The INO project

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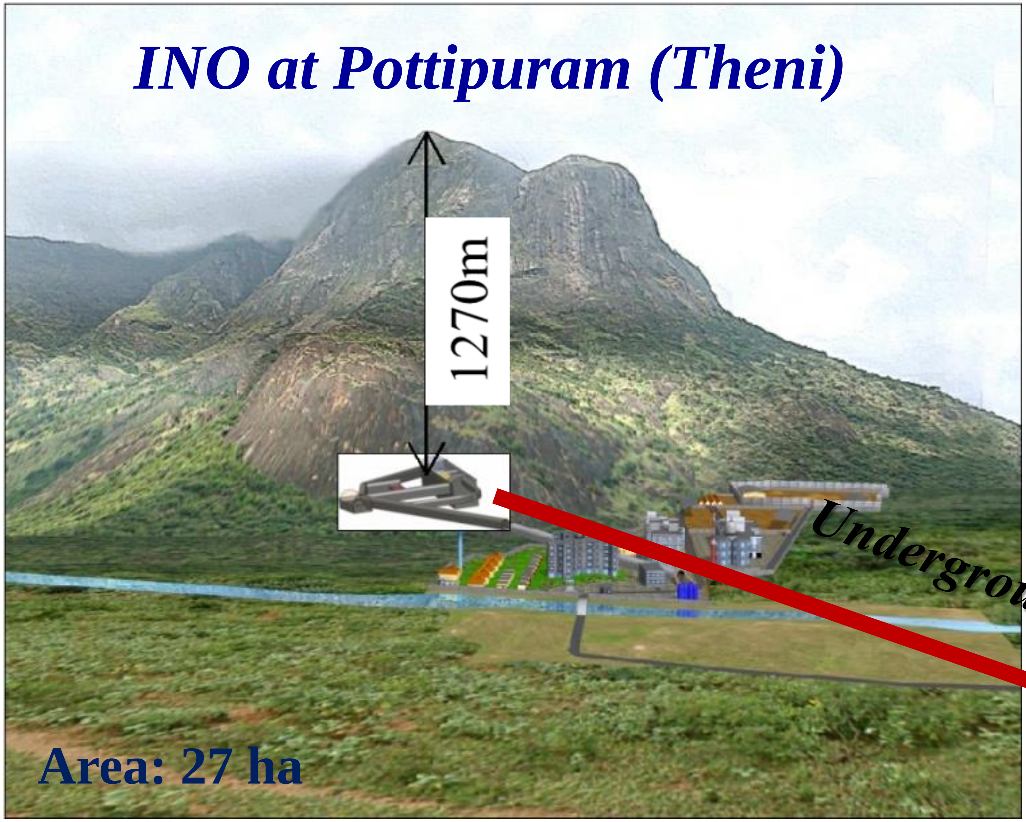
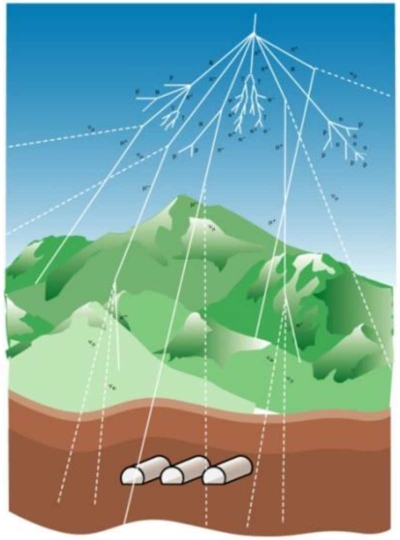
Mumbai-400005

EILH-2016, AMU, Nov 2-6, 2016

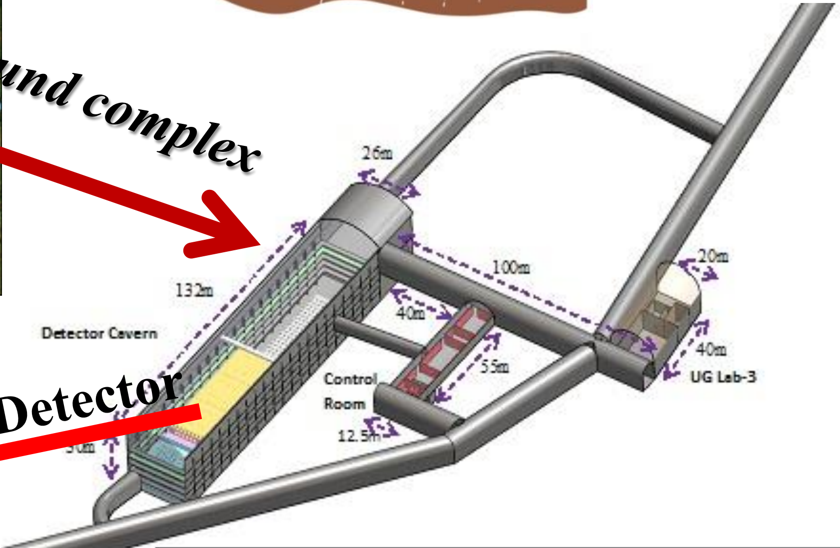
INO at Pottipuram (Theni)



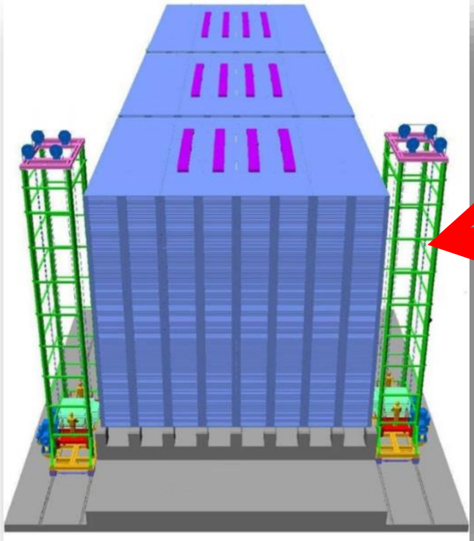
Area: 27 ha



Underground complex

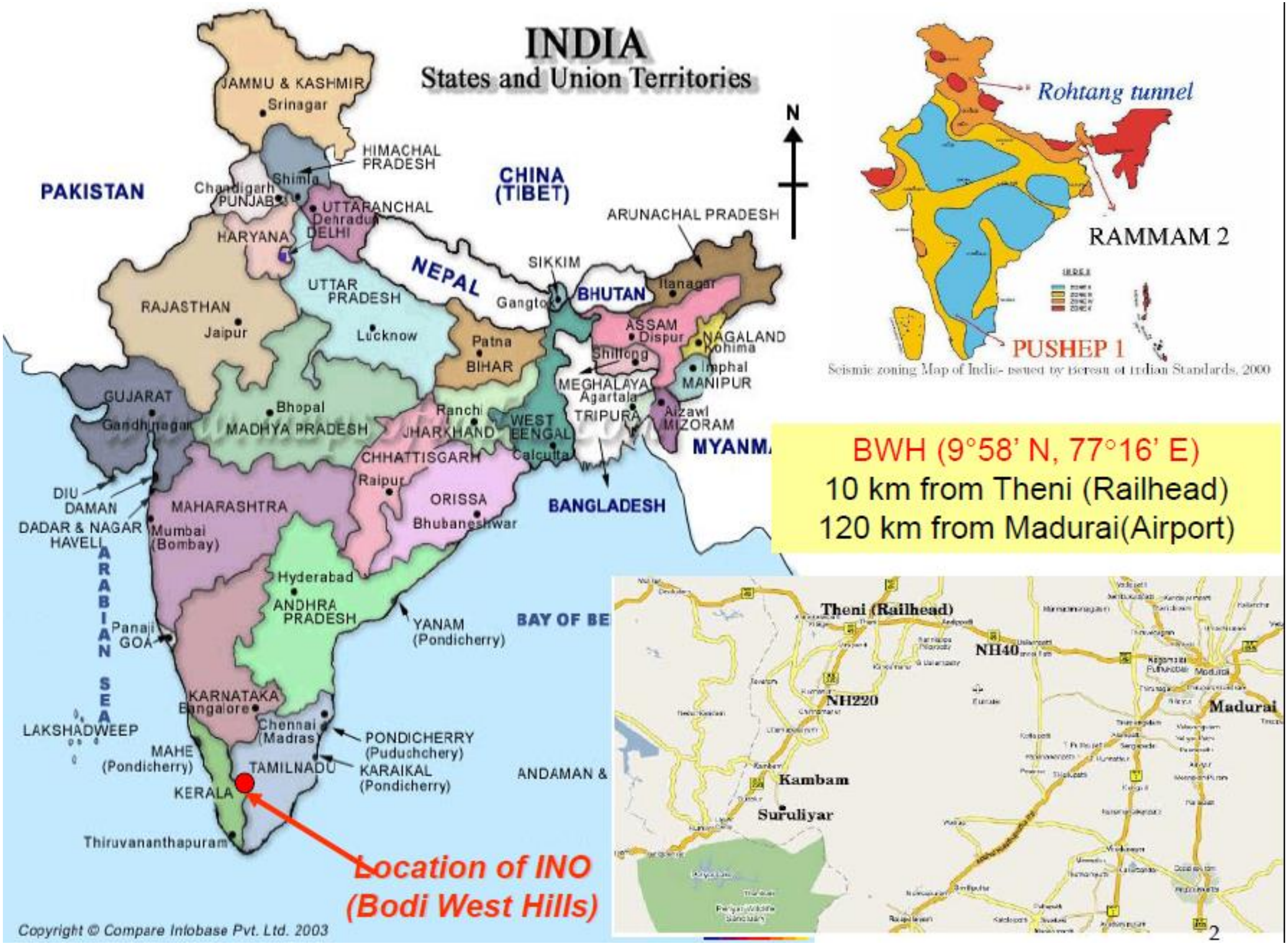


51 kton ICAL Neutrino Detector



3×17 kton ICAL modules
2×2m^2×28800 glass RPCs
~3.7M electronic channels

IICHEP, Madurai (Area: 12.6 ha)



BWH (9°58' N, 77°16' E)
10 km from Theni (Railhead)
120 km from Madurai(Airport)

~25 institutions (national labs, Universities, IITs) participating

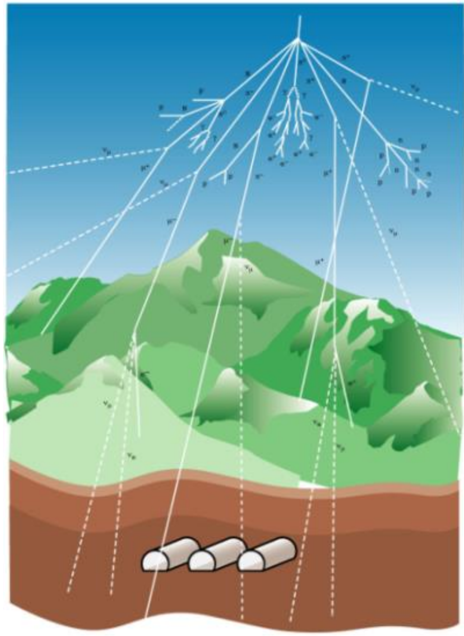
Why INO?

- An underground lab to study neutrinos, dark matter…
- Measure neutrino mass ordering, will help us understand how universe evolved (matter-antimatter asymmetry)
- Help us go beyond Standard Model of Particle Physics
- Development of biggest electromagnet, state of art technologies for particle detectors, electronics …
- Will involve students to participate in building, testing detector components. Will spread experimental culture in area of HEP in particular, science in general
- **Pottipuram best place to do it – for TN and India**

Outline

1. Iron Calorimeter (ICAL) detector
2. Current status of ICAL and INO
3. Other experiments at INO

1. Iron Calorimeter (ICAL) detector



- ➢ Atmospheric neutrinos – provide a range of energies (E_ν~1-10 GeV) and matter propagation lengths ~ 1 – 13000 kms (**free!**)

- ➢ Measurements hitherto did not distinguish between **neutrinos** (ν) and **anti-neutrinos** ($\bar{\nu}$)

ν_μ , $\bar{\nu}_\mu$ *identified via charged current interaction*

$$\nu_\mu + n \to \mu^- + p \, , \quad \bar{\nu}_\mu + p \to \mu^+ + n$$

Why does one need a huge magnet?

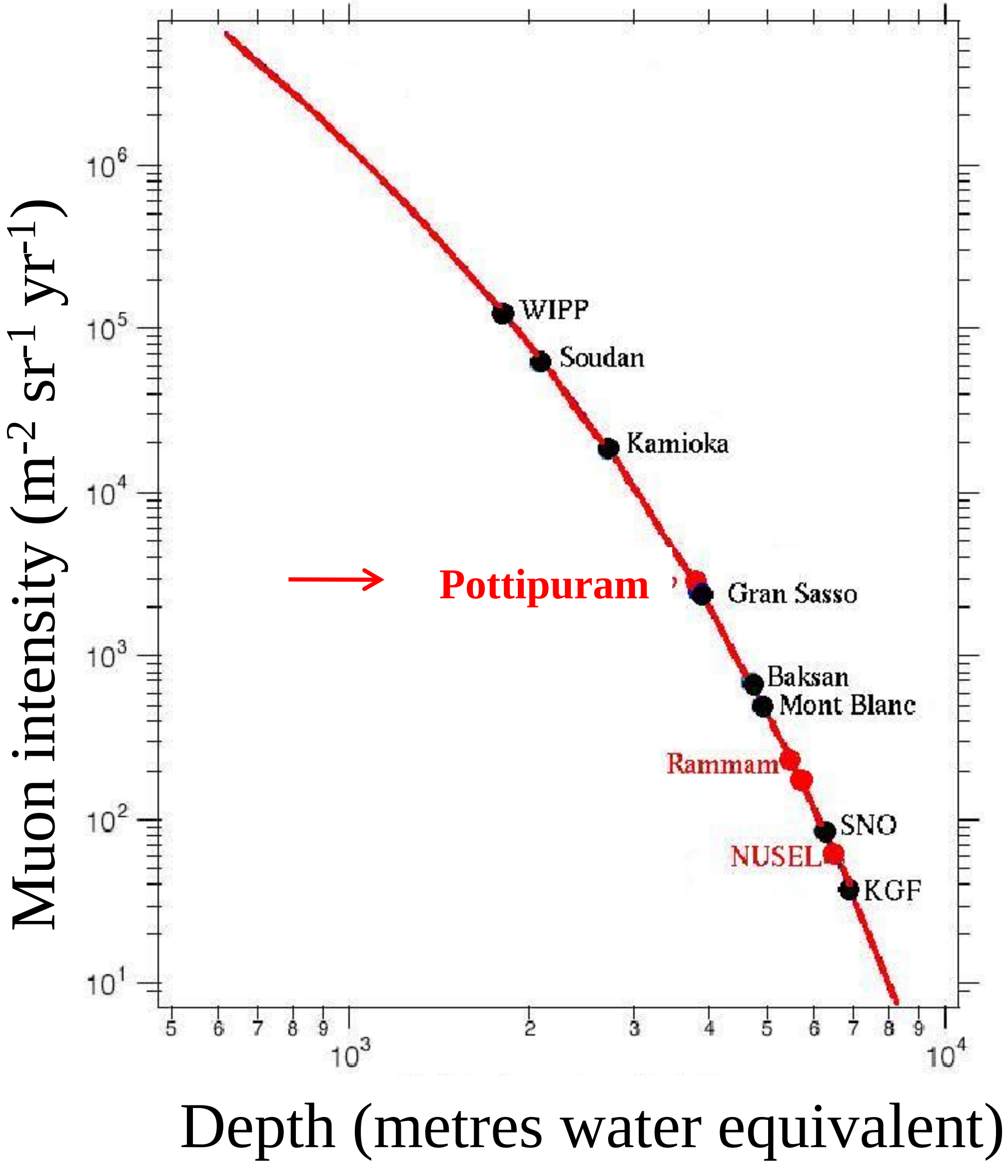
- **Neutrinos** cannot be detected *directly* but only via **charged particles** produced in ν-matter weak interaction
- **Muon neutrinos** interact (CC) with Fe of magnet producing $\mu^{\pm}$ with opposite curvature in **B**-field

Range of 1 GeV muon in Fe/H_2O : 0.6 m/5m

Radius (bending) of muon in B=1 Tesla: 1 m

Up/Down direction using timing information

Muon flux as a function of depth

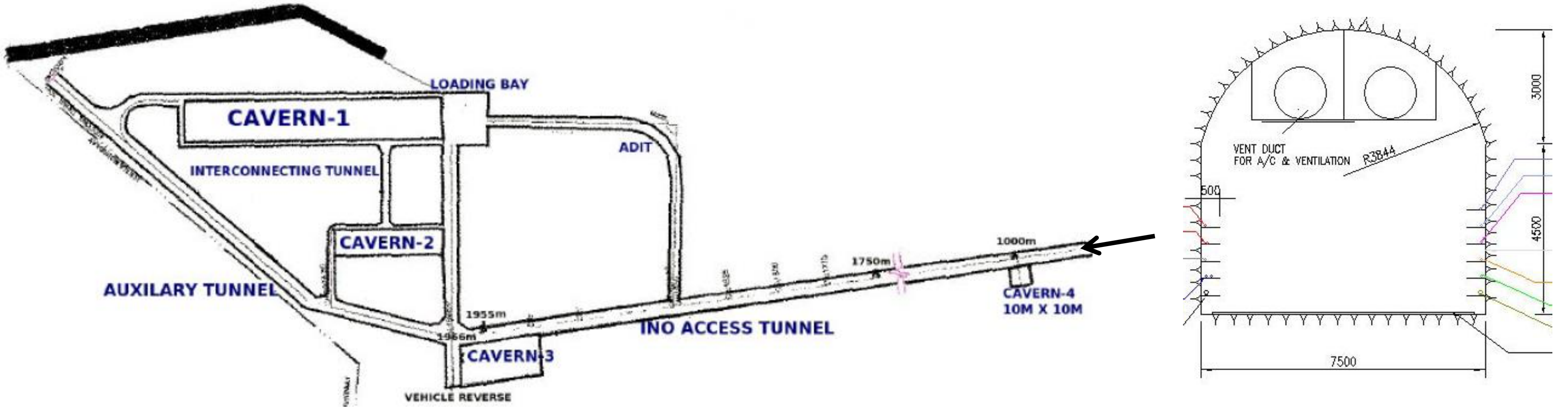


How deep underground ?

