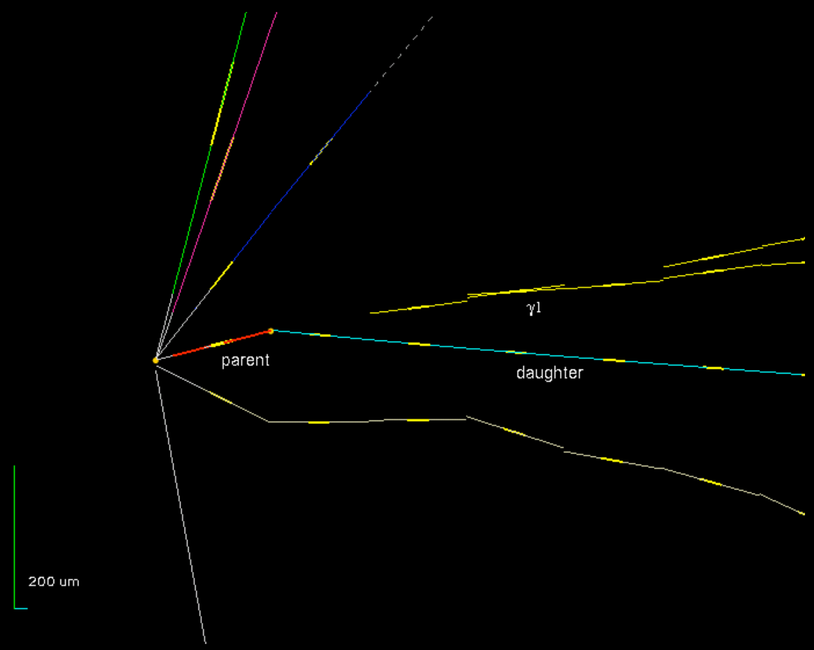
Neutrino (oscillation) experiments



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University of Bern

Flavianet School –Bern – July 2010

Content*

- General information and history: what is special with the neutrino ?
- Neutrino oscillations: hottest topic in neutrino physics
- Forced selection of oscillation experiment subtopics: a not exhaustive list of oscillation experiments (which gave or are going to give results soon) is presented below:

Homestake, Gallex, Sage, GNO, SNO, Kamiokande, Super-Kamiokande, Borexino, MACRO, Soudan2, CHOOZ, Double-Chooz, Palo Verde, Kamland, Reno, Daya-Bay, K2K, MINOS, OPERA, T2K, NOVA, ICARUS, LSND, Karmen, MiniBoone, CHORUS, NOMAD, ….

IMPOSSIBLE TO ACCOUNT FOR ALL OF THEM!

- An arbitrary selection is imposed…apologies….

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*Thanks to E. Lisi and P. Lipari for the use of some of their excellent slide material

The Discovery of the Neutrino

Prediction of its existence (1930)
(Wolfgang Pauli)

Neutrino Theory (1933)
(Enrico Fermi)

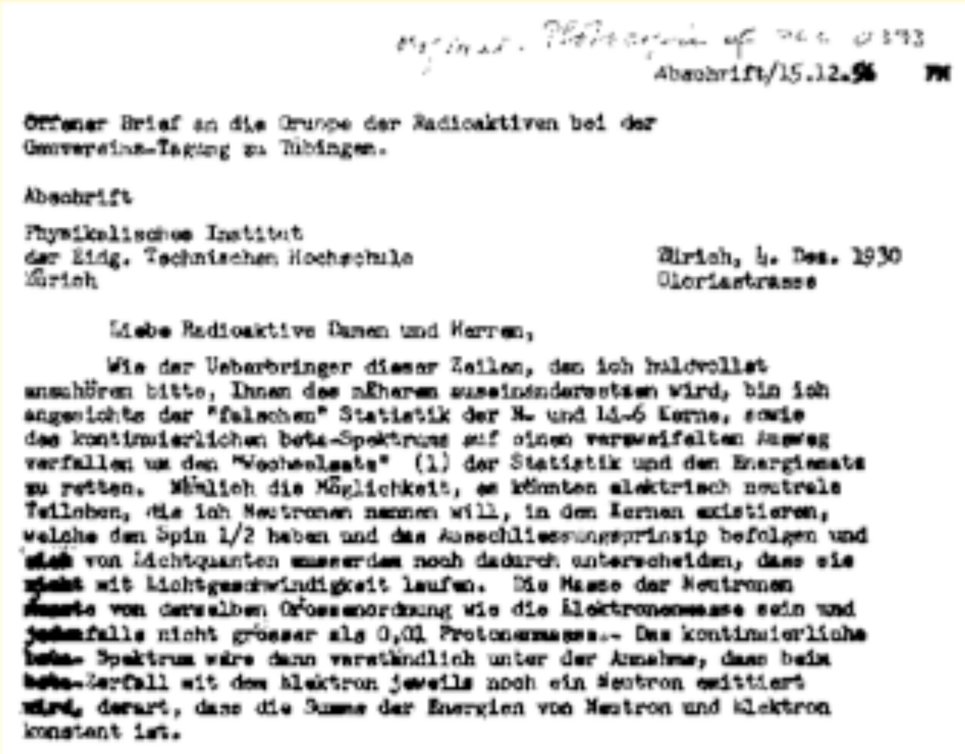
First Detection (1953)
(F. Reines, C. Cowan)

1930:
PREDICTION of the EXISTENCE
of the NEUTRINO.

Wolfgang PAULI

Study of Nuclear
Beta Decay

One of the most famous letters of particle physics



Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

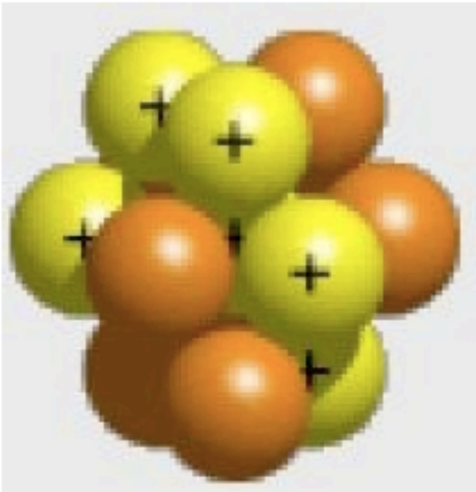
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

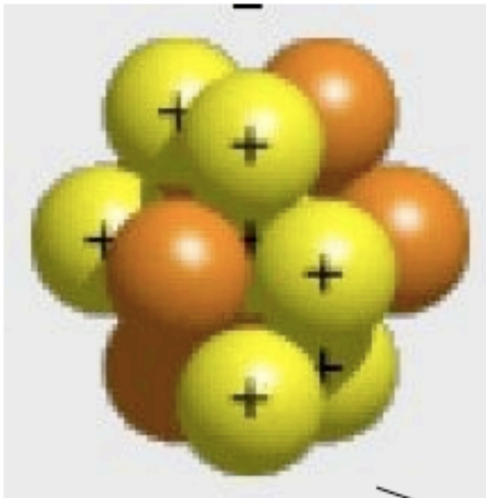
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nuclear BETA Decay





Not conserving

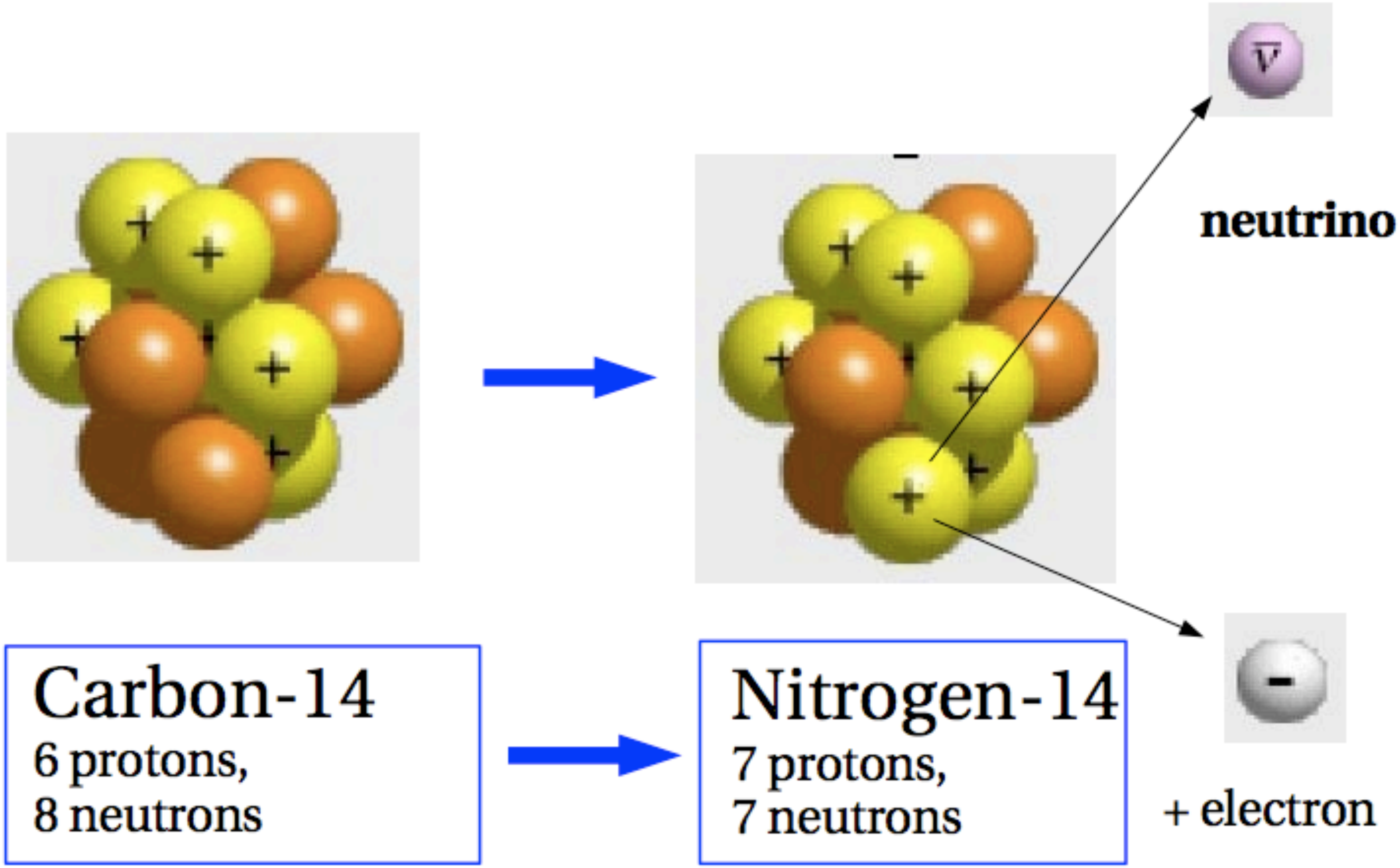
Energy
Momentum
Angular Momentum

Carbon-14
6 protons,
8 neutrons

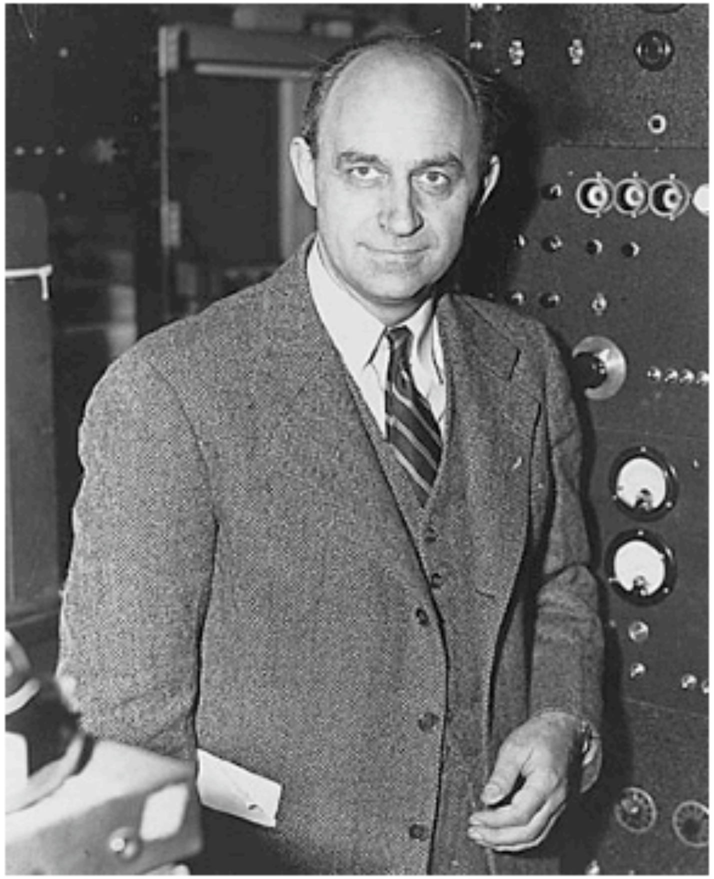
Nitrogen-14
7 protons,
7 neutrons

+ electron

Nuclear BETA Decay



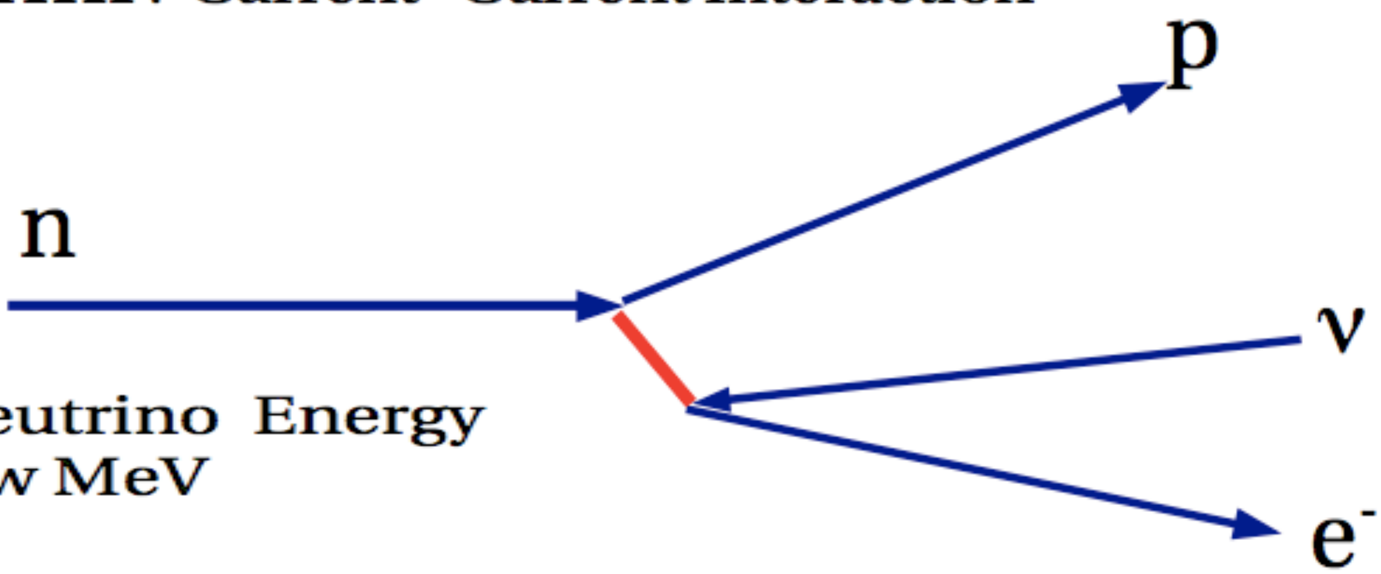
1933
Enrico Fermi
[Nobel Prize in 1938]



develops
the theory
of Beta Decay

Current-Current
Interaction

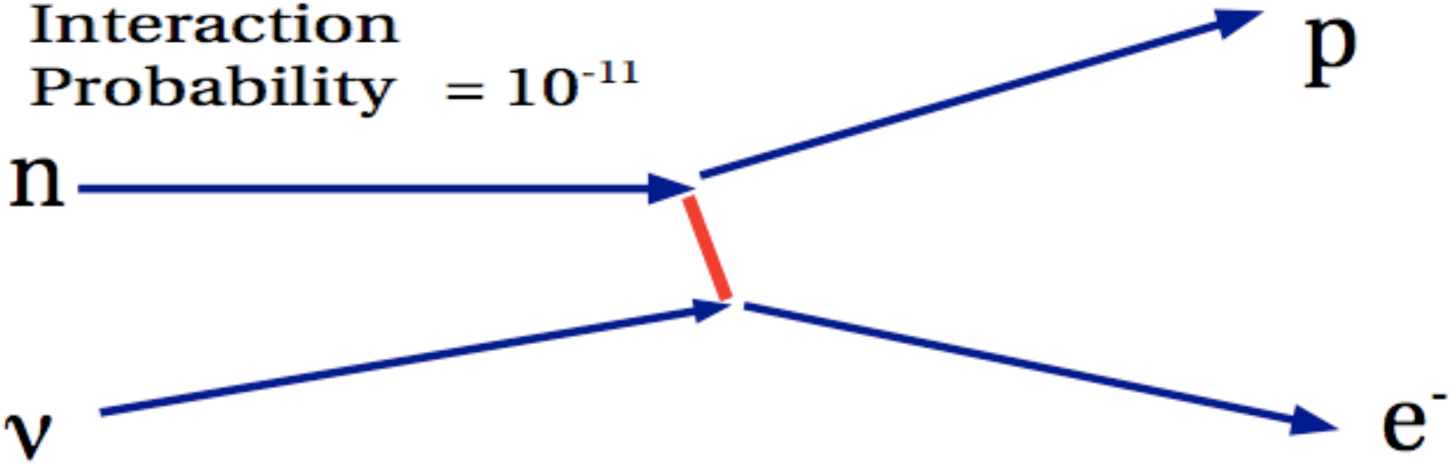
Fermi : Current- Current Interaction



Neutrino Energy
few MeV

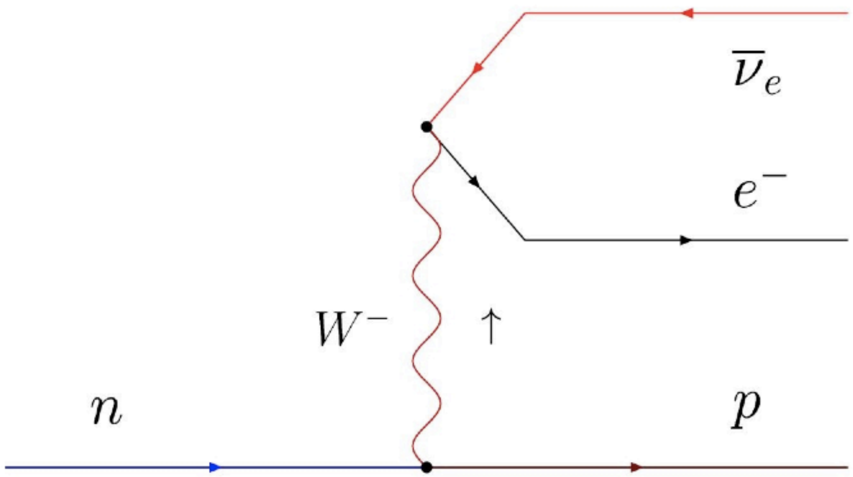
$\sigma = 10^{-44}$ cm^2

Interaction
Probability $= 10^{-11}$

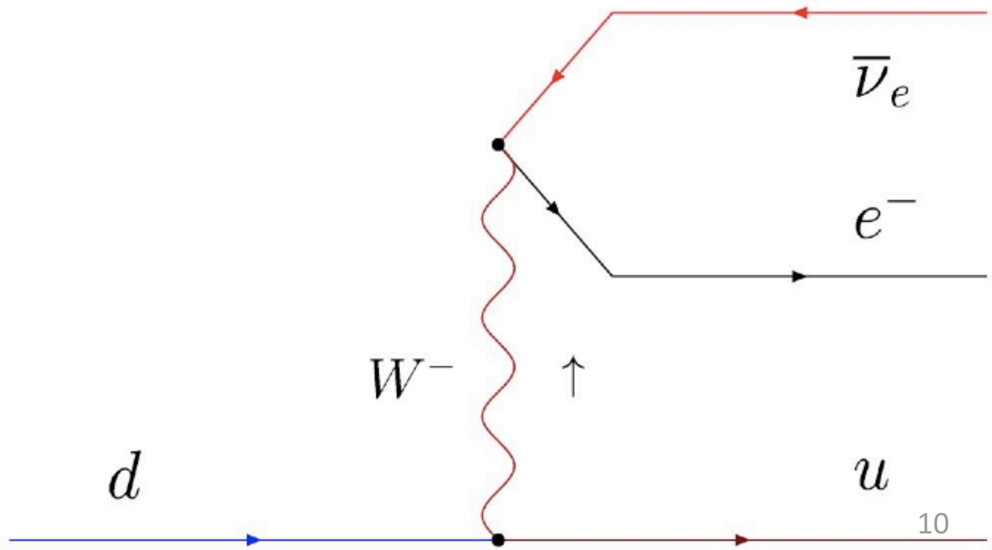


Feynman Diagram for Neutron Beta Decay

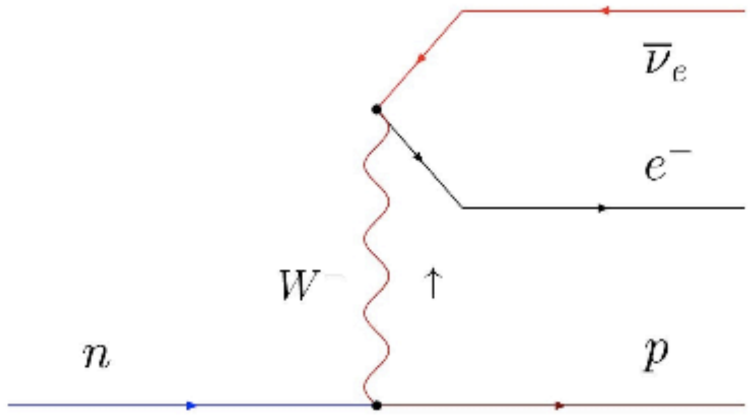
$$n \to p + e^- + \overline{\nu_e}$$



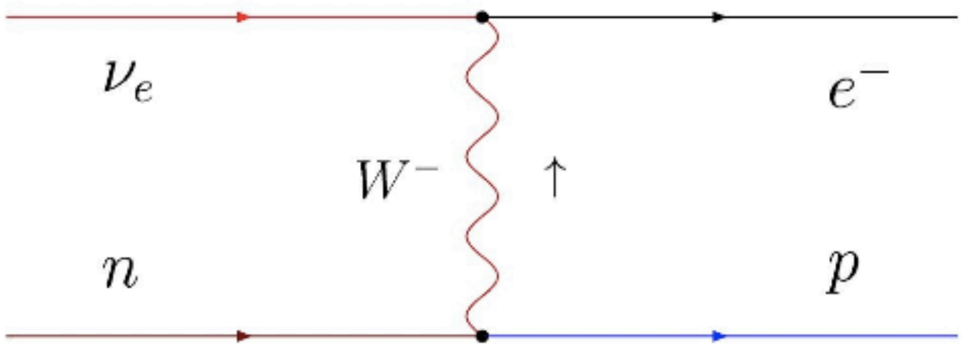
Decay at the Quark Level



$$n \to p + e^- + \overline{\nu_e}$$

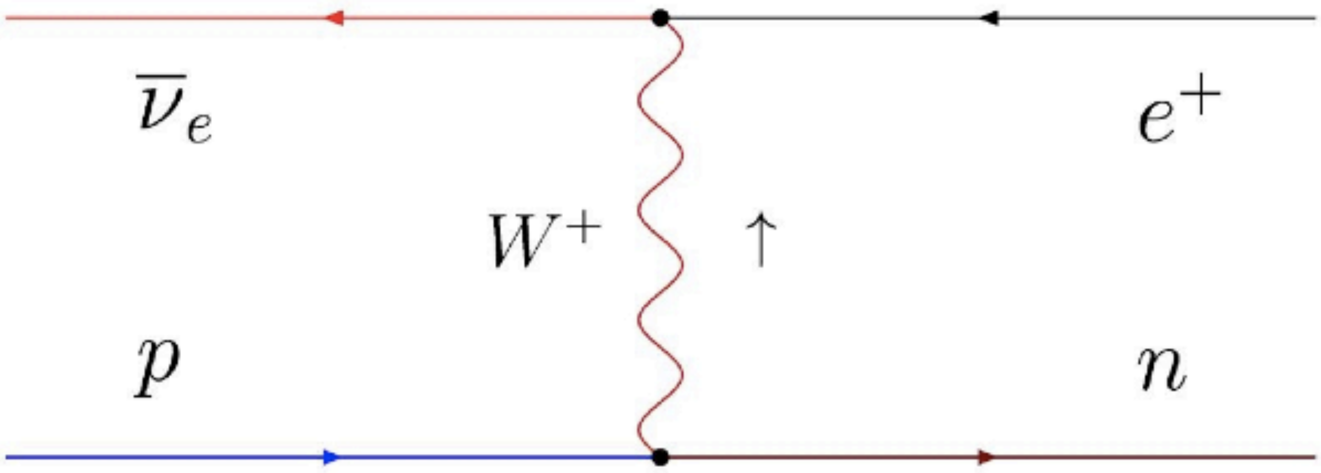


$$\nu_e + n \to p + e^-$$



Detection Method

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



Better detection method....

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

Neutrino Discovery (antineutrinos from Nuclear Reactors

Reines e Cowan
1953-1956

Delayed neutron capture
(after thermalization of the neutron)

$$n + p \rightarrow d + \gamma(2.2 \text{ MeV})$$

Spin ½ Particles are described by
4 components "Dirac Spinors"

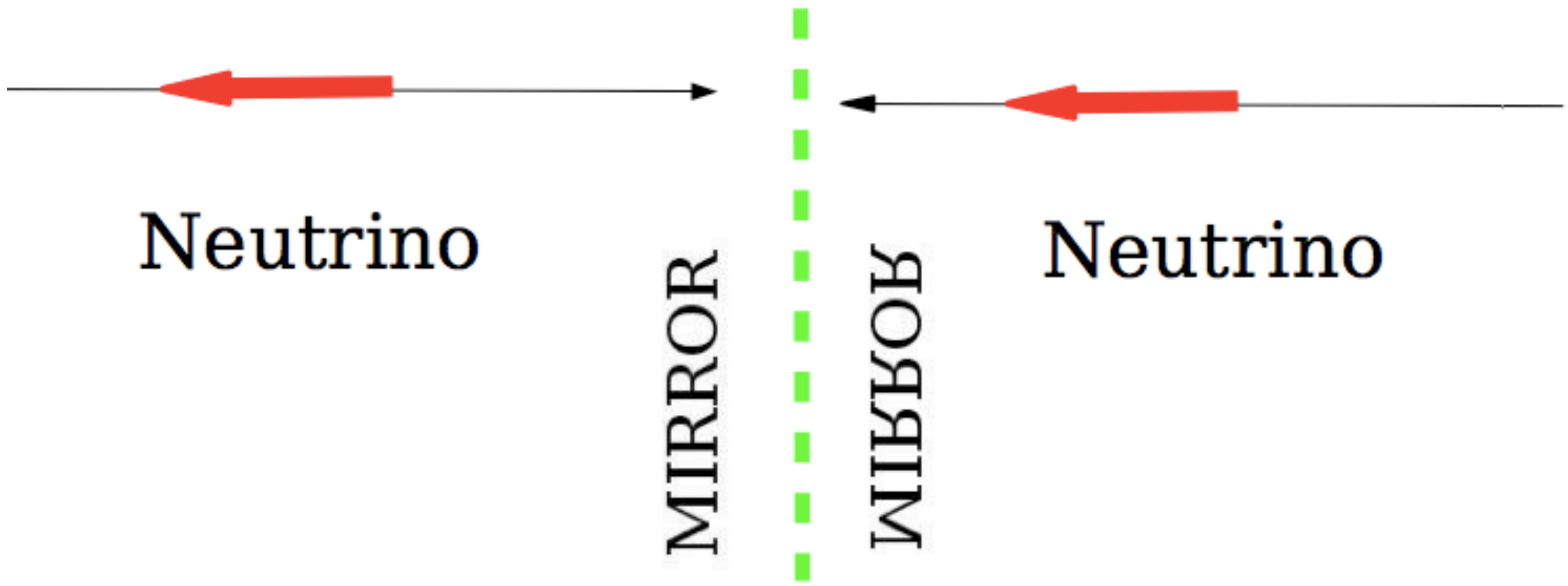
Left and Right
Chirality Projectors

$$\psi_L = \left(\frac{1-\gamma_5}{2}\right) \psi$$

$$\psi_R = \left(\frac{1+\gamma_5}{2}\right) \psi$$

Only the
Left-Chirality
component of a fermion
interacts with the W bosons.

For a massless particle
CHIRALITY = HELICITY

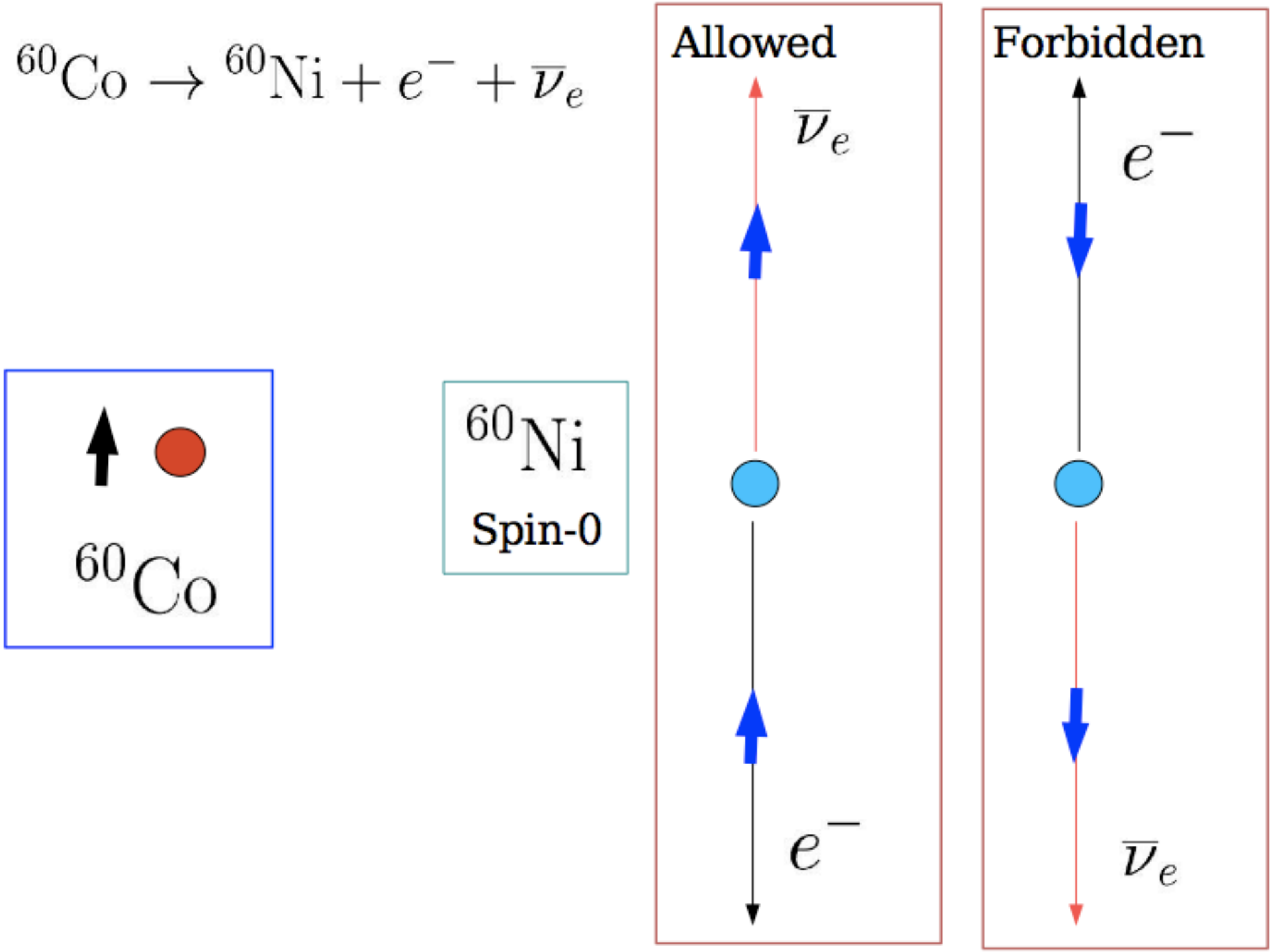


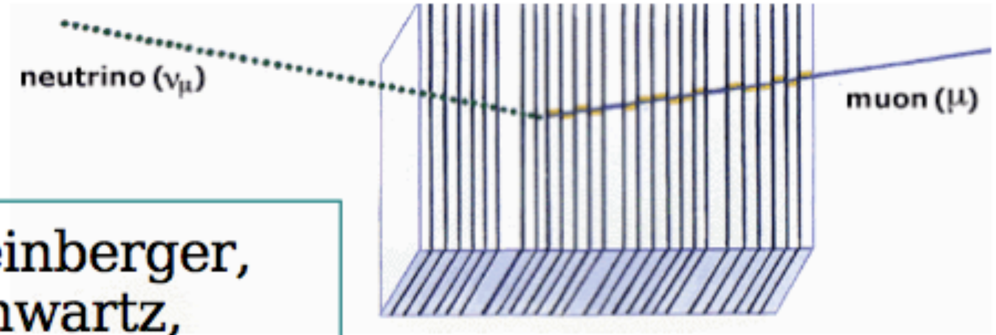
Possible
Picture

Impossible
Picture

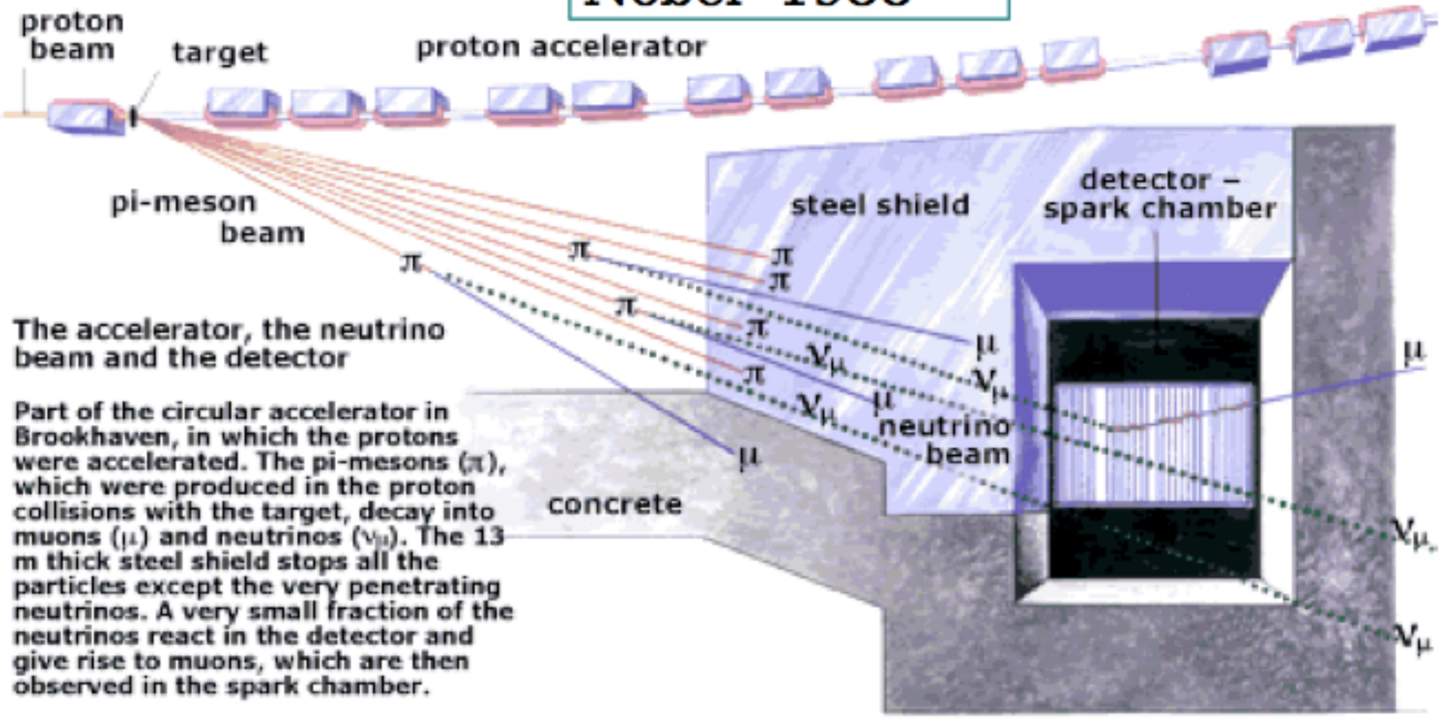
PARITY VIOLATION

$$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + e^- + \overline{\nu}_e$$





Steinberger,
Schwartz,
Lederman
Measure (1962)
Nobel -1988



The accelerator, the neutrino beam and the detector

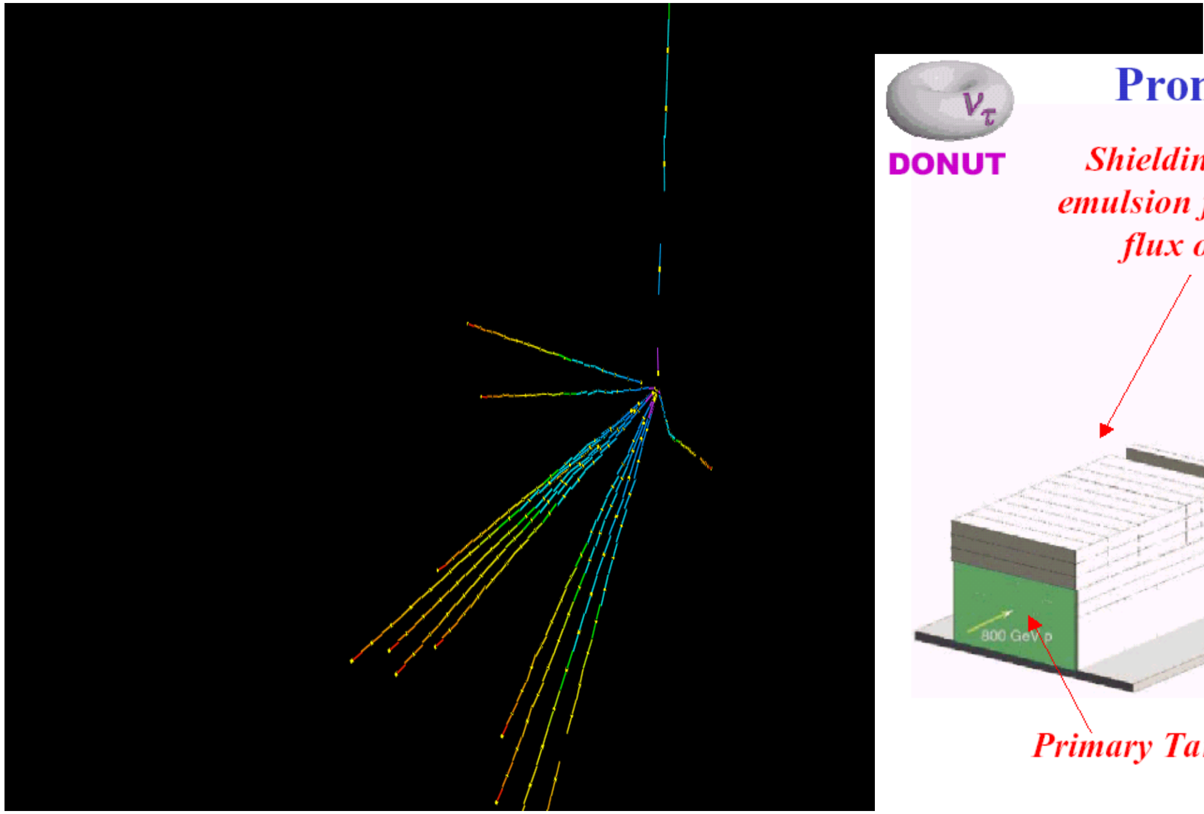
Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons (π), which were produced in the proton collisions with the target, decay into muons (μ) and neutrinos (ν_μ). The 13 m thick steel shield stops all the particles except the very penetrating neutrinos.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

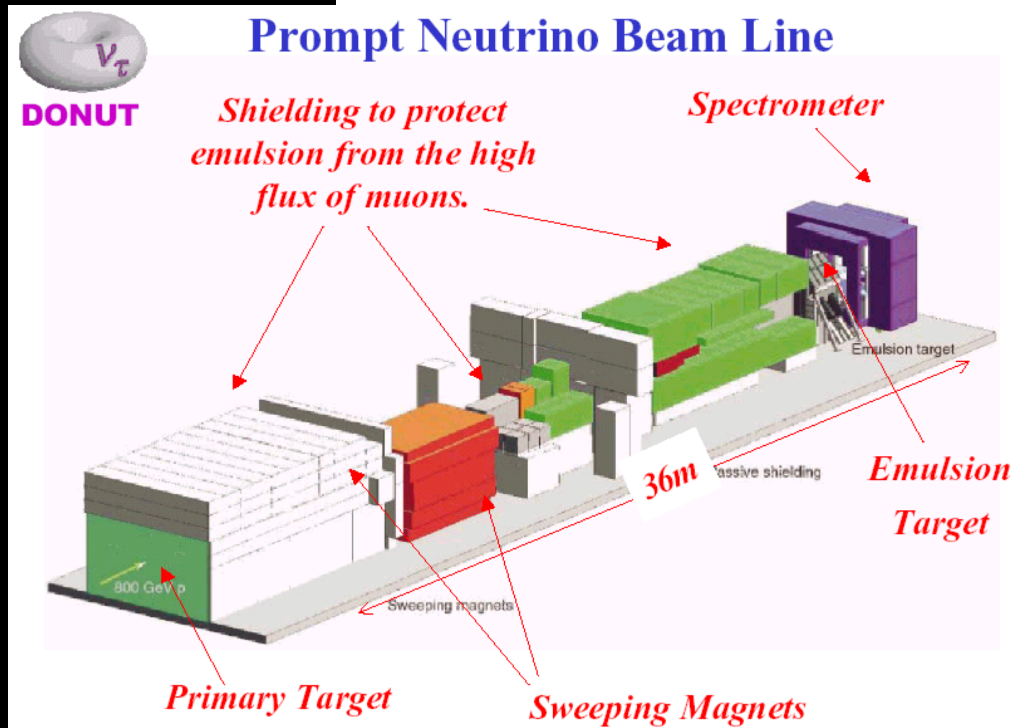
Based on a drawing in Scientific American, March 1963.

A third neutrino flavor!

DONUT experiment at FERMILAB: first detection of ν_τ with an ECC based detector (K. Niwa and collaborators): 9 τ events, 1.5 BG.

K. Kodama et al. (DONuT Collaboration), Phys. Lett. B 504, 218 (2001).





How Many Light Neutrinos Exist ?

Answer : 3

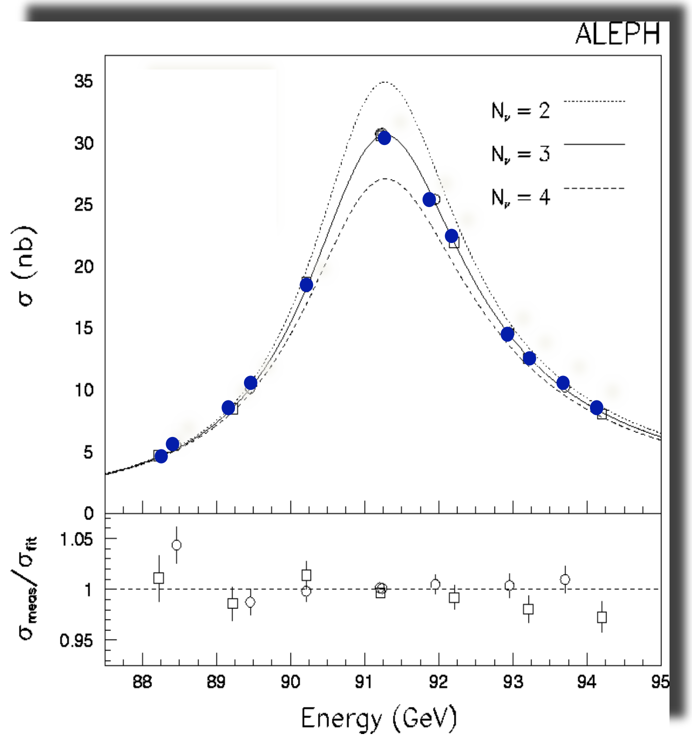
$$Z^0 \rightarrow \nu_\alpha + \overline{\nu}_\alpha$$

$$\Gamma_{\nu\bar{\nu}} = 166.9 \text{ MeV}$$

$$\Gamma_{\text{invisible}} = N_\nu \, \Gamma_{\nu\overline{\nu}}$$

$$\Gamma_{\text{invisible}} = \Gamma_{\text{tot}} - \Gamma_{\text{vis}} = 498 \pm 4.2 \text{ MeV}$$

$$N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_{\nu\bar{\nu}}} = 2.994 \pm 0.012$$



A series of key experiments conducted in the last three decades with atmospheric and solar neutrinos, and confirmed with reactor and accelerator neutrinos, has allowed to firmly establish the first evidence of physics beyond the Standard Model of Particles and Interactions:

neutrino oscillations

Bruno Pontecorvo

B. Pontecorvo, Zh. Eksp. Teor. Fiz. 33 (1957) 549 [Sov. Phys. JETP 6 (1957) 429];
B. Pontecorvo, Zh. Eksp. Teor. Fiz. 34 (1957), 247 [Sov. Phys. JETP 7 (1958) 172].
B. Pontecorvo, Zh. Eksp. Teor. Fiz. 53 (1967) 1717 [Sov. Phys. JETP 26 (1968) 984].

