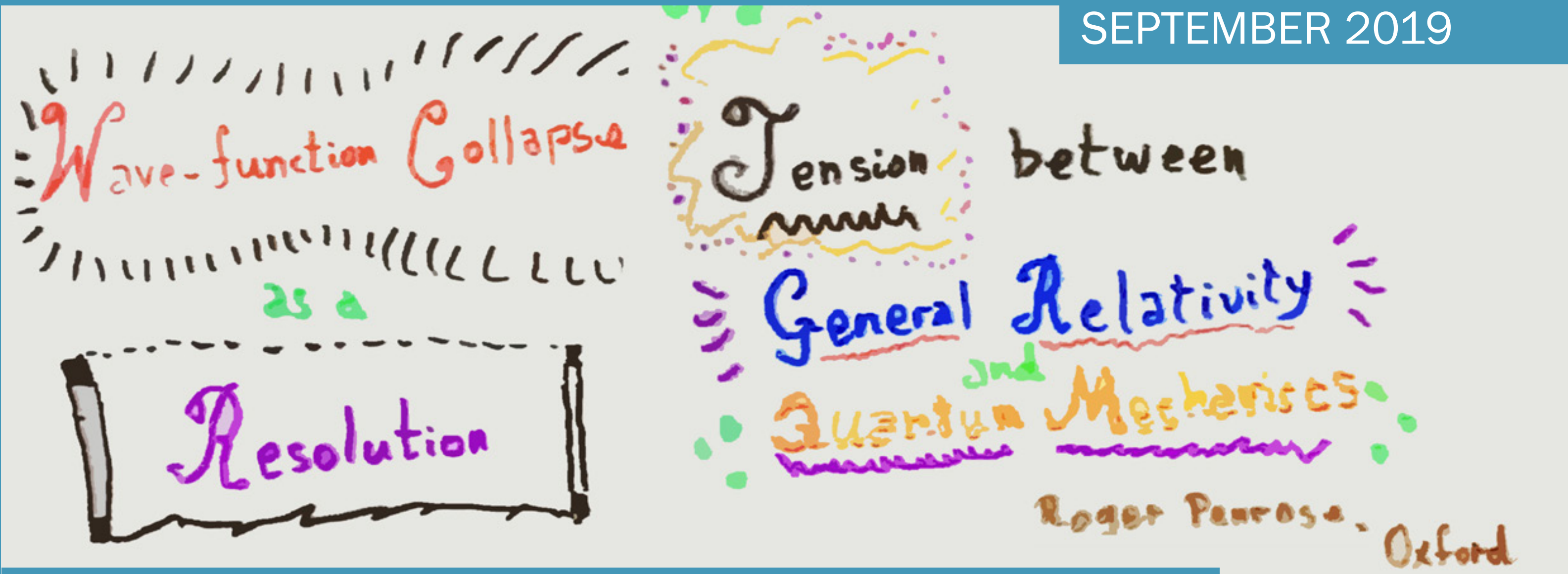
SEPTEMBER 2019



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Istituto Nazionale di Fisica Nucleare

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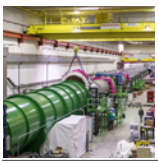

» INTERVIEW

QUANTUM MECHANICS VS GENERAL RELATIVITY

Interview with Roger Penrose, emeritus professor of the University of Oxford, winner with Stephen Hawking of the Wolf Prize for physics, in 1988, for the formulation of the theorems on the Penrose-Hawking singularity.

