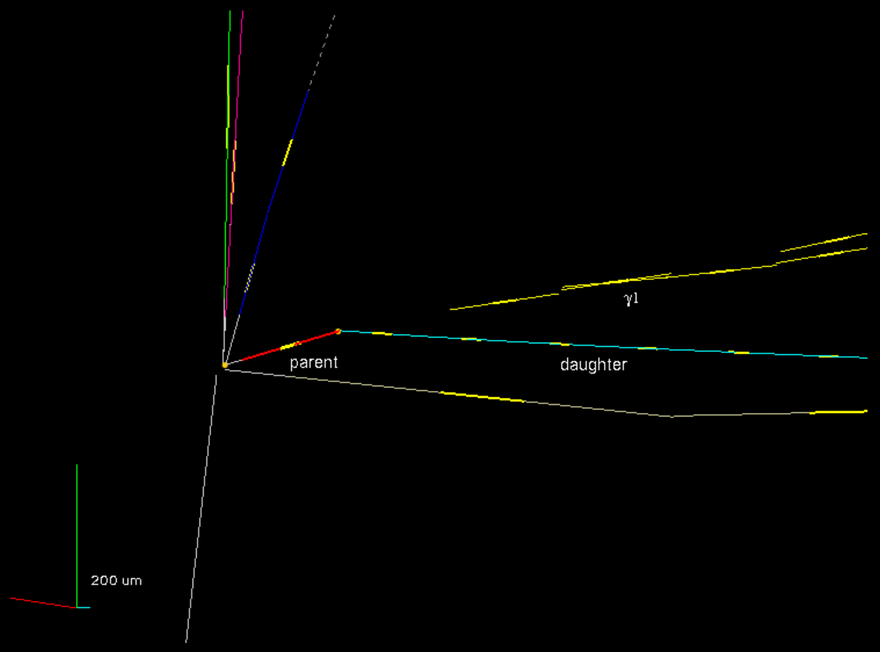
Neutrino (mostly oscillation) physics



Antonio Ereditato
A. Einstein Center for Fundamental Physics,
Laboratory for High Energy Physics,
University of Bern

CERN Academic Training – April 2012

Content*

- General information and history: what is special with the neutrino ?
- Neutrino oscillations: hottest topic in neutrino physics
- Examples of oscillation experiments (not exhaustive list): past, ongoing, future
- An almost arbitrary selection is imposed…apologies….

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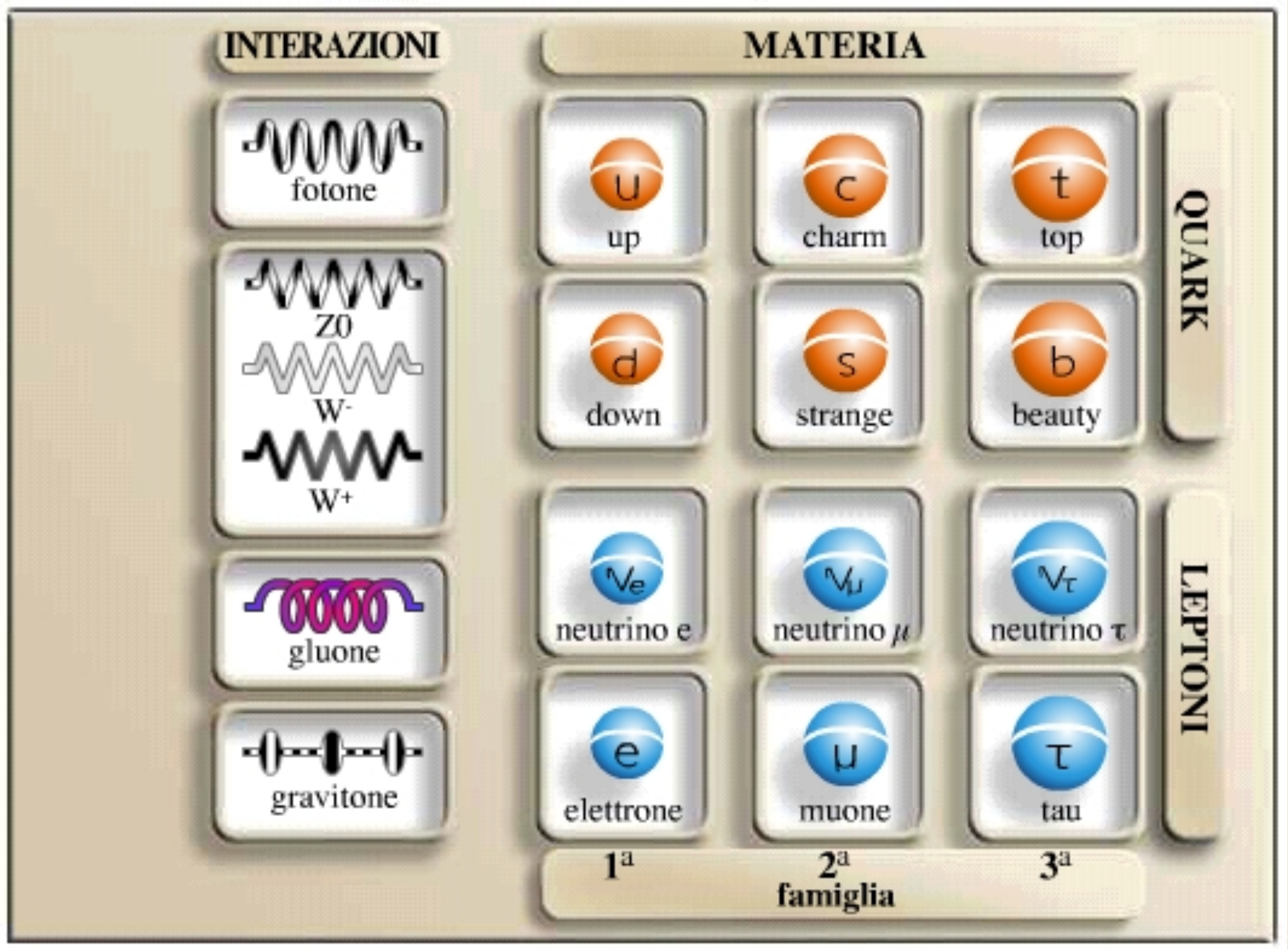
*Thanks to many colleagues for the use of some of their excellent slide material

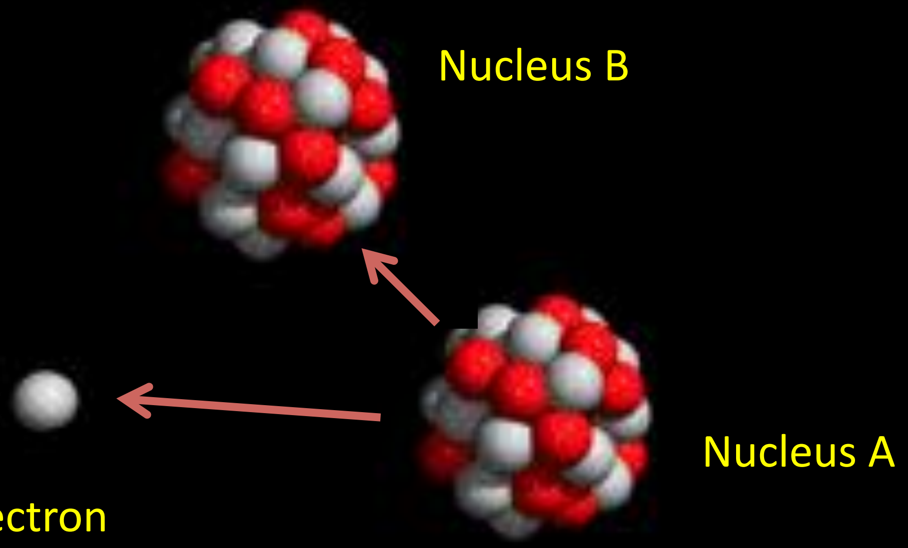
"Zoo" of elementary particles:
electrons, protons, neutrons, photons, quarks,…

and…. NEUTRINOS ν



The story of the neutrino begins, as for any of us, with its birth…

Nuclear “beta” decay circa the beginning of last century



Nucleus B

Nucleus A

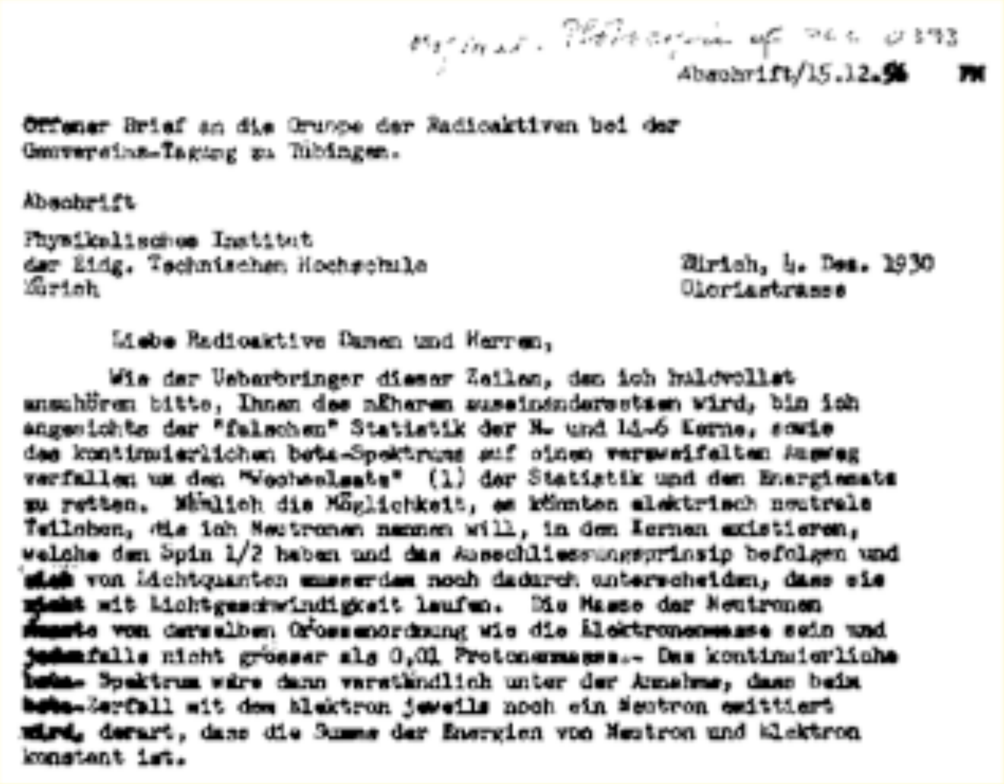
electron

Pauli (1930)

and the “desperate remedy”

of the “neutron”

One of the most famous letters of particle physics



Original: Photocopie of PLC 0393

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.

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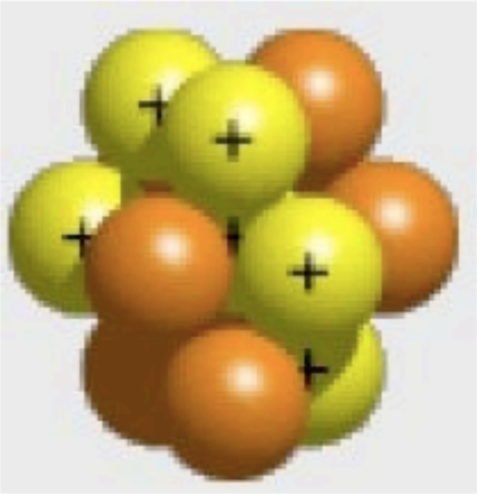
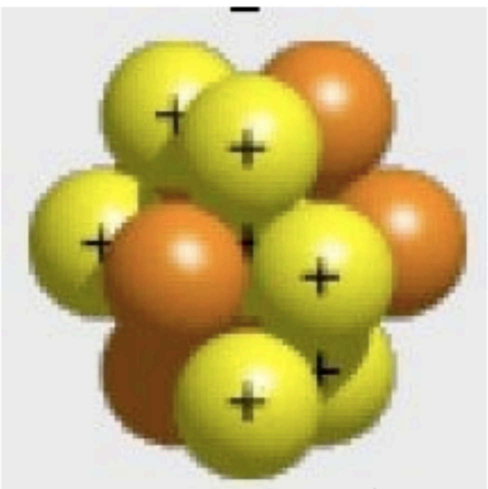
Nuclear BETA Decay





Not conserving

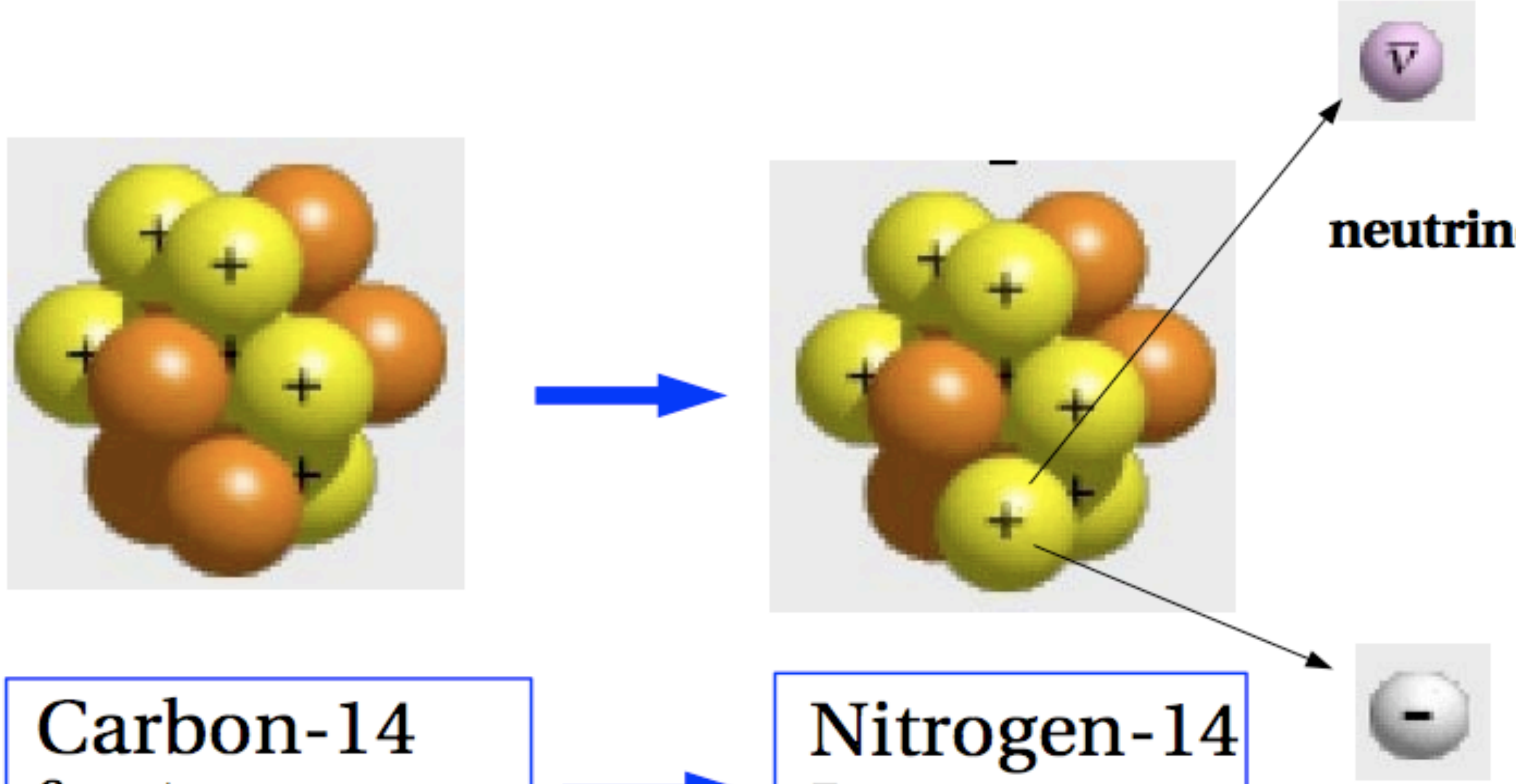
Energy
Momentum
Angular Momentum

Carbon-14
6 protons,
8 neutrons

Nitrogen-14
7 protons,
7 neutrons

+ electron

Nuclear BETA Decay



neutrino

Carbon-14
6 protons,
8 neutrons

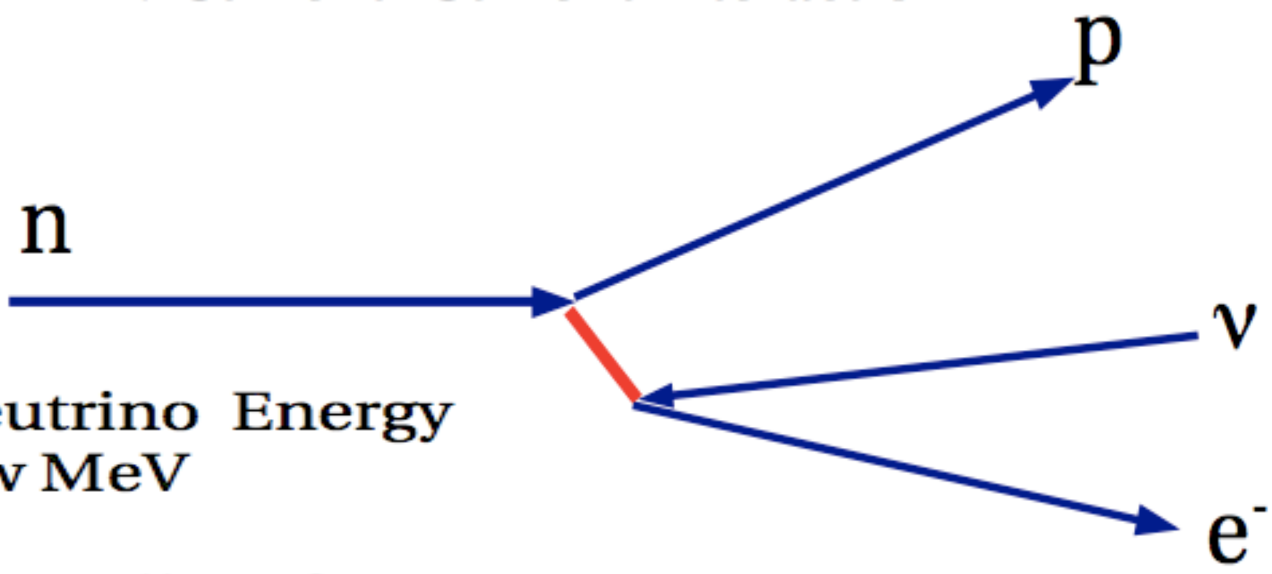
Nitrogen-14
7 protons,
7 neutrons

+ electron

Fermi (1933)

and the first theory
of the “neutrino”

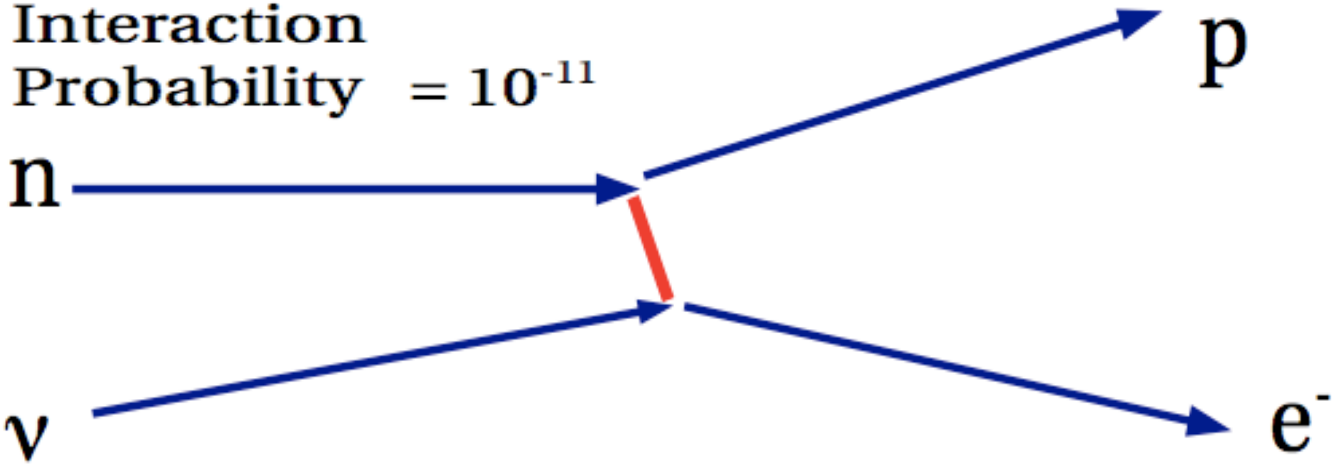
Fermi : Current- Current Interaction



Neutrino Energy
few MeV

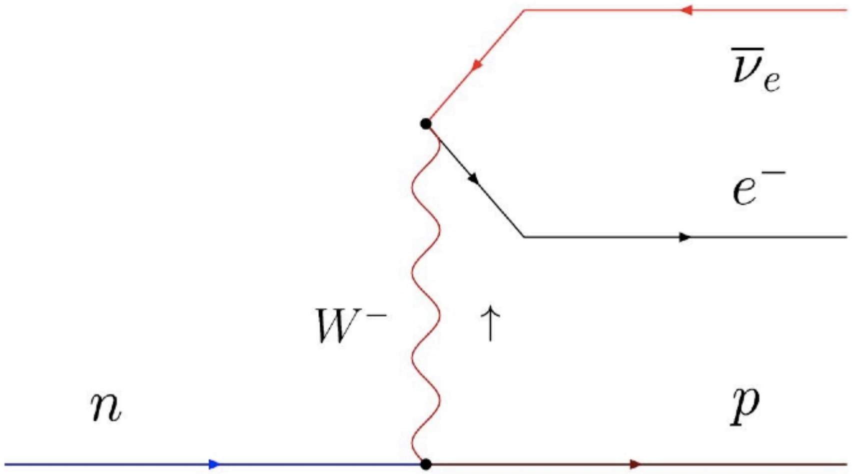
$\sigma = 10^{-44}\ \mathrm{cm}^2$

Interaction
Probability $= 10^{-11}$

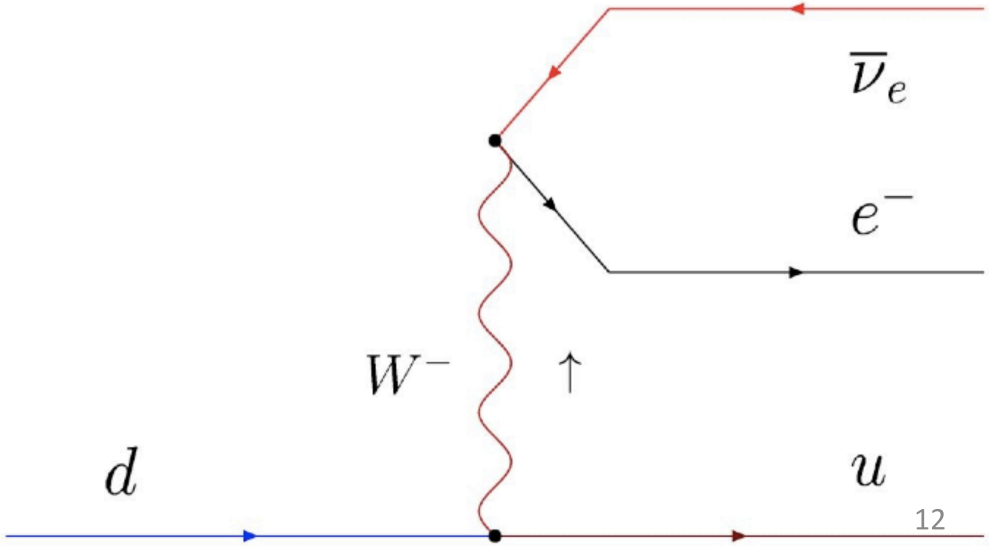


Feynman Diagram for Neutron Beta Decay

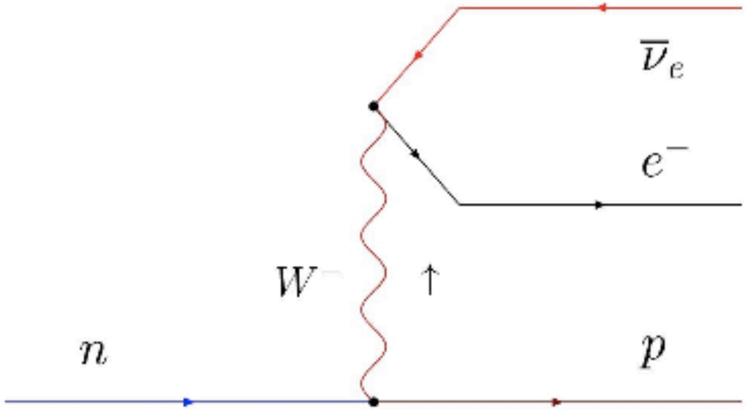
$$n \rightarrow p + e^{-} + \overline{\nu_e}$$



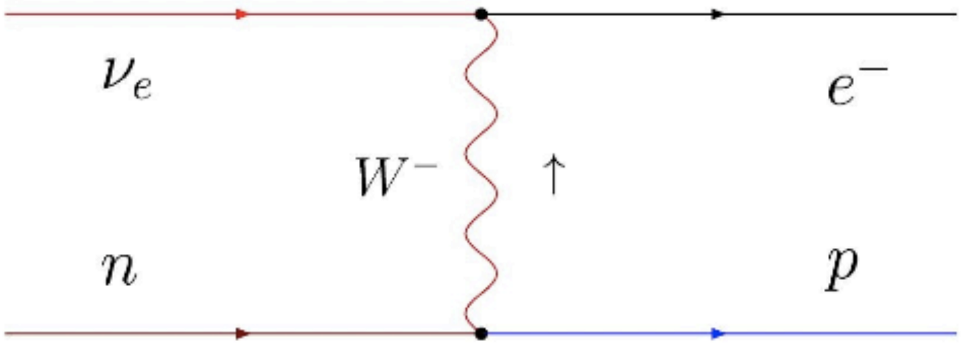
Decay at the Quark Level



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

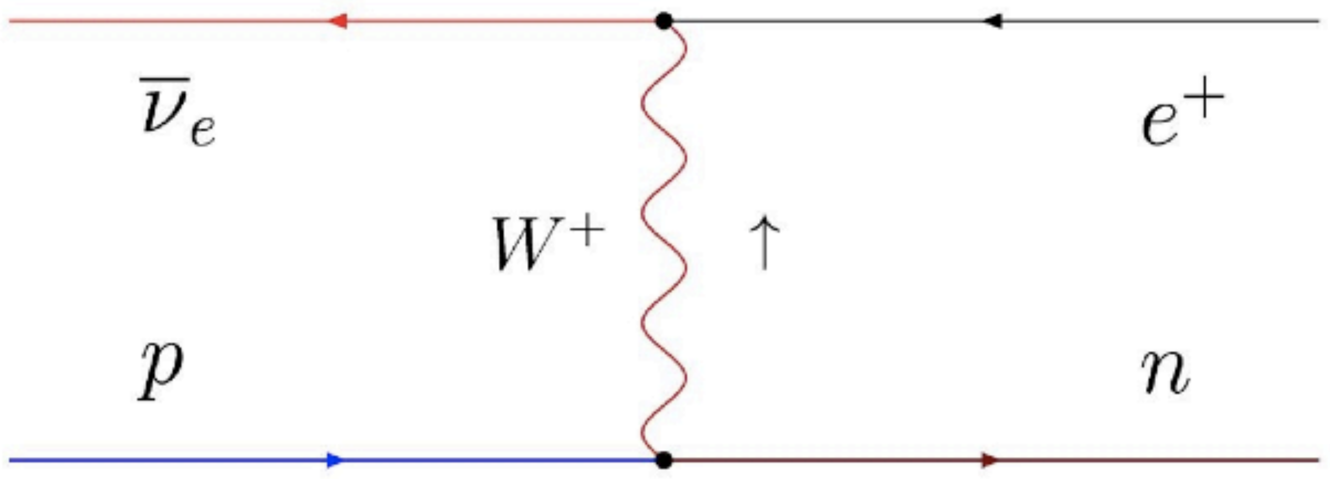


$$\nu_e + n \rightarrow p + e^{-}$$



Detection Method

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



Better detection method....

Some features of the neutrino (at the time of Fermi)

- Mass-less or almost mass-less particle

- Electrically neutral

- “Fermion” (particle with “spin”): a spinner made of nothing !?

- Extremely small matter interaction probability:

can travel tens of light years in matter without interacting !!

- For this reason it took 25 years to discover the neutrino →

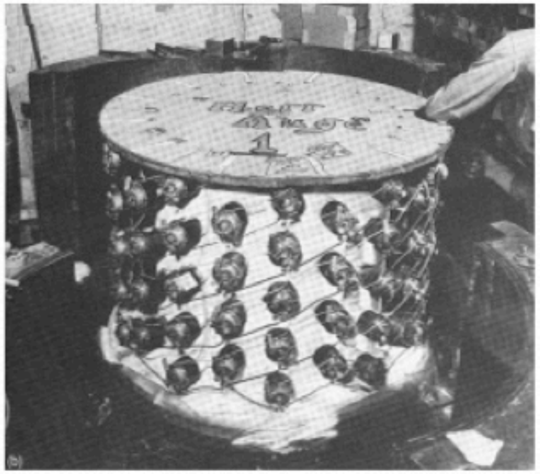
Artificial neutrinos?

10^{20} = 100 billion of billions

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

Neutrino Discovery (antineutrinos from Nuclear Reactors

Reines e Cowan
1953-1956



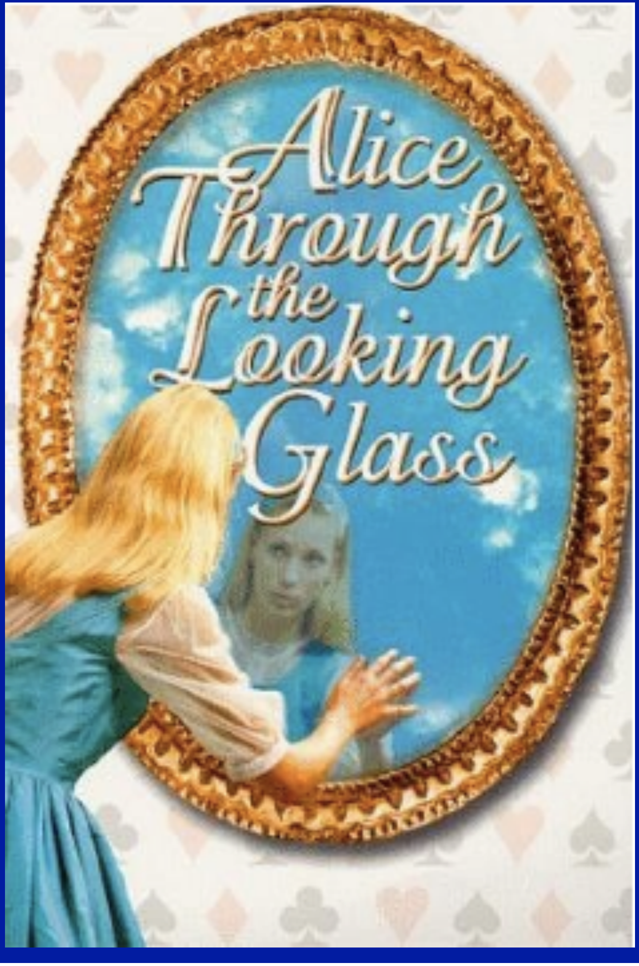
Delayed neutron capture
(after thermalization of the neutron)

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

Soon after its discovery the neutrino contributed in solving a long standing problem:

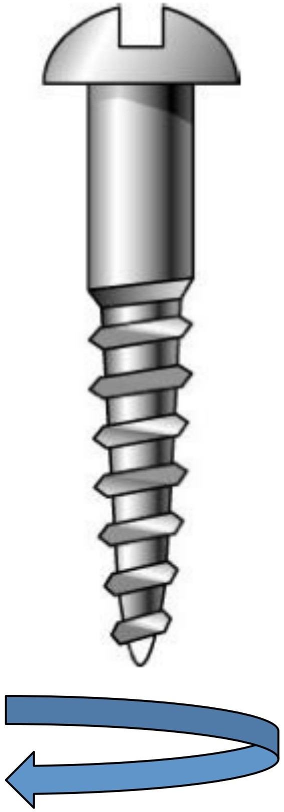
can one distinguish left from right ?

Or better: can we distinguish our “real” word from the one in the mirror ?

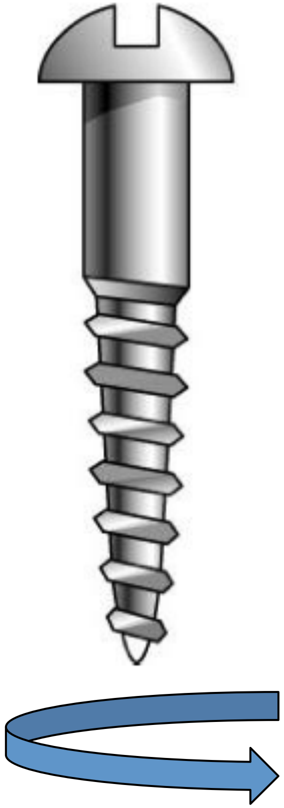


neutrinos and parity violation

Reality: neutrino left-handed

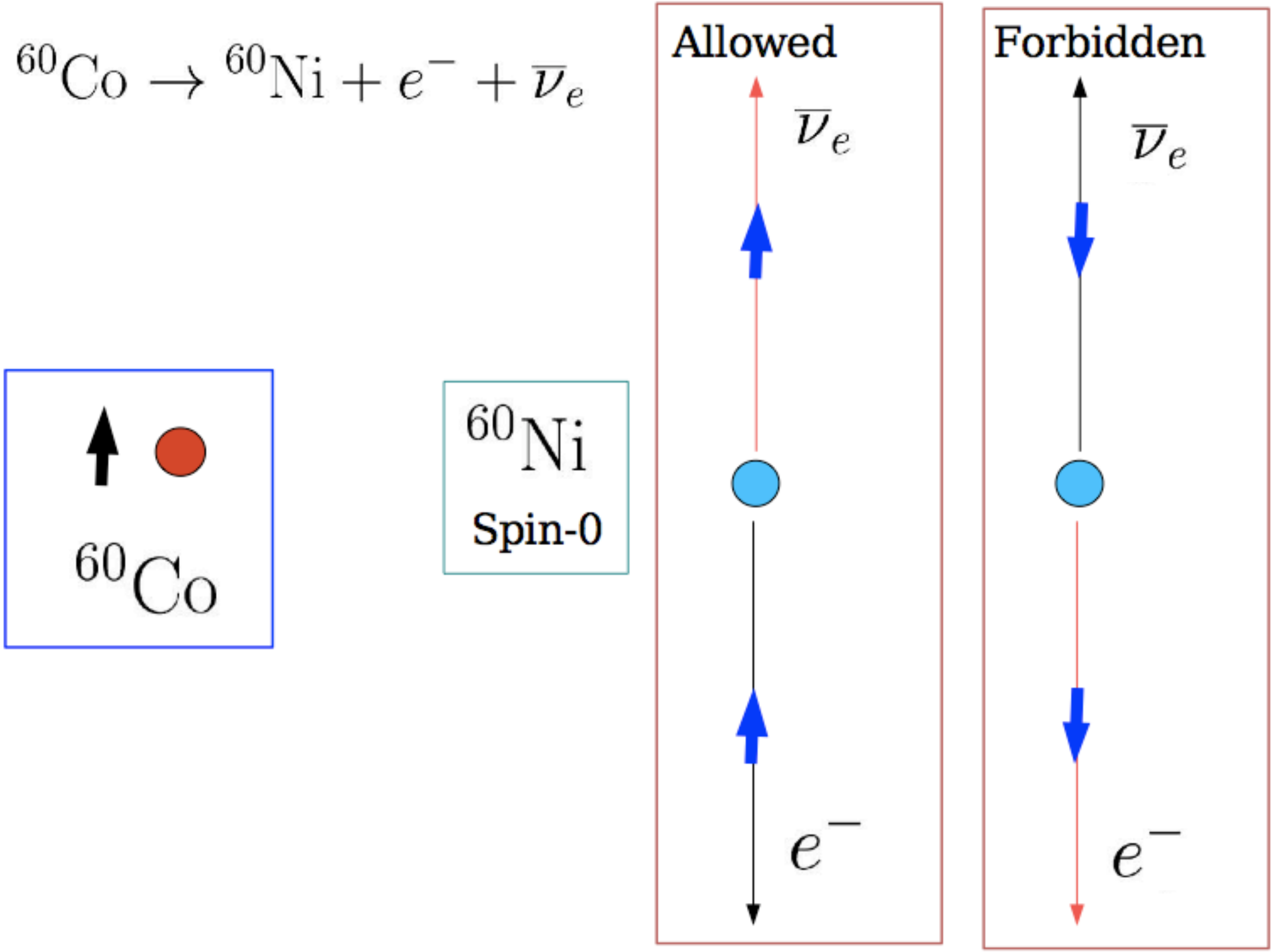


Mirror image: neutrino right-handed



DOES NOT EXIST !!

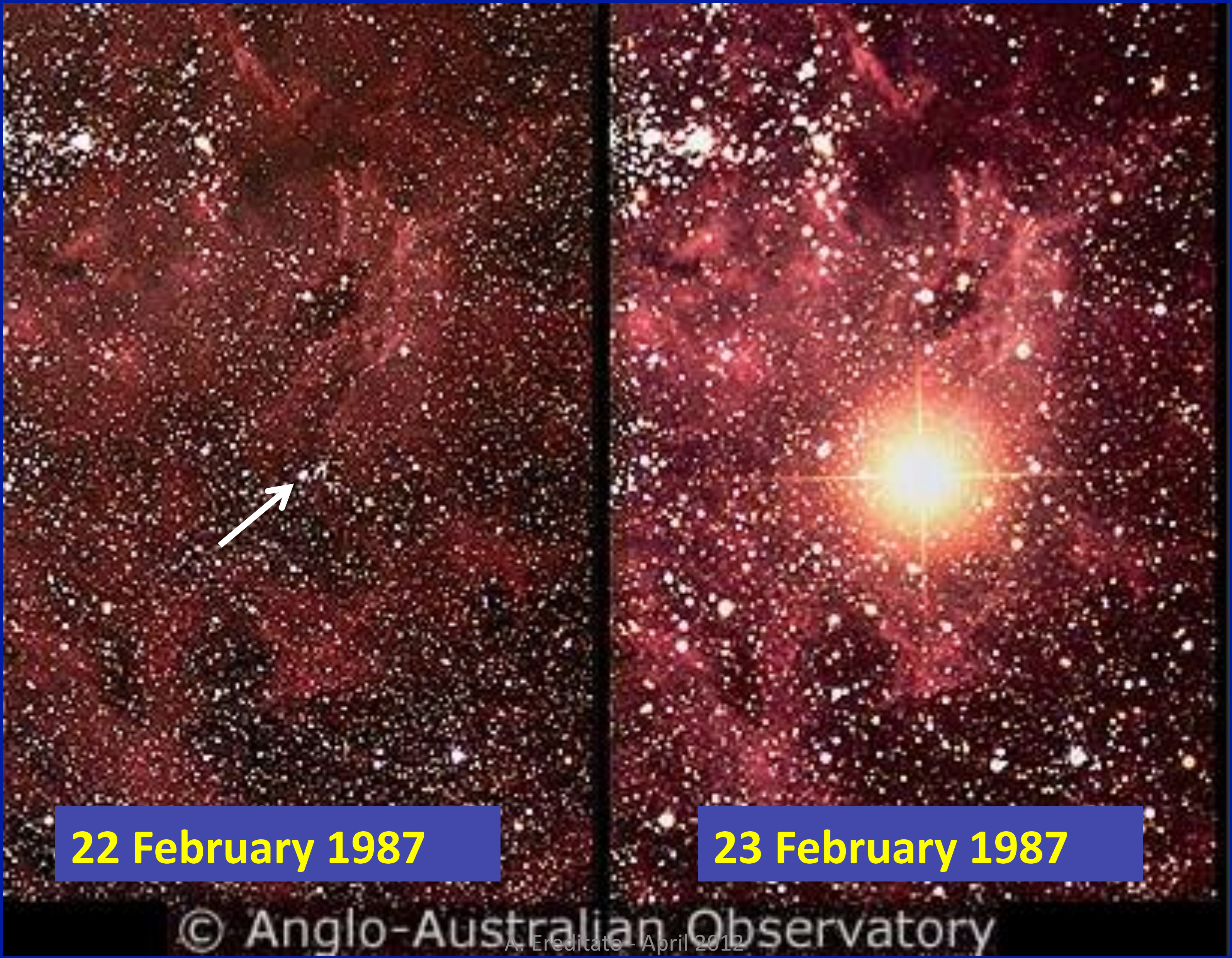
$$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + e^- + \overline{\nu}_e$$



Where do neutrinos come from? …and how many are they?

one second after the Big Bang….

Explosion of Supernova 1987a



22 February 1987

23 February 1987

A supernova emits per minute as much energy as that irradiated by the Sun in 200 years. For several days after explosion, the brightest object in the night sky.

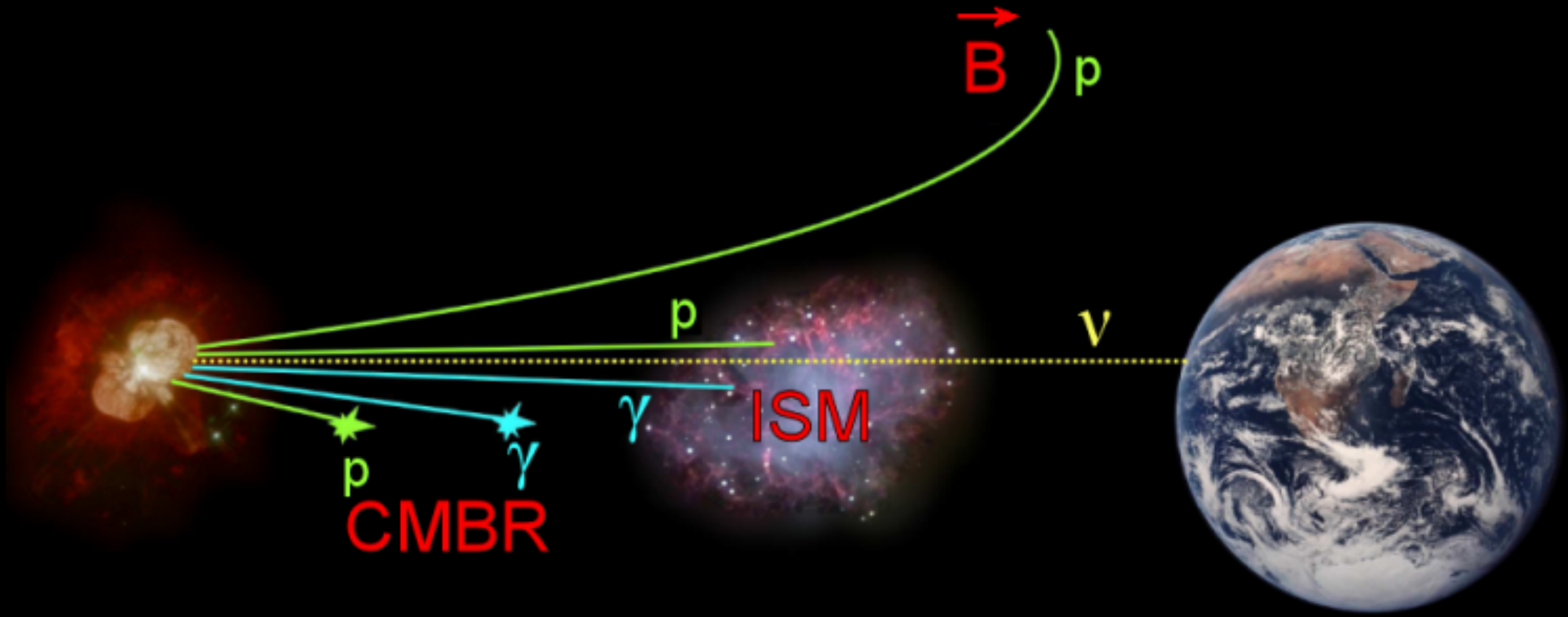
And neutrinos ??
Only 0.1% of the explosion energy goes into visible light: 99.9% goes into neutrino energy!

On 23 February 1987 each human being was crossed by 10000 billion of those neutrinos. One million people had one of those neutrinos interacting in their body!

