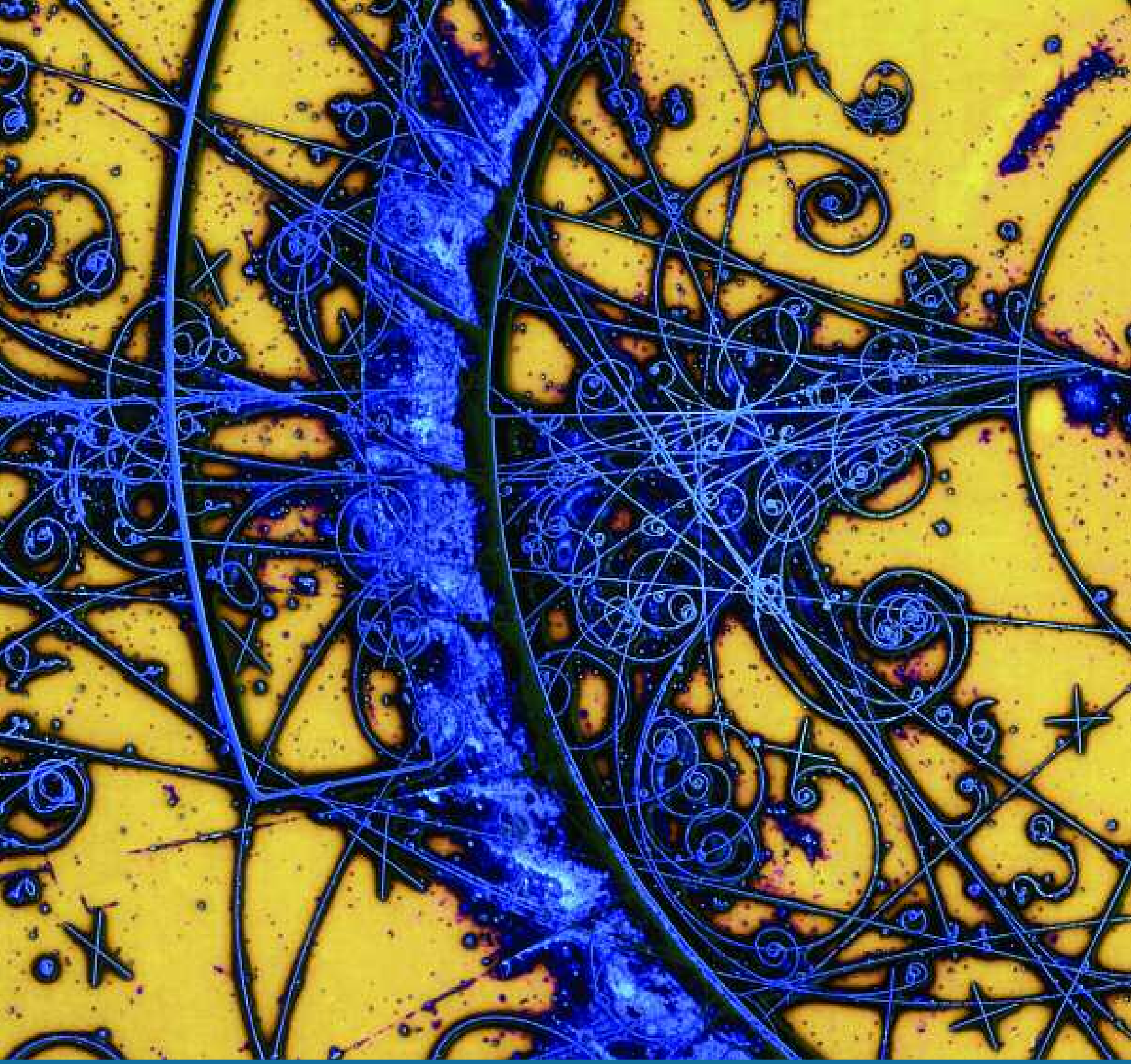


Exploring the Subatomic Realm

SUBATOMIC
PHYSICS
IN CANADA

Superconducting accelerating cavity prototypes for the future International Linear Collider (ILC). The ILC will be a reality in the next ten years, and Canadian physicists hope to be a major part of the project.

In this century, subatomic physics will change our understanding of the world and help establish our place in the cosmos. Canadians must participate in these discoveries.

Subatomic Physics at a glance

WHAT ARE THINGS MADE OF?
HOW ARE THEY HELD TOGETHER?
HOW DO THEY WORK?
WHERE DO THEY COME FROM?

Subatomic physics is the study of the simplest building blocks of our universe. Today we have a detailed, but still incomplete, understanding of matter down to a scale of about one one-thousandth of the size of an atomic nucleus, and back to a fraction of a second after the Big Bang, about 13 billion years ago. Canadian physicists are leaders in the world-wide effort to extend this knowledge.

Experiments in which Canadians play key roles may lead to dramatic breakthroughs in our understanding of nature in the next decade.

HOW DOES SUBATOMIC PHYSICS IMPACT OUR LIVES?

The science-driven demands of subatomic physics lead to innovations that benefit society as a whole.

For example, accelerator technology that was originally developed for basic subatomic physics is now widely used for such diverse applications as cancer therapy, studying the structure of viruses, designing new drugs and developing new semiconductors and microchips.

