Answers to some of the questions

Q1. Where do the following relation come from?

$$\Gamma_\nu \propto 1,\quad \Gamma_L \propto 1-4x_w+8x_w^2,\quad \Gamma_U \propto 1-\frac{8}{3}x_w+\frac{32}{9}x_w^2,\quad \Gamma_D \propto 1-\frac{4}{3}x_w+\frac{8}{9}x_w^2$$

$$x_w = \sin\theta_w \sim 0.23$$

A1. In the standard model, the couplings of $Z^0 \to f\bar{f}$ are,

$$L_{Zff} = -ig_Z\left[\bar{f}\gamma^\mu\left(a-b\gamma^5\right)f\right]Z_\mu^0 \quad \rightarrow \quad \Gamma_{Zff} \propto |a|^2+|b|^2$$

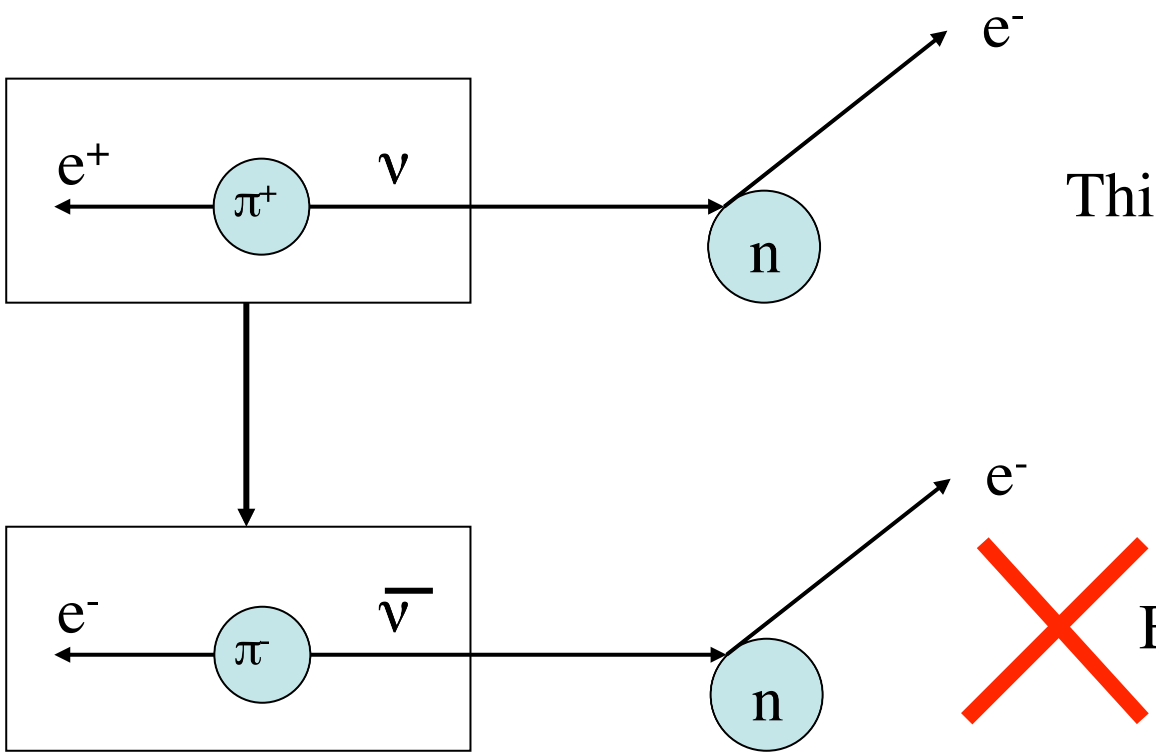
	a	b (=(a-4$Q_f x_w$))	$\Gamma/2$
ν_e, ν_μ, ν_τ	1	1	1
e, μ, τ	-1	-1+4x_w	$1-4x_w+8x_w^2$
u, c, t	1	1-8/3x_w	$1-(8/3)x_w+(32/9)x_w^2$
d, s, u	-1	-1+4/3x_w	$1-(4/3)x_w+(8/9)x_w^2$

Q2. You said ν and $\bar{\nu}$ are different particle from the Davis's negative result at reactor. But if neutrino is Majorana, they can be same.

A1. Yes. It is exactly the introductory discussion about the $0\nu2\beta$ experiment. To explain this, I will borrow next 3 slides from tomorrows lecture. What I meant yesterday were that at that time of the experiment, before the idea of Majorana particle, the experimental result could be understood so.

from tomorrows slide -1

So far neutrino and anti-neutrino are considered to be different particle because



This takes place.

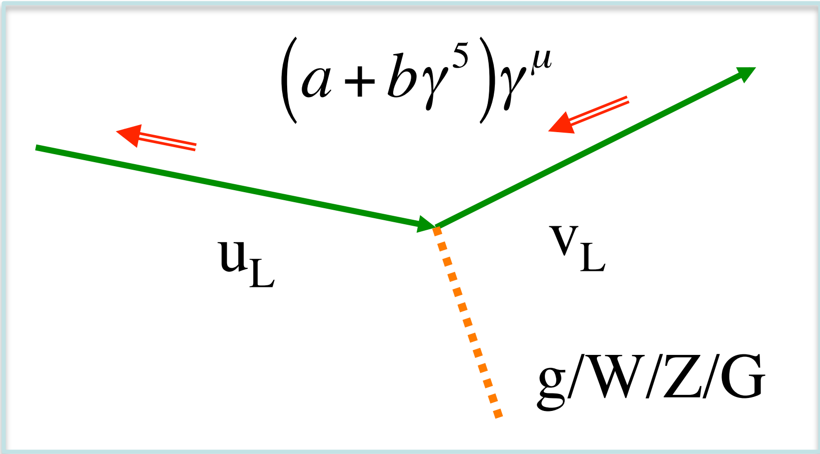
But not this.

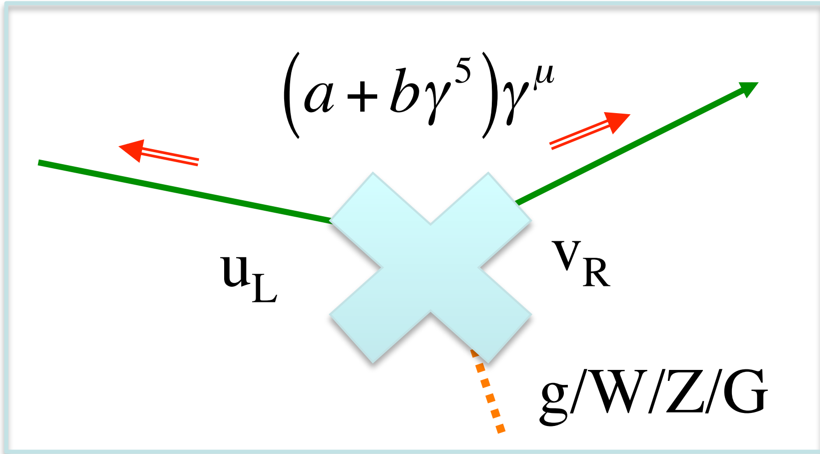
So that $\bar{\nu} \neq \nu$

from tomorrows slide -2

Chirality Conservation

$$\bar{u}_R\left(a+b\gamma^5\right)u_L=0$$

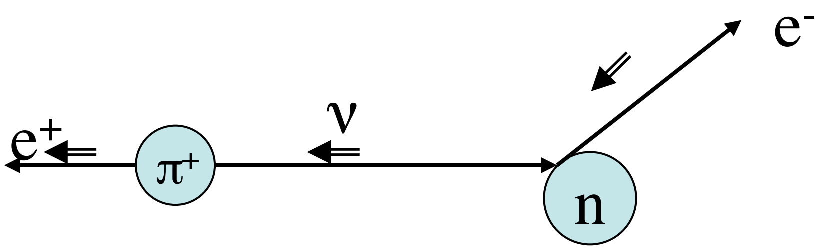




For EM, Weak and Strong interactions, the final chiralirty is always same as initial chirality

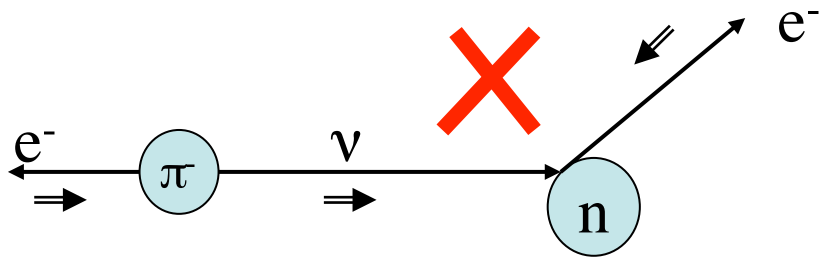
from tomorrows slide -3

Another possibility



Chirarity conserves

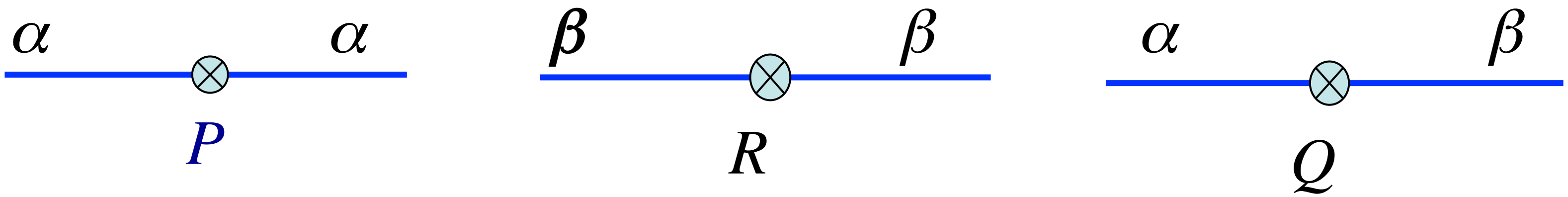
The neutrino produced with positron has positive chirarity and can not produce negative chirarity electron through weak interaction.



Chirarity changes

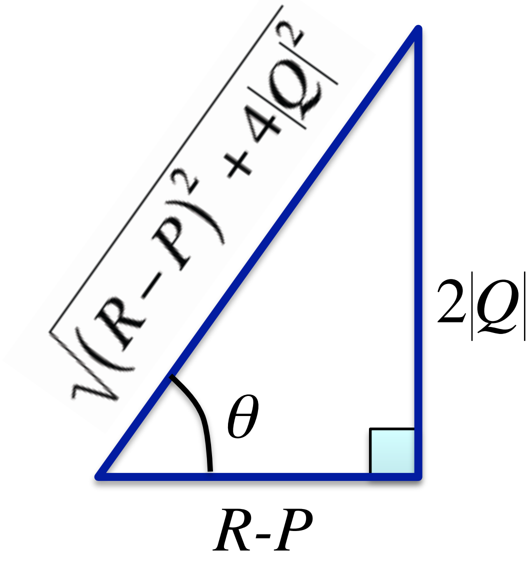
So that ν and $\overline{\nu}$ are not necessarily different particle

The point of of yesterday's lecture



Whatever the *a*, *b* are, the time dependent general state is

$$\psi(t) = \left(C_1 \cos(\theta/2) e^{-iE_+ t} - C_2 \sin(\theta/2) e^{-iE_- t}\right)|\alpha\rangle + \left(C_1 \sin(\theta/2) e^{-iE_+ t} + C_2 \cos(\theta/2) e^{-iE_- t}\right)|\beta\rangle$$



where, θ is defined in the right figure;

$$\tan\theta \equiv \frac{2|Q|}{R-P}$$

and $$E_\pm \equiv \frac{1}{2}\left((P+R) \pm \sqrt{(P-R)^2 + 4|Q|^2}\right)$$

The point of of yesterday's lecture

If initial condition is pure $|\alpha\rangle$ state, $\psi(0)=|\alpha\rangle$, C_1=cos(θ/2), C_2=-sin(θ/2) and the wave function at later time *t* is,

$$\psi(t)=\left(\cos^2(\theta/2)e^{-iE_+t}+\sin^2(\theta/2)e^{-iE_-t}\right)|\alpha\rangle+\frac{1}{2}\sin\theta\left(e^{-iE_+t}-e^{-iE_-t}\right)|\beta\rangle$$

Then the probability we observe $|\beta\rangle$ state is

$$P_{\alpha\to\beta}(t)=\left|\frac{\sin\theta}{2}\left(e^{-iE_+t}-e^{-iE_-t}\right)\right|^2=\sin^2\theta\sin^2\frac{E_+-E_-}{2}t$$

If α, β are neutrino flavor state; ν_e, ν_μ, it is called neutrino oscillation.
If they are spin under magnetic field, it is called spin precession.

The point of of yesterday's lecture

If we choose, C_1=1, C_2=0, we get an energy eigenstate

$$\psi_+(t) = \left(\cos(\theta/2)|\alpha\rangle + \sin(\theta/2)|\beta\rangle\right)e^{-iE_+t} \equiv |+\rangle e^{-iE_+t}$$

If we choose, C_1=0, C_2=1, we get another energy eigenstate

$$\psi_-(t) = \left(-\sin(\theta/2)|\alpha\rangle + \cos(\theta/2)|\beta\rangle\right)e^{-iE_-t} \equiv |-\rangle e^{-iE_-t}$$

The relation between the energy eigenstates and the state α,β is

$$\begin{pmatrix} |+\rangle \\ |-\rangle \end{pmatrix} = \begin{pmatrix} \cos(\theta/2) & \sin(\theta/2) \\ -\sin(\theta/2) & \cos(\theta/2) \end{pmatrix} \begin{pmatrix} |\alpha\rangle \\ |\beta\rangle \end{pmatrix}$$

$\theta/2$ is called mixing angle.

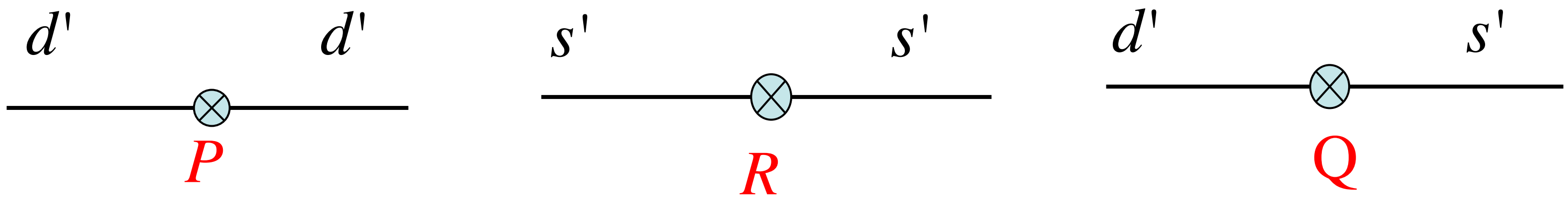
That's all.

Answer to another very good question

Q3, What is the "magnetic field" of ν oscillation?

A3, We do not know.

It is the very physics we study by ν oscillation (and mass).
For the case of quarks (quarks oscillate as well) there are transition amplitudes (T.A.);



The quark masses are generated from the T.A.

$$\begin{cases} m_d = \frac{1}{2}\left((P+R) - \sqrt{(P-R)^2 + 4|Q|^2}\right) \\ m_u = \frac{1}{2}\left((P+R) + \sqrt{(P-R)^2 + 4|Q|^2}\right) \end{cases}$$

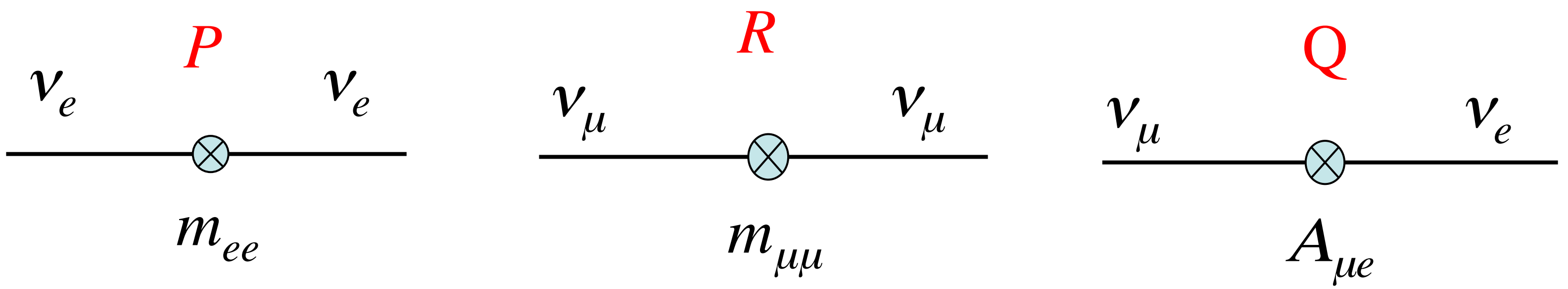
We understand the quark masses are generated from the coupling to the Higgs potential.
=> <u>The "magnetic field" of the quark T.A. is the Higgs field.</u>

We may think the "magnetic filed" of ν flavor transition is the Higgs field as well. However the coupling constant (m_ν) is very small compared with quark's (m_q) and theorists do not like it. Theorists believes there should be other mechanism to generate ν T.A., such as the see-saw mechanism, which naturally explains smallness of m_ν, while keeping ν T.A. similar size of quark's.
To study these kinds of things is an ultimate purpose of current neutrino physics. To do so, experimentalists' mission is to measure the T.A.'s, to check if $\nu = \bar{\nu}$, to measure imaginary component of T.A. (CP violation), etc. ... And theorists' mission is to explain them and explain our world using the information.

(I am happy the analogy of spin worked very well so as to lead this explanation)

Back to the ν Oscillation: ν at rest

We assume there are transition amplitudes between ν_e and ν_μ

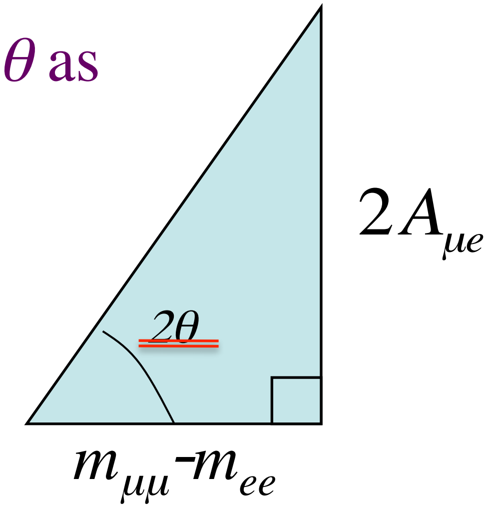


Caution!! from now on we define the angle θ as

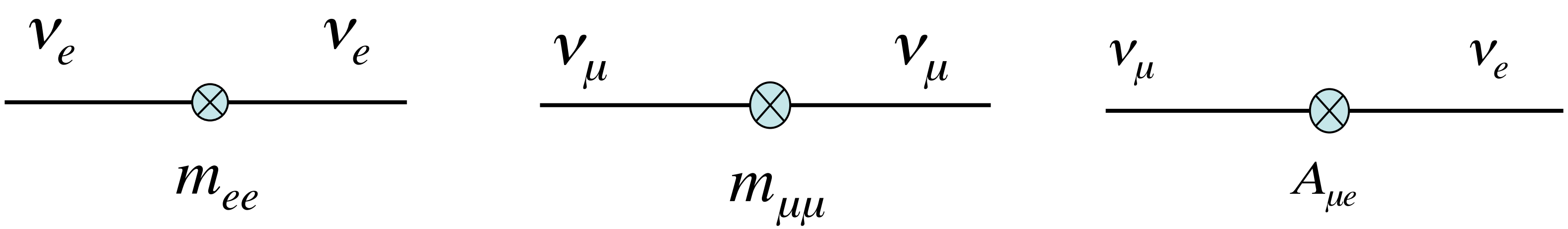
$$\tan 2\theta \equiv \frac{2A_{\mu e}}{m_{\mu\mu} - m_{ee}} = \frac{2Q}{R-P}$$

just for convention

of neutrino oscillation people

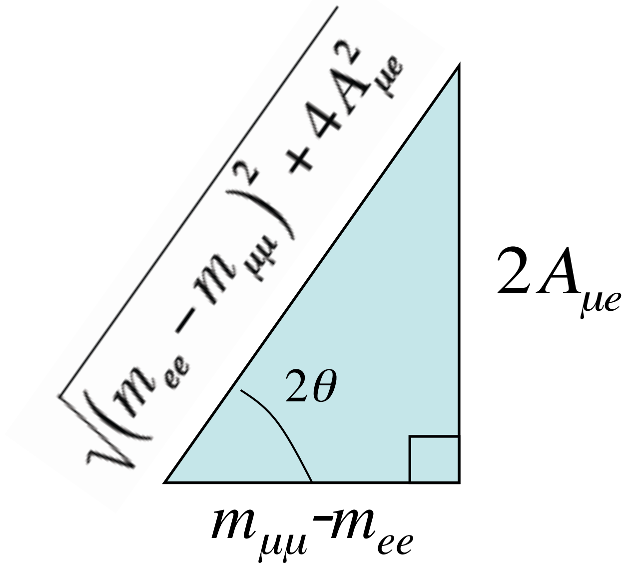


ν Oscillations: ν at rest



Then the energy eigenstates and their energy can be obtained borrowing spin result

$$\begin{pmatrix} |\nu_+\rangle \\ |\nu_-\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\nu_\mu\rangle \\ |\nu_e\rangle \end{pmatrix}$$



$$\begin{cases} m_- = \dfrac{m_{ee}+m_{\mu\mu}}{2} - \sqrt{(m_{ee}-m_{\mu\mu})^2/4 + A_{\mu e}^2} \\ m_+ = \dfrac{m_{ee}+m_{\mu\mu}}{2} + \sqrt{(m_{ee}-m_{\mu\mu})^2/4 + A_{\mu e}^2} \end{cases}$$

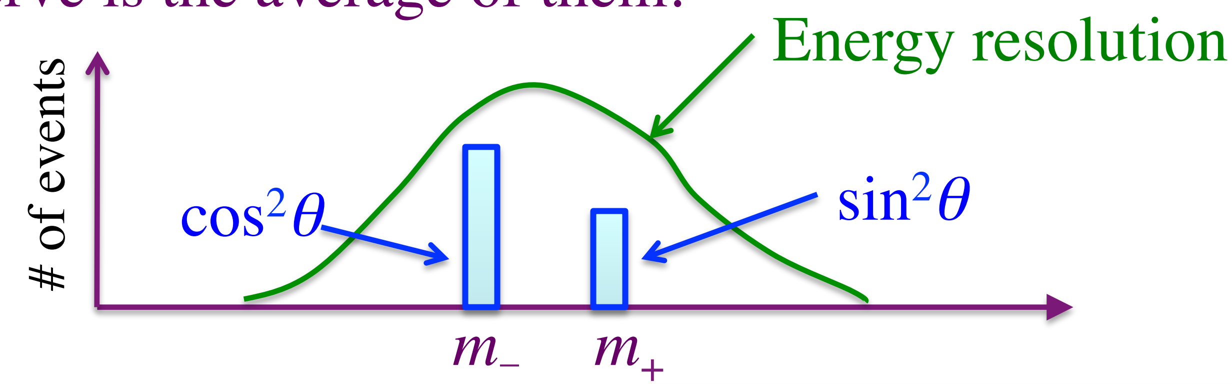
$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left[\frac{m_+ - m_-}{2} t\right]$$

Mass of ν_e

This title sounds to be a paradoxical since ν_e is not mass eigenstate and does not have fixed mass;

$$\nu_e = \cos\theta \nu_- + \sin\theta \nu_+$$

But this wve function means if we measure ν_e mass, m_- is observed with probability $\cos^2\theta$ and m_+ is observed with probability $\sin^2\theta$. If the experiment does not have enough accuracy to separate m_+ and m_- (and this is always so if we know we measure ν_e property) what we observe is the average of them.

