A New View of our Universe from a Hole in the Ground

David Sinclair
Carleton and Triumf

A new view of our universe from a hole in the ground

Or

How to get in from the rain

David Sinclair
Carleton and TRIUMF

What are we looking for

- There are many particles in our universe which are not very familiar to us but we would like to study them
- We know about protons and neutrons and electrons
- There are 10,000,000,000 times as many 'neutrinos' in our universe than electrons or protons
- There should be other exotic particles about
- How do we see them in the 'rain' of cosmic rays?

What is a Neutrino?

- One of the ‘fundamental’ particles of nature
- First evidence in nuclear β decay
- Among the most abundant particles in the Universe (10 Billion times as common as electrons, protons or neutrons)

What is β Decay?

- Within the nucleus

Neutron -> Proton + electron

Or

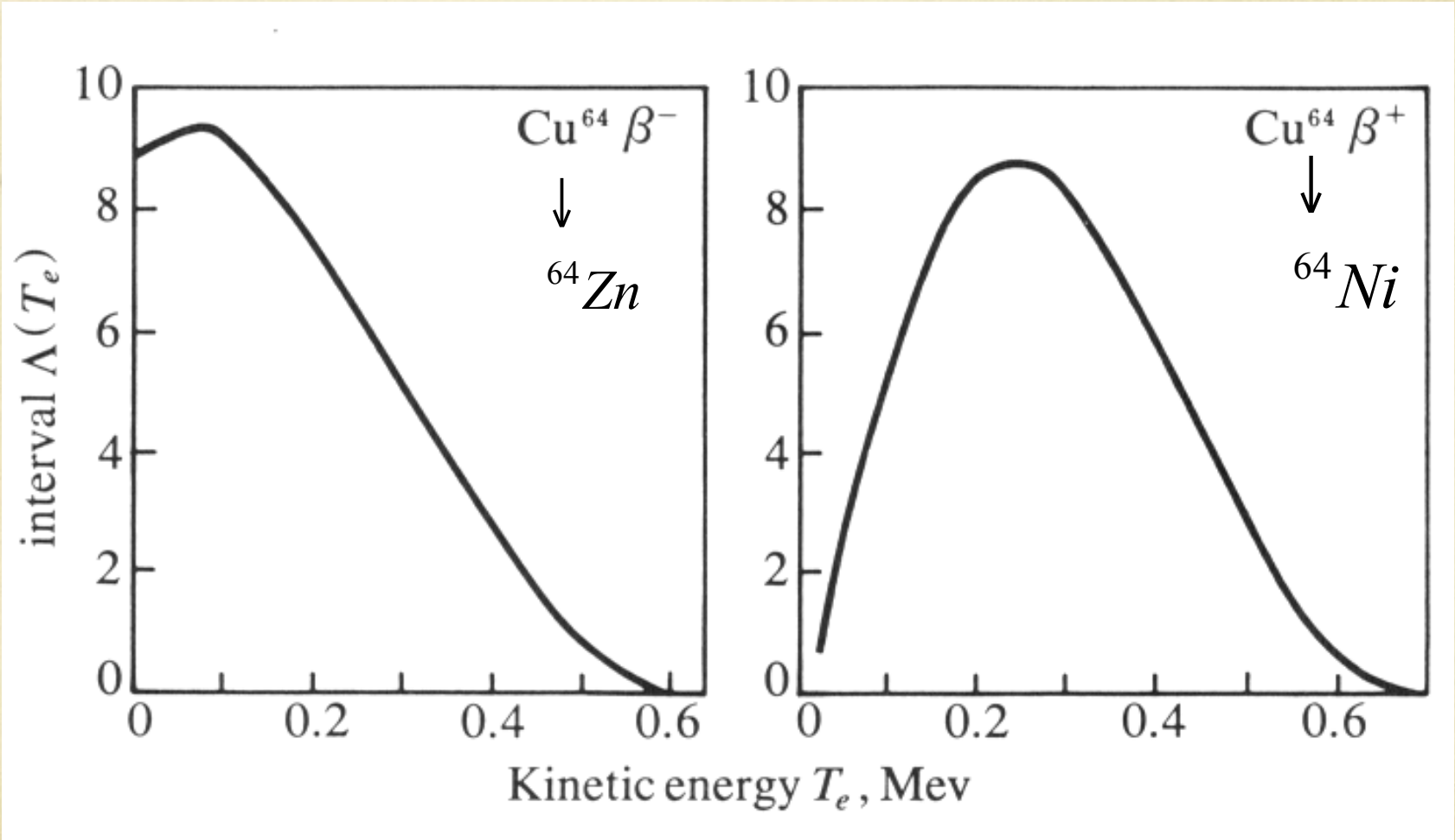
Proton -> Neutron + positron

Example $^{14}C \rightarrow {}^{14}N + e^-$

β-Decay – Our first look at Weak Interaction

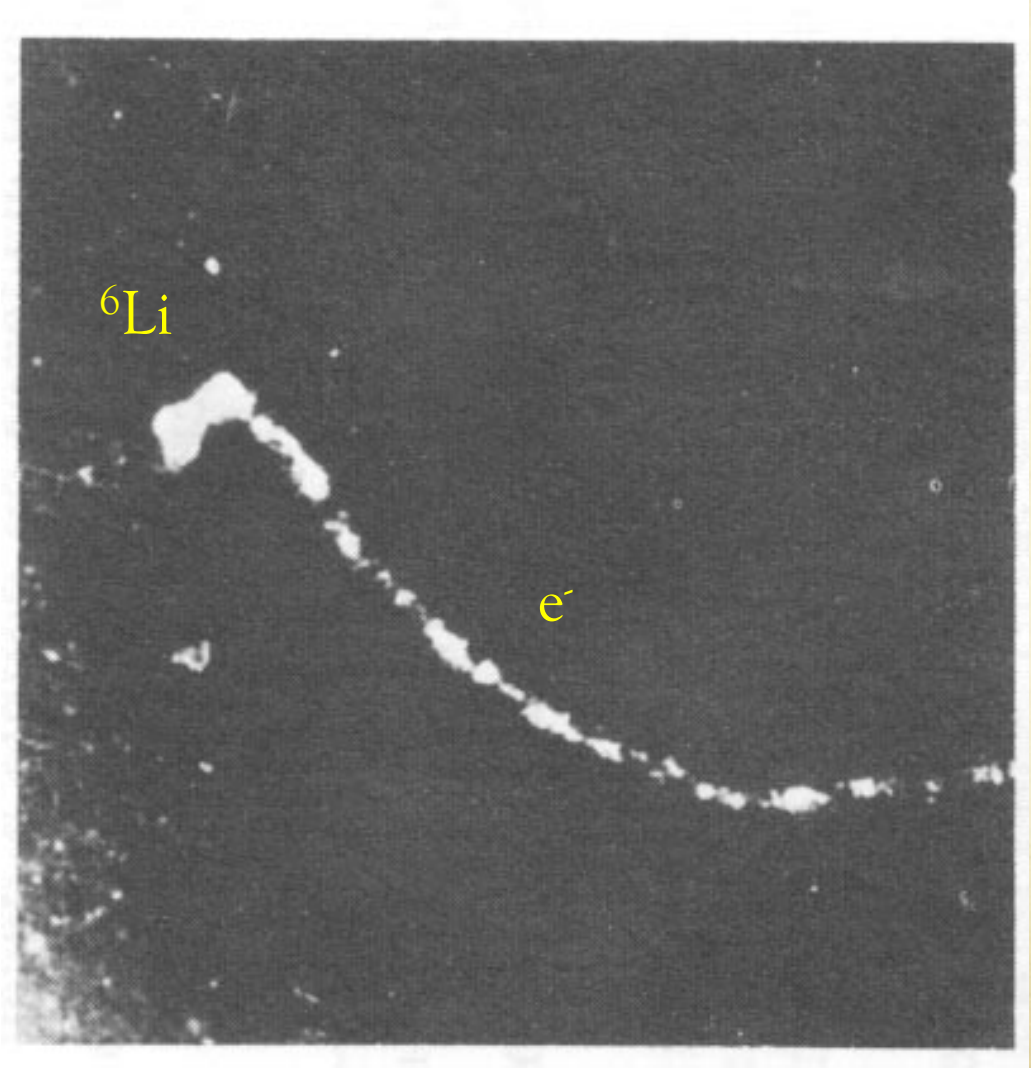
- First studied in early 1900's
- Appears to violate fundamental laws of Physics

β-Decay and Energy Conservation



Appears to violate Energy Conservation

β-Decay and Momentum Conservation



$^6He \rightarrow {}^6Li + e^-$

Appears to violate
Momentum Conservation

Wolfgang Pauli Proposes Neutrino

- 1930 – Neutral particle could carry off missing energy and momentum
- Shortly after Chadwick discovers neutron
- Neutrons have the wrong properties

Enrico Fermi Provides Quantitative Theory of β Decay

- Good agreement with energy spectra obtained
- Neutrino concept essential
- Name Neutrino (Little Neutral one) Introduced

Neutrinos can React but Chance TINY

- 1934 – Fermi and Peierls calculate reaction rates
- Reactions are opposite of decay
- If 10,000,000,000 neutrinos strike the earth, all but one pass through!

$$\nu_e + n \rightarrow e^- + p$$

Rudolf Peierls

Some basic facts on Neutrinos

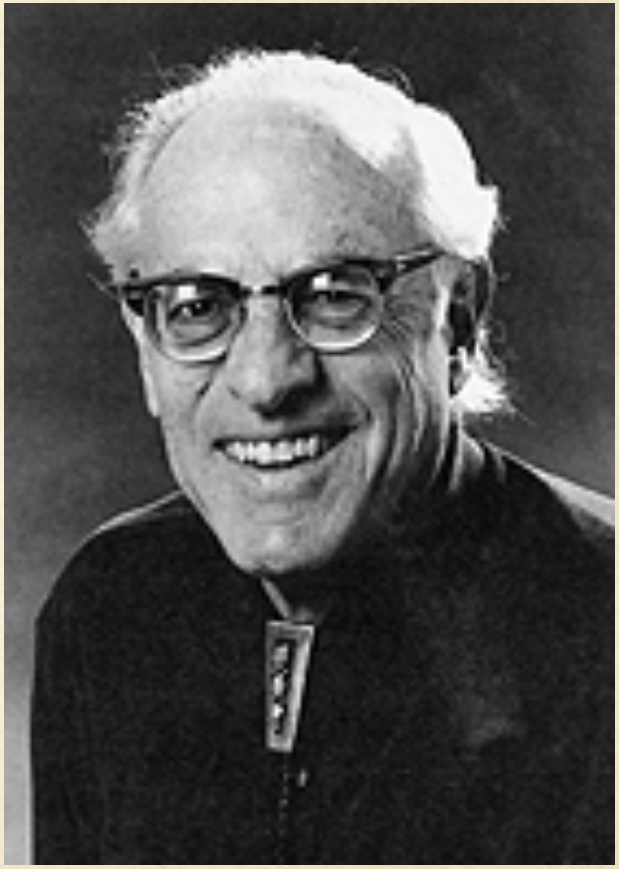
- Mass must be very small (<1/100,000 m_e)
- No Charge
- Only weak interactions
- Produced any time a neutron changes to a proton or proton to neutron
- Symbol ν

Nuclear Reactors are neutrino sources

- In a reactor uranium fissions to form lighter fragments
- Fragments are very neutron rich
- Neutrons decay to protons to form more stable nuclei giving neutrinos

Neutrinos Finally Found

- Reines and Cowan (1957)
- Detected neutrinos from a reactor
- Efforts at Chalk River by John Robson ended due to reactor problem



Fred Reines

Read all about it!

