



# FYST17 LECTURE 3 NEUTRINOS

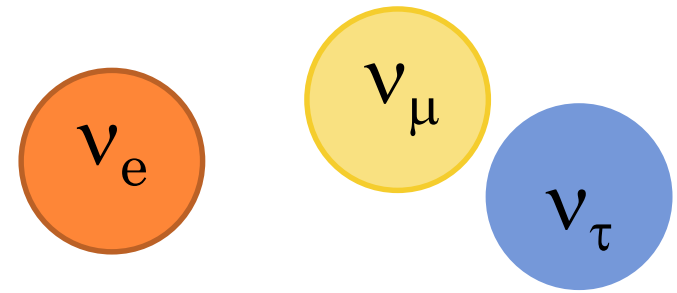
1

Thanks to V. Hedberg , S. Euler, S. Ricciardi

# TODAY:

- Neutrinos and their discovery
- Atmospheric neutrinos
- Solar neutrinos
- Neutrino oscillations
- Neutrino mass
  - The nature of neutrinos
- Searches for exotic neutrinos
- Long baseline experiments

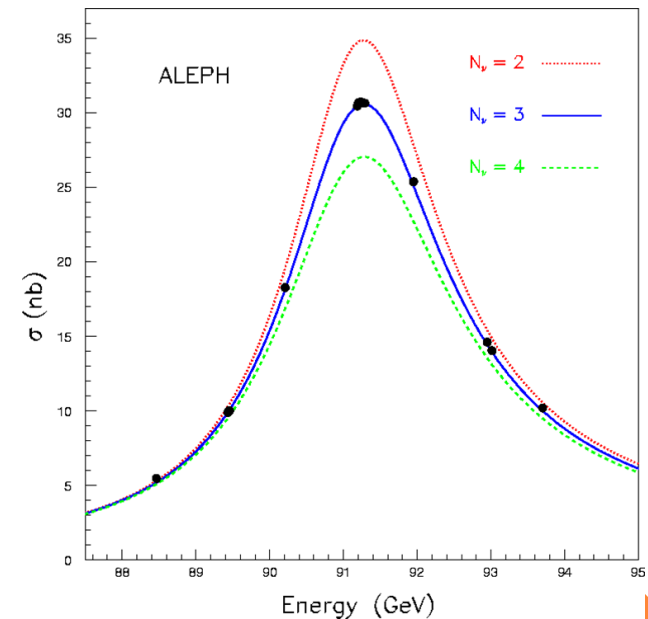
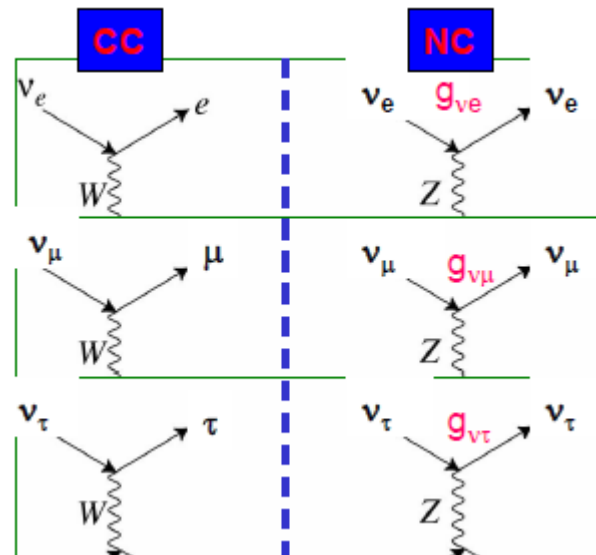
# NEUTRINOS



- In the Standard Model neutrinos have no charge and no mass → **only interacts weakly**
- In recent years we know they do have a mass → gravitational interaction as well

- From Z lineshape at LEP:

$\nu$ 's come in  
three (active)  
flavors

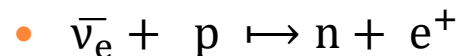


# DISCOVERY OF (ANTI) $\nu_E$ 1956

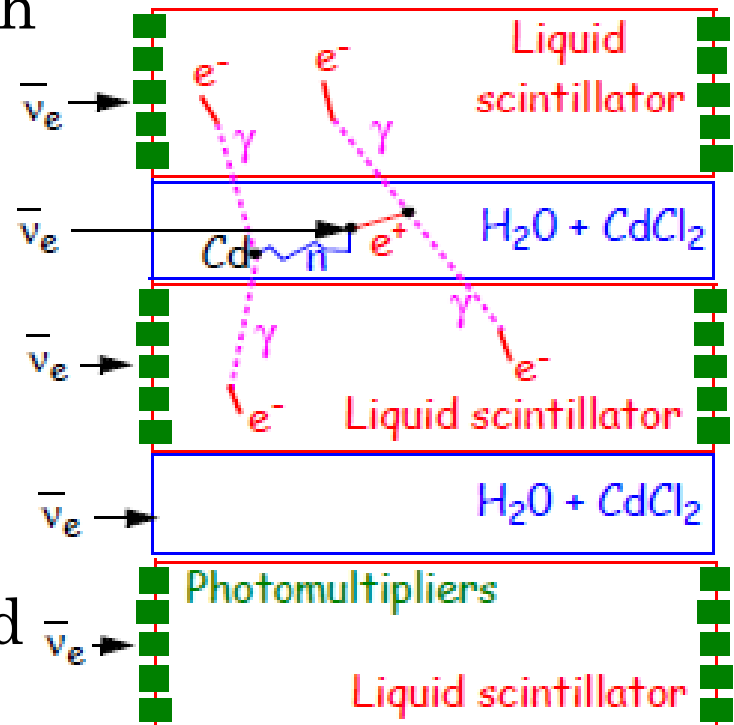
- At nuclear reactor in Savannah
- Decays of neutrons from the reactor



- And then detect the  $\nu$ 's via

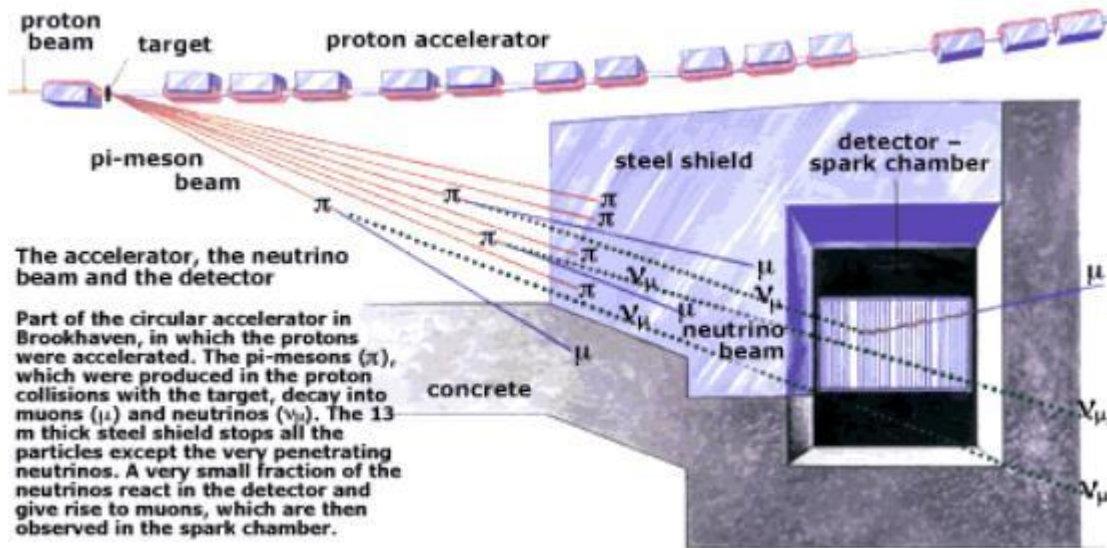


- They got 2  $\bar{\nu}_e$  and 1 background event / hour , on average

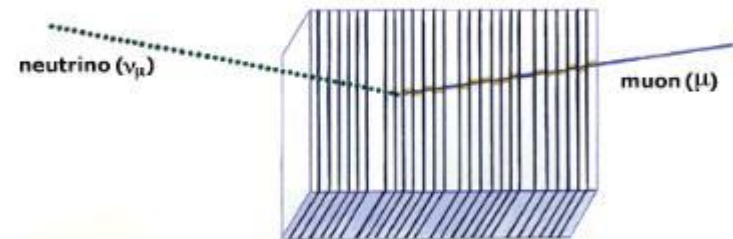


# DISCOVERY OF $\nu_\mu$ (1962)

- Secondary beam of pions from the AGS accelerator
  - $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$  ( $10^{-8}$  s)
  - $\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$  ( $10^{-6}$  s)



Sandwich of Aluminium plates and spark chambers



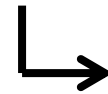
A muon produced in a neutrino reaction gives rise to discharges observed in the spark chamber.



# DISCOVERY OF $\nu_\tau$ (2000)

Dedicated experiment DONUT at Fermilab

High E protons hit target :  $p + p \rightarrow D_s + X$

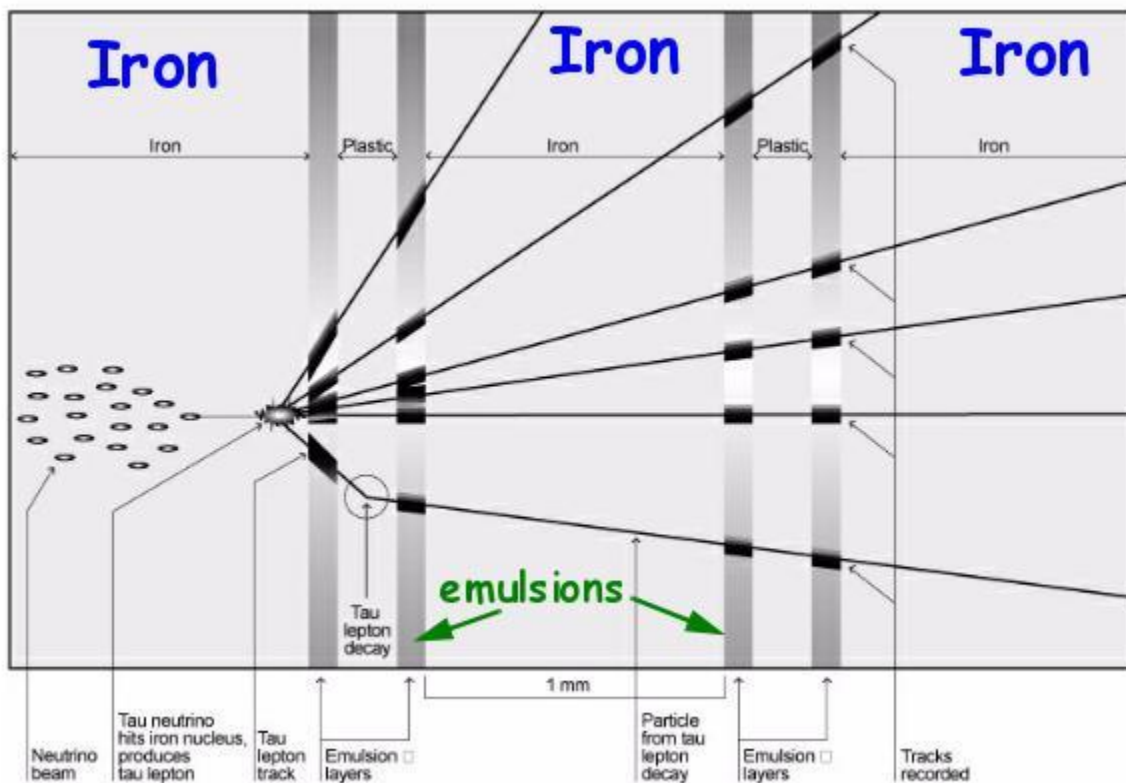


$\tau^- + \text{anti-}\nu_\tau$

With  $\tau \rightarrow \nu_\tau + \ell + \bar{\nu}_\ell$

Identify  $\nu_\tau$  from  
reaction with n

It took 6M events to  
select 4  $\nu_\tau$  candidates



# NEUTRINO SOURCES

- **Artificial:**

- nuclear reactors
- particle accelerators

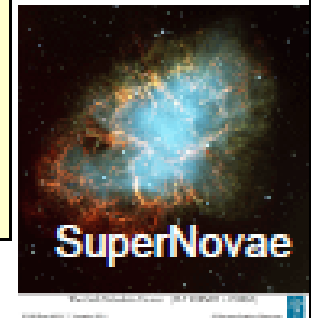
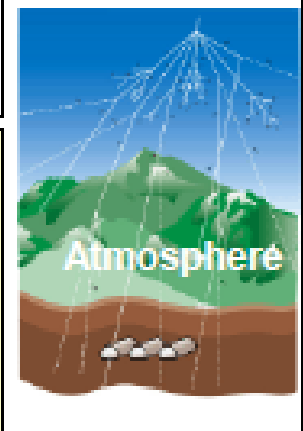
First detected neutrinos

- **Natural:**

- Sun
- Atmosphere
- SuperNovae
- fission in the Earth core (geoNeutrinos)
- Astrophysical origin (AGN..)

