EIROforum is a partnership of Europe's eight largest intergovernmental research organisations. As world leaders within their respective fields, the member organisations of EIROforum constitute the vanguard of European science. Operating some of the largest research infrastructures in Europe devoted to the exploration of key questions on the origins and evolution of matter and biological life in the universe, these organisations enable European scientists to engage in truly cutting-edge research – and to be competitive on a global scale.

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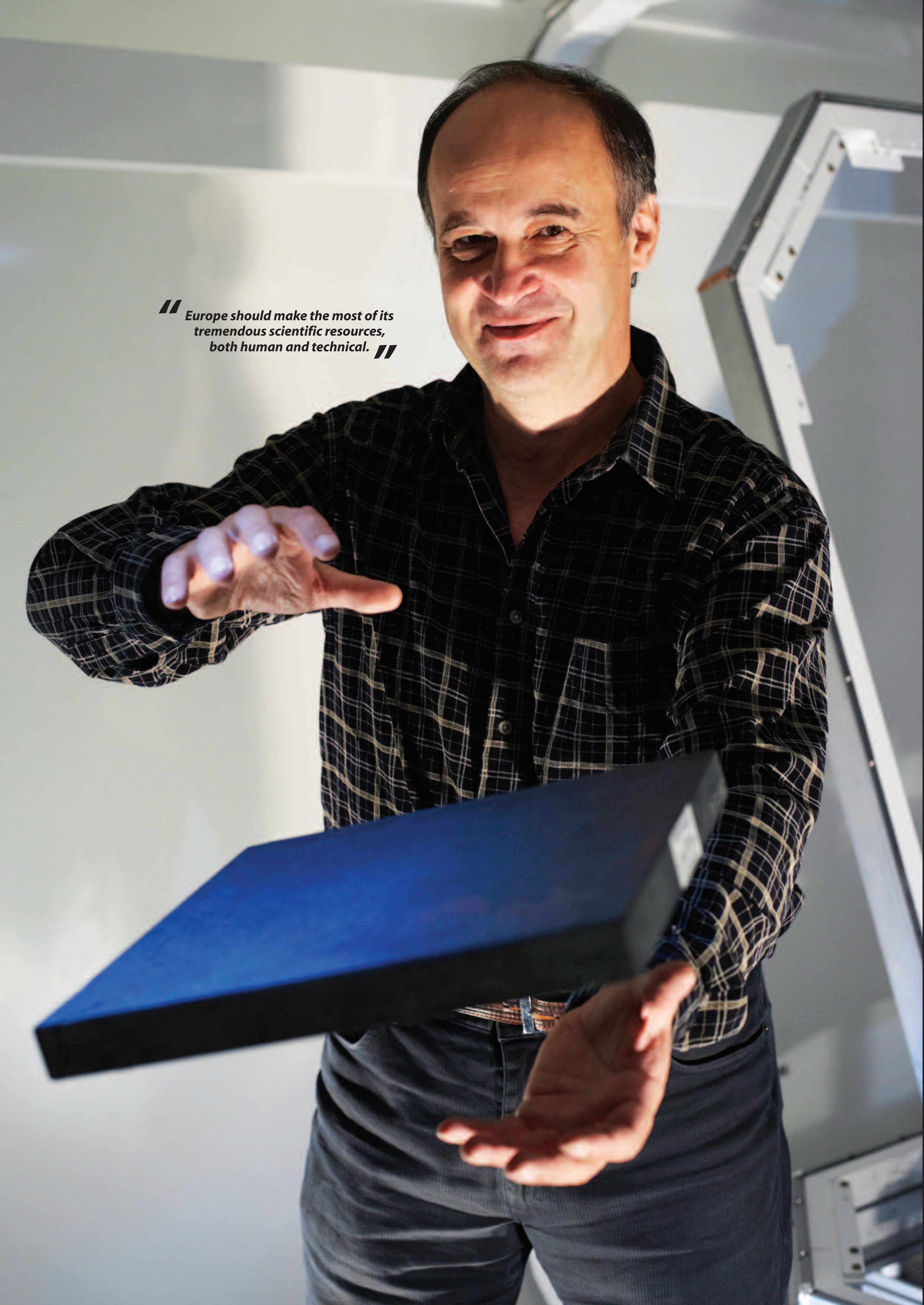


"Europe should make the most of its tremendous scientific resources, both human and technical."

Contents

Introduction

Europe faces many challenges – the economy, the environment and the health and security of its citizens. So it is essential that a collective strategy for sustainable growth should make the most of European society's tremendous scientific resources, both human and technical.

The partners in EIROforum – the eight largest European intergovernmental research organisations (EIROs) – must be central to any such strategy. Their world-leading facilities provide scientists with the infrastructure for frontier research across diverse fields – from the origins of the universe to life beyond the Milky Way; from understanding the molecules that govern human biology to developing the materials that will provide tomorrow's technologies for cleaner energy and faster computers.

The EIROs' strengths also lie in their experience of the challenges faced by any European organisation involved in research and innovation. They have driven the development of much of the technology that enables Europe to maintain a competitive edge in many areas of experimental science. They have sustained a deep commitment to training the next generation of scientists. And they have engaged with Europe's citizens to ensure that the public recognises the value of scientific endeavour.

EIROforum celebrates its tenth anniversary this year, a timely occasion to look back at research findings made at the EIROs across the breathtakingly broad sweep of science and technology that they serve. This publication records some of those recent successes. It also looks forward to the challenges facing European science and innovation – and the key role that the EIROforum partners can play in meeting them.

Andrew Harrison, Director, ILL

EIROforum

From discovery to delivery: the centrality of science in Europe's future

Research and innovation – the creation and exploitation of new scientific knowledge – are central to Europe's strategy to build a strong and sustainable economy that benefits all citizens. Such knowledge is created in universities, in industry and in research infrastructures – notably in the eight European intergovernmental research organisations (EIROs) that together constitute EIROforum.

The EIROs are world-leading facilities for fundamental research, including development of many of the technologies that enable breakthroughs now and into the future. They represent a 'research area that works' – each with numerous collaborations across many countries; and each funded and guided by a consortium of member states, thus serving as an exemplar to Europe.

The EIROs also have long experience of education and public outreach. They are committed to attracting, training and retaining the very best scientists, technicians and engineers. And they strive to broaden access to newer EU member states with developing scientific communities.

It is clear that the EIROs should play a key role in implementing Europe's strategy for research, innovation and sustainable growth. Now more than ever, the people of Europe need science and technology to address the many problems they face and to offer potential solutions. Much of the fundamental knowledge and technological expertise that are needed lie in the human and technical resources of the EIROs.

Initiatives in basic science, such as those pursued by the EIROs, should be ambitious, perhaps risky – and offering the promise of real leaps forward in human understanding and capability. But for the EIROs to develop their full potential in the service of these aims and other top priorities in the wider domain of European research and innovation, they must rise to several challenges.

Data challenges

A key technical challenge is management of the vast amount of data that the EIROs produce. They must look to provide better means of storage, processing and access. The sheer quantity of information involved will demand distributed computing infrastructures, such as the grid and cloud computing.

Once the data have been stored safely, they must also be accessible. This requires efficient archiving based on commonly held standards, as well as a change of culture in many research fields in the way in which primary data and metadata are collected and stored. There are also likely to be strong synergies with other areas for which large, easily accessible forms of data storage are important, such as weather forecasting and the study of environmental change.

For the potential benefits to society of these data to be fully realised and exploited, it is vital to establish a framework for who can have access, when and in what form. There are increasing pressures too from society for scientists to be more accountable for what they study – and to share their results more systematically with the public.

While it is unlikely that there will be widespread demand to access primary data, it seems probable that, in the foreseeable future, published, publicly funded research must become freely available to the taxpayer. Recent months have seen developments in establishing a working framework for free public access to publications that satisfies economic and legal constraints and is also acceptable to the scientific community.

Technology challenges

A second technical challenge for the EIROs concerns the continuous development and application of cutting-edge instruments in their experimental and computational work. Scientific discoveries in any research infrastructure require top-class instruments that use component technologies that continually advance the 'state-of-the-art' in different fields.

There are strong potential synergies between such developments across the EIROs, as well as with universities and industry. But fresh thinking is required to realise cost savings, to encourage greater coordination and to combine skills and knowledge to produce even better instruments. It is also essential to engage much more effectively with industrial partners for the development, manufacture and commercial exploitation of such technologies.

Human challenges

Public outreach is another significant challenge for the EIROs – and for the broader European agenda to deliver research, innovation and growth. Outreach is an essential means for securing public commitment to that agenda, enabling citizens to make informed decisions, for example, when voting on such issues. One way of supporting that goal would be to ensure not only that the public has access to scientific publications but also that research results – and their potential applications – are presented in a comprehensible format.

EIROforum has long been committed to such communication efforts, as well as to the related challenge of attracting younger generations into careers in science. That process begins with education through such initiatives as the 'Science in School' publication, which brings science alive for teachers and students, conveying the excitement of recent discoveries at the EIROs. But for such activities to become truly effective, there should be closer collaboration between the European institutions that focus on research and education.

It is also vital that once people are attracted into a career in science and technology, the barriers to mobility between research institutions and countries are as low as possible. This is not only important for individual researchers, enriching their experience and providing part of the motivation for many of them to continue in their chosen field. It is also essential for distributing the very specialised and often rare skills and knowledge between research infrastructures, as well as encouraging the interchange of ideas that lies at the heart of science.

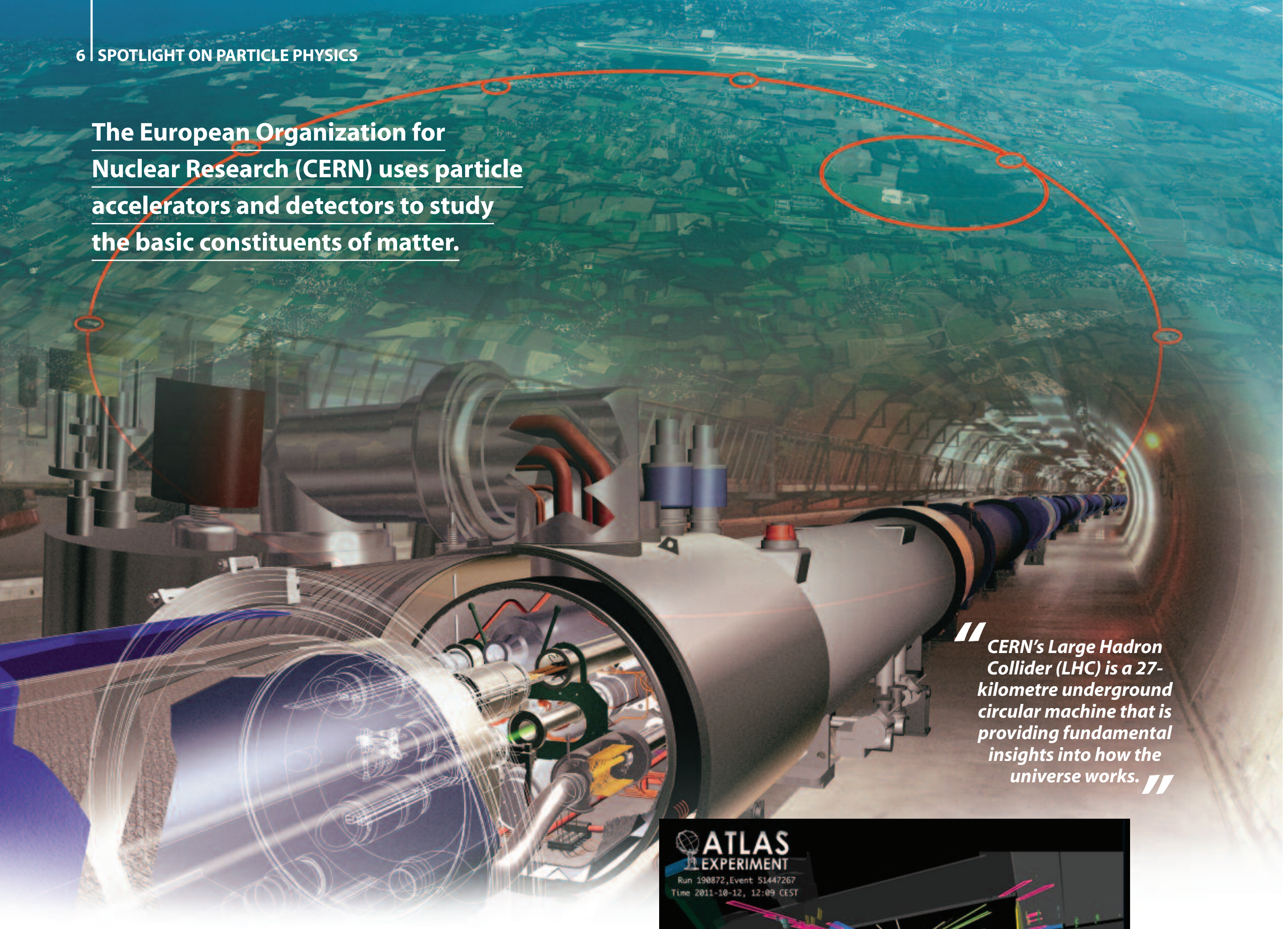
The highly successful Marie Curie scheme has played a key role in establishing mobility of talent as part of the European scientific landscape. There should be no question that it is continued at least at the same level. But further concerted action is needed to enable those who work in science and technology to enjoy a career that can cross national boundaries seamlessly, with no concerns about transferability of qualifications, benefits and pensions.

