What can you tell from a hole in the ground?

And why would you want to know anyway??

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Outline of talk

- Some background: the Sun
  - History
  - In the beginning: The force of gravity
  - Radiation pressure versus gravity
  - The mass of a nucleon to the mass of nuclei
  - Nuclear fusion
  - From the Sun to other Stars

Outline of talk

- Some more background: Particle Physics
  - What are fundamental particles?
  - Neutrinos in particular
  - The solar neutrino puzzle
  - Neutrino oscillations
  - The Nobel Prize

Outline of talk

- Now that we know *why* we care, what about the hole in the ground?
  - The India-based Neutrino Observatory: INO
  - Some physical facts about INO
  - Some physics facts that we can learn from INO
  - Where will INO be located?
  - The bottom line: current status of INO

How does the Sun shine?

Some Solar Hypotheses

19th C Hypotheses of solar energy and age of Solar system

➢ The radiated heat is due to the gravitational contraction of a large mass. von Helmholtz, 1854

➢ The Sun's heat is produced by meteors continually falling on the Sun and the primary source of solar energy was the gravitational energy of these metoers. Kelvin, 1854

➢ Darwin needed the Earth to be at least 300 million years old in order to produce the observed erosion of the great Weald (valley) in the south of England. He concluded this time-scale was long enough for natural selection to have produced such diversity of species as are found to exist.

➢ Since the Sun's heat is responsible for life on Earth, the Sun must be at least as old.

More history: Age of the Earth

- No, said Kelvin: The (modified) meteor theory would allow for a maximum of 30 million years. If you take an object with the Sun's mass and divide by known luminosity (measured on Earth), you get the Sun's lifetime to be 30 million years. Just fine. No other chemical reaction would give a lifetime larger than 3000 years!

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- The main realisation of Kelvin was that his second law of thermodynamics would make the Sun (and Earth) colder and colder by radiating away their heat, unless there is a *long-lived* source of energy within the Sun. This, he believed, could only be gravitational energy.

- The age of the Earth, then and now, and the origin of solar energy (and how long it would last!) were / are important questions for physics, astronomy, geology, biology, ...

In the beginning: The force of gravity

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- The matter already at the centre gets more and more compressed. It becomes spherical, since gravity is a symmetric force.

Radiation pressure versus gravity

- Gravity is a long-range force (in fact, its range is infinite: $1/r^2$). It's always there! It's also always attractive.

- Ultimately, therefore, gravity will overcome the repulsion between electrons (both the electrostatic repulsion and the Pauli blocking), thus bringing protons together. Remember: these are positively charged objects!

- The compressed matter becomes hot. The temperature of the gas (and its density) increases to a point where nuclear fusion can occur. So nuclear fusion is indeed enabled by compression due to gravitational energy (Kelvin). But Kelvin did not know about nuclear energy.

- Before we say anything more on fusion, some facts.

The true story . . .

. . . as we know it now

- Radioactivity releases enormous amounts of energy, million times larger than from chemical transformations.

$$\begin{array}{rcl} 1\ \text{Å} & \leftrightarrow & 1\ \text{fm} \\ 10^{-10}\ \text{m} & \leftrightarrow & 10^{-15}\ \text{m} \\ 1 & : & 10^{-5} \end{array}$$

  Generally, $E \sim$ 1/distance or $E(\text{nuclear}) \sim 10^5\ \text{E}(\text{atomic})$.

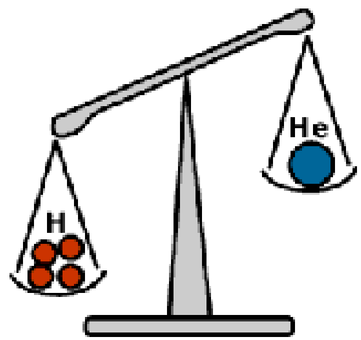
  This follows from Heisenberg's Uncertainty relation:

$$\begin{array}{rcl} \Delta x\, \Delta p \text{c} & \sim & \hbar\ \text{c} \\ \text{c} \Delta t \Delta E & \sim & \hbar\ \text{c} \end{array}$$

- Where does this large nuclear energy come from?

Nuclear energy

Nuclear energy comes from transforming mass to energy, according to Einstein's equation, $E = mc^2$. In the case of nuclear fusion, it comes from Aston's discovery (1920) that 4 hydrogen nuclei are heavier than a helium nucleus.



The difference arises due to nuclear binding.

Words like nuclear binding, mass defect, etc., including why we are made of stardust, are parts of another story!

The key to the old puzzle

In 1920, Eddington used the results of Aston to argue that hydrogen could burn into helium in stars like the Sun, and in principle, that there was enough energy in the Sun for it to shine for 100 billion years.

“If, indeed, the sub-atomic energy in the stars is being freely used to maintain their great furnaces, it seems to bring a little nearer to fulfillment our dream of controlling this latent power for the well-being of the human race—or for its suicide.”– Eddington.

“We scientists recognise our inescapable responsibility to carry to our fellow citizens an understanding of atomic energy and its implications for society. In this lies our only security and our only hope–we believe an informed citizenry will act for life and not for death.”– Einstein

All this is also part of another story!!

Technical points about nuclear fusion

Question: How can two protons (which have the same electric charge) come close enough together for them to fuse?

This does not happen classically. However, in 1928, Gamow used quantum mechanics to show that this could indeed happen. The *Gamow factor* calculates this probability of overlap.

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$$p + p + p + p \rightarrow {}^{4}\mathrm{He} + 2\,e^{+} + 2\nu_e + 26.7 \text{ MeV} \,.$$

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What is the world made up of?

What is the world made of?

- Matter and radiation.
- Matter is made up of particles: atoms or molecules. Einstein proved this in 1905 (Brownian Motion).
- Light is made up of waves. It has a *wave* nature. Established conclusively by end of 19th century (Maxwell's equations of electrodynamics).
- Light also behaves as a particle, called *photon*. The photon is a light quantum. Its discovery lead to the birth of quantum theory. Established by Eistein's explanation of the photoelectric effect (1905; got 1921 Nobel prize for this. Planck originally proposed $E = h\nu$. Also by Compton in Compton Scattering (1927 Nobel)).
- Hence light is said to have a dual nature.

Flip-flop

- Electrons also have a dual nature (de Broglie, 1929 Nobel).
- Quantum mechanics was formulated in 1926 by Schrödinger and Heisenberg. Inconsistent with Special theory of relativity.
- Dirac, 1928, formulated a new relativistic wave equation: two new ideas: *spin* and *antiparticle*.
- Matter and antimatter have related properties like same mass, opposite charge, etc. Eg: p^+, $\bar{p}^-$, e^-, $\bar{e}^+$.
- Some symmetries surely exist that allow for such similarity. Quantum mechanics $+$ principles of symmetry $+$ invariance under special relativity $=$ Quantum Field theory.

What is a quantum field theory?

- A QFT describes the properties and interaction of particles. All particles interact by exchanging other particles which are the carriers of the interaction.
- Eg: Quantum Electrodynamics QED (Feynman): interaction of charged particles and radiation (photons); most precise theory known today. Eg: two electrons repel, electron and proton attract.

