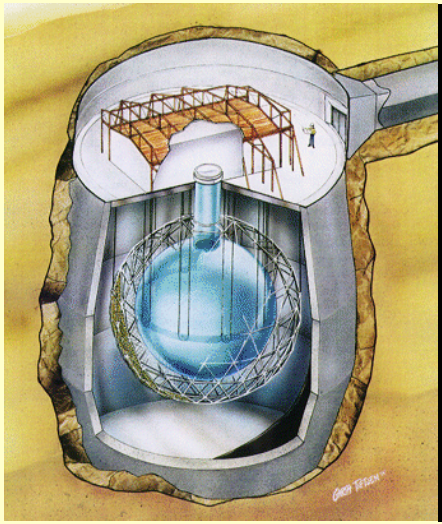
Understanding the Universe from Deep Underground

Sudbury
Neutrino
Observatory



Art McDonald, Professor Emeritus

Queen's University, Kingston, Ontario, Canada

With our laboratory deep underground we have created a very low radioactivity location where we study some of the most basic scientific questions:

- **How do stars like our Sun burn and create the elements from which we are made?**

- **What are the basic Laws of Physics for the smallest fundamental particles?**

- **What is the composition of our Universe and how has it evolved to the present ?**

How do you make measurements that can provide answers to enormous questions like these?

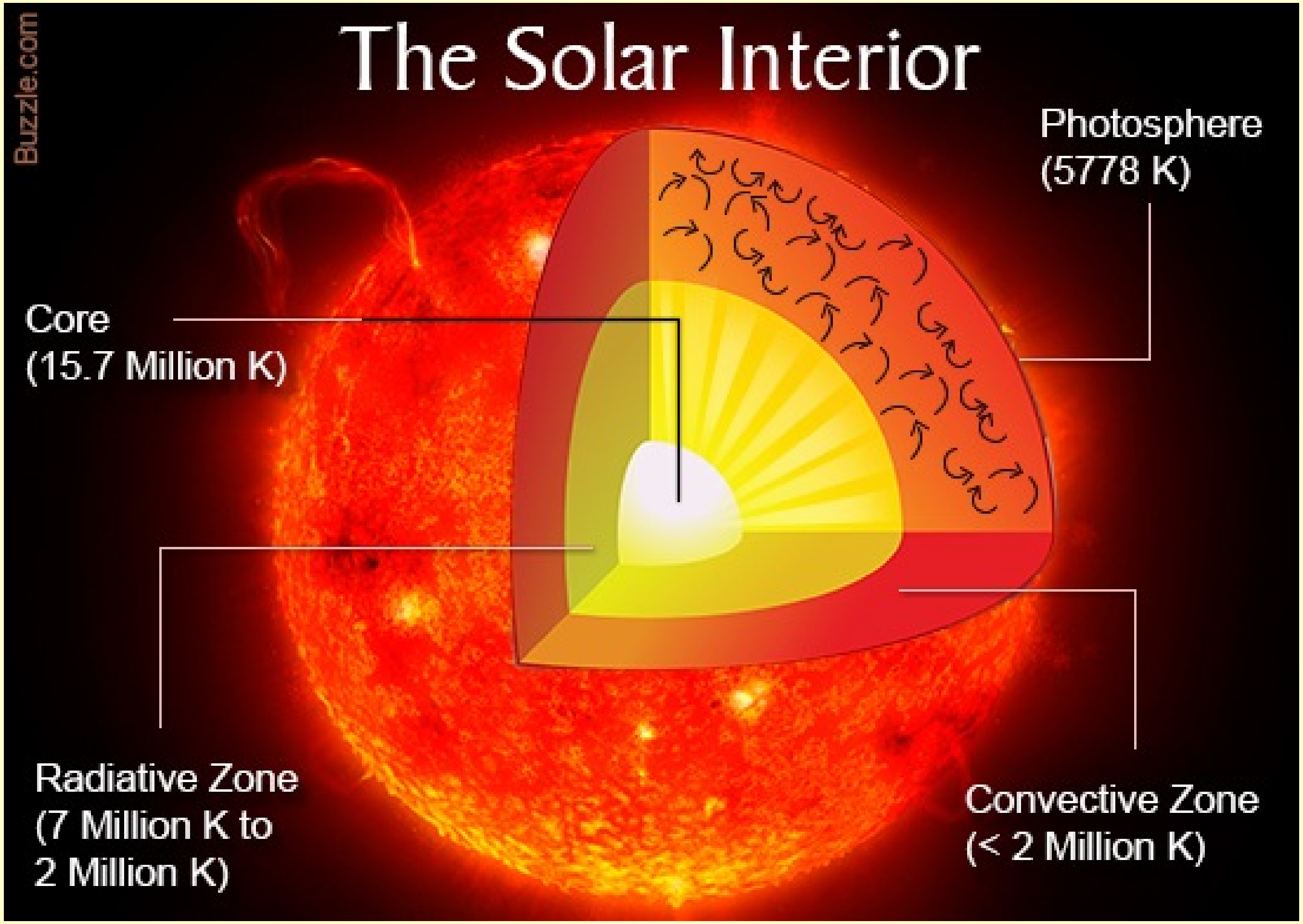
Answers:

1: Measure elusive particles called NEUTRINOS that come from the deepest reaches of the Sun where the energy is generated and from cosmic rays interacting in the atmosphere.

2: Measure fundamental particles (DARK MATTER) that are left over from the original formation of the Universe.

3. Measure rare forms of radioactivity (DOUBLE BETA DECAY) that can tell us more about fundamental laws of physics.

Neutrinos from the Sun



The middle of the sun is so hot that the centers of the atoms (nuclei) fuse together, giving off lots of energy and neutrinos. The neutrinos penetrate easily through the dense material in the Sun and reach the earth.

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.

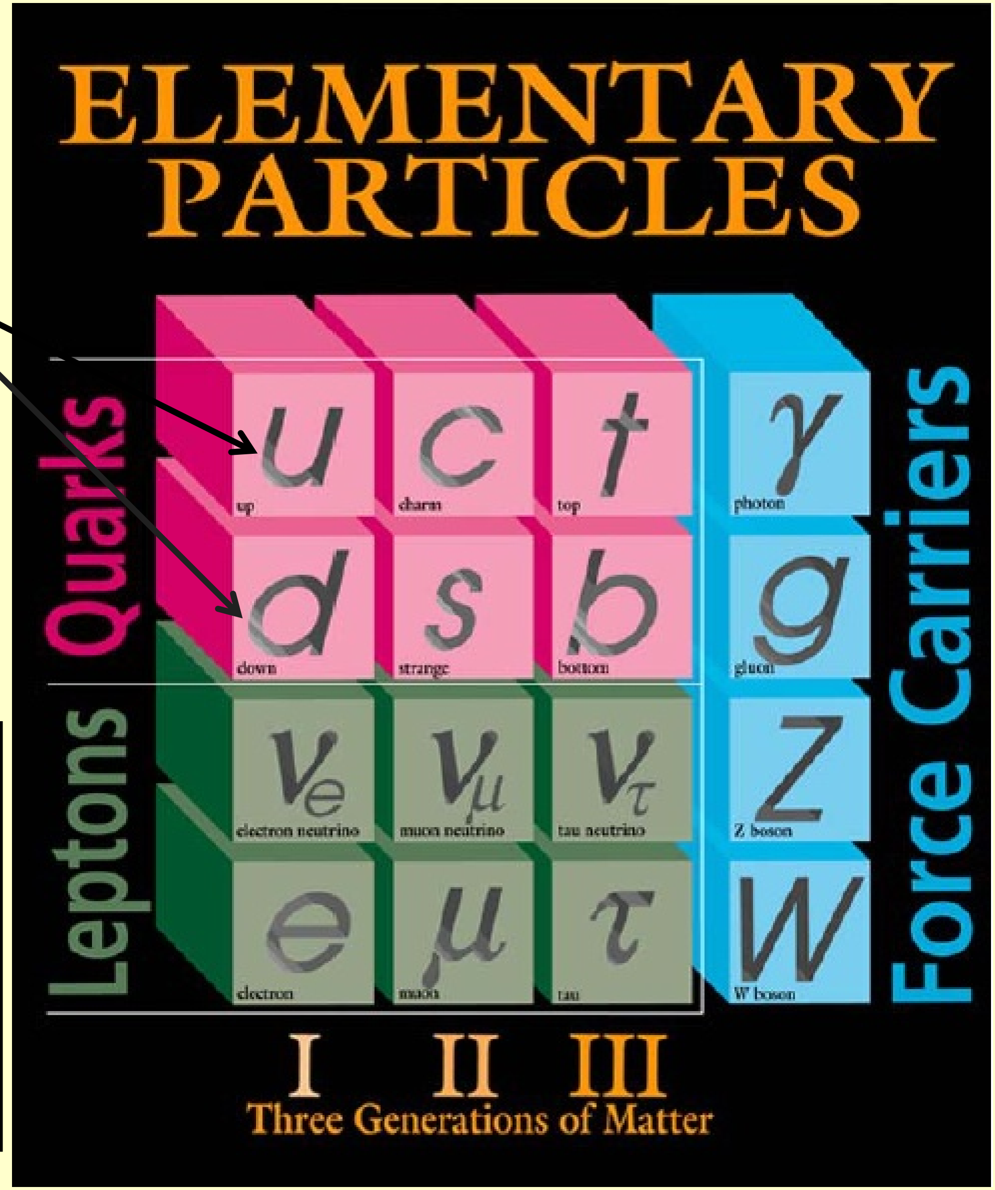
•They only stop if they hit the nucleus of an atom or an electron head-on and can pass through a million billion kilometers of lead without stopping. They only feel the Weak Force.

• Therefore they are very difficult to detect and their properties have been the least known among the basic 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) and are produced in some forms of radioactivity or in nuclear or particle reactions involving the transformation of quarks.



+
Higgs
Boson

The original Standard Model included neutrinos with zero mass and never changing from one type to another. We and others have shown that this is not correct.

Why is it important for us to know these details about neutrinos and the sun?

1. **Neutrinos**: Neutrinos are produced extensively in the Big Bang and depending on their mass, can have a significant influence on **how the Universe evolves**.

2. **The Sun**: Most of the elements from which we are made **(C, N, O)** were **produced** in the nuclear processes in the center of stars like the sun.

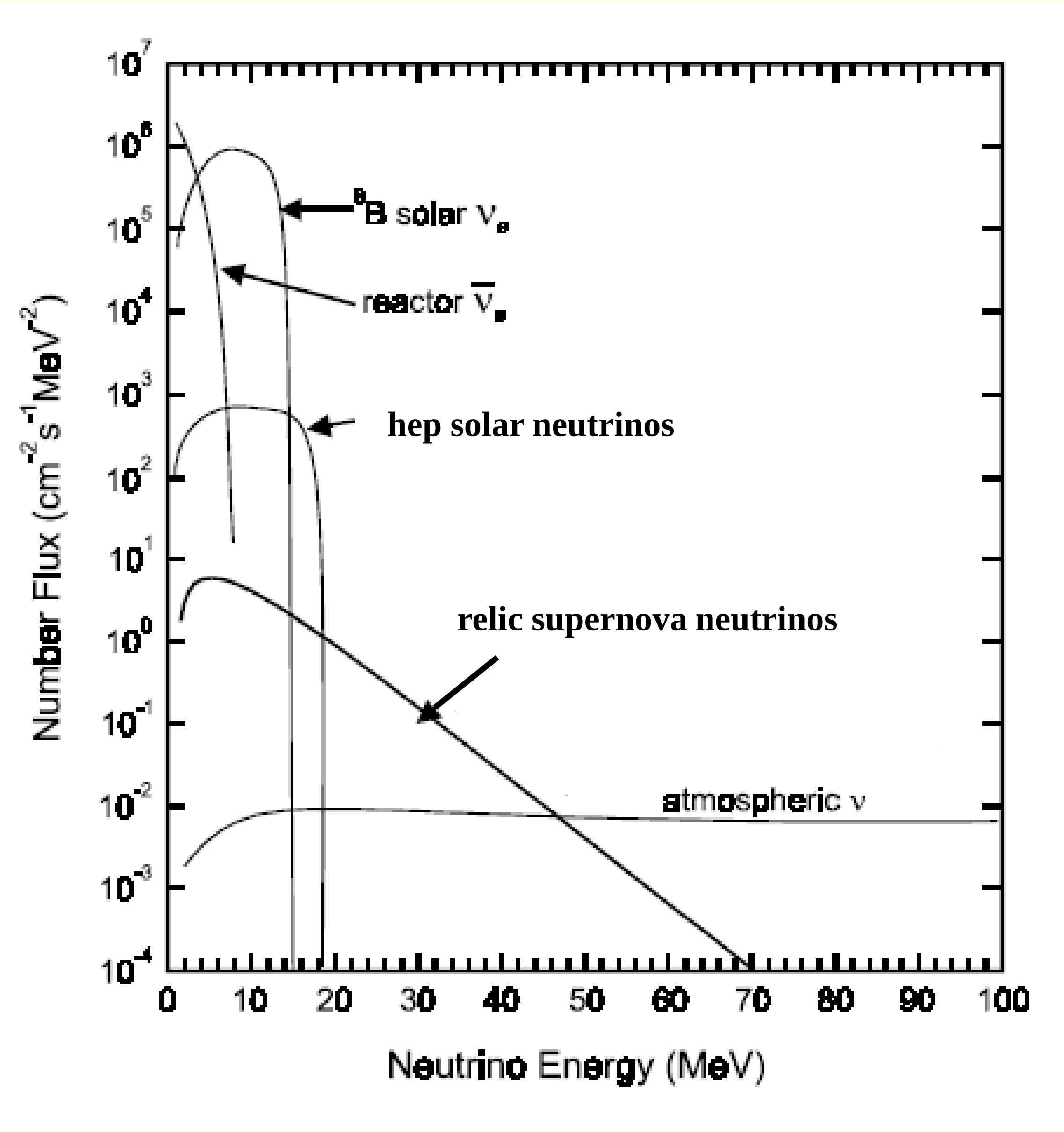
3. **Neutrinos** are an essential part of the production of all the elements heavier than iron in collapsing stars called **supernovae.**

4. **The Sun**: People are trying to reproduce the sun's energy generation here on earth, confined by magnetic fields instead of gravity. It is called a **fusion power source**. We have proven that calculations of sun are very accurate, and they are very similar to the calculations needed for **fusion power here on earth.**

5. **Neutrino Astronomy** can be used to study far distant parts of our Universe.

