The Sudbury Neutrino Observatory

Trapping Elusive Particles Sent by the Sun

Deep in a mine in northern Ontario, Canada, the Sudbury Neutrino Observatory (SNO) counts tiny particles emitted in abundance by the Sun. Billions of them are passing through your thumbnail right now! Miniscule and inconspicuous, these neutrinos have less than one chance in a trillion of being stopped by the entire mass of our planet.

Still, using a 1000-tonne heavy water neutrino trap, SNO is able to catch a few solar neutrinos per day.

The experiment has been a resounding success, resolving a decades-old mystery about the inner workings of the Sun.

Aerial View of Inco's Creighton Mine
Sudbury, Ontario, Canada
The above-ground facilities of the Sudbury Neutrino Observatory are nearby, but the detector is two kilometres below ground.

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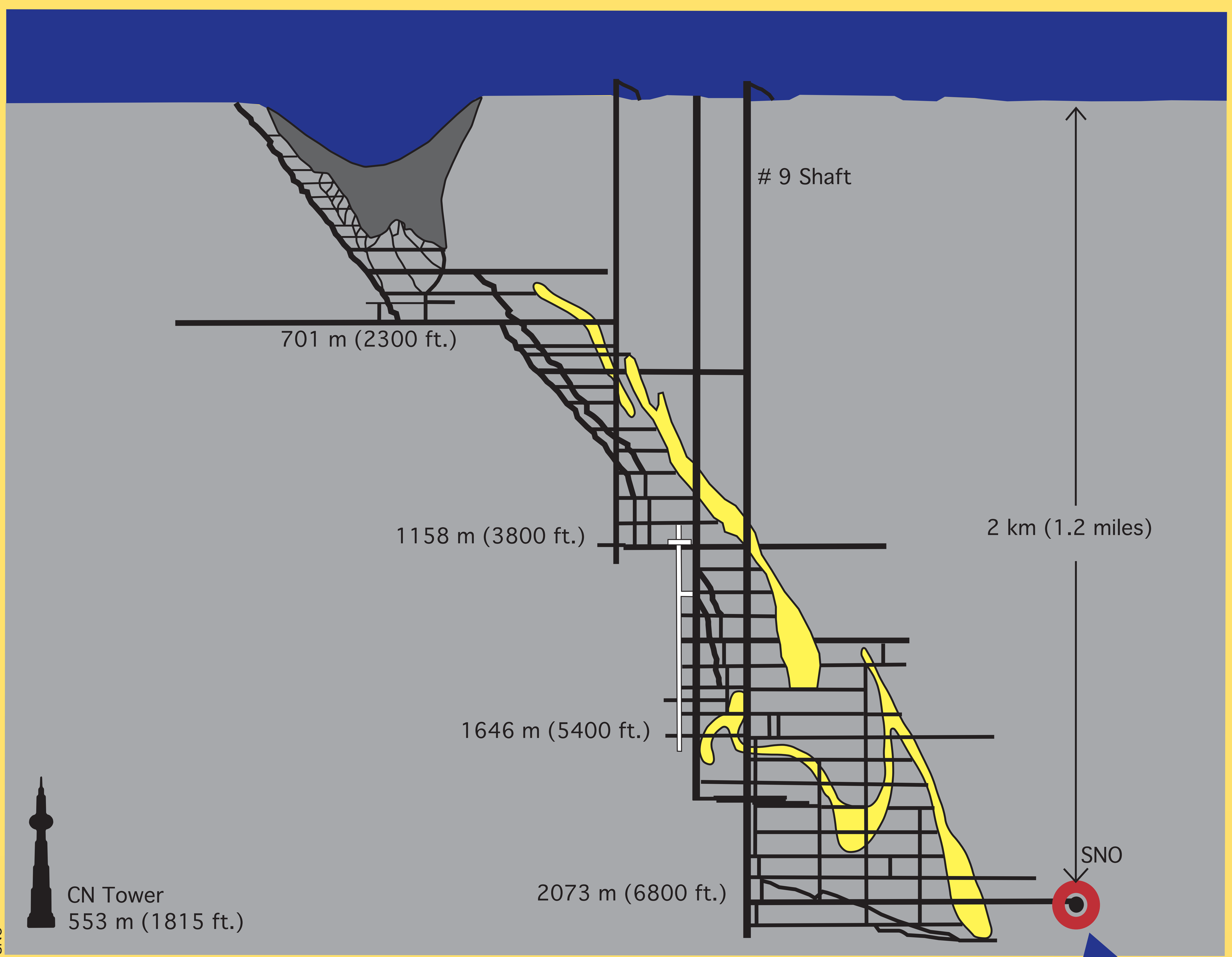
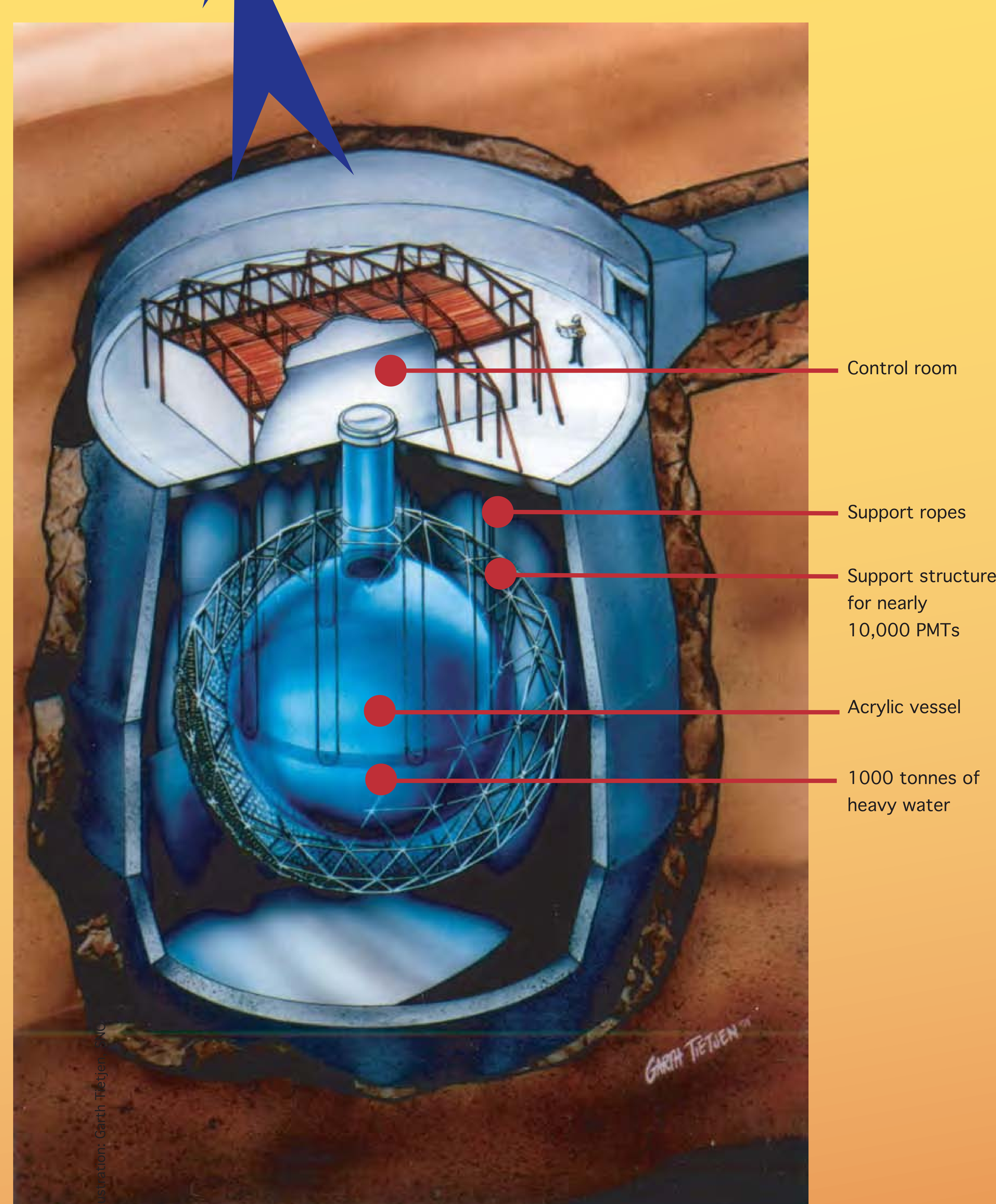
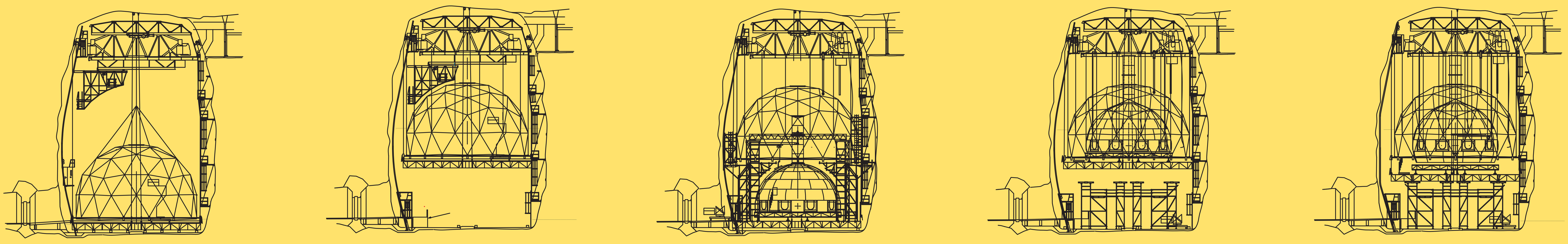


Profile of Inco's Creighton mine, showing the location of SNO

Artist's concept of the SNO detector, showing the acrylic vessel and supporting structures and facilities





What is the function of the Sudbury Neutrino Observatory?

A

To study sunspots and solar flares?

B

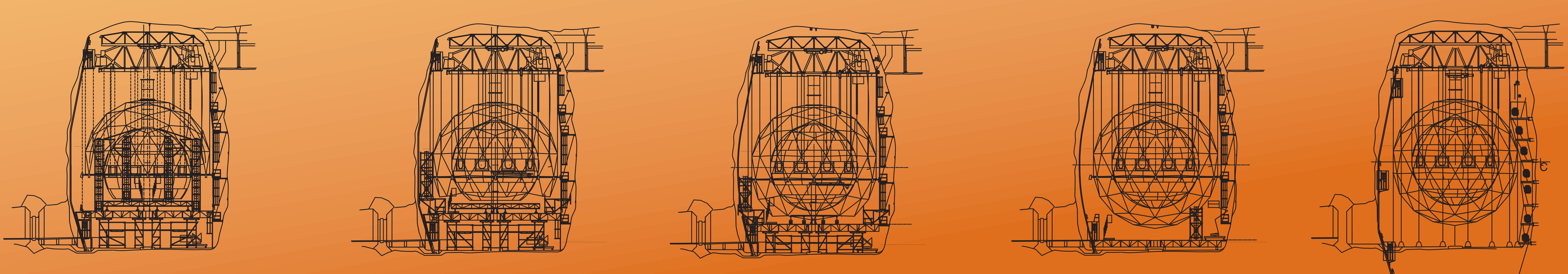
To count the hard-to-catch particles produced deep within the Sun?

C

To investigate the atomic structure of radioactive substances?

ANSWER:

B) To count the hard-to-catch particles produced deep within the Sun.



