

### CV of Egor Babaev

- Fellow of the Royal Swedish Academy of Science hosted at the Royal Institute of Technology Sweden
- Assistant Professor Physics Department University of Massachusetts Amherst USA

Personal homepages: <http://www.theophys.kth.se/~egor/> <http://people.umass.edu/egorb/>

### EDUCATION

**Undergraduate studies:** A. F. Ioffe Institute of Physics and Technology (Russia)

**Graduate studies:** Department of Theoretical Physics University of Uppsala (Sweden) PhD (2001).

### POSTDOCTORAL APPOINTMENTS

**Sept. 2001-Aug. 2003** Postdoctoral research associate at Inst. for Theoretical Physics Uppsala University

**Sept. 2003-July 2006** Postdoctoral research associate at Cornell University

### FACULTY POSITIONS

**Sept. 2006-Aug. 2007** (on leave from the University of Massachusetts Amherst):

Assistant Professor at the Department for Theoretical Physics Royal Institute of Technology (KTH), Sweden.

**Sept. 2007- present** Assistant Professor Physics Department University of Massachusetts Amherst

**Sept. 2008-present** Fellow of the Royal Swedish Academy of Science hosted at the Royal Institute of Technology Sweden

### AWARDS

**2010: Tage Erlander prize in Physics of the Royal Swedish Academy of Sciences**

*Citation: "For groundbreaking theoretical work that predicts new states of matter in the form of quantum fluids with novel properties"*

**2010: US National Science Foundation CAREER Award**

*Description: "The CAREER Program is a Foundation-wide activity that offers the National Science Foundation's most prestigious awards in support of junior faculty."*

**2008: Knut and Alice Wallenberg award from the Swedish Royal Academy of Science/  
Elected Fellow of the Swedish Royal Academy of Science**

*Description: "The award is given by the Royal Swedish Academy to exceptionally gifted researchers to conduct their research in Sweden."*

**2005:** Junior Faculty grant from Swedish Research Council

### GRANTS

**Major Grants** (not all funds were used in the past because of affiliation changes):

**2010: US\$ 425 000** US National Science Foundation CAREER Award US

**2009: ~ US\$ 1.5 million** "Novel Quantum Fluids". [This proposal was initially submitted in 2008 to the European Research Council "Starting Grant" where it was recommended for funding by the ERC panel with the amount of 1,15 million Euro but because of the ERC budget cut it was funded by the backstop funds provided by the Swedish Research Council.]

**2008: ~ US\$ 1 million** a grant for 5 years for teaching relief and research funding from Knut and Alice Wallenberg foundation.

**2006: ~ US\$ 500 000** Swedish Research Council Junior Faculty Grant (Forskarassistent) "Novel Quantum Fluids: From Liquid Metallic Hydrogen to Triplet Superconductors and Quantum Antiferromagnets"

**2003: ~US\$ 200 000-** Personal grant from Norwegian Research Council "Multicomponent Superconductivity"

**2002: ~ US\$ 100 000** Swedish Research Council "Multicomponent Superconductivity"

**Smaller Grants/conference and travel funding:**

**2010: ~US\$ 10 000** Funds awarded by the Royal Swedish Academy of Sciences to support Tage Erlanders symposium "Frontiers in Condensed Matter Physics"

**2009: ~US\$ 15 000** Grant from Swedish Research Council for conference "Frontiers in Quantum Solids, Liquids and Gases (with 4 co-applicants).

**2009: ~US\$ 50 000-** Support of the international workshop “Quantum Solids, Fluids and Gases” from Nordic Institute for Theoretical Physics (with 4 co-applicants)

**2007: ~US\$ 70 000-** Support for the international workshop “Quantum Fluids” from Nordic Institute for Theoretical Physics (with 4 co-applicants)

**2002: ~US\$ 10 000** -Personal travel grant from NORFA

### **EDITORIAL ACTIVITY**

ad hoc Divisional Associate Editor Physical Review Letters.

Editorial Board member “Springer Briefs in Physics”

### **REFEREE**

1. Nature Physics, 2. Physical Review Letters, 3. Physical Review A, 4. Physical Review B, 5. Physical Review D, 6. Physical Review E, 7. New Journal of Physics, 8. Annals of Physics, 9. Journal of Physics A: Mathematical and General, 10. Europhysics Letters, 11. Journal of Physics Condensed Matter, 12. Journal of Mathematical Physics, 13. European Physical Journal, 14. Modern Physics Letters, 15. International Journal of Modern Physics, 16. European Journal of Physics. 17. Physica C, 18. Central European Journal of Physics, 19. Superconductor Science and Technology, 20. Journal of Low Temperature Physics, 21. Physics Letters A.

