**Annex 1.**

***Form of opening (renewal) for Theme /***

***Large Research Infrastructure Project***

 **APPROVED**

 **JINR Vice-Director**

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**THEME PROPOSAL FORM**

**Opening/renewal of a theme/large research infrastructure project within the Topical plan of JINR**

**1. General information on the theme / large research infrastructure project (hereinafter LRIP)**

**1.1. Theme code: 01-3-1138-2019**

**1.2. Laboratory:** **Bogoliubov Laboratory of Theoretical Physics**

**1.3. Scientific field: Theoretical Physics**

**1.4.** **The title of the Theme: Modern Mathematical Physics: Integrability, Gravity and Supersymmetry**

**1.5. Theme Leader(s) : Isaev A.P., Krivonos S.O.**

**2. Scientific case and theme organization**

**2.1. Annotation**

Development of mathematical methods for solving the most important problems of modern theoretical physics, namely, the development of new mathematical methods for studying and describing a wide class of classical and quantum integrable systems and their exact solutions, analyzing and searching for solutions to a wide range of problems of supersymmetric theories, including models of strings and other extended objects; study of nonperturbative regimes in supersymmetric gauge theories, development of cosmological models of the early Universe, gravitational waves and black holes.

Mathematical physics in recent years has been characterized by a growing interest in revealing and effectively using the properties of integrability in its various fields, in applying powerful mathematical methods of quantum groups, supersymmetry, and noncommutative geometry both in quantum theories of fundamental interactions and in classical models. When solving the problems of the project «Integrable systems and Symmetries», the decisive factor will be the use of these methods.

The project «Supersymmetry, Higher Spins, Gravity» in the theme is devoted to the construction of new theories with extended supersymmetry and gauge invariance in various dimensions, the study of their quantum structure and classical solutions of the soliton type with cosmological applications. The main efforts will be concentrated on the construction of new supersymmetric gauge theories, including higher spins and the development of new approaches and methods for studying their quantum structure. The projects involve the solutions of a large number of actual problems which are posed by the modern development of the supersymmetric field theory and superstring/brane theory.

Within the project «Quantum Gravity, Cosmology and Strings» of the present theme it is planned to solve the fundamental problems of classical and quantum gravity and conducting advanced theoretical research at the national and world level in this area at BLTP JINR. In classical gravity, the project is focused on studying all kinds of gravitational wave phenomena, including shock waves in General Relativity, as well as various sources of gravitational wave background, such as cosmic strings. One of the directions of the researches is the elaboration of cosmological models that explain the properties of the observable Universe based on field theory methods and modified gravity. In the field of quantum gravity, it is planned to develop the apparatus of quantum field theory in an external classical gravitational background and new methods for an approximate estimation of the effective gravitational action in various regimes. Asymptotic symmetries in gravity, the relationship between gravity, thermodynamics and quantum entanglement, the holographic properties of gravity, and the AdS/CFT correspondence will also be explored.

**2.2. Projects in the Theme / LRIP subprojects**

1. **Integrable Systems and Symmetries**

Leaders: **Tyurin N.A., Isaev A.P., Krivonos S.O**.

1. **Supersymmetry, Higher Spins, Gravity**

Leader: **Ivanov E.A**.

Deputy leader : **Fedoruk S.A.**

1. **Quantum Gravity, Cosmology and Strings**

**Leaders: Pirozhenko I.G., Fursaev D.V.**

**2.3. Scientific case**

**Integrable Systems and Symmetries**

Symmetries play a central role in modern mathematical physics. In classical domain, they are indispenable for constructing explicit solutions to equations of motion. Celebrated applications vary from the Kepler problem to the geodesic motion in black hole spacetime [B. Carter, Phys. Rev. 174 (1968) 1559]]. In quantum theory, they facilitate the construction of eigenstates of the Hamiltonian by purely algebraic means, the Calogero model [F. Calogero, J. Math. Phys. 12 (1971) 419] being a classical example.

A system is called integrable if it possesses as many integrals of motion as the number of degrees of freedom. If there are extra integrals over and above those, it is called superintegrable. Extensive studies of models with abundant symmetries over the last forty years paved the way for a separate ramification of modern mathematical physics entitled Integrable systems.

The A(n) Calogero Hamiltonian [2], describing one-dimensional particles with inverse-square

pairwise interactions, plays a significant role in mathematical and theoretical physics. Being the

prime example of an integrable and solvable many-body system, it appears in many areas of modern mathematical physics, from high-energy to condensed-matter physics (see, e.g., the review [A. Polychronakos, J. Phys. A 39 (2006) 12793]). An intriguing hypothesis suggests that the large-n limit of the n-particle N=4 superconformal rational Calogero model provides a microscopic description of the extremal Reissner-Nordstrom black hole in the near-horizon limit [G. Gibbons, P. Townsend, Phys. Lett. B 454 (1999) 187]. Since then, the task of constructing an (at least) N=4 supersymmetric n-particle rational Calogero model has been the subject of a number of papers [A. Galajinsky, O. Lechtenfeld, K. Polovnikov, JHEP 0711 (2007) 008; S. Bellucci, S. Krivonos, A. Sutulin, Nucl. Phys. B 805 (2008) 24; S. Fedoruk, E. Ivanov, O. Lechtenfeld, Phys. Rev. D 79 (2009) 105015; S. Krivonos, O. Lechtenfeld, JHEP 1102 (2012) 042], however with only partial success. Despite the simplicity of the Calogero Hamiltonian, all attempts to find an N=4 supersymmetric version beyond the four particle case were unsuccessful. In contrast, the N=2 supersymmetric Calogero model was found many years ago [D.Z. Freedman, P.F. Mende, Nucl. Phys. B 344 (1990) 317].

It seems that a guiding principle was missing for the construction of extended supersymmetric Calogero models. Indeed, while for n ≤ 3 translation and (super-)conformal symmetry almost completely define the system, the n ≥ 4 cases admit a lot of freedom which cannot a priori be fixed. In the bosonic case, such a guiding principle exists [D. Kazhdan, B. Konstant, A. Sternberg, Comm. Pure Appl. Math. 31 (1978) 48124]. The Calogero model as well as its different extensions (see, e.g. [S. Wojciechowski, Phys. Lett. A 111 (1985) 101, J. Gibbons, T. Hermsen, Physica D 11 (1984) 337, J. Arnlind, M. Bordemann, J. Hoppe, C. Lee, Lett. Math. Phys. 84 (2008) 89]]) are closely related with matrix models and can be obtained from them by a reduction procedure (see [A. Polychronakos, Phys. Lett. B 266 (1991) 29].

