Neutrino – A New Window To The Universe

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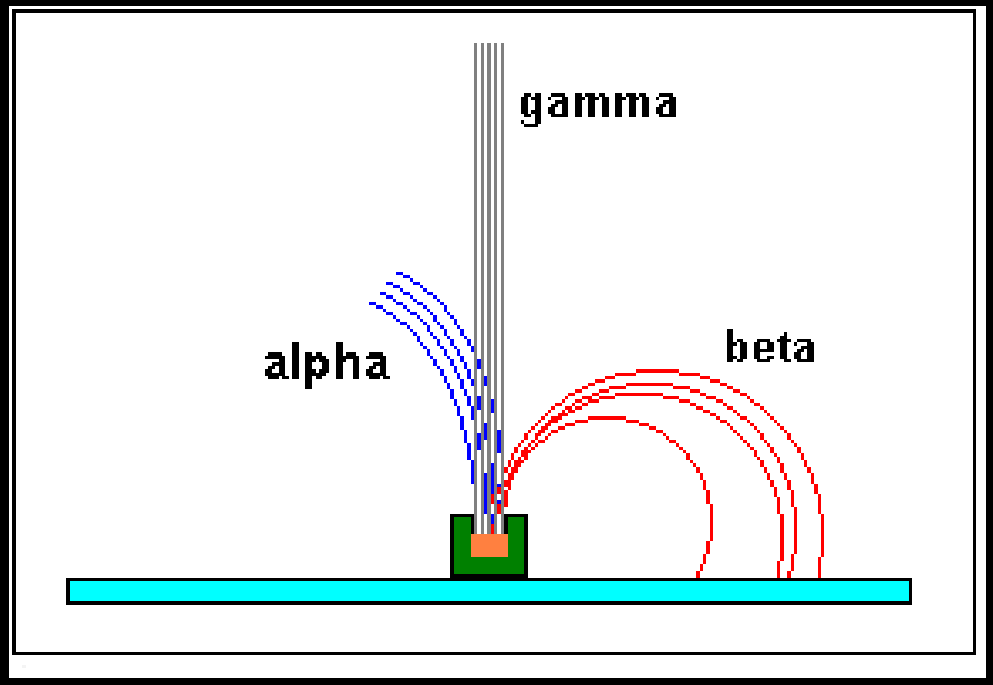
α, β, γ Rays



Puzzle with β-Spectrum

- Three-types of radioactivity: α, β, γ
- Both α, γ discrete spectrum because

$$E_{\alpha,\gamma} = E_i - E_f$$

- But β spectrum continuous

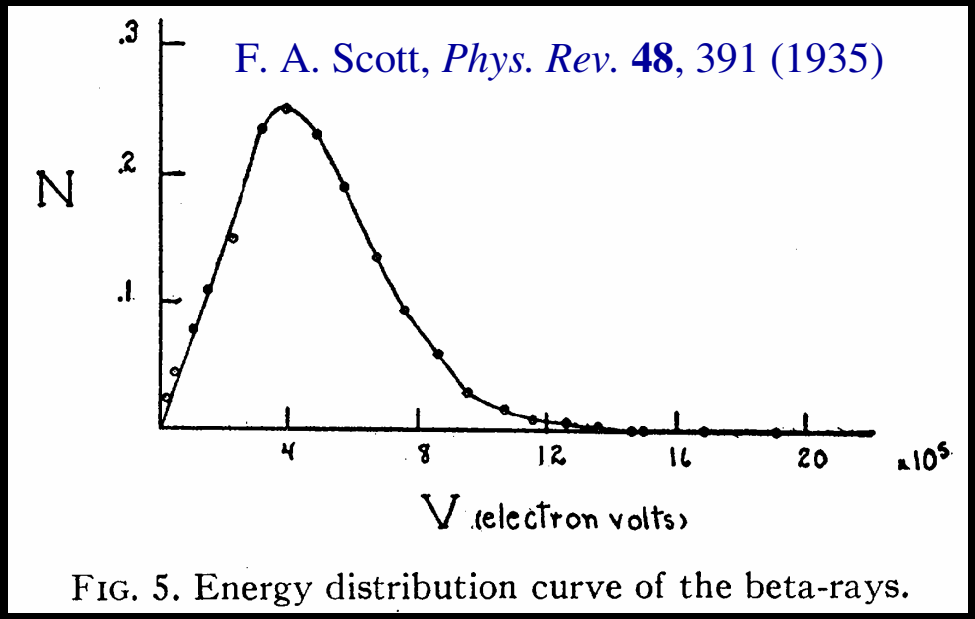
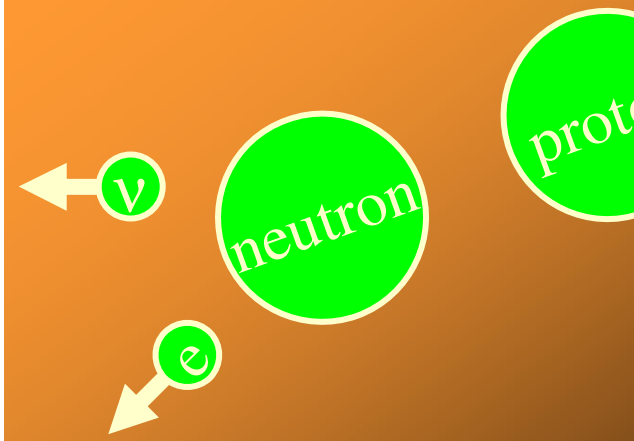


FIG. 5. Energy distribution curve of the beta-rays.

Bohr: *At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β-ray disintegrations*

β decay



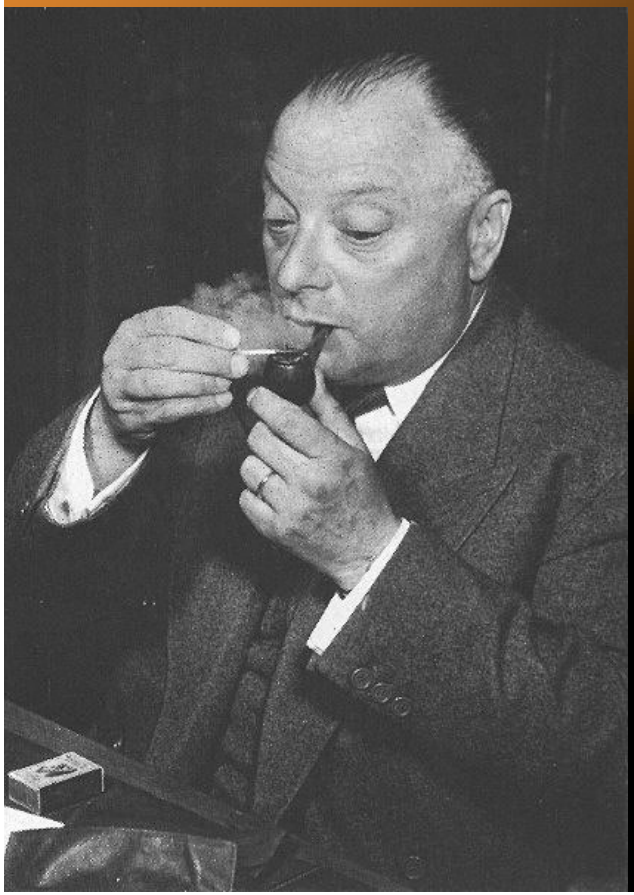
December 4, 1930

Dear radioactive ladies and gentlemen,

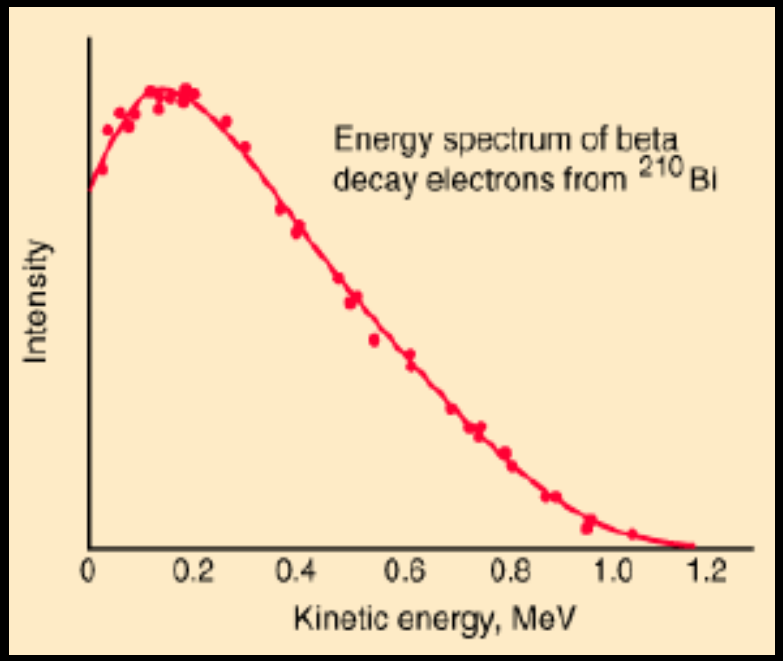
...I have hit upon a 'desperate remedy' to save...the law of conservation of energy. Namely the possibility that there exists in the nuclei electrically neutral particles, that I call neutrons...I agree that my remedy could seem incredible...but only the one who dare can win...

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

Your humble servant
W. Pauli



A Neutral Particle - Desperate remedy from Pauli



Beta Decay of Radioactive nucleus

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

Energy Momentum conservation demands-

$$E_e = \left(\frac{m_n^{\,2} - m_p^{\,2} + m_e^{\,2}}{2m_n} \right) c^2$$

- **Pauli suggested the existence of a new particle.**

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

- **Discovered by Reines and Cowen in 1956**

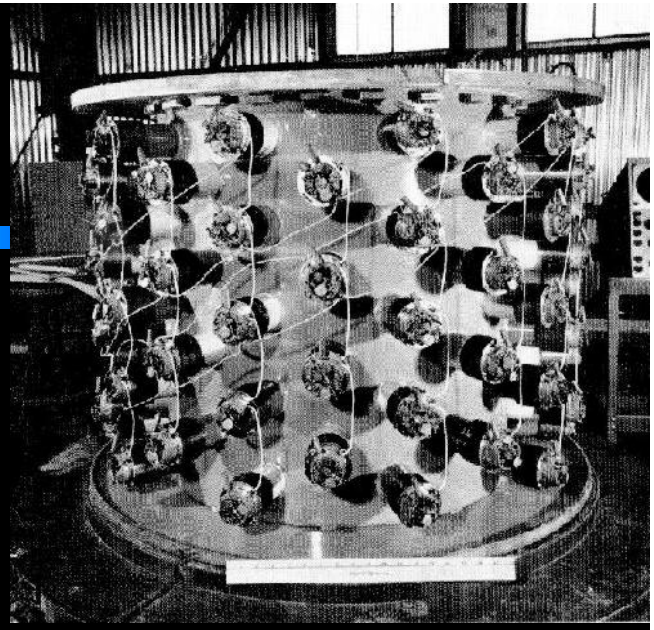
$$\bar{\nu} + p^{+} \rightarrow n + e^{+}$$

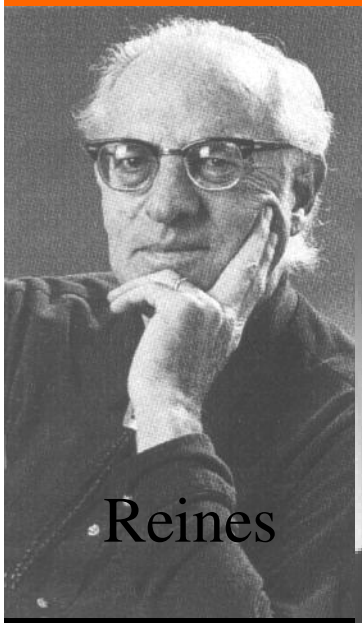
Project Poltergeist 1956

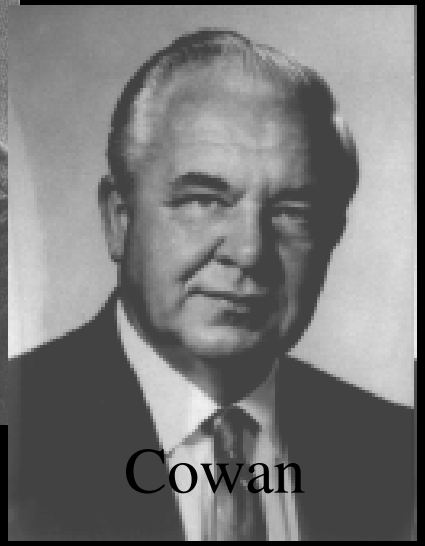
$$\nu + p^+ \rightarrow n^o + e^+$$

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

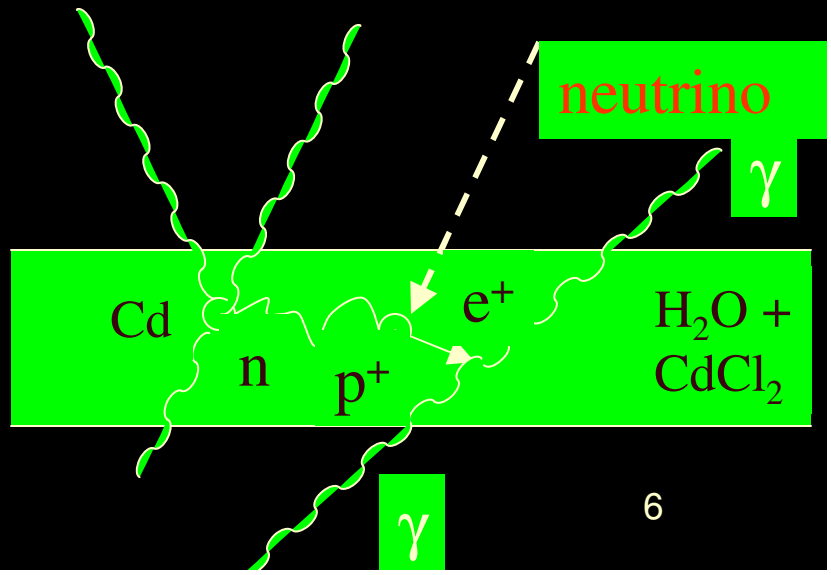
$$n^o + \mathrm{Cd} \rightarrow (\text{several})\,\gamma$$





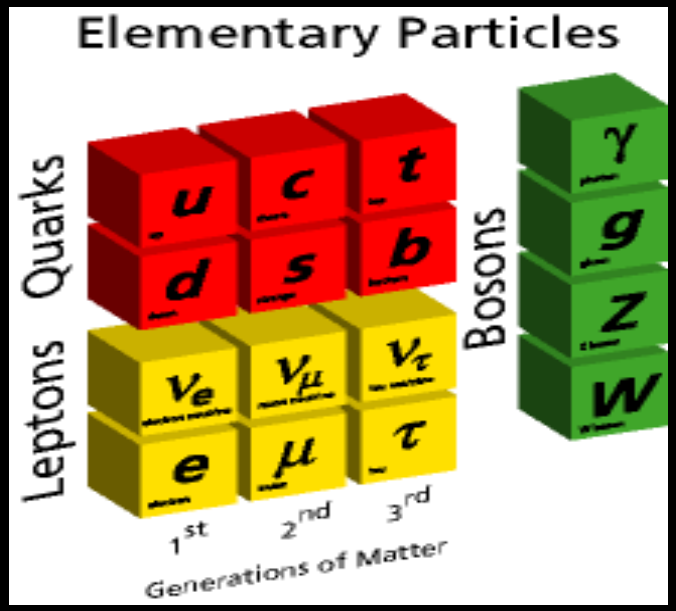


Signal 2γ, then several γ ~few μs later



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

Neutrino Time Line



1930 : Proposed by Pauli

1934 : Fermi's Theory of beta decay

1956: Discovery of ν_e
Nobel Prize in 1995

1962 : Discovery of ν_μ
Nobel Prize in 1988

1965 : First detection of atmospheric neutrinos

1968 : Detection of solar neutrinos and the beginning of solar neutrino puzzle

1987 : Detection of Supernova neutrinos
Nobel Prize in 2002

The stuff of the Universe

- *We are made out of Protons, Neutrons and Electrons*
- *Or more correctly --- Up & Doun Quarks and Electrons*

Is the whole universe made of Protons, Neutrons and Electrons ?

