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TATA INSTITUTE OF FUNDAMENTAL RESEARCH

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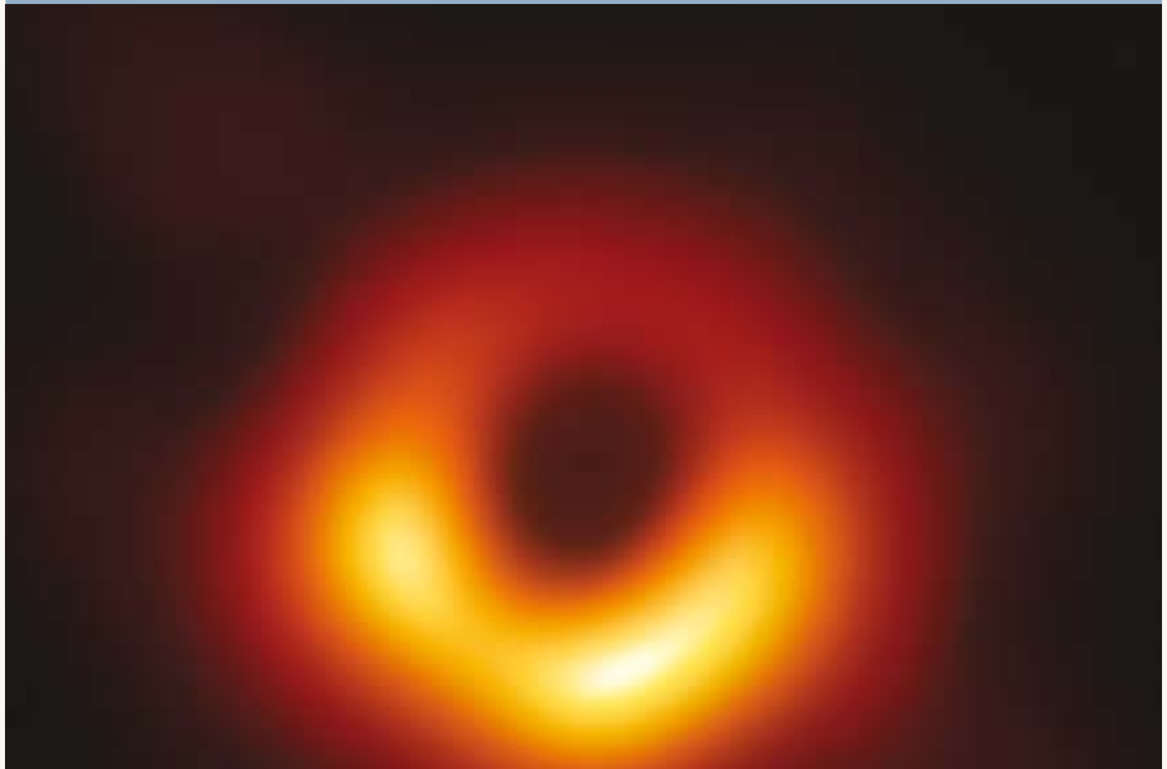

BACKSTORY OF A BLACK HOLE: THE DARK CENTRE OF THE RING IN THE GALAXY M87 | PAGE 1

QUANTUM TECHNOLOGIES | PAGE 2

SPACETIME FROM ERROR CORRECTING CODES | PAGE 1

AN INTERVIEW WITH **FERNANDO QUEVEDO** | PAGE 3

Editor- ANANYA DASGUPTA • Design - JUNY K. WILFRED

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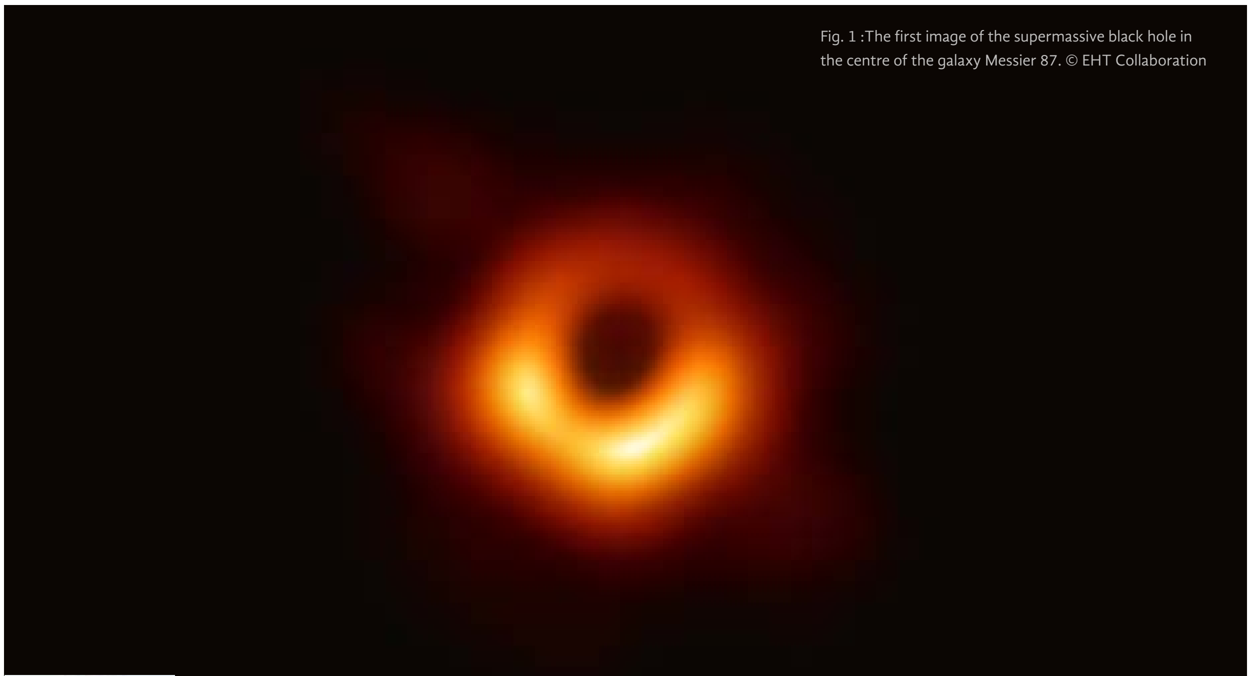

Fig. 1 :The first image of the supermassive black hole in the centre of the galaxy Messier 87. © EHT Collaboration

BACKSTORY OF A BLACK HOLE:

THE DARK CENTRE OF THE RING IN THE GALAXY M87

RAJARAM NITYANANDA

The recent picture of an uneven ring in a distant galaxy has excited astronomers, physicists and the general public. It is being advertised as the first direct view of a black hole – if the absence of radiation inside the ring can be called a view. This experiment – known as the EHT (Event Horizon Telescope) – is extreme in every way. It called for the shortest wavelengths, the best clocks, telescopes at high mountains or at the Earth's freezing poles, massive amounts of data and number crunching, sophisticated theory and modelling. The six papers which the collaboration sprang on the world in April this year have over three hundred authors from more than a hundred institutions, who worked together for several years.

Premonitions

This image did not spring out of the blue – it is a major milestone in a journey which involved repeated back-and-forth exchanges between physics, astronomy, and technology. The story begins as long ago as 1784 when John Michell, an English clergyman, dared to think of a body from which light could not escape, and how it might be detected by observing its effects on surrounding bodies. Alas, fame adheres to the already famous, so this early premonition of a black hole is more often credited to the French scientist Pierre-Simon Laplace, justly viewed as Newton's successor in taming the complex movements of the planets with equally complex mathematics. His independent speculation on what we now call black holes was published in 1799. Both Michell and Laplace imagined a body as dense as the Sun but five hundred times larger in size and hence 125 million (5003) times more massive than the Sun. Their simplistic calculations showed that such an object should be able to trap light. They used the concept of escape velocity – which is just 11.2 kilometres per second for the earth. The value increases with mass, but also decreases as the radius shrinks, since the gravity becomes strong. The combination, mass divided by

... continued on Page 10 ...

SPACETIME FROM ERROR CORRECTING CODES

DANIEL HARLOW

Our current physical understanding of the world we live in rests on two fundamental theories: quantum mechanics and general relativity. Quantum mechanics describes the behaviour of systems with small numbers of elementary particles, such as the hydrogen atom. General relativity, Einstein's theory of gravity, describes the behaviour of large systems whose gravitational pull is powerful enough to overwhelm any other force: examples include the spacetime near a black hole and the expansion of the universe as a whole. Both theories have passed remarkable experimental tests, for example the Large Hadron Collider (LHC) in Geneva regularly tests quantum mechanics to high accuracy and the recent observation of gravitational waves at gravitational wave observatories (such as the one currently being planned in Maharashtra) confirmed an essential prediction of general relativity.

Despite these successes, theoretical physicists are not happy with the current state of affairs. There are several reasons for this, but perhaps the most severe is that it seems there is a fundamental incompatibility between our most successful quantum mechanical theories, called quantum field theories, and general relativity. A quantum field theory, such as the standard model of particle physics, is a system with independent degrees of freedom at each point at space. One example is the electric field, which we learn as undergraduates can vary from place to place. Unfortunately, however, this local structure of the degrees of freedom is in tension with our understanding of black holes in general relativity. A black hole is an object which has undergone a complete gravitational collapse, leading to a gravitational attraction which is so strong that even light cannot escape from its vicinity. There are compelling arguments due to Jacob Bekenstein and Stephen Hawking that the number of independent

... continued on Page 4 ...