Masatoshi Koshiba

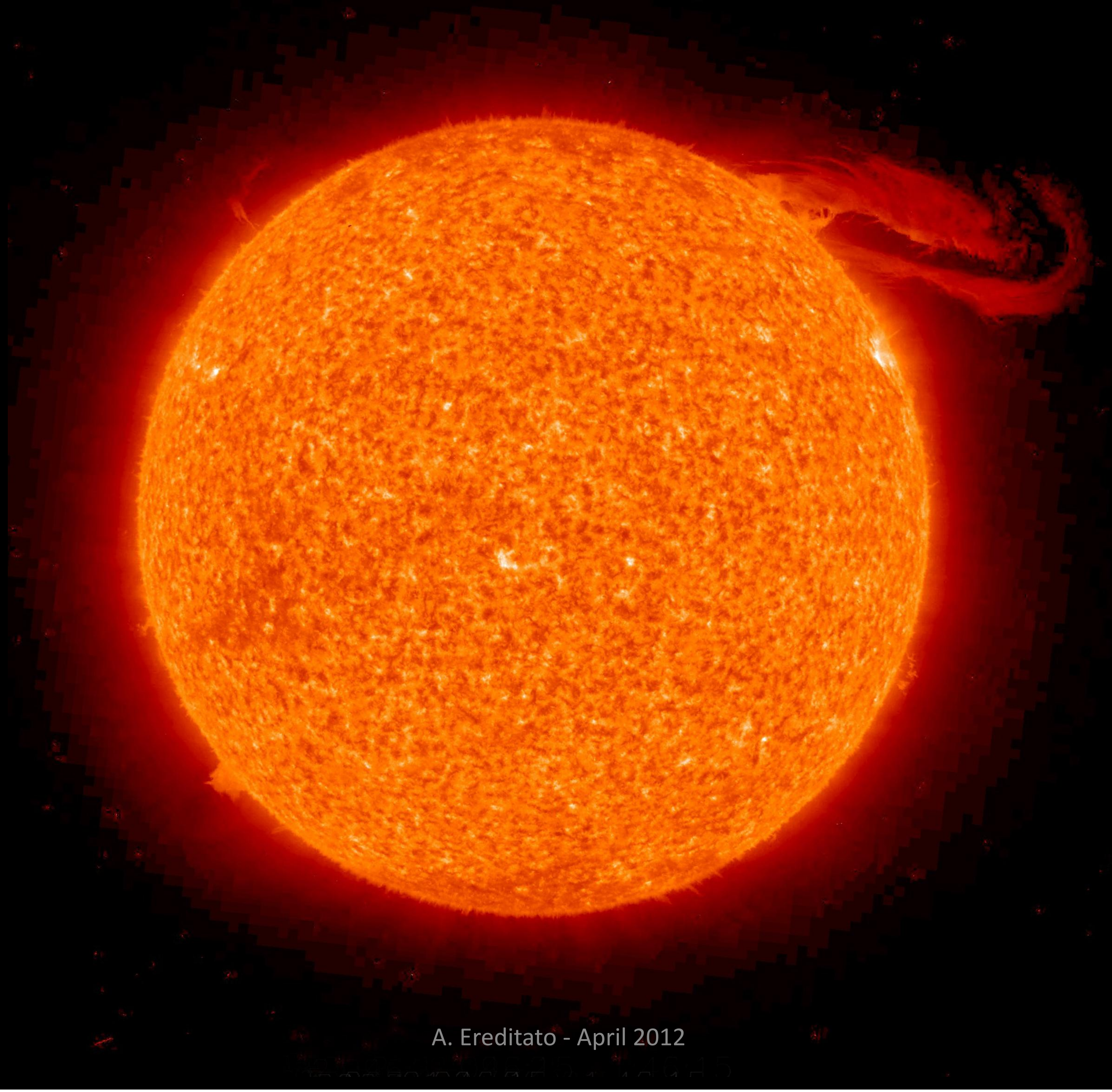
2002 Nobel Prize for the introduction of neutrino astronomy
(detection of SN1987A neutrinos)

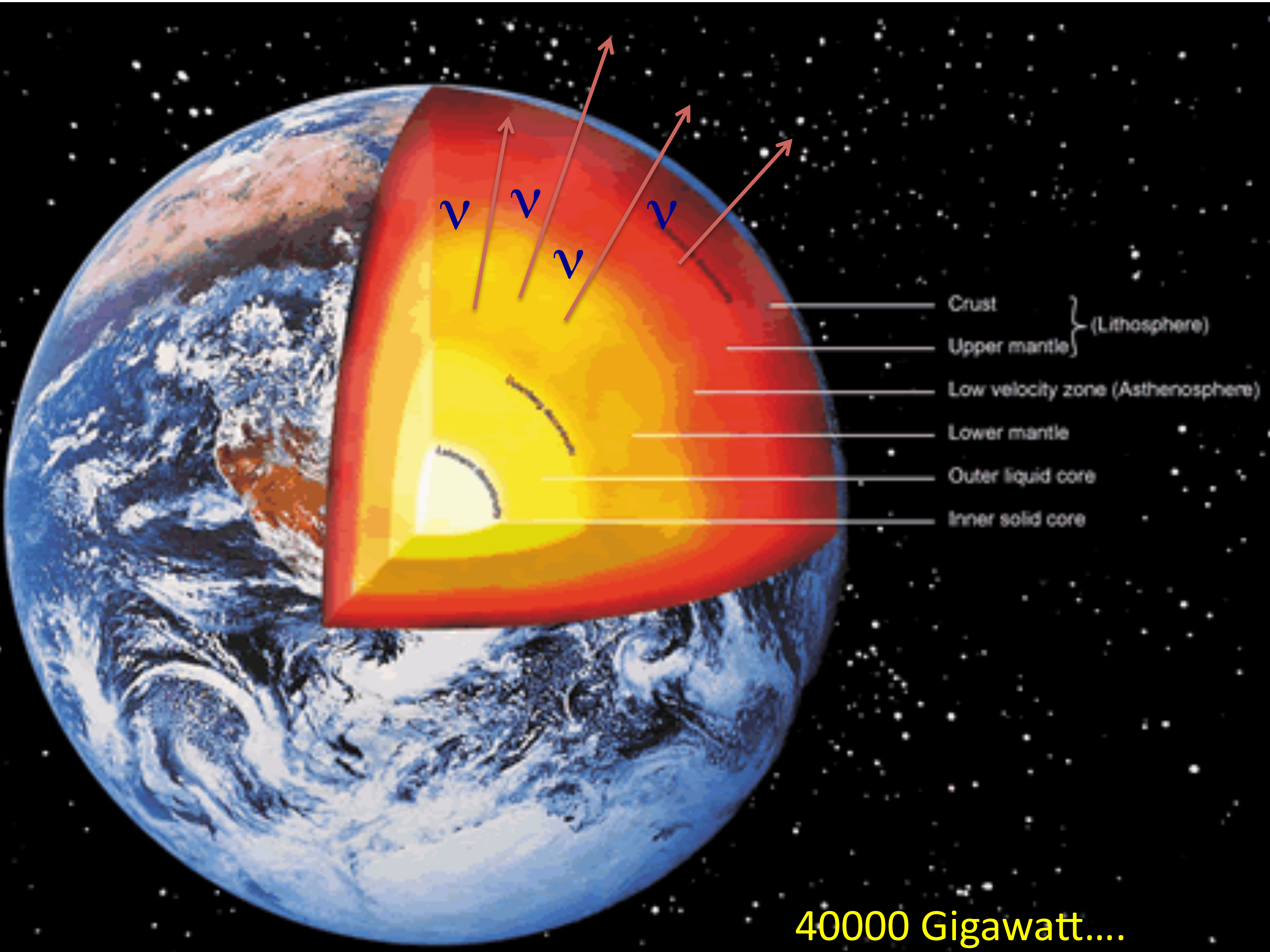
Neutrino astronomy



400000 billion….

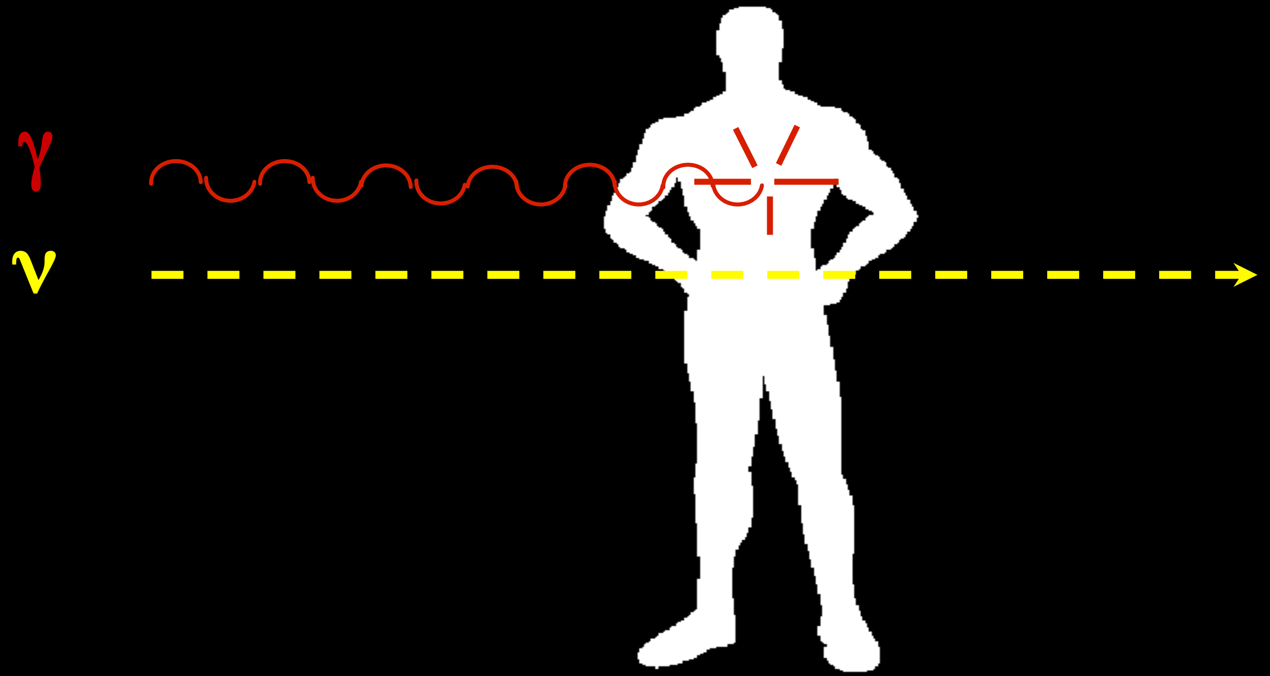
Solar Model and neutrinos…





40000 Gigawatt….

Neutrinos and human beings



Is neutrino a Dirac or a Majorana particle ?

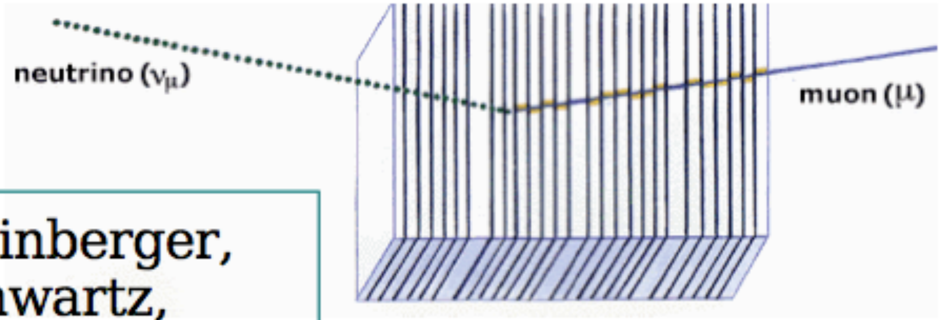
$\nu \neq \bar{\nu}$

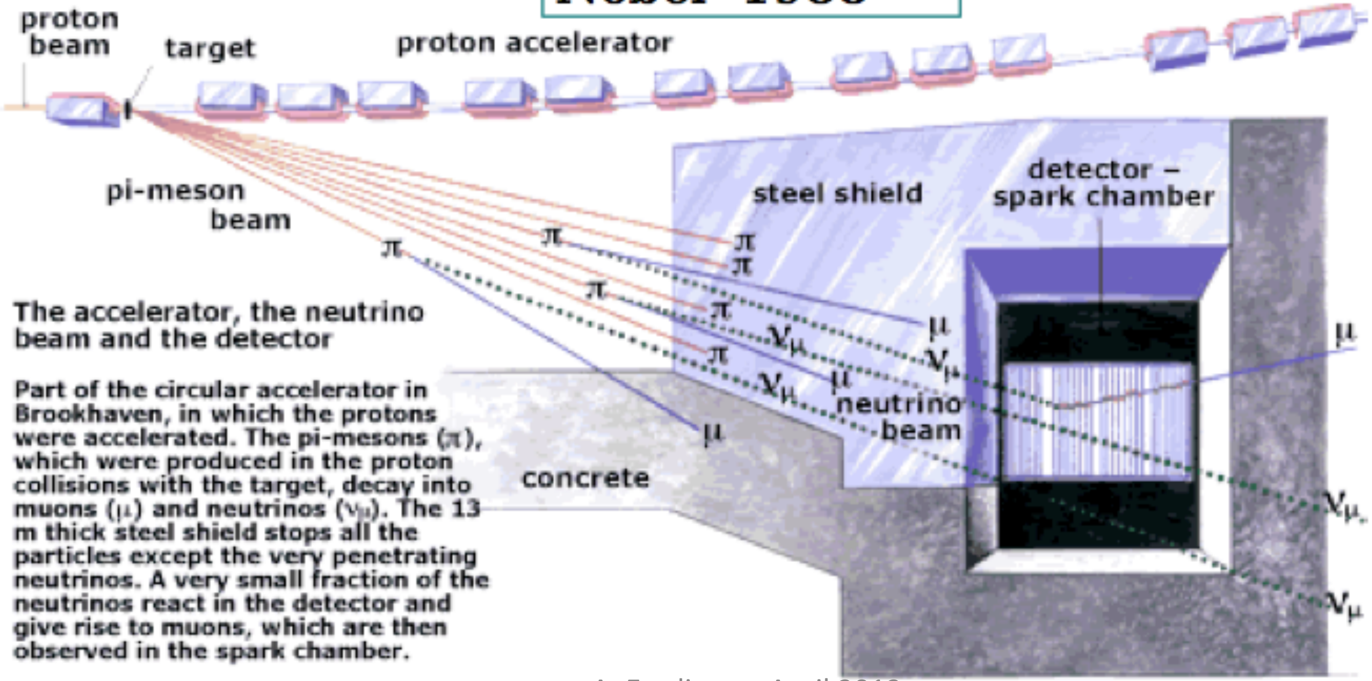
$\nu = \bar{\nu}$

occurrence of neutrino-less double beta decay -> Majorana

The second neutrino flavor

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





The accelerator, the neutrino beam and the detector

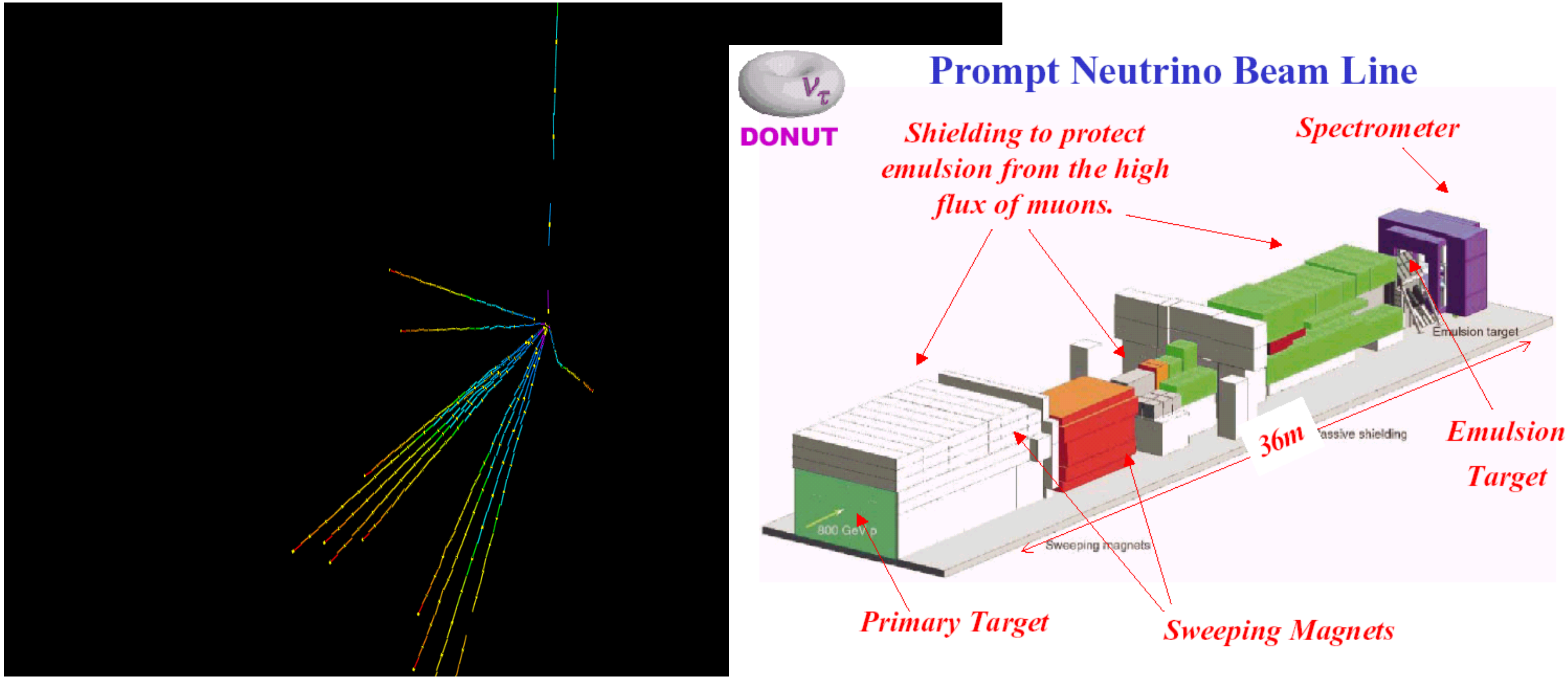
Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons (π), which were produced in the proton collisions with the target, decay into muons (μ) and neutrinos (ν_μ). The 13 m thick steel shield stops all the particles except the very penetrating neutrinos. 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.

The third neutrino flavor

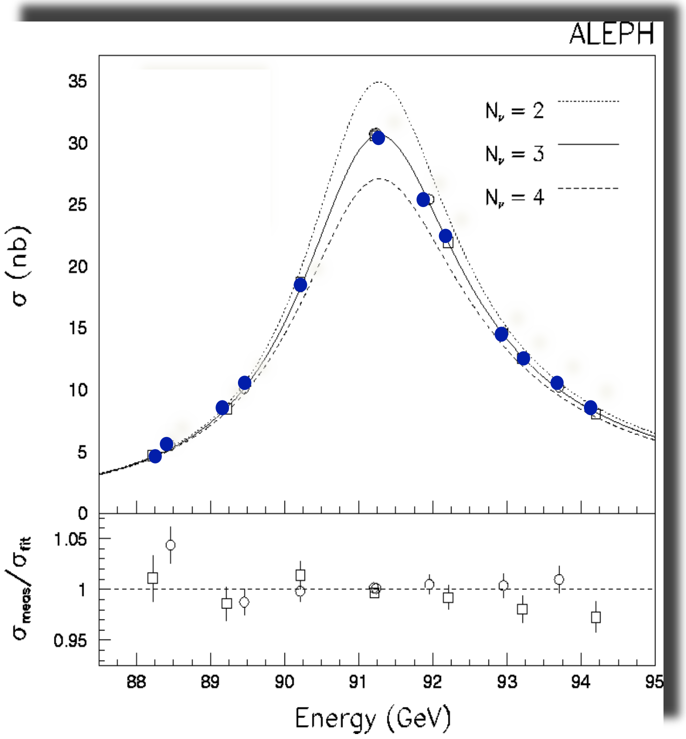
DONUT experiment at FERMILAB: first detection of ν_τ with an ECC based detector (K. Niwa and collaborators): 9 τ events, 1.5 BG.

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



How Many Light Neutrinos Exist ?

Answer : **3**



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

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

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

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

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

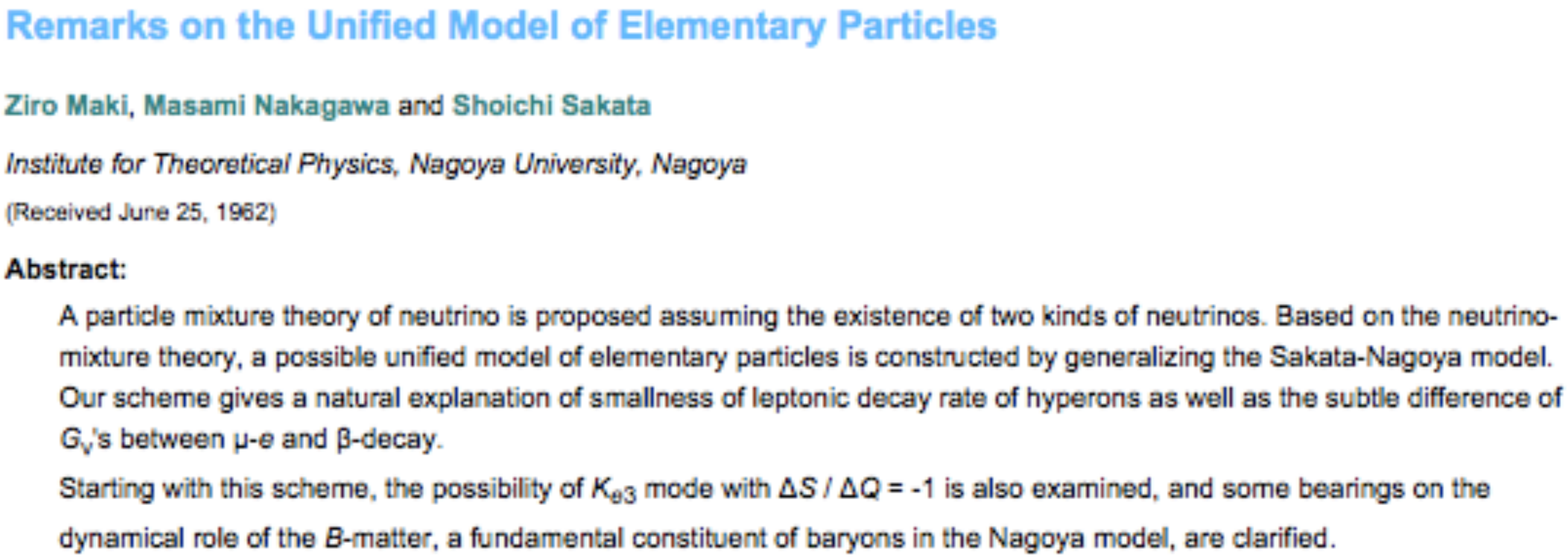
A series of key experiments conducted in the last three decades with atmospheric and solar neutrinos, and confirmed with reactor and accelerator neutrinos, has allowed to firmly establish the first evidence of physics beyond the Standard Model of Particles and Interactions:

neutrino oscillations

Bruno Pontecorvo

Бруно Понтекорво

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].



Remarks on the Unified Model of Elementary Particles

Ziro Maki, **Masami Nakagawa** and **Shoichi Sakata**

Institute for Theoretical Physics, Nagoya University, Nagoya

(Received June 25, 1962)

Abstract:

A particle mixture theory of neutrino is proposed assuming the existence of two kinds of neutrinos. Based on the neutrino-mixture theory, a possible unified model of elementary particles is constructed by generalizing the Sakata-Nagoya model. Our scheme gives a natural explanation of smallness of leptonic decay rate of hyperons as well as the subtle difference of G_V's between μ-e and β-decay.

Starting with this scheme, the possibility of K_{e3} mode with $\Delta S / \Delta Q = -1$ is also examined, and some bearings on the dynamical role of the *B*-matter, a fundamental constituent of baryons in the Nagoya model, are clarified.

3 Neutrinos states: 3 masses m_1, m_2, m_3

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

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

Flavor basis

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

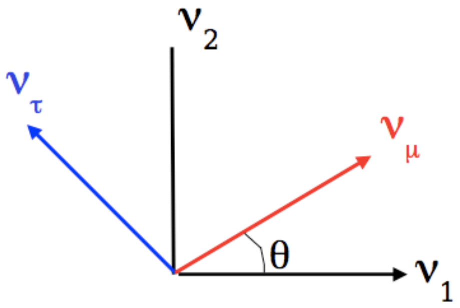
Mass basis

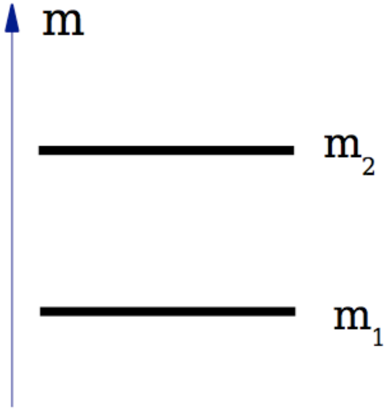
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V^{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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





$$\begin{aligned} |\nu_\mu\rangle &= \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle \\ |\nu_\tau\rangle &= -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle \end{aligned}$$

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

Neutrino Propagation

ν_μ created at t =0 with momentum **p**

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

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

Different mass components have different energy

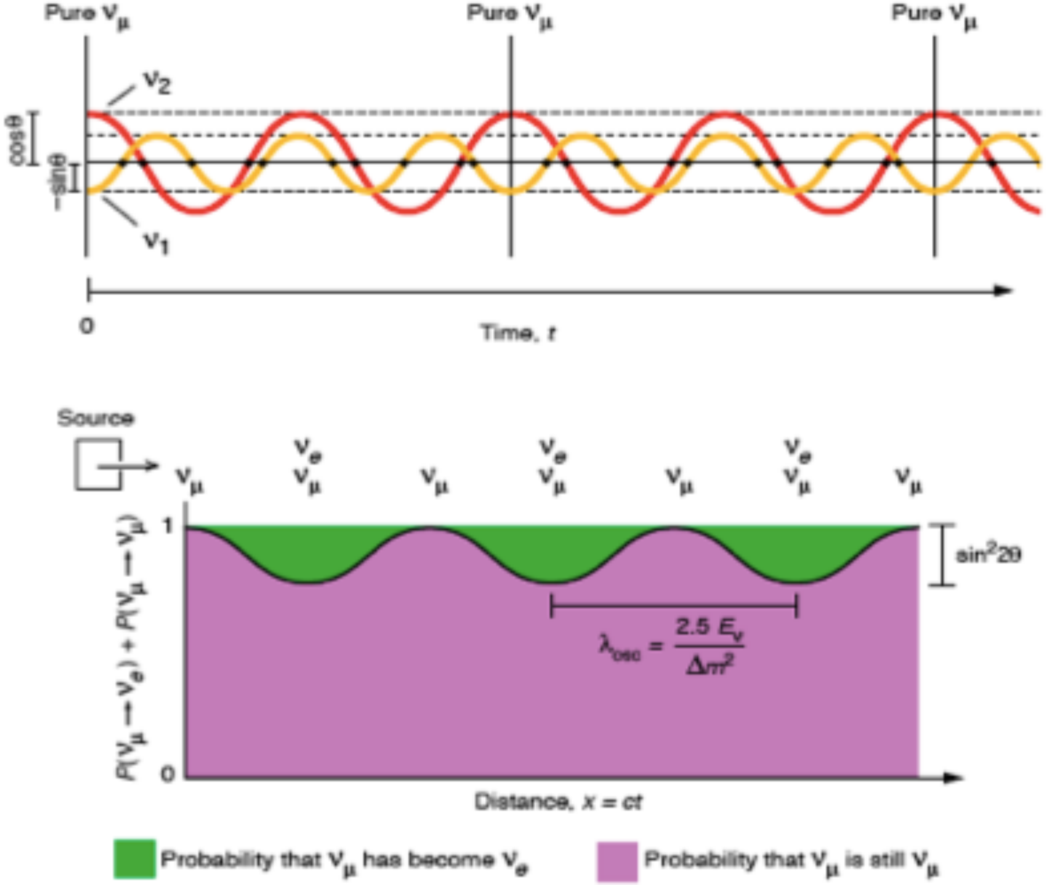
$$|\nu(t)\rangle = \cos\theta\, e^{-iE_1 t}|\nu_1\rangle + \sin\theta\, e^{-iE_2 t}|\nu_2\rangle$$

ν state at time t

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

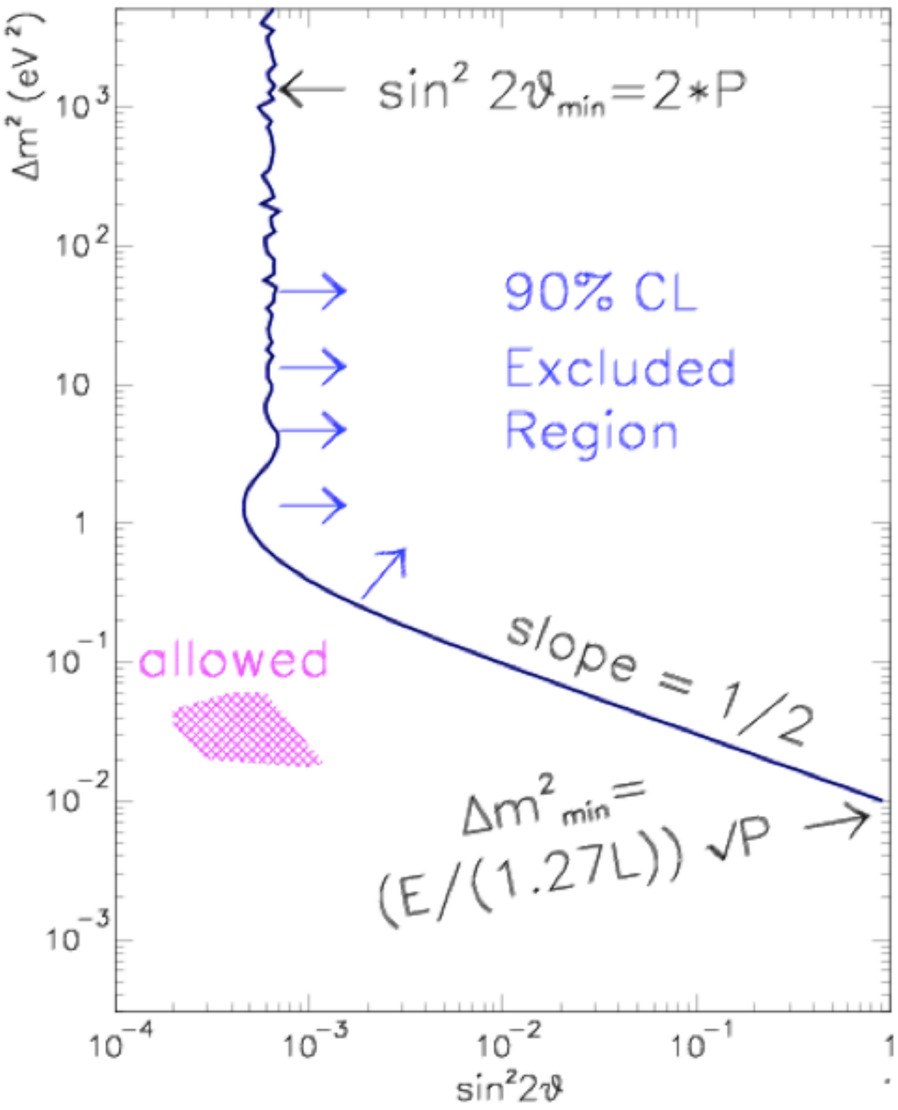
$$\begin{aligned}
&= |\langle \nu_\tau | \nu(t) \rangle|^2 \\
&= |\{-\sin\theta\,\langle\nu_1| + \cos\theta\,\langle\nu_2|\}|\{\cos\theta\, e^{-iE_1t}|\nu_1\rangle + \sin\theta\, e^{-iE_2t}|\nu_2\rangle\}|^2 \\
&= \cos^2\theta\,\sin^2\theta\,\left|e^{-iE_2t} - e^{-iE_1t}\right|^2 \\
&= 2\cos^2\theta\,\sin^2\theta\,\{1 - \cos[(E_2 - E_1)t\} \\
&= \sin^2 2\theta\,\sin^2\left[\frac{\Delta m^2}{4E}t\right]
\end{aligned}$$

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

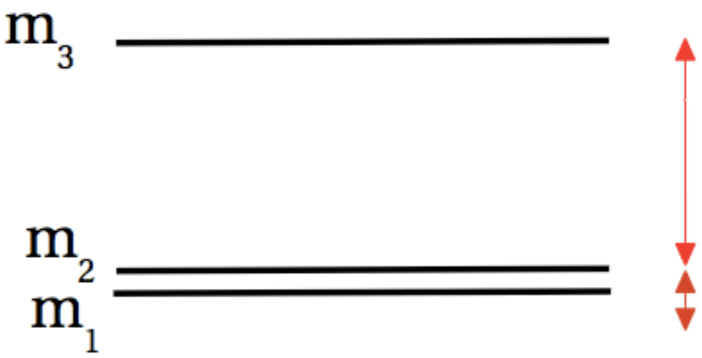

Pure ν_μ
Pure ν_μ
Pure ν_μ
ν_2
ν_1
$\cos\theta$
$-\sin\theta$
0
Time, t
Source
ν_μ
ν_e ν_μ
ν_μ
ν_e ν_μ
ν_μ
ν_e ν_μ
ν_μ
$P(\nu_\mu \to \nu_e) + P(\nu_\mu \to \nu_\mu)$
1
0
$\sin^2 2\theta$
$\lambda_{osc} = \frac{2.5\,E_\nu}{\Delta m^2}$
Distance, $x = ct$
🟩 Probability that ν_μ has become ν_e
🟪 Probability that ν_μ is still ν_μ

$$P(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12}\frac{L}{E})$$

- L and E determine Δm^2 sensitivity
- θ_{12} sensitivity determined by statistics, backgrounds, and uncertainties
- No signal: exclusion curve
- Signal: allowed region



3 Flavor Oscillations

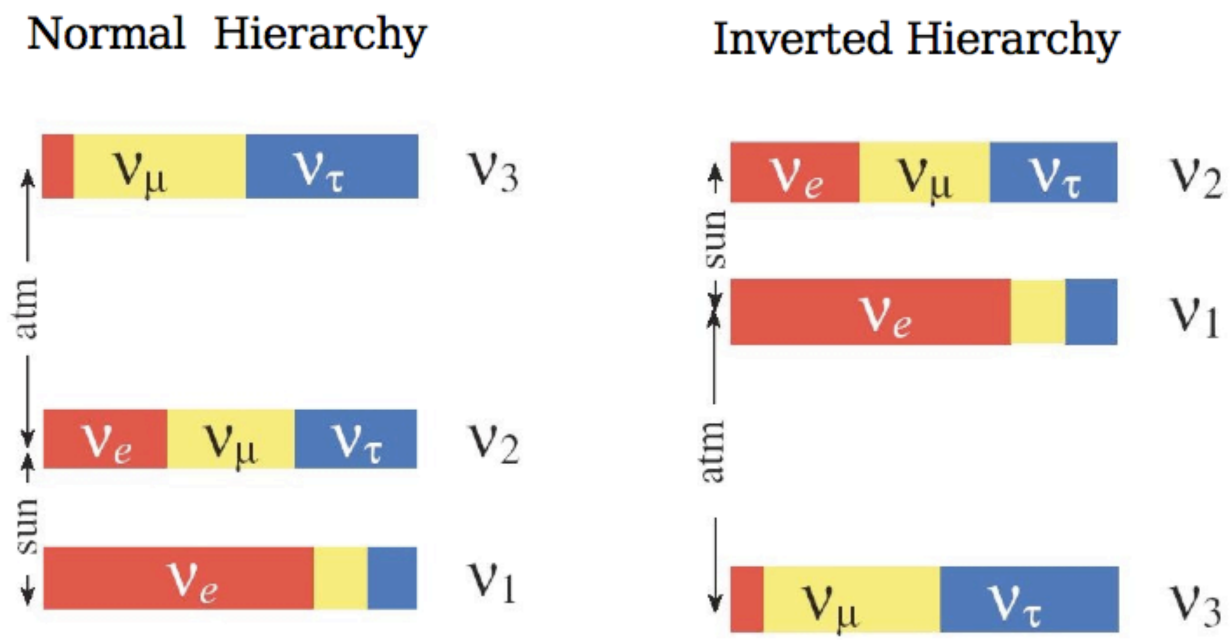


$$
\begin{aligned}
|\nu_e\rangle &= U^*_{e1}\,|\nu_1\rangle + U^*_{e2}\,|\nu_2\rangle + U^*_{e3}\,|\nu_3\rangle \\
|\nu_\mu\rangle &= U^*_{\mu1}\,|\nu_1\rangle + U^*_{\mu2}\,|\nu_2\rangle + U^*_{\mu3}\,|\nu_3\rangle \\
|\nu_\tau\rangle &= U^*_{\tau1}\,|\nu_1\rangle + U^*_{\tau2}\,|\nu_2\rangle + U^*_{\tau3}\,|\nu_3\rangle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

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

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

Neutrino state cross-composition


Normal Hierarchy

Inverted Hierarchy

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

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

$$\begin{aligned}
P_1 &= \sin^2\theta_{23}\boxed{\sin^2 2\theta_{13}}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2} && \text{atmospheric part}\\
P_2 &= \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2} && \text{solar part}\\
P_3 &= \boxed{J\cos\delta}\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2} && \text{interference}\\
P_4 &= \boxed{\mp J\sin\delta}\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}
\end{aligned}$$

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

where

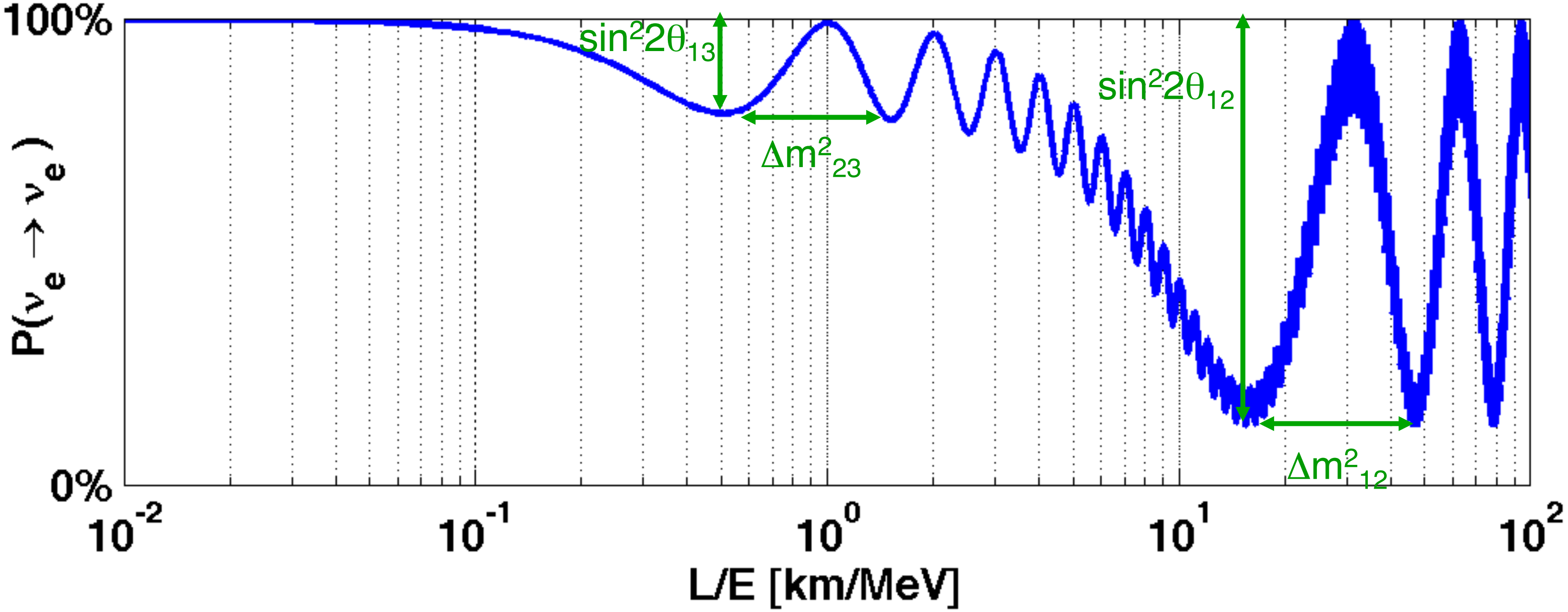
$$\begin{aligned}
\Delta_{ij} &= \frac{\Delta m^2_{ij}}{2E_\nu}\\
A &= \sqrt{2}G_F n_e\\
B_\pm &= |A \pm \Delta_{13}|\\
J &= \cos\theta_{13}\sin 2\theta_{12}\boxed{\sin 2\theta_{13}}\sin 2\theta_{23}
\end{aligned}$$

and the ± 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

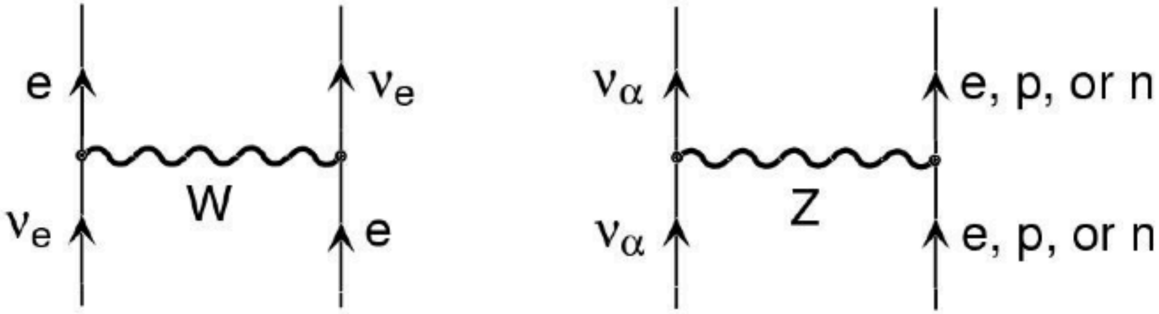


Matter oscillations (MSW effect)

The effect of the presence of matter
along the path of a neutrino
is equivalent to
the Refractive Index for
photon propagation
in a transparent medium.

Or equivalently
to the presence
of an **Effective Potential**

Effective Potential in Ordinary Matter



$$V_{\nu_\mu e} = V_{\nu_\tau e} = \quad V^Z_{\nu_e e} = \quad -\frac{\sqrt{2}}{2} G_F N_e$$

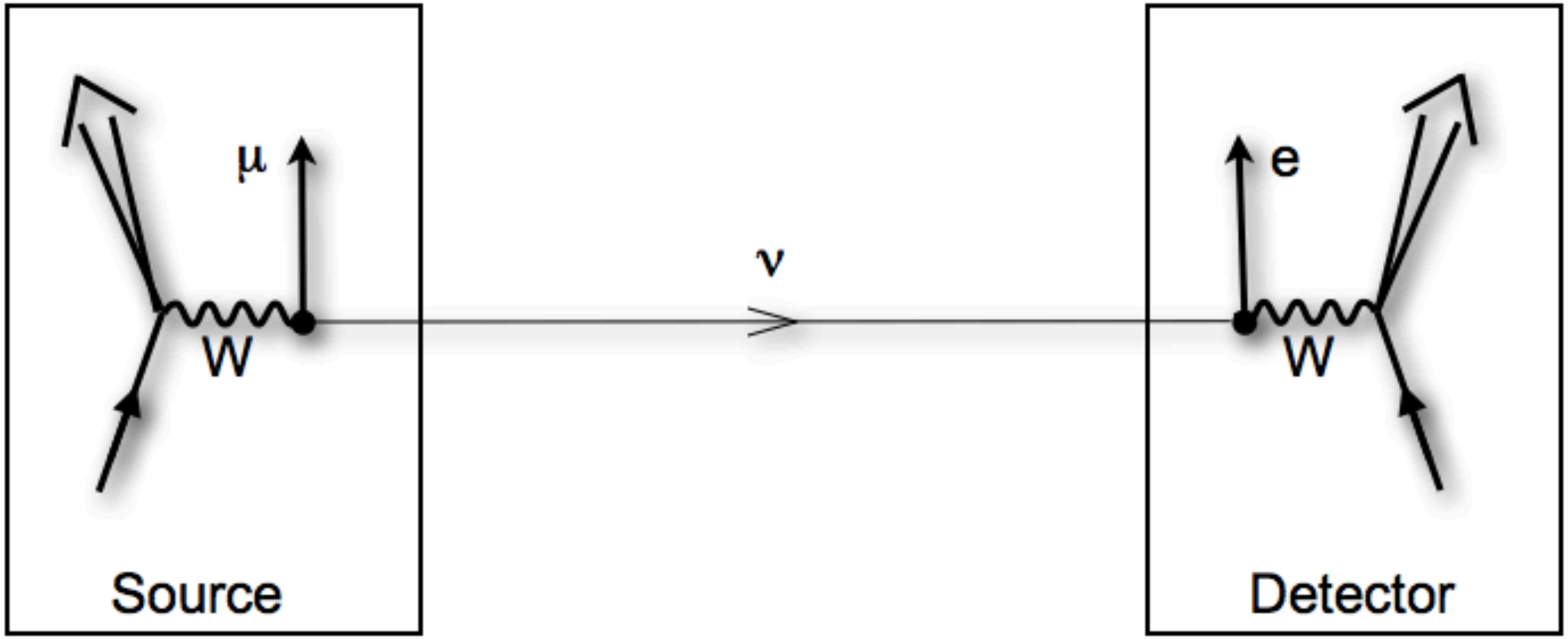
$$V_{\nu_\mu p} = V_{\nu_\tau p} = \quad V_{\nu_e p} = \quad +\frac{\sqrt{2}}{2} G_F N_p$$

$$V_{\nu_\mu n} = V_{\nu_\tau n} = \quad V_{\nu_e n} = \quad -\frac{\sqrt{2}}{2} G_F N_n$$

$$V_{\nu_e e} = V^Z_{\nu_e e} + V^W_{\nu_e e} = -\frac{\sqrt{2}}{2} G_F N_e + \sqrt{2} G_F N_e$$

- different potential for different flavors (there are no muons or tau in ordinary matter)
- the effective potential affects the flavor propagation in matter
- matter effective potentials have opposite signs for neutrinos and antineutrinos

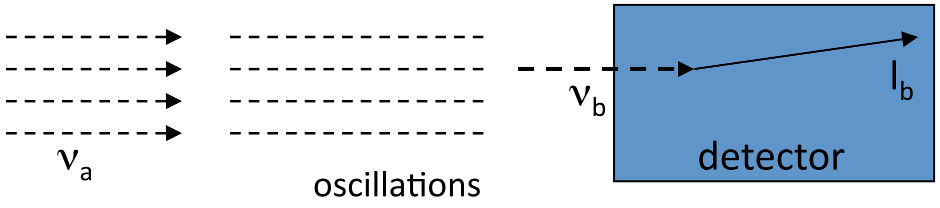
How to detect neutrino oscillations?