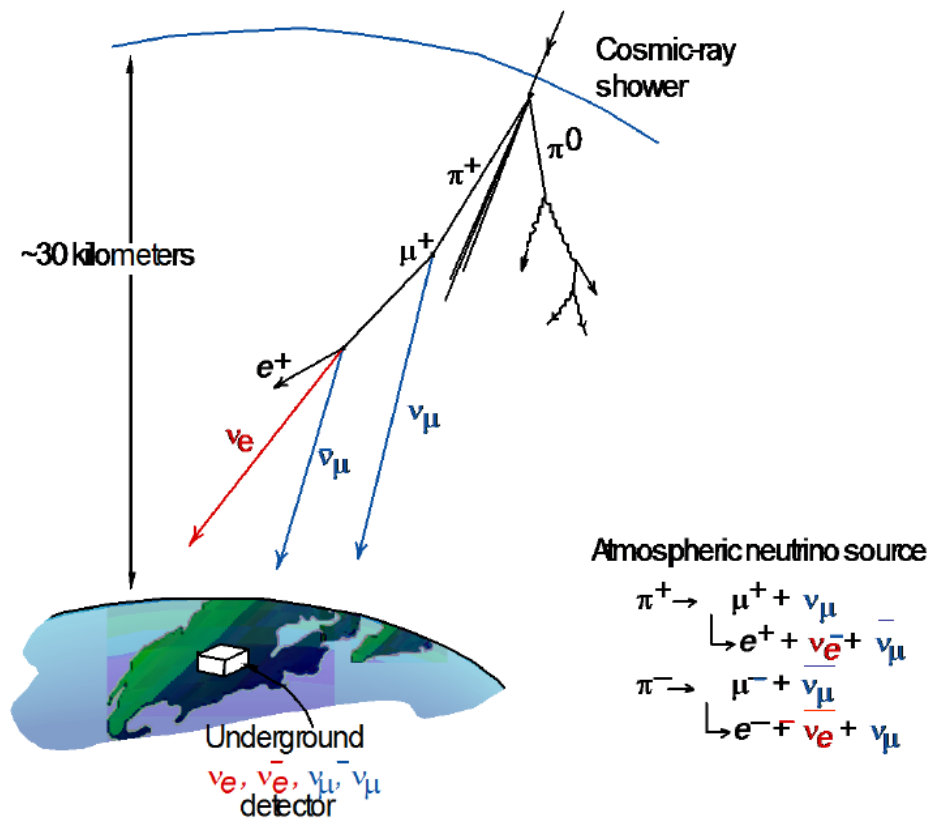
Expected, but undetected so far,:

- relic neutrinos from BigBang ( $\sim 300/\text{cm}^3$ )



*Neutrinos are everywhere!*

# NEUTRINO PRODUCTION IN THE ATMOSPHERE



Absolute  $\nu$  flux has  
 $\sim 10\%$  uncertainty  
 But muon/electron neutrino  
 ratio is known with  $\sim 3\%$   
 uncertainty. Expected:

$$\frac{\phi(\nu_\mu + \bar{\nu}_\mu)}{\phi(\nu_e + \bar{\nu}_e)} \approx 2$$



# SUPER KAMIOKANDE (SUPER-K)

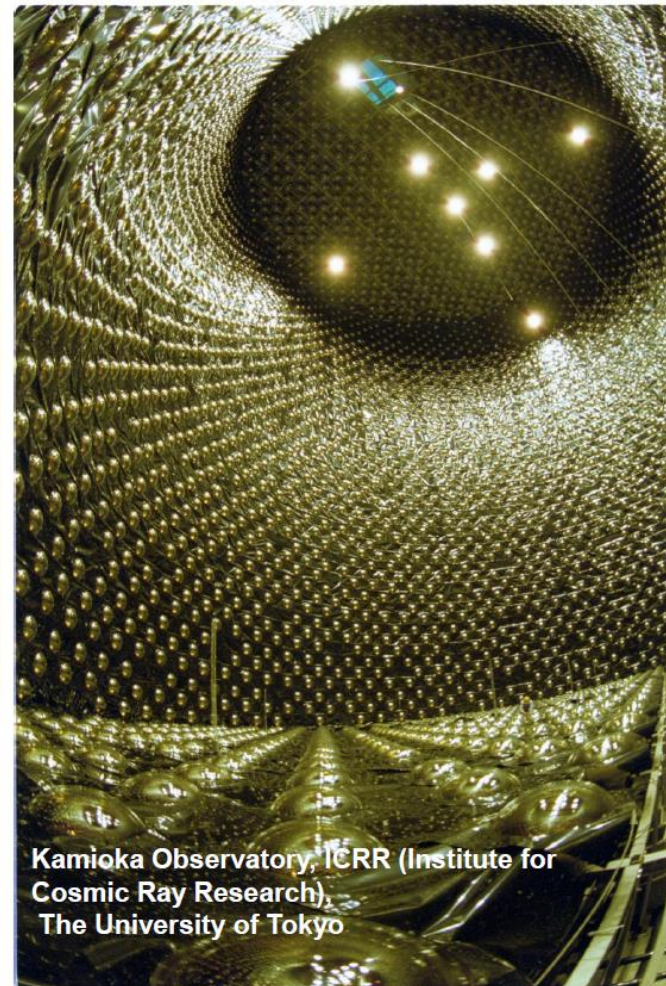
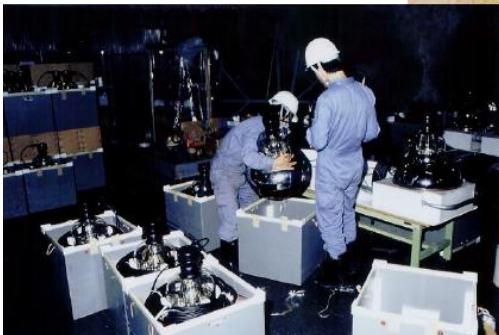
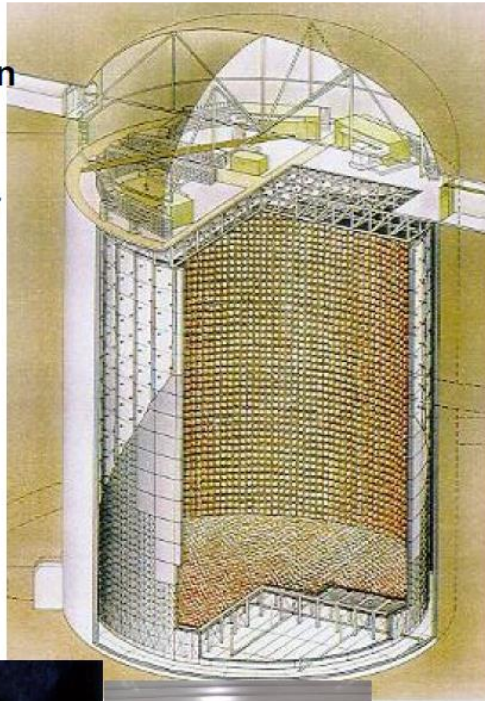
**Kamioka Mine in Japan**

