# A Thrilling Journey into the World of Neutrinos

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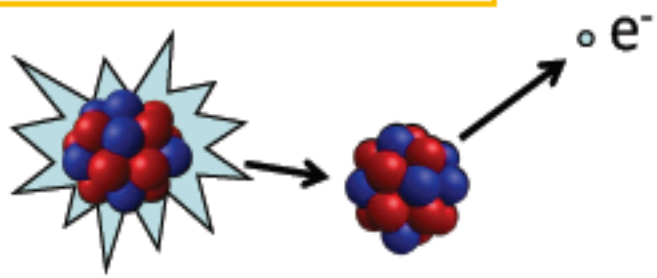
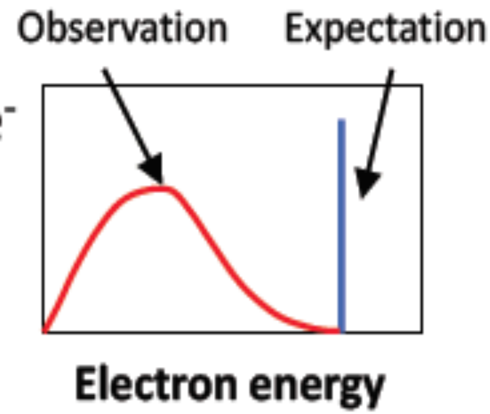
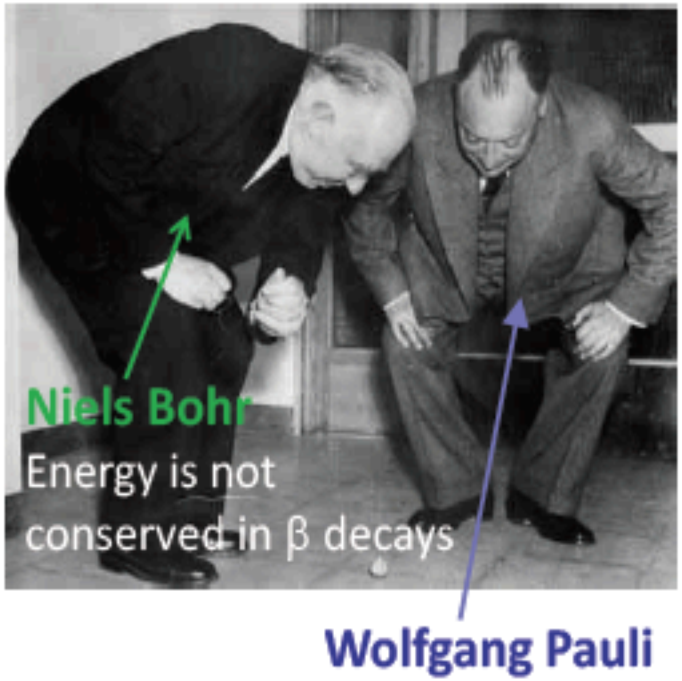
**The problem (1914)**

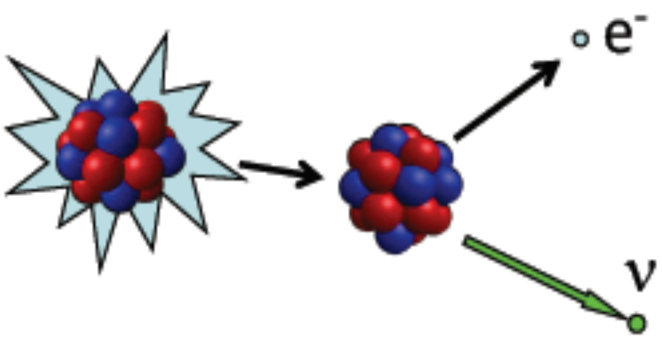



$n \rightarrow p + e^-$




**The desperate remedy (1930)**




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

There is a neutral particle able to cross all detectors without leaving any trace and carrying all the missing energy

> *«I have done a terrible thing. I have postulated a particle that cannot be detected.» (1930)*

Fortunately Pauli was wrong and neutrinos have been detected successfully

# Discovery of Invisible Neutrinos

- **Electron neutrino $\nu_e$ : 1956**

**Reactor anti-neutrinos:** $\bar{\nu}_e + p \to n + e^+$

**Nobel Prize to Frederick Reines in 1995**


Clyde Cowan


Frederick Reines

- **Muon neutrino $\nu_\mu$ : 1962**

**Neutrinos from pion decay:**

$$\pi^- \to \mu^- + \nu_{(\mu)}$$

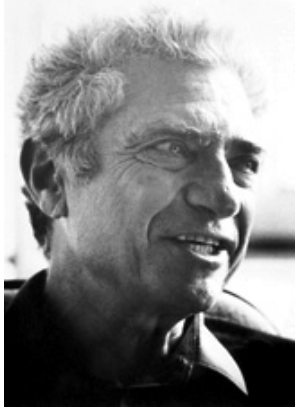
$$\nu_{(\mu)} + N \to N' + \mu^-$$

**Always a muon, never an $e^-$ / $e^+$**

**Nobel Prize in 1988**


Leon M. Lederman

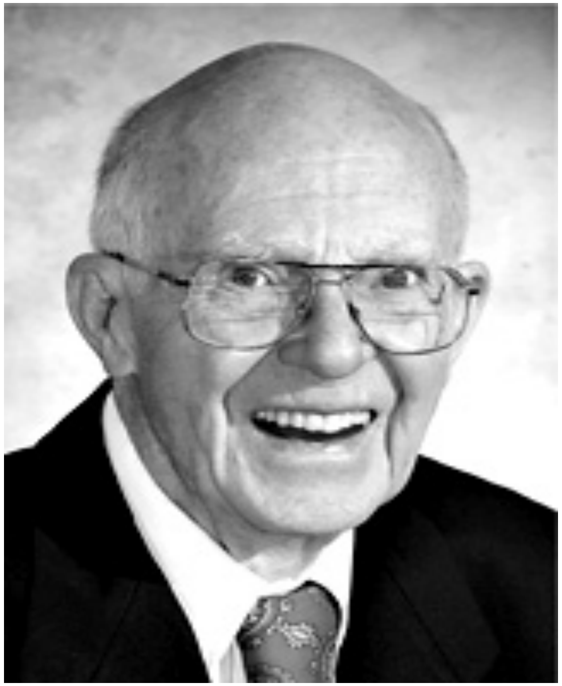

Melvin Schwartz


Jack Steinberger

- **Tau neutrino $\nu_\tau$ : 2000**

**DONUT experiment at Fermilab:** $\nu_\tau + N \to \tau + N'$

## The Nobel Prize in Physics 2002



**Raymod Davis Jr.**

**Masatoshi Koshiba**

**Detected Solar Neutrinos**

**Detected Supernova Neutrinos**

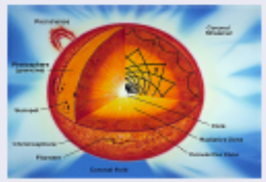
**Detection of Cosmic Neutrinos ➔ A New Window on the Universe**

**Era of Neutrino Astronomy began**

# *Discovery of Neutrino Oscillations: Neutrinos have mass*

## The Nobel Prize in Physics 2015

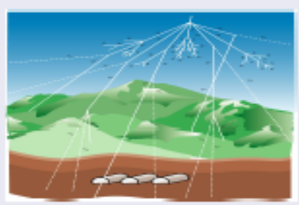
**Solar neutrino puzzle: 1960s – 2002**



- Only about half the expected $\nu_e$ observed!
- Possible solution: $\nu_e$ change to $\nu_\mu/\nu_\tau$

**Arthur B. McDonald solved this puzzle at SNO**

**Atmospheric neutrino puzzle: 1980s – 1998**



- Half the $\nu_\mu$ lost in the Earth!
- Possible solution: $\nu_\mu$ change to $\nu_\tau$

**Takaaki Kajita solved this puzzle at Super-Kamiokande**

**Neutrinos change their flavor ➔ Neutrinos have mass**

# *Few Unique Features of Neutrinos*

- **After photon, neutrino is the most abundant particle in the universe**

  **About 100 trillion neutrinos pass through our body every second**

  **Hundred trillion = 100 000 000 000 000**

- **Nature's most elusive messenger, interacts very rarely, very hard to detect**

  **100 billion neutrinos + the whole Earth = only one interaction**

  **Stopping radiation with lead shielding: 50 cm for α, β, γ**

  **Stopping neutrinos from the Sun: light years of lead**

- **Arrives 'unscathed' from the farthest reaches of the Universe**

  **Brings information from deep within the starts (Not possible with light)**

# *Few Unique Features of Neutrinos*

- **Known to undergo flavor change**

  **(neutrino mass: first clue of physics beyond the Standard Model)**

- **Masses are anomalously low**

  **(from CMB data $m_\nu < 0.2$ eV/$c^2$ = 0.0000004 $m_e$)**

- **Only fundamental fermion that can be its own anti-particle**

  **(Majorana particle)**

- **May open window on the GUT Scale ($\Lambda_{GUT} \sim 10^{16}$ GeV)**

  **(via seesaw mechanism)**

- **Could explain the matter/anti-matter asymmetry of the Universe**

  **(leptogenesis)**

# *Neutrinos are omnipresent*

Detected (1950s)

✓ Nuclear Reactors

Detected (1960s)

Sun ✓

Created & Detected (1960s)

✓ Particle Accelerators

CERN

Detected (1980s)

Supernovae (Stellar Collapse) SN 1987A ✓

Detected (1960s)

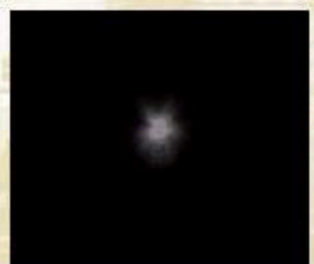
✓ Earth Atmosphere (Cosmic Rays)

IceCube reports the detection of 54 extremely HE events above TeV energy

Astrophysical Accelerators Soon ?

Detected (2000s)

✓ Earth Crust (Natural Radioactivity)



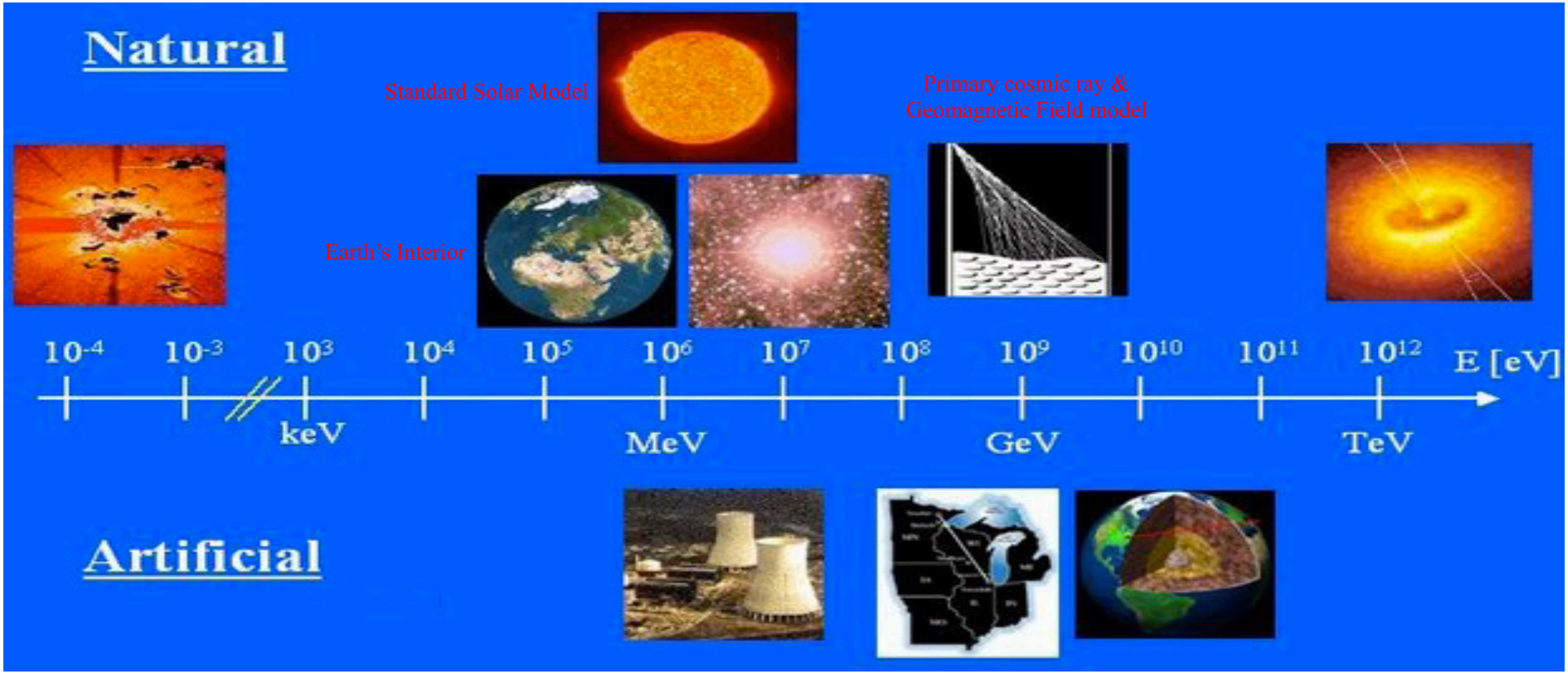
Not even close

Cosmic Big Bang (Today $330\ \nu/cm^3$) Indirect Evidence

Extremely rich and diverse neutrino physics program

# Neutrinos: Exceptional Probe for Environments

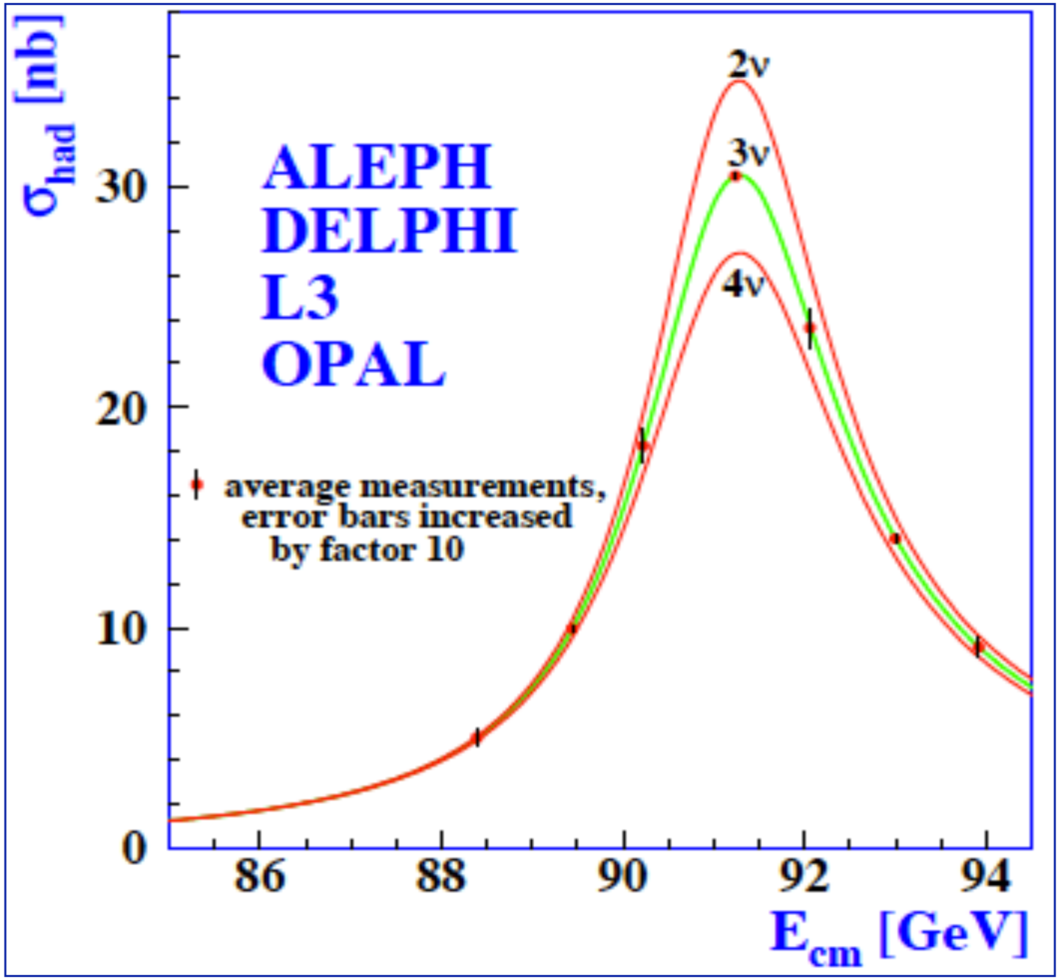
*Neutrino Observation: Go Beyond optical and radio observation*




***Detect neutrinos from the Sun, Supernovae, AGN, GRBs: Era of Neutrino Astronomy***

***ν detection involves several methods on surface, underground, under the sea, or in the ice***

***ν detector masses range from few kgs to megatons, with volumes from few $m^3$ to $km^3$***




***Precision data of the Z-decay width at the $e^+e^-$ collider at LEP***

$$e^+e^- \to Z \xrightarrow{\text{invisible}} \sum_{a=\text{active}} \nu_a \bar{\nu}_a$$

$$N_{\nu_{\text{active}}} = 2.9840 \pm 0.0082$$

[LEP, Phys. Rept. 427 (2006) 257, hep-ex/0509008]

3 light active flavor neutrinos

$\nu_e \;\; \nu_\mu \;\; \nu_\tau$

# The Standard Model: Massless Neutrinos

The Standard Model is a gauge theory & it unifies strong, weak & electromagnetic forces!

