Bulgarian Academy of Sciences
Institute for Nuclear Research and Nuclear Energy
Report for scientific and applied activities for 2015

Project Title	New Aspects in String Theory and Gravity
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Keywords	strings, p-branes, black holes, wormholes, nonlinear electrodynamics, f(R)-gravity, modified gravity theories, supersymmetry & supergravity - spontaneous breaking of supersymmetry, gauge/gravity duality, integrability, anisotropic fluid models, collapsing and radiating stars, rapidly rotating neutron stars, scalar-tensor gravity theories, dark energy & dark matter, Colombeau generalized functions

Summary of activities and results for **2015**

During 2015 altogether **27 scientific papers with total impact-factor 54.50** have been published or accepted for publication, containing research on the topic of the current project.

The collection of **papers [1-11]** contain results belonging to the following closely related and actively developing modern research areas in gravity and cosmology ((A)-(E)):

(A) Unified description of the evolution of early and late (modern epoch) Universe – papers [1,2,5,6]

We have proposed a new model of gravity plus matter defined in terms of two independent non-Riemannian volume forms on the pertinent spacetime manifold. The initial Lagrangian action is constructed in such a way that is invariant under global Weyl-scale transformations. As a result of spontaneous breakdown of global Weyl-scale symmetry and upon passing to the physical "Einstein-frame" we find the following remarkable effects: (i) We obtain an effective potential for the cosmological scalar field possessing two infinitely large flat regions, which allows for an unified description of both the "inflationary" phase of the early Universe as well as the current "dark energy"-dominated epoch; (ii) For a specific range of the parameters of the model we find a non-singular solution of an "emergent" universe, which describes an initial phase of a non-singular (no "Big-Bang") beginning/creation of the Universe preceding the era of "inflation". One of the main features of the new approach in the theory of cosmological evolution proposed in **papers [1,2,5,6]** is the prediction (under minimal plausible assumptions) for the values of some fundamental magnitudes such as the energy scale of "inflation" and the scale of the cosmological energy density in the current "dark energy"-dominated epoch, which match the recent much talked about experimental data of Planck Collaboration.

(B) Unifying description of the dynamics of “dark energy” and “dark matter” – papers [7-10]

Using the method of non-Riemanian spacetime volume-forms (metric-independent generally-covariant integration measure densities) we have constructed a new non-canonical cosmological model of gravity interacting with a single scalar field, which explicitly yields a self-consistent unified description of “dark energy” as a dynamically generated cosmological constant, and “dark matter” as a dust fluid flowing along spacetime geodesics, by unifying them as an exact sum of two separate contributions to the pertinent scalar field energy-momentum tensor. In other words, this unified description shows that “dark energy” and “dark matter” may be viewed as two different manifestations of one single matter source. The fundamental reason for the unification of both “dark” species of the Universe is the presence of the non-Riemannian volume-form in the Lagrangian action of the scalar field which: (i) dynamically generates a cosmological constant (the “dark” energy density) as an arbitrary integration constant in the equations of motion of the auxiliary gauge fields defining the non-Riemannian volume-form; (ii) leads to a remarkable strongly nonlinear hidden Noether symmetry whose associated Noether conserved current is responsible for the dust-fluid nature of the “dark matter”. We also find a remarkable duality between the above system of gravity interacting with a single scalar field having a non-canonical Lagrangian action, on one hand, and a special type of the so called purely kinetic “k-essence” (("quintessential inflation") models in the standard meaning of duality as “weak-versus-strong-coupling”. Among other things, our model explains the reason for the capability of the purely kinetic “k-essence” models to describe approximately the unification of “dark energy” and “dark matter”, whereas this description becomes exact in the “k-essence” strong coupling limit – the latter limit cannot be performed while staying within the “k-essence” model. To this end one has to invoke the dual correspondence of the latter with the proposed by us non-canonical gravity+single-scalar field theory incorporating a non-Riemannina volume-form in the scalar field action.

(C) Dynamical spontaneous breaking of supersymmetry – paper [3].