The conference "Wave-function collapse as a resolution of a tension between General Relativity and Quantum Mechanics" by Sir Roger Penrose, emeritus professor of mathematics at the University of Oxford, was held on 25 September 2019 at the Bruno Touschek Auditorium of the INFN Frascati National Laboratories. During the seminar, professor Penrose illustrated his idea on the possibility of resolving the conflict between General Relativity and Quantum Mechanics.
The seminar was organized as part of the workshop "Is quantum theory exact? From quantum foundations to quantum applications" that took place at the INFN Frascati National Laboratories between 23 and 27 September 2019.
Roger Penrose is the author of important contributions to the mathematical physics of General Relativity and cosmology. He received numerous prizes and awards, including, in 1988, the Wolf Prize for physics together with Stephen Hawking for the theorems on the singularity of Penrose-Hawking, the Dirac Medal (1989) and the Einstein Medal (1990). We asked him to explain some of the founding ideas of his prolific mathematical thinking.

Professor Penrose, how could General Relativity and Quantum Mechanics be combined?
It's a common view that we have to make General Relativity subject to the laws of quantum mechanics, because big things are made from small things and quantum mechanics is a theory of the small, while General Relativity is a theory of the large. My view is different: I think Quantum Mechanics needs help. It's not a fully consistent theory and I'm more concerned with what you might call gravitising Quantum Mechanics than quantising Gravity. There are experiments which will show how Quantum Mechanics needs to be modified to be consistent with Einstein's theory of general relativity: that will be an important development in the future.

How can experimental physics do better to contribute to our knowledge of the universe?
One of the things where I believe experimental physics will change our view in a radical way is in experiments

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in which you see violations of standard Quantum Mechanics. So, if I have a body that could be in this or that place, Quantum Mechanics says that it could be in this and in that place at the same time. So there's the famous mental experiment proposed by Schrödinger who suggested you could have a cat (in a box), which was dead and alive at the same time. People call that Schrödinger's cat. Now, doing this experiment with a cat is not a good idea, but maybe you could use some very small object. Can you put the object in here and there at the same time? Or does that change the way we look at Quantum Mechanics and, ultimately, at physics as a whole? I think the most important experiments, which could be carried out in the near future, are those that stretch Quantum Mechanics to beyond the limits, which we have seen so far, and may well see deviations from standard Quantum Mechanics.

You have hypothesised that Quantum Mechanics may explain the mechanisms of the brain.
According to my view, conscious experience cannot be explained with simply classical ideas. But I'm more radical than many people: I believe it cannot even be explained by Quantum Mechanics as we currently understand it, but by the Quantum Mechanics that needs to be changed.
In current Quantum Mechanics, you could have an object in one place or another together at the same time. And, in my view, that won't happen for large objects. My view is that the way the conscious brain operates (I'm talking now about conscious experience) is not just using Quantum Mechanics, but it's where Quantum Mechanics needs to be extended in order that things don't remain in two places at once but they suddenly become one or the other. We need a theory of that: what people call collapse of the wave function. In my view, when we have such a theory we may perhaps be able to explain the working of the conscious brain better than we can now.

You and Stephen Hawking have given an important contribution to the physics of black holes. How has your collaboration started?
In the 1960s, there were observations of things called quasars, which were very mysterious objects that seem to produce a lot of energy. They were very small and they seemed to be the result of what is called "gravitational collapse".
People did not understand the concept of gravitational collapse very well. At the time there was a theory that seemed to have proved that when you have bodies that collapse gravitationally they would swirl around and come out again. And this was not known. I didn't know either. So I started to think about this problem very seriously. And it became clear to me that when the collapse reaches a certain point there is no help: the object would definitely collapse and form what we now call a singularity, a black hole. And then you would have these singular states where the curvature densities of space-time become infinite. So I wrote

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a theorem, which was published in Physical Review Letters, and I gave a talk about this, at King's College, London. According to the film ("The Theory of Everything", 2014, n.d.r.) Stephen Hawking was there, but he was not. However I gave a repeat of that lecture in Cambridge and Stephen Hawking was present. Afterwards I talked to Stephen and George Ellis privately and I discussed the techniques I was using in this proof of the black holes. Stephen Hawking then generalised these arguments to apply them to the Big Bang and to cosmology as a whole. He developed the arguments in clever ways and, then, we got together and used the arguments to have a theorem, which we published, after several papers of his own, in the Royal Society. This paper included most of the results we had and it had to do with cosmology and mainly with the big bang and black hole singularities. So that was the collaboration with Stephen. It was in the late 1960s.