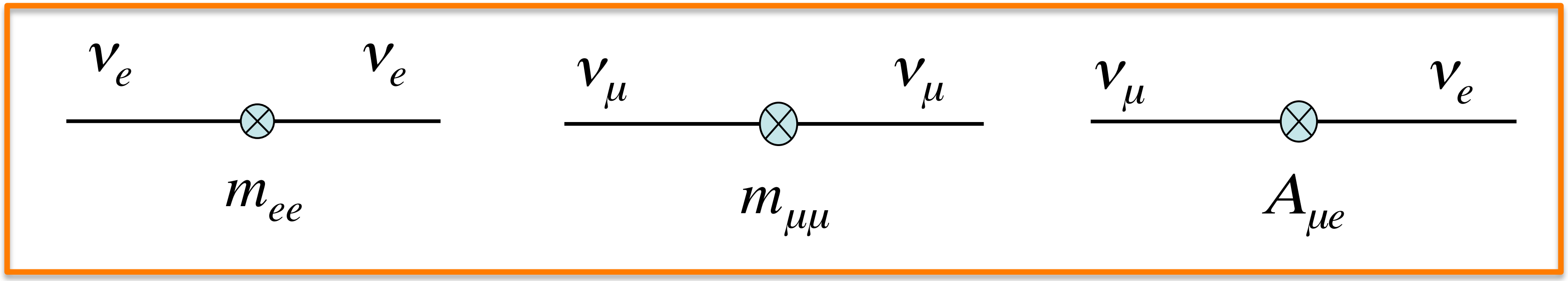


What we observe by experiment $\langle m_{\nu_e} \rangle = m_- \cos^2\theta + m_+ \sin^2\theta = m_{ee}$

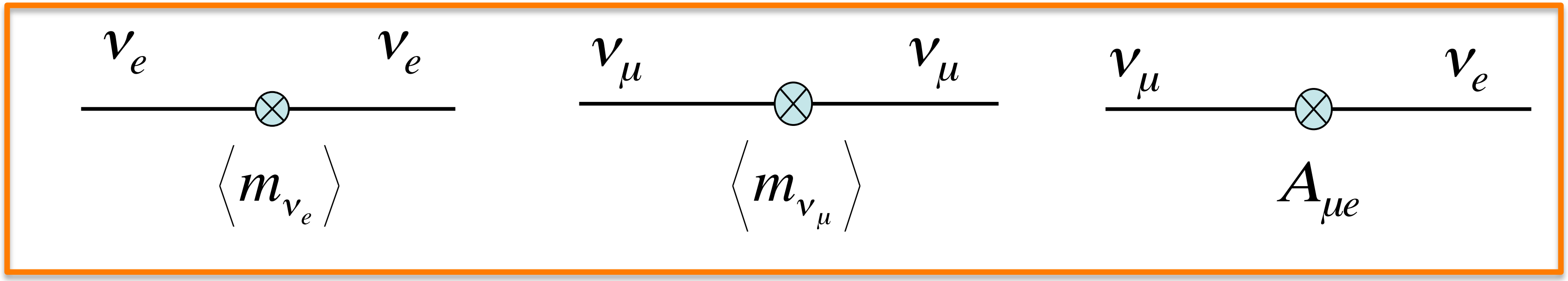
Relation between average ν_e mass and T.A.

And likewise $\langle m_{\nu_\mu} \rangle = m_+ \cos^2\theta + m_- \sin^2\theta = m_{\mu\mu}$

In that sense, we can call the transition amplitudes m_{ee} ($m_{\mu\mu}$) as "electron (muon) neutrino mass", respectively.



If you like, you may re-write.



Oscillation of relativistic ν

Usually text books explain it starting from

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \sin^2\left[\frac{E_+ - E_-}{2} t\right]$$

Then because,

$$E_\pm = \sqrt{p^2 + m_\pm^2} \sim p^2 + \frac{m_\pm^2}{2p} \quad \Rightarrow \quad (E_+ - E_-)t \sim \frac{(m_+^2 - m_-^2)L}{2E\beta^2} \sim \frac{m_+^2 - m_-^2}{2E} L$$

And finally get the standard formula

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \sin^2\left[\frac{\Delta m^2}{4E} L\right]$$

But why we can say p is same?
What is the E in the final formula?
This delivation is based on plain waves. It it OK?

Oscillation of relativistic ν

Actually the formalism of oscillation of relativistic neutrino is not easy.
A prominent theorist said,

> There are still some discussions about the theory of neutrino oscillations even in vacuum. .. The issues become important.. where the uncertainty in energy is much smaller than the oscillation frequency.
> by A.Y.Smirnov@Neutrino2008, Arxive/hep-ph0810.2668

Even nowadays sometimes I see preprints discussing this issue on arXive.
So probably most of us do not understand it yet.

But experimentalists know neutrino is oscillating by heart from their data.
So I would like to push theorists to let us understand it!

Oscillation of relativistic ν

Because most of us do not understand it, it may be allowed to think of it as following way.
It makes an issue of ν oscillation experiment clear.

If neutrino oscillation at rest is seen from the system which moves with velocity $-\beta$ with respect to the system, from Lorentz transformation,

$$\sin^2 \frac{m_+ - m_-}{2} t \xrightarrow{LorentzTrans. \quad @x=\beta t} \sin^2 \frac{m_+ - m_-}{2} \left(\frac{t}{\gamma} \right)$$

ν-Oscillation at rest

where, Lorenz factor: $\gamma = \dfrac{1}{\sqrt{1-\beta^2}}$

Oscillation of relativistic ν

From this system the neutrino energy looks as,

$$E_- = \gamma m_-, \quad E_+ = \gamma m_+ \quad \Rightarrow \quad \gamma = \frac{E_+ + E_-}{m_+ + m_-} = \frac{2\langle E\rangle}{m_+ + m_-}$$

$$\sin^2 \frac{m_+ - m_-}{2}\left(\frac{t}{\gamma}\right) \xrightarrow{\gamma=2\langle E\rangle/(m_+ + m_-)} \sin^2 \frac{m_+^2 - m_-^2}{4\langle E\rangle} t$$

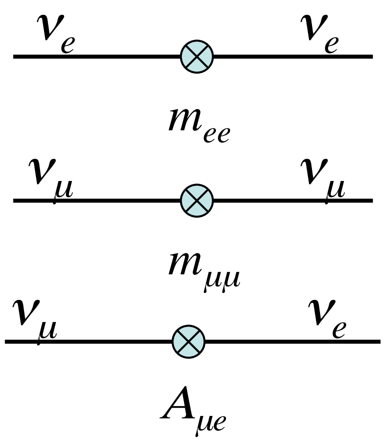
=> Since we do not know the absolute ν masses, we do not know Lorentz factor γ even if we know the energy. This introduces additional uncertainty when extracting T.A. from the data.
(It is not the case for K^0 oscillation and quark oscillation.)

(It should be OK to use $\gamma = E_-/m_-$ and use $\sin^2 \frac{(m_+ - m_-)m_-}{2E_-} t$ as well.)

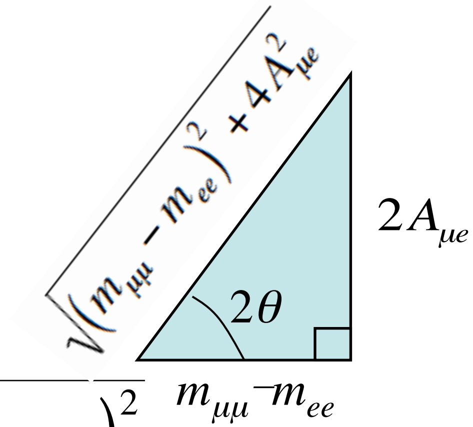
What We Measure by ν Oscillation?

$$P_{\nu_e \to \nu_\mu} = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4E} L$$

Relation between observable and T.A.



$$\begin{cases} \sin^2 2\theta = \dfrac{1}{1+\left(m_{\mu\mu}-m_{ee}\right)^2 / 4A_{\mu e}^2}, \\ \Delta m^2 = \left(m_{\mu\mu}^2 - m_{ee}^2\right)\sqrt{1+4A_{\mu e}^2 / \left(m_{\mu\mu}-m_{ee}\right)^2} \end{cases}$$



Both mass and mixing are combinations of flavor transition amplitudes.

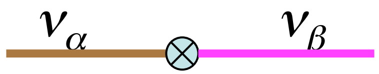
⇒Measurement of mixing angle is as important as measurement of mass.

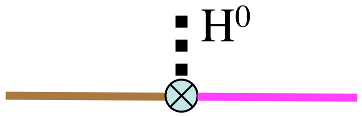
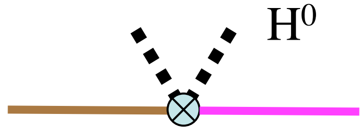
If we could measure Δm^2, θ, and $\langle m_{\nu_e} \rangle$ all the transition amplitude can be determines.

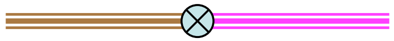
$$\begin{cases} m_{ee} = \langle m_{\nu_e} \rangle \\ m_{\mu\mu} = \sqrt{\langle m_{\nu_e} \rangle^2 + \Delta m^2 \cos 2\theta} \\ A_{\mu e} = \frac{1}{2}\left(\sqrt{\langle m_{\nu_e} \rangle^2 + \Delta m^2 \cos 2\theta} - \langle m_{\nu_e} \rangle \right) \tan 2\theta \end{cases}$$

Purpose of ν Oscillation experiments

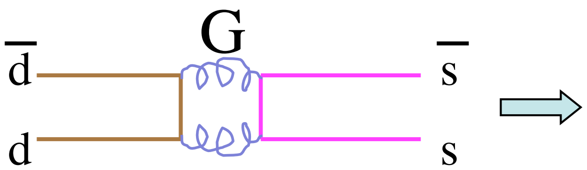
Physics of ν oscillation is to measure the flavor transition amplitudes and think of its origin

Now we know  exists.

Non Standard Higgs?  or  ?

Sub Structure?? 

PS mixing

For Example, 

$$\begin{pmatrix}\pi^0\\ \eta\\ \eta'\end{pmatrix} \sim \begin{pmatrix}0.7 & 0.7 & 0\\ -0.4 & 0.4 & 0.8\\ 0.6 & -0.6 & 0.6\end{pmatrix}\begin{pmatrix}|u\bar{u}\rangle\\ |d\bar{d}\rangle\\ |s\bar{s}\rangle\end{pmatrix}$$

Or something else?? 

ν Oscillation Experiments so far

Atmospheric ν
* SuperKamiokande
* MACRO
* Soudan-2

Accelerator ν
* LSND
* K2K
* T2K
* MINIBOONE
* MINOS
* OPERA

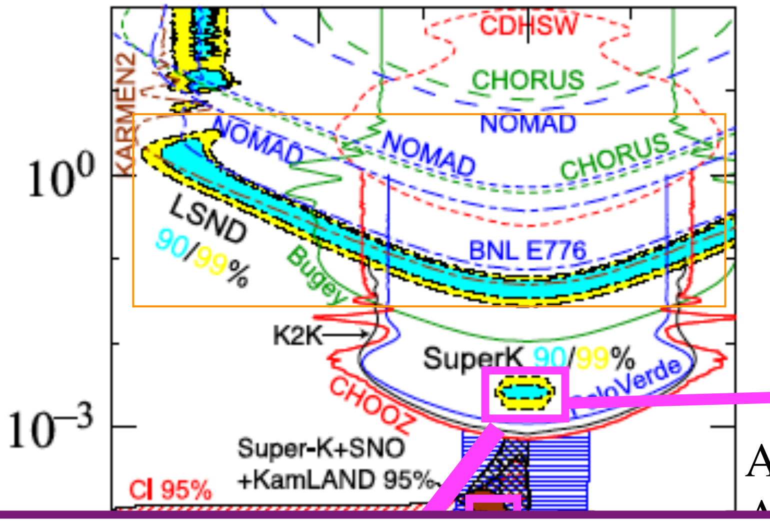
Solar ν
* Homestake
* SAGE
* GALLEX/GNO
* SuperKamiokande
* SNO

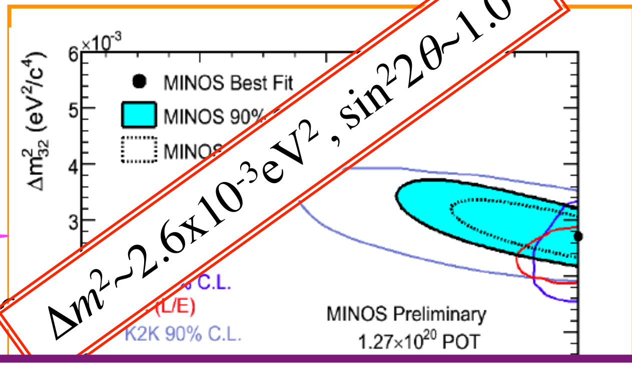
Reacotor ν
* Chooz
* Paloverde
* KamLAND

Murayama

How they were measured?

2 oscillations measured

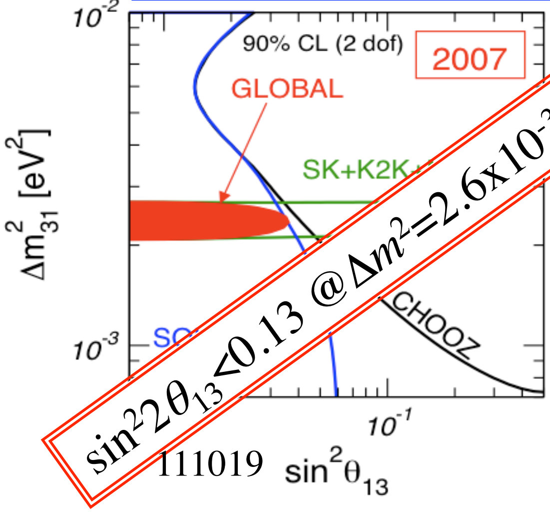




Atmospheric
Accelerator

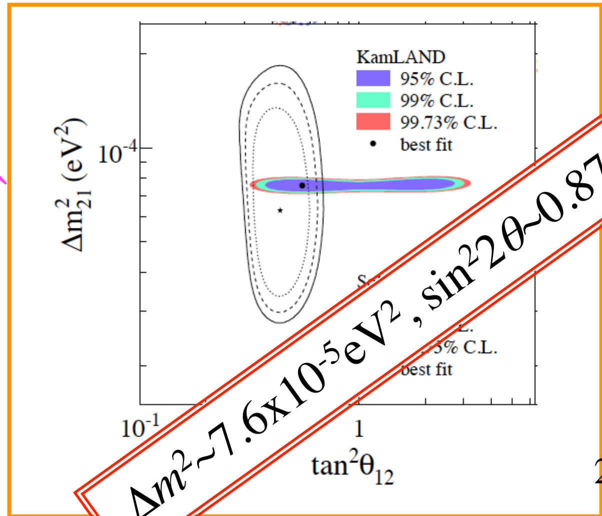
$\Delta m^2 \sim 2.6\mathrm{x}10^{-3}\mathrm{eV}^2$, $\sin^2 2\theta \sim 1.0$

1 upper limit measured



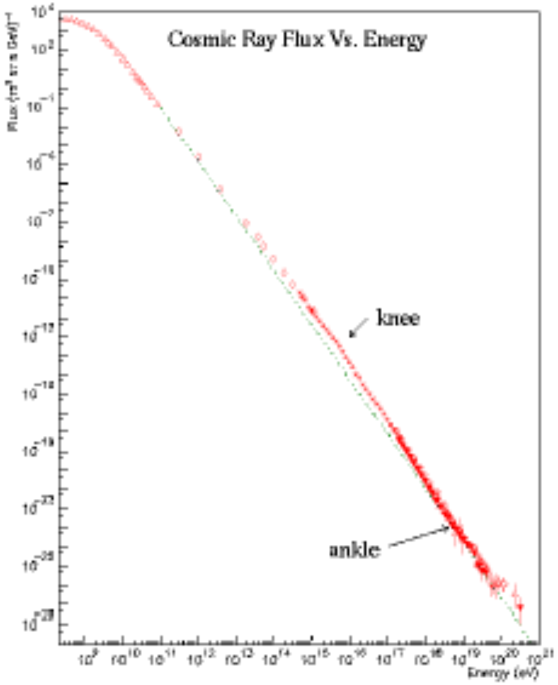
$\sin^2 2\theta_{13} < 0.13$ @ $\Delta m^2 = 2.6\mathrm{x}10^{-3}\mathrm{eV}^2$

Solar
Reactor

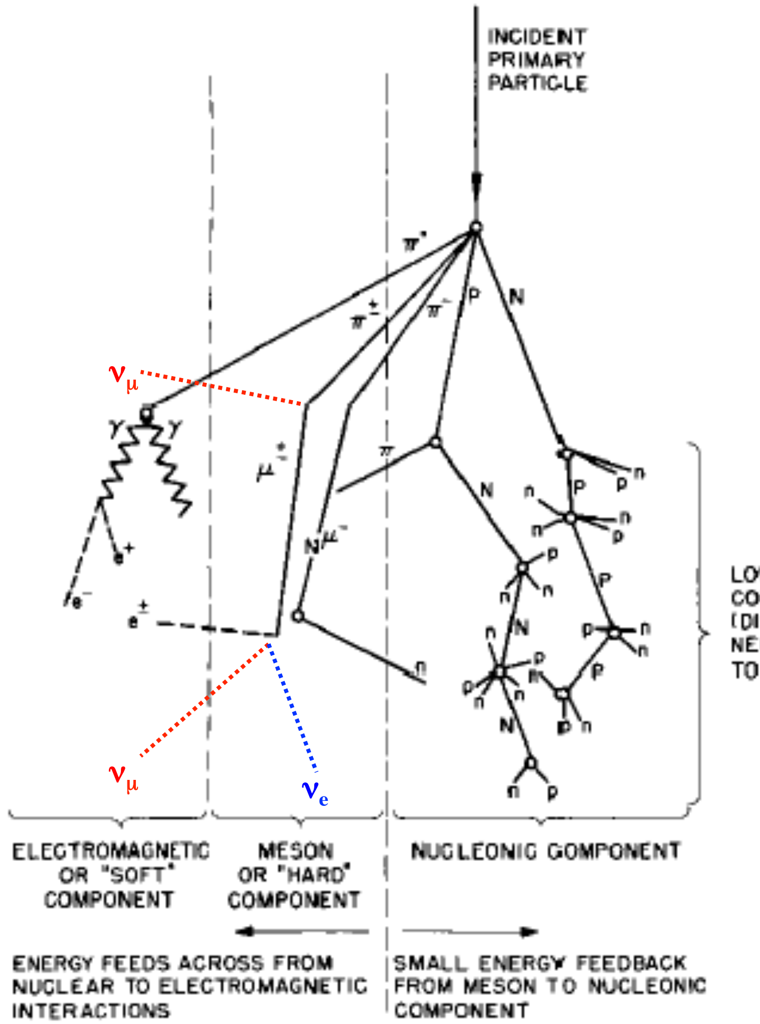


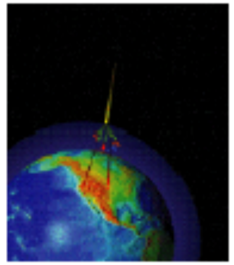
$\Delta m^2 \sim 7.6\mathrm{x}10^{-5}\mathrm{eV}^2$, $\sin^2 2\theta \sim 0.87$

Atmospheric ν



Cosmic Ray Flux vs Energy

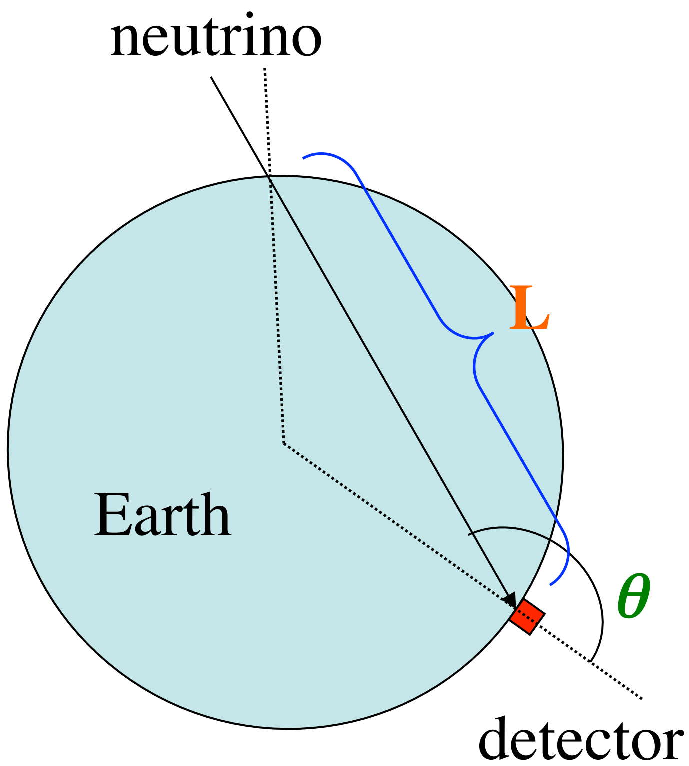




Atmospheric ν anomaly

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad\qquad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

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

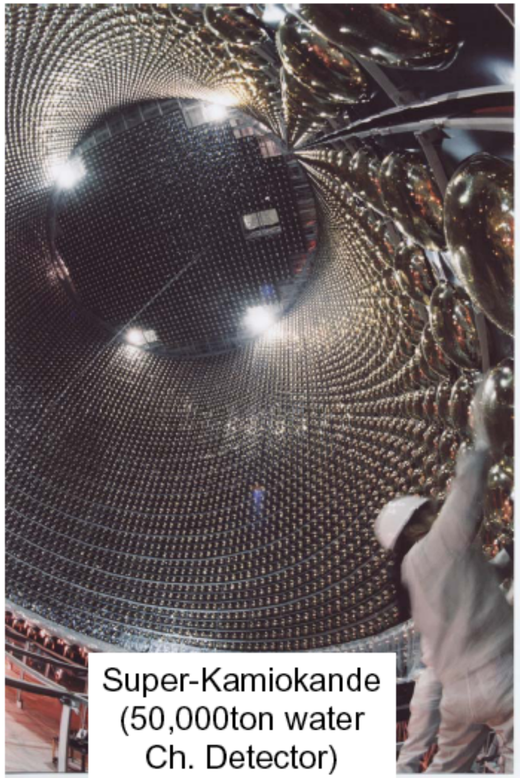


$$R = \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \sim 2$$ Expected.