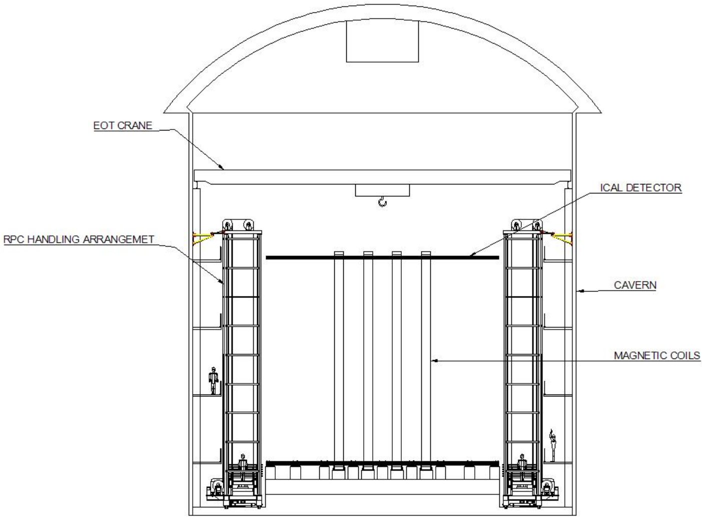
Low ν event rates ~ 3/day

Cosmic muons most important background, reduced by ~10^6 if detector depth = 1 km, deeper, the better ⇒ mines or **tunnels**

Access tunnel and caverns



- 2 km long tunnel , D-shape 7.5 m wide, down-slope at 1 in 13.5
- 1270 m vertical rock cover, 1 km on all sides
- ~3 yrs for making tunnel, caverns



ICAL cavern

Choice of detector

- Possible detectors:
  - ☐ liq. Argon (“modern” cloud chamber based on ionization chamber) - **magnetic field difficult**
  - ☐ sampling calorimeter with Iron - **magnetic field easy**

    Iron + plastic scintillator (MINOS)

    Iron + Resistive Plate Chamber (ICAL@INO)

Choice of configuration

- Magnet for target material and B-field

⇒**Iron based electromagnet** is natural choice

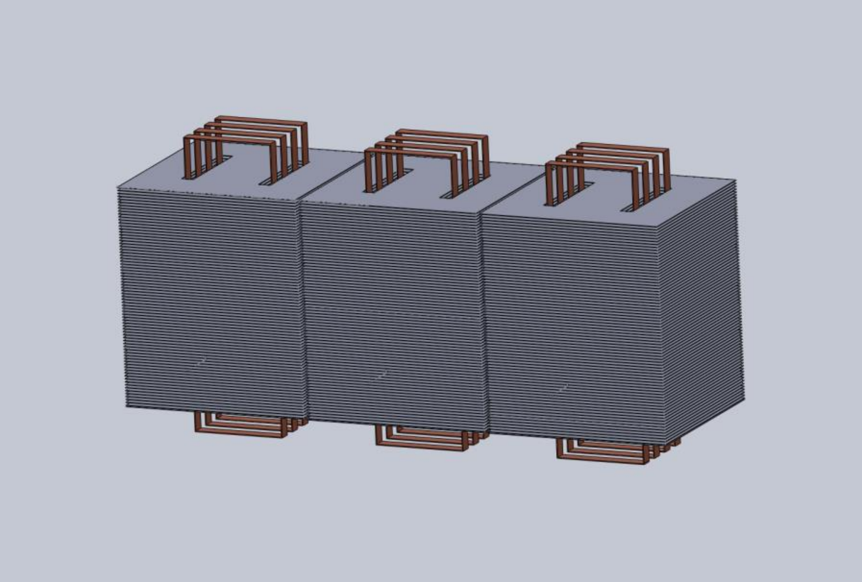
Permanent magnet too expensive, reversing field too time consuming! High T_c SC based magnet complicated.

Two possibilities:

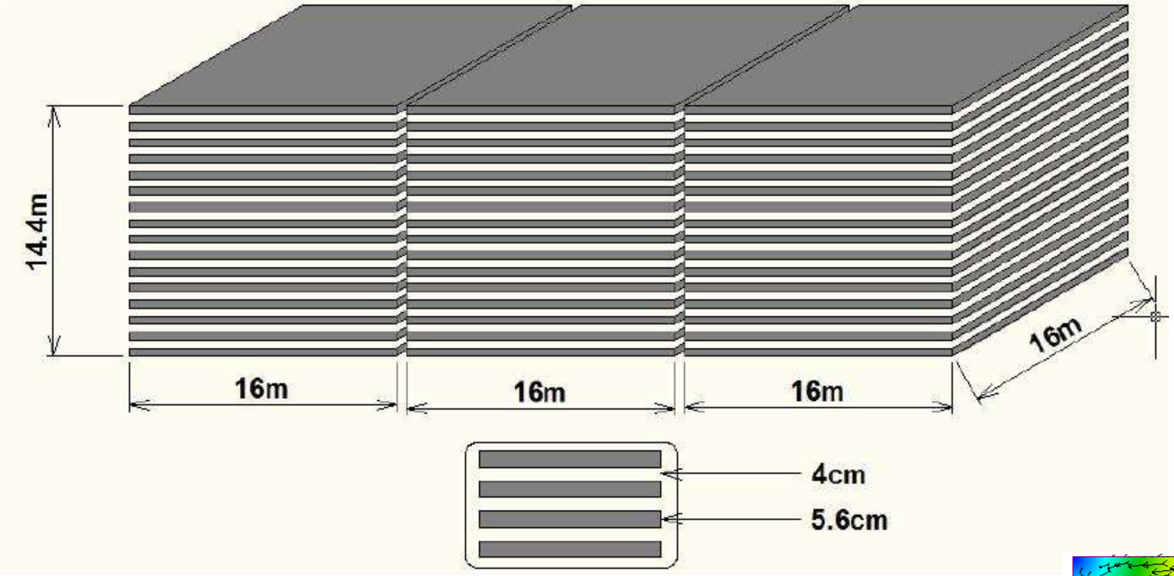
- Toroidal field with axial conductor (MINOS, Soudan)
- Layered magnet with rectangular coil (as in MONOLITH @ Gran Sasso)

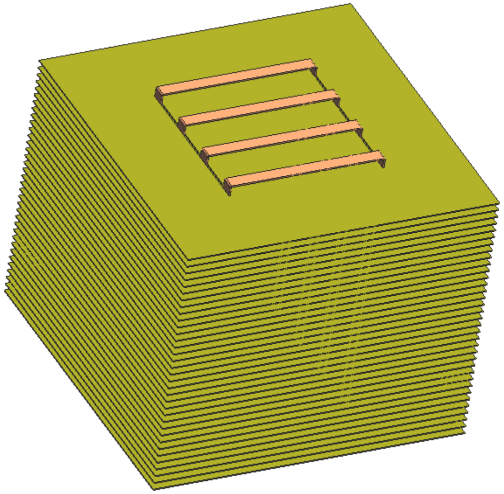
MINOS Far detector (5.4 kton)

Schematic of ICAL modules (3×17 kton)

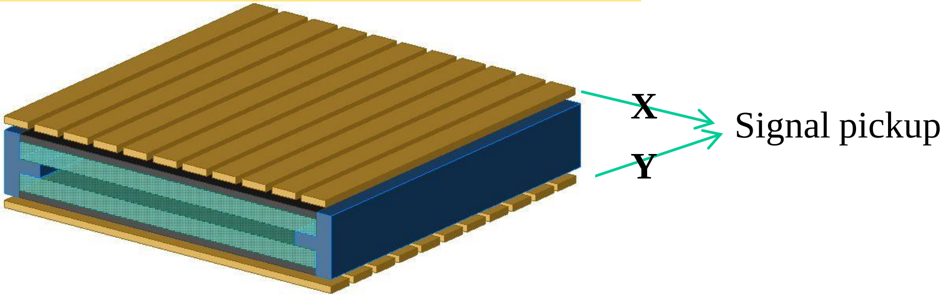


Schematic of Iron Calorimetric detector

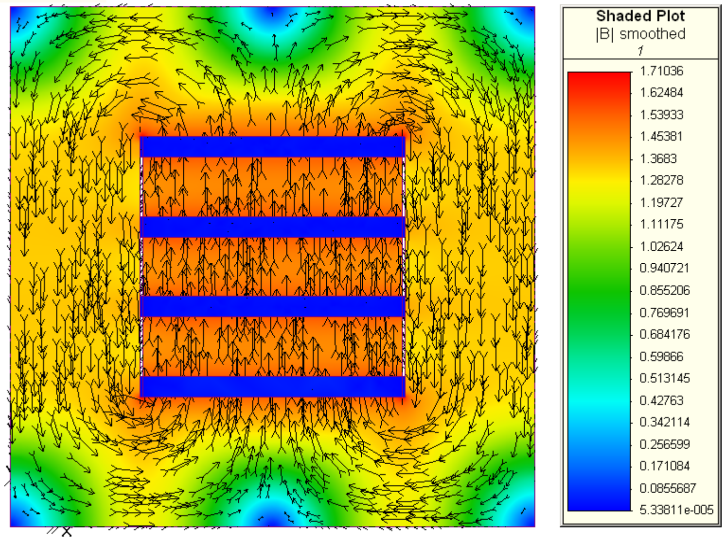




3 modules × 17 kton
Each with 150 layers Fe+RPC
B-field > 1 Tesla (90%)



Glass RPC for detecting charged particles



B-field for 60 kA-turns, typical low C steel

Features of 17 kton ICAL magnet

- Different from normal gap magnets with field between pole pieces – here field is essentially within the Fe plates
- Each module ~ 17 kton (will be largest Fe based electromagnet in world!)
- 150 layers of soft iron (low carbon steel) of dimensions 16m × 16m tiled with 4m × 2m × 56mm
- Gap between successive layers of soft iron : 40mm

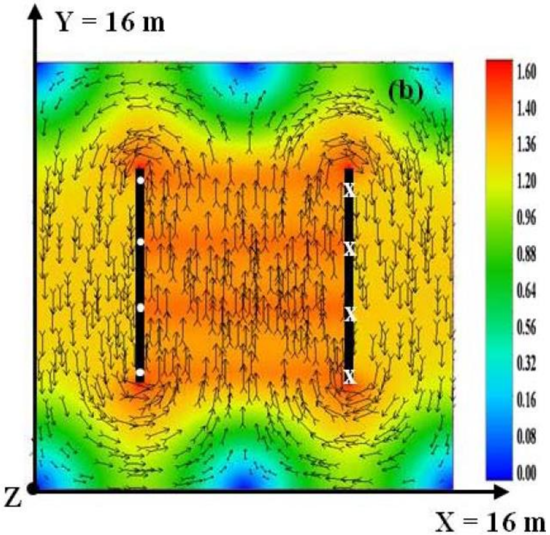
  for glass Resistive Plate Chambers ~ 35mm thick
- Magnetic field > 1 Tesla, 1.5 Tesla desirable

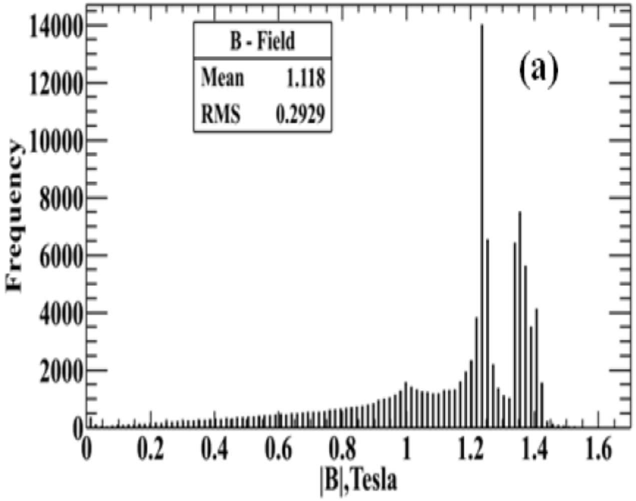
Challenges and Issues

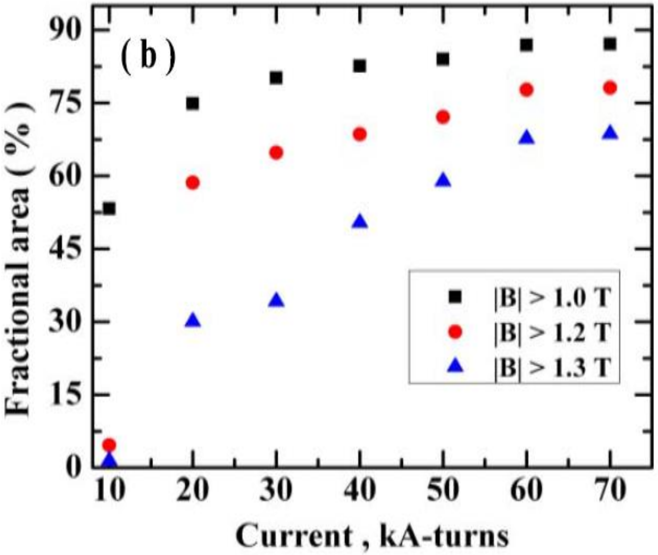
- Large size (3 nos of 16m×16m×14m)
    - Large copper coils (8m×15m, 80 kA turns, ~150 tons)
    - Large mass (**largest electromagnet**) 3 × 17 kton
    - Assembly minimizing gaps, preserving planarity
- Piece-wise uniformity of B-field (> 1 T over 90% area)
    - Measurement of interior B-field (open problem)
    - Stability – mechanical, B-field (~1%)
- Large no. of RPCs ~ 30,000 (World total ~ 10K)
- Electronics ~4 M channels, fast (nsec), P/ch < 50mW

