FYST17 LECTURE 3
NEUTRINOS

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

TODAY:

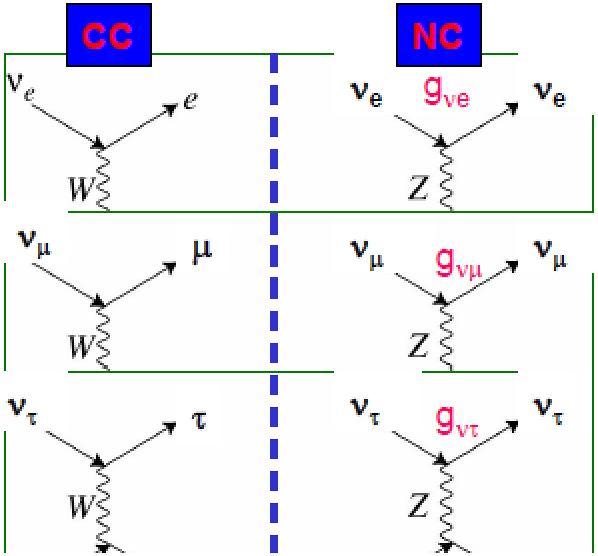
- Neutrinos and their discovery
- Atmospheric neutrinos
- Solar neutrinos
- Neutrino oscillations
- Neutrino mass
  - The nature of neutrinos
- Searches for exotic neutrinos
- Long baseline experiments

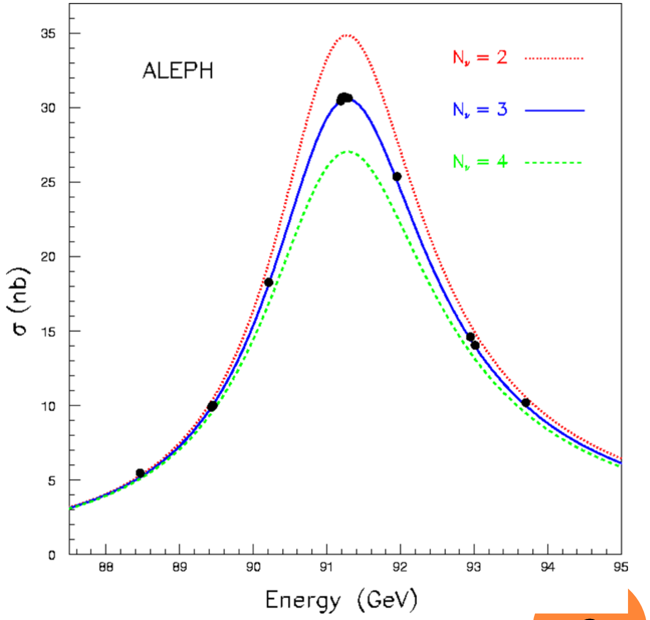
NEUTRINOS

ν_e ν_μ ν_τ

- 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:

ν's come in three (active) flavors



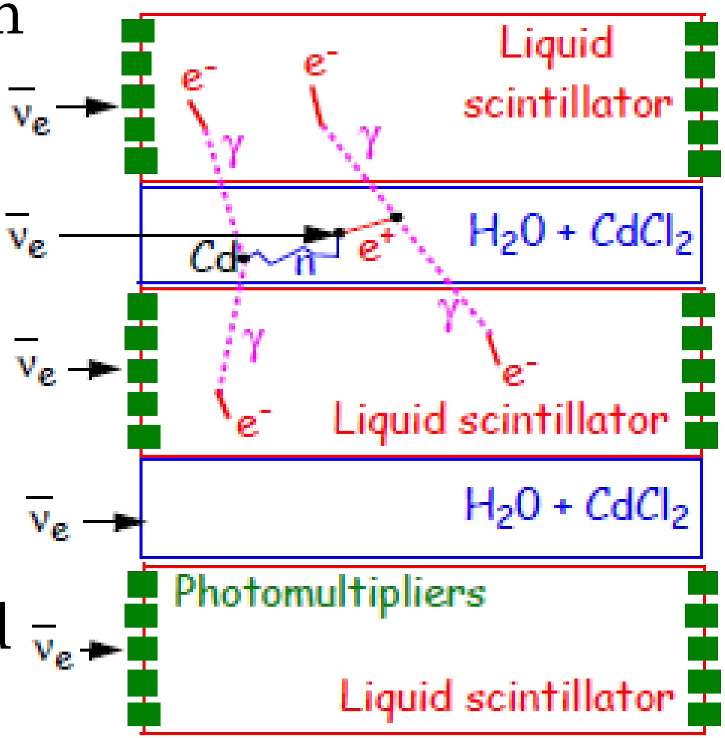


DISCOVERY OF (ANTI) ν_E 1956

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

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

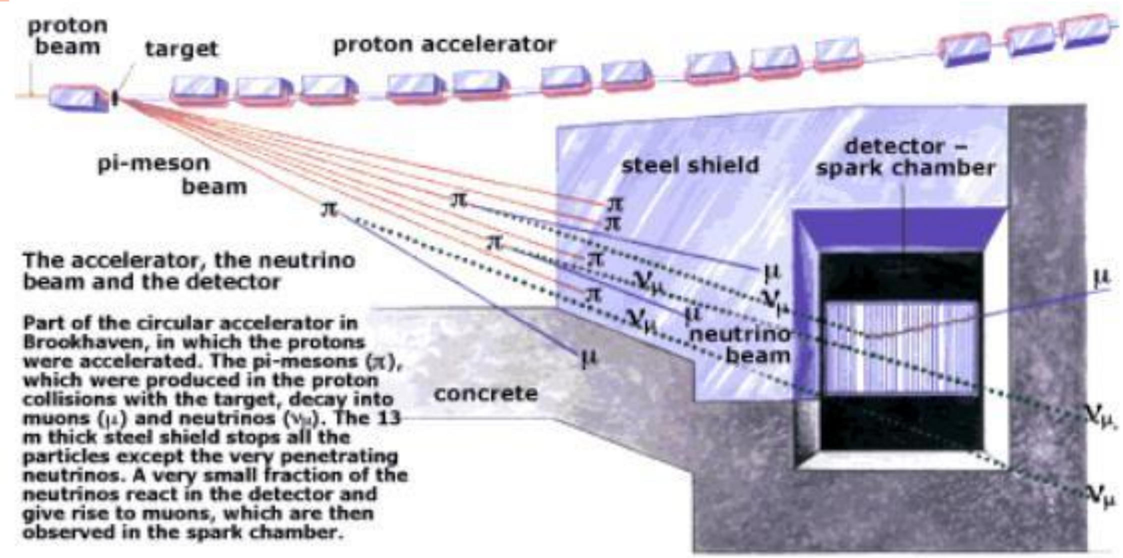
- And then detect the ν's via
  - $\bar{\nu}_e + p \longmapsto n + e^{+}$



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

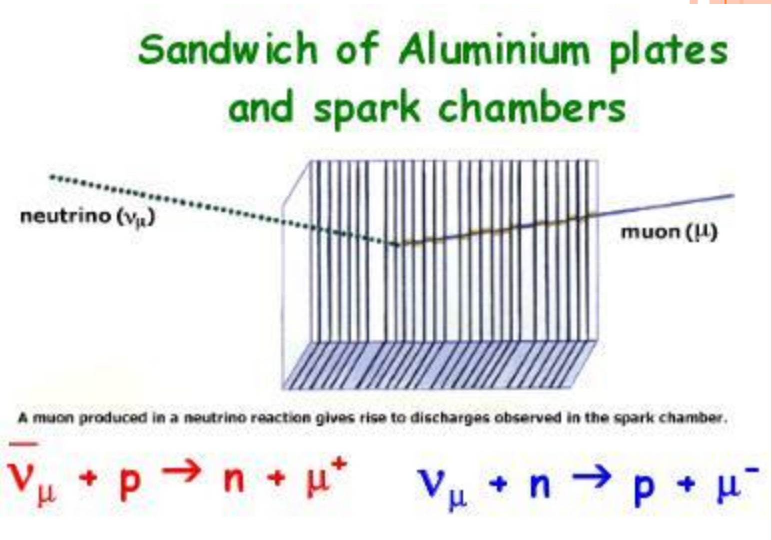
DISCOVERY OF ν_μ (1962)

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



The accelerator, the neutrino beam and the detector

Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons (π), which were produced in the proton collisions with the target, decay into muons (μ) and neutrinos (ν_μ). The 13 m thick steel shield stops all the particles except the very penetrating neutrinos. A very small fraction of the neutrinos react in the detector and give rise to muons, which are then observed in the spark chamber.



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

$$\overline{\nu_\mu} + p \rightarrow n + \mu^+ \qquad \nu_\mu + n \rightarrow p + \mu^-$$

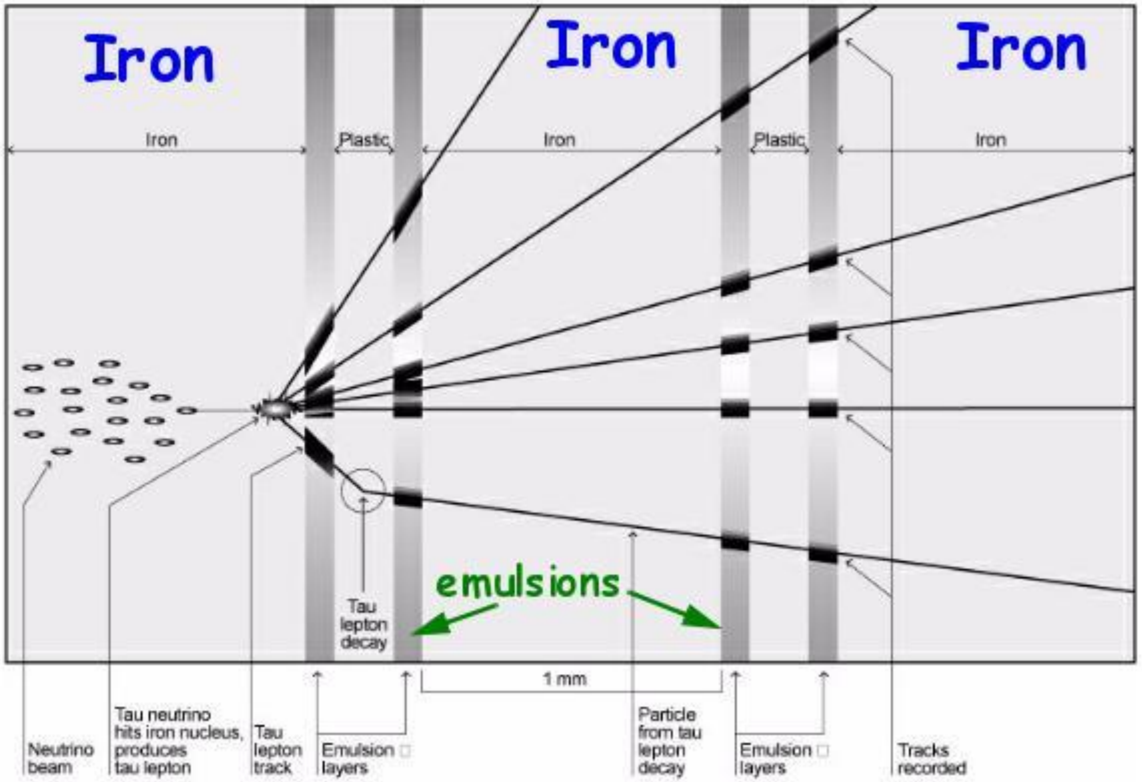
DISCOVERY OF ν_τ (2000)

