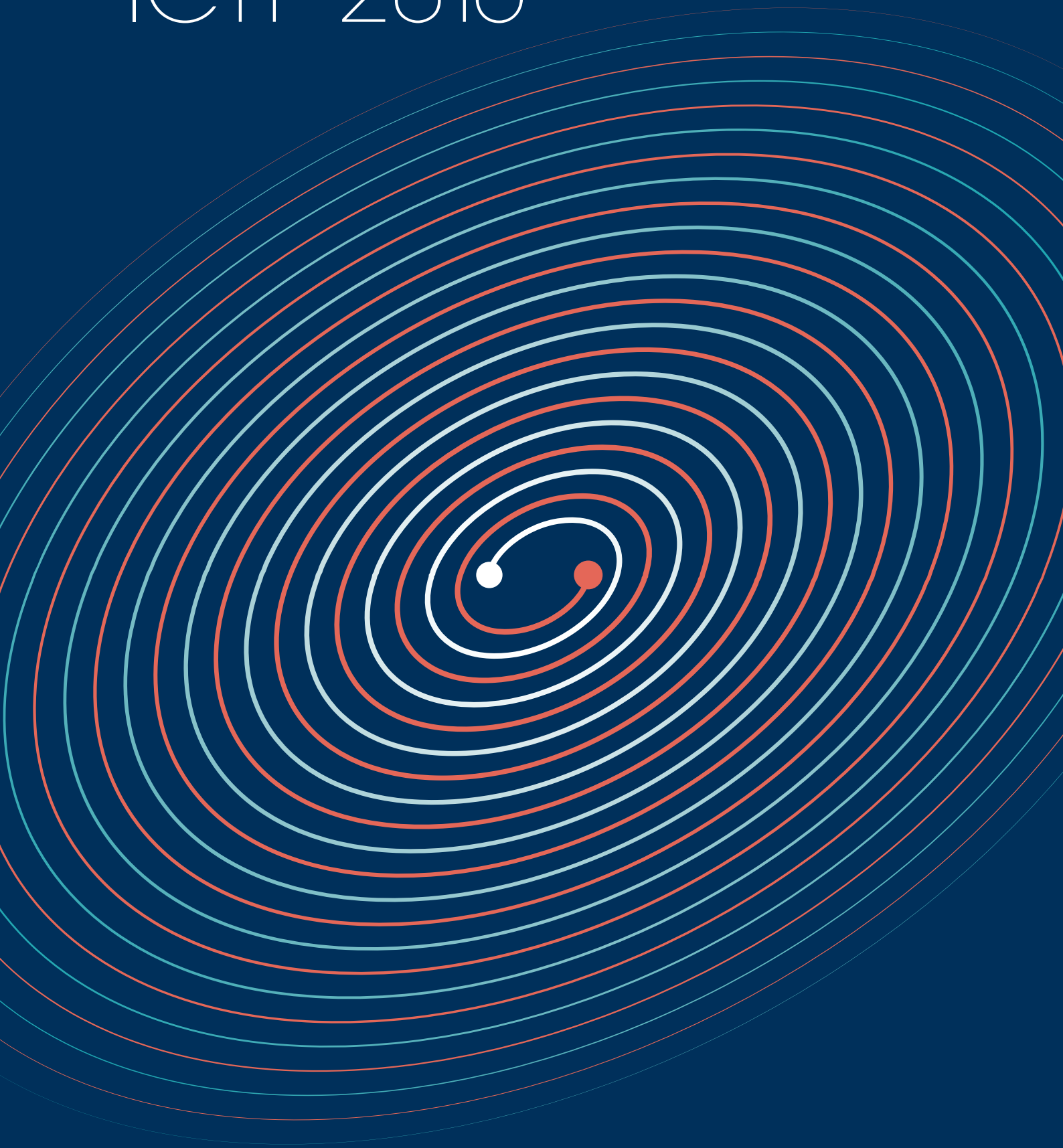
Summary of Activities

ICTP 2016



The Abdus Salam
International Centre
for Theoretical Physics

Summary of Activities 2016
The Abdus Salam International Centre for Theoretical Physics

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Summary of Activities
ICTP 2016

Foreword

In 2016, ICTP proved once again that its unique, international mission has far-reaching, successful impacts, thanks to its top-quality scientists and its dedicated staff. Its scientific production during the year, boosted by recent young hires, reflected ICTP's high research standards. One concrete highlight in this regard was the recognition by *Physics World* of a quantum computing article from *Nature* co-authored by young ICTP scientist Marcello Dalmonte as one of the top 10 physics breakthroughs of the year. In addition, ICTP emeritus scientist Alexei Smirnov received the prestigious Einstein Medal for his important contributions to the physics of neutrinos.

Thanks to its expanded number of educational programs, ICTP now has more pre-PhD students studying on its campus, adding to its diversity. In 2016, 74 students from the ICTP flagship Postgraduate Diploma Program (covering two academic years) were joined by more than 40 masters students in the Centre's Medical Physics and High Performance Computing programs, along with more than 20 in the joint ICTP-SISSA PhD program. Additionally, generous support from the OPEC Fund for International Development enabled the ICTP-IAEA Sandwich Training Education Program (STEP) to increase the total number of STEP students to 40. Students in the joint Master in Medical Physics with the University of Trieste benefit from fellowships mostly funded by the IAEA; the program has proven to make a substantial difference once the students return to their countries to pursue their careers. This has increased the number of students at a given time at ICTP to over 200, more than at any time in ICTP's history.

ICTP hosted a number of high-profile science events in 2016. Its Salam Distinguished Lectures, funded by the Kuwait Foundation for the Advancement of Science, were masterfully delivered by Sir Brian Hoskins on the timely subject of climate change. On 8 August, Dirac's birthday, the Centre continued its annual tradition of announcing its Dirac Medallists. For 2016, the recipients were Nathan Seiberg, Mikhail Shifman and Arkady Vainshtein. On the same day, ICTP held a ceremony for the 2015 awardees: Alexei Kitaev, Gregory Moore and Nicholas Rea. The prestige of the Dirac Medal was confirmed once more after three medallists (Joesph Polchinski, Andrew Strominger, Cumrun Vafa) received the Breakthrough Prize; in addition, 2012 Dirac Medallist Duncan Haldane was awarded the 2016 Physics Nobel Prize. The Ramanujan Prize ceremony was combined with a special public talk by Ken Ono, associate producer and mathematical consultant of the film based on Ramanujan's life, "The Man Who Knew Infinity". This was an excellent way to honor the great Indian mathematician.

Two ICTP scientists were recognized by the American Physical Society. Sandro Scandolo was made a member for his scientific and outreach work, and Joseph Niemela was awarded the Dwight Nicholson Medal for Outreach for his leadership role in organizing the International Year of Light (2015).

ICTP's partner in Brazil, the ICTP-South American Institute for Fundamental Research (ICTP-SAIFR), contributed to a major scientific discovery of the year—gravitational waves—with one of its young scientists involved in the LIGO experiment. ICTP-SAIFR and its host institute, São Paulo State University, were included in Nature's 2016 index of rising stars. In November ICTP-SAIFR celebrated its 5th anniversary. This major, successful ICTP initiative sets a standard for future partner institutions.

ICTP was honored to host the final meeting of the United Nations Scientific Advisory Board (UNSAB, pictured at left), an elite group of scientists who were preparing their final report to the UN Secretary General. Coordinated by UNESCO and by request of the Italian government, the meeting allowed ICTP to join efforts with other international scientific institutions in Trieste (The World Academy of Sciences, the InterAcademy Panel and the International Centre for Genetic Engineering and Biotechnology).

In 2016 important scientific supporters of ICTP passed away: Roberto Petronzio, a former INFN director who served as the Italian representative on ICTP's Steering Committee from 2006 to 2014; Giuseppe Furlan, who led many activities at ICTP over the years, in particular the TRIL program; and Jean Christophe Yoccoz, a Fields Medallist and member of the ICTP Scientific Council from 2004 to 2013. Also, Dirac Medallist Thomas Kibble (UK) and Nobel prize winners Ahmed Zewail (Egypt) and Walter Kohn (USA), regular visitors and supporters of ICTP activities, passed away in 2016. ICTP will always be grateful for their generous contributions in support of our mission and science in general. In April, ICTP established the Walter Kohn prize, co-funded by the Quantum Espresso Foundation, to recognize contributions in the field of quantum-mechanical materials and molecular modeling made by developing country scientists.

Finally, ICTP is experiencing an important transition period in which a large number of senior scientists and administrators are reaching retirement age, and some restructuring is taking place. I want to take this opportunity to thank all the retired staff for their enduring commitment to ICTP's mission. I am confident that through a joint effort among scientists and administrative staff, with the guidance of the Steering Committee and Scientific Council, ICTP will continue to run as efficiently as possible, ensuring that this unique institution delivers its important services to the scientific community worldwide.

— Fernando Quevedo, Director, ICTP

ICTP Highlights 2016

January

The family of ICTP founder Abdus Salam announces the winners of the 2016 Spirit of Abdus Salam Award: Faheem Hussain, a member of ICTP's High Energy, Cosmology and Astroparticle Physics section who passed away in 2009; Seifallah Randjbar-Daemi, former ICTP Acting Deputy Director and head of the High Energy, Cosmology and Astroparticle Physics before his retirement in 2015; and Galileo Violini, who founded and led the growth of the Centro Internacional de Fisica (CIF) in Colombia.

February

01 ICTP emeritus scientist Alexei Smirnov is awarded the 2016 Albert Einstein Medal by the Bern, Switzerland-based Albert Einstein Society for his pioneering studies on neutrino oscillations, the ability of these elusive particles to change identities as they travel from their source to neutrino detectors on Earth.

02 ICTP and the International Commission for Optics (ICO) announce the recipients of their 2016 ICO/ICTP Gallieno Denardo Award: Jehan Akbar of Hazara University, Pakistan, and Mati Horprathum of the National Electronics and Computer Technology Center, Thailand. Akbar is cited for his breakthrough contributions in the design and fabrication of high performance semiconductor lasers and amplifiers, while Horprathum is cited for his valuable contributions to the development of optical thin film technology for innovative surface functionality.