Another area in which there is much to be done to exploit the full potential of Europe's resources in research and innovation is to ensure that all EU member states can gain access and contribute to its research infrastructures and industry. The challenge here is to fund the membership of emerging scientific communities in a way that is acceptable to existing members who already pay their own way. The use of structural funds to support access – and train the science base – should be explored to ensure that the EIROs are accessible across the whole EU.

Looking back, looking forward

The following pages provide a brief introduction to some of the outstanding scientific achievements of the EIROs in recent years and the many benefits that these research findings are bringing to the lives of Europe's citizens – in healthcare, in energy security, in environmental protection and much more. Many exciting research programmes are in progress and in prospect and these initiatives promise countless further achievements – both individually by the EIROs and collectively through EIROforum.

EIROforum also offers a unique resource for advising the European Commission and the many other organisations across Europe striving to compete on the world stage in research and innovation. As a partnership of institutions that already exemplifies a 'Europe that works' and which already has longstanding experience in many of the structural issues that the EU is trying to overcome, EIROforum has a unique role to play in advising European-level policy-makers.



The European Organization for Nuclear Research (CERN) uses particle accelerators and detectors to study the basic constituents of matter.

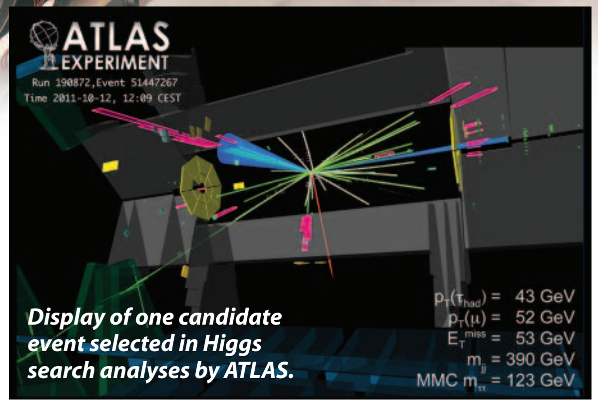
> ***"CERN's Large Hadron Collider (LHC) is a 27-kilometre underground circular machine that is providing fundamental insights into how the universe works."***

Particle physics in the era of the Large Hadron Collider

The scientific instruments used at CERN are particle accelerators and detectors. Accelerators boost beams of particles to high energies before they are made to collide with each other or with stationary targets. Detectors observe and record the results of these collisions.

CERN's Large Hadron Collider (LHC), which started physics operations in 2010, is a 27-kilometre underground circular collider that is providing fundamental insights into how the universe works. Since the start of the LHC, particle physicists from around the world have been collecting enormous amounts of data and harvesting its rich physics programme. Among the early findings are the following.

The search for the Higgs boson: in the summer of 2012, two experiments at CERN – ATLAS (A Toroidal LHC Apparatus) and CMS (Compact Muon Solenoid) – reported finding a new particle in proton-proton collisions that might be the long-sought Higgs boson. The existence of this particle, which has been searched for in many previous experiments, was predicted by something called the Brout-Englert-Higgs mechanism, which explains why elementary particles have mass.



Display of one candidate event selected in Higgs search analyses by ATLAS.

After the Big Bang: data from another experiment at CERN – ALICE (A Large Ion Collider Experiment) – will allow physicists to study a state of matter known as quark-gluon plasma ('quark soup'), which is believed to have existed in the first moments after the Big Bang. In the ALICE experiment, the LHC collides lead ions to recreate in the laboratory the conditions just after the Big Bang.

Matter and anti-matter: by studying a type of particle called the 'beauty quark' or 'b quark', another CERN experiment – LHCb (Large Hadron Collider beauty) – will help to explain why the universe appears to be composed almost entirely of matter but no anti-matter. The LHCb experiment specialises in investigating the slight differences between matter and anti-matter.

Dark secrets: both the ATLAS and CMS experiments will try to shed light on some of the grand mysteries of the universe: 'dark matter', which composes 23 per cent of the universe; and 'dark energy', which composes 73 per cent of the universe.

From physics to medicine

Over recent decades, many important diagnostic and therapeutic techniques have been built either on the basic principles of physics or by using the accelerators and detectors developed to conduct research in particle physics.

Fighting cancer: particle accelerators are routinely used in hospitals for conventional cancer radiotherapy with X-rays. The high precision irradiation of deep-seated tumours with hadron beams means that the radiation dose to surrounding healthy tissue is minimised.

MRI scans: superconducting magnets, which were perfected by physicists to steer the high energy beams of protons in the LHC, are producing medical images of ever increasing quality. The technique used in MRI (magnetic resonance imaging) is based on the principles of nuclear magnetic resonance.

Drugs and radioisotopes: accelerators are used to produce radioisotopes, which have become vital components of scientific research. Accelerators also provide X-rays for the development of new drugs.

PET scans: particle detectors are now widely used in medical imaging. The PET technique (positron emission tomography) stemmed directly from detectors initially designed for particle physics experiments to detect photons.

Eye surgery: silicon tracking detectors, which are sensitive to the passage of single particles, are now used in neuroscience experiments to investigate the workings of the retina. This is leading to the development of retinal prosthetics for artificial vision.

Diagnosis and therapy: cross-fertilisation between particle physics detectors and imaging tools is constantly bringing benefits to the medical field. These are related not only to diagnosis but also to therapy, as faster and more sensitive detectors can allow for in-vivo monitoring during irradiation.

Biomedical benefits of computing advances: grid computing, which allows multiple users to share computing power and storage capacity distributed across the world, also provides ideal tools for a wide range of biomedical fields – from screening drug candidates to image analysis to sharing and processing health records.

Simulation tools developed for particle physics are commonly used in a wide range of medical applications, as they can accurately model geometries and interactions of particles with matter. CERN developed grid computing to cope with the data handling and analysis needs of the LHC: the organisation is now a leader in this field.

Collaboration for therapies: CERN is known not only for its sophisticated technologies but also for an openness that is typical of the field of high energy physics. An example of its catalysing role in many international collaborations is the European Network for Light Ion Hadron Therapy, launched at CERN in 2002. This network includes the European Society for Therapeutic Radiation Oncology, the European Organisation for Research and Treatment of Cancer and groups promoting carbon ion and proton therapy in Europe.

> ***"Superconducting magnets, which steer the high energy beams of protons in the LHC, are helping to produce medical images of ever increasing quality."***

The European Fusion Development Agreement (EFDA) and its JET experiment explore the potential of fusion as an energy source.

The world's largest magnetic confinement fusion experiment

In a world needing alternatives to fossil fuels, fusion offers the possibility of an environmentally responsible source of energy that will ensure long-term sustainability and security of supply. The Joint European Torus (JET) – the world's largest magnetic confinement fusion experiment – investigates the potential of fusion power as a safe, clean and virtually limitless energy source. JET is exploited by all Europe's fusion laboratories under EFDA.

To produce fusion reactions, the burning fuels – typically deuterium and tritium, which are isotopes of hydrogen – have to be heated to very high temperatures of over 100 million degrees Kelvin. At these temperatures, matter is in the 'plasma' state and must be confined by intense magnetic fields.

In 1997, JET achieved a record 16MW fusion power for two seconds, with 25MW injected, and demonstrated plasma heating by the alpha particles generated in the fusion reactions. Dominant alpha particle heating is needed to produce burning plasmas, in which the plasma is self-heated by the fusion alphas.

JET paves the way for ITER (originally an acronym of 'international thermonuclear experimental reactor'), a project currently under construction in southern France. ITER is designed to be the first fusion experiment to investigate burning plasmas and release more energy than is needed to power it. It aims to achieve a fusion power of 500MW, with only 50MW of power injected. The duration of ITER's burning plasmas will be up to one hour.

One of the main challenges for fusion reactors is the compatibility between the plasma and the materials facing the plasma – the Wall. Due to the extreme temperatures required for fusion, the maximum circulating power through the plasma facing components is of the same order of magnitude of the power flux through the sun's surface. Handling this level of heat requires not only optimising the magnetic field configuration but also choosing the most appropriate plasma facing materials.

