when the single-particle Hamiltonian is ill defined.

16. GRIBOV: RQFT IN MAJORANA-WEYL SUPERFLUID $^3$HE-A, MOSCOW ZERO, QUARK CONFINEMENT

During the years, Gribov’s help was extremely important to me. Although he was usually very critical during seminars at the Landau Institute, he patiently answered my questions, perhaps because I did not belong to the high-energy community, and sometimes he even shared his ideas with me. Gribov clarified to me different issues related to emergent RQFT in Weyl superfluid $^3$He-A. In one case I was puzzled by the logarithmically diverging term in the action for $^3$He-A. It was the ultraviolet
cut-off (see Sec. 21 for definition of the synthetic gauge field below Eq. (7)). This term becomes imaginary for $E > B^2$, what to do with that? From the discussion with Gribov it became clear that this is nothing but the vacuum instability towards the Schwinger pair production, which occurs when the synthetic electric field exceeds the synthetic magnetic field.

The logarithmic divergence is the condensed matter analog of the zero charge effect – the famous "Moscow zero" by Abrikosov, Khalatnikov and Landau [97]. The zero charge effect is natural for the $U(1)$ gauge field. However, to my surprise, the synthetic $SU(2)$ gauge field, which emerges in $^3$He-A too, also obeys the zero charge behavior instead of the expected asymptotic freedom found by Gross, Wilczek and Politzer [98]. The discussion with Gribov clarified this issue too. He simply asked me the question: "How many bosons and fermions do you have in your helium?" It appeared that the number of the fermionic species is small compared to the number of bosonic fields. However, the fermions dominate because of the much larger ultraviolet cut-off $E_{cut}$.

Gribov explained to me also the origin of the Wess-Zumino term in the hydrodynamic action, and some other things. All this resulted in the paper on anomalies in $^3$He-A [99] with acknowledgement to Gribov for numerous and helpful discussions. The term in Eq. (4.9) there appeared after Gribov shared with me his view on the problem of zero charge effect for massless fermions, and then I realized that the same term with the same prefactor exists in superfluid hydrodynamics of $^3$He-A. It is the Eq. (25) in the Gribov paper [100].

Gribov was also the first one to tell me that Bogoliubov quasiparticles in $^3$He-A are Majorana fermions. The zero energy modes found by Kopnin in the core of the $^3$He-A vortex [101], see Sec. 22, appeared to be Majoranas. Later I checked that the zero energy level does not shift from zero even in the presence of impurities [102], which is an important signature of the Majorana nature of the mode.

I continued the discussions with Gribov, even after he moved to Hungary, in particular in relation to the quark confinement. My proposal to explain the confinement in terms of the ferromagnetic quantum vacuum, after discussion with Gribov appeared to be the modification of the idea of the Savvidy vacuum [103].

More recently, with Klinkhamer, we tried to extend the Gribov picture of confinement in QCD as diverging mass at low $k$ [104]. We came to the following estimation for the vacuum energy density (cosmological constant $\Lambda$) in the present epoch [105]:

$$\Lambda = \rho_{vac} \sim H \Lambda_{QCD}^2,$$  

where $H$ is the Hubble parameter, and $\Lambda_{QCD}$ is the QCD energy scale. The linear dependence on $H$ obtained in the phenomenological theory of confinement, has been also proposed in other approaches to QCD [106, 107]. For the de-Sitter universe one has $\Lambda \sim H^2 E_{Planck}^2$, which gives

$$\Lambda \sim \frac{\Lambda_{QCD}^6}{E_{Planck}^2}.$$  

Unfortunately the helpful Gribov criticism is now missing.

On the other hand, since $\Lambda_{QCD}$ is on the order of proton mass $m_p$, the equation (5) corresponds to the early suggestion by Zeldovich, $\Lambda \sim Gm_p^6$ [108] (see also recent paper by Kamenshchik, Starobinsky and co-authors on the Pauli-Zeldovich mechanism of cancellation of the vacuum energy divergences [109]).

17. GOR’KOV: UNCONVENTIONAL SUPERCONDUCTIVITY, WEYL POINTS AND DIRAC LINES

Our collaboration with Gor’kov started when he returned from a conference, where new heavy-fermion superconductors had been discussed. Our collaboration led to the symmetry classification of the superconducting states [110,111]. Most of the unconventional superconducting states have nodes in the energy spectrum: Weyl points, Dirac points and Dirac nodal lines. One of the configurations with 8 Weyl points (4 right and 4 left) is in Fig. 10. The extension of this configuration to 4D space produces the 4D analog of graphene [112,113], with 8 left and 8 right Weyl fermions, as in each generation of the Standard Model fermions (see also the paper in memory of Gor’kov [114], where the superconducting state with 48 Weyl fermions is discussed).

The Dirac lines also appear in many classes of superconductivity, including cuprate superconductors. The Dirac line has an important effect on the thermodynamics of superconductors [115]. The reason is that in the presence of a supercurrent, the nodes in the spectrum transform to Fermi surfaces, see Fig. 11. Such Fermi surfaces emerge in superconductors due to broken time reversal symmetry or parity, and now they are called the Bogoliubov Fermi surfaces [116]. The Bogoliubov Fermi surface provides the nonzero density of states (DoS), which in the case of the nodal line is proportional to the superfluid velocity. For the Abrikosov
Fig. 11. Figure from Ref. [111]. Arrangement of the nodes in the energy spectrum in superconductors of class $O(D_2)$. The points denote four Weyl nodes with topological charge $N = +1$ (the winding number of the hedgehog with spins outwards), and crosses denote four Weyl nodes with $N = -1$ (the winding number of the hedgehog with spins inwards). In the vicinity of each Weyl node with $N = +1$ the chiral right-handed Weyl fermions emerge, while $N = -1$ is the topological charge of the left-handed quasiparticles. This arrangement of Weyl nodes can be compared with 8 right-handed and 8 left-handed particles (quarks and leptons) in each generation of Standard Model fermions.

Fig. 12. Nodal line in the polar phase of $^3$He (left) and its transformation to Bogoliubov Fermi surface under superflow (right).

vortex lattice the flow around vortices produces a DoS which is proportional to $\sqrt{B}$ [115, 117]. Gor’kov called this phenomenon "koreshok" – the diminutive form of the Russian word koren’ (root).

18. DZYALOSHINSKII, POLYAKOV AND WIEGMANN PAPER AND $\theta$-TERM IN $^3$HE-A

The paper by Dzyaloshinskii, Polyakov and Wiegmann [118] inspired the work on the possible $\theta$-term in thin films of chiral superfluid $^3$He-A [119]. The consequences of that are the intrinsic quantum Hall effect, spin quantum Hall effect, and exotic spin and statistics of solitons, which depend on film thickness [120]. These works were made under extremely useful discussions with Wiegmann.

19. YAKOYVENKO, GRINEVICH AND TOPOLOGY IN MOMENTUM SPACE

During our collaboration with Yakovenko, we expressed the intrinsic quantum Hall and spin quantum Hall effects via the $\pi_3$ topological Chern numbers in terms of the Green’s function [121]. The same invariants, but where the integral is around the Weyl point in the 4D $p_\nu$ space:

$$N = \frac{1}{24\pi^2} \epsilon_{\mu\nu\lambda\gamma} \text{tr} \int dS^\gamma G_{\mu\nu} G^{-1} G_{\nu\lambda} G^{-1} G_{\lambda\gamma} G^{-1},$$

have been used in our paper with Grinevich for description of the topological protection of the Weyl fermions [96]. Here $\sigma$ is the closed 3D surface around the point in 4D momentum-frequency space. The value of this Chern number in Eq.(6) is equal to the charge of the ABH monopole in Fig. 3 (right). It is the instanton description of the Polyakov hedgehog-monopole in momentum space, see Sec. 15.

