Non-accelerator experiments: a window for new physics?

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A wide variety of experiments…..

- Underground experiments

  Proton (nucleon) decay, Neutrinos, WIMP searches, $0\nu2\beta$-decay

  ….

- Surface experiments

  Telescopes (Optical, Radio, X-ray, γ-ray),

  cosmic rays, gravitational wave detectors , search for

  magnetic monopole, axions, n-$\bar{n}$ oscillation (ΔB = 2),

  EDM of *n*, *e* …..

Plan of talk

1. Status of India based Neutrino Observatory
2. Feasibility study of ^{124}Sn cryogenic bolometer for $0\nu2\beta$ decay
3. Dark matter experiment(s) at INO ?
4. LENS in India?

1. Status of India based Neutrino Observatory

Some history….

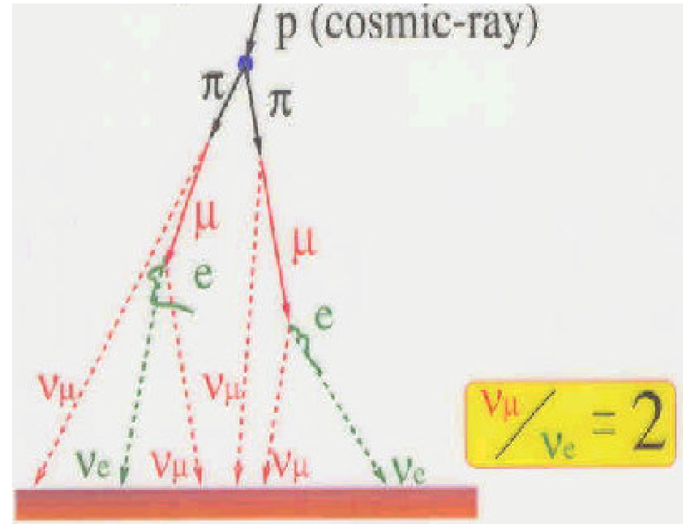
- **Search for proton decay at Kolar Gold Field** : 1st such experiment to put a lower bound on nucleon lifetime ~ 10^{30} years (~1981-82) Phys. Lett. **106B**, 339 & *ibid* **115B**, 349
- Other experiments worldwide (IMB, Kamioka, SuperKamioka..) put tighter bounds on possible baryon # violating decays

  e.g. $\tau(p \rightarrow e^{+}\pi^{0}) > 10^{34}$ **years** **(SK 2009)**
- Irreducible background due to atmospheric neutrinos, but is signal for neutrino oscillations! (1998)

Atmospheric neutrinos

- $p + {}^{14}N$, ${}^{16}O$ collisions in upper atmosphere
- First detected at Kolar Gold Field mine

by TIFR-Osaka-Durham team



Phys. Lett. 18, 196 (1965), dated 15th Aug 1965

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

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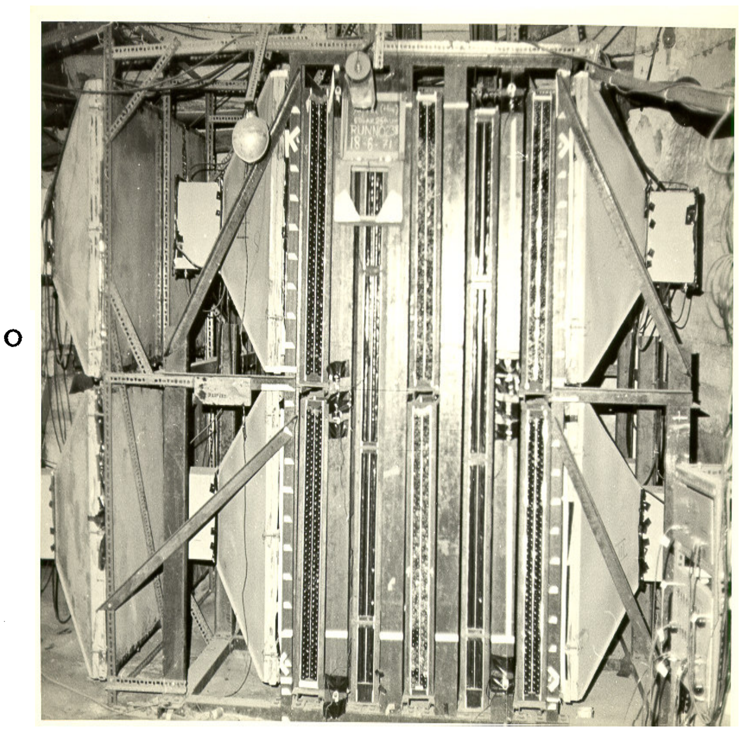
D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965



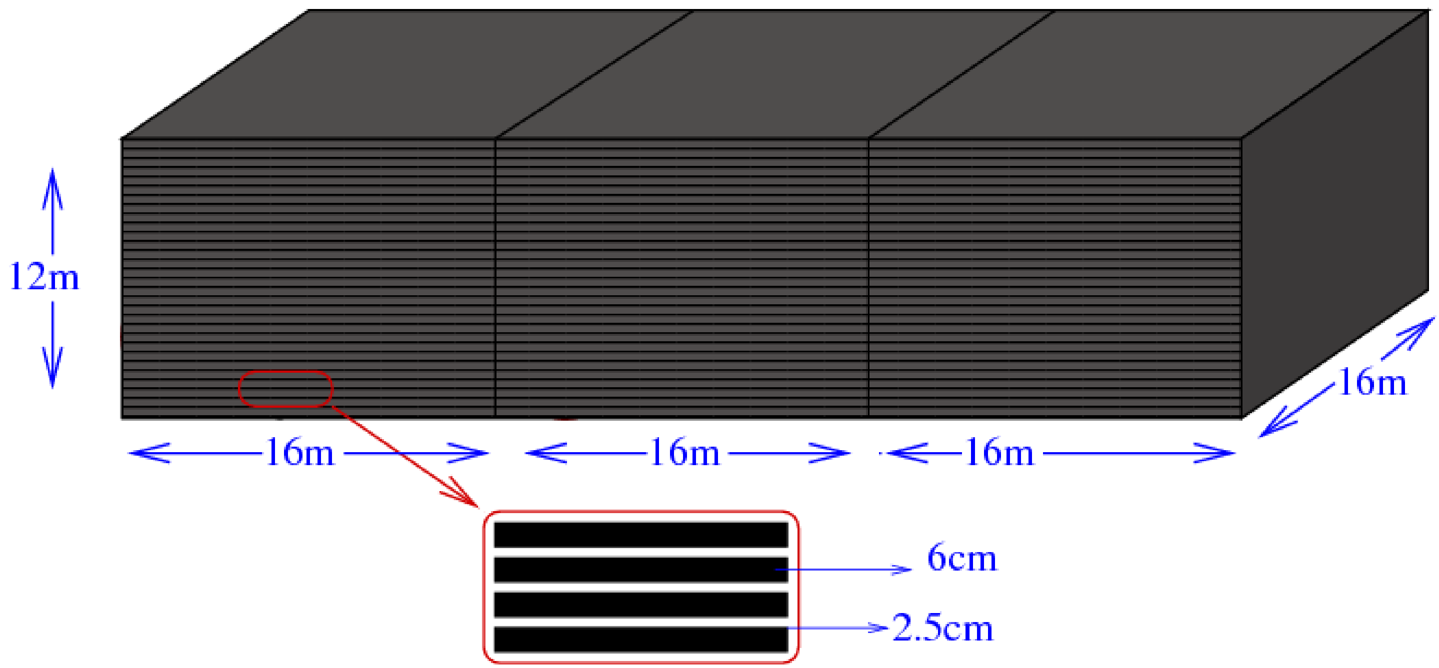
Physics goals

- ICAL goals – neutrino oscillation parameters for ν_μ and ν_μ
- If $\theta_{13} > 7°$ address ν-mass hierarchy (normal or inverted)
- Measure VHE muons (> TeV)
- Study "KGF events"
- Phase 2, bid for LB detector for Neutrino Factory (magic baseline ~7000 km if at CERN/JPARC) - CP-violation in ν sector

- NDBD with ^{124}Sn cryogenic bolometric detector (ongoing feasibility)
- Dark matter search (1^{st} collaboration meeting in Dec 2011 @ SINP)
- 1 MV accelerator for nuclear astrophysics (σ ~ Gamow peak)

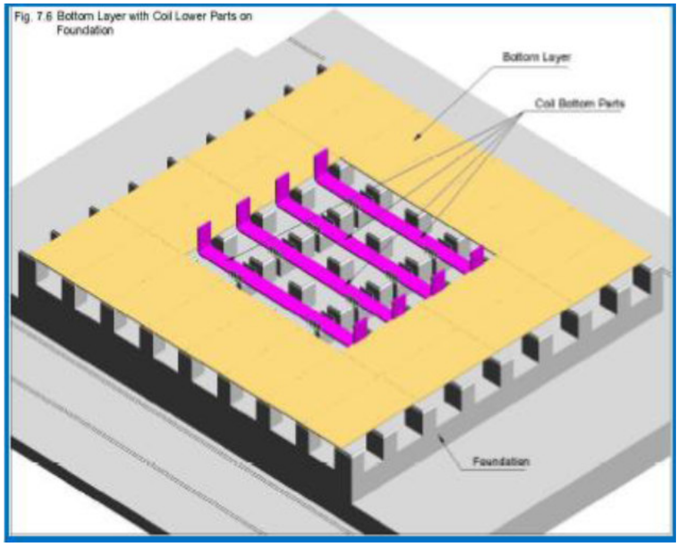
Our choice

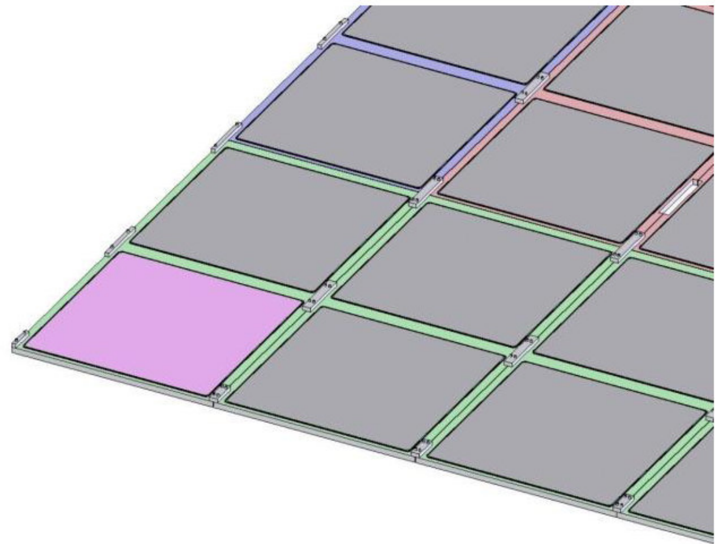
- Detector – physics reach, our capabilities & limitations led INO Collaboration to choose 50-100 kT Iron Calorimeter (ICAL) to measure atmospheric ν_μ & **anti-ν_μ**
- Site requirement – 1 km rock cover all round detector