Classification of neutrino oscillation experiments

APPEARANCE experiments

ν_a - ν_b oscillations



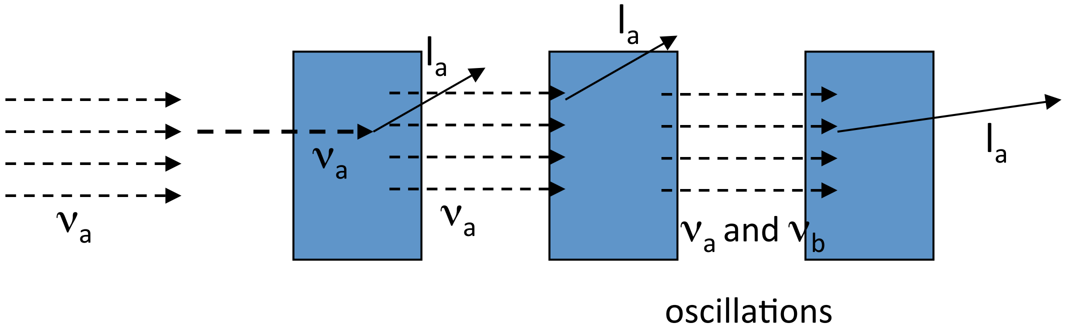
CC interaction of ν_b producing the charged lepton b, whose appearance is detected

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

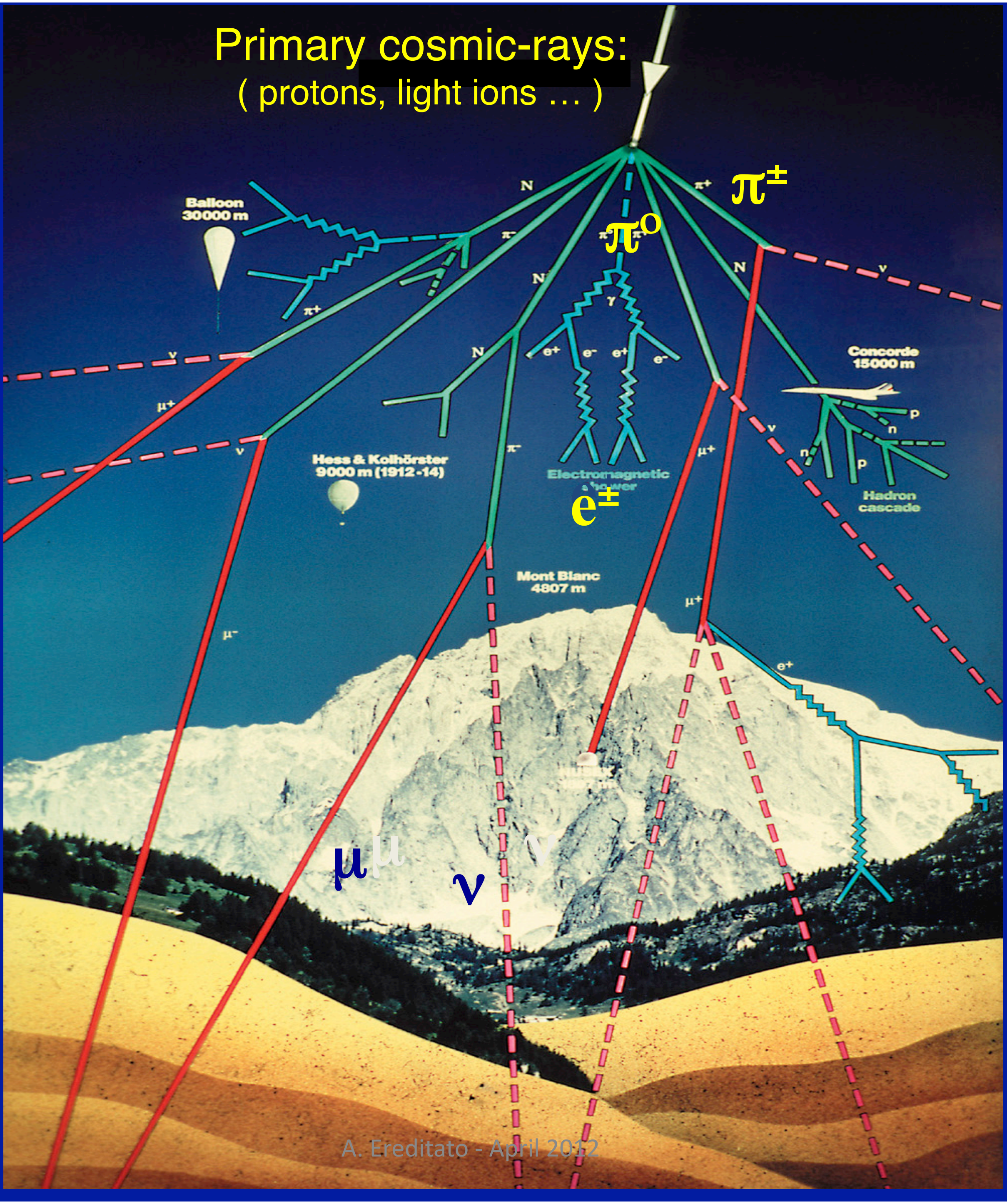


CC interaction of ν_a producing the charged lepton a, measured where oscillations do-not/do occur

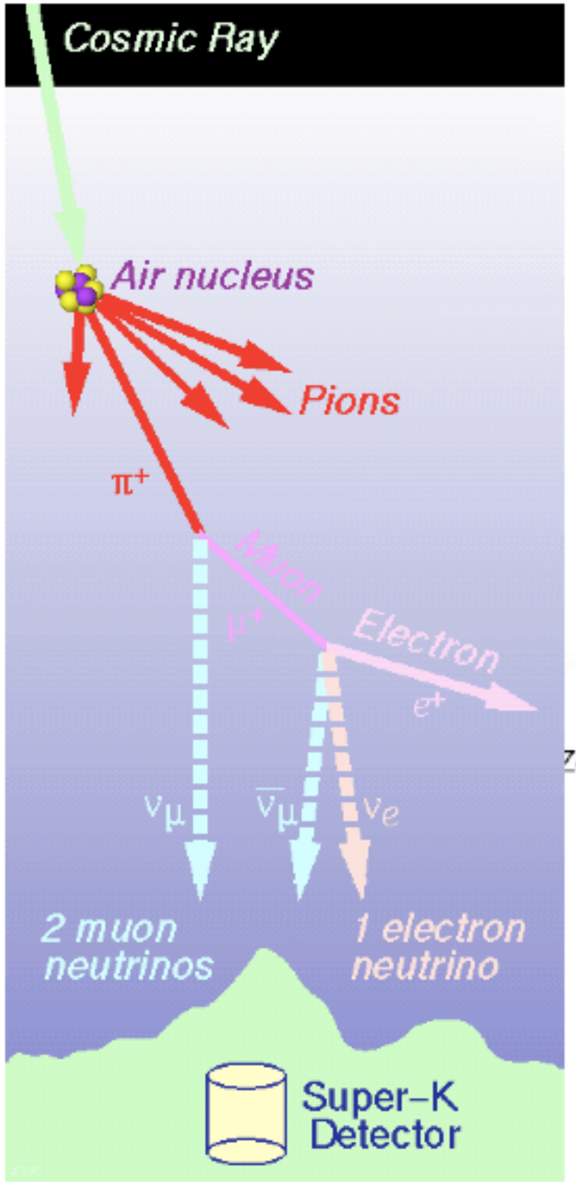
NEED:

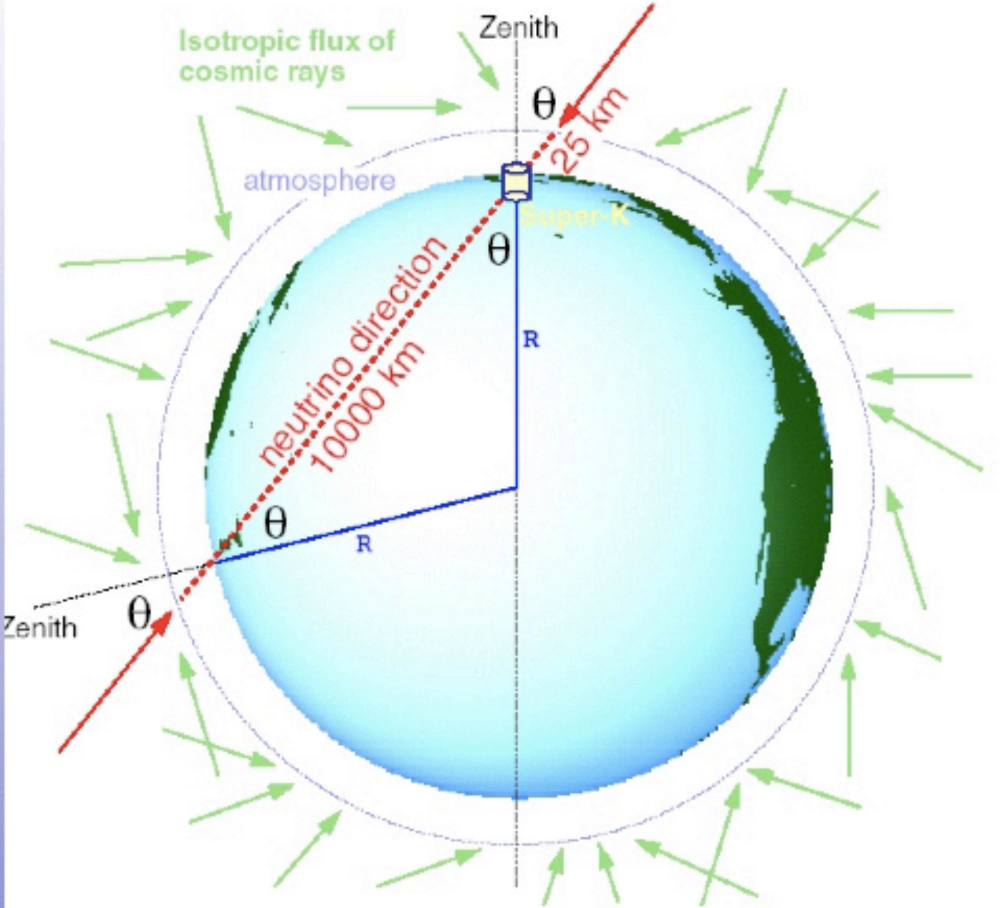
1) tiny effects: very good knowledge of the beam, and good control of detector systematics
2) useful to have 'near' and 'far' detector of the same type (mass scaling with L^2)
3) look for spectrum distortions

Primary cosmic-rays:
(protons, light ions …)



ATMOSPHERIC NEUTRINOS





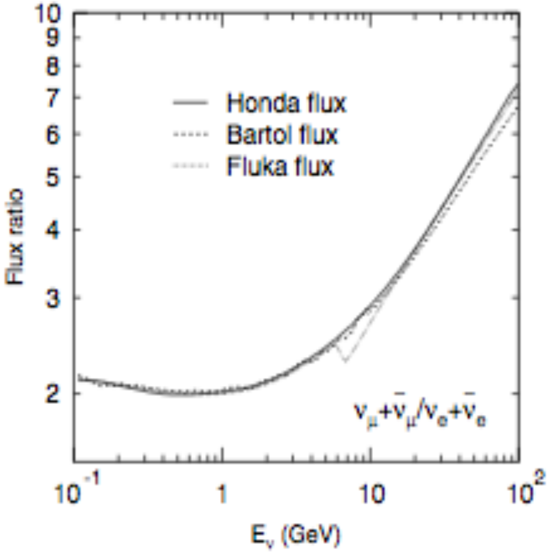
Up-Down Symmetric Flux
(for E$_\nu$ > few GeV)

$$\boxed{\begin{array}{l}\pi^{+} \rightarrow \nu_\mu \; \mu^{+} \rightarrow \nu_\mu \; \overline{\nu}_\mu \; \nu_e \; e^{+} \\ \pi^{-} \rightarrow \overline{\nu}_\mu \; \mu^{-} \rightarrow \overline{\nu}_\mu \; \nu_\mu \; \overline{\nu}_e \; e^{-}\end{array}}$$

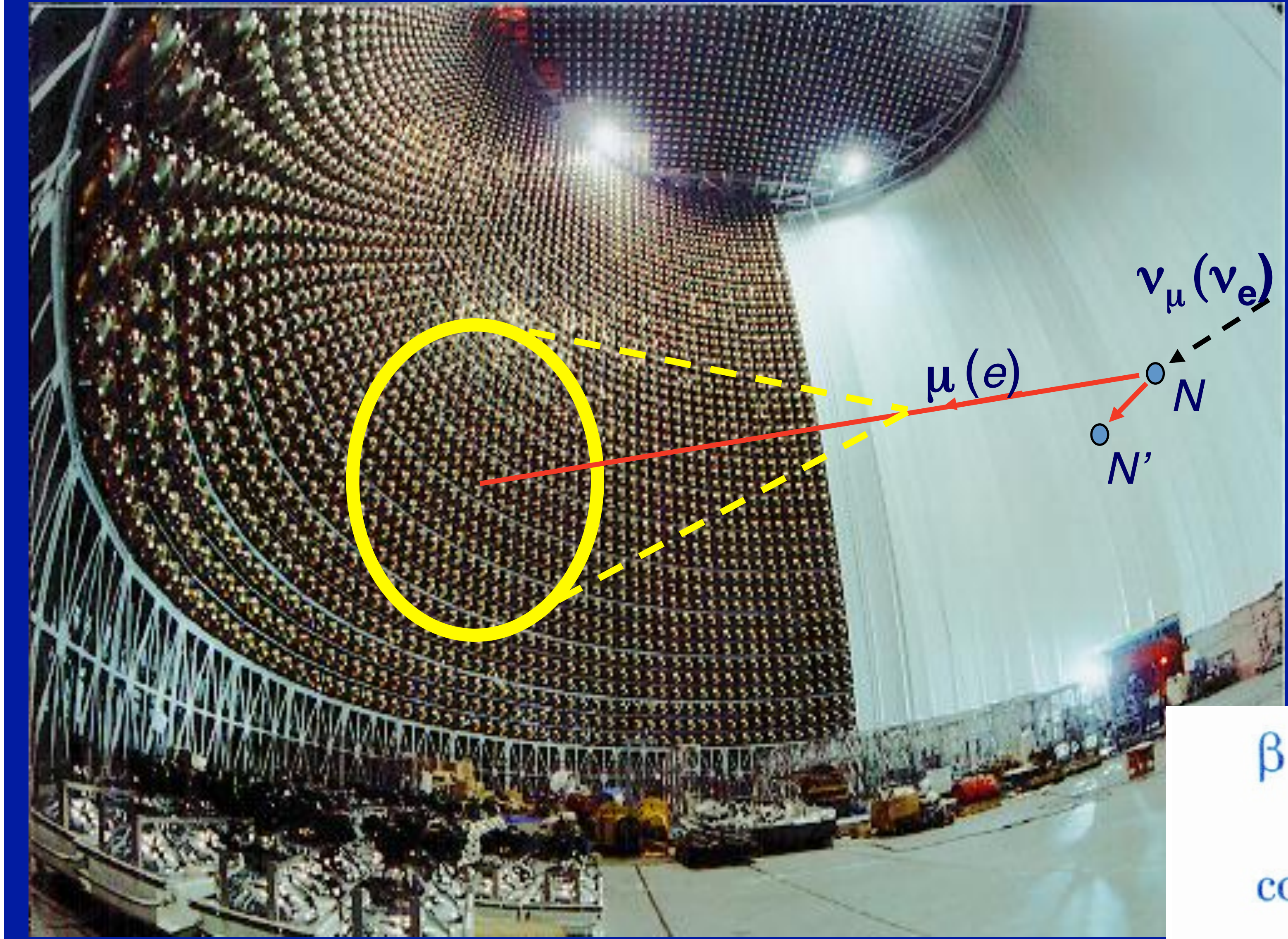
$$\frac{\nu_e}{\overline{\nu}_e} \simeq \frac{\pi^+}{\pi^-} \simeq 1.2 \qquad \frac{\nu_\mu}{\overline{\nu}_\mu} \simeq 1$$

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

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



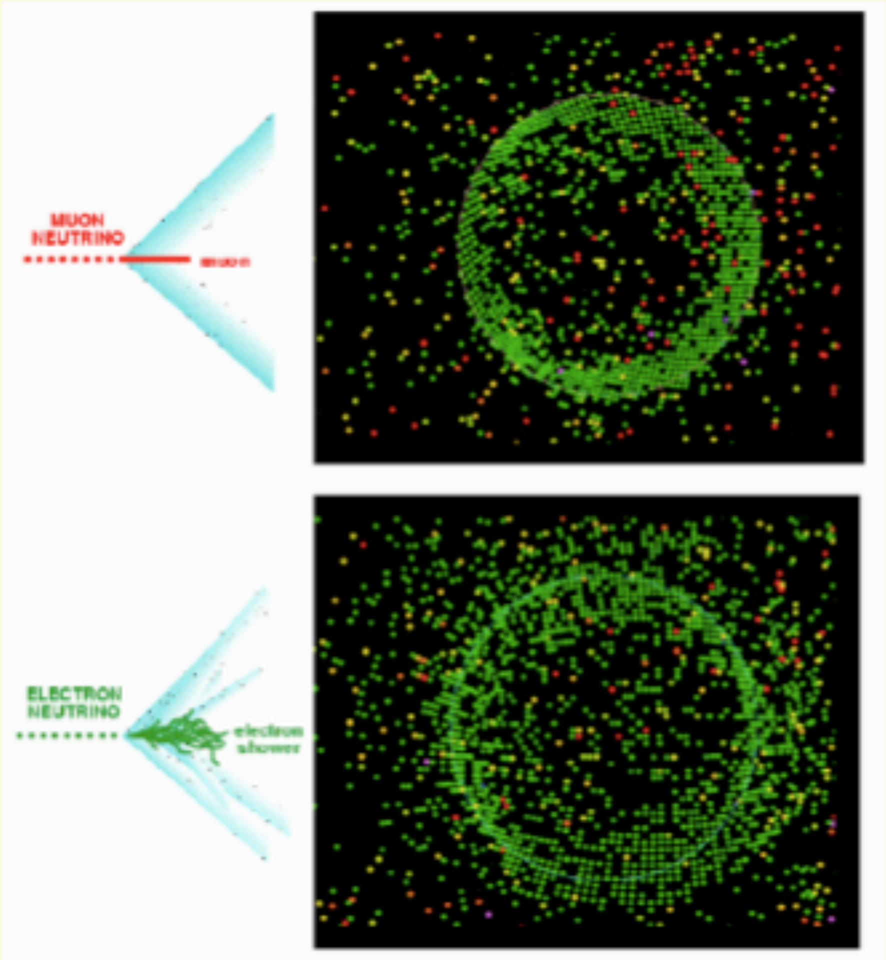
Cerenkov ring detection in Super-Kamiokande

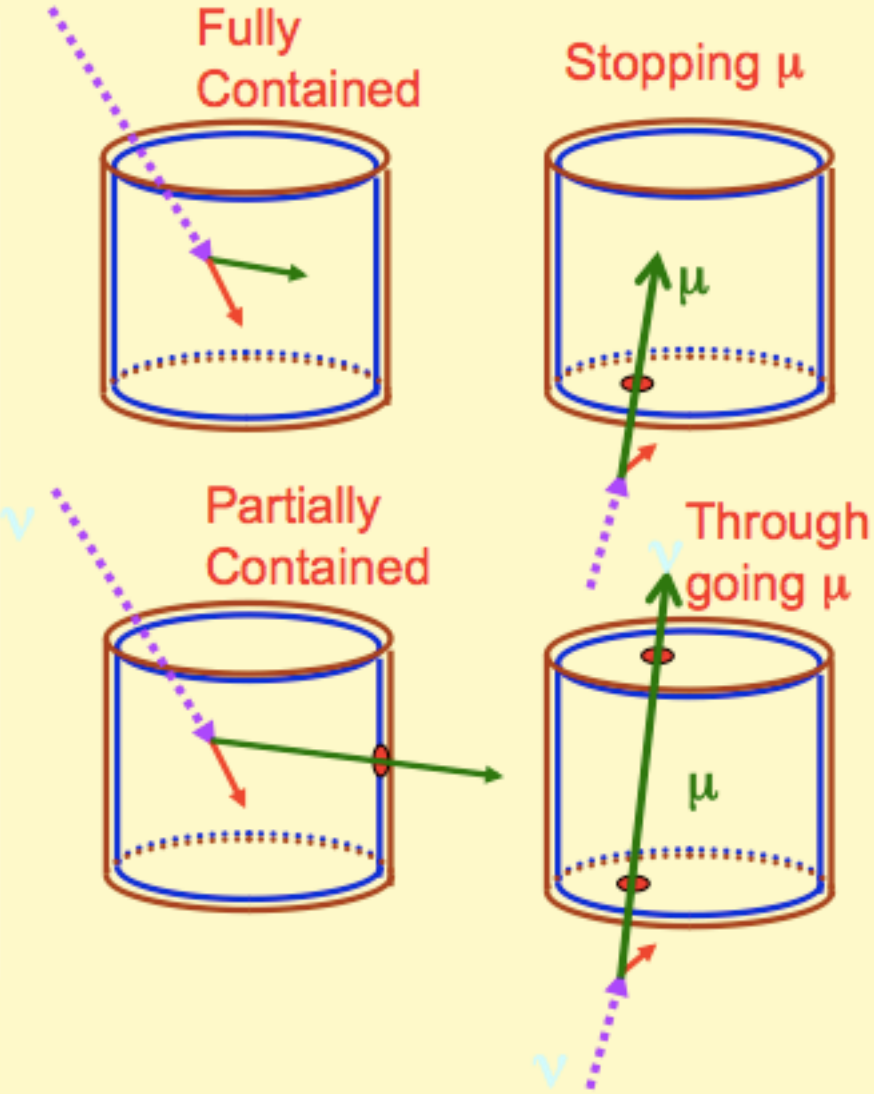


$$\beta \left(= \frac{v}{c}\right) > \frac{1}{n}$$

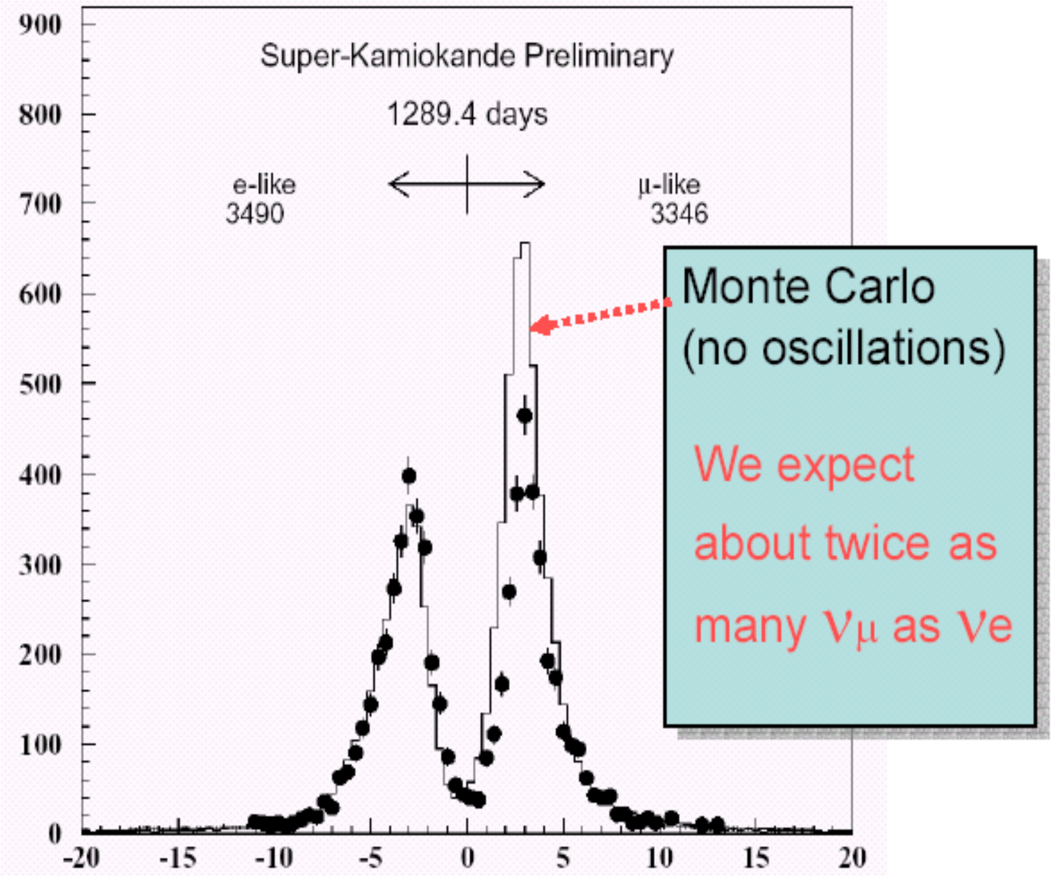
$$\cos \theta_{Ch} = \frac{1}{\beta n}$$

in water, $n = 1.33$
as β -> 1, θ_{Ch} -> 41 degrees


MUON NEUTRINO
muon
ELECTRON NEUTRINO
electron shower

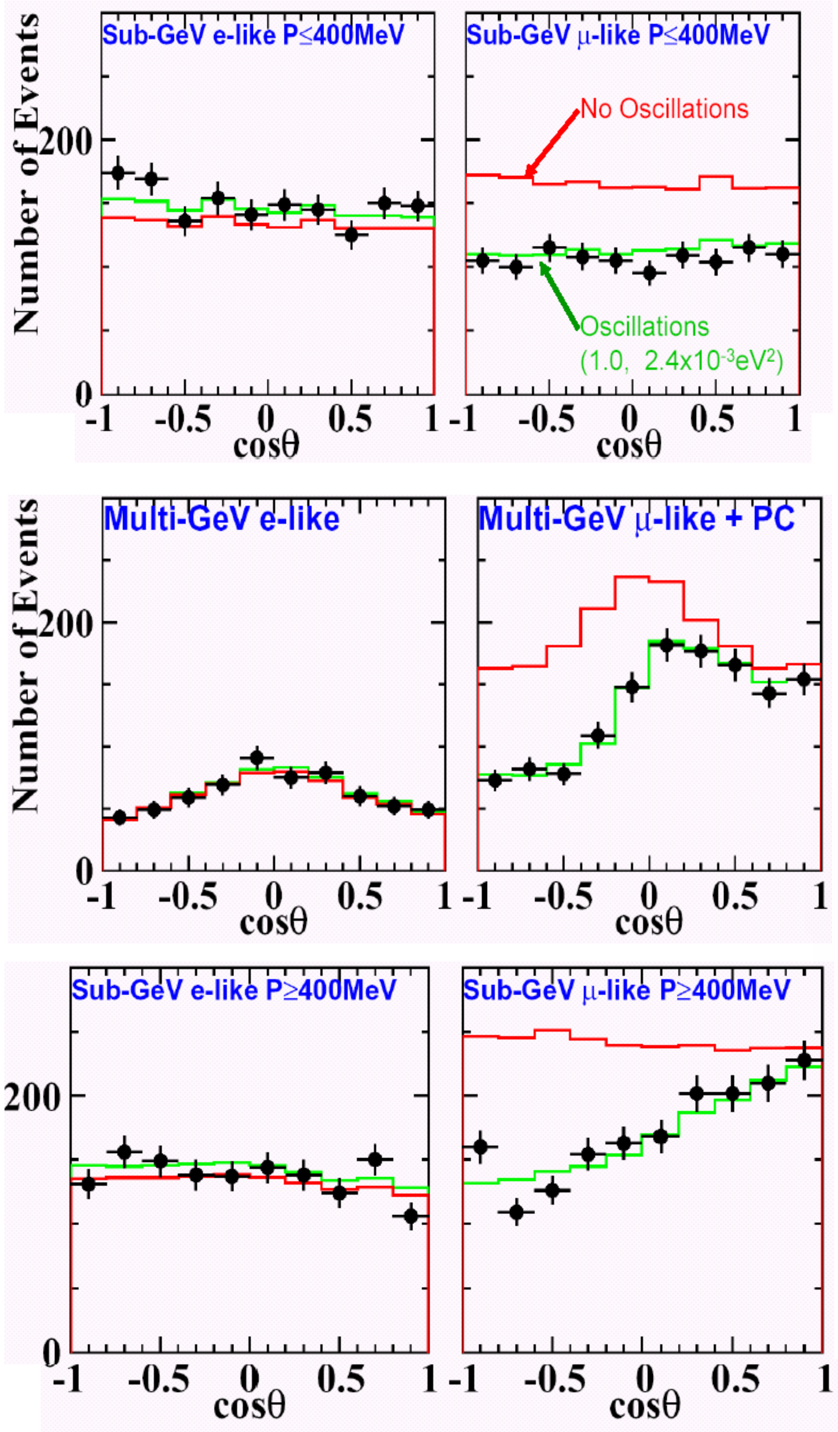

Fully Contained
Stopping μ
μ
ν
Partially Contained
Through going μ
ν
μ
ν

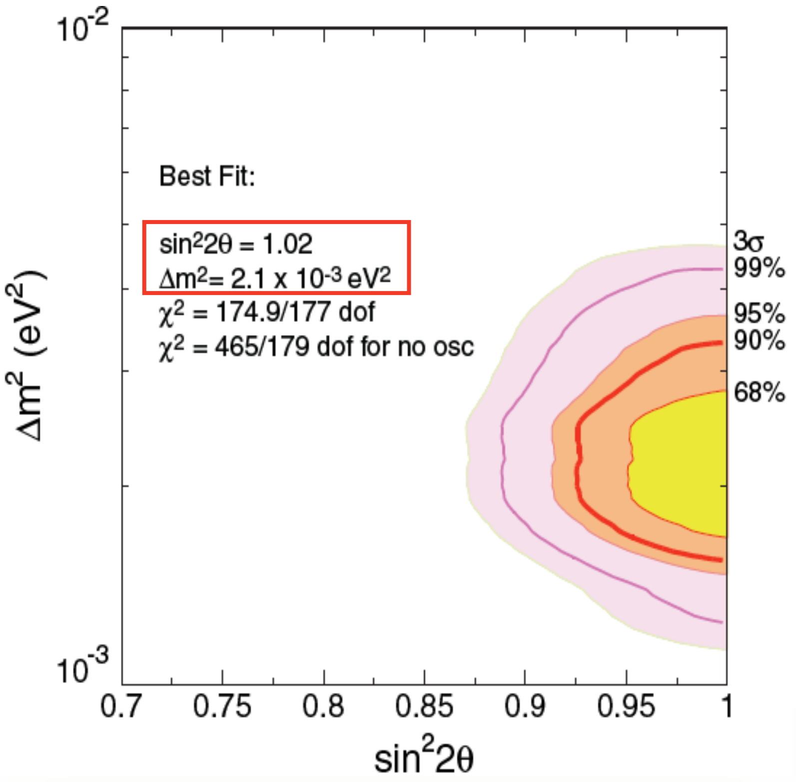
A first problem: integral electron and muon distributions



Monte Carlo
(no oscillations)

We expect about twice as many ν_μ as ν_e





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

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

Energy Threshold for CC interactions of ν_τ

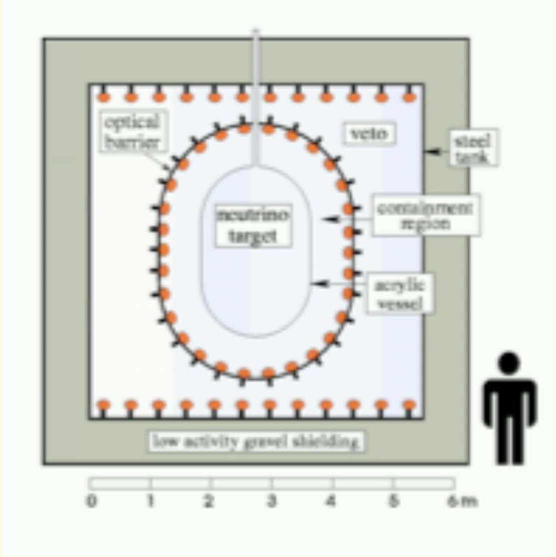
$$\boxed{E(\nu_\tau) \geq m_\tau + m_\tau^2 / 2m_p \approx 3.5\ \mathrm{GeV}}$$

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

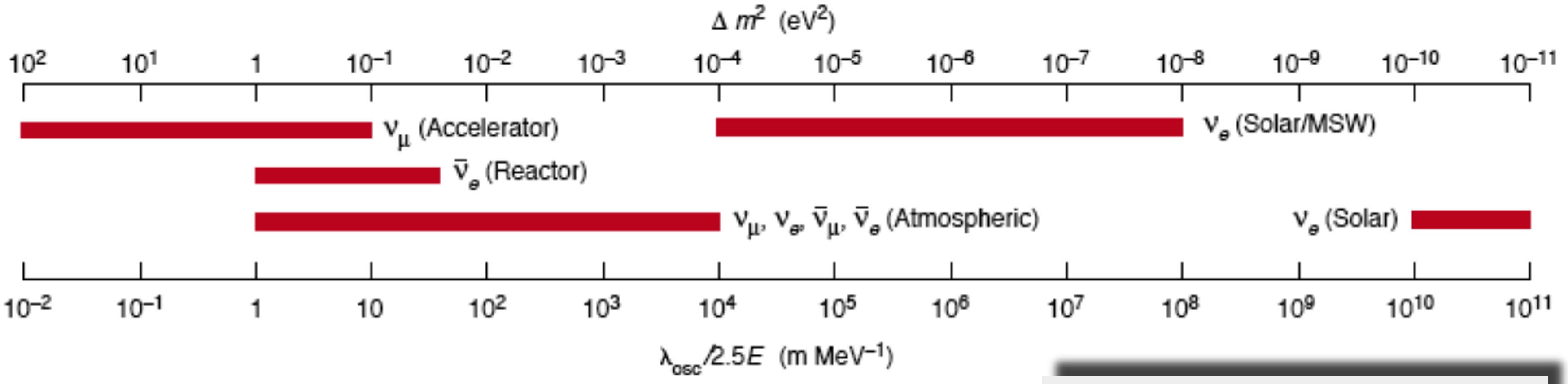
No ν_e-ν_x oscillations in the same parameter region as atmospheric neutrinos: it must predominantly be $\nu_\mu - \nu_\tau$

The short-baseline reactor experiment CHOOZ

~1 km →



Sensitivity range of neutrino oscillation experiments



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

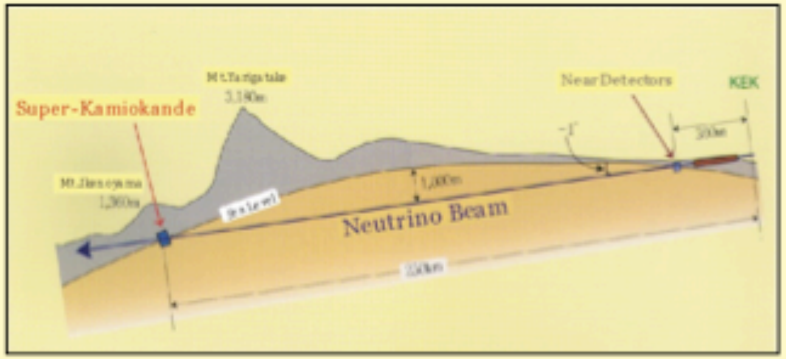
Following the results obtained with atmospheric neutrinos:

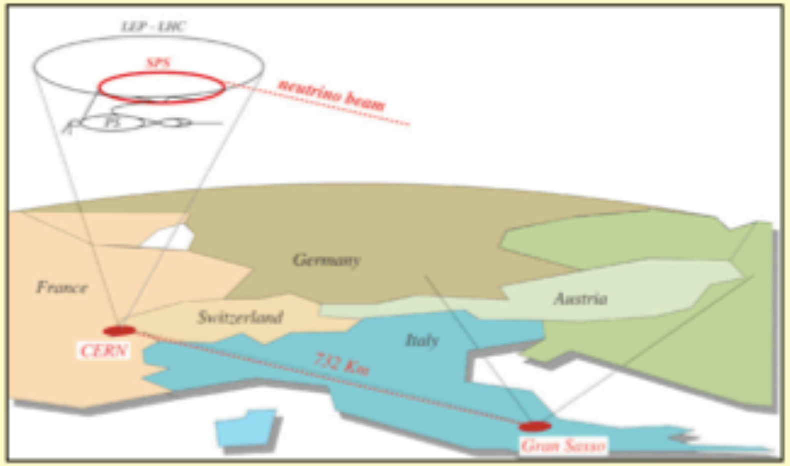
experiments with artificial (accelerator) neutrinos sensitive to the same oscillation parameters

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

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

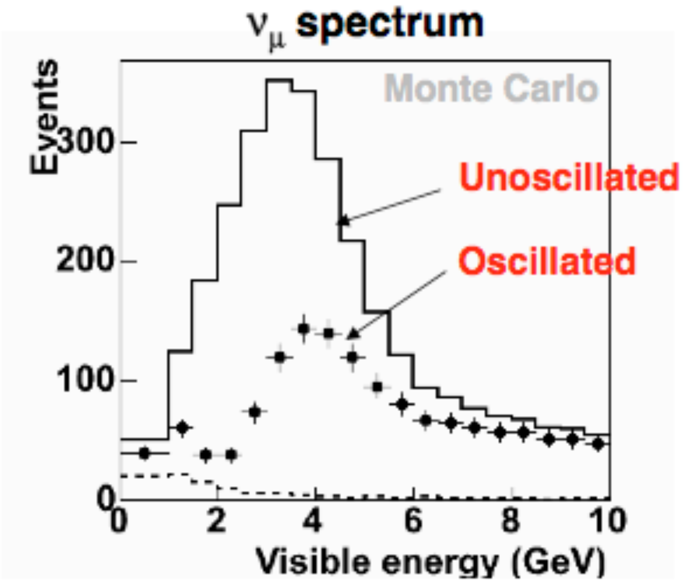
"Reproducing atmospheric ν_μ physics" in controlled conditions

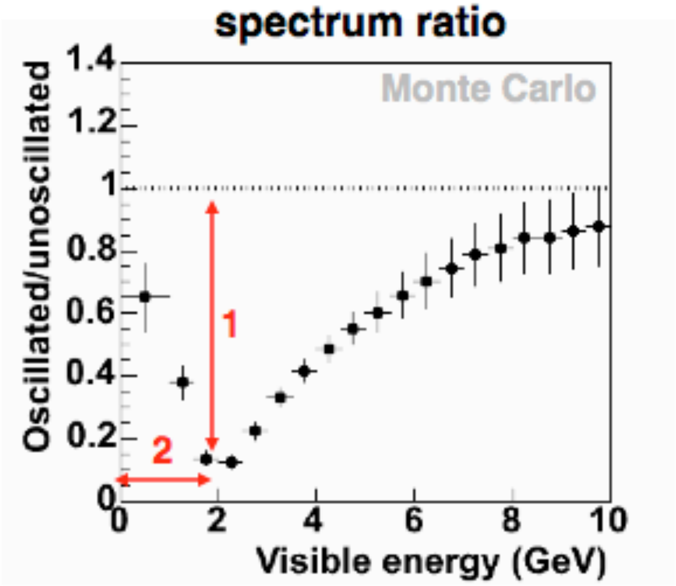




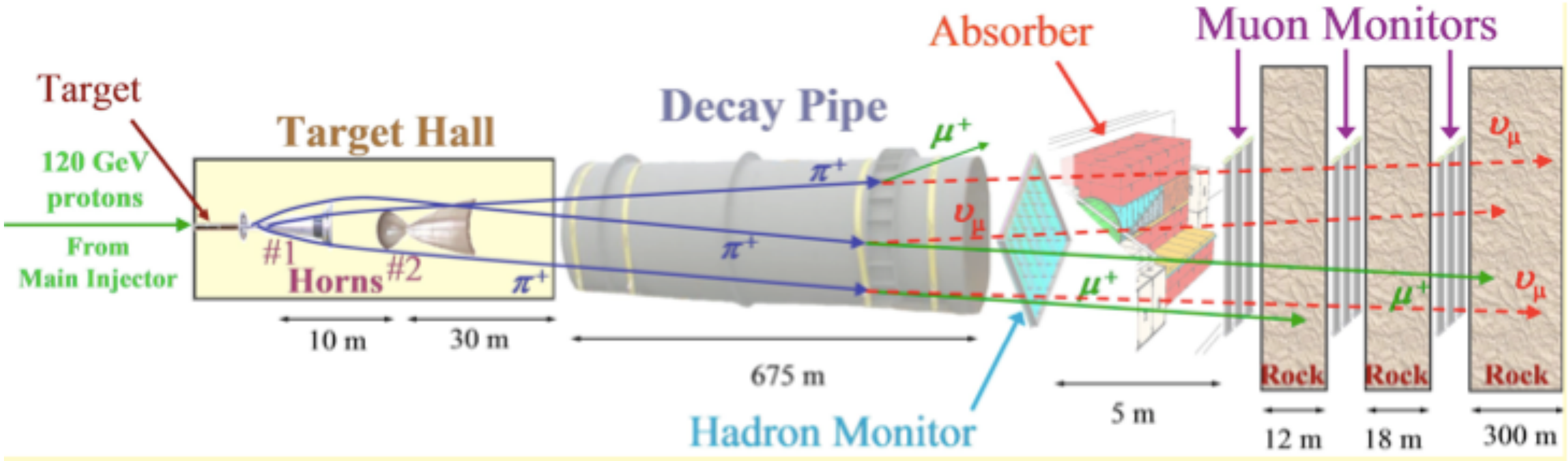
Example of a ν_μ disappearance measurement

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

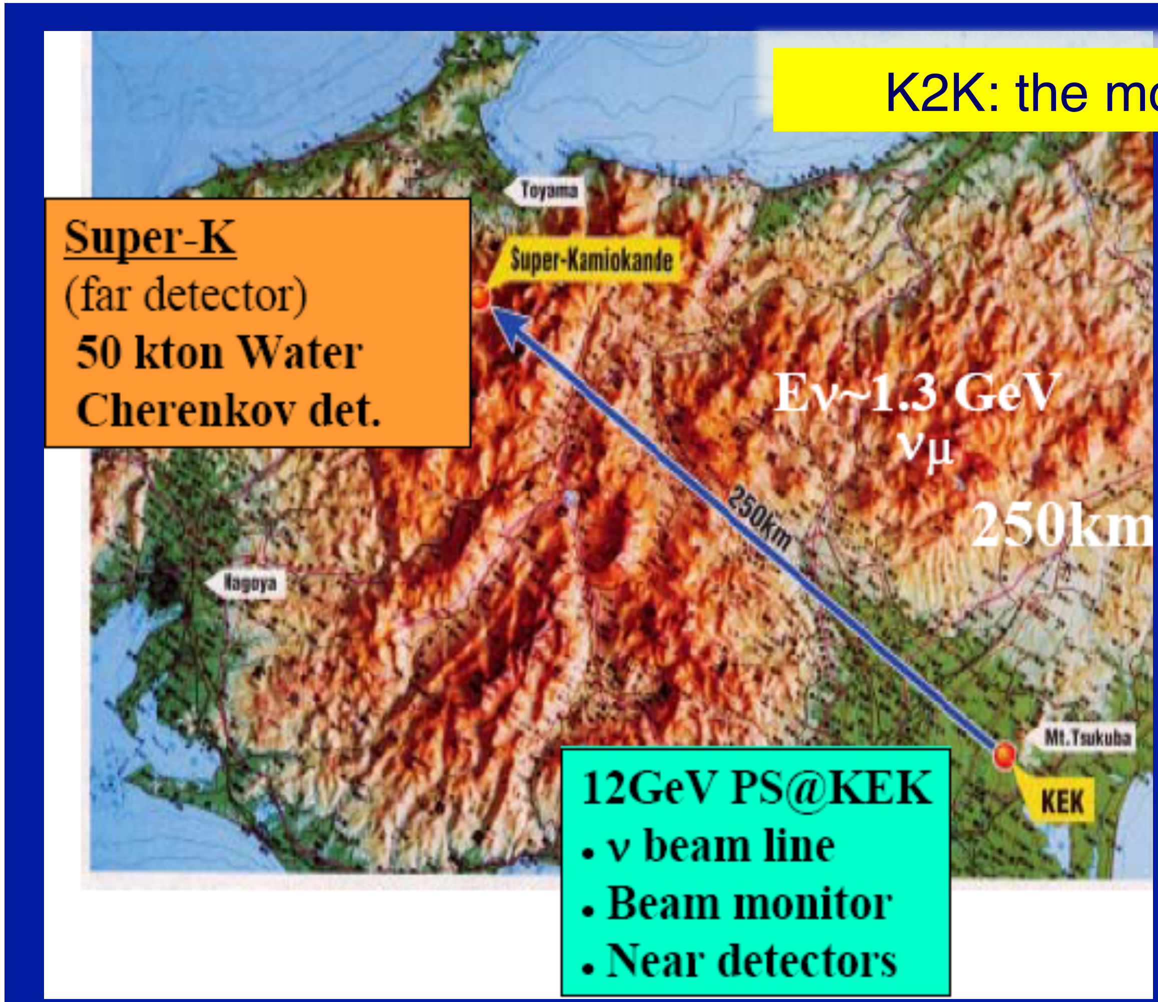

ν_μ spectrum


spectrum ratio

Typical accelerator neutrino beam (NUMI, Fermilab)



K2K: the mother of all LBL experiments

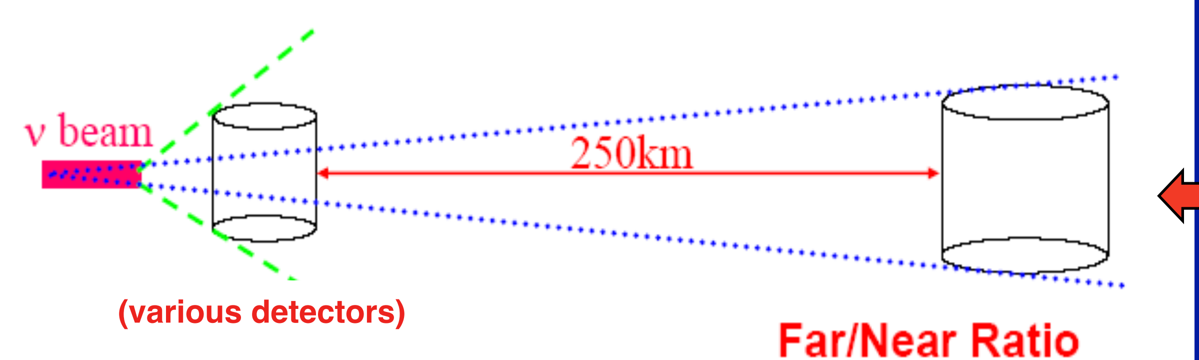


Super-K
(far detector)
50 kton Water
Cherenkov det.

12GeV PS@KEK

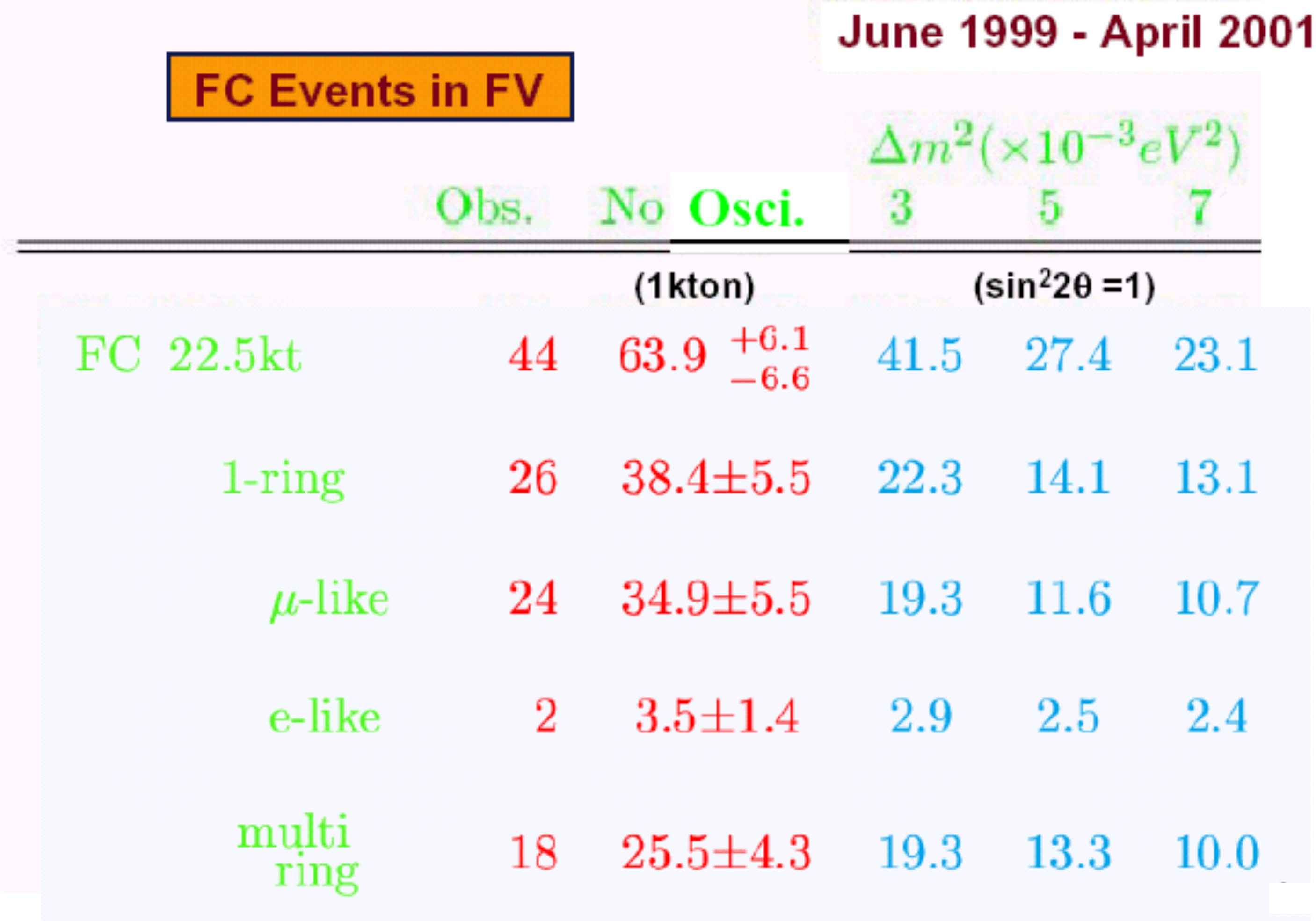
- **ν beam line**
- **Beam monitor**
- **Near detectors**

ν_μ disappearance experiment to probe the SK atmospheric neutrino result.