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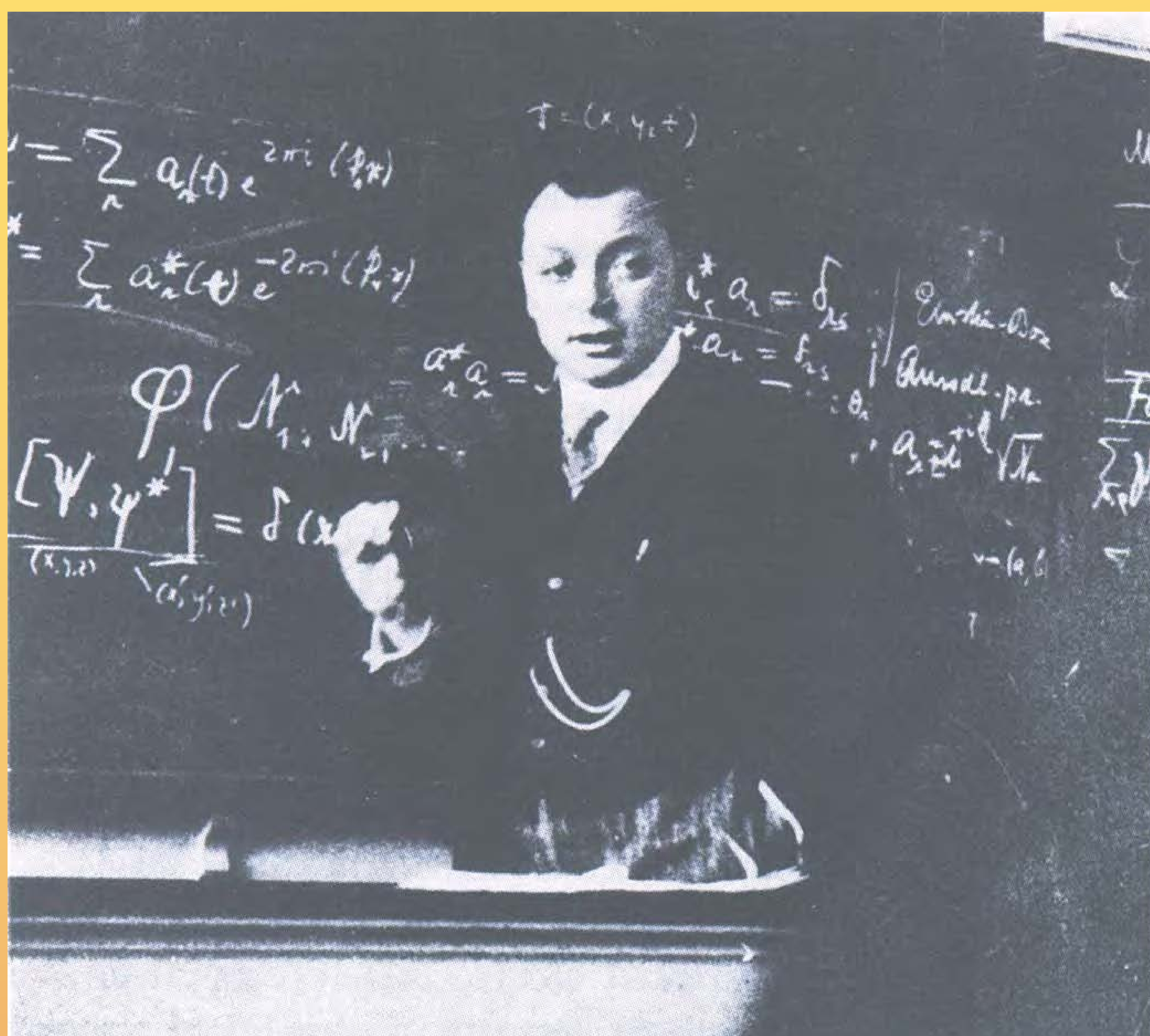
Why we did the experiment

The Neutrino Story

In 1930, in order to solve a baffling physics problem of disappearing energy, Wolfgang Pauli predicted an invisible particle: the “neutrino”. By the 1960s, physicists were able to use computers to calculate how many neutrinos might be generated by the Sun’s energy-producing processes. But measuring these particles was extremely difficult, because they pass right through the Earth, rarely interacting with a single atom.

“ I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do.”

— Wolfgang Pauli (1932)



Wolfgang Pauli 1900–1958
In 1930, Wolfgang Pauli first conceived of neutrinos—originally as a solution to a problem in nuclear physics. Neutrinos are so elusive that it would be 26 years before they were actually detected.

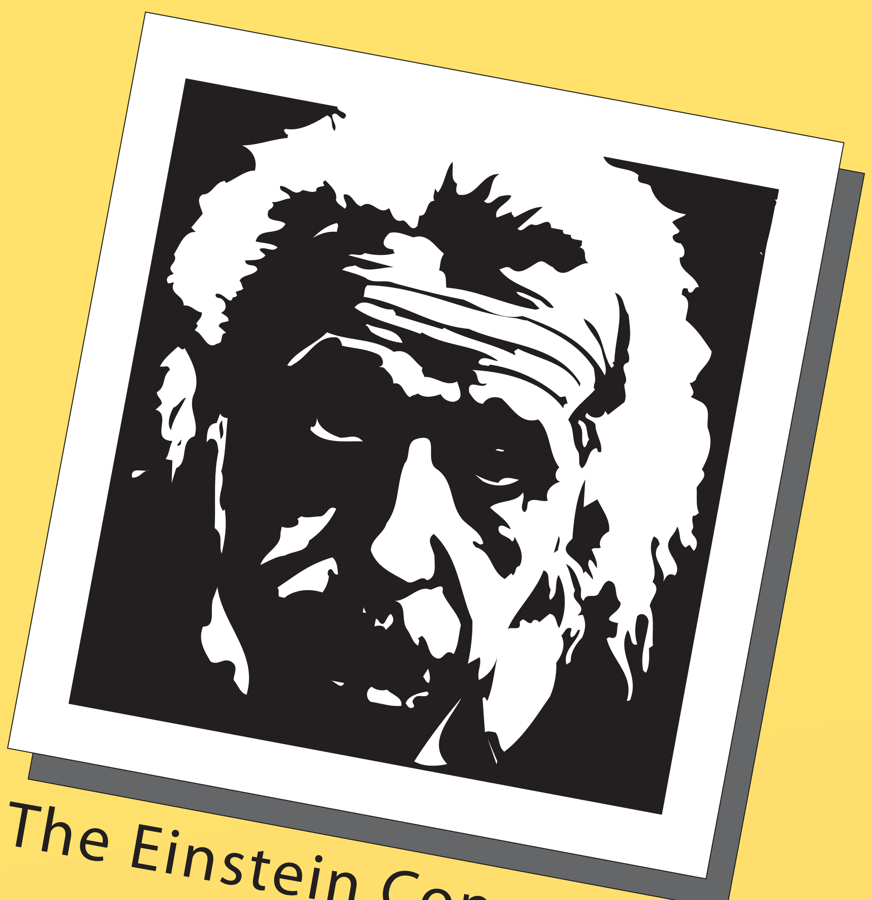
How the Sun Shines

Special Relativity and $E=mc^2$

(Energy equals mass times the speed of light squared)

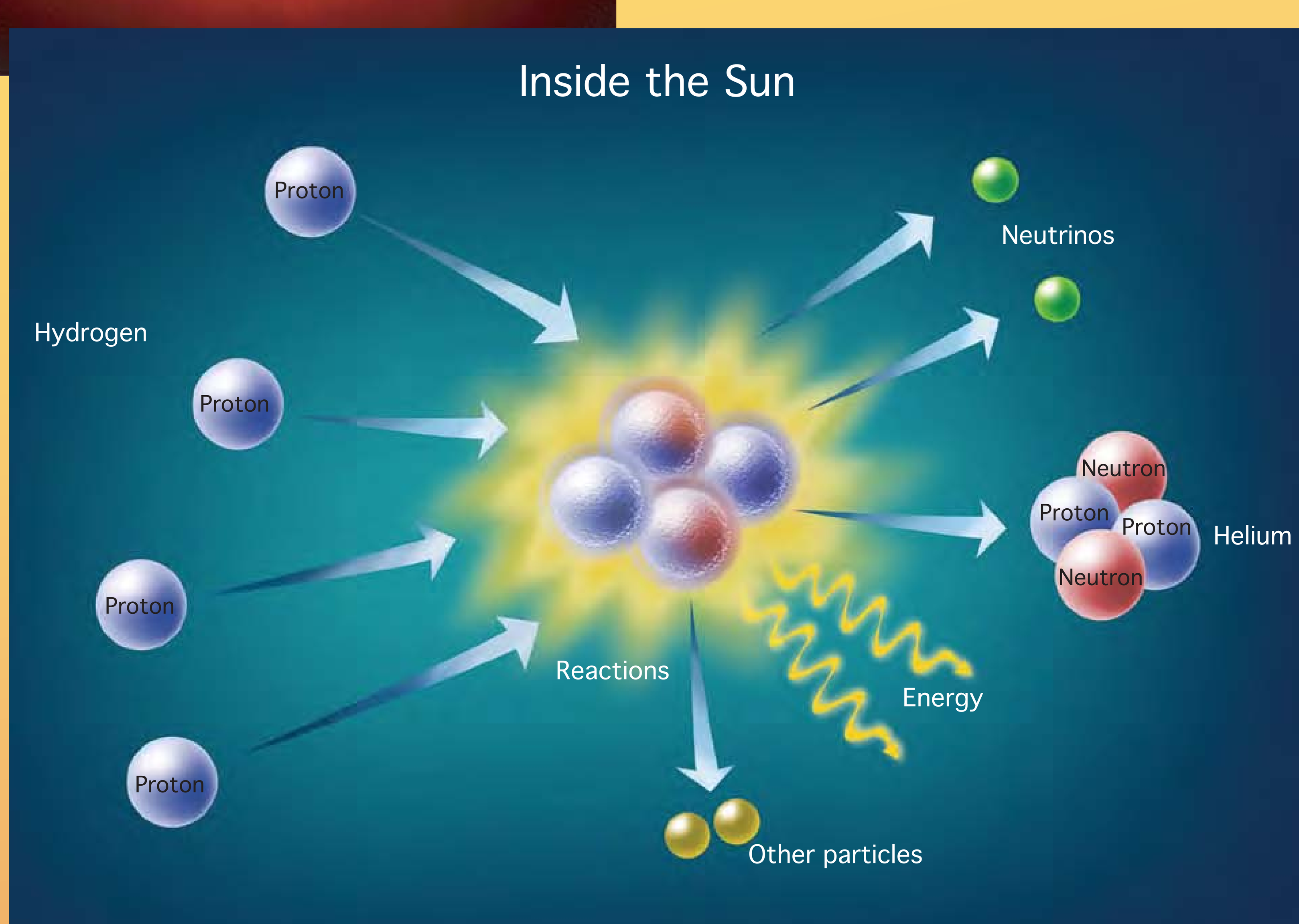
In 1905, as Einstein contemplated how the laws of physics governing light and motion would change at high speed, he came to a startling conclusion: matter and energy must be different aspects of the same thing!

Deep in the Sun's core, four hydrogen atoms fuse into one helium atom, which is lighter than all four original hydrogen atoms combined. That extra mass is converted to energy and eventually released into space as rays of light.



The Einstein Connection

Activity on the surface of the Sun is an indirect indicator of activity in its core. Neutrinos provide a direct link to the Sun's nuclear powerhouse, and provide a way of checking theories about the reactions that heat the Sun—and us here on Earth.



When hydrogen fuses into helium, it releases energy and tiny neutrinos. Scientists originally predicted that, in any given second, about 5.1 million high energy solar neutrinos are passing through each square centimetre of Earth's surface.

The Missing Solar Neutrinos

A Longstanding Mystery

In 1968, when scientist Raymond Davis, Jr. began to count solar neutrinos, he found only one-third the expected number.

Did that mean scientists didn't understand the Sun? Or did Davis make a mistake?

This problem puzzled physicists for over thirty years.

Raymond Davis Jr., 1999

In 1968, Raymond Davis was the first to successfully detect neutrinos from the Sun. He used this tank, 6 metres (20 feet) in diameter and 15 metres (48 feet) long, underground in the Homestake mine, South Dakota. The tank held 400,000 litres (100,000 gallons) of dry-cleaning fluid (perchloroethylene).

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Neapolitan Neutrinos

Chocolate, Strawberry and Vanilla

Since the 1970s, scientists have been convinced that neutrinos can have three different “flavours”: electron-neutrino, muon-neutrino and tau-neutrino. They also suspected that neutrinos might be able to switch between flavours. The Sun produces only electron-neutrinos or “vanilla” neutrinos.

Davis’s experiment was designed to identify these vanilla neutrinos. Did his experiment count too few of them because neutrinos change flavour on their way from the Sun to the Earth? Did the chocolate and strawberry ones just pass through undetected?

