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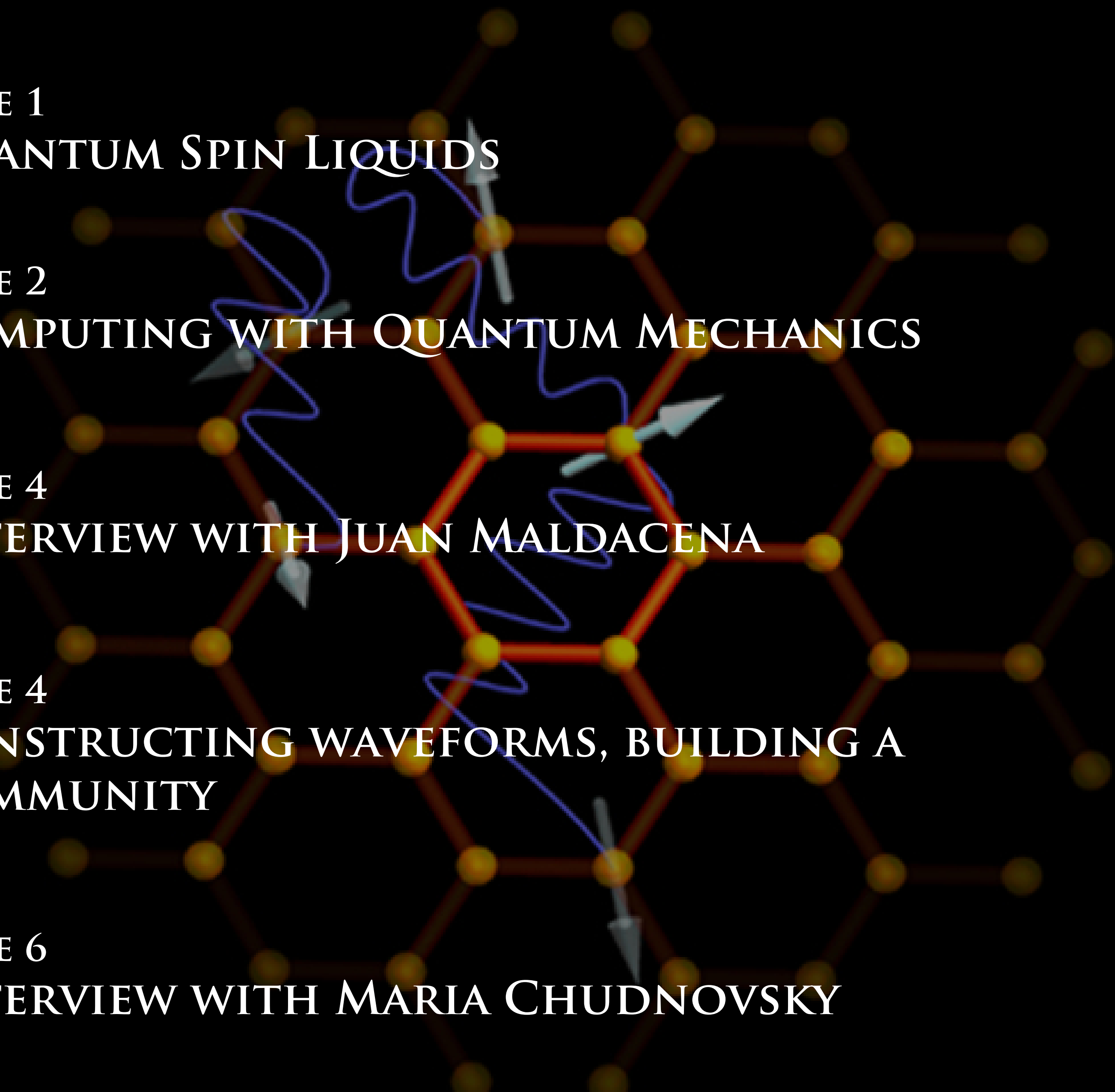

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Quantum Spin Liquids

Subhro Bhattacharjee

Our universe derives its richness from complexity. Examples of complex phenomena include stars and galaxies, turbulent fluid flows and weather patterns and life itself. At the heart of such complex natural phenomena are myriads of emergent 'organizing principles' that owe their origin in the collective behavior of a large number of mutually interacting units – electrons, atoms, molecules etc., that form these, complex systems'. [1,2]

A particular class of complex systems that have a tremendous influence on our lives are materials with interesting emergent electronic properties. Familiar materials like metals, semiconductors, magnets and superconductors owe their distinctive properties to the relatively simple emergent behavior of complex systems consisting of a large number of electrons. Several recent technological advancements – from power cables to computers, smartphones and MRI machines are direct outcomes of our ability to harness such complex electronic behavior. Each of these systems is useful to us due to its particular 'organizing principle' [1,2], e.g., a piece of lodestone whose emergent magnetic properties are useful in constructing magnetic compass needles.

Symmetries and phases of matter: The framework to understand and classify electronic phases of matter – condensed matter theory – has been immensely successful. One of the organizing principles of this framework is that different phases of matter can often be classified on the basis of symmetries [3]. For instance, solids and fluids are both governed by microscopic equations that are translationally invariant. While fluid phases respect translational invariance, however, this invariance is spontaneously broken in a crystalline solid in which atoms occupy discretely different positions to form a lattice. This spontaneous breaking of symmetry quantitatively accounts for many of the differences in properties between fluids and solids. Research, over a good part of the last century, has consolidated this and associated ideas within a sophisticated mathematical framework that presently form much of the basis of our understanding of phases of matter.

Phases beyond spontaneous symmetry breaking: The above symmetry based classification is, however, incomplete in more than one way [4]. While the earliest indications of the failure of the above paradigm came from the experiments and subsequent theoretical understanding of integer and fractional quantum Hall effects in 1980s [5], more recent developments (both experiments and theory) in the field of quantum magnetism have driven home the limitations of the above framework in a wider setting [6,7].