20. LARKIN AND DISORDER

A suprising result of Larkin is that even small disorder destroys the Abrikosov vortex lattice [122]. In magnets the similar effect is the destruction of orientational long-range order by weak random anisotropy [123]. Following this trend in the Landau Institute, it was suggested that a similar effect can be realized in $^3$He-A in aerogel, where the weak random anisotropy provided by the disordered aerogel strands may destroy the long-range orientational order [124], see Fig. 12. This disordered state, which we called the Larkin-Imry-Ma state, has been observed in NMR experiments [125, 126], which opened the route to study experimentally many different types of spin and orbital glasses in superfluid $^3$He [90].

21. KOPNIN AND IORDANSKII FORCES

Starting with 1981, I had collaboration with the experimental team in Helsinki, which studied different types of vortices and other topological defects in a unique rotating cryostat operating at milliKelvin temperatures. For this I had to study the vortex dynamics
which at that time has been developed by Kopnin in superconductors.

At first glance the Kopnin theory of vortex dynamics [127,128] looked rather complicated. Fortunately, it happened that his theory could be reformulated in more simple terms. The vortex represents the chiral system, and the spectrum of the fermionic modes localized in the vortex core has the anomalous branch which as function of the discrete angular momentum $L_z$ "crosses" zero, see Fig. 13 (top left) and (bottom left). It appears that the spectral flow along this anomalous branch is responsible for the Kopnin force acting on the vortex. Thus the Kopnin force can be explained in terms of the chiral anomaly as the analog of the Callan-Harvey effect [129]. The chirality here is generated by the vorticity: the number of the anomalous branches, which "cross" zero, is determined by the vortex winding number $N$.

The Kopnin spectral flow force adds to the conventional Magnus force acting on the vortex, which exists in conventional liquids, and to Iordanskii force already well known in two fluid dynamics of superfluids [130,131]. The Kopnin spectral flow force is of fermionic origin and exists only in fermionic superfluids and in superconductors.

![Fig. 13. Larkin-Imry-Ma state of $^3$He-A in aerogel. Long-range orientational order is destroyed by weak interaction with aerogel strands, which provide the random anisotropy. Here $L$ is the length scale at which the long-range order is destroyed. It is much bigger than the characteristic scale of the quenched random anisotropy.](image1)

Electrons on vortex in $s$-wave superconductors

$E (L_z, p_z=0)$

$E (p_z, L_z)$

Quasiparticles on $^3$He-A vortex

$E (L_z, p_z=0)$

$E (p_z, L_z)$

![Fig. 14. (top left): Chiral branch of fermions living in the core of Abrikosov vortices in $s$-wave superconductors. The spectrum is the function of discrete angular momentum $L_z$. The spectral flow along this anomalous branch is the origin of the extra force acting on a vortex – the Kopnin force. (top right): The spectrum as function of $p_z$ at fixed values of $L_z$. The spectrum has a minigap of the order $\omega_0 = \Delta^2 / E_F$. (bottom left): Chiral branch of fermions living in the core of vortices in chiral $p$-wave superfluid. This spectrum contains Majorana zero energy mode. (bottom right): The spectrum as function of $p_z$ in superfluid $^3$He-A, where the branch with $L_z = 0$ represents the flat band of Majorana fermions.](image2)
After the origin of Kopnin force was clarified, our cooperation with Kopnin on vortex dynamics was developed [132, 133]. Finally, the Kopnin theory has been confirmed in experiments on vortices in \(^3\)He-B [27]: the measured temperature dependence of the Kopnin force agreed with his calculations. Note that superfluid \(^3\)He does not contain impurities, and vortices are not pinned. This allowed us to measure the Kopnin, Iordanskii and Magnus forces in their pure form, see Fig. 14.

In case of continuous vortices in \(^3\)He-A – skyrmions – the Kopnin force can be fully described by the Adler-Bell-Jackiw equation for chiral anomaly:

\[
\partial_\mu J_\mu^\alpha = \frac{1}{4\pi^2} g^2 \mathbf{B} \cdot \mathbf{E},
\]

which confirms the chiral anomaly origin of the Kopnin force in the general case. In Eq. (7), the synthetic gauge fields come from the time and space dependence of the position of the node \(\mathbf{K}(r, t)\) in the spectrum of Weyl quasiparticles in the presence of the moving skyrmions: \(\mathbf{B} = \nabla \times \mathbf{K}\) and \(\mathbf{E} = \partial_t \mathbf{K}\). In the weak coupling approximation, the Kopnin force compensates the Magnus force practically at any temperature, which has been confirmed in experiments on vortices in \(^3\)He-A [27].

The Kopnin force was also very important in study of turbulence in the flow of superfluid \(^3\)He. Since the Kopnin force has similar dependence on velocity as the mutual friction force between the normal component of the liquid and quantized vortices, the corresponding Reynolds number \(R(T) = \omega_0 \tau\) does not depend on velocity and is only determined by temperature, where \(\omega_0\) is the minigap and \(1/\tau\) is the width of the vortex core levels. The transition from the laminar to turbulent flow takes place at temperature when \(R(T) \sim 1\). Such a transition governed by this novel Reynolds number has been experimentally observed, see the review [134].

22. KOPNIN, MAJORANA FERMIONS AND FLAT BAND SUPERCONDUCTIVITY

A very interesting result obtained by Kopnin concerns the fermion modes living in the core of the singular \(N = 1\) vortex in chiral superfluid \(^3\)He-A in Fig. 13 (bottom) [101]. It was found that the branch of the spectrum with zero angular momentum \(L_z = 0\) is dispersionless, \(E_0(p_z) = 0\) in some region of momenta, \(-p_F < p_z < p_F\), see Fig. 13 (bottom). This observation inspired to look for the topological origin of this 1D flat band with zero energy. It appeared that in the 2D case the state with exactly zero energy corresponds to the Majorana mode on the vortex [102,135]. In the 3D case, the existence of the 1D Majorana flat band is connected to the existence of the Weyl nodes in bulk: the boundaries of the flat band are determined by the projections of the Weyl nodes in bulk to the vortex line [136]. This is one of the many examples of bulk-boundary and bulk-vortex correspondence in topological materials.

Even more important example is the 2D topological flat band on the surface of semimetals having nodal lines in the bulk spectrum. The boundary of the surface flat band is determined by projection of the nodal line to the surface of the semimetal [137], see Fig. 15. The singular density of states in the flat band leads to the flat band superconductivity [138–140]. The flat band superconductivity is characterized by the linear dependence of the transition temperature on the interaction \(g\) in the Cooper pair channel, \(T_c \sim gV_{FB}\), where \(V_{FB}\) is the volume or the area of the flat band [141]. This is in contrast to the conventional superconductivity in metals with Fermi surfaces, where \(T_c\) is exponentially suppressed.

Recently superconductivity has been observed in the twisted bilayer graphene [142,143]. The maximum of \(T_c\) takes place at the "magic angle" of twist, at which the electronic band structure becomes nearly flat, see discussion in Ref. [144] and Ref. [145] (Fig. 16).
Fig. 16. Bulk-surface correspondence in semimetals with nodal line in bulk. Dirac nodal line gives rise to flat band on the surface. The boundary of the flat band coincides with the projection of the Dirac line to the surface.

