Neutrino: The Elusive Particle Bringing us Closer to the World of Quantum Gravity

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The last September I had the privilege to be present at the fifth international conference to study the prospects of finding experimental evidence for quantum gravity, held at the Frankfurt Institute for Advanced Studies, which has brought together theoretical and experimental physicists from many different areas in this young and lively research field which is generally referred to as "quantum-gravity phenomenology".

The quantum-gravity phenomenology is, without a doubt, one of the most ambitious programs in physics today. For many years, what is generally called the "quantum-gravity problem" has been discussed assuming that no guidance could be obtained from experiments. This sort of prejudice is very well motivated by the smallness of the scale length (the Planck length $\sim 10^{-35}$ m) where the Standard Model of particle physics and General Relativity are both non-negligible and where one must take into account the quantization of the gravitational force by the, still unknown, theory of Quantum Gravity. Just to make clear how small the Planck length is, in order to reach the Planck regime we should build a particle accelerator 10^{15} (one followed by 15 zeros!) times more powerful than the Large Hadron Collider in Geneva, which is the world's largest and most powerful particle collider. And it will remain so for many years to come. Its power is of about 13 TeV, which means that with the Large Hadron Collider we are able today to probe scale length of the order of 10^{-20} m (compare it with the Planck length!).

The alert reader may ask at this point: "So then, how is it possible to even talk about a quantum-gravity phenomenology? And why should we care about it?". The latter question has an obvious answer: every theory, including a theory of Quantum Gravity, in order to be *physical* needs to be in accord with experiments; it doesn't matter how elegant, beautiful and mathematically consistent your theory is, in order

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to be *physical* it must be in agreement with nature, i.e. experiments. To quote Richard Feynman:"If it doesn't agree with experiment, it's wrong".

The first question, instead, is a very good question, whose answer is not so obvious. One way to answer this question is to think about molecules. They are very small and invisible to us, as the Planck length is very small and "invisible" relative to the physical regime we can achieve in our experiments. But the effects of molecules can be macroscopically significant in a length scale much bigger than the radius of a molecule ($\sim 10^{-4}\ \mu$m). So bigger that in 1827 their macroscopical effects were observed for the first time by the botanic Robert Brown at scales of the radius of pollen grains ($\sim 10\ \mu$m), in what is now called the Brownian motion. This analogy with molecules is useful to give us the idea that "very small" doesn't mean necessary "invisible", and it may happen that microscopical effects can be amplified at macroscopical scales accessible to us.

In this sense many physicists working on quantum-gravity phenomenology are developing theories and toy models in which Planck scale effects may be observed in current (or soon) available experiments. This is a tough work because not only it is difficult to make falsifiable predictions from a theory of Quantum Gravity, but also because in order to spot in some experiments a Planck scale effect you need to exclude, at least with a good level of confidence, other possible explanations given by the "standard physics", i.e. the Standard Model of particle physics and the theory of General Relativity. Let me stress this point a bit more. We all know the "Occam's razor" and we use it properly in everyday life. This basic principle, which simply states that the simpler explanation for an occurrence is usually the better, also applies in science. For instance, Occam's razor arises naturally in the context of Bayesian inference, which is in science a useful method of model selection. At this point you can soon realize that, given a possible explanation in the context of one of the many plausible theories of Quantum Gravity and one in the context of the Standard Model or General Relativity, scientists will usually prefer the latter just because today the Standard Model and General Relativity are very well known and understood fundamental physical theories which give an accurate descriptions of the physical reality we have explored so far.

From this point of view of looking for strong deviations from the Standard Model or General Relativity, one of the most appealing field research in physics is "Neutrino Physics".

The neutrino is the most abundant particle in the universe. Every second 65 billion neutrinos pass through every square centimeter of our body and the Earth. Neutrinos do not carry electric charge, which means that they are not affected by the electromagnetic forces that act on charged particles such as electrons and protons. They are also extremely tiny because of which they travel mostly undisturbed through matter. This makes neutrino not only one of the most abundant particle in the universe, but also the most elusive.

Its appeal in quantum-gravity phenomenology is given by the fact that neutrinos have properties which are not still understood in the context of the Standard Model. Indeed neutrino is the only particle which provides the first solid hint towards physics beyond the Standard Model. The Standard Model includes three massless neutrinos: the electric neutrino, the muon neutrino and the tau neutrino, associated with the electron, muon, and tau, respectively. Physicists call this three species a "flavor". However, the experimental observation of neutrinos changing from a flavor to another, a phenomenon known as neutrino oscillation, first theoretically predicted by Bruno Pontecorvo in 1957, has motivated people to suggest that neutrinos are actually massive. The mass of the neutrino is much smaller than that of the other known elementary particles, and this is the reason for which has been difficult to detect such effect. The experimental discovery of neutrino oscillation, and thus neutrino mass, by the Super-Kamiokande Observatory (in Japan) and the Sudbury Neutrino Observatory (in Canada) was recognized with the 2015 Nobel Prize for Physics.

As I stressed before, neutrinos are extremely hard to detect, and the harder (Fig. 1) a particle is to detect, the bigger and more sophisticated the detectors have to be. This is why neutrino observatories, such as the Super-Kamiokande Observatory or the most recent IceCube Neutrino Observatory, are huge structures, situated many meters below the ground surface in order to shield the detectors from other sources of radiation.

Current research looks for an extension of the Standard Model to include neutrino masses. Some physicists, such as professor Heinrich Päs, who gave during the Experimental Search for Quantum Gravity conference in Frankfurt an interesting presentation about neutrino physics, argue that the anomalous neutrino oscillations may be regarded as traces of the quantum nature of gravity. This makes indeed neutrino a perfect probe for quantum gravity.