Magnetism: While humans have been aware of magnetic properties of materials explicitly, through lodestones, from as early as 6th century BC, comprehensive understanding of the phenomena had to wait till the development of quantum mechanics in the beginning of last century. We now understand that magnetic properties have their basis in a property of quantum particles (electrons, protons and neutrons) called their spin. For example, the spin of an electron can be very roughly thought of as a minute magnetic compass needle whose properties are dictated by laws of quantum mechanics.

In a class of crystalline solids, called magnetic insulators, the repulsion between electrons (due to Coulomb's law) immobilizes them, forcing them to sit on ionic sites. While the spatial positions of electrons are frozen, their spins can continue to fluctuate, and the magnetic behavior of the system is determined by how such typically 10^{23} mutually interacting spins behave cooperatively.

Experimentally, examples of such spin systems are aplenty and many of them undergo a magnetic ordering transition below a critical temperature. In such substances the spins order in a particular pattern on an average. Such spontaneous picking of a pattern is very similar to the ordering of atoms in solids described above. Exploring the analogy with solids, we can denote such an ordered structure as a 'spin-solid' as opposed to the high temperature 'spin-fluid' state where the spins do not form any pattern. The spin patterns in spin-solids can be captured within the framework of spontaneous symmetry breaking just like regular solids, but for spontaneous breaking of spin-rotation symmetry [3]. Usually, such ordering is seen in systems where the interaction between the spins is globally minimized by choosing a particular ordering pattern.

Quantum Spin Liquids: However, for a class of quantum magnets, due to the nature of the interactions, such energy minimization is not achieved. These systems do not undergo magnetic ordering transitions and remain in a spin-fluid state even at arbitrarily low temperatures. The low temperature properties of such spin-fluids are governed by quantum mechanics. The strong interactions between spins at low temperatures make these substances 'spin liquids' rather than 'spin gases'. Such a cooperatively quantum-fluctuating state (as opposed to a thermally fluctuating state) formed by a large number of spins obeying quantum mechanics has been dubbed as a 'quantum spin liquid' (QSL). [6,7,8]

The predominance of quantum effects is a central feature of such a QSL state. According to our present understanding, at the heart of a QSL state is long-range quantum entanglement which does not have any counterpart in classical systems [4]. The presence of such entanglement can lead to a variety of novel properties, particular to this class of systems. This is a new type of emergent phenomenon of condensed matter.

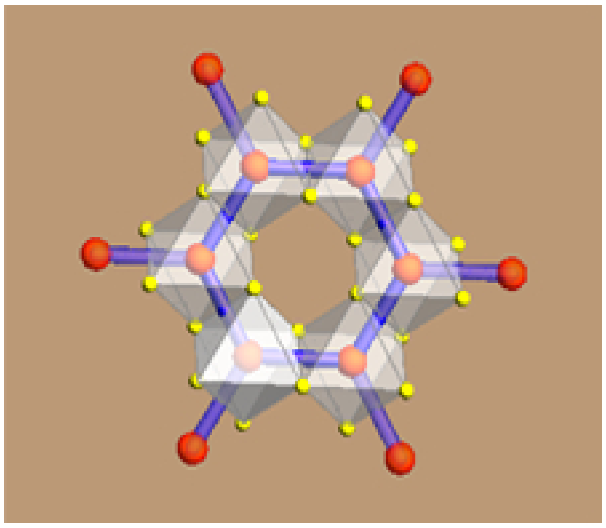
A startling feature of a QSL state is its exotic excitations. For example, physicists have long believed that properties such as quantum numbers of sub-atomic particles like electrons, i.e. their spin and charge to be fundamental. We now understand that, depending on the nature of a QSL, such states can support collective excitations that bear quantum numbers which are fractions of the quantum numbers of fundamental particles like electrons. Much richer structures – like Majorana fermions, spin-charge fractionalization, photons or magnetic monopoles – can emerge due to collective behavior of macroscopic number of electronic spins residing on the lattice [6,7,8].

Experimental search of Quantum spin liquid and α-Ruthenium Chloride: Amazingly, some of the materials that support such low temperature properties occur naturally around us or can be synthesized in laboratories [6,7,9]. Indeed, several experimental candidates have been intensely investigated over the last decade or so in search of QSL physics. While the final word on these materials is yet to be said, these are probably some of the most exciting times in the field as we are witnessing the first glimpses of experimental fingerprints of QSLs. The growing understanding in the field of material sciences has ensured that there is no dearth of such candidate materials, an extremely encouraging sign.

Recently, a class of materials – the so called 4d and 5d transition metal oxides, containing Ruthenium or Iridium, has attracted a lot of attention as a new playground for stabilizing new electronic phases including QSLs [9]. Due to the high atomic number of these elements, they have considerably strong spin-orbit coupling (SOC).

The interplay of such strong SOC and coulomb repulsion between electrons opens up a whole new set of possibilities that are being explored currently. One of the outcomes of this research, as shown in a seminal paper by G. Jackeli and G. Khaliullin [10], is particular low energy spin systems for spin-1/2s on a honeycomb lattice. This particular observation has garnered a lot of excitement as in a previous, extremely influential work. A. Kitaev [11] has shown that such a spin system supports a particular QSL state whose low energy excitation includes an elusive Majorana fermion mode into which the spin fractionalizes. Such Majorana modes, though not directly observable, are then expected to leave tell-tale signatures in experimentally accessible quantities such spin-spin correlation functions, routinely measured in neutron scattering experiments, and other thermodynamics quantities.

