Neutrinos – A New Window To The Universe

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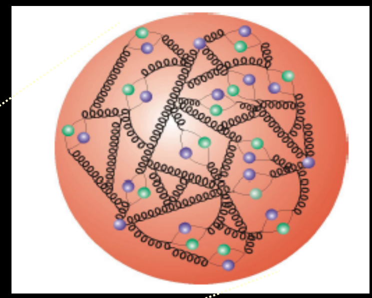
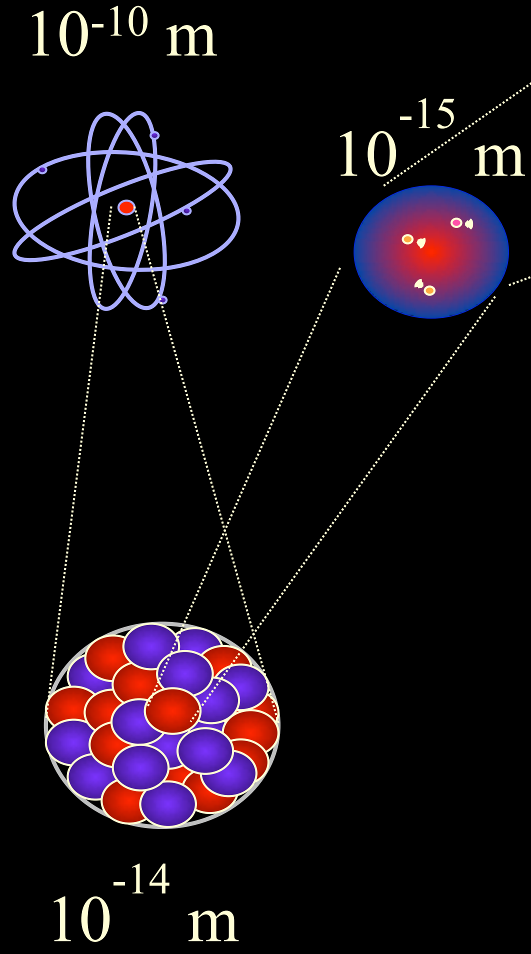
Looking inside

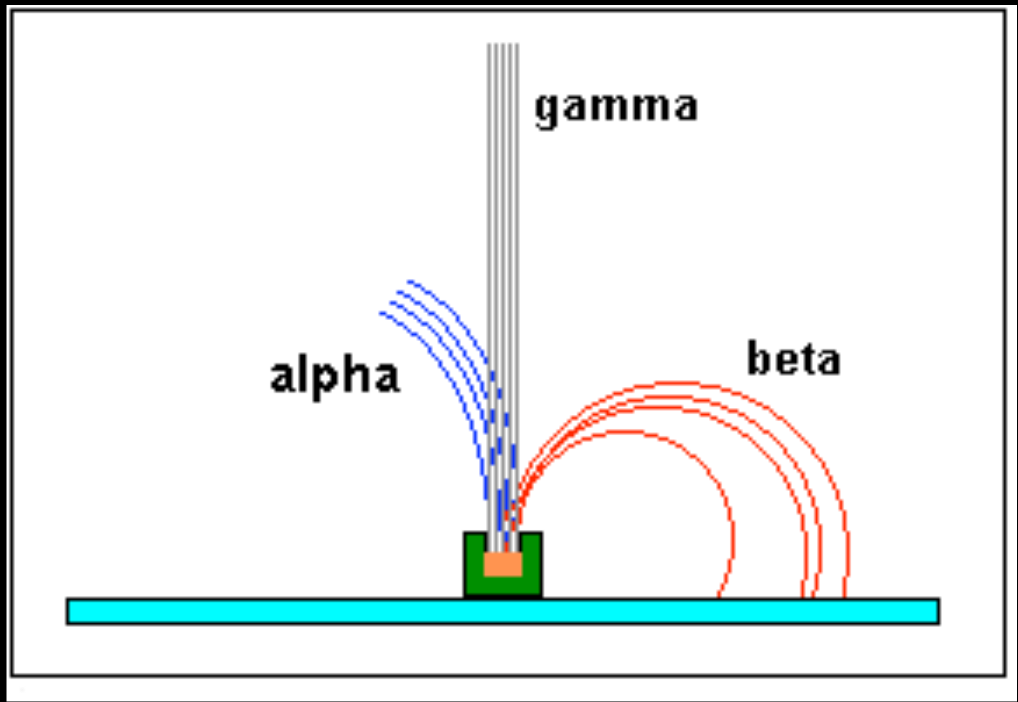




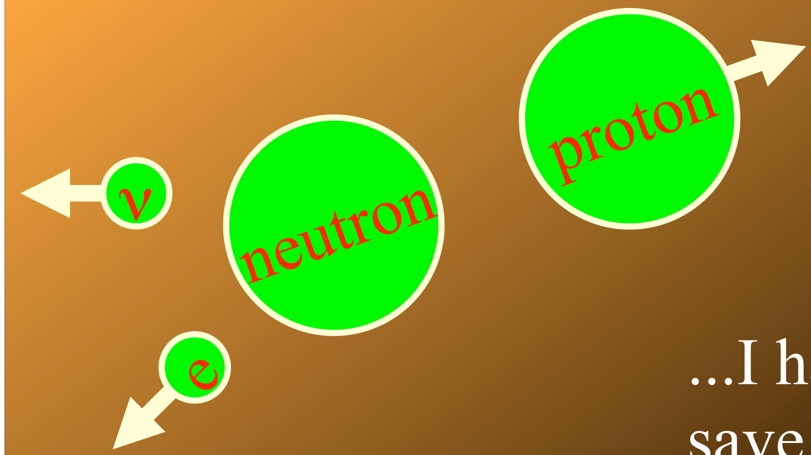
Atom is made out of electrons, protons and neutrons.

Protons and neutrons are made out of quarks.

α, β, γ Rays



β decay



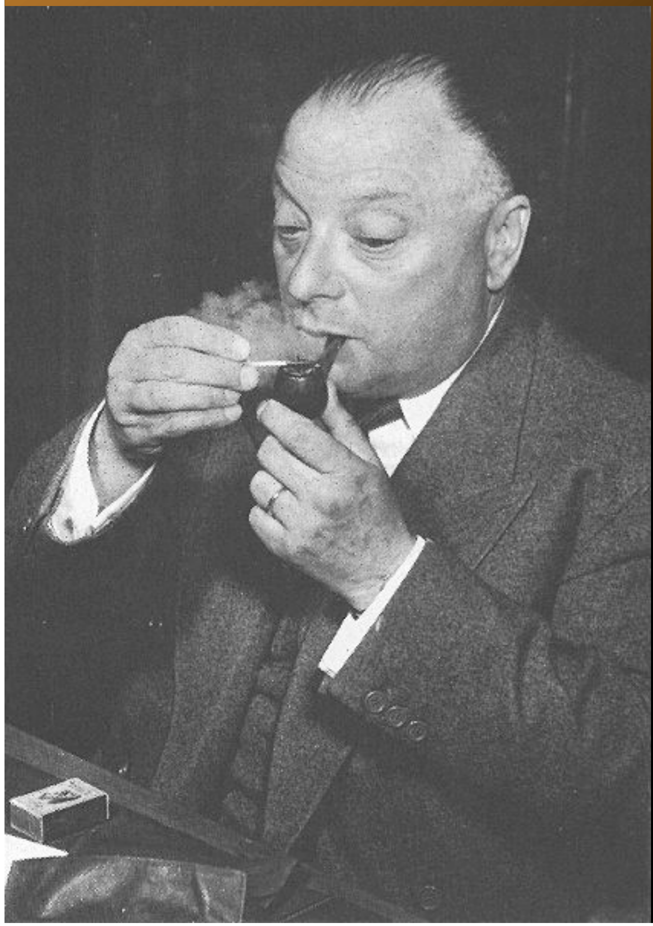
December 4, 1930

Dear radioactive ladies and gentlemen,

...I have hit upon a ‘desperate remedy’ to save...the law of conservation of energy. Namely the possibility that there exists in the nuclei electrically neutral particles, that I call neutrons...I agree that my remedy could seem incredible...but only the one who dare can win...

Unfortunately I cannot appear in person, since I am indispensable at a ball here in Zurich.

Your humble servant
W. Pauli

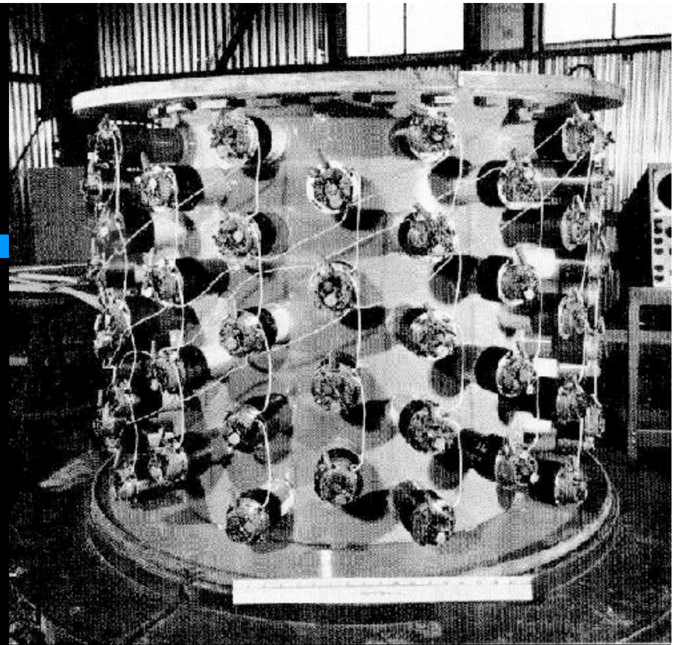


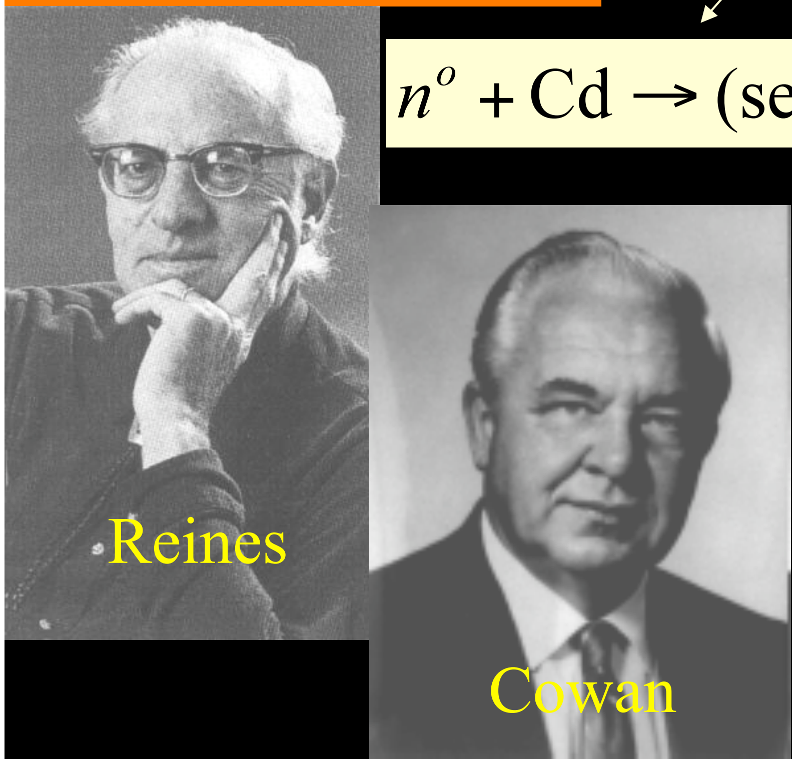
Project Poltergeist 1956

$$\nu + p^{+} \rightarrow n^{o} + e^{+}$$

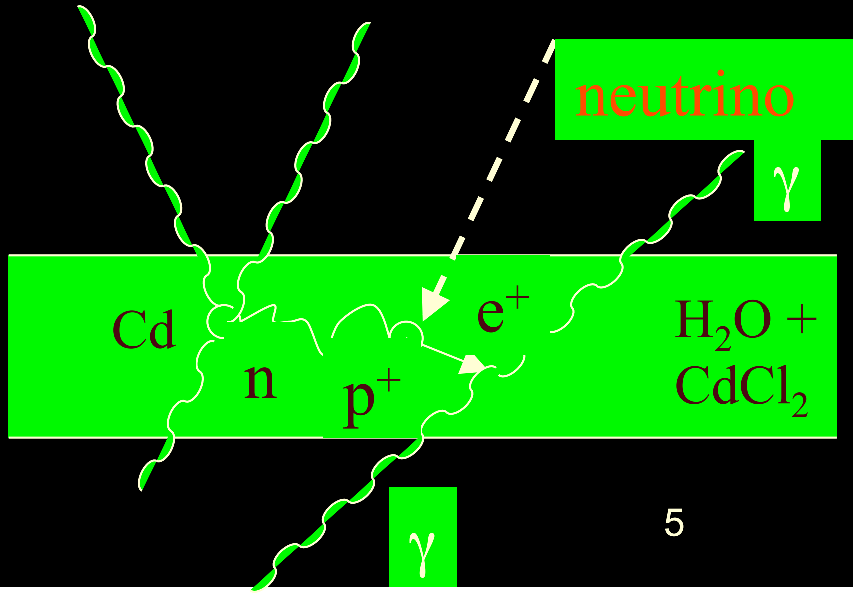
$$e^{+} + e^{-} \rightarrow 2\gamma$$

$$n^{o} + \mathrm{Cd} \rightarrow (\mathrm{several})\,\gamma$$



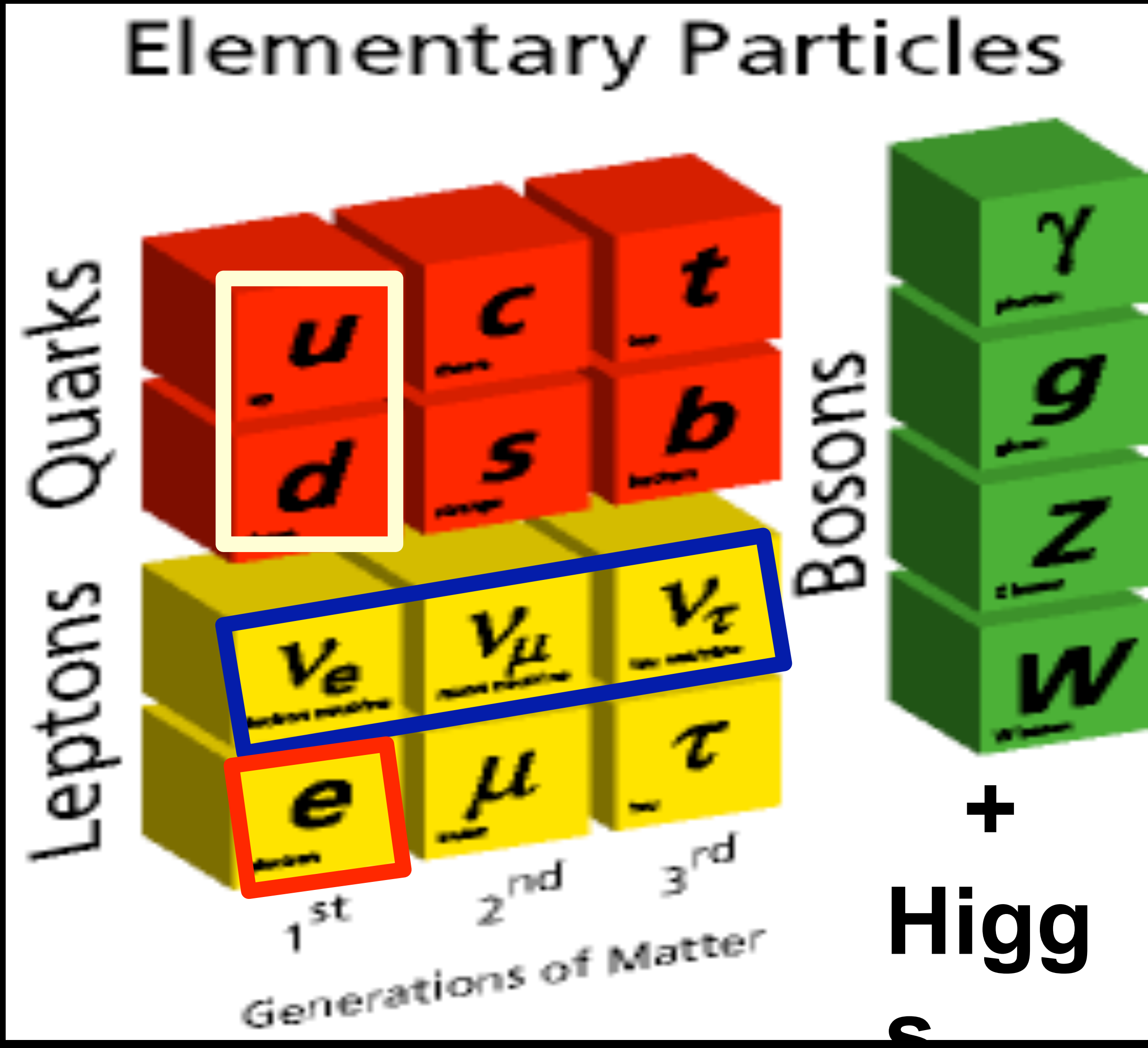


Signal 2γ, then several γ ~few μs later



Experiment attempted at Hanford in 1953, too much background. Repeated at Savannah River in 1955. [Flux: 10^{13} neutrinos/(cm^2 s)]

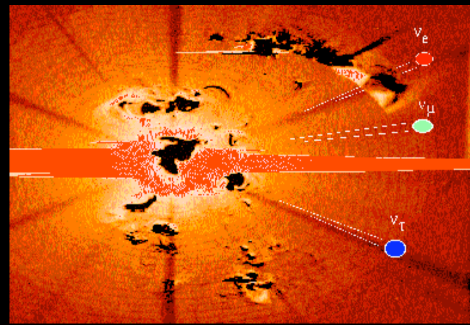
Elementary particles



Where do neutrinos come from?