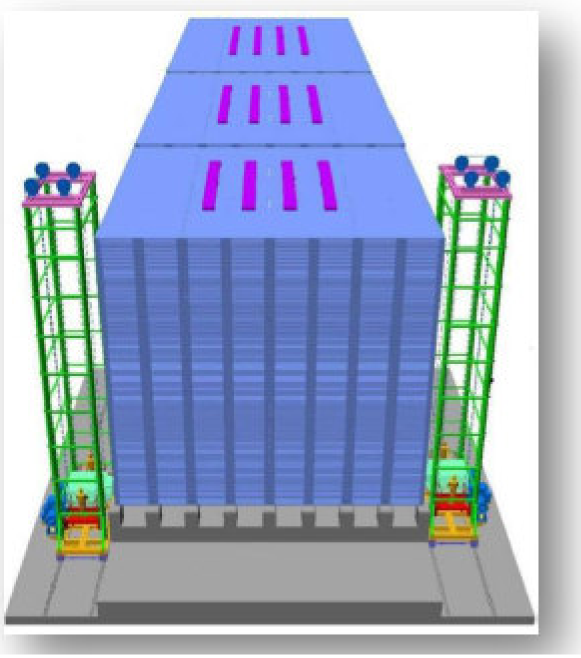


- Magnetic field using low carbon steel (B ~ 1.3 Tesla)
- nsec timing (from RPC) $\Rightarrow$ up/down discrimination of muons
- X-Y-Z tracking by RPC $\Rightarrow$ $\boldsymbol{p}/q$ $\Rightarrow$ L/E for μ^+ and μ^- events

Proposed assembly of 16 kton magnet (TCE report)

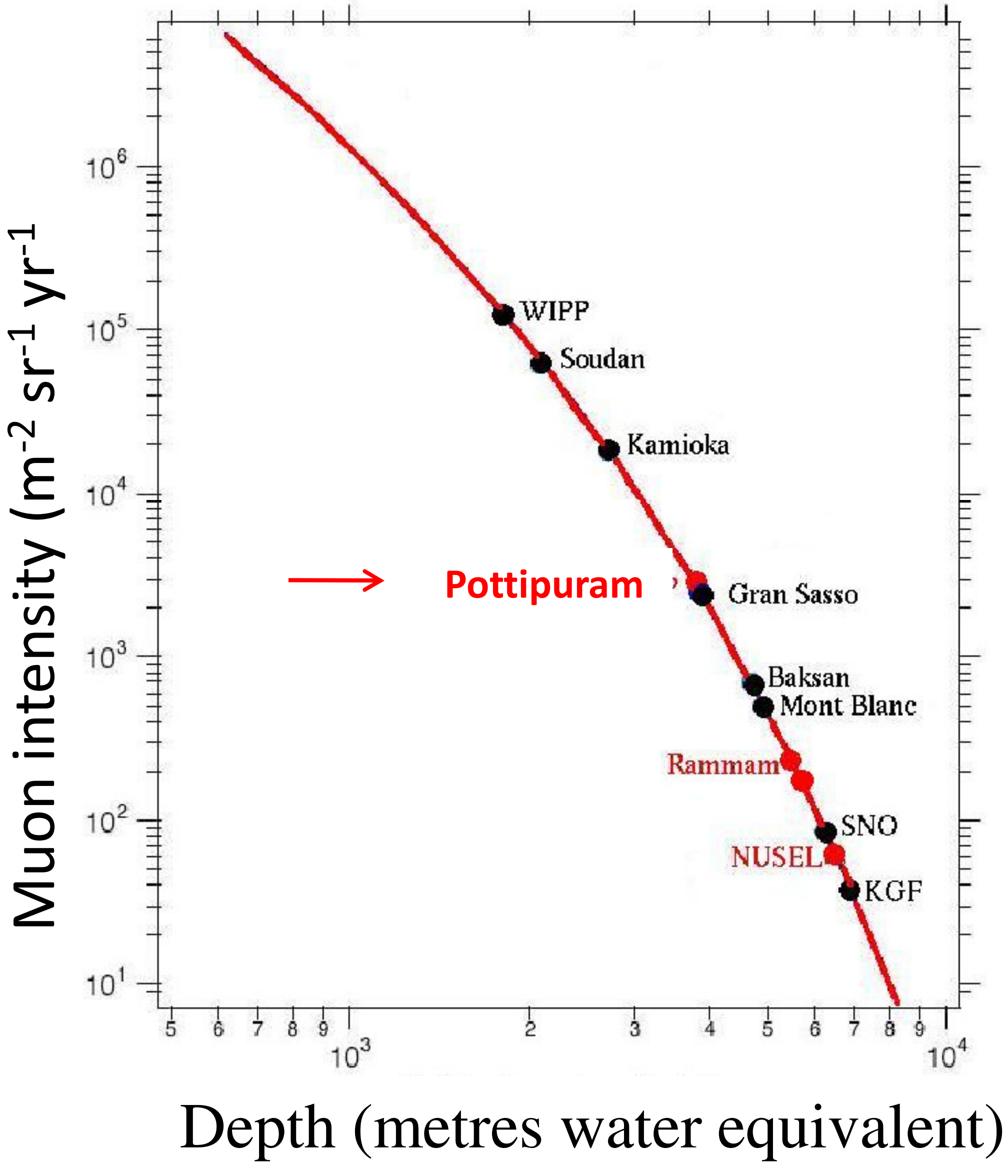






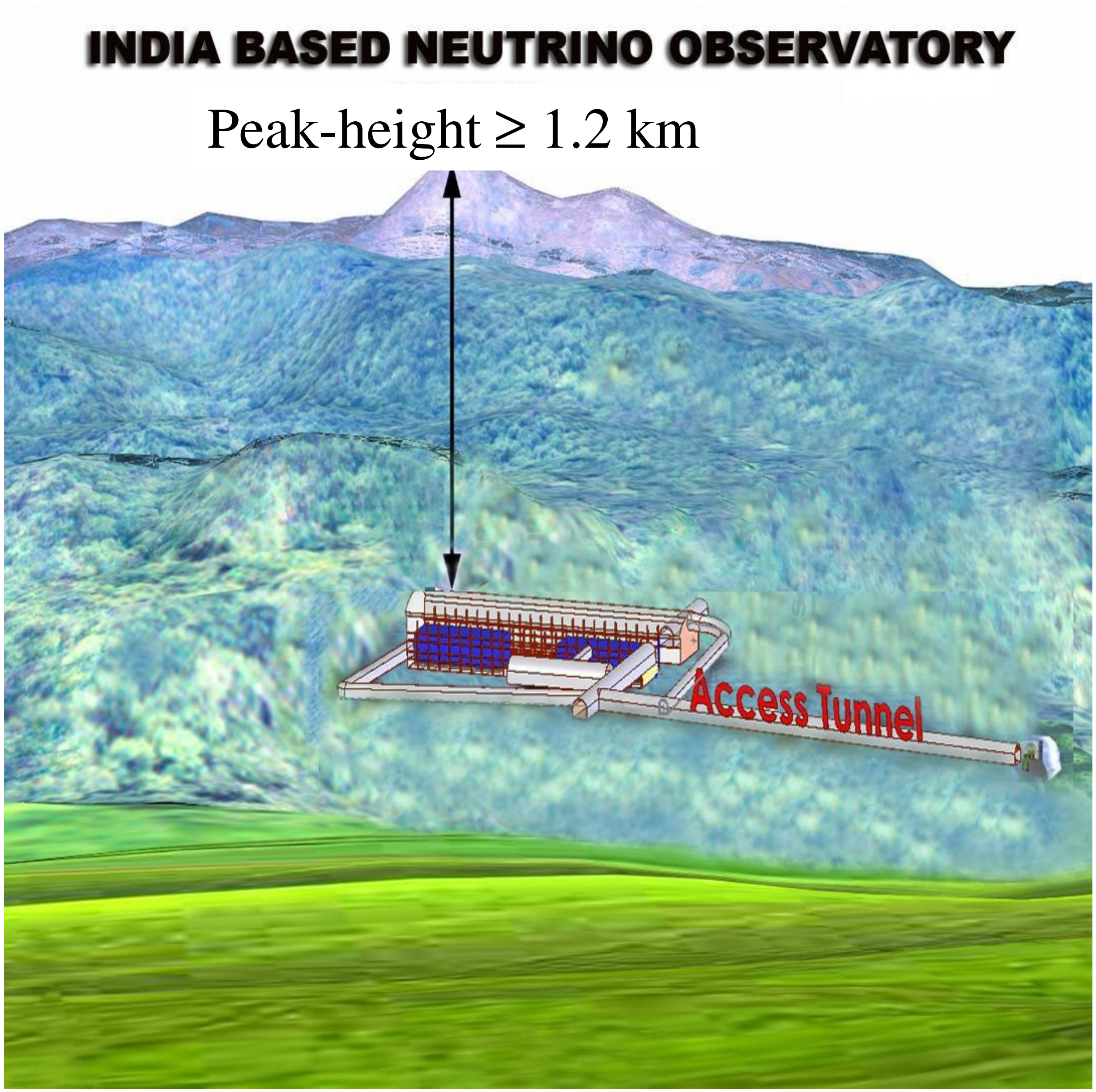
- ➢ BARC team will use this report as a starting point to finalize the mechanical design & assembly using SPM
- ➢ 1/30th scaled down version to be built in the ~2 years