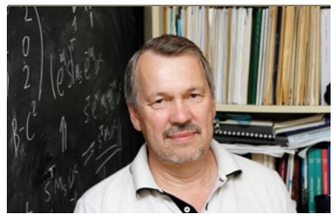
May

03 ICTP's Salam Distinguished Lecture Series features renowned British climatologist Sir Brian Hoskins, who offers a timely sketch of climate change science and the implications for our rapidly changing planet.

04 ICTP and three other scientific institutes in Trieste host a major United Nations conference on 24 and 25 May attended by elite scientists of the UN Secretary-General's Scientific Advisory Board (UNSAB), who are tasked to provide insights and recommendations on the crucial role of science in achieving the Sustainable Development Goals (SDGs) that were adopted by the United Nations in late 2015.

June

05 A new partnership between ICTP and the OPEC Fund for International Development (OFID) is launched—the OFID Postgraduate Fellowships Program—securing collaboration and research opportunities at ICTP for students from developing countries working toward their PhDs.



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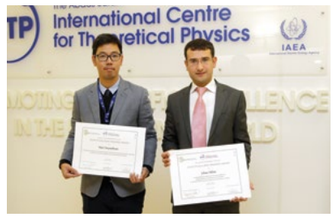

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June

06 ICTP announces that the 2016 Ramanujan Prize for Young Mathematicians from Developing Countries has been awarded to Chenyang Xu of Beijing International Center of Mathematical Research in China. Xu was cited for his outstanding works in algebraic geometry, notably in the area of birational geometry. The prize also recognizes Xu's contribution to the strengthening of algebraic geometry in China.

August

07 ICTP awards its 2016 Dirac Medal and Prize to Nathan Seiberg (Institute for Advanced Study, Princeton), Mikhail Shifman (University of Minnesota) and Arkady Vainshtein (University of Minnesota) for their important contributions to a better understanding of field theories in the non-perturbative regime and in particular for exact results in supersymmetric field theories.

08 Thirty-five students from 20 countries receive ICTP Postgraduate Diplomas after a year of intense coursework. Seventeen are now enrolled in PhD programs while two are pursuing masters degrees.

November

09 ICTP awards its 2016 ICTP Prize to Aninda Sinha of the Center for High Energy Physics, Indian Institute of Science, for his key contributions to aspects of quantum field theory using the AdS/CFT correspondence.

The South American Institute for Fundamental Research (ICTP-SAIFR), an ICTP partner institute, celebrates its fifth anniversary. ICTP-SAIFR was the first of ICTP's partner institutions, independent research centers modeled after ICTP, with a similar program of schools, conferences, and visiting scientist programs.

December

10 Thirteen students earn degrees in the joint ICTP-University of Trieste Masters in Medical Physics Program (MMP), giving them the knowledge and technical skills needed to forge safer, more efficient medical radiation treatment in the developing world.

Research to which ICTP condensed matter scientist Marcello Dalmonte contributed is chosen by *Physics World* as one of the top ten physics breakthroughs of the year for 2016. A paper on the research, "Real-time dynamics of lattice gauge theories with a few-qubit quantum computer", was published in *Nature* in June 2016 (doi:10.1038/nature18318).

Did you know?

Research at ICTP has contributed directly, or indirectly, to at least four Nobel Prizes. These include:

- ICTP founder Abdus Salam's award in 1979 for his contribution to the theory of the unified weak and electromagnetic interaction between elementary particles;
- the close involvement of Filippo Giorgi, head of ICTP's Earth System Physics section, with the Intergovernmental Panel on Climate Change, which shared the 2007 Nobel Peace Prize;
- ICTP's contribution, led by Bobby Acharya of the Centre's High Energy Physics section, to CERN's ATLAS experiment, which helped confirm the existence of the Higgs Boson that had been theorized by François Englert and Peter W. Higgs, who shared the 2013 Nobel Prize in Physics;
- the theoretical work on neutrino oscillation by ICTP scientist Alexei Smirnov and colleagues, which was confirmed by one of the recipients of the 2015 Nobel Prize in Physics, Arthur McDonald.

ICTP Research

ICTP's unique strength lies in its ability to bring together large numbers of gifted scientists from developing and developed countries to participate in joint research. From its early focus on theoretical high energy physics, the Centre's research areas have evolved in response to the needs of physicists and mathematicians from the developing world, and now include:

- **High Energy, Cosmology and Astroparticle Physics**
- **Condensed Matter and Statistical Physics (with a new research area in renewable energy)**
- **Mathematics**
- **Earth System Physics**
- **Applied Physics**
- **Quantitative Life Sciences**

ICTP's visiting researchers are immediately caught up in the culture of the Centre. Strategically placed blackboards welcome them to linger over physics and math problems, while bulletin boards announce a feast of upcoming seminars and colloquia. ICTP research is further strengthened by the Centre's infrastructure, including its recent investment in high performance computing equipment and its highly regarded Marie Curie Library.

The following pages provide a glimpse of ICTP's research activities during 2016.

High Energy, Cosmology and Astroparticle Physics

Four broad areas are explored by the High Energy, Cosmology and Astroparticle Physics (HECAP) section at ICTP: cosmology; physics at the Large Hadron Collider (LHC); phenomenology of particle physics; and gravity, strings and higher dimensional theories. In 2016 the section has investigated such phenomena as the nature of dark matter, the mass of exotic particles, the cosmological constant and quantum cosmology.

The Dark Side of Hidden Sector Portals

Mysterious dark matter makes up more than 80% of the universe's mass, but its precise nature has eluded physicists for decades. It seems to require a new species of stable particle that lies outside the standard model of particle physics. Many theorists believe that supersymmetric theories, in which the known particles have "superpartners," would provide a tidy solution. In particular, in the simplest class of supersymmetric models, the lightest such superpartner would be stable against decay, making it a leading dark matter candidate.

However, a paper by ICTP's Bobby S. Acharya and co-workers has now argued that the lightest superpartner is likely to be unstable if string theory is true. Supersymmetric models derived from string theory typically involve extra hidden sectors of particles in addition to the visible sector of standard model particles and their superpartners. Moreover, such models typically include interactions known as portals, which could induce decay of the lightest superpartner to a hidden sector particle that is even lighter.

Theorists had discussed aspects of this argument before. The new paper emphasizes that the conditions for instability are quite generic among string-based models. Dark matter is thus likely to reside in a hidden sector, which may be very hard to investigate experimentally.

Reference:

Acharya, B. S., Ellis, S. A. R., Kane, G. L., Nelson, B. D., Perry, M. J. (2016). The lightest visible-sector supersymmetric particle is likely to be unstable. Phys. Rev. Lett. 117, 181802, arXiv:1604.05320 [hep-ph]

Weighing Hot Axions on a Lattice

Numerical computations by Giovanni Villadoro and colleagues have revealed that previous estimates of an exotic particle's mass could be off by nearly a factor of ten. The particle is the axion, which was first postulated to resolve a problem in quantum chromodynamics (QCD), the theory of the strong interactions between quarks and gluons. The axion could also constitute dark matter, if it was produced in the right quantities, which depends on its mass at the high temperatures of the early universe. However, calculating those properties of hot axions is extremely difficult. An approach called the dilute instanton gas approximation (DIGA) is expected to be accurate at ultrahigh temperatures, but might be unreliable in less extreme conditions.

Villadoro and colleagues therefore performed lattice gauge computations, in which space is approximated as a discrete lattice, somewhat like a chessboard with squares smaller than the radius of a proton. Importantly, they included up, down, and strange quarks with physical masses on their lattice, and they varied the temperature from zero to partway into the range where DIGA is used (the simulations hit a roadblock at higher temperatures). The results indicate that when the temperature rises, the axion mass decreases at a much slower rate than DIGA predicts. This behavior suggests that the axion could form dark matter even if its mass in today's chilly universe is as small as one-tenth of the value predicted using DIGA.

Reference:

Bonati, C., D'Elia, M., Mariti, M., Martinelli, G., Mesiti, M., Negro, F., Sanfilippo, F., Villadoro, G. (2016). Axion phenomenology and θ-dependence from Nf=2+1 lattice QCD, JHEP 1603, 155, arXiv:1512.06746 [hep-lat]

Relaxing the Cosmological Constant

Arguably the biggest conundrum in physics today relates to the observation that the universe is expanding at an accelerating rate. The acceleration is generally attributed to dark energy or a cosmological constant – a term added to the equations of general relativity. The cosmological constant must be extremely small (but not zero) to account for the relatively mild level of acceleration. But this tiny value is violently contradicted by straightforward quantum field theory calculations, which produce values dozens of orders of magnitude larger.

To resolve this enigma, ICTP researchers Paolo Creminelli, Andrei Khmelnitsky, and co-workers have proposed a scenario involving two new scalar fields. The dynamics of the first field cause an initially large cosmological constant to relax down to the value that we observe. On its own, however, this would produce an empty universe. Instead, the relaxed state triggers a phase transition in the second scalar field, which has exotic properties (violation of the "null energy condition") that allow it to build up energy without disturbing the small cosmological constant. Further interactions transfer this energy out of the scalar field, producing a hot inflating universe with a small cosmological constant, as is required at the beginning of the conventional Big Bang scenario. The researchers concede that their baroque model is unlikely to be how the universe works, but it serves as a proof of principle of a "technically natural" solution to the problem.

