APRIL 2019

NEWSLETTER 58

Istituto Nazionale di Fisica Nucleare

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THE FIRST IMAGE OF A BLACK HOLE FROM THE EVENT HORIZON TELESCOPE

Interview with Mariafelicia De Laurentis, INFN researcher, Professor at the University of Naples Federico II, and scientist at the EHT collaboration that announced the new interesting result.

On April 10th, the EHT Event Horizon Telescope project - an international collaboration - presented the first direct visual proof of a black hole and its shadow, an image that toured the world, dominating the front pages of newspapers. The EHT is an international project that was established with the aim of studying the environment surrounding Saggitarius A, the supermassive black hole situated at the centre of our galaxy (the Milky Way), as well as the M87* black hole at the centre of the supergiant elliptical galaxy Virgo A, which is reconstructed in the image.*
The construction of the EHT and the results obtained represent the culmination of decades of observational, technical, and theoretical work: a piece of global teamwork that required close collaboration by researchers around the world. Led by Harvard University's Sheperd Doeleman, the EHT collaboration involves more than 200 researchers from Africa, Asia, Europe, and North and South America. Supported by significant international investment(1), the project connects existing telescopes using new systems, creating a fundamentally new instrument with the highest angular resolving power that's ever been obtained. The US National Science Foundation (NSF), the European Research Council (ERC) and East Asian funding agencies provided the key financial support. Italy made scientific contributions through INFN and the University of Naples Federico II, and the Italian National Institute for Astrophysics (INAF).
The telescopes involved in this achievement were ALMA, APEX, the IRAM 30-metre telescope, the IRAM NOEMA Observatory, the James Clerk Maxwell Telescope (JCMT), the Large Millimeter Telescope Alfonso Serrano (LMT), the Submillimeter Array (SMA), the Submillimeter Telescope (SMT), the South Pole Telescope (SPT), the Kitt Peak Telescope and the Greenland Telescope (GLT).
We asked Mariafelicia De Laurentis, INFN researcher and Professor at the University of Naples Federico II, who is part of the EHT collaboration and contributed to the research, to explain to us the scientific and technological significance of the results and how they were achieved.

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What does this image represent?

With this "photograph", we have the first direct visual proof of a black hole and its shadow. It is the image of the event horizon of the supermassive black hole that has a mass equivalent to 6.5 billion solar masses and is located 55 million light years from the Earth, at the centre of the Messier 87 galaxy in the nearby Virgo Cluster. In particular, we see an incandescent ring in the image that surrounds a dark region. The luminous part of the image is the plasma (ionised gas) that, we can conclude, is rotating: in fact, you can clearly see that one half of the ring is more luminous than the other half. This is because the gas, while it rotates, has parts that move towards us, while other parts move away from us. Those that move towards us emit a more intense light, while those that move away from us emit a dimmer light. It is a relativistic effect known as "Doppler beaming" or "boosting". At the centre of the image you see a dark disk, and there it is: that is the black hole. Or rather, that is its "shadow", as it is called. This is the region that - not emitting any light - is recognisable as the black hole. The edge of the black hole, the event horizon from which the EHT project takes its name (Event Horizon Telescope), is around 2.5 times smaller than the shadow that it projects and measures a little less than 40 billion kilometres in diameter. From what we've observed, moreover, this black hole is perfectly compatible with Einstein's theory - the theory that we know best, the simplest and most natural one. However, we can't exclude the possibility that with future measurements and a more detailed theoretical modelling, combined with shorter wavelength and high angular resolution observations, and polarimetric measurements (which provide information on magnetic fields), we could provide further verification of alternative theories to Einstein's relativity.

What are black holes?

It's not an exaggeration to say that one of the most exciting predictions of Einstein's theory of gravitation is the existence of black holes. A black hole is a region in space-time where the gravitational field is so strong that anything that approaches its vicinity is attracted to and captured by it without any possibility of escaping outside. The boundary that delimits the region of no return is called the "event horizon".