What do you think of the black holes hair theory that Stephen Hawing proposed to solve the loss of information problem?

Stephen Hawking's main contribution to black holes was his theoretical discovery that black holes radiate. Previously, scientists thought that black holes were completely black: everything falls in. What Stephen Hawking showed was the use of combining theories from quantum field theory, Quantum Mechanics and General Relativity, to explain that black holes would have a very very slight radiation, which was called Hawking radiation. This was a very important theoretical concept.

The problem was that information would be swallowed by black holes and Stephen Hawing originally had the idea that black holes, effectively, swallow information. That's the expectation: I believed that myself and I thought he was correct.

Later on, in a bet he had with some other people, he changed his mind, and took the view that somehow, the information was not destroyed and came out again. I took the view that this was a mistake, that his first idea was the correct one and I continued to disagree with him on this. So we had many arguments about this. Somebody told me that he changed his opinion back again. I'm not sure about that. Certainly, in his later paper with other collaborators he was developing the idea that there were things like soft hair, and maybe radiations could carry the information out again. My own view was that he was correct in his first analysis and that the information is destroyed in black holes and that this is important for the sort of cosmological scheme, which had developed later.

Imagination is quite important in your work...

Imagination is very vital in physics. And I think when I was thinking about this collapse to a black hole, I tried to imagine what it was like inside it with the matter collapsing all around me and I think I got inspired by the very good books by George Gamow called *Mr. Tompkins in wonderland* and *Mr. Tompkins explores the atom*.

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In *Mr Tompkins in wonderland*, Gamow imagined the collapsing universe and there, all the bodies were coming inwards. And so the imagination of what it might be like of collapsing in a black hole was important to me, because I think I realised that it could not be simply a local thing: is it just that the equations blow up locally or is it something to do with the global feature? And that was an important realisation in the singularity theorem, which I developed with Stephen Hawking.
And this is only one example: imagination is in many cases where the ideas may be. I very often imagine geometrical pictures. I think very visually, so the ideas are spatial images and they can be very rigorous. The images can be not simply to get a general feeling but often they can be very precise in our geometrical insights. So imagination in all sorts of ways, either physical imagination or geometrical imagination or imagination that has to do with logics, is very important.

Do you think mathematical entities are real objects?
In my view, mathematical entities are real in the sense of the platonic world of things. For example, the number 3 is not a real thing, it's a concept, which is absolute. In the platonic view, there is a world, which is objective and not simply part of our creation and that exists independently of ourselves. This is not the world of physical reality, it's the world of mathematical reality.
It's very hard to understand how there could be laws of physics before there were conscious beings if it had to be conscious beings, who created mathematics. How do you create physical laws where there are not conscious beings? So I take the view that there is a world, the platonic world, the world of Plato's ideas, where the ideas of mathematical notions have a reality of their own. It's not the same as physical reality. And this world relates to physical reality and it relates to conscious experience. So, I tend to draw a picture where you have the physical world, the world of mentality and the world of mathematics: they are not the same as each other but they all interrelate with each other in important ways.

You are the author of many popular science books, written for a general audience. Do you think popularisation of science is an added value to science and to society?
I think there's a very important role in trying to make science accessible to the general public. This is why I wrote my first popular book, *The Emperor's New Mind*.
Once I heard on the radio a talk by Marvin Minsky and Edward Fredkin and they were talking about computers, and our computers would get cleverer and cleverer, much cleverer than us. And I could see where they came from, but I did not agree that we're just computers.
I had a reason for thinking otherwise from a course of lectures I went to when I was a graduate student in Cambridge, which were not to do with what I was doing. One was a course on mathematical logic that taught