Reference:

Alberte, L., Creminelli, P., Khmelnitsky, A., Pirtskhalava, D., Trincherini, E. (2016). Relaxing the Cosmological Constant: a proof of concept, JHEP 1612, 022 arXiv:1608.05715 [hep-th]

Quantum Cosmology Near Two Dimensions

Atish Dabholkar and co-workers have been examining possible cosmological consequences of nonlocal terms in the quantum effective action for gravity. The classical action of physical theories, such as Einstein's general theory of relativity, includes only "local" terms, representing particles or fields interacting at localized points in spacetime. However, quantum interactions of massless particles can lead to nonlocal terms, which are notoriously difficult to compute. Dabholkar had earlier proposed that these terms can be deduced from Weyl "anomalies," which correspond to quantum violations of a classical Weyl symmetry.

Now he and a co-worker have implemented this proposal in a model "near" two dimensions and are able to compute these nonlocal quantum corrections, which modify Einstein's equations. Consequently, the Friedmann equations for the expansion of the universe are also modified, with interesting consequences. The conventional description of the universe begins with a period of exponential expansion called inflation, and in the present day the universe is expanding at a slowly accelerating rate. Dabholkar's two-dimensional model exhibits a type of inflation (with a power law instead of exponential expansion) driven entirely by vacuum energy and the nonlocal terms. The model exhibits both inflation in the early universe and the present-day acceleration without needing to add any other fields. The group is working on the four-dimensional case to see if the nonlocal effects can be computed and whether they can have appreciable consequences for cosmology.

Reference:

Bautista, T., Dabholkar, A. (2016). Quantum cosmology near two dimensions, Phys. Rev. D 94, 044017 arXiv:1511.07450 [hep-th]

Condensed Matter and Statistical Physics

Strange and unexpected behaviours may emerge when large numbers of particles collect together. Researchers in the Condensed Matter and Statistical Physics (CMSP) section at ICTP are tackling this challenging realm with a variety of analytical and numerical techniques, with a particular focus on the development of new methods of numerical simulation. Their research work in 2016 is summarized below.

Understanding Proton Behavior in a Future Anti-Cancer Agent

The molecule known as ellipticine is naturally good at inhibiting cancer and HIV activity. With such talents, the plant-derived alkaloid has been increasingly investigated, with both experimentalists and theorists trying to understand the root of its anti-cancer, anti-HIV abilities. ICTP physicists Ali Hassanali and Ralph Gebauer were part of a team, including former ICTP post-doctoral fellow P. Ghosh, that used simulations of ellipticine's molecular dynamics to understand the behavior of the molecule in water, a common biological solvent. In the quest to understand how ellipticine could be more efficiently delivered to tumor cells, experimentalists often study a molecule's optical properties. Experiments revealed some interesting behaviors of ellipticine, which Hassanali and Gebauer's new theoretical paper helps make sense of, particularly the behaviors of the protons in the molecule. The paper highlights the important role that nuclear quantum effects have on the behavior of ellipticine's protons, and develops the understanding of its optical properties on the road to turning it into an effective tool against cancer. The paper was named as a 2016 Editor's Choice paper by the *Journal of Chemical Physics*.

Reference:
Sappati, S., Hassanali, A., Gebauer, R., & Ghosh, P. (2016). Nuclear quantum effects in a HIV/cancer inhibitor: The case of ellipticine. The Journal of Chemical Physics, 145(20), 205102. doi:10.1063/1.4968046

Investigating Phase Transitions in Non-Equilibrium Systems

Phase transitions are ubiquitous in nature and can occur in out-of-equilibrium situations. A team composed of scientists from ICTP, SNS-Pisa, ENS-Paris, Madrid, St. Andrews and Dalian have theoretically demonstrated the key role of short-range fluctuations in dissipative phase transitions, findings that can be experimentally reproduced using trapped ions, Rydberg states of atoms, or microwave circuits.

A phase transition is a transformation between two different states of matter that often involves a symmetry-breaking process (e.g., that between liquid water and ice). The theory of phase transitions in equilibrium systems is one of the triumphs of 20th-century science that showed that apparently disparate physical systems undergo transitions in the same way; the details on small length scales do not matter. Phase transitions can also occur in an out-of-equilibrium context. Famous examples include systems of moving cars into traffic jams, or individual flying birds exhibiting collective flocking. All of these situations are related to each other by the fact that the appearance of different steady-state ordering is of intimate dynamical origin and cannot be reduced to the equilibrium results. The team studied a quantum dynamical phase transition in a dissipative environment and demonstrated that, contrary to what is observed in standard thermodynamics, short-range fluctuations drastically affect the steady-state phase diagram of driven-dissipative quantum systems.

These results hopefully will stimulate novel investigations of nonequilibrium critical phenomena, placing them in a completely different light compared with the paradigm for equilibrium systems.

Reference:
Jin, J., Biella, A., Viyuela, O., Mazza, L., Keeling, J., Fazio, R., & Rossini, D. (2016). Cluster Mean-Field Approach to the Steady-State Phase Diagram of Dissipative Spin Systems. Physical Review X, 6(3). doi:10.1103/physrevx.6.031011

Manipulating Nano Devices With Microwaves

As electronic devices become ever smaller—shrinking to the nanoscale—knowledge of the physical processes taking place at that scale is needed. These processes are exciting due to nano-mechanics, a promising field of research in condensed matter physics.

Within this field, ICTP scientists Anton Parafilo and Mikhail Kiselev perform theoretical research on nanoelectromechanical (NEM) systems—devices in which you can control a single electron transport. In these very limited size systems, current can affect, or couple with, oscillations of the mechanical part of device. They posed the following question: how can we manipulate the processes in NEM devices with the help of an external electromagnetic field, for instance microwaves?

Due to the mismatch between their frequencies and mechanical vibrations, microwaves are usually not expected to affect the mechanical operation of a nano-device. This paper has shown how an external microwave irradiation could induce mechanical vibration in NEM devices and how to manipulate them. Says lead author Parafilo: "We demonstrated that electron spin provides a way for coupling both microwave radiation and mechanical oscillations, allowing it to act as a link between the two." The study's findings increase knowledge of processes taking place at small scales, with potential applications for the future electronic devices.

Reference:
Parafilo, A., Kulinich, S., Gorelik, L., Kiselev, M., Shekhter, R., & Jonson, M. (2016). Spin-mediated Photomechanical Coupling of a Nanoelectromechanical Shuttle. Physical Review Letters, 117(5). doi:10.1103/physrevlett.117.057202

Molecular Gymnastics of Water Under Pressure

Although water—common on Earth, and a necessity for life—has been extensively studied, it is still the subject of extensive research. ICTP physicist Sandro Scandolo was part of a team that examined the dynamics of water at a molecular level when subjected to pressure. The structural and dynamical properties of water are often related through the hydrogen-bond network between water molecules, and this research looks at how that network and water molecules themselves may change shape and behavior under pressure.

Using a range of techniques, including molecular dynamics simulations, anvil cell high-pressure technology, and femtosecond two-dimensional infrared spectroscopy, the team studied the spectral diffusion of an impurity in water under pressure. It turns out that the spectral diffusion rate is almost completely insensitive to pressure. The chemical structure of water molecules and their hydrogen bond network helps explain why the molecular configuration remains unchanged with pressure.

Reference:
Lapini, A., Pagliai, M., Fanetti, S., Citroni, M., Scandolo, S., Bini, R., & Righini, R. (2016). Pressure Dependence of Hydrogen-Bond Dynamics in Liquid Water Probed by Ultrafast Infrared Spectroscopy. The Journal of Physical Chemistry Letters, 7(18), 3579-3584. doi:10.1021/acs.jpclett.6b01375

Energy and Spin Moving Through Disordered Quantum Systems

Functioning quantum systems are getting closer to becoming reality, with experimental work simulating isolated quantum systems. Theorists have a fairly good picture of what is happening in the ground states of these systems, but the understanding of their properties when away from the ground state, the system dynamics, is much less clear.

ICTP physicists Antonello Scardicchio and Vipin Varma, together with Marko Žnidarič of the University of Ljubljana, recently published a paper exploring the various regimes existing in disordered quantum systems, using a one-dimensional anisotropic Heisenberg model. This particular model let the authors examine transport of energy and spin through a quantum spin chain with disorder.

Focusing on spin transport and using state of the art numerical techniques, the group managed to study much larger systems, up to 400 spins, than was previously done and this allowed them to clear up previously conflicting results. The authors show that a very large crossover length exists that controls the passage of a clean-system dominated dynamics.

References:
Žnidarič, M., Scardicchio, A., & Varma, V. K. (2016). Diffusive and Subdiffusive Spin Transport in the Ergodic Phase of a Many-Body Localizable System. Physical Review Letters, 117(4). doi:10.1103/physrevlett.117.040601

Mathematics

ICTP's Mathematics Section emphasizes two core functions: the creation of new mathematical knowledge and its global dissemination, in particular to developing countries. Members of the section build connections to groups and institutes in developing countries through a variety of activities. Research by the Mathematics Section reflects the important synergy between mathematics and physics, as well as the role of mathematics in driving the rapid development of technological advances. Its members focus on algebraic geometry, commutative algebra, differential geometry, dynamical systems, and analysis and number theory.

Liquid Droplets in Hyperspace

Francesco Maggi and a coworker have proven a result that has applications in capillarity problems, as well as having intrinsic geometric interest. Capillarity problems describe situations in which two fluids are in contact, with the boundary between them carrying some surface tension. A classic example is water rising in a thin tube (the second fluid is air). A key feature is the "mean curvature" at each point on the surface. For instance, a spherical droplet of water (perhaps floating in the International Space Station) has constant mean curvature, but so do other shapes such as bulges connected by small tapering necks of the right proportions.

A real-world water droplet has a two-dimensional surface in three-dimensional space, but mathematicians are interested in hypersurfaces of arbitrary dimension (two dimensions or higher). The new theorem showed that if a compact hypersurface has nearly constant mean curvature, then it must have a shape that is close to that of a number of hyperspheres (all of the same radius) joined together, like pearls bonded with specks of glue. The theorem provides quantitative limits on how far the surface may vary from this shape, and gives conditions that ensure that the approximate shape must in fact be a single hypersphere. It enables a new quantitative description of the geometry of surfaces that occur in capillarity problems.