So our measurements help with our understanding of the Universe large and small as well as providing practical information for new energy systems on earth.

Neutrinos Reaching the Earth



+ accelerator neutrinos with smaller numbers at large distance and higher energies.

INDIA WAS A PIONEER IN THE FIELD OF NEUTRINO PHYSICS IN UNDFRGROUND LABORATORIES: The First Reported Measurement of Neutrinos Produced by Cosmic rays hitting the Atmosphere was made in the Kolar Gold Fields 50 years ago.

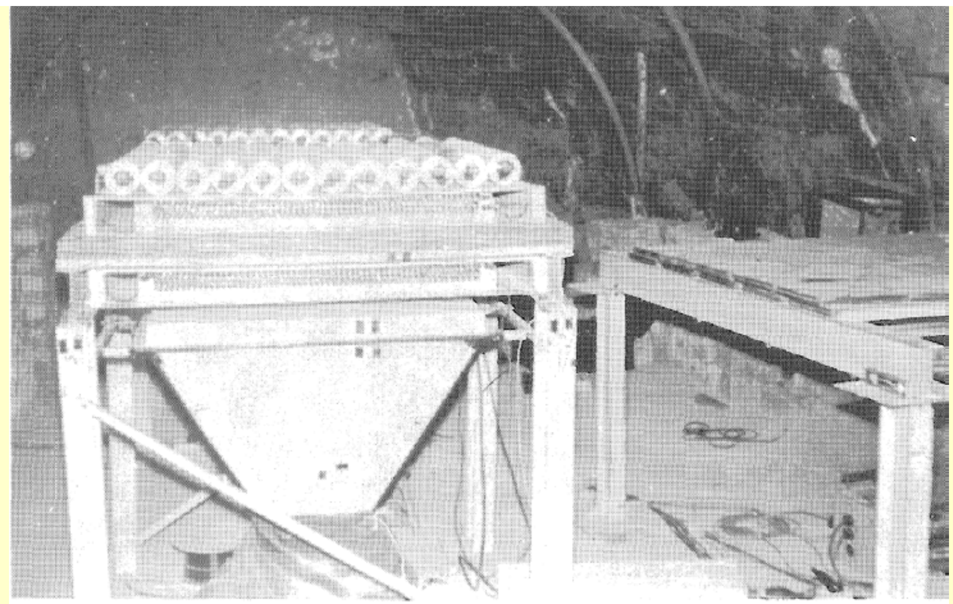
THE K. G. F. NEUTRINO EXPERIMENT*

C. V. Achar, M. G. K. Menon, V. S. Narasimham, P. V. Ramana Murthy
and B. V. Sreekantan
Tata Institute of Fundamental Research, Bombay, India

K. Hinotani and S. Miyake
Osaka City University, Osaka, Japan

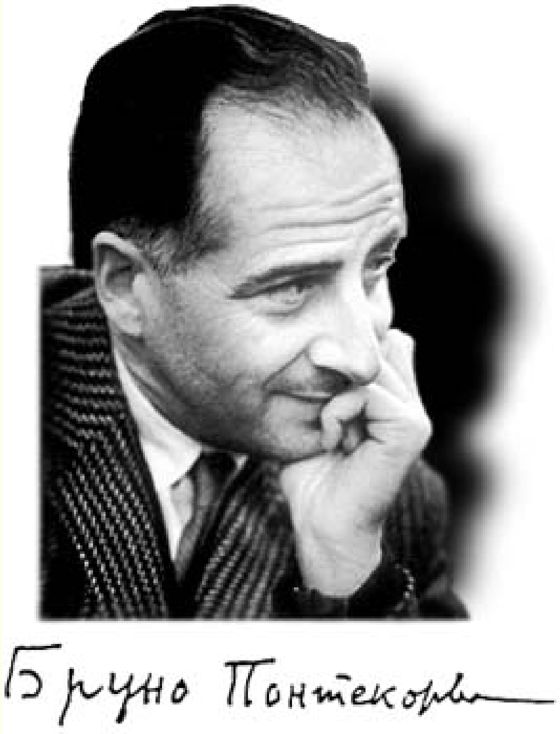
and
D. R. Creed, J. L. Osborne, J. B. M. Pattison and A. W. Wolfendale
University of Durham, Durham, U. K.

KGF Group, 7600 feet underground, 1965



Experimental Apparatus, 1965

Other Pioneers of Solar Neutrino Physics: Davis, Bahcall, Pontecorvo & Gribov



1968: Davis' Measurements with Chlorine-based detector show 3 times fewer than Bahcall's calculations.

Ray Davis: Nobel Laureate 2002

1968: Gribov and Pontecorvo suggest flavor change (oscillation) of electron neutrinos to muon neutrinos as a possible reason.

The major scientific question that SNO set out to answer

• THE NUCLEAR REACTIONS WHICH POWER THE SUN MAKE ENORMOUS NUMBERS OF NEUTRINOS.

• HOWEVER, ALL NEUTRINO MEASUREMENTS FOR 30 YEARS BEFORE SNO OBSERVED TOO FEW OF THE ELECTRON FLAVOUR NEUTRINOS PRODUCED IN THE SUN, COMPARED TO SOLAR MODEL CALCULATIONS

(The Solar Neutrino Problem).

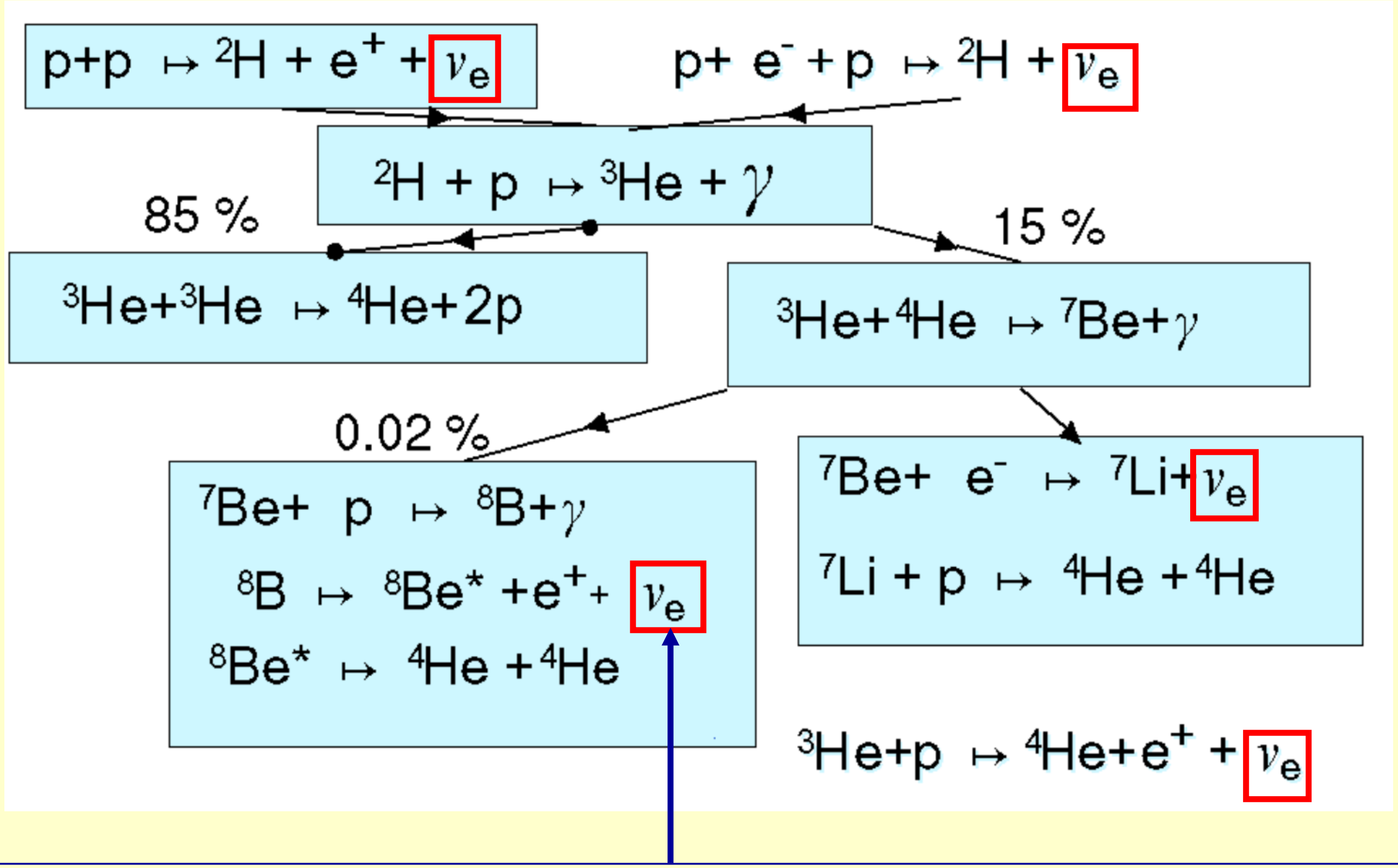
• **EITHER :**

1. THE SOLAR MODEL CALCULATIONS WERE INCOMPLETE OR INCORRECT

OR

2.THE ELECTRON NEUTRINOS CREATED IN THE SUN ARE CHANGING TO ANOTHER FLAVOUR AND ELUDING THE PAST EXPERIMENTS THAT WERE SENSITIVE ALMOST EXCLUSIVELY TO ELECTRON NEUTRINOS.

SOLAR FUSION CHAIN



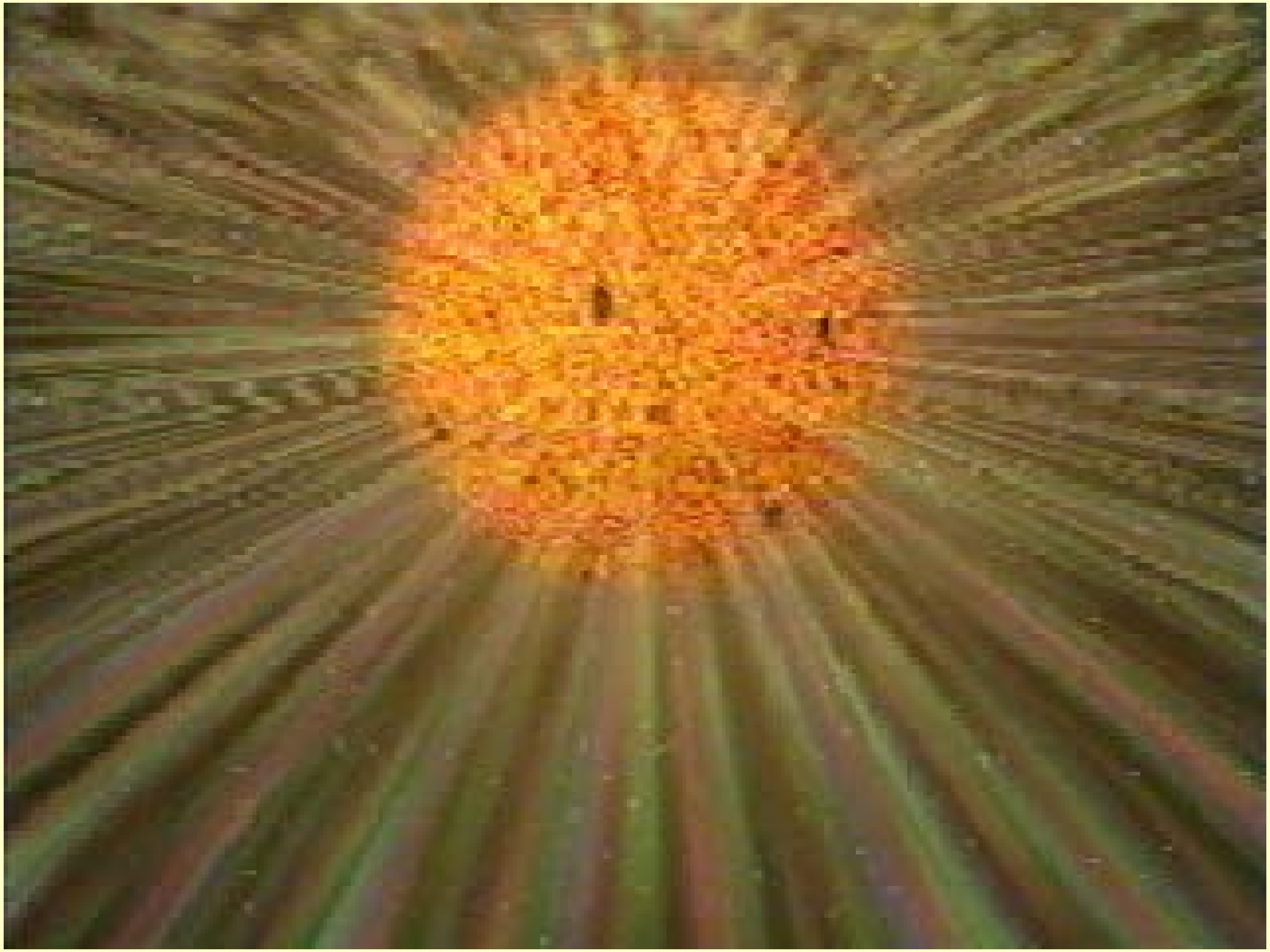
1984: Chen proposes heavy water to search for direct evidence of flavor transformation for neutrinos from ^{8}B decay in the Sun.

Electron neutrinos and all active neutrinos are measured separately to show flavor change independent of solar model calculations.