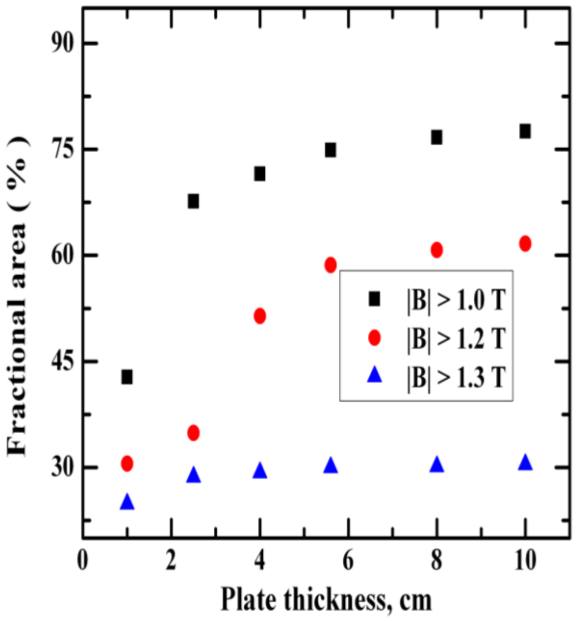
Electromagnetic simulation study of ICAL magnet

- B-field simulation using 3D finite element commercial software
- B-field uniformity studied for various plate thicknesses, tiling configurations, air gaps, slots (for Cu coils), coil configurations. *NI*, 2 low carbon steels
- Muon momentum response (from reconstructed trajectory) studied for a few coil currents, plate thicknesses

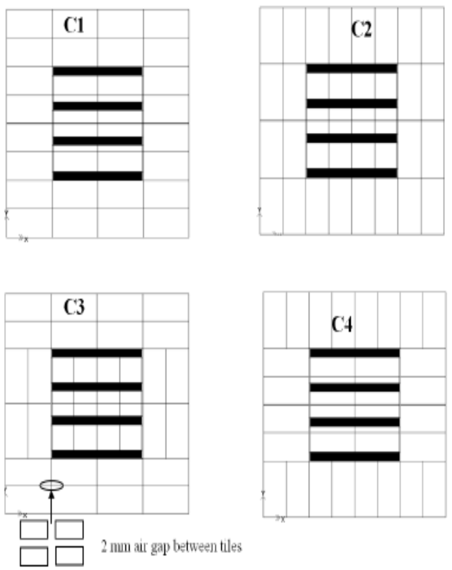


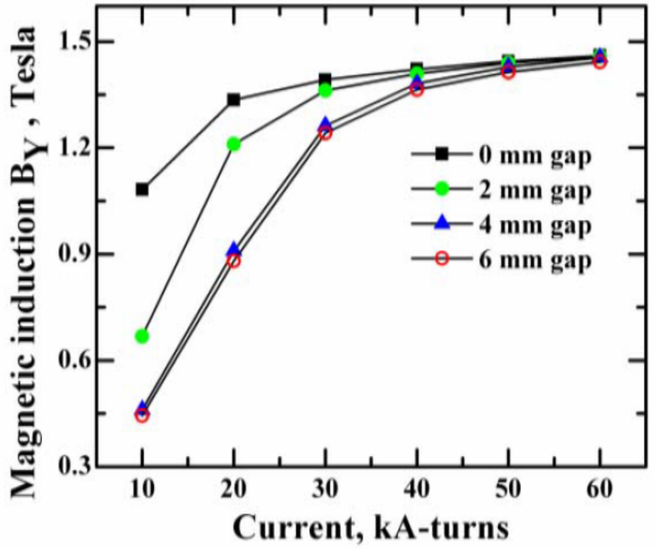




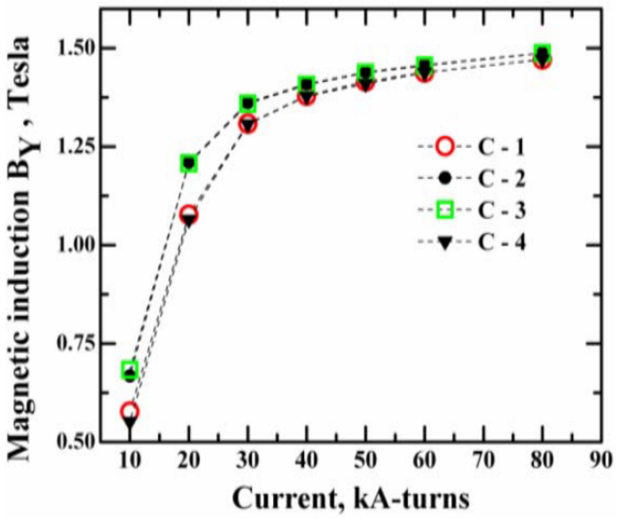


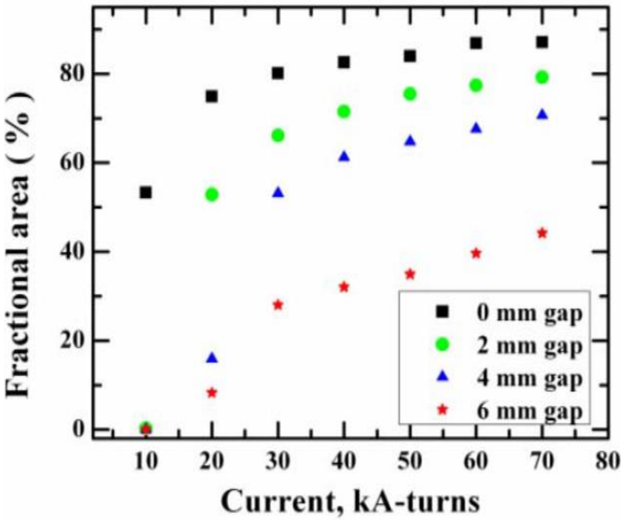
B-field uniformity for NI=20 kA.turns





C2 for different gaps

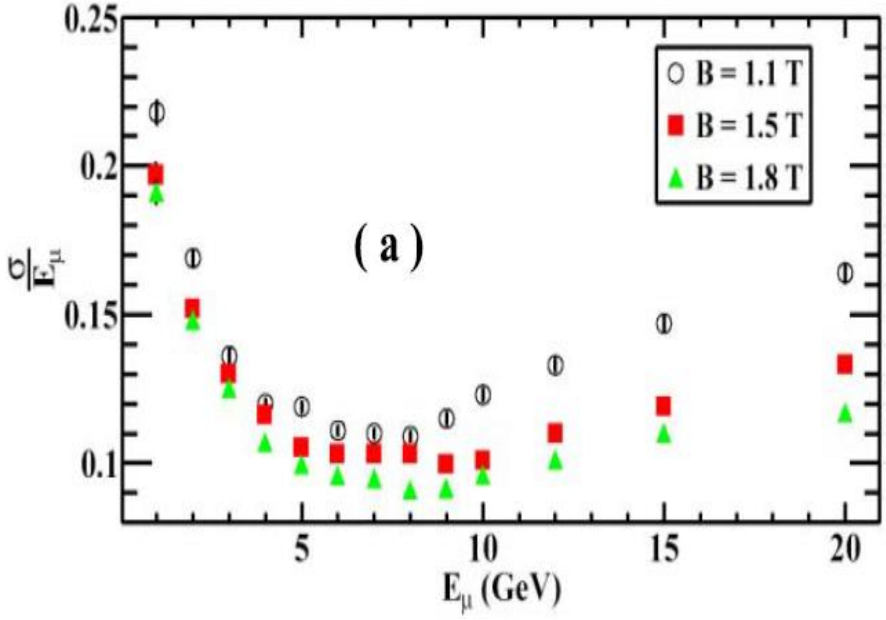


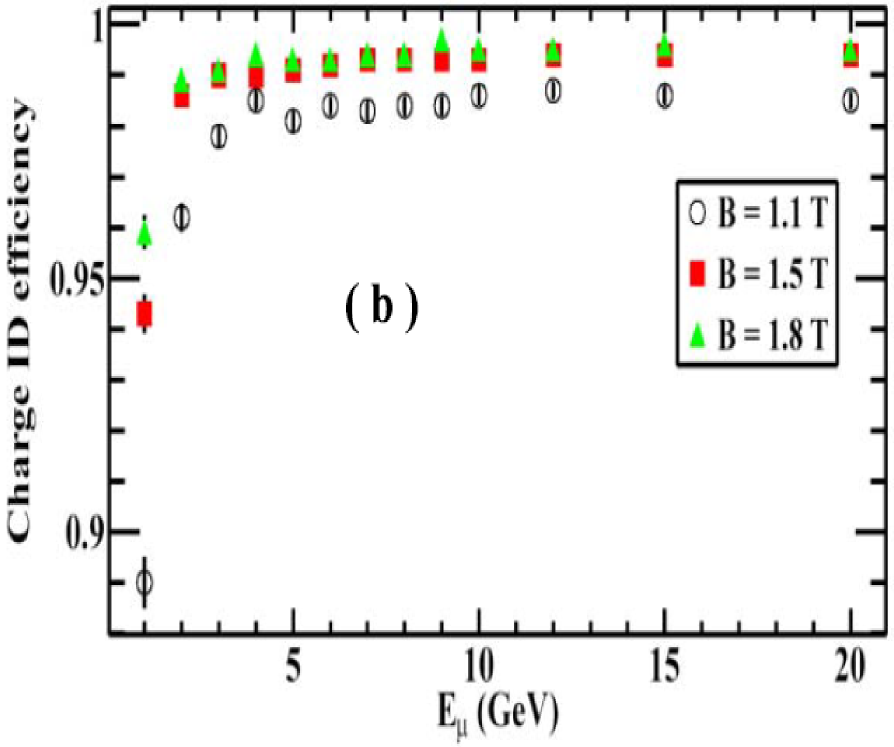


Fractional area with B > 1 T

S.P. Behera et al., IEEE Magnetics **51**, 7000409 (2015)

Muon response of ICAL for various B-field strengths





Physics with Iron Calorimeter detector

ICAL will measure atmospheric muon neutrinos and muon-antineutrinos

Energy range: 1 GeV $\leq E_\nu \leq$ 20 GeV

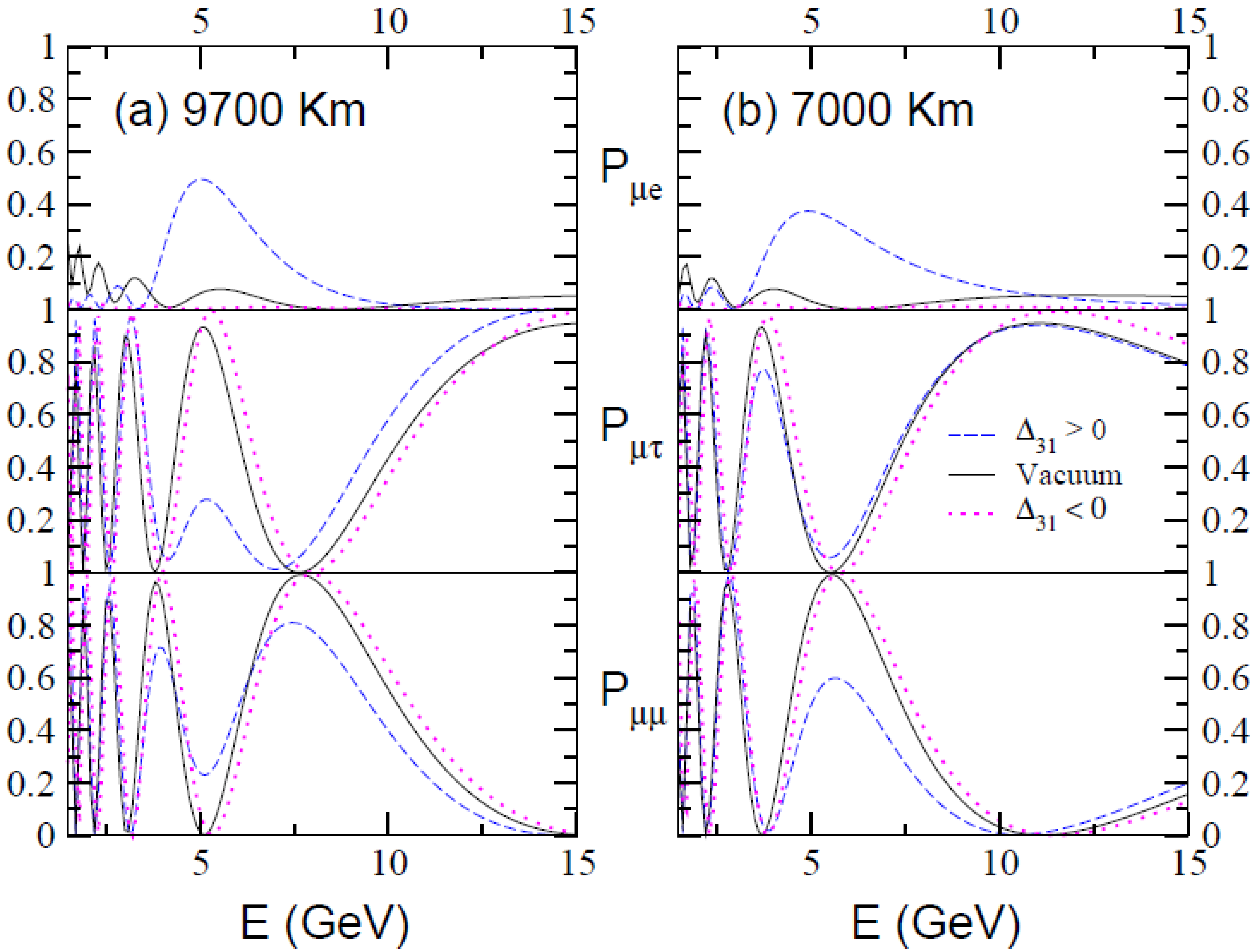
Zenith angles: $0° \leq \theta_\nu \leq 70°$, $110° \leq \theta_\nu \leq 180°$

- Neutrino mass hierarchy – normal or inverted
- Neutrino mixing parameters (Δm_{23}^2 , θ_{23})
- Non-standard interactions
- Ultra high energy cosmic muons

White paper on "Physics Potential of the ICAL detector at INO"

under review in Pramana (2016); arXiv:1505.07380

Matter effect on oscillation probabilities vs. E_ν

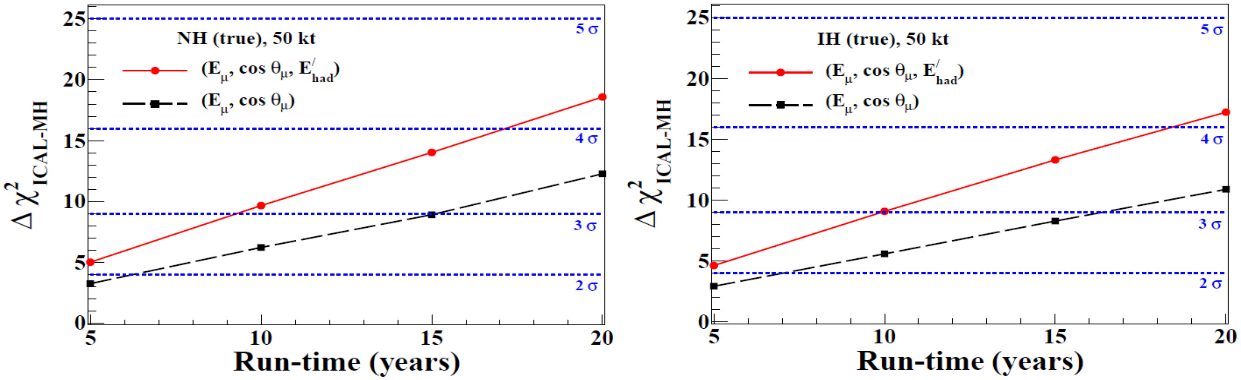


R. Gandhi et al., PRL **94**, 051801 (2005)

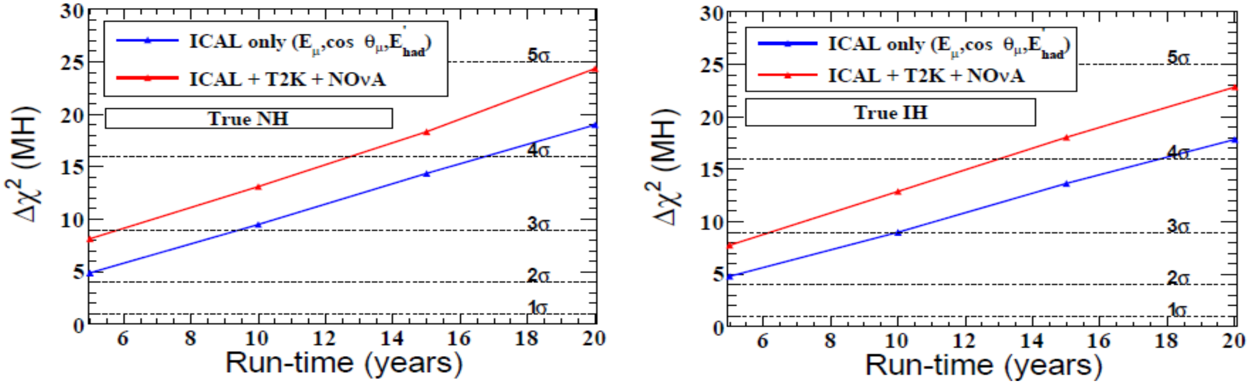
Mass hierarchy of neutrinos – sensitivity of ICAL