- The World Wide Web was originally developed by subatomic physicists as a means of sharing data
- Modern medical radioactive tracers were a product of particle accelerator research
- MRI machines use high-field superconducting magnets for medical imaging, first used in subatomic research
- Cancer therapy now uses accelerated proton beam technology
- The "Grid" – sharing of computing power over the internet – is a spinoff of particle physics experiments

SUBATOMIC PARTICLES

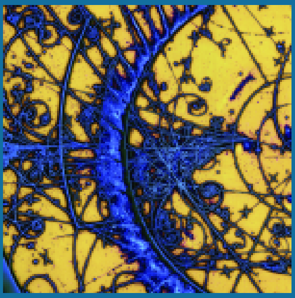
QUARKS

u UP	c CHARM	t TOP	γ PHOTON
d DOWN	s STRANGE	b BOTTOM	g GLUON
ν_e ELECTRON NEUTRINO	ν_μ MUON NEUTRINO	ν_τ TAU NEUTRINO	Z Z BOSON
e ELECTRON	μ MUON	τ TAU	W W BOSON

LEPTONS

FORCE CARRIERS

THE TABLE OF FUNDAMENTAL PARTICLES
Quarks, Leptons and Force Carriers comprise the basic known subatomic world.



ON THE COVER:
The cover shows a colourized photograph of particle interactions in a bubble chamber. Although bubble chambers are no longer used in state-of-the-art detectors, subatomic researchers still seek to visualize the particle collisions they study.

The Canadian Contribution

IN WHICH AREAS DO CANADIANS EXCEL?

Canada has world-class research facilities and institutes where Canadians, and their international collaborators, pursue the exciting questions of subatomic physics. These facilities and institutes include the TRIUMF laboratory in Vancouver, SNOLab in Sudbury and the Perimeter Institute for Theoretical Physics in Waterloo.

Canadian researchers from universities across the country pursue subatomic physics research at their home institutions, at these facilities, and at laboratories in Europe, the US and Japan.

CANADIAN SUBATOMIC RESEARCH FACILITIES AND UNIVERSITY RESEARCH GROUPS

RESEARCH FACILITIES

British Columbia
TRIUMF

Ontario
SNOLab

UNIVERSITY RESEARCH GROUPS

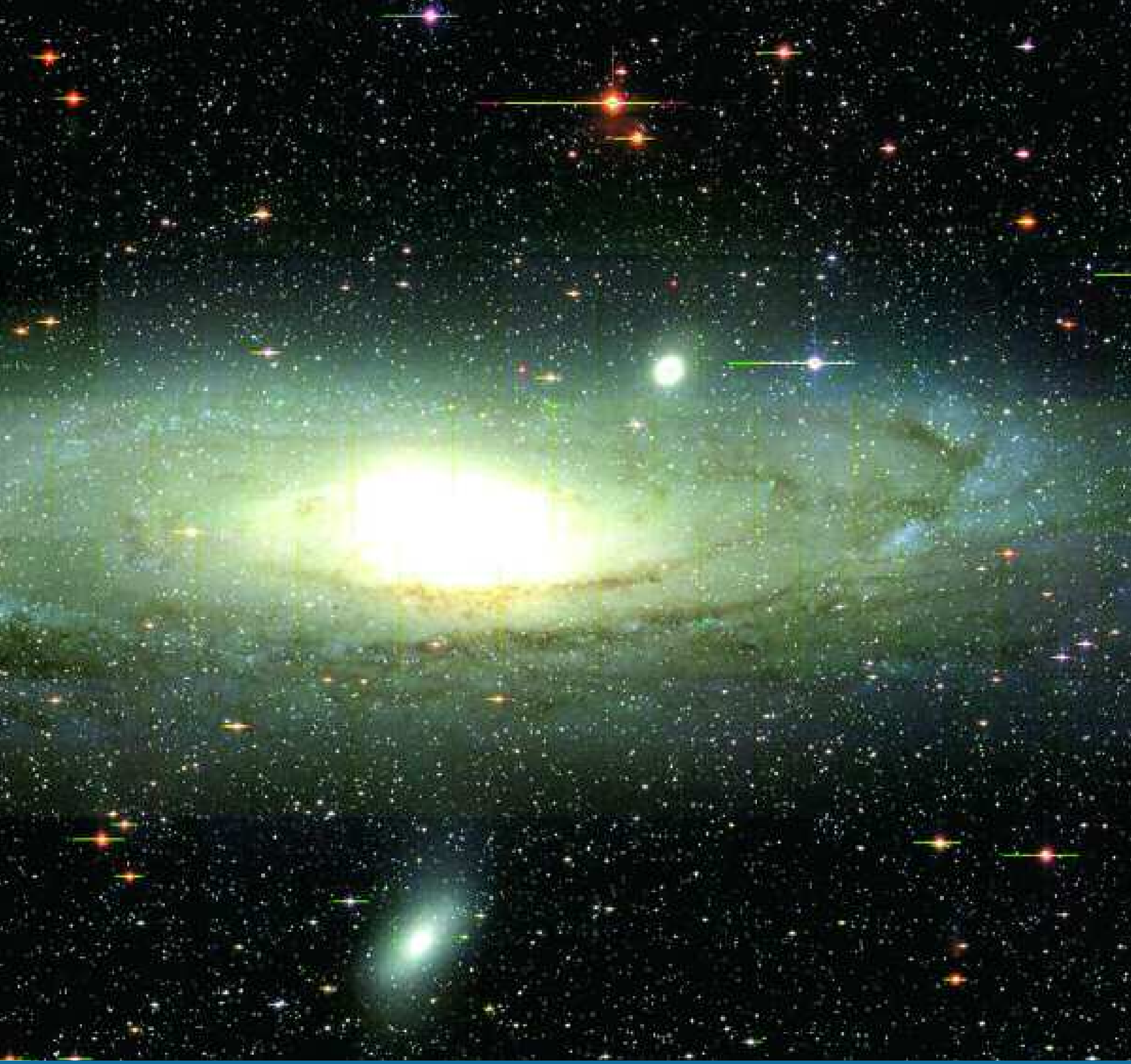
British Columbia
University of British Columbia
University of Northern British Columbia
Simon Fraser University
University of Victoria