NO!

The universe is made of Protons, Neutrons, Electrons, Dark Energy, Dark Matter and Neutrinos

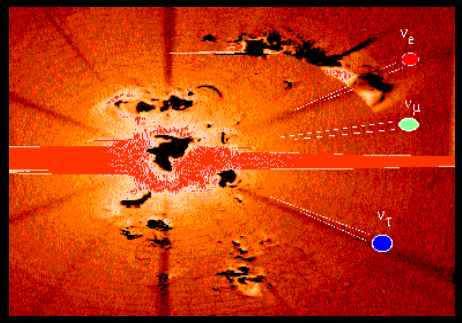
For every Proton & Neutron the universe contains a billion neutrinos!

To understand the universe, we must understand the neutrinos

Where do neutrinos come from?

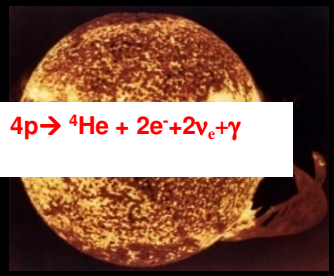
- ***Neutrinos from Big bang:***

  330 ν/cm^3 ; E_ν ~ 4 X 10^{-4}eV
  Decoupled about 1 min. after the Big bang



- ***Neutrinos from Sun:***

  Sun burns through nuclear Reaction
  E_ν ~ 0.1 ~ 20 MeV; Flux ~10^{12} /cm^2/s



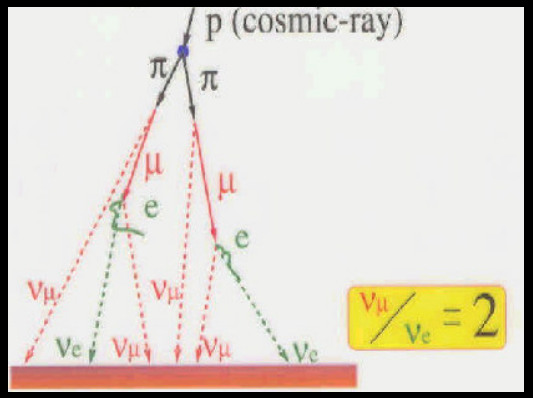
- ***Explosion of Star:***

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

E_b~10^{53} ergs, E_ν~10-30 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-***
  - *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.*

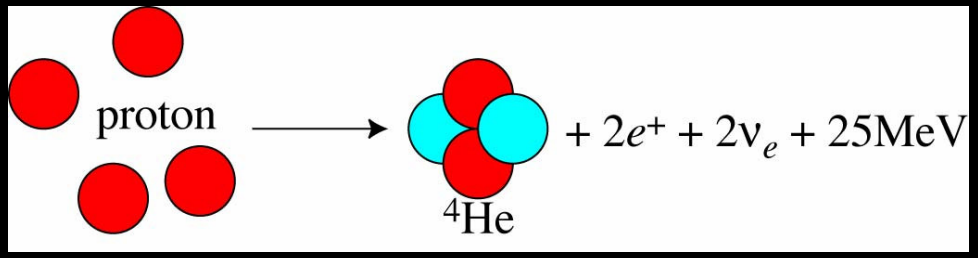
  - *Our body contains about 20 milligrams of ^{40}K which is b radioactive. We emit about 340 millions neutrinos/day. Which run from our body at the speed of light until the end of the universe.*
  - *Our body also contains about 30 million big bang neutrinos. For neutrinos our body is just an empty space.*

Are neutrinos important to our lives ?

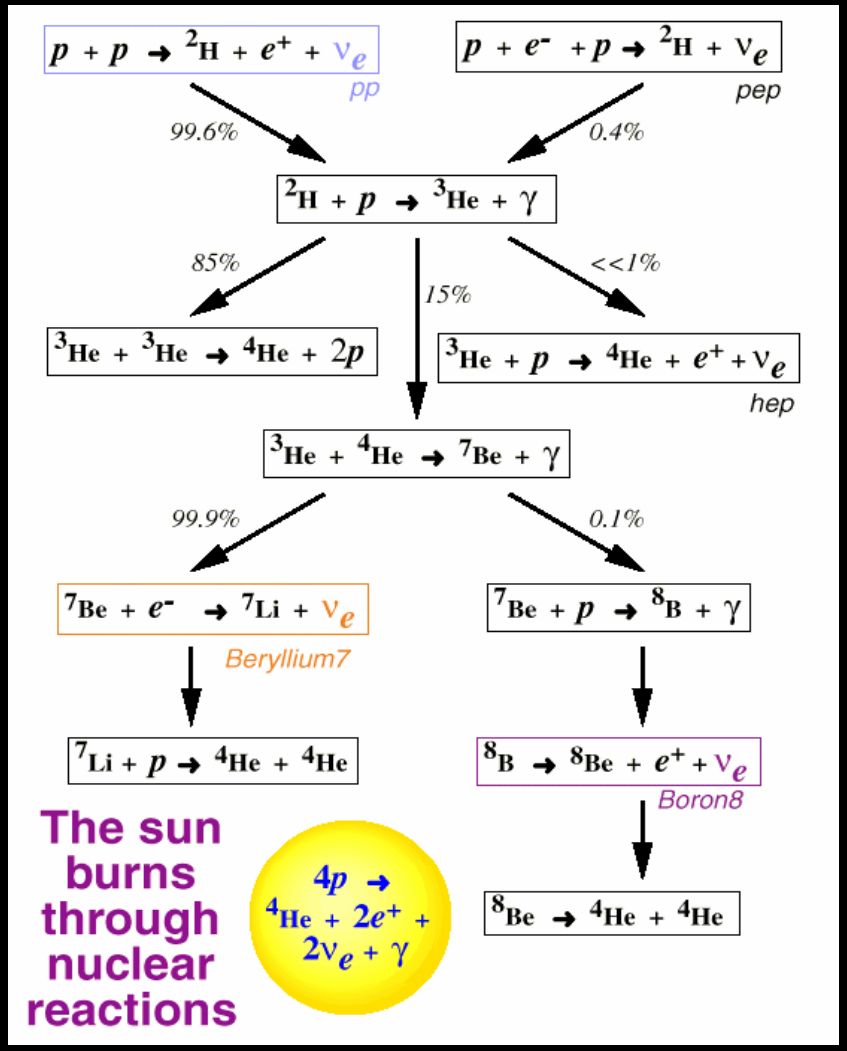
- *If there were no neutrinos- the sun and stars would not shine.*
  - *No energy from the sun to keep us warm.*
  - *No atoms more complicated than hydrogen.*
  - *No carbon, no oxygen, no water.*
  - *No earth, no moon, no us.*
- *We depend on small amount of heavy chemical elements like zinc, selenium.*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

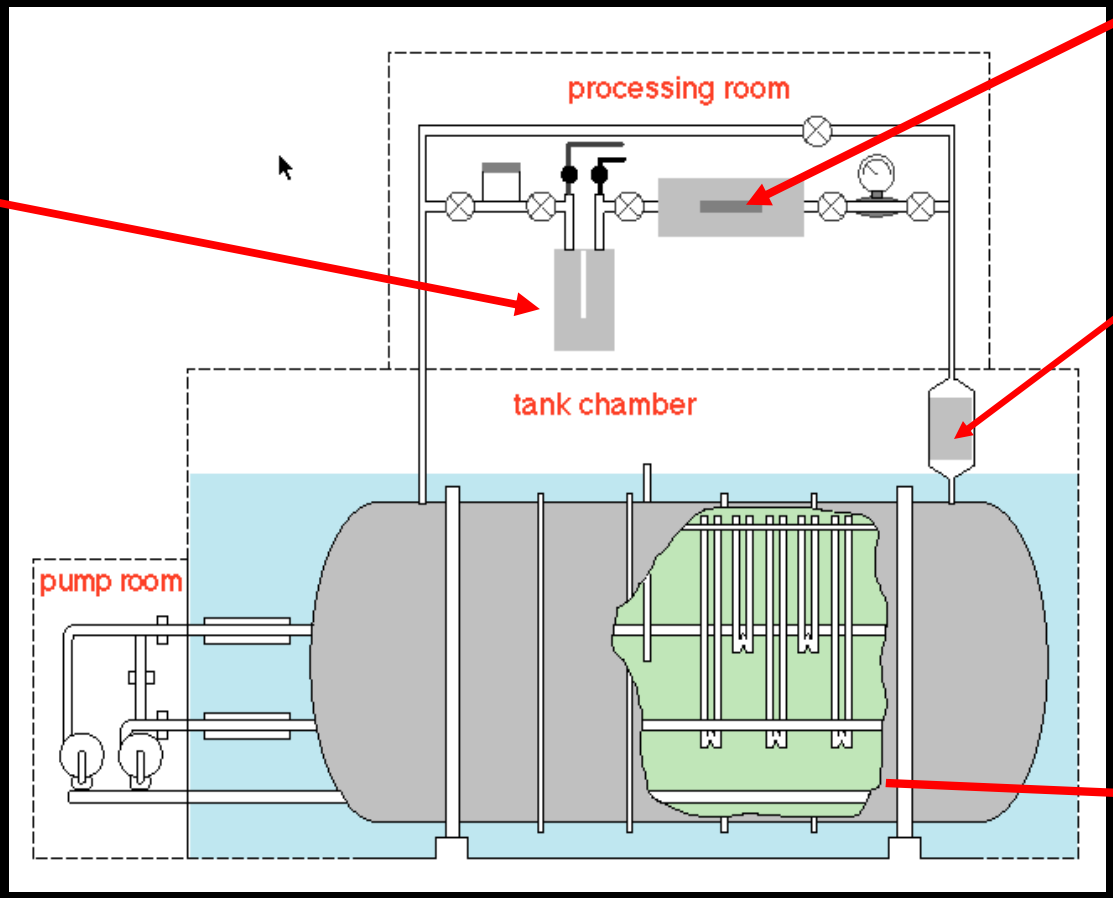
- ***1946: B. Pontecorvo :*** $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-, E_{th} = 0.814 MeV$

- ***1949: L. Alvarez: Made specific suggestions on the chemical procedures, expected neutrino capture cross sections as well as an estimate for possible background effects.***

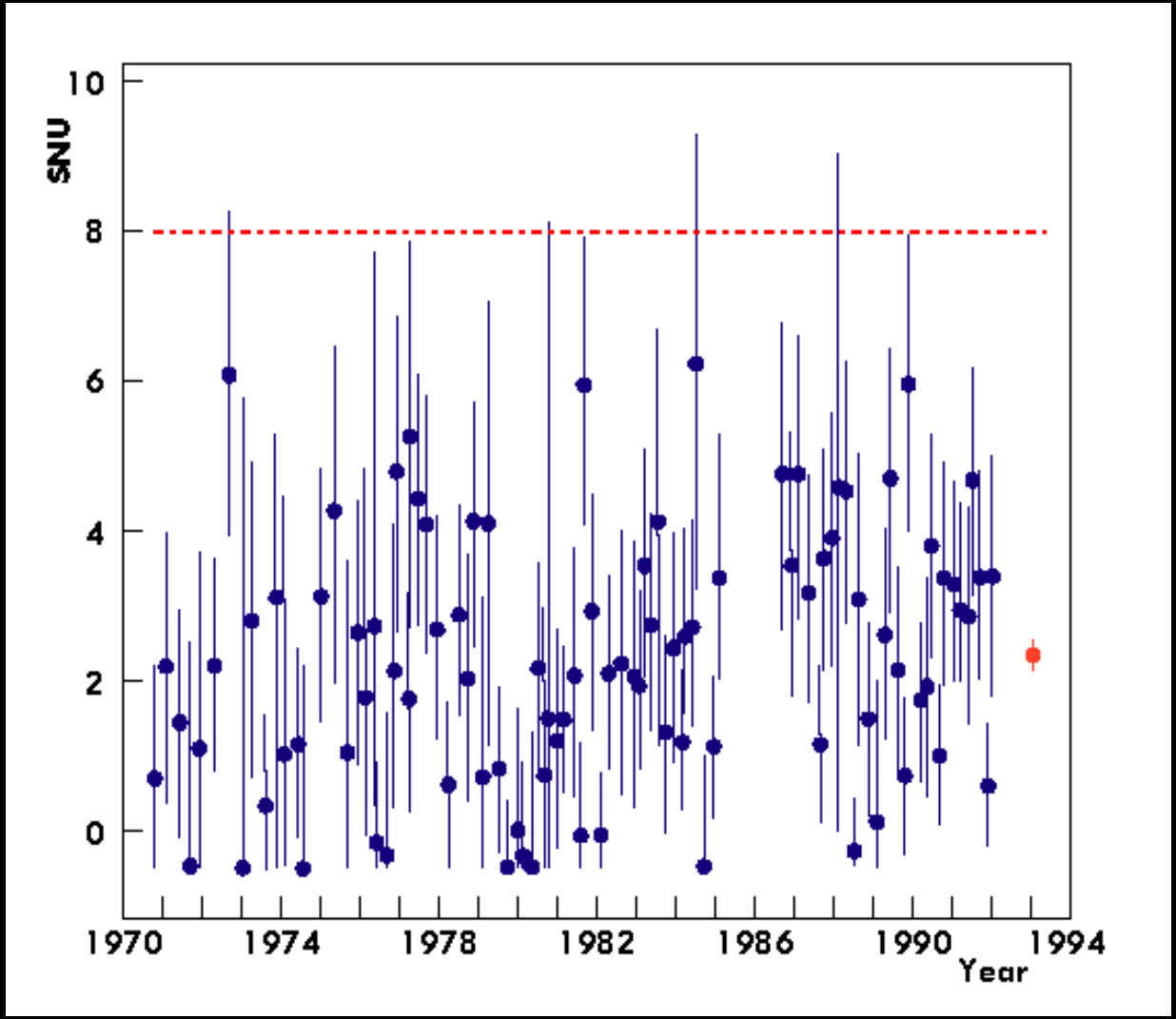
- ***First Attempt by Davis: Burried a 1000 gallon tank of C_2Cl_4 near the reactor at Brookhaven. Put limits on neutrinos from Sun as $< 10^{14}$ neutrinos-cm^{-2}sec^{-1}***