Interaction	Mediator	Matter	Physical Consequence
EM	Photon	e, p	Atoms formed
Weak	W, Z	e, μ, quarks	Radioactivity
Strong	gluons	quarks	Nucleus formed
Gravity	graviton	All matter	Universe

Leptons and the Standard Model

- There are four fundamental forces in nature: gravity, electro-magnetic, strong and weak.
- Leptons are those particles that *do not* experience strong forces (which baryons do).
- Weak forces are like beta decay or the fusion processes that power the Sun. (The fusion in a fusion bomb is a *strong interaction process.*)

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Particle	electro-magnetic	strong	weak
p^+	✔	✔	✔
n^0	✔	✔	✔
e^-	✔	✘	✔
ν_e	✘	✘	✔

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- Weak forces are like beta decay or the fusion processes that power the Sun. (The fusion in a fusion bomb is a *strong interaction process.*)
- Leptons come in three *flavours* or *types* or *generations*:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

μ and τ heavier versions of e. Reason for their existence (and no. of generations) a mystery.

All neutrinos are assumed massless within the Standard Model.

The ν_e neutrino is precisely that which is predicted to occur in the fusion processes in the Sun.

Does the Sun really shine in neutrinos?

The proof of the pudding . . .

The proof of the pudding . . .

. . . is in looking for, and finding the neutrinos!

Since neutrinos interact only weakly with matter, notoriously hard to detect.

First attempts were made as early as 1960's.

Early solar neutrino experiments

Davis and collaborators, first results in 1968.

600 tons of perchloroethylene (drycleaning fluid!) containing Chlorine.

$$\nu_e + {}^{37}\text{Cl} \to {}^{37}\text{Ar} + e^- \ .$$

Event rate about 1 in 3 days.

$$\begin{aligned} R^{CC} &= \frac{\text{Number of events observed}}{\text{Number of events expected}} \\ &\simeq \frac{1}{3} \ . \end{aligned}$$

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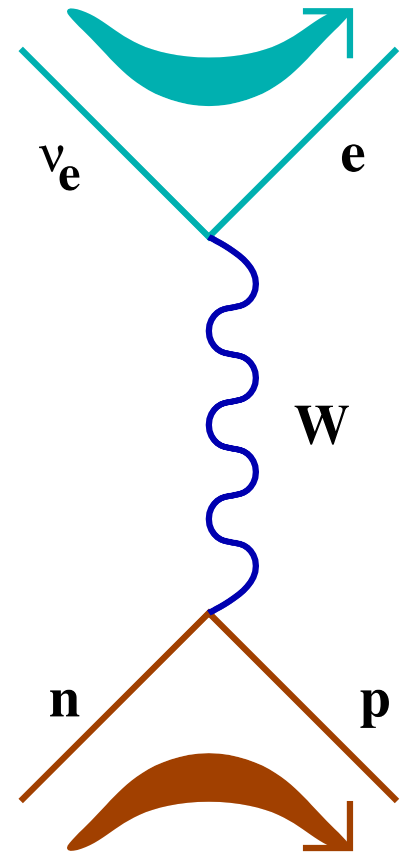

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Are they solar neutrinos?

An important criticism of Davis' experiment was that there was no guarantee that the neutrinos he observed were indeed from the Sun.

Koshiba, Totsuka and collaborators, 1986, Kamioka in Japan, followed by Super-Kamioka, used a tank of water to detect neutrinos. The detection is by elastic scattering of neutrinos on water.

$$\nu_X + e \to \nu_X + e \ .$$

All flavours contribute, but mostly (6:1) e-type neutrinos.

The Super-K solar data

Super-K: 22,500 tons of (pure) water. About 3 events per day.

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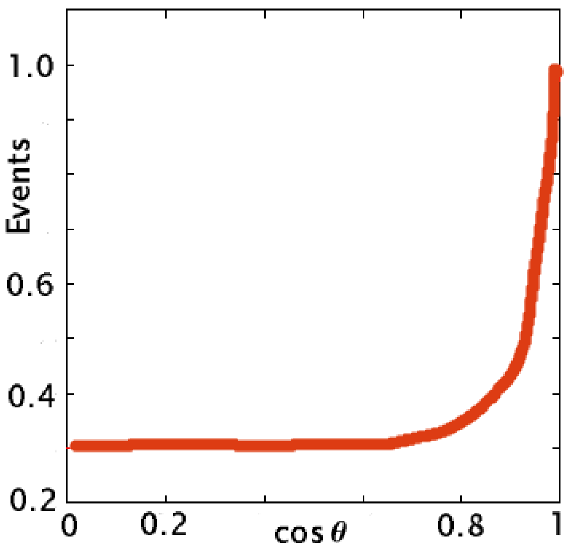


First evidence that the Sun does shine due to nuclear fusion.

Confirmation from GALLEX (GNO) (down to small neutrino energy 0.24 MeV):

$$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^- \; .$$

New puzzle: Rates lower than expected.

The Solar Neutrino Puzzle

Some technical details

Unfortunately unavoidable!

Neutrino oscillations

Neutrinos come in more than one *flavour* or *type*. Consider, for simplicity, two-flavours, ν_e and ν_μ.

If neutrinos are massive (different masses), and, further, show the quantum mechanical phenomenom called *flavour mixing*, then neutrinos can *oscillate* between flavours.

$$\begin{aligned} \nu_e &= \cos\theta\ \nu_1 + \sin\theta\ \nu_2\ , \\ \nu_\mu &= -\sin\theta\ \nu_1 + \cos\theta\ \nu_2\ . \end{aligned}$$

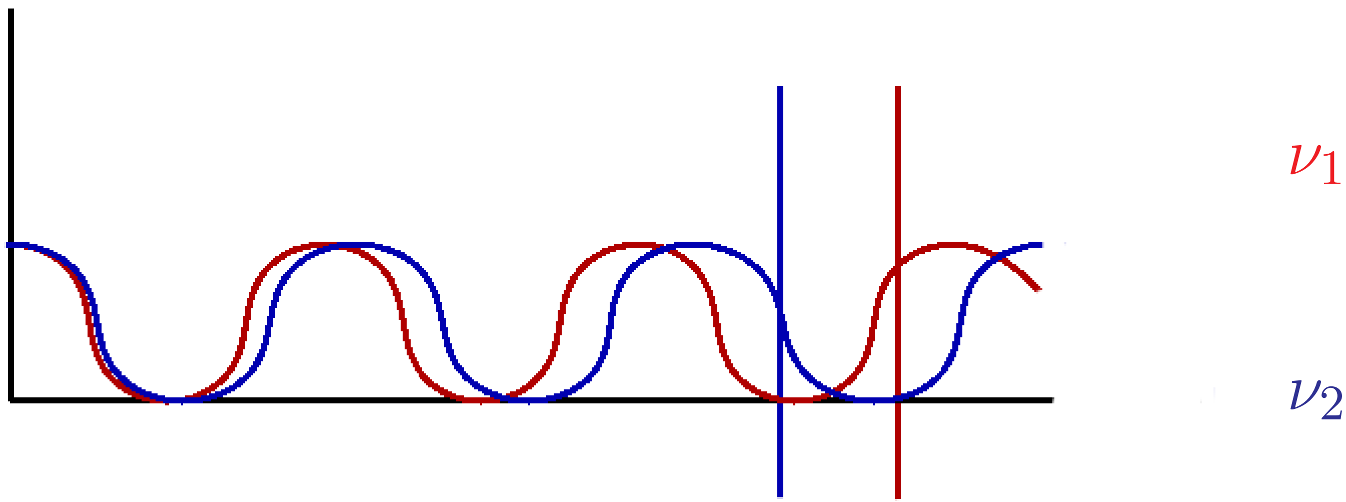
ν_1 and ν_2 are quantum mechanical states with given energy (and momentum) (mass eigenstates). They evolve according to

$$\nu_i(t) = \exp\left[-iE_i t\right] \nu_i(0)\ .$$

Neutrino oscillations

Can then ask what is the probability that a ν_e that is produced at $t = 0$ remains ν_e at a given time $t = t$.