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

K2K results (oscillation parameters)

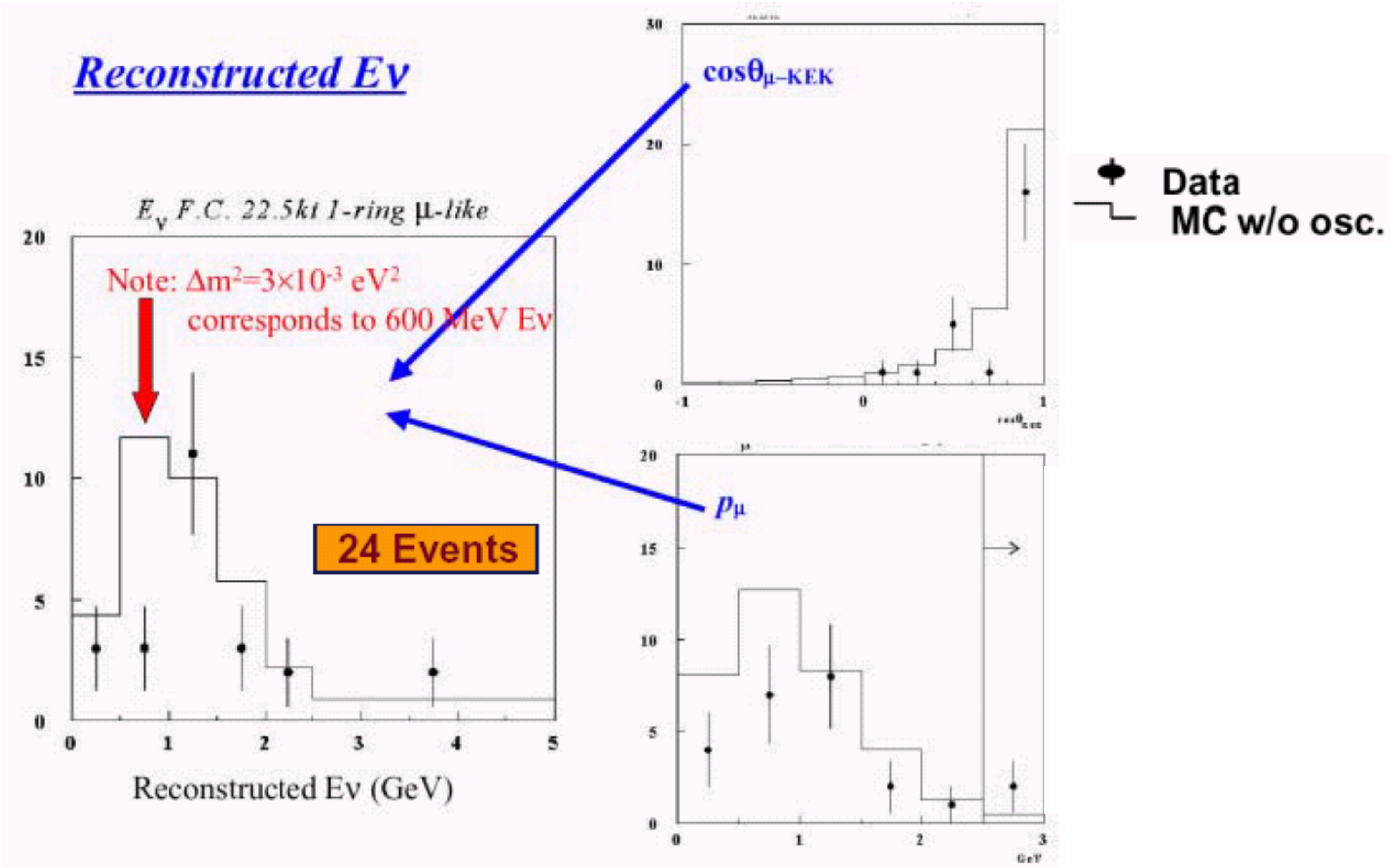


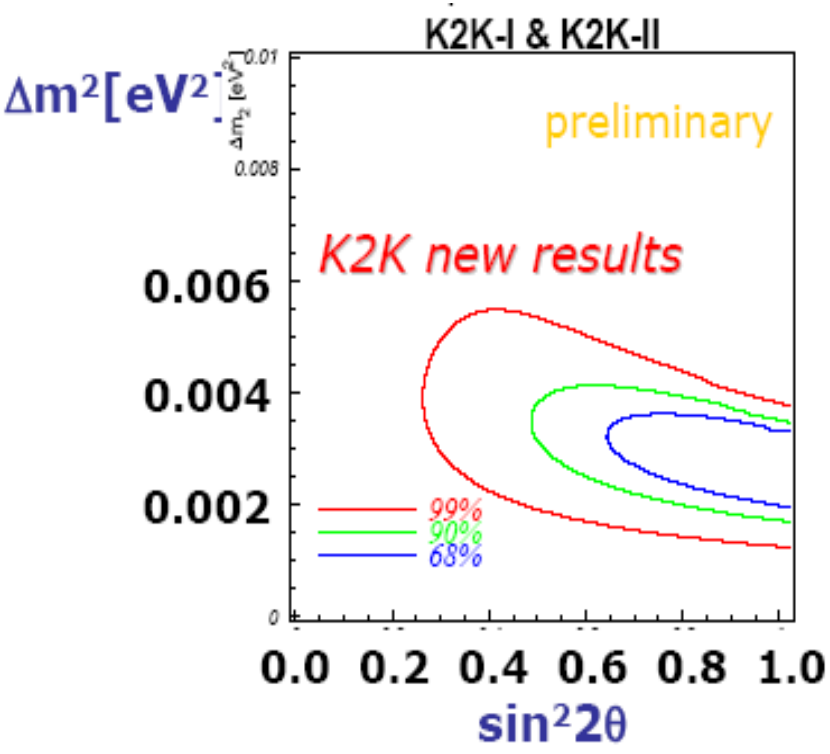
FC Events in FV

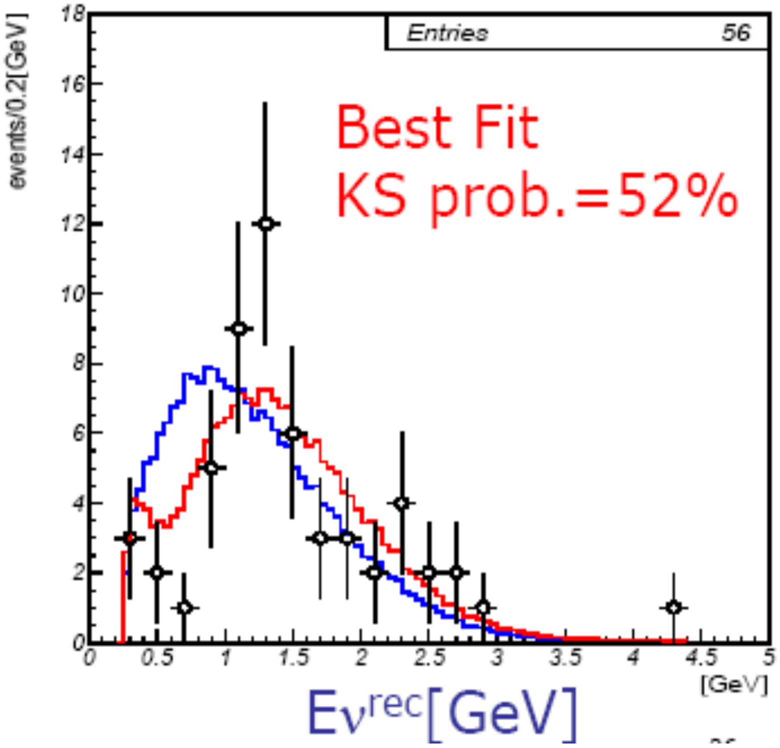
June 1999 - April 2001

	Obs.	No **Osci.** (1kton)	$\Delta m^2(\times 10^{-3} eV^2)$ 3	 5	(sin$^2 2\theta$ =1) 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

K2K event energy dependence







K2K results:

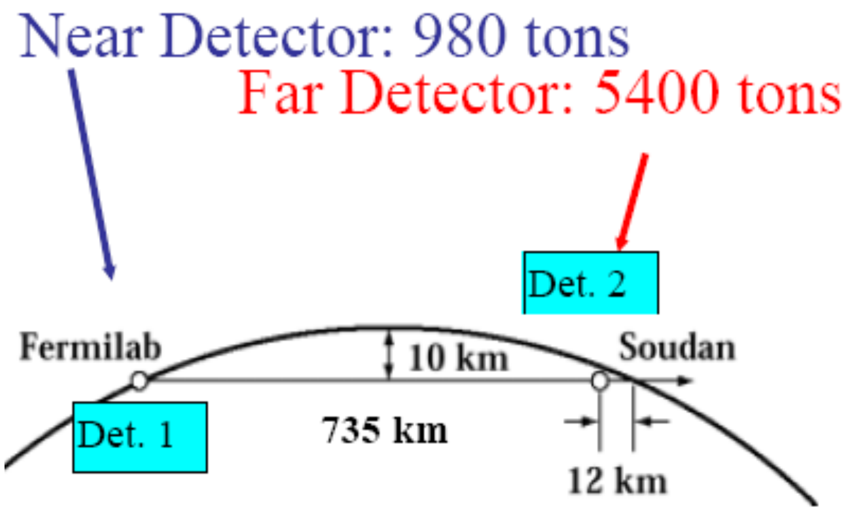
$1.7 < \Delta m^2 < 3.5$ eV^2 for $\sin^2 2\theta = 1$ (90% CL)

(ν_μ disappearance plus shape distortion)

K2K confirmed SK:

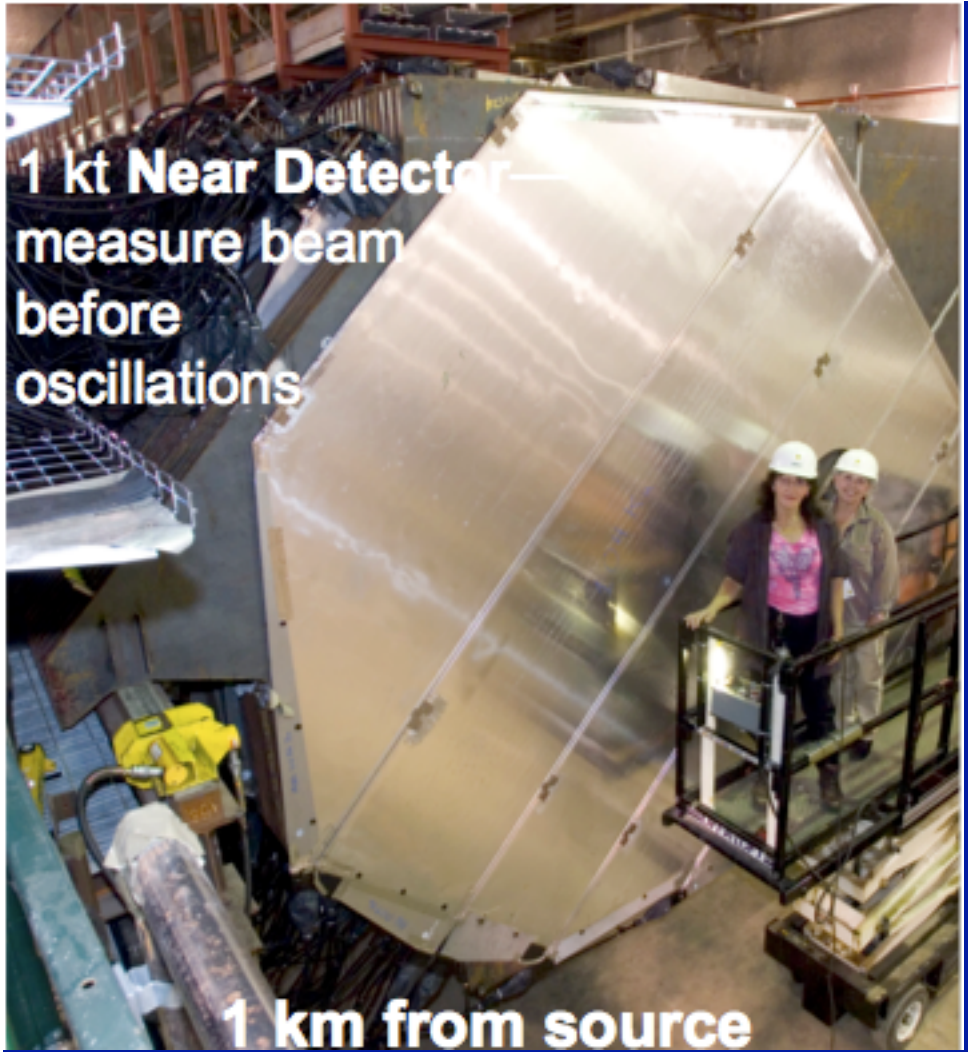
$1.5 < \Delta m^2 < 3.4$ eV^2 for $\sin^2 2\theta > 0.93$ (90% CL)

MINOS in the NuMi neutrino beam



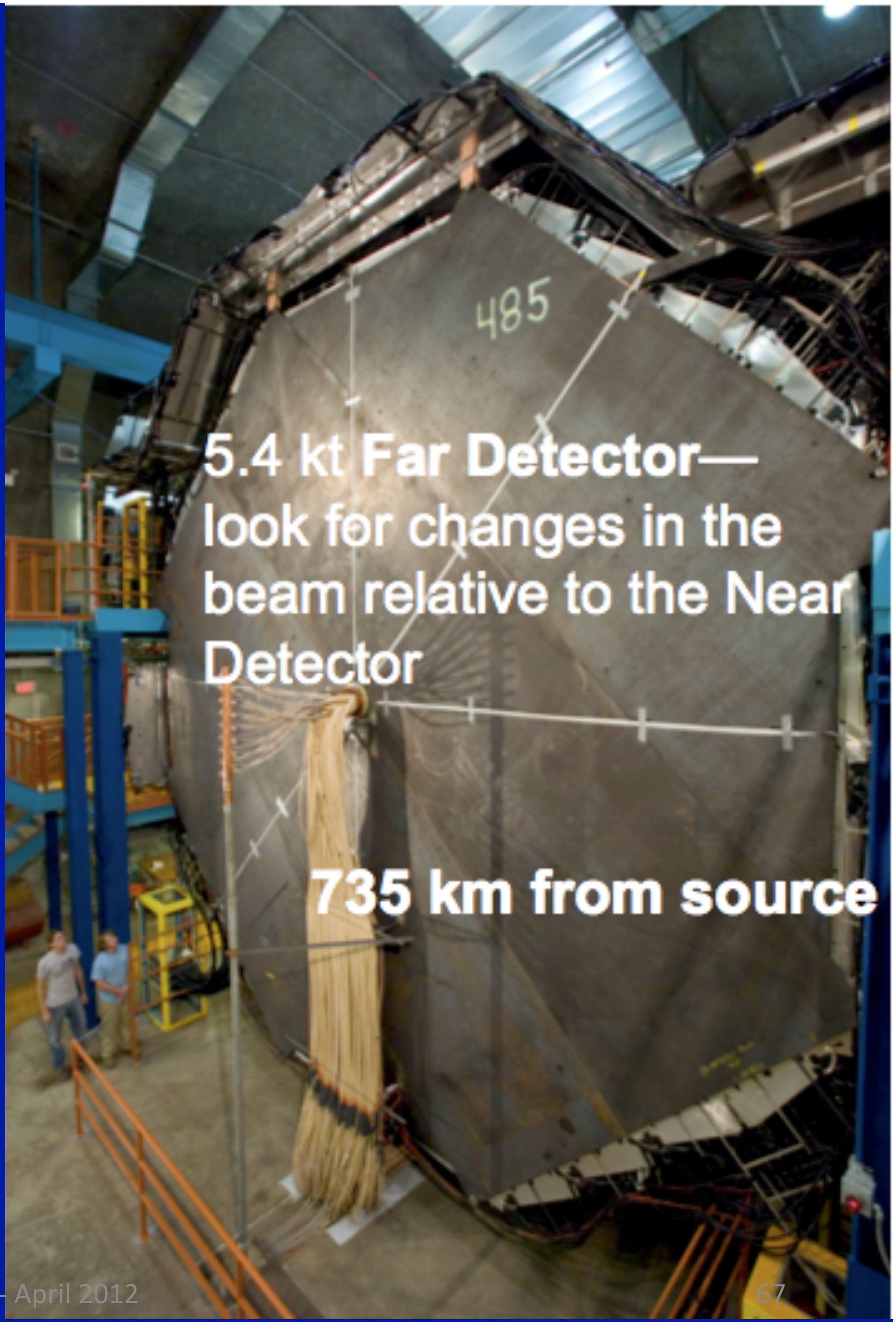
Magnetized steel/scintillator calorimeter

- 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

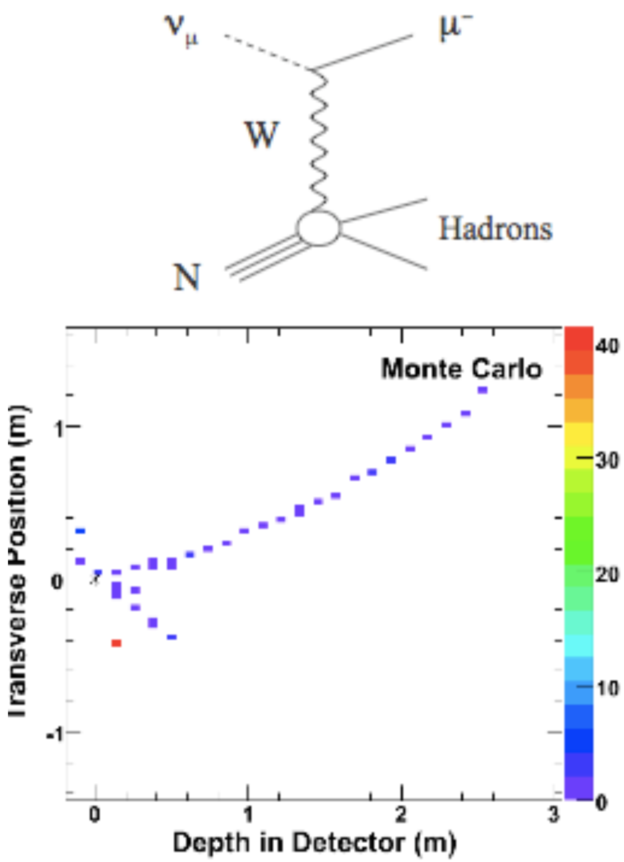
1 km from source



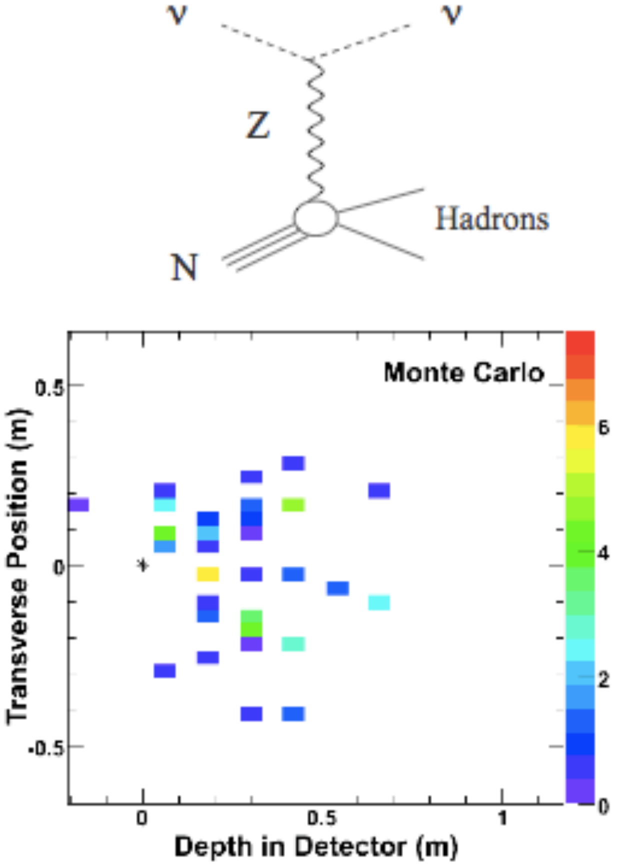
5.4 kt **Far Detector**—look for changes in the beam relative to the Near Detector

735 km from source

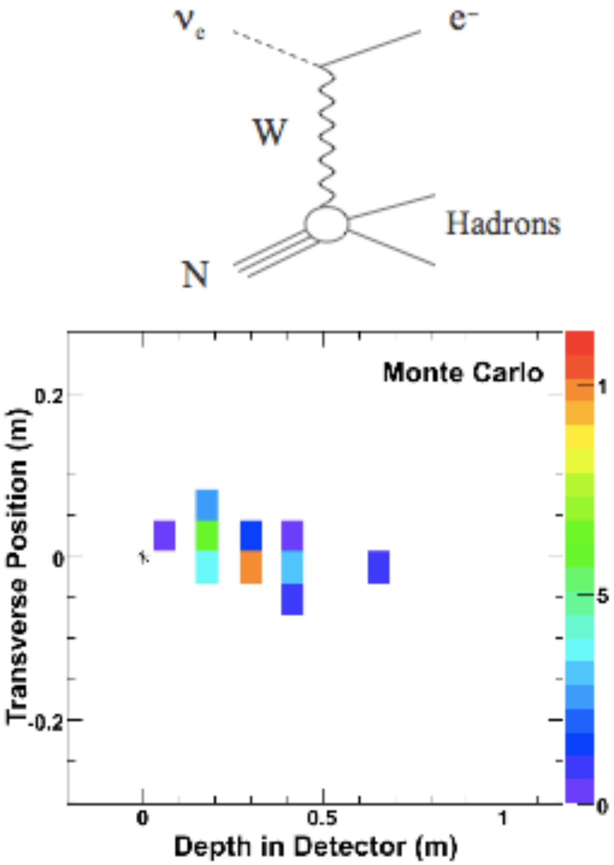
ν_μ CC Event

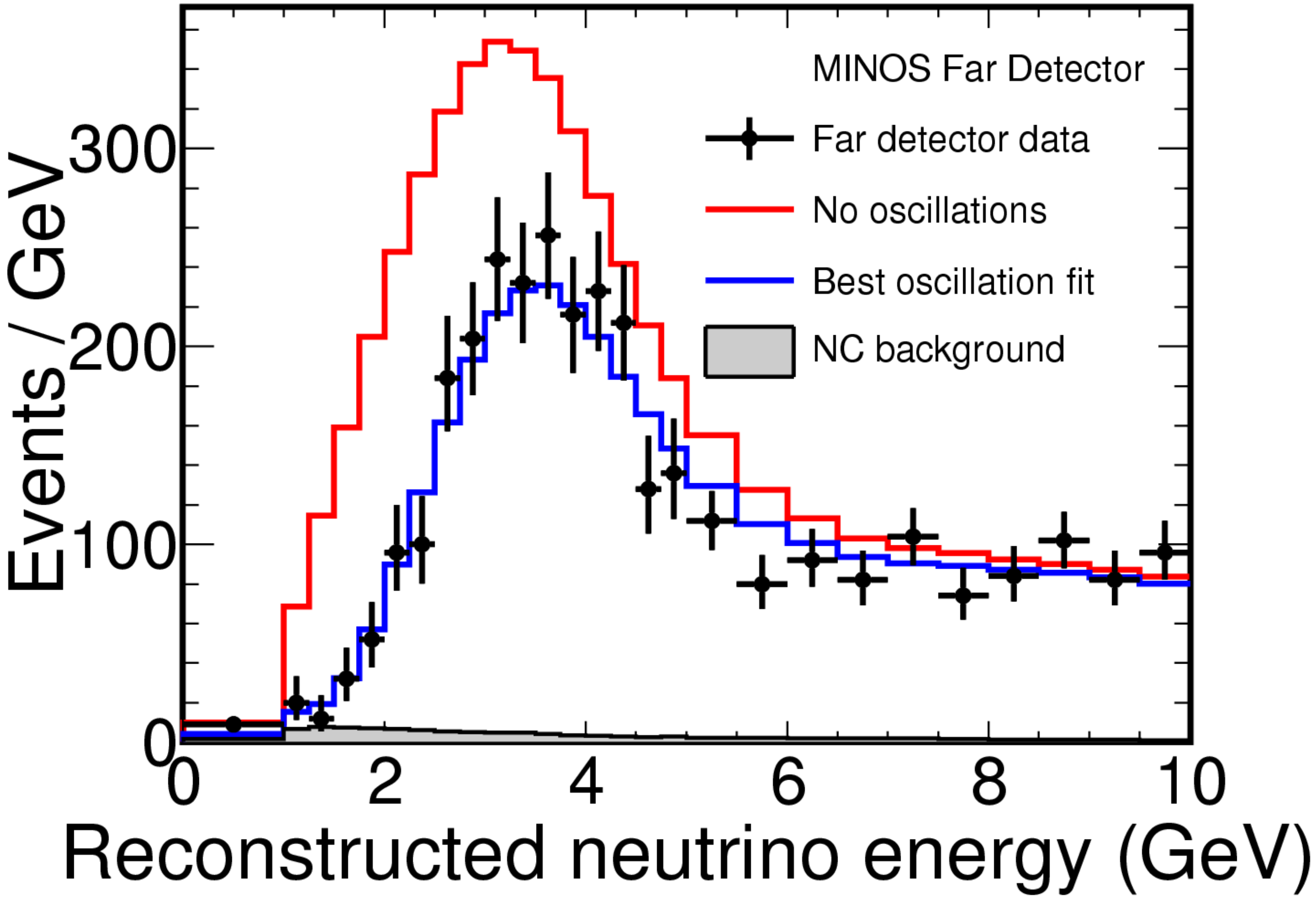


NC Event

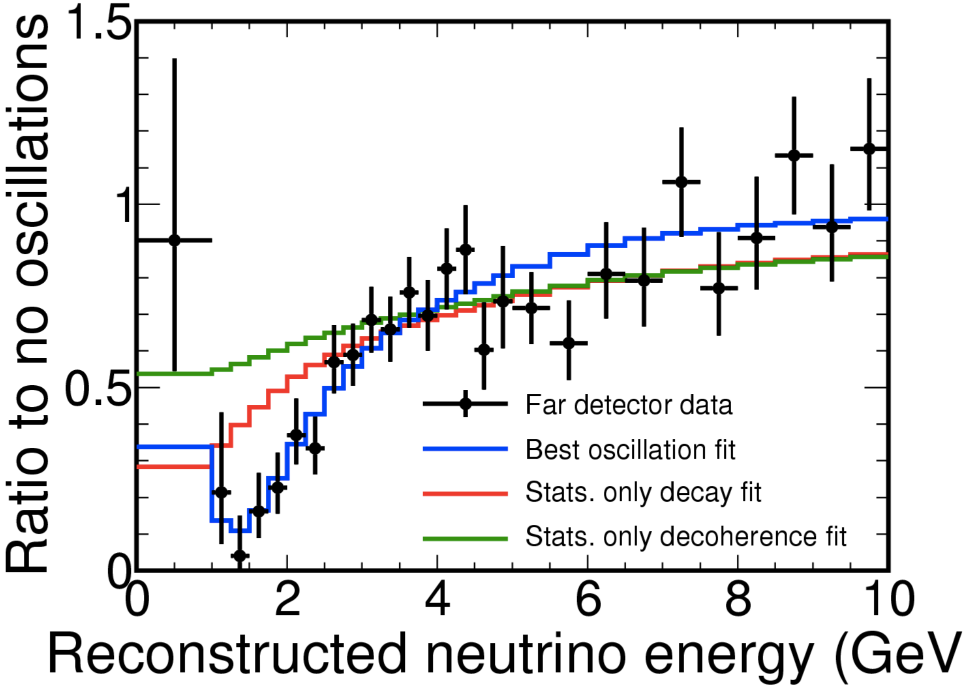


ν_e CC Event

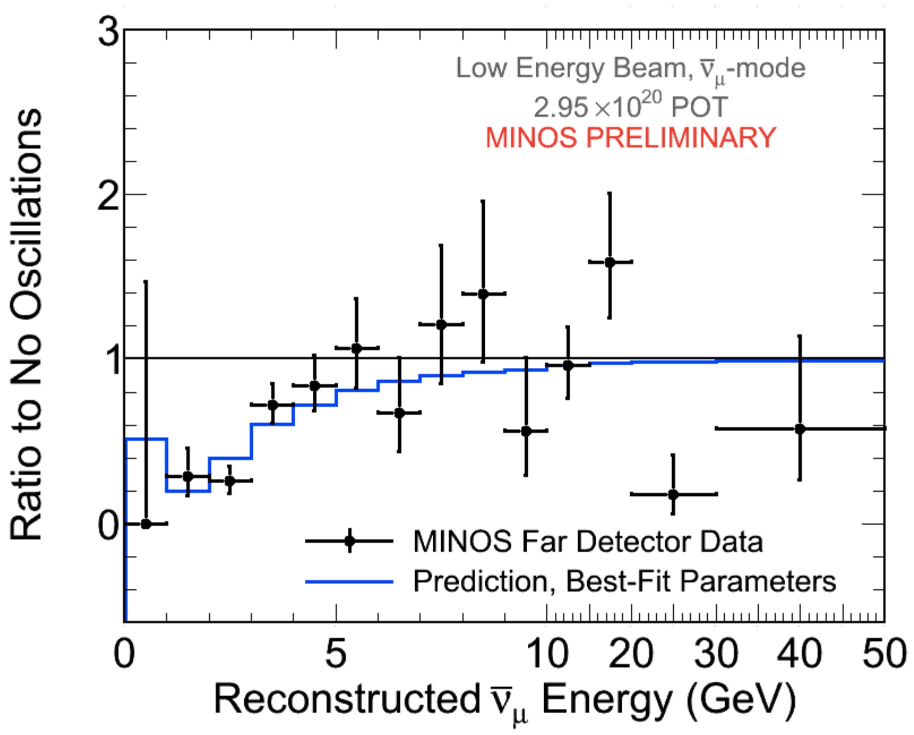


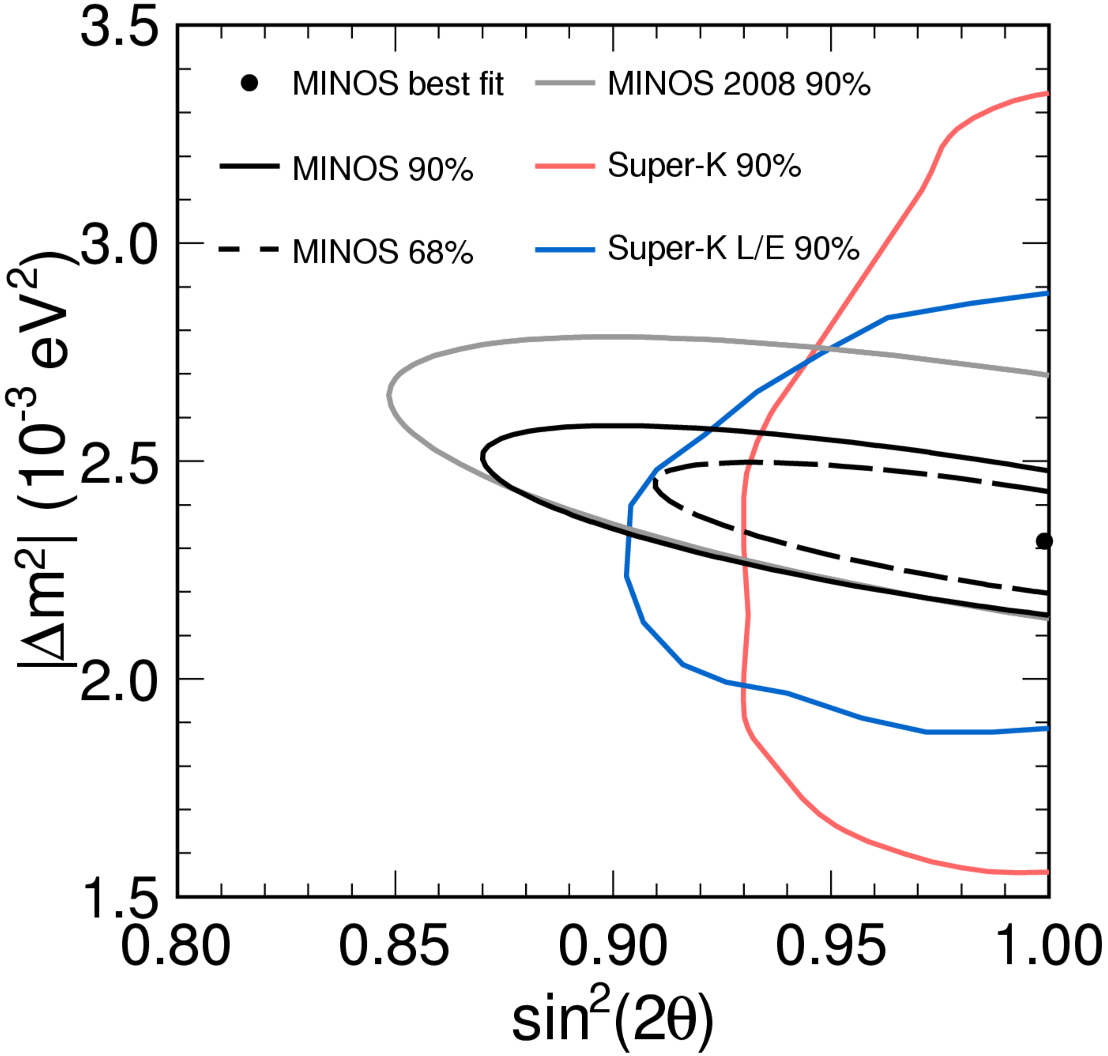

MINOS Far Detector
Far detector data
No oscillations
Best oscillation fit
NC background
Events / GeV
0
100
200
300
0
2
4
6
8
10
Reconstructed neutrino energy (GeV)

$\nu_\mu - \nu_\tau$



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




3.5
3.0
2.5
2.0
1.5
0.80
0.85
0.90
0.95
1.00
$|\Delta m^2|$ (10^{-3} eV^2)
$\sin^2(2\theta)$
● MINOS best fit
MINOS 2008 90%
MINOS 90%
Super-K 90%
MINOS 68%
Super-K L/E 90%

One can also look for oscillation appearance…

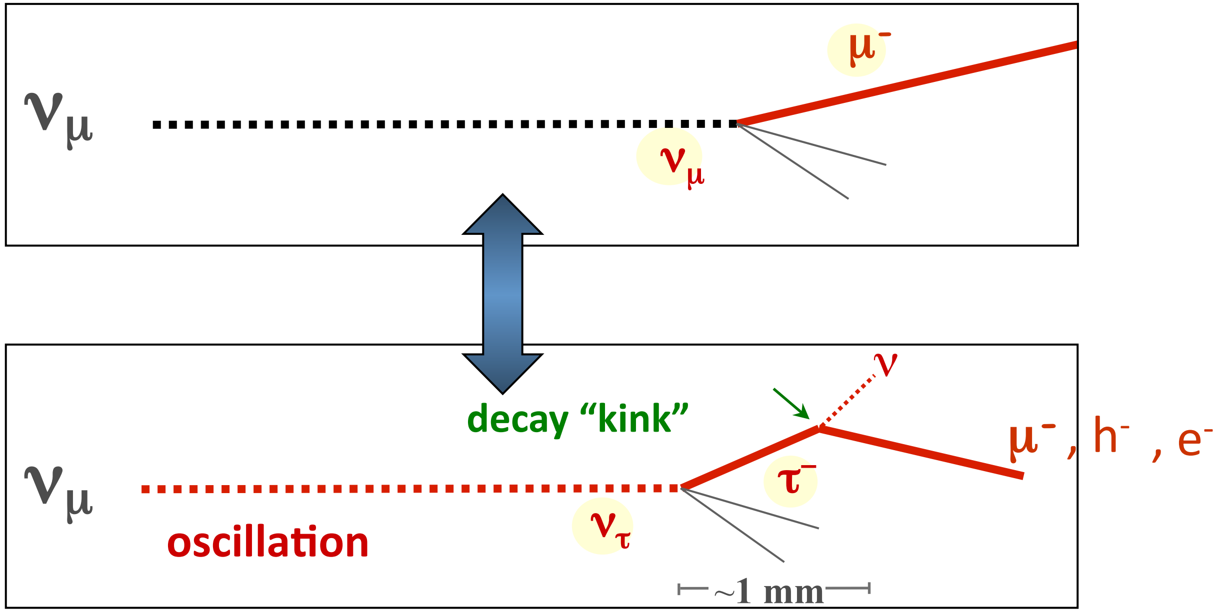
OPERA: first direct detection of neutrino oscillations in appearance mode

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:

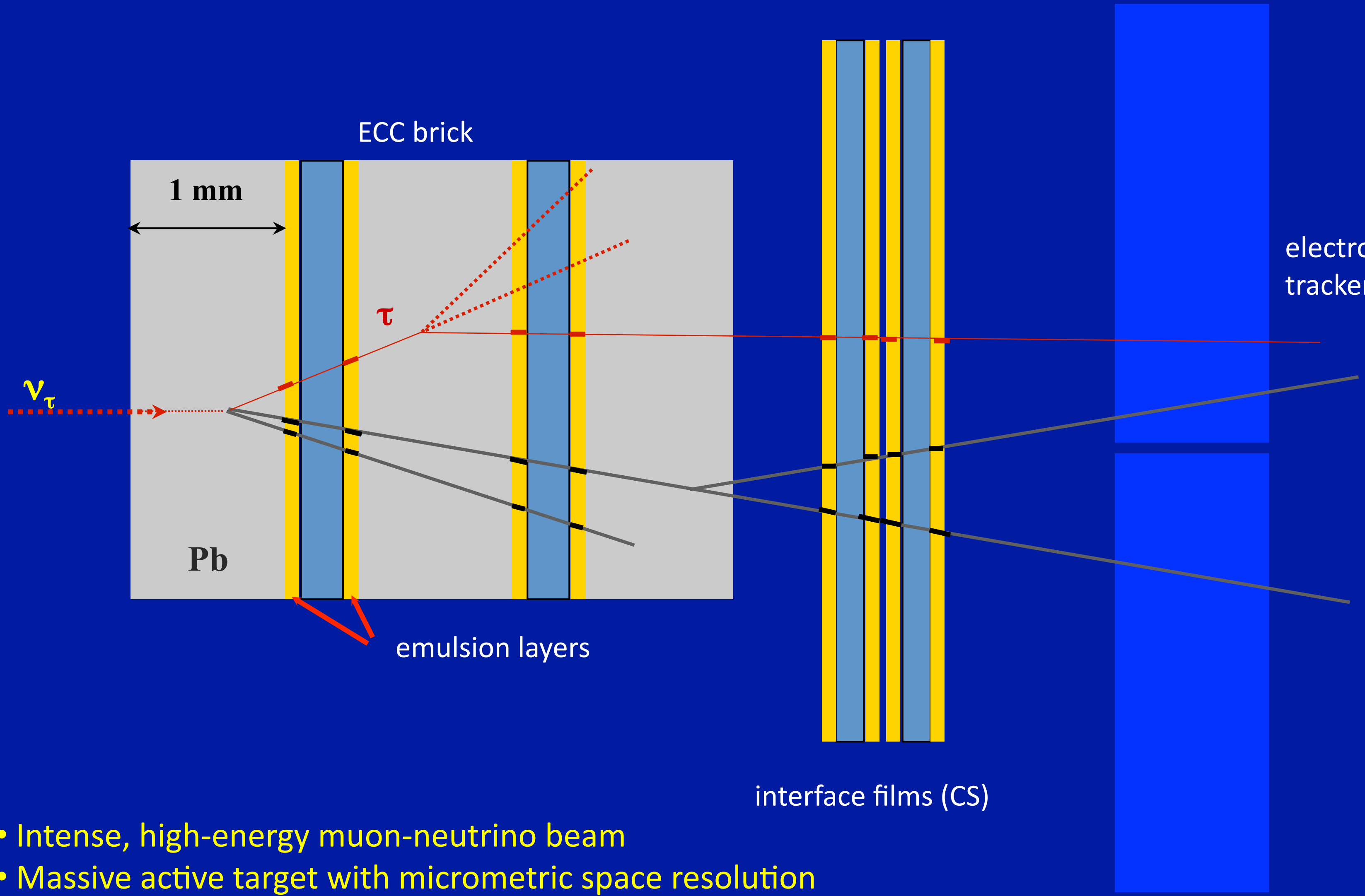
1) long baseline, 2) high neutrino energy, 3) high beam intensity, 4) detect short lived τ's



plus 3-prong decay modes

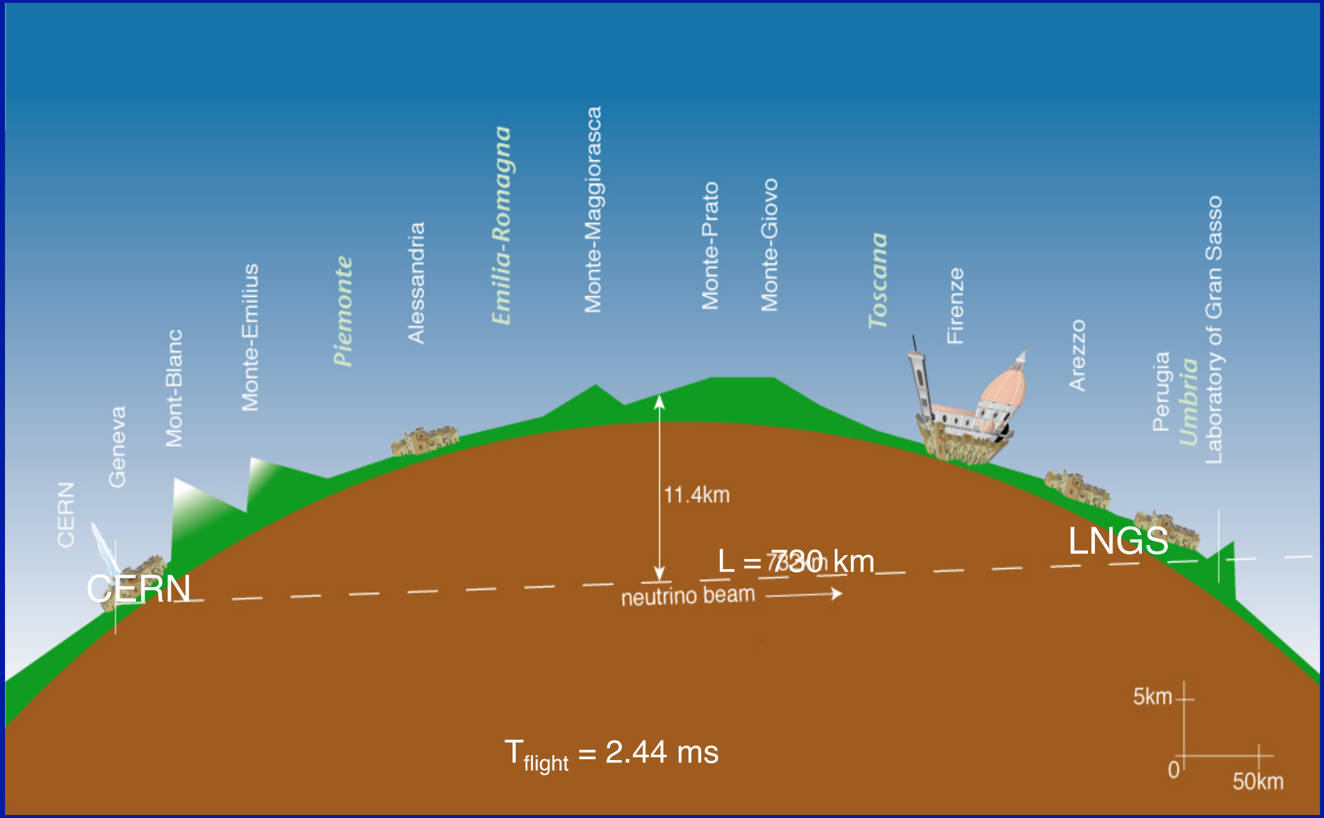
A. Ereditato - April 2012

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 from CERN)

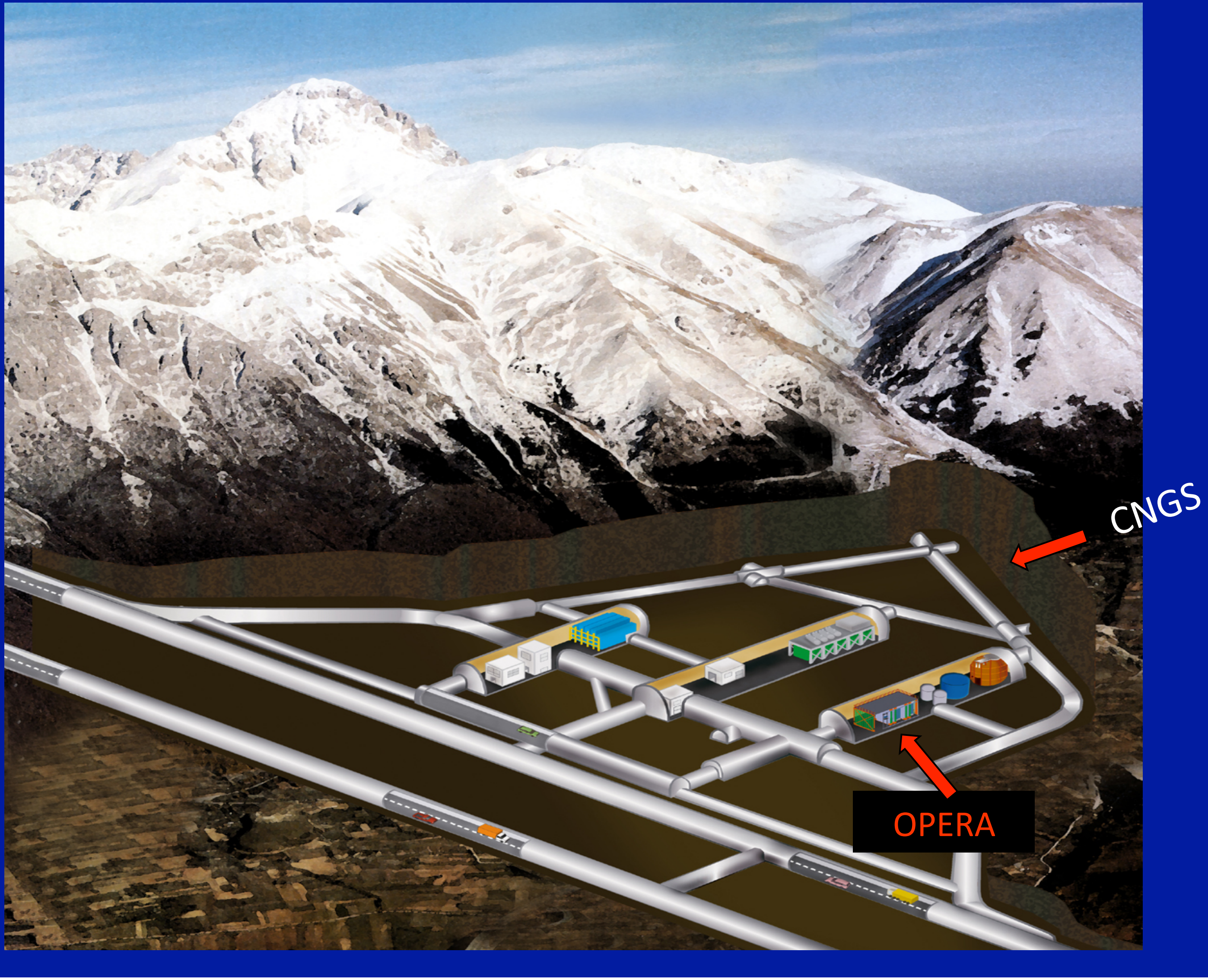


< E >	17 GeV
L	730 km
$(\nu_e + \bar{\nu}_e) / \nu_\mu$ (CC)	0.87%
$\nu_\mu / \bar{\nu}_\mu$ (CC)	2.1%
ν_τ prompt	negligible

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)

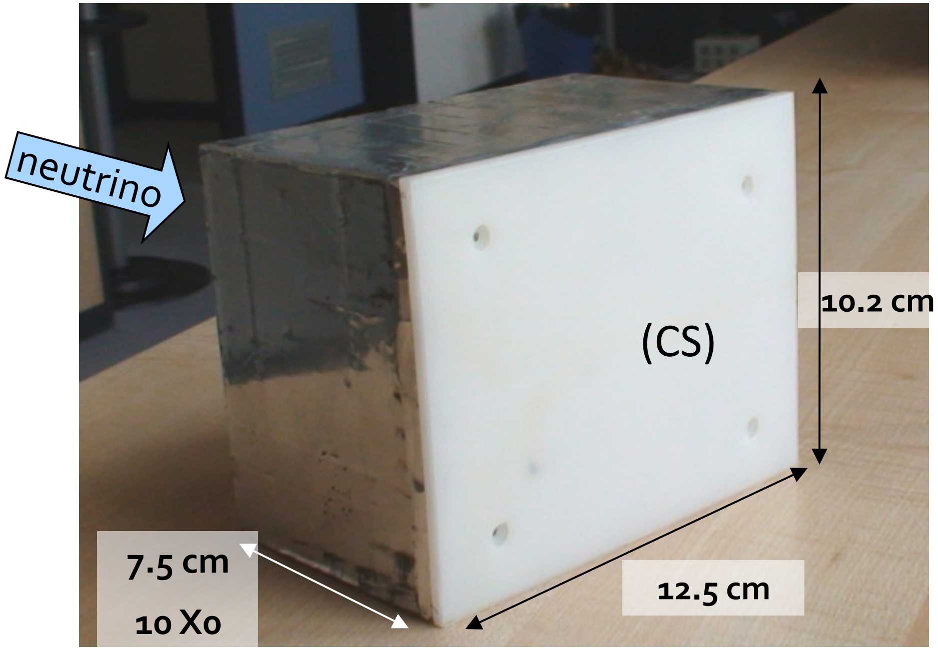
LNGS of INFN, the world largest underground physics laboratory:

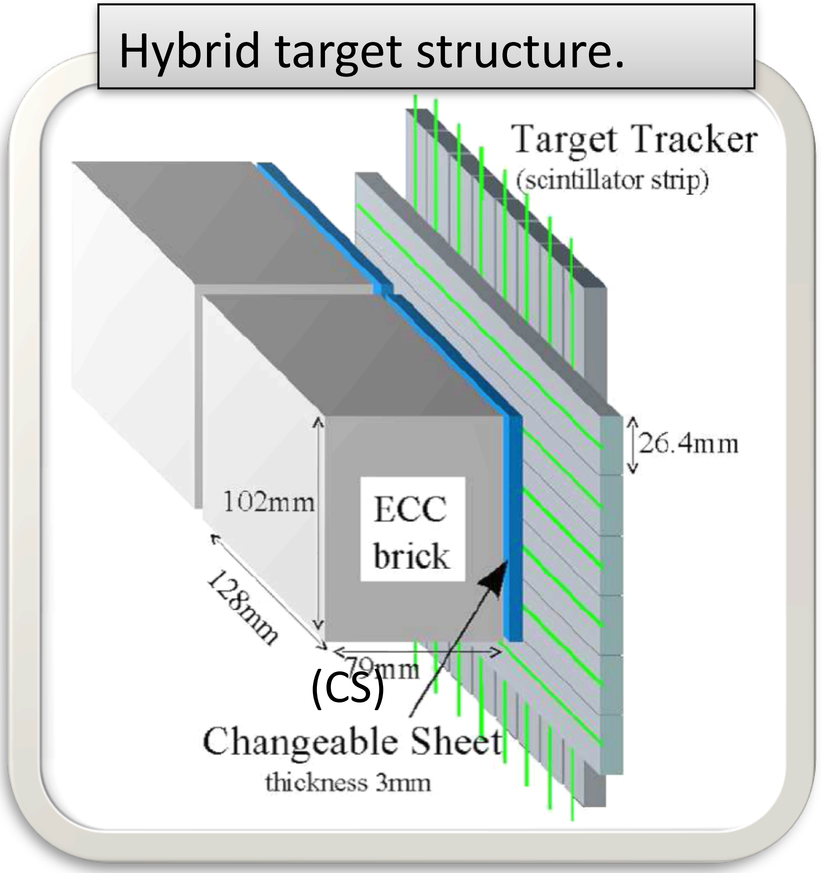
~180000 m^3 caverns’ volume, ~3100 m.w.e. overburden, ~1 cosmic μ / m^2 x hour, experimental infrastructure, variety of experiments. Perfectly fit to host detector and related facilities, caverns oriented towards CERN.