Dedicated experiment DONUT at Fermilab

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

$\hookrightarrow \tau^- +$ anti-ν_τ

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



Identify ν_τ from reaction with n

It took 6M events to select 4 ν_τ candidates

NEUTRINO SOURCES

- Artificial:
  - nuclear reactors
  - particle accelerators

First detected neutrinos

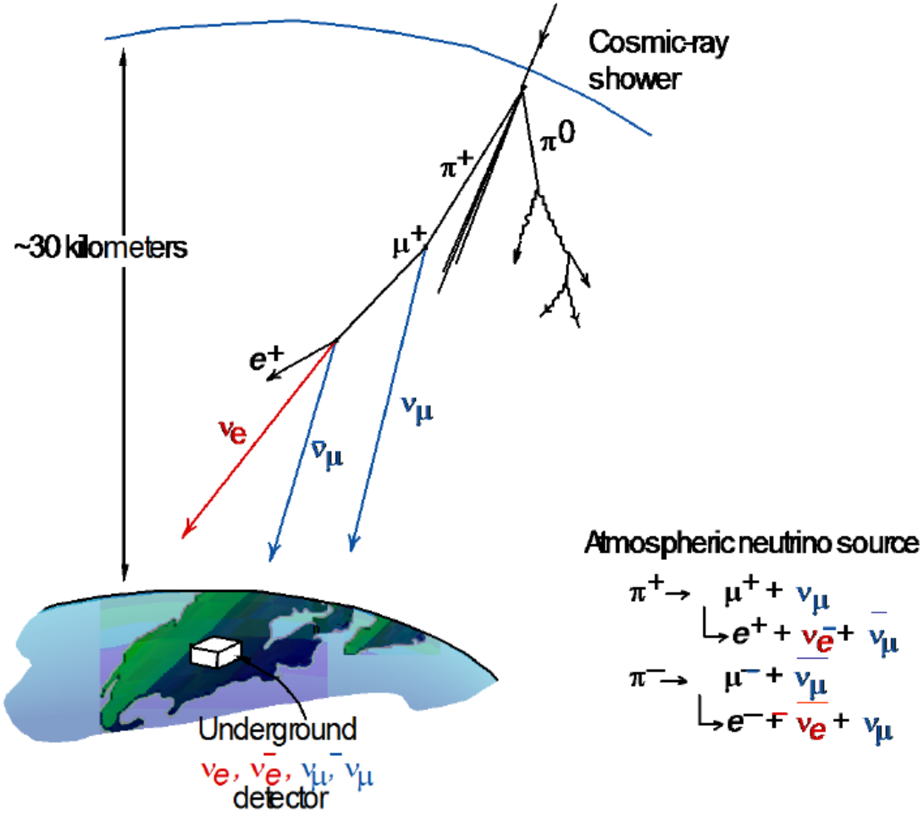
- Natural:
  - **Sun**
  - **Atmosphere**
  - SuperNovae
  - fission in the Earth core (geoNeutrinos)
  - Astrophysical origin (AGN..)

Expected, but undetected so far,:

- relic neutrinos from BigBang (~300/cm^3)

Neutrinos are everywhere!

NEUTRINO PRODUCTION IN THE ATMOSPHERE



Atmospheric neutrino source

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Absolute ν flux has ~10% uncertainty

But muon/electron neutrino ratio is known with ~3% uncertainty. Expected:

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

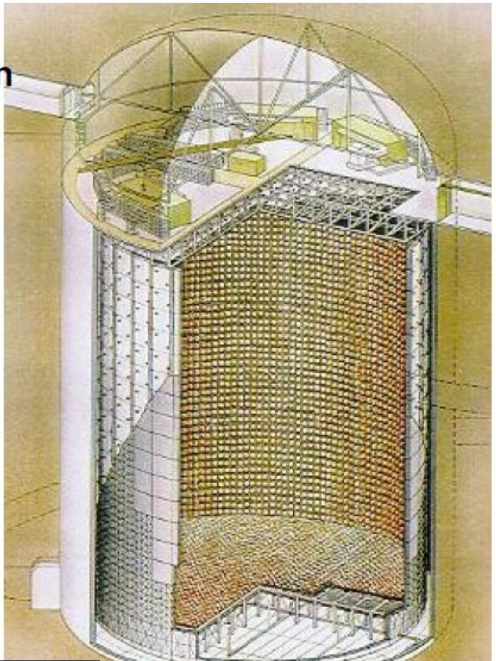
SUPER KAMIOKANDE (SUPER-K)

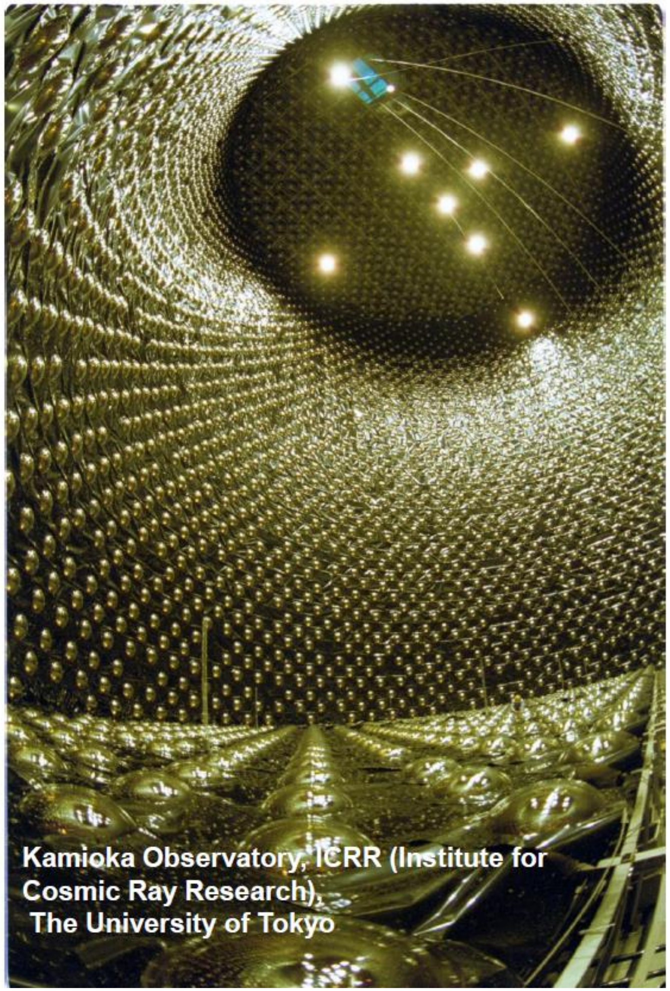
Kamioka Mine in Japan

- 1400m underground

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

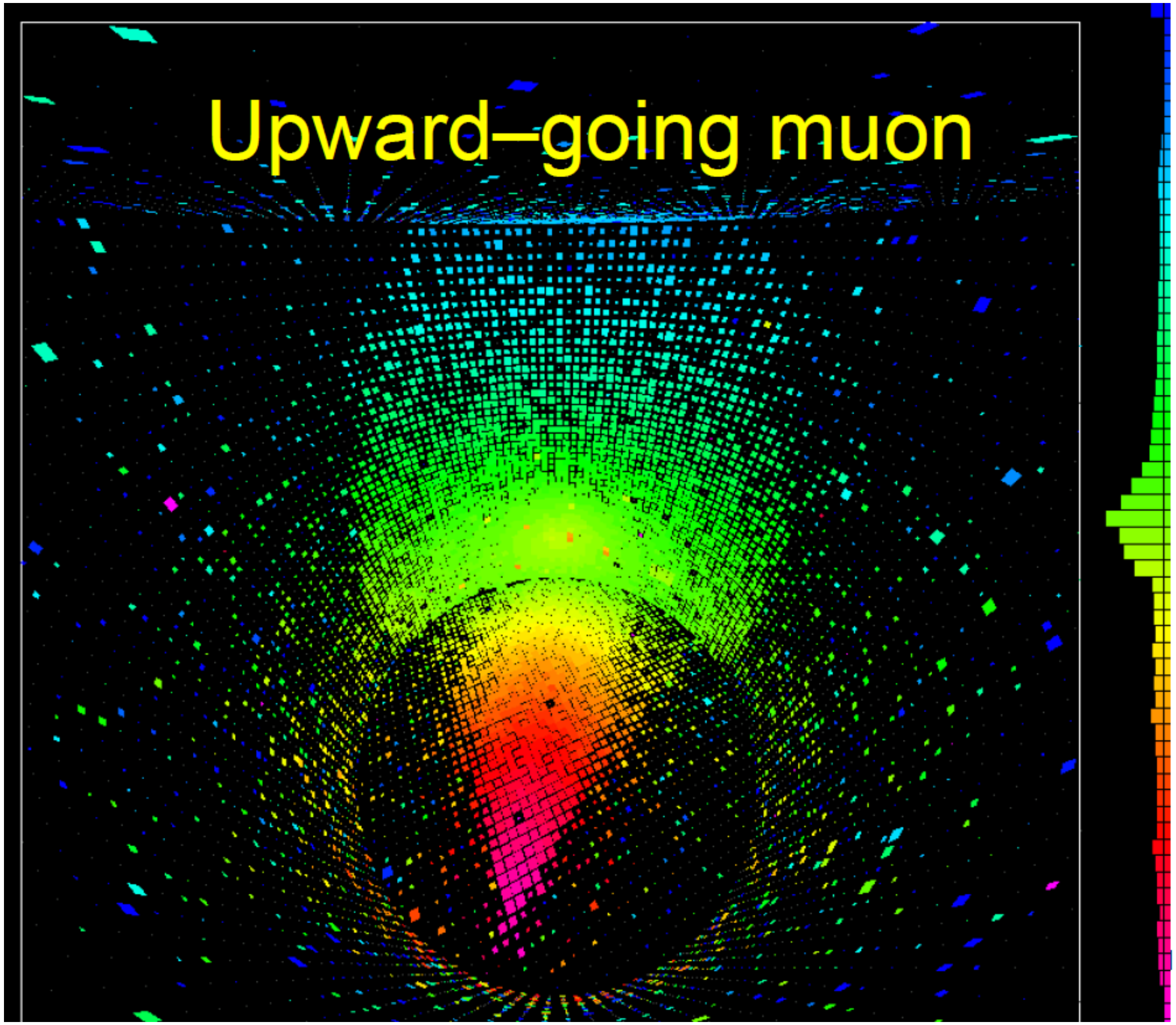
- 10,000 PMT inner detector
- 2,000 PMT outer detector (cosmic ray veto)



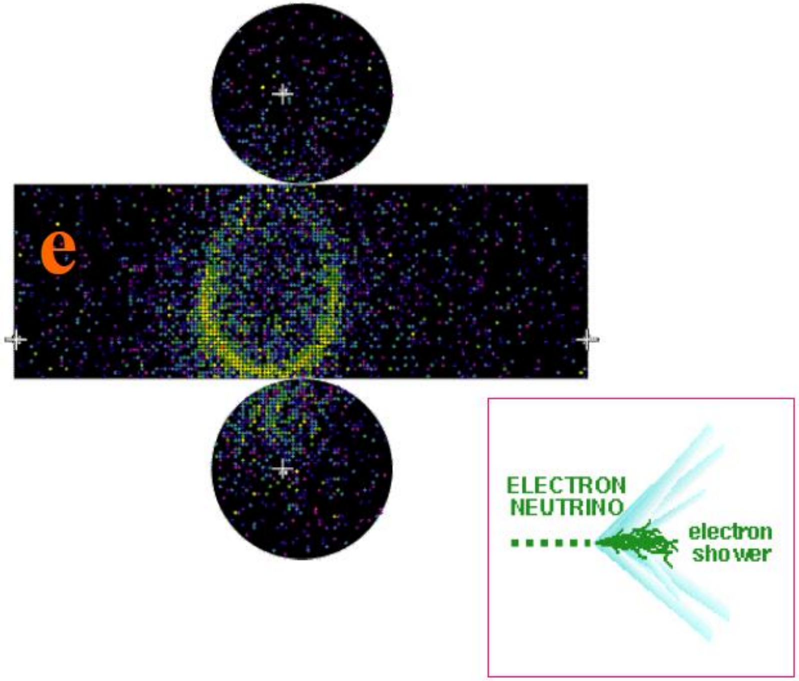


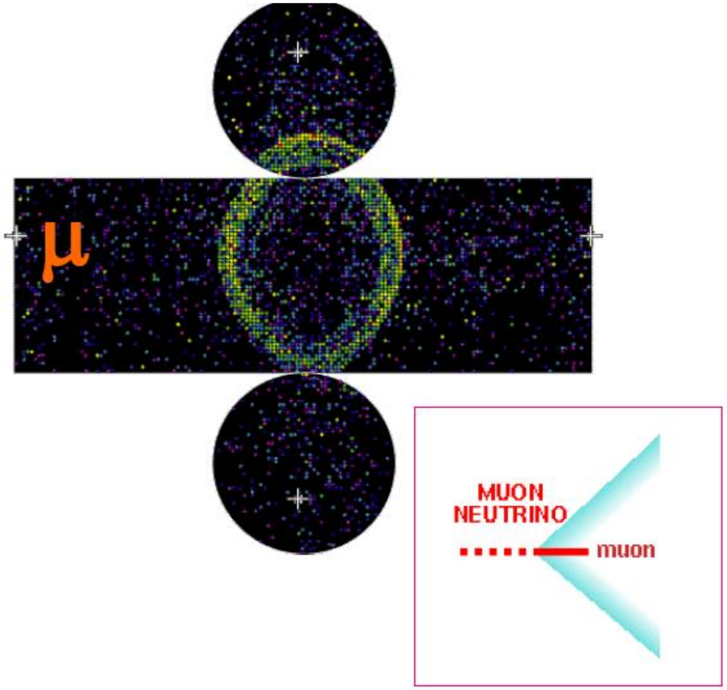
Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