$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$

| $(1,2)_{-\frac{1}{2}}$ | $(3,2)_{\frac{1}{6}}$ | $(1,1)_{-1}$ | $(3,1)_{\frac{2}{3}}$ | $(3,1)_{-\frac{1}{3}}$ |
|---|---|---|---|---|
| $\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$ | $\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$ | $e_R$ | $u^i_R$ | $d^i_R$ |
| $\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$ | $\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$ | $\mu_R$ | $c^i_R$ | $s^i_R$ |
| $\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$ | $\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$ | $\tau_R$ | $t^i_R$ | $b^i_R$ |

3-fold repetition of the same representation!

- 3 *active* neutrinos: $\nu_e$ , $\nu_\mu$ , $\nu_\tau$
- Neutral elementary particles of Spin ½
- Only couple to *weak force* (& gravity)
- Only *left handed* neutrinos
- There are no right-handed neutrinos
- *No* Dirac Mass term: $m(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$

***Neutrinos are massless in the Basic SM***

- ❑ Over the past decade, marvelous data from world class neutrino experiments firmly established that they change flavor after propagating a finite distance

- ❑ Neutrino flavor change (oscillation) demands non-zero mass and mixing

***Non-zero ν mass: first experimental proof for physics beyond the Standard Model***

***!! An extension of the Standard Model is necessary !!***

# Neutrino Physics: An Exercise in Patience

Three most fundamental questions were being asked in the past century…

1. How tiny is the neutrino mass? (Pauli, Fermi, '30s)

Planck + BAO + WMAP polarization data: upper limit of 0.23 eV for the sum of ν masses!

**Planck Collaboration, arXiv:1303.5076 [astro-ph.CO]**

2. Can a neutrino turn into its own antiparticle? (Majorana, '30s)

Hunt for ν-less Double-β decay (Z,A → Z+2, A) is still on, demands lepton number violation!

**Nice Review by Avignone, Elliott, Engel, Rev.Mod.Phys. 80 (2008) 481-516**

3. Do different ν flavors 'oscillate' into one another? (Pontecorvo, Maki-Nakagawa-Sakata, '60s)

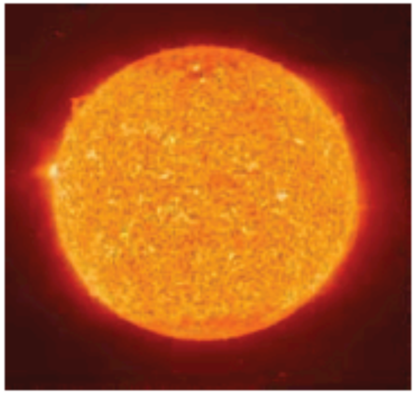
**B. Pontecorvo, Sov. Phys. JETP 26, 984 (1968) [Zh. Eksp. Teor. Fiz. 53, 1717 (1967)]**

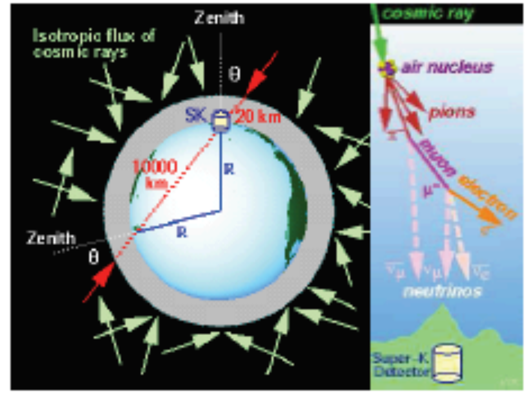
Last question positively answered only in recent years. Now an established fact that **neutrinos are massive** and leptonic flavors are not **symmetries of Nature**!

Recent measurement of $\boldsymbol{\theta_{13}}$, a clear first order picture of the 3-flavor lepton mixing matrix has emerged, signifies a major breakthrough in ν physics!

# Golden Age of Neutrino Physics (1998 – 2015 & Beyond)

| sun | reactors | atmosphere | accelerators |
|---|---|---|---|







| sun | reactors | atmosphere | accelerators |
|---|---|---|---|
| Homestake, SAGE, GALLEX<br>SuperK, SNO, Borexino | KamLAND, CHOOZ<br>Double Chooz, Daya Bay, RENO | SuperKamiokande<br>IceCube | K2K, MINOS, T2K<br>NOvA |

***Over the last seventeen years or so, precious data from world-class experiments***

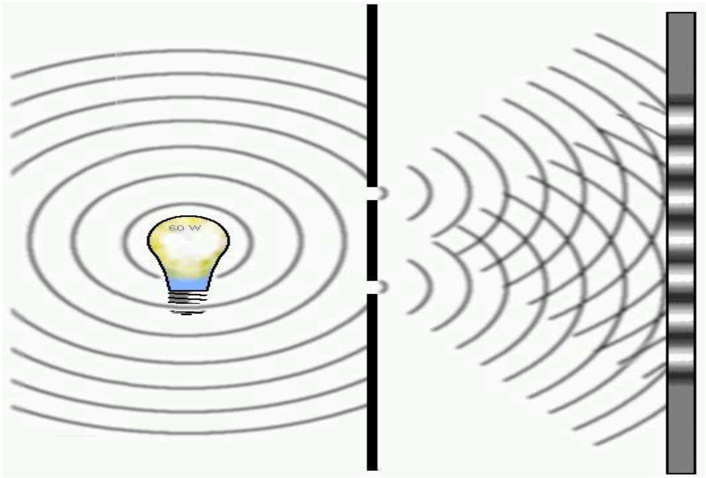
- Solar neutrinos $(\nu_e)$
- Atmospheric neutrinos $(\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e)$
- Reactor anti-neutrinos $(\bar{\nu}_e)$
- Accelerator neutrinos $(\nu_\mu, \bar{\nu}_\mu)$

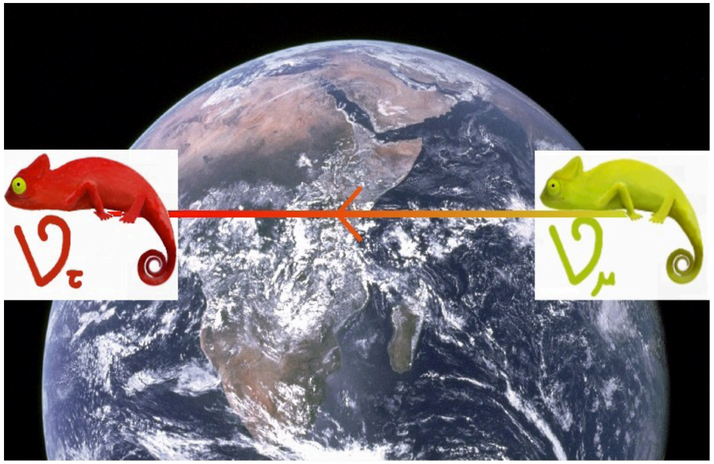
→ ***Data from various neutrino sources and vastly different energy and distance scales***

We have just started our journey in the mysterious world of neutrinos

# Neutrino Flavor Oscillations

**1957: Bruno Pontecorvo proposed Neutrino Oscillations in analogy with $K^0 \leftrightarrows \bar{K}^0$ oscillations (Gell-Mann and Pais, 1955)**



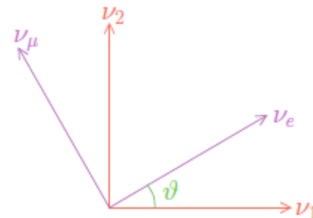




- ***Neutrino oscillation: Quantum Mechanical interference phenomenon***
- ***Like electrons in the double slit experiment***
- ***In Neutrino Oscillation: Neutrino changes flavor as it propagates***
- ***It happens if neutrinos have masses (non-degenerate) and there is mixing***

- **Flavor States :** $\nu_e$ and $\nu_\mu$ (produced in Weak Interactions)
- **Mass Eigenstates :** $\nu_1$ and $\nu_2$ (propagate from Source to Detector)

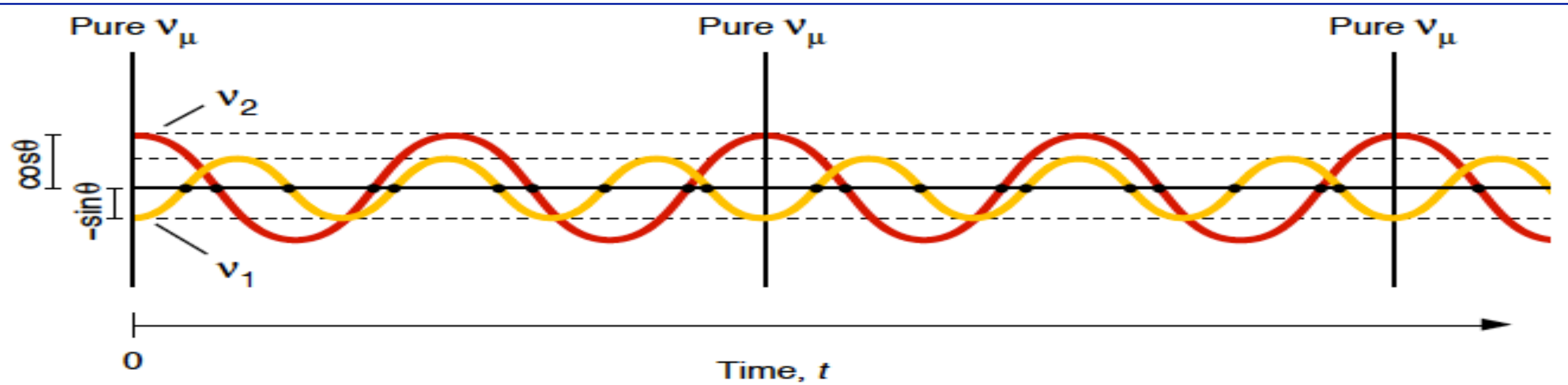
**A Flavor State is a linear superposition of Mass Eigenstates**

$$|\nu_\alpha\rangle = \sum_{k=1}^{2} U_{\alpha k} |\nu_k\rangle \qquad (\alpha = e, \mu)$$



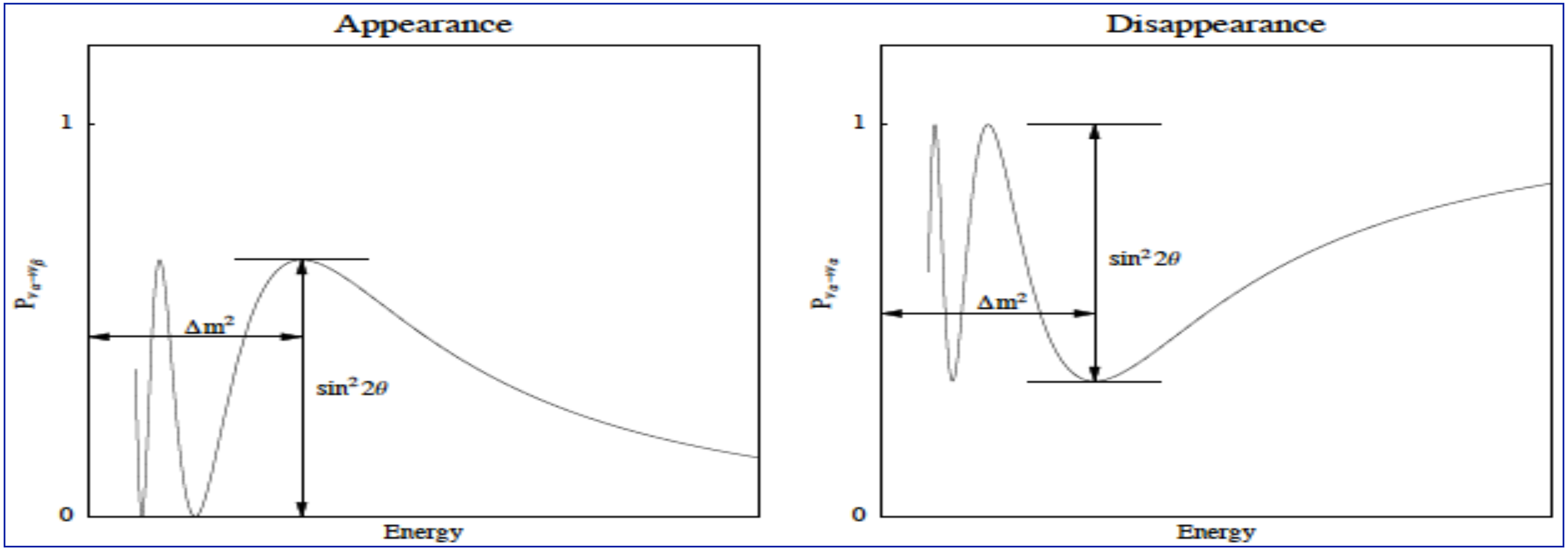

$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

$$|\nu_e\rangle = \cos\vartheta\,|\nu_1\rangle + \sin\vartheta\,|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\vartheta\,|\nu_1\rangle + \cos\vartheta\,|\nu_2\rangle$$




***If the masses of these two states are different then they will take different times to reach the same point and there will be a phase difference and hence interference***

# Oscillation Probabilities in 2 Flavors




$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \ \sin^2(1.27 \Delta m^2 \frac{L}{E})$$

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\theta \ \sin^2(1.27 \Delta m^2 \frac{L}{E})$$

$\Delta m^2$ is in $\mathrm{eV}^2$, $L$ is in m (km) and $E$ in MeV (GeV)

$$\lambda = 2.47\mathrm{km} \left(\frac{E}{\mathrm{GeV}}\right) \left(\frac{\mathrm{eV}^2}{\Delta m^2}\right) \Rightarrow \text{oscillation length}$$

***Neutrino Oscillations** only sensitive to mass squared difference but not to the absolute Neutrino mass scale*

# Neutrino Oscillations in 3 Flavors

$c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\theta_{23}$ : $P(\nu_\mu \to \nu_\mu)$ by Atoms. ν and ν beam

$\theta_{13}$: $P(\nu_e \to \nu_e)$ by Reactor ν
$\theta_{13}$ & δ: $P(\nu_\mu \to \nu_e)$ by ν beam

$\theta_{12}$ : $P(\nu_e \to \nu_e)$ by Reactor and solar ν

Three mixing angles: $\theta_{23}$ , $\theta_{13}$ , $\theta_{12}$ and one CP violating (Dirac) phase $\delta_{CP}$

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}; \quad U_{e3} \equiv \sin\theta_{13}e^{-i\delta}$$

3 mixing angles simply related to flavor components of 3 mass eigenstates

Over a distance L, changes in the relative phases of the mass states may induce flavor change!

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin^2\Delta_{ij} - 2\sum_{i>j} \mathrm{Im}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin 2\Delta_{ij}$$

$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

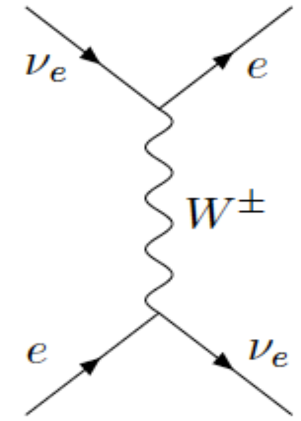
$$\Delta m^2_{ij} = m^2_i - m^2_j$$

2 independent mass splittings $\Delta m^2_{21}$ and $\Delta m^2_{32}$ , for anti-neutrinos replace $\delta_{CP}$ by $-\delta_{CP}$

Neutrino propagation through matter modify the oscillations significantly

Coherent forward elastic scattering of neutrinos with matter particles

Charged current interaction of $\nu_e$ with electrons creates an extra potential for $\nu_e$




Wolfenstein matter term: $A = \pm 2\sqrt{2} G_F N_e E$ or $A(\text{eV}^2) = 0.76 \times 10^{-4} \rho \ (\text{g/cc}) E(\text{GeV})$

$N_e$ = electron number density , + (-) for neutrinos (anti-neutrinos) , ρ = matter density in Earth

**Matter term changes sign when we switch from neutrino mode to anti-neutrino mode**

$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$ → ***even if $\delta_{CP} = 0$, causes fake CP asymmetry***

**Matter term modifies oscillation probability differently depending on the sign of $\Delta m^2$**

$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\text{res}}^{\text{Earth}} = 6 - 8\,\text{GeV}$ → ***Resonant conversion – Matter effect***

| | $\nu$ | $\bar{\nu}$ |
|---|---|---|
| $\Delta m^2 > 0$ | MSW | - |
| $\Delta m^2 < 0$ | - | MSW |

→ ***Resonance occurs for neutrinos (anti-neutrinos) if $\Delta m^2$ is positive (negative)***

# *Present Status of Oscillation Parameters*

| | bfp $\pm 1\sigma$ | $3\sigma$ range | Relative 1σ Precision |
|---|---|---|---|
| $\sin^2\theta_{12}$ | $0.304^{+0.012}_{-0.012}$ | $0.270 \to 0.344$ | 4% |
| $\theta_{12}/^\circ$ | $33.48^{+0.77}_{-0.74}$ | $31.30 \to 35.90$ | |
| $\sin^2\theta_{23}$ | $[0.451^{+0.001}_{-0.001}] \oplus 0.577^{+0.027}_{-0.035}$ | $0.385 \to 0.644$ | 9.6% |
| $\theta_{23}/^\circ$ | $[42.2^{+0.1}_{-0.1}] \oplus 49.4^{+1.6}_{-2.0}$ | $38.4 \to 53.3$ | |
| $\sin^2\theta_{13}$ | $0.0219^{+0.0010}_{-0.0011}$ | $0.0188 \to 0.0251$ | 4.8% |
| $\theta_{13}/^\circ$ | $8.52^{+0.20}_{-0.21}$ | $7.87 \to 9.11$ | |
| $\delta_{CP}/^\circ$ | $251^{+67}_{-59}$ | $0 \to 360$ | (Not Known) |
| $\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$ | $7.50^{+0.19}_{-0.17}$ | $7.03 \to 8.09$ | 2.4% |
| $\frac{\Delta m^2_{31}}{10^{-3}\ \text{eV}^2}$ (N) | $[+2.458^{+0.002}_{-0.002}]$ | $+2.325 \to +2.599$ | 1.9% |
| $\frac{\Delta m^2_{32}}{10^{-3}\ \text{eV}^2}$ (I) | $-2.448^{+0.047}_{-0.047}$ | $-2.590 \to -2.307$ | |