Prairies
University of Alberta
University of Brandon
University of Lethbridge
University of Manitoba
University of Regina
University of Saskatchewan
University of Winnipeg

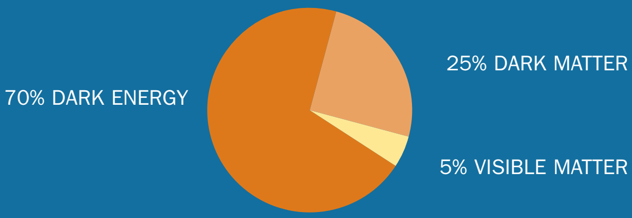
Ontario
Carleton University
Guelph University
Laurentian University
McMaster University
Perimeter Institute for Theoretical Physics
Queen's University
University of Toronto
University of Waterloo
University of Western Ontario
York University

Quebec
Bishop's University
Concordia University
Université Laval
McGill University
Université de Montréal
Université du Québec à Montréal

Atlantic
Acadia University
Dalhousie University
Université de Moncton
Mount Allison University
Saint Mary's University



A LOOK AT THE UNIVERSE



Discoveries in subatomic physics are answering riddles of the cosmos, including the prevalence of dark matter. Scientists now believe that visible matter comprises only 5% of the universe, with the remainder being dark matter and dark energy. Detecting this dark matter is a key area of study for Canadian physicists.

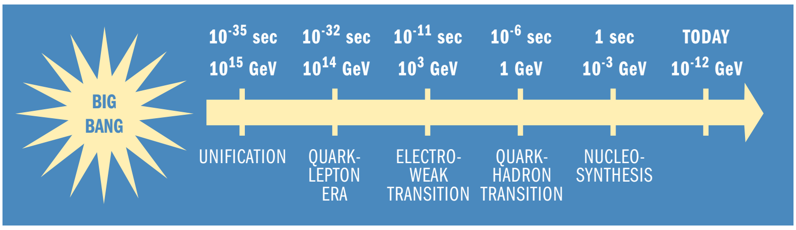
The Critical Questions

Recent discoveries indicate that roughly 95% of the universe consists of “dark” matter and energy – forms completely unknown to us. Normal matter, including all we see around us, constitutes only 5% of the universe. Discovering what the dark matter and dark energy are, and what their existence means for the evolution of the universe, is one of the most exciting areas of science today. Some of the critical questions are:

The distribution of mass in Messier 31, the largest galaxy in the neighbourhood of the Milky Way, led to the recognition that galaxies are filled with dark matter.

- What is gravity? How does it work? Can a unified theory of gravity and particles be developed?
- How do particles acquire mass?
- How did the universe come to be? How is it evolving? What are the dark matter and dark energy?
- Why does the visible universe consist of matter? When and how was the symmetry between matter and anti-matter broken?
- After the creation of the primordial hydrogen and helium in the Big Bang, what mechanism produced the heavy elements?

Answering these profound questions requires experimental efforts and theoretical analysis involving subatomic physics, cosmology and astronomy. These three sciences are closely linked because of the emergence of today’s universe from the particles produced in the Big Bang. The goal of subatomic physics is, ultimately, to understand the evolution of the universe and the matter within it.



The extremely hot and dense early universe of the Big Bang gave rise to a sea of particles in constant interaction with one another, governed by a single force. As it expanded and cooled, it underwent a series of changes from a very hot soup of particles called quarks and leptons, to nuclear matter that was to make up the first stars.

The extreme conditions of that early universe can be recreated in laboratories using accelerators. Physicists in Canada working in the sub-disciplines of nuclear physics, particle physics and particle astrophysics probe all of the physics depicted in the time-line in order to answer the fundamental questions listed above.