Observation => R<2 ??
Atmospheric ν anomaly.

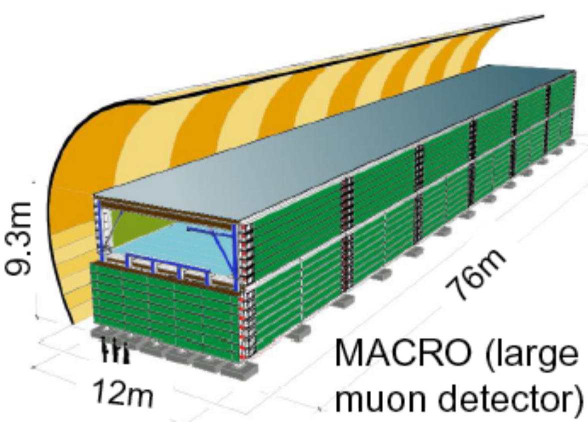
Detect ν from the other side of the Earth.
L=2Rcosθ
=> L dependence of atmospheric ν disappearance.

Atmospheric n experiments



Super-Kamiokande (50,000ton water Ch. Detector)

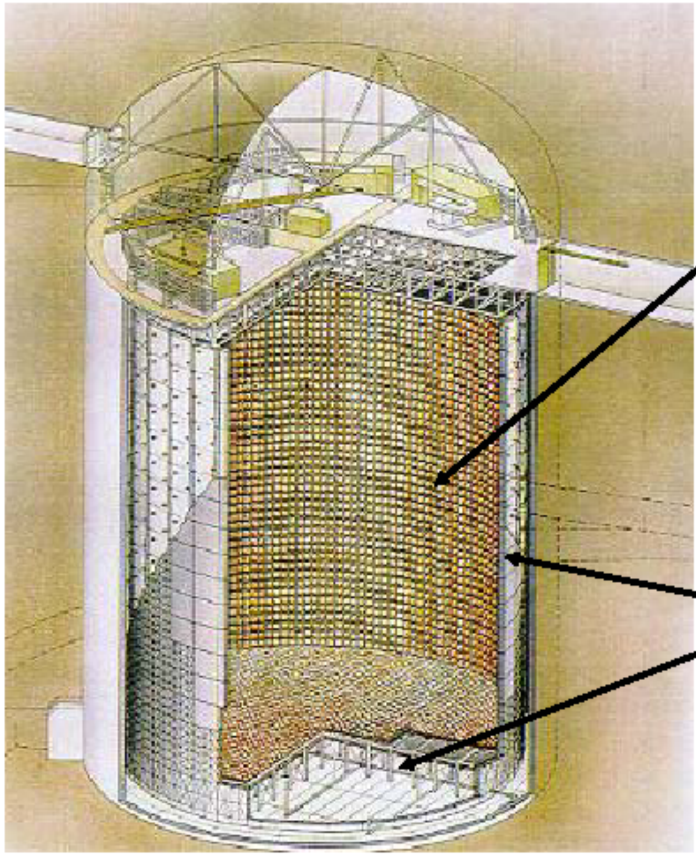
Soudan-2 (1kton



MACRO (large muon detector)

1997: 1st Discovery of neutrino oscillation by atmospheric neutrinos

Super-Kamiokande



11,146×(50cm ϕ PMT) : Inner detector

40% photo-cathode coverage

Number of observed Ch photons ∼ 6 /MeV (excluding scattered or reflected photons)

1,885×(20cm ϕ PMT) : Outer detector

2m active detector region + 0.6m layer (no photon detection)

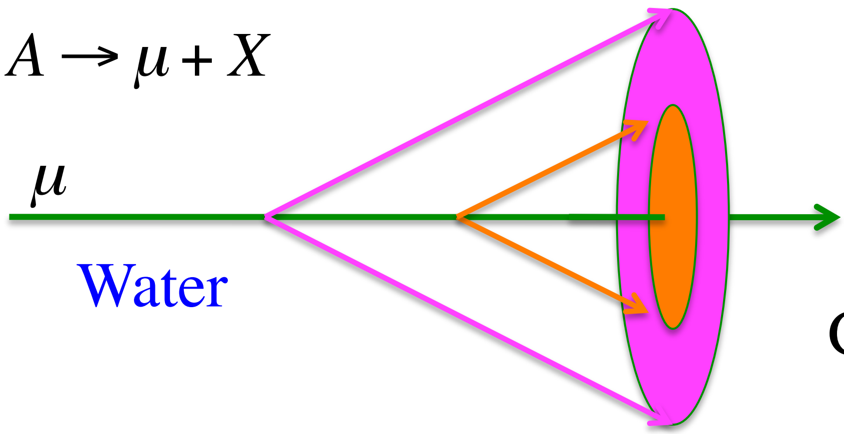
⇨ γ (and neutron) shield

50,000 ton water Cherenkov detector

(Fid. Mass is 22,500 tons)

Detection of Atmospheric ν by water cherenkov detector

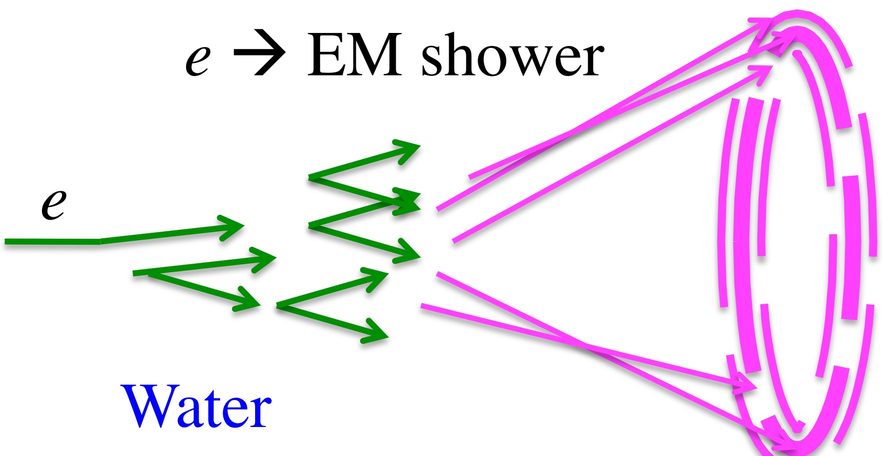
$$\nu_\mu + A \rightarrow \mu + X$$



Clear Cherenkov ring

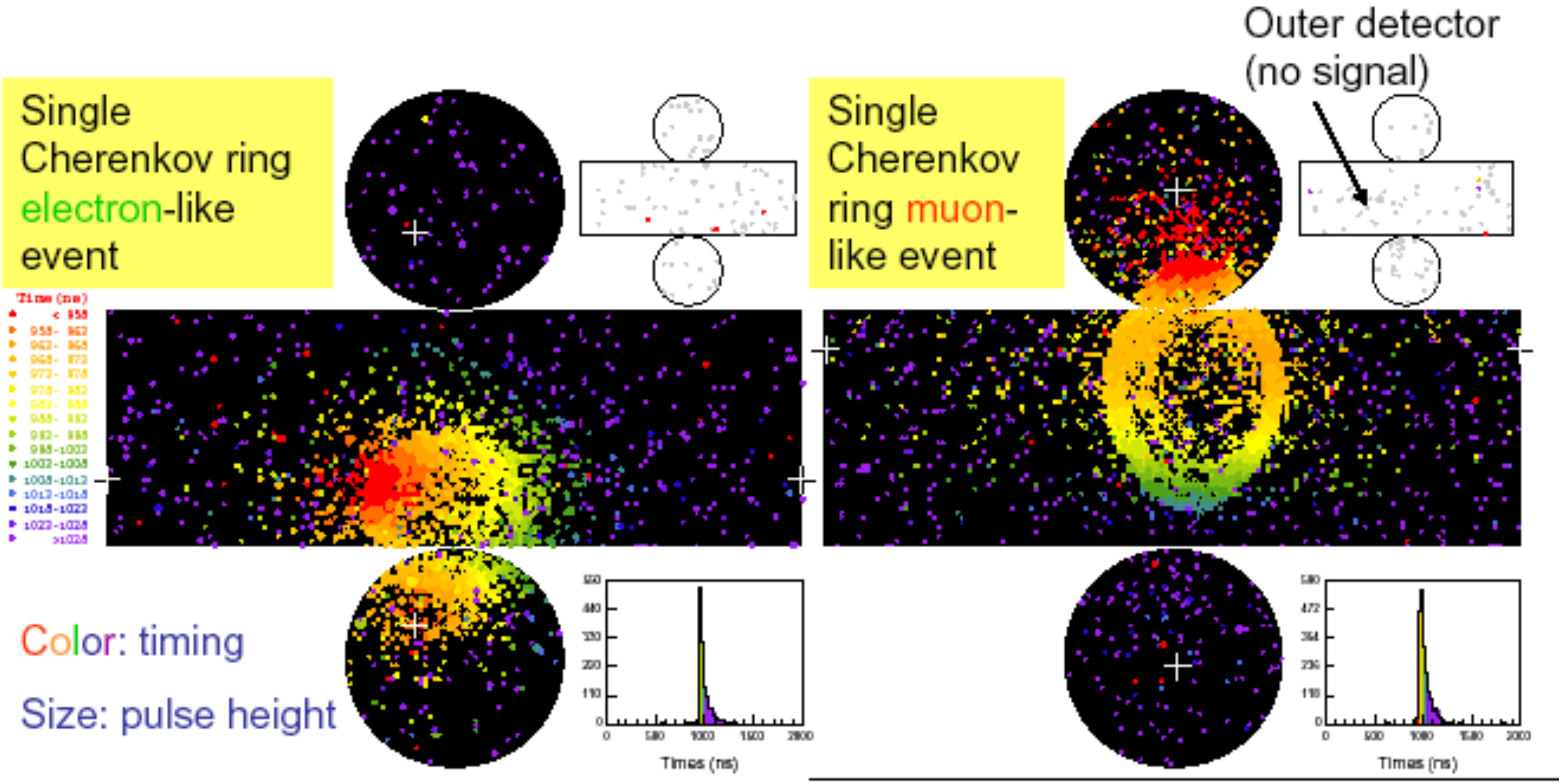
$$\nu_e + A \rightarrow e + X$$

e → EM shower



Blurred Cherenkov ring

Particle identification



Particle ID

$$\log(L) = \sum_{\theta<70\deg} \left(\frac{p.e.(obs'd) - p.e._{e \text{ or } \mu}(expected)}{\sigma_{p.e.}} \right)^2$$

Evidence for oscillation of atmospheric neutrinos

The Super-Kamiokande Collaboration

Y.Fukuda[a], T.Hayakawa[a], E.Ichihara[a], K.Inoue[a], K.Ishihara[a], H.Ishino[a], Y.Itow[a], T.Kajita[a], J.Kameda[a], S.Kasuga[a], K.Kobayashi[a], Y.Kobayashi[a], Y.Koshio[a], M.Miura[a], M.Nakahata[a], S.Nakayama[a], A.Okada[a], K.Okumura[a], N.Sakurai[a], M.Shiozawa[a], Y.Suzuki[a], Y.Takeuchi[a], Y.Totsuka[a], S.Yamada[a], M.Earl[b], A.Habig[b], E.Kearns[b], M.D.Messier[b], K.Scholberg[b], J.L.Stone[b], L.R.Sulak[b], C.W.Walter[b], M.Goldhaber[c], T.Barszczak[d], D.Casper[d], W.Gajewski[d], P.G.Halverson[d,*], J.Hsu[d], W.R.Kropp[d], L.R. Price[d], F.Reines[d], M.Smy[d], H.W.Sobel[d], M.R.Vagins[d], K.S.Ganezer[e], W.E.Keig[e], R.W.Ellsworth[f], S.Tasaka[g], J.W.Flanagan[h,†] A.Kibayashi[h], J.G.Learned[h], S.Matsuno[h], V.J.Stenger[h], D.Takemori[h], T.Ishii[i], J.Kanzaki[i], T.Kobayashi[i], S.Mine[i], K.Nakamura[i], K.Nishikawa[i], Y.Oyama[i], A.Sakai[i], M.Sakuda[i], O.Sasaki[i], S.Echigo[j], M.Kohama[j], A.T.Suzuki[j], T.J.Haines[k,d] E.Blaufuss[l], B.K.Kim[l], R.Sanford[l], R.Svoboda[l], M.L.Chen[m], Z.Conner[m,‡] J.A.Goodman[m], G.W.Sullivan[m], J.Hill[n], C.K.Jung[n], K.Martens[n], C.Mauger[n], C.McGrew[n], E.Sharkey[n], B.Viren[n], C.Yanagisawa[n], W.Doki[o], K.Miyano[o], H.Okazawa[o], C.Saji[o], M.Takahata[o], Y.Nagashima[p], M.Takita[p], T.Yamaguchi[p], M.Yoshida[p], S.B.Kim[q], M.Etoh[r], K.Fujita[r], A.Hasegawa[r], T.Hasegawa[r], S.Hatakeyama[r], T.Iwamoto[r], M.Koga[r], T.Maruyama[r], H.Ogawa[r], J.Shirai[r], A.Suzuki[r], F.Tsushima[r], M.Koshiba[s], M.Nemoto[t], K.Nishijima[t], T.Futagami[u], Y.Hayato[u,§], Y.Kanaya[u], K.Kaneyuki[u], Y.Watanabe[u], D.Kielczewska[v,d], R.A.Doyle[w], J.S.George[w], A.L.Stachyra[w], L.L.Wai[w,**], R.J.Wilkes[w], K.K.Young[w]

1998

3588 cites (as of 15/Sep/2011)

(1)Deficit of ν_μ

(2) ν_e as expected

$= \nu_\mu \to \nu_\tau$ Oscillation

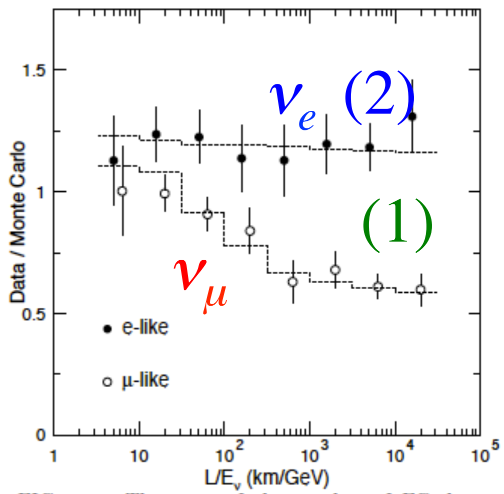


FIG. 4. The ratio of the number of FC data events to FC Monte Carlo events versus reconstructed L/E_ν. The points show the ratio of observed data to MC expectation in the absence of oscillations. The dashed lines show the expected shape for $\nu_\mu \leftrightarrow \nu_\tau$ at $\Delta m^2 = 2.2 \times 10^{-3}\mathrm{eV}^2$ and $\sin^2 2\theta = 1$. The slight L/E_ν dependence for e-like events is due to contamination (2-7%) of ν_μ CC interactions.

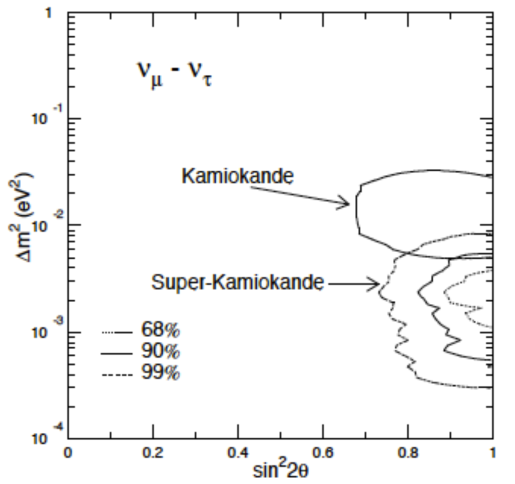
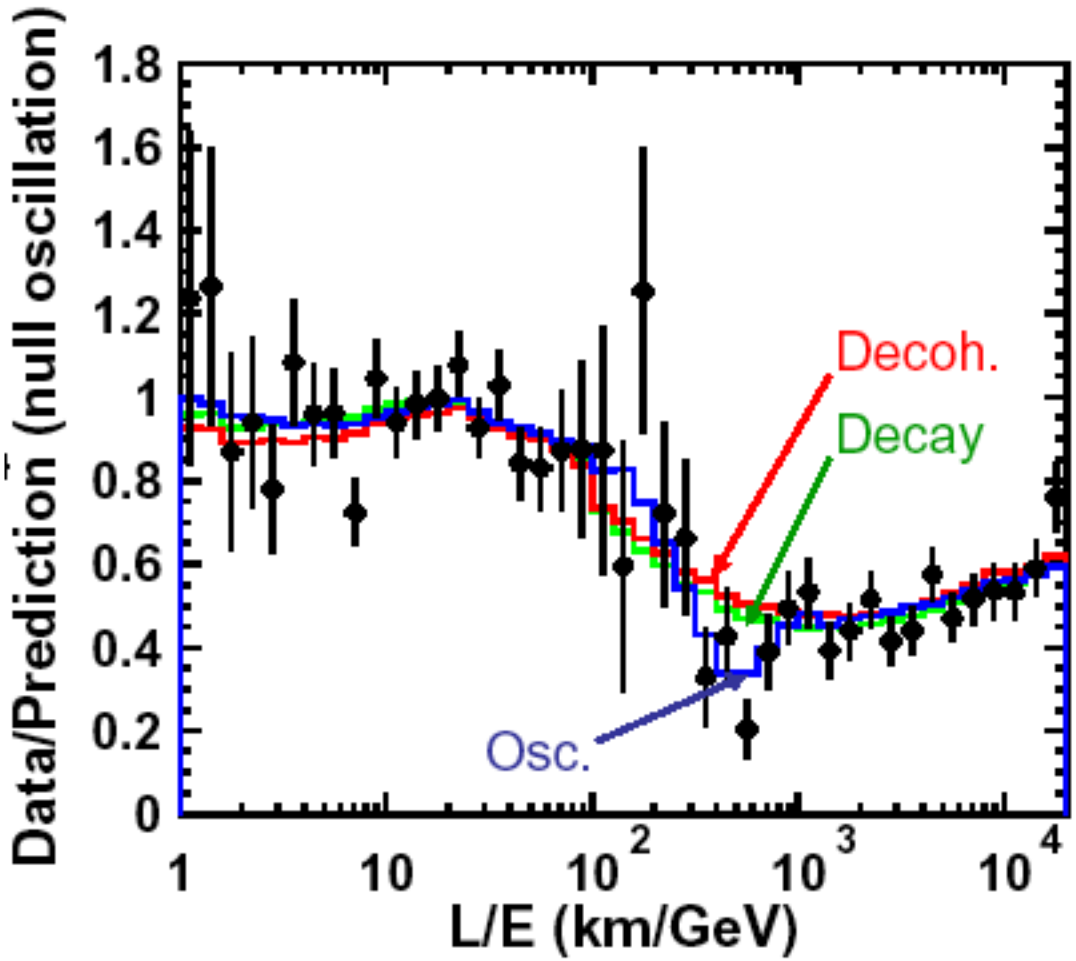


FIG. 2. The 68%, 90% and 99% confidence intervals are shown for $\sin^2 2\theta$ and Δm^2 for $\nu_\mu \leftrightarrow \nu_\tau$ two-neutrino oscillations based on 33.0 kiloton-years of Super–Kamiokande data. The 90% confidence interval obtained by the Kamiokande experiment is also shown.

