Neutrino Oscillations: Experiments and Current Knowledge

Particle Physics Phenomenology II
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Introduction

- Remember the case of two neutrinos flavors, for instance ν_e and ν_μ, with $\nu_{1,2}$ being the mass eigenstates, and θ the mixing angle:

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

- or

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta$$
$$\nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta$$

- the survival probability: $\nu_e \rightarrow \nu_e$ after a distance x was:

$$P(\nu_e \rightarrow \nu_e, x) = 1 - \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{x}{E}\right)$$

- with x given in m (km) and E in MeV (GeV)

Introduction

- The transition probability $\nu_e \rightarrow \nu_\mu$ after a distance x was:

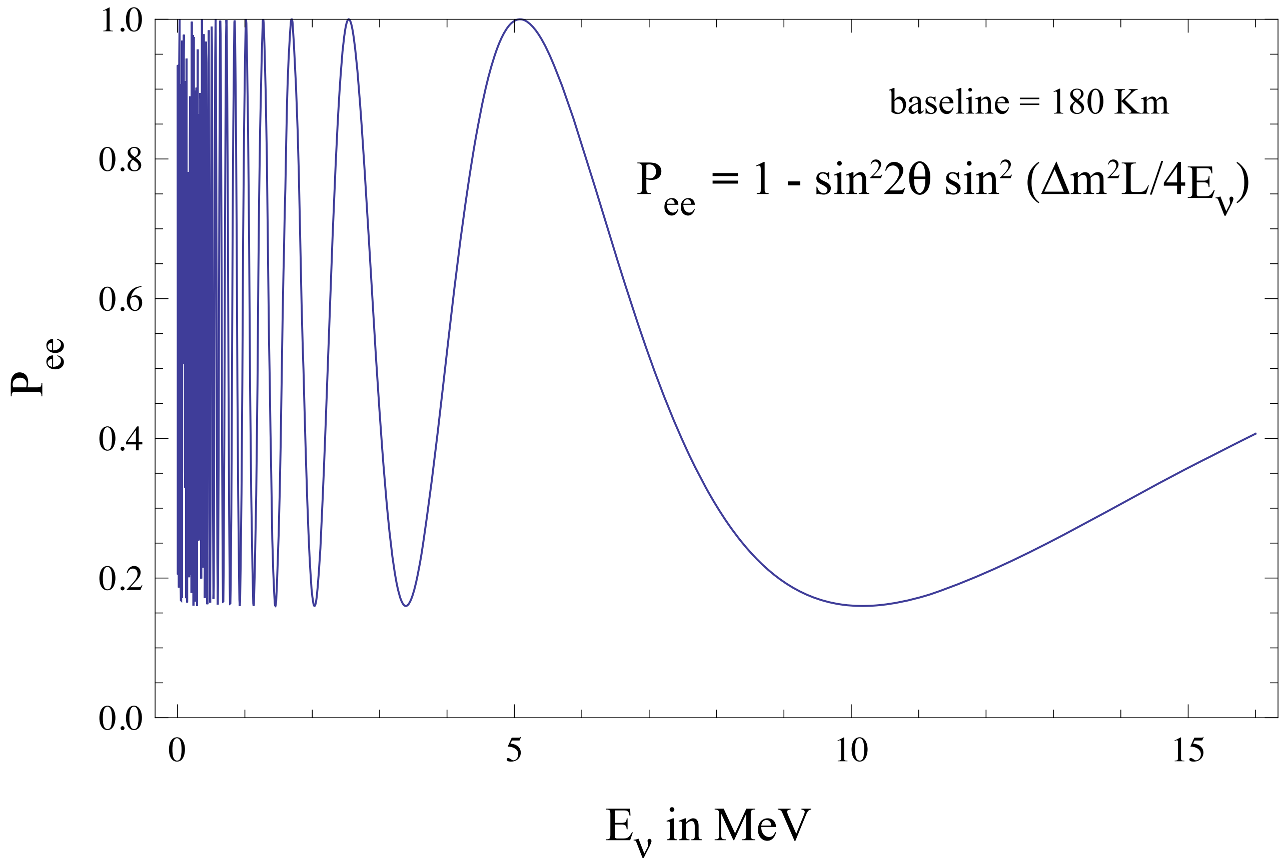
$$P(\nu_e \rightarrow \nu_\mu, x) = 1 - P(\nu_e \rightarrow \nu_e) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{x}{E}\right)$$

- with $\Delta m^2 = \left|m_1^2 - m_2^2\right|$
- numerical coefficient: $\frac{1}{4}\hbar c = 1.27$ falls $[x] = km;\ [\Delta m^2] = \left(\frac{eV}{c^2}\right)^2;\ [E] = GeV$

=> oscillations occur if: $\Delta m^2 \neq 0$

$\theta \neq 0$

- Example: the $\nu_e \rightarrow \nu_e$ survival probability as a function of the neutrino energy for L = 180 km, $\Delta m^2 = 7 \times 10^{-5}$ eV^2 and $\sin^2 2\theta = 0.84$



Introduction

- We have also looked at the more general case of oscillations between 3 neutrino flavors:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_1 \\ \nu_3 \end{pmatrix}$$

- with the flavor transition probability in the case of CP invariance (U = U*) given by:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{j>i} U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j} sin^2 \frac{\Delta m_{ij}^2 x}{4E}$$

In general, we have 3 mixing angles, 1 CP violating phase, 3 different Δm^2 (only 2 being independent)

=> **no information about the absolute ν-mass scale**

Experimental Considerations

- We had defined the *oscillation length* λ_{osc}:

$$\lambda_{osc} = \frac{4\pi E}{\Delta m^2}$$

- and we rewrote the transition probability in terms of:

$$P(\nu_\alpha \to \nu_\beta) = \underbrace{sin^2 2\theta}_{\text{mixing term}} \cdot \underbrace{sin^2\left(\pi \frac{x}{\lambda_{osc}}\right)}_{\text{oscillation term}}$$

- LHS: determined by an experiment, by counting events and normalizing to the exp. parameters
- RHS: the mixing angle is fixed, hence also the amplitude of the oscillation; however, as an experimenter one can influence the oscillation term, by choosing the *source-detector distance x* and the *neutrino energy E* (by selecting the production process)

  ➡ thus we have an influence on λ_{osc}

Experimental Considerations

- 1) We first consider the case in which $\frac{L}{\lambda_{osc}} \ll 1$
- We can then approximate the argument of the oscillation term by the first term of the Taylor series:

$$sin^2\left(\pi\frac{L}{\lambda_{osc}}\right) \simeq \left(\pi\frac{L}{\lambda_{osc}}\right)^2$$

- Since the transition probability is small, we can not measure any effect ($L << \lambda_{osc}$):

$$\frac{L}{E} \ll \frac{1}{\Delta m^2}$$

- 2) In the case in which $\frac{L}{E} \sim \frac{1}{\Delta m^2}$

- $L \sim \lambda_{osc}$ and the sensitivity to the mixing term is maximal

$$1.27\Delta m^2\frac{L}{E} \sim \frac{\pi}{2}$$

Experimental Considerations

- 3) We consider now the case in which $\dfrac{L}{\lambda_{osc}} \gg 1$

- or $$\frac{L}{E} \gg \frac{1}{\Delta m^2}$$

- *the sine factor oscillates rapidly*, and we measure only an average transition probability, due to *uncertainties in L* (neutrino source is extended) *and E* (the neutrinos are being produced with an energy spectrum, or the energy is not measured in the detector)

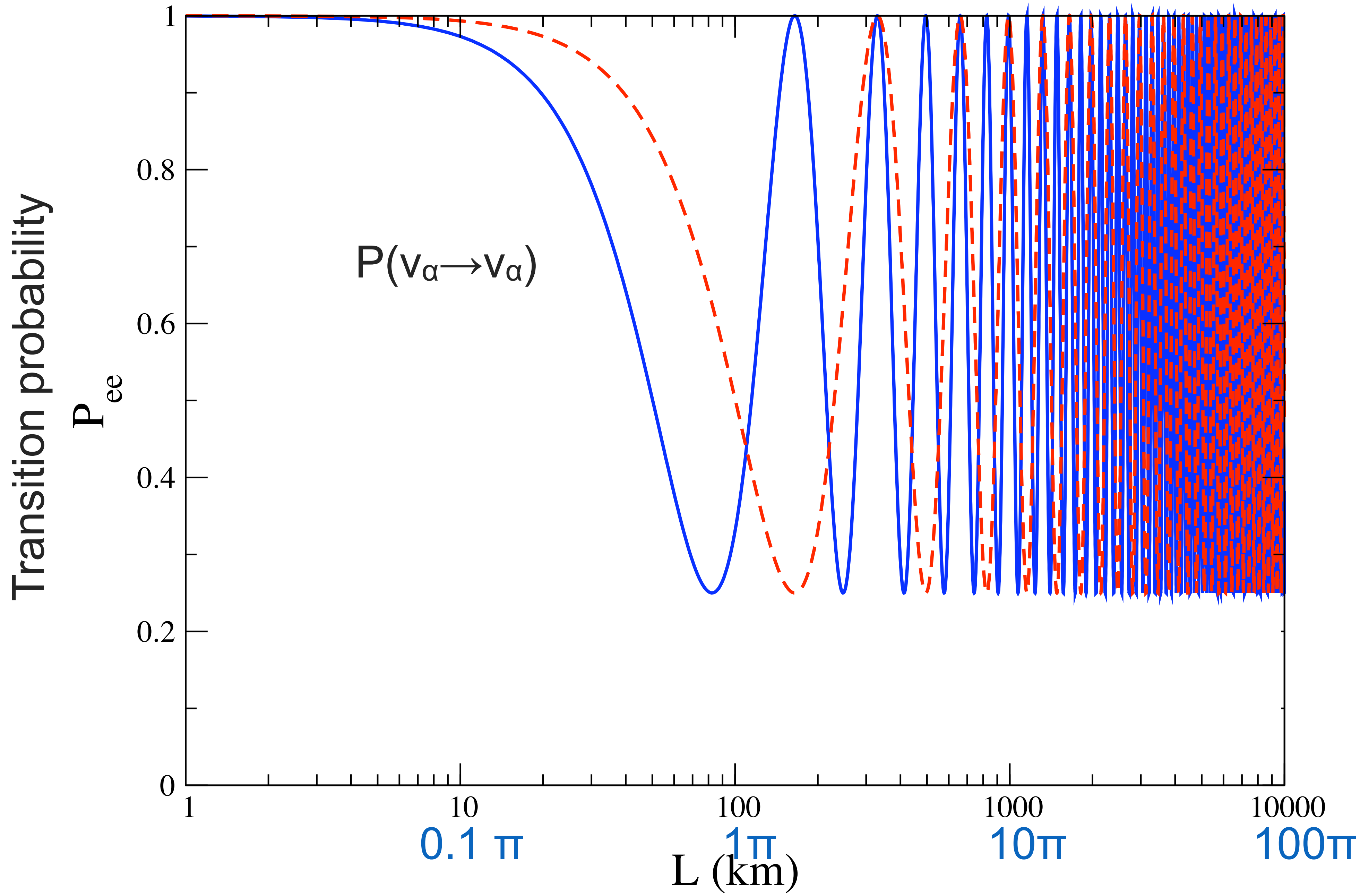
$$\langle sin^2\left(\pi\frac{L}{\lambda_{osc}}\right)\rangle = \frac{1}{2}$$

$$P(\nu_\alpha \to \nu_\beta) = \frac{1}{2}sin^2 2\theta$$

- this still allows us to determine the mixing angle

Example for the three cases

$\frac{L}{E} \ll \frac{1}{\Delta m^2}$ $\frac{L}{E} \sim \frac{1}{\Delta m^2}$ $\frac{L}{E} \gg \frac{1}{\Delta m^2}$



$1.27\ \Delta m^2\ L/E$

Oscillation Experiments

- 'Appearance' experiments: one searches for a ν-flavor that is not present in the original beam
- 'Disappearance' experiments: one looks for a deficit in the expected neutrino flux from the original beam

  ➡ in both cases, one looks for the *x/E-dependance* of the oscillation probability

- The most important neutrino sources are:

  ➡ Reactors: $\bar{\nu}_e$

  ➡ Accelerators: $\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$

  ➡ The atmosphere: $\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$

  ➡ The Sun: ν_e

Table 13.1: Sensitivity of different oscillation experiments.

Source	Type of ν	$\overline{E}$[MeV]	L[km]	min(Δm^2)[eV^2]
Reactor	$\overline{\nu}_e$	~ 1	1	$\sim 10^{-3}$
Reactor	$\overline{\nu}_e$	~ 1	100	$\sim 10^{-5}$
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	$\sim 10^3$	1	~ 1
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	$\sim 10^3$	1000	$\sim 10^{-3}$
Atmospheric ν's	$\nu_{\mu,e}, \overline{\nu}_{\mu,e}$	$\sim 10^3$	10^4	$\sim 10^{-4}$
Sun	ν_e	~ 1	1.5×10^8	$\sim 10^{11}$

PDG2010

Overview: experimental hints for ν-oscillations

- The deficit of solar neutrinos

  ➡ experiments detecting solar neutrinos measure a smaller ν_e-rate as expected; the results are consistent with:

$$\nu_e \to \nu_\mu$$

$$\Delta m^2_{sol} \sim 8 \times 10^{-5}\, eV^2$$

- these results are confirmed by reactor neutrino experiments, measuring a deficit in the $\bar{\nu}_e$ rate

- Deficit of atmospheric neutrinos

  ➡ experiments detecting atmospheric neutrinos measure a ν_μ / ν_e - ratio that is smaller than expected; the results are consistent with:

$$\nu_\mu \to \nu_\tau$$

$$\Delta m^2_{atm} \sim 2.5 \times 10^{-3}\, eV^2$$

- these result are confirmed by accelerator experiments that observe a deficit in ν_μ (plus a first hint of ν_τ appearance)

Atmospheric Neutrinos

- From decays of mesons and muons that are being produced in interactions of primary CR in the atmosphere
- Energies: GeV-range, L = 10 km - 10^4 km (Earth diameter)

$$\frac{L}{E} \simeq 10 - 10^4$$

- one can thus test: $\Delta m^2 \geq 10^{-4} eV^2$

The absolute neutrino fluxes are plagued by large uncertainties; for this reason, one look at ratios, taking into account

➡ primary cosmic ray flux and its modulation

➡ cross sections for the production of secondary particles in the atmosphere

➡ cross sections for ν interactions in the detector

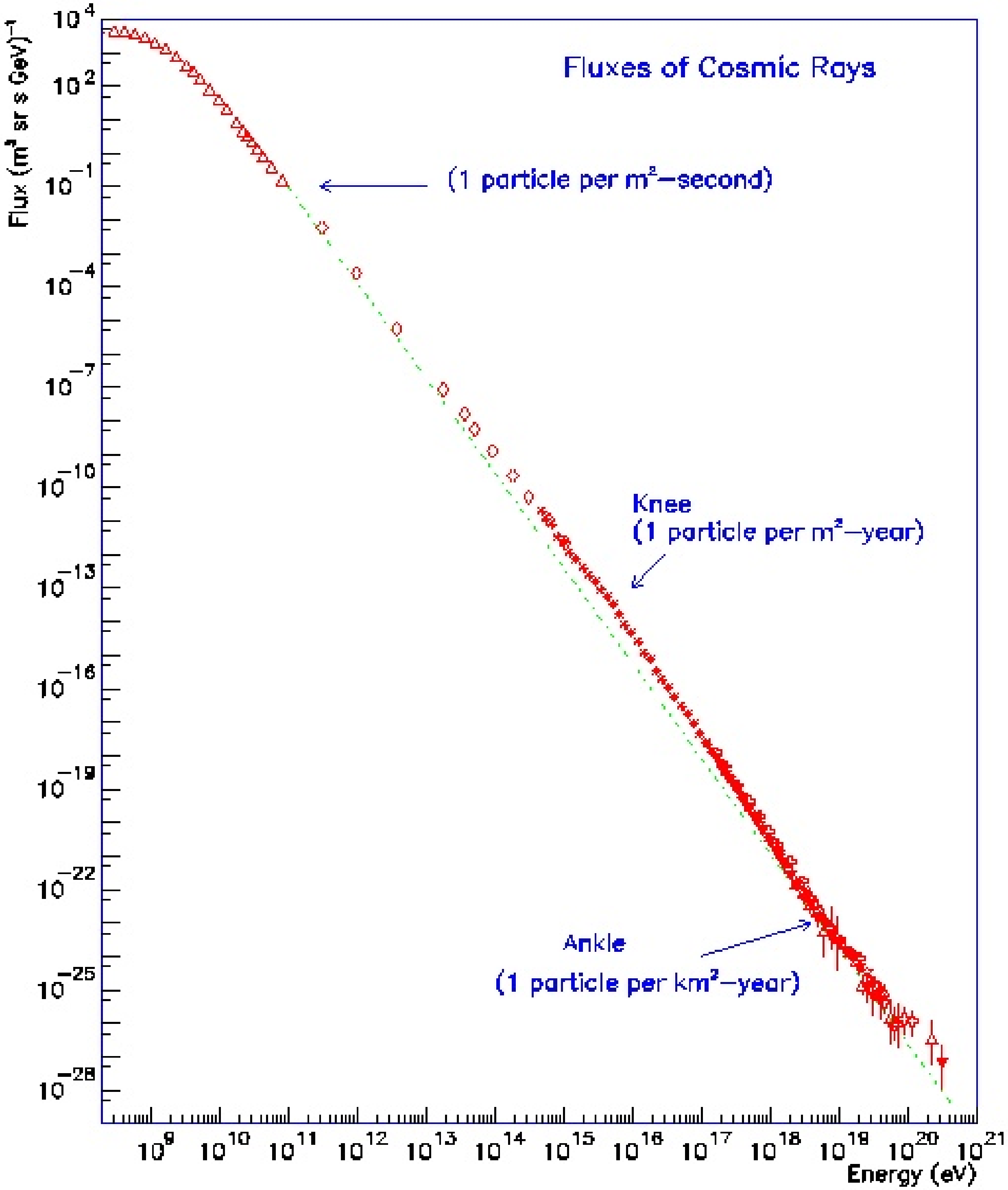
➡ acceptance and efficiency of the detector