Canadian Successes

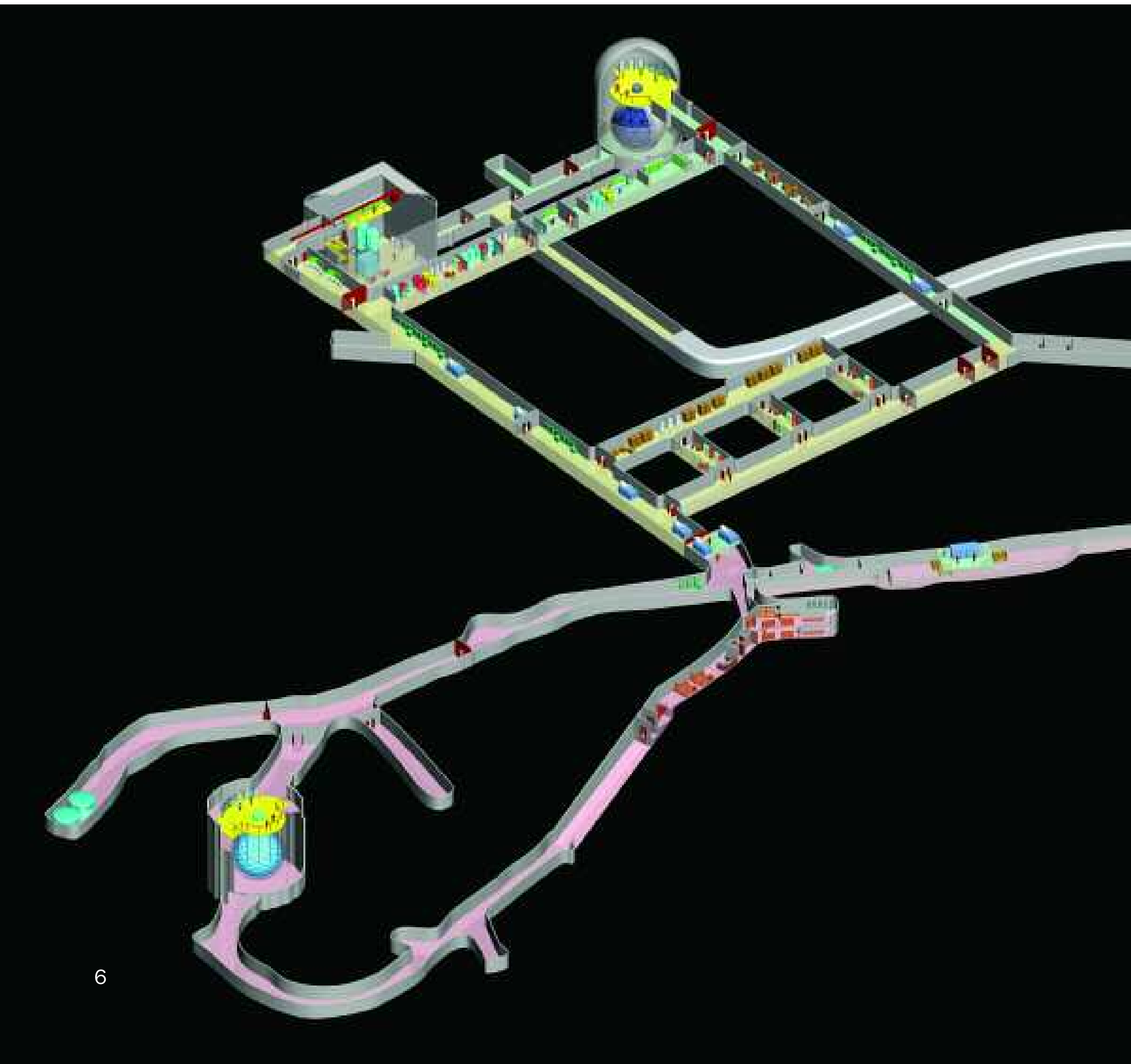
The SNO detector before the cavern was filled with water. SNO is nearly 2 km underground near Sudbury.

SOLAR NEUTRINO STUDIES

Subatomic physics is an international endeavour, and Canadians have made important contributions. One of these is the resolution of the so-called "solar neutrino problem" by the Sudbury Neutrino Observatory (SNO), which answered important questions about the Sun as well as discovering fundamental new properties of sub-atomic particles called neutrinos.

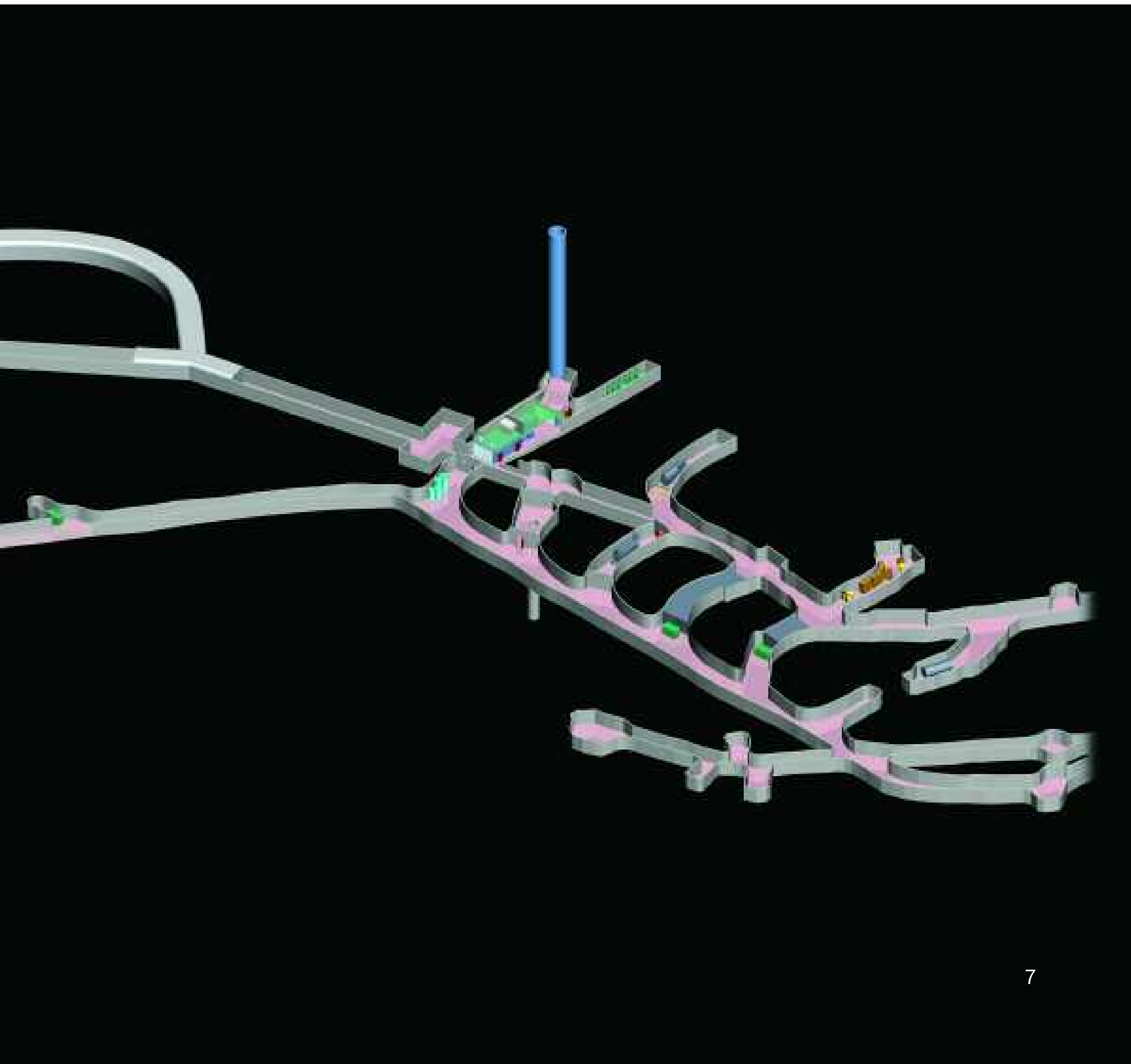
For over thirty years scientists have observed fewer neutrinos emitted by the Sun than predicted by solar models. Either our understanding of the Sun was fundamentally flawed, or the neutrinos were not behaving as they should.