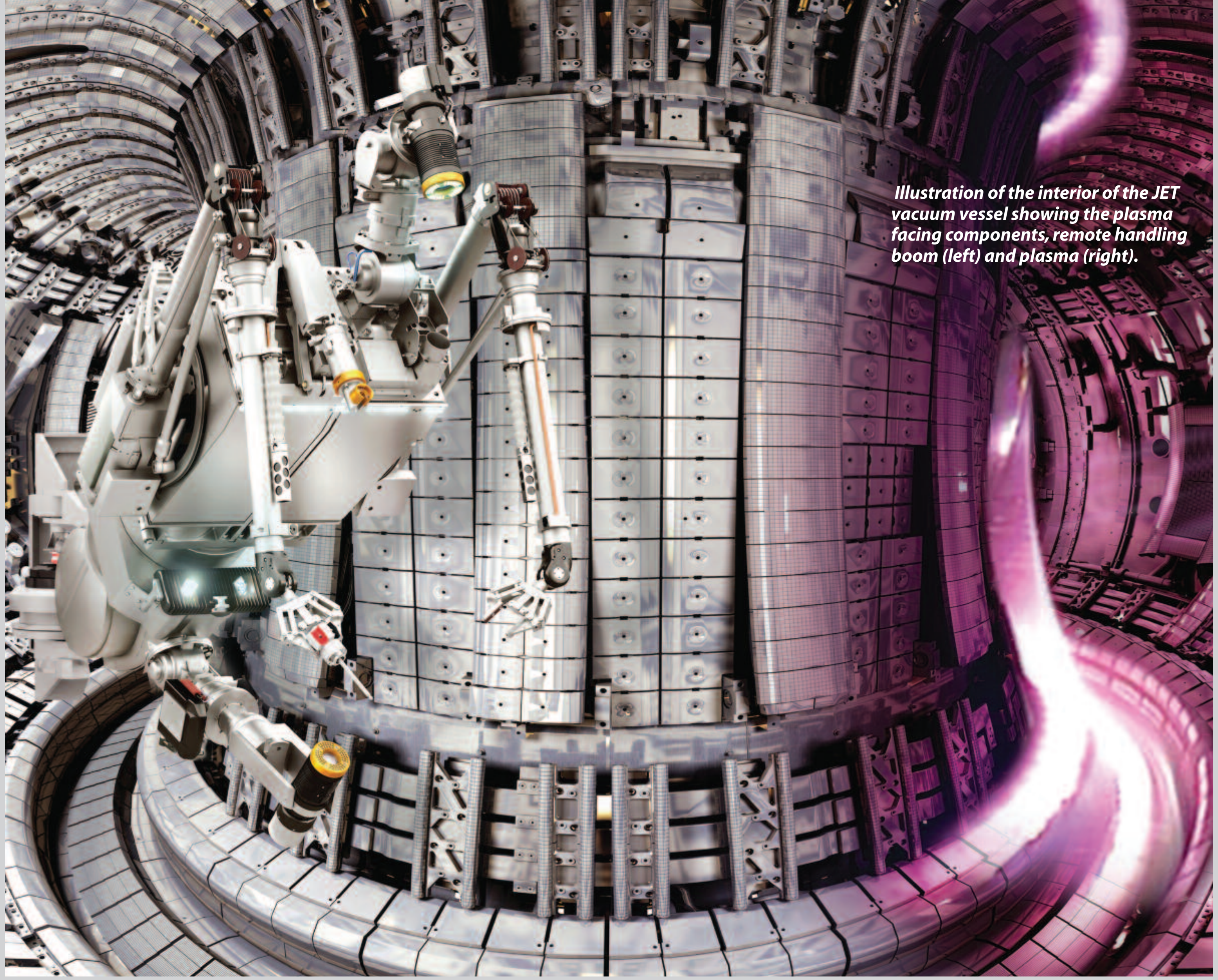


Illustration of the interior of the JET vacuum vessel showing the plasma facing components, remote handling boom (left) and plasma (right).

Carbon's large evaporation temperature and low atomic number makes it an ideal choice for the fusion device's plasma facing components. But carbon's chemistry also leads to the formation of hydrocarbon compounds that retain unacceptable amounts of tritium, one of the fusion fuels.

ITER's designers have therefore selected a combination of tungsten – which is characterised by a high melting point and a high atomic number – and beryllium – which has a low melting point and a low atomic number. This combination of metals is a compromise between minimising the melting of the plasma facing components and minimising the effects of impurities on the plasma, which are greater with higher atomic numbers.

JET: the natural testbed for ITER

JET has recently been upgraded by replacing its plasma facing materials with tungsten and beryllium – an ITER-like Wall. After an 18-month shutdown and four months of commissioning, JET was back in operation in August 2011.

The JET shutdown involved the replacement and installation of over 86,000 components using remote handling techniques. Remote handling is a key technology for fusion. In the presence of activated components and the possible presence of toxic materials such as beryllium, most in-vessel work is done by remote handling. And future operations of fusion devices will rely on effective remote handing maintenance.

The presence of new materials in JET also required optimisation of the plasma parameters, such as the magnetic field configuration. The reactor needs to be able to sustain the heat loads caused by the steady flow of energy from the plasma or by transient bursts of energy that might be released when the plasma is unstable.

With the successful operation of JET's ITER-like Wall in 2011 and 2012, an extensive scientific exploitation programme has been started in support of ITER. The first experiments have focused on the development of low fuel retention with beryllium and tungsten plasma facing surfaces.

Comparisons with experiments with carbon plasma facing components have shown that about ten times less fuel is retained in the wall. These are important results for ITER and they will be followed by a series of experiments aimed at recreating, as far as is possible, the extreme conditions expected in ITER.

Full exploitation of the ITER-like Wall at JET foresees deuterium-tritium (DT) experiments in line with ITER's needs. A key aspect of the DT experiments will be to confirm theoretical expectations of the impact of the alpha particles created by fusion on the stability of the plasma. Recent JET results, using ions accelerated by radio frequency waves to mimic the effect of alpha particles, confirm theoretical insights into the control of plasma stability.

The exploitation of the ITER-like Wall will continue in 2013 with the main aim of demonstrating satisfactory operation in the presence of shallow melting of tungsten. The progressive increase of plasma performance approaching ITER conditions will be the objective of the 2014 and 2015 experimental campaigns.

Along with other key experiments, JET's planned DT campaign will study plasmas in the presence of alpha particles ahead of ITER's DT operation phase planned for the late 2020s. These experiments will provide the required preparation in support of ITER.

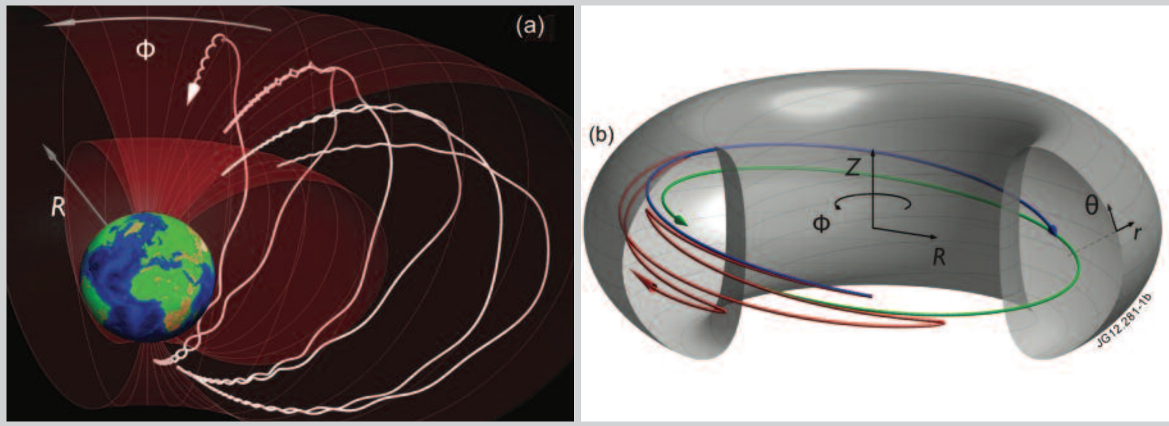
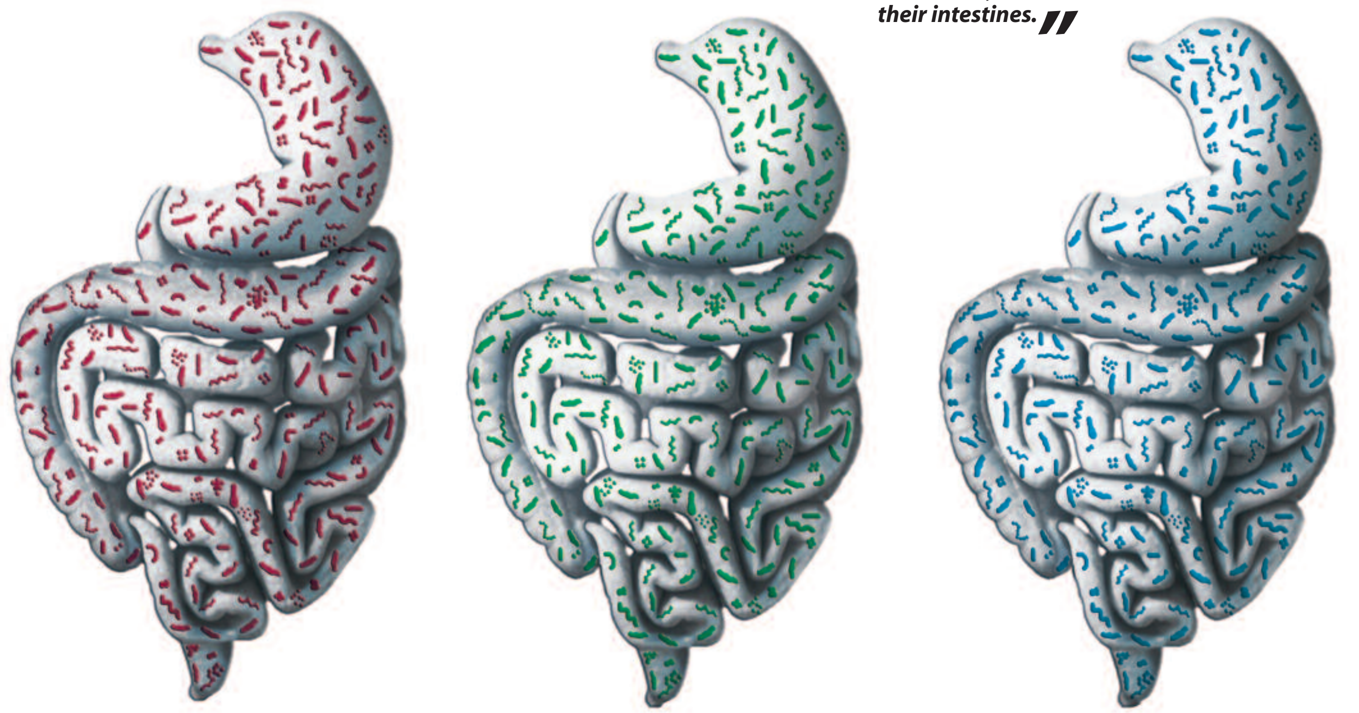


Illustration of magnetically trapped particle trajectories in the earth's magnetosphere (a), and magnetically confined particle trajectories in a tokamak fusion reactor (b).

The European Molecular Biology Laboratory (EMBL) is Europe's flagship laboratory for the life sciences.

"Humans have three different types of 'bacterial ecosystem' in their intestines."



Credits: EMBL/Petra Riedinger

The big picture: systems biology

Studying how ecosystems, cells and even genomes function as whole systems provides biological insights that would be unattainable by simply analysing their components. Significant recent findings by EMBL scientists and collaborators from around the world include the following.

Gut reactions: humans have three different types of 'bacterial ecosystem' in their intestines, according to scientists at EMBL Heidelberg. Their work has also uncovered microbial genetic markers that are related to an individual's age, gender and body mass index. These findings could be used in the diagnosis of diseases such as colo-rectal cancer, helping to predict outcomes and inform treatment.

The human genome: what has hitherto been called 'junk DNA' or the 'dark matter of the genome' is actually a massive, three-dimensional (3D) switchboard turning genes on and off. That is one of the conclusions of the Encyclopaedia of DNA Elements (ENCODE) project, in which hundreds of scientists have been systematically exploring the functions of the human genome. The ENCODE project has also found that while only two per cent of human DNA is genes, a much bigger part of the genome (at least 20 per cent) is involved in controlling when and where those genes are active.

Brain tumours: an inherited mutation in a gene is the likely link between exploding chromosomes and paediatric brain tumours, which are the second most common cause of childhood mortality in developed countries. Scientists at EMBL Heidelberg made this discovery when they sequenced the whole genome of cells from patients with the tumours, known as medulloblastomas.