➤ **1400m underground**

**50 ktons of pure water**  
(Fiducial volume for analysis 22.5 ktons)

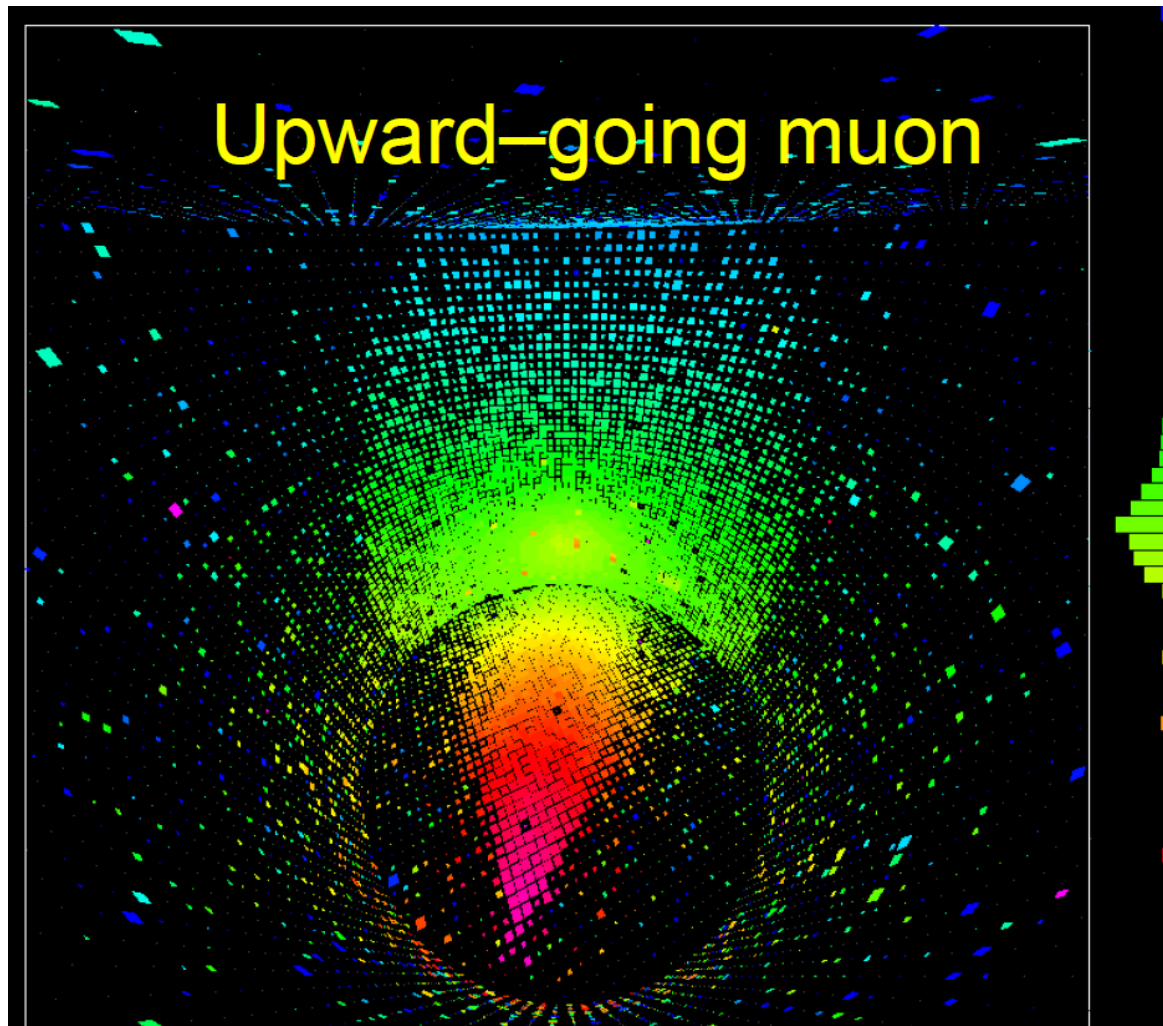
➤ **10,000 PMT inner detector**

➤ **2,000 PMT outer detector (cosmic ray veto)**



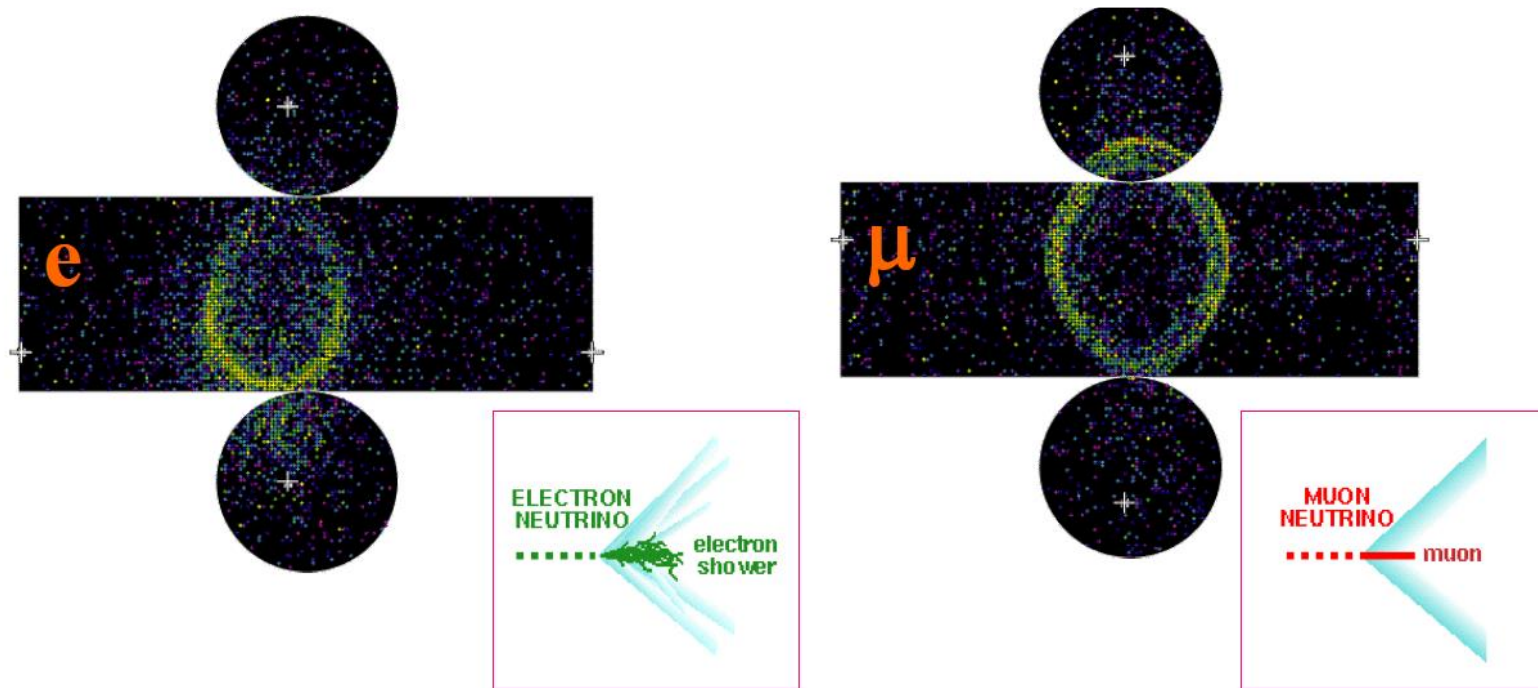
Kamioka Observatory, ICRR (Institute for Cosmic Ray Research),  
The University of Tokyo

# EVENT FROM SUPER-K





# ELECTRON AND MUON IDENTIFICATION

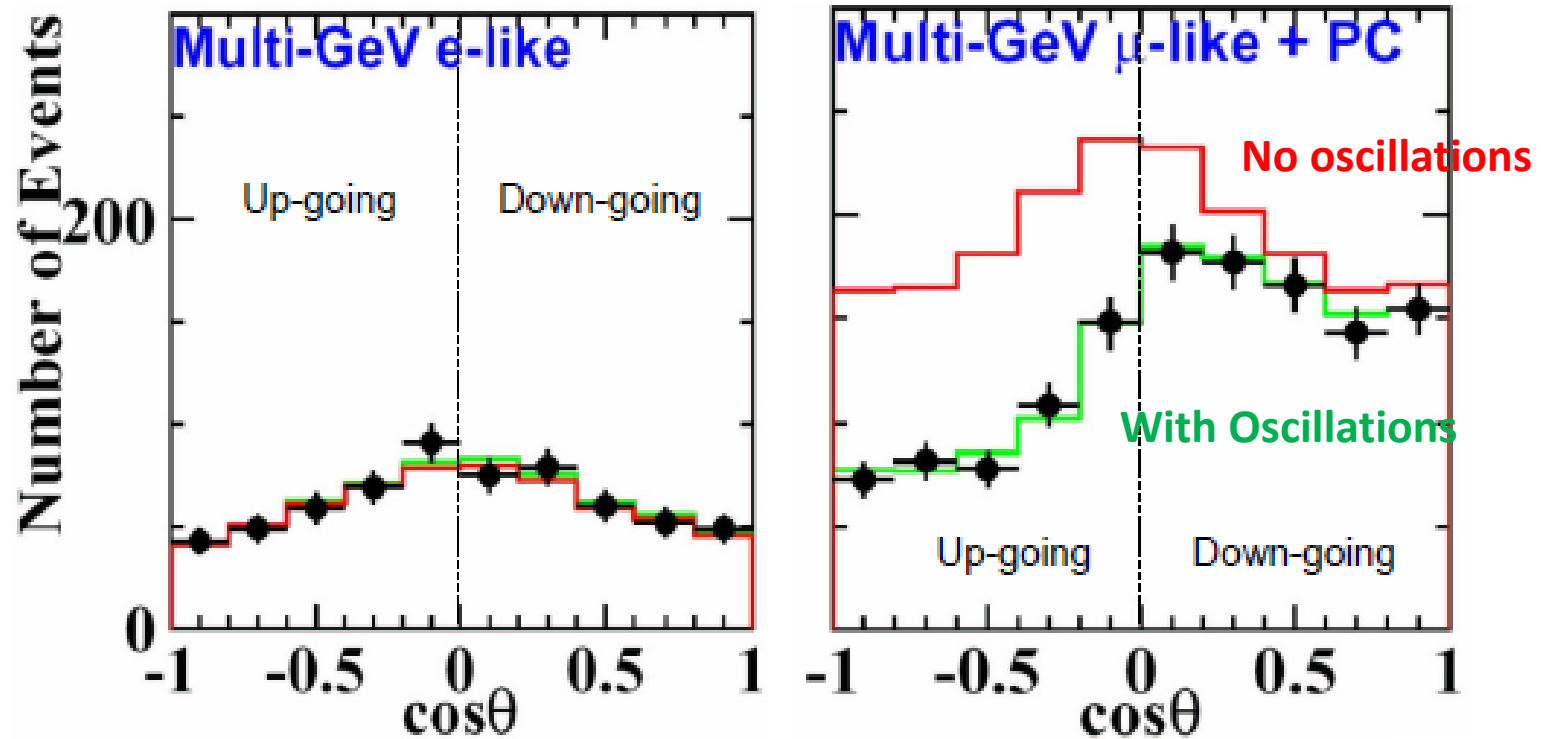


Electron ring is fuzzier than muon ring. Electron produces shower of gammas, electrons and positrons. Gammas don't produce Cherenkov light. Electrons and positrons do. In the shower each of them flies at a little bit different angle and each of them makes its own weak Cherenkov ring. All those rings added together produce the observed fuzzy ring. This difference in sharpness of muon and electron rings is used to identify muons and electrons in Super-Kamiokande.

From the Official SuperK WEBSITE: <http://www-sk.icrr.u-tokyo.ac.jp/doc/sk/index.html>

# NEUTRINOS OSCILLATE!

## Zenith angle Distribution



Half of the  $\nu_\mu$  are lost!

# NEUTRINO OSCILLATIONS

- The **time  $t$** , in an experiment looking for neutrino oscillations, is determined by the **distance** between the detector and the source of neutrinos.
- The probability that a neutrino with flavour 1 oscillate to flavour 2 can therefore be written as

$$P(\nu_1 \rightarrow \nu_2) = \sin^2(2\theta) \sin^2\left(1.27 \frac{\Delta m^2 L}{E_\nu}\right)$$

where

$\theta$  is the mixing angle between flavour 1 and 2

$L$  is the neutrino flight path in km

$E_\nu$  is the neutrino energy in GeV

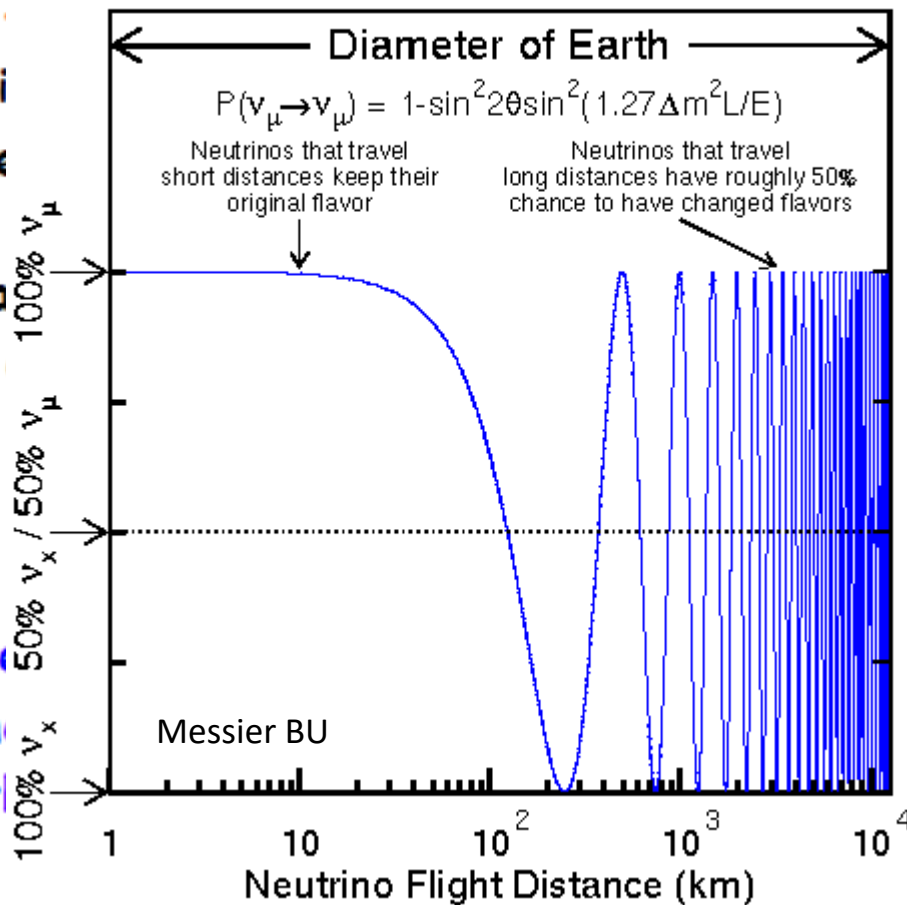
$\Delta m^2 = |m_1^2 - m_2^2|$  is the squared mass difference in  $\text{eV}^2$

# NEUTRINO OSCILLATIONS

- The time is determined by the source

- The probability of flavour 2

$\theta$  is the  
 $L$  is the  
 $E_\nu$  is the  
 $\Delta m^2 =$



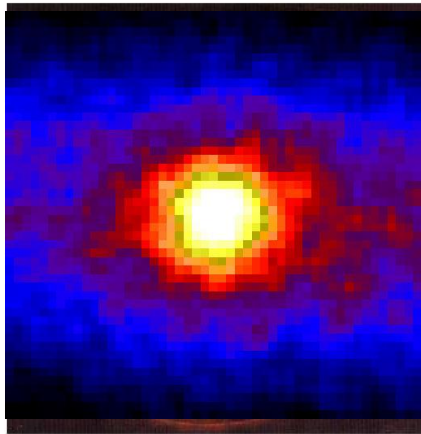
oscillations,  
 or and

late to

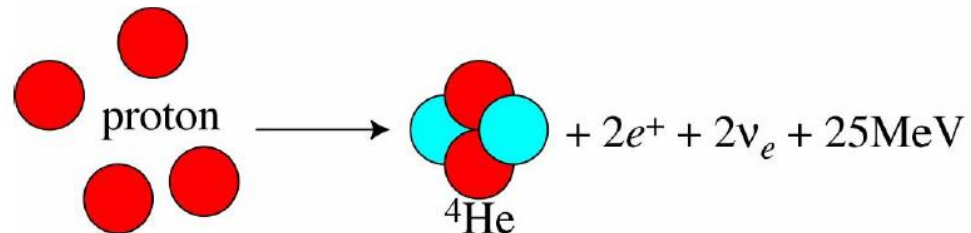
$E$  in  $\text{eV}^2$

# SOLAR NEUTRINOS

## The Standard Solar Model (SSM)



Hydrogen fusion in the Sun:



Observables:

- Mass
- Luminosity
- Radius,
- Metal content of the photosphere
- Age

Inferences on solar interior ( $\rho$ ,  $P$ ,  $T$ )

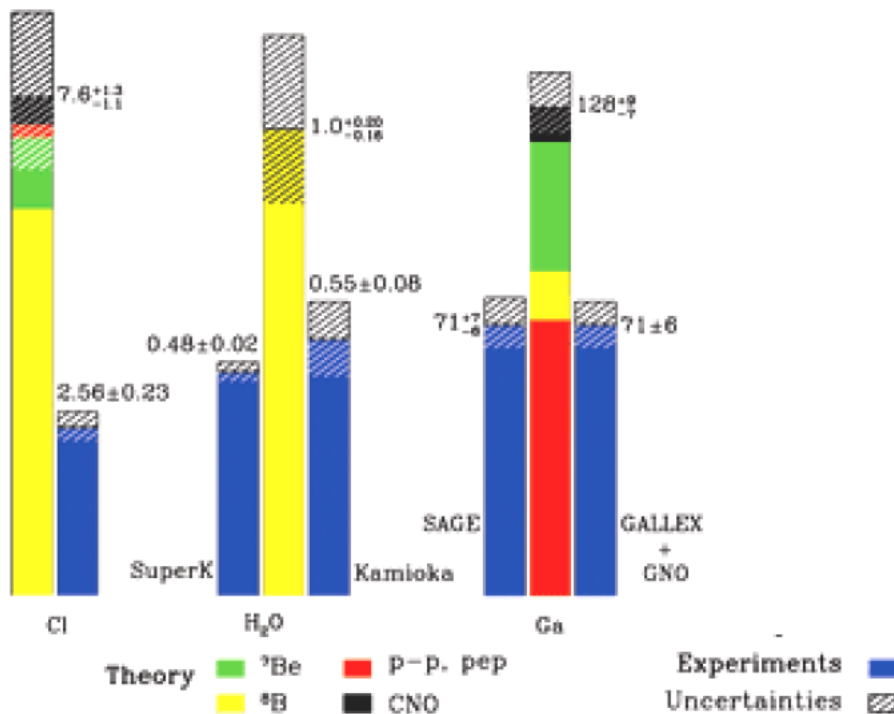
SSM describes the evolution of an initially homogeneous solar mass  $M_0$  up to the sun age  $t$  so as to reproduce  $L_0$ ,  $R_0$  and  $(Z/X)_{\text{photo}}$

⇒ Predicts solar neutrino flux (intensity and spectrum)

# SOLAR NEUTRINO PROBLEM

- We see too few!

Total Rates: Standard Model vs. Experiment  
Bahcall-Pinsonneault 2000



What can be wrong?

- Sun model
- Experiments
- $\nu$  propagation from SUN to Earth

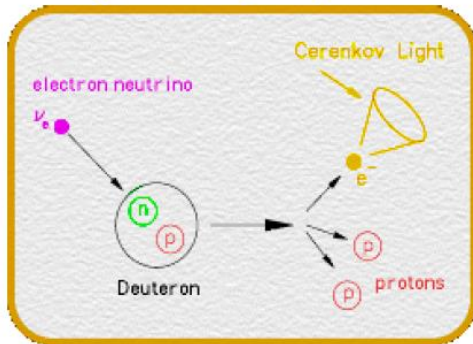
>30 years of debate!

Also this could be explained by  $\nu$  oscillations



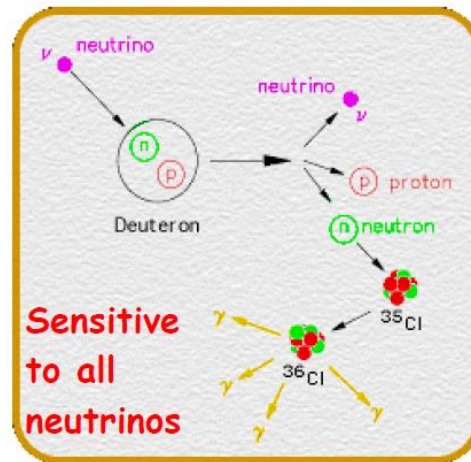
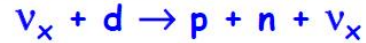
The SNO experiment measures neutrinos in three ways:

### Charged current reactions



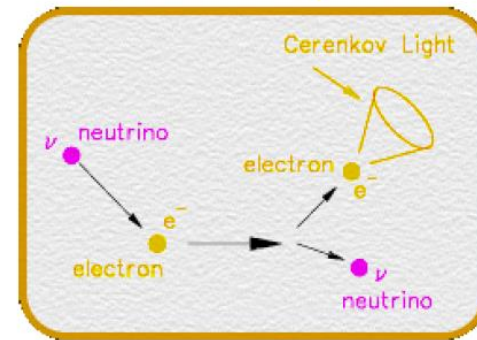
The amount of Cerenkov light and the pattern of photo multipliers with a signal could be used to determine the neutrino energy and direction. This process was **only sensitive to electron neutrinos**.

### Neutral current reactions



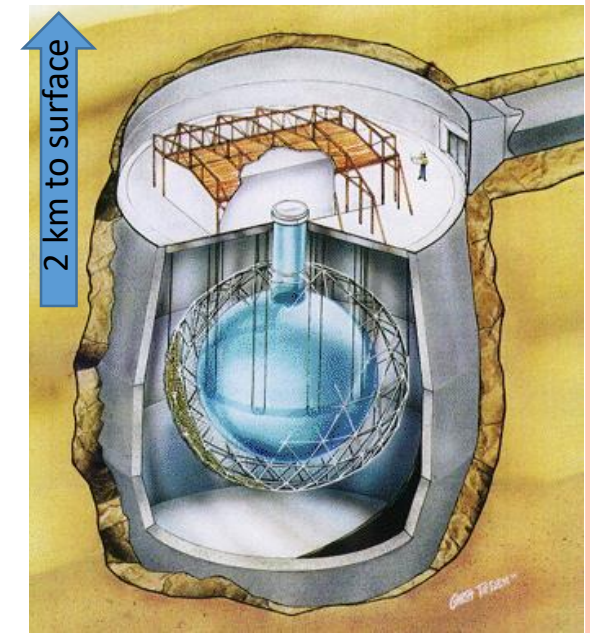
The photons would Compton scatter electrons that would produce Cerenkov lights. Proportional counters in the water was also used to measure this process directly.

### Electron scattering



This process was **mostly sensitive to electron neutrinos**.

## SNO EXPERIMENT



# SNO EXPERIMENT

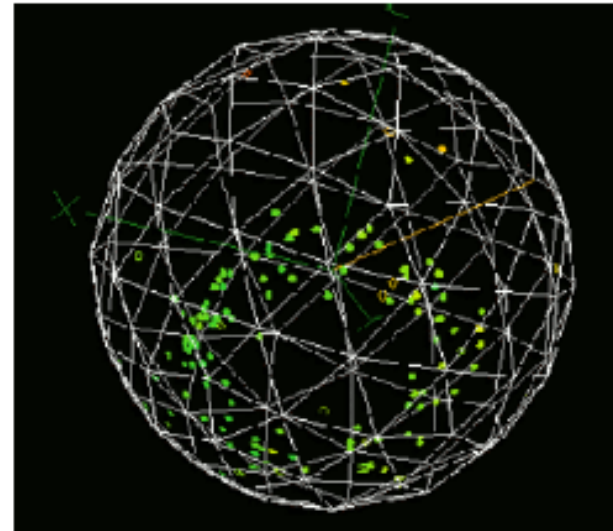
- The difference between the SNO experiment and other previous experiments was that it could **measure** both the **electron neutrino flux** and the **total neutrino flux**.

- **Neutral** current measurement:

$$\frac{\text{Measured total neutrino flux}}{\text{Predicted total neutrino flux}} = 1.01 \pm 0.12$$

- **Charged** current measurement:

$$\frac{\text{Measured electron neutrino flux}}{\text{Predicted electron neutrino flux}} = 0.35 \pm 0.02$$



- The conclusion was that the **solar model** was **correct** and that the missing electron neutrinos were due to neutrino oscillations.
- The results combined with other experiments gave:

$$\Delta m^2 = 7.6 \times 10^{-5} \text{ eV}^2$$
$$\tan^2(\theta) = 0.468$$

# OSCILLATIONS WITH THREE FLAVORS

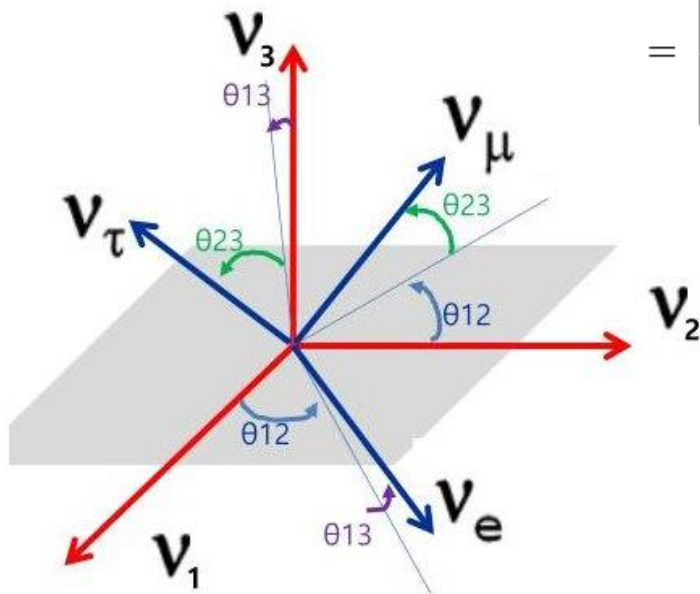
Can be written as three separate rotations

$$|\nu_\ell\rangle = U |\nu_\tau\rangle$$

where

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (c=\cos, s=\sin)$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$



CP-violating phases!

What about the charged leptons?

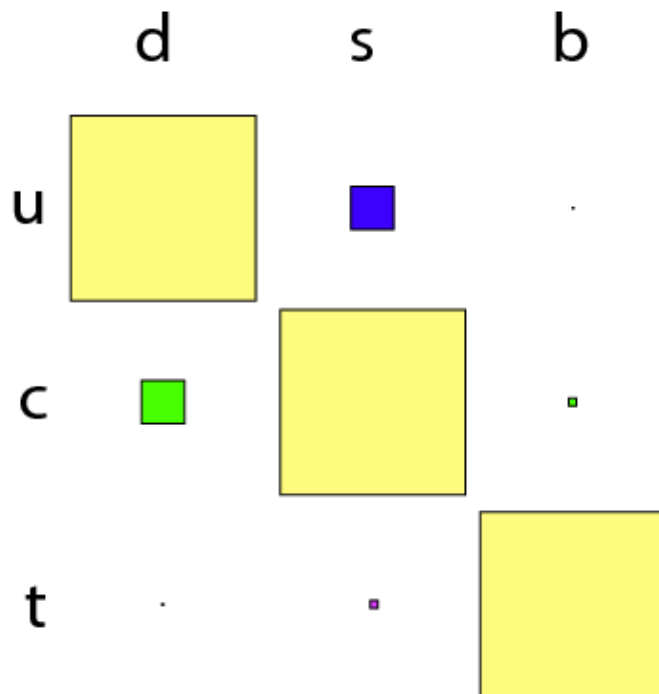
Given the violation of lepton flavor number in (long baseline) neutrino interactions, expect to see lepton number violation also in the charged sector – no evidence of that yet.

