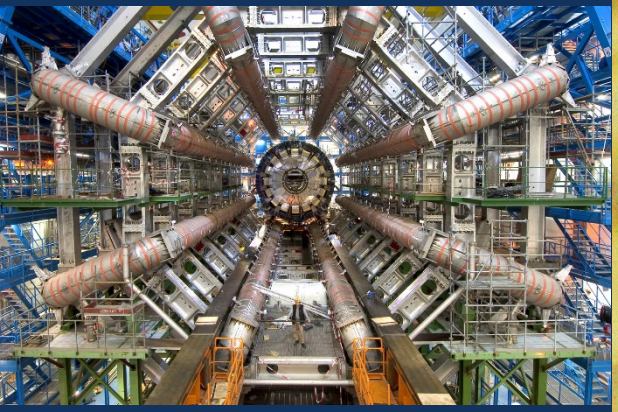
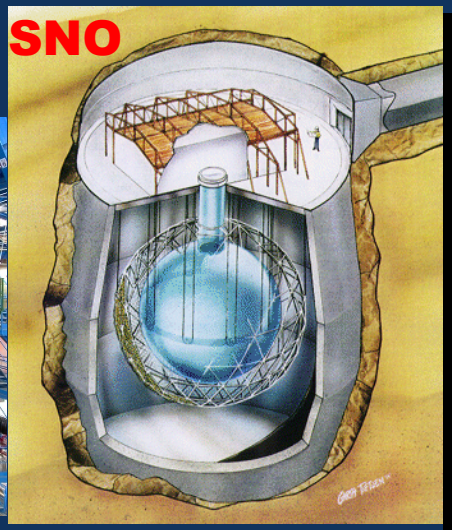
From the Tiniest Particles to the Farthest Reaches of the Universe

ATLAS at CERN



SNO

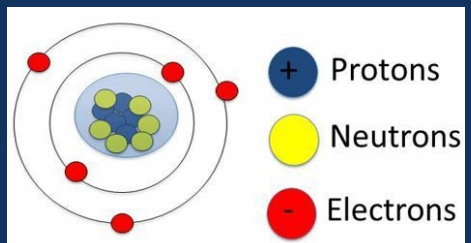


Our Cosmic Address

Our sun is one of 400 billion stars in the Milky Way galaxy, which is one of more than 100 billion galaxies in the visible universe.

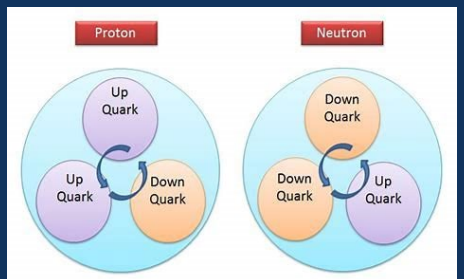
ATOMS

10^{-10} meters



Quarks in Protons, Neutrons

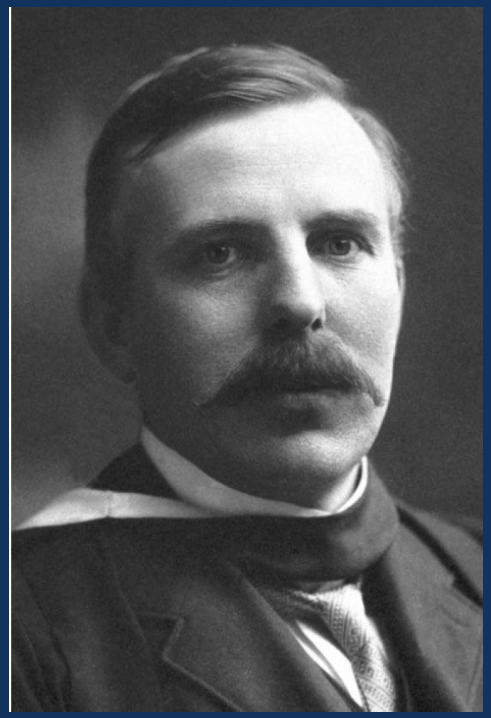
$< 10^{-15}$ meters



Neutrinos

$< 10^{-18}$ meters

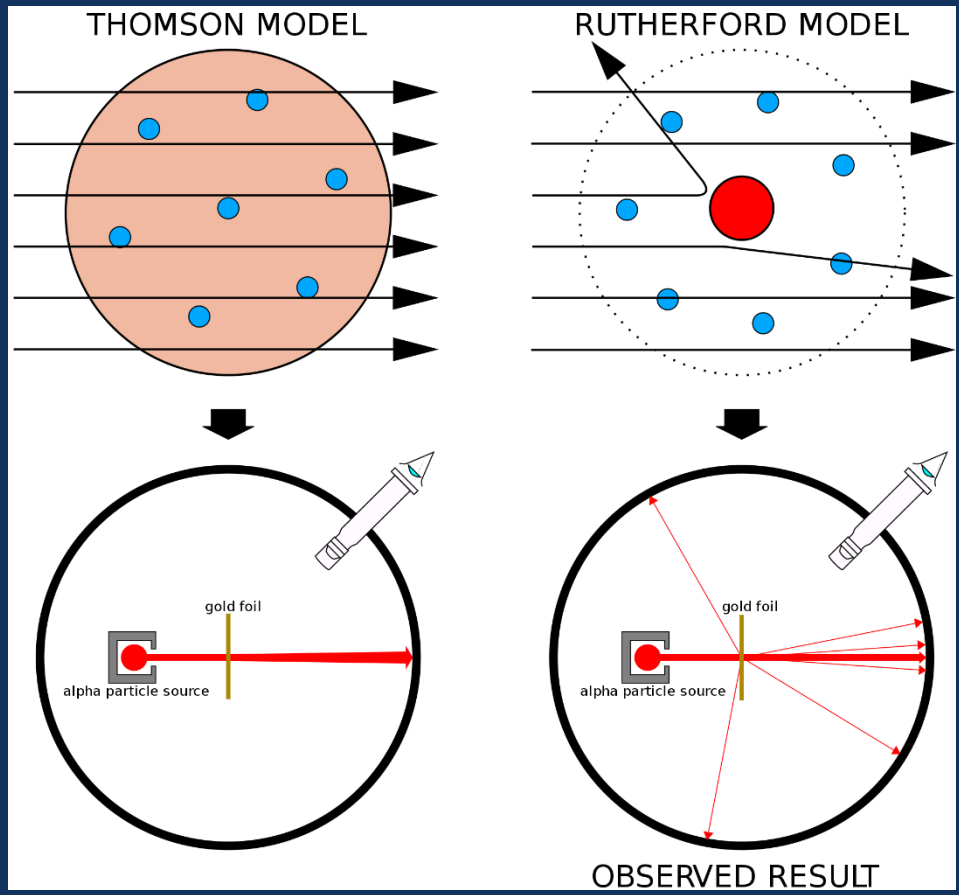
CANADIAN SCIENTISTS HAVE A LONG TRADITION IN PARTICLE PHYSICS



Ernest Rutherford, native of New Zealand

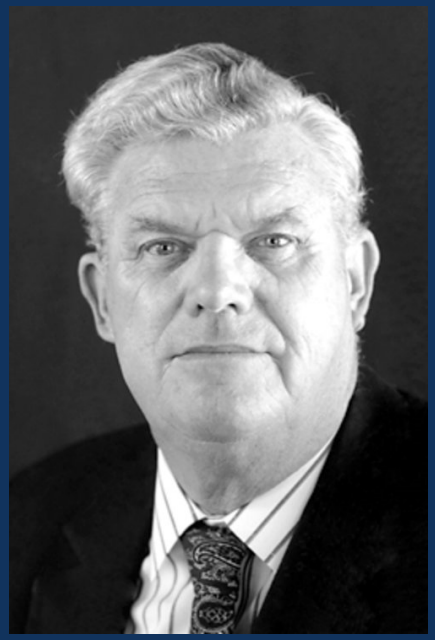
Prof. at McGill 1898-1907

Nobel Prize in Chemistry 1908 for discovery of radioactivity at McGill



With Geiger and Marsden, in 1908, discovered that atoms have a nucleus at the center

CANADIAN SCIENTISTS HAVE A LONG TRADITION IN PARTICLE PHYSICS



Stanford Linear Accelerator

Richard Taylor, born in Medicine Hat, Alberta

Prof. at Stanford University

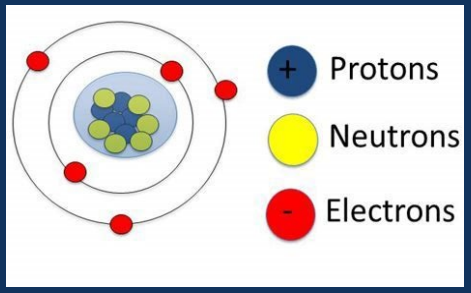
Co-winner of Nobel Prize in Physics in 1990 for demonstrating the Quark Structure of Protons and Neutrons

Technique is similar to Rutherford, scattering high energy electrons from protons and neutrons, but the results are more complicated as Quarks are very strongly bound within protons and never are found individually in nature.

SUMMARY

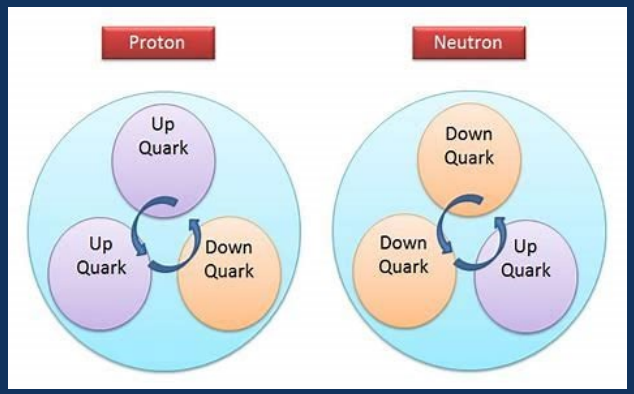
ATOMS

10^{-10} meters



Quarks in Protons, Neutrons

< 10^{-15} meters



Neutrinos

< 10^{-18} meters

- Neutrinos are emitted when a Quark changes into a different Quark, emitting an electron-like particle and a neutrino.

- Neutrinos are produced in enormous quantities in the nuclear fusion reactions that power the sun.