Muon flux as a function of depth

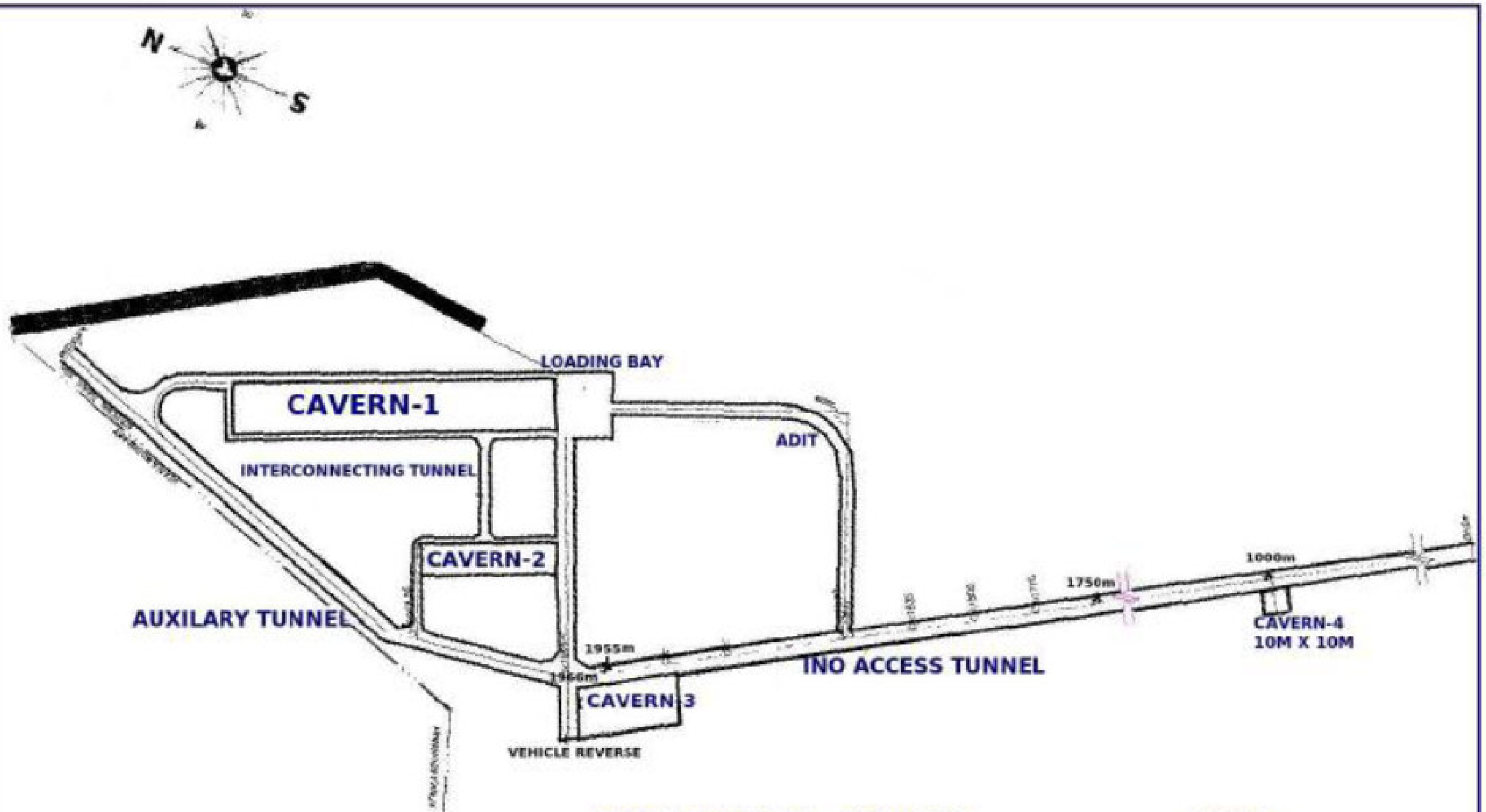


How deep underground ?

Due to low ν event rates *cosmic ray muons* are most important background. Can be reduced to manageable levels by locating the ν detector deep underground (depth ≥ 1 km) in mines or **tunnels**


INDIA BASED NEUTRINO OBSERVATORY
Peak-height ≥ 1.2 km
Access Tunnel

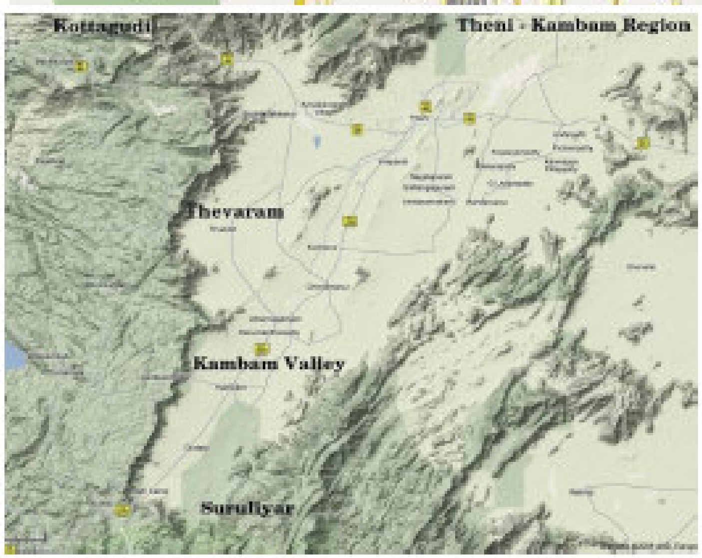
Layout of underground lab



ACCESS TUNNEL 7.5m, 'D' SHAPED :1966.0m
ADDITIONALLY DRIVEN INT. TUNNEL 5.5m 'D' SHAPED: 175.4m
AUXILARY TUNNEL 7.5m 'D' SHAPED : 224.6m
INTERCONNECTING TUNNEL 3.5m 'D' SHAPED : 72.5m
ADDITIONAL TUNNEL 7.5m 'D' SHAPED (future expn) : 50.0m

CAVERN -1 : 132m x 26M x 32.5m
CAVERN -2 : 55m x 12.5m x 8.6m
CAVERN -3 : 40m x 10m x 10m
CAVERN -4 : 10m x 10m x 10m

INO site at Pottipuram, Tamil Nadu



Tamil Nadu Govt. has allotted land at Pottipuram (~25 ha)

Requirements of active detector

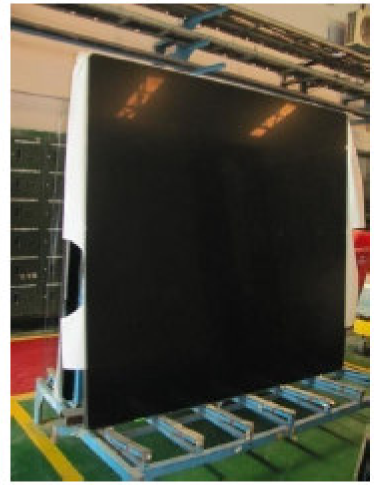
- Position resolution ~ 2 cm, time resolution ~ 1 nsec

  curvature of track ⇒ ***p***, fast timing ⇒ up-down

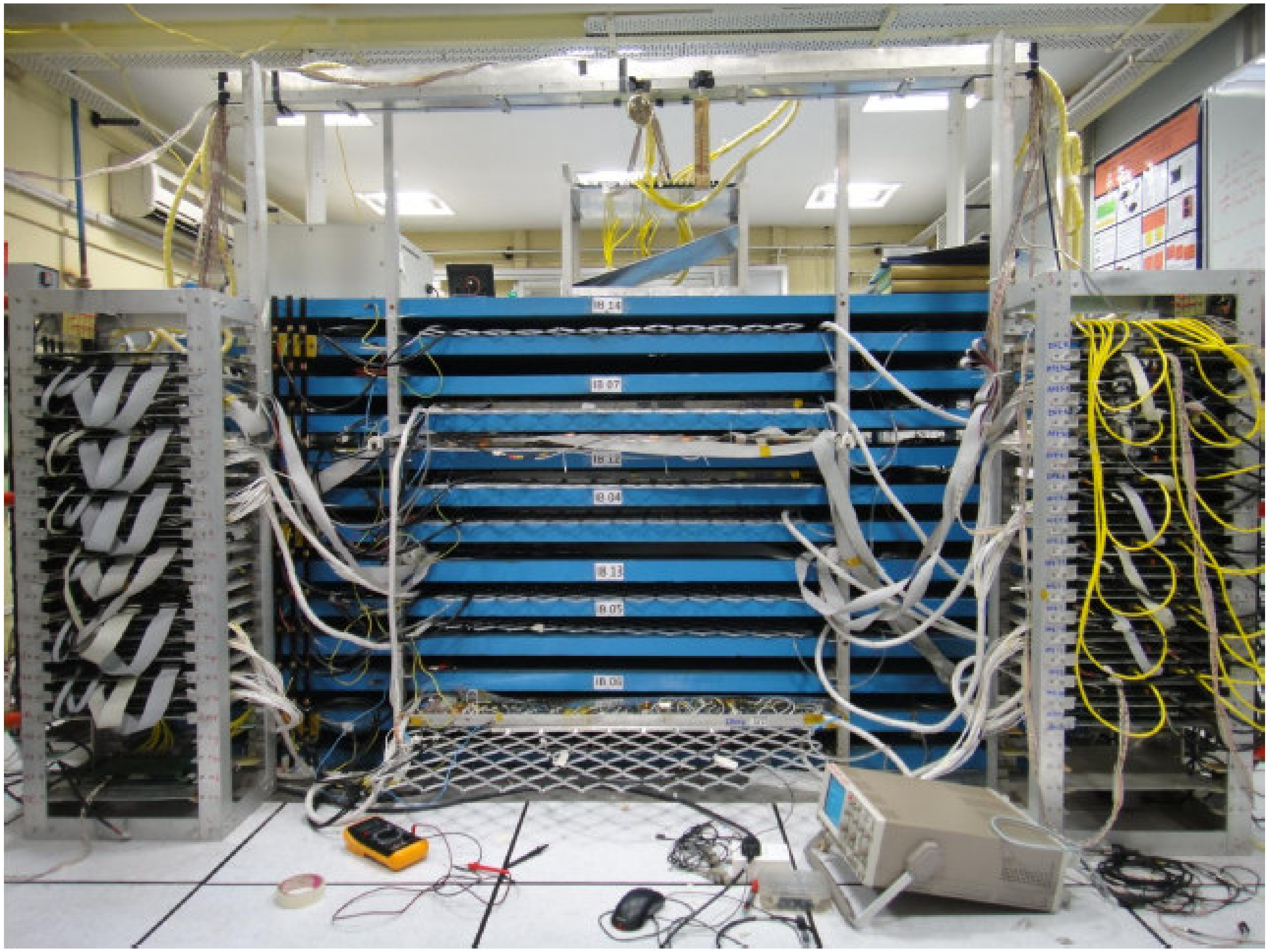
  both of these ⇒ charge identification (μ^+ or μ^-)
- Modular design
- Large size (total area for 50 kT detector ~ 10^5 m^2)
- Large numbers so should be cheap, rugged, reliable
- Chose large area gas detectors (glass resistive plate chambers, RPCs) over plastic scintillators

