Pontecorvo's idea (III)

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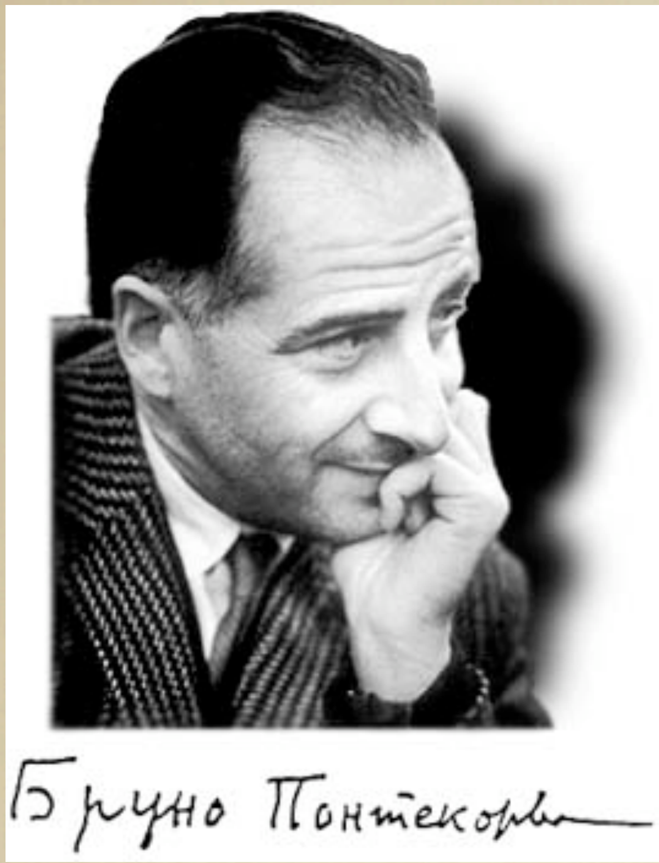
CERN Summer Student Lectures
2008

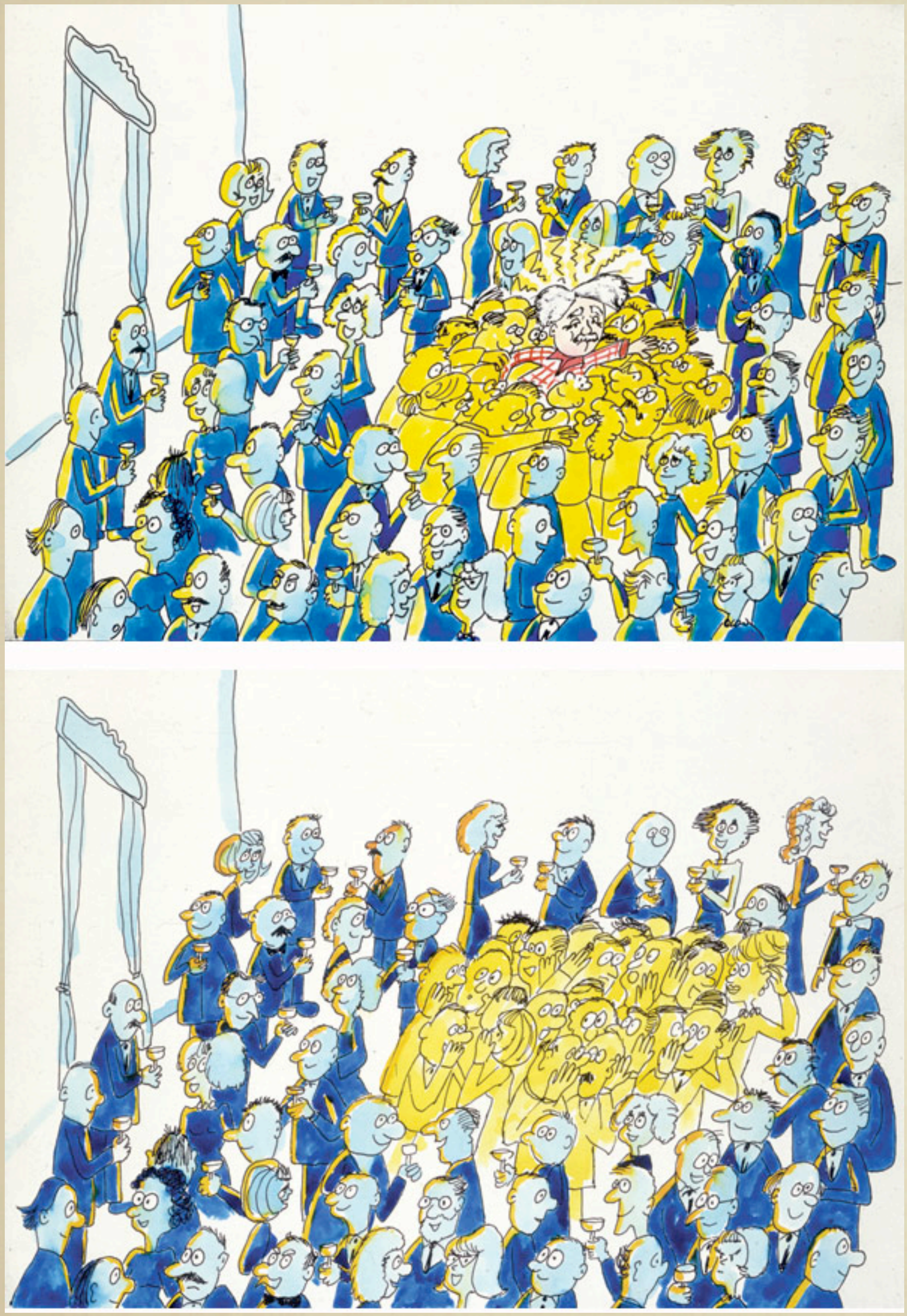


Bruno Pontecorvo was one of the
"Ragazzi de via Panisperma" together with another genius, Ettore Majorana.
Assistant of Fermi, he made numerous contributions to physics
Convinced socialist he is also famous for his move in 1950 to the USSR.

Among his scientific ideas:

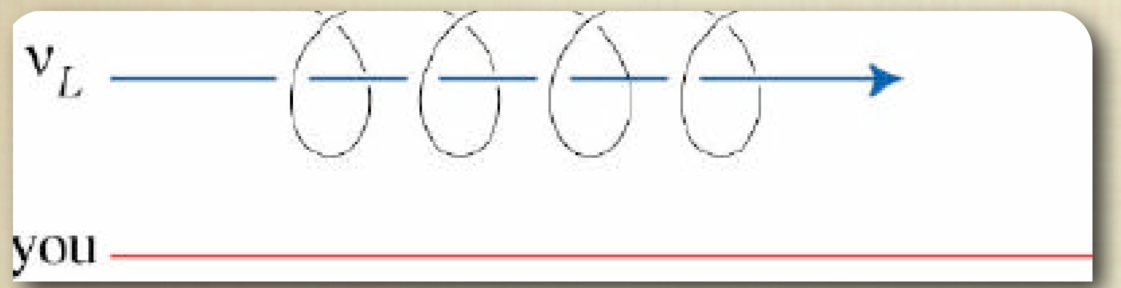
1) The delayed coincidence that made possible Reines & Cowan experiment (discoviery of nue)
2) The prediction that electron neutrinos are not the same than muon neutrinos
3) The mechanism of neutrino oscillations

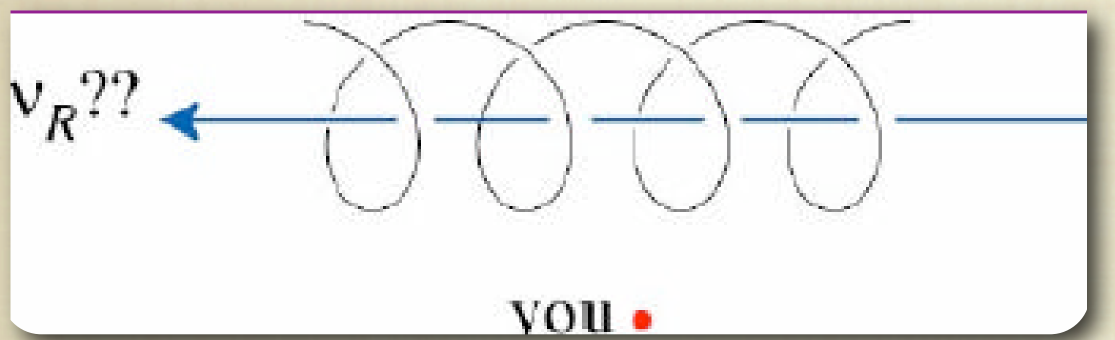
Fermion masses & Higgs Boson



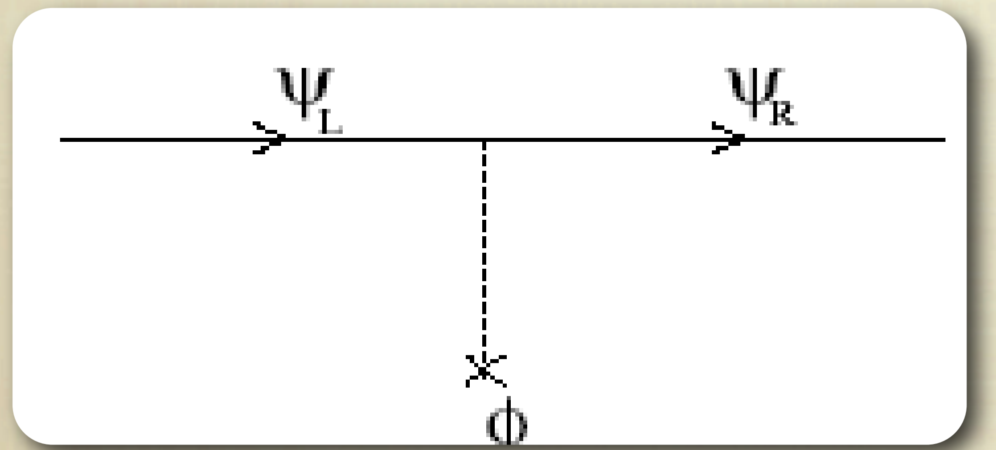
The behaviour of physicists in a crowded social event at a conference is an analogy for the Higgs mechanism, as proposed by David Miller (University College London). The physicists represent a non-trivial medium permeating space. In the upper panel, the physicists cluster around a famous scientist who enters the room, slowing the scientist's progress. In much the same way, a particle passing through the Higgs–Brout–Englert field slows down and acquires a mass. In the lower panel, a rumor propagates. This is an excitation of the medium — the group of physicists — itself, forming a body with a large mass; this is analogous to the formation of a Higgs boson.

Left and right handed particles





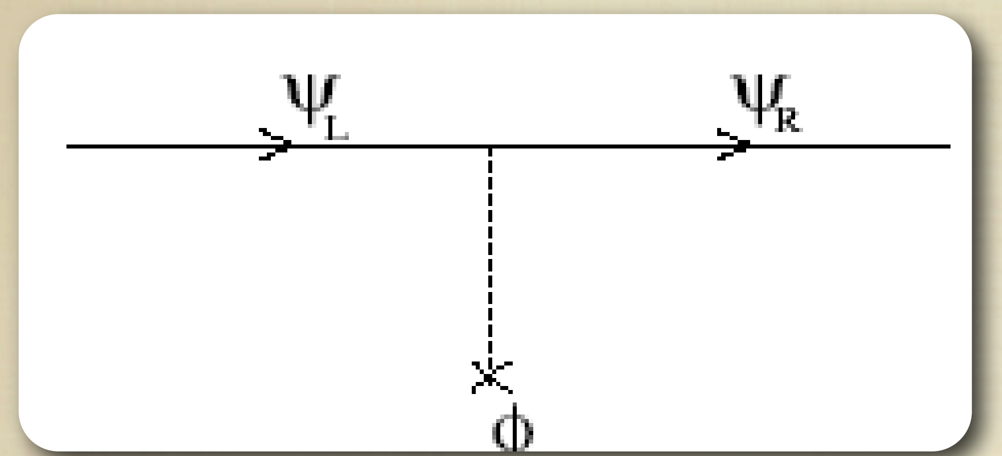
If a particle is massive left and right states must exist



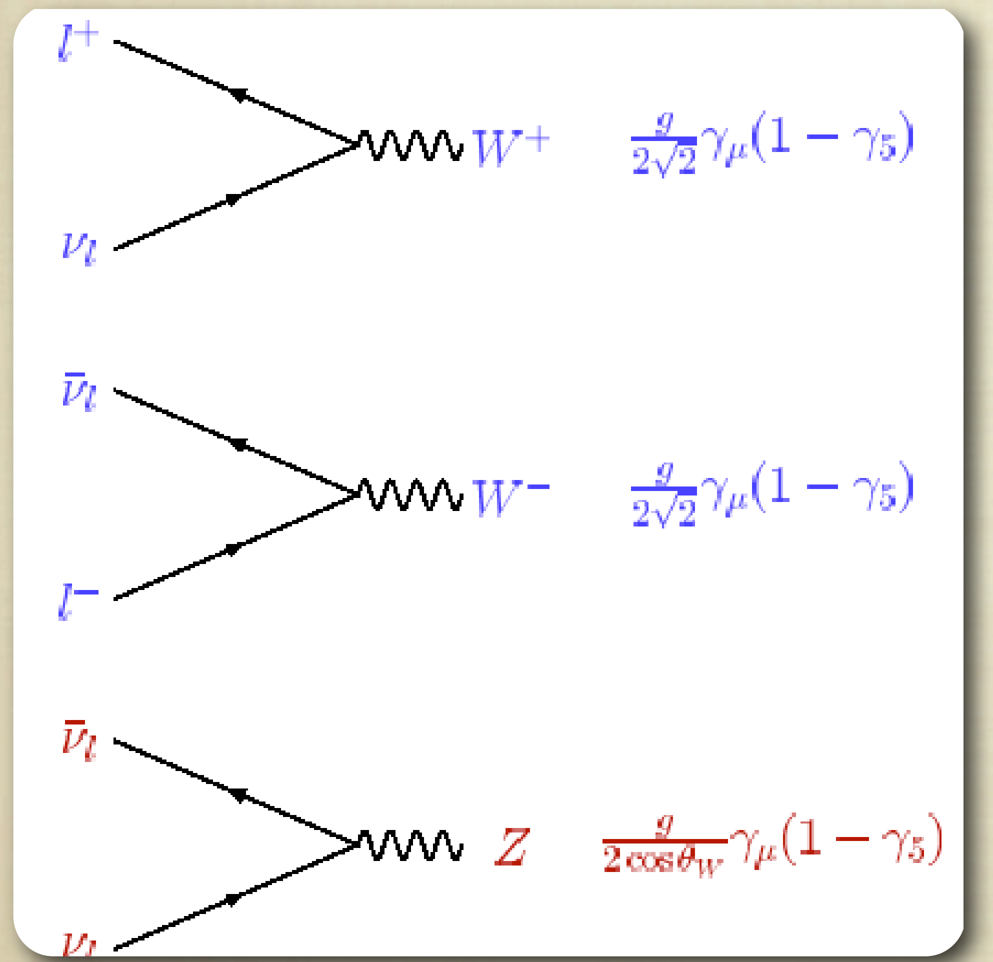
A (electrically) charged fermion such as the electron has left and right states for particle and antiparticle (which are distinct by electric charge)

Charged fermions couple left-right states to a scalar (the Higgs) to generate masses

Mass and flavor eigenstates



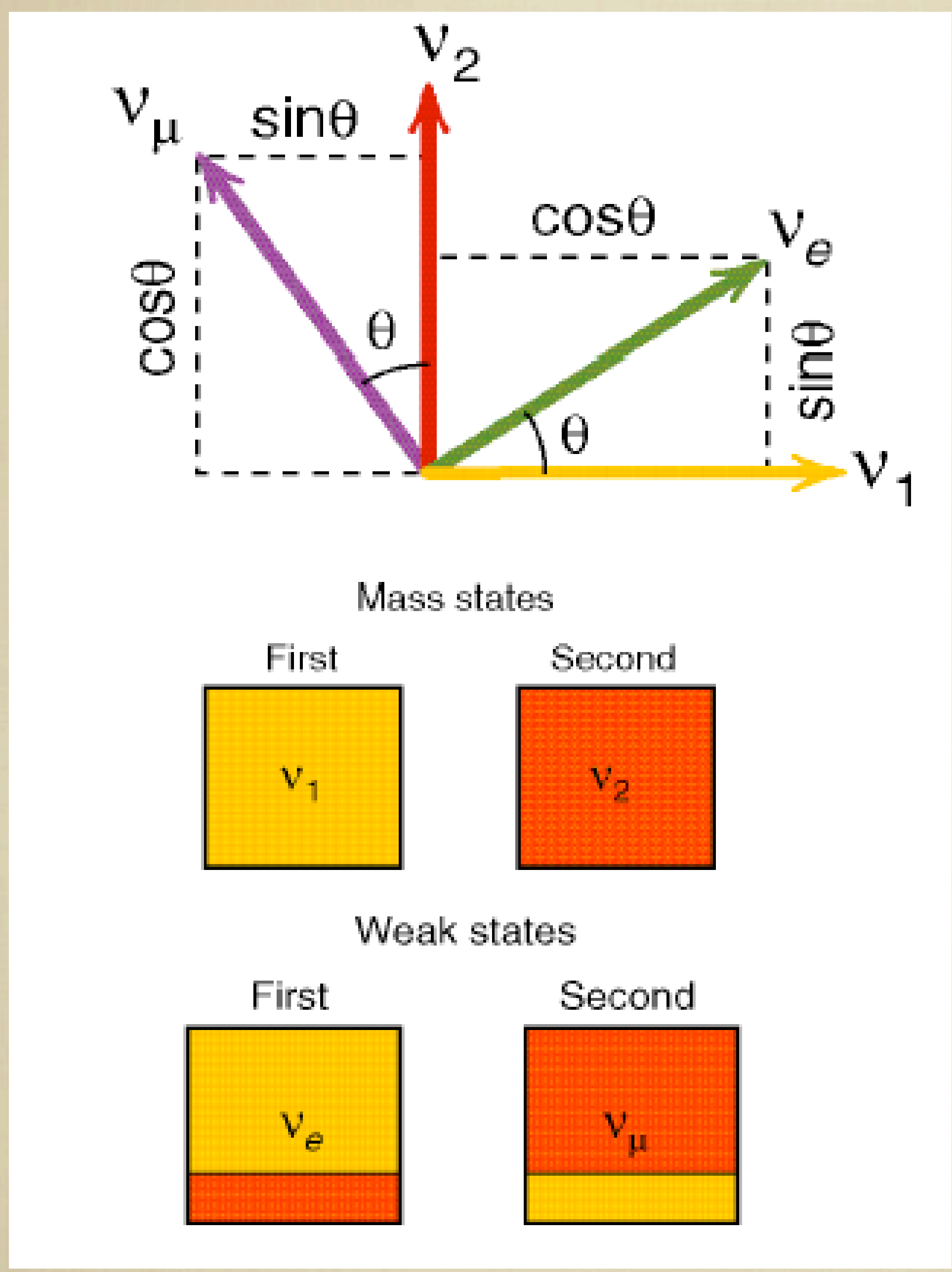
Mass States: Objects that couple to Higgs.



Weak States: Objects that couple to weak bosons.

Are those two types of objects identical?

