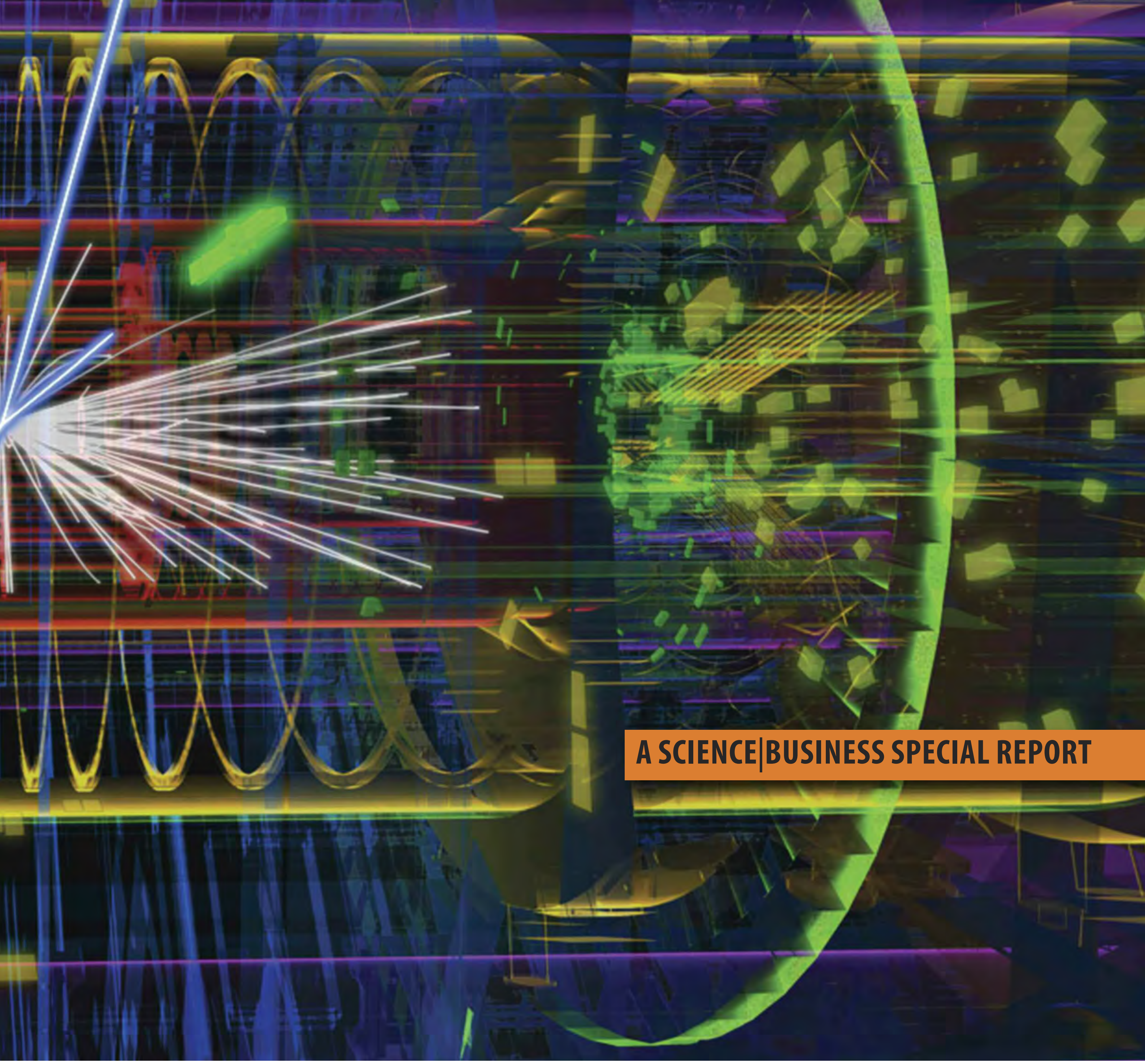
SCIENCE|BUSINESS

BIG SCIENCE: What's It Worth?

The world spends millions a year on telescopes, synchrotrons, colliders, DNA databases and other 'big science' projects. What does it get for that money?



A SCIENCE|BUSINESS SPECIAL REPORT

CERN

Aalto University

ESADE
Ramon Llull University

This special report is a Science|Business effort to address one of the abiding political disputes in research funding: How to get more economic and social value from EU investments in research and innovation? It was produced with the support of CERN, ESADE Business School and Aalto University. All three are members of the Science|Business Network of universities, companies and research organisations and agencies.

Cover image: CERN Atlas event with four muons

How to get value from science

What is an idea worth?

The answer, of course, depends on the idea. How much is it worth to society for someone to figure out how to inter-link documents on line? To devise a scanner that can image cancers under the skin? Or to stop chocolate from turning white when it's on the shelf too long?

From the mundane to the profound: These are all ideas that owe at least part of their development to big science projects: accelerators and detectors developed at CERN, for example, or telescopes and IT infrastructures in the service of science. In today's global scientific enterprise, such projects are magnets for smart people, leading to cutting-edge technologies and world-changing innovations.

In the political debates over these projects, however, it's often forgotten that such ideas do not happen in a vacuum. They are born of collaboration between basic research and applied science, between idea and innovation. Yet people often speak of basic and applied as if we have a choice. We do not. Basic and applied science form a virtuous circle, and we break it at our peril.

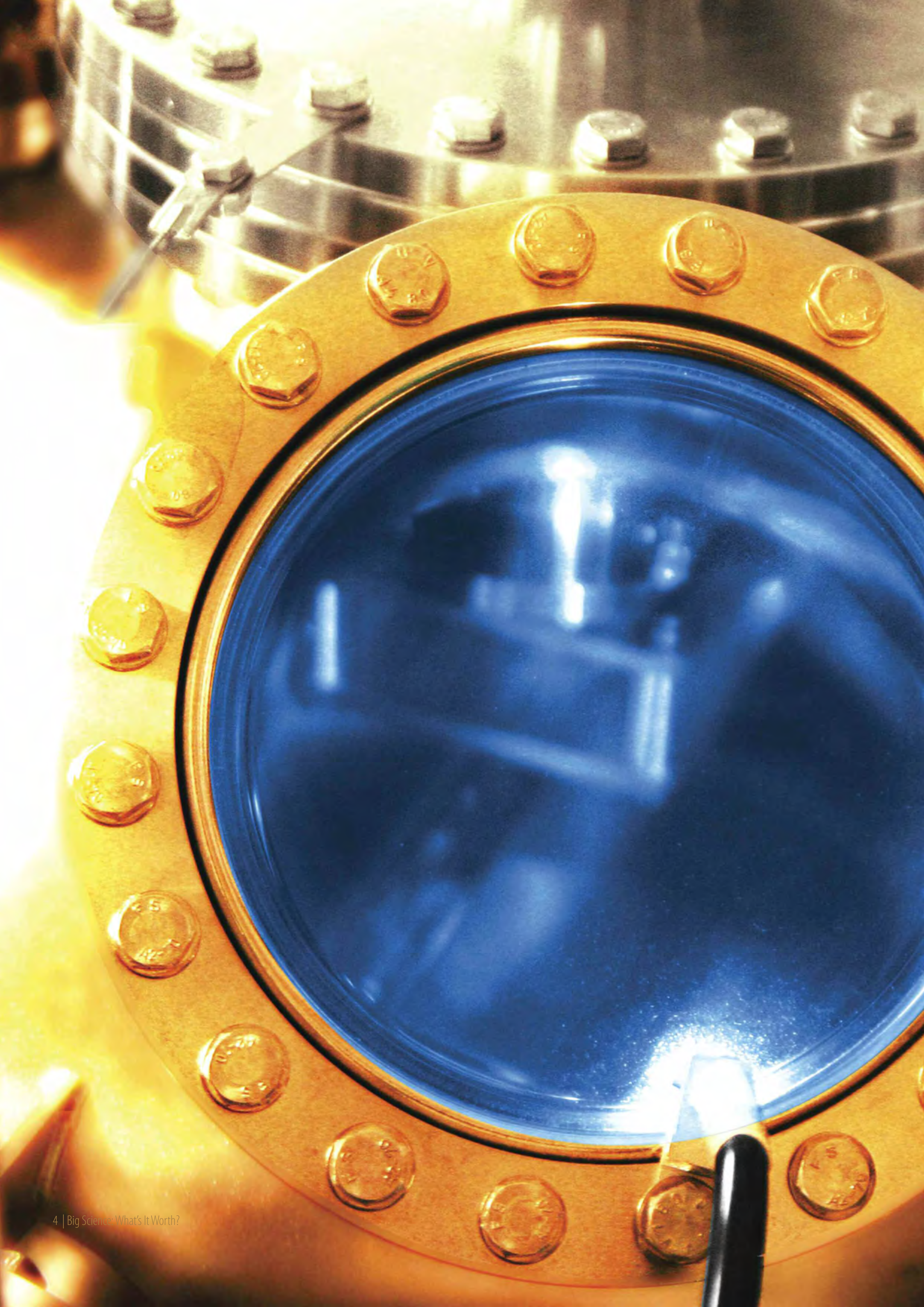
Take the example of electric lighting. A mere 150 years ago the candle was the main source of artificial light. By then, it had already been developed to a very sophisticated degree. But no amount of research on the candle would have given us the electric light bulb. For that, you need basic science to prepare the way.

But basic science alone would not have given us the light bulb. Scientific progress needs Edisons as well as Faradays. And when applied research finds utility in a discovery such as electricity, it not only improves society, but gives new tools back to the basic research endeavour: the virtuous circle.

At CERN, we are striving to keep the virtuous circle turning, and we do that by combining basic and applied, science and industry, ideas and capital. We have, for instance, invested great effort in the development of detector and imaging technologies. This is what permitted us to 'see' the Higgs Boson in 2012. Now, with a wide range of partners including ESADE Business School and Aalto University, we are turning to open innovation methods to further connect those technologies with the market, and to ensure our own future development.

If society is to get real value from its investment in research, it must encourage basic and applied research to work together. What's an idea worth? In this case, it's priceless.

Rolf Heuer
Director-General, CERN



EXECUTIVE SUMMARY

Knowledge is not cheap. The world spends more than $1 trillion a year on research and development, including basic research. The biggest projects—"research infrastructure" like particle accelerators and DNA databases—carry correspondingly big price tags. ITER, the experimental, international fusion reactor in the south of France, is taking years and more than €13 billion to build. The Square Kilometre Array, the world's biggest radio telescope now under development in South Africa and other southern countries, will cost well more than €1.5 billion.

It's all great science, no doubt. But is it a great investment?

That is the main question we pose in this special report. It is a timely question, as budget austerity has been forcing governments around the world since 2008 to weigh carefully the economic and social benefits of all their investments—from labs, to farms, to hospitals. In the crudest terms: Is a new synchrotron more important than a new highway?

Your answer depends a lot on your state of economic development and the relative importance of research and innovation in your economy and society. But, our comprehensive expert interviews and literature survey suggests, there is a simple answer: Yes, it's worth it. How much, in what sectors, under what circumstances and over what time span are more complex questions—on which there have been many studies and few agreed answers. But one way or another, a comprehensive accounting of inputs and outputs from research infrastructure suggests that they do have broad economic and social spin-outs—and concerted, well-organised efforts to amplify these spin-outs (for instance through special investment funds, training schemes, or public-private partnerships) can make the bet more certain.

Counting the benefits

This report gathers the available evidence on how big science can pay its way. It looks at the issue broadly—starting first with the benefits of basic research generally, and then with the additional benefits of big science projects that, because they concentrate expertise and effort, play a special role in innovation.

For basic science, the numbers vary wildly from one study to the other. A few examples:

Battelle Memorial Institute found that for every dollar of US federal investment in the Human Genome Project, $141 was generated in the economy as a result.

A George Washington University professor, Henry R. Hertzfeld, analysed a number of economic studies of NASA to find that estimated returns ranged between 20% and 14 to 1. "It is clear that no one measure is a comprehensive indicator of NASA impacts and benefits," he found.

The London-based Centre for Economics and Business Research estimated that in Europe physics-based industries account for €3.8 trillion in turnover, employ 15.4 million directly and, for every one of those, another 2.73 jobs elsewhere in the economy.

Experiment in a beamline ESRF, Grenoble

CERN, Geneva

STFC, Daresbury

So what has it done for you lately?

The evidence on big science builds on this kind of research, but tends to be more anecdotal, or localised to a specific project. For instance, technologists agree, many of our most important modern innovations had their seed, or got fertilised at a critical moment, at big science centres:

Capacitive touch screen—A key invention in 1973, introduced into CERN control systems in 1976, but now used on billions of smart phones and tablets world-wide.

Pharmaceuticals—Five of the top 20 drugs in use in the world today were developed using synchrotrons.

Scratch-resistant eyeglasses—Developed by NASA to provide scratch-proof coatings for astronauts' visors, most eyeglasses now feature it.

WiFi—The Fast Fourier Transformations technology at the core of most WiFi-equipped devices—whether computers, tablets, mobile phones or others—was based on technology developed by Australian astronomers to study radiation from black holes.

Hypertext Markup Language—The key idea that transformed the academic Internet into the commercial World Wide Web came from a CERN computer scientist trying to make it easier for physicists to interlink their documents.

There are many more: cochlear implants for hearing loss, the 'shears of life' to rescue car-accident victims, 'memory foam' for pillows and bedding, dental lasers, the foot and mouth disease vaccine, and more. Of course, how much of the value created in each case is due specifically to the originating lab is disputable; a complex cycle of innovation was required, involving many actors, private and public. But that there was a vital contribution from the lab—often the initiating idea—is beyond dispute.

How it works

But how does big science create its economic benefits? Specialists identify the following mechanisms:

Human development. Most scientists engaged in big science projects go on to forge careers in other areas, ranging from product development in industry to managing high finance. They take with them the knowledge, skills and contacts acquired in pursuing scientific goals leading to an

Aalto University

ESADE, Barcelona

injection of new ideas and a consequent massive boost in economic activity and efficiency. No study has yet quantified the overall impact, but an analysis in 2009 of 25,600 active companies founded by living MIT alumni, found that they employed 3.3 million people and generated annual revenues of nearly $2 trillion. If it were its own nation, MIT would have been the 11th-largest economy in the world.

Innovation. Big Science requires the development of new technologies. Perhaps the most notable example of this is the World Wide Web, with a key technical step towards it occurring at CERN. But there are many other examples ranging from the lasers in bar code scanners and compact disc players to the big data techniques used to sort through the massive amounts of information produced by scientific instruments.

Improving industry. The Big Science facilities themselves can offer services directly to industry. Laser light sources developed for condensed-matter physics, for example, have found a major application in the pharmaceutical industry where they play a vital role in developing new drugs.

Knowledge hubs. Big Science draws knowledge- and technology-based businesses, creating centres of expertise and excellence.

Entrepreneurs. Research Infrastructure create spin-offs. Almost every big facility spawns its own community of start-ups.

Inspiration. Big Science inspires. It can raise a host nation's international image and self-esteem, encouraging a country to compete in the global knowledge economy, so raising living standards for all.