Challenges: 30,000 m^2 carpet area, 4 M electronic channels
200 m^3 gas inventory in closed loop system

Glass RPC at Asahi Float Glass Co. at Navi Mumbai

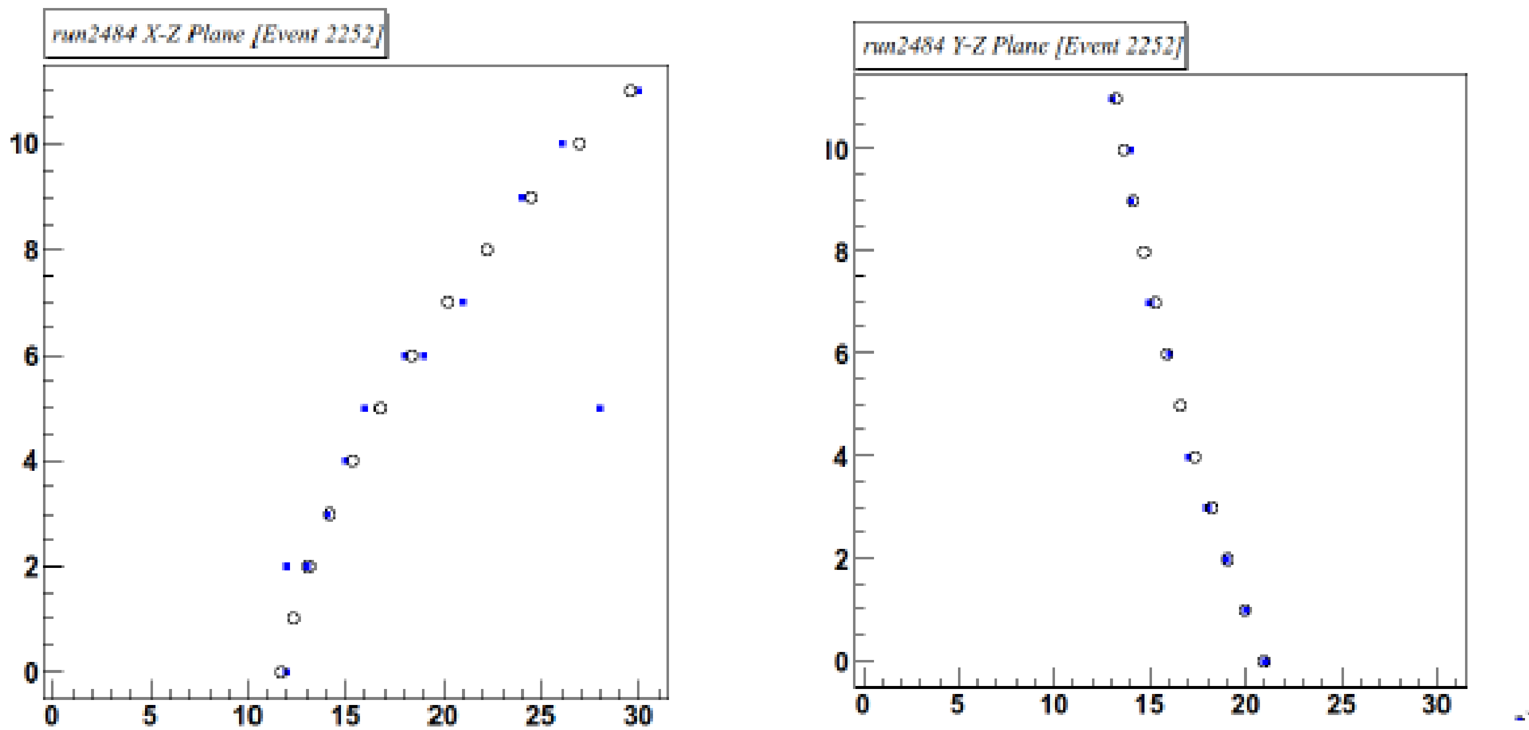


35 ton ICAL “prototype” at VECC, Kolkata

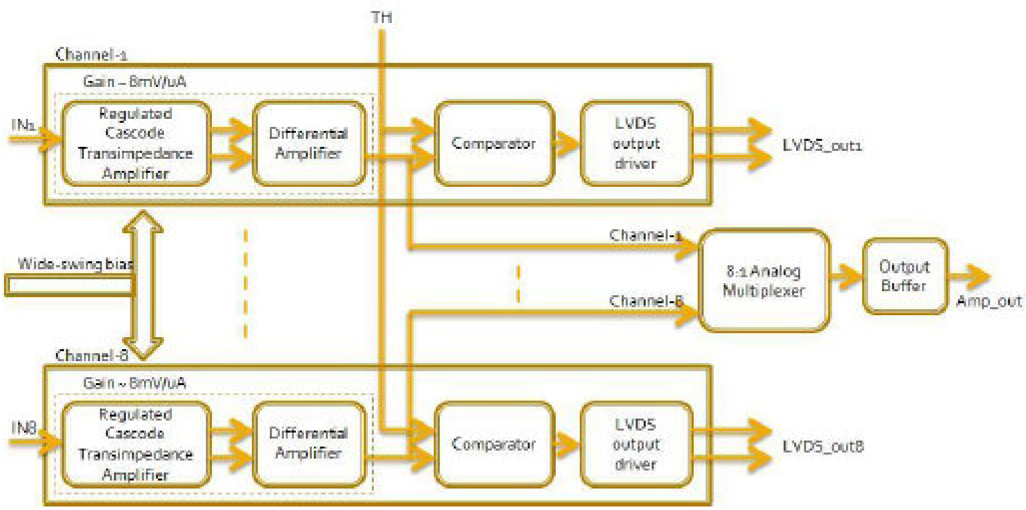


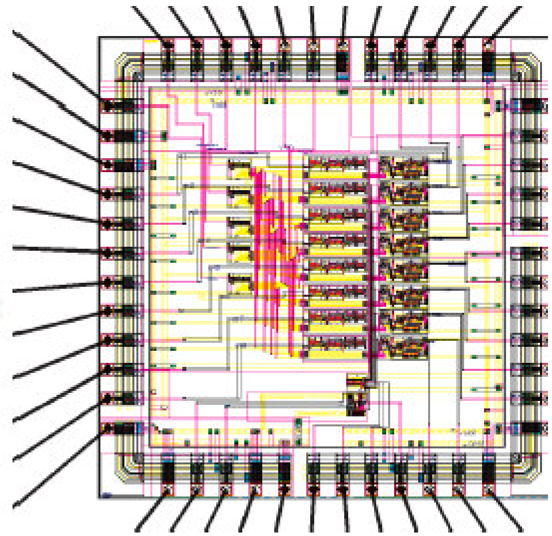
Took cosmic muon data during Feb-May 2011 campaign. Data being analyzed.

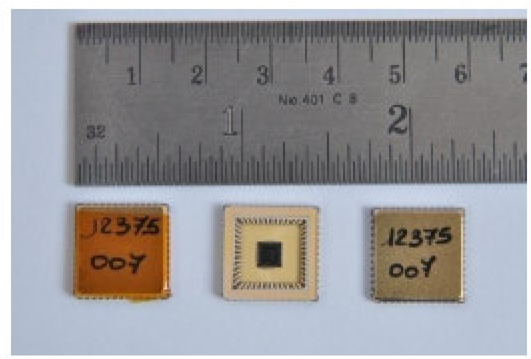
Muon tracks at B ~ 1.5 Tesla in central region….