Reference:

G. Ciraolo, F. Maggi, On the shape of compact hypersurfaces with almost-constant mean curvature, Comm. Pure Appl. Math. 70, 665–716 (2017). arXiv:1503.06674 [math.AP]

Computing K-theoretic Invariants

Invariant quantities show up across a wide range of mathematics, and are used for classifying objects such as knots and surfaces. They are quantities that do not vary when the object is continuously deformed in some way. ICTP mathematician Lothar Göttsche has developed an algorithm for computing the "K-theoretic Donaldson invariants" for rational surfaces. The result builds on many years of work by Göttsche and his coworkers.

Donaldson invariants relate to smooth four-dimensional manifolds, and are also connected to particle physics theories such as supersymmetric Yang-Mills theories. Göttsche's work involves invariants for rational surfaces, which are a type of complex surface, meaning they have two complex dimensions, or four real dimensions plus some extra structure. These invariants can be viewed as K-theoretic analogues of Donaldson invariants. K-theory originated in the 1950s in algebraic geometry (the "K" comes from the German "Klasse" for "class"), but it has subsequently invaded areas as diverse as number theory, noncommutative geometry, string theory, and condensed matter physics. The invariants are also the analogues for complex surfaces of the conformal blocks on complex curves, which are computed by the famous Verlinde formula of conformal field theory. This makes the formulas determined by Göttsche higher-dimensional analogues of the Verlinde formula. Göttsche also relates the results to the "strange duality conjecture," which has been proven for curves but not for surfaces.

Reference:

L. Göttsche, Verlinde-type formulas for rational surfaces, J. Euro. Math. Soc. To appear. arXiv:1609.07327 [math.AG]

Resolving Conical Singularities

Consider an ant crawling on the surface of a cone, the apex of which comes to a perfect mathematical point. As long as the ant stays away from the apex, the surface will seem as smooth as a flat plane. In mathematical terms, the surface is a "variety," which is like a manifold except that it may have singular points, such as the singularity at the cone's apex. In recent years, mathematicians have been intensively studying how various singularities can be "resolved." The goal is to determine when something like the point of the cone can be repaired, and to what extent the nice properties that the variety satisfies elsewhere can be neatly extended across the region that replaces the singular point.

A paper by ICTP mathematician Claudio Arezzo and a coworker has advanced this work in the case of so-called Kähler varieties of complex dimension three or greater, with conical singularities (technically, the singular points are "modeled on Calabi-Yau cones"). The paper shows that when the variety has constant scalar curvature outside of the singular points, the singularities can be resolved to produce a Kähler manifold that has constant scalar curvature everywhere. The resolution involves a mathematical gluing procedure to attach a resolution of each cone and then deform them to achieve the curvature property.

Reference:

C. Arezzo, C. Spotti, On cscK resolutions of conically singular cscK varieties, J. Funct. Anal. 271, no. 2, 474–494 (2016). arXiv:1507.08144 [math.DG]

Integrability of Continuous Bundles

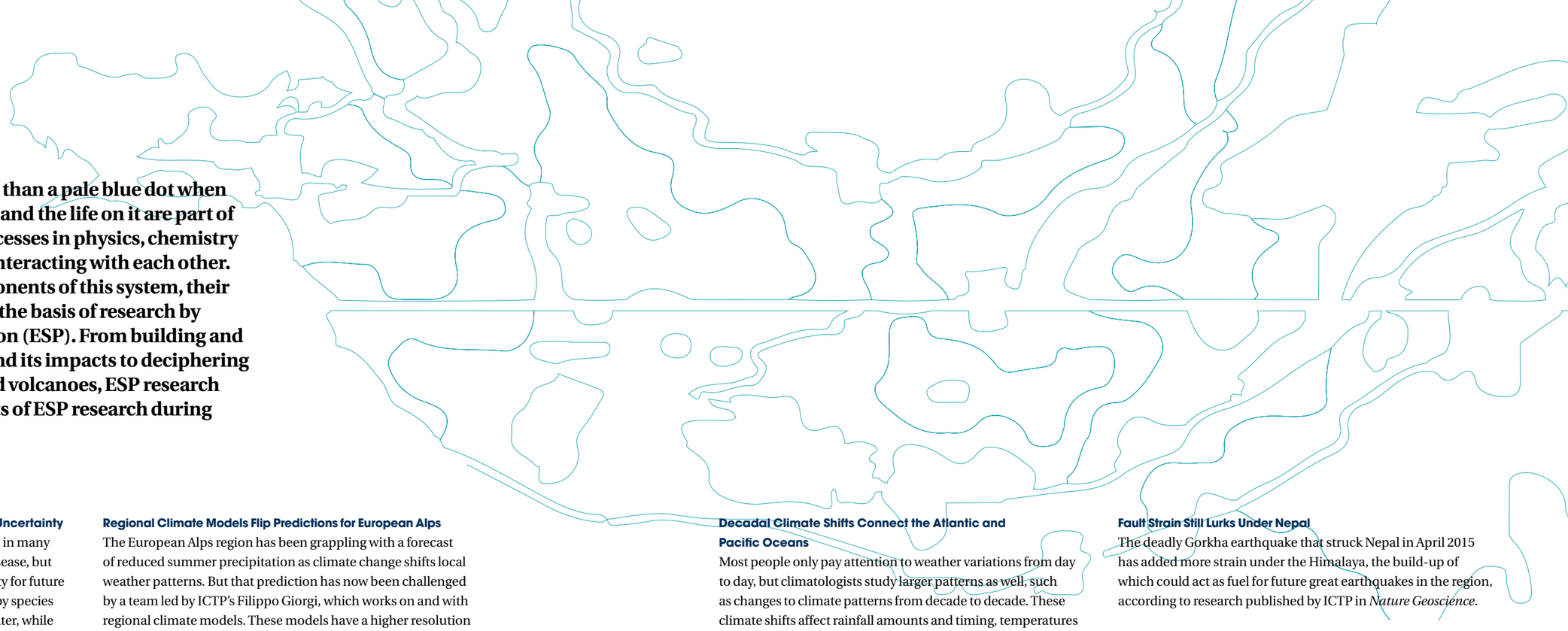
A trio of ICTP mathematicians have proven a theorem with applications to dynamical systems and to differential equations more generally. The result also has intrinsic interest for differential geometry, providing so-called integrability conditions for tangent subbundles of manifolds, with broader applicability than any previous such conditions. The work was carried out by Stefano Luzzatto, Sina Tureli (then a SISSA PhD student from Turkey, now at Imperial College, London), and Khadim War (then an ICTP/SISSA PhD student from Senegal, now at Ruhr-University Bochum, Germany).

The question of integrability is a classical problem dating back to the mid-1800s: when do systems of differential equations have solutions, and when are those solutions unique? Early results dealt with cases where the equations involve continuously differentiable functions, meaning that the theorems only work for functions that are sufficiently smooth and well-behaved. In the modern language of geometry and topology, this translates to results for continuously differentiable subbundles. Previous efforts to find analogous results for less well-behaved equations or subbundles always required some form of weak differentiability, leaving subbundles that are merely continuous out of the picture. Abandoning the differentiability assumption, the ICTP trio found a condition for continuous subbundles which guarantees they will be integrable, and another condition which guarantees their unique integrability. Applied to dynamical systems, the new conditions unified many results that had previously been proven by an assortment of methods.

Reference:

S. Luzzatto, S. Tureli, K. War, Integrability of continuous bundles, J. Reine Angew. Math. (Crelle's Journal). To appear. (Published online October 2016, doi: 10.1515/crelle-2016-0049) arXiv:1606.00343 [math.CA]

Earth System Physics



Our Earth may appear as no more than a pale blue dot when seen from space. But this blue dot and the life on it are part of a complex system of intricate processes in physics, chemistry and biology that are continually interacting with each other. Understanding the various components of this system, their interactions and processes forms the basis of research by ICTP's Earth System Physics section (ESP). From building and using models of climate change and its impacts to deciphering the mechanics of earthquakes and volcanoes, ESP research covers a wide spectrum. Highlights of ESP research during 2016 are summarized here.

The Fight Against Malaria Faces Climate Change Uncertainty

Malaria still presents a major public health problem in many of the world's tropical regions. It is a well-studied disease, but climate change imposes a large degree of uncertainty for future malaria spread and intensity. The disease is spread by species of mosquitoes that depend on seasonal standing water, while temperature affects the vector and parasite lifecycles. Changing rainfall and temperatures are bringing malaria to previously untouched regions, shifting the fight against malaria yet again. ICTP's Adrian Tompkins and his collaborators studied what affects these changes in malaria spread in Eastern Africa, looking at differences in malaria projections from two dynamic malaria transmission models.

The team found that predicted change in malaria incidence was driven by temperature changes more than rainfall changes, a fortuitous finding as future precipitation or drought predictions for Eastern Africa are still uncertain. With temperature as the main driver of malaria mosquito spread and survival, the disease is predicted to move to higher altitudes in the region, some of which have never seen malaria, with lowland zones predicted to see a decrease in cases. However, the magnitude of the impact of climate varied between the two models, illustrating that the uncertainty due to the mathematical representation of malaria transmission rivaled that of the driving climate models.

Reference:

Leedale, J., Tompkins, A. M., Caminade, C., Jones, A.E., Nikulin, G., Morse, A.P. (2016) Projecting malaria hazard from climate change in eastern Africa using large ensembles to estimate uncertainty. Geospat. Health, 11, doi: 10.4081/gh.2016.393

Regional Climate Models Flip Predictions for European Alps

The European Alps region has been grappling with a forecast of reduced summer precipitation as climate change shifts local weather patterns. But that prediction has now been challenged by a team led by ICTP's Filippo Giorgi, which works on and with regional climate models. These models have a higher resolution than the global climate prediction models that have forecast droughts for the Alps. The coarser resolution of the global models means that the effects of local topography have been averaged out or simplified. Topography—the bumpiness of mountains and valleys—can change rainfall patterns by presenting barriers to weather system flow, or causing moisture to be stored in the soil, affecting convection and rainfall patterns.