Fig. 17. Spectrum of electrons in twisted bilayer graphene, where the flat band emerges at magic angle of twist (from Ref. [145]).

For vortices in superfluids and superconductors with nodal lines in bulk, the singularities in thermodynamics come from the regions far away from the vortex, see the discussion on "koreshok" in Sec. 17. For cuprate superconductors they are discussed in [115] and in our paper with Kopnin [146].

23. FOMIN, COHERENT PRECESSION, MAGNON BEC

Fomin got the London Prize together with experimentalists from Kapitza Institute, Bunkov and Dmitriev, for the discovery of the spontaneously formed coherent precession of magnetization in superfluid $^3$He-B [147–149], see Fig. 17. This is a unique example of spontaneous self-organization in a quantum system. Spins, which were originally precessing with different frequencies, form the collective state in which all the spins precess with the same frequency and with the same phase. This state lives for a long time without external drive and despite the inhomogeneity of the system.

For me, this phenomenon was not very clear. However, it worked. Due to connection between Kapitza Institute and Low Temperature Lab in Helsinki, this phenomenon was brought to Helsinki, where the HPD appeared to be very useful as a tool for experimental investigation of topological defects in $^3$He-B – vortices and solitons. In particular, using HPD the exotic topological object – combined spin-mass vortex with soliton tail – has been observed and identified [150]. So, I had to study this phenomenon in detail.

Again, as in the case with Kopinin theory of vortex dynamics, the Fomin theory of HPD was beautiful, but it was very difficult for me to apply it to our
And again, it happened that Fomin’s theory could be reformulated in a more simple way: in terms of the Bose-Einstein condensate (BEC) of quasiparticles – magnons [151], see also review [152]. The reason for that is that the coherent precession has the off-diagonal long-range order (ODLRO) signature similar to that in conventional superfluid:

\[ S_x + i S_y = \langle \hat{S}^+ \rangle = S \sin \beta e^{i(\alpha + \omega t)}, \tag{8} \]

where \( S^+ \) is the operator of creation of spin and \( \beta \) is the tipping angle of magnetization. Using Holstein-Primakoff transformation one can rewrite this in terms of magnon BEC, where the order parameter is the quasi-average of the operator of annihilation of magnon number:

\[ \Psi = \langle \hat{\Psi} \rangle = \sqrt{\frac{2S}{\hbar}} \sin \frac{\beta}{2} e^{i(\alpha + \mu t)}, \tag{9} \]

The role of the global phase of precession \( \omega \) is played by the chemical potential \( \mu \) of the pumped magnons.

As a result the dynamics of the precessing system can be determined by the corresponding Landau-Khalatnikov hydrodynamics, applied now to magnon superfluid. Then all the phenomena related to the coherent precession, old and new, could be described in the same way: spin current Josephson effect; magnon BEC in magnetic and textural trap; Goldstone mode of precession – phonon in magnon BEC; magnonic analog of MIT bag model of hadrons [153]; magnonic analog of relativistic Q-ball [154]; etc.

The coherent precession has also some signatures of the so-called time crystal [155]. If the spin-orbit interaction is neglected, the magnon number is conserved, and the precessing state is the ground state of the system with fixed number of magnons. So, we have the oscillations in the ground state, as suggested by Wilczek [156]. But without spin-orbit interaction these oscillations are not observable.

Theory of magnon BEC in solid state materials (yttrium iron garnet films) has been considered by Pokrovsky, see review [157].

24. POLYAKOV, STAROBINSKY, COSMOLOGICAL CONSTANT AND VACUUM DECAY

The counterpart of the Polyakov hedgehog-monopole in momentum space – the Weyl point – naturally gives rise to the emergent gravitational field acting on Weyl fermions. This again sparked my interest in topics related to gravity, but now on a more serious ground than the analogy with superfluid \( ^4\text{He} \) in Sec. 2. In this respect the consultations with Starobinsky became highly important and extremely useful.

One of the directions was black hole radiation, which was started by Zel’dovich [158] and Starobinsky [159] for rotating black holes, and continued by Hawking for nonrotating black holes. In Landau Institute, this issue has been rather popular: I can mention Belinski [160] with whom I had many discussions and Byalko [161].

It appeared that the Zel’dovich-Starobinsky radiation by a rotating black hole can be simulated by a body rotating in a superfluid vacuum [162,163], while the Hawking radiation using superflow or moving texture [6,7]. Also both the Hawking radiation and the Zel’dovich-Starobinsky radiation can be described in terms of the semiclassical tunneling. The same semiclassical approach can be applied to the radiation from the de Sitter cosmological horizon. But the latter already touches a different direction – the problems related to the vacuum energy and cosmological constant. In this direction, the Starobinsky inflation [164,165] is the key issue.
In a series of papers with Klinkhamer [166–168], we introduced the so-called \( q \)-theory, where the vacuum is described by a dynamical variable introduced by Hawking, the 4-form field [169]. The nonlinear extension of the Hawking theory allowed us to study the thermodynamics and dynamics of the quantum vacuum. The approach appeared to be rather general. Instead of the Hawking 4-form field one may use the other variables, which can describe the physical vacuum, but they lead to the same dynamical equations. One of such variable \([170]\) has been inspired by the papers by Kats and Lebedev on a freely suspended film \([171]\). The main advantage of such an approach is that in full equilibrium the properly defined vacuum energy, which enters Einstein equations as cosmological constant, is zero without fine tuning. The mechanism of cancellation is purely thermodynamic and does not depend on whether the vacuum is relativistic or not. In this respect it is very different from the Pauli-Zeldovich mechanism discussed by Kamenshchik and Starobinsky [109], which relies on the cancellation of contributions of relativistic bosons and relativistic fermions.

The thermodynamic approach solves the main cosmological constant problem: in the Minkowski vacuum the huge vacuum energy is naturally cancelled. The problem remains, however, in the dynamics. If one assumes that the Big Bang has started in the originally equilibrium vacuum, then from our equations without dissipation it follows that the cosmological constant, which is very large immediately after the Big Bang, relaxes with oscillations and its magnitude averaged over fast oscillations reaches the present value in the present time \( \langle A(t_{\text{present}}) \rangle \sim E_{\text{Planck}}^2/t_{\text{present}}^2 \sim 10^{-120}E_{\text{Planck}}^3 \) [167], see Fig. 18. This process looks similar to the Starobinsky inflation, except for the magnitude of the oscillation frequency, which in our case is of the Planck scale instead of the Higgs inflaton mass.

The similar oscillating decay takes place in superconductors after quench \([172–174]\), see Fig. 18. Such oscillations with the frequency equal the mass (gap) of the Higgs amplitude mode, \( \omega = 2\Delta \), have been observed \([175,176]\). In superfluids and superconductors the role of the vacuum energy is played by \( \Delta^2(t) - \Delta_0^2 \), see Sec. 7.3.6 in [11]. Then one has \( A(t) \propto \omega^3 \text{sin}^2 \frac{\omega}{2} t \), and \( \langle A(t) \rangle \propto \omega^3 t \).

But if the initial conditions are different, then from our equations (again still without dissipation) it follows that the Universe relaxes to the de Sitter spacetime instead of the Minkowski vacuum state. The question arises: what is the fate of the de Sitter vacuum? Does Hawking radiation lead to the decrease of the vacuum energy? Is the de Sitter vacuum unstable? The instability of the de Sitter vacuum is supported by Polyakov \([177–180]\), but is not supported by Starobinsky. My view on that problem is in the papers \([181]\), which is closer to the Starobinsky view.