Front end preamp-timing discriminator chip for RPC designed at BARC

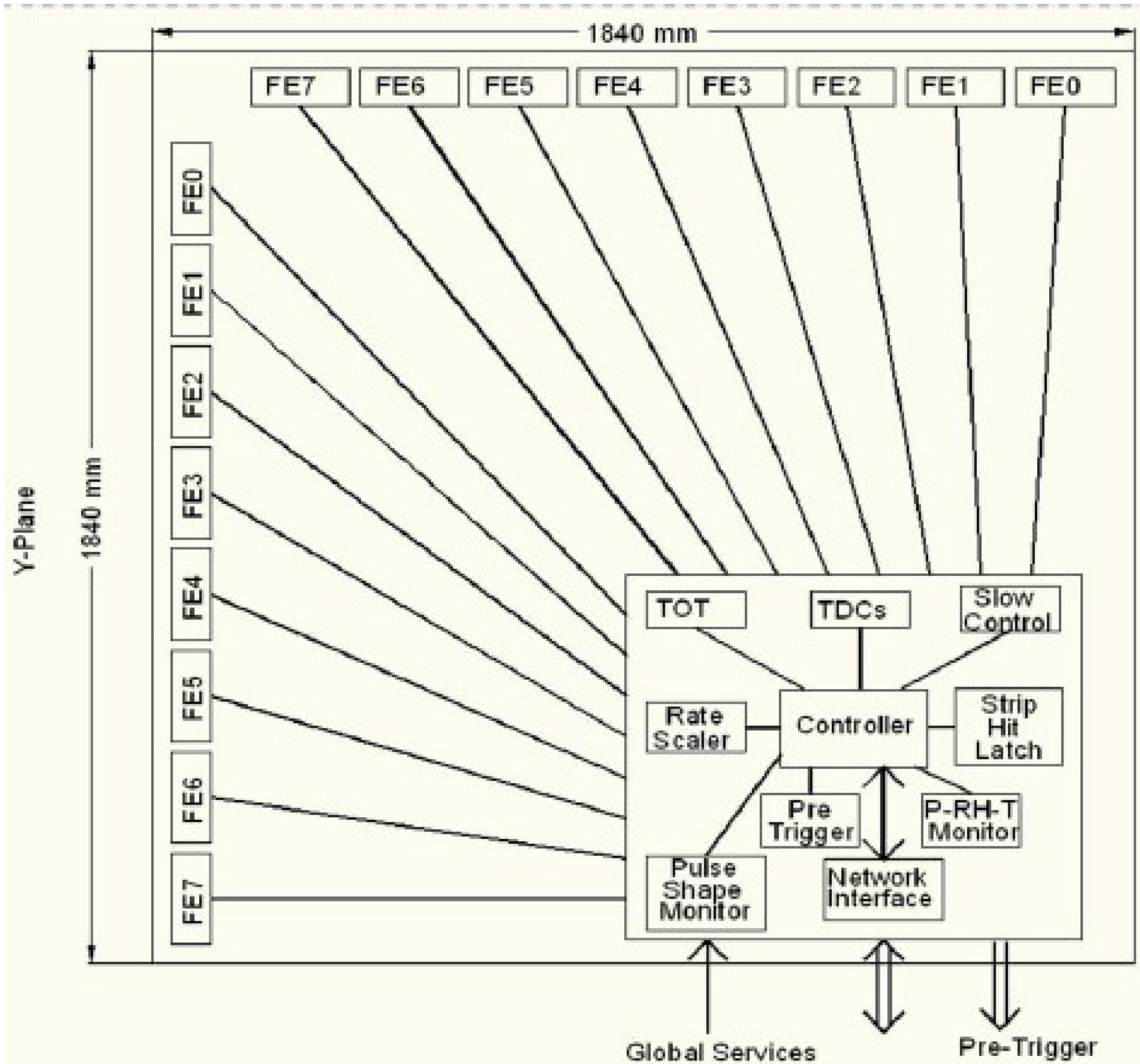




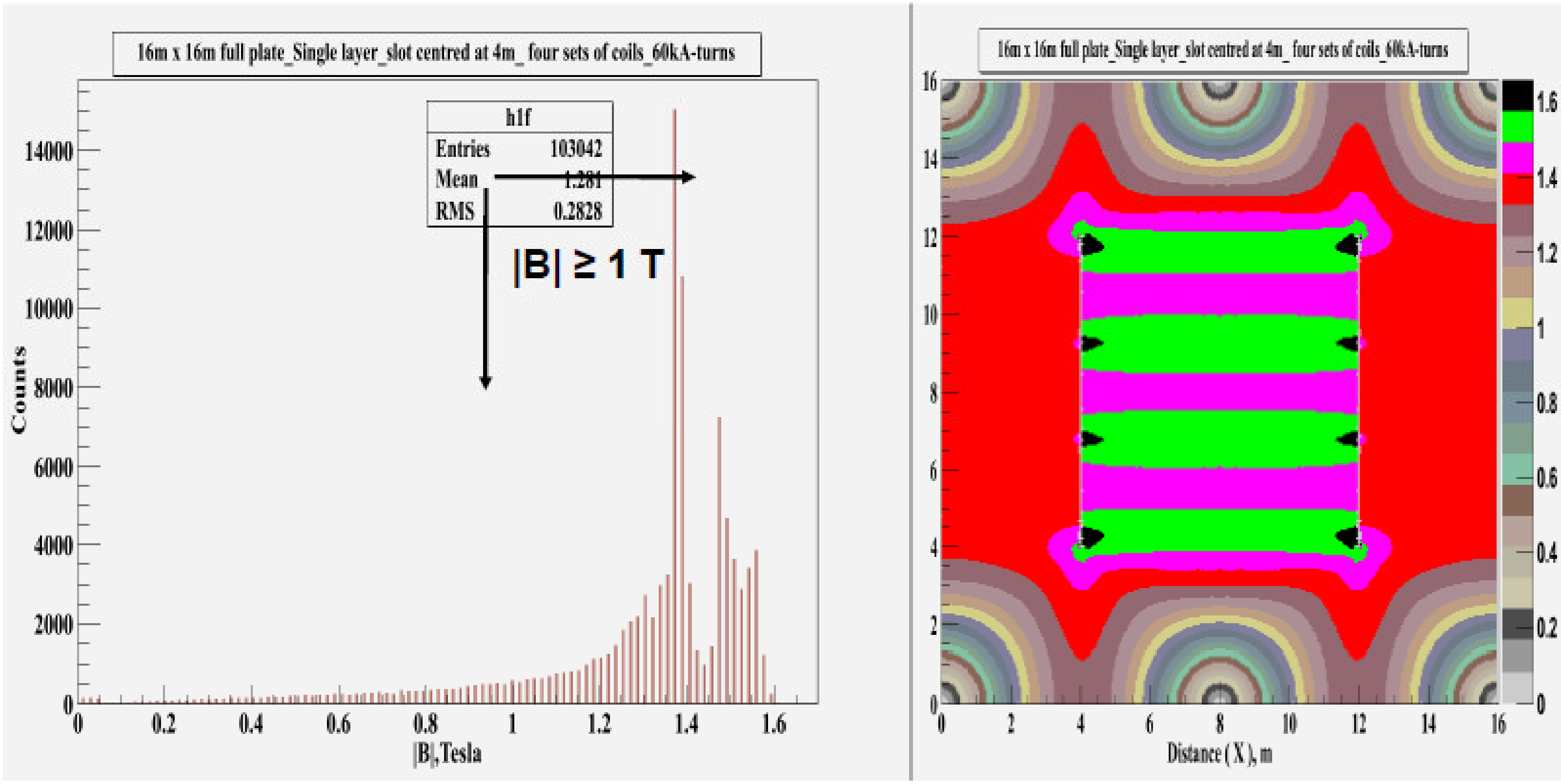


1st batch oo ASIC (fab: Euro Practice IC Services) being tested

On board controller card for every RPC



ICAL magnet 3D-simulation



Surface plot of |B|

INO PhD student programme

- Started in 2008-09, 4th batch presently doing course work
- affiliated to Homi Bhabha National Institute, a deemed

University

- Total of 19 students (including present batch)
- PhD advisors from all Dept of Atomic Energy Institutes in

INO collaboration and IIT(B), IIT(M)

PERT CHART

SN	Description of work	2011-12				2012-13				2013-14				2014-15				2015-16				2016-17			
	Civil work at Pottipuram																								
1	Land acquisition and pre-project work	←	→																						
2	Architectural and Engineering consultancy	←	—	→																					
3	Tendering and award of contracts			↔																					
4	Mining of access portal					←	→																		
5	Excavation of tunnel							←	—	—	—	—	→												
6	Excavation of caverns													←	—	—	—	—	→						
7	Installation of services, cranes, lifts etc.																	←	—	→					
8	Civil work for magnet support bed																			↔					
9	Surface facilities					←	—	—	—	—	—	—	—	—	—	→									
	Magnet																								
10	Procurement of steel plates									←	—	—	—	→											
11	Machining job for steel plates													←	—	—	—	—	→						
12	Transportation of machined plates at site																		←	→					
13	Procurement of copper coils																←	—	—	→					
14	Assembly/erection of magnet (3 modules)																				←	—	—	→	
	RPC																								
15	Finalization of all design details, tendering	←	—	—	→																				
16	Procurement of components			←	—	→																			
17	Fabrication and assembly of 30000 pcs						←	—	—	—	—	—	—	—	—	—	—	—	→						
18	Transportation to site and tests																←	—	—	—	—	→			
19	Procurement of electronics, gas handling								←	—	—	—	—	—	—	→									
20	Installation and commissioning																					←	—	—	→

Present status

- Financial sanction for engineering module (8m × 8m × 20 layers) + pre-project infrastructure at INO site and Madurai (~ 67 cr ₹ ≈ 13M$) expected shortly
- Atomic Energy Commission approval for full project awaited (to be followed by request for Cabinet approval)
- Forest and environmental clearances obtained
- 26 ha land at Pottipuram (INO site) sanctioned by Chief Minister, TN a couple of weeks ago, approval for 10 ha for "INO Centre" at Madurai in final stages

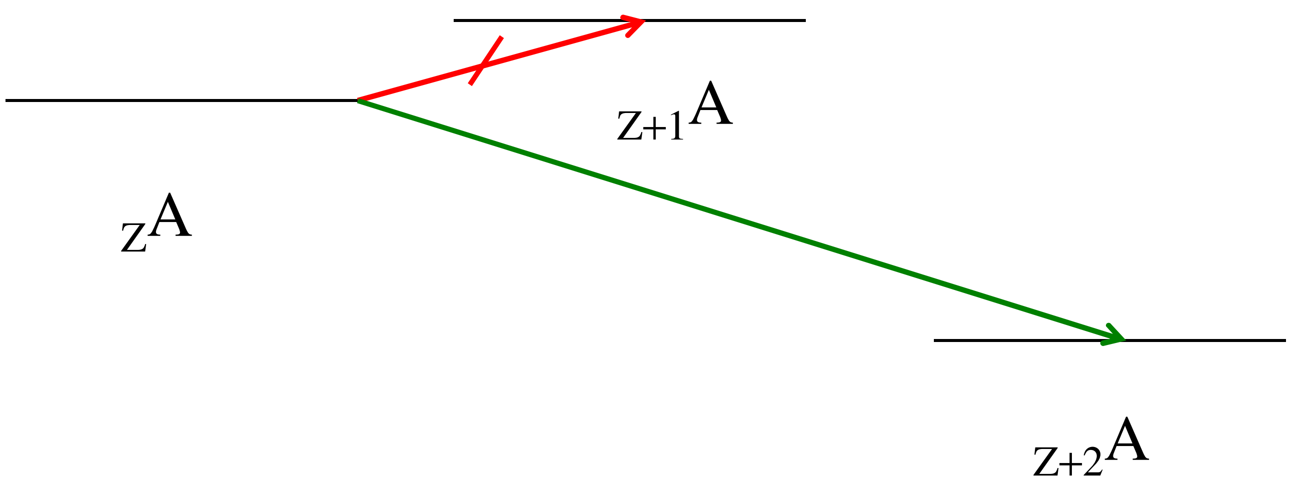
INO Collaboration meeting at Madurai (Feb 2011)

2. Feasibility study for ^{124}Sn cryogenic detector for 0ν2β decay

Goal: To measure neutrinoless double beta decay (NDBD) in ^{124}Sn

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



First calculated by Maria Goeppart Mayer (following suggestion of Wigner) *Phys. Rev.* ***48**, 512 (1935)*

Why is measuring NDBD important?