In the case of the European Alps, Giorgi's team found their regional model predicts increased, not decreased, precipitation across the region. More summer rainfall is driven by moist soil driving connective rainfall, a detail not predicted by the global models. This provides one of the first examples of the added value and increased information added to climate predictions by regional climate models, a specialty of ICTP's climate scientists.

Reference:

Giorgi, F., Torma, C., Coppola, E., Ban, N., Schär, C., & Somot, S. (2016). Enhanced summer convective rainfall at Alpine high elevations in response to climate warming. Nature Geoscience, 9(8), 584-589. doi:10.1038/ngeo2761

Decadal Climate Shifts Connect the Atlantic and Pacific Oceans

Most people only pay attention to weather variations from day to day, but climatologists study larger patterns as well, such as changes to climate patterns from decade to decade. These climate shifts affect rainfall amounts and timing, temperatures and winds, factors that can have acute effects on people and economies. Climatologists are still striving to understand these shifts, especially in the Pacific, and especially with climate change throwing a huge wrench into natural patterns.

A team that includes ICTP climatologists Fred Kucharski, Riccardo Farneti, and Graziano Giuliani has connected decadal shifts in the Pacific Ocean to a pattern in the Atlantic Ocean called the Atlantic Multidecadal Oscillation (AMO). Using a set of simulations, the group coupled the ICTPAGCM (ICTP General Circulation Model) to the NEMO/OPA ocean model (the ocean dynamics component of the Nucleus of the European Modeling of the Ocean) along with observed Atlantic sea surface temperatures, and found that the AMO has had a strong influence on decadal climate shifts in the Pacific.

Looking at the last one hundred years, the group found three periods where the AMO had particularly strong influence on climate patterns in the Pacific. They determined that the modification of an air flow pattern called the Walker circulation is the physical mechanism underlying these periods of influence, with a strong AMO leading to an overall warmer tropical Atlantic. This, in turn, modifies the Walker circulation patterns in both the Atlantic and Pacific Oceans. The world's climate patterns are more connected than we think.

Reference:

Kucharski, F., Ikram, F., Molteni, F., Farneti, R., Kang, I., No, H., King, M. P., Giuliani, G., & Mogensen, K. (2015). Atlantic forcing of Pacific decadal variability. Climate Dynamics, 46(7-8), 2337-2351. doi:10.1007/s00382-015-2705-z

Fault Strain Still Lurks Under Nepal

The deadly Gorkha earthquake that struck Nepal in April 2015 has added more strain under the Himalaya, the build-up of which could act as fuel for future great earthquakes in the region, according to research published by ICTP in *Nature Geoscience*.

The research results came from a collaborative earthquake-response project that monitored Nepal's post-seismic deformation following the 2015 quake. Coordinated by ICTP geophysicist Karim Aoudia, Roger Bilham from the Cooperative Institute for Research in Environmental Sciences (CIRES), and Bishal Upreti from Tribhuvan University and the Nepal Academy of Science and Technology (NAST), the project used existing and new GPS instruments that were deployed in the epicentral area, some of which were donated by ICTP.

The Nepal 2015 earthquake, like other historical earthquakes in the region, failed to rupture the frontal part of the fault that dives beneath the Himalayas, south of Kathmandu. Based on GPS readings that showed limited post-seismic deformation on the frontal part of the fault, along with a rigorous analysis of historical earthquake ruptures, the researchers believe that a significant amount of relict strain prevails throughout the main Himalayan fault and could be released in a future, powerful earthquake larger than the recent Gorkha one.

Reference:

Mencin, D., Bendick, R., Upreti, B. N., Adhikari, D. P., Gajurel, A., Bhattarai, R. R., Shrestha, H.R., Bhattarai, T.R., Manandhar, N., Galetzka, J., Knappe, E., Pratt-Sitaula, B., Aoudia, A., Bilham, R. (2016). Himalayan strain reservoir inferred from limited afterslip following the Gorkha earthquake. Nature Geoscience, 9(7), 533-537. doi:10.1038/ngeo2734

Applied Physics

From archaeology to X-ray imaging, and from optics and lasers to satellite navigation and turbulent fluid flows, ICTP's Applied Physics section encompasses diverse areas of research that respond to the most critical needs of the ICTP scientific community. The areas are, in fact, among the activities for which the demand in developing countries is enormous and growing.

The bulk of the work carried out in the Applied Physics section takes place in its three laboratories:

- Multidisciplinary Laboratory (MLab)
- Applied Physics Laboratory (at Trieste's Elettra Sincrotrone)
- Telecommunications/ICT for Development Laboratory

plus three other shared laboratories:

- Laser Laboratory (at Elletra)
- ICTP-SPIE-INFN Quantum Cascade Laser Laboratory (Area Science Park, Trieste)
- Optical Tweezer Laboratory (at the Istituto Officina dei Materiali (IOM), Trieste)

ICTP's MLab promotes interdisciplinary experimental activities based on advanced instruments and methods developed in basic physics research. MLab activities include scientific instrumentation development, novel detector and electronic circuit design and prototyping, X-ray imaging, and accelerator-based analytical techniques.

In 2016, MLab scientists continued their participation in the COMPASS high energy physics experiment at the Super Proton Synchrotron at CERN. The MLab also continued its development work on applications of Silicon Drift detectors for synchrotron applications with Italy's National Institute for Nuclear Physics. Ongoing work using X-ray imaging and other scientific analyses for cultural heritage saw the extension of a project to characterize the microstructure, composition and age of materials, as well as a new research program to study ancient cultural landscapes through geophysical and remote sensing techniques.

The Telecommunications/ICT for Development Laboratory (T/ICT4D) researches ionospheric radiopropagation, with a particular focus on ionospheric effects on satellite navigation and positioning systems (the Lab's proprietary NeQuick model is used by scientists around the world for this purpose). Research in 2016 included studies on the effects of space weather events originated in the Sun on the ionosphere, particularly in the low latitude region of the Earth. The Lab also does research and training on wireless communications. Its Guglielmo Marconi ICT Wireless Laboratory houses training programs on wireless communications technologies, providing much-needed support in wireless technology education to students and researchers from developing countries.

A longtime goal of the wireless research at ICTP has been to provide reliable and sustainable wireless solutions to help foster science and research in developing countries. Research activities on the Internet of Things (IoT) and TV White spaces continue. T/ICT4D scientists Marco Zennaro and Ermanno Pietrosemoli carried out an experiment on High Capacity Long Distance Wireless Link successfully between Monte Amiata and Monte Limbara, Italy, on May 2-6, 2016 (see story on opposite page).

ICTP's Applied Physics Laboratory, located at Elettra, conducts basic research activities and supports advanced courses for PhD students in turbulent fluid mechanics, as well as providing support for joint synchrotron-related lab experiments.

The ICTP Laser Laboratory is a collaborative experimental facility serving the needs of both ICTP and Trieste's Elettra Sincrotrone. Students and researchers in the Lab investigate the physics and applications of short pulse lasers, specifically femtosecond lasers used in the seeding of the FERMI Free Electron Laser at Elettra. Many ICTP Associates take advantage of this laboratory during their visits to ICTP.

Under the ICTP-SPIE Anchor Research Program, researchers at the ICTP-INFN-SPIE Quantum Cascade Laser Laboratory are developing quantum cascade lasers (QCL) for numerous applications, from fundamental measurements of the proton charge radius to applications in environmental sensing.

Other research in the Applied Physics section focuses on Synchrotron Radiation Related Theory, where researchers are investigating electronic, magnetic and structural properties of systems with strong electron correlations, including transition-metal oxides and related materials; and the physics of low-dimensional systems and nanostructures. There is close collaboration with experimentalists at the nearby synchrotron radiation source Elettra and at other similar facilities.

Applied Physics Research Highlight

Wireless World Record

ICTP assists in new technology breakthrough for long-distance wireless broadband

ICTP researchers are among a team who have developed a breakthrough in long-distance wireless technology. Using off-the-shelf equipment, the team established a wireless network spanning 304 km, from Sardinia to Tuscany, that reached data exchange rates of 354 megabits per second (Mbps), a world record for long-range wireless broadband.

The accomplishment originated from a collaborative project on digital technology for broadband communication. ICTP researchers Ermanno Pietrosemoli and Marco Zennaro of the Centre's Telecommunications/ICT for Development (T/ICT4D) Wireless Laboratory coordinated the scientific features, while radio amateurs of Centro Italiano Sperimentazione e Attività Radiantistiche (CISAR) provided the towers to install the equipment at both ends and the manpower to perform the installation. Ubiquiti Networks provided the radio equipment used in the experiment.

Trying to link Italian coastal land through the Tyrrhenian Sea, the team installed 1.2-meter parabolic reflector antennas on Mount Amiata (Tuscany) and Mount Limbara (Sardinia), to provide signals strong enough to support the maximum throughput over the designed path. Despite the long distances involved and the vagaries of the weather on the top of the mountains, the whole installation took less than three days, although the measurements of the performance are still ongoing and the gathering of the data will continue.

"These performance measurements are quite useful to provide Internet access on many islands still lacking broadband access, especially in countries with limited financial means," says Zennaro.

"What makes this accomplishment significant is the extremely high data rate and spectral efficiency, which is the information rate that can be transmitted over a given bandwidth in a communication system," adds Pietrosemoli.

Quantitative Life Sciences

The effects of inequality on economies; detecting key strands of DNA; bird flight and turbulence; decision-making for survival: scientists in ICTP's newest research section, Quantitative Life Sciences are uncovering the underlying physics in the broad domain of life sciences that encompasses disciplines ranging from molecular and cell biology to terrestrial and oceanic ecology, and economics and quantitative finance. Research highlights from 2016 are as follows.