Local economy. At the other end of the scale, there are also local benefits, ranging from contracting local suppliers to build and manage complexes and injecting spending power into the area immediately surrounding a facility to improving local schools and inspiring local children to learn about science.

The policy prescription

So big science matters. But for policy makers, the key question is how to make it matter even more? How to maximise the economic and social benefit, without loss of scientific integrity?

On 5 March 2014, Science|Business gathered some of Europe's most important experts on

Lawrence Berkeley National Lab

Imperial College Business School

research infrastructure to explore the answers. Five recommendations emerged:

- **Broaden the debate, so the policy decisions taken when shaping new projects factor in broader economic and social needs. We must enlarge the contact between research infrastructures and society.**

- **Study what works and how, and explain it better. Economists have yet to devise good, consistent ways to measure the impact of spin-outs from research; that should be a priority, that can help guide policy. We need to tell the story, and tell it very well.**

- **Open the innovation process at the labs. More contact—with industry, entrepreneurs, investors and other value-creators is needed to turn more ideas faster to good use. For instance, CERN, ESADE Business School in Barcelona, and Aalto University in Helsinki, are developing a new initiative to open detector and imaging technologies used at CERN to entrepreneurs and businesses, to stimulate new services and products. We need to develop a porous system between science and commercial exploitation. And we need to create a place where this kind of thing can happen.**

- **Focus on people and training. The greatest benefits of big science are in human resources. Smart people, gathered together, do surprising things—including training other smart people who can go on to do other surprising things, in industry, finance, services and policy.**

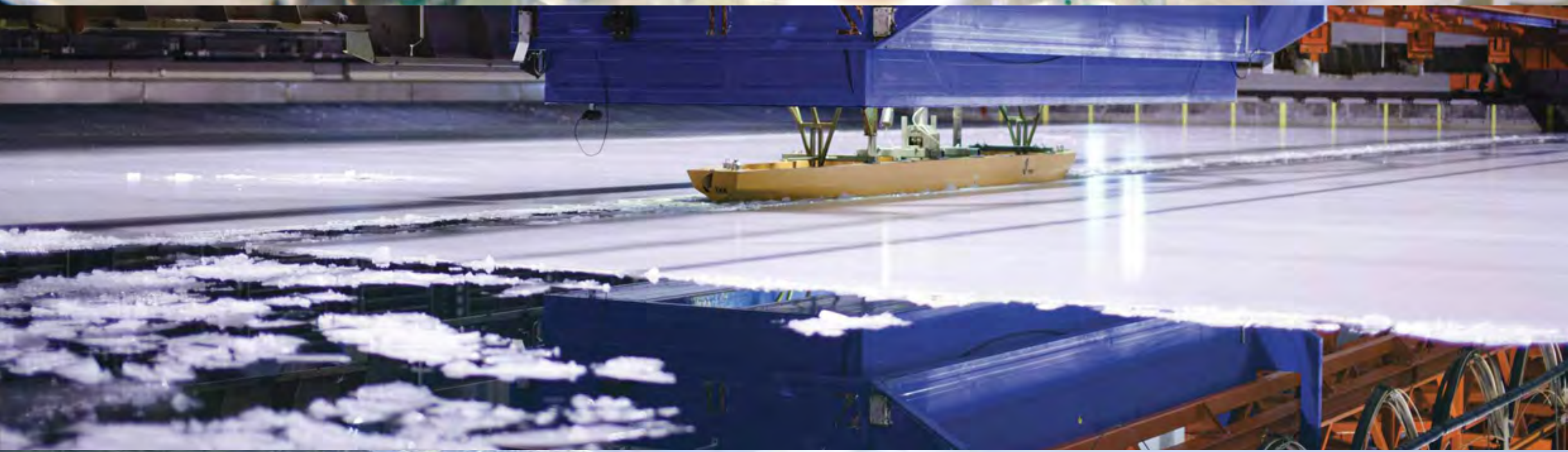
- **Bridge the cultural gap between science and industry, through original public-private projects, programmes and policies. Different communities have different sociologies. Venture capitalists don't care about prestige; scientists care a lot about prestige. This is where governments or governance are important.**

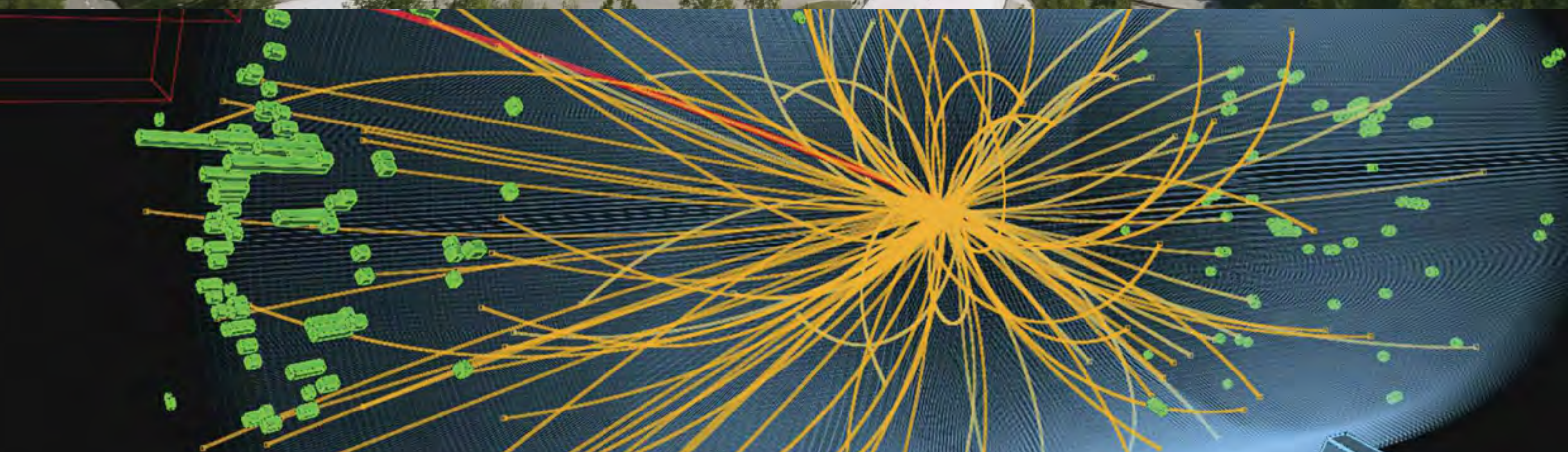
Of course, all this begs a broader question: Should we take economic impact into consideration when deciding whether to fund research infrastructure?

The consensus among most researchers is: No, but. You either back pure science or you don't back it. But you need to be aware of the economic value and the fact that you are competing for public funds with many other needs. And politicians must be aware of the benefits they forego if they don't fund it.

Science might be expensive. But ignoring it will prove to be much more expensive.

Micro and Nanotechnology Centre, cleanrooms at STFC's Rutherford Appleton Laboratory (right)

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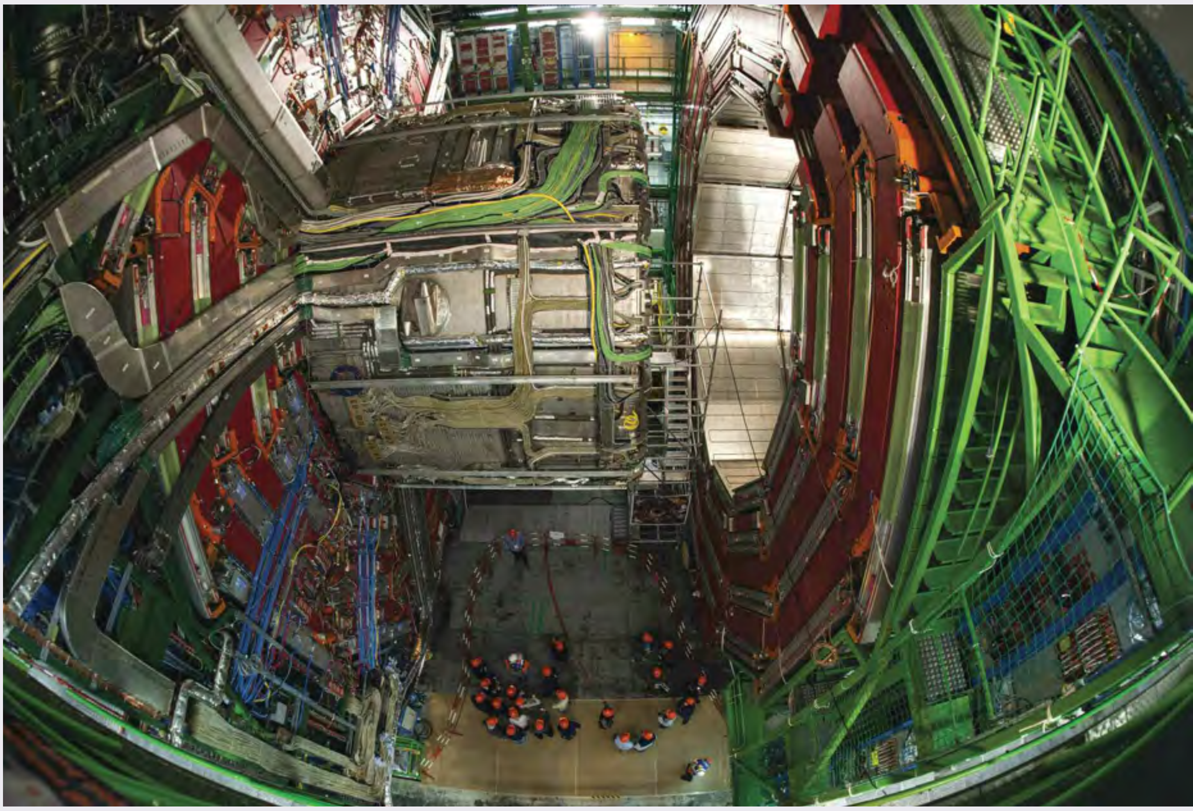


(Left top to bottom) Biotechnology and Chemical Technology Experiments at Aalto School of Chemical Technology; Experiments on level ice loading on an icebreaking tanker, Department of Applied Mechanics Aalto School of Engineering; ESRF, Grenoble; Collision events recorded with the CMS detector, CERN; ESO, Antennas of the Atacama Array (ALMA)

CMS detector, CERN (right)

How does big science produce economic value?

Whether antibiotics, the transistor, nuclear power or the lithium battery, there is virtually no new major economic activity that does not start with a scientific discovery. But it is the nature of discovery that when you embark on your voyage, you never quite know where you are going to end up.

This is what Carlo Rizzuto, Director General of the Trieste Synchrotron and former Chairman of the European Strategy Forum on Research Infrastructures (ESFRI), calls the serendipity of discovery. And this is what makes it so difficult to assess ahead of time from an economic point of view.

To make matters worse, the financing of big science—the €500 million plus endeavours requiring very large scale research infrastructures—inevitably falls on the public purse. It is simply too expensive for the private sector.

"The economic returns of research are so long-range that they show up as a loss on the books of private industry," says Rizzuto. But as it happens, he adds, industry most often is less interested in the final result than what is learned along the way.

Sport, war and science require a lot of technology development, continues Rizzuto. "Skis are continuously improved so skiers can break records. That generates economic value. And war, as awful as it is, has probably generated huge economic value through the development of new weapons technologies that go on to find more peaceful applications. As with sport and war, science also creates economic value, not as a goal but as a byproduct."

Research, development and innovation are three different things that often get confused, says Rizzuto. "Research is the production of new knowledge. Development uses existing knowledge to solve existing problems. It creates new inventions as assessed by the industry concerned. Innovation allows an activity to become more competitive, and its success is determined by the market."

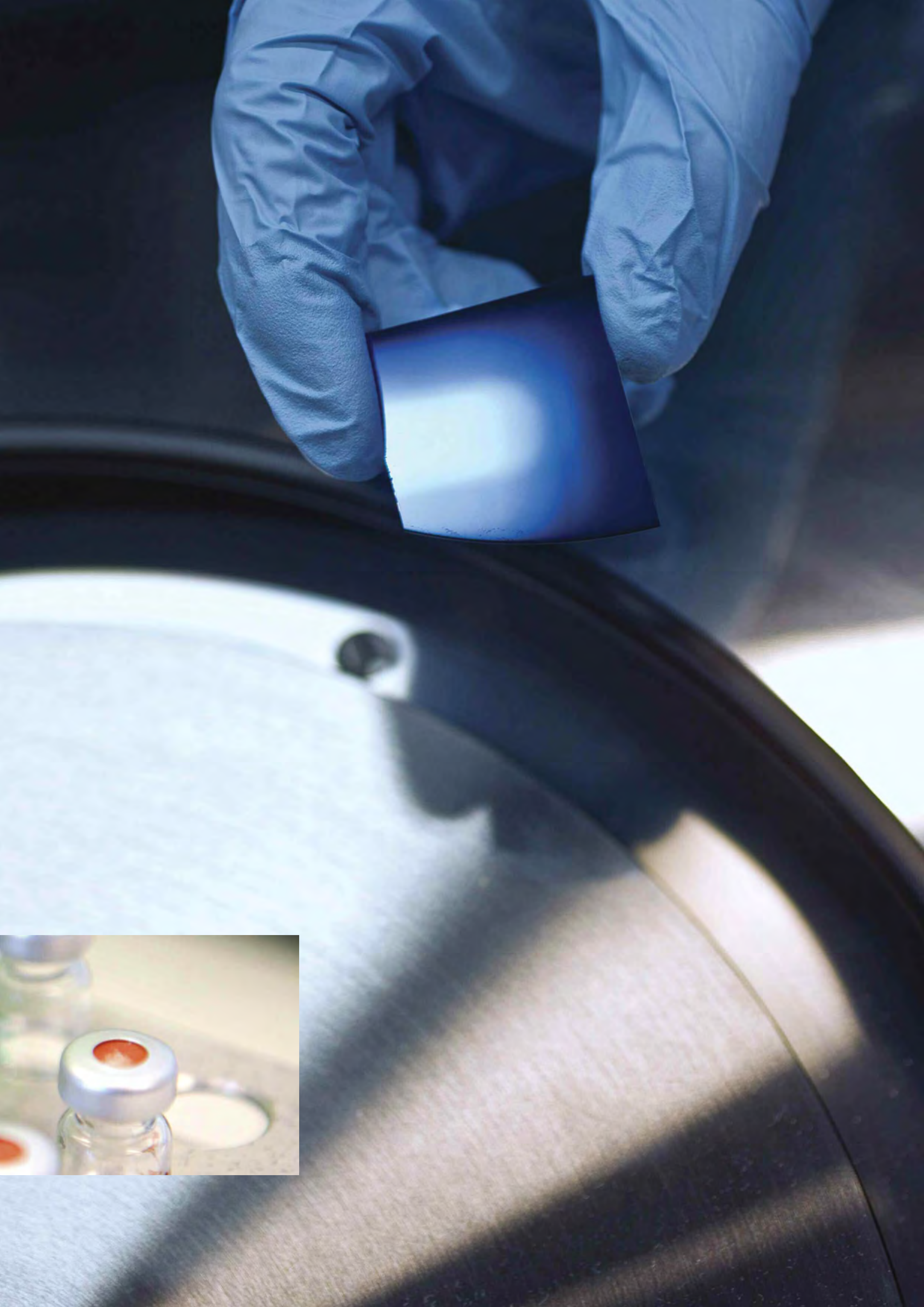
In real life, however, researchers spend less than 10% of their time producing knowledge, says Rizzuto. "The rest of the time is spent perfecting developments that facilitate the research, and innovating so that they are ahead of rivals. Researchers actually make very good developers and innovators but this usually goes unrecognised, especially in Europe where research is still largely measured by the final product."