50 Years Ago Today

Tomorrow's Weather
CLOUDY, MILDER
-SNOWFLURRIES

The Sudbury Daily Star

NORTHERN ONTARIO'S LARGEST NEWSPAPER

Northern Ontario EDITION — EARLIEST WITH THE LATEST

45th Year | Net DAILY Circulation Average During October 20,691 | SUDBURY, THURSDAY, JANUARY 8, 1953 | Not Over 5c a Copy Delivered Weekly 30c | 226—20 Pages

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Said Under Way

BERLIN (AP) — A full-scale purge is under way against the 2,700 Jews remaining in Communist-ruled East Germany, West Berlin Jews said Wednesday.

These informants reported Communist bosses, carrying out Kremlin orders, are driving the Jews out of public life. The action extends to Jews holding minor jobs in the nationalist economy and those who take part in community cultural affairs, they said.

Some East German Jews, who saw the handwriting on the wall, fled to West Berlin only a few days ago.

One of these was Dr. Leo Zuckermann, 50, director of a Communist law college at nearby Potsdam. Fearing threatened prosecution, he fled to West Berlin with his wife and two children.

Jewish circles here said that all party officers in East Germany were ordered by Moscow to start sweeping the Jews out.

The order became effective after the Czechoslovak treason trial last fall in Prague. There, the one-time Communist boss of Czechoslovakia, Rudolf Slansky, a Jew himself, was executed along with 10 colleagues.

It was reported that Red interrogators spent hours with Gerhart Eisler, a Jew, on Dec. 29, only two days before his East Zone propaganda office in East Berlin was dissolved.

PLAN 10-STOREY APT.

TORONTO (CP) — A 10-storey apartment building containing 121 living units will be built in midtown Toronto. The plan which includes provision for 11 inside and 50 outside parking spaces, was approved Wednesday by the civic property committee.

were necessary to clarify and amplify certain parts of the army treaty and the West German peace contract because "many developments have taken place" since the pacts were signed last May.

Parliamentary observers in Paris said there appeared to be an al-

THE WATER'S FINE—Two members of the Montreal Polar Bears enjoy their annual swim in the icy waters of Lake St. Louis with the water temperature a chill 32 degrees. Ice is chopped to make a hole for the plunge and floats around the hardy pair.

years, compiled by the city police department for The Sudbury Daily Star, are:

	1953	1952
Killed	0	0
Injured	2	0
Accidents	25	12

BC Election Speed-up Promised by Bennett

VICTORIA (CP) — Streamlining of British Columbia's Elections Act, aimed at speeding up the entire election machinery, is being planned by Premier W. A. C. Bennett's Social Credit government, it was learned Wednesday.

While Premier Bennett has not revealed the government's specific plans there appear to be two possibilities.

1. Abolition or drastic revamping of the absentee voting system, to cut down the three-week waiting period between election day and the day counting of alternative votes starts.

2. Considerable reduction in the 63-day waiting period now required between the calling of the election and polling day.

In the June general election, it was 50 days after election day before the new government was sworn into office.

'Gas Masks for Everybody' Ontario Civil Defence Aim

NIAGARA FALLS, Ont. (CP)—Ontario civil defence authorities are preparing for the day when every person in the province's nine target areas will have a gas mask and every home will have a stirrup pump and four water pails, Maj. J. H. Adams, chief civil defence instructor for Ontario, said Wednesday.

He said the civil defence organization now has 10 per cent of the equipment required for its training program stocked in its Toronto warehouses.

years ago to about $6,500 and it affected putting u

Leak in Atomic 'Furna Halts Search for Neutr

CHALK RIVER, Ont. (CP) — An atomic scientist is chasing ghosts that have speed but no weight in a drive to unravel some of the age-old mystery of what holds substance together.

After three years of tremendous labor, working with infinitely tiny measurements, of time and space, John M. Robson was just getting places when his chief tool—the world's most powerful atomic furnace—broke down.

Now the 32-year-old British scientist must wait many months before the atom-splitting reactor is healed and he can resume his task.

"I believe I can achieve success in my experiments six months after the reactor starts working," says the lanky, London-born research man, believed by colleagues to be the only person in the world attempting to catalogue the existence of the neutrino.

The neutrino is believed to contain speed but barely any form or substance. In its ghostly weight it is sufficiently powerful to pass through the entire earth without hindrance.

The world's top scientists are convinced that it exists, that it forms part of the atom core, that it is born and dies and that it holds the key to a great mass of information required in the atomic age.

The scientist, a graduate of Cambridge University, has the job of proving its existence. This lofty ambition emphasizes the two sides to Canada's atomic operations at Chalk River, the timeless experimentation with the very substance of life and the great bustle to produce life-giving materials for the sick.

For men in both fields the breakdown of the furnace on Dec. 12 has proved a great tragedy. But as Dr. C. J. Mackenzie, Canada's atomic chief, told 20 visiting reporters, the tragedy was anticipated. The reactor had lasted well beyond its expected life-span.

It will take months, but Chalk River is determined to nurse its powerful isotope cooker back to health. A major overhaul is planned. Seven times before the reactor has been out of order for from three to eight weeks.

Meantime, the breakdown has infused a sense of urgency in construction of a new $30,000,000 furnace, bigger and better than its mate.

Perhaps five or 10 years hence, says Dr. W. B. Lewis, head research man, Chalk River may begin thinking of building still another reactor more powerful than the new one.

Canada leads in peacetime atomic pursuits and her scientists are determined she shall hold that position.

While the old furnace, ruptured inside and leaking dangerous radio-

active waters, is a
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More properties of Neutrinos

- Comes in 3 types (ν_e ν_μ ν_τ) forming families with charged electron, muon and tau. Collectively called Leptons
- Each has a distinct antiparticle
- There appears to be a set of conservation laws – Lepton number conservation
  - E.g. Number of electron family particles is constant