If we want to employ this principle also for finding extended supersymmetric Calogero models, then the two main steps are

• supersymmetrization of the matrix model

• supersymmetrization of the reduction procedure or proper gauge fixing.

This idea was employed in [S. Fedoruk, E. Ivanov, O. Lechtenfeld, Phys. Rev. D 79 (2009) 105015, S. Fedoruk, E. Ivanov, O. Lechtenfeld, Phys. Atom. Nucl. 74 (2011) 870; S. Fedoruk, E. Ivanov, JHEP 1611 (2016) 103]. The resulting supersymmetric systems feature

• a large number of fermions – far more than 4n fermions expected in an N=4 nparticle system within the standard (but unsuccessful!) approach,

• a rather complicated structure of the supercharges and the Hamiltonian with fermionic polynomials of maximal degree,

• a variety of bosonic potentials, including su(2) spin-Calogero interactions, but they do not contain the genuine N=4 supersymmetric Calogero model, i.e. one with a mere pairwise inverse-square no-spin bosonic potential.

A common property of all these models is that starting from a supersymmetrization of the Hermitian matrix model, the resulting matrix fermionic degrees of freedom are packaged in N=4 superfields. Within the framework of this approach, systems with various bosonic potentials were obtained, including systems with Calogero su (2) spin interactions. However, the constructed systems do not contain a genuine N = 4 supersymmetric Calogero model, that is, a model with a pairwise inverse-square spinless bosonic potential.

Within the framework of this project, we plan to build N-extended supersymmetric Calogero models with the standard form of supercharges, that is, cubic in fermions.

As is well known, the Calogero model can be understood as the non-relativistic limit of the

Ruijsenaars-Schneider integrable system [S. Ruijsenaars, H. Schneider, Annals Phys. 170 (1986) 370], which is invariant under the Poincare group in 1+1 dimensions. Despite permanent interest in the Ruijsenaars-Schneider models over the last few decades, its supersymmetric extensions remain almost completely unexplored. Recently, the N=2 supersymmetric extensions for the rational and two hyperbolic variants of the 3-body Ruijsenaars - Schneider model were built. Within this project, we plan to continue this study and consider the possibility of constructing N=2 and N=4 supersymmetric extensions of the Ruijsenaars - Schneider model for an arbitrary number of identical particles. It is also planned to study the nonrelativistic limit and establish the correspondence with the known supersymmetric extensions of the Calogero model.

Among various symmetry transformations, which are of use in mathematical physics, conformal groups enjoy a distinguished status. In two dimensions, conformal algebra is infinite dimensional and underlies superstring/M-theory . Conformal symmetry plays a key role in the description of critical phenomena in statistical mechanics. It is central to the gauge/gravity duality, which links conformal field theory to string theory on an anti de Sitter background . The near-horizon geometry of an extremally rotating black hole exhibits a conformal isometry, which paves the way for the Kerr/CFT-correspondence . These examples may suffice to convince oneself that conformal symmetry is ubiquitous in contemporary mathematical physics. One of the principal objective of this project is to systematically study integrable systems which enjoy conformal invariance.

Recently, there has been a surge of interest in SL(2,R)-invariant higher-derivative dynamical systems. In particular, such systems naturally arise in the low-energy limit of the so-called Sachdev-Ye-Kitaev model — an exactly solvable quantum system that exhibits maximally chaotic behavior (see, e.g., [T.G. Mertens, G.J. Turiaci, H.L. Verlinde JHEP1708(2017) 136;H.T. Lam, T.G. Mertens, G.J. Turiaci, H. Verlinde, JHEP 1811 (2018) 182]). The models are described in terms of the Schwarzian derivative [A. Cayley, Tans. Camb. Phil. Soc. 13 (1881) 5; V. Ovsienko, S. Tabachnikov, Notices of the AMS 56 (2009) 34] and are commonly referred to as the Schwarzian mechanics. Supersymmetric extensions of Schwarzian mechanics remain almost completely unexplored. Within this project we plan to systematically study N=2 and N=4 supersymmetric extensions of Schwarzian mechanics.

Thematically, the project belongs to the field of high energy physics, considered in the context of holographic duality. This is a dynamically developing field in which unsolved problems of a fundamental nature are considered, causing the ongoing interest of physicists and mathematicians. It should also be noted that the relevance and rapid development of the chosen topic implies a certain possibility of modifying the specifics of the initially set tasks in the process of their implementation within the project, but not their nature.

This part of the project is aimed at studying the properties of important integrable structures found in various holographic systems. Of fundamental importance here is the principle of holographic correspondence, which makes it possible to realize a non-trivial dualism between gravitational and gauge theories in different dimensions and with different communication modes. The latter significantly expands the possibilities of studying complex models with interesting effects.

The principle of holography [J. M. Maldacena, Adv. Theor. Math. Phys.2, 231 (1998) [Int. J. Theor. Phys.38, 1113 (1999)] [arXiv:hep-th/9711200]; S. S. Gubser, I. R. Klebanov and A. M. Polyakov, Phys. Lett. B428, 105 (1998) [arXiv:hep-th/9802109]; E. Witten,Adv. Theor. Math. Phys.2, 253 (1998) [arXiv:hep-th/9802150]] allows for a correspondence between the gravitational theory in a space with a certain number of dimensions and the quantum field theory living on the boundary of this space. The advantage of holographic duality is its ability to connect different modes of interaction in two theories. In this sense, calculations in the weak-coupling mode of one of the theories can be transferred to the strong-coupling mode of another theory. The study of the properties of this duality turns out to be an extremely non-trivial task, requiring the use of a number of different methods and techniques. In this regard, one of the most effective ways to study holographic systems is integrability. Powerful methods developed in the framework of integrable systems can be directly applied to the study of holographic dual theories. The presence of integrable structures in these models leads to nontrivial tests of the holographic principle [I. Bena, J. Polchinski and R. Roiban, Phys. Rev. D69, 046002 (2004) [arXiv:hep-th/0305116]; D. Berenstein, J. Maldacena and H. Nastase, JHEP0204(2002) 013; hep-th/0202021; S. S. Gubser, I. R. Klebanov, A. M. Polyakov, Nucl.Phys. B636(2002) 99-114,hep-th/0204051; J. A. Minahan and K. Zarembo, JHEP0303, 013 (2003) [arXiv:hep-th/0212208] and opens up new interesting horizons in high-energy and condensed matter physics .