In theory, you can compare a black hole to a celestial body, with a large mass, that contracts, increases in density, and collapses under its own weight, concentrating its own mass in a single point called the black hole. In general, they form from the gravitational collapse that sometimes accompanies the death of a star. Paradoxically, black holes are the simplest objects to describe. You only need two quantities: the mass and the rotational velocity. All the information about the complex structure of the star from which they originated - such as the type of material composing it, its shape, or the magnetic field - disappears as

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soon as it crosses the event horizon.

These objects' presence influences the surrounding environment in an extreme way, distorting space-time and superheating any surrounding material. If immersed in a luminous region, such as a disk of incandescent gas, we expect that a black hole will create a dark region similar to a shadow, an effect that was predicted by Einstein's theory of general relativity, and which we had never before been able to directly observe. This shadow, caused by the gravitational curve and by the fact that light is withheld by the event horizon, reveals a lot about the nature of these fascinating objects and has allowed us to measure the enormous mass of the M87 black hole.

Why are black holes such interesting objects?

There are countless reasons to be fascinated by these objects, but the real reason why so many physicists study them is that they really test the laws of nature that we know and that we know function beautifully. Black holes are important to studying the physics of gravity because they are a perfect testing ground for understanding the most intense gravitational fields, that is, for confirming or excluding the various relativistic theories of gravitation that were formulated alongside General Relativity (Einstein's theory may not, in fact, be the final theory of the universe, which, perhaps, we have yet to discover), and for better understanding various scenarios of stellar evolution.

But there's also a surprising, unexpected reason why black holes are considered so important and that is their central role in research into a connection between quantum mechanics and gravity.

I would say, then, that black holes are the perfect stage for understanding how to obtain a theory capable of explaining phenomena that, though present in nature, are still not understood. To this day, this theory represents the objective of physicists who, for centuries, have striven to fully understand what we are made of, where we come from, and where we're going. Only a true, objective, and deep understanding of what surrounds us will allow us to answer these fundamental questions.

What techniques were used in taking the photograph?

The EHT observations were made possible thanks to the technique known as Very-Long Baseline Interferometry (VLBI) that uses atomic clocks to synchronise telescope facilities around the world. The technique exploits the rotation of our planet to create an enormous telescope (because the bigger a telescope's dish, the greater the image's contrast) that equals Earth’s dimensions and is capable of observing at a wavelength of 1.3 mm (equal to a frequency of around 230 GHz). The VLBI technique allowed us to attain an angular resolution of 20 micro-arcseconds.

Each telescope involved in measuring produced enormous quantities of data (around 350 tetrabytes per

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day) that were archived on high-performance helium-filled hard drives. These data were transferred to highly specialised supercomputers (known as correlators) at the Max Planck Institute for Radio Astronomy and at the Massachusetts Institute of Technology MIT Haystack Observatory to be lined up. The data were then painstakingly converted into an image using new computational tools that the collaboration developed.

What is its scientific and technological significance?
The importance of these results is linked not only to the direct observation of another astrophysical object but also to the fact that they provide proof of our correct understanding of the properties of space and time in extremely strong gravitational fields.
The first thing that the photo tells us is that we are on the right path for understanding what black holes truly are. It encourages us to use the same technique to study other, similar masses in the universe. More especially, with the data in our possession, we will be able to explore other places where black holes are found. It is a great occasion, one without precedent.
From a technological standpoint, the practical consequences of scientific discoveries are usually seen some years after the discovery. For example, studies in x-ray astronomy led to the detectors used in airport security, and to medical applications in refined diagnostics. In this case, I expect that many of the technological solutions that have been used for this instrument will have consequences for society. There are certainly ever wider implications for the processing of big sets of data (so-called Big Data), but the ability to assign a time to single measurements with very high precision could also have future uses in some other daily activities.