- ***1966: Davis built 100,000 Gallon Clorine Experiment in Homestake mine.***

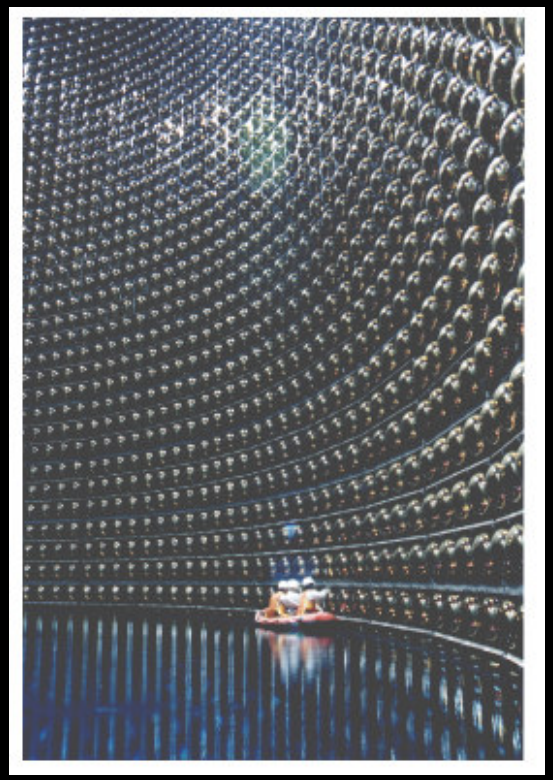
Homestake Detector

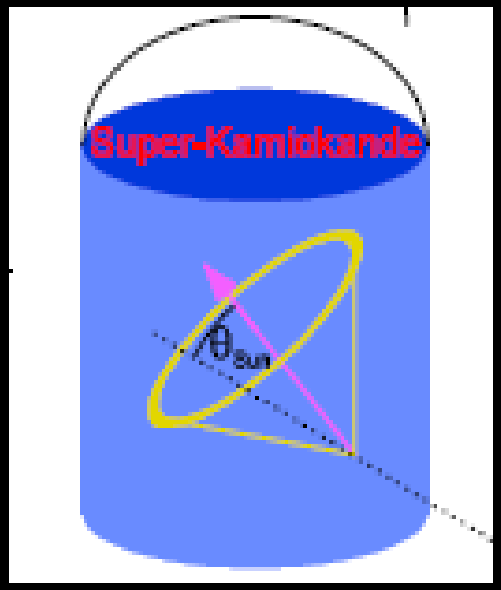


Homestake results



Kamiokande Detector & Data





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

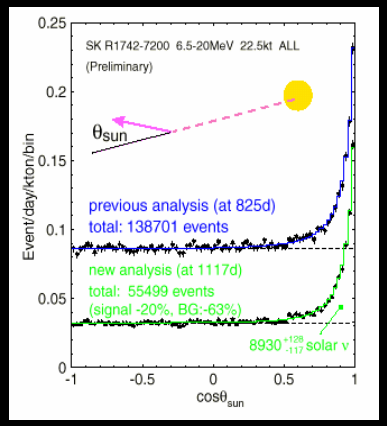
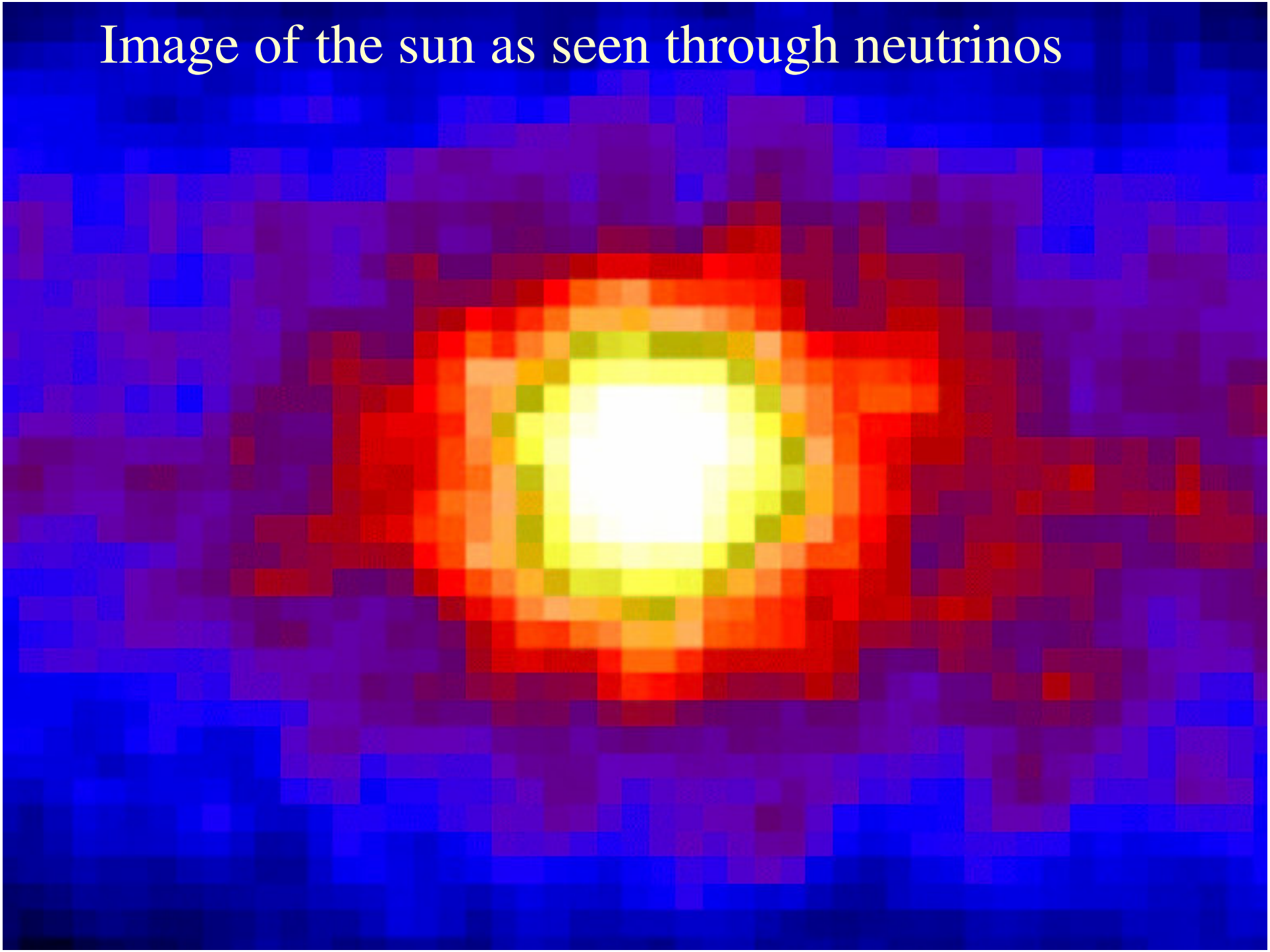
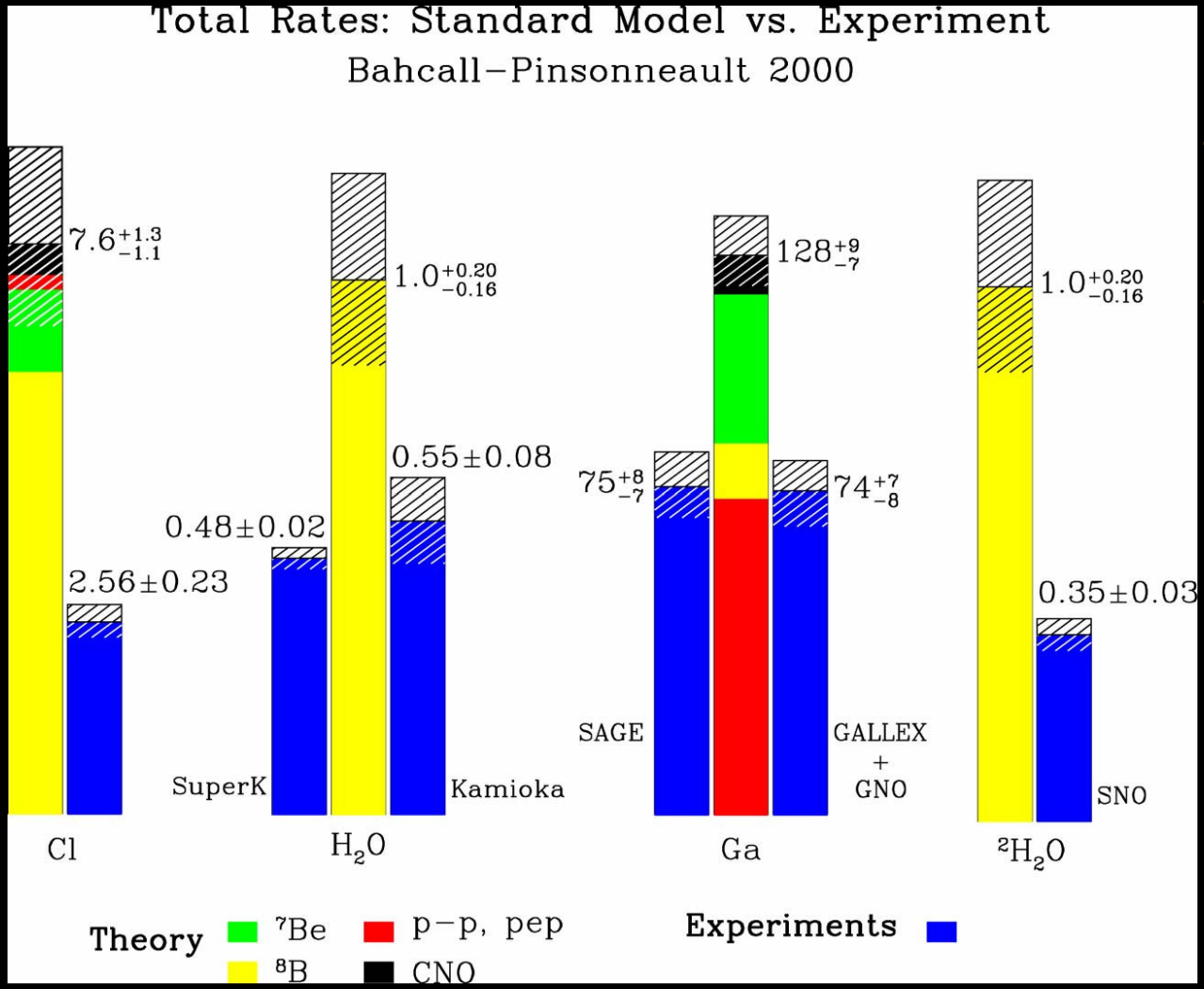


Image of the sun as seen through neutrinos



We don't get enough



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

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
  - It can be a ν_e or a ν_μ or a ν_τ

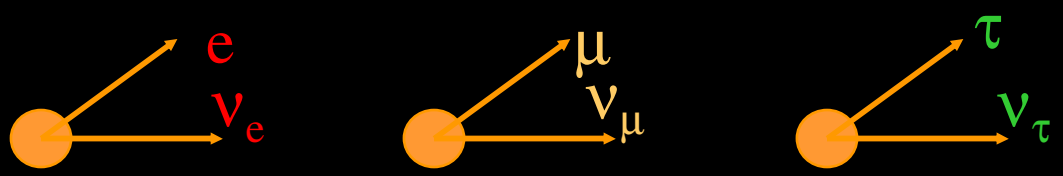
- But a proton is a proton is a proton. It does not convert into something else.
- How does a ν_e converts into a ν_μ or a ν_τ ?

- Answer : ν_e is not a particle to begin with.
- There are neutrino particles: ν_1, ν_2, ν_3

Neutrino Soup

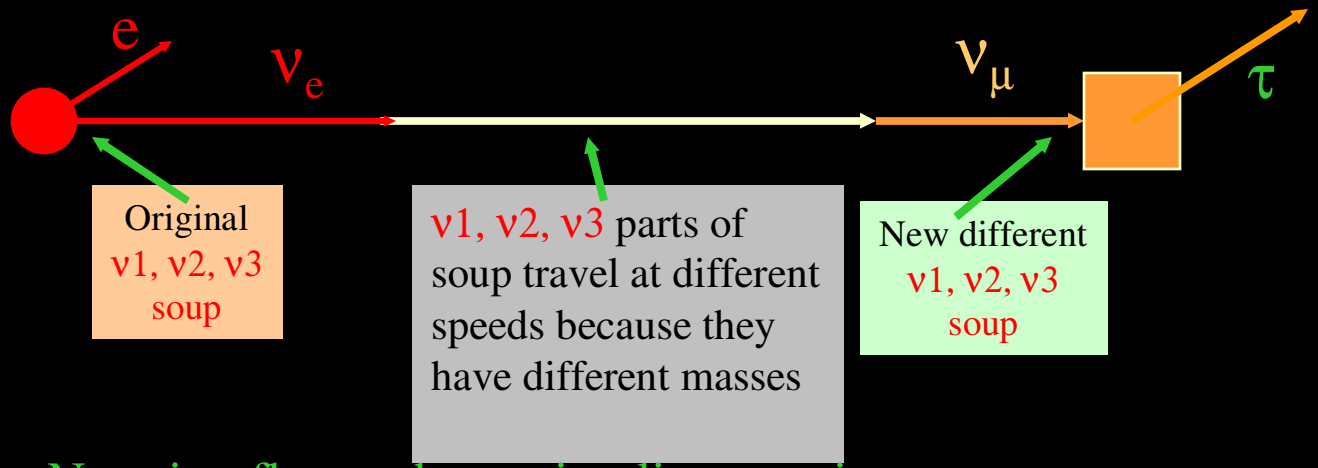
ν_e , ν_μ , ν_τ are different mixtures of ν_1, ν_2, ν_3

In each of ⟶



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

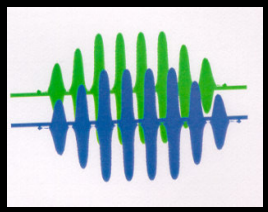


Neutrino flavor change implies neutrino mass

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*

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

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

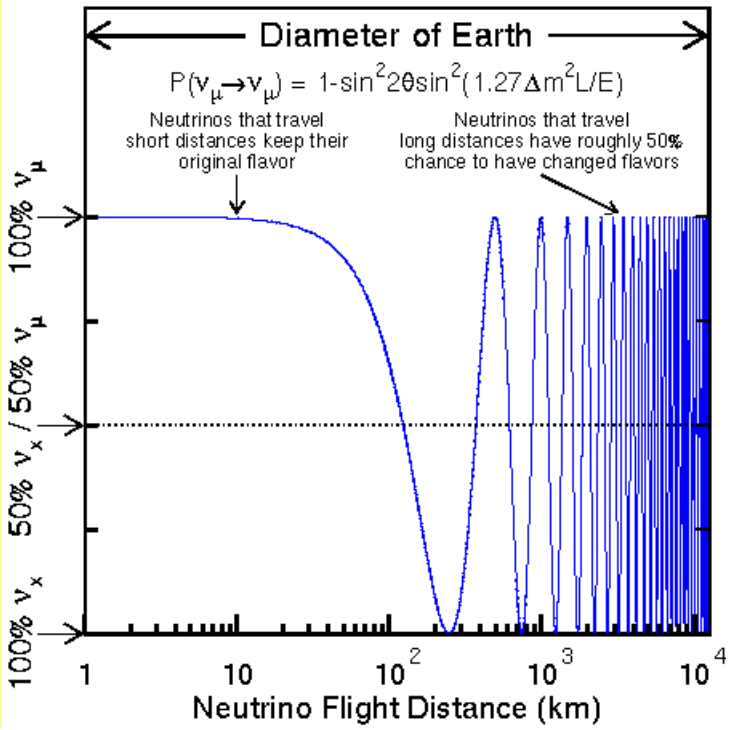
$$E_2 - E_1 = \frac{m_2^{\,2} - m_1^{\,2}}{2E} = \frac{\Delta m^2}{2E}$$

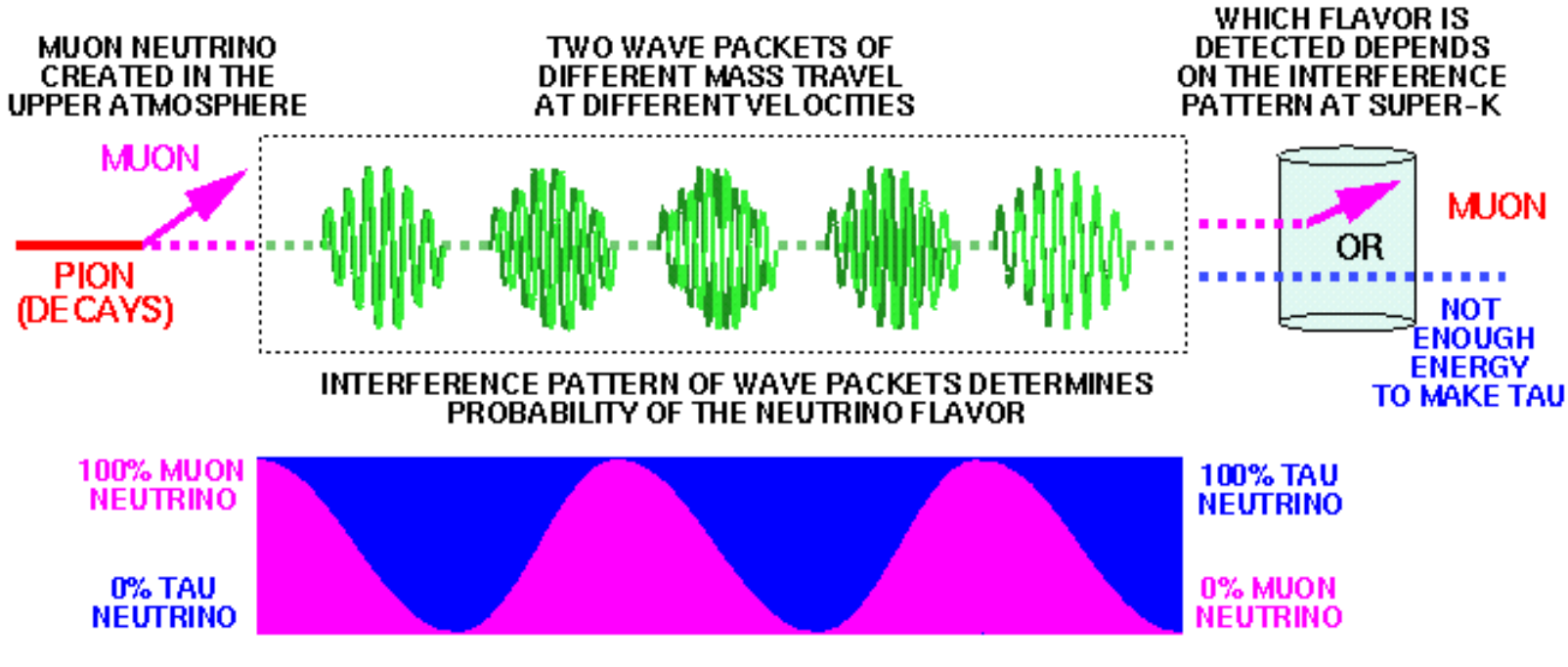
$$P(\nu_e \to \nu_f; L) = \sin^2 2\theta \ \ \sin^2 \frac{1.27\Delta m^2 L}{E}$$