Cosmic Rays

- Primary: 98% hadrons, 2% electrons
- Hadronic component:
  - ➡ p (~87%)
  - ➡ α (~ 11%)
  - ➡ heavy nuclei (~ 2%)
- The differential energy spectrum is:

  (with γ = 2.7 for E < 10^{15} eV)

$$N(E)dE \propto E^{-\gamma}dE$$



Cosmic Rays

- The part of the cosmic ray spectrum that is relevant for atmospheric neutrinos (< 1 TeV):

$$p/n + N \rightarrow \pi^+ / K^+ + \ldots \rightarrow \mu^+ + \nu_\mu \rightarrow (e^+ + \bar{\nu}_\mu + \nu_e) + \nu_\mu$$

$$p/n + N \rightarrow \pi^- / K^- + \ldots \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow (e^- + \nu_\mu + \bar{\nu}_e) + \bar{\nu}_\mu$$

- the ratio of the fluxes can be predicted with ~ 5% uncertainty:

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

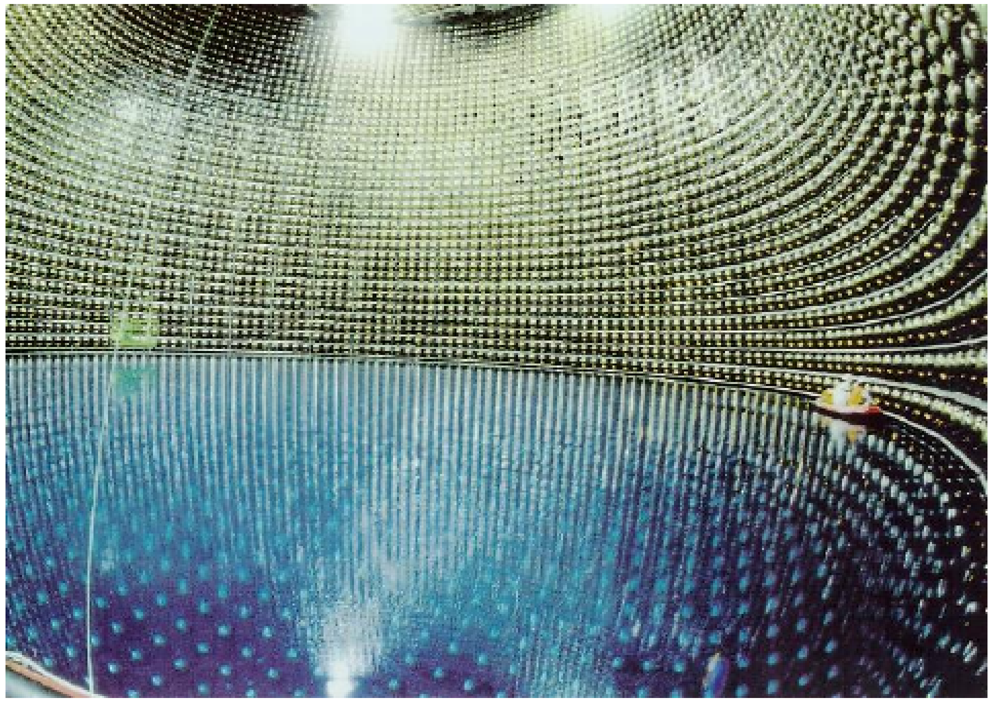
- However, experiments operated deep underground observe a ratio of reactions, in which muons are produced to reactions, where electrons are produced of $R = 1$

➡ this is consistent with neutrino flavor oscillations

The SuperKamiokande Experiment

- The first compelling evidence for neutrinos oscillations: SK in 1998
- The detector is operated in the Kamioka Observatory, Japan
- 50 kton (22.5 kton fiducial) water Cerenkov detector with 11 x 10^3 50 cm PMTs + outer veto with 1885 PMTs (20 cm)
- The detector can distinguish between e-events and μ-events based on the pattern of the produced Cerenkov light (e: diffuse - because of EM showers in the target; μ: sharp rings)
- One defines the *experimental ratio* R_{exp} as:

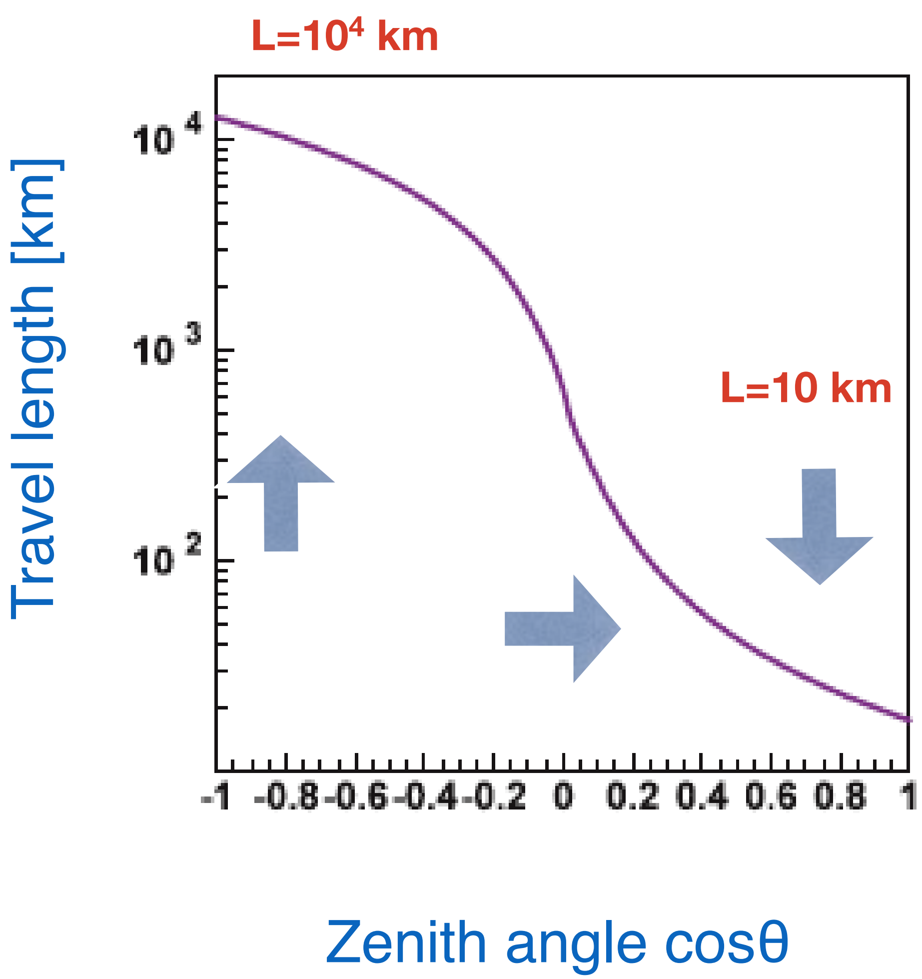
$$R_{exp} = \frac{[N(\mu - like)/N(e - like)]_{obs}}{[N(\mu - like)/N(e - like)]_{theo}}$$

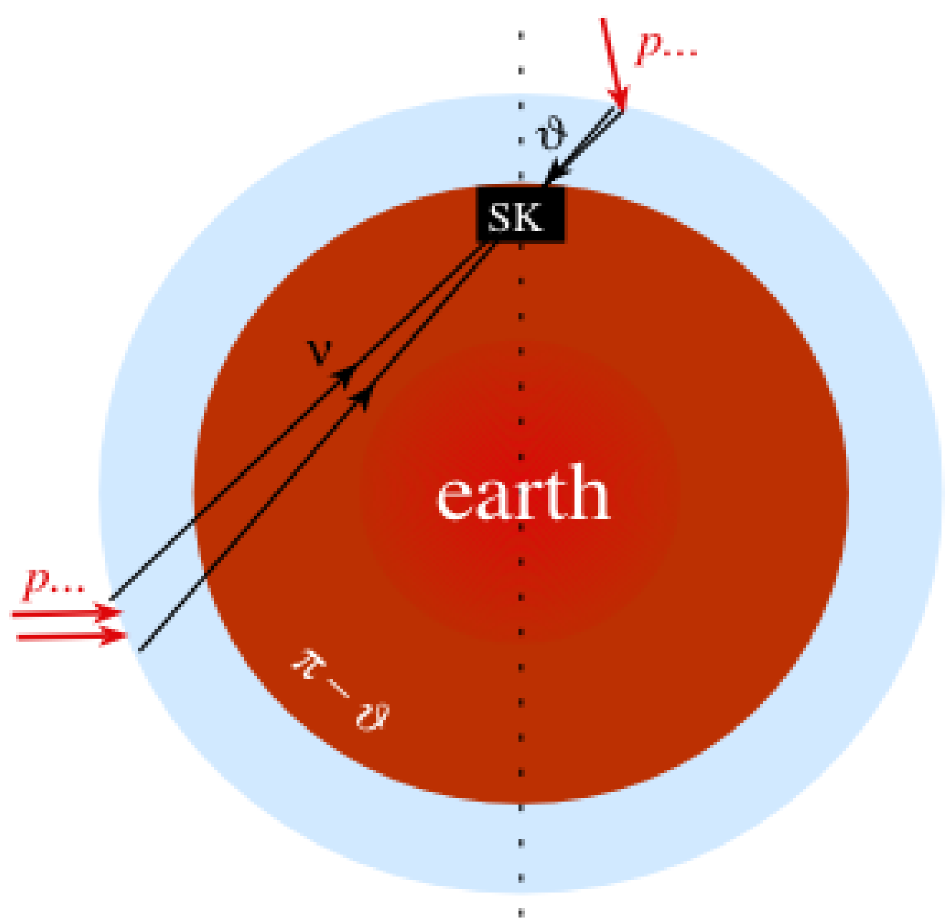


- No oscillations would mean: $R_{exp} = 1$
- *Observed ratio:* $R_{exp} \approx 0.6$

SuperKamiokande: zenith-angle dependance

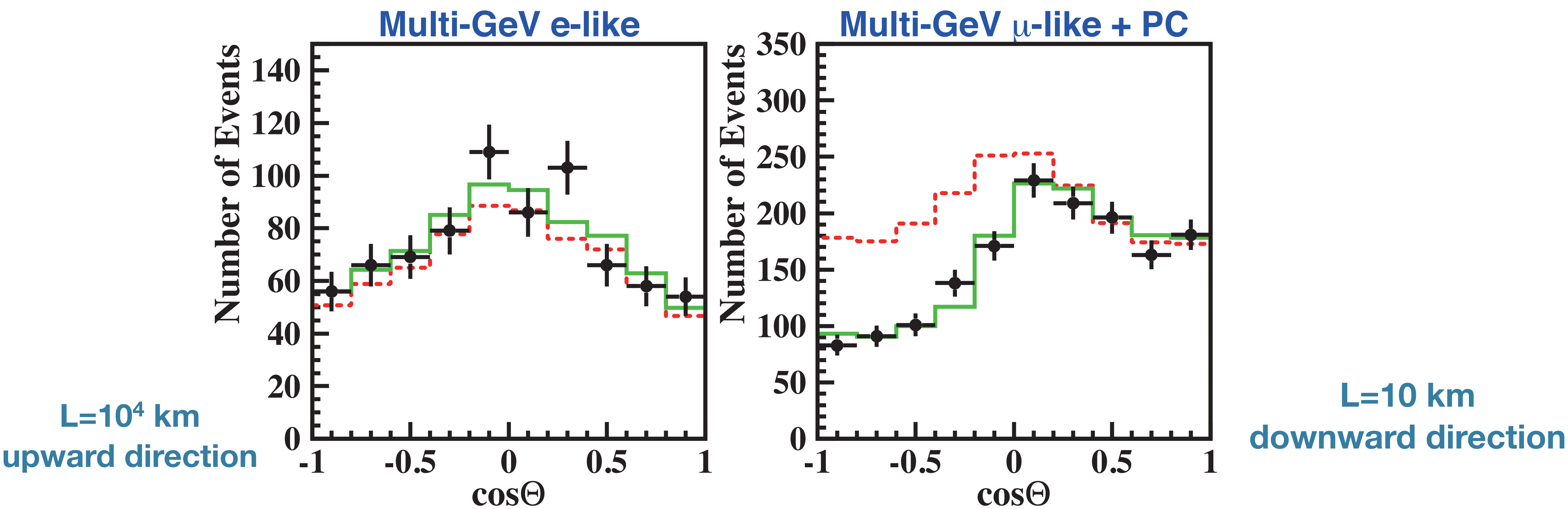
- Neutrinos produced above the detector ('downward neutrinos'): cosθ=1; L ≈ 10 km
- Neutrinos coming from below the detector ('upward neutrinos'): cos θ = -1; L ≈ 1.2×10^4 km
- The production in the atmosphere is isotropic: one expects the up/down-flux to be symmetric (the increased flux dilution from the opposite site, $\sim r^{-2}$, is compensated by the larger production surface, $\sim r^2$)