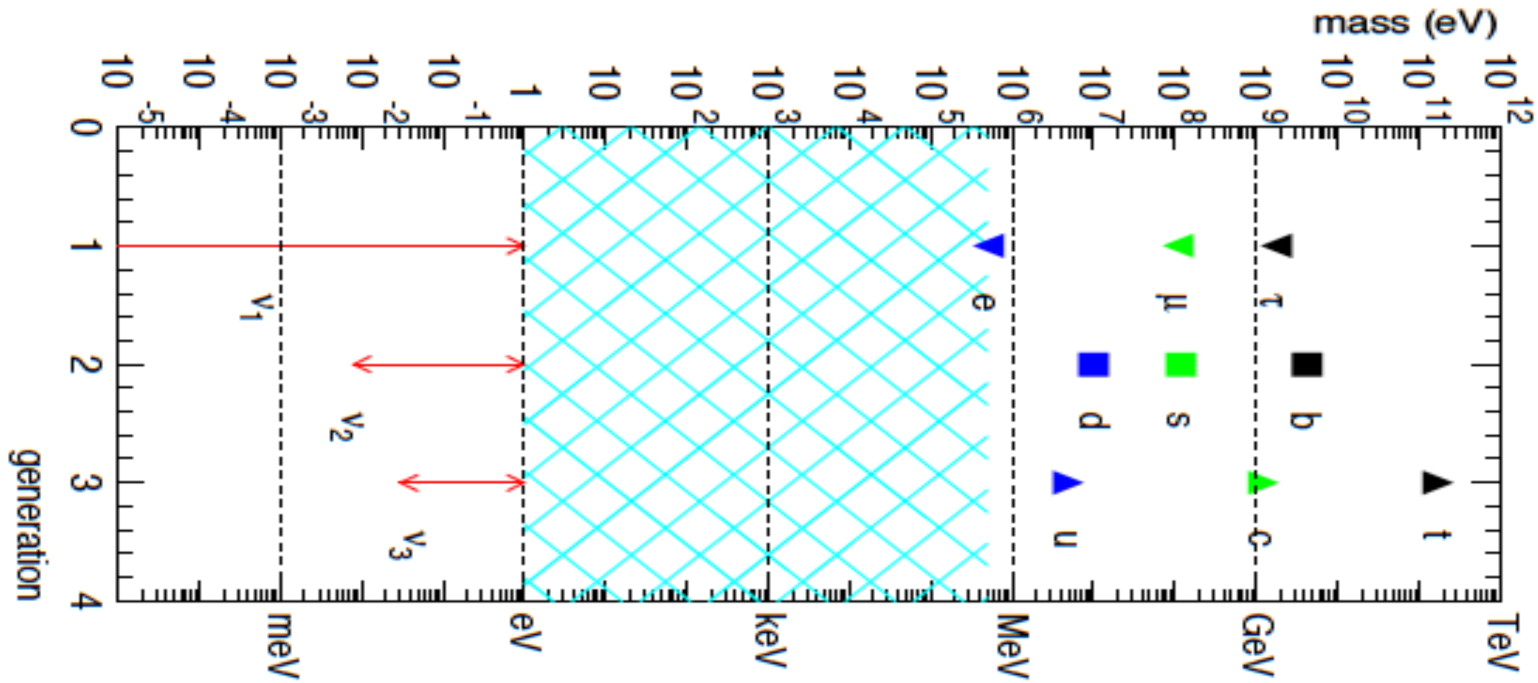
Non-maximal $> 1.4\sigma$

Non-zero $> 10\sigma$

$\sin\delta_{CP} < 0$ at 90% C.L.

Gonzalez-Garcia, Maltoni, Salvado, Schwetz, http://www.nu-fit.org

# The Two Fundamental Questions




**Why are neutrinos so light? The origin of Neutrino Mass!**

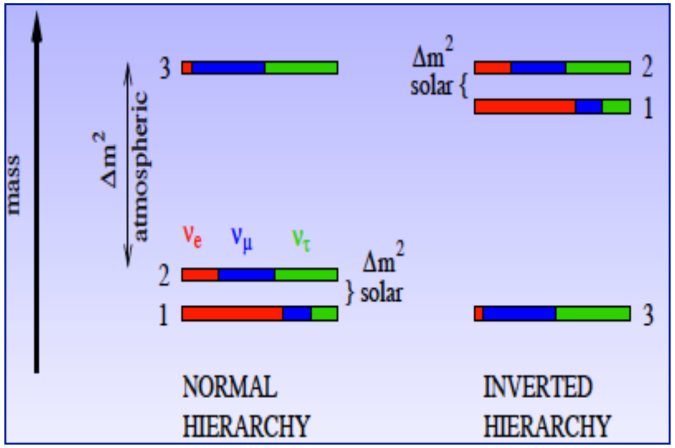
| | Neutrinos (PMNS) | Quarks (CKM) |
|---|---|---|
| $\theta_{12}$ | 35° | 13° |
| $\theta_{32}$ | 43° | 2° |
| $\theta_{13}$ | 9° | 0.2° |
| $\delta$ | unknown | 68° |

**Why are lepton mixings so different from quark mixings?**

**The Flavor Puzzle!**

# Fundamental Unknowns in Neutrino Oscillation

**1. What is the hierarchy of the neutrino mass spectrum, normal or inverted?**




- *The sign of* $\Delta m^2_{31} = m^2_3 - m^2_1$ *is not known!*
- *Currently do not know which neutrino is the heaviest?*
- *Only have a lower bound on the mass of the heaviest ν!*

$$\sqrt{2.5 \cdot 10^{-3}\mathrm{eV}^2} \sim 0.05\ \mathrm{eV}$$

**2. What is the octant of the 2-3 mixing angle, lower ($\theta_{23} < 45°$) or higher ($\theta_{23} > 45°$)?**

*Measure $\theta_{23}$ precisely, Establish deviation from maximality at higher C.L. Then look for Octant*

**2. Is there CP violation in the leptonic sector, as in the quark sector?**

*Mixing can cause CP violation in the leptonic sector (if $\delta_{CP}$ differs from 0° and 180°)*
*Need to measure the CP-odd asymmetries:* $\Delta P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta;\, L) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta;\, L)$ $(\alpha \neq \beta)$

With current knowledge of $\theta_{13}$, resolving these unknowns fall within our reach
Sub-leading 3 flavor effects are extremely crucial in current & future oscillation expts

**An Indian Initiative to build a world-class underground laboratory to pursue non-accelerator based high energy and nuclear physics research**

**The initial goal of INO is to study fundamental properties of neutrinos**

For more updates visit: http://www.ino.tifr.res.in/ino/

You can join us at: https://www.facebook.com/ino.neutrino

# Press Release on INO

**TATA INSTITUTE OF FUNDAMENTAL RESEARCH**
*National Centre of the Government of India for Nuclear Science & Mathematics*
**HOMI BHABHA ROAD, COLABA, MUMBAI- 400 005**

**Telephone : 2278-2227**
**Fax : 2280-4610**

05.01.2015

**Press Release**

The Union Cabinet of the Govt. of India chaired by the Prime Minister, Shri Narendra Modi, has given its approval for the establishment of India-based Neutrino Observatory (INO) at an estimated cost of Rs. 1500 crores.

The INO project is jointly supported by the Department of Atomic Energy and the Department of Science and Technology. Infrastructural support is provided by the Government of Tamil Nadu where the project is located. Tata Institute of Fundamental Research (TIFR), Mumbai is the host institute for INO.

Finally the wait of 15 years is over! But, we have miles to go…

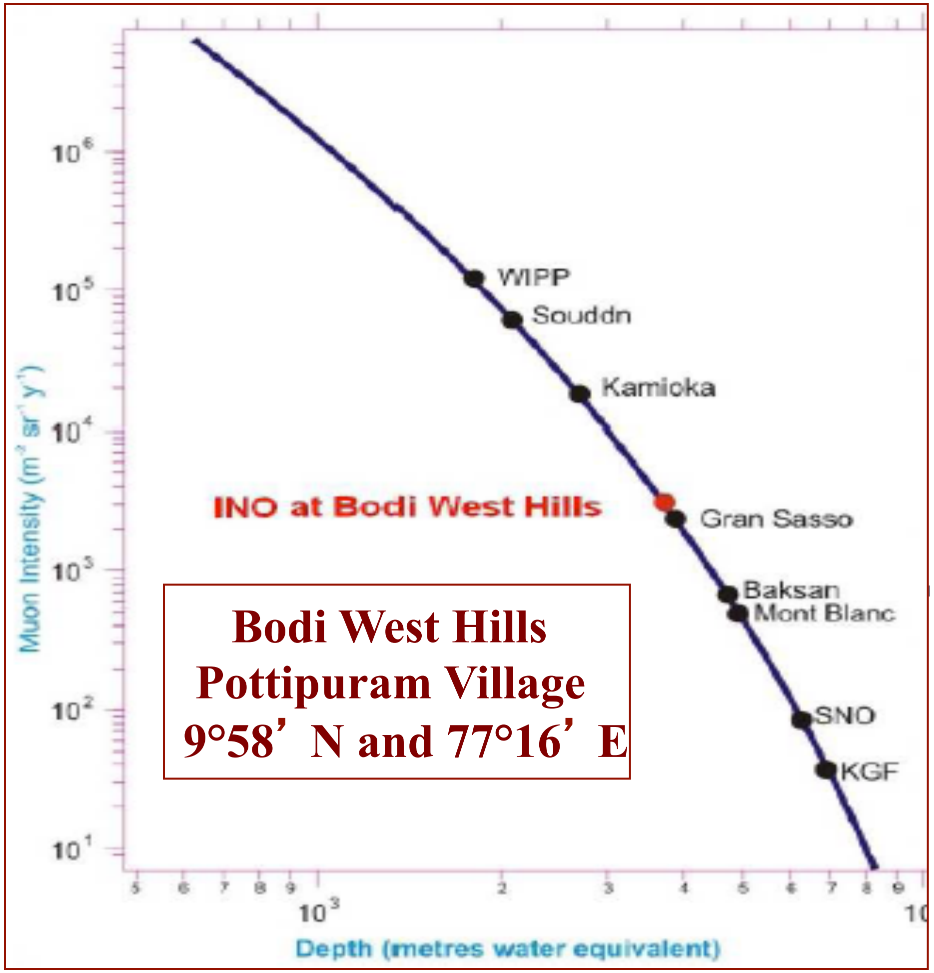
# Introducing INO Collaboration


Ahmadabad: Physical Research Laboratory
Aligarh: Aligarh Muslim University
Allahabad: HRI
Bhubaneswar: IoP, Utkal University
Calicut: University of Calicut
Chandigarh: Panjab University
Chennai: IIT-Madras, IMSc
Delhi: University of Delhi
Kalpakkam: IGCAR
Kolkata: SINP, VECC, University of Calcutta
Lucknow: Lucknow University
Madurai: American College
Mumbai: BARC, IIT-Bombay, TIFR, CMEMS
Mysore: University of Mysore
Srinagar: University of Kashmir
Varanasi: Banaras Hindu University

Nearly 100 scientists from 23 research institutes & universities all over India

One of the largest basic science projects in India in terms of man power & cost as well

**We are growing day by day**





**Located 115 km west of the Madurai city in the Theni district of Tamil Nadu**

**Madurai has an International Airport**

# Approved projects under INO

- *Come up with an underground lab & surface facilities near Pottipuram village in Theni district of Tamil Nadu*

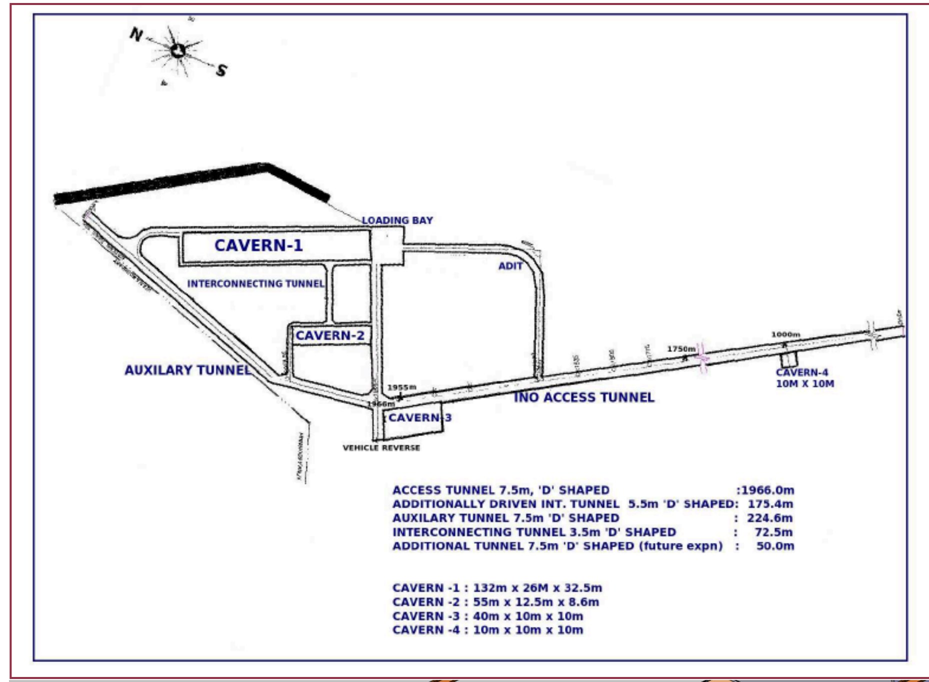
- *Build massive 50 kt magnetized Iron calorimeter (ICAL) detector to study properties of neutrinos*

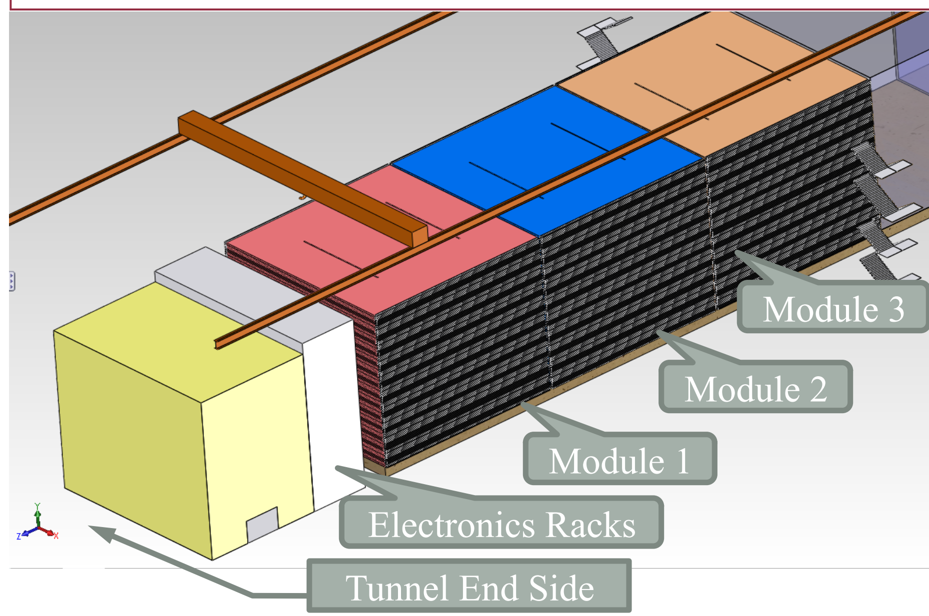
- *Construction of INO centre at Madurai: Inter-Institutional Centre for High Energy Physics (IICHEP)*

- *Human Resource Development (INO Graduate Training Program)*

- *Completely in-house Detector R&D with substantial INO-Industry interface*

- *Time Frame for 1st module: 2020*



**Study Atmospheric neutrinos w/ a wide range of Baselines & Energies**

**Recent discovery of large $\theta_{13}$ : A good news for ICAL-INO**

## *What do we want to achieve?*

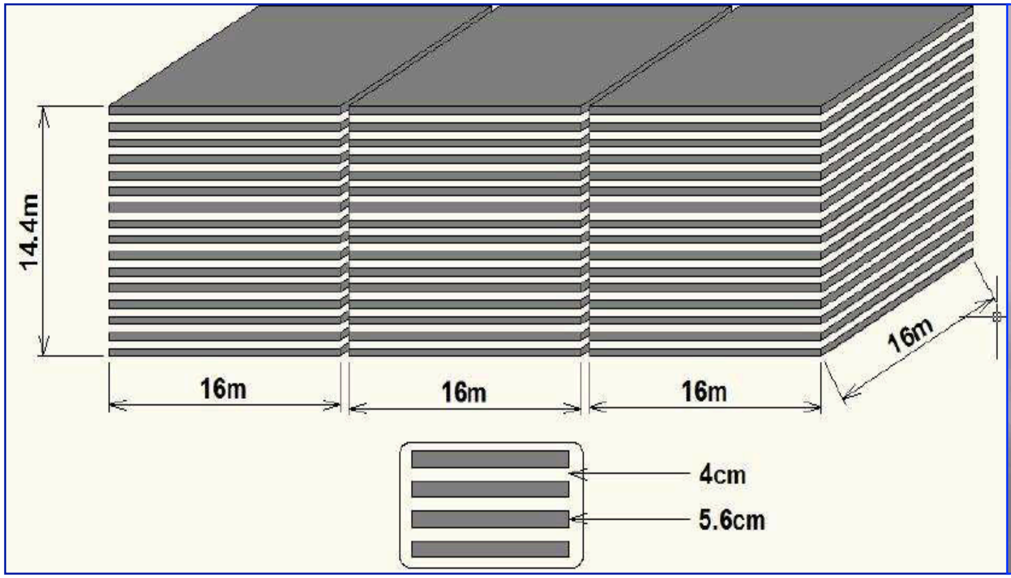
- ***Reconfirm neutrino oscillations using neutrinos and anti-neutrinos separately***
- ***Improved precision of atmospheric oscillation parameters***
- ***Determine neutrino mass hierarchy using matter effects via charge discrimination***
- ***Measure the deviation of 2-3 mixing angle from its maximal value and its octant***
- ***Test bed for various new physics like NSI, CPT violation, long range forces***
- ***Detect Ultra High Energy Neutrinos, Cosmic Muons, Indirect searches of DM***