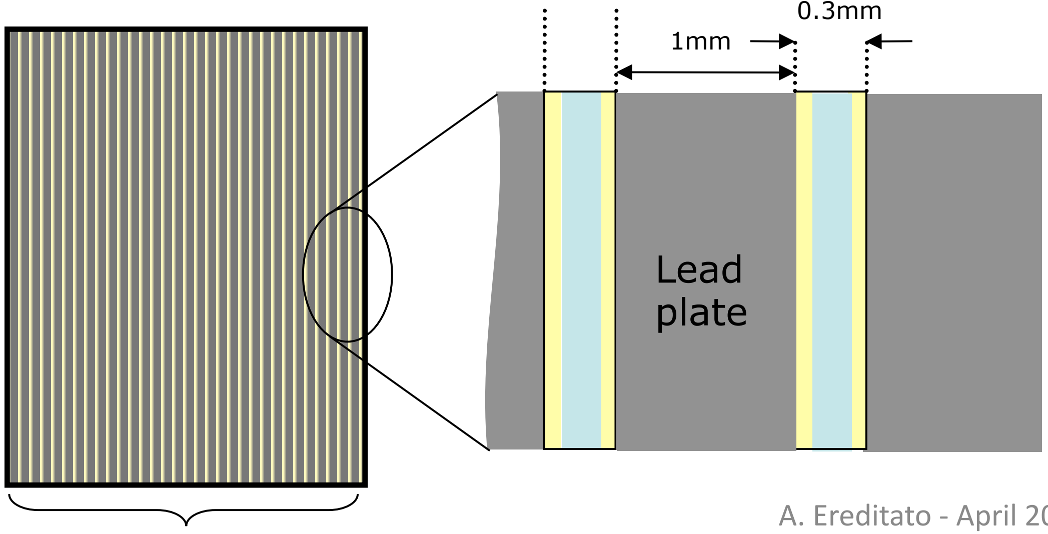


Two target super-modules, each with an iron spectrometer for muon detection (BG rejection and tau-into-muon decay channel)

The heart of the experiment:
THE ECC TARGET BRICKS




Hybrid target structure.



57 OPERA films, 56 lead plates

The OPERA target consists of 150’000 ECC bricks.

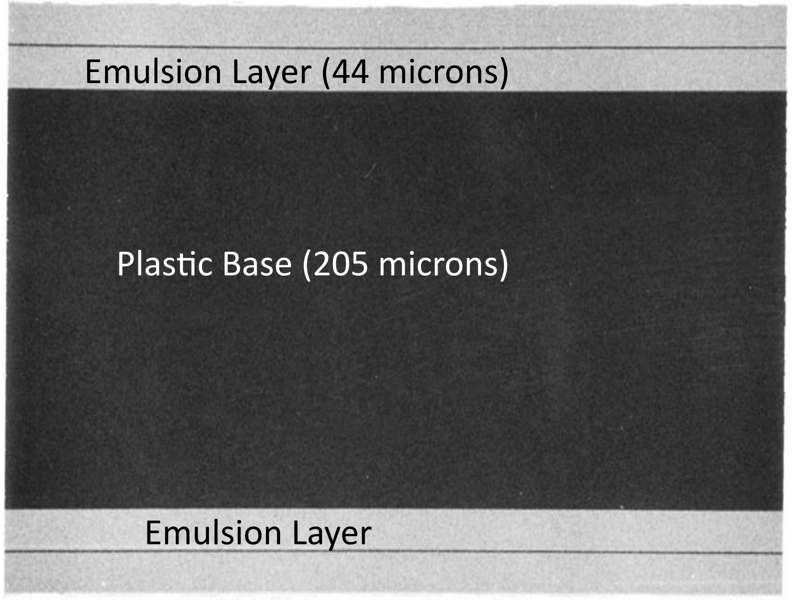
Total 105’000 m^2 of lead surface

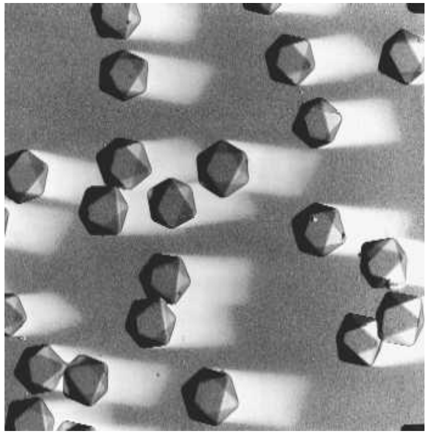
and 111’000 m^2 of film surface

(~ 8.9 million films)

Total target mass: 1.25 kton

INDUSTRIAL EMULSION FILMS BY *FUJI FILM*





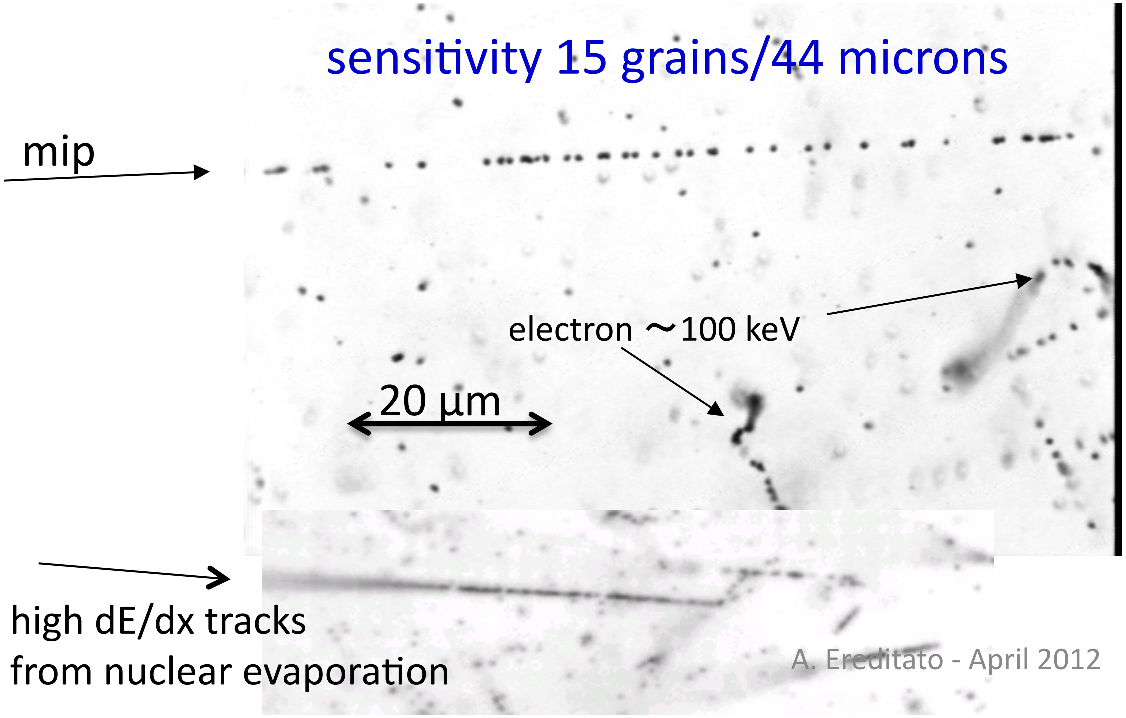
basic detector: AgBr crystal,

size = 0.2 micron

detection eff.= 0.16/crystal

10^{13} "detectors" per film

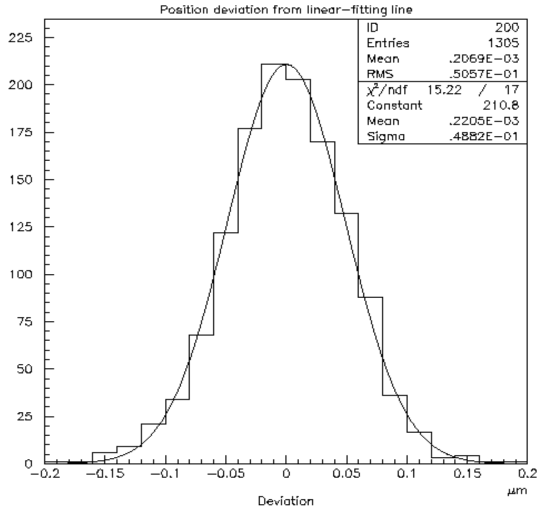
sensitivity 15 grains/44 microns



high dE/dx tracks
from nuclear evaporation

intrinsic resolution: 50 nm

deviation from linear-fit line. (2D)



PARALLEL ANALYSIS OF BRICKS

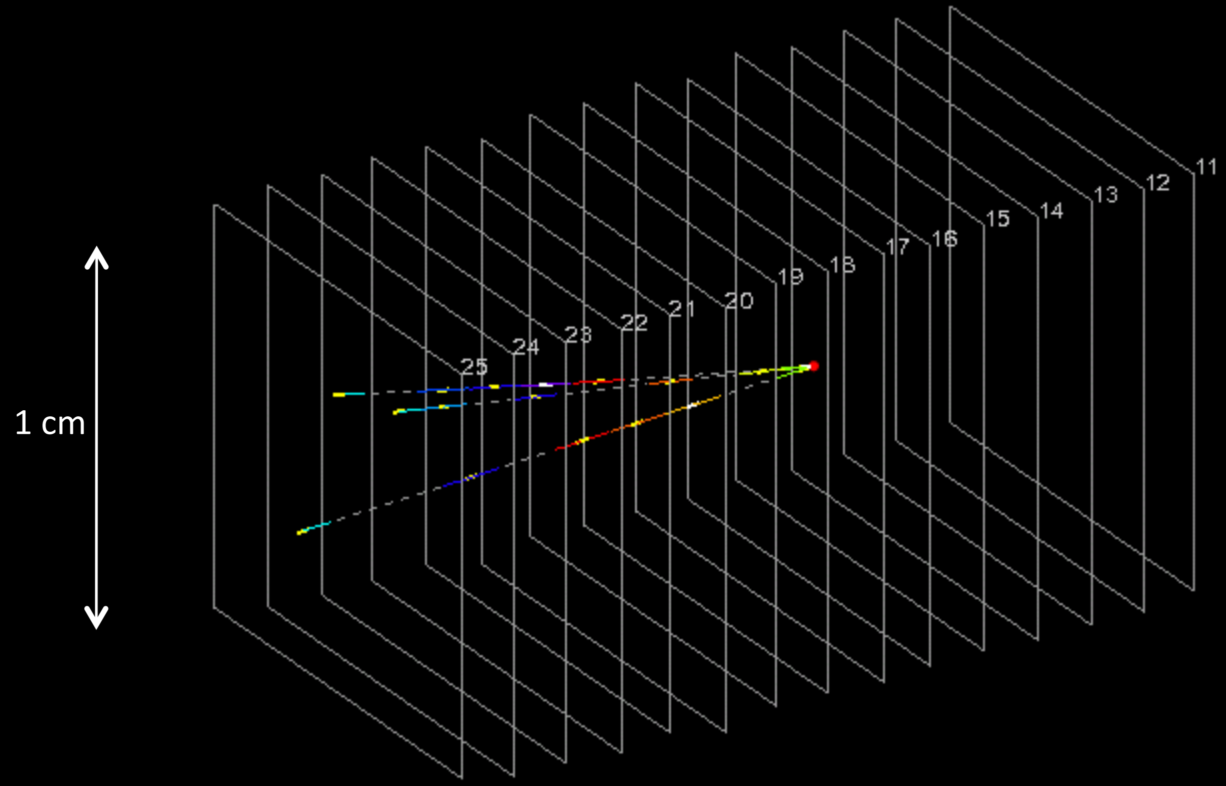
selected bricks sent
to scanning labs

Bern scanning lab

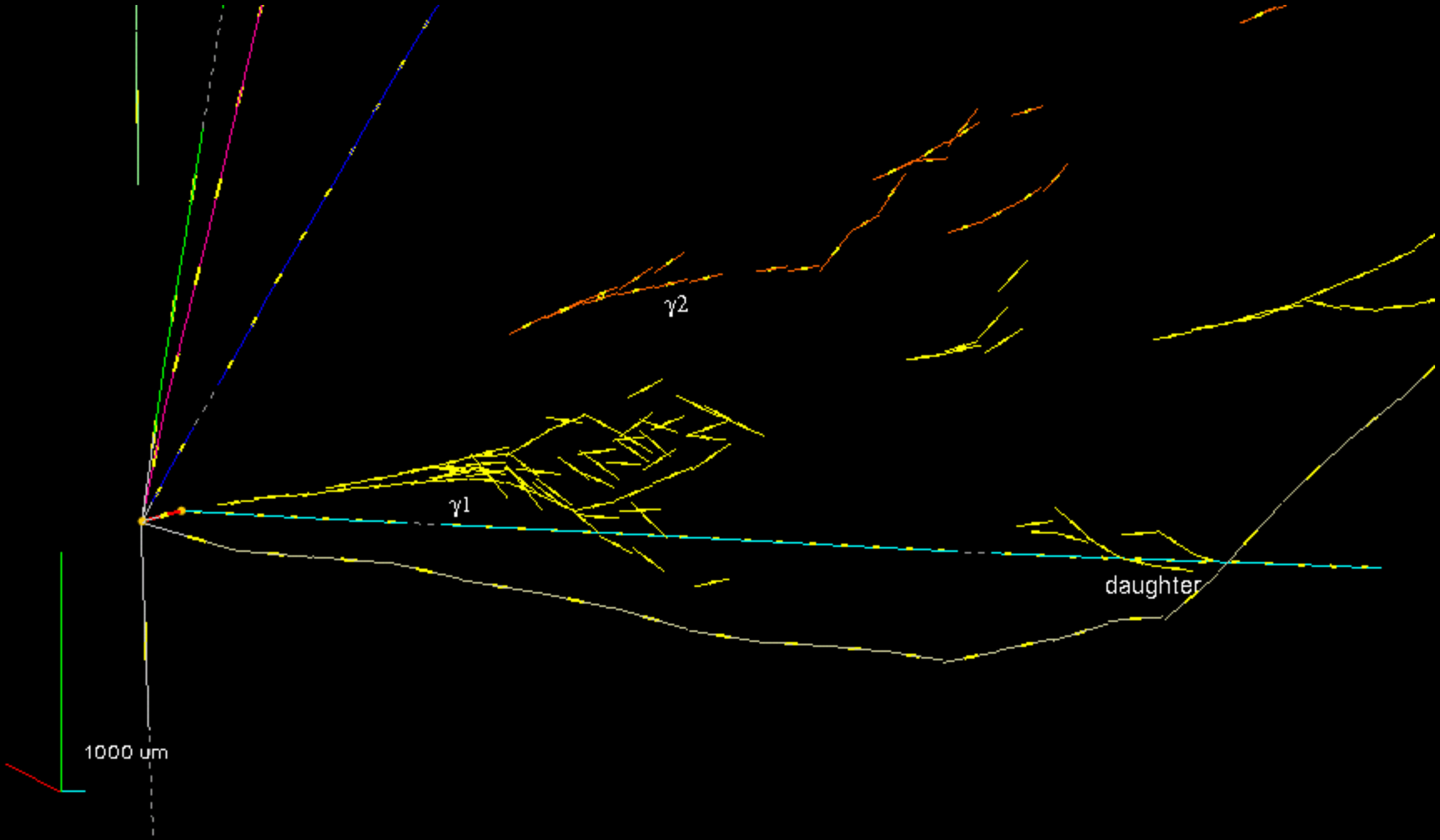
Located neutrino interaction

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.



First tau-neutrino candidate event



SOLAR NEUTRINOS

Source of Energy of the SUN : Nuclear Fusion

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

Energy Released per each Cycle

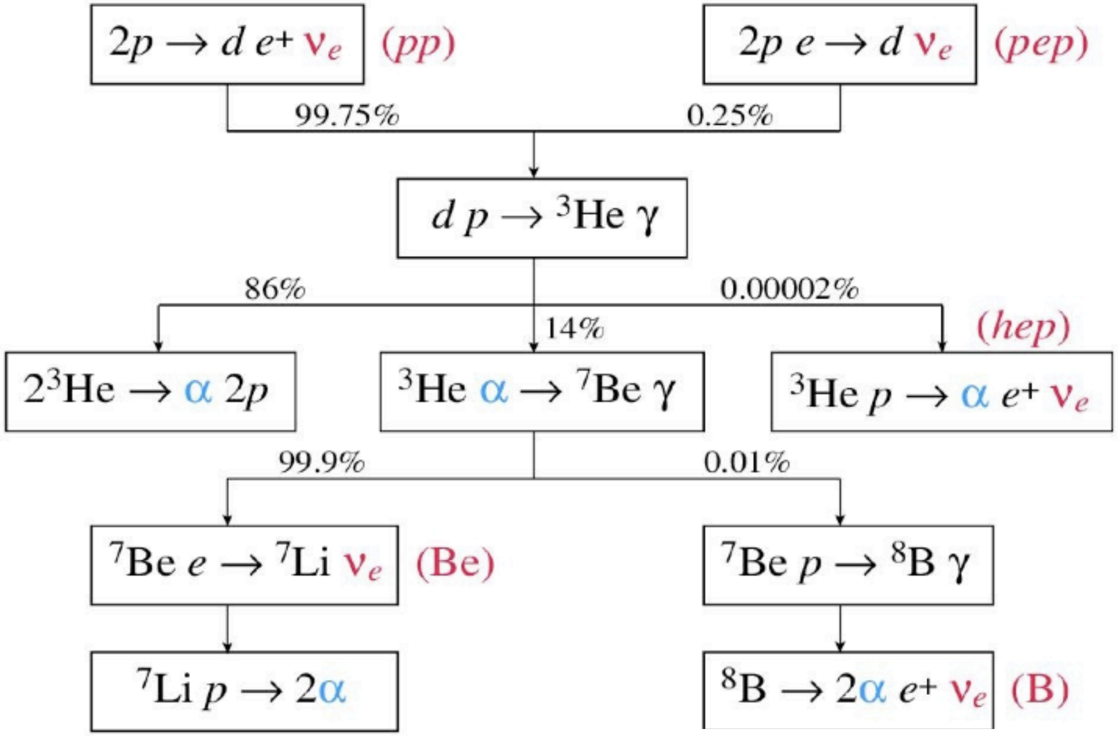
$$Q = 4m_p + 2m_e - m_{He} = 26.73\ \mathrm{MeV}$$

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

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

Neutrino Flux

PP cycles



$2p \rightarrow d\, e^+ \nu_e$ (pp)

$2p\, e \rightarrow d\, \nu_e$ (pep)

99.75%

0.25%

$d\, p \rightarrow {}^3\mathrm{He}\, \gamma$

86%

14%

0.00002%

(hep)

$2\,{}^3\mathrm{He} \rightarrow \alpha\, 2p$

${}^3\mathrm{He}\, \alpha \rightarrow {}^7\mathrm{Be}\, \gamma$

${}^3\mathrm{He}\, p \rightarrow \alpha\, e^+ \nu_e$

99.9%

0.01%

${}^7\mathrm{Be}\, e \rightarrow {}^7\mathrm{Li}\, \nu_e$ (Be)

${}^7\mathrm{Be}\, p \rightarrow {}^8\mathrm{B}\, \gamma$

${}^7\mathrm{Li}\, p \rightarrow 2\alpha$

${}^8\mathrm{B} \rightarrow 2\alpha\, e^+ \nu_e$ (B)

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

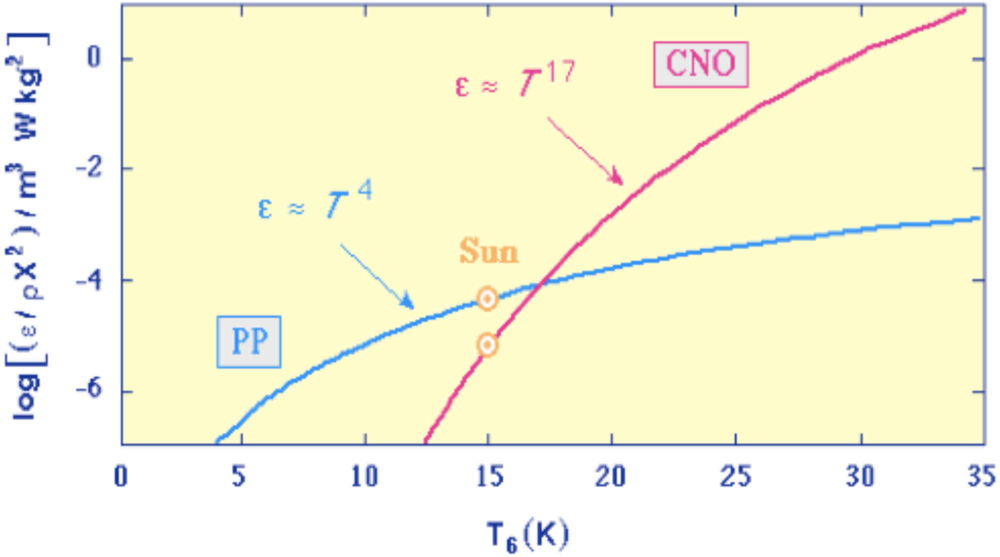
${}^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C}+e^++\nu_e$ (1.2 MeV)

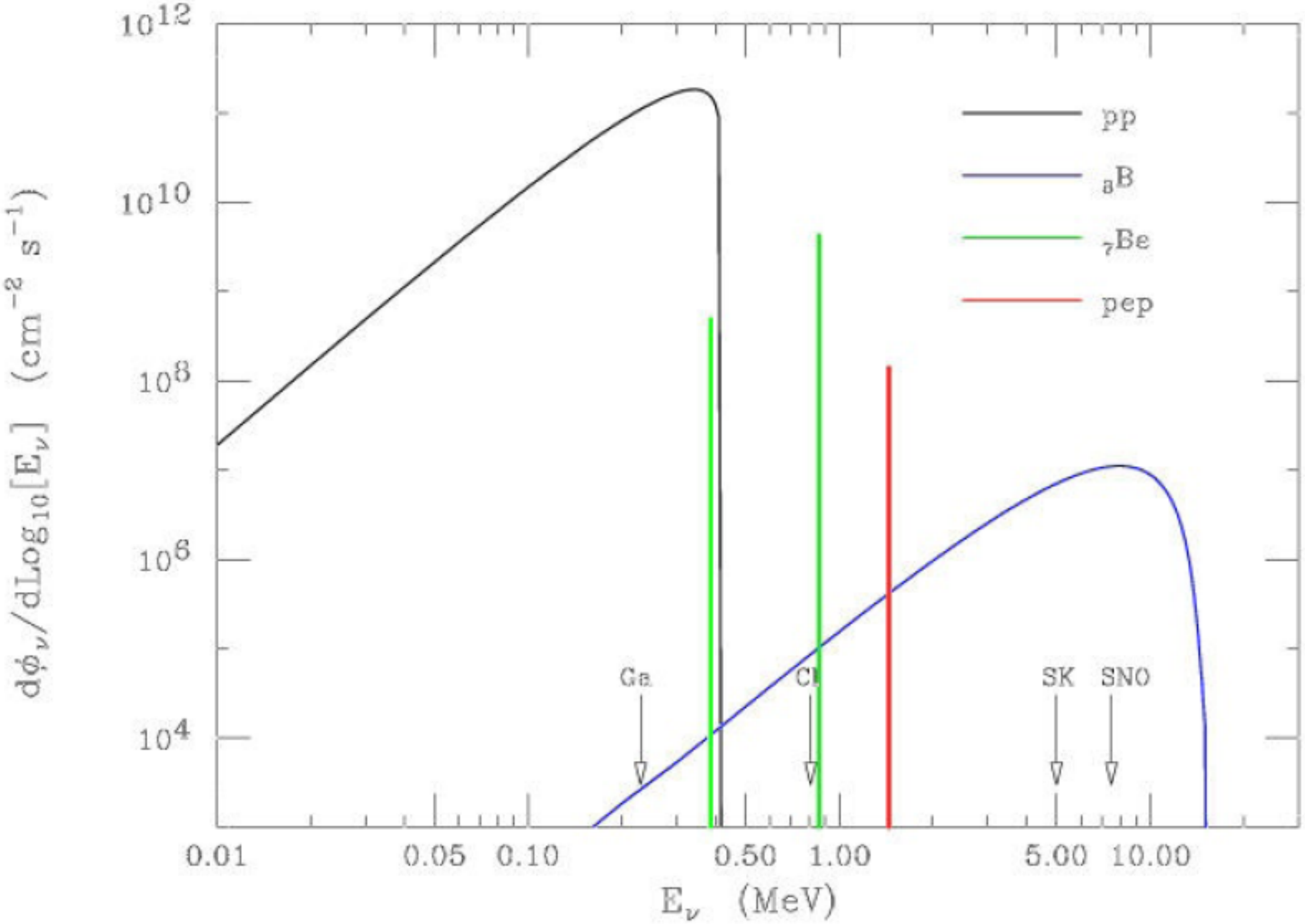
${}^{13}\mathrm{C}+p \rightarrow {}^{14}\mathrm{N}+\gamma$

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

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

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




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)

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

Gallium Experiments
[Gallex, Sage]

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

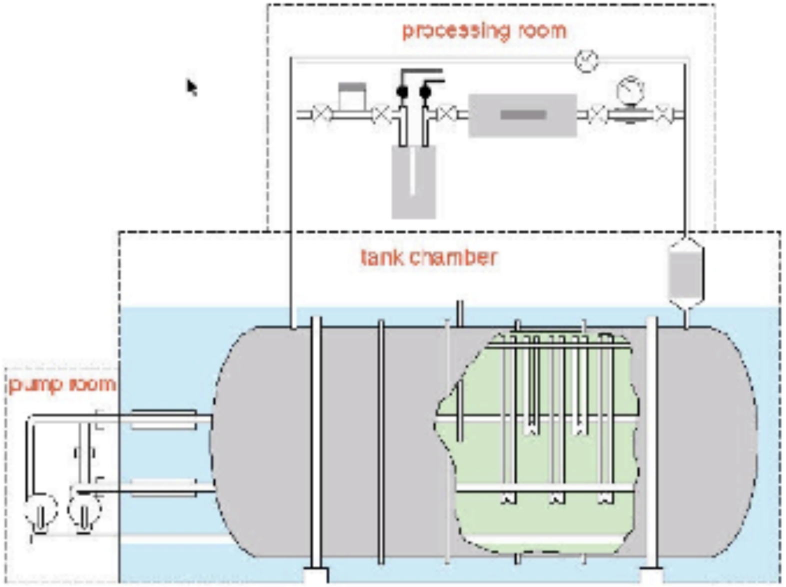
(Super)-Kamiokande
Electron Scattering

$$\boxed{\nu_x + e^- \rightarrow \nu_x + e^-}$$

Heavy Water [SNO]

$$\boxed{\nu_e + d \rightarrow e^- + p + p}$$

$$\boxed{\nu_x + d \rightarrow \nu_x + p + n}$$

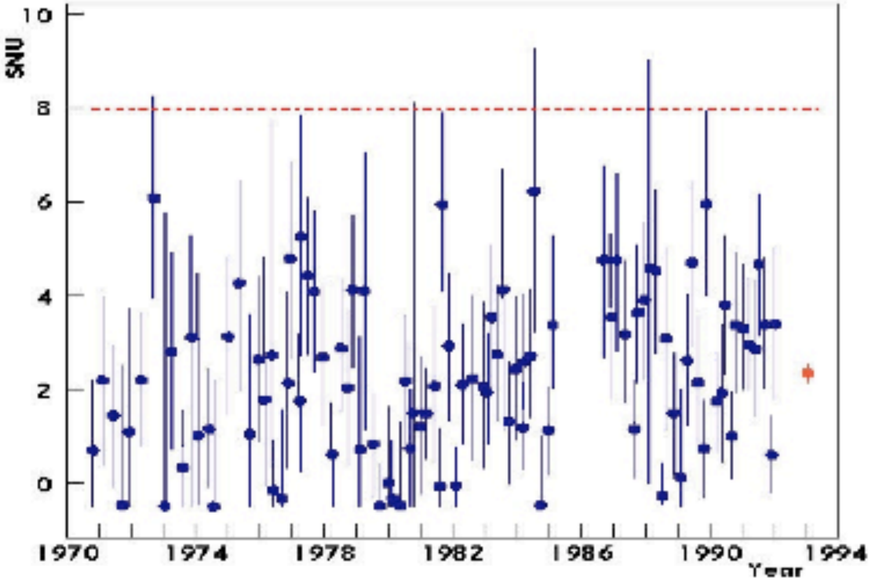


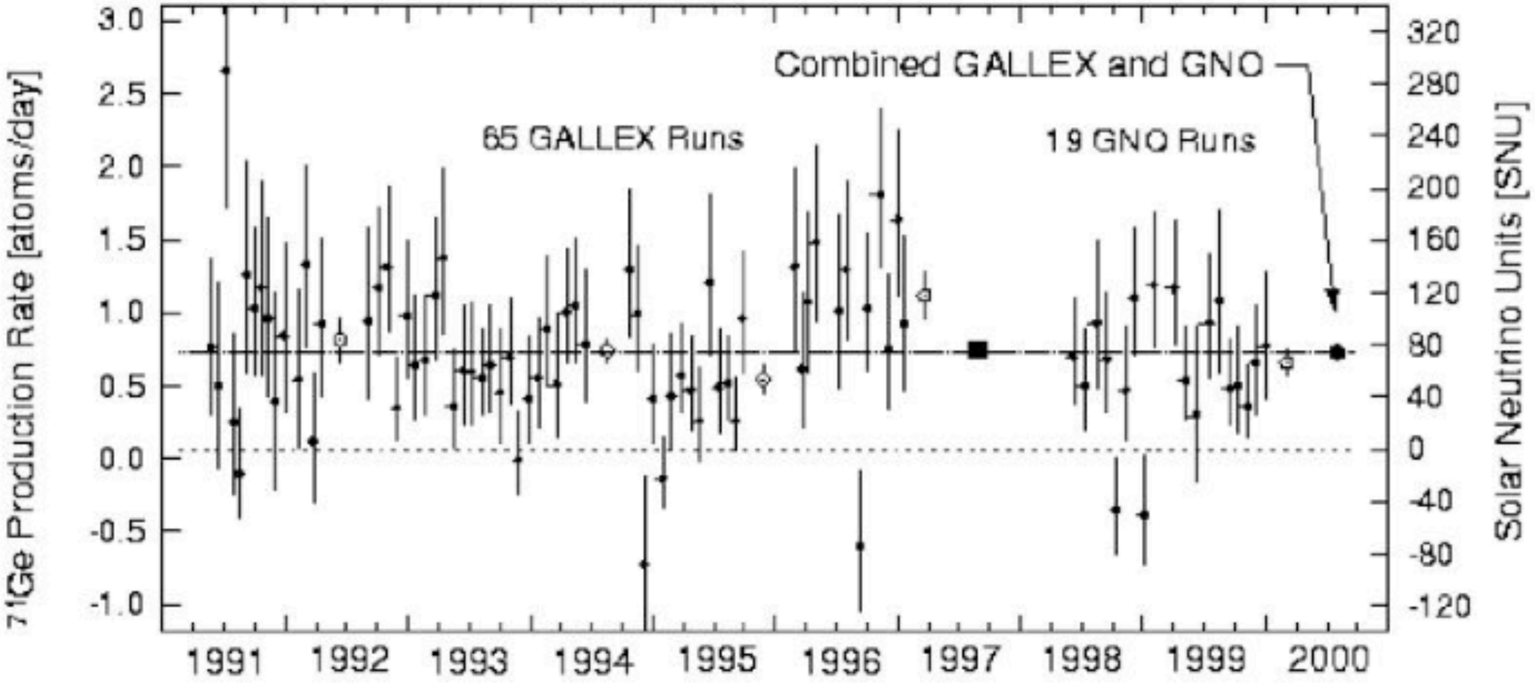
Davis experiment

Chlorine

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

615 tons C_2Cl_4

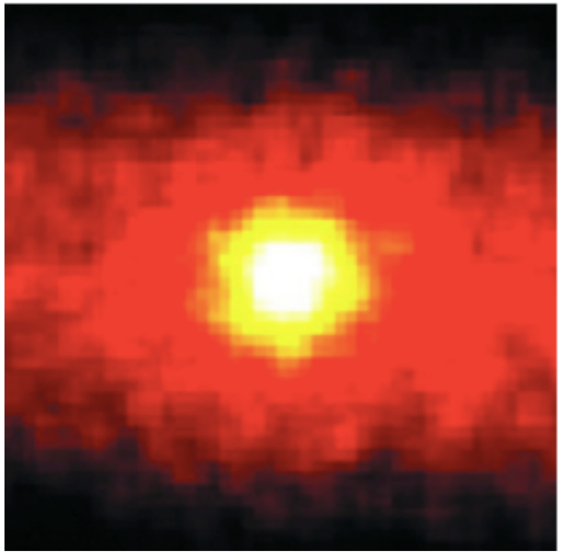




Experiment	(SNU) Prediction	Data	Data/Prediction
Chlorine	$7.6^{+1.3}_{-1.1}$	2.56 ± 0.23	0.34 ± 0.06
GALLEX + GNO	128^{+9}_{-7}	$74.1^{+6.7}_{-7.8}$	0.58 ± 0.07
SAGE	128^{+9}_{-7}	$75.4^{+7.8}_{-7.4}$	0.59 ± 0.07

Electron Scattering

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



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

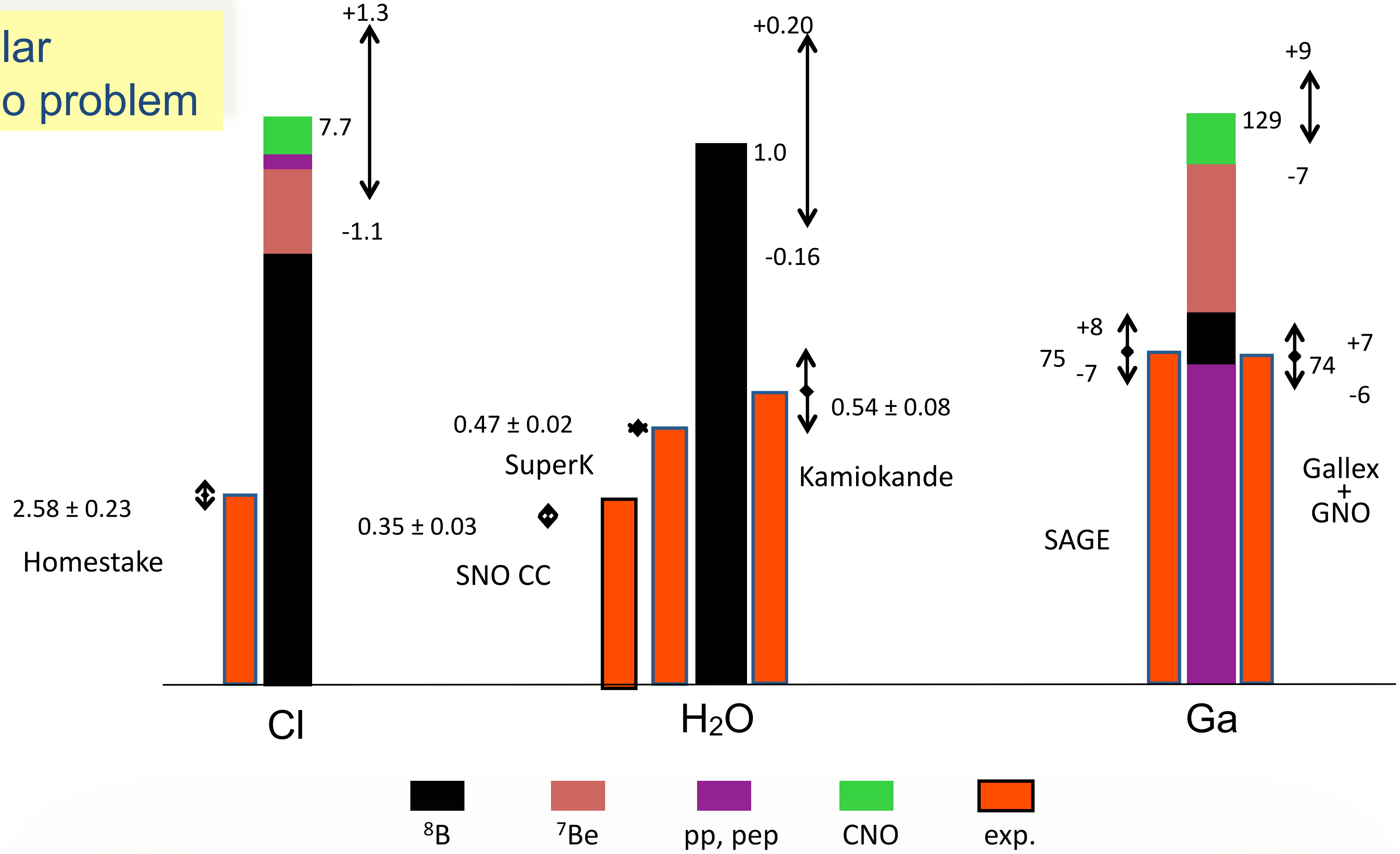
T = Kinetic Energy of
the final state electron

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

Cross section strongly
peaked for electron emission
in the neutrino direction

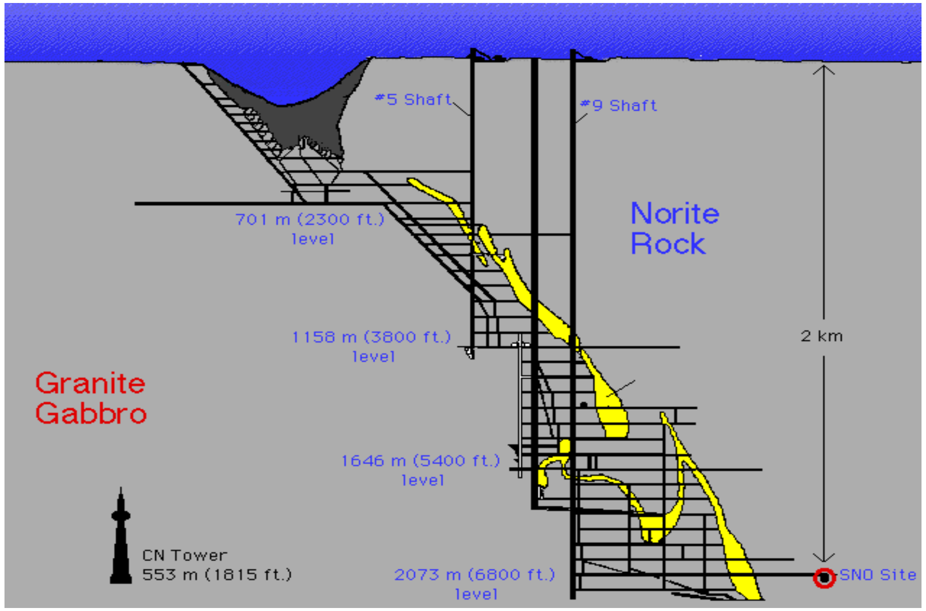
$$g_R^2 = \begin{cases} \sin^4\theta_W & \simeq \ 0.0538 \quad , \quad \nu_e \\ \left(\frac{1}{2} + \sin^2\theta_W\right)^2 & \simeq \ 0.536 \quad , \quad \bar{\nu}_e \\ \sin^4\theta_W & \simeq \ 0.0538 \quad , \quad \nu_i \\ \left(-\frac{1}{2} + \sin^2\theta_W\right)^2 & \simeq \ 0.0719 \quad , \quad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

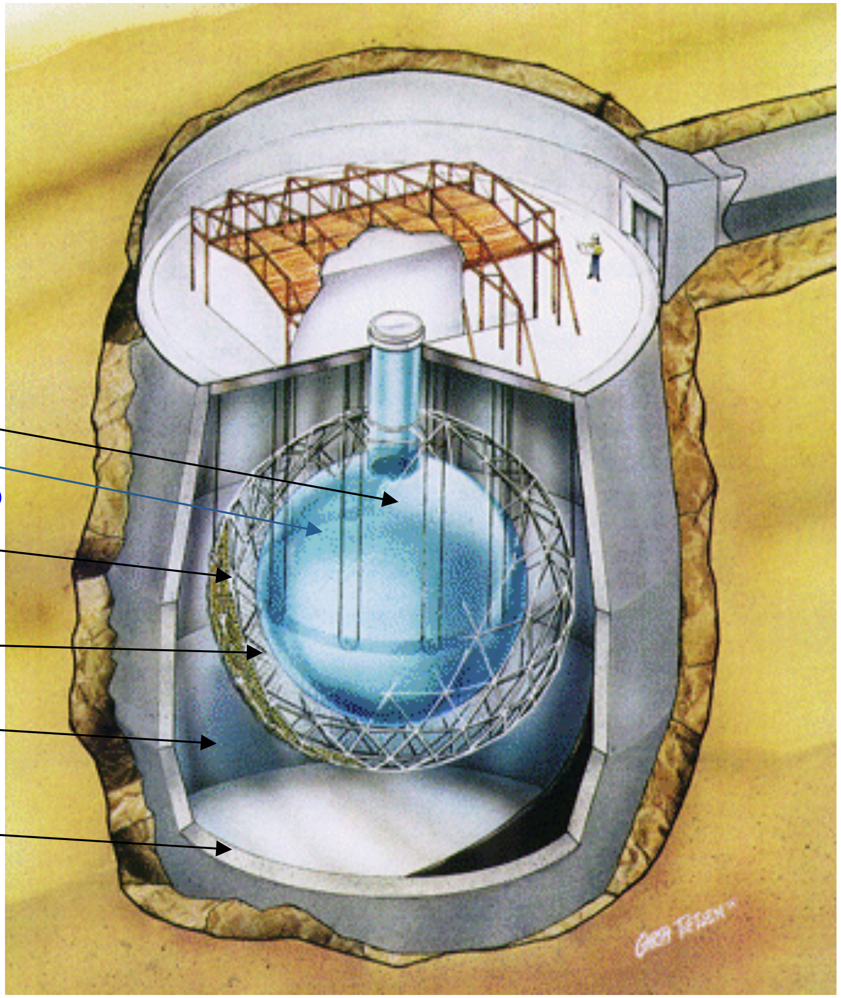
The solar neutrino problem



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 $\nu_e + \mathrm{d} \longrightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^-$