Examples of Lepton Conservation

$$n \rightarrow p + e^{-} + \overline{\nu}_{e}$$

$$p \rightarrow n + e^{+} + \nu_{e}$$

$$\mu^{+} \rightarrow e^{+} + \nu_{e} + \overline{\nu}_{\mu}$$

$$\nu_{e} + n \rightarrow p + e^{-}$$

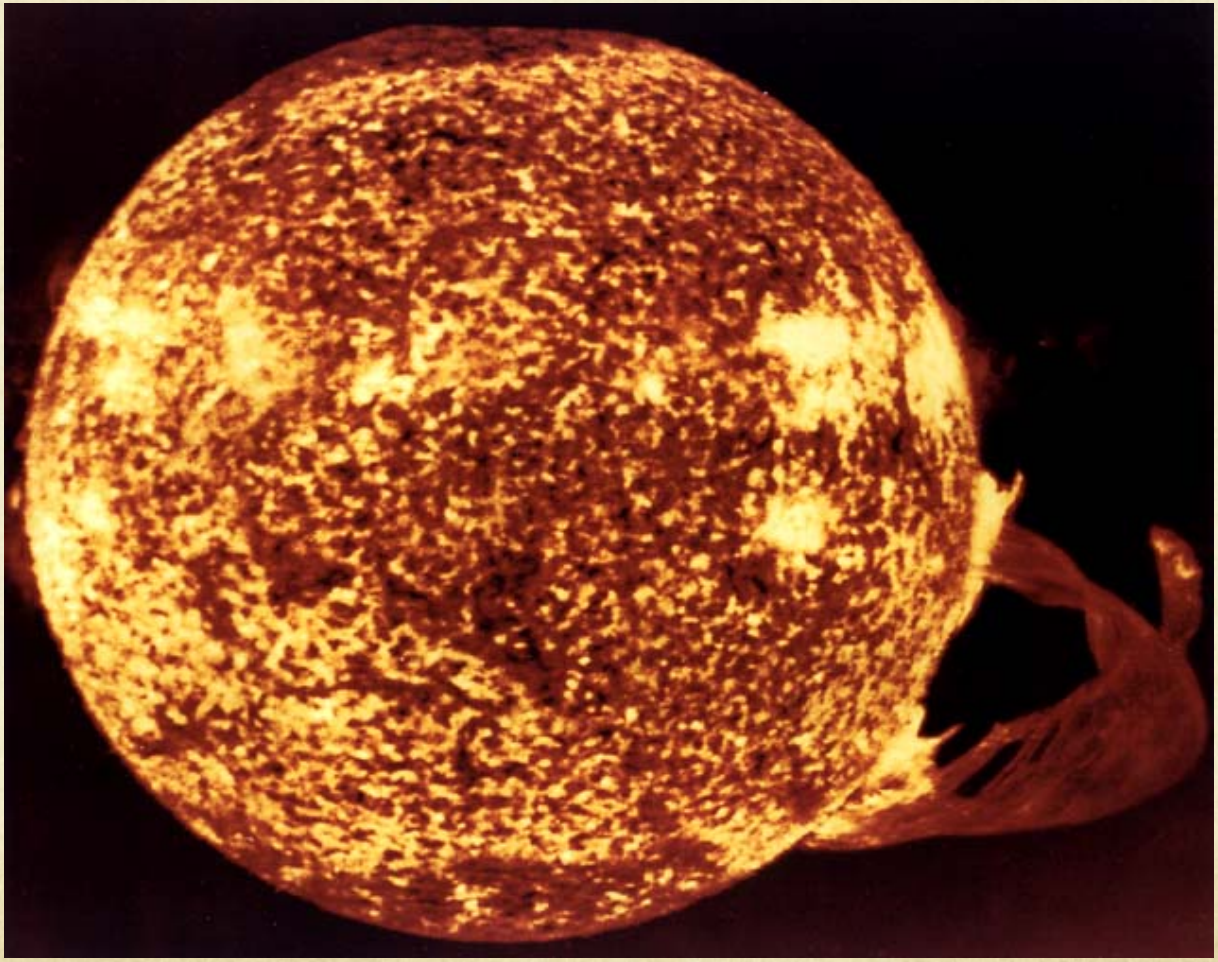
Lepton Conservation Forbids

$$\nu_\mu + n \rightarrow p + e^-$$

$$\mu \rightarrow e + \gamma$$

These are never observed

Lets banish the rain and think about the Sun

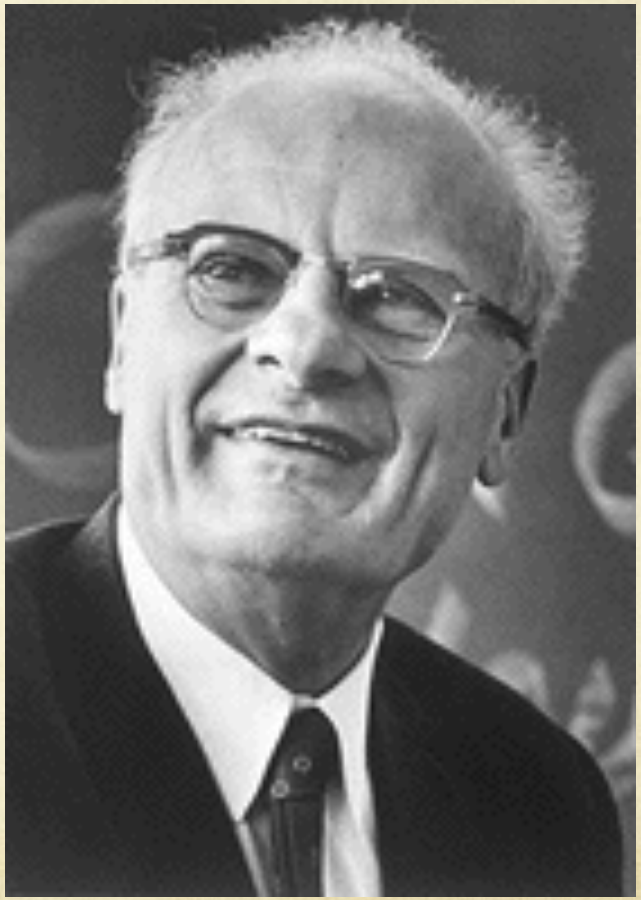


What makes the Sun Shine?

- Can it be chemical burning?
- No! The Sun would burn up in ~1000 years
- Can it be gravity
- No! It would last longer but not nearly long enough
- We think the sunshine is powered by ‘nuclear burning’

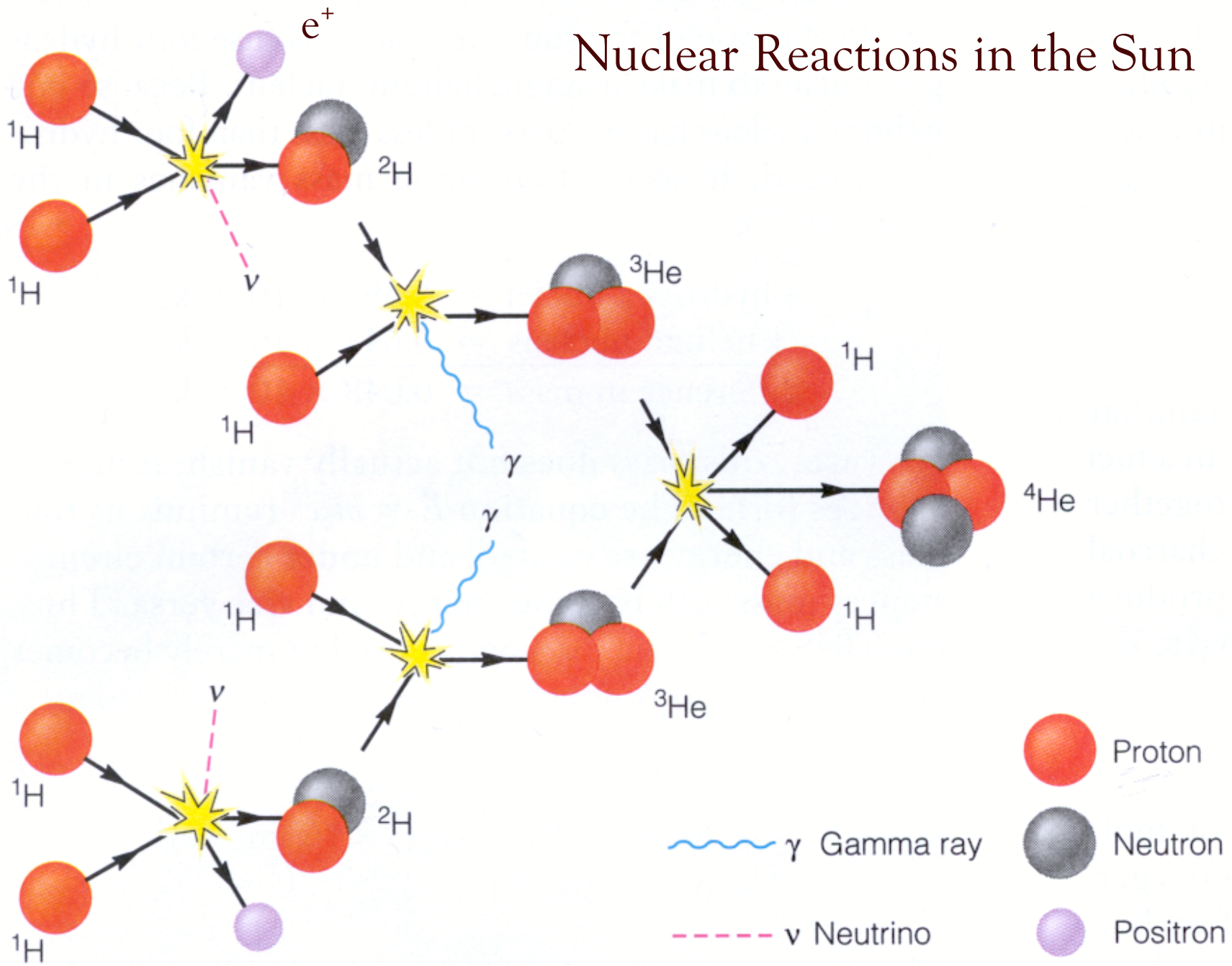
Energy From the Sun

- 1925 Eddington showed energy source must be nuclear
- 1934 Hans Bethe produces detailed model



Hans Bethe

Nuclear Reactions in the Sun



Solar Energy and Neutrinos

- For every ^{4}He formed, 2 protons change into 2 neutrons.
- For every ^{4}He formed, 2 neutrinos produced
- We know how much energy we get by making ^{4}He and how much energy reaches the earth from the Sun
- 100,000,000,000 neutrinos/cm^2/second hit Earth
- Measuring neutrinos should allow a study of energy production in Sun

First Search for Solar Neutrinos

- Ray Davis looked for neutrinos using a tank of dry-cleaning fluid deep underground. Based on a suggestion of Pontecorvo at Chalk River
- Look for process

$$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$$

^{37}Ar is removed from tank every month

Look for decay of Ar back to Cl

Production rate is 1 atom per week

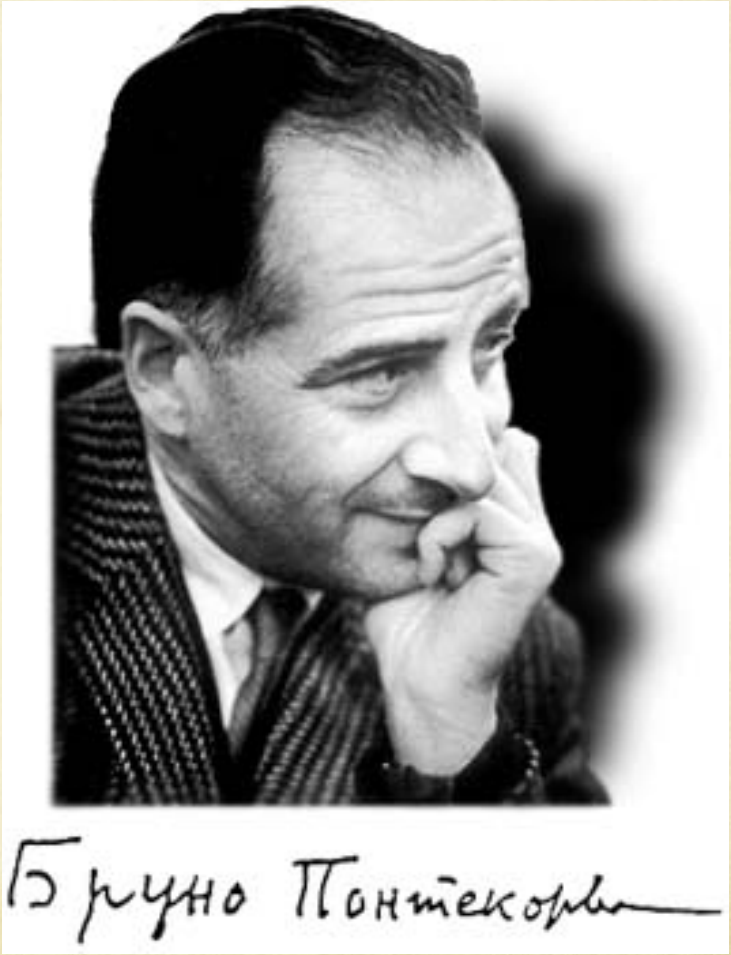
Ray Davis and his
Chlorine based
Detector
Deep underground