This is a further development of the originally proposed by us qualitatively new mechanism for a dynamical spontaneous supersymmetry breaking – the supersymmetric Brout-Englert-Higgs effect. Specifically, we consider a modified formulation of standard minimal N=1 supergravity based on an idea of introducing an alternative non-Riemannian (metric-independent) spacetime volume form in the pertinent Lagrangian action, defined in terms of auxiliary (pure-gauge) fields, i.e., the latter do not change the number of the physical (propagating) field-theoretic degrees of freedom. Invariance under supersymmetry of the new modified N=1 supergravity action is explicitly preserved due to the addition of an appropriate compensating (pure-gauge) antisymmetric tensor gauge field. We find as a result of the above modification, that a non-zero cosmological constant is naturally produced as an arbitrary integration constant when solving some of the relevant (supersymmetric) equations of motion. It is this dynamically generated non-zero cosmological constant which signifies the appearance of the spontaneous breakdown of supersymmetry. Furthermore, upon applying the same formalism using non-Riemannian spacetime volume-forms to N=1 anti-de Sitter supegravity we succeed through an appropriate choice of the above mentioned free integration constant to obtain simultaneously a very small physical observable cosmological constant and a very large physical observable gravitino mass – exactly what is required in modern cosmological scenarios of the slowly expanding universe of today's epoch.

(D) Electrovacuum gravitational "bags" – paper [4].

In this paper the new gravity-matter model proposed in papers [1,2,5,6] in terms of two independent non-Riemannian spacetime volume-forms is extended by an inclusion of an additional interaction with a special kind of non-standard non-linear electrodynamics containing a square-root of the standard Maxwell's Lagrangian for the electromagnetic field. The latter in flat spacetime (no gravity) is known to describe electric charge confinement analogous to the quark confinement in quantum chromodynamics. In the presence of gravity (plus a "dilaton" scalar field) we find new physically interesting effects: (i) non-trivial phase structure – existence of phases of charge confinement and phases of deconfinement (charge "liberation"); (ii) creation of electrovacuum gravitational "bags" with properties analogous to the well-known "MIT bags" and the solitonic "constituent quark" models within the phenomenological theories of QCD quark confinement.

(E) Lightlike thin-shell wormholes - [11].

Extended objects (strings and p-branes) are of primary importance for the construction of self-consistent unified modern theory of fundamental forces in Nature. In a series of previous papers we have proposed a new class of (mem)brane theories which are qualitatively distinct from the standard Nambu-Goto type brane models and provide a systematic Lagrangian description of ***lightlike*** branes (or lightlike thin-shells). As it is well known lightlike branes are of substantial interest in general relativity as they describe impulsive lightlike signals arising in various violent astrophysical events, e.g., final explosion in cataclysmic processes such as supernovae and collision of neutron stars. Lightlike branes also play important role in the description of various other physically important cosmological and astrophysical phenomena such as the "membrane paradigm" of black hole physics and the thin-wall approach to domain walls coupled to gravity. Lightlike branes also play a significant role in the context of modern non-perturbative string theory of fundamental forces in

Nature.

Paper [11] is a significant development of previous works of ours where for the first time in the literature we discovered a significant drawback (after more than 70 years!) in the classic article by Einstein and Rosen from 1935, where they proposed the celebrated “Einstein-Rosen bridge” – historically the first example of a traversable wormhole. Namely, we show that the mathematically consistent formulation of the classic “Einstein-Rosen bridge” requires the presence on the “throat” connecting the two universes of a special kind of “exotic” matter, which must be a lightlike brane – a particular case within the broad class of lightlike branes proposed by us. This latter result is absent in the classic article from 1935. The essential progress in **paper [11]** consists in our construction of the Kruskal-Penrose extension of the spacetime manifold underlying the “Einstein-Rosen bridge” as a specific example of a traversable one-throat wormhole. This results is subsequently generalized for the case of the physically more interesting traversable “tube-like” wormhole with two throats, i.e., two non-compact universes connected via one middle “tube-like” universe with final spacial extent. The two throats are occupied by two oppositely charged lightlike branes, where the whole electric flux produced between them is trapped within the middle tube-like universe – an effect completely analogous to the quark confinement in quantum chromodynamics.