How we did the experiment

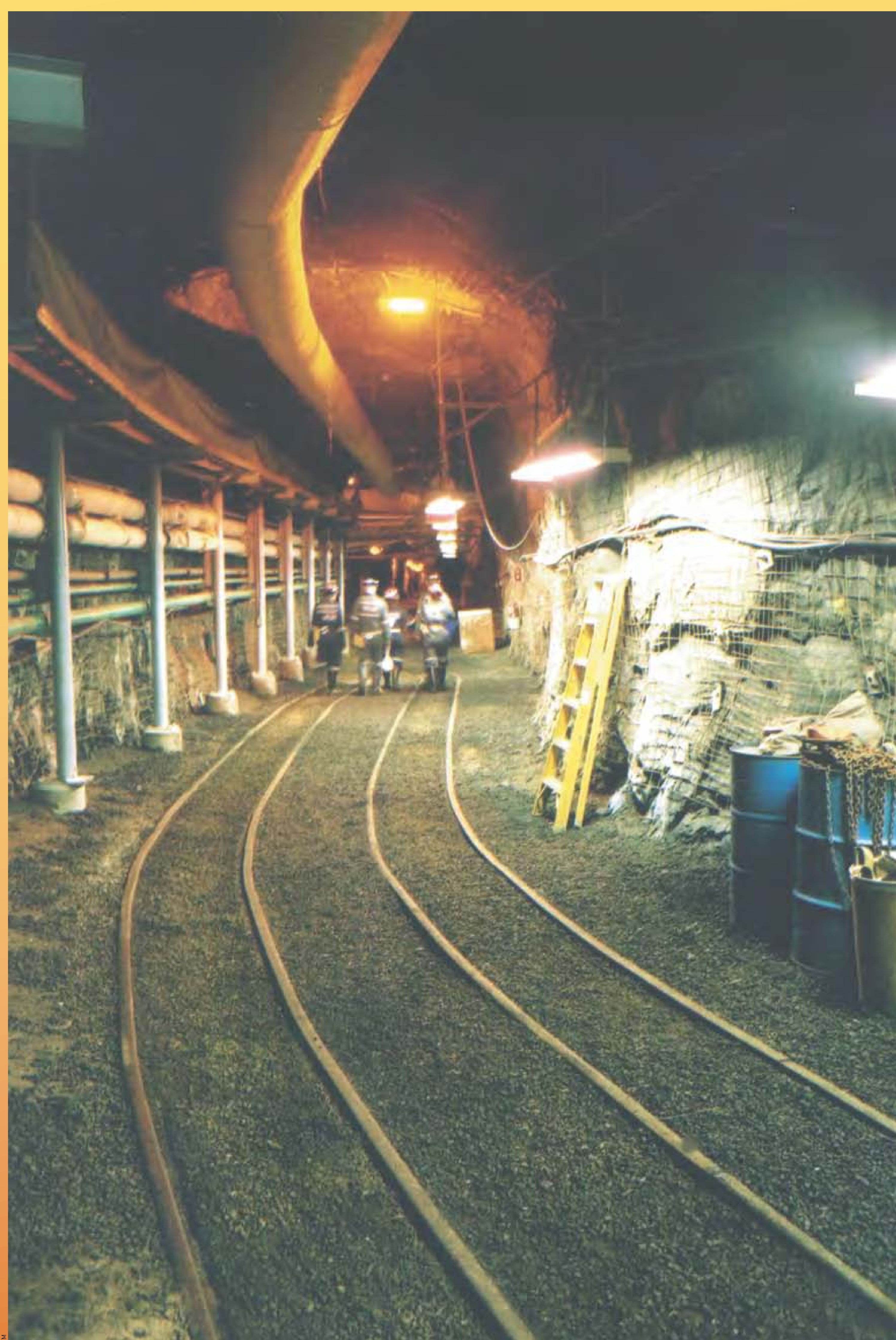
Cosmic Intruders

A Shield of Solid Rock

Particles from outer space, known as cosmic rays, constantly bombard the Earth, drowning out any neutrinos.

Because of this, the SNO detector is located in a mine, two kilometres underground. The rock shield reduces cosmic rays to a minimum.

But this protective rock has no effect on the neutrinos, which reach SNO in almost equal numbers day and night, as they continually pass through the Earth.

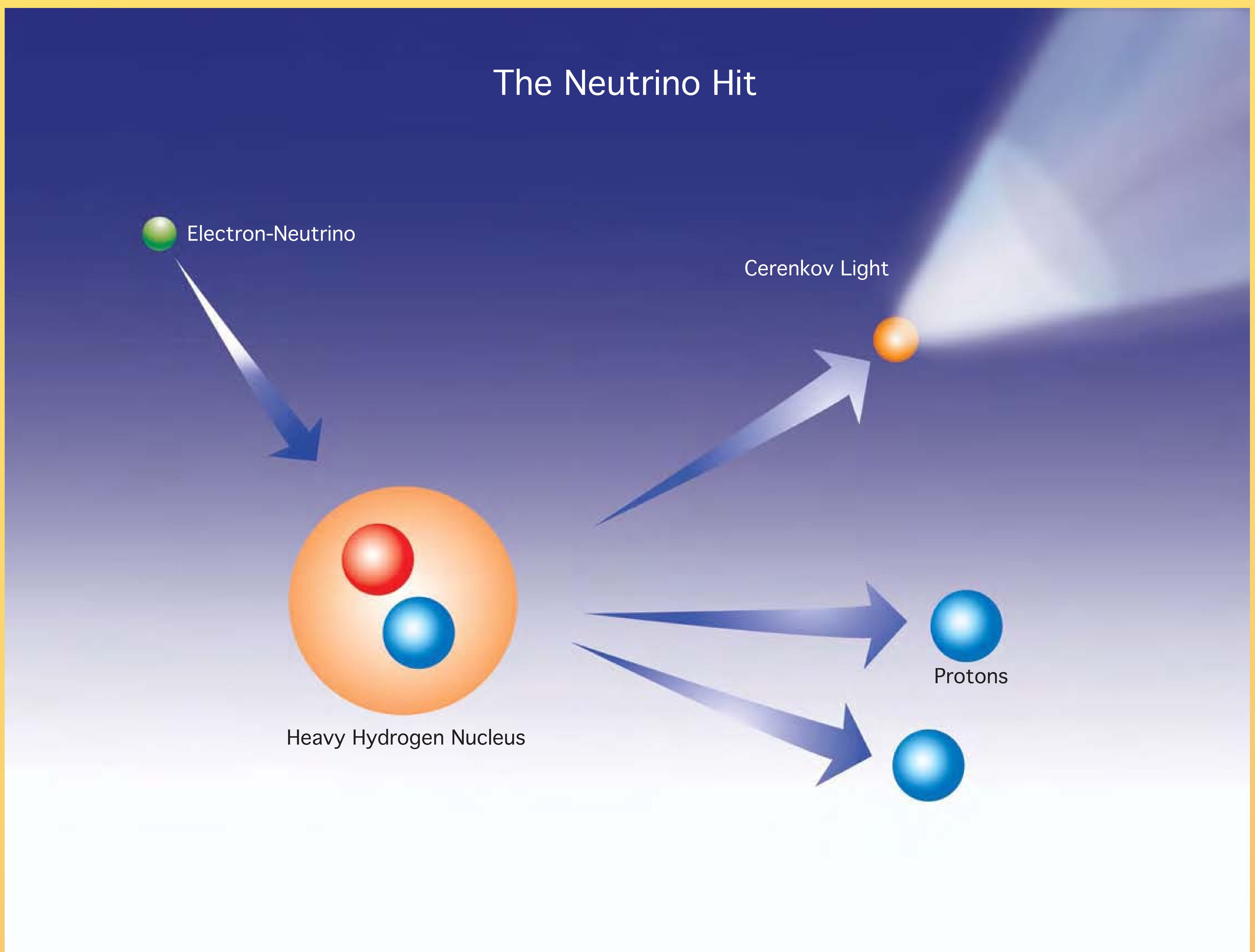


Setting the Bait

SNO Snares Neutrinos in Heavy Water

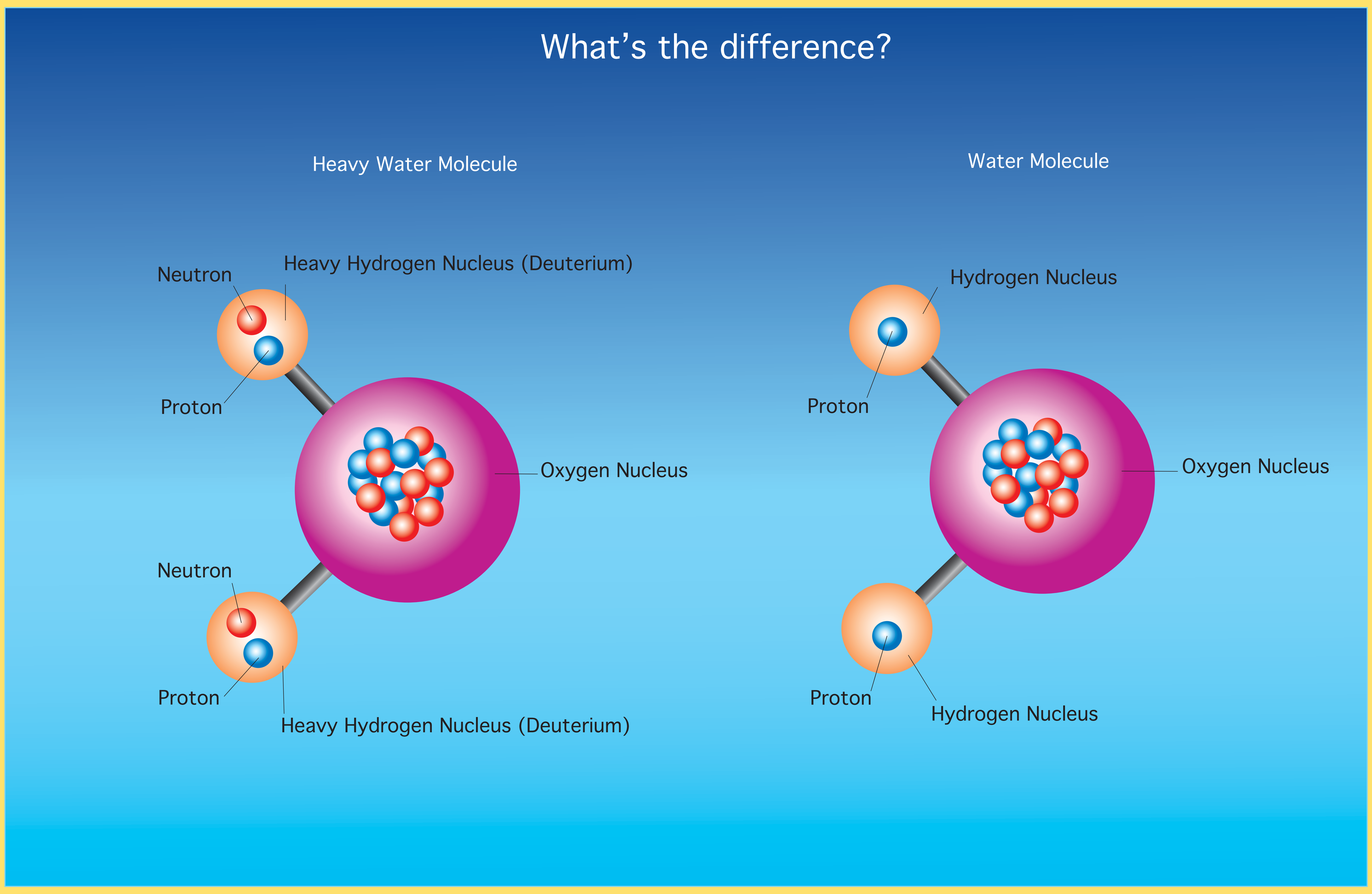
The secret of SNO's success is in the heavy water, which contains one more neutron in each hydrogen nucleus than in ordinary water. Any flavour of neutrino can break the nucleus up, freeing the proton and neutron. However, only an electron-neutrino, the "vanilla" neutrino, can change that neutron into a proton and an electron. And the SNO detector can tell the difference between the two reactions.

That's how SNO can tell the vanilla neutrinos, from the other two flavours.



The electron-neutrino collides with a heavy hydrogen nucleus, containing a neutron and proton, releasing two protons and an electron. The electron causes a small flash of cone-shaped light.

Heavy Water



In the molecule of heavy water, notice the neutron in the nucleus of the heavy hydrogen (deuterium).