Fortunately, a few material compounds have already been synthesized which can potentially fall in this class, the latest of these series being α-$RuCl_3$ (α-Ruthenium Chloride). Here the spins sit on a honeycomb lattice – structurally somewhat similar to graphene. Though this compound orders magnetically at around 7 K, recent neutron scattering experiments, reported in the July issue of Nature Materials [12], reveal unconventional spin-spin correlation functions that not only survive to quite high temperatures (approx 70 K), but has uncanny resemblance to what would be expected from the QSL studied by Kitaev. Both these observations are extremely interesting as they are extremely unconventional for a magnetic system. This raises interesting questions regarding (1) the proximity of $RuCl_3$ to the potential QSL state that can support fractionalized Majorana fermions at low energies, and, (2) the possibility to chemically (by changing chemical composition) or physically (by applying hydrostatic pressure) tune the material to the QSL state. Initial analysis of the present magnetic spin-wave spectrum, presented in the same work, corroborates with the tantalizing possibility of a proximate QSL physics for this system. While, further experiments and theoretical calculations are required to understand the situation better, the present findings are indeed very encouraging. The above scenario for this material is immensely interesting as it sits on the crossroads of several important issues of condensed matter. Not only that the QSL, if obtained, would be a milestone in our understanding of fundamentally new state of quantum condensed



The basic unit of α-$RuCl_3$: Edge sharing chlorine octahedra in which the Ruthenium atoms, forming a honeycomb lattice, sits

matter, but, the associated phases transitions, whose exact nature is yet to be understood, would also be extremely interesting.

Outlook: In summary, quantum spin liquids present a glimpse of a highly non-trivial world whose nature we have just started to understand. A better understanding of quantum spin liquids holds out the possibility of both technological as well as conceptual advances. On the technological front the exotic excitations in QSLs have been proposed to be useful in realizing quantum computers. At the conceptual level, quantum spin liquids raise two classes of interesting questions. First, what is the general framework to describe highly quantum entangled condensed matter phases? A framework based on spontaneously broken symmetry does not appear to be useful here and needs to be generalized. Second, does the fact that excitations such as photons, and anyons, Majorana fermions sometimes emerge as collective low energy excitations in simple spin systems have any implications for particle physics? Is it possible that 'elementary' particles that we consider to be 'fundamental' to our universe are actually collective excitations of their other interacting degrees of freedom just like a QSL? As a very preliminary step to understand the second question, we can write down the example of lattice models of spins where fermions and gauge field can emerge as a collective low energy excitation. These extremely interesting issues surely require more studies and certainly could well occupy the centre-stage of research in theoretical physics in the foreseeable future.

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Computing with Quantum Mechanics

R. Vijayaraghavan

Most of us have used a telephone directory at some point in our lives. These fat books contained all the names of people living in a city along with their phone numbers. The list was alphabetically sorted so that it was easy to find a particular name. Now consider the opposite problem, where I give you a phone number and ask you to find the name of the person. This is not an easy task and the only way is to look at each entry sequentially (or randomly) till one finds a match. If you are lucky, you will find it quickly but you might have to go through the entire book before finding the number. If there are N entries in the book, you will have to look through N/2 entries on average to find the number. A computer program will also have to follow the same procedure and the time to search increases linearly with N. One cannot do any better using the computers that exist today.

An Indian scientist named Lov Grover discovered a different algorithm where one can find the number with approximately √N steps. While this is significantly better, one needs a very different kind of machine called a quantum computer to run this algorithm. And this machine has not yet been built.

Another famous quantum algorithm is Peter Shor's algorithm for finding prime factors of large numbers. For example, the prime factors of 15 are 3 and 5 i.e. 15 = 3 x 5. This mathematical problem is even more complex than the search problem I discussed earlier. As the number becomes larger in size, the number of steps, and hence the time to solve it grows exponentially when using today's classical computers. Shor invented a quantum algorithm where the number of steps grows polynomially and hence can solve the problem a lot more efficiently and quickly. The mathematical complexity of finding prime factors using classical computers is at the heart of encryption algorithms used for secure communication over Inter net, credit card transactions etc. and hence is of tremendous importance. But how does one build such a quantum computer? To understand that, we first need to learn a little bit about quantum physics.

At the dawn of the 20th century, certain experiments involving light did not agree with the theoretical predictions made using what is now called classical physics. With the efforts of several scientists, which included Planck, Einstein, De Broglie, Schrodinger, Bohr and others, a new theory was put forward to explain the properties of light and in addition, the nature of the physical world at the atomic scale. This new theory was quantum mechanics and is one of the most successful theories till date. However, the description of the physical world according to quantum mechanics is very strange and counter intuitive. For example, the notion that an electron goes around the nucleus in well-defined orbits had to be replaced by the idea that one can only compute the probability distribution of finding the electron in a certain region of space. It was also observed that light, which was very well explained as an electromagnetic wave till that time using Maxwell's theory, was sometimes found to behave like a particle. These "light particles" were called photons and their energy was quantized. Similarly, it was also found that electrons, which were thought to be particles, could show interference, a phenomenon usually attributed to waves. Schrodinger wrote down the wave equation that explained how these waves evolved and these were later interpreted as probability amplitude waves. The solution to Schrodinger's wave equation provided a method to calculate the probability distribution e.g. that of finding an electron in a certain region around the nucleus.

We can now discuss the basic idea behind a quantum computer using the idea of electron orbitals in an atom. Quantum theory predicts the existence of different orbitals that have different energy. If we consider any two orbitals OA and OB, we can encode one bit of information by identifying OA with the number 0 and OB with the number 1. So far this is not very different from classical information where we store one bit of information in a physical system that can take two configurations e.g. magnetic domains in a hard drive with different magnetization. However, the two orbitals are solutions to a linear wave equation and hence their sum is also a valid solution. Such states are called superposition states. In plain language, the electron is in both orbitals at the same time. Such a two-state system is called a quantum bit or qubit in analogy with the classical bit and a quantum computer will be composed of many such qubits operating together.

To understand the power of a quantum computer, one needs to consider the nature of quantum superposition when extended to multiple qubits. One classical bit can take one of two possible values i.e. 0 and 1 while two classical bits can take one of four possible values: 00, 01, 10 or 11. Two quantum bits however can be prepared in a superposition of all four states simultaneously. Extending this idea to N qubits, one can prepare such a system in a superposition of 2^N states. Even for a modest value of N = 100 qubits, the number of possible states 2^N is an enormous number and exceeds the number of atoms in the visible universe. The key point is that a 100-qubit system can be prepared in a superposition of all those states and more crucially one can manipulate all those states at the same time. A quantum algorithm is essentially the proper preparation and manipulation of such states and derives its power by the ability to manipulate an enormous number of states simultaneously.