3 Neutrinos states: 3 masses m_1, m_2, m_3

States with definite masses
in general do **not** coincide with the "flavor" states

$$\{ |\nu_e\rangle \quad , \quad |\nu_\mu\rangle \quad , \quad |\nu_\tau\rangle \}$$

Flavor basis

$$\{ |\nu_1\rangle \quad , \quad |\nu_2\rangle \quad , \quad |\nu_3\rangle \}$$

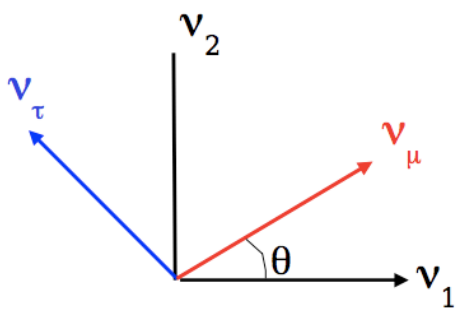
Mass basis

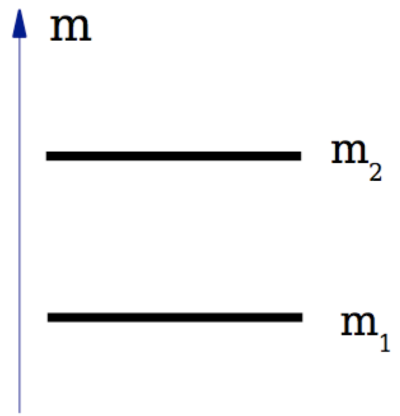
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V^{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Quantum mechanical mixing can take place,
as it happens for quarks

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U^{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

2 Flavor case





$$|\nu_\mu\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$|\nu_\tau\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

$$\Delta m^2 = m_2^2 - m_1^2$$

Neutrino Propagation

$$|\nu(0)\rangle = |\nu_\mu\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

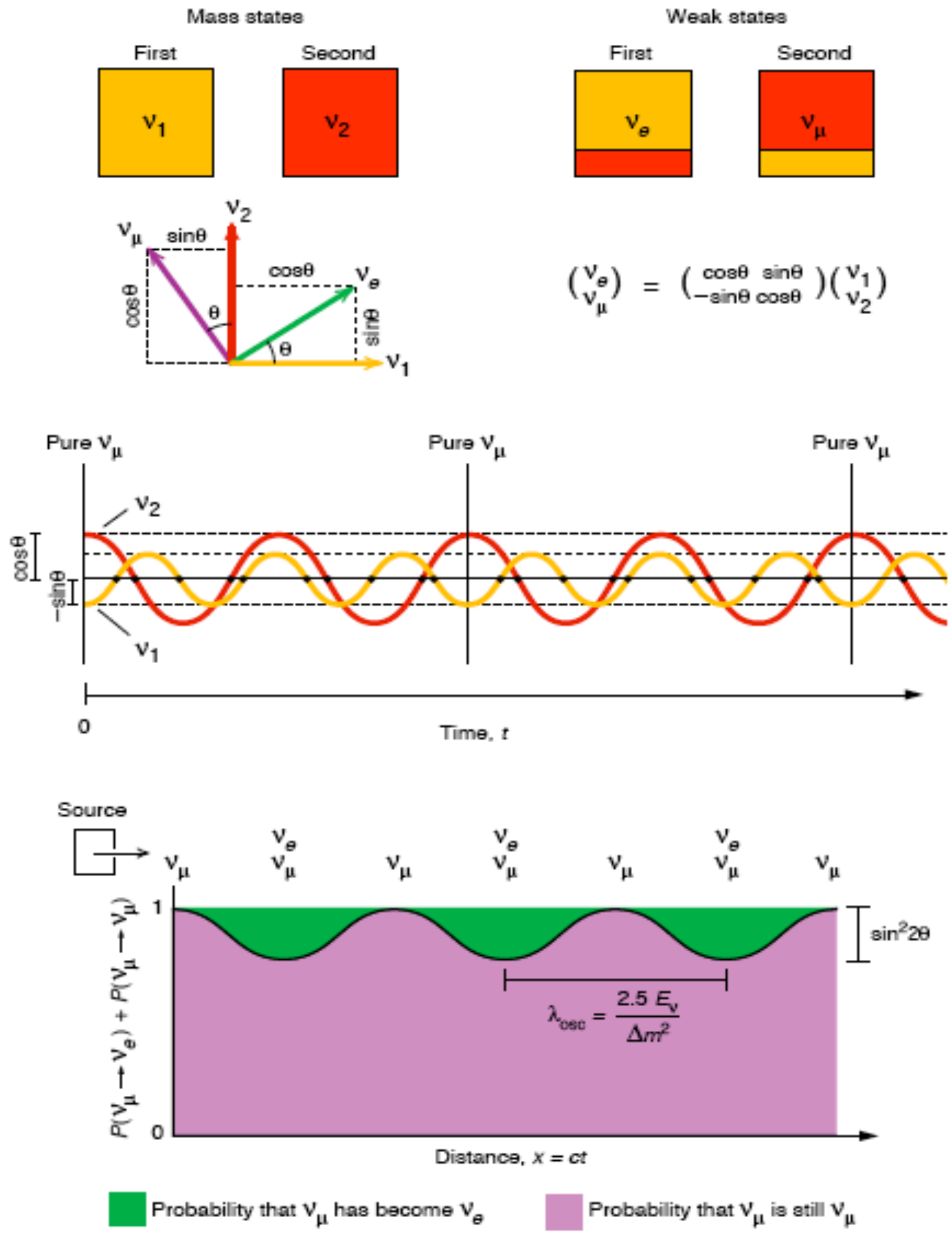
ν_μ created at t =0 with momentum p

$$E_i = \sqrt{p^2 + m_i^2} \simeq p + \frac{m_i^2}{2p} \simeq E + \frac{m_i^2}{2E}$$

Different mass components have different energy

$$|\nu(t)\rangle = \cos\theta\, e^{-iE_1 t}|\nu_1\rangle + \sin\theta\, e^{-iE_2 t}|\nu_2\rangle$$

ν state at time t



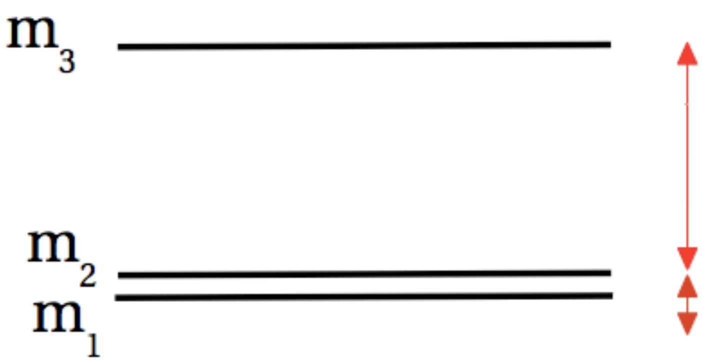
Mass states
First
Second
ν_1
ν_2
Weak states
First
Second
ν_e
ν_μ
ν_μ
ν_2
ν_e
ν_1
sinθ
cosθ
θ
$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$
Pure ν_μ
$-\sin\theta$
Time, t
0
Source
$P(\nu_\mu \to \nu_e) + P(\nu_\mu \to \nu_\mu)$
1
$\sin^2 2\theta$
$\lambda_{osc} = \frac{2.5\, E_\nu}{\Delta m^2}$
Distance, $x = ct$
Probability that ν_μ has become ν_e
Probability that ν_μ is still ν_μ

$$P(\nu_\mu \to \nu_\tau;\, t) =$$

$$\begin{aligned}
&= |\langle \nu_\tau | \nu(t) \rangle|^2 \\
&= |\{-\sin\theta\,\langle \nu_1| + \cos\theta\,\langle \nu_2|\}|\{\cos\theta\, e^{-iE_1 t}|\nu_1\rangle + \sin\theta\, e^{-iE_2 t}|\nu_2\rangle\}|^2 \\
&= \cos^2\theta\, \sin^2\theta\, \left| e^{-iE_2 t} - e^{-iE_1 t} \right|^2 \\
&= 2\cos^2\theta\, \sin^2\theta\, \{1 - \cos[(E_2 - E_1)t\} \\
&= \sin^2 2\theta\, \sin^2\left[\frac{\Delta m^2}{4E} t\right]
\end{aligned}$$

$$P(\nu_\mu \to \nu_\tau;\, L) = \sin^2 2\theta\, \sin^2\left[1.27\,\Delta m^2(\mathrm{eV}^2)\,\frac{L(\mathrm{Km})}{E(\mathrm{GeV})}\right]$$

3 Flavor Oscillations



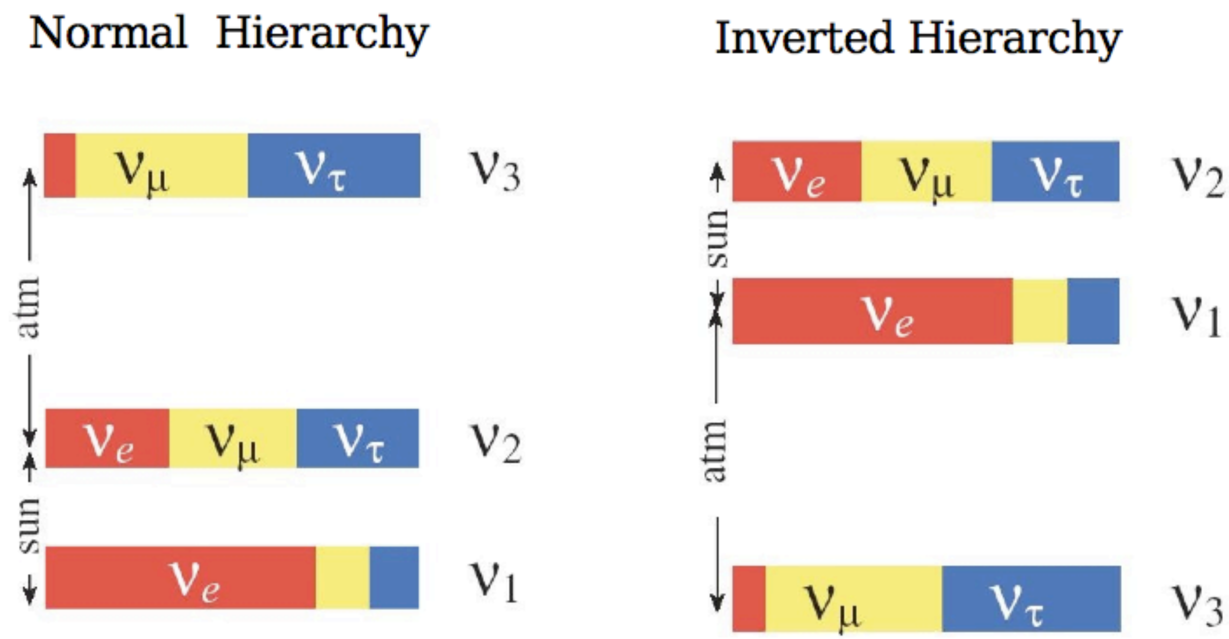
$$
\begin{aligned}
|\nu_e\rangle &= U^*_{e1}\,|\nu_1\rangle + U^*_{e2}\,|\nu_2\rangle + U^*_{e3}\,|\nu_3\rangle \\
|\nu_\mu\rangle &= U^*_{\mu1}\,|\nu_1\rangle + U^*_{\mu2}\,|\nu_2\rangle + U^*_{\mu3}\,|\nu_3\rangle \\
|\nu_\tau\rangle &= U^*_{\tau1}\,|\nu_1\rangle + U^*_{\tau2}\,|\nu_2\rangle + U^*_{\tau3}\,|\nu_3\rangle
\end{aligned}
$$

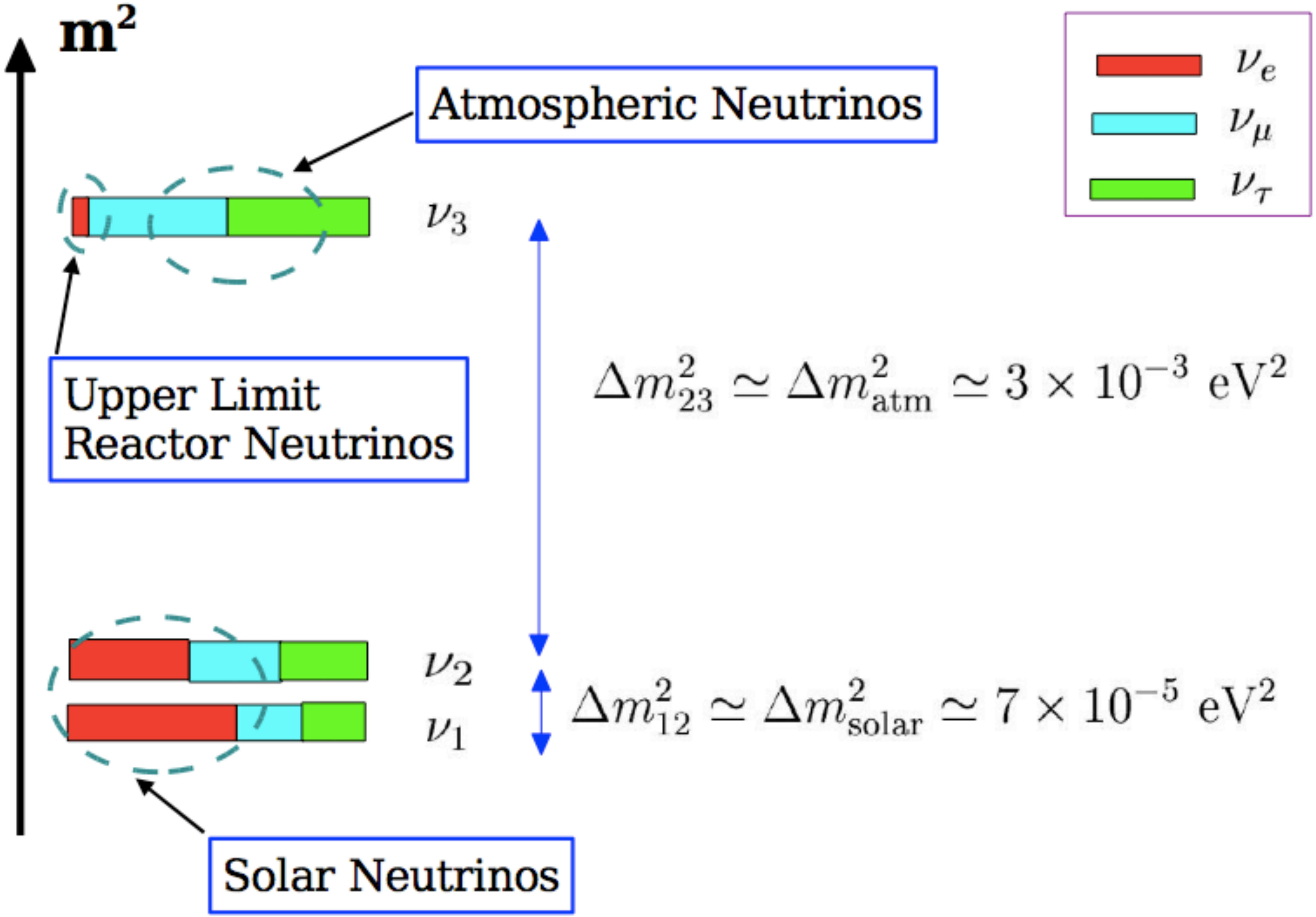
$$
U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\,e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}
$$

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

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U_{\beta j} U^*_{\alpha j}\, e^{-i\, m_j^2 \frac{L}{2E_\nu}} \right|^2$$

Neutrino state cross-composition





m^2
Atmospheric Neutrinos
Upper Limit Reactor Neutrinos
Solar Neutrinos
ν_3
ν_2
ν_1
ν_e
ν_μ
ν_τ
$\Delta m^2_{23} \simeq \Delta m^2_{\text{atm}} \simeq 3 \times 10^{-3}\ \text{eV}^2$
$\Delta m^2_{12} \simeq \Delta m^2_{\text{solar}} \simeq 7 \times 10^{-5}\ \text{eV}^2$

For the special case of $\nu_\mu \rightarrow \nu_e$ oscillations, we have:

$$P(\nu_\mu \rightarrow \nu_e) = \Sigma_{i=1,4} P_i$$

$$P_1 = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2} \quad \text{atmospheric part}$$

$$P_2 = \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2} \quad \text{solar part}$$

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2} \quad \text{interference}$$

$$P_4 = \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

θ_{13} is the link between solar and atmospheric oscillations

where

$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$$

$$A = \sqrt{2}G_F n_e$$

$$B_\pm = |A \pm \Delta_{13}|$$

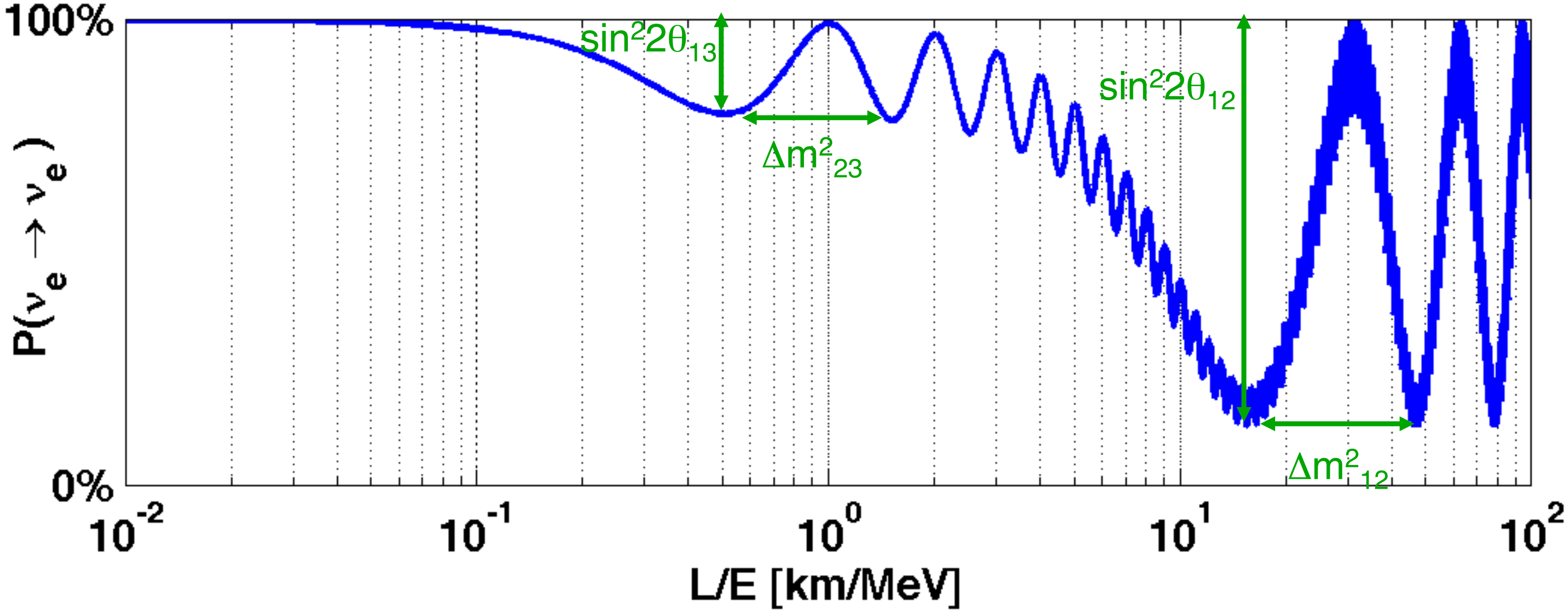
$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

and the $\pm$ signifies neutrinos or antineutrinos

In vacuum, at leading order:

$$P(\nu_\mu \rightarrow \nu_e) \propto \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\frac{\Delta m^2_{23}L}{4E}$$

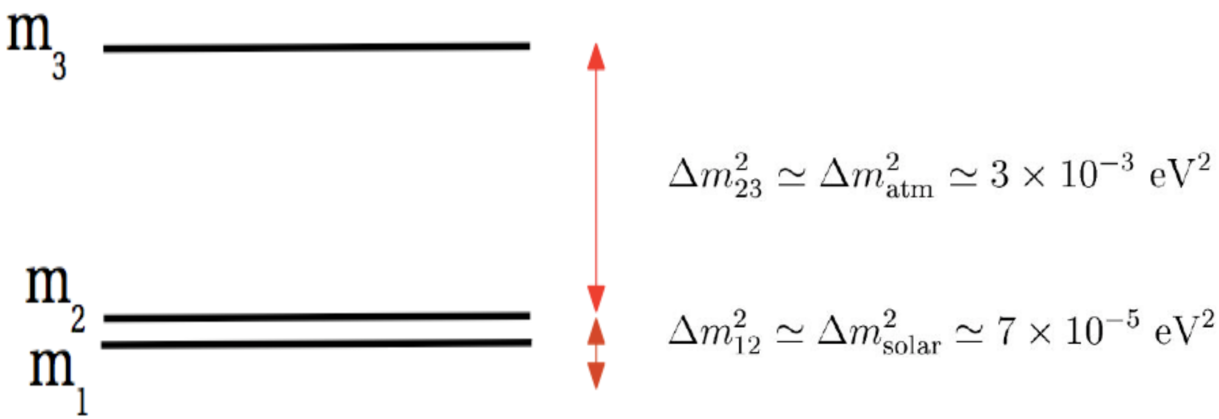
Example: ν_e survival probability as a function of L/E



Anticipate a fundamental question

The occurrence of neutrino oscillations implies that the neutrino has a mass (actually 3 non-degenerate mass eigenvalues)

From oscillation experiments we cannot set the mass scale, but only a lower limit: if $m_1 \sim 0 \rightarrow m_3 > \surd\ 3\text{x}10^{-3}\ \text{eV}^2 \sim 50$ meV. From cosmological and direct mass measurements it turns out that the neutrino mass is smaller than ~1 eV.



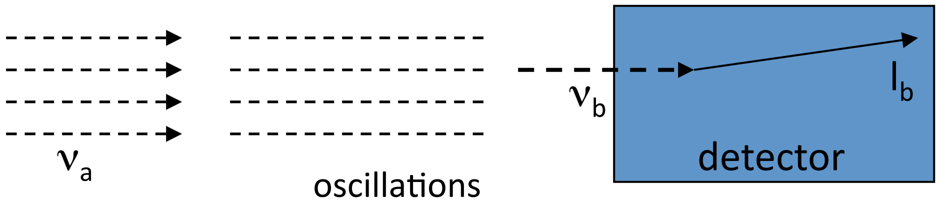
The question is then: why the neutrino mass is so much smaller that that of the other fermions?

Maybe because the neutrino is a Majorana particle….

Classification of neutrino oscillation experiments

APPEARANCE experiments

ν_a - ν_b oscillations



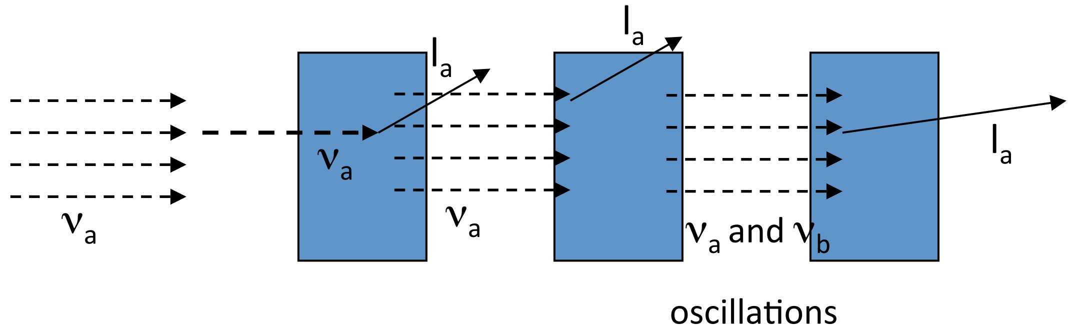
CC interaction of ν_b producing the charged lepton b, whose appearance is detected

NEED:

1) no ν_b in the initial beam (or a small fraction very well known)
2) E_ν sufficient to produce a b lepton
3) high efficiency in detecting the b lepton

DISAPPEARANCE experiments

ν_a - ν_x oscillations



CC interaction of ν_a producing the charged lepton a, measured where oscillations do-not/do occur

NEED:

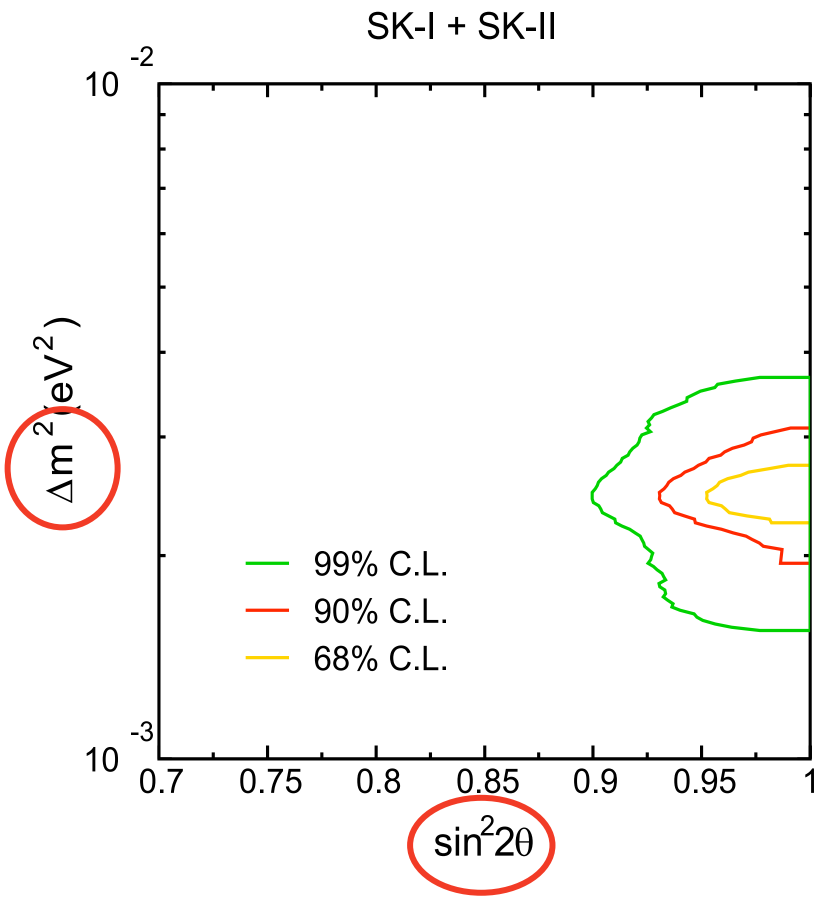
1) tiny effects: very good knowledge of the beam, and good control of detector systematics
2) useful to have 'near' and 'far' detector of the same type (mass scaling with L^2)
3) look for spectrum distortions

How neutrino oscillation results are presented

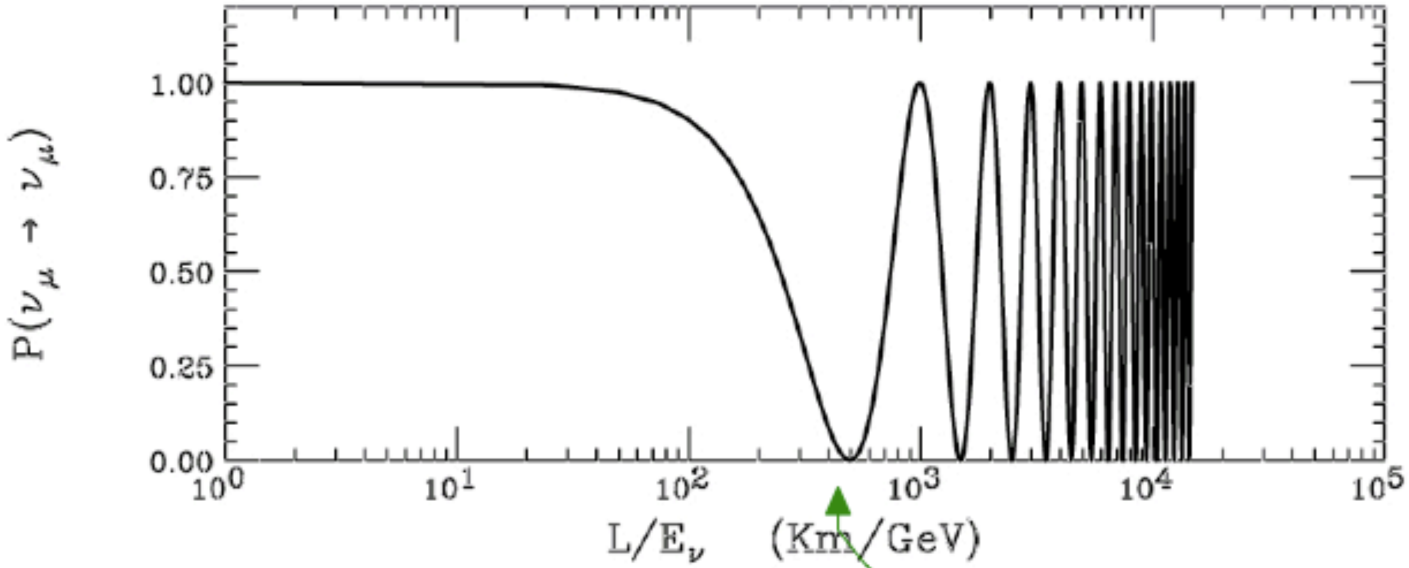
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2\theta_{23} \cdot \sin^2\left(\frac{1.27\Delta m_{23}^2 L}{E}\right), \quad (\Delta m_{23}^2 = \left|m_{\nu_3}{}^2 - m_{\nu_2}{}^2\right| eV^2)$$

$$P(\nu_\mu \to \nu_\tau) = 1 - P(\nu_\mu \to \nu_\mu) \qquad E(GeV),\ L(km)$$

Example:



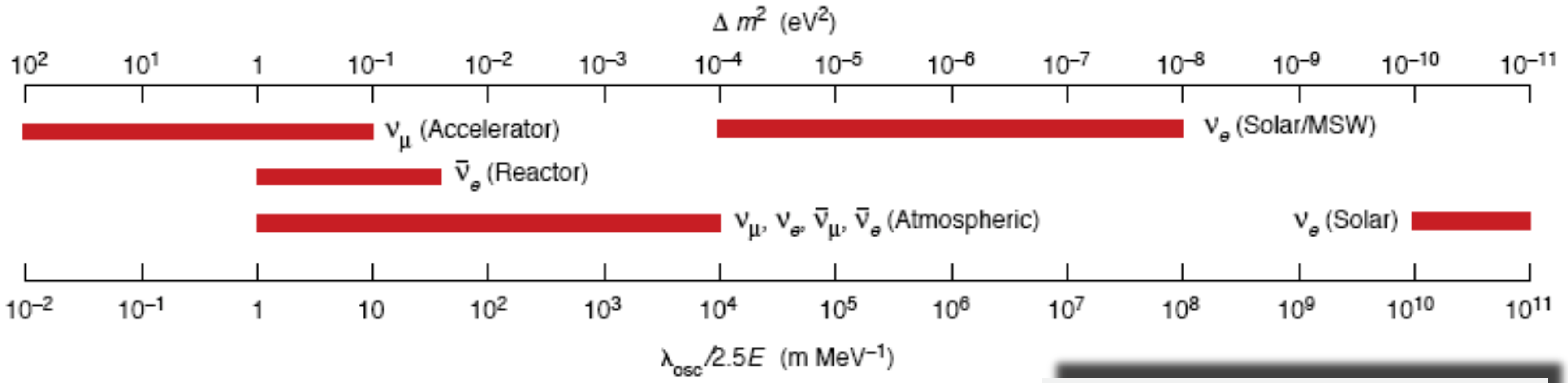
$$P_{\nu_\mu \to \nu_\mu}(L, E_\nu) = 1 - \sin^2 2\theta \ \sin^2\left[\frac{\Delta m^2 \, L}{4E_\nu}\right]$$



$$P_{\nu_\mu \to \nu_\mu} = \begin{cases} 1 & \text{for } L \text{ small,} \\ 1 - \frac{\sin^2 2\theta}{2} & \text{for } L \text{ large.} \end{cases}$$

$$\simeq \frac{\lambda^*_{\text{osc}}}{2} \simeq \frac{2\pi \langle E_\nu \rangle}{|\Delta m^2|}$$

Sensitivity range of neutrino oscillation experiments



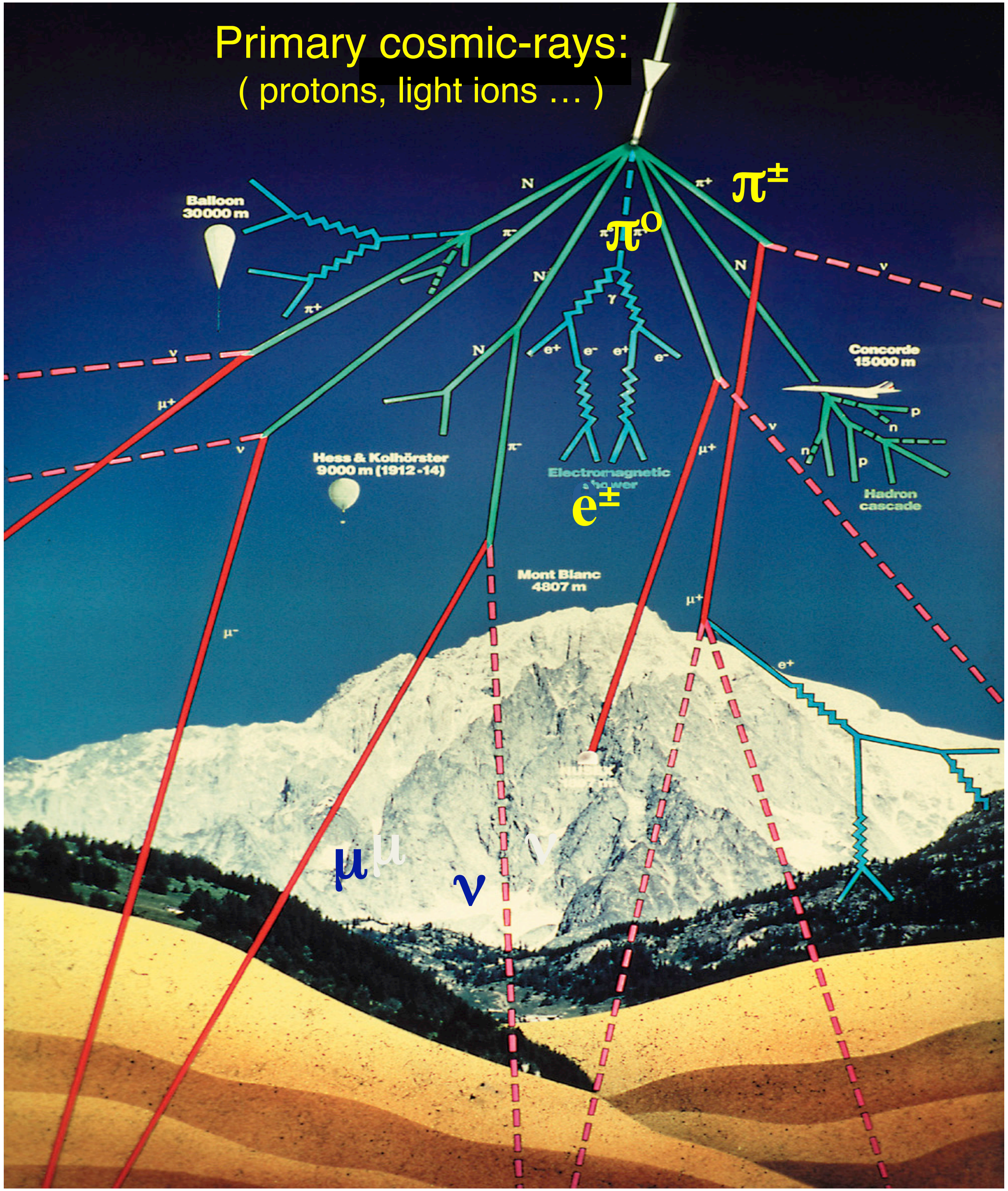
$$\lambda_{osc} = \frac{\pi E_\nu}{1.27 \Delta m^2} \approx \frac{2.5 E_\nu}{\Delta m^2}$$

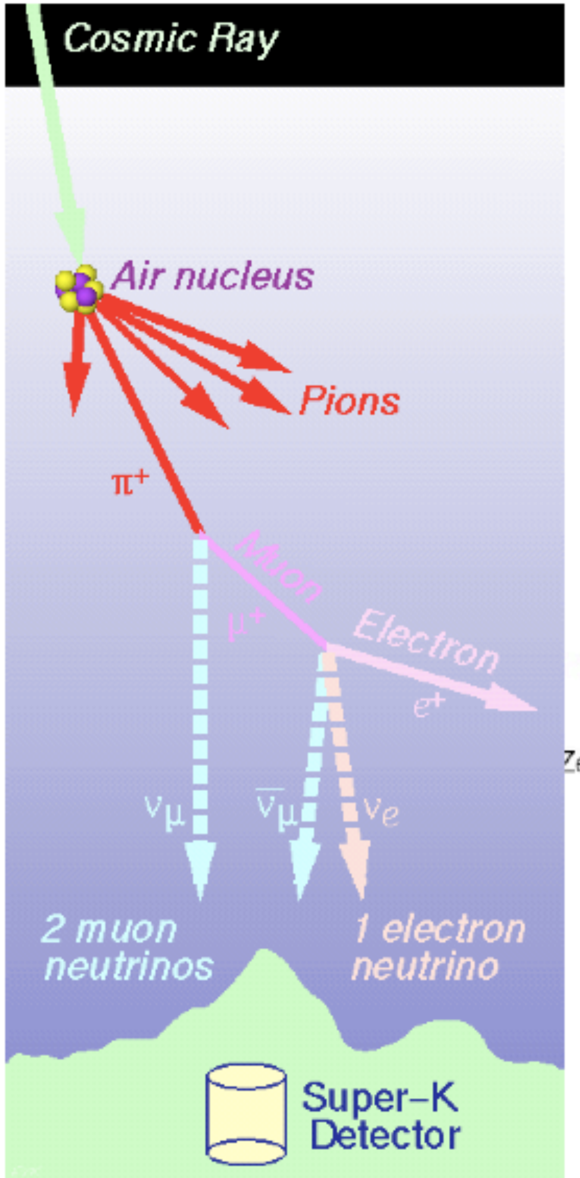
Following the results obtained with atmospheric neutrinos:

experiments with artificial (accelerator) neutrinos sensitive to the same oscillation parameters

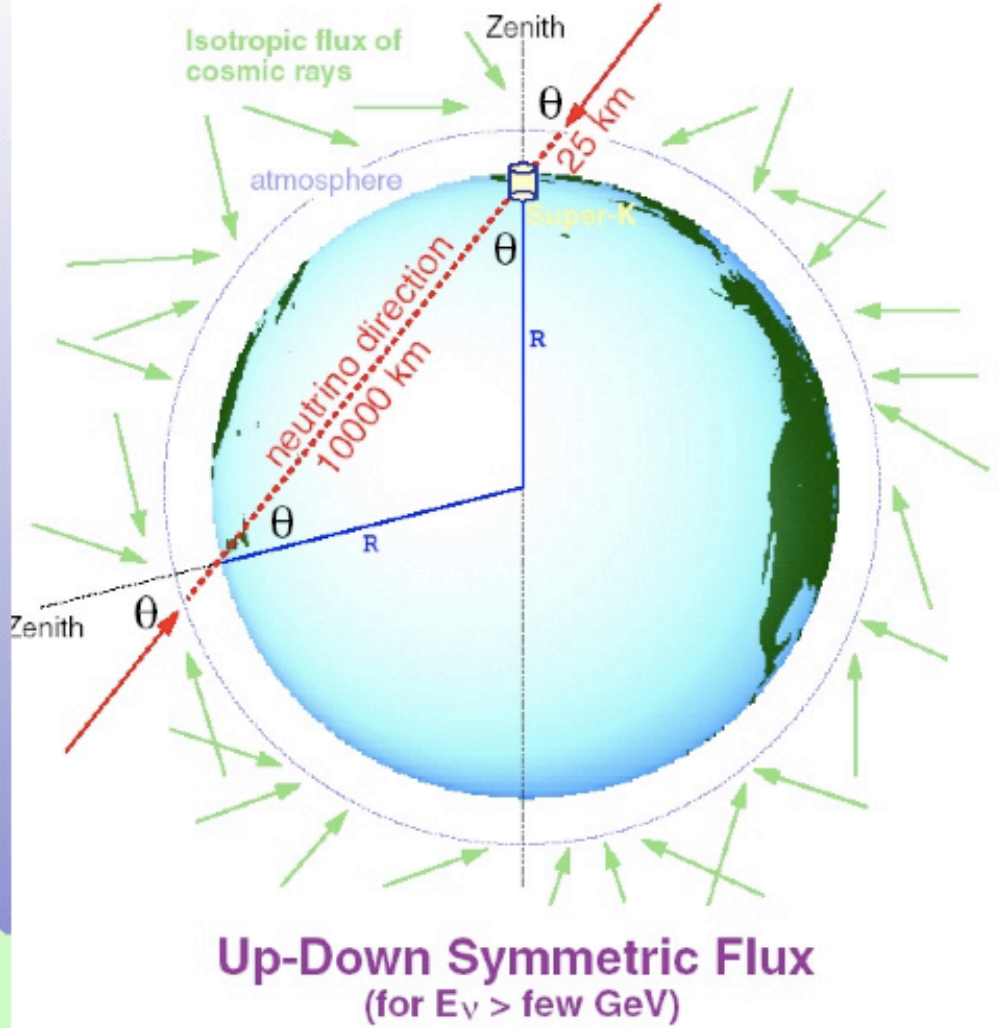
$$P_{osc} \sim \sin^2(\Delta m^2 L/4E)$$

oscillation	Δm^2 (eV^2)	L (km)	E (GeV)	source	typical Experiment
atmospheric	$\sim 10^{-3}$	100-1000	1-10	accelerator	K2K, MINOS, OPERA, T2K
solar	$\sim 10^{-5}$	10-100	10^{-3}-10^{-2}	reactor	CHOOZ, KamLAND

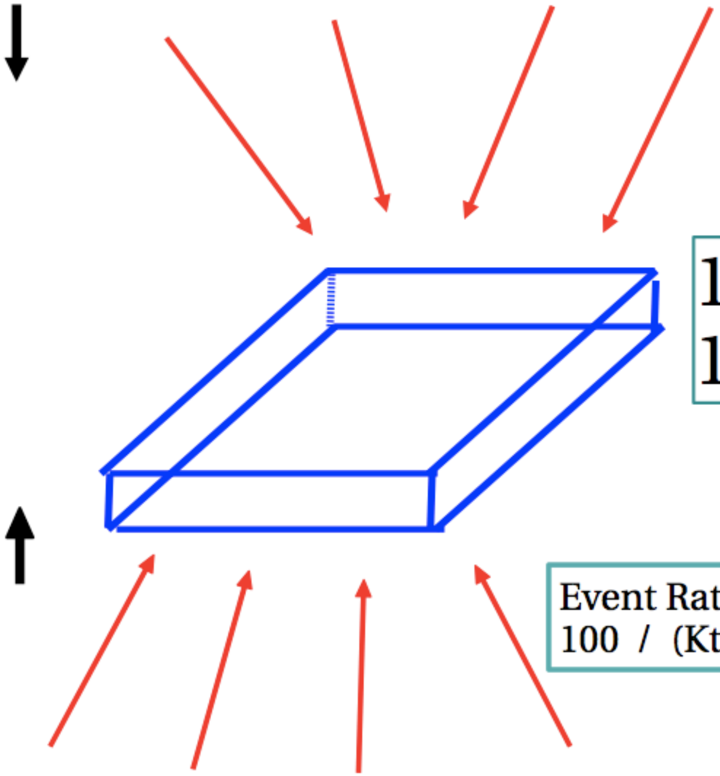

Primary cosmic-rays:
(protons, light ions …)
π±
πo
e±
μ
ν
Balloon 30000 m
Hess & Kolhörster 9000 m (1912-14)
Concorde 15000 m
Mont Blanc 4807 m
Electromagnetic shower
Hadron cascade
N
π+
π-
γ
e+
e-
μ+
μ-
ν
p
n



ATMOSPHERIC NEUTRINOS



$\approx 3000\ \nu_\mu$
$\approx 3000\ \bar{\nu}_\mu$
$\approx 1600\ \nu_e$
$\approx 1400\ \bar{\nu}_e$



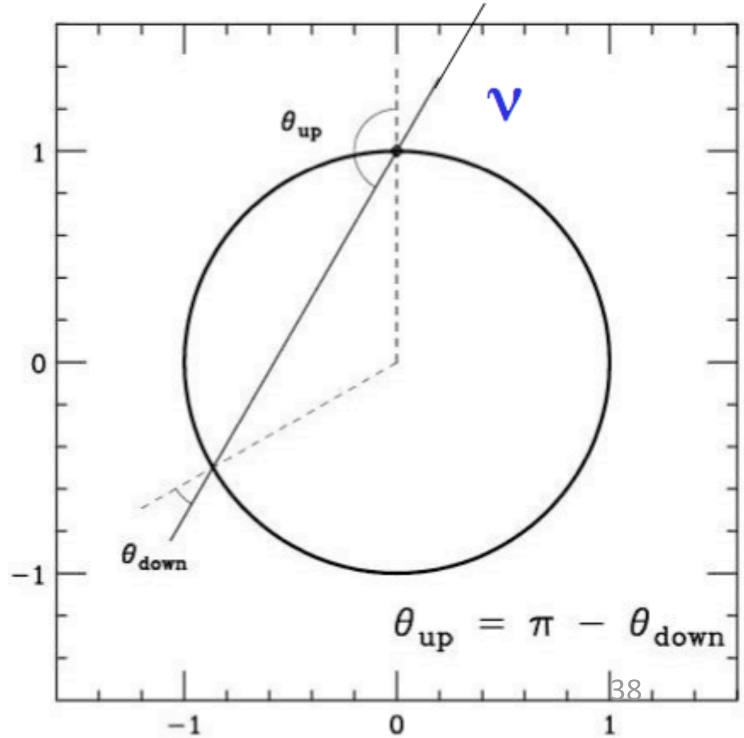
$1\ m^2$
$1\ sec$

Expected

$\approx 3000\ \nu_\mu$
$\approx 3000\ \bar{\nu}_\mu$
$\approx 1600\ \nu_e$
$\approx 1400\ \bar{\nu}_e$

Event Rate
100 / (Kton year)

$$\phi_{\nu_\alpha}(E,\theta) = \phi_{\nu_\alpha}(E,\pi-\theta)$$



$$p + A_{\text{Air}} \rightarrow p, n, \pi^{\circ}, \pi^{\pm}, K^{\pm}, K_L \ldots$$

Leading nucleon
50% of energy

$\pi^{\circ} \rightarrow \gamma\gamma$
Electromagnetic
Shower

Decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \nu_e + \overline{\nu}_\mu$$