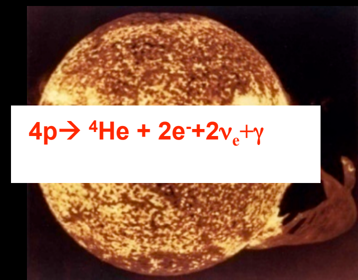
- ***Neutrinos from Big bang:***

330 ν/cm³ ; $E_\nu \sim 4 \times 10^{-4}$eV
Decoupled about 1 min. after the Big bang



- ***Neutrinos from Sun:***

Sun burns through nuclear Reaction
$E_\nu \sim 0.1 \sim 20$ MeV; Flux ~10^{12} /cm²/s



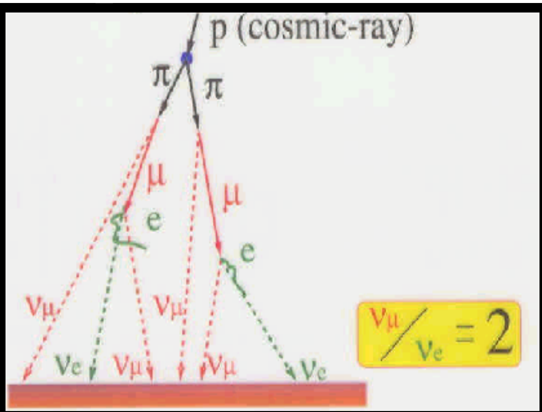
- ***Explosion of Star:***

Most of the binding energy released When a neutron star is born is emitted in the form of neutrinos

$E_b \sim 10^{53}$ ergs, $E_\nu \sim 10\text{-}30$ MeV, T ~10 sec

Where do neutrinos come from?

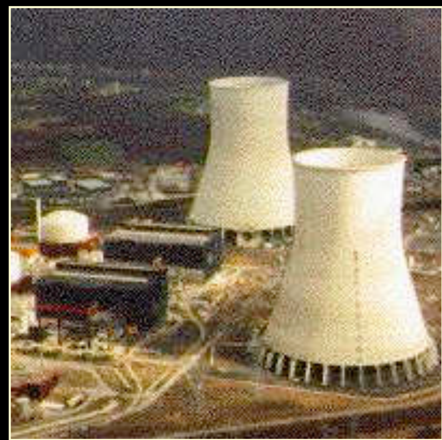
- ***Atmospheric neutrinos:***



- ***UHE (10^{12}) eV Neutrinos :***
  - *AGN, GRBs*
- *Cosmic Ray sources (> 5 X 10^{19}eV)*
- *Neutrinos from the Earth Core:*
  - ***Radioactivity at the core of the earth:***
    - ***Power ~16 Terra Watts.***
    - ***Flux ~ 6 X 10^6 /cm^2/sec.***

- ***Neutrinos from Man made activities:***
  - ***Neutrinos produced by particle accelerators***

  - *Reactor Neutrinos:*
    - ***E_ν~ 4 MeV, Flux ~5 X 10^{20}/sec from a standard nuclear plant.***



Close Encounter with Neutrinos

- *When you take your morning walk on the green nature-*
  - *Every second Your body receives*
    - *400000 billions neutrinos from the sun*
    - *50 billion neutrinos from the natural radioactivity of the earth*
    - *10-100 billion neutrinos from nuclear plants all over the world*

    You can still enjoy your walk. Typically a neutrino has to zip through 10,000,000,000,000,000,000 people before doing anything.

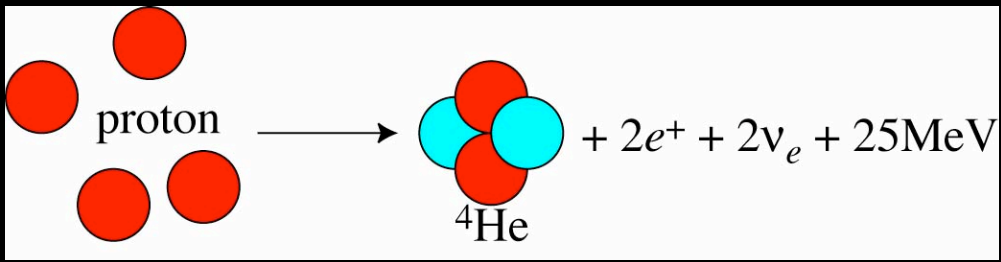
  - *Our body contains about 20 milligrams of ^{40}K which is β radioactive. We emit about 340 millions neutrinos/day. Which run from our body at the speed of light until the end of the universe.*

Are neutrinos important to our lives ?

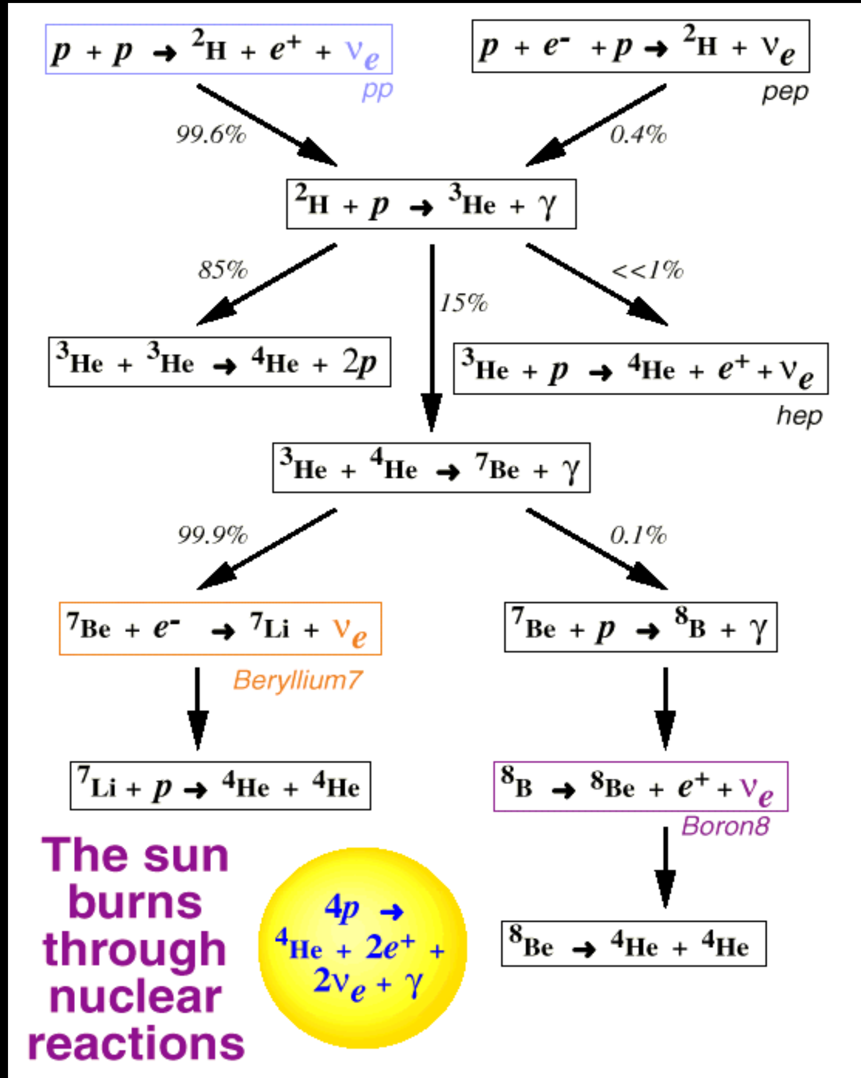
- ***If there were no neutrinos- the sun and stars would not shine.***
  - ***No energy from the sun to keep us warm.***
  - ***No atoms more complicated than hydrogen.***
  - ***No carbon, no oxygen, no water.***
  - ***No earth, no moon, no us.***
- ***We depend on small amount of heavy chemical elements like zinc, selenium.***
  - ***These heavy elements are produced only in supernova explosion.***
  - ***If there were no neutrinos, there would be no supernova explosions.***

No neutrinos – will be a very very bad news for you and me.

Bethe's Theory of Stellar Evolution



$$\Phi_\nu = \frac{2L_{\text{sun}}}{25\text{MeV}} \frac{1}{4\pi(1\text{AU})^2} = 7 \cdot 10^{10}\ \text{sec}^{-1}\ \text{cm}^{-2}$$



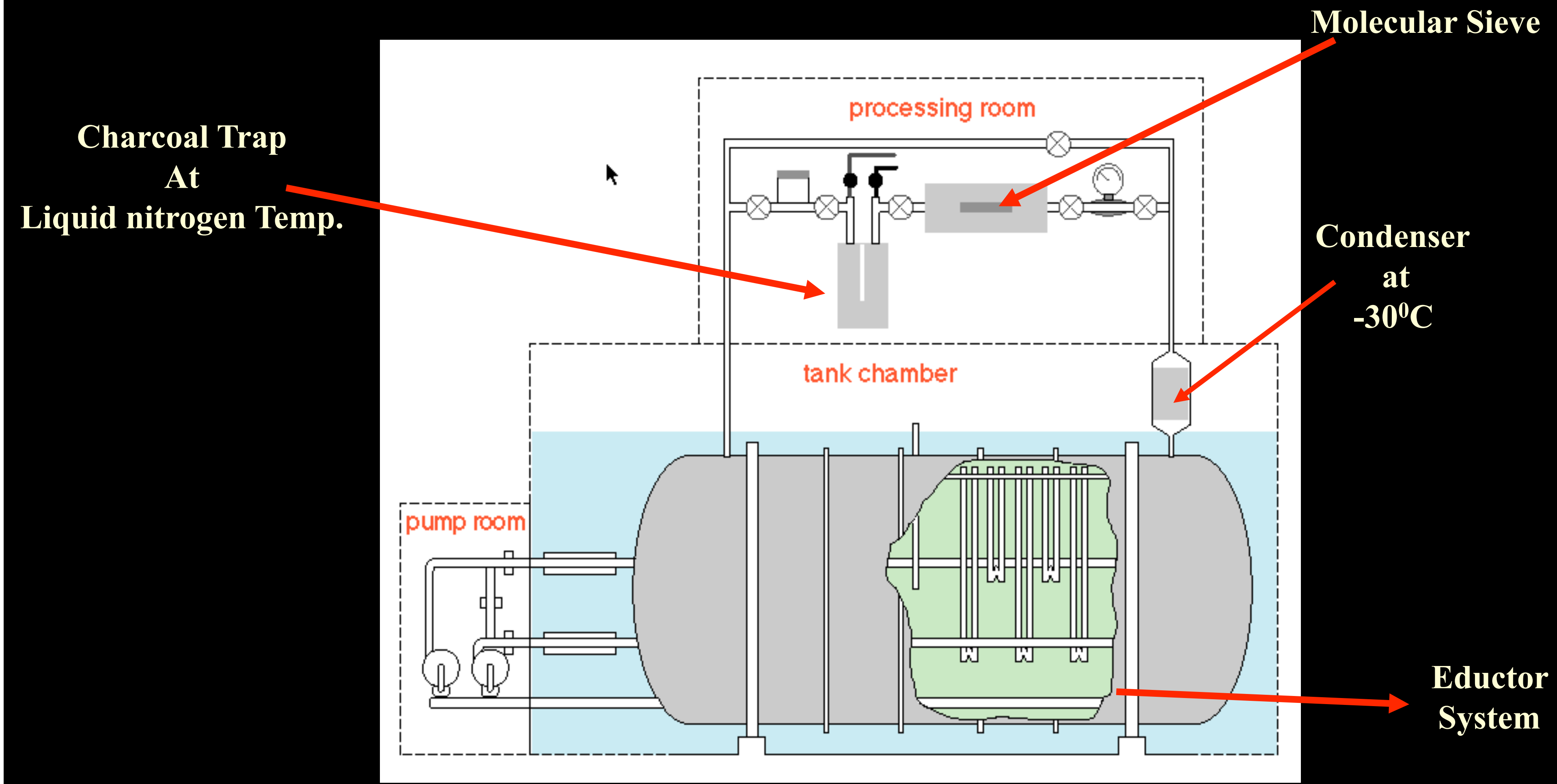
Neutrinos from sun- Beginning of neutrino astronomy

- ***Is there a way to test Bethe's theory on steller evolution?***
- ***Light takes about 10 million years to leak out from the center of the sun.***
- ***It only tells us about the condition in the outer region of the sun.***
- ***Neutrinos is the only way out.***
- ***A solar neutrino passing through the entire earth has less than one chance in a thousand billion of being stopped by terrestrial matter.***

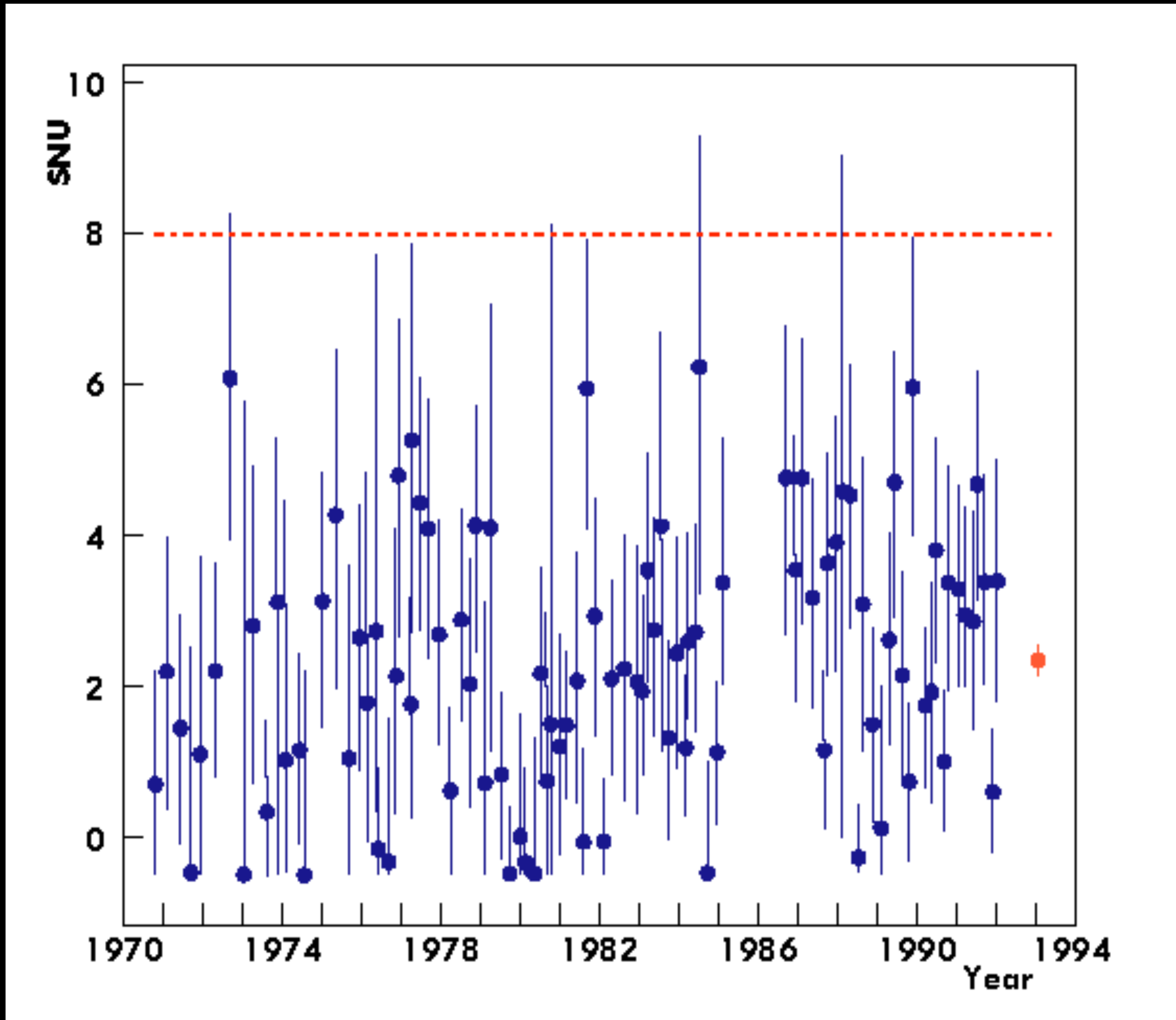
How to Detect Neutrinos from Sun ?