- $m_1 < m_2 < m_3$ (NH) or $m_3 < m_1 < m_2$ (IH) ?
- ICAL can identify MH using matter effect on atmospheric ν_μ , $\underline{\nu}_\mu$

  (at 3σ level with ICAL alone: ~ 9 years, +acc. Expts: 6 years)
- With accelerator based expts. can probe CP violation in ν-sector



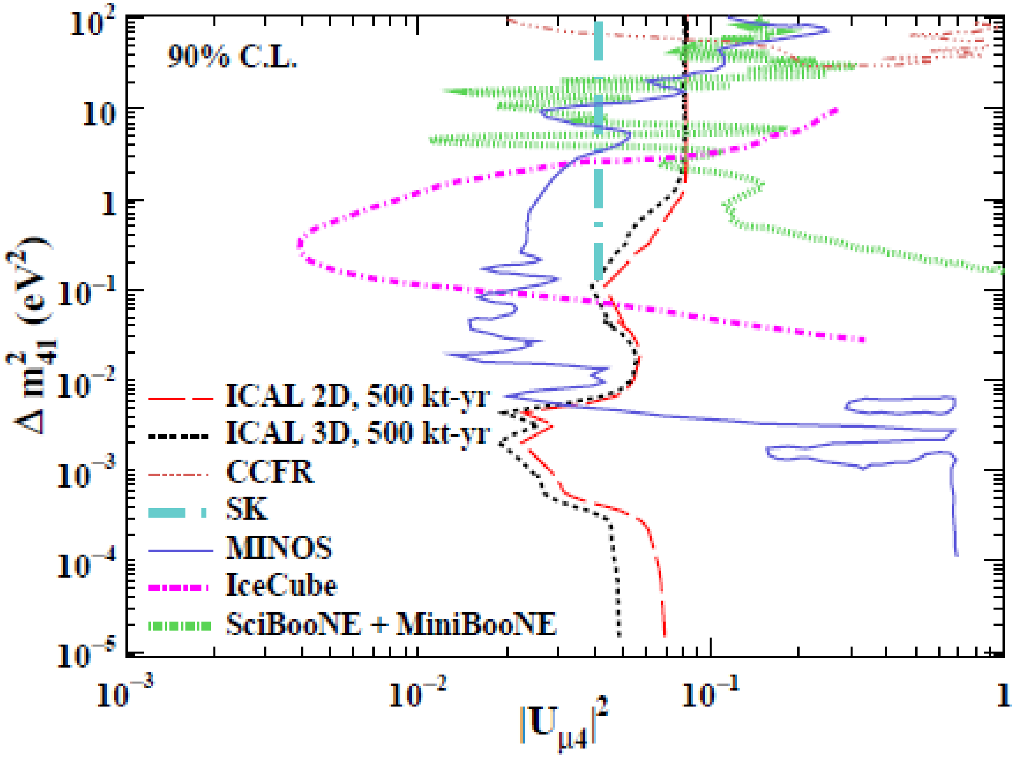
ICAL only



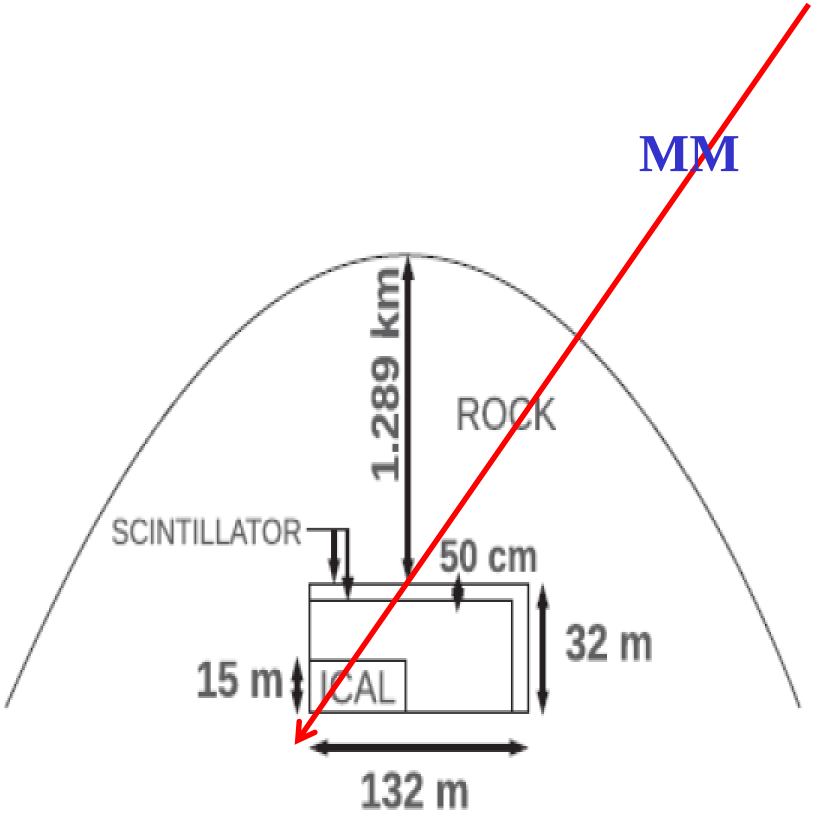
ICAL + T2K + NovA

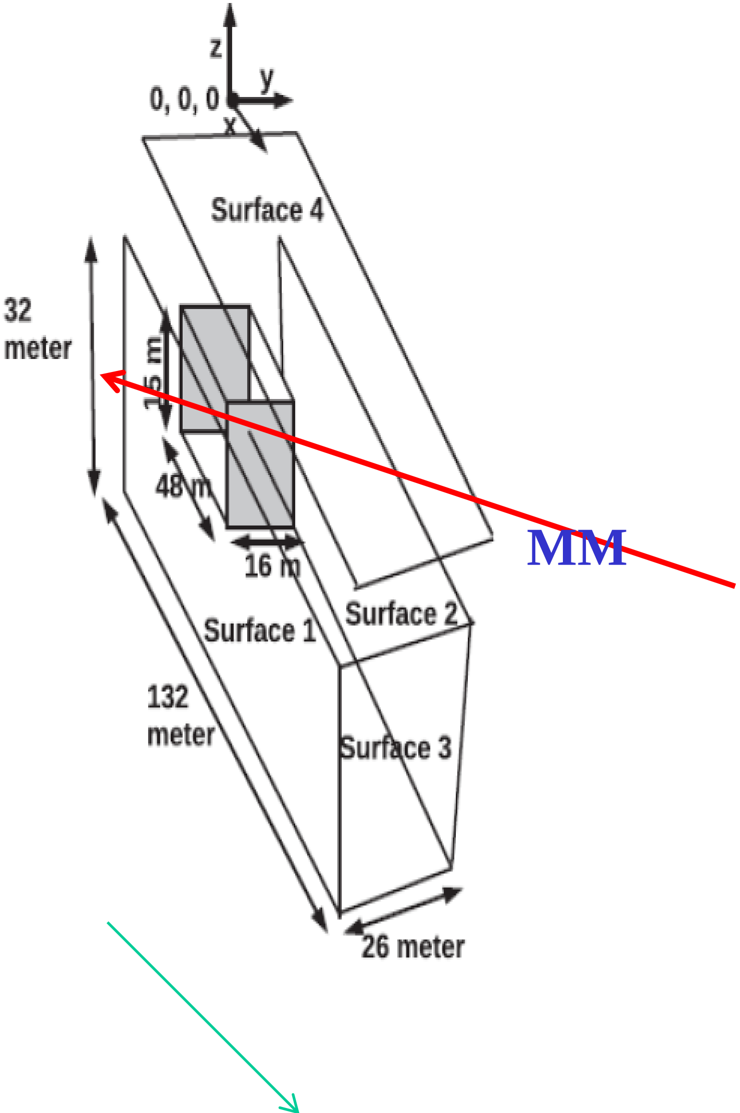
Other physics possibilities

- ➢ Long range forces with $L_e – L_\mu$ gauge: limits of . $\alpha \sim 10^{-52}$ may be obtained (IOP group)
- ➢ Sterile neutrinos: ICAL can probe very low Δm_{14}^2 (IOP, TIFR)

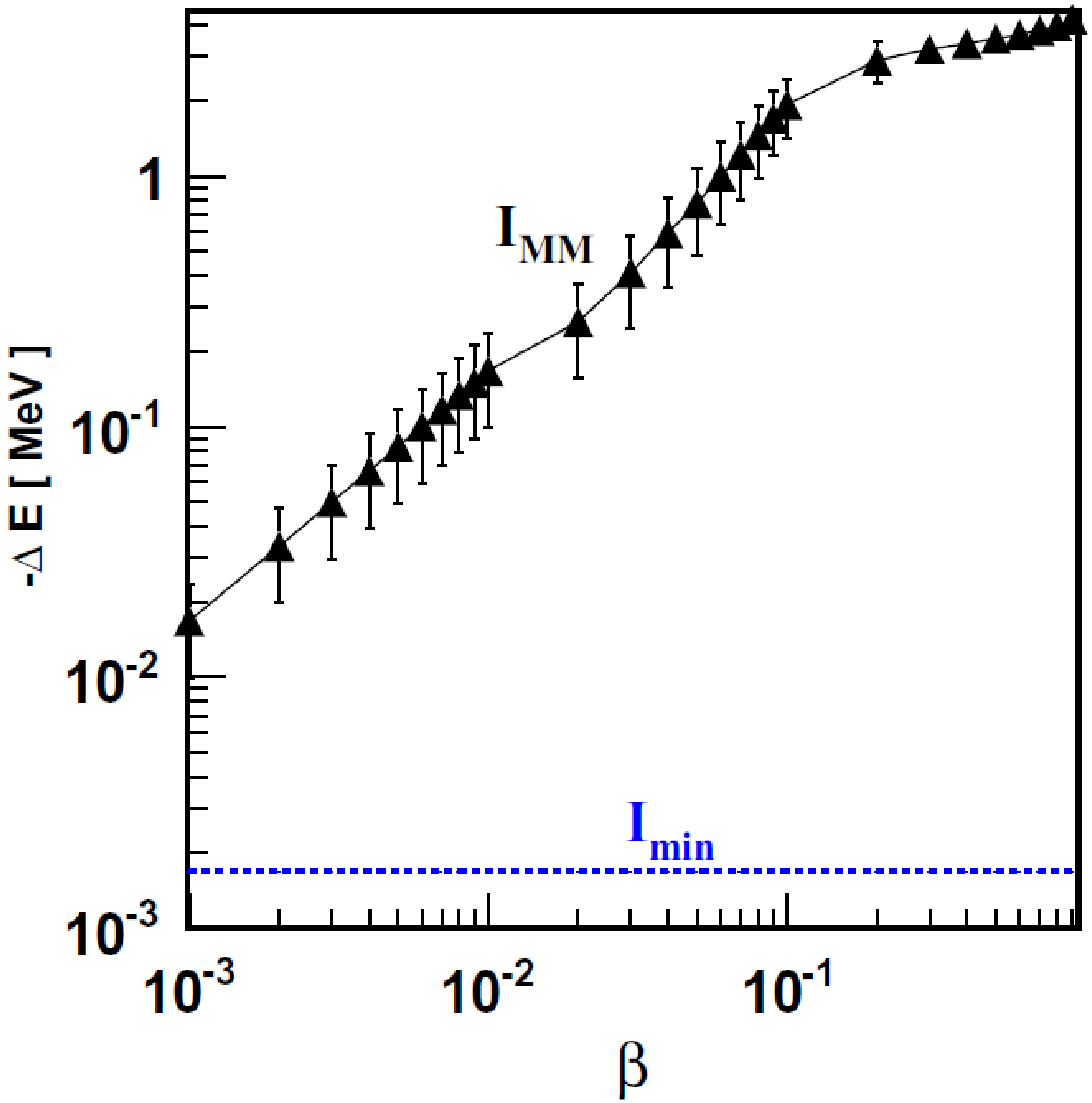


Searching magnetic monopoles at ICAL@INO





Energy loss of MM in 2mm RPC gas



KE ($\beta=10^{-3}$) for

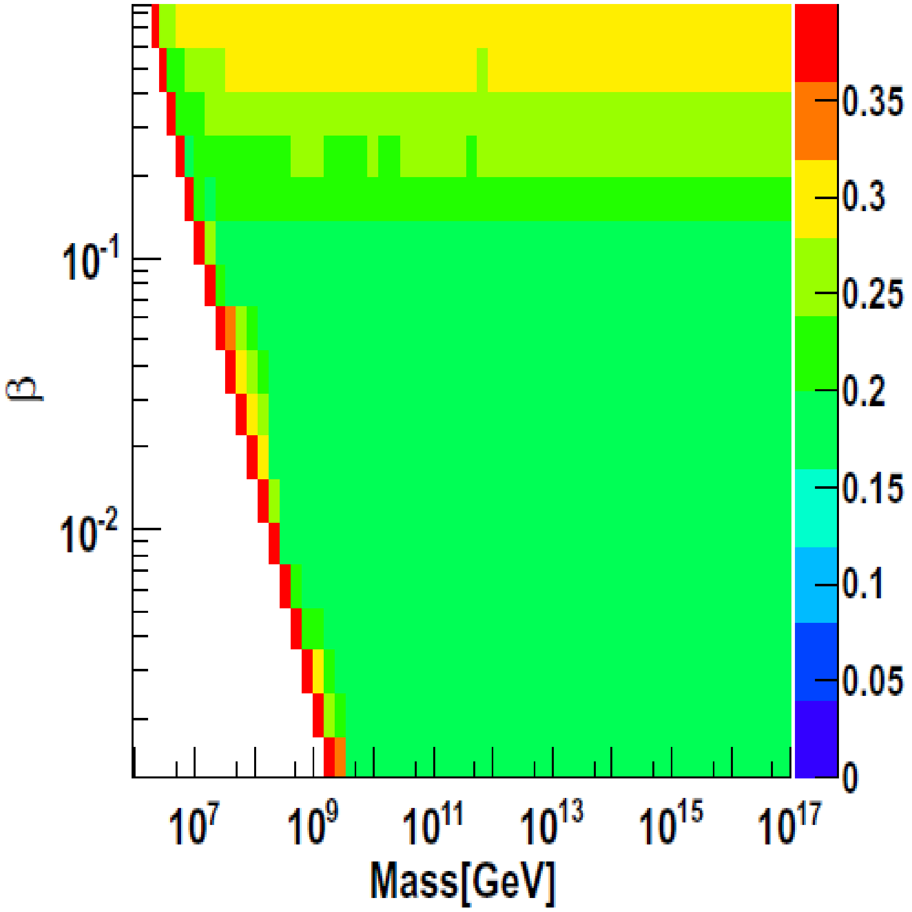
$m_{MM}=10^{15}$ GeV/c^2

~10^9 GeV !