# Detector Characteristics

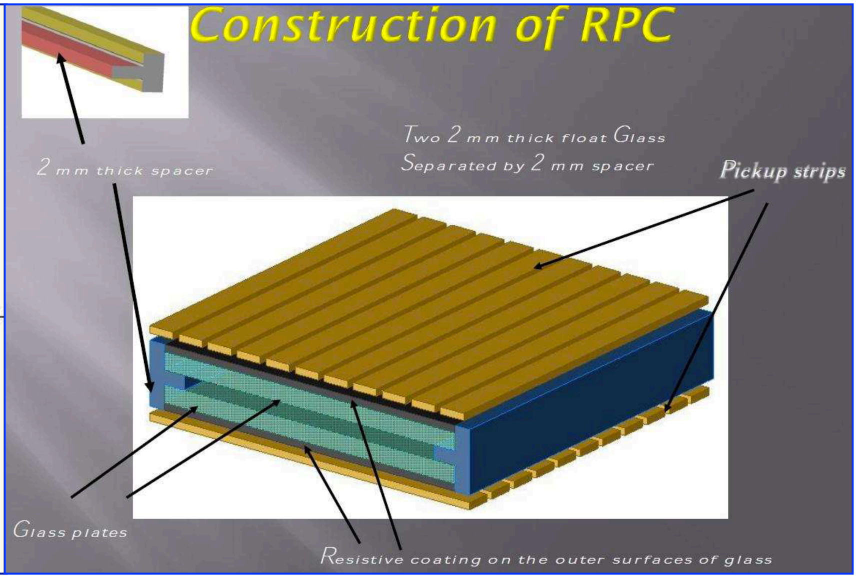
- *Should have large target mass (50 – 100 kt)*
- *Good tracking and Energy resolution (tracking calorimeter)*
- *Good directionality for up/down discrimination (nano-second time resolution)*
- *Charge identification (need to have uniform, homogeneous magnetic field)*
- *Ease of construction & Modularity*
- *Complementary to the other existing and proposed detectors*

**Our choice**

*Magnetized iron (target mass): ICAL*



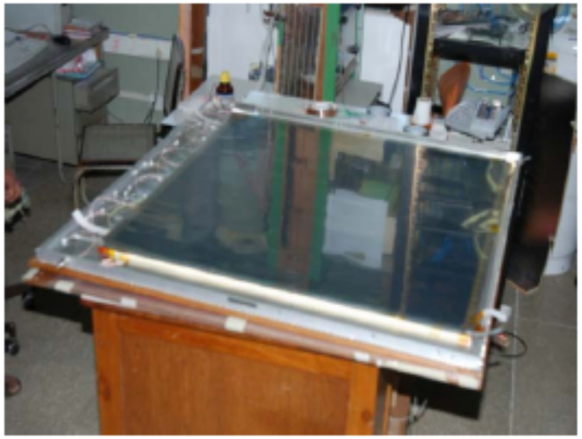

*RPC (active detector element)*

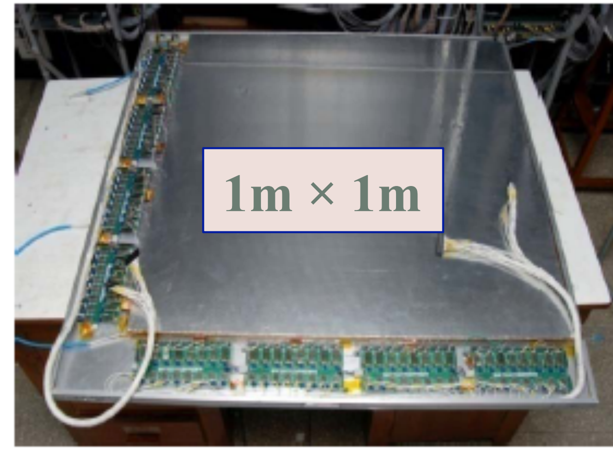


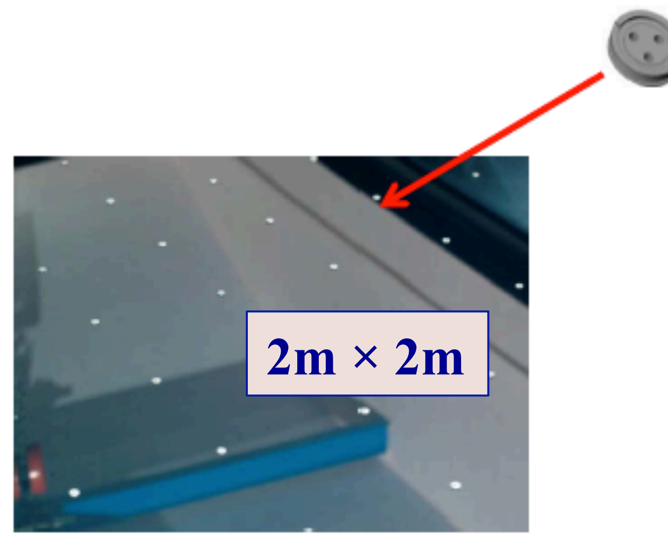
# Specifications of the ICAL Detector

| | |
|---|---|
| No  of modules | 3 |
| Module dimension | 16 m X 16 m X 14.4m |
| Detector dimension | 48.4 m X 16 m X 14.4m |
| No of layers | 150 |
| Iron plate thickness | 5.6cm |
| Gap for RPC trays | 4 cm |
| Magnetic field | 1.4 Tesla |
| RPC unit dimension | 195 cm x 184 cm x 2.4 cm |
| Readout strip width | 3 cm |
| No. of RPCs/Road/Layer | 8 |
| No. of Roads/Layer/Module | 8 |
| No. of RPC units/Layer | 192 |
| Total no of RPC units | 28800 |
| No of Electronic channels | $3.7 \times 10^6$ |

# *Fabricating Glass RPCs for ICAL*

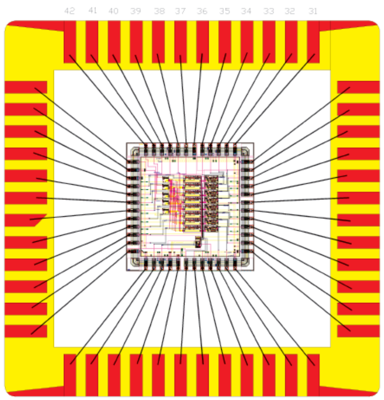




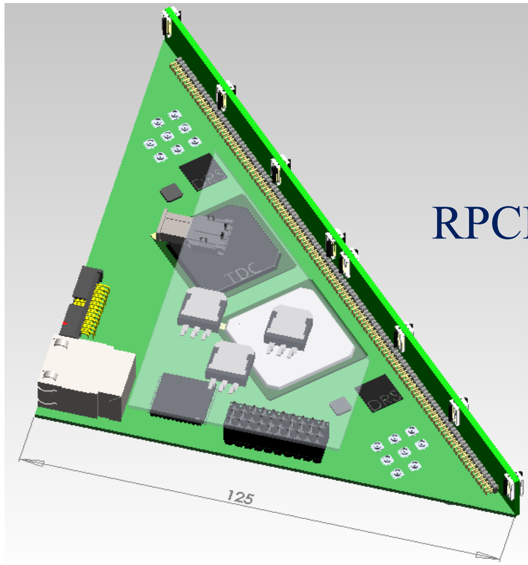




- ***30 glass RPCs of 1m × 1m developed, tested for long in avalanche mode***
- ***5 glass RPCs of 2m × 2m successfully assembled and tested***

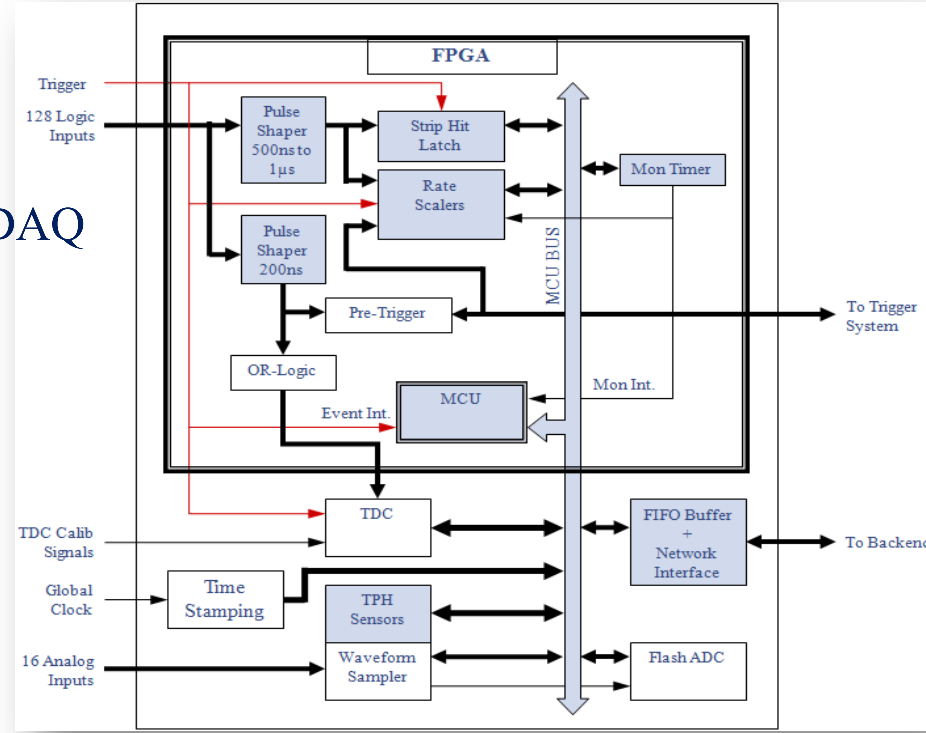
# *Various Components of ICAL Electronics*

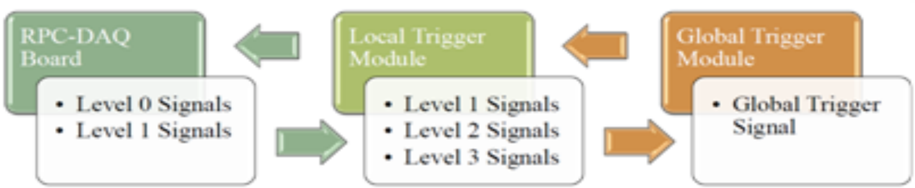


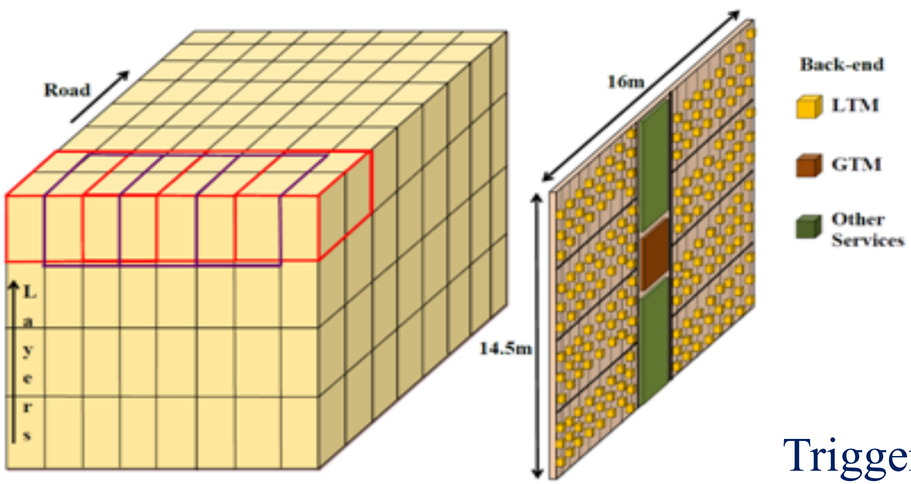
Front-end ASIC



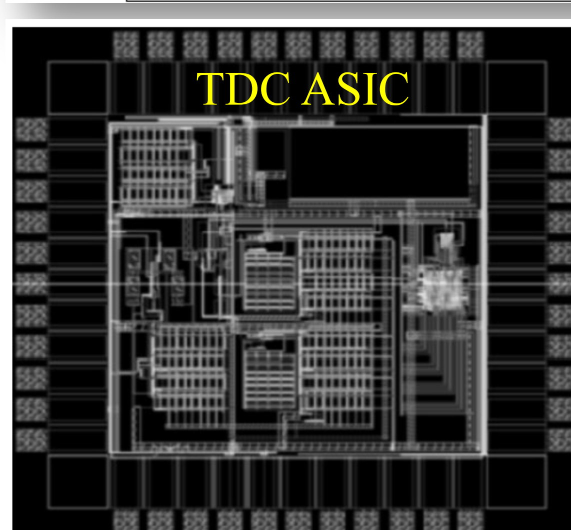

RPCDAQ

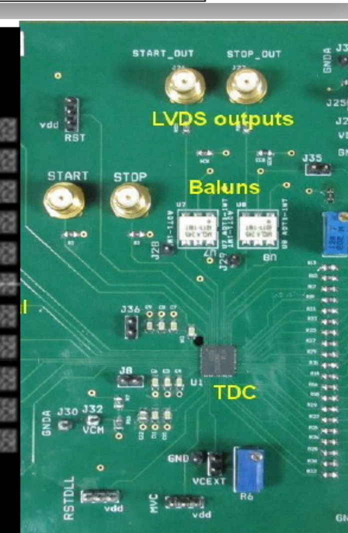



Trigger



# Current Status of INO

**Pre-project activities started with an initial grant of ~ 15 M$**

- Site infrastructure development
- Development of INO centre at Madurai city (110 km from underground lab)
  - Inter-Institutional Centre for High Energy Physics (IICHEP)
- Construction of an 1/8$^{th}$ size engineering prototype module

- Detector R&D is now over
- Detailed Project Report for Detector and DAQ system is ready
- Soon go for industrial production of RPCs & associated front-end electronics
- Full project approved by PM's cabinet committee to start construction


17/05/2013 08:22


10/10/2013 11:16


12/05/2014 11:36


20/05/2014 10:48


survey work
18/03/2014 13:09


fencing work
16/05/2014 12:34


receiving sump with 12 lakhs litre capacity
18/06/2014 12:50


14/03/2014 15:24

# Human Resource Development and Training




- INO Graduate Training Program started in August 2008, students are affiliated to HBNI
- At present students being trained for 1 year at TIFR in both experimental techniques & theory
- After completion of coursework, attached to Ph.D. guides at various collaborating institutions
- Many short/long term visits to RPC labs (Mumbai & Kolkata) of students & faculties from Universities in last several years
- Several students from 1st batch (2008) and 2nd batch (2009) are already working as post-docs at different places
- 8th batch of 3 students have started their course work at TIFR in 2015