If $E_2 > E_1$, oscillation period of ν_2 greater than that of ν_1.



Real $\nu_e(t) = \cos\theta \circlearrowright + \sin\theta \circlearrowright$

Hence as the neutrino travels to the Earth it oscillates between different flavours of neutrinos.

Caution: No matter effects: neutrinos get modified as they come out of the super-dense (150 gm/cc) core of the Sun.

The final denouement

An obvious test of the oscillation hypothesis is to look for the other flavours of neutrinos, from the Sun.

The SNO detector, Sudbury, Canada, 1000 tons of heavy water D_2O, announced their first results in 2002, and then in 2003.

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&\simeq \frac{1}{3}\ (\text{Cl and Ga}). \\
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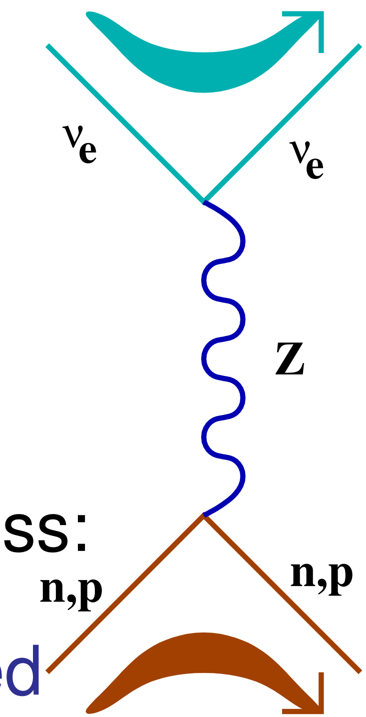

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Hence the Standard Solar Model is vindicated in the neutral current sector.

Outlook

The Sun does shine via weak nuclear fusion. Solar neutrinos have been unambiguously detected.

Solar neutrinos exhibit *oscillation* and hence are massive (at least one neutrino is massive). This is new physics beyond the Standard Model of Particle Physics.

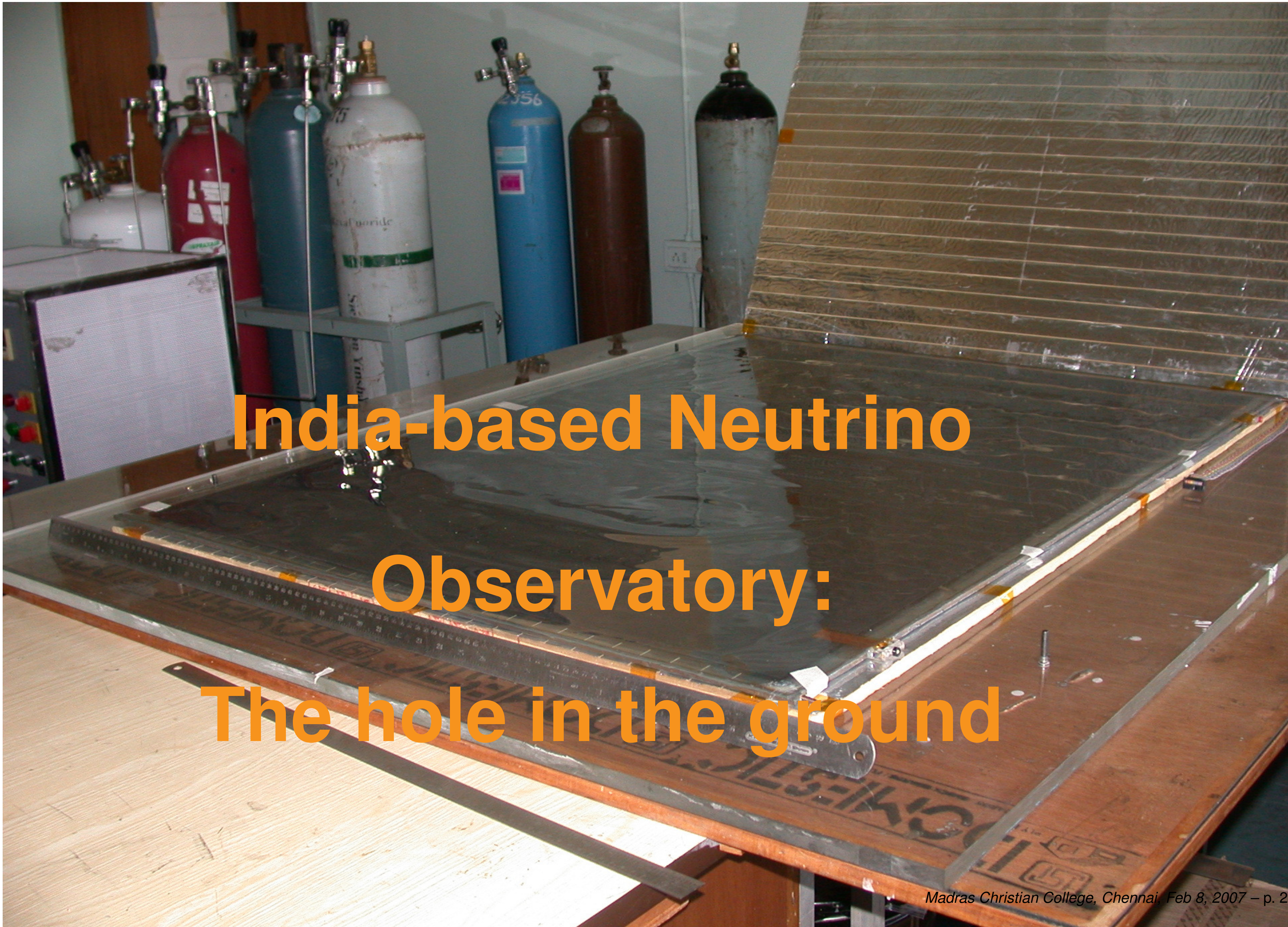
Look for oscillations in other neutrino-related phenomena: atmospheric neutrinos, accelerator neutrinos, reactor (anti)neutrinos, etc.

Very exciting results that relate to fundamental properties of neutrinos and their interactions.

A proposal, the India-based Neutrino Observatory (INO) is exploring the possibility to build an underground neutrino detector in India.