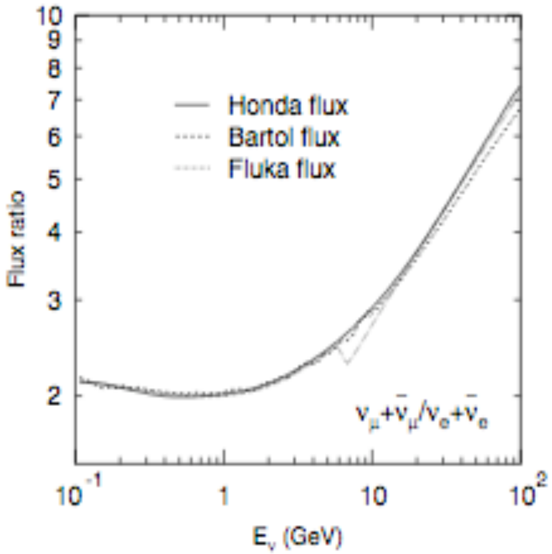
Interaction

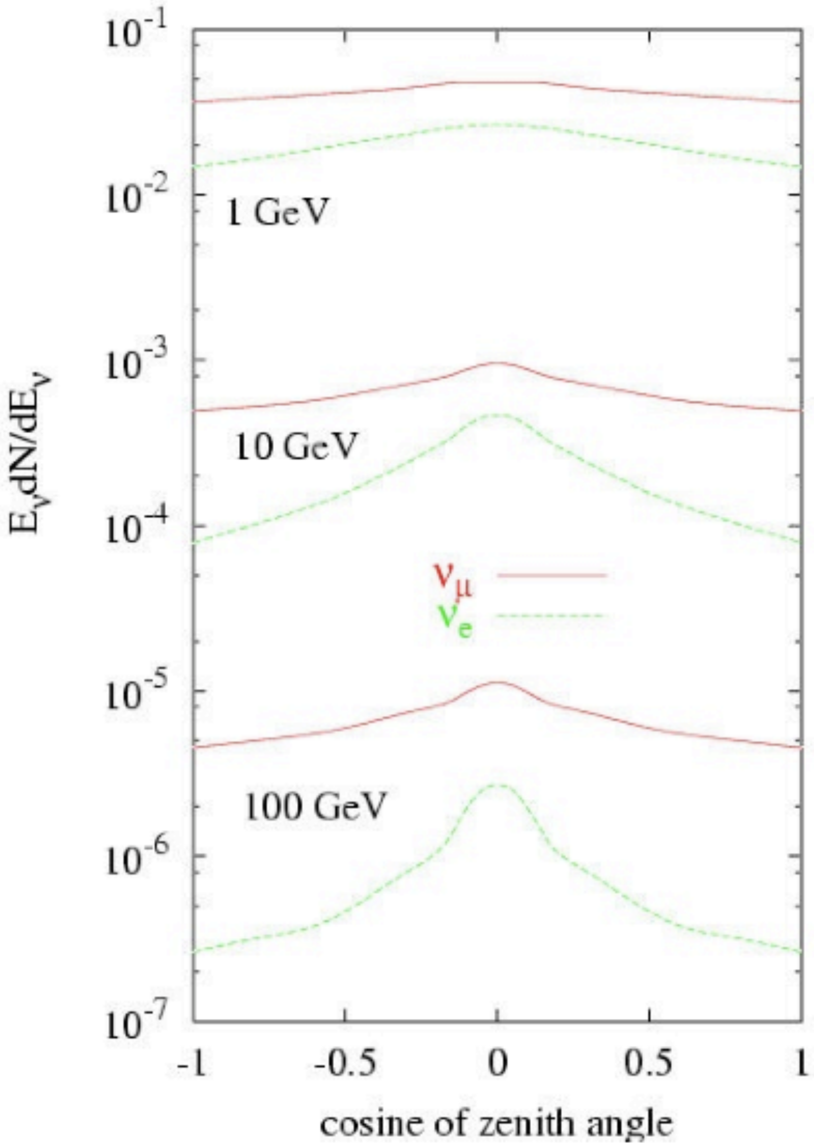
$$\pi^+ \to \nu_\mu \, \mu^+ \to \nu_\mu \, \overline{\nu}_\mu \, \nu_e \, e^+$$
$$\pi^- \to \overline{\nu}_\mu \, \mu^- \to \overline{\nu}_\mu \, \nu_\mu \, \overline{\nu}_e \, e^-$$

$$\frac{\nu_e}{\overline{\nu}_e} \simeq \frac{\pi^+}{\pi^-} \simeq 1.2 \qquad \frac{\nu_\mu}{\overline{\nu}_\mu} \simeq 1$$

$$\frac{\nu_\mu + \overline{\nu}_\mu}{\nu_e + \overline{\nu}_e} \simeq 2$$

Assume all muons decay
AND
an important kinematical fact.
All 3 neutrinos in decay
have approximately the same
energy





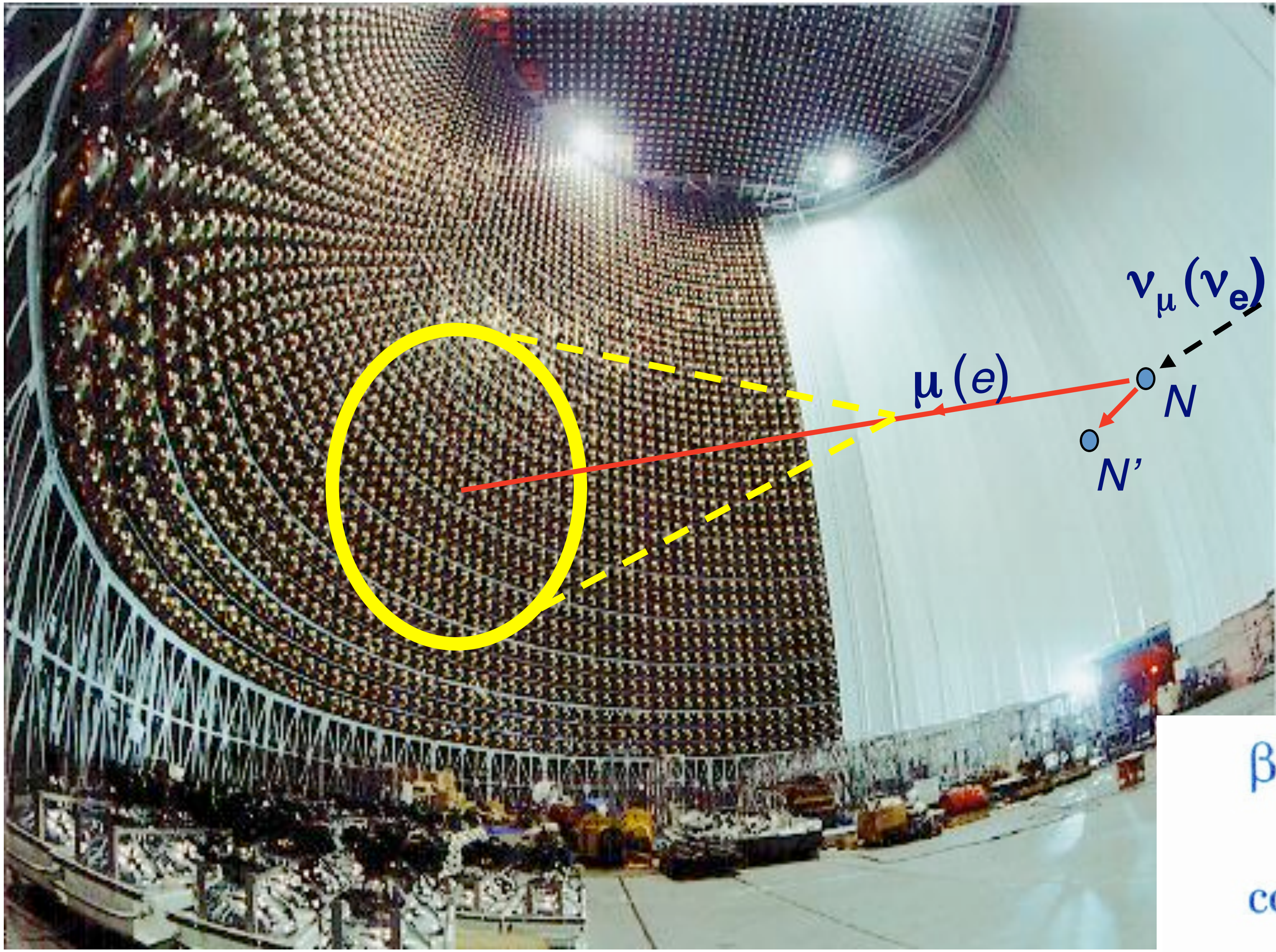
Zenith angle distribution is Up-Down symmetric

Zenith angle distribution
maximum $|\cos\theta| = 0$
minimum $|\cos\theta| = 1$
(μ and π decay effect)

Ratio ν_μ/ν_e
is energy dependent
(grows with increasing energy)

Ratio ν_μ/ν_e
is zenith angle dependent
(grows with $|\cos\theta|$)

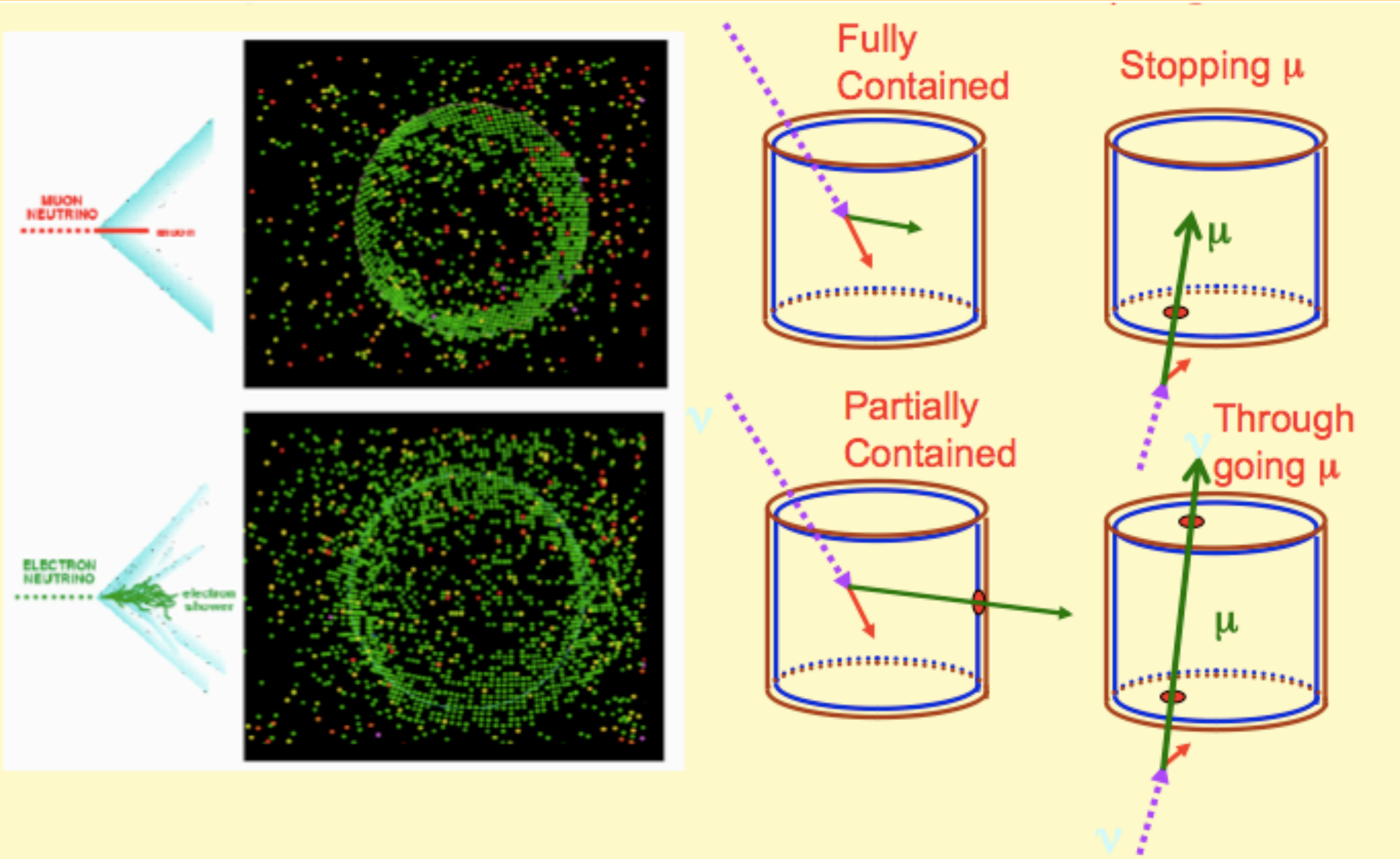
Cerenkov ring detection in Super-Kamiokande



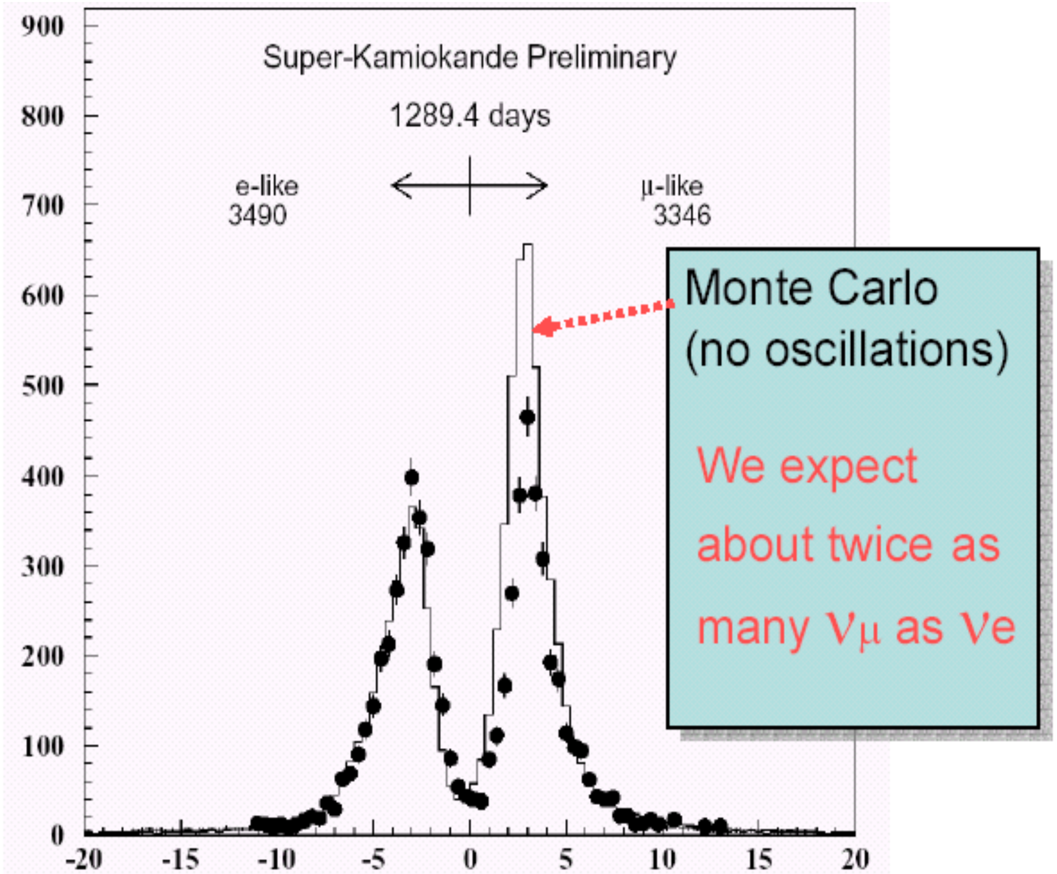
$$\beta \left(=\frac{v}{c}\right) > \frac{1}{n}$$

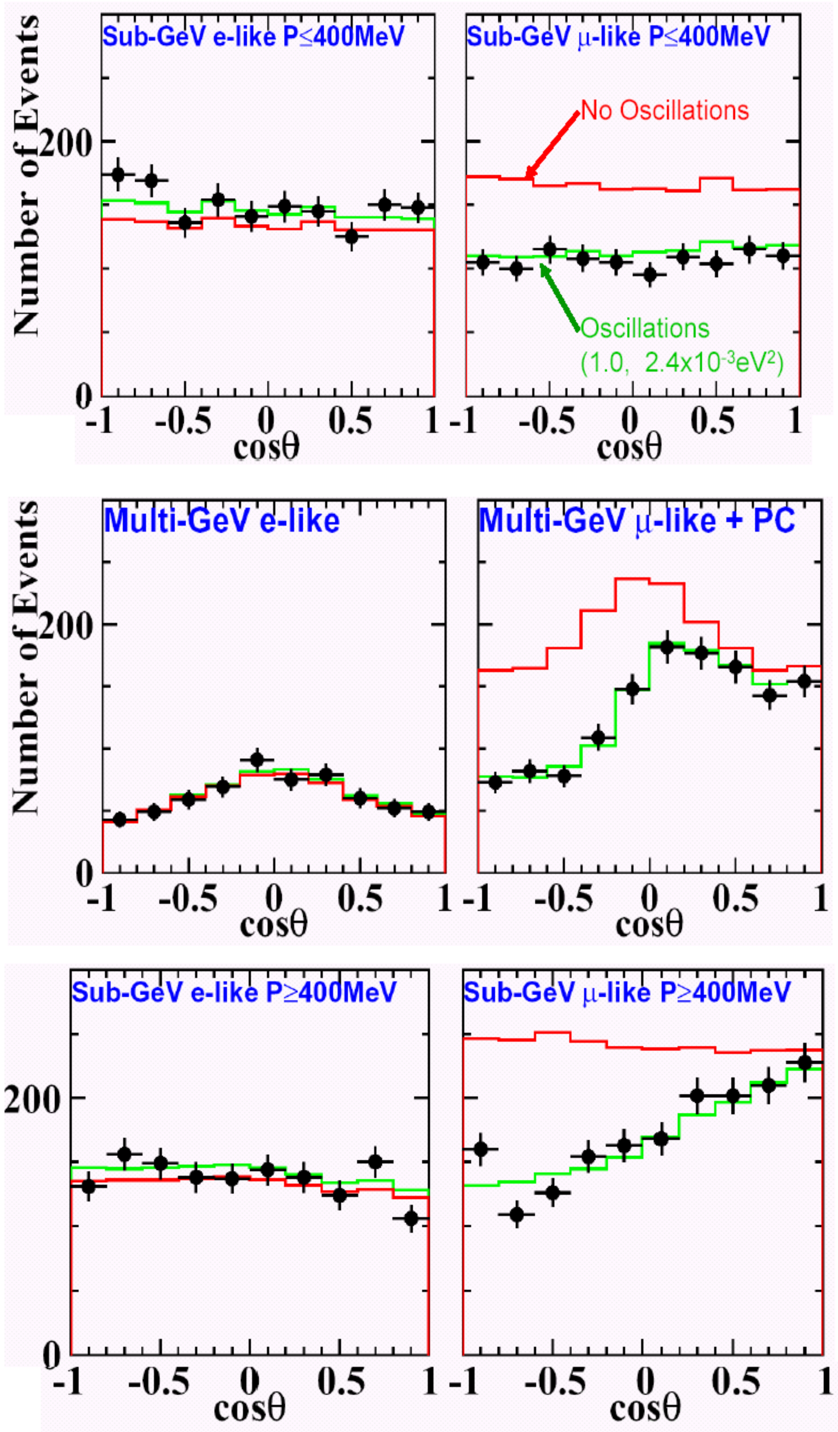
$$\cos\theta_{Ch} = \frac{1}{\beta n}$$

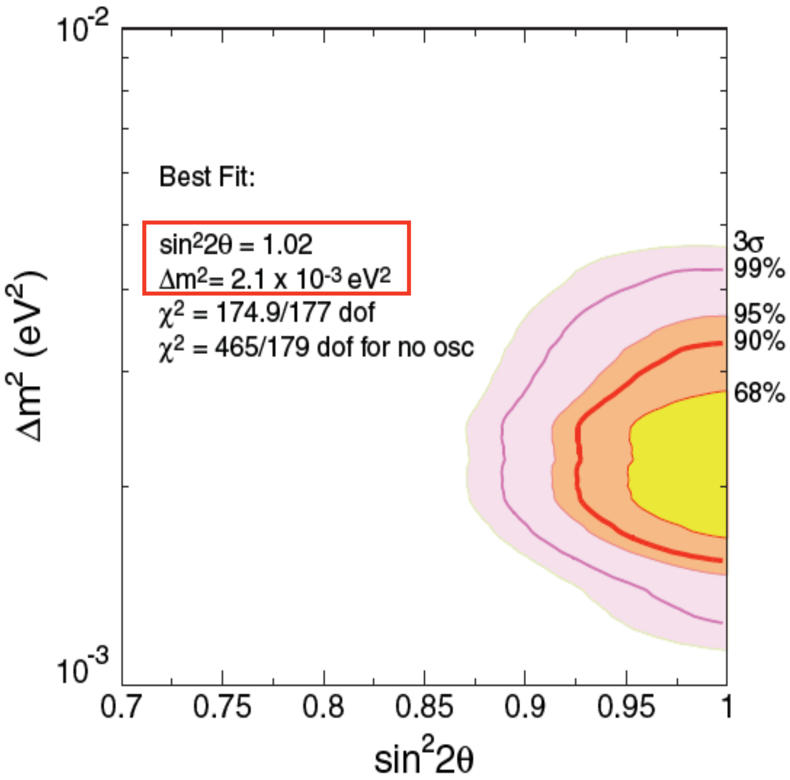
in water, $n = 1.33$
as $\beta \to 1$, $\theta_{Ch} \to 41$ degrees


MUON NEUTRINO
muon
ELECTRON NEUTRINO
electron shower
Fully Contained
Stopping μ
μ
ν
Partially Contained
Through going μ
μ
ν

A first problem: integral electron and muon distributions





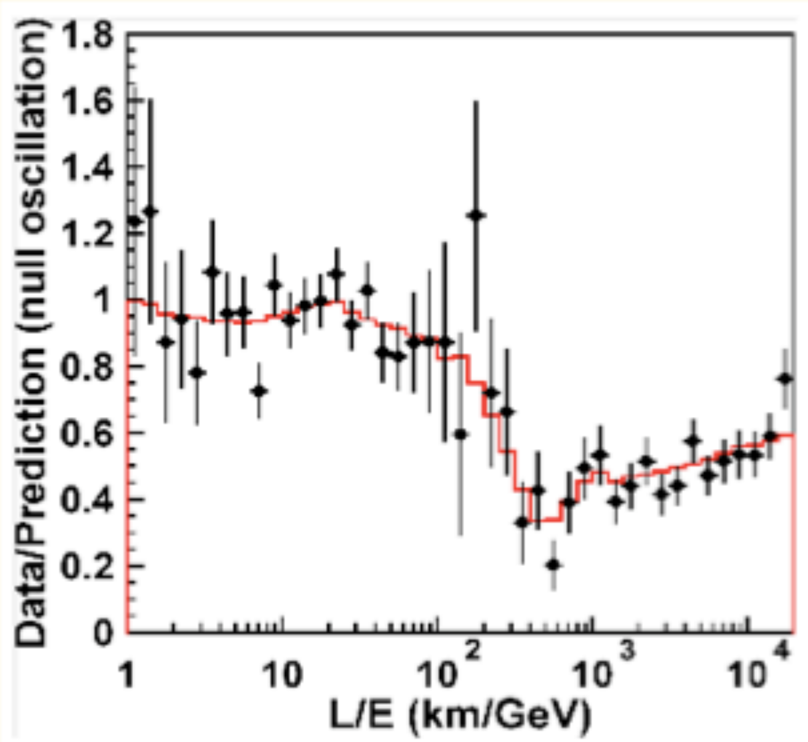


$$P_{osc} = \sin^2 2\theta \, \sin^2 (\Delta m^2 L/4E)$$

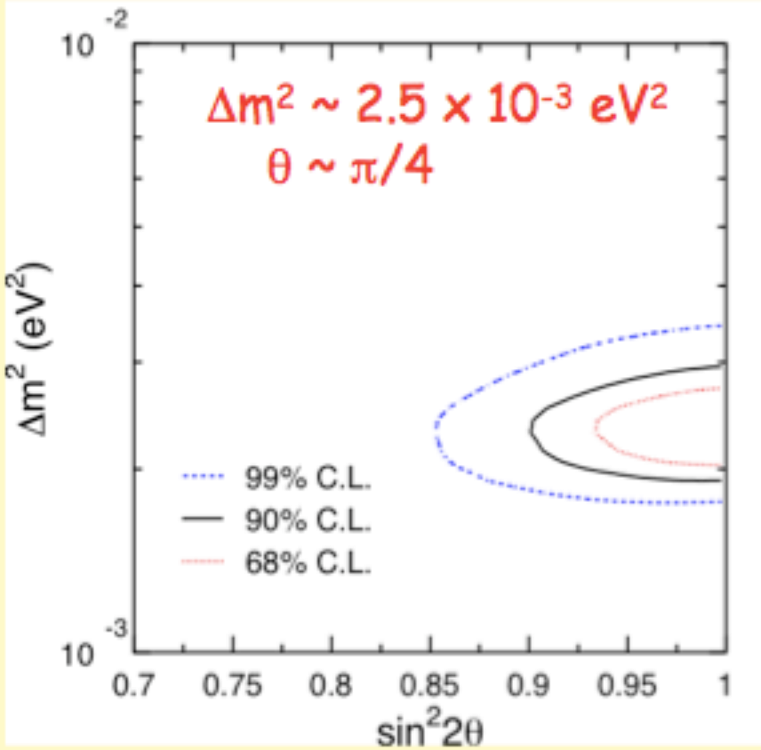
The data also indicate that the atmospheric neutrino deficit is due to $\nu_\mu \rightarrow \nu_\tau$ oscillations

Dedicated L/E analysis in SK "sees" half-period of oscillations

1st oscillation dip still visible despite large L & E smearing



Strong constraints on the parameters (Δm^2, θ)



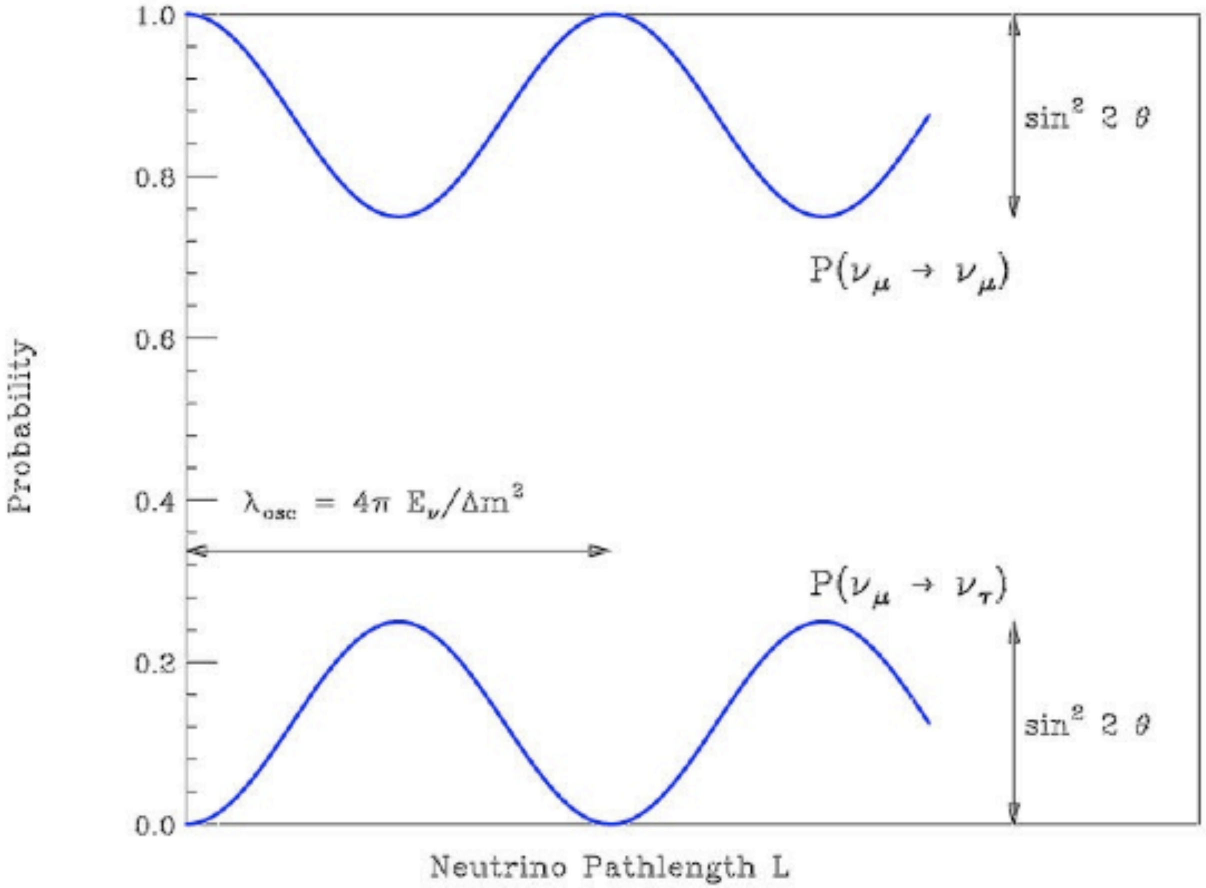
Energy Threshold for CC interactions of ν_τ

$$E(\nu_\tau) \geq m_\tau + m_\tau^2 / 2m_p \approx 3.5 \text{ GeV}$$

In atmospheric neutrinos most ν_τ are below threshold for CC interactions and therefore simply "disappear".

2-flavor Oscillation Probability

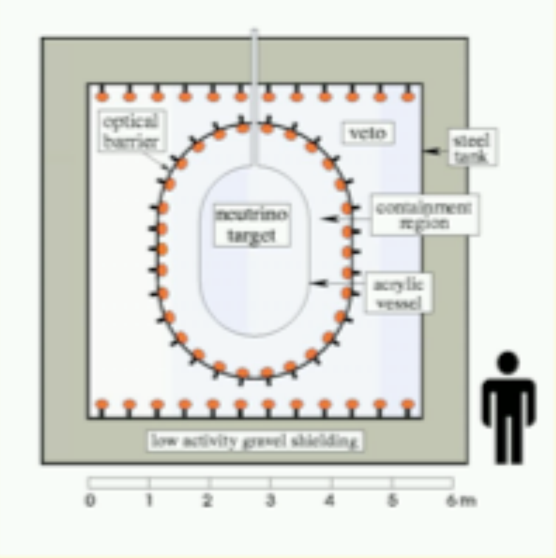
$$P(\nu_\mu \to \nu_\tau;\, L) = \sin^2 2\theta\, \sin^2\left[1.27\,\Delta m^2(\text{eV}^2)\frac{L(\text{Km})}{E(\text{GeV})}\right]$$



No ν_e-ν_x oscillations in the same parameter region as atmospheric neutrinos

The short-baseline reactor experiment CHOOZ

~1 km →



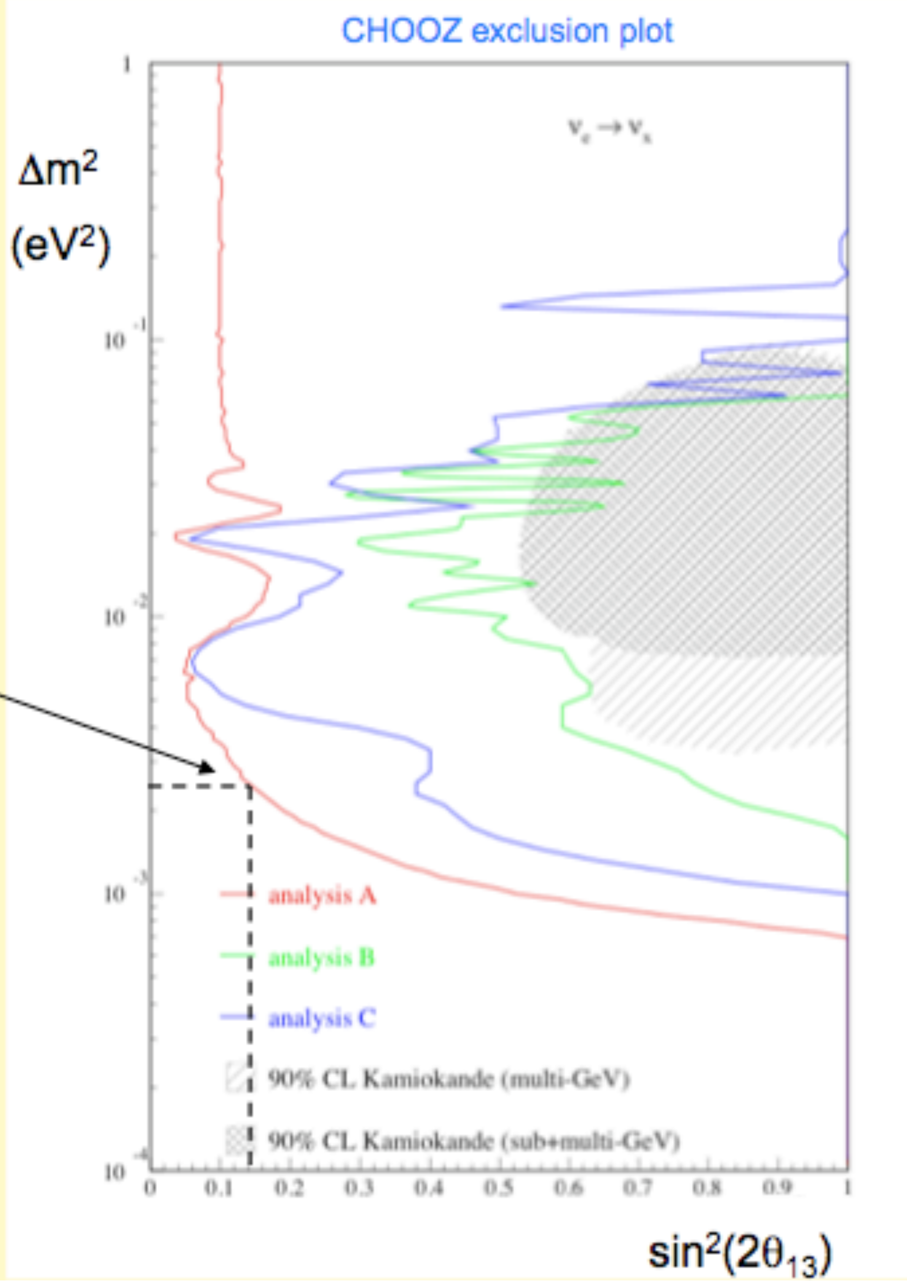
Interpretation

One mass scale dominance:
$P_{ee} = 1 - \sin^2(2\theta_{13}) \sin^2(\Delta m^2 L/4E_\nu)$

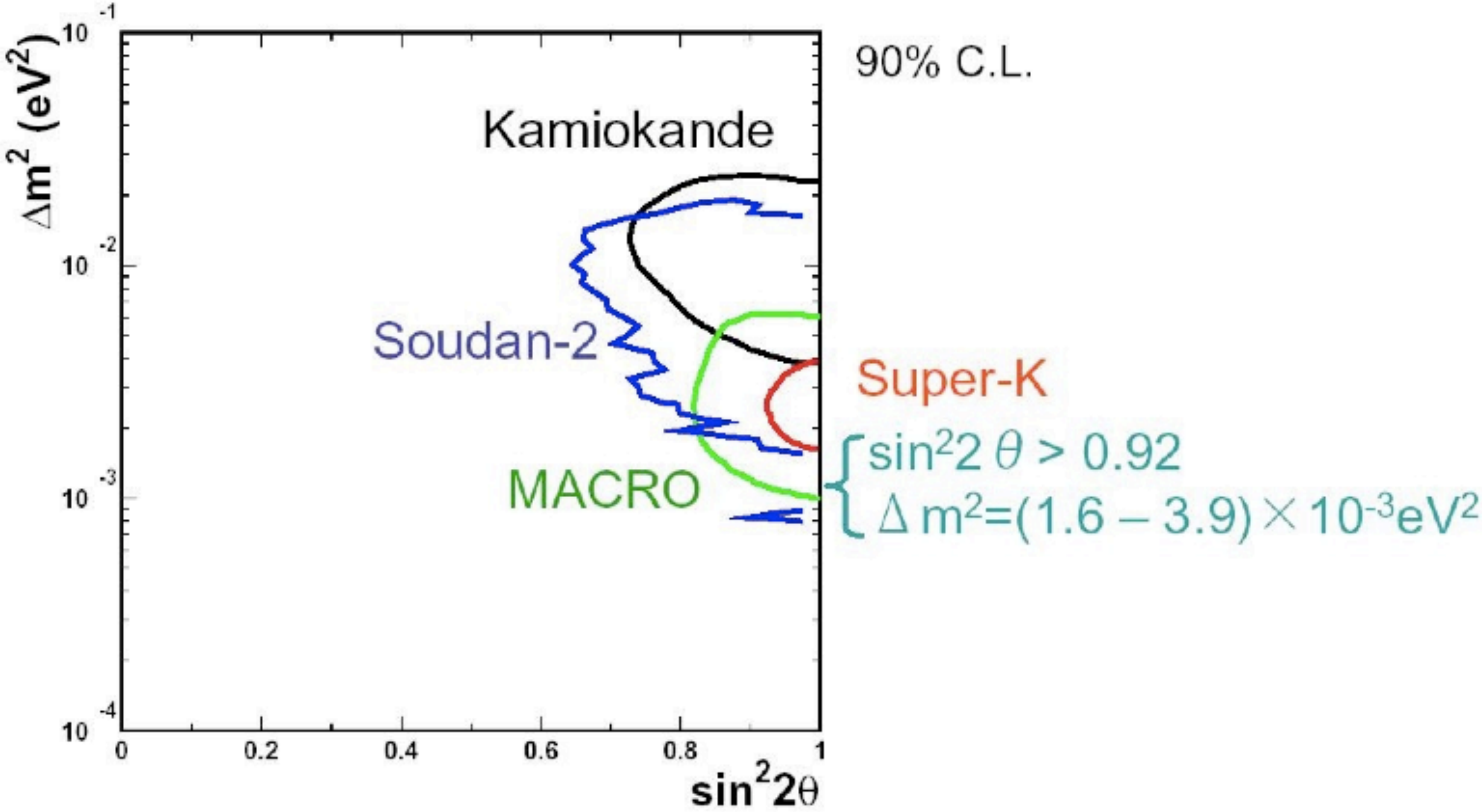
For any value of Δm^2 in the range allowed by atmospheric data (see next), get stringent upper bound on θ_{13}

$\sin^2 \theta_{13}$ < few %

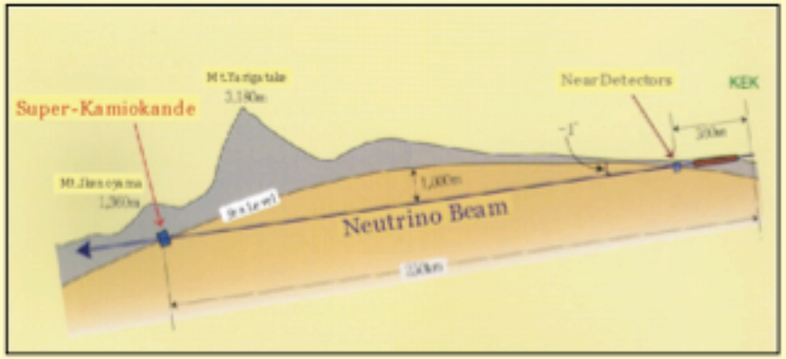
Feverish world-wide activity to build new reactor experiment with higher θ_{13} sensitivity → need to use a second (close) detector to reduce systematics

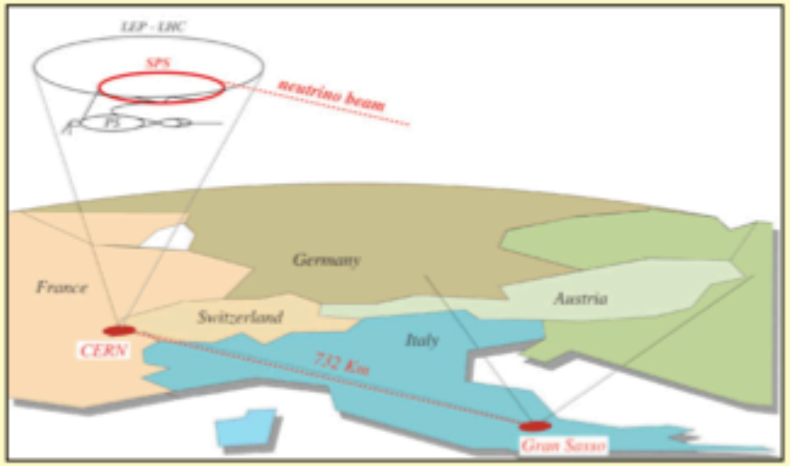


90% C.L. Allowed Regions

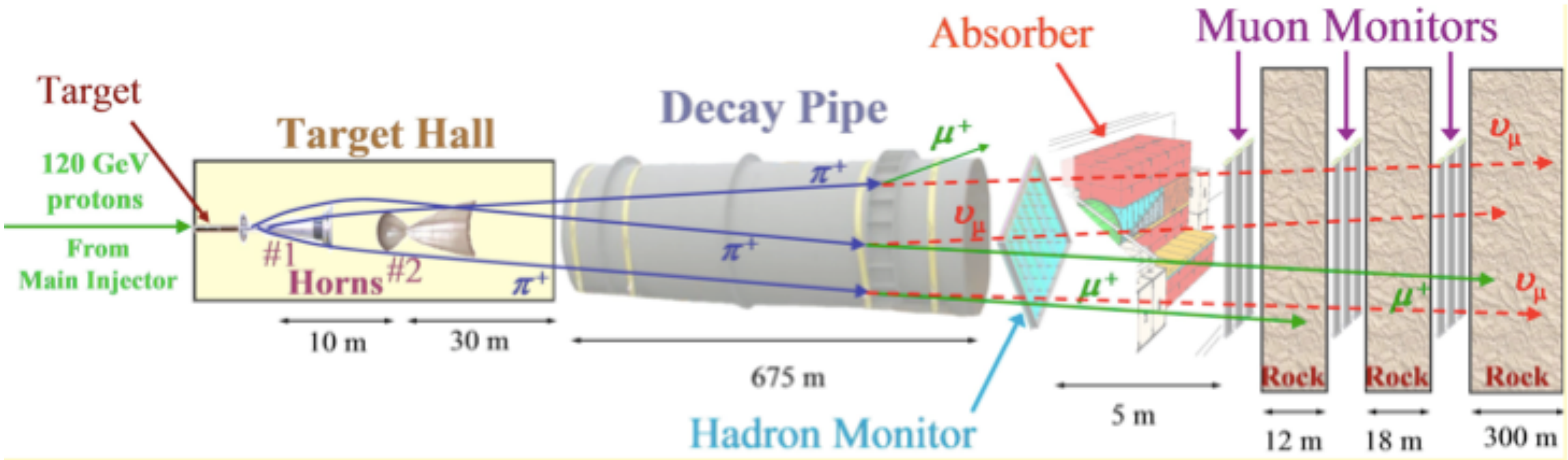


"Reproducing atmospheric ν_μ physics" in controlled conditions

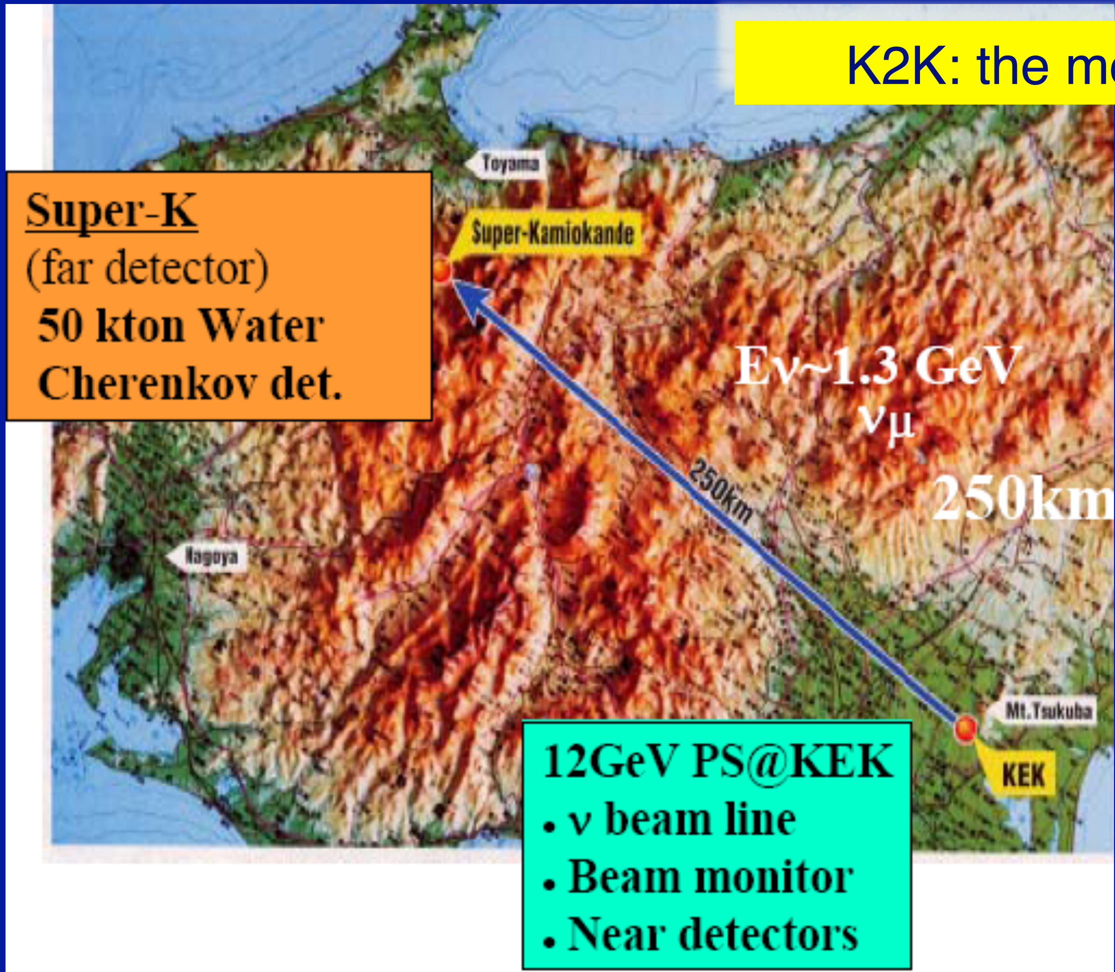




Typical accelerator neutrino beam (NUMI, Fermilab)



K2K: the mother of all LBL experiments



ν_μ disappearance experiment to probe the SK atmospheric neutrino result.

near/far detectors comparison: event rate and energy spectrum shape

K2K physics goals

- Neutrino Oscillations
  - confirm SuperK atm neutrino oscillation results
  - muon neutrino disappearance (99% pure ν_μ beam)