QUANTUM TECHNOLOGIES

ADITI SEN (DE)

The early twentieth century witnessed the formulation of quantum physics by scientists around the globe. During that period, several striking and counter-intuitive phenomena were discovered which cannot be explained by the laws of classical mechanics. Among them, the prominent ones are wave-particle duality, uncertainty principle, and quantum correlations, specifically entanglement. The last one is the property of a quantum system having multiple parties and in this article, we will discuss its important role in the development of quantum technologies.

In the classical world, complete information of a pure state, consisting of several subsystems, can be obtained by adding information content of each subsystem. However, such a simple law does not hold for a composite quantum mechanical system due to the existence of entangled states. Entanglement was first noticed in the seminal paper by Albert Einstein, Boris Podolsky, and Nathan Rosen (EPR) back in 1935. The authors questioned whether the theory of quantum mechanics is 'incomplete', based on two assumptions – 'locality' and 'reality'. The locality-assumption implies that when two parties are situated in two distant locations, the outcomes of the observables in the second particle do not depend on any action of the first particle. On the other hand, the assumption of reality says that before measurement, the system already has pre-assigned measurement values and so measurement only uncovers the results. This paper led to a long debate on the completeness of quantum mechanics until the year of 1964 when John S. Bell found a mathematical but testable inequality. It was shown to be satisfied by any local-realistic physical theory, and to be violated by some entangled quantum states.

Apart from the fundamental importance of the theory of entanglement, it has been realised in the last decade of the twentieth century that entangled states can be used to increase efficiencies in several communication and computational tasks. In other words, one of the basic ingredients for quantum technologies (that are more advantageous than their classical analogs) is entanglement. Before proceeding further, let us give a formal definition of entangled states for two parties. A state shared between two parties, say, Alice and Bob, is said to be unentangled (separable) if they can prepare the state by performing quantum mechanically allowed local operations only on their subsystems, followed by classical communication. Otherwise, the state is entangled.

Bipartite pure states are called maximally entangled if information contents of their subsystems are random, having maximal uncertainty although purity ensures the complete information about the entire system.

Notable protocols showing entanglement as resource include entanglement-based quantum cryptography introduced by Arthur Ekert in 1991 [2], quantum dense coding by Charles Bennett and Stephen J. Wiesner in 1992 [3] and quantum teleportation by Charles Bennett, Giils Brassard, Claude Crépeau, Richard Jozsa, Asher Peres, and William K. Wootters in 1993 [4]. All the quantum protocols show improvements in efficiencies compared to currently available communication strategies with and without security.

Existing communication schemes, related to our day-to-day life, ranging from telephones and television to internet banking deals with classical messages which are sent through classical channels. Classical messages can always be expressed in bits (binary digits) which is an array of 0s and 1s. A bit is also the basic unit of a computer that we presently use. Channels, carrying such messages by following laws of classical mechanics are called classical channels.

Bennett and Wiesner showed that encoding of classical messages in quantum states can help to increase the efficiency of the protocol. Let us discuss the quantum story which evolves between two parties, the sender, Alice and the receiver, Bob, located at two distant locations, say, Bangalore and Allahabad respectively. Alice wants to send some classical information, say 2 bits, to Bob. For example, the messages are today's result of India-Australia match and today's weather in Bangalore. Classically, Alice can encode the information in different distinguishable objects, say lights with four different wavelengths producing red, green, blue, and yellow lights. In other words, Alice requires a four-dimensional object to encode four possible messages (see Table).

The question that we are now going to ask is – can we reduce the space of encoding (like four different colours of light) with the help of quantum states? To answer this query, the first step is – Alice and Bob share a maximally entangled state. Depending on the message, Alice performs quantum mechanically allowed operations (unitary operations) on her part. (See Table for illustration).

Alice's message (pink-colored words indicate the difference in the message with the first one)	**Classical Protocol**	**Quantum Strategy**
India wins and Bengaluru is sunny	Red light	U1 (Identity)
India wins and Bengaluru is not sunny	Green light	U2 (Pauli spin operator 1)
Australia wins and Bengaluru is sunny	Blue light	U3 (Pauli spin operator 2)
Australia wins and Bengaluru is not sunny	Yellow light	U4 (Pauli spin operator 3)

Four different unitary operations based on four different messages on Alice's side help Alice and Bob to share four distinguishable two-party quantum states, specifically four maximally entangled states. After this, Alice sends her part of a quantum state to Bob and so Bob is in possession of two quantum particles which are distinguishable due to orthogonality. Therefore, by the virtue of quantum mechanics, Bob can design a protocol by which he can distinguish them, and hence can decode the message. In this quantum scheme, encoding of information at Alice's side requires only two dimensions instead of four dimensions, thereby doubling the capacity. Since in the quantum strategy, Alice can put the same amount of information in a smaller space, the described protocol is called quantum dense coding.

The above protocol deals with sending classical information encoded in quantum states but do not care about the security aspect. On the other hand, in a cryptographic protocol, Alice and Bob have to execute their strategy in such a way that a third party cannot get any information about their message. Securities of current cryptographic schemes are based on the fact that certain mathematical problems cannot be solved in any currently available computer within a reasonable time (polynomial time).

One such mathematical problem is to find prime factors of a given N-digit integer, known as prime factorisation problem. Interestingly, it was shown in 1994 by Peter W. Shor [5] that algorithm based on quantum physics can solve this problem in polynomial time, thereby showing the importance of building a quantum computer. Like bits in a classical computer, arbitrary quantum state in two dimension, called qubit (quantum bit), turns out to be the basic unit of a quantum computer. The discovery of factorisation algorithm has a huge impact in our society since quantum computer can, in principle, break all the existing classical cryptography protocols, thereby making personal banking to national security schemes insecure.

To get rid of such a crisis, quantum mechanics again comes as a rescuer. It has been shown that cryptography based on quantum theory can remain secure between Alice and Bob, even when the third party can have access to a quantum computer. Moreover, quantum mechanics ensures that any disturbance made by the third party for gathering information flowing from Alice to Bob and vice-versa can be detected. This is due to the fact that there exists mutually indistinguishable (nonorthogonal) quantum states which cannot be copied, thereby implying the nonexistence of a universal quantum copying machine.

Till now, we have discussed the role of quantum mechanics for sending classical information securely or in an unsecured manner. Let us finally move to a scenario when Alice wants to send some unknown two-dimensional quantum state (qubit) to Bob. This is because pure state of a qubit can be any point on the surface of the Bloch sphere and to specify any particular states, one requires infinite amount of precision. In a quantum case, suppose that Alice and Bob again apriori share a maximally entangled state. If Alice now performs a joint measurement on her part and on the box, and sends the measurement results to Bob by using two bits of classical communication (say, phone calls), the box can be sent exactly to Bob, provided Bob also performs some quantum operations on his part after receiving the phone calls. This is the famous quantum teleportation scheme, establishing infinite resource reduction with quantum states.

After these path-breaking inventions, the journey of building quantum devices has now begun. However, the rapid development of the subject of quantum information science was only possible due to the successful experimental implementation of these protocols over the last twenty years. For example, quantum communication protocols described above have been successfully realised with photons, starting from the late 1990s and later on by several physical systems like ions, superconducting qubits, nuclear magnetic resonance (NMR).

Current experimental progress in this field includes quantum teleportation over around thousand kilometres or more, commercial availability of quantum cryptographic solutions, and small-scale functional quantum computers. The current trends strongly indicate that the technologies that we currently use will possibly be replaced by the quantum ones in near future, thereby increasing our capacities for sending data or manipulating data. □

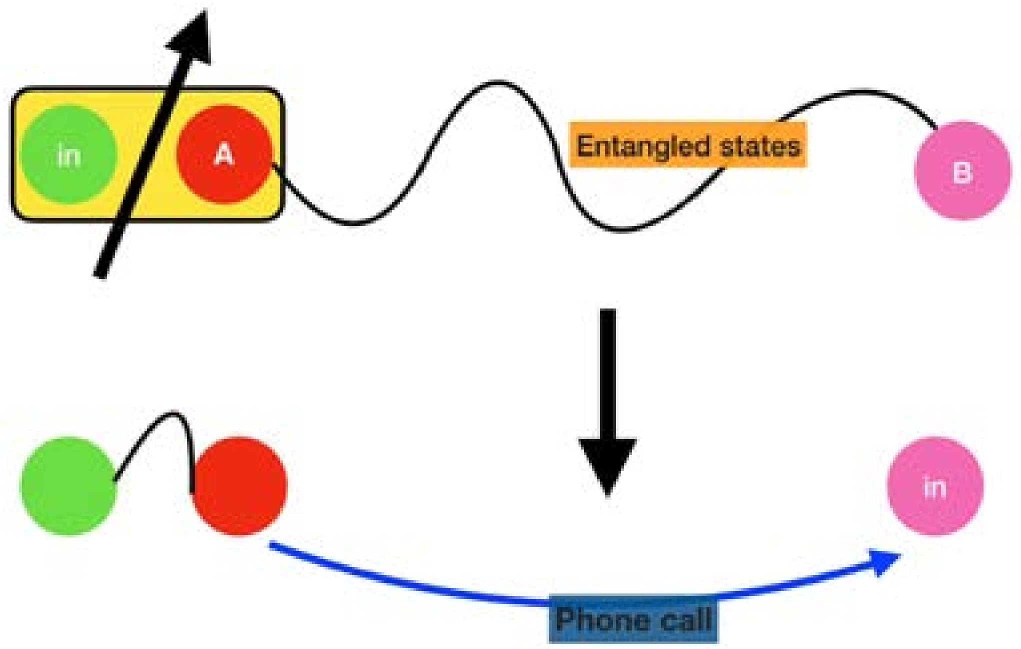

Fig. 2: Schematic diagram of Quantum teleportation

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[3] Communication via one- and two-particle operators on Einstein-Podolsky-Rosen states, C. H. Bennett and S. J. Wiesner. Phys. Rev. Lett. 69, 2881 (1992).