- *1946: B. Pontecorvo :* $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$, $E_{th} = 0.814$ *MeV*
- *1949: L. Alvarez: Made specific suggestions on the chemical procedures, expected neutrino capture cross sections as well as an estimate for possible background effects.*
- *First Attempt by Davis: Burried a 1000 gallon tank of* C_2Cl_4 *near the reactor at Brookhaven. Put limits on neutrinos from Sun as* $< 10^{14}$ *neutrinos-cm*$^{-2}$*sec*$^{-1}$
- *1966: Davis built 100,000 Gallon Clorine Experiment in Homestake mine.*

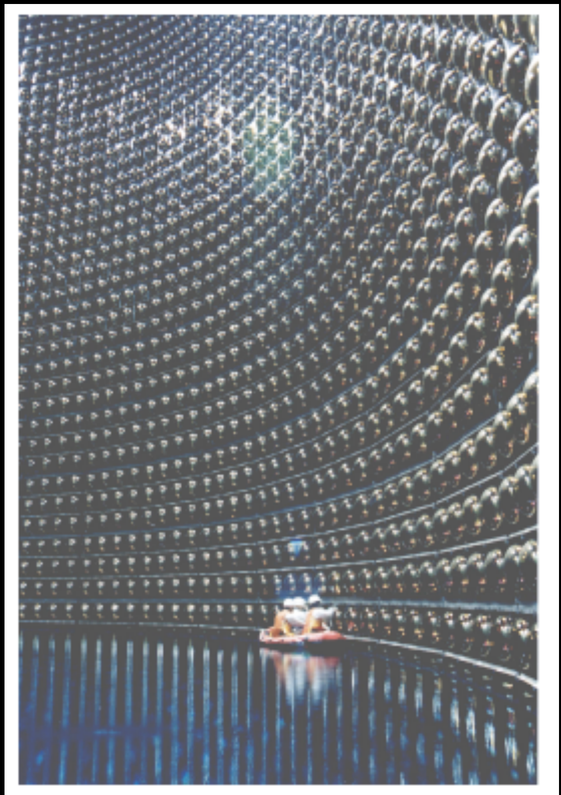
Homestake Detector

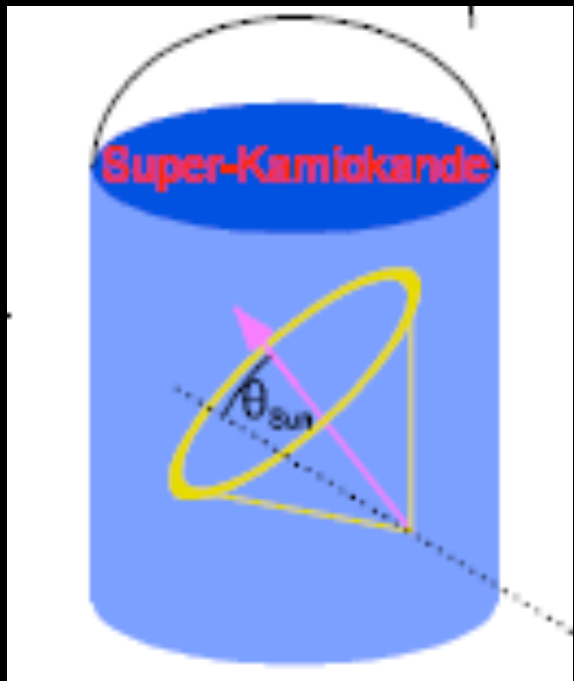


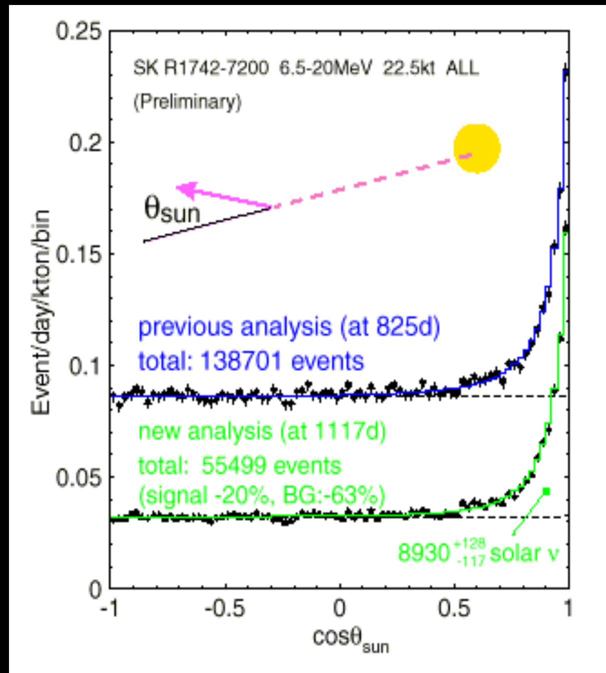
Homestake results



Kamiokande Detector & Data

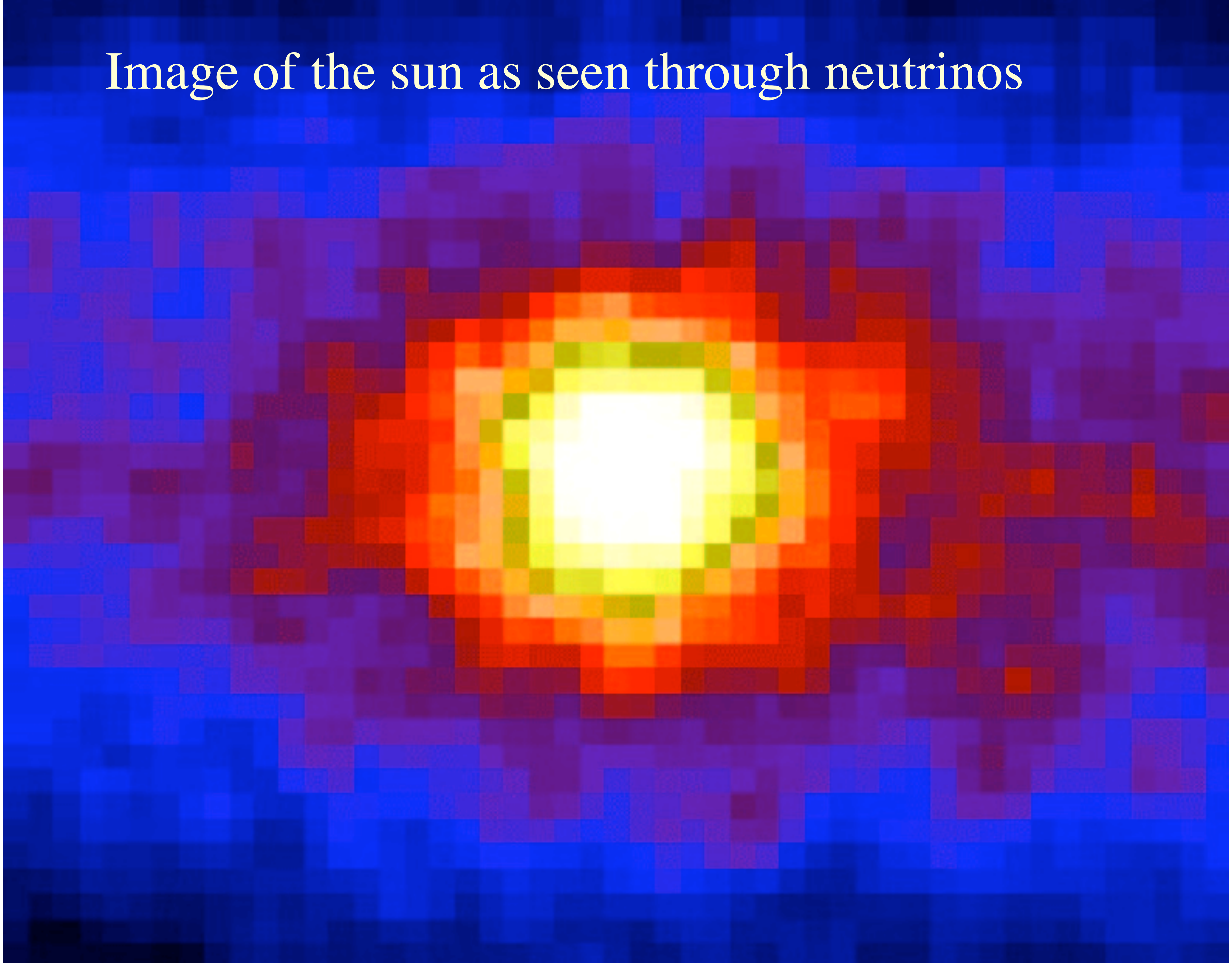




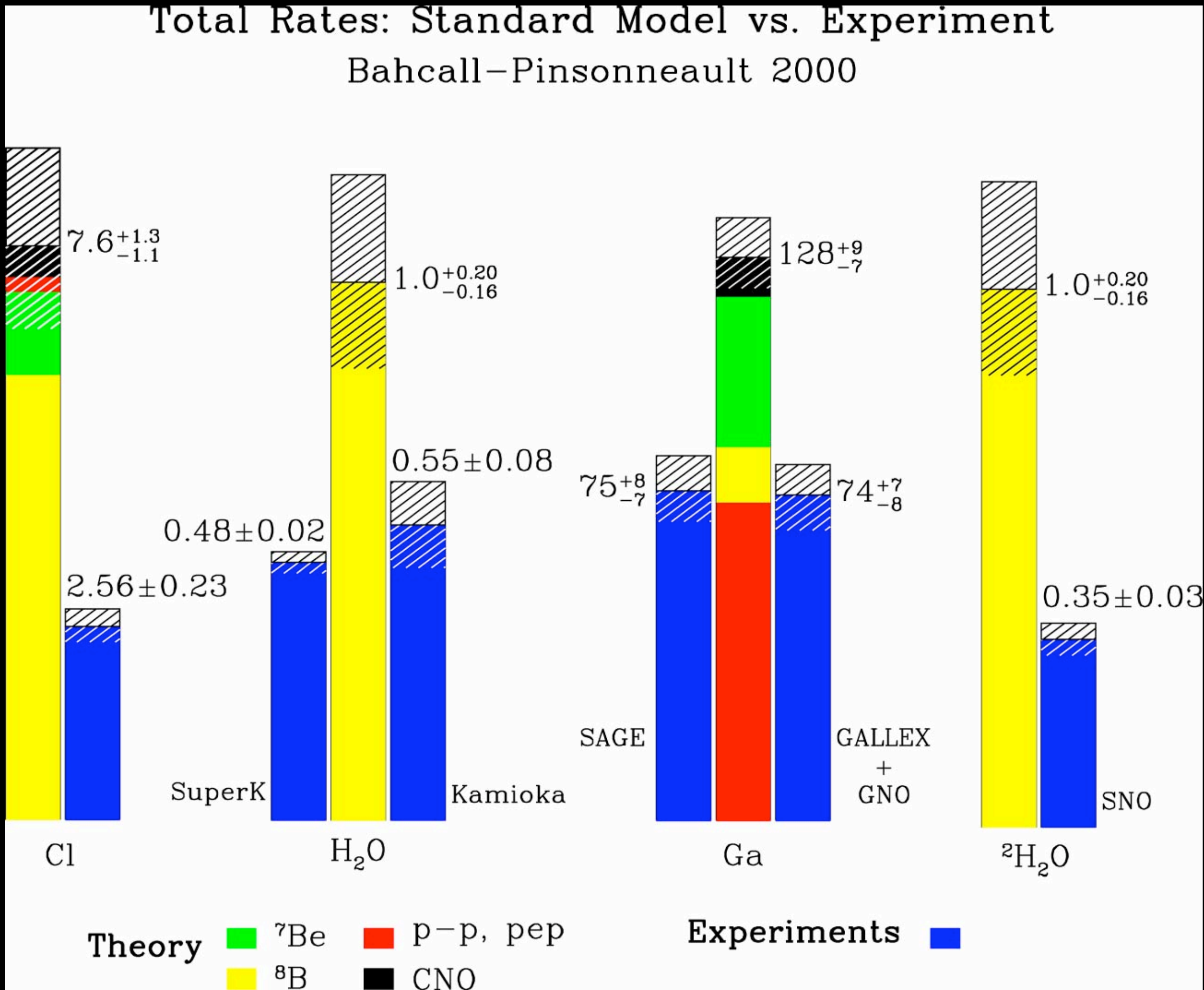


$$\nu_x + e^- \rightarrow \nu_x + e^-$$

Image of the sun as seen through neutrinos



We don't get enough



- Something wrong with our understanding of the Sun?
- Neutrino oscillation?

Quantum Mechanics

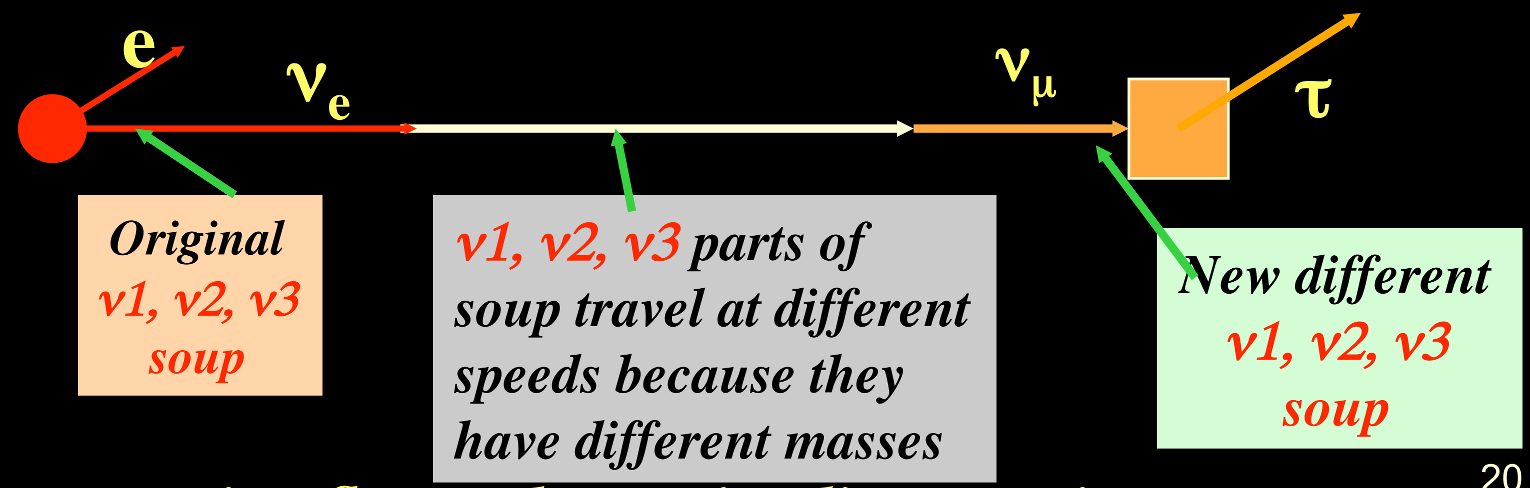
- The world of tiny particles is governed by quantum mechanics.
- Quantum mechanics involves uncertainty at its core.
  - An object can be may be here or may be there
  - It can be may be this or may be that
  - A can be a ν_e or a ν_μ or a ν_τ
- But a proton is a proton. It does not convert into something else.
- How does a ν_e converts into a ν_μ or a ν_τ ?
- Answer : ν_e is not a particle to begin with.
- There are neutrino particles: ν_1, ν_2, ν_3

Neutrino Soup

- ν_e , ν_μ, ν_τ are different mixtures of ν_1, ν_2, ν_3

- The emitted neutrino (ν_e) is actually a mixture of ν_1 , ν_2 & ν_3

- ν_e , ν_μ, ν_τ are different soups all made from the same ingredients ν_1, ν_2, ν_3

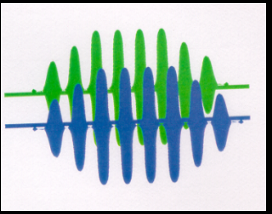


Neutrino flavor change implies neutrino mass

Neutrino Oscillations

- *For neutrinos weak eigenstates may be different from mass eigenstates.*

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta$$
$$\nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta$$



- *In a weak decay one produces a definite weak eigenstate*
- *Then at a later time t*

$$\nu(t) = \nu_1 e^{-iE_1 t} \cos\theta + \nu_2 e^{-iE_2 t} \sin\theta \quad = \quad C_e(t)\nu_e + C(t)_f \nu_f$$

$$P(\nu_e \to \nu_f; t) = \sin^2 2\theta \sin^2[\frac{1}{2}(E_2 - E_1)t]$$

$$E_2 - E_1 = \frac{m_2{}^2 - m_1{}^2}{2E} = \frac{\Delta m^2}{2E}$$

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

SNO comes to the rescue

- Charged Current: ν_e

$$\Phi^{\rm SNO}_{\rm CC} = 1.59^{+0.08+0.06}_{-0.07-0.08} \times 10^6 {\rm cm}^{-2}{\rm s}^{-1}$$

- Neutral Current: $\nu_e + \nu_\mu + \nu_\tau$

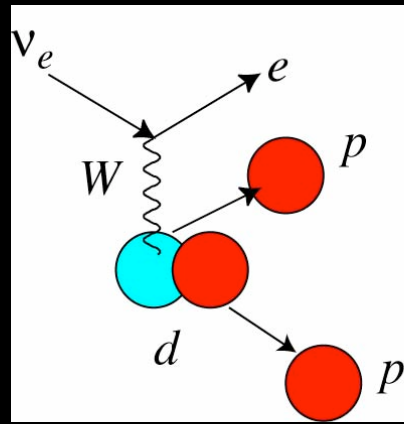
$$\Phi^{\rm SNO}_{\rm NC} = 5.21 \pm 0.27 \pm 0.38 \times 10^6 {\rm cm}^{-2}{\rm s}^{-1}$$

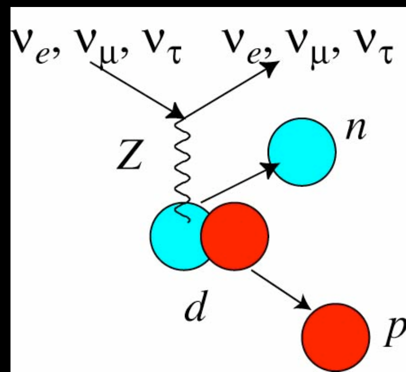
- 7.6σ difference

$\Rightarrow$ $\nu_{\mu,\tau}$ are coming from the Sun!