Cell resources: the bacterium that causes atypical pneumonia is helping to uncover how cells make the most of limited resources. By measuring all the proteins that this bacterium produces, scientists at EMBL Heidelberg have found that the secret is fine-tuning: the bacterium tweaks each of its proteins in several ways so that one protein can perform a variety of tasks.

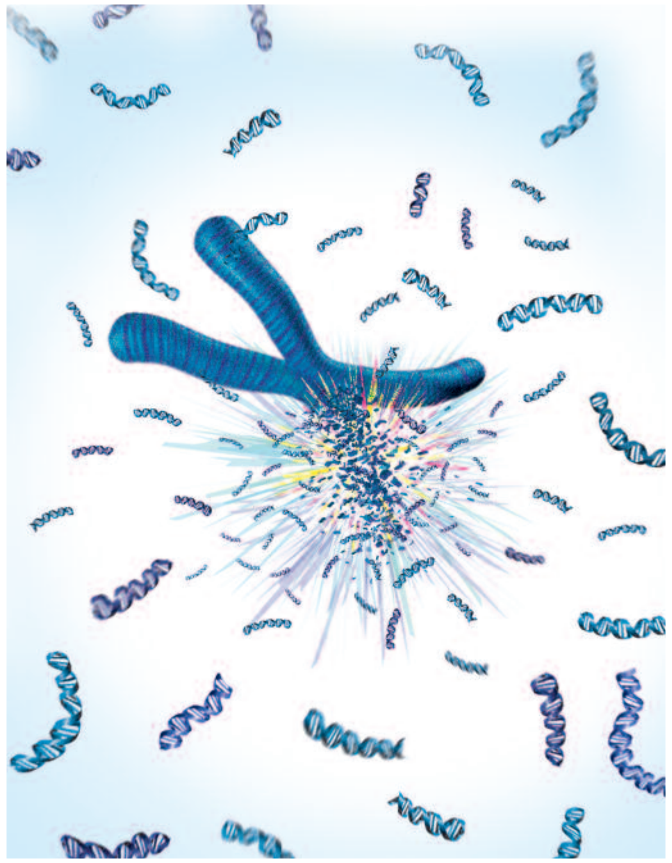
Looking at life: microscopy

New techniques and instruments developed by EMBL scientists are enabling them to record everything from the movement of tiny molecules to the development of a whole embryo.

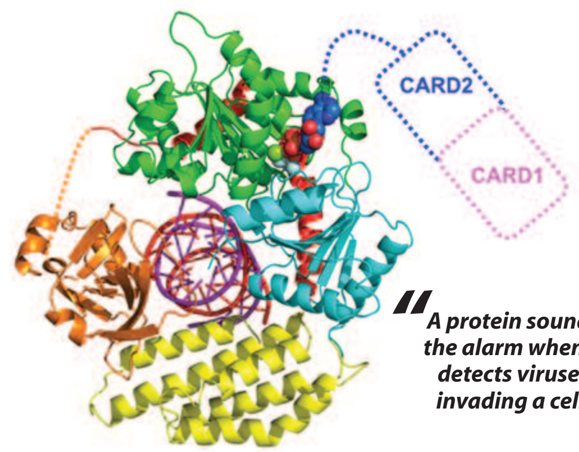
Cells in motion: scientists at EMBL Heidelberg have combined the power of two kinds of microscope to produce a 3D film of how cells 'swallow' nutrients and other molecules by engulfing them. Their study was the first to follow changes in the shape of the cell's membrane and to track the proteins thought to influence those changes. The technique is also being employed to investigate how viruses invade and leave their host's cells.

Animal movies: a new microscope developed by scientists at EMBL Heidelberg scans a sample layer by layer from four different angles. They have used the instrument to film a fruit fly embryo in 3D – from when it was about two-and-a-half hours old until it crawled away from the microscope as a larva. Future plans include using the microscope to investigate how organs and tissues form in a range of other animals.

"An inherited mutation in the TP53 gene may cause chromosome 'explosions' with links to cancer."



Credits: EMBL/Petra Riedinger



"A protein sounds the alarm when it detects viruses invading a cell."

Credits: EMBL/Stephen Cusack

Mind and body

To uncover the workings of the human body, how it forms and how it responds to injury and disease, EMBL scientists study everything from tiny proteins to whole animals.

Wiring the brain: as a mouse embryo develops, cells called microglia 'prune' the connections between neurons, according to scientists at EMBL Monterotondo. Their research is revealing the ways in which microglia shape how the brain is wired and how they affect brain function.

Brain injury: studies of the adult brain of the zebrafish by scientists at EMBL Heidelberg have revealed exactly how microglia detect the site of brain injury. This finding paves the way for new medical approaches to conditions where microglia's ability to locate hazardous material is compromised, such as Alzheimer's disease and Parkinson's disease.

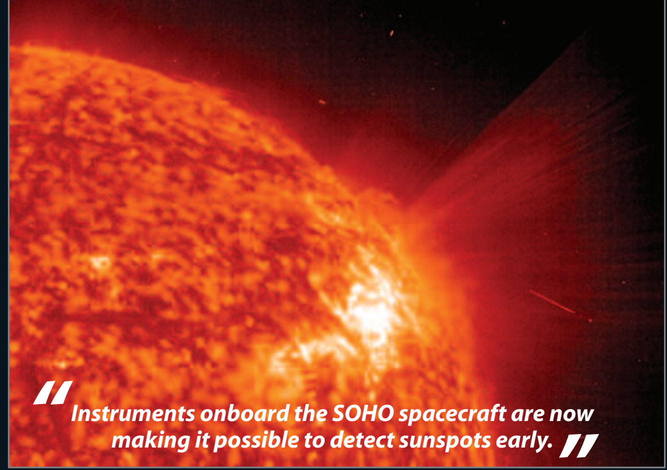
Virus alerts: scientists at EMBL Grenoble have discovered how a protein sounds the alarm when it detects viruses invading a cell. This is an important development in understanding bodies' innate immune responses. It sheds light on how cells respond rapidly to a wide range of viruses, including influenza, rabies and hepatitis.

The flu: RNA polymerase is an enzyme that is crucial for replication of the influenza virus. In a study of the influenza strain from the 2009 pandemic, scientists at EMBL Grenoble have determined the detailed 3D structure of part of the enzyme. Their findings will help in the design of innovative drugs against all strains of influenza.

Muscle shape: the elastic part of myomesin, a protein that links muscle filaments, can stretch to two and a half times its original length, unfolding in a way that was hitherto unknown. This discovery by scientists at EMBL Hamburg helps to explain how muscles keep their shape as they flex and contract.

The European Space Agency (ESA) builds missions to explore the solar system and the wider universe.

Forecasting sunspots



Credits: SOHO (ESA & NASA)

Sunspots can be detected as much as two days before they reach the surface of the sun. Scientists made this breakthrough in 2011 using data from the Solar and Heliospheric Observatory (SOHO), a collaboration between ESA and its US counterpart, the National Aeronautics and Space Administration (NASA), designed to study the sun from its deep core to the outer corona and the solar wind.

Sunspots are the 'butterfly's wings' of solar storms. Visible to the human eye as dark blemishes on the solar disk, sunspots are the starting points of explosive flares and 'coronal mass ejections', which sometimes hit the Earth 150 million kilometres away. The consequences range from the Northern Lights to radio blackouts and power outages.

After more than 400 years of studying sunspots, astronomers have pieced together their basic characteristics: they are planet-sized islands of magnetism that float in solar plasma. Most researchers agree that sunspots are born deep inside the sun through the action of its inner magnetic dynamo. From there they bob to the top, carried upwards by magnetic buoyancy. A sunspot coming to the sun's surface is something like a submarine emerging from the ocean depths.

The detection of sunspots that are still submerged uses a technique called 'helioseismology', similar to an approach used in the study of earthquakes. Just as seismic waves travelling through the body of the Earth reveal what is inside the planet, acoustic waves travelling through the body of the sun can reveal what is inside the star.

Instruments onboard the SOHO spacecraft, which ESA and NASA launched in 1995, have been constantly monitoring the sun for acoustic activity, now making it possible to detect sunspots early. The new findings will not only help to understand how sunspots form within the sun's interior: they also have implications for early warnings of major solar flares and forecasting 'space weather'.

A star is born

Many of the clouds of gas and dust in which stars are born are filamentary in nature, with young 'proto-stars' strung along the filaments. This discovery, made using ESA's Herschel Space Observatory, provides clues as to how these 'giant molecular clouds' collapse under gravity. It also helps to explain how stars form within the clouds and how key properties – such as their mass – may be determined by this filamentary collapse.

The Vela Molecular Ridge is a vast star-forming complex in the plane of the Milky Way galaxy. Observing this region at far-infrared wavelengths, Herschel has obtained an extraordinarily detailed image of the most massive component of this molecular complex, known as Vela-C.

Located roughly 2,300 light years away, Vela-C saw the onset of star formation less than a million years ago – relatively recently on astronomical timescales. Stars of all sizes are being born in this region, making it an ideal laboratory to study the birth of different populations of stars.

The images from Herschel's instruments reveal previously unseen detail in the mixture of gas and dust that pervades the region. Cosmic dust is a minor but crucial component of the interstellar medium and at the prevailing extremely low temperatures, it shines most brightly at the far-infrared wavelengths that Herschel is designed to observe. By detecting emissions from cosmic dust, astronomers can unravel the distribution of the raw materials from which stars are made.

Studies using Herschel data indicate that the ridge-like filaments in star-forming regions such as Vela-C emerged from converging flows of matter in the interstellar medium. Clumps of matter within the filaments collapse under their own gravity to form stars spanning a wide range of masses, with the highest-mass ones being born in the densest regions at the confluence of several individual filaments.

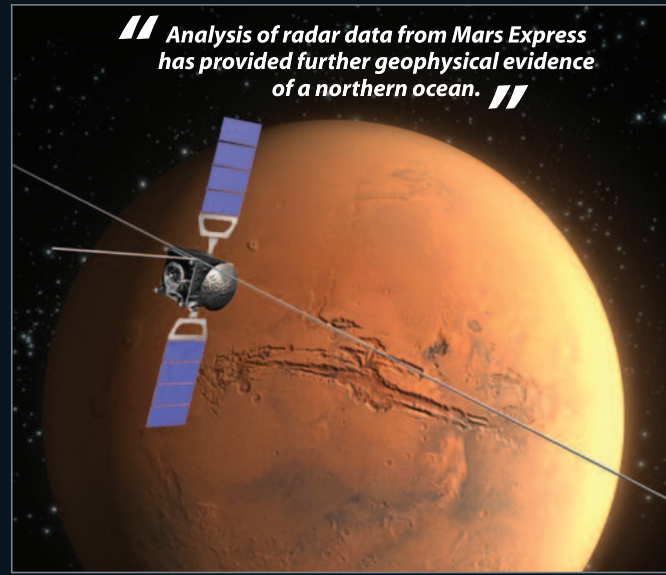
The waters of Mars

ESA's Mars Express mission has discovered large amounts of low-density material buried below the surface of the planet. Although Mars is currently a frozen desert where liquid water cannot exist on the surface for more than a few seconds, there is plenty of evidence that the planet was once much wetter. Four billion years ago, when it was warmer, there were probably oceans covering most of the surface; then, as the planet cooled, the water disappeared underground into ice.

But there is evidence that over the next two billion years, this sub-surface ice occasionally melted, resulting in temporary oceans. Particularly striking are the enormous dry channels, which may have been carved by raging torrents of sediment-laden water, while topographical observations have revealed the presence of shorelines eroded by waves on an ancient ocean.