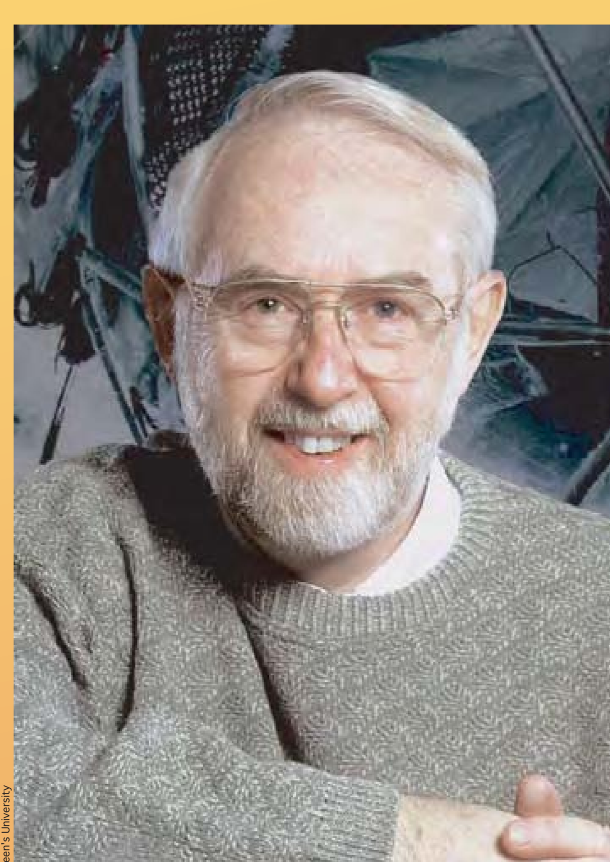
Why build this in Canada?

In the Canadian Shield, we already have a deep mine in Sudbury: Inco's Creighton mine. Nickel production is the primary function of this hard rock mine, but trapping neutrinos has made the mine famous around the world.

Our CANDU heavy water reactor technology and expertise means that there is an abundance of heavy water available for the SNO experiment.

We have qualified scientists, and institutions that support basic research.

Dr. Walter Davidson (left), National Research Council, one of the founding members of the project, with John MacDougall, former Member of Parliament for Temiskaming, an early advocate for SNO



Dr. Arthur McDonald, Queen's University, Kingston, Ontario, Director of the SNO Institute

Dr. Doug Hallman, Laurentian University, Sudbury, Ontario SNO Communications Director

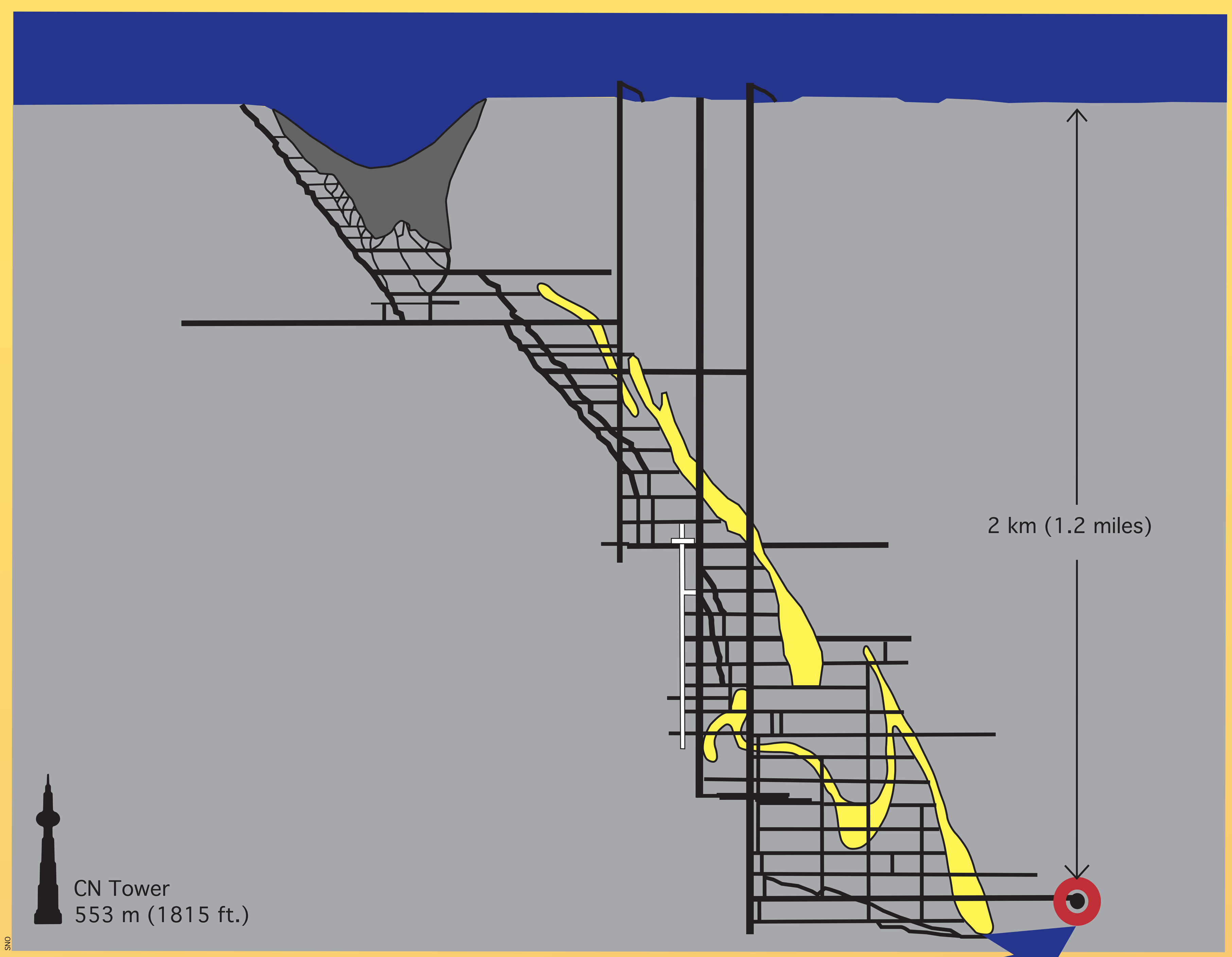
Dr. David Sinclair, Carleton University, Ottawa, Ontario, SNO Associate Director

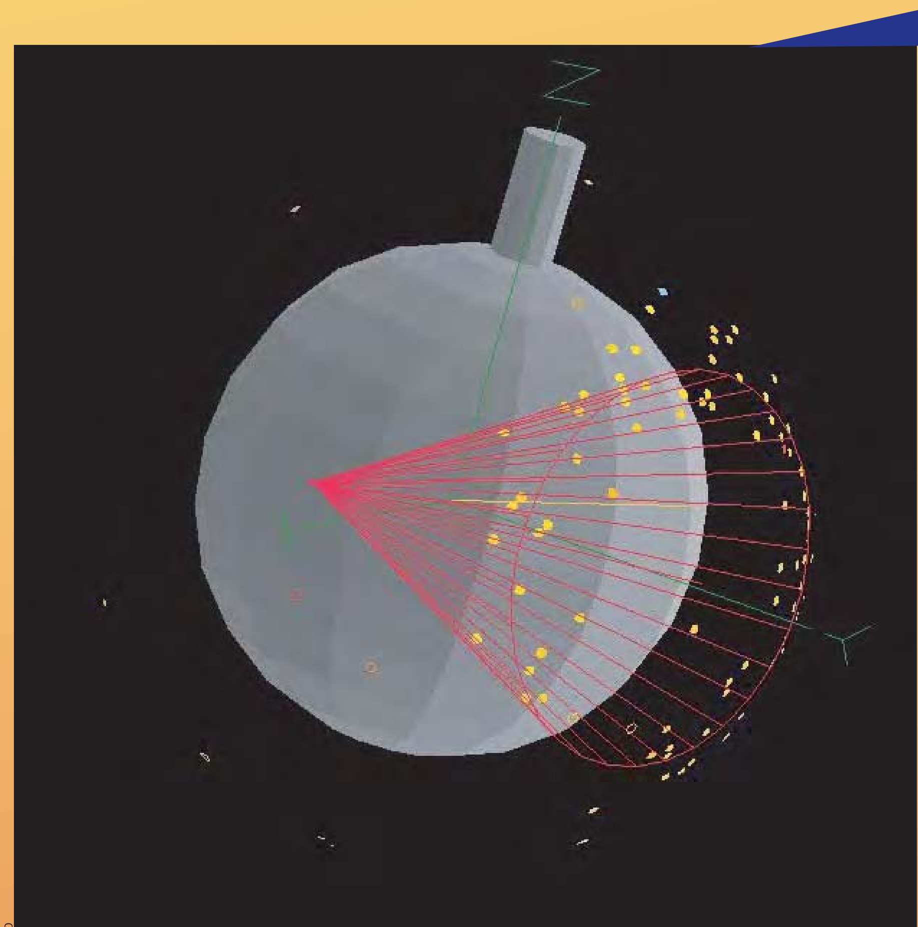
The Great Solar Neutrino Ambush

Hiding, Watching and Waiting

To trap the solar neutrinos, an enormous volume of heavy water was placed deep underground in a cavity ten storeys high. The heavy water was suspended in a colossal transparent sphere so that electronic "eyes" called photomultiplier tubes could watch from all sides for telltale flashes of light.

All the detector materials and the surroundings were purified to new standards. Then the experiment was sealed off to await one of nature's most unlikely occurrences: the interaction of a neutrino.





A solar neutrino is "captured" when it hits a molecule of heavy water. This results in a tiny flash of light that is detected by light-sensitive tubes. This collision happens once every two hours or so.

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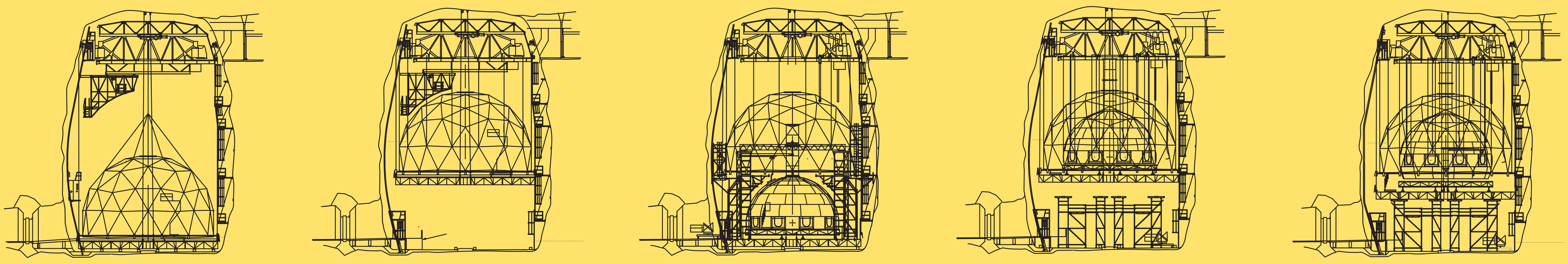
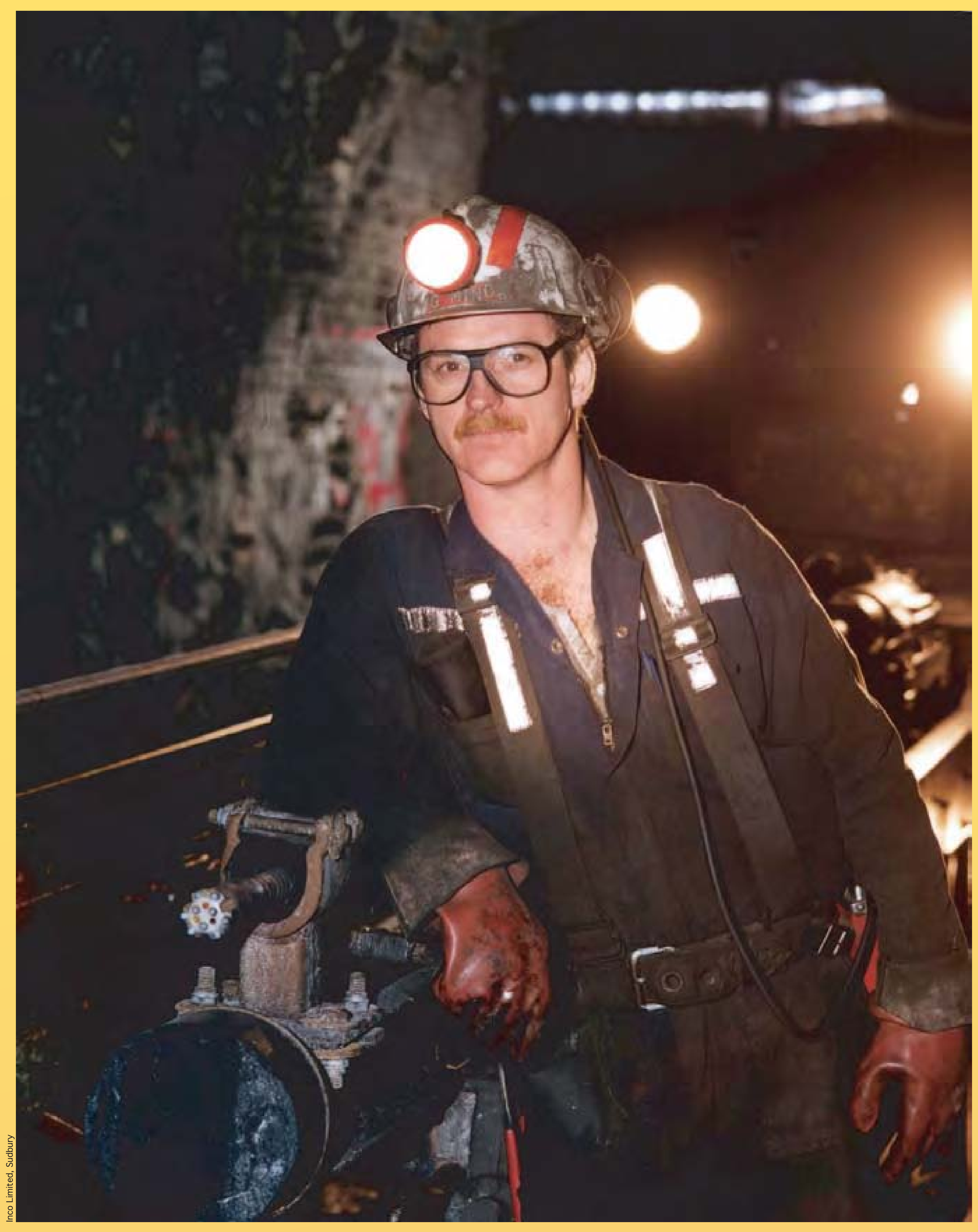