EVENT FROM SUPER-K



ELECTRON AND MUON IDENTIFICATION

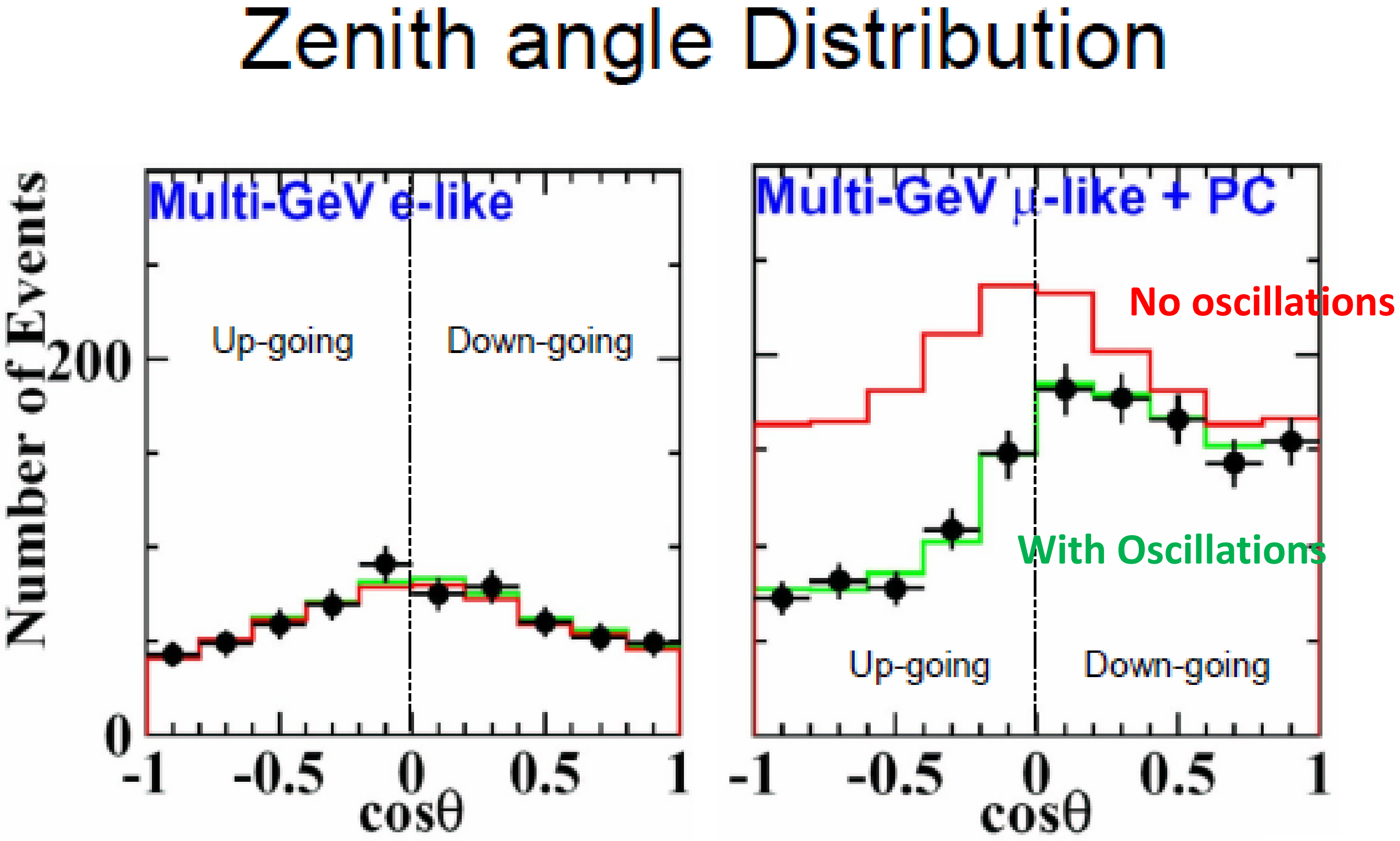




Electron ring is fuzzier than muon ring. Electron produces shower of gammas, electrons and positrons. Gammas don't produce Cherenkov light. Electrons and positrons do. In the shower each of them flies at a little bit different angle and each of them makes its own weak Cherenkov ring. All those rings 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!



Half of the ν_μ are lost!

NEUTRINO OSCILLATONS

- 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

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

where

θ is the mixing angle between flavour 1 and 2

L is the neutrino flight path in km

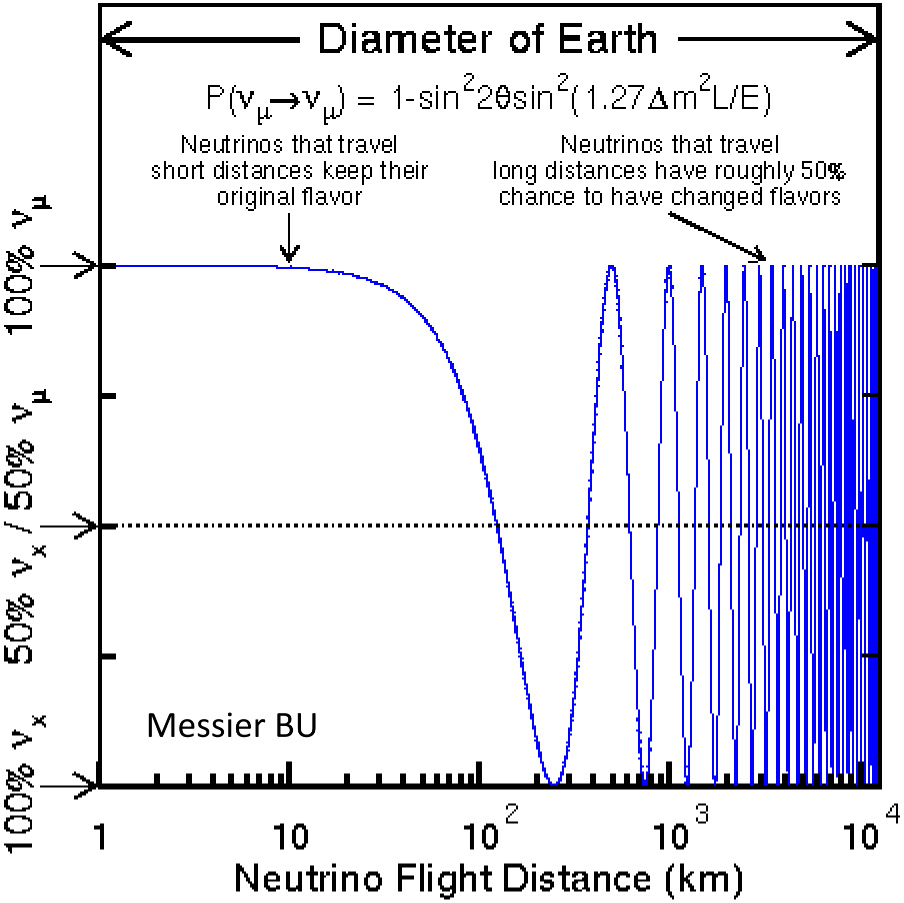
E_ν is the neutrino energy in GeV

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

NEUTRINO OSCILLATONS

- The time
  scillations,
  is determi
  r and
  the source

- The proba
  late to
  flavour 2



θ is th

L is th

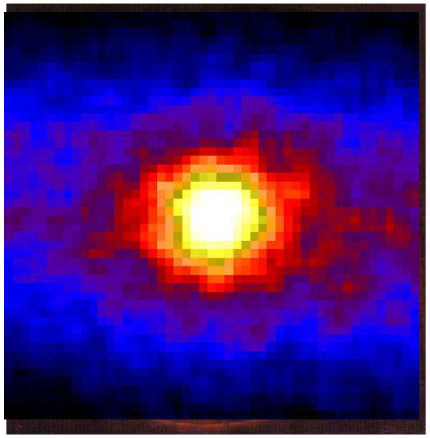
E_ν is t

Δm^2 =

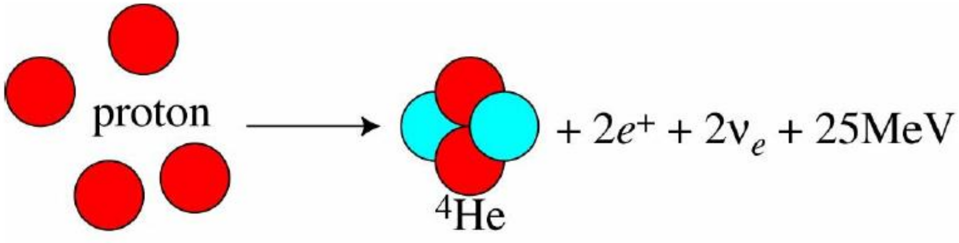
in eV^2

SOLAR NEUTRINOS

The Standard Solar Model (SSM)



Hydrogen fusion in the Sun:



Observables:

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

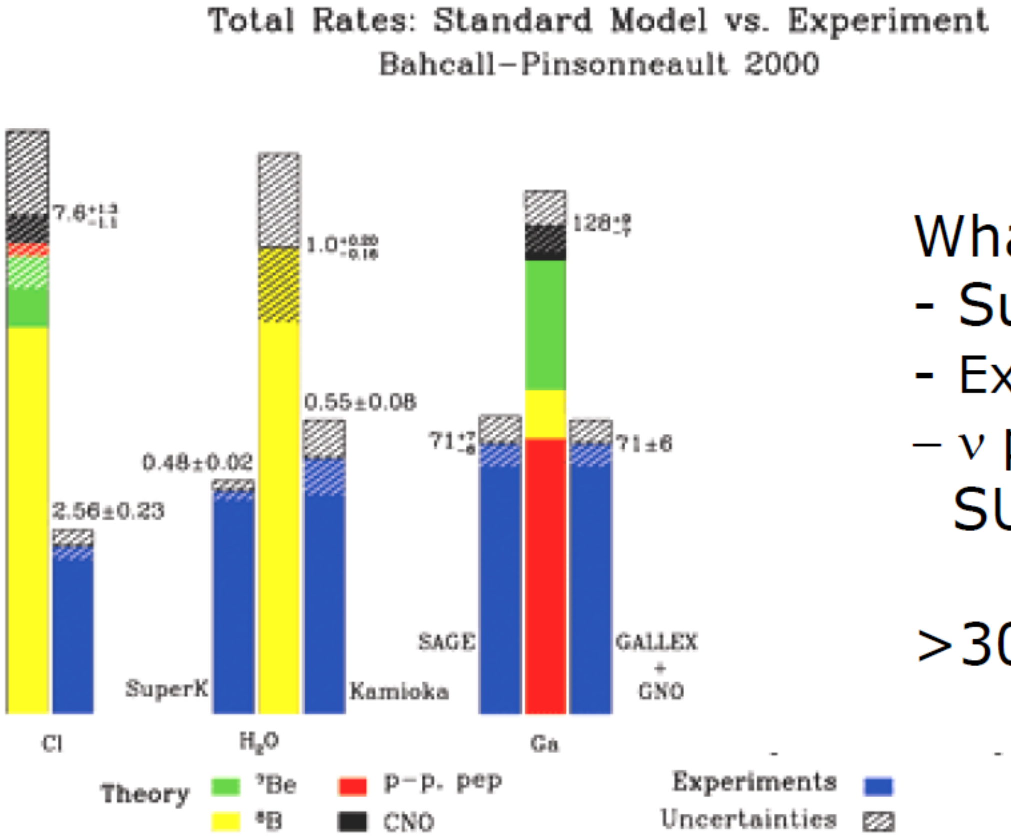
Inferences on solar interior (ρ, P, T)

SSM describes the evolution of an initially homogeneous solar mass M_o up to the sun age t so as to reproduce L_o, R_o and $(Z/X)_{photo}$

$\Rightarrow$ Predicts solar neutrino flux (intensity and spectrum)

SOLAR NEUTRINO PROBLEM

- We see too few!