## 25. CONCLUSION

The overwhelming majority of my work emerges from the Landau Institute environment, and/or in collaboration with the experimental ROTA group in the Low Temperature Laboratory of Aalto University. I did not mention here the inspiration from or/and the direct collaboration with Edel’stein \([182]\), Elishberg, Kats \([184]\), Khmel’nitskii \([183]\), Makhlin \([74,185]\), Mel’nikov \([182]\), Pokrovsky, Rashba, Sinai and the other members of Landau Institute in different areas of physics, who were also gathered by Khalatnikov into the unique Institute.

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**REFERENCES**

1. I.M. Khalatnikov, Teoriya sverkhkuthesti, M.: Nauka, 1971.
2. W. G. Unruh, Experimental black hole evaporation, Phys. Rev. D 14, 1351–1353 (1981).
3. R. Schützhold and W.G. Unruh, Gravity wave analogs of black holes, Phys. Rev. D 66, 044019 (2002).
4. A.J.S. Hamilton, J.P. Lisle, The river model of black holes, Am. J. Phys. 76, 519–532 (2008), gr-qc/0411060.
5. P. Painlevé, La mécanique classique et la théorie de la relativité, C. R. Acad. Sci. (Paris) 173, 677 (1921); A. Gullstrand, Allgemeine Lösung des statischen Einkörper-problems in der Einsteinschen Gravitations-theorie, Archiv. Mat. Astron. Fys. 16(8), 1 (1922).
6. T.A. Jacobson and G.E. Volovik, Event horizons and ergoregions in \(^3\)He, Phys. Rev. D 58, 064021 (1998).
7. G.E. Volovik, Simulation of Painlevé-Gullstrand black hole in thin \(^3\)He-A film, Pisma ZhETF 69, 662–668 (1999); JETP Lett. 69, 705 – 713 (1999).
8. M.K. Parikh and F. Wilczek, Hawking radiation as tunneling, Phys. Rev. Lett. 85, 5042 (2000).

9. J. Nissinen and G.E. Volovik, Effective Minkowski-to-Euclidean signature change of the magnon BEC pseudo-Goldstone mode in polar $^3$He, Pis'ma ZhETF 106, 220–221 (2017), JETP Lett. 106, 234–241 (2017).

10. S. Autti, V.V. Dmitriev, J.T. Mäkinen, J. Rysti, A.A. Soldatov, G.E. Volovik, A.N. Yudin, and V.B. Eltsov, Bose-Einstein condensation of magnons and spin superfluidity in the polar phase of $^3$He, Phys. Rev. Lett. 121, 025303 (2018).

11. G.E. Volovik, The Universe in a Helium Droplet, Clarendon Press, Oxford (2003).

12. G.E. Volovik, Black hole and Hawking radiation by type-II Weyl fermions, Pis'ma ZhETF 104, 600–601 (2016), JETP Lett. 104, 645–648 (2016).

13. J. Nissinen and G.E. Volovik, Dimensional crossover of effective orbital dynamics in polar distorted $^3$He-A: Transitions to anti-spacetime, Phys. Rev. D 97, 025018 (2018).

14. S.V. Iordanskii, Vortex ring formation in a superfluid, ZhETF 48, 708–714 (1965), JETP 21, 467–471 (1965).

15. S.V. Iordanskii, A.M. Finkelshtein, Effect of quantum fluctuations on the lifetimes of metastable states in solids, ZhETF 62, 403–414 (1972), JETP 35, 215–221 (1972).

16. S.V. Iordanskii, A.M. Finkelshtein, Quantum formation of nucleation centers in a metastable crystal, J. Low Temp. Phys. 10, 423–447 (1973).

17. G.E. Volovik, Quantum mechanical creation of vortices in superfluids, Pisma ZhETF 15, 116–120 (1972); JETP Lett. 15, 81–83 (1972).

18. A.M. Polyakov, Quantum geometry of bosonic strings, Phys. Lett. B 103, 207–210 (1981).

19. G. Blatter, M.V. Feigel’man, V.B. Geshkenbein, A.I. Larkin, V.M. Vinokur, Vortices in high-temperature superconductors, Rev. Mod. Phys. 66, 1125–1388 (1994).

20. G.E. Volovik, V.P. Mineev, I.M. Khalatnikov, Theory of the solution of the superfluid fermi liquid in superfluid Bose liquid, JETP 42, 342–348 (1975).

21. A.F. Andreev and E.P. Bashkin, Three-velocity hydrodynamics of superfluid solutions, JETP 42, 164–167 (1975).

22. G.E. Volovik, Orbital momentum and orbital waves in the anisotropic A-phase of superfluid $^3$He, Pis'ma ZhETF 22, 234–237 (1975); JETP Lett. 22, 108–110 (1975); Dispersion of the orbital waves in the A-phase of superfluid $^3$He, Pis'ma ZhETF 22, 412–415 (1975), JETP Lett. 22, 198–200 (1975).

23. G.E. Volovik, V.P. Mineev, The hydrodynamics of the A-phase of superfluid $^3$He, JETP 44, 591–599 (1976).

24. A.V. Balatskii, G.E. Volovik, V.A. Konyshev, On the chiral anomaly in superfluid $^3$He-A, ZhETF 90, 2038–2056 (1986), JETP 63, 1194–1204 (1986).

25. G.E. Volovik, Chiral anomaly and the law of conservation of momentum in $^3$He-A, Pisma ZhETF 43, 428–431 (1986), JETP lett. 43, 551–554 (1986).

26. I.M. Khalatnikov, V.V. Lebedev, Hamiltonian equations of hydrodynamics of anisotropic superfluid liquid $^3$He-A, Phys. Lett. A 61, 319–320 (1977); Lagrange and Hamilton equations of hydrodynamics for anisotropic superfluid $^3$He-A liquid, JETP 46, 808–813 (1977).

27. T.D.C. Bevan, A.J. Manninen, J.B. Cook, J.R. Hook, H.E. Hall, T. Vachaspati and G.E. Volovik, Momentum creation by vortices in superfluid $^3$He as a model of primordial baryogenesis, Nature, 386, 689–692 (1997).

28. G.E. Volovik, Orbital momentum of chiral superfluids and spectral asymmetry of edge states, Pis'ma ZhETF 100, 843–846 (2014); JETP Lett. 100, 742–745 (2014).

29. Yasuhiro Tada, Non-thermodynamic nature of the orbital angular momentum in neutral fermionic superfluids, arXiv:1805.11226.

30. A.M. Polyakov, Particle spectrum in quantum field theory, JETP Lett. 20, 194–195 (1974).

31. G. ’t Hooft, Magnetic monopoles in unified gauge theories, Nucl. Phys. 79, 276–284 (1974).

32. G.E. Volovik, V.P. Mineev, Vortices with free ends in superfluid $^3$He-A, Pis’ma ZhETF 23, 647–650 (1976), JETP lett. 23, 593–596 (1976).

33. S. Blaha, Quantization rules for point singularities in superfluid $^3$He and liquid crystals, Phys. Rev. Lett. 36, 874 (1976).