### **PROJECTS REVIEWER/REFEREE FOR GRANTS APPLICATIONS**

1. US National Science Foundation
2. US Department of Energy
3. European Research Council, referee for ERC Advanced Grant program
4. The Research Foundation Flanders (main Belgian science funding agency)
5. Qatar National Research Fund

### **CITED EXPERT** for

1. Physical Review Focus,
2. Science Magazine’s ScienceNOW
3. PhysicsWorld and PhysicsWeb
4. Cited expert on Swedish science funding reform in the Swedish Research Council Magazine Tentakel which is main Swedish Science magazine (interdisciplinary analogue of Physics Today)

### **OUTREACH / MEDIA COVERAGE**

Multiple media articles in various languages (in German, French, Russian, Korean, Farsi, Dutch, Swedish, Norwegian, Vietnamese).

### **Selected research coverage in media/general audience publications**

“Back to square one for superfluidity” Physics World December 2004;

“Metallic superfluid seen in computer” PhysicsWeb news article <http://physicsworld.com/cws/article/news/23234>;

“Simulations reveal metallic superfluid” Physics World November 2005;

“Known unknowns in high-pressure hydrogen” The central research highlight in the first issue of Nature Physics;

“Possible Quantum-liquid Metallic Phase of Hydrogen at high Pressures and its Properties” Feature in the Journal Club for Condensed Matter Physics October 23 (2006) <http://www.condmatjournalclub.org/?p=34>,

“Superfluids break the law” Cover story in Nature Physics n.3, v.8 (2007);

“Nya teorier om metalliska supervätskor ger kvantfysiken nytt blod”(in Swedish)

<http://www.newsdesk.se/pressroom/kth/pressrelease/view/156090>;

“A Super Mix Inside Neutron Stars” Physical Review Focus <http://focus.aps.org/story/v22/st3>;

“Type-1.5 superconductor shows its stripes” PhysicsWeb [http:// physicsworld.com/cws/article/news/37806](http://physicsworld.com/cws/article/news/37806);

“New Type of Superconductivity Spotted” ScienceNOW news story

<http://sciencenow.sciencemag.org/cgi/content/citation/2009/313/1>;

“Materials in extreme environments” in Physics Today 62 November 32 (2009)

Research highlighted in the Department on Energy Report on “*Basic Research Needs for Materials under Extreme Environments*”

### **CONFERENCE ORGANIZATION**

**15 August- 30 September 2007** The principal organizer of the international NORDITA's Quantum Fluids Program at new NORDITA) (inaugural program of new NORDITA in Stockholm co-organizers H.Hansson, A. Karlhede, M.Wallin, F.Wilczek)

<http://www.nordita.org/~qf2007>

**18 July-23 August 2010** The organizer of the international program “Quantum Gases Liquids and Solids” at NORDITA in Stockholm co-organizers E. Lundh, J.Martikainen, C.Pethick, M.Wallin)

<http://agenda.albanova.se/conferenceDisplay.py?confId=1127>

**09-20 August 2010** The organizer of the international conference “Frontiers in Quantum Gases Liquids and Solids” co-organizers E. Lundh, J.Martikainen, C.Pethick, M.Wallin)

<http://agenda.albanova.se/conferenceDisplay.py?confId=2219>

**January 3-8, 2011** Tage Erlander’s award symposium “Frontiers in Condensed Matter Physics”

**LONG-TERM VISITS** **Spring 2002** University of Iceland **April 2005** Institute for Nuclear Theory at the University of Washington, member. **Winter 2006** Kavli Institute for Theoretical Physics UCSB

**Spring 2007** Oslo Institute for Advanced Study, (Spin and Charge Flow in Nanostructures program)

### **COURSES TAUGHT:**

- Statistical Mechanics (**Spring 2007, Spring 2008, Spring 2009**)

- Superconductivity and Superfluidity (**Autumn 2007**)

### **COMMITTEES WORK:**

UMass Graduate Admission Committee; UMass Publicity Content Committee; Condensed Matter Seminar co-organizer at UMass.

### **TALKS/COLLOQIA (invited unless stated contributed) since 2002**

#### **2002:**

“*Knotted solitons*” at Mathematical Department University of Iceland

“*Fractional vortices in multicomponent superconductors*” at Physics Department University of Iceland

“*Fractional vortices and knot solitons in multicomponent superconductors*” at University of Montpellier, France

“*Fractional vortices and knot solitons in multicomponent superconductors*” at Institute for Nuclear Physics Orsay, France

“*Possibility of knotted solitons formation in neutron stars*” at Observatory of Paris at Meudon, France

#### **2003:**

“*Fractional vortices and knot solitons in two-gap superconductors*” at Vortex III conference Crete, Greece.