Mixing

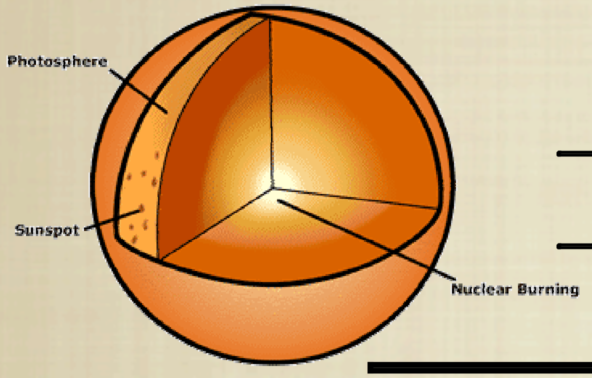


$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Mass and weak states are distinct and connected by means of an unitary transformation, the PMNS mixing matrix, which depends of a single parameter, the mixing angle θ

Oscillations

source

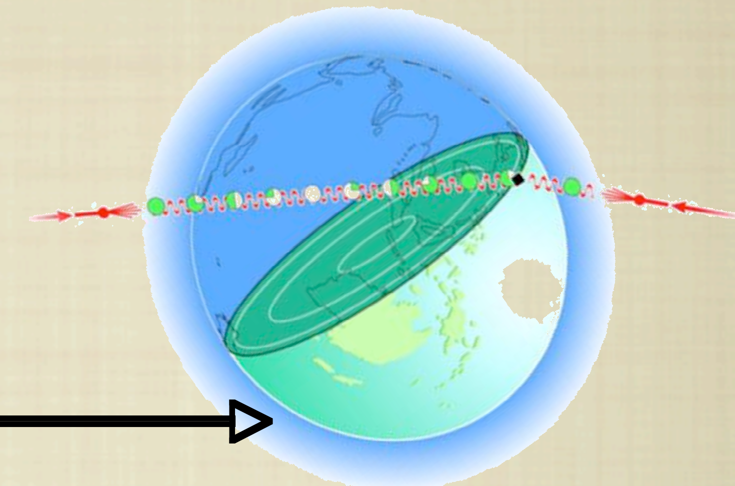


ν_e

propagation

L

detection



The weak interaction produces neutrinos of a given flavor

$$|\nu(x_0)\rangle = |\nu_e\rangle$$
$$= c|\nu_1\rangle + s|\nu_2\rangle$$

The mass eigenstates Propagate at different velocities

$$|\nu(x)\rangle = c|\nu_1\rangle e^{i(Et - \vec{k_1}\vec{x})}$$
$$+ \quad s|\nu_2\rangle e^{i(Et - \vec{k_2}\vec{x})}$$

Detection again via weak interaction

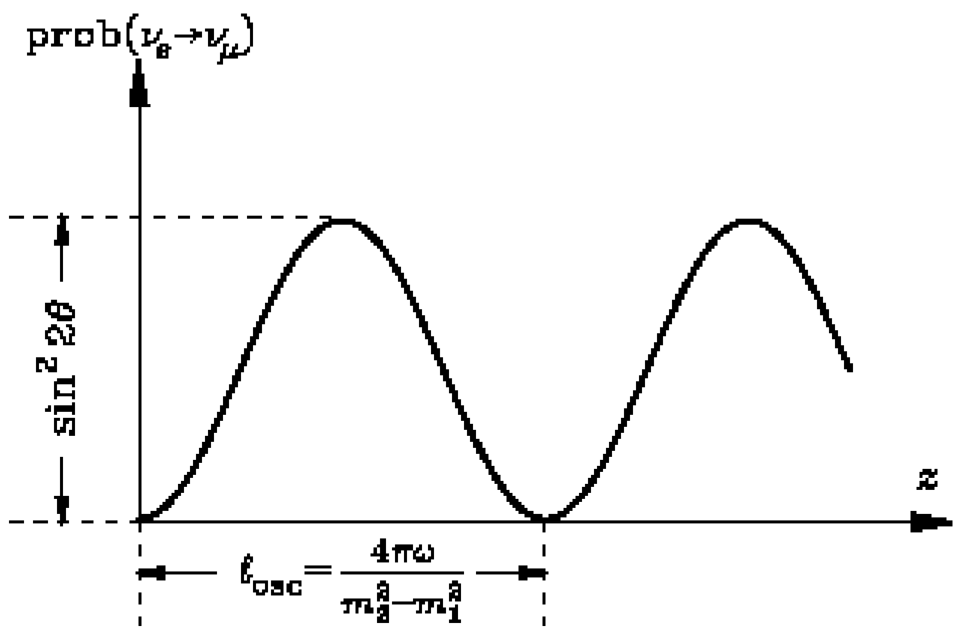
$$\nu_\mu N \to \mu^- X$$
$$\nu_e N \to e^- X$$

$$P(\nu_e \to \nu_\mu) = |<\nu_\mu | \nu(t)>|^2$$

Oscillation Probability

$$P_{\nu_e \to \nu_\mu}(L) = \sin^2(2\theta)\sin^2(1.27\frac{\Delta m^2(eV^2)}{E(GeV)}L(km))$$

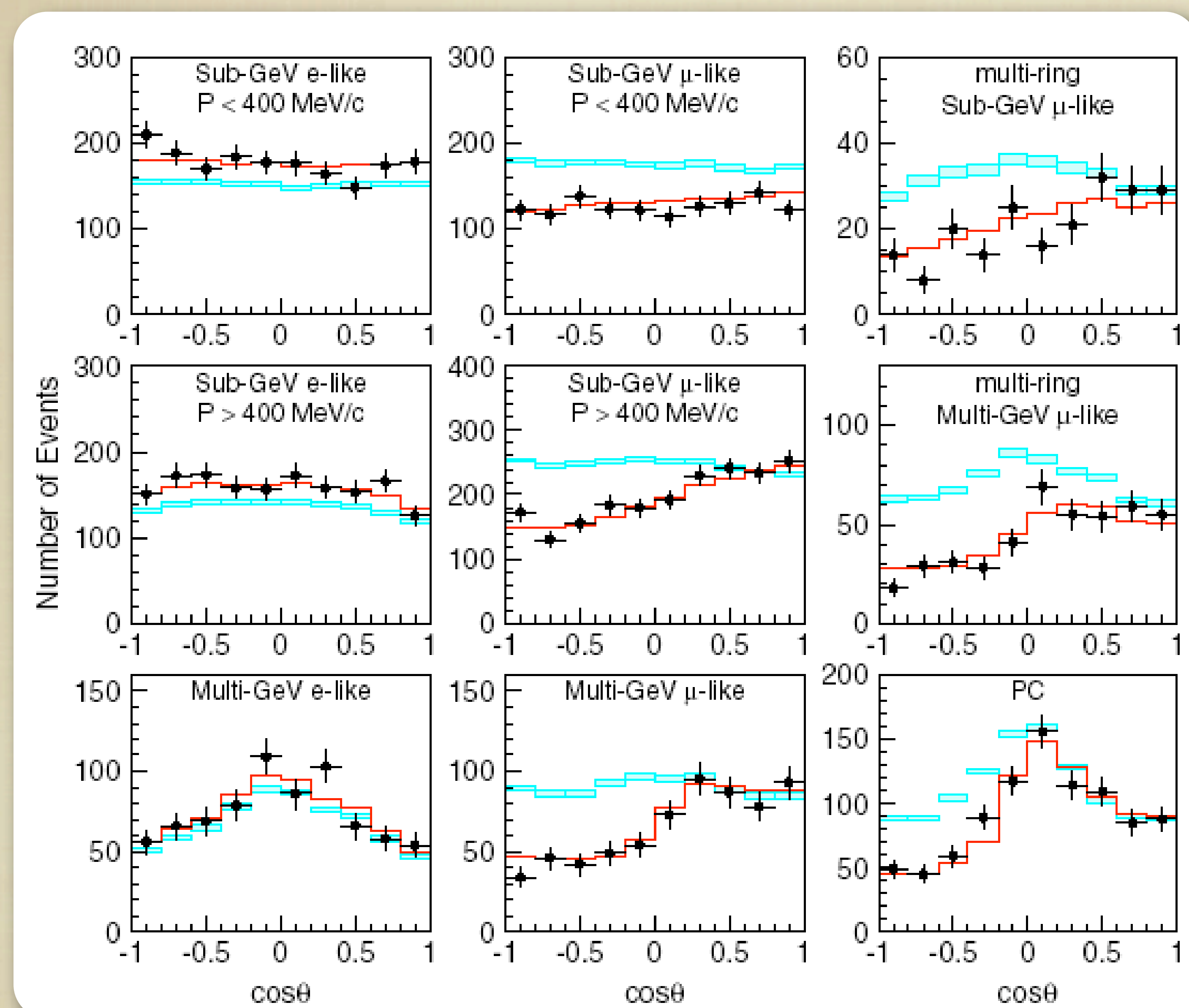
$$P_{\nu_e \to \nu_e}(L) = 1 - P_{\nu_e \to \nu_\mu}(t)$$

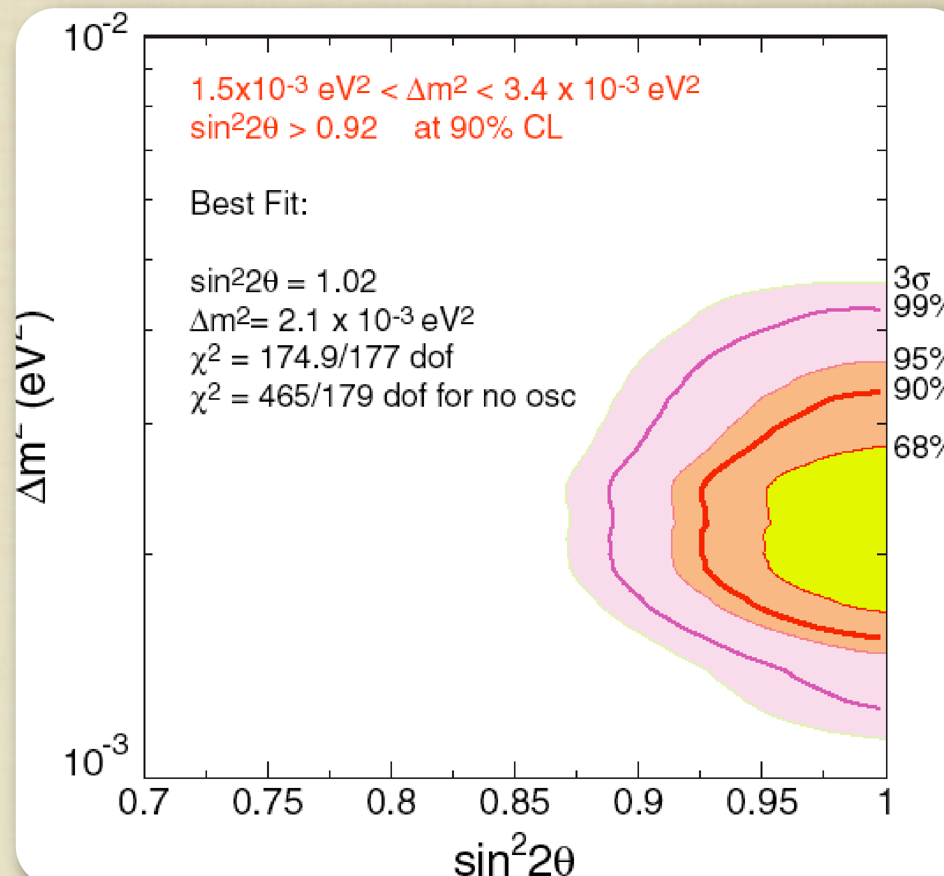


$$\Delta m^2 = m_2^2 - m_1^2$$

$$L_{osc}(Km) \approx \frac{E(GeV)}{1.27\Delta m^2(eV^2)}$$

Atmospheric neutrino problem



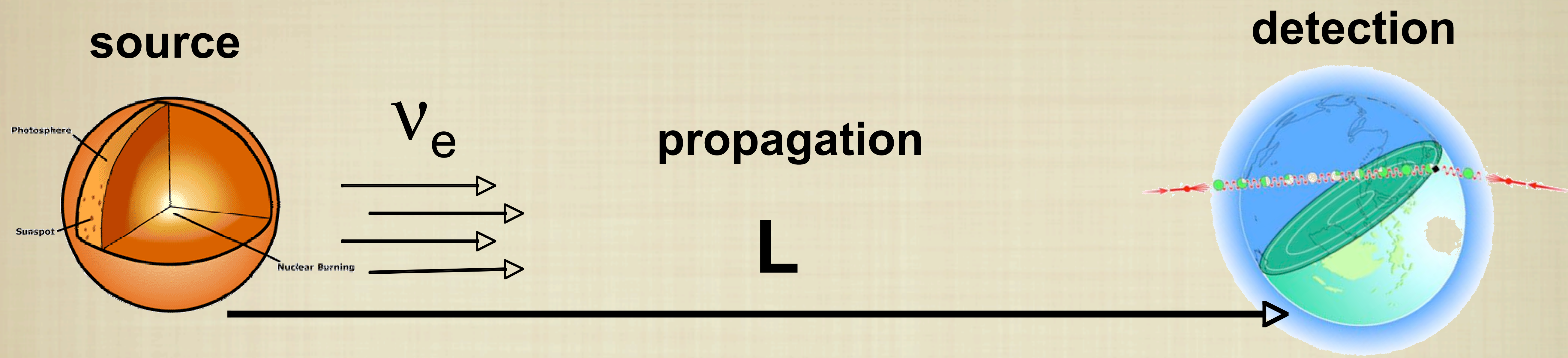


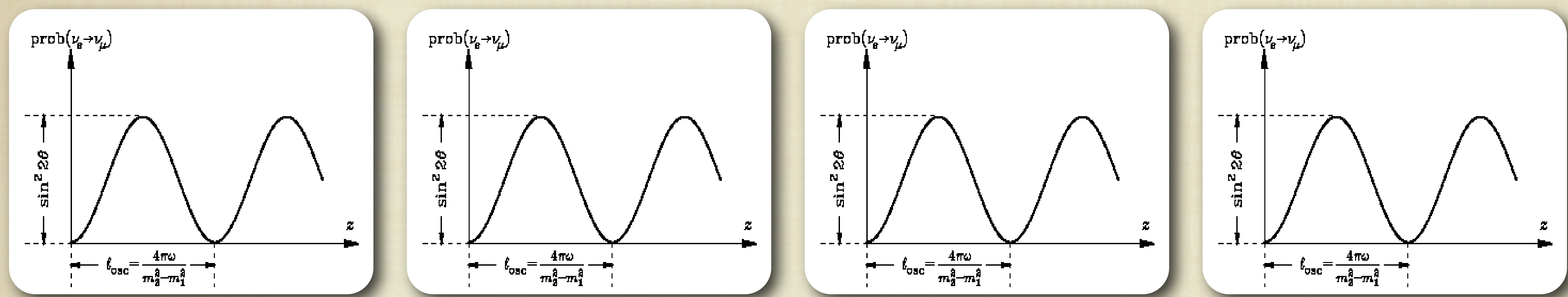
$\nu_\mu \to \nu_\tau$ *oscillations*

$\Delta m^2 = 2.1 \cdot 10^{-3} eV^2$

$\sin^2 2\theta \approx 1$

Solar neutrinos & fine tuning

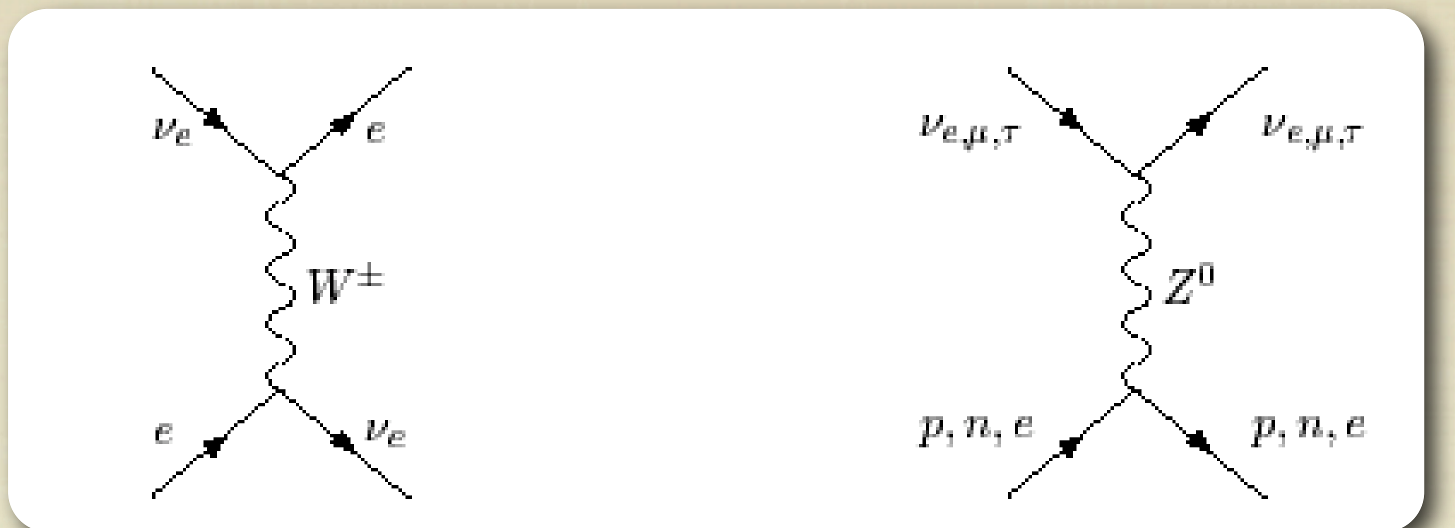




$$L_{osc}(Km) \approx \frac{E(GeV)}{1.27\Delta m^2(eV^2)}$$

Δm^2 and solar neutrino energy must be chosen to provide a L_{osc} that matches exactly distance from sun to earth.

Neutrino oscillation in Matter



Of all the three neutrinos, v_μ and v_τ interact via neutral currents with p, n and e. But v_e is the only neutrino that can interact via CC and NC with the electrons of the medium.

This fact changes the oscillation probability with neutrinos propagate in dense matter. There can be a resonant enhancement of the oscillation probability. The Mikheyev-Smirnov-Wolfenstein (MSW) effect.

P_{osc}^{matter} can be large (1) even if mixing angle in vacuum is small.
In practice this implies that (if MSW is at work) n_e can oscillate to n_m, n_t BEFORE exiting the sun

Oscillation Probability in matter

The probability of oscillation in matter has the same form as in vacuum

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\tilde{\theta} \sin^2(2\pi \frac{L}{\tilde{L}_{osc}}), \quad \tilde{L}_{osc} = \frac{2\pi E(GeV)}{1.27\Delta\tilde{m}^2(eV^2)}$$

MSW resonance

For constant matter density there is an energy such that mixing in matter is maximal independently from the vacuum value.

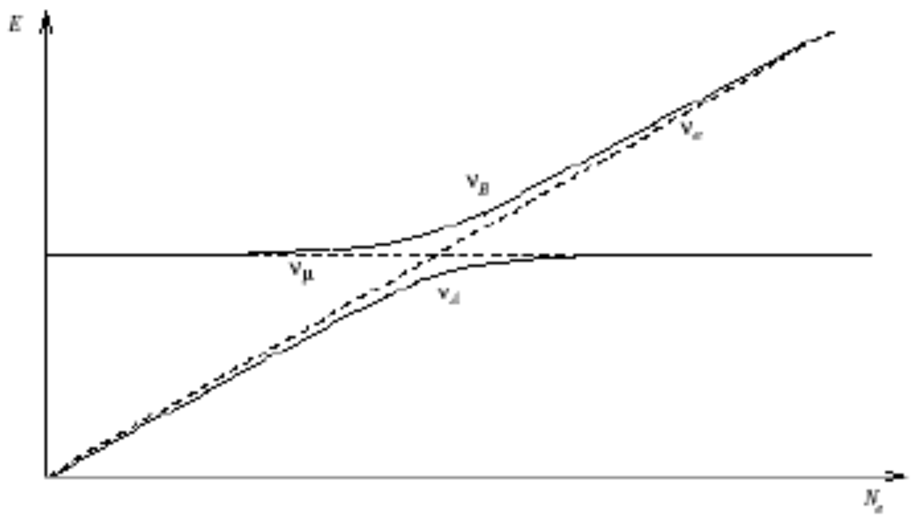
$$\text{if } \Delta m^2 \cos 2\theta = A = \pm\sqrt{2} E G N_e$$

$$\sin^2 2\tilde{\theta} = \frac{(\Delta m^2)^2 \sin^2 2\theta}{(\Delta m^2 \cos 2\theta - A)^2 + (\Delta m^2)^2 \sin^2 2\theta} = 1$$

Thus the probability of neutrino transition in matter can be large even if the mixing angle is small

Adiabatic approximation

In the sun Ne is not constant. However if the variation is sufficiently slow the eigenstates of H change slowly with the density and one can assume that the neutrino remains an eigenstate along the trajectory: adiabatic approximation



$$\tilde{\nu}_1 = \nu_e \cos\tilde{\theta} + \nu_\mu \sin\tilde{\theta}$$

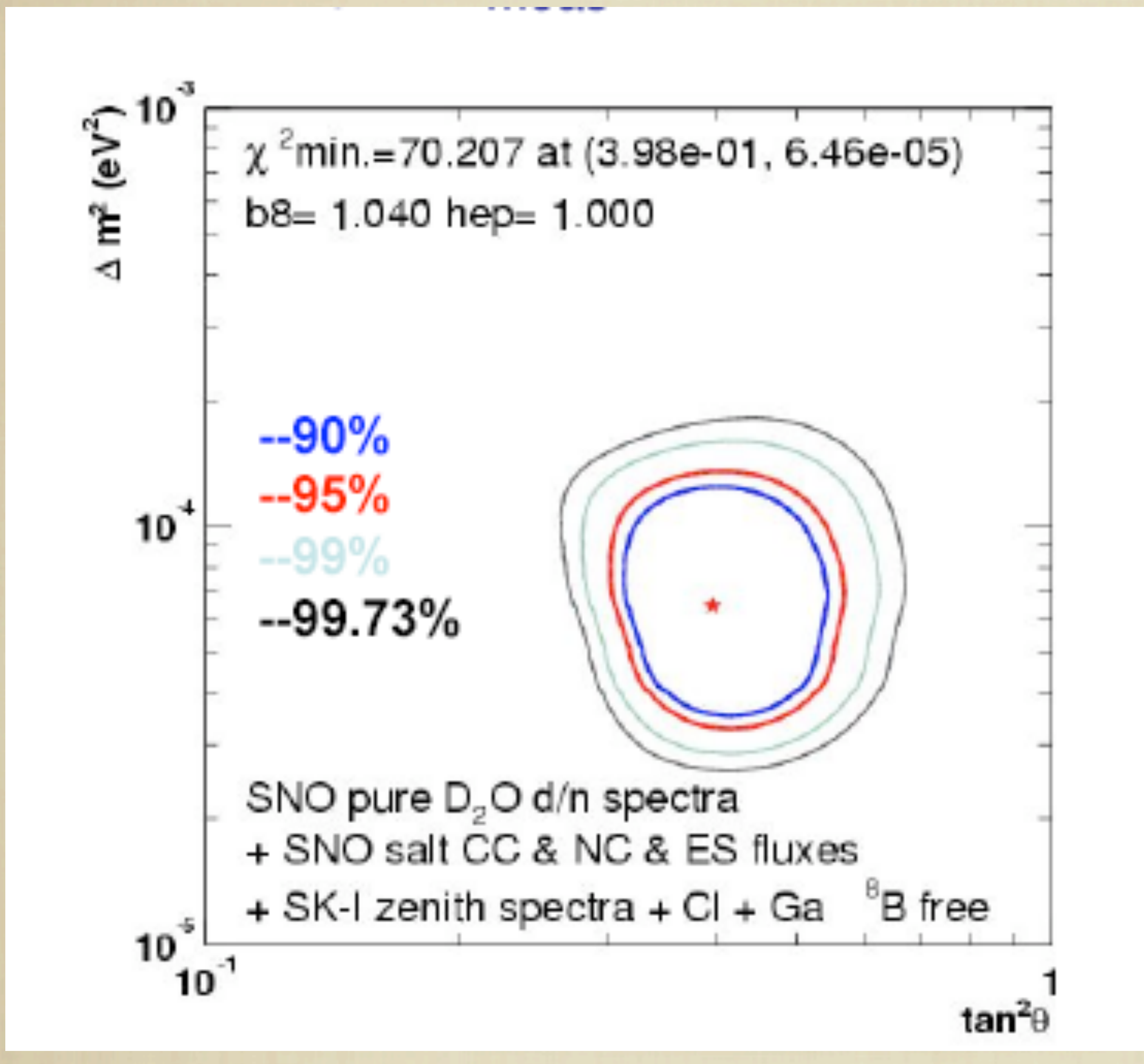
$$\tilde{\nu}_2 = -\nu_e \sin\tilde{\theta} + \nu_\mu \cos\tilde{\theta}$$

$$x = 0 \quad if\ A \gg \Delta m^2 \cos 2\theta \rightarrow \tilde{\theta} \approx \frac{\pi}{2} \Rightarrow \quad \nu_e \simeq \tilde{\nu}_2$$

$$x = R_{sun} \quad N_e = 0 \rightarrow \tilde{\theta} \approx \theta \Rightarrow \quad \nu_\mu \simeq \tilde{\nu}_2$$