$\sin^2 2\theta \sim 1$

$\Delta m^2 \sim 2\text{x}10^{-3}\mathrm{eV}^2$

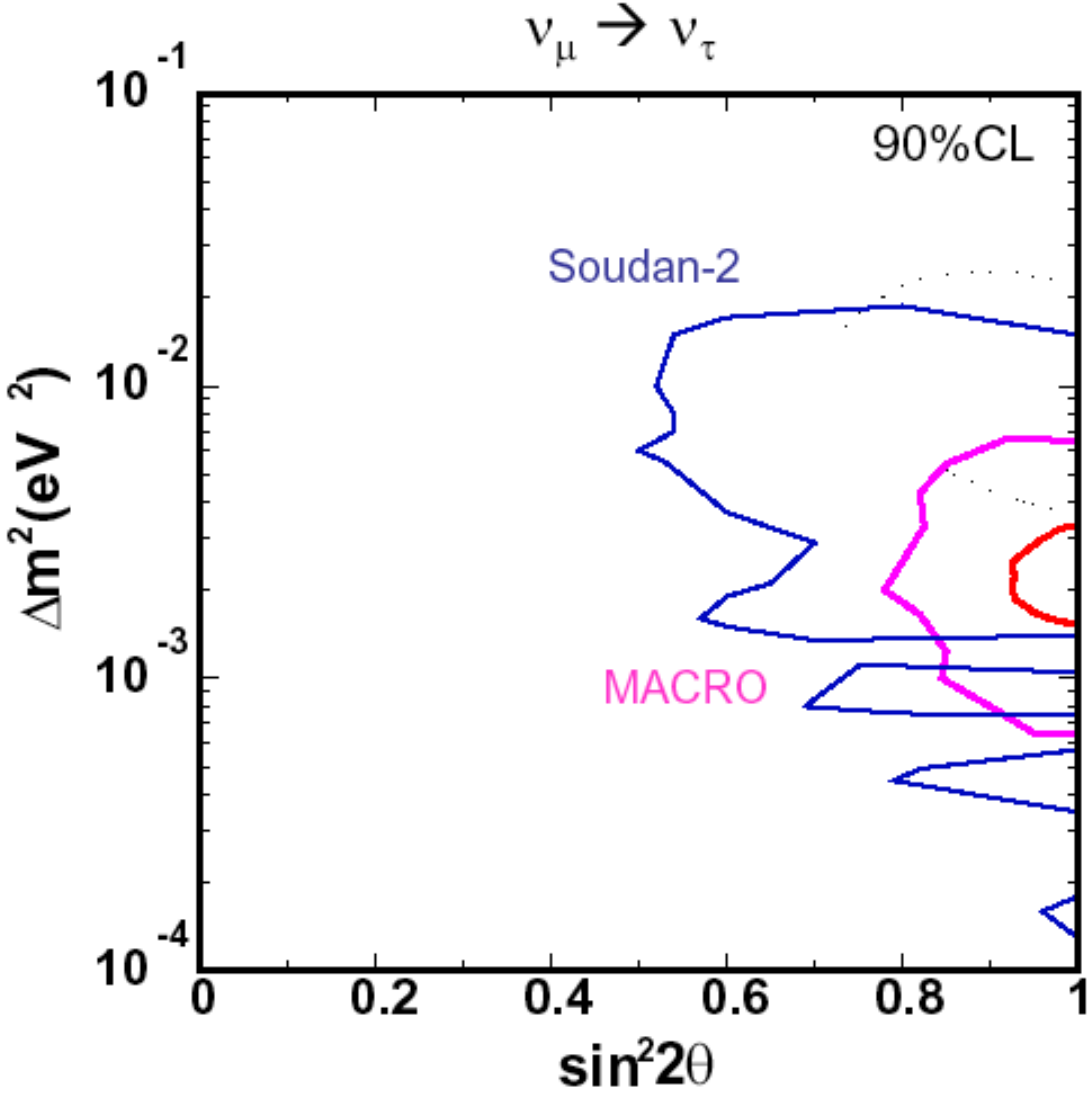


Recovery of event rate in L only occurs by oscillation.
Not by one-way processes like decay and decoherence

2004

Decay and decoherence disfavored at 3.4 and 3.8σ level, respectively.

Neutrino oscillation parameters



$$\begin{cases} 1.5 < \Delta m_{23}^2 < 3.4 \times 10^{-3} (eV^2) \\ \sin^2 2\theta_{23} > 0.92 \end{cases}$$

Long Baseline Accelerator Experiments
(=high energy ν_μ beam)

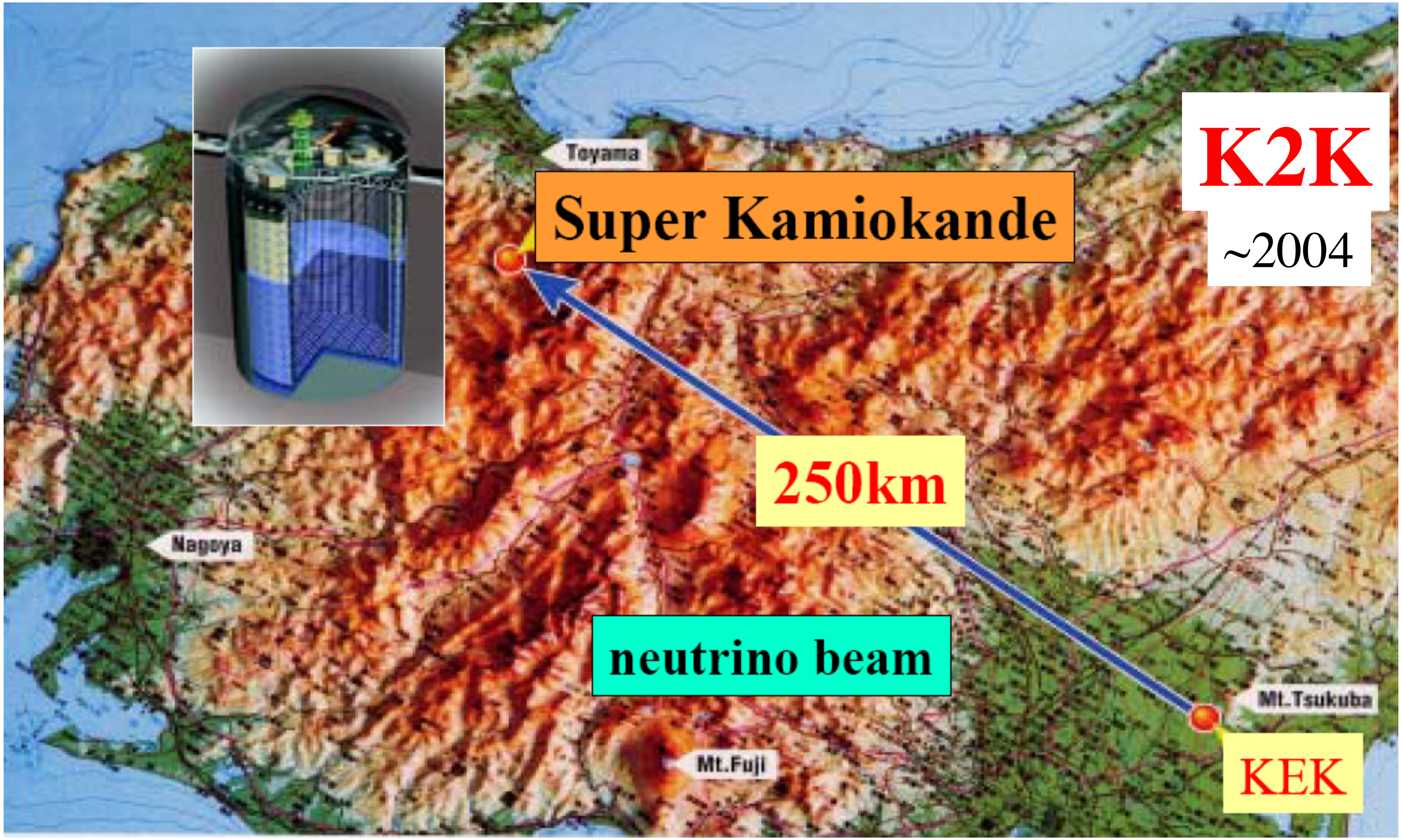
K2K/T2K

MINOS

(NOVA)

OPERA

K2K=KEK to Kamioka



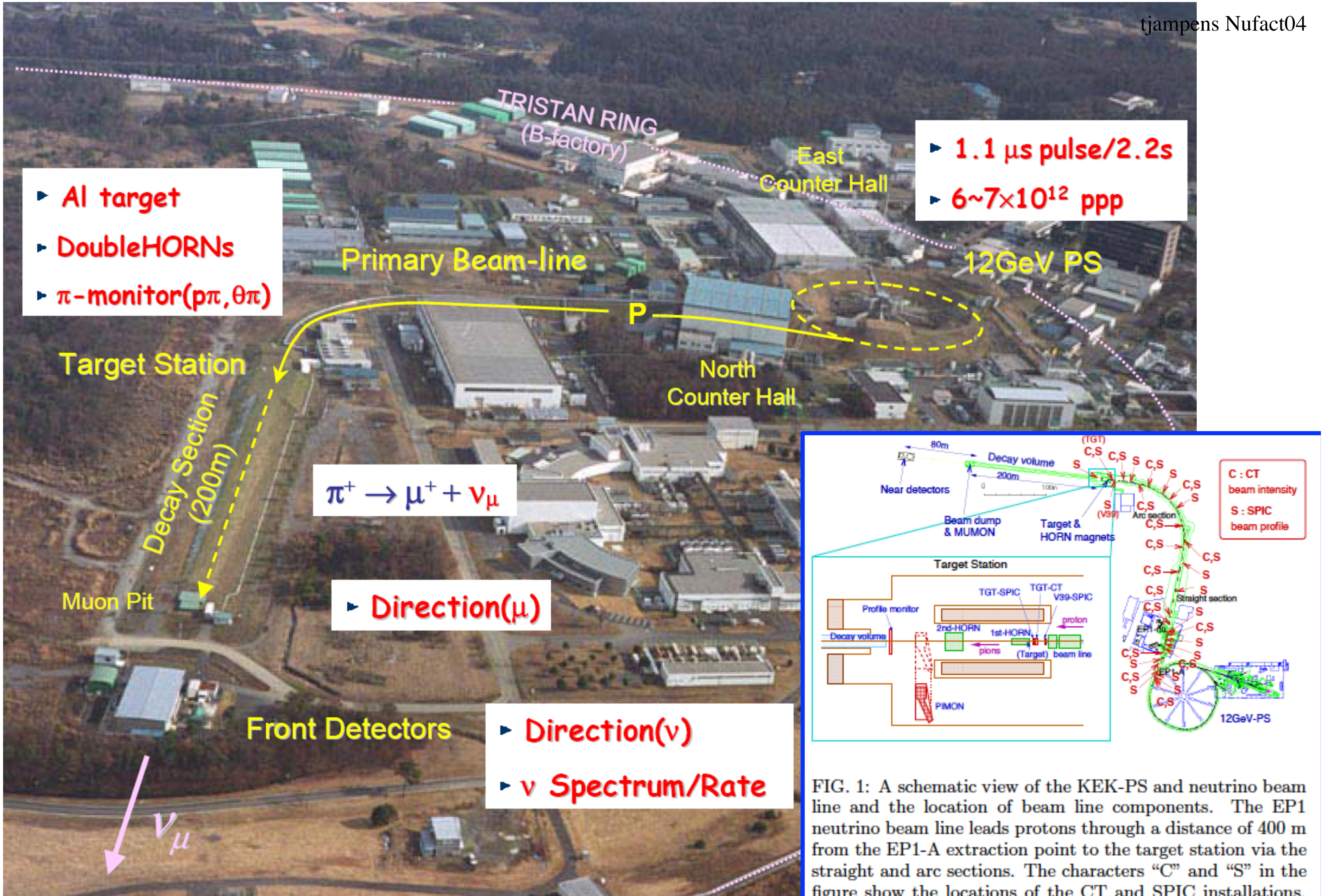
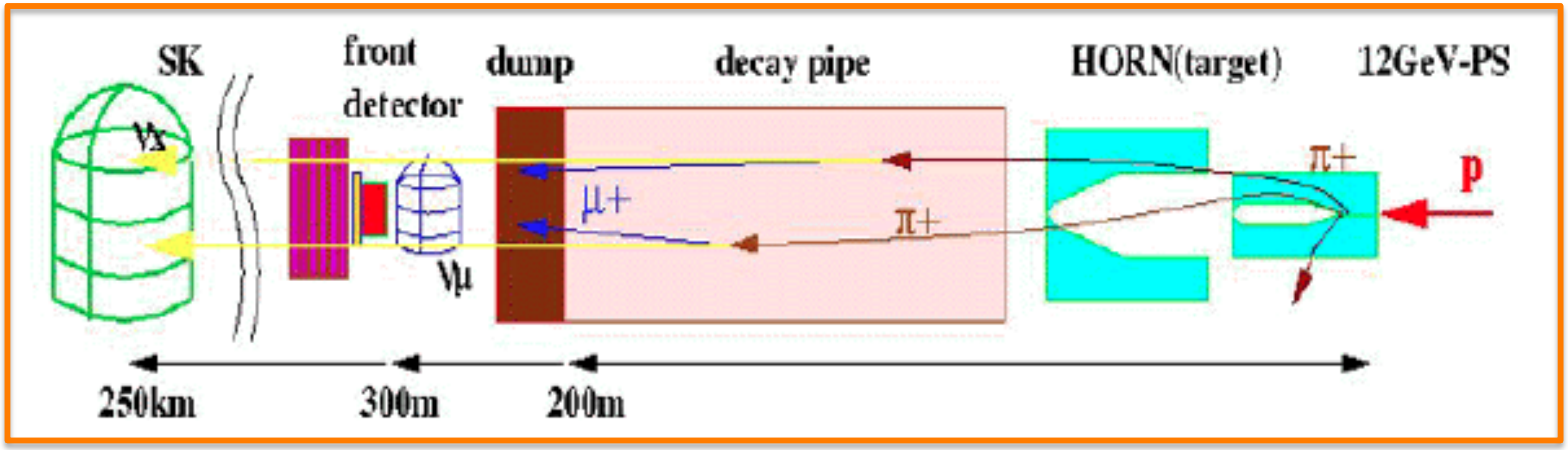


FIG. 1: A schematic view of the KEK-PS and neutrino beam line and the location of beam line components. The EP1 neutrino beam line leads protons through a distance of 400 m from the EP1-A extraction point to the target station via the straight and arc sections. The characters "C" and "S" in the figure show the locations of the CT and SPIC installations, respectively. The lower-left inset is a magnified view of the target station. The production target and a set of horn magnets are located in the target station. A pion monitor was installed on two occasions downstream the horn magnets.

How ν beam is generated

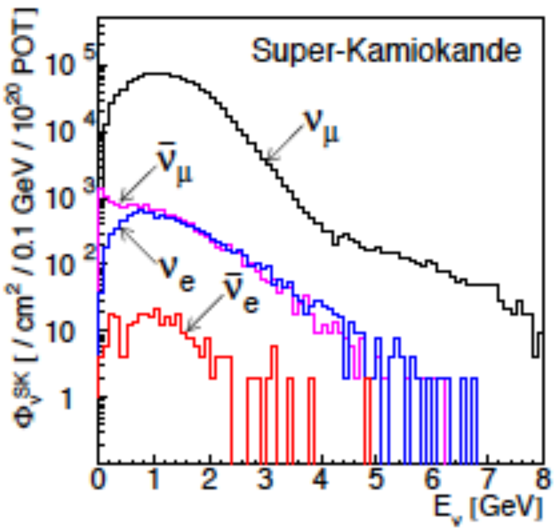


$$p + A \to \pi^+ : \quad \pi^+ \to \mu^+ + \nu_\mu$$

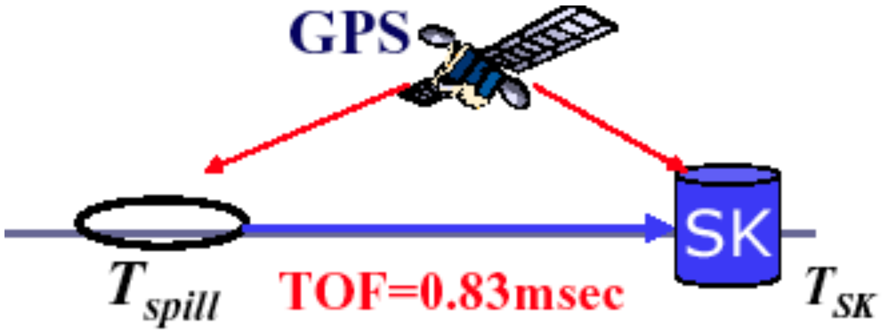
$$\frac{\pi^+ \to e^+ + \nu_e}{\pi^+ \to \mu^+ + \nu_\mu} \sim 10^{-4}$$ (Helicity Suppression
=> Almost pure ν_μ

Main ν_e contamination comes from

$$\frac{p + A \to K^+ + X}{p + A \to \pi^+ + X} \times \frac{K^+ \to \pi^0 + e^+ + \nu_e}{K^+ \to all} \sim \varepsilon \times 5\%$$



Synchronization of timing
=Removal of Backgrounds



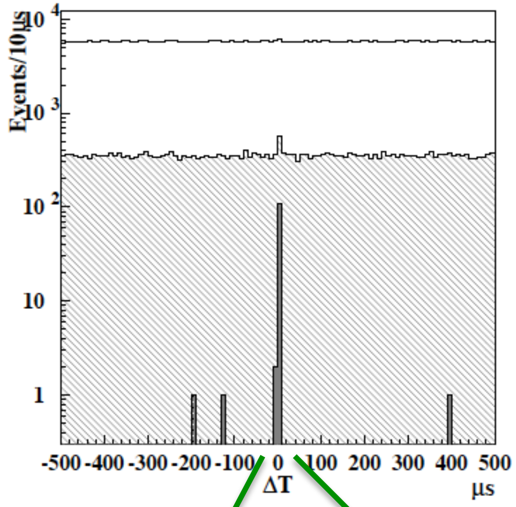


FIG. 34: The ΔT distribution at each reduction step. Clear, hatched and shaded histograms are after pre-activity cut, total p.e. cut, and fiducial volume cut, respectively.

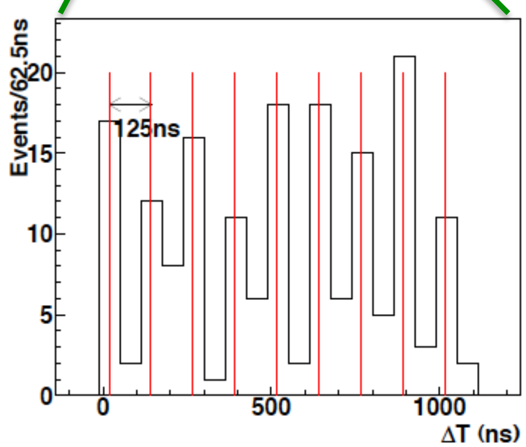


FIG. 35: The ΔT distribution for fully contained events. The nine micro-bunch structure present in the beam is clearly seen.

$P(\nu_\mu \to \nu_\mu)$

K2K result

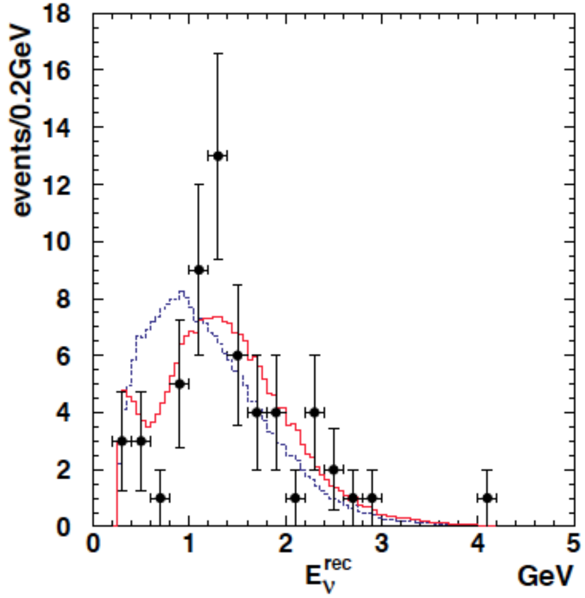


FIG. 43: The reconstructed E_ν distribution for the 1-ring μ-like sample. Points with error bars are data. The solid line is the best fit spectrum with neutrino oscillation and the dashed line is the expectation without oscillation. These histograms are normalized by the number of events observed (58).

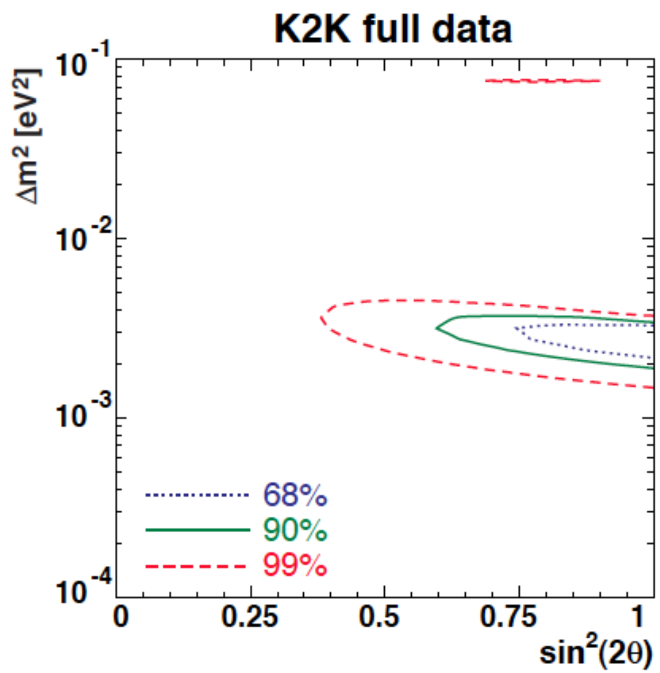


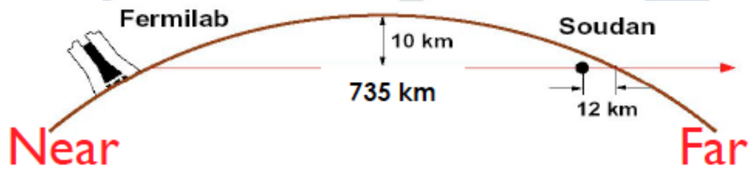
FIG. 44: Allowed regions of oscillation parameters. Three contours correspond to the 68% (dotted line), 90% (solid line) and 99% (dashed line) CL. allowed regions, respectively.