Subterranean Architecture

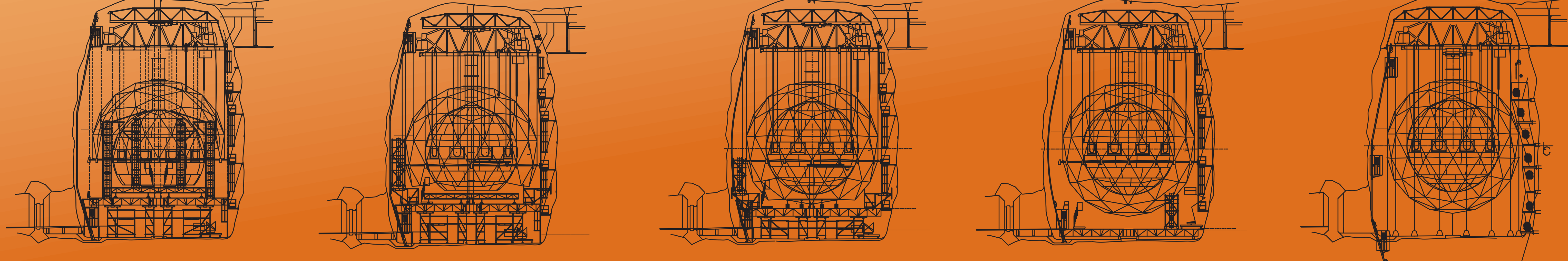
Extreme Mining

"For over three years, we miners worked in the deepest part of the Creighton Mine, blasting, shovelling and hauling out over 60,000 tonnes of rock, to carve out the cavern that would house that neutrino experiment.

"Inco developed cutting-edge excavation technology to support us. After all, we were digging the largest cavity at that depth in the world!"



The excavated cavity, two kilometres (1.2 miles) below Earth's surface, required the latest in mining techniques.



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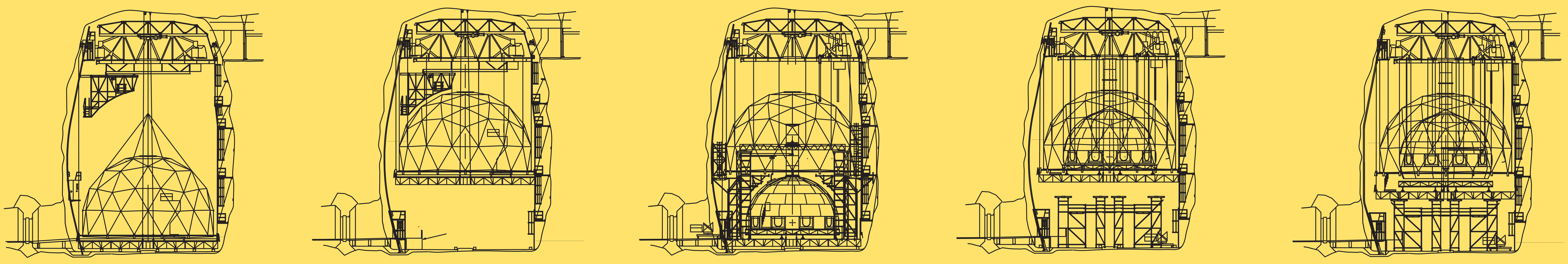
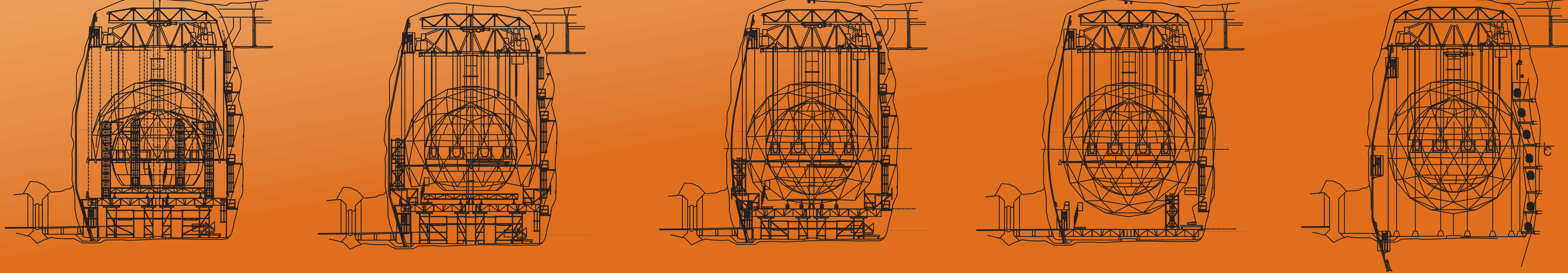


Clean as a whistle

To avoid contamination of the sensitive experiment, not only are visitors “cleaned” before they enter the Observatory, but the water and the heavy water used in SNO are purified to unprecedented levels. The SNO water purification system was designed by Carleton University physicists and built by Sepratech in Ottawa.



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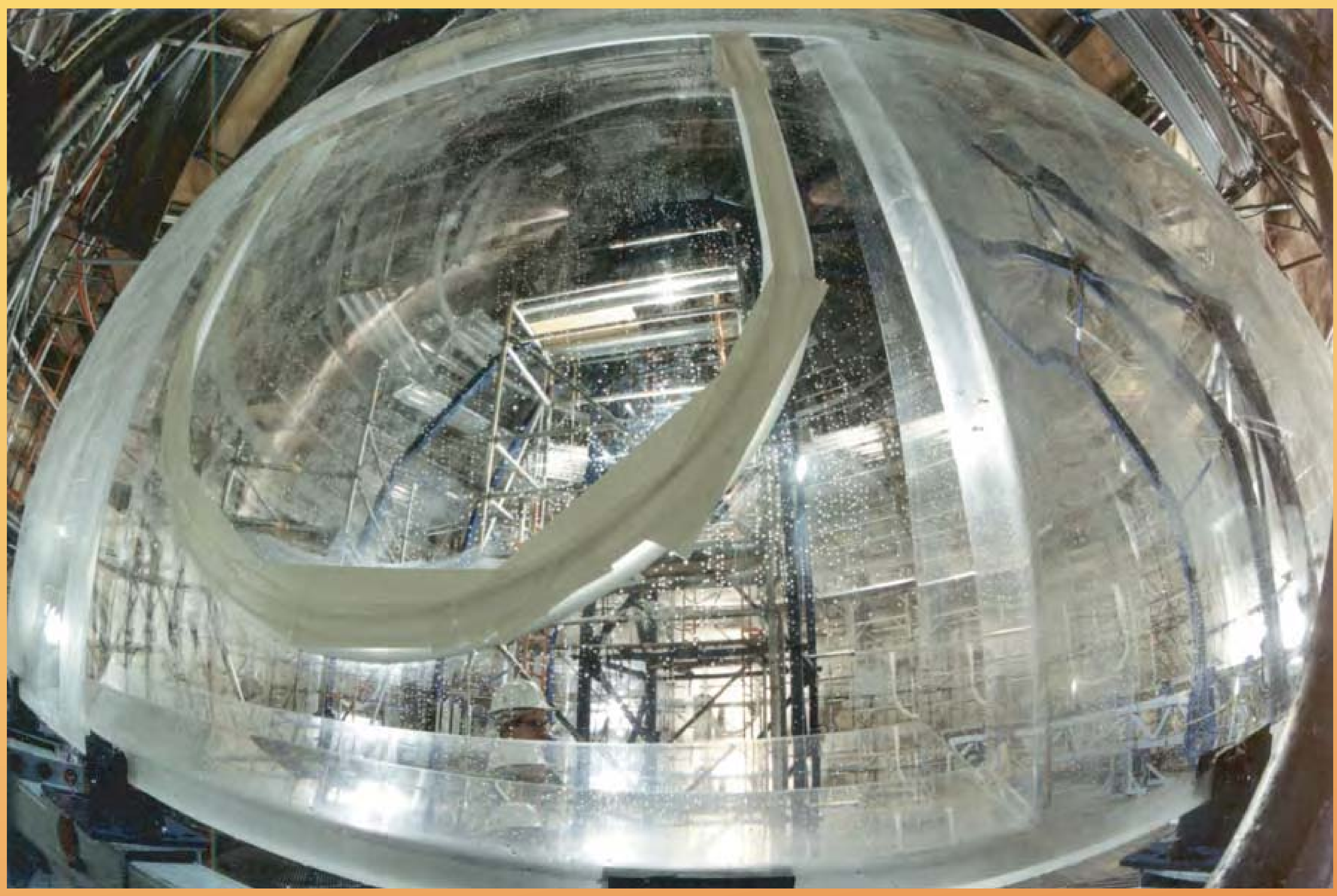
Floating Ball of Water

A Whale of a Thing

The world's largest acrylic vessel holds the heavy water. At 12 metres (39 feet) in diameter, the sphere could not fit into the mine hoist shaft! As a result, it had to be assembled underground from 125 pre-formed panels.

Ropes hold the sphere in place, but they do not have to support all of its weight. Like a colossal whale, the vessel is bouyed up in a bath of ordinary water, which fills the cavity.

The acrylic vessel, built to hold the heavy water which is essential to the experiment, is being inspected.