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Aditi Sen (De) is a theoretical physicist. She is a faculty member at the Harish-Chandra Research Institute, Allahabad.

It is very inspiring to be in ICTP, says Fernando Quevedo

Fernando Quevedo is a theoretical physicist. He has been the director of the International Centre for Theoretical Physics, Trieste, since October 2009. As he steps down from his position this November, he looks back at a very fulfilling ten years. Here are the excerpts from his interview with Ananya Dasgupta.

Can you tell us a bit about your education in Guatemala? How did you get into physics, whether you had a mentor who inspired you?

Well, as you know, Guatemala is a very poor country. And, unfortunately, without any tradition in science. Like many other kids, I was interested in some scientific issues, I read popular science books. But I didn't know that one could study physics and make it a career. I went to the National University to study systems engineering. But I picked all the physics and mathematics courses. There was one professor whom I liked very much. And during the two years I spent there, I learnt that one could study only physics.

What was the professor's name?

His name was Centeno. He recommended the famous Feynman lectures for me to read. And I was fascinated. In the meantime, I learnt from some friends that there was another university in Guatemala, a small university, where you could study physics and mathematics. I started getting interested in that. I met a few people who were actually doing what I wanted to do. But, of course, I was already studying engineering. Then something big happened. In 1976, there was a big earthquake in Guatemala. Many people died and it was a very sad incident. At that time, they were talking about closing the National University because a lot was going into efforts to repair the country. I didn't want to stop studying so a few friends and I transferred to the other university. And that's how I became a physicist. It was an unfortunate event, but it changed my life for the better as I became a physicist. That's the Guatemala part of my story.

Then you went on to the University of Texas to study under Steven Weinberg?

Yes, and there's another story here. For which I am always very grateful. And that is why I think it is always important to help giving opportunities to people. In the 1960s, there was a professor at the University of Texas named Robert Little. The National Science Foundation sent him to Central America to see how the education there was. He saw that there was almost no physics and the people who were teaching physics were all engineers. He decided to have some of them go to the University of Texas and study physics. So two or three of our professors went to Texas and then came

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HARLOW | *continued from Page 1 ...*

degrees of freedom any black hole possesses is given by its surface area measured in Planck units, or in other words the number of squares of size 3x10^(-35) meters we need to cover its surface. This may seem to be quite a lot of degrees of freedom, but in fact it is too few to be explained by quantum field theory. The reason is that in a theory with degrees of freedom at each point, the number of degrees of freedom in a region must be proportional to the volume of the region. Gravity however seems to be telling us that at least for black holes the number of degrees of freedom in a region is only proportional to its surface area. A theory which combines quantum mechanics and gravity, and thus is able to describe the quantum properties of black holes, must therefore have rather different properties than those of the quantum field theories we use to describe the rest of physics.

There are various proposals for how to formulate a theory of quantum gravity. None are complete, but so far the strongest is a set of ideas collectively referred to as string theory. The basic idea of string theory is to replace the local degrees of freedom of quantum field theory with extended objects such as strings, sheets, and more exotic higher-dimensional objects. So far string theory has only been formulated precisely in certain limits, but there is one very special limit that leads to one of the most remarkable discoveries of the last fifty years: The AdS/CFT correspondence. This correspondence gives a complete description of quantum gravity in a special set of spacetimes, those which are 'asymptotically Anti-de Sitter (AdS)', in terms of a conformal field theory (CFT) living in one fewer spacetime dimension (a CFT is just a special kind of quantum field theory). In the rest of this essay I will describe this correspondence, and then explain how it has recently been discovered to be closely related to interesting phenomena in the theory of quantum computation.

The basic idea of the AdS/CFT correspondence is shown in Fig. 3: a quantum gravitational theory living in the interior of a spacetime cylinder whose geometry is negatively curved, as in the famous drawings of M.C. Escher, is mathematically equivalent to a non-gravitational quantum field theory living at the boundary of the cylinder. In this figure time increases in the vertical direction, so the geometry of a slice of fixed time is precisely that of Escher (the figure only shows two spatial dimensions). The great power of this correspondence is that it equates something we do not understand (quantum gravity) with something that we do (quantum field theory in one dimension fewer). And moreover it shows us how quantum gravity is able to produce an area-scaling for the entropy of a black hole: because actually there is one fewer spatial dimension than we had thought!

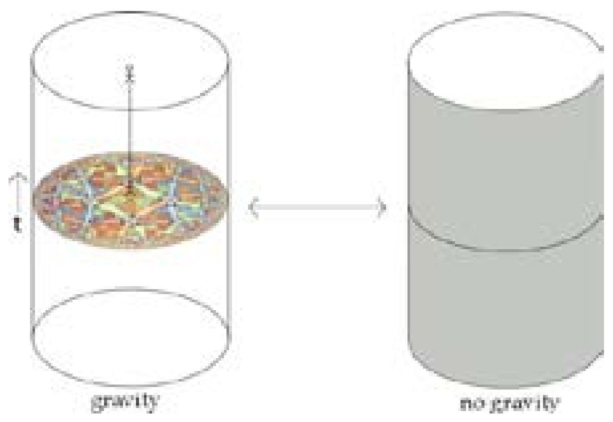


Fig. 3

There is, however, an obvious puzzle about this correspondence: if the world secretly has fewer spatial dimensions than we thought, how is it that we are fooled into thinking otherwise? In other words, how are we supposed to think about the radial direction in the cylinder from the point of view of the boundary quantum field theory? After all local quantum field theory in three spatial dimensions gives an excellent description of all the physics of everyday life, so a dual two-dimensional boundary quantum field theory must be able to pretend to be a three-dimensional quantum field theory coupled to gravity to high accuracy in all regimes where it has so far been tested. This puzzle can be phrased more precisely in the following way: how can the degrees of freedom in the center of the Escher painting be independent of those near its edges when actually the edge degrees of freedom are all there is?

In fact, this question has also appeared in a rather different setting: the field of quantum computation. Quantum computers are hypothetical devices which could harness the power of quantum mechanics to perform calculations which are far beyond the reach of conventional computers. In a conventional computer the memory consists of a string of bits, each of which is either zero or one. In a quantum computer these are replaced by qubits, which can be in any normalized linear combination of zero and one with complex coefficients. Each qubit therefore stores two complex numbers instead of just a single bit, and, although the rules of quantum mechanics make it impossible to have complete control over those numbers, they nonetheless permit us to make use of them in ways which are impossible for a conventional computer to mimic. There is a downside however: preserving this additional information in a quantum memory requires it to be extraordinarily isolated from the outside world, since due to a phenomenon called decoherence very small external perturbations can quite easily disrupt it. And even worse, to actually use the computer one needs to regularly act on the memory with logical operations – completely isolating the memory would make it useless. To overcome this problem, we need to write the state to memory in a way that protects it against external perturbations which affect any few of the qubits. In other words, we want the information being processed to behave as if it were independent of the individual qubits making up the memory, even though ultimately it is stored in those qubits. This is precisely the same problem we were confronting in AdS/CFT in the previous paragraph! Moreover, although it may sound impossible to solve, in fact a solution exists: we can encode the state in memory using a quantum error-correcting code.

The key feature of any error-correcting code is redundancy. For example, the Voyager 2 spacecraft is now at a distance of order 10^10 km from earth, and we are still communicating with it. The way we do are able to do so is basically the following: every time we want to send a bit of information to Voyager 2, we send it many times. Even if many of the bits are corrupted, as long as it is less than half the message will eventually get through. This simple method does not work for quantum information, since a famous theorem says that it is impossible to make copies of quantum information, but there is an alternative which works. This alternative makes use of what is perhaps the most mysterious feature of quantum mechanics, quantum entanglement. It is hard to explain entanglement precisely without using equations, but the rough idea is that in quantum mechanics it is possible to have two independent systems which together are in a definite configuration but separately both seem to be random. The way it works is that the fluctuations of the two systems are perfectly correlated, in such a way that when viewed together there are not actually any fluctuations. For this essay the important consequence of this is that entanglement provides a kind of redundancy: the perfect correlation between the separated systems is close enough to having a copy of the state that it can be used to protect quantum information from errors affecting small numbers of qubits. The slogan is that in a quantum error-correcting code the information which is relevant for the computation is stored non-locally in the entanglement between the qubits in the memory.