India-based Neutrino Observatory:

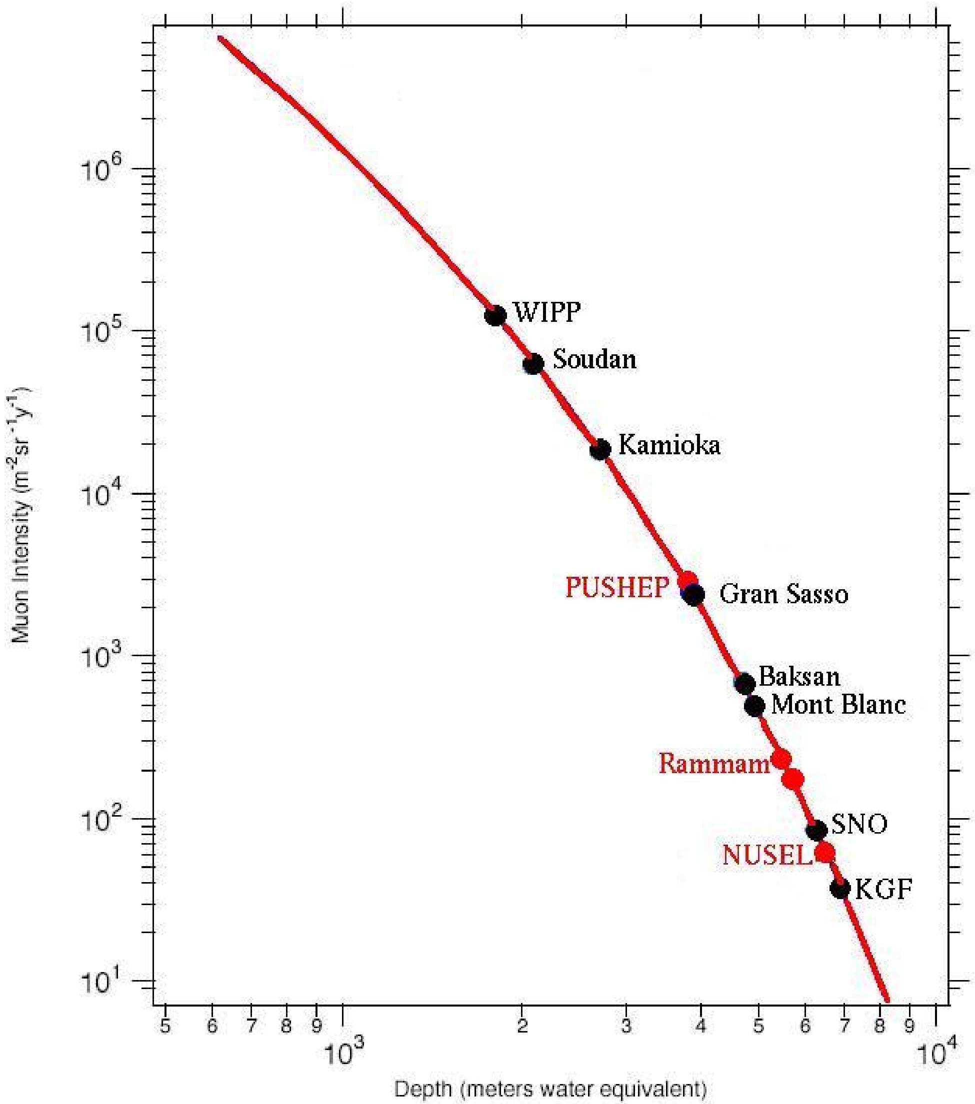
The hole in the ground



Where is the hole to be dug?

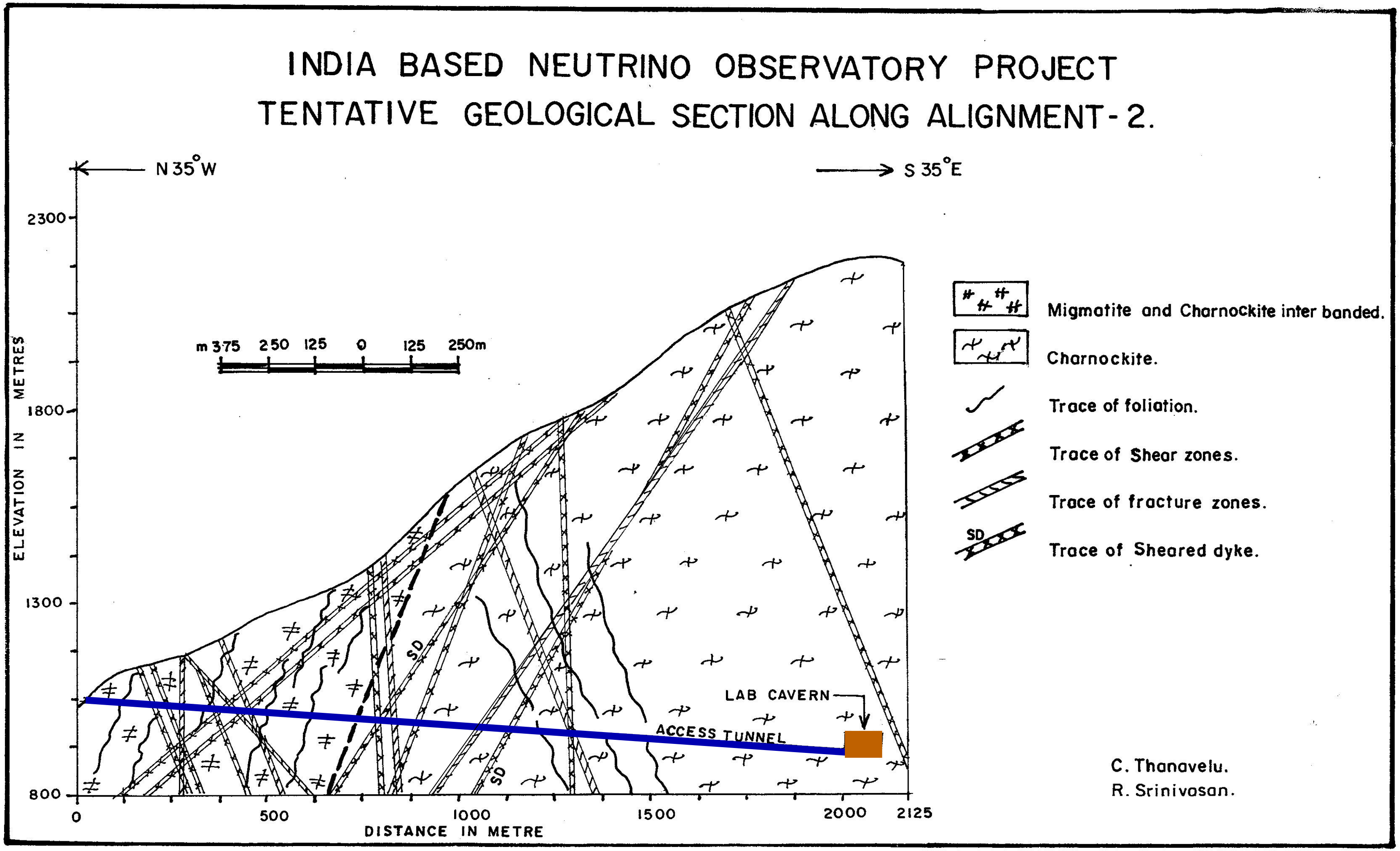
PUSHEP in the Nilagiris, near Ooty (Masinagudi)

Why go underground?



- 2.1 km long access tunnel into mountain; cavern beneath the peak
- Experimental hall I: $25m \times 130m \times 30m$ (height) built to accommodate 50 kton + 50 kton modules (future expansion)
- Experimental Hall II: about half the size, to accommodate other, smaller experiment(s).

Walk in to my parlour . . .