What can be wrong?
- Sun model
- Experiments
– ν propagation from SUN to Earth

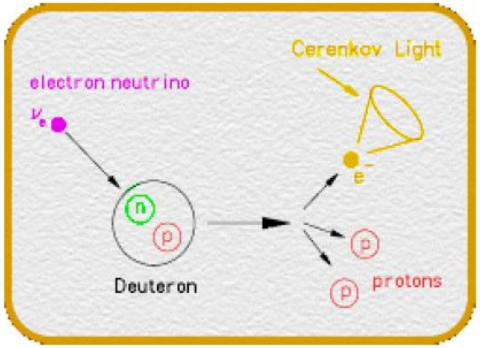
>30 years of debate!

Also this could be explained by ν oscillations

The SNO experiment measures neutrinos in three ways:

Charged current reactions

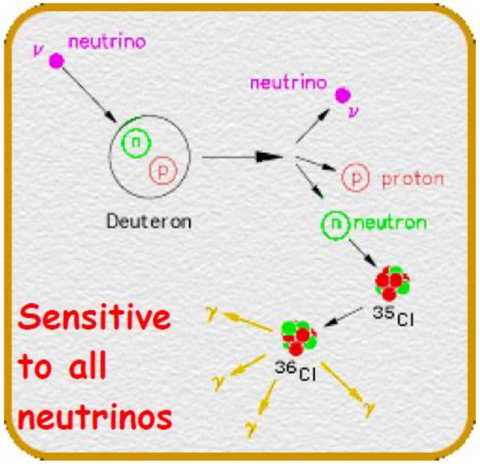
$\nu_e + d \rightarrow p + p + e^-$



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

$\nu_x + d \rightarrow p + n + \nu_x$

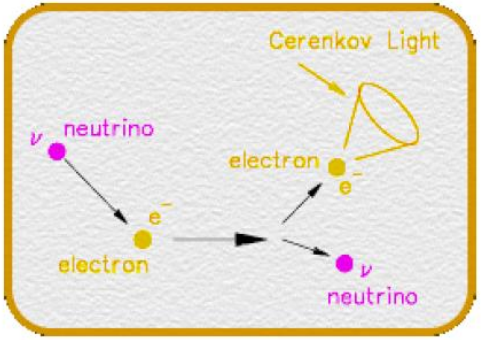


Sensitive to all neutrinos

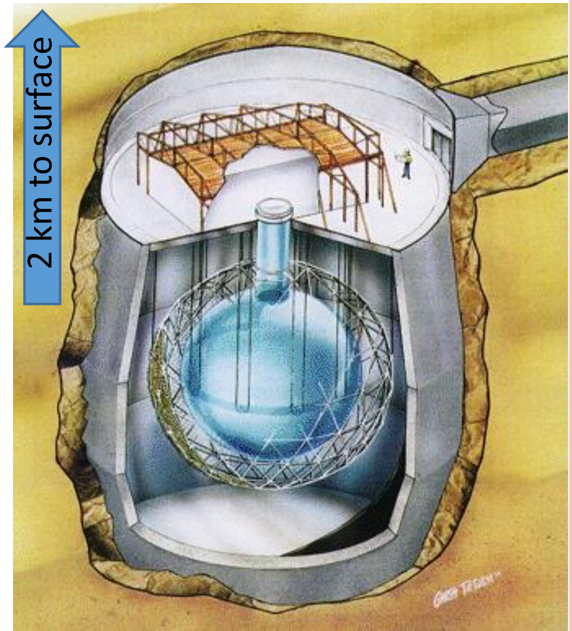
The photons would Compton scatter electrons that would produce Cerenkov lights. Proportional counters in the water was also used to measure this process directly.

Electron scattering

$\nu_x + e- \rightarrow \nu_x + e^-$



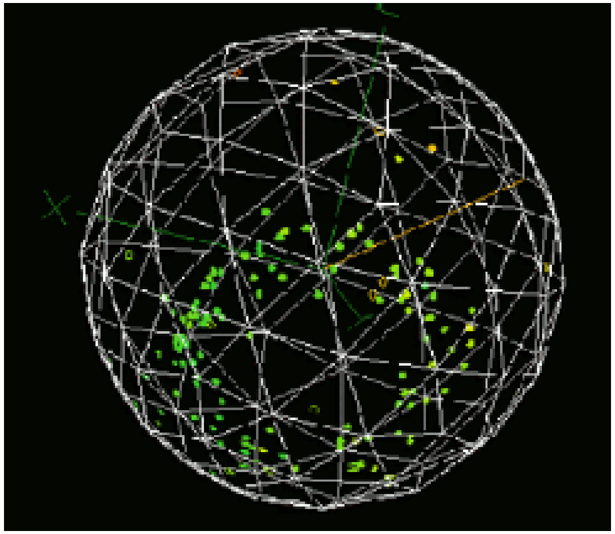
This process was mostly sensitive to electron neutrinos.



SNO EXPERIMENT

SNO EXPERIMENT

- The difference bewteen 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:

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

OSCILLATIONS WITH THREE FLAVORS

Can be written as three separate rotations

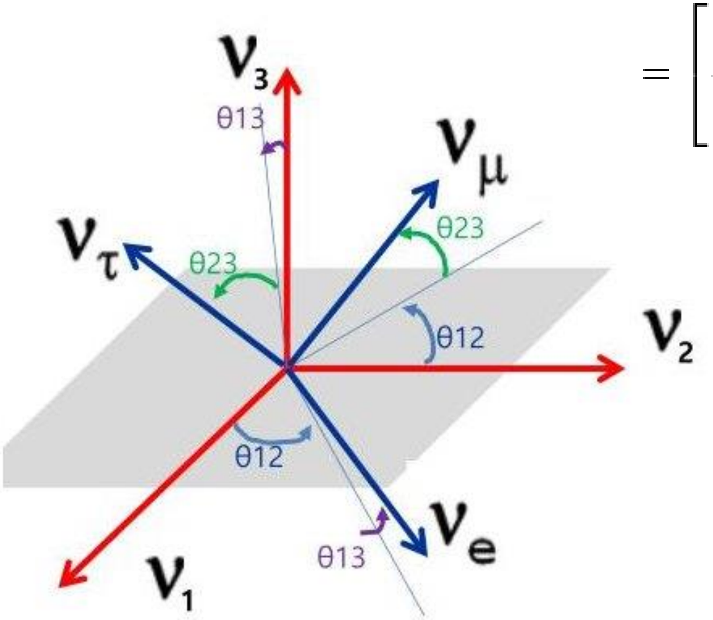
$$|\nu_\ell > = U \,|\, \nu_\tau >$$

where

(c=cos, s=sin)

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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



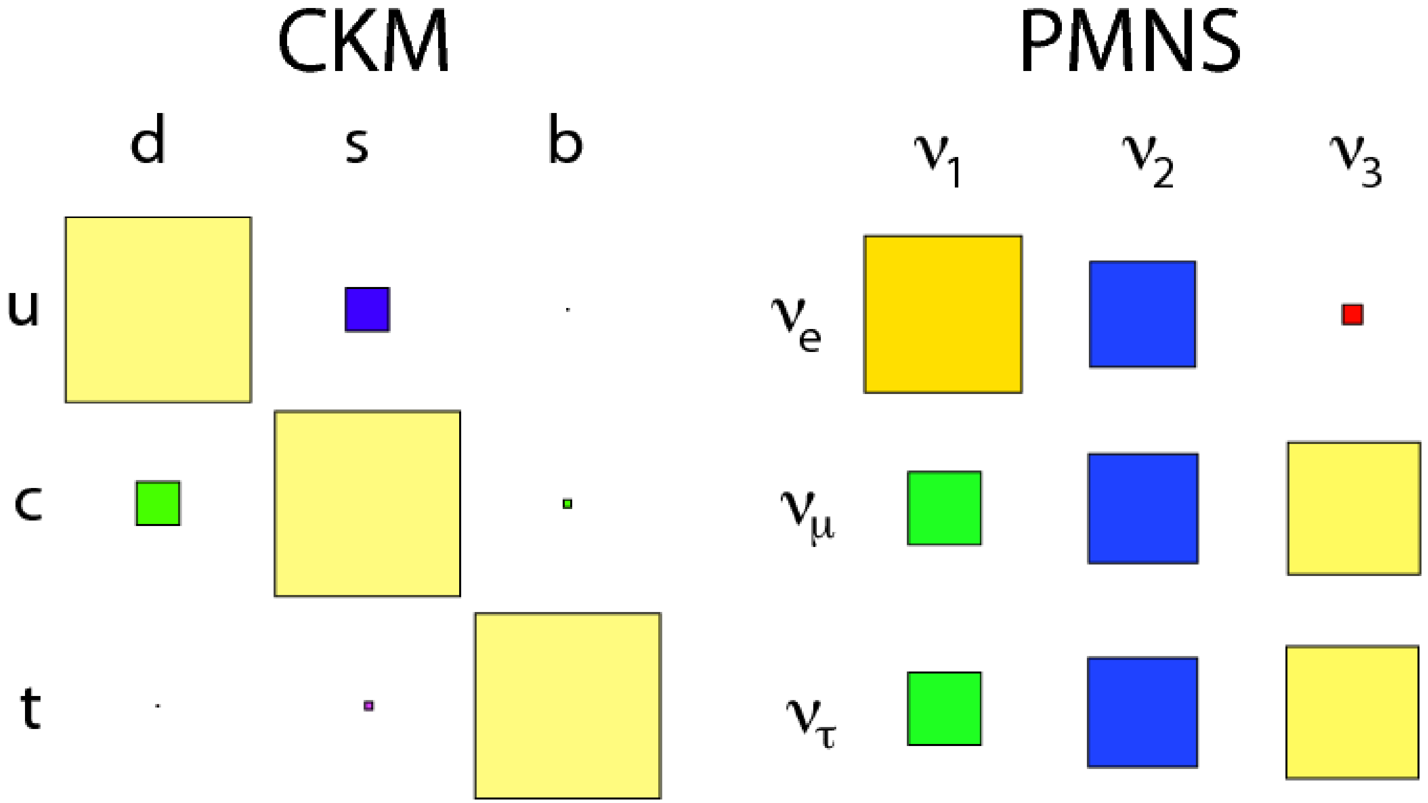
CP-violating phases!