Results of the Chlorine Experiment

- First data - 1968
- Production of Argon is ¼ expected rate
  - Experiment may be wrong
  - Model of Sun may be wrong
  - Model of neutrino may be wrong
- Solar Neutrino Problem is Born

Pontecorvo Questions Neutrino

- Perhaps neutrinos 'oscillate'
- That is, a neutrino created as electron type might change to muon type and back again



Bruno Pontecorvo

Physics Community Reaction

- Oscillation not generally accepted
- Physicists could understand a small mixing
- Solar Neutrino Problem required complete mixing of 3 neutrino types

Mikheyev and Smirnov to the Rescue

- Neutrino mixing can be greatly enhanced in matter
- Even small mixing can explain solar neutrino problem
- Seems so elegant nature has to use this

New Experiments add to Mystery

- Two gallium experiments built (Italy and Russia)
  - See ½ expected rate
  - Sensitive to low energies
- Water detector built (Japan)
  - Sees <1/2 expected rate
- No agreement with Solar models

John Bahcall
Guru of Solar Models

It's Not Just the Sun
Dark Matter

- There appears to be much more mass in the universe than we can account for.
- Neutrinos are the most abundant particle in the Universe
- If neutrinos have mass could they be the Dark Matter?
- Dark matter determines fate of the Universe

It's Not Just the Sun
Dark Matter

- Rotation of matter in galaxies shows too much mass
- Gravitational lensing shows too much mass
- Big Bang theory gives total mass of neutrons and protons is ~4% of total
- If lightest neutrinos account for solar neutrino problem then heaviest has right mass (See-Saw Model) for Dark Matter

It's Not Just the Sun

Supernovae

- A Supernova occurs at the end of the life of massive stars (>8 M_O)
- Core Collapses to produce a neutron star

Crab Nebula – a Supernova Remnant from 1057

It's Not Just the Sun

Supernovae

- Neutrinos carry off 99% of the energy of the supernova in a few seconds
- This burst outshines the visible universe
- Why does the supernova explode?
- Neutrinos could drive the explosion but best models fail to explode
- Neutrino oscillations would help if the mass is large enough

Sudbury Neutrino Observatory

- A Project started in 1984 to solve the Solar Neutrino Problem
- Proposed by Herb Chen (U.C. Irvine)
- Heart of experiment is 1000 tonnes of heavy water used to detect neutrinos from Sun

Neutrino Detection in Heavy Water

- Heavy water is D_2O – D is Deuterium
- Deuterium nucleus is weakly bound proton and neutron

$$\nu_e + d \rightarrow p + p + e^- \quad \text{CC}$$

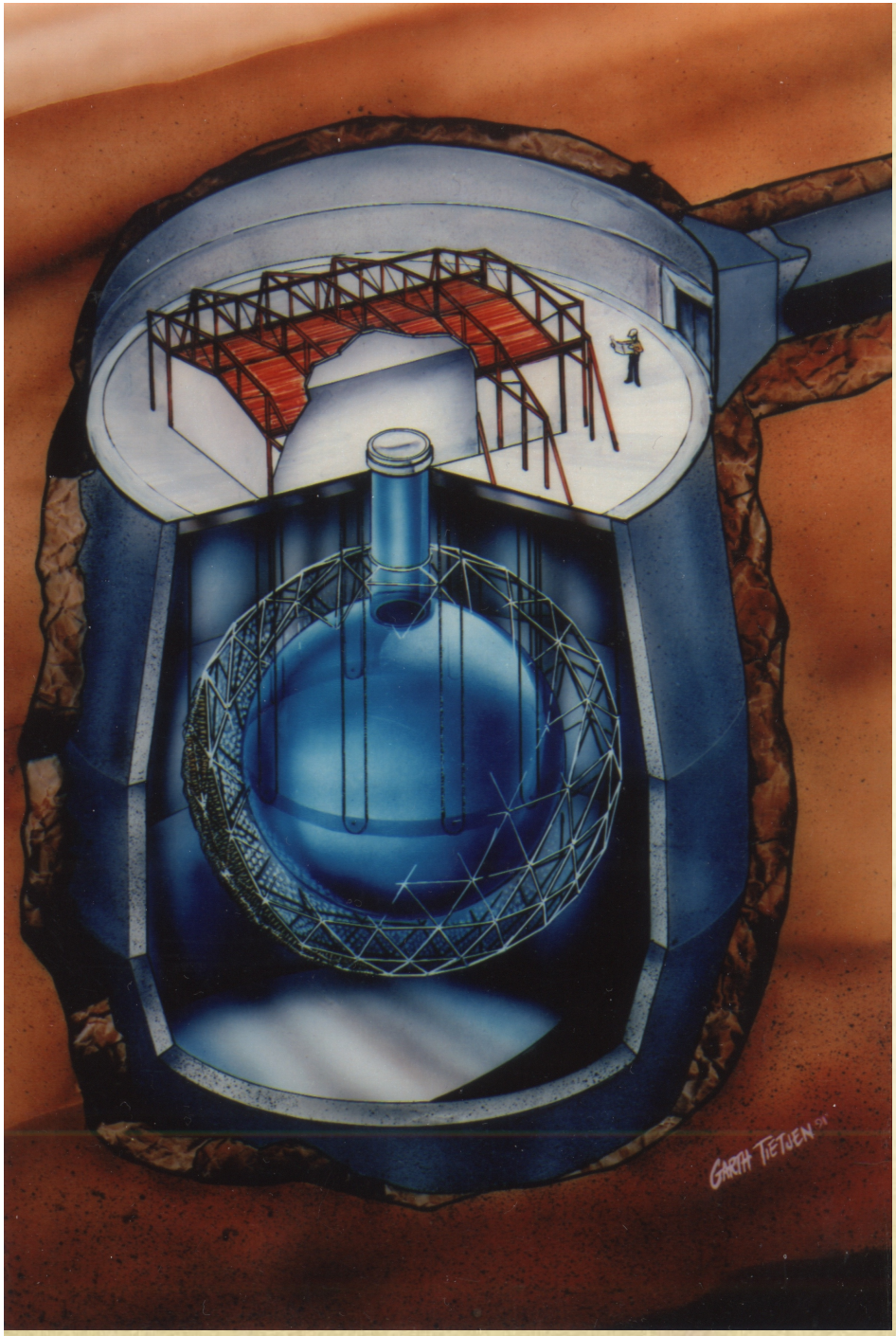
$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{ES}$$

$$\nu_x + d \rightarrow n + p + \nu_x \quad \text{NC}$$

x means any neutrino type

Cherenkov Detectors

- Electrons produced in reactions move close to speed of light (Light in water moves slower)
- Sets up shock similar to supersonic boom
- Takes form of flash of light
- About as bright as a candle on the moon



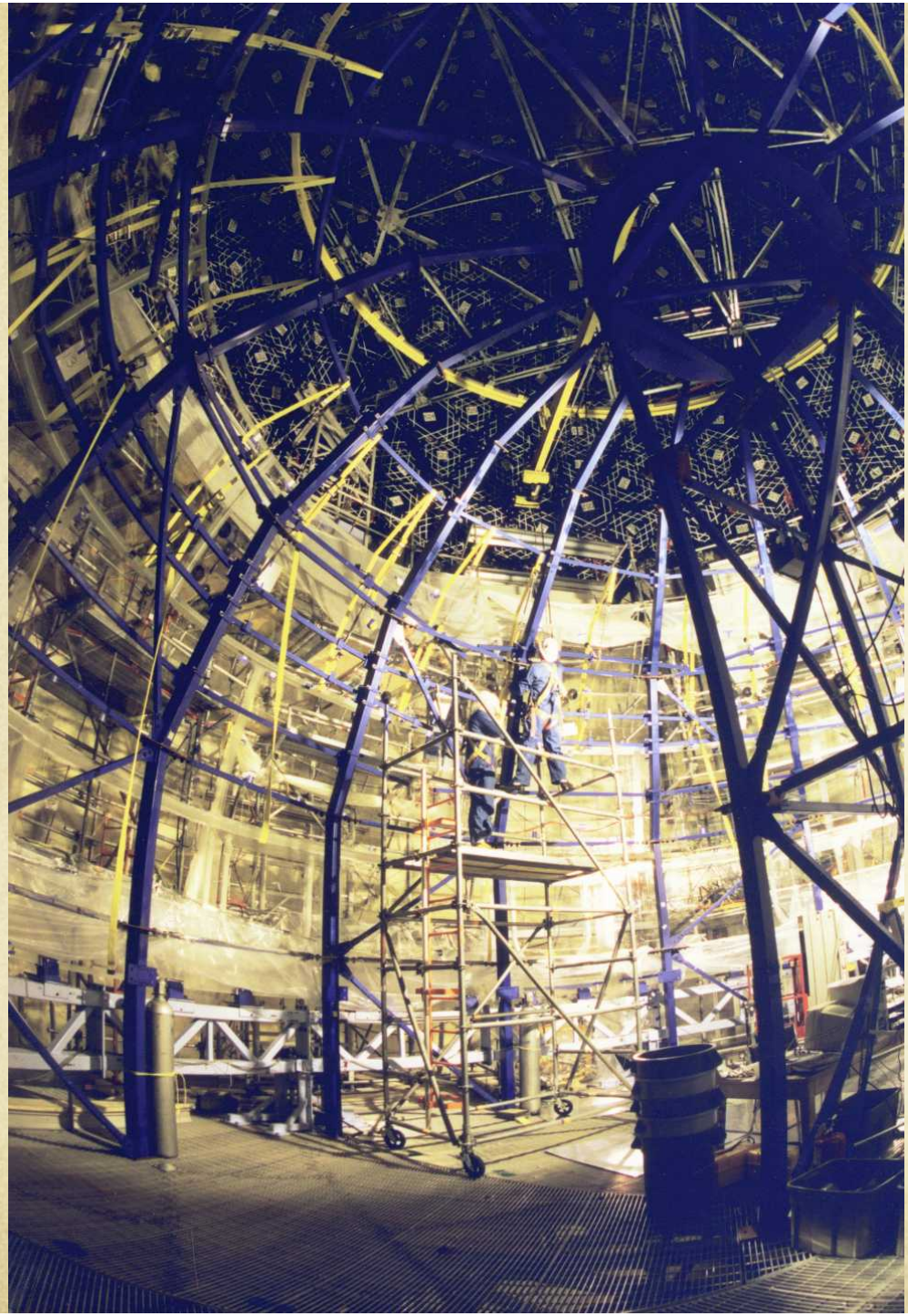
The SNO Detector

- 1000 Tonnes of D_2O
- 12 M Acrylic vessel
- 10,000 phototubes
- 8000 Tonnes of pure light water
- 2000 m deep in Mine
- World's largest deep cavern
- All materials very pure