Radar data from Mars Express have provided further geophysical evidence of an ocean that once covered much of the northern hemisphere. The low-frequency radar probes the nature of the planet's sub-surface to depths of 60 to 80 metres by revealing contrasts in a measure known as the dielectric constant.

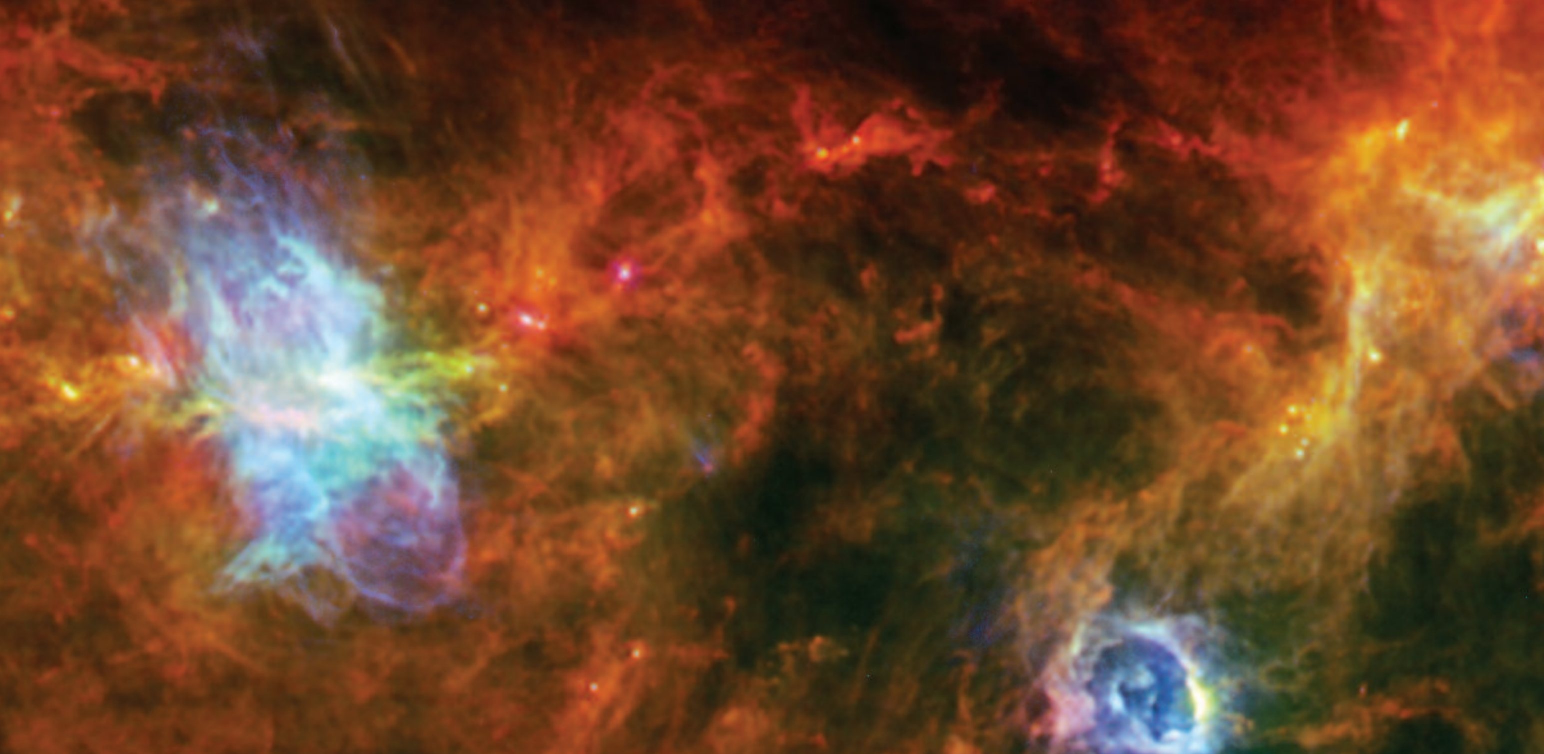
On Mars, these variations are caused by two parameters: the density of material and the amount of ice. A high



Credits: Mars Express (ESA, C. Carreau)

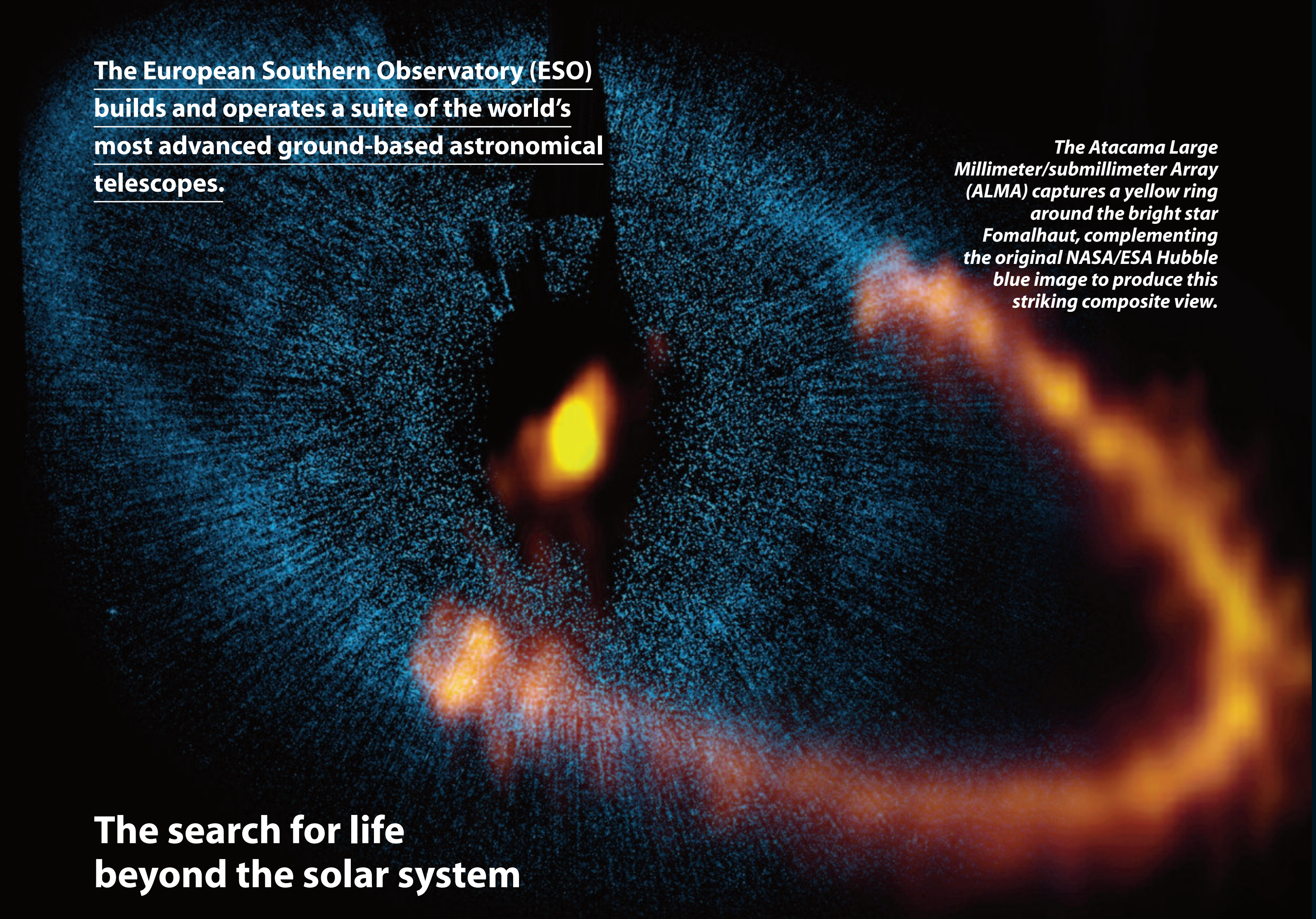
dielectric value indicates the presence of dense materials whereas a low value shows a fairly low density due to sedimentary material and/or a high ice content: much of the northern hemisphere of Mars shows a low dielectric constant.

So three billion years ago, an 'Oceanus Borealis' may have emerged to cover the region for perhaps a million years before disappearing. A key question remains: what happened to the water – did it freeze back below the surface or turn into vapour and escape through the atmosphere?



ESA's Herschel Space Observatory has obtained this extraordinarily detailed far-infrared image of the Vela Molecular Ridge, a vast star-forming complex in the plane of the Milky Way galaxy.

Credits: Herschel (ESA, SPIRE, PACS, HOBYS consortia)



The European Southern Observatory (ESO) builds and operates a suite of the world's most advanced ground-based astronomical telescopes.

The Atacama Large Millimeter/submillimeter Array (ALMA) captures a yellow ring around the bright star Fomalhaut, complementing the original NASA/ESA Hubble blue image to produce this striking composite view.

The search for life beyond the solar system

The Milky Way galaxy may contain billions of rocky planets of similar size to Earth and capable of supporting biological life. ESO's telescopes are discovering planets with masses only slightly larger than the Earth's, orbiting stars in the 'habitable zone' where liquid water could exist.

When planetary systems around stars other than the sun were first detected in the mid-1990s, it was a watershed in the search for life elsewhere in the universe. But it was not until 2010 that the first direct image of a planet outside the solar system was recorded. ESO's Very Large Telescope, which made that breakthrough, has observed several more planets since.

Detecting planets demands exquisite instrumental precision and stability. There are essentially three techniques. The first is direct imaging of reflected starlight or intrinsic thermal (infrared) light. The second is measuring the effect of the mutual gravitational attraction between a planet and its parent star. And the third, which is only possible when orbits are at the right angle to be viewed from Earth, is observing small variations in light as the planet passes in front of or behind its star.

ESO's facilities have used all three methods to find and characterise planets. One telescope has been dedicated to measuring tiny changes in the velocity of stars due to the 'wobble' induced by orbiting planets.

The instruments at ESO are also beginning to reveal the composition of planetary atmospheres. One way to do this is by direct observation via 'adaptive optics', which correct for distortions induced by the passage of light through the Earth's atmosphere. Another is a method called transmission spectroscopy, which analyses small changes in the light of the parent star during and outside a planetary transit.

Future research efforts will dig deeper into the nature of planets in the habitable zone, including a search for biological markers. And a huge new international facility in which ESO is a major partner – the Atacama Large Millimeter/submillimeter Array in northern Chile – will investigate how new planets form around young stars. By detecting heat from the new planets and gaps in the rings of matter around the young stars, this work will provide insights into the origins of solar systems.

All these developments are laying the foundations for a new science of astrobiology, in which the synergies between physics, chemistry and biology enjoy a natural and potentially highly productive meeting ground.

The accelerated expansion of the universe

The universe has been expanding since the Big Bang – but it has not expanded at a uniform rate. According to a profound cosmological discovery involving major use of ESO telescopes, expansion has accelerated over the second half of the lifetime of the universe as a result of what has become known as 'dark energy'. The two international research teams that made this discovery were honoured with the 2011 Nobel Prize for Physics.