A ν_e produced at the sun core is the eigenstate ν_2 but this eigenstate outside the sun is mostly ν_μ. There is maximum $\nu_e \rightarrow \nu_\mu$ conversion

Solar oscillations

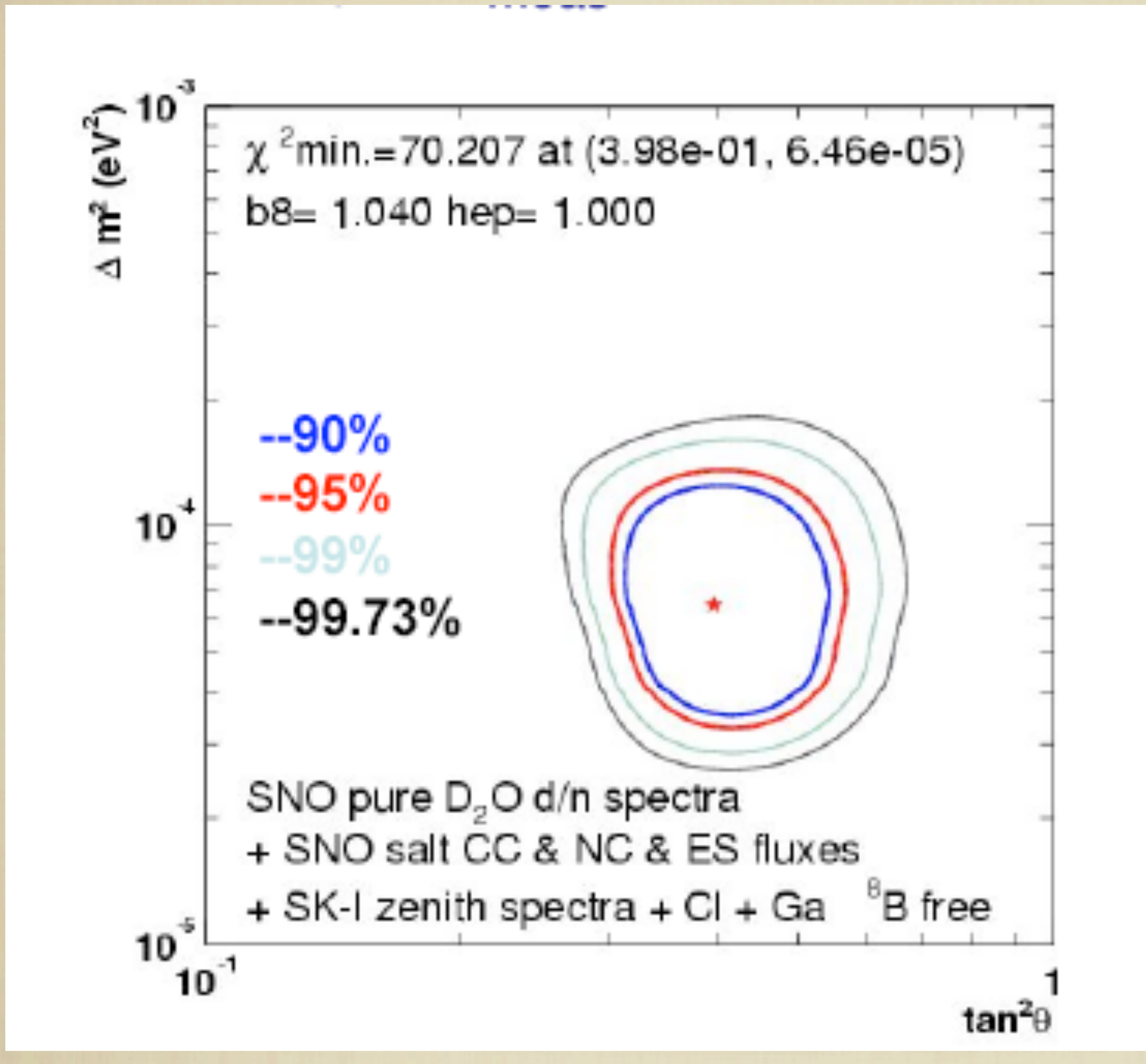


Neutrinos produced at the sun (ν_e) oscillate to other neutrinos via matter-enhanced MSW.

$\Delta m^2 = 8 \times 10^{-5}\ eV^2$

$\theta \approx 30^0$

Solar oscillations



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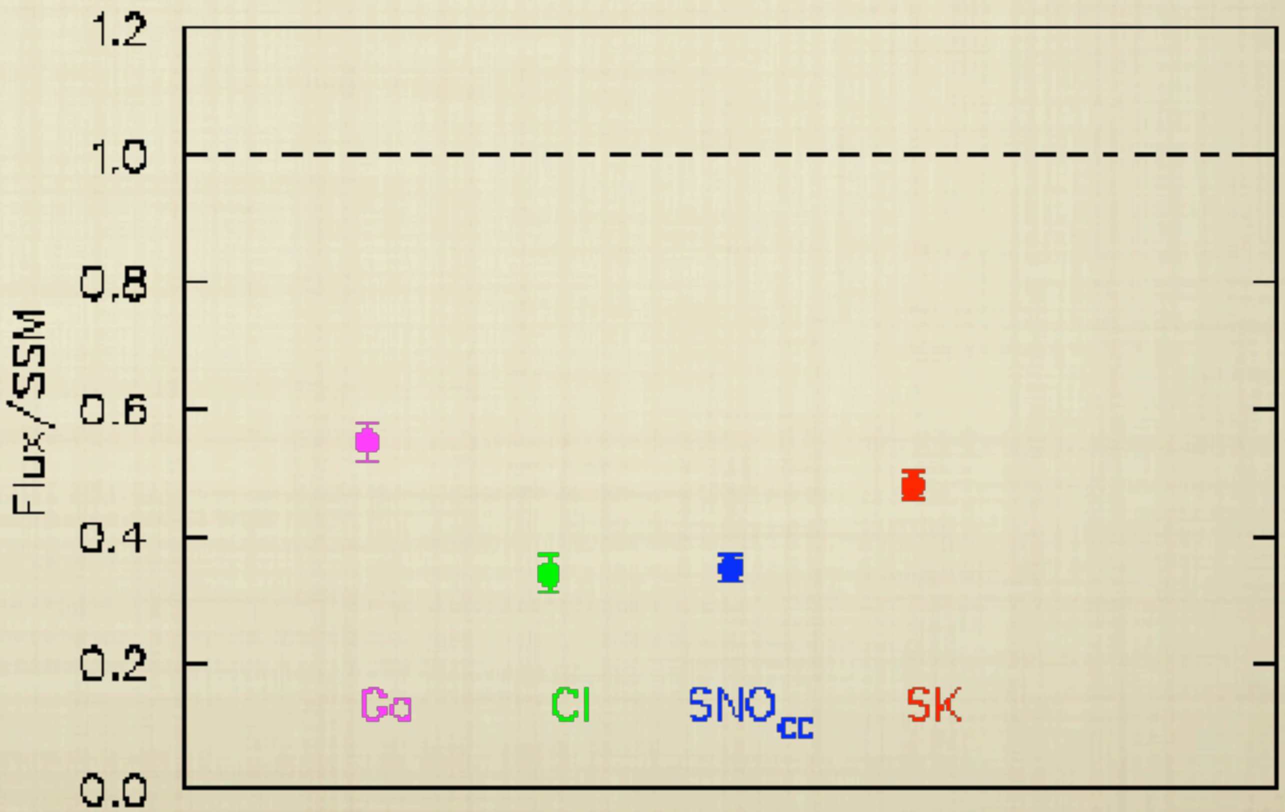
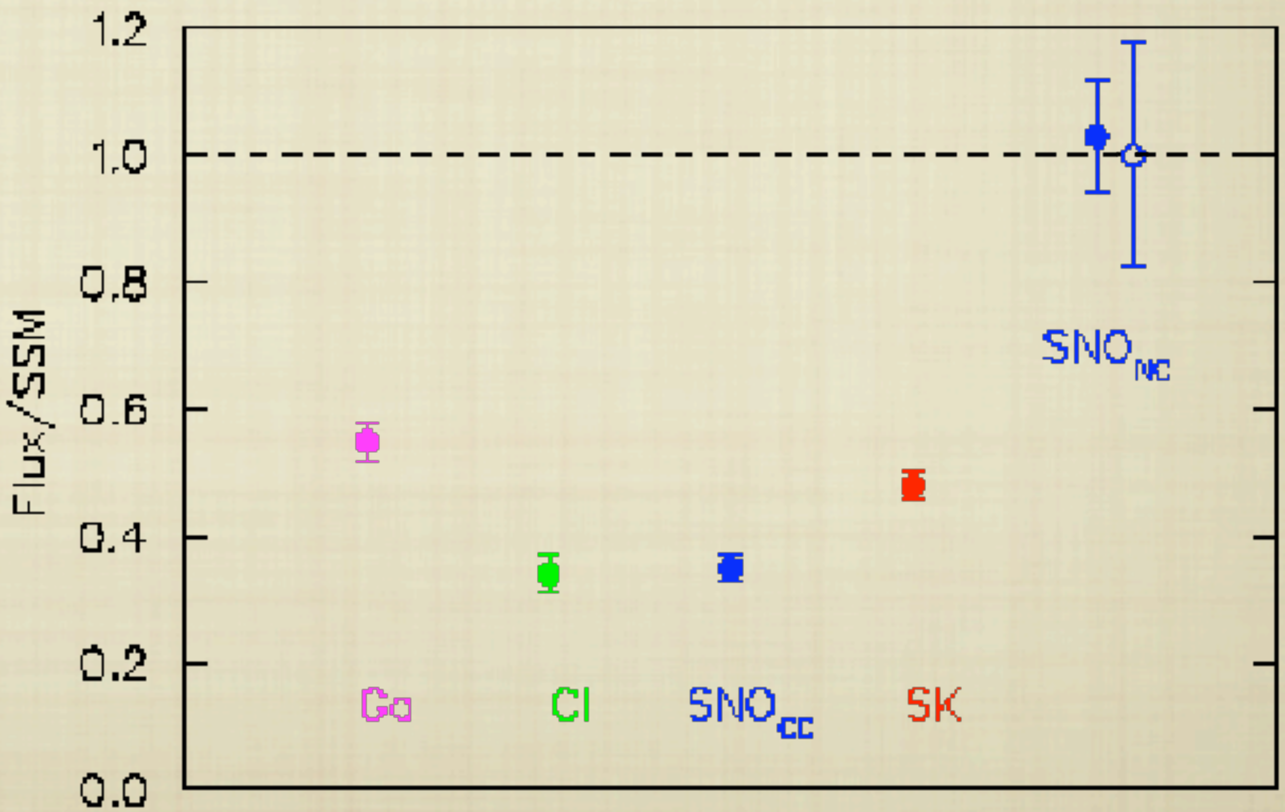
Solar neutrino oscillations

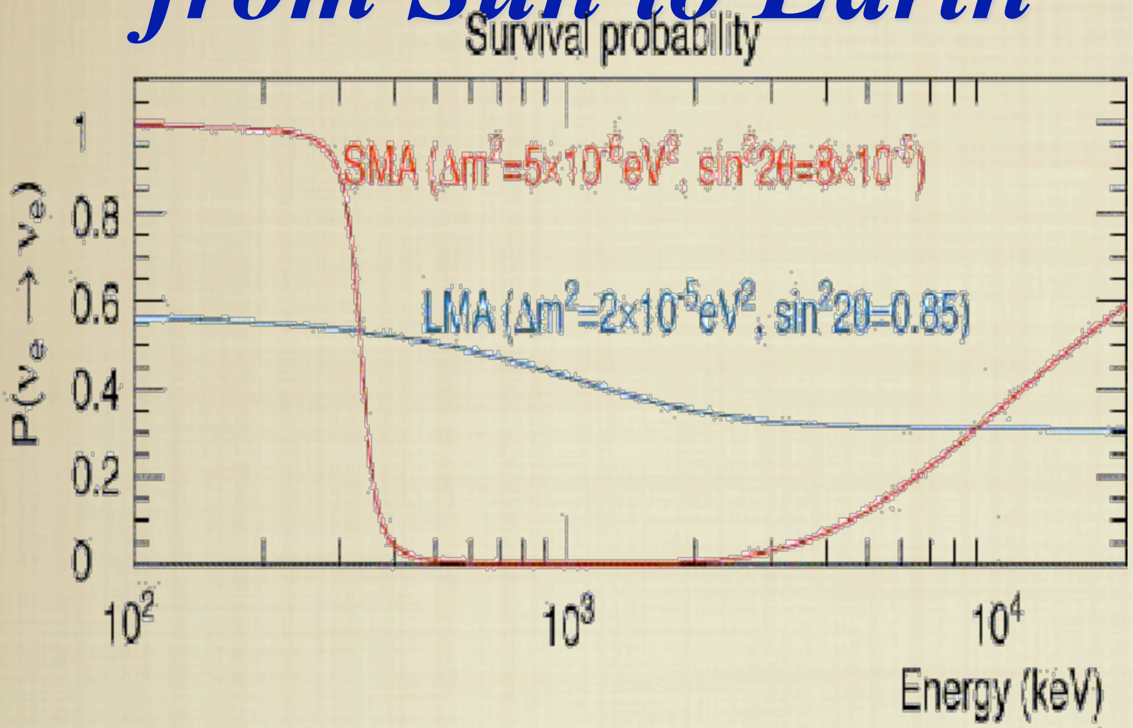


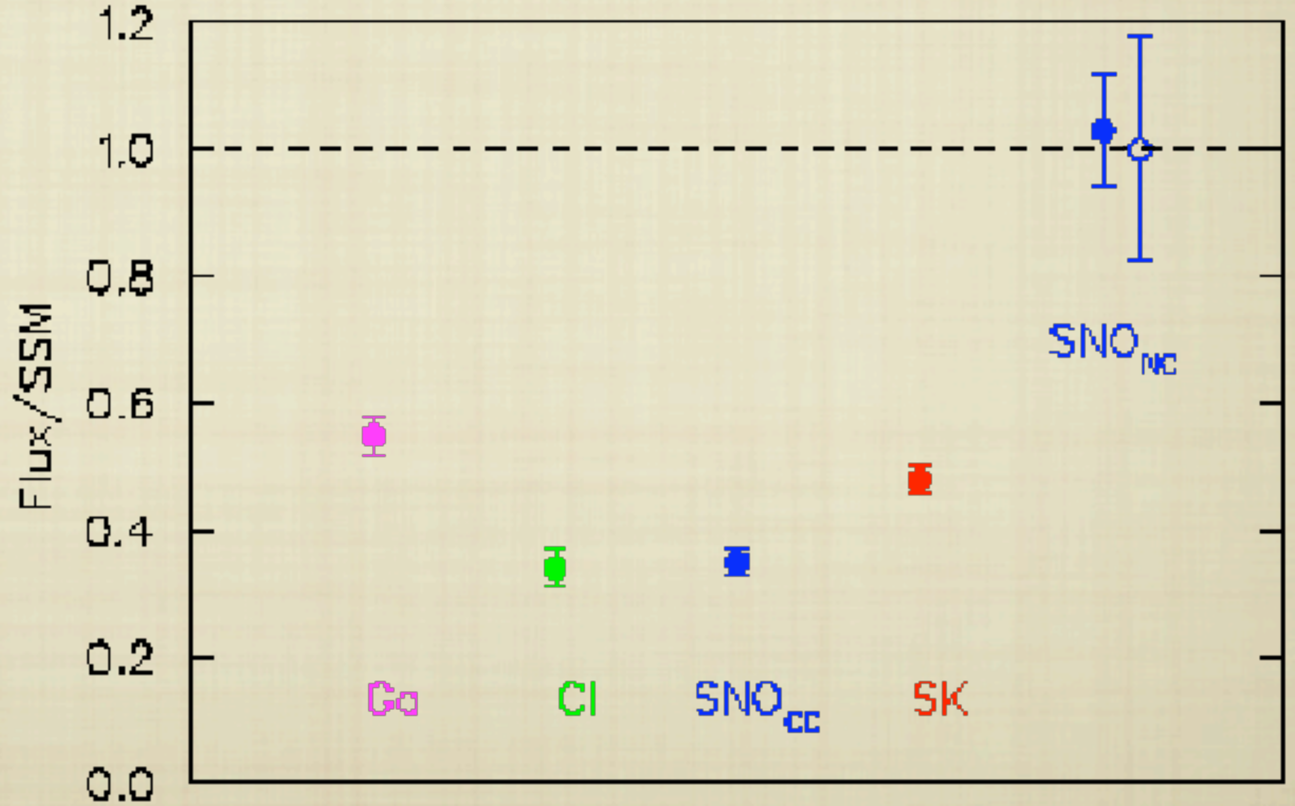
Solar neutrino oscillations



Solar neutrino oscillations

Matter effect on ν_e from Sun to Earth





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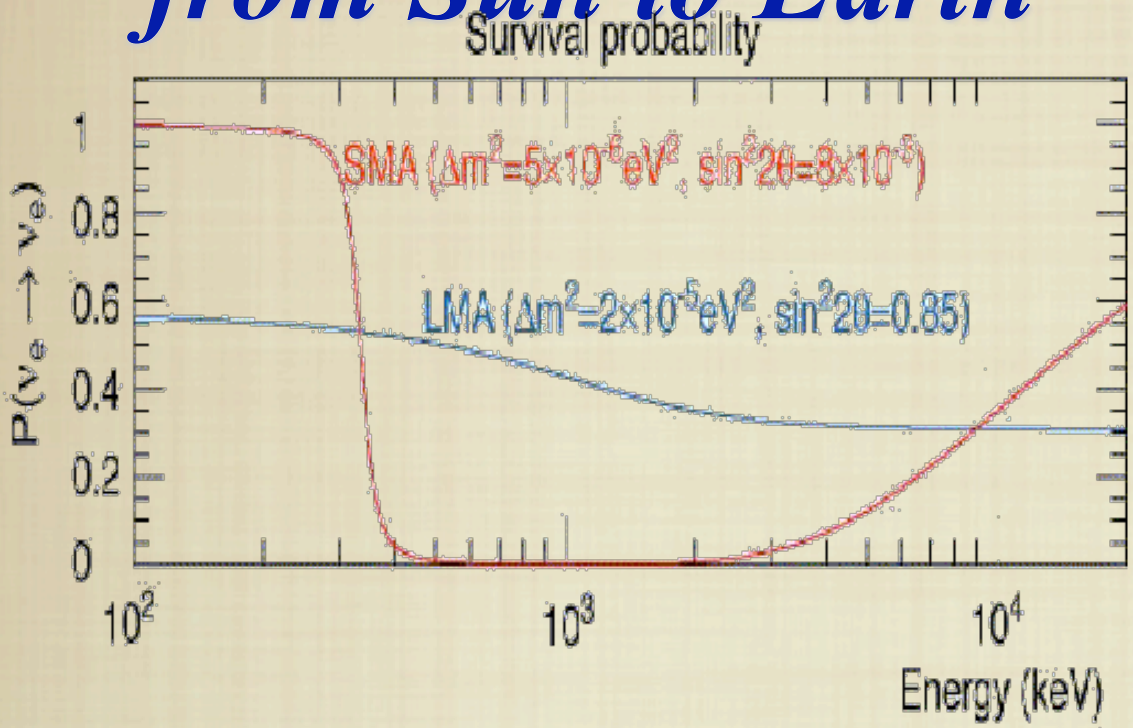