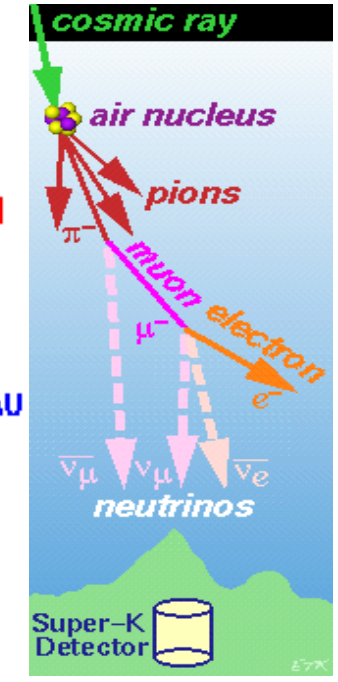
Massive Neutrinos Simple Math

$$P(\nu_e \rightarrow \nu_\mu) \cong \sin^2(2\theta)\sin^2[\frac{\Delta m^2}{4}\frac{L}{E}]$$

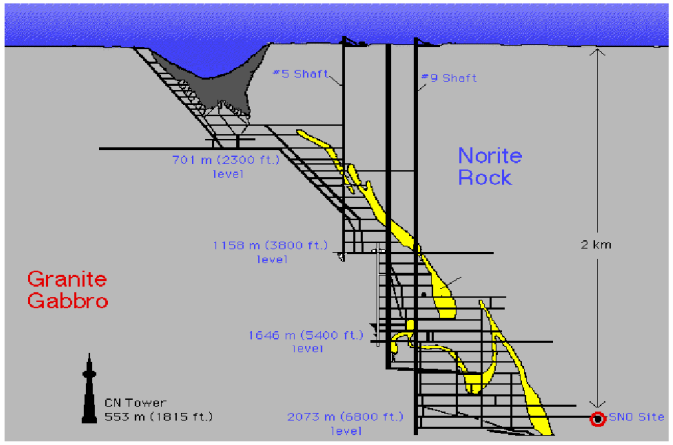
$$m_1 \neq m_2$$







Sudbury Neutrino Observatory



1000 tonnes D_2O

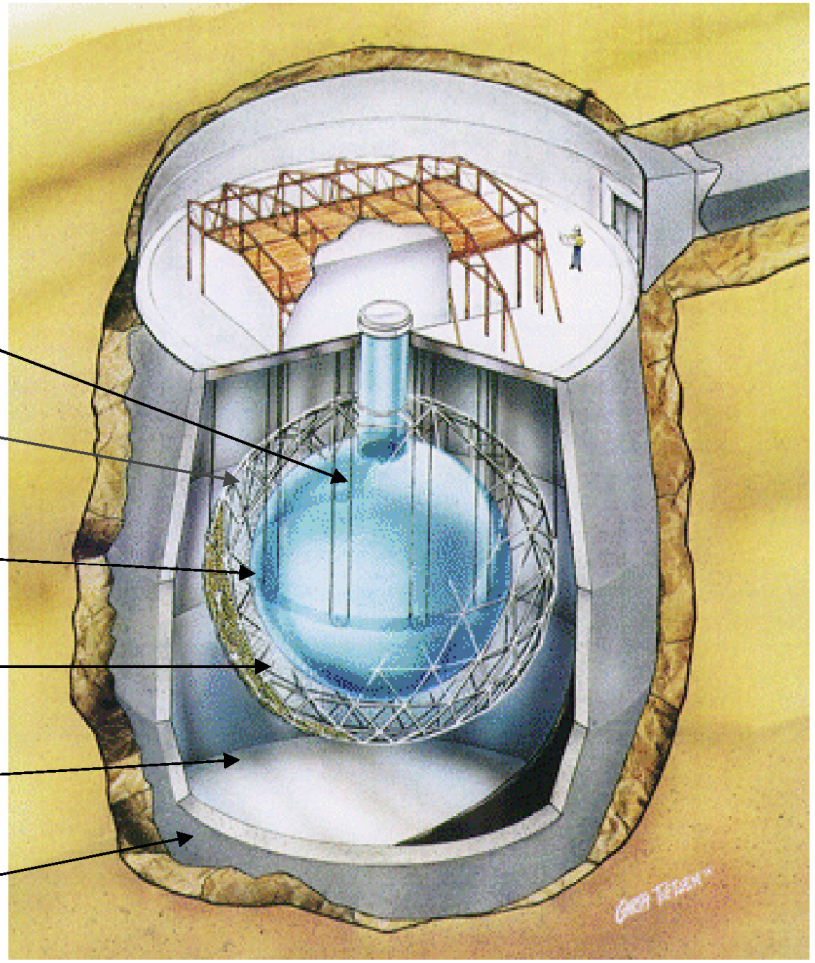
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal



SNO comes to the rescue

- Charged Current: ν_e

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

- Neutral Current:

  $\nu_e + \nu_\mu + \nu_\tau$

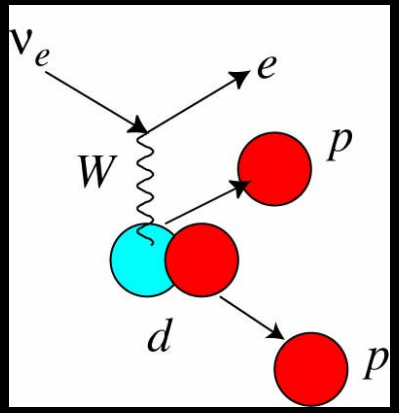
$$\Phi_{\mathrm{NC}}^{\mathrm{SNO}} = 5.21 \pm 0.27 \pm 0.38 \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