In **paper [12]** we derive the 3-point correlation function between two giant magnons heavy string states and the light dilaton operator with zero momentum in the η -deformed $AdS5\times S5$ valid for any value of the conserved string angular momentum J and the deformation parameter η in the semiclassical limit. We show that this result satisfies a consistency relation between the 3-point correlation function and the conformal dimension of the giant magnon. We also provide the leading finite J correction explicitly.

We compute in **paper [13]**some three-point correlation functions in the η-deformed AdS_5×S^5 in the framework of the semiclassical approach. This is done for the cases when the "heavy" string states are finite-size giant magnons carrying one angular momentum and for three different choices of the "light" state: primary scalar operators, dilaton operator with nonzero momentum, singlet scalar operators on higher string levels.

In **paper [14]** we present part of our investigations related to p-branes and Dp-branes dynamics, duality between string theories/M-theory and (conformal) field theories, as well as some semiclassical results for three-point correlation functions, including finite-size effects on them.

Papers [15,16] are devoted to the study of electromagnetic quasinormal and quasibound modes of Kerr black holes.
The perturbations of the Kerr metric play a critical role in the comparison of predictions of general relativity with astrophysical observations of compact massive objects. In this article, we solve numerically the spectral system formed by the exact solutions of the Teukolsky angular and radial equations in terms of confluent Heun function and we obtain the electromagnetic spectra of the Kerr black hole. Additionally to the well-known quasinormal modes, we found also the symmetric with

respect to the real axis quasibound modes and a spurious spectrum who is radially unstable. The novelty in this approach is that it allows a way to distinguish between the physical modes and the non-physical numerical artefacts based on their radial stability, which may be important considering the recent interest in the spectra of the electromagnetic counterparts of events producing gravitational waves.
The future research plans on the above topic include continuation of the study of quasinormal modes with different spin and their application in the astrophysics. This is particularly important considering the growing number of observations of stellar compact massive objects where the type of the object (black hole or neutron star) cannot be determined only based on its mass.

Papers [17,18] are devoted to the study of problems of gravitational collapse – one of the main research trends in modern relativistic astrophysics. Many arguments have been given for anisotropic collapse with radiation. The main equation then is given by the junction condition to an exterior solution. We study the most general case of anisotropic fluid with expansion, acceleration and shear. A physically meaningful object is introduced, called the horizon function. It enters directly the expressions for many stellar characteristics and satisfies a Riccati equation. Different solutions of this equation have been found, including geodesic ones.

Modelling of singularities given by distributions or discontinuous functions by means of the generalized functions of Colombeau has proved useful in many physical problems such as geodesics for impulsive gravitational waves, jump conditions in hyperbolic systems and others. In the papers below, methods based on algebra of generalized Colombeau functions are applied to obtain new results for singular products of Schwartz distributions.
In **paper [19]** the method described above is applied to studying series of singular distributional products in multidimensional case in the framework of Colombeau algebra. The results are obtained for discontinuous functions and derivatives of Dirac δ-function that exist as Schwarz distributions.
In **paper [20]** generalized functions of Colombeau that model distributions with singular point support are studied. Following the idea of Jan Mikusinski of balanced products, series of results are obtained that represent Schwartz distributions.

Paper [22] is devoted to gravitational wave asteroseismology relations for rapidly rotating neutron stars. More precisely, we studied what kind of relations between the parameters of the star (such as mass, radius, moment of inertia and angular velocity) on one hand and the gravitational wave frequencies and damping/growth times on the other hand have to be used in order to be able to extract accurately these parameters from future observation of gravitational waves emitted by oscillating neutron stars. In addition, these relations should be independent of the nuclear matter equation of state up to a large extend, since the current uncertainties in the equation of state are quite large. Several classes of asteroseismology relations were derived and it was shown that they are particularly suitable for the case of supramassive neutron stars (neutron stars that are supported against collapse by rotation and do not have a stable nonrotating limit) rotating with frequencies close to Kepler one (the mass-shedding limit). Such neutron star models are particularly important because they can develop secular instabilities and thus emit strong gravitational radiation. It was shown that with the help of these relations, the parameters of the star can be obtained with high accuracy using future gravitational wave observations.