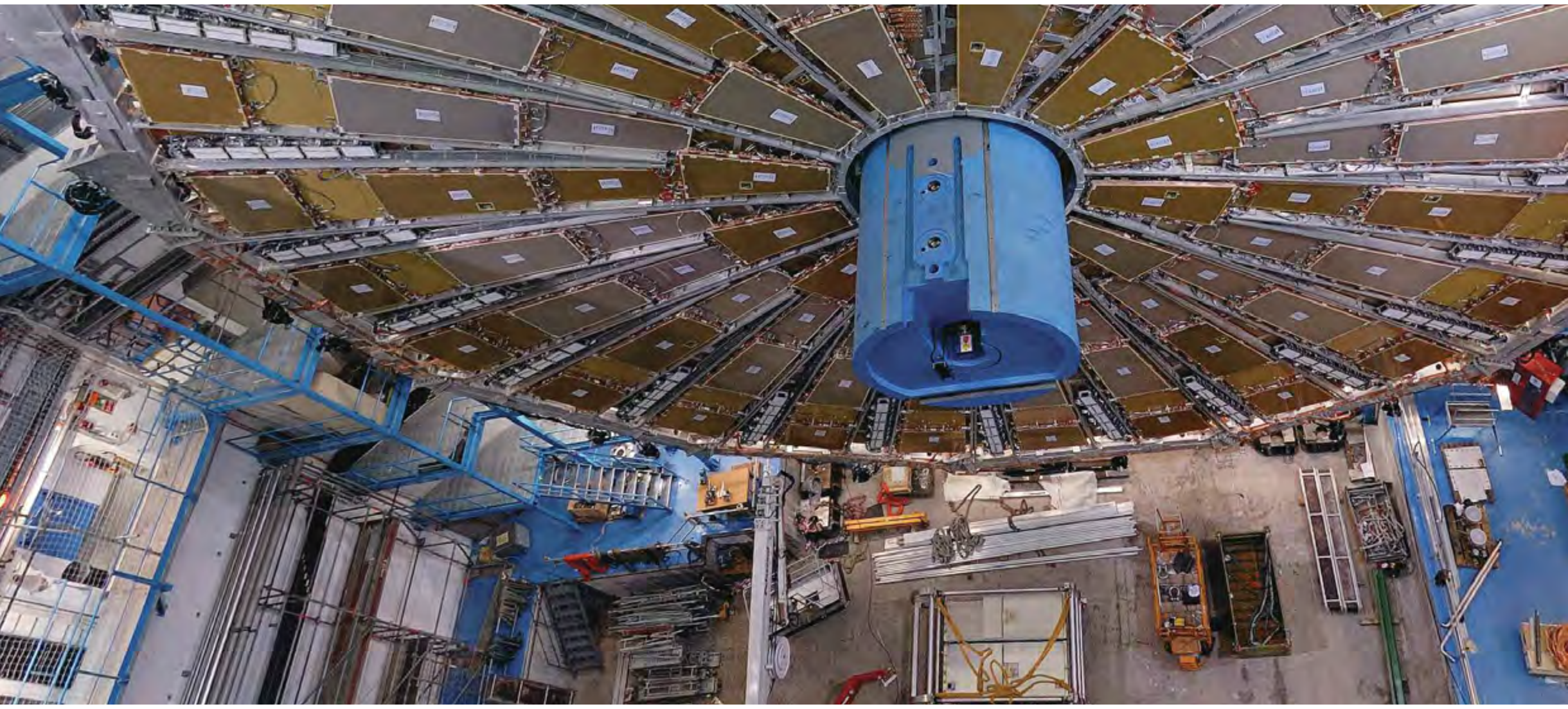
"In the US, where ties between academic research and industry are stronger, they can appreciate

Biotechnology and Chemical Technology Experiments, Aalto School of Chemical Technology

"Research is the production of new knowledge. Development uses existing knowledge to solve existing problems."

CARLO RIZZUTO





more the development and innovation value of research, and people trained in research go more often into industry rather than continue in academia as in Europe—where they may even see a move into industry as a failure. But once in industry, our US colleagues retain their contacts in academia."

It is this circulation of trained people that may in fact turn out to be one of big science's biggest benefits, says John Wood, Secretary-General of the London-based Association of Commonwealth Universities (ACU) and Rizzuto's predecessor at ESFRI.

"Some years ago MIT did an analysis and it showed that their alumni contributed most to the economy of America—not their inventions or anything else," he says.

The report, titled "Entrepreneurial Impact: The Role of MIT" and published in 2009 by the Kauffman Foundation[1], found that at the end of 2006, there were 25,600 active companies founded by living MIT alumni, employing 3.3 million people and generating annual world revenues of nearly $2 trillion. This group of companies, if it were its own nation, would be the 11th-largest economy in the world.

Big science has a similar impact, he says. As well as unraveling the mysteries of matter and time, "the big thing that big science projects such as CERN provides is the added value to people," says Wood.

"Not only do they train a lot of people—physicists, systems and electronics engineers and computing people—but the real value is that they are working in multidisciplinary teams and they learn about project management and they learn about international negotiation. And the fact that they understand complex systems is really important.

"A lot of people go on from CERN to take leadership roles in big businesses," he says.

In the 1990s Wood ran the UK's prestigious Rutherford-Appleton and Daresbury Laboratories.

"We were as much a training organisation as a science one," says Wood. "Look at the companies around Rutherford and you will see how this is true." He names Formula One Williams, Oxford Instruments, Oxford Magnetics and Bookham Technologies. "All were based on technologies from people who had trained at the Rutherford at some point or other."

There is a natural link between science and industry, agrees Raymond Orbach, Under Secretary for Science at the US Department of Energy, 2006-2009. It is a symbiotic relationship.

"When you do basic research, not to couple it to applications and industry is crazy. It's a two-way street. You learn from applications and industry needs, where the opportunities are. Anyway, where

"It is this circulation of trained people that may in fact turn out to be one of big science's biggest benefits"

JOHN WOOD
Secretary-General of the London-based Association of Commonwealth Universities

Installation of the first of the big wheels of the ATLAS muon spectrometer, CERN

does basic stop and applied begin? It's useless to separate the two. They feed off one another.

"Light sources, for example, were created for condensed-matter physics," says Orbach, "but it turned out that their major use is in the biology community and the pharmaceutical industry." And they now help finance the research facilities which are still being used by the physicists.

Another way in which a big science research facility provides economic impact is in the effect it has on a local community.

The Square Kilometre Array (SKA) will be the world's biggest science project by area covered, as well as one of its most ambitious. It is due to be fully up and running in the course of the next decade and is being hosted in three countries, with telescopes in Australia and South Africa and headquarters in the UK.

The national and local economies in all three countries will draw advantages from their involvement with SKA, says Philip Diamond, Director General of the SKA Organisation in Macclesfield, UK.

"The UK profits from the prestige and financial benefits of hosting an international organisation—the local taxi company alone has had to hire three more people because of us; local hotels and restaurants have benefited from our visitors; and those of us that work at the headquarters spend the bulk of our salaries in the area," he says.

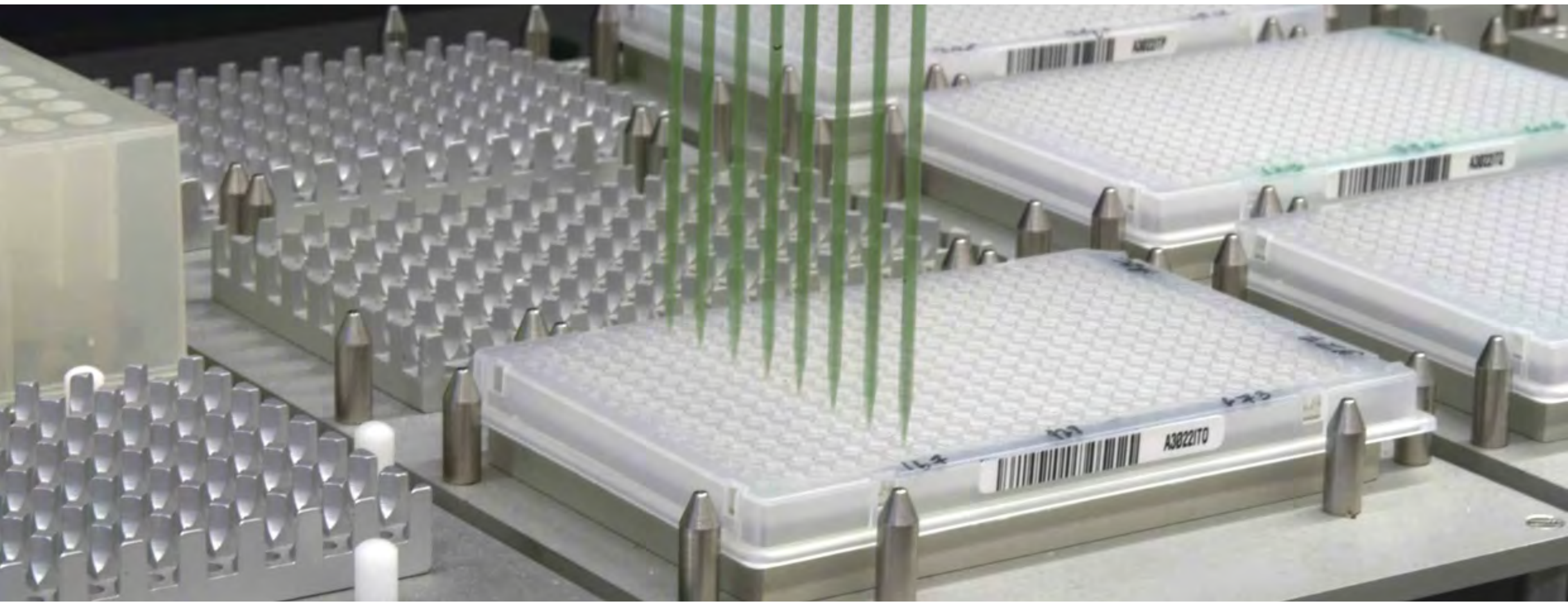
"In Australia and South Africa, there will be salaries and other spending related to operations, but there also be payrolls of local suppliers to support from engineering companies maintaining the facilities, through the security firms guarding it, cleaners and caterers to the local hoteliers and taxi companies catering for visitors to the facilities."

The benefits stretch beyond money, says Diamond.

"The South Africans have a very interesting human capital development programme which provides bursaries to South African and even other African students interested in science and engineering. It includes as many people as possible from the Northern Cape province where the schools have tended to have been not that good."

Chip maker Intel, one of the technology companies involved with SKA, has launched several projects to propel the surrounding communities into the information age, supplying computers,

Automated DNA sequencing at the National Human Genome Research Institute



educational materials, teacher training and Internet access to the Carnarvon community centre and five schools in the three towns closest to the main SKA site—Carnarvon, Williston and Van Wyksvlei.

Adrian Tiplady, who worked on South Africa's pitch to co-host SKA as the Bid Manager and remains involved as the project moves into its implementation, points to another major, if less tangible benefit: The transformation of South Africa in the eyes of the global community "from a country in Africa to a country that can compete in the global knowledge economy and which can develop its own technology."

"This is not just important to the country's scientific community or its government but to the man on the street, not just in South Africa but on the whole continent," says Tiplady, "as we make our way in the global knowledge economy."

"The siting of a big science project could keep an important industrial partner in a country or area," says the ACU's Wood. How do you value that?

Another major area of impact from big science is in information and communication technologies such as computing. "Some see computing as the third pillar of scientific discovery, alongside experiment and theory," says former US Under Secretary Orbach.

"These high end computers that are the size of a building, use megawatts of power and cost many millions of dollars to build, allow scientists to model and simulate experiments that could never be performed in a laboratory. These include understanding combustion processes, modelling fusion reactions, analysing climate change data, revealing the chemical mechanisms of catalysts and studying the collapse of a supernova, among scores of other applications."

And that benefits industry.

"When I was at the Department of Energy we built one of these things and gave industry free time on the computer," says Orbach.

"This gave US industry a competitive edge by allowing it to perform virtual prototyping of complex systems and products, substantially reducing development costs and shortening time to market.

"Aircraft company Boeing, for example, was able to reduce the amount of wind tunnel tests from eleven to four. And aircraft engine maker Pratt & Whitney's new jet engines use designs for combustion that were done on the computer.

"These are very difficult problems and require very high sophistication. No industry on its own can afford to build one of these things and operate it on its own. And science benefits because of the impact increasingly sophisticated industry problems have on developing computing capabilities."

"We can expect great benefits from applying computing and data handling techniques pioneered in particle physics and astronomy to science areas which have not had their benefit in the past, such as biomedical research"

JOHN WOMERSLEY
Chief Executive of the UK's Science and Technology Facilities Council

Computing

Some science projects almost turn into computing projects, says John Womersley, Chief Executive of the UK's Science and Technology Facilities Council (STFC).

ELIXIR, coordinated from Cambridge, is a bioinformatics infrastructure applying big data and computing to biological and medical work. It brings together bioinformatic centres across Europe into a unified shared data arrangement allowing much-better-informed research to be carried out.

"Increasingly, it's not the physical facility that is the source of the innovation but the data that the facility produces," says Wormersley.

"We can expect great benefits from applying computing and data handling techniques pioneered in particle physics and astronomy to science areas which have not had their benefit in the past, such as biomedical research.

Elixir farmer

"For example, there is an idea about simulating an entire organism—all the way from understanding the genetic code of a single cell to how the entire organism is put together."

And this kind of pioneering work in big data will provide benefits beyond science, stresses Womersley.

"There are lots of areas where these kinds of computing and big data techniques can be applied commercially to give companies competitive advantage, and as they become more affordable, as the techniques become more easily applicable and as the people who have been trained in using them realise their value, we can expect them to pervade the economy.

"Lloyds of London, for example, are interested in improving their understanding of the risks of major climate events and want to be able to connect better weather forecasting techniques and flood management and monitoring techniques with information about property values, and to be able to simulate using high performance computing the hundred thousand ways in which 2015 could turn out to make sure that they are appropriately covered and reinsured against the risk."

In their seminal work on the topic, "The Relationship Between Publicly Funded Basic Research and Economic Performance" [2] published in 1996, Ben Martin and Ammon Salter saw the benefits of basic research as:

> Increasing the stock of information, the development of new instrumentation and methodologies, the creation of skilled graduates and of professional networks, the solving of complex technological problems and the creation of new firms.