SuperKamiokande: zenith-angle dependance

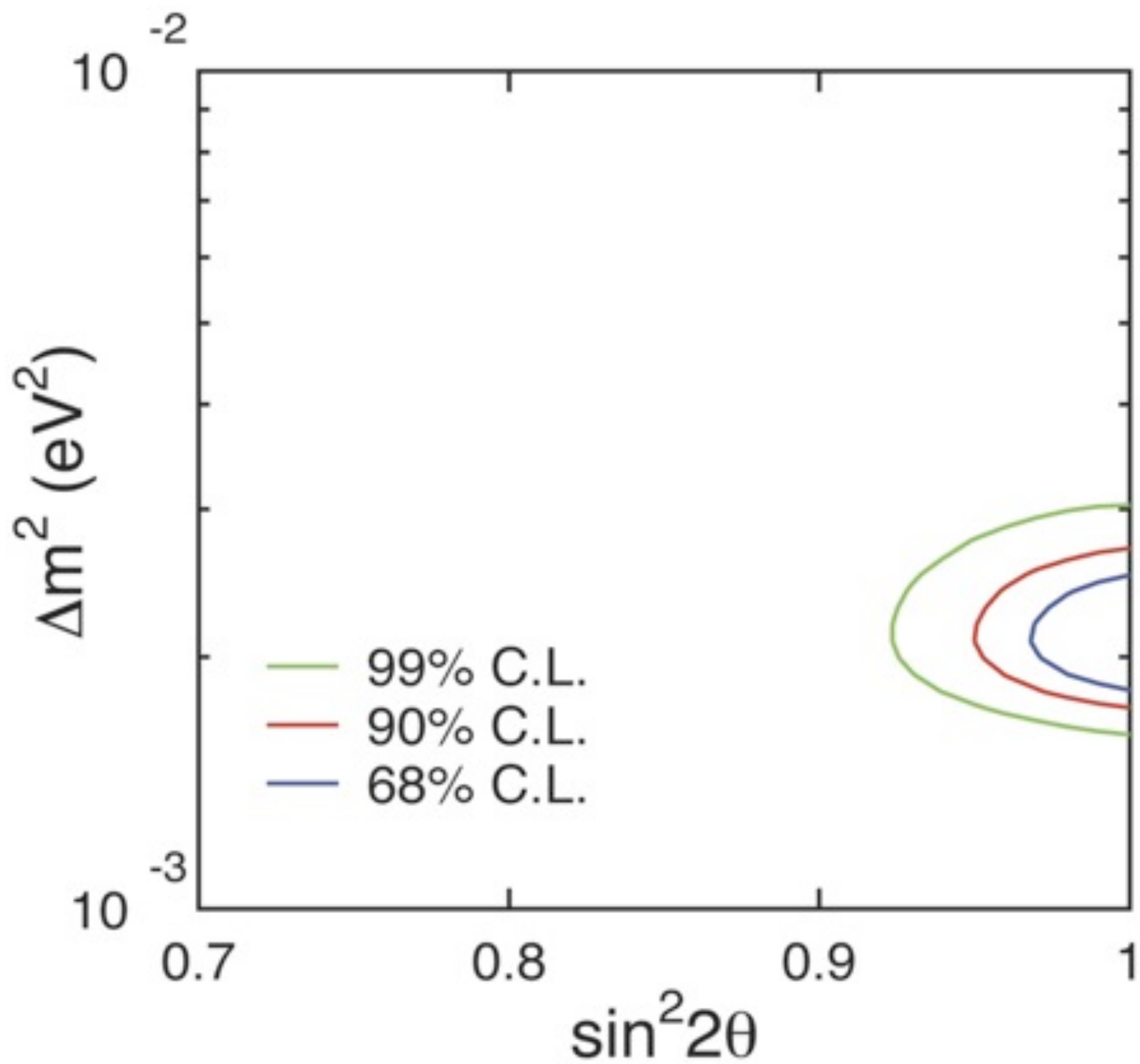
- Observation:
    - ➡ Electron-like: no zenith angle dependance
    - ➡ Muon-like: ‘upwards going’ μ strongly suppressed compared to ‘downwards going’ μ



Dotted histograms: expectations for no oscillations; Solid histograms: best fits for $\nu_\mu \to \nu_\tau$
Multi-GeV: visible energy > 1.3 GeV

With E = 1 ~ 10 GeV and L = 10^4 km -> this suggests $\Delta m^2 \sim 10^{-3} - 10^{-4}\ eV^2$

SuperKamiokande Results

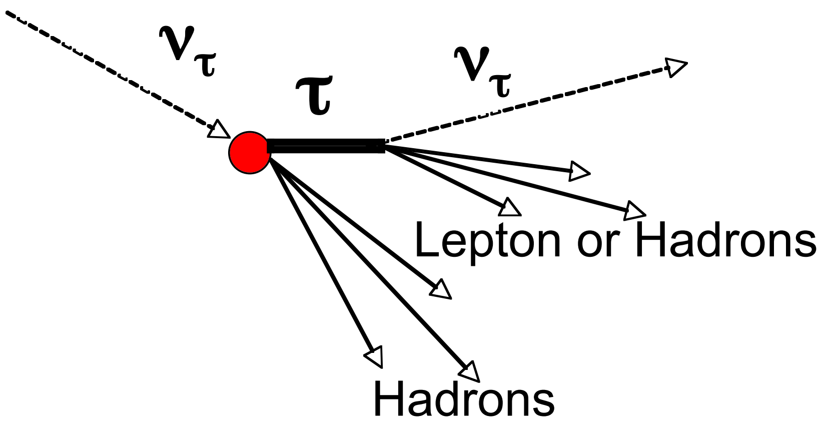


'Best Fit' of all data yields:

$$\sin^2 2\theta = 1.00$$

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

Question: into what are the ν_μ oscillating?
Best answer: into ν_τ (weak evidence for ν_τ 'appearance' in SuperK)



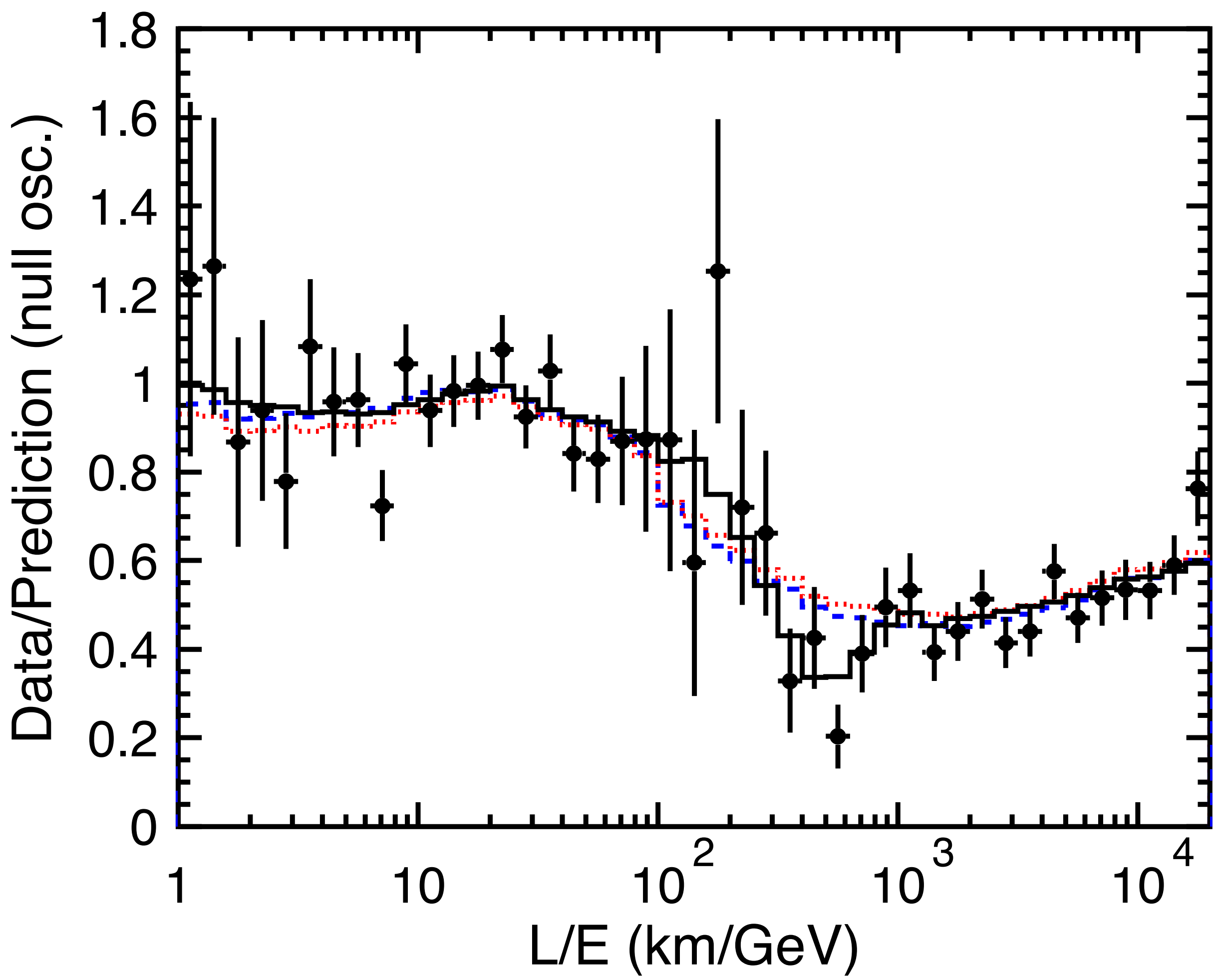
SuperKamiokande Results

- One needs to cross-check if the oscillation hypothesis is correct, by confirming the sinusoidal behavior of the transition probability as a function of L/E:

  ➡ plot the ratio of data to prediction without oscillations versus the reconstructed L/E

  ➡ *one half-period of the oscillation thus becomes "visible"*

- Assumption for the fit (solid line): $\nu_\mu \rightarrow \nu_\tau$ is the dominating channel for oscillations

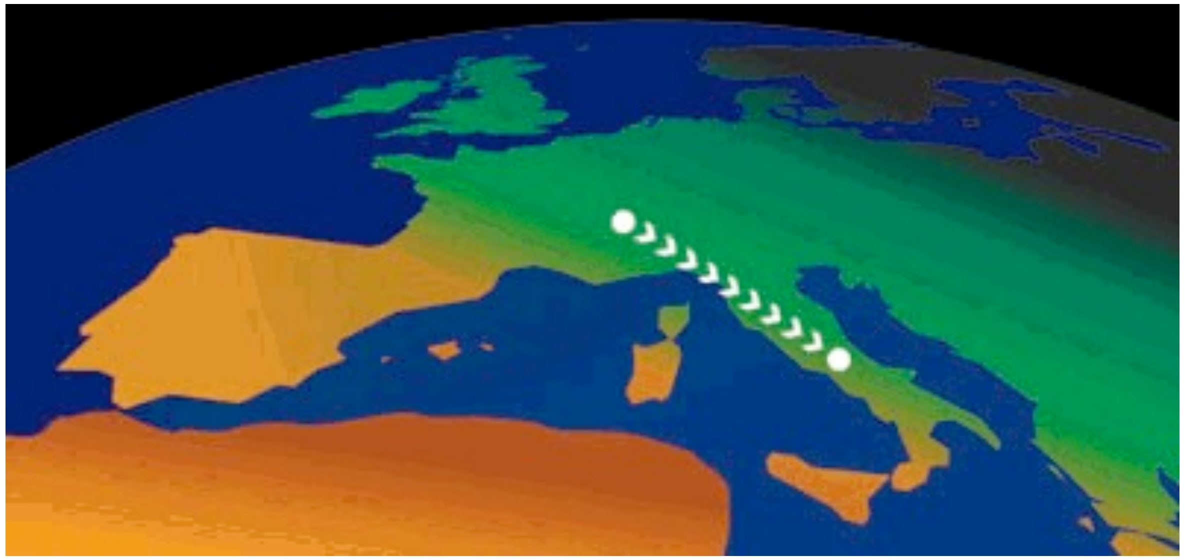


Dominant probability:

$$P(\nu_\mu \rightarrow \nu_\tau) = sin^2 2\theta_{23} \cdot sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

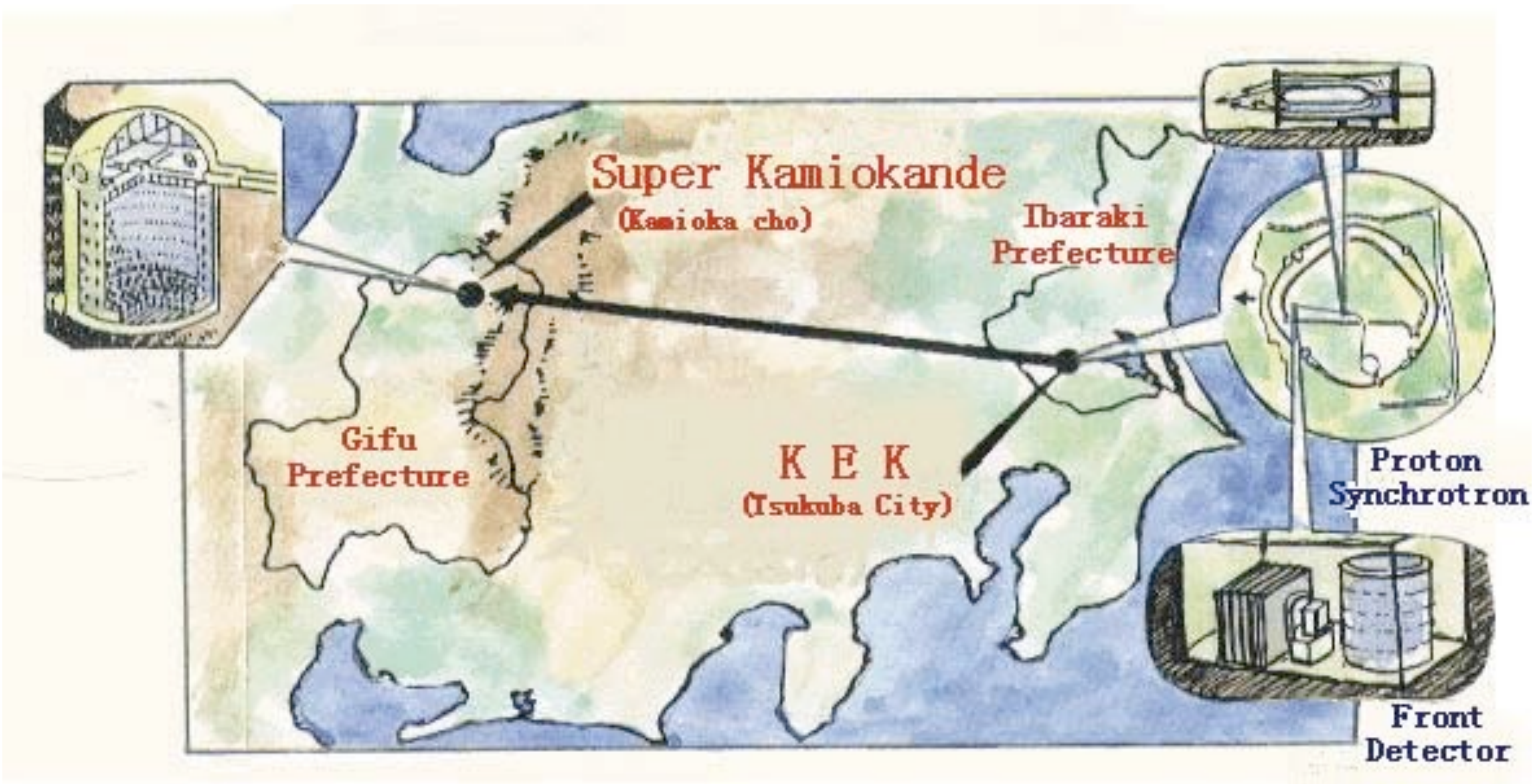
Long-Baseline Experiments

- To study $\nu_\mu \rightarrow \nu_\tau$ (or ν_μ 'disappearance') in detail, one uses accelerator experiments
    - ➡ control of the oscillation length L (typical distances are several hundred km)
    - ➡ control over the neutrino energy E (typical energies are E ~ 1 GeV)
    - ➡ determination of backgrounds through 'beam on' and 'beam off' comparison
- **Ideal case:** confirm ν_μ 'disappearance' and operate a ν_τ 'appearance' experiment, where one must consider the energy threshold for production of τ's (≈ 3.5 GeV)
- **In general:** a neutrino beam is sent over a distance L, and both a near and a far detector are being operated



Long-Baseline Experiments

- K2K, T2K: ν-beam from KEK, JPARC -> SuperKamiokande, Kamioka Observatory; L = 250 km, 295 km
- MINOS: ν-beam from Fermilab -> MINOS-Experiment, Soudan Laboratory, Minnesota; L = 735 km
- CNGS: ν-beam from CERN -> OPERA-Experiment, Gran Sasso Laboratory, Italy; L = 732 km