Sudbury Neutrino Observatory (SNO) Collaboration Meeting, Chalk River, 1986

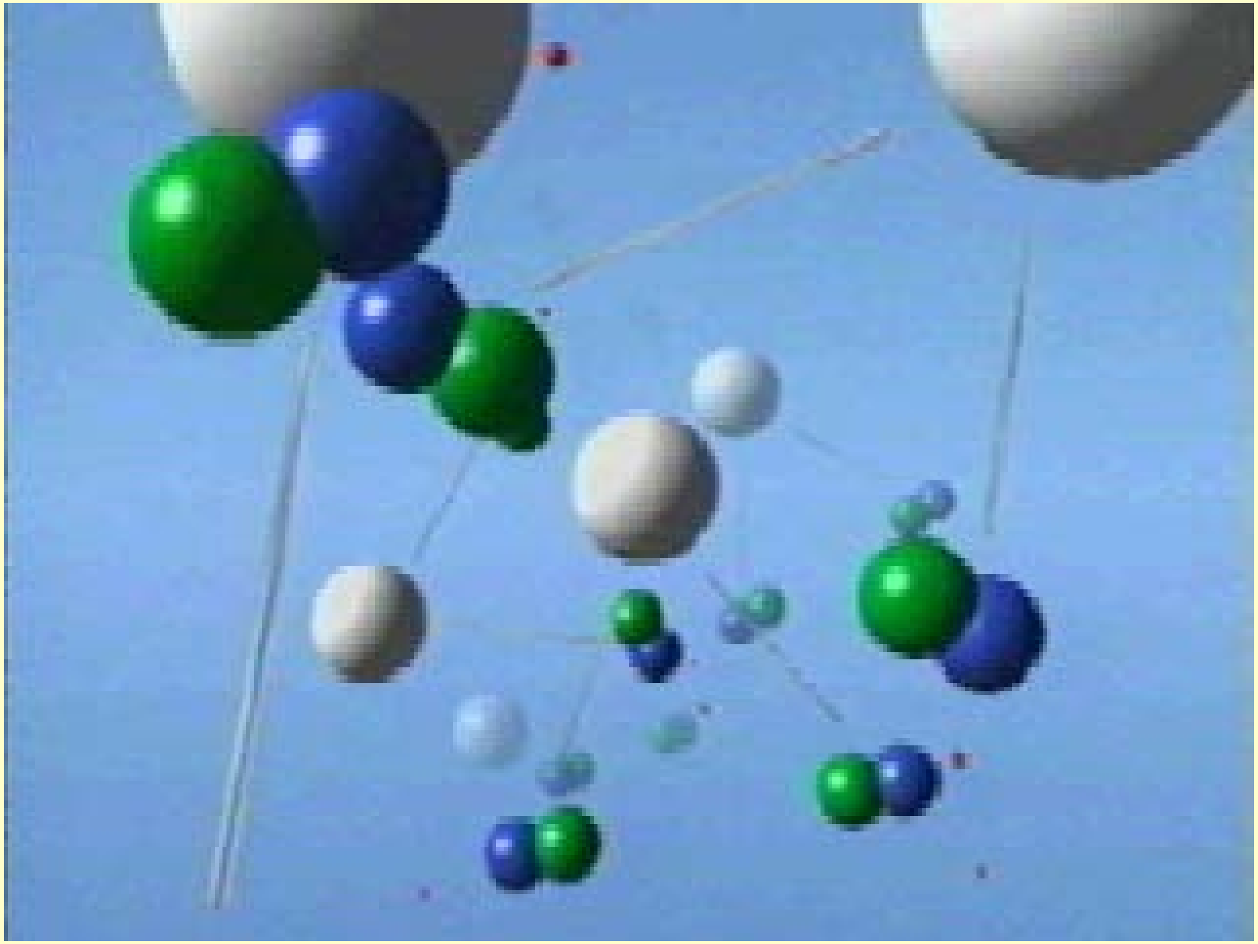
PROPOSAL TO BUILD A NEUTRINO OBSERVATORY IN SUDBURY, CANADA
D. Sinclair, A.L. Carter, D. Kessler, E.D. Earle, P. Jagam, J.J. Simpson, R.C. Allen, H.H. Chen, P.J. Doe, E.D. Hallman, W.F. Davidson, A.B. McDonald, R.S. Storey, G.T. Ewan, H.-B. Mak, B.C. Robertson Il Nuovo Cimento C9, 308 (1986)

How does SNO detect neutrinos from the Sun?



Billions of them stream out every second from the nuclear reactions powering the Sun and strike our detector. Once an hour they make a burst of light that we can detect.

Two different bursts of light occur when a neutrino strikes heavy water.



White = Oxygen
Green = Proton
Blue = Neutron
Red = Electron

Heavy water has an extra neutron (blue) in the hydrogen nucleus. 1 in 6400 water molecules are like this.

The first type of burst is sensitive to all flavours of neutrinos: electron, mu and tau neutrinos

The second type of burst is only sensitive to the electron neutrinos produced in the Sun.

Comparing the numbers observed for the two bursts tells us whether electron neutrinos have changed to other flavours before reaching our detector.

Sudbury Neutrino Observatory (SNO)

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

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

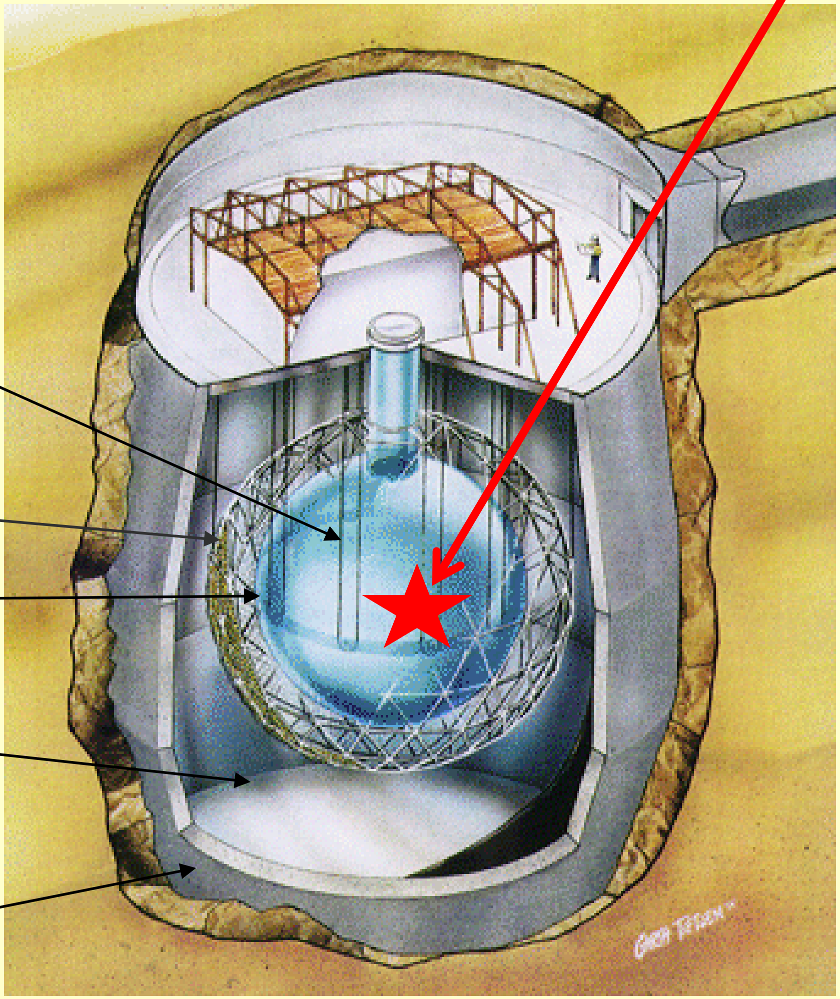
9500 light sensors

12 m Diameter Acrylic Container

Ultra-pure Water: H_2O.

Urylon Liner and Radon Seal

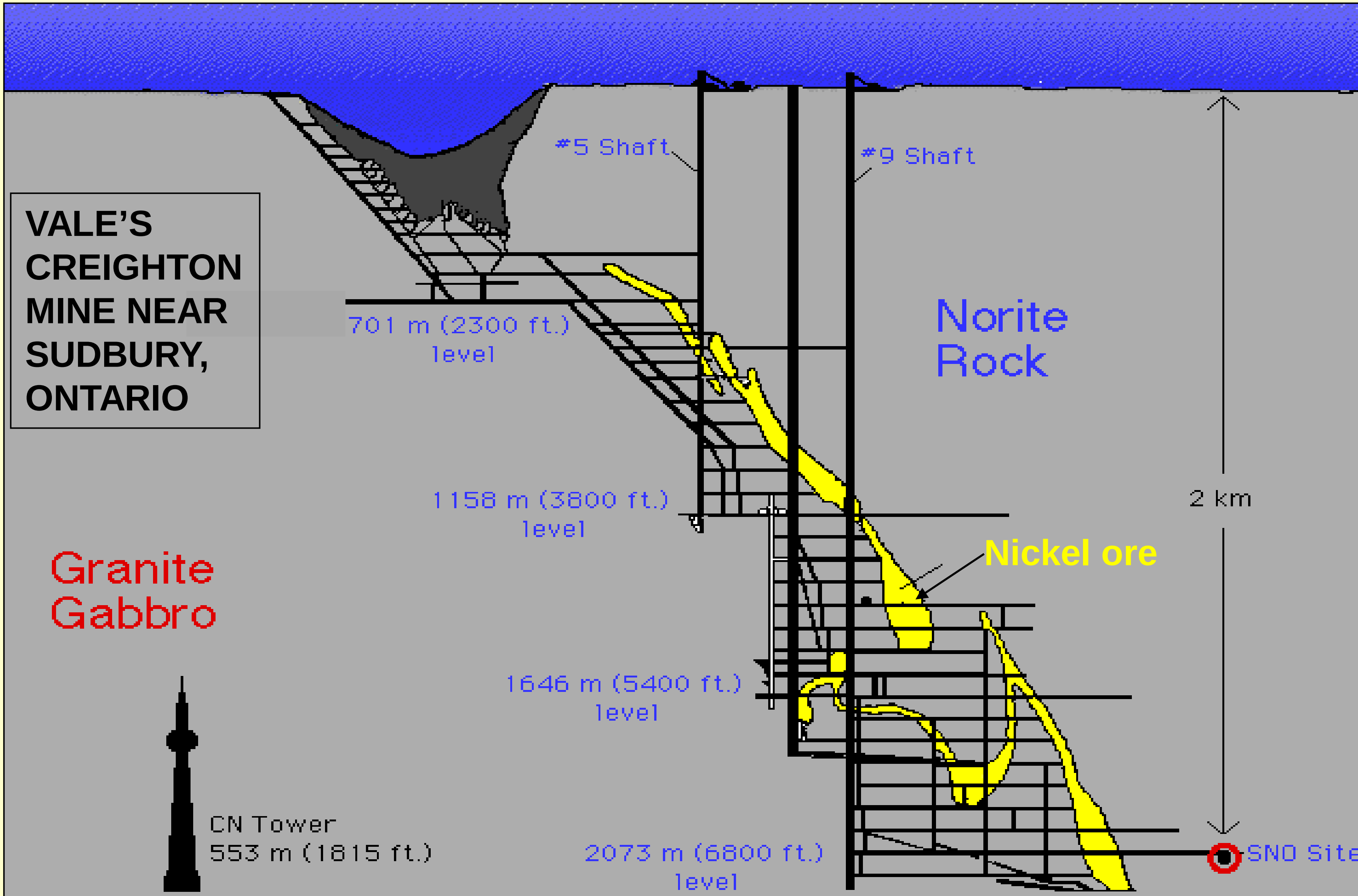
NEUTRINO

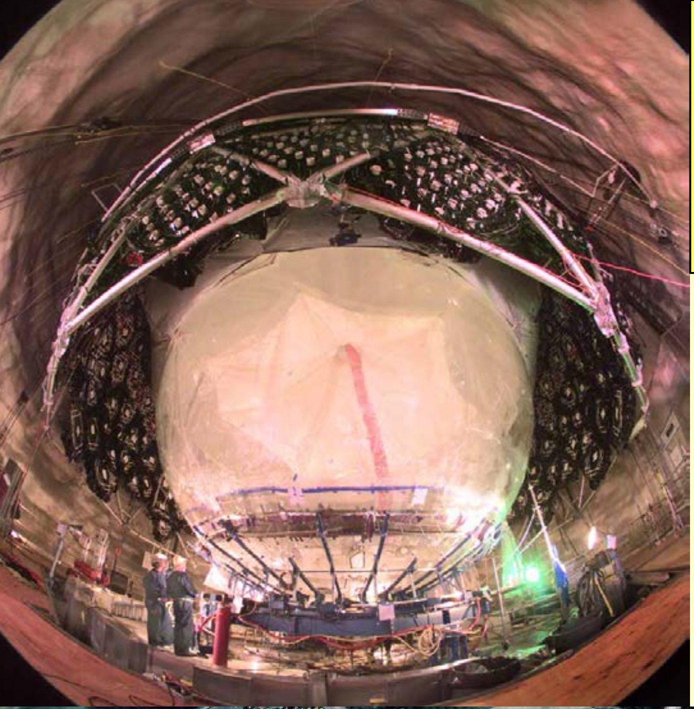


34 m or ~ Ten Stories High!