34. Y. Nambu, String-like configurations in the Weinberg-Salam theory, Nucl. Phys. B 130, 505 (1977).

35. M. W. Ray, E. Ruokokoski, S. Kandel, M. Möttönen, and D. S. Hall, Observation of Dirac monopoles in a synthetic magnetic field, Nature 505, 657 (2014).
36. G.E. Volovik, Linear momentum in ferromagnets, J. Phys. C 20, L83–L87 (1987).
37. S. E. Barnes and S. Mackawa, Phys. Rev. Lett. 98, 246601 (2007).
38. Y. Yamane, Spin-motive force due to domain wall motion in the presence of Dzyaloshinskii-Moriya Interaction, arxiv:1808.10076.
39. S.I. Anisimov, I.E. Dzyaloshinskii, A new type of disclination in liquid crystals and the stability of disclinations of various type, JETP 36, 774–779 (1973).
40. G.E. Volovik, V.P. Mineev, Line and point singularities in superfluid $^3$He, Pis'ma ZhETF 24, 605–608 (1976), JETP Lett. 24, 561–563 (1976).
41. G.E. Volovik, V.P. Mineev, Investigation of singularities in superfluid $^3$He and liquid crystals by homotopic topology methods, JETP 45 1186–1196 (1977).
42. A.S. Schwarz, Field theories with no local conservation of the electric charge, Nucl. Phys. B 208, 141-158 (1982).
43. A.A. Belavin, A.M. Polyakov, A.S. Schwartz, Yu.S. Tyupkin, Pseudoparticle solutions of the Yang-Mills equations, Phys. Lett. B 59, 85–87 (1975).
44. S. Autf, V.V. Dmitriev, J.T. Mäkinen, A.A. Soldatov, G.E. Volovik, A.N. Yudin, V.V. Zavjalov, and V.B. Eltsov, Observation of half-quantum vortices in superfluid $^3$He, Phys. Rev. Lett. 117, 255301 (2016).
45. J.T. Mäkinen, V.V. Dmitriev, J. Nissinen, J. Rysti, G.E. Volovik, A.N. Yudin, K. Zhang, V.B. Eltsov, Half-quantum vortices and walls bounded by strings in the polar-distorted phases of topological superfluid $^3$He, arXiv:1807.04328.
46. T.W.B. Kibble, G. Lazarides and Q. Shafi, Walls bounded by strings. Phys. Rev. D 26, 435–439 (1982).
47. G.E. Volovik, Two roads to antispacetime in polar distorted B phase: Kibble wall and half-quantum vortex, arXiv:1903.02418.
48. V.L. Berezinskii, Destruction of long-range order in one-dimensional and two-dimensional systems having a continuous symmetry group I. Classical systems, JETP 32, 493–500 (1971); II. Quantum systems, JETP 34, 610–616 (1972).
49. J.M. Kosterlitz and D.J. Thouless, Ordering, metastability and phase transitions in two-dimensional systems, Journal of Physics C: Solid State Physics 6, 1181–1203 (1973).
50. G.E. Volovik, M.V. Khazan, Dynamics of the A-phase of $^3$He at low pressure, ZhETF 82, 1498–1506 (1982); JETP 55, 867–871 (1982); Classification of the collective modes of the order parameter in superfluid $^3$He, ZhETF 85, 948–956 (1983), JETP 58, 551–555 (1983).
51. S.P. Novikov, Russian Math. Surveys 37, 1-56 (1982).
52. A.A. Belavin, A.M. Polyakov, Metastable states of two-dimensional isotropic ferromagnets, JETP Lett. 22, 245–247 (1975).
53. S.E. Trullinger, V.E. Zakharov, V.L. Pokrovskij (eds.), Solitons, Modern Problems in Condensed Matter Sciences, Vol. 17. Amsterdam (1986).
54. V.L. Golo and M.I. Monastyrsky, Gauge groups and topological invariants of vacuum manifolds, Annales de l'I.H.P. Physique theorique, 28, 50–72 (1978).
55. V.P. Mineyev, G.E. Volovik, Planar and linear solitons in superfluid $^3$He, Phys. Rev. B 18, 3197–3203 (1983).
56. G.E. Volovik, V.P. Mineev, Particle like solitons in superfluid $^3$He phases, ZhETF 73, 567–773 (1977), JETP Lett. 46, 401–404 (1977).
57. R. Shankar, Applications of topology to the study of ordered systems. J. Phys. France 38, 1405-1412 (1977).
58. W. Lee, A.H. Gheorghe, K. Tiurev, T. Ollikainen, M. Möttönen, and D.S. Hall, Synthetic electromagnetic knot in a three-dimensional skyrmion, Science Advances 4, eaao3820 (2018).
59. V.M.H. Ruutu, Ü. Parts, J.H. Köivuniemi, M. Kruus, E.V. Thuneberg, G.E. Volovik, The intersection of a vortex line with a transverse soliton plane in rotating $^3$He-A: $\pi_3$ topology, JETP Lett. 60, 667–671 (1994).
60. Yu.G. Makhlin, T.Sh. Misirpashaev, Topology of vortex-soliton intersection: invariants and torus homotopy, Pisma ZhETF 61, 48–53 (1995); JETP Lett. 61, 49–55 (1995).
61. G.E. Volovik, N.B. Kopnin, On the rotating $^3$He-A, Pisma ZhETF 25, 26–28 (1977), JETP Lett. 25, 22–24 (1977).
62. H.K. Seppälä, P.J. Hakonen, M. Kruus, T. Ohmi, M.M. Salomaa, J.T. Simola, and G.E. Volovik, Continuous vortices with broken symmetry in rotating superfluid $^3$He-A, Phys. Rev. Lett. 52, 1802 - 1805 (1984).
63. J.P. Pekola, K. Torizuka, A.J. Manninen, J.M. Kyunäärinen and G.E. Volovik, Observation of a topological transition in the $^3$He-A vortices, Phys. Rev. Lett. 65, 3293–3296 (1990).

64. L.I. Burlachkov and N.B. Kopnin, Magnetic properties of triplet superconductors in the nonunitary state, JETP 65, 630–633 (1987).

65. R. Hänninen, R. Blaauwgeers, V.B. Eltsov, A.P. Finne, M. Krusius, E.V. Thuneberg, G.E. Volovik, Structure of surface vortex sheet between two rotating $^3$He superfluids, Phys. Rev. Lett. 90, 225301 (2003).

66. I.L. Bekarevich, I.M. Khalednikov, Phenomenological derivation of the equations of vortex motion in He II, JETP 13, 643–646 (1961).

67. R. Blaauwgeers, V.B. Eltsov, G. Eska, A.P. Finne, R.P. Haley, M. Krusius, J.J. Ruohio, L. Skrbek, and G.E. Volovik, Shear flow and Kelvin-Helmholtz instability in superfluids, Phys. Rev. Lett. 89, 155301 (2002).

68. G.E. Volovik, On Kelvin-Helmholtz instability in superfluids, Pisma ZhETF 75, 491–495 (2002), JETP Lett. 75, 418–422 (2002).

69. S.E. Korshunov, Instability of superfluid helium free surface in the presence of heat flow, Europhys. Lett. 16, 673–675 (1991).

70. S.E. Korshunov, Analog of Kelvin-Helmholtz instability on a free surface of a superfluid liquid, Pisma v ZhETF 75, 496–498 (2002), JETP Lett. 75, 423–425 (2002).

71. E.A. Kuznetsov and P.M. Lushnikov, Nonlinear theory of excitation of waves by Kelvin-Helmholtz instability, ZhETF 108, 614–630 (1995), JETP 81, 332–340 (1995).