“*Fractional vortices and knot solitons in two-gap superconductors*” at the Third Workshop of the ESF Programme COSLAB (Cosmology in the Laboratory) Bilbao, Spain .

“*Fractional vortices and knot solitons in two-gap superconductors*” at the workshop “Vortices in Superfluids and Superconductors” Oulu, Finland

#### **2004:**

“*Topological defects in multicomponent superconductors*” at the fourth workshop of the ESF Programme COSLAB (Cosmology in the Laboratory) Lancaster, UK .

“*A superconductor to superfluid phase transition in liquid metallic hydrogen*” at NANOMAT Meeting, Oslo, Norway

“*Knotted solitons and fractional vortices in two-gap and triplet superconductors*” (contributed) at APS March Meeting, Montreal, Canada

#### **2005:**

*“Topological aspects in physics of multicomponent superconductors”* at Harvard University USA  
*“Topological aspects in physics of multicomponent superconductors”* at University of Illinois of Urbana-Champaign  
*“A superconductor to superfluid phase transition in liquid metallic hydrogen”* (contributed) at APS March Meeting, Los Angeles, USA  
*“A superconductor to superfluid phase transition in liquid metallic hydrogen”* at University of Washington at Seattle, USA  
*“A superconductor to superfluid phase transition in liquid metallic hydrogen”* at Uppsala University, Sweden  
*“A superconductor to superfluid phase transition in liquid metallic hydrogen”* at The Royal Institute of Technology, Stockholm, Sweden  
*A superconductor to superfluid phase transition in liquid metallic hydrogen”* at Goteborg University, Sweden  
*“Liquid metallic hydrogen: a projected novel quantum fluid ”* at the Second international conference on Hydrogen in Matter (ISOHIM-2) Uppsala Sweden  
*“Novel quantum fluids”* at NANOMAT Meeting in Hell, Hell, Norway.  
*Novel quantum fluids”* at Oxford University, UK

**2006:**

*“A superconductor to superfluid phase transition and non-Meissner electrodynamics in the projected liquid metallic state of hydrogen”* at University of California at San Diego, USA  
*“A superconductor to superfluid phase transition and non-Meissner electrodynamics in the projected liquid metallic state of hydrogen”* at Princeton University, USA  
*“A superconductor to superfluid phase transition and non-Meissner electrodynamics in the projected liquid metallic state of hydrogen”* at University of Massachusetts in Amherst, USA  
*“Observability of the Projected New State of Matter: metallic superfluid”* (contributed) at APS March Meeting, Baltimore, USA.  
*“Projected novel states of matter in compressed hydrogen: from metallic superfluidity to non-Meissner electrodynamics”* at Gordon Conference “Research at High Pressure”, Biddeford, ME, USA  
*“Liquid metallic hydrogen: a quest for novel quantum fluid”* at The Royal Institute of Technology, Sweden.

**2007:**

*“Topological defects, magnetic charges” and coherence in dipolar condensates”* (contributed) at APS March meeting, Denver USA  
*“Rotating superfluids: macroscopic manifestations of the microworld laws”* **A talk for general audience** at the Center for Advanced Study Norwegian Academy of Science and Letters  
*“Liquid metallic hydrogen: a quest for new quantum fluid”* at the workshop “Superfluids Under Rotation 2007” Jerusalem, Israel  
*“London Law and its violation in multicomponent superconductors”* at “SPINOR2007”, Oslo, Norway  
*“Liquid metallic hydrogen: a quest for new quantum fluid”* at the University of Oslo  
*“Liquid metallic hydrogen: projected novel quantum fluid”* at “Quantum Fluids 2007” program at NORDITA Stockholm

**2008:**

*“Liquid metallic hydrogen: projected novel quantum fluid”* at “New Horizons in Condensed Matter Physics” winter conference at Aspen center for Physics  
*“Liquid metallic hydrogen a quest for novel quantum fluid”* **Colloquium** at the University of Wisconsin Milwaukee  
*“Violation of the London law and Onsager--Feynman quantization in multicomponent superconductors ”* (contributed) at APS March Meeting New Orleans.  
*“Counterflow condensates: from projected metallic hydrogen to Bose-Einstein and excitonic condensates”* at Harvard University, USA  
*“Counterflow condensates: from projected metallic hydrogen to Bose-Einstein and excitonic condensates”* at

Cornell University.