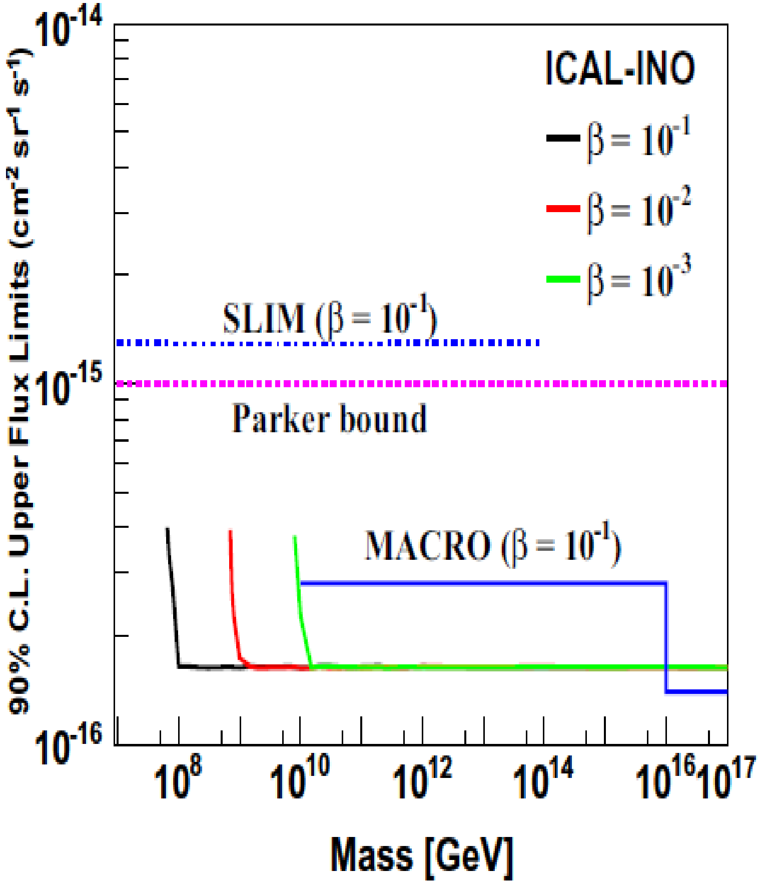
ΔE (10m Fe) ~ 10^2 GeV

ΔE ($2R_E$) ~ 10^8 GeV

Upper bound on MM flux for 10 yrs of ICAL (10^{-15} cm^{-2} sr^{-1} s^{-1})



Upper bound on MM flux for 0 observed events

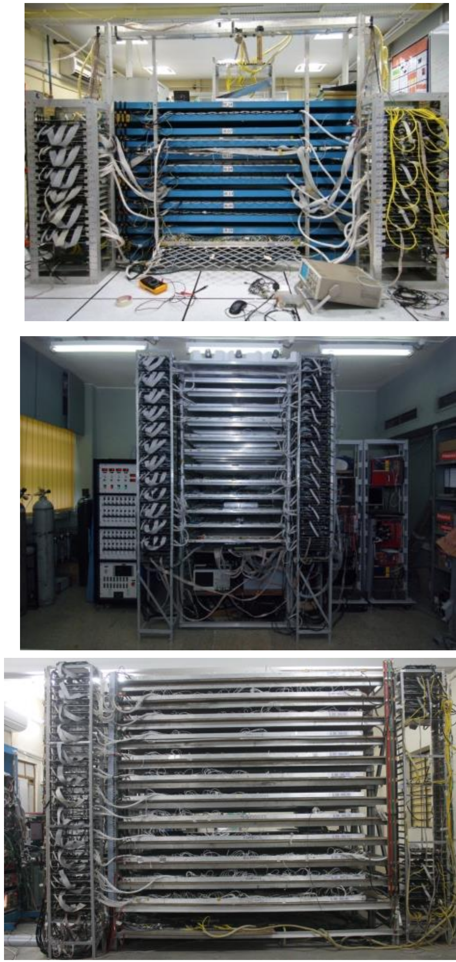


N. Dash et al., Astroparticle Physics **70**, 33 (2015)

Searching for anomalous KGF events at ICAL

- About 7 anomalous events found during 25 years of running the proton decay experiment – multiple tracks leading back to an **origin not in detector or rock but in air**
- If KGF events are genuine, we should see many more with ICAL as cavern & detector ~ 10 times larger
- With additional detectors on 4 sides, should be able to provide data for/against KGF events in 2-3 years of running time

2. Current status of ICAL and INO



- **Magnet:** 35 ton 1st prototype ICAL detector @ VECC, Kolkata with B_{max} ~ 1.5 Tesla. 8m×8m×20 layers prototype ICAL design ready for IICHEP, on hold. 600T steel, OFHC Cu procured. Building 70 ton mini-ICAL (4m×4m×11 layers)
- **RPCs:** 2m ×2m (12 nos) industry made glass RPCs working @ Madurai lab. ~60/400 nos. delivered
- **Electronics:** FE boards with ASIC, DAQ boards, DC-DC HV units, Trigger system, DAQ software: testing or under fabrication.

- **IICHEP site @ Madurai:** 12.6 ha plot fenced Awaiting reclassification.


20/05/2014 10:48

- **INO underground lab site @ Pottipuram:** 27 ha plot fenced. Water storage tank completed.


18/05/2014 12:34

- **Pre-project** infrastructure work (road, water, electric power) partly done. Work halted due to PIL in Madurai bench of Madras HC.

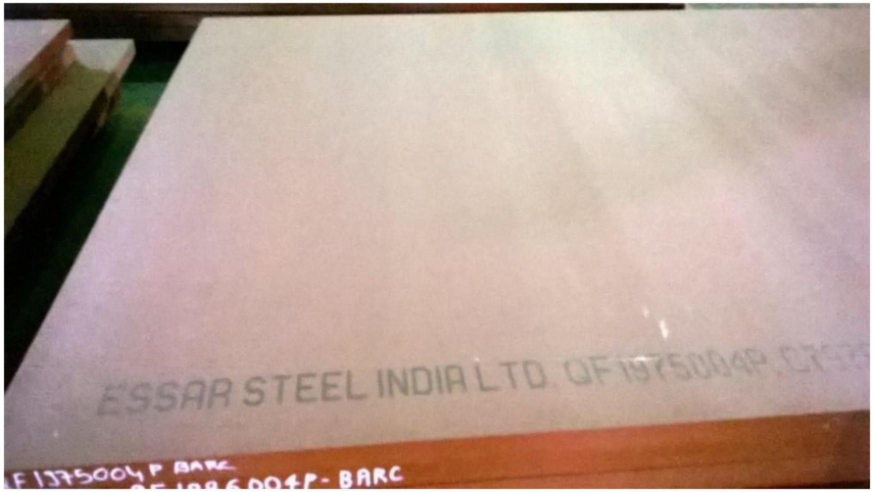

18/05/2014 12:50

- **Financial approval for INO project** in Dec 2014 given by Union Cabinet (~ Rs. 1583 crores)
- 30 PhD students (BARC@HBNI) have been part of INO-GTP

1st batch 2008-2009

Soft Iron Plates for IICHEP, Madurai

- 168 (for 21 layers) soft iron plates, OFHC Cu coil procured



Soft iron plate

Soft iron plates at M/S Essar

8 plates in 32 ton trailer/trip

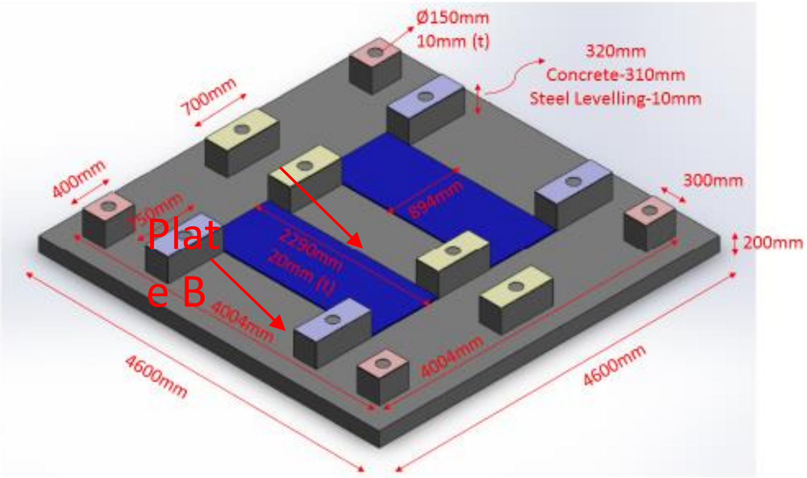
OFHC Cu coil

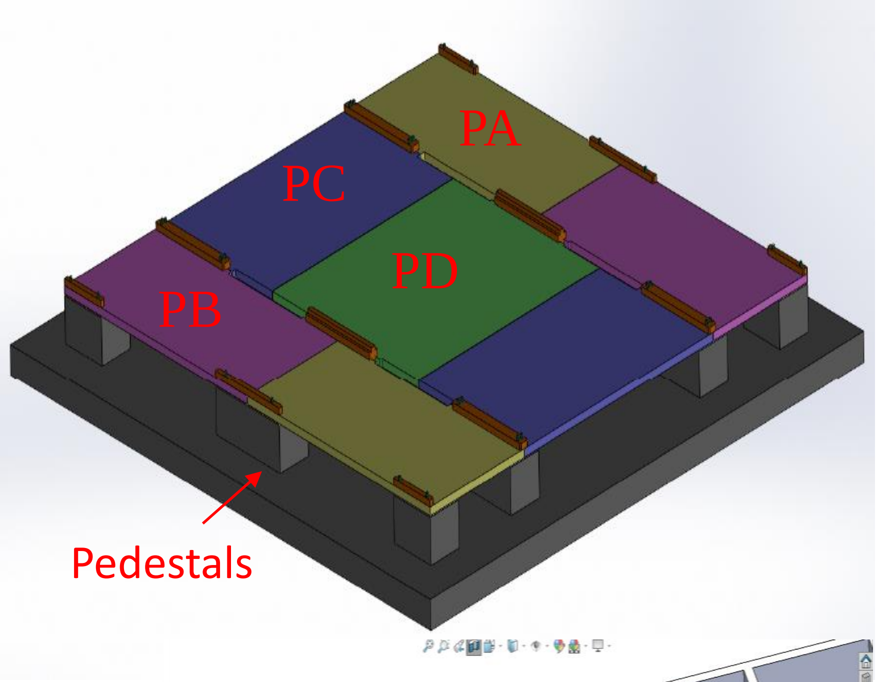
RPC handling trolley for engg. module

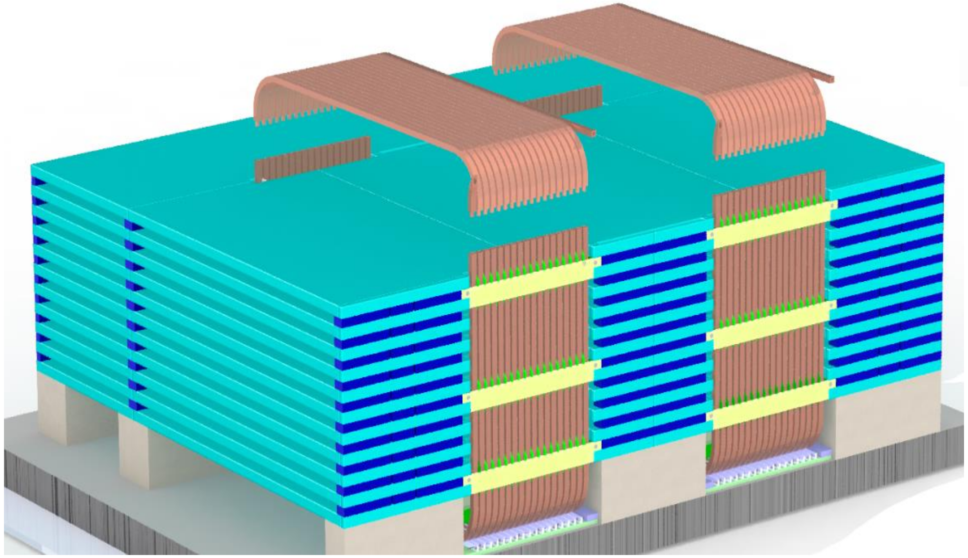
Parameters	Prototype
Weight	19 ton
Size	6.5 m x 3m x 12.5 m
Rail	A75
Horizontal travel	13.5 m
Vertical travel	8 m
Vertical speed	4 m/min max
Horizontal speed	4 m/min max
RPC shelf (Elec. operated)	Stroke length 750 mm
Shelf speed	92 mm/min max
Modular type lift support structure	

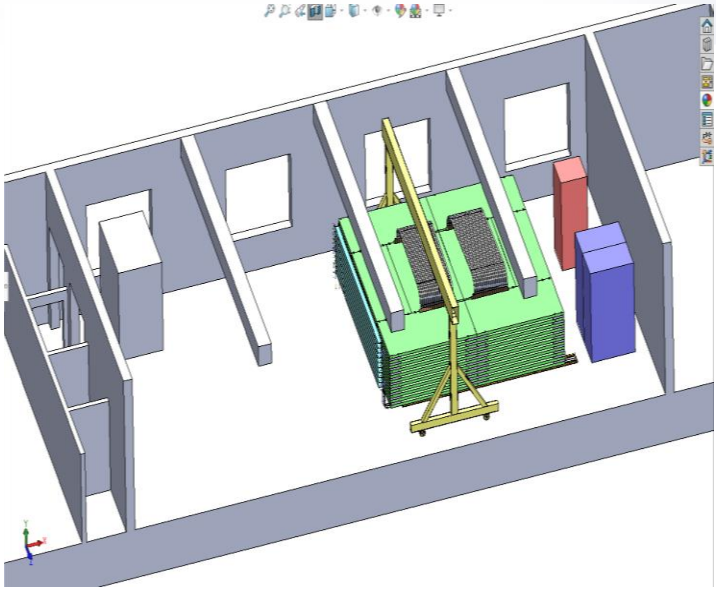
RPC handling trolley delivered at IICHEP Madurai in April 2016

mini-ICAL at IICHEP (rented premises)