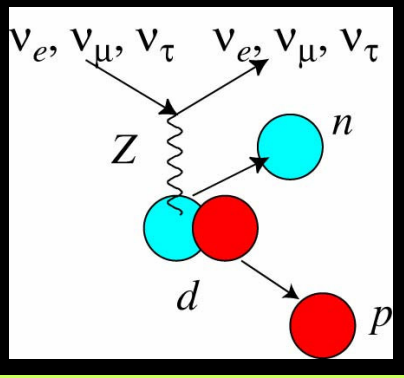
- 7.6σ difference

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

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

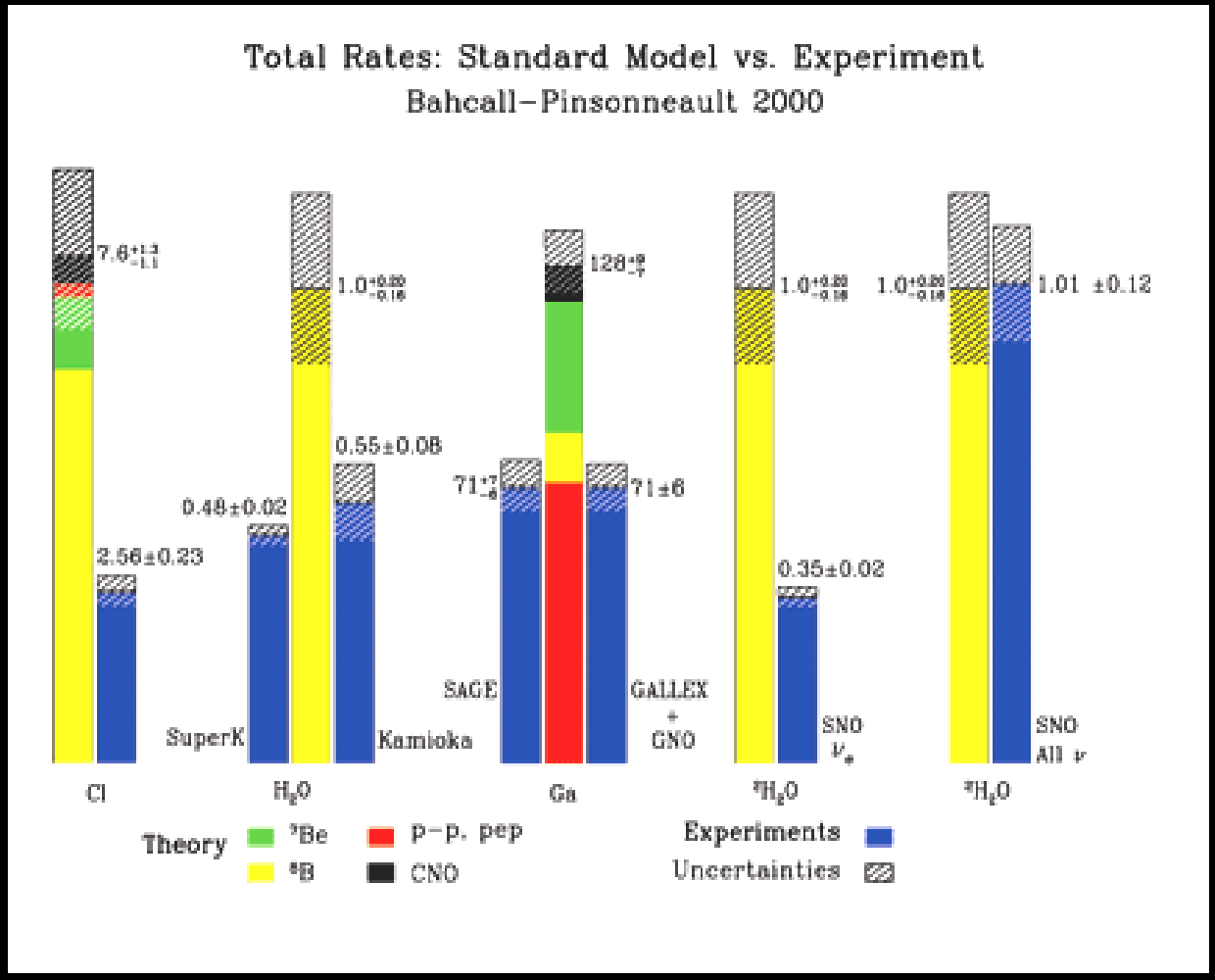
$$\nu_e + d \rightarrow p + p + e^-$$



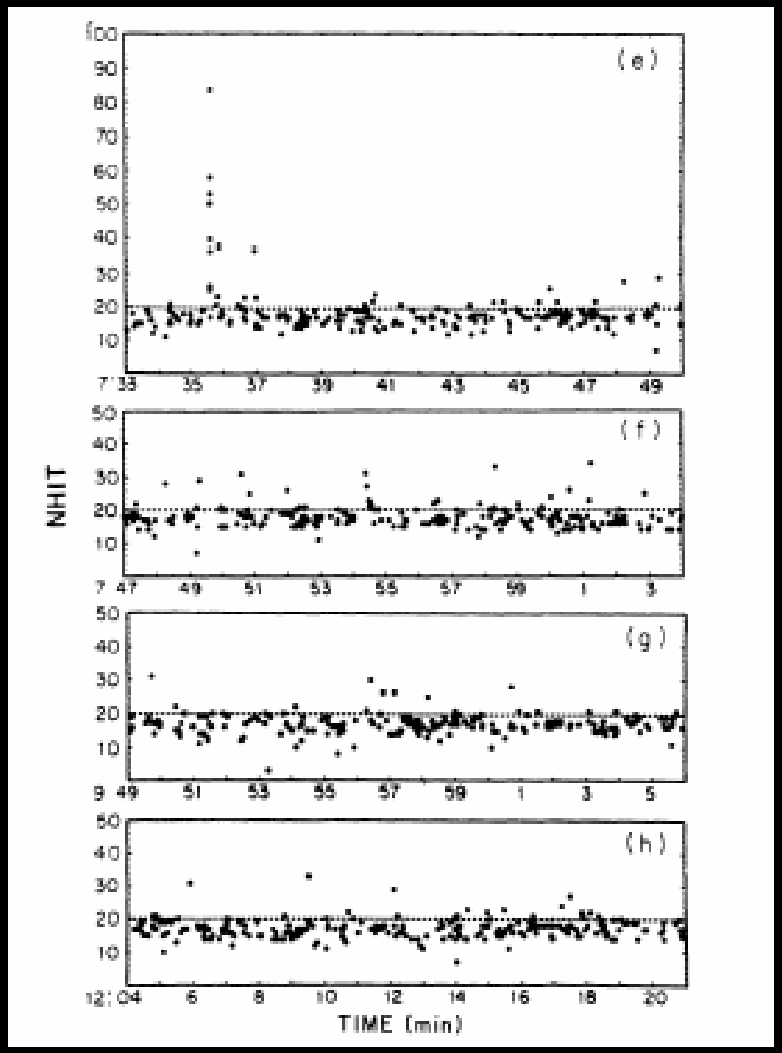


$$\nu_x + d \rightarrow \nu_x + p + n$$

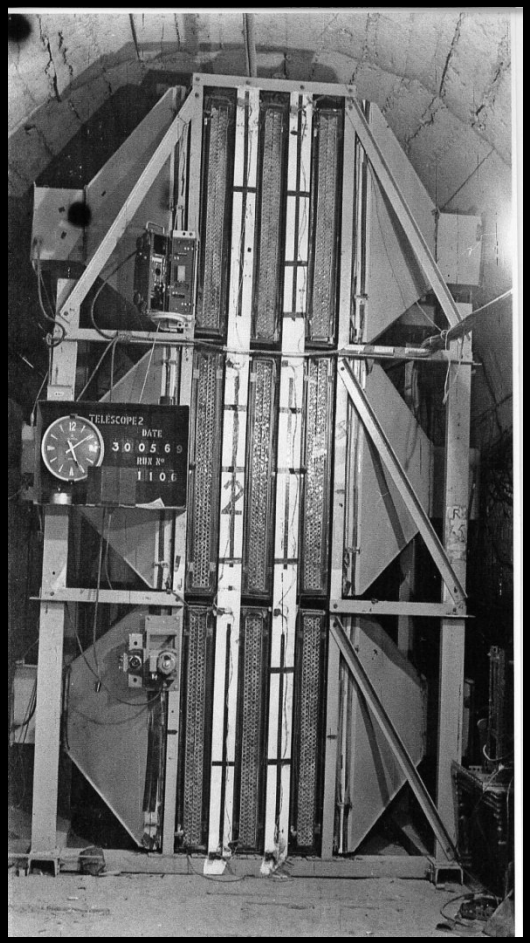
Solar Neutrino Results



Super Nova 1987A



Atmospheric neutrino detection in 1965



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

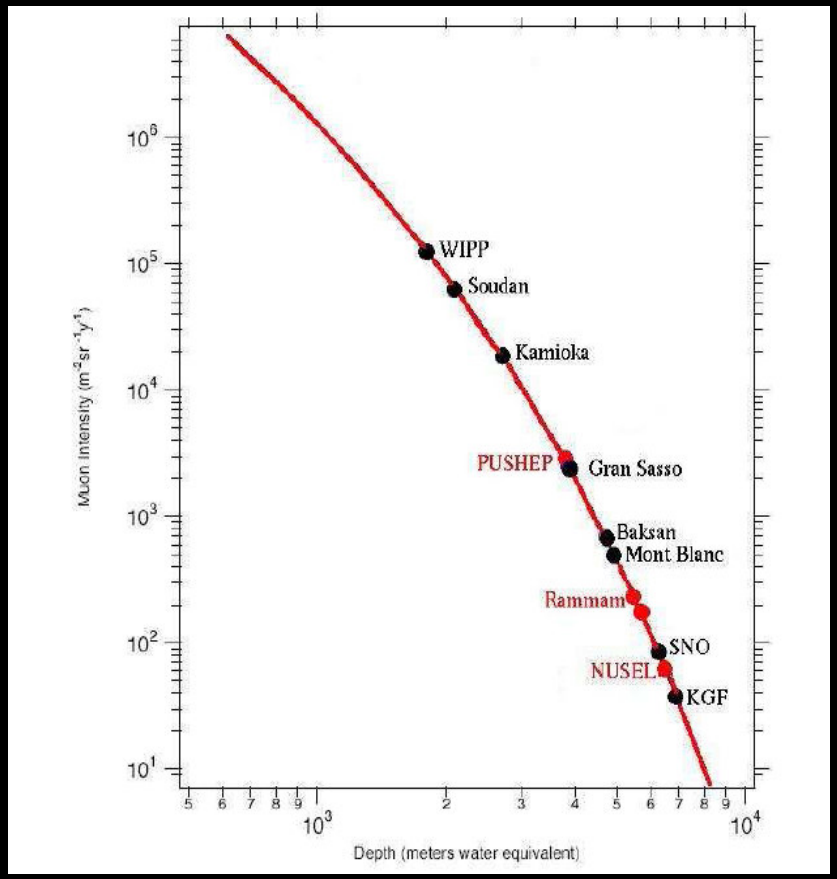
and

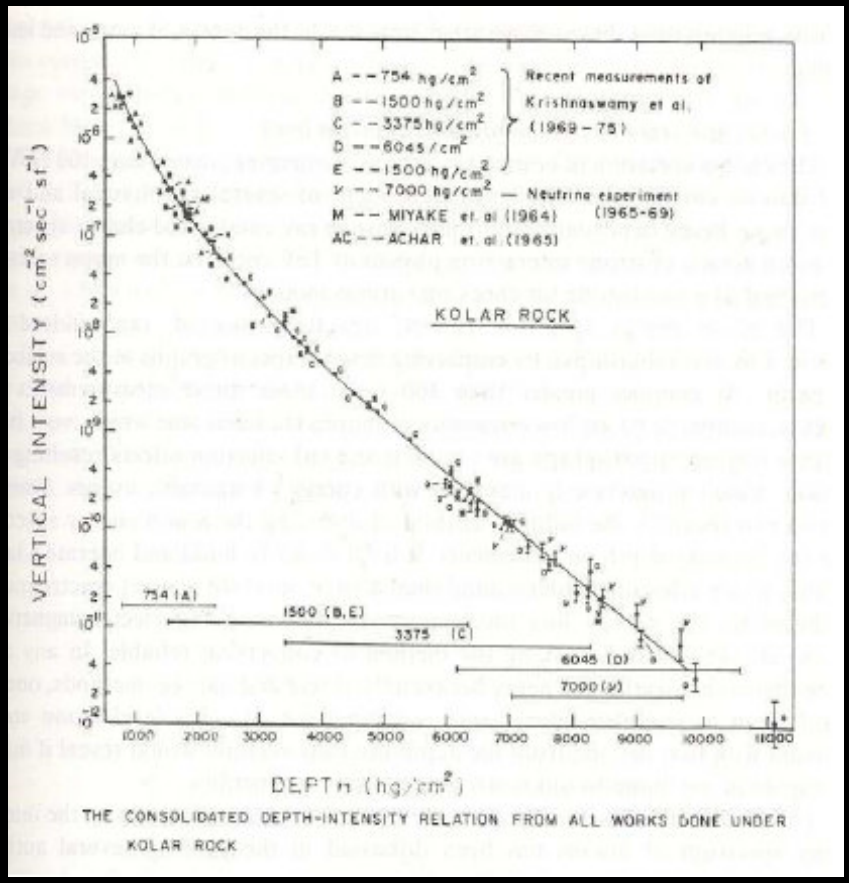
J. P. F. Sellschop and B. Meyer

University of the Witwatersrand, Johannesburg, Republic of South Africa
(Received 26 July 1965)

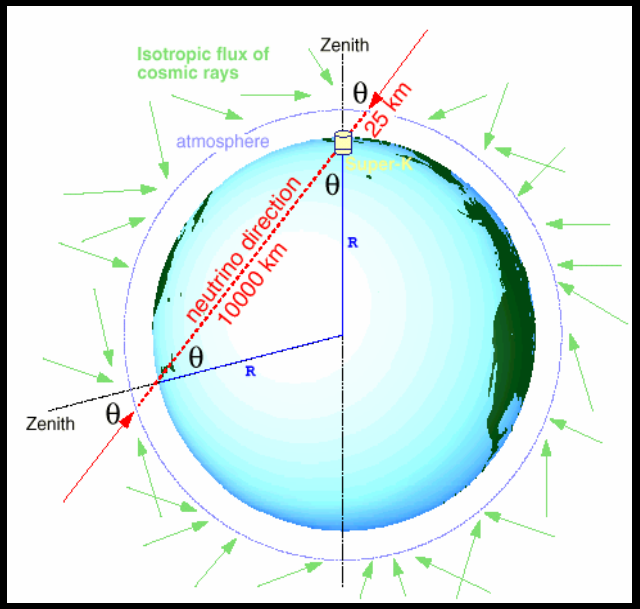
PRL 15, (1965), 429, dated 30th Aug. 1965

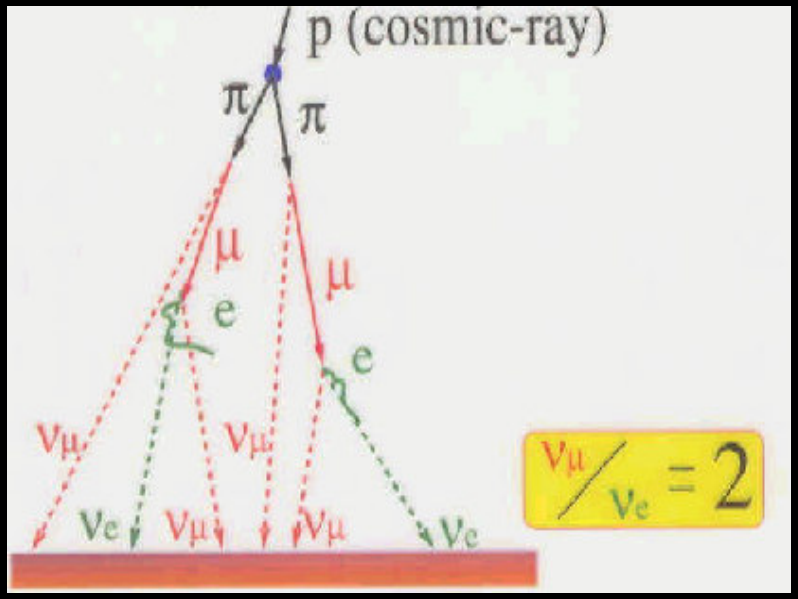
KGF

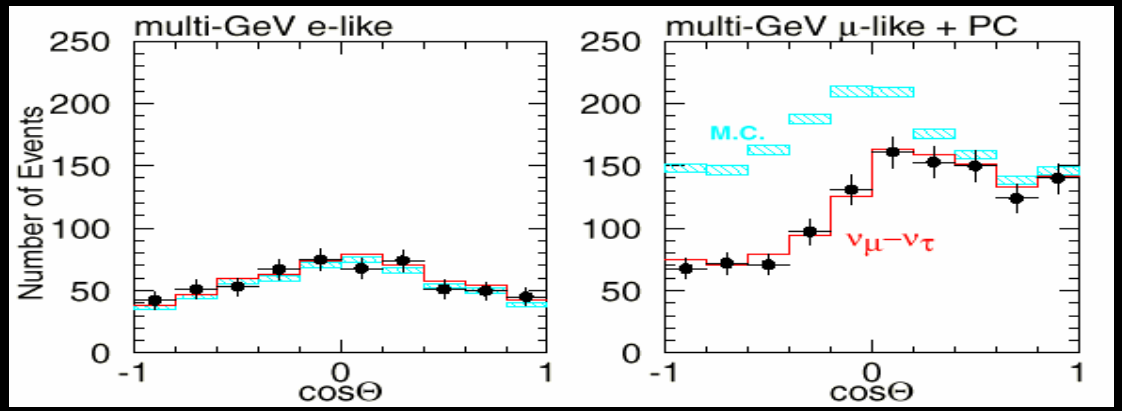

Muon intensity (m^{-2}sr^{-1}y^{-1})
Depth (meters water equivalent)
WIPP
Soudan
Kamioka
PUSHEP
Gran Sasso
Baksan
Mont Blanc
Rammam
SNO
NUSEL
KGF


VERTICAL INTENSITY (cm^{-2} sec^{-1} st^{-1})
DEPTH (hg/cm^2)
A -- 754 hg/cm^2
B -- 1500 hg/cm^2
C -- 3375 hg/cm^2
D -- 6045 /cm^2
E -- 1500 hg/cm^2
ν -- 7000 hg/cm^2
Recent measurements of Krishnaswamy et al. (1969 – 75)
Neutrino experiment (1965-69)
M -- MIYAKE et al (1964)
AC -- ACHAR et al (1965)
KOLAR ROCK
754 (A)
1500 (B,E)
3375 (C)
6045 (D)
7000 (ν)
THE CONSOLIDATED DEPTH-INTENSITY RELATION FROM ALL WORKS DONE UNDER KOLAR ROCK

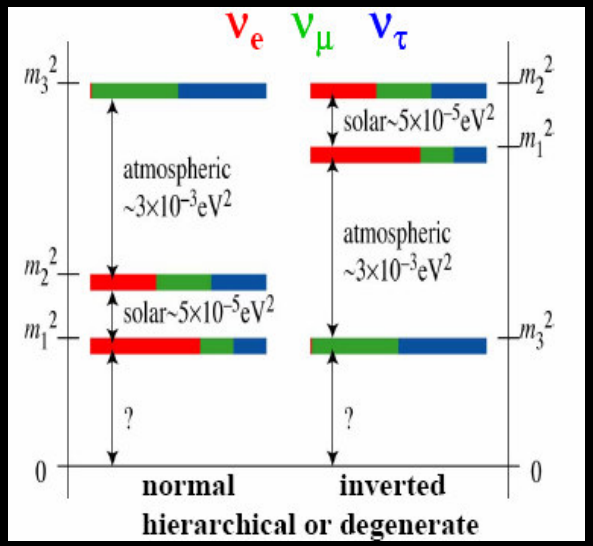
Atmospheric Neutrinos







Neutrino Masses and Mixing: Three Generations

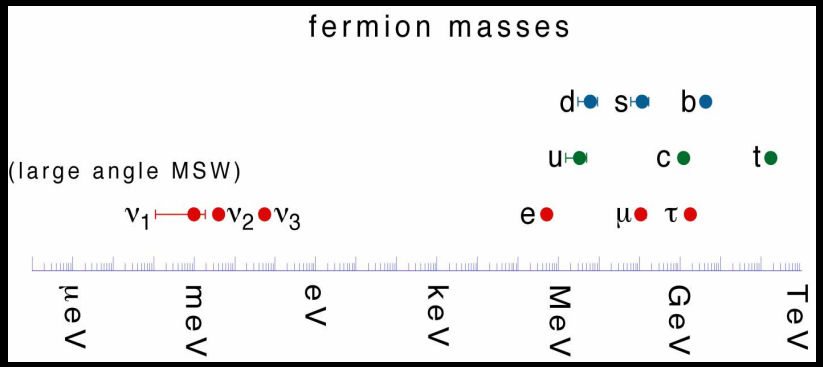


$$\begin{bmatrix} \nu_e & \nu_\mu & \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

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

$\Delta m^2_{21} = (8.2 \pm 0.3) * 10^{-5}\ \text{eV}^2$
$\tan^2\theta_{12} = 0.39 \pm 0.05$
$\Delta m^2_{31} = (2.5 \pm 0.6) * 10^{-3}\ \text{eV}^2$
$\tan^2\theta_{23} = 1.0 \pm 0.3$
$\sin^2 2\theta_{13} < 0.16$ Chooz

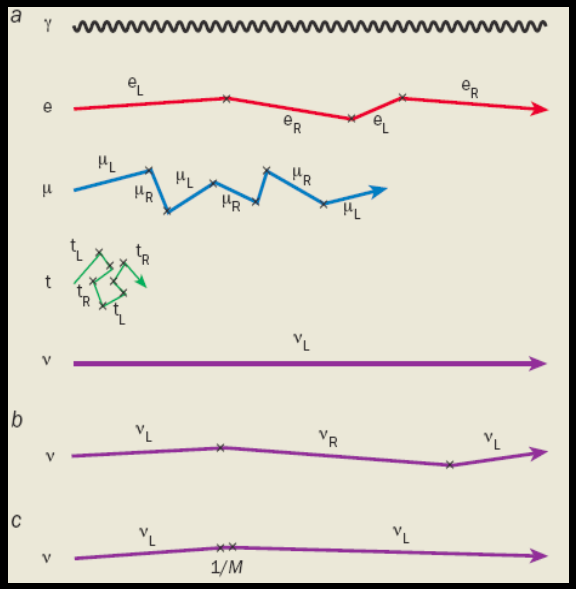
Why so fuss about neutrino mass ?



- *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



Add right-handed neutrino:

• gives mass to neutrinos

• has no interactions (beyond gravitational) – does not spoil the agreement with observations

But: why neutrino mass so small??

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. – how small is θ_{13} ? 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.*

Current neutrino mass bounds:

$\nu_e < 2.2$ eV →
$\nu_\mu < 170$ KeV
ν_τ <15.5 MeV

India-based Neutrino Observatory Project

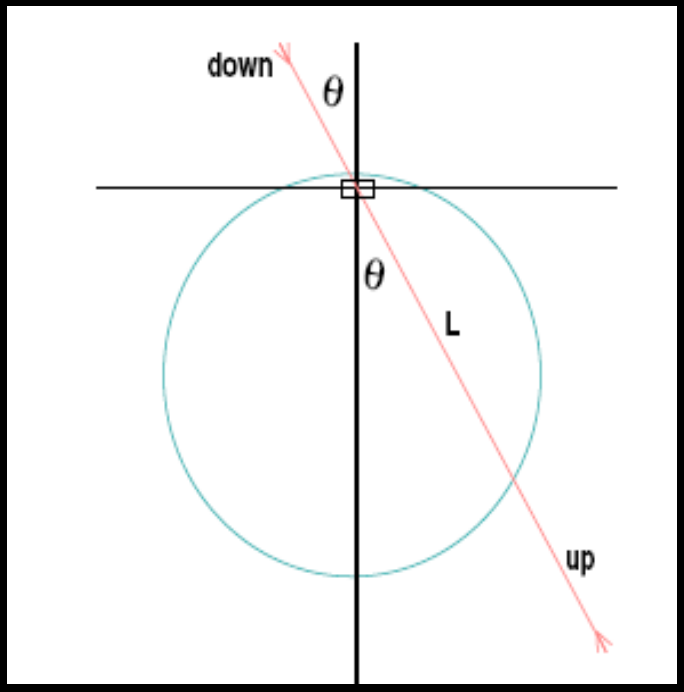
- *India-based Neutrino observatory is a Mega Science Project funded by Dept. of Science & Technology and Dept. of Atomic Energy, Govt. of India . The project will lead to:*
- *Creation of a world class underground laboratory in the country for carrying out research in the emerging field of neutrino physics. Will develop into a full fledged underground laboratory over the years for other studies.*
- *Involvement of Universities in a big way for carrying out large basic science projects- healthy development of University-Research lab partnership.*
- *A Centre for particle physics and detector technology and its varied applications in areas like medical imaging.*
- *INO graduate training program will lead to Ph.D. in particle physics and more importantly creating highly skilled scientific manpower for experimental high energy and nuclear physics. Hands on training on all aspect of experiments with strong emphasis on detector development.*