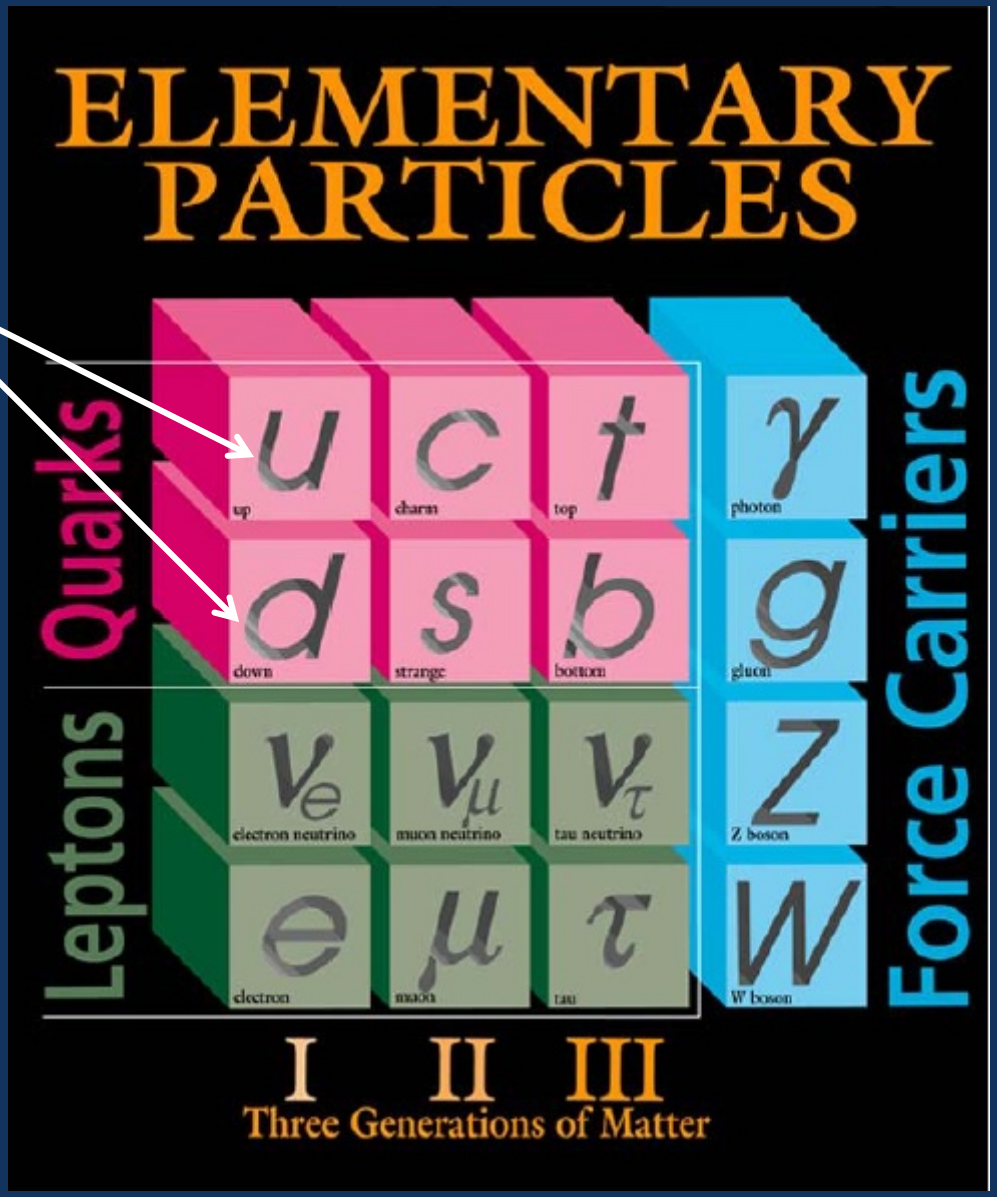
Standard Model for Elementary Particles

- Three up and/or down Quarks are combined to make a proton or neutron.

- An atom is composed of electrons circling a nucleus containing protons and neutrons.

- Neutrinos feel only the weak force (and gravity). Produced in radioactive decay or nuclear fusion in the Sun.

- Each particle has a matching particle made of anti-matter.

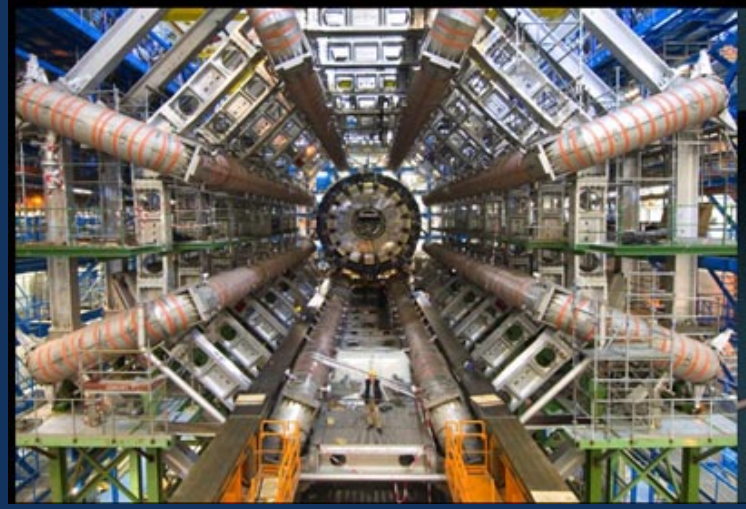


+ Higgs Boson

+ Anti-Matter Particles

The Standard Model provides a basis for the Electromagnetic, Weak and Strong forces, but does not yet include Gravity.

Large Hadron Collider at CERN in Geneva Switzerland



Canadian scientists were significant members of the ATLAS Experimental Collaboration that co-discovered the Higgs Particle that gives mass to the other particles in the Standard Model, leading to the Nobel Prize for Higgs, Englert in 2013

- There are many proposals for accelerators for future studies in particle physics beyond the intensity increase being implemented at CERN.

- These include much larger circular rings and linear accelerators at CERN and in China and Japan, to seek new discoveries at higher energies.

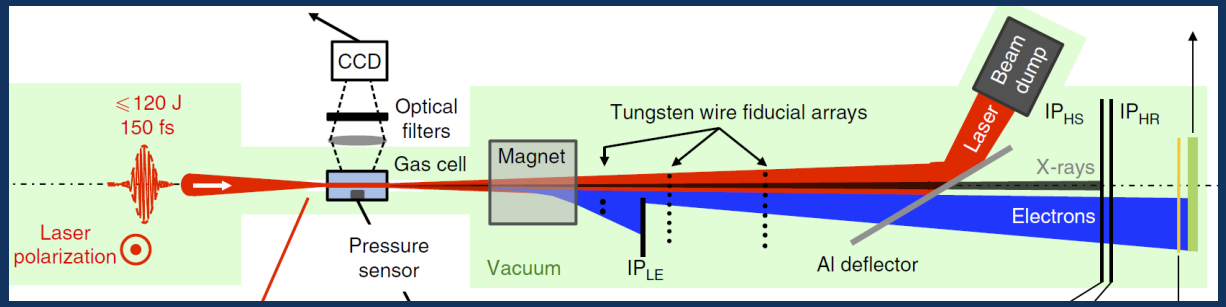
- The objectives of present and future experiments is to demonstrate more comprehensive models providing a "Theory of Everything", including Gravity.

- These include SuperSymmetry, SuperGravity, String Theory and many others. None have been verified to date.

A novel technique receiving new attention recently is Plasma Wakefield Acceleration based in part on the technique of chirped laser pulse amplification developed originally by:

- Canadian Donna Strckland, co-winner of the 2018 Nobel Prize with Gerard Mourou "for the method of generating high-intensity, ultra-short optical pulses."

Early Studies Plasma Wakefield Accelerator



SEE ALSO:
https://home.cern/science/experiments/awake

Neutrino facts:

- **Neutrinos, along with electrons and quarks, are basic particles of nature that we do not know how to sub-divide further.**

- **Neutrinos come in three "flavours" (electron, mu, tau) as described in The Standard Model of Elementary Particles, a fundamental theory of microscopic particle physics.**

- **They only feel the Weak Force. Therefore, they only stop if they hit the nucleus of an atom or an electron head-on and can pass through ten thousand billion kilometers of lead without stopping.**

- **That makes them very difficult to detect and their properties have been the least known among the basic particles.**

- **The Standard Model said that they should not change their flavor or oscillate between flavors. If the do oscillate, as we have shown, it implies that they have a mass greater than zero.**

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

Sudbury Neutrino Observatory (SNO)

Neutrinos are very difficult to detect so our detector had to be very big with low radioactivity deep underground.

NEUTRINO FROM THE SUN

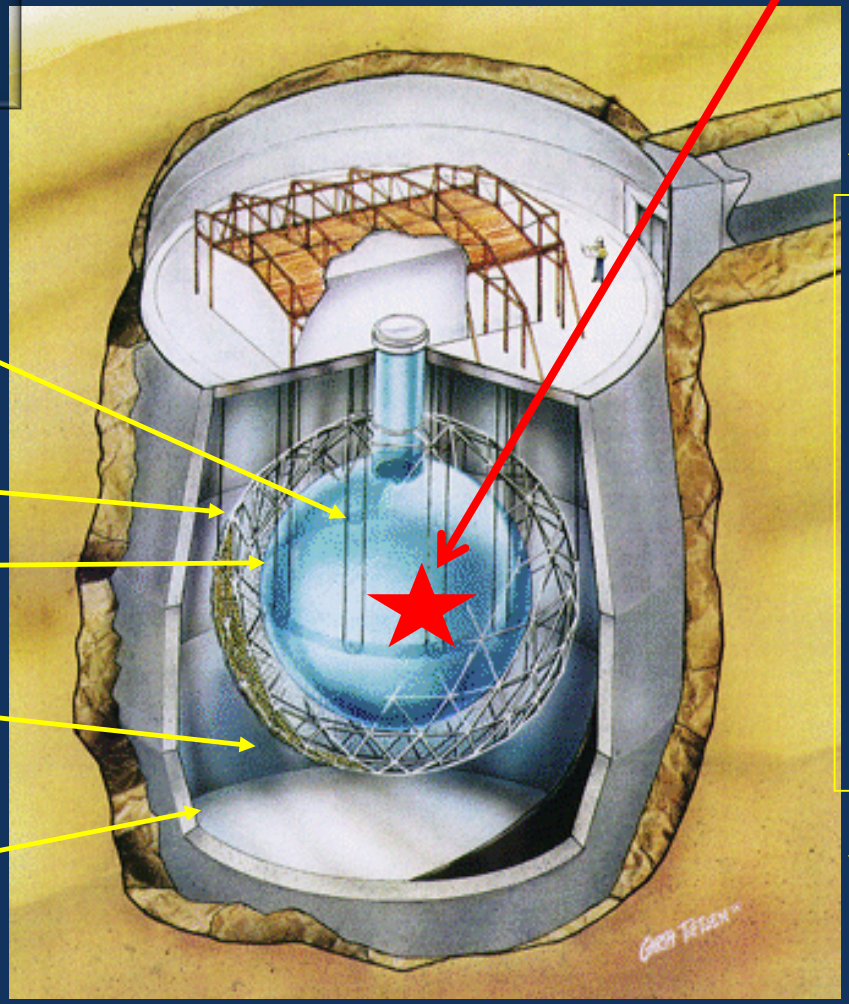
1000 tonnes of heavy water: D_2O $ 300 million on Loan for $1.00

9500 light sensors

12 m Diameter Acrylic Container

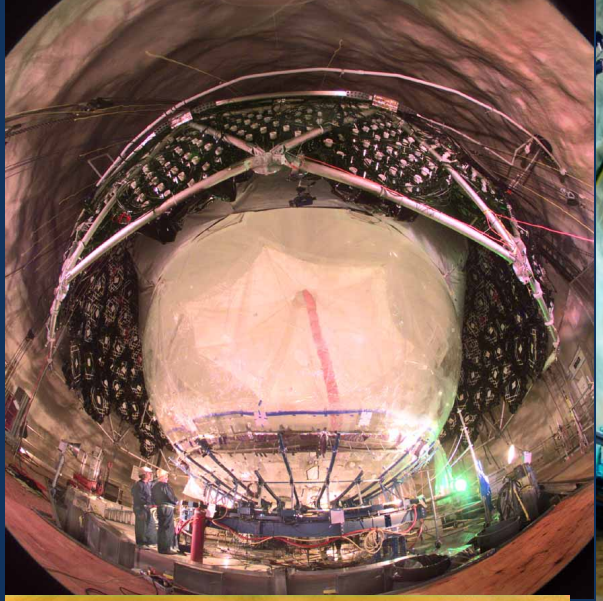
Ultra-pure Water: H_2O.