72. P.M. Lushnikov, N.M. Zubarev, Exact solutions for nonlinear development of a Kelvin-Helmholtz instability for the counterflow of superfluid and normal components of Helium II, Phys. Rev. Lett. 120, 204504 (2018).

73. T.W.B. Kibble, Topology of cosmic domains and strings, J. Phys. A9, 1387–1398 (1976).

74. V.M.H. Ruutu, V.B. Eltsov, A.J. Gill, T.W.B. Kibble, M. Krusius, Yu.G. Makhlin, B. Placais, G.E. Volovik, Wen Xu, Vortex formation in neutron-irradiated superfluid $^3$He as an analogue of cosmological defect formation, Nature 382, 334–336 (1996).

75. T.W.B. Kibble and G.E. Volovik, On phase ordering behind the propagating front of a second-order transition, JETP Lett. 65, 102–107 (1997).

76. N.B. Kopnin and E.V. Thuneberg, Time-dependent Ginzburg-Landau analysis of inhomogeneous normal-superfluid transitions, Phys. Rev. Lett. 83, 116–119 (1999).

77. I.S. Aranson, N.B. Kopnin and V.M. Vinokur Nucleation of vortices by rapid thermal quench, Phys. Rev. Lett. 83, 2600–2603 (1999); Dynamics of vortex nucleation by rapid thermal quench, Phys. Rev. B 63, 184501 (2001).

78. S.V. Manakov, V.G. Kamensky, On the creation of vortices under phase transitions, Proceedings in Nonlinear Science, Chap. 42, 477–482 (1990); V.G. Kamensky and S.V. Manakov, Unstable Ginzburg-Landau equation, unpublished.

79. A.M. Polyakov, Compact gauge fields and the infrared catastrophe, Phys. Lett. B59, 82–84 (1975).

80. G.E. Volovik, Phase slippage without vortices and vector oscillations in $^3$He-A, Pisma ZhETF 27, 605–608 (1978), JETP Lett. 27, 573–576 (1978).

81. D.N. Paulson, M. Krusius, and J.C. Wheatley, Experiments on orbital dynamics in superfluid $^3$He-A, Phys. Rev. Lett. 36, 1332 (1976).

82. B.I. Ilyev and N.B. Kopnin, Resistive state of superconductors, JETP Lett. 28, 592–595 (1978).

83. I. Dzyaloshinskii, A thermodynamic theory of "weak" ferromagnetism of antiferromagnetics, Journal of Physics and Chemistry of Solids 4, 241 (1958).

84. T. Moriya, Anisotropic superexchange interaction and weak ferromagnetism, Phys. Rev. 120, 91 (1960).

85. J. Villain, Spin glass with non-random interactions, J. Phys. C: Solid State Phys. 10, 1717–1734 (1977).

86. I.E. Dzyaloshinskii, G.E. Volovik, On the concept of local invariance in the theory of spin glasses, J. de Physique 39, 693–700 (1978).

87. I.E. Dzyaloshinskii, and G.E. Volovich, Poisson brackets in condensed matter, Ann. Phys. 125, 67–97 (1980).

88. G.E. Volovik, V.S. Dotsenko (jr), Poisson brackets and continual dynamics of the vortex lattice in rotating HeII, Pisma ZhETF 29, 630–633 (1979); JETP Lett. 29, 576–579 (1979).

89. J. Nissinen and G.E. Volovik, Tetrads in solids: from elasticity theory to topological quantum Hall systems and Weyl fermions, to appear in ZhETF, arXiv:1803.09234.

90. G.E. Volovik, J. Rysti, J.T. Makinen, V.B. Eltsov, Spin, orbital, Weyl and other glasses in topological superfluids, arXiv:1806.08177.
91. G.E. Volovik, Zeros in the fermion spectrum in superfluid systems as diabolical points, Pisma ZhETF 46, 81–84 (1987), JETP Lett. 46, 98–102 (1987).

92. S.P. Novikov, Magnetic Bloch functions and vector bundles. Typical dispersion laws and their quantum numbers, Sov. Math., Dokl. 23, 298–303 (1981).

93. A.A. Abrikosov and S.D. Beneslavskii, Possible existence of substances intermediate between metals and dielectrics, JETP 32, 699–798 (1971).

94. A.A. Abrikosov, Some properties of gapless semiconductors of the second kind, J. Low Temp. Phys. 5, 141–154 (1972).

95. A. A. Abrikosov, Quantum magnetoresistance, Phys. Rev. B 58, 2788 (1998).

96. P.G. Grinevich, G. E. Volovik, Topology of gap nodes in superfluid $^3$He: $\pi_4$ homotopy group for $^3$He-B disclination, J. Low Temp. Phys. 72, 371–380 (1988).

97. L.D. Landau, A. A. Abrikosov and I.M. Khalatnikov, Dokl. Akad. Nauk SSSR 95, 497, 773, 1177 (1954).

98. D.J. Gross and F. Wilczek, Ultraviolet behavior of non-abelian gauge theories, Phys. Rev. Lett. 30, 1343–1346 (1973); H.D. Politzer, Reliable perturbative results for strong interactions, Phys. Rev. Lett. 30, 1346–1349 (1973).

99. G.E. Volovik, Peculiarities in the dynamics of superfluid $^3$He-A: analog of chiral anomaly and of zero-charge, ZhETF 92, 2116–2132 (1987), JETP 65, 1193–1201 (1987).

100. V.N. Gribov, Anomalies and a possible solution of problems of zero-charge and infra-red instability, Phys. Lett. B 194, 119–124 (1987).

101. N.B. Kopnin and M.M. Salomaa, Mutual friction in superfluid $^3$He: Effects of bound states in the vortex core, Phys. Rev. B 44, 9667–9677 (1991).

102. G.E. Volovik, Fermion zero modes on vortices in chiral superconductors, Pisma ZhETF 70, 601–606 (1999); JETP Lett. 70, 609–614 (1999).

103. G.K. Savvidy, Infrared instability of the vacuum state of gauge theories and asymptotic freedom, Phys. Lett. B 1, 133–134 (1977).

104. V.N. Gribov, Quantization of non-Abelian gauge theories, Nucl. Phys. B 139, 1 (1978).

105. F.R. Klinkhamer and G.E. Volovik, Gluonic vacuum, $q$-theory, and the cosmological constant, Phys. Rev. D 79, 063527 (2009).

106. F.R. Urban, A.R. Zhitnitsky, The QCD nature of Dark Energy, Nucl.P hys. B 835, 135–173 (2010).

107. A.R. Zhitnitsky Inflaton as an auxiliary topological field in a QCD-like system, Phys. Rev. D 89, 063529 (2014).

108. Y.B. Zeldovich, Cosmological constant and elementary particles, JETP Lett. 6, 316–317 (1967).

109. A.Yu. Kamenshchik, A.A. Starobinsky, A. Tronconi, T. Vardanyan, G. Venturi, Pauli-Zeldovich cancellation of the vacuum energy divergences, auxiliary fields and supersymmetry, European Physical Journal C 78, 200 (2018).

110. G.E. Volovik, L.P. Gor’kov, An unusual superconductivity in $UB_{13}$, Pis’ma ZhETF 39, 550–553 (1984), JETP Letters39, 674–677 (1984).

111. G.E. Volovik, L.P. Gor’kov, Superconductivity classes in the heavy fermion systems, ZhETF 88, 1412–1428 (1985), JETP 61, 843–854 (1985).