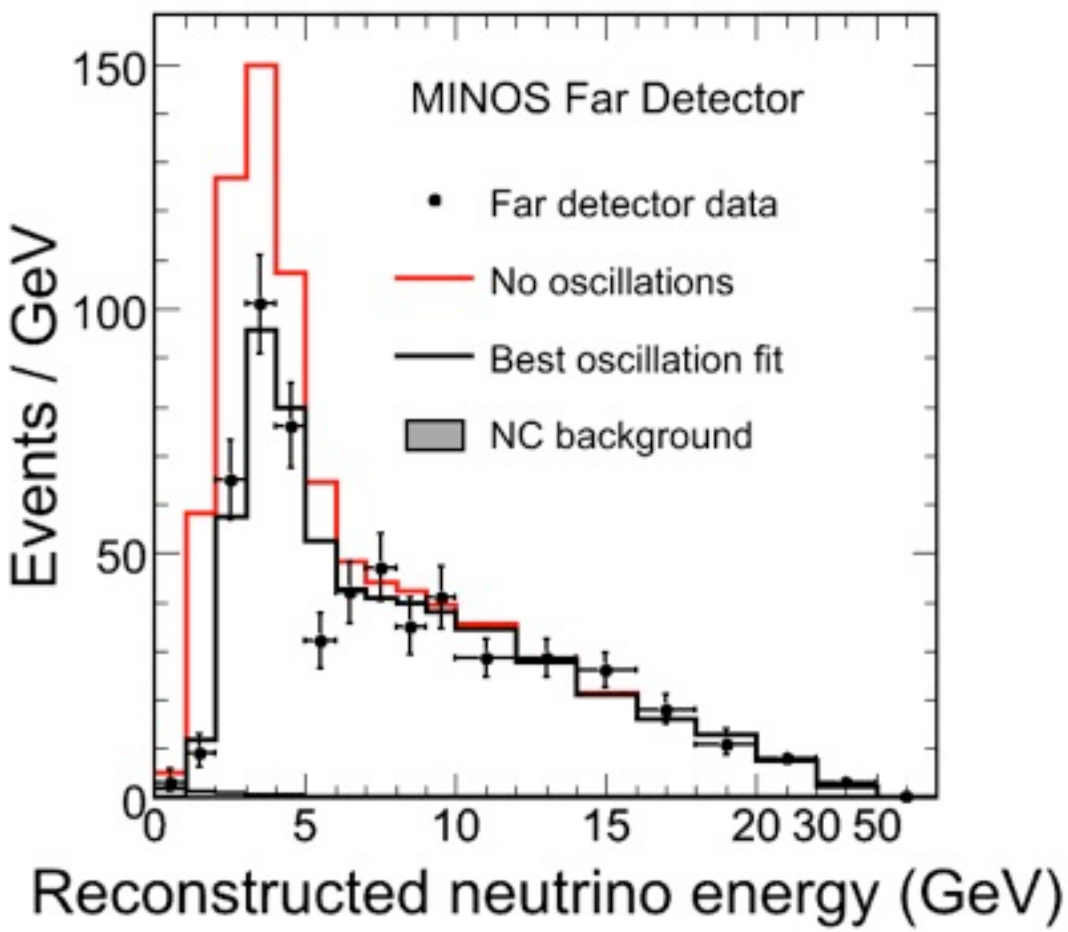


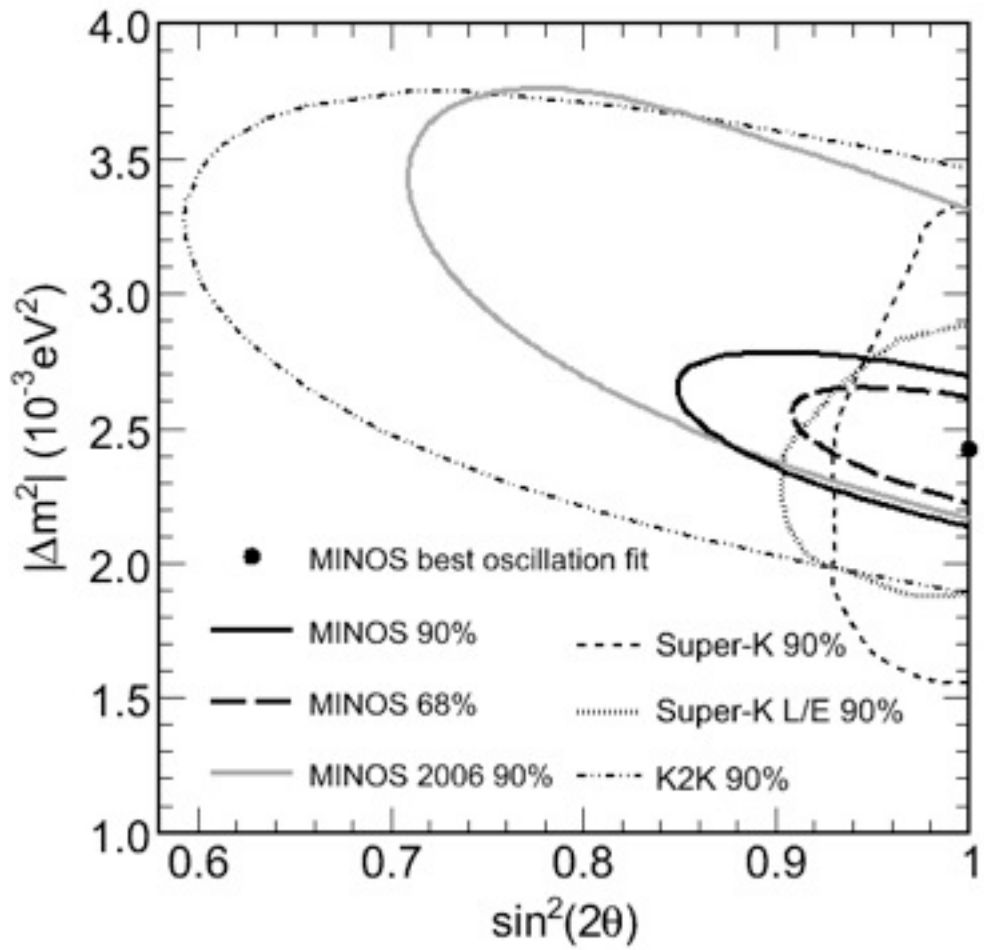
The MINOS Experiment

- 120 GeV p-beam at Fermilab, mean energy of neutrinos: 3 GeV
- Near detector (NuMi-Tunnel, 0.98 kton, 1.04 km), far detector (Soudan Mine, 5.4 kton - 2.54 cm steel plates with 1 cm thick scintillators in between, 1.5 T Magnet)

MINOS Results

- Evidence for ν_μ disappearance; consistent with previous experiments, and with K2K



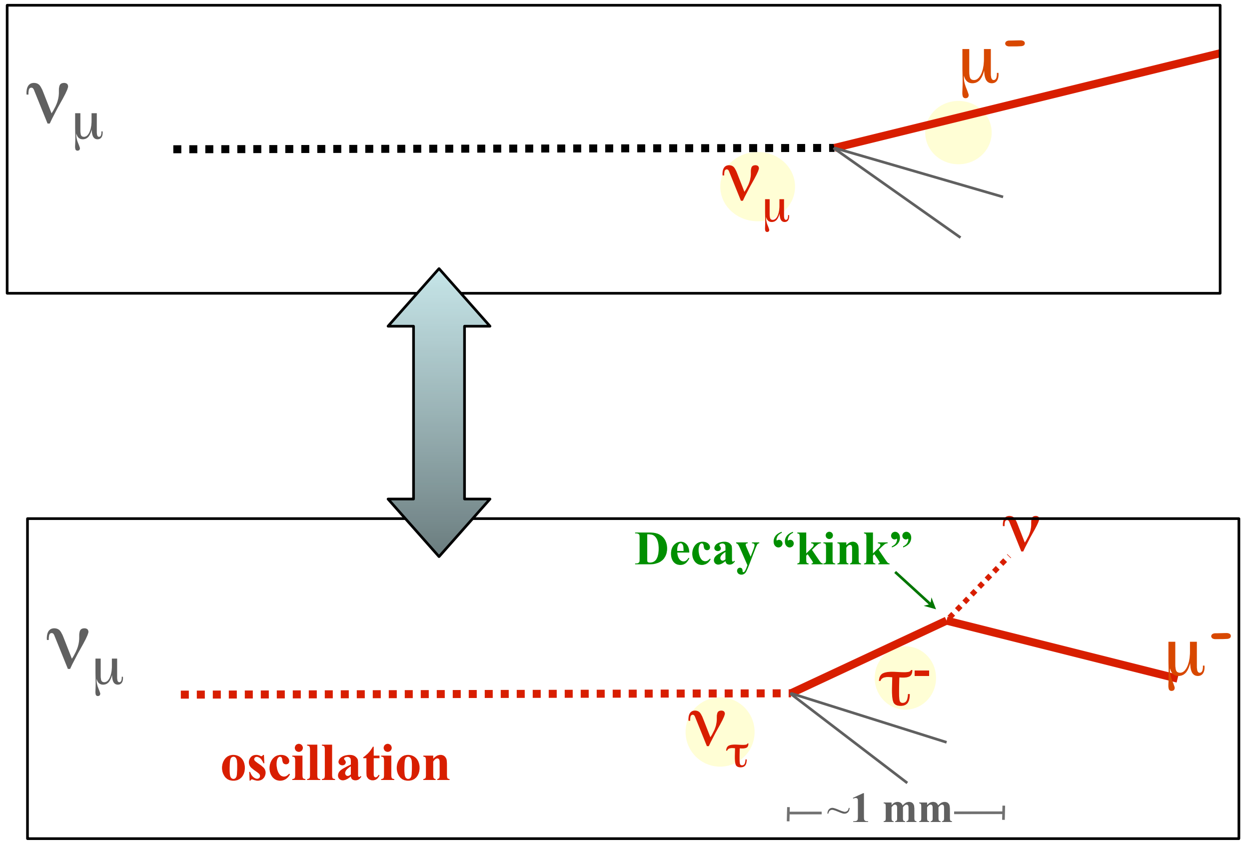


$$\sin^2 2\theta = 1.00 \pm 0.05$$

$$\Delta m^2 = 2.43 \times 10^{-3} eV^2$$

The OPERA Experiment

- 450 GeV p-beam from the CERN SPS; mean neutrino energy 17 GeV, goal: study ν_τ 'appearance'
- OPERA: Hybrid-detector (Pb, emulsion counter), 2 kton; produce a τ in a charged-current interaction and observe the decays $\tau \rightarrow e,\mu,\pi$; about 10 events are expected for 5 years of data taking
- Data taking since June 2008; a first observation a kink and hence of ν_τ 'appearance' in late 2010



The solar neutrino deficit

- First evidence for neutrino oscillations: the Homestake Experiment in South-Dakota (^{37}Cl-Target)
- The results were confirmed by:
    - ➡ radiochemical experiments: SAGE, GALLEX, GNO (^{71}Ga targets)
    - ➡ water Cerenkov detectors: Kamiokande, SuperKamiokande
    - ➡ the SNO Experiment
    - ➡ the Borexino Experiment
    - ➡ and by KamLAND (using reactor neutrinos)

- Experiments: these have different kinematic thresholds and hence test different parts of the energy spectrum of solar neutrinos

Solar neutrinos

- Distance Sun-Earth: ~ 1.5 x 10^8 km; neutrino energies ~ 1 MeV

  => one can thus test the following mass squared difference:

$$\Delta m^2 \approx 10^{-10}\, eV^2$$

- The Sun shines by converting protons to alpha particles:

$$4p \rightarrow \alpha + 2e^+ + 2\nu_e$$

- the positrons annihilate with two electrons

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

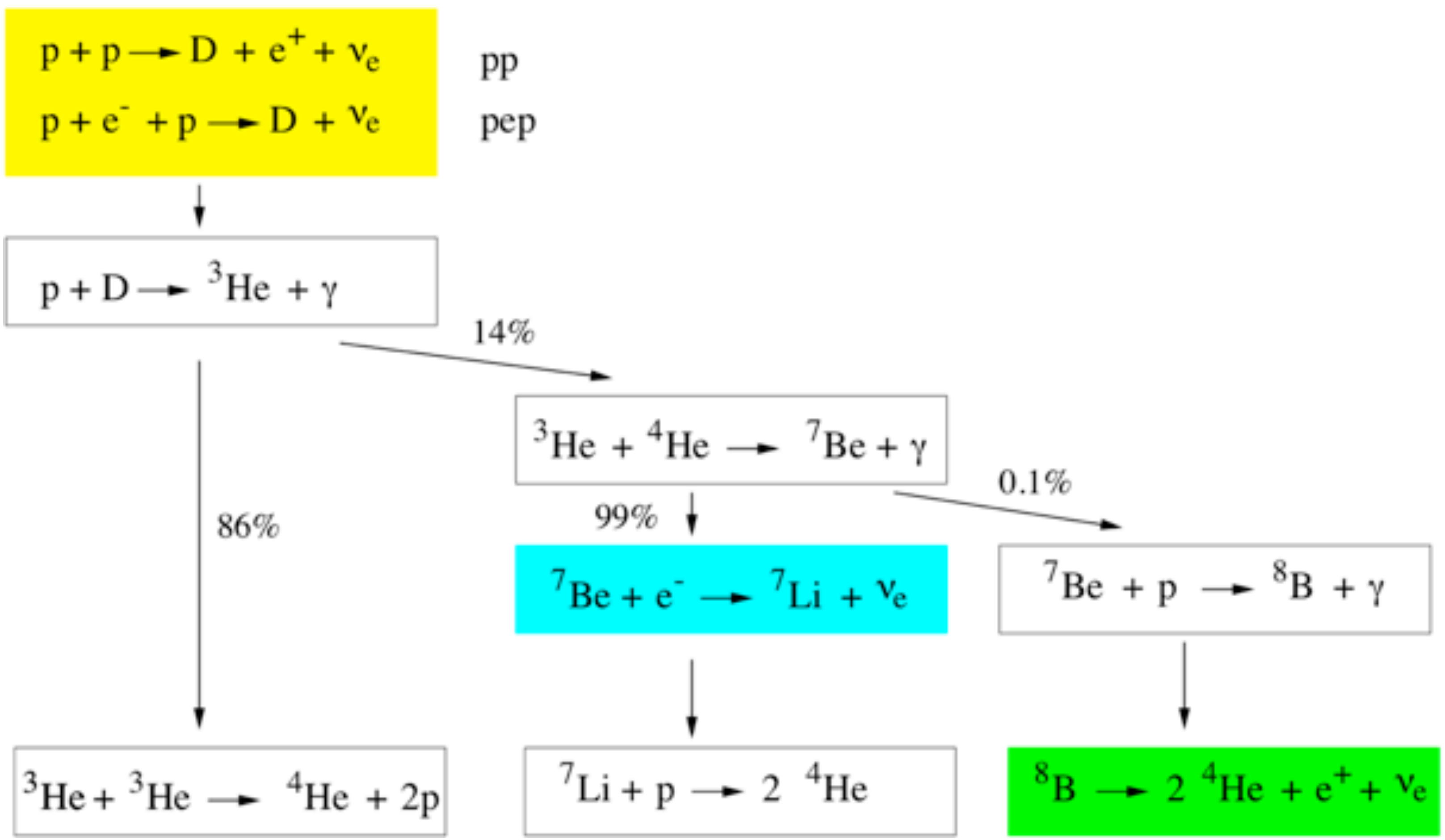
➡ an energy of $Q = 2m_e + 4m_p - m_\alpha = 26.73\,MeV$ is liberated per fusion reaction, - E_ν =<0.6 MeV>

➡ using the solar constant of S = 8.5 x 10^{11} MeV $cm^{-2}s^{-1}$ on Earth, this gives a neutrino flux of:

$$\phi_\nu \approx \frac{S}{13 \text{ MeV per } \nu_e} = 6.5 \times 10^{10}\, \text{cm}^{-2}\text{s}^{-1}$$