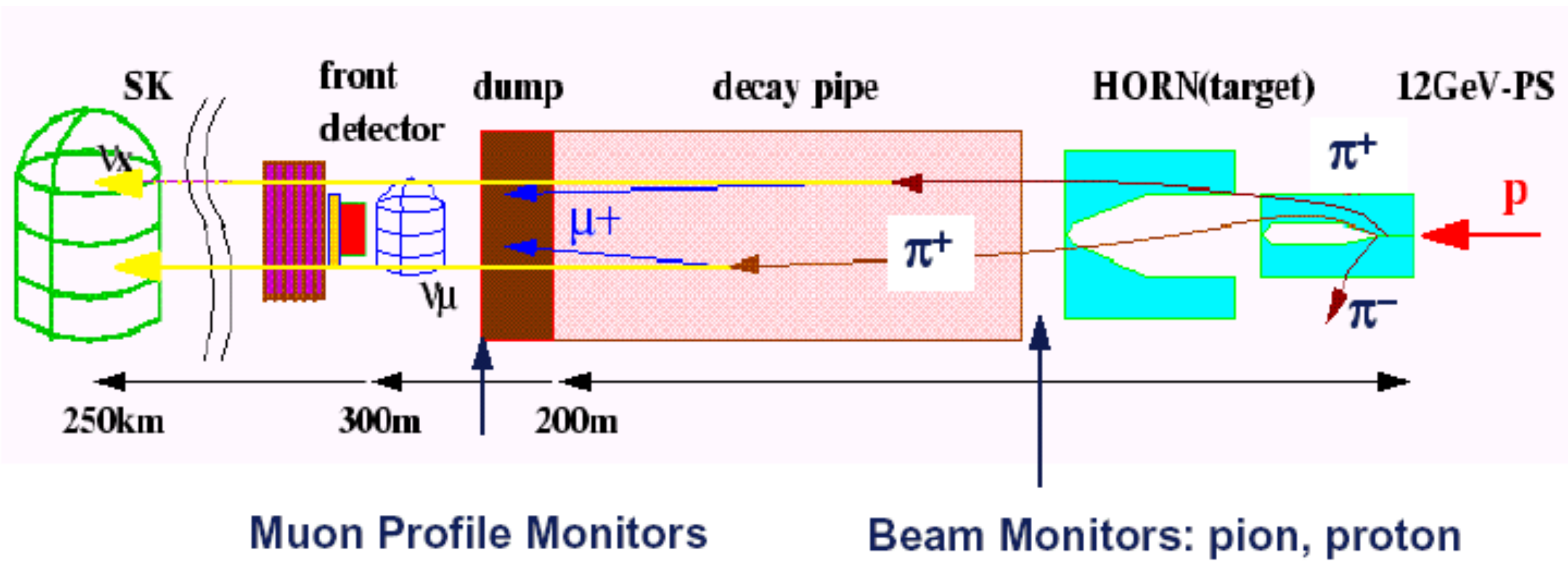
    1) simple counting: observed/expected # of events

    2) distortion in observed energy spectrum

    ==> direct observation of energy dependent neutrino oscillation
- Neutrino Cross-section Measurements
  - NC π^0 production cross-section

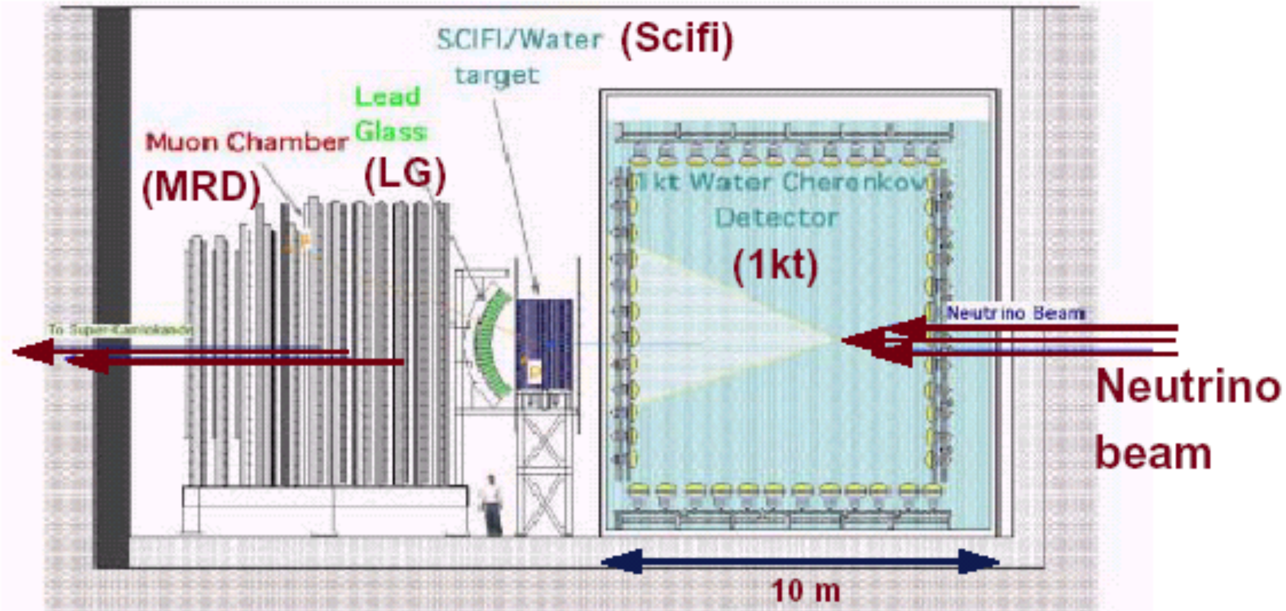
    ==> application to ν_μ --> ν_τ vs. ν_μ --> ν_s discrimination in SuperK atmospheric neutrino analysis
- Study of Neutrino Background to Proton Decay Searches

The K2K beam line

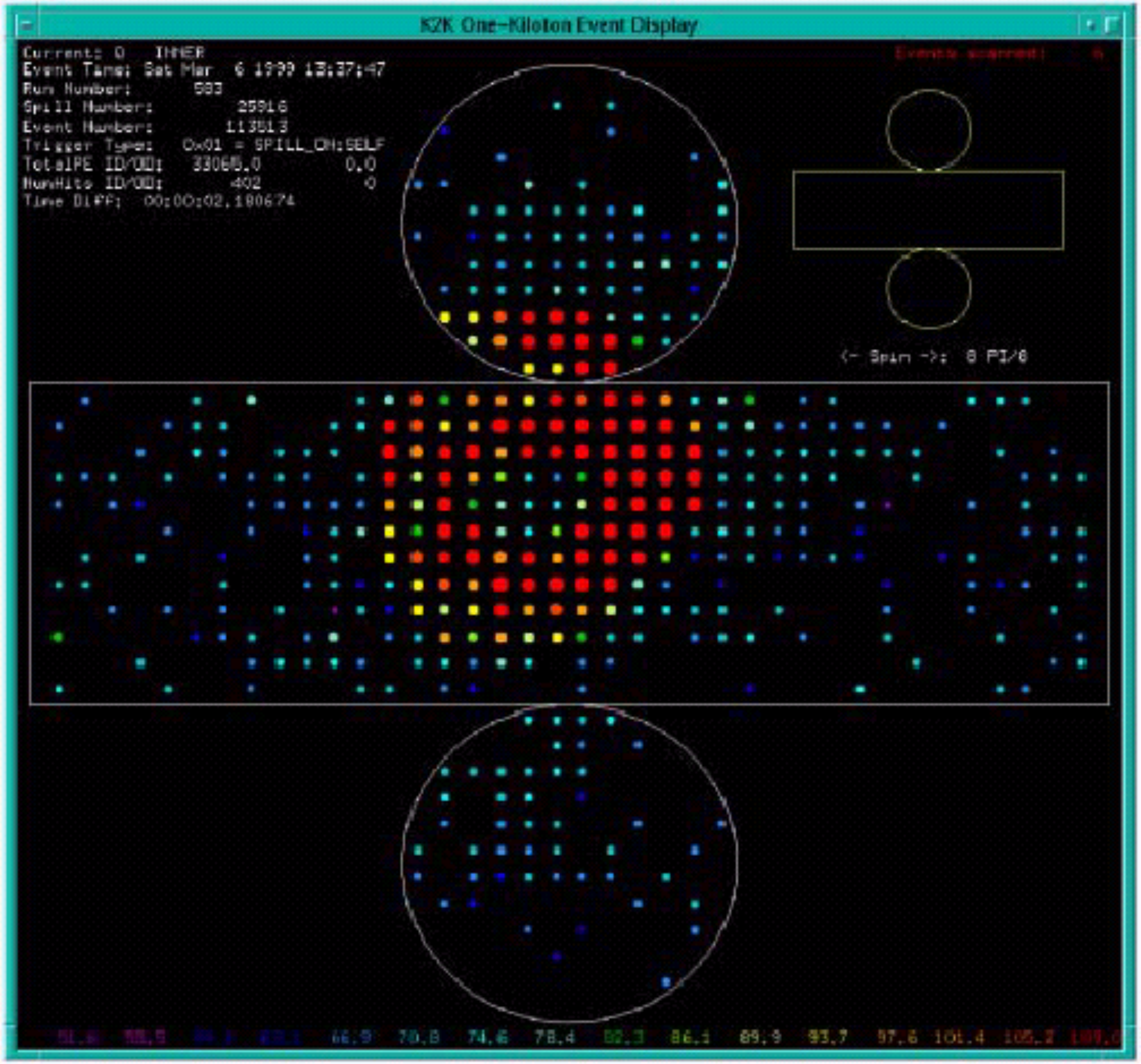


K2K near detectors

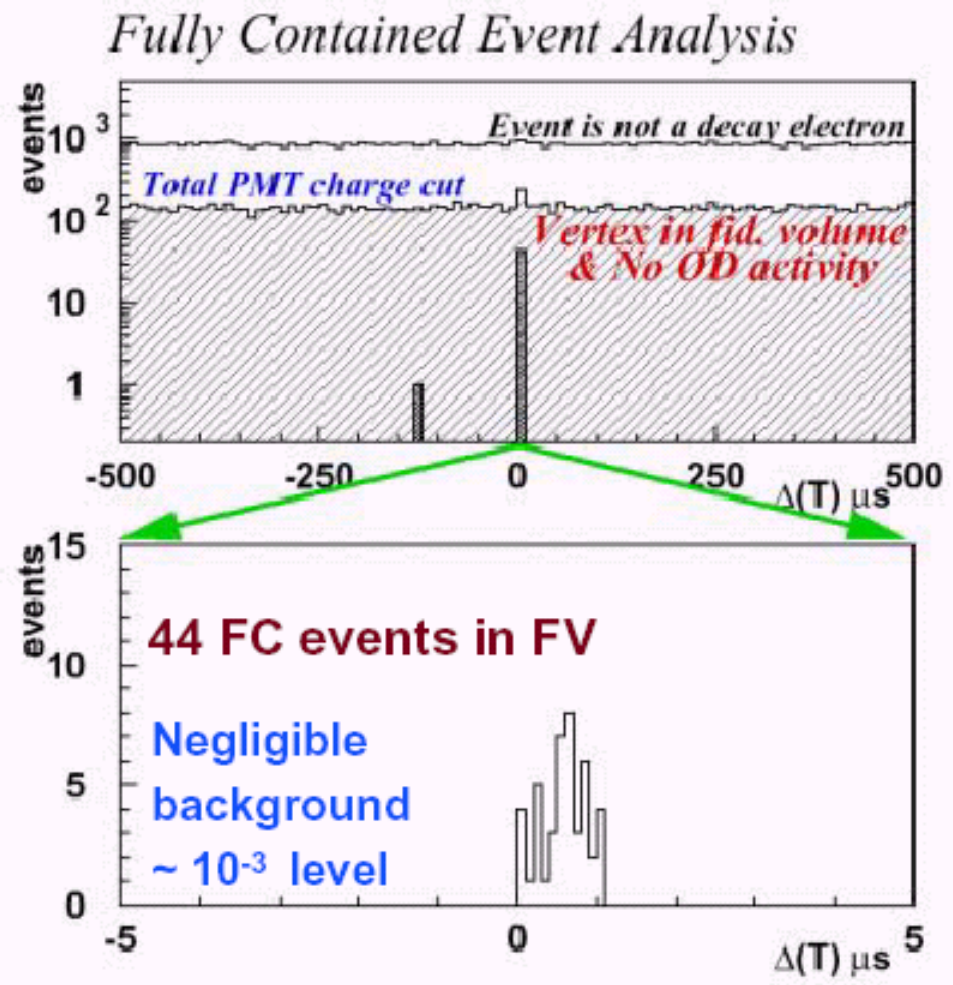
- 1kt (mini-SuperK): similar systematics as SuperK
- Scifi (scintillating fiber tracker): 19 layers of 6 cm thick water target w/ 20 layers of scifi (x,y), precision tracking
- LG (Lead Glass calorimeter): Measure ν_e contamination
- MRD (muon range detector): 12 layers of iron plates w/ D.C.s

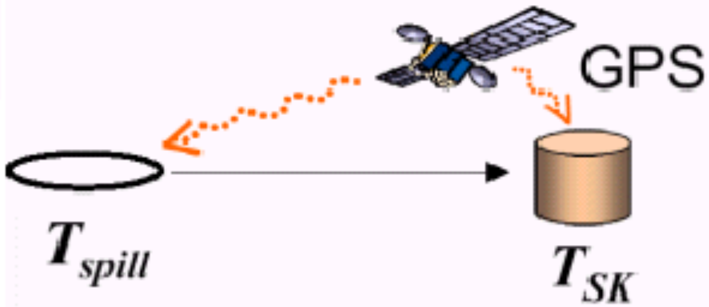


K2K (SuperKamiokande) event



$$-0.2 \le \Delta T \equiv T_{SK} - T_{Spill} - \text{TOF} \le 1.3\mu\,\text{sec}$$

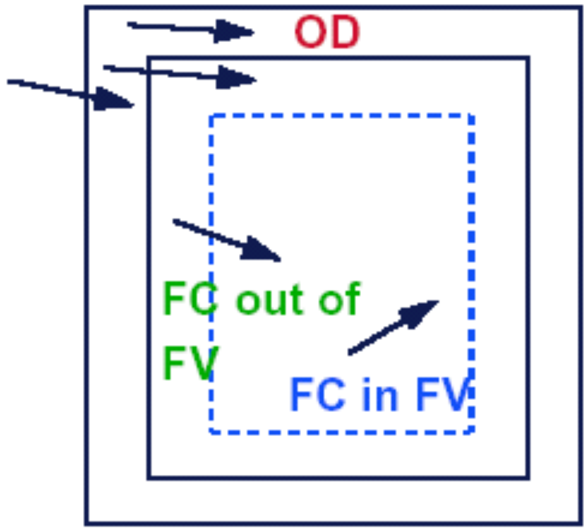




T_{Spill}: Abs. time of spill start

T_{SK}: Abs. time of SK event

TOF: 0.83ms (KEK to Kamioka)



K2K results (oscillation parameters)

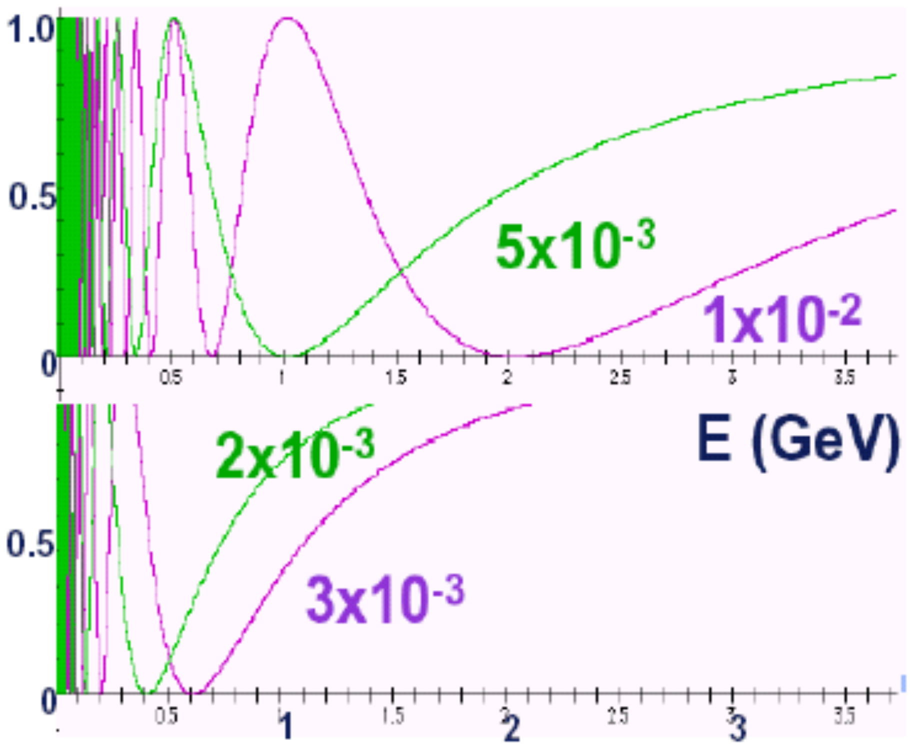
June 1999 - April 2001

FC Events in FV

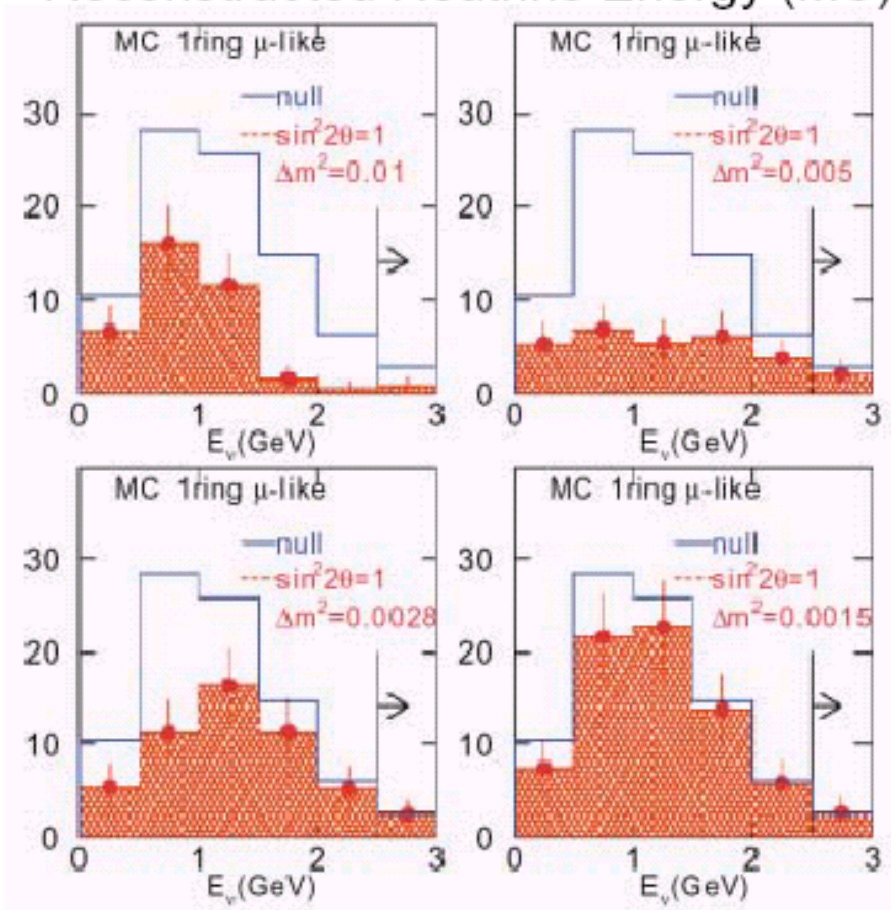
	Obs.	No Osci. (1kton)	$\Delta m^2(\times 10^{-3} eV^2)$ 3 (sin²2θ =1)	5	7
FC 22.5kt	44	$63.9^{+6.1}_{-6.6}$	41.5	27.4	23.1
1-ring	26	38.4±5.5	22.3	14.1	13.1
μ-like	24	34.9±5.5	19.3	11.6	10.7
e-like	2	3.5±1.4	2.9	2.5	2.4
multi ring	18	25.5±4.3	19.3	13.3	10.0

$P_{\nu \longrightarrow \nu} = 1 - \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E)$

with $\sin^2 2\theta = 1.0$, L=250km

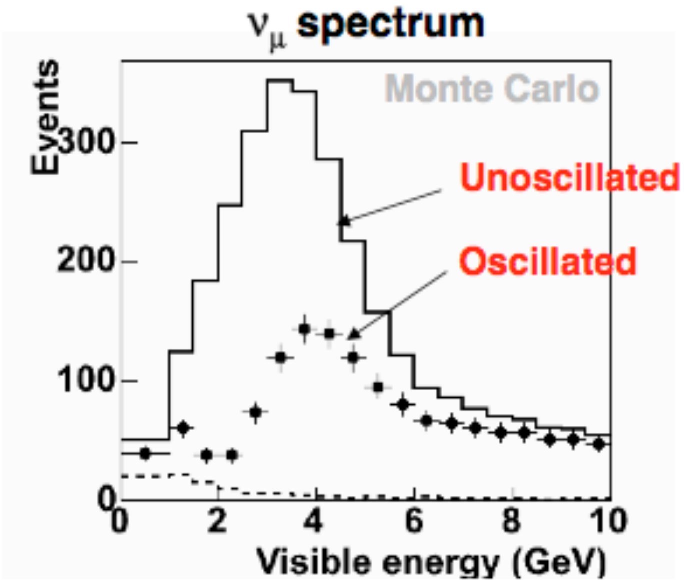


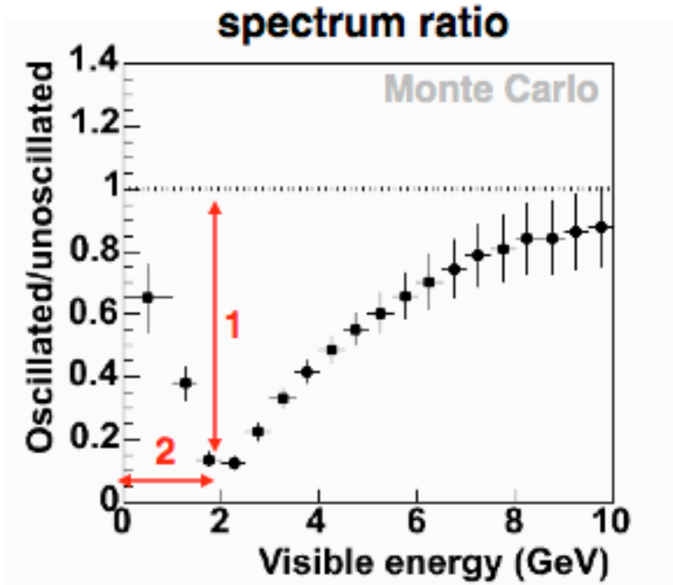
Reconstructed Neutrino Energy (MC)



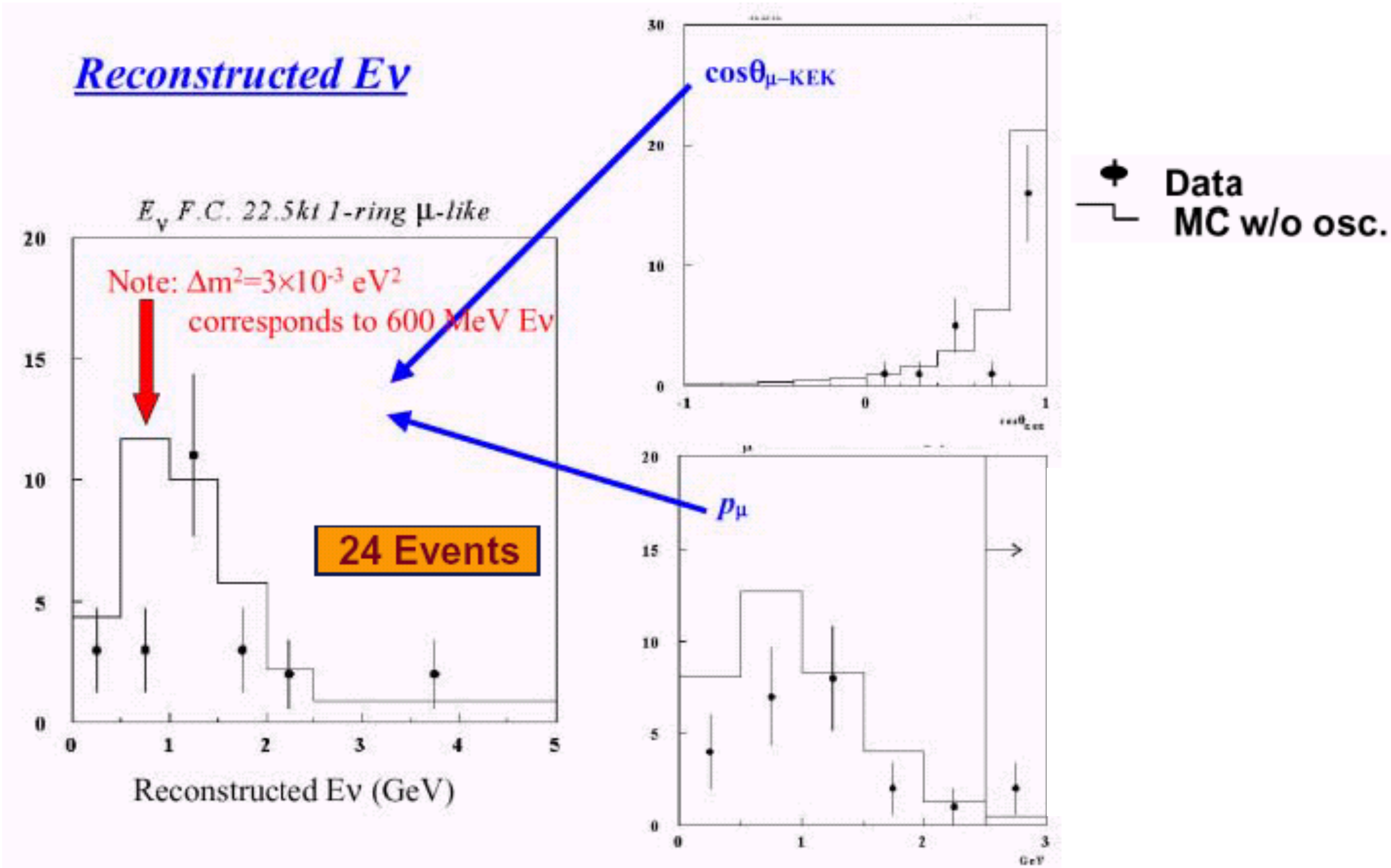
Example of a ν_μ disappearance measurement

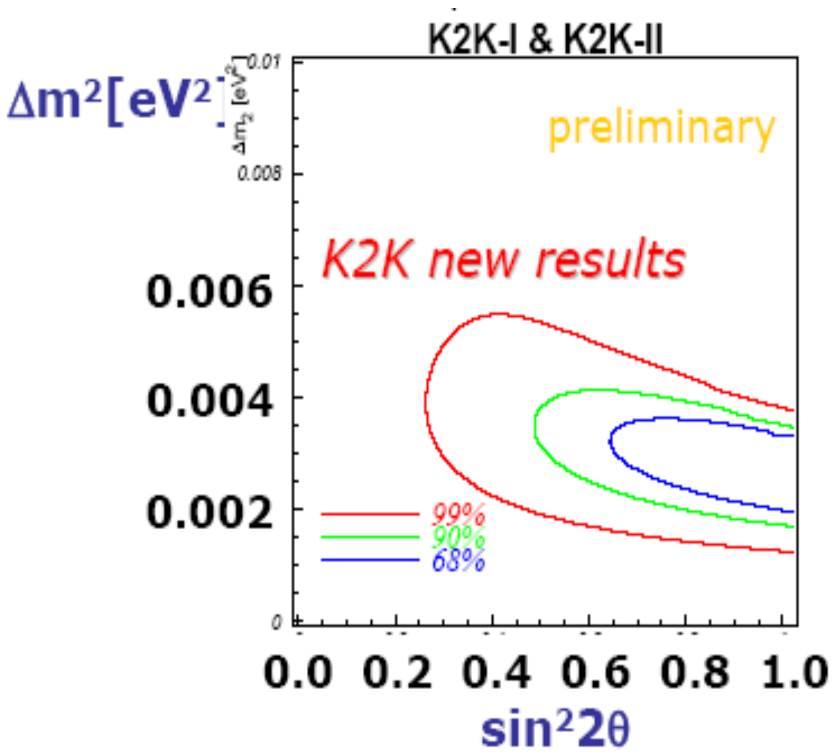
$$P(\nu_\mu \to \nu_\mu) = 1 - \boxed{\sin^2 2\theta}_{1} \sin^2(1.267 \boxed{\Delta m^2}_{2} L / E)$$

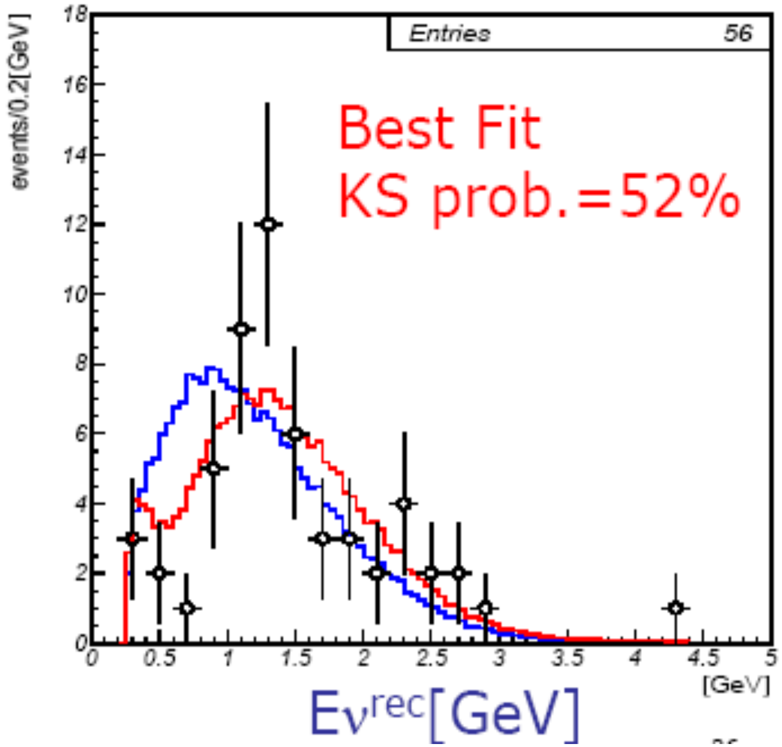




K2K event energy dependence







K2K results:

$1.7 < \Delta m^2 < 3.5$ eV² for $\sin^2 2\theta = 1$ (90% CL)

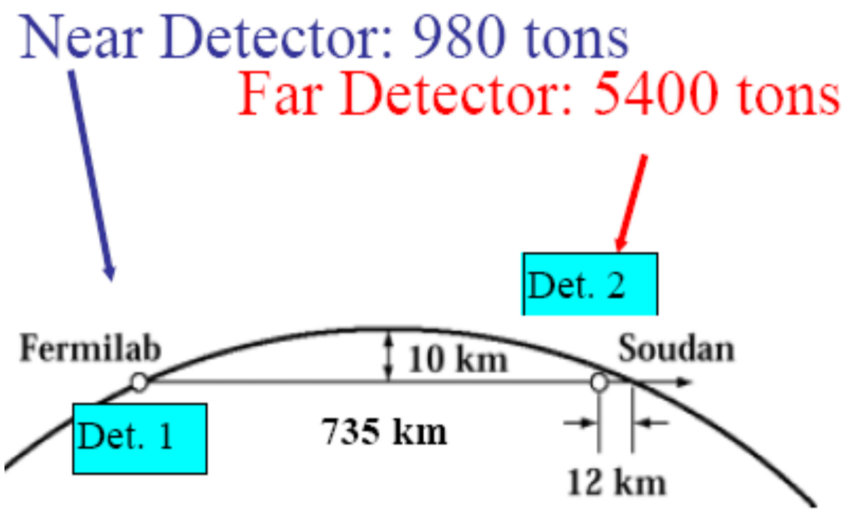
(ν_μ disappearance plus shape distortion)

oscillation hypothesis confirmed at 3.9 σ

K2K confirms SK:

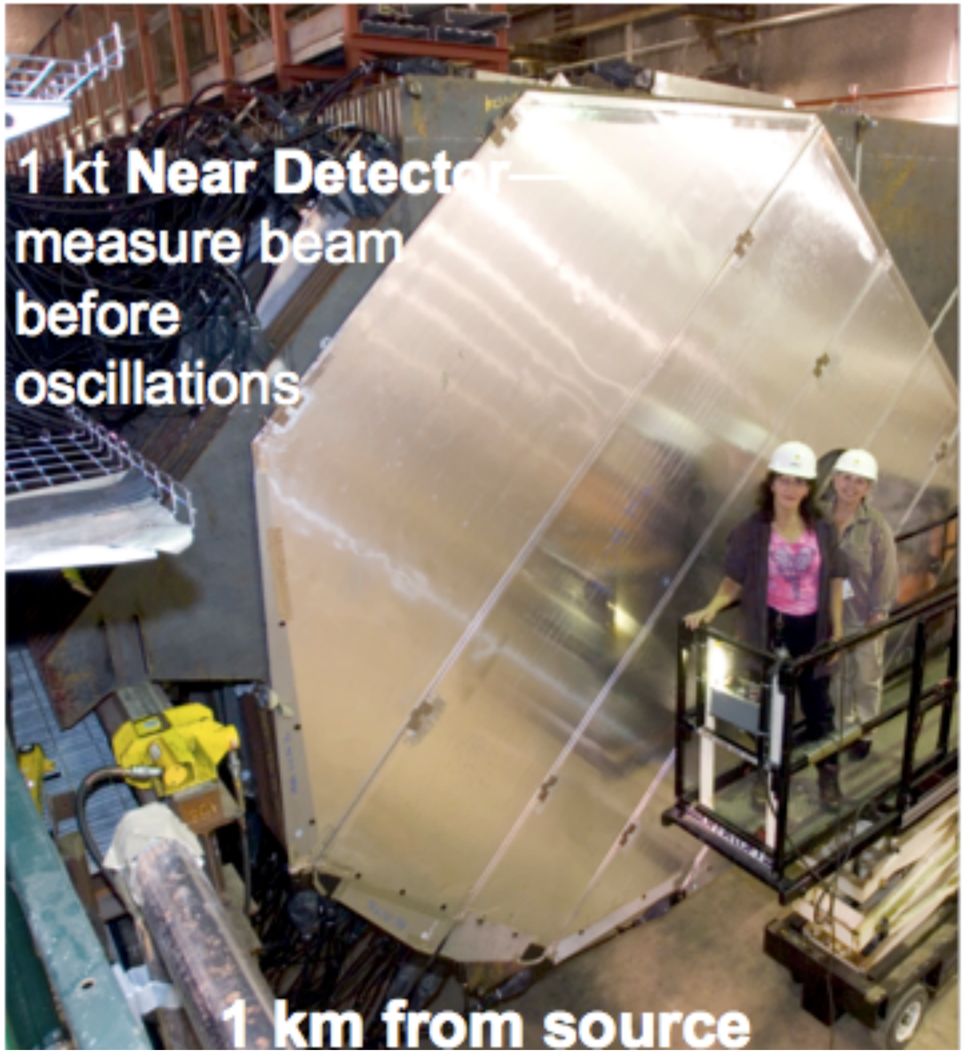
$1.5 < \Delta m^2 < 3.4$ eV² for $\sin^2 2\theta > 0.93$ (90% CL)

MINOS in the NuMi neutrino beam

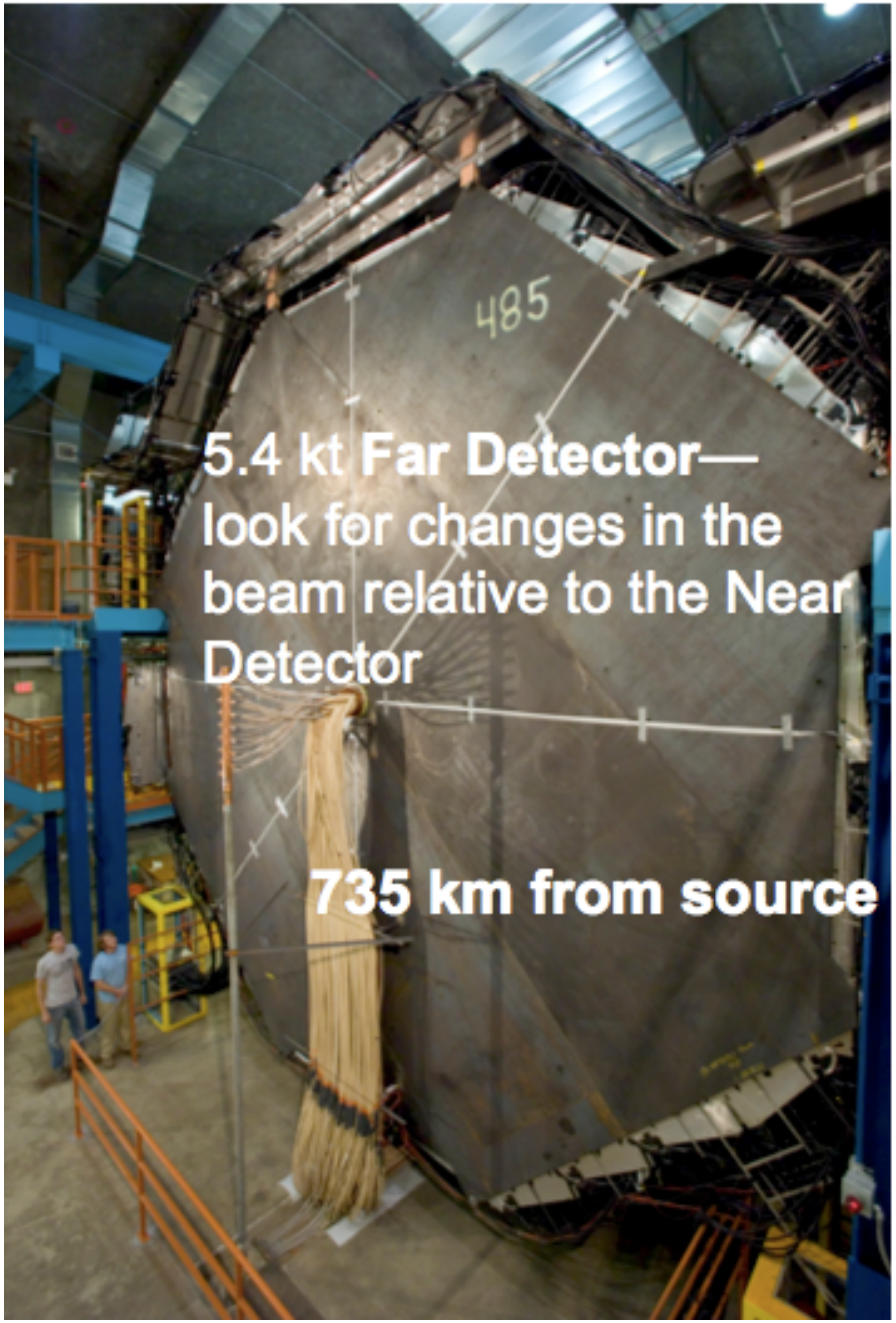


Magnetized steel/scintillator calorimeter

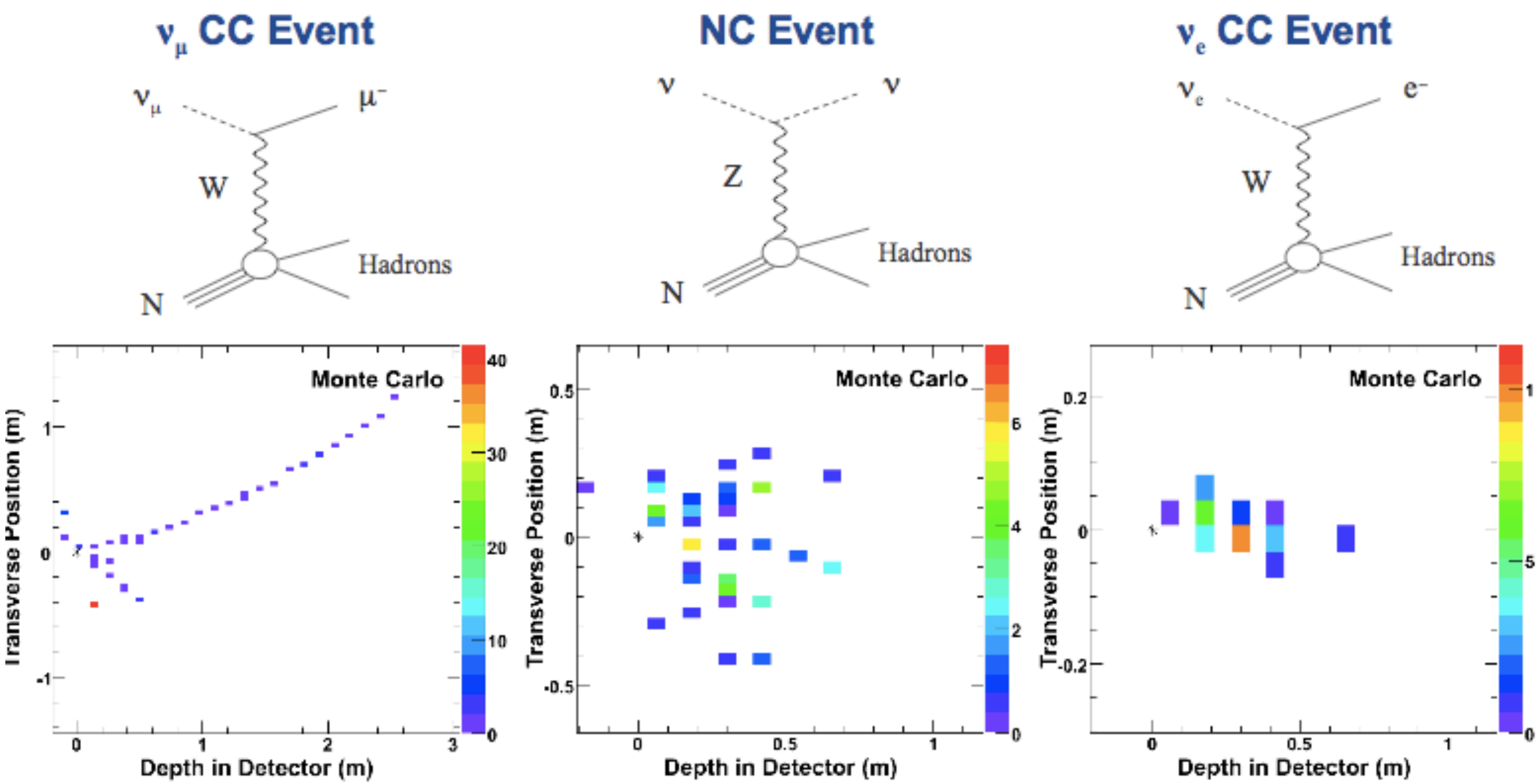
- low E neutrinos (few GeV): ν_μ disappearance experiment
- 4 x10^{20} pot/year → 2500 ν_μ CC/year
- compare Det1-Det2 response vs E → sensitivity to Δm^2_{atm}
- main goal: reduce errors on Δm^2_{23} and $\sin^2 2\theta_{23}$ as needed to measure $\sin^2 2\theta_{13}$
- some sensitivity to θ_{13}



1 kt Near Detector—
measure beam
before
oscillations
1 km from source



485
5.4 kt Far Detector—
look for changes in the
beam relative to the Near
Detector
735 km from source



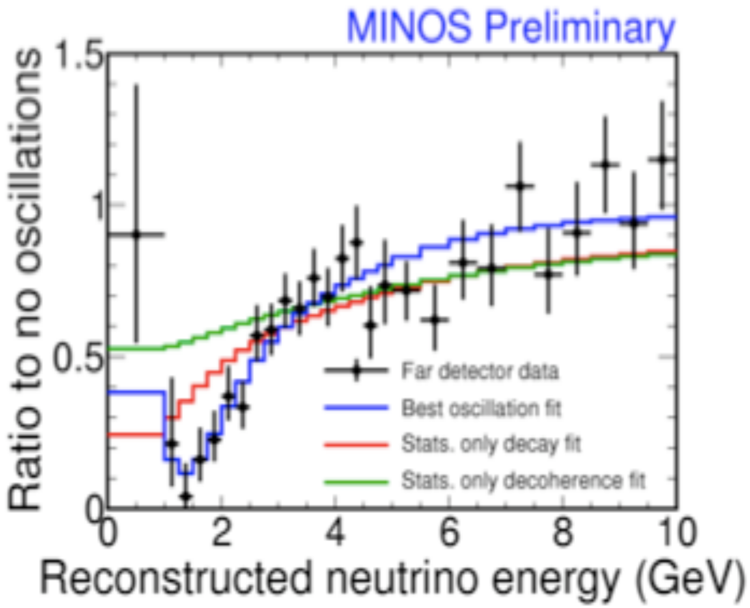
νμ CC Event
νμ
μ⁻
W
N
Hadrons
NC Event
ν
ν
Z
N
Hadrons
νe CC Event
νe
e⁻
W
N
Hadrons
Monte Carlo
Transverse Position (m)
Depth in Detector (m)
Monte Carlo
Transverse Position (m)
Depth in Detector (m)
Monte Carlo
Transverse Position (m)
Depth in Detector (m)

Numbers of observed and expected events

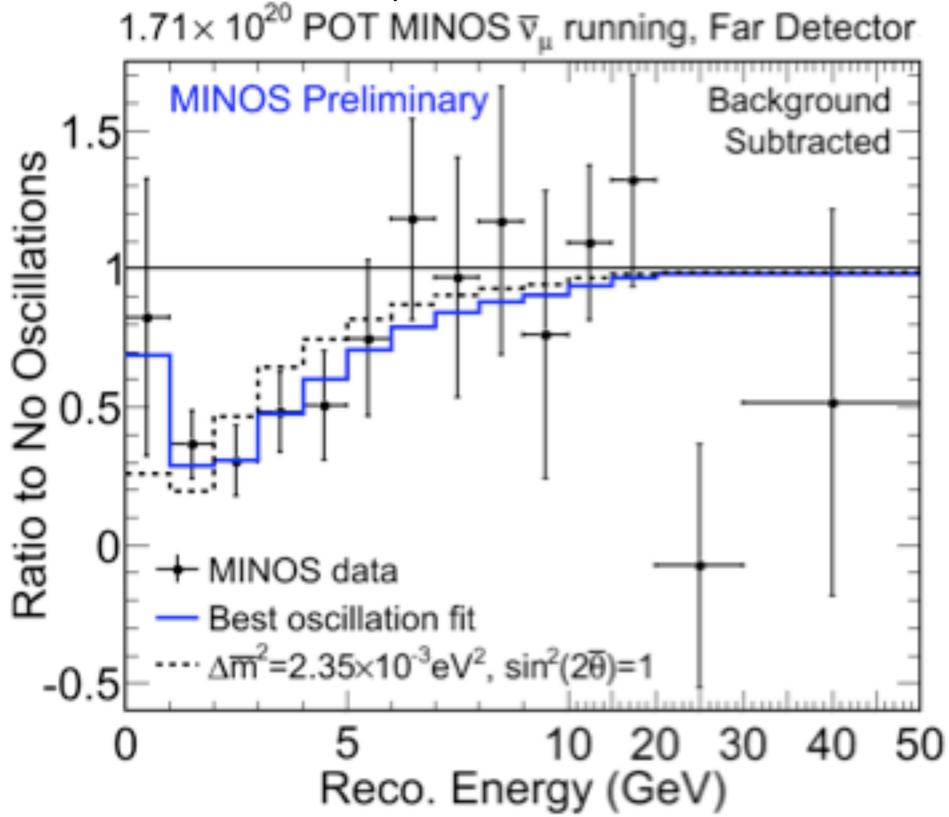
Data sample	observed	expected	ratio	significance
All CC-like events ($\nu_\mu+\bar{\nu}_\mu$)	204	298±15	0.69	4.1σ
ν_μ only (<30 GeV)	166	249±14	0.67	4.0σ
ν_μ only (<10 GeV)	92	177±11	0.52	5.0σ