Urylon Liner and Radon Seal

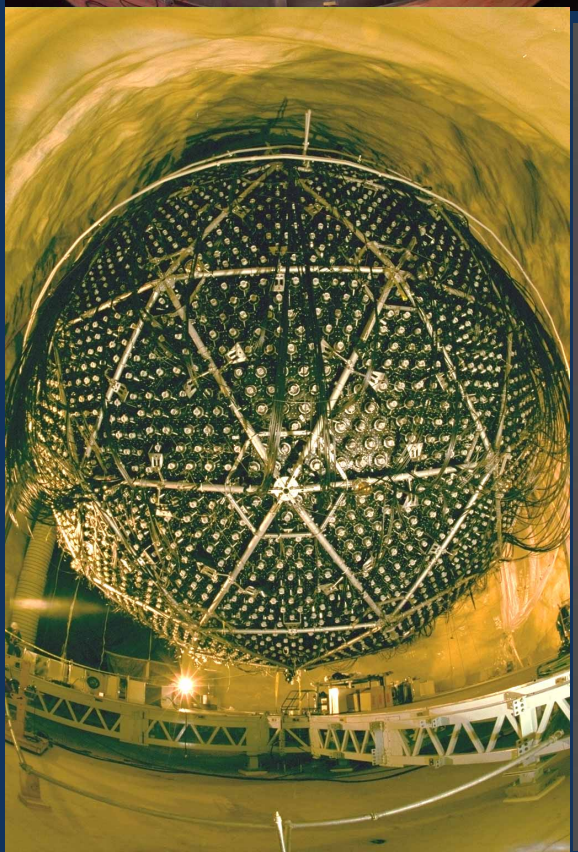


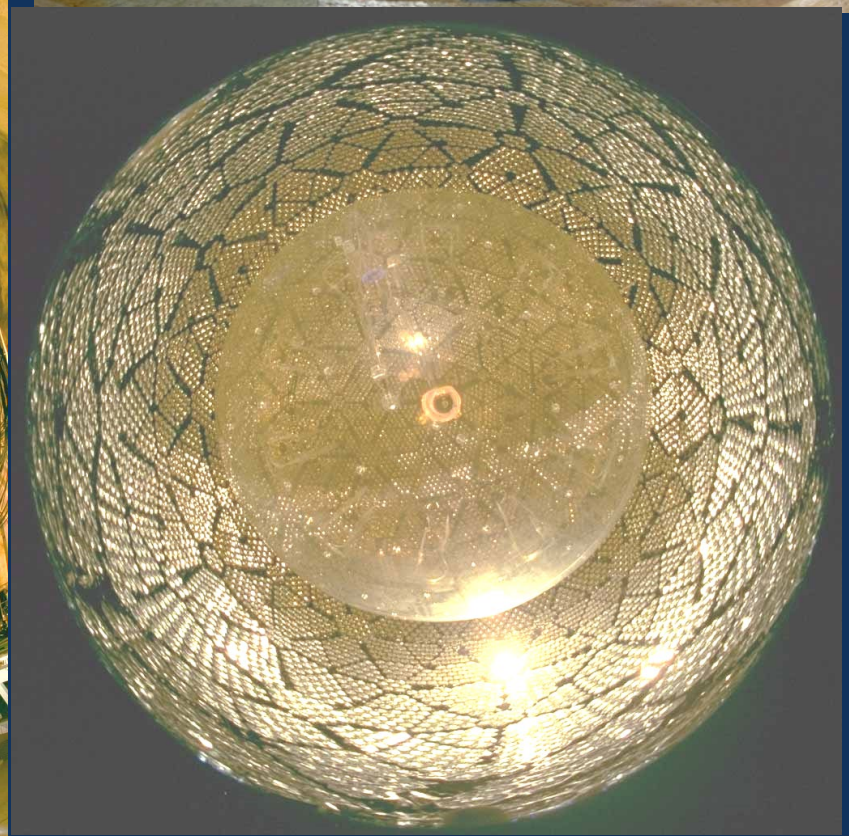
34 m or ~ Ten Stories High!

2 km below the ground



Over 70,000 showers for personnel





One million pieces transported down in the 3 m by 4 m mine cage and re-assembled.

RESULTS FROM THE SNO EXPERIMENT

1. Two thirds of the solar electron neutrinos change into mu or tau neutrinos before reaching the earth.

2. This implies that neutrinos have a finite mass and **requires additions to the Standard Model.**

3. The total number of neutrinos emitted by the sun matches calculations within 10%: **We know with great accuracy how the sun burns.**

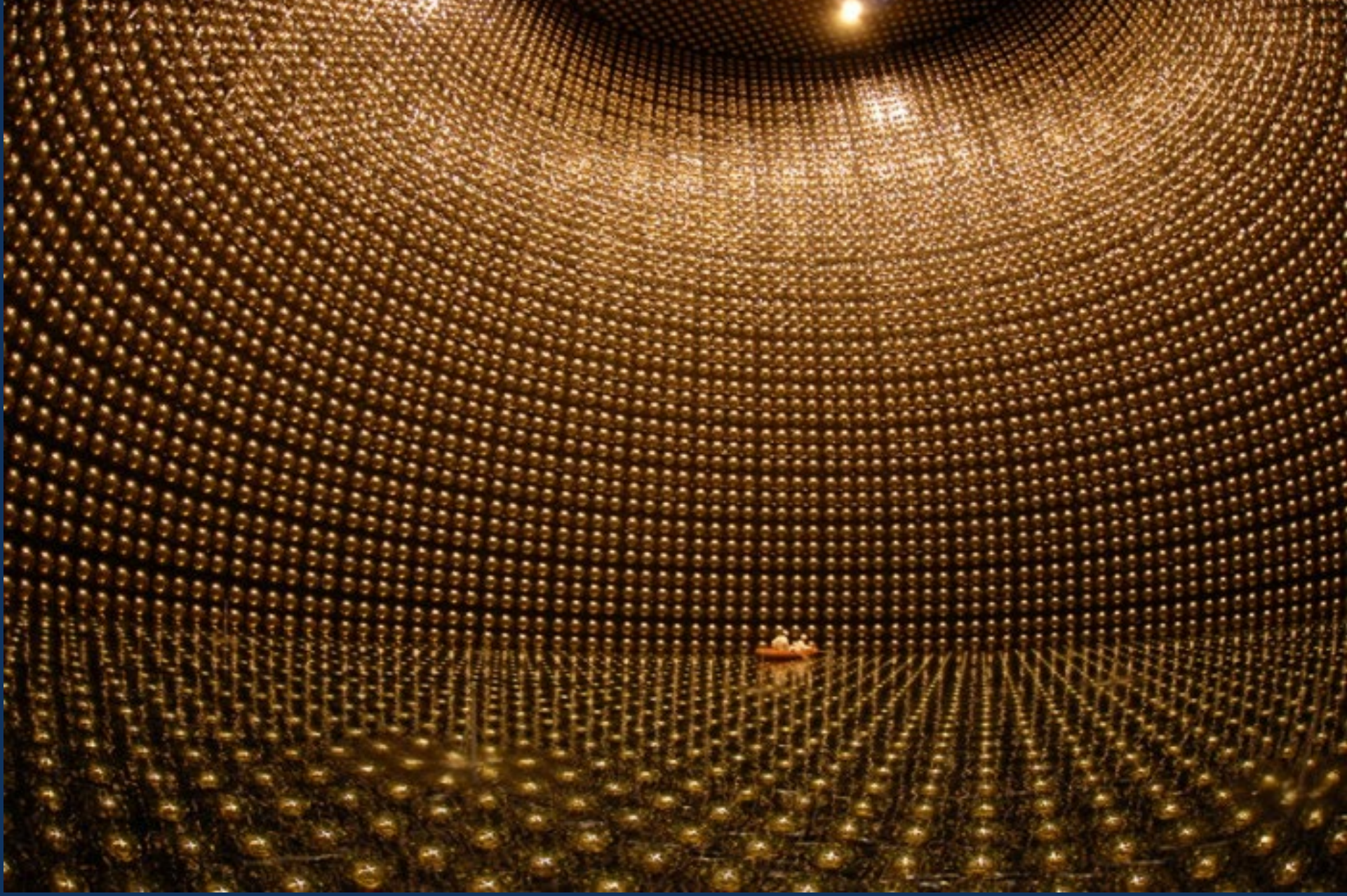
Sudbury Neutrino Observatory (SNO)

BUT SERIOUSLY, WHY SHOULD YOU CARE ABOUT OUR RESULTS?

Besides adding to the Laws of Physics at a microscopic scale:

- **We now know that the physics of nuclear fusion in the sun, confined by gravity can be calculated with great accuracy.**
  - Same calculations as for Nuclear Fusion Power Production here on earth: The ITER Project where the remaining challenge is engineering to confine "the sun" with magnetic fields.

- **The major elements from which we are made (C,N,O) are produced in stars like our sun. One can predict the abundances of all the elements on earth up to iron within a factor of two.**
  - It is our DNA match of the elements from the early Universe.

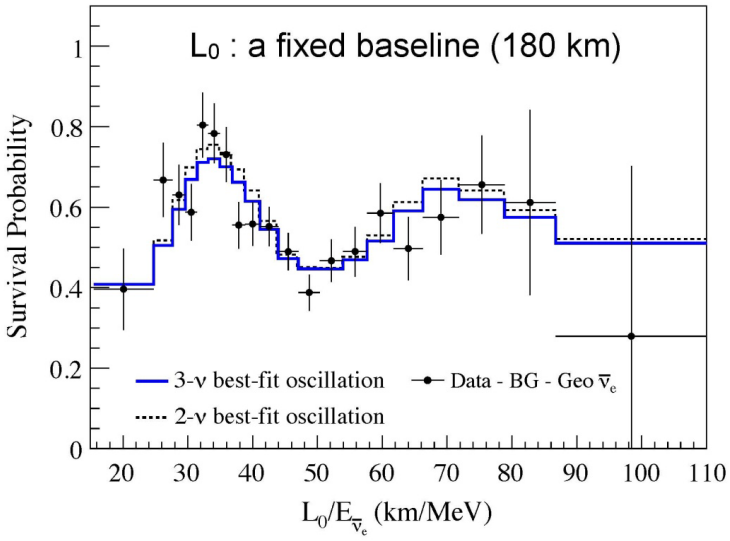


SuperKamiokande in Japan observed oscillation of neutrinos from the atmosphere in an enormous underground detector

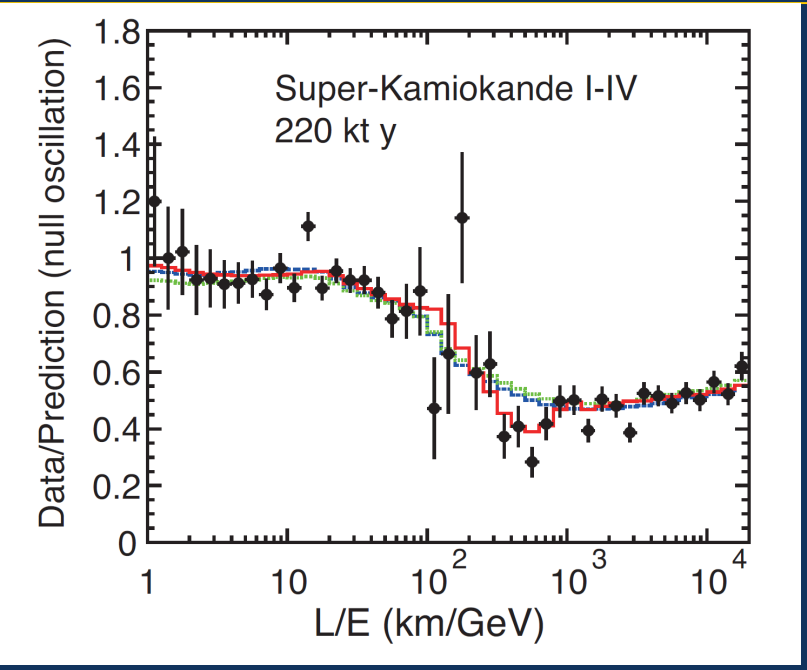
Nobel Prize 2015

Oscillation Patterns (Various Neutrino Sources)