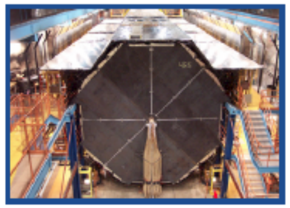
$$\sin^2 2\theta \sim 1$$

$$\Delta m^2 = \left(2.8^{+0.7}_{-0.9}\right) \times 10^{-3} \left[eV^2\right] (90\% CL)$$

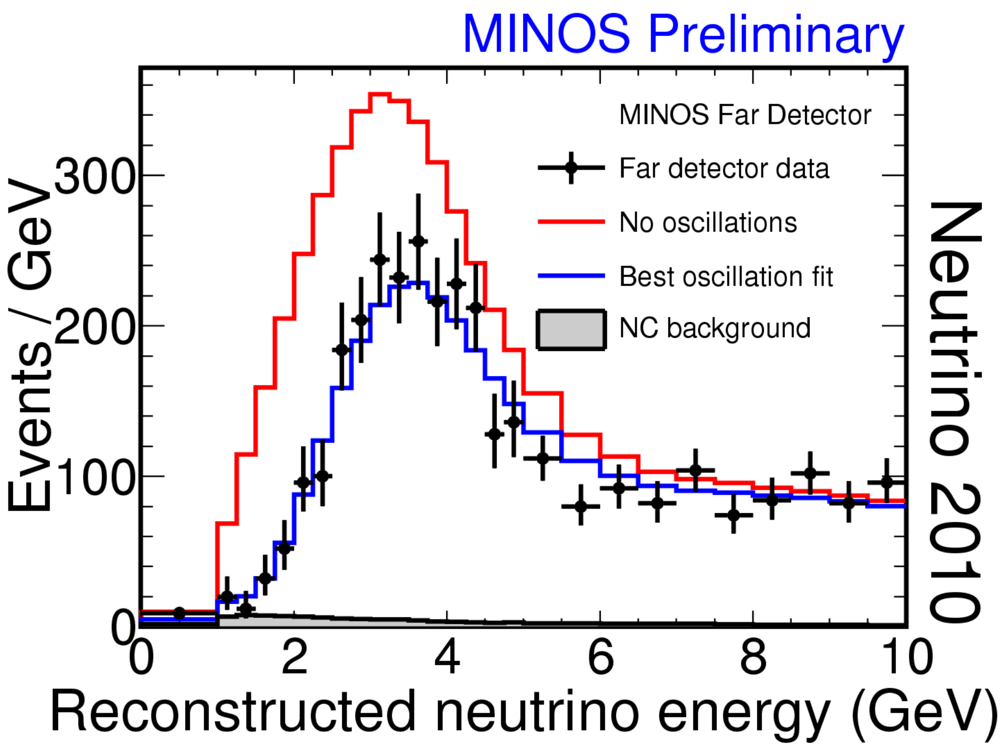
MINOS Overview

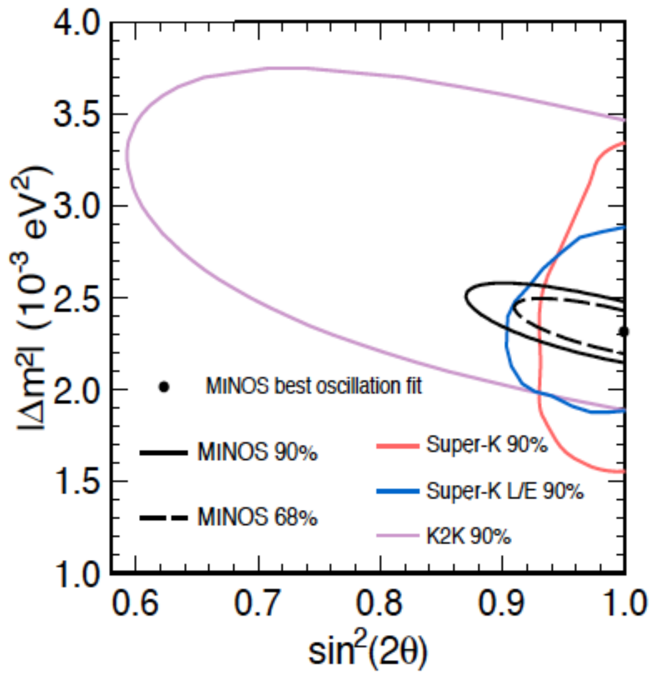
- **MINOS (Main Injector Neutrino Oscillation Search)**
  - High intensity **NuMI ν_μ beam** produced at Fermilab
  - **Near Detector** at Fermilab
  - **Far Detector**, 735 km away, in the Soudan mine, MN
- Magnetized detectors allow unique ability to distinguish between ν_μ and $\bar{\nu}_\mu$ charged-current interactions on an event-by-event basis
- Compare Far Detector observations with extrapolation of Near Detector measurement to study neutrino oscillations





MINOS $\nu_\mu \rightarrow \nu_\mu$ oscillation measurement





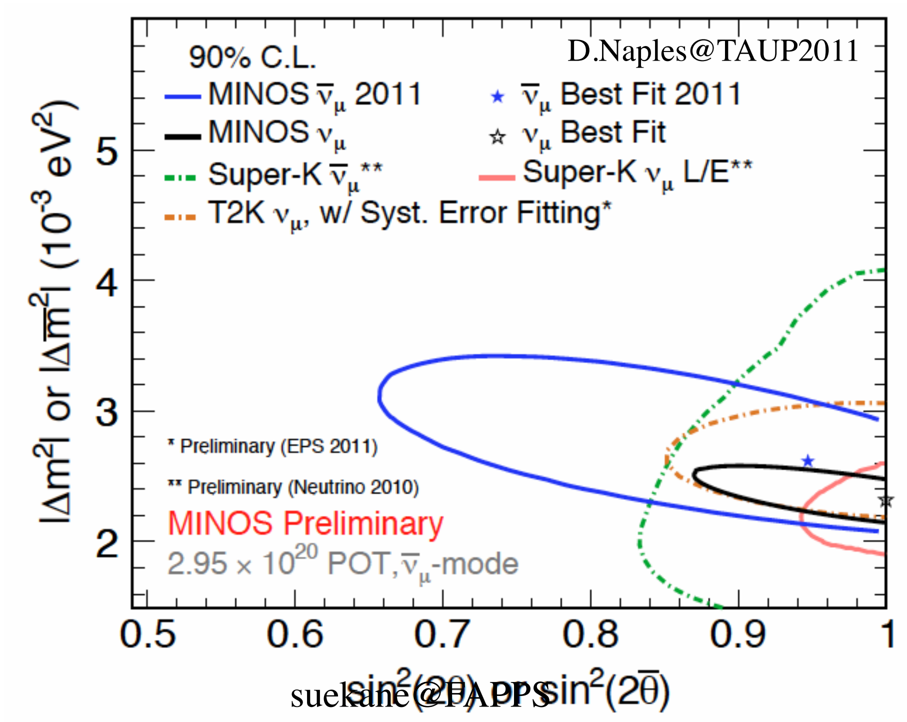
MINOS $\bar{\nu}_\mu \to \bar{\nu}_\mu$ oscillation measurement

$$p + Z \to n\pi^- + m\pi^+ + X$$

$$\pi^+ \to \nu_\mu + \mu^+ : \boxed{\nu_\mu \to \nu_X} : \nu_\mu + A \to \mu^- + X$$

$$\pi^- \to \bar{\nu}_\mu + \mu^- : \boxed{\bar{\nu}_\mu \to \bar{\nu}_X} : \bar{\nu}_\mu + A \to \mu^+ + X'$$

Change the polarity of the magnets in the beam line



CPT is OK

OPERA: Oscillation Project with Emulsion tRacking Apparatus

- High-energy long baseline ν_μ beam
- Direct search for $\nu_\mu \rightarrow \nu_\tau$ oscillations by looking at the **appearance** of ν_τ in a pure ν_μ beam
- Search for the sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations for Θ_{13} measurement

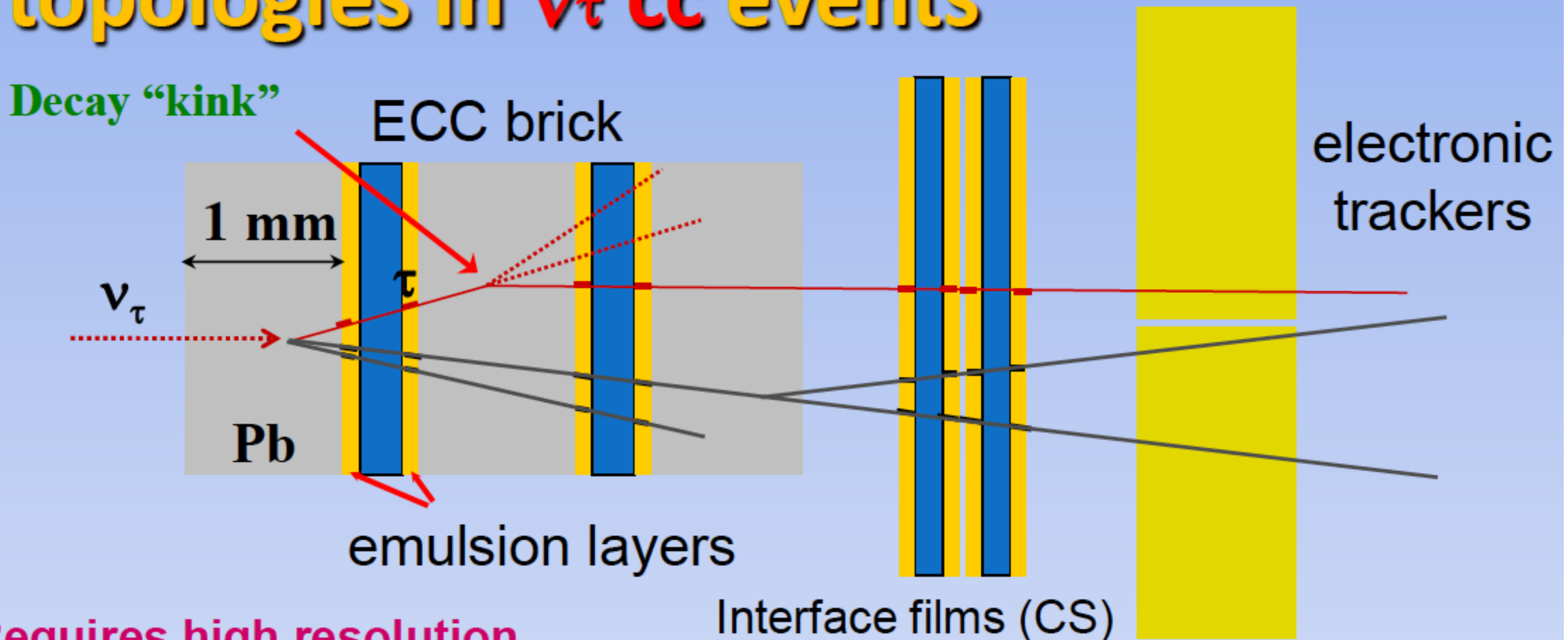
7 september 2011 OPERA experiment, A. Chukanov 3

OPERA

* Appearance of $\nu_\mu \rightarrow \nu_\tau$
* ν_τ+X → τ+X' and identify τ by nuclear emulsion hybrid detector.
* Maybe the 1st experiment to confirm appearance.
(So far all the ν oscillation experiments measured disappearance)

* Difficulty are that the m_τ is large and difficult to produce τ (En>3.5GeV)
and that τ is difficult to identify.
It decays to μ or e within 1mm and difficult to separate from ν_μ+X → μ+X' unless decay vertex is identified.

Direct observation of τ decay topologies in ν_τ cc events



Requires high resolution detector (δx~1 μm, δθ~1 mrad)

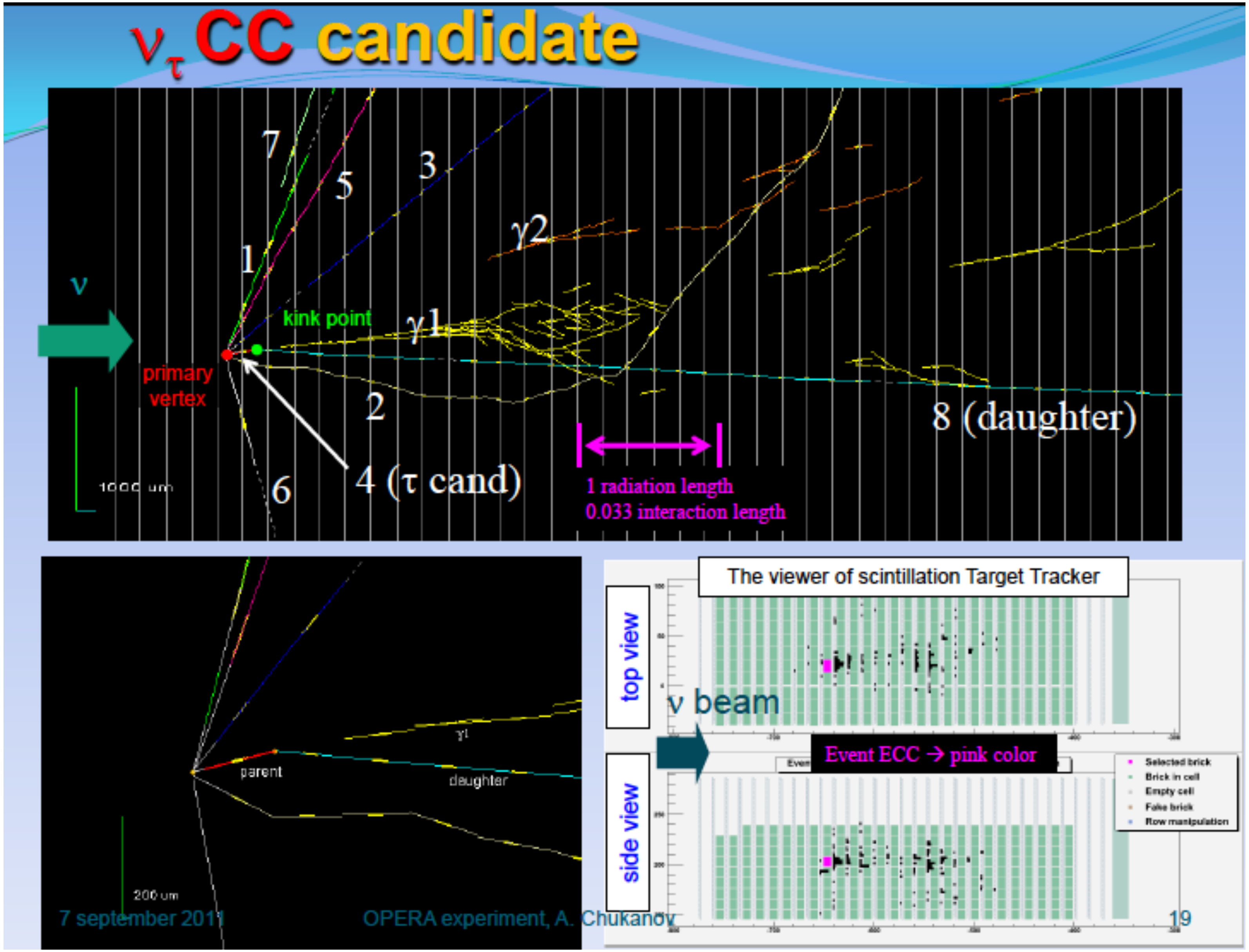
Needs large target mass

Prediction the region of the target where each event occurred

- use nuclear emulsions
- alternate emulsion films with lead layer
- Electronic trackers

OPERA Detector

7 september 2011 OPERA experiment, A. Chukanov 11


ντ CC candidate
ν
primary vertex
kink point
7
5
3
1
γ2
γ1
2
4 (τ cand)
6
8 (daughter)
1000 um
1 radiation length
0.033 interaction length
parent
daughter
200 um
7 september 2011
OPERA experiment, A. Chukanov
19
The viewer of scintillation Target Tracker
top view
side view
ν beam
Event ECC → pink color
Selected brick
Brick in cell
Empty cell
False brick
Row manipulation

This is more famous now for OPERA

CERN Press Release 11/09/28 15:50

Press Release

OPERA experiment reports anomaly in flight time of neutrinos from CERN to Gran Sasso

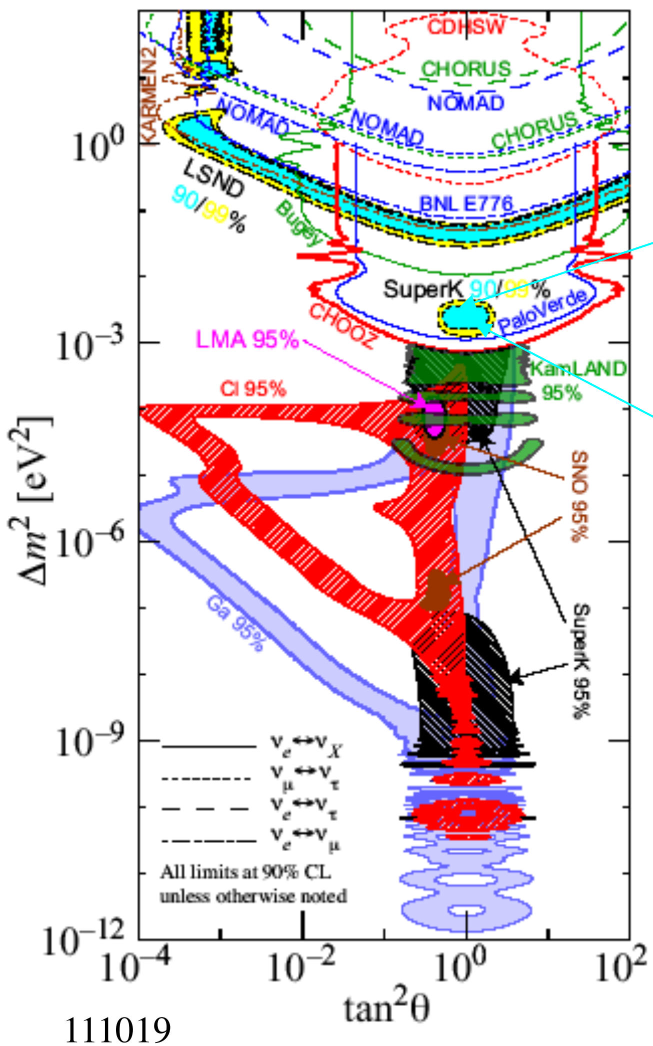
PR19.11
23.09.2011

Geneva, 23 September 2011. The OPERA[1] experiment, which observes a neutrino beam from CERN[2] 730 km away at Italy's INFN Gran Sasso Laboratory, will present new results in a seminar at CERN this afternoon at 16:00 CEST. The seminar will be webcast at http://webcast.cern.ch. Journalists wishing to ask questions may do so via twitter using the hash tag #nuquestions, or via the usual CERN press office channels.

The OPERA result is based on the observation of over 15000 neutrino events measured at Gran Sasso, and appears to indicate that the neutrinos travel at a velocity 20 parts per million above the speed of light, nature's cosmic speed limit. Given the potential far-reaching consequences of such a result, independent measurements are needed before the effect can either be refuted or firmly established. This is why the OPERA collaboration has decided to open the result to broader scrutiny. The collaboration's result is available on the preprint server arxiv.org: http://arxiv.org/abs/1109.4897.

It is a great discovery if it is true. But needs independent tests.