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us about Godel's Theorem and about Turing machines, which is a theoretical underpinning of a modern computer. During that course, I was convinced that what we understand with our conscious understanding is not a computational thing, and so I held this belief for a long time, but I didn't think it was anything special. Only when I heard Marvin Minsky and Edward Fredkin talking about it I thought: look, that's not my view, there's something else going on, which is not computation. And I thought: well, I will write a book, trying to explain things in physics. But the ultimate thing was trying to show that in our conscious understanding we are doing something different from a computer. So the title of the book was *The Emperor's New Mind*. The title was based on *The Emperor's New Clothes*, the famous story about the emperor who had no clothes but since everybody had to believe what they thought they could all say: "Clap, clap, he has clothes!" And it took a little boy to see that he had no clothes. The idea was: it's obvious we're doing something other than a computer, but the story was somehow that we are told that it's all computers and we have to believe that. ■

RESEARCH

THE DAMPE SPACE MISSION REVEALS NEW PROPERTIES OF COSMIC GALACTIC RAYS

At the end of September 2019, the DAMPE (DArk Matter Particle Explorer) experiment, in orbit around the Earth since December 2015, published on Science Advances the direct measurement of the flow of cosmic protons up to high energies, in the range of 100 TeV (approximately 100,000 times the energy corresponding to the resting mass of a proton). Protons are the main component of cosmic rays and, to date, no apparatus had ever directly measured the intensity of their flow with such accuracy and at such high energies. In detail, DAMPE has found an unexpected behavior: the flow of protons, which decreases continuously with increasing energies, around 10 TeV has a much more marked attenuation than expected. Other experiments have previously explored this energy region but with less precise results due to both statistical and systematic uncertainties.

DAMPE was launched into orbit in December 2015 by the Chinese Space Agency aboard the Long March 2D vector with the scientific goal of searching for dark matter by studying high-energy astroparticles, in particular the flow of cosmic rays that comes incessantly to our planet. The experiment is an international collaboration among the National Institute of Nuclear Physics (INFN) - with the divisions of Perugia, Bari and Lecce and the GSSI - the Chinese Academy of Sciences (CAS), the Universities of Perugia, Bari and Salento, and the University of Geneva. The collaboration is led by the Purple Mountain Observatory (PMO) of Nanjing and counts more than 100 partecipants among researchers, technicians and PhD students. ■

RESEARCH

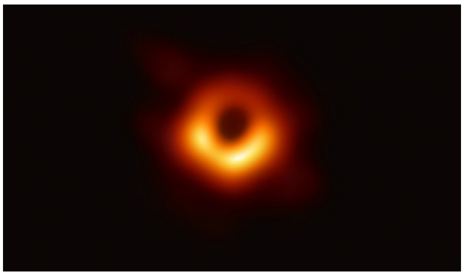
GERDA MARKS A NEW RECORD IN MAJORANA'S NEUTRINO RESEARCH

The GERDA experiment, at INFN Gran Sasso National Laboratories (LNGS), has achieved another important scientific milestone, reaching a new record in sensitivity in research into the extremely rare neutrinoless double beta decay. If detected, this decay would provide essential information on the nature of neutrinos and on why there is much more matter than antimatter in the current universe. In particular, it would demonstrate that the neutrino is a Majorana particle; it coincides with its antiparticle. Being excluded by the Standard Model, the process would provide important clues on the existence of New Physics, beyond the Standard Model. If observed, the neutrinoless double beta decay would be the rarest of decays, with a half-life many times greater than the age of the universe. It is understandable, then, how crucial it is to reduce the "background processes": much more common natural events that simulate the signal being looked for, thus contaminating it and making it difficult to detect.
The decay has so far escaped observation, but GERDA is the first experiment to reach a sensitivity, in measuring the half-life of the nuclei (that is, the time that must pass before half of the nuclei give way to decay) of more than 10^{26} years, which is greater than the age of the universe.
The result - published on 5 September in the scientific journal Science - was obtained after having collected uninterrupted data for two and a half years and having reduced the events that constitute the background noise to a very low level. ■