One of the innovative nonperturbative approaches used to analyze the properties of integrable systems is the method of isomonodromic deformations. In the framework of this approach, we seek to translate the initially arising boundary value problem of linear differential equations of motion, which describes the models of interest, into the original problem for nonlinear equations of the Painlevé type. At first glance, the price to be paid is the replacement of simpler linear equations with more complex non-linear ones, but thanks to progress in understanding the properties of the Painlevé equations, the latter can give very non-trivial results. The search for a connection between linear differential equations and integrable nonlinear equations is not a new problem and goes back to the classical works of Fuchs, Garnier and Schlesinger. In the 1980s, this research was enriched by the pioneering work of Jimbo, Miwa, and Ueno, who brought the topic into the modern context of integrable systems. Moreover, these authors find a close connection between the nonlinear Painlevé equations and isomonodromic transformations of the linear Fuchs equations. Another breakthrough in the theory of isomonodromic deformations of linear systems was made by Kitaev, Itz, and Novokshonov, who studied the asymptotic properties of solutions to the Painlevé equations. These and other similar developments in the theory of linear and nonlinear ordinary differential equations quickly find practical application in various fields of physics, such as: conformal field theories, the theory of random matrix models, supersymmetric theories, integrable systems, black holes and others.

The approaches used to analyze such systems are mainly based on the well-established methods of group theory, algebra, differential geometry, and integrable systems. The presence of integrable structures in some models leads to a nontrivial verification of the holographic principle and opens up new horizons in high energy physics. In this case, the most common equations describing the properties of the models under consideration are the Fuchs equations, the theory of which is well developed and can be directly applied to the analysis of the systems under study. On the other hand, various algebraic and differential transformations, such as the Möbius transformation, the Schwartz derivative (Schwarzian), the Schwartz-Christoffel transformation, and others that encode non-trivial information about the nature of these models, are a powerful tool for studying integrable models. The appearance of these structures in complex systems facilitates their analytical processing and often leads to the discovery of new interesting relationships between seemingly different objects.

The investigations being carried out are related to theories containing fields with higher spins. Such theories are associated with the expansion of gravitational models that can be leading in the future to the possibility of describing quantum gravity. General problem is related to unitary irreducible representations of multidimensional Poincare groups and symmetry groups of AdS (anti-de Sitter) spaces. According to Wigner, each unitary irreducible representation of the four-dimensional Poincare group is associated with an elementary particle (field). This conception is generalized to the case of arbitrary dimension and to the case of groups other than the Poincaré group (including supergroups). Therefore, when studying various field models, the first question is the classification and explicit construction of unitary irreducible representations of the symmetry group of the desired theory.

The project will be devoted to some explicit constructions of representations of the Poincaré groups and symmetry groups of AdS spaces. The general classification of unitary irreducible representations of ISO(1,D-1) (Poincare groups in D-dimensional spacetime) is well known, but constructing the corresponding fields explicitly involves various difficulties. First, starting from the dimension D>4, there appear unitary irreducible representations of the so-called mixed type of symmetry (parametrized by Young diagrams), whose covariant form (in terms of tensor fields) is known only for some classes of Young diagrams. To solve this problem, there are several different approaches, for example, in the work [A.P. Isaev, and M.A.Podoinitsyn. "D-dimensional spin projection operators for arbitrary type of symmetry via Brauer algebra idempotents." Journal of Physics A: Mathematical and Theoretical 53.39 (2020): 395202] this problem was reduced to the Brauer algebra formalism. Secondly, using the Wigner scheme (constructing unitary irreducible representations of the Poincaré groups as induced from the representations of the test momentum stability subgroup), we obtain a non-covariant construction – the Wigner wave function. The Wigner generalized operator method can be applied to construct the corresponding local relativistic field from the Wigner wave function. In a dimension equal to four, this method was applied to massive representations in the work [A.P. Isaev and M.A.Podoinitsyn. "Two-spinor description of massive particles and relativistic spin projection operators." Nuclear Physics B 929 (2018): 452-484)], for representations with continuous (infinite) spin in [I.Buchbinder, A, Isaev, M, Podoinitsyn, S. Fedoruk, "Generalization of Bargman - Wigner construction for description of infinite spin fields" (2023), in print in Theor. Mat. Fiz] and for massless representations in work [I. Buchbinder, A. Isaev, M. Podoinitsyn, S. Fedoruk, "Generalized Wigner operators and relativistic gauge fields" (2023) in press in PEPAN Letters]. This method sometimes makes it possible to automatically find the equations of motion for relativistic fields. It is very attractive from the point of view of constructing the corresponding Lagrangian theory.

The symmetry group of a D-dimensional anti-de Sitter space is the SO(D-1,2) group. The classification of its unitary irreducible representations is known and in general they are characterized by two parameters (E,Y) , where E is a real number and Y is the Young diagram associated with the representation of the SO(D-1) group. When studying these representations, the conception of the so-called unitarity bound arises. This is a restriction on the parameter E, which, for the representation to be unitary, must be greater than or equal to some number associated with the diagram Y. It is also known that for a given representation (E,Y) this number coincides with the conformal dimension of the conserved current. It is some representation (which corresponds to a Y-type diagram) of the conformal group of the (D-1)-dimensional Minkowski space. Note that when E is equal to the corresponding conformal dimension of the conserved current, representations arise that are associated with gauge fields in AdS. Here, the explicit constructions of fields in AdS in various dimensions are also of interest, especially in connection with studies within the framework of the AdS/CFT correspondence or its variant, the so-called higher-spin holography .