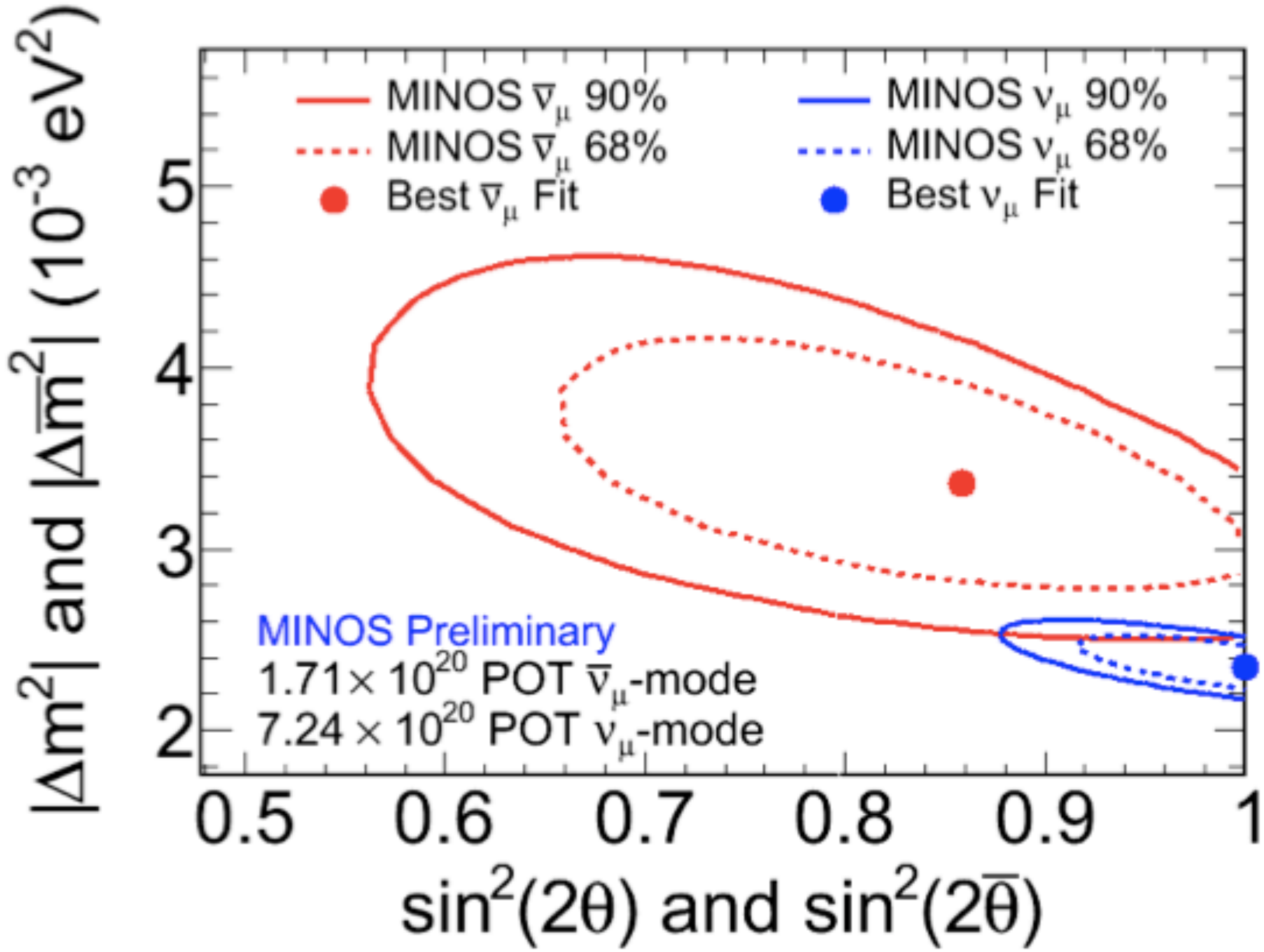
- We observe a 33% deficit of events between 0 and 30 GeV with respect to the no oscillation expectation.
  - Numbers are consistent for $\nu_\mu+\bar{\nu}_\mu$ sample and for the ν_μ-only sample
- **The statistical significance of this effect is 5 standard deviations**

$\nu_\mu - \nu_\tau$



$\bar{\nu}_\mu - \bar{\nu}_\tau$





MINOS $\bar{\nu}_\mu$ 90%
MINOS $\bar{\nu}_\mu$ 68%
Best $\bar{\nu}_\mu$ Fit
MINOS ν_μ 90%
MINOS ν_μ 68%
Best ν_μ Fit
MINOS Preliminary
1.71×10^{20} POT $\bar{\nu}_\mu$-mode
7.24×10^{20} POT ν_μ-mode
$|\Delta m^2|$ and $|\Delta \bar{m}^2|$ (10^{-3} eV^2)
$\sin^2(2\theta)$ and $\sin^2(2\bar{\theta})$

OPERA: first direct detection of neutrino oscillations in appearance mode

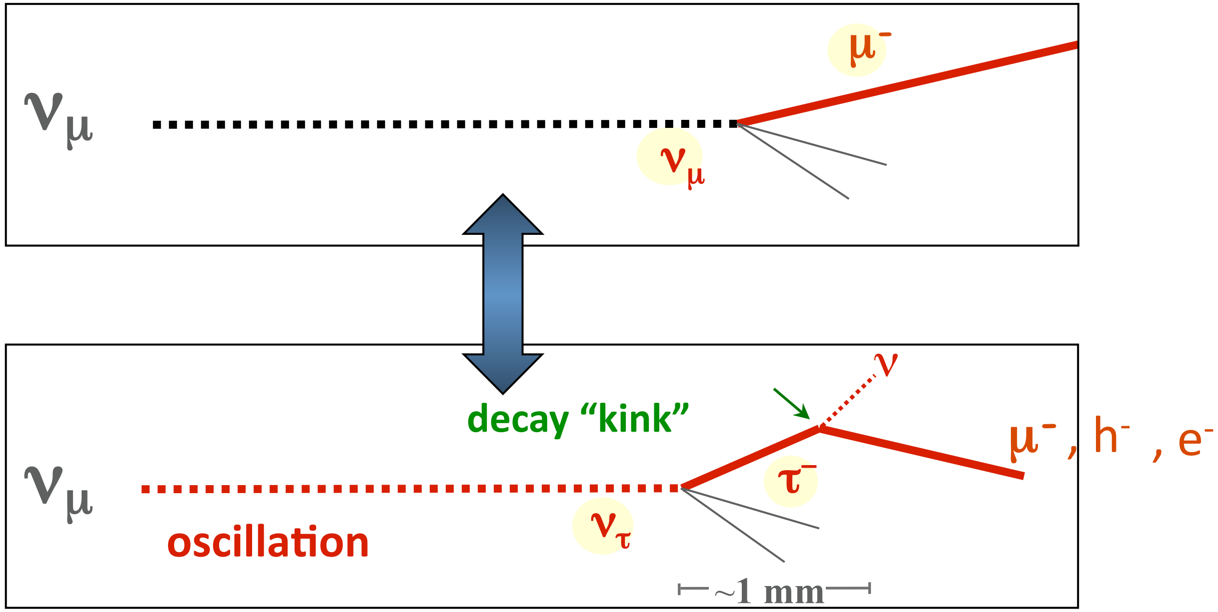
following the Super- Kamiokande discovery of oscillations with atmospheric neutrinos and the confirmation obtained with solar neutrinos and accelerator beams. Important, missing tile in the oscillation picture.

The PMNS 3-flavor oscillation formalism predicts:

$$P(\nu_\mu \rightarrow \nu_\tau) \sim \sin^2 2\theta_{23} \cos^4\theta_{13} \sin^2(\Delta m^2_{23} L/4E)$$

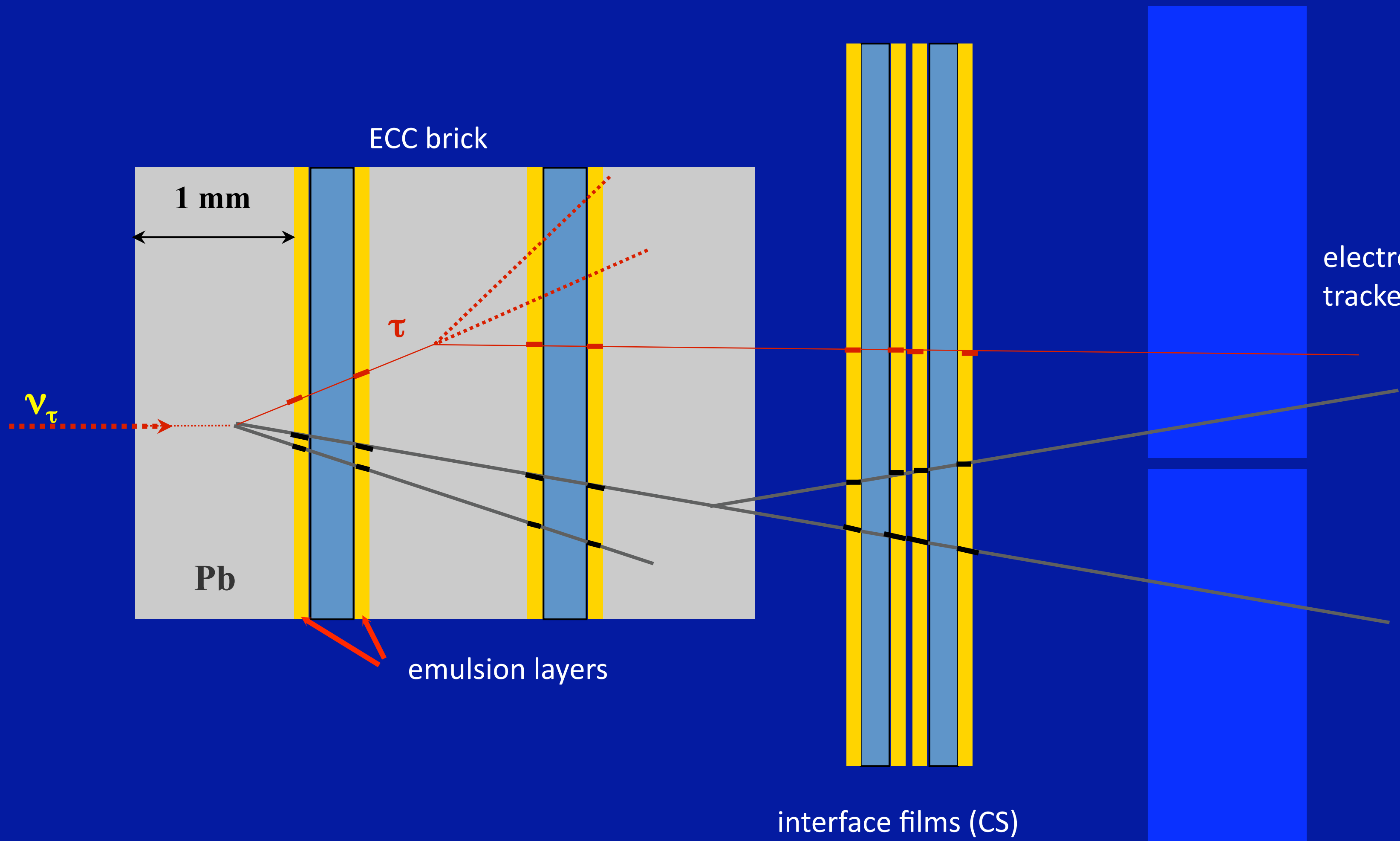
Requirements:

1) long baseline, 2) high neutrino energy, 3) high beam intensity, 4) detect short lived τ's



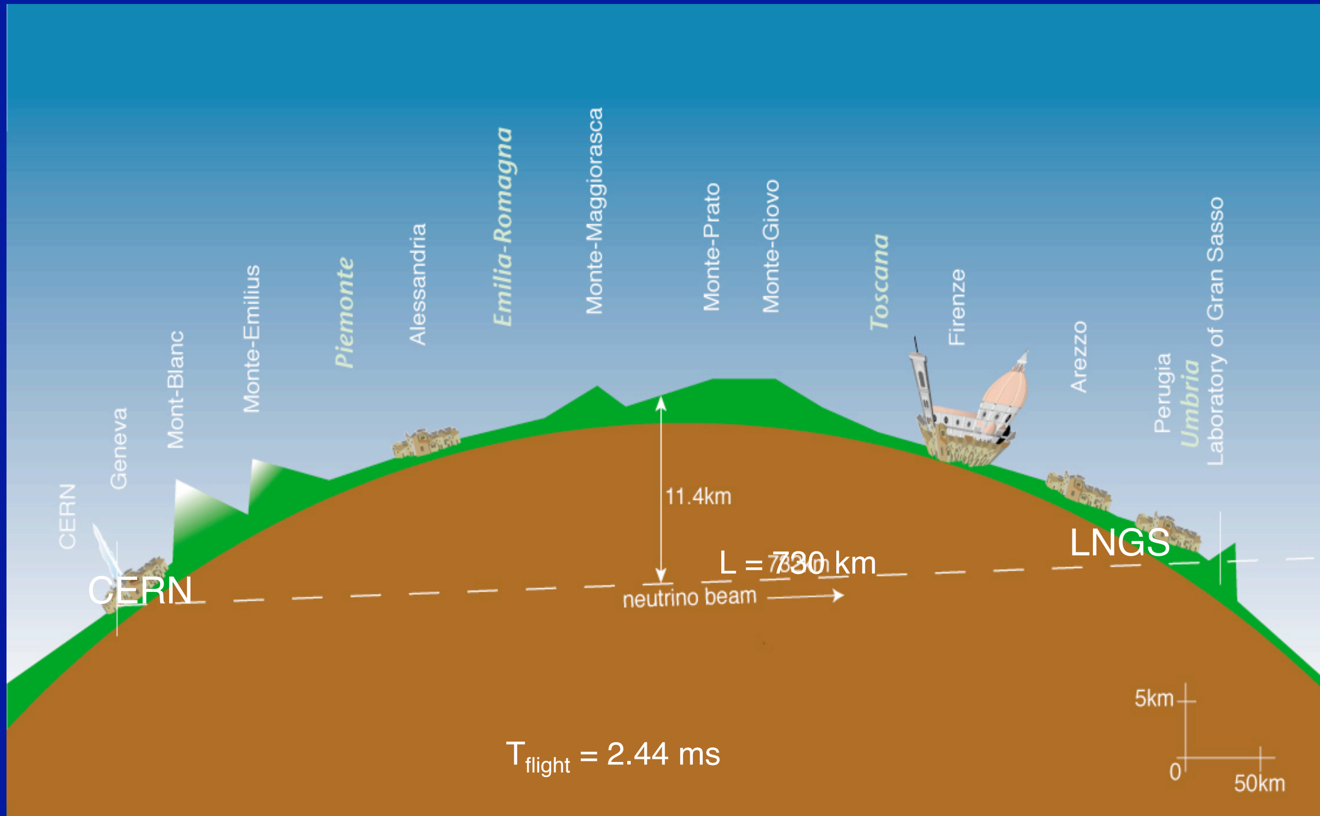
plus 3-prong decay modes

THE PRINCIPLE OF THE EXPERIMENT: ECC + ELECTRONIC DETECTORS



- Intense, high-energy muon-neutrino beam
- Massive active target with micrometric space resolution
- Detect tau-lepton production and decay
- Use electronic detectors to provide "time resolution" to the emulsions and preselect the interaction region

CNGS beam: tuned for ν_τ-appearance at LNGS (730 km away from CERN)

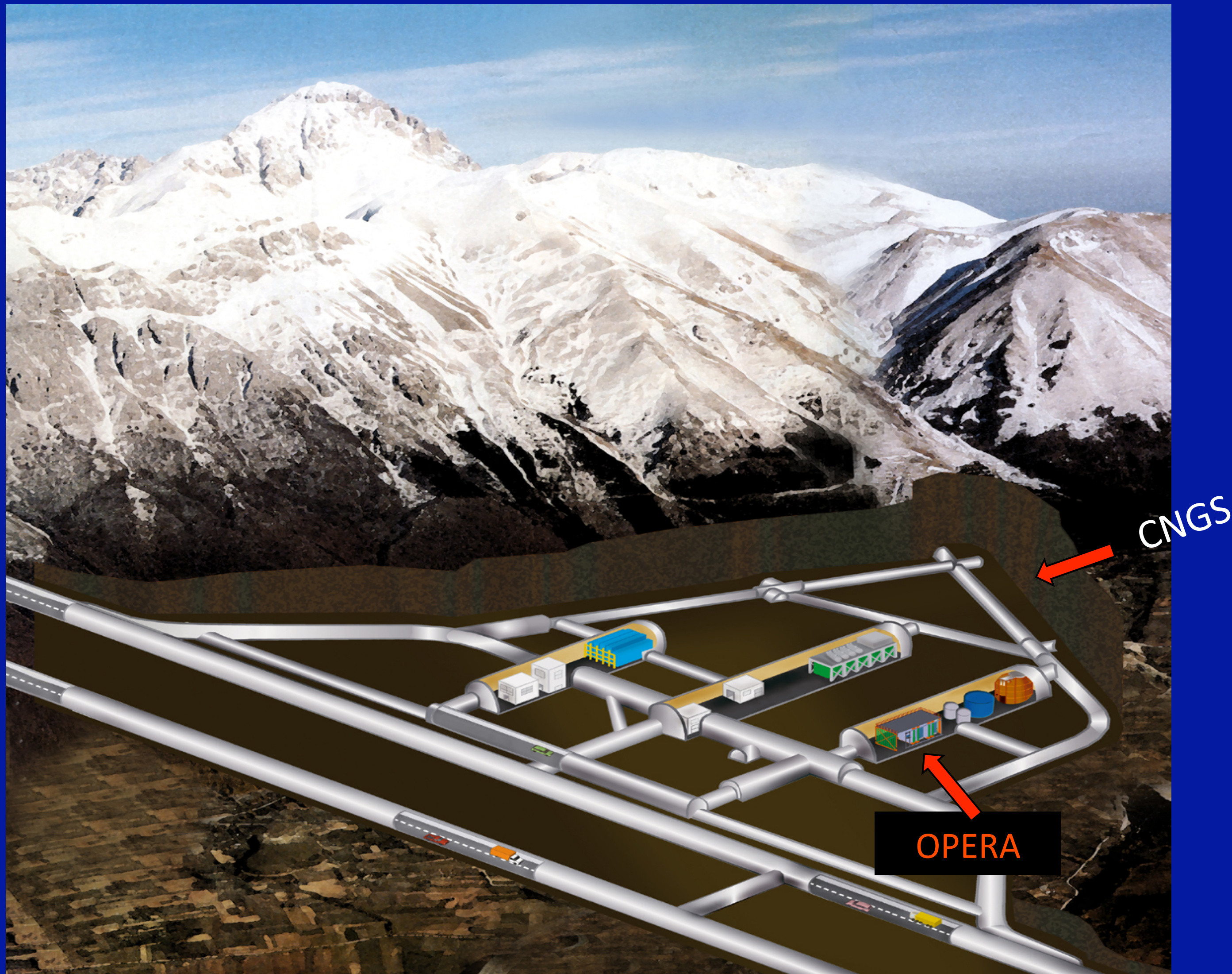


< E >	17 GeV
L	730 km
$(\nu_e + \bar{\nu}_e) / \nu_\mu$ (CC)	0.87%
$\nu_\mu / \bar{\nu}_\mu$ (CC)	2.1%
ν_τ prompt	negligible

Expected neutrino interactions for 22.5×10^{19} pot:
~ 23600 ν_μ CC + NC
~ 160 $\nu_e + \bar{\nu}_e$ CC
~ 115 ν_τ CC ($\Delta m^2 = 2.5 \times 10^{-3}$ eV^2)

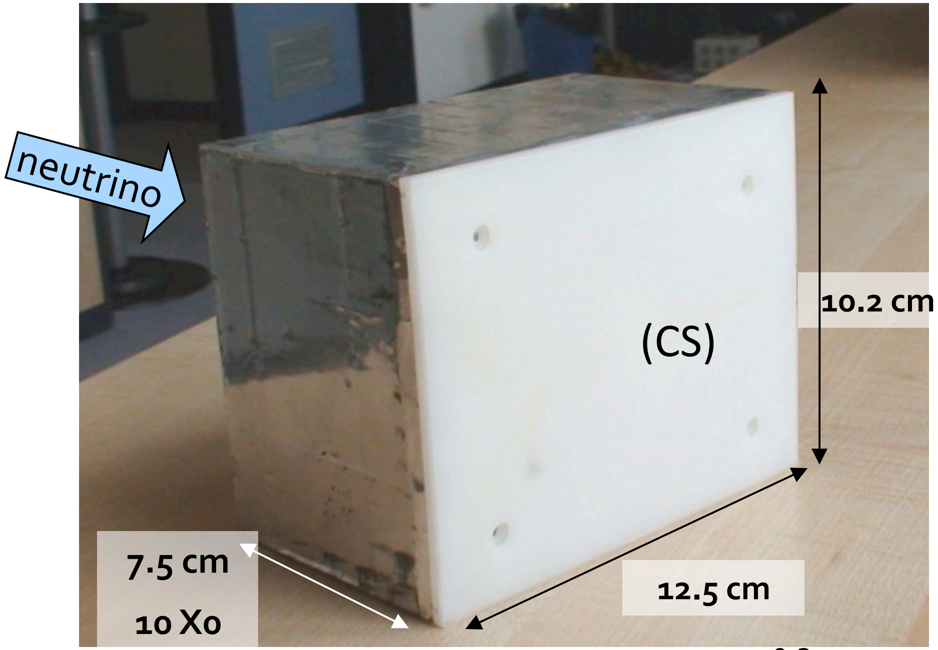
LNGS of INFN, the world largest underground physics laboratory:

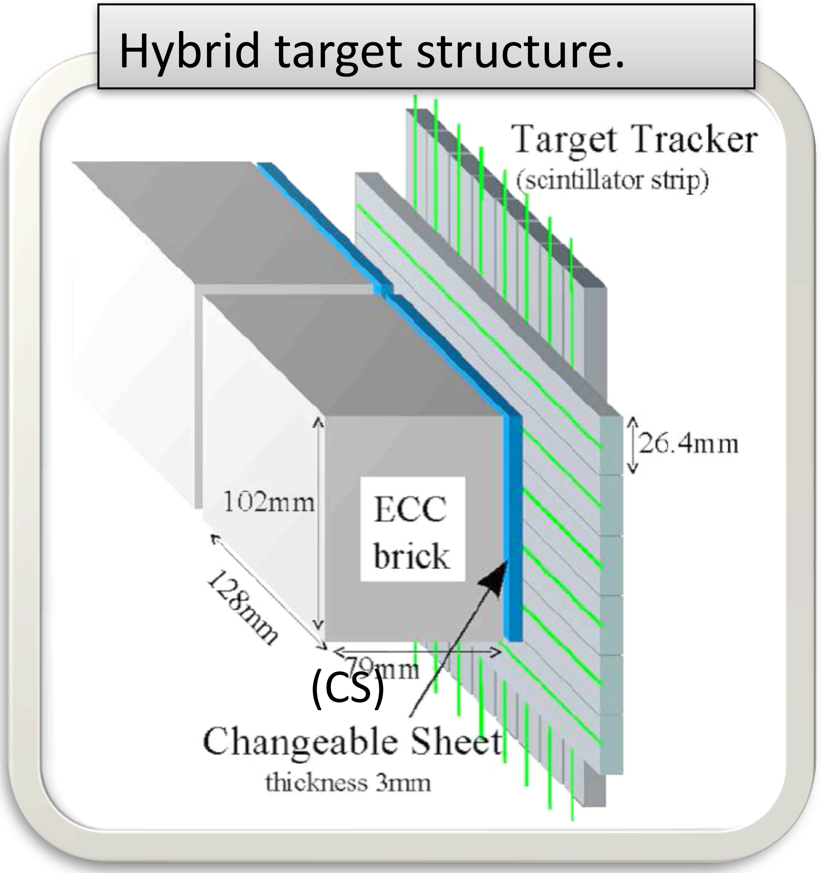
~180'000 m^3 caverns' volume, ~3'100 m.w.e. overburden, ~1 cosmic μ / m^2 x hour, experimental infrastructure, variety of experiments. Perfectly fit to host detector and related facilities, caverns oriented towards CERN.

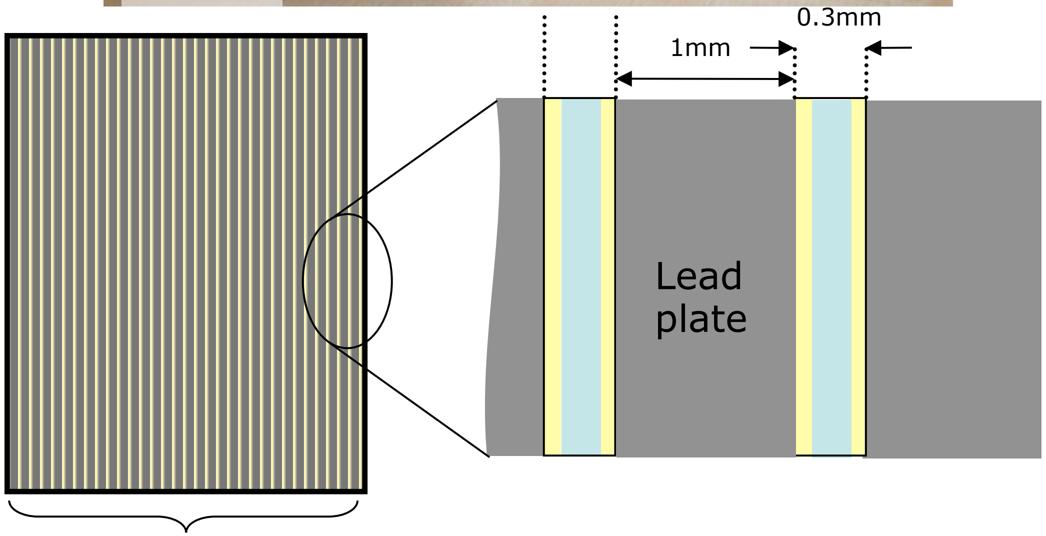


Two target super-modules, each with an iron spectrometer for muon detection (BG rejection and tau-into-muon decay channel)

The heart of the experiment:
THE ECC TARGET BRICKS







57 OPERA films, 56 lead plates

The OPERA target consists of 150'000 ECC bricks.

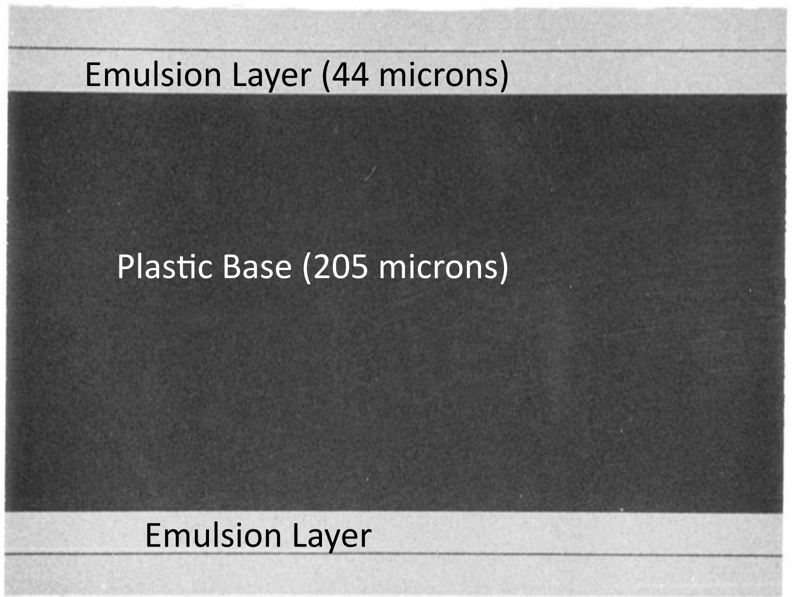
Total 105'000 m^2 of lead surface

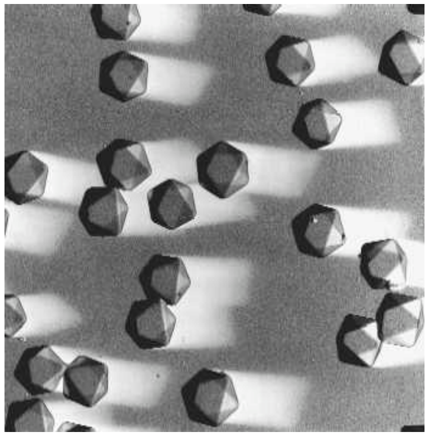
and 111'000 m^2 of film surface

(~ 8.9 million films)

Total target mass: 1.25 kton

INDUSTRIAL EMULSION FILMS BY *FUJI FILM*



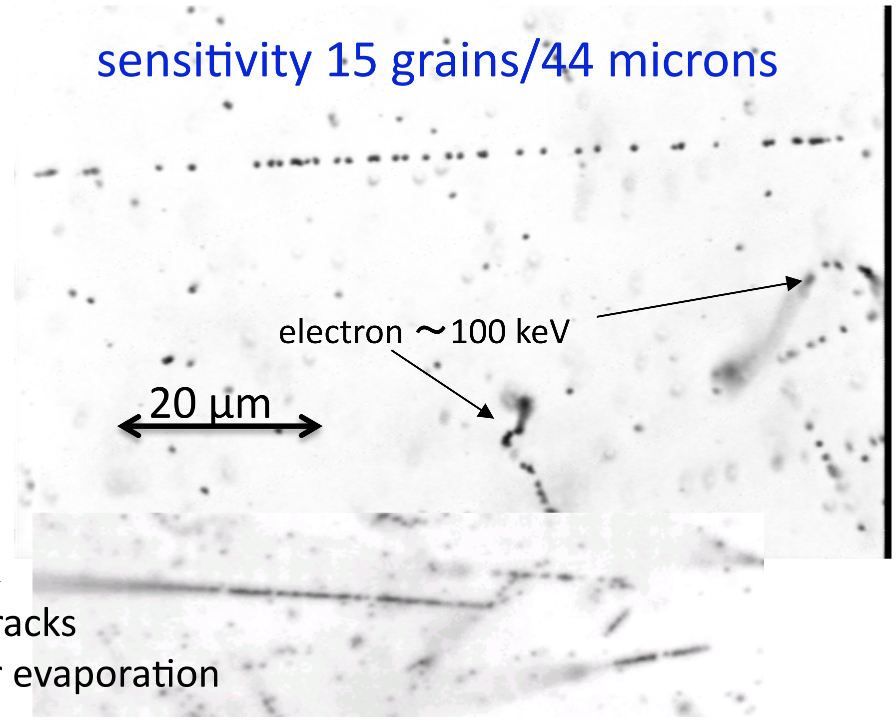


basic detector: AgBr crystal,

size = 0.2 micron

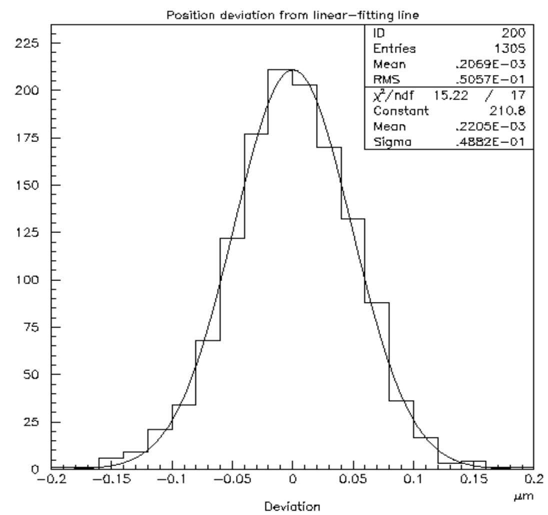
detection eff.= 0.16/crystal

10^{13} “detectors” per film



intrinsic resolution: 50 nm

deviation from linear-fit line. (2D)



PARALLEL ANALYSIS OF BRICKS

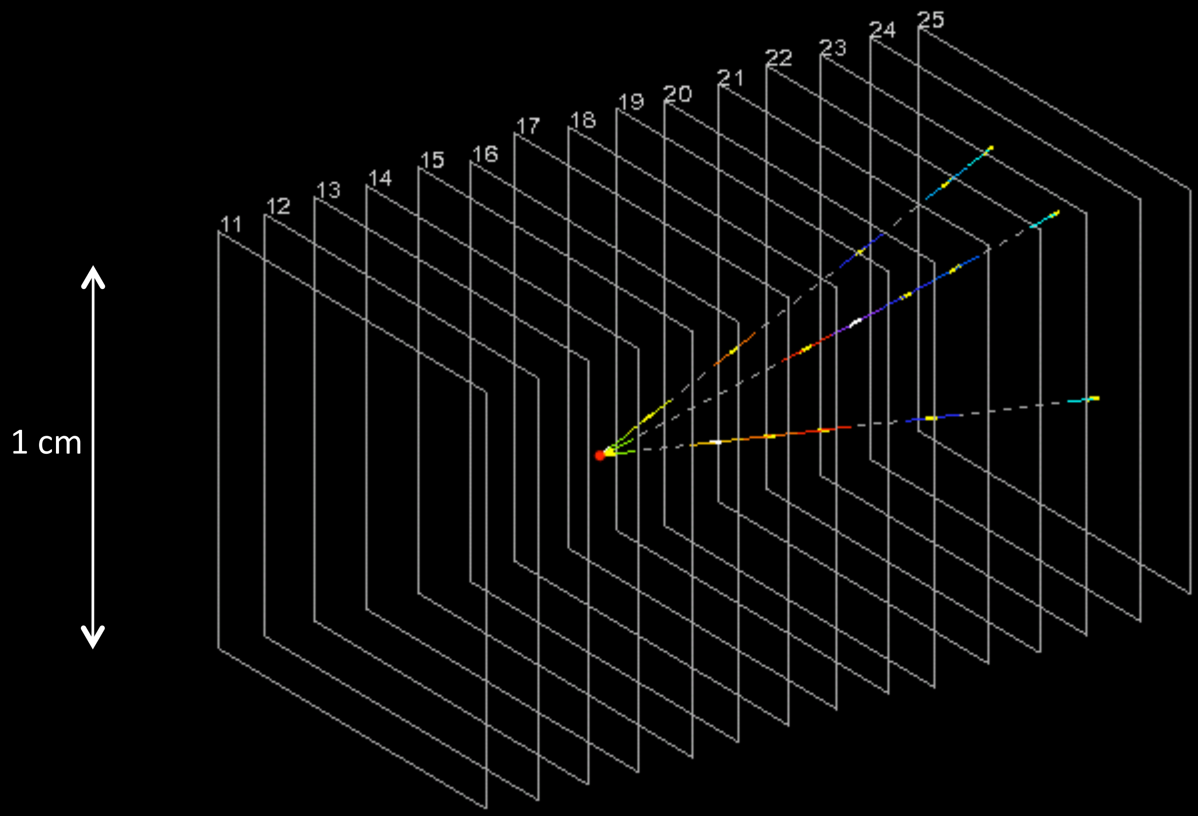
selected bricks sent to scanning labs (**presently 12**)

one of the brick scanning labs

Located neutrino interaction

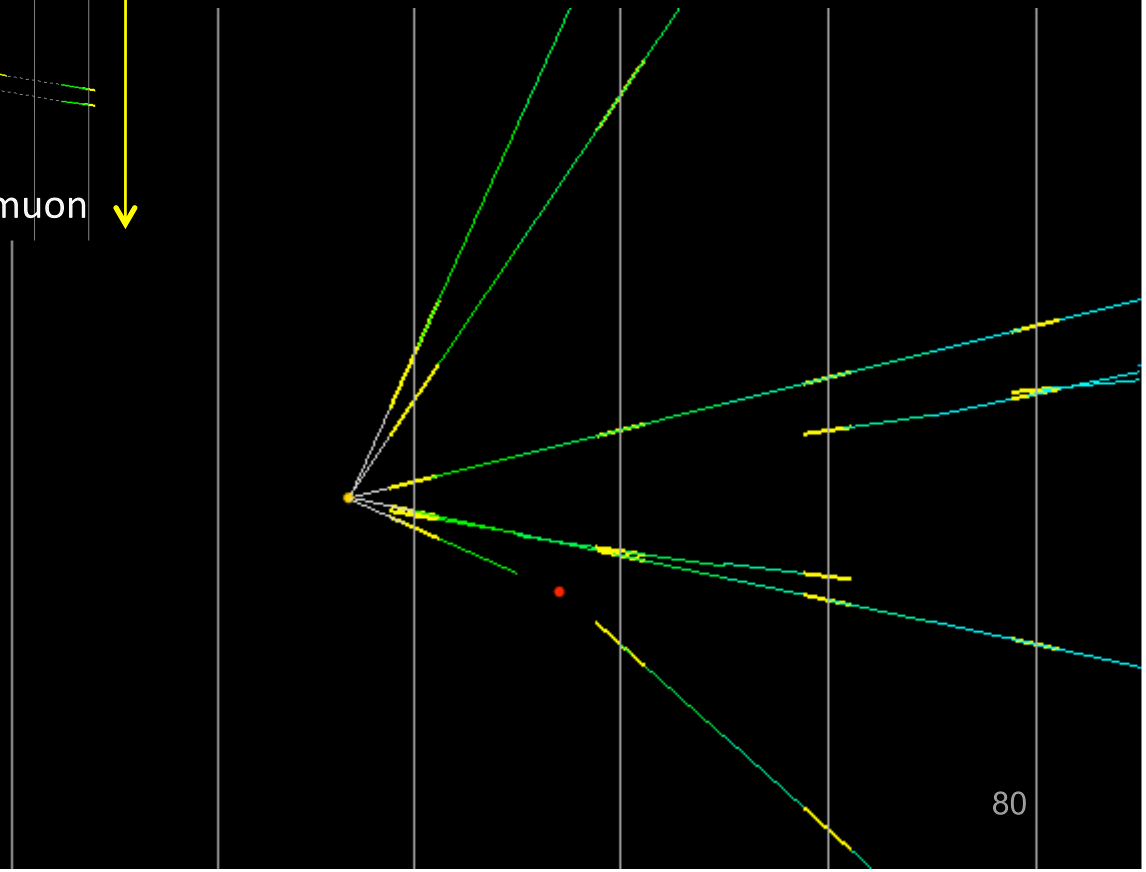
Emulsions give 3D vector data, with micrometric precision of the vertexing accuracy.

The frames correspond to the scanning area. Yellow short lines → measured tracks.
Other colored lines → interpolation or extrapolation.

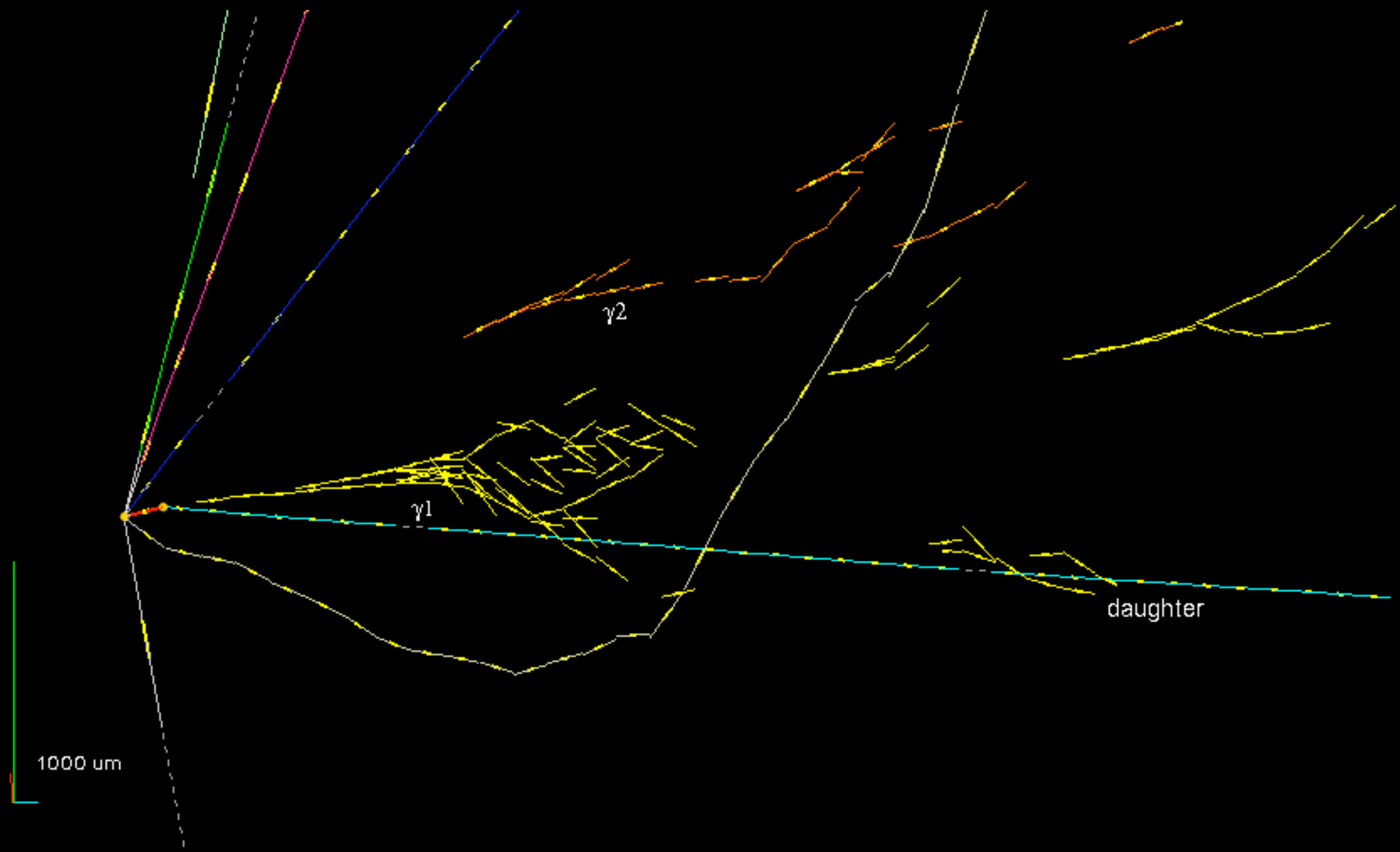


Charm candidate event (dimuon)

flight length: 1330 microns
kink angle: 209 mrad
IP of daughter: 262 microns
daughter muon: 2.2 GeV/c
decay Pt: 0.46 GeV/c

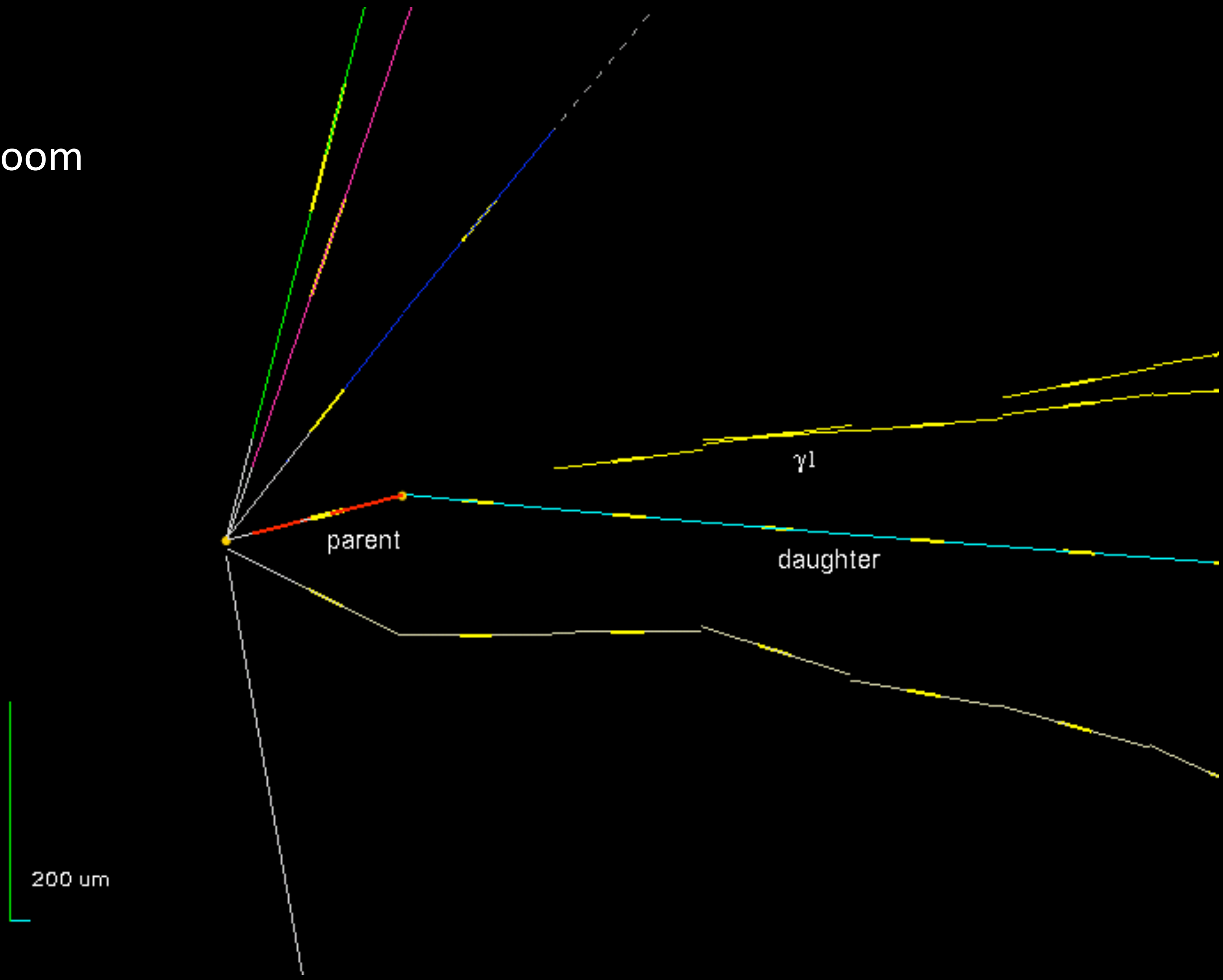


Event reconstruction (1)



Event reconstruction (2)

Zoom



OPERA has observed 1 event in the 1-prong hadron τ decay channel, with a background expectation (~ 50% error for each component) of:

0.011 events (reinteractions)
0.007 events (charm)

↓

0.018 ± 0.007 (syst) events 1-prong hadron

all decay modes: 1-prong hadron, 3-prongs + 1-prong μ + 1-prong *e :*

0.045 ± 0.020 (syst) events total BG

By considering the 1-prong hadron channel only, the probability to observe 1 event due to a background fluctuation is 1.8%, for a statistical significance of 2.36 σ on the measurement of a first ν_τ candidate event in OPERA.

If one considers all τ decay modes which were included in the search, the probability to observe 1 event for a background fluctuation is 4.5%.
This corresponds to a significance of 2.01 σ.