(However, see [arXiv:1704.05435](https://arxiv.org/abs/1704.05435) for interpretation of LHCb result)

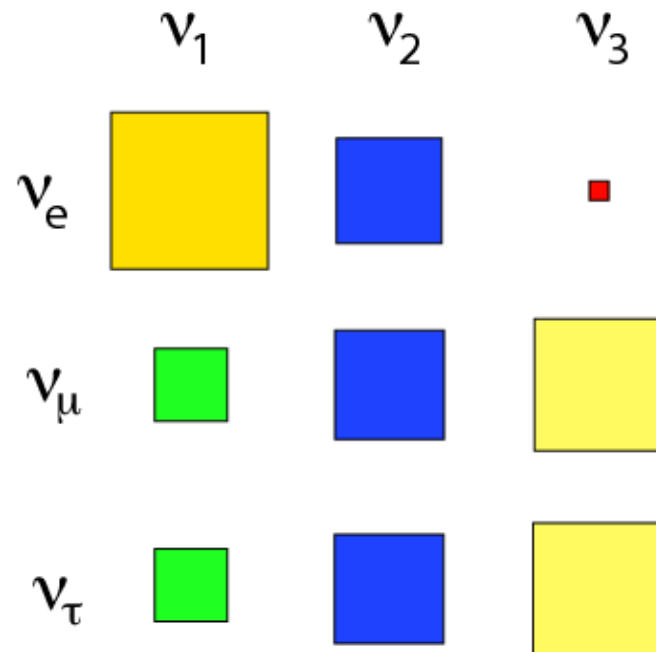
# PMNS MATRIX (PONTECORVO-MAKI-NAKAGAWA-SAKATA)

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} 0.82 \pm 0.01 & 0.54 \pm 0.02 & 0.15 \pm 0.03 \\ 0.35 \pm 0.06 & 0.70 \pm 0.06 & 0.62 \pm 0.06 \\ 0.44 \pm 0.06 & 0.45 \pm 0.06 & 0.77 \pm 0.06 \end{bmatrix}$$

CKM



PMNS





# What we have learnt from mixing: neutrino mass lower bound

Weak eigenstates  $\nu_e, \nu_\mu, \nu_\tau$  superposition of mass eigenstates  $\nu_1, \nu_2, \nu_3$   
numbered in increasing order of  $\nu_e$  content, given by  $|U_{ei}|^2$  (shown in red in figure)

$\nu_1 \sim 70\% \nu_e, \nu_2 \sim 30\% \nu_e, \nu_3 \sim 2.5\% \nu_e$

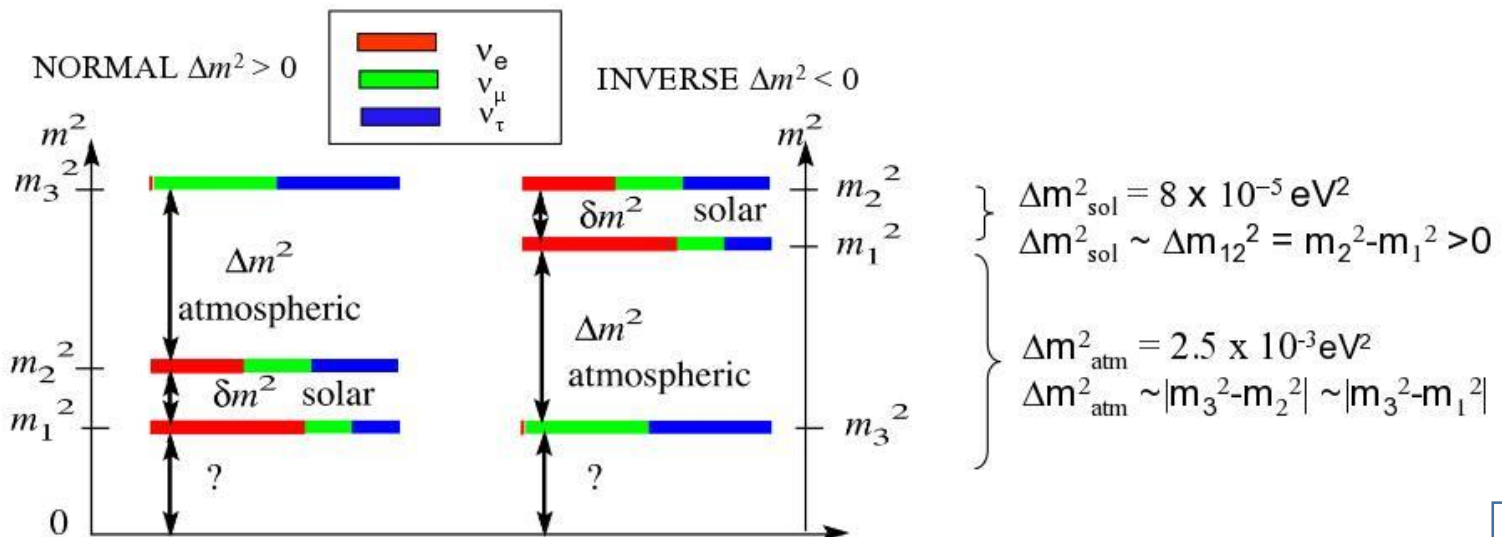
- What is the absolute value of neutrino masses?

Neutrino oscillation experiments can measure only mass differences.

However note that  $\Delta m_{\text{atm}}^2 \sim 2.5 \cdot 10^{-3} \text{ eV}^2$

$\Rightarrow$  at least one neutrino with mass  $> \sqrt{\Delta m_{23}^2} \sim 50 \text{ meV}$

Is it  $m_2$  or  $m_3$ ? Depends on the mass hierarchy!



**Neutrinos oscillate  $\Rightarrow$  they must have non-zero ( different ) masses**

# NEUTRINO MASS

- One of the major question in particle physics is if neutrinos have a mass. Attempts at **direct measurement** of the **neutrino mass** has only produced upper limits.

- Direct measurement of the  $\nu_e$  mass using  **$\beta$ -spectrum**:

$$m_\nu < 2.1 \text{ eV}$$

- Direct measurement of the  $\nu_\mu$  mass using **pion decays at rest** ( $\pi^+ \rightarrow \mu^+ + \nu_\mu$ ):

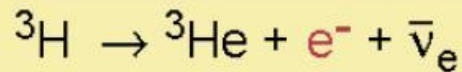
$$m_\nu < 170 \text{ keV}$$

- Direct measurement of the  $\nu_\tau$  mass using  **$Z^0 \rightarrow \tau^+ \tau^-$**  at LEP:

$$m_\nu < 18.2 \text{ MeV}$$

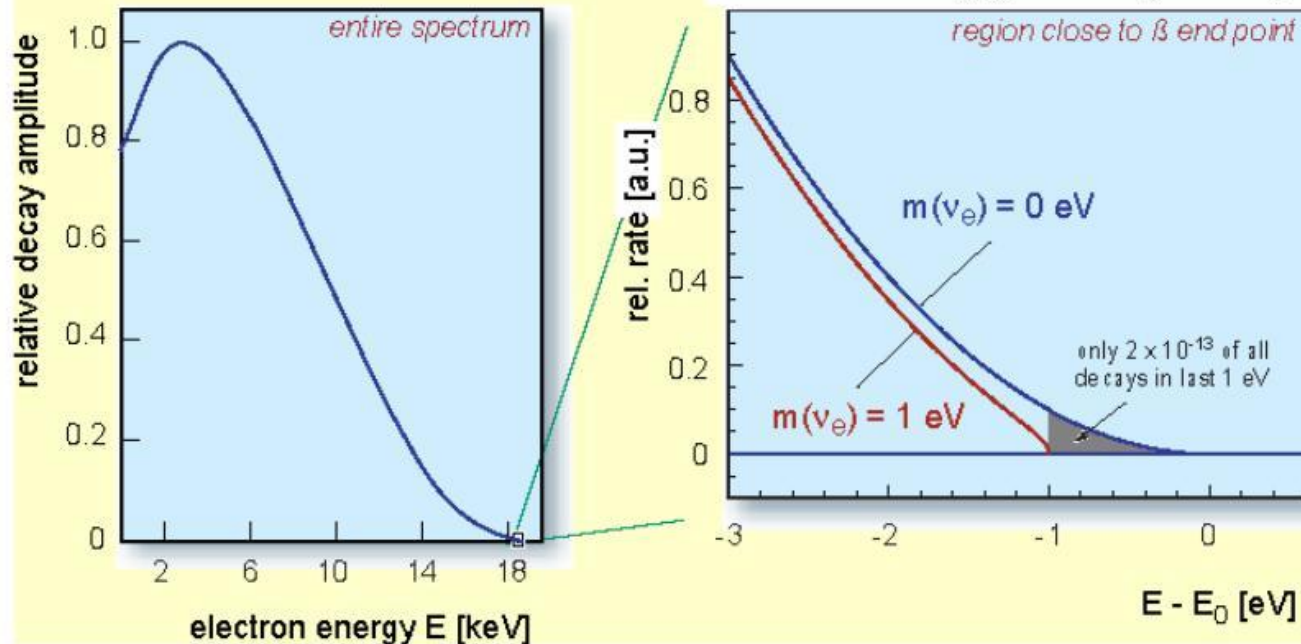
# Direct Mass Measurement in $\beta$ decay

## tritium $\beta$ -decay and the neutrino rest mass



*superaallowed*

- Neutrino mass modifies the shape of the electron spectrum.
- Challenge: determination of shape and absolute energy in the few eV below the endpoint energy  $E_0 = 18.57$  keV with O(1eV) precision or better. Needs excellent control of resolution, absolute scale and background
- Current limit  $m(\nu_e) < 2.2$  eV (95% CL) by “Mainz” experiment



# DIRAC OR MAJORANA PARTICLE?

- Dirac particles: (SM) The known spin  $\frac{1}{2}$  fermions
  - Fulfills Dirac eqn  $i\hbar\gamma^\mu\partial_\mu\psi - mc\psi = 0$
  - Lepton number would be conserved
- Majorana particles:
  - Particle = anti-particle (ex:  $\gamma$ ,  $Z^0$ ,  $\pi^0$  . But not  $n$ ,  $K^0$ )
  - Lepton number would not be conserved
- How come we don't know?!
  - We observe only  $\nu_L$  and anti- $\nu_R$  so cannot compare same polarization directly.
  - For inst:
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$  Left-handed always       $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$  Right-handed always
  - Is the different interaction due to different polarization, or real  $\nu - \bar{\nu}$  difference?
  - If  $m_\nu \equiv 0$  we wouldn't care



# GENERATING NEUTRINO MASS

Standard Higgs  
mechanism!