Using the Brauer algebra formalism, it is planned to find explicit constructions of relativistic fields of mixed symmetry type corresponding to the most general Young diagrams. Also, within the project it is planned to study the connection between covariant SO(D-1,2)-tensors (found as idempotents of the Brauer algebra, taken in the corresponding representation) with unitary irreducible representations of the symmetry group of AdS spaces. Further with the help of the generalized Wigner operator, representations of Poincaré groups in the dimension D>4 will be studied. For example, for the dimension D=6 in the work [I.L. Buchbinder, S.A. Fedoruk, A.P. Isaev, M.A. Podoinitsyn. "Massless finite and infinite spin representations of Poincaré group in six dimensions." Physics Letters B 813 (2021): 136064] a detailed classification of massless representations with finite helicity and representations with continuous (infinite) spin was described. The results of this work can be used to find the explicit construction of the corresponding relativistic fields by the method of the generalized Wigner operator.

**Supersymmetry, higher spins, gravity**

The project is aimed at solving fundamental problems of modern theoretical physics associated with the development of superfield methods in gauge theories with extended supersymmetry in various dimensions, including extended supersymmetric mechanics. The implementation of the project includes the construction of new field and quantum-mechanical models with global and gauge symmetries, the development of new, including geometric, methods for studying the structure of such models at the classical and quantum levels, the study of the structure of the corresponding quantum effective actions and classical solutions of these models, including black holes. All tasks of the project are set by the modern development of theoretical physics and are organically joined by the unity of methods and approaches.

One of the leading trends in the development of modern theoretical physics is the development of new approaches to the problem of constructing unified theory of all fundamental interactions, including the description of gravity at the quantum level. A natural ingredient of all such approaches is supersymmetry.

Supersymmetric gauge theories in various dimensions have remarkable properties at the classical and quantum levels. Such theories are closely related to the low-energy limit of superstring theory or M-theory (see, for example, the reviews [A. Giveon, D. Kutasov, Rev. Mod. Phys, 71 (1999) 983]; [O. Aharony et al., Phys. Repts., 323 (2000) 183] [C. Becker, M. Becker, J. H. Schwartz, String Theory and M-Theory, Cambridge Univ. Press, 2007] [J. Bagger, N. Lambert, C., Mukhi and C. Papageorgakis, Phys. Rept., 527 (2013) 1] and references therein). This circumstance opens up the possibility of studying low-energy superstring quantum effects using quantum field theory methods. More precisely, low-energy effective actions due to D- or M-brane interactions can be found within supersymmetric gauge quantum field theory in terms of low-energy quantum effective action. The study of the quantum structure of supersymmetric gauge theories in higher dimensions was carried out by various authors using different methods and approaches (see, for example, [E.S. Fradkin, A.A. Tseytlin, Nucl. Phys. B 227 (1983) 252]; [P.S. Howe, K.S. Stelle, Phys Lett. B137 (1984) 175; Phys. Lett. B554 (2003) 190] [G. Bossard, P. S. Howe, K. S. Stelle, Gen. Rel. Grav. 41 (2009) 919; Phys. Lett. B 682 (2009) 137]; [L.V. Bork, D.I. Kazakov, M.V. Kompaniets, D.M. Tolkachev, D.E. Vlasenko, JHEP, 1511 (2015) 059] and references there). Of particular interest in theories with extended supersymmetry in higher dimensions is the problem of ultraviolet divergences. On the one hand, since the gauge coupling constant in such theories is dimensional, it is natural to expect that the theories under consideration are non-renormalizable in power counting. On the other hand, extended supersymmetry can somewhat improve the ultraviolet behavior of the effective action. Indeed, in the above papers, arguments were given that, for example, in the six-dimensional maximally extended globally symmetric gauge theory, the on-shell effective action in the sector of the gauge field turns out to be finite in one- and two-loop approximations. The problem of describing the off-shell structure of effective action in such a theory remained open for a long time.

In recent works of this project participants [I.L. Buchbinder, E.A. Ivanov, B.S. Merzlikin, K.V. Stepanyantz, Phys. Lett. B 820 (2021) 136516; JHEP 08(2020) 169; Nucl. Phys. B 961 (2020) 115249; Phys. Lett. B 798 (2019) 134957; Phys. Lett. B 763 (2016) 375; Phys. Lett. B 778 (2018) 252; Nucl. Phys. B 936 (2018) 638], a new, completely off-shell approach was developed to study the structure of the effective action in the maximally extended global supersymmetric Yang-Mills theory. It is known that in six dimensions the simplest representations of a superalgebra are N=(1,0) and N=(0,1) supersymmetries. From this point of view, the maximally extended global supergauge theory has N=(1,1)=(1,0)+(0,1) supersymmetry and corresponds to the interacting N=(1,0) gauge multiplet and hypermultiplet. The considered N=(1,1) supersymmetric theory can be formulated in 6D, N=(1,0) harmonic superspace, where N=(1,0) supersymmetry is manifest, the second N=(0,1) remains hidden.

The theory of higher spin fields is one of the actively developing areas of modern theoretical and mathematical. We point out only the direction associated with the Lagrangian formulation of higher-spin gauge superfields. In the case of D4, N=1 supersymmetry, such an approach was developed by S.M. Kuzenko and collaborators in terms of N=1 superspace and then developed by many authors. In particular, examples of theories with N=2 supersymmetry have been constructed in terms of N=1 superfields. The general formulation of the theory of higher spin fields with manifest N=2 supersymmetry remained an open problem for a long time. Progress in this direction has been made in the recent works of this project participants [I. Buchbinder, E. Ivanov, N. Zaigraev, JHEP, 12 (2021) 016, 27; 05 (2022) 104; 03 (2023) 036], where, using the methods of harmonic superspace, a manifest N=2 supersymmetric Lagrangian description of free N=2 supergauge higher spin fields was presented and a cubic vertex of their interaction with a hypermultiplet was found . The works mentioned above open up opportunities for posing a large number of new problems and finding methods for solving them. It is planned to consider these problems within the framework of this project.

Quantum aspects of the higher spin field theory have been little studied. In the context of this project, we note the works [X. Bekaert, E. Joung, J. Mourad, JHEP, 1102 (2011) 048; L. Bonora, M. Cvitan, P. Dominis Prester, S. Giaccari, M. Stemberga, JHEP, 12 (2016) 084; 03 (2018) 80; Eur. Phys. J. C 79 (2019) 258; HS flat spacetime. YM-like models, arXiv:1812.05030] related to the construction of the induced quantum effective action in the theory of scalar and spinor fields in an external highe spin field gauge fields. The study of such issues in the theories of higher spin fields with explicit N=2 supersymmetry has never been carried out. Within the framework of this project, it is planned to calculate the induced effective action in the theory of a hypermultiplet in an external N=2 higher spin supergauge fields. The corresponding classical theory was developd in the works of the project participants (see above).