The INO Collaboration

- Spokesperson: N K Mondal, TIFR, Mumbai, nkm@tifr.res.in
- Collaborating Institutions: AMU, BHU, BARC, CU, DU, HRI, UoH, HPU, IITB, IITKh, IGCAR, IMSc, IOP, LU, NBU, PU, PRL, SINP, SMIT, TIFR, VECC

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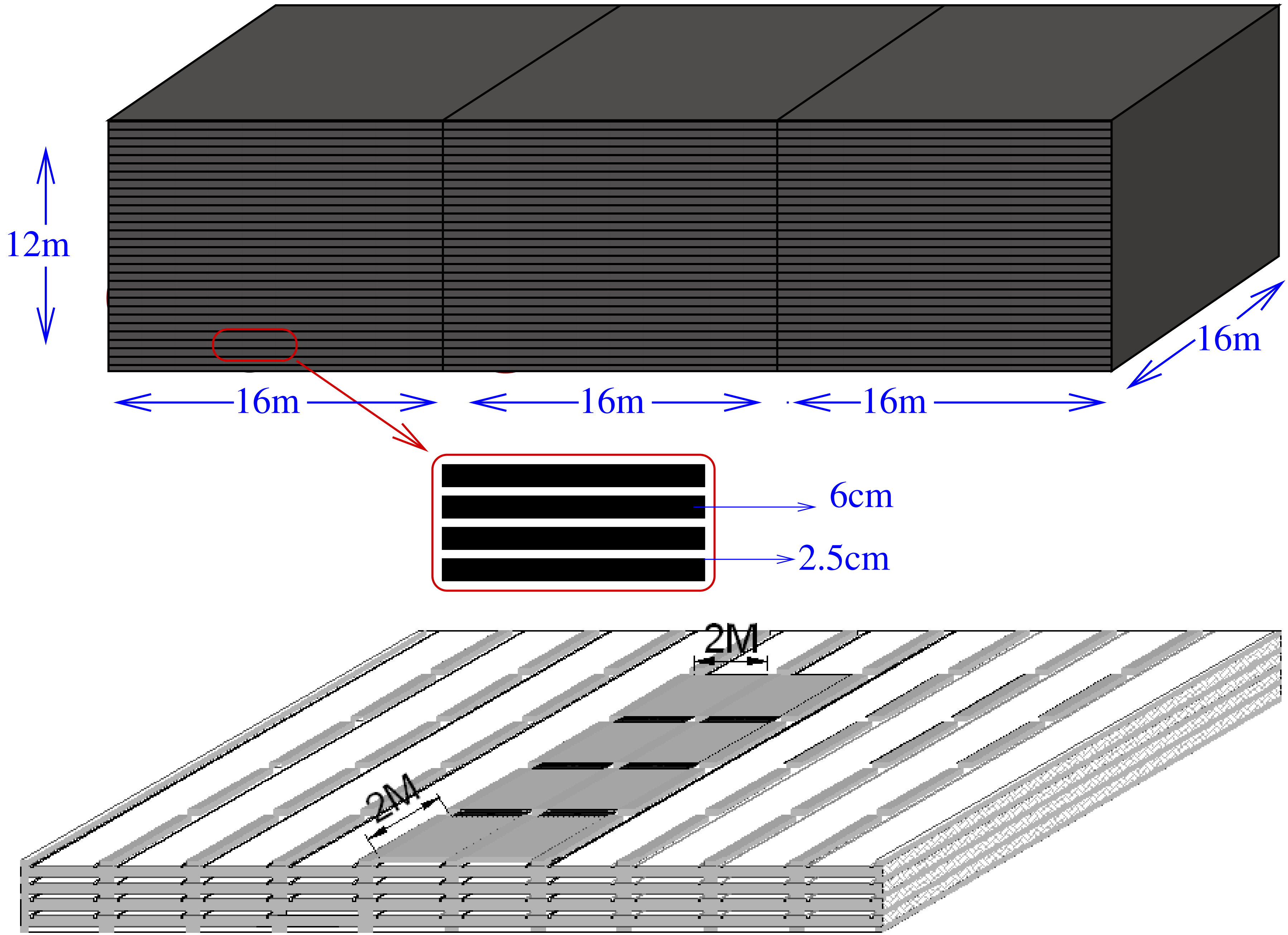
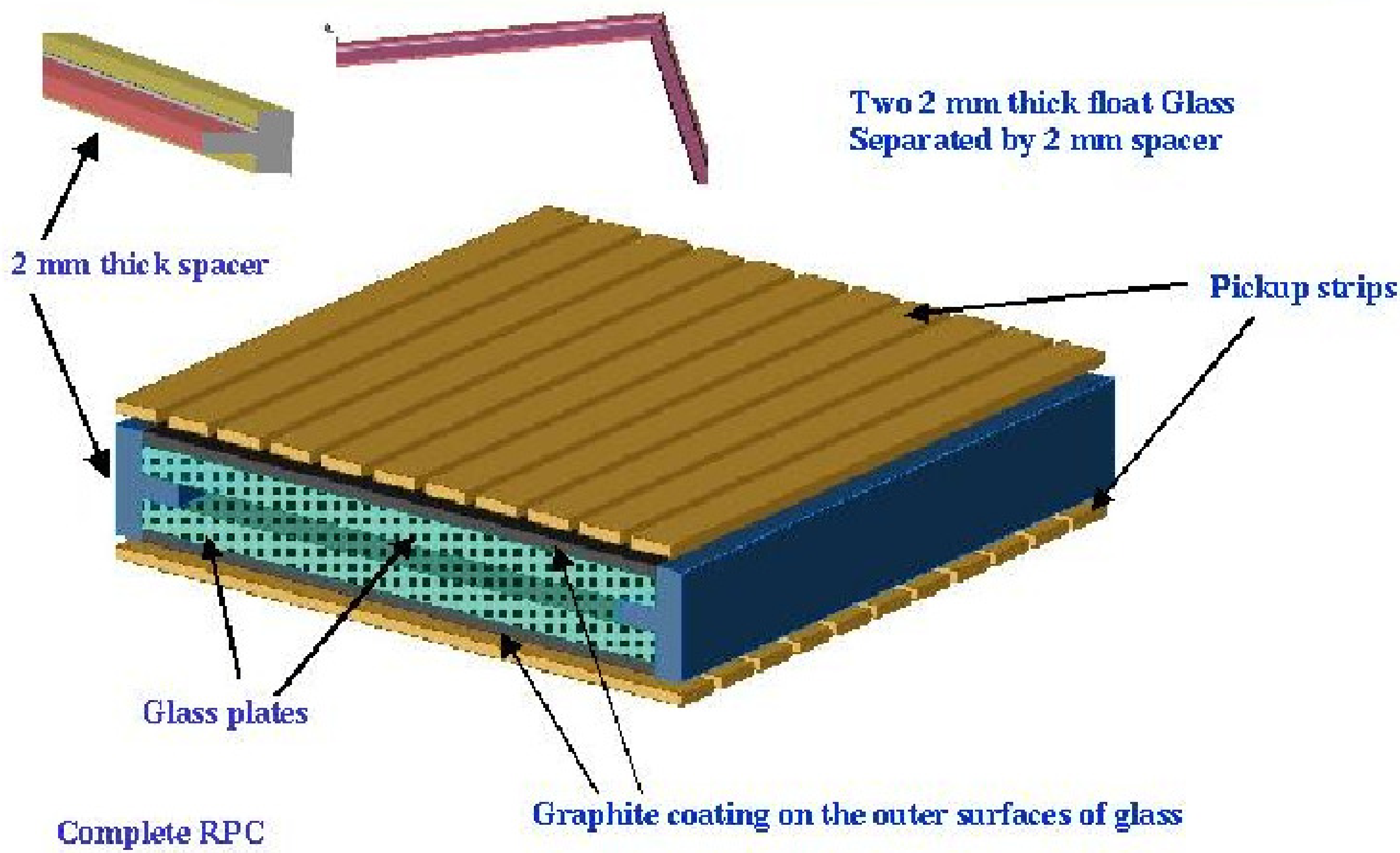
- Should be an international facility