Solar neutrinos

- pp-chain

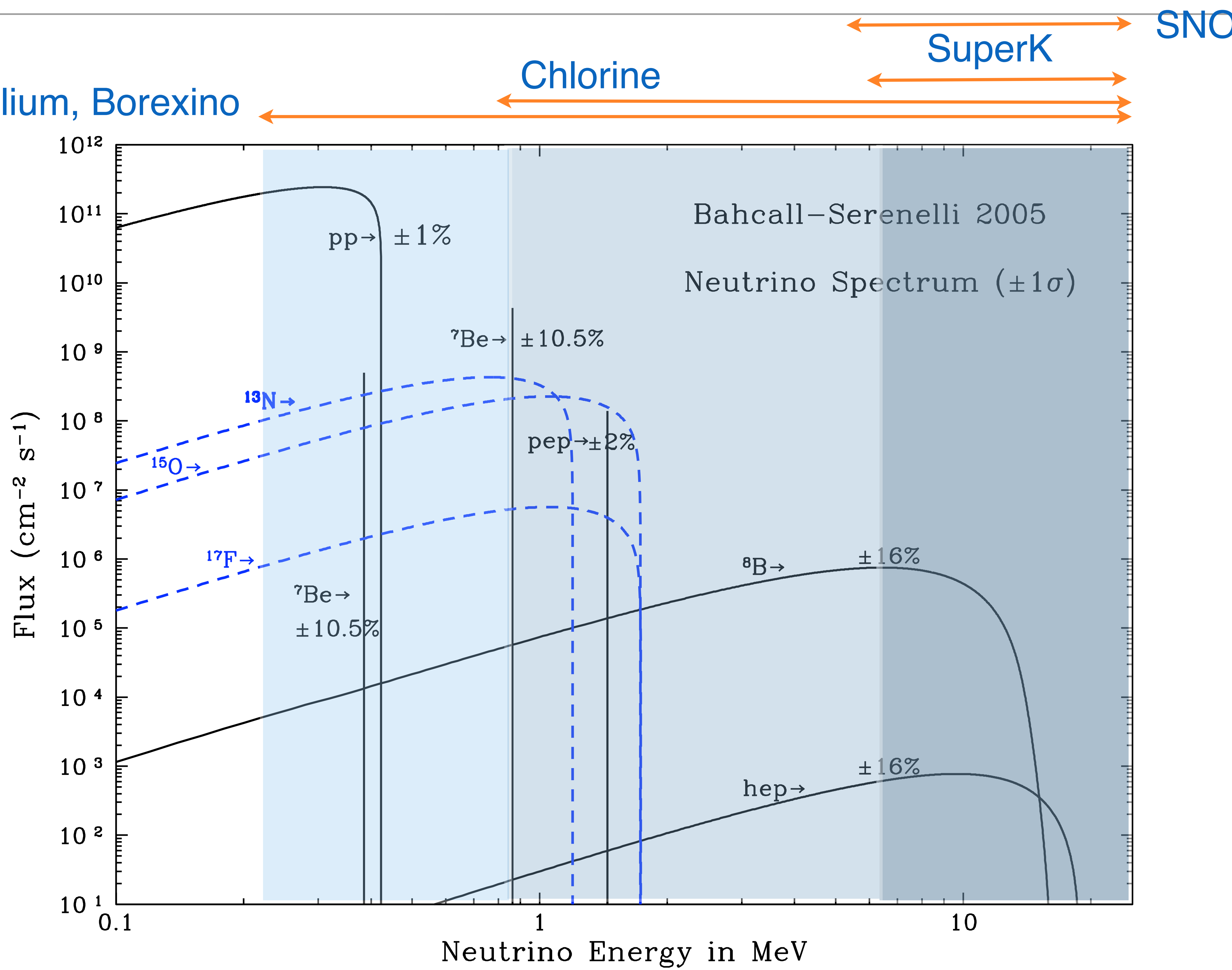


Predicted neutrino fluxes

Source	Flux ($10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)
pp	$5.9(1 \pm 0.01)$
pep	$0.014(1 \pm 0.02)$
he$p$	$8(1 \pm 0.2) \times 10^{-7}$
^{7}Be	$0.49(1 \pm 0.12)$
^{8}B	$5.8 \times 10^{-4}(1 \pm 0.23)$
^{13}N	$0.06(1 \pm 0.4)$
^{15}O	$0.05(1 \pm 0.4)$
^{17}F	$6(1 \pm 0.4) \times 10^{-4}$

- The measurement of neutrino fluxes can test solar models
- With $\sigma_\nu \sim 10^{-43}$ cm^2 one gets for the mfp in the Sun: $l_\nu=(n \cdot \sigma_\nu)^{-1}=10^{17}$ cm (n= particle density in the solar centre ~ 10^{26}cm^{-3}) => direct observation of the solar reactor

The solar neutrino spectrum



Experiments

- Two different kinds of experiments:

  radiochemical:

$$\nu_e + {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X + e^-$$

  The daughter nucleus must be unstable, and decay with a reasonable $T_{1/2}$. The decay is used for the detection process.

  The production rate of the daughter nucleus is given by:

$$R = N\int \phi(E)\sigma(E)\mathrm{d}E$$

- with N = number of target atoms; ϕ = neutrino flux; σ = cross section
- Using $\sigma_\nu \approx 10^{-45}$ cm^2 (E-dependent) and ν-fluxes ≈ 10^{10} cm^{-2}s^{-1}

  => 10^{30} target atoms for the detection of 1 event/day are needed

Definition: 1 SNU = 10^{-36} captures/(target atom second)

SNU = Solar Neutrino Unit

Experiments

- Two different kinds of experiments:

  'Real time' experiments, that make use of the elastic neutrino-electron scattering

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

  - one detects the scattered electron

  - the direction of this electron and the direction of the incoming neutrino are correlated

  - for $E_\nu >> m_\nu$ one gets:

$$\theta \leq \left(\frac{2m_e}{E_\nu}\right)^{1/2}$$

=> hence one can obtain a direct image of the Sun using neutrinos

The Homestake experiment

- The first solar neutrino experiment, took data for 20 years, since 1978. The used reaction is (E_{th} =814 keV):

$$\nu_e + {}^{37}_{17}Cl \rightarrow {}^{37}_{18}Ar + e^-$$

- The detection method uses the decay ($T_{1/2}$ = 35 d):

$$^{37}_{18}Ar \rightarrow {}^{37}_{17}Cl + e^+ + \nu_e$$

615 t C_2Cl_4 (Tetrachlorethylen) => 2.2 x 10^{30} ^{37}Cl atoms

- the Ar atoms are extracted every 60-70 days (using He-Gas)
- the Ar is concentrated and measured with special proportional counters

1 Ar/day ~ 5.35 SNU

- Prediction SSM: (7.1±1.0) SNU

1 SNU = 10^{-36} captures/(target atom s)

- Measurement: (2.56±1.6) SNU

=> defined the so-called solar neutrino problem

Gallium experiments

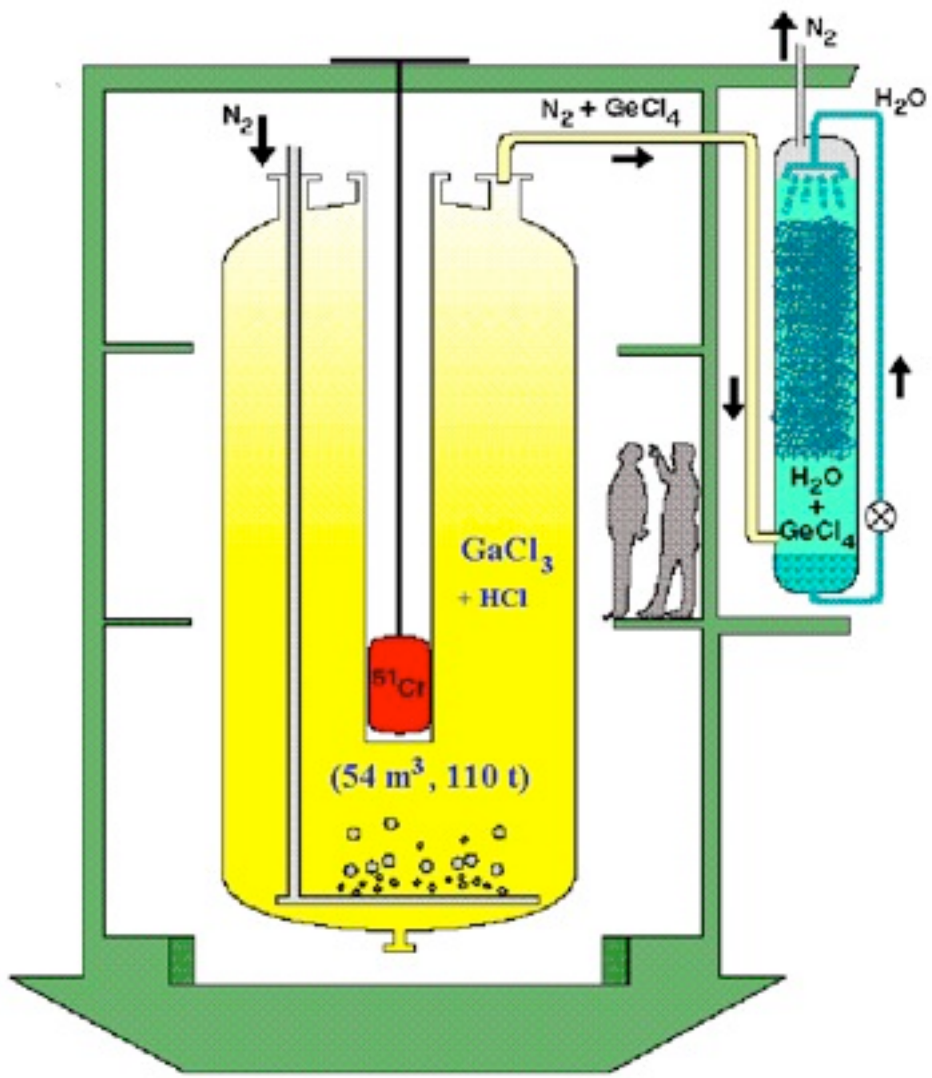
- GALLEX/GNO and SAGE
- The reaction (E_{th} = 233 keV => also pp neutrinos):

$$\nu_e + {}^{71}_{33}Ga \rightarrow {}^{71}_{32}Ge + e^-$$

- ^{71}Ge decays with $T_{1/2}$ = 11.4 d, by electron capture:

$$^{71}_{32}Ge + e^- \rightarrow \nu_e + {}^{71}_{33}Ga$$

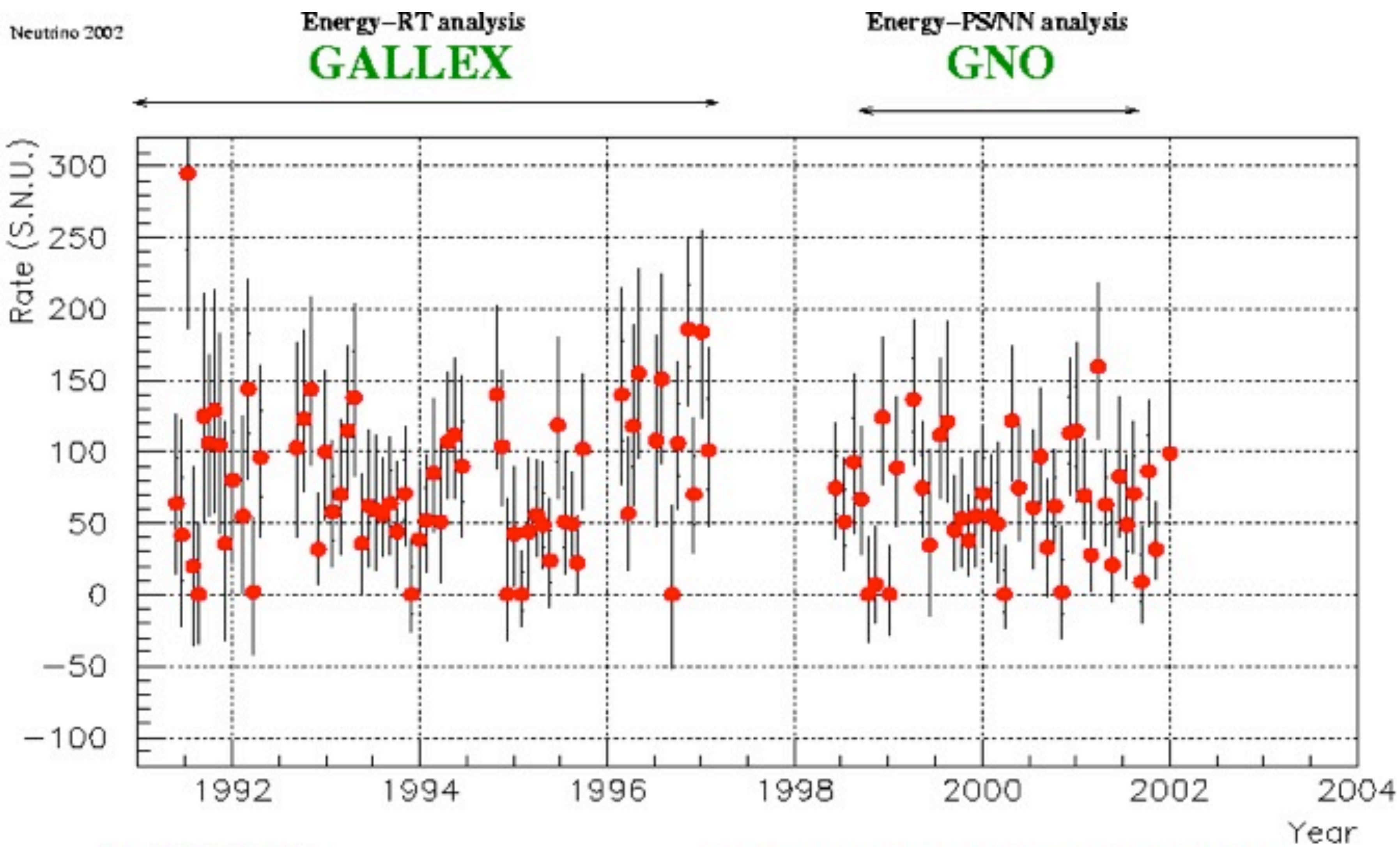
- GALLEX/GNO: at the Gran Sasso Laboratory
- GALLEX: 30 t Ga in 110 t $GaCl_3$ solution (10^{29} ^{71}Ga)
- SAGE: Baksan, 57 t metallic Ga



- Prediction SSM: (129±8) SNU
- Observation (mean value over many years of data):

(70.8 ± 4.5 ± 3.8) SNU

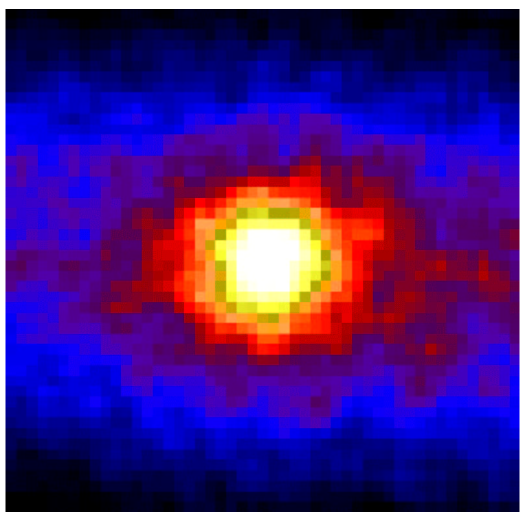
GALLEX and GNO Results



GALLEX	65 SR	77.5 +– 6.2 (stat) +– 4.5 (sys) SNU
GNO	43 SR	65.2 +– 6.4 (stat) +– 3.0 (sys) SNU
GNO+GALLEX	108 SR	70.8 +– 4.5 (stat) +– 3.8 (sys) SNU

SuperKamiokande

- Real time experiment: information about the arrival time and direction of neutrinos
- Also, a direct evidence that neutrinos are coming from the Sun

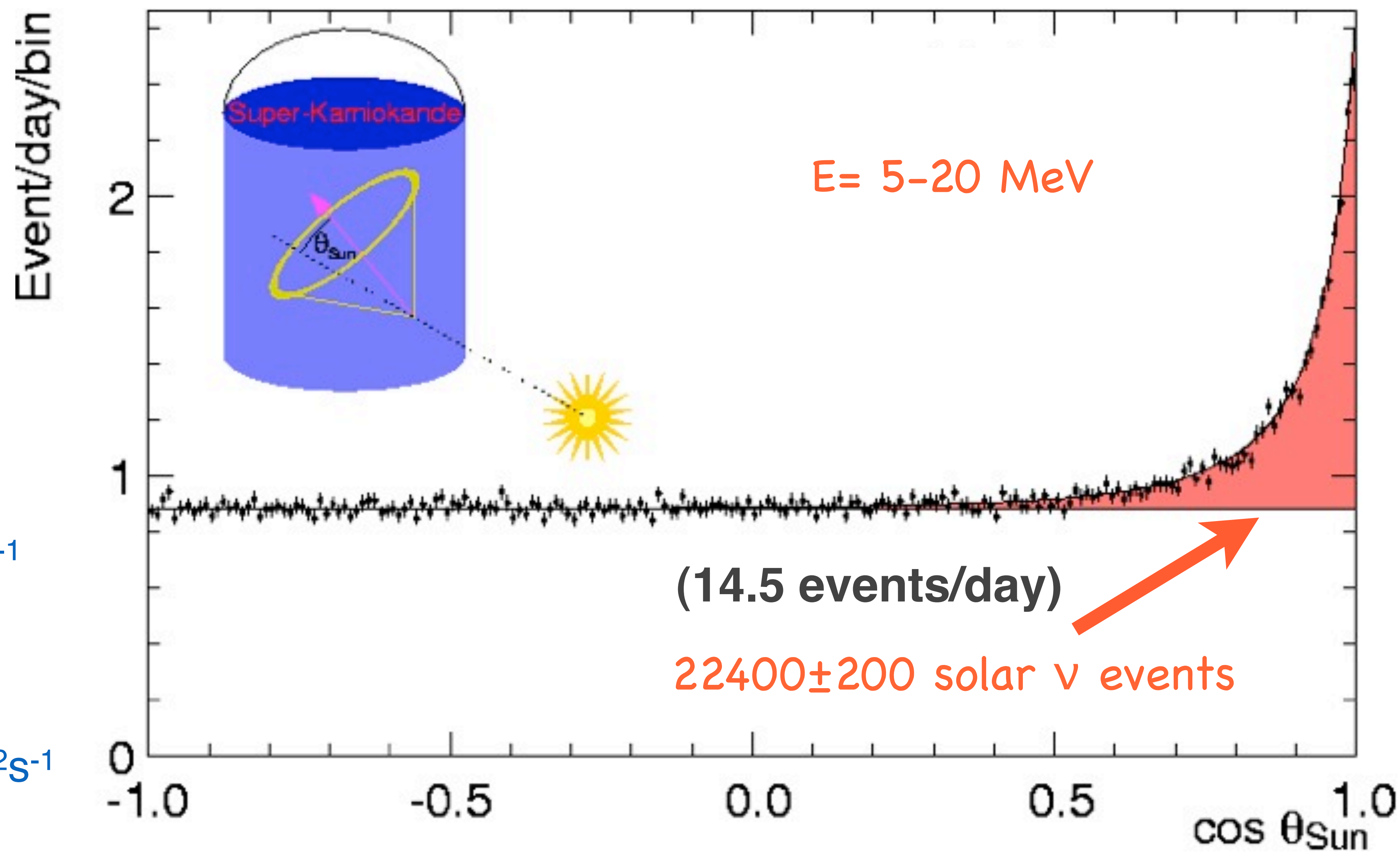


Prediction SSM:

$(5.05 \pm 0.2)\times10^{6}\ cm^{-2}s^{-1}$

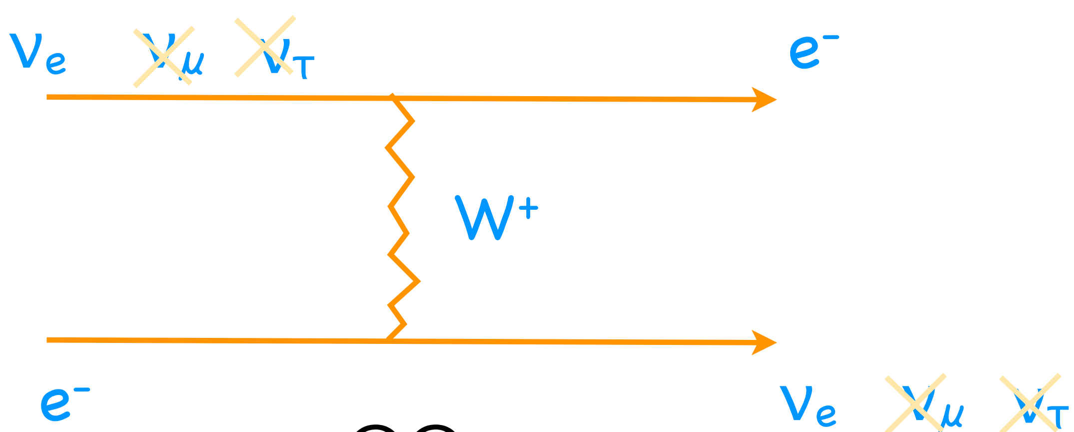
Measurement:

$(2.35 \pm 0.08)\times10^{6}\ cm^{-2}s^{-1}$

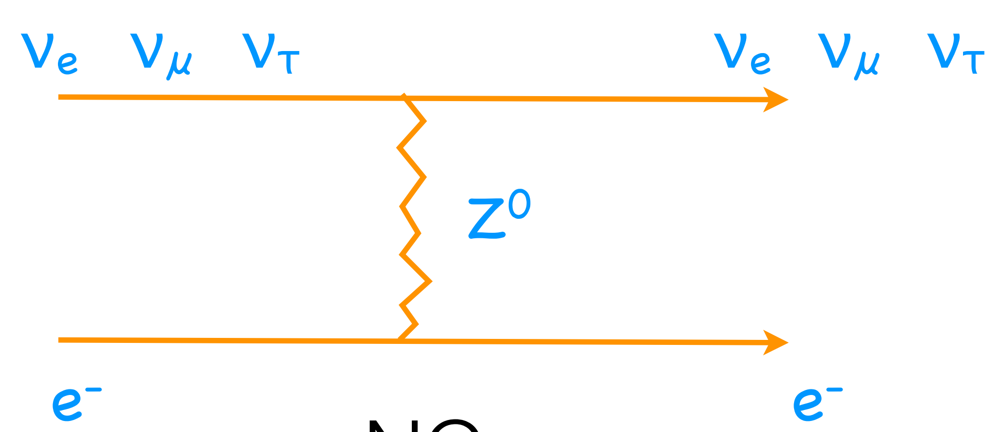


SuperKamiokande

- Cross sections:



CC



NC

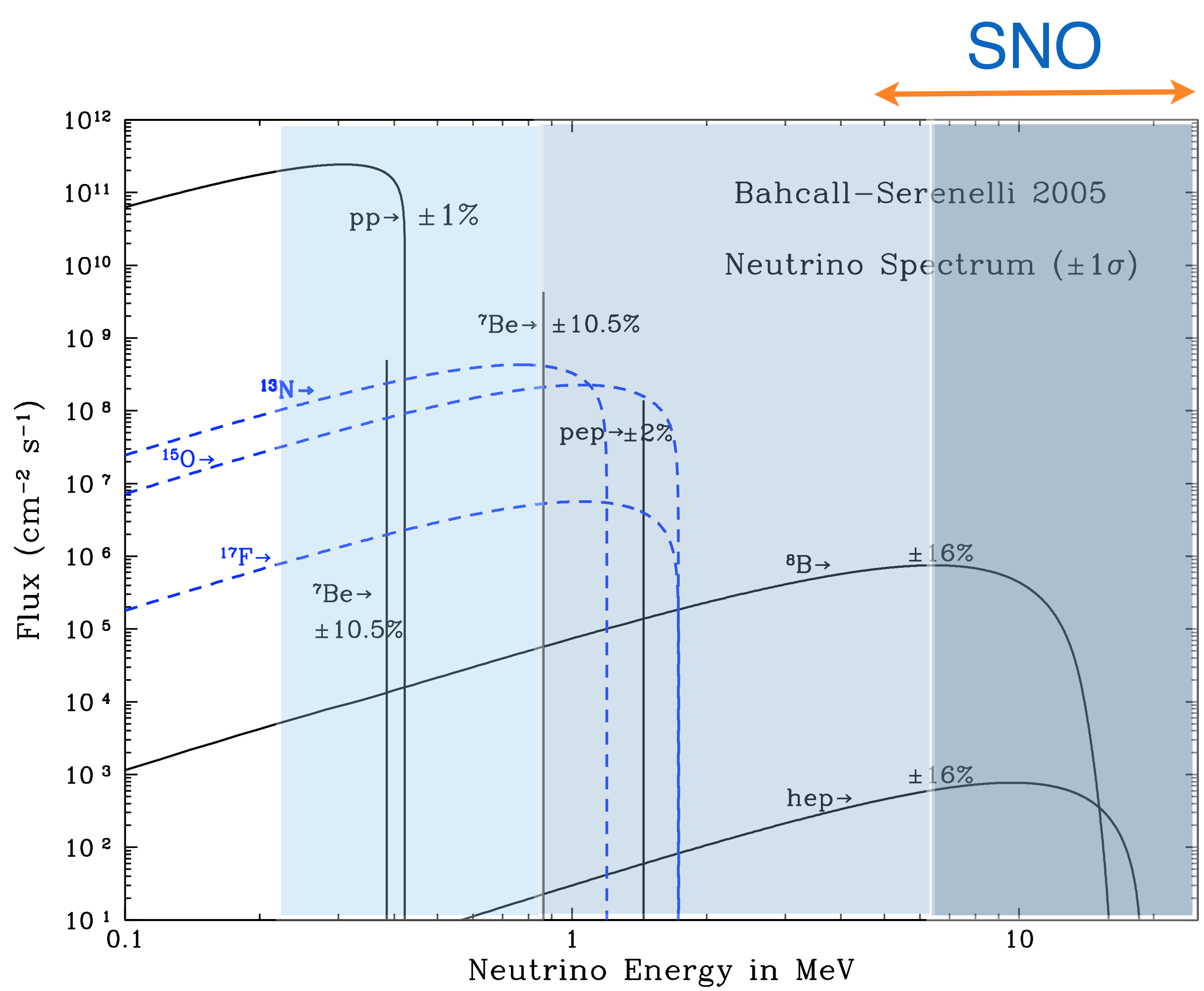
$\sigma_{tot} \approx 1.6 \times 10^{-44}\ cm^2$ for ν_μ, ν_τ

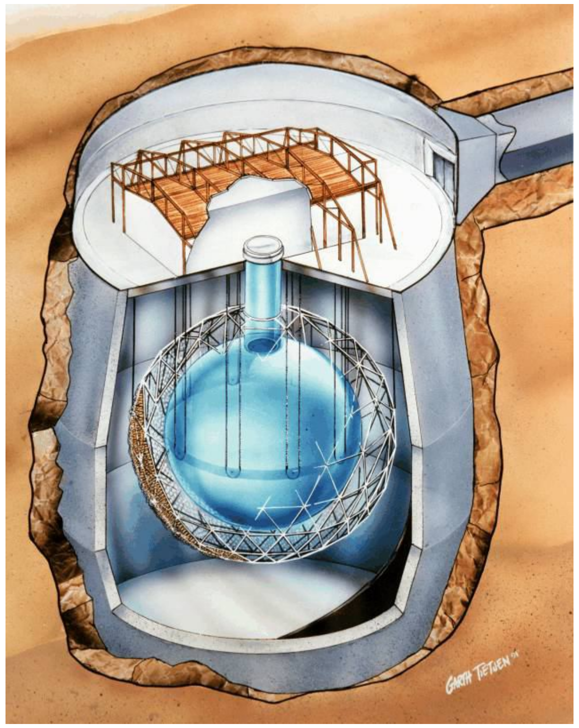
$\sigma_{tot} \approx 9 \times 10^{-44}\ cm^2$ for ν_e

The observed flux is thus a superposition of ν_e, ν_μ and ν_τ dominated by ν_e interactions, because of the larger cross section

The SNO experiment

- Cerenkov detector, with 10^3 tons of heavy water (D_2O)
- 9700 PMTs and 7300 t water shield; E_{th}=5 MeV
- Located at SnoLAB, Sudbury/Canada
- SNO observes the ν's from the ^8B decay, given its E_{th}





SNO: the neutrino reactions in detail

- **Charged-current reaction**

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

- E_{th} = 1.442 MeV; sensitive only to ν_e
- **Neutral-current reactions**

$$\nu + d \rightarrow \nu + p + n$$

- E_{th} = 2.225 MeV; sensitive to all neutrino flavors $\nu_e + \nu_\mu + \nu_\tau$
- **Elastic scattering:**

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

- Sensitive to all neutrino flavors, but ν_e scattering dominates $\nu_e + 0.15(\nu_\mu + \nu_\tau)$
- The neutrons are detected through the 6.3 MeV gammas from the following reaction:

$$n + d \rightarrow {}^3He + \gamma$$

‘Smoking Gun’ for neutrino oscillations

- Is the total neutrino flux coming from the Sun equal to the ν_e-flux?
- One can measure the following ratios:

In case:

$$\frac{CC}{NC} = \frac{\phi(\nu_e)}{\phi(\nu_e) + \phi(\nu_\mu + \nu_\tau)} \quad \Rightarrow \quad \phi^{CC}(\nu_e) < \phi^{NC}(\nu_x)$$

$$\frac{CC}{ES} = \frac{\phi(\nu_e)}{\phi(\nu_e) + \left[0.15\phi(\nu_\mu + \nu_\tau)\right]} \quad \Rightarrow \quad \phi^{CC}(\nu_e) < \phi^{Es}(\nu_x)$$

$$\phi(\nu_{\mu,\tau}) > 0 \quad \Rightarrow \quad P(\nu_e \rightarrow \nu_{\mu,\tau}) \neq 0$$

=> Transformation into a different ν-flavor

SNO results

- The following ratio was measured from the first 2 reactions (breaking D):

$$\frac{\phi(\nu_e)}{\phi(\nu_e) + \phi(\nu_\mu + \nu_\tau)} = 0.30 \pm 0.023_{stat} \pm 0.03_{syst}$$

- This means that $\phi(\nu_\mu + \nu_\tau)$ is definitely not zero
- It provides clear evidence, that ν_e, that are produced in the center of the Sun change their flavor on their way to Earth

- More evidence comes from the observation of the reaction:

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

SNO results

CC Fluß: ϕ^{CC} = [1.75 ± 0.07 (stat) ± 0.11 (syst)]×10^{6} cm^{-2}s^{-1} $\quad \nu_e$

ES Fluß: ϕ^{ES} = [2.39 ± 0.34 (stat) ± 0.15 (syst)] ×10^{6} cm^{-2}s^{-1} $\quad \nu_e + 0.15(\nu_\mu + \nu_\tau)$

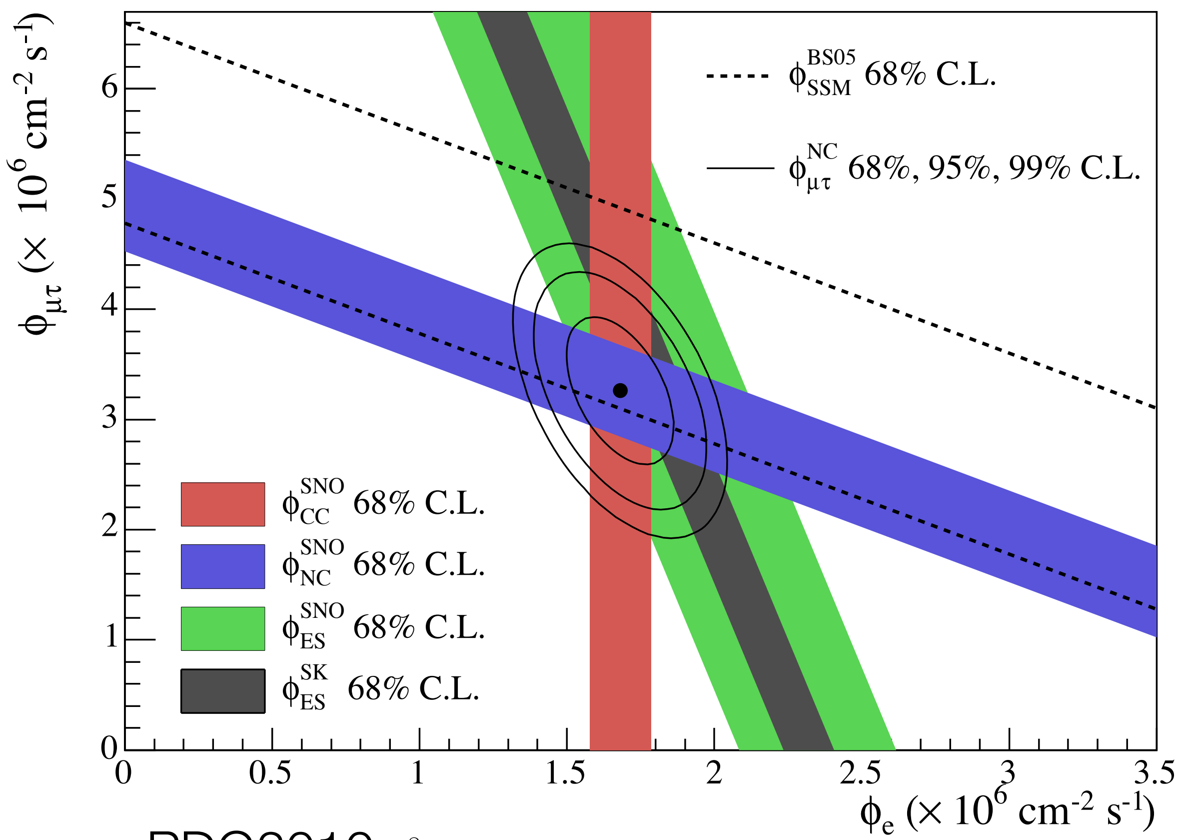
NC Fluß: ϕ^{NC} = [5.21 ± 0.27 (stat) ± 0.38 (syst)] ×10^{6} cm^{-2}s^{-1} $\quad \nu_e + \nu_\mu + \nu_\tau$