This puzzle was solved by the Sudbury Neutrino Observatory, in one of the great scientific discoveries of the last decade. SNO was based on two unique Canadian resources: 1000 tonnes of heavy water available via the CANDU reactor program, and a location two kilometres underground in an INCO nickel mine near Sudbury, Ontario.



SNO determined that the neutrinos from the Sun were changing their identity – mutating – during their trip to Earth, and that the total number of neutrinos in fact agreed with the solar model predictions. This behaviour, called “oscillation”, is only possible for neutrinos having mass; prior to the SNO results, neutrinos were believed to be massless.

The discovery that neutrinos have mass has raised intriguing new questions about their behaviour. Using the expertise acquired while building and operating SNO, Canadian scientists have now moved ahead with the construction of an expanded laboratory at the SNO site called SNOLab, funded by the Canada Foundation for Innovation. Experiments at SNOLab – the best deep underground lab in the world – will help to address these new questions, improving our knowledge of neutrinos, dark matter, and their role in the evolution of the universe.



A schematic layout of the 6800-foot level of the Creighton mine, near Sudbury. The cavern on the far left is approximately 25-m high and houses the SNO experiment; the new SNOLab facility is the square set of tunnels at the top-left of the figure.

Two panoramic views of the ISAC beamlines at TRIUMF in Vancouver.

Canadian Successes

Nuclear Structure and Nuclear Astrophysics Studies

Only the lightest elements (hydrogen, helium and lithium) were created in the Big Bang; all of the heavier elements, including everything we are made of, have been synthesized through nuclear reactions involving unstable exotic nuclei in normal stars and explosive astrophysical environments. The study of the structure and reactions of these exotic nuclei in the laboratory is the field of Nuclear Structure and Nuclear Astrophysics, and again Canadian scientists are leaders.

The Isotope Separator and Accelerator Complex (ISAC) facility at TRIUMF, Canada’s national nuclear and particle physics laboratory in Vancouver, is recognized as the world’s most advanced laboratory for the production of exotic isotopes. Canadian physicists, working with state-of-the-art detection systems at ISAC, are world leaders in

The world's largest cyclotron, at TRIUMF.

studying the structures and reactions of nuclear matter under extreme conditions. Early studies have already led to a better understanding of the production of radioactive isotopes in explosive astrophysical environments.

Canadian scientists are now completing a major upgrade to ISAC, called ISAC-II. ISAC-II will accelerate heavier exotic beams to higher energies, and use these beams to study nuclei involved in the production of the heaviest elements. The combination of ISAC and ISAC-II will shed new light on the life cycle of stars and the origin of the elements, and ensure continued Canadian leadership in this exciting field of science.