*"Electrodynamics with effective "magnetic charges" in dipolar excitonic condensates."* at the 1st Greater Boston Area Quantum Matter Meeting. Harvard University.

**2009:**

*"Projected Novel Quantum Fluids in light elements under extreme compression"* **Colloquium** University of Massachusetts Amherst;

*"Semi-Meissner state and neither type-I nor type-II superconductivity in multicomponent systems"* at Joint JSPS-ESF International Conference on Nanoscience and Engineering in Superconductivity, Tsukuba, Japan

*"Semi-Meissner state and neither type-I nor type-II superconductivity in multicomponent systems"* At Sixth International Conference on Vortex Matter in Nanostructured Superconductors (VORTEX VI) Rhodes, Greece

*"Hidden vortex lattices in a thermally paired superfluids"* At Aspen Center for Theoretical Physics. Program "Quantum Vortices and Fluctuations in Superconductors and Superfluids.

*"Composite vortices and thermally paired superfluids concepts in condensed matter and cold atoms: Possible relevance for neutron star physics"*. At the Nordita International Workshop Neutron stars - The crust and beyond.

**2010: (this year I declined/postponed multiple invitations because of other time consuming commitments)**

*"Type-1.5 superconductivity"* **Colloquium** Williams College (**planned/postponed**);

*"Hidden vortex lattices in a thermally paired superfluid"*(**contributed**) APS March Meeting 2010 Portland, Oregon

*"Type-1.5 superconductivity"* at the "Frontiers in Quantum Solids Liquids and Gases" conference Stockholm

*"Vortex core structure and type-1.5 superconductivity in two-band systems"* International Workshop on Nanoscale Superconductivity, Fluxonics and Plasmonics. Crete, Greece, September 21-26, 2010

*"Topological defects in superconductors with complex broken symmetries"* Department of Mathematics University of Massachusetts Amherst (**planned**)

*"Exotic properties of multicomponent quantum matter"* **Colloquium** UMass Boston; (**planned**)

*"Type-1.5 superconductivity"* University of California Davis (**planned**)

## SCIENTIFIC RESULTS

I was always interested whether the concepts of "super" states of matter can be extended beyond superfluid liquids, vapors, supersolids and superconductors. I.e, if other "aggregate" super states of matter are possible. In the year 2000, while being a student at Uppsala University, I directed my attention to the ultra-high pressure physics, namely on the projected liquid metallic state of hydrogen. In the series of works on the subject in 2001-2010 I showed that ordered states of metallic hydrogen in the quantum domain are endowed with exotic properties and do not fall into any known categories of quantum fluids but represent a projected new state of matter. In 2001 I published an e-print (which later appeared in Phys.Rev.Lett. 89 (2002) 067001) where I have shown, that the projected liquid metallic state of hydrogen [where N.W. Ashcroft predicted existence of Cooper pairing in a liquid state and pairing instabilities for both electrons and protons] possess superfluid modes, which are composite and inextricably intertwined with superconducting modes with a number of physical consequences. In a separate eprint late in 2001 (which was later published in Nucl. Phys. B686, 397 (2004)) I discussed that in a planar geometry the liquid metallic hydrogen, even in the presence of both electronic and protonic Cooper pairs, can have quasi-long-range order only in the phase sum of electronic and protonic order parameters and thus **exhibit only superfluid properties without superconductivity** in spite consisting only of charged particles (later for this state the term "**metallic superfluid**" was coined). That is, the system in this state has electrical resistance while at the same time featuring frictionless flow of mass when electronic Cooper pairs flow is accompanied by the protonic Cooper pairs flow (that is a flow with no net charge transfer, though there is no conventional real-space pairing between electrons and protons in that state, but rather the effect is dictated by topological features of multicomponent gauge theory, leading to ordering only in the phase sum of the order parameters). Since there are obvious difficulties in controlling two-dimensionality of a system at ultra-high pressure, in 2003 I directed my attention to searching a possible counterpart of this phenomenon in three dimensions. Also, because I wanted to learn more about ultra-high pressure physics in 2003 I moved to Cornell to work with N.W. Ashcroft. There I was informed that in diamond anvil cells experiments it is possible to make a number of measurements involving external magnetic field which prompted me to study the states of liquid metallic