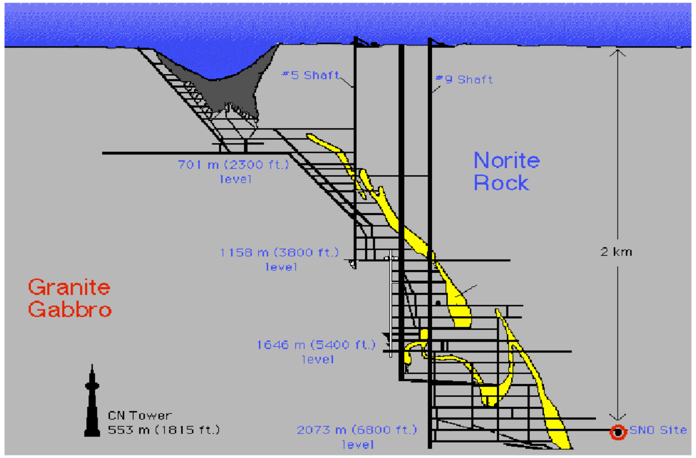
$$\nu_x + e^- \rightarrow \nu_x + e^-$$

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





$$\nu_x + d \rightarrow \nu_x + p + n$$



Sudbury Neutrino Observatory

1000 tonnes D_2O

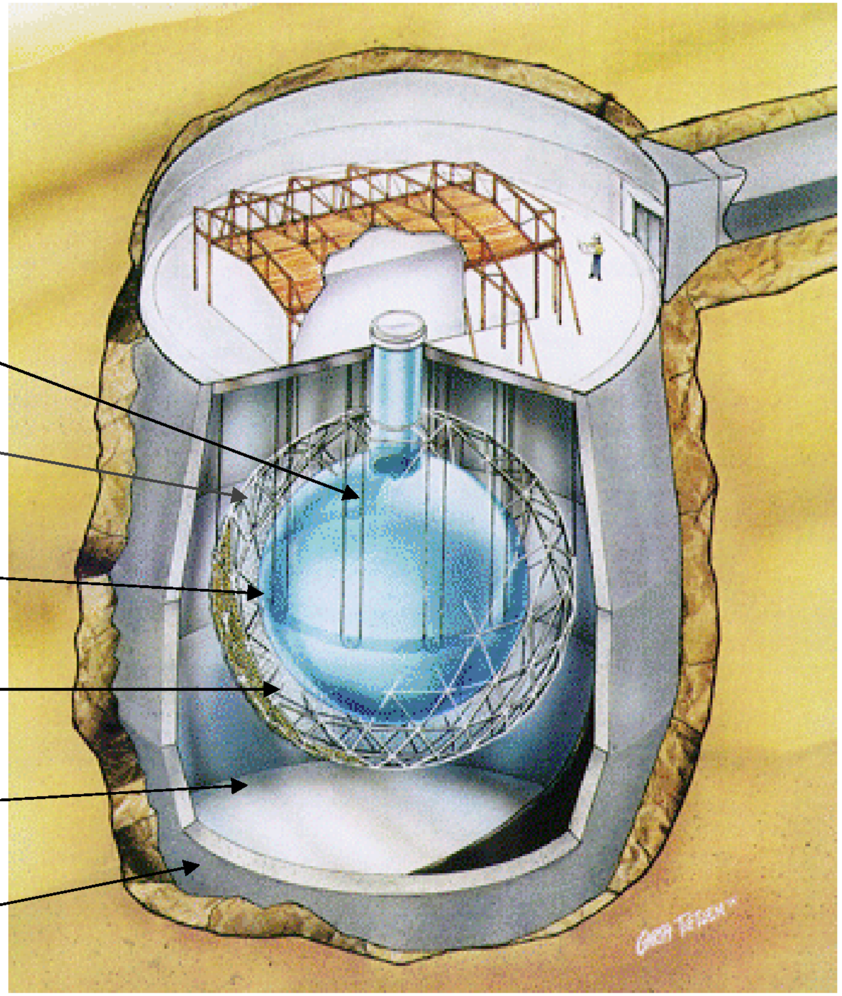
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

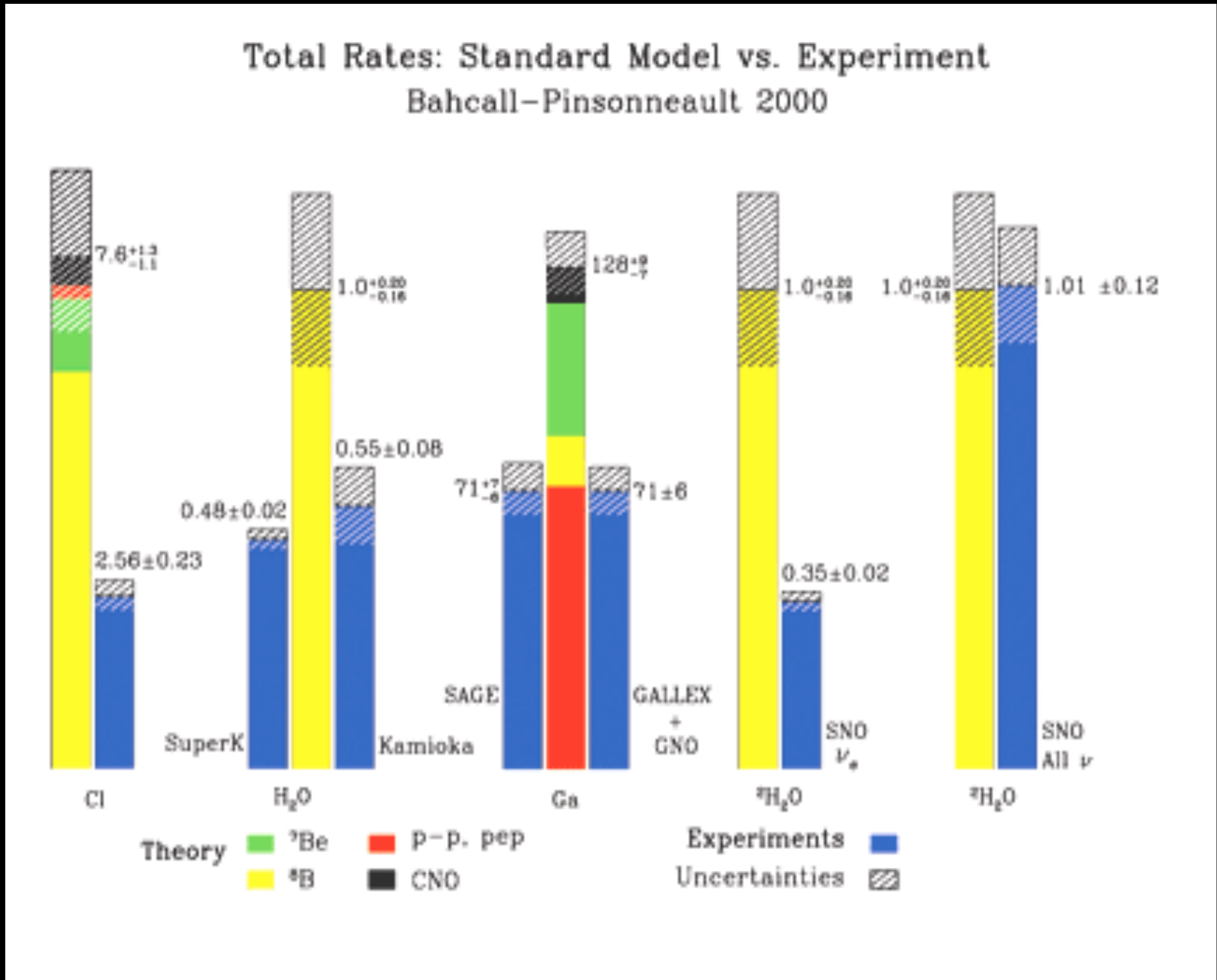
1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

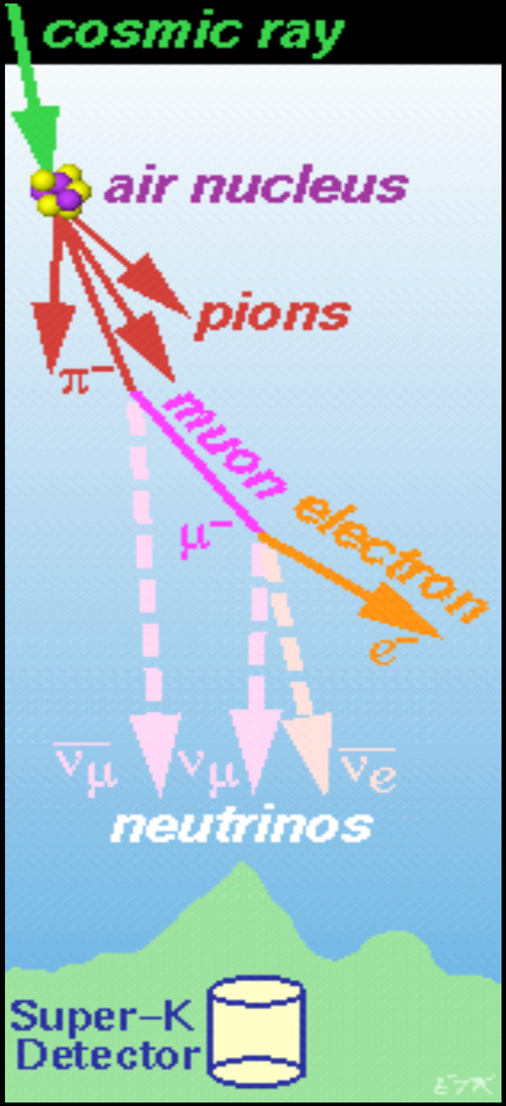
Urylon Liner and Radon Seal

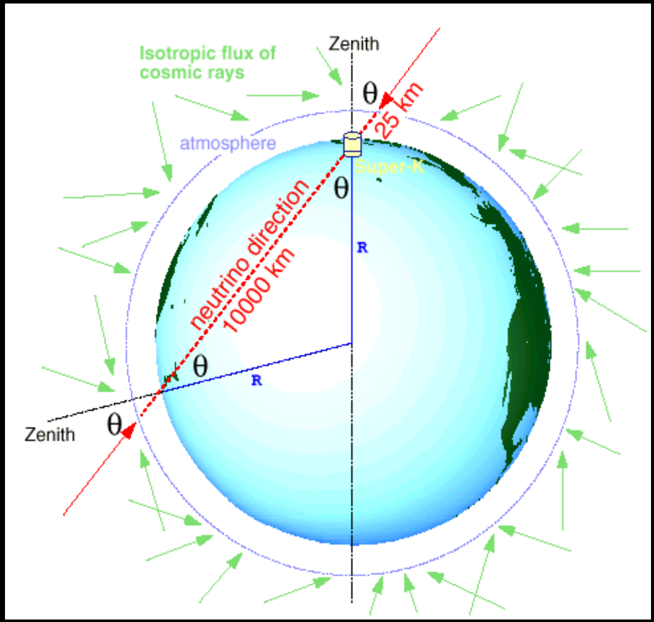


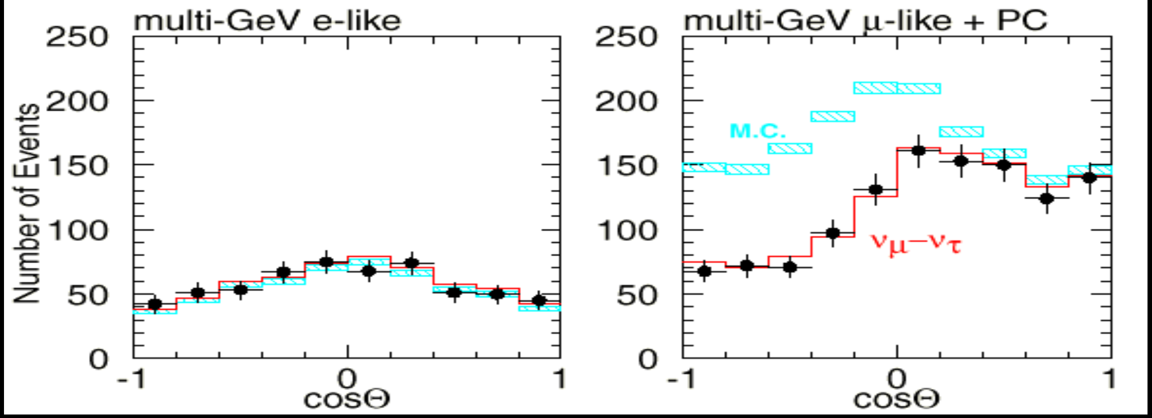
Puzzle solved



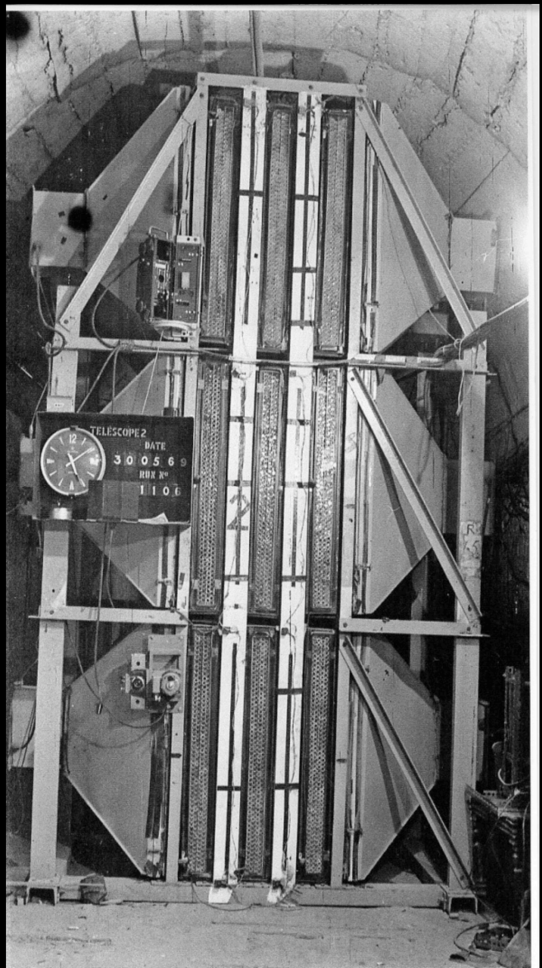
Atmospheric Neutrinos







Atmospheric neutrinos – India connection



Atmospheric neutrino detector at Kolar Gold Field –1965

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

Physics Letters 18, (1965) 196, dated 15th Aug 1965

EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith

Case Institute of Technology, Cleveland, Ohio

and

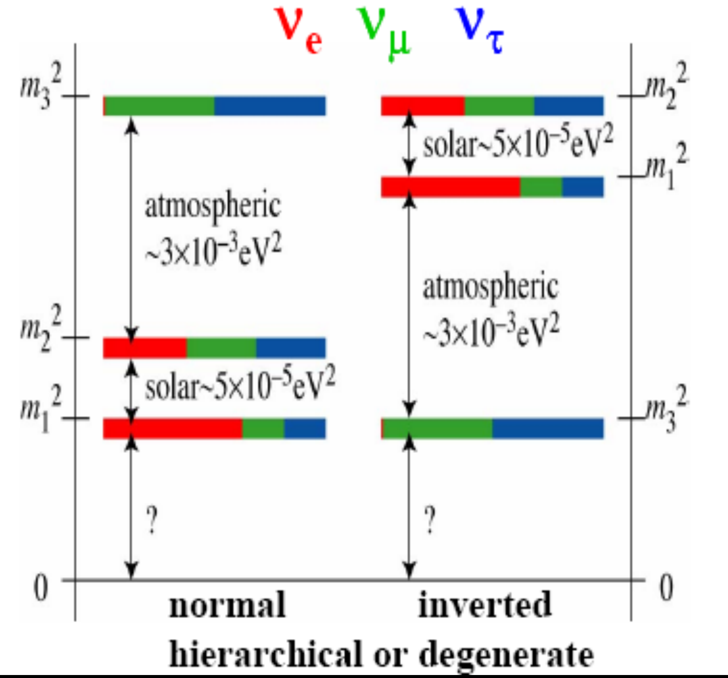
J. P. F. Sellschop and B. Meyer

University of the Witwatersrand, Johannesburg, Republic of South Africa

(Received 26 July 1965)

PRL 15, (1965), 429, dated 30th Aug. 1965

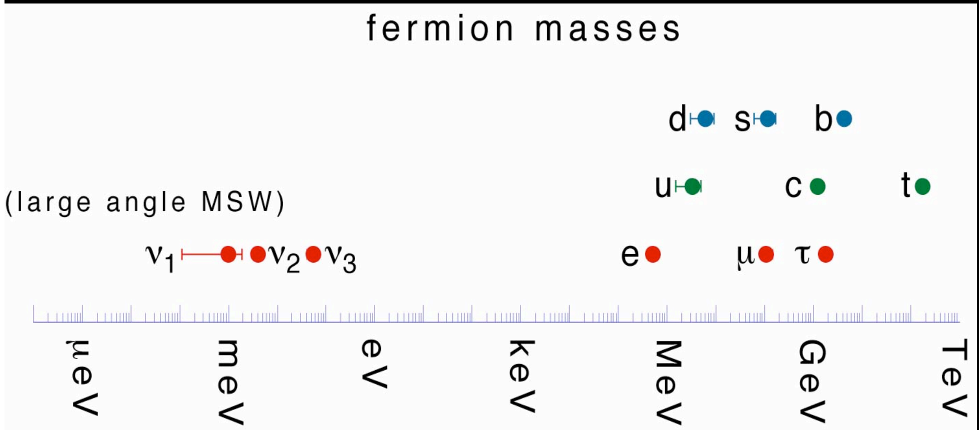
Neutrino Masses and Mixing: Three Generations

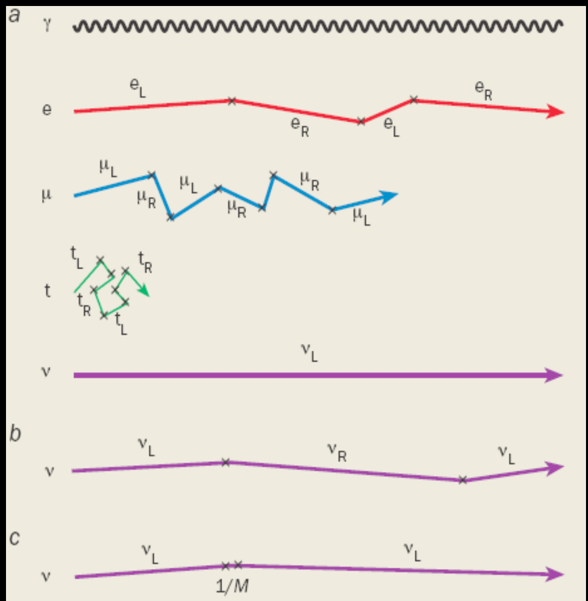


$$\begin{bmatrix}\nu_e & \nu_\mu & \nu_\tau\end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{bmatrix}\begin{bmatrix}\nu_1 \\ \nu_2 \\ \nu_3\end{bmatrix}$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \mathrm{diag}(e^{i\alpha}, e^{i\beta}, 1)$$

Why so fuss about neutrino mass ?