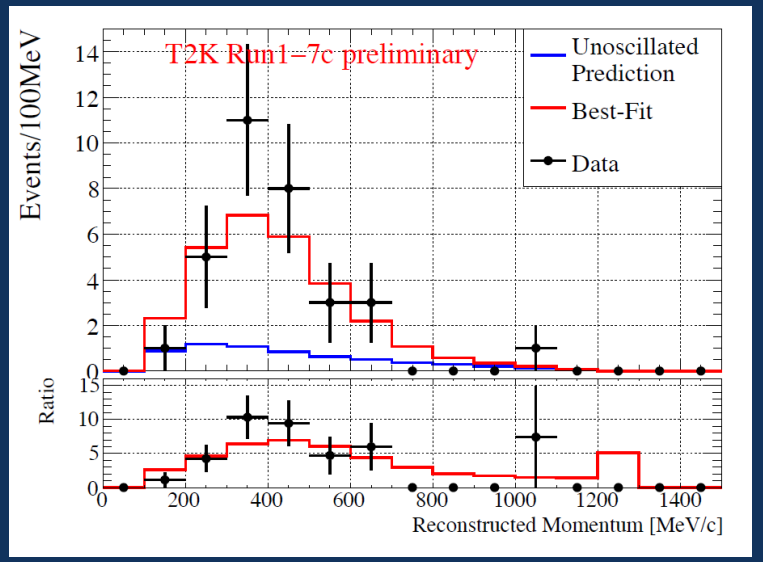
KamLAND Reactor Neutrinos



Atmospheric Neutrinos: SuperKamiokande, Nobel Prize: Kajita 2015



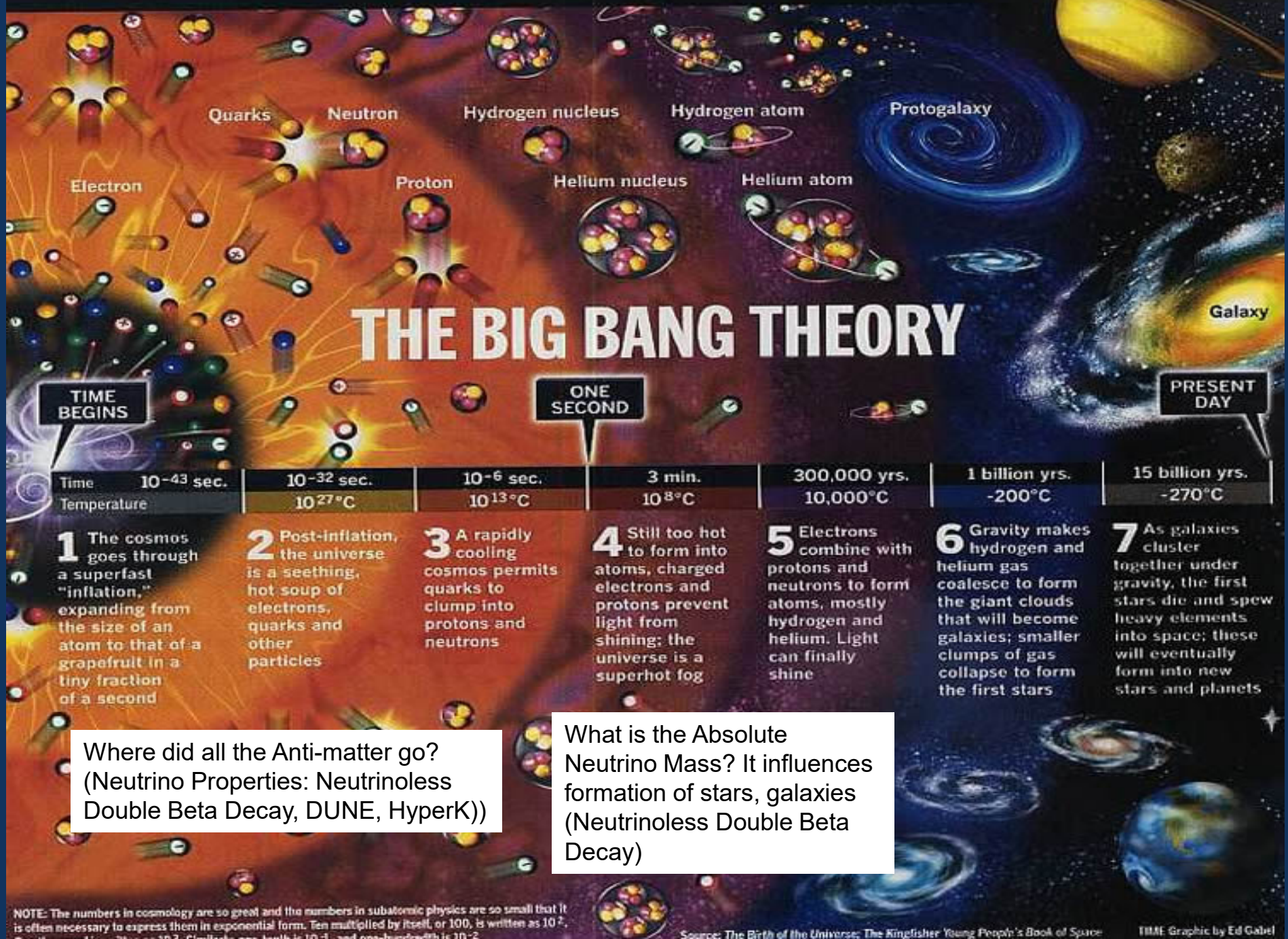
Accelerator Neutrinos: T2K, MINOS, NOVA



Such oscillations can only occur if neutrinos have the ability to "sense" elapsed time in their rest frame and change type as time evolves. If they can do that, Einstein's theory of relativity requires that they travel at slightly less than the speed of light and thus have a small finite rest mass.

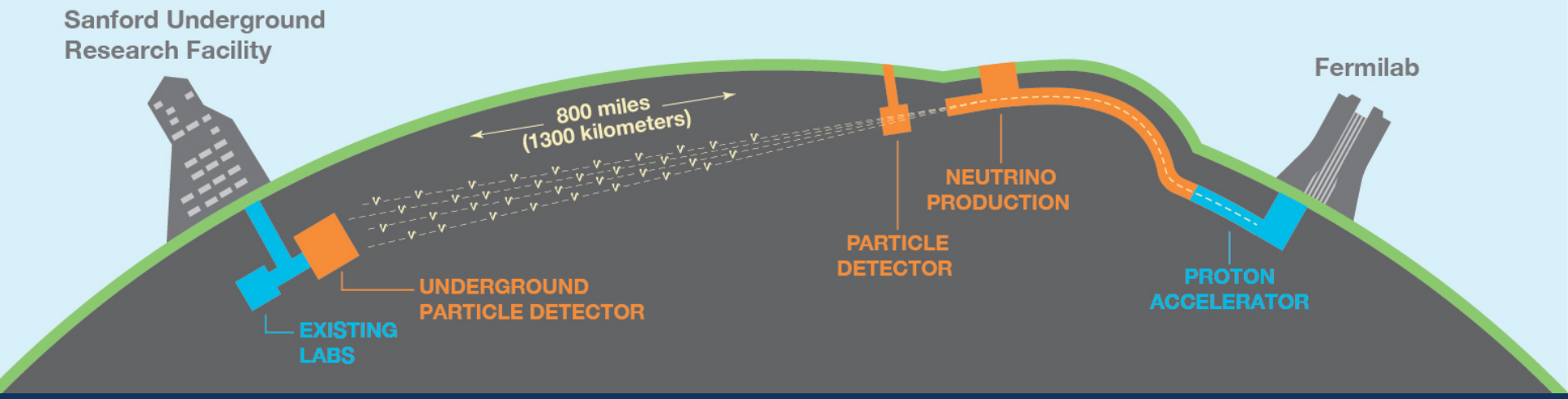
Attendance at a taping of the Big Bang Theory: As "Geek of the Week"

Prof. David Salzberg, UCLA Technical Advisor to "Big Bang Theory". Former student of ours at Princeton.



Where did all the Anti-matter go? (Neutrino Properties: Neutrinoless Double Beta Decay, DUNE, HyperK))

What is the Absolute Neutrino Mass? It influences formation of stars, galaxies (Neutrinoless Double Beta Decay)



Two large future experiments:

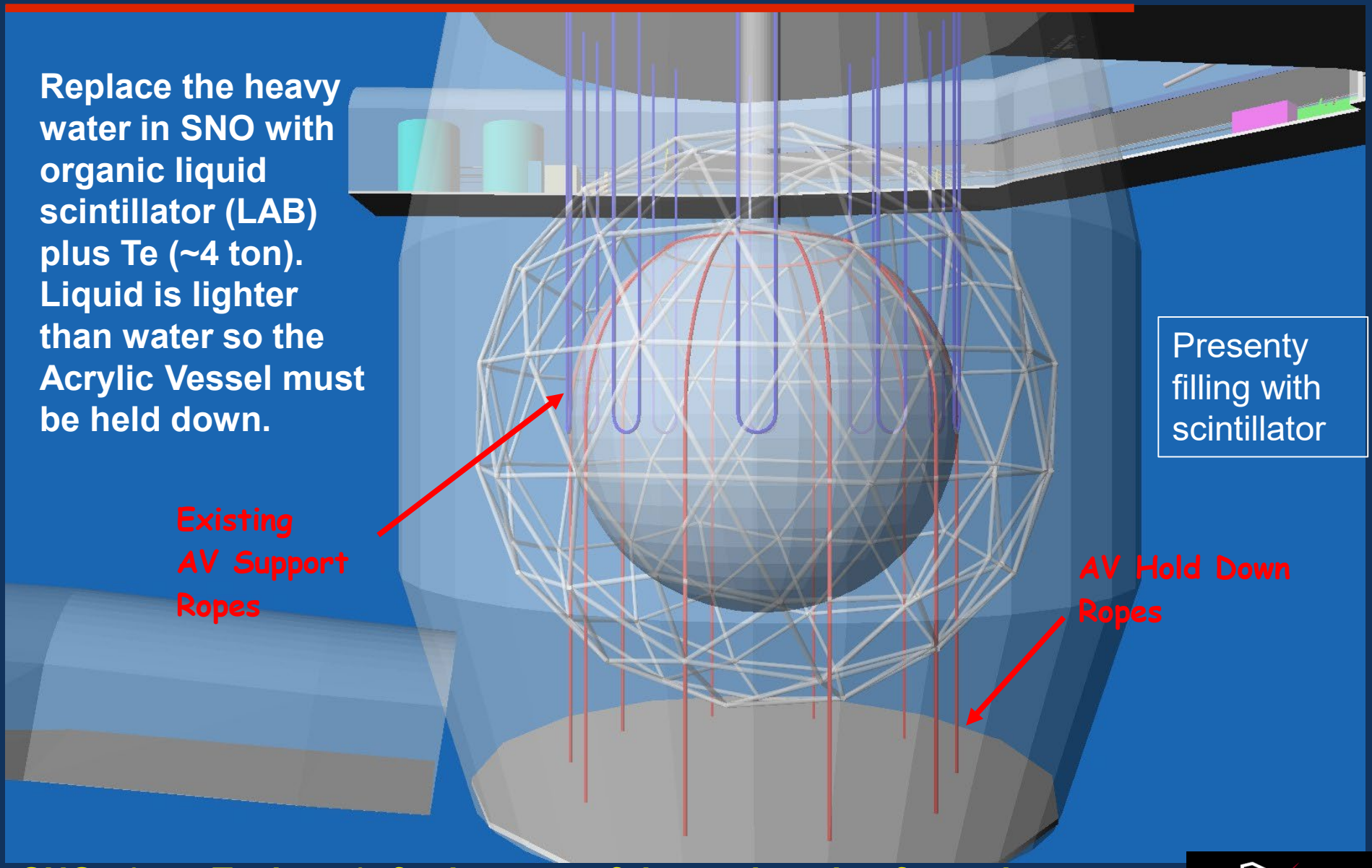
- DUNE in the US and Hyper-Kamiokande in Japan

Compare neutrino oscillations initiated by muon neutrinos and their anti-particles.