Papers [21], [23], [24], [25] are devoted to building models of neutron stars in alternative theories of gravity and examined their astrophysical implications. We focused on the so-called f (R) theories of gravity, which are ones of the most natural and widely used alternative theories. Their motivation comes also from the fact that they are used as an alternative explanation of the dark energy phenomenon. As a first step we considered the leading term in the f (R) theories, which has the largest contribution on astrophysical scales, namely the so-called R^2 theories of gravity.

Paper [25] is devoted to the construction of rapidly rotating neutron stars models in R^2 gravity. A numerical code is developed for this purpose and the results are compared in detail with general relativity. We should note that these are ones of the first results for rapidly rotating neutron stars in alternative theories of gravity. The construction of such models is important because rapid rotation can lead to stronger deviations from general relativity compared to the static case, as we have shown recently. Indeed, this is also observed for the solutions obtained in **paper [25]** – neutron stars rotating close to the Kepler (mass shedding) limit differ significantly from the general relativistic case. This can be used for testing f (R) theories of gravity using future observations of compact stars.

In **papers [21], [23], [24]** the following astrophysical applications of neutron stars in f (R) theories of gravity are considered with the purpose of exploring the possibilities to impose constraints on the strong field regime of gravity.
A number of models offer a direct connection between the orbital and epicyclic frequencies of particles moving on a circular orbits around compact objects, on the one hand, and the frequencies of the quasi-periodic oscillations (QPO) observed in the X-ray spectrum of some pulsars and black holes, on the other side. It is expected that these QPOs originate from the inner edge of the accretion disks, deep into the gravitational field of the compact objects. Therefore, the QPOs can be an excellent tool for testing the strong field regime of gravity and therefore, the alternative theories of gravity.

Paper [21] studies the orbital and epicyclic frequencies of particles moving on circular orbits around compact stars in R^2 theory of gravity and a detailed comparison with the general relativistic case is done. The results suggest that the differences between the two gravitational theories can reach 20%.

Paper [23] studies the relation between the normalized moment of inertia (I) and quadrupole moment (Q) for rotating neutron stars in general relativity. These relations became quite popular recently, because it turns out that after appropriate normalization they can become practically independent of the equation of state. One of their applications is to test (or restrict) the possible deviations from general relativity in the strong field regime. This is important since in many cases the effects due to alternative theories of gravity are qualitatively and quantitatively similar to the effects due to uncertainties in nuclear matter equation of state. The results show that the normalized I-Q relations in R^2 theories of gravity remain practically independent of equation of state, similar to the general relativistic case. The most interesting result in **paper [23]**, however, is that the differences with Einstein's theory can be large, reaching more than 20%. This is qualitatively different from most of the alternative theories of gravity, where the normalized I-Q relations are almost indistinguishable from pure Einstein’s theory of gravity. This case be used to impose observational constraints on f (R) theories.

Paper [24] is devoted to asteroseismology relation for neutron stars in f (R) theories of gravity. The fundamental f-modes are considered because they are ones of the most promising gravitational wave emitters. Several different classes of asteroseismology relations are built in order to achieve completeness of results. The main objective is to determine to what extent these relations are equation of state independent and whether the deviations from general relativity are large enough to be observed in practice. The results show that the differences between general relativity and R^2 theories are generally small, within 10% and therefore they cannot be observed by the next generation of gravitational wave detectors. On the other hand the small deviations in some of the asteroseismology relations shows that these relations are not only independent of the equation of state, but they are also not very sensitive to the particular theory of gravity. That is why solving the inverse problem can give us quite robust estimates of the neutron star parameters.

[iR1]

Publications for **2015**:

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