112. M. Creutz, Four-dimensional graphene and chiral fermions, JHEP 0804:017 (2008).

113. M. Creutz, Emergent spin, Annals Phys. 342, 21–30 (2014).

114. G.E. Volovik, Dirac and Weyl fermions: from Gor’kov equations to Standard Model (in memory of Lev Petrovich Gorkov), Pis’ma ZhETF 105, 245–246 (2017), JETP Lett. 105, 273–277 (2017).

115. G.E. Volovik, Superconductivity with lines of gap nodes: Density of states in the vortex, Pisma ZhETF 58, 457–461 (1993), JETP Lett. 58, 469–473 (1993).

116. P. M. R. Brydon, D. F. Agterberg, H. Menke and C. Timm, Bogoliubov Fermi surfaces: General theory, magnetic order, and topology, arXiv:1806.03773.

117. G. E. Volovik, On the vortex lattice transition in the heavy fermionic $UPt_3$, J. Phys. C 21, L221–L224 (1988).

118. I. Dzyaloshinskii, A. Polyakov, P. Wiegmann, Neutral fermions in paramagnetic insulators, Phys. Lett. A 127, 112–114 (1988).

119. G. E. Volovik, $\theta$-term and statistics of topological objects in superfluid Helium-3 film, Physca Scripta 38, 321–323 (1988).

120. G.E. Volovik, A. Solovyev, V.M. Yakovenko, 1989, Spin and statistics of solitons in superfluid $^3$He-A film, Pisma ZhETF 49, 55–57 (1989), JETP Lett. 49, 65–67 (1989).
121. G.E. Volovik, V.M. Yakovenko, Fractional charge, spin and statistics of solitons in superfluid $^3$He film, J. Phys.: Cond. Matter 1 , 5263–5274 (1989).

122. A.I. Larkin, Effect of inhomogeneities on the structure of the mixed state of superconductors, ZhETF 58, 1466–1470 (1970), JETP 31, 784–786 (1970).

123. Y. Imry and S.K. Ma, Random-field instability of the ordered state of continuous symmetry, Phys. Rev. Lett. 35, 1399 (1975).

124. G.E. Volovik, Glass state of superfluid $^3$He-A in aerogel, Pis’ma ZhETF 63, 281–284 (1996); JETP Lett. 63, 301–304 (1996).

125. V.V. Dmitriev, D.A. Krasnikhin, N. Mulders, A.A. Senin, G.E. Volovik and A.N. Yudin, Orbital glass and spin glass states of $^3$He-A in aerogel, Pis’ma ZhETF 91, 669–675 (2010); JETP Lett. 91, 599–606 (2010).

126. R.Sh. Askhadullin, V.V. Dmitriev, P.N. Martynov, A.A. Osipov, A.A. Senin, A.N. Yudin, Anisotropic 2D Larkin-Imry-Ma state in polar distorted ABM phase of $^3$He in ”schematically ordered” aerogel, JETP Lett. 100, 662-668 (2015).

127. N.B. Kopnin and V.E. Kravtsov, Conductivity and the Hall effect in pure type-II superconductors at low temperatures, Pis’ma v ZhETF 23, 631–634 (1976), JETP Lett. 23, 578–571 (1976).

128. N.B. Kopnin, "Theory of Nonequilibrium Superconductivity", Oxford University Press (2001).

129. G.E. Volovik, Vortex motion in fermi superfluids and Callan-Harvey effect, Pis’ma ZhETF 57, 233–237 (1993); JETP Lett. 57, 244–248 (1993).

130. S.V. Iordanskii, On the mutual friction between the normal and superfluid components in a rotating Bose gas, Ann. Phys. 29, 335–349 (1964).

131. S.V. Iordanskii, Mutual friction force in a rotating Bose gas, JETP 49, 160–167 (1966).

132. N.B. Kopnin, G.E. Volovik, and Ü. Parts, Spectral flow in vortex dynamics of superfluid $^3$He-B and superconductors, Europhys. Lett. 32, 651-656 (1995).

133. N.B. Kopnin and G.E. Volovik, Flux-flow in d-wave superconductors: Low temperature universality and scaling, Phys. Rev. Lett. 79, 1377–1380 (1997).

134. A.P. Finne, V.B. Eltsos, R. Hanninen, N.B. Kopnin, J. Kopn, M. Krusius, M. Tsubota and G.E. Volovik, Dynamics of vortices and interfaces in superfluid $^3$He, Rep. Prog. Phys. 69, 3157–3230 (2006); cond-mat/0606619.

135. D.A. Ivanov, Non-Abelian statistics of half-quantum vortices in p-wave superconductors, Phys. Rev. Lett. 86, 268 (2001).

136. G.E. Volovik, Flat band in the core of topological defects: bulk-vortex correspondence in topological superfluids with Fermi points, Pis’ma ZhETF 93, 69–72 (2011); JETP Lett. 93, 66–69 (2011).

137. T.T. Heikkilä and G.E. Volovik, Dimensional crossover in topological matter: Evolution of the multiple Dirac point in the layered system to the flat band on the surface, Pis’ma ZhETF 93, 63–68 (2011); JETP Lett. 93, 59–65 (2011).

138. N.B. Kopnin, Surface superconductivity in multilayered rhombohedral graphene: Supercurrent, JETP Lett. 94, 81 (2011).

139. N.B. Kopnin, T.T. Heikkilä and G.E. Volovik, High-temperature surface superconductivity in topological flat-band systems, Phys. Rev. B 83, 220503(R) (2011).

140. N.B. Kopnin, M. Ijäs, A. Harju, T.T. Heikkilä, High-temperature surface superconductivity in rhombohedral graphite, Phys. Rev. B 87, 140503(R) (2013).

141. V.A. Khodel and V.R. Shaginyan, Superfluidity in system with fermion condensate, JETP Lett. 51, 555–555 (1990).

142. Yuan Cao, V. Fatemi, Shiang Fang, K. Watanabe, T. Taniguchi, E. Kaxiras and P. Jarillo-Herrero, Unconventional superconductivity in magic-angle graphene superlattices, Nature 556, 43–50 (2018).

143. Yuan Cao, V. Fatemi, A. Demir, Shiang Fang, S.L. Tomarken, J.Y. Luo, J.D. Sanchez-Yamagishi, K. Watanabe, T. Taniguchi, E. Kaxiras, R.C. Ashoori and P. Jarillo-Herrero, Correlated insulator behaviour at half-filling in magic-angle graphene superlattices, Nature 556, 80–84 (2018).

144. G.E. Volovik, Graphite, graphene and the flat band superconductivity, Pis’ma ZhETF 107, 537–538 (2018), JETP Lett. 107, 516–517 (2018).

145. T.J. Peltonen, R. Ojajärvi and T.T. Heikkilä, Mean-field theory for superconductivity in twisted bilayer graphene, arXiv:1805.01039.

146. N.B. Kopnin and G.E. Volovik, Singularity of the Vortex Density of States in d-wave Superconductors, Pis’ma ZhETF64, 641–645 (1996), JETP Lett. 64, 690 (1996).

147. I.A. Fomin, Long-lived induction signal and spatially nonuniform spin precession in $^3$He-B, JETP Lett. 40, 1037–1040 (1984).
[148] I.A. Fomin, Separation of magnetization precession in $^3$He-B into two magnetic domains. Theory, JETP 61, 1207–1213 (1985).

[149] A.S. Borovik-Romanov, Yu.M. Bunkov, V.V. Dmitriev, Yu.M. Mukharskiy and K. Flahbart K. Stratification of $^3$He spin precession in two magnetic domains, JETP 61, 1199 (1985).