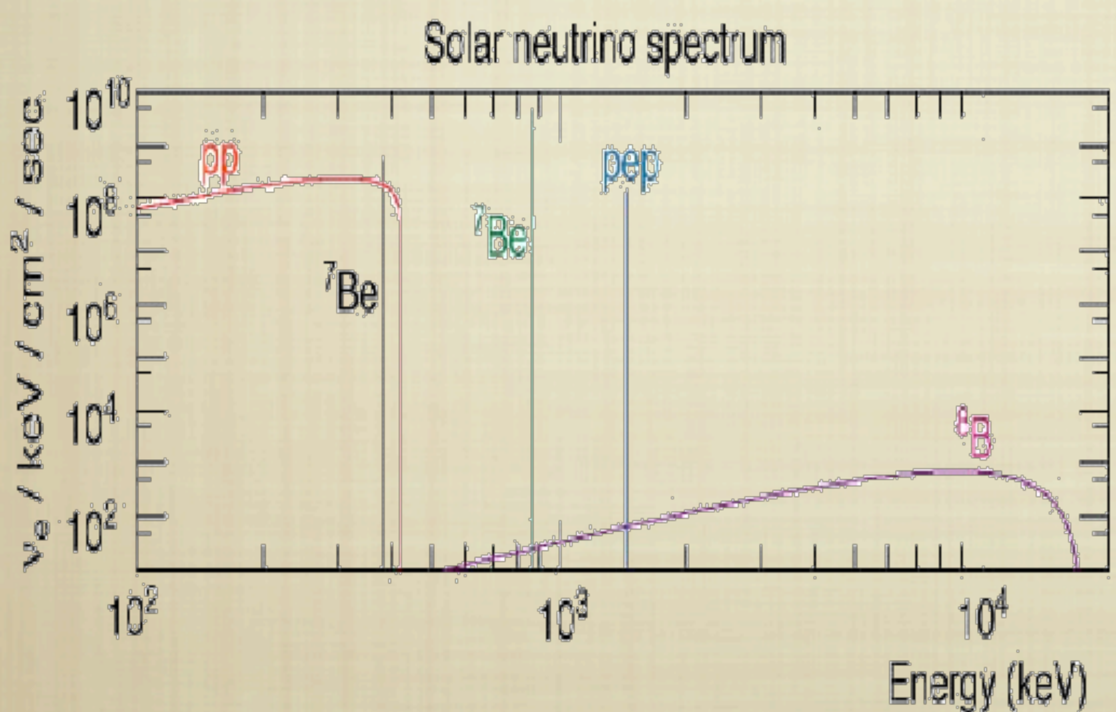

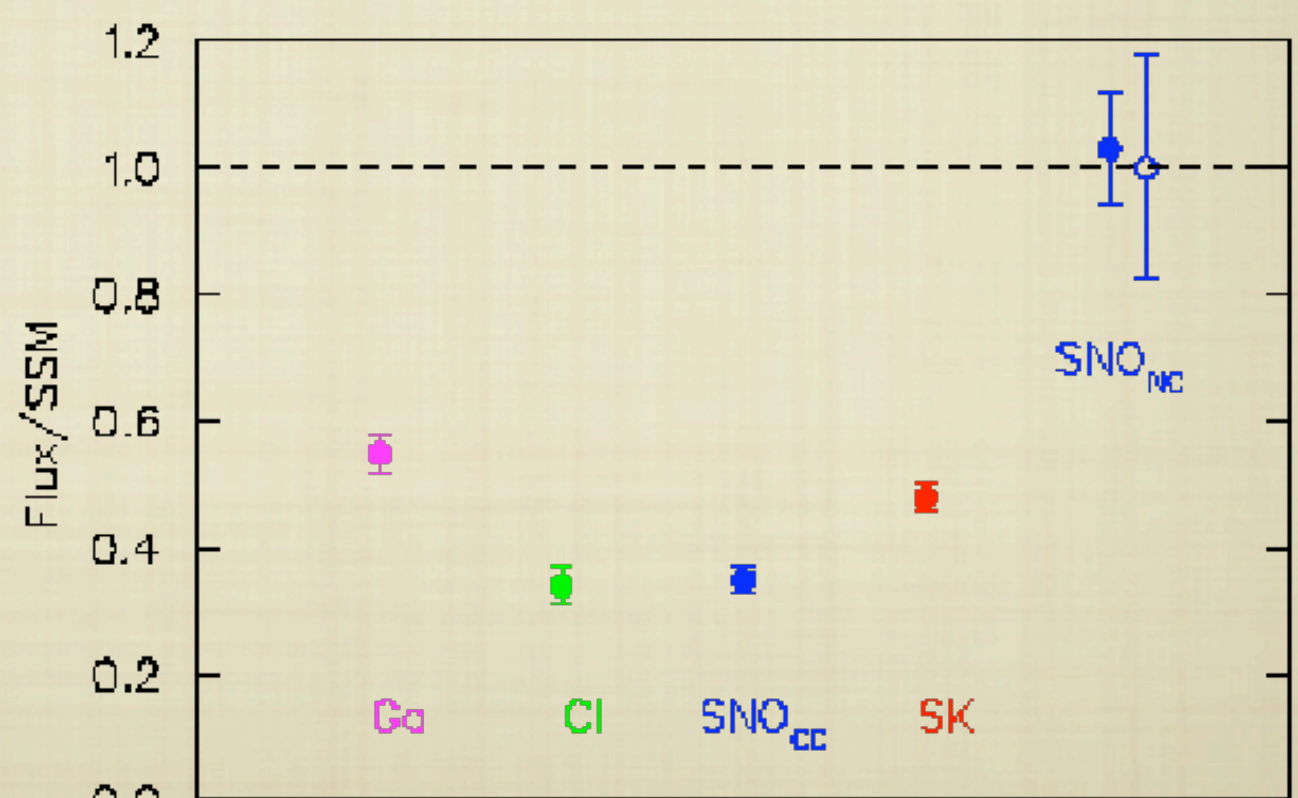

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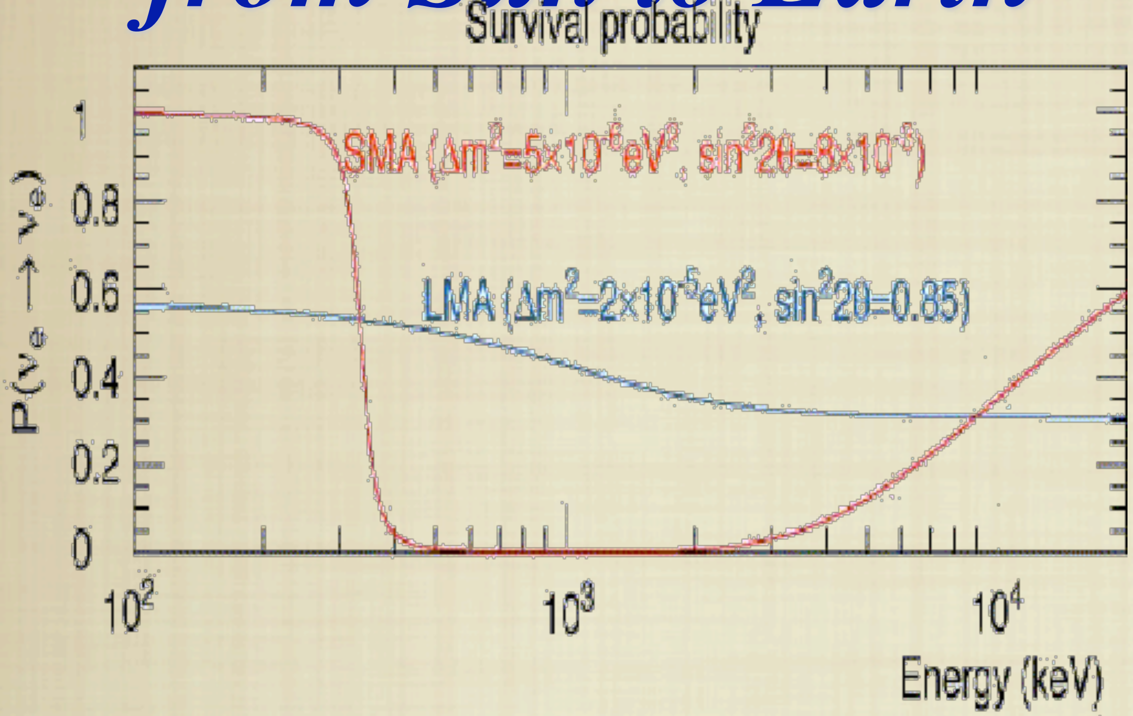

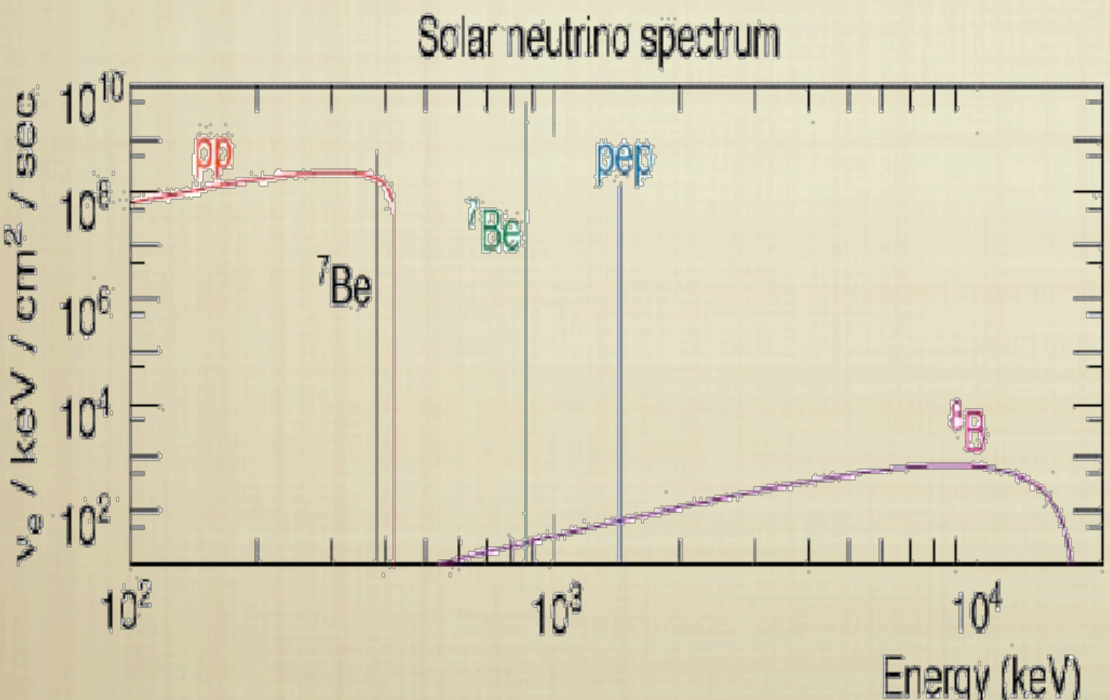

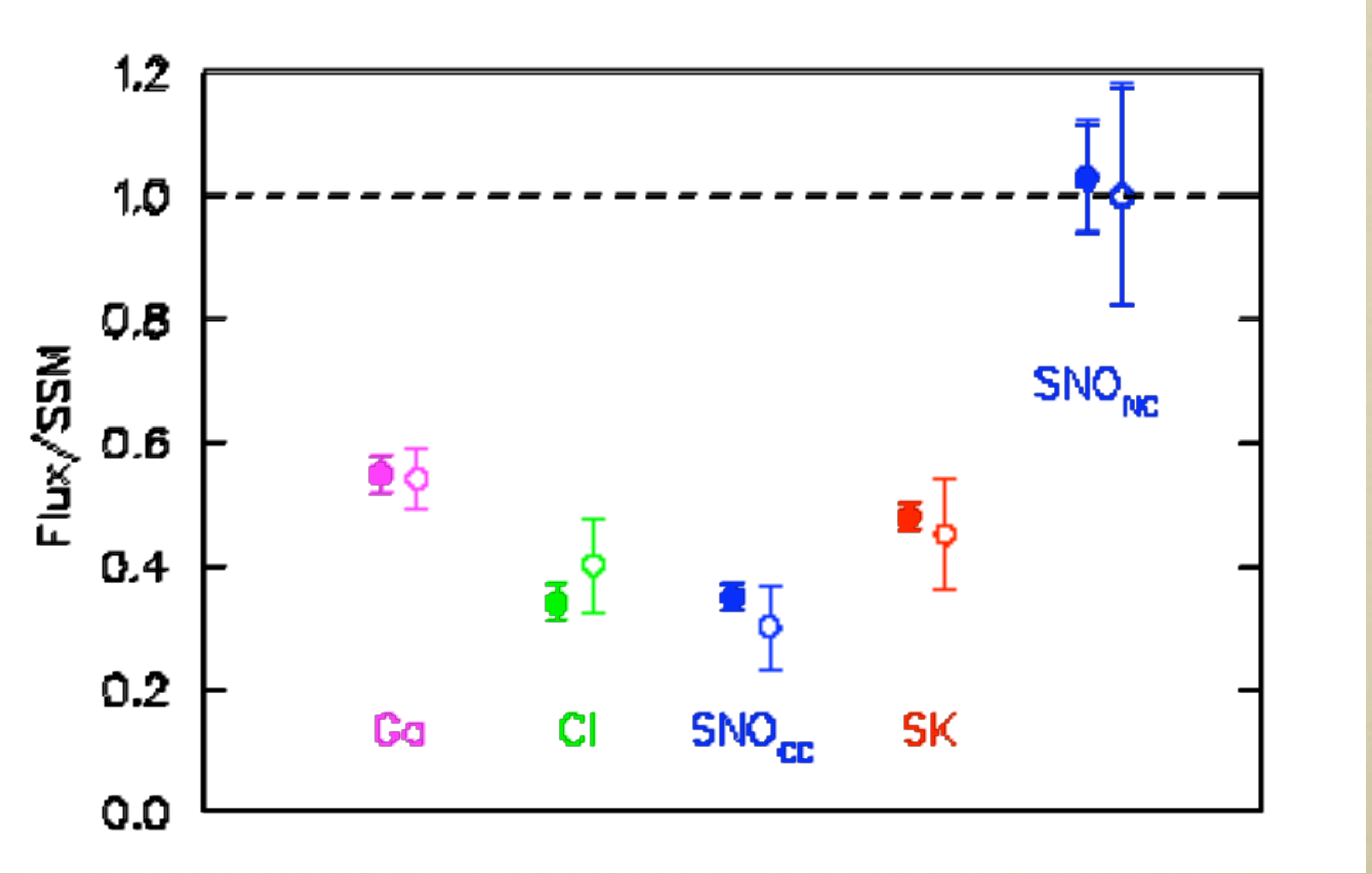

Solar neutrino oscillations

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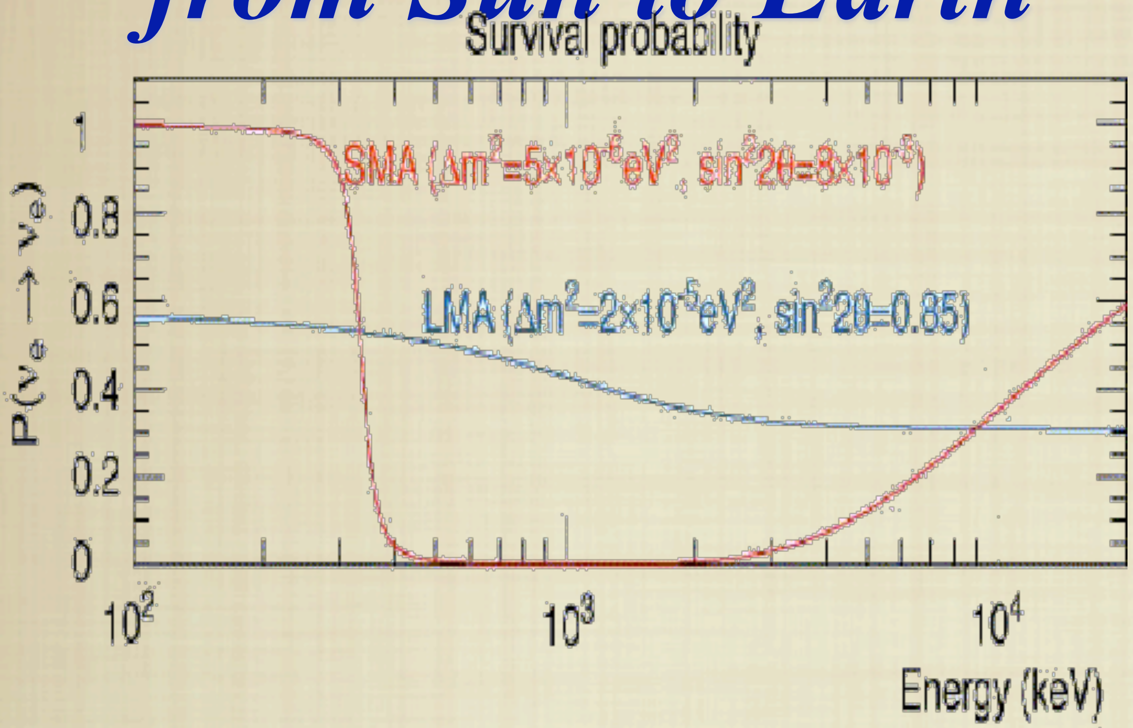
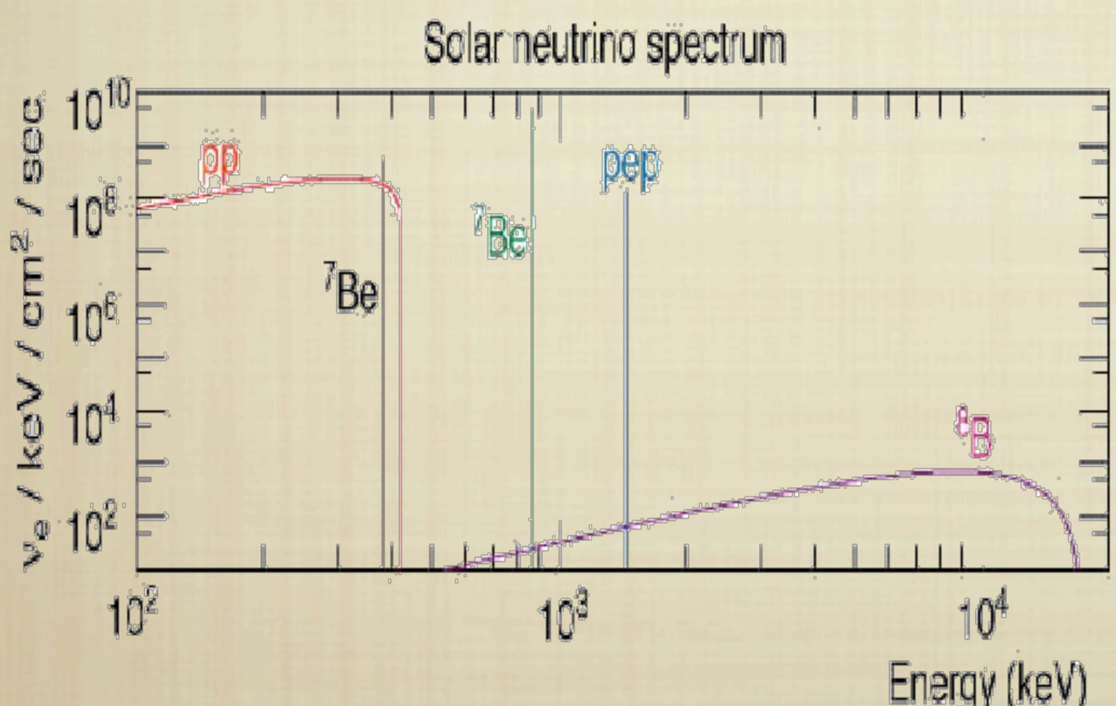