The Freezing Power of Inequality

Inequality is one of the big concerns of our societies. But when is inequality too much? A team from ICTP and the University of São Paulo (USP) have found that point beyond which inequality can completely paralyze an economy. Vilifredo Pareto observed, more than a century ago, that the distribution of wealth is very unequal in our societies, and it empirically takes the form of a power law. Empirical data shows that Pareto's observation still holds for our modern societies, but inequality has been rising considerably and is back at pre-World War One levels.

The ICTP-USP team studied the consequences of inequality using a stylized model of an economy. They found an inverse relation between inequality and liquidity, i.e. the frequency of economic exchanges in the economy: when inequality increases, fewer people can spend money and keep the economy spinning. Increasing inequality means wealth concentrates in the hands of fewer and fewer people and companies, leading to the flow of goods congesting around these few. With liquidity low as the Pareto index reaches one, the economy freezes up and ceases to function.

Reference:

Jerico, J. P., Landes, F. P., Marsili, M., Castillo, I. P., & Volpati, V. (2016). When does inequality freeze an economy? Journal of Statistical Mechanics: Theory and Experiment, 2016(7), 073402. doi:10.1088/1742-5468/2016/07/073402

Detecting Key Strands of DNA

Evolution is driven by random mutations to genes, in a process that saw elephants evolve from bacteria. Selection acts on this process by preserving those advantage-bestowing mutations while removing deleterious ones. A footprint of this process is left in the statistics of the sequences of amino-acids of functional proteins in different organisms. ICTP physicist Matteo Marsili and his co-authors devised a method, called Critical Variable Selection, to identify those parts of the amino acid sequence that are "protected" from random mutations. The algorithm behind Critical Variable Selection works through detecting those sub-sets of amino acids that recur with a broad frequency distribution. Marsili et al. found that this method provides robust results that can help researchers in the fields of genomics, quantitative biology, and biophysics.

Reference:

Grigolon, S., Franz, S., & Marsili, M. (2016). Identifying relevant positions in proteins by Critical Variable Selection. Mol. BioSyst., 12(7), 2147-2158. doi:10.1039/c6mb00047a

Gliding Through Turbulent Air

Birds do not need to flap their wings continuously to stay aloft: most can coast and float sometimes on rising warm air currents, or thermals. This helps them conserve their energy and extend their flying range, big advantages in the struggle to survive. ICTP physicist Antonio Celani and his co-authors studied how birds use the thermals, especially how they deal with the high level of turbulence inherent in the air currents. Numerical simulations of atmospheric air flow helped Celani et al identify strategies birds used to adapt to the turbulence. The team studied how the birds' strategies change as turbulence levels increase or decrease, and how the birds "read", or detect the turbulence. These theoretical studies may one day help human-crafted autonomous gliders conserve energy as they take to the skies.

Reference:

Reddy, G., Celani, A., Sejnowski, T. J., & Vergassola, M. (2016). Learning to soar in turbulent environments. Proc. of the Nat. Acad. of Sci. doi: 10.1073/pnas1606075113

How to Make Decisions When Your Survival Depends On It

Animals have to make decisions all the time. Should they go this way, or that way, to find food or water or shelter? In the quest for the resources needed to survive and reproduce, animals have to employ strategies to try to make the best decisions. When a bee is looking for the flowers that will provide the best nectar, for example, the decision is difficult for two reasons: one, the outcome is uncertain, as a promising flower may turn out to be empty. Two, decisions are exclusive: the bee has only a certain amount of time, and visiting one flower means it can't visit others.

ICTP physicist Antonio Celani and his coauthors studied what the best strategy would be for the bee, examining what the right balance between exploitation, or picking the best flowers based on past experience, and exploration, or venturing into uncharted territory to see if there's any treasure out there. The bees need to find a balance between investigating and being rebellious, and relying on what they know will work.

Celani et al. found that seeking to increase information about the maximum return that can be obtained is actually a very good strategy. The study provides an insight about how to develop the notion of a "goal-oriented" information theory.

Reference:

Reddy, G., Celani, A., & Vergassola, M. (2016). Infomax Strategies for an Optimal Balance Between Exploration and Exploitation. Journal of Statistical Physics, 163(6), 1454-1476. doi:10.1007/s10955-016-1521-0

Training and Education

As an international crossroad of scientific excellence, ICTP offers a unique environment for scientists at all stages of their careers to advance their knowledge in physics and mathematics. Each year, more than 5000 scientists from about 150 countries pass through ICTP, taking advantage of the Centre's worldwide reputation for truly outstanding workshops, conferences and advanced educational programs that explore topics at the cutting edge of physics and mathematics.

From the Centre's Postgraduate Diploma Program, an intense, year-long course of study that gives young scientists from developing countries the boost they need for acceptance into doctoral programs anywhere in the world, to the Centre's Associates Scheme, which supports visits of several months at a time over a three year period, ICTP provides a lifeline for a lifetime of learning.

Today, ICTP alumni can be found in 188 countries around the world, serving as science ambassadors in their home countries and sharing their knowledge with new generations of scientists.

The full spectrum of ICTP's training and education programs are described here; for a glimpse of their global impact in 2016, please see the inside back cover of this report.

ICTP Degree Programs

- **Joint Master in Physics** *(with University of Trieste)*
- **Master of Arts in Economics** *(with University of Turin)*
- **Master of Complex Systems** *(with consortium of European universities)*
- **Masters in Medical Physics** *(with University of Trieste)*
- **Masters in High Performance Computing** *(with SISSA)*
- **PhD in Physics and Mathematics** *(with SISSA)*
- **PhD in Earth Science and Fluid Mechanics** *(with University of Trieste)*

ICTP degree programs

ICTP is investing in scientific capacity building by supporting the studies of students from developing countries who qualify to enroll in the Centre's joint masters and doctorate programs. ICTP's seven degree programs offer instruction in fields ranging from physics and mathematics to medical physics and high performance computing. In 2016, 26 students achieved a level of academic success that is unavailable in their home countries. They include:

- one student from Nigeria and one from Sudan who earned masters' degrees in physics through ICTP's joint program with the University of Trieste; both are now enrolled in PhD programs;
- 13 students from nine developing countries who completed the course requirements for ICTP's Master in Medical Physics degree with the University of Trieste and received diplomas at a graduation ceremony in December 2016;
- two students (from Colombia and Cuba) who successfully earned degrees in the joint ICTP-SISSA Master in High Performance Computing program;
- four students (from Colombia, Senegal, Venezuela and Vietnam) who completed their studies in physics or mathematics to earn their PhDs through ICTP's joint doctoral program with SISSA;
- five students in the joint ICTP-University of Trieste PhD program in earth science and fluid mechanics who earned their doctoral degrees.

The start of an educational journey

ICTP recognizes that many students from developing countries lack the vigorous educational training needed to succeed in doctoral studies. Since 1991, the Centre's Postgraduate Diploma Program has addressed this need by offering an intense, 12-month course of study for talented young science students who have limited possibilities to pursue advanced studies in their home countries. More than 900 students from 78 countries have graduated from the program; of these, 75% have gone on to attain doctoral degrees. For the academic year 2015-2016, 38 students from 23 different countries completed the rigorous program. Of those, 20 have enrolled in PhD programs.

Doctoral students in the developing world often face a local shortage of expertise in their field or laboratories necessary to complete their desired research. ICTP, along with its UN partner the IAEA, has developed a Sandwich Training Education Program (STEP) for these young researchers. STEP is a visiting program that provides support for three- to six-month stays each year for three successive years at either ICTP or a collaborating institute, providing students with the opportunity to work alongside world-class researchers who they may not have had access to in their home countries. Launched in 2003, STEP has assisted 184 students from 48 countries accomplish their educational objectives.

Life-long learning
Scientists from the developing world often need opportunities to break the intellectual isolation many of them experience in less-advantaged countries. That is why ICTP developed its Associateship Scheme: a sabbatical program for scientists at different stages of their careers to maintain long-term, formal contact with the Centre and its well established network of world-renowned scientists as well as its modern facilities. Over the years ICTP has supported 2,761 Associates from 108 countries. In 2016, 196 Associates made 202 visits to ICTP.

A similar scheme between ICTP and developing-country institutes, called Federated Institutes, allows the institutes to send young scientists (up to age 40) to ICTP for shorter stays. In 2016, ICTP had a total of 80 Federated Institutes, from 29 countries. The total number of visits under the program was 53.

A gateway to Italian laboratories, and new skills
ICTP's Training and Research in Italian Laboratories (TRIL) program offers scientists from developing countries the opportunity to undertake training and research in an Italian laboratory in different branches of the physical sciences. The aim of the program is to promote, through direct contacts and side-by-side high-level research, collaborations between the Italian scientific community and individuals, groups and institutions in developing countries. Since its inception in 1983, the TRIL program has supported the visits of 1,342 scientists from 89 countries. In 2016, 53 fellows from 28 countries received support to carry out research in Italy.

Another laboratory-based opportunity, the ICTP-Elettra Users Program, offers access to Trieste's Elettra Sinchrotrone radiation facility for scientists from developing countries who work in those countries. In 2016, ICTP supported 59 visits of participants coming from eight developing countries.

ICTP's Scientific Fabrication Laboratory, or SciFabLab, which opened in 2014, is the first "fabrication laboratory" in Italy's Friuli-Venezia-Giulia region. It is devoted to creativity, invention and research. FabLabs are becoming of special relevance to scientists in developing countries because they can offer powerful new ways to carry out research and facilitate the realization of new ideas at affordable costs. ICTP's SciFabLab offers modern and versatile computer-controlled rapid prototyping tools such as 3D printers, 3D scanners, laser engraving and cutting machines. The SciFabLab hosted hundreds of visits in 2016 by visiting scientists and non-scientists, as well as individuals and groups from the Trieste region, including decision makers, ministers, scientists, politicians, teachers and school classes, and journalists.

