BLACK HOLES' NEW HORIZONS

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1 General Information

The BIRS-CMO workshop Black Holes' New Horizons 16w5008 was held in Oaxaca, Mexico, from May 15 to May 20, 2016. It gathered leading black-hole experts from 14 countries. In particular, there were 11 scientists from Canada and 8 scientists from Mexico. 8 PhD students and postdocs attended this event.

2 Overview of the Field

Black holes are one of the most intriguing objects of modern science. They were predicted by General Relativity, the theory Albert Einstein finished formulating in 1915. The first paper on black holes was published by Karl Schwarzschild in 1916. This paper presented an exact spherically symmetric vacuum solution of the Einstein equations. One of the goals of our workshop was to celebrate the hundredth anniversary of black hole theory. During the past one hundred years black hole science became an important branch of modern theoretical physics and astrophysics. Numerous observations have given evidence confirming the existence of black holes. And finally, in September of 2015, black holes were even more directly discovered by the LIGO gravitational wave observatory, which registered the gravitational waves emitted by the coalescence of two black holes [1]. The many confirmations of the existence of black holes have had a great impact on theoretical research on black holes.

The main subjects of the workshop were theoretical and mathematical aspects of black holes. However, we specially invited two recognized experts to give review talks on the discovery of black holes and their modern astrophysical status. All the participants appreciated these talks very much, and many of them used this opportunity get more updated information about this fast developing area.

Black holes are a very "hot" subject of modern theoretical physics [16, 17]. We have more and more evidence that black holes are objects which play the role of probes of new fundamental physical ideas (e.g. string theory, extra dimensions, entanglement entropy and so on). At the same time problems and puzzles of black holes stimulate development of mathematical tools. The goal of the workshop was to gather leading experts working in the field of theoretical physics and mathematics of black holes to discuss the "hot spots" of this area, the main unsolved problems, and various perspectives and possible approaches to the solution of these problems.

3 Recent Developments and Open Problems

3.1 Black hole entropy problem

The quantum radiation of black holes, predicted by Hawking [18, 19], is thermal. Since black holes have a temperature, they must also have entropy. The problem is that this entropy is huge. For example, the entropy of the black hole in the center of our Galaxy is higher than the thermal entropy of the visible Universe. What is the origin of the black hole entropy? A lot of work was done in the attempt to answer this question. The most developed string motivated approach is using the formalism of the conformal field theory [10]. Within it the black hole entropy is counted by using the Cardy formula [9], after proper specification of the central charge of the Virasoro algebra. There exist other approaches for the explanation of the black hole entropy. An open question is how all these different approaches, which should give the same known value of the entropy, are related. This is the so-called problem of the universality of th black hole entropy. Since different approaches use different mathematical models, there is an interesting mathematical problem of their relations. The situation here is somehow reminiscent of the situation at the beginning of the theory of quantum mechanics. There were two different formalisms: wave functions (by Schroedinger) and matrix mechanics (by Heisenberg). Both gave the same answer for atomic spectra. And only after some time it was understood that they are just two different realisation of the same Hilbert space. We believe that the discussion of the universality problem might produce mathematically interesting results.

3.2 The black-hole information puzzle

By an adopted definition, a black hole is a spacetime region from which information-carrying signals cannot escape to infinity. This means that the global causal structure of the spacetime in the presence of a black hole is non-trivial. Quantum effects result in the evaporation of the black hole. If it disappears in this process and the information captured by the black hole does not return to the external space, one would effectively deal with the breakdown of the unitarity property of quantum theory. This is a longstanding problem [20, 28]; however recently it has attracted a lot of new attention (see e.g. the review [26] and references therein). String theory strongly advocates a point of view that information is not fundamentally lost in black hole formation and evaporation, but this view is not yet universally accepted, and in fact there are many unresolved issues connected with how information may get back out. One recent very hot topic is the argument for firewalls at the horizon of a sufficiently old black hole [3], with about one hundred papers on this question in the past year alone. A firewall is a very unpalatable conclusion, but many researchers do not see a plausible way to get around it, so it has become a key paradox in our present incomplete understanding of black holes. In one of his recent publications [21], Hawking expressed his opinion that the adopted mathematical definition of the black hole must be modified in order to include a possibility of unitarity restoration. This as well as the firewall proposal has generated a lot of discussion.