Recently, there has been an increased interest in the study of particles and fields associated with various representations of physical symmetry groups, in particular, with infinite (continuous) spin representations of the Poincaré group. An interest in such unitary representations is caused by the similarity of the spectrum of states in the infinite spin theory with the spectra in the higher spin theory, as well as by the potential relationship of this theory to string theory, the main candidate for the quantum theory of gravity. Various problems related to the quantum-mechanical and field description of such states have been considered in a number of works devoted to particles and fields of infinite spin (see, for example, the review [X. Bekaert, E.D. Skvortsov, Int. J. Mod. Phys. A32 (2017) 1730019] and links there). In recent papers [I.L. Buchbinder, S. Fedoruk, A.P. Isaev, A. Rusnak, JHEP 1807 (2018) 031; I.L. Buchbinder, S. Fedoruk, A.P. Isaev, Nucl. Phys. B945 (2019) 114660] the participants of this project have developed a new approach to the description of particles and fields of infinite spin. The proposed formulation is based on a generalization of the twistor formulation of the standard (with fixed helicity) massless particle to the case of infinite spin massless representations. After quantizing the proposed twistor model, infinite spin twistor fields were obtained, which have expansions into infinite sum of states with all fixed helicities. It was shown that this D=4 twistor model reproduces the D=4 Wigner-Bargmann space-time formulation with an additional spin four-vector coordinate, as well as the space-time formulation of the infinite integer spin fields with an additional even spinor coordinate [I.L. Buchbinder, V.A. Krykhtin, H. Takata, Phys. Lett. B785 (2018) 315]. In addition, using twistor field transformation, the authors of the project obtained a space-time - spinor formulation of infinite spin fields with half-integer helicities. This formulation allows us to construct the infinite spin supermultiplet and to describe its properties. It should be noted that the aspects of infinite spin supersymmetry have practically not been considered earlier in the literature. In subsequent works, using BRST methods, the project participants constructed actions for gauge fields describing states of an infinite spin with integer and half-integer helicities [I.L. Buchbinder, V.A. Krykhtin, H. Takata, Phys. Lett. B785 (2018) 315; I.L. Buchbinder, S. Fedoruk, A.P. Isaev, V.A. Krykhtin, Nucl. Phys. B958 (2020) 115114]. In recent papers [I.L. Buchbinder, S. Fedoruk, A.P. Isaev, Nucl. Phys. 973 (2021) 115576, Eur.Phys.J. C82 (2022) 733] twistor formulation of the 6D infinite spin particle and its the field light-cone description are constructed. It should be emphasized here that the twistor methods have found recently very wide application in connection with problems related to the description and calculation of various Feynman diagrams, in particular, the so-called MHV amplitudes and their generalizations.

Supersymmetric field theories in one-dimensional space are important in the study of various versions of superconformal mechanics, an interest in which arose in connection with the AdS/CFT correspondence, since such models describe the motion of (super)particle in the near-horizon (AdS) geometry of black holes as solutions of supergravity in diverse dimensions. Namely, the radial motion of massive charged particle near the horizon of extreme Reissner-Nordström black hole is described by the "relativistic" type of conformal mechanics, which is reduced to the standard conformal mechanics [V. de Alfaro, S. Fubini, G. Furlan, Nuovo Cim. A34 (1976) 569] in the "nonrelativistic" limit. On the other hand, conformal symmetry characterizes an important class of integrable many-particle systems discovered by F. Calogero in his pioneering papers [F. Calogero, J. Math. Phys. 10 (1969) 2191; 10 (1969) 2197]. This close relationship of integrable models with the AdS/CFT correspondence stimulated further work on the study of various models of supersymmetric mechanics, in particular, supersymmetric generalizations of many-particle integrable models and extended superconformal mechanics models.

In the case of N=2 supersymmetry, a supersymmetric extension of the multiparticle rational Calogero system was constructed in [D.Z. Freedman, P.F. Mende, Nucl. Phys. B344 (1990) 317]. But the construction of supersymmetric generalizations with four supersymmetries, as well as with larger number of them, ran into difficult problems (see, for example, [N. Wyllard, J. Math. Phys. 41 (2000) 2826; S. Bellucci, A. Galajinsky, S. Krivonos, Phys. Rev. D68 (2003) 064010; S. Bellucci, A. Galajinsky, E. Latini, Phys. Rev. D71 (2005) 044023]). One of the successful ways to solve this problem was proposed in the works of the project participants [S. Fedoruk, E. Ivanov, O. Lechtenfeld, Phys. Rev. D79 (2009) 105015; JHEP 0908 (2009) 081; JHEP 1004 (2010) 129]. It was shown that such systems arise as a result of superfield gauging of isometries of certain supersymmetric models of matrix mechanics, which also contain semi-dynamical isospin degrees of freedom in addition to dynamical and purely auxiliary degrees.

Based on the Hamiltonian description of N=2 supersymmetric Calogero models associated with the classical *An*, *Bn*, *Cn* and *Dn* series, including both rational and trigonometric/hyperbolic systems, there was found in [A.Sutulin, Proc. Sci, ISSN:1824-8039, Изд:SISSA, 394, 2021; S.Krivonos, O.Lechtenfeld, A.Sutulin, JHEP 05 (2020) 132] their superspace description in terms of the constrained superfields. The constructed N = 2 superfield actions lead at the component level to supersymmetric extensions of the corresponding bosonic Calogero models.

N=4, 1D supersymmetry, as its special feature, involves two different classes of supermultiplets that are "mirror" to each other [E. Ivanov, J. Niederle, Phys. Rev. D 80 (2009) 065027]. They are equivalent and differ only in the mutual replacement of two independent SU(2) of the full automorphism group SO(4) ~ SU(2) x SU(2). On the other hand, multiplets and their mirror counterparts cease to be equivalent after deformation to SU(2|1), 1D supersymmetry [E. Ivanov, S. Sidorov, Class. Quant. Grav. 33 (2016) 055001]. It also turned out to be an important property that some mirror multiplets are described by chiral superfields and, as a result, they can interact with the chiral multiplet (2,4,2) in chiral superspace [S. Sidorov, J. Phys. A 54 (2021) 035205].