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 for interpretation of LHCb result)

PMNS matrix (Pontecorvo-Maki-Nakagawa-Sakata)

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



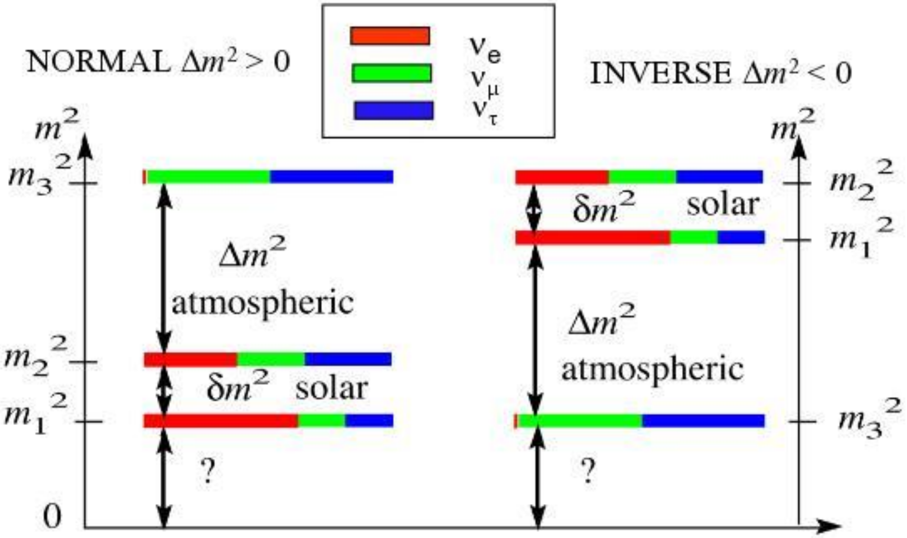
What we have learnt from mixing: neutrino mass lower bound

Weak eigenstates ν_e, ν_μ, ν_τ superposition of mass eigenstates ν_1, ν_2, ν_3 numbered in increasing order of ν_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 $\Delta m^2_{atm} \sim 2.5 \; 10^{-3}$ eV^2
  $\Rightarrow$ at least one neutrino with mass > $\sqrt{\Delta m^2_{23}} \sim 50$ meV
  Is it m_2 or m_3? Depends on the mass hierarchy!



$\Delta m^2_{sol} = 8 \times 10^{-5}$ eV^2
$\Delta m^2_{sol} \sim \Delta m_{12}{}^2 = m_2{}^2 - m_1{}^2 > 0$

$\Delta m^2_{atm} = 2.5 \times 10^{-3}$ eV^2
$\Delta m^2_{atm} \sim |m_3{}^2 - m_2{}^2| \sim |m_3{}^2 - m_1{}^2|$

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 ν_e mass using β-spectrum:

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

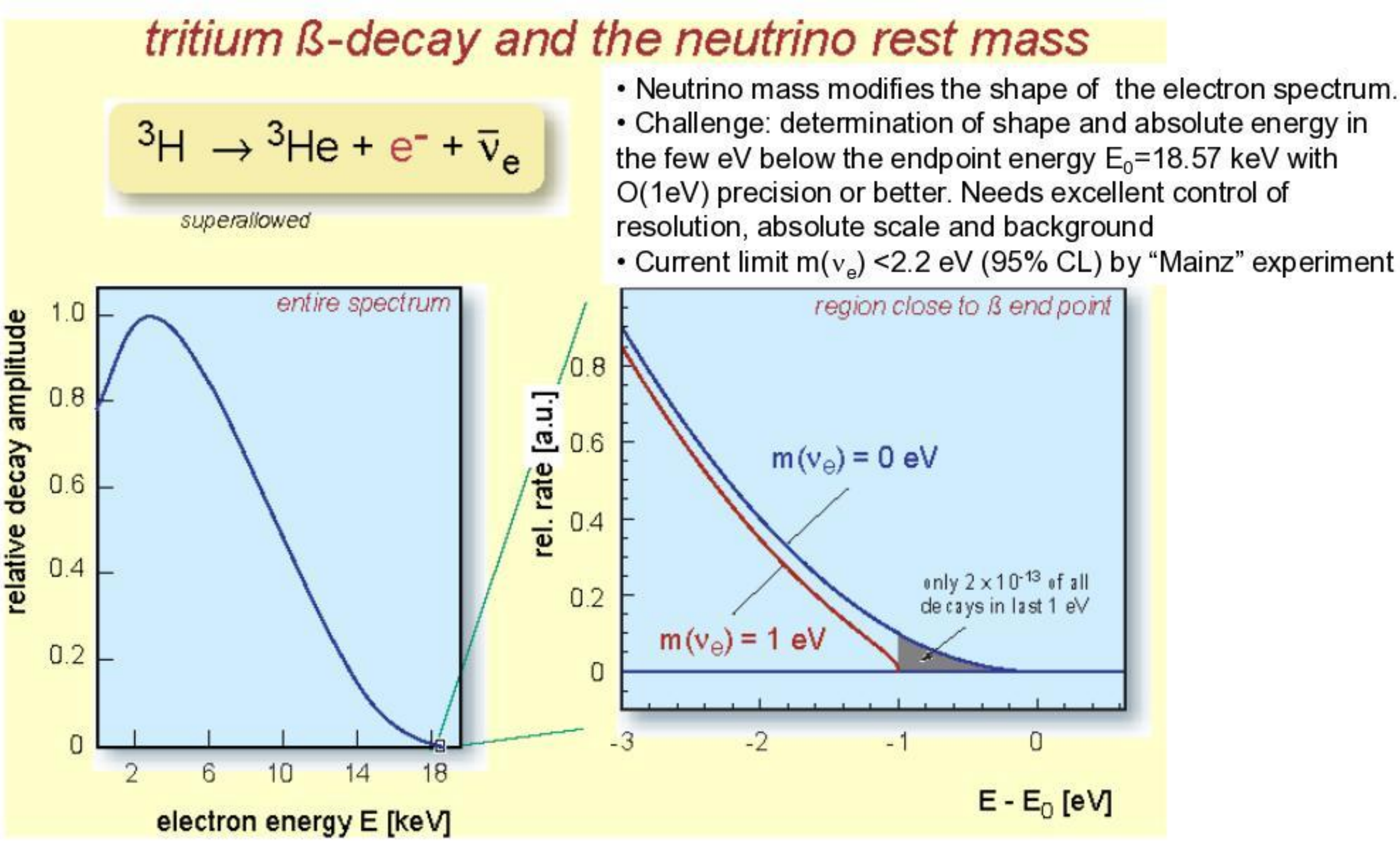
- Direct measurement of the ν_μ mass using pion decays at rest ($\pi^+ \rightarrow \mu^+ + \nu_\mu$):

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

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

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

Direct Mass Measurement in β decay



tritium ß-decay and the neutrino rest mass

$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

superallowed

- 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 ½ 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: γ, Z^0, π^0 . But not n, K^0)
  - Lepton number would not be conserved
- How come we don't know?!
  - We observe only ν_L and anti-ν_R so cannot compare same polarization directly.
  - For inst:
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$ Left-handed always $\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$ 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**: $\mathcal{L} = m_D\,(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$ i.e. need both L and R fields! Thus, $m_\nu \equiv 0$ in the SM
- **Majorana ν:** ν and anti-ν different states of same particle ⇒ Both Dirac and Majorana mass terms:

$$(\psi_L\ \overline{\psi_L^c})\begin{bmatrix} m_L & m_D \\ m_D & m_R \end{bmatrix}\begin{pmatrix} \psi_R^c \\ \psi_R \end{pmatrix}$$

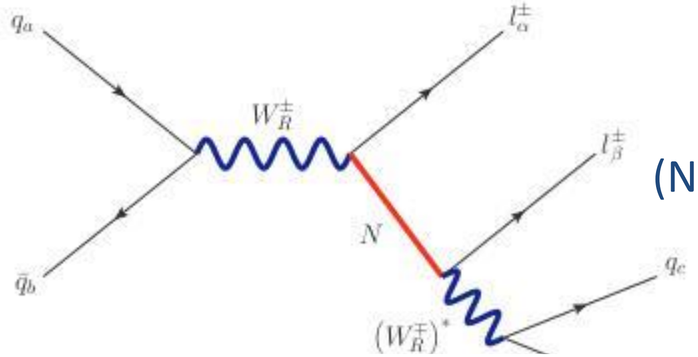
See-saw mechanism: $m_L=0$, $m_R \gg m_D$ ie $\begin{bmatrix} 0 & m_\upsilon \\ m_\upsilon & M_R \end{bmatrix}$

Diagonalization of matrix gives 2 mass eigenstates/ flavor:

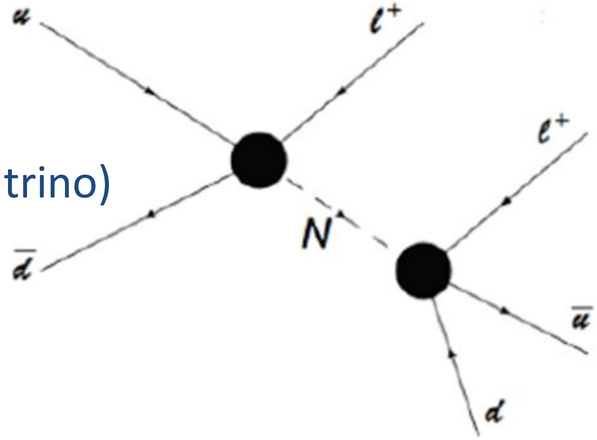
- $M_{light} = m_\nu^2 / M$, *mostly L-handed*
- $M_{heavy} \cong M$, *mostly R-handed* (not yet observed due to its large mass)

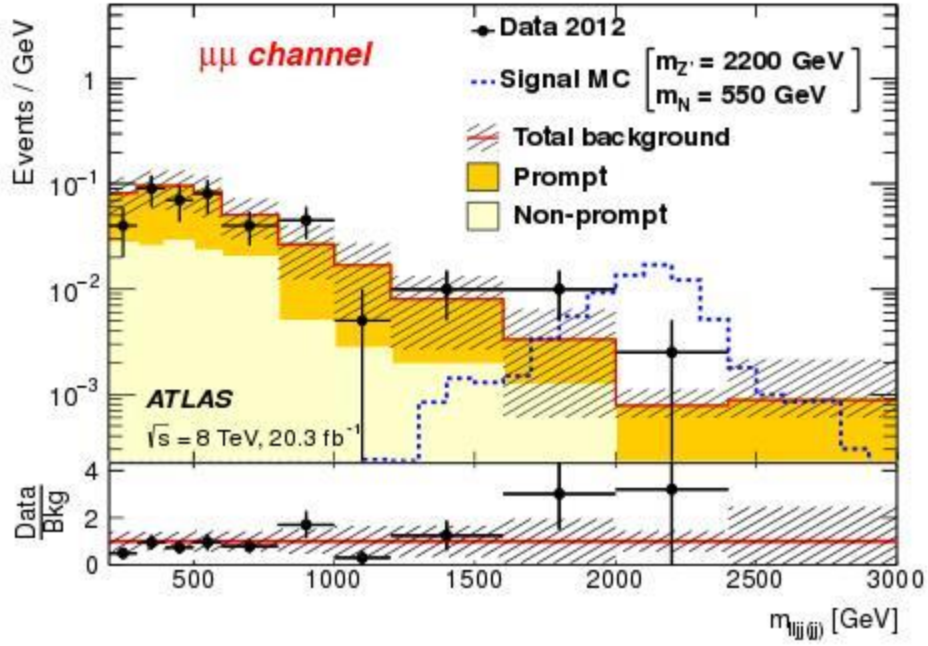
SEARCHES FOR MAJORANA NEUTRINOS @ THE LHC AND HEAVY NEUTRINOS

Reconstruct in cascade with W_R or Effective lagrangian operators



(N = heavy neutrino)