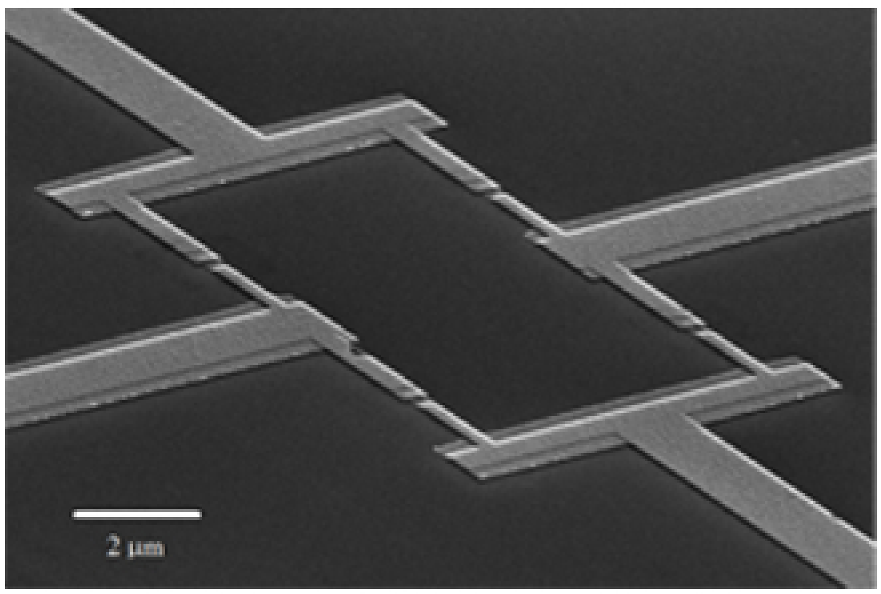

Image taken using a Scanning Electron Microscope of a superconducting qubit circuit made in TIFR, Mumbai

The discovery of powerful algorithms in the mid-1990s like the Shor's algorithm, gave an impetus to experimental research for actually trying to build a piece of quantum hardware. But first, one has to choose a physical system to construct the quantum bits. Some of the earliest attempts used the electronic energy levels of ions that were trapped in a vacuum environment using electromagnetic fields and manipulated using laser beams. Another approach was to manipulate individual photons trapped in microwave cavities. These early works paved the way for several different approaches for implementing quantum hardware and resulted in the Nobel Prize in 2012 for Dave Wineland (trapped ions) and Serge Haroche (photons). It was natural to use microscopic objects like ions and photons since quantum mechanics was developed to explain their behavior. However, it turns out that one can use much larger objects to implement qubits provided one is able to sufficiently isolate them from the rest of the environment. Individual ions and photons are naturally isolated from their environment and that helps them retain their quantum properties. But that very fact makes it difficult to get them to interact with each other and that is important to create multi-qubit superposition states. Nuclear Magnetic Resonance (NMR) has also been used to demonstrate several proof-of-principal quantum algorithms but there is no clear path to scale this technology to large number of qubits.

A promising alternative is to use superconducting electrical circuits that are engineered to show properties similar to that of individual ions but can be made to interact very easily with each other due to their larger size. Moreover, these circuits are fabricated using techniques similar to those used in the electronic chip manufacturing industry and hence fabricating chips with larger number of qubits is relatively easier. A significant challenge with such circuits is to isolate them sufficiently from the environment so that they can retain their quantum properties. Several techniques are used to achieve that and include cooling them down to near absolute zero (~ 10 mK), enclosing the circuit in light-tight boxes to protect them from stray electromagnetic radiation and heavily filtering the control and measurement lines used for manipulating such qubits.

Tremendous progress has been made in the past two decades in improving the performance of superconducting qubits with several proof-of-principal demonstrations of quantum algorithms. In addition to academic laboratories, several industrial labs are also working in this area and include IBM and Google. A Canadian company D-Wave has built a machine that uses superconducting circuits to solve problems using spin annealing techniques. However, the scientific community is not yet convinced that this machine is a true quantum machine. More recently, several start-ups have also cropped up in the United States and are working on developing quantum technologies using superconducting circuits. The race to build a quantum computer is really heating up but there are still several outstanding problems to be solved. A significant challenge is to scale the system, currently at 5-10 qubits, to a sufficiently large number to be able to observe quantum advantage. And as one scales up the system, the problem of isolating them from the environment will also become difficult. Several different strategies are being explored and the mood is optimistic, especially since one hasn't encountered any fundamental roadblock towards building a quantum computer.

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'ICTS CAN PLAY A CRUCIAL ROLE'

INTERVIEW WITH JUAN MALDACENA

Juan Maldacena is a theoretical physicist and a faculty member at the Institute for Advanced Study Princeton. His discovery in 1997 of dualities between quantum theories of gravity and quantum field theories – the so called AdS/CFT correspondence - is widely regarded as one of the most important advances in theoretical physics in the last twenty years. His awards include the Dirac Medal and the Breakthrough Prize in Fundamental Physics.

How did you get interested in physics? Was it a family influence? Was there a role model?
My father is an engineer. He has his own business in the form of a small elevator company. My mother is an English translator. My father is very practical and likes to fix things in the house. As a child I used to follow him around, fixing things. So that gave me some interest in the technical things, in engineering, how things work. That also led to an interest in physics. I always wanted to know what makes things work. Then, when I was in high school I started reading some of the popular physics books. I had some idea about what studying engineering would be like but no idea about physics. So I decided to study physics in the university. I thought if I didn't like it I could always switch. But then I liked physics very much and continued.

This was in Bari Loche?
I started in Buenos Aires for a couple of years. Then I went to Bari Loche.