Summary of atom. & LBL accel. ν experiments



Atmospheric
K2K

K2K(positive)

MINOS

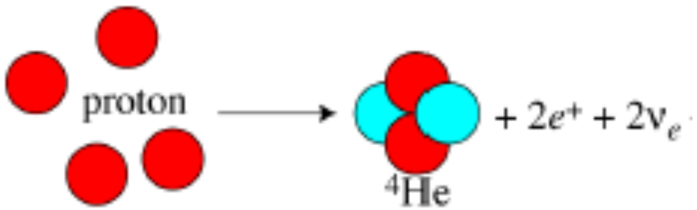
T2K

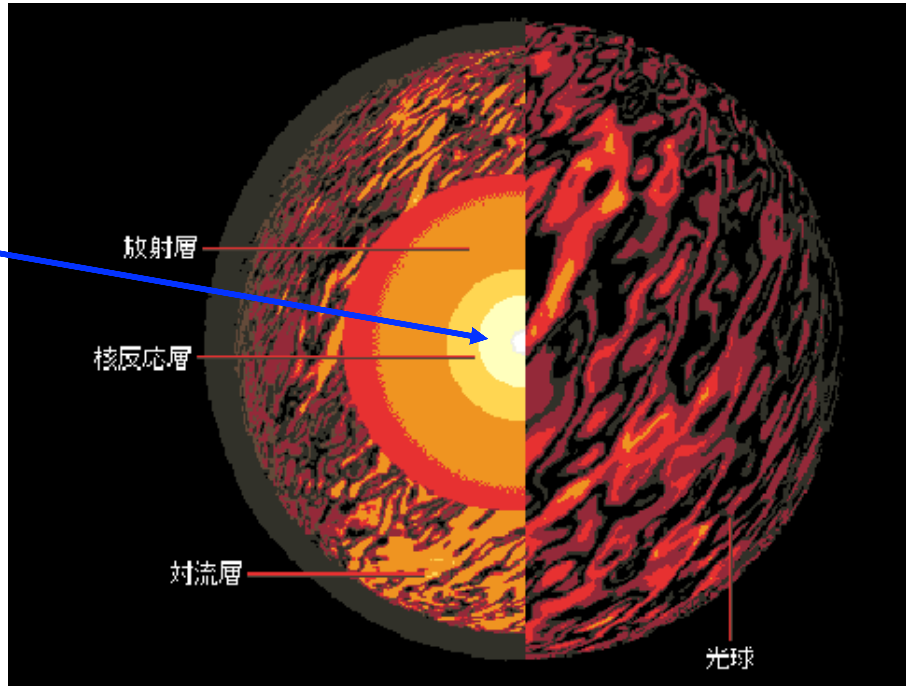
$$\sin^2 2\theta \sim 1, \quad \Delta m^2 \sim 2.5\times 10^{-3}\left[eV^2\right]$$

Solar ν
(=low energy ν_e)

Production of solar ν

$$\rho_c \approx 150\,g/cc, \quad T_c \approx 1.6\,KeV$$





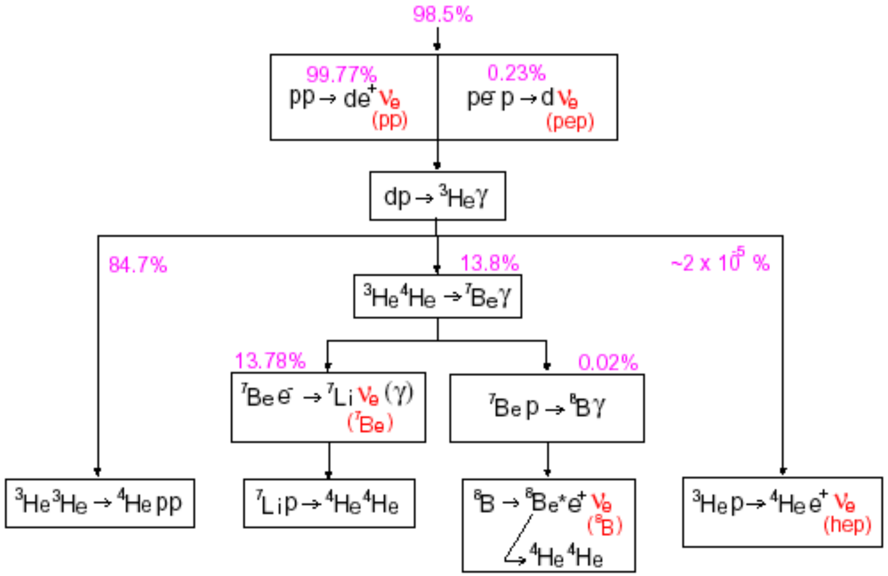
$$4p + 2e^- \rightarrow {}^4He + \underline{2\nu_e} + 26.73MeV - E_\nu$$

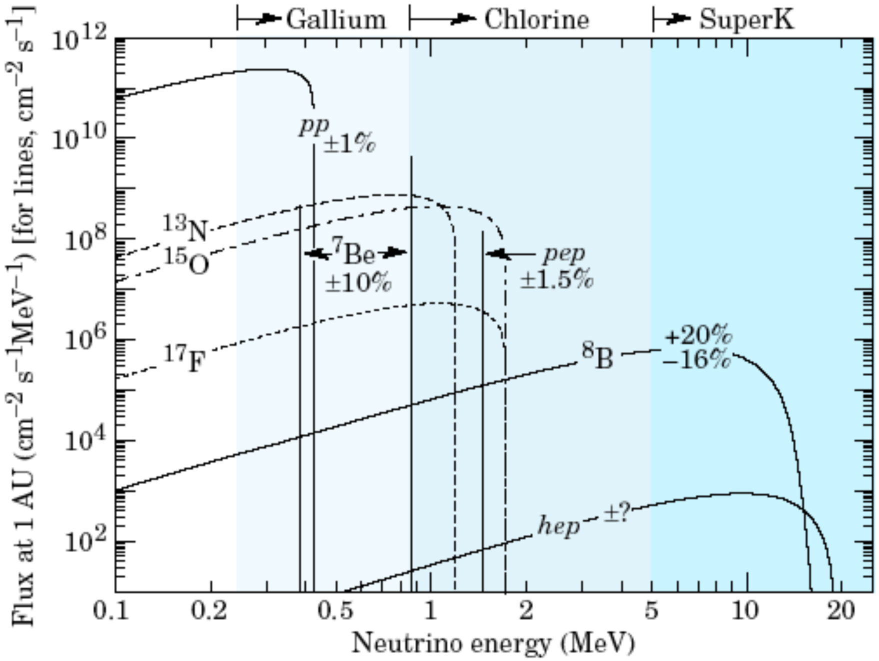
$$\langle E_\nu \rangle \sim 0.6MeV$$

ν flux @ Earth

$$J_\nu = \frac{n_\nu}{Q} J_Q \approx \frac{2\nu}{26.1MeV} \times 8.56 \times 10^{11} \left[MeV/cm^2/s \right] = 6.6 \times 10^{10} \left[\nu/cm^2/s \right]$$

Solar neutrino spectrum





Solar Neutrino Experiments

	ν target	Eth	rate/SSM
Homestake	Cl	^{8}B	0.31
GALLEX/GNO	Ga	pp	0.51
SAGE	Ga	pp	0.53
SK/Kamiokande	H2O	^{8}B	0.465
SNO	D20	^{8}B	1 (neutral current)

The 1st solar neutrino detection & indication of solar ν deficit

Pioneer of Solar Neutrino Science

$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

$$ {}^{37}Ar \rightarrow {}^{37}Cl + e^- + \nu_e$$

R=Data/Prediction ~0.31

*Homestake (615ton), (1968~)

Ga experiments

Issue for Homestake(Cl) experiment.

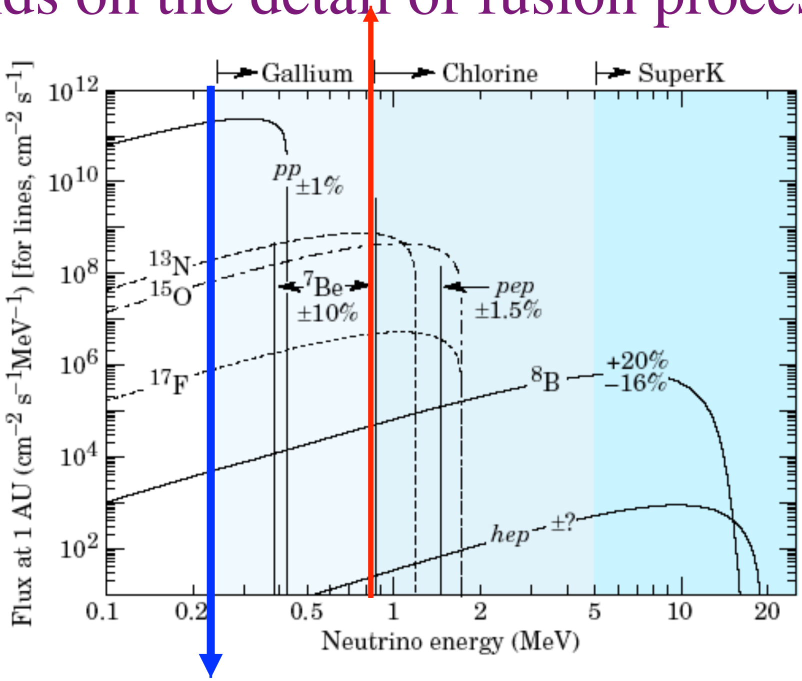
→ The energy threshold is high and can not detect pp-ν .

→ Flux very much depends on the detail of fusion process.

→ possilbe ambiguity.

$$\nu_e + {}^{37}Ga \rightarrow e^- + {}^{37}Ge$$

$$\left(E_{th} = 233KeV\right)$$



Low energy threshold and pp-ν can be detected.

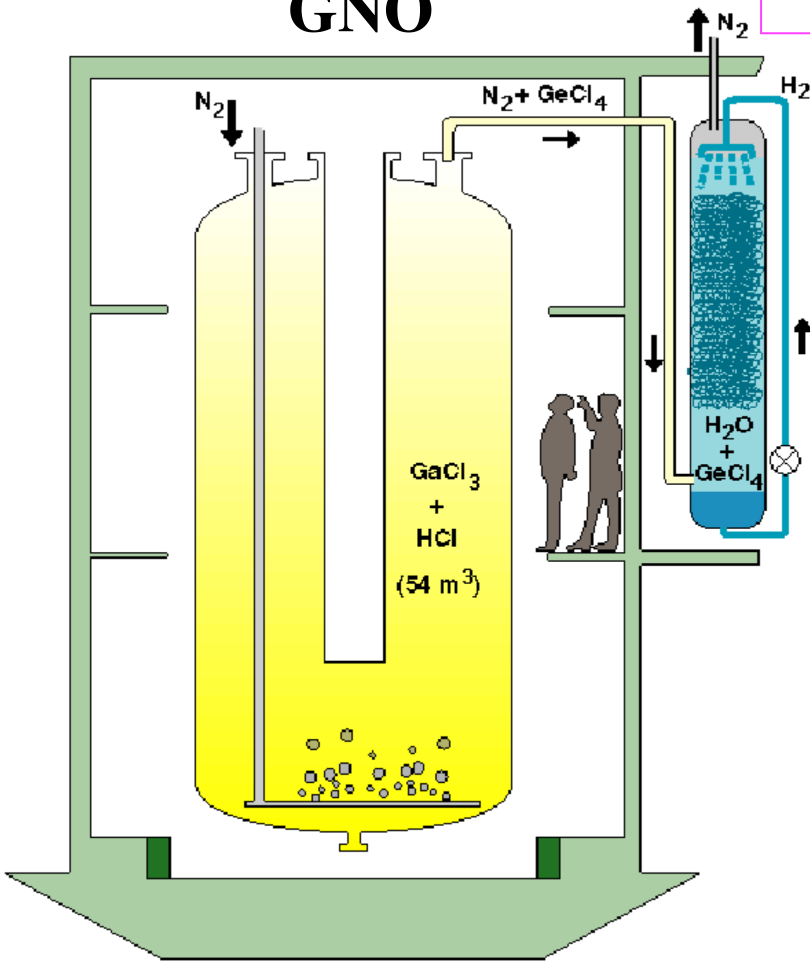
ν flux is independent for detail of the fusion process in the sun and reliable prediction of ν flux is possible.

GNO/GALLEX

$$\nu_e + {}^{37}Ga \rightarrow e^- + {}^{37}Ge \quad \left(E_{th} = 233KeV\right)$$

$$ {}^{37}Ge \rightarrow {}^{37}Ga + e^-(Auger) + \nu_e \left(\tau_{1/2} \sim 11days\right)$$

GNO



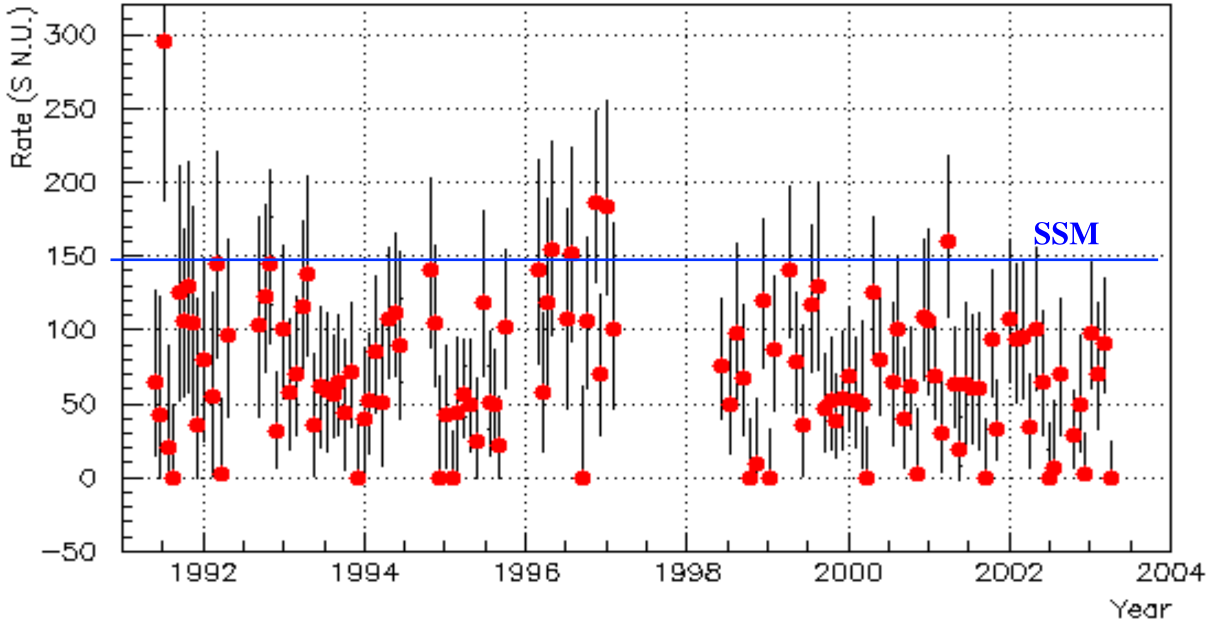
(1) leave $GaCl_3$ target for a few weeks and accumulate $GeCl_3$ in the target.

(2) Purge out $GeCl_4$ and dissolve it in water.

(3) Detect the β-decay)^{37}Ge->^{37}Ga+e-

(4) Perform (1)~(3) many times for years.

Results of GNO/GALLEX



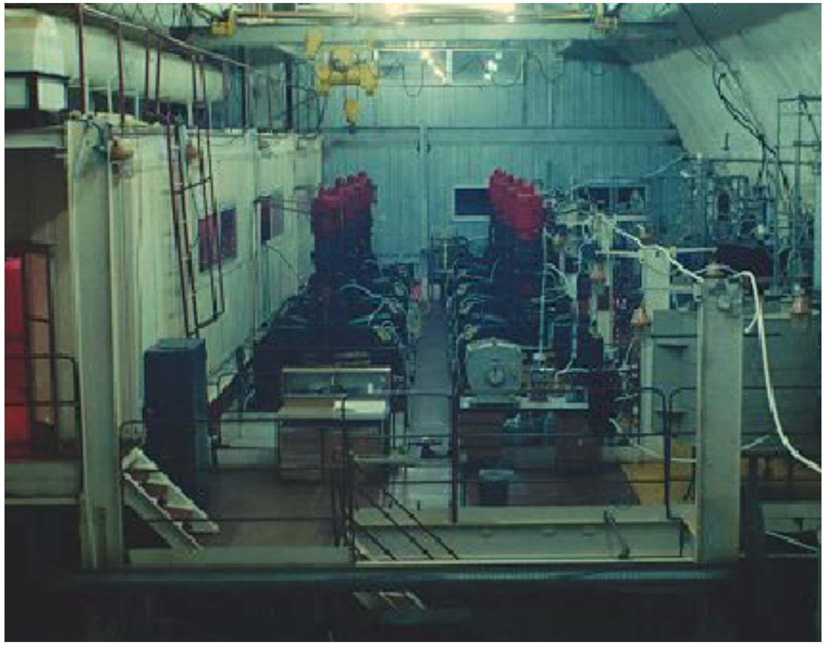
)

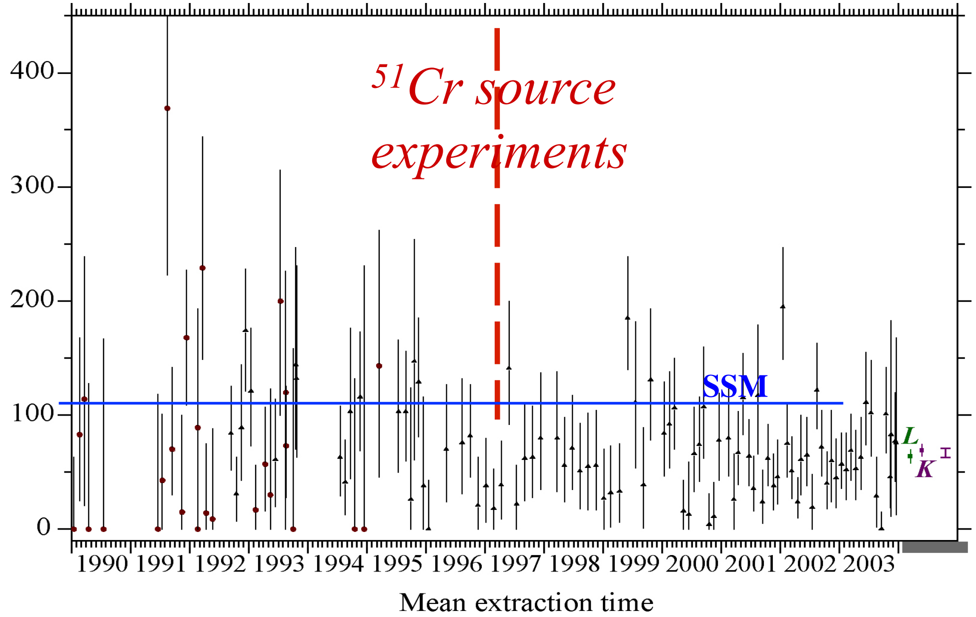
＊GALLEX(GALLium EXperiment),
(30tons), (1991~)

＊GNO(Gallium Neutrino Observatory),
(30->100tons ~2003)

$$GNO + GALLEX \qquad Data / \Pr ediction = 0.51 \pm 0.04$$

SAGE(Soviet American Ga Experiment) 1990~





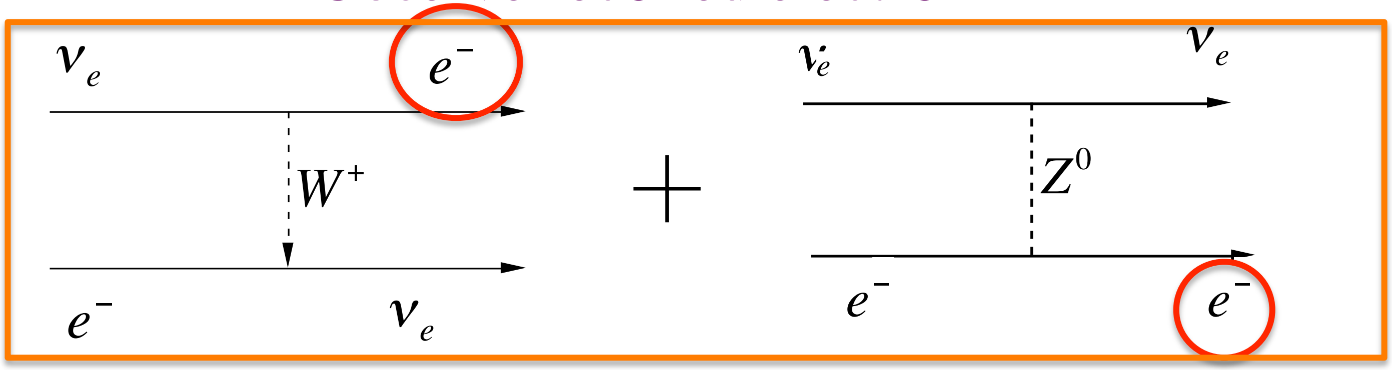
$$Data/Prediction = 0.53^{+0.042}_{-0.040}$$

Solar ν detection by electron scattering

(Kamokande/SuperKamiokande/SNO)

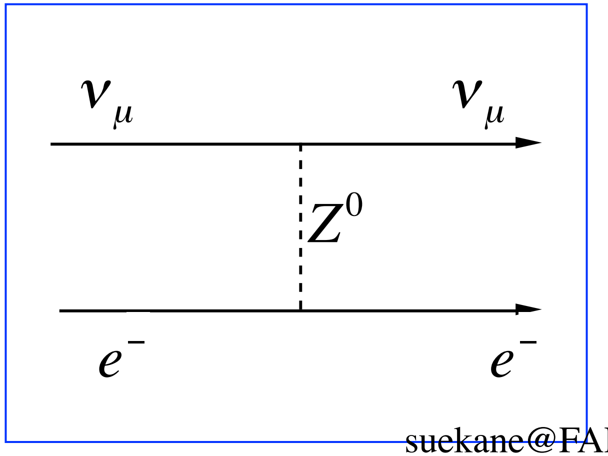
Observe recoiled electron

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



$$\sigma_{\nu_e e} \sim \frac{2G_F^2 m_e E_\nu}{\pi}\left[\left(\frac{1}{2}+x_W\right)^2 + \frac{1}{3}x_W^2\right] \sim 0.9\times10^{-44} E_\nu[MeV]cm^2$$