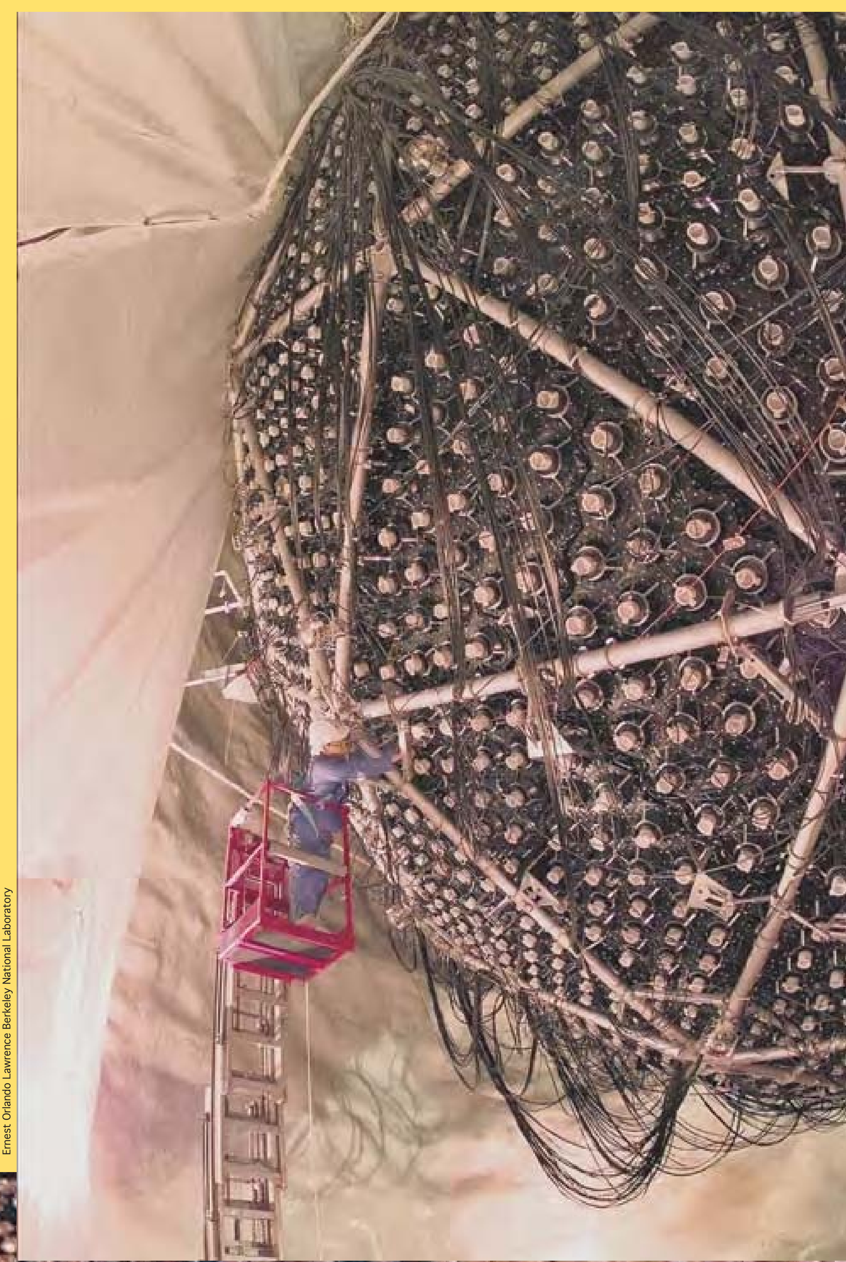
Wire ropes, looped through channels in the shell, support the vessel from above. The tension on these wires is monitored and is adjusted automatically.

Seeing the Light

Keeping an Eye on the Heavy Water

Neutrino interactions in heavy water release an electron which travels so fast that it generates a cone of light that spreads out like a sonic boom. A device called a photomultiplier tube (PMT) can convert this light into an electric current.

Almost 10,000 photomultiplier tubes surround the sphere of heavy water, looking for the tiny flash which signals that a neutrino has been snagged.

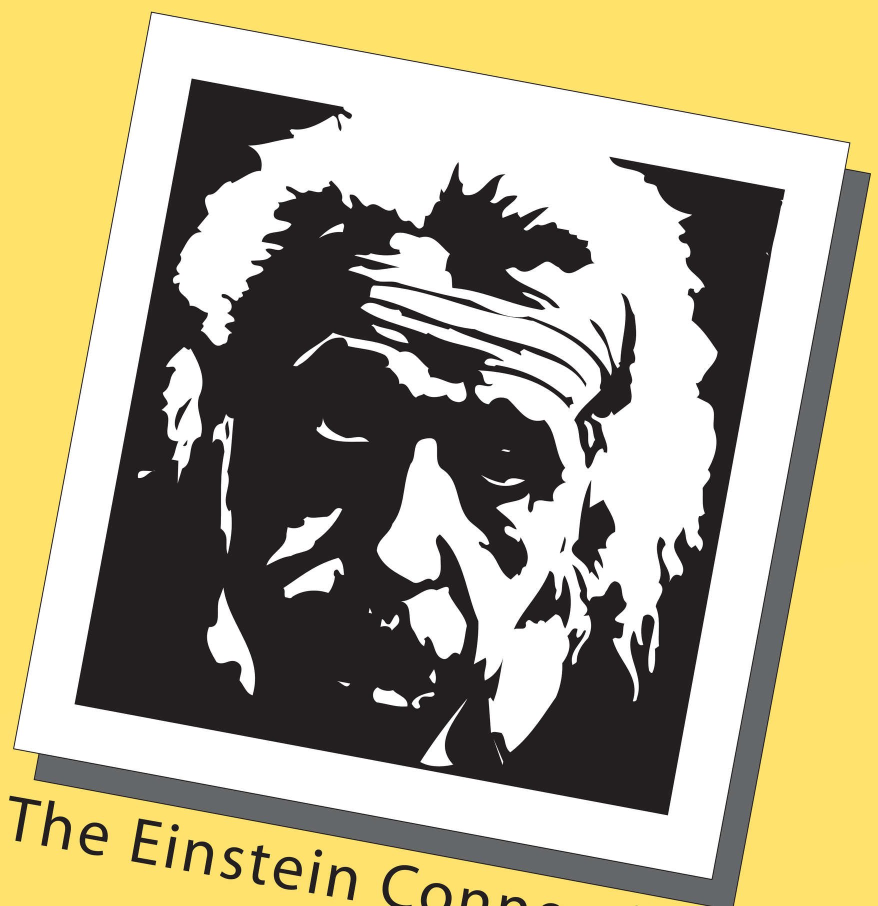


The Photoelectric Effect

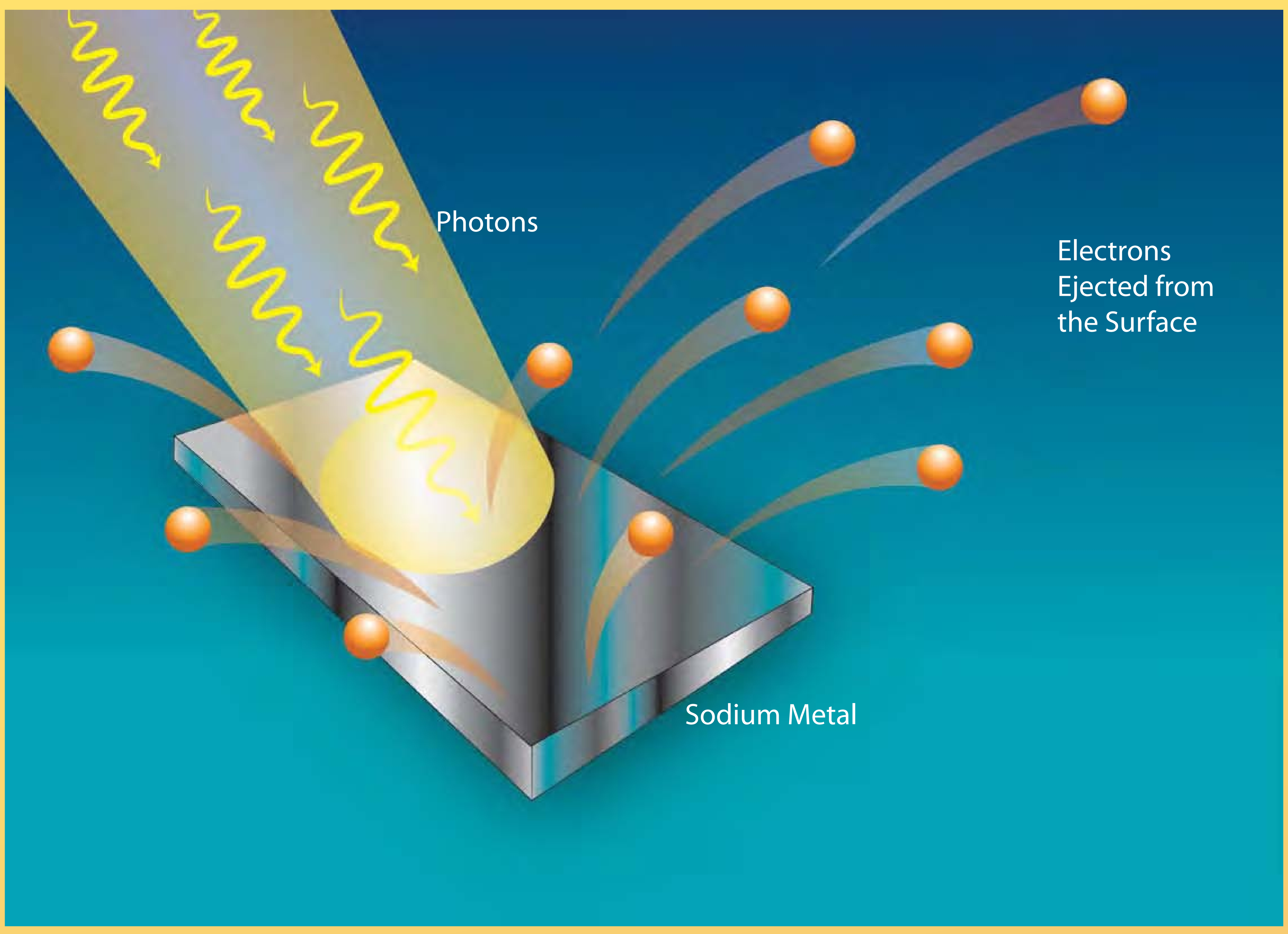
A Quantum Leap Forward

For over 100 years, it has been known that some metals emit electrons when light shines on them: the brighter the light, the more electrons. Einstein explained the effect by describing light as a stream of particles, or photons.

Einstein's conclusion supported the development of Quantum Mechanics. This theory describes positions and energies over very tiny distances, where events are determined by chance. Ironically, Einstein became an opponent of this theory, famously asserting that "God does not play dice with the Universe."



The Einstein Connection



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CHECKING 1, 2, 3 . . .

As it moves about within the sphere of heavy water, the laserball emits a tiny flash of light that is registered by every photomultiplier tube (PMT). This helps scientists understand the transparency of both the heavy water and the acrylic sphere. The laserball calibration device was developed by members of the Physics Department at Queen's University in Kingston, Ontario.

Queen's University collaborator, Dr. Peter Skensved, Århus University, Denmark, prepares to calibrate the PMTs, August 2000.

I'm HIT!

Recognizing a Neutrino

In the SNO detector control room, operators monitor data acquisition and electronic systems 24 hours a day.

The cone of light triggered by a neutrino interaction hits a ring of photomultiplier tubes. They then send their signal to banks of electronics for digitization and computer processing.

Racks of specially designed electronics monitor the nearly 10,000 PMTs. They relay data, including precise timecodes, from "events" in the heavy water to the computer, which sounds an alarm when a neutrino event may have occurred.

What did we find?