All these benefits can also be attributed to big science, but on a correspondingly bigger scale. The interviews conducted for this report suggest that we can also add the value of contracts awarded to suppliers, spill-over effects on education beyond actual participants in the research, encouraging inward investment and contributions to a country's or region's prestige.

In her 2010 report "New Light on Science—The Social & Economic Impact of the Daresbury Synchrotron Radiation Source, (1981-2008)," [3] Claire Dougan-McCaillie, Head of Impact Evaluation at the STFC, also identifies the creation of new knowledge outside of the intended field of research, improving the performance of industry, and helping to communicate the importance of science to a broader audience as major benefits.

And then there is something bigger, broader and harder to describe:

When the ACU's Wood, recently took 24 investment bankers to CERN and showed them of all places, the busy cafeteria, they all said they were convinced this is a good investment. "We need ',people colliders,' critical mass of intellect and passion," says Wood.

Over 10,000 men and women from all parts of the globe have worked on CERN's Large Hadron Collider zone over the years. And Atlas has 3,000 PhD students. "At CERN, the people collider is not just technical—not just about writing formulae. It's about growth of ideas, development of trust and a common language," says Sergio Bertolucci, CERN's director of research. It's about inspiration to achieve what was once thought unthinkable, and move humanity along on every level.

Examples of research infrastructures and their scientific, technology and societal impacts

RESEARCH INFRASTRUCTURE	WHAT IS IT?	SCIENTIFIC IMPACT
CERN, Geneva	Particle accelerator and other high energy physics infrastructure—using some of the world's most advanced equipment to study the tiniest particles in the universe.	Discovery of subatomic particles including the W and Z bosons in 1983 and the Higgs in 2012, confirming the Standard Model of what the universe is made of. Contributed to at least two Nobel Prizes.
Diamond, Harwell	Third generation synchrotron producing beams of light 10,000 times brighter than the sun allowing scientists to deduce the structure of complex molecules and study the makeup of materials.	Over 1,000 papers published a year in the field of life, physical and environmental sciences. Over 500 protein structures solved and deposited in the Protein Data Bank.
EMBL, multi-site	European Molecular Biology Laboratory—Europe's flagship laboratory for the life sciences seeking fundamental understanding of basic biological processes in model organisms.	Some 200 scholarly papers produced a year. Contributed to at least one Nobel Prize including one for the first systematic genetic analysis of embryonic development in the fruit fly.
ESO, multisite	The European Southern Observatory, a 15-nation intergovernmental research organisation which lays claim to be the world's most productive astronomical observatory. One of its projects is the Very Large Telescope or VLT in Antofagasta, Chile.	The VLT alone produces at least one peer reviewed paper a day. Firsts include observation of stars orbiting the black hole in the Milky Way, the accelerating universe, imaging the first planet outside of our solar system and measuring the age of the oldest known star in the Milky Way.
ESRF, Grenoble	European Synchrotron Radiation Facility. A collaboration between 20 countries, it is the most powerful synchrotron radiation source in Europe.	Every year at least 6,000 scientists use the facility. Among synchrotrons worldwide, ESRF has the most external users and refereed publications. Contributed to at least two Nobel Prizes.
Human Genome Project	World's largest collaborative biological project seeking to identify and map all of the genes of the human genome.	The project was declared completed in 2003, some 20,500 genes and 3.3 billion DNA base-pairs having been identified and sequenced, opening new avenues for advances in medicine and biotechnology.
Lawrence Berkeley National Lab	Centre for physics research addressing the world's most urgent scientific challenges by advancing sustainable energy, protecting human health, creating new materials and revealing the origin and fate of the universe Observation of the antiproton, discovery of several transuranic	elements, and of the accelerating universe and dark energy. The Lab has been associated with 13 Nobel Prizes.
Square Kilometre Array, multi-site	Radio telescope 50 times larger than any in existence.	Goal is to discover the nature of the first stars in the Universe, the cosmic history of the Universe, the nature of dark matter and dark energy, theories of gravity and black holes and the origin of cosmic magnetism.
SRS, Daresbury	World's first second generation synchrotron—ceased operations in 2008 after 28 years of operation and two million hours of science but it impact will be felt for years to come.	5,000 papers published and 1,200 protein structures deposited in the worldwide Protein Data Bank. Two Nobel Prizes.

TECHNOLOGY IMPACT	SOCIETAL IMPACT	RESEARCH INFRASTRUCTURE
Hypertext Markup Language that enabled the WWW. Capacitative touch screen. Grid computing. Advancement of detectors, accelerators, and magnets used in many fields including medical imaging and treatments. And much more.	WWW alone produces $4 trillion annual economic activity—if it were a country it would be the world's fifth largest. Leader in design and coordination of physicists, engineers, biologists and physicians for revolutionary hadron-based cancer therapy. Pioneer of big data.	CERN, Geneva
Method for discovery of hidden content in ancient documents. Decoding of complex structure of histamine receptors.	New drugs and therapies from side-effect free allergy treatments to training T- cells to attack cancer. Safer flying thanks to better insights into materials. Training platform for researchers. About a fifth of all operating time devoted to industry.	Diamond, Harwell
Instrumentation for DNA sequencing, cell fractionation, light and electron microscopy methods, mass spectrometry of proteins, X-ray imaging plates, synchrotron beam-lines and automated cell micro injectors. An area of prolific current activity is in the development of software and databases for the life sciences.	New medicines for a range of ailments including cystic fibrosis, insights into conditions and diseases such as autism and cancer, information management techniques that can be applied to many areas within and beyond science.	EMBL, multi-site
Pioneer of active and adaptive optics as well as interferometry, all of which have found applications beyond astronomy including medical imaging and military.	ESO offers numerous possibilities for technology spin-offs and transfer, together with high technology contract opportunities and is a dramatic showcase for European industry.	ESO, multisite
X-ray optics, sample handling and sample environment, detectors and electronics and data analysis and other software developments at ESRF are now in use beyond the organisation, including in other synchrotrons around the globe.	Applications across the oil industry including exploration, reservoir engineering, drilling, pipelines, refining and CO2 sequestration are allowing us to make significant advances in making the most of dwindling reserves. Magneto-electronics may enable the next generation of computer memory and even computer processing.	ESRF, Grenoble
Tests to show dispositions for diseases. More specific treatments.	As well as providing the basis for advances in human medicine, agriculture, energy, and environment, it is suggested that the $3.8 billion investment in the project drove $796 billion in economic impact, personal income exceeding $244 billion and 3.8 million job-years of employment.	Human Genome Project
Antimalaria and anti-AIDS drugs; a cooking stove which uses one-quarter of the firewood of traditional stoves; electronic ballasts for more efficient lighting; a do-it-yourself home energy audit tool; a pocket-sized DNA sample; smart windows with embedded electrodes that enable window glass to respond to changes in sunlight; and much more.	Economic impact on the US per year assessed at $3.2 billion if the effect of the 30 or so startups it has spawned is taken into account. $1.6 billion without.	Lawrence Berkeley National Lab
SKA will be powered entirely by regenerative energy and apply data processing approaches of the next generation, all of which has to be developed for the project but will have benefits far beyond.	The benefits in terms of innovation, capacity and capability enhancement, and indirect societal impacts, particularly but not only in the countries where the array is sited, are expected to be significant and important.	Square Kilometre Array, multi-site
Pioneered protein crystallography unmasking multitude of processes that take place within living organisms at a molecular level.	Medicines in areas such as host-graft rejection and HIV/AIDS. Key to developing a Foot & Mouth vaccine potentially saving hundreds of millions of euros and understanding species-hopping Avian Flu. Denser electronic memories for portable devices. Build costs alone contributed £992 million to the economy of North West England.	SRS, Daresbury

Big science: The human factor

Three profiles of how research infrastructure can train and nurture leaders—who go on to new and unpredictable fields.

Understanding complexity

CHRIS COUYOUMTZELIS, Investment Advisor Private Banking, Julius Baer, Geneva, and former research physicist at CERN.

Chris Couyoumtzelis had already worked at Fermi in Chicago when he came to CERN in1995 to complete his PhD. At CERN, his work centred around creating a small chip that would be used in the tracker for ATLAS, one of the big detector experiments deep in the underground collider ring.

It was not only a unique educational experience but a great personal development one, says Couyoumtzelis. "It taught me independence, how to teach myself, work long hours and manage a complex project. All things that I have found invaluable as a banker."

After he left CERN, Couyoumtzelis's first job in banking was with Banque Privée Edmond de Rothschild in Geneva in 2000 where he was advising relationship managers about bonds. "I had to teach myself about finance, so the ability to teach myself which I picked up at CERN was very important."

"I had to teach myself about finance, so the ability to teach myself which I picked up at CERN was very important."

Couyoumtzelis was able to put skills he had developed at CERN with spreadsheets and the Internet to use to create tools for relationship managers. "It was my idea. I had to take it from scratch and see it all the way through to the end, including selling the idea to the bank's board along the way. This is something a physicist has to do all the time: present and persuade."

"I also got to use all my analytical skills and experience of working with engineers and knowing what was really possible."

The next challenge was to put in place the bank's structured products desk.

"There are a lot of maths involved when you are working with structured products," says Couyoumtzelis. "I had to start with a blank sheet again, and teach myself. My physics background gave me the tools. The bank knew this would allow me to truly appreciate the risks involved. CERN also taught me about managing risk and taking decisions."

Couyoumtzelis is now an investment advisor for private clients at Julius Baer. This too is about people and presentations and analysis and understanding complex problems with different inputs of different patterns. "All experience I gained at CERN."

An inquiring mind

RICHARD WARD, research scientist became chief executive at Lloyds of London.

"As a scientist you have to be willing to continuously challenge and question what you are doing, and look for ways of doing it better. This, to my mind, is also what business should be about."

"The inquisitive, enquiring mind that I formed as a scientist has served me well in my business career," says Richard Ward. "As a scientist you have to be willing to continuously challenge and question what you are doing, and look for ways of doing it better. This, to my mind, is also what business should be about."

Before turning to the world of finance, Ward was a research chemist *cum* physicist exploring the potential of thin films using the spallation neutron source at the Rutherford Appleton Laboratory, and publishing some 70 papers between 1982 and 1988.

Ward went into industry in 1988, first as a research scientist—looking at the effects of processes to turn gas into petrol at BP—but in 1991, the energy company put him on their leadership development programme. As a result he became a derivatives trader and marketer in oil trading.

The move from science to industry was a jump, says Ward, but the move from research to the trading desk "was the really big jump of my career. I had to start from scratch. Go back to basics. I was put in the deep end and left to sink or swim. I had to figure it all out for myself."

"So I asked, why are we doing this. I broke the complexity of it all down. That's what got me through.

After a short spell as a commodities broker, in 1995 Ward joined the International Petroleum Exchange. He ended up chief executive at IPE, the successor company of which, IntercontinentalExchange, today owns the New York Stock Exchange, the world's largest stock market.

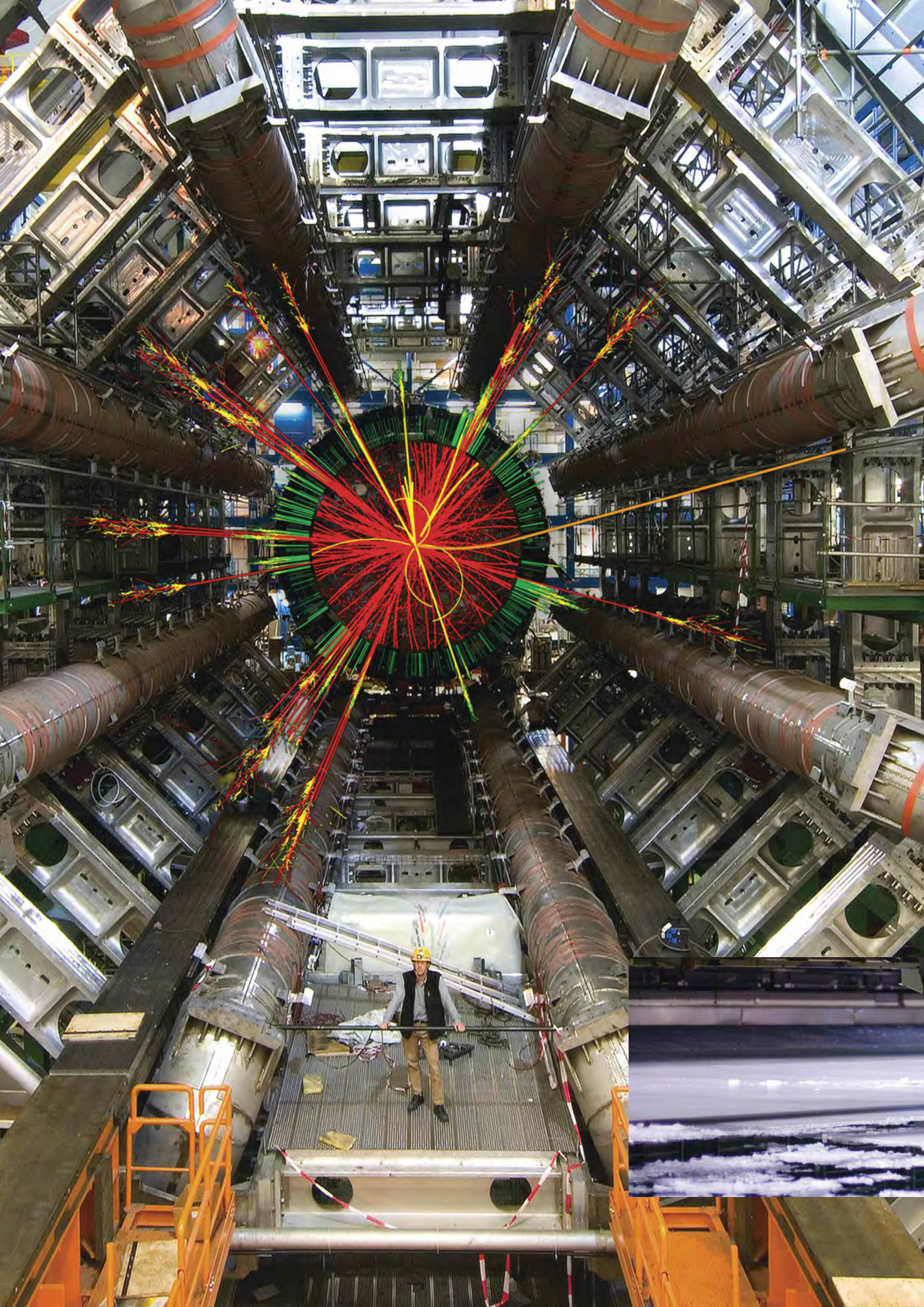
Next step was Lloyds in 2006.

Everybody expected him to automate it all, as he had at IPE. But after spending six months learning everything, understanding and analysing the problem, he decided replacing the trading floor with with screens would not have been right. So Ward left it much the same as it was.