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

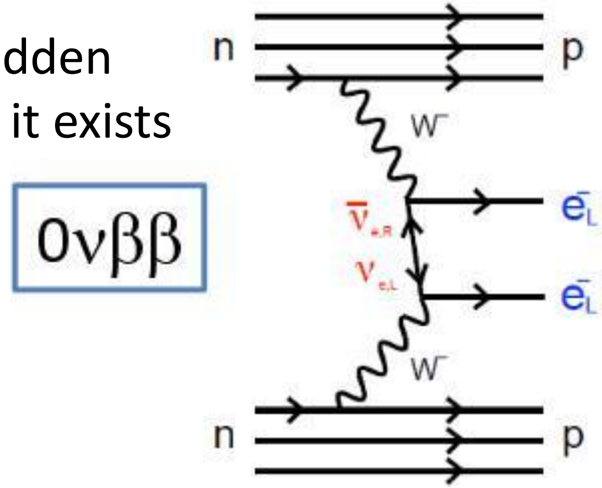
Current mass limit on N is ~2 TeV

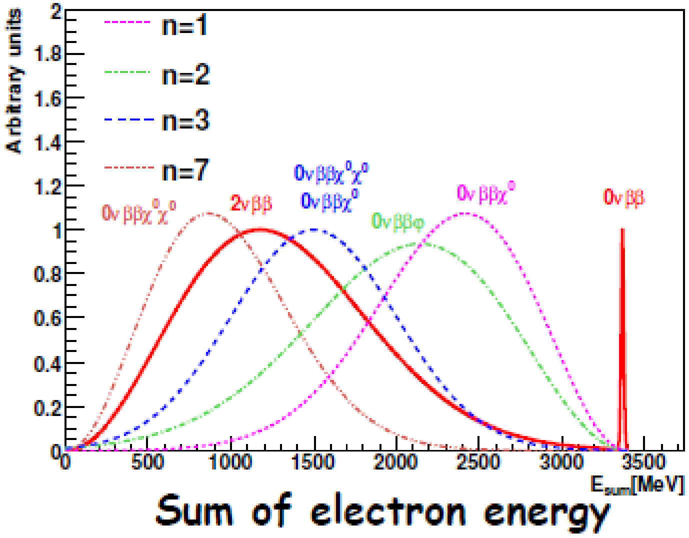
SEARCHES FOR NEUTRINO-LESS DOUBLE BETA DECAY

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

Several sensitive to lepton flavor violation in general

Certain radioactive isotopes: single β decay forbidden
Should then be possible to see double β decay if it exists
Current limits say $m_{\beta\beta} < 250\text{-}300$ meV





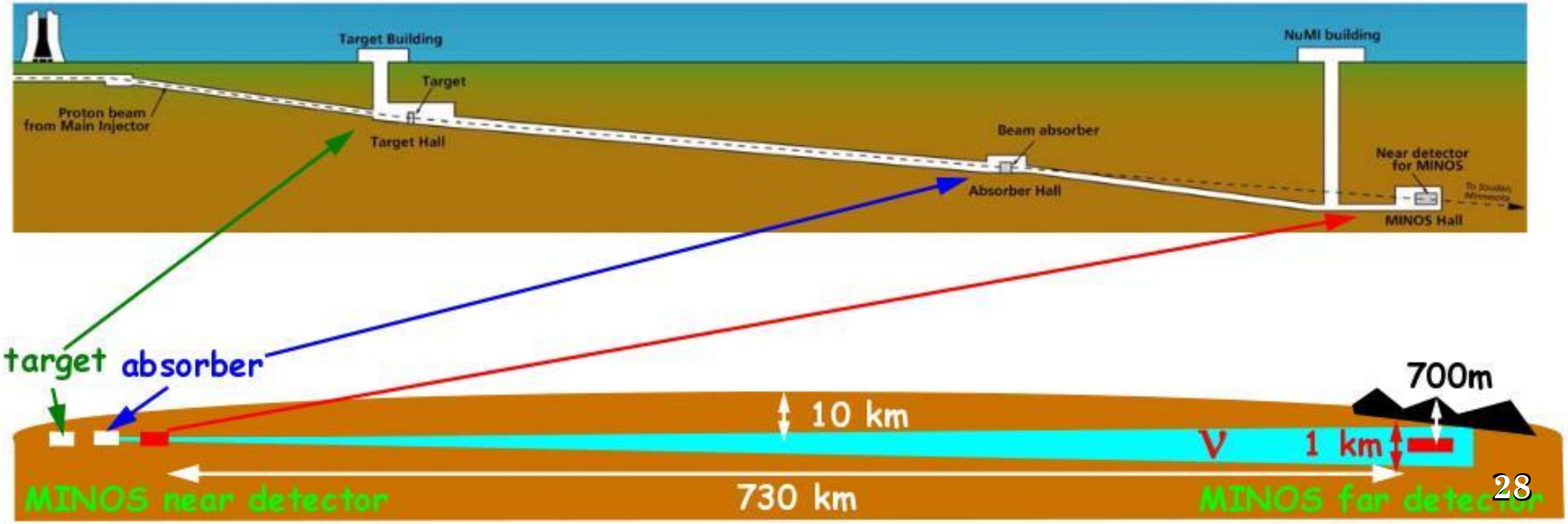
The neutrino-less version would Indicate Majorana neutrinos! (and lepton flavor violation)

Long baseline neutrino experiments

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

➡ The NuMI beam from Fermilab

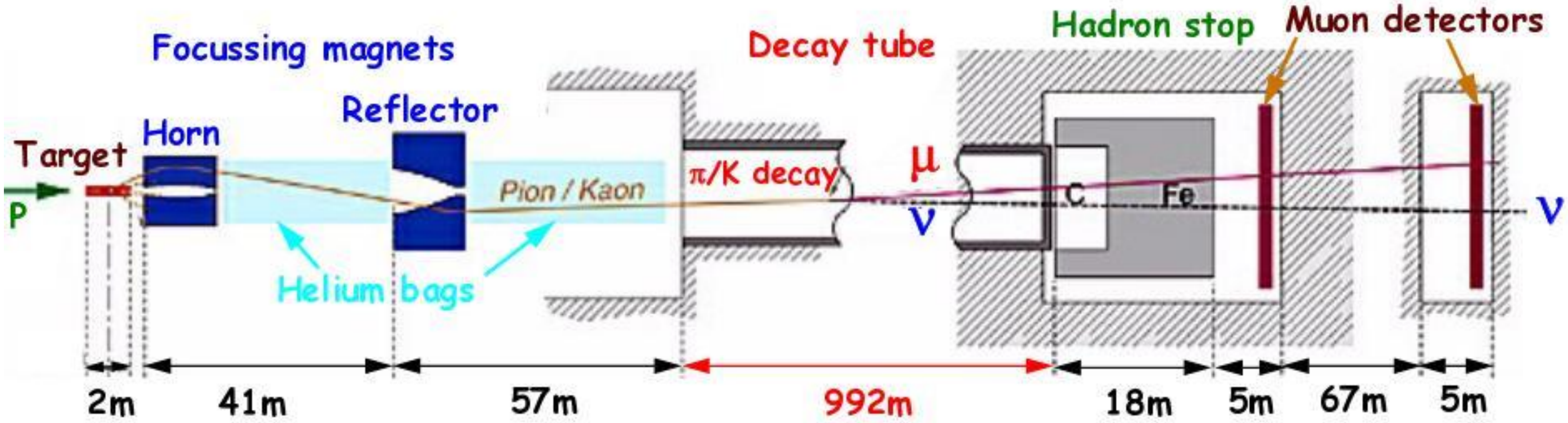
- One such a facility is the NuMI beam created at Fermilab and pointing at experiments situated in mines some 730 km away.



Long baseline neutrino experiments

➡ CNGS - CERN Neutrinos to Gran Sasso

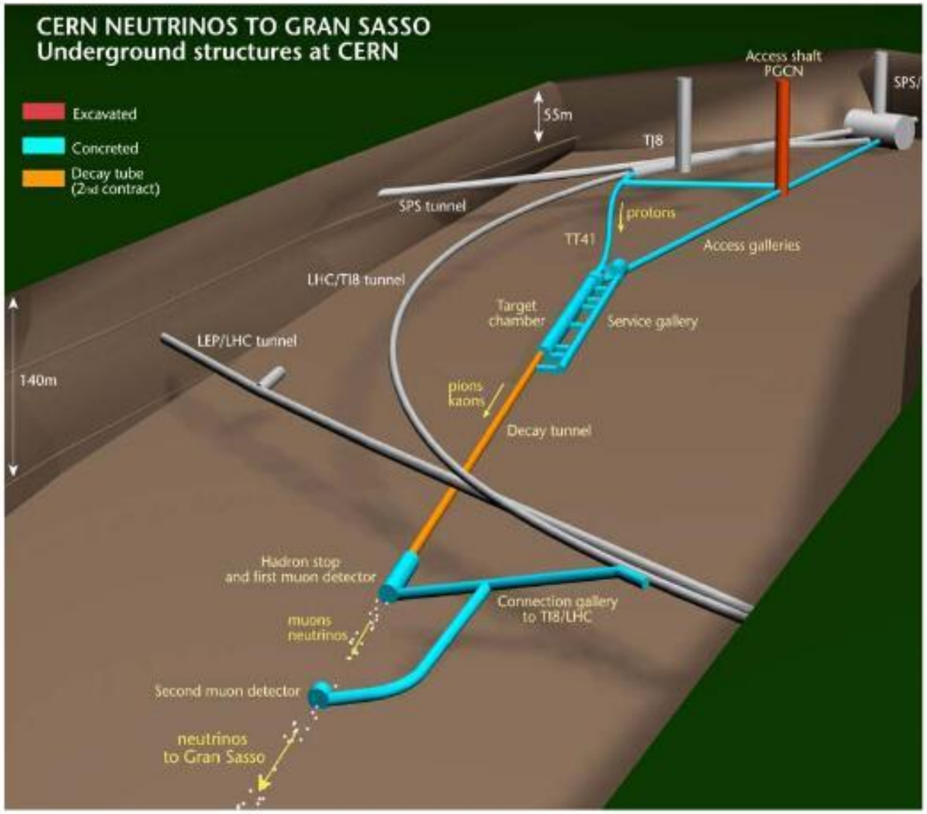
- The Kamiokande and Minos measurements are example of disapperance studies, i.e., one looks for the disapperance of ν_μ.
- Much more difficult are apperance measurements in which one looks for ν_τ to appear in a ν_μ beam.
- The layout of the CNGS neutrino facility at CERN is shown below:



Long baseline neutrino experiments

CNGS - CERN Neutrinos to Gran Sasso

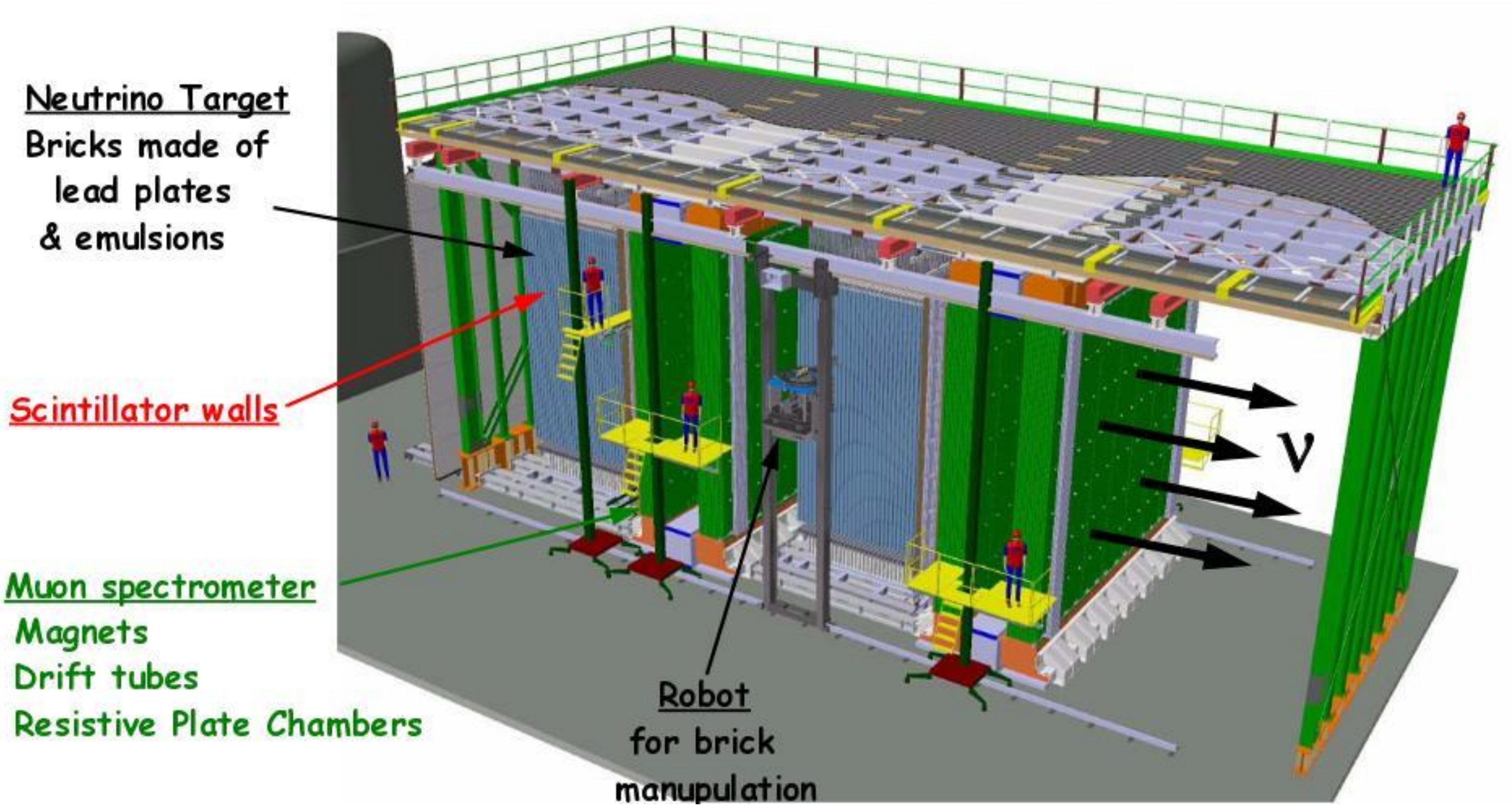
- **CNGS at CERN shoots neutrinos on experiments located 732 km away in Italy.**



OPERA

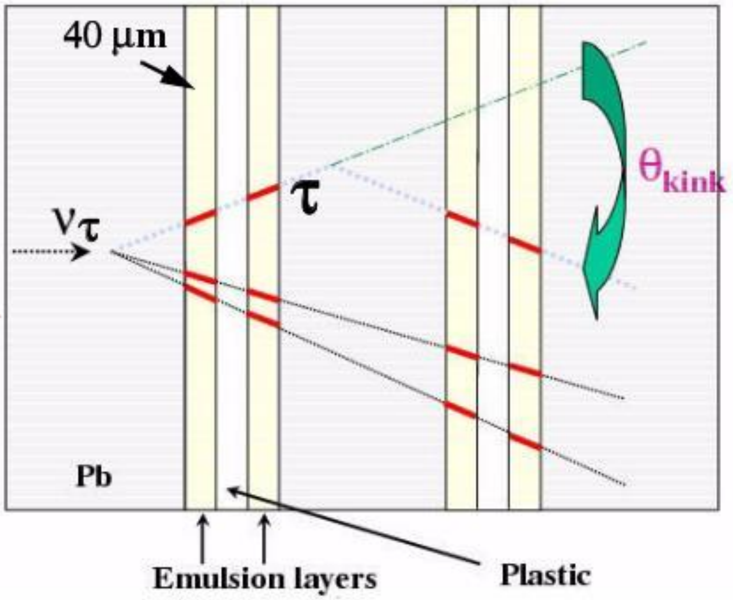
➡ The OPERA experiment

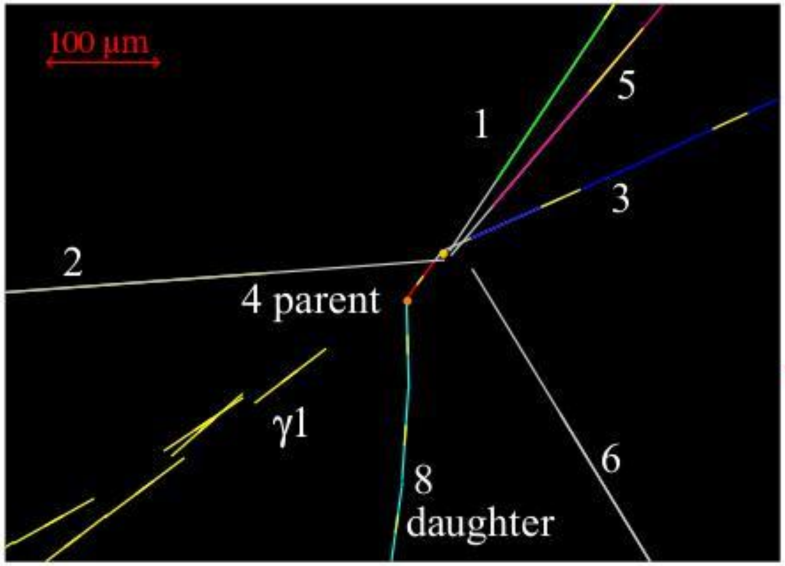
- The Opera experiment is using **photographic emulsions** to look for ν_τ.



OPERA

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

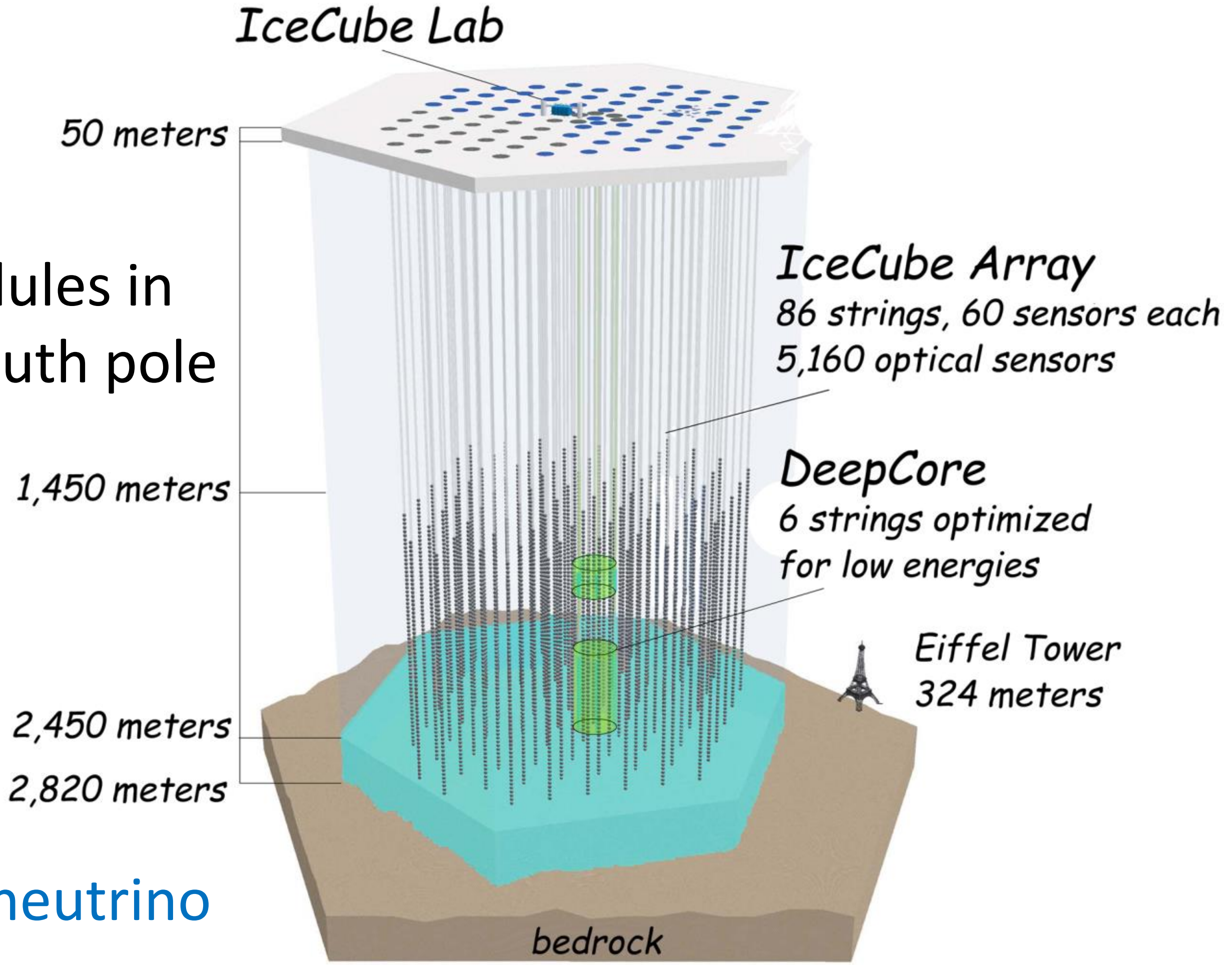




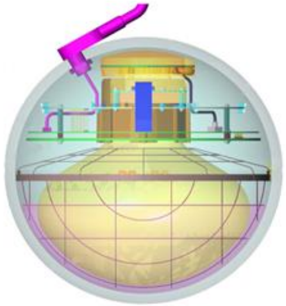
- *Five* ~~Two~~ candidates for ν_τ events have sofar been observed.

ICECUBE

Strings of optical modules in holes drilled in the South pole ice
The clear ice acts as Cherenkov medium

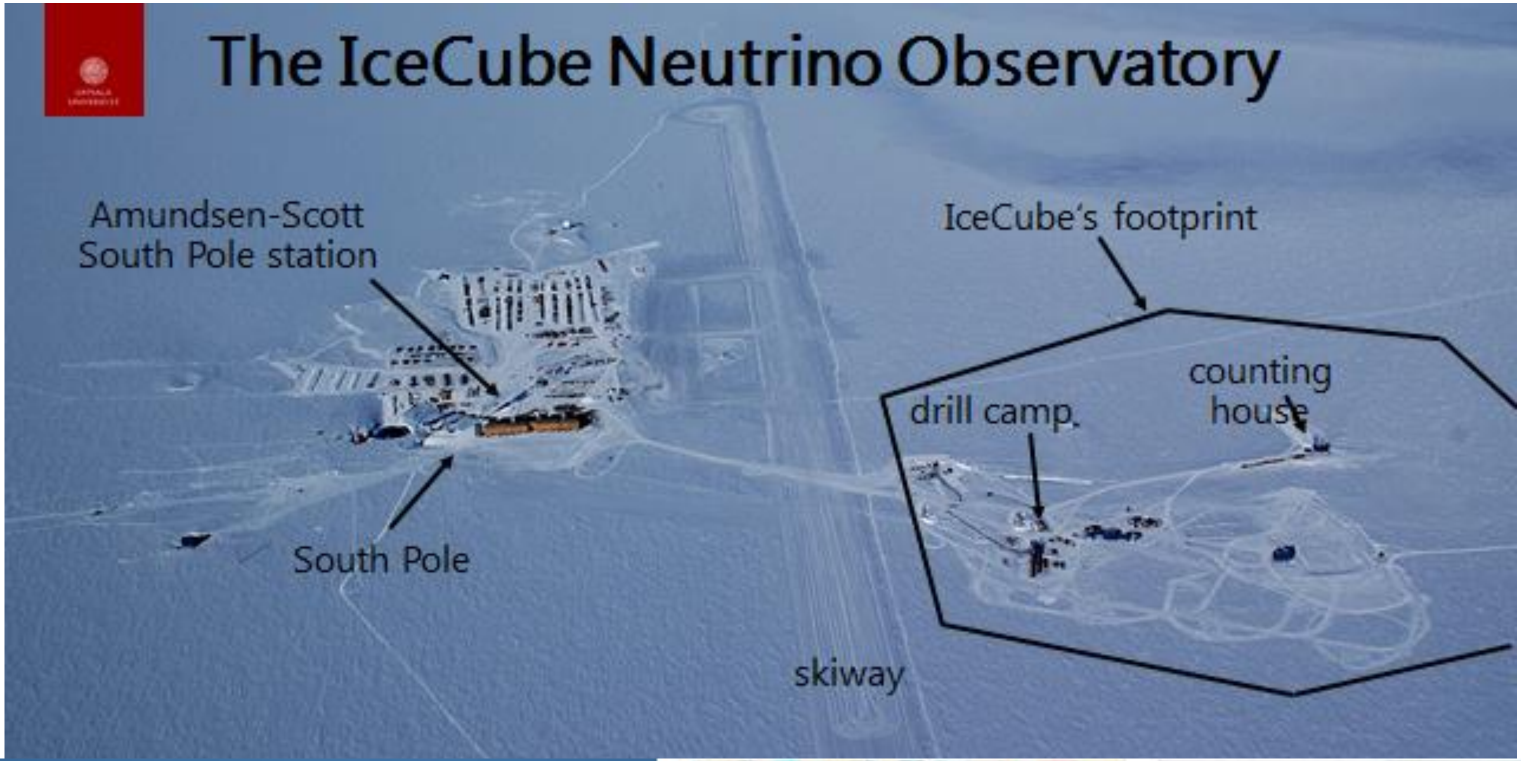


- Measurements of neutrino oscillations
- Astrophysical fluxes
- Searches for dark matter and extra galactic neutrinos