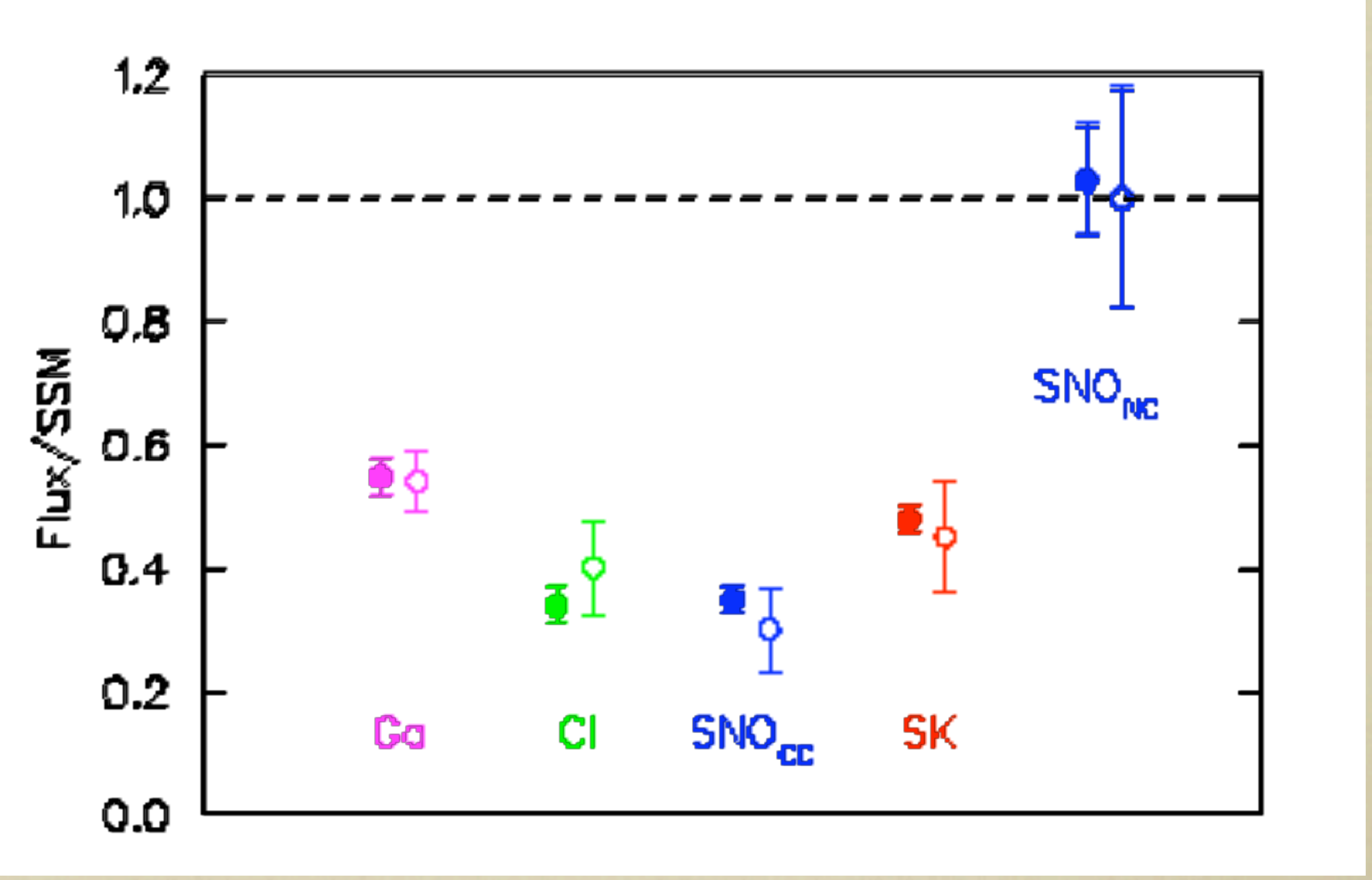
The LMA solar solution

\+

matter effects

explain beautifully

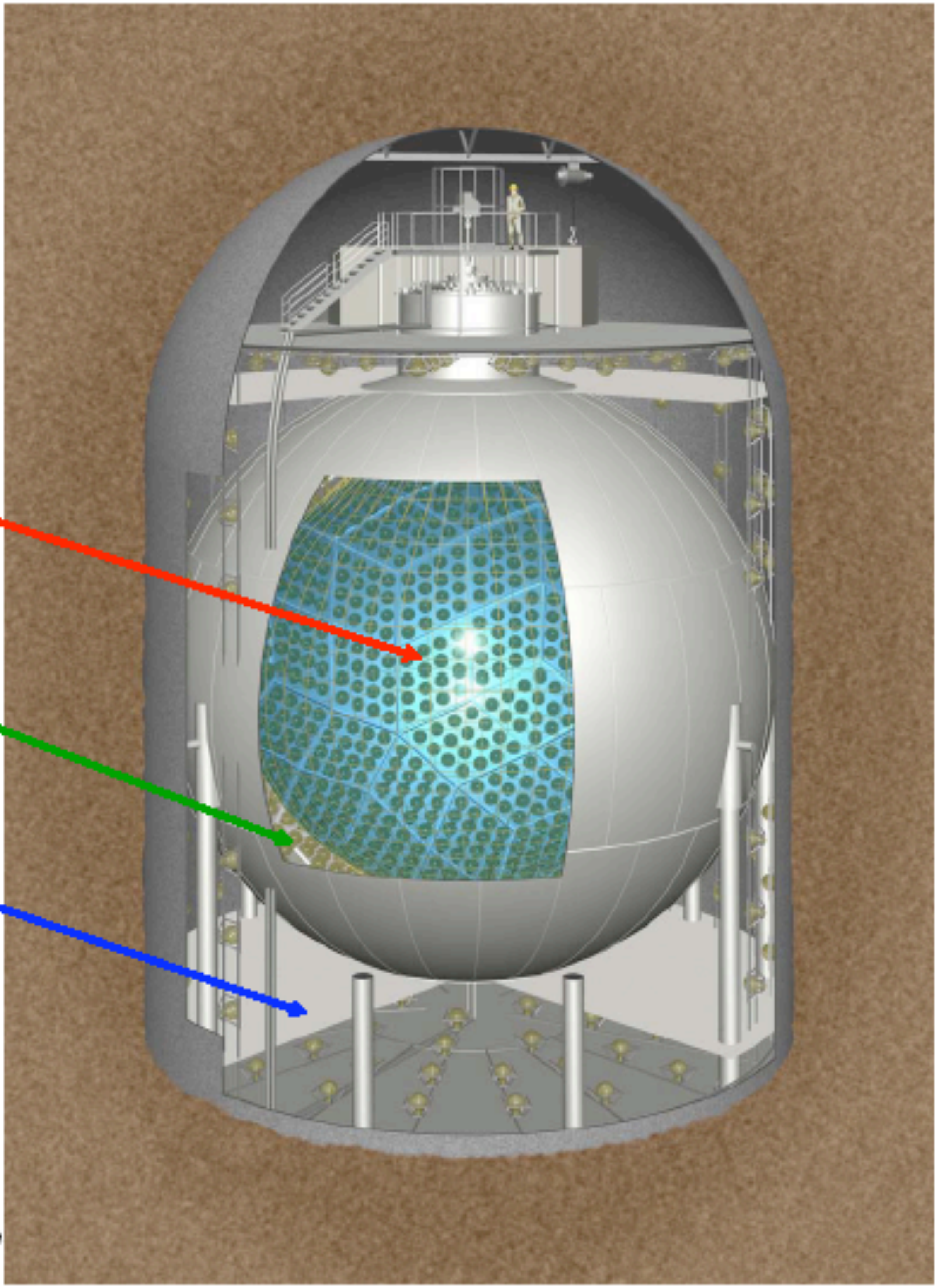
all solar neutrino experiments



Kamland

KamLAND:
Kamioka Liquid scintillator AntiNeutrino Detector

- 1 kton liq. Scint. Detector in the Kamiokande cavern
- 1325 17" fast PMTs
- 554 20" large area PMTs
- 34% photocathode coverage
- H_2O Cerenkov veto counter



Kamland location & flux

Many reactors contribute to the antineutrino flux at KamLAND

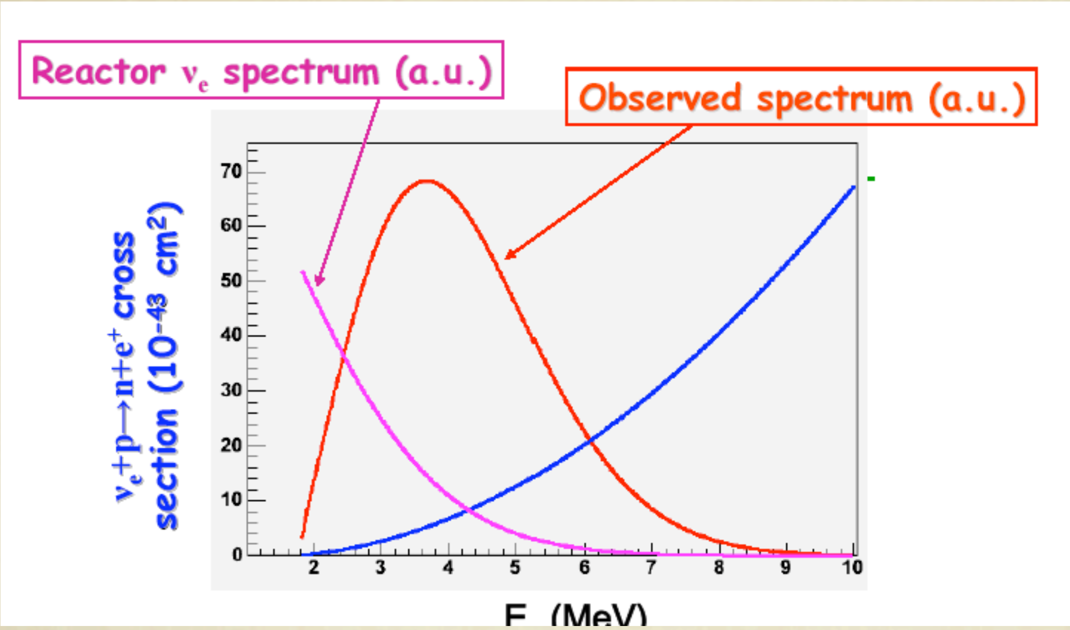
	Site	Dist (km)	Cores (#)	P_{therm} (GW)	Flux ($cm^{-2}\,s^{-1}$)	Rate noosc* ($yr^{-1}\,kt^{-1}$)
Japan	Kashiwazaki	160	7	24.3	$4.1\cdot10^5$	254.0
	Ohi	179	4	13.7	$1.9\cdot10^5$	114.3
	Takahama	191	4	10.2	$1.2\cdot10^5$	74.3
	Tsuruga	138	2	4.5	$1.0\cdot10^5$	62.5
	Hamaoka	214	4	10.6	$1.0\cdot10^5$	62.0
	Mihama	146	3	4.9	$1.0\cdot10^5$	62.0
	Sika	88	1	1.6	$9.0\cdot10^4$	55.2
	Fukushima1	349	6	14.2	$5.1\cdot10^4$	31.1
	Fukushima2	345	4	13.2	$4.8\cdot10^4$	29.5
	Tokai2	295	1	3.3	$1.6\cdot10^4$	10.1
	Onagawa	431	3	6.5	$1.5\cdot10^4$	9.3
	Simane	401	2	3.8	$1.0\cdot10^4$	6.3
	Ikata	561	3	6.0	$8.3\cdot10^3$	5.1
	Genkai	755	4	10.1	$7.8\cdot10^3$	4.8
	Sendai	830	2	5.3	$3.4\cdot10^3$	2.1
	Tomari	783	2	3.3	$2.3\cdot10^3$	1.4
South Korea	Ulchin	712	4	11.5	$9.9\cdot10^3$	6.1
	Yonggwang	986	6	17.4	$7.8\cdot10^3$	4.8
	Kori	735	4	9.2	$7.5\cdot10^3$	4.6
	Wolsong	709	4	8.2	$7.1\cdot10^3$	4.3
Total Nominal		-	70	181.7	$1.3\cdot10^6$	803.8

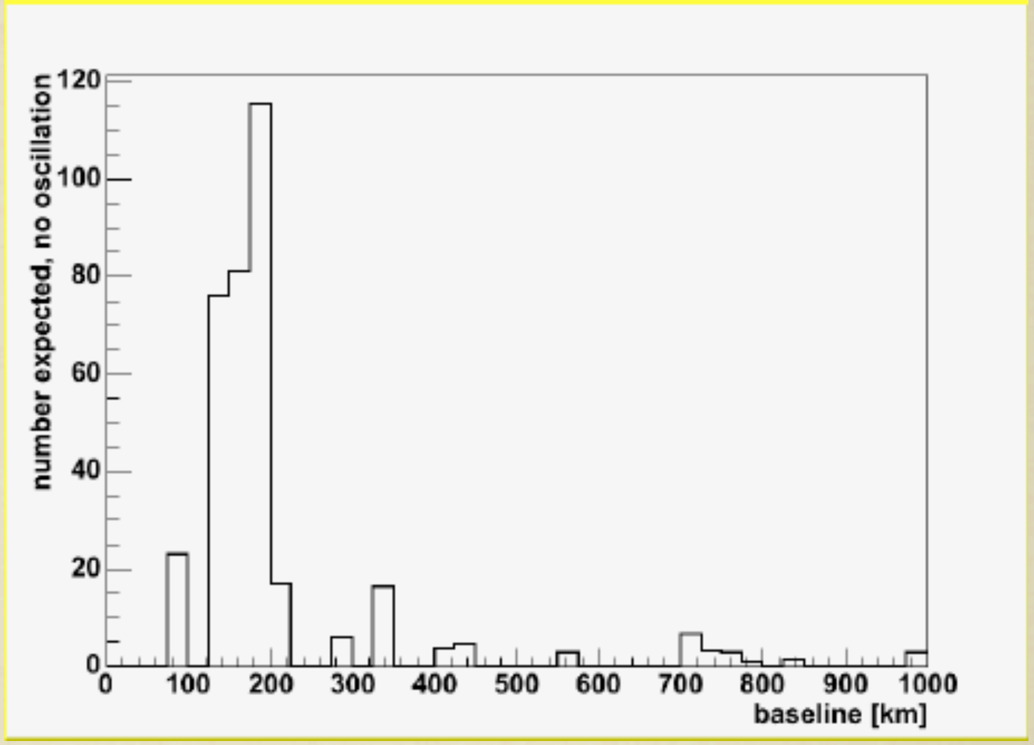
*$E_\nu>3.4$MeV ($E_{prompt}>2.6$MeV)

Detailed power and fuel Composition calculation used (Japan)

From electrical power Japanese average fuel used (South Korea)

Spectrum and baselines





$$L_{osc}(Km) \approx \frac{E(GeV)}{1.27\Delta m^2(eV^2)}$$

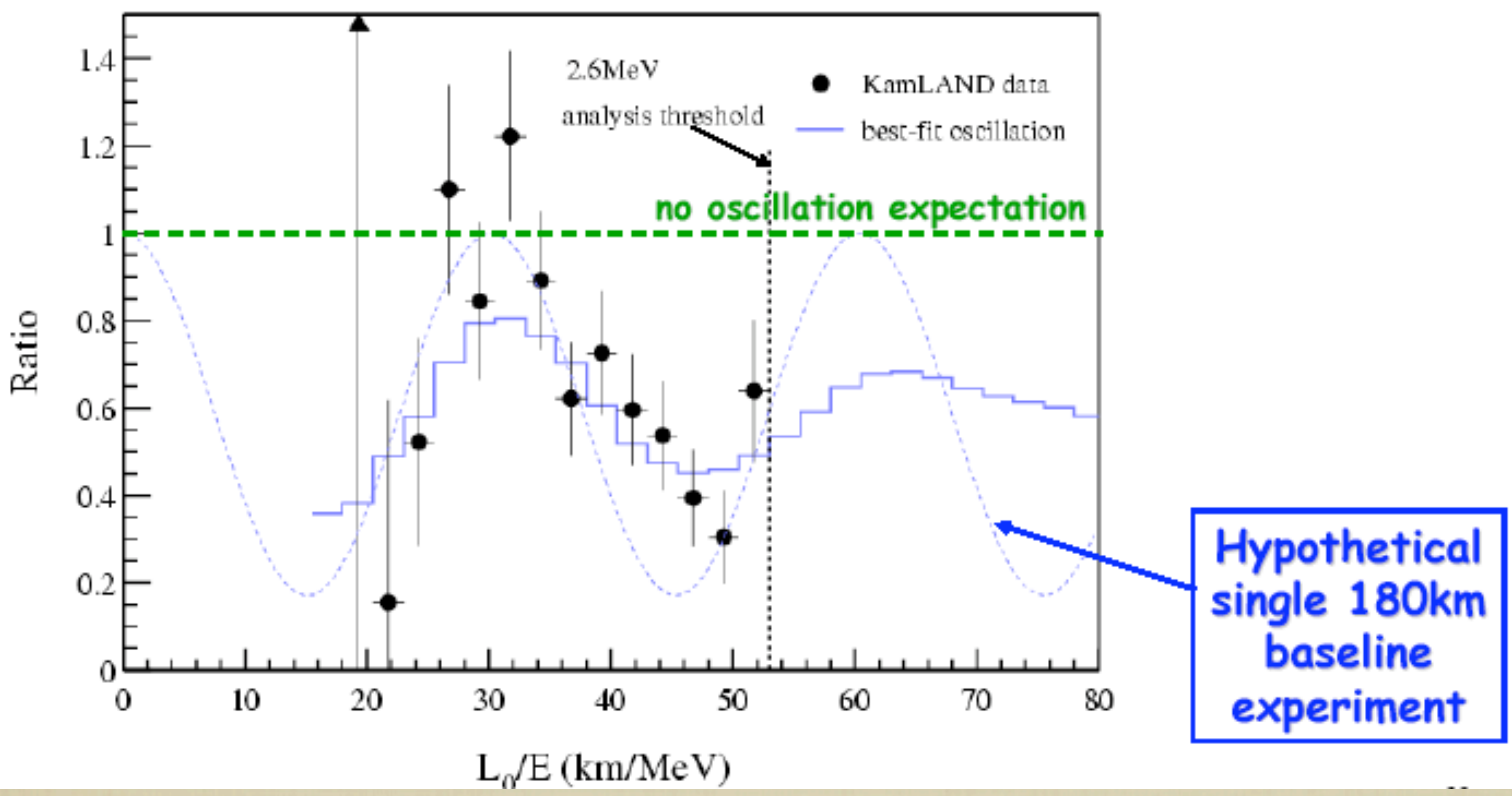
$$E \approx 3MeV, \quad \Delta m^2 \approx 10^{-5} eV^2$$

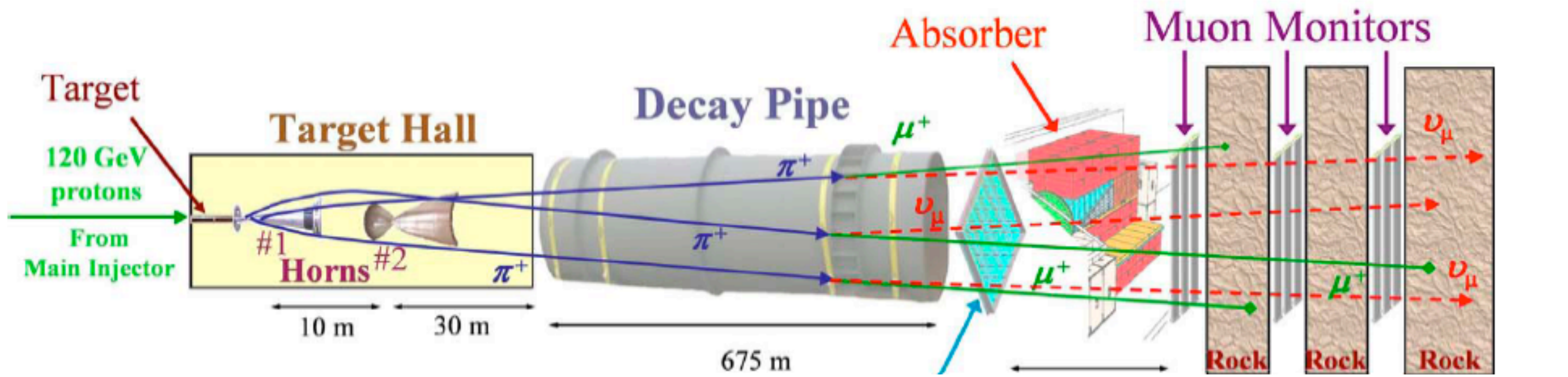
$$L_{osc} \approx 200 Km$$

L/E effect in Kamland

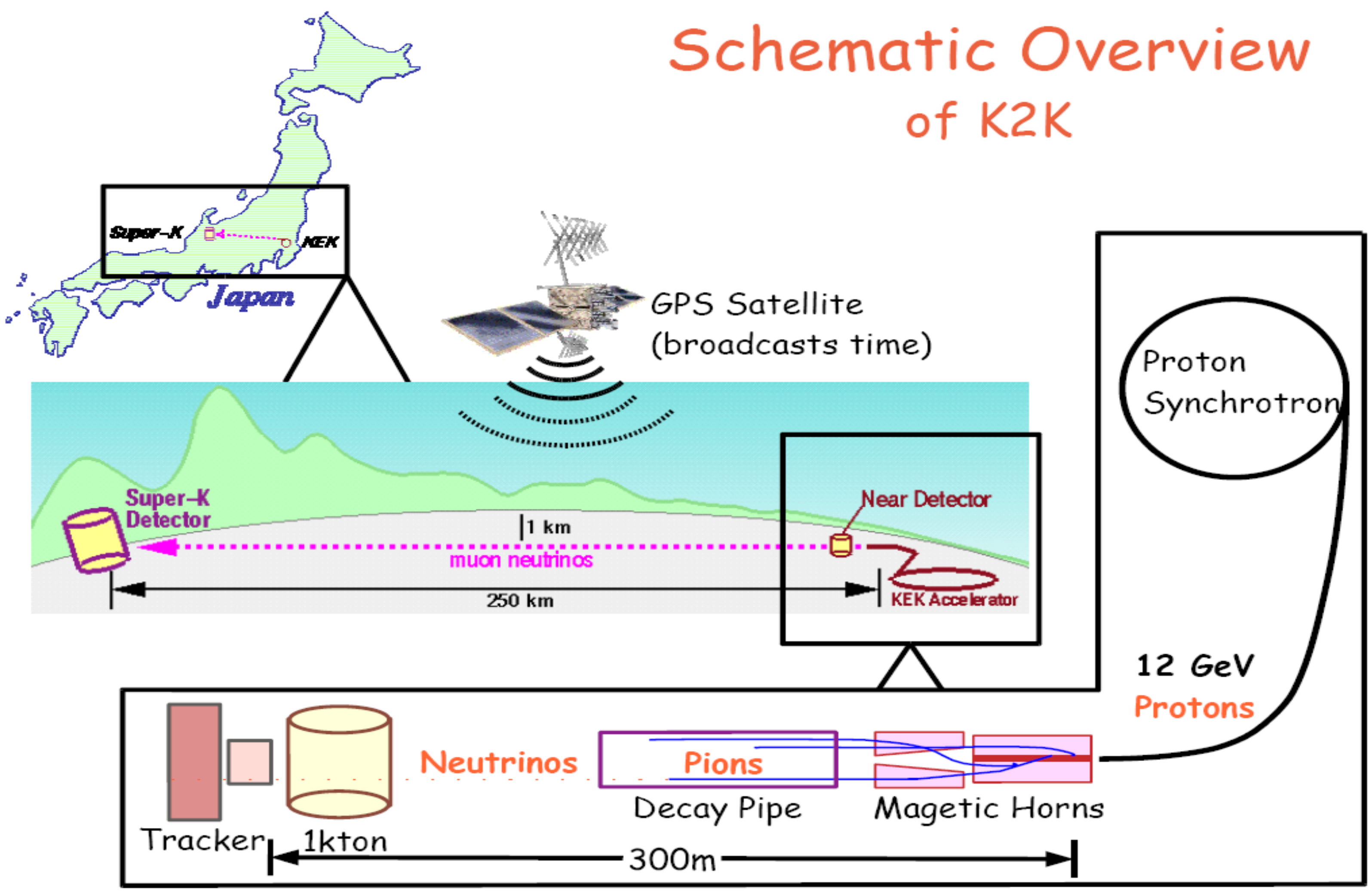
KamLAND uses a range of L and
it cannot assign a specific L to each event