The Iron Calorimenter detector, ICAL

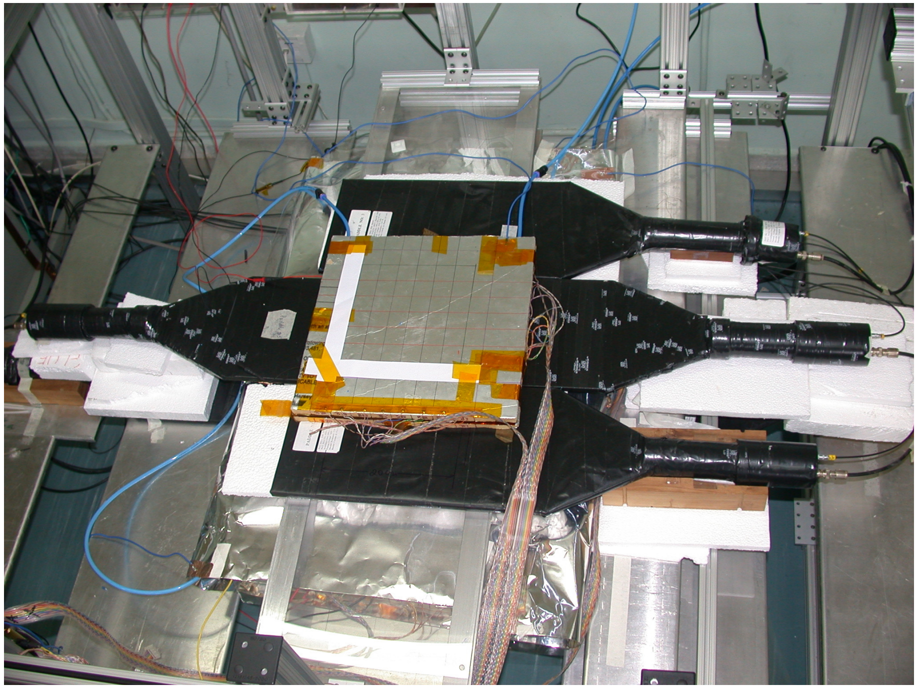


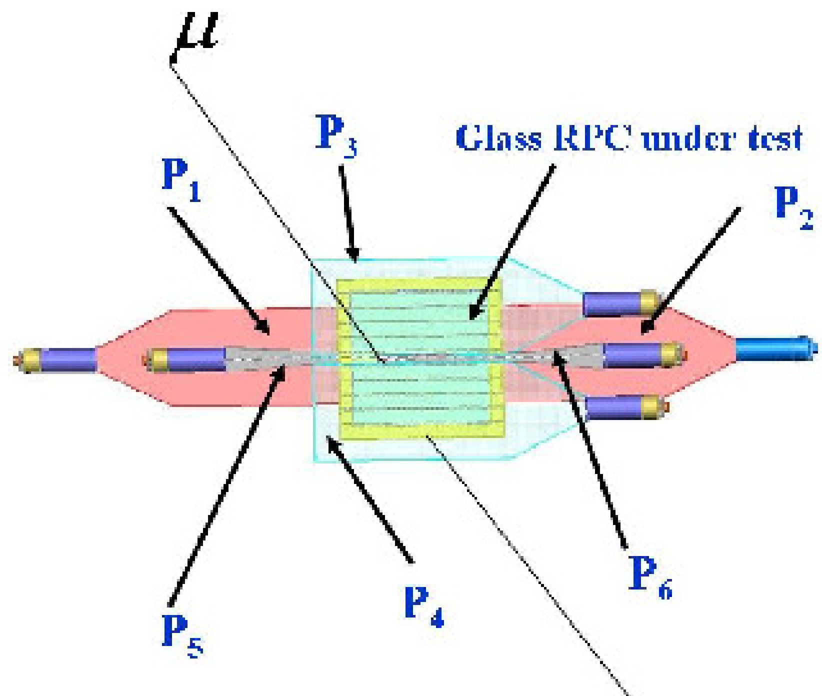
The active detector elements: RPC

RPC Construction: Float glass, graphite, and spacers