Ward says science gave him "a lot of self confidence."

"As a scientist you have to deal with people from all walks of life. You can't fire, you can't hire and you can't determine remuneration but somehow you have to get the collective to work together to achieve a favourable outcome.

"That is great experience. It encourages you to get on with people and work out what makes them tick. And I have applied that experience in the business world."



How Can the Value of Big Science be Quantified?

Intuitively, we all know the value of science. But putting a price tag on it has proved exceedingly difficult. For big science, the difficulty is, well, equally big.

Part of the challenge lies in big science itself. Part lies in the science of economics. The impacts of big science are as vast, varied and largely as unexplored as the scientific themes themselves. And the interest shown by economists in measuring these impacts was until relatively recently, negligible.

This may be changing.

"Ten years ago almost any economist you met would have said there was no economic benefit from research, says Carlo Rizzuto, Director General of the Trieste Synchrotron and former Chairman of the European Strategy Forum on Research Infrastructures (ESFRI). "That has changed. Most can now see the link."

The reason is the closer scrutiny of public finances. Tax payers are not as willing to trust governments to spend their money wisely as, for example, in the decades immediate following World War II. And, technology—with its intimate relationship to science—is increasingly being recognised as a highly effective means to both produce economic growth—and through that jobs, wealth and affluence for the electorate—and boost economic efficiency, making regions and nations more competitive in the global economy.

Annual research and development spending world-wide is running at around $1.6 trillion according to research[4] by the Battelle Memorial Institute in collaboration with R&D Magazine, or put another way takes up around 2% of the world's gross domestic product. The vast majority is spent by the private sector, with, for example, the US government projected to provide just $123 billion of the $465 billion (or 2.9% of GDP) expected to be injected into research in the US in 2014.

The Lisbon Strategy, the EU's 1990 blueprint for growth, set an objective of devoting 3% of its GDP to research and development activities by 2010. The target was not reached—but the 3% ambition has been maintained, forming one of five key targets within the EU's current strategy.

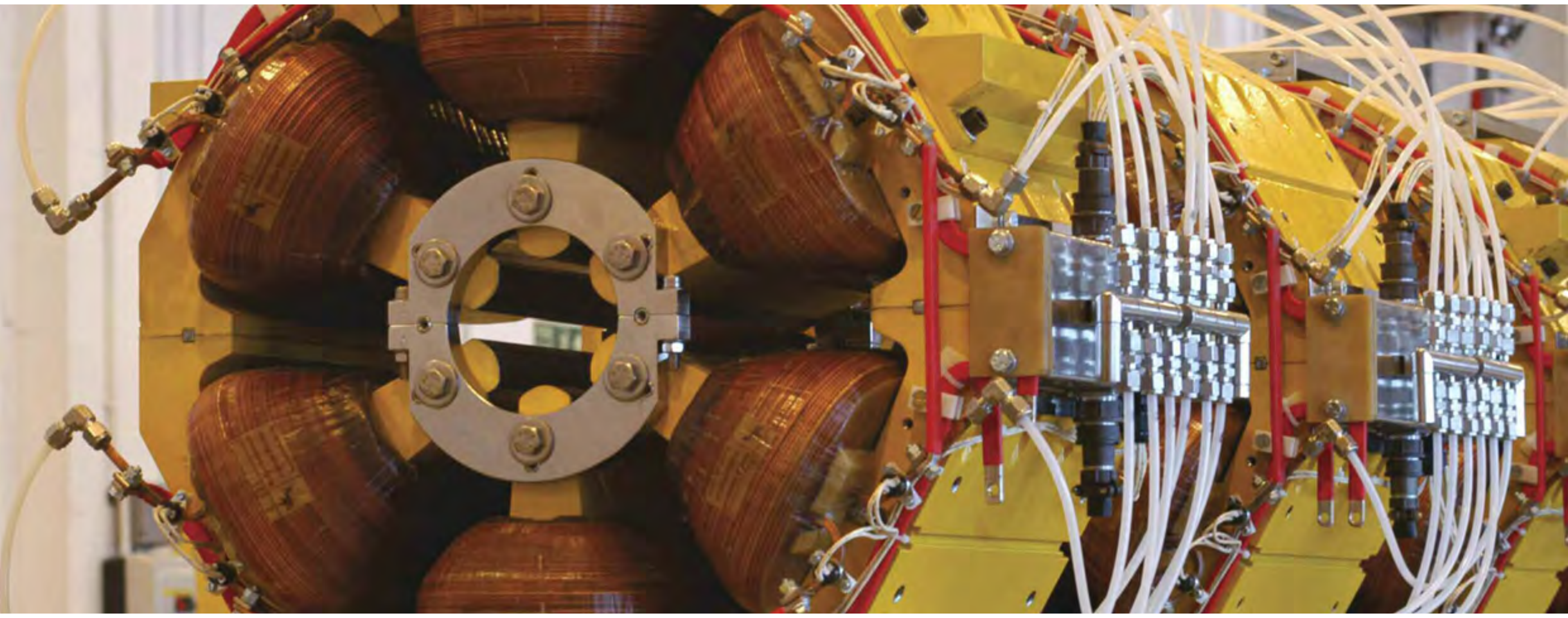
In Europe, physics-based industries alone account for €3.8 trillion or 15% of the 27 member countries' turnover, according to an analysis of Eurostat data from 2010 compiled by the Centre for Economics and Business Research[5]. Furthermore, it employs 15.4 million or 13% of the people

Atlas experiment, CERN (left)

Experiments on level ice loading on an icebreaking tanker, Department of Applied Mechanics Aalto School of Engineering

"Who would have guessed that the laser would have led to the compact disc player or bar code reader?"

JONATHAN HASKEL



employed in Europe's business economy, and for every one of these jobs a further 2.73 jobs are supported elsewhere in the economy.

So with the growing perceived economic importance of science, since the mid-1980s, there have been a growing number of studies on the returns from investment in science. Results vary greatly, however.

At one end of the scale is one of the earliest and most influential studies. In 1991, Edwin Mansfield published a survey[6] of 76 US companies operating in seven countries, in which he found that 11% of new products and 9% of new processes could not have been developed without a substantial delay in the absence of academic research. Based on this observation, Mansfield estimated the rate of return from public money invested in academic research to be 28%.

He noted later that the trend was accelerating—the success of US companies was becoming unceasingly dependent on science. In a follow-up study published in 1998[7], Mansfield noted that 15% of new products and 11% of new processes had been significantly aided by academic research. In total, he said, innovations that could not have developed without academic research accounted for 5% of total sales for the firms.

International

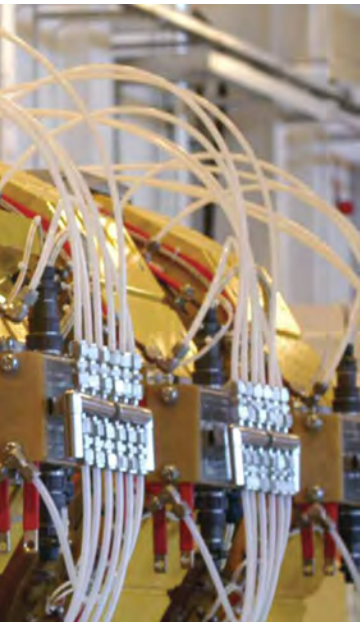
And it wasn't just a US phenomenon. In 1999, Marian Beise and Harald Stahl replicated Mansfield's survey[8] in Germany but with a much larger sample of 2,300 manufacturing firms. They also found that approximately 5% of new product sales could not have developed without academic research.

At the other end of the scale, however, is the 2011 "Economic Impact of the Human Genome Project," [9] from the Battelle Memorial Institute. It found that a $3.8 billion investment in the sequencing of the human genome drove $796 billion in economic impact, personal income exceeding $244 billion and 3.8 million job-years of employment. The report states: Every $1 of federal investment contributed to the generation of $141 in the economy.

In 2010 alone, the genomics-enabled industry generated over $3.7 billion in federal taxes and $2.3 billion in US state and local taxes—revenues returned to government nearly equaled the entire 13-year investment, says the report. The $3.8 billion investment could be the "best single investment ever made in science," it concludes.

A survey of other published literature on the topic reveals "returns" covering most of the ground between these two extremes—28% and 14,000%—prompting the question: How can they vary so much?

"What we are all trying to get at is the rate of the return. But this is a very, very hard



ESRF sextapole magnet

measurement task," says Jonathan Haskel, Professor of Economics at London's Imperial College Business School. "It's not like taking a pound to the bank where there is an observable market transaction. In the vast majority of these cases we simply don't have an observable marketable transaction, either because it gets given away for free or because it gets inculcated into so many different products that it's just impossible to measure all the different potential flows of payment that there might be between the various people who are using it."

"If you look at the effect of the microchip or laser, for example, they are pretty much everywhere. Who would have guessed that the laser would have led to the compact disc player or bar code reader? So the rates of return will depend on the measurement approach that you take: do you do it very wide or not? Measurement can be very difficult. That's fundamentally why the observations are so disparate."

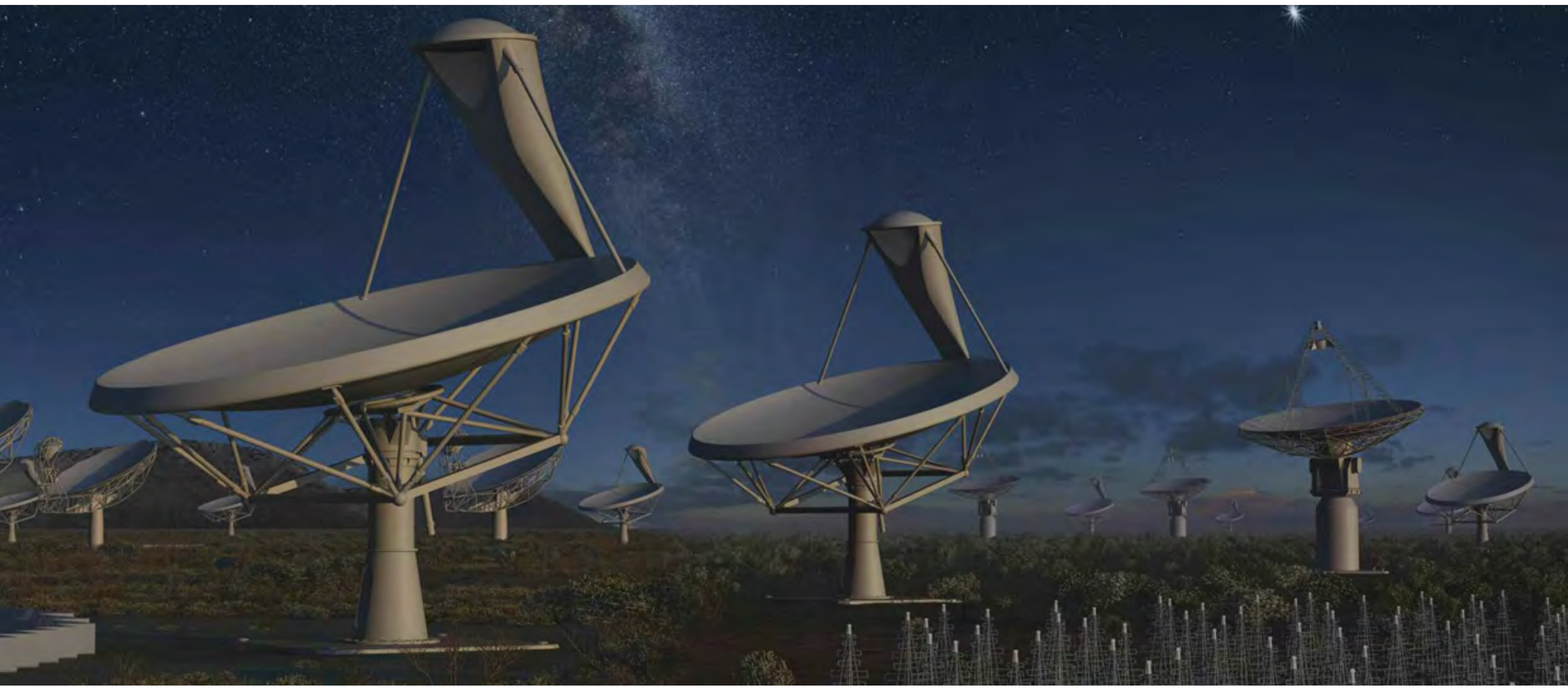
Haskel has himself opted to look at the impact of public research spending on productivity in the private sector.

A 2010 analysis of public support for innovation in the UK by Haskel and Gavin Wallis of University College London[10], found "strong evidence of market sector productivity benefits from public spending on research councils with a very high, but diminishing, estimated rate of return. At the same time, they found no evidence of market sector spillovers from public spending on civil or defence research and development," and suggested as a result "that in a world of constraints, policy should focus on direct spending on innovation, specifically research councils, rather than through tax incentives, such as the research and development tax credit, to firms."

Haskel's is not the most adopted approach though. Input-output analyses are the most common, but even these split into ones based on multipliers found in government-produced look-up tables and others painstakingly researched.

Then there are direct, indirect and even induced effects. Other approaches include the

SKA dish array



use of surveys. Some just take a qualitative approach, based on interviews, forgoing the mathematics and statistics entirely.

In Claire Dougan-McCallie's life-time evaluation of the Synchrotron Radiation Source in Daresbury she estimated that in pure economic terms (the money spent generates extra money through wages and supply-chain effects), the return on investment for the whole facility was between two and three times the amount of money put in. But as the Head of Impact Evaluation at the UK's Science and Technology Facilities Council explains, this kind of modelling does not take account of the far-greater scientific impact of the facility.

"If pressed, I would say this would be at least 10 times the investment, although that is just guess work," she says. "You can't track all the economic output—you have to make assumptions—it's definitely not an exact science."

Fuzziness

As an example Dougan-McCaillie points to the unravelling of the molecular chain of the foot and mouth virus undertaken at Daresbury. This work allowed a vaccine to be developed, which she estimates has a potential £84 million impact. "If you look at the case study [in the report] on drug development in industry, the economic impact may be as high as hundreds of millions of pounds," she adds.

"There were literally thousands of experiments on the SRS so you can see why it's so hard to model. And these are long-term impacts, spanning many decades, facilities and actors."

"Not everything can be expressed in a quantitative way," says Frank Lehner, responsible for international co-operation and strategic partnerships at German synchrotron DESY in Hamburg, and who is currently preparing a similar report to the Daresbury one but about the impacts of the Doris synchrotron radiation source. He cites Salter and Martin[11] in pointing out that there is a fuzzy boundary between economic and social benefits. "For example, if a new medical treatment improves health and reduces the days of work lost to a particular illness, are the benefits economic or social?"

As a result of this fuzziness, they defined 'economic' quite broadly and considered not just economic benefits in the form of directly useful knowledge but also other less direct economic benefits such as competencies, techniques, instruments, networks and the ability to solve complex problems.

"Although it may be extremely difficult to quantify these benefits with precision, this does not mean they are not real and substantial."