Recently we initiated the study of integrable system with Kahler phase space given by noncompact analog of complex projective space [E.Khastyan, A.Nersessian, H.Shmavonyan*,* Int. J.Mod. Phys. A **36** (2021) 08n09 2150055], as well as their supersymmetric extensions whose phase spaces are non-compact analogs of complex projective superspace [E.Khastyan, S.Krivonos, A.Nersessian, Phys.Rev. D **105** (2022) 025007]. In 2024-2028 we plan to continue these studies by considering the integrable systems with other Kahler phase spaces, and to construct their supersymmetric extensions.

Black holes, boson stars and other cosmological objects are at the focus of research activity of many groups. In 2014 a new type of spinning solutions has been founded, it represents spinning hairy black holes continiously linked to the Kerr solution [C Herdeiro and E. Radu, Phys. Rev. Lett. 112 (2014) 221101)]. Such solutions can be considered as a cloud of scalar particles localized in the ergosphere of the black hole. Here the angular velocity of rotation of the event horizon must be synchronized with the internal frequency of the complex scalar field, then there is not fluy of the matter field through the event horizon and the configuration remains stable [C. L. Benone, L. C. B. Crispino, C. Herdeiro and E. Radu, Phys. Rev. D 90 (2014) 10, 104024]. Another generalization of this system represents electrically charged scalar field synchronized with the Kerr-Newman black hole [C. Herdeiro, I. Perapechka, E. Radu and Y. Shnir, JHEP 1902 (2019) 111]. It was also shown that self-interaction of the scalar fields allows for existence of non-linear clouds in the space-time with Kerr geometry. It was shown in 2020 that another type of charged non-linear scalar clouds may exist in the vicinity of the spherically symmetric Reissner-Nordstem black hole [J. P. Hong, M. Suzuki and M. Yamada, Phys. Rev. Lett. 125 (2020) 111104]. Multicomponent systems of boson stars in the Einstein-Klein-Gordon theory have been constructed in 2021 [C.Herdeiro, J.Kunz, I.Perapechka, E.Radu, Ya.Shnir, Phys. Lett. B812 (2021) 136027].

**Quantum Gravity, Cosmology and Strings**

The last decade has become an important stage in the development of fundamentally new experimental methods for studying gravitational phenomena. These include: direct detection of gravitational waves, the creation of a new generation of telescopes in different ranges of the electromagnetic spectrum, in particular, those that allow observing ultra-compact sources (shadows of black holes), instruments for observing a stochastic gravitational background, and studies of the effects of post-Newtonian corrections.

One of the fundamental areas of research is the construction of cosmological models that explain certain properties of the observable Universe based on field theory methods and modified gravity. Simultaneously with the qualitative change in experimental data in the field of gravitational physics, it is necessary to note the emergence of fundamentally new concepts of classical and quantum gravity. Among them are the intriguing connection between gravity, thermodynamics and quantum entanglement, the holographic properties of gravity, and the AdS/CFT correspondence [J. Maldacena, 1998]. The notion of the generalized gravitational entropy, which is the entropy associated with minimal surfaces, emerged in the works by D.V. Fursaev [ D.[V. Fursaev](https://inspirehep.net/authors/1009171), Proof of the holographic formula for entanglement entropy, *JHEP* 09 (2006) 018, e-Print: hep-th/0606184 [hep-th]; D.[V. Fursaev](https://inspirehep.net/authors/1009171), Entanglement entropy in quantum gravity and the Plateau groblem Phys.Rev. D 77 (2008) 124002, e-Print: [0711.1221](https://arxiv.org/abs/0711.1221) [hep-th]], and later by Maldacena and Levkovich [A. Lewkowycz, J. Maldacena, JHEP 08 (2013) 090].

Interest in the Bondi-Metzner-Sachs (BMS) formalism, created in the 1960s, and the group of asymptotic BMS transformations at null infinity, was revived in connection with the study of gravitational wave phenomena, as well as the understanding that asymptotic symmetries of gravity can play an important role in explaining the black hole entropy. The description of the hypothetical process of black hole creation in collisions of high-energy particles revealed the importance of studying shock waves in the General relativity.

After Hawking's work on the quantum evaporation of black holes, the apparatus of quantum field theory in an external classical gravitational background received significant development, and new methods arose for an approximate estimate of the effective gravitational action in various regimes. Some of these approximations, in the high-temperature regime, are based on the methods of spectral geometry and can be used to study quark-gluon matter, taking into account the effects of rotation and acceleration. In connection with the development of experimental methods for studying the gravitational-wave background, interest has been revived in possible sources of this background and, in particular, in cosmic strings, both those arising within the Kibble mechanism, and strings whose appearance is associated with Planck scales. The hot points of gravitational physics listed above are, of course, only a part of the achievements and interesting results of recent decades.

Specific areas of research within this project include:

- study of classical effects in the gravitational field of shock gravitational waves, including the case of the gravitational induced by null cosmic strings (cosmic strings moving at the speed of light);

- study of gravitational (electromagnetic) radiation induced by the motion of null cosmic strings near massive (charged) sources, description on this basis of experimental estimates for the parameters of these objects;

- study of physical effects associated with the formation of caustics and other defects on the world surface of the null cosmic string as possible sources of gravitational bursts;

- quantization and study of quantum effects in the gravitational field of shock gravitational waves, calculation of the expectation value of renormalized energy-momentum tensor;

- derivation and studying the properties of exact solutions of the Einstein equations related to the subject of this project, for example, the search for non-trivial solutions that have global hyperbolic isometry and allow the introduction of holonomy associated with these transformations;

- the study of the gravitational entropy associated with various surfaces in Riemannian geometry, in particular, the study of the entropy formed when the light cones of the past and the future (causal diamonds) intersect, as well as the study of quantum corrections and renormalization of this quantity;