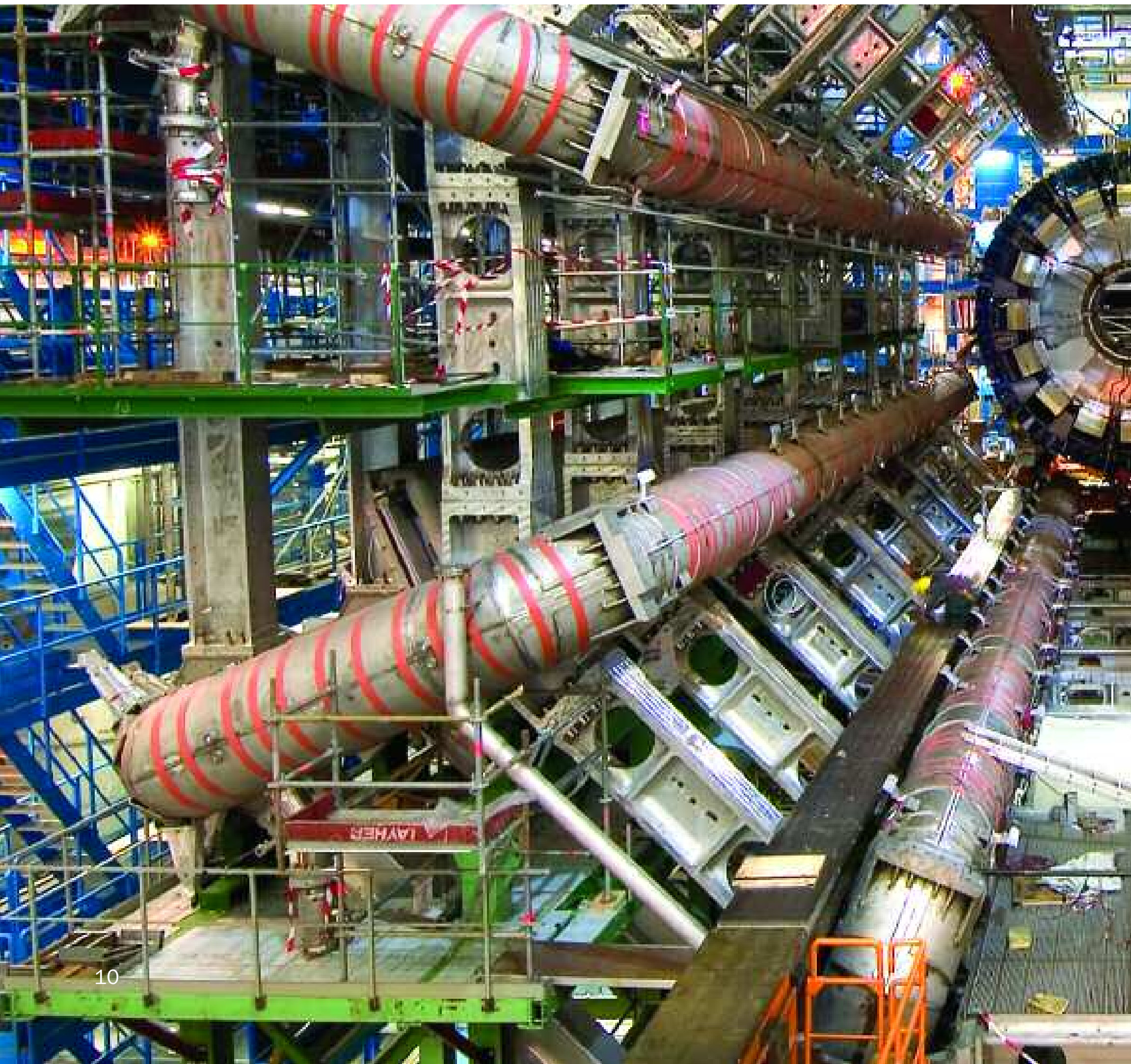
Canadian Successes

Some of the more than 1800 scientists from around the world who are members of the ATLAS collaboration.

PHYSICS AT THE VERY HIGHEST ENERGIES – THE LHC & THE ILC

Canadian physicists are heavily involved in the ATLAS project, studying proton-proton collisions at the highest energies available on earth. ATLAS will start taking data in 2007 at the Large Hadron Collider (LHC) at the CERN laboratory in Switzerland. The high energy of the LHC collisions will allow new particles to be discovered and studied. Among the most anxiously awaited is the so-called Higgs boson. In the current theoretical framework of subatomic physics, called the Standard Model, the Higgs is predicted to be the particle responsible for endowing mass.

The Standard Model has been an excellent description of particle physics to date, but we know that it is not a complete theory – it includes neither dark matter, nor gravity. Numerous extensions to the Standard Model exist, and embed dramatic new concepts like extra space-time dimensions beyond the four we know. Canadians have been leaders in developing and testing these theories.