Excavating the Cavity

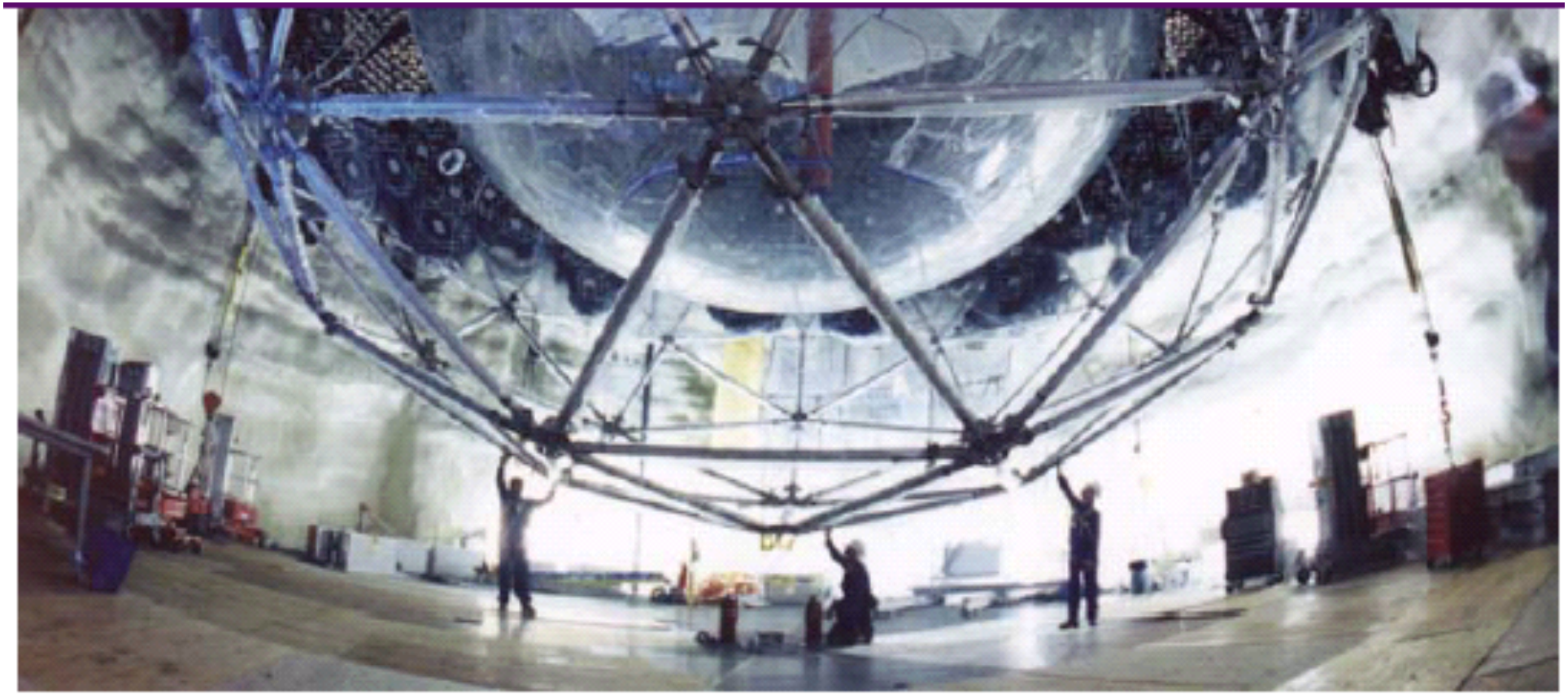
SNO is as large
As a 10 story
Building

Largest cavity
excavated
At this depth



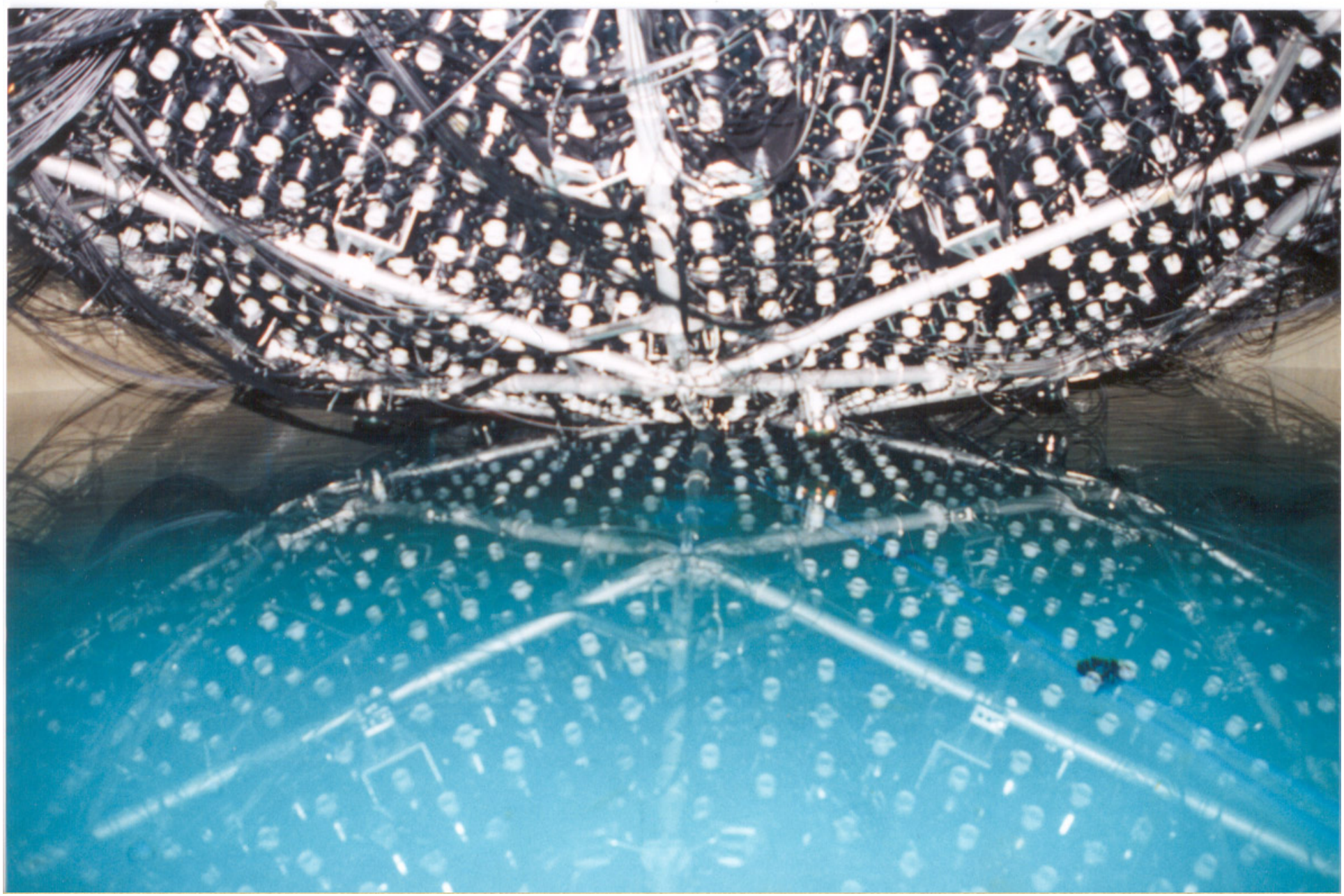
Constructing the Acrylic Vessel

This is the largest All acrylic structure built

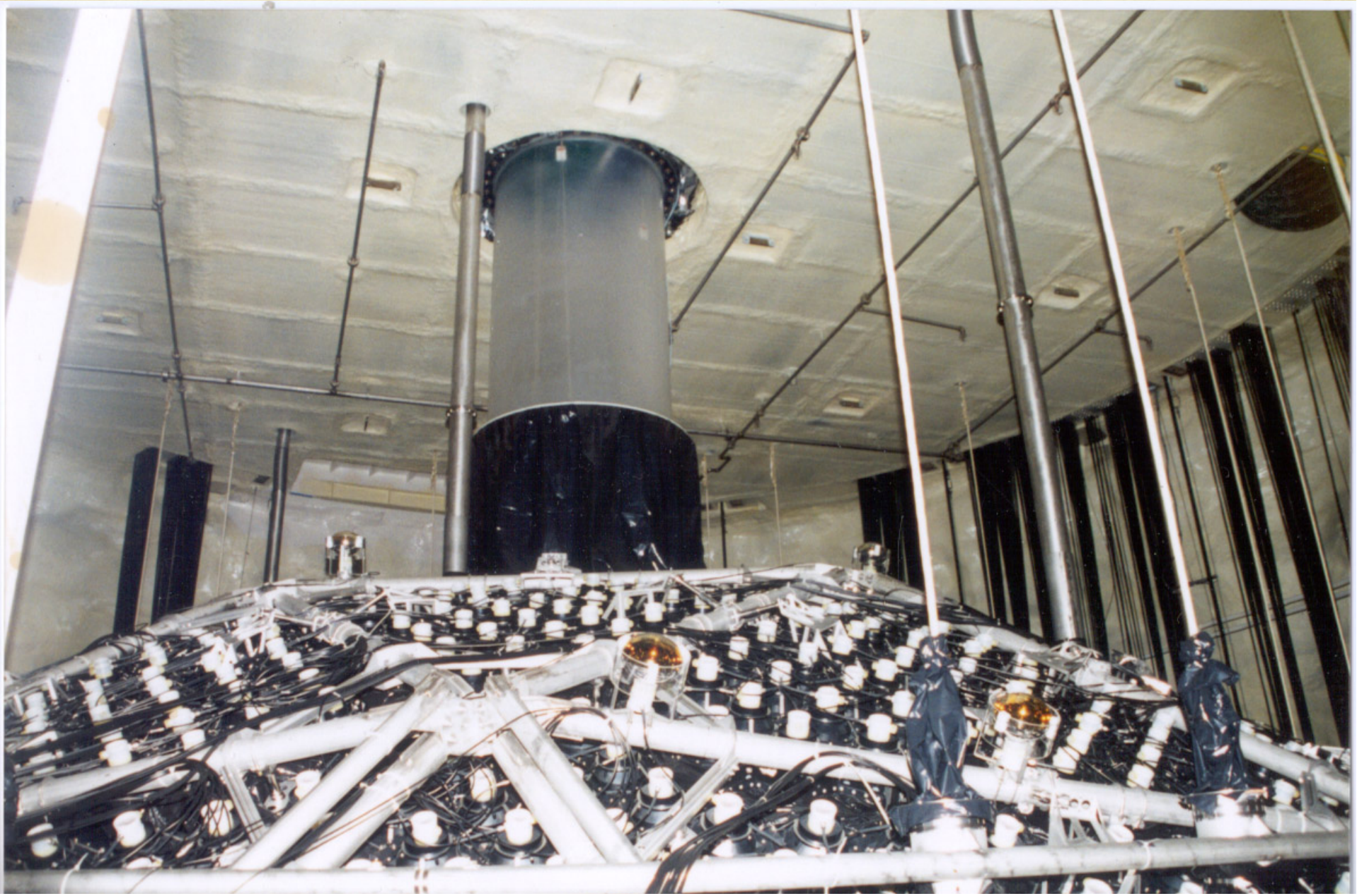


Partially completed detector acrylic vessel and
Geodesic structure used to hold phototubes