- Is the neutrino its own anti-particle?

  $\nu = \bar{\nu}$ (Majorana) or $\nu \neq \bar{\nu}$ (Dirac)

- Addresses absolute mass scale of neutrino

  Neutrino oscillation experiments only measure Δm^2_{ij}

  Complementary to $m(\nu_e)$ from ^{3}H β-spectrum measurements

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

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

- $\Gamma_{2\beta0\nu} \propto$ [phase-space] $\times$ [Nuclear ME]$^2 \times \langle m_\nu \rangle^2$

$\Downarrow$

[Q-value]^5

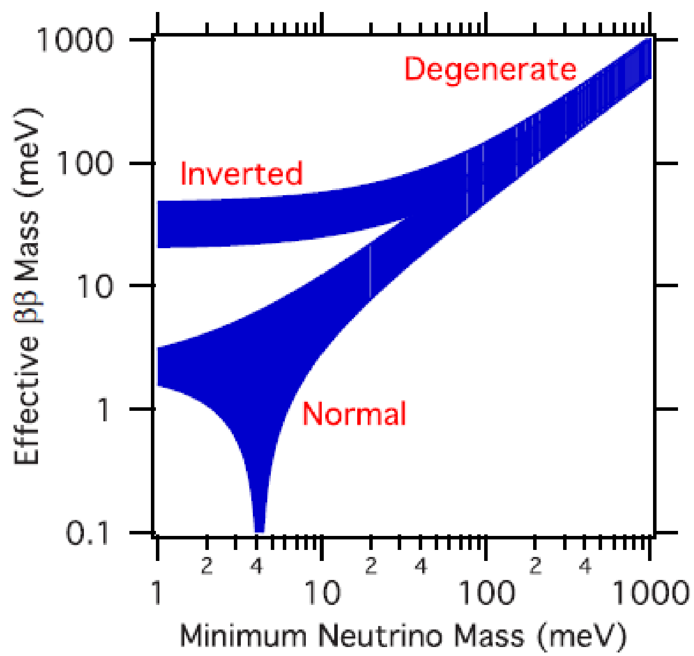
- High $Q_{2\beta}$ desirable for background from radioactivity and for measurement (traversing dead layers in tracking detectors)

Here $\langle m_\nu \rangle = \sum m_i U_{ei}^2$

$$U_{e1} = c_{12}c_{13}$$
$$U_{e2} = s_{12}c_{13}$$
$$U_{e3} = s_{13}e^{-i\delta}$$

$m_3 > m_2 > m_1$ **Normal hierarchy**

$m_2 > m_1 > m_3$ **Inverted hierarchy**



Detector strategies

1. DBD nuclei integral part of detector

    - ^{76}Ge, $^{128,130}Te$

   Calorimetry (temperature, ionization, scintillation)

   ΔE_{FWHM} (2 MeV) ~ 10 keV   ≥3 keV   100 keV

2. DBD nuclei external to detector

   Tracking of β^- (in magnetic field) + Vertex + Fast coincidence

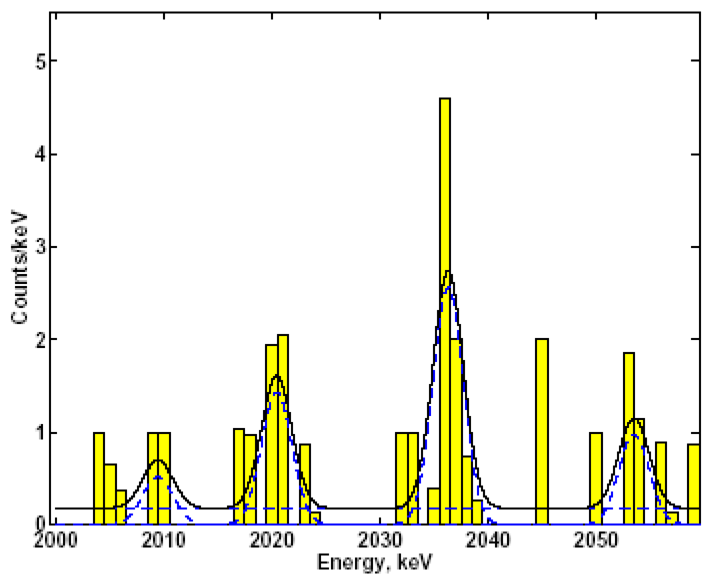
   Poorer $\Delta E_{FWHM}/E$ ~ 10 %

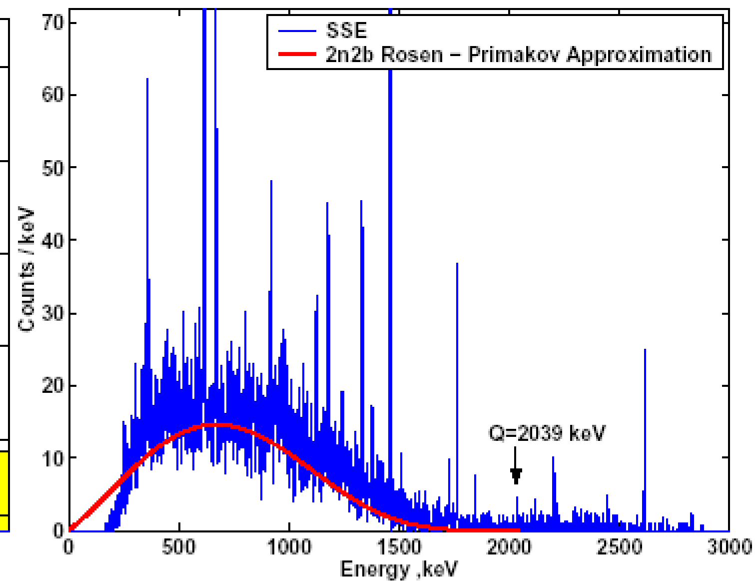
- With several ongoing experiments why one more?

When NDBD is finally found, preferably by at least one more experiment, the nuclear matrix element (NME) will limit the precision of the extracted effective Majorana mass

- ^{124}Sn has proton shell filled. Structure calculations relevant to NDBD NME perhaps more accurate than in other cases
- Sn bolometers have been made as μ-calorimeters (as X-ray detectors with ΔE_{FWHM} (@ 6 keV) ~ 5 eV

Results from Heidelberg-Moscow expt. @ Gran Sasso with 5 HPGe detectors, enriched to ~ 87% ^{76}Ge



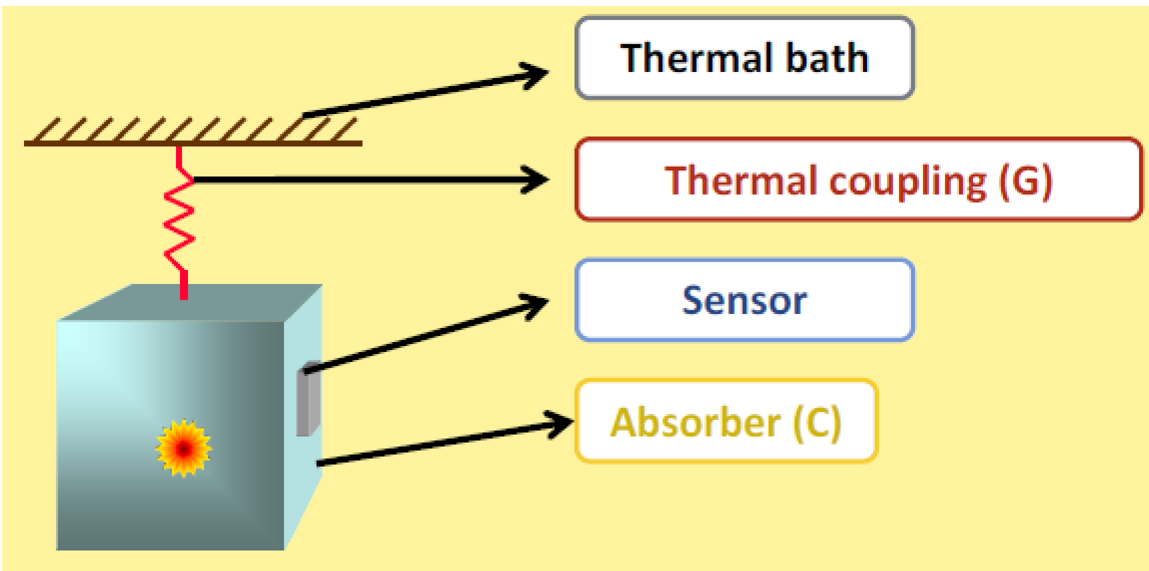


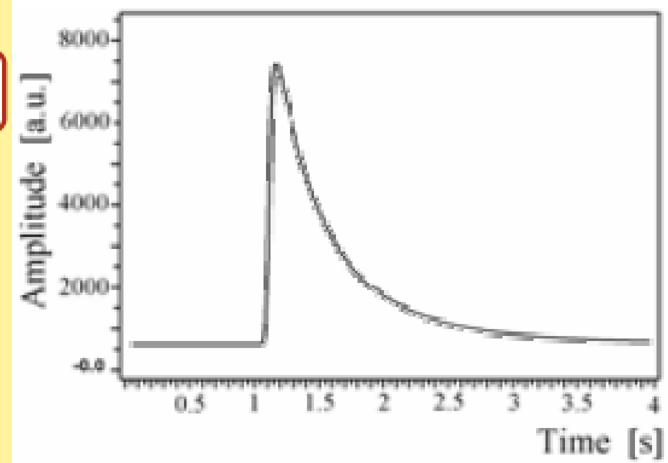
Pulse shape selected spectrum (1995-2003) in 2000-2060 keV and 100-3000 keV. Red curve is $2\beta 2\nu$ spectrum