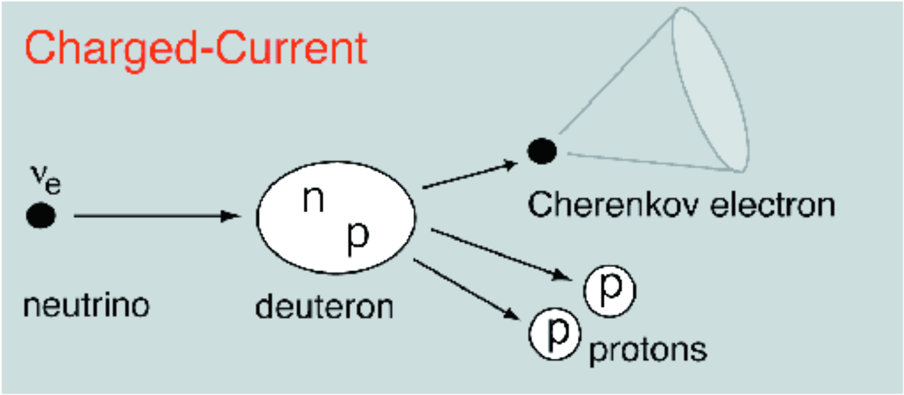
- Q = 1.445 MeV
- good measurement of ν_e energy spectrum
- some directional info $\propto (1 - 1/3 \cos\theta)$
- ν_e only

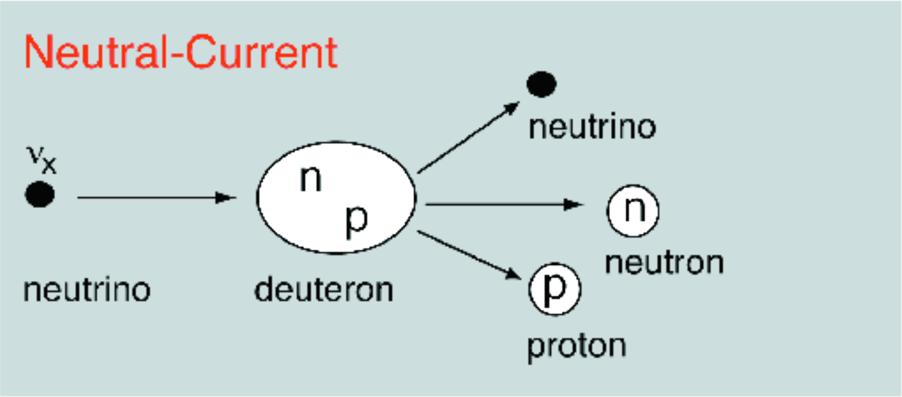
NC $\nu_x + \mathrm{d} \longrightarrow \mathrm{p} + \mathrm{n} + \nu_x$

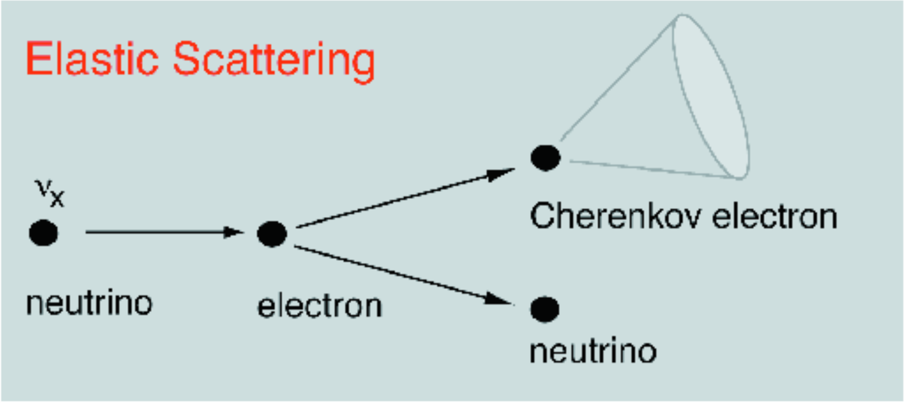
- Q = 2.22 MeV
- measures total ^{8}B ν flux from the Sun
- equal cross section for all active ν flavors

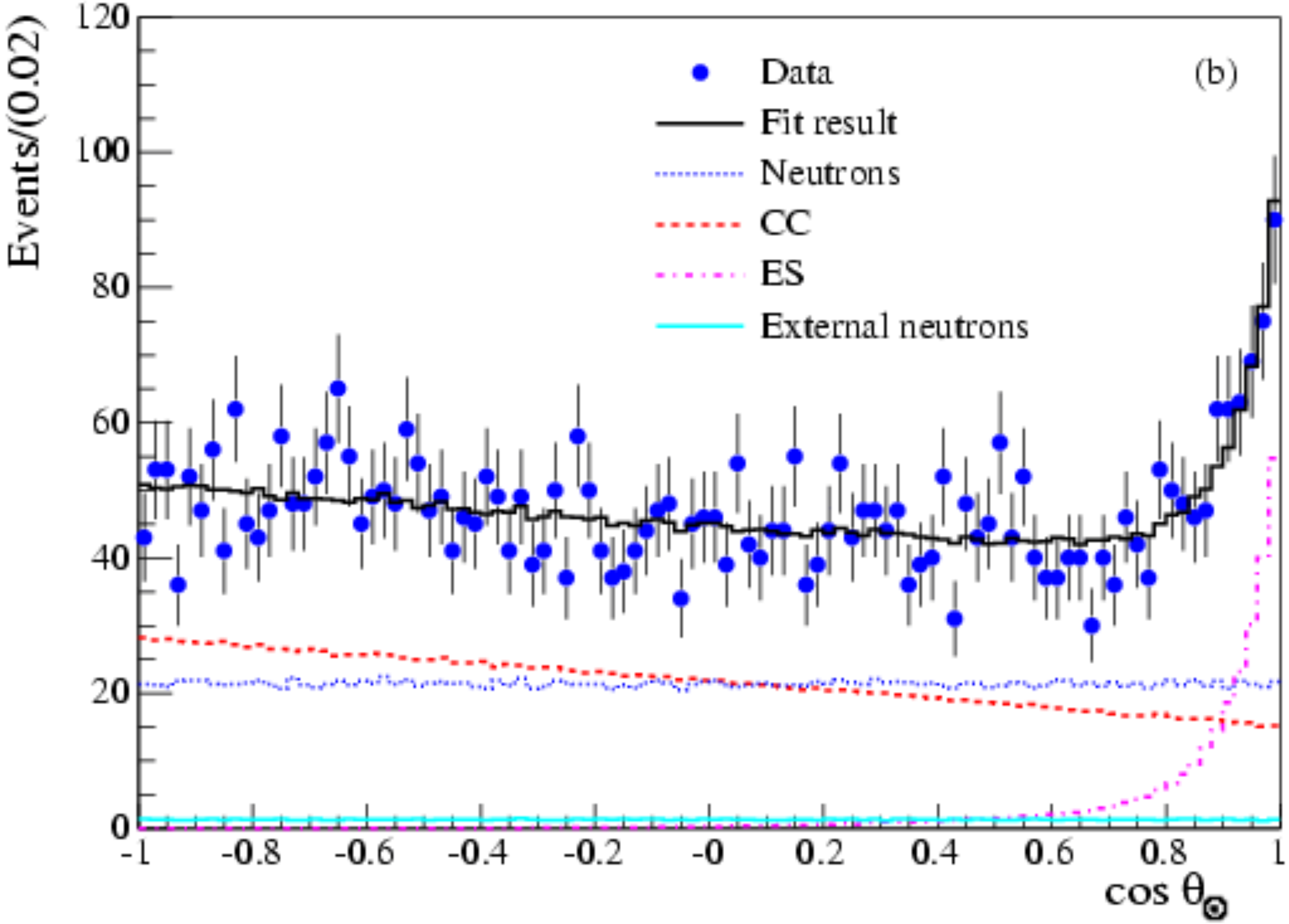
ES $\nu_x + \mathrm{e}^- \longrightarrow \nu_x + \mathrm{e}^-$

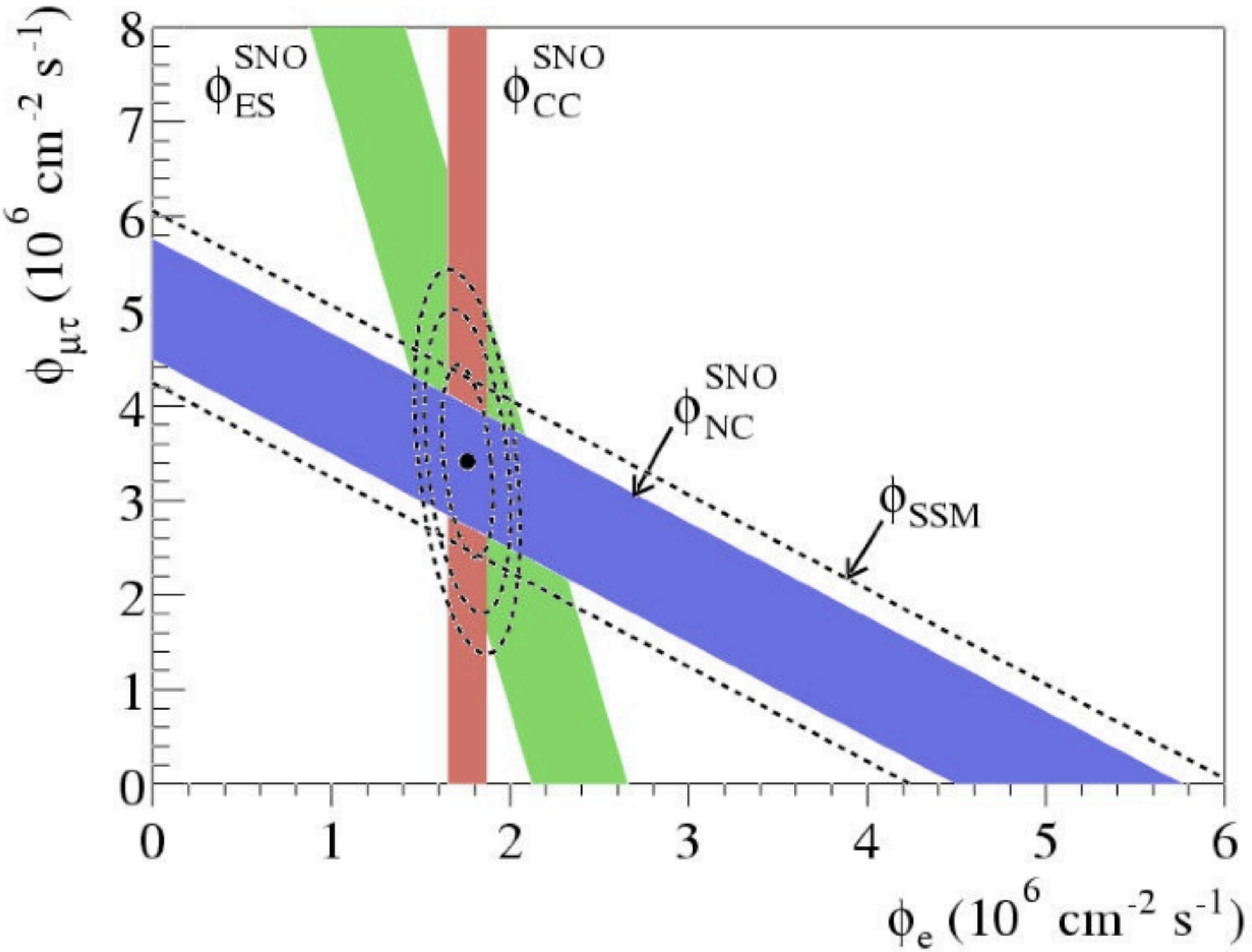
- low statistics
- mainly sensitive to ν_e, some ν_μ and ν_τ
- strong directional sensitivity





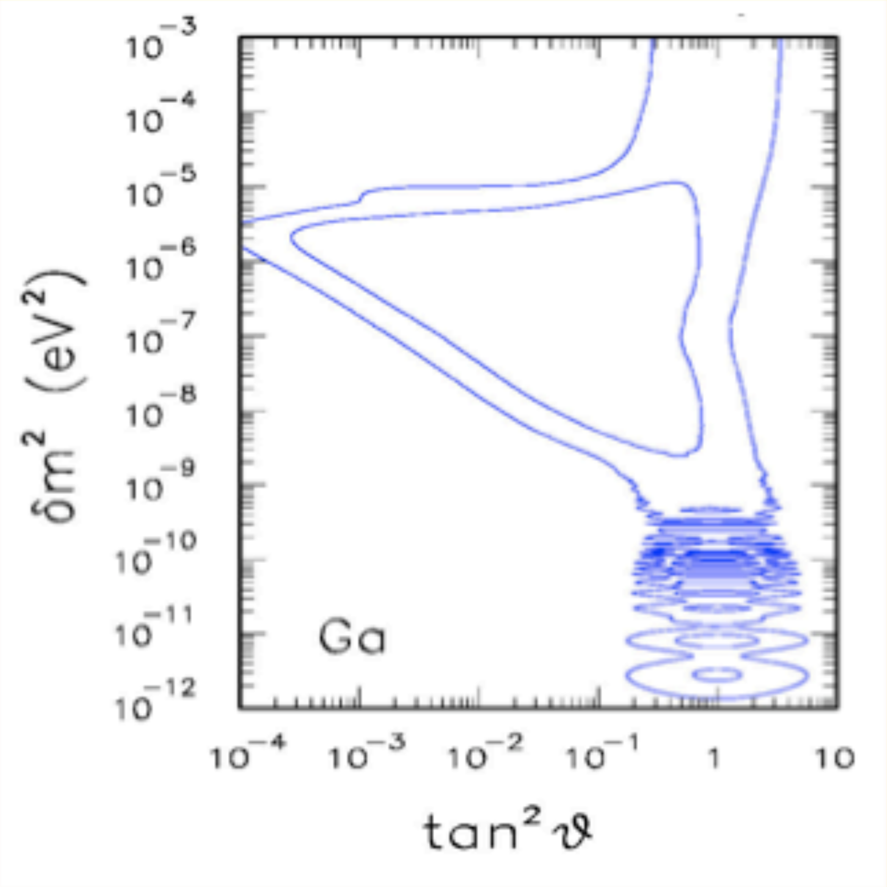



Events/(0.02)
0
20
40
60
80
100
120
-1
-0.8
-0.6
-0.4
-0.2
-0
0.2
0.4
0.6
0.8
1
cos $\theta_\odot$
(b)
Data
Fit result
Neutrons
CC
ES
External neutrons


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")



E.g., in Gallium expts:

"matter" (MSW) solutions

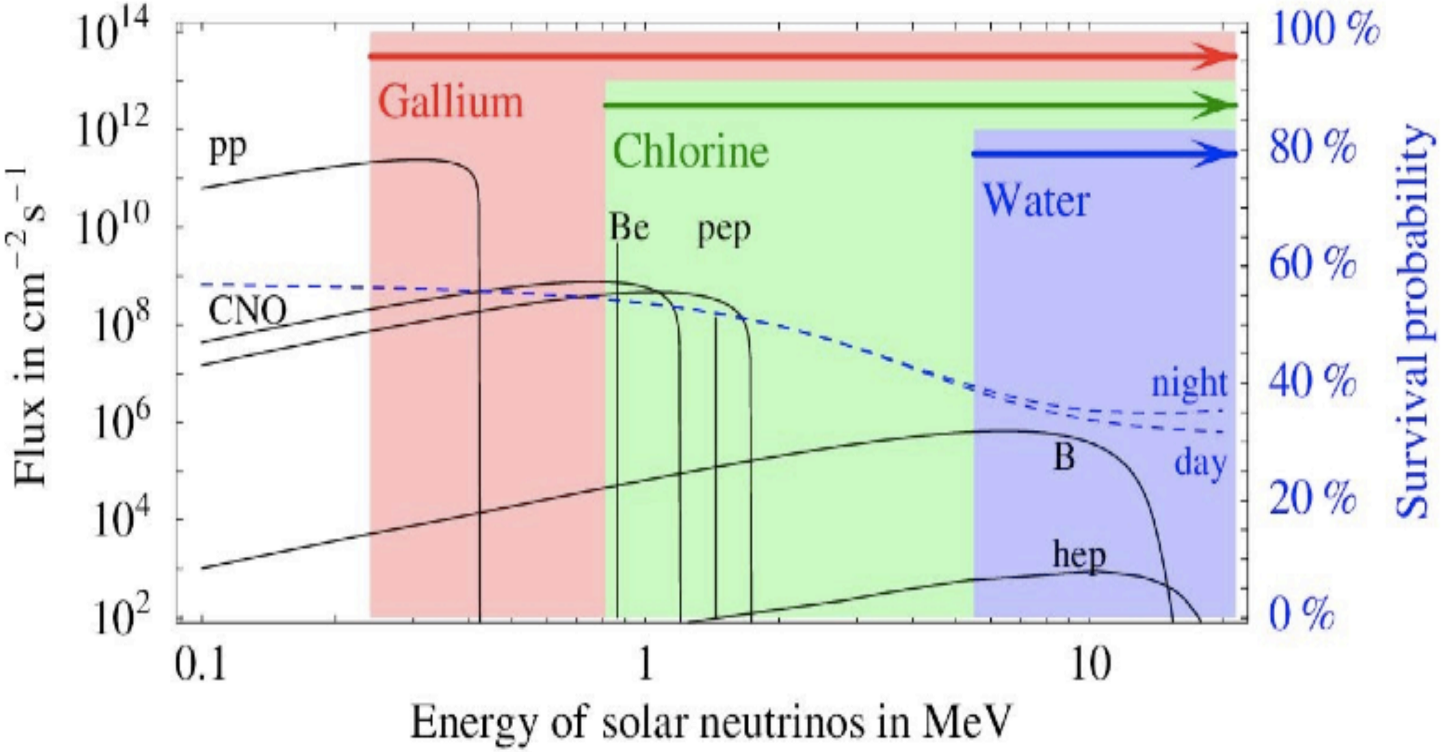
"vacuum" solutions

"small" mixing

"large" mixing

+ many "exotic" or non-oscillatory solutions…

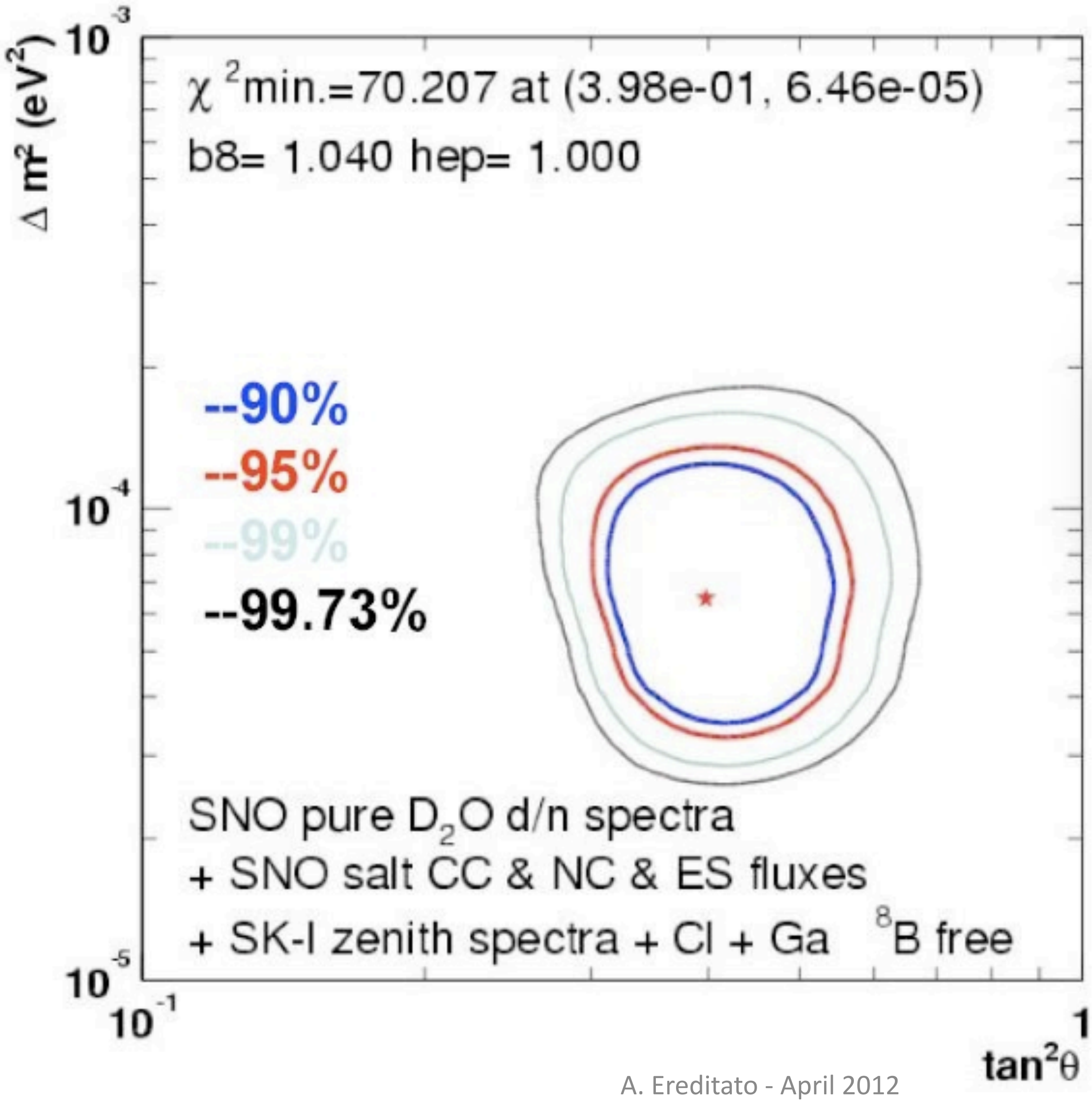
…this millennium (after the SNO result of 2002):
everything points to MSW matter oscillations in the Sun



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) ≃ $\sin^2\theta_{12}$

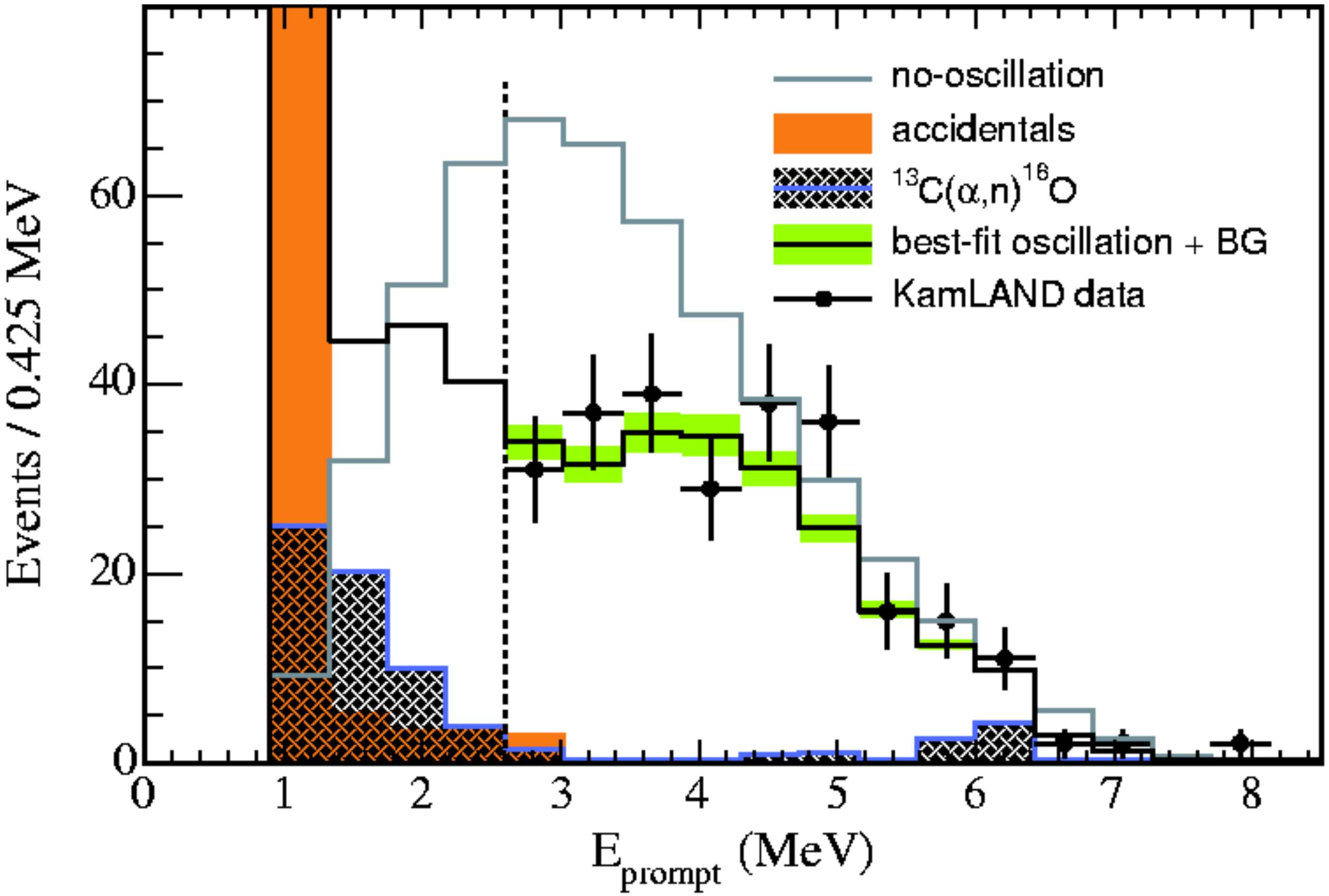
Combining all solar neutrino results



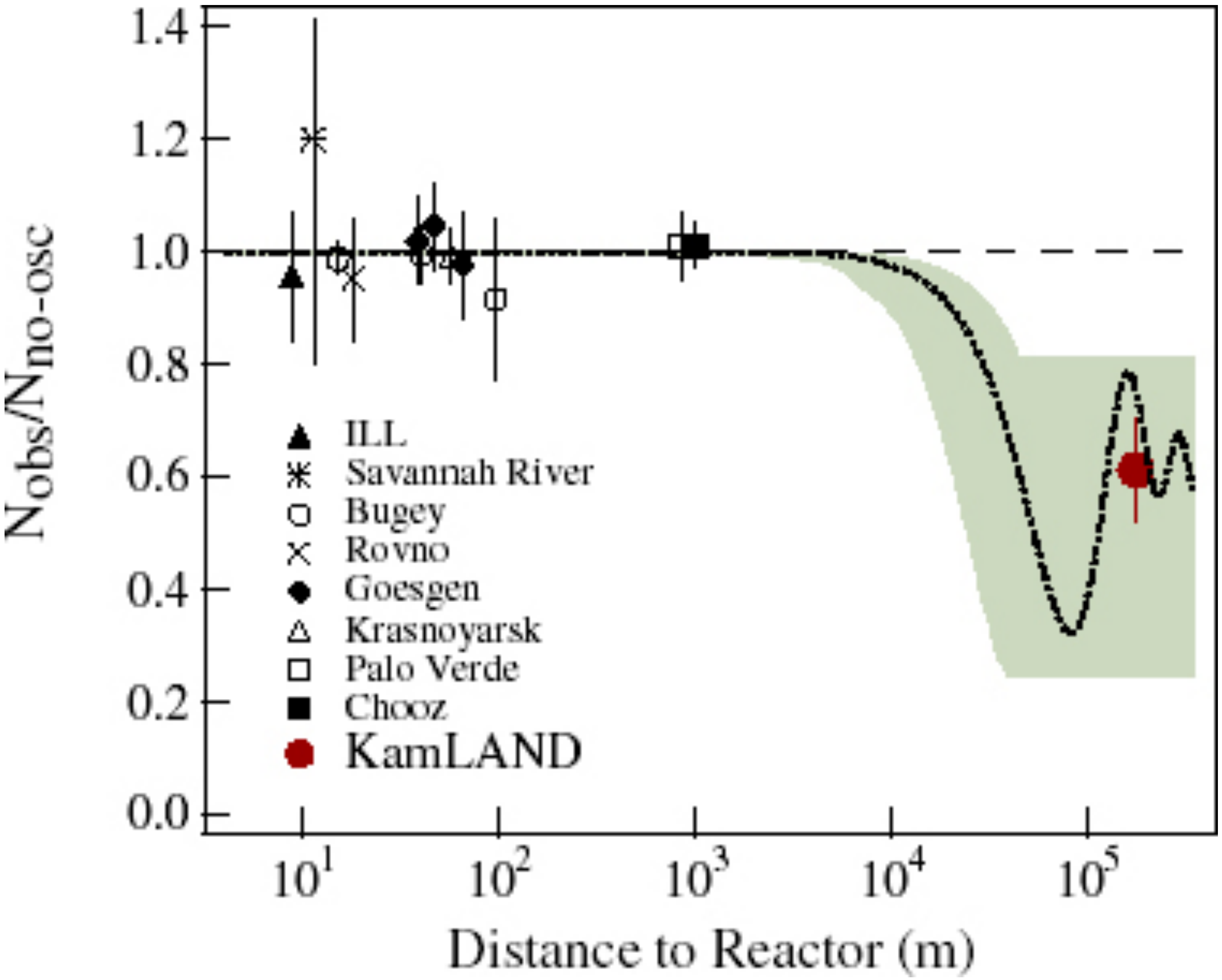
$\theta_{12} \sim 34^0$

$\Delta m^2_{12} \sim 7.6 \times 10^{-5}$ eV^2

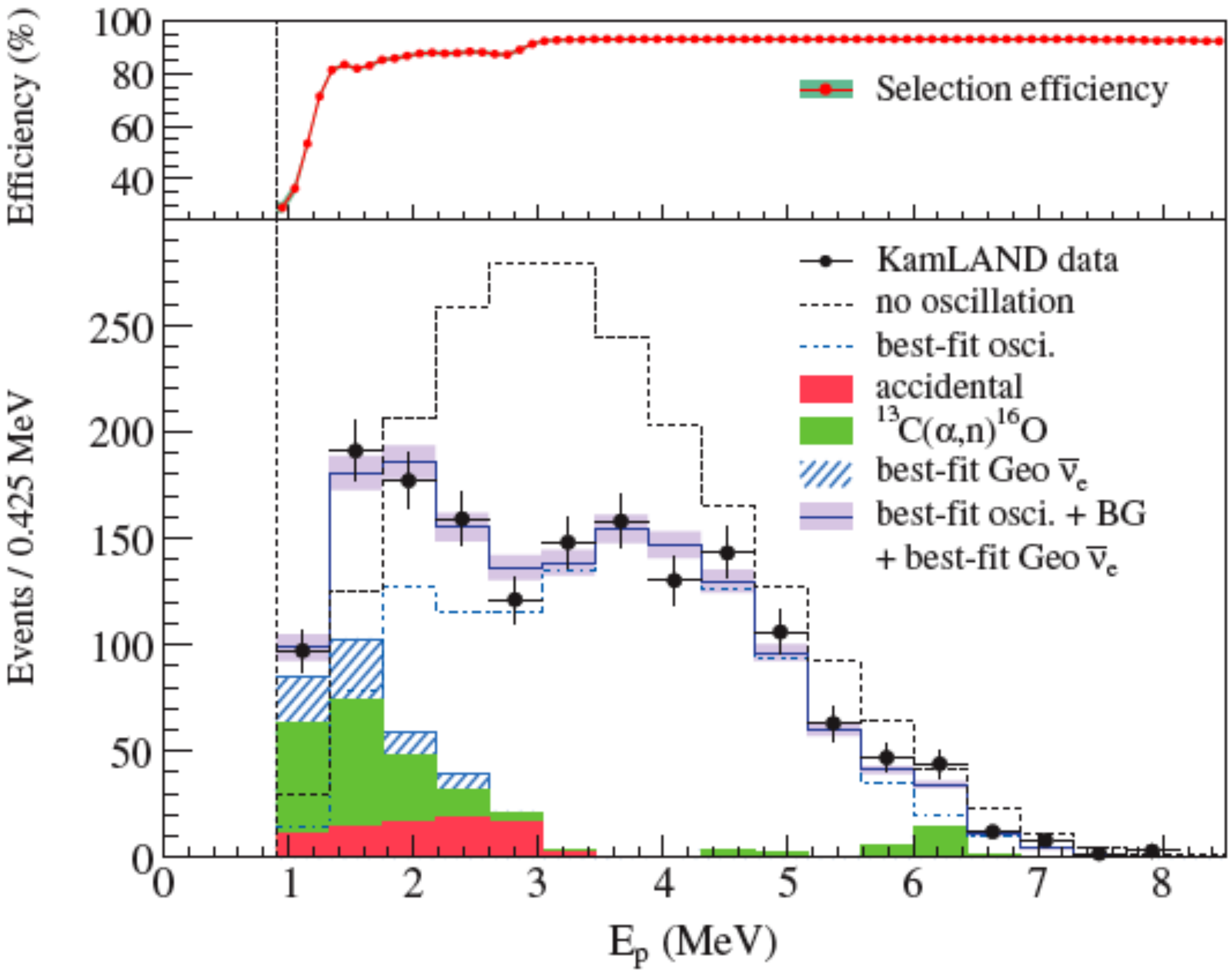
Clarifying result: KAMLAND (2002)



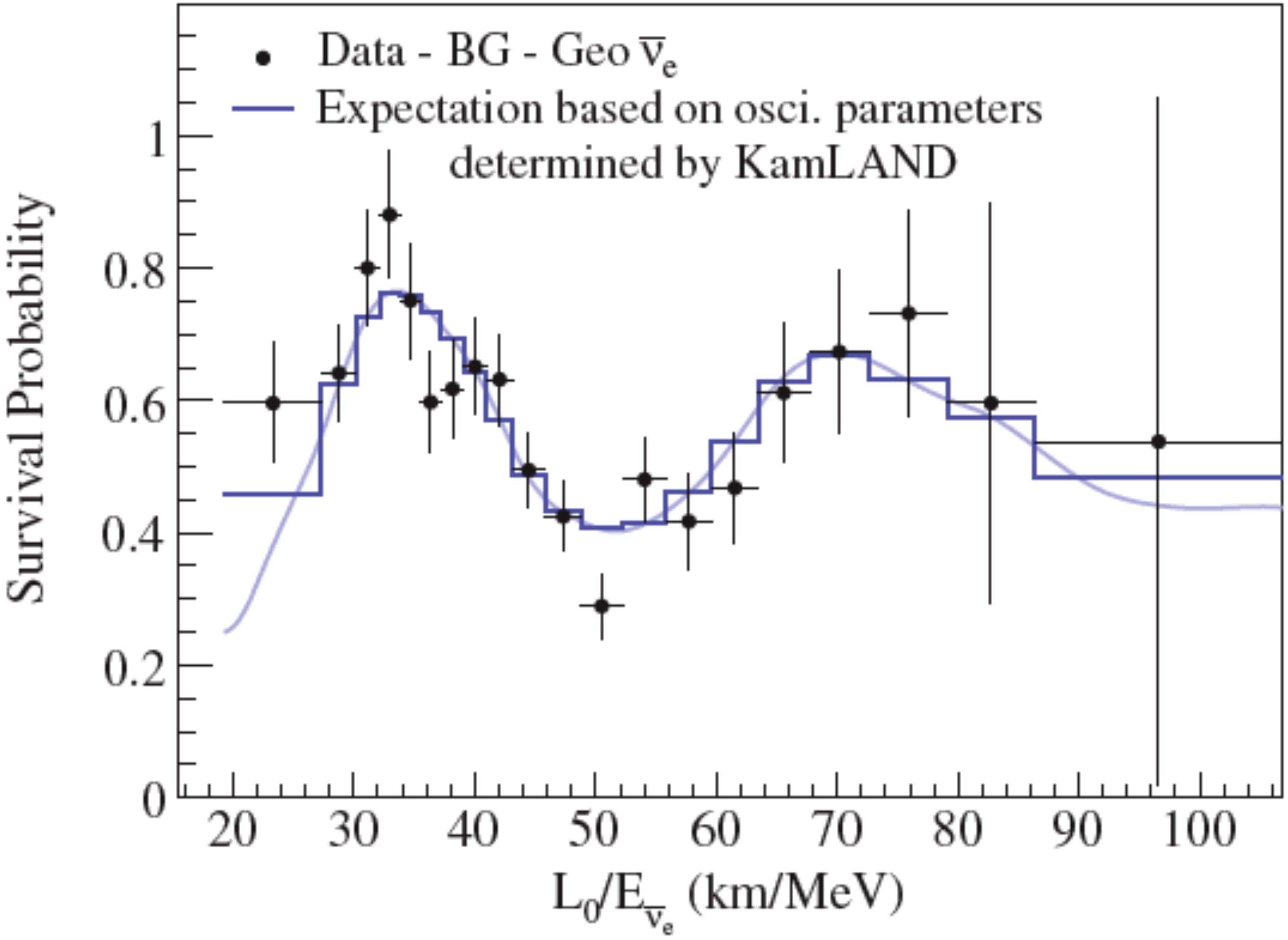
KAMLAND (2002)



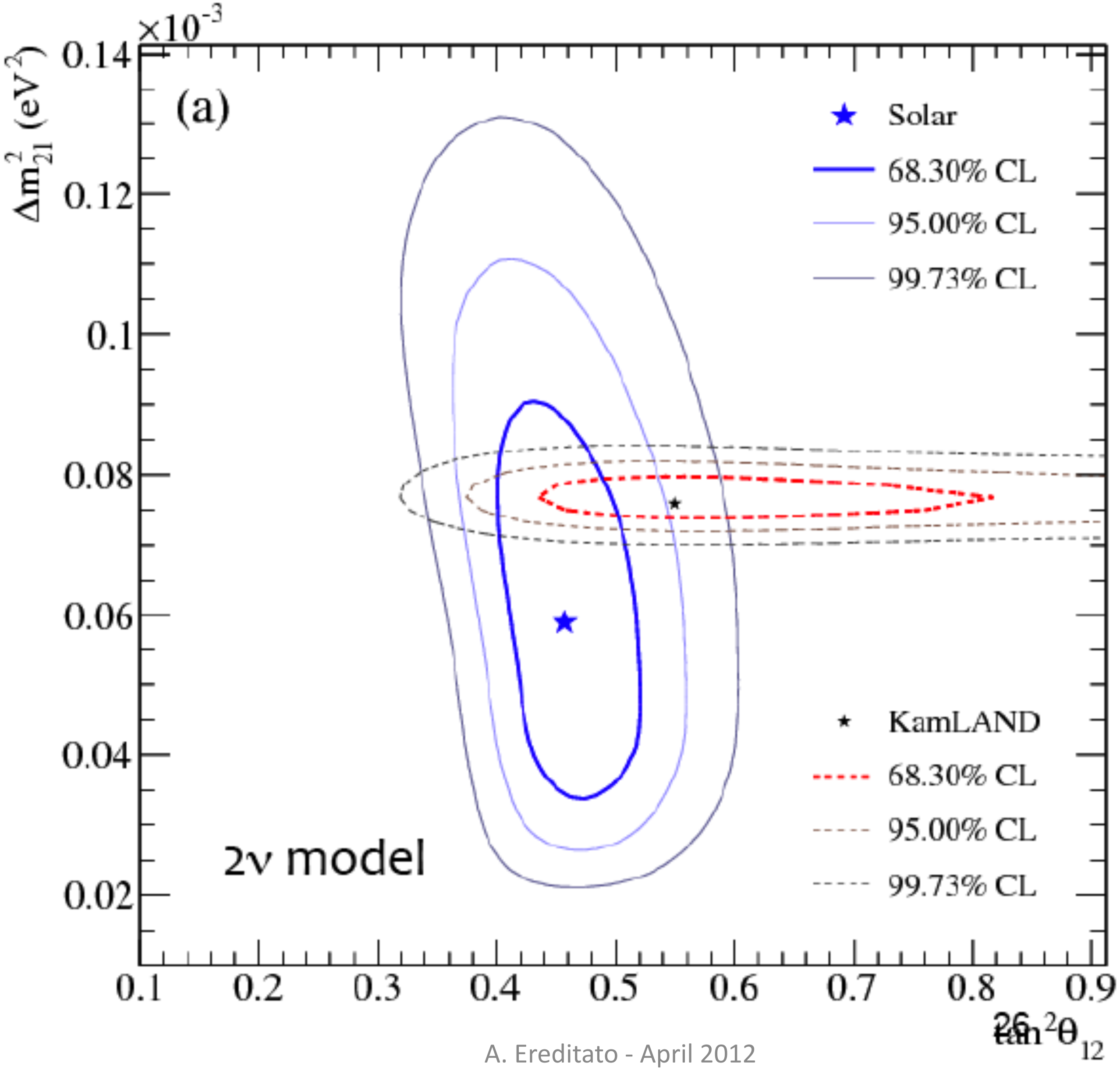
KAMLAND results (2007)



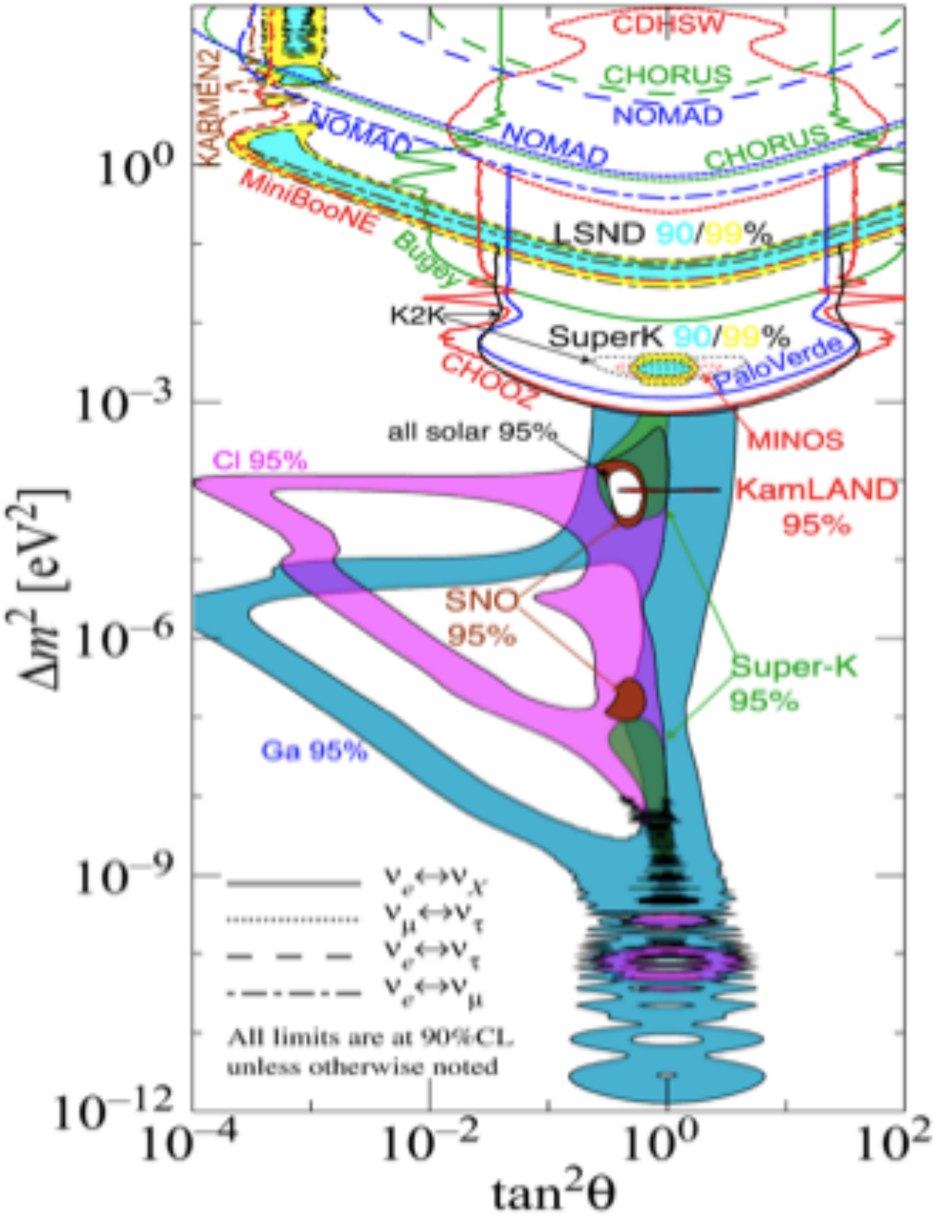
KAMLAND results (2007)



KAMLAND results complementary to solar neutrino experiments

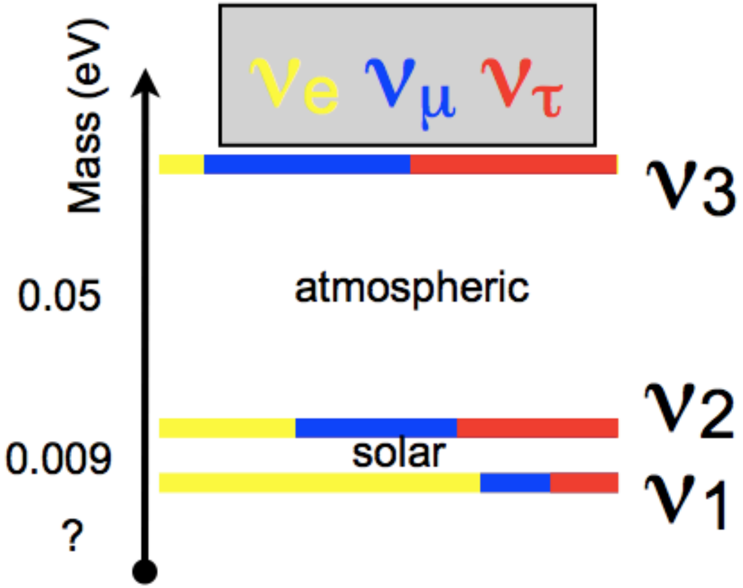


In summary, out of all these experiments….