hydrogen in an external field. I suggested in 2004 that **external magnetic field can cause in three-dimensional samples of liquid metallic hydrogen phase transitions from superconductivity to superfluidity and vice versa**. Based on this a paper was written Nature 431, 666 (2004) (selected as a cover story). The experimental conditions required in hydrogen to establish these transitions appear to be accessible in the not so distant future: the required pressure is  $\sim 400$  GPa, (now experiments achieve static pressures  $\sim 340$  GPa). Breakthrough in high pressure physics in 2009 allowed to achieve pressures as high as 1.4 TPa for short periods of time in terrestrial laboratory and a rapid progress in static compression experiments is expected. That paper in Nature introduced (along with my previous study of two-dimensional systems) a novel state when, for topological reasons, a three dimensional two-component superconductor in an external magnetic field (or a fluctuating planar two-component superconductor) loses its ability to sustain dissipationless electric current at the same time being capable of sustaining a dissipationless mass flow (though *no direct real-space pairing of particles takes place*). The possible phase transitions in the ordered quantum states of liquid metallic state hydrogen were subsequently studied in great detail in numerical computations done in collaboration with A. Sudbo, E. Smorgrav and J. Smiseth and were published in Phys.Rev.Lett. 94 096401 (2005); Phys. Rev. Lett. 95, 135301 (2005). Collaborating with the team at NTNU Trondheim (Sudbo, Smiseth and Smorgrav) a quite detailed theory of these transitions and of three-dimensional N-component vortex matter was subsequently developed and studied numerically (we published a 41-pages paper on this topic Phys.Rev. B71 (2005) 214509). This study was followed up recently by the more detailed numerical study in collaboration with Egil Herland and A. Sudbo Phys. Rev. B 82, 134511 (2010).

In 2005 I was thinking about bridging these theoretical works with feasible experimental probes. In Phys. Rev. Lett. 95, 105301 (2005) I proposed the experimental techniques which could confirm the existence of this state of matter in ultra-high pressure diamond anvil cells experiments. Before that publication there were no published proposals how one can study experimentally the properties of the projected protonic or deuteronic superconductivity in the extreme conditions under which they are expected to form. This paper was endorsed as the central Research Highlight "Known Unknowns in High Pressure Hydrogen" in the first issue of the Nature Physics magazine. The paper in Nature along with the papers with Smorgrav, Smiseth and Sudbo Phys.Rev.Lett. 94 096401 (2005); Phys. Rev. Lett. 95, 135301 (2005); Phys.Rev. B71 (2005) 214509 on its verification in numerical simulations were endorsed by the Bell Labs Condensed Matter Journal Club. In the next my paper in that series (published in Nature Physics 3, 530 - 533 (2007) where it also selected as a cover story) it was shown that **superflow in liquid metallic hydrogen violates the Onsager-Feynman quantization. Also the London law (which describes the universal rotational response of electronic superconductors is violated)** and therefore from the point of view of the rotational response (the quintessential state-defining property of superconductors and superfluids) **the liquid metallic hydrogen should represent a projected novel state of matter**.

Other results in that project can be summarized as follows: **Vortices solutions carrying an arbitrary fraction of flux quantum** were obtained for multicomponent superconductors (published in Phys. Rev. Lett. 89 067001 (2002)). I also described generic integer flux vortex solutions in a two-band superconductor. Subsequently with J. M. Speight and Juha Jaykka (Phys. Rev. Lett 103, 237002 (2009)) we performed more detailed analytical and numerical analysis of topological excitations with fractional flux in multicomponent gauged theories, demonstrating novel effects: namely we found that generically **magnetic flux in fractionally quantized topological excitations is not exponentially localized** and moreover for vortices carrying certain fractions of magnetic flux quantum there is a **flux inversion effect**: the vortex's magnetic field inverts its direction at a certain distance from the center of a topological defect. This non-exponential behavior of magnetic field is highly unusual a counter-intuitive for a system with the Meissner-Higgs effect (which dictates monotonic and exponential decay of magnetic field in a superconductor). I found that at a deeper level this manifestation of non-Meissner electrodynamics originates in the effect on which we worked earlier with Faddeev and Niemi in a different context: that is, we found that when several superconducting components are coupled by the same gauge field, the electromagnetic properties of the system are no longer described by just the Meissner-Higgs effect but the fluctuating gauge field generates Skyrme-like terms (I elaborate on this below).