- **Dirac mass term:**  $\mathcal{L} = m_D (\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$  i.e. need both L and R fields! Thus,  $m_\nu \equiv 0$  in the SM
- **Majorana v:**  $\nu$  and anti- $\nu$  different states of same particle  $\Rightarrow$  Both Dirac and Majorana mass terms:

$$(\psi_L \quad \bar{\psi}_L^c) \begin{bmatrix} m_L & m_D \\ m_D & m_R \end{bmatrix} \begin{pmatrix} \psi_R^c \\ \psi_R \end{pmatrix}$$

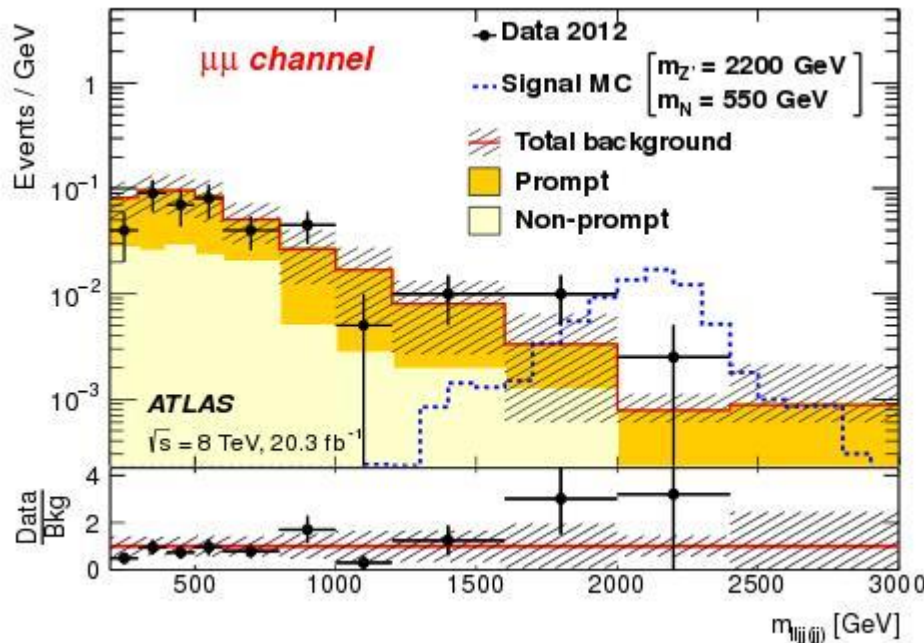
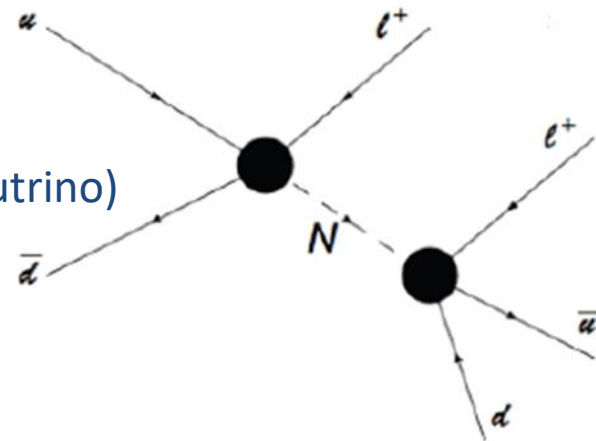
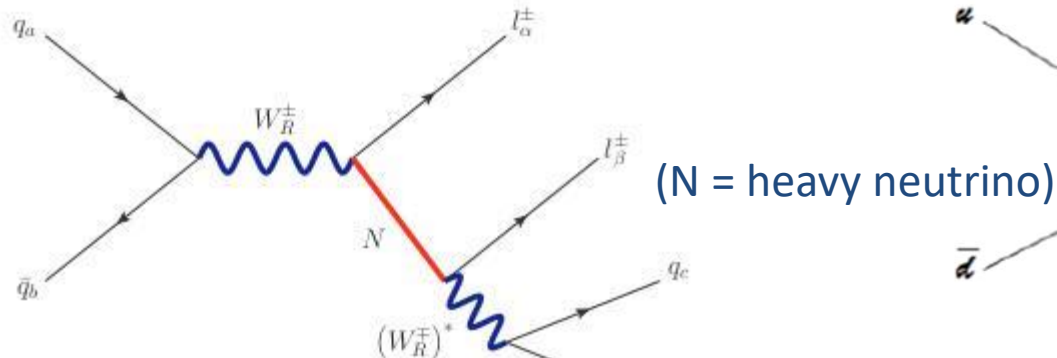
**See-saw mechanism:**  $m_L=0$ ,  $m_R \gg m_D$  ie  $\begin{bmatrix} 0 & m_\nu \\ m_\nu & M_R \end{bmatrix}$

Diagonalization of matrix gives 2 mass eigenstates/  
flavor:

- $M_{\text{light}} = m_\nu^2 / M$ , *mostly L-handed*
- $M_{\text{heavy}} \cong M$ , *mostly R-handed* (not yet observed due to its large mass)

# SEARCHES FOR MAJORANA NEUTRINOS @ THE LHC AND HEAVY NEUTRINOS

Reconstruct in cascade with  $W_R$  or Effective lagrangian operators



Signature is same-sign dileptons and jets  
 (if the nature of N is Dirac, instead opposite-sign leptons)

Current mass limit on N is  $\sim 2$  TeV<sup>26</sup>

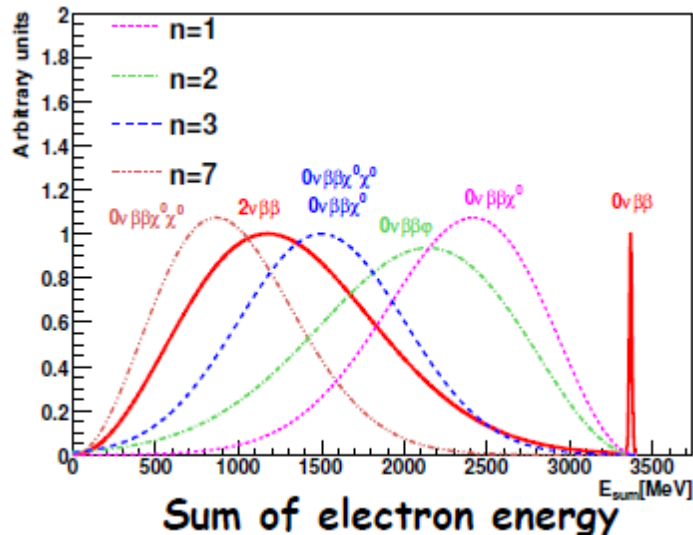
# SEARCHES FOR NEUTRINO-LESS DOUBLE BETA DECAY

Several dedicated experiments: NEMO, SNO, EXO, KamLAND etc

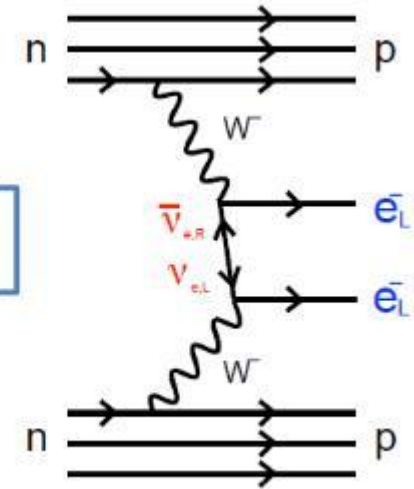
Several sensitive to lepton flavor violation in general

Certain radioactive isotopes: single  $\beta$  decay forbidden  
Should then be possible to see double  $\beta$  decay if it exists

Current limits say  $m_{\beta\beta} < 250\text{-}300\text{ meV}$



$$0\nu\beta\beta$$



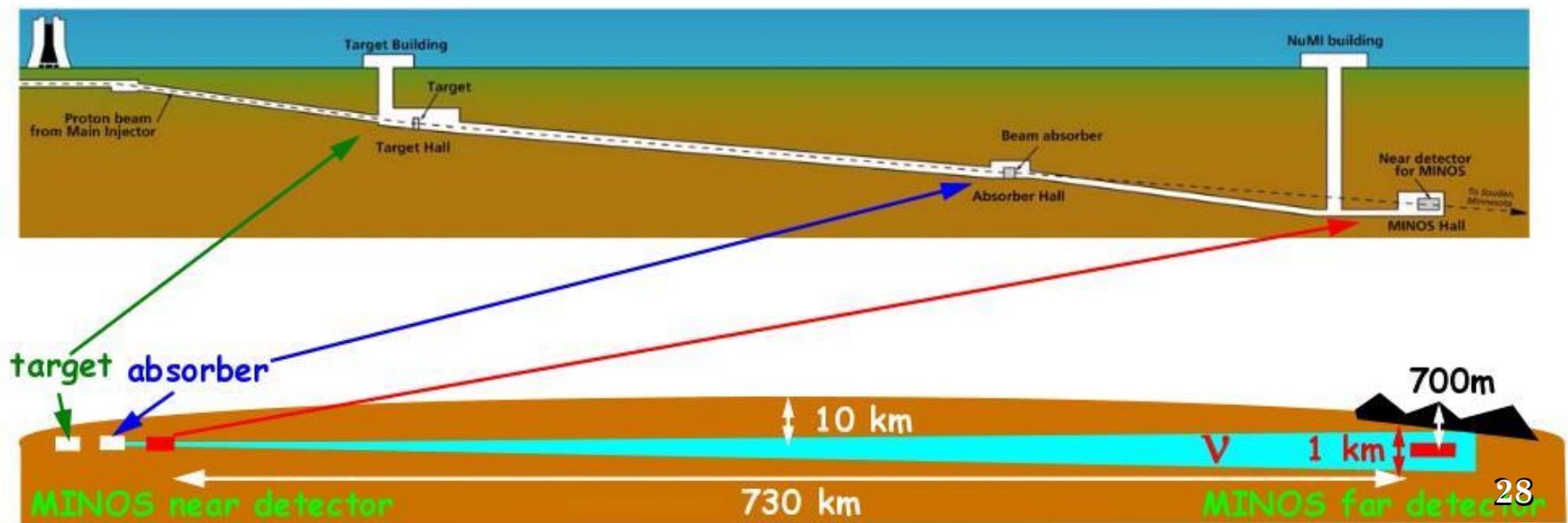
The neutrino-less version would  
Indicate Majorana neutrinos!  
(and lepton flavor violation)

# Long baseline neutrino experiments

- If an experiment is located hundreds of kilometers away from the target one is talking about a **long baseline experiment**.

➡ The NuMI beam from Fermilab

- One such a facility is the **NuMI beam** created at **Fermilab** and pointing at experiments situated in mines some **730 km** away.