2 km below the ground

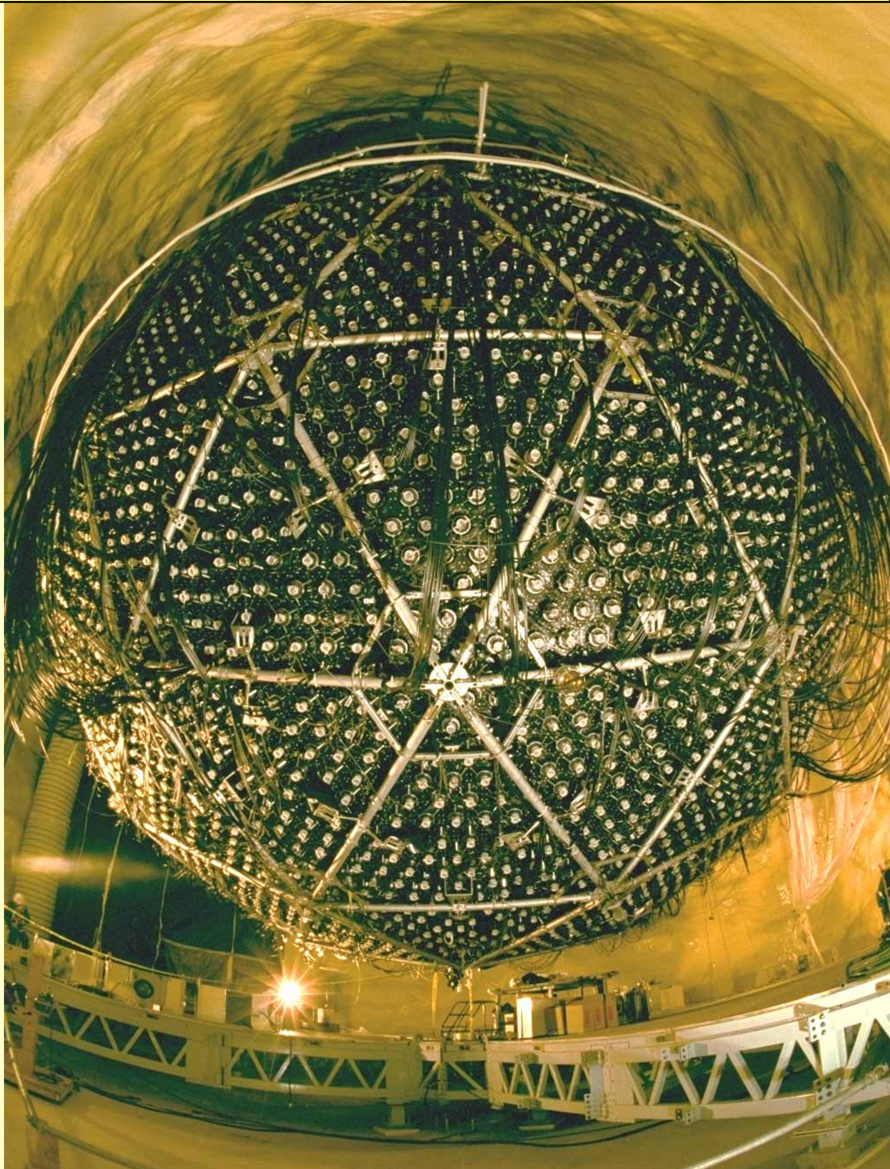
To study Neutrinos with little radioactive background, we went 2 km underground to reduce cosmic rays and built an ultra-clean detector: SNO





SNO: One million pieces transported down in the 3 m x 3 m x 4 m mine cage and re-assembled under ultra-clean conditions. Every worker takes a shower and wears clean, lint-free clothing.

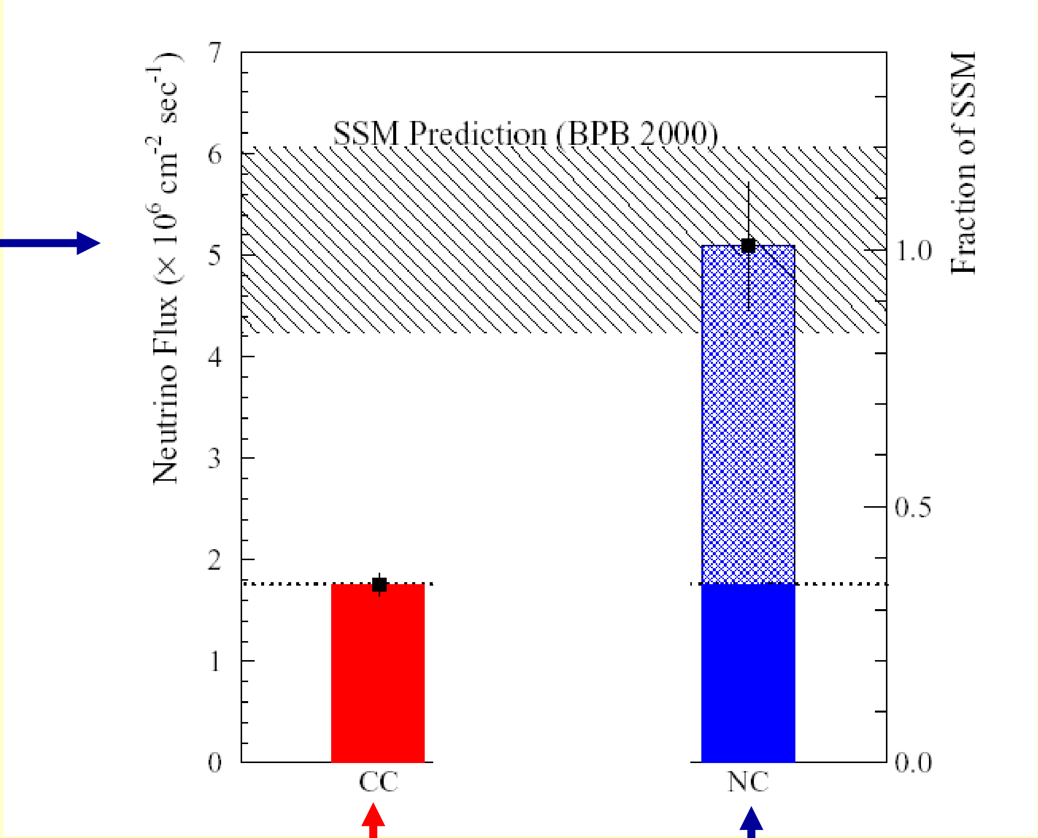
70,000 showers during the course of the SNO project



Water systems were developed to provide low radioactivity water and heavy water: 1 billion times better than tap water. Less than one radioactive decay per day per ton of water!!

Steven Hawking's Visit Posed some special Challenges – INCO Designed a special Rail car for him.

SOLAR MODEL



Excellent Agreement With the Solar Model Calculations

SNO USED HEAVY WATER TO MEASURE TWO SEPARATE THINGS

LESS THAN ONE CHANCE IN 10 MILLION FOR “NO CHANGE IN NEUTRINO TYPE”

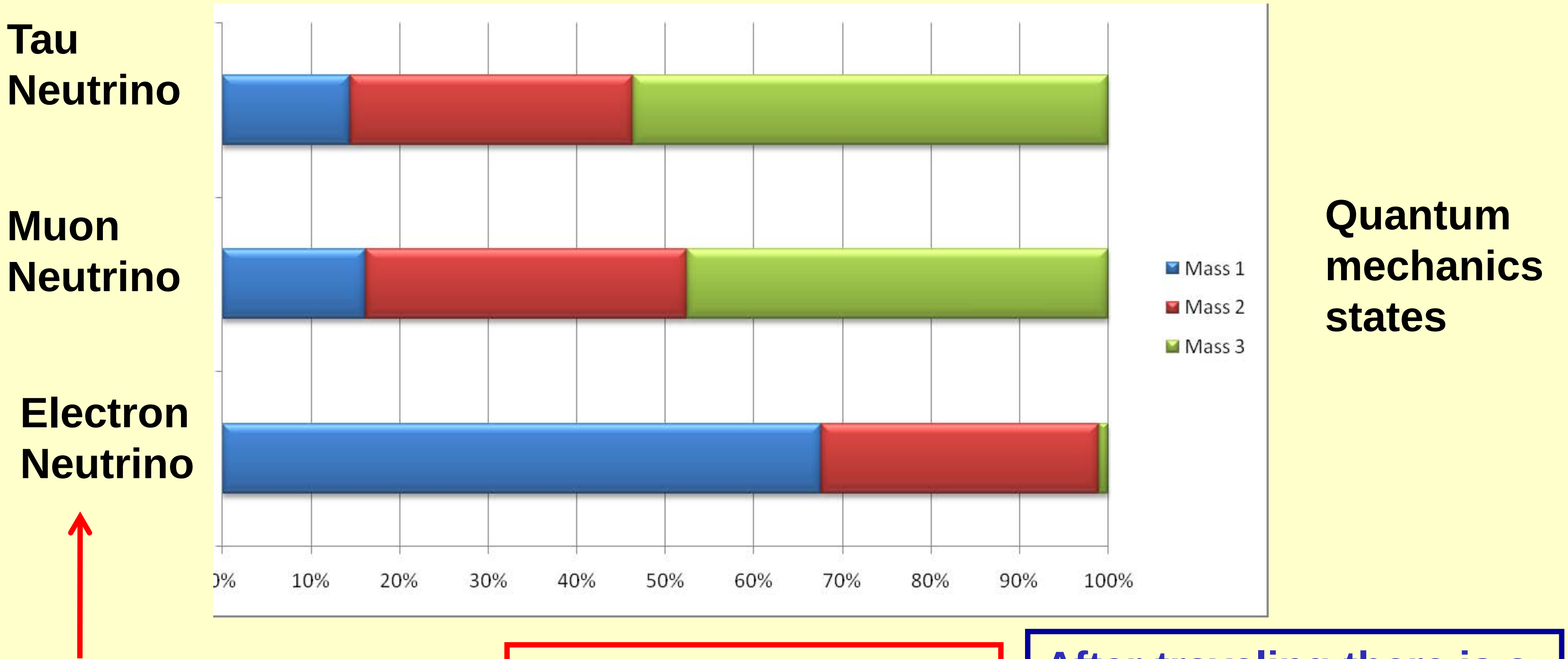
ELECTRON NEUTRINOS

ALL NEUTRINO TYPES

A CLEAR DEMONSTRATION NEUTRINOS CHANGE THEIR TYPE: 2/3 OF THE ELECTRON NEUTRINOS HAVE CHANGED TO MU, TAU NEUTRINOS ON THE WAY FROM THE SOLAR CORE TO EARTH. THIS REQUIRES THAT THEY HAVE A FINITE MASS.

NEUTRINO OSCILLATIONS AND NEUTRINO MASS

Neutrino Flavors (Electron, Muon, Tau) can be expressed as combinations of Masses (1,2,3)

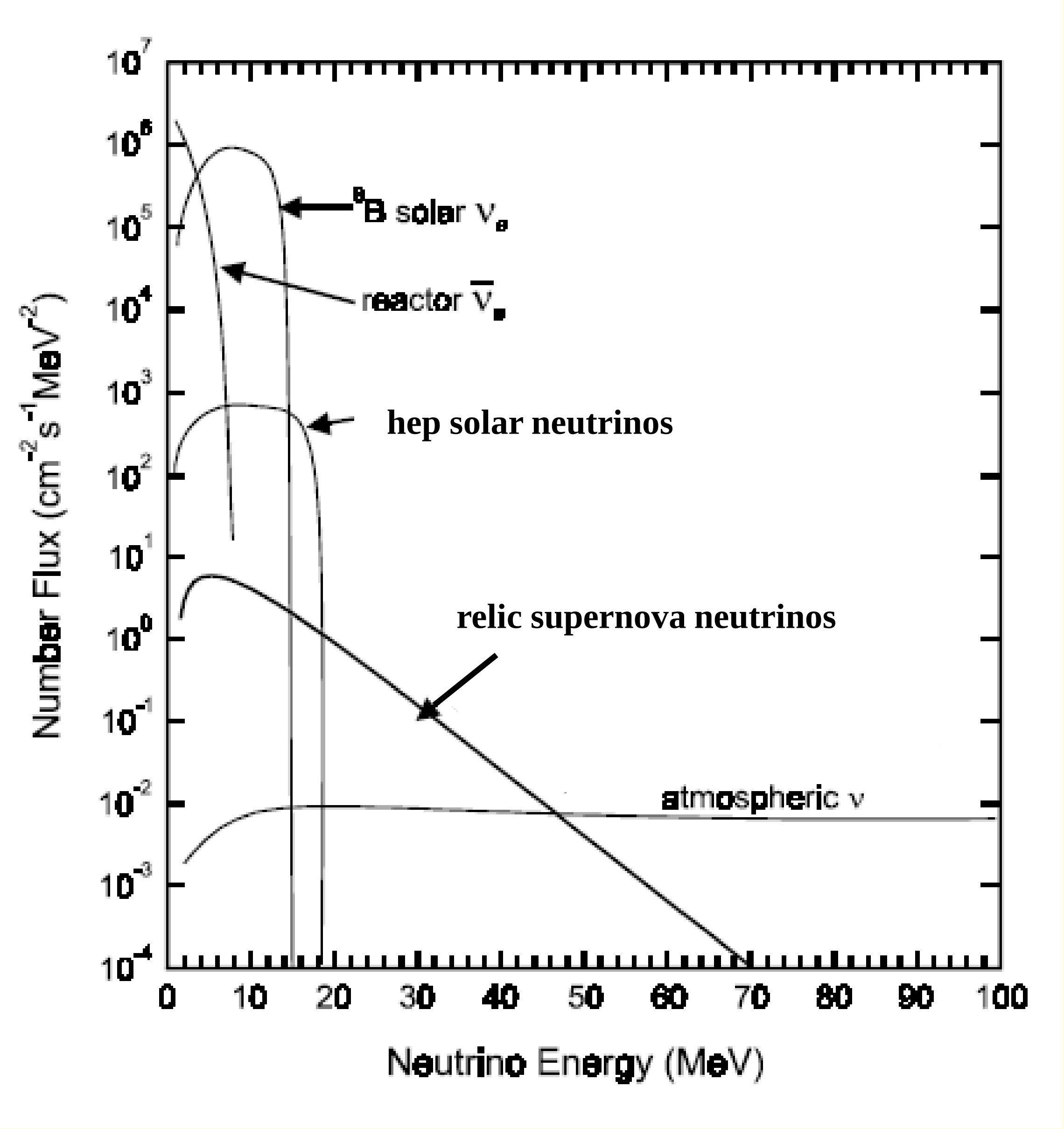


Created in a unique Flavor State

The mass fractions change as the neutrino travels

After traveling there is a finite probability to be detected as a different flavor type

Other Neutrino fluxes at the Earth



+ accelerator neutrinos

As of today: Oscillation of 3 massive active neutrinos is clearly the dominant effect:

If neutrinos have mass: $$|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$$

For 3 Active neutrinos.

l = Flavour, i = mass

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata matrix

(Double β decay only)

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

✔ **Atmospheric, Accel.** | ? **CP Violating Phase** | ✔ **Reactor, Accel.** | ✔ **Solar,Reactor** | ? **Majorana CP Phases**

Range defined for Δm_{12}, Δm_{23} ✔

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$

For two neutrino oscillation in a vacuum: (a valid approximation in many cases)

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2(1.27\frac{\Delta m^2 L}{E})$$

CP Violating Phase or Majorana Phases: Antimatter/matter asymmetry in Early Universe?