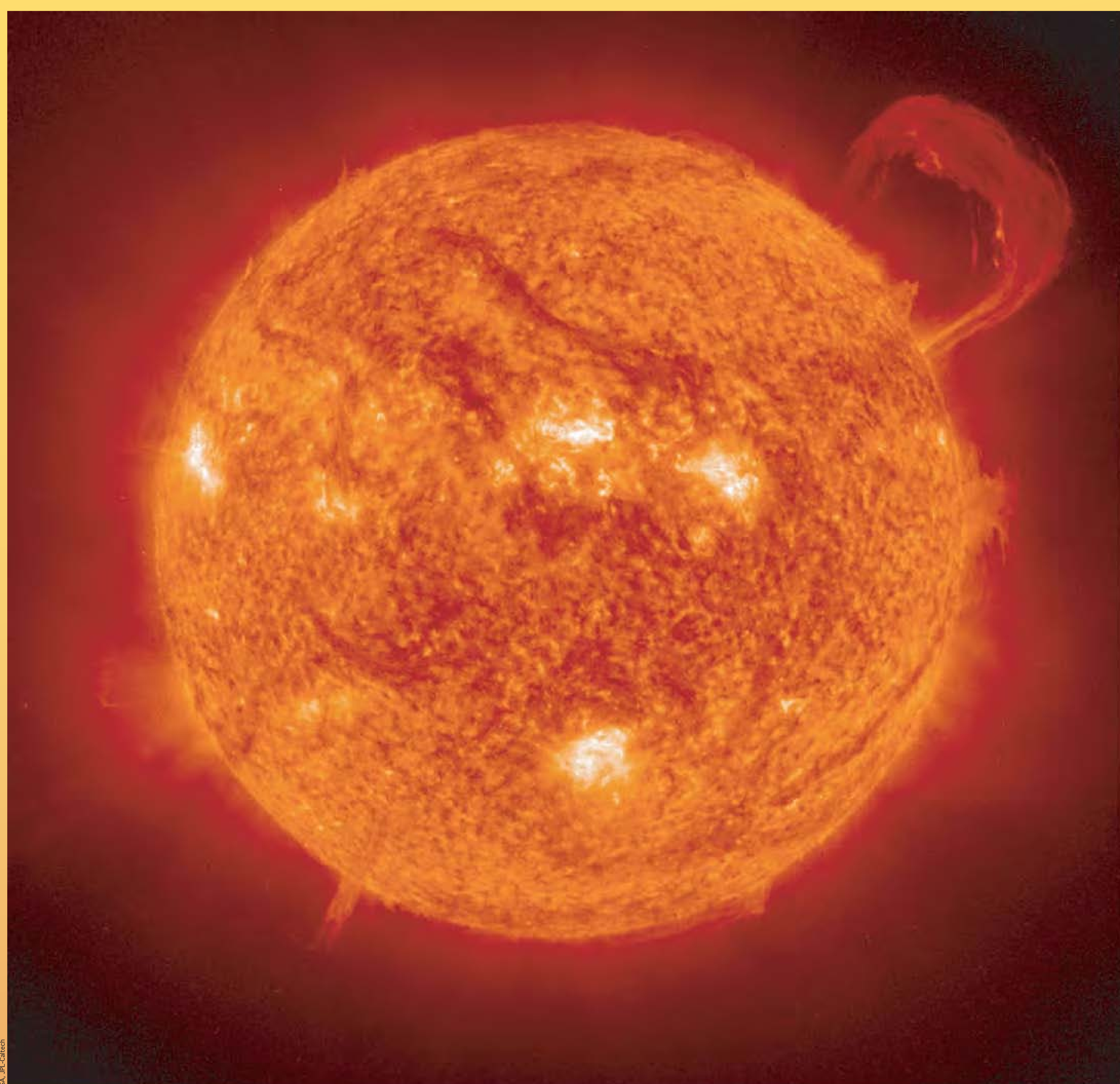
The Breakdown

Gotcha!

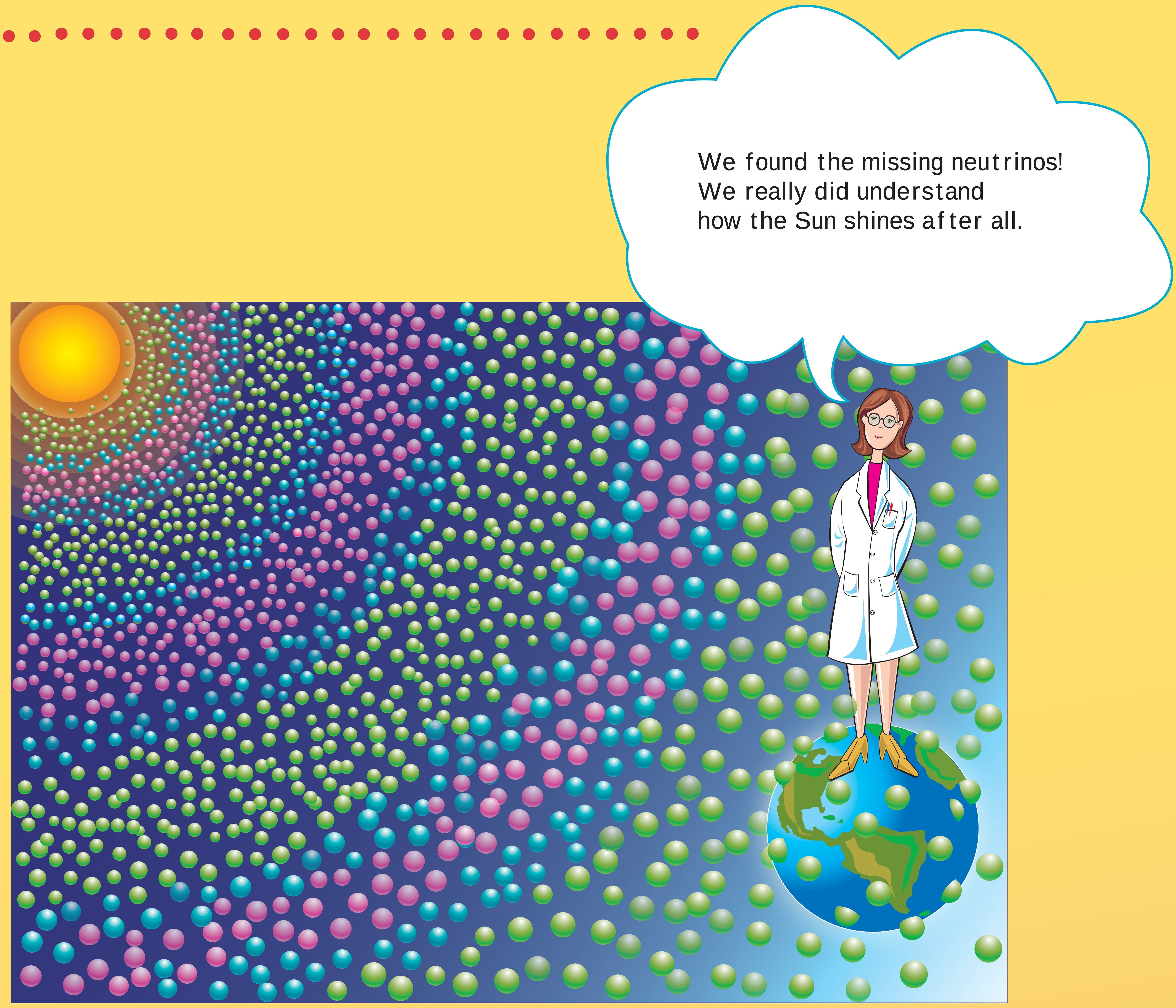
SNO counted the same total number of solar neutrinos reaching Earth as predicted, confirming that the nuclear fusion model for the Sun is accurate.

But only one-third of the solar neutrinos captured by SNO were electron-neutrinos. We know the Sun only produces this variety. This means that two-thirds of the neutrinos must have changed flavour en route.

As for those missing solar neutrinos: Davis's 1968 equipment could only detect electron-neutrinos. No wonder he missed the other two-thirds!



Success!



Based on results gathered since 1968, scientists detected only one-third of the number of neutrinos they expected to find.

By 2002, however, they were able to measure all three flavours of this elusive particle, thanks to SNO. This time, they found 5.1 million high energy neutrinos per square centimetre every second, which is what the theory originally told them to expect.

What Does It Mean?

The Neutrino Contribution

Long before SNO, it was known that the mass of a neutrino must be extremely small. Many physicists thought that they had zero mass. However, it turns out that for neutrinos to change flavour, they must have at least a little mass.

That mass is tiny—far less than the mass of an electron. But neutrinos are so numerous that the total mass of all of the neutrinos in the Universe is about as much as the mass of all the visible stars combined!

This Hubble ultra-deep-field photo is studded with distant stars and galaxies.

Many of the SNO collaborators met in February 2004 to discuss the results and progress of the SNO experiments.

The following Institutions are currently participating in SNO:

- Queen's University (Ontario, Canada)
- Carleton University (Ontario, Canada)
- University of Guelph (Ontario, Canada)
- Laurentian University (Ontario, Canada)
- University of British Columbia (Canada)
- University of Pennsylvania (USA)
- Los Alamos National Laboratory (New Mexico, USA)
- Lawrence Berkeley National Laboratory (California, USA)
- University of Washington (USA)
- Oxford University (UK)
- Brookhaven National Laboratory (New York, USA)
- University of Texas at Austin (USA)

Major funding, material or facilities support for SNO has been provided by:

- Canadian Foundation for Innovation
- National Research Council of Canada
- Atomic Energy of Canada
- Inco Limited

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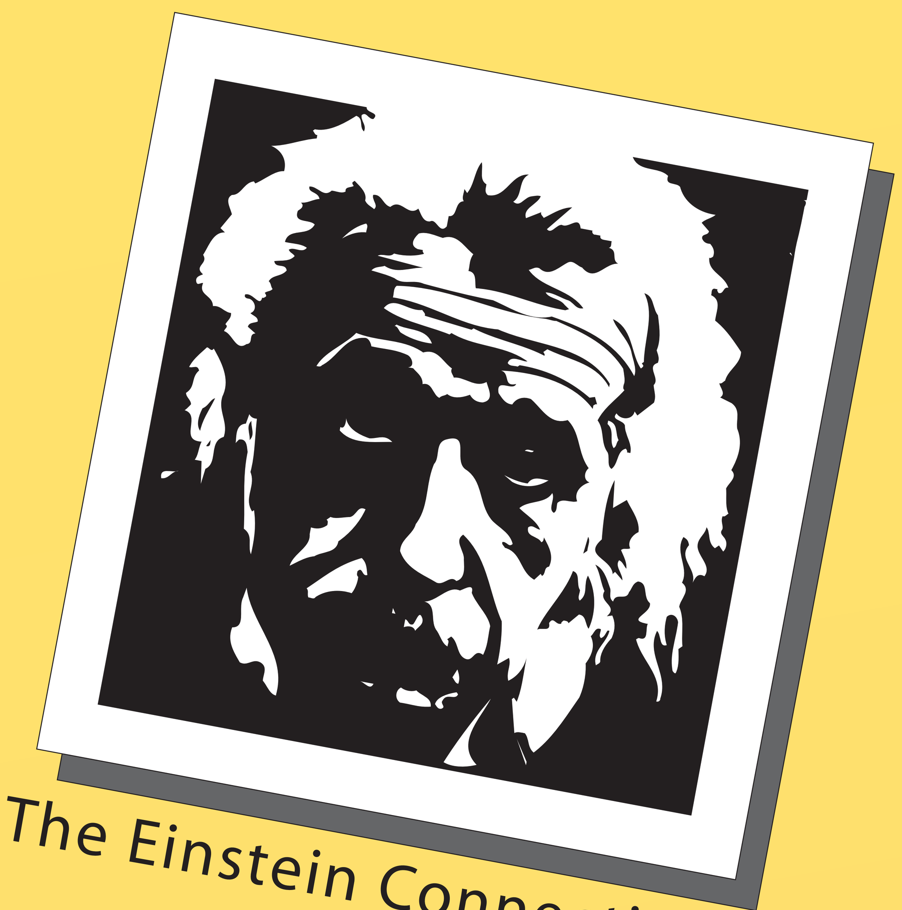
Neutrinos and the Cosmos

Einstein's General Relativity

By 1916, Einstein had extended his theory of relativity and demonstrated that gravity is just the warping of space and time by a massive object.

The equations of general relativity underlie modern cosmology. Later theories, building on these mathematical equations, tell us that the Universe began with a Big Bang, and that it continues to expand.