Neutrino oscillation is not the only way in which neutrinos may provide us some hints towards a quantum theory of gravity. In recent years we have been witnesses to the birth of a new kind of astronomy: the "neutrino astronomy". Since Galileo Galilei pointed for the first time in 1610 his telescope to the sky we have always been observing the universe in photons. This has been for centuries the only possible way of doing astronomy and this has led people to refer to "photon astronomy" simply as "astronomy". But photon is not the only particle which can travel through space freely for millions of years bringing us informations about stars, galaxies and

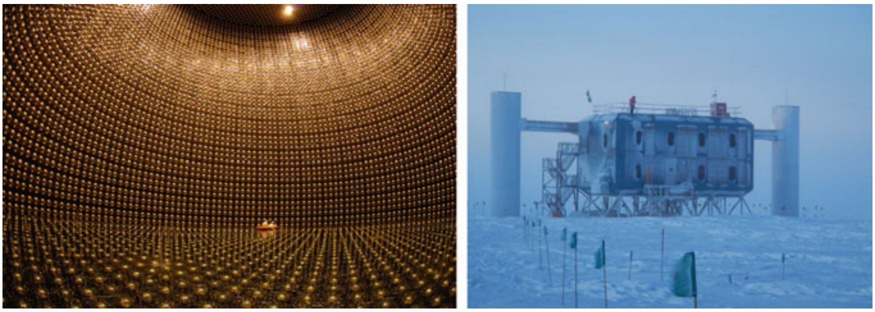

Fig. 1 Engineers examining instruments inside the half-filled Super-Kamiokande tank in a row boat (*Left*). The IceCube Laboratory at the South Pole in Antarctica (*Right*)

other mysterious and exotic things in the universe. We know that there is another particle that can do this job even better than photon: of course I am talking about neutrino. The problem is that we do not have eyes for neutrinos, we only have eyes for photons which make us see the universe around us, and since now, due to the elusive nature of neutrino, our technology was not capable of building "artificial ayes", i.e. detectors, that can "see" neutrinos coming directly from space. But fortunately things are changing and thanks to theoretical improvements in neutrino physics and experimental improvements in neutrino observatory, such as the IceCube Neutrino Observatory, we are now able to detect neutrinos from space.

The neutrino astronomy will give us the opportunity to see the universe in a totally different way, revealing us what cannot be directly observed using only photons. Take for instance the star nearest to us, the Sun. Only the surface of the Sun can be directly observed. Any light produced in the core of a star will interact with gas particles in the outer layers of the star, taking hundreds of thousands of years to make it to the surface, making it impossible to observe the core directly. Since neutrinos are also created in the cores of stars (as a result of stellar fusion), the core can be observed using neutrino astronomy.

But how can the newborn neutrino astronomy be relevant for the quantum-gravity phenomenology? Of course at this moment there is no clear answer to this questions. It is like guessing before Galileo Galilei gave birth to astronomy, how astronomy would have changed our knowledge of the universe and of the laws of physics. However there are already some physicists, such as professor Giovanni Amelino-Camelia, another speaker in the Experimental Search for Quantum Gravity conference in Frankfurt, who are proposing astrophysical neutrinos to test some Planck scale effects. Their proposal is to use astrophysical neutrinos to test Lorentz-invariance deformations, which is an effect predicted in some scenarios of Quantum Gravity.

Lorentz invariance is one of the two postulates on which is based Special Relativity, i.e. General Relativity on flat spacetime. This postulate states that the laws of physics are invariant (i.e. identical) in all inertial systems (non-accelerating frames of reference). In Special Relativity if you want to move from an inertial frame to another, in order to preserve the laws of physics, you must use the Lorentz transformation.

One consequence of deforming Lorentz invariance is an energy-dependent speed of light. If the energy-dependence is first oder in the particle's energy over the Planck energy ($\sim 10^{19}$ GeV), then it would become observable in the travel-time of highly energetic particles from distant gamma ray bursts. The most energetic the particle is the stronger the effect will be, till the point where we can discard that the feature we are observing could be the result of some (so far unknown) astrophysical properties of the sources. One of the major challenges in observing Lorentz-invariance deformations in photons is that the most energetic photons observed from gamma ray bursts are of energy in the range of 10 GeV. This implies that the expected size of the effects is between a few and ~ 100 seconds, which may well be the time scale of some mechanisms intrinsic of gamma ray bursts. The most energetic neutrinos of astrophysical origin so far observed, by the IceCube neutrino observatory, have instead energy in the range of 100 TeV (4 orders of magnitude in energy bigger than 10 GeV). This lead the size of the effect under investigation being of the order of a couple of days, so that one can safely neglect that such feature (if observed) may be of astrophysical origin. This studies for neutrinos, while inconclusive, preliminary favor Lorentz-invariance deformations, but more data are needed.

The phenomenology of quantum gravity is a young and ambitious program that brings together theoretical and experimental physicists from many areas. Here it has been presented shortly, and without entering into technical details, just one areas of physics, the neutrino physics, that may help physicists finally observe the first experimental evidence of quantum gravity, i.e. of Planck scale effects. To date we have no experimental signature for such quantum gravitational effects. This goal may be achieved in the next decades or maybe in the next centuries. We do not know it. But conferences like the one held in Frankfurt, with physicists bringing their ideas and creativity in the experimental search for quantum gravity, brought us closer to this goal. The payoff that could be expected appears to be well worth the effort, since such experimental signature for quantum gravitational effects will certainly revolutionize physics and our understanding of space and time.