One of my first papers in that series from 2002 (Arxiv:cond-mat/0201547, published in Nucl. Phys. B686, 397 (2004)) was the first work which introduced “**thermally paired**” **states in multicomponent bosonic systems** resulting from proliferation of composite topological defects (later similar constructions became popular in cold atoms physics). The pairing in these systems of multiple charged bosonic fields occurs as a result of thermal fluctuations (i.e. from heating) and it leads to states where either Onsager superflow quantization becomes fractionalized or **effective superconducting states with doubled electric charge (or in case of N component to superconducting states with 2Ne effective charge)**. Also I discussed the phase transitions into the states were only counter-flows of two electrically charged components are dissipationless. In studying these states we developed a theory of plasma of closed strings which are characterized by certain density of electric charges of several colors and interacting via several colors of electric fields. In particular we studied screening properties of such plasmas of string-like objects. **Other questions studies in this series of papers: Realizations of “supersolid vortex matter”** was shown for certain states of multicomponent superconductors and superfluids. This state is a vortex liquid which nonetheless breaks translation symmetry and where vortices can be mapped onto world-lines of bosons in a supersolid. **A novel vortex sublattice melting transition** has been studied in three dimensional multicomponent vortex matter (with E. Smorgrav, J. Smiseth, A. Sudbo, published in Phys.Rev.Lett. 94 096401 (2005)).

**Type-1.5 superconductivity.** The textbook classification of superconductors, divides them into two classes, according to their behavior in an external field. Type-I superconductors expel low magnetic fields, while elevated fields produce macroscopic normal domains in the interior of the superconductor. Type-II superconductors possess stable vortex excitations which can form a vortex lattice as the energetically preferred state in an applied magnetic field. This picture of type-II superconductivity, as well as the essence of the more complex physics of fluctuating vortex matter, relies on the fact that the interaction between co-directed vortices is purely repulsive. In 2003 I showed that under certain conditions a two-component system, as a consequence of the existence of three fundamental length scales should exhibit a behavior in external field which can be regarded **neither as type I nor as type II** but rather represents a special case arxiv:cond-mat/030221. That is, it was demonstrated that in multicomponent system there can be **thermodynamically stable vortices with intervortex interaction which is attractive at longer range and repulsive at short range** (in contrast to purely repulsive interaction between vortices in single-component superconductors). With J.M. Speight in 2004 we obtained accurate **numerical solutions for these thermodynamically stable vortices with nonmonotonic interaction and for non-axisymmetric “vortex molecules”** (Phys.Rev. B72 180502 (2005)). We have shown that these superconductors can form a new state in external field which we called the “**Semi-Meissner state**” which is a mixture of domains of two-component Meissner state and domains of vortex states. In this phase-separated state the system has *two kinds of normal-to-superconducting states boundaries*: one type of boundary can be identified as the vortex core boundary inside the vortex cluster, the other type of boundary is a boundary between the vortex droplet and the Meissner state. **We have shown that in two-gap and two-band systems one of these boundaries can have negative energy while at the same time another one can have positive energy making this state fall outside the usual type-I/type-II dichotomy.** In 2009 there appeared two experimental works by Moshchalkov et al who claimed the first observation of this new kind of superconducting state in ultra clean samples of two-band superconductor MgB<sub>2</sub>. Moshchalkov termed this state “**type-1.5 superconductivity**” in Phys. Rev. Lett. 102, 117001 (2009). See also <http://sciencenow.sciencemag.org/cgi/content/full/2009/313/1>. In 2009 with Carlstrom and Speight (Phys. Rev. Lett. 105, 067003 (2010)) we found that type-1.5 superconductivity can be a more generic phenomenon in multiband systems, than what was initially thought by demonstrating that **long-range intervortex attraction does not require full-fledged superconductivity in two bands but can be caused by interband proximity effect which is a rather generic effect in two-band superconductors**. In 2010 with Carlstrom and Speight we wrote an extensive study on appearance of type-1.5 superconductivity in the presence of various substantially strong interband couplings. We found that interband impurity scattering process in fact can promote type-1.5 regime via a mechanism which formal aspects are closely related to “Seesaw mechanism” in neutrino physics (arXiv:1009.2196).