Once we realize that quantum error correction is possible, it is quite natural to conjecture, as I did with Ahmed Almheiri and Xi Dong back in 2014, that AdS/CFT is nothing but a rather sophisticated example of a quantum error-correcting code. And indeed the mathematics back this up: many of the features of the correspondence can be reproduced within the formalism of quantum error correction, and by using general results of quantum error correction we can improve our understanding of the correspondence. I would like to highlight in particular three problems in quantum gravity which have been illuminated using quantum error-correcting techniques. The first is emergence of the radial spatial dimension, which I've already discussed. The second is the possible set of symmetries in quantum gravity – it has long been suspected that no global symmetries are possible in quantum gravity, but so far the arguments for this have been primarily heuristic. Last year however Hirosi Ooguri and I were able to use the quantum error-correcting properties of AdS/CFT to show that no global symmetries of the gravitational theory are possible. The final problem is perhaps the most important: how to describe the interiors of black holes in quantum gravity. Perhaps the biggest unsolved problem in AdS/CFT is how to describe using CFT degrees of freedom the experiences of an observer who jumps into a black hole on the gravity side of the correspondence. The short answer is that we do not know, but there have been many interesting proposals put forward (Suvrat Raju of ICTS and Kyriakos Papadodimas of ICTP, Trieste, have been some of the key players in this field.), including the somewhat radical suggestion that such a description is impossible. Using quantum error correction it has been possible to show that at least in some special cases it is possible to see behind black hole horizons using AdS/CFT, and quite recently exciting work by Patrick Hayden, Geoff Penington, Ahmed Almheiri, Netta Engelhardt, Don Marolf, and Henry Maxfield has suggested a new picture for how this might work. Many details remain to be filled in, but it seems clear that the techniques of quantum error correction give us a powerful new window into what is possible in a theory of quantum gravity. And indeed it seems that quantum gravity also has lessons for quantum information theory, perhaps in the future these lessons may even be applied in practical quantum devices. □

Daniel Harlow is a theoretical physicist. He is a faculty member at the Massachusetts Institute of Technology.

BETWEEN THE SCIENCE

CHANDAN DASGUPTA, Simons Visiting Professor and Chair of our Program Committee, has been awarded the SERB Distinguished Fellowship. The Fellowship is awarded to superannuated eminent senior scientists actively involved in research.

RAJESH GOPAKUMAR, Centre Director ICTS–TIFR, has received the IIT Kanpur Distinguished Alumnus Award (DAA)2019. The Distinguished Alumnus Award is the highest award given by IIT Kanpur to its alumni in recognition of their outstanding achievements; As an alumnus of IIT Kanpur, Prof. Gopakumar delivered a talk at the pan–IIT Bay Area Leadership Conference, 2019. Watch the video at https://www.youtube.com/watch?v=uuJRkIL1_h8

SAMRIDDHI SANKAR RAY received the Dr APJ Abdul Kalam Cray HPC Award for 2019. Scientists with outstanding contributions in research related to or relying on high performance computing (HPC) are chosen for this award each year. Samriddhi was recognised for his contributions in using numerical simulations to understand turbulence and turbulent transport from the point of view of statistical physics.

SPENTA R. WADIA, Founding Director, Infosys Homi Bhabha Chair Professor and Professor Emeritus, ICTS-TIFR, did an interview with Lorraine Walsh of the Simons Center for Geometry and Physics (SBU, New York). Read the interview at https://scgp.stonybrook.edu/archives/29976

ICTS-TIFR won the '*Best Ornamental Garden in Bangalore*' award, for the third time in a row. The award was presented by the Mysore Horticultural Society, Lalbagh.

QUEVEDO | *continued from Page 3 ...*

back. And that became our only channel to go abroad. Because no recommendations we might have got would have any impact, the level was not particularly high. But this professor was very influential for us. He helped in organizing schools in Central America, trying to build a community.

So when I graduated, the only place where I essentially applied was at the University of Texas. And I was lucky that Steven Weinberg was also working there.

How was the atmosphere at the University of Texas then? Who were the other famous people around?

Oh, there were several. We felt we were at the centre of the world at that time. There was, of course, Weinberg. There were other senior people like Bryce DeWitt and John Wheeler, the advisor of Feynman. There was George Sudarshan, Yuval Neeman. The group also had a lot of young people, like Joe Polchinski, Claudio Teitelboim, Willy Fischler and Philip Candelas. It was the right time to be at the University of Texas. There were many very bright people, from all perspectives. The atmosphere was very exciting.

After the University of Texas, where did you go?

After I finished my PhD at the University of Texas, I went to CERN for a postdoc. I spent two years in CERN and then I went to McGill University in Canada. After that to the Los Alamos National Lab in the US. Then back to Switzerland to the Institut de Physique in Neuchatel, for a long-term position. After that I got a position in Mexico as a professor. A year and a half later, I got the offer from Cambridge.

All along this journey, did you keep in touch with the physics in Latin America?

Yes, all the time. For several reasons. I had many classmates in Texas who were all Latin American and we always kept in touch with each other. I kept in touch particularly with Guatemala, my country. Every time I went back to Guatemala, I was trying to help, giving talks and lectures, being in touch with students and my fellow professors. And then, perhaps 15 years or so ago, I made contact with my old professor, Centeno. At the time he was the scientific advisor to the President. He asked me if we could do something together to promote science. With his support I created the network of Guatemalan scientists. We were very few in number, but spread widely around the world. There were not only physicists, but mathematicians, chemists, biologists also. We organize activities every year and all scientists in the network come to Guatemala for this week. They then work with several scientists and students, even high school students. All to promote science in the country. We have been doing this for 14 years now. So now I go every year – with ups and downs depending on the government, of course. But have essentially managed to go every single year.

And do students from Guatemala come here? To ICTP?

Yes, we have 5-6 students here right now. One is in the diploma course, one is doing a PhD in the University of Trieste, one is doing a PhD in medical physics at the University of Trieste. One just finished a PhD in SISSA. So, yes, there is a natural flow of Guatemalan students.

Looking back, what do you think has been your most important contribution to physics?

That is a difficult question to answer. So let me think. Well, around 1990, some colleagues and I wrote a paper called 'Strong-weak coupling duality and non-perturbative effects in string theory.' And we named it S-duality. It was a very speculative paper. But around the years 1994-95, people started finding evidence of duality in a more formalized way. We felt very proud that we were the first to have had the idea and also invent the name. Now, whenever I hear someone talking about S-duality, I think 'Wow, we invented that name!' And the funny thing is that there was another duality, which was earlier only called duality. So when we invented S-duality, this also needed a name. So we named it T-duality. Even though it wasn't a contribution from me, we just invented the name. But it is good to see the people following it. So, that could be one of my significant contributions.

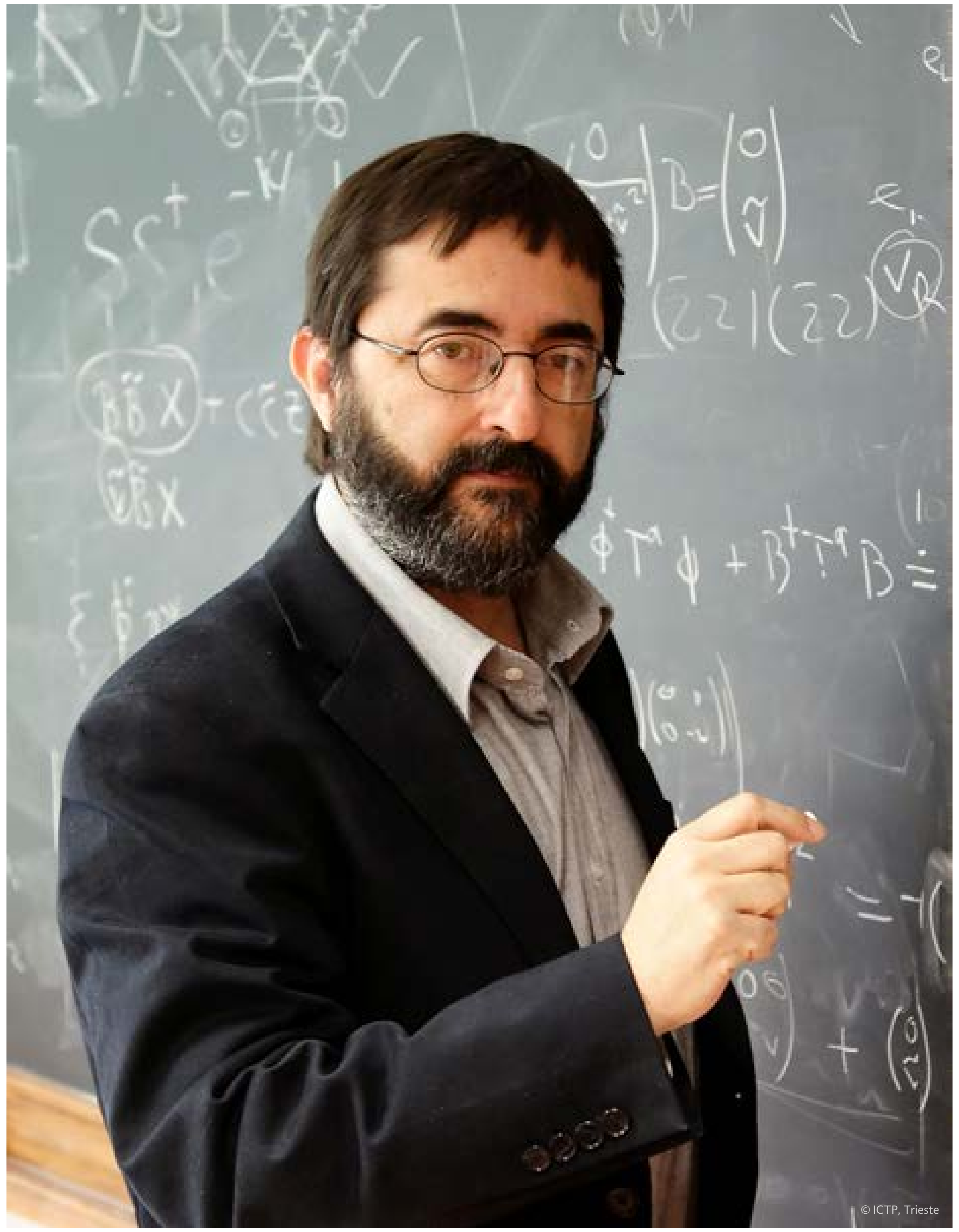
Also, this might be a time dependent statement, but we introduced the large volume scenario that is very much used in cosmology and string phenomenology. I like this very much but I guess only history will tell how important this was. Sometimes, you are very proud of your work and then you happen to do something on the side. And then that something on the side becomes more important.