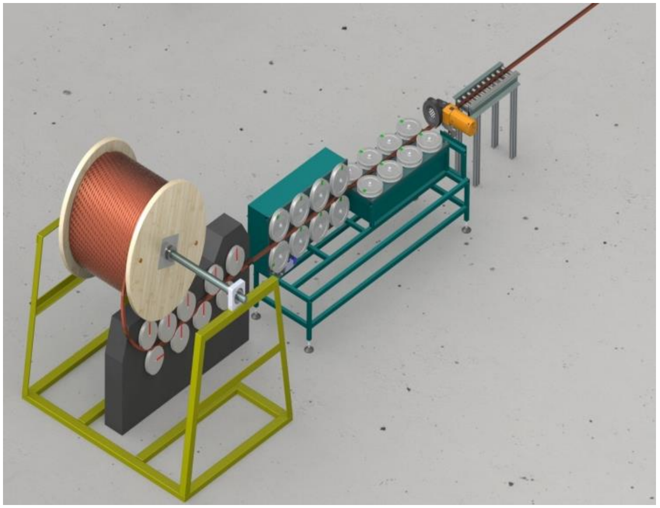




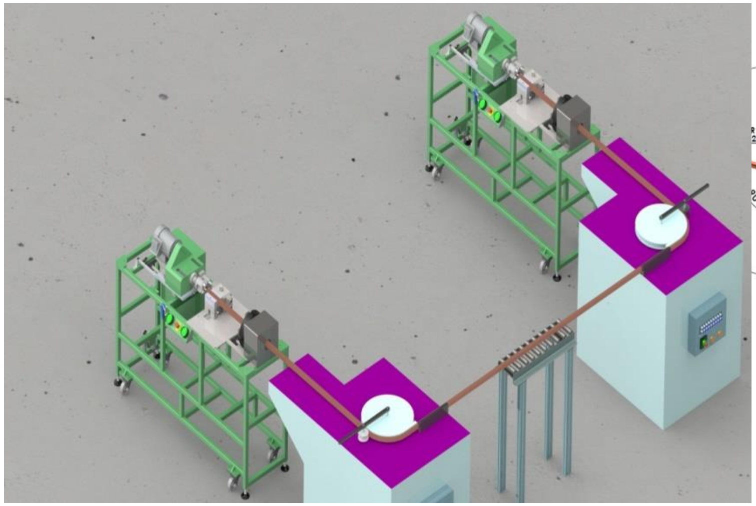
Target date: 31 March 2017

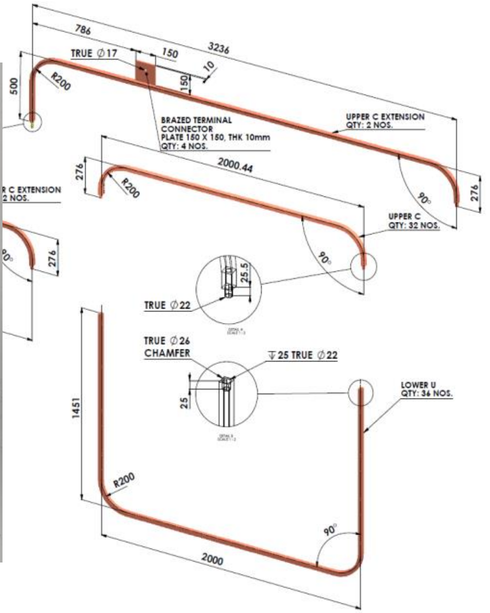
Making the Cu coil

Straighten

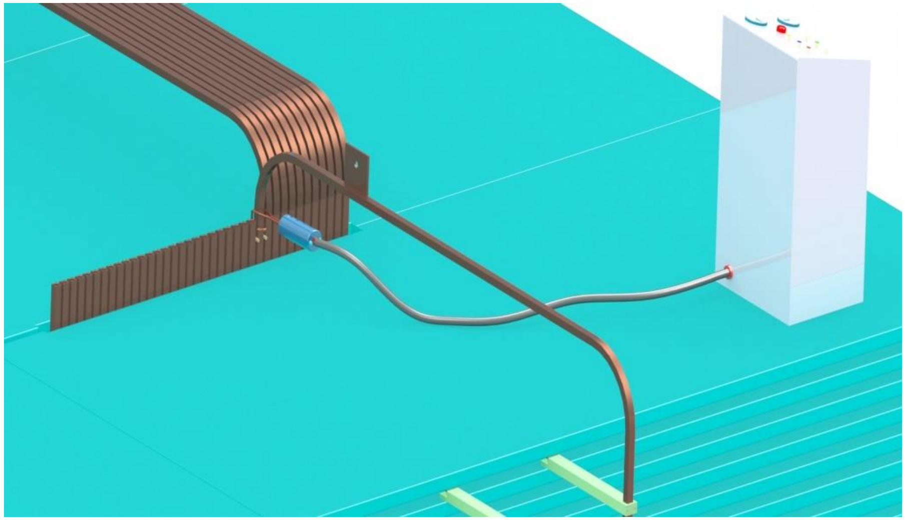


Bend

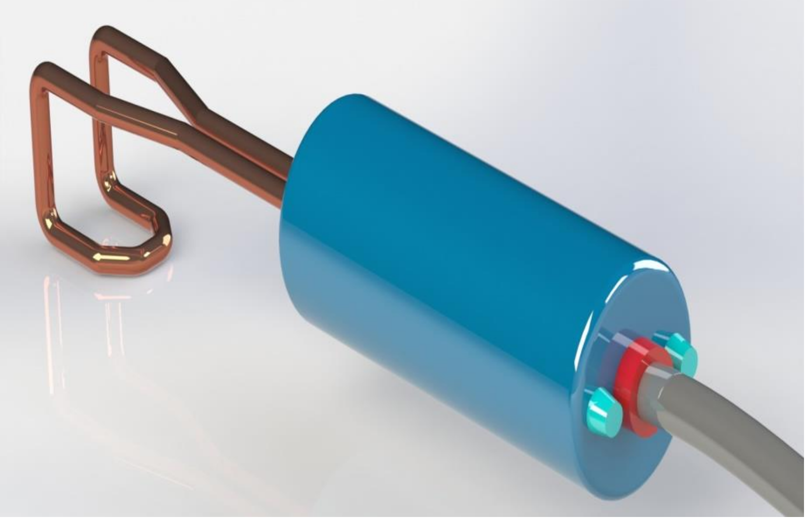




In-situ silver brazing



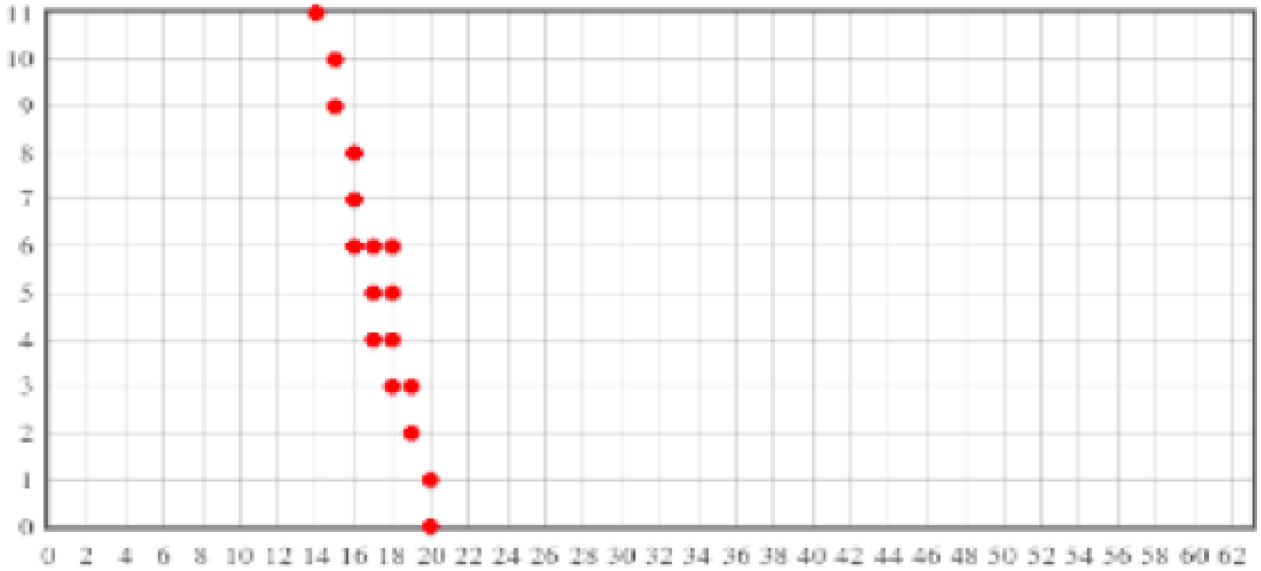
Induction brazing tool

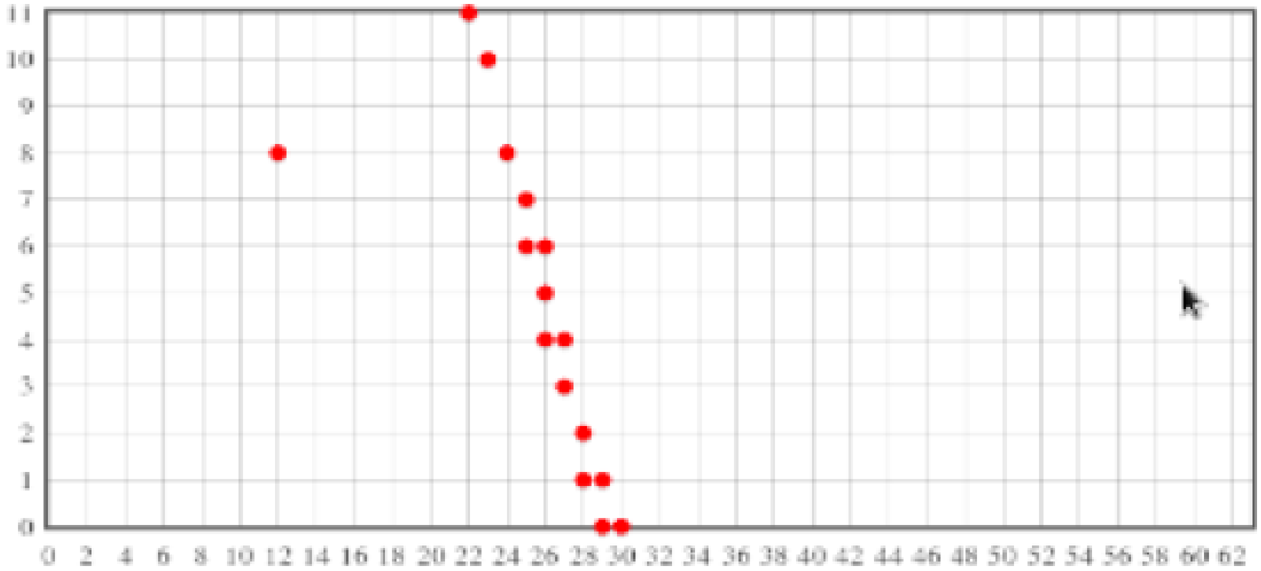


RPCs, Electronics & Trigger, DAQ

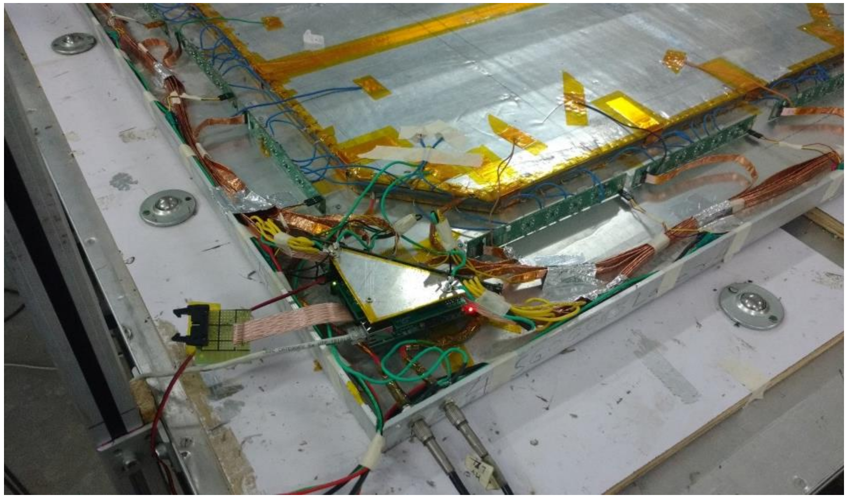
Madurai RPC stack and few Events

Madurai RPC stack and few Events

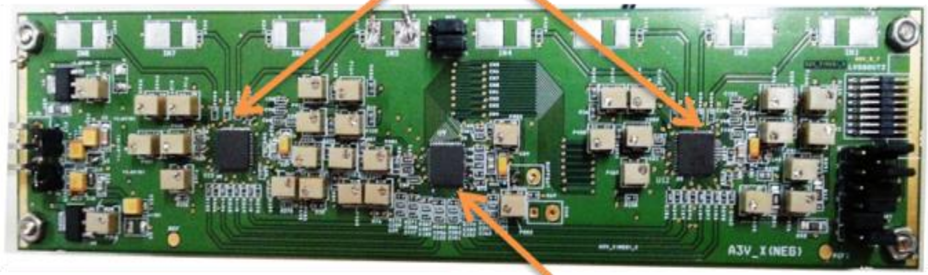

X Side Hits


Y Side Hits

RPC-DAQ corner board + NINO FE

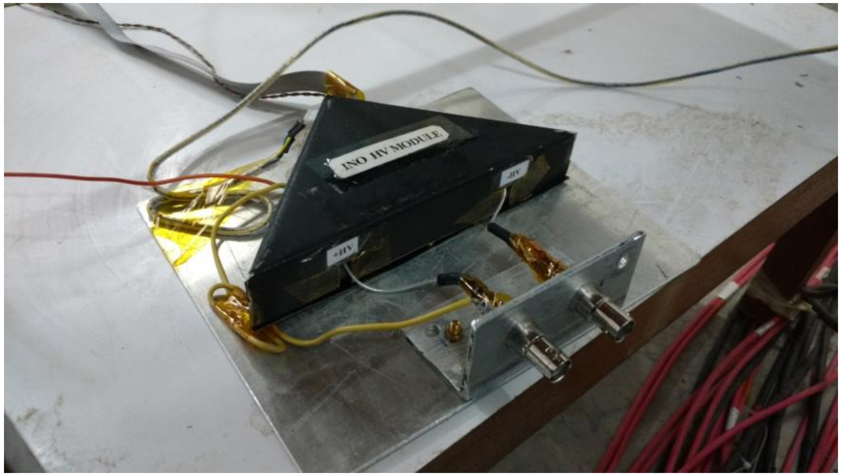


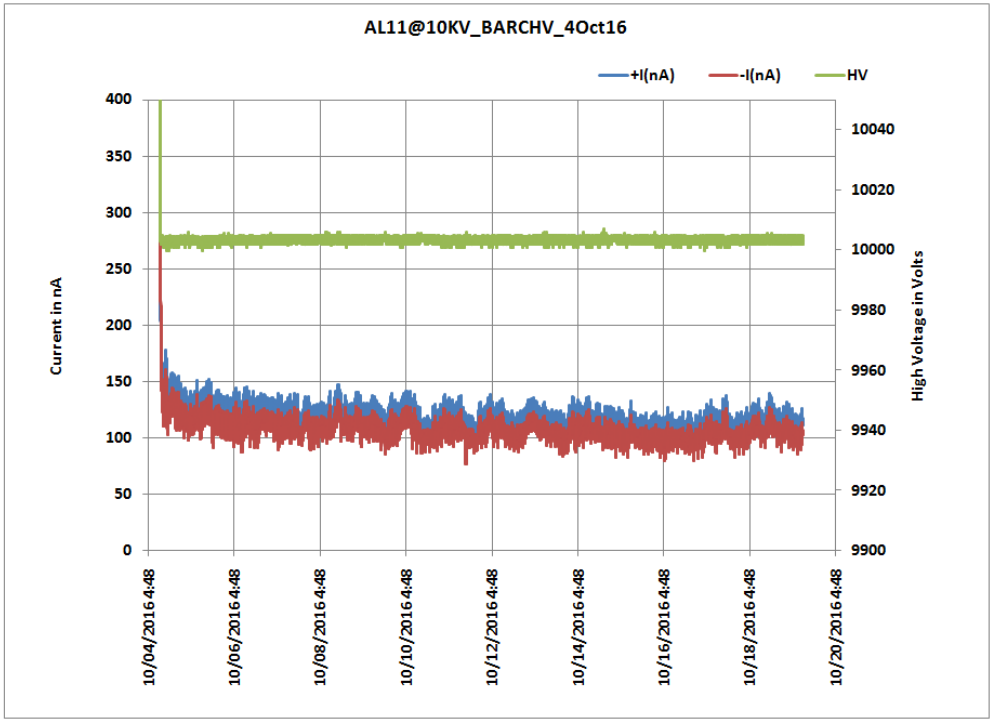
ANUSPARSH-IIIA ASIC: Quad Amplifier ASIC



ANUSPARSH-IIID ASIC: Octal Discriminator ASIC

On board DC-DC HV module





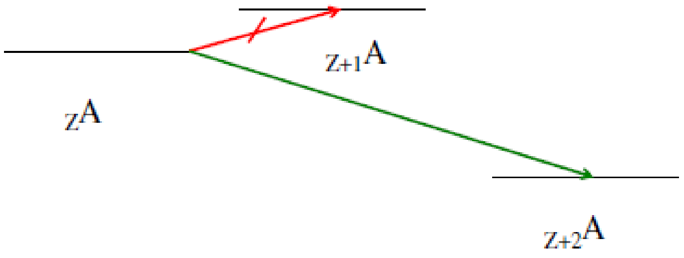
3. Other experimental possibilities at INO

- **Neutrinoless Double Beta Decay in ^{124}Sn** using a cryogenic bolometric detector (R&D ongoing for TINTIN)
- **Dark Matter** search using a cryogenic CsI detector for low mass WIMPs (5-30 GeV/c^2) (R&D ongoing for DINO)
- **Low energy accelerator for nuclear reaction cross sections ~ Gamow energy** of astrophysical interest (Univ. groups working on proposal)

Neutrinoless double beta decay – is $\nu = \bar{\nu}$?