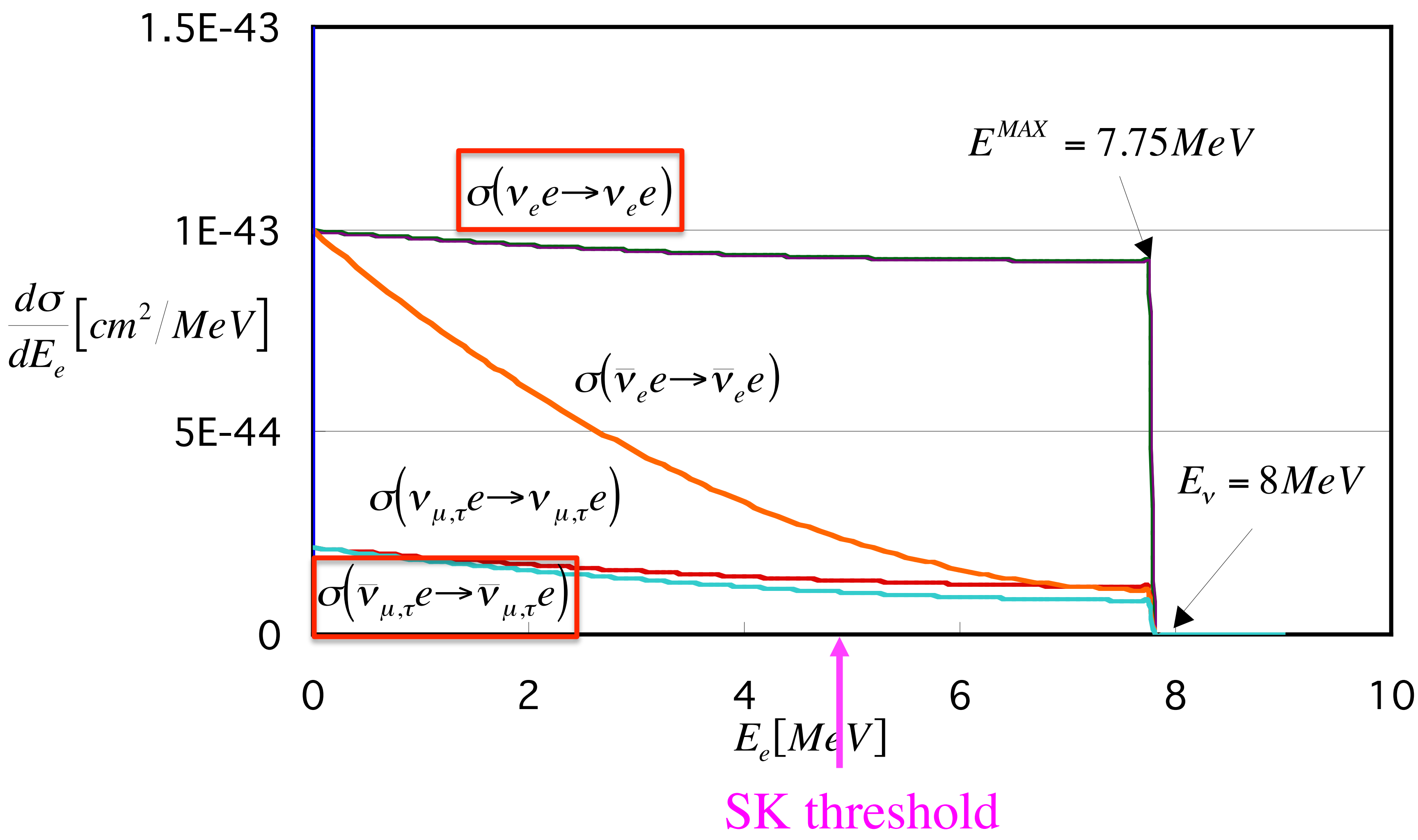
$$\nu_{\mu,\tau} e^- \rightarrow \nu_{\mu,\tau} e^-$$



$$\sigma_{\nu_\mu e} \sim 0.16\times10^{-44} E_\nu[MeV]cm^2$$

$$\sim \frac{1}{6}\sigma_{\nu_e e}$$

Recoiled electron energy distribution of E_ν=8MeV

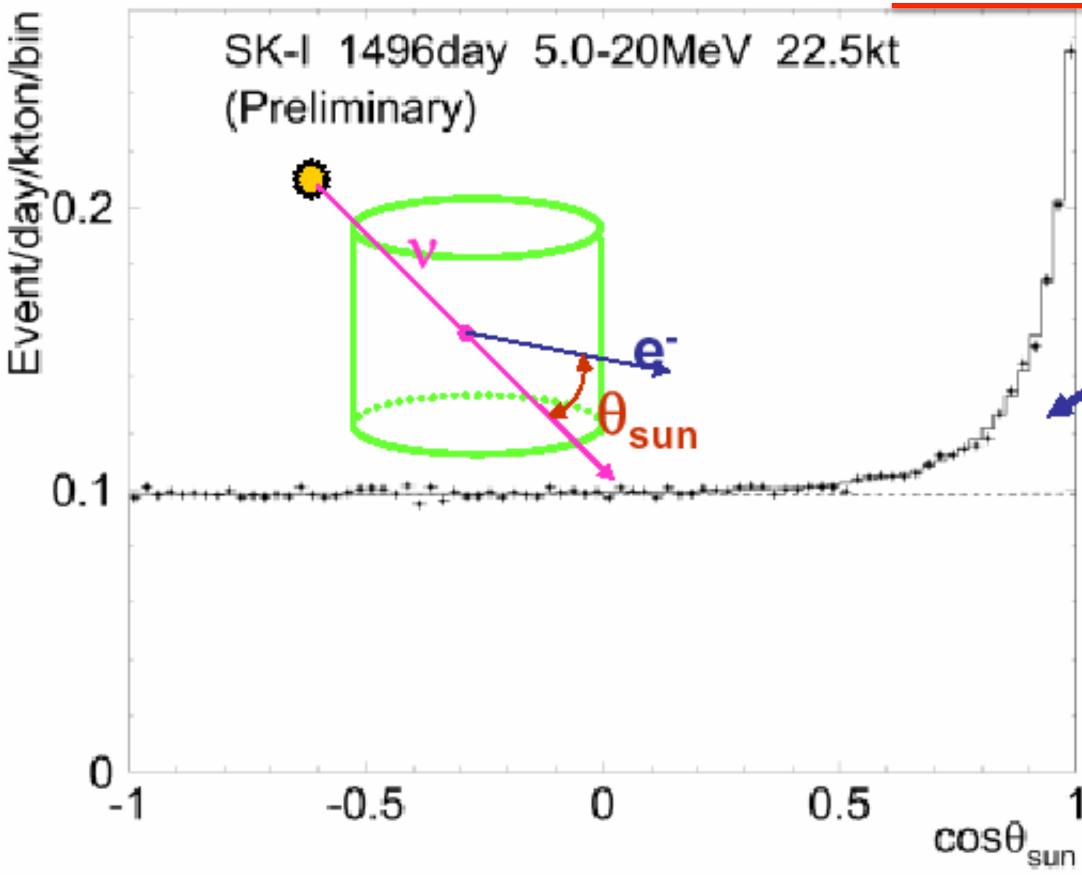


Solar neutrino data from Super-K

flux is

$2.35 \pm 0.02(\text{stat.}) \pm 0.08(\text{sys.}) \times 10^6/\text{cm}^2\cdot\text{s}$

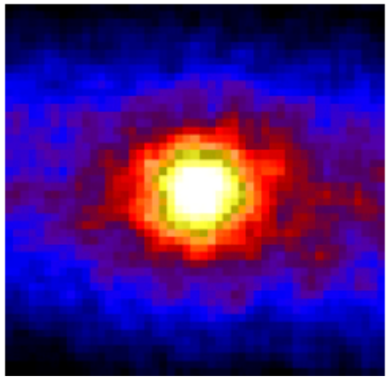
or $0.465 \pm 0.005(\text{stat.})^{+0.016}_{-0.015}(\text{sys.}) \times \text{SSM}$



$\nu e \rightarrow \nu e$

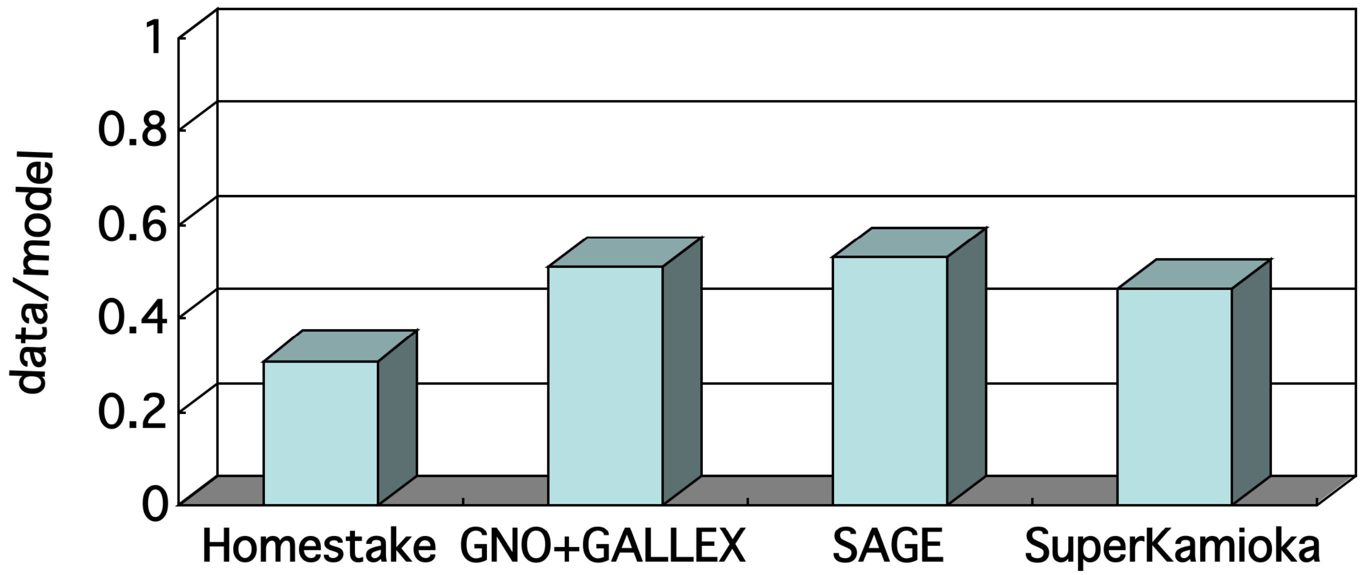
22,400 events

above 5MeV



Solar image by neutrinos

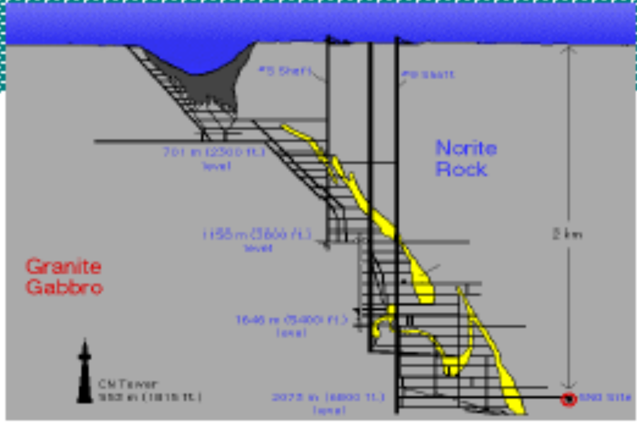
The solar neutrino anomaly



For all the experiments, the observed neutrino fluxes are smaller than predicted value.

Is it due to neutrino oscillation ?
Solar model may be wrong.
➔ It is important to measure neutral current interaction and measure the total (flavor independent) ν flux.

Sudbury Neutrino Observatory



Measure the Neutral Current

1000 tonnes D_2O

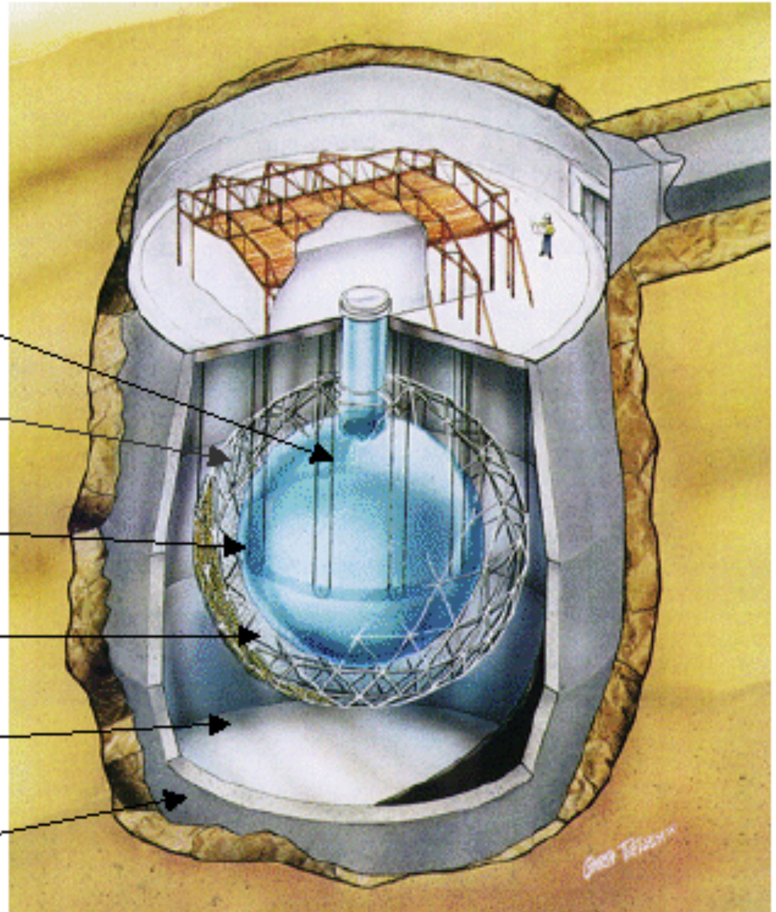
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

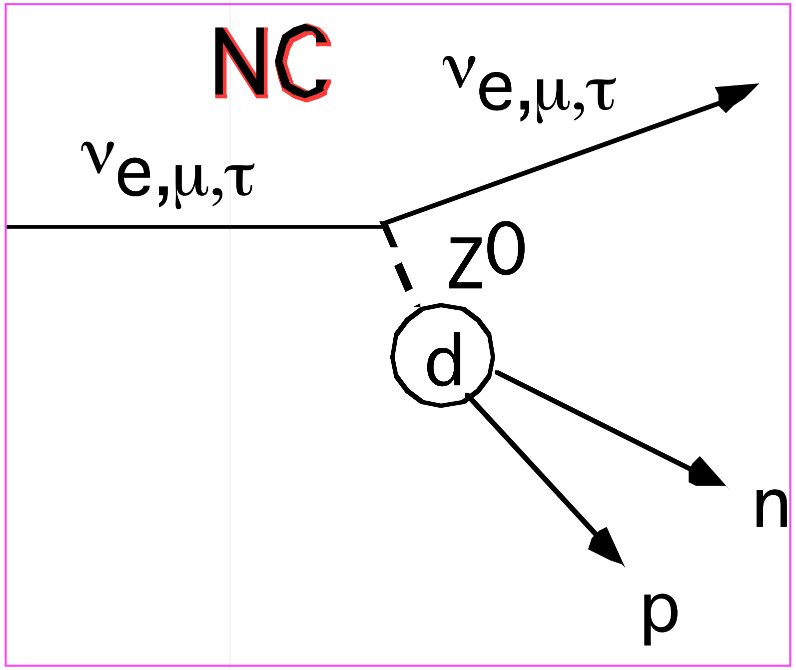
1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal



Why D_2O?



All flavor has same cross section.

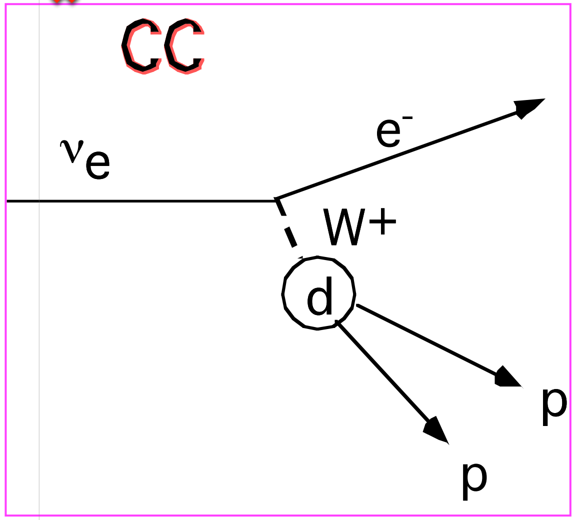
The total ν flux can be measured independently from oscillation.

➔ Solar model can be checked.

$$\phi_e + \phi_\mu + \phi_\tau$$

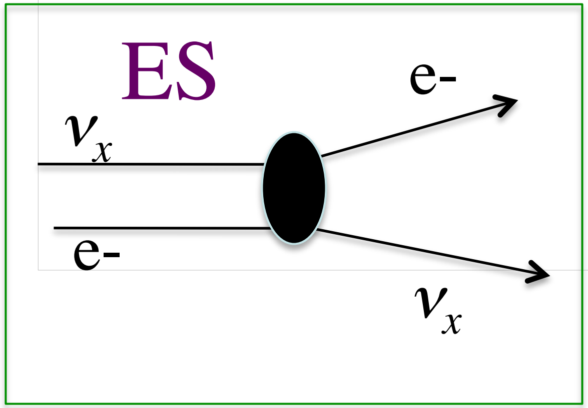
$$n + d \rightarrow t + \gamma(6.25\,MeV)$$

Why D_2O?



Measurement of pure ν_e flux.

$$\phi_e$$



Electron scattering

$$\phi_e+(\phi_\mu+\phi_\tau)/7$$

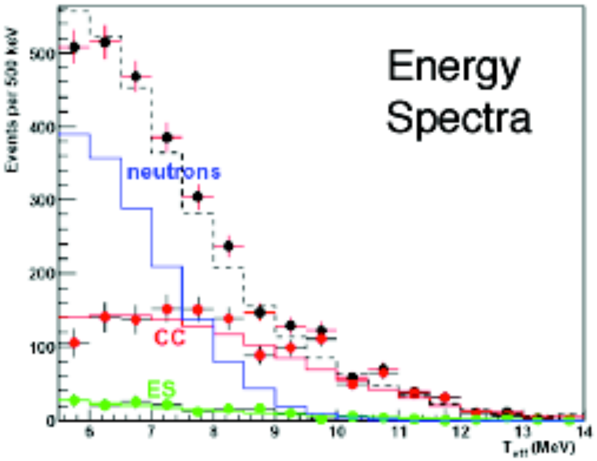
Event Distributions (PRL 92, 181301, 2004)

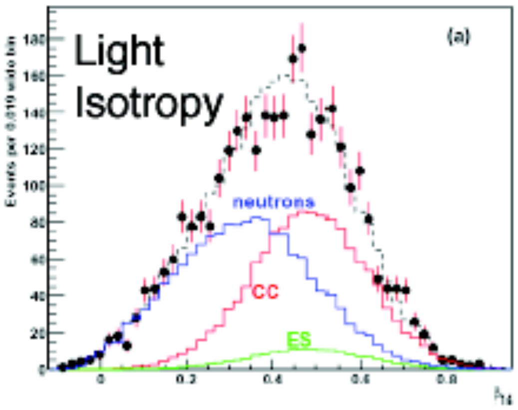
Salt Phase

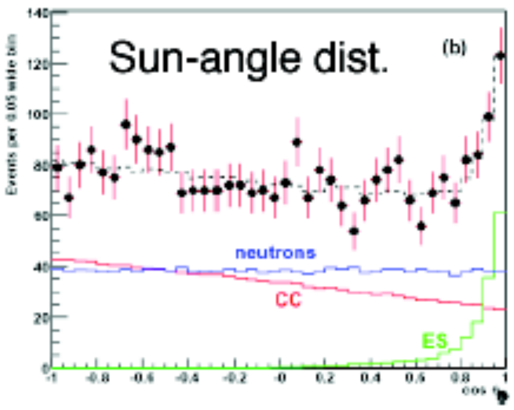
$$\frac{\phi_{\rm CC}^{\rm SNO}}{\phi_{\rm NC}^{\rm SNO}} = 0.306 \pm 0.026\ ({\rm stat}) \pm 0.024\ ({\rm syst})$$

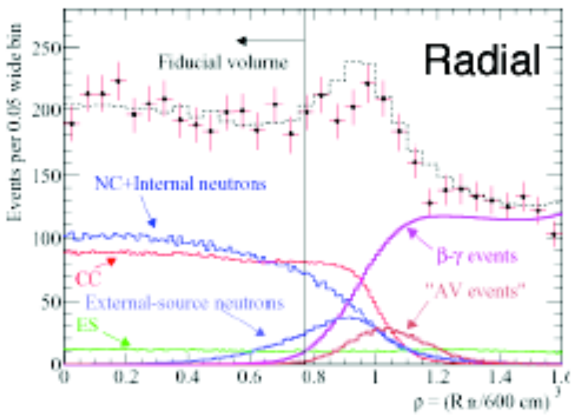
#EVENTS

CC	$1339.6^{+63.8}_{-61.5}$
ES	$170.3^{+23.9}_{-20.1}$
NC	$1344.2^{+69.8}_{-69.0}$







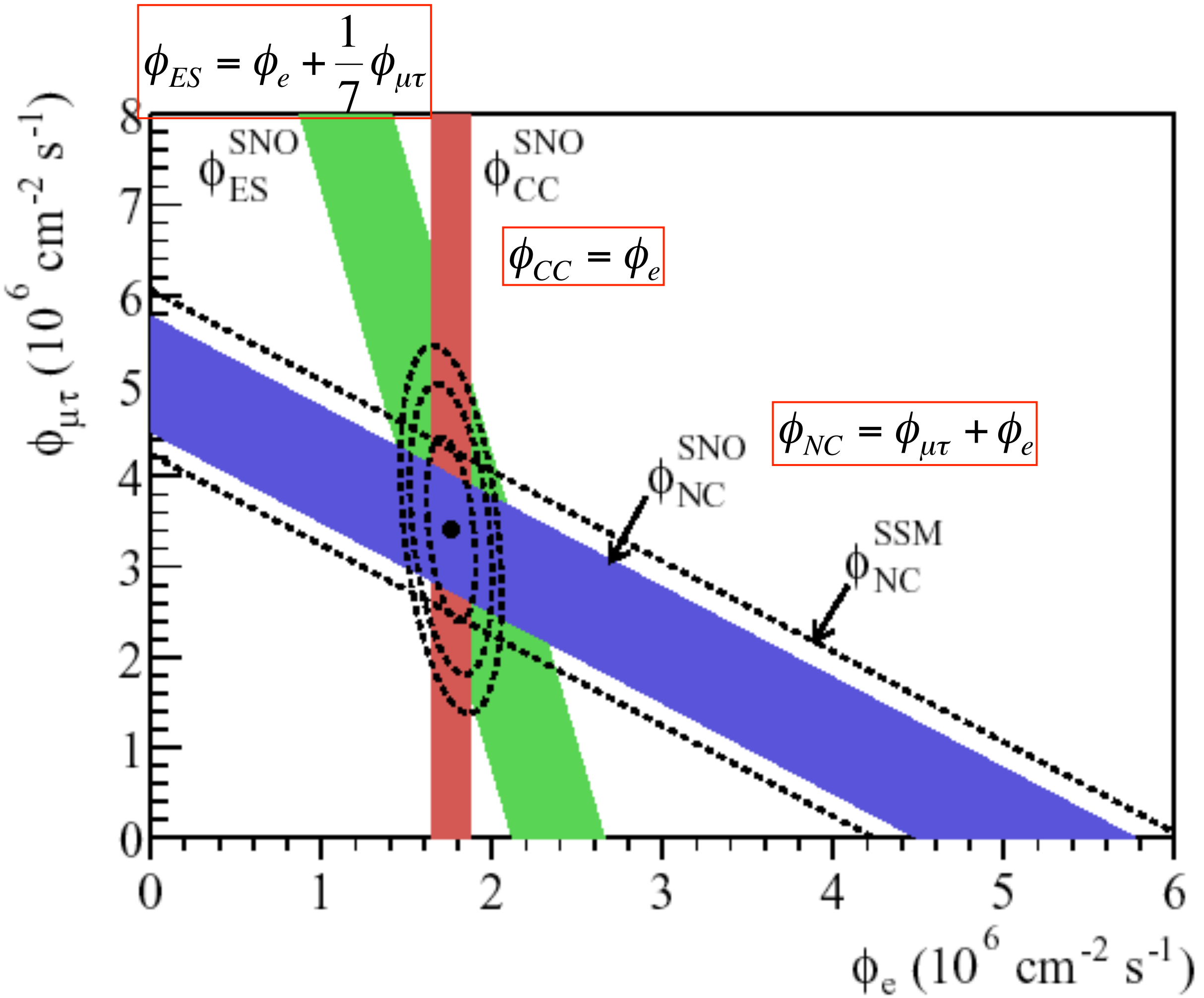


J.F. Wilkerson on behalf of the SNO Collaboration — June 14, 2004 — Neutrino 2004