Specialized training
ICTP complements its broad selection of conferences, programs and laboratory opportunities with specialized training activities in fluid mechanics, information and communication technology (ICT), optics and lasers, and telecommunications and wireless technologies. A sample of those activities that took place in 2016 includes:

- 1st Summer School on the Internet of Things, Bogota, Colombia
- 19th International Beacon Satellite Symposium, Trieste

ICTP specialized training extends to the Middle East. Since 2009, the Centre and the Jordan-based Synchrotron Light for Experimental Science and Applications in the Middle East (SESAME), a third-generation light source operating under the auspices of UNESCO, have coordinated a program of joint training activities taking place at both the Middle East facility and in Trieste. SESAME is the Middle East's first major international research centre; when the facility starts operations, scientists from the Middle East and neighbouring countries, in collaboration with the international synchrotron light community, will have the possibility of performing world-class scientific studies. In 2016, ICTP offered trainign and research opportunities to about 35 scietnists from SESAME member countries.

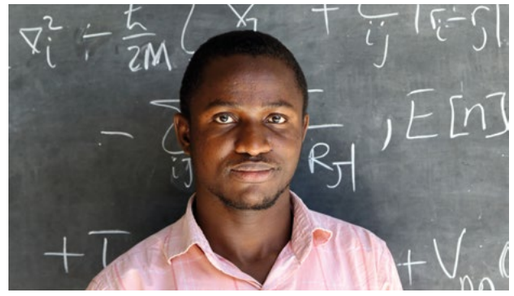
Diploma Success
A spotlight on four 2016 graduates

Name: Vahatra Rabodonandrianandraina
Country: Madagascar
Research interest: Mathematics
After ICTP: PhD program, University of Amsterdam

""I would like to make a connection between my home university and ICTP. If you are in a developing country, few people will study something like algebra. Because we are poor they will think it will not help them for their future. I want to show them that math and other abstract studies are useful and very important."

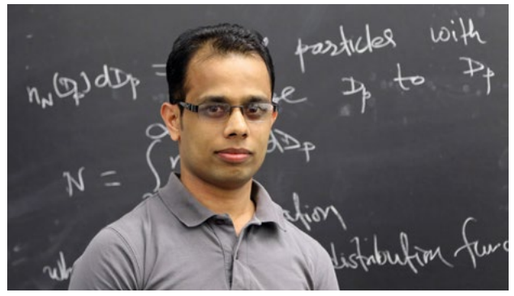
Name: Ali Rida Khalife
Country: Lebanon
Research interest: High Energy Physics
After ICTP: Joint ICTP-SISSA PhD Program

"After ICTP I think I have a duty to help my country, to motivate and support science there. Society is not accepting of the idea that we need scientists and basic research, that it's useful for the future."



Name: Yusuf Shaidu
Country: Nigeria
Research interest: Condensed Matter Physics
After ICTP: Joint ICTP-SISSA PhD Program

"I've seen some irregularities in the way of teaching at all levels in Nigeria, and I'd like to be part of the team that will come up with ideas to improve it."



Name: Janak Raj Joshi
Country: Nepal
Research interest: Atmospheric Sciences
After ICTP: PhD program, University of Maryland

"After doing some postdocs in the US, I want to return to my country. I would like to establish research in aerosols and atmospheric physics there."

Scientific Outreach

Office of External Activities

ICTP's Office of External Activities (OEA) supports research and training activities of physicists and mathematicians living and working in developing countries, primarily by providing assistance for regional activities. Such support complements the training and research that is provided to developing-country scientists at ICTP. Its goal is to boost the scientific level of individuals, groups or institutes in developing countries to an international level through North-South collaboration, and to stimulate networking of scientists in the developing regions to reach a critical mass of researchers through South-South collaboration.

The OEA also provides funds for graduate schools to support student grants, fellowships for young researchers, visits of research collaborators and other activities.

Assistance is carried out through Affiliated Centres (there were seven in 2016 in Africa, Asia and Eastern Europe), support to institutes for graduate students (five institutes supported in 2016), research group networks (eight in 2016), support for scientific meetings (40 in 2016), and support for visiting scholars and consultants (12 in 2016). The full extent of the OEA's global reach can be seen on the map on pages 32-33 of this publication.

Regional centres of excellence

ICTP has opened regional branches to bring its unique blend of high-quality physics and mathematics education and high-level science meetings closer to scientists in the developing world.

The ICTP-South American Institute for Fundamental Research (ICTP-SAIFR), in São Paulo, Brazil, was created in collaboration with the State University of São Paulo (UNESP) and the São Paulo Research Funding Agency (FAPESP). It is located on the campus of the Instituto de Fisica Teorica (IFT-UNESP). In 2016 ICTP-SAIFR celebrated its fifth anniversary by holding a three-day Symposium on Advancement of Science in South America. The event featured public lectures by a Nobel Prize laureate and the spokesperson of the LIGO gravitational wave observatory, plenary seminars on ground-breaking physics research by leading young theoretical physicists, parallel research talks by the 60 distinguished ICTP-SAIFR associated members from across South America, and roundtable discussions with presidents of South American science funding agencies and directors and ex-directors of leading theoretical physics institutes. Website: **ictp-saifr.org**

The Mesoamerican Centre for Theoretical Physics (MCTP), in Chiapas, Mexico, offers conferences, schools and seminars on physics, mathematics, energy and the environment. It also works with ICTP to create a program for students at universities in Central America and the Caribbean to earn physics or mathematics PhD degrees, which currently are not offered in the region. In 2016, MCTP attracted 1208 visitors and held 23 scientific meetings. Website: **mctp.mx**

The ICTP–Eurasian Centre for Advanced Research (ICTP-ECAR), in Izmir, Turkey, is hosted by the Izmir Institute of Technology. ICTP-ECAR serves as a meeting point for scientists, researchers and students of the broad Eurasia region. Activities in 2016 included a workshop on Physical, Biological and Chemical Foundations of Bioelectronics, Biophotonics and Biosensors. The Centre also held numerous seminars and colloquia, and helped to organize the Izmir Young Physicists Congress, which attracted more than 100 graduate and undergraduate student participants. Website: **ictp-ecar.org**

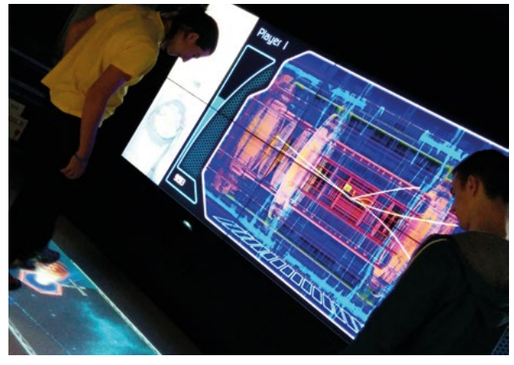
Physics Without Frontiers

Physics Without Frontiers (PWF) is an ICTP outreach program targeting the far reaches of the developing world to inspire and engage undergraduate and masters physics students. Founded by former ICTP high energy physics postdoctoral fellow Kate Shaw, the program embarks on physics roadshows, run by working groups comprising young PhD students and postdocs who visit university physics or maths departments in a developing country to give one-day, intensive masterclasses to undergraduate and master students. Students have the opportunity to analyze real data from the LHC at CERN, which Shaw has been involved with as a member of the INFN Udine/ICTP ATLAS group. The outreach is extended to high school students, the general public and policy makers via events throughout a country. In 2016, PWF organized four such physics roadshows in Nepal, Lebanon, Venezuela and Palestine, inspiring about 370 students.

PWF also brings high-level masters courses to universities that lack such courses. The program has organized a masters course in particle physics in Palestine for the past four years, with remote teaching and face-to-face tutorials. In 2016, PWF also taught courses at the University of Tunis-El Manar, Tunisia, and Tribhuvan University in Nepal, instructing a total of 35 masters students.

Public Outreach

Throughout the year, ICTP engages with the public through numerous outreach activities aimed at spreading the joy of science to the young and old. Some events are highlighted here.



Trieste Mini Maker Faire 2016, 20 - 22 May

ICTP organized and hosted the third incarnation of the Trieste Mini Maker Faire (TSMMF), a successful weekend packed full of makers, creations, experiments, and an estimated 16,000 visitors. This year, TSMMF co-organizers Enrique Canessa and Carlo Fonda of ICTP's Science Dissemination Unit (SDU) and SciFabLab added a second event to the festivities for the first time: a Science Picnic for students of all ages, where scientists and volunteers presented hands-on experiments and demonstrations, focusing more on basic science concepts instead of technology. A popular exhibit at the event was CERN's Virtual Tunnel LHC, an interactive installation where people could play with Higgs bosons, moving in a 3D virtual environment. ICTP's Science Picnic was the first of its kind to be held in Italy.

Che Terremoto

Outreach event for local schools about earthquakes, 5 May

TriesteNext

A public celebration of science in Trieste, 23 to 25 September

Facilities / Services

ICTP places fundamental support services at the disposal of its scientists. The Centre's Marie Curie Library—containing some 72,000 books, as well as 120 subscriptions to print journals and electronic access to 3,177 journals—offers visitors one of the largest collections of literature in physical and mathematical sciences in Europe.

ICTP's Information and Communication Technology Section (ICTS) maintains the Centre's advanced computing facilities. It also plays a key role in all ICTP activities related to technology for high-performance computing, parallel programming and scientific software development, including ICTP's Master's in High-Performance Computing (MHPC), a joint degree program run with the International School for Advanced Studies (SISSA). The program is centered around the two institutes' high-performance computing center. Launched in 2014, the facility expands opportunities not only for MHPC students, but also for staff researchers and the thousands of scientists from developing countries doing collaborative research with the Centre. From simulating molecular interactions to calculating climate forecasts, supercomputers are becoming an increasingly important tool for scientists seeking to solve complex scientific computational problems. The results of these supercomputing exercises are being used in important, practical ways, from the development of improved solar energy cells to input into international agreements such as the Intergovernmental Panel on Climate Change (IPCC) climate assessment reports.