So your family played a very important role in sparking your interest in physics. But then later on in college, was there someone who inspired you?
I studied in the physics institute and there were many professors who were actively doing research. So many of them played a big role in showing me what research was all about and inspired me to follow a research oriented academic career. I knew what an engineer could do – work in a company, in the industry. But I learnt all about an academic career there.

Coming to much later, to the Maldacena conjecture. It's widely regarded as one of the major advances of theoretical physics in the last quarter. When you were working on it, how confident were you that it was right? Did you realize how important it was going to be?
Yes I thought it had a very good chance of being right. I knew it was important and interesting but didn't realize how important it would be. All the applications that people found later – so yes, it did turn out to be more important than I had imagined. I also didn't know how easy it would be check it. It was in some sense similar to a previous statement that's called matrix theory. But that ran into some difficulties – it was difficult to apply and use. The gauge gravity duality on the other hand was talking about theories that were a little more familiar. Then they found some applications as well. So it's true that in the beginning I thought it would be hard to check. And it is true that some things are indeed hard to check. We have this relationship and the original objective was to understand the Black Hole. But there are many questions there that we haven't answered. So the search for something more continues.

That brings me to the next question. What are the fundamental problems that you would like to see solved in the near future?
Well, the one problem that I am really interested in is about understanding the information paradox. I would call it understanding the interior of the Black Hole. Using the same variables that we used to understand how black hole information is preserved on the outside. Gauge gravity duality gives us the explicit formalism that shows that information is preserved if you remain on the outside. However, the same formalism makes it difficult to understand how one should describe the interior. Maybe something is missing, maybe there is another description of the interior. I think to fully solve the information paradox we need to understand both the interior and the exterior of the Black Hole using the same variables. So using General Relativity we can understand how to go into the interior but we cannot understand how information is preserved. So we have one set of variables in which one thing is manifest and not the other. And we don't understand the translation between the two.

Do you think physics is becoming more global? That more and more advances are happening elsewhere other than the US and Europe?
Yes I think so. With the internet and travel it is possible to have very active groups elsewhere. India is a very good example.

I was going to ask you about India. What role do you think Indian string theory plays globally?
A: India has one of the best String Theory groups in the world. Some outstanding Indian physicists have managed to create these groups. There is a critical mass of researchers they can mentor. Some very good students have come up. In fact we have been hiring some of them as post docs in this institute. Then they go back and join the faculty there.

Like Loganayagam, who is now a faculty at ICTS.
Yes that's right.

Are you still actively involved in development of physics in Argentina?
Yes. Whenever I go there I talk to the local physicists working in the area. Particularly one person – Horacio Casini, who is doing very interesting work. We have collaborated in some papers. This is also in some ways an example of physics becoming more global. There is some excellent work done in Argentina.

ICTP must have played a role in development of physics in Argentina?
Yes it did. For me particularly. Not because I went to ICTP but because my advisor in Argentina, Gerardo Aldazábal, had gone there. So my advisor finished his PhD and then went to ICTP. And this was during the time of the String revolution. It seems he talked to Salam, who told him, 'you can work on what you want to. But then you will have no one to talk to. Or you can work on String Theory.' So he started working on String Theory and when he returned to Argentina he was the only one in the field. Then he had some students including me. He had in fact returned a year before I started working with him. Now there are more people working in this area. They also have a very good group working on Quantum Field theory.

Are you in any way involved with ICTP South America?
Yes in some way. ICTP is creating these associated centres where people can hold conferences. They are planning one in Brazil and also another in Buenos Aires.

Now back to India and more specifically ICTS. What role do you think ICTS can play in developing science in the country?
It can play a very important role. It is a place where people meet. Not only from India but from around the world. Research in these areas is very specialized and it might become difficult to talk to people around. Sometimes one can get isolated. So it's very important to have a centre where one can meet at workshops. ICTS can play a very important role for India, also for the entire Asian region. It is also important to bring in people from outside. People from around the world might also want to go and spend a sabbatical there. The infrastructure seems to be very good.
I remember when they first started talking about it. I remember Spenta Wadia mentioning it. And I am surprised how much it has developed in a very short time. They now have a very nice campus. They have started getting more and more good researchers. They are showing the potential of becoming a great centre.

CONSTRUCTING WAVEFORMS, BUILDING A COMMUNITY

BALA R. IYER

When I joined RRI in 1980, N.D. Hari Dass proposed that we work on Gravitational Wave (GW) computations using source theory methods. Unfortunately, he left for Utrecht a year later and my tryst with GWs was aborted. My reconnect with GWs occurred in 1987 at a Cargese School on

Gravitation in Astrophysics (organized by B. Carter and J. Hartle) where Thibault Damour and Bernard Schutz gave lectures and during the first ICGC meeting in Goa where Richard Isaacson and Damour gave plenary talks.

However, the initiation into GW research occurred during my sabbatical with Thibault Damour at DARC, Meudon and IHES, Bures-Sur-Yvette during 1989-90. I began working on the Multipolar Post Minkowskian (MPM) formalism of Luc Blanchet and Thibault Damour. The MPM formalism matching to a post-Newtonian (PN) source constructed by them to estimate 1PN radiation reaction corrections in the Binary Pulsar Analysis is a good example of the advantage that a complete and mathematically rigorous treatment of a problem can eventually bring in the future for unanticipated and more demanding applications that could be around the corner. My first project with Thibault was to obtain the multipole expansion of linearized gravity using symmetric trace-free (STF) tensors and to compare it with existing results obtained using the more usual conventional tensor spherical harmonics. The second project was on obtaining 1PN current quadrupole with compact support. Both these projects and the papers allowed us to go to higher order post-Newtonian results later via the Blanchet-Damour-Iyer moments.