0ν events		$\langle m_\nu \rangle$ eV
28.8 ± 6.9 (1990-2003)	71.7 kg.yr	$0.44^{+0.14}_{-0.20}$
23.0 ± 5.7 (1995-2003)	56.7 kg.yr	$0.45^{+0.14}_{-0.22}$

Cryogenic bolometer for NDBD

Principle of method:





In insulators at low temperature, specific heat $C \propto T^3$

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

Brofferio, Neutrino 2008

- Sn has SC transition temperature of T_C ~ 3.7 K
- Electronic specific heat falls off exponentially below T_C
- Only lattice specific heat (~T^3) below ~ 500 mK

$Q_{\beta\beta}$ (^{124}Sn) =2288.1 ± 1.6 keV

bolometer

$^{124}Sn \rightarrow ^{124}Te^*$

$T_{1/2}$ >0.8-1.2 x 10^{21} yrs Nucl. Phys. A **807**, 269 (2008)

Make a natural Sn bolometric detector ~ 0.5–1 Kg

Bolometer development, Sensor development, NTME calculations, background studies, ^{124}Sn enrichment

- Precision Q value measurement is necessary ($Q_{\beta\beta}$=2288.1±1.6keV)

Once prototype detector successful…

Build a large scale detector (~ 1 ton) at INO lab

Fn $= G^{0\nu} |M^{0\nu}|^2 = 8.6 \times 10^{-13}\ yr^{-1}$ *(PHFB)*

$= 1.4 \times 10^{-13}\ yr^{-1}$ *(SM)*

With 90 % enrichment, background ~ 0.01 counts/ keV.kg.yr

m_ν~ 100 meV in 1 yr (SM) , m_ν~ 50 meV in 1 yr (PHFB)

Tata Institute of Fundamental Research, Mumbai : Vivek Singh, Neha Dokania, S. Mathimalar (INO Graduate students), Yashwant G.(visiting fellow), V. Nanal, R.G. Pillay, N. Krishnan, S. Ramakrishnan, R. Palit, S. Wategaonkar

Bhabha Atomic Research Centre, Mumbai: V.M. Datar, A. Shrivastava

IIT Kharagpur, IIT Ropar : P.K. Raina , S. Ghourai, Soumik Das

Univ. of Lucknow : P.K. Rath, Akhilesh Ranjan, Dr. Ramesh Chandra

Physical Research Laboratory, Ahmedabad: V.K.B. Kota

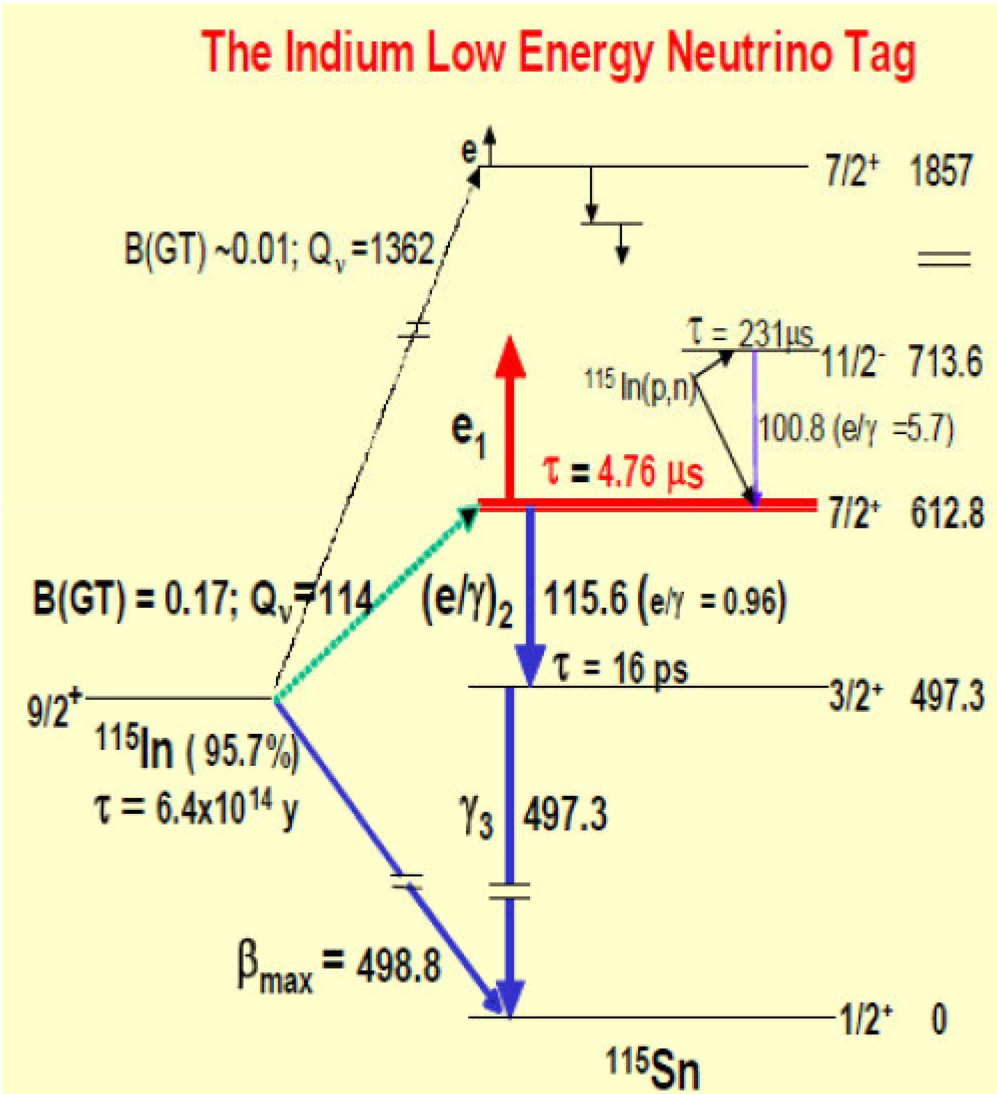
Variable Energy Cyclotron Centre, Kolkata: Parnika Das

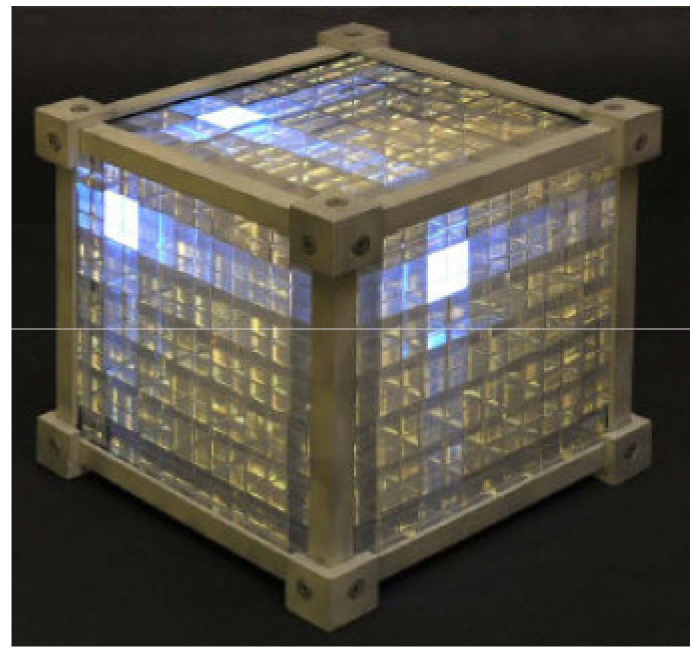
3. Dark Matter experiment(s) at INO

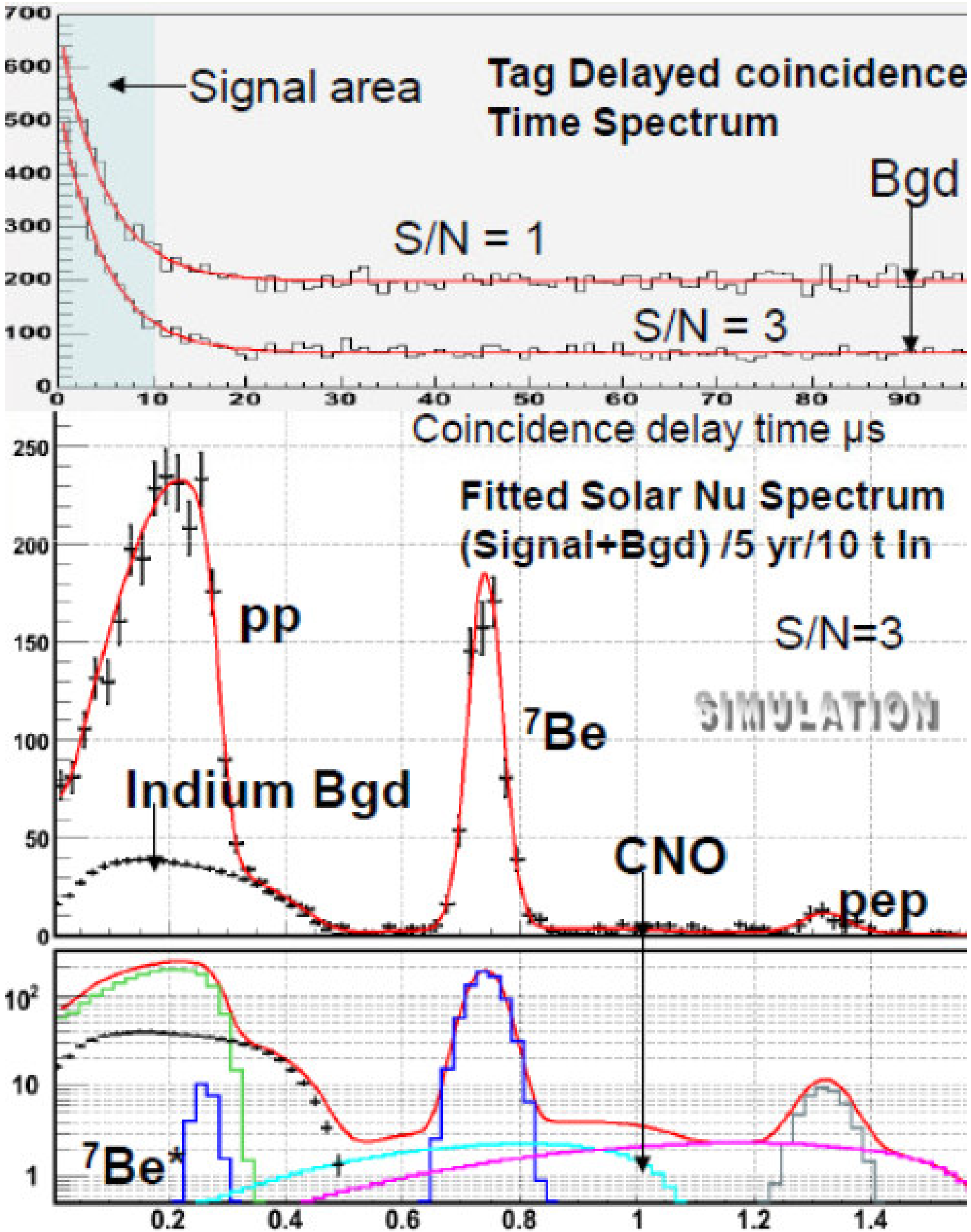
- Exploratory meeting at Lepton-Photon 2011 at TIFR to form Collaboration
- First meeting planned on 23-24 Dec, 2011 at SINP Kolkata
- SINP, Texas A & M (*CDMS upgrade at SNO Lab*), IIT(B), Oxford, TIFR, BARC collaborating institutions....
- Look into silicon as a possible cryogenic detector for light WIMPs
- SINP has expertise on superheated liquid gels (deployed at SNO Lab)