Detector partially filled



Top of Detector

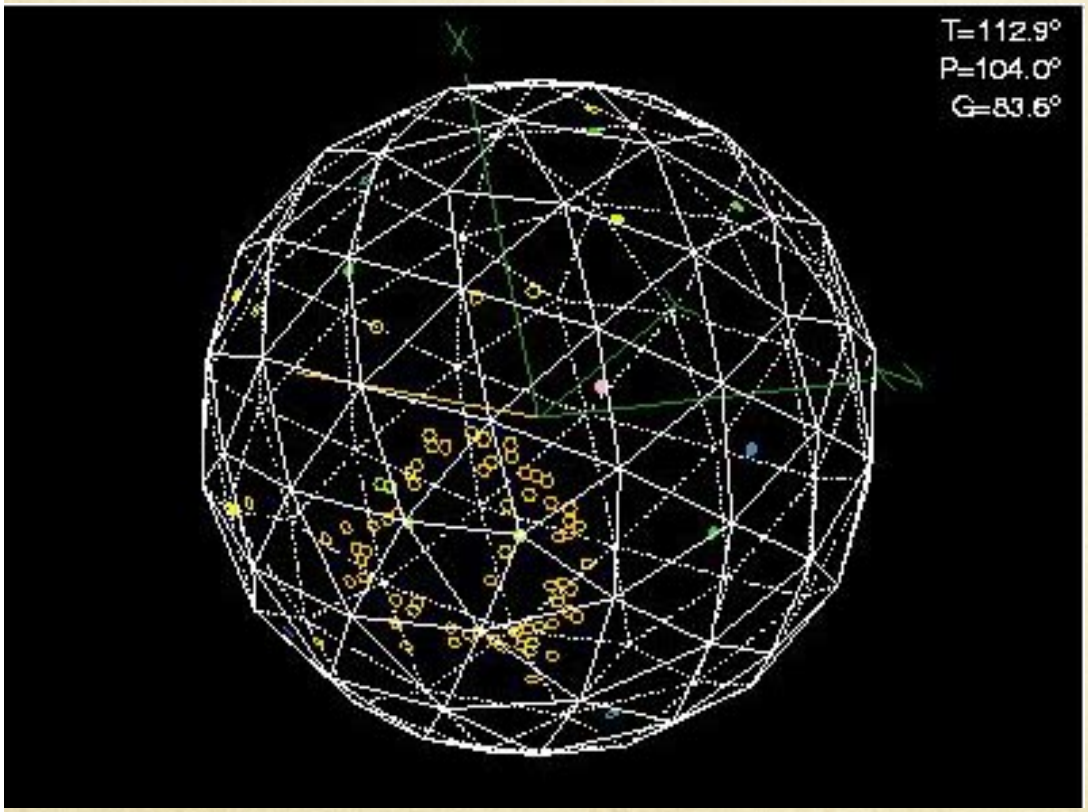


Heavy Water Train leaves for the Mine

Heavy water enters the Cage

A part of the Heavy Water Purification System

Typical Neutrino Reaction in SNO

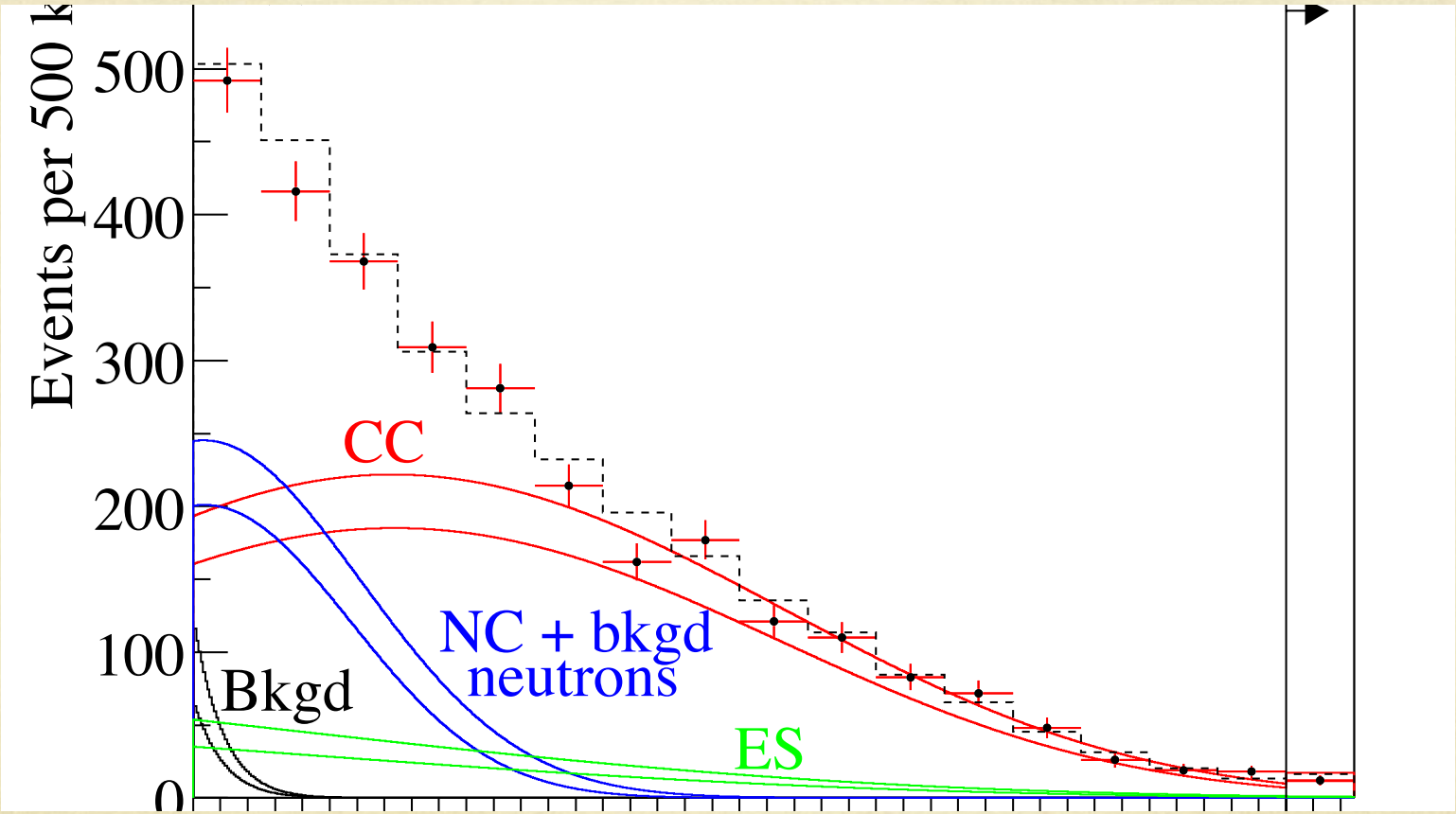


- Ring represents hit phototubes
- Number of hits gives energy
- Timing gives location
- Pattern gives direction