LUC BLANCHET

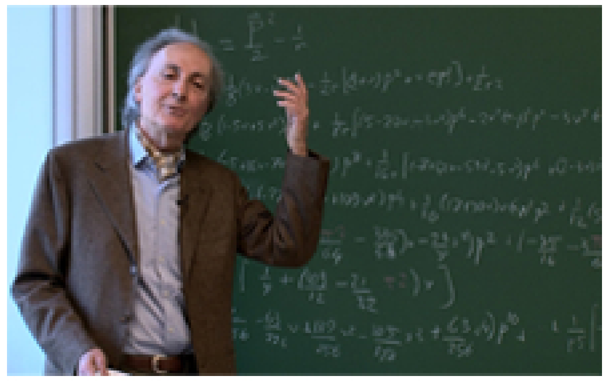
After the funding of LIGO (USA), work on constructing templates for GW detection were intensely investigated by Kip Thorne's group at Caltech and summarized in a PRL entitled The Last three minutes: Issues in Gravitational Wave Measurements of Coalescing Compact Binaries. In 1994 an international meeting was convened by Kip to brainstorm this issue and highlight the need to address this problem in time. Luc Blanchet and I were participants at this meeting as was Sanjeev Dhurandhar. With his insight and familiarity with the formalism, Luc felt it could be effectively generalised to higher orders, beyond the existing 'first post-Newtonian' (1PN) order. (Corrections of the order of (v/c)^2 beyond the leading order are called 1PN). He soon demonstrated the 2PN generation of GWs.

Around this time, I was visiting Thibault at IHES and this led to a collaboration between the three of us. We computed the GW flux to order (v/c)^4 beyond the Einstein formula and completed the calculation of 2PN phasing for inspiraling compact binaries (1995). The new insight it required was the careful treatment of the cubic non-linearities. The availability of the 2PN equation of motion from the binary pulsar work facilitated the computation of 2PN phasing of ICB by two independent methods: the MPM-PN method used by us and independently, results obtained by Will and Wiseman in the USA using the Direct Integration of Relaxed Einstein equations (DIRE formalism). A global virtual village for GW computations was coming to life. The rather quick extension to 2PN phasing led us to tackle the extension to 3PN which was realized to be important to deal with the more relativistic binary black hole systems. The control of this 3PN order turned out to be more formidable due to the unexpected limitation of earlier regularisation methods for the self-field. Only after almost a decade of struggle and by complementing our computations using Hadamard regularization by the use of the gauge invariant dimensional regularisation, the problem was finally resolved and completed.

During 1995-2014, the group around me at RRI worked systematically on extending the work on quasi-circular inspiral to the quasi-eccentric case to 3PN (Gopakumar, Arun, Qusailah, Sinha, Mishra; Blanchet, Faye). Currently MPM-PN is the most successful since it can deal with all aspects of the required computations: the conservative equation of motion, radiation field at infinity, non-linear effects related to tails, tails of tails and non-linear memory. It has evolved over the last twenty five years into a consistent algorithmic approach to analytical GW computations. (See L. Blanchet: http://www.livingreviews.org/lrr-2014-2). The PN results are also the starting inputs for the construction of extensions using the effective one body and phenomenological approaches of Parameswaran Ajith and collaborators to describe merger and ringdown and also validate early phases of the numerical relativity waveforms of coalescing compact binaries. Thus they play a critical role in the construction of templates for detection and parameter estimation. Damour, Sathyaprakash and I developed tools (Effectualness, Faithfulness, Window Functions, Inequivalent PN families, Pade resummation) to deal quantitatively with template construction, understand template characterisation issues in GW data analysis and extend domain of validity of PN approximants. In collaboration with Sathyaprakash at Cardiff, students in my group (Arun, Sundarrajan, Sinha, Mishra) investigated implications for parameter estimation, tests of gravity, implications of full waveform for astrophysics and cosmology for LISA and Einstein Telescope and participated in related design studies of future missions. Ajith was a visiting research student in my group for a year before he went to Hannover for his Ph.D.

Our work on Source Modelling was complemented by that in GW Data Analysis at IUCAA in a group around Dhurandhar. The IUCAA group made seminal contributions to GW data analysis (e.g. template placement, hierarchical search, radiometer searches, coherent searches), collaborated with most international GW groups and was a member of the LIGO Scientific Collaboration (LSC) for a decade since 2000.

With the first generation detectors achieving design sensitivity, we realized it was time to jump start Indian participation in GW experiment and science before it was too late. It was also clear to us that it was too big for any single institute. It had to be a national initiative and we would need to identify and



THIBAULT DAMOUR

bring together colleagues from different institutions with complementary expertise and skills. In addition, students and post-docs from the GW groups at IUCAA and RRI, after post-doc stints in leading GW groups abroad, were currently heading back to faculty positions at different institutions in India and they would help build the pan-Indian group in the LSC. This led to the formation of the IndIGO Consortium in 2009. The IndIGO consortium explored participation in the Australian AIGO and later in LIGO-Australia and this eventually led to the LIGO-India opportunity. In June 2011 began the preliminary discussions for relocating the second Advanced LIGO interferometer in Hanford to India. In July 2011, IndIGO was accepted as member of Gravitational Wave International Committee (GWIC) and in September 2011 as a member group of LIGO Scientific Collaboration (LSC). The formal offer by LIGO-Lab to collaborate on LIGO-India was received in October 2011. Immediately after that, in November 2011, a proposal was submitted to the Department of Atomic Energy (DAE) and the Department of Science & Technology (DST) and presented at the DST meeting on Mega Projects. By December 2011 IPR, IUCAA and RRCAT were identified as lead institutions for LIGO-India. After four LIGO-Lab visits to Indian institutions to assess scientific interest, technical and management capabilities and three NSF reviews in April 2012, LIGO-India was included as a DAE Mega Project in the Atomic Energy Commission (AEC) meeting. In August 2012 the National Science Board, USA, approved the proposed change in scope of the Advanced LIGO Project, enabling plans for the relocation of an advanced detector to India. In December 2012, LIGO-India was included in the list of Mega Projects in the report of National Development Council to approve the Twelfth Five-Year Plan.