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*

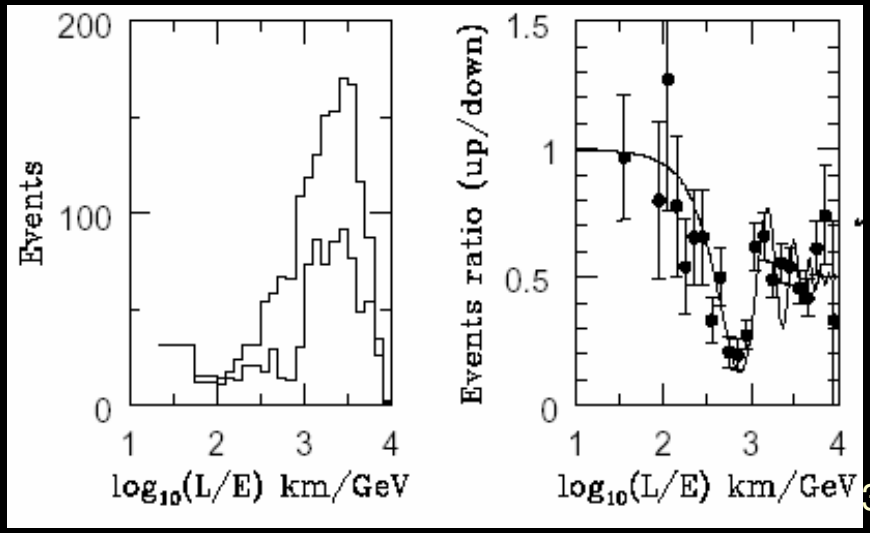
Disappearance of ν_μ vs. L/E

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

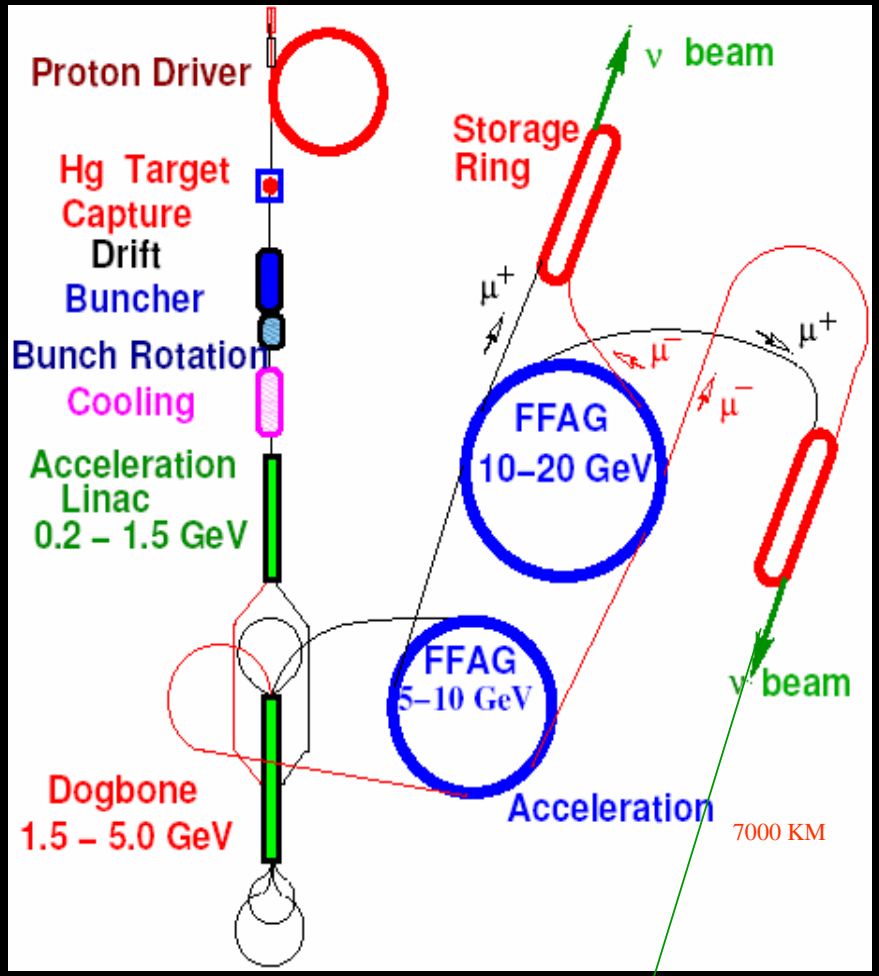


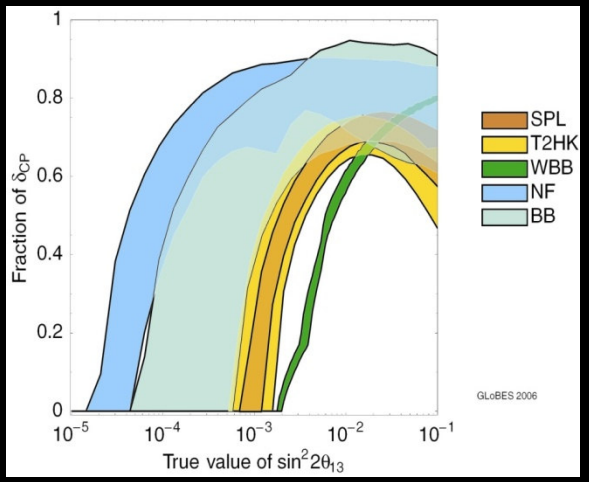
$$\frac{N_{up}(L/E)}{N_{down}(L'/E)} = P(\nu_\mu \rightarrow \nu_\mu; L/E)$$

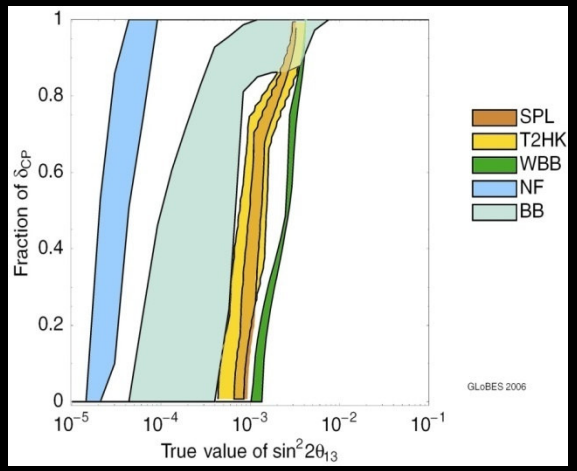
$$= 1 - \sin^2(2\Theta)\sin^2(1.27\,\Delta m^2\,L/E)$$

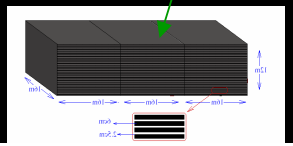


Neutrino Factory

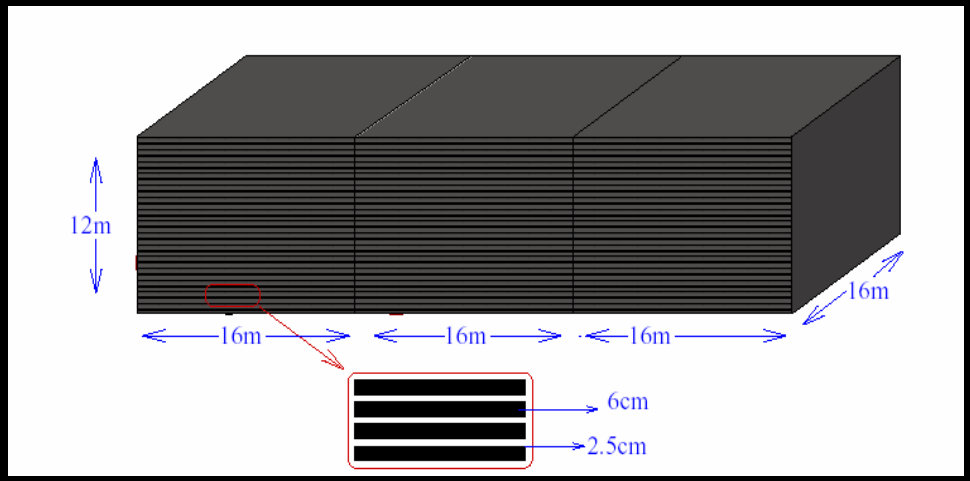


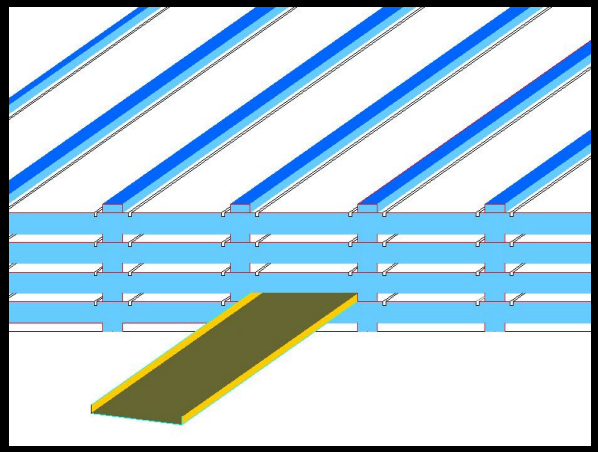


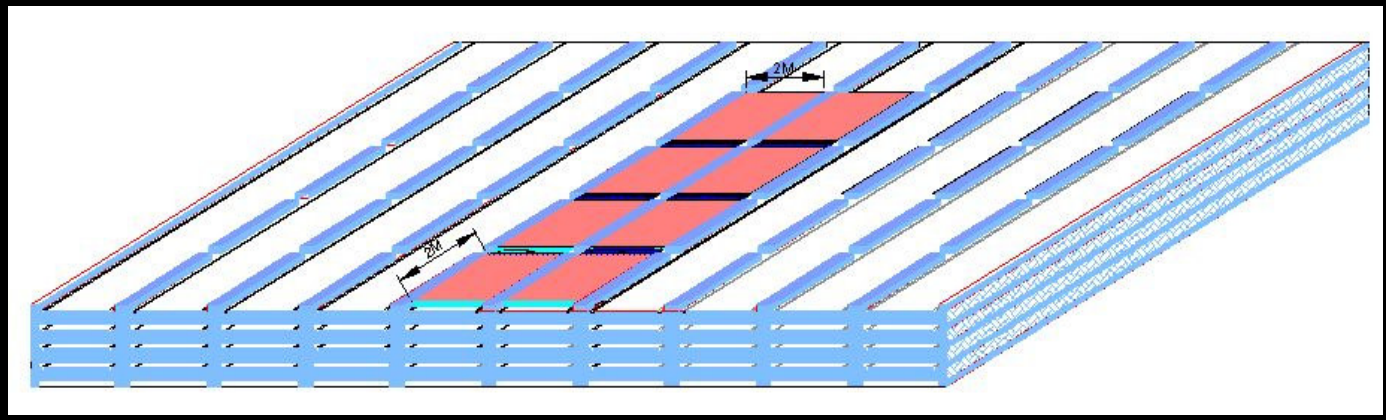




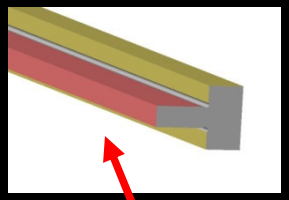
INO Detector Concept







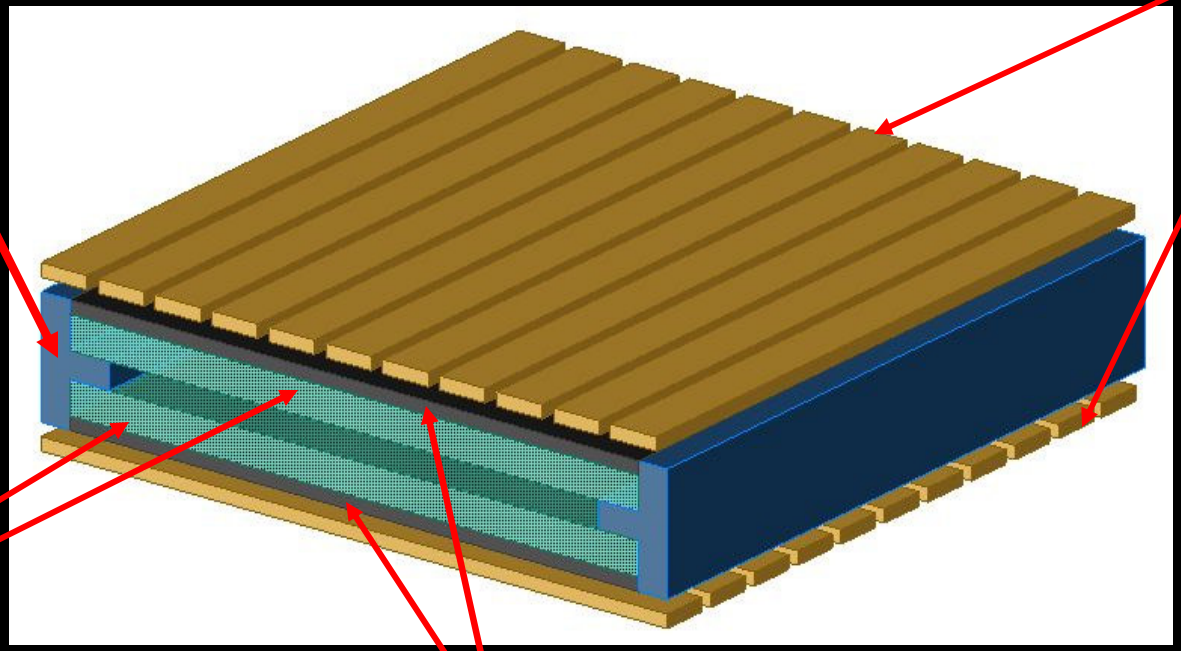
Construction of RPC



Two 2 mm thick float Glass
Separated by 2 mm spacer

2 mm thick spacer

Pickup strips

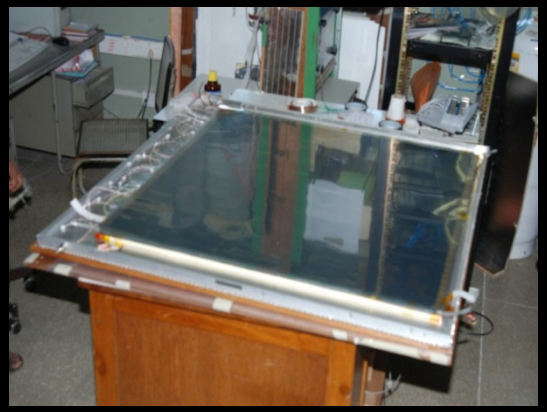


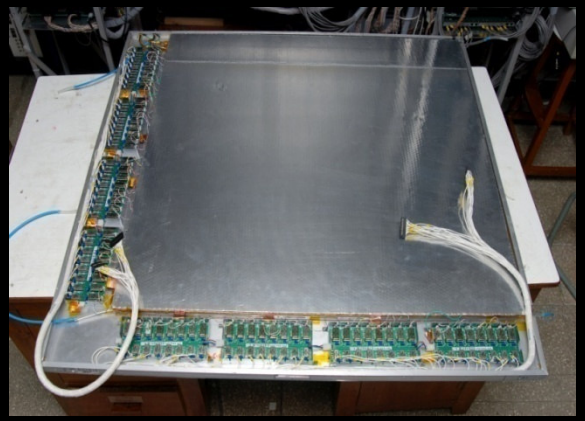
Glass plates

Resistive coating on the outer surfaces of glass

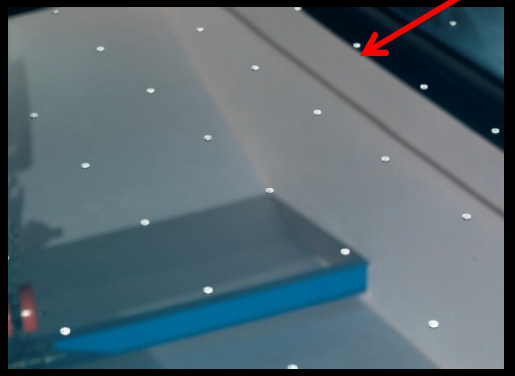
Fabrication of 1m x 1m RPCs

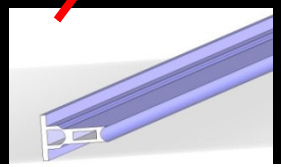


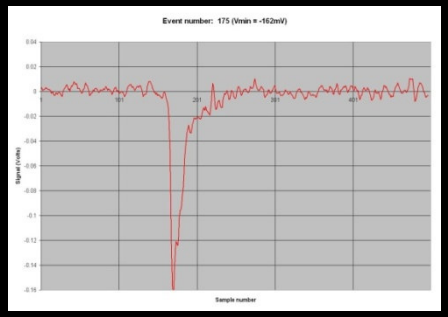


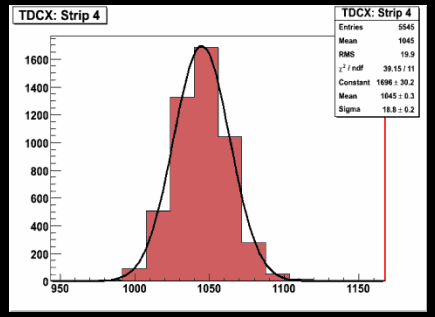
Final RPC Frontier - Making of 2m x 2m RPCs