3.3 Black Holes in Modified Gravity

There are many suggestions that Einstein's theory of gravity should be modified in the range of both very large and very small scales. The recent discovery of the acceleration of the expansion of our Universe has led to some suggestions that Einstein gravity should be modified at large scales. There is even more motivation from considerations of quantum gravity to modify Einstein gravity at small scales. One of the widely discussed proposals is to modify the Einstein action, which contains the Ricci scalar R, by one which contains an arbitrary function $f(R)$. A natural question is how this and other proposed modifications of the theory of gravity affect the properties of black holes. This problem is closely related to the famous no-hair conjecture formulated almost half a century ago, which is still a hot research topic [33].

3.4 Ghost-free gravity and non-singular black hole models.

According to classical General Relativity, there inevitably exist singularities inside black holes. This is a manifestation of the generic problem of the ultraviolet (UV) incompleteness of Einstein gravity. It is also UV incomplete in the quantum domain. It is generally believed that such incompleteness must be "cured" by a proper modification of Einstein gravity at small scales (high energies). The Einstein-Hilbert action contains the simplest curvature invariant, the Ricci scalar. There were many attempts to modify the action by adding higher in curvature invariants of the corresponding (pseudo)-Riemannian manifold. This helps to improve the UV behavior of the theory. However, practically inevitably, another problem arises. The corresponding modified theory generally contains unphysical degrees of freedom, ghosts, so that such a theory is inconsistent and (often) unstable. Recently, a new idea was proposed for how to improve UV behavior of the theory without introducing ghosts. This approach is called ghost-free gravity [32, 7, 31]. There were obtained some promising results, when this approach was applied to the problem of black-hole singularities [27]. At the same time there exists an open problem of its mathematically accurate formulation and treatment. The reason is that the ghost-free theories are, in fact, non-local. We do not know how to formulate properly the initial and boundary value problems for such a theory [5, 4]. How should one treat the non-local problems in a spacetime with large curvature? How can one perform numerical simulations in this theory, and which mathematical methods are suitable for these calculations? It may happen that after the removal of the singularity the global causal structure of the spacetime would change, and information, originally hidden inside the black hole, may become available to an external observer after the evaporation of the black hole. This option is interesting in connection with the information paradox.

3.5 Black holes, hidden symmetries and complete integrability

It has been known for a long time that the geodesic equations in the Kerr metric are completely integrable. Recently it was discovered that complete integrability is a characteristic common property of all stationary higher-dimensional black holes with horizons having spherical topology [14]. Geodesic equations in these spacetimes are new physically interesting cases of completely integrable systems. In fact, it is a puzzle, why namely this class of solutions of the Einstein equations has such a remarkable property. There exist also a number of interesting, more "practical" mathematical problems, such as the construction of Lax pairs for such systems and the application of the Kolmogorov-Arnold-Moser method for studying the general properties of these dynamical systems. It was shown that the same hidden symmetries which are responsible for the complete integrability of the geodesic equations, also imply complete separation of variables for physically interesting field equations [13]. The ordinary differential equations obtained by such a separation are second-order linear equations with polynomial coefficients. The power of these polynomials grows when one increases the number of the spacetime dimensions. The Sturm-Liouville problem for 'angular' eigen-modes and general properties of the 'radial equations' are open problems, with interesting physical applications. It is practically unknown how far these remarkable properties of isolated vacuum black holes can be generalized to non-vacuum black holes and to supergravity.

4 Presentation Highlights and Scientific Progress Made

4.1 Partners

In the quantum effect of particle production by an external field, particles are created in pairs. For quantization of such a system one uses a symplectic (canonical) form defined by the Lagrangian, quadratic in the field. A Bogolyubov transformation, generated by the canonical transformation in the symplectic space, determines the S-matrix, describing the creation of particles. For each of the created particles there exists a well defined "partner". A particle and its partner form an entangled state. In the standard description of the Hawking effect, an external observer registered only particles, which reach infinity, while their partners, falling into the black hole, remain invisible. An interesting problem is: what happens with partners if the black hole evaporates completely and they can escape to the external space after its evaporation [22]. An interesting new idea was presented and discussed at the workshop. Namely, it was demonstrated that partners, emitted after the complete evaporation, can be indistinguishable from the flat-spacetime vacuum fluctuations. This opens a new possibility for solving the information loss paradox.