Some things are of course quantifiable. NASA, for example, has produced 1,750 commercial spin-offs since its creation in 1958. And in a 2014 study by Christos Kolympiris[12] concentrating on government investments in biotechnology research and the resulting launch of start-ups in a given metropolitan area, it was found that an additional $1 million of public research funding awarded to universities over a five year period could be expected to generate in the following year an increase of 5.93% in local firm births.

Henry R. Hertzfeld, a research professor for George Washington University's Space Policy Institute, produced in 1998 a compilation[13] of economic studies focused on NASA. Estimates of the economic value of NASA vary greatly—from a 20% return on investment, to a 14:1 ratio of revenue to spending. "It is clear that no one measure is a comprehensive indicator of NASA impacts and benefits," he found.

But it was equally clear that "there are many things we just do better thanks to space investment, big things," such as telecommunications, Hertzfeld said.

Hubble Telescope, NASA

Impacts on different segments of the economy

Big science affects many different areas of the economy in many different ways. The following is by no means a complete list; just a small sampling of its impact.

Energy and Environment

Catalytic converters—Laser light sources are playing a key role in obtaining more efficient catalytic converters. X-ray Absorption Spectroscopy (XAS) has demonstrated to be a powerful technique to study physical and chemical properties of catalytic surfaces.

Fuel cells—Today's hydrogen fuel cell technologies are too heavy for practical use in cars. Neutron diffraction at ISIS in Oxford is allowing the investigation of hundreds of potential candidates for materials that store and cycle almost ten times more hydrogen than is currently attainable.

Petrochemistry—Synchrotron radiation-based research at the ESRF in Grenoble, is playing a key role making the most of dwindling oil reserves, with applications across the industry including exploration, reservoir engineering, drilling, pipelines, refining and CO2 sequestration.

Solar panels—gradually lose the vacuum that allows them to effectively convert the sun's rays into usable energy. CERN vacuum technology originally developed for its particle colliders, will extend the life of solar panels and make their use possible in areas where the sun does not shine so brightly.

Health and Safety

Life shears—Developed to detach the space shuttle from its rocket boosters as it leaves the Earth's atmosphere, life shears are now in regular use worldwide to free people trapped in cars or collapsed buildings.

Safety grooving—Cutting grooves into concrete to increase traction and prevent injury was first developed by NASA to reduce aircraft accidents on wet runways. Now it is used on auto routes world-wide.

Space blanket—Developed by NASA in 1964, today they are often included in first aid kits.

Consumer goods

Better chocolate—Scientists from the Netherlands used the European Synchrotron Radiation Facility (ESRF) in Grenoble to work out from the molecular structure of chocolate, what it was that turned it white with time, and how they could prevent it.

Cordless vacuum cleaner—NASA wanted a portable, self-contained drill capable of extracting core samples from below the lunar surface. Black & Decker was tasked with the job; it went on to use what it had learned to develop the Dustbuster cordless vacuum cleaner.

Electronics—Soft X-ray magnetic scattering at the Daresbury SRS in the UK has allowed researchers to probe the use of the spin of particles to store information, paving the way for personal devices such as iPods with yet higher storage capacities.

Imaging and optics

ArterioVision—the software developed by NASA so astronomers could discern more from the images they create is now also being used by doctors to diagnose and monitor treatments for hardening of the arteries in its early stages, before it causes heart attacks and strokes.

Scratch-resistant eyeglasses—Developed by NASA to provide scratch-proof coatings for astronauts' visors, most eyeglasses now feature it.

Super-sensitive charge-coupled device—developed by NASA to increase the quality of the images Hubble could capture, now allows doctors to perform lower-cost but more precise non-intrusive tests on women who may have breast cancer, lessening the need for more intrusive investigations such as tissue sampling and biopsy.

Computing

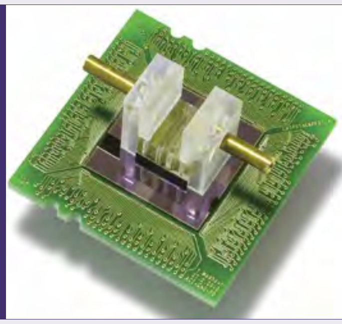
Big data—Big science produces big data. CERN's Large Hadron Collider, for example, produces 15 petabytes of data a year, enough to store the DNA of the entire US population and then clone them, twice. The software techniques pioneered to capture, store and analyse this scale of data are now finding their way into areas such as banking and medicine.

Capacitive Touch Screen—Invented in 1973 by Frank Beck and Bent Stumpe at CERN, introduced into internal CERN control systems in 1976 but now used on billions of smart phones, tablets and media players world wide.

Computer grids— CERN has pioneered grid computing technology that harnesses the power of thousands of computers into a seamless whole allowing scientists in fields as far apart as astrophysics and drug discovery to "sift for digital gold."

Exascale computing—The SKA astronomy project will need to process thousands of petabytes (=exabytes) a day, double the entire traffic on today's Internet, a task beyond today's



computers. It has teamed up with IBM to research exascale computing using 3D stacked chips with novel optical interconnect technologies and nanophotonics to optimize large data transfers.

Hypertext Markup Language—Invented in 1989 by Tim Berners-Lee while working at CERN. At the time it was a means to solving a document access, management and sharing challenge; but it spurred a series of innovations that has created our modern World Wide Web, a platform on which trillions of dollars of economic activity and hundreds of thousands of jobs are based.

WiFi—The Fast Fourier Transformations technology at the core of most of the world's billion plus WiFi equipped devices—whether computers, tablets, mobile phones or others—was based on technology developed to study radiation from black holes.

Materials

Memory foam—developed in 1966 under contract to NASA to improve the safety of aircraft cushions. Now used in airplane seats and mattresses world-wide.

Perfect glass—Researchers at the ESFR in Grenoble and ISIS near Oxford are using a combination of synchrotron and neutron techniques to investigate the perfect glass, physically and chemically stronger than that based on sand.

Powdered lubricants—NASA developed PS300, a solid lubricant coating deposited by thermal spraying to protect foil air bearings. It has gone on to be used in aircraft engines, refrigeration units and turbochargers, among many applications throughout industry.

Medicine

Adaptive optics—Scientists at the ESO's Very Large Telescope, the world's most advanced optical telescope, have come up with a use of computing power to create adaptive optics, allowing them to see through atmospheric turbulence. The technique has been adopted in biomedical imaging where physicians face a similar issue when light passes through tissue to reach the object of interest—a cell, the retina or a tumour.

Cochlear implants—Hearing impaired NASA engineer Adam Kissiah Jr. used his knowledge of denying systems, telemetry and sound and vibration sensors to reinvent the hearing aid so that rather than just making sounds louder, it bypassed damaged hair cells in cochleas to stimulate directly auditory nerve endings to transmit signals to the brain. It has revolutionised treatment of the deaf.

Combined PET-CT—CERN scientist David Townsend, inspired by a doctor at the nearby Geneva Cantonal Hospital, took detector technologies designed for particle research and applied them to create the most advanced medical scanners in use today, giving physicians close to 20/20 vision for diagnosing and planning treatment of cancer.

Dental treatment—It turns out that the techniques developed to create the high-precision aspherical cylindrical lenses for the Very Large Telescope are also needed for the precision lasers used in the latest reduced-pain and noise-free dental treatments.

Foot and mouth vaccine—The SRS light source in Daresbury, UK, was used to provide a three-dimensional model of the foot and mouth cattle virus that has in turn led to the development of a vaccine. If it plays just a 1% contribution to stopping the next outbreak, it would save the country £84 million.

Hadron therapy—Cancer is the third biggest killer of humans. CERN is helping to develop the use of targeted streams of heavy sub atomic particles—hadrons—to destroy tumours while minimising collateral damage, allowing it to be used in instances where conventional X-ray radiation therapy cannot.

Insulin pump—Based on NASA technology designed to monitor the vital signs of astronauts engaged on long journeys in space, now used as the basis for insulin pumps, which unlike insulin dispensers provide insulin according to need.

Pharmaceuticals—A quarter of the world's 20 most-used drugs were developed using synchrotron research infrastructures created for physics. Malaria, flu and AIDS all have new treatments thanks to synchrotrons.

Superconducting magnets and MRI—As well as the detectors, particle physics also contributes the technologies underlying the superconducting magnets used in medical imagers such as magnetic resonance imaging (MRI) scanners. In 2010, over 30 million MRI procedures were undertaken world-wide.




Medical revolutionary

DAVID TOWNSEND, Director of the A*STAR-NUS Clinical Imaging Research Centre in Singapore and former CERN scientist.

The combination of positron emission tomography with computerised tomography in the form of PET/CT scanners has revolutionised medical imaging, particularly the staging of cancer and monitoring the treatment.

"We knew that to be successful one would have to gain the support of physicians."

Assembly of a silicon micro-strip detector module for the LHC, CERN (left)

By adding precise localisation to functional imaging, PET/CT goes beyond providing information about the location and size of a lesion to answer questions like: is a tumour malignant or benign such as inflammatory change, and has the cancer spread? It remains the state of the art 23 years after its invention that was based on technology developed partially at CERN.

David Townsend spent nine years at CERN as a research physicist and data analyst during which time he found himself involved with the application to medicine of detector technologies developed for particle physics. Eventually, he moved from CERN to the University of Geneva Hospital where he proposed and built the first rotating partial ring PET scanner using bismuth germanium oxide (BGO) block detectors. In 1991, on the suggestion of a clinician at Geneva Cantonal Hospital, Townsend came up with the idea of placing a CT scanner in the gaps between the banks of BGO detectors—the birth of the PET/CT—but it took until 1998 for Townsend to create with Ron Nutt the first working combined PET and CT scanner, and it would not be till 2001 that commercial systems would emerge, first from GE but followed soon after by Siemens and Philips. Today five manufacturers worldwide make PET/CT scanners with the addition of Hitachi and Toshiba to the list, and there are estimated to be 4,000 units in use worldwide.

Within three years of PET/CT coming to the market, PET only systems had essentially disappeared, says Townsend. But the reasons they took off so quickly were not just because they were better imaging tools, he adds. The decision by the US Medicare funding system to reimburse patients for certain PET scans was a major factor. Also key in the technology's success was the early support by the clinicians at the University of Pittsburgh Medical Center (UPMC). "We knew that to be successful one would have to gain the support of physicians—first the Geneva Cantonal Hospital and then UPMC provided that."

Today, Townsend is Director of the A*STAR-NUS Clinical Imaging Research Centre in Singapore which focuses on developing multi-modal imaging capabilities in clinical areas of key relevance to Singapore such as neuroscience, cardiology, oncology and metabolic diseases. It is more of a clinical role but it allows him to remain at the forefront of new technologies, such as the use of silicon photo-multipliers (SiPMs), which he says "will one day likely be featured in all PET scanners, because they are stable, compact, high gain and fast" and hopefully eventually cheaper than the photo-multiplier tubes used today. Developed initially in the context of PET/MR, Philips has recently announced the first commercial PET/CT scanner based on SiPMs.

Science or Mammon?

Should science organisations take creating economic value into consideration when making key decisions? And if so, how can they do this while ensuring their core aims are fully supported?

"All science organisations and research laboratories must contribute to the development of a modern knowledge-and-technology society by finding answers to open questions and solutions to the grand challenges," says Helmut Dosch, Chairman of the Board of Directors at Deutsches Elektronen-Synchrotron (DESY) in Hamburg.

That's how knowledge and technology transfers into society, he adds. And industrial impact "must have a firm place in the strategy of today´s modern science organisations."

"Even research laboratories with a clear focus on basic science are continuously pushing the limits of what is technologically possible by devising and constructing novel and complex research infrastructures. This clearly carries the potential for creating economic value which should be leveraged in a strategic way."

But that doesn't mean that economic impact should be the over-riding consideration.

"The truth is, you either back pure science or you don't back it," says John Wood, Secretary General of the Association of Commonwealth Universities.

"You don't make it rely on commercial reasons as much as some politicians would like it to be. That is something that turns scientists off and you don't get good value from them. You have to protect them."

This is especially true for big science projects, says John Womersley, Chief Executive Officer of the UK's Science and Technology Facilities Council (STFC). "They need to remain scientifically excellent if they are not to fall at the first hurdle.

"When we decide what to support at STFC, we put scientific excellence as the first criterion. We don't want to compromise the scientific excellence by looking for projects that have other impact. But if we are faced with a choice between two otherwise identical projects, one of which is going to have economic impact and one of which is not, this may become a deciding factor in which one to support," Womersley explains.

"The stakes are of course raised when we are looking at hundreds of millions of pounds of new investment. Then, there is an opportunity cost that politicians will ask: Why should I invest in this

ESO Very Large Telescope in action (left)

"The truth is, you either back pure science or you don't back it."

JOHN WOOD

science project rather than roads or schools or other priorities?

"When science becomes so big that it is a national investment decision, it needs to be aware that the investments will be judged on more than pure scientific merit. You are competing with other national investment priorities and politicians need to be reassured."

"The UK is very positive on investing in science and research and sees it as a very important thing in positioning the country within the knowledge-based economy in an increasingly competitive global environment," says Womersley. "So when it came to presenting the case for the Square Kilometre Array (SKA), for example, it was important to also talk about the impact on computing, electronics and data processing."

The SKA is transformational in terms of IT—more data will have to be transferred from those antennas in the 2020s than from the entire global Internet today, says Womersley. And that's why companies such as IBM and Intel are very interested. "It will force the development of computing technologies that will go way beyond what you can currently buy or is being developed commercially," he says.

"SKA is to some extent an IT project with an astronomy question as a driver," says Womersley.

Boundaries

All science pushes the boundaries of knowledge but the big science conducted in the world's 20 or so billion-dollar-plus research infrastructures has ambition to push those boundaries on the largest scale imaginable.

It uses the most powerful computers, telescopes and microscopes, connected by the fastest networks to the most massive forms of data storage, the largest and smallest physical structures, the brightest light sources, the hottest and coldest temperatures, the thinest vacuums, the highest voltages, the most sensitive detectors and the largest arrays of detectors, the strongest magnetic fields and the purest materials. And it employs some of the most brilliant minds.

But it is so expensive to set up and run that it can only be financed out of public funds. For that, it delivers results on an epic scale—demystifying the origins of the Universe and of life.

Physician-turned-biologist-turned-biophysicist-biochemist-philosopher, Stuart Kauffman is best known for proposing a famous theory for the origin of life. But another of his theories is that of adjacent possibilities. It is a theory that applies to very many things, but could also explain why big science is worth every penny—and maybe a few more besides.

"When Turing created the Turing Machine, he certainly did not envision the Web," says Kauffman.

"The Turing Machine created an array of adjacent possibilities—things that became possible that were not possible before. Turing did not set out to invent them all. Nor did he foresee them all. We cannot pre-state what the possibilities [unleashed by discovery or invention] are ahead of time."

"The Turing machine enabled the invention of the mainframe computer as one of its adjacent possibilities. And the mainframe enabled the invention of the personal computer with its adjacent possibilities. The personal computer, word processing. Word processing, file sharing. File sharing, the modem. The modem, the World Wide Web. The Web, content. Content, content search machines such as Google. Google, Google Glass….."