Digital
Optical
Module

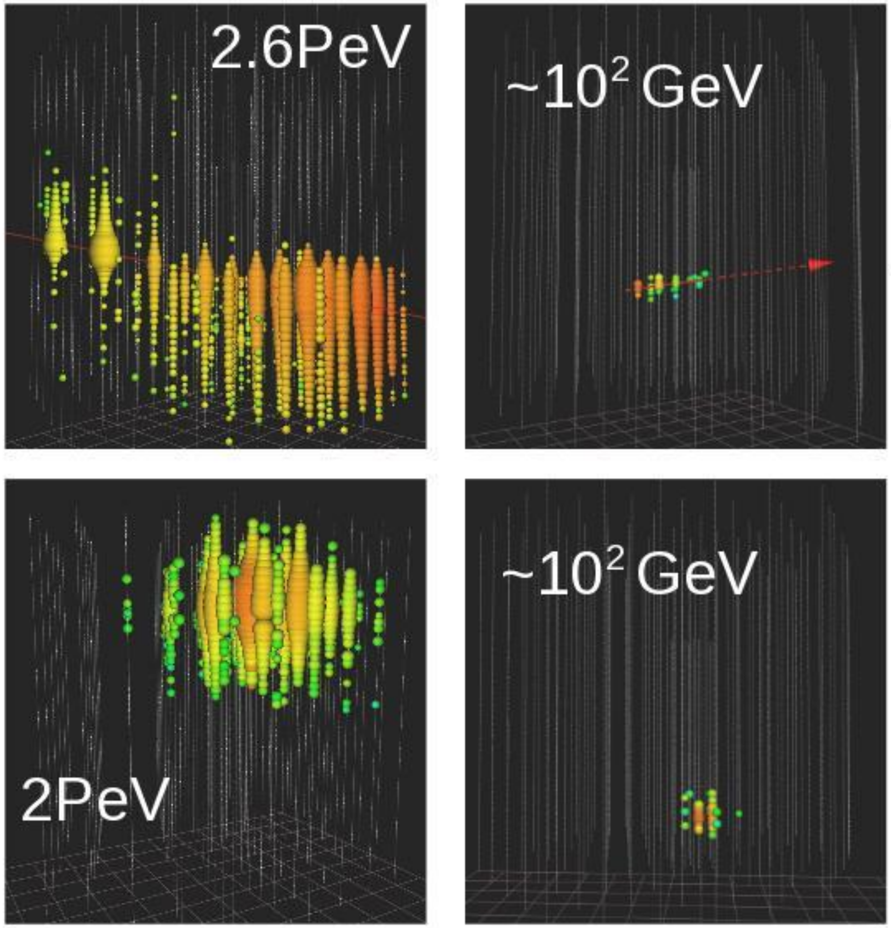
The IceCube Neutrino Observatory



(Participation from groups at NBI Copenhagen and Uppsala)

ICECUBE

Event Signatures



<u>Tracks</u>

CC: $\nu_\mu \to \mu$

elongated
far ranged

Pointing (~3°)
Up-going ν-pure
Extended eff. Vol.

<u>Cascades</u>

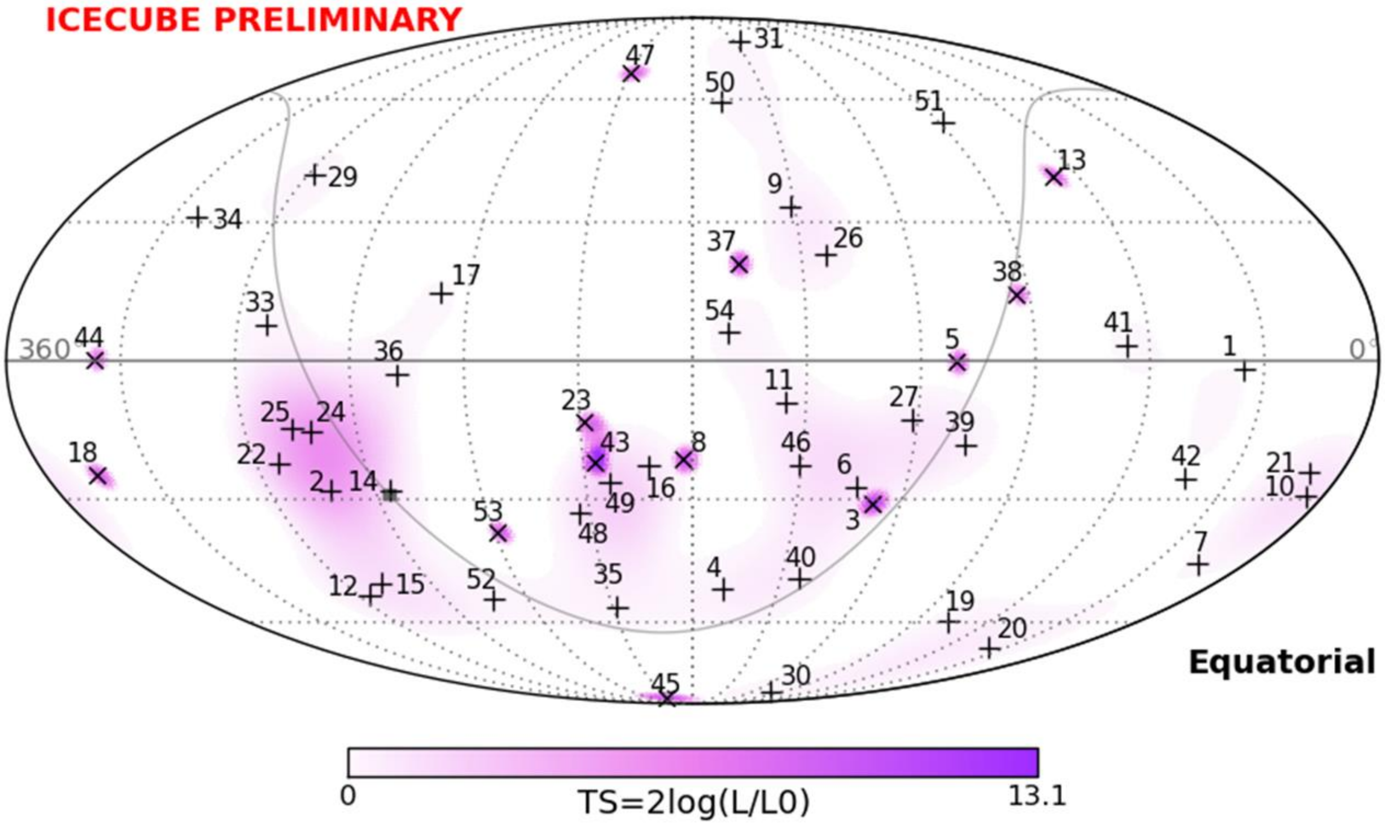
CC: $\nu \to e,\tau$
NC: $\nu \to \nu'$
all flavor

spherical
localized

Limited pointing
(30°-15° degree)
Good Energy est.
Plentiful,
because NC+CC

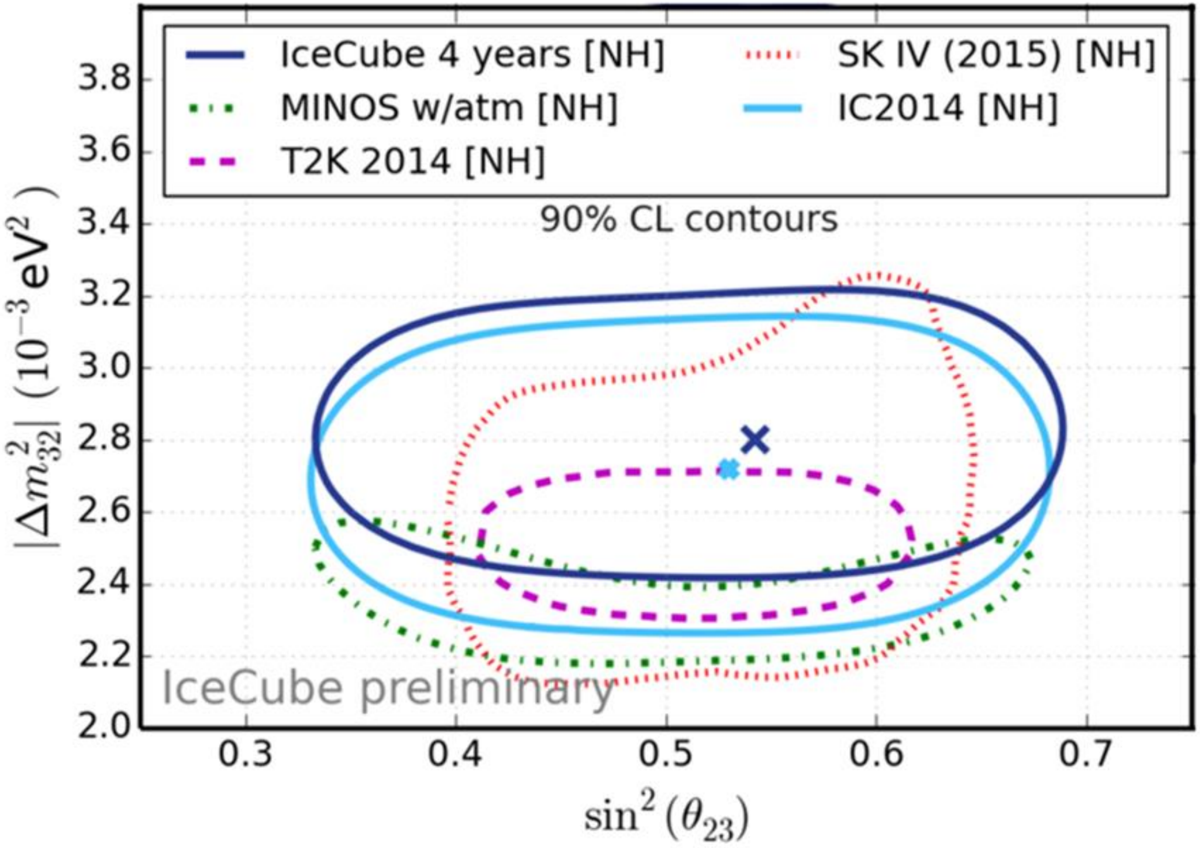
SOME ICECUBE RESULTS

- Astrophysical neutrinos
- No point sources found, limits on gramma 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?