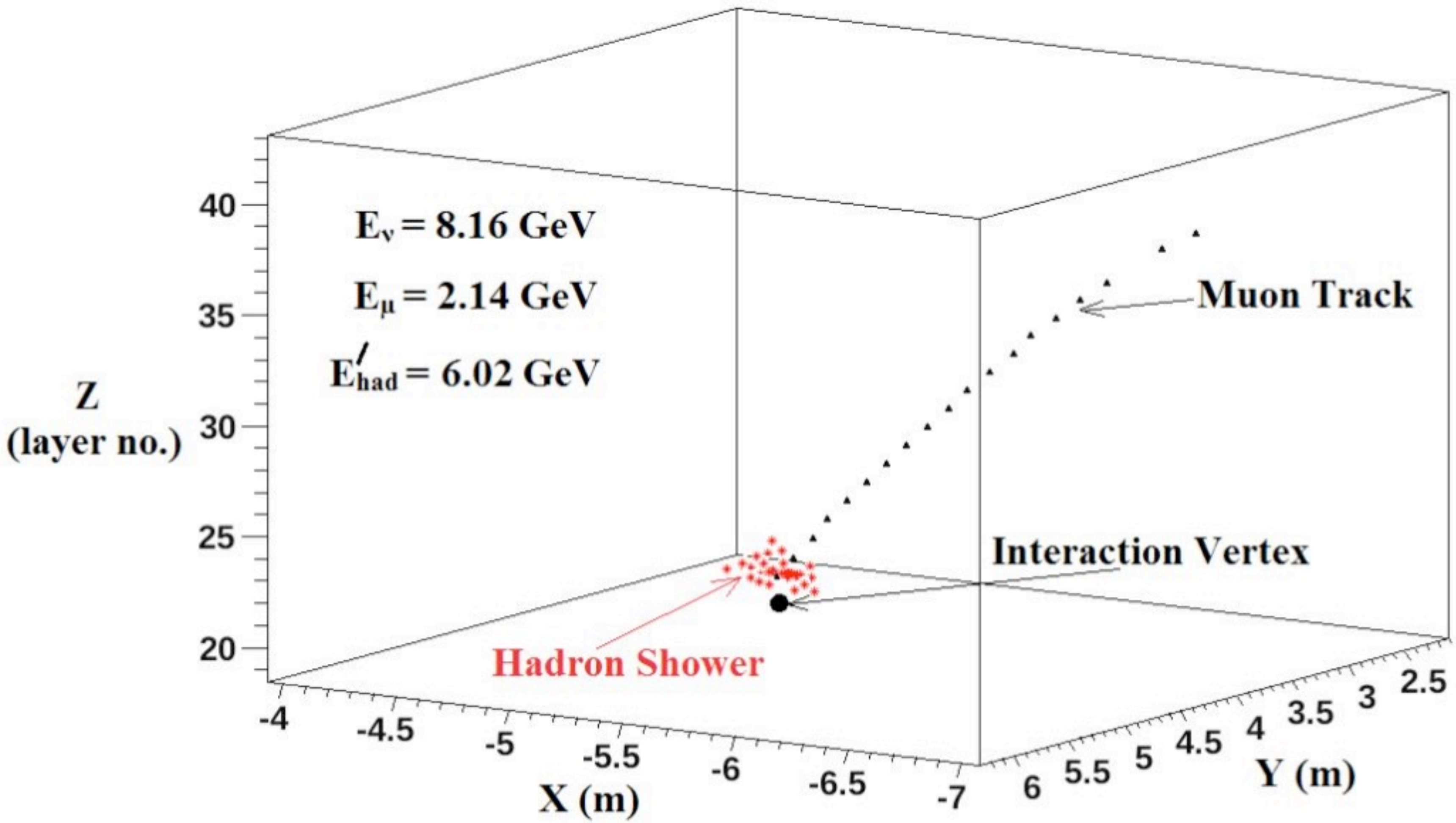
INO/ICAL/PHY/NOTE/2015-01

# Physics Potential of the ICAL detector at the India-based Neutrino Observatory (INO)

The ICAL Collaboration

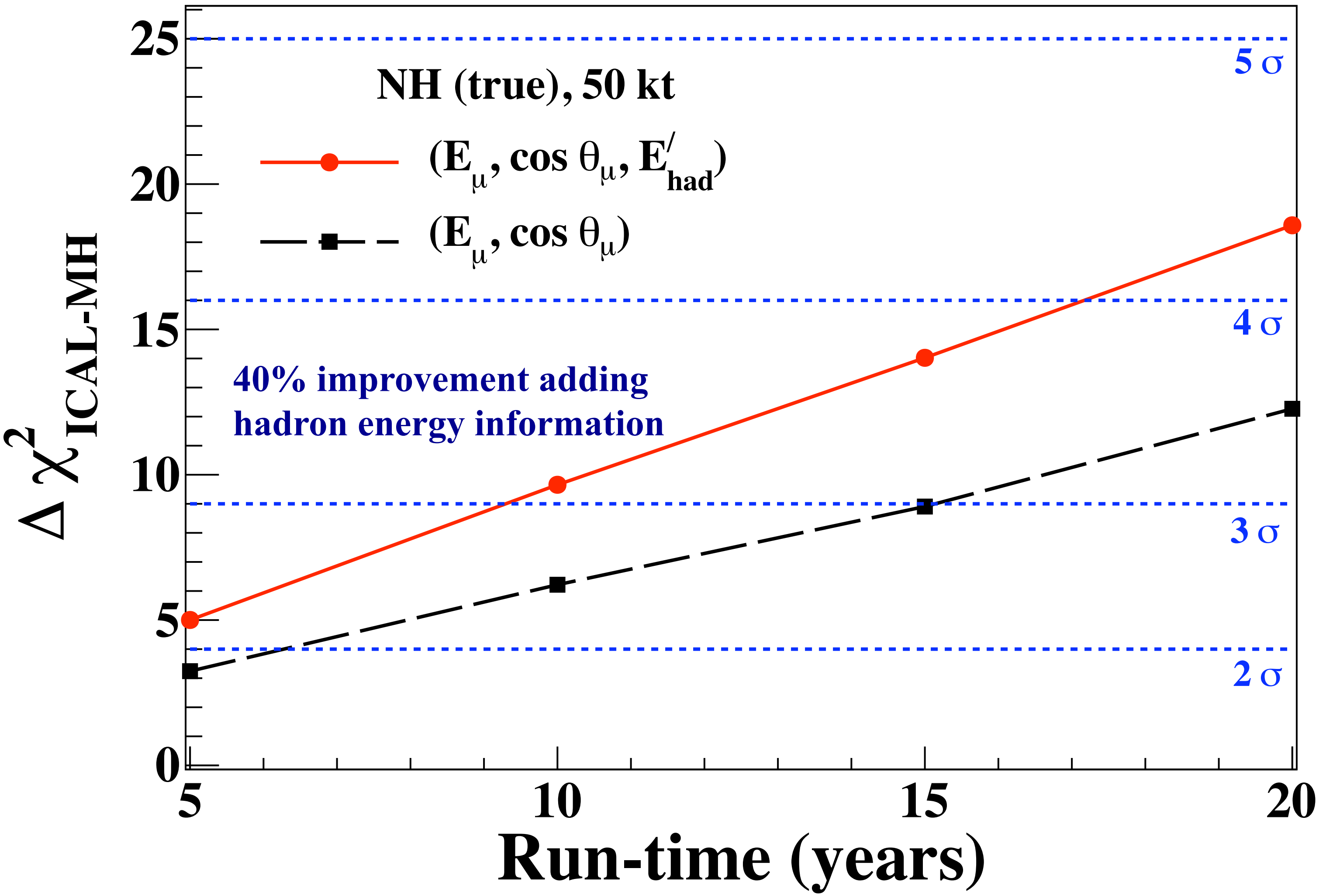
arXiv:1505.07380v1 [physics.ins-det] 27 May 2015

# *Event Display Inside the ICAL Detector*




**Using GEANT4 simulation**

**Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)**

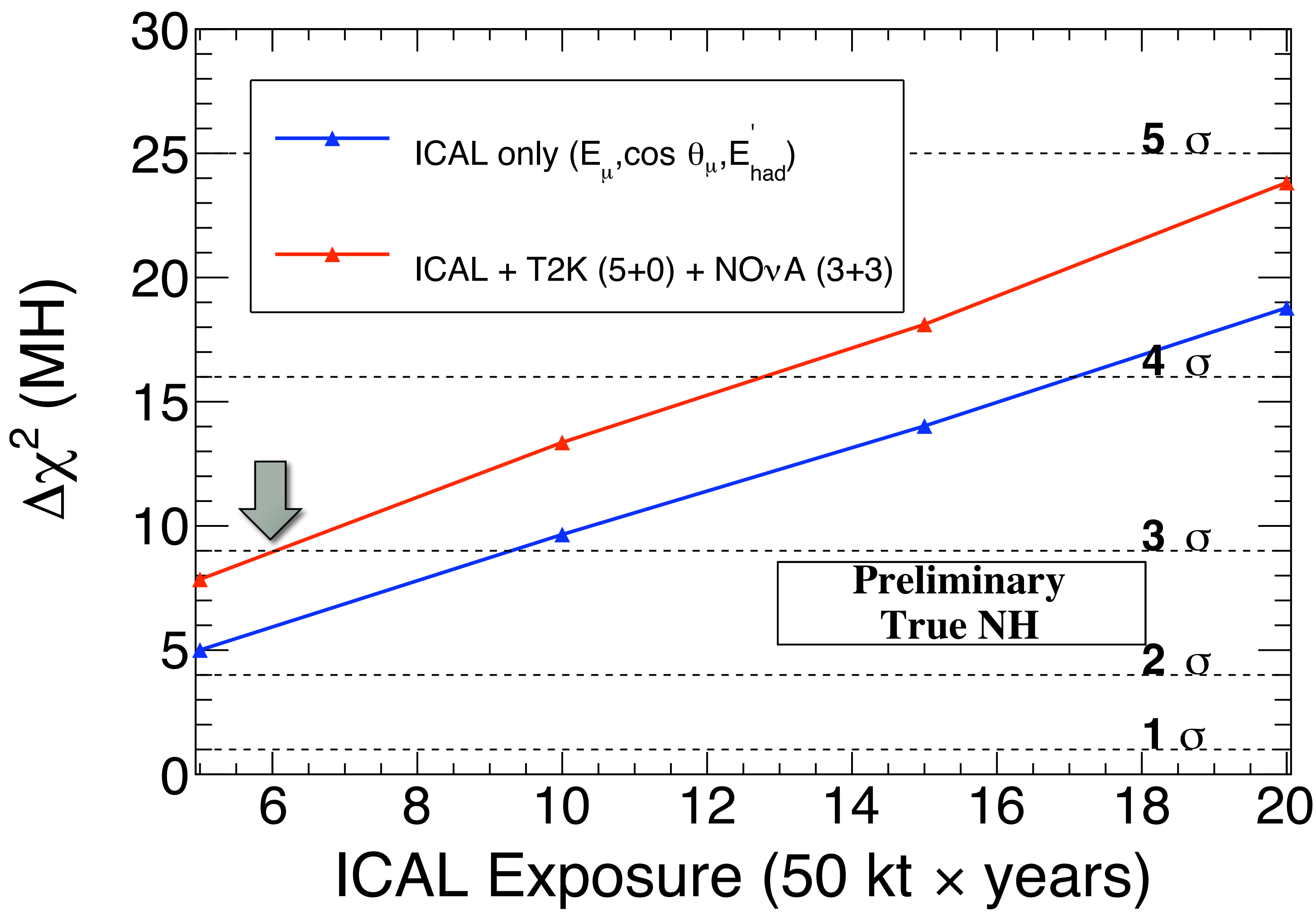



**Median Sensitivity**

**Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)**

50 kt ICAL can rule out the wrong hierarchy with $\Delta\chi^2 \approx 9.5$ in 10 years

# MH Discovery with ICAL+T2K+NOvA




Agarwalla, Chatterjee, Thakore, work in progress (INO Collaboration)

3σ median sensitivity can be achieved in 6 years

# *Concluding Remarks from Prof. Art McDonald*

- **Particle Astrophysics is an exciting field where measurements are helping us to understand our Universe more completely on scales reaching from the very small to the farthest reaches in space and the earliest times.**

- **Going underground can enable scientists to make unique measurements that would otherwise be obscured by background from cosmic radiation.**

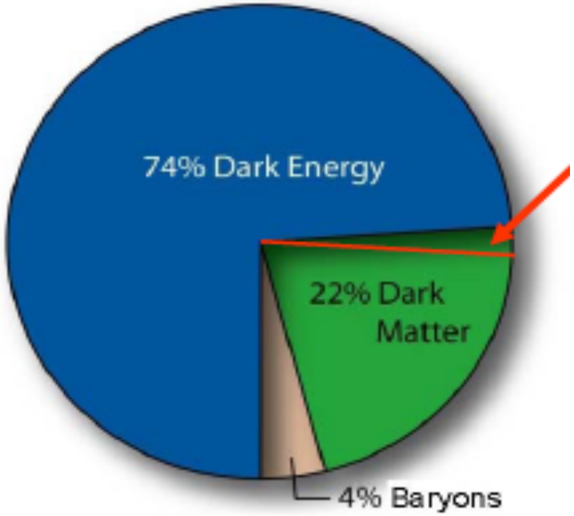
- **India has an excellent opportunity to contribute strongly to this rapidly growing area of fundamental research through its work in *particle physics at international accelerators* and in the INDIAN NEUTRINO OBSERVATORY (INO).**

- **This is one of the most exciting and greatest intellectual exercises of all time….Understanding Our Universe.**

**Concluding Remarks from Prof. Art McDonald at the 103rd Indian Science Congress meeting, University of Mysore, January 3, 2016**

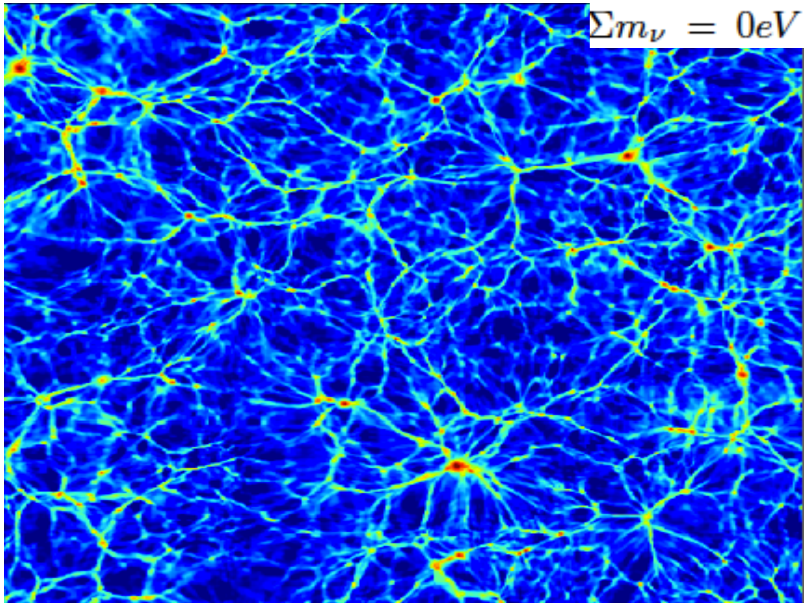
# Backup Slides

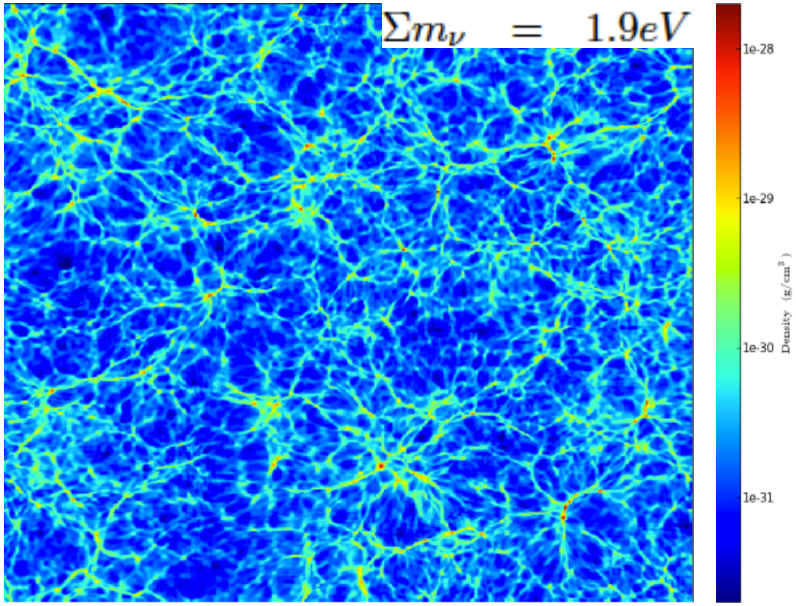
# Neutrinos and Dark Matter




**Neutrinos constitute a hot dark matter component and affect the formation of clusters of galaxies**

Neutrinos are too hot for being trapped in the gravitational wells in the early Universe (free streaming) and move freely, smoothing out the structures (galaxies) at small (cosmological) distances

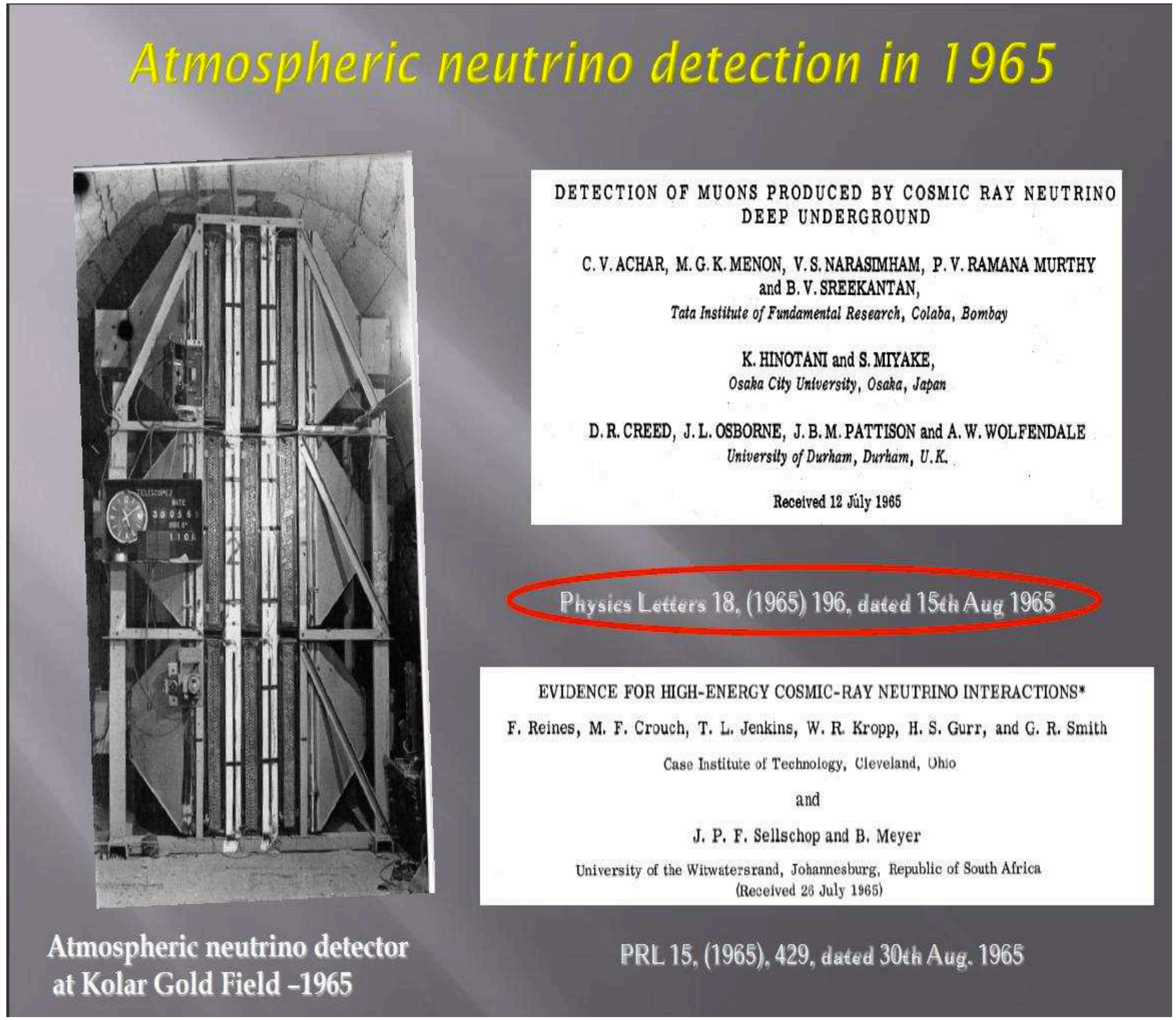



Agarwal, Feldman, arXiv:1006.0689 [astro-ph.CO]