I also wanted to ask how did you get into string phenomenology? Weinberg was not a string theorist, right?

You see in the 1980s Weinberg was doing supergravity phenomenology. This was the time when I was starting at the University of Texas. Then the first revolution in string theory happened – and everybody in the group, including Weinberg started working on string theory. In different branches of string theory. But after a while, Weinberg stopped doing string theory. And interestingly, it wasn't because he didn't like string theory, he always had great respect for string theory. He just felt that he would make better contributions to other fields.

Now coming to ICTP, what prompted you to take up the directorship here?

Actually the offer took me a bit by surprise. It was true that I had been quite active in promoting science in Guatemala. I had also started a fellowship to honour Prof. Little of the University of Texas. So I felt very motivated to help give opportunities to people from the third world countries, particularly my own country. I had great motivation to do this as I had also benefitted from this. But, of course, I had my career in Cambridge and I was very involved there. Until I received a message from the former director of ICTP and he asked me if I was interested to apply for the position. I was shocked that someone might have considered me as a candidate for this position. I had never done administration. But, you know, when we were students we would often dream of doing something big for our country or our



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region. And Salam had already done that, in a much more ambitious manner than we could ever imagine. I used to visit ICTP and had met Salam. And I knew that anytime I had an opportunity to work for ICTP, I would make myself available. I was always in touch with the people here. So I was surprised that someone considered me, but I decided to give it a try. Even though I had no experience. Luckily I was selected.

And how different was it to be in ICTP compared to Cambridge. Both in the broader sense and also your work?

Totally different. The student communities in the two places are totally different. In Cambridge, we are very lucky to get the best of the best. But many of these students have got all the opportunities because of where they were born. Whereas here, most of the students have been struggling all their life to get an opportunity and then held on to one because it's been once in a lifetime. In that sense it is very inspiring to be here. Of course, to be in Cambridge is also extremely inspiring from the scientific point of view. You are sharing your offices with Stephen Hawking or Michael Greene and others. Here, I have had to play a leading role. We have a very good set of scientists but the most important part is the mission of ICTP. It has changed my life completely. For instance, I stopped taking PhD students. In Cambridge, I used to work very closely with PhD students and I really enjoyed that. Luckily I have a grant to hire postdocs. So I changed my research style to work with postdocs and of course my previous collaborators.

Research, of course, has also reduced substantially. I need to give so much time to administrative issues. Mainly because I had no experience in the past – so I had to spend a lot of time to be able to get involved. But I made a resolution that I will not give up research. I actually talked to the two previous directors of ICTP and they gave me a lot of advice. And they told me the same thing – never give up research. The previous director K.R. Sreenivasan, told me that, 'If you had not done research, someone like you wouldn't be applying for a job. So then you can motivate other people to take up jobs like this. Because then they will see that it is not the end of their career.' I thought it was very good advice and I took it very seriously. If you are not an active scientist, you cannot have the right to lead an institution. And I consider it crucial for ICTP. Then, of course, Salam had already set an example. He was continuing to do great research and at the same time creating ICTP. A lot of work he did afterwards was very impressive. I think that is one of the duties we have as directors of ICTP, to follow the example of Salam.

I have to admit that my research is not the same as before. I have less papers. But I try my best to stay active and spend 2—3 hours every day on research.

Talking about Salam, do you remember your interactions with him?

I didn't have a lot of interaction with him. But the few I had, have been very important for me. So first, in 1982—83 he came for one of the Solvay conferences. I was totally fascinated by his talk. His flamboyance, his charismatic personality. I was just a youngster and I didn't talk to him at that time. Then when I applied for postdocs, he gave me my first postdoc offer. He sent me a telegram with the offer. At the end I went to CERN but he invited me to come here for three weeks before I joined CERN. In those three weeks, I managed to have several conversations with him. He was extremely kind and inspiring. He questioned me about my dreams of doing something big for Guatemala. I was very passionate about that. People used to queue up outside his office to tell him about the research they were doing. Once, he asked me to stay in his office while he talked to people and gave them advice. For me this experience was wonderful. You know, to see Salam in action. There were some other opportunities for me to interact with him, when he came to CERN or I visited ICTP. But in those three weeks I got to know him better and he had a lot of influence on my thinking.

Under your stewardship, ICTP has made major expansions. It's now in Brazil, in Rwanda, in China. What are the ties that ICTP, Trieste, still maintains with these centres?

The first thing that I did when I came here was to call a brainstorm meeting with all the scientists. After that I wrote up a strategic plan for the next five years. In that brainstorming meeting, one of the suggestions that came up was to expand the scope of ICTP to some key countries. At that time, I had three countries in mind – China, Brazil and India. These were the countries that had been on the receiving side of ICTP but over the years had developed and become financially richer and scientifically much stronger. So it made sense to join with these countries and create something for the region.

As it happened that there was a professor in Sao Paulo, Nathan Berkovits, who was already thinking of doing something similar there. So at some point we got in touch with each other and decided to try and create this new institute. That is how ICTP in Sao Paulo started and has been running for 7-8 years now.

Once we started in Brazil, other countries started showing interest. I tried to explore a bit in India and China, without much success. I realized there were many other complications. But Mexico and Turkey approached us. In the meantime, UNESCO came to us and said we cannot just create centres like this. This is because we are a category 1 UNESCO and we need permission from them. So we had to formalize the plans and needed to apply for ICTP, Brazil, to become a category 2 UNESCO institute.

Four countries also applied to UNESCO – Brazil, China, Mexico and Rwanda. It's very interesting because it covered four different continents. They were approved by the general council of UNESCO in 2015. The one in Brazil was very straightforward but the other three have taken some time. For Rwanda and China, they needed to sign a ratification agreement with UNESCO. They signed it more than a year ago. So from October 2018, ICTP Rwanda and China have started functioning. In Mexico, they created a small centre and according to the signature between the countries and UNESCO, that would be the category 2 centre. But that hasn't happened as yet. The centre is still running and we are collaborating with them but in an indirect manner. It is too early to say how the centres in Rwanda and China will evolve with time. They are totally different, of course. You see Brazil and China are very much advanced. Rwanda has a different history – it's not the biggest nor the richest country in Africa, but it has a lot of support for science from the government. It is a very transparent country, very safe for foreign visitors, safe for people to invest. And they were very keen for us to go there. Though their level of science is very low. So we have to do a lot of work there and our scientists need to be very actively involved. We do all the interviews for hiring faculty, we decide the content of the courses, we also go there and teach. So we are very very involved. And now there are four faculty members, the director and three more. They can start doing things by themselves but we still need to be involved.

In Brazil, I am always in touch with the director, Nathan. I am also the chairman of their steering committee so I have to keep going there. We have a meeting every year. Peter Goddard, who is the chairman of the academic council, and I always go together. We then discuss everything – including hirings, tenure track, approvals for meetings and conferences. We also try to collaborate. So, in ICTP we have a meeting on cosmology every year. The year we don't have it here, we hold it in Brazil. The same thing with phenomenology. So, we are very close to them.

In Brazil we don't have the masters program, whereas in Rwanda we have come up with one in collaboration with the University of Rwanda. This will help to raise the level and bring students from the region. In China, we are just starting – we had the meeting of the scientific council just last week. It is very ambitious, even more than Brazil. The hope is that the international component of ICTP will be able to attract scientists, who are not necessarily Chinese to work in the institution. And to use the centre to promote science in the region. Our aim is to go there and expand the mission of ICTP – to work together with the Chinese centre to promote science throughout the world. We are very keen to work with China because there is tremendous potential there. We had the opening conference last week and another will happen at the end of this year. There is open competition for faculty positions. They have a principal of 230 faculty positions, which is a lot for any scientific institution. The plan is to hire a few pre year so that we can slowly reach that number. The point is to attract the highest possible level of scientists. We are very excited about this new centre.

So all the four faculty members hired in Rwanda, are they local people?