Look for matter/anti-matter differences to understand the early universe.

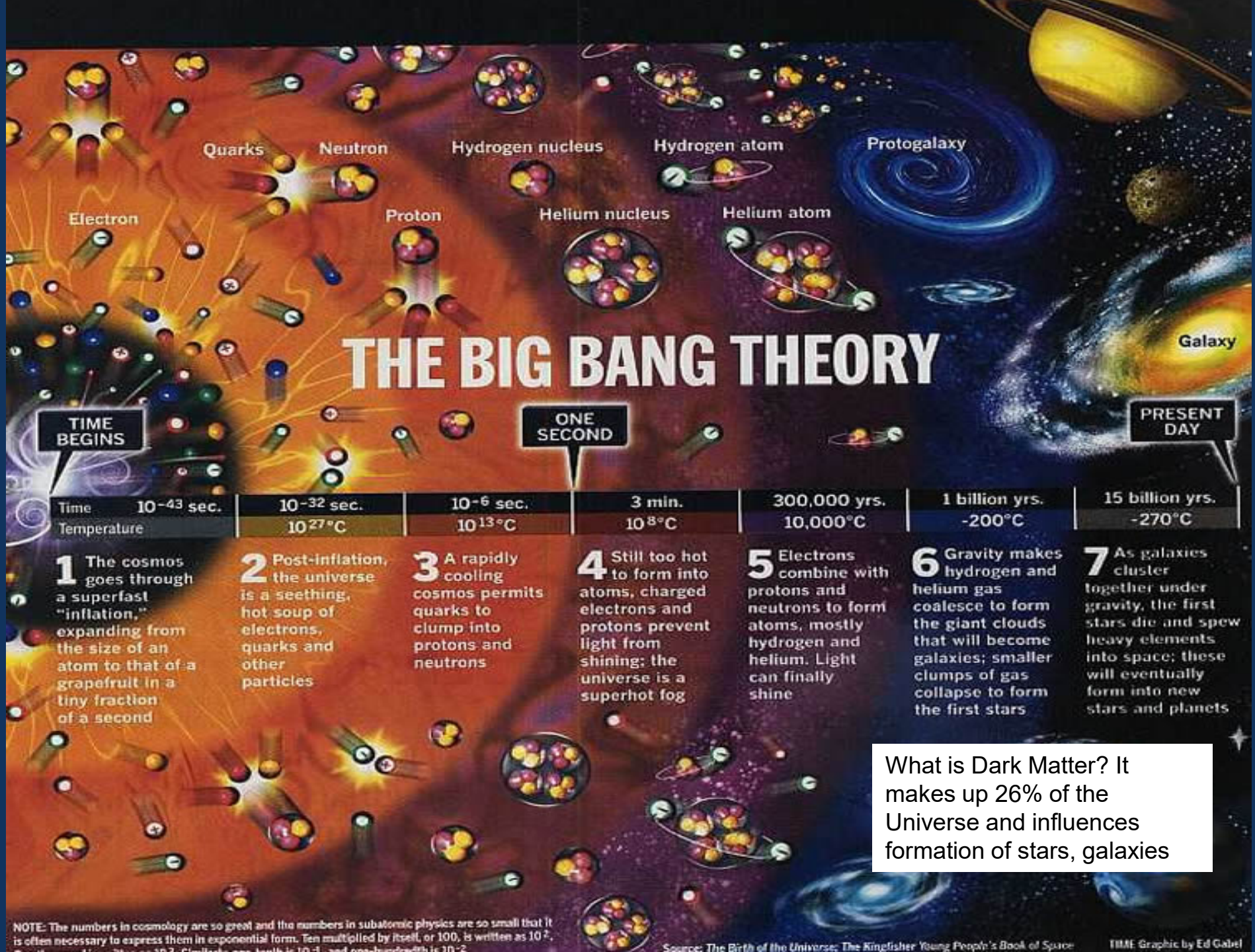
Neutrino-less Double Beta Decay: SNO+

Replace the heavy water in SNO with organic liquid scintillator (LAB) plus Te (~4 ton). Liquid is lighter than water so the Acrylic Vessel must be held down.



SNO+ (rare Te decay): further part of the explanation for anti-matter decay in the early Universe and also an absolute mass for neutrinos

SNOLAB
Mining for knowledge
Creuser pour trouver... l'excellence

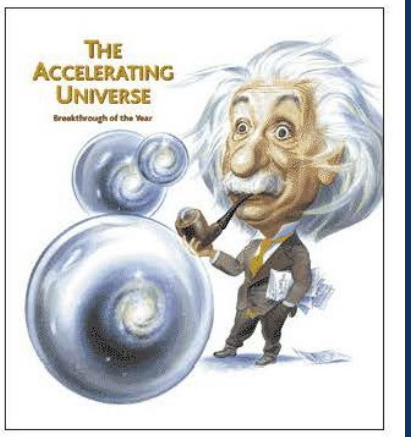

Quarks
Neutron
Hydrogen nucleus
Hydrogen atom
Protogalaxy
Electron
Proton
Helium nucleus
Helium atom
Galaxy
THE BIG BANG THEORY
TIME BEGINS
ONE SECOND
PRESENT DAY
Time 10⁻⁴³ sec. | 10⁻³² sec. | 10⁻⁶ sec. | 3 min. | 300,000 yrs. | 1 billion yrs. | 15 billion yrs.
Temperature | 10²⁷°C | 10¹³°C | 10⁸°C | 10,000°C | -200°C | -270°C
1 The cosmos goes through a superfast "inflation," expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second
2 Post-inflation, the universe is a seething, hot soup of electrons, quarks and other particles
3 A rapidly cooling cosmos permits quarks to clump into protons and neutrons
4 Still too hot to form into atoms, charged electrons and protons prevent light from shining; the universe is a superhot fog
5 Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine
6 Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars
7 As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets
What is Dark Matter? It makes up 26% of the Universe and influences formation of stars, galaxies
NOTE: The numbers in cosmology are so great and the numbers in subatomic physics are so small that it is often necessary to express them in exponential form. Ten multiplied by itself, or 100, is written as 10²,
Source: The Birth of the Universe; The Kingfisher Young People's Book of Space
TIME Graphic by Ed Gabel

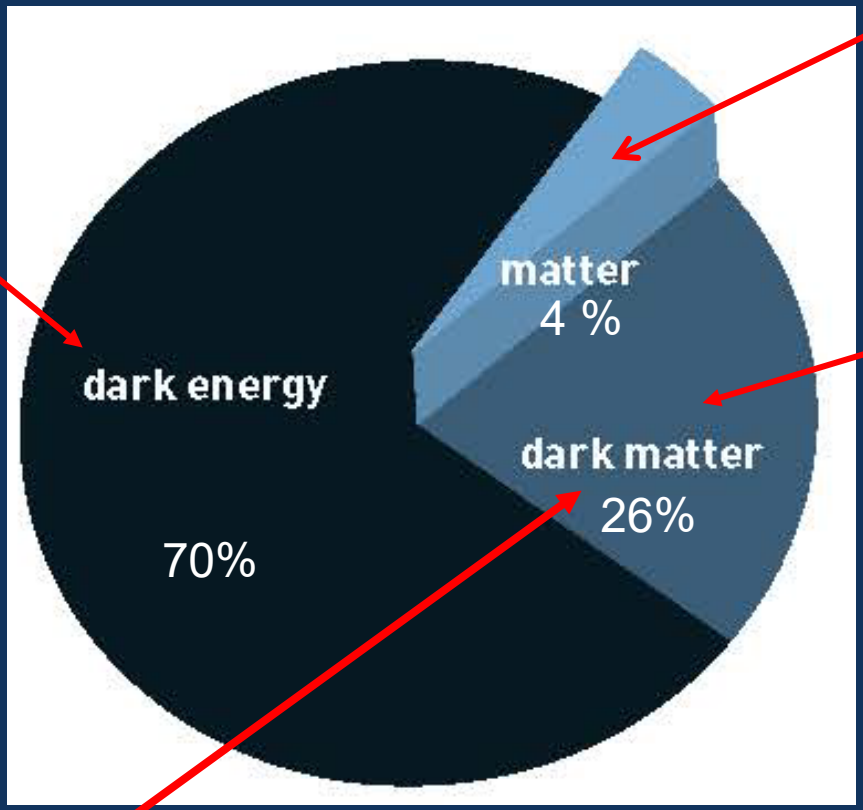
Composition of the Universe as we understand it today

(Very different than 20 years ago thanks to very sensitive astronomical and astrophysical experiments such as measurements of the cosmic microwave background, large scale structure and distant supernovae.)

US!!!

Responsible for accelerating the Universe's expansion





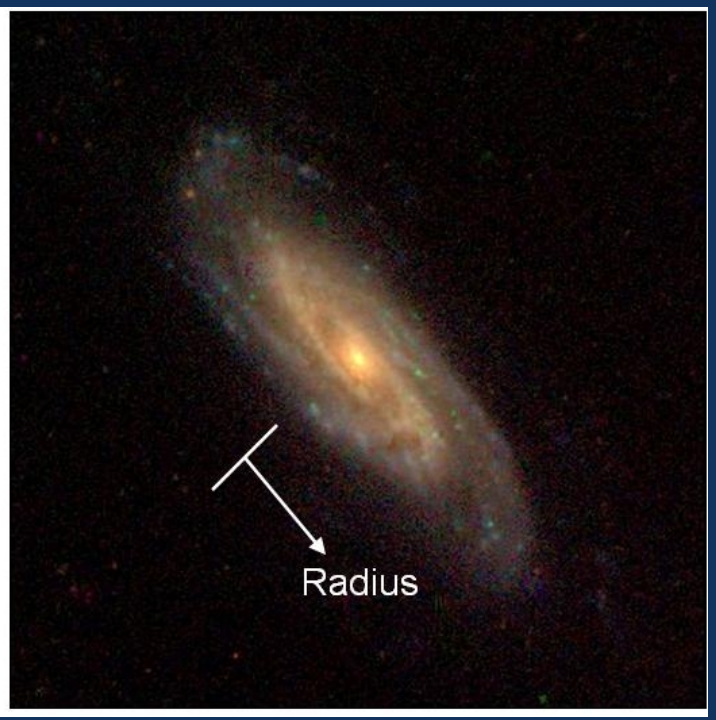
Neutrinos Are only a few %

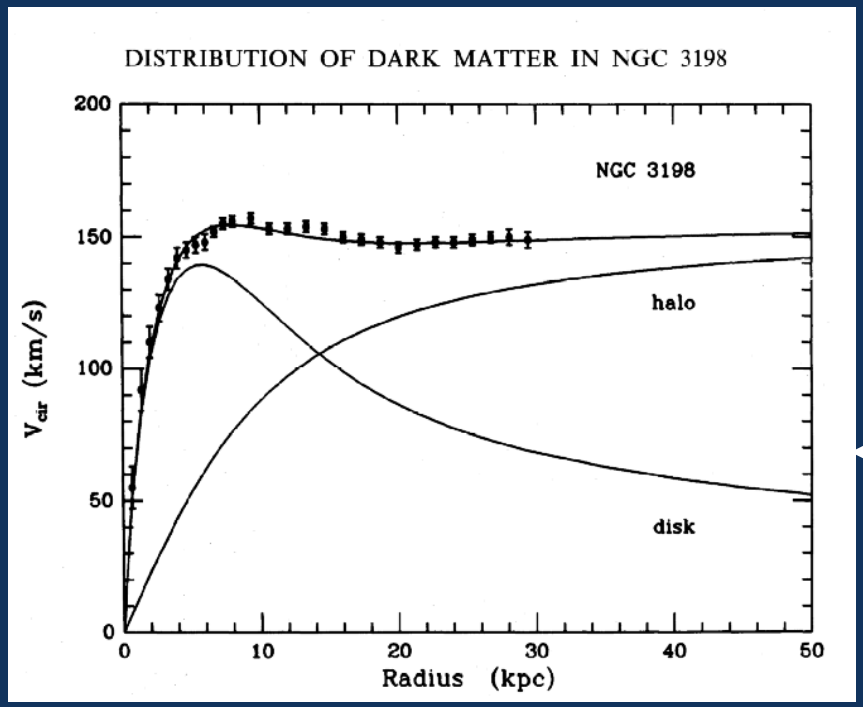
With SNOLAB we look for Dark Matter particles left from the Big Bang, with ultra-low radioactive background.