COMPUTING

EXANEST: SUCCESS FOR THE EUROPEAN SUPERCOMPUTER PROTOTYPE

ExaNeSt, the precursor of an exascale computer all made in Europe, has been successfully tested. Italy is taking part in the project with INFN, the National Institute of Astrophysics (INAF) and a group of SMEs (Small and Medium Enterprises). High performance computing (HPC) is one of the fundamental pillars of global scientific and technological research and a key factor to support the digital revolution associated with big data. Making an exascale computer means producing a supercomputer capable of performing billions of billions of operations per second (exaflops) and all the software tools to use it. Europe has long been working to make this supercomputer a reality thanks to the European Horizon 2020 program through projects like ExaNeSt. In just over three years from the end of 2015, ExaNeSt built the first prototype with high computing performance and high energy efficiency: energy consumed to solve a computational problem on this new platform is 3 to 10 times lower than that required by traditional HPC platforms. A result that went far beyond expectations thanks to an innovative liquid cooling system, the implementation of a high-performance dedicated network architecture, and a new type of computational accelerators based on programmable components. A 'computational laboratory' of this type is a decisive platform for preserving and improving the competitive capacity at the industrial level, for enhancing security strategies and cybersecurity, and obviously for responding to the scientific research challenges over the next decade. ■



AWARDS

THE 2020 BREAKTHROUGH PRIZE GOES TO THE 347 SCIENTISTS OF THE EVENT HORIZON TELESCOPE COLLABORATION

The Event Horizon Telescope collaboration (EHT) was awarded the 2020 Breakthrough Prize for Fundamental Physics "for the first image of a supermassive black hole, taken by means of an Earth-sized alliance of telescopes", which was announced on 10 April 2019. The prize, which is worth some three million dollars, will be divided between the collaboration's 347 scientists, in which researchers from the Italian Institute for Nuclear Physics (INFN) and from the National Institute for Astrophysics (INAF) participate. These researchers include Mariafelicia De Laurentis, INFN researcher and professor of astrophysics at the Federico II University of Naples, who, as a member of the EHT collaboration, coordinated the experiment's theoretical analysis group.

EHT is a distributed network across the Earth, composed of a set of radio telescopes that operate in a coordinated way to construct a single instrument of global dimensions and unprecedented sensitivity and resolution. Specifically designed with the purpose of capturing the image of a black hole, EHT presented the first direct visual proof of a black hole and of its shadow on 10 April. More specifically, the image captured the event horizon of the supermassive black hole, with a mass equivalent to 6.5 billion solar masses, which is located 55 million light years from the Earth, at the centre of the Messier 87 galaxy. The result was described in six scientific articles published in The Astrophysical Journal Letters. ■.

COMPUTING

THE EUROPEAN IOTWINS PROJECT LAUNCHED IN BOLOGNA

IoTwins was launched in Bologna on 4 September. It is a new European big data project financed to the tune of 20 million Euros. INFN is contributing with both its infrastructure and its know-how to the project.

The project's aim is to create digital twins, or virtual copies of industrial processes, for large scale virtual applications, via the creation of 12 computer platforms for the management of Big Data with artificial intelligence. These platforms will support the industrial world in fields such as predictive maintenance and the optimisation of the industrial process.

IoTwins falls under the European Framework Programme for research and innovation, Horizon 2020, and is coordinated by the Italian company "Bonfiglioli Riduttori". The project involves 23 partners from eight European nations. Alongside INFN, the Italian partners include the University of Bologna, CINECA, the Emilia-Romagna Region, through the regional company Art-ER, and the Marposs company. ■