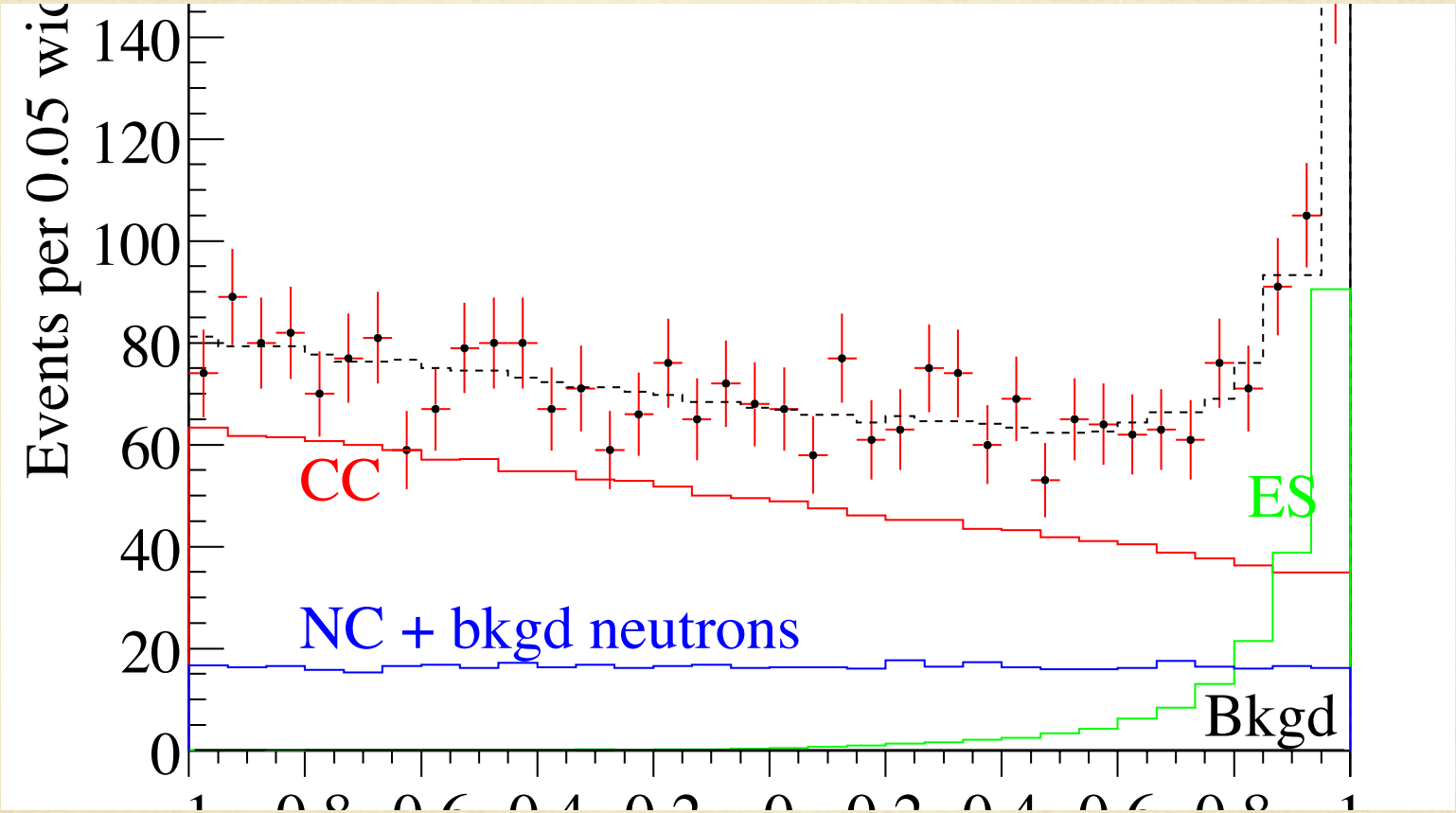
Background is Everything

- Expect about 10 neutrino events per day
- Go Deep to avoid cosmic rays
- All materials must be chosen with care to avoid radioactivity
- Build detector in clean conditions to avoid dust
- Extensive analysis to get rid of instrumental backgrounds

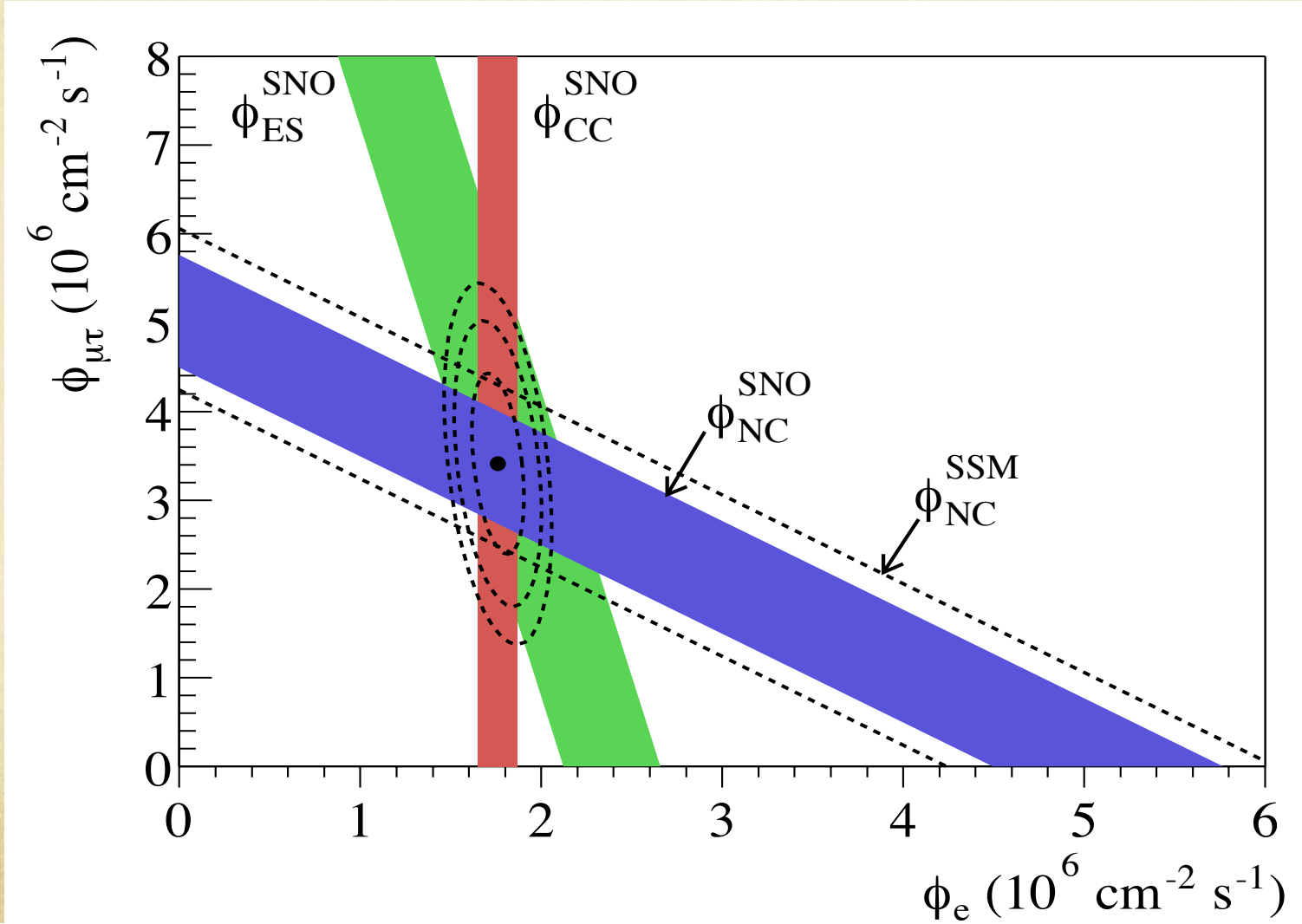
SNO Energy Spectrum



Data plotted as function of Direction to Sun



Graphical Presentation of SNO RESULT



The Basic SNO Result

- Flux of Electron type Neutrinos

$$1.76 \pm 0.11 \times 10^{6} cm^{-2} s^{-1}$$

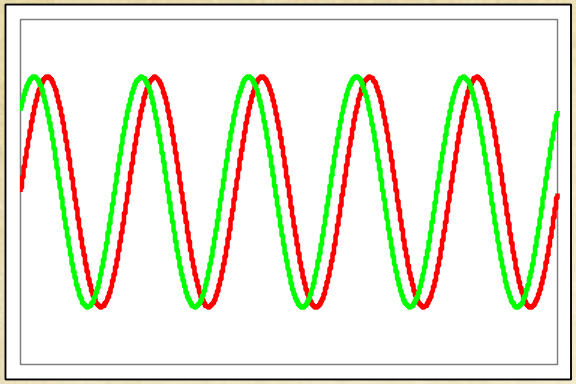
- Flux of All Neutrinos
- High Energy Only

$$5.09 \pm 0.66 \times 10^{6} cm^{-2} s^{-1}$$

These numbers are different
Direct Evidence for Neutrino Oscillation

What Does it Mean for The Sun?

- Standard Solar Model is Accurate
- Prediction 5.05×10^6
- SNO Measures 5.09×10^6
- Flux varies as T^{25}
- Central temperature fixed to <1%
- (Central temperature ~ 15,000,000 K)



What Does it Mean for Neutrino Oscillations?

- Neutrinos Oscillate
- Neutrinos have Mass
- Neutrinos have large mixing

What Does it Mean for Dark Matter

- Neutrinos are too light to make up Dark Matter (May contribute a few % like normal matter)
- We need another particle – Search underway!
- Recently Dark Energy found
- Maybe whole picture is wrong!

What Does it Mean for Supernovae

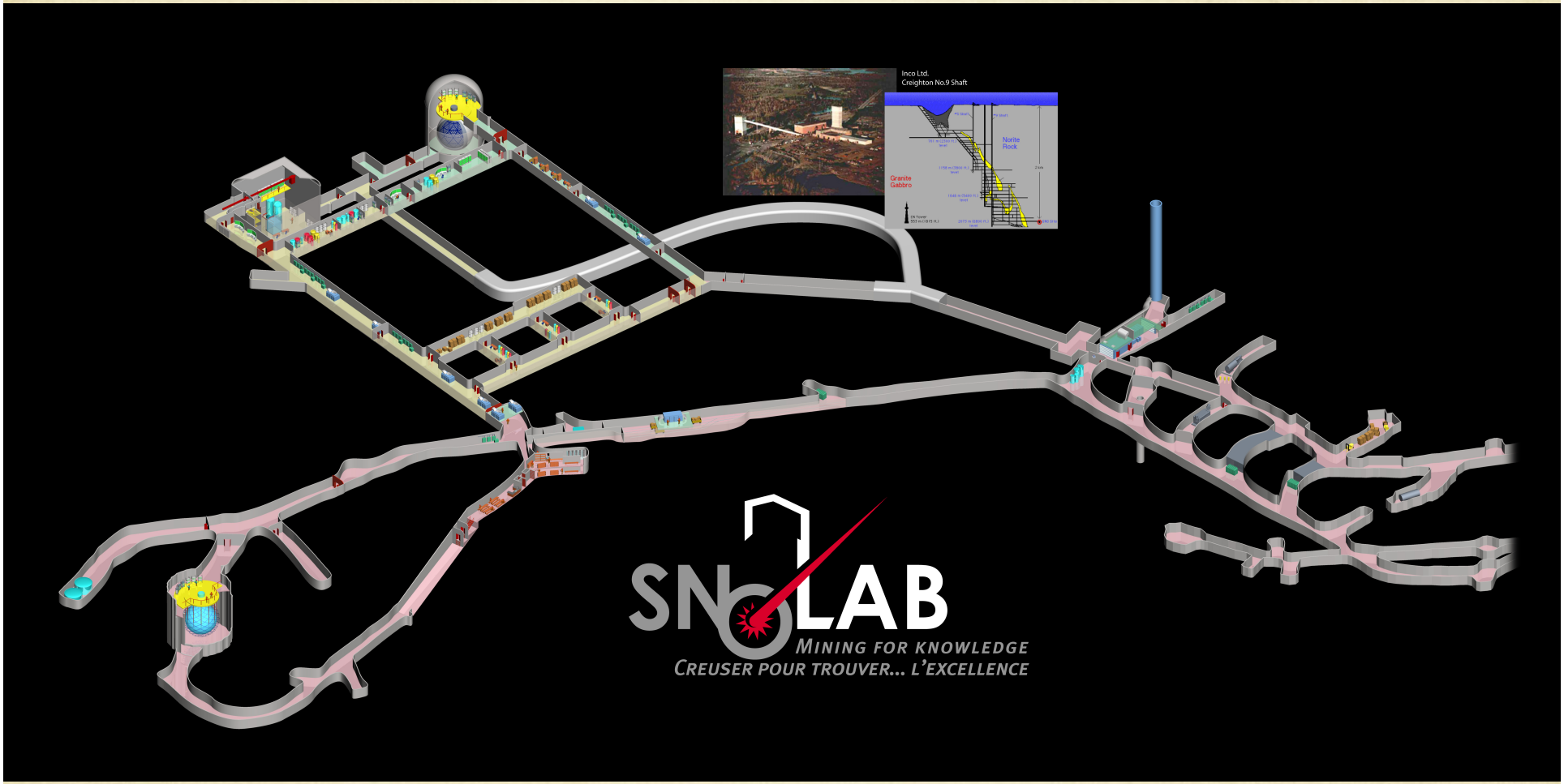
- Neutrino Masses too light for Resonant Oscillation to be effective
- New High Performance Computers (like HPCVL) allow 3d modelling
- With effects of turbulence Supernovae explode (still driven by neutrinos!)