4. *pp* neutrinos from sun - LENS in India?

- ^{115}In detector proposed by Raghavan [PRL **37**, 259 (1976)]
- Low threshold ~ 114 keV (pp ν_e s!): $\nu_e + {}^{115}\text{In} \rightarrow e + {}^{115}\text{Sn}^*$ (delayed 116, 492 keV γ-cascade) $T_{1/2}$ ~ 4.76 μsec
- Recent ideas on segmentation of In-loaded liquid scintillator led to revival of proposal
- **Main goal : is solar luminosity same in EM & ν_e $L_{photon} = L_\nu$?**
- **Could address sterile neutrino with Δm^2 ~ eV^2 (^{51}Cr source)**
- Possible Indian collaboration explored in couple of visits by Raju Raghavan before his untimely death ~ 2 weeks ago


The Indium Low Energy Neutrino Tag
e
7/2+ 1857
B(GT) ~0.01; Qν =1362
τ = 231μs
11/2- 713.6
115 In(p,n)
100.8 (e/γ =5.7)
e1
τ = 4.76 μs
7/2+ 612.8
B(GT) = 0.17; Qν=114
(e/γ)2
115.6 (e/γ = 0.96)
τ = 16 ps
3/2+ 497.3
9/2+
115In (95.7%)
τ = 6.4x10^14 y
γ3
497.3
βmax = 498.8
1/2+ 0
115Sn





Simulated solar neutrino response for 125 ton In-loaded LS

Thank you

Extra slides

2b. Neutrino mixing & oscillations

Two flavor case: ν-flavor (e, μ) & mass eigenstates (1,2) could be different, in general

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

In a weak process flavor eigenstates are produced which propagate in time as

$$\nu(t) = \nu_1 e^{-iE_1 t}\cos\theta + \nu_2 e^{-iE_2 t}\sin\theta$$
$$= C_e(t)\nu_e + C_\mu(t)\nu_\mu$$

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

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

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

Neutrino mass mixing matrix for 3-flavours

Expand $|\nu_\alpha\rangle$ flavour eigenstates in mass eigenstates basis $|\nu_i\rangle$

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle \qquad \text{where}$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

is the unitary Maki-Nakazawa-Sakata (1962) matrix diagonalizing M_ν^2
Here c_{12}= cos θ_{12} , s_{12}= sin θ_{12} etc., δ is the CP-violating phase

The vacuum $\alpha \to \beta$ flavour changing probability in path length L is

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}] \sin^2\left(\frac{\pi L}{\lambda_{ij}}\right) + 2 \sum_{i>j} \mathrm{Im}[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}] \sin\left(2\frac{\pi L}{\lambda_{ij}}\right)$$

where $\lambda_{ij} \approx 2.5\ (E\ /\mathrm{GeV})\ (\mathrm{eV}^2/\Delta_{ij})$, $\Delta_{ij} = m_i^2 - m_j^2$, L in km

Matter effects…

ν_e interacts with matter electrons (neutral current common to all ν_α)

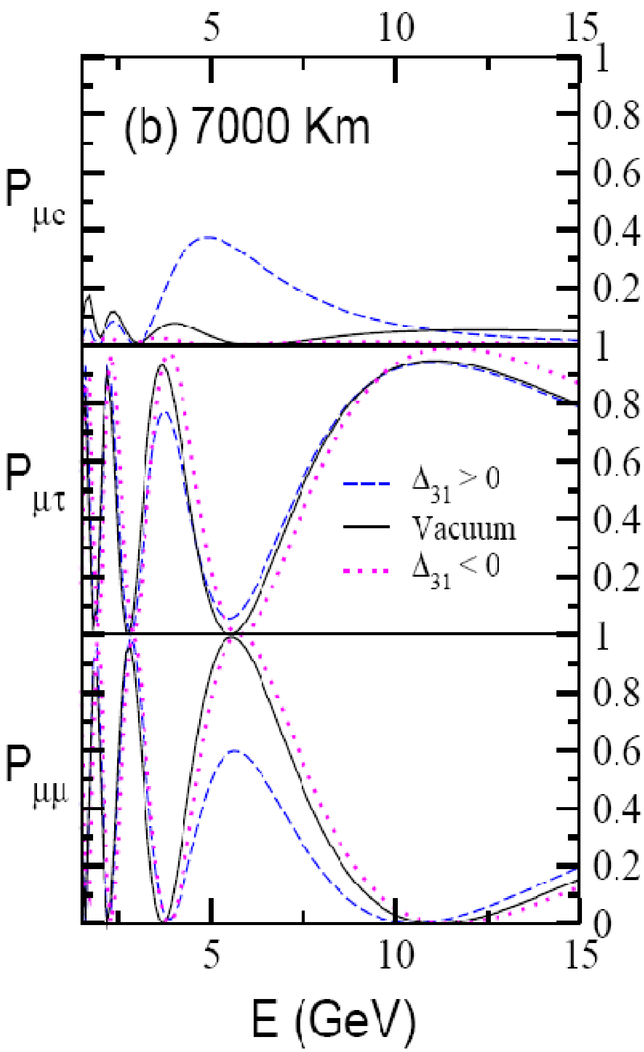
$\Rightarrow$ Change in mixing angle and mass

$$\sin^2 2\theta_m = \frac{\Delta_{21}^2 \sin^2 2\theta}{(\Delta_{21} \cos 2\theta - A)^2 + \Delta_{21}^2 \sin^2 2\theta}$$

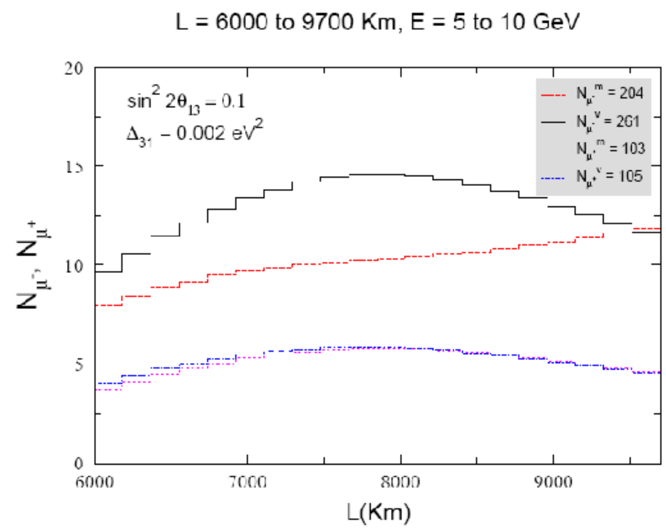
$$\Delta_{21}^m = M_2^2 - M_1^2 = \sqrt{(\Delta_{21} \cos 2\theta - A)^2 + {\Delta_{21}}^2 \sin^2 2\theta}$$

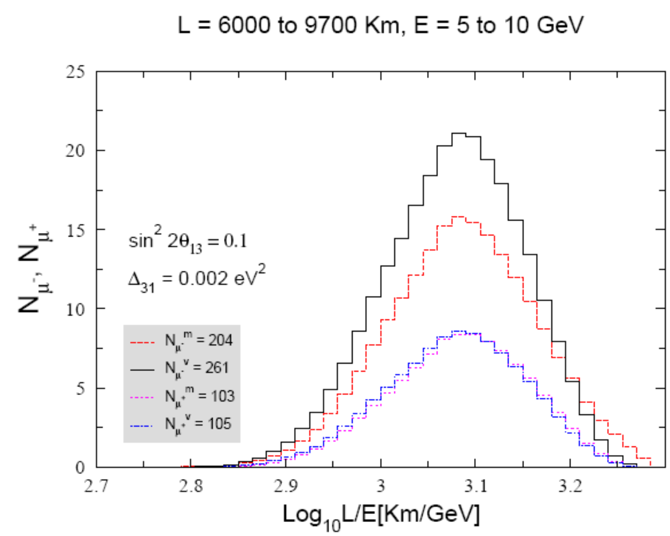
where $A \simeq 2\sqrt{(2)} G_F n_e E$, n_e is the electron density, G_F is the Fermi coupling

Appearance/survival probabilities for $\nu_\mu \rightarrow \nu_e$, ν_τ, ν_μ in vacuum and matter for normal and inverted hierarchies & event rates for atmos. ν_μ



for $\sin^2 2\theta_{13} = 0.1$





R. Gandhi et al., hep-ph/0411252

- 2nd order process in which virtual neutrino absorbed by another nucleon and energy released given to 2 betas.

- NDBD forbidden in SM since $\nu_e \neq \bar{\nu}_e$

However if $\nu_e = \bar{\nu}_e$ (Majorana particle) then process allowed

- Since (virtual) emission and absorption of ν governed by

  different helicities the amplitude is $\propto m_\nu$