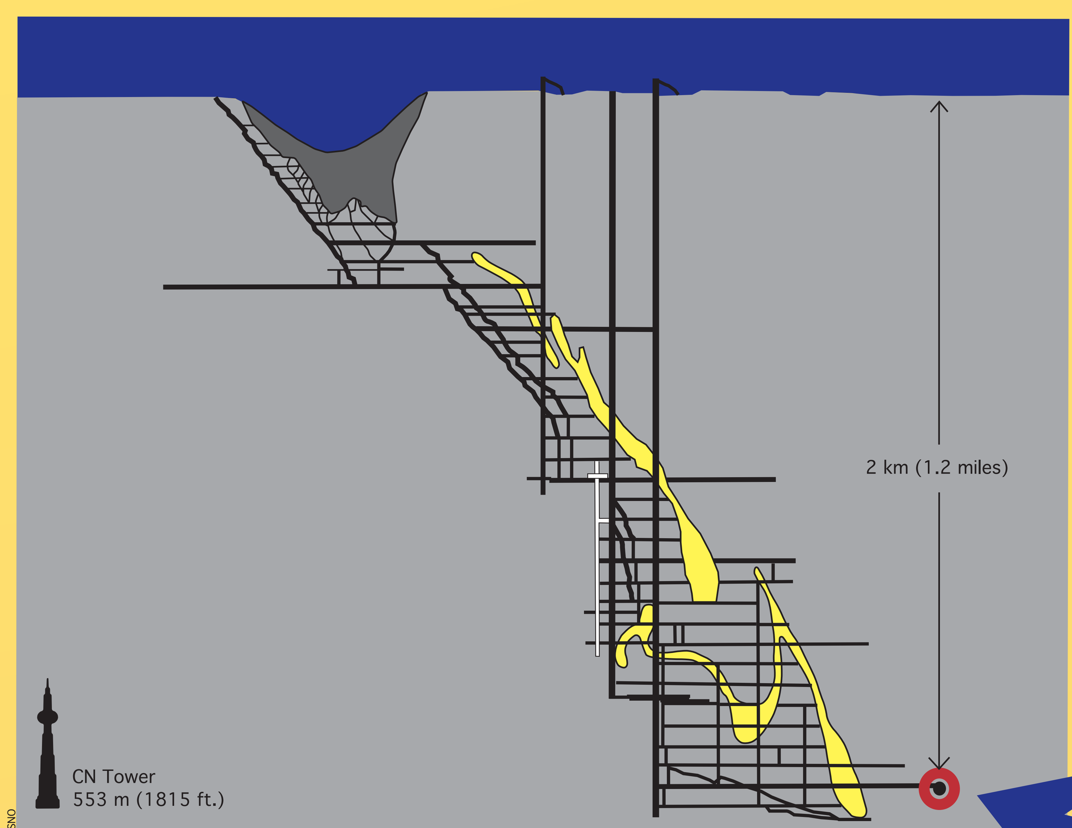
Einstein would have been interested in the SNO results. The mass of neutrinos has an influence on whether the Universe will expand forever, or eventually collapse in a big crunch.

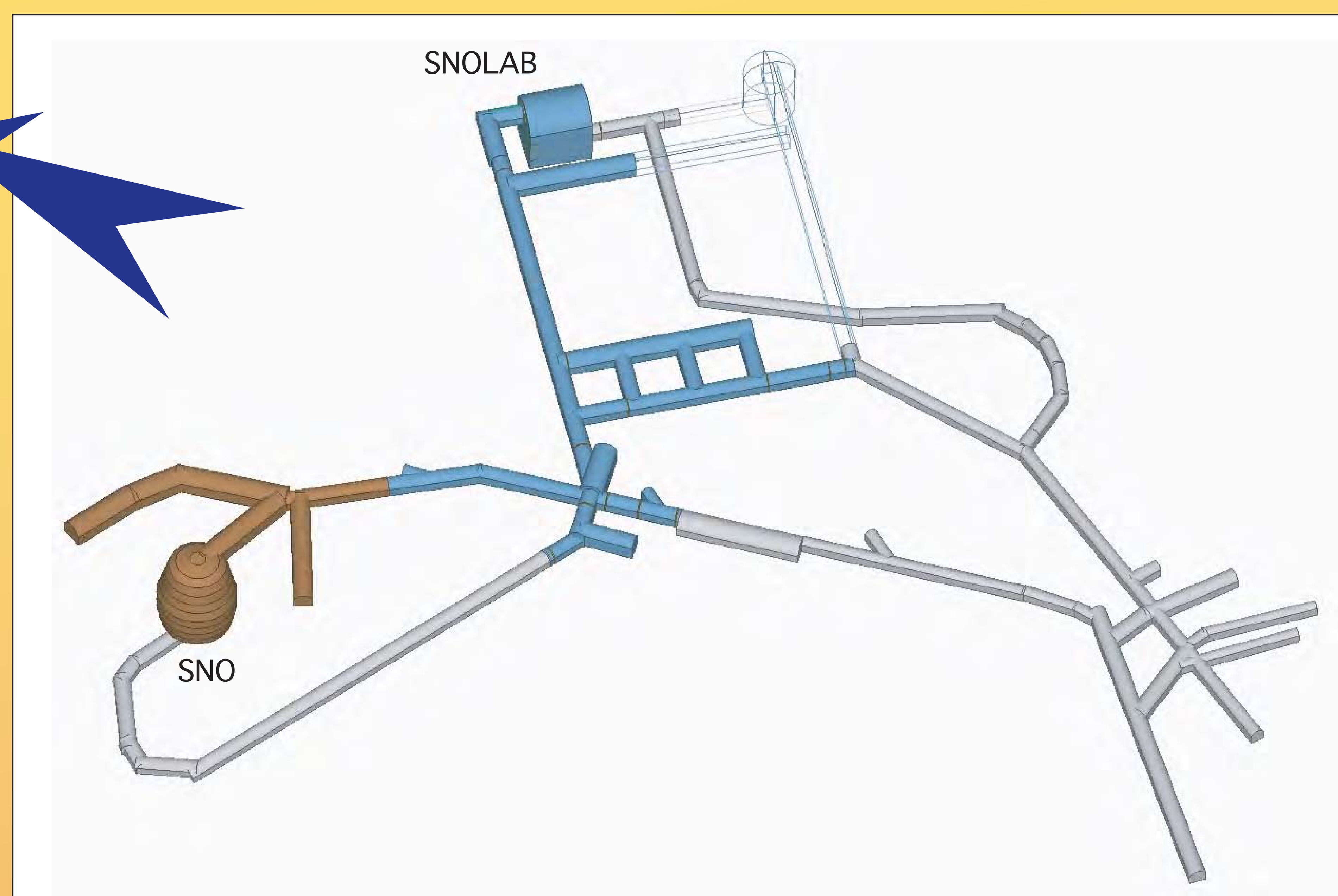


The Einstein Connection

Where do we go from here?

SNOLAB will be the new permanent facility in Canada for ultra-clean, low background radiation experiments. Collaborators from around the world now clamour for a place at SNOLAB, deep in the Sudbury mine.





Deep in the Creighton mine, SNOLAB, which includes the SNO chamber, is scheduled to open in 2007.

No Sunset for SNO

The Search for Dark Matter

Galaxies, made of stars, dust and gas, spin rapidly. But when astronomers add up all the mass that they can see, plus the neutrino mass, it still isn't enough to keep the galaxies from flying apart. Either Einstein's theory of gravity is wrong, or there is still some hidden matter.

That hidden matter has become known as Dark Matter. An experiment called PICASSO will search for Dark Matter in the new SNOLAB.

Even with all the visible mass held by the billions and billions of galaxies we can see, plus the mass of the neutrinos confirmed by SNO, we can only account for less than 20% of the mass of the Universe.

Exploration and Discovery

Why Does It Matter?

Portrait of Ernest Rutherford by R. G. Matthews 1907; courtesy of the Rutherford Museum, McGill University

In 1898 New Zealand–born **Ernest Rutherford** accepted a posting as Professor of Experimental Physics at McGill University in Montreal, Quebec, Canada.

For over 100 years—since Rutherford first studied radioactive decay at McGill University—particle physicists have been solving fundamental mysteries in Canada.

Innovations such as radiation therapy to treat cancer, and even the World Wide Web, have trickled down to everyday life from these scientists' discoveries. But that isn't why they do it.

Scientists, like kids, are driven to explore by their curiosity. Ultimately, the greatest impact may not be a material benefit, just a deeper appreciation for the wonder of our existence.

A Prizewinning Recipe

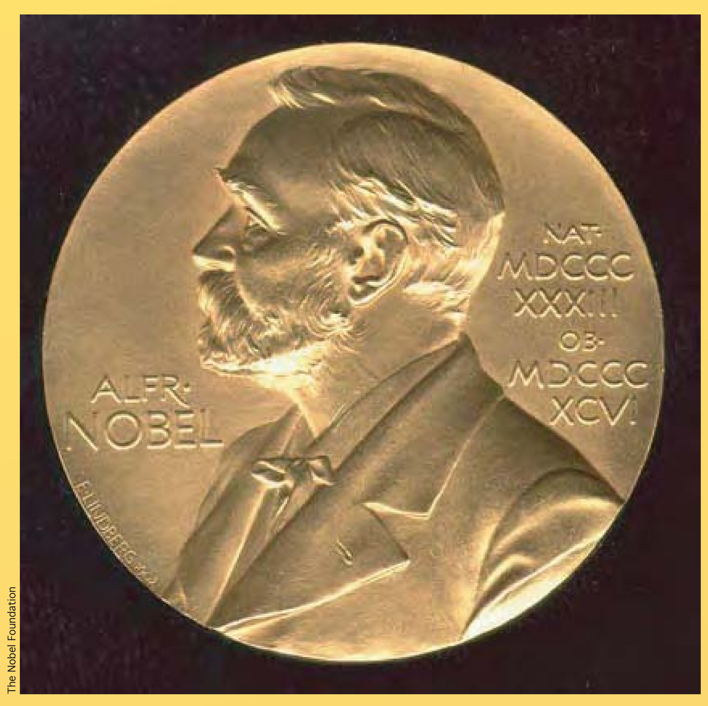
Canada on the World Stage

SNO solved a problem that had been troubling researchers for over thirty years.

The papers describing SNO results are among the most often cited in all of physics. The work was named the top physics story of 2002 by the American Institute of Physics and the American Association for the Advancement of Science.

SNO results and the results from other neutrino experiments such as Super-Kamiokande in Japan are shaking up the scientific world. Do you think these discoveries are worthy of a Nobel Prize?


Stockholm City Hall



The Nobel Foundation

Selected Honours to Members of the Sudbury Neutrino Collaboration

CANADA

Alain Bellerive, Carleton University
Canada Research Chair, 2001

Walter Davidson, National Research Council Canada
Fellow, Royal Society of Canada, 2003

George Ewan, Queen's University
D.Sc, honoris causa, University of Guelph, 2001
D.Sc, honoris causa, Laurentian University, 2002

Arthur McDonald, Queen's University (SNO Project Manager)
LL.D., honoris causa, Dalhousie University, 1997
Fellow, Royal Society of Canada, 1997
Killam Research Fellowship, 1998
LL.D., honoris causa, University College of Cape Breton, 1999
D.Sc., honoris causa, Royal Military College, 2001
Queen's University Research Chair, 2002
T.W. Bonner Prize in Nuclear Physics from the American Physical Society, 2003
Canadian Association of Physicists Medal for Lifetime Achievement in Physics, 2003
Natural Sciences and Engineering Research Council of Canada Award of Excellence, 2003
Gerhard Herzberg Canada Gold Medal for Science and Engineering, 2003
U.K.-Canada Rutherford Lecturer for the Royal Society, 2003
Bruno Pontecorvo Prize, 2005

Tony Noble, Queen's University (SNO Institute Director)
Canada Research Chair, 2002

Scott Oser, University of British Columbia
Canada Research Chair, 2003

David Sinclair, Carleton University (SNO Deputy Director until 2002, SNOLAB Director)
Davidson Dunton Research Lecturer, 2002
Carleton Research Achievement Award, 2002
Fellow, Royal Society of Canada, 2003

Sudbury Neutrino Observatory
Ontario Association of Certified Engineering Technicians and Technologists Award for Outstanding Technical Achievement in Engineering and Project Management, 1995

UNITED STATES

Mark Boulay, Los Alamos National Laboratory
Los Alamos National Laboratory Distinguished Post Doctoral Fellow Award, 2004

Richard L. Hahn, Brookhaven National Laboratory
American Chemical Society National Award in Nuclear Chemistry, 2000
Brookhaven National Laboratory Research & Development Award, 1997

Karsten Heeger, University of Washington
American Physical Society Nuclear Physics Dissertation Award, 2003
Case Western Reserve University Michelson Postdoctoral Lectureship, 2004

Andrew Hime, Los Alamos National Laboratory
Fellow, American Physical Society, 2004

Josh Klein, University of Texas
Sambamurti Prize Lectureship, Brookhaven National Laboratory, 2004
Outstanding Junior Investigator Award, U.S. Department of Energy, 2004

Kevin Lesko, Lawrence Berkeley National Laboratory
Fellow, American Physical Society, 2000

Hamish Robertson, University of Washington
T.W. Bonner Prize in Nuclear Physics from the American Physical Society, 1997
Fellow, American Academy of Arts and Sciences, 2003

UNITED KINGDOM

David Wark, Rutherford Appleton Laboratory and Oxford University
Rutherford Prize, 2004

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