Main SNO result (2002, pure D_2O phase)

$$\Phi_{ssm} = 5.05^{+1.01}_{-0.81} \quad \Phi_{sno} = 5.09^{+0.44}_{-0.43}{}^{+0.46}_{-0.43}$$

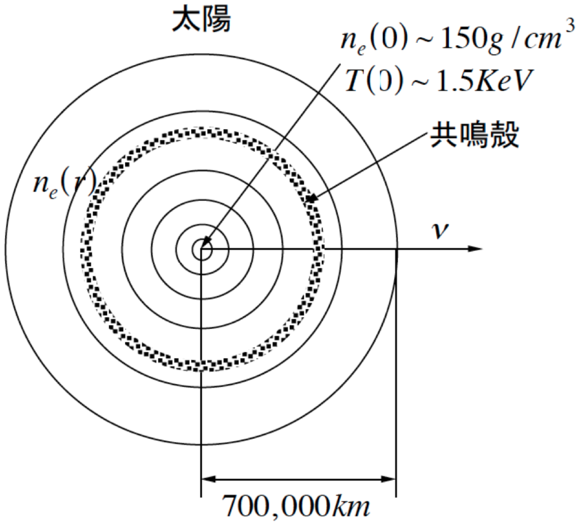
$\Phi_{\mu\tau}$ is 5.3 σ from zero

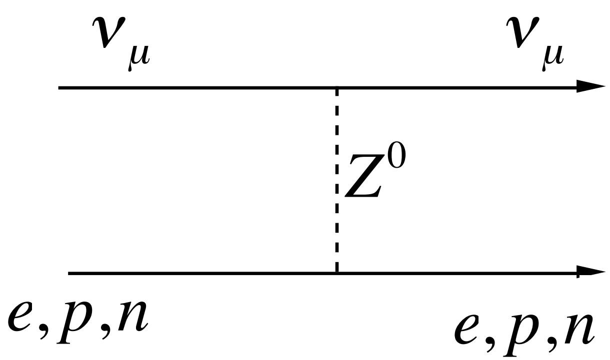


Evidence for solar neutrino oscillation

How to understand the solar neutrino results

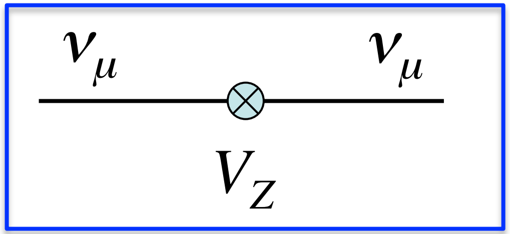
It is necessary to take into account the matter effect in the sun (Mikheyev, Smirnov, Wolfenstein)





$$M_I = \frac{G_F}{\sqrt{2}}\left[\overline{\nu}_{\mu L}\gamma_\rho \nu_{\mu L}\right]\sum_{f=e,p,n}\left[\bar{f}\gamma^\rho\left(g_V^f - g_A^f\gamma_5\right)f\right]$$

The equation of motion is, $\dot{\nu}_\mu = -iV_Z\nu_\mu$

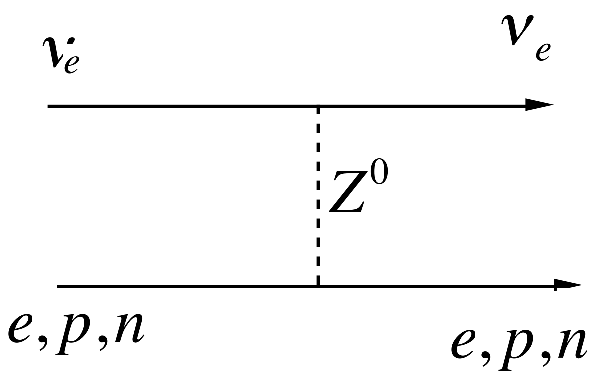


$$V_Z = \frac{G_F}{\sqrt{2}}\gamma_0\gamma_\rho\sum_{f=e,p,n}\left[\bar{f}\gamma^\rho\left(g_V^f - g_A^f\gamma_5\right)f\right]$$

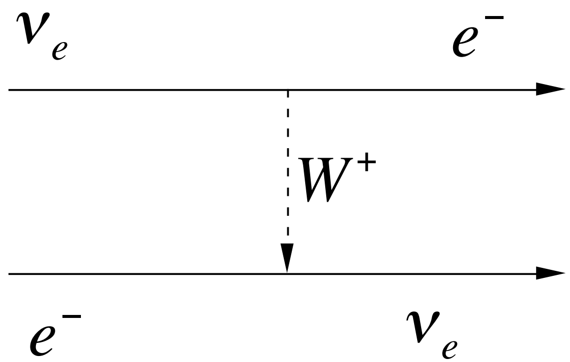
MSW effect

For ν_e

* $\nu_e + e,p,n \rightarrow \nu_e + e,p,n$

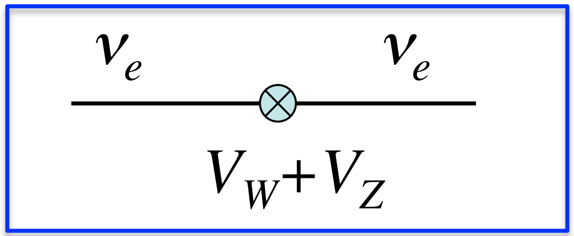


+



$$M_I \rightarrow \frac{G_F}{\sqrt{2}}\left[\bar{\nu}_{eL}\gamma_\rho \nu_{eL}\right]\left\{\sum_{f=e,p,n}\left[\bar{f}\gamma^\rho\left(g_V^f - g_A^f\gamma_5\right)f\right]+\left[\bar{e}_L\gamma^\rho e_L\right]\right\}$$

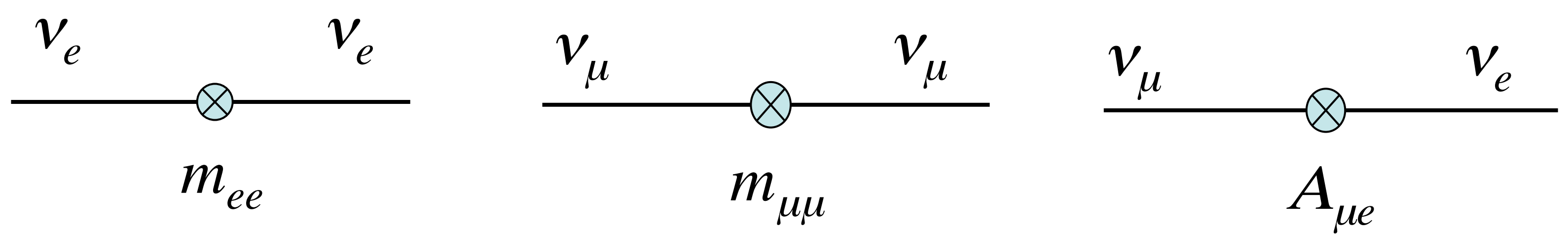
The equation of motion is, $\dot{\nu}_e = -i\left(V_Z + V_W\right)\nu_e$



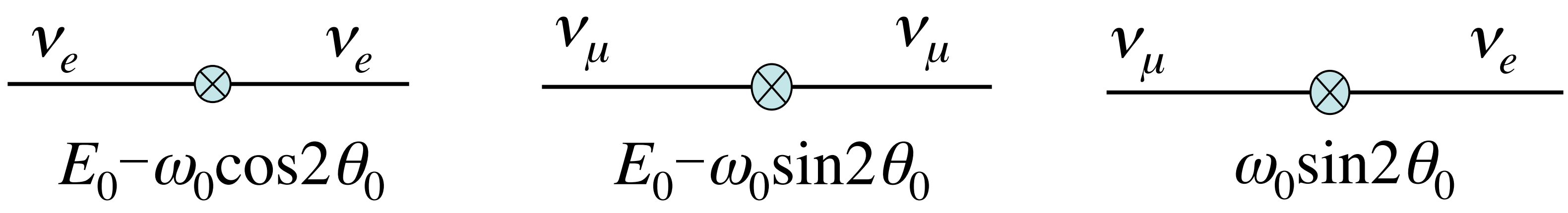
$$V_W = \frac{G_F}{\sqrt{2}}\gamma_0\gamma_\rho\left[\bar{e}_L\gamma^\rho e_L\right] \rightarrow \sqrt{2}G_F\rho_e$$

relativistic ν equation of motion in vacuume

Effective equation of motion in the vacuum for relativistic ν



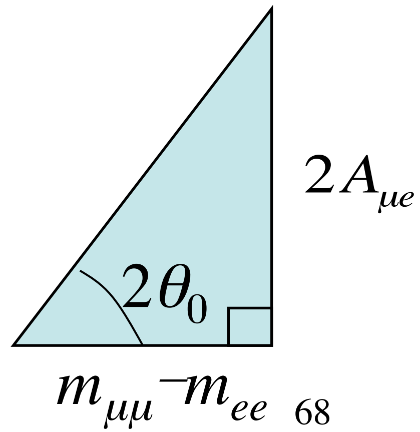
$E_\nu >> m_\nu$



$$\begin{pmatrix} \dot{\nu}_e \\ \dot{\nu}_\mu \end{pmatrix} = -i\omega_0 \begin{pmatrix} -\cos 2\theta_0 & \sin 2\theta_0 \\ \sin 2\theta_0 & \cos 2\theta_0 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

(E_0 is common and does not affect oscillation and ignored for simplicity.)

$$\omega_0 = \frac{m_+^2 - m_-^2}{4E} > 0$$



In the sun, we have to add potential of the matter effect

$\nu_e \to \nu_e$	$\nu_\mu \to \nu_\mu$	$\nu_\mu \to \nu_e$
$E_0-\omega_0\cos 2\theta_0+V_Z+V_W$	$E_0+\omega_0\sin 2\theta_0+V_Z$	$\omega_0\sin 2\theta_0$

then

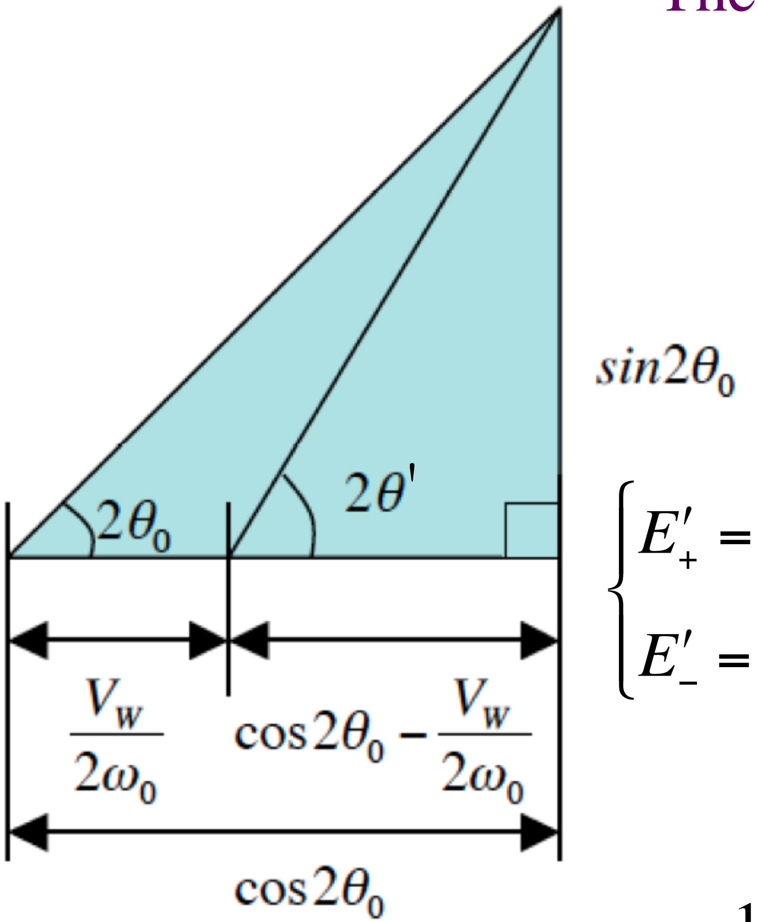
$$\begin{pmatrix}\dot{\nu}_e\\ \dot{\nu}_\mu\end{pmatrix}=-i\begin{pmatrix}-\omega_0\cos 2\theta_0+V_W & \omega_0\sin 2\theta_0\\ \omega_0\sin 2\theta_0 & \omega_0\cos 2\theta_0\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

(V_Z is common and does not affect to oscillation and ignored for simplicity)

$V_W=\sqrt{2}G_F\rho\sim 1\times 10^{-11}eV$ for ρ_0=150g/cm^3 (center of the sun)

On the other hand, for E=1MeV, $\omega_0=\Delta m_{+-}^2/4E\sim 2\times 10^{-11}eV$

So that V_W and ω_0 are coincidentally similar value.



The mass eigenstate in the sum is as always

$$\begin{pmatrix} \nu_- \\ \nu_+ \end{pmatrix} = \begin{pmatrix} \cos\theta' & \sin\theta' \\ -\sin\theta' & \cos\theta' \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

Energies are,

$$\begin{cases} E'_+ = E_0 + \sqrt{(2\omega_0 \cos 2\theta_0 - V_W)^2 + 4\omega_0^2 \sin^2 2\theta_0} \\ E'_- = E_0 - \sqrt{(2\omega_0 \cos 2\theta_0 - V_W)^2 + 4\omega_0^2 \sin^2 2\theta_0} \end{cases}$$

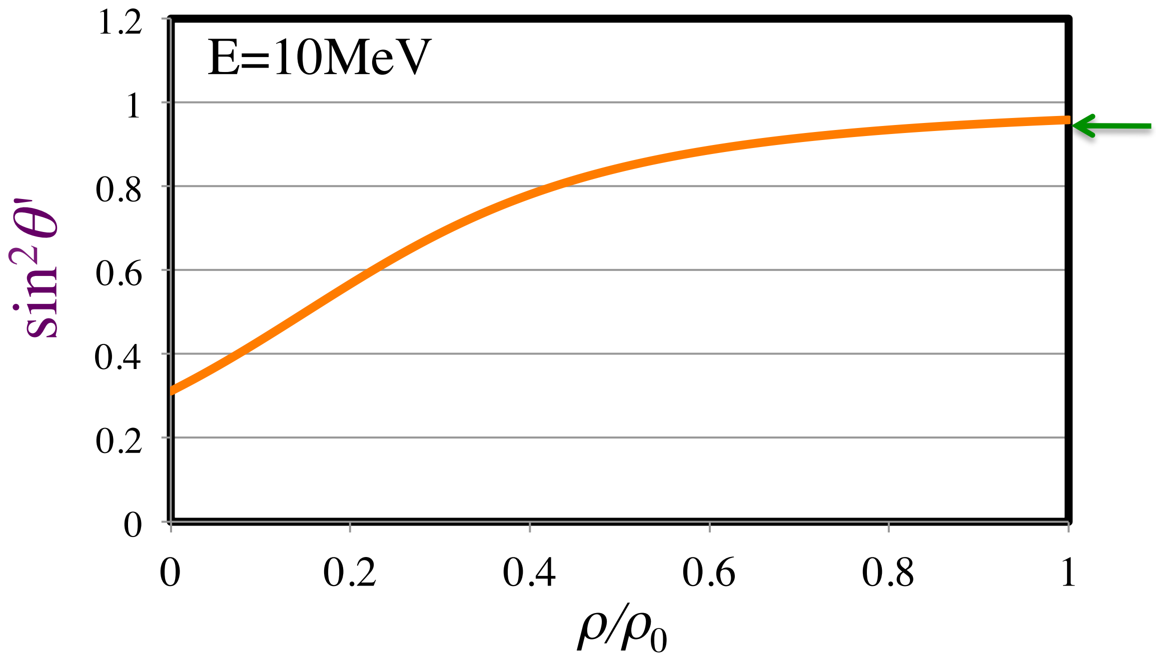
$$\sin^2\theta' = \frac{1}{2}\left(1 - \frac{(2\omega_0 \cos 2\theta_0 - V_W)}{\sqrt{(2\omega_0 \cos 2\theta_0 - V_W)^2 + 4\omega_0^2 \sin^2 2\theta_0}}\right)$$

We know

$$\begin{cases} \theta_0 \sim 34^\circ \\ \Delta m^2 \sim 7.7\times 10^{-5}\left[eV^2\right] \\ \rho_0 \sim 150\left[g/cm^3\right] \end{cases}$$

➔

$$\begin{cases} \omega_0[eV] = 2\times 10^{-11}/E[MeV] \\ V_W[eV] = 1\times 10^{-11}(\rho/\rho_0) \end{cases}$$



If ν_e (E=10MeV) is generated near the center of the sun, it corresponds to the heavier neutrino state.

$$\nu_e \sim \nu_+$$

ν oscillation in the sun

$$\begin{cases} \nu_e(t) = \cos\theta' \nu_- e^{-iE'_- t} - \sin\theta' \nu_+ e^{-iE'_+ t} \\ \nu_\mu(t) = \sin\theta' \nu_- e^{-iE'_- t} + \cos\theta' \nu_+ e^{-iE'_+ t} \end{cases}$$

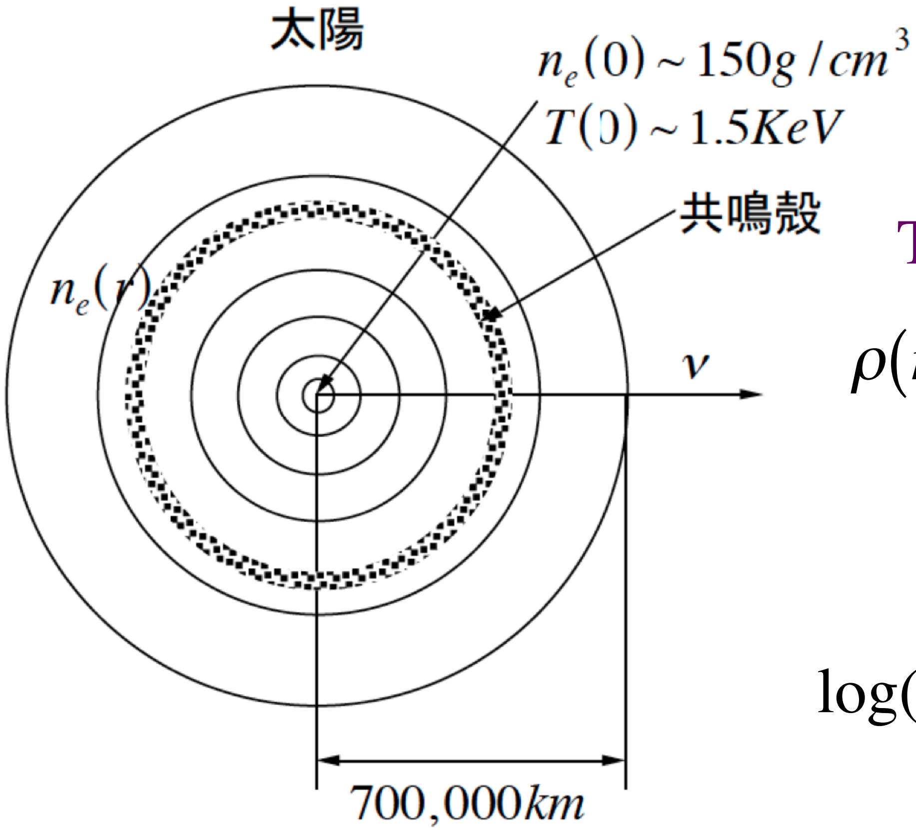
Then as always,

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta' \sin^2\left(\frac{\Delta E'}{2} L\right) = \sin^2 2\theta' \sin^2\left(2\pi \frac{L}{\lambda'}\right)$$

Oscillation length in the sun

$$\lambda' = \frac{\lambda_0}{\sqrt{\left(\cos 2\theta_0 - 4E[MeV]/(\rho/\rho_0)\right)^2 + \sin^2 2\theta_0}} < 2\times 10^3\,km << R_{SUN}$$

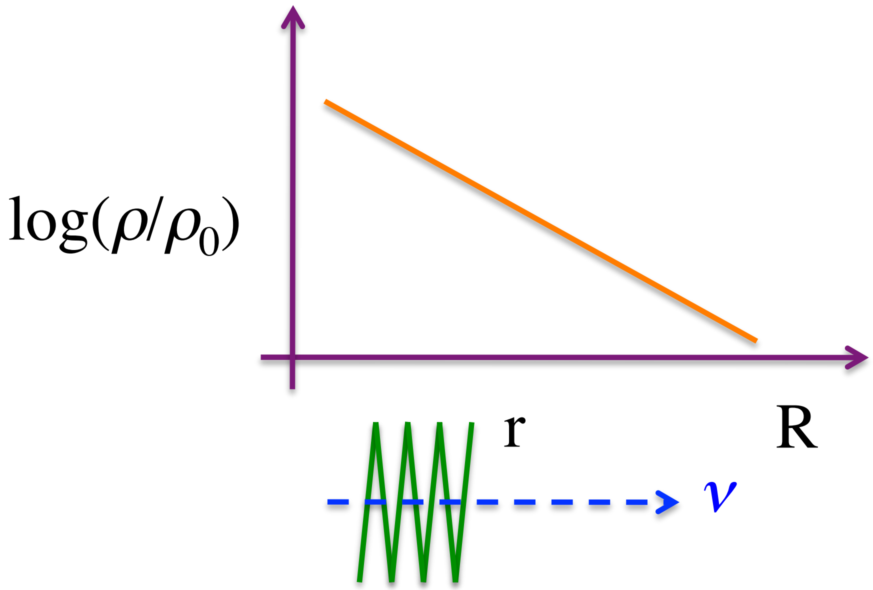
ν oscillates many times in the sun



While traveling in the sun,
ν experiences changing density

The density distribution in the sun is

$$\rho(r) \sim \rho_0 \exp\left[-10.5\frac{r}{R}\right]; \quad (0.2 < r/R < 1)$$



$$\left|\frac{1}{\rho}\frac{d\rho}{dr}\lambda'\right| < 0.03 << 1$$

For 1 turn of the oscillation,
the density change rate is small.

This is called adiabatic condition