**Non-Meissner electrodynamics in multicomponent superconductors.** In 2001 work (with L.D. Faddeev and A. J. Niemi published in Phys. Rev. B65, 100512(R) (2002)) and in my further work on the subject (Phys. Rev. B 79, 104506 (2009)) it was shown that at some length scale two-component superconductors are described by a special version of a Skyrme-Faddeev model. That is, we discussed that the electrodynamics of the multicomponent system is not described only by a massive vector field (as in the Meissner-Higgs effect) but at a certain length scale the fluctuating gauge field generates a Skyrme-like term which in some cases dominate physical responses. An exact equivalence was proven between the two-flavour Ginzburg-Landau model and a version of the Skyrme-Faddeev model in certain regimes. This work introduced a type of topological excitation in condensed matter physics: **the knotted solitons**. The existence of these defects should have important physical consequences. In a physical situation where there is a superflow locally in space this flow should satisfy the single-valuedness condition of the condensate wave function. Thus it can be created by exciting vortex loops with quantized superfluid velocity circulation, or magnetic flux. Consequently, many key properties of quantum fluids depend dramatically on properties of the vortex loops. In presently known and well investigated superfluids and superconductors the main characteristic which vortex loops have in common is the fact that their energies depend monotonically on the loop sizes. Indeed, this fact is very important for the physics of how a quantum fluid restores symmetry (via entropy driven proliferation of vortex loops), reacts to a quench (via a relaxation of a quench induced vortex loops), for the physics of superfluid turbulence, etc. All these properties would be quite dramatically altered if some quantum fluid would allow vortex loops with *nonmonotonic energy dependence on the loop size* (i.e. if the energy of the vortex loop would grow not only if the vortex loop expands but also if it shrinks below a certain characteristic size). In these cases quench-induced defects would be protected from decay and simple reconnections by potential barriers resulting in large-scale remnant post-quench vorticity. It may also produce hysteretic behavior in entropy generated topological defects and thus change the order of the superconducting phase transitions etc. In my paper in Phys Rev B in 2008 I demonstrated that at least a class of Ginzburg-Landau models indeed possesses knotted solitons which energy is a nonmonotonic function of the defect size. The theoretical framework of our first work on the topic with Faddeev and Niemi turned out to be useful in different contexts beyond the condensed matter, presently that paper has accumulated many citations from different branches of physics (besides condensed matter also high-energy, nuclear, atomic and mathematical physics). In 2002 I have shown that similar situation arise under certain conditions in certain models of spin-triplet superconductors (published in Phys. Rev. Lett. 88 17702 (2002) PRL). In 2003 I found that because of the Andreev-Bashkin effect which is strong in dense nuclear matter, an effective Faddeev-Skyrme model describes at certain length scale the physics of the condensate in neutron stars (published in Phys.Rev. D70, 043001 (2004)).

In Phys.Rev.Lett. 94 137001 (2005) I discussed **a theoretical possibility of a new state: “spin-superfluidity” without superconductivity in spin-triplet superconductors** (which is a state featuring dissipationless spin-currents when all charge currents are dissipative).

I am also interested in the physics of interacting multicomponent Bose-Einstein condensates. In this field we studied phase transitions associated with **proliferation of a gas of several types competing topological defects in multicomponent Bose-Einstein condensates** with dissipationless drag interactions (with E. Dahl, S. Kragset and A. Sudbo Phys. Rev. B 77, 144519 (2008)) where we introduced a notion of a “preemptive” vortex loops proliferation transition where discontinuous proliferation transition leading to a restoration of symmetry in some sector of the model is triggered by a change of topological defects background in a different sector of the model, which is quite different physical picture compared to what is encountered in one-component Kosterlitz-Thouless and vortex loops proliferation theories. Further we described properties of these systems under rotation Phys. Rev. B78, 144510 (2008), introducing the notion of **“hidden vortex lattice” (momentum-bearing highly disordered vortex tangle which breaks translation symmetry only in statistical sense)**. Such a vortex state is in a way antipodal to vortex liquids in superconductors where a vortex liquid usually bears short-range lattice order well above melting point. Next we studied the rotational response of a system with negative intercomponent drag describing in particular a

**modulated vortex liquid state** there Phys. Rev. Lett. 101, 255301 (2008). These results should be useful for experimentally studying the phase transitions in interacting BEC mixtures into paired and super-counter-fluid states via rotational response.

In Phys. Rev. B 77, 054512 (2008) **I showed that excitonic condensates in bilayered semiconductors can be described by an effective model which has a planar electrodynamics with effective “magnetic charges”**. I also found new solutions for vortices in these systems. I pointed out a generalization of this concept and introduced the notion of **“multicolor” dipolar superfluidity** for multilayer systems. Furthermore I described **a mapping of a vortex liquid state in layered superconductors to the ostensibly unrelated problem of a dipolar excitonic condensate**.

**Dynamics of neutron stars.** In 2003 the usual neutron star interior model (that is, a mixture of strongly interacting hadronic superfluids) was cast in doubt because it was argued by B. Link, that in its framework a strong interaction between superfluid and magnetic field carrying components (as comes from microscopic calculations of dense nuclear matter) could not be constrained with the long-period precession found in a very few pulsars. **I pointed out a new effect which, at the hydrodynamic level, in a narrow range of parameters, can lead to a giant (several orders of magnitude) reduction of coupling between the superfluid and magnetic-field carrying components of hadronic condensates.** As a result the interaction energy may fall below the temperature scale in some region of a neutron star’s interior leading to effective decoupling of the hadronic components which may offer an explanation of the effect of long-period precession found in some pulsars (Phys. Rev. Lett. 103, 231101 (2009)).