${}_{Z}A \rightarrow {}_{Z+2}A + 2\beta^{-} + 2\bar{\nu}_e$ Normal lepton#-conserving DBD

${}_{Z}A \rightarrow {}_{Z+2}A + 2\beta^{-}$ Lepton#-violating DBD



Maria Goeppart Mayer, *Phys. Rev.* ***48***, *512 (1935)*

$\Gamma_{2\beta0\nu} \propto [Q_{0\nu}]^5 \times [NME]^2 \times \langle m_\nu \rangle^2$

$\Rightarrow$Large Q-value preferred

${}^{48}Ca$, ${}^{150}Nd$, ${}^{100}Mo$, ${}^{116}Cd$, ${}^{124}Te$

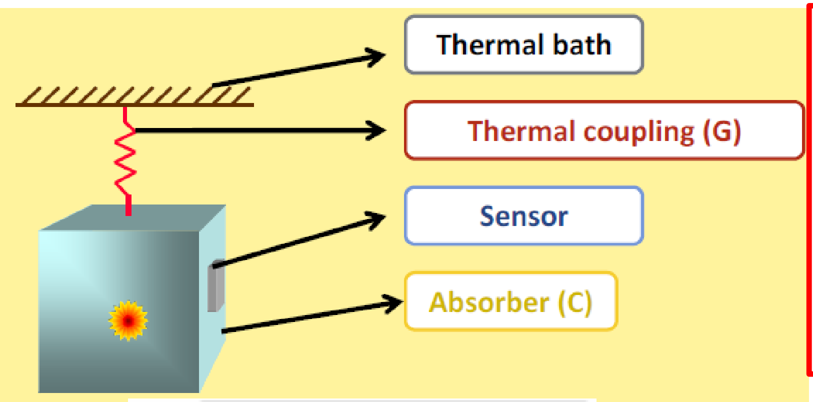
Why measure NDBD?

- Majorana or Dirac ?
- Absolute mass scale of ν

NDBD $\langle m_\nu \rangle_{\beta\beta} = |\, U_{ei}^{2}\, m_i\, e^{i\varphi(i)} \,|$

β-decay $\langle m_\nu \rangle_{\beta} = \{\Sigma\, |U_{ei}|^2\, m_i^{\,2}\, \}^{1/2}$

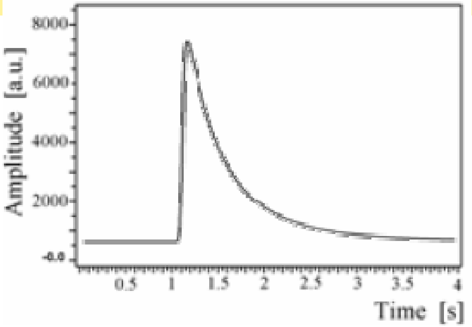
Cryogenic bolometer for NDBD



Insulators at low T, specific heat $C \propto T^3$

$\Rightarrow \Delta T_{rise} = E/(mC) \propto 1/T^3$

In SC at $T<T_c$, C_e drops, so lattice $C \propto T^3$

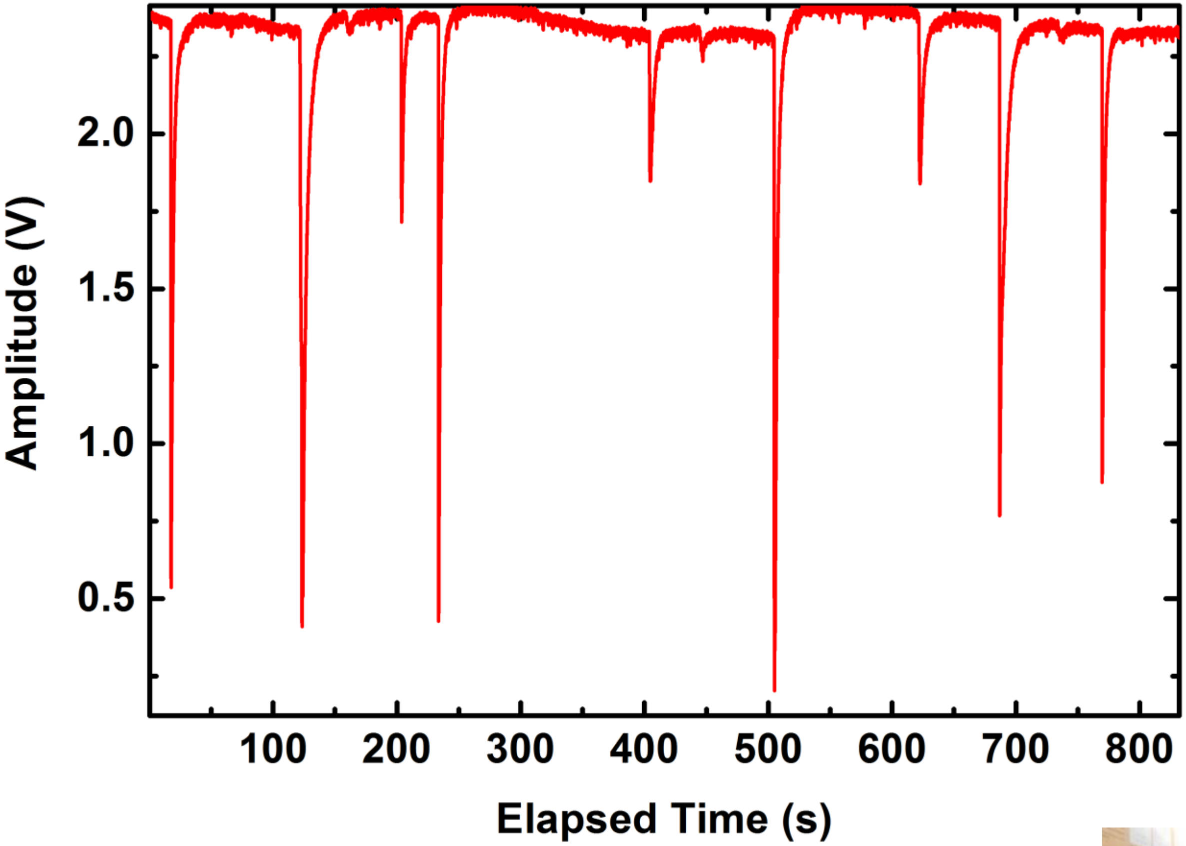


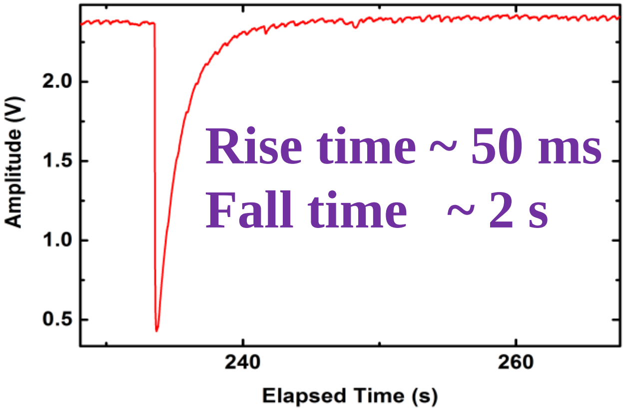
Cryogen free dilution refrigerator @ TIFR

- **Base Temp. ~7 mK**
- **Refrig power 1.4 mW @ 120mK**

Goal: 1 kg ^{nat}Sn bolometer

with NTD Ge sensor



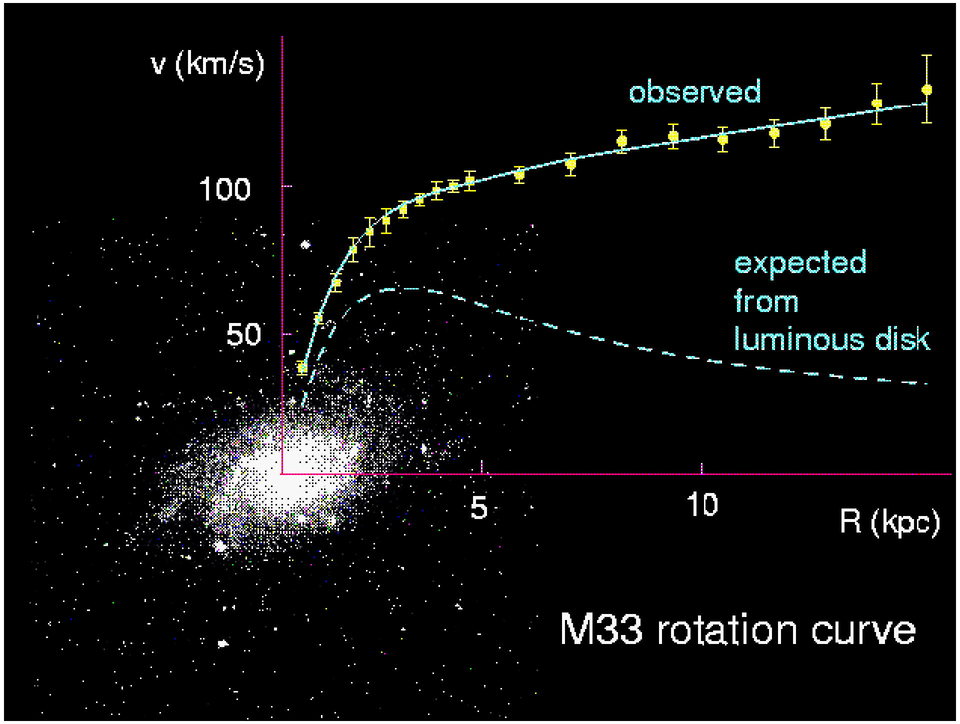


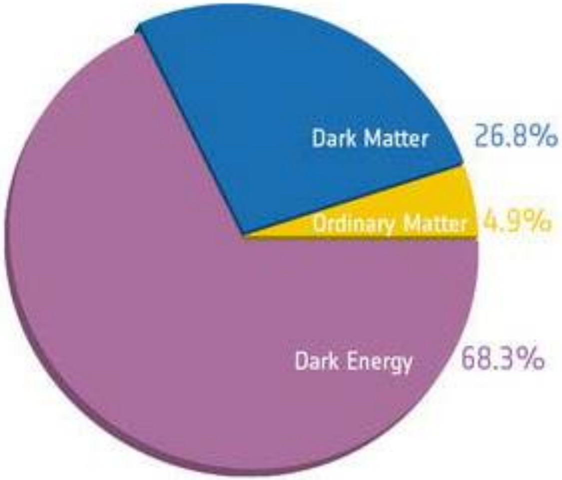
Rise time ~ 50 ms
Fall time ~ 2 s

Preliminary results with improved electronics (Oct. 2015)

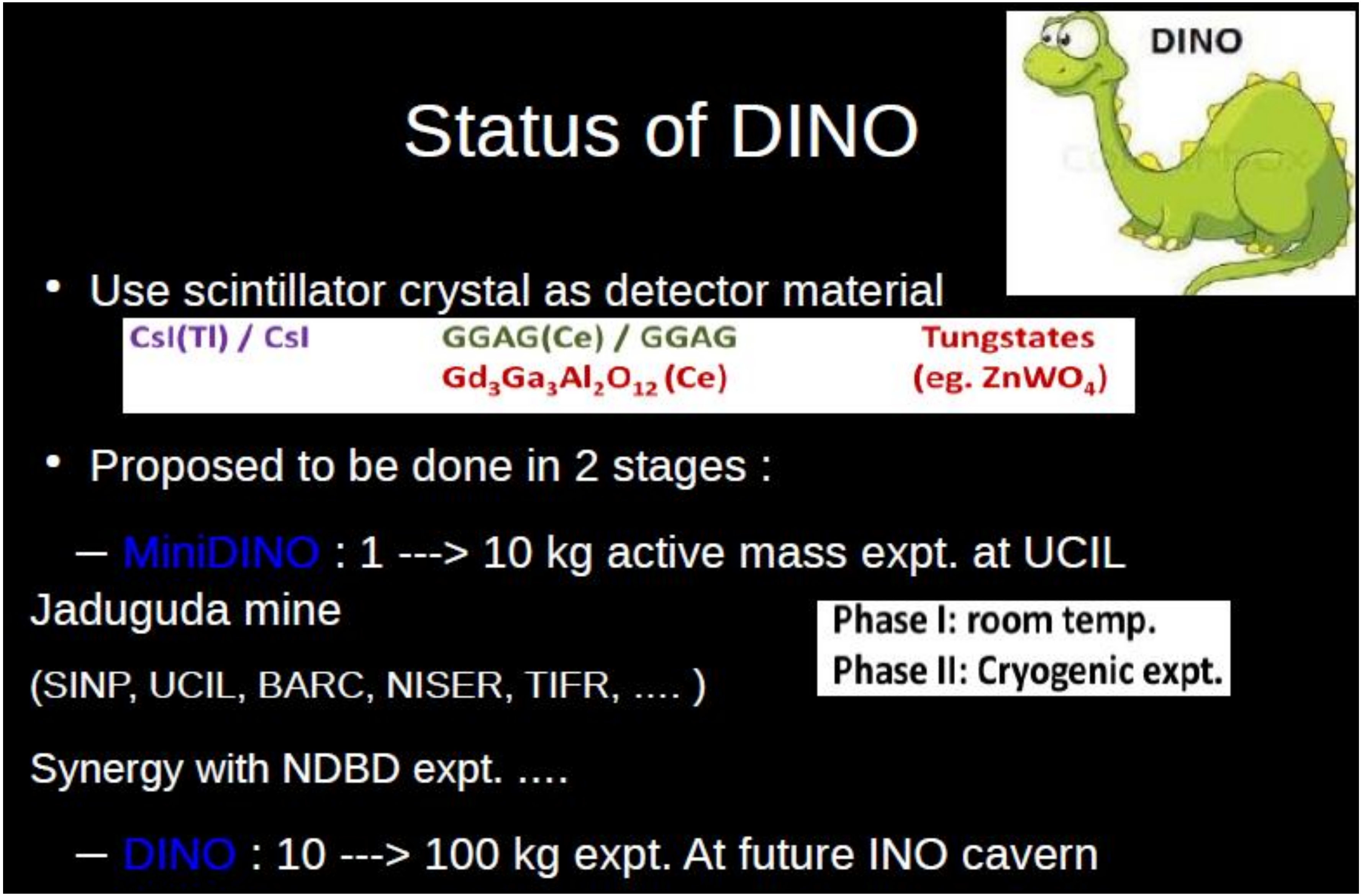
V. Nanal, INO Collab meeting
25th Oct 2016

Dark Matter search at INO – **DINO** **(SINP)**





Dark Matter believed to consist of Weakly Interacting Massive Particles (WIMPs) of mass 5-100 GeV/c^2



Status of DINO

- Use scintillator crystal as detector material

$CsI(Tl)$ / CsI

GGAG(Ce) / GGAG

$Gd_3Ga_3Al_2O_{12}$ (Ce)

Tungstates

(eg. $ZnWO_4$)

- Proposed to be done in 2 stages :

  – MiniDINO : 1 ---> 10 kg active mass expt. at UCIL Jaduguda mine

  (SINP, UCIL, BARC, NISER, TIFR, ...)

  Synergy with NDBD expt. ....