No, no. The director is from Nigeria, who happens to be a former postdoc of ICTP. So he knows all about ICTP. One is Italian, who is also a former ICTP postdoc. The other two – one is from Cameroon and the other from Pakistan. You see it's important for us to keep this international dynamic. It is a challenge to keep it active and alive. We have to struggle a bit with the technicalities in order to implement what we want to achieve. There is a problem about funding as well, unlike Brazil and China where there is a lot of local funding. The government provided with the building – so we have a nice 4-5 story building. Faculty is also provided by the university. But funding for conferences, schools, fellowships for students (especially those who are not from Rwanda) is hard work to achieve. We provide some help from ICTP or work with other institutions. In Brazil, we are very lucky that the state of Sao Paulo has very good funding for science. They have the FAPESP, which is local to Sao Paulo. One per cent of the taxes of the state of Sao Paulo goes here, for science. So we first got a five-year grant, now it has been extended to another five years. We can use this for conferences and in that sense we have plenty of funds. This has made a great difference. In China also, there is the Chinese Academy of Science which has a lot of resources. For programs, we can collaborate with the Natural Science Foundation of China. So in this sense, Rwanda is the most challenging. And also Mexico, if it materializes, will not be so straightforward.

What do you think about Indian science, not necessarily string theory, compared to say China or Brazil? And also rest of the world?

I have always admired scientists from India. From when I was a student, I have had many friends from India. The level of science there is extremely high. I have great admiration for the tradition of top Indian scientists going back to their country, and not settling down in the United States. Their achievements, in physics, mathematics, chemistry, are significant. And India is the number one country for ICTP. We have a country report for every country, the number one is India. There are different levels among the scientists – some come from the top institutions and the others from universities where they have a lot of teaching. We keep our eyes on the IITs because they are the source of great minds from India. We want to work together with them and other institutions to help them give more time to research. Most of them give all their time to teaching and that is the difference we see between them and the people who come from TIFR, or HRI.

I see a lot of potential to collaborate with India and we have a very good experience in working with Indians. We have a diploma program in physics where we have a rule to not take students from India, China, Brazil, Argentina. This is because we know that the level in those countries is very high. In spite of this India we get the maximum students from India. Especially for the TRIL, Training and Research in Italian Laboratories, which is most used by Indian scientists. So the Indians who come to the centre are theorists, but the ones we work most extensively are the experimentalists. They visit labs all over Italy. So we have the agreement with the labs by which the scientists just visit the labs – so we don't see them. And this is the program most used by the Indians. And it is this way because the labs want the best scientists to work with them and the level in India is so high that they often get selected for this programme. Iran is also one country where the level is high.

Also we have the prizes – the ICTP Prize etc. I always say that every year we have to make a great effort not to give the prize to India. The quality of science done by Indian scientists in India is extremely high.

Now if I have to compare, say India and China – I would say that China is increasing the investment in science. But still, especially in theoretical high energy physics, India is ahead.

What roles have Indian scientists played in ICTP?

Very important roles. Indian scientists come here regularly in big numbers. Several of them have been working with us as faculty. Narain, Atish as well. People like Ashoke Sen are very generous with their time. Spenta, Rajesh, Shiraz, Rohini, Sunil. You just need to look at the list of prize winners. We had a case two years ago – husband and wife won the prize in the same year. Aninda Sinha and Urbasi. I knew Aninda very well from Cambridge. So you can see Indians have been continuously contributing and being role models to ICTP.

Then, of course, the director before me was Indian, Sreenivasan. Also something that needs to be mentioned here – Salam surrounded himself with leading scientists from developing countries and had many projects with them. And one of the key figures was CNR Rao. He was a very close friend of Salam. Together they created TWAS, CNR Rao was the president for a while. He played an important role in influencing Salam in many ways. He was kind enough to come for our 45th and 50th anniversaries.

So I feel Indian scientists have been crucial collaborators for ICTP, receiving from us as well as helping enormously.

What do you think about ICTS? What role do you think it can play not only in Indian science but in the world?

Oh I am a big fan of Spenta Wadia. I have talked to him a lot when he was planning and planning. It was a great pleasure to visit his institute. We went in helmets the first time to see the site and the construction. Then I saw it when it was finished and then again for Spenta's celebration. It is an impressive place – the location is fabulous, the facilities are wonderful and the conditions are excellent for visitors. The level of scientists working there is very very high. I have great admiration for Spenta and am very pleased that he has managed to achieve this.

So it is a wonderful institution and is very important for India and the world. I was with Spenta last week in China. He is helping us with the centre there and is in the academic council. He mentioned there that ICTS has been very influenced by ICTP. Of course he realized that it was better to put *'Science'* instead of *'Physics'* so that there is scope for expansion. I think after more than 50 years we know that our name limits the work that we do. I think Spenta has the right mission. Now we are collaborating – we have the regular winter school in biology. Our students have gone there as postdocs. So it's wonderful to have an institution like that.

It is a very attractive place for visitors from around the world. It has to be scientifically attractive also – you want to go somewhere where there are top scientists – and ICTS has that. Also the place offers you everything you want. It is very well-planned. And I think they have been doing great outreach work for the area as well. It is very important to promote science. They can and are playing a big role there. I have a very positive opinion of ICTS.

Last question – you are moving back to Cambridge in November. What will you miss about ICTP?

Everything. Well, everything except the problems of administration which can sometimes get very difficult. But I love ICTP and I have been very happy here. I miss it very much. Cambridge is my institution and I am very happy to go back. But over the years I have become very emotionally attached to ICTP. But then this is life and it's time to move on and make place for younger people with new ideas. And for me it has been ten years and that is a long time. It will be good to go back to a calmer and normal life. The last ten years have been very intense. ☐

ICTS BLOG

IN CONVERSATION WITH ALESSANDRA BUONANNO

Alessandra Buonanno is a theoretical physicist working in the field of gravitational waves. She is at present a Director at the Max Planck Institute for Gravitational Physics in Potsdam, Germany. On a recent visit to ICTS, to participate in the Future of Gravitational-Wave Astronomy program held between 19–22 August 2019, she spoke to Ipsita Herlekar on her journey as a scientist and the exciting work on gravitational waves being done in India.


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IH: ***How did you get interested in the field of gravitational waves?***

AB: I started studying gravitational waves by chance. I was initially trained as a theoretical physicist and a particle physicist. My Ph.D. thesis was on cosmology of the early universe. I worked on models of cosmic inflation inspired by string theory. Cosmic inflation is a phenomenon that we believe occurred at very early times in the history of the universe, within a miniscule fraction of a second after it was born.

After my Ph.D. thesis, I spent nine months at CERN, and then I started a postdoctoral fellowship at the Institute des Hautes Etudes Scientifiques (IHES) in France, outside Paris. It was there that I began working on gravitational waves from binary systems with Dr. Thibault Damour, after spending the first year working with him on cosmology and cosmic strings.

After finishing my time at IHES, I had to choose between joining Dr. Kip Thorne's group at Caltech to study gravitational waves and Fermilab outside Chicago to study cosmology. After a lot of thinking, I chose the former as during the late 90s, gravitational waves were still an unexplored and new field, and it seemed promising and exciting to me. Experiments were still being built and no-one knew when gravitational waves would be first detected on Earth. Caltech also hosted a very large group of scientists working on theoretical, experimental and data-analysis aspects of gravitational waves. I took advantage of this unique opportunity and learned a lot of science related to gravitational waves, and I also acquired new skills.

IH: ***Share with us your journey as a woman in science.***

AB: I am very much aware of the issues that many women encounter in science and academia. But I have been very fortunate to have not experienced them first-hand. During my training as a postdoctoral scholar or even previous to that, I cannot recall of any experience where I felt I was being discriminated because of my gender. I have always been very focused on my work and I have worked hard to achieve my goals. Perhaps because I was very self-critical of my work and very determined to not be distracted from my goals, it didn't occur to me that such discrimination did exist around me.

Growing up I always had the support of my family in whatever I chose to do and I was never discriminated or treated differently for being a girl. No one at home told me I couldn't do research because I was a girl. I also have been very lucky to have had excellent mentors and colleagues. I had fruitful and pleasant collaborations with other graduate students and post-docs, and I have very fond memories of my post-doc days. My Ph.D. supervisor Dr. Michele Maggiore, Dr. Gabriele Veneziano my post-doc supervisor at CERN, Dr. Thibault Damour at IHES, and Dr. Kip Thorne at Caltech, have all inspired me and have provided me with invaluable advice during my professional career. All I can say is that I have been very lucky and am very grateful to them. But I do know there exists a gender gap in academia. Many women quit research after their Ph.D. thesis or post-docs, and the numbers reduce as one goes higher up in the academia ladder. And of course, I see this pattern in the Max Planck Society also. The number of women directors is still small. Also, the area in which I work, that is theoretical physics, has very few women scientists - even lesser than other areas such as astrophysics. That's something I have noticed here at ICTS too. But yes, there is a lot to be done to retain more women in science and it has to start much before women enter university. It should begin much earlier in life; both at school and at home. Boys and girls have to be treated equally since early on in their childhood, and young girls should be encouraged to be confident, to believe in themselves, and take up science, if that is what they wish to do.

At the Max Planck Institute we have researchers and scientists from all over the world. The work we do goes beyond geo-political boundaries. There are many countries that are still not economically strong enough to support world class research facilities and infrastructures, and the people of these countries have less opportunities to take up science as a career. Science should have no boundaries and as scientists, we should ensure it is done that way. It is true that we need more women in science, but we must also work towards increasing diversity that goes beyond the gender category.