At the Large Hadron Collider in the CERN laboratory in Geneva: Researchers try to create it for the first time since the Big Bang. In the future: higher beam intensity (CERN, ATLAS)

The evidence for *dark matter* is strong from astrophysics measurements:

For example: SPIRAL GALAXIES LIKE OUR MILKY WAY WOULD FLY APART IF COMPOSED OF ONLY THE GLOWING MATTER





DARK MATTER (WIMPS)

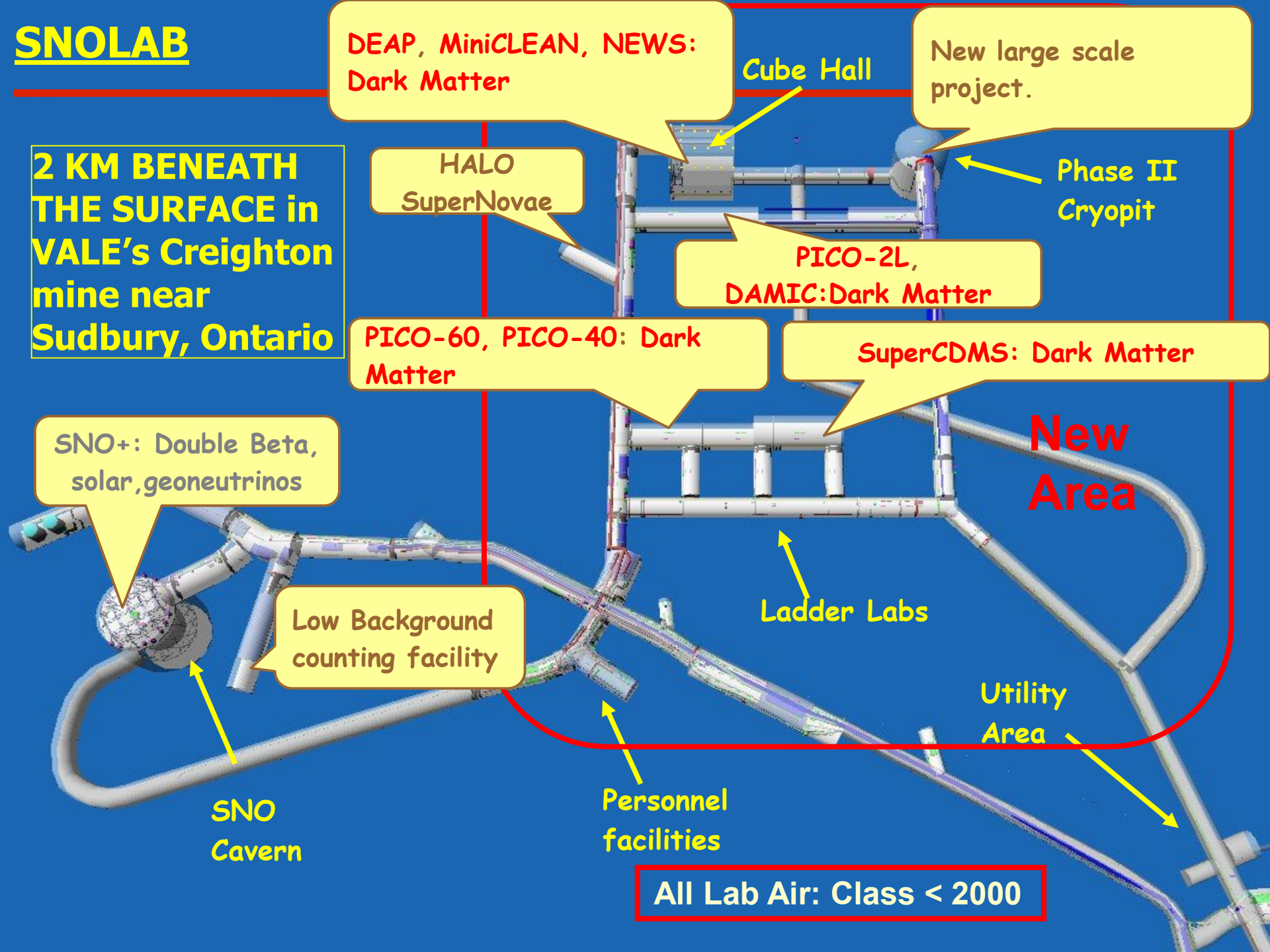
GLOWING MATTER

- **HOWEVER, WE DO NOT KNOW WHAT THE WEAKLY INTERACTING MASSIVE PARTICLES (WIMPS) ARE. THEY MUST BE SO MASSIVE THAT EVEN THE HIGHEST ENERGY ACCELERATOR AT CERN IN GENEVA HAS NOT PRODUCED THEM YET.**

- **WE ARE LOOKING FOR WIMPS FROM OUR GALAXY STRIKING OUR DETECTORS AND PRODUCING LIGHT, HEAT OR BUBBLES.**

SNOLAB

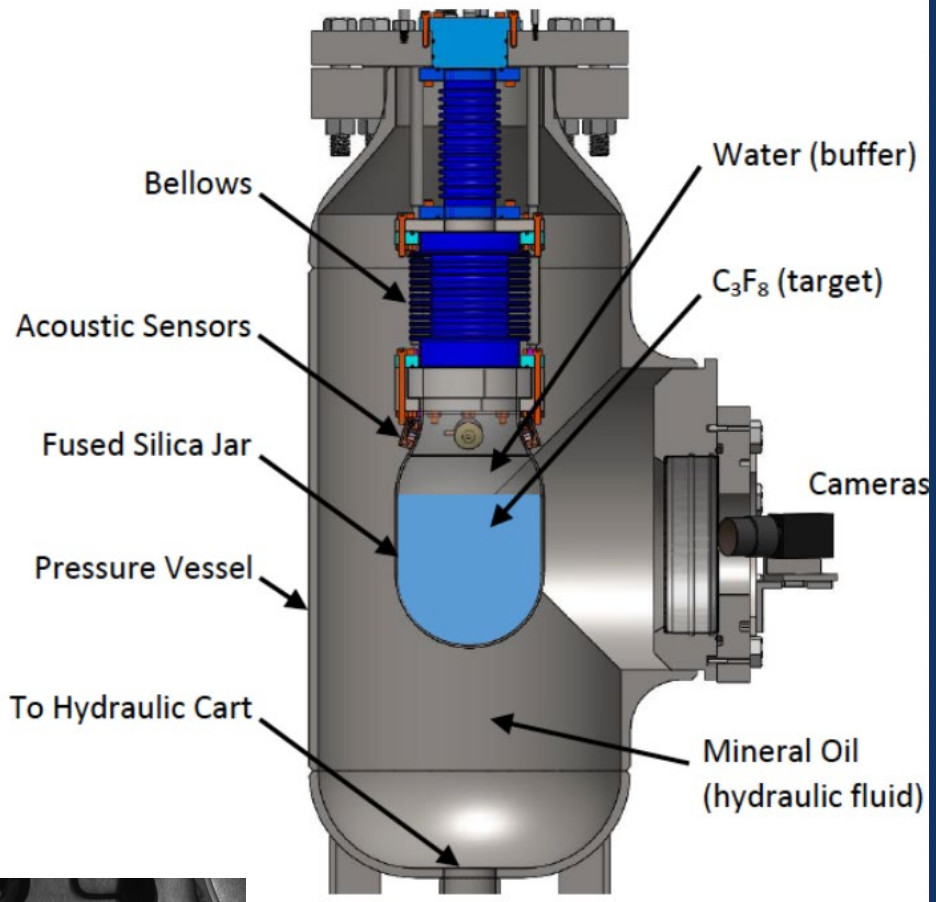
2 KM BENEATH THE SURFACE in VALE's Creighton mine near Sudbury, Ontario



SNOLAB Experimental Area

Stephen Hawking and fans observing the CRYOPIT area in September 2012

PICO-2L (2 Liters)



Bubble Formation with low threshold for WIMPS, good discrimination against radioactive background

PICO-60 (40 Liters)

Sequence of experiments: PICO-40, PICO-500

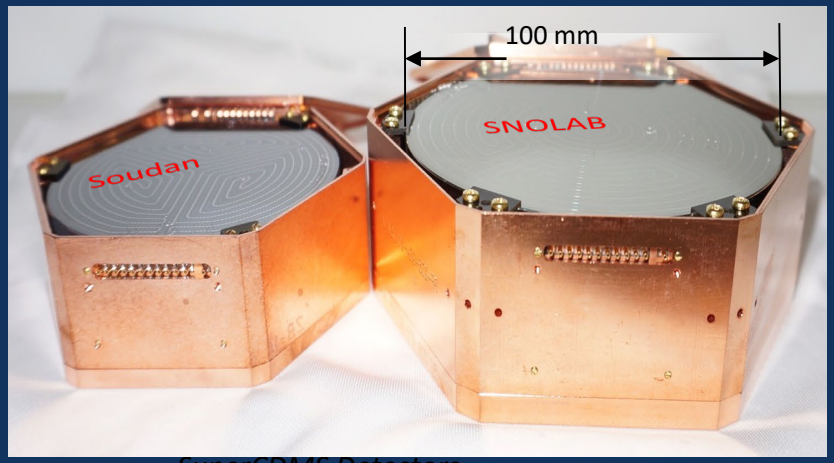
SuperCDMS @ SNOLAB

Super Cold Dark Matter Search Collaboration
Initial installation: ~30-40 detectors