  – DINO : 10 ---> 100 kg expt. At future INO cavern

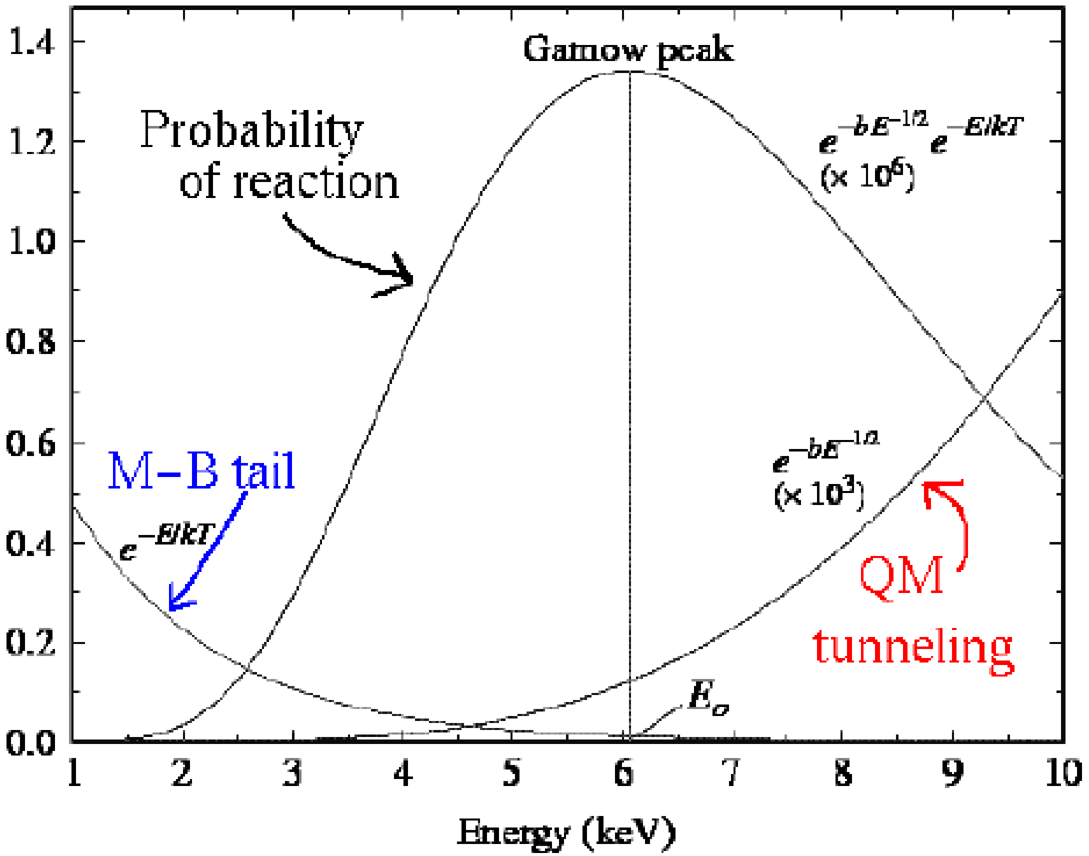
Phase I: room temp.

Phase II: Cryogenic expt.

from Pijushpani Bhattacharjee (INO Collab meeting 25 Oct 2016)

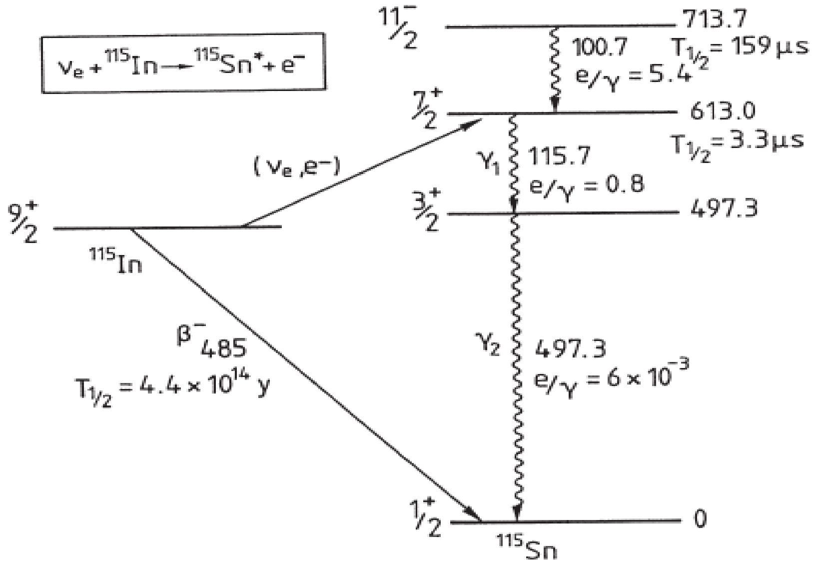
Future Possibilities

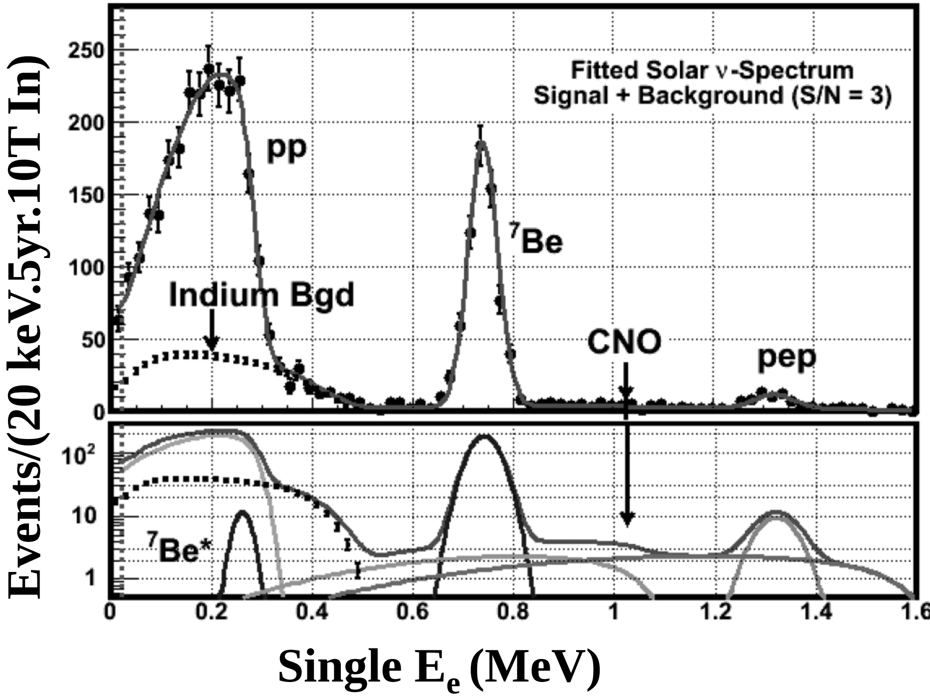
- Low energy ion accelerator for Nuclear Astrophysics for measuring reactions going on in core of stars



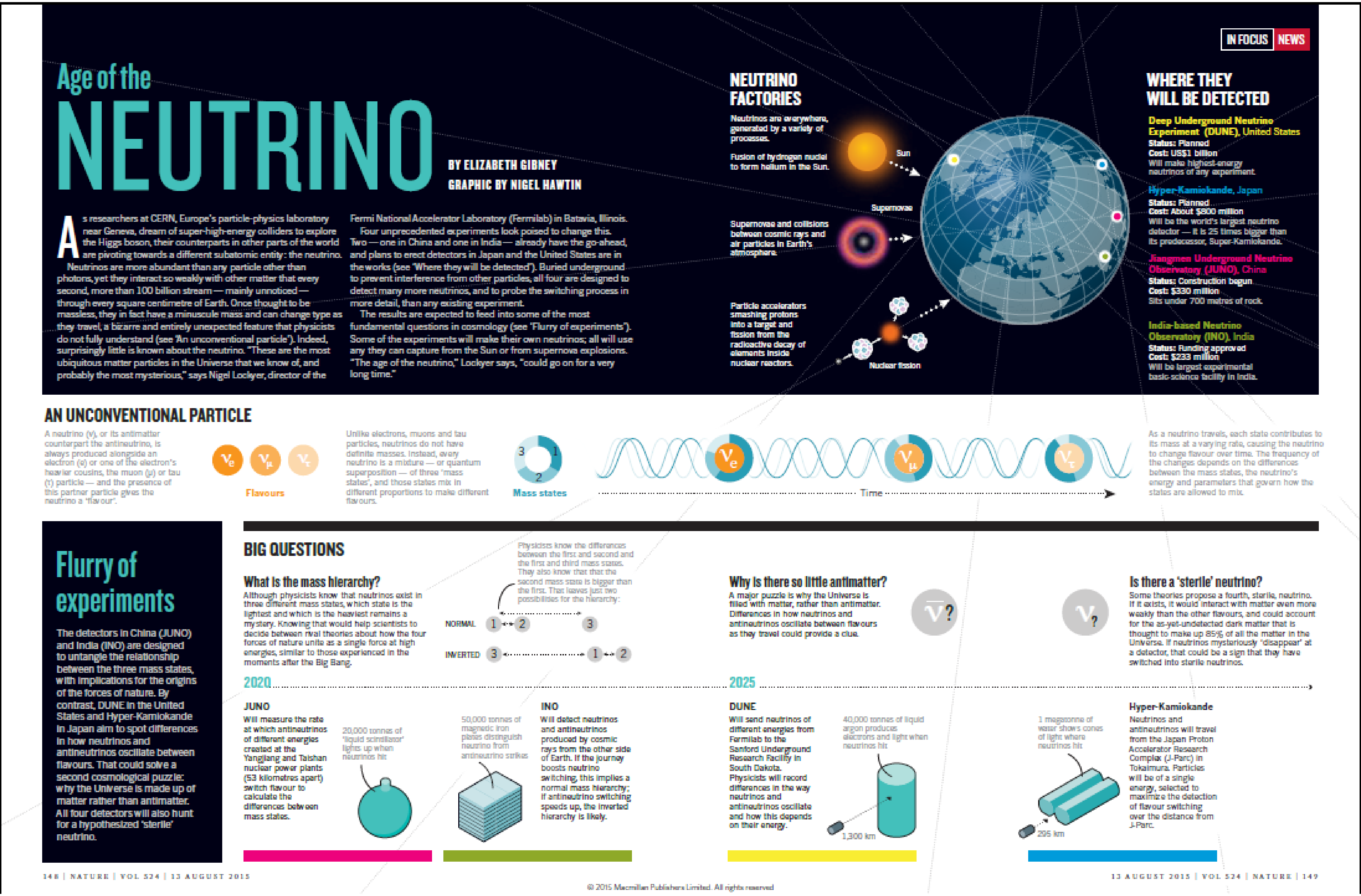
A cryogenic Indium detector for solar ν_e ?

- 100 Ton 8% In-loaded liquid scintillator for solar ν_e proposed by Raghavan (1976, 2007) to measure T_{core} ***directly*** via shift + broadening of *pp*, ^{7}*Be* energy spectrum (Bahcall 1993)
- Cryogenic detector (*qp* current): Compact (1m^3), High resolution (few keV), segmented.





India based Neutrino Observatory (INO) in Nature (13 Aug 2015)



IN FOCUS NEWS

Age of the NEUTRINO

BY ELIZABETH GIBNEY

GRAPHIC BY NIGEL HAWTIN

As researchers at CERN, Europe's particle-physics laboratory near Geneva, dream of super-high-energy colliders to explore the Higgs boson, their counterparts in other parts of the world are pivoting towards a different subatomic entity: the neutrino.

Neutrinos are more abundant than any particle other than photons, yet they interact so weakly with other matter that every second, more than 100 billion stream — mainly unnoticed — through every square centimetre of Earth. Once thought to be massless, they in fact have a minuscule mass and can change type as they travel, a bizarre and entirely unexpected feature that physicists do not fully understand (see 'An unconventional particle'). Indeed, surprisingly little is known about the neutrino. "These are the most ubiquitous matter particles in the Universe that we know of, and probably the most mysterious," says Nigel Lockyer, director of the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois.

Four unprecedented experiments look poised to change this. Two — one in China and one in India — already have the go-ahead, and plans to erect detectors in Japan and the United States are in the works (see 'Where they will be detected'). Buried underground to prevent interference from other particles, all four are designed to detect many more neutrinos, and to probe the switching process in more detail, than any existing experiment.

The results are expected to feed into some of the most fundamental questions in cosmology (see 'Flurry of experiments'). Some of the experiments will make their own neutrinos; all will use any they can capture from the Sun or from supernova explosions. "The age of the neutrino," Lockyer says, "could go on for a very long time."

NEUTRINO FACTORIES

Neutrinos are everywhere, generated by a variety of processes.

Fusion of hydrogen nuclei to form helium in the Sun.

Supernovae and collisions between cosmic rays and air particles in Earth's atmosphere.

Particle accelerators smashing protons into a target and fission from the radioactive decay of elements inside nuclear reactors.

WHERE THEY WILL BE DETECTED

Deep Underground Neutrino Experiment (DUNE), United States
Status: Planned
Cost: US$1 billion
Will make highest-energy neutrinos of any experiment.

Hyper-Kamiokande, Japan
Status: Planned
Cost: About $800 million
Will be the world's largest neutrino detector — it is 25 times bigger than its predecessor, Super-Kamiokande.

Jiangmen Underground Neutrino Observatory (JUNO), China
Status: Construction begun
Cost: $330 million
Sits under 700 metres of rock.

India-based Neutrino Observatory (INO), India
Status: Funding approved
Cost: $233 million
Will be largest experimental basic-science facility in India.

AN UNCONVENTIONAL PARTICLE

A neutrino (ν), or its antimatter counterpart the antineutrino, is always produced alongside an electron (e) or one of the electron's heavier cousins, the muon (μ) or tau (τ) particle — and the presence of this partner particle gives the neutrino a 'flavour'.

Unlike electrons, muons and tau particles, neutrinos do not have definite masses. Instead, every neutrino is a mixture — or quantum superposition — of three 'mass states', and those states mix in different proportions to make different flavours.

As a neutrino travels, each state contributes to its mass at a varying rate, causing the neutrino to change flavour over time. The frequency of the changes depends on the differences between the mass states, the neutrino's energy and parameters that govern how the states are allowed to mix.

Flurry of experiments

The detectors in China (JUNO) and India (INO) are designed to untangle the relationship between the three mass states, with implications for the origins of the forces of nature. By contrast, DUNE in the United States and Hyper-Kamiokande in Japan aim to spot differences in how neutrinos and antineutrinos oscillate between flavours. That could solve a second cosmological puzzle: why the Universe is made up of matter rather than antimatter. All four detectors will also hunt for a hypothesized 'sterile' neutrino.

BIG QUESTIONS

What is the mass hierarchy?

Although physicists know that neutrinos exist in three different mass states, which state is the lightest and which is the heaviest remains a mystery. Knowing that would help scientists to decide between rival theories about how the four forces of nature unite as a single force at high energies, similar to those experienced in the moments after the Big Bang.

Physicists know the differences between the first and second and the first and third mass states. They also know that that the second mass state is bigger than the first. That leaves just two possibilities for the hierarchy:

Why is there so little antimatter?

A major puzzle is why the Universe is filled with matter, rather than antimatter. Differences in how neutrinos and antineutrinos oscillate between flavours as they travel could provide a clue.

Is there a 'sterile' neutrino?

Some theories propose a fourth, sterile, neutrino. If it exists, it would interact with matter even more weakly than the other flavours, and could account for the as-yet-undetected dark matter that is thought to make up 85% of all the matter in the Universe. If neutrinos mysteriously 'disappear' at a detector, that could be a sign that they have switched into sterile neutrinos.

2020

JUNO

Will measure the rate at which antineutrinos of different energies created at the Yangjiang and Taishan nuclear power plants (53 kilometres apart) switch flavour to calculate the differences between mass states.

20,000 tonnes of 'liquid scintillator' lights up when neutrinos hit

50,000 tonnes of magnetic iron plates distinguish neutrino from antineutrino strikes

INO

Will detect neutrinos and antineutrinos produced by cosmic rays from the other side of Earth. If the journey boosts neutrino switching, this implies a normal mass hierarchy; if antineutrino switching speeds up, the inverted hierarchy is likely.

2025

DUNE

Will send neutrinos of different energies from Fermilab to the Sanford Underground Research Facility in South Dakota. Physicists will record differences in the way neutrinos and antineutrinos oscillate and how this depends on their energy.

40,000 tonnes of liquid argon produces electrons and light when neutrinos hit

1 megatonne of water shows cones of light where neutrinos hit

Hyper-Kamiokande

Neutrinos and antineutrinos will travel from the Japan Proton Accelerator Research Complex (J-Parc) in Tokaimura. Particles will be of a single energy, selected to maximize the detection of flavour switching over the distance from J-Parc.

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Thank you!