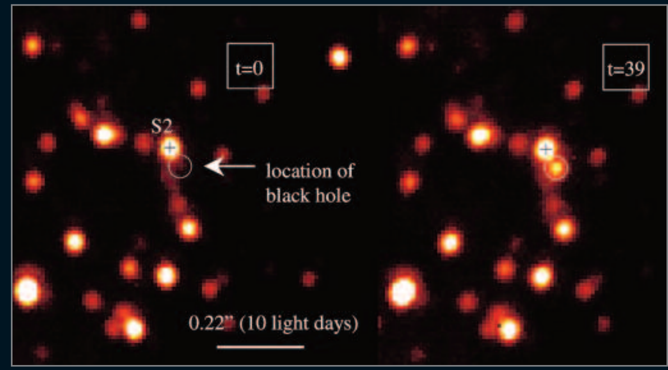
Prior to this research, it was expected that the expansion of space would slow down over time because of the effects of gravity. The rate of this deceleration would allow measurement of the average mass density of the universe – and determine, among other things, the age of the universe.

Direct measurements of distance over a large part of the history of cosmic expansion have been able to map out how the universe has increased in scale over time. A particular class of violent stellar explosion – what is called a type Ia supernova – provides a 'standard-candle' for this measurement.

The two research teams have used ESO telescopes over a long period to observe both nearby and distant supernovae. Their investigations find that while the first half of the lifetime of the universe was dominated by deceleration, there is compelling evidence for accelerated expansion since then.

Future observations with the European Extremely Large Telescope will provide the opportunity to observe the expansion directly, making it possible to understand the precise dynamics of the universe.

"A Type Ia supernova provides a 'standard-candle' for the measurement of the expansion of the universe."



ESO's Very Large Telescope observes infrared flares from the black hole at the Galactic Centre.

The massive black hole at the centre of the Milky Way

At the centre of the Milky Way galaxy lies a black hole with a mass four million times the mass of the sun. There is now compelling evidence from ESO's telescopes of the presence of this massive space phenomenon. And while many black holes at the core of other galaxies are extremely bright – sometimes brighter than the light from all the stars in the galaxy – this black hole seems remarkably quiescent.

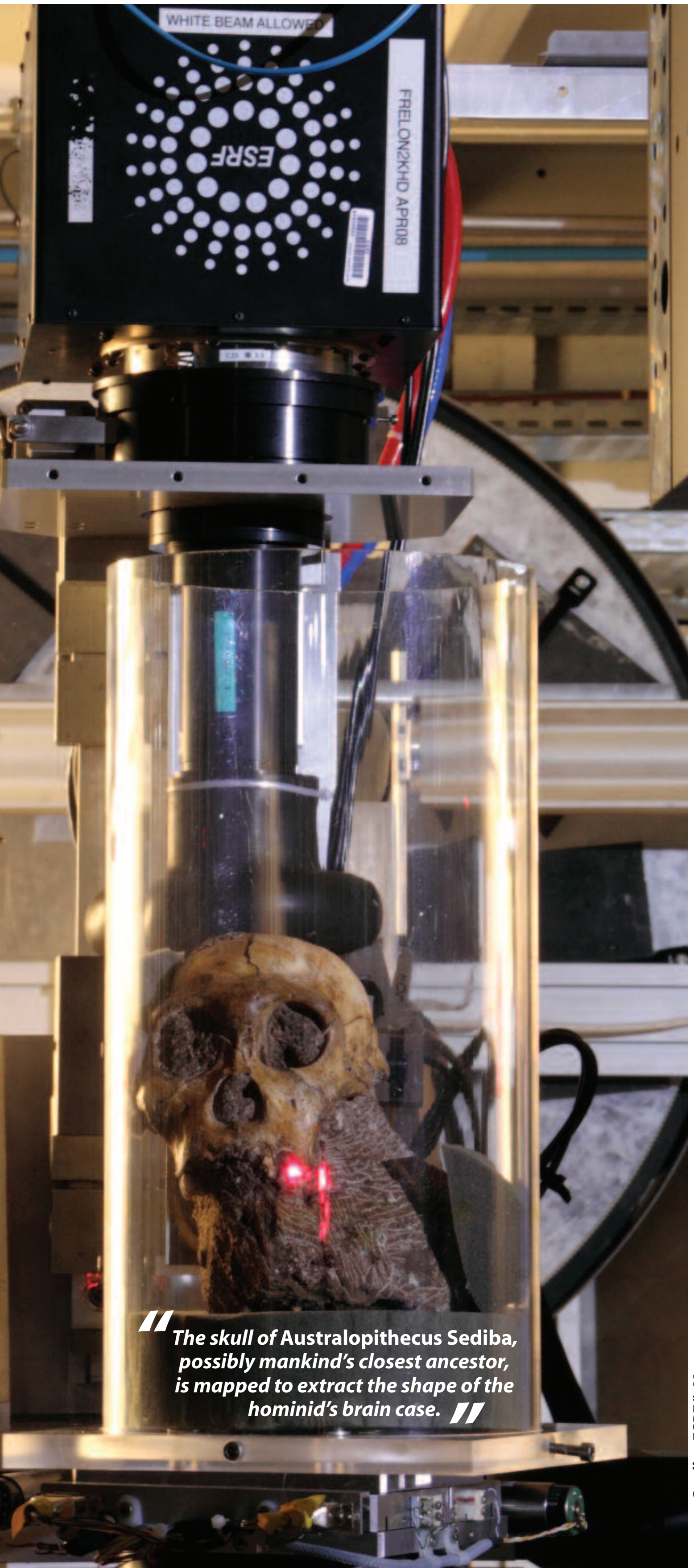
The detection and measurement of black holes have been a goal of astrophysics since the general theory of relativity first predicted their existence decades ago. Ruling out alternative explanations for measurements of very large mass concentrations in small volumes has been a long process. But painstaking infrared observations with several ESO telescopes over nearly two decades now unequivocally demonstrate a huge mass concentration within a radius of a few light hours.

Researchers have also now realised that far from being isolated curiosities, massive black holes at the core of galaxies are ubiquitous. It seems clear that these phenomena play a fundamental role in the formation and growth of all these stellar systems.

In 2012, ESO instruments detected a gas cloud on a trajectory taking it directly towards the black hole. In 2013, there will be a unique opportunity to see the cloud falling into the black hole.

ESO is also building new instruments to provide the positional accuracy for astronomers to probe distances as close as the 'event horizon' of the black hole. This will become a critical test of general relativity in a strong gravitational field.

The European Synchrotron Radiation Facility (ESRF) is a powerful X-ray light source and the global leader in photon science by users and output.



"The skull of Australopithecus Sediba, possibly mankind's closest ancestor, is mapped to extract the shape of the hominid's brain case."

Credits: ESRF/J. Montero

A synchrotron is a stadium-sized machine that produces many beams of bright X-ray light. Each beam is guided through a set of lenses and instruments called a beamline, where the X-rays illuminate and interact with samples of material being studied.

Dozens of highly specialised techniques exist for using synchrotron X-rays, each with specific strengths and applications. The ESRF is first and foremost a user facility that provides visiting scientists ('users') with access to these techniques. Companies too send researchers, notably in the fields of pharmaceuticals, cosmetics, petrochemicals and microelectronics.

Some 2,000 academic applications for beam time are received and reviewed each year: 40-45 per cent of these are accepted, resulting in more than 1,800 peer-refereed publications a year, of which an average of 30 are in the journals *Science* and *Nature*. This not only reflects work by physicists, chemists and materials scientists: biologists, medical doctors, meteorologists, geophysicists and archaeologists are also regular users. Significant recent findings that the X-ray light at the ESRF has made possible include the following.

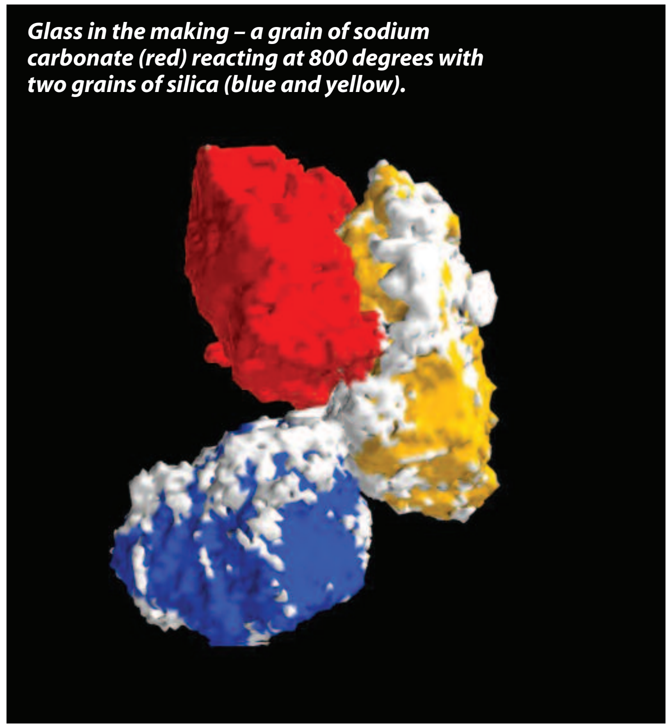
X-ray imaging: from the past to the future

Producing images with X-rays was pioneered in 1895. Nearly 120 years on, the extraordinary properties of synchrotron X-rays are pushing the capabilities of this technique beyond what was imagined even just a decade ago.

Human evolution: two million years ago, one of the first hominids, *Australopithecus Sediba*, exhibited many very advanced features in its brain. Researchers working at the ESRF used X-rays to map the brain case of this species in 3-D, which provided evidence that *Sediba* is indeed humans' closest ancestor.

Detecting cancer: high-energy X-rays provide highly detailed images of soft matter and can help to detect breast cancer in its early stages. Equally Sloped Tomography is a new technique tested at the ESRF that reduces the dose of radiation during a hospital CT scan by a factor of four. This will mean that a 2-D mammography can be complemented with a complete 3-D CT scan even for radiosensitive organs, such as breasts.

Inside cells: cyan fluorescent proteins (CFPs) are very popular in cell biology, where they are used to make processes visible inside a living cell, almost as if in a film. New CFPs with a record efficiency of 93 per cent have been developed at the ESRF. Thanks to a novel approach in this development, scientists now hope to design improved fluorescent proteins emitting light of different colours for use in other applications.



Glass in the making – a grain of sodium carbonate (red) reacting at 800 degrees with two grains of silica (blue and yellow).

Credits: St. Gobain/CNRS/E. Gouillart

Materials: from atoms to devices

Synchrotron X-rays can penetrate deep into materials and devices, making it possible to unlock the full potential of new materials and innovative working devices.

Air pollution: catalysis is involved in all industrial chemistry and an increasing number of devices, not least in cars where catalytic converters eliminate noxious exhaust gases. X-rays at the ESRF delve deep into these converters, studying the chemical reactions on the catalyst's surface at the atomic scale. This analysis has helped the world's biggest car manufacturer to improve the lifetime of car exhaust catalysers.

Making glass: global glass manufacturing uses as much energy for melting powders into liquid glass as the Dutch consume electricity. France's biggest glassmaker has used X-rays at the ESRF to visualise the transition from powder to glass in microscopic detail. The complex process revealed by this research is the first step towards achieving lower temperatures for industrial glass manufacturing. This would make production both more sustainable and more competitive.

Electronics: the performance of such devices as fuel cells, batteries and electronics often depends on processes deep inside the device – for example, in membranes or on the surface of semiconductors – which can be revealed by deeply penetrating X-rays. At the ESRF, tomorrow's quantum dot-based semiconductors are studied today, promising to extend dramatically the capabilities of silicon integrated electronics.

Health: from molecules to drugs

X-ray diffraction techniques were key to discoveries by 24 Nobel laureates in Medicine and Chemistry between 1946 and 2012. The ESRF is a leader in this field with 47 per cent of all structures deposited by European synchrotrons since 1996 in the Protein Data Bank, a repository for data on biological molecules.