# An Old Saga of Underground Laboratory in India

- *KGF: Deepest underground lab in world till 1992 > 6500 MWE*
- *In 1965, at KGF at a depth of 2.3km, first atmospheric neutrino was observed by the TIFR-Osaka-Durham group*
- *During early 80s dedicated detectors were setup at KGF by TIFR-Osaka collaboration to look for proton decay*



# *India-Based Neutrino Observatory*

- *A multi-institutional attempt to build a world-class underground facility to study fundamental issues in science with special emphasis on neutrinos*

- *With ~1 km all-round rock cover accessed through a 2 km long tunnel. A large and several smaller caverns to pursue many experimental programs*

- *Complementary to ongoing efforts worldwide to explore neutrino properties*

- *A mega-science project (~250 M$) in India, jointly funded (50:50) by the Department of Atomic Energy and the Department of Science and Technology*

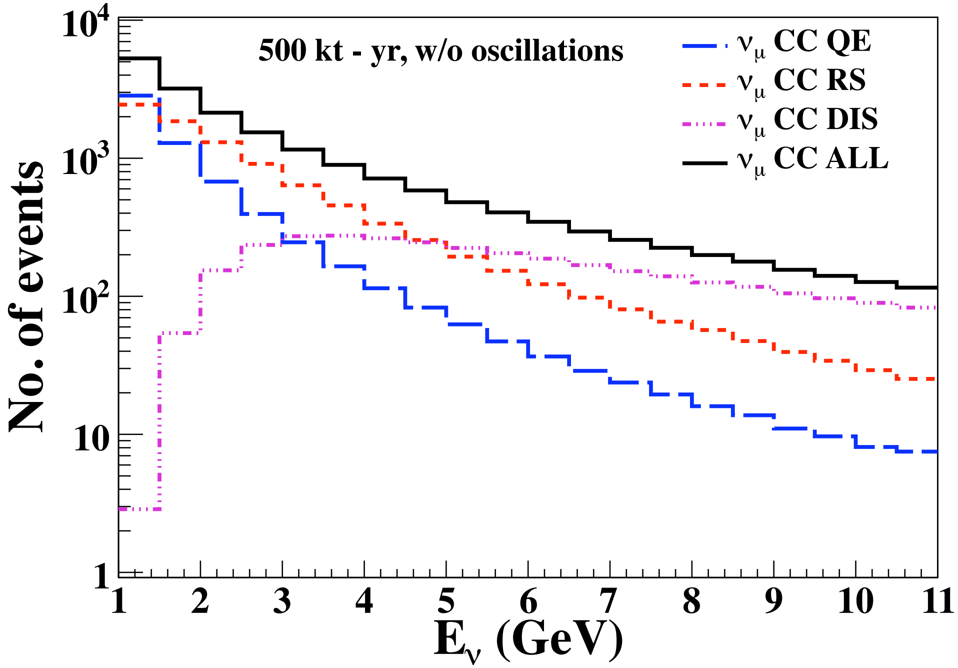
- *International Community is welcome to participate in ICAL@INO activity. INO facility is also available to the entire community for setting up experiments like Neutrino-less Double Beta Decay, Direct Dark Matter searches*

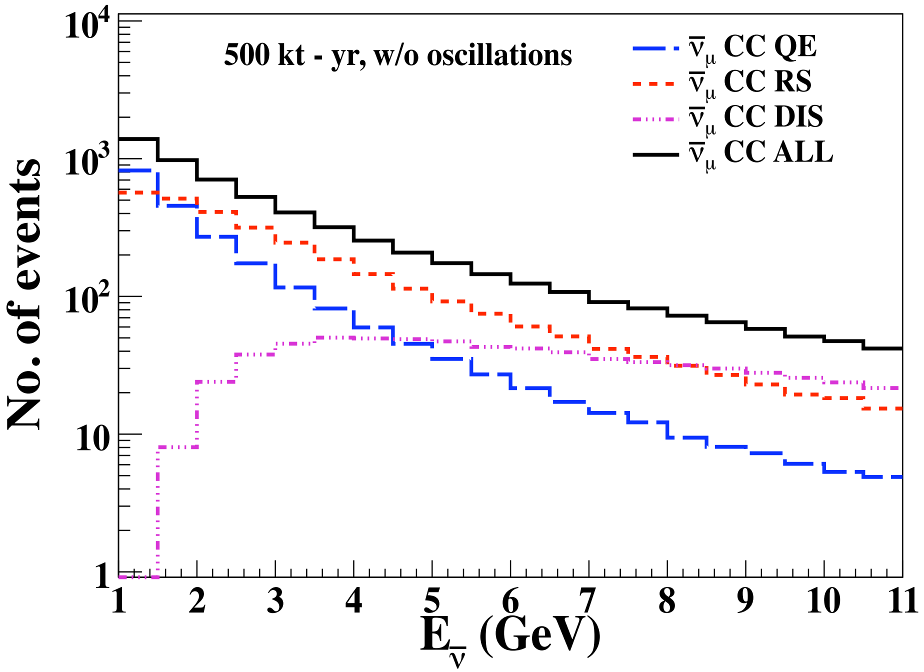
# *Overview of Simulation Framework*

| | | |
|---|---|---|
| NUANCE<br><br>work in progress to adopt GENIE | **Neutrino Event Generation**<br>$\nu_\ell + N \rightarrow \ell + X$ .<br>Generates particles that result from a random interaction of a neutrino with matter using theoretical models for both neutrino fluxes and cross-sections. | **Output:**<br>(i) Reaction Channel<br>(ii) Vertex and time information<br>(iii) Energy and momentum of all final state particles |
| GEANT | **Event Simulation**<br>$\ell + X$ through simulated ICAL<br>Simulates propagation of particles through the ICAL detector with RPCs and magnetic field. | **Output:**<br>(i) $x, y, z, t$ of the particles as they propagate through detector<br>(ii) Energy deposited<br>(iii) Momentum information |
| DIGITISATION | **Event Digitisation**<br>$(X, Y, Z, T)$ of final states on including noise and detector efficieny<br>Add detector efficiency and noise to the hits. | **Output:**<br>(i) Digitised output of the previous stage |
| ANALYSIS | **Event Reconstruction**<br>$(E, \vec{p})$ of $\ell$, $X$ (total hadrons)<br>Fit the muon tracks using Kalman filter techniques to reconstruct muon energy and momentum; use hits in hadron shower to reconstruct hadron information. | **Output:**<br>(i) Energy and momentum of muons and hadrons, for use in physics analyses. |

**Simulation work is under progress in full swing!**

# *Events in Various Channels*

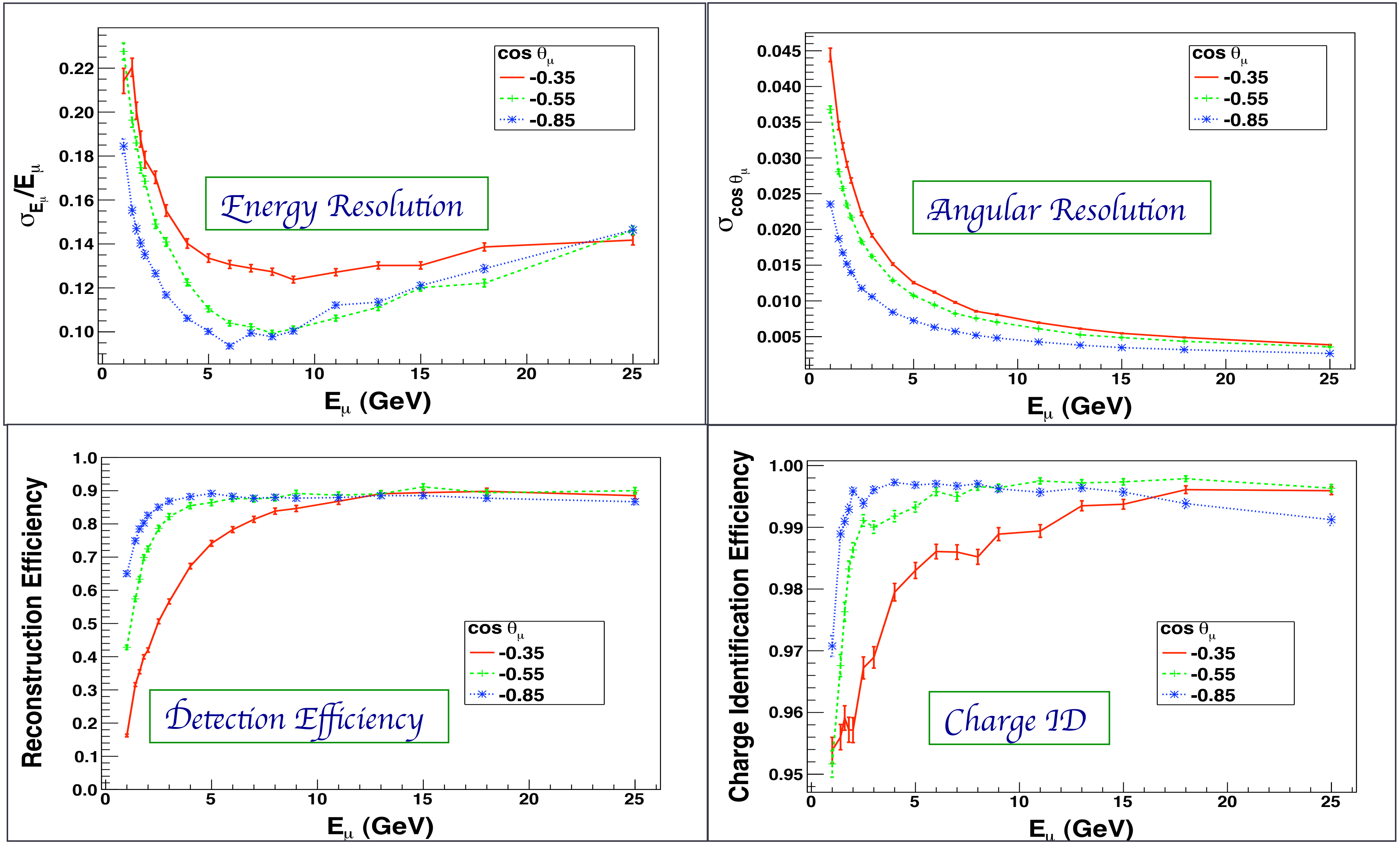



**Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)**

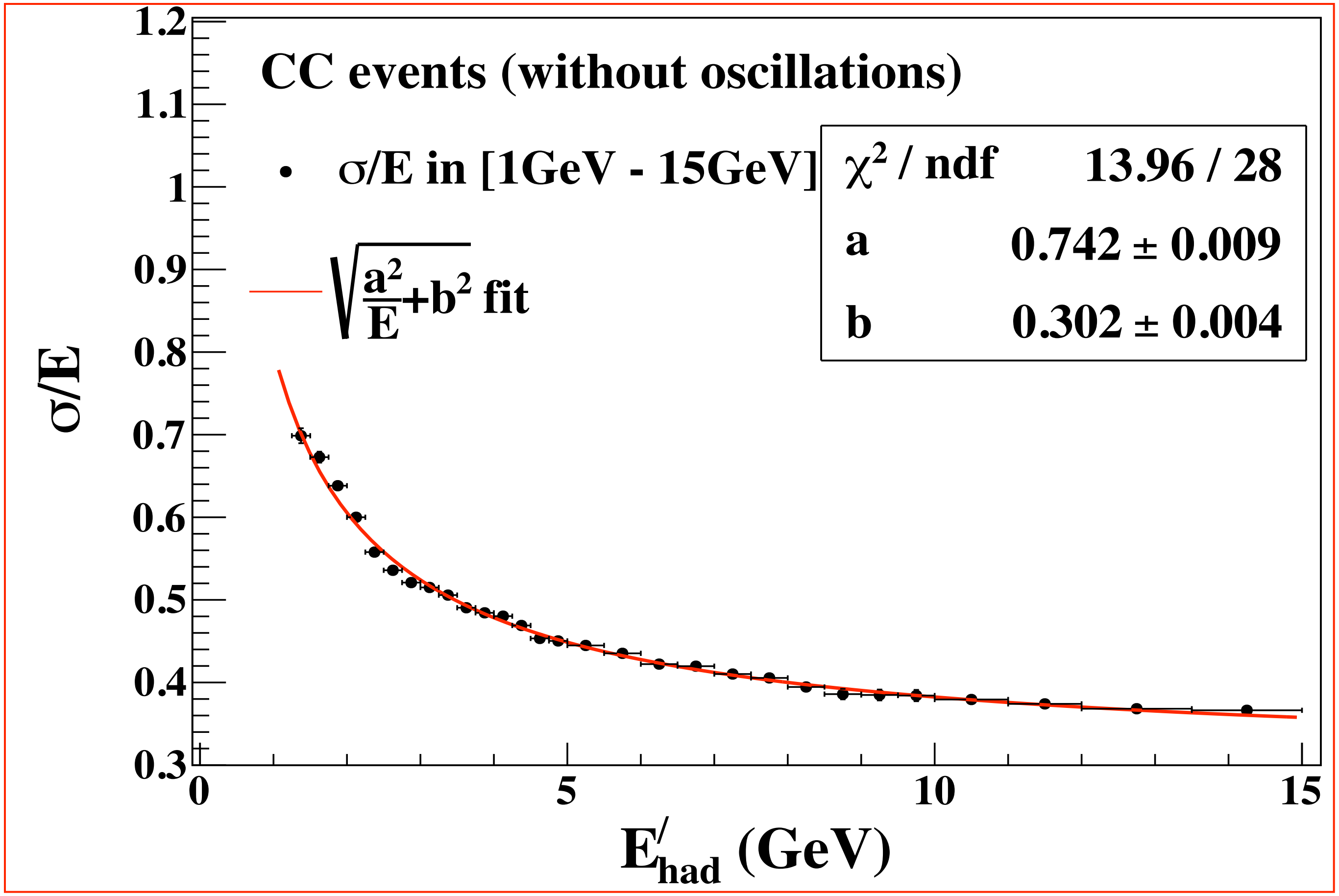
Relative contributions of three cross-section processes to the total events in the absence of oscillation and without detector efficiency and resolutions

# Muon Efficiencies and Resolutions




Animesh Chatterjee, Meghna K.K., Kanishka Rawat, Tarak Thakore etal., arXiv:1405.7243 [physics.ins-det]

# *Hadron Energy Response of ICAL*




**$E'_h = E_\nu - E_\mu$ (from hadron hit calibration)**

**Hadron energy resolution: 85% at 1 GeV and 36% at 15 GeV**

Moon Moon Devi, Anushree Ghosh, Daljeet Kaur, Lakshmi S. Mohan etal., JINST 8 (2013) P11003

# The $\chi^2$ Analysis

We define the Poissonian $\chi^2_-$ for $\mu^-$ events as :

$$\chi^2_- = \min_{\xi_l} \sum_{i=1}^{N_{E'_{\rm had}}} \sum_{j=1}^{N_{E_\mu}} \sum_{k=1}^{N_{\cos\theta_\mu}} \left[ 2(N_{ijk}^{\rm theory} - N_{ijk}^{\rm data}) - 2N_{ijk}^{\rm data} \ln\left(\frac{N_{ijk}^{\rm theory}}{N_{ijk}^{\rm data}}\right)\right] + \sum_{l=1}^{5} \xi_l^2 ,$$

where

$$N_{ijk}^{\rm theory} = N_{ijk}^0 \left(1 + \sum_{l=1}^{5} \pi_{ijk}^l \xi_l \right) .$$

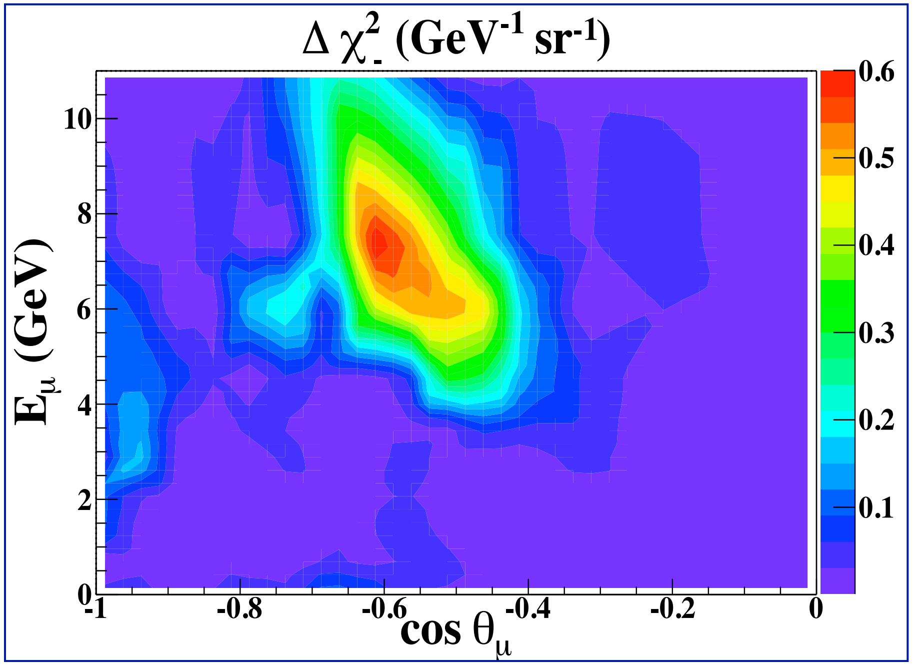
| Observable | Range | Bin width | Total bins | |
|---|---|---|---|---|
| $E_\mu$ (GeV) | $[1, 4)$ | 0.5 | 6 | 10 |
| | $[4, 7)$ | 1 | 3 | |
| | $[7, 11)$ | 4 | 1 | |
| $\cos\theta_\mu$ | $[-1.0, -0.4)$ | 0.05 | 12 | 21 |
| | $[-0.4, 0.0)$ | 0.1 | 4 | |
| | $[0.0, 1.0]$ | 0.2 | 5 | |
| $E'_{\rm had}$ (GeV) | $[0, 2)$ | 1 | 2 | 4 |
| | $[2, 4)$ | 2 | 1 | |
| | $[4, 15)$ | 11 | 1 | |