Another service that ICTP provides to scientists from around the world is the possibility to follow all ICTP conferences and courses online. As part of that offering, the Centre's Science Dissemination Unit (SDU) has recorded all Postgraduate Diploma Program courses, as well as many conferences and workshops, using their automated EyA system for the webcasting of physics and mathematics. As of 2016, ICTP's more than 15,300 hours of online Diploma Program lectures had received more than one million unique visitors, around 52% of whom come from developing countries. These numbers suggest that the lectures, taught in English by ICTP scientists, are a useful learning resource for students in developing countries. Some parts of the world, however, are restricted both by language barriers and bandwidth constraints. To tackle these issues, SDU has implemented the project "Didactica para el Desarrollo" with educational scientific lectures in different languages.

Other SDU services include the development, implementation and management of open source applications, especially in support of science and education in developing countries via mobile science and learning platforms, and the provision of grants and training for the low-cost production of scientific contents by institutions and scholars.

African Review of Physics

ICTP has published the *African Review of Physics* (www.aphysrev.org) since 2007. The free, open access, on-line, peer reviewed, international publication is the official journal of the African Physical Society. It publishes high quality reviews, research articles, and brief communications in all branches of experimental and theoretical physics. In 2016, more than 57% of submitted papers were from African scientists who were working in their home countries. Dark energy and dark matter were the major themes in theoretical astrophysics and cosmology; other areas covered included medical physics, condensed matter, Earth systems, and applied mathematical physics.

Governance

ICTP Steering Committee

The ICTP Steering Committee, comprising representatives from UNESCO, IAEA and the Italian government, sets general guidelines for the Centre's activities, determines budgeting levels, and considers proposals from the director for the program, work plans, financial plans, and budget. The ICTP director is the ex-officio chairperson of the Steering Committee. The chairperson of the Scientific Council attends the Steering Committee meeting in an advisory capacity.

UNESCO — **Flavia Schlegel**
Assistant Director General for Natural Sciences

IAEA — **Aldo Malavasi**
Deputy Director General
Department of Nuclear Sciences and Applications

Italian Government — **Fabio Zwirner**
Department of Physics and Astronomy, University of Padua

ICTP Scientific Council

ICTP's Scientific Council is composed of distinguished specialists in disciplines relevant to the Centre's activities and representing a broad geographical range. The Council advises ICTP on its programs of activities, taking into consideration major academic, scientific, educational and cultural trends relevant to the Centre's objectives.

F.K.A. Allotey
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Legon-Accra, Ghana

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Institute of Physics, The Federal University of Rio de Janeiro
Rio de Janeiro, Brazil

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Department of Physics
Princeton University
Princeton, NJ, USA

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Laboratoire de Physique Théorique de l'ENS
Paris, France

Ingrid Daubechies
Duke University
Department of Mathematics
Durham, NC, USA

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Massachusetts Institute of Technology
Cambridge, MA, USA

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Department of Physics
Stanford University
Stanford, CA, USA

Luciano Maiani (Chairman)
Dipartimento di Fisica
Università di Roma La Sapienza
Rome, Italy

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Institute for Advanced Study
Princeton, NJ, USA

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Centre for Applicable Mathematics
Bangalore, India

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Department of Chemistry and Applied Biosciences
ETH Zurich
Lugano, Switzerland

Martin Rees
Institute of Astronomy
Cambridge, UK

Valery A. Rubakov
Russian Academy of Sciences
Institute For Nuclear Research
Moscow, Russian Federation

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Ashoke Sen
Harish-Chandra Research Institute
Allahabad, India

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Mechanical and Aerospace Engineering Department
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Department of Mathematics
Princeton University
Princeton, NJ, USA

Cumrun Vafa
Department of Physics
Harvard University
Cambridge, MA, USA

Finances

ICTP is funded largely through generous contributions made by the Italian government, which has served as ICTP's chief benefactor since the Centre's inception. ICTP operates under a joint administrative framework established by the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the International Atomic Energy Agency (IAEA). UNESCO also serves as the Centre's leading administrative agency.

Income for 2016 (in Euros)

Government	
Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR), Italy (Statutory contribution)	20,592,448.00
Ministry of Science and Technology, Islamabad, Pakistan	89,699.77
Ministry of Science, Research and Technology, Tehran, Iran	54,000.00
Indian Institute of Tropical Meteorology (IITM), Pune, India	44,349.83
Department of Science and Technology, India	13,454.97
Total government contributions:	**20,793,952.57**
UN Agencies	
IAEA (Statutory contribution)	2,360,827.56
IAEA (other)	729,070.47
UNESCO (Statutory contribution)	356,029.30
The World Academy of Sciences (TWAS)	79,103.33
ITU	25,951.05
InterAcademy Partnership (IAP)	22,136.30
International Centre for Genetic Engineering and Biotechnology	22,136.30
WMO	22,009.20
Adjustments of funds of previous years	(74,507.72)
Total UN agency contributions	**3,542,755.79**
Contributions from other donors	**2,063,172.73**
Total income:	**26,399,881.09**

Donors

Aix Marseille Université - Institut de Mathématiques de Marseille
Allianz SpA, Italy
Asian Pacific Centre for Theoretical Physics (APCTP), Korea
Assicurazioni Generali SpA, Italy
Boston College, USA
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Committee on Data for Sciences and Technology
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Consiglio Nazionale delle Ricerche (CNR), Italy
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European Commission (EC)
European Geosciences Union, Germany
European Organization for Nuclear Research (CERN), ATLAS, Switzerland
European Space Agency (ESA)
Eurotech, Italy
Foundation Compositio Matematica, Netherlands
GODAN Global Open Data, UK
Indian Institute of Science, India
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International Assoc. of Seismology and Physics of the Earth's Interior, Norway
International Commission of Optics (ICO), USA
International Union of Geodesy and Geophysics (IUGG), Germany
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Istituto Nazionale di Alta Matematica, Italy
Istituto Nazionale di Fisica Nucleare (INFN), Italy
Istituto Nazionale di Oceanografia e Geofisica Sperimentale (OGS), Italy
King Abdulaziz University, Saudi Arabia
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Kuwait Foundation for the Advancement of Sciences, Kuwait
LENS - European Laboratory for Non-Linear Spectroscopy, Italy
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National Academy of Science, USA
NCCR Marvel, Switzerland
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Psi-k - Daresbury Laboratory, UK
Quantum ESPRESSO Foundation, UK
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Robot Factory SrL, Italy
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Mary Ann Williams
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SDU Coordinator
Technical Officer
Technician, SDU
Program Support Officer
Sci. Prog. Expert and Sys. Admin.
Senior Administrative Officer
System and Network Analyst
Supervisor, Housing and Guesthouses
Institute Advancement Officer
Associate Project Officer
Head, ICTS
Human Resources Officer
Head, Library Services
Public Information Officer

In addition, ICTP employed
117 General Service staff in 2016.

Director's Office

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Mojtaba Khodadadi

Scientific Consultants:
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Pierluigi Cascioli
Otto Emiliano Gonzalez Vazquez
Ennio Gozzi
Carlos Ordoñez
Verónica Riquer
Alessandro Rossetti
Tahir Shah
Claudio Tuniz

ICTP and the Developing World: Scientific Outreach 2016

ICTP Partner Institutes (5)
Brazil, Mexico, Turkey, Rwanda, China

Schools and Workshops (22)
Argentina (2), Brazil (1), Chile (1), Colombia (1), Costa Rica (1), Ghana (2), India (4), Iran (2), Malaysia (1), Mexico (1), China (1), Rwanda (2), Senegal (1), Singapore (1), Viet Nam (1)

ICTP-OEA Affiliated Centres (7)
Armenia, Belarus, Benin, Egypt, Senegal, South Korea, Tunisia

ICTP-OEA Projects (5)
Argentina, Ghana, India, Serbia, Uzbekistan

ICTP-OEA Network Hubs (8)
Algeria (Egypt, Morocco, Sudan); **Senegal** (All African continent); **South Africa** (Burkina Faso, Cameroon, Congo, Côte d'Ivoire, Egypt, Ethiopia, Morocco, Namibia, Nigeria, Rwanda, Senegal, Tunisia, Zimbabwe); **Tunisia** (Algeria, Burkina Faso, Cameroon, Central African Rep., Chad, Ethiopia, Philippines, Senegal); **Armenia** (Brazil, Iran, Morocco, Turkey); **Nepal** (Bangladesh, India); **Cuba** (Colombia, Mexico, Venezuela and Caribbean countries); **Cuba** (Brazil, Colombia, Mexico)

ICTP-OEA Scientific Meetings (40)
6 in Africa: Burkina Faso, Egypt, Mauritania, Namibia, Nigeria, Tanzania
21 in Asia: Armenia (2), China (1), India (3), Indonesia (1), Iran (4), Jordan (2), Pakistan (6), Philippines (1), Viet Nam (1)
9 in Latin America and the Caribbean: Argentina (3), Brazil (1), Colombia (1), Cuba (1), Guatemala (1), Mexico (1), Uruguay (1)
4 in other countries: Croatia, France, Italy, Serbia

ICTP in Numbers 2016

Visitors: 5,827

Percentage female: 25%

Postdocs on campus: 59

From developing countries: 47%

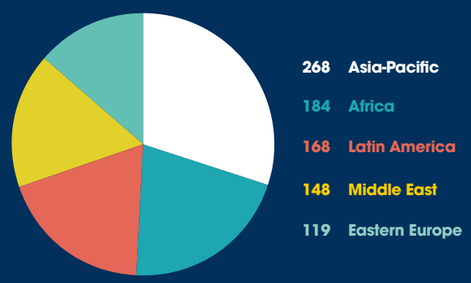
Enrollment in ICTP educational programs: 232

- 119 Master, PhD Students
- 74 Postgraduate Diploma Students in academic years 2015-2016, 2016-17
- 39 STEP Fellows

Scientists engaged in career development programs: 367

- 202 Associate Members
- 53 TRIL Fellows
- 53 Affiliates
- 59 ICTP-Elettra students

Region of origin, female visitors, 2016



ICTP training activities, 2016