Matter Effects – the MSW effect

(Mikheyev, Smirnov, Wolfenstein)

$$i\frac{d}{dt}\begin{bmatrix}\nu_e \\ \nu_x\end{bmatrix} = H\begin{bmatrix}\nu_e \\ \nu_x\end{bmatrix}$$

$$\mathrm{H} = \begin{bmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \boxed{\sqrt{2}G_F N_e} & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{bmatrix}$$

The extra term arises because solar ν_e have an extra interaction via W exchange with electrons in the Sun or Earth.

In the oscillation formula:

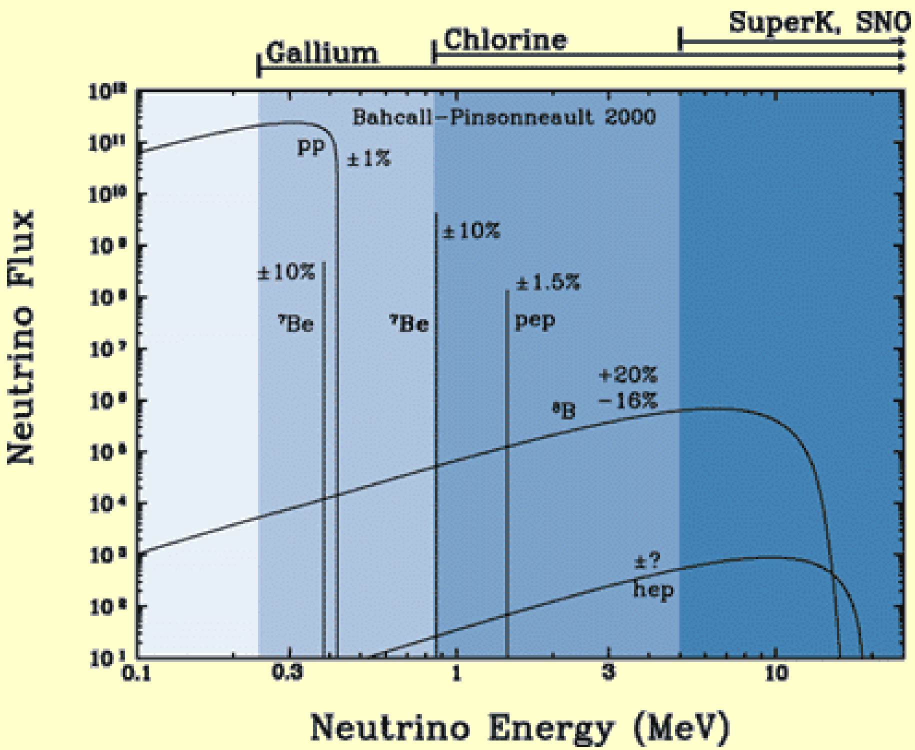
$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\omega - \cos 2\theta)^2 + \sin^2 2\theta}$$

$$\omega = -\sqrt{2}G_F N_e E / \Delta m^2$$

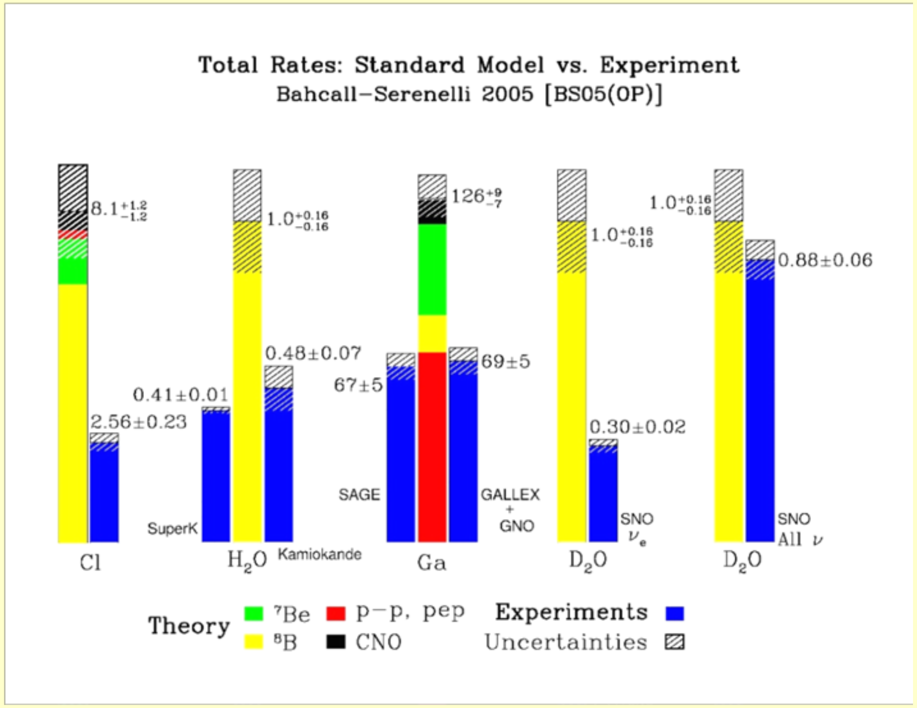
The MSW effect occurs for electron neutrinos going through the sun showing that mass 2 is greater than mass 1. It will also affect muon neutrinos going through the earth. The India-based Neutrino Observatory (INO) will use this to determine whether mass 3 is heavier than the others.

Combining SNO with other solar measurements

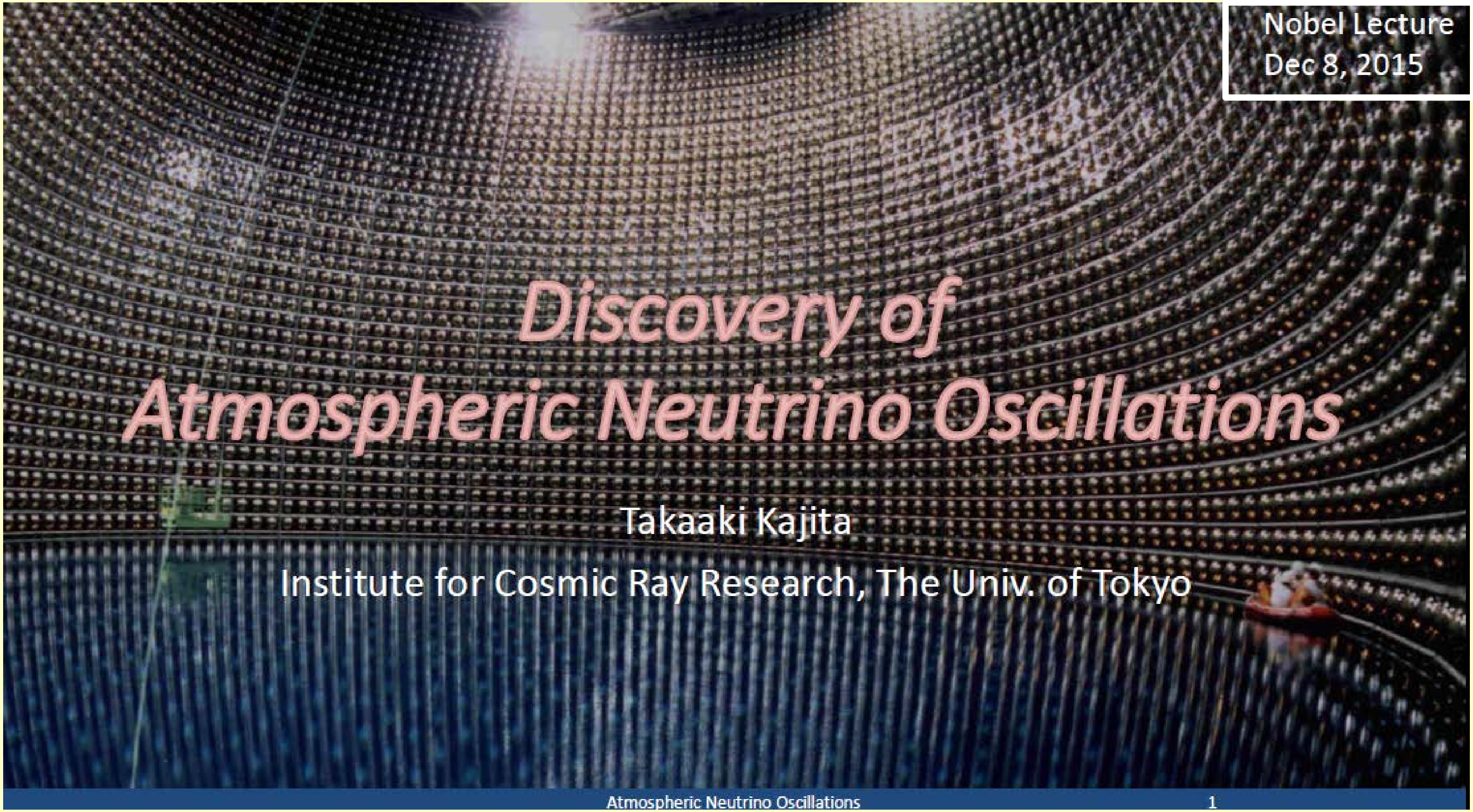
Solar Fluxes: Bahcall et al



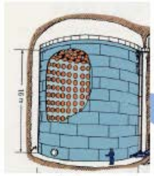
Experiment vs Solar Models



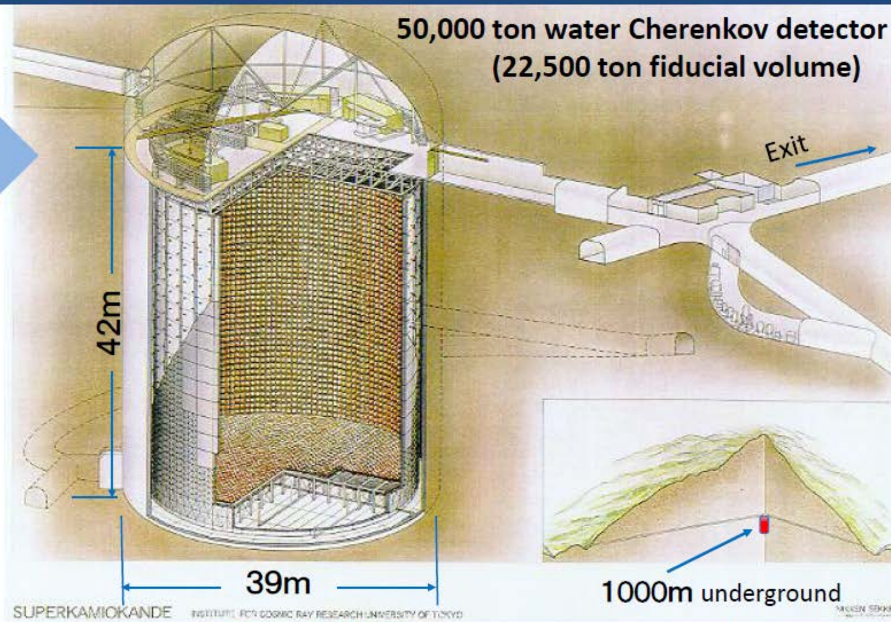
The analysis concludes that the electron neutrinos are converted to a pure Mass 2 state by interaction with the dense electrons in the sun via the Mikheyev-Smirnov-Wolfenstein (MSW) effect. This interaction determines that Mass 2 is greater than Mass 1 as well as determining Δm_{12}^2 and the mixing parameter θ_{12}


Nobel Lecture
Dec 8, 2015
Discovery of
Atmospheric Neutrino Oscillations
Takaaki Kajita
Institute for Cosmic Ray Research, The Univ. of Tokyo
Atmospheric Neutrino Oscillations
1

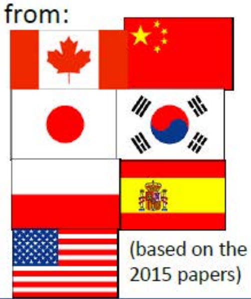
Super-Kamiokande detector



More than 20 times larger mass

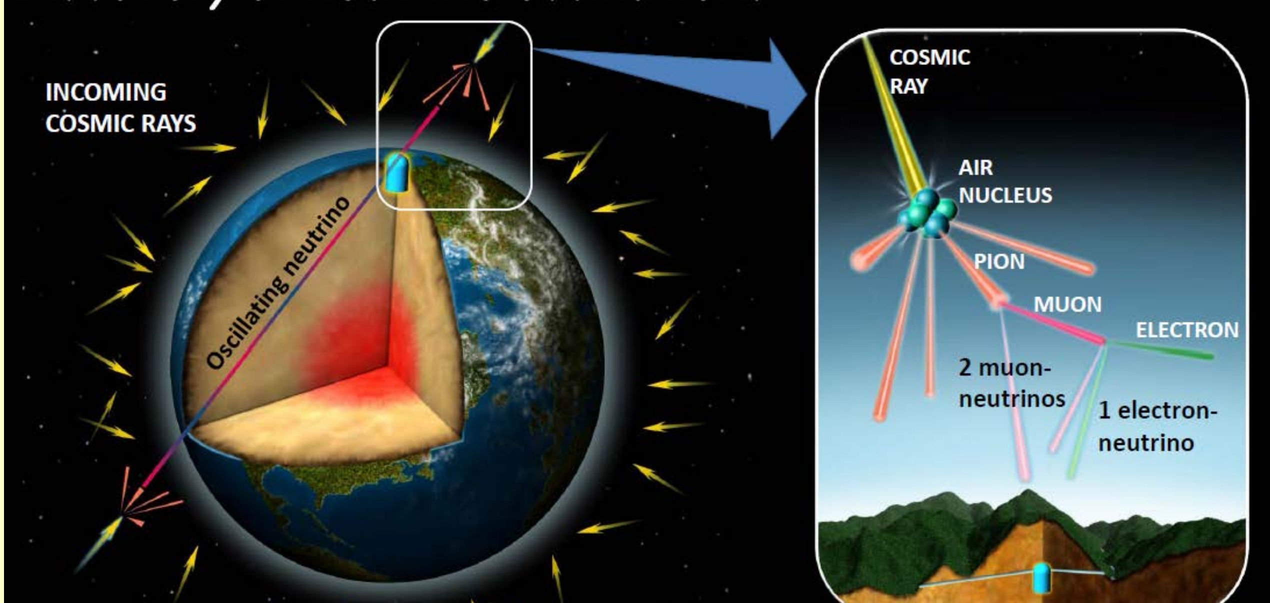


~120 collaborators from:



(based on the 2015 papers)

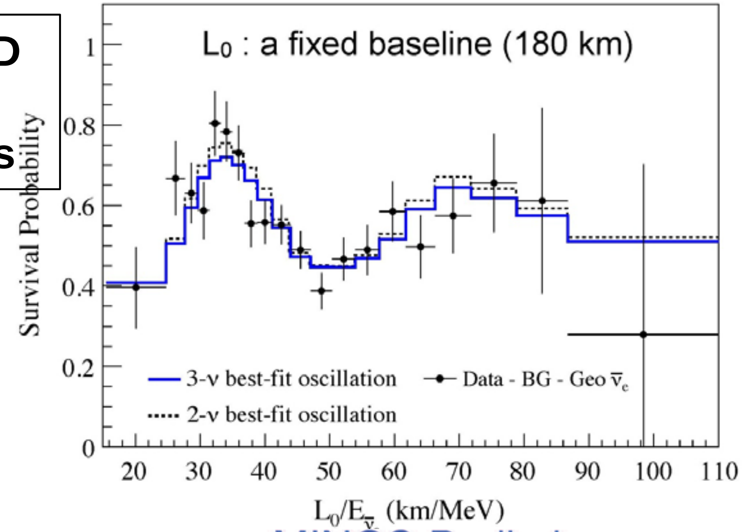
Discovery of neutrino oscillations



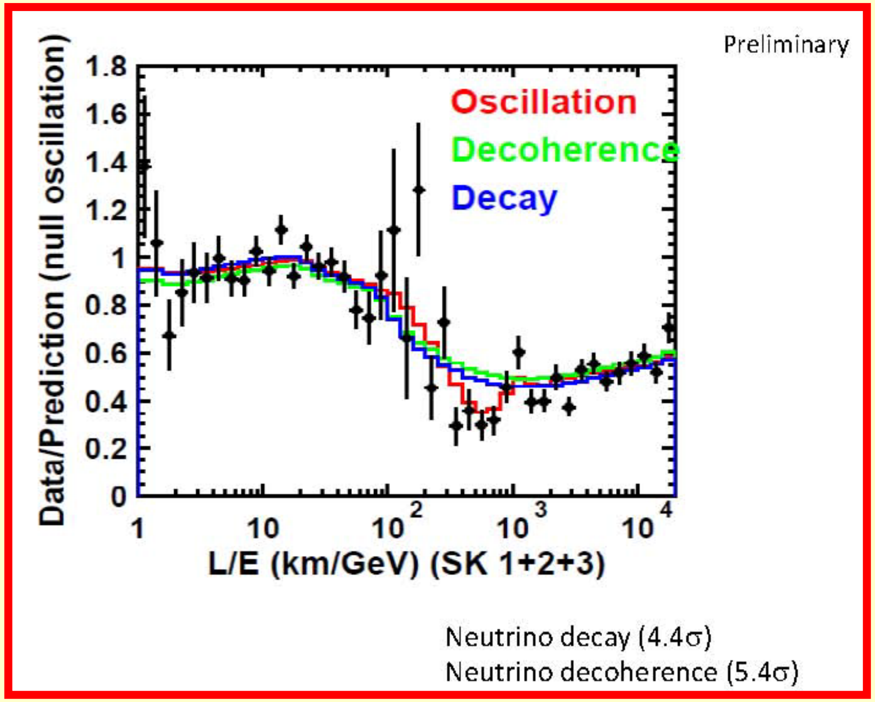
Oscillation Patterns

$$P_{ee} = 1 - \sin^2 2\theta \sin^2\left[\frac{\pm 1.27\Delta m^2 L}{E}\right]$$

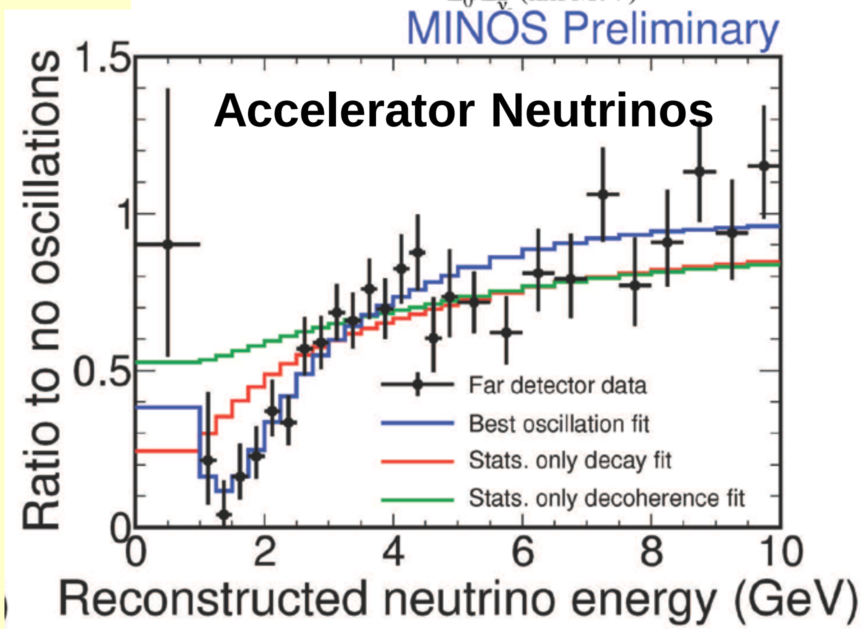
KamLAND Reactor Neutrinos



Atmospheric Neutrinos: SuperKamiokande



Accelerator Neutrinos



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 do that, Einstein's theory of relativity requires that they have a small finite mass and travel at slightly less than the speed of light .

Particle Data Group

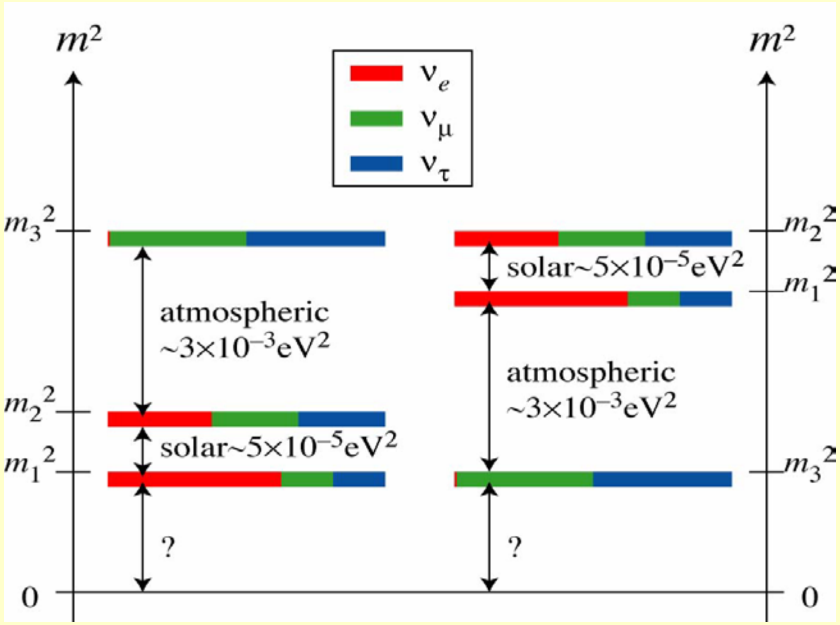
SUMMARY OF RESULTS FOR THREE ACTIVE ν TYPES

Neutrino Oscillation Parameters

Parameter	best-fit ($\pm 1\sigma$)
$\Delta m^2_{\odot}$ $[10^{-5}$ eV $^2]$	$7.58^{+0.22}_{-0.26}$
$\lvert\Delta m^2_A\rvert$ $[10^{-3}$ eV $^2]$	$2.35^{+0.12}_{-0.09}$
$\sin^2\theta_{12}$	$0.306\ (0.312)^{+0.018}_{-0.015}$
$\sin^2\theta_{23}$	$0.42^{+0.08}_{-0.03}$
$\sin^2\theta_{13}$ [140]	$0.021\ (0.025)^{+0.007}_{-0.008}$
$\sin^2\theta_{13}$ [142]	0.0251 ± 0.0034

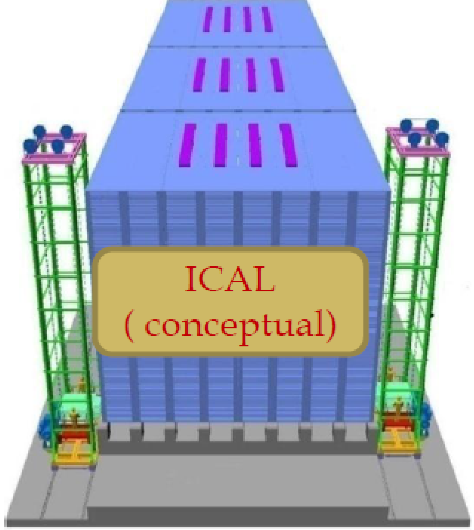
Future measurements will improve accuracy and seek to measure **matter/antimatter asymmetry** parameters. Indian particle physicists are participants in the proposed **DUNE** experiment using Fermilab accelerator and the Sanford Underground Lab in the US.

Mass Hierarchies



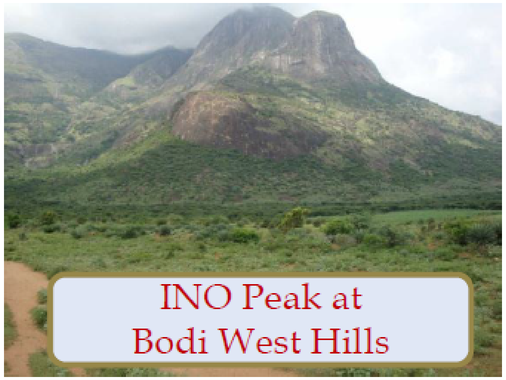
Normal Inverted

A very important question for the future is **Normal or Inverted Hierarchy:** It can be measured using Atmospheric Neutrinos with the **Indian Neutrino Observatory (INO)**



ICAL (conceptual)

India-Based Neutrino Observatory (INO)



INO Peak at Bodi West Hills

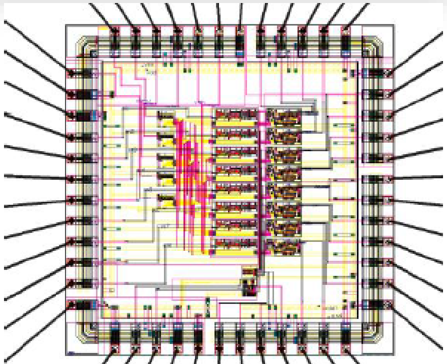
Spokesperson: Prof. N. Mondal, Tata Institute, Mumbai

Experiments in INO can use **naturally occurring neutrinos from the atmosphere** to measure the mass order of the three neutrino types, an important part of fundamental theories of physics that go beyond the Standard Model of Elementary Particles. Also studies of Dark Matter and Double Beta Decay

Ahmedabad: Physical Research Laboratory (PRL); **Aligarh:** Aligarh Muslim University (AMU); **Allahabad:** Harish Chandra Research Institute (HRI); **Bhuwanewar:** Institute of Physics (IOP); Utkal University; **Calicut :** University of Calicut; **Chandigarh:** Panjab University (PU); **Chennai :** Indian Institute of Technology, Madras (IITM); The Institute of Mathematical Sciences (IMSc) ; **Delhi :** Delhi University (DU); Jawaharlal Nehru University (JNU); **Kolkata :** Saha Institute of Nuclear Physics (SINP); University of Calcutta (CU) ; Variable Energy Cyclotron Centre (VECC) ; **Lucknow :** Lucknow University (LU); **Madurai :** American College; **Mumbai :** Bhabha Atomic Research Centre (BARC) ; Indian Institute of Technology, Bombay (IITB) ; Tata Institute of Fundamental Research (TIFR); **Mysuru :** University of Mysore (MU) ; **Srinagar :** University of Kashmir; **Varanasi :** Banaras Hindu University (BHU)