Nevertheless the ratio of detected/expected
for L_0/E (or 1/E) is an interesting quantity, as it decouples
the ***oscillation pattern*** *from the reactor energy spectrum*

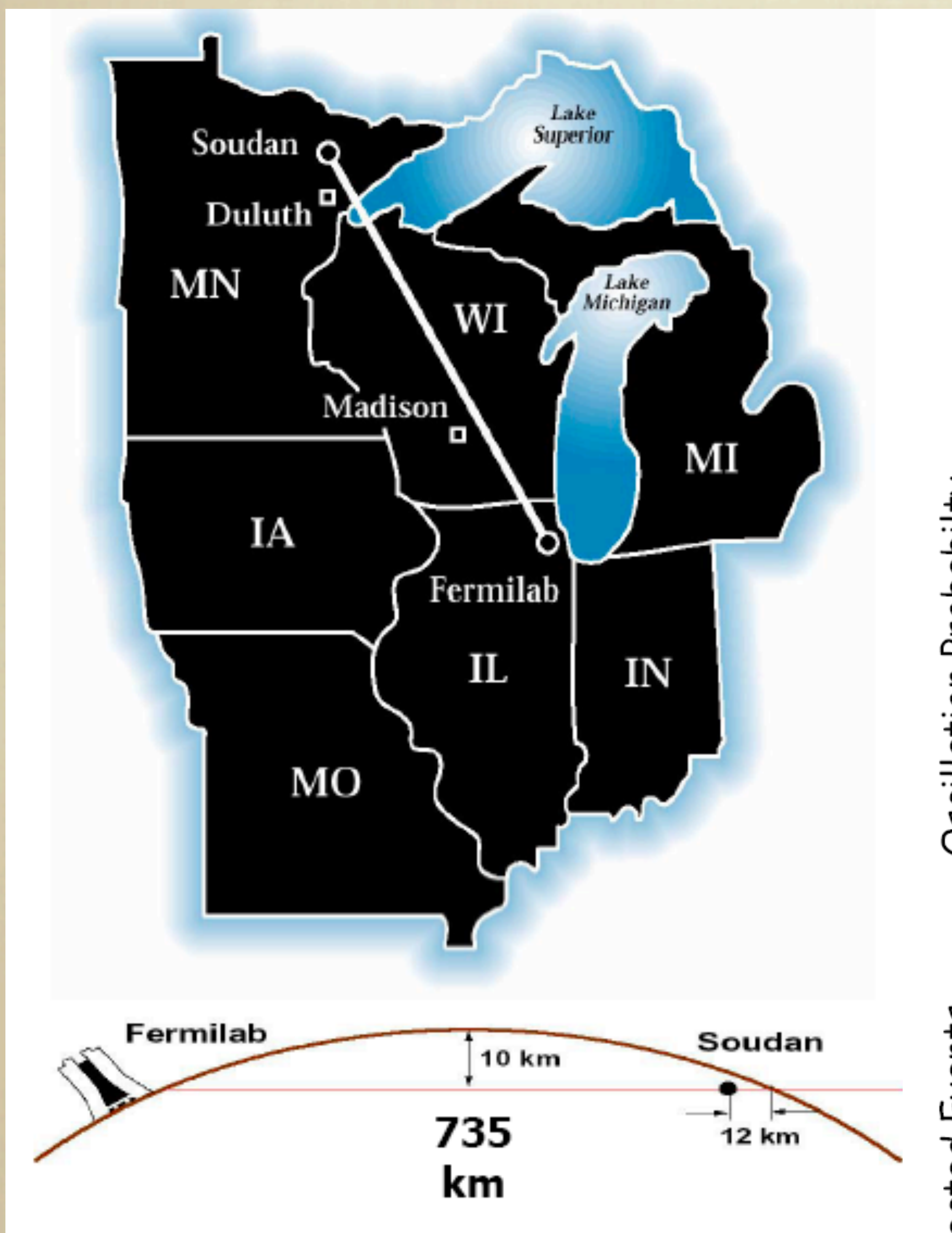


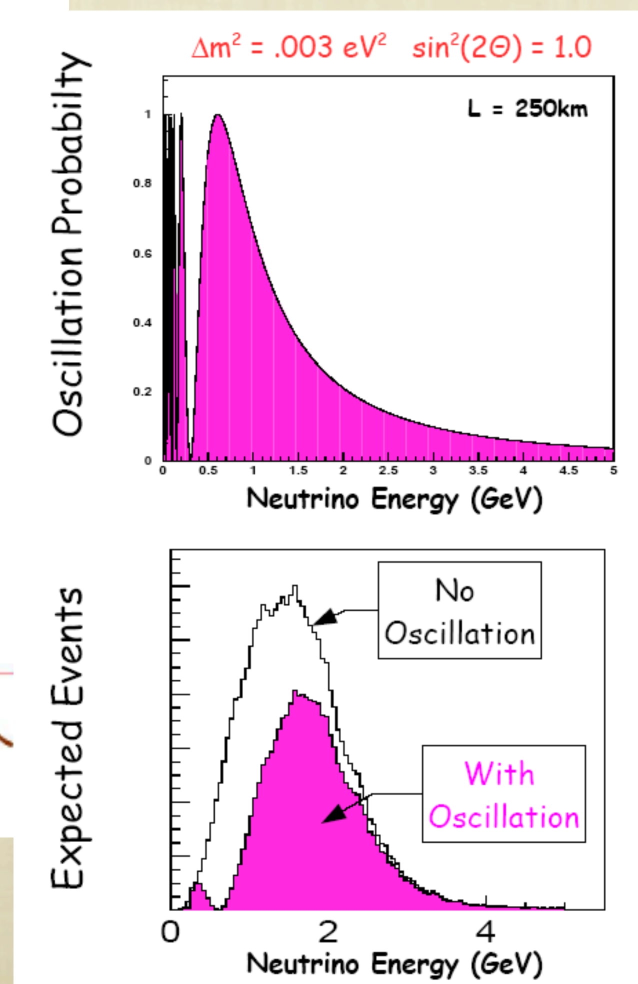


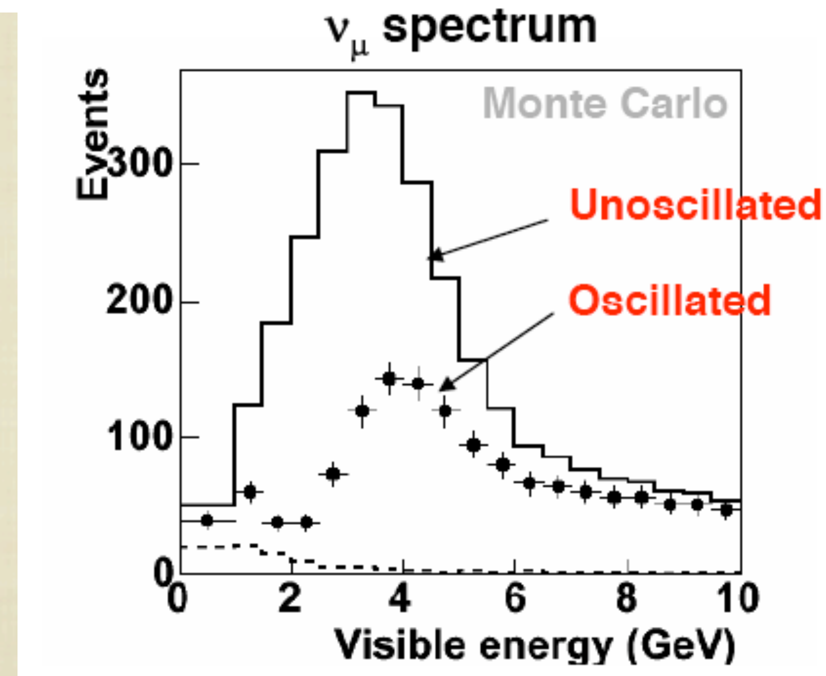
Minos & K2K: new skin for the old ceremony