Fabricating



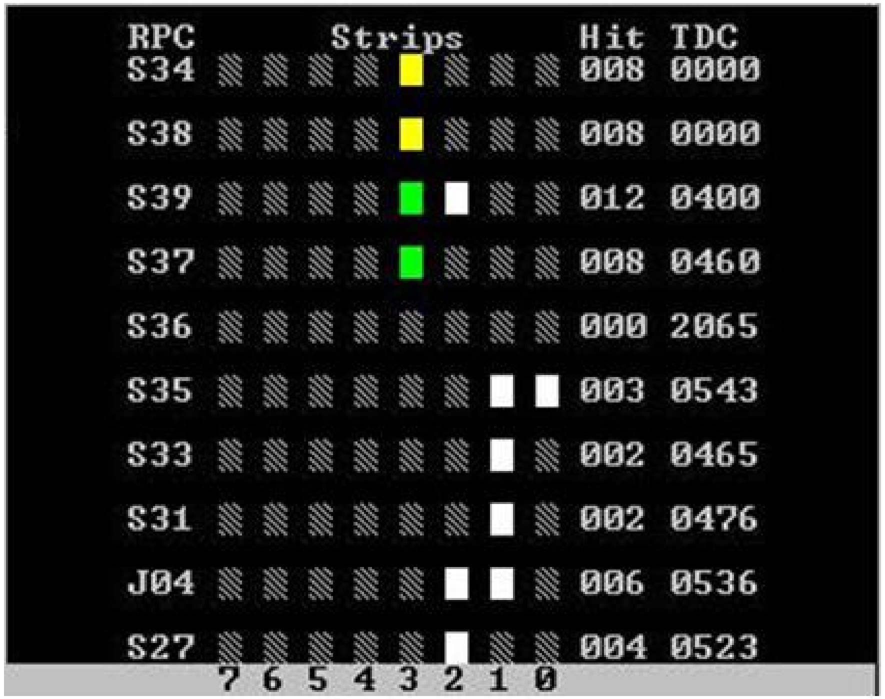


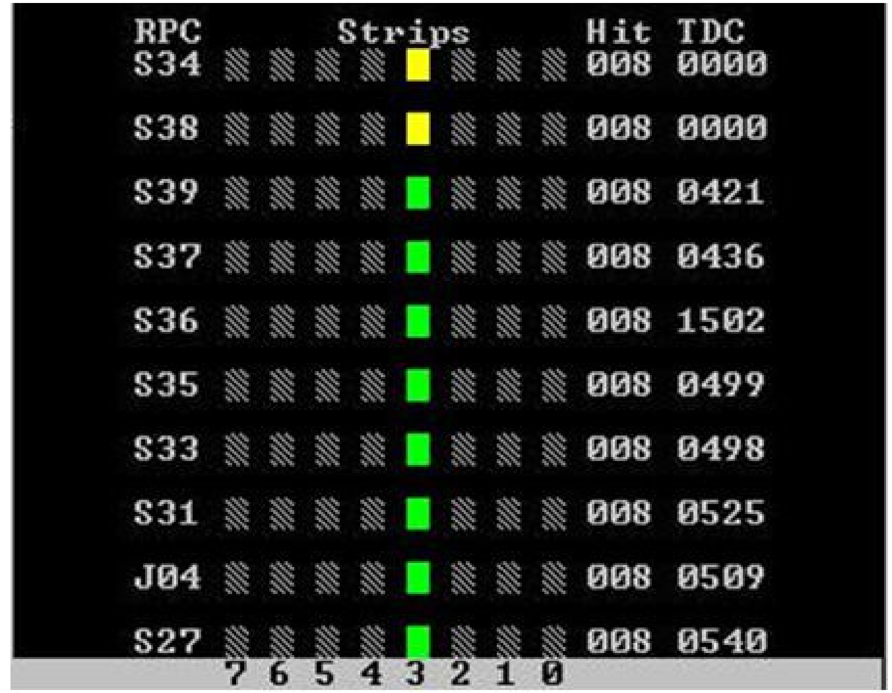
Small ↑

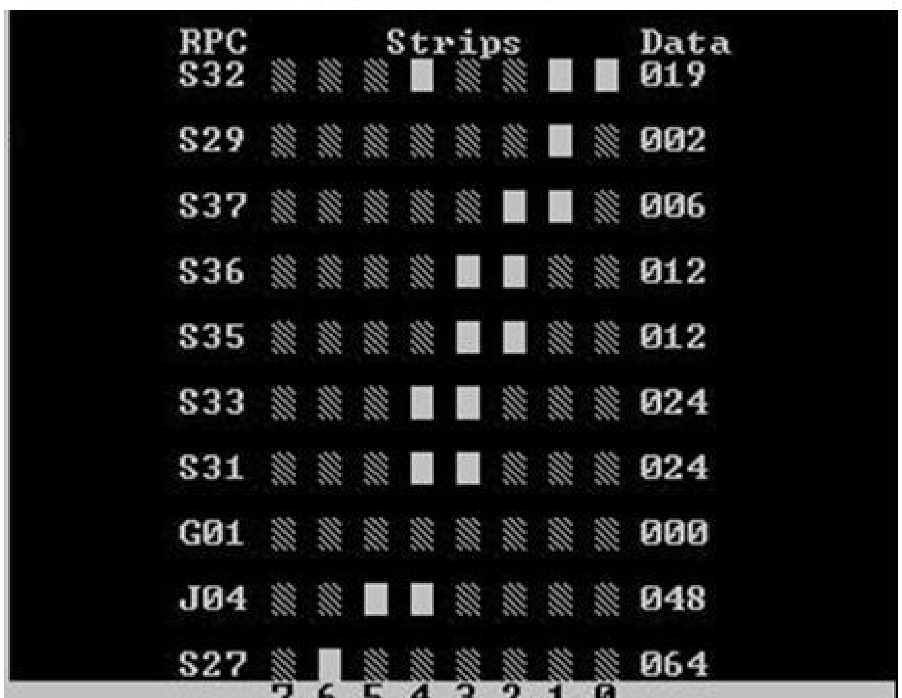
Large →

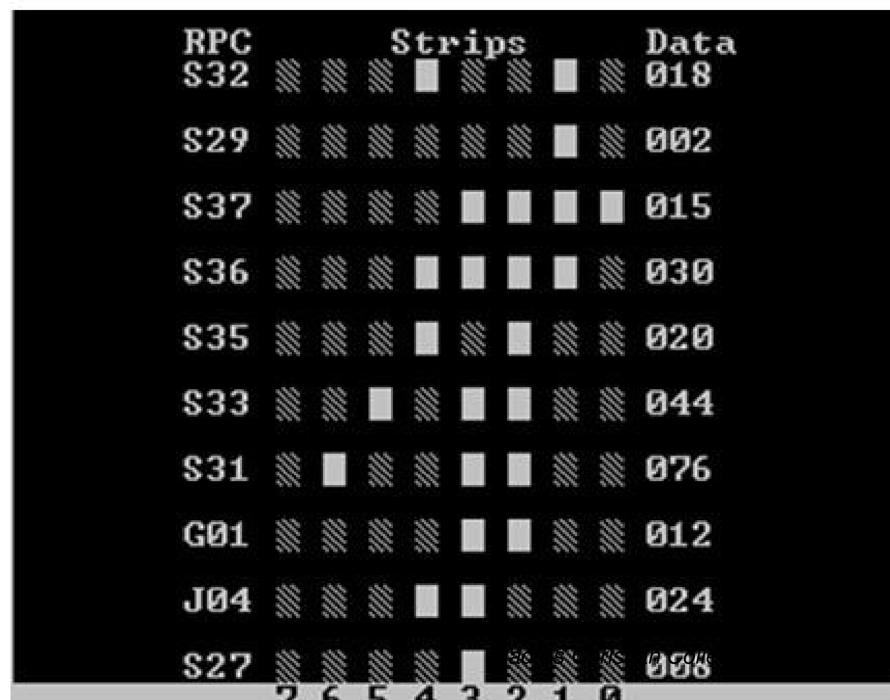
For the prototype . . .