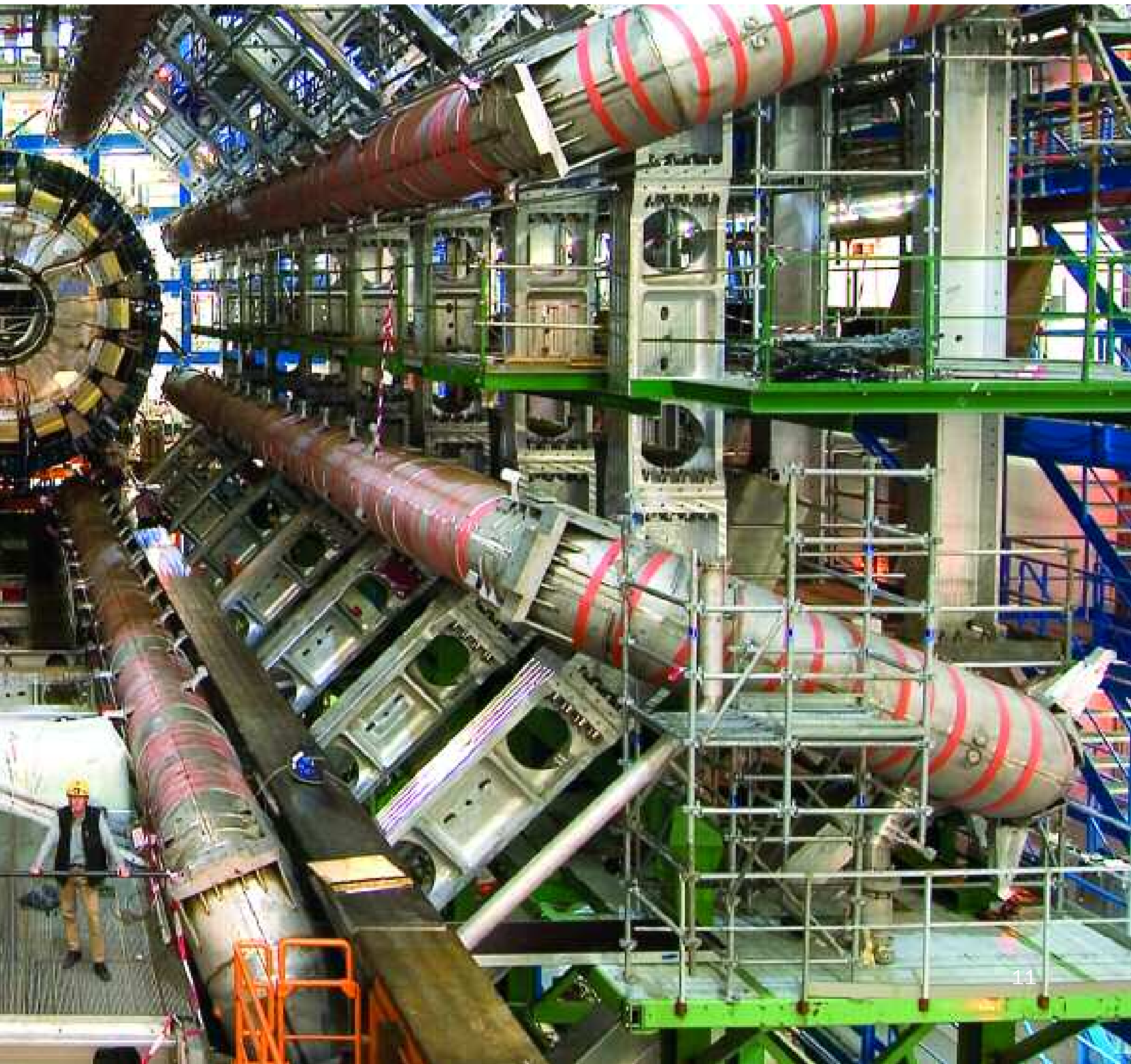


First evidence for them would be a breakthrough of monumental proportions, and may come from the ATLAS experiment.

ATLAS and the LHC are likely to operate for more than a decade, and are expected to produce a vast array of exciting results, giving rise in turn to new questions. Further in the future is the proposed International Linear Collider (ILC). The ILC, colliding electrons and positrons (anti-electrons), will provide cleaner conditions than those of the LHC, helping to clarify and extend discoveries made there. The complementary approaches of the LHC and the ILC will be essential to understand physics beyond the Standard Model.

Canadian physicists are key players in ATLAS; new investment in our science will ensure that we remain among the leaders in the ILC project and the discoveries that will be made there.

The partially-assembled ATLAS detector at CERN's LHC accelerator, as it appeared in late 2005. To set the scale, note the man standing at the bottom-centre of the photograph.



Subatomic Physics and the Economy

SUBATOMIC PHYSICS TRAINING IS AN INVESTMENT IN A TECHNOLOGICALLY INNOVATIVE ECONOMY

Modern experiments in subatomic physics are challenging and require technical innovation. For example, the goal may be to measure the rare decay of a new particle in order to challenge a prevailing theory. This may require a detector of unprecedented resolution, or a novel way to suppress background sources. As a result, experiments in subatomic physics drive detector and electronics innovation, often leading to new technologies. Examples include high precision particle detectors at the heart of medical imaging devices; the World Wide Web, invented to allow subatomic physicists to share data world-wide; radioisotopes produced at particle accelerators that aid in the detection and treatment of disease; and high performance computing, driven by the insatiable demands of large particle physics experiments, that today aids in the development of new pharmaceuticals.

Of course, the results of basic research such as subatomic physics cannot be predicted, but it is clear that the outcomes are often of practical and economic importance. Studies have estimated that the annual return on investment in basic research ranges from 28% to 50%, and that Canada's investment in subatomic physics research has paid for itself many times over.

As Canada's economy shifts from resource- to knowledge-based, scientists and technologists are essential to ensure that basic research advances are transformed into new industrial processes and products. Subatomic physics research pushes the frontiers of human knowledge, but also lays the foundations for new technologies in the physical and life sciences, changing the way we travel, communicate and work.

Canadian subatomic physicists have developed technology, such as these test-tube sized radiation detectors, that is now sold around the world.

I'm a physicist in the pulp and paper sector. Designing the experiments, analyzing and documenting the results, and offering simplified explanations without losing the science are all skills that I learned during my Ph.D. in experimental high energy physics.

Reena Meijer-Drees, Ph.D.
(University of British Columbia, 1991)
Principal Research Scientist, Honeywell

In subatomic physics one has many opportunities to see how successful scientists understand a system at various levels of abstractions, from black box all the way down to root cause when required. IBM's Blue Gene/L supercomputer is a nice demonstration of the value of training in subatomic physics.

Burkard Steinmacher-Burow, Ph.D.
(University of Toronto, 1994)
Blue Gene/L System Development, IBM

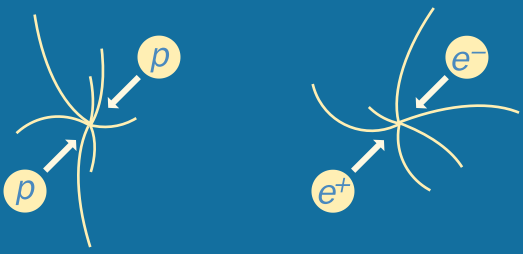
My training led me to a postdoctoral stay at the Fermi National Accelerator Lab near Chicago studying proton-antiproton collisions at the highest energies, and then back to Montreal for a faculty job where I'm now working on the ATLAS experiment at CERN. To contribute to a project of the magnitude and scientific importance of ATLAS is a once-in-a-lifetime opportunity.

Brigitte Vachon, Ph.D.
(University of Victoria, 2002)
Canada Research Chair, McGill University

Obtaining a physics Ph.D. is a valuable discipline to learn; it means tackling a large, complex problem to which the solution cannot immediately be seen. The patience, persistence and detachment necessary to complete the research are skills that translate readily to the business world.

LeeAnn Janissen, Ph.D.
(Carleton University, 1993)
Vice President & Director, TD Securities

2 PATHS TOWARDS DISCOVERY



In the near future, the Large Hadron Collider (LHC) will collide protons (left). Beyond that, the International Linear Collider (ILC), shown in the picture above, will produce electron-positron collisions (right). Studies at the ILC will be necessary to understand any new particles discovered at the LHC.