Europe has a decisive role thanks to the ERC European Research Council's contribution and to the work of many scientists.
The ERC has funded scientists involved in the EHT collaboration through the BlackHoleCam (BHCam) Sinergy Grant project, investing some 14 million Euros. The goal of BHCam is to reconstruct images of black holes for measuring and studying them, in order to test gravitational theories and, finally, to find new radio pulsars in the black hole's vicinity at the centre of our galaxy and combine these measurements with advanced computer simulations. Since 2014 this research project, which is supposed to last six years, has been led by three eminent researchers and their teams: Professor Heino Falcke of Radboud University in Nimega (also chairperson of the EHT scientific council); Michael Kramer of the Max Planck Institute

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for radio astronomy; and the Italian Luciano Rezzolla of the Goethe University in Frankfurt. In particular, Luciano Rezzolla's group, which I'm part of, has made a big contribution to the theoretical and numerical study of black holes, constructing a large library of analytical and semi-analytical models based on ray tracing and relativistic magnetohydrodynamic (GRMHD) simulations. The Frankfurt group is the only one in the world able to do these types of simulations.
Europe, then, has to be proud of this scientific success, which demonstrates its organisational, technological, and knowledge capabilities, and must continue to be a leader in basic scientific research. Its future depends upon it - our future. Money spent on fundamental scientific research is not a cost, it's an investment. You achieve results working together, putting national and European research funding together in the same basket, opening Europe to international collaborations.

(1) The EHT collaboration comprises 13 funding institutions: the Academia Sinica Institute of Astronomy and Astrophysics, the University of Arizona, the University of Chicago, the East Asian Observatory, the Goethe University Frankfurt, the Istituto di Radioastronomia di Bologna, the Large Millimeter Telescope, the Max Planck Institute for Radio Astronomy, the MIT Haystack Observatory, the National Astronomical Observatory of Japan, the Perimeter Institute for Theoretical Physics, Radboud University, and the Smithsonian Astrophysical Observatory. ■

RESEARCH COLLABORATIONS

INFN-ITHEMBA AGREEMENT SIGNED IN CAPE TOWN

On April 2nd, INFN [the Italian Institute for Nuclear Physics] and the National Research Foundation (NRF) signed a Memorandum of Understanding with iThemba Laboratory for Accelerator Based Science in Cape Town, South Africa. The agreement reaffirms the long collaboration between INFN and the principal South African nuclear physics research laboratory but is also more broadly important in representing a significant new step for scientific cooperation between Italy and South Africa.

In fact, the agreement constitutes an important milestone for the collaboration between iThemba and INFN (with its Legnaro and Southern National Laboratories) in the field of nuclear physics and its applications. The focus is especially on research into nuclear astrophysics, the planning and development of facilities for the production of unstable nuclear beams, and biomedical applications, such as the production of new radioisotopes for medicine, radiobiology, and particle therapy.

INFN's president, Fernando Ferroni, and iThemba's director, Faïçal Azaiez, signed the collaboration agreement in the presence of the Italian consul Emanuele Pollio; the NRF's executive director for strategic collaboration, Aldo Stroebel; INFN's vice president, Eugenio Nappi; and the directors of INFN's Legnaro and Southern National Laboratories, Diego Bettoni and Giacomo Cuttone. ■

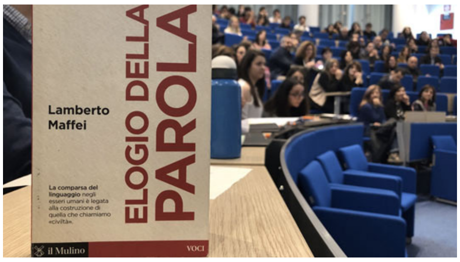
RESEARCH INFRASTRUCTURES

ALMOST 70 MILLION TO THE INFN FOR THE DEVELOPMENT OF RESEARCH INFRASTRUCTURES

Eight research facilities affiliated with INFN, as applicant or partner, will receive almost 70 million euros in total funding from the PON [Italy's National Operational Programme for Research and Competitiveness] "Research and Innovation 2014-2020" fund, as part of Italy's Ministry of Education, Universities and Research's (MIUR) National Programme for Research Infrastructure (PNIR).