4.2 Firewalls

In order to save unitarity in the process of quantum evaporation of a black hole, the authors of the paper [3] assumed that a peculiar object, a firewall, is formed, which lies near the event horizon and which should not be observable except by infalling observers. Such observers are presumably terminated at the firewall. This paper received a lot of publicity. In the talk, presented at the workshop, this conjecture was criticized. It was argued, that if the firewall is located close to the horizon, the quantum fluctuations of the latter could make it naked and lying arbitrarily far outside the horizon [11]. For this reason the firewall concept cannot be considered as the "most conservative solution to the information loss paradox". This talk opened a wide discussion of firewalls. The dominant point of view was that firewalls are a very unpalatable conclusion and that there exist other more attactive proposals for the solution of the information loss paradox.

4.3 Black hole tunneling

Black holes have a nonzero temperature. As a result of this small black holes can act as nucleation seeds for the decay of a metastable vacuum. This possibility and its consequences were discussed at the workshop. It was argued that for a definite range of parameters, the vacuum decay process dominates over the Hawking evaporation process [8]. These kind of phase transitions might have interesting astrophysical applications, so that a detailed study of such phase transitions is an intriguing open problem.

4.4 Non-singular black holes and dilaton gravity

Recently there was a lot of interest in the study of so-called non-singular models of black holes. However, an open question is how to construct a modification of Einstein gravity which produces these kinds of solutions. For modelling properties of realistic four dimensional solutions of the equations of gravity, so called two-dimensional gravity models are often used. In one of the talks presented at the workshop it was demonstrated that there exist a special model of the dilaton gravity, which, in particular, has static non-singular black hole solutions [24]. There was an interesting discussion how to use such a theory for solving the dynamical equations for the formation and further evaporation of black holes. For such a problem one needs to obtain global solution of 2D non-linear hyperbolic equations. An open question is whether such a dynamical metric always is a globally non-singular.

4.5 Black hole entropy of an extremal black hole

According to the famous work by Bekenstein [6], the entropy of a black hole is proportional to its surface area. This statement was later confirmed by Hawking [18, 19], whose formula for the black hole temperature determined the constant of proportionality, $S = A/4$. However, there exists a special case, when the black hole with charge and/or angular momentum is extreme. Such a black hole has zero surface gravity, and its Hawking temperature vanishes. For this special case some of the calculations gave the result, which differed from the "standard" one. This paradox was discussed at the workshop, and an interesting resolution was proposed [25]. Namely, the limit of the extremal black hole possesses an ambiguity. In this limit, the spatial distance from a fixed radius to the position of the black hole horizon infinitely grows. To specify the thermal canonical ensemble, one needs to specify the position of the boundary where the temperature is kept fixed. It was demonstrated that the value of the black hole entropy may depend on how the position of the boundary in chosen in the limit of extremality.

4.6 Higher dimensional black holes

There were several talks in higher-dimensional black holes, which contained interesting new results and ideas.

4.6.1 Higher dimensional black hole bomb

Long time ago, Press and Teukolsky [29] demonstrated that by placing a mirror around a rotating black hole, one can make the system unstable. This effect, connected with the existence of so-called superradiant modes, got the name of the "black hole bomb". Recently a similar effect was discussed for the case in which a rotating black hole in placed in anti-de Sitter (AdS) spacetime. In a talk presented at the workshop, it was demonstrated that this result can be extended to all higher dimensions, at least for slowly rotating charged AdS black holes with a single angular momentum [2]. In the discussions, it was stressed that it would be interesting to find a complete analytic solution of this problem for arbitrary rotating black holes in the AdS spacetime. This result would be highly interesting for two reasons: (i) It is directly connected with a general problem of stability of higher dimensional black holes, and (ii) it might have an important application to the so called AdS-CFT correspondence.