Tracks from atmospheric muons

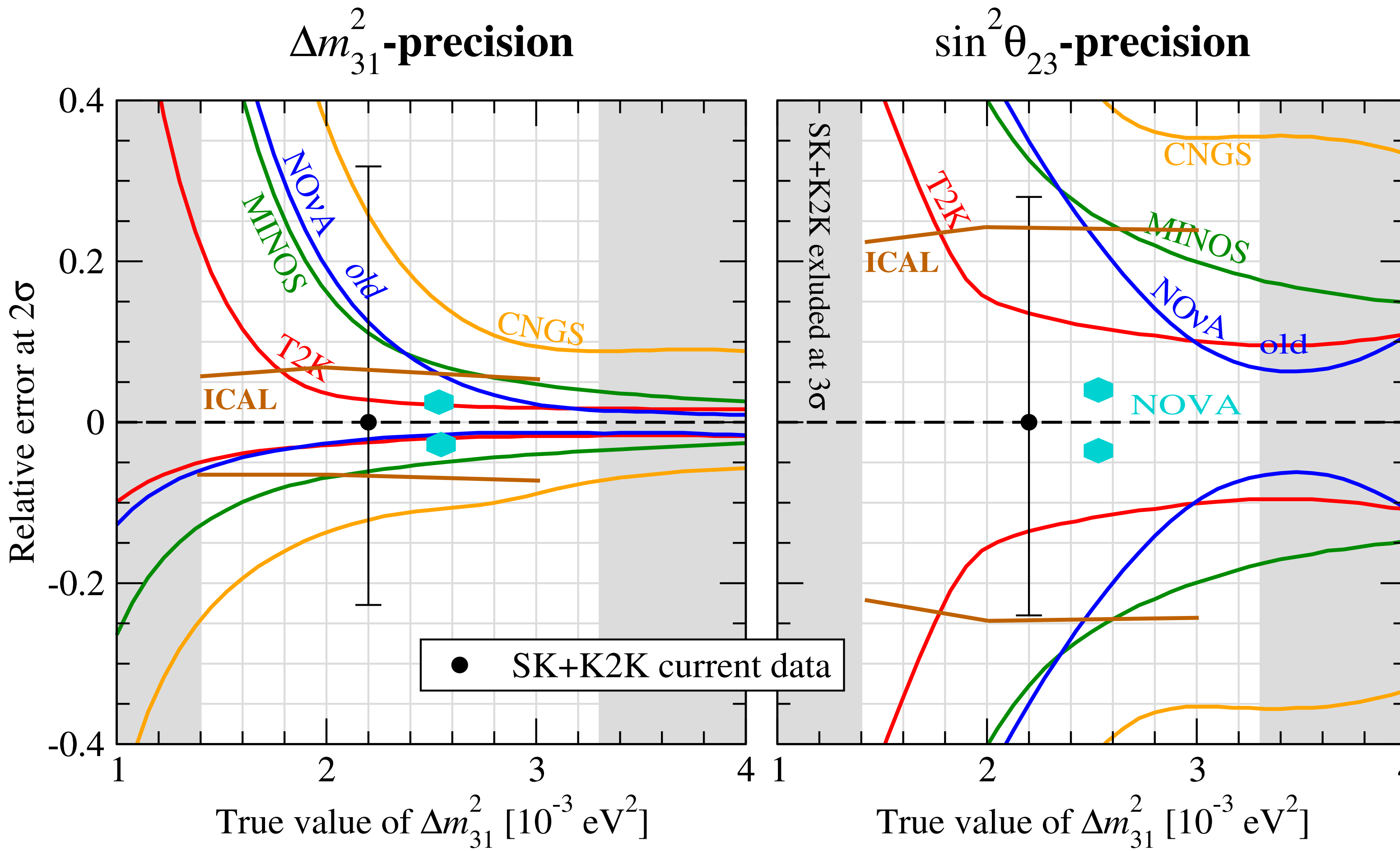








Physics Studies with ICAL



5 years' running; new NOVA 25kton, 6 yrs (6×10^{21} pot).

Adapted from: P. Huber, M. Lindner, M. Rolinec, T. Schwetz and W. Winter, hep-ph/0412133.

Electronics and Data Acquisition System

- When a neutrino enters the detector, it interacts with the iron.
- If a charged current interaction occurs, the neutrino is converted to a charged particle. For example, a ν_μ is converted to a μ which is a muon or a "heavy electron".
- When energetic charged particles traverse the detector, the RPCs discharge; these register as signals/"hits" in the electronics.
- The anode/cathode pick-up signals (induced on X- and Y-pickup strips) are sent to timing discriminators
- Need fast current preamplifiers (risetime ~ 1 nanosec) with gain 10–30.
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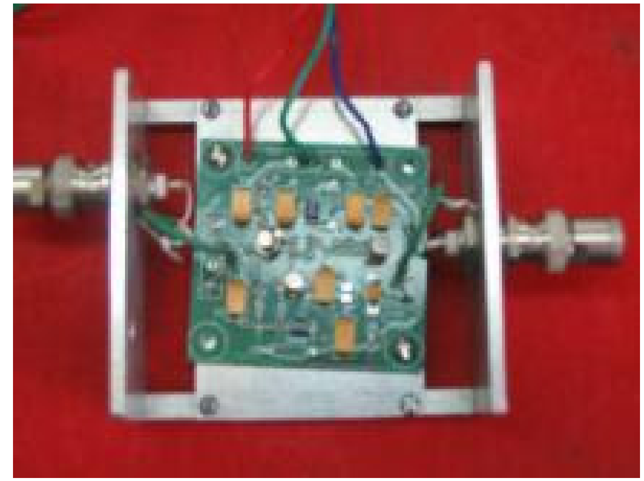
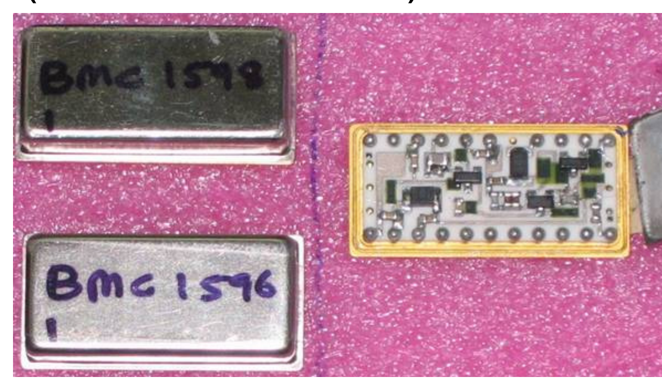
Discrete comp. pre-amp



Hybrid versions (BEL-ED/BARC)

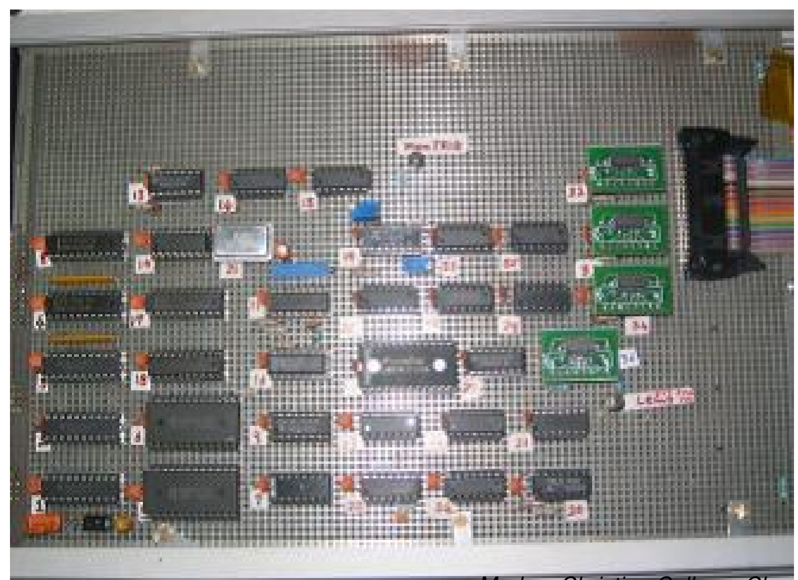


Data Acquisition DAQ, etc

- Physics-based choice of trigger initiates DAQ
- Event trigger generated by FPGA-based home-built module
- VME-based DAQ coupled to PCs with Linux OS
- In-house electronics development (TIFR): Full FPGA based data acquisition system for prototype fabricated and being tested

16-ch analog front end module

DAQ control



INO: Current Status

- May, 2005: INO interim report was presented to the funding authorities as well as to the general scientific community at a meeting in TIFR, Mumbai
- August 2005: Presented to the SAC-PM committee
- April 2006: It was endorsed by the community at a meeting in Mumbai to define the joint road-map for HEP and NP research in the country
- August 2006: Recommended by the committee set up by the Planning Commission to the Mega Science projects for funding
- October 2006: Reports from the international panel of referees received by Chairman, INO-PMC (Director, TIFR)
- The technical review of the INO proposal is complete and is favourable. It is now with the funding agencies for approval.

In short . . .

The outlook looks good! This is a massive project:

Looking for active collaboration both within India and abroad

The INO Collaboration[1]

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[1]This is an open collaboration and experimentalists are especially encouraged to join.
[2]since retired
[3]Replacing Abdul Salam who was a member until March 5, 2005