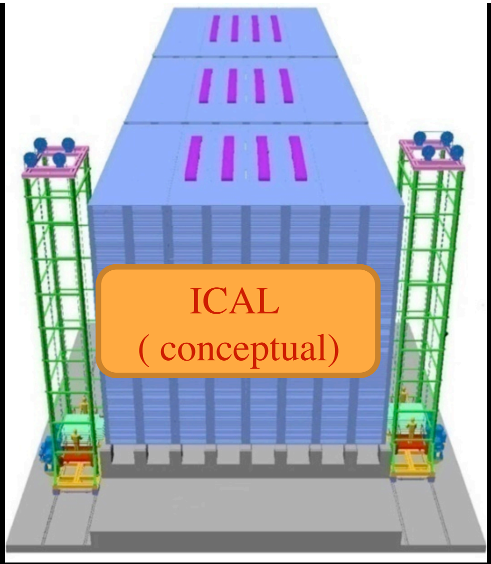
- *Space is filled with Higgs field*
- *Massless particles traveling with speed of light scatter off the Higgs field.*
- *These collisions slow them down and flip their helicity => mass.*

•In the Standard Model there is no right-handed neutrino ⇒ neutrinos must be massless

•Neutrinos have mass ⇒ physics beyond the Standard Model

Goals for future neutrino experiments

- *Determining the masses of neutrinos – absolute mass scale.*
- *Mass ordering – sign of Δm^2_{32}*
- *Are neutrinos majorana particle ?*
- *Precision measurement of neutrino oscillation parameters.*
  Is θ_{23} maximal ?
- *L/E pattern of oscillation.*
- *CP violation in neutrino sector.*
- *Detection of Ultra High Energy neutrinos from astrophysical sources.*
- *Maping the earth core using geoneutrinos.*



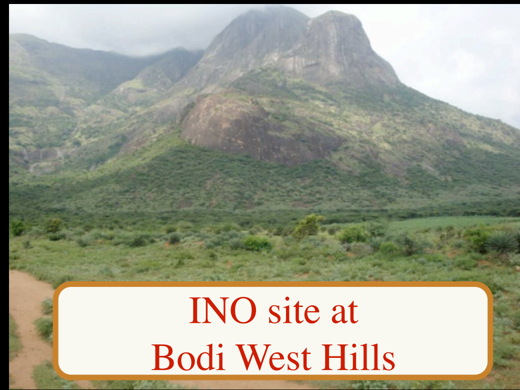
ICAL (conceptual)

RPC Test stand at TIFR

Prototype ICAL at VECC

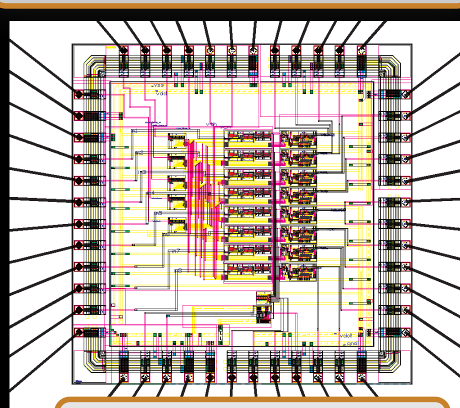
India-Based Neutrino Observatory (INO)

Ahmedabad: Physical Research Laboratory (PRL); Aligarh: Aligarh Muslim University (AMU); Allahabad: Harish Chandra Research Institute (HRI); Calicut : University of Calicut; Chandigarh: Panjab University (PU); Chennai : Indian Institute of Technology, Madras (IITM); Chennai : The Institute of Mathematical Sciences (IMSc) ; Delhi : Delhi University (DU); Guwahati : Indian Institute of Technology (IITG); Hawaii (USA) : University of Hawaii (UHW); Indore: Indian Institute of Technology (IITInd); Jammu : University of Jammu (JU) ; Kalpakkam : Indira Gandhi Center for Atomic Research (IGCAR); Kolkata : Ramakrishna Mission Vivekananda University (RMVU); Kolkata : Saha Institute of Nuclear Physics (SINP); Kolkata : University of Calcutta (CU) ; Kolkata : Variable Energy Cyclotron Centre (VECC) ; Lucknow : Lucknow University (LU); Madurai : American College; Mumbai : Bhabha Atomic Research Centre (BARC) ; Mumbai : Indian Institute of Technology, Bombay (IITB) ; Mumbai : Tata Institute of Fundamental Research (TIFR); Mysore : University of Mysore (MU) ; Sambalpur : Sambalpur University; Srinagar : University of Kashmir; Varanasi : Banaras Hindu University (BHU)



INO site at Bodi West Hills

2mX2m RPC Test Stand at TIFR

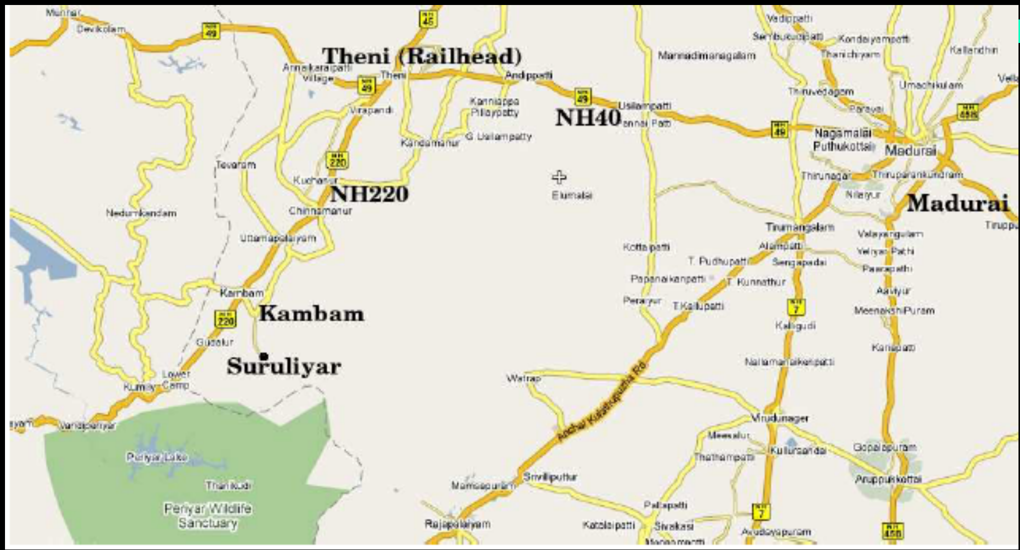


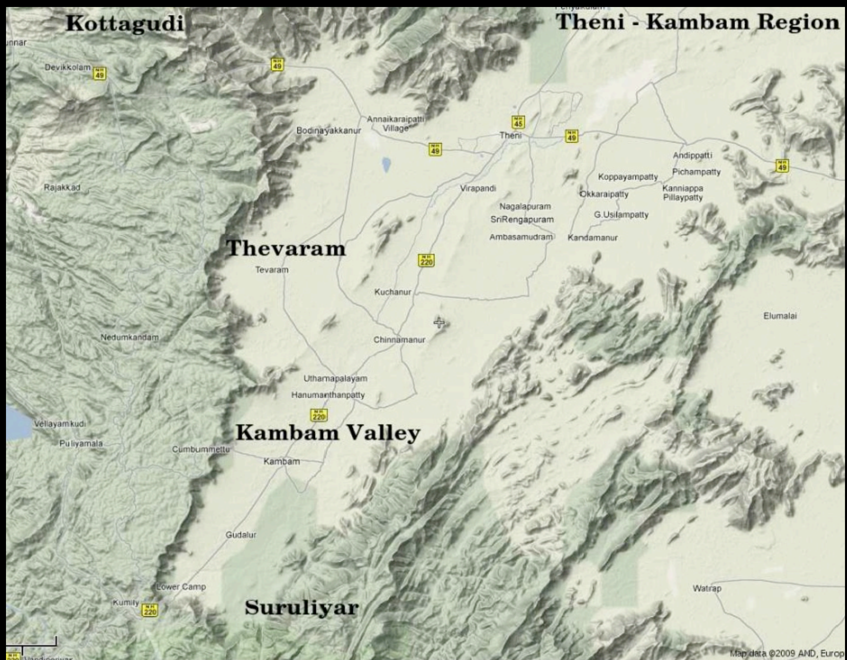
ASIC for RPC designed at BARC

INO : Salient Features

- *Underground laboratory with ~1 km all-round rock cover accessed through a 1.9 km long tunnel. A large and several smaller caverns to facilitate many experimental programs.*
- *Frontline neutrino issues e.g., mass parameters and other properties, will be explored using atmospheric neutrinos in a manner complementary to ongoing efforts worldwide.*
- *The ICAL detector, with its charge identification ability, will be able to address questions about the neutrino mixing parameter space.*
- *Will support several other experiments when operational. Neutrino-less Double Beta Decay and Dark Matter Search experiments foreseen in the immediate future.*
- *Involvement of Universities in a big way for carrying out large basic science projects- healthy development of University-Research lab partnership.*

INO site : Bodi West Hills

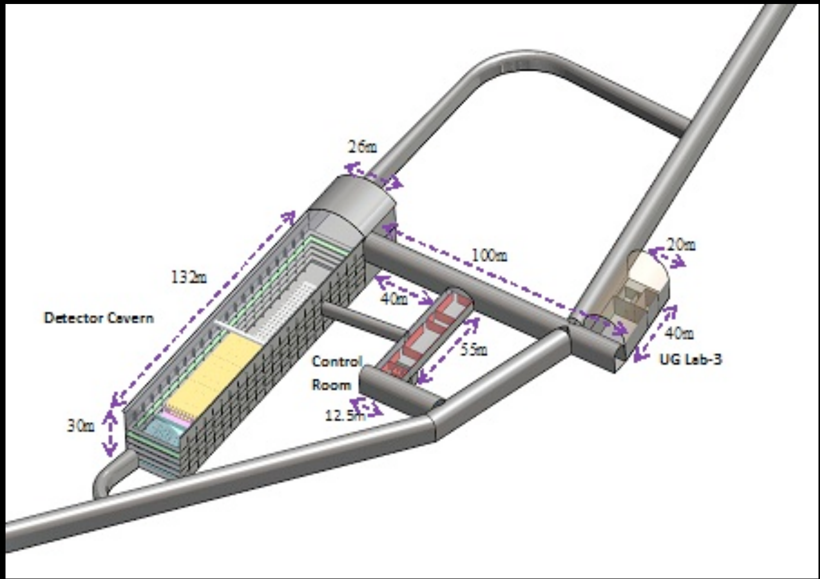


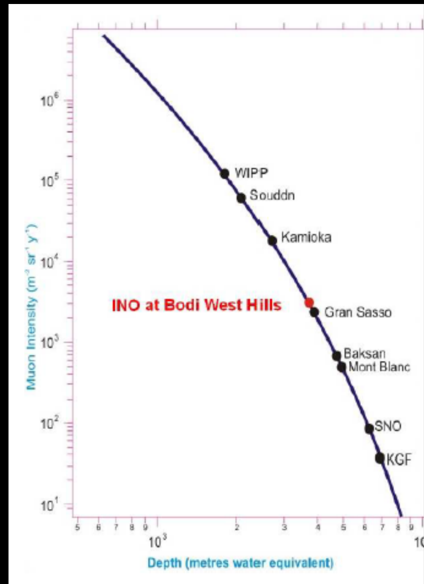


Contact us:

- *9^0 58' N, 77^0 16' E*
- *Pottipuram Village*
- *Theni District*
- *Tamil Nadu State*

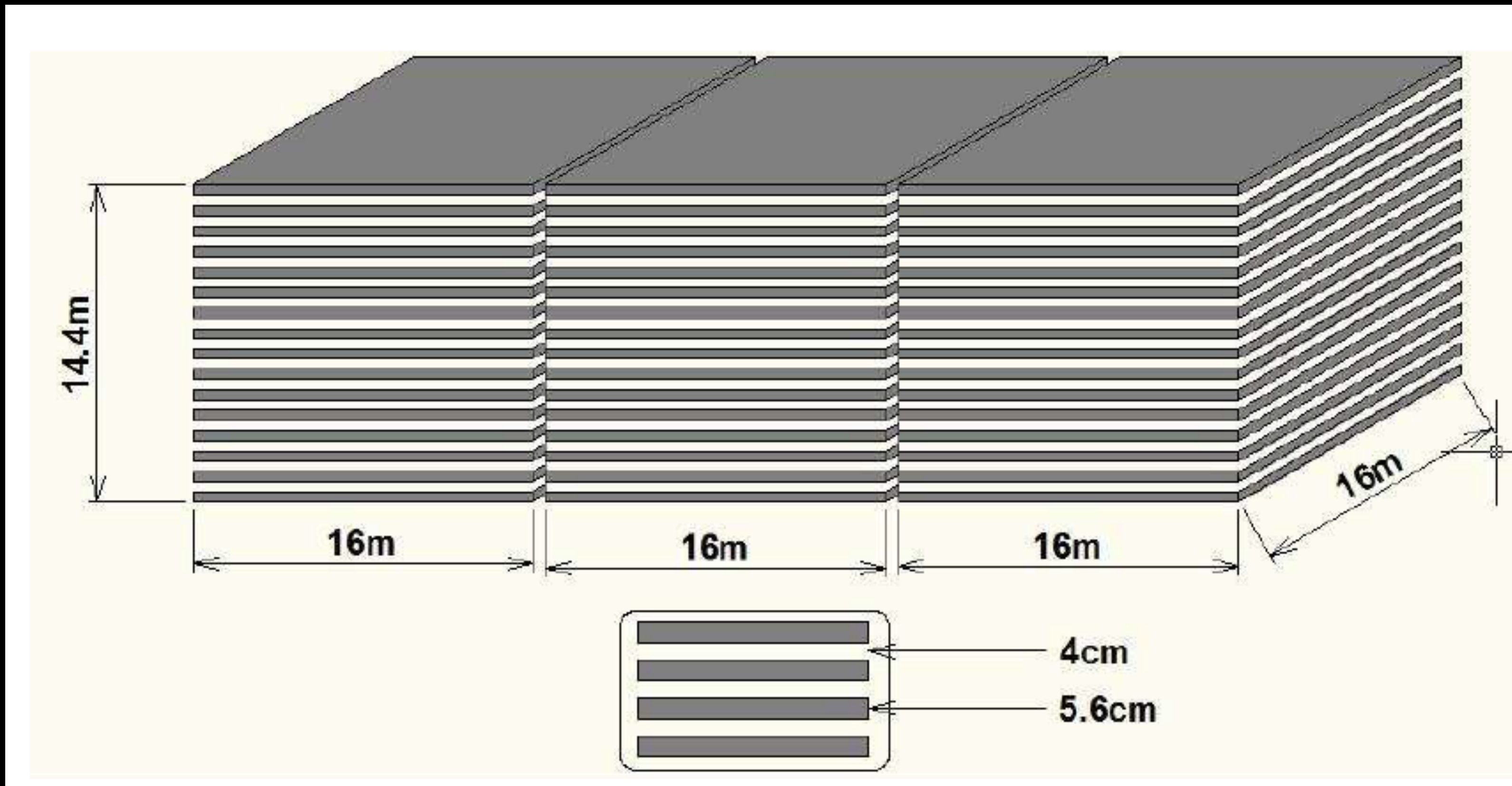
Underground Laboratory Layout



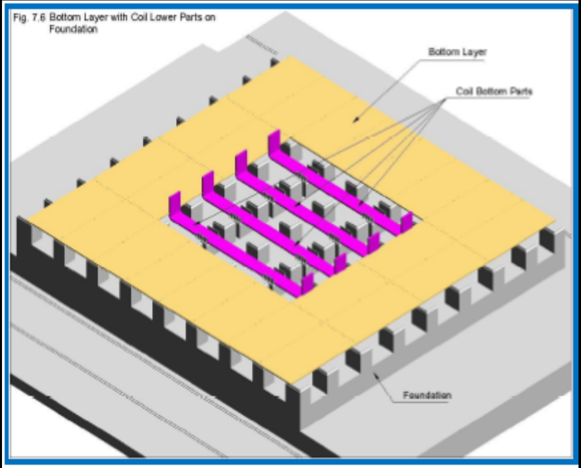


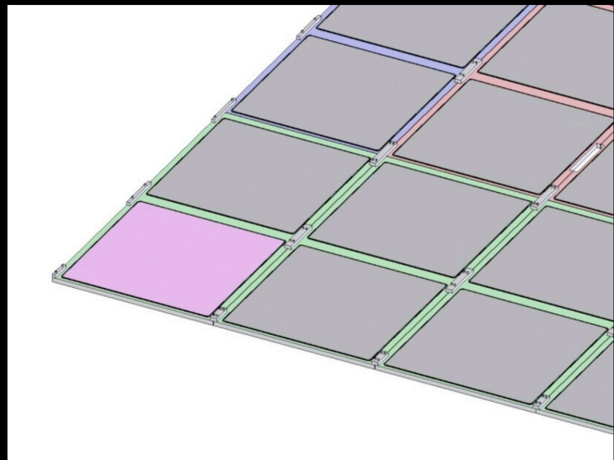
- *The cavern is set under 1589 m peak with vertical rock cover of 1289 m.*
- *Accessible through a 2 km long tunnel*
- *Cavern -1 will host 50 kt ICAL detector. Space available for additional 50 kt.*
- *Cavern-2 & 3 available for other experiments.*