"Big Science creates adjacent possibilities which we become," says Kauffman.

SKA Dish Array

Impacts beyond brief

Big science has produced major innovations seemingly outside their original remit—from physics laboratories that help produce drugs to treat illnesses to telescopes that help us communicate. This section looks at the impacts of big science beyond their original brief.

CASE STUDY 1: **THE WEB**

By 2016, the Internet economy will reach $4.2 trillion in the G-20 economies alone. The Internet as most of us know it began with a seemingly small technical idea at CERN.

Fifth largest economy

In 1980, while a freelancer at CERN, Tim Berners Lee wrote but never published his first program for storing information, Enquire. In 1989, as a full-time employee faced with the challenge of making more accessible the growing volume of research of interest to CERN's scientists, he proposed a global hypertext project, to be known as the World Wide Web.

Based on the earlier Enquire work, it was designed to allow people to work together by combining their knowledge in a Web of hypertext documents. He wrote the first World Wide Web server, "httpd", and the first client, "WorldWideWeb," a what-you-see-is-what-you-get hypertext browser and editor which ran in the NeXTStep environment. This work was started in October 1990; and the program "WorldWideWeb" was made available within CERN in December, and on the Internet at large in the summer of 1991.

Of course, that was just the start; many other people, companies and organisations picked up on the initial idea and developed it into a critical piece of the global economy. According to a study[14] of G8 countries, McKinsey showed that the Internet accounted for 10% of gross domestic product (GDP) over the 15 years between 1995 and 2009. But it also showed that its contribution to GDP growth in the last five years of the study period had doubled to 21%. McKinsey also found that most of the economic value the Internet creates falls outside of the technology sector with companies in more traditional industries capturing 75% of the benefits.

In 2012, Boston Consulting Group predicted[15] that by 2016, there will be 3 billion Internet users globally—almost half the world's population, and that the Internet economy will reach $4.2 trillion in the G-20 economies alone. If it were a national economy, the report's authors said, the Internet economy would rank in the world's top five, behind only the US, China, Japan, and India, and ahead of Germany, France or the UK's.

"No one—no individual, business, or government—can afford to ignore its ability to deliver more wealth to more people more broadly than any economic development since the industrial revolution," it concluded.

Tim Berners Lee, CERN

"No one can afford to ignore the Internet's ability to deliver more wealth to more people more broadly than any economic development since the industrial revolution."

CASE STUDY 2: **ATTRACT**

A new initiative aims to pioneer a model to stimulate start-up companies, train young entrepreneurs, and speed up the delivery of economic spin-offs from scientific research.

Leveraging science investment

ATTRACT, breAkThrough innovaTion pRogrAmme for the deteCtor, is an open initiative first proposed by CERN and ESADE designed to harness the abundance of creativity, knowledge and skills within big science. Its aim is to boost European innovation, competitiveness and sustainability, and create breakthrough solutions to address the societal challenges that Europe will face in the coming decades. At the same time, it will leverage the EU's research infrastructure investment through open innovation—pioneering a model to stimulate start-up companies, train young entrepreneurs, and speed up the delivery of economic spin-offs from scientific research.

ATTRACT builds on the technological challanges and synergies required by cutting-edge detections and imaging technologies demanded by large European research Infrastructures. The goal is to create a co-innovative collaboration with industry that will strongly contribute to achieving a European Research Area (ERA) in which researchers, scientific knowledge and technology circulate freely with the main objective of increasing the European capacity to generate, absorb and use of new technology.

After a pilot phase at CERN's IDEALAB, the ATTRACT model could be rolled out to other research infrastructures across Europe. In particular, ATTRACT is proposed to focus on the themes of breakthrough information and communication technology; high performance materials; and health physics technology.

ATTRACT responds directly to an existing demand expressed by the European Commission (EC) of the need to establish novel collaborative frameworks between European Research Infrastructures (RIs) and industry, overcoming barriers and therefore creating attractive conditions for industry, and it aligns and fully contributes to the objectives of the EU's Europe 2020 growth strategy.

ATTRACT's main objective is to increase Europe's capacity to generate, absorb and use new technology.

CASE STUDY 3: **SRS AT DARESBURY**

The SRS at Daresbury supported cutting-edge research in many fields. In 2011, the UK's STFC produced a study into the impact of its over its 28-years of operation. This is a brief overview.

An impact felt near and wide

It is estimated that the total financial impact in the North West of England was nearly £1 billion.

The Synchrotron Radiation Source (SRS), located at the UK's Science and Technology Facilities Council's (STFC) Daresbury Laboratory, was an advanced, multi-user, X-ray synchrotron radiation facility. The SRS produced beams of light so intense that they revealed the structure of atoms and molecules inside a wide range of different materials.

Before ceasing operations in 2008 after 28 years of operation and two million hours of science, it helped to produce over 5,000 papers and solved over 1,200 protein structures which have been deposited in the worldwide Protein Data Bank database repository. Contributions were made to the development of new medicines and medical research such as control of host-graft rejection and HIV/AIDS, the production of new materials for use in electronics and clothing, the development of new detergents. It helped at least one scientist gain a Nobel Prize—John Walker who was awarded the Nobel Prize for Chemistry in 1997 for his work on ATPase.

It even played a role in improving the taste of chocolate and the safety of aircraft by looking at the crystal formations in chocolate and metal. And it paved the way for bigger iPod memories and unraveled the crystal structure of the Foot and Mouth Disease Virus, allowing vaccines to be developed.

All this had direct impact on people's quality of life. It also had a financial impact. For example the Foot and Mouth outbreak in 2001 cost the Government and industry £8.4 billion. As well as save money, the vaccine defrays some of the negative economical and social impacts which the disease produces, not just in the UK but world-wide.

There were also many indirect impacts.

It helped improve the performance of UK industry—There were some 200 commercial users over the facility's lifetime. The industries that benefited the most were the pharmaceutical, chemical and healthcare industries, including companies like ICI, BP, Unilever, Shell, GSK, AstraZeneca and Pfizer.

It spawned start-ups—Skills, technology and knowledge gained at SRS have helped in the creation of nine new companies and one commercial service provider, in areas such as scientific instrumentation, detectors, cholesterol monitoring, software, cryogenics, mechanical instrumentation and drug discovery. It delivered new skills to the labour market—Over 11,000 individual users from 25 countries used the SRS during its lifetime, including some 4,000 students who used the SRS as part of their degrees or doctorates, and 2,000 post-doctoral researchers using the SRS for their research. It also helped 100 engineers, technicians and instrumentation developers hone their skills which they then transferred to academia, industry and other synchrotrons around the world.

It stimulated growth in the surrounding economy—through new jobs created from the facility's construction and operation. This represented a direct financial impact of £600 million, the majority of which was spent in the locality. Due to multiplier effects, it is estimated that the total financial impact in the North West of England was nearly £1 billion.

It created a knowledge hub—that continues to develop. In addition to the scientific facilities already on the site, the Campus has led to the establishment of a world class centre for accelerator science, the Cockcroft Institute, and will further benefit from two other centres based on computational science and detector systems in the near future. Some 100 high tech businesses in sectors such as biomedical, energy, environmental, advanced engineering and instrumentation are also located in the Campus's Daresbury Innovation Centre. In 2008/2009, these companies delivered £14.9 million in sales, secured £20.5 million in investment and had an average growth turnover of 67%.

CASE STUDY 4: **IBM AND SKA**

SKA is an ambitious multi-billion-euro programme to delve into the depths of the universe and the events at the very beginning of time. It will be only possible with significant advances in computing, that will also end up benefiting computer users everywhere.

Pushing computing beyond its limits

"These are things that you can't do just as innovation within ICT. You need the challenges of a mammoth project such as SKA to make you innovate."

The SKA is a radio telescope project—50 times more powerful and 10,000 times faster than any other—that will consist of thousands of dishes and other antennae, the combined area of which gives rise to its name, the Square Kilometre Array or SKA. There will be activities in some 20 countries on five continents, including the siting of the telescopes themselves in both Africa and Australia. When complete, SKA will be used to explore evolving galaxies, dark matter and the very origins of the universe—events that happened up to 13 billion years ago.

Total project costs will run into billions of euros, with much of this being spent on relaying, storing and analysing the data captured by the antennae; a task which will require processing power estimated to be equal to several millions of today's fastest computers. The communications and storage challenge is great: It will generate data at a rate estimated between twice and ten times the daily traffic on the entire World Wide Web today.

This will require the development of a lot of new technology. To help create this, SKA participant ASTRON, the Netherlands Institute for Radio Astronomy, with the financial support of the Province of Drenthe, the Netherlands, and from the Dutch Ministry of Economic Affairs, has teamed up with global technology giant IBM in a collaboration called Dome to form a lab called the Center for Exascale Technology located at the ASTRON campus.

Conventional technology, for example, would require a few gigawatts of electrical power to keep it all running. "We are aiming to do it with 10 megawatts," says Albert-Jan Boonstra, Dome scientific director at ASTRON. "Our goal is not to build the world's largest computer," says Alexander Brink, Chairman of the Steering Committee, Dome Project, IBM , "but certainly one of the most efficient at handling big data."

To achieve this gigantic leap in processing ability accompanied by a dramatic slashing of electrical power consumption, ASTRON and IBM will have to push the boundaries of a number of technologies.

Miniaturisation: "Most of the power goes in transporting data from point A to point B," says Boonstra. "We need to miniaturise to address this;"

Nanophotonics: Only light can cope with the very fast data transfer rates—100s of gigabits a second—needed within the processors;

Data storage: high-performance storage systems based on next-generation tape systems and novel phase-change memory technologies;

Algorithms: "We will need a novel way of processing all of the big data, with clever new algorithms" says Boonstra.

"The combination of all these things will hopefully allow us to make the required advances," he adds.

The Dome project budget is around €33 million over five years, which IBM and ASTRON will use to hire staff to focus on R&D. But the money IBM makes out of the project is unlikely to cover its costs.

"The profit is measured in knowledge. The real benefit to us is by helping us to realise our long-term vision of a smarter planet based on big data analytics and sustainable computing," says IBM's Brink.

It allows the company to develop the knowledge and technologies which will keep it at the leading edge of computing. This in turn will benefit computer users in many spheres from finance to government through industry and medicine to other science researchers.

SKA challenges big data to the extreme, says Brink.

"There's lot of redundancy with today's server-based architectures. It's not just a case of increasing capacity; we have to do it smarter, if only to reduce the energy bill.

"And by addressing the energy issue, it will also allow computing to go further.

"These are things that you can't do just as innovation within ICT. You need the challenges of a mammoth project such as SKA to make you innovate. If we don't do it, the curve of increasing computing capacity will slow," says Brink.

IBM nanophotonics

CASE STUDY 5: **COBALT LIGHT SYSTEMS**

Interview with Pavel Matousek, Chief Scientific Officer of Cobalt Light Systems Ltd., senior fellow at the Rutherford Appleton Laboratory (RAL) and inventor of the technology behind Cobalt Light Systems's products.

Keeping us safe

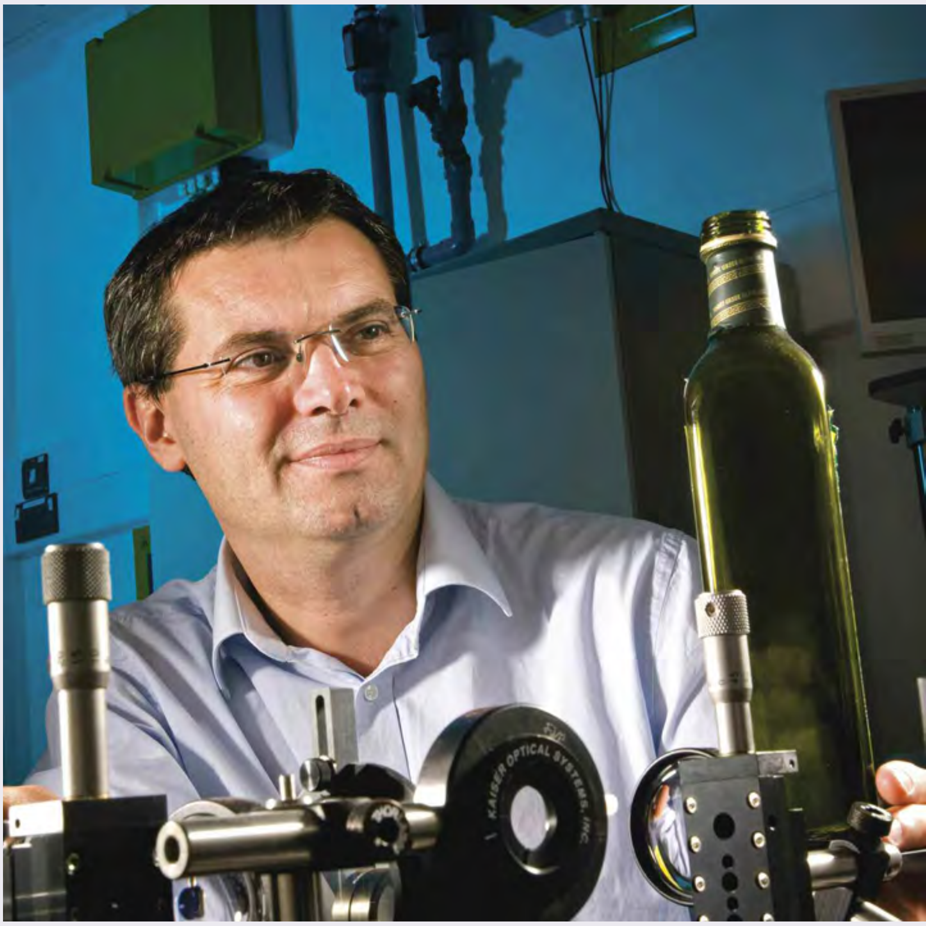
Shining a laser light on chemicals and deducing their composition by measuring the reflected photon signal was an established technique when scientists at Rutherford Appleton Laboratory came up with a novel variation that would let them do this, even if the chemicals were locked away inside an opaque bottle. The result is a new venture capital startup with three new products that promise to dramatically improve the quality controls of pharmaceuticals and make flying safer.

In essence, rather than just analysing the direct reflections, photon streams are analysed from two spots several millimetres apart, and mathematical processing is used to identify and remove the information about the bottle wall allowing just the contents to be studied.

"It is similar to looking at the stars. You can see them at night but can't see them during the day because at night, there is no interfering sunlight," says Pavel Matousek, Chief Scientific Officer of Abingdon-based venture-capital-funded start-up Cobalt Light Systems Ltd.

The company has developed three products: two for quality assurance in the pharmaceutical industry and one for security applications.

In the first pharmaceutical application, it allows the non-intrusive checking of the raw materials of a medicine before they reach the production line, and in the second the non-intrusive quality testing of medicines—whether tablets, capsules, powders or liquids—coming off the production line. In both cases, the process time is cut from hours to seconds compared with conventional chemical analysis methods, and with the additional bonuses of simplifying the procedures and avoiding the possibility of cross-contamination.