[150] Y. Kondo, J.S. Korhonen, M. Krusius, V.V. Dmitriev, E.V. Thuneberg and G.E. Volovik, Combined spin-mass vortices with soliton tail in superfluid $^3$He-B, Phys. Rev. Lett. 68, 3331 (1992).

[151] G.E. Volovik, Twenty years of magnon Bose condensation and spin current superfluidity in $^3$He-B, J. Low Temp. Phys. 153, 266–284 (2008).

[152] Yu.M. Bunkov and G.E. Volovik, Spin superfluidity and magnon Bose-Einstein condensation, in: Novel Superfluids, eds. K. H. Bennemann and J. B. Ketterson, International Series of Monographs on Physics 156, Volume 1, Chapter 4, pp. 253–311 (2013).

[153] S. Autti, V.B. Eltsov and G.E. Volovik, Bose analogs of MIT bag model of hadrons in coherent precession, Pis’ma ZhETF 95, 610–614 (2012); JETP Lett. 95, 544–548 (2012).

[154] S. Autti, P.J. Heikkinen, G.E. Volovik, Bose analogs of MIT bag model of hadrons in coherent precession, Pis’ma ZhETF 95, 610–614 (2012); JETP Lett. 95, 544–548 (2012).

[155] S. Autti, V.B. Eltsov and G.E. Volovik, Observation of a time quasicrystal and its transition to a superfluid time crystal, Phys. Rev. Lett. 120, 215301 (2018), arXiv:1712.06877.

[156] F. Wilczek, Superfluidity and space-time translation symmetry breaking, Phys. Rev. Lett. 111, 250402 (2013).

[157] C. Sun, T. Nattermann, V.L. Pokrovsky, Bose-Einstein condensation and superfluidity of magnons in yttrium iron garnet films, J. Phys. D 50, 143002 (2017).

[158] Ya.B. Zel’dovich, Generation of waves by a rotating body, JETP Lett. 14, 180–181 (1971).

[159] A.A. Starobinskii, Amplification of waves during reflection from a rotating "black hole", ZhETF 64, 48–57 (1973), JETP 37, 28–32 (1973).

[160] V.A. Belinski, On the existence of quantum evaporation of a black hole, Phys. Lett. A 209, 13–20 (1995).

[161] A.V. Byalko, The hydrodynamics of black hole vaporization, JETP Lett. 29, 176–179 (1979).

[162] A. Calogeracos and G. E. Volovik, Rotational quantum friction in superfluids: Radiation from object rotating in superfluid vacuum, Pis’ma ZhETF 69, 257–262 (1999), JETP Lett. 69, 281–287 (1999).

[163] H. Takeuchi, M. Tsubota and G.E. Volovik Zel’dovich-Starobinsky effect in atomic Bose-Einstein condensates: Analogy to Kerr black hole, J. Low Temp. Phys. 150, 624–629 (2008);

[164] A.A. Starobinsky and J. Yokoyama, Equilibrium state of a selfinteracting scalar field in the De Sitter background, Phys. Rev. D 56, 3258 (1997).

[165] L. Kofman, A. Linde, and A.A. Starobinsky, Towards the theory of reheating after inflation, Phys. Rev. D 56, 3258 (1997).

[166] F.R. Klinkhamer and G.E. Volovik, Self-tuning vacuum variable and cosmological constant, Phys. Rev. D 77, 085015 (2008).

[167] F.R. Klinkhamer and G.E. Volovik, Dynamic vacuum variable and equilibrium approach in cosmology, Phys. Rev. D 78, 063528 (2008).

[168] F.R. Klinkhamer and G.E. Volovik, $f(R)$ cosmology from $q$-theory, Pis’ma ZhETF 88, 339–344 (2008); JETP Lett. 88, 289–294 (2008).

[169] S.W. Hawking, The cosmological constant is probably zero, Phys. Lett. B 134, 403 (1984); M.J. Duff, The cosmological constant is possibly zero, but the proof is probably wrong, Phys. Lett. B 226, 36 (1989); Z.C. Wu, The cosmological constant is probably zero, and a proof is possibly right, Phys. Lett. B 659, 891 (2008).

[170] F.R. Klinkhamer and G.E. Volovik, Brane realization of q-theory and the cosmological constant problem, Pis’ma ZhETF 103, 711–714 (2016); JETP Lett. 103, 627 (2016).

[171] E.I. Kats and V.V. Lebedev, Nonlinear fluctuation effects in dynamics of freely suspended films, Phys. Rev. E 91, 032415 (2015).

[172] A.F. Volkov and S.M. Kogan, Collisionless relaxation of the energy gap in superconductors, JETP 38, 1018–1021 (1974).

[173] R. A. Barankov, L. S. Levitov, and B. Z. Spivak, Collective Rabi oscillations and solitons in a time-dependent BCS pairing problem, Phys. Rev. Lett. 93, 160401 (2004).

[174] M.S. Foster, V. Gurarie, M. Dzero, E.A. Yuzbashyan, Quench-induced Floquet topological $p$-wave superfluids, Phys. Rev. Lett. 113, 076403 (2014).
175. R. Matsunaga, Y.I. Hamada, K. Makise, Y. Uzawa, H. Terai, Zhen Wang, R. Shimano, The Higgs ampli-
tude mode in BCS superconductors Nb$_{1-x}$Ti$_x$N in-
duced by terahertz pulse excitation, Phys. Rev. Lett. 111, 057002 (2013).

176. R. Matsunaga, N. Tsuji, H. Fujita, A. Sugioka, K. Makise, Y.i Uzawa, H. Terai, Light-induced collective pseudospin precession resonating with Higgs mode in a superconductor, Science 345, 1145–1149 (2014).

177. A.M. Polyakov, De Sitter space and eternity, Nucl. Phys. B 797, 199 (2008).

178. A.M. Polyakov, Decay of vacuum energy, Nucl. Phys. B 834, 316–329 (2010).

179. D. Krotov and A.M. Polyakov, Infrared sensitivity of unstable vacua, Nucl. Phys. B 849, 410–432 (2011).

180. G.L. Pimentel, A.M. Polyakov, G.M. Tarnopolsky, Vacua on the brink of decay, Reviews in Mathemati-
cal Physics 30, 1840013 (2018), arXiv:1803.09168.

181. G.E. Volovik, Particle decay in de Sitter space-
time via quantum tunneling, Pis'ma ZhETF 90, 3–6 (2009); JETP Lett. 90, 1–4 (2009); On de Sitter radiation via quantum tunneling, Int. Journal Mod. Phys. D 18, 1227–1241 (2009).

182. G.E. Volovik, V.I. Mel'nikov, V.M.Edel'stein, The mobility of the polaron with strong coupling, Pisma ZhETF 40, 138–141 (1973), JETP Lett. 18, 81–83 (1973).

183. G.E. Volovik, D.E. Khmel'nitskii, Phase transition splitting caused in exotic superconductors by impu-
rities, Pisma ZhETF 40, 469–472(1984), JETP Lett. 40, 1299–1302 (1984).

184. A.A. Balinskii, G.E. Volovik, E.I. Kats, Disclination symmetry in uniaxial and biaxial nematic liquid crys-
tals, ZhETF 87, 1305–1314 (1984), JETP 60, 748–753 (1984).

185. Yu.G. Makhlin and G.E. Volovik, Spectral flow in Josephson junctions and effective Magnus force, Pisma ZhETF 62, 923–928 (1995), JETP Lett. 62, 941–946 (1995).