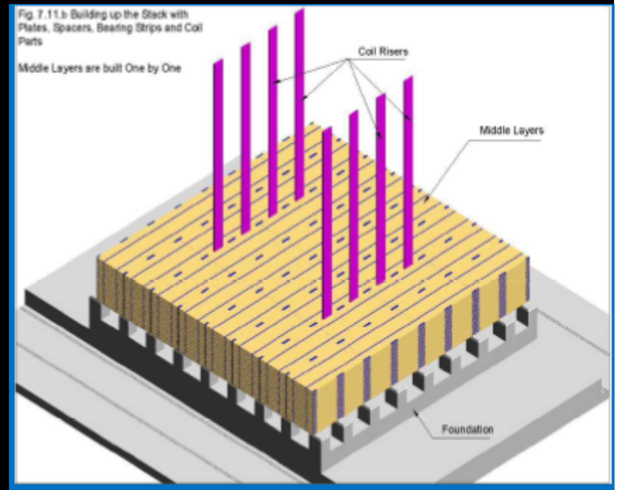
INO-ICAL Detector

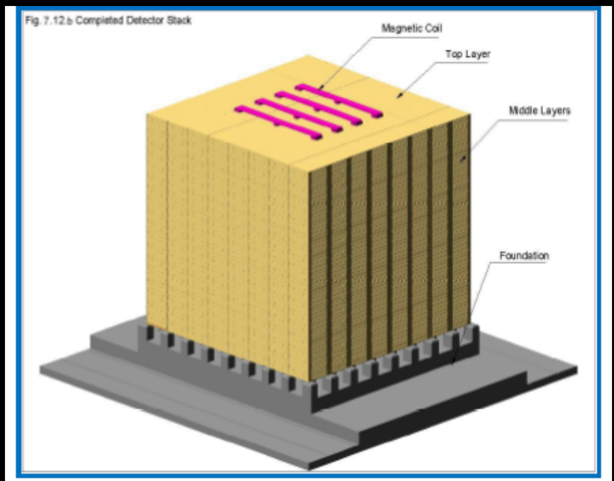


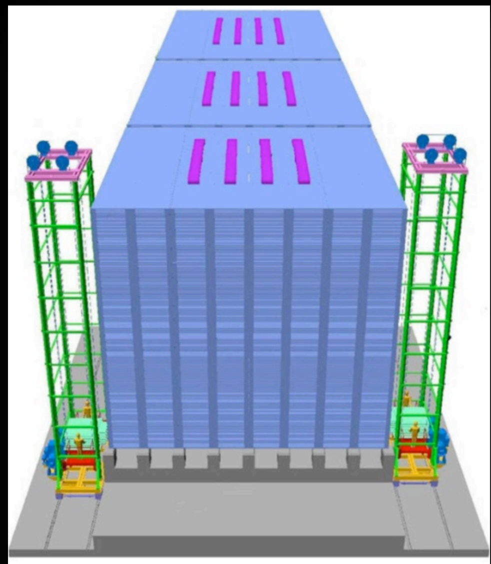
Construction of the ICAL detector

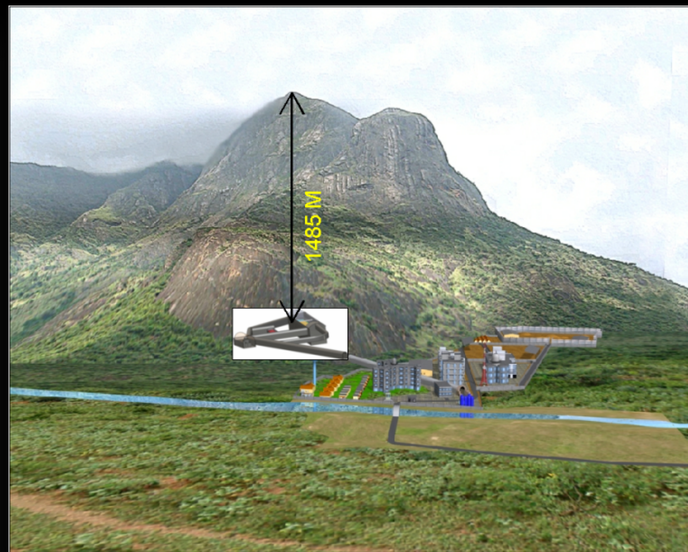










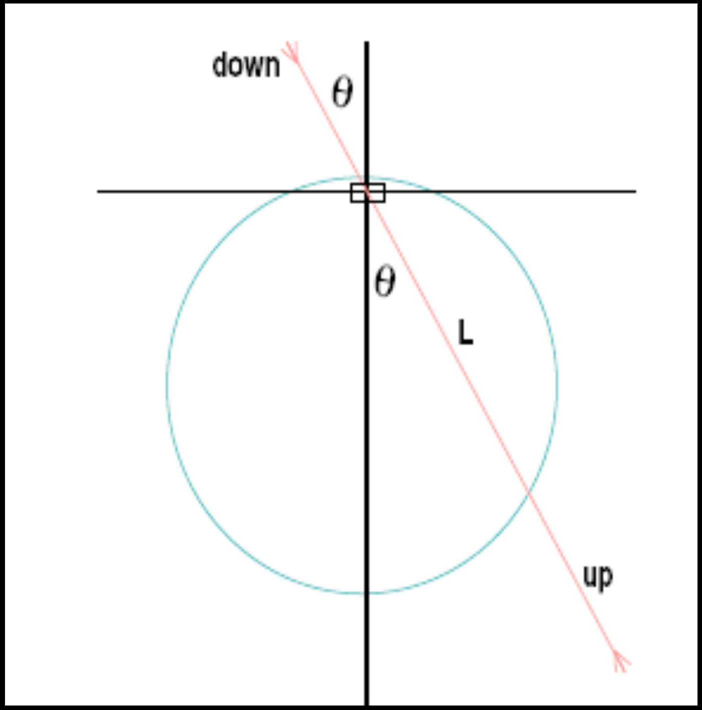


Physics using atmospheric neutrinos during Phase I

- *Reconfirm atmospheric neutrino oscillation*
- *Improved measurement of oscillation parameters*
- *Search for potential matter effect in neutrino oscillation*
- *Determining the sign of Δm^2_{23} using matter effect*
- *Measuring deviation from maximal mixing for θ_{23}*
- *Probing CP and CPT violation*
- *Constraining long range leptonic forces*
- *Ultra high energy neutrinos and muons*

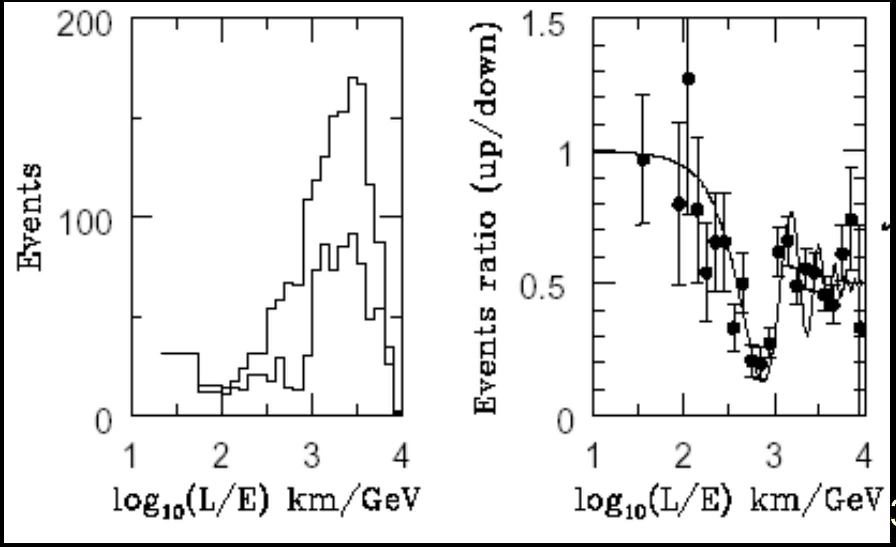
Disappearance of ν_μ vs. L/E

The disappearance probability can be measured with a single detector and two equal sources:

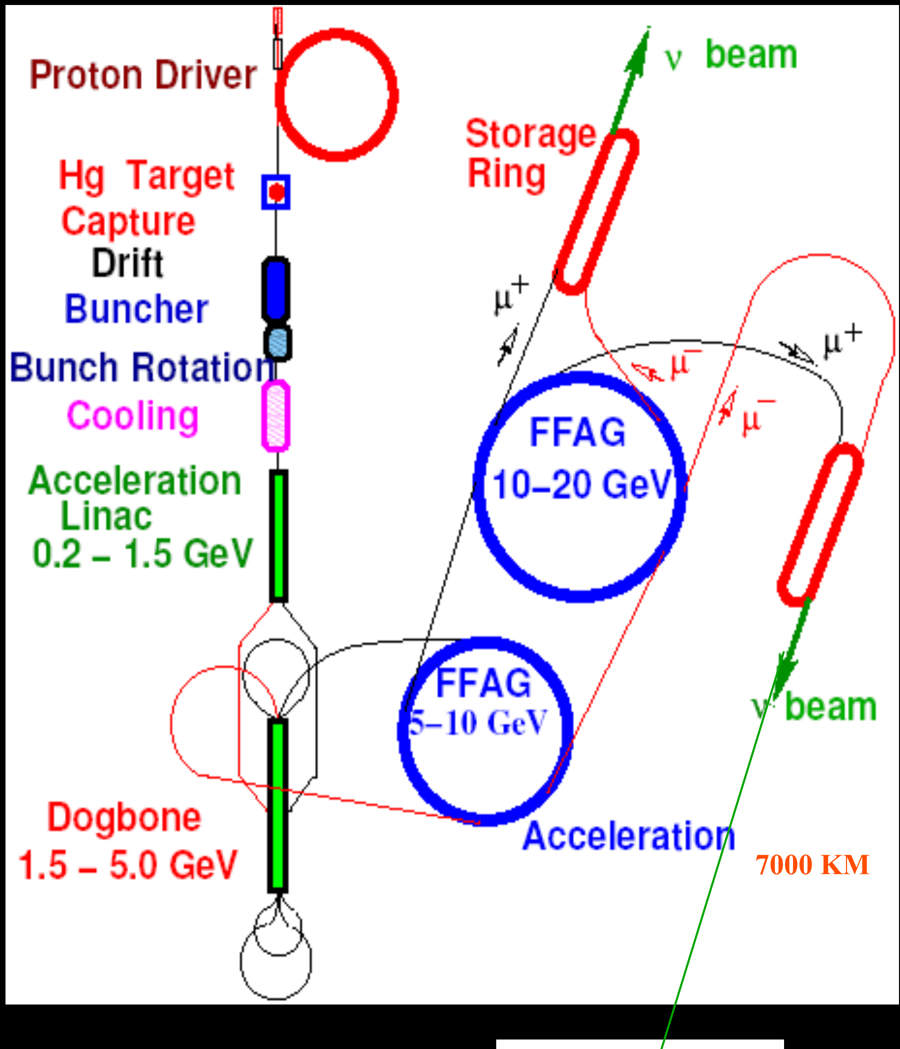


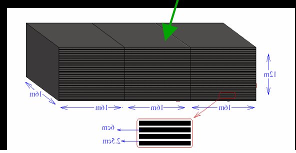
$$\frac{N_{up}(L/E)}{N_{down}(L'/E)} = P(\nu_\mu \rightarrow \nu_\mu; L/E)$$

$$= 1 - \sin^2(2\Theta)\,\sin^2(1.27\,\Delta m^2\,L/E)$$

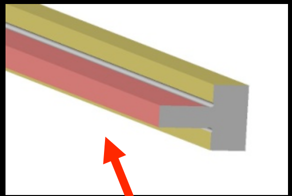


Neutrino Factory





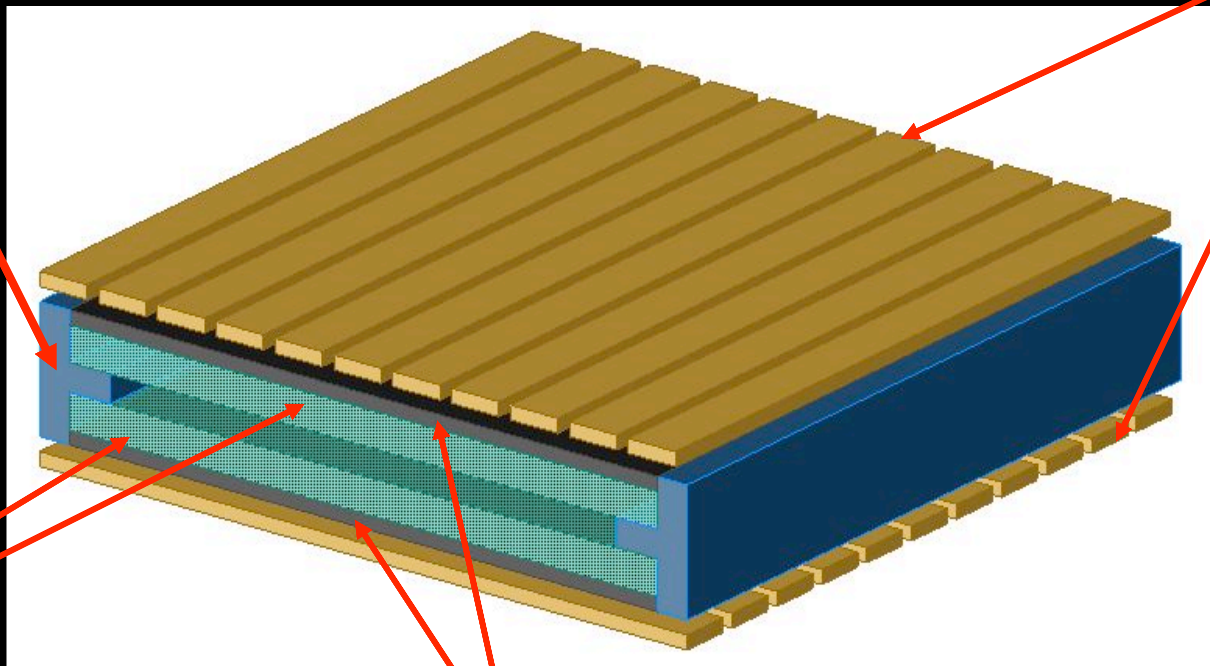
Construction of RPC



Two 2 mm thick float Glass
Separated by 2 mm spacer

Pickup strips

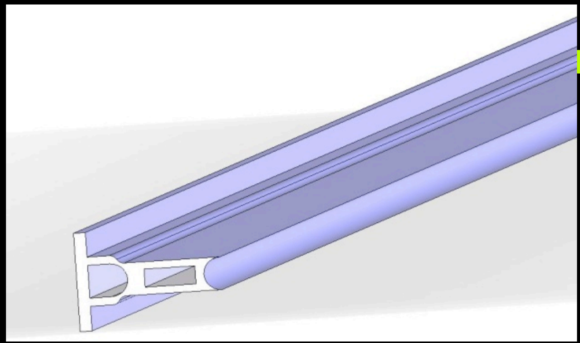
2 mm thick spacer

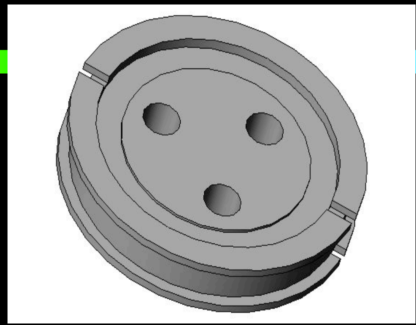


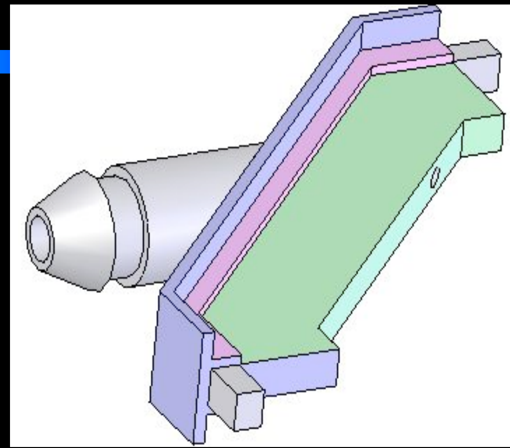
Glass plates

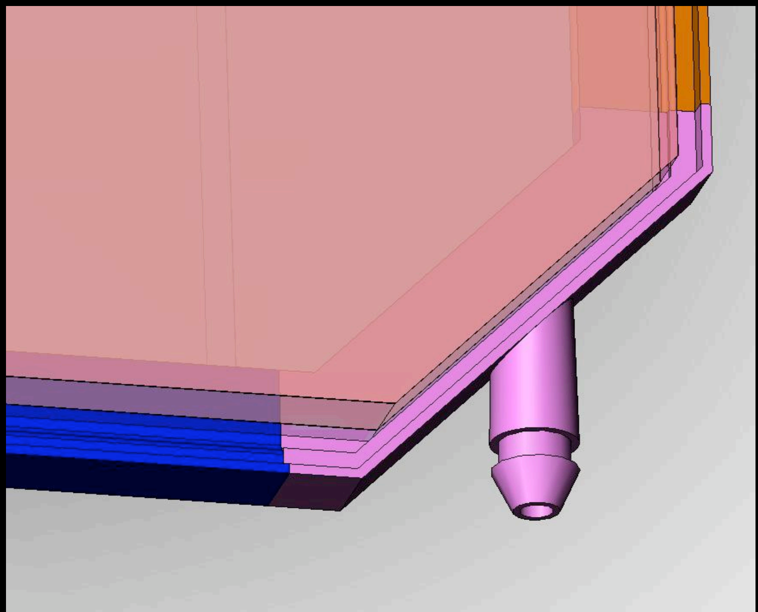
Resistive coating on the outer surfaces of glass

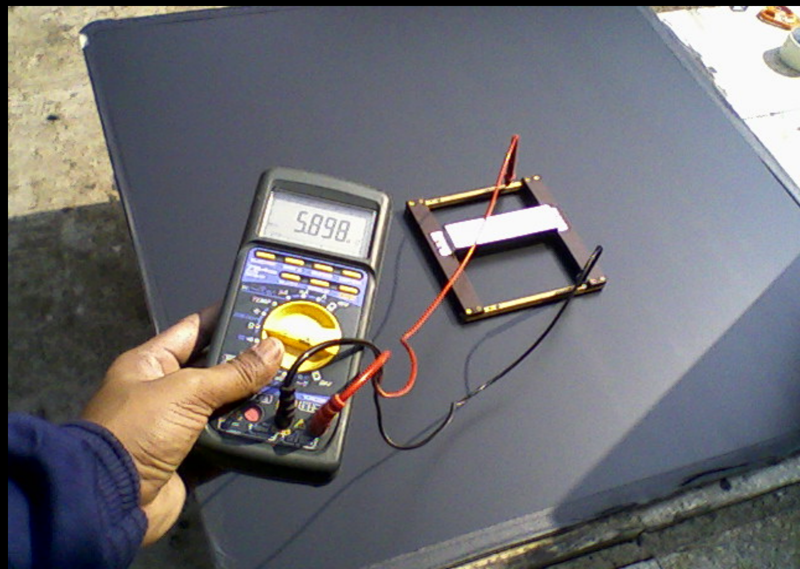
RPC building blocks











A journey through RPC road

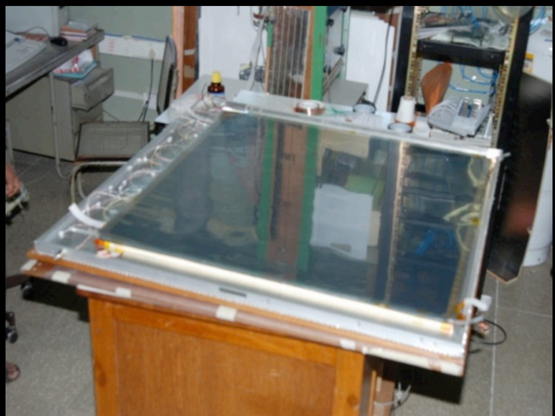
200 cm x 200 cm

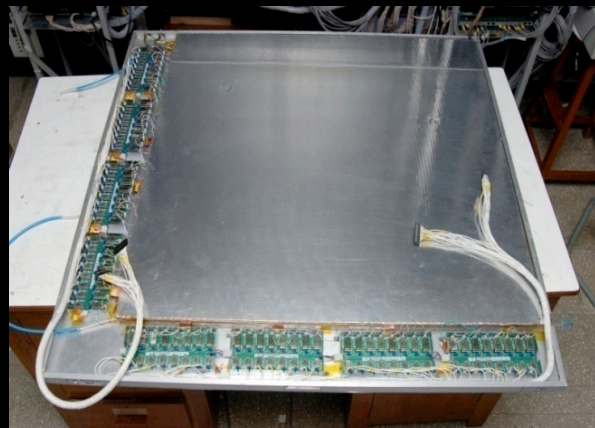
30 cm x 30 cm

10 cm x 30 cm

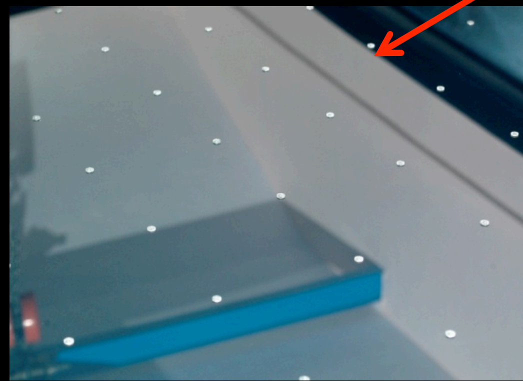
100 cm x 100 cm

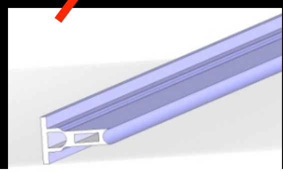
Fabrication of 1m x 1m RPCs





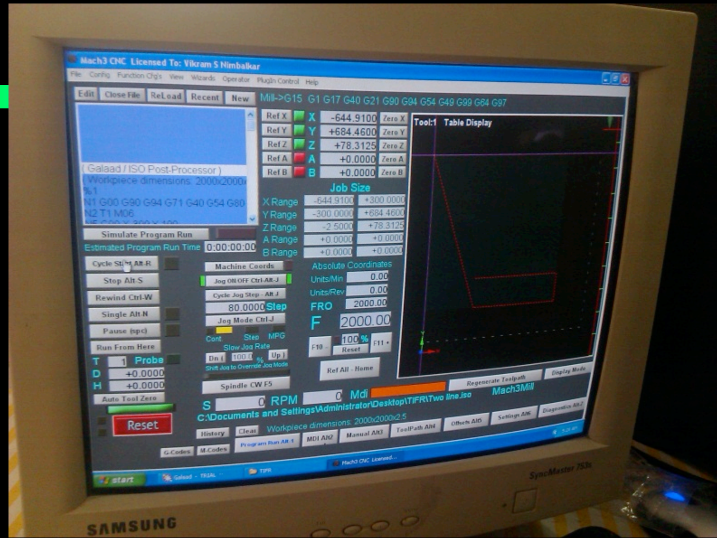
Final RPC Frontier - Making of 2m x 2m RPCs