Pavel Matousek

In the security application, bottles of liquids carried by airline passengers can be deemed safe or unsafe within five seconds. Several hundred are being tested at major airport hubs across Europe.

The process between invention and commercialisation was fairly lengthy. The patent was filed in 2004 and the STFC's spinout company set up in 2008 after venture capital

"Basic research is the foundation for everything. It generates the seeds that can lead to commercial fruits but it's not a process that you can direct."

funding was secured.

Cobalt Light Systems now has over 25 employees and hopes to be acquired by another company at some point, allowing the investors and STFC to exit as well as allow the new owner to seek out and develop other opportunities for the technology.

Despite the commercial success of his invention, Matousek emphasises that it would not have happened had it not been for the pure science research that led to it: "Basic research is the foundation for everything. It generates the seeds that can lead to commercial fruits but it's not a process that you can direct. The goal of fundamental research cannot be the invention of a new specific product. If you made that the goal, the inventions simply would not happen. You need the long-term funding stability and focus on a particular topic that scientific discovery provides, so you can come across new phenomena and find new ways of doing things that may turn out to have potential somewhere else."

Nevertheless, close attention has to be paid to the commercialisation process if it is to be successful, says Matousek. "Funding fundamental science is crucial but we have to have in place processes that streamline the commercial delivery when something is uncovered. Scientists are not necessarily business minded. We need help to make sure that we don't make mistakes. The use of professional technology transfer teams and availability of funding to support early stages of development are the keys to getting it right," he says.

CASE STUDY 6: **WIFI**

WiFi as most of us know it would not have been possible without astronomy and Stephen Hawking. Not a lot of people know that.

It came from outer space

"It turned out that the problems we had to solve in radio astronomy back then with the black holes and later with the WLAN were remarkably similar."

WiFi is everywhere today. In 2012 alone, 1.5 billion WiFi-equipped devices were shipped, and market researchers predict that by 2016 almost half the world's households will have WiFi in the home. But this all began with astronomy and British physicist Sir Stephen Hawking.

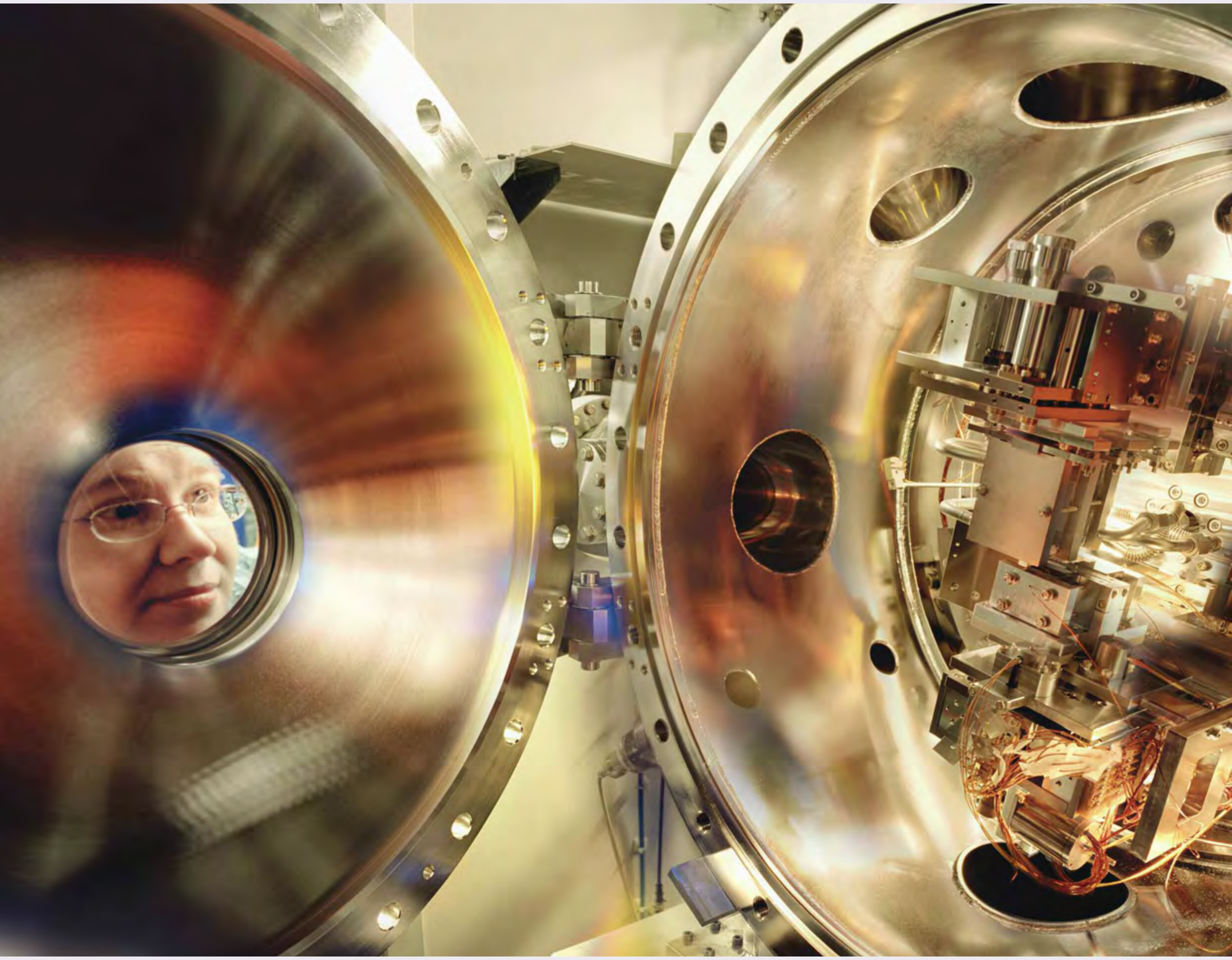
In 1974, Hawking suggested that black holes might not be black after all, and that they may emit radiation, since termed Hawking Radiation. John O'Sullivan, a young Australian electrical engineering PhD working at ASTRON, the Netherlands Institute for Radio Astronomy, came up with a plan to test the theory.

"There were a number of research groups trying to find evidence for the Hawking Radiation. We used complex technologies, fine-tuned radio telescopes, improved spectrometers and recorded hundreds of metres of film. But although we looked at the characteristic traits of the signal, we did not find the smoking gun. However, while working with the data and the equipment it occurred to me that there should be ways to better, more effectively and efficiently process the data through a digital hardware which would perform fast Fourier transformation (FFT)."

In 1991, O'Sullivan returned to Australia to head up the signal processing group at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia, and part of his brief was to find commercial applications of the technologies they had invented for scientific research. One of the avenues he and his team pursued was the application of the same FFT techniques used to delve into black holes to increasing the speed of wireless local area networks.

"In essence it turned out that the problems we had to solve in radio astronomy back then with the black holes and later with the WLAN were remarkably similar, and FFT was a key component of the upcoming solution," said O'Sullivan.

Along with Terence Percival, Graham Daniels, Diethelm Ostry and John Deane, O'Sullivan finessed the idea so that they could apply in 1992 for a provisional patent. In the early 2000s the first commercial WiFi products using the technology emerged. The origin was disputed, however and a court action ensued. CSIRO won, with O'Sullivan's and his team's ideas providing it with its most lucrative patent ever—estimated at over a billion dollars. And following a period working in industry, O'Sullivan has returned to CSIRO to work on the system design for the Square Kilometre Array.



ESRF beamline for X-ray microscopy

Conclusion and recommendations

Science, like many other human related activities, has always had to justify its existence. The added challenge for big science is that big science is bigger and longer, up to 50 years; a lot longer than any political term.

Because of its scale, however, big science needs a political decision. So we need to communicate its inherent value very well. The good news is that there is a receptive audience out there: people still trust science in ways that have been lost with many other institutions.

For policy makers, the key question is how to make it matter even more? How to maximise the economic and social benefit, without loss of scientific integrity?

On 5 March 2014, Science|Business gathered some of Europe's most important experts on research infrastructure to explore the answers. Five recommendations emerged:

Broaden the debate. So the policy decisions taken when shaping new projects translate more directly into broader economic and social benefits. The importance of big science is not fully understood by politicians—to them, the costs are huge, the funding is complex, governance is complex, managing intellectual property rights is difficult, scientific goals are hard to understand and benefits are hard to trace. What matters most to them is the social, human value: training, career development opportunities, networking, connections to national economics, plus the local impacts of research infrastructures such as spin-offs, purchasing, employment creation, etc. We need to enlarge the contact between research infrastructures and society, but in a structured way that can be surveyed and monitored without restricting its growth, a coherent ecosystem with fair governance.

Study what works and how, and explain it better. Economists have yet to devise good, consistent ways to measure spin-out from research; that should be a priority, that can help guide policy. We need to understand the barriers that prevent us from doing the good stuff. Bankers, for example, will not give much time to revenues that come in after 15 years, but they will they will be interested in follow-on projects. We need people who understand politics, technology, statistics and finance to get the innovation circle rolling.

Open the innovation process at the labs. Why did Xerox not manage to monetise its many great inventions such as Ethernet and Postscript? Because they did it secretly. It was a closed process; not open innovation. It was missing a set of peers who could assess and organise these things so that they could be developed in a sustained way. This is still insufficiently addressed in today's innovation processes. More contact with industry, entrepreneurs, investors and other value-creators right from the outset of the innovation process is needed to turn more ideas faster to good use. Initiatives like ATTRACT are working in that direction. We need to develop a porous system between science and commercial exploitation. And we need to create a place where this kind of thing can happen.

Focus on people and training. One of the greatest benefits of big science is in human resources. Smart people, gathered together, do surprising things—including training other smart people who can go on to do other surprising things, in industry, finance, services and policy. We need to find methods, processes and places, whether real or virtual, where people from different backgrounds and skill sets can "collide" and exchange knowledge and ideas: innovation factories where "coincidences" can be planned and managed. Perhaps also involving big and small companies, non-governmental and other organizations as well as students and professors. The IdeaLab pilot experiment at CERN among others, is an example of such a process.

Bridge the cultural gap between big science and industry. Just as between scientists and politicians, there is a gulf between industry and basic science. Venture capitalists, for example, care very little about prestige; scientists care a lot about prestige. This is where governments or governance are important. There is a need for better communications, all round. A common language need to be developed. Big science needs to offer more public investment options, cohesion between different research infrastructures, demonstrate capacity building. A map is needed of what research infrastructures have to offer to industry. At CERN, for example, procurement offers good opportunities to industry but addressing the societal challenges of humankind requires new co-innovation models, especially between industry and research infrastructures. Technology transfer needs to be formalised, like PET from CERN: To gain the maximum benefit, the time from idea or discovery to the marketing of something useful needs to be shortened.

Big science projects—such as CERN, the Human Genome Project and the International Space Station—provide vivid demonstrations that mankind is able to do the most complex of things; produce enormous achievements. These capabilities are important for the survival of our species, not just because of the new knowledge they generate but because they show us how to work together, no matter what our differences may be.

And big science is particularly important for Europe. The continent produces one-third of new knowledge but it is losing ground. It must stay ahead in creating new knowledge if it is to continue to thrive. It is the cheapest life insurance for Europe's future.

Or put another way, big science might look expensive but ignorance will cost a lot more.

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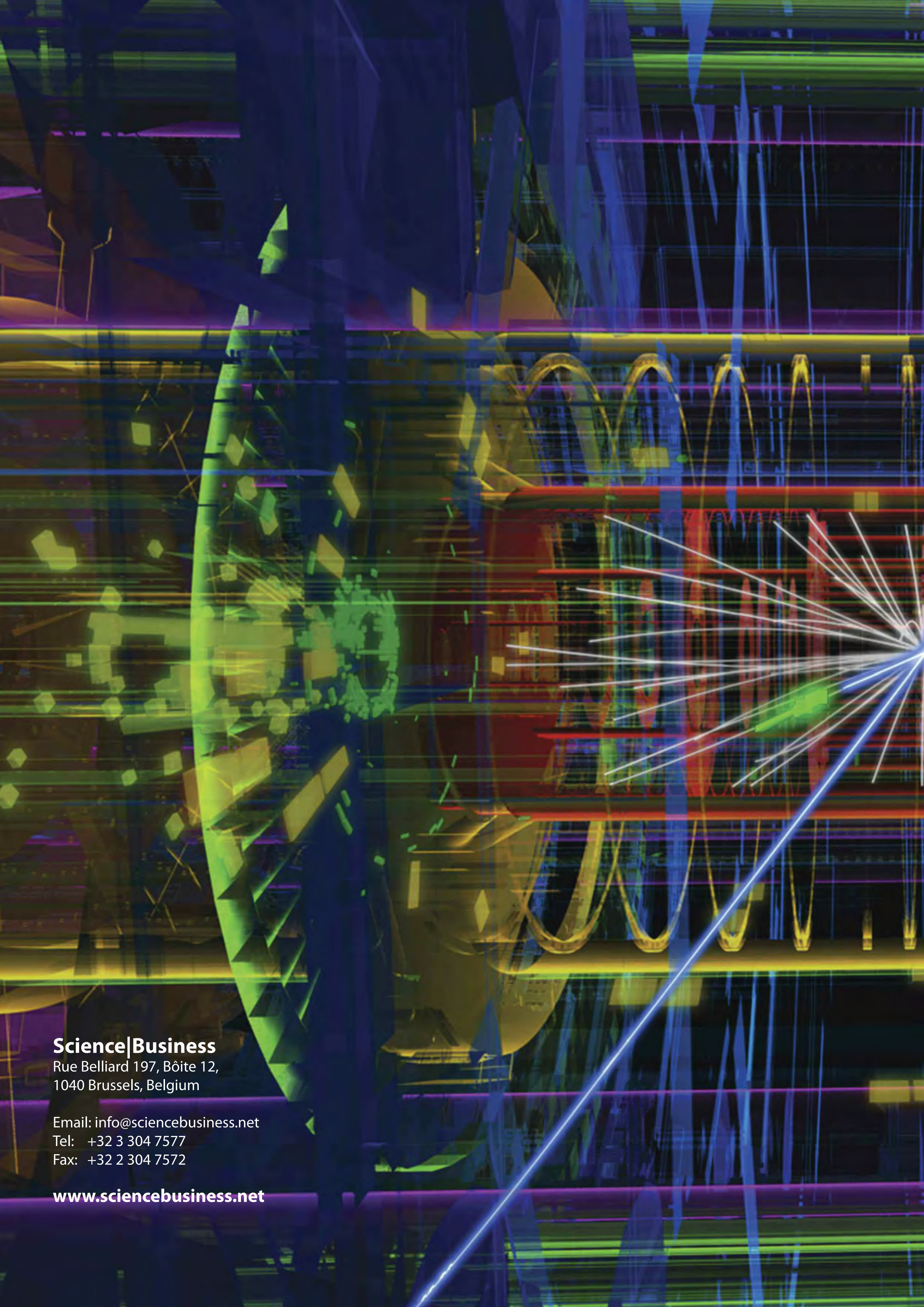

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