1) Overall 5% systematic uncertainty
2) Overall flux normalization: 20%
3) Overall cross-section normalization: 10%

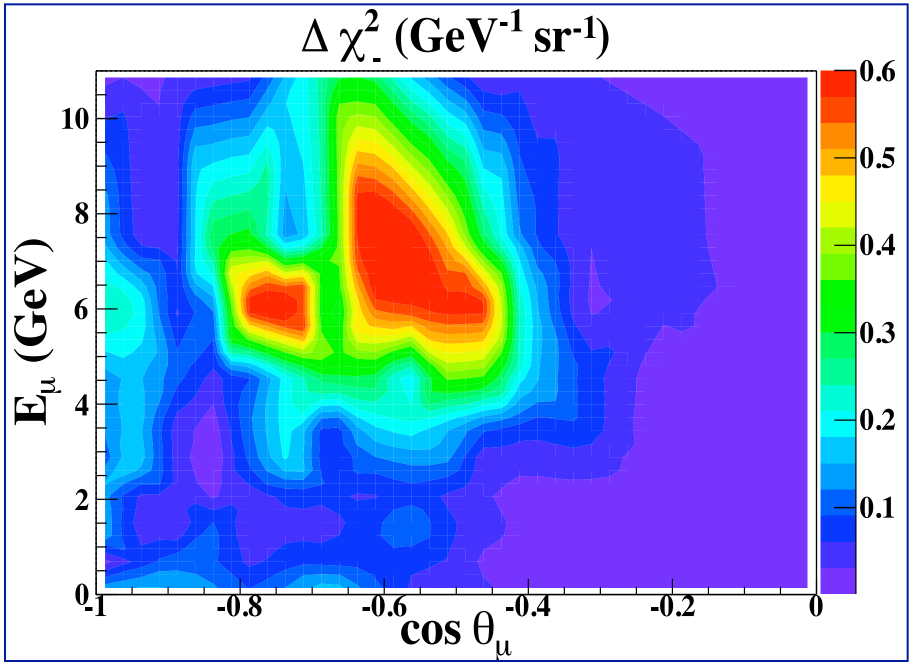
4) 5% uncertainty on the zenith angle dependence of the fluxes
5) Energy dependent tilt factor:
$\Phi_\delta(E) = \Phi_0(E)\,[E/E_0]^\delta \approx \Phi_0(E)\,[1+\delta \ln E/E_0]$
where $E_0 = 2$ GeV and
$\delta$ is the $1\sigma$ systematic error of 5%

# *Neutrino Mass Hierarchy Discrimination*

Distribution of $\Delta\chi^2$ [$\chi^2$ (IH) - $\chi^2$ (NH)] for mass hierarchy discrimination considering $\mu^-$ events



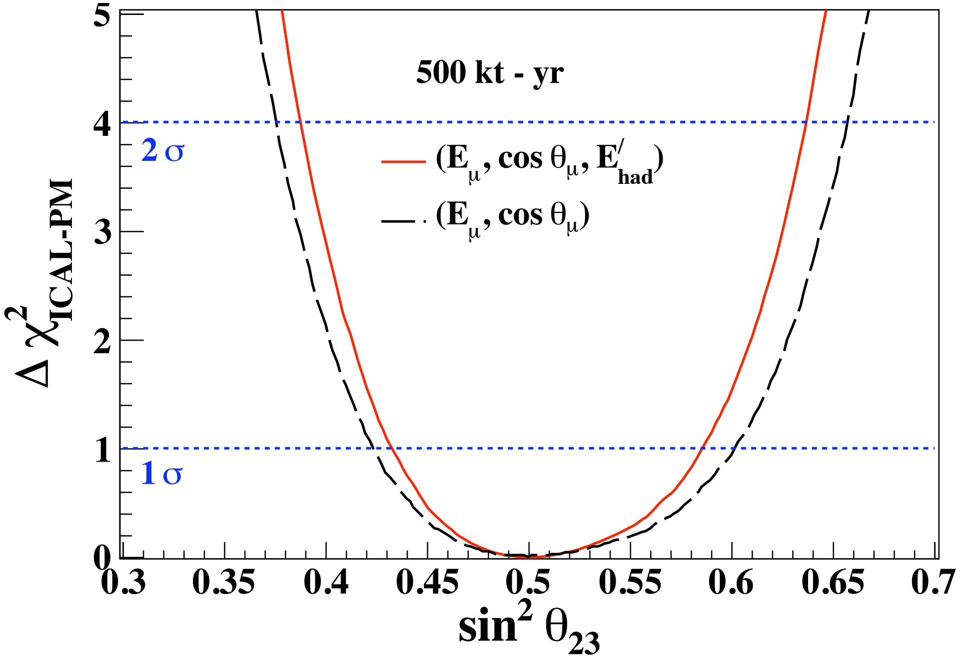

Hadron energy information not used

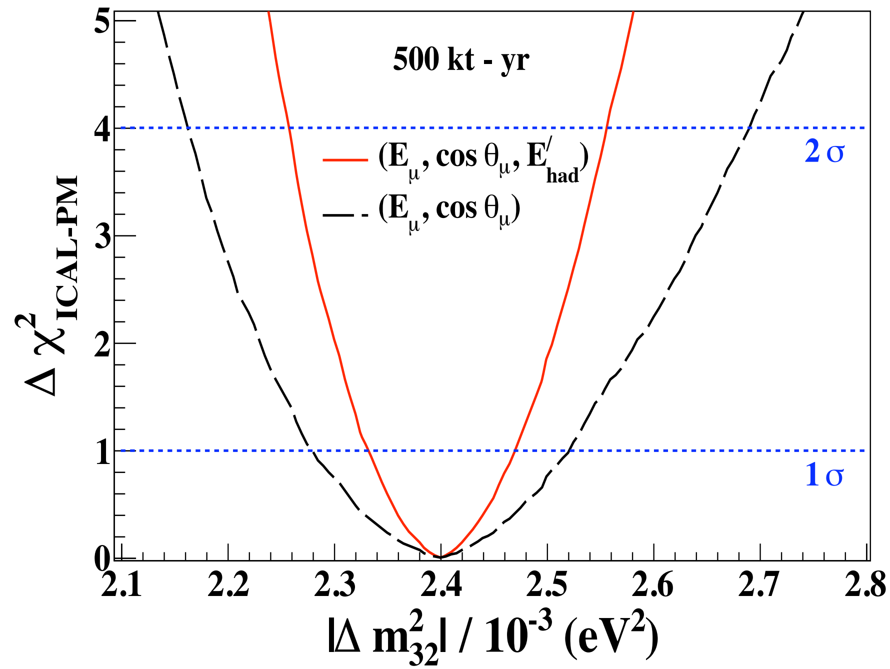



Hadron energy information used

- Further subdivide the events into four hadron energy bins
- Hadron energy carries crucial information
- Correlation between hadron energy and muon momentum is very important

# *Precision of Atmospheric Oscillation Parameters*



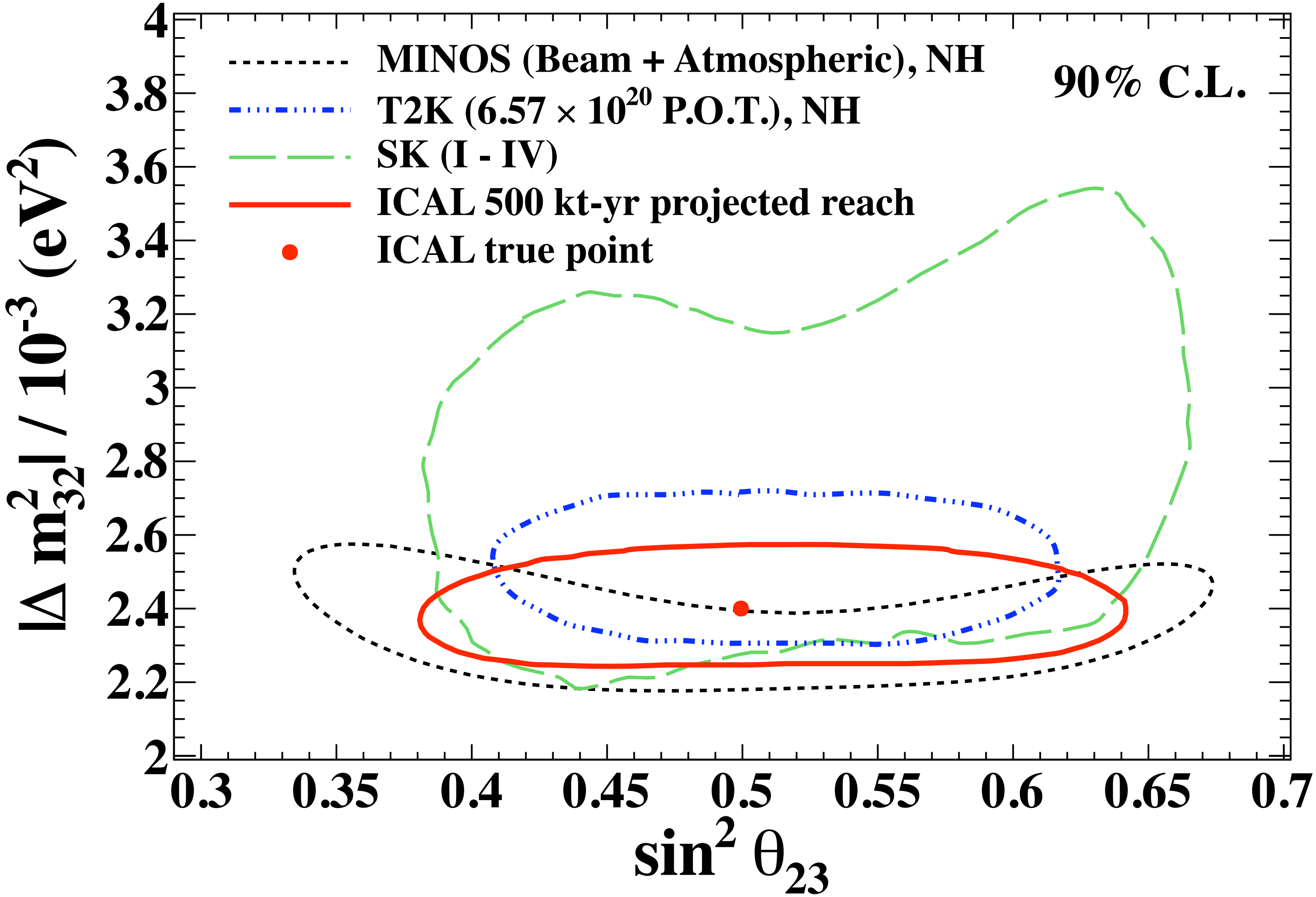

**Relative 1σ precision: 12%**

**Relative 1σ precision: 2.9%**

**Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)**

Significant improvement in the precision measurement of atmospheric mass splitting by adding hadron energy information with muon momentum

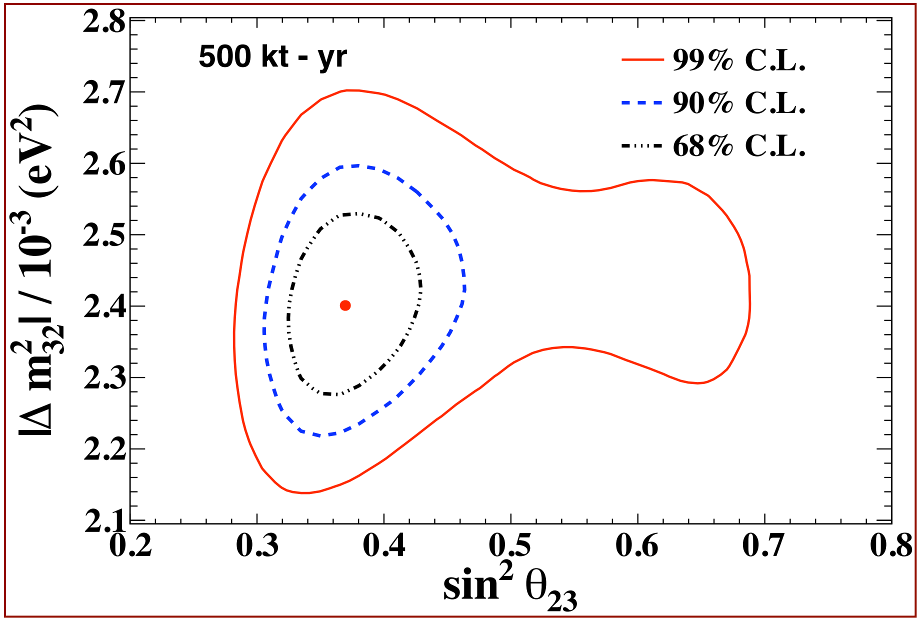
# *Precision Measurement of Atmospheric Parameters*

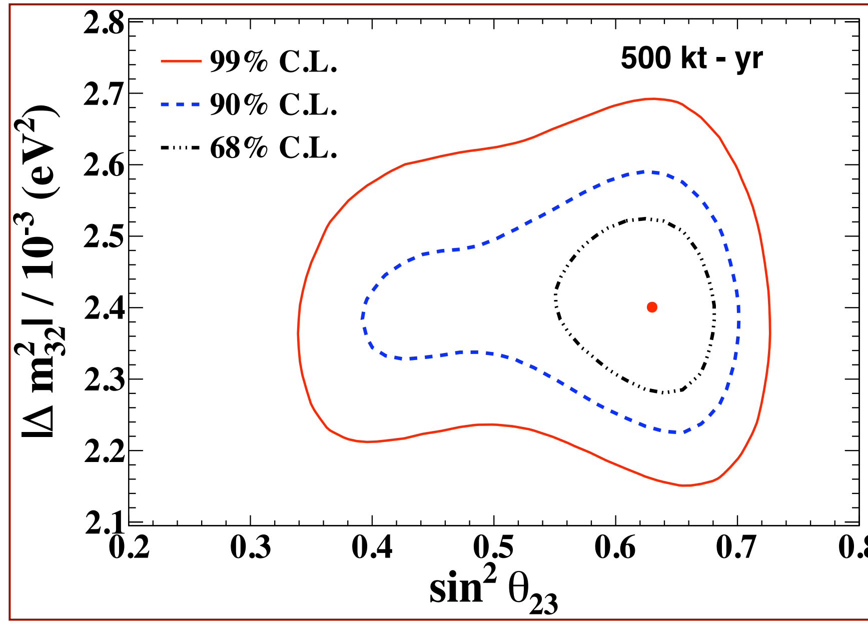


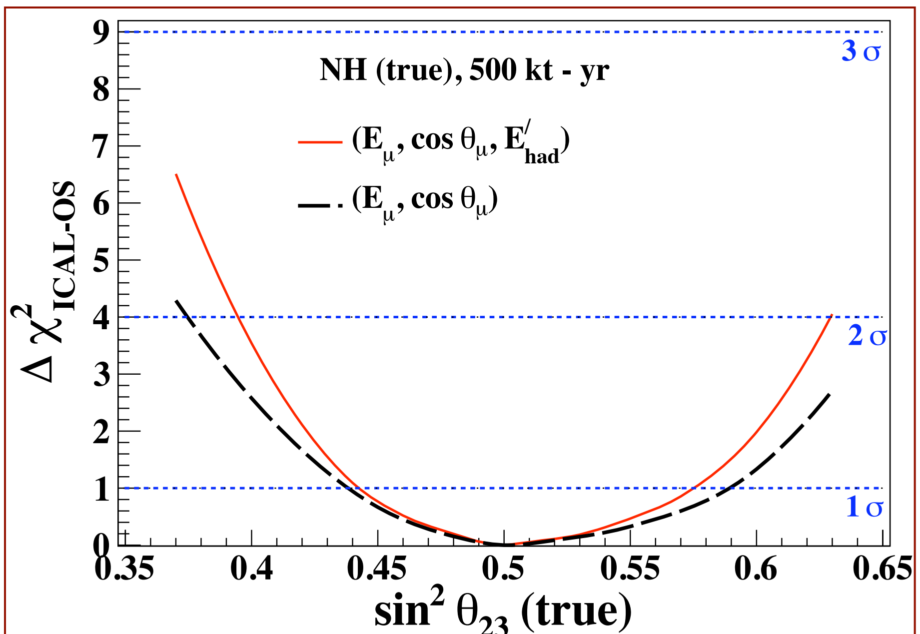

Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

ICAL's expected precision on atmospheric mass splitting is better than SK

# *Octant of $\theta_{23}$ with ICAL-INO*



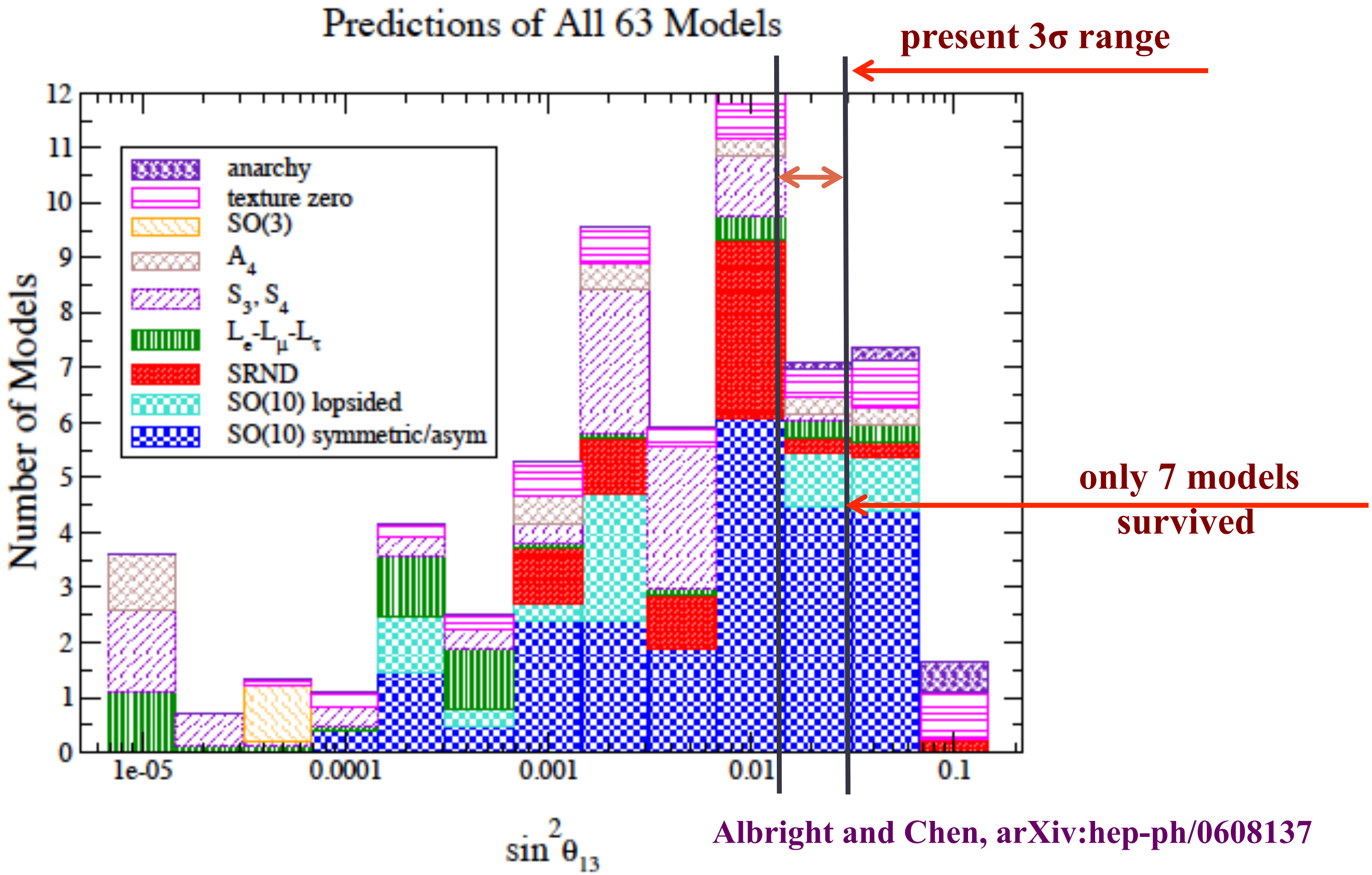




**Median 2σ discovery of $\theta_{23}$ octant is possible if $\theta_{23}$ is sufficiently away from maximal value**

Devi, Thakore, Agarwalla, Dighe, arXiv: 1406.3689
(INO Collaboration)