K2K/Minos: confirm atmospheric oscillation with a controled beam





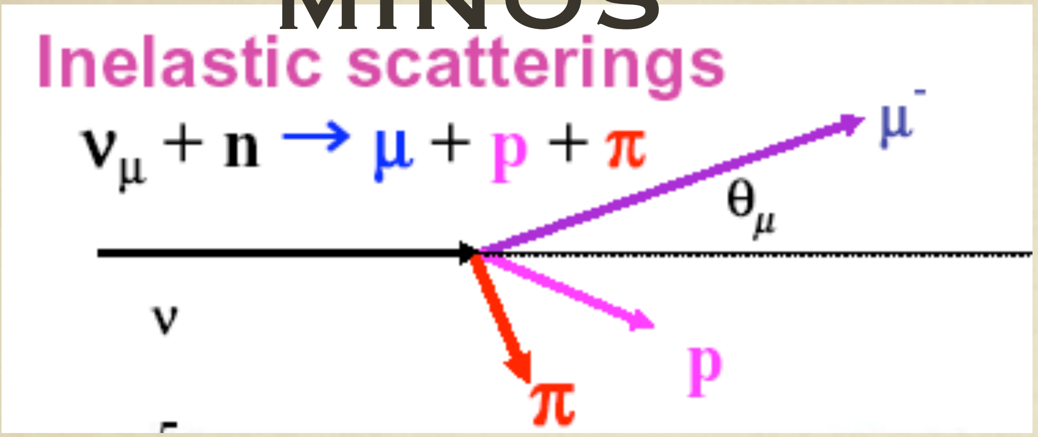


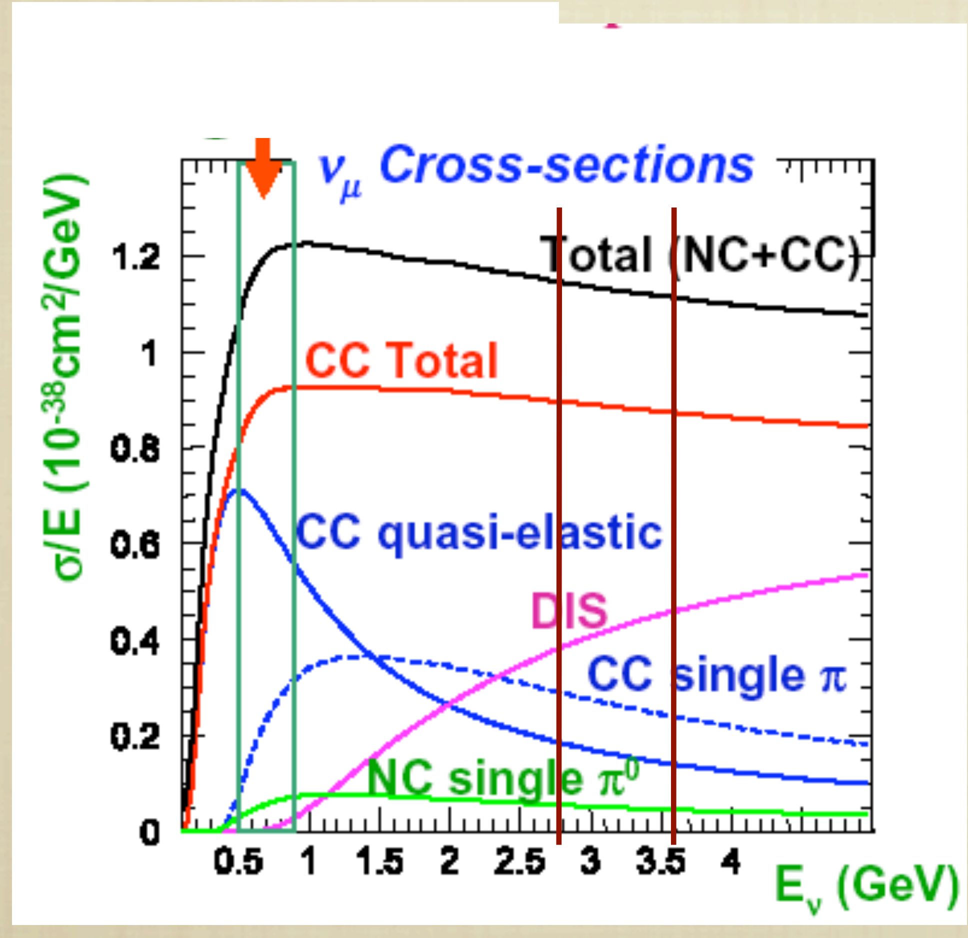
E_{K2K} ~1GeV=> L~250 Km

E_{Numi} ~3GeV => L~750 Km

Cross sections and energy reconstruction

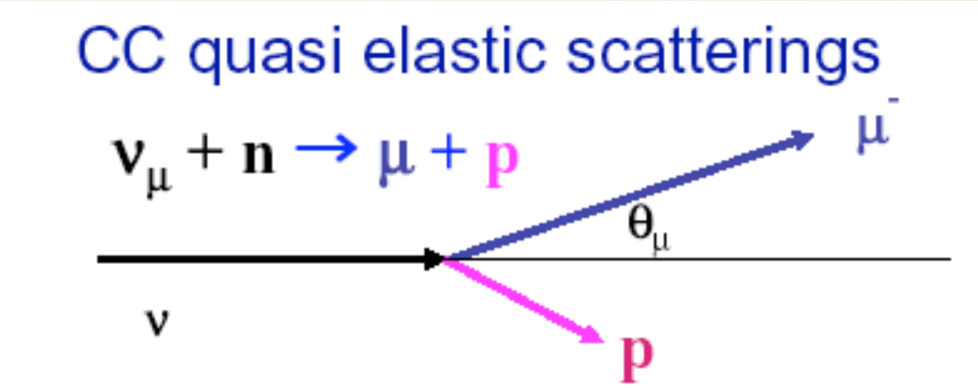
Numi/ MINOS

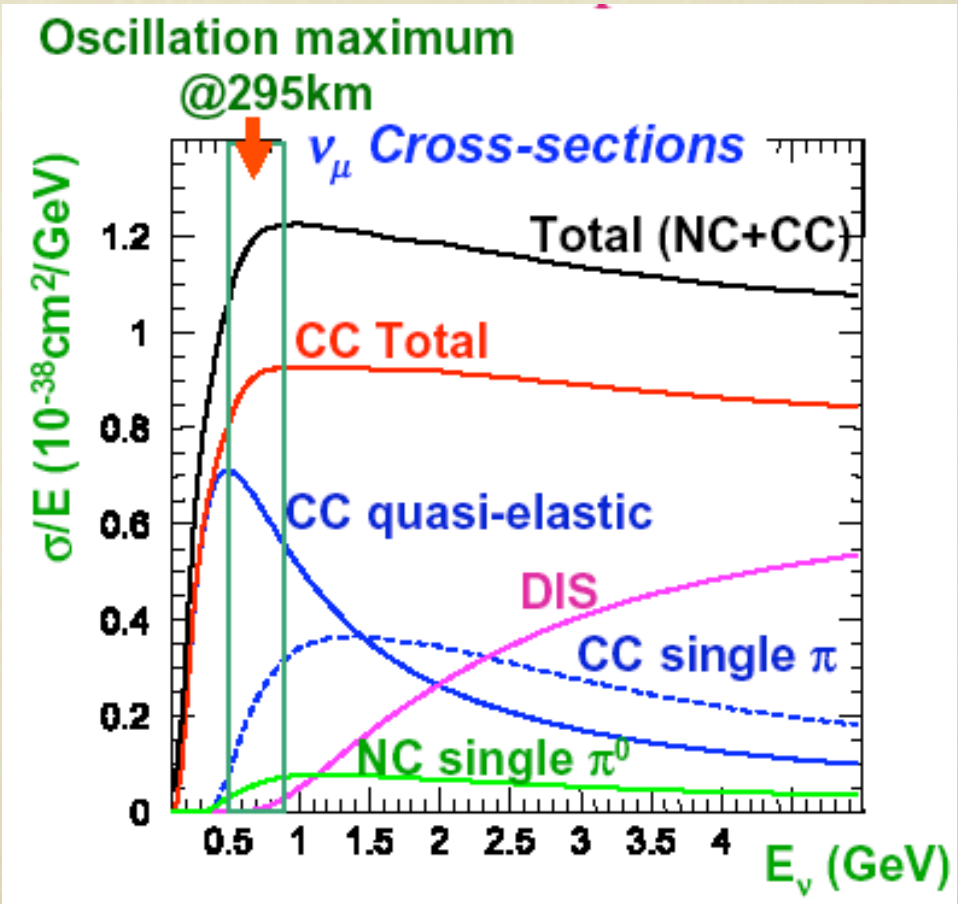




Oscillation maximum@750 km

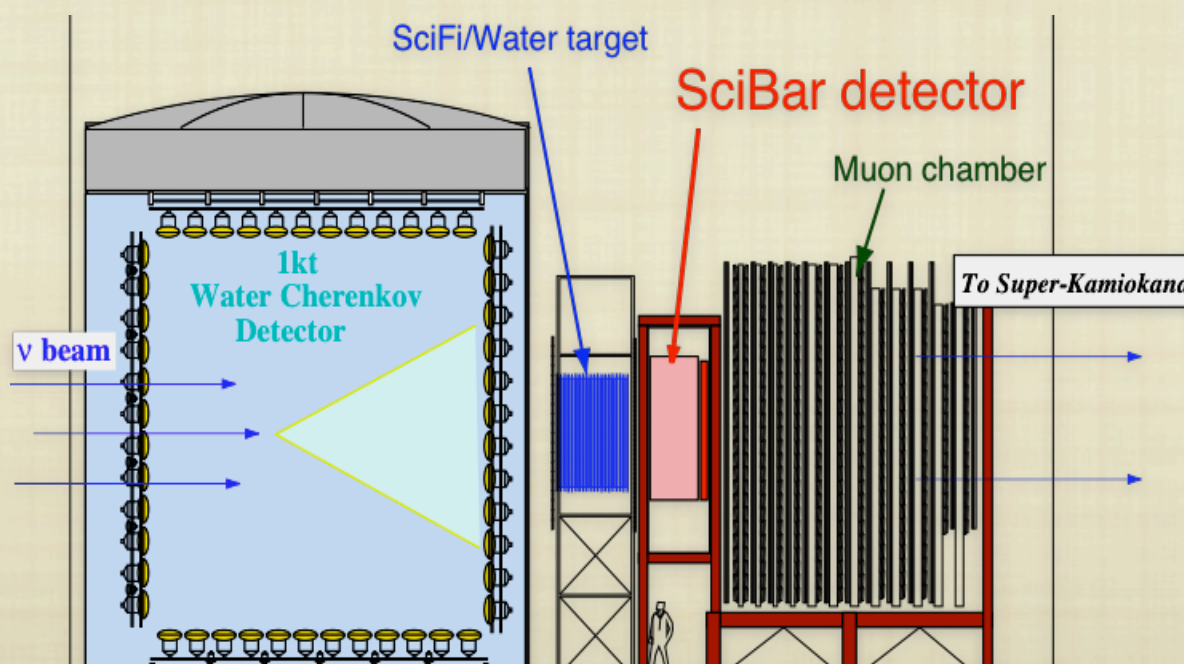
K2K

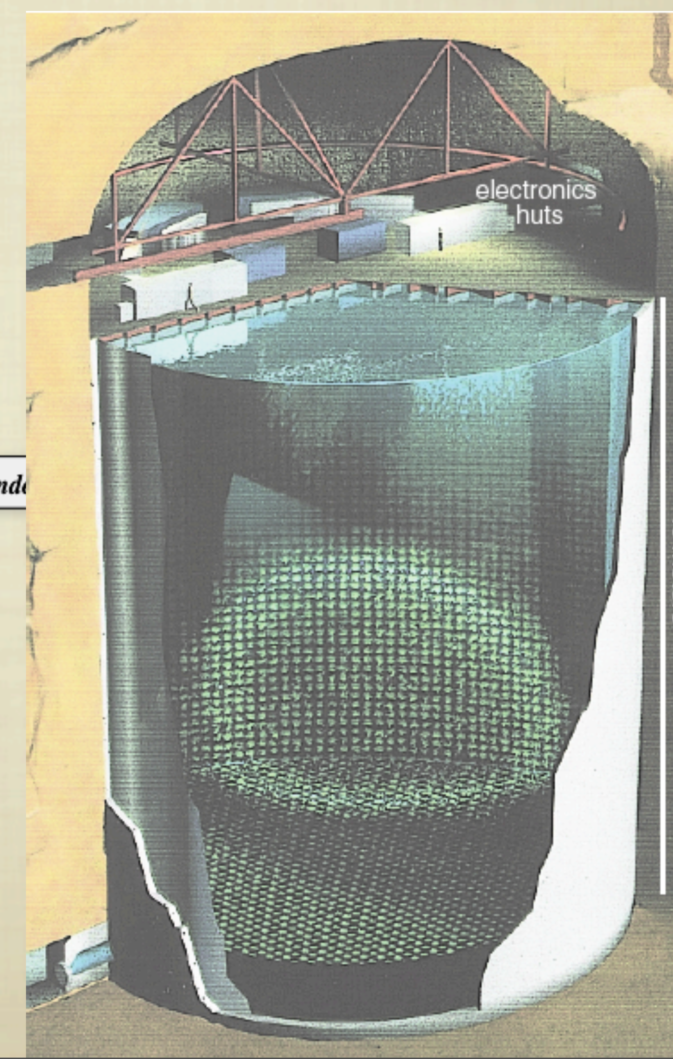


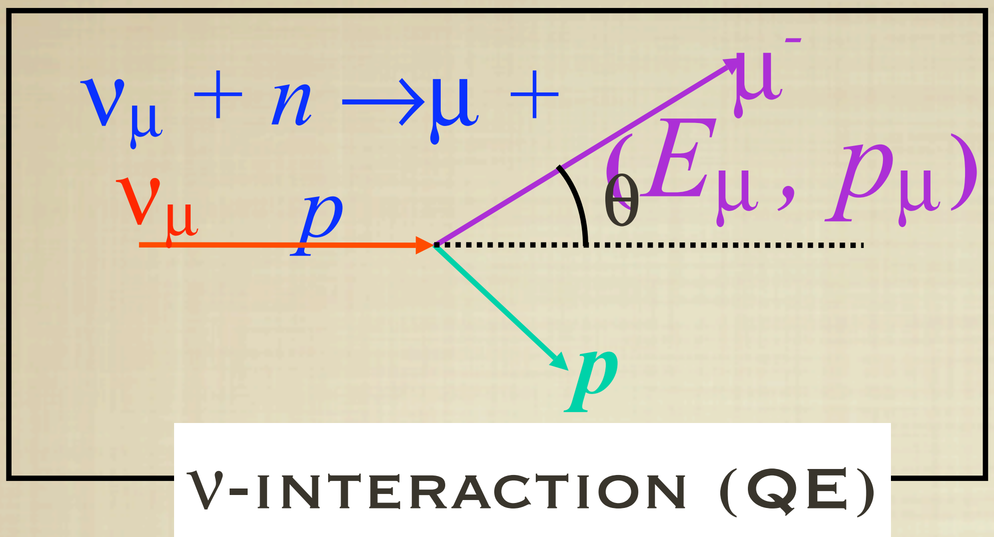


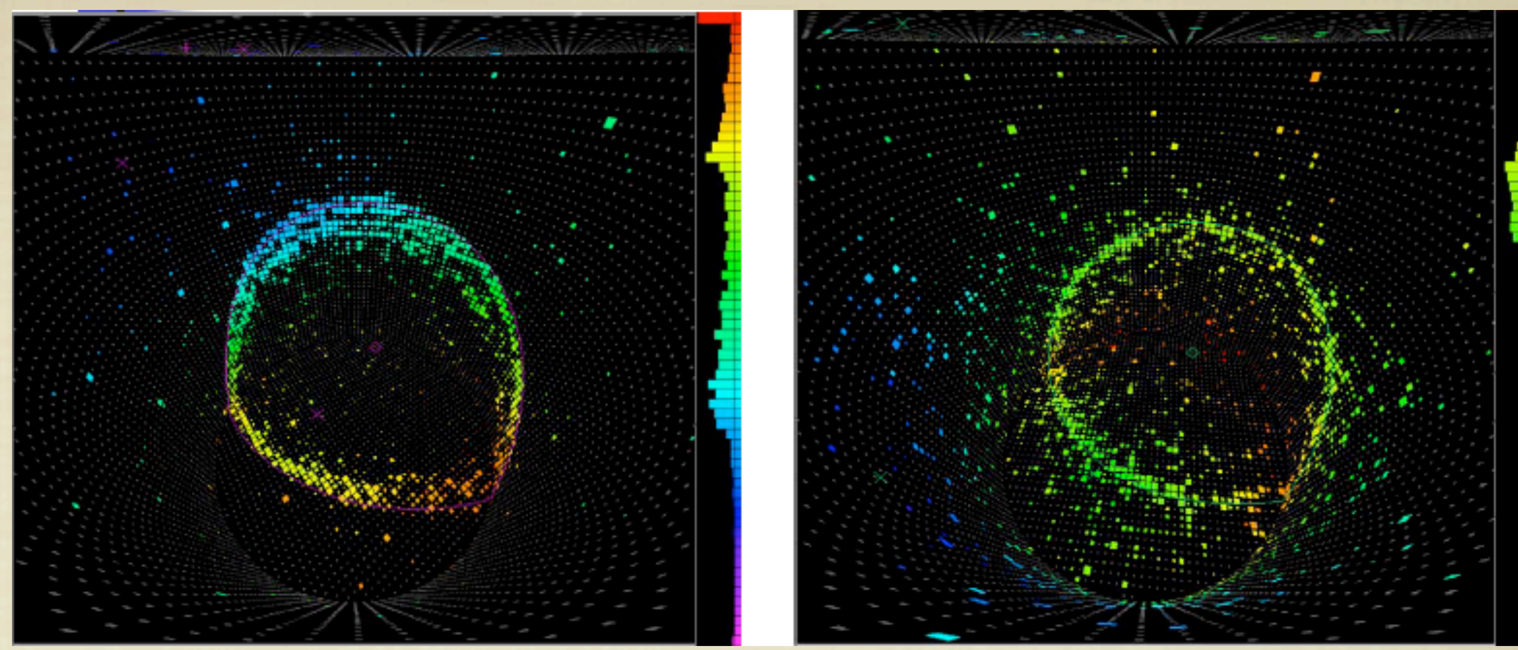
Detectors

Two different technologies: Water & Iron

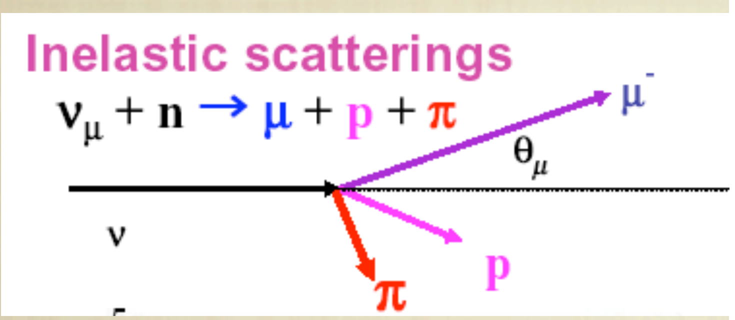


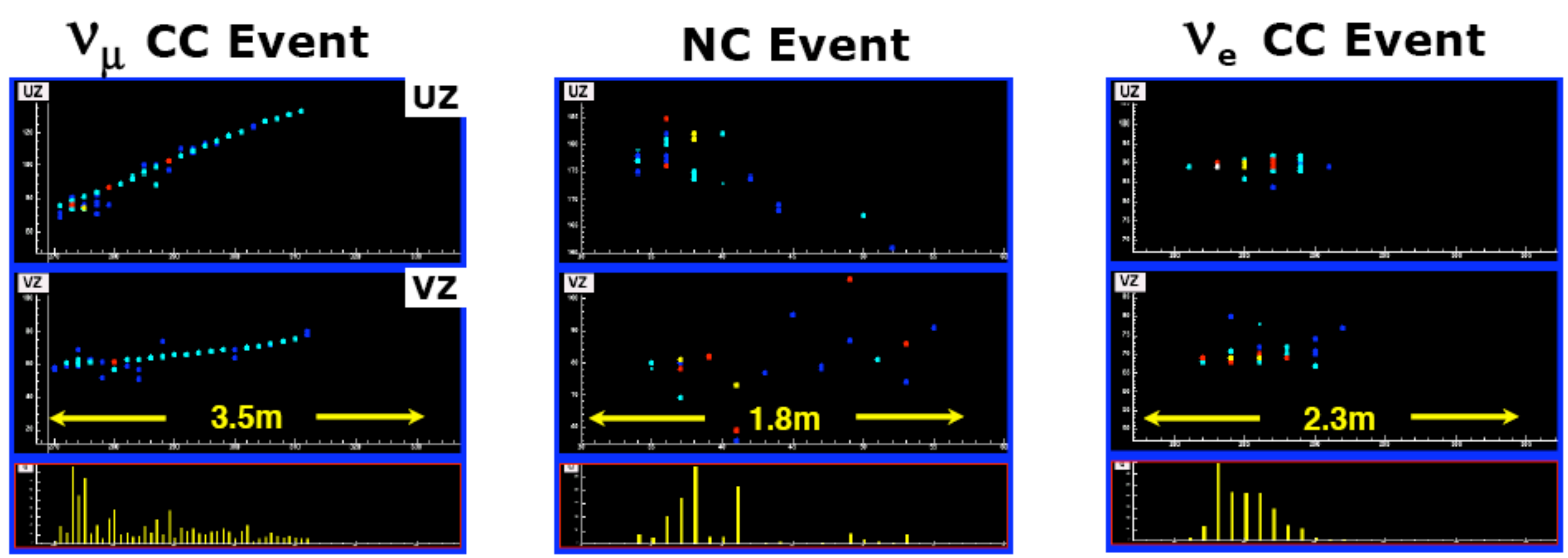






Neutrinos in water & iron

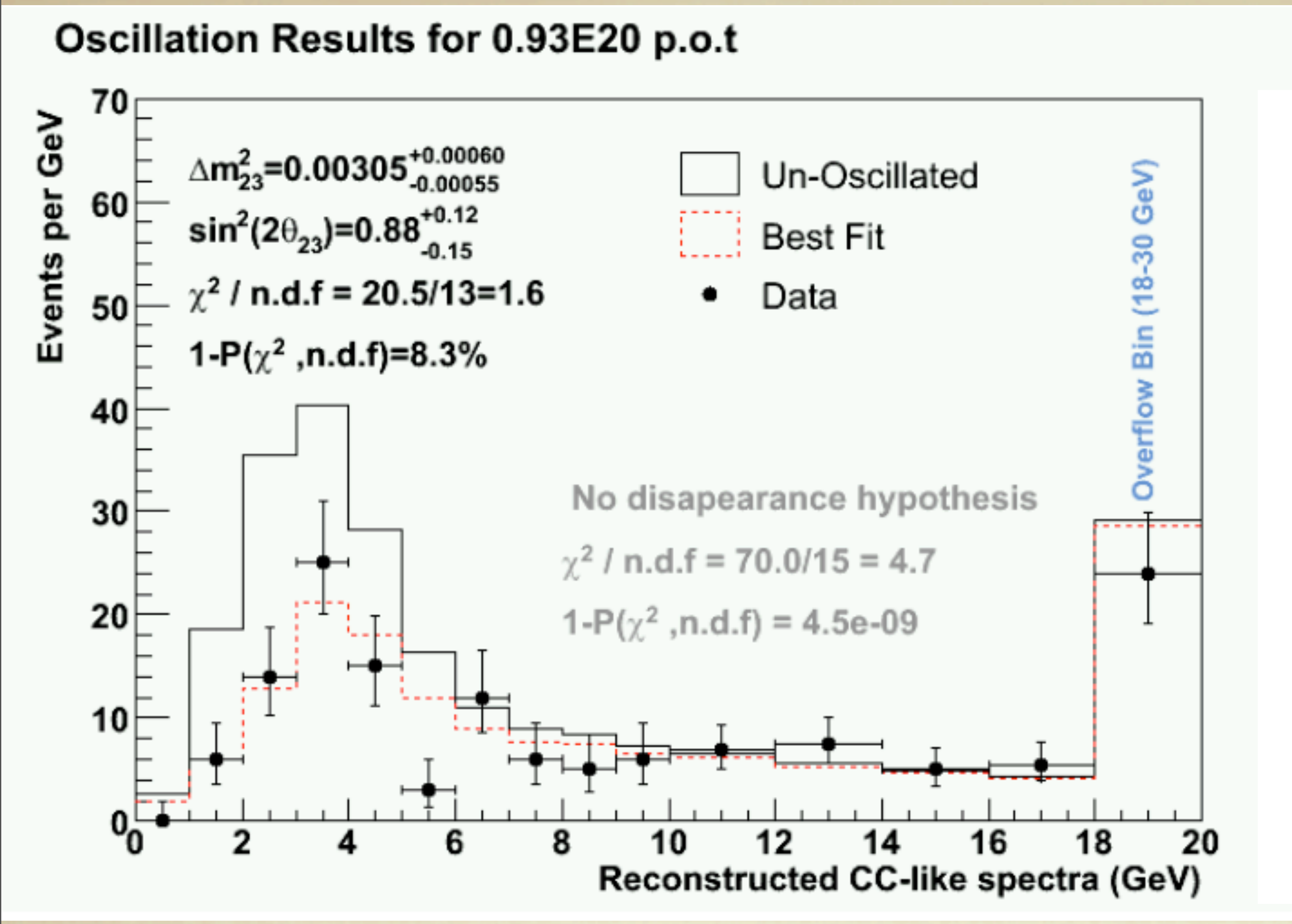


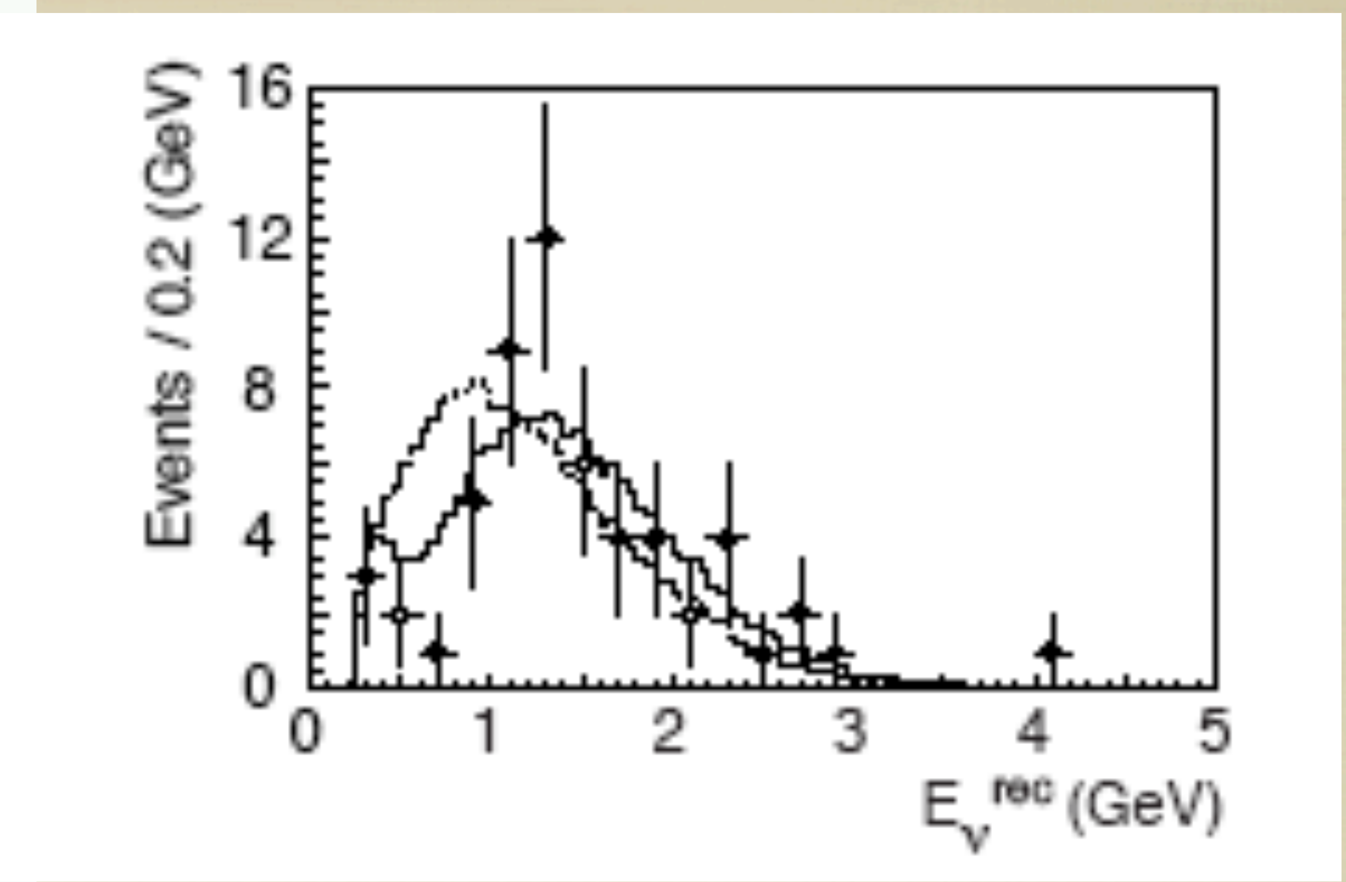


- long μ track+ hadronic activity at vertex
- short event, often diffuse
- short, with typical EM shower profile