Read the full interview on the ICTS Blog at https://blog.icts.res.in/blog/conversation-alessandra-buonanno. ICTS blog features articles related to research, interviews of scientists and brief reports on workshops, events and programs organised on campus. Visit https://blog.icts.res.in/ for more articles.

PROGRAMS

Perfectoid Spaces
9–20 September 2019 ✦ *Organisers* – Debargha Banerjee, Denis Benois, Chitrabhanu Chaudhuri and Narasimha Kumar Cheraku

Multi-scale Analysis and Theory of Homogenization
26 August–6 September 2019 ✦ *Organisers* – Patrizia Donato, Editha Jose, Akambadath Nandakumaran and Daniel Onofrei

Advances in Applied Probability
5–17 August 2019 ✦ *Organisers* – Vivek Borkar, Sandeep Juneja, Kavita Ramanan, Devavrat Shah and Piyush Srivastava

Cauchy-Riemann Equations in Higher Dimensions
15 July–2 August 2019 ✦ *Organisers* – Sivaguru, Diganta Borah and Debraj Chakrabarti

Summer School on Gravitational Wave Astronomy
15–26 July 2019 ✦ *Organisers* – Parameswaran Ajith, K. G. Arun and Bala R. Iyer

Mathematical and Statistical Explorations in Disease Modelling and Public Health
1–11 July 2019 ✦ *Organisers* – Nagasuma Chandra, Martin Lopez-Garcia, Carmen Molina-Paris and Saumyadipta Pyne

Bangalore School on Statistical Physics - X
17 June–28 June 2019 ✦ *Organisers* – Abhishek Dhar and Sanjib Sabhapandit

Summer Research Program on Dynamics of Complex Systems
15 May–12 July 2019 ✦ *Organisers* – Amit Apte, Soumitro Banerjee, Pranay Goel, Partha Guha, Neelima Gupte, Govindan Rangarajan and Somdatta Sinha

Summer School for Women in Mathematics and Statistics
13–24 May, 2019 ✦ *Organisers* — Siva Athreya and Anita Naolekar

DISCUSSION MEETINGS

The Future of Gravitational-Wave Astronomy
19–22 August 2019 ✦ *Organisers* — Parameswaran Ajith, K. G. Arun, B. S. Sathyaprakash, Tarun Souradeep and G. Srinivasan

Education Systems in South Asia: Present Status and Future Evolution
1–3 August 2019 ✦ *Organisers* — Rekha Pappu, Padma Sarangapani and Leena Chandran Wadia

Edge dynamics in topological phases
10–14 June 2019 ✦ *Organisers* – Subhro Bhattacharjee, Yuval Gefen, Ganpathy Murthy and Sumathi Rao

Thirsting for Theoretical Biology
3–7 June 2019 ✦ *Organisers* – Vijaykumar Krishnamurthy and Vidyanand Nanjundiah

LECTURES

INFOSYS—ICTS CHANDRASEKHAR LECTURE SERIES

Metamaterials and Topological Mechanics
24 June 2019 ✦ *Speaker* — Tom Lubensky *(University of Pennsylvania, Pennsylvania)*

INFOSYS—ICTS TURING LECTURE SERIES

The Power of Sampling
14 August 2019 ✦ *Speaker* — Peter W. Glynn *(Stanford University)*

INFOSYS—ICTS DISTINGUISHED LECTURE

The Making of High-Precision Gravitational Waves
10 April 2019 ✦ *Speaker* — Alessandra Buonanno *(Albert Einstein Institute, Germany)*

INFOSYS—ICTS STRING THEORY LECTURES

Baryons, Determinants and Integrability at Large N
14–16 October 2019 ✦ *Speaker* — Shota Komatsu *(Institute for Advanced Study, Princeton)*

A Modern Take on the Information Paradox and Progress Towards its Resolution
30 September–3 October 2019 ✦ *Speaker* — Ahmed Almheiri *(Institute of Advanced Study, Princeton)*

The Fishnet Model
24–26 June 2019 ✦ *Speaker* — Amit Sever *(Tel Aviv University, Israel and CERN, Geneva)*

Integrability in Planar AdS/CFT, Yangian Symmetry and Applications
13–15 May 2019 ✦ *Speaker* — Niklas Beisert *(ETH Zurich)*

PUBLIC LECTURE

Big Bang, Black Holes & Gravitational Waves
21 August 2019 ✦ *Speaker* — Abhay Ashtekar *(AInstitute for Gravitation & the Cosmos and Physics Department, The Pennsylvania State University)*

KAAPI WITH KURIOSITY

Elementary arrangements
20 October 2019 ✦ *Speaker* — Arnab Bhattacharya *(TIFR, Mumbai)* ✦ *Venue* — J. N. Planetarium, Bangalore

Thinking ecologically about Indian cities
22 September 2019 ✦ *Speaker* — Harini Nagendra *(Azim Premji University, Bangalore)* ✦ *Venue* — J. N. Planetarium, Bangalore

The Culture of Science
18 August 2019 ✦ *Speaker* — Jayant Narlikar *(Emeritus Professor, IUCAA, Pune)* ✦ *Venue* — J. N. Planetarium, Bangalore

A Mathematical Adventure in Immunology
7 July 2019 ✦ *Speaker* — Carmen Molina-Paris *(School of Mathematics, University of Leeds, UK)* ✦ *Venue* – J. N. Planetarium, Bangalore

Quantum Technologies
16 June 2019 ✦ *Speaker* — Aditi De *(HRI, Allahabad)* ✦ *Venue* – J. N. Planetarium, Bangalore

NITYANANDA | *continued from Page 1 ...*

radius, determines when this speed reaches the speed of light.

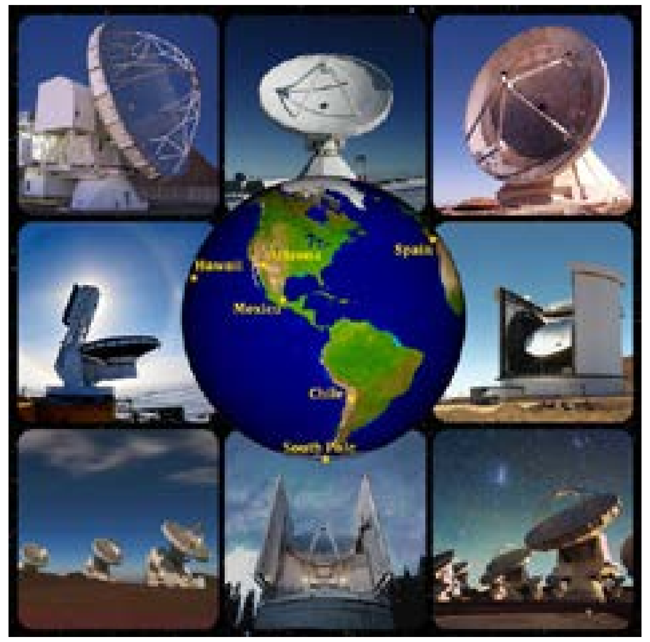
Messier 87

Meanwhile in 1781, the French astronomer Charles Messier published a catalogue of more than a hundred fuzzy-looking objects – definitely not stars – which were fixed in the sky. Our ring is located at the centre of object number 87 in his list. His catalogue was simply meant for his fellow comet hunters to ignore. This tribe kept their telescopes trained to look for moving fuzzy objects which could then be named after them. (Halley's comet is a well-known example, predating Messier). The nature of these Messier objects or 'nebulae' – so called for their vague resemblance to clouds – remained a mystery. Today we know there are many different kinds of objects which present themselves as nebulae.

Enter Einstein

The astronomy of the solar system pioneered by Laplace moved from triumph to triumph in the nineteenth century, with only the motion of Mercury refusing to fall into place. This tiny discrepancy was the first inkling (from observation) that Newton's gravity needed repair. From the theoretical side, Einstein was unhappy from day one, in 1905, with instantaneous action at a distance. He had just banished the concept of absolute simultaneity in his special theory of relativity. It took him ten years to fix this problem, by banishing gravitational force as well! He replaced it with the curved geometry of space and time. In 1915 he was able to find approximate solutions of his own ten complicated equations, which explained the orbit of Mercury, predicted the bending of light as it passes a massive object, and the reddening of light as it climbs away from a massive body. We should not, however, attribute the first theoretical glimpse of black holes to Einstein. That honour goes to the astronomer Karl Schwarzschild, who was serving in the German army in the First World War when Einstein's paper came out. Schwarzschild quickly found the first exact solution of the equations that Einstein had proposed which is forever known by his name. Contrary to popular opinion, Einstein was not an expert mathematician! Tragically, Schwarzschild barely lived long enough to see his work in print in 1916.

Fig. 4: Antennas of the Event Horizon Telescope used in April 2017 *(Clockwise from upper left)* APEX, Pico Veleta, LMT, JCMT, ALMA, SMT (Heinrich Hertz Telescope), SMA, SPT.
© APEX, IRAM, G. Narayanan, J. McMahon, JCMT/JAC, S. Hostler, D. Harvey, ESO/C. Malin



The universe is made of galaxies

In 1918, Heber Curtis in the United States saw a strange, unprecedented streak in his photographs of the centre of M87. By 1920, he had to defend his view that many of Messier's objects were huge collections of stars, like our own galaxy, so distant that we only saw them as blurred images on photographs. The leading authority on the subject, Harlow Shapley of Harvard, did not believe Curtis. But he was soon proved wrong when Edwin Hubble saw individual stars in our neighbour, the Andromeda galaxy. This had the same impact as Galileo seeing the stars of our own Milky Way – humanity was cut down to size once more. The study of galaxies and the expanding universe they inhabit is a major chapter in the progress of astronomy, but not a theme of this piece.