What Does it Mean for Big Bang?

- Universe seems to be made of matter not anti matter
- Unexpected large mixing of neutrinos could allow this in the Big Bang
- Will require huge experimental effort to explore this

Where Do We Go Next

- Build new laboratory to
  - Look at low energy neutrinos from Sun
  - Look for Dark Matter
  - Look for new neutrino properties
  - Look for supernovae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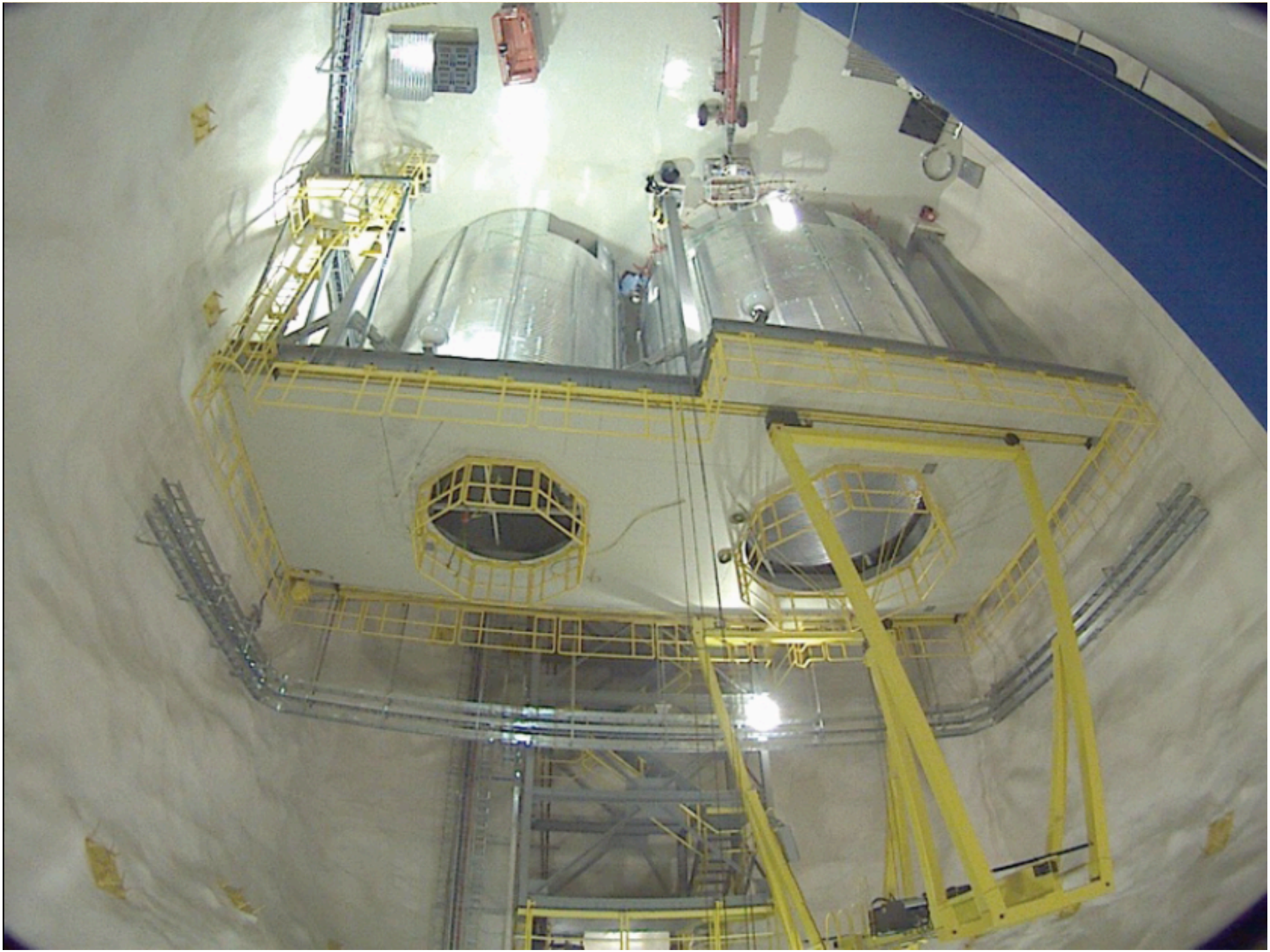
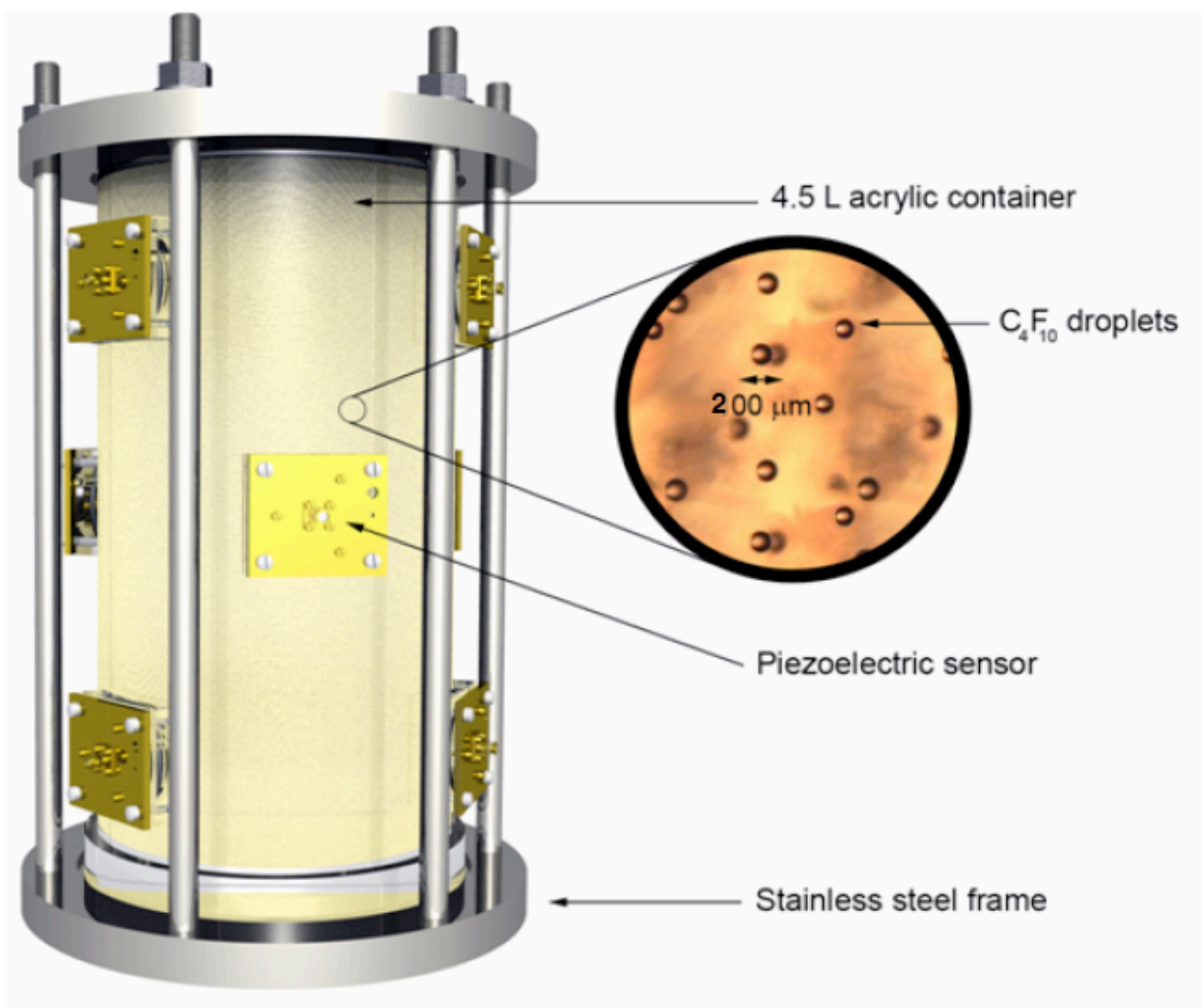
Creuser pour trouver... l'excellence



Picasso – Search for Dark Matter using Superheated Droplets

(SNOLAB will have 5 different experiments looking for Dark Matter)



Final Thoughts

- There are many unsolved problems in 'astroparticle physics'
  - What is Dark matter?
  - Why is the universe made of matter?
  - What really happens in a Supernova
- To study these we need to get out of the 'rain' of cosmic rays to allow very sensitive measurements
- Looking at the universe from a hole in the ground gives us a new laboratory to explore these fundamental questions