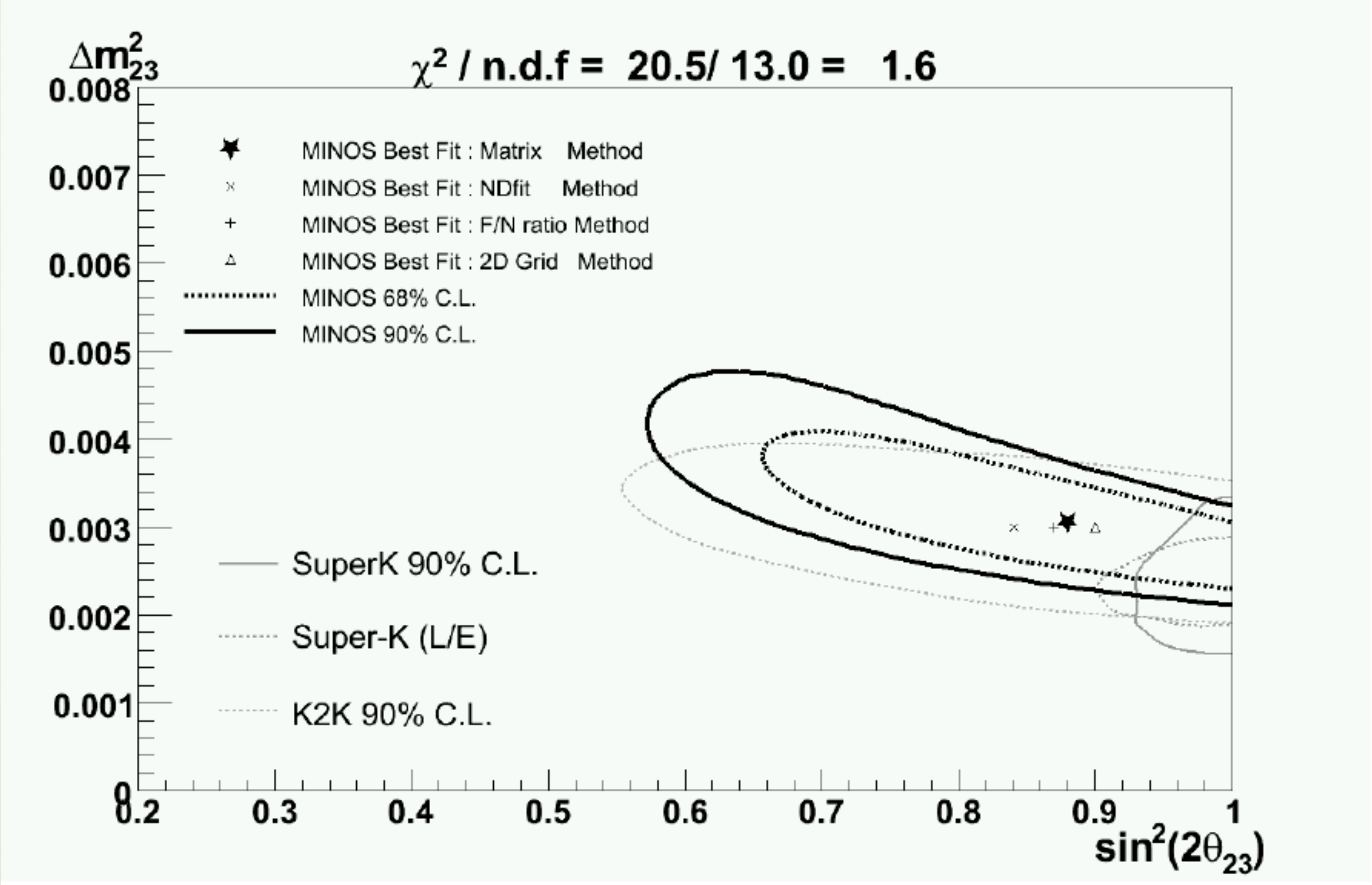
$$E_\nu = E_{shower} + P_\mu$$

55%/√E 6% range, 10% curvature



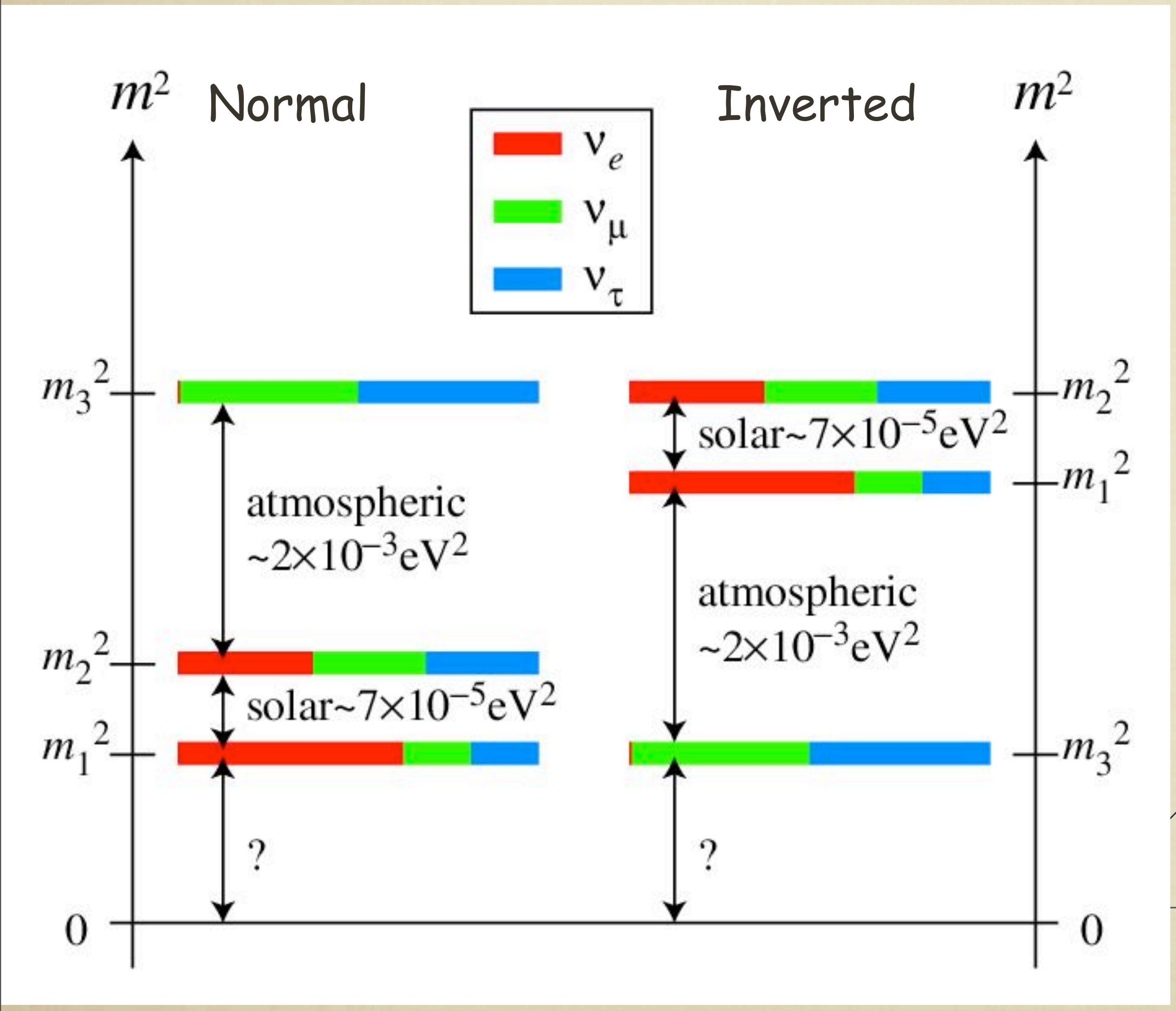


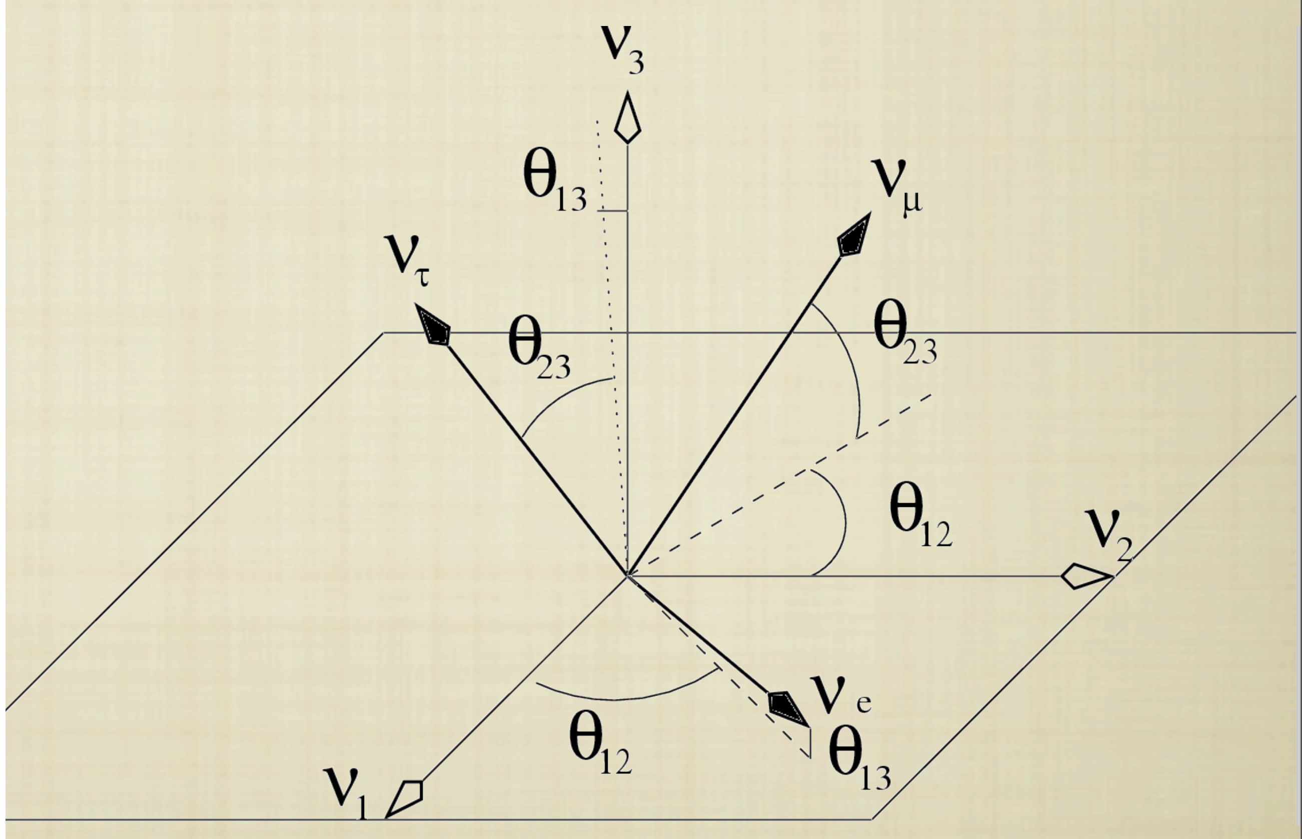
ATMOSPHERIC OSCILLATION CONFIRMED!



Oscillations revisited

Parameter	Best-fit value	3σ range
θ_{12}	$33.2°$	$28.7° .. 38.1°$
θ_{23}	$45.0°$	$35.7° .. 55.6°$
θ_{13}	$0.0°$	$0° .. 12.5°$





The PNMS matrix

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

Unless the other two angles θ_{13} is small (experimental upper limit $\theta_{13} < 10^0$)

If $\delta \neq 0, \pi, 2\pi$...then weak interactions violate CP symmetry in the lepton sector (as in the quark sector)

CP violation phase

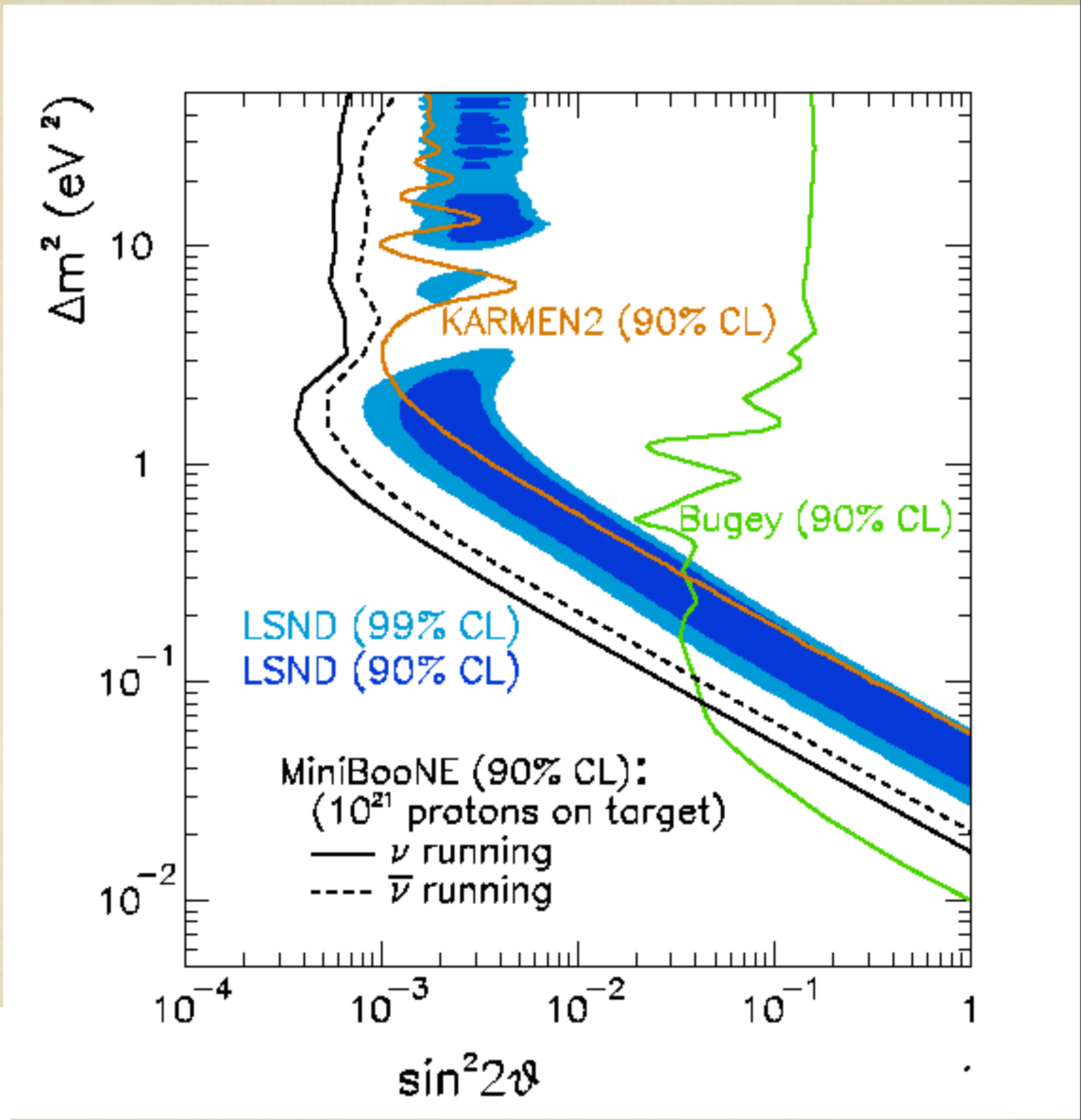
atmospheric

solar

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

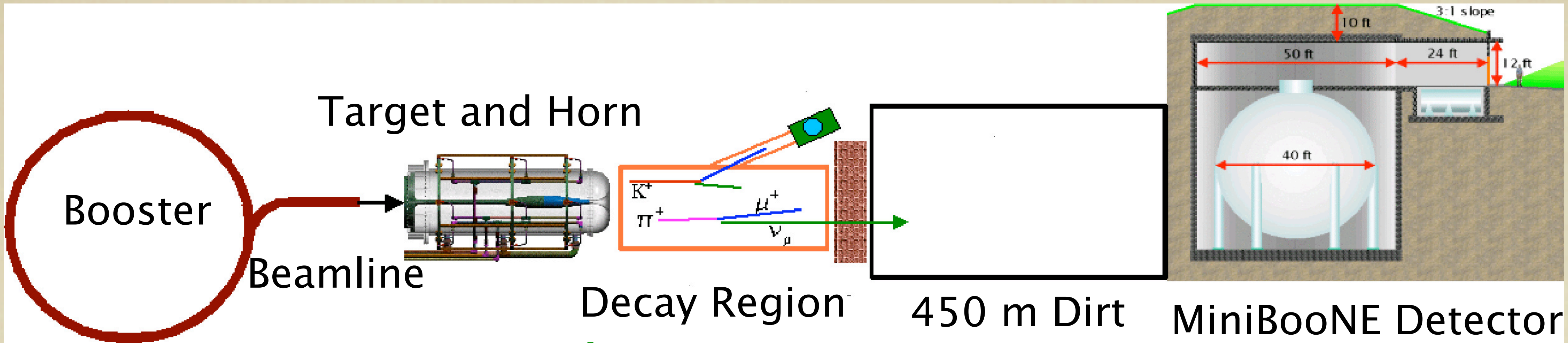
Links atmospheric & solar sectors

The last anomaly



$\bar{\nu}_\mu \to \bar{\nu}_e$?

MiniBooNE



Secondary Beam

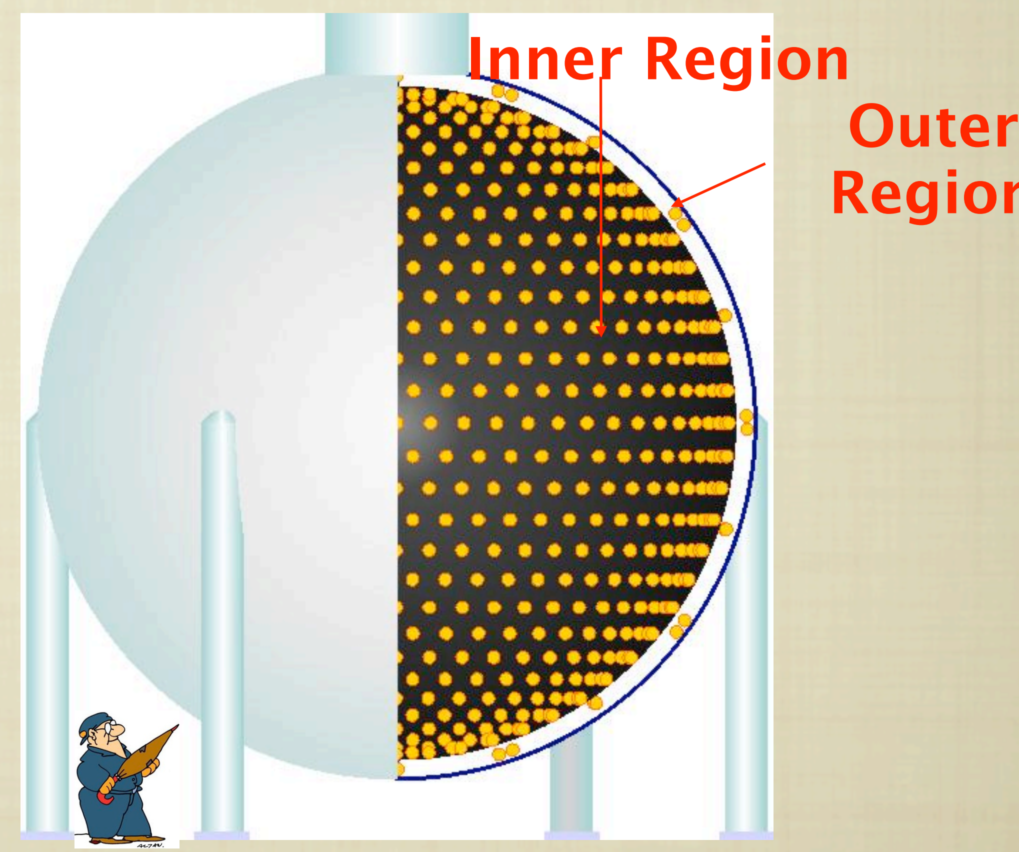
Primary Beam (protons) → **Secondary Beam** (mesons) → **Neutrino Beam**

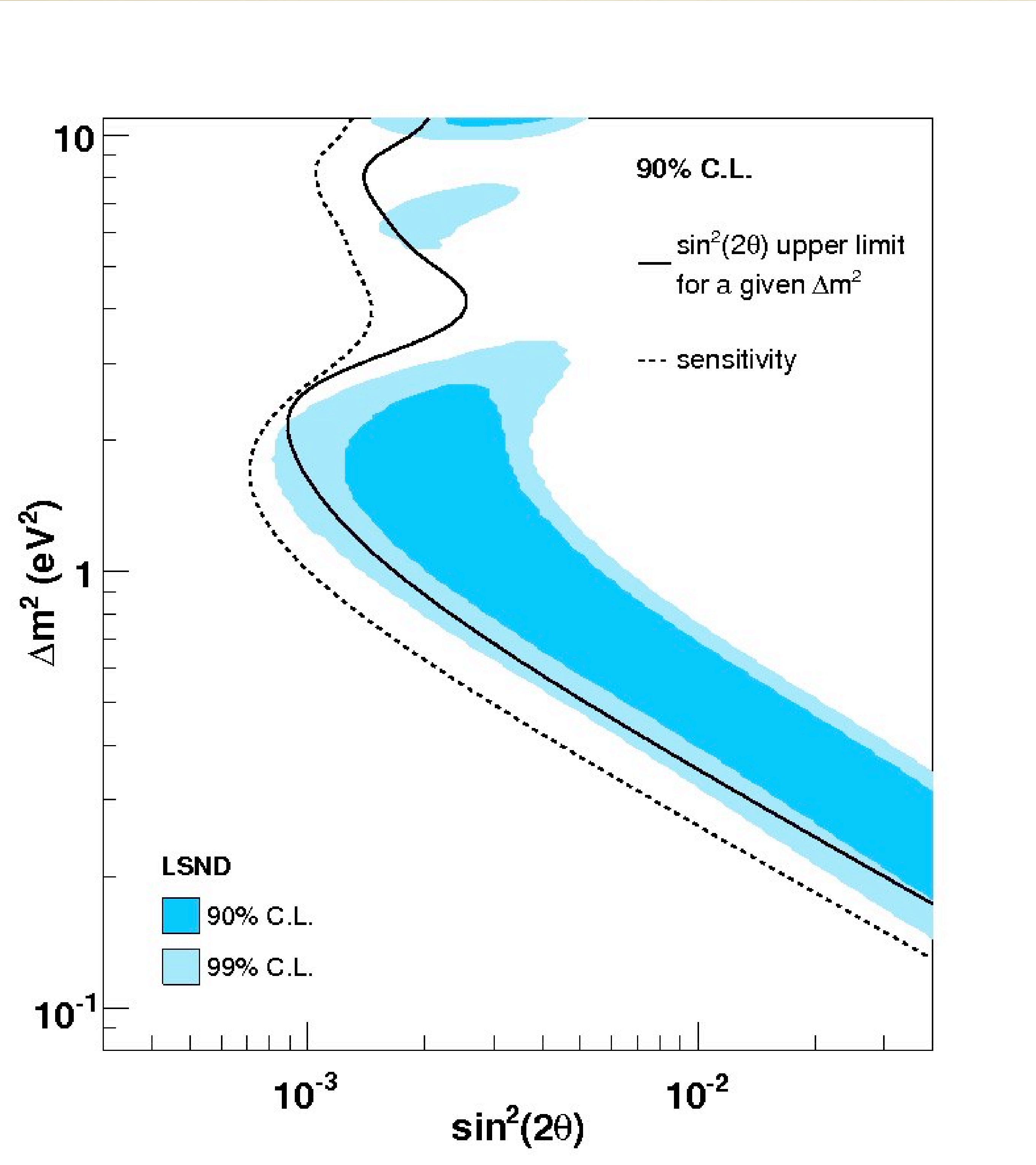
Beam

- ~0.5-1 GeV neutrinos or antineutrinos produced from FNAL Booster

Detector

- 12 m in diameter sphere filled with 800 t of undoped mineral oil
- Neutrino interactions in oil seen via Cherenkov and scintillation light





- No overlap in 90% CL allowed LSND and MiniBooNE regions
- MiniBooNE **excludes** two neutrino appearance-only oscillations as the explanation of the LSND anomaly at **~98% CL**
- Any interpetation of the LSND anomaly that would produce a significant excess for E_ν>475 MeV at MiniBooNE is also ruled out