Citation for the 2022 (the 10th) Nishina Asia Award

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For his original and influential insights into the resolution of the black hole information paradox and the principle of holography in quantum gravity.

The black hole information paradox has been a longstanding problem in quantum gravity since the discovery of Hawking radiation and black hole evaporation in the 1970s. Although some of the important questions on a quantum black hole have been clarified in the light of string theory, the information paradox which jeopardizes quantum unitarity remains a critical issue. Dr. Raju made an original and essential contribution to the subject by pointing out the characteristic feature of the quantum Hilbert space of a black hole with Hawking radiation, which can describe the states inside and outside of the black hole horizon at the same time. His proposal has significantly influenced the recent research on the black hole information paradox, such as on the island proposal, and has drawn attention to the importance of the non-split property of the black hole Hilbert space.

Detailed description

Understanding of quantum gravity is one of the most fundamental and difficult problems in high-energy physics. While string theory has provided an elegant solution to the well-known difficulty of uncontrollable ultraviolet divergence encountered in quantizing gravity, quantum gravity comprises yet much deeper conundrums of a serious nature.

This started long ago from the recognition that surprisingly general relativity exhibits the structure of thermodynamics and in particular, as argued by J. Bekenstein, a black hole is a thermodynamic object with (in general) finite temperature and carries the entropy proportional to the area of its horizon (not to the volume of a black hole as one would expect). Moreover, S. Hawking found that a black hole, when the quantum effect is taken into account in a semi-classical approximation, can emit quanta the spectrum of which is exactly that of radiation emitted by a blackbody.

These findings implied that quantum black holes must have truly enigmatic and troublesome properties: (i) There appears to be a violation of unitarity in the time evolution from an initial pure state that collapses to a black hole and ends up in a mixed state which emits thermal radiation. (ii) This would in particular imply that the information thrown into a black hole will be eternally lost, in acute contradiction with the principle of quantum mechanics. (iii) As the entropy measures the logarithm of the number of possible microscopic quantum states under a specified macroscopic condition, how can it be proportional to the area while the black hole is a three-dimensional object?

The last question prompted such people as G. 't Hooft and L. Susskind to put forward a bold idea that all the information is stored on the horizon just as in holography. Further, J. Maldacena made this idea much more precise with concrete examples and proposed the "bulk/boundary duality", where a gravitational theory in the bulk of spacetime can be equivalent to a suitable non-gravitational theory defined on the boundary. If this conjecture is fully substantiated, the serious problems listed above may be solved provided that the boundary theory respects unitarity. Namely, the corresponding bulk theory with the emergent gravitational degrees of freedom will also be unitary, and if treated exactly the apparent problem of information loss by a black hole should disappear.

However, upon close examination, it appears that a naive application of this promising idea gives rise to another serious problem. S. Mathur and J. Polchinski and his collaborators independently pointed out that if one assumes the unitarity of the boundary theory, a region with highly excited quanta, dubbed "firewall", would form in the neighborhood of the black hole horizon, and the celebrated equivalence principle of general relativity would breakdown. Then spacetime would end at the horizon and the interior of a black hole together with the information stored within cannot be described by the boundary theory.

In this context, Dr. Raju, together with K. Papadodimas, presented a novel ingenious idea to resolve this impasse. They used the thermo-field double description of field theory at finite temperature, which uses a highly entangled system of two copies of the original system under consideration. In the limit of large N for the typical boundary theory with $SU(N)$ gauge symmetry, they demonstrated that one can construct an effective operator, in terms of a non-trivial combination of operators of the first copy describing the system outside the horizon, which when acted on the thermo-field double state can create a state in the second system in a characteristic state-dependent way. They further argued that this second copy can be interpreted as the Hilbert space describing the interior of a black hole. Thus, their idea materialized the notion of so-called "black hole complementarity" and asserts that the information inside a black hole can already be fully encoded in the system outside.

Although their work aroused a substantial amount of interest, the due influence of its essential importance has started to become apparent rather recently. In the past couple of years, substantial progress has been made by the recognition that the failure of unitarity inferred from the original computation of Hawking is due to the omission of the important contribution from a semi-classical saddle, called an "island", roughly inside the black hole horizon. Although this has been established in the path-integral formulation, it appears quite significant that the degrees of freedom of the island are made up of complicated state-dependent combinations of Hawking radiation modes. This of course is highly reminiscent of Papadodimas-Raju construction.

The deep influence of the work by Dr. Raju, including those after the Papadonimas- Raju paper, can also be seen in the recent significant work by S. Leutheusser and Liu tries to create the emergent “time” in the interior of a black hole. It was duly emphasized that of intrinsic importance is the so-called “non-split property” of the Hilbert space, namely that the Hilbert space of a black hole cannot be factored as the tensor product $\mathcal{H}_{inside} \otimes \mathcal{H}_{outside}$.

Their work in turn prompted Witten and his collaborators to study a change in the properties of the von Neumann algebra of observables when the $1/N$ gravitational corrections from the large N limit are taken into account in the holographic framework. It should be recognized that these promising developments can be said to have their roots in the work of Dr. Raju and K. Papadodimas.

We must mention also that more recently Dr. Raju has produced further influential contributions to the holographic principle in quantum gravity and the black hole paradox by analyzing these problems for more realistic situations. One such work is the study of holography in four-dimensional flat spacetime, performed with his collaborators. They showed that, at least for massless excitations, all the information present at future null infinity is also present near its past boundary. This original proposal for flat space holography is a significant step toward understanding quantum gravity in a realistic spacetime.

Another recent work of Dr. Raju and his collaborators is a critical assessment of the “island proposal” for the recovery of unitarity mentioned above. They pointed out that such a proposal is applicable only in the presence of a non-gravitational bath and massive gravitons. Also as a more robust approach to understanding the unitarity of black hole evaporation, it was emphasized that the aforementioned non-split property of the Hilbert space and the associated structure of the von Neumann algebra of the observables must be duly taken into account in the presence of gravity.

With his outstanding scientific achievements described above and his strong leadership established in India, it is clear that Dr. Raju is irrefutably qualified for receiving the Nishina Asia Award.

References

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