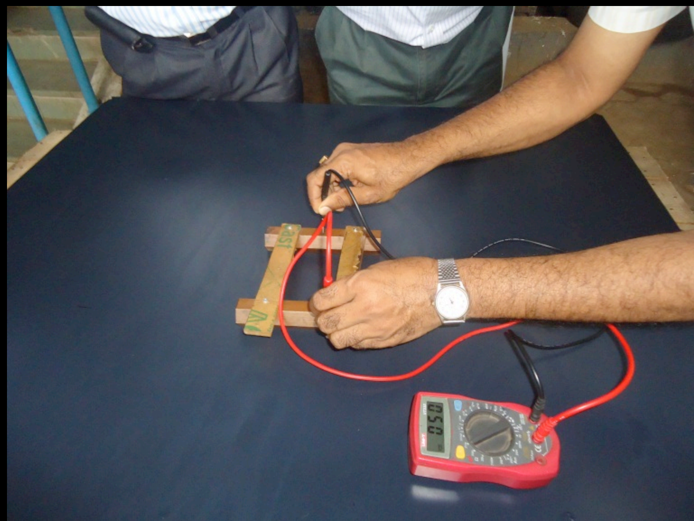


RPC fabrication at Asahi Float Glass Co.

Tools for RPC mass production

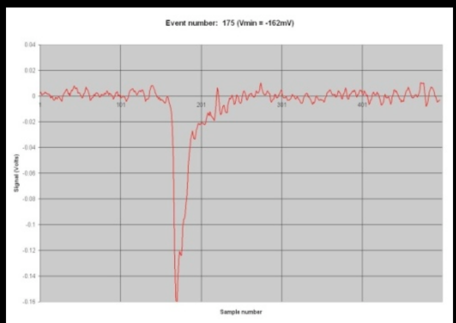


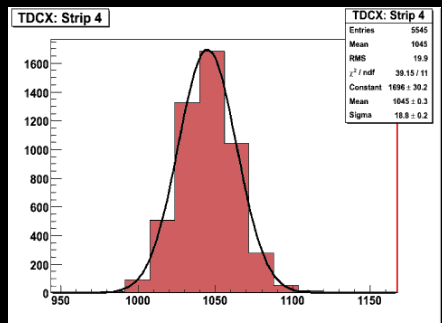
Automatic glue & button dispensing machine

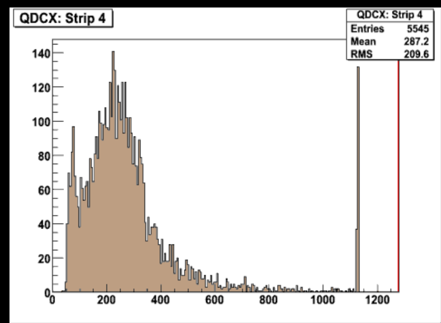


Automatic graphite coating machine

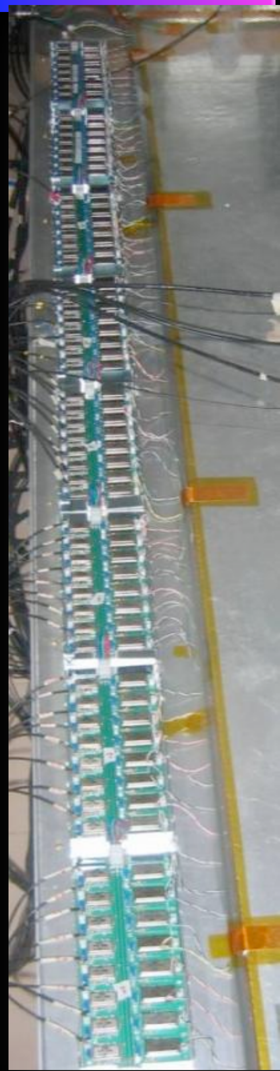
Prototype RPC Stack at TIFR tracking Muons



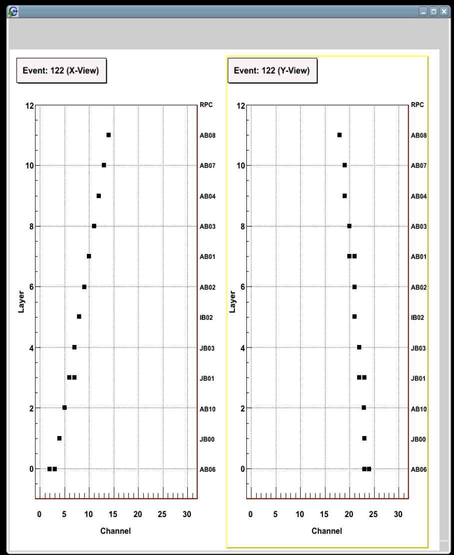


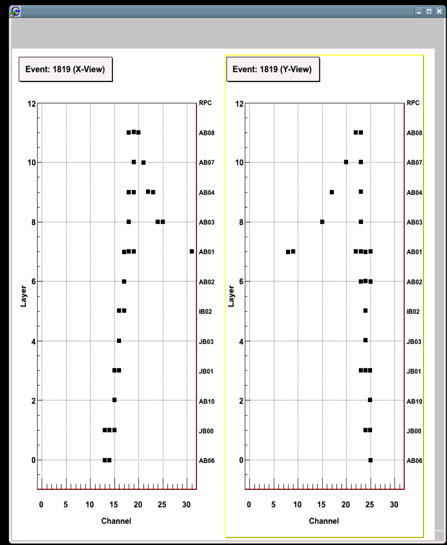


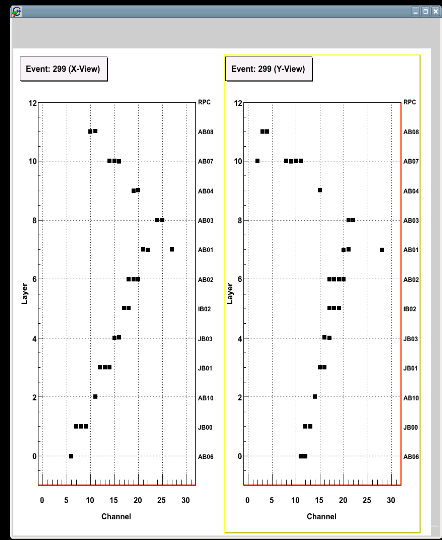
2m x 2m glass RPC test stand

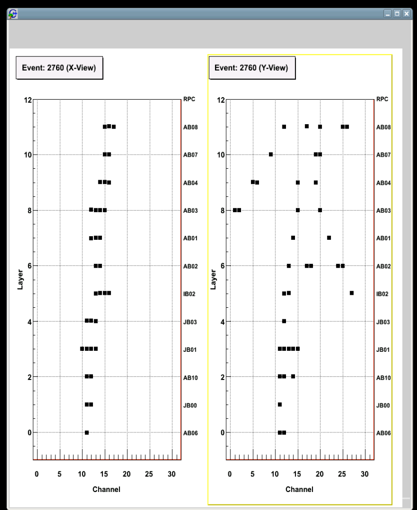


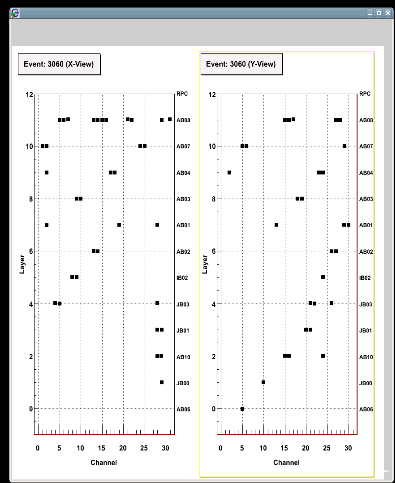
Some interesting cosmic ray tracks

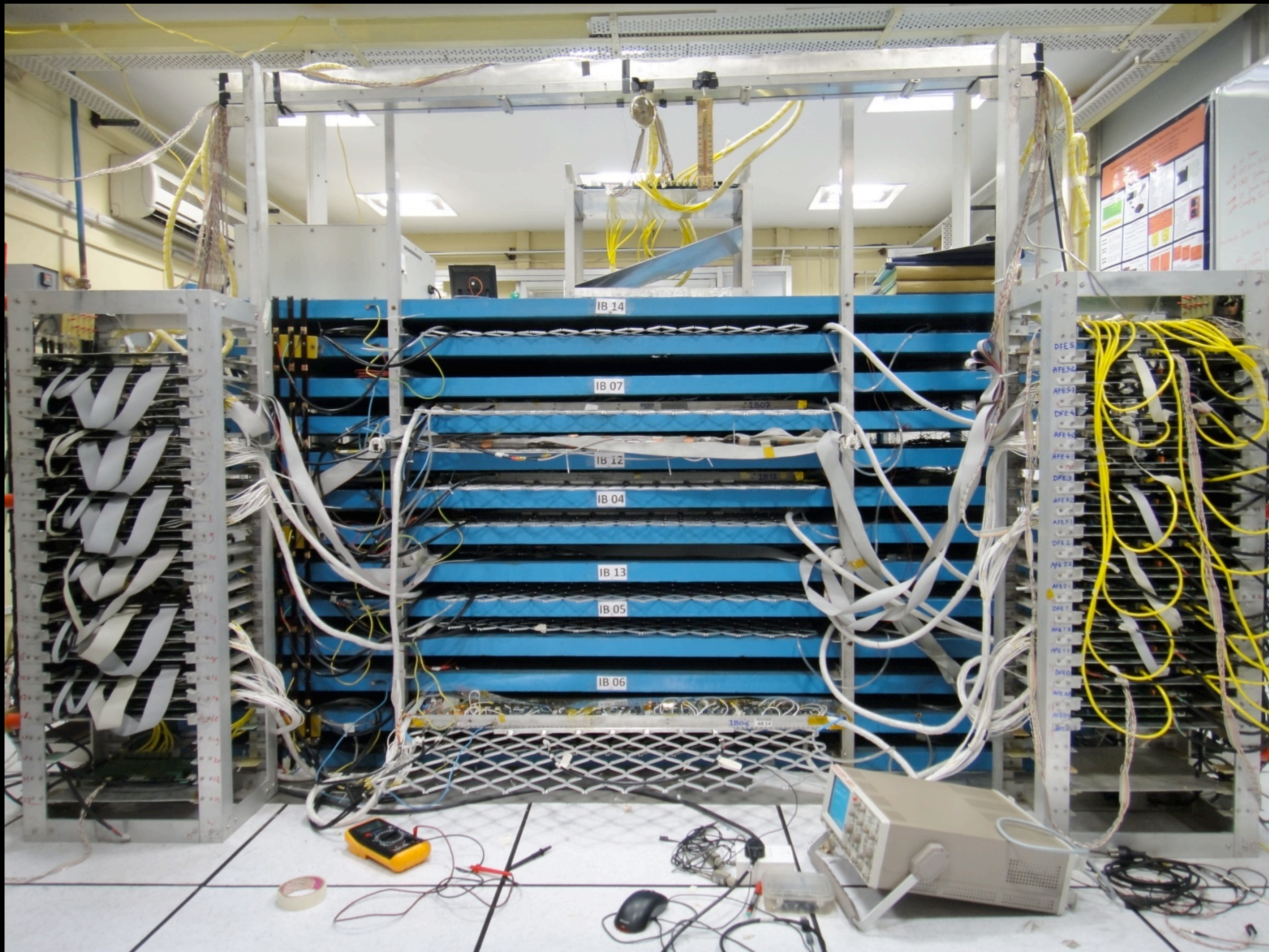




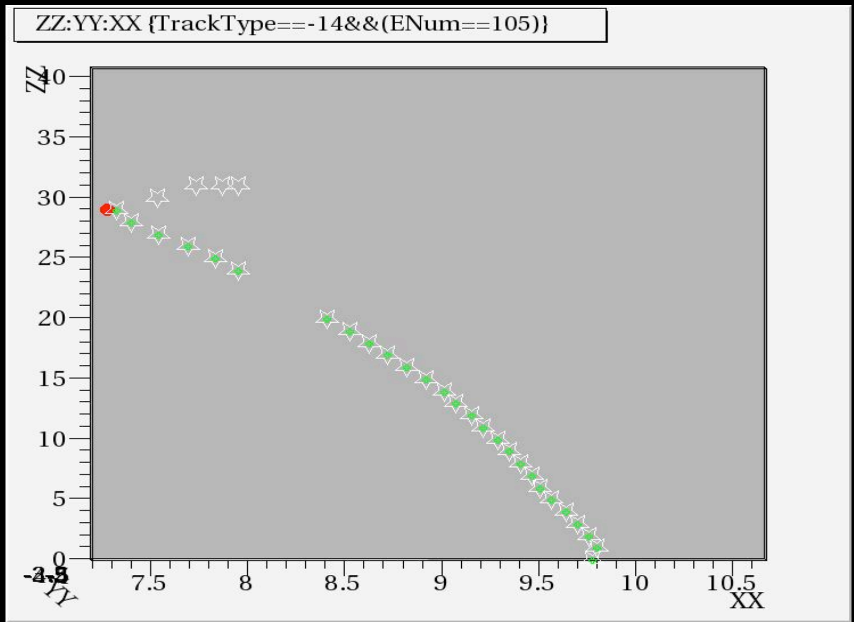


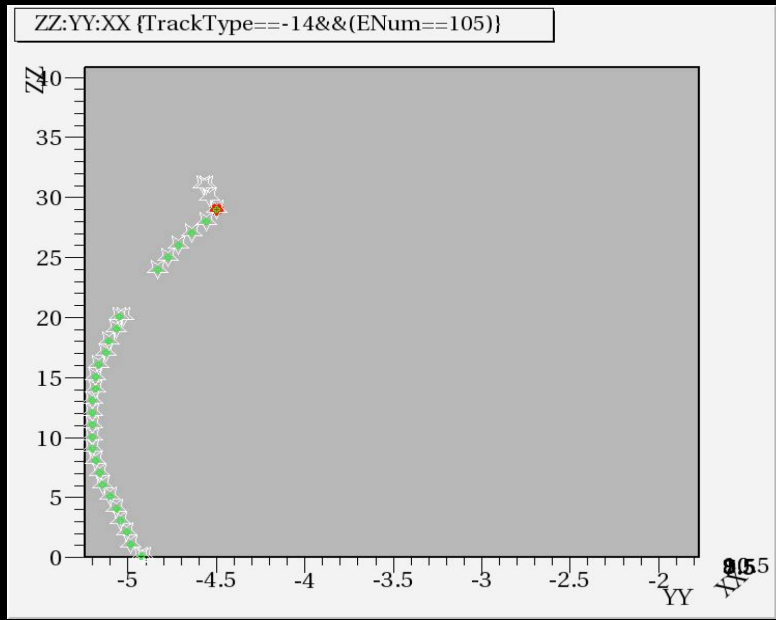




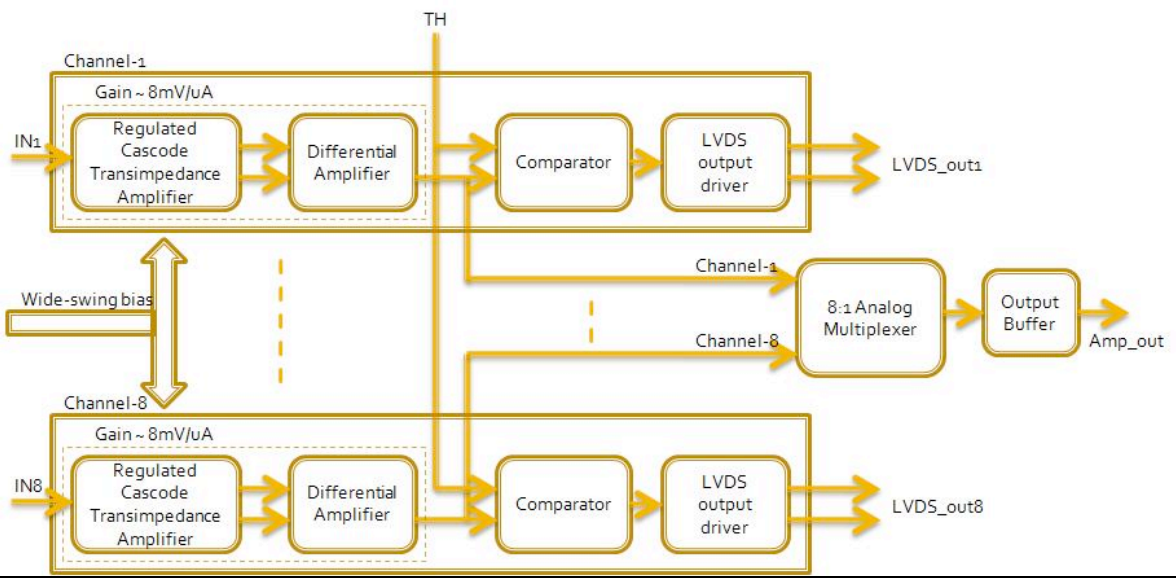

IB 14
IB 07
IB 12
IB 04
IB 13
IB 05
IB 06

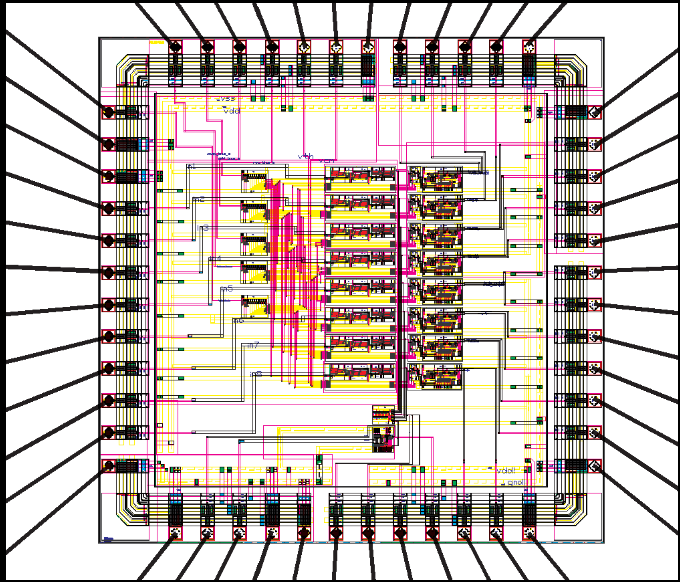
Simulated Neutrino events in INO-ICAL Detector