Protein construction: in the mid-1990s, Ada Yonath and Venkatraman Ramakrishnan used the ESRF to collect the data on the structure and function of the ribosome found in all living cells. The research earned them, together with Thomas Steitz, the 2009 Nobel Prize in Chemistry. Their groups continue to be frequent ESRF users, visiting Grenoble up to once a month to collect diffraction data from complex protein crystals.

Cell communication: in 2007, Brian Kobilka and colleagues cracked the structure of 'G protein coupled receptors' (GPCRs) at the ESRF. GPCRs are tiny molecules embedded in cellular membranes that spring into action when a specific molecule passes by. They allow cells to communicate and play a role in the delivery of drugs to the interior of cells. In October 2012, Kobilka was awarded the Nobel Prize in Chemistry.

Fighting flu: in 2012, a world-leading pharmaceutical company signed a €240 million agreement with Savira GmbH, an EMBL spin-off company that works on new candidates for drugs to fight influenza. These drugs are based on fundamental research at the ESRF, which revealed in 2009 how influenza viruses take control of several key processes in human cells, turning their hosts into virus-replicating machines.

Nobel laureate Ada Yonath from the Weizman Institute with one of her collaborators at ESRF beamline ID23, where she frequently collects protein crystallography data.

© Micheline Pelletier and Cyril Bruneau.

The European XFEL (X-ray free-electron laser) will generate extremely intense X-ray flashes for a wide range of research uses.

Due to start operation in 2016, the European XFEL will be an X-ray laser with unique characteristics. It will generate ultrashort X-ray flashes – 27,000 times per second and with a brilliance that is a billion times higher than that of the best conventional X-ray radiation sources.

To generate the X-ray flashes, bunches of electrons will first be accelerated to high energies and then directed through special arrangements of magnets known as undulators. In the process, the particles will emit radiation that is increasingly amplified until ultimately an extremely short and intense X-ray flash is created.

The facility will open up research areas that were previously inaccessible for a range of scientific fields, including biology, chemistry, materials science, medicine, nanotechnology, pharmacy and physics. Researchers will be able to map the atomic details of viruses, decipher the molecular composition of cells, take three-dimensional images of the nanoworld, film chemical reactions and study processes such as those happening deep inside planets.

Better pictures from the nanoworld

In 2010, researchers from the Deutsches Elektronen-Synchrotron and the European XFEL devised a dramatic improvement in the already remarkable features of these large machines by placing a special crystal in the path of the radiation. In 2011, their colleagues from the Linac Coherent Light Source (LCLS) in the US and the Technological Institute for Superhard and Novel Carbon Materials in Russia implemented the setting and confirmed the predicted outcome.

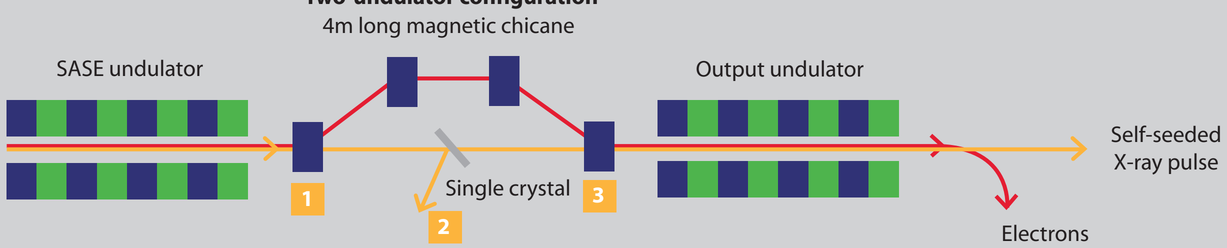
This breakthrough was obtained by improving a parameter of the X-ray beam called 'longitudinal coherence'. As with a regular camera, which needs sufficient light to generate a good photograph, the quality of the pictures or films taken by an XFEL significantly improves with the coherence and intensity of the X-ray flashes used.

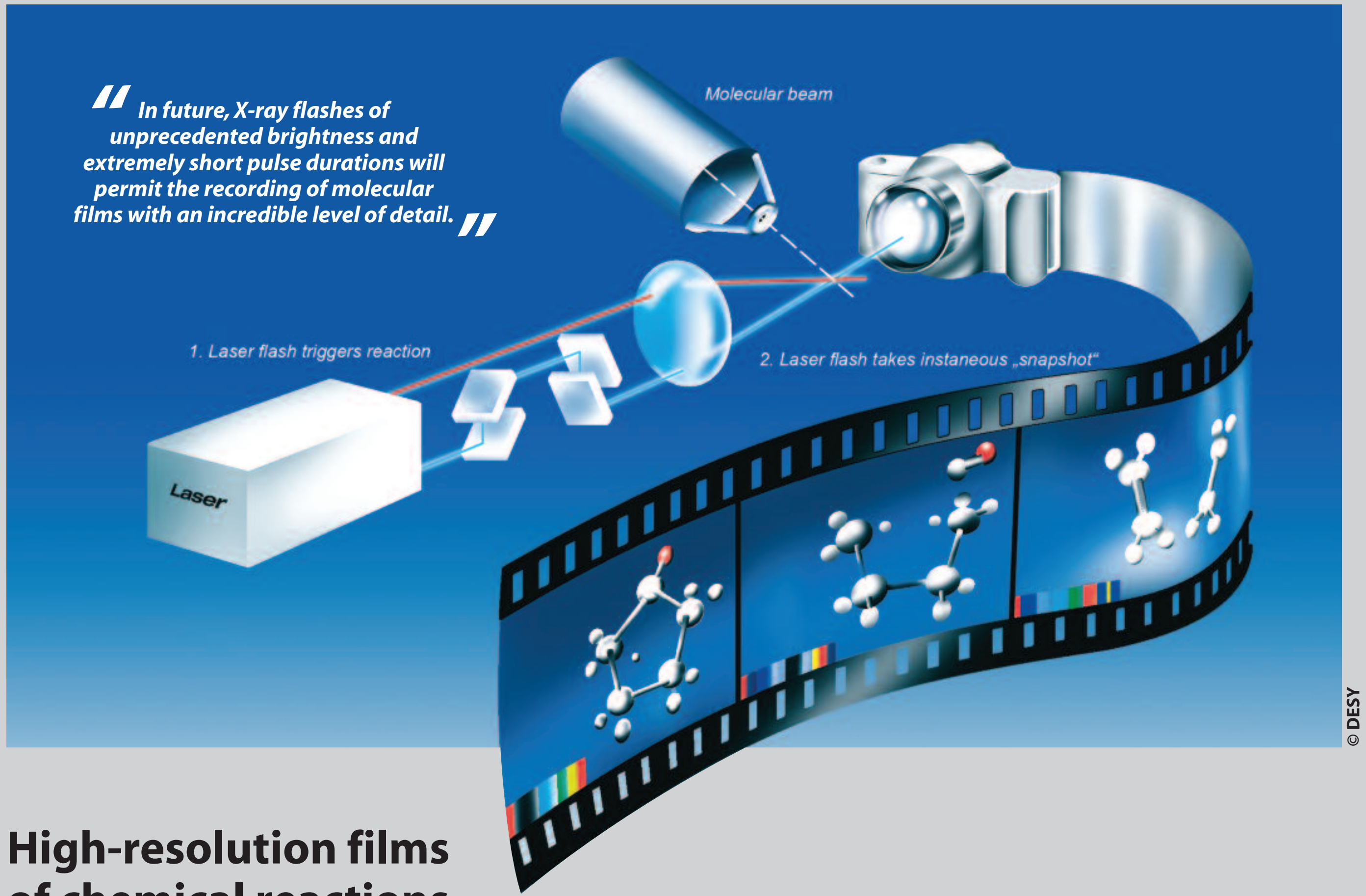
To improve the X-ray flashes, the physicists inserted the special crystal between the magnetic structures (undulators) that create them. When the light generated in the first part of the undulator hits the crystal at a certain angle, most of the light passes through the crystal, keeping the same properties as the incoming beam.

But because of the specific properties of the crystal, the first pulse is followed by a second one, slightly delayed and monochromatic – that is, consisting of only one wavelength of light. These high-quality X-rays are used to seed the generation of very intense and coherent flashes in the second part of the undulator – a procedure known as 'self seeding'.

These new results are a further step towards creating an X-ray beam that can take high-resolution pictures of single protein molecules. Currently, scientists still have to grow crystals of proteins to get such pictures. This is a very time-consuming process that can take years or, in many important cases, is not possible at all.

Two-undulator configuration





High-resolution films of chemical reactions

XFELs will bring motion into the understanding of chemical reactivity. This will open the door to the development of new products and more efficient chemical production processes.

At present, what is observed in chemical reactions is a sudden change from reactants to products. In future, X-ray flashes of unprecedented brightness and extremely short pulse durations will permit the recording of molecular films with an incredible level of detail. It will become possible to understand the elementary steps taking place inside molecules long before chemical reactions are completed.

In 2011, researchers from the European XFEL initiated an international collaboration to perform novel experiments with the goal of producing a 'motion picture' of the complex processes in a chemical reaction. The changes that they aim to record occur on the timescale of a femtosecond – one millionth of one billionth of a second.

In a first series of experiments at two synchrotron radiation sources – the ESRF (see pages 16-17) and the Advanced Photon Source in the US – the research team used different complementary X-ray techniques in a single measurement to study the processes occurring in transition metal complexes that have been 'photo-excited'.

These molecules not only change their structure but also their magnetic state on a timescale that is not yet known. The researchers were able to elucidate these changes inside molecules (using the techniques of X-ray absorption and emission spectroscopies) and also the response of the caging solvent following the reaction (using a technique called X-ray diffuse scattering).

Because the time resolution for such experiments at synchrotrons is at least 1,000 times too slow to resolve changes in real time, they successfully carried this study to the next level at the LCLS with 300 femtoseconds time resolution. The time resolution is expected to improve further to below 100 femtoseconds, which would make it possible to capture the changes of chemical and biological systems on the fly.

The result will be a uniquely rich molecular film – not only of the changing atomic structure but also of the driving forces behind the changes, which are governed by the electrons that form chemical bonds and the molecular spin inside molecules.

Future research at the European XFEL based on the insights generated by these experiments will eventually result in more efficient chemical tools, such as energy-optimised solar energy converters or catalysts.

The Institut Laue-Langevin (ILL) operates the world's most intense neutron source to reveal the fundamental properties of materials.

Neutrons are neutral elementary particles that can explore matter at the atomic and molecular scale, providing deep insights into the structure and behaviour of materials. At the ILL, the world's most powerful source of neutrons for research and a suite of high-performance instruments are used for a wide range of studies across the physical and life sciences.

"The world's most powerful source of neutrons for research."

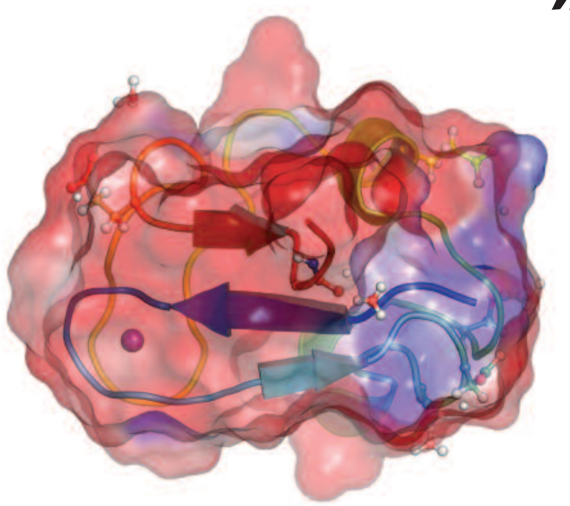
Next generation materials

The tiny 'magnetic moment' of the neutron makes it the most incisive probe of magnetism at the atomic level, providing unsurpassed information about magnets and related phenomena, such as superconductivity.