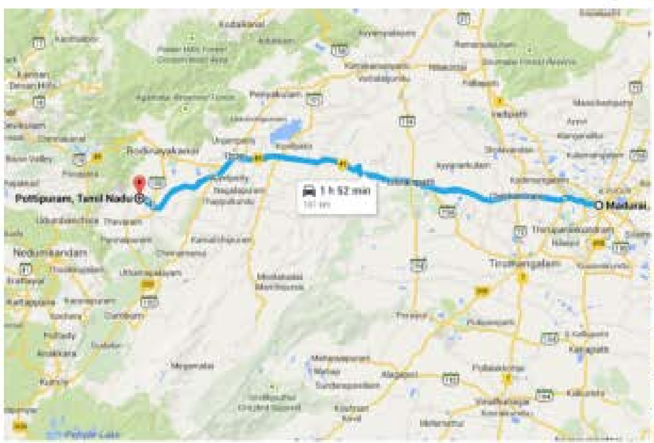
90+ Collaborators from 22 Institutions

2mX2m RPC Test Stand at TIFR

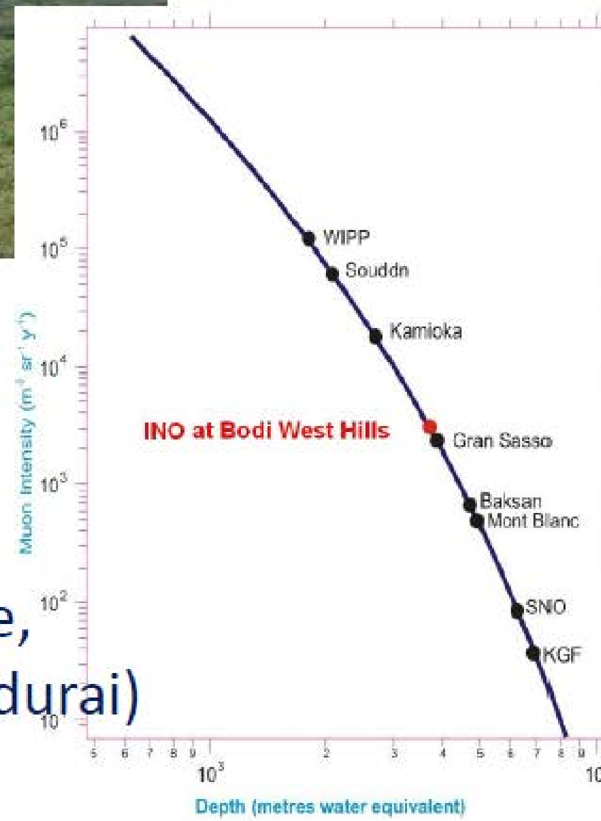


ASIC for RPC designed at BARC

The location of INO

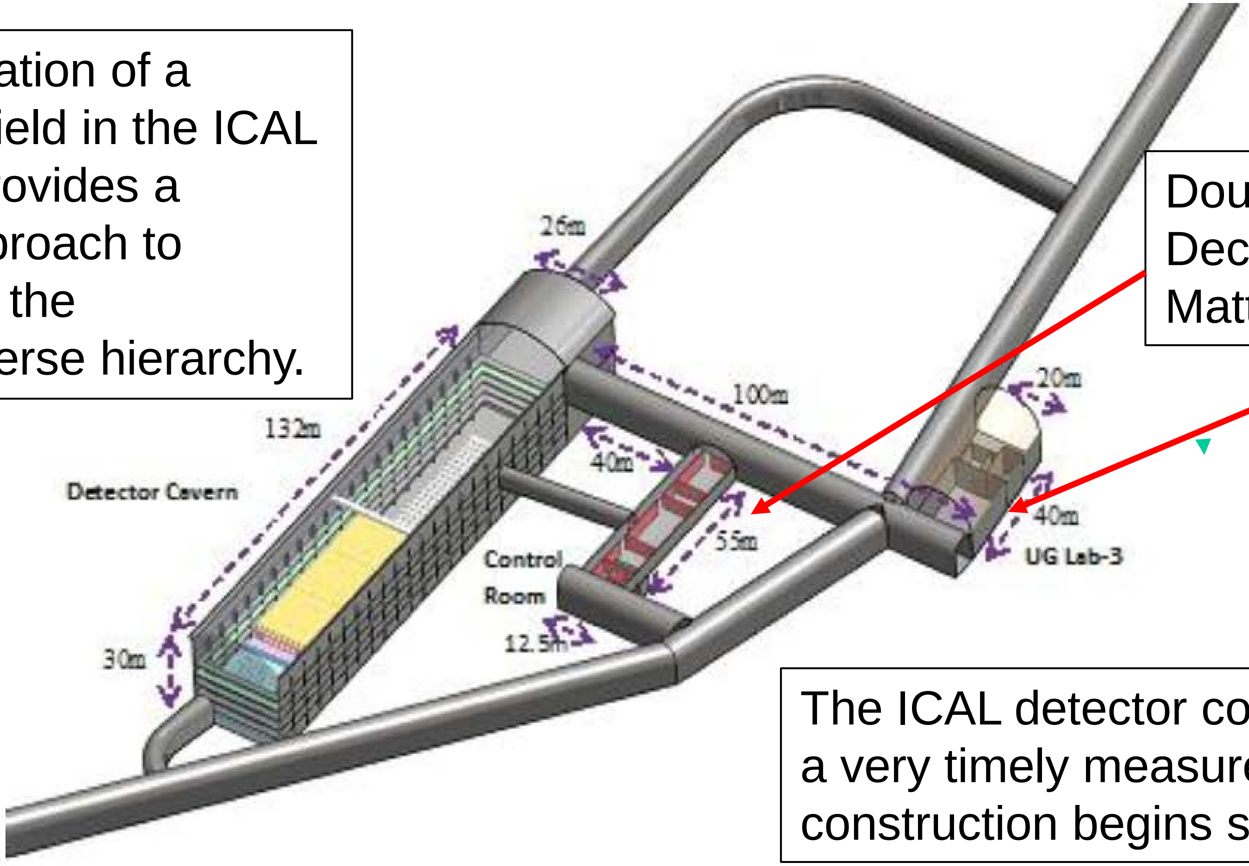


Bodi West Hills,
Pottipuram Village,
(100 km from Madurai)
Tamil Nadu State



Underground Laboratory Layout

The application of a magnetic field in the ICAL detector provides a unique approach to measuring the normal/inverse hierarchy.



Double Beta Decay and Dark Matter detection

The ICAL detector could provide a very timely measurement if construction begins soon.

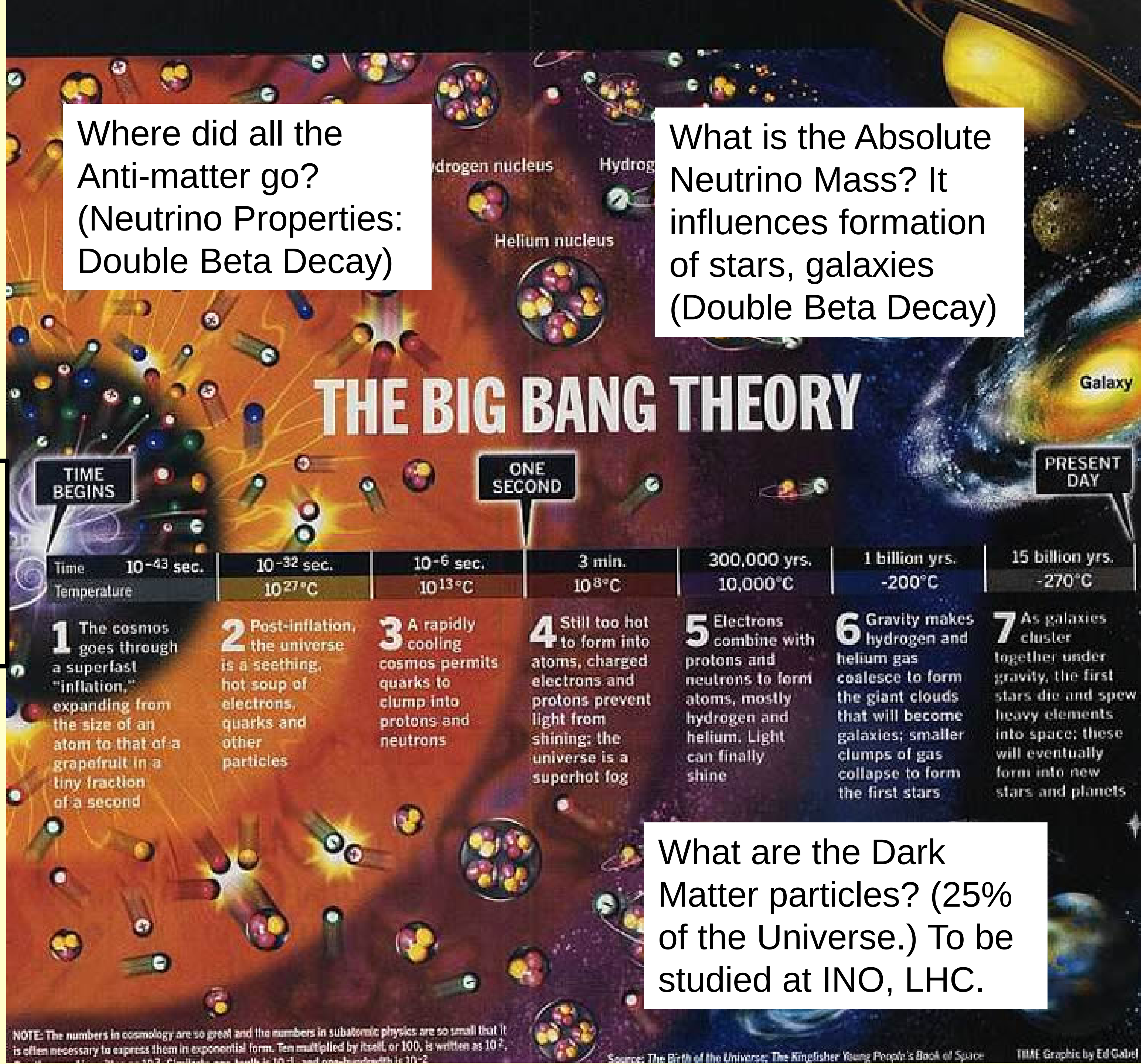
One large cavern for ICAL and 2 small cavern for other experiments such as Neutrino-less double beta decay (NDBD) and search for dark matter etc.

Understanding our Universe more completely

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

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

What are the Dark Matter particles? (25% of the Universe.) To be studied at INO, LHC.

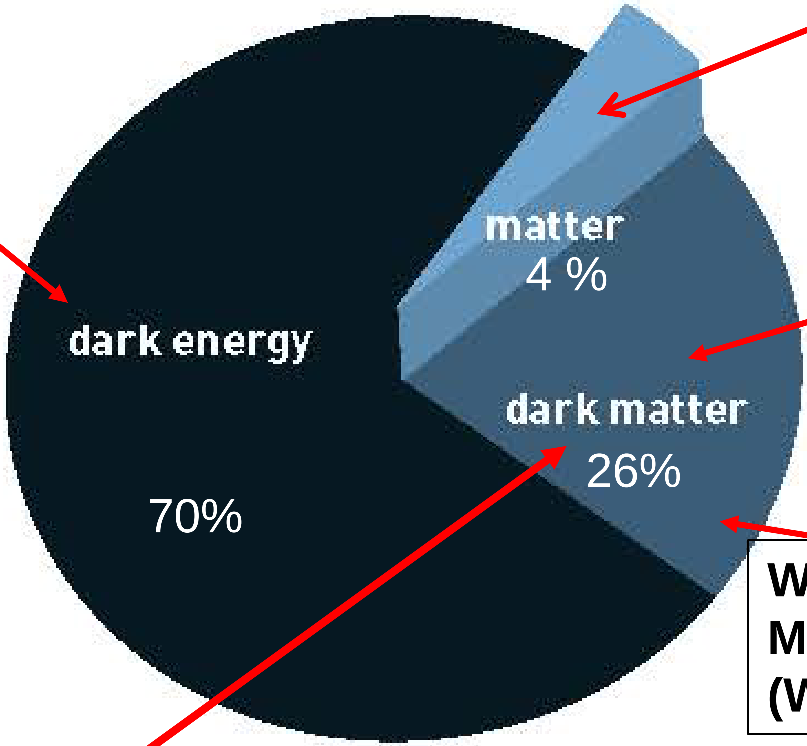


Composition of the Universe as we understand it today

(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.)

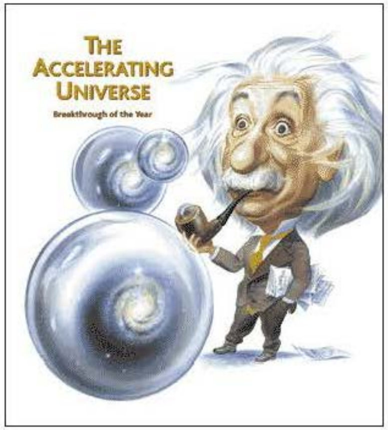
US!!!