- the study of finite-temperature QFT on stationary manifolds of a general form, using the spectral geometry of nonlinear spectral problems, as well as the application of this theory to calculate the effects of quark-gluon matter, taking into account rotation and acceleration, further development of spectral geometry methods as applied to nonlinear spectral problems;

- the study of other aspects of quantum field theory at a finite temperature, for example, dissipation processes in irreversible processes, the development of rigorous mathematical approaches to describe these phenomena (for example, the justification of the fluctuation-dissipation theorem, etc.);

- the study of cosmological models of modified gravity, an attempt to explain on their basis the key characteristics of the observed cosmology, such as the accelerated expansion of the Universe;

- construction of integrable cosmological potentials for spatially flat cosmologies with one scalar field for searching and constructing realistic completely integrable inflationary models with a phase transition;

- development of methods for studying vacuum instability in scalar field theories with a wide class of unbounded potentials, for which there are no Coleman instantons,

- study of phase transitions in quantum theory, including gravity, and the formation dynamics of walls separating regions with different field values, the development of the thick-wall approximation method taking into account gravity, as well as the construction and study of exactly solvable inflationary models with phase transitions;

- development of methods in the framework of the Picard-Lefschetz theory and their application for calculating Lorentz path integrals in problems of quantum field theory, gravity and cosmology [J.Feldbrugge, J.-L. Lehners, and N. Turok, Phys. Rev. D95, 103508 (2017)], and, in particular, in problems of describing the lensing of gravitational waves;

- development of methods that allow finding corrections to the trajectories of particles and light in a gravitational field due to perturbations of the metric.

**2.4. Participating JINR laboratories**

**BLTP in collaboration with LIT.**

**2.5. Participating countries, scientific and educational organisations:**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Organization** | **Country** | **City** | **Participants** | **Type****of agreement** |
| UWA | Australia | Perth | Kuzenko S.Buchbinder E. | Visits exchangeCollaborations |
| University | Australia | Sydney | Molev A. | Collaborations |
| Yerevan Physics Institute | Armenia | Yerevan | Hakobian Т.Manvelyan R.Mkrtchyan R.Demirchian H.Khastyan E.Avetisyan M. | Visits exchangeCollaborations |
| Institute for Physical Research | Armenia | Ashtarak | Ishkhanyan A. | Visits exchange |
| Institute of radiophysics and electronics | Armenia | Ashtarak | Gevorkian Z.Davtyan M. | Collaborations |
| INRNE BAS | Bulgaria | Sofia | Dobrev V.Iliev B.Todorov I.T. | Visits exchange |
| Sofia Univ.St.Kliment Ohridski | Bulgaria | Sofia | Rashkov R.Ivanov C. | Visits exchangeCollaborations |
| UFES | Brazil | Juiz de Fora | Shapiro I.Deriglazov A. | Collaborations |
| University | Brazil | Sao Paulo | Ferreyra L. | Collaborations |
| СMСС –University ABC | Brazil | Santo Andre | Vassilevich D. | Visits exchange |
| University | UK | Glasgow | Feigin M. | Collaborations |
| University | UK | Cambridge | Osborn H. | Visits exchange |
| Imperial College | UK | London | Stelle К.Tseytlin А. | Visits exchange |
| University | UK | Durham | Dory P.Sutcliff P. | Visits exchangeCollaborations |
| University | UK | Kent | Krush S. | Collaborations |
| University | Germany | Hanover | Lechtenfeld O.Dragon N. | Collaborations |
| University | Germany | Bonn | Rusetsky A. | Visits exchange |
| IPO | Germany | Oldenburg | Grunau S.Kleihaus B.Kunz J.Azad B. | Collaborations |
| University | Germany | Leipzig | Bordag M. | Collaborations |
| University | Germany | Muniсh | Mukhanov V. | Collaborations |
| AEI | Germany | Potsdam | Nicolai H.Theisen S. | Visits exchange |
| University | Greece | Athens | Zoupanos G. | Collaborations |
| Racah Institute of Physics | Jerusalem | Israel | Rabonivici E. | Visits exchange |
| IPM | Iran | Tehran | Sabejan S.Sheikh-Jabbari M. | Agreement |
| University | Iran | Isfahan | Loran F. | Collaborations |
| School of theoretical physics | Ireland | Dublin | Tchrakian D. | Visits exchange |
| ICE-CSIC | Spain | Barcelona | Odintsov S. | Visits exchange Collaborations |
| UPV/EHU | Spain | Bilbao | Bandos I. | Visits exchange Collaborations |
| IFIC | Spain | Valencia | De Azcarraga J. | Visits exchange Collaborations |
| University | Spain | Вальядолид | Castanieda J. | Visits exchange Collaborations |
| University | Italy | Padova | Basseto A.Sorokin D. | Agreement |
| SISSA/ISAS | Italy | Trieste | Bonora L. | Agreement |
| University | Italy | Torino | Fre P. | Collaborations |
| INFN/LNF | Italy | Frascati | Bellucci S. | Collaborations |
| Henan University | China | Henan | Gudnason S. | Visits exchange |
| University | China | Shanghai | Korobkov M. | Visits exchange |
| University | Poland | Wroclaw | Popowicz Z.Borowiec A.Lukierski J.Frydryszak A. | Visits exchange Collaborations |
| University | Poland | Bialystok | Odzievich A. | Visits exchange |
| JagiellonianUniversity | Poland | Krakow | Romanczukiewicz Т.Wereszczynski А. | Visits exchange |
| University of Aveiro | Portugal | Aveiro | Radu E.Herdeiro C. | Visits exchange Collaborations |
| ITEP | Russian Federation | Moscow | Morozov A.Mironov A.Rosly A.Olshanetsky M. | Visits exchange |
| MSU | Russian Federation | Moscow | Galtsov D.Sveshnikov K.Talalaev D.Shafarevich А.Stepanyantz К. | Visits exchange Collaborations |
| MIRAS | Russian Federation | Moscow | Arefeva I.Orlov D.Slavnov N.Volovich I.Katanaev M. | Visits exchange |
| Lebedev Physical Institute | Russian Federation | Moscow | Barvinsky А.Vasiliev М.Metsaev R. | Visits exchange |
| Ishinsky Institute for Problems in Mechanics | Russian Federation | Moscow | Dobrohotov S. | Visits exchange |
| MIPT | Р Russian Federation Ф | Долгопрудный | Musaev E.Bondal А. | Collaborations |
| Sternberg Astronomical Institute | Russian Federation | Moscow | Toporensky A. | Visits exchange |
| Higher School of Economics | Russian Federation | Moscow | Pushkar P. | Visits exchange |
| Skoltech | Russian Federation | Skolkovo | Kazaryan М. | Visits exchange |
| IHEP | Russian Federation | Protvino | Zinoviev Yu. | Collaborations |
| St. Petersburg Department of Steklov Mathematical Institute | Russian Federation | St. Petersburg | Derkachev S. | Collaborations |
| Voronezh University | Russian Federation | Voronezh | Minakov А. | Visits exchange |
| KPFU | Russian Federation | Kazan | Sushkov S.Popov А. | Collaborations |
| Sobolev Mathematical Institute | Russian Federation | Novosibirsk | Mironov А. | Visits exchange |
| Tomsk Polytechnic University | Russian Federation | Tomsk | Galajinsky А. | Collaborations |
| Tomsk State Pedagogical University | Russian Federation | Tomsk | Lavrov P.Krychtin V.Snegirev Т.Merzlikin B. | Collaborations |
| Landau Institute for Theoretical Physics | Russian Federation | Chernogolovka | Belavin А.Sokolov V.Starobinsky А. | Visits exchange |
| University | Serbia | Nis | Djordjevic S. | Visits exchange |
| University of Maryland | USA | College Park | Gates J.Koutrolikos К. | Visits exchange |
| University of Miami | USA | Coral Gables | Mezincescu L. | Collaborations |
| University of Pennsylvania | USA | Philsdelphia | Ovrut B. | Collaborations |
| CUNY | USA | New York | Akulov V.Korepin V.Shuryak Е.Catto S. | Visits exchange |
| Institute of theoretical physics | USA | New York | Zamolodchikov A. | Visits exchange |
| Technical University | Czech Republic | Prague | Burdik Ch. | Visits exchange Collaborations |
| LAPTH | France | Annecy-le-Vieux | Ragoucy E.Sokatchev E. | Visits exchange Collaborations |
| ENS Lyon | France | Lyon | Sorba P.Delduc F.. | Collaborations |
| CPT | France | Marseille | Кокоро Р.Ogievetsky O. | Collaborations |
| University | France | Tours | Volkov M.S.Garaud J.Solodukhin S. | Collaborations |
| SUBATECH | France | Nant | Smilga A. | Collaborations |
| Obsrvatoire de Paris | France | Paris | Gourgoulhon E. | Collaborations |
| ENS | France | Paris | Policastro G. | Collaborations |
| CERN | Switzerland | Geneva | Alvarez-Gaume L.Antoniadis I.Ferrara S. | Agreement |
| Institute of Science and Technology | Japan | Okinawa | Tsulaia M. | Visits exchange Collaborations |
| Tokyo Universityof Science | Japan | Tokyo | Sawado N.Yuki A. | Visits exchangeCollaborations |
| University | Japan | Keio | Nitta M. | Visits exchange |