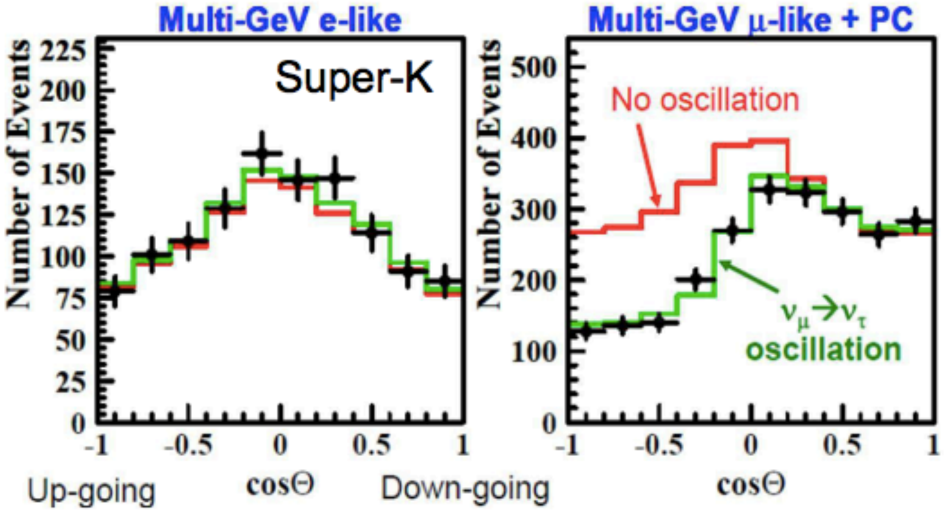


$$\overset{\text{flavor}}{\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}}=\overset{\text{atmospheric}}{\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}}\overset{\text{cross-mixing}}{\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\0&1&0\\-s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}}\overset{\text{solar}}{\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}}\overset{\text{mass}}{\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}}$$

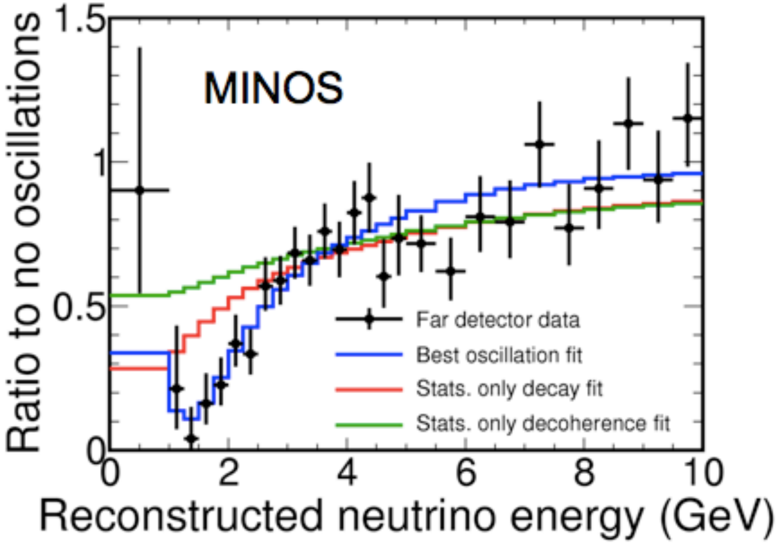
where $c_{ij}=\cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij}$



$$\begin{array}{ccccccccc}
\text{flavor} & & \text{atmospheric} & & \text{cross-mixing} & & \text{solar} & & \text{mass} \\
\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} & = & \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} & & \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} & & \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} & & \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}
\end{array}$$



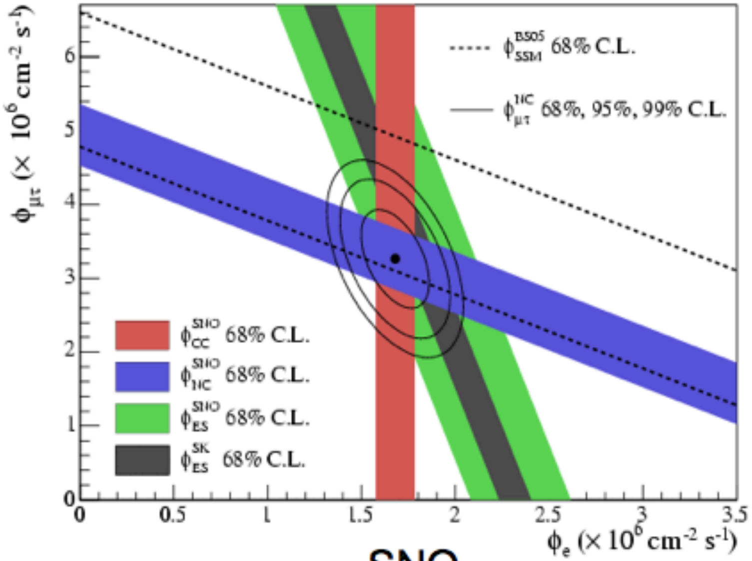
Phys.Rev.Lett.81.1562(1998)



PhysRevLett.101.131802

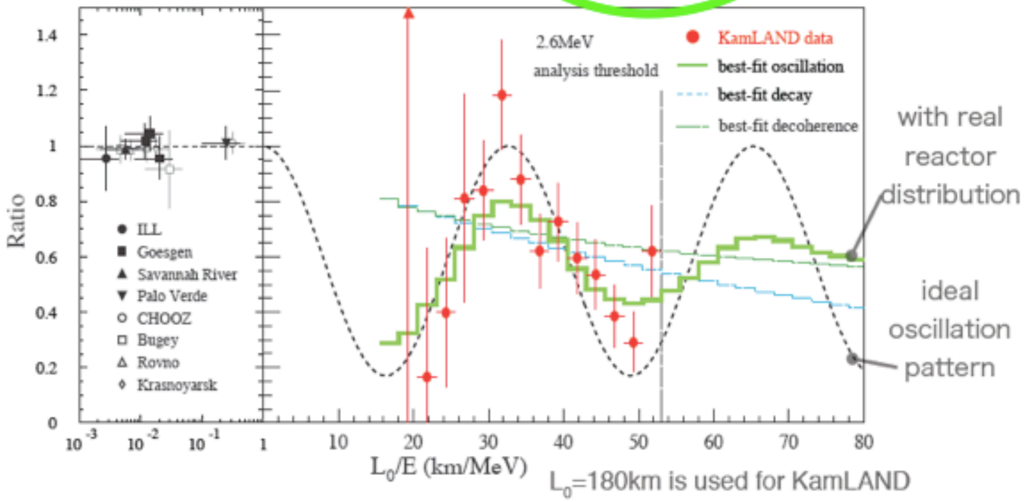
flavor — atmospheric — cross-mixing — solar — mass

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



SNO

Phys.Rev.Lett.89.011301 (2002)



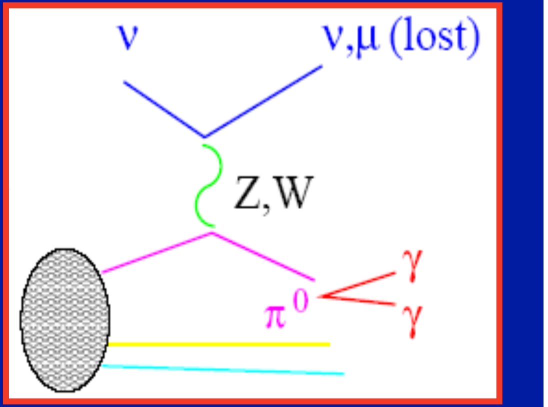
KamLAND

Phys.Rev.Lett.100.221803 (2008)

The last mixing angle: θ_{13}

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

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



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

$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ with reactor experiments: a serious option!

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

reactor: $P(\bar{\nu}_e \rightarrow \bar{\nu}_x) \sim \sin^2\theta_{13} \sin^2(\Delta m^2_{23} L/4E)$

Measurement of 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**

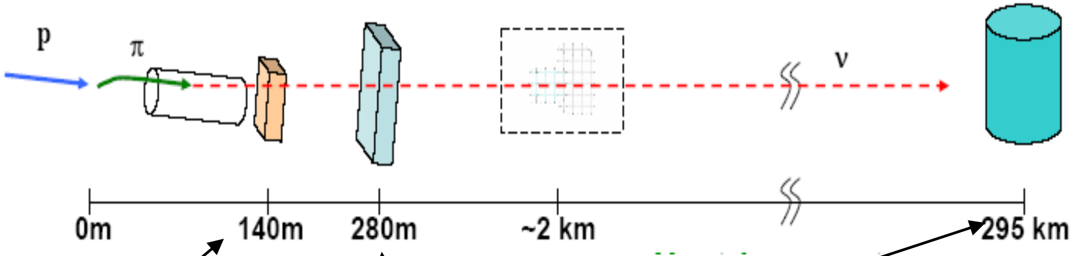
$$\boxed{\textbf{CP odd term in } \nu_\mu \to \nu_e \textbf{ prob.} \propto \sin\delta \cdot s_{12} \cdot s_{23} \cdot s_{13}}$$

$\sin\theta_{12}$~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?

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

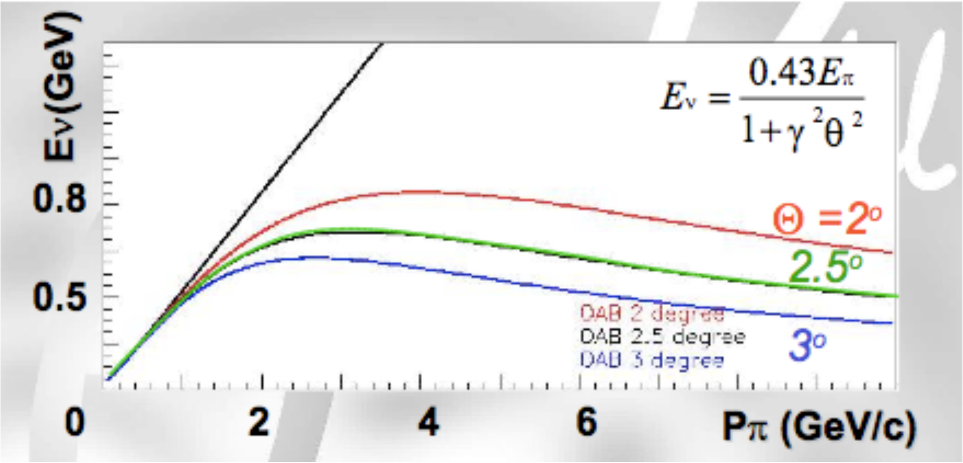
- low E_ν (<1 GeV) Super-Beam: 10^{21} pot/year
- @ 2° → 3000 ν_μ CC/year (x10 w.r.t. K2K)
- 0.2% ν_e contamination and $\pi°$ BG

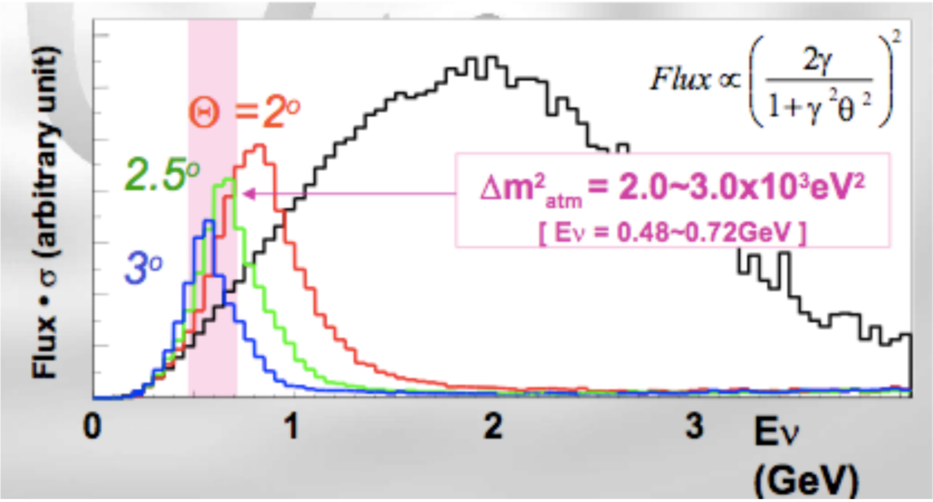


μ monitor (beam direction and intensity)

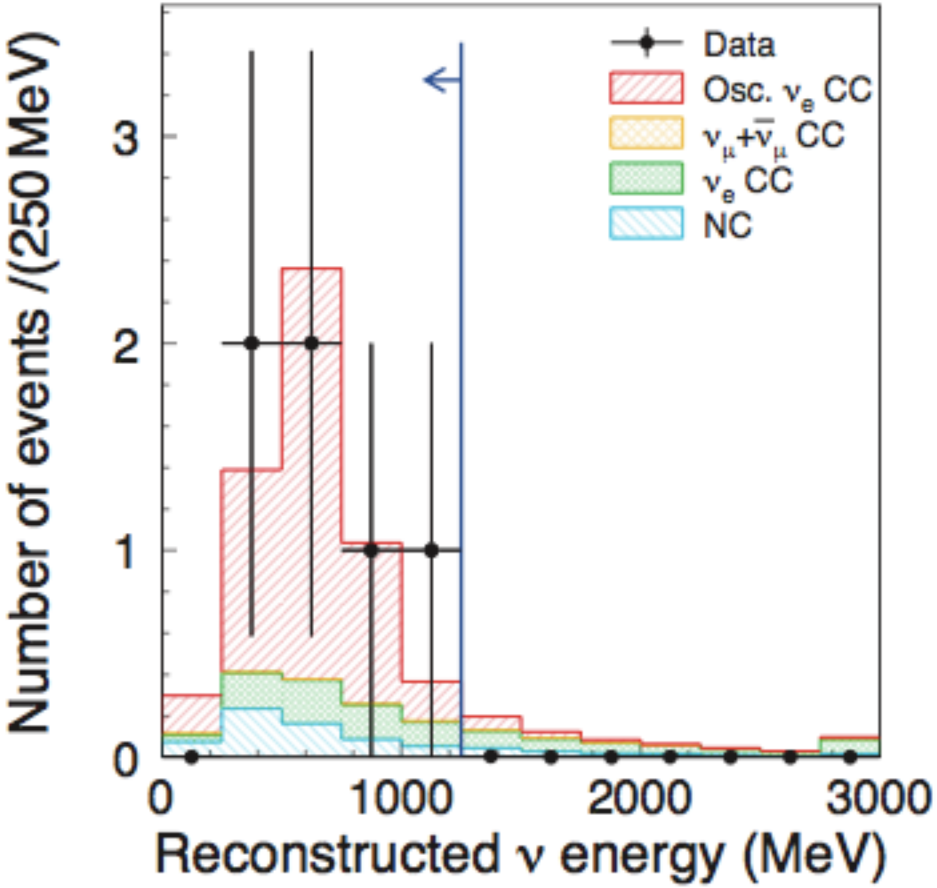
ν energy spectrum and intensity

Detect LBL events with SK



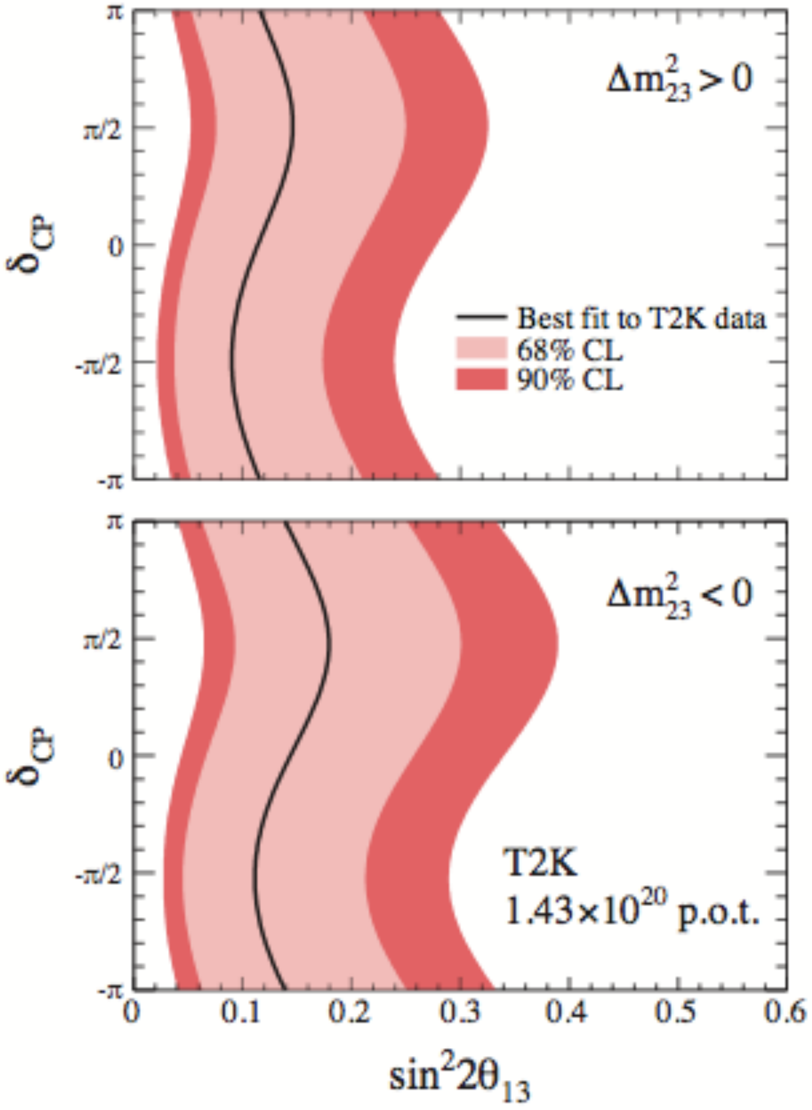


ν_e **appearance**: first measurement of θ_{13} in 2010



$0.03(0.04) < \sin^2 2\theta_{13} < 0.28\ (0.34)$ for $\delta CP=0$ and a normal (inverted) hierarchy at 90% C.L. for 1.43×10^{20} p.o.t. (2.5 sigma)

PRL107,041801(2011)



ν_μ disappearance with T2K

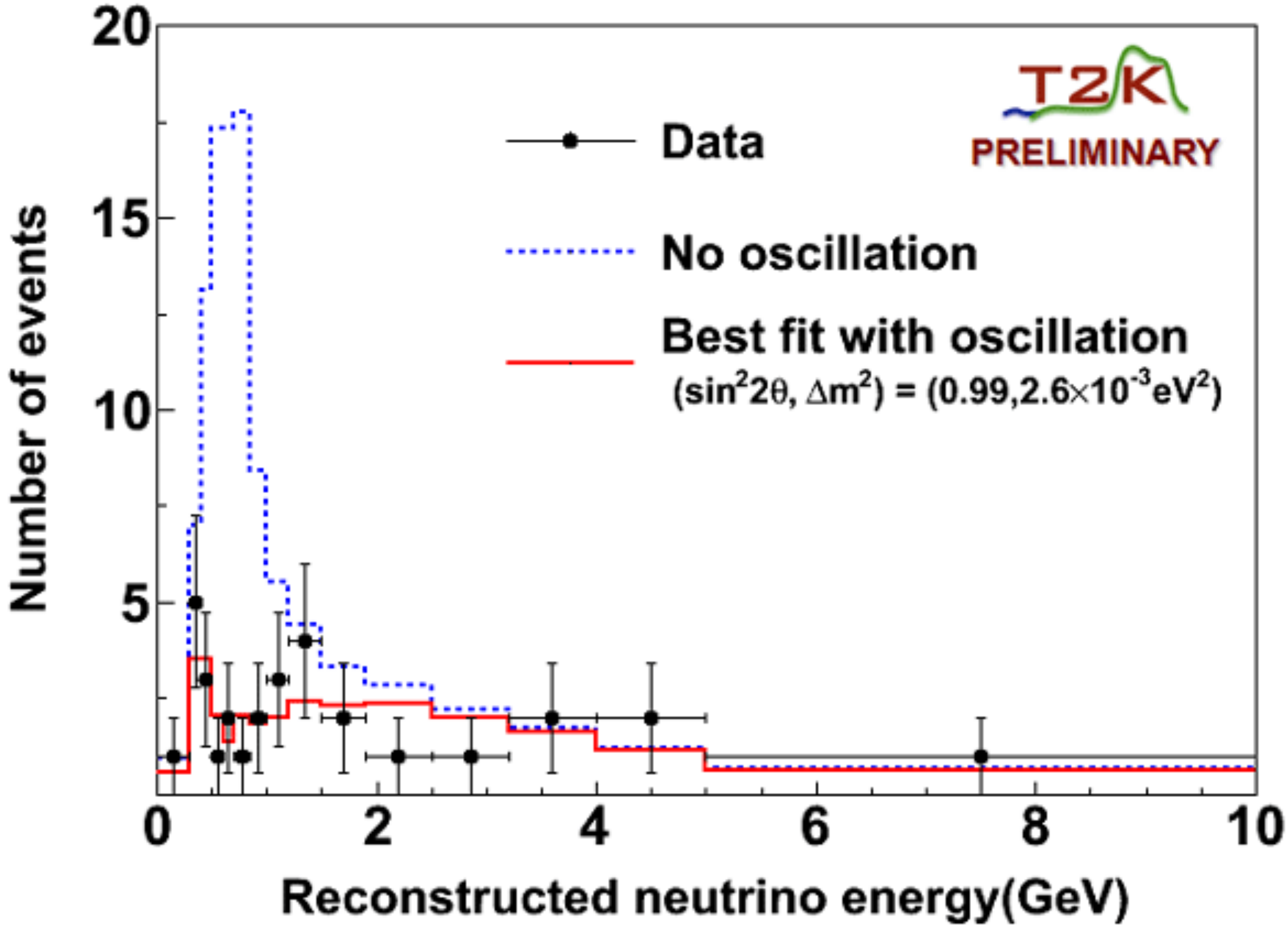
ν_μ disappearance analysis performed with 1.43×10^{20} p.o.t.

31 single-ring muon-like events observed at Super-Kamiokande while 104 were expected without oscillations.

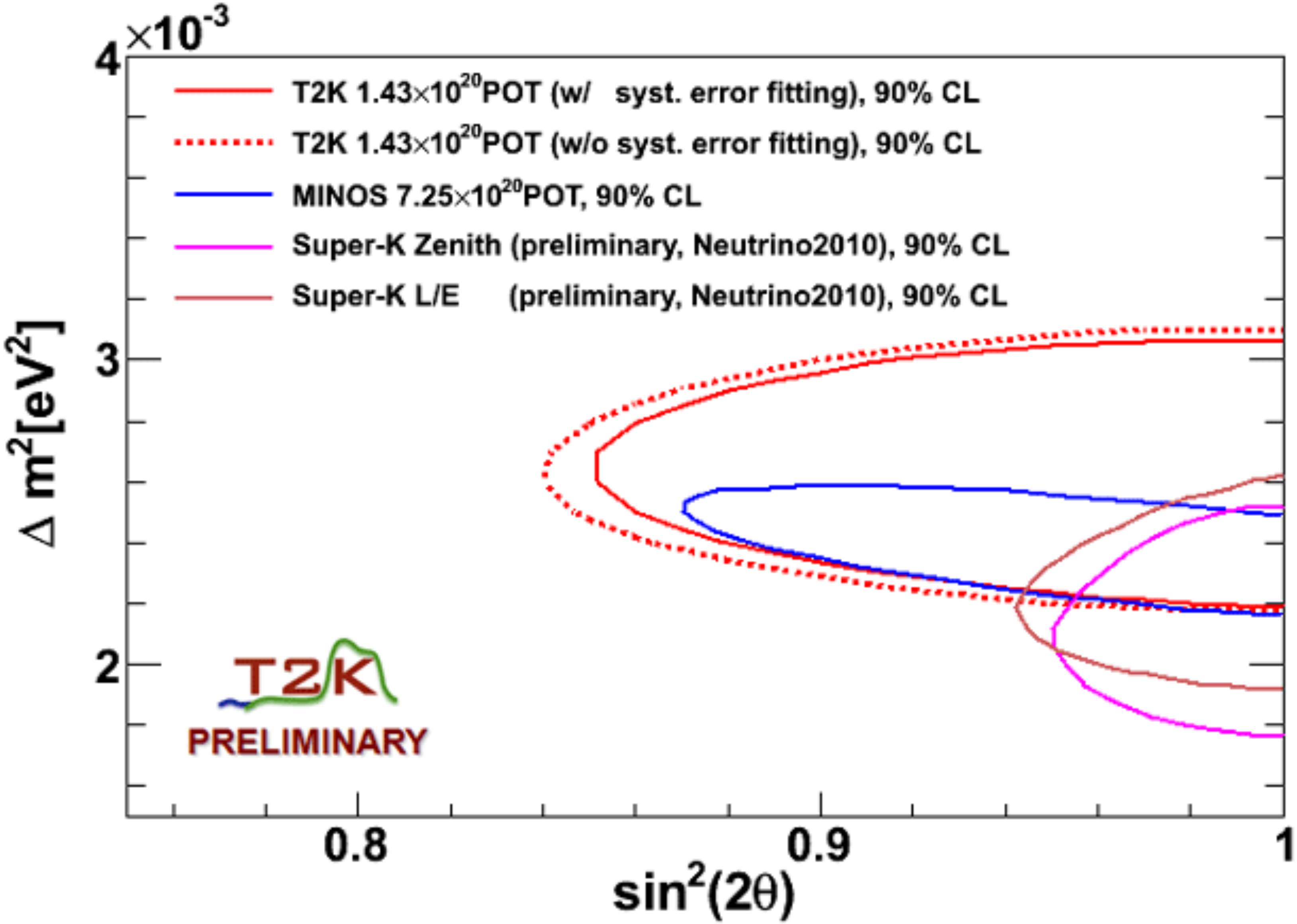
No oscillation hypothesis is excluded at 4.5σ.

An allowed region of $\sin^2(2\theta_{23})$ and Δm^2_{23} is obtained:

$\sin^2(2\theta_{23}) > 0.85$ and $2.1\times10^{-3} < \Delta m^2_{23}(\mathrm{eV}^2) < 3.1\times10^{-3}$ at 90% C.L.

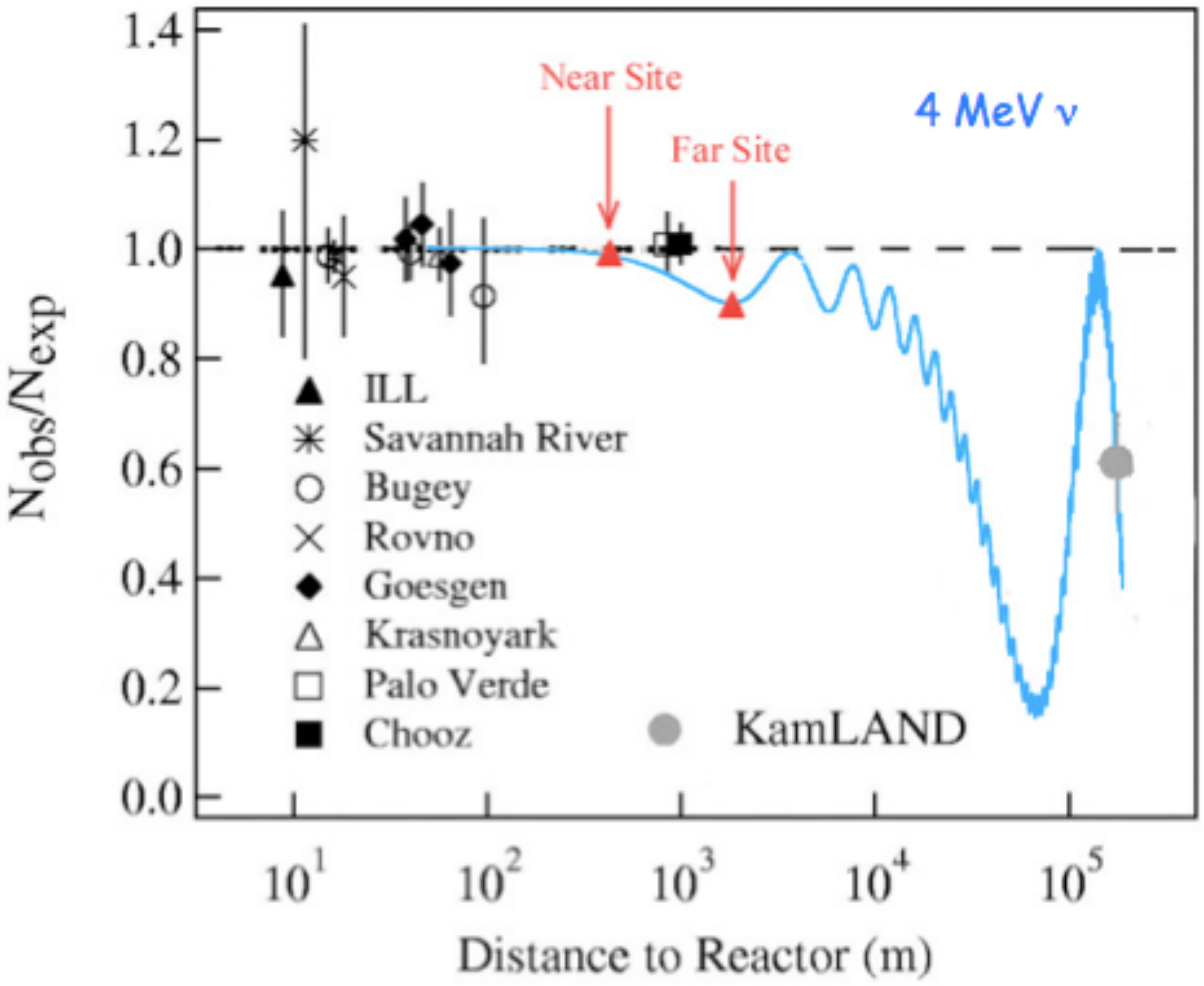

Number of events
20
15
10
5
0
2
4
6
8
10
Reconstructed neutrino energy(GeV)
Data
No oscillation
Best fit with oscillation
$(\sin^2 2\theta, \Delta m^2) = (0.99, 2.6\times10^{-3}\mathrm{eV}^2)$
T2K
PRELIMINARY

PRD85,031103(2012)

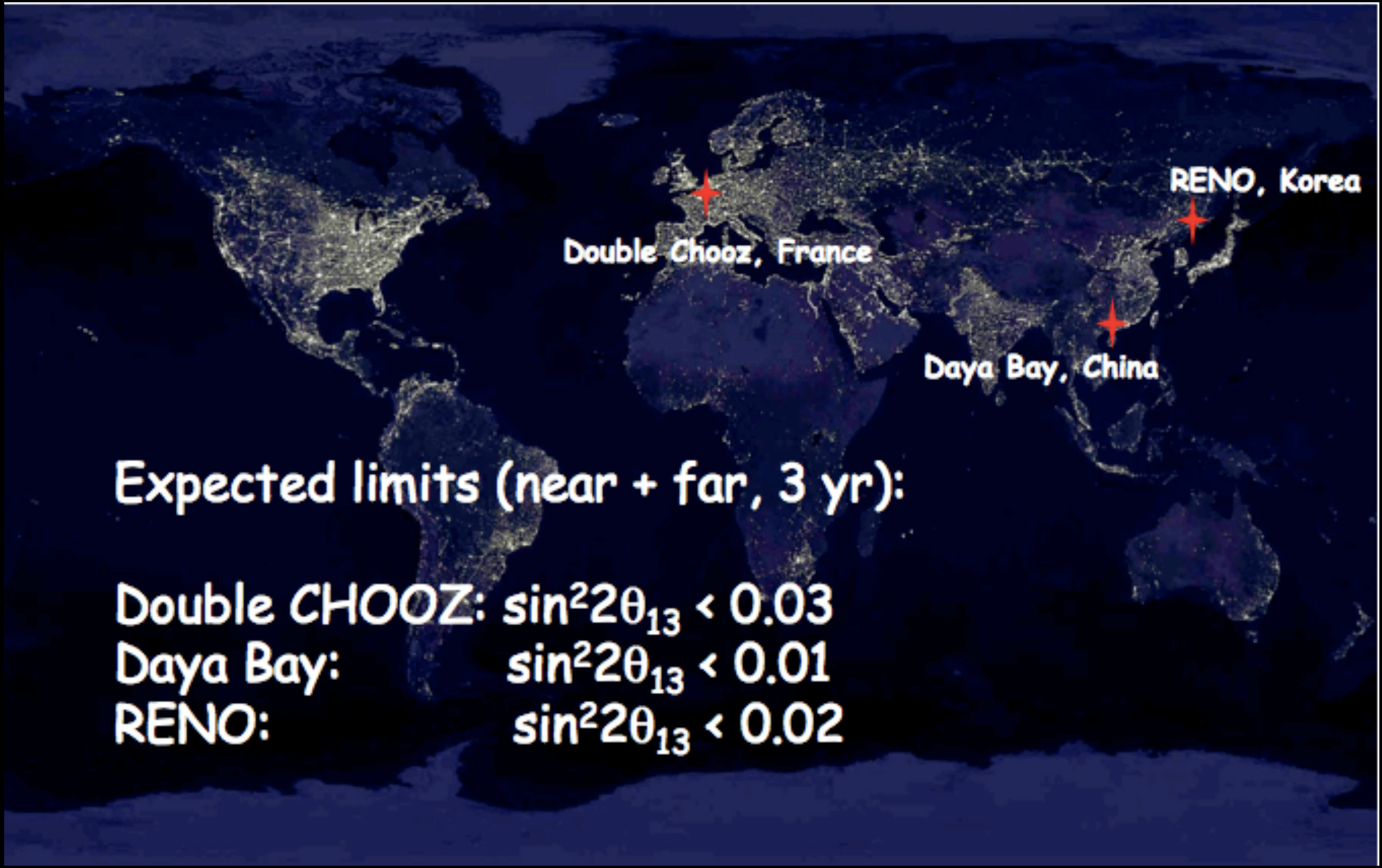


Measurement of θ_{13} with LBL reactor experiments

Example: one “near” and one “far” detector



Detectors and sensitivities



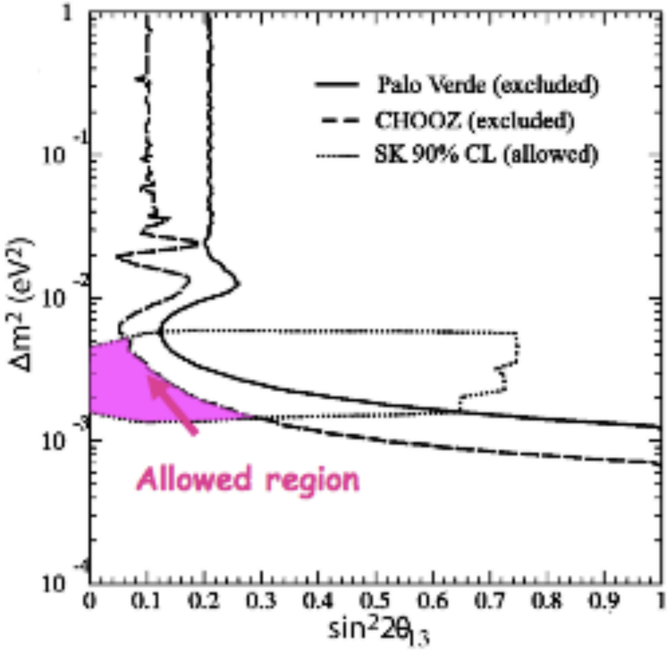
Expected limits (near + far, 3 yr):

Double CHOOZ: $\sin^2 2\theta_{13} < 0.03$
Daya Bay: $\sin^2 2\theta_{13} < 0.01$
RENO: $\sin^2 2\theta_{13} < 0.02$

Measurements of θ_{13} before Daya-Bay

- **Palo Verde & Chooz: no signal**

$\sin^2 2\theta_{13} < 0.12$ @ 90%C.L.
if $\Delta M^2_{23} = 0.0024\ \mathrm{eV}^2$



- **T2K: 2.5 σ over bkg**

$0.03 < \sin^2 2\theta_{13} < 0.28$ @ 90%C.L. for NH
$0.04 < \sin^2 2\theta_{13} < 0.34$ @ 90%C.L. for IH

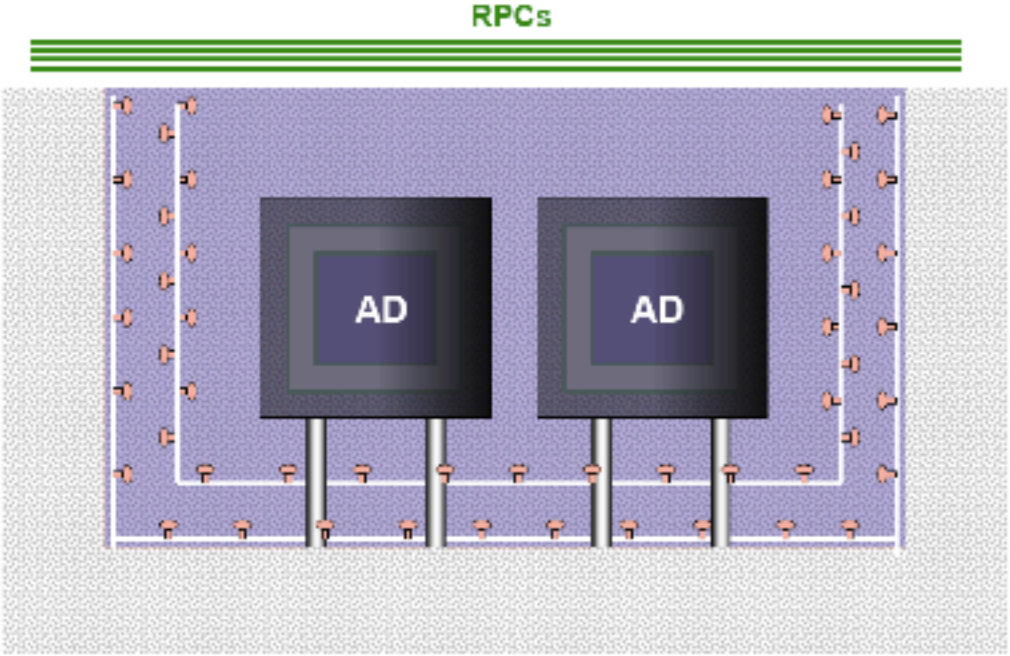
- **Minos: 1.7 σ over bkg**

$0 < \sin^2 2\theta_{13} < 0.12$ @ 90%C.L. NH
$0 < \sin^2 2\theta_{13} < 0.19$ @ 90%C.L. IH

- **Double Chooz: 1.7 σ**

$\sin^2 2\theta_{13} = 0.086 \pm 0.041(\mathrm{stat}) \pm 0.030(\mathrm{sys})$

Daya-Bay: reactors and detectors

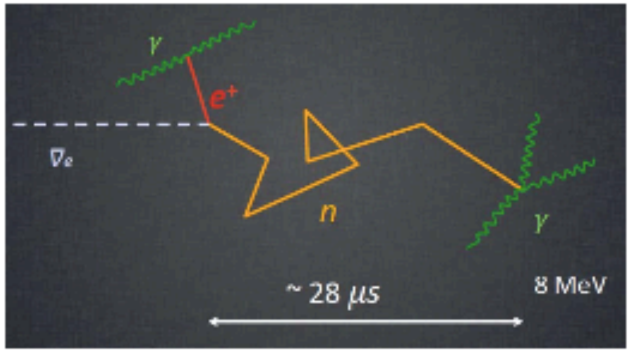


- Relative measurement to cancel Corr. Syst. Err.
  - ⇨ 2 near sites, 1 far site
- Multiple AD modules at each site to reduce Uncorr. Syst. Err.
  - ⇨ Far: 4 modules, near: 2 modules
- Multiple muon detectors to reduce veto eff. uncertainties
  - ⇨ Water Cherenkov: 2 layers
  - ⇨ RPC: 4 layers at the top + telescopes

Detection method

Neutrino Detection: Gd-loaded Liquid Scintillator

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

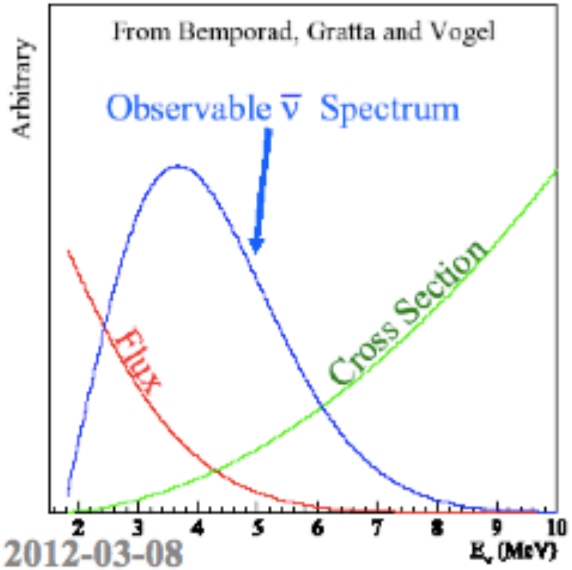


τ ≈ 28 μs(0.1% Gd)

n + p → d + γ (2.2 MeV)

n + Gd → Gd* + γ (8 MeV)

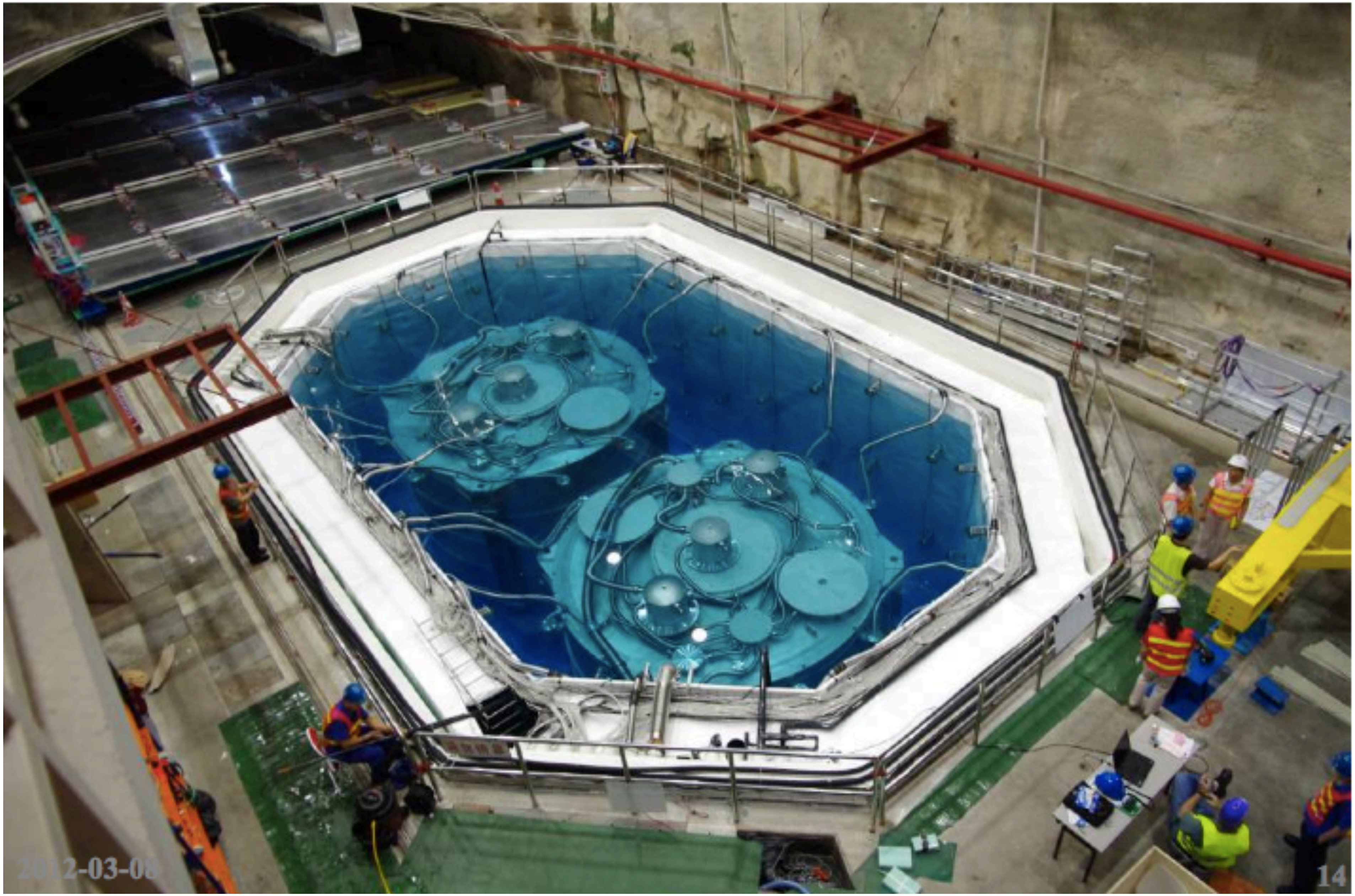
Neutrino Event: coincidence in time, space and energy

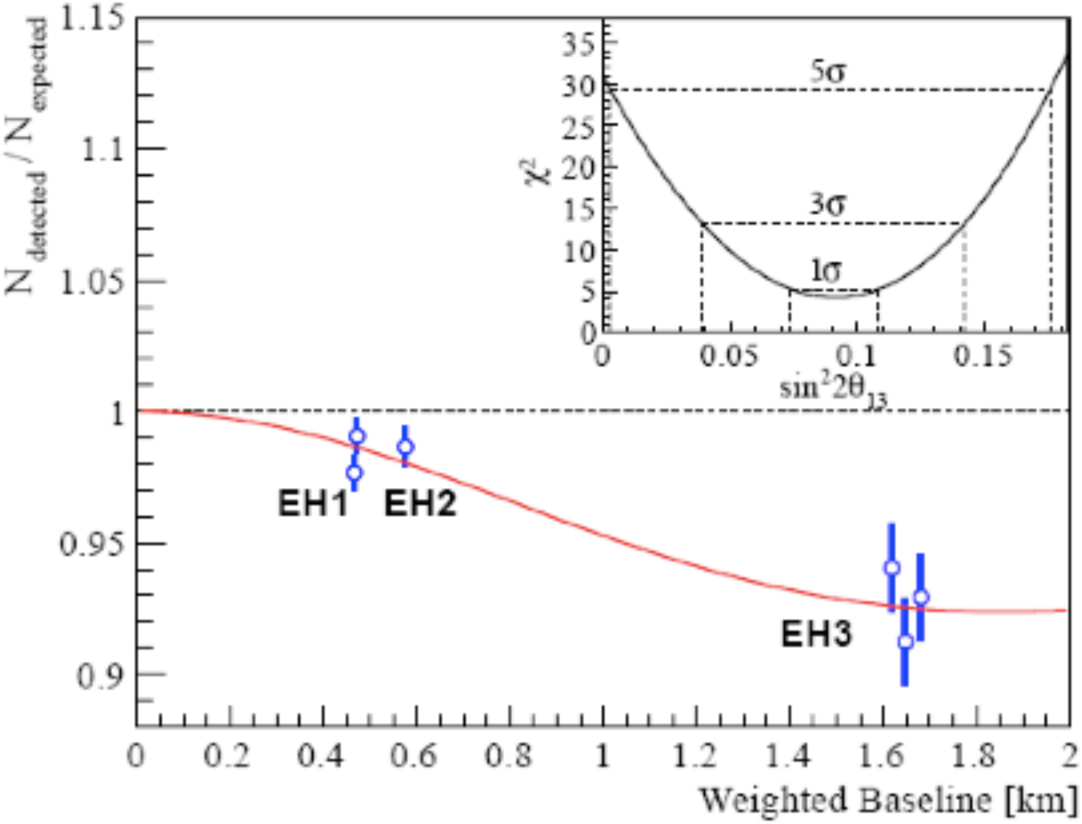

From Bemporad, Gratta and Vogel

Neutrino energy:

$$E_{\bar{\nu}} \cong \boxed{T_{e^+}} + \underbrace{T_n}_{10\text{-}40\ keV} + \underbrace{(M_n - M_p) + m_{e^+}}_{1.8\ MeV:\ \text{Threshold}}$$

Two Antineutrino Detectors (AD)





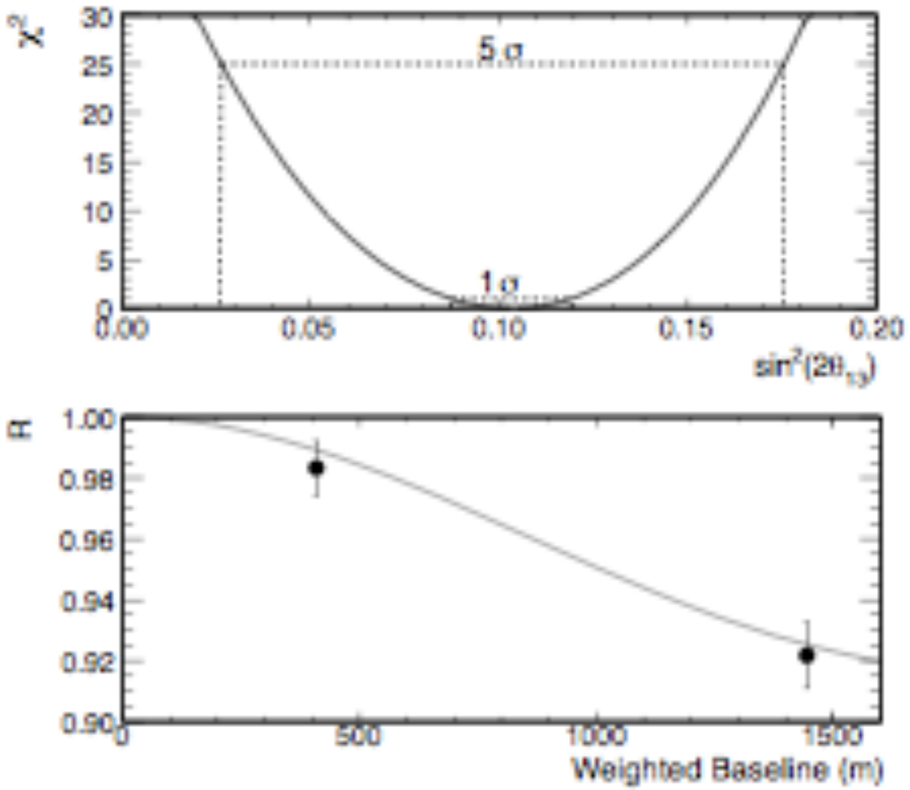
$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

$\chi^2/\text{NDF} = 4.26/4$

5.2 σ for non-zero θ_{13}

Discovery of a non zero θ_{13} angle !