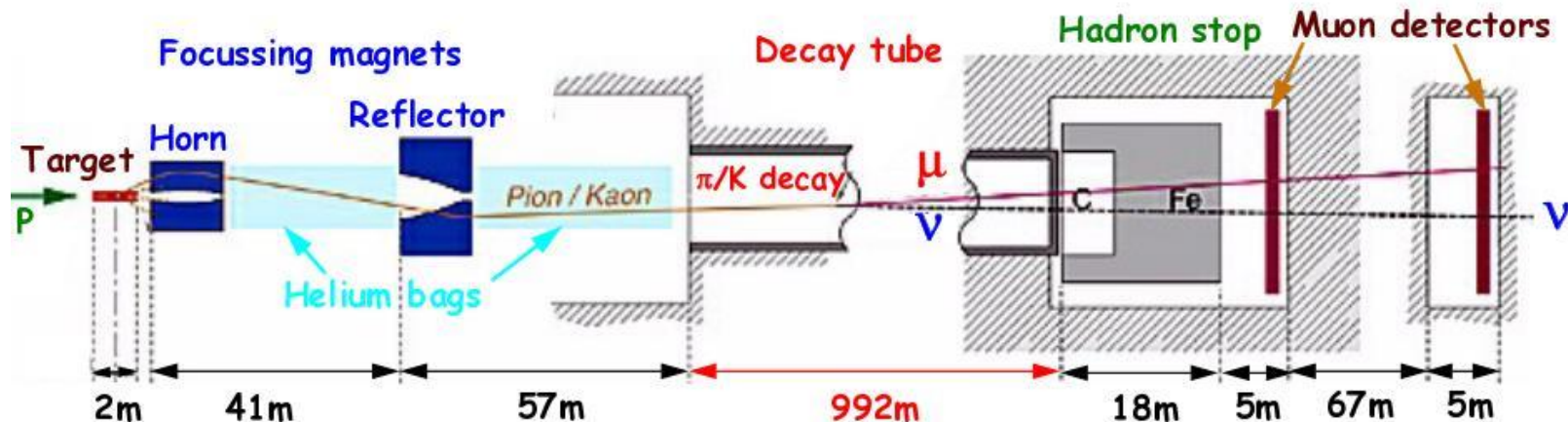




# Long baseline neutrino experiments

## ➔ CNGS - CERN Neutrinos to Gran Sasso

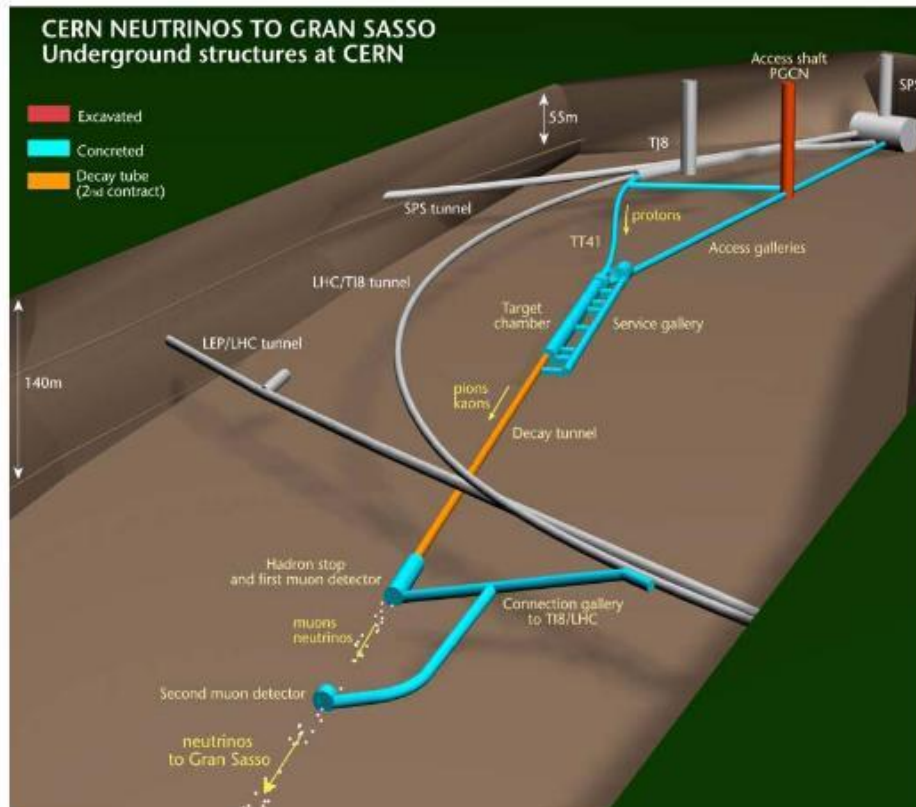
- The Kamiokande and Minos measurements are example of disappearance studies, i.e., one looks for the **disappearance of  $\nu_\mu$** .
- Much more difficult are **appearance measurements** in which one looks for  $\nu_\tau$  to appear in a  $\nu_\mu$  beam.
- The layout of the **CNGS neutrino facility** at CERN is shown below:



# Long baseline neutrino experiments

## ➡ CNGS - CERN Neutrinos to Gran Sasso

- CNGS at CERN shoots neutrinos on experiments located 732 km away in Italy.

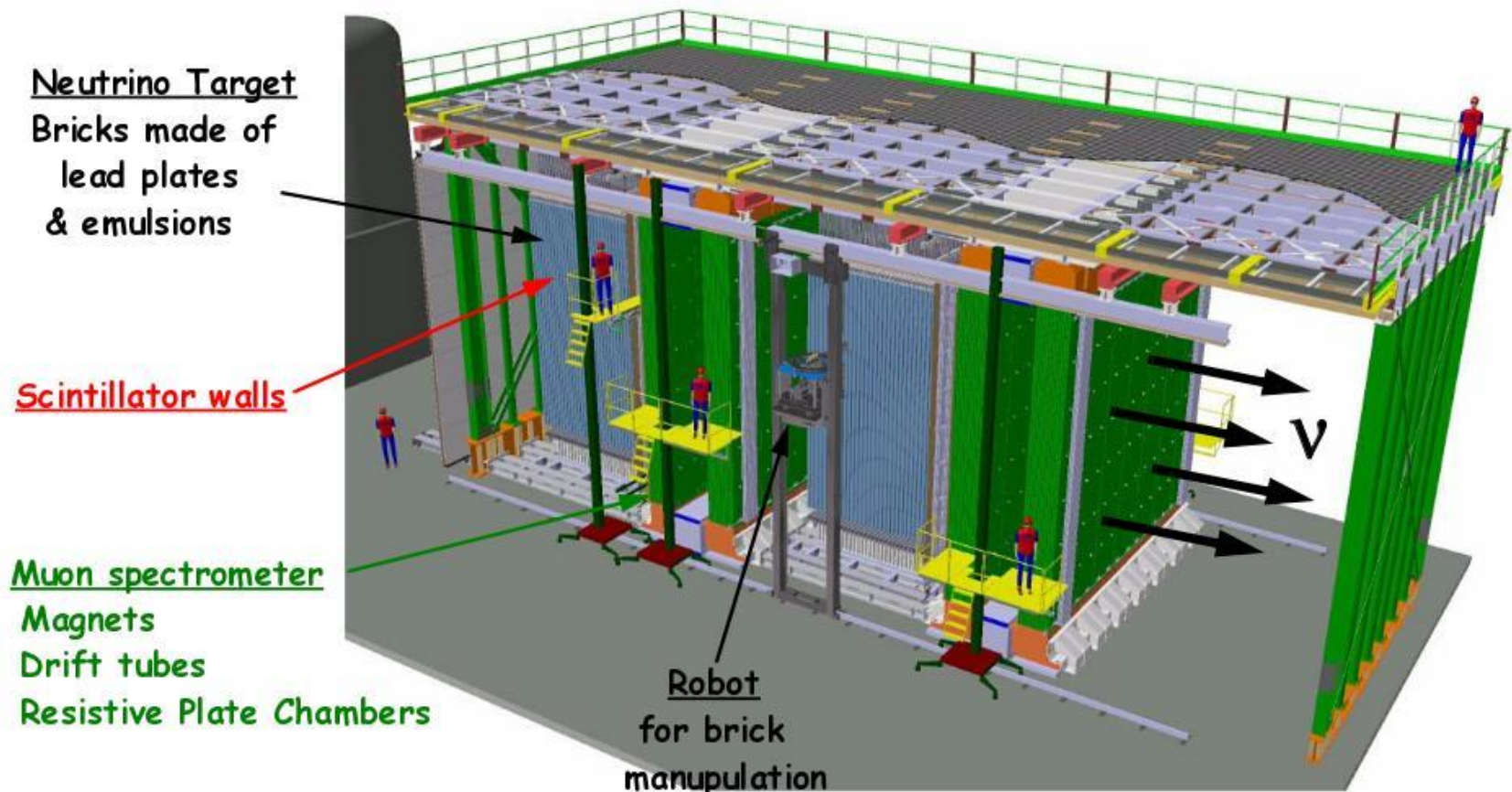




# OPERA

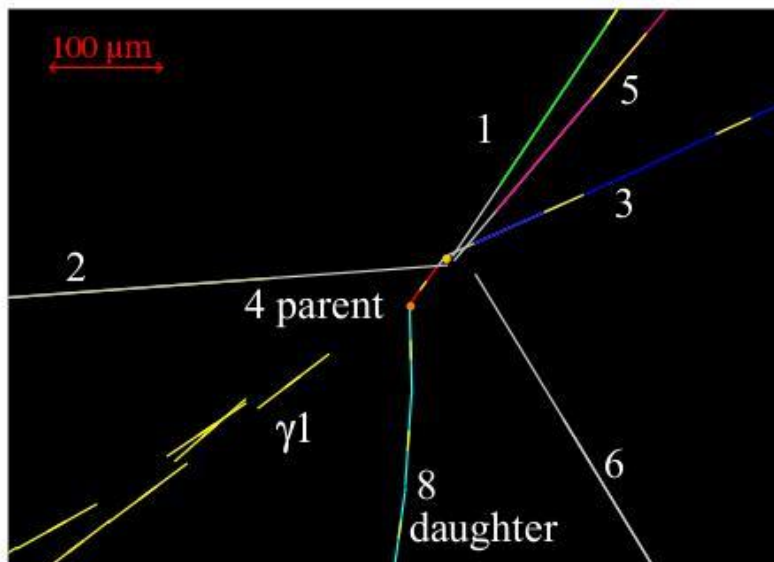
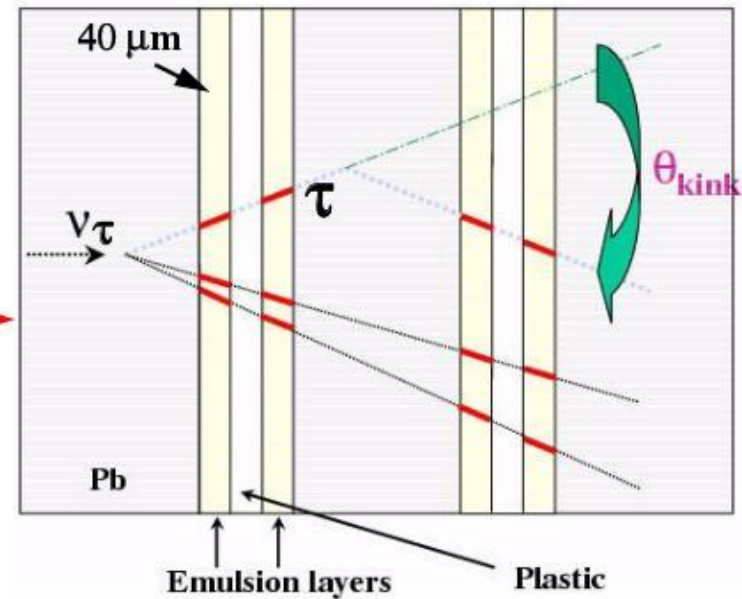
## → The OPERA experiment

- The Opera experiment is using **photographic emulsions** to look for  $\nu_\tau$ .



# OPERA

- The experiment is looking for **events with kinks** which show that tau neutrinos have interacted with the lead plates. **2-3  $\nu_\tau$  events per year** are expected if oscillation occur.



*Five*

- ~~Two~~ candidates for  $\nu_\tau$  events have so far **been observed.**

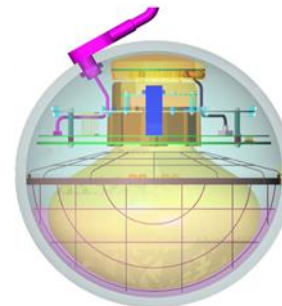
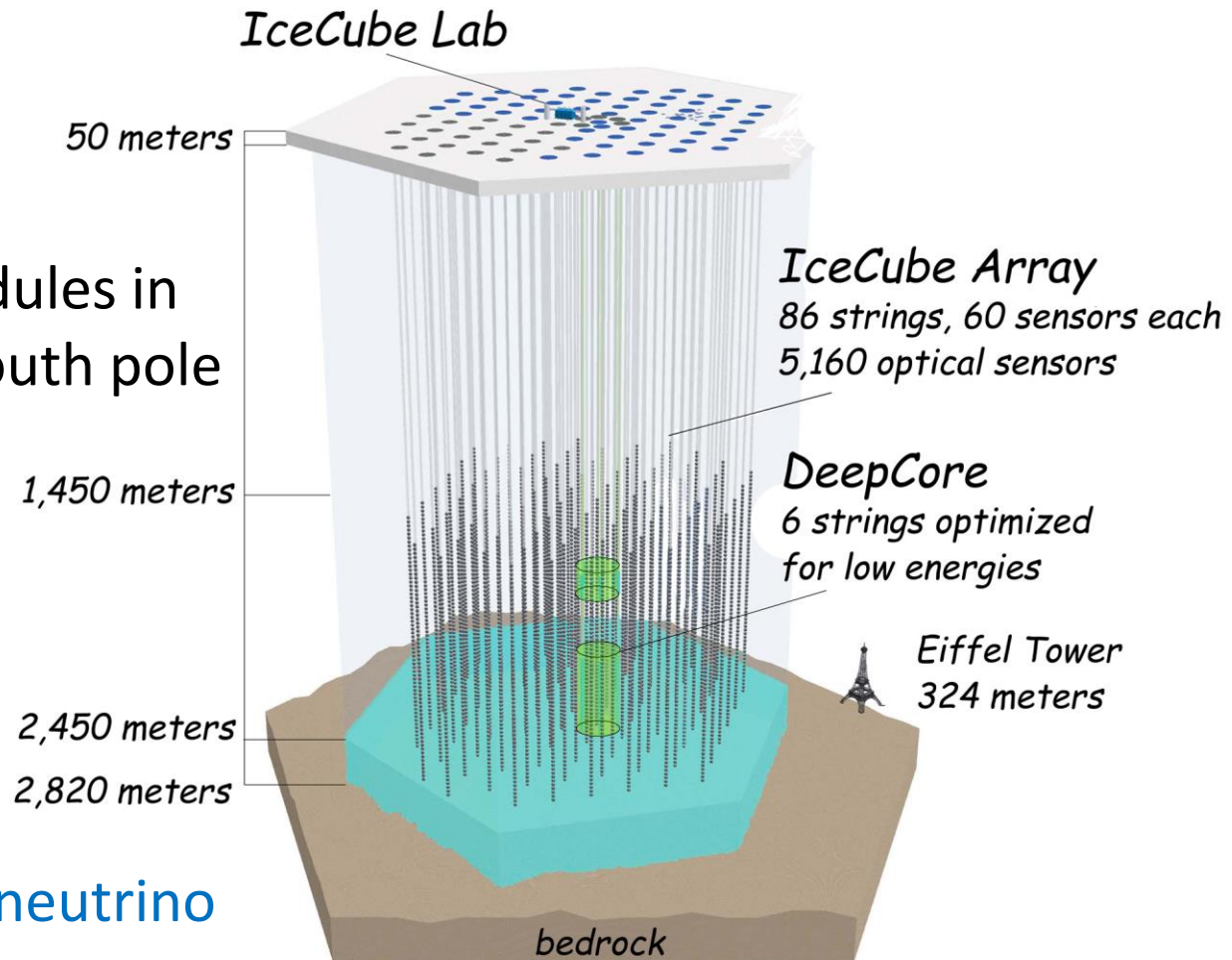