4.6.2 Degenerate subclasses of higher-dimensional Kerr-NUT-AdS metrics

The complete integrability of the geodesic equations in the spacetime of a rotating higher-dimensional black hole is a consequence of the existence of a special geometric structure, called a principal conformal closed Killing-Yano tensor (or briefly "principal tensor"). This is a non-degenerate closed conformal rank-2 Killing-Yano form. The most general solution of the higher dimensional Einstein equations with the cosmological term, which admits such a structure, is the Kerr-NUT-AdS metric. Such a metric contains a number of free parameters. An interesting open question is to describe limiting metrics, when some of these parameter take special limits. Partial progress in solving this problem was reported at the workshop. Namely, it was demonstrated that there exists a special limit, in which the principal tensor becomes degenerate, and yet the property of complete integrability of the geodesics is preserved [23]. At the discussion it was proposed to study higher-dimensional metrics with geodesic complete integrability and their possible relations with the Kerr-NUT-AdS class of metrics.

4.7 Ghost-free gravity

Ghost-free gravity is a promising model of the UV completion of gravity theory. However, it is non-local and, as a result, it has several potential problems [30]. This subject was discussed in the talks presented at the workshop. In particular, there were presented results concerning scalar theories of interacting delocalized fields, with the delocalization being specified by nonlocal integral kernels. It was shown that one can impose conditions on such theories to insure UV finiteness and unitarity of quantum amplitudes. Also there was a detailed discussion of the classical initial value problem for the partial integro-differential equations of motion.

Other topics in ghost-free gravity presented and discussed at the workshop included the following: (i) formulation and properties of the ghost-free gravity equations in the high-curvature limit, (ii) criteria for resolving the cosmological singularity in infinite-derivative gravity [12], and (iii) properties of solutions of the linearized equations of the ghost-free theory [15].

4.8 Black holes in $f(R)$ gravity

Several talks were devoted to discussion of the black hole solutions in $f(R)$ gravity. It is well known that such a theory in vacuum admits the Schwarzschild solution. New results, presented at the workshop, demonstrated that in the presence of matter (such as an accretion disk) surrounding the black hole, the solutions of the $f(R)$ theory might be more complicated. In particular, numerical simulations show that the internal structure of such black holes might be quite different from the Schwarzschild black hole.

5 Special Sessions

One of the founder of modern black hole theory, physicist Jacob Bekenstein, a professor at the Hebrew University of Jerusalem, passed away on August 16, 2015. To celebrate his life and his contribution to black hole theory we organized a special session devoted to his memory. Two special talks were presented: Barack Kol spoke about Jacob and some facts of his life, and Bill Unruh spoke about the scientific contributions of Jacob.

This year we are celebrating the hundredth anniversary of the first publication on black holes by Karl Schwarzschild. We organized a special session at the last day of the meeting. We asked participants to answer the question "100 years of BLACK HOLES: WHAT IS NEXT?" This idea was very fruitful. The discussion was very lively. It covered not only the formulation of the most important open questions of black holes, which should be attacked in the near future (say 5-10 years), but also more "fantastic" proposals, such as how a well-developed civilization may use black holes as virtually unlimited sources of energy in the distant future.

6 Outcome of the Meeting

Speaking with many participants during and after the meeting, we got the strong impression that it was very successful. There were many participant testimonials which support this point of view. In particular, Terry Tomboulis, a distinguished professor from UCLA, wrote "... meeting for the first time in person some workers in adjacent areas of research was very beneficial and enjoyable. Overall, this workshop proved very fruitful for my current research." Jeffrey McClintock, Senior Astrophysicist of the Harvard-Smithsonian Center for Astrophysics, wrote: "It was a privilege to attend and participate, and to consider with experts the deepest problem in the physical sciences. The venue was outstanding." Barak Kol (Hebrew University of Jerusalem) wrote: "I enjoyed the workshop very much."

We invited many PhD students and postdocs to our meeting. There were also four specially invited young Mexican scientists. We got very enthusiastic support from them. For example, Claudia Moreno Gonzalez from the University of Guadalajara wrote: "The event fulfilled my expectations, helped me to update my knowledge and let me learn more about the physics of black holes. I could interact with researchers of high prestige in the world as well as learn new research projects." Sergio Cardona from UNAM wrote, "My main research field is complex geometry. I found the workshop at CMO very stimulating."

We would like to thank all the staff members of BIRS and CMO, who helped us in the organizing of this meeting. All of us enjoyed the friendly environment of Casa Matemtica Oaxaca.

We need only to add that the chosen subject of physics and mathematics of black holes was very timely. Practically all the participants demonstrated the desire to attend other meetings on a similar subject.

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