The long gestation of the black hole idea

The physical meaning of Schwarzschild's mathematics remained unclear for decades. In Einstein's theory, the same physical object can take many different mathematical guises, not all of which are easy to interpret. Our current understanding is that Schwarzschild's solution describes a black hole. This is a sphere from which even light cannot escape and within which any matter falls inexorably to a still ill-understood fate. This sphere is called the 'event horizon' and gives its name to the EHT. This modern understanding of the black hole had to wait till a 1958 paper by David Finkelstein, whose name should be better known than it is. To the mathematically literate and inclined, work by Roger Penrose and Stephen Hawking in the mid-1960's added further evidence. They showed very generally that Einstein's equations can lead to 'singularities' – the big bang birth of our universe and the sticky end of infalling matter being two examples.

First radio signals from M87

Jump-cut to the Australian and British scientists who had been pressed into service to work on radar technology in the Second World War. Once released, they pioneered a new area: radio astronomy. In 1948, the Sydney based scientists John Bolton and Gordon Stanley found a strong source of radio waves in the constellation of Virgo. They proposed, tentatively, that these came from Messier 87, even though the object was known to be more than a hundred million light years away. The technique they used is called interferometry - the signals from two radio telescopes are combined to measure the difference in arrival time and infer the direction of the source. For waves, this shows up as a misalignment of crests and troughs at the two telescopes. (A similar effect plays a role in how we and most animals determine the direction of sound waves using two ears and appropriate hardware/software in the brain). Cleverly, they used just one telescope mounted on a cliff in New Zealand. The second was provided gratis by its image reflected in the sea, which is a good mirror for long radio waves. Leaving out this last twist, the same principle – of accurately recording and comparing signals at separated telescopes – underlies most of radio astronomy today, and lies at the foundation of the EHT effort. The fundamental principle is that a small change in the direction of a radio source will cause a delay between the two waves proportional to the distance between the two telescopes. The shorter the wavelength, the easier it is to detect small changes in direction, and hence make images with fine detail. Radio astronomy progressed by going to shorter wavelengths and increasing the separation between the telescopes

The technological progress needed for the EHT to work is evident from the numbers. In 1948, the telescopes were separated by 600 metres, and operated at a wavelength of 2 metres. The 'pictures' were blurred by one-fifth of a degree – our eyes do ten times better. By 1993, enough was known about the black hole in M87 to make a rough guess about the angle subtended at earth. This is one part in a hundred million of a degree. Clearly, the separation had to increase, and the wavelength had to decrease, to achieve this level of acuity. In 2017, when the EHT took its data, the telescopes were separated by up to 10,000 kilometres, at a wavelength of 1.3 millimetres. A greater separation is not possible on earth, and in fact, the source was setting in Spain as it was rising in Hawaii!

Black holes take root

From the theoretical viewpoint, the Schwarzschild black hole was still a work in progress in the 1960s. It is not enough to produce one solution of Einstein's equations – one has to make sure it is stable. One would need extraordinary precision to make an unstable object in the real world, such as a pencil balancing on its sharp point. This issue was settled definitively, at least for small disturbances, by C.V. Visweshwara in his 1970 PhD thesis at the University of Maryland. This pioneering calculation corrected incomplete work done earlier by two famous people, Tullio Regge and John Wheeler, which did not properly account for the true nature of the event horizon. Stability in this context means that the formation of a black hole is accompanied by damped oscillations. These were detected by the LIGO observatory in 2016 when it observed the gravitational waves from two merging black holes. The observed signal from this event closely matches the earlier theory of small oscillations, and also matches the output when powerful computers loaded with ingenious programs are fed with Einstein's equations. Between them, theory, computation, and observation have removed all reasonable doubt about our overall picture of black holes. This is true not just for the Schwarzschild black hole but the rotating, flattened generalisation, which Roy Kerr of New Zealand found in 1963. The long time gaps are good indicators of the technical and conceptual challenges of working with Einstein's theory. All astronomical objects rotate – barring possibly the entire universe. Black holes are no exception, so the Kerr solution is part of the toolkit of every practicing and aspiring black hole astrophysicist today.

Astronomers did not wait for the theorists to dot all the i's and cross all the t's. By the mid-1960s it was clear that the centres of many galaxies – not just M87 – harboured prodigious energy sources: a trillion suns worth or more just in radio waves! Edwin Salpeter and Yakov Zeldovich, two pioneers of theoretical astrophysics on opposite sides of the Iron Curtain, invoked black holes as the 'central engines' as early as 1964, though it took another decade for this insight to be generally accepted. It is an interesting paradox that when astronomers see explosion or outflow, they invoke the opposite process of implosion – fall under gravity. A falling body picks up speed, and part of this energy can be converted, with sufficient ingenuity, to other forms such as radiation or an outflowing jet. The combination of rotation – always present – and electrical conduction makes for magnetic fields – a kind of dynamo believed to operate in a disc of inspiraling matter and indeed at the very surface of the rotating black hole. By the late twentieth and early twenty-first century, elaborate computer models with all these ingredients had been created and tuned to match the observations of these 'active galaxies' like M87. The increasing success of these models suggested that one should now look for the central black hole directly, by radio interferometry. Heino Falcke in Germany showed that this goal was difficult but within reach. Sheperd Doeleman observed the centres of galaxies at the smallest possible angular scale for his PhD thesis at MIT in the US. The two, who joined forces, were born around the time Hawking and Penrose were trying to put black holes on a firm theoretical footing and are now two of the leaders of the EHT effort.

The image was hardly produced in real time. The radio signals – and the time accurate to nanoseconds – was separately recorded at each telescope. The hard disks were then shipped to two nodal locations in Germany and in the US. The highly computer-intensive comparison of the different signals followed by preparation of the image, and innumerable cross checks for such a major claim, happened over two years, while the astronomical community waited.

Is the image what is to be expected? The team included people who had worked for years on modelling the processes as matter circles and then falls into a rotating black hole, including radio emission. The radiation does not come straight to us – it is bent by gravity, and in principle some of it can even arrive here after circling the black hole more than once! What we see is thus a rather distorted version of what is present at the source. The radiation originates from the innermost regions of the gas which is spiraling into the black hole, where the temperature, magnetic field, and density are the highest.

All this was allowed for, by elaborate computer simulation, in the analysis of the data presented in the first paper which came out simultaneously with the press release. The image is often called the 'photon ring.' This phrase refers to a property of a black hole which has been known from the early days of the general theory of relativity. For a non-rotating black hole, it is possible for light to travel in a circular path at one and a half times the radius of the event horizon. This is an unstable situation. The slightest error in the radius, and the light either escapes to infinity or falls into the black hole. While it is true that we see those rays that escaped to infinity, later papers have pointed out that paths near the ring do not dominate the image, so this terminology is not strictly accurate, but perhaps the name has stuck!

Models fitting the observed ring in detail have been constructed. What is clear is that we don't see any radiation coming straight from the black hole – that's not allowed. And in that darkness, like Sherlock Holmes' dog that did not bark in the night time, lies the discovery.

One of the most sensitive telescopes in the collaboration is on the peak of Mauna Kea in Hawaii. Thanks to its altitude and clear skies, a veritable forest of radio and optical observatories have sprung up. The original inhabitants had to surrender land which they regarded as sacred, and indeed have so far successfully stalled, in court, a major proposed international project for a 30-metre optical telescope which India has already bought into. Perhaps as a concession to local sentiment, the EHT team has proposed the name 'Powehi' for this object. It means something like 'endless dark source of creation' in one of the local myths. Black holes will now move decisively from widely held, compelling myth to observed reality and to routine use in understanding astronomical observations. As the old adage from particle physics states, *"Yesterday's discovery is today's calibration and tomorrow's background."* They are as much part of our universe as stars, and astrophysicists of the future will probe them for more details with ever improving observation and theory. ☐

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DISCUSSION MEETING

THE FUTURE OF GRAVITATIONAL–WAVE ASTRONOMY

A four-day discussion meeting was organized to celebrate the work of Bala Iyer, pioneering Indian gravitational–wave physicist and Simons Visiting Professor at ICTS–TIFR. This meeting brought together researchers from various aspects of gravitational wave (GW) science and related areas. As GW observations are emerging as a powerful probe of the fundamental physics and astrophysics, this meeting tried to identity the future challenges and opportunities. Some of the participants at the meeting were Abhay Ashtekar *(Penn State University)*, Alessandra Buonanno *(Albert Einstein Institute, Germany)*, Ashoke Sen *(HRI Allahabad)*, B. S. Sathyaprakash *(Penn State University* and *Cardiff University)*, Jayant Narlikar, Somak Raychaudhury, Tarun Souradeep *(IUCAA, Pune)* and Stan Whitcomb *(LIGO/Caltech)*.


Alessandra Buonanno delivers the ICTS Distinguished Lecture


Bala Iyer, Sanjeev Dhurandhar


Tarun Souradeep, Rana Adhikari, Unnikrishnan C. S., Bala Iyer


Group photo of the participants