**The chiral phase transition:** The well known model for chiral symmetry breakdown in QCD, the Nambu-Jona-Lasinio (NJL) model (for which the Nobel Prize was awarded in 2008), has been formulated by Nambu and Jona-Lasinio in analogy with the BCS theory of superconductivity. During the last years of my undergraduate studies and first years of my graduate studies I was wondering if the popular in Condensed Matter (but then essentially unknown in the High Energy Physics) concept of the BCS-BEC crossover and the pseudogap state could have a counterpart in particle physics. That is, a model of generation of constituent quark mass was proposed in analogy with BCS phase transition in Condensed Matter. However the BCS scenario indeed holds only when mean-field approximation is accurate (small ratio of the binding and Fermi energies). When this condition does not hold, the Cooper pair formation temperature does not coincide with Cooper pair condensation transition resulting in a pseudogap phase. In my last years of undergraduate studies and first years of graduate studies I speculated about the scenario of the generation of quark mass via a pseudogap-like mechanism in Gross-Neveu and finite temperature Nambu-Jona-Lasinio-like models at low  $N$  (where mean-field scenario may not be accurate) and a possibility of a new phase in these models sandwiched between hadron matter and quark-gluon plasma which would feature quarks with nonzero constituent mass in a state with restored chiral symmetry in analogy with noncondensed states of pre-formed Cooper pairs (hep-th/9909052 Int. J. Mod. Phys. A16 1175 (2001)). To substantiate these speculations I considered low-dimensional models and **demonstrated the existence of the pseudogap phase in four-fermion “toy models” of chiral symmetry breakdown (low-dimensional versions of the Chiral Gross-Neveu model and Nambu-Jona-Lasinio model)** (Phys. Lett. B497 323 (2001), Phys.Lett. B438, 311 (1998)). These results were subsequently confirmed in large-scale numerical simulations performed at the University of Illinois at Urbana-Champaign and at the Swansea University [S. Hands, J. Kogut, C.Strouthos Phys. Lett. B 515 407 (2001), Phys.Rev. D 65 (2002) 114507, Phys. Rev. D **67**, 034505 (2003)]. Along these lines I also was first to voice the relevance of the pseudogap concept for color superconductivity at moderate densities which has received recently a more substantial theoretical backing.

**Other questions in the theory of superconductivity and superfluidity.** With Steinar Kragset and Asle Sudbo we investigated **states of vortex matter arising in finite and inhomogeneous situations relevant for trapped dilute Bose Condensates** (published in Phys. Rev. A 77, 043605 (2008); Phys. Rev. Lett. 97, 170403 (2006)).

## PUBLICATIONS

1. Egor Babaev, Johan Carlstrom, Martin Speight  
Type-1.5 superconductivity in multiband systems: the effects of interband couplings  
arXiv:1009.2196  
submitted to Phys. Rev. B
2. Egil V. Herland, Egor Babaev, Asle Sudbo  
Phase transitions in a three dimensional  $U(1) \times U(1)$  lattice London superconductor. Metallic superfluid and charge-4e states  
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3. Egor Babaev, Johan Carlstrom, Martin Speight  
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4. Egor Babaev, Johan Carlstrom  
*Type-1.5 superconductivity in two-band systems*  
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5. Egor Babaev  
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7. E. K. Dahl, E. Babaev, A. Sudbo  
*Unusual states of vortex matter in mixtures of Bose-Einstein Condensates on rotating optical lattices*  
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*Hidden vortex lattices in a thermally paired superfluid*  
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10. E. Dahl, E. Babaev, S. Kragset, A. Sudbo  
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13. Egor Babaev  
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23. Egor Babaev  
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24. Egor Babaev  
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*Vortices carrying an arbitrary fraction of magnetic flux quantum in two-gap superconductors*  
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#### **NON-REFEREED PUBLICATIONS**

39. Egor Babaev

*Neither a type-I nor a type-II superconductivity in a two-gap system*

(merged with the mentioned above joint paper with J.M. Speight)

cond-mat/0302218

40. Egor Babaev

*Aspects of topology of condensates and knotted solitons in condensed matter systems*

(merged with the mentioned above joint paper with L.D. Faddeev and A. Niemi)

arXiv:cond-mat/0009438