SOLAR NEUTRINOS

Source of Energy of the SUN : Nuclear Fusion

$$4p + 2e^- \rightarrow {}^4\text{He} + 2\nu_e$$

Energy Released per each Cycle

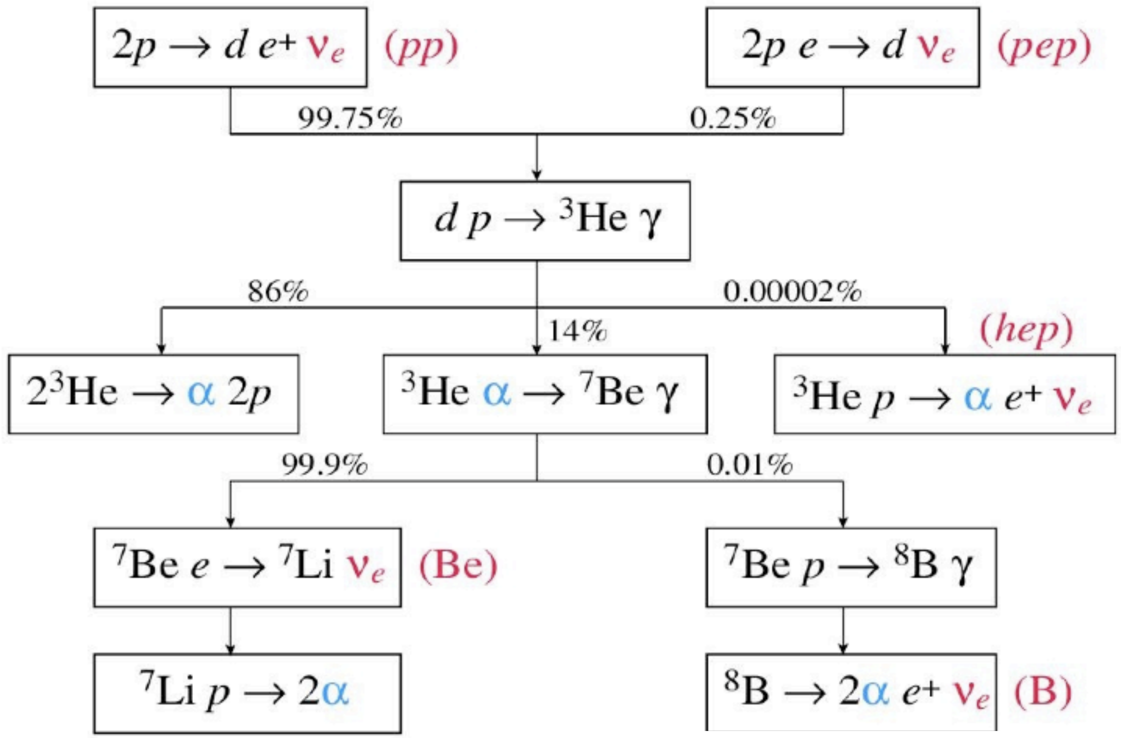
$$Q = 4m_p + 2m_e - m_{He} = 26.73 \text{ MeV}$$

$$\Phi_{\nu_e} \simeq \frac{1}{4\pi\, d_\odot^2} \frac{2\, L_\odot}{(Q - \langle E_\nu \rangle)}$$

$$\phi_{\nu_\odot} \sim 6 \times 10^{10} \ (\text{cm}^2 \ \text{s})^{-1}$$

Neutrino Flux

PP cycles



${}^{12}C + p \to {}^{13}N + \gamma$

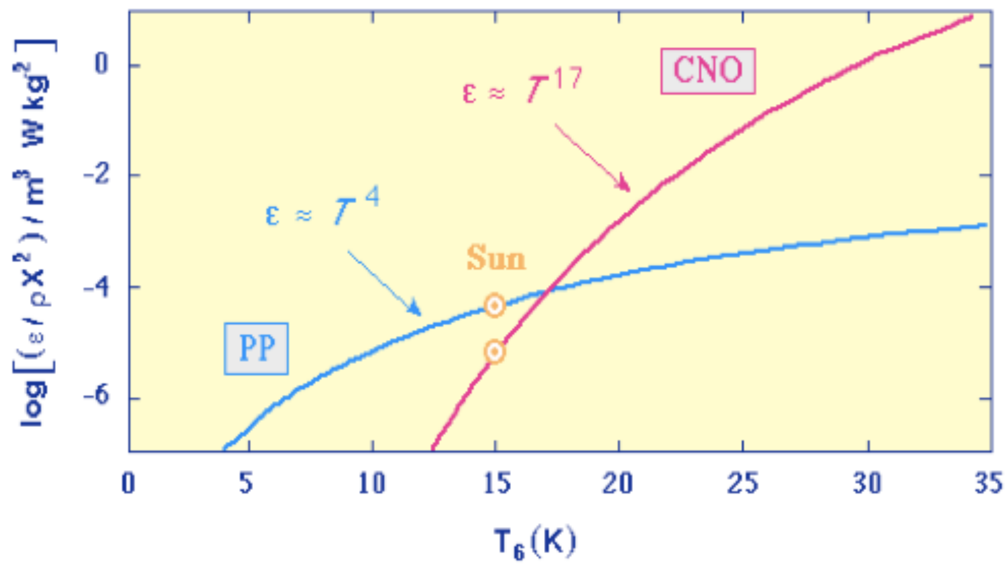
${}^{13}N \to {}^{13}C + e^+ + \nu_e$ (1.2 MeV)

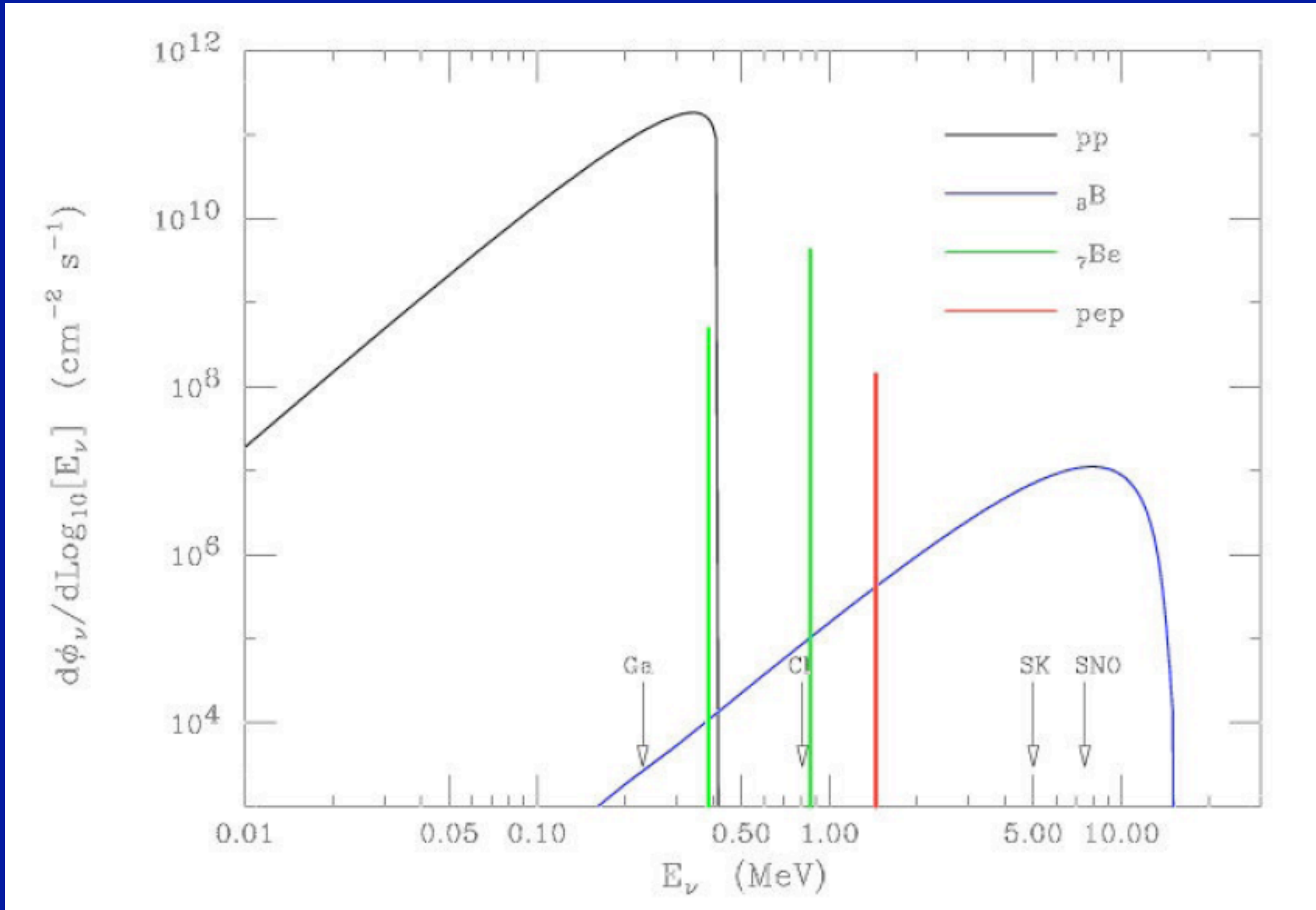
${}^{13}C + p \to {}^{14}N + \gamma$

${}^{14}N + p \to {}^{15}O + \gamma$

${}^{15}O \to {}^{15}N + e^+ + \nu_e$ (1.73 MeV)

${}^{15}N + p \to {}^{12}C + {}^4He$





10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
$d\phi_\nu/dLog_{10}[E_\nu]$ $(cm^{-2}\ s^{-1})$
pp
$_8B$
$_7Be$
pep
Ga
Cl
SK
SNO
0.01
0.05
0.10
0.50
1.00
5.00
10.00
E_ν (MeV)

Detection of Solar Neutrinos:

Chlorine Experiment
(Ray Davis)

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

Gallium Experiments
[Gallex, Sage]

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$

(Super)-Kamiokande
Electron Scattering

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

Heavy Water [SNO]

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

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

Radio-Chemical Experiments

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

$$C_j = \int dE\ \phi_{\nu_\odot}(E)\ \sigma_j(E)$$

Capture Rate

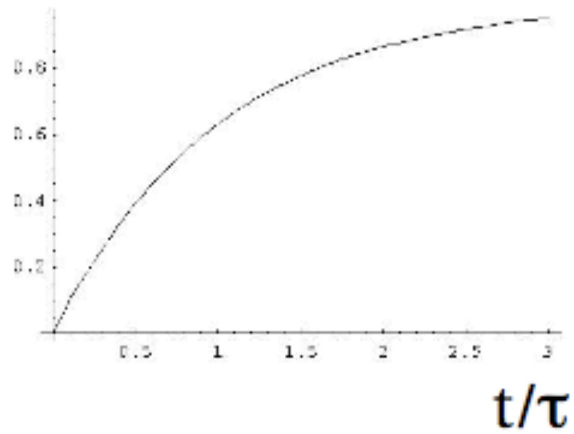
$$1\ \mathrm{SNU} \equiv 1\ \mathrm{Solar\ Neutrino\ Unit} = 10^{-36}\ \mathrm{sec}^{-1}$$

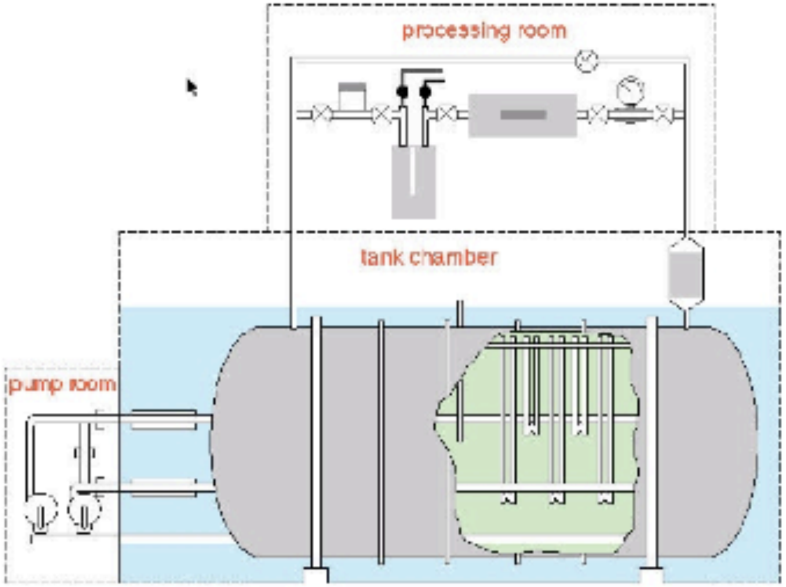
$${}^{37}\mathrm{Ar} + e^- \to {}^{37}\mathrm{Ar} + \nu_e$$

DECAY $T_{1/2} = 35$ days

$$\frac{dN_{\mathrm{Ar}}}{dt} = N_{\mathrm{Cl}}\ C_{(\mathrm{Cl}\to\mathrm{Ar})} - \frac{N_{\mathrm{Ar}}}{\tau_{\mathrm{Ar}}}$$

$$N_{\mathrm{Ar}}(t) = N_{\mathrm{Cl}}\ C\ \tau_{\mathrm{Ar}}\ [1 - \exp(-t/\tau_{\mathrm{Ar}})]$$



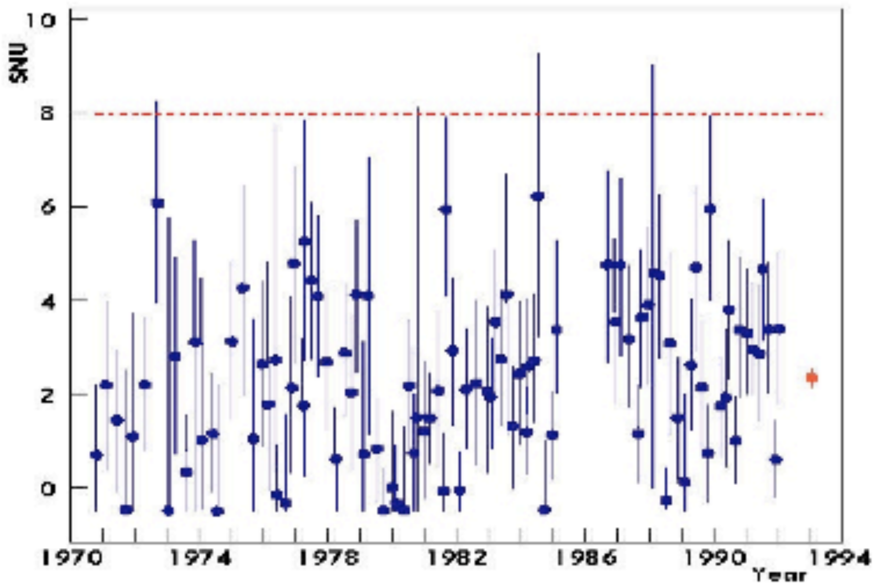


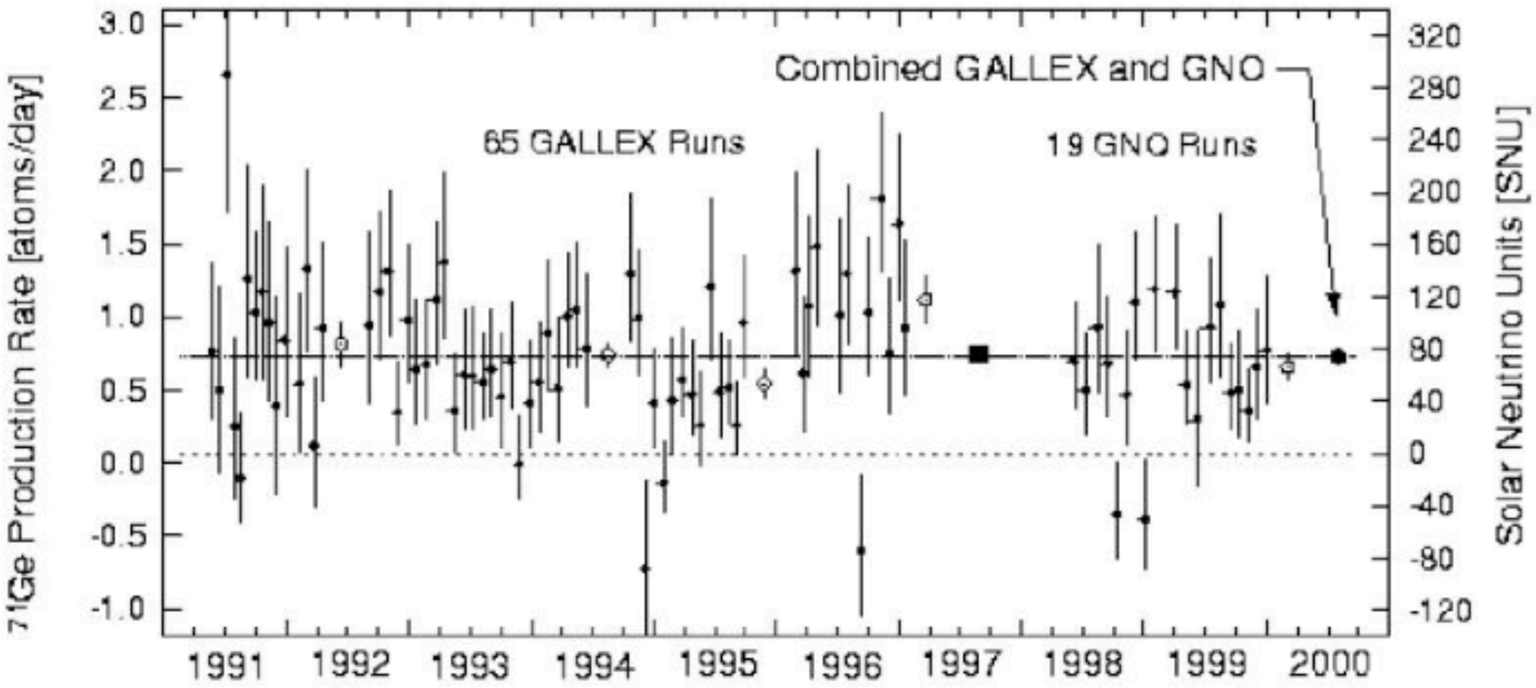
Davis experiment

Chlorine

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

615 tons C_2Cl_4

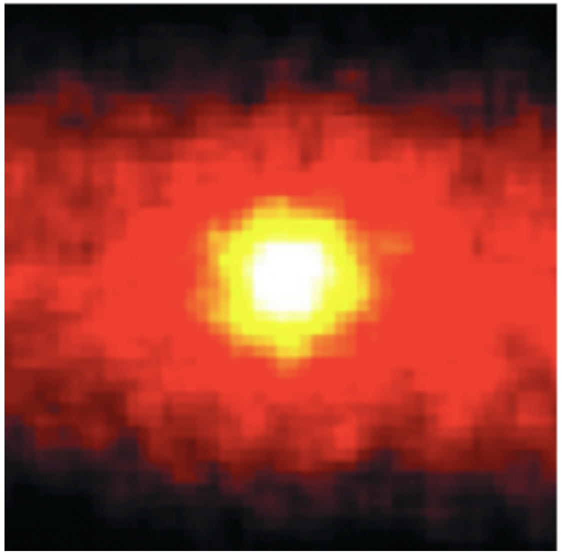




Experiment	(SNU) Prediction	Data	Data/Prediction
Chlorine	$7.6^{+1.3}_{-1.1}$	2.56 ± 0.23	0.34 ± 0.06
GALLEX + GNO	128^{+9}_{-7}	$74.1^{+6.7}_{-7.8}$	0.58 ± 0.07
SAGE	128^{+9}_{-7}	$75.4^{+7.8}_{-7.4}$	0.59 ± 0.07

Electron Scattering

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



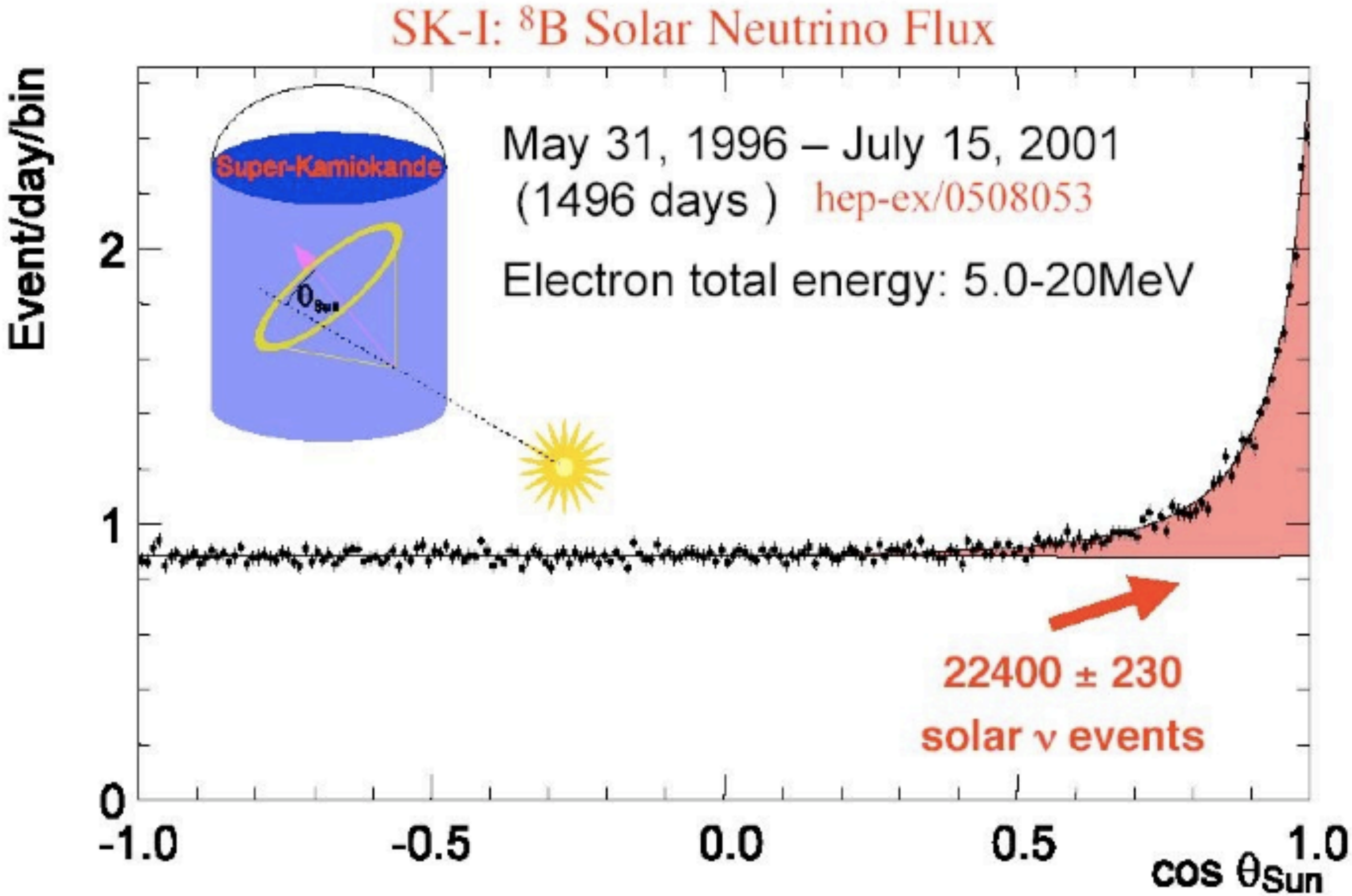
$$\frac{d\sigma_{\nu_x e}}{dT} = \frac{2G_F^2 m_e^2}{\pi}\left[g_L^2 + g_R^2\left(1 - \frac{T}{E_\nu}\right)^2 - g_L\, g_R\, \frac{m_e c^2 T}{E_\nu^2}\right]$$

T = Kinetic Energy of
the final state electron

$$g_L^2 = \begin{cases} \left(\frac{1}{2} + \sin^2\theta_W\right)^2 & \simeq 0.536 \quad , \quad \nu_e \\ \sin^4\theta_W & \simeq 0.0538 \quad , \quad \bar{\nu}_e \\ \left(-\frac{1}{2} + \sin^2\theta_W\right)^2 & \simeq 0.0719 \quad , \quad \nu_i \\ \sin^4\theta_W & \simeq 0.0538 \quad , \quad \bar{\nu}_i \end{cases}$$

Cross section strongly
peaked for electron emission
in the neutrino direction

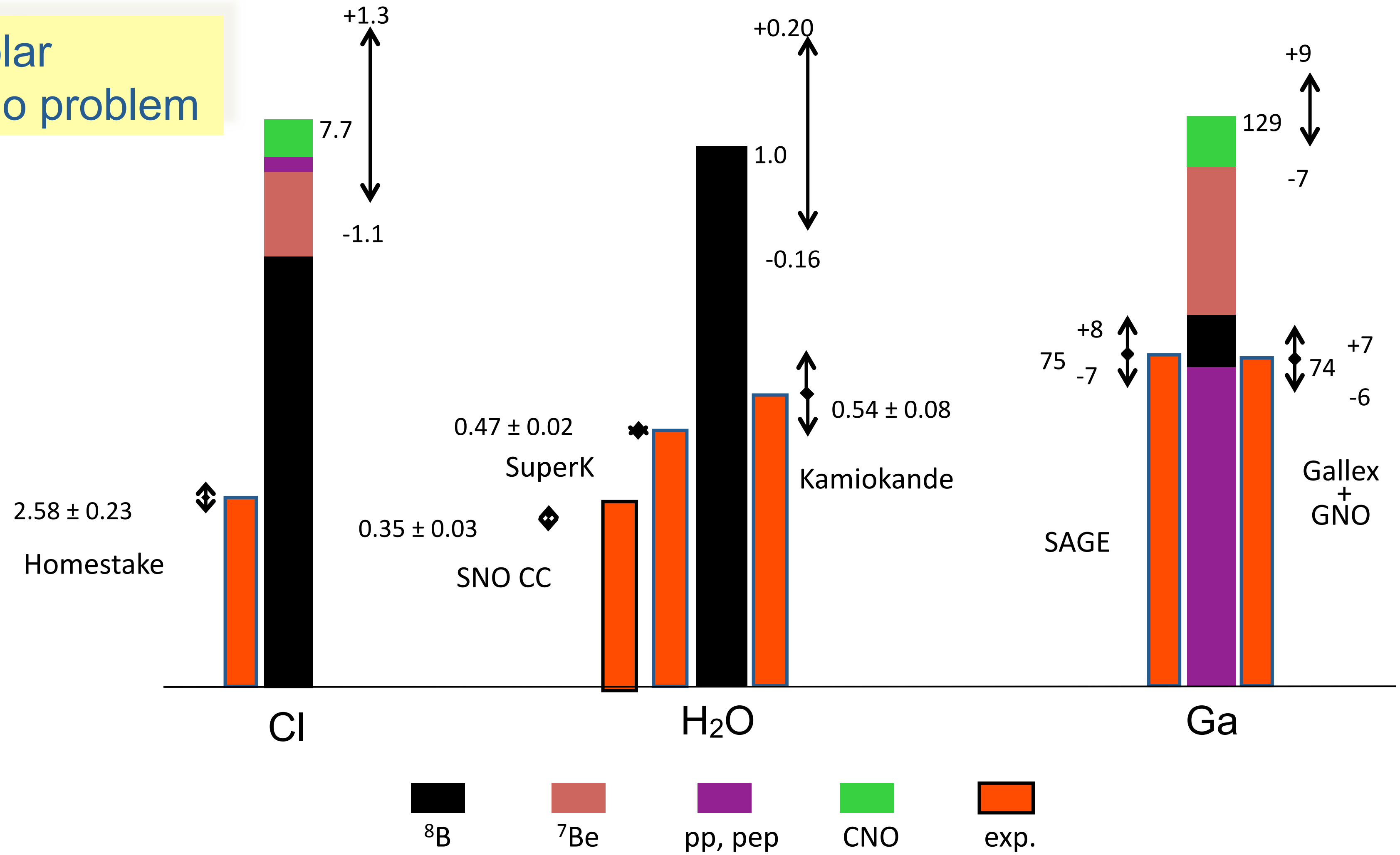
$$g_R^2 = \begin{cases} \sin^4\theta_W & \simeq 0.0538 \quad , \quad \nu_e \\ \left(\frac{1}{2} + \sin^2\theta_W\right)^2 & \simeq 0.536 \quad , \quad \bar{\nu}_e \\ \sin^4\theta_W & \simeq 0.0538 \quad , \quad \nu_i \\ \left(-\frac{1}{2} + \sin^2\theta_W\right)^2 & \simeq 0.0719 \quad , \quad \bar{\nu}_i \end{cases}$$



$\phi_{ES} = 2.35 \pm 0.02 \pm 0.08$ [$\times 10^6/cm^2/s$]

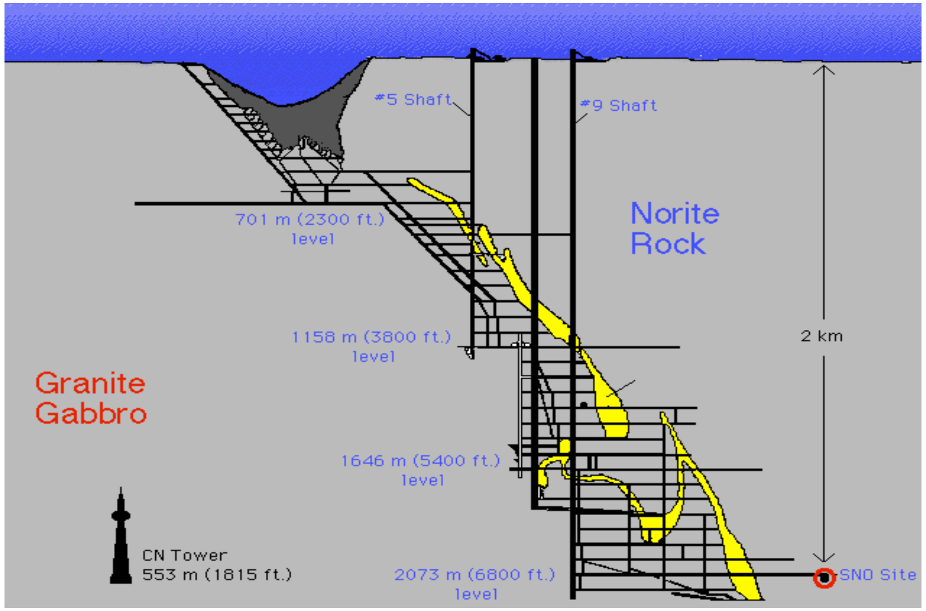
$\text{DATA/SM} = 0.465 \pm 0.015$

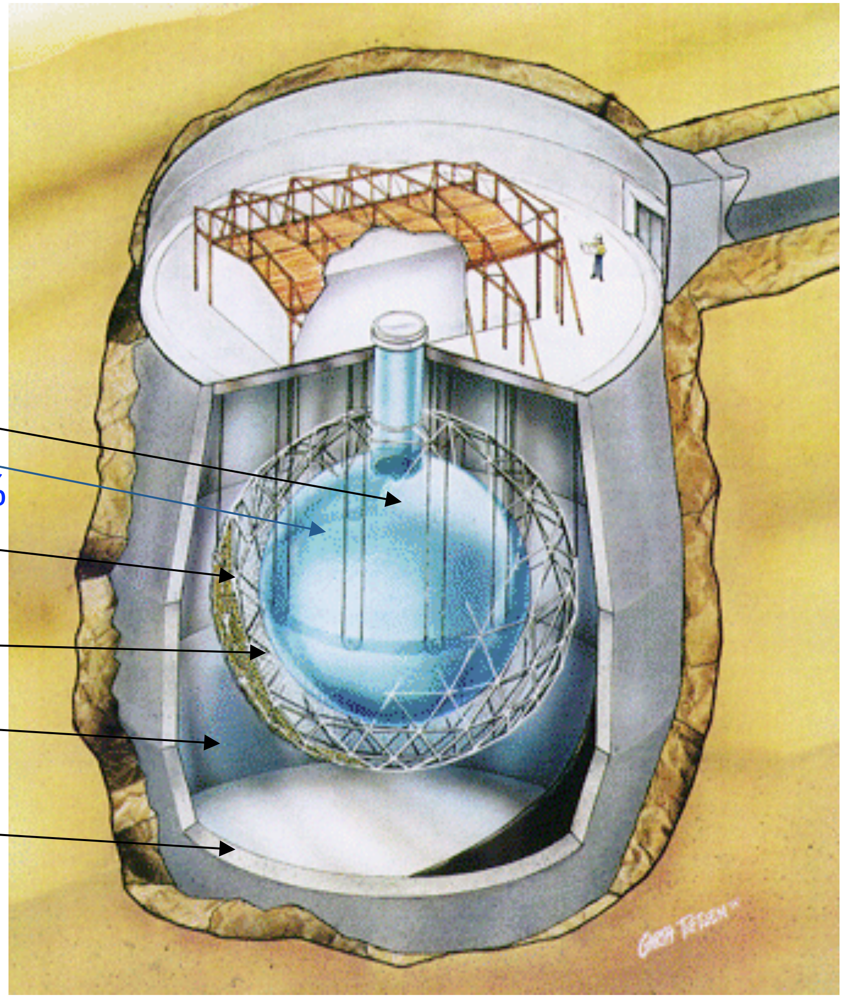
The solar neutrino problem



By fitting data from all the experiments: the detected ^{7}Be flux is consistent with 0 while the ^{8}B flux is reduced by about one half. But ^{8}B neutrinos are produced from ^{7}Be !

Sudbury Neutrino Observatory





1000 tonnes D_2O

12 m diameter Acrylic Vessel

18 m diameter support structure; 9500 PMTs (~60% photocathode coverage)

1700 tonnes inner shielding H_2O

5300 tonnes outer shielding H_2O

Urylon liner radon seal

depth: 2092 m (~6010 m.w.e.) ~70 muons/day

Neutrino Reactions in SNO

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

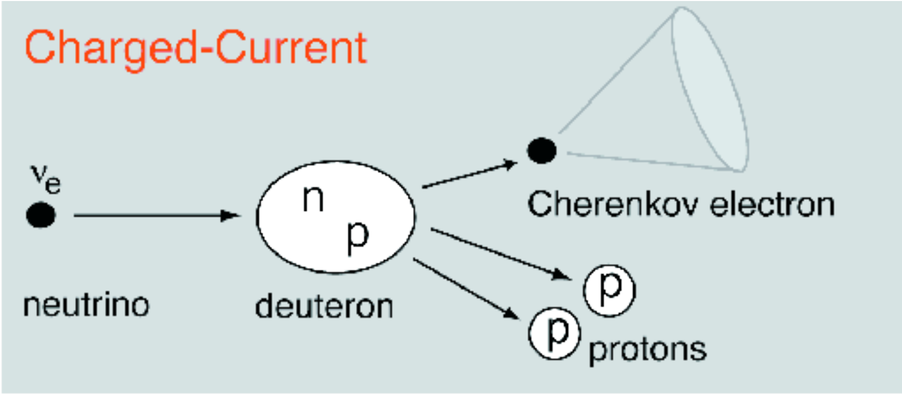
- Q = 1.445 MeV
- good measurement of ν_e energy spectrum
- some directional info ∝ (1 – 1/3 cosθ)
- ν_e only

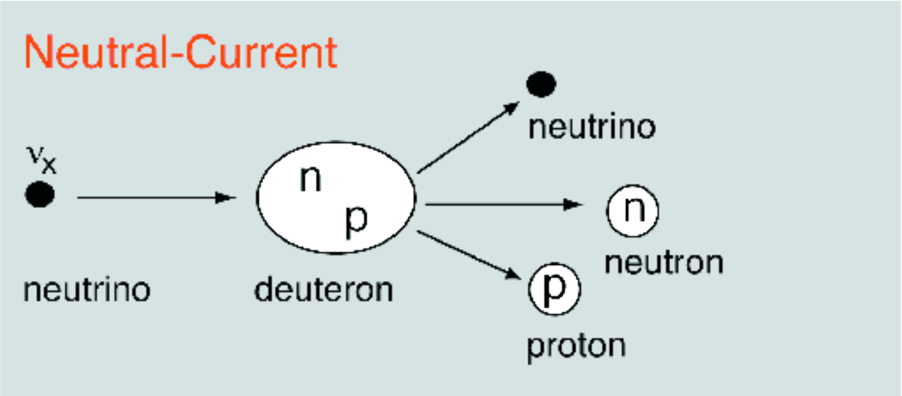
NC $\nu_x + d \rightarrow p + n + \nu_x$

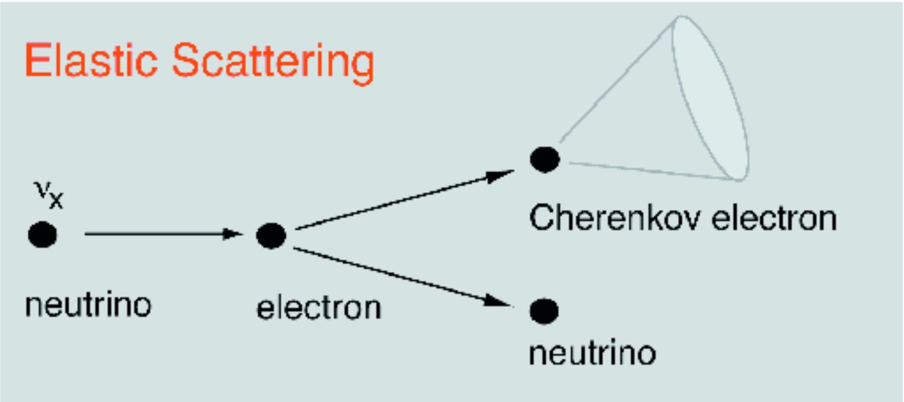
- Q = 2.22 MeV
- measures total ^8B ν flux from the Sun
- equal cross section for all active ν flavors

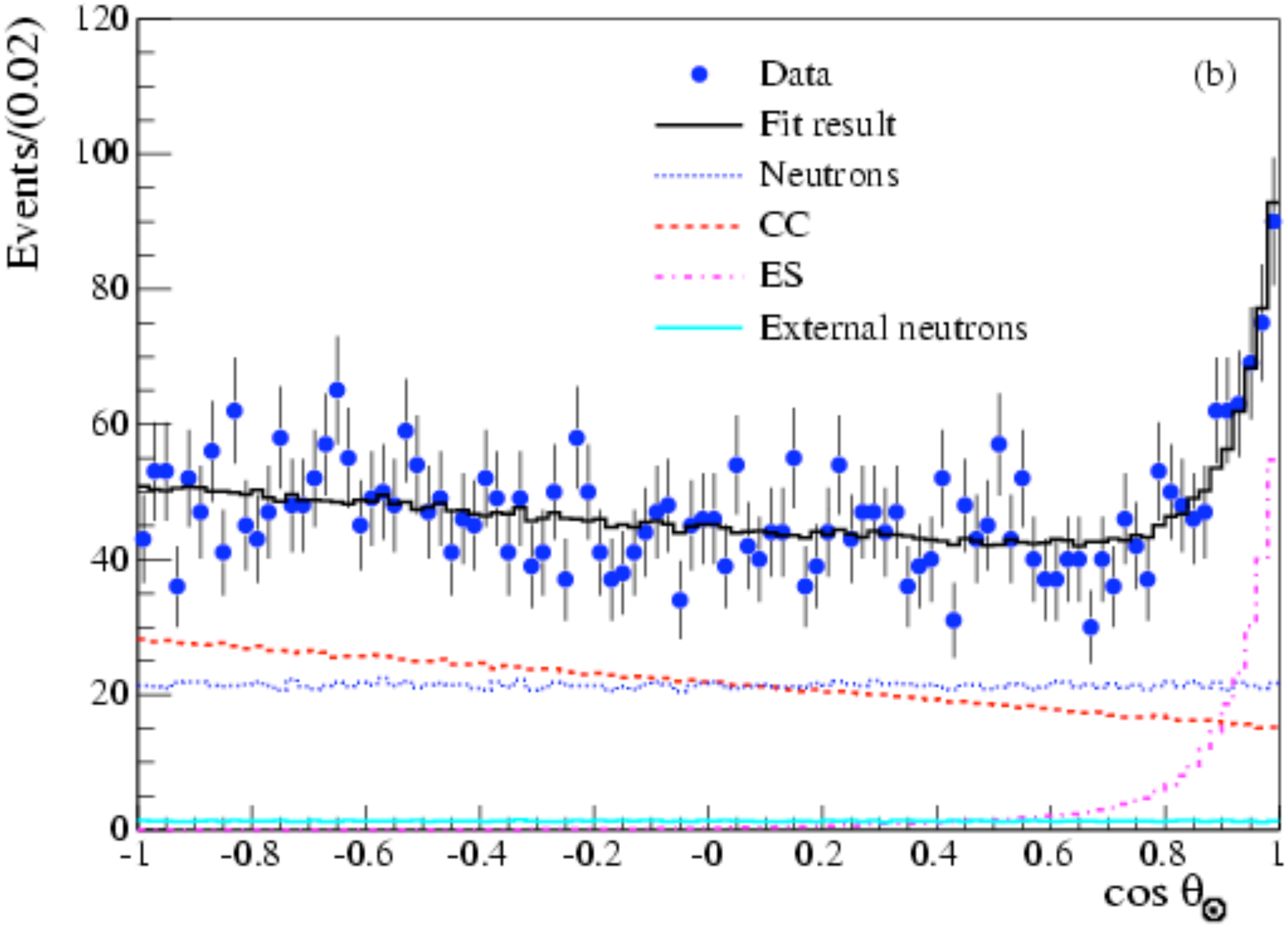
ES $\nu_x + e^- \rightarrow \nu_x + e^-$

- low statistics
- mainly sensitive to ν_e, some ν_μ and ν_τ
- strong directional sensitivity









Events/(0.02)
120
100
80
60
40
20
0
Data
(b)
Fit result
Neutrons
CC
ES
External neutrons
-1
-0.8
-0.6
-0.4
-0.2
-0
0.2
0.4
0.6
0.8
1
cos θ⊙

Fluxes ($\times 10^6$ cm^{-2} sec^{-1})

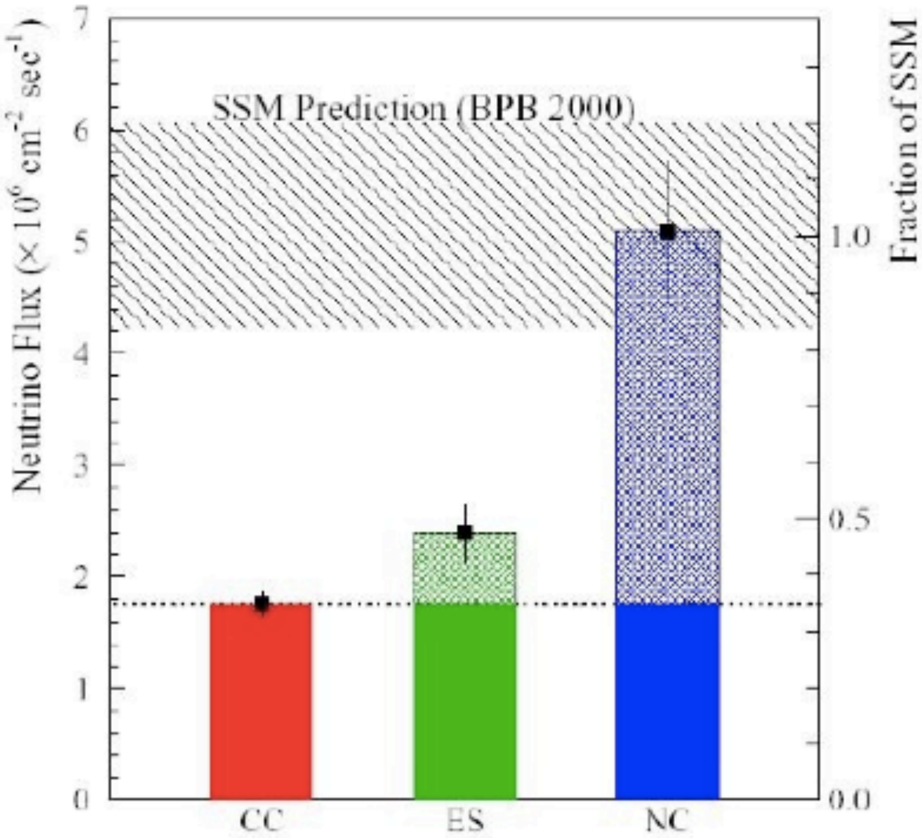
$$\phi_{CC} = 1.76^{+0.06}_{-0.05}\,(\text{stat.}) \pm 0.09\,(\text{sys.})$$

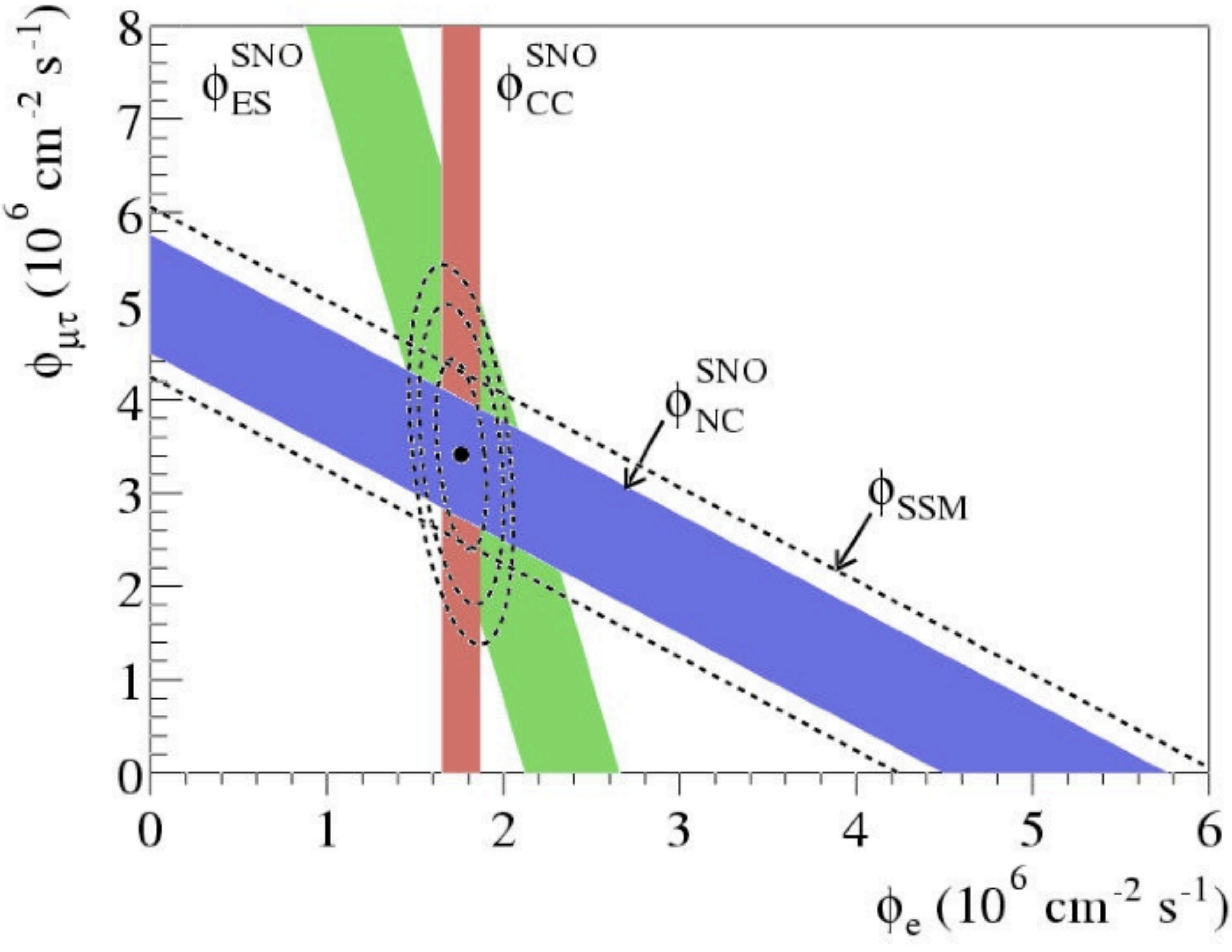
$$\phi_{ES} = 2.39^{+0.24}_{-0.23}\,(\text{stat.}) \pm 0.12\,(\text{sys.})$$

$$\phi_{NC} = 5.09^{+0.44}_{-0.43}\,(\text{stat.})^{+0.46}_{-0.43}\,(\text{sys.})$$