Responsible for accelerating the Universe's expansion



Neutrinos Are only a few %

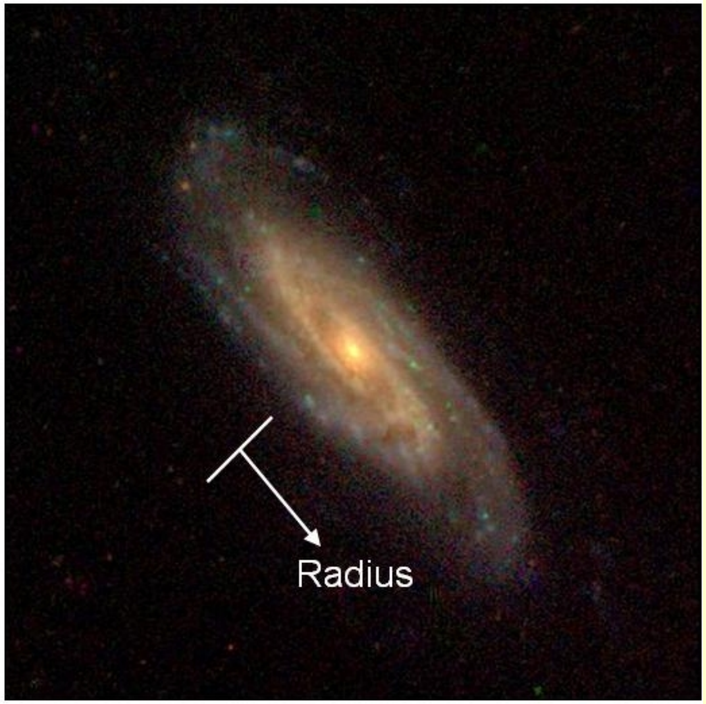
Weakly Interacting Massive Particles (WIMPS)

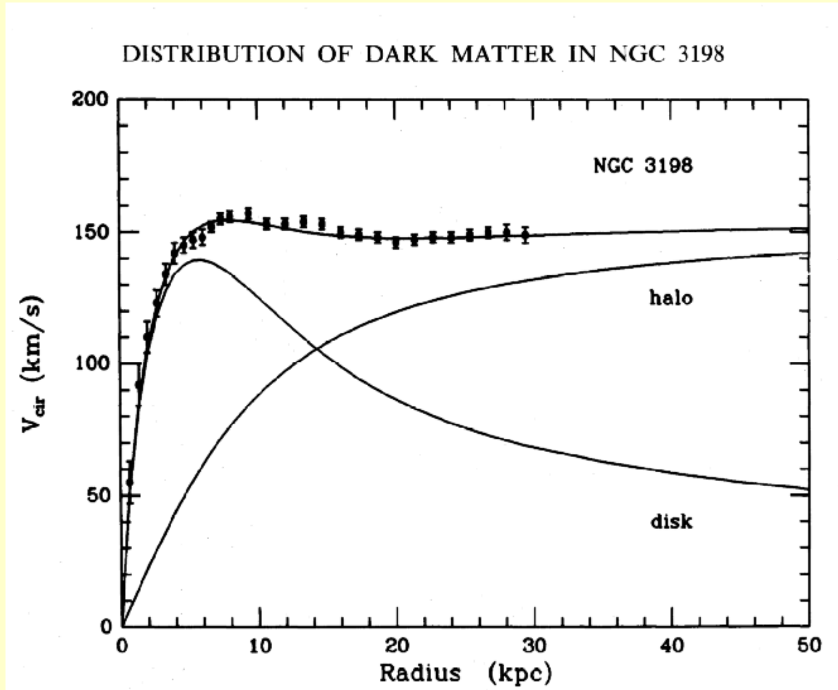


With underground labs we look for Dark Matter particles left from the Big Bang, with ultra-low radioactive background.
At CERN: Try to create it for the first time since the Big Bang

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

For example: SPIRAL GALAXY CLUSTERS WOULD FLY APART IF THEY ARE COMPOSED OF ONLY THE GLOWING MATTER





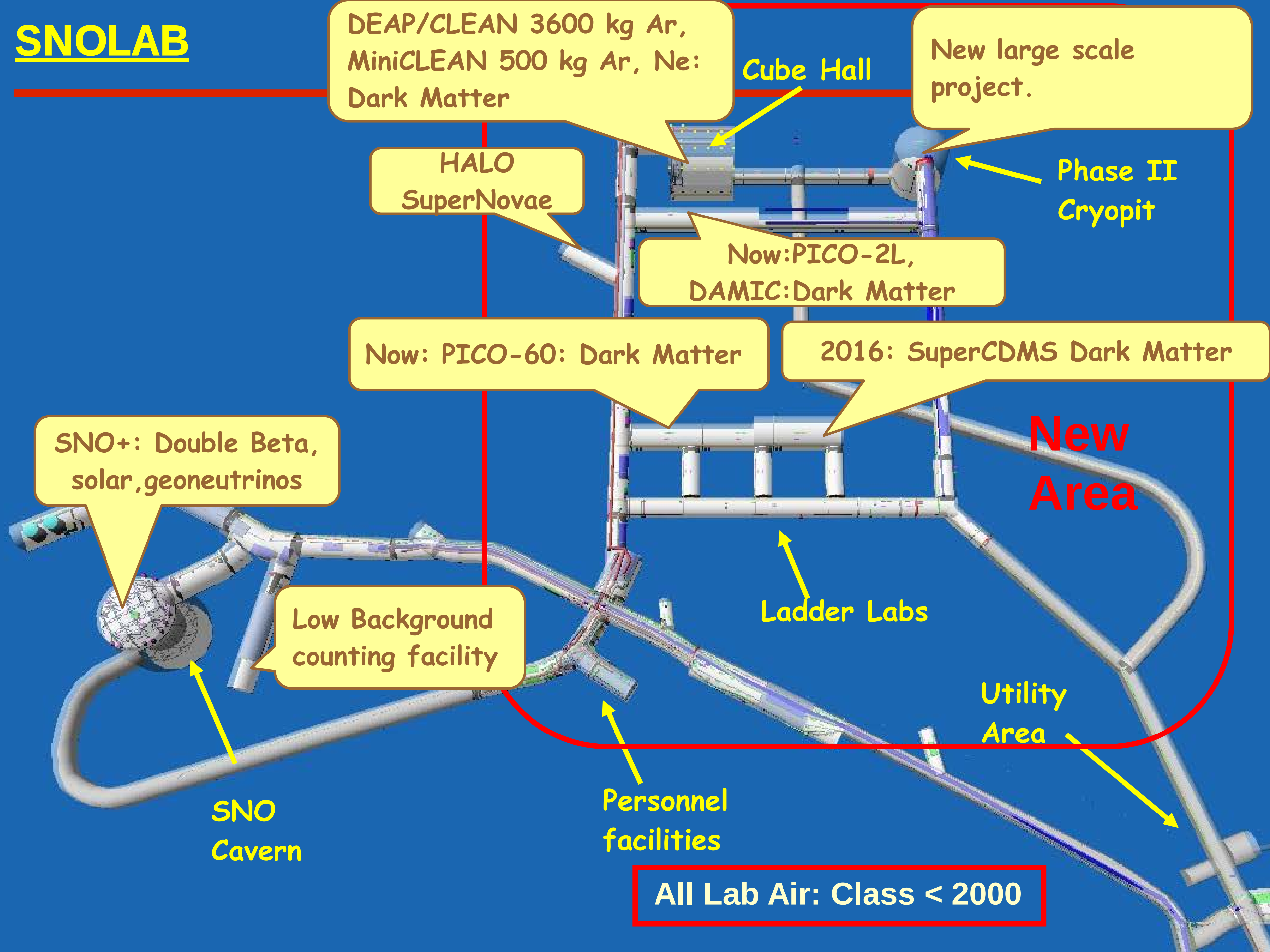
DARK MATTER

GLOWING MATTER

HOWEVER, WE DO NOT KNOW WHAT THE "WIMPS" ARE. THEY MUST BE STABLE ENOUGH TO SURVIVE 13 BILLION YEARS AND MUST BE SO MASSIVE THAT THE HIGHEST ENERGY ACCELERATORS HAVE NOT PRODUCED THEM YET.

WE LOOK FOR THEM STRIKING OUR DETECTORS PRODUCING LIGHT.
THE ACCELERATOR AT CERN (LHC) (WITH INDIAN COLLABORATORS) IS ALSO TRYING TO PRODUCE THEM FOR THE FIRST TIME SINCE THE BIG BANG.

SNOLAB



DEAP/CLEAN 3600 kg Ar, MiniCLEAN 500 kg Ar, Ne: Dark Matter
Cube Hall
New large scale project.
HALO SuperNovae
Phase II Cryopit
Now:PICO-2L, DAMIC:Dark Matter
Now: PICO-60: Dark Matter
2016: SuperCDMS Dark Matter
SNO+: Double Beta, solar,geoneutrinos
New Area
Ladder Labs
Low Background counting facility
Utility Area
SNO Cavern
Personnel facilities
All Lab Air: Class < 2000

262 SNO Physics Paper Authors: Adam Cox, Aksel L. Hallin, Alain Bellerive, Alan Smith, Alan Poon, Alexander Wright, Allan Myers, Alysia Marino, André Krüger, André Roberge, Andre Krumins, Andrew Ferraris, Andrew Hime, Anett Schülke, Anthony Noble, Araz Hamian, Arthur McDonald, Aubra Anthony, Azriel Goldschmidt, Barry Robertson, Bassam Aharmim, Bei Cai, Benjamin Monreal, Bernard Nickel, Berta Beltran, Bhaskar Sur, Blair Jamieson, Brandon Wall, Brent VanDevender, Brian Morissette, Bruce Cleveland, Bryan Fulsom, Bryce Moffat, Carsten Krauss, Catherine Mifflin, Charles Currat, Charles Duba, Charlotte Sims, Christian Nally, Christian Ouellet, Christine Kraus, Christopher Kyba, Christopher Howard, Christopher Jillings, Christopher Tunnell, Christopher Waltham, Clarence Virtue, Colin Okada, Darren Grant, David Anglin, David Sinclair, David Waller, David Wark, Davis Earle, Diane Reitzner, Dimpal Chauhan, Doug Hallman, Douglas Cowen, Douglas McDonald, Duncan Hepburn, Ed Frank, Edward Clifford, Michael Dragowsky, Emmanuel Bonvin, Eric Norman, Erik Saettler, Etienne Rollin, Eugene Guillian, Eugene Beier, Fabrice Fleurot, Feng Zhang, Ferenc Dalnoki-Veress, Fraser Duncan, Gabriel D. Orebi Gann, Geoffrey Miller, George Doucas, George Ewan, Gerhard Bühler, Gersende Prior, Gordana Tešić, Gordon,McGregor, Gregory Harper, Guy Jonkmans, Gwen Milton, Hadi Fergani, Hans Bichsel, Hans Mes, Hardy Seifert, Hay Boon Mak, Heidi Munn, Helen M. O'Keeffe, Hendrick Labranche, Henry Lee, Hok Seum Wan Chan Tseung, Huaizhang Deng, Hugh Evans, Hui-Siong Ng, Ian Lawson, Ilan Levine, Ira Blevis,Jacques Farine, James Cameron, James Hall, James Loach, James Leslie, Jaret Heise, Jason Detwiler, Jason Hewett, Jason Pun, Jason Goon, Jeanne Wilson, Jeffrey Secrest, Jeremy Lyon, Jerry Wilhelmy, Jessica Dunmore, Jian-Xiong Wang, Jimmy Law, Jocelyn Monroe, John Amsbaugh, John Boger, John Orrell, John Simpson, John Wilkerson, Jon Hykawy, Jose Maneira, Joseph Formaggio, Joseph Banar, Joseph Germani, Joshua Klein, Juergen Wendland, Kai Zuber, Kara Keeter, Kareem Kazkaz, Karsten Heeger, Katherine Frame, Kathryn Schaffer, Keith Rielage, Kennneth McFarlane, Kevin Graham, Kevin Lesko, Kevin McBryde, Khalil Boudjemline, Klaus Kirch, Laura Kormos, Laura Stonehill, Laurel Sinclair, Louise Heelan, Malcolm Fowler, Manuel Anaya, Marc Bergevin, Marcus Thomson, Maria Isaac, Marie DiMarco, Mark Boulay, Mark Chen, Mark Howe, Mark Kos, Mark Neubauer, Martin Moorhead, Masa Omori, Melin Huang, Melissa Jerkins, Michael Bowler, Michael Browne, Michael Lay, Michael Lowry, Michael Miller, Michael Thorman, Michal Shatkay, Mike Schwendener, Miles Smith, Minfang Yeh, Miriam Diamond, Mitchell Newcomer, Monica Dunford, Morley O'Neill, Mort Bercovitch, Myung Chol Chon, Naeem Ahmed, Nathaniel Tagg, Neil McCauley, Nicholas Jelley, Nicholas West, Nikolai Starinsky, Nikolai Tolich, Noah Oblath, Noel Gagnon, Nuno Barros, Olivier Simard, Patrick Tsang, Paul Keener, Peter Wittich, Peter Doe, Peter Watson, Peter Skensved, Peter Thornewell, Philip Harvey, Pierre Luc Drouin, Pillalamarr Jagam, R.G. Hamish Robertson, Ranpal Dosanjh, Reda Tafirout, Reena Meijer Drees, Reyco Henning, Richard Allen, Richard Ford, Richard Helmer, Richard Hemingway, Richard Kouzes, Richard L. Hahn, Richard Lange, Richard Ott, Richard Taplin, Richard Van Berg, Richard Van de Water, Rizwan Haq, Robert Black, Robert Boardman, Robert G. Stokstad, Robert Heaton, Robert Komar, Robin Ollerhead, Rushdy Ahmad, Ryan MacLellan, Ryan Martin, Ryuta Hazama, Salvador Gil, Sarah Rosendahl, Scott Oser, Sean McGee, Shahnoor Habib, Sherry Majerus, Simon J. M. Peeters, Stanley R Seibert, Steffon Luoma, Steven Elliott, Steven D. Bille, Steven J. Brice, Teresa Spreitzer, Thomas Andersen, Thomas J. Radcliffe, Thomas J. Bowles, Thomas Kutter, Thomas Sonley, Thomas Steiger, Timothy Van Wechel, Tom Burritt, Tudor Costin, Tyron Tsui, Vadim Rusu, Vladimir Novikov, Walter Davidson, William Frati, William Handler, William J. Heintzelman, William Locke, William McLatchie, Xin Chen, Xin Dai, Yaroslav Tserkovnyak, Yasuo Takeuchi, Yekaterina Opachich, Yuen-Dat Chan **And 11 who have passed away:** Herbert Chen, John C. Barton, John Cowan, Andre Hamer, Clifford Hargrove, Barry C. Knox, Jan Wouters, Peter Trent, Robert Storey, J. Keith Rowley and Neil W. Tanner

CONCLUSIONS

- **Particle Astrophysics is an exciting field where measurements are helping us to understand our Universe more completely on scales reaching from the very small to the farthest reaches in space and the earliest times.**

- **Going underground can enable scientists to make unique measurements that would otherwise be obscured by background from cosmic radiation.**

- **India has an excellent opportunity to contribute strongly to this rapidly growing area of fundamental research through its work in *particle physics at international accelerators* and in the INDIAN NEUTRINO OBSERVATORY (INO).**

- **This is one of the most exciting and greatest intellectual exercises of all time….Understanding Our Universe.**