# *Latest Results on $\theta_{13}$ : What happened to Mass models?*




**Albright and Chen, arXiv:hep-ph/0608137**

Survey of 63 ν mass models in June 2006 by Carl H. Albright and Mu-Chun Chen

Future high precision measurements of mixing angles, new information on neutrino mass ordering and CP phase will severely constrain these presently allowed models

# Implications of Recent Measurement of $\theta_{13}$

## Simplest models that are ruled out!

- Bimaximal mixing: [Vissani (97), Barger, Pakvasa, Weiler, Whisnant (98)]

  It predicts: $\theta_{12} = 45°$, $\theta_{23} = 45°$, and $\theta_{13} = 0°$

predicted in flavor symmetry models with symmetry groups like A4, S4, A5

- Tri-bimaximal mixing: [Vissani (97), Harrison, Perkins, Scot (02)]

$$U_{\rm TBM} = R_{32}\left(\theta_{32} = \frac{\pi}{4}\right) R_{13}(\theta_{13} = 0)\, R\left(\theta_{21} = \tan^{-1}\left(\frac{1}{\sqrt{2}}\right)\right) = \frac{1}{\sqrt{6}}\begin{pmatrix} 2 & \sqrt{2} & 0 \\ -1 & \sqrt{2} & \sqrt{3} \\ 1 & -\sqrt{2} & \sqrt{3} \end{pmatrix}$$

- Golden ratio: [Datta, Ling, Ramond (03), Kajiyama, Raidal, Strumia (07)]

  It predicts: $\theta_{12} = 31.7°$, $\theta_{23} = 45°$, and $\theta_{13} = 0°$

## Simplest models that are still alive!

- Anarchy ($\nu$ mass matrix completely random): [Hal, Murayama, Weiner (99), de Gouvea, Murayama (03, 12)]

  It predicts: large $\theta_{13}$, okay with observed value of $\theta_{13}$

- Quark-Lepton Complementarity: [Minakata, Smirnov (94), Raidal (04)]

  Based on observation: $\theta_{12}$ (PMNS) + $\theta_{12}$ (CKM) = 45°

  It predicts: $\sin\theta_{13} \approx \sin\theta_C / \sqrt{2} \approx 0.16$ (close to the observed value, other relations needs to be tested!)

# The New Minimal Standard Model

- Minimal Extensions to give Mass to the Neutrino:

  $*$ Introduce $\nu_R$ AND impose $L$ conservation $\Rightarrow$ Dirac $\nu \neq \nu^c$:

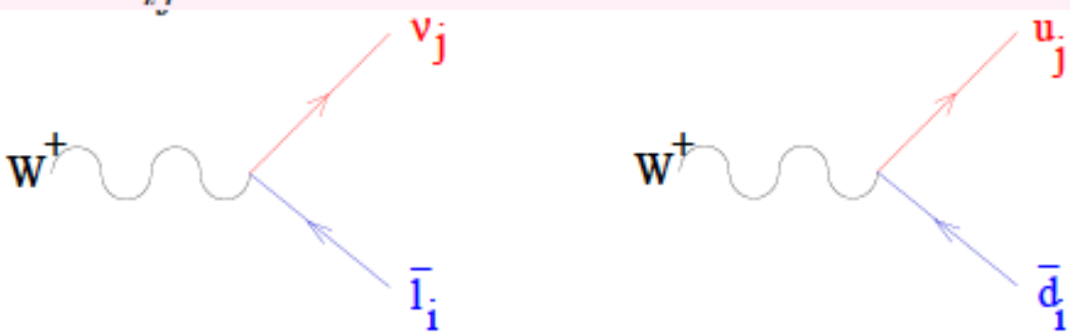
  $$\mathcal{L} = \mathcal{L}_{SM} - M_\nu \overline{\nu_L} \nu_R + h.c.$$

  $*$ NOT impose $L$ conservation $\Rightarrow$ Majorana $\nu = \nu^c$

  $$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} M_\nu \overline{\nu_L} \nu_L^C + h.c.$$

- The charged current interactions of leptons are not diagonal (same as quarks)

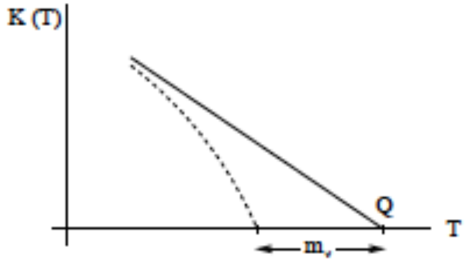
$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} \left( U_{\rm LEP}^{ij}\, \overline{\ell^i}\, \gamma^\mu\, L\, \nu^j \;+\; U_{\rm CKM}^{ij}\, \overline{U^i}\, \gamma^\mu\, L\, D^j \right) \;+\; h.c.$$




Courtesy to Concha Gonzalez-Garcia

# Neutrino Mass Scale

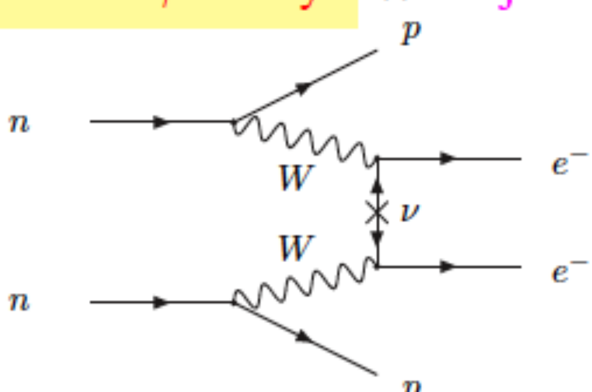
Single $\beta$ decay : Dirac or Majorana $\nu$ mass modify spectrum endpoint




$$m^2_{\nu_e} = \sum m^2_j |U_{ej}|^2 = c^2_{13} c^2_{12} m^2_1 + c^2_{13} s^2_{12} m^2_2 + s^2_{13} m^2_3$$

$\nu$-less Double-$\beta$ decay: $\Leftrightarrow$ Majorana $\nu' s$ sensitive to Majorana phases

If $m_\nu$ only source of $\Delta L$ $\quad (T^{0\nu}_{1/2})^{-1} \propto (m_{ee})^2$




$$m_{ee} = |\sum U^2_{ej} m_j|$$
$$= \left| c^2_{13} c^2_{12} m_1 \, e^{i\eta_1} + c^2_{13} s^2_{12} m_2 \, e^{i\eta_2} + s^2_{13} m_3 \, e^{-i\delta_{CP}} \right|$$

COSMO Neutrino mass (Dirac or Majorana)
modify the growth of structures

$$\sum m_i$$

**Courtesy to Concha Gonzalez-Garcia**

# Experimental Limits

| Isotope | 0νββ half life | Experiment | <m> eV |
| --- | --- | --- | --- |
| $^{48}Ca$ | $> 1.4*10^{22}$ (90%CL) | ELEGANT-VI | < 7 - 44 |
| $^{76}Ge$ | $> 1.9*10^{25}$ (90%CL) | Heidelberg-Moscow | < 0.35 |
| $^{76}Ge$ | $2230^{+440}_{-310}$ (90%CL) | Subset of HM coll. | 0.32 +/- 0.03 |
| $^{76}Ge$ | $> 2.1*10^{25}$ (90%CL) | *GERDA†* | < 0.2 – 0.4 |
| $^{82}Se$ | $> 2.1*10^{23}$ (90%CL) | NEMO-3 | <1.2 – 3.2 |
| $^{100}Mo$ | $> 5.8*10^{23}$ (90%CL) | NEMO-3 | < 0.6 – 2.7 |
| $^{116}Cd$ | $> 1.7*10^{23}$ (90%CL) | Solotvino | < 1.7 |
| $^{130}Te$ | $> 2.8*10^{24}$ (90%CL) | Cuoricino | < 0.41 – 0.98 |
| $^{136}Xe$ | $> 1.9*10^{25}$ (90%CL) | *KamLAND-Zen††* | < 0.12 – 0.25 |
| $^{136}Xe$ | $> 1.6\times10^{25}$ (90%CL) | *EXO-200†††* | < 0.14 – 0.38 |
| $^{150}Nd$ | $> 1.8*10^{22}$ (90%CL) | NEMO-3 | |

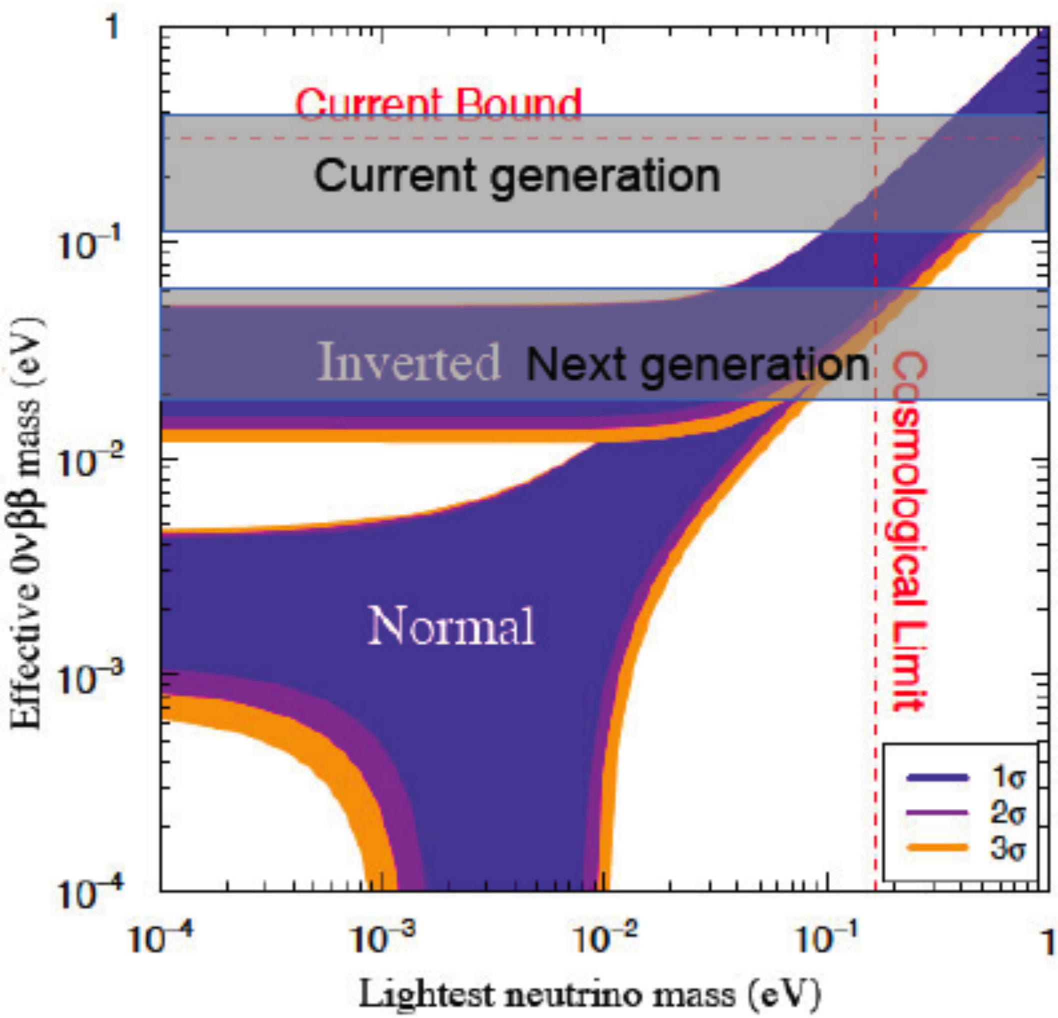
**Courtesy to Liang Yang**

[F. Avignone, S. Elliot, J. Engel, arXiv:0708: 1033v2 (2007)]
† [GERDA Collaboration, arXiv:1307.4720 (2013)]
†† [KamLAND-Zen Collaboration, Phys. Rev. Lett. 110, 062502(2013)]
††† [EXO Collaboration, Phys. Rev. Lett.109, 0322505 (2012)]

} New results within the last year!

# Experimental Sensitivity to Neutrino Mass

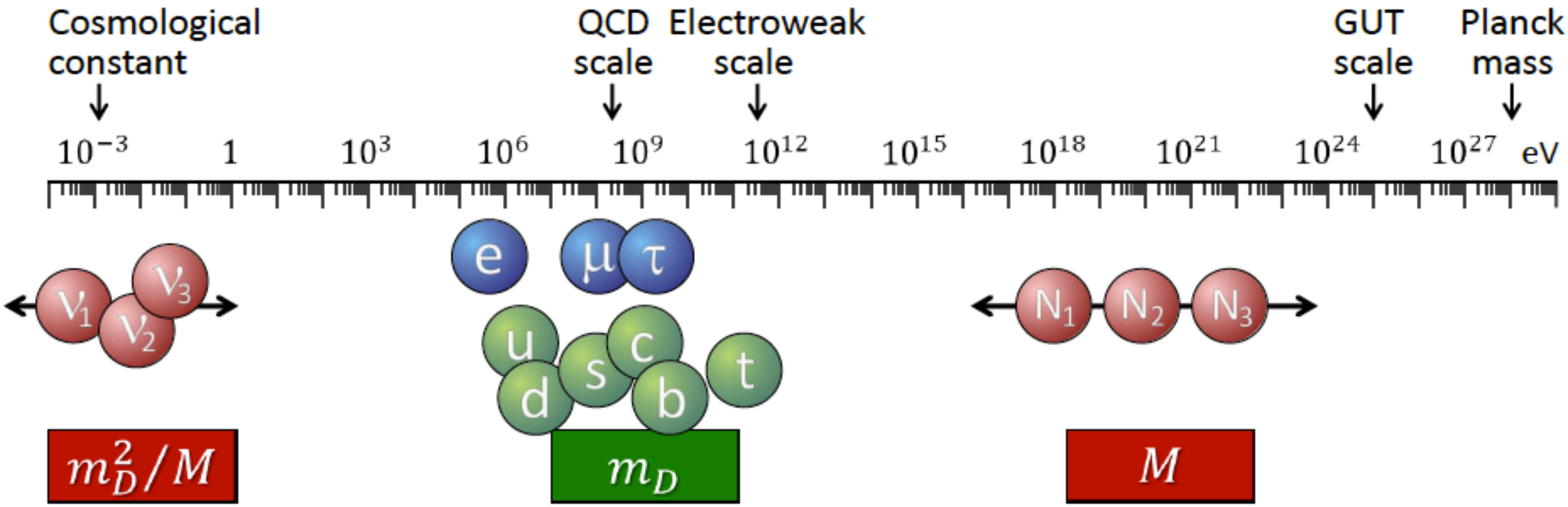
| Isotope Mass | Background |
| --- | --- |
| 10-100 kg | 10-100cts/yr/ton |
| 1-10 ton | 0.1-1cts/yr/ton |




arXiv:1203.5250v1

Courtesy to Liang Yang

# Backup Slides (See-Saw & Neutrino Mass)




Mass matrix for one family of ordinary and heavy r.h. neutrinos

$$(\overline{\nu}_L, \overline{N}_R)\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

Diagonalization

$$(\overline{\nu}_L, \overline{N}_R)\begin{pmatrix} m_D^2/M & 0 \\ 0 & M \end{pmatrix}\begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

One light and one heavy Majorana neutrino

Courtesy to George Raffelt