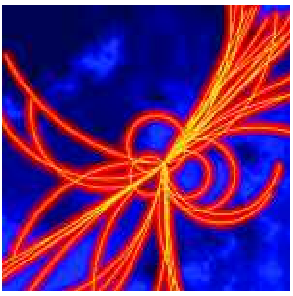
The Next Decade for Subatomic Physics in Canada

An artist's conception of the future International Linear Collider (ILC), which will collide electrons and positrons at an energy of approximately 500 GeV and will start operations in the next decade.

Canada has a strong position in subatomic physics, with a record of accomplishment and the people to retain that position. Physicists in Canada have focussed on the most important questions in this field. Increased research funding over the next several years would enable us to make full use of the facilities and experiments we have helped to develop – including the world-class SNOLab and ISAC facilities in Canada – and to be leaders in the exciting new physics that will be done there.

Over the longer term such support would ensure that we participate in the next generation of leading-edge physics at facilities such as the International Linear Collider, while maintaining the diversity of research efforts that is necessary for the health of our field.

Increased funding for subatomic physics would enable Canada to maintain its position at the very forefront of our science, participating in the excitement that will emerge from today's laboratories and leading the new projects that will help to answer some of the most compelling questions in science.



A simulation of particles emerging from the decay of a Higgs particle produced in a high-energy electron-positron interaction.

A view of the ATLAS Hadronic Endcap Calorimeter prior to installation. The HEC was constructed in Canada and assembled at TRIUMF.

With continued strong support, Canada will be a leader in the next renaissance in science.

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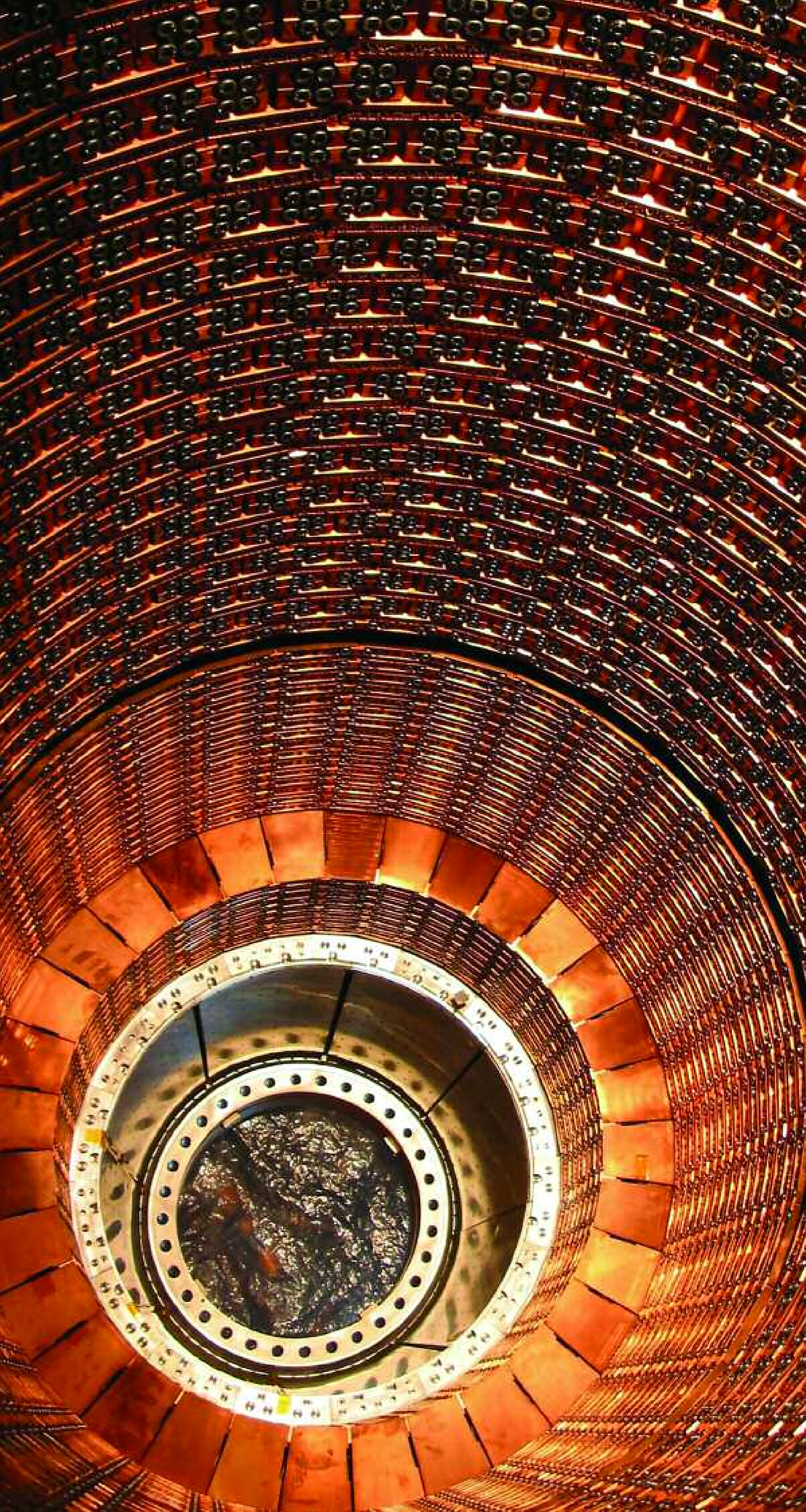

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