**2.6. Key partners** *(those collaborators whose financial, infrastructural participation is substantial for the implementation of the research program on the theme. Example – JINR participation in the LHC experiments at CERN).*

**3. Manpower**

**3.1. Manpower needs in the first year of implementation**

|  |  |  |  |
| --- | --- | --- | --- |
| **No.** | **Personnel category** | **JINR staff,****FTE amount** | **JINR associated personnel,****FTE amount** |
| 1. | research scientists | 31(FTE-29) | 0 |
| 2. | engineers | 0 | 0 |
| 3. | specialists | 0 | ~~0~~ |
|  | **Total:** | **31** | **0** |

**3.2. Available manpower**

**3.2.1. JINR staff** (total number of participants)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **No.** | **Personnel category** | **Division** | **Position** | **Amount****FTE** |
| 1. | research scientists | MMP-dept. | Head of the sector | 3 |
|  |  |  | Main scient. researcher | 2+1/2 |
|  |  |  | Leading scient. researcher | 5+3\*1/2 |
|  |  |  | Senior scient. researcher | 10 |
|  |  |  | Scient. researcher | 2 |
|  |  |  | Research assistant | 3 |
| 2. | engineers |  |  |  |
| 3. | specialists |  |  |  |
|  | **Total:** |  |  | **27+4\*1/2** |

**3.2.2. JINR associated personnel**

|  |  |  |  |
| --- | --- | --- | --- |
| **No.** | **Personnel category** | **Partner organization** | **Amount of FTE** |
| 1. | research scientists |  |  |
| 2. | engineers |  |  |
|  | **Total:** |  |  |

**4. Financing**

**4.1. Total estimated cost of the theme / LRIP**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **No.** | **Items of expenditure** | **Cost** | **Expenditure per year****(thousands of the US dollars)** |  |  |
| 1styear | 1styear | 1styear | 1styear | 1styear |
| 1. | International cooperation | 253,6 | 45,2 | 48,4 | 51,3 | 53,3 | 55,4 |
| **TOTAL:** | **253,6** | **45,2** | **48,4** | **51,3** | **53,3** | **55,4** |

**4.2. Extra funding sources**

Expected extra funding from partners/customers (total for all projects).

**AGREED:**

**Chief Scientific Secretary Laboratory Director**

 **/\_\_\_\_\_\_\_ / /\_\_\_\_ /**

**" " 202\_г. " " 202\_г.**

**Head of BEPD Scientific Secretary of the Laboratory**

 **/\_\_\_\_\_\_\_ / /\_\_\_\_ /**

**" " 202\_г. " " 202\_г.**

**Head of DSOA Laboratory Economist**

 **/\_\_\_\_\_\_\_ / /\_\_\_\_ /**

**" " 202\_ г. " " 202\_г.**

**Head of HRRMD Theme leader**

 **/\_\_\_\_\_\_\_ / /\_\_\_\_ /**

**" " 202\_г. " " 202\_г.**

**Project leader (project code) /**

**(LRIP subproject code)**

 **/ /**

 **“ “ 202\_г.**

**Project leader (project code) /**

**(LRIP subproject code)**

 **/ /**

 **“ “ 202\_г.**

**Project leader (project code) /**

**(LRIP subproject code)**

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 **“ “ 202\_г.**