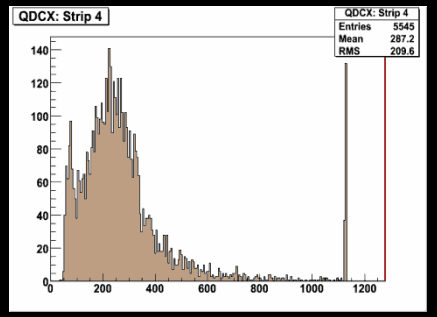




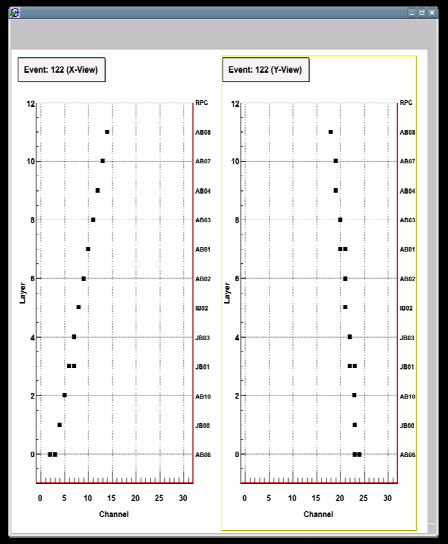
Prototype RPC Stack at TIFR tracking Muons