My tenure at RRI ended in Dec 2014. ICTS offered me a visiting professorship and invaluable support that allowed me to continue my contributions to the IndIGO Consortium and the LIGO-India proposal. With remarkable foresight, ICTS set up the Astrophysical Relativity group with focus on GW research under Ajith. This group has established iteslf in a very short time. Under the leadership of Ajith, it rose to the occasion during the analyses of GW150914 by contributing to aspects related to test of general relativity in the discovery paper. Using results from available supercomputer simulations, members of this group contributed to the accurate estimation of the mass and spin of the final black hole. Yet another test proposed and implemented by the group involved measuring the mass and spin of the final black hole from the 'inspiral' part of the signal and checking their consistency with the same parameters measured from the post-merger' signal. Analyses performed on the two events have revealed that the observations are fully consistent with the theory's prediction within measurement uncertainties providing some of the first tests of Einstein's theory in the regime of extreme gravity and velocities.

The GW strains from the coalescence of a binary black hole into a single black hole 1.3 billion years ago rang in LIGO-India, the critical element in the global GW network to transform routine GW detections to a new GW astronomy. On February 17, 2016, LIGO-India received its in-principle approval. On March 31 the MoU between NSF, USA and DAE-DST India was signed during Prime Minister Modi's visit to the USA. Not only was Chandra doubly right in Astronomy being the Natural home of General Relativity but as the Bard said:

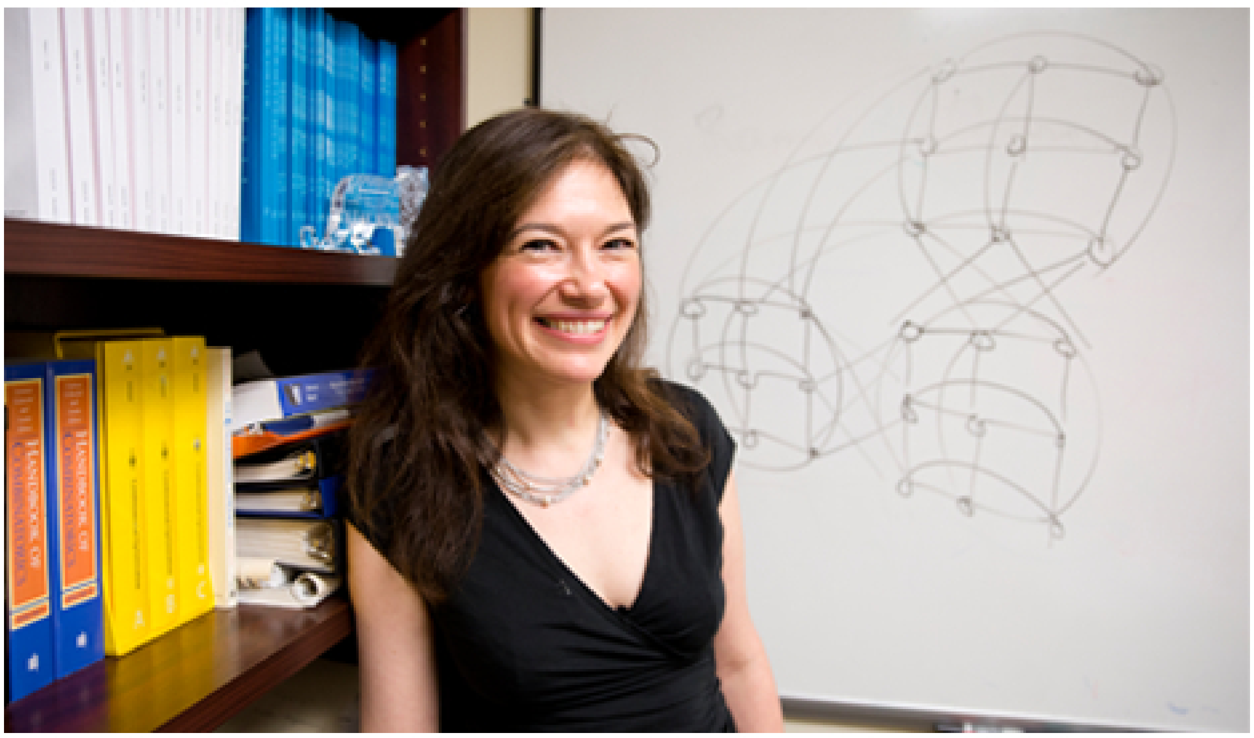
And therefore as a stranger give it welcome,
There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy

Bala R. Iyer is an astrophysicist and a visiting professor at ICTS. He is Chair, IndIGO Consortium and PI, IndIGO participation in LIGO Scientific Collaboration (LSC)

'THERE IS NOTHING THAT CANNOT BE OVERCOME'

INTERVIEW WITH MARIA CHUDNOVSKY

Maria Chudnovsky is a Clay Research Fellow and an assistant professor at Princeton University. Her research interests are in discrete mathematics and, in particular, graph theory. While pursuing her PhD at Princeton University, she and her collaborators solved the Strong Perfect Graph Theorem, a forty-year old conjecture.



How did you choose to study graph theory? Could you tell us a bit about graph theory? What are its applications?

When I applied to graduate school I knew I wanted to study discrete mathematics, but the exact flavor of it was going to be determined by the place where I would go. I ended up at Princeton, studying with Paul Seymour, who is a huge figure in graph theory. So I became a graph theorist.

Graph theory is a branch of mathematics that studies the properties of objects called 'graphs'. A graph is a collection of points (called 'vertices'), some pairs of which are in a relation (we say they are 'adjacent') and other pairs are not (we say they are 'non-adjacent'). There are many beautiful theoretical questions you can ask about these objects. They are also a useful tool for modeling various real life situations. One example is computer networks, where the points represent computers, and two computers are 'adjacent' if they can talk to each directly (say they are connected by a wire, or something like that). Another straightforward situation where a graph is a good model is network of roads or railways connect ing towns. But one can also be cleverer, and use graphs in places where it is less obvious.

When you and your collaborators solved the Strong Perfect Graph Theorem during your doctoral studies, how confident were you that the proof was correct? Could you explain the theorem?