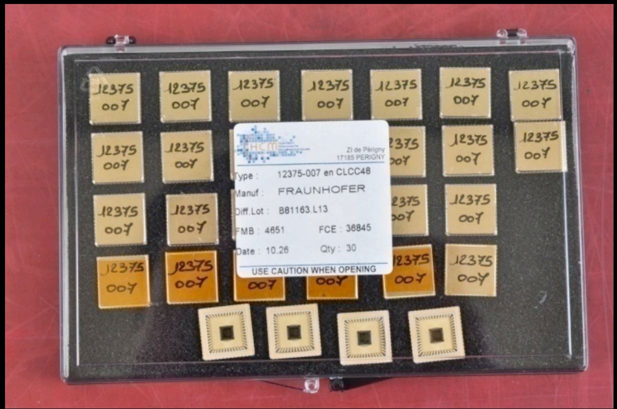


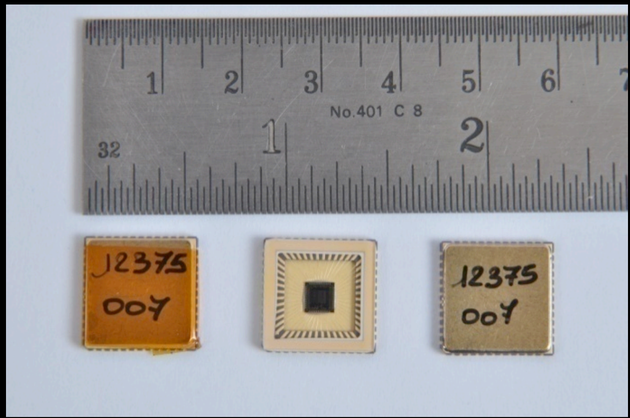


ICAL Front End Electronics chip developed at BARC Electronics Division









Where are the scientists ?

INO Training School:

- *We have already started INO graduate training program from August 2008.*
- *Affiliated to HBNI.*
- *At present INO students are being trained for one year at TIFR, Mumbai in both experimental techniques and theory.*
- *Being attached to Ph.D. guides at various collaborating institutions for a Ph. D. degree after completion of coursework*
- *Many Short/long term visits to RPC labs (Mumbai & Kolkata) of students and faculties from Universities in last several years.*

Why India should be interested in a project like INO ?

- ***Excitement of carrying out front ranking research in the exciting area of neutrino physics.***
- ***Will address a key question in neutrino physics- Neutrino mass ordering.***
- ***Help us to pick up the correct theory beyond Standard Model of particle Physics.***
- ***Will learn how matter behaved at extremely high energies existed in the early stage of our universe.***
- ***Will develop various cutting edge technologies for developing state of the art particle detectors.***
  - ***Massive 50 kton magnet***
  - ***Sophisticated state of the art electronics***
  - ***Online monitoring and Data Acquisition System***
- ***Science students across the country will have the opportunity to participate in building each of these components from scratch . Many are already doing it.***
- ***It will create an ambiance of doing things with our own hands. A culture that is lacking in India***

Collaborative Science Project

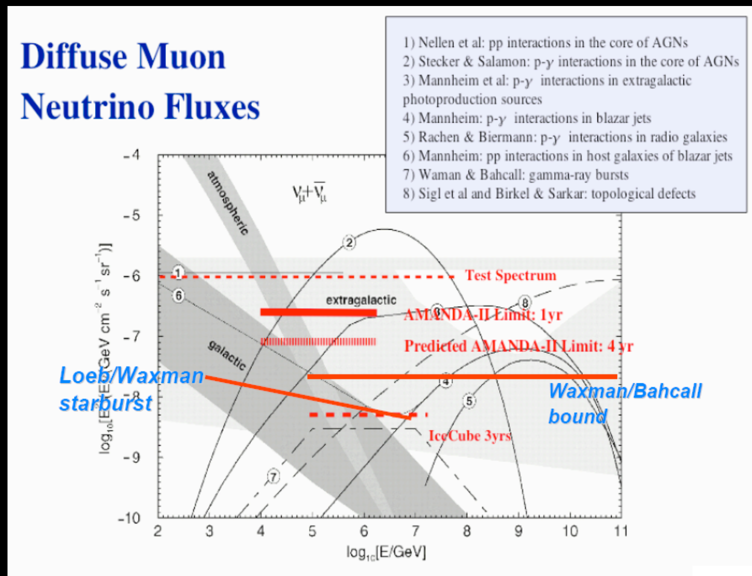
- *No single institute in India has the ability or resources of doing it alone.*
- *Already 25 research institutes, universities and IITs have joined hands to build INO laboratory and ICAL detector.*
  - *Some developing detectors.*
  - *Some electronics*
  - *Some working on various engineering aspects.*
  - *Some optimising the detector using computer simulation.*

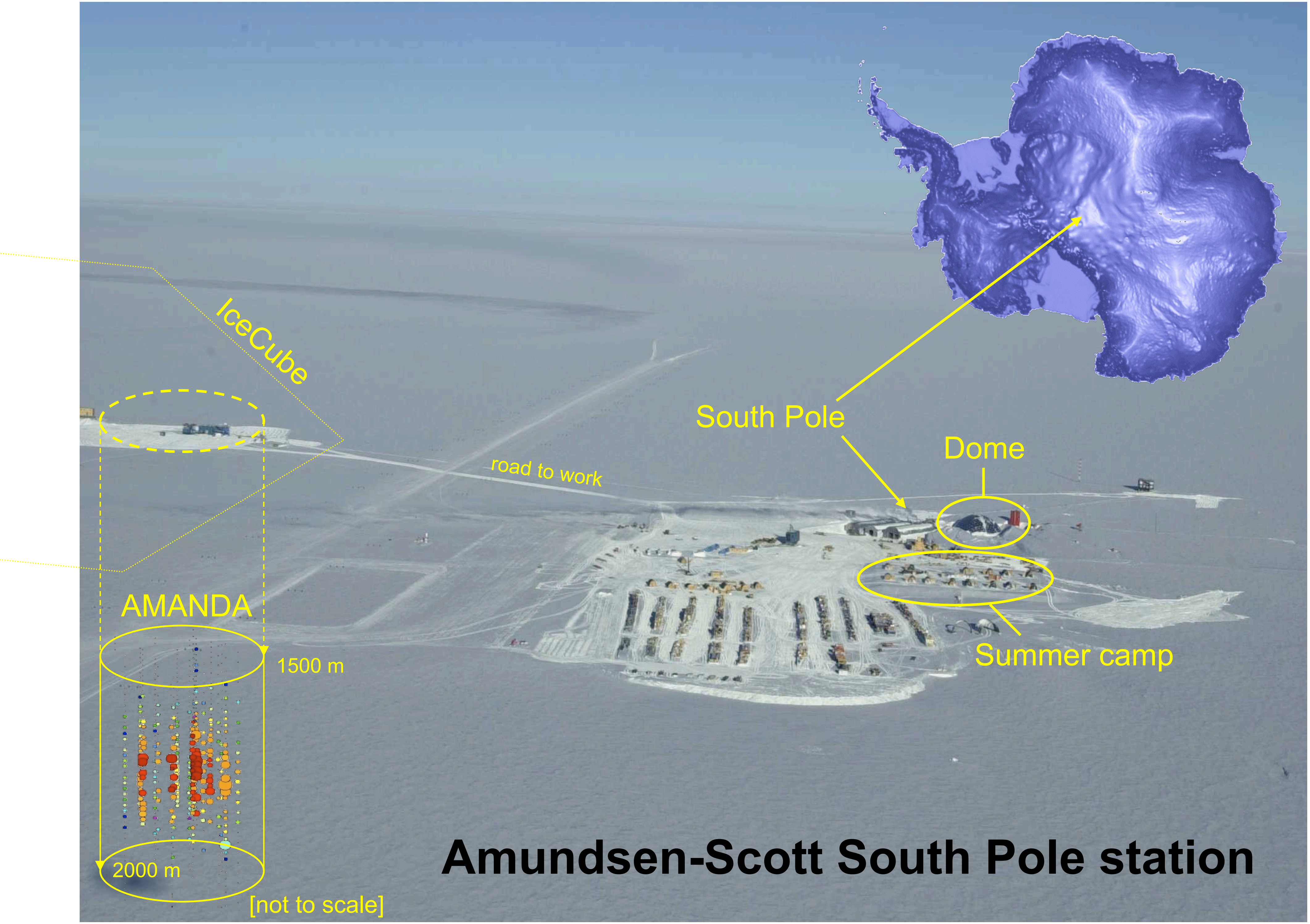
Culture of cooperation and collaboration is another benefit that will emerge from a mega science project like INO.

We do hope when we complete the INO project, we will have a scientifically richer nation.

Neutrino Astrophysics

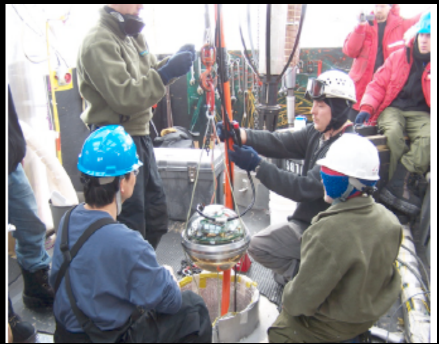
- ***Some big astrophysics questions of our time which neutrino observations can help answer:***
  - ***Cosmic ray acceleration sites***
    - ***TeV gamma-ray sources***
    - ***Gamma-ray bursts***
  - ***"GZK" cutoff***
  - ***Dark matter, Supersymmetry***

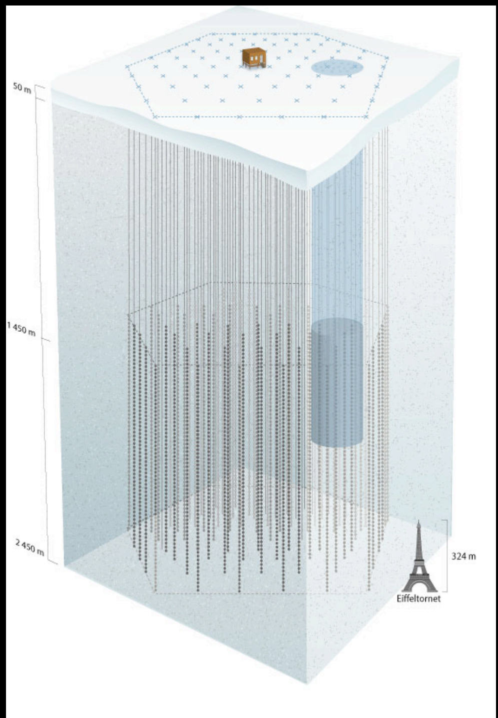


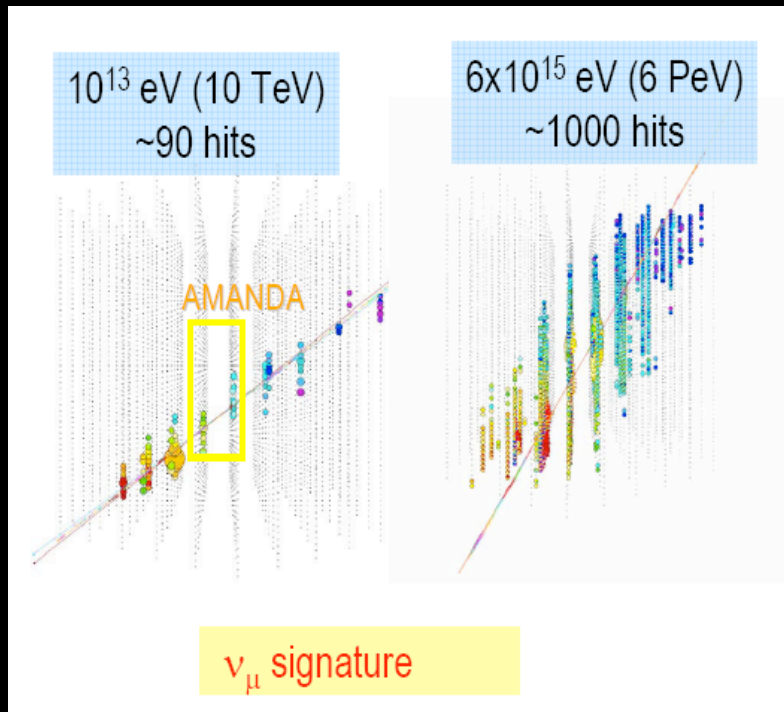


IceCube
South Pole
Dome
road to work
AMANDA
1500 m
Summer camp
2000 m
[not to scale]
Amundsen-Scott South Pole station

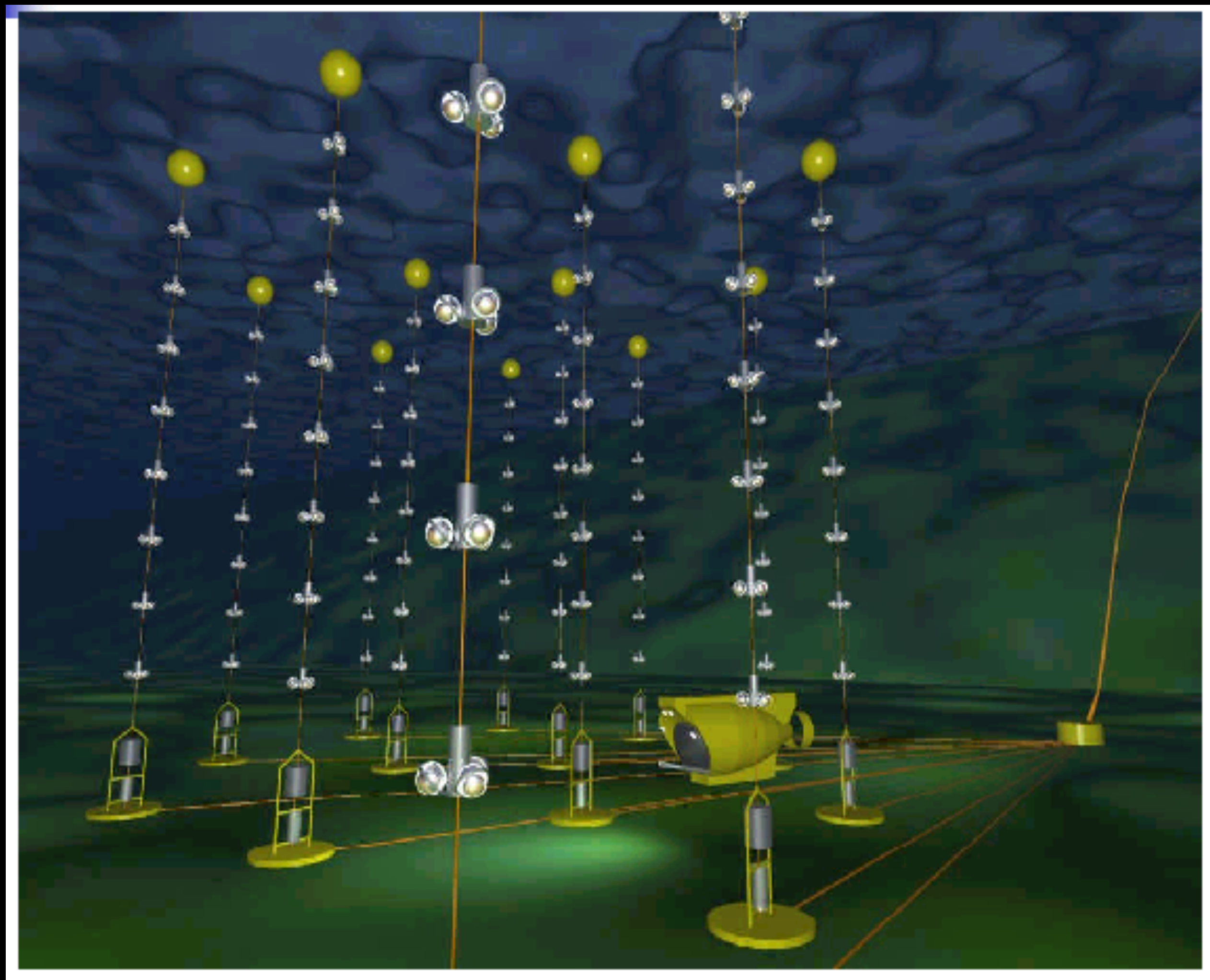
Making of ICECUBE







ANTARES



ANTARES + NEMO + NESTOR -→ KM3NeT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Thank You