# ICECUBE

Strings of optical modules in  
holes drilled in the South pole  
ice

The clear ice acts as  
Cherenkov medium

- Measurements of neutrino oscillations
- Astrophysical fluxes
- Searches for dark matter and extra galactic neutrinos



**Digital  
Optical  
Module**



# The IceCube Neutrino Observatory



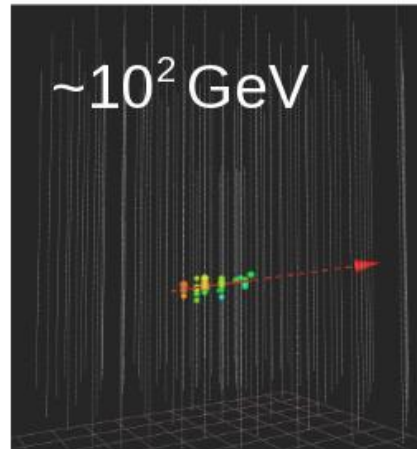
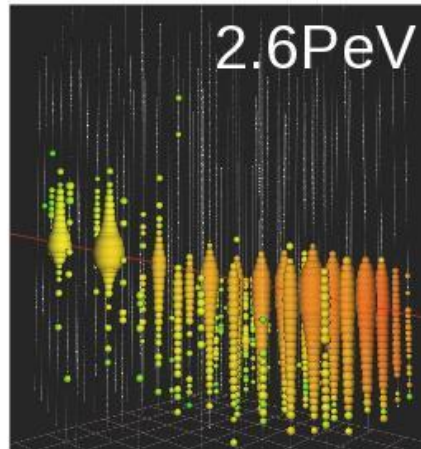
# ICECUBE

## *Event Signatures*

### Tracks

CC:  $\nu_{\mu} \rightarrow \mu$

elongated  
far ranged



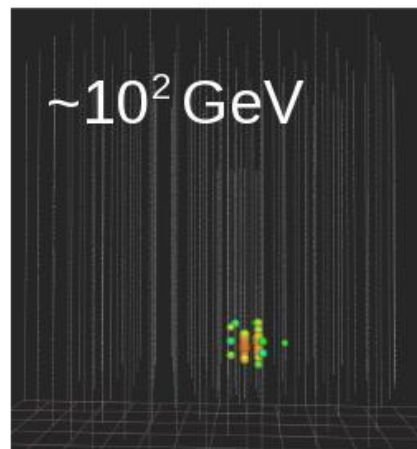
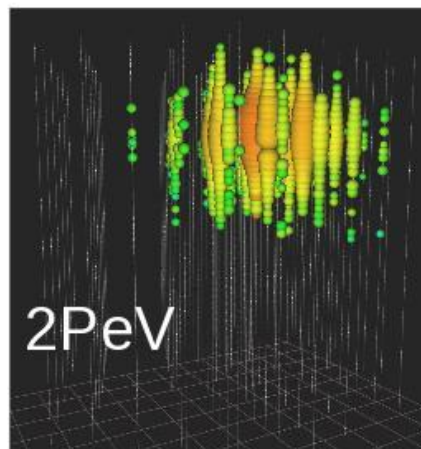
Pointing ( $\sim 3^\circ$ )  
Up-going  $\nu$ -pure  
Extended eff. Vol.

### Cascades

CC:  $\nu \rightarrow e, \tau$

NC:  $\nu \rightarrow \nu'$   
all flavor

spherical  
localized

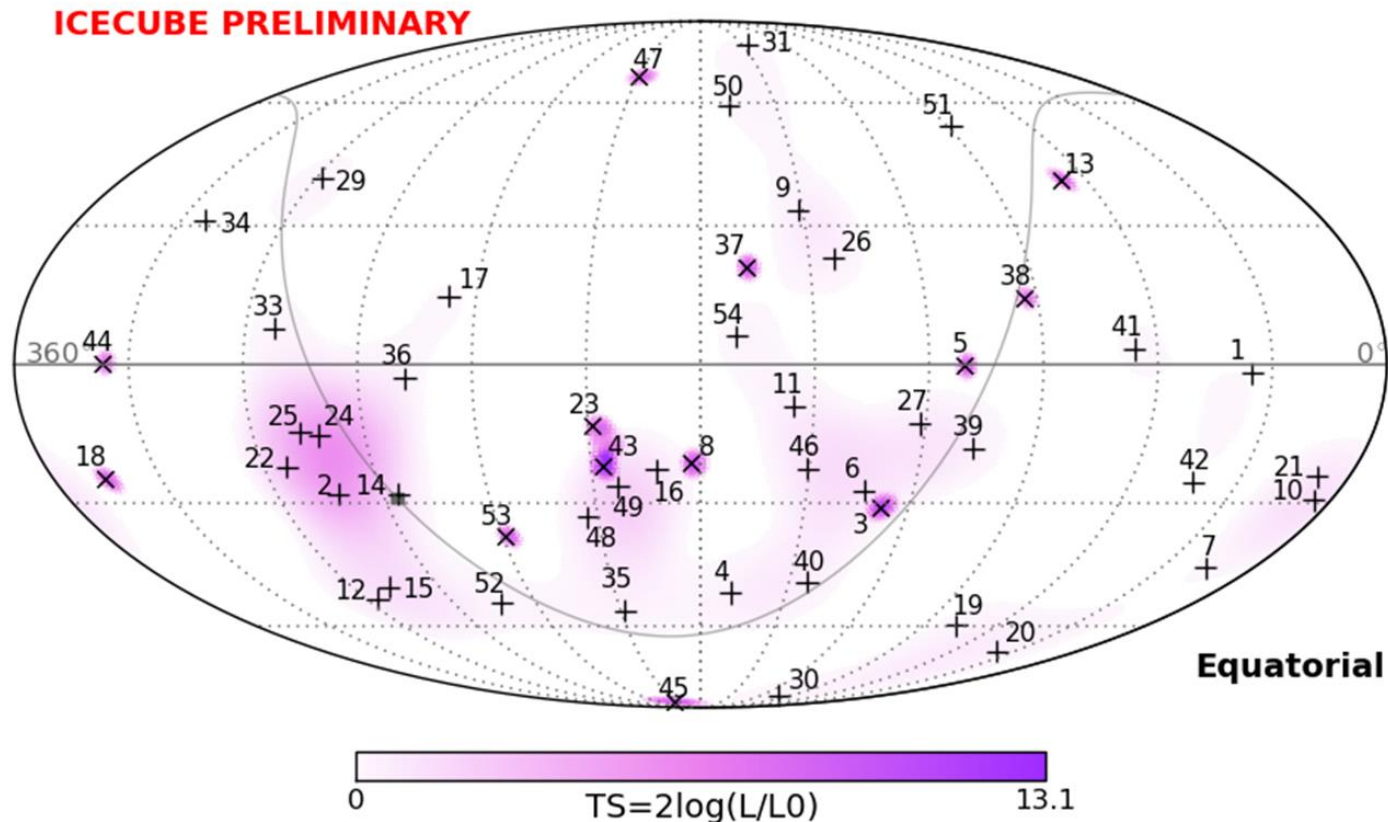


Limited pointing  
( $30^\circ$ - $15^\circ$  degree)  
Good Energy est.  
Plentiful,  
because NC+CC



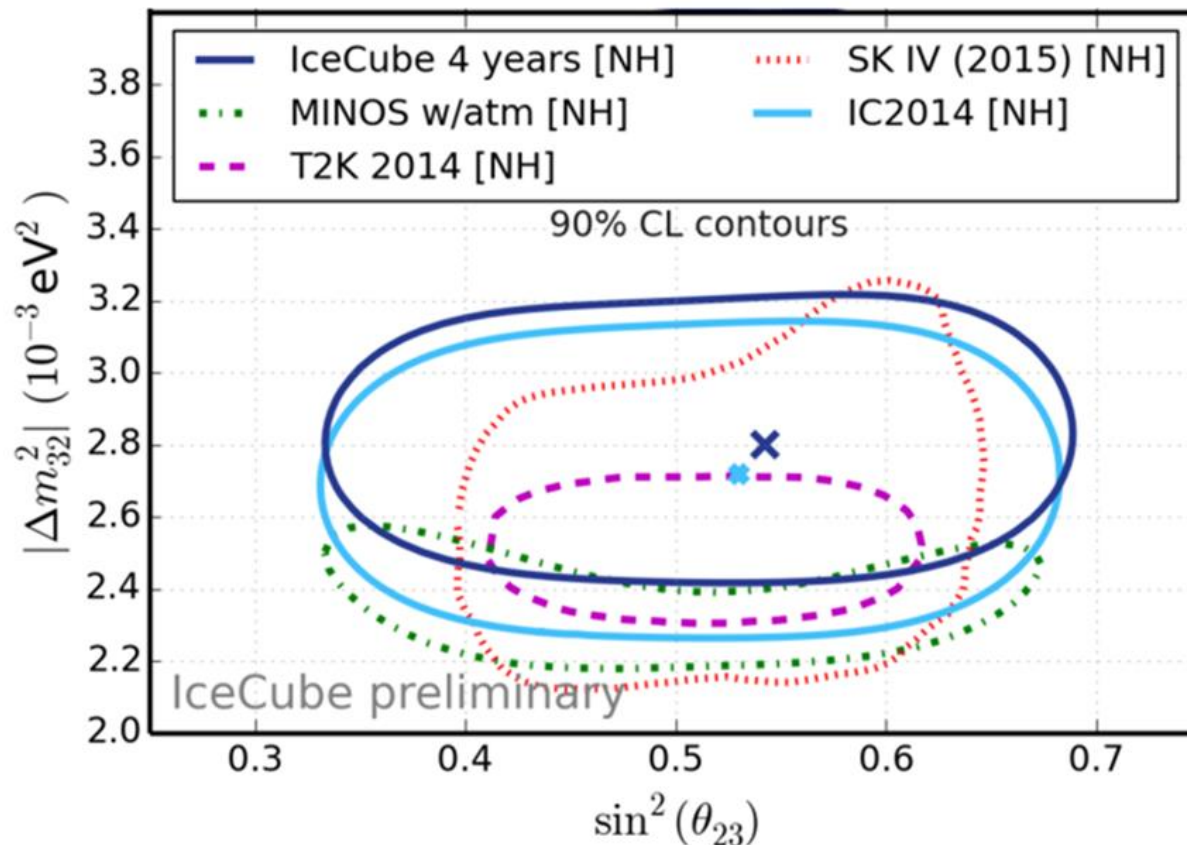
# SOME ICECUBE RESULTS

- Astrophysical neutrinos
- No point sources found, limits on gamma ray bursts



# NEUTRINO OSCILLATIONS

- Precision similar to the dedicated oscillations experiments





# CONCLUSIONS

- Neutrinos have (had) many surprises in store for us
- We already have evidence for physics beyond the SM in the neutrino sector!
- Measurements often requires dedicated experiments
  - - but the neutrino experiments can tell us about much more than just neutrinos (such as dark matter, astrophysics, proton decay etc)
- Many unanswered questions, for instance:
  - Are there more neutrinos? Right-handed neutrinos, Majorana or sterile neutrinos.
  - What is the mass hierarchy?