In particular, the four projects that INFN applied and won funding for concern the research of rare events at the Gran Sasso National Laboratories, the development of underwater equipment for research in neutrinos physics and for biology and geophysics interdisciplinary studies, the development of infrastructure for managing scientific calculation and big data, and the development of a facility for the production of high intensity ion beams. INFN's partner facilities will mainly be concerned with environmental research activities: from studies into atmospheric pollution, to the study of marine ecosystems, to the distributed management of biodiversity data, to computation in bioinformatics.

PNIR, which is an integral part of the National Research Programme (PNR), provides investment in research infrastructure in order to further support basic research. PNIR thus influences the "research system" in supporting the development of competitive facilities, not only in relation to scientific and technological challenges but also economic and social ones, improving the overall quality of national research and increasing its competitiveness on the international scene. ■



PUBLIC ENGAGEMENT

ASIMOV PRIZE 2019 TO THE BEST SCIENCE OUTREACH BOOK AND TO STUDENTS' REVIEWS

Lamberto Maffei's book tells the story of science via a hymn to our species' greatest evolutionary advantage, the word: it is a heartfelt invite to recognise the value of the word, to use it, and to love it. Entitled 'Elogio della parola' - In Praise of the Word (published by Il Mulino), the work won the fourth edition of the Asimov Prize, having been selected by a jury of thousands of secondary school students from 11 Italian regions. It was judged best cultural or popular scientific book published in the last two years in Italy. The award ceremony will take place on May 9th (at 4:30 p.m.), during an event organised at the Turin International Book Fair.

Established in 2015 by INFN and the Gran Sasso Science Institute (GSSI), the Asimov Prize for popular science publications is a competition that involves not just the authors of the works being judged but also the high school students who declare the winner in their reviews, which are then awarded prizes. The prize's scientific committee is composed of 250 members, half of which are high school teachers and half of which are university professors, researchers, PhD students, journalists, writers, and representatives of the cultural world. In recent months, these members selected the seven books to be submitted to the students' judgement. Other books that participated in the final competition, apart from Maffei's, included: Guido Barbujani and Andrea Brunelli's Il giro del mondo in sei milioni di anni (Around the world in six million years) (Il Mulino); James Gleick's Time Travel (Codice); Jerry Kaplan's Intelligenza artificiale. Guida al futuro prossimo (Artificial Intelligence: What Everyone Needs to Know) (Luiss Edizioni, Il Mulino); Giorgio Manzi's Ultime notizie sull'evoluzione umana (The Latest News on Human Evolution) (Il Mulino); Guido Saracco's Chimica verde 2.0 (Green Chemistry 2.0) (Zanichelli); and Sara Sesti and Liliana Moro's Scienziate nel tempo. 100 biografie (Scientists Over Time: 100 Biographies) (Ledizioni). ■

PUBLIC ENGAGEMENT

INFN AT THE NATIONAL GEOGRAPHIC SCIENCE FESTIVAL

The 14^{th} edition of the National Geographic Science Festival closed mid-April having attracted 70,000 visitors. INFN contributed to the festival with a full schedule of events and activities. More than 500 events – from conferences, to shows, to exhibitions, to interactive and laboratory exhibits – allowed visitors to explore the theme of the Invention. It was a celebration of three particularly important anniversaries: 500 years since the death of Leonardo da Vinci, the 50^{th} anniversary of the moon landing, and 150 years since the invention of the Periodic Table.

From research into the "Big Bang Echo" to the birth of multi-messenger astronomy, from the story of Italy on Mars to the observation of Earth from space, from the inventions triggered by basic research to nuclear astrophysics: these are just some of themes that researchers from INFN and other Italian research organisations engaged with as they took part in the numerous meetings and dialogues scheduled during the festival. INFN also added to the festival's success with two evening conference-shows, two exhibitions (Il cosmo in un bicchiere, Scienza fra le nuvole - The Cosmos in a Glass and Science among the Clouds), a virtual-lab on particle detectors, and the projection of the documentary film The Most Unknown.