PUBLIC ENGAGEMENT

INFN EUROPEAN RESEARCHERS' NIGHT

Hundreds of events all over Italy, nine national projects, more than 100 cities involved, thousands of researchers and a lot of curiosity: these are the main ingredients of the "European Researchers' Night" that returned this year on the last Friday of September.
Held for the first time in 2005, supported by the European Commission, the "white night" of research has become an eagerly awaited event. It also represents an important occasion for meeting and exchanging ideas between researchers and citizens who are passionate about science or just curious. INFN is participating in five of the projects financed by the European Commission in Italy: Sharper, Society, Bees, Bright and ERN Apulia.
Thanks to the active presence, at a local level, of national divisions and laboratories, the INFN community has thus been one of the event's protagonists. INFN organised initiatives all over Italy for 27 September: open labs, meetings, conferences, seminars, shows, experiments, interactive games, aperitifs, concerts, and much more. ■

» FOCUS

NA62: HUNTING OUT THE SECRETS OF THE KAON

In September 2019, at the KAON 2019 conference in Perugia and at a seminar at CERN, in Geneva, the collaboration of the NA62 experiment at CERN, in which INFN physicists and technologists participate, presented its new results on the very rare decay of a charged kaon into a pion, a neutrino and an anti-neutrino. The results show two events recorded in the data gathered by the experiment in 2017 and add to one decay event recorded in the 2016 dataset.

In addition to these events, the NA62 collaboration presented new measures, obtained with unprecedented sensitivity, of the decay of a neutral pion into particles that are invisible to the experiment, like neutrinos or not yet known particles.

At the moment, the collaboration is analysing the data collected in 2018 and the experiment is getting ready for the new data-acquisition phase that will start in 2021, with an upgrade of the experimental apparatus aimed mainly at the reduction of the background, in order to perform high-precision measurements of the very rare kaon decay. The aim is to discover any anomalies in this process, to find behaviours that the Standard Model does not predict. The rare processes represent, in fact, a privileged access channel to what physicists define as New Physics, the physics that we do not yet know and that goes beyond our current theories.

The results obtained so far on over 2000 billion kaon decays are in line with the predictions of the Standard Model. However, by analyzing ever larger and ever more sensitive samples of data, divergences could emerge.

NA62 is an experiment that uses a beam of protons extracted from the Super Proton Synchrotron (SPS). These protons are collided with a beryllium target to generate an intense secondary beam with a significant percentage of kaons, the subject of the experiment's study. In contrast to the experiments that have, until

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now, studied this rare decay, such as E787 and E949 of the Brookhaven National Laboratory in the United States, NA62 studies the kaons “in flight”, inside a volume under vacuum, which is more than 60 metres long. The "in flight" detection technique, does not require to "stop" the beam, it hence allows to study kaons of greater energy, with a consequent increase in the total number of observable decays.
The experiment is composed of numerous, high-performance, particle detectors (calorimeters, veto systems for charged and neutral particles, tracking and particle identification systems). Of particular interest, for its advanced technology, is the beam tracing system, developed with the coordination of INFN. The system allows to determine very accurately the position and time of the passage of the particles, thanks to thin silicon detectors, with a thickness of a few hundred microns, in which an innovative microchannel cooling system in carbon is used to dissipate the energy of the about 109 charged particles passing through it for every second of activity.
With the new data-taking phase, NA62 researchers hope to identify even particles that have never been revealed, as possible candidates for dark matter. They will study the products of the interactions between the proton beam and a very thick target, known as beam dump. It is expected that in the impact, all the energy of the beam will be absorbed by the target. However, some weakly interacting and still unknown particles could cross it: the challenge in this case would be to identify them.
The NA62 collaboration, led by the Italian Cristina Lazzeroni of the University of Birmingham, involves around 200 physicists in Europe, the United States, Canada, Mexico, and Russia, and INFN’s commitment to the project stands out. Around one third of the participants are INFN researchers: more than 70 physicists and technologists contribute in a decisive way to the success of the experiment with important responsibilities both for the detector and for the experiment’s complex data acquisition system. ■

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COVER
Graphics taken from a slide of the conference "Wave-function collapse as a resolution of a tension between General Relativity and Quantum Mechanics" by Sir Roger Penrose

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