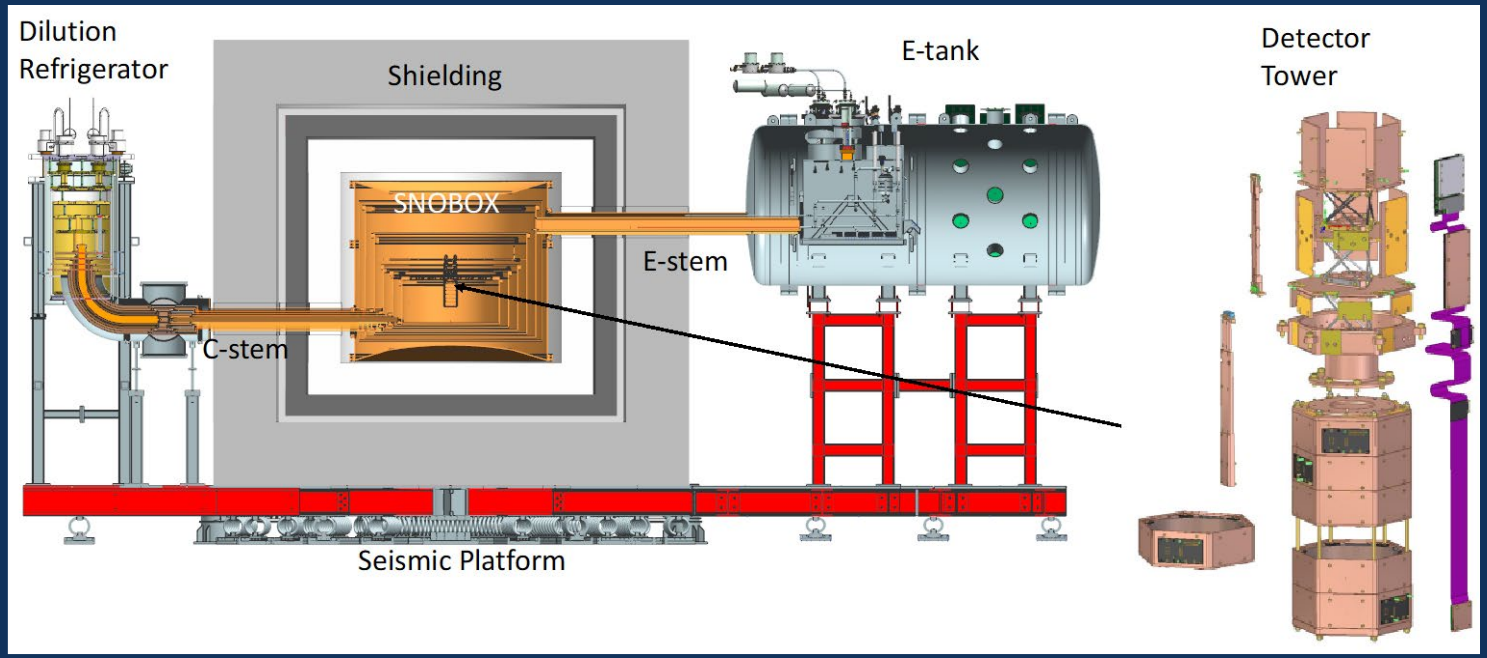
- These detectors are operated close to absolute zero as thermal sensors and ionization detectors.

- Little bursts of heat and little bursts of electrons are caused by WIMPS and their ratio is different than for ordinary radiation:

Use to Discriminate Against Background

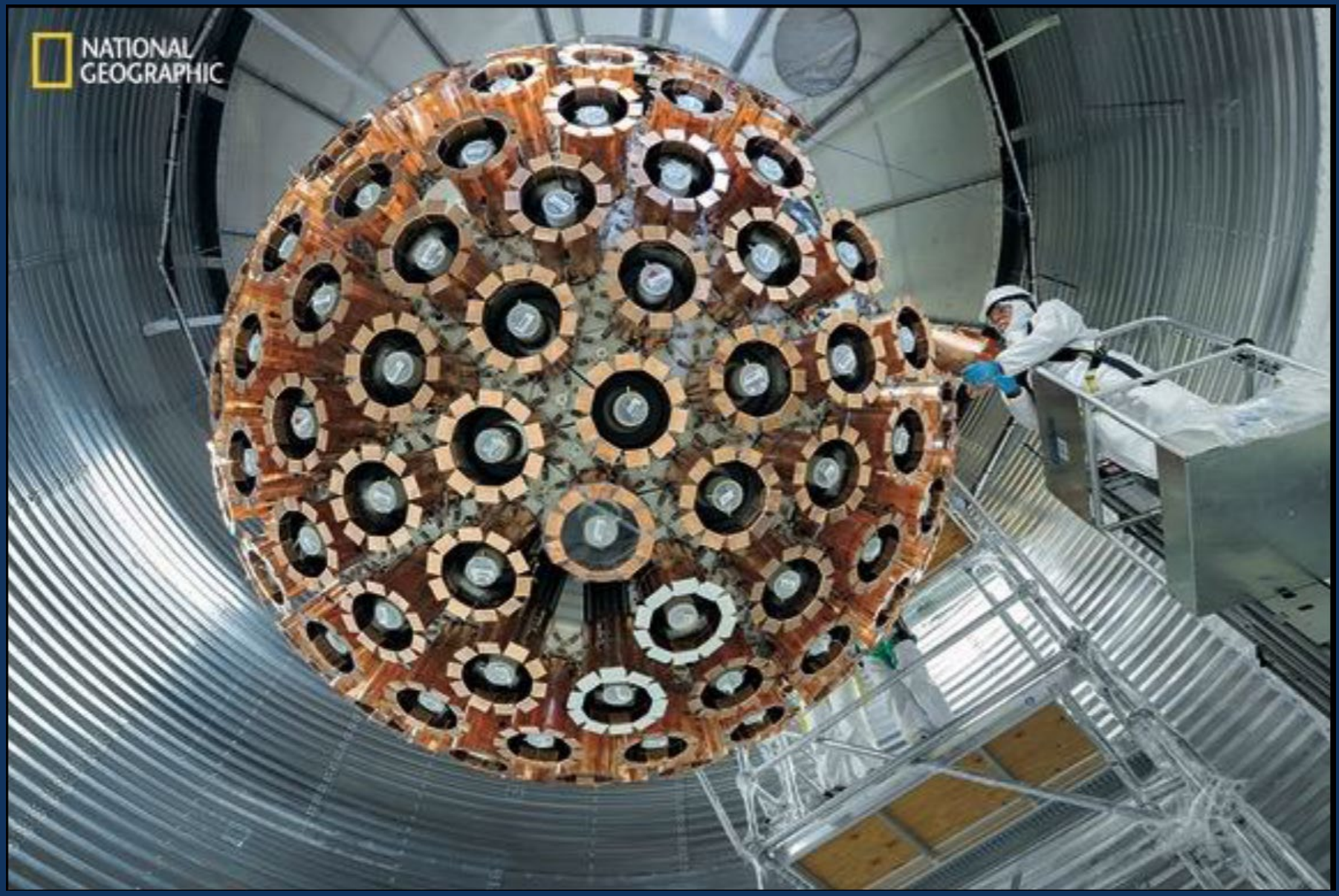


SuperCDMS Detectors



Expected start in 2020

DEAP EXPERIMENT – 3 Tonnes of Liquid Argon



Global Argon Dark Matter Collaboration

- 68 institutes
- 416 researchers
- Strong assistance from CERN, FERMILAB
- 14 nations:

Brazil, Canada, China, France, Greece, Italy, Mexico, Poland, Romania, Spain, Switzerland, UK, USA, Russia

Sequence of experiments:

- DEAP: 3 tonnes
- DarkSide: 50 tonnes:Italy
- Argo: 400 tons (SNOLAB) to reach the “Neutrino Floor”

Very High Energy Neutrinos at the South Pole

IceCube
South Pole Neutrino Observatory

IceCube Laboratory

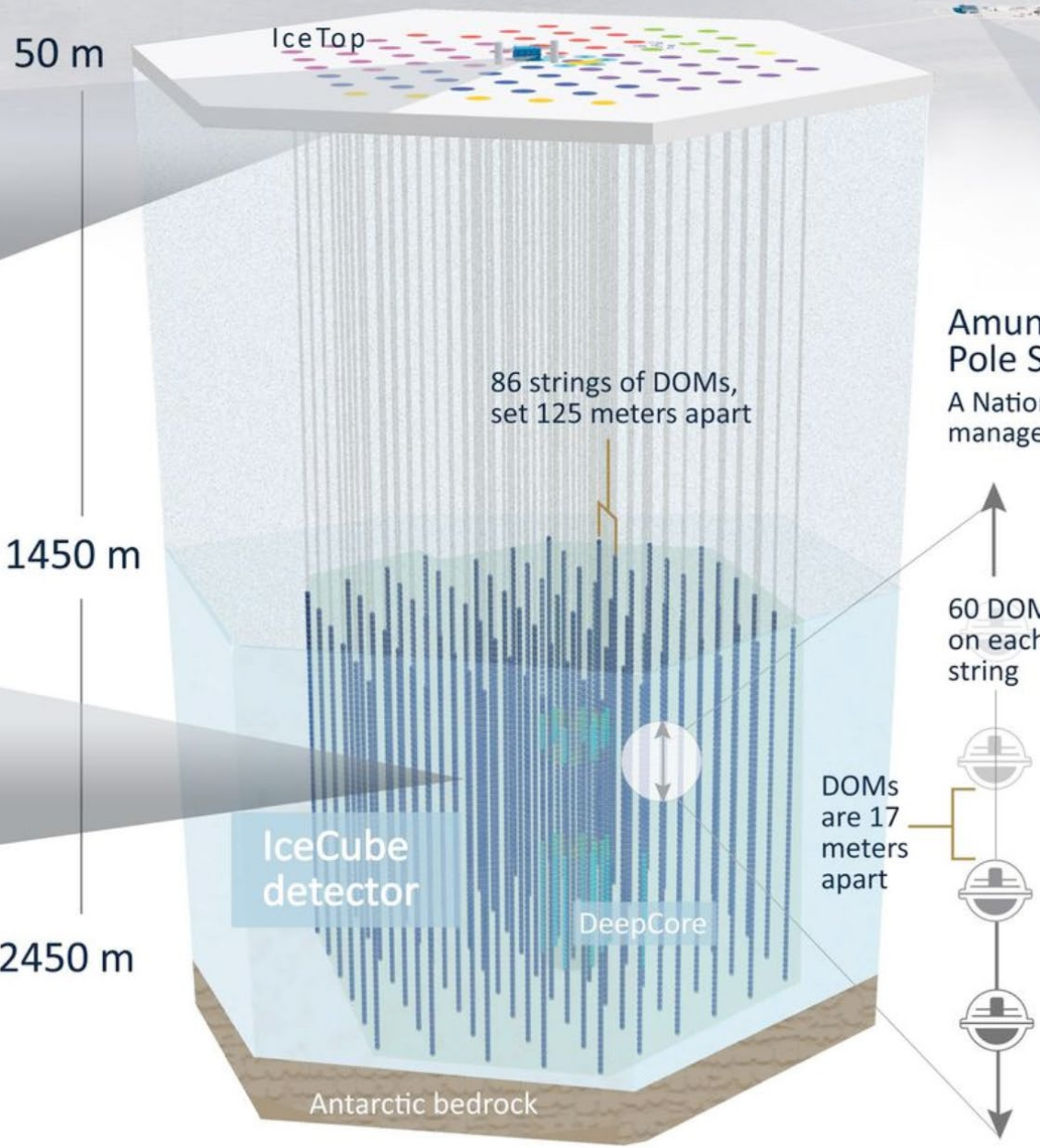
Data is collected here and sent by satellite to the data warehouse at UW–Madison

Digital Optical Module (DOM)