Very recent confirmation from another reactor experiment: RENO, in South Korea



$\sin^2 2\theta_{13} = 0.103 \pm 0.013$ (stat.) $\pm\ 0.011$ (syst.)

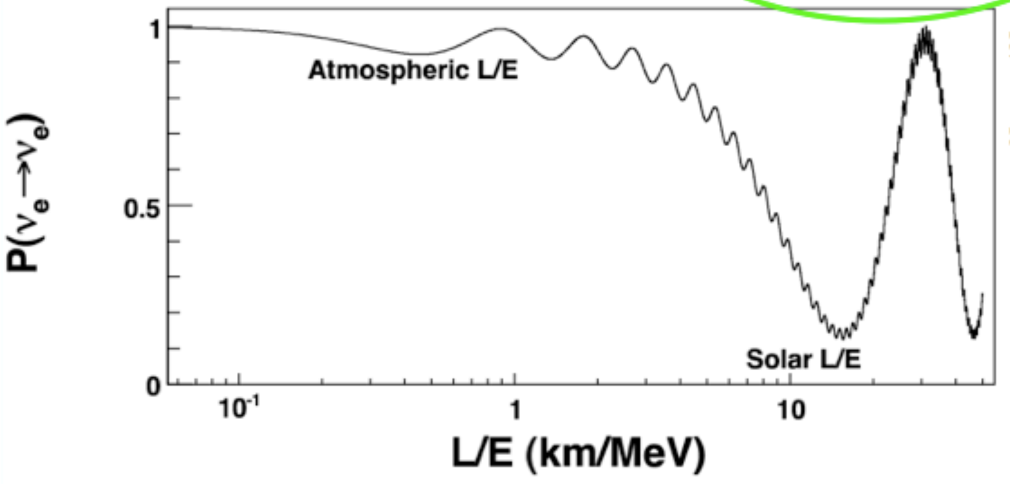
6.3 standard deviations!

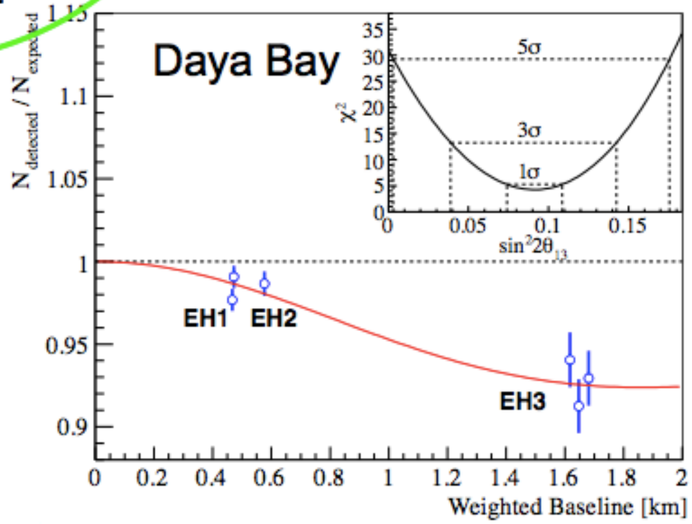
Summary of the cross-mixing sector

flavor atmospheric cross-mixing solar mass

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

10-2



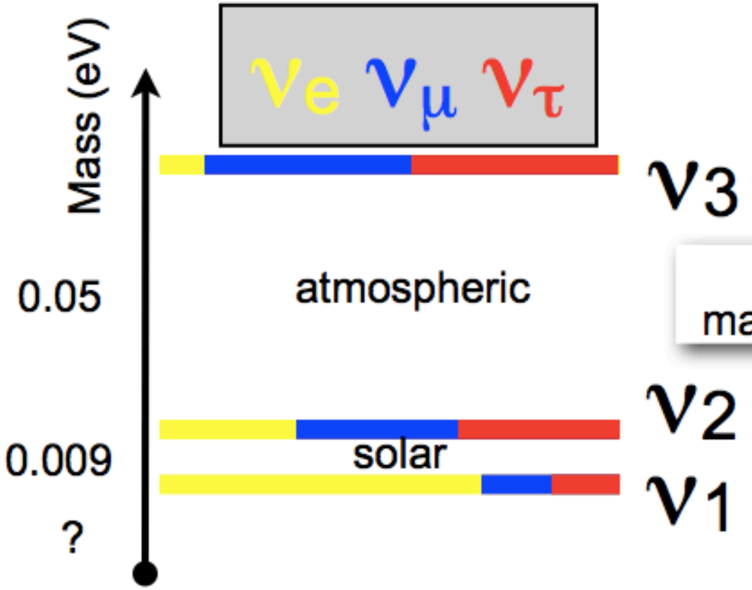


arXiv:1203.1669v1

The final 3 flavor mixing scheme

$$\begin{array}{ccccc} \text{flavor} & \text{atmospheric} & \text{cross-mixing} & \text{solar} & \text{mass} \\ \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = & \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} & \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} & \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} & \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \end{array}$$

where cij=cosθij, sij=sinθij



Non-zero δ:
matter vs antimatter

	VALUE
Δm^2_{23}	2.35E-03 (eV^2)
Δm^2_{12}	7.58E-05 (eV^2)
$\sin^2\theta_{12}$	0.306
$\sin^2\theta_{23}$	0.42
$\sin^2\theta_{13}$	0.02 !
δ	?

arXiv:1106.6028 [hep-ph]

Fine, but maybe the "simple" three flavor mixing scheme is too simple?

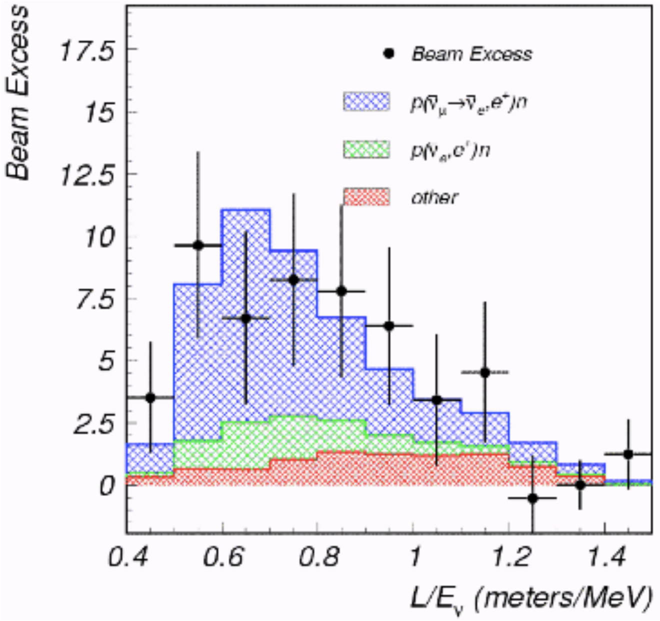
Sterile neutrinos??

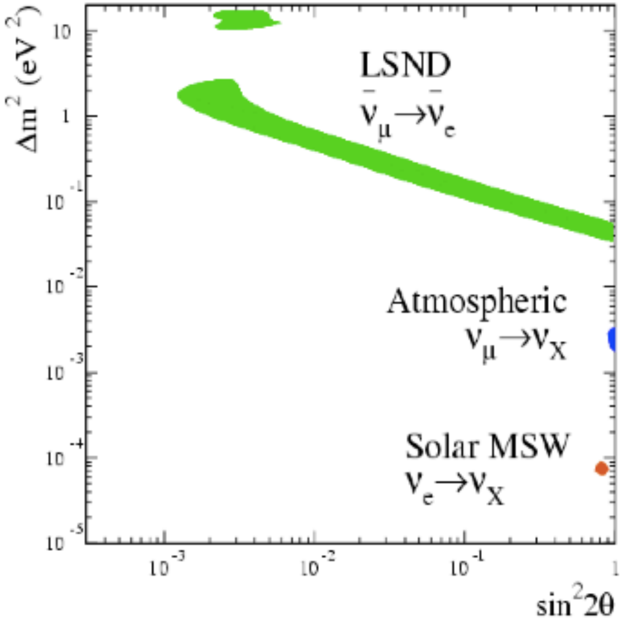
The LSND experiment observed a small excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam.

Data excess: 87.9 ± 22.4 ± 6.0 (3.8 σ)

Best fit: $\Delta m^2 \sim 1\ \mathrm{eV}^2$, $\sin^2 2\theta \sim 0.003$

Phys.Rev.D 64, 112007 (2001)

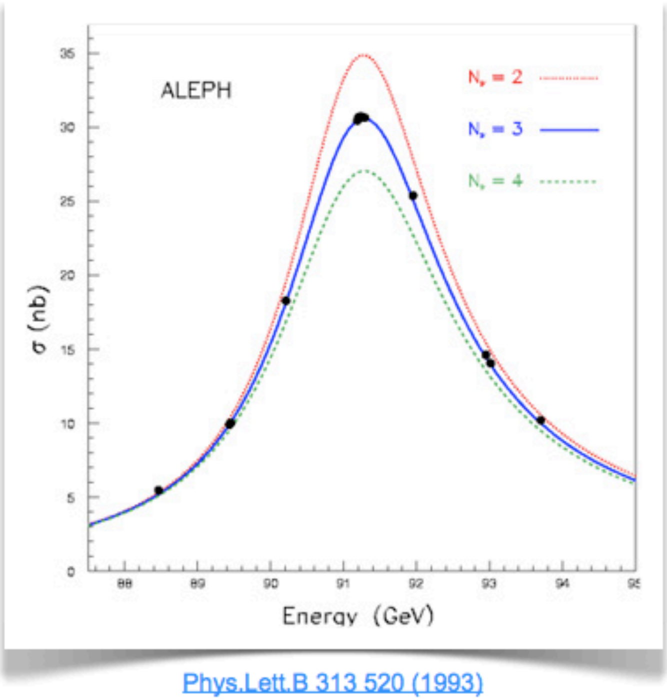




Sterile neutrinos ??

- LEP experiments measured the number of light neutrinos: 3
- Only two independent Δm^2 values for 3 neutrinos
  - $2.5 \times 10^{-3} + 7.6 \times 10^{-5} \neq 1$
- LSND signal involves *sterile neutrinos*, if it is due to neutrino oscillation

  ➡ They do not interact via the weak force



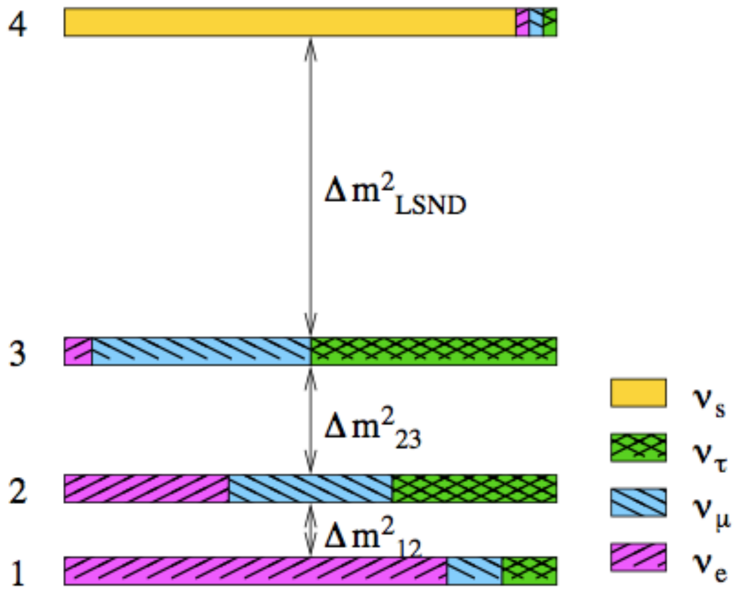
Phys.Lett.B 313 520 (1993)

- Sterile neutrinos could still mix with active neutrinos!

A simple realisation of the sterile neutrino is a right-handed neutrino ν_R , which can be mixed with active ν_L.

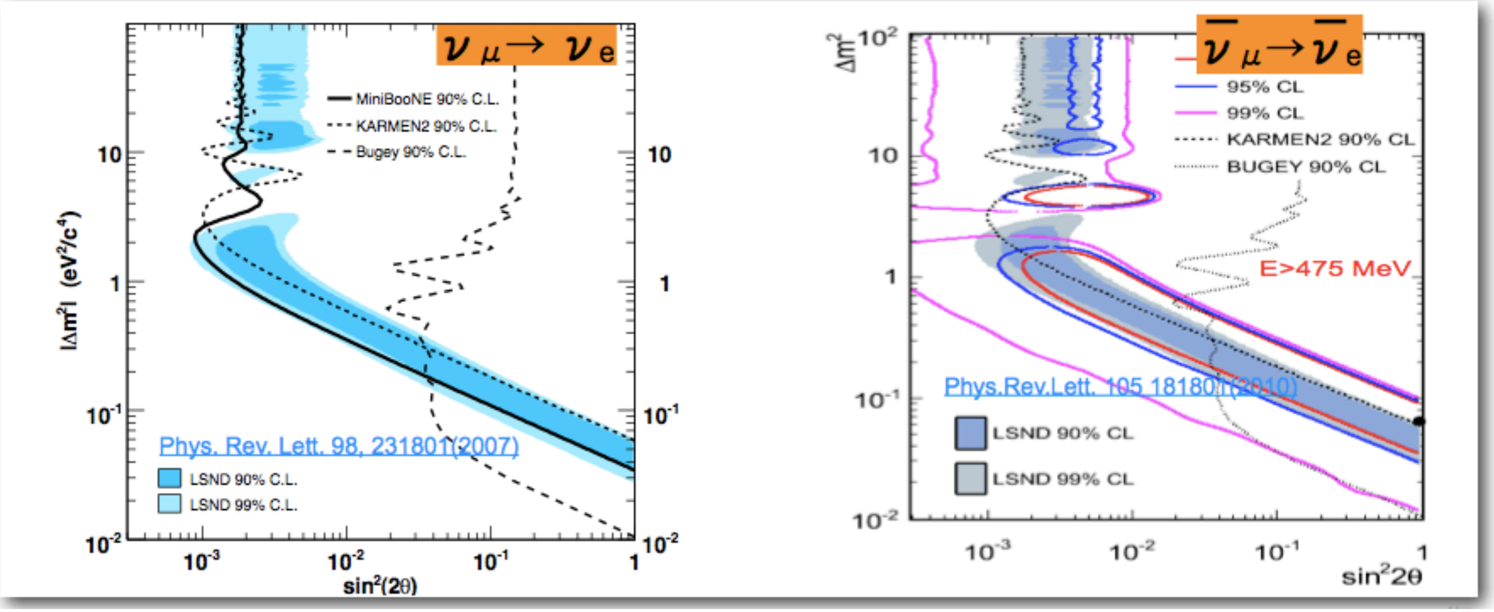
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \cdots \end{pmatrix}$$

3+1 sterile neutrino scheme



MiniBooNE ν_e Results

- MiniBooNE recently tested the LSND signal.
- Ruled out most of LSND region in $\nu_\mu \rightarrow \nu_e$ search.
- However, observed (small) $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ excess.
  - Consistent with LSND???



Affaire à suivre….

But after new results, new questions….

1) Is the mixing between ν_μ and ν_τ states non maximal?
is $\theta_{23} \neq 45°$?

2) Which is the mass hierarchy ?
is $\Delta m_{23} > 0$?

3) Since $\theta_{13} \neq 0$, we could hope to find CP violation in the lepton sector.
is $\delta_{CP} \neq 0$?

4) Is there room for sterile neutrinos?
is the mixing matrix not 3x3 ?

5) Is the neutrino a Dirac or a Majorana particle?
is $\nu = \bar{\nu}$?

6), 7), ….

Quark vs lepton mixing

Quark mixing

Neutrino mixing

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix} \Longleftrightarrow \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{MNSP} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

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

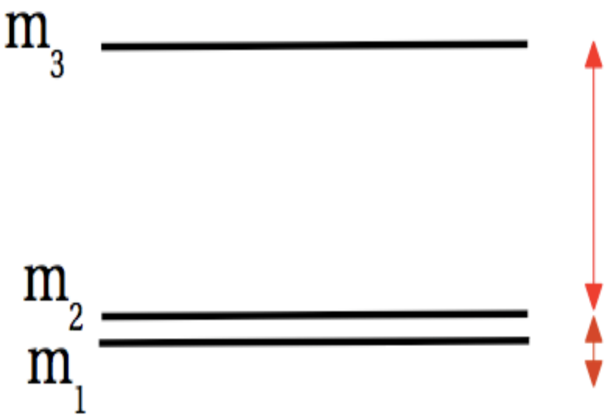
θ_{12}=13°	⟺	θ_{12}=33±3°
θ_{23}=2.4°		θ_{23}=45±8°
θ_{13}=0.21°		θ_{13} ~ 10°

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

Why the neutrino mass is so small ?

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 $m_1 \sim 0 \rightarrow m_3 > \sqrt{3\times10^{-3}\ \mathrm{eV}^2} \sim 50$ meV. From cosmological and direct mass measurements it turns out that the neutrino mass is smaller than ~1 eV.



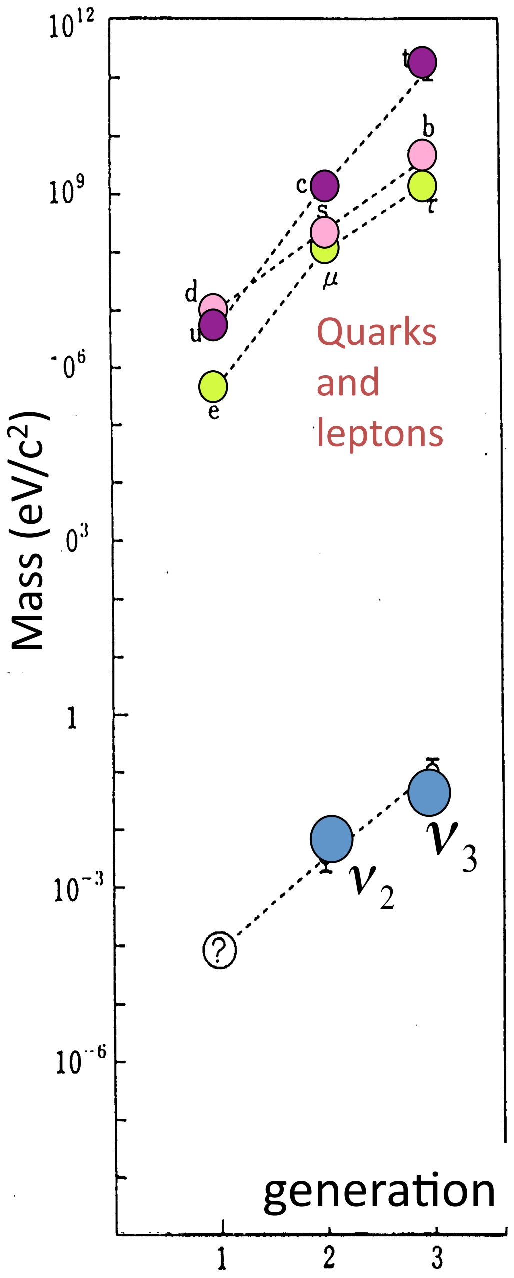
$$\Delta m^2_{23} \simeq \Delta m^2_{\mathrm{atm}} \simeq 3 \times 10^{-3}\ \mathrm{eV}^2$$

$$\Delta m^2_{12} \simeq \Delta m^2_{\mathrm{solar}} \simeq 7 \times 10^{-5}\ \mathrm{eV}^2$$

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….

Why the neutrino mass is so small ?



$$\left(\frac{m(\nu_3)}{m(top\ quark)}\right) \approx \left(\frac{1}{3\times10^{12}}\right)$$

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!

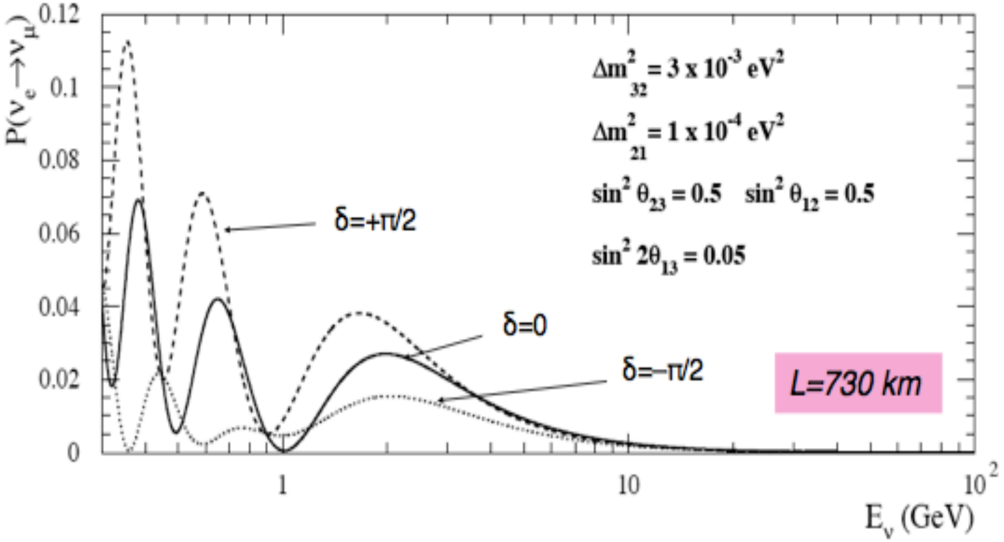
Measuring the CP phase

$$
\begin{aligned}
P(\nu_e \rightarrow \nu_\mu) \quad = & \\
& 4c_{13}^2 \left[\sin^2 \Delta_{23} s_{12}^2 s_{13}^2 s_{23}^2 + c_{12}^2 \left(\sin^2 \Delta_{13} s_{13}^2 s_{23}^2 + \sin^2 \Delta_{12} s_{12}^2 \left(1 - \left(1 + s_{13}^2\right) s_{23}^2\right)\right)\right] \\
& -\frac{1}{2} \cos \delta c_{13}^2 \sin(2\theta_{12}) s_{13} \sin(2\theta_{23}) \left[\cos 2\Delta_{13} - \cos 2\Delta_{23} - 2\cos(2\theta_{12}) \sin^2 \Delta_{12}\right] \quad \text{CP-even} \\
& +\frac{1}{2} \sin \delta c_{13}^2 \sin(2\theta_{12}) s_{13} \sin(2\theta_{23}) \left[\sin 2\Delta_{12} - \sin 2\Delta_{13} + \sin 2\Delta_{23}\right] \quad \text{CP-odd}
\end{aligned}
$$

AR, Venice (NOVE) 2003
arXiv:hep-ph/0402110v1

$$\Delta_{jk} \equiv \Delta m_{jk}^2 \frac{L}{4E_\nu}$$

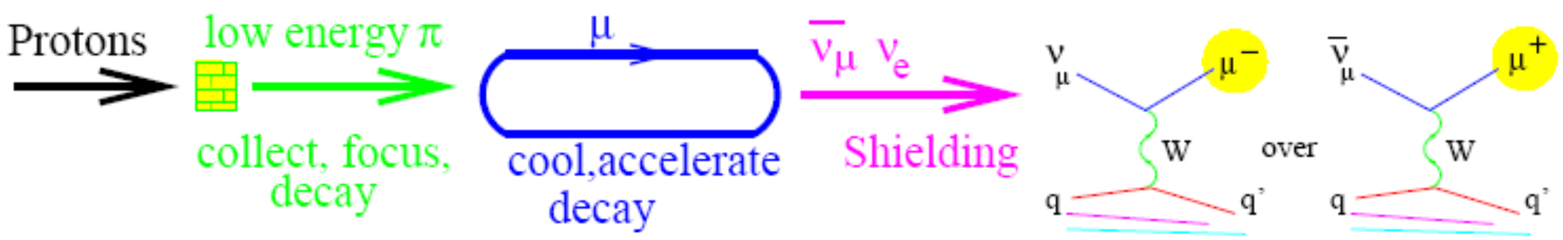
The phase can only be observed in appearance mode since disappearance is a T-symmetric process.
The effect for antineutrinos should be opposite to neutrinos (δ→–δ).
It should have the expected L/E dependence.



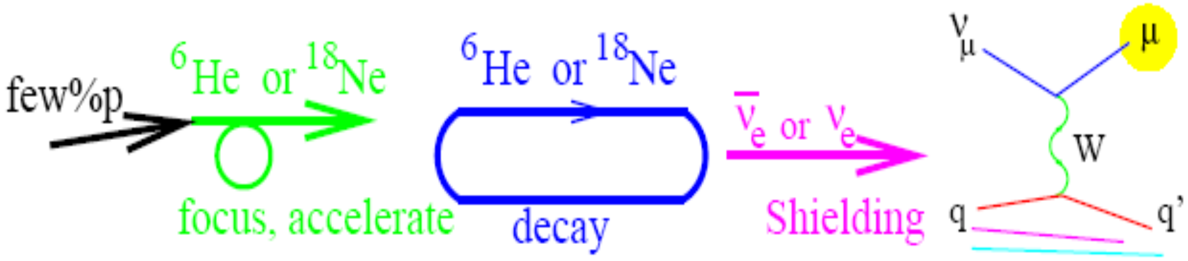
By the way, measuring CP phase might imply a new generation of neutrino beam facilities and experiments (beyond the scopes of these lectures).

Example: the ultimate neutrino facilities:

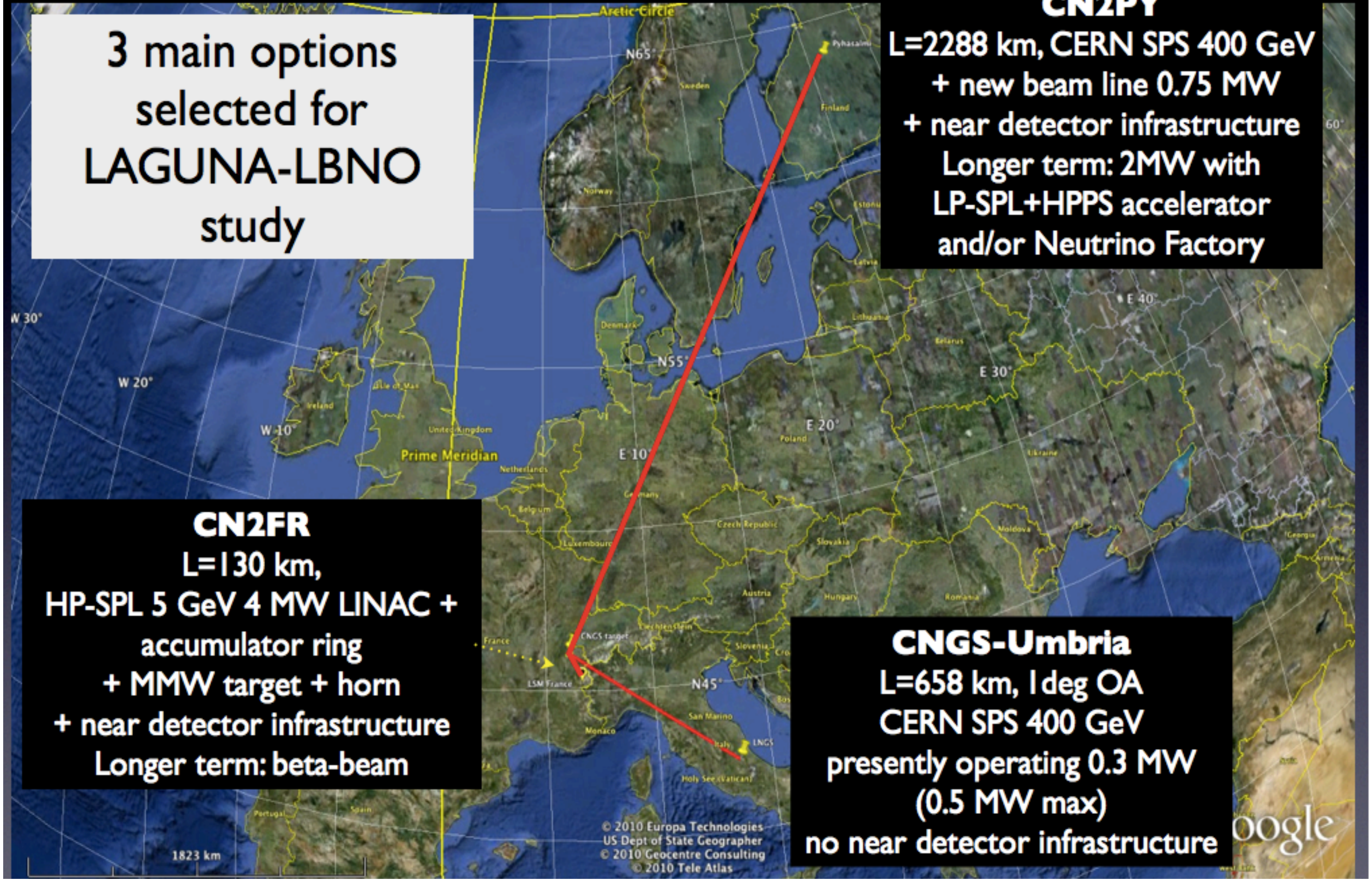
NEUTRINO FACTORIES



BETA-BEAMS



LAGUNA-LBNO study cases



3 main options selected for LAGUNA-LBNO study

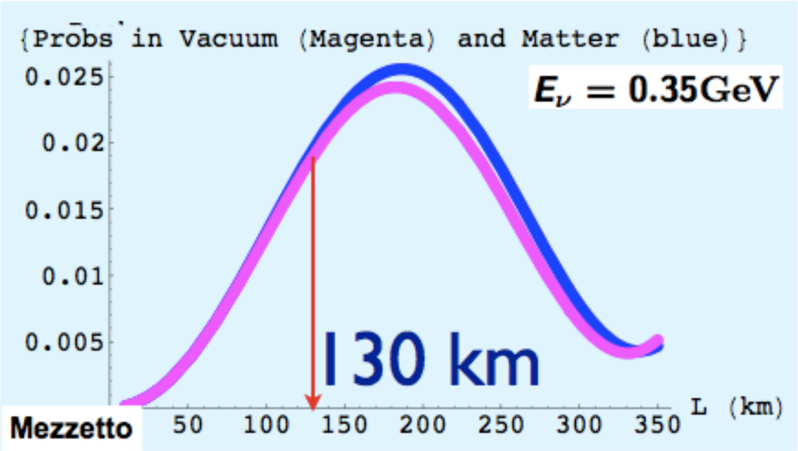
CN2PY
L=2288 km, CERN SPS 400 GeV
+ new beam line 0.75 MW
+ near detector infrastructure
Longer term: 2MW with LP-SPL+HPPS accelerator and/or Neutrino Factory

CN2FR
L=130 km,
HP-SPL 5 GeV 4 MW LINAC + accumulator ring
+ MMW target + horn
+ near detector infrastructure
Longer term: beta-beam

CNGS-Umbria
L=658 km, 1deg OA
CERN SPS 400 GeV
presently operating 0.3 MW
(0.5 MW max)
no near detector infrastructure

Very short/long baseline concept

CERN-Fréjus offers a very short baseline not considered elsewhere in the world ➠ unique physics opportunities in Europe

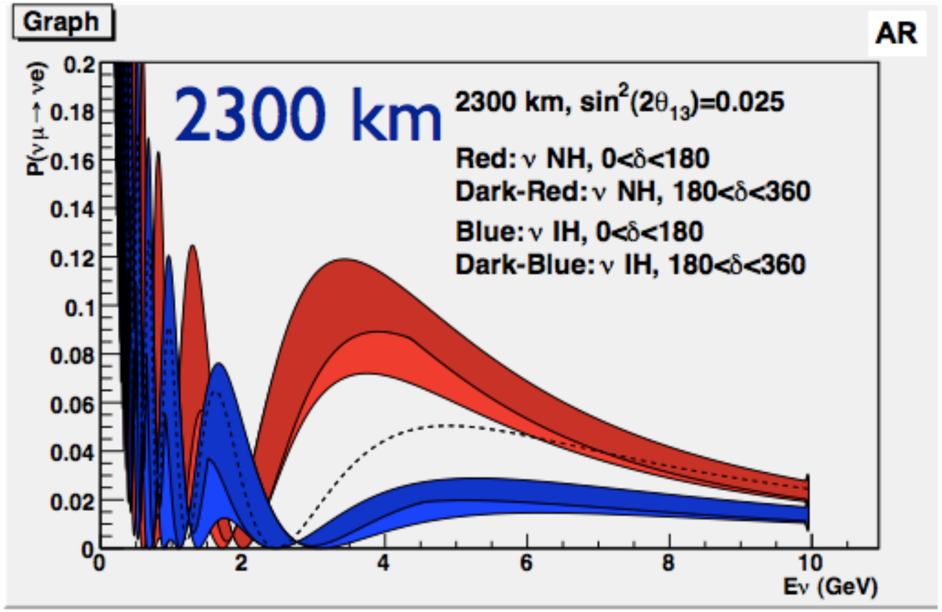


Determine CPV by comparison of neutrinos/ antineutrinos in absence of competing matter effects

need very low energy beam and huge detector

Adequate baseline/energy for betabeam

CERN-Pyhäsalmi offers a very long baseline not considered elsewhere in the world ➠ unique physics opportunities in Europe

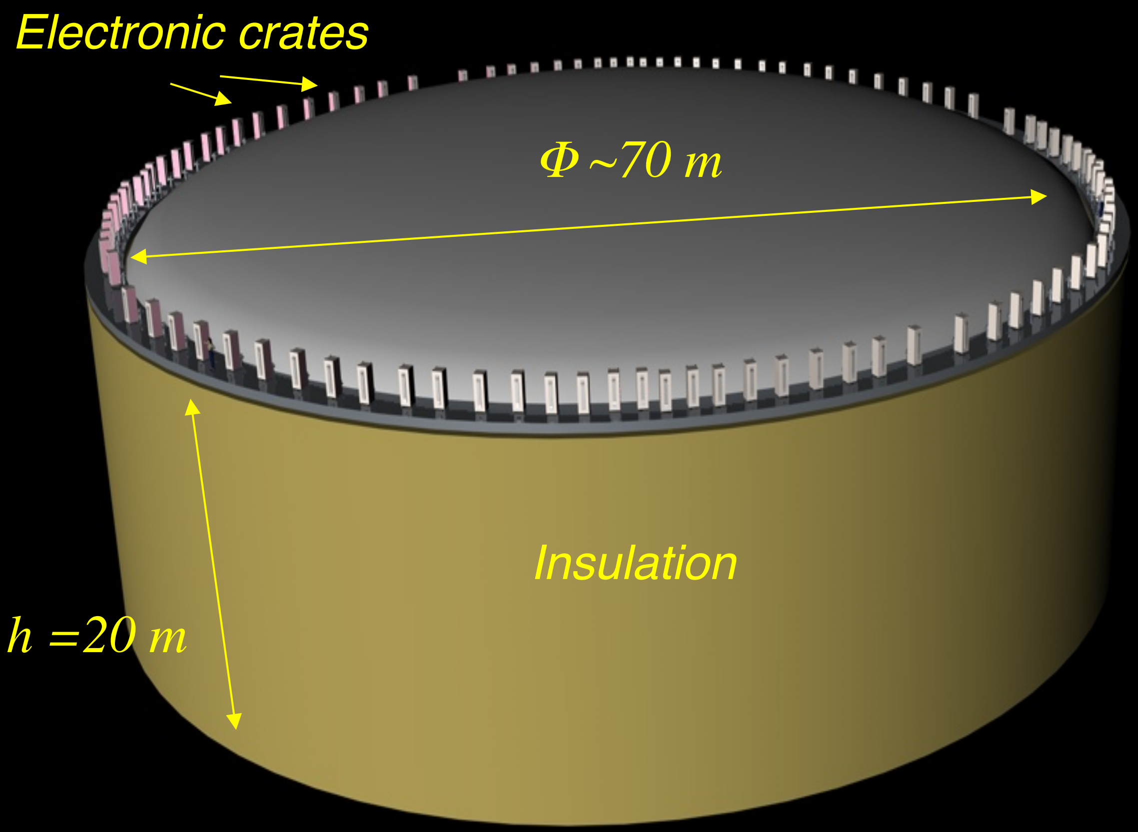


Determine CPV and mass hierarchy by spectrum measurement and resolve degeneracies and so-called "π-transit" effect

arXiv:0908.3741v1 for "Magic distance"

Adequate baseline for neutrino factory

HUGE DETECTORS!



XXXL Liquid Argon TPC's

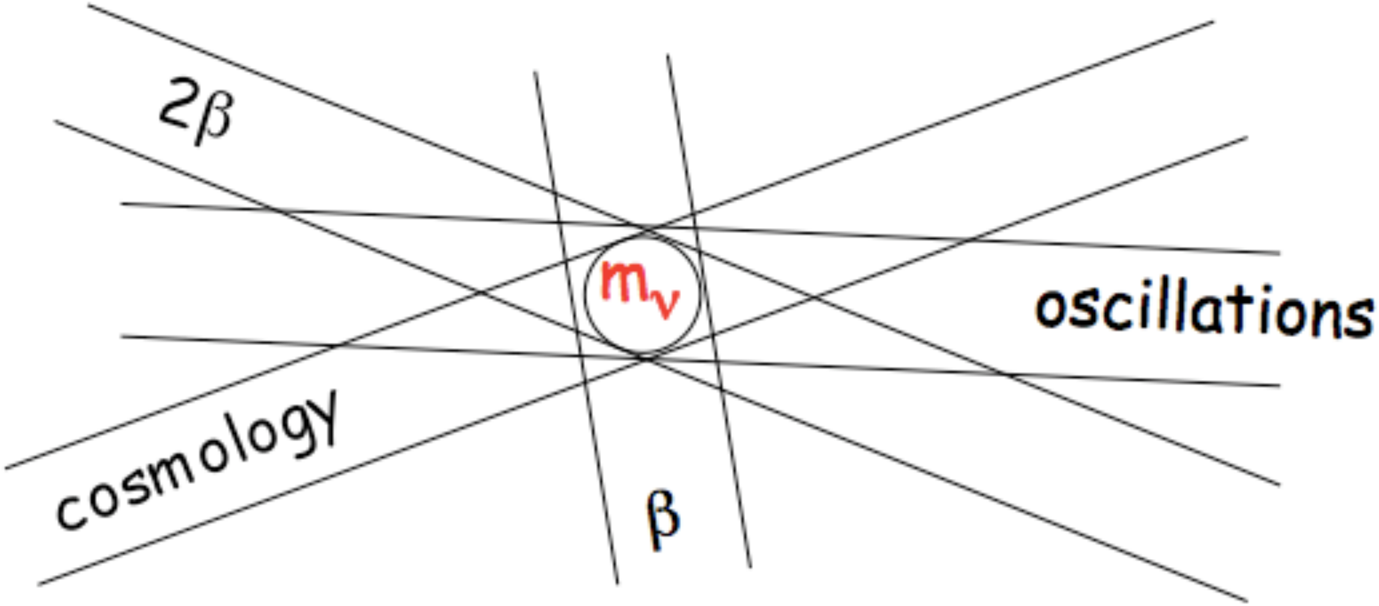
In one sentence, the study of neutrino physics will successfully continue for decades keeping physicists very busy…

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

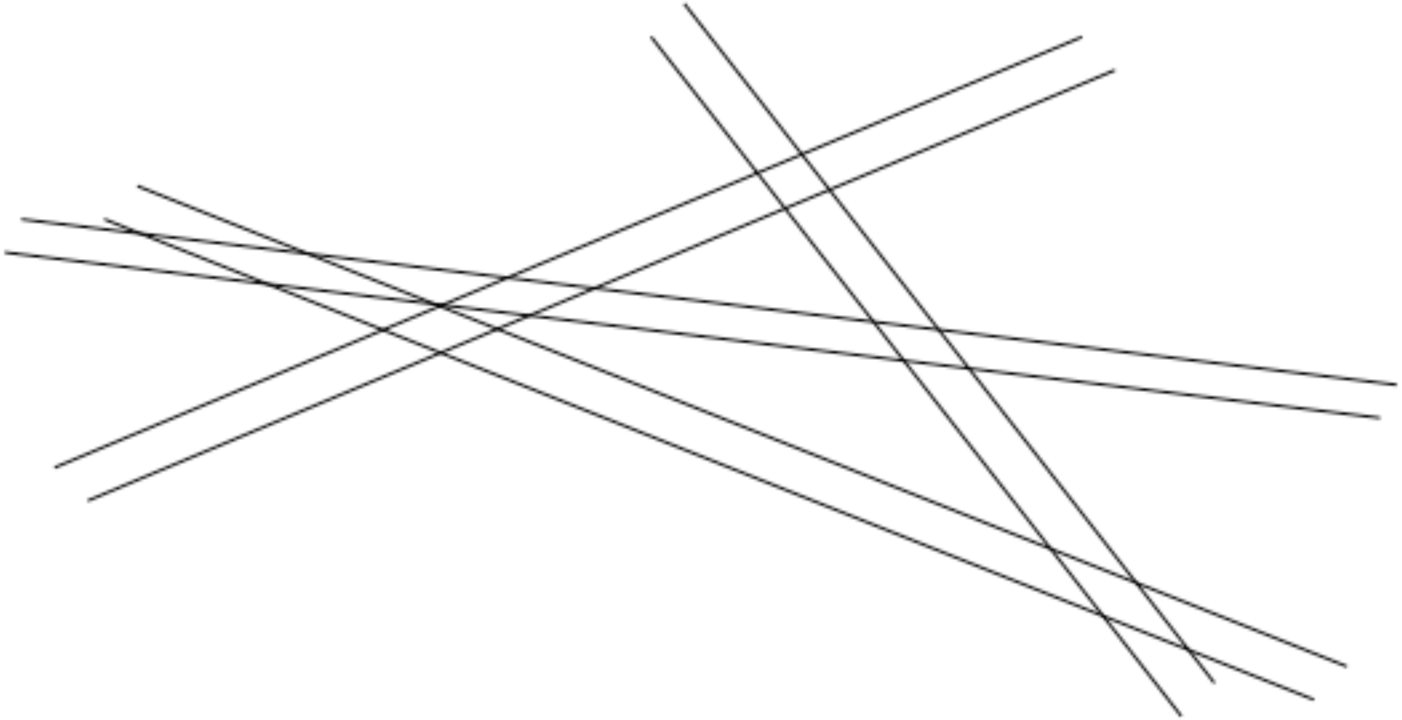
and with measurements on the neutrino-less double-beta decay…

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

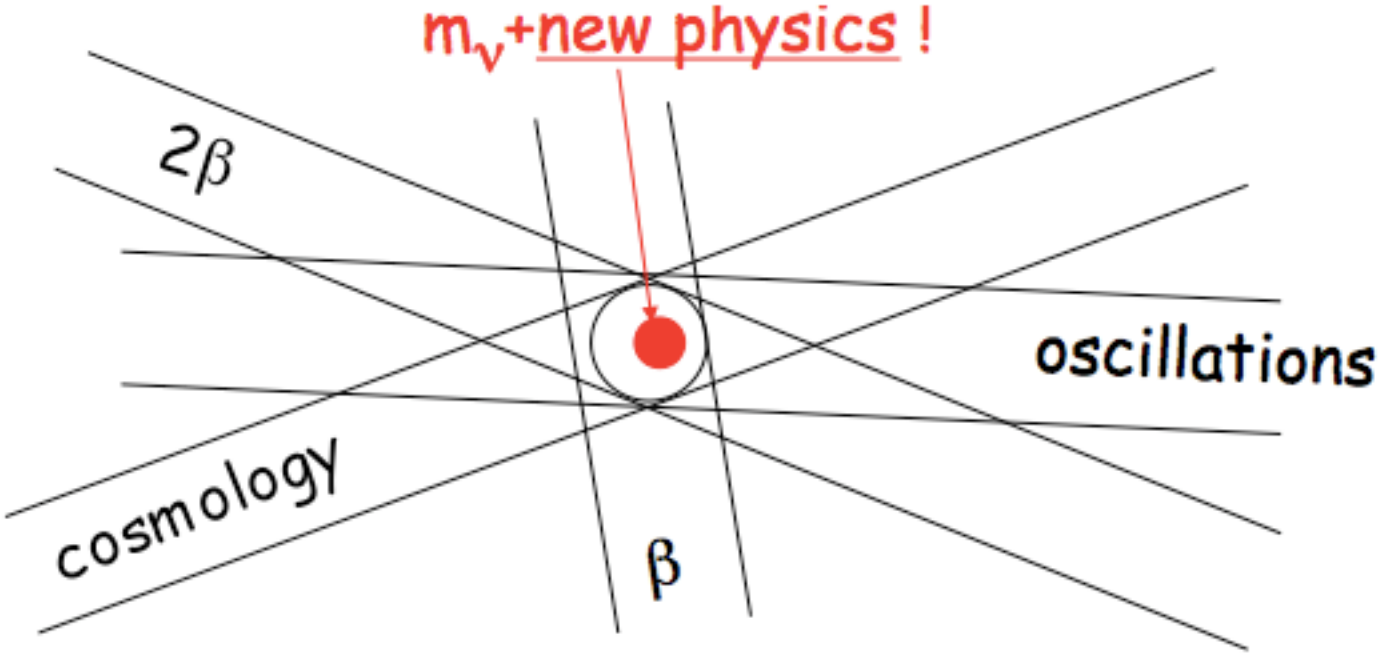
Dream ??



or nightmare ??



Maybe even better than a dream!!



- 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!