#EVENTS

CC	$1967.7^{+61.9}_{+60.9}$
ES	$263.6^{+26.4}_{+25.6}$
NC	$576.5^{+49.5}_{+48.9}$

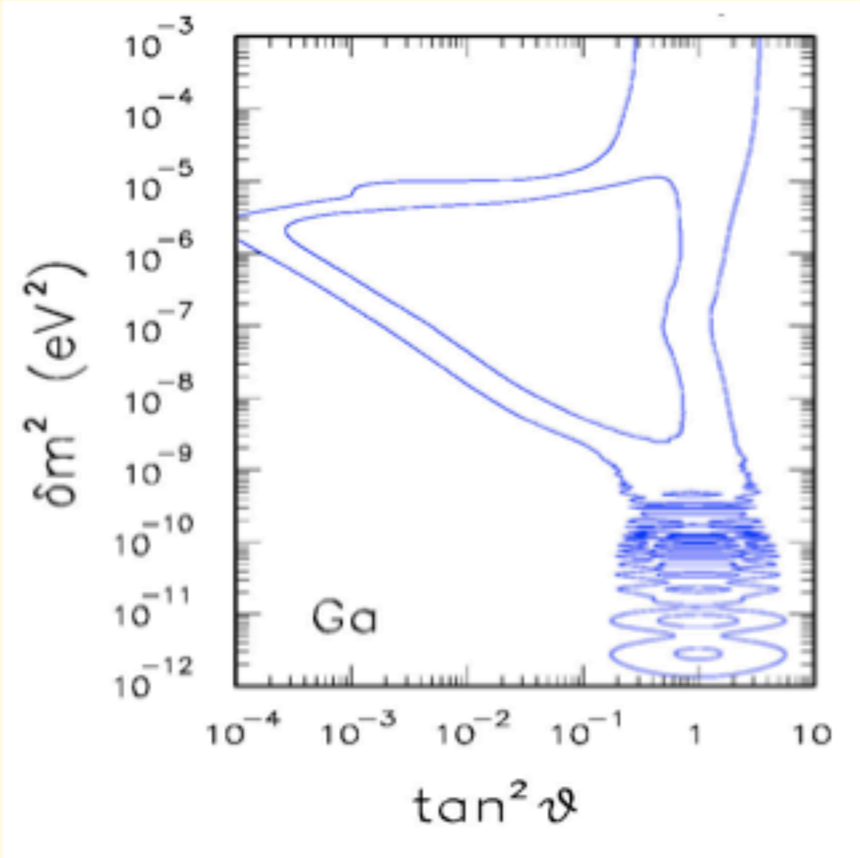




ϕ_{ES}^{SNO}
ϕ_{CC}^{SNO}
ϕ_{NC}^{SNO}
ϕ_{SSM}
$\phi_{\mu\tau}$ (10^6 cm^{-2} s^{-1})
ϕ_e (10^6 cm^{-2} s^{-1})
0
1
2
3
4
5
6
7
8

Interpretation

In the "past millennium": Oscillations? Maybe, but…
- large uncertainties in the parameter space or solar model
- no unmistakable evidence for flavor transitions ("smoking gun")



"small" mixing "large" mixing

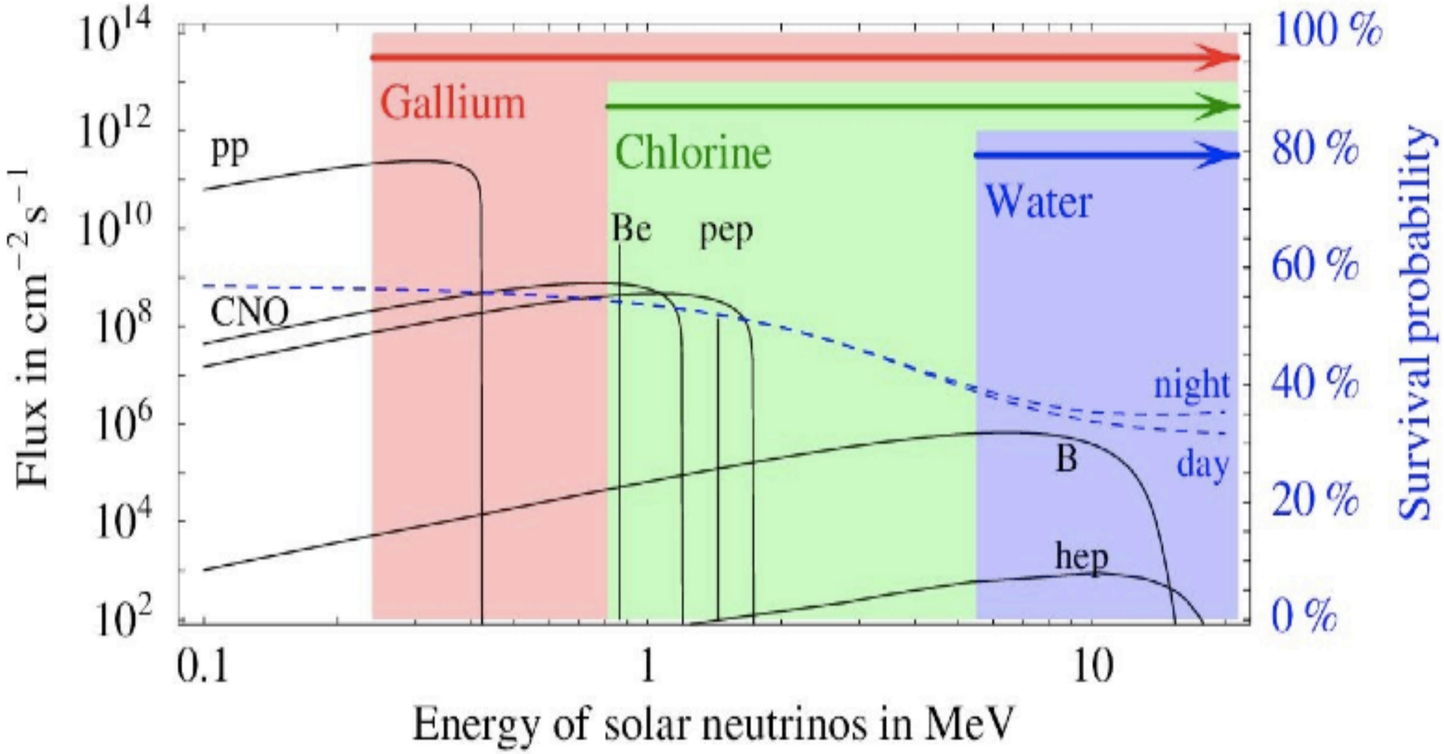
E.g., in Gallium expts:

"matter" (MSW) solutions

"vacuum" solutions

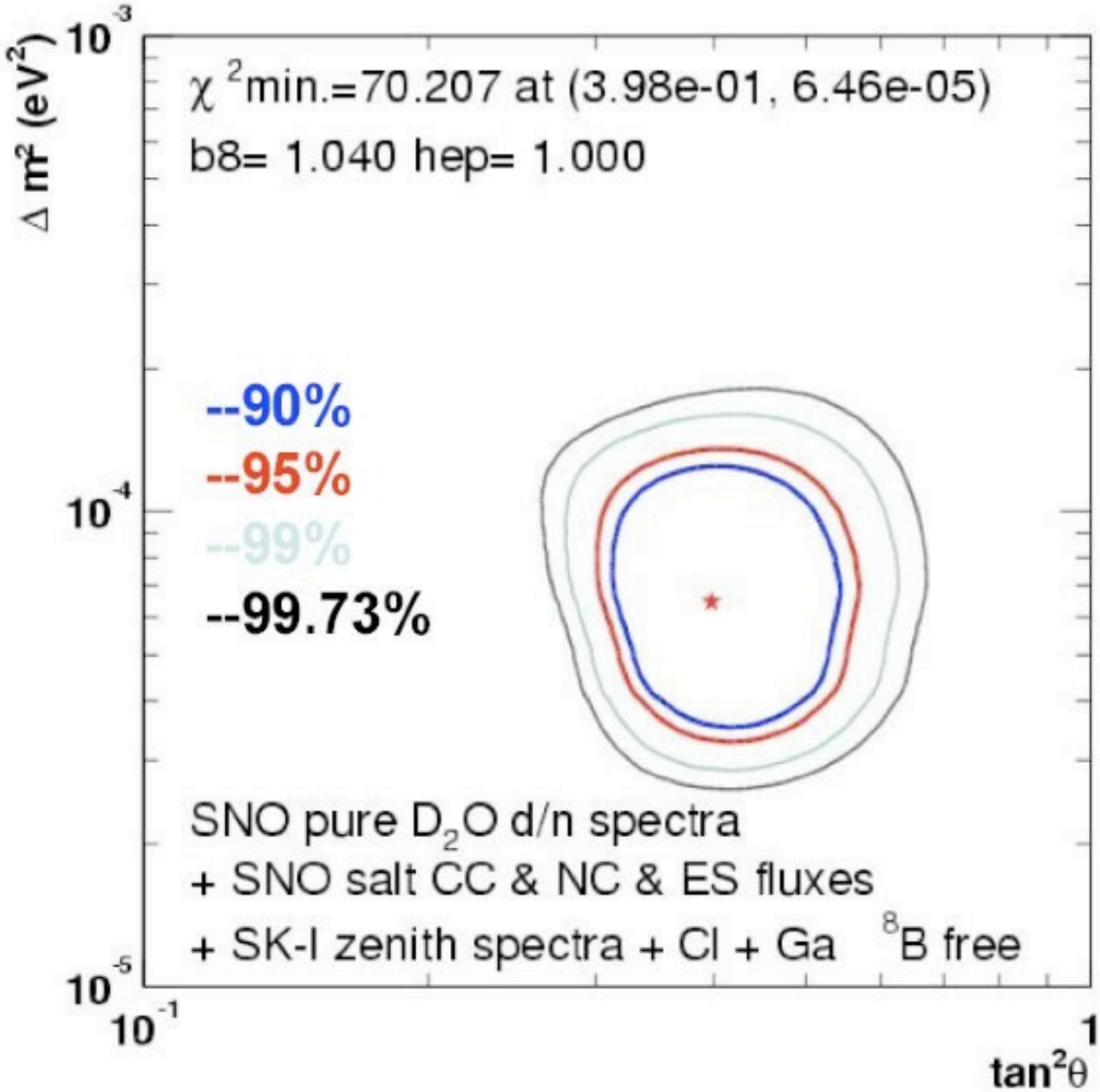
+ many "exotic" or non-oscillatory solutions…

…this millennium (after the SNO result of 2002):
everything points to MSW matter oscillations in the Sun



Solar neutrinos produced in the Sun core with E ≤ 2 MeV only experience averaged vacuum oscillations in the Sun with P(survival) ≃ $1 - 1/2 \sin^2 2\theta_{12} \geq 1/2$

If E ≥ 2 MeV than P(survival) ≃ $\sin^2 \theta_{12}$


χ^2min.=70.207 at (3.98e-01, 6.46e-05)
b8= 1.040 hep= 1.000
--90%
--95%
--99%
--99.73%
SNO pure D_2O d/n spectra
+ SNO salt CC & NC & ES fluxes
+ SK-I zenith spectra + Cl + Ga ^{8}B free
Δm^2 (eV^2)
10^{-3}
10^{-4}
10^{-5}
10^{-1}
1
$\tan^2\theta$

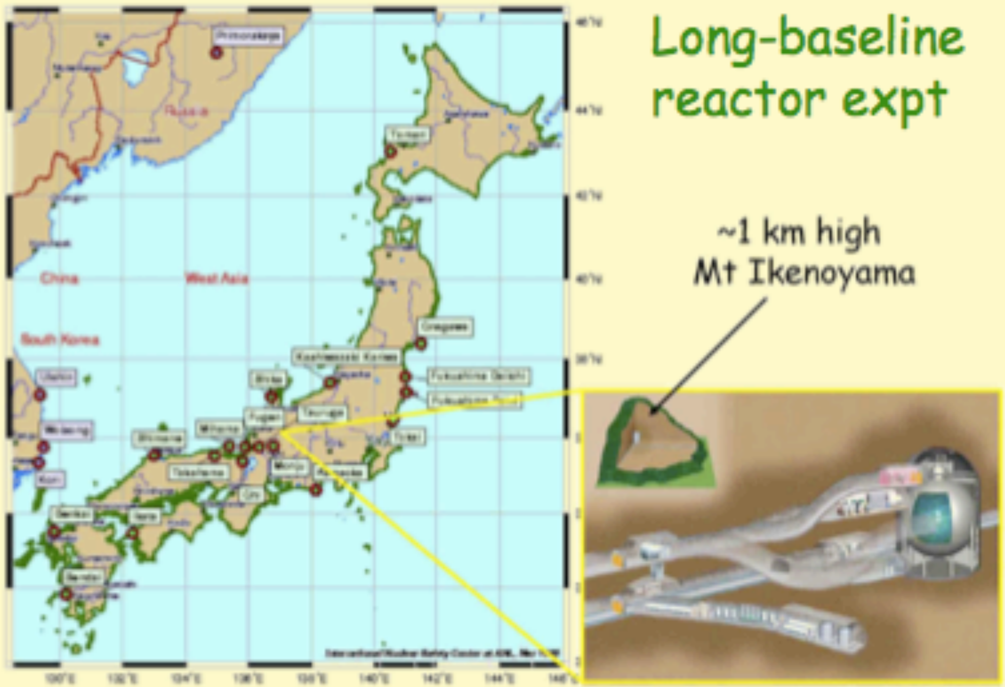
Also in 2002... KamLAND: 1000 ton mineral oil detector, "surrounded" by nuclear reactors producing anti-ν_e. Characteristics:

$A/\delta m^2 \ll 1$ in Earth crust
(vacuum approxim. OK)
$L \sim 100\text{-}200$ km
$E_\nu \sim$ few MeV

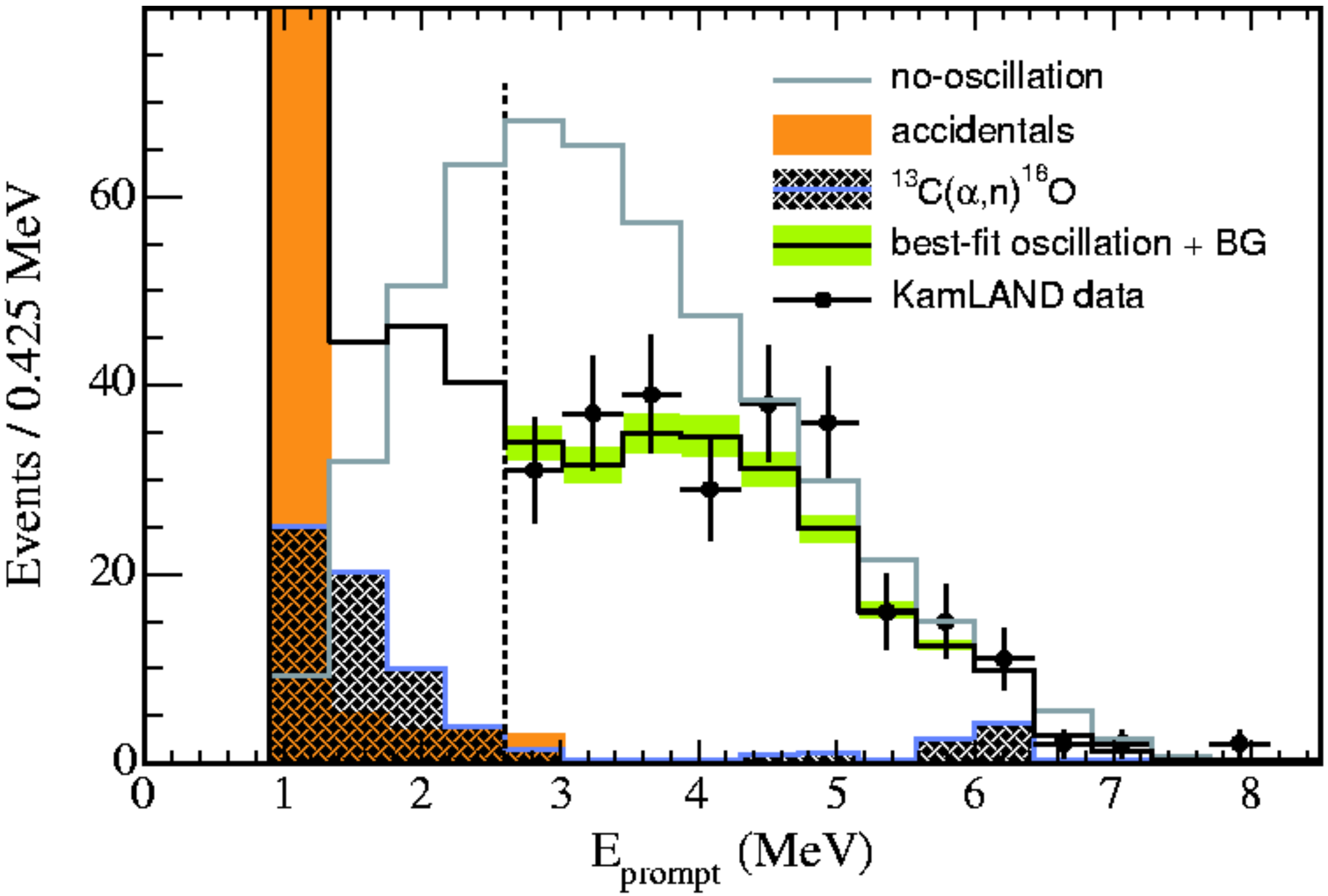
⇨

With previous $(\delta m^2, \theta)$ parameters it is $(\delta m^2 L/4E) \sim O(1)$ and reactor neutrinos should oscillate with large amplitude (large θ)

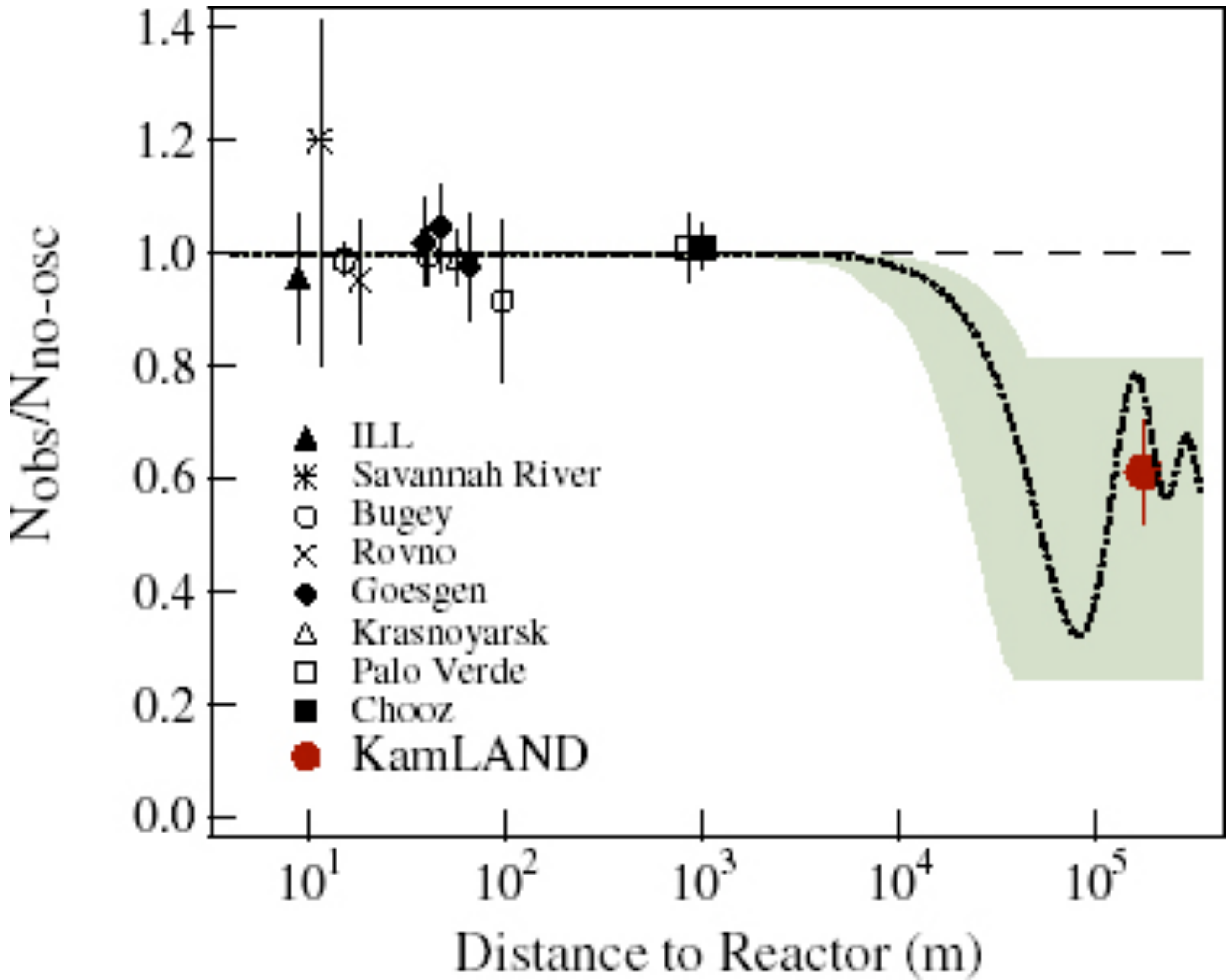
Long-baseline
reactor expt



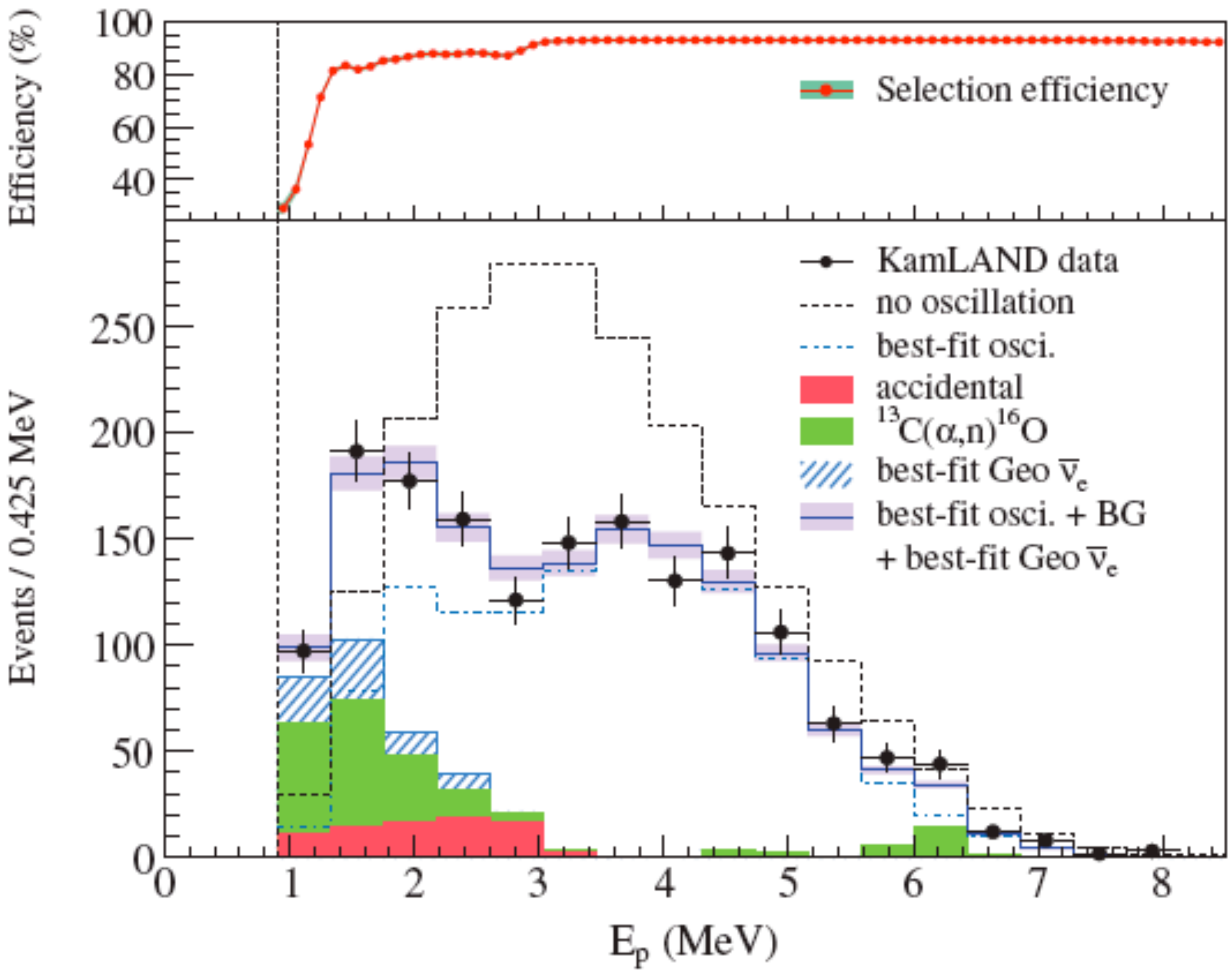
KAMLAND results (2002)



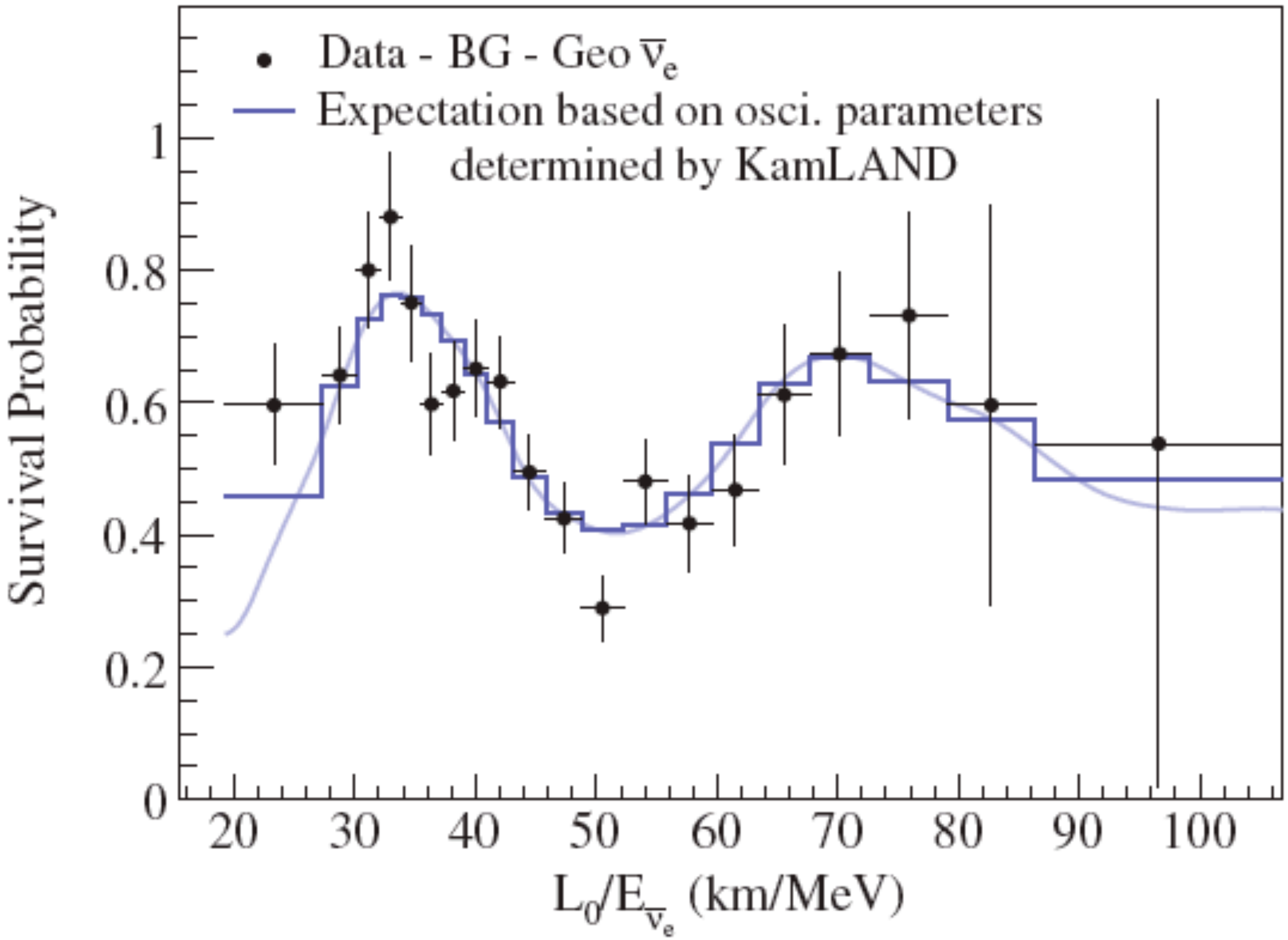
KAMLAND results (2002)



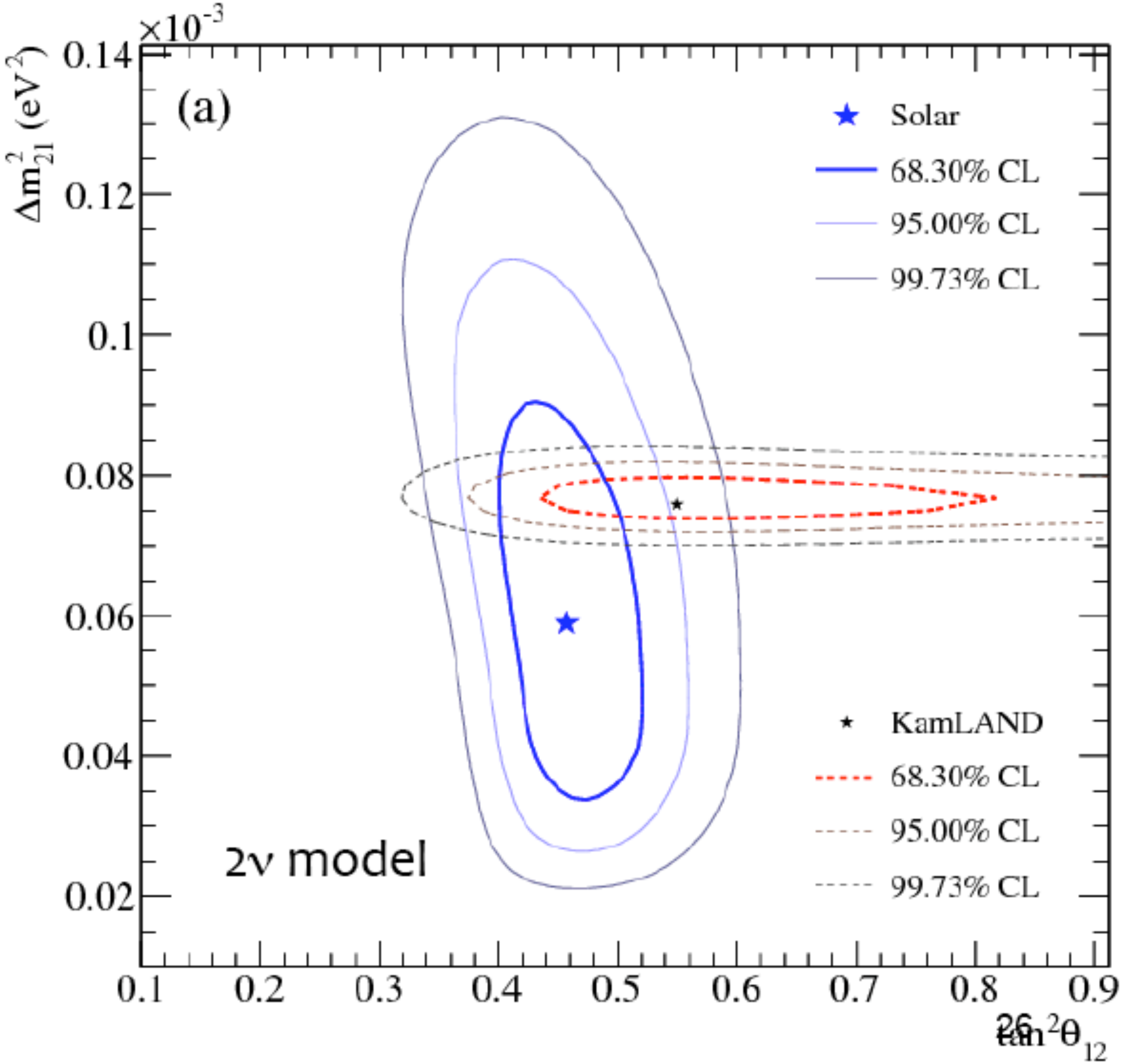
KAMLAND results (2007)



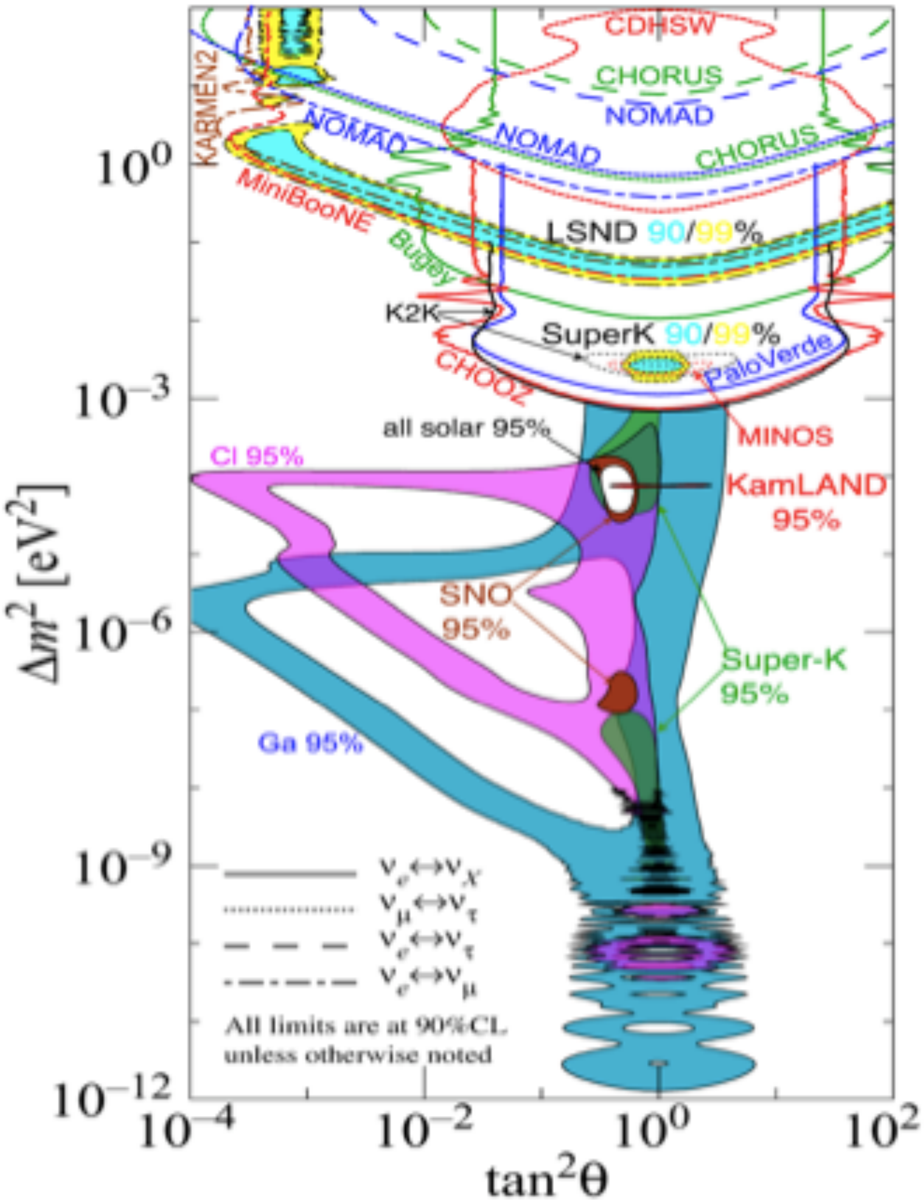
KAMLAND results (2007)



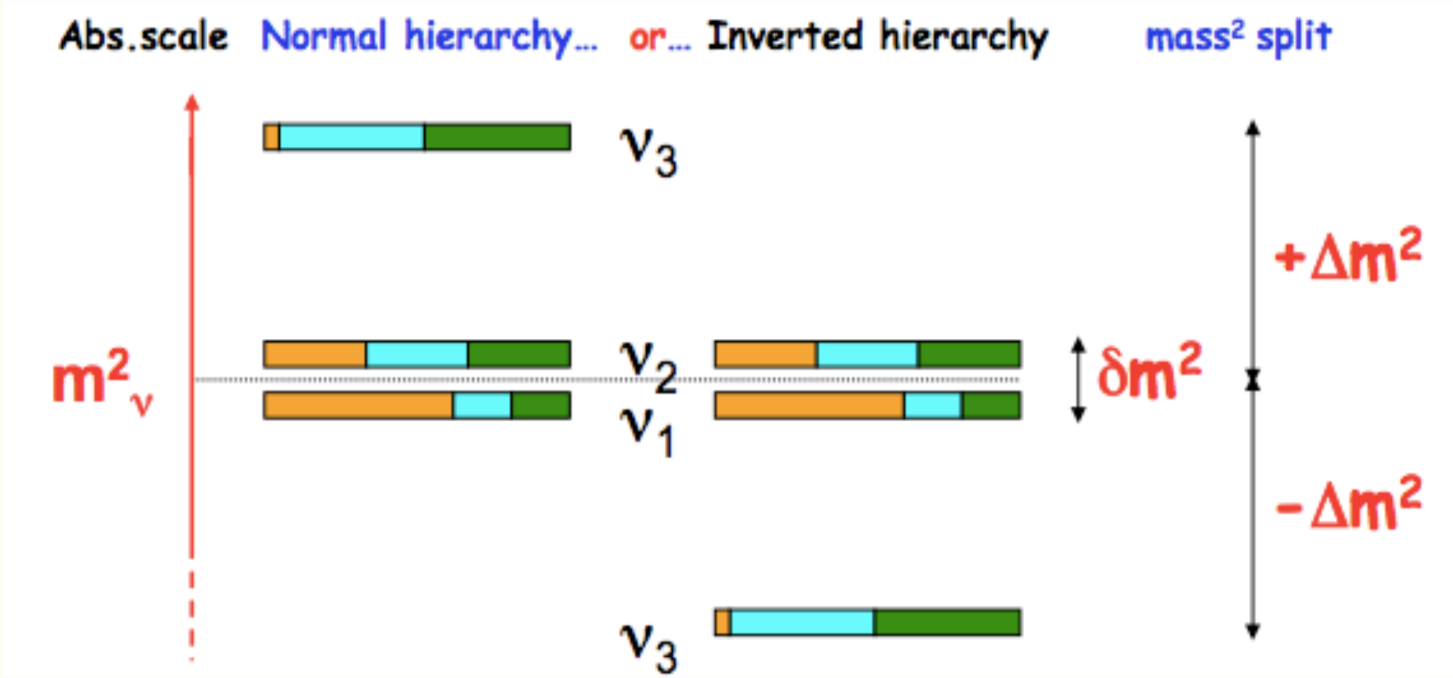
KAMLAND results complementary to Solar neutrino experiments



In summary, out of all these experiments….



SUMMARY (Flavors = e μ τ)



$\delta m^2 \sim 8 \times 10^{-5}$ eV^2 $\sin^2\theta_{12} \sim 0.3$

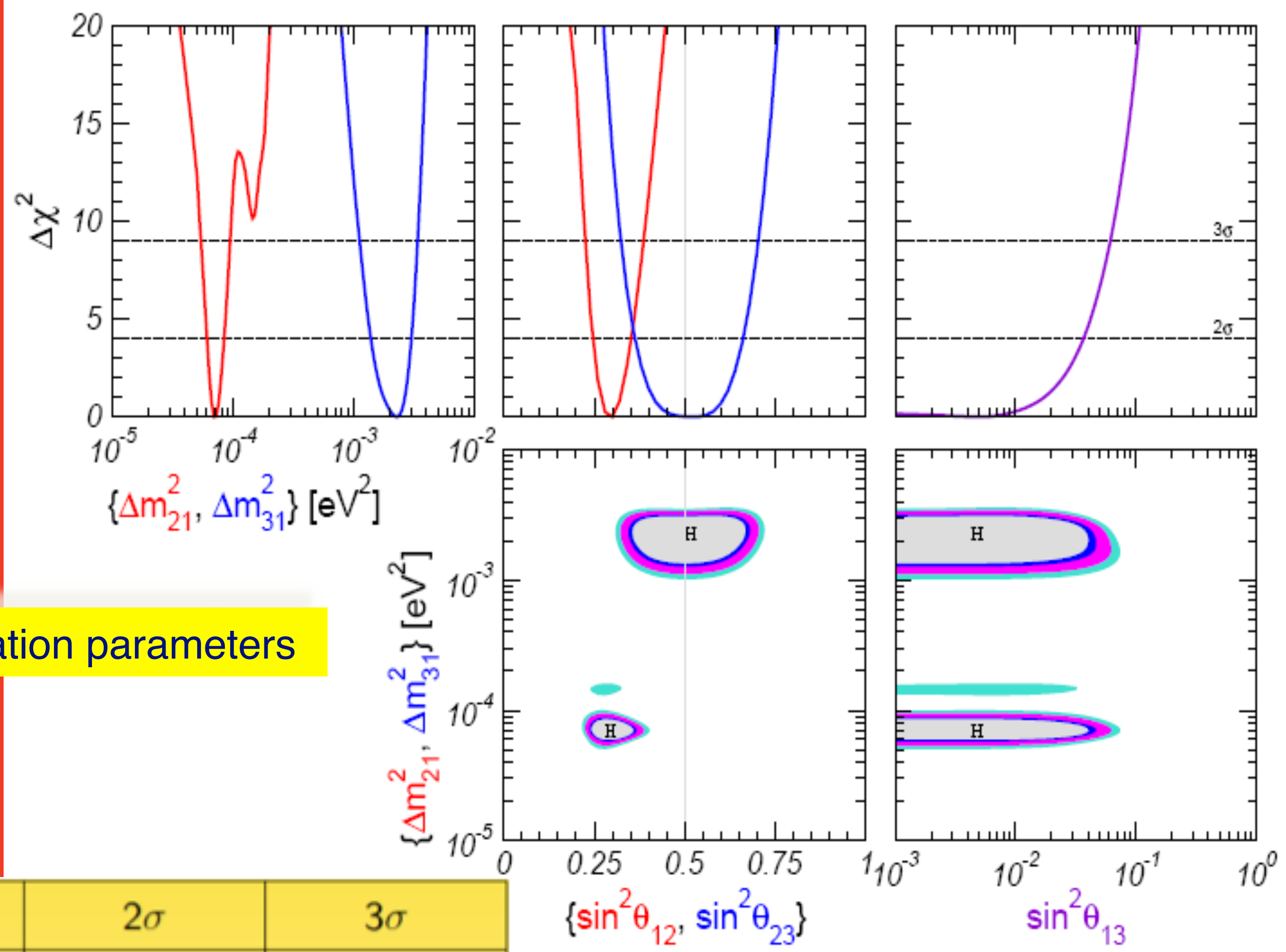
$\Delta m^2 \sim 3 \times 10^{-3}$ eV^2 $\sin^2\theta_{23} \sim 0.5$

} established

$m_\nu < O(1)$ eV $\sin^2\theta_{13} <$ few%

sign($\pm\Delta m^2$) unknown δ (CP) unknown

} open issues



Our knowledge of the oscillation parameters

parameter	best-fit$^{+1\sigma}_{-1\sigma}$	2σ	3σ
Δm^2_{21} [10^{-5} eV^2]	$7.59^{+0.23}_{-0.18}$	7.22 – 8.03	7.03 – 8.27
$\|\Delta m^2_{31}\|$ [10^{-3} eV^2]	$2.40^{+0.12}_{-0.11}$	2.18 – 2.64	2.07 – 2.75
$\sin^2\theta_{12}$	$0.318^{+0.019}_{-0.016}$	0.29 – 0.36	0.27 – 0.38
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39 – 0.63	0.36 – 0.67
$\sin^2\theta_{13}$	$0.013^{+0.013}_{-0.009}$	≤ 0.039	≤ 0.053

Note that:
$\sin^2\theta_{13} < 0.04 \rightarrow$
$\sin^2 2\theta_{13} < 0.15$ and
$\theta_{13} < 11°$

Quark vs lepton mixing

Quark mixing

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

⟺

Neutrino mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{MNSP} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

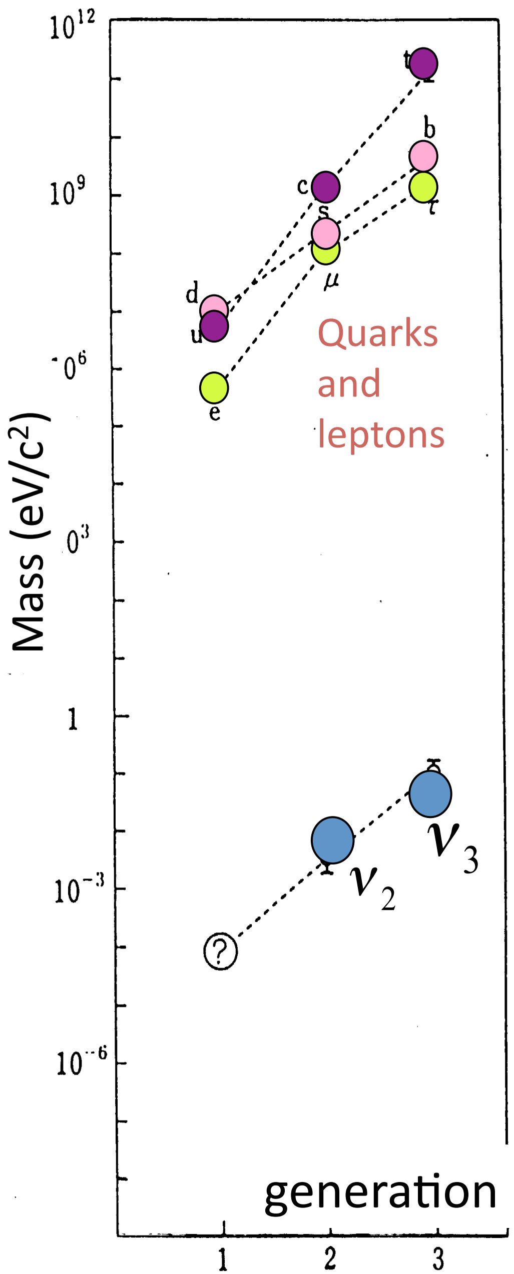
$$V_{CKM} \approx U_{PMNS} \; ?$$

(3 mixing angles in V_{CKM} and U_{PMNS}?)

| --- | --- |
$\theta_{12}=13^o$	$\theta_{12}=33\pm3^o$
$\theta_{23}=2.4^o$	$\theta_{23}=45\pm8^o$
$\theta_{13}=0.21^o$	$\theta_{13}<11^o$

Very different: need a precision study of the neutrino mixing matrix

Why the neutrino mass is so small ?



$$\left(\frac{m(\nu_3)}{m(top\ quark)}\right) \approx \left(\frac{1}{3\times 10^{12}}\right)$$

See-saw mechanism

Minkowsky, Yanagida,
Gell-mann, Ramond, Slansky

$$m_\nu \approx \frac{m_q^{\ 2}}{m_N}$$

If we input $m_{\nu 3}$ and m_q (m_{top} is used),
we get $m_N = 10^{15}$ GeV

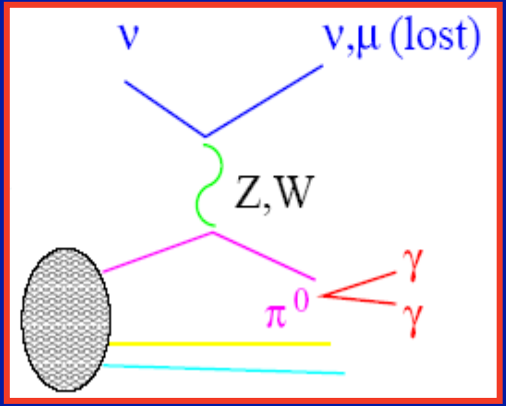
This suggests that physics of neutrino mass could be related to physics of Grand Unification!