Data storage: a key application of magnetic materials is in devices for data storage, such as computer hard drives and mp3 players. The techniques of 'neutron scattering' used at the ILL are showing how individual molecules can be polarised magnetically, which may provide the basis for data storage at very high density.

This research on 'single molecule magnets' is also investigating the possibility of storing information by exploiting the 'quantum' properties of individual atoms. Such work may unlock the door to practical quantum computing, a potentially transformative technology highlighted by the 2012 Nobel Prize in Physics.

"Neutrons provide the most precise way to pinpoint the protons on which the very molecules of life depend."



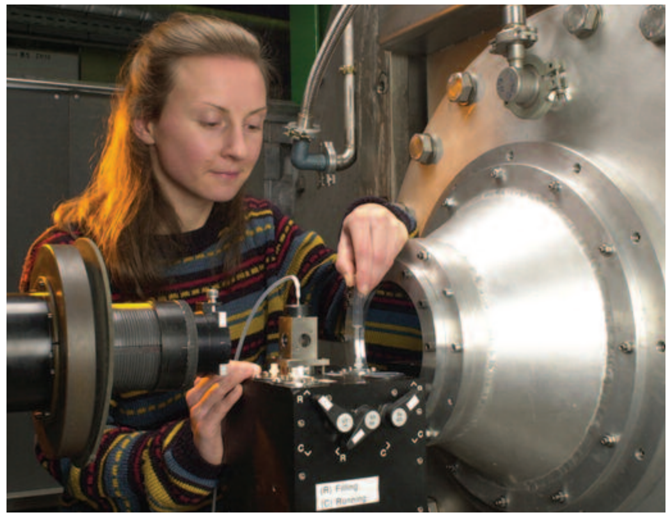
Superconductors: neutrons have recently provided the clearest evidence that magnetic excitations play a key role in high-temperature superconductivity. Understanding this state could lead to the development of a new generation of functional materials, potentially affecting technologies from body scanners and ultra-fast computer chips to high-efficiency transmission of electricity.

Magnetic soap: neutrons have revealed the detergent properties of the world's first magnetic soap. This material could be used to clean up oil spills, binding to the pollutants and gathering them together for disposal with a powerful magnet.

The molecules of life

A key feature of the neutron is that it is scattered very differently by hydrogen atoms and by atoms of the hydrogen isotope, deuterium. This is valuable for analysing the structure and behaviour of materials that contain hydrogen. Such materials include fuel cells and batteries, as well as the molecules on which life depends.

Biological antifreeze: neutrons have shown how proteins in the bodily fluids of an arctic fish act as 'antifreeze', allowing them to survive in temperatures at which water would normally freeze. The biological antifreeze proteins protect the fish by binding to ice crystal nuclei as soon as they start to form, preventing them from growing into ice crystals. ILL data also demonstrates how the proteins recognise the ice crystal nuclei but do not attach to liquid water, which would lead the fish to dehydrate.



Exploring the properties of the world's first magnetic soap.

These results could provide diverse benefits: improving cryosurgery; enhancing the preservation of tissues for transplant or transfusion; lengthening the shelf-life of frozen foods; increasing the freeze tolerance of crop plants; improving farm fish production; and extending the harvest season in cooler climates.

Cholesterol: neutrons provide the most reliable measurements of the speed at which cholesterol moves within and between cells, a crucial function in transporting chemical signals and conveying nerve impulses around the body. The process turns out to be far slower than previously thought.

Neutrons can also be used to analyse the effect of adding molecular agents to inhibit or enhance the motion of cholesterol. This is offering new insights into the treatment of disorders relating to cholesterol, including Alzheimer's disease.

Gravity and quantum states

The neutrons produced at the ILL are being used to probe some of the most fundamental questions in science: the nature of forces and matter; and the basic properties of the neutron itself.

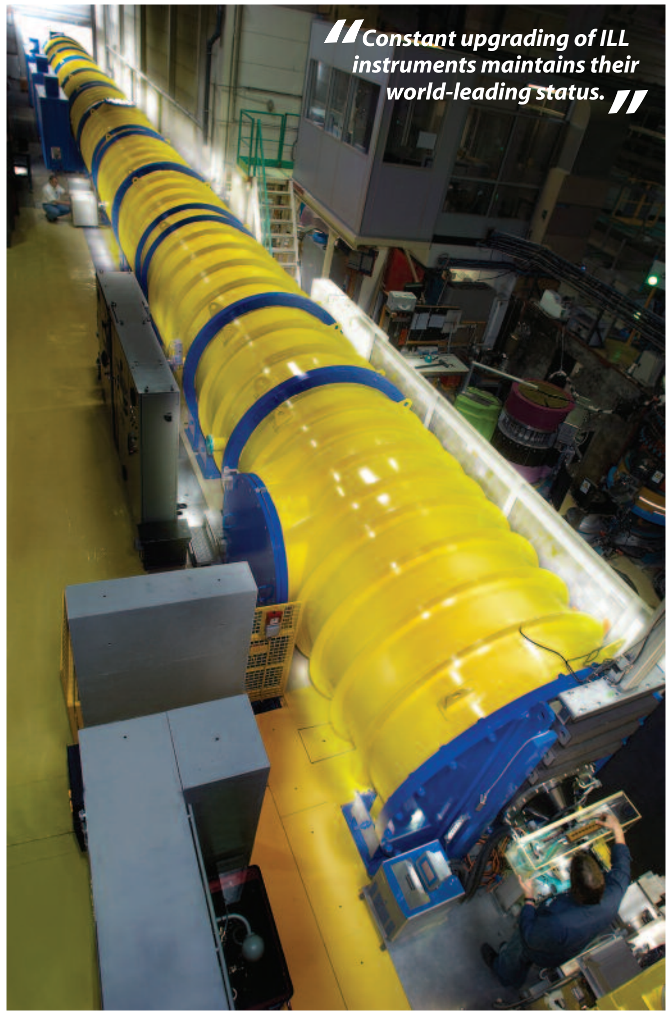
The whispering gallery effect: recent research at the ILL has shown that neutrons bounce around curved surfaces just as sound is transmitted over long distances in a whispering gallery. Ultra-sensitive measurements of the reflections of very cold neutrons off a very smooth, curved piece of silicon reveal that they exist in discreet, quantum states in relation to the surface.

This observation fits elegantly with an earlier ILL demonstration of what happens with neutrons travelling over the surface of a very smooth, flat mirror. They too adopt quantum states in the Earth's gravitational field, which are equivalent to the centrifugal states over the curved surface.

Historic experiments: highly precise neutron measurements at the ILL are exploring another fundamental question about the gravitational force: does the principle that gravity accelerates all objects equally, regardless of their mass, still hold at the atomic or sub-atomic scale?

Some of the most eye-catching experiments in history have confirmed this principle at the human scale, including those by Galileo at the leaning tower of Pisa and by Apollo astronaut Dave Scott, who dropped a hammer and a feather on the moon. At the atomic scale, the forces involved are far weaker and deviations from the 'classical' laws of gravity extremely challenging to measure.

An instrument devised at the ILL builds on the methods established to demonstrate that neutrons could adopt quantum gravitational states relative to the surface of a mirror. It will make it possible to measure very small deviations from 'Newtonian' gravity at the atomic scale. Such deviations could provide insights into the existence of 'dark matter' particles or the extra dimensions suggested by string theory.



"Constant upgrading of ILL instruments maintains their world-leading status."

CERN, the **European Organization for Nuclear Research**, operates the world's leading laboratory for particle physics. Its business is fundamental physics, finding out what the Universe is made of and how it works. Founded in 1954, CERN has become a prime example of international collaboration, with currently 20 Member States. Additional nations from around the globe also contribute to and participate in the research programmes. Its new flagship research facility, the Large Hadron Collider, is housed in a 27 kilometre tunnel and is the most powerful particle accelerator in the world. www.cern.ch

The **European Fusion Development Agreement** (EFDA), is the umbrella agreement of all fusion research laboratories in Europe. EFDA's shared experiment, in the UK – the Joint European Torus (JET), the world's largest tokamak fusion reactor – investigates the potential of fusion power as a safe, clean and virtually limitless energy source. JET paves the way for ITER, a project under construction in southern France, designed to be the first fusion reactor to release more energy than is needed to power it. www.jet.efda.org.

The **European Molecular Biology Laboratory** (EMBL) is the flagship of molecular life sciences in Europe. EMBL research ranges from the smallest units at the level of proteins and genes via cells and organisms up to structural biology operating beamlines. Researchers everywhere may use the databases developed and maintained by EMBL's European Bioinformatics Institute in the UK. In 2010, the EMBL Advanced Training Centre, a building in the form of a double helix, was inaugurated at EMBL's headquarters in Heidelberg. www.embl.org

The **European Space Agency** (ESA), in Paris, is Europe's gateway to space. Its mission is to shape the development of Europe's space capability and ensure that investment in space continues to deliver benefits to the citizens of Europe and the world. ESA leads research and applications programmes across a broad array of disciplines, including earth observation, human spaceflight, launchers, navigation, telecommunications and space science. ESA builds missions to explore the sun, the solar system and to observe the wider universe across the electromagnetic spectrum. www.esa.int

The **European Southern Observatory** (ESO), in Germany and Chile, is the foremost intergovernmental astronomy organisation in Europe and the world's most productive ground-based astronomical observatory. It carries out an ambitious programme focused on the design, construction and operation of powerful instruments, enabling astronomers to make important scientific discoveries. ESO operates three observing sites in Chile – La Silla, Paranal and Chajnantor – and is planning a 40-metre-class European Extremely Large Telescope, which will become 'the world's biggest eye on the sky'. www.eso.org

The **European Synchrotron Radiation Facility** (ESRF), in Grenoble, is Europe's most powerful synchrotron radiation source. Synchrotrons are stadium-sized machines producing laser-like beams of X-ray light. There are ten in Europe; and the ESRF is the world leader by users (12,500 scientists in 2009-12), scientific output (over 1,800 publications a year) and the reliability and quality of services. Forty specialised instrument stations serve fundamental and applied science, often linked to social challenges: advanced materials, sustainable energy, chemical processing, drugs and healthcare. Industrial research covers pharmaceuticals, petrochemicals and microelectronics. www.esrf.eu

The **European XFEL** (XFEL), in the Hamburg area, is an X-ray laser with unique characteristics, due to start operation in 2016. With 27,000 X-ray flashes per second and a very high brilliance, the facility will open up new research opportunities for a range of scientific fields, including medicine, pharmacy, biology, chemistry, physics, materials science and nanotechnology. Researchers will be able to investigate nanometre-scale structures, fast processes and extreme states, taking 3D images of viruses and proteins and filming chemical reactions. www.xfel.eu

The **Institut Laue-Langevin** (ILL), in Grenoble, operates the world's most intense neutron source. It provides a unique probe of the structure and dynamics of materials, and the fundamental properties of matter. Applications include exploring the properties of new materials for computing and information technology, measurement of stresses in mechanical materials and investigations of the behaviour of complex molecular assemblies. Recent research includes the world's first magnetic soap, developments in gamma-ray optics and potential treatments for Alzheimer's disease. www.ill.eu

"Research and innovation are central to building a strong and sustainable economy that benefits all citizens."