The National Geographic Science Festival was produced by the Fondazione Musica per Roma, planned in partnership with Codice Edizioni, and held in conjunction with National Geographic and in collaboration with MIUR - Italy's Ministry of Education, Universities and Research. It was promoted by Rome's Office of Cultural Growth and also held in partnership with ASI - the Italian Space Agency - and INFN, with the participation of the principal Italian research organisations and diverse cultural associations and organisations. ■

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XENON1T MEASURES THE RAREST DECAY PROCESS EVER OBSERVED IN THE UNIVERSE

The universe is almost 14 billion years old. An inconceivable length of time by human standards, yet compared to some physical processes, it is but a moment. There are radioactive nuclei that decay on much longer time scales. XENON1T, a detector for the search of dark matter at INFN Gran Sasso National Laboratory, has now directly measured for the first time the so-called double electron capture of xenon-124, that is the rarest decay process ever recorded in a detector. The half-life measured for xenon-124 - the time after which half of the radioactive nuclei have decayed away - is about one trillion times longer than the age of the universe. The new result, published on April 25th on Nature, provides information about the nuclear structure relevant for further investigations on rare processes.

XENON1T has as its main scientific goal the direct search for dark matter in the form of WIMP (weakly interacting massive particles), and is currently the largest detector ever made for this purpose, with a sensitive mass of 2 tonnes of xenon, and at the same time it presents the smallest background ever obtained. Thanks to these characteristics, since 2017 it is the most sensitive experiment for WIMP search. It is based on a time projection chamber with liquid/gas xenon: it is a cylindrical detector, about one meter in diameter and height, filled with liquid xenon at a temperature of -95 °C. In XENON1T the interaction of a particle with a xenon nucleus is given by a weak flash of scintillation light accompanied by a few electrons, which are converted into a flash of light once in the gaseous xenon. Both light signals are recorded thanks to ultra-sensitive photosensors, and allow information on the 3D position and energy of each event.

In the double electron capture process, during which the xenon-124 is transformed into tellurium-124, two protons of the xenon nucleus simultaneously capture two electrons of the first surrounding level, transforming into two neutrons, with the emission of two neutrinos. The electronic cloud reacts to the lack of two electrons captured with a cascade process, which leads to the emission of a fixed amount of energy. In the case of

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xenon, this energy corresponds to about 64 keV. The measure therefore consisted in seeking an excess of events with energy equal to the expected one, compared to the background, almost constant in energy, present in the detector. Using an internal mass of xenon equal to 1.5 tonnes, and a data acquisition time of approximately 180 days, 126 events were observed in the expected energy region. Using this first-ever measurement, the scientists calculated the enormously long half-life of 1.8×10^{22} years for the process.

The new results show how effective the XENON1T detector is in detecting rare processes and rejecting background signals. Having observed this process directly, in fact, demonstrates how powerful the XENON1T detection method actually is – also for signals that are not from dark matter – thanks to the effort put in reducing the natural radioactive background of the experiment.

XENON1T acquired data from 2016 until December 2018 when it was switched off. The scientists are currently upgrading the experiment for the new XENONnT phase which will feature a three times larger active detector mass, together with a reduced background level. This upgrade will boost the detector's sensitivity.

The INFN, with the LNGS and the divisions of Bologna and Turin, has been part of the XENON1T project since its inception in 2009. With the more recent contribution of researchers from the INFN divisions of Naples and Ferrara, the Italian groups are also involved in the current extension of the project, with the XENONnT detector, under construction at the LNGS. ■

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Cover

The first image of a black hole, which is located in the M87 galaxy, at a distance of 55 billion light years from Earth (source: EHT collaboration)