The next goal: measure θ_{13}

$\nu_\mu \rightarrow \nu_e$ oscillation as a tool to measure θ_{13} with accelerator neutrino experiments.

Future reactor experiments will have sensitivity to large θ_{13} values. Existing or planned atmospheric neutrino detectors can be limited by statistics.

- small effect (< 5%)
- prompt ν_e contamination at % level (accelerator neutrino beams)
- main BG: $\pi°$ production in NC and CC interactions
- additional BG: low energy muons and pions can fake electrons

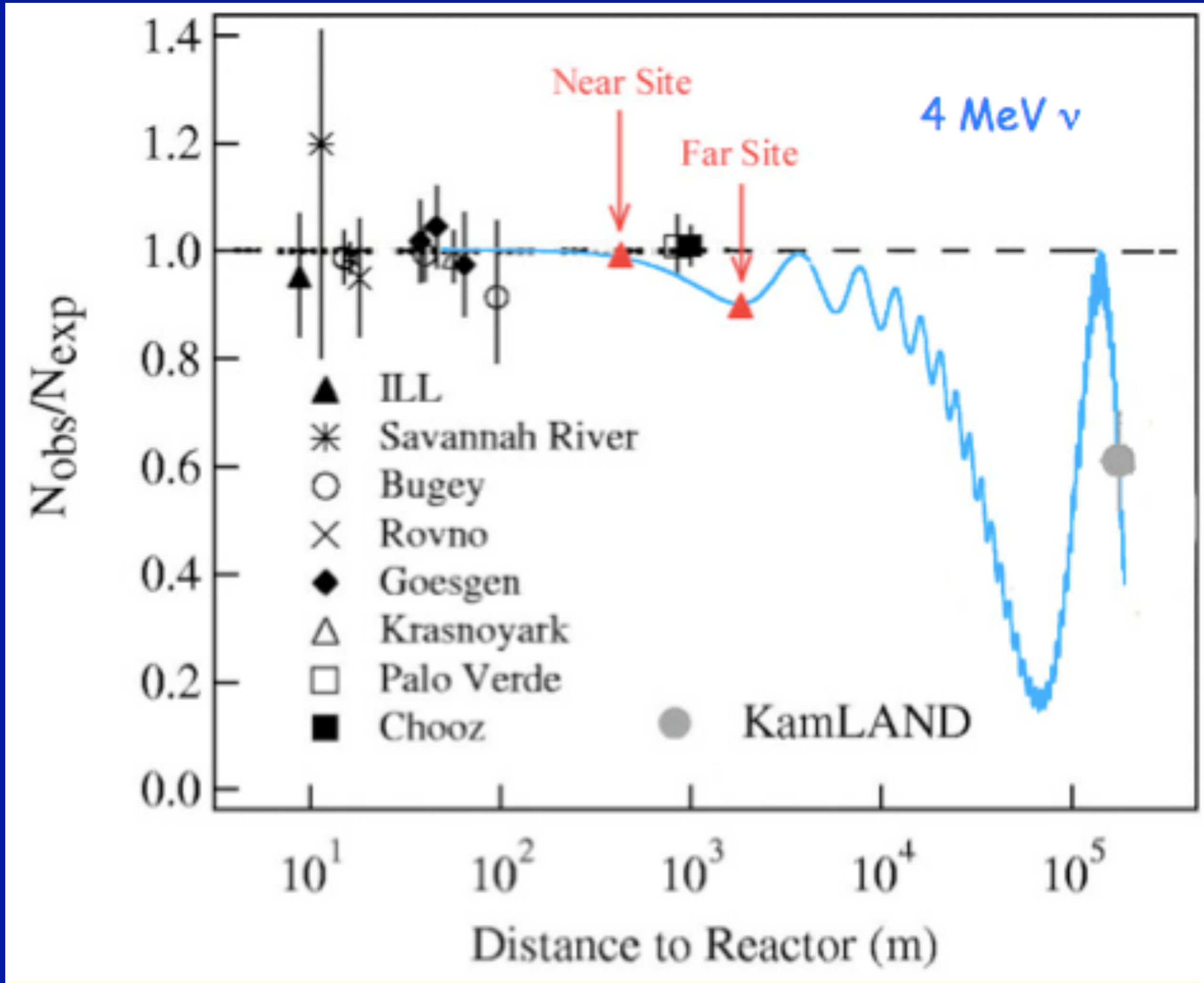


$\nu_e \rightarrow \nu_\mu$ oscillations can solve most of the problems but hard to make ν_e beams (wait for a next generation facilities)

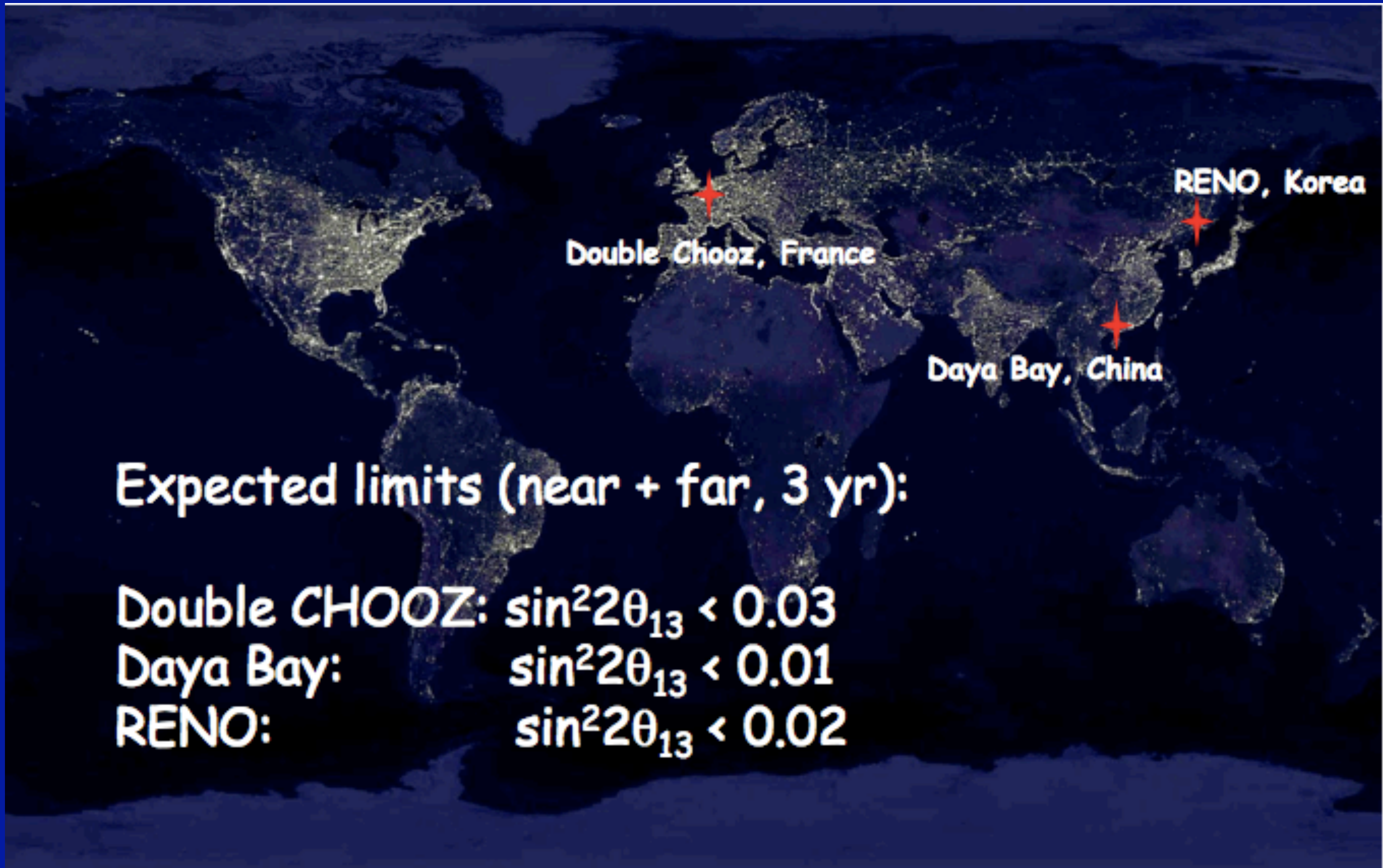
In any case high intensity is a must !

$$P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{23} L/4E)$$

Measure θ_{13} with nuclear reactors ?



Measure θ_{13} with nuclear reactors ?



Measure θ_{13} with LBL accelerator experiments?

T2K (Tokai to Kamioka) experiment

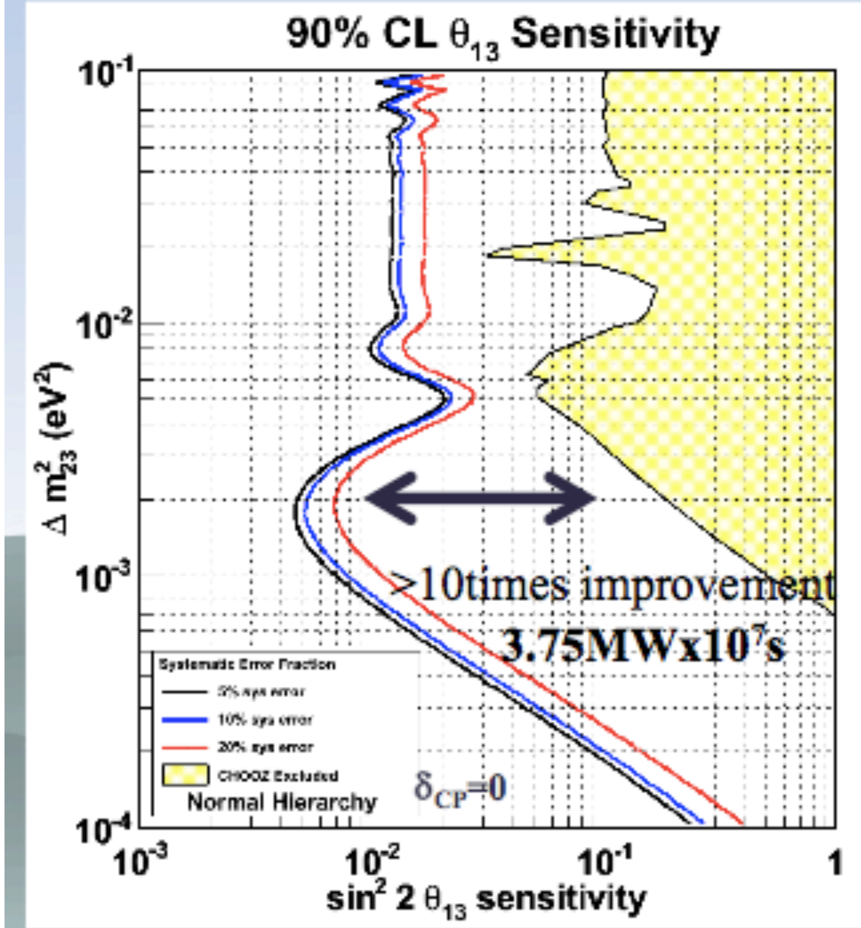
- High intensity ν_μ beam from J-PARC MR to Super-Kamiokande @ 295km
- **Discovery of ν_e appearance → Determine θ_{13}**
  - **Last unknown mixing angle**
  - **Open possibility to explore CPV in lepton sector**

CP odd term in $\nu_\mu \rightarrow \nu_e$ **prob.** $\propto \sin\delta \cdot s_{12} \cdot s_{23} \cdot s_{13}$ **$\sin\theta_{12}$~0.5, $\sin\theta_{23}$~0.7, $\sin\theta_{13}$<0.2)**

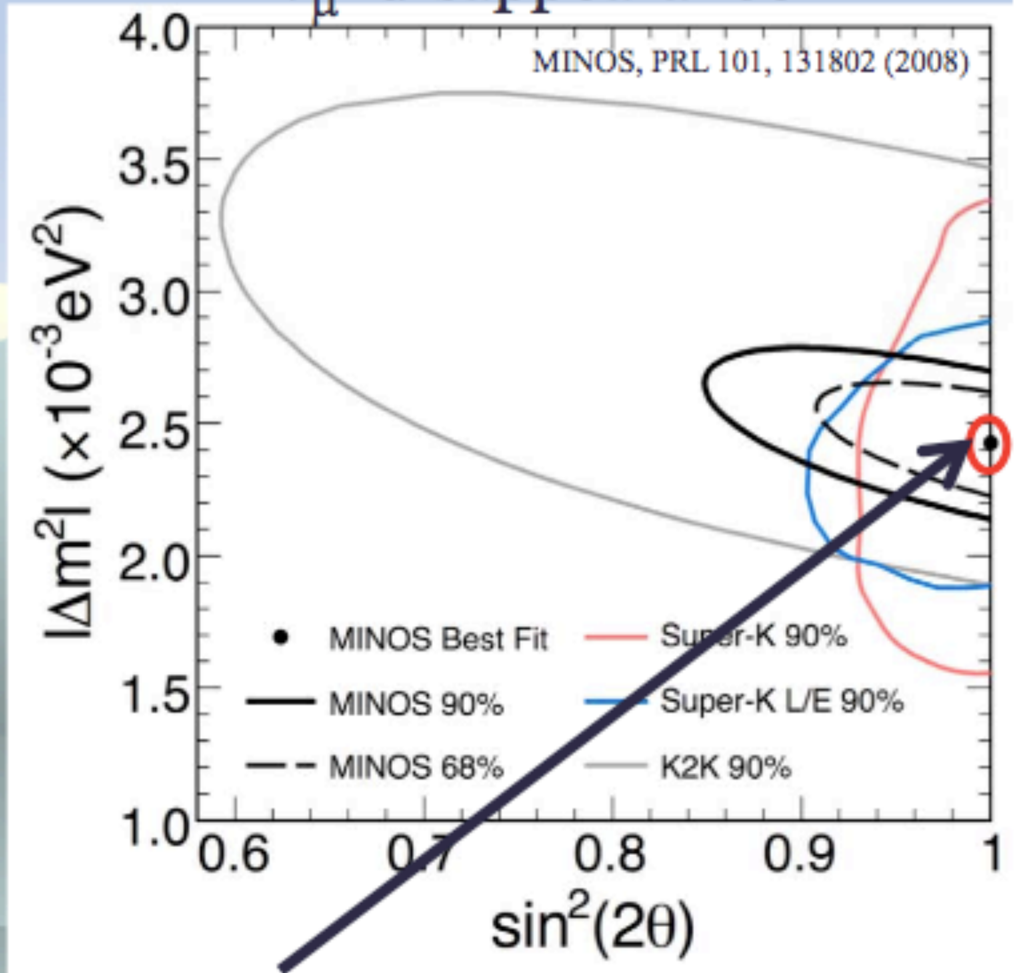
- **Precise meas. of ν_μ disappearance → θ_{23}, Δm_{23}^2**
  - Really maximum mixing? Any symmetry? Anytihng unexpected?

Expected Sensitivity of T2K

$\nu_\mu \rightarrow \nu_e$ appearance



ν_μ disappearance



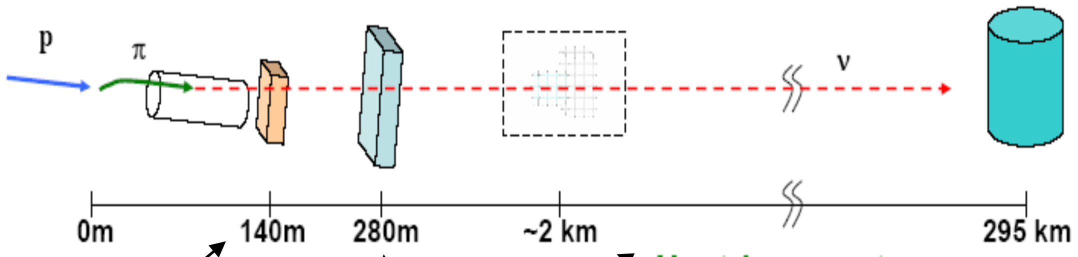
Goal @ 3.75MWx10^7s:

$\delta(\sin^2 2\theta_{23})$~0.01,

$\delta(\Delta m^2_{23}) < 1\times10^{-4}$ [eV^2]

The first Super-Beam: off-axis T2K, from JAERI at Tokai to SK

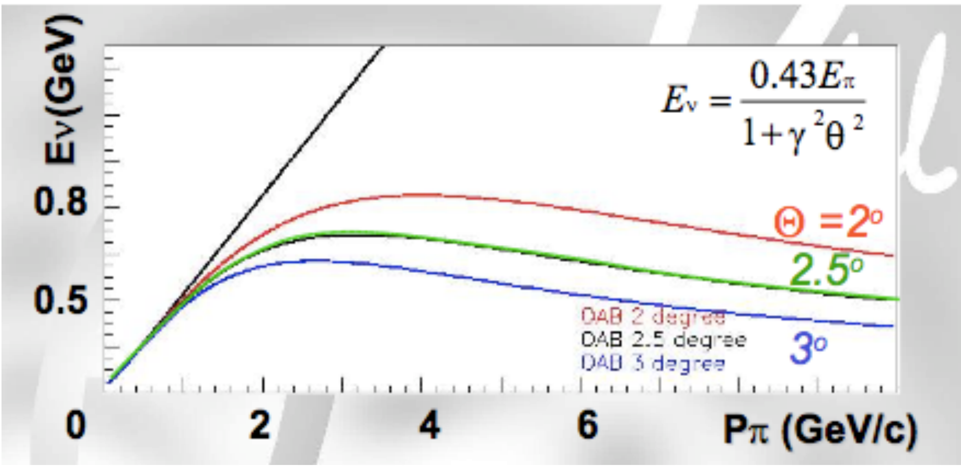
- low E_ν (<1 GeV) Super-Beam: 10^{21} pot/year
- @ 2° → 3000 ν_μ CC/year (x10 w.r.t. K2K)
- 0.2% ν_e contamination and π° BG

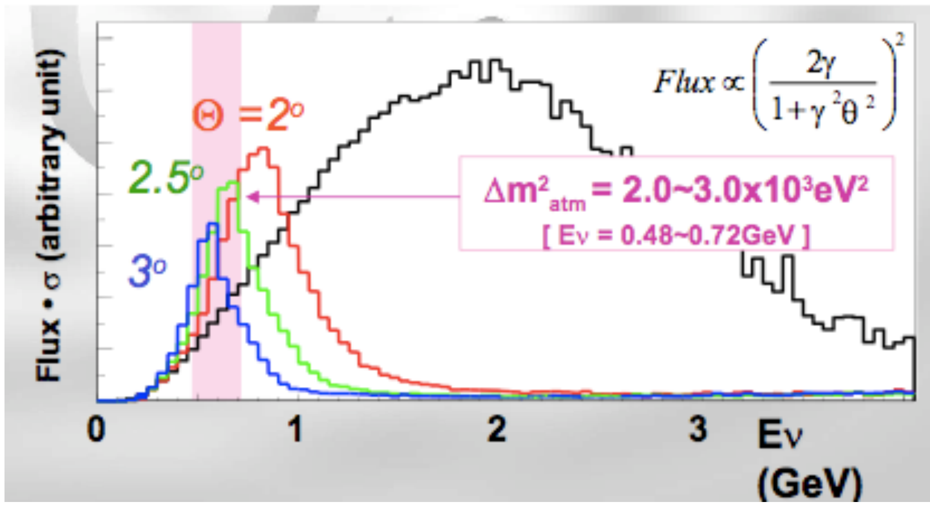


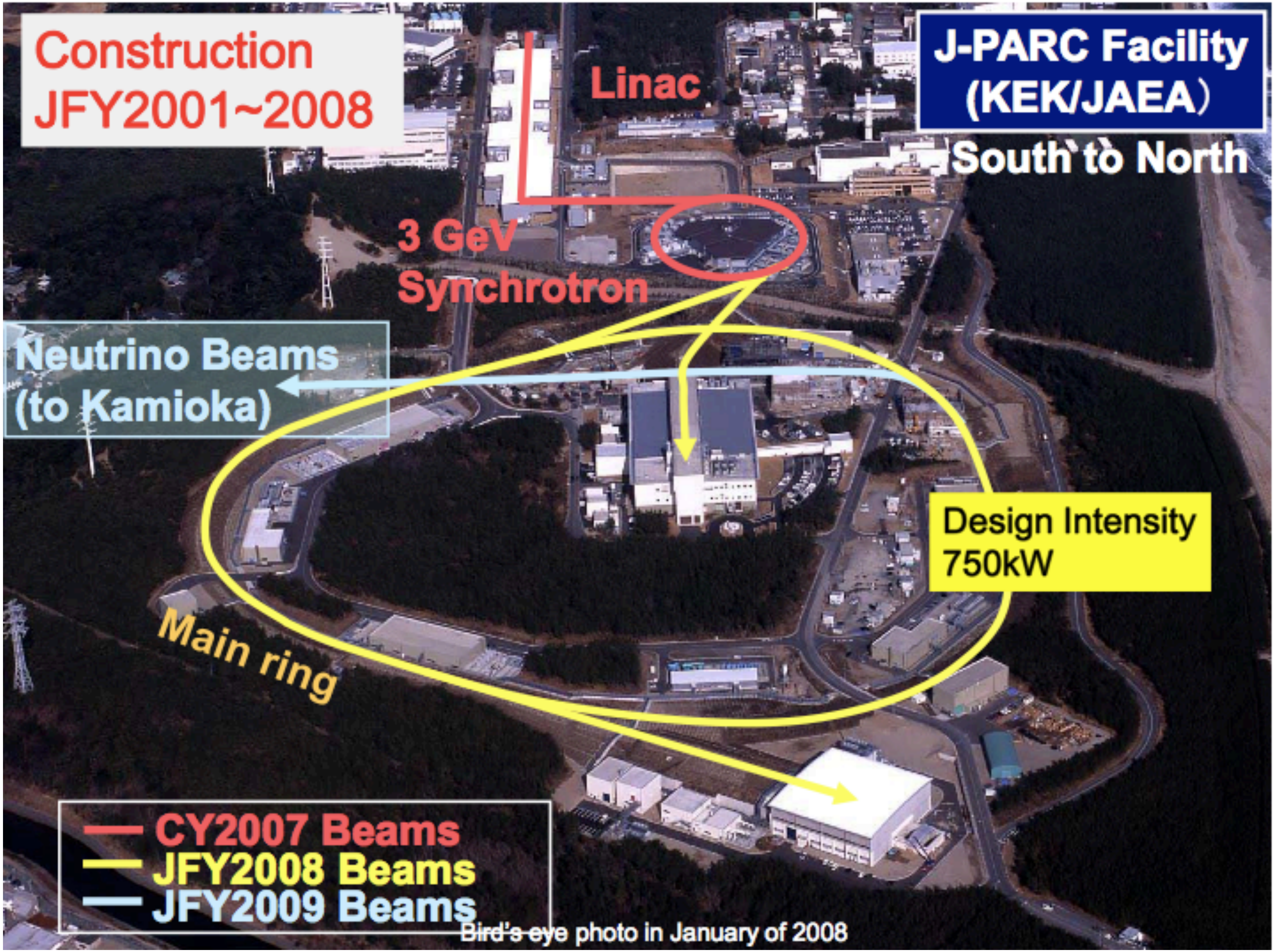
μ monitor (beam direction and intensity)

ν energy spectrum and intensity

Same spectrum as SK, BG measurement






Construction
JFY2001~2008
Linac
J-PARC Facility
(KEK/JAEA)
South to North
3 GeV
Synchrotron
Neutrino Beams
(to Kamioka)
Design Intensity
750kW
Main ring
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's-eye photo in January of 2008

But after new results, new questions….

1) Is there a non-maximal mixing between the ν_μ and ν_τ states?

Is $\theta_{23} \neq 45°$?

2) What's the mass hierarchy?

Is $\Delta m^2_{32} > 0$?

3) Is there an ν_e component to the ν_3 mass state?

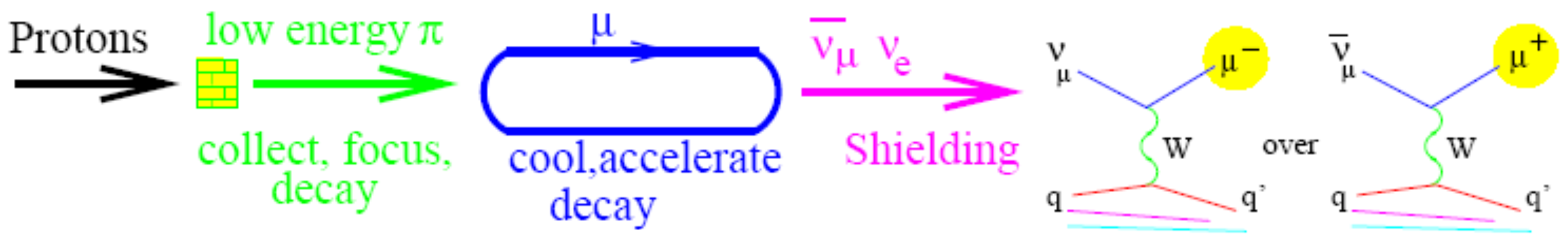
Is $\theta_{13} \neq 0$?

4) Is there CP violation in the lepton sector?

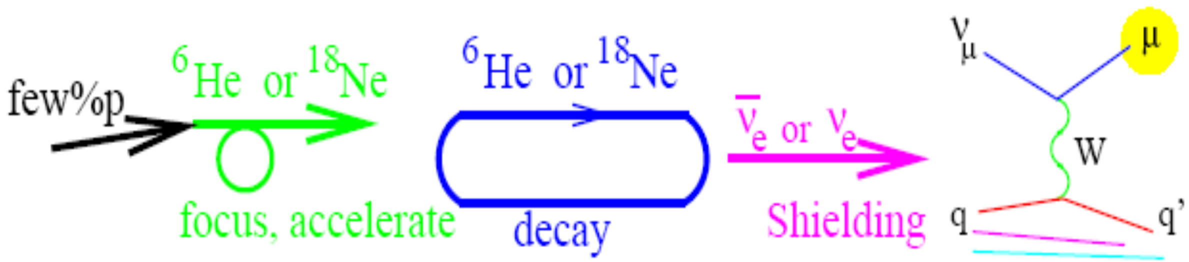
Is $\delta_{CP} \neq 0$? (Is $\theta_{13} \neq 0$?)

By the way, measuring CP phase will imply a new generation of neutrino beam facilities and experiments
(beyond the scopes of these lectures!)

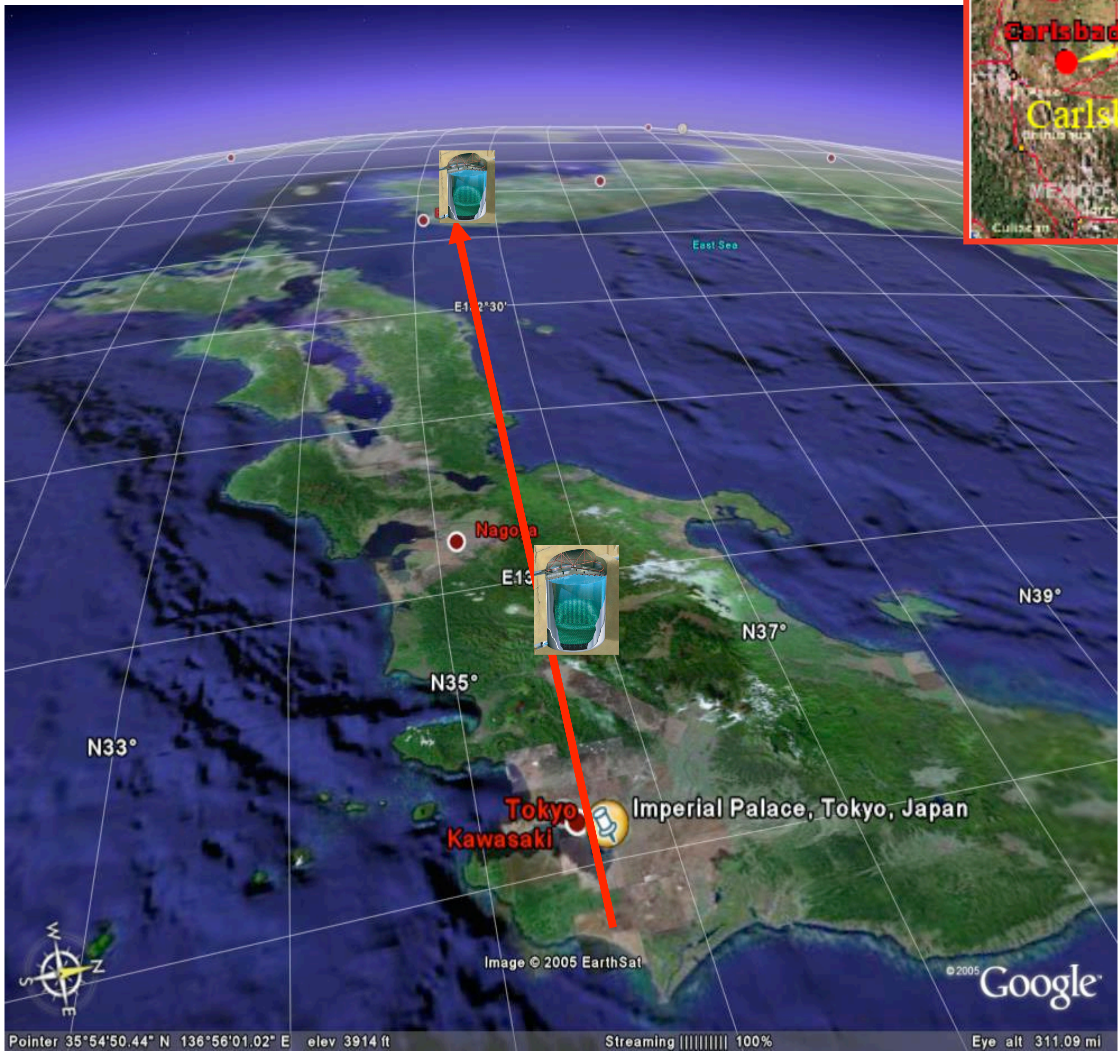
NEUTRINO FACTORIES

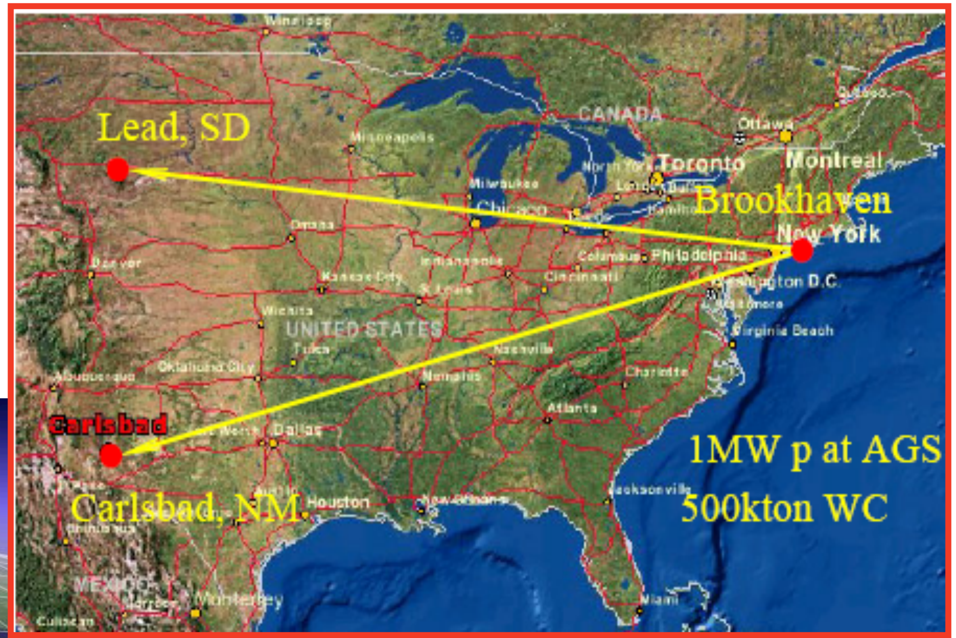


BETA-BEAMS

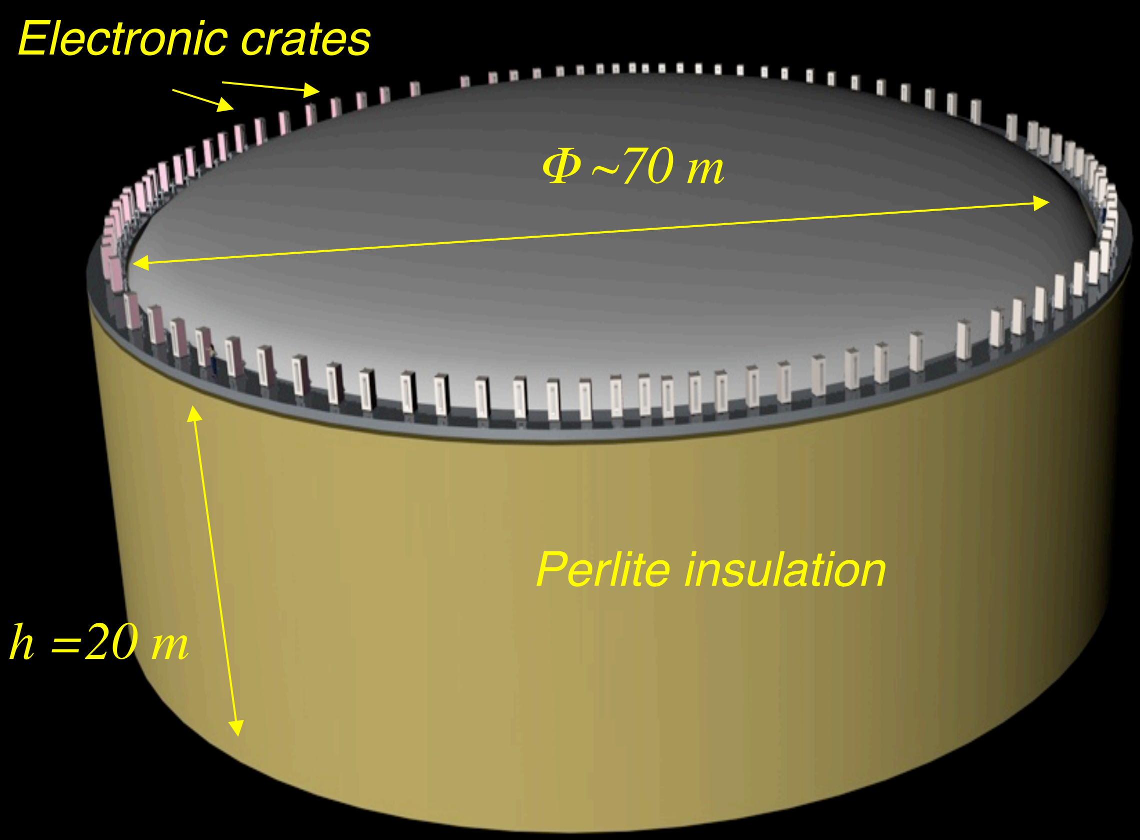


VERY LONG BASELINES !





HUGE DETECTORS!



XXXL Liquid Argon TPC's *

* go to our Grosslabor for a 1/100000 scale prototype….

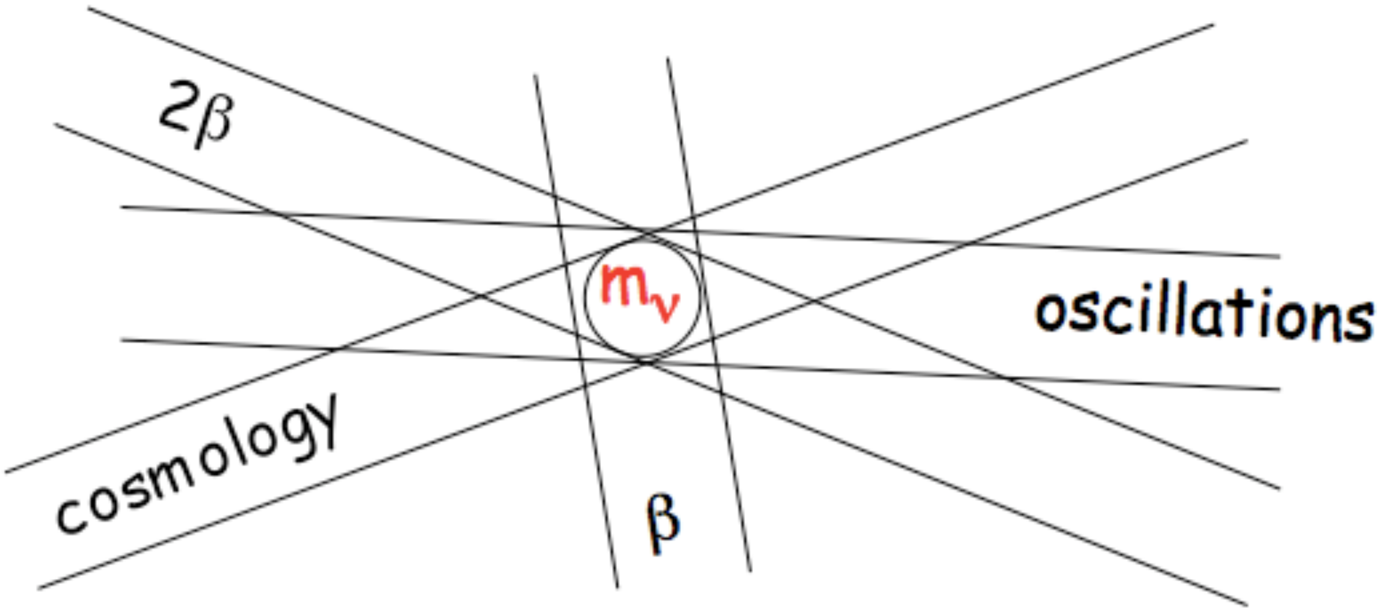
In one sentence, the study of neutrino physics will successfully continue for decades keeping physicists very busy…

We will combine results from oscillation experiments to direct mass measurement experiments (with beta-decay)…

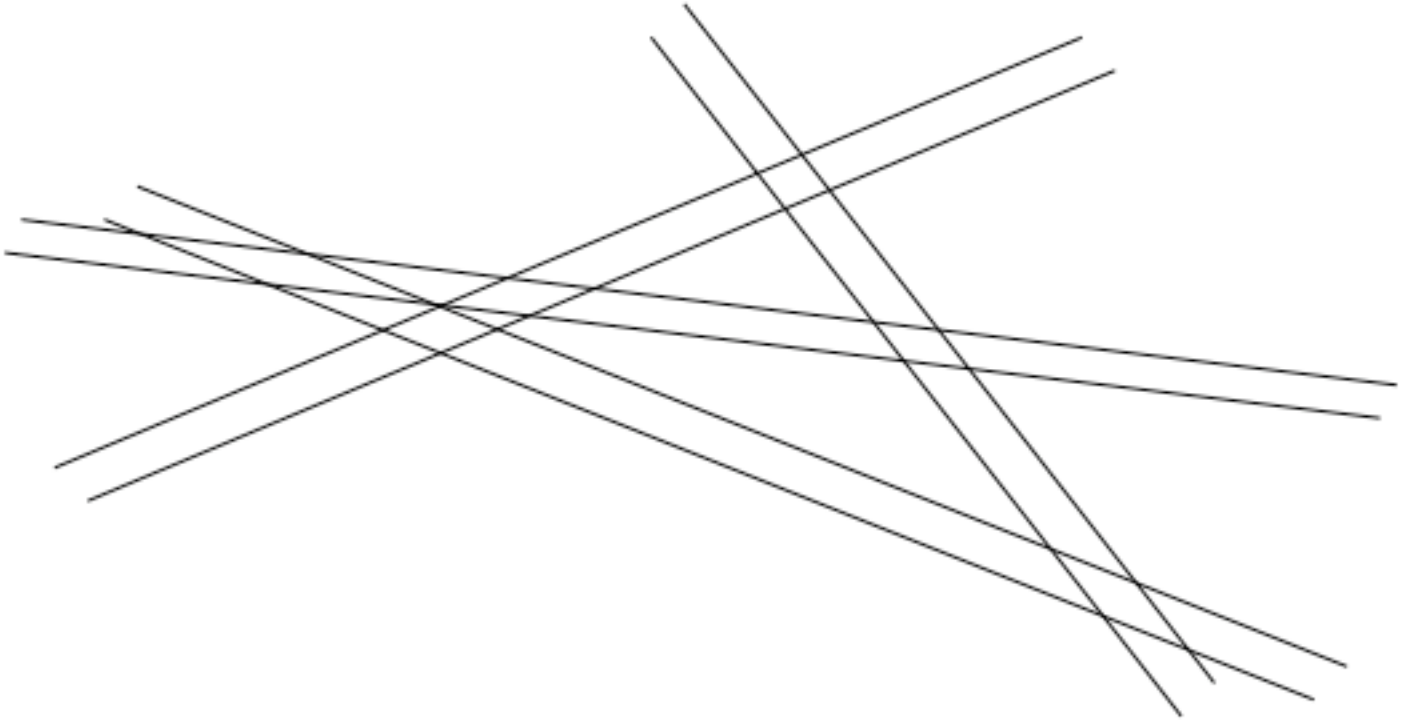
and with measurements on the neutrinoless double-beta decay…

…in addition to the (already now!) sensitive measurements of the neutrino properties from cosmological observations…

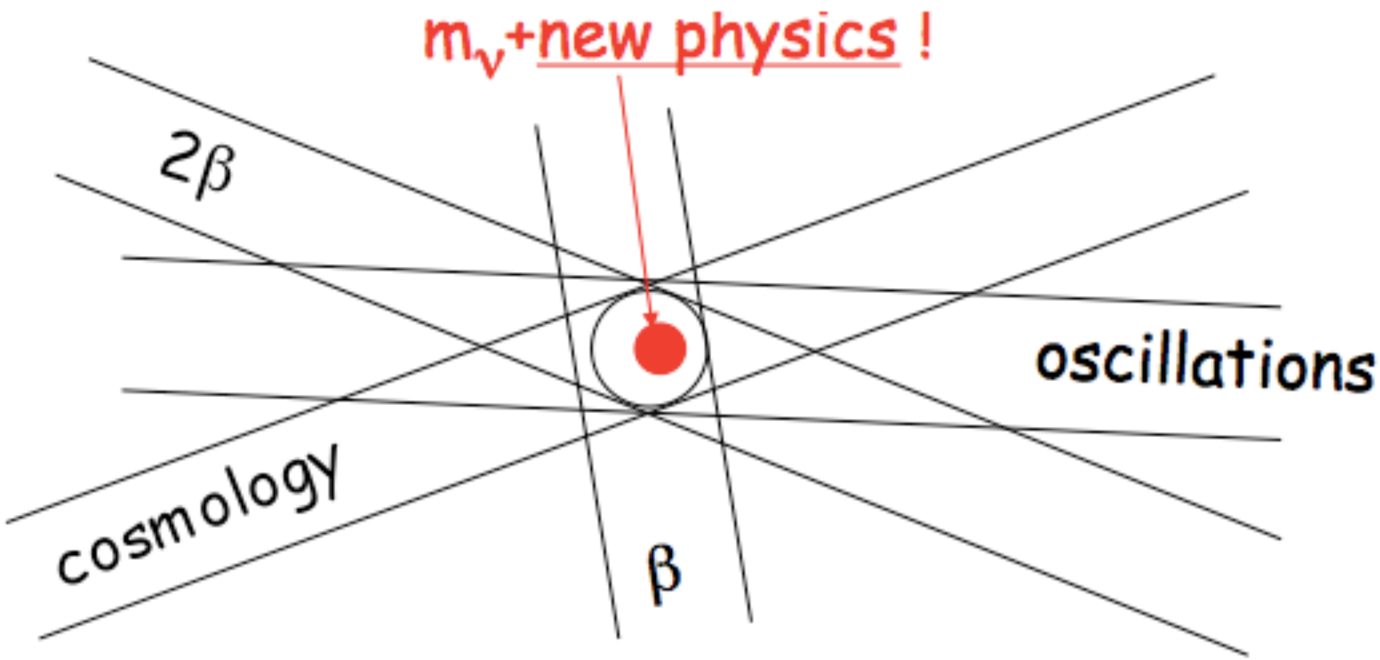
Dream ??



or nightmare ??



Maybe even better than a dream!!



A possible conclusion

out of $(1/m_\nu)^n$

• The neutrino was born as a desperate remedy

• It became soon an intriguing source of mysteries, while being in many cases also a powerful tool to assess new physics

• Combined to other results from astrophysics, cosmology and LHC physics, neutrinos will certainly bring new "problems" to physicists, in perfect agreement with their nature

• Neutrino oscillations

yesterday:	a (ir)realistic possibility and then an explanation;
today:	a solid evidence opening a window to the unknown;
tomorrow:	a unique tool to pin down new physics?

Thank you for your attention!