5,160 DOMs deployed in the ice

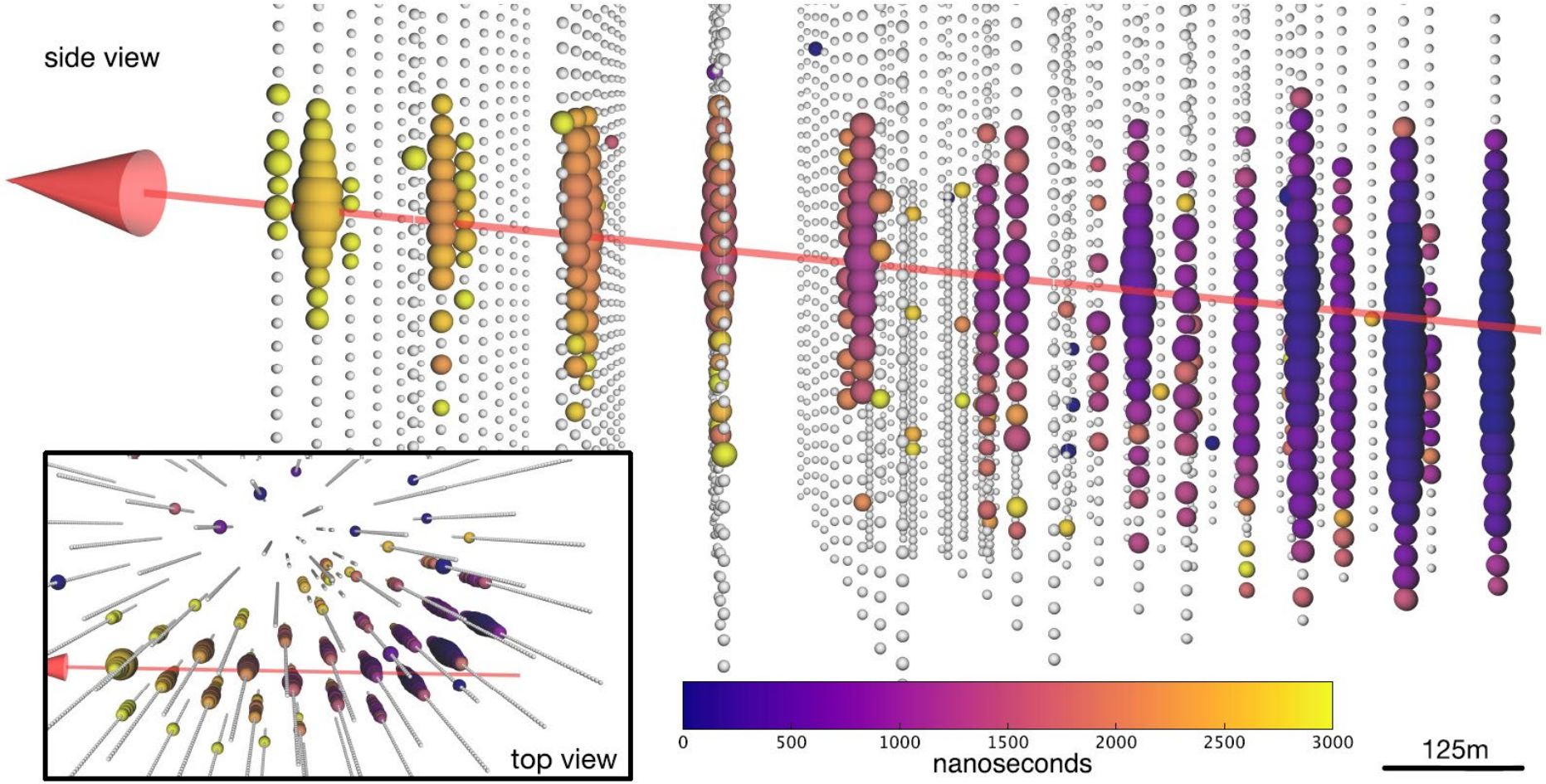
Amundsen–Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility



- This neutrino signal in 2017 with an energy 20 times higher than the CERN LHC accelerator was observed by ICECUBE, coincident with a flare of gamma rays observed by a satellite from a "BLAZAR" thought to be a Supermassive Black Hole emitting a beam of particles in a flare pointing in our direction.

- Great Example of "Multi-Messenger Astronomy"

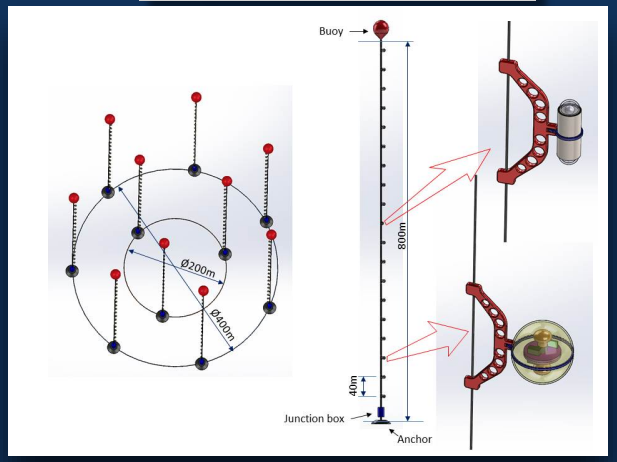


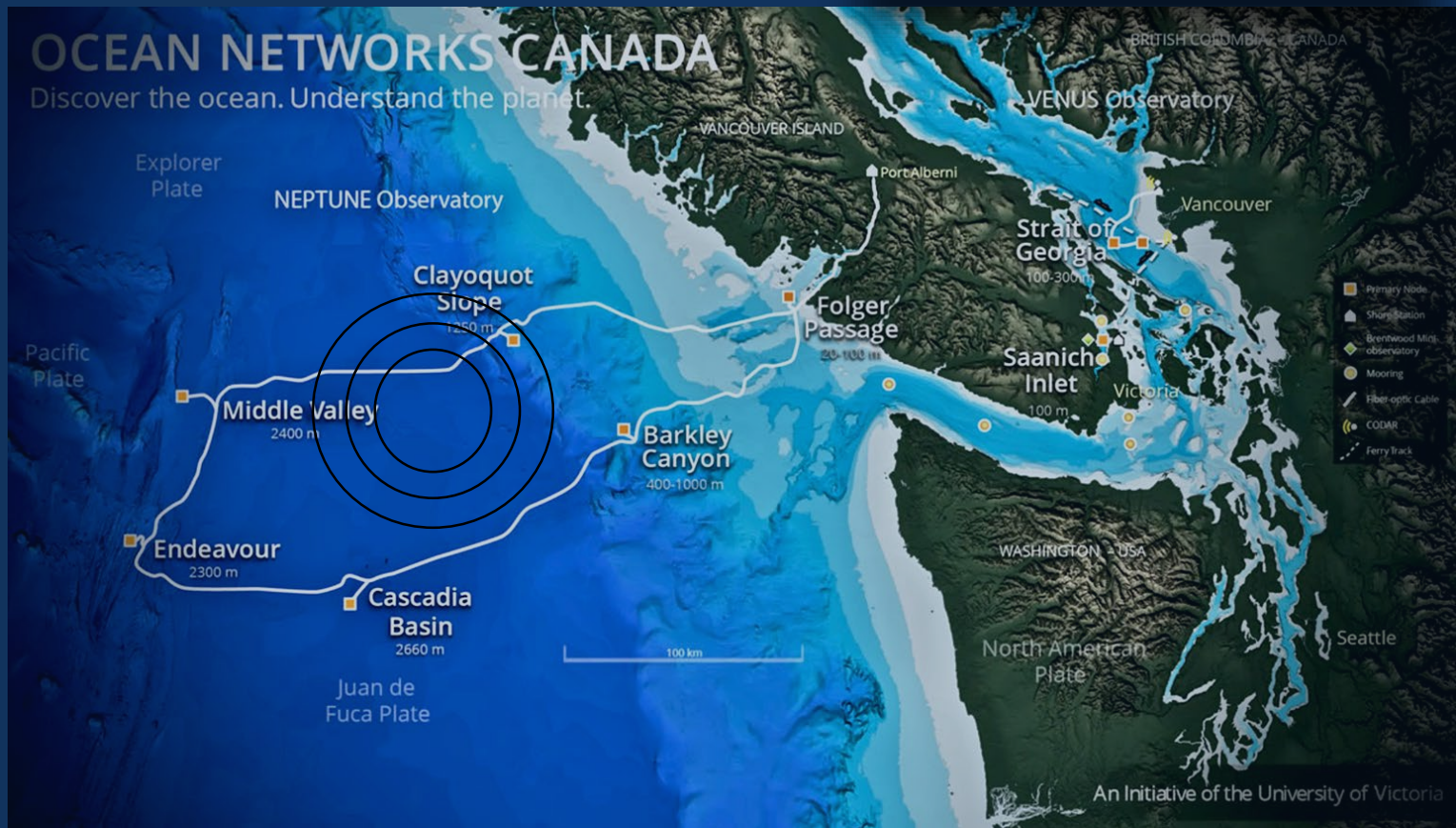
Canadian Scientists are proposing to establish a high energy neutrino detector using an existing underwater network off Vancouver Island

Pacific Ocean Neutrino Explorer (P-ONE)

First 10 String Bundle

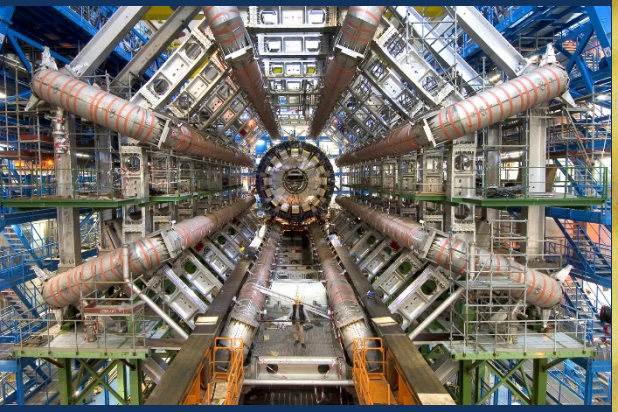
10 x 800 metre strings
20 photosensors



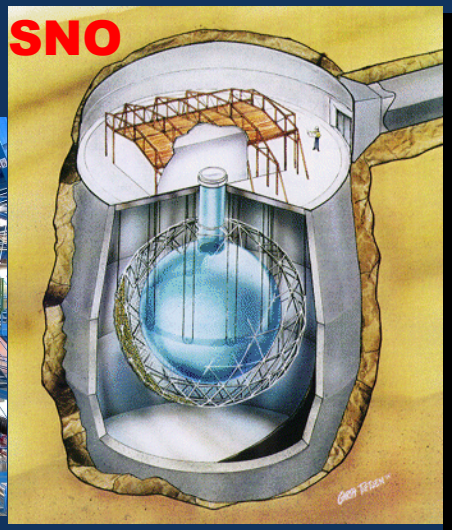


From the Tiniest Particles to the Farthest Reaches of the Universe

ATLAS at CERN



SNO

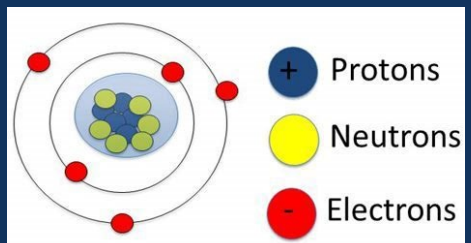


Our Cosmic Address

Our sun is one of 400 billion stars in the Milky Way galaxy, which is one of more than 100 billion galaxies in the visible universe.

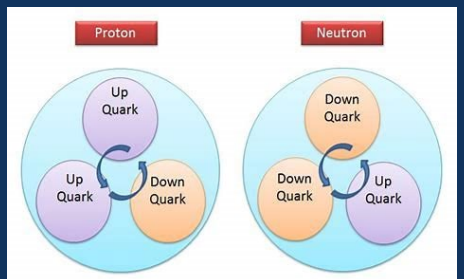
ATOMS

10^{-10} meters



Quarks in Protons, Neutrons

$< 10^{-15}$ meters



Neutrinos

$< 10^{-18}$ meters