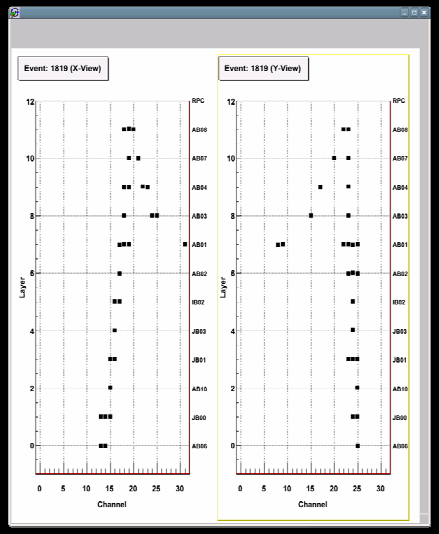


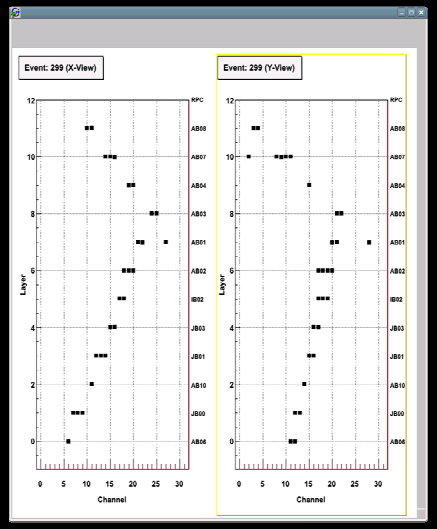


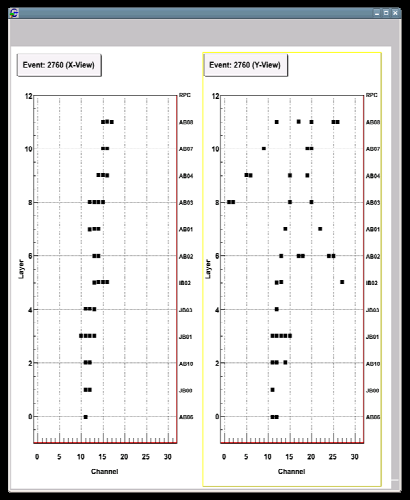


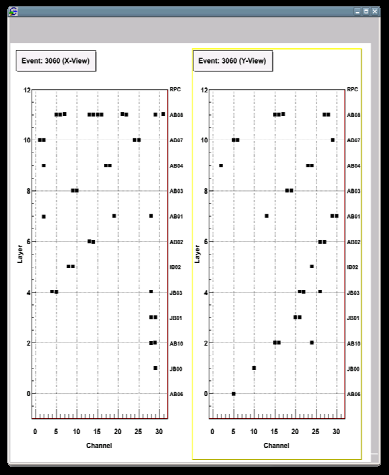
Some interesting cosmic ray tracks



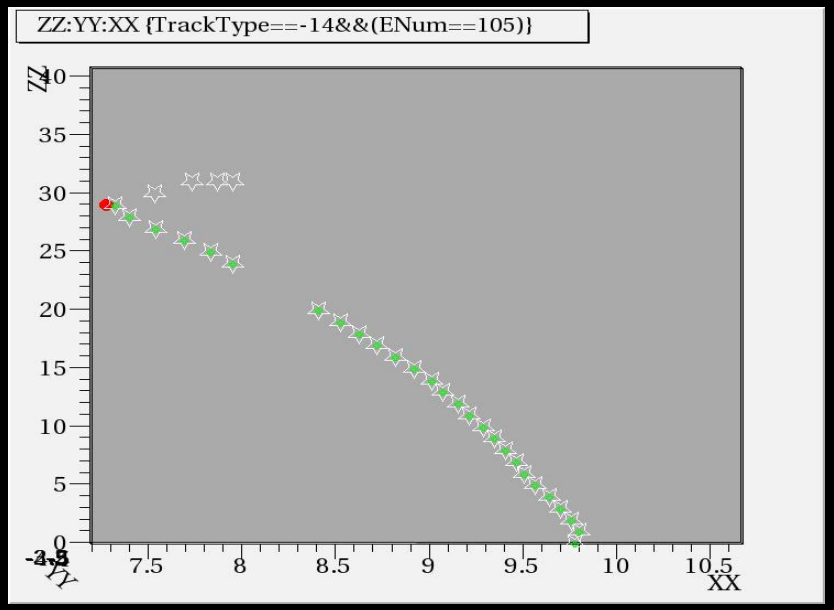


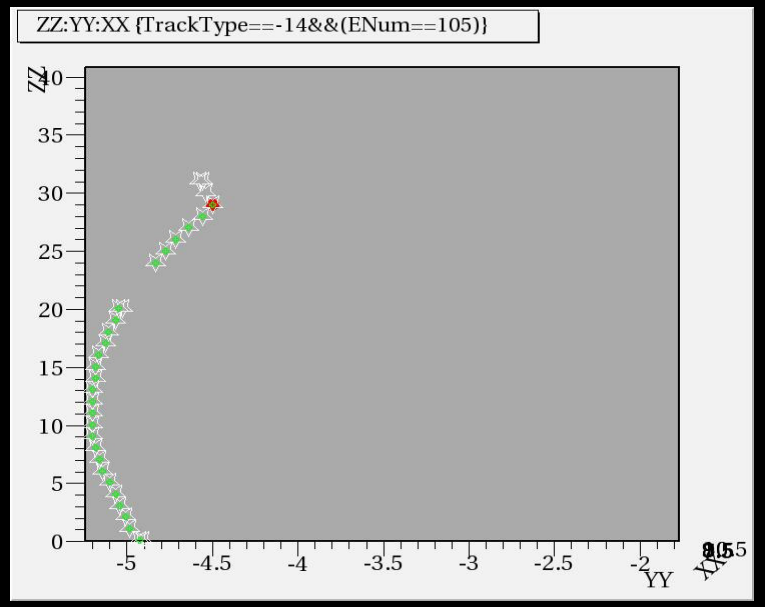




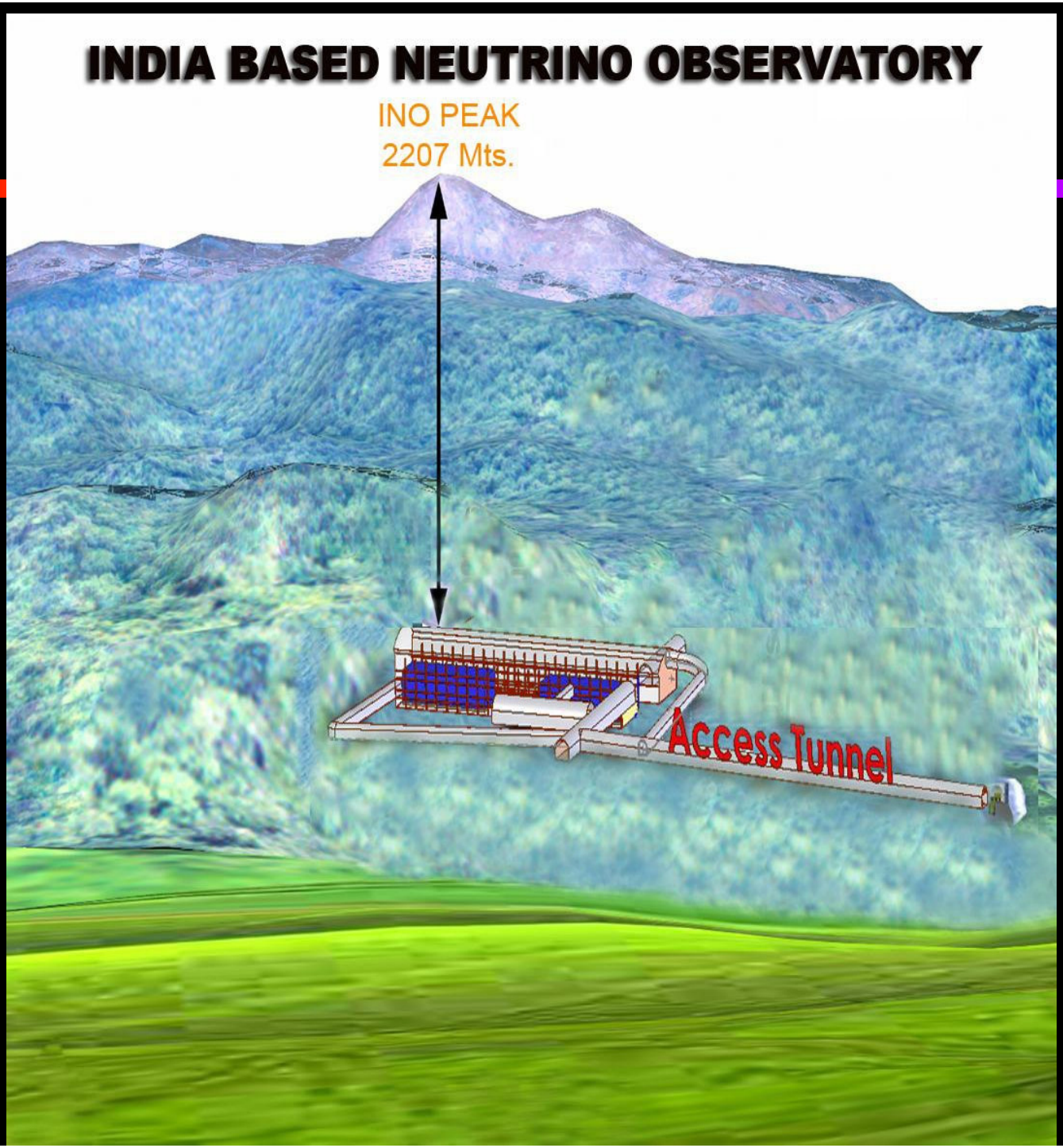


Simulated Neutrino events in INO-ICAL Detector



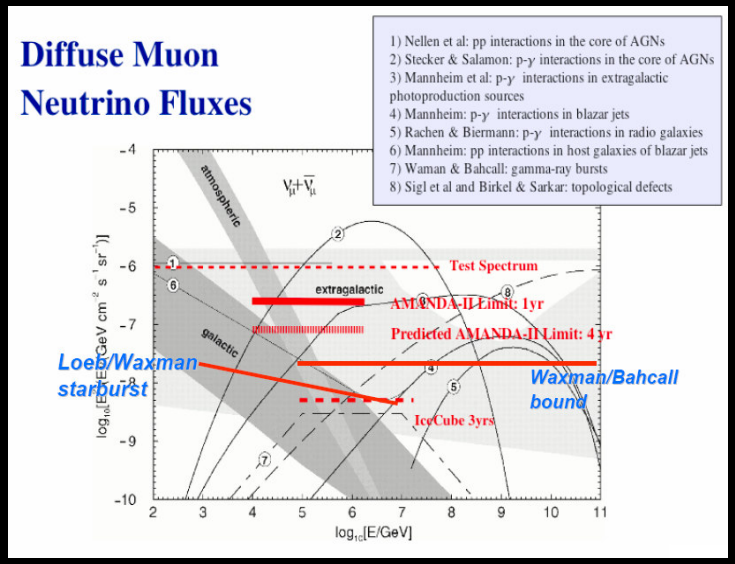


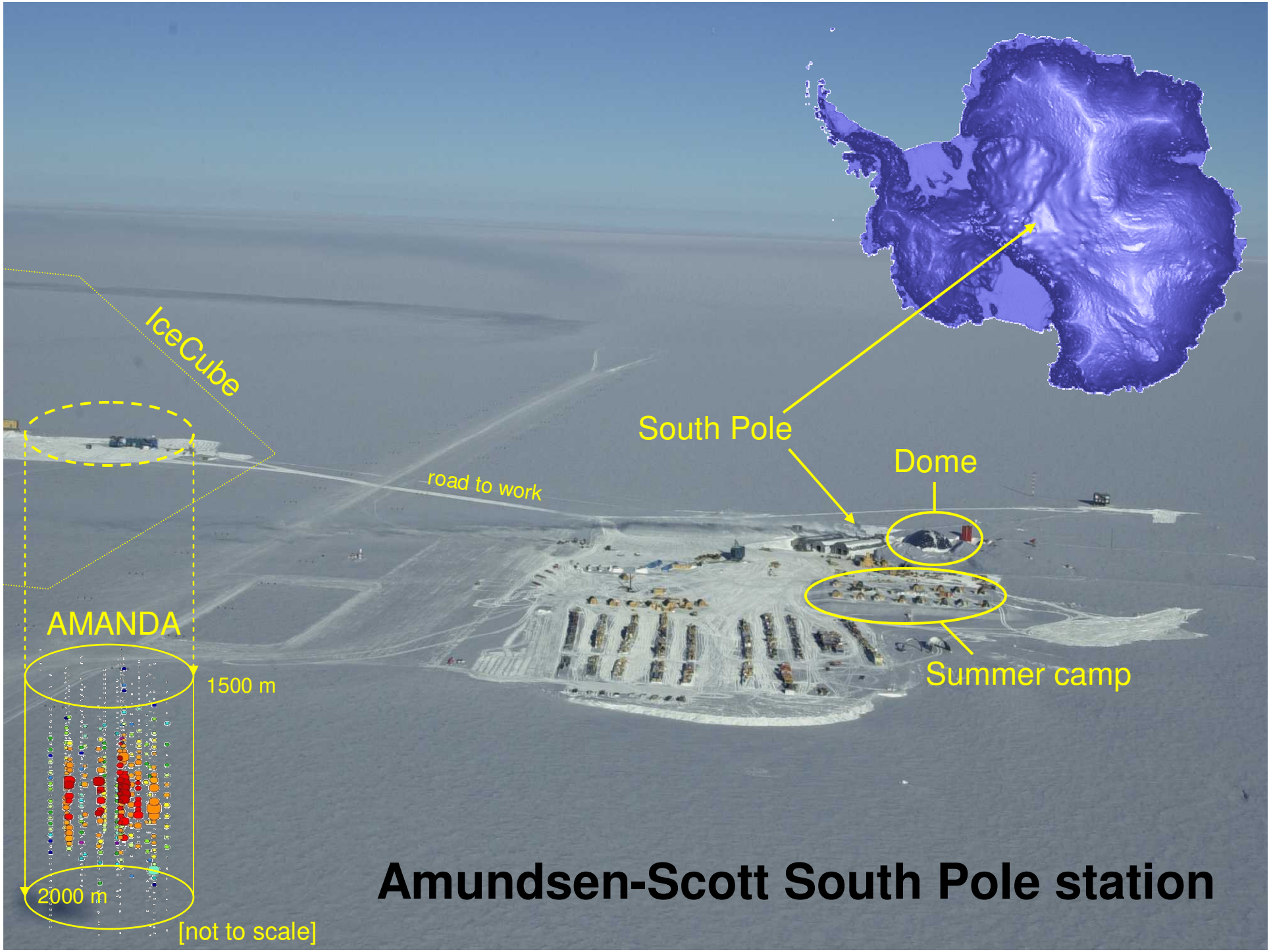
INDIA BASED NEUTRINO OBSERVATORY



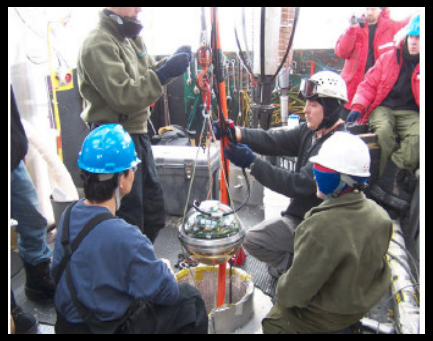
Neutrino Astrophysics

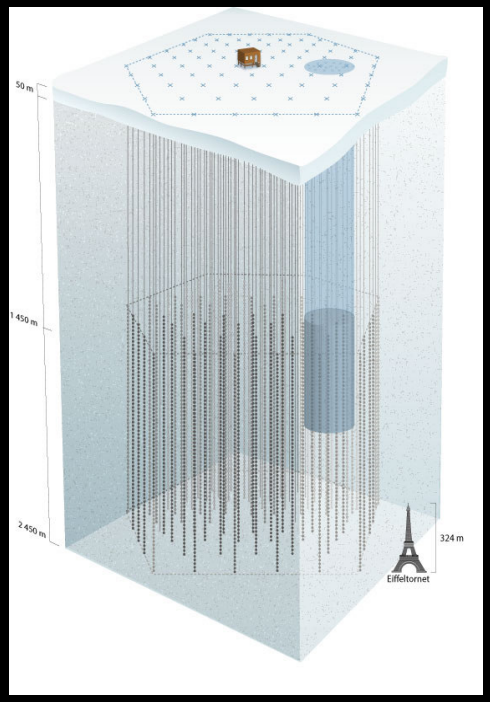
- ***Some big astrophysics questions of our time which neutrino observations can help answer:***
  - ***Cosmic ray acceleration sites***
    - ***TeV gamma-ray sources***
    - ***Gamma-ray bursts***
  - ***"GZK" cutoff***
  - ***Dark matter, Supersymmetry***

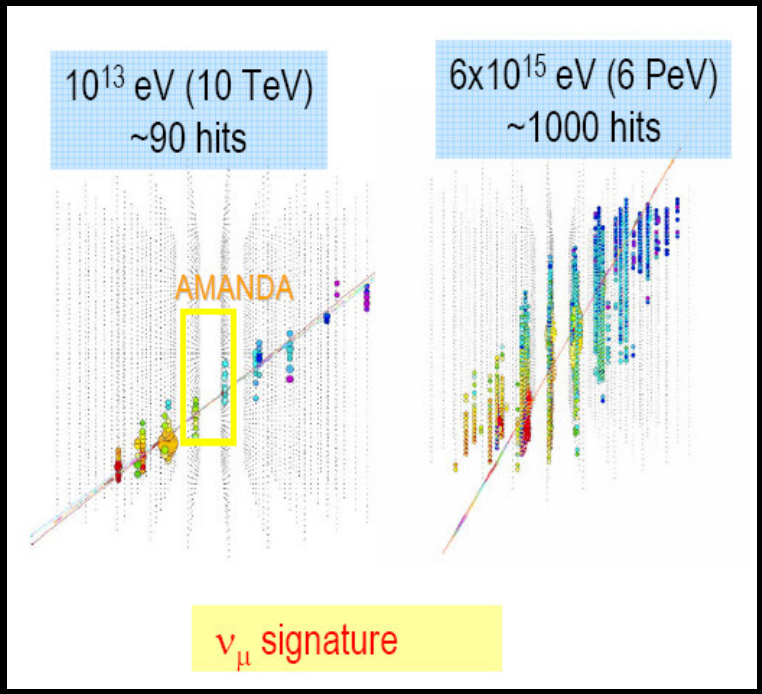



IceCube
AMANDA
1500 m
2000 m
[not to scale]
road to work
South Pole
Dome
Summer camp
Amundsen-Scott South Pole station

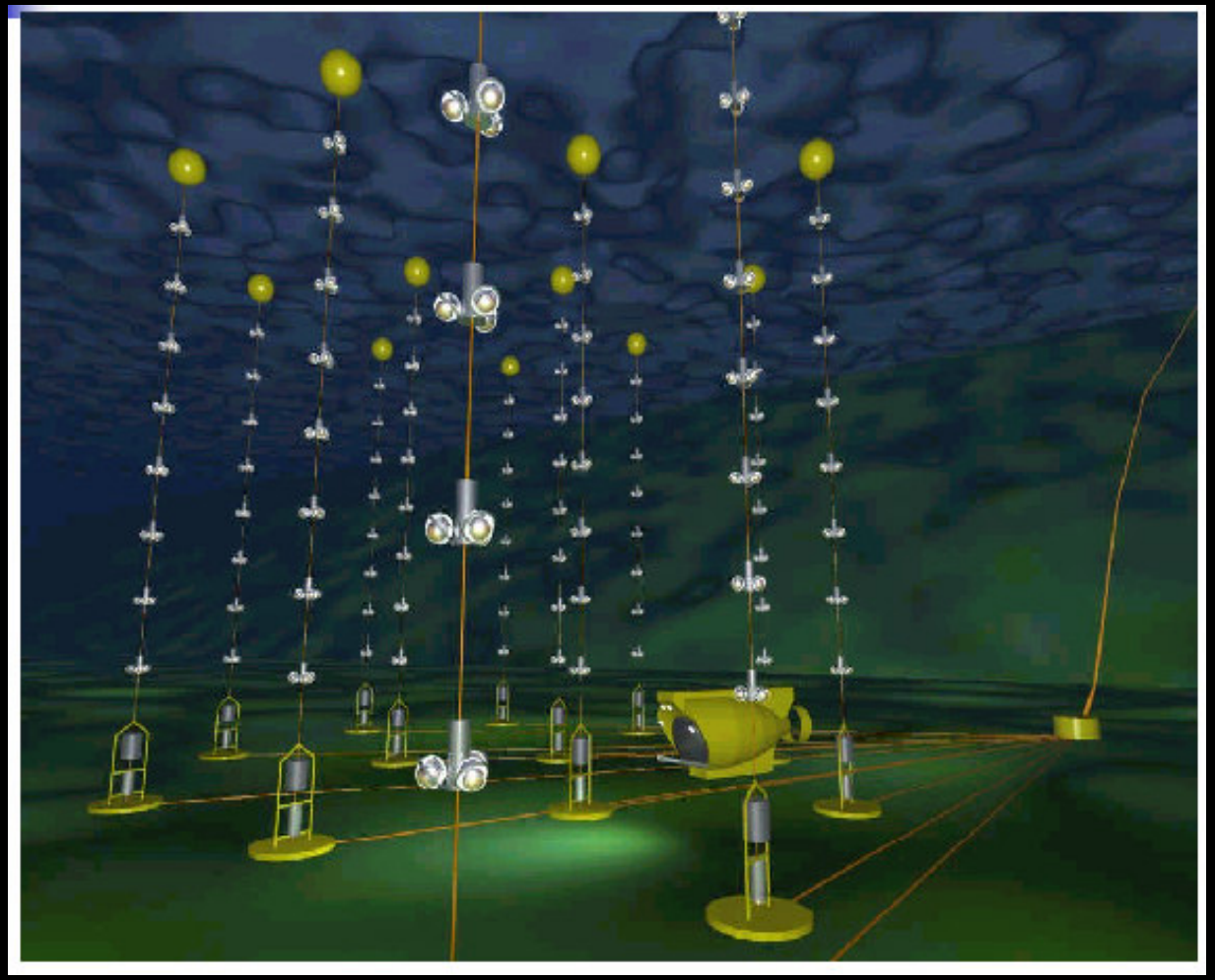
Making of ICECUBE







ANTARES



ANTARES + NEMO + NESTOR - → KM3NeT

Far Future:

- *Uses/Applications of Neutrinos:*
- *Many obvious ones: As Probes to study interiors of many objects such as Nuclei, Nucleons, the Earth, the Sun, other stars, early universe……..*
- *More ambitious/imaginative proposals……..*

Neutrinos and Nuclear Disarmament:

For Near Future:

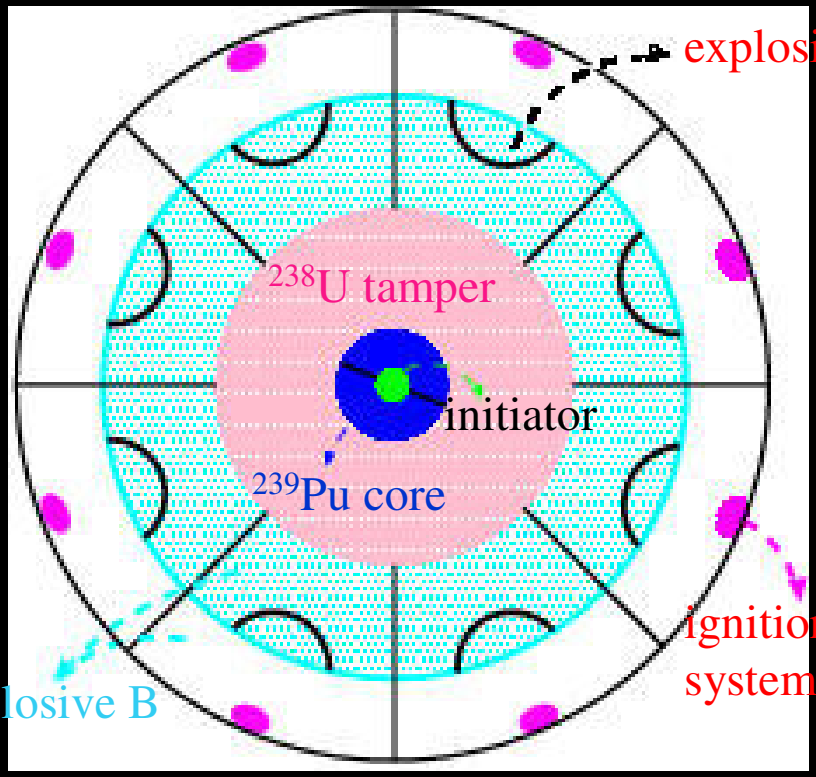
Close-up nu monitoring of cooperative reactors

Ideas for very long term future:

1. Searching/monitoring Rogue Nuclear Reactors

2. Destroying Nuclear Weapons (Sugawara et al)

What is a nuclear weapon?



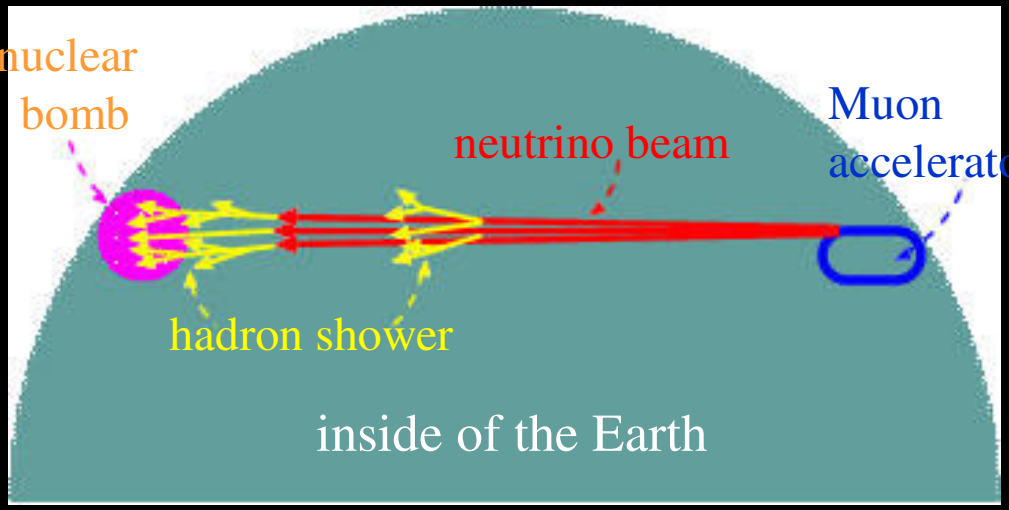
1. Ignition by explosives
2. Shock wave is created, density wave makes ^{239}Pu and ^{238}U go beyond the critical point
3. Initiator gets broken (aluminum foil)
4. In 10^{-6} sec super-critical fission reaction occurs everywhere in the core
5. Tamper works to suppress “fizzle explosion”
6. Full explosion produces a bomb yield of ~20 kt

How to eliminate them from the other side of the Earth?

Basic Idea:

E_ν ~ 100 – 1000 TeV

Mean free path = diameter of the Earth



① Hadron shower hits the target bomb and causes sub-critical nuclear fissions

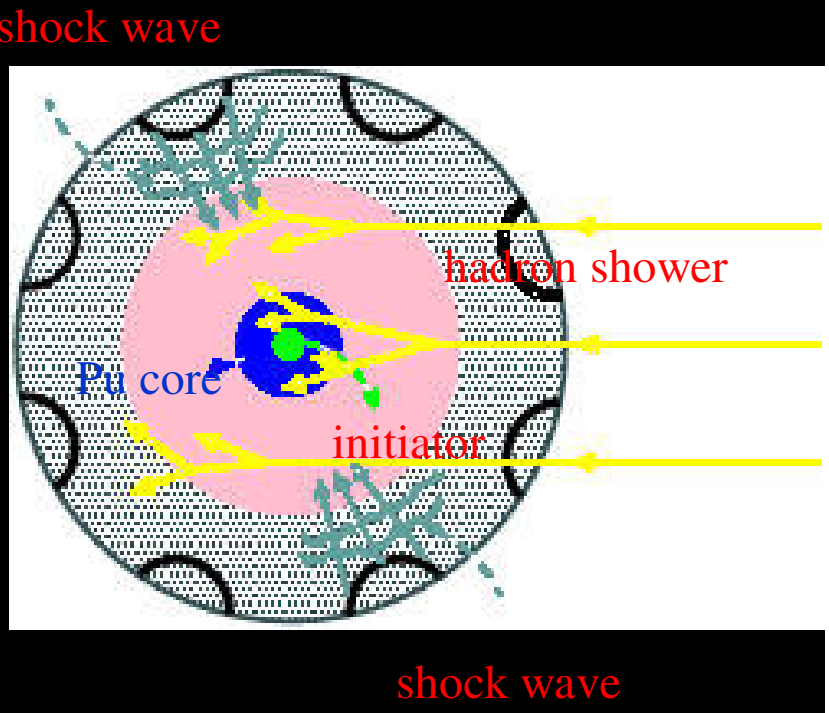
② The temperature of the bomb increases

③ Above 250 degrees the surrounding explosives (dynamite) get ignited

④ The rest of the process is the same as the `ordinary' nuclear bomb explosion

The important difference!

1. The bomb is exposed to hadron beams which play the role of initiator.
2. The beams cause sub-critical chain reactions to start before the shock wave reaches the center
3. Such a phenomenon is well known as the ``fizzle explosion”
4. This makes the destruction of the nuclear bomb relatively safe.



Conclusions

- Neutrinos are *weird*
- Strong evidence for neutrino mass
- Small but finite neutrino mass:
  - Need drastic ideas to understand it
- *Neutrino mass may be responsible for our existence (or even the universe itself)*
- A lot more to learn about neutrinos
- INO detector expected to play a major role