With a proof of that length, it is always hard to be 100% sure. You keep checking and checking. You check the places where you have doubts, then everything, the doubtful places again... And then you become fairly confident, and you start giving talks. This is a good test, because suddenly your arguments are being followed by hundreds of new people, who do not have your fixed assumptions in their heads. Then the paper is published and people start reading and checking more details. Given that it is an important problem that people care about, I think if there was a mistake, it would be found by now.

There is a well-known concept in graph theory, called graph coloring. That means partitioning the vertex set of the graph into subsets, so that the vertices in each subset are all non-adjacent to each other, and the question is what is the smallest number of subsets one has to use? There is an obvious lower bound on the number of subsets needed, namely the largest number of vertices that are all pair-wise adjacent. If you simplify slightly perfect graphs are precisely the graphs that achieve this lower bound. In 1961 a French mathematician Claude Berge made a conjecture describing the structure of all perfect graphs. It became known as the Strong Perfect Graph Conjecture, and after we proved it, it turned into the Strong Perfect Graph Theorem.

Would you have any advice for young mathematicians, especially aspiring women mathematicians?

Don't give up too quickly. Even if sometimes you feel like the stupidest person in the room. Almost everybody feels that way every now and then. When you are working on a problem nobody has solved before, as one does in math, you are bound to find yourself going down wrong paths, or sometimes no paths at all.

Mathematics has been traditionally a male dominated area. As a woman mathematician, did you encounter any extra obstacles?

The social aspect is a bit harder; you are always a bit different from most people around you. But nothing that cannot be overcome, I think.

Have you ever visited India? Do you have any academic connections with India?

Not yet. A friend once invited me to come to a relative's wedding, but I was interviewing for jobs at the time, and felt that I could not take off the time (I can't believe I was so young and naive and did not jump on this opportunity! Though, I did get a job). I have had no academic connections so far.

I read somewhere that you worked out the seating arrangement at your wedding. Did graph theory help you work that out?

I did not use graph theory explicitly, but when I went back and thought about what I did, it became clear to me that I just ran an easy graph algorithm in my head. The graph you define has the wedding guests as vertices, and two guests are 'adjacent' if they don't like each other very much and should not sit at the same table. The problem of creating a sitting chart becomes the 'coloring problem'. This is a well studied problem, that is hard in general, but if every vertex is only adjacent to not very many others (i.e. your friends and relatives mostly get along), then finding a solution becomes pretty easy.

BETWEEN THE SCIENCE

R. Loganayagam was awarded the Ramanujan Fellowship by the Department of Science and Technology, Govt. of India.

Subhro Bhattacharjee and his collaborators' work has featured on the cover of the July issue of Nature Materials.

Subhro Bhattacharjee was selected as an associate of the Indian Academy of Sciences, Bangalore.

Abhishek Dhar and **Anupam Kundu** received the Indo-French CRFIPRA grant. The grant was jointly received with Sanjib Sabhapandit of RRI.

PROGRAMS

Summer Research Program on Dynamics of Complex Systems

ORGANIZERS

Amit Apte, Soumitro Banerjee, Pranay Goel, Partha Guha, Neelima Gupte, Govindan Rangarajan and Somdatta Sinha

DATES

23 May-23 July, 2016

VENUE

Madhava Lecture Hall, ICTS-TIFR, Bengaluru

School on Current Frontiers in Condensed Matter Research

ORGANIZERS

Subhro Bhattacharjee, Jainendra Jain, H R Krishnamurthy, Krishnendu Sengupta and Rajdeep Sensarma

DATES

20-29 June, 2016

VENUE

Ramanujan Lecture Hall, ICTS-TIFR, Bengaluru

Bangalore School on Statistical Physics - VII

ORGANIZERS

Abhishek Dhar, Sanjib Sabhapandit

DATES

1-15 July, 2016

VENUE

Ramanujan Lecture Hall, ICTS-TIFR, Bengaluru

Summer School on Gravitational-Wave Astronomy

ORGANIZERS

Parameswaran Ajith, K. G. Arun and Bala Iyer

DATES

25 July-5 August, 2016

VENUE

Madhava Lecture Hall, ICTS-TIFR, Bengaluru

Discussion Meetings

The Future of Gravitational-Wave Astronomy

ORGANIZERS

Parameswaran Ajith, K. G. Arun and Bala R. Iyer

DATES

4-8 April, 2016

VENUE

Ramanujan Lecture Hall, ICTS-TIFR, Bengaluru

750 GeV Excess @LHC under scrutiny

ORGANIZERS

Biplob Bhattacherjee, Fawzi Boudjema, Rohini Godbole and Sudhir Vempati

DATES

5 May, 2016

VENUE

Ramanujan Lecture Hall, ICTS-TIFR, Bengaluru

Games, Epidemics and Behavior

ORGANIZERS

Deeparnab Chakrabarty, Niloy Ganguly, Rajmohan Rajaraman and Ravi Sundaram

DATES

27 June-1 July, 2016

VENUE

Madhava Lecture Hall, ICTS-TIFR, Bengaluru

Bangalore Area String Meeting

ORGANIZERS

R. Loganayagam, Suvrat Raju

DATES

25-27 July, 2016

VENUE

Ramanujan Lecture Hall, ICTS-TIFR, Bengaluru

The Legacy of Emmy Noether

ORGANIZERS

A. Adimurthi, Rukmini Dey and R. Loganayagam

DATES

25-27 July, 2016

VENUE

Ramanujan Lecture Hall, ICTS-TIFR, Bengaluru

LECTURE SERIES

TURING LECTURES

Complexity, Phase Transitions, and Inference

SPEAKER

Christopher Moore (Santa Fe Institute, USA)

DATE

28 June, 2016

VENUE

ICTS-TIFR

EINSTEIN LECTURES

Black Holes, Waves of Gravity, and other Warped Ideas of Dr Einstein

SPEAKER

Clifford M Will (University of Florida, Gainesville, USA and Institute of Astrophysics, Paris, France)

DATE

29 July, 2016

VENUE

St. Joseph's College, Bengaluru