Predicted NC flux

(5.49 ± 0.9) x 10^{6} cm^{-2}s^{-1}

⇒ good agreement with the SSM:

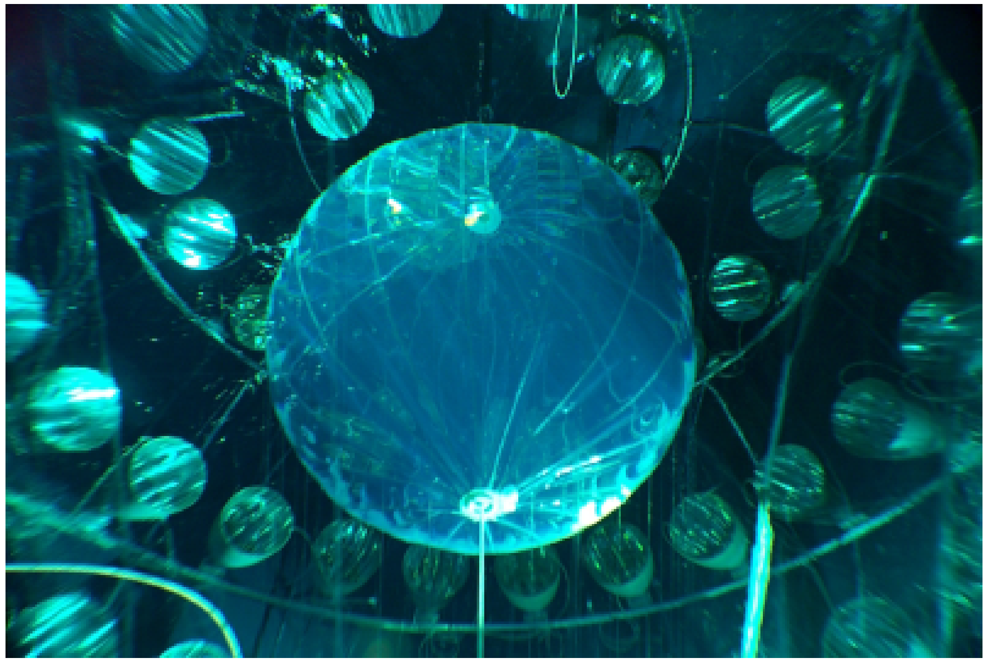
⇒ direct evidence, that neutrino oscillations occur

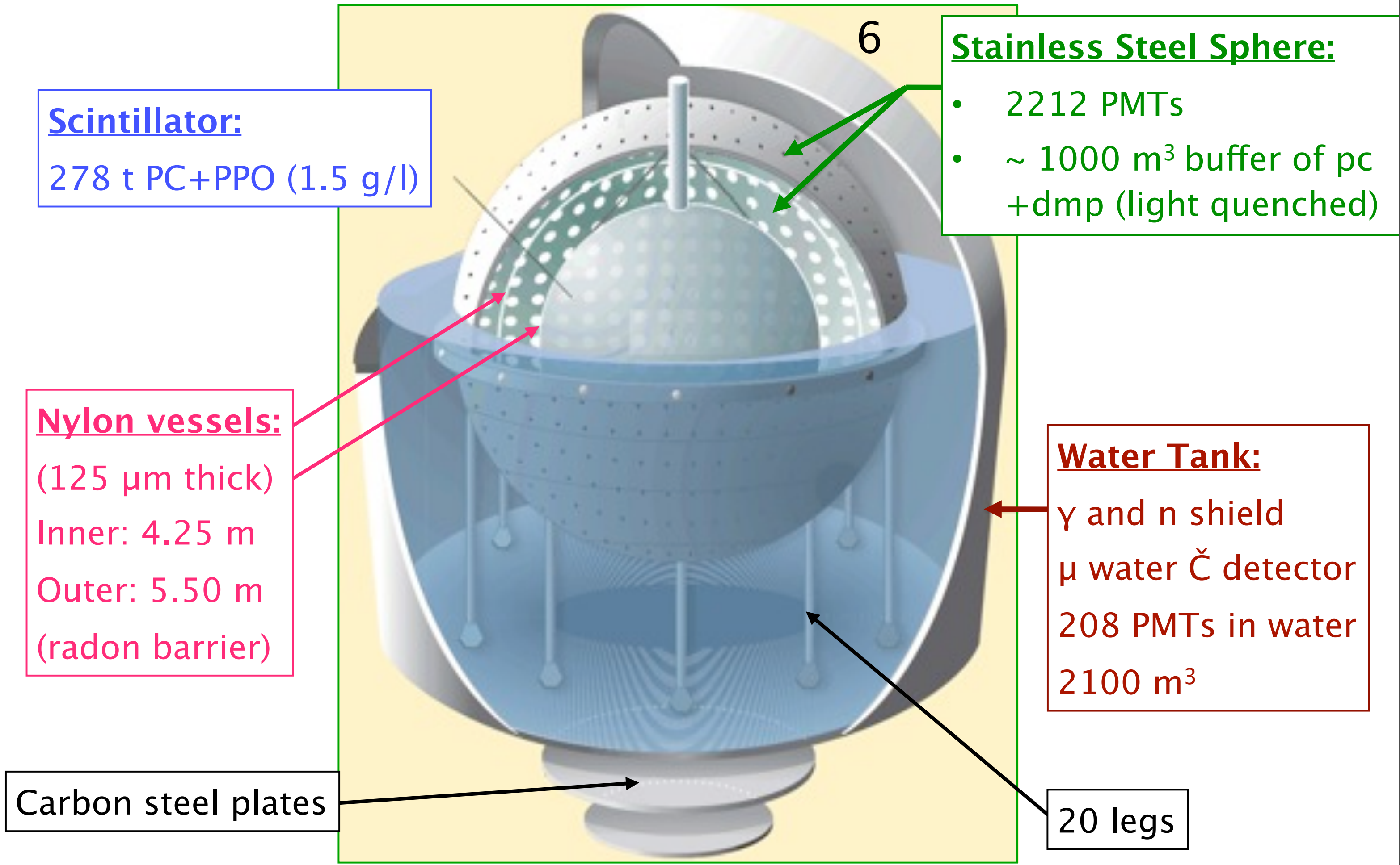


PDG2010

The BOREXINO experiment

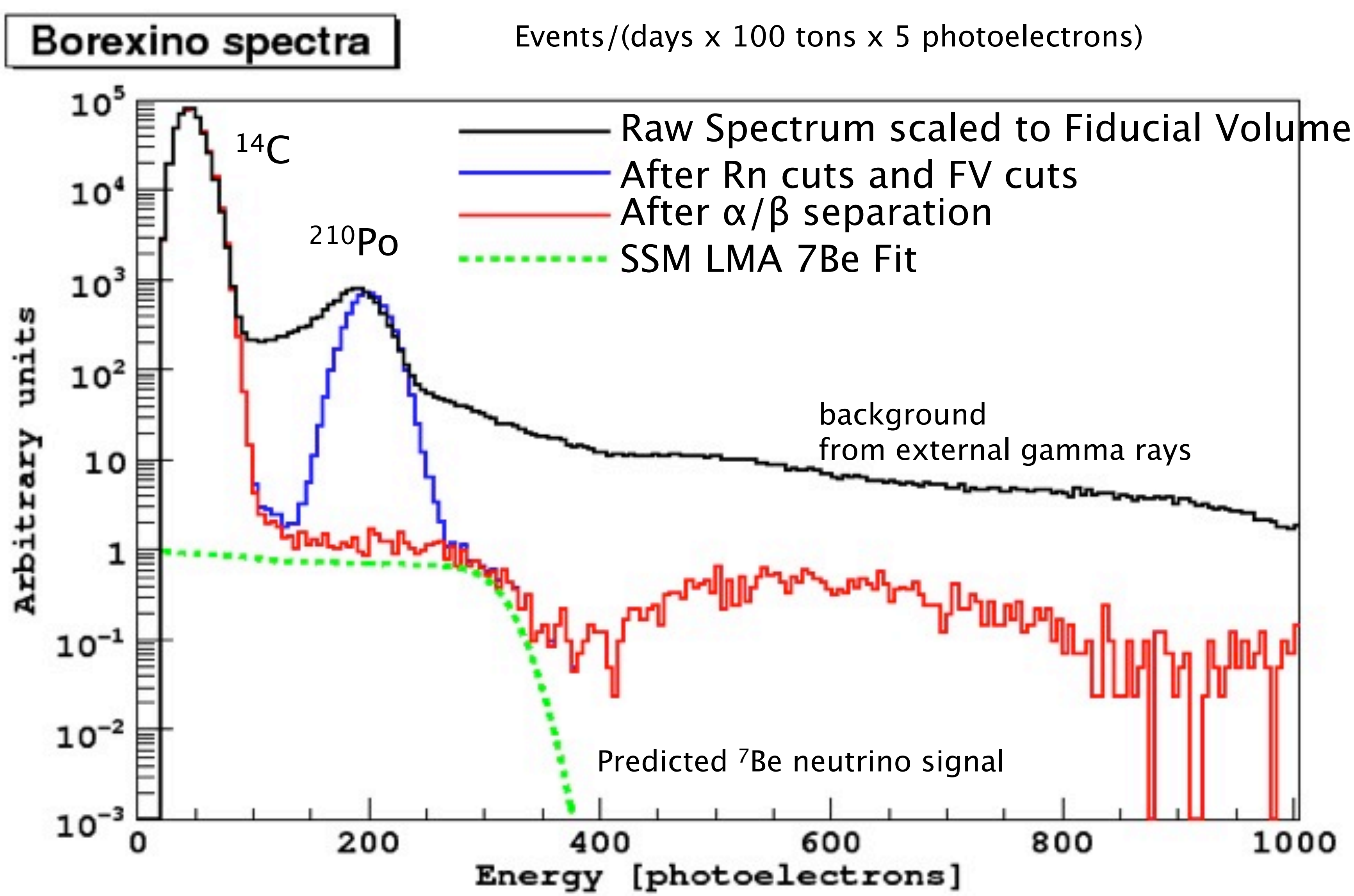
- Scintillator experiment (278 t) at the Gran Sasso Laboratory, Italy
- 2212 PMTs + outer water shield
- Goal: real-time observation of ^{7}Be neutrinos
- $E_{\nu}(^{7}Be) = 0.862$ MeV





BOREXINO: first results

- Observation: scintillation light from ν - e⁻ scattering



^{7}Be ν observed rate:
($47 \pm 7_{stat} \pm 12_{syst}$)
events/day/100 t

No flavor change:
(75 ± 4)
events/day/100 t

Considering the ^{8}B ν's measurements, one predicts for Borexino:

(49 ± 4)
events/day/100 t

Interpretation of the solar neutrino results

- 2 possibilities

  ➡ the ν_e oscillate in vacuum on their way from Sun → Earth

  ➡ with $\Delta m^2 \approx 10^{-10}$ eV^2 and $\sin^2 2\theta = 0.7$ -1 (this solution is now excluded with > 99% probability)

  ➡ the neutrinos are converted in the Sun, via so-called matter effects

- The MSW-Effekt (Mikheyev-Smirnov-Wolfenstein) for ν-oscillations in matter

  ➡ Basic idea: matter influences the propagation of neutrinos by elastic scattering

  ➡ the effect comes from the fact that different ν-flavors interact differently with matter, leading to different "effective masses" of ν_e and ν_μ/ν_τ as they travel through matter

  ➡ the fact that ν_e interact also via the CC reaction will lead to a phase shift of the mass eigenstates during propagation

The MSW effect

- ν_e *interact with e^- both via CC and NC, while* ν_μ, ν_τ *interact only via the NC*
- The Hamiltonian of the neutrino system differs in matter from the Hamiltonian in vacuum (H_{int} describes the interaction of neutrinos with the particles of matter, relevant effects come from ν_e and ν_μ elastic scattering):

$$H_{matter} = H_{vacuum} + H_{\text{int}}$$

- The time evolution of the ν-flavor fields to (n_e = number density of electrons in matter, G_F = Fermi constant) is changed to:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F n_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix}$$

The MSW effect

- This increases the oscillation probability to:

$$P(\nu_e \rightarrow \nu_\mu, L) = (\sin^2 2\theta / W^2)\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

- with $W^2 = \sin^2 2\theta + (\sqrt{2}G_F n_e(2E/\Delta m^2) - \cos 2\theta)^2$

- and n_e = density of electrons ($n_e = 0$ in vacuum) and θ = mixing angle in vacuum

- In the Sun: n_e varies rapidly => resonances = strong increase in the oscillation probability
- Best fit of all experimental data so far (‘LMA’ - solution, LMA = Large Mixing Angle)

$$\Delta m^2 \approx 7.9 \times 10^{-5} eV^2$$

$$\sin^2 2\theta \approx 0.30$$

Reactor Experiments

- Reactors: provide the strongest neutrino sources on Earth
- Beta decays of isotopes produced in ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu fission reactions
- Mean yield ~ 6 anti-neutrinos/fission; the energy spectrum has a maximum around ≈ 2-3 MeV
- The following reaction is used for detecting these neutrinos (E_{th} = 1.8 MeV):

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

- with a cross section of:

$$\sigma = 9.23 \times 10^{-42} \left(\frac{E_\nu}{10\,MeV} \right)^2 cm^2$$

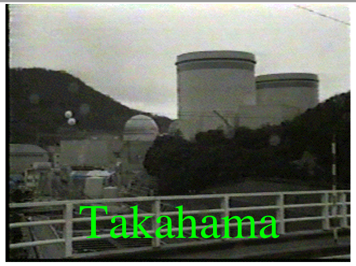
The KamLAND experiment

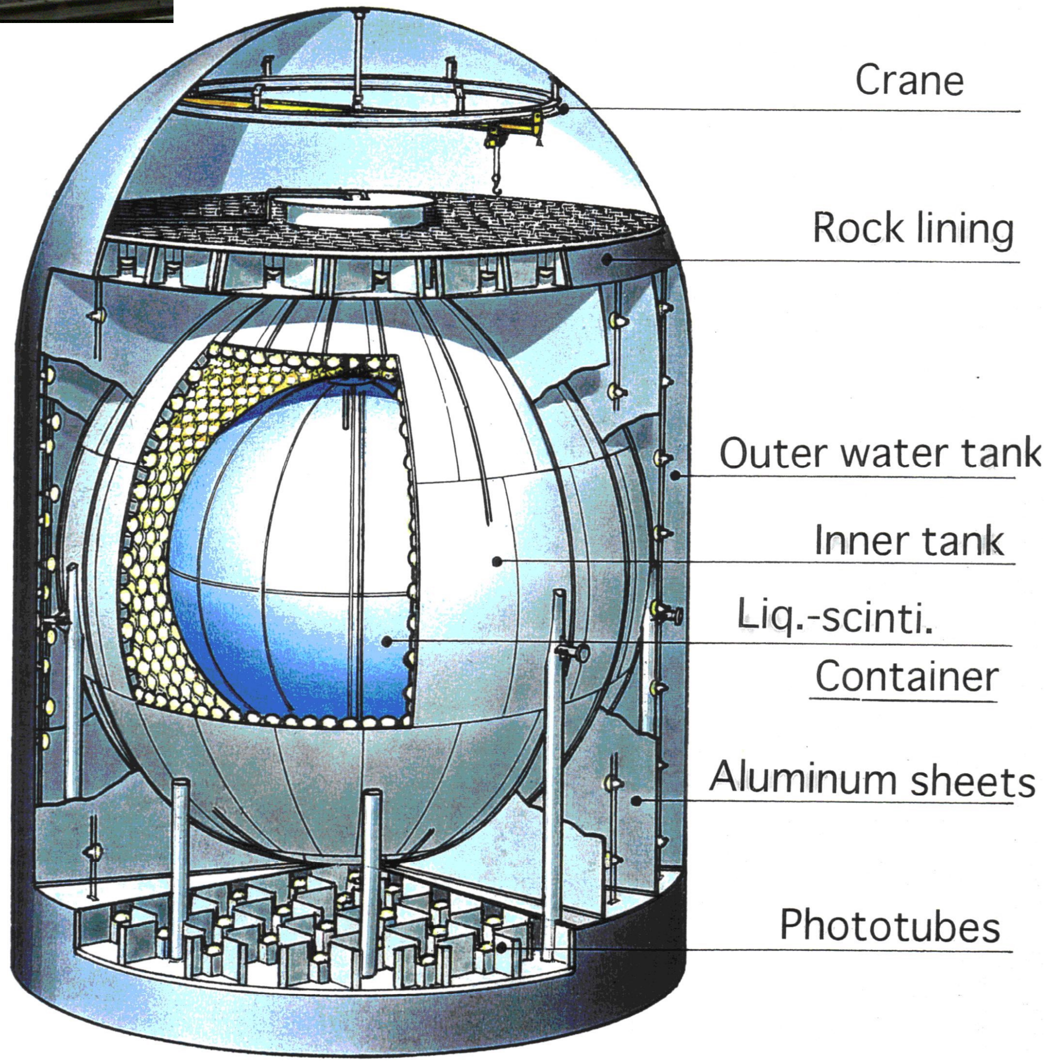
- In the Kamioka Observatory
- 1 kton of ultra-pure liquid scintillator
- 70 GW (7% of the entire world production) are produced 130-220 km around Kamioka
- 'Effective' L ~ 180 km
- The anti-neutrinos are detected through the inverse beta decay reaction:

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

$$e^+ + e^- \rightarrow 2\gamma$$ prompt

$$n + p \rightarrow d + \gamma \ \ (2.2 MeV)$$ delayed, ~ 200μs





KamLAND: expectations and results

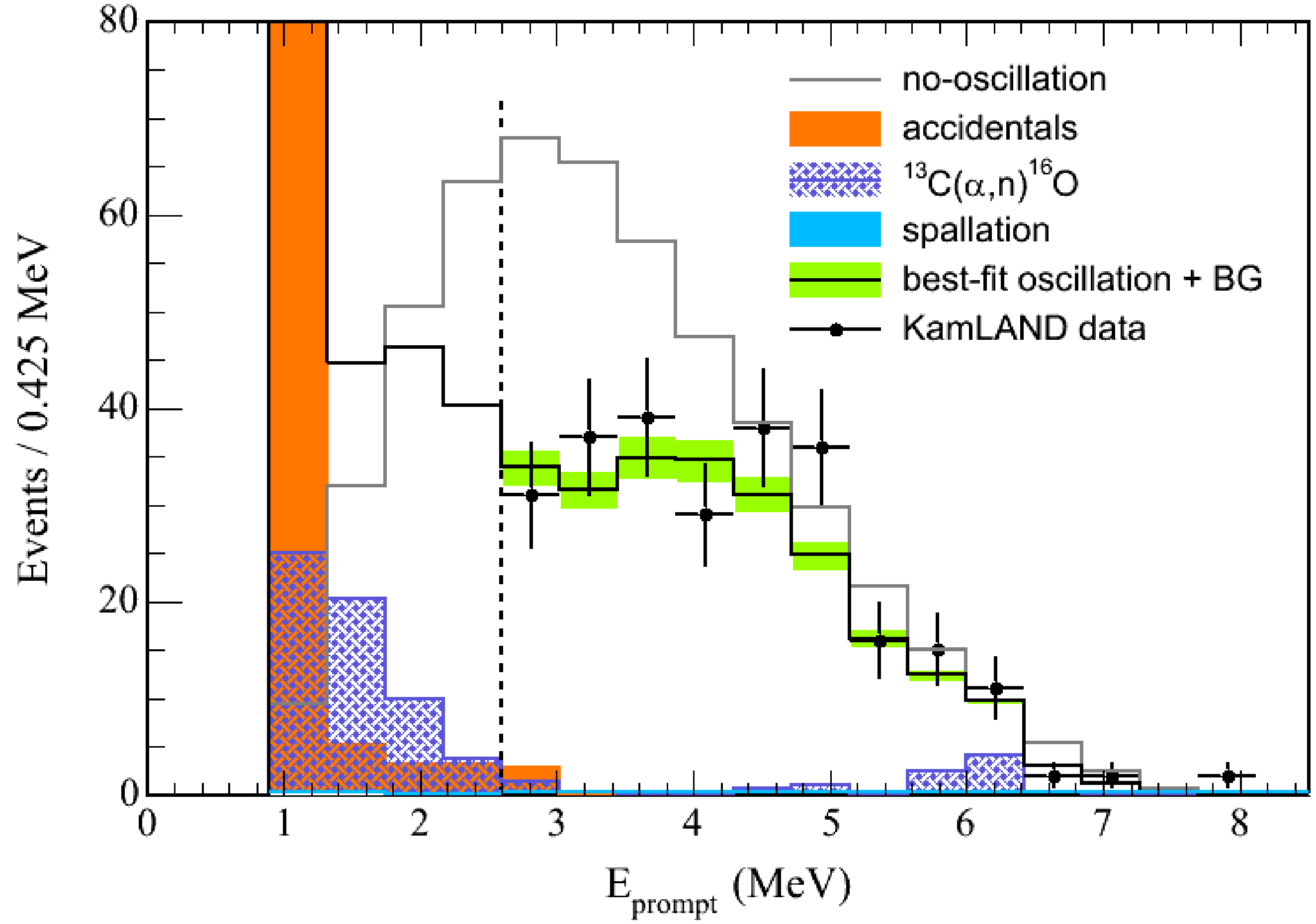
- Considering the maximum neutrino energy (8 MeV) and an analysis threshold for the prompt channel of 2.6 MeV, Δm^2 can be probed down to ~ 10^{-5} eV^2

- If the "LMA" is the solution to the solar neutrino problem, and assuming CPT invariance, KamLAND should observe a disappearance of reactor anti-neutrinos

- Expected number of events: 365.2 ± 23.7 in 515 live days

- Observed signal: 258 events

  => Neutrino 'disappearance', with R = 0.611 ± 0.085 ± 0.0041



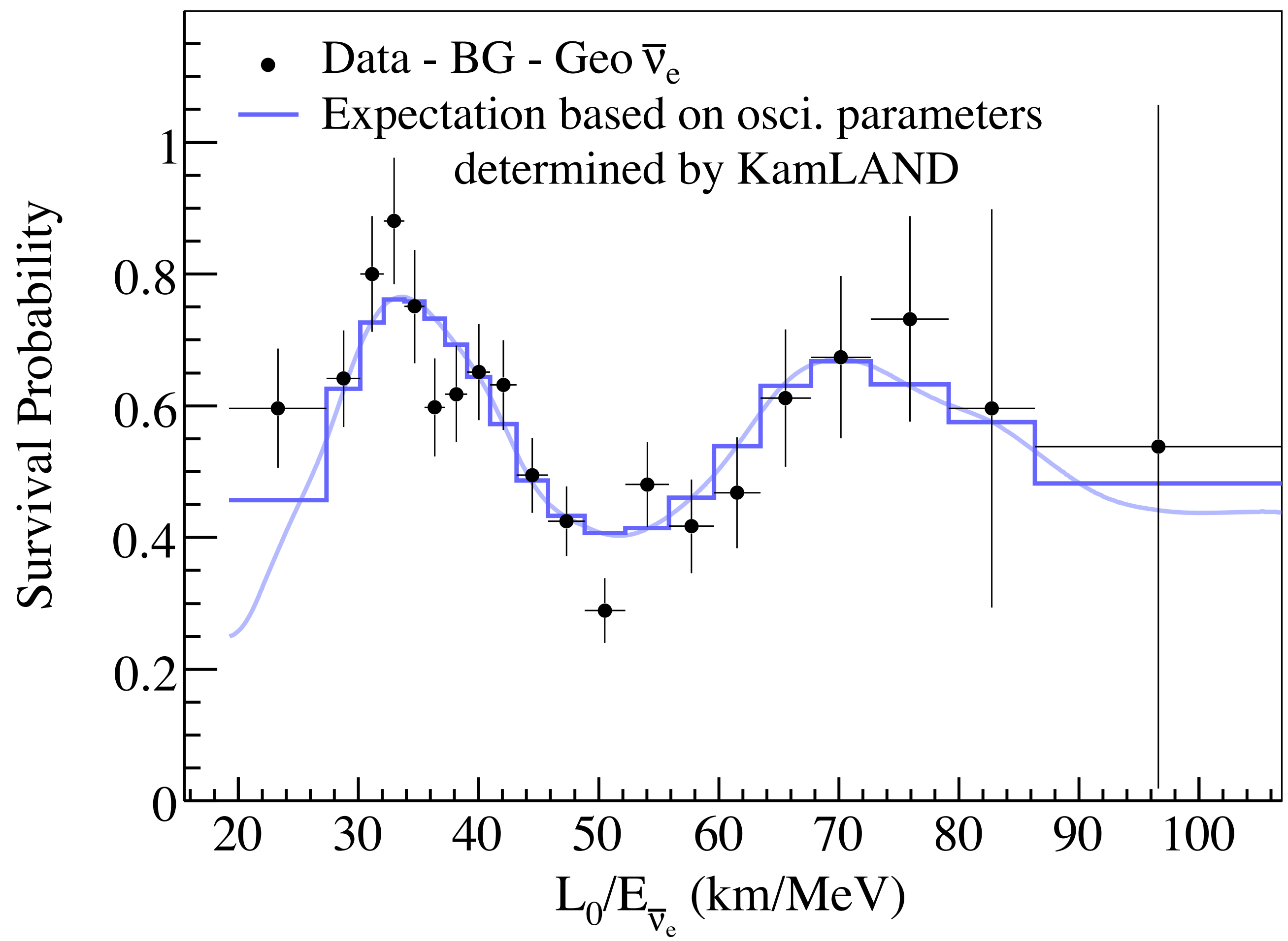
KamLAND Results

Observed survival probability $P(\bar{\nu}_e \rightarrow \bar{\nu}_e, L)$

-> since L is not known for each individual ν, L_0 = flux-weighted average distance

-> KamLAND observed not only the distortion of the anti-neutrino spectrum, but also the periodic feature of the anti-neutrino survival probability expected from neutrino oscillations

Ratio of the anti-neutrino spectrum to the predicted one without oscillations (survival probability) as a function of L_0/E, where L_0 = 180 km



Summary: what do we know so far?

- From experiments with terrestrial, atmospheric and solar neutrinos:

  ➡ evidence for flavor transitions and mixing of massive neutrinos

- From the oscillation results, we have two distinct mass scales:

$$\Delta m^2_{atm} \sim 2 \times 10^{-3} eV^2$$
$$\Delta m^2_{sol} \sim 8 \times 10^{-5} eV^2$$

  ➡ these define the relative masses, and two possible mass spectra

- Having three active neutrino flavors, and three mass eigenstates:

$$m_1, m_2, m_3$$

Summary: what do we know so far?

- we obtain two independent Δm^2:

$$\Delta m^2_{12} = m^2_2 - m^2_1$$

$$\Delta m^2_{23} = m^2_3 - m^2_2$$

$$\Delta m^2_{13} = m^2_3 - m^2_1 = \Delta m^2_{23} + \Delta m^2_{12}$$

- The mixing matrix is:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- and we define $\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}$; $\tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}$; $U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$

Global interpretation of results

- From the discussed experiments we know:
  - ➡ the mass squared differences are hierarchical
  - ➡ one mixing angle is small
- **the two puzzles decouple, and we can interpret the results as follows:**

Solar neutrinos determine	$\Delta m_{12}^2 = \Delta m_{sol}^2$	θ_{12}
Atmospheric ν's determine	$\Delta m_{23}^2 = \Delta m_{atm}^2$	θ_{23}

➡ since θ_{13} is small, we know that $|\Delta m_{13}^2|$ - effects are small for solar neutrinos

➡ since $|\Delta m_{12}^2| << |\Delta m_{23}^2|$, we know that $|\Delta m_{12}^2|$ - effects are small for atmospheric and accelerator neutrinos

- **Question**: what is the ν-mass hierarchy? We have two possibilities:

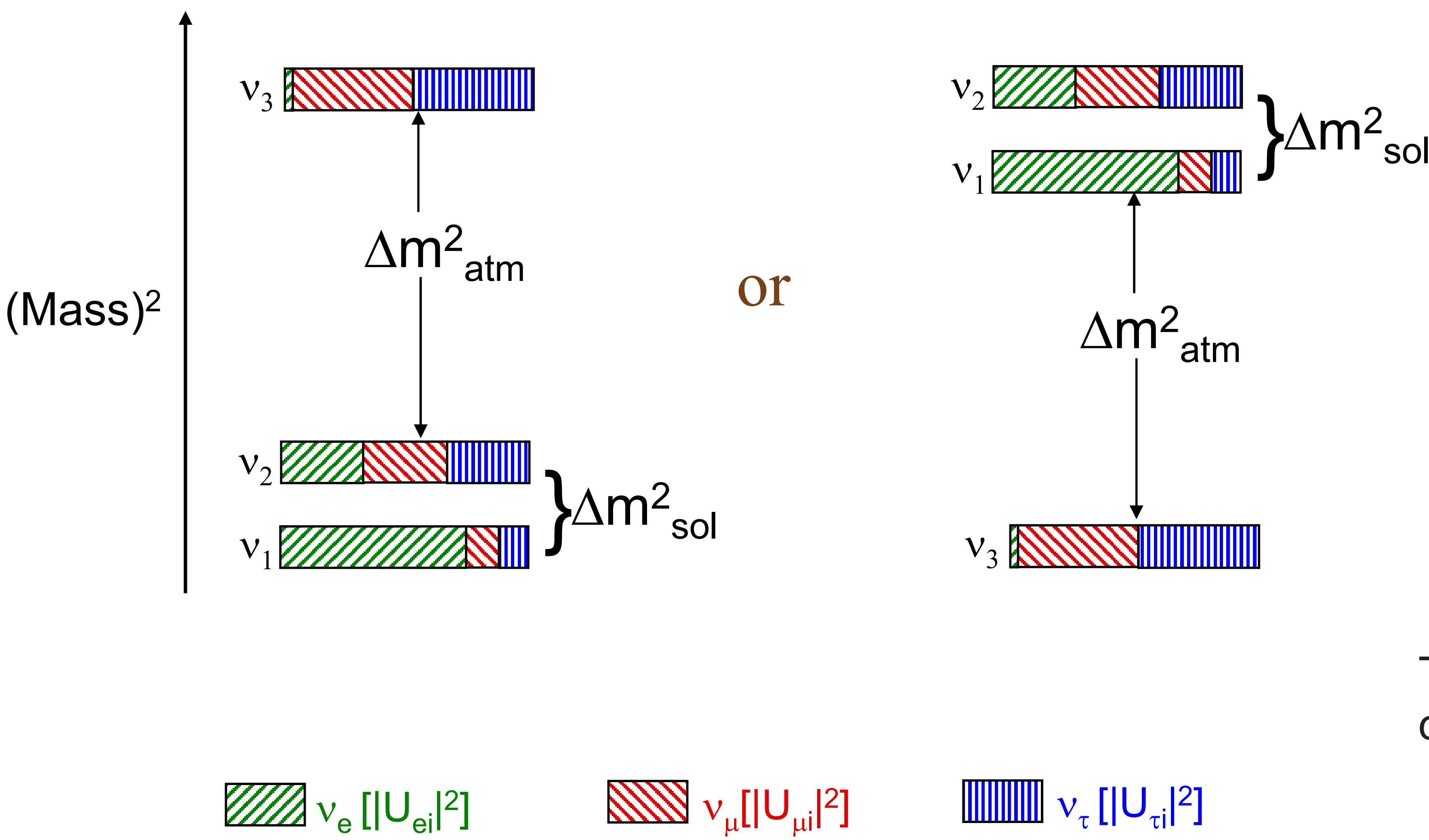
Global interpretation of results

Normal hierarchy

$$m(\nu_1) < m(\nu_2) \ll m(\nu_3)$$

Inverted hierarchy

$$m(\nu_3) \ll m(\nu_1) < m(\nu_2)$$



The mass of the heaviest state can not be smaller than:

$$m \geq \sqrt{\Delta m^2_{atm}} \simeq 45\ meV$$

$$\Delta m^2_{atm} \quad 2 \times 10^{-3}\, eV^2$$

$$\Delta m^2_{sol} \quad 8 \times 10^{-5}\, eV^2$$

Global interpretation of results

- In the case of 3 neutrino mixing, one of the two independent neutrino mass squared differences is thus much smaller in value than the second one $\left|\Delta m_{12}^2\right| \ll \left|\Delta m_{13}^2\right|$
- with $\dfrac{\left|\Delta m_{12}^2\right|}{\left|\Delta m_{13}^2\right|} \cong 0.032$
- Neglecting now effect due to Δm_{12}^2 we get for the survival probability of electron (anti-)neutrinos:

$$P(\nu_e \to \nu_e) = P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - 2\left|U_{e3}\right|^2 \left(1 - \left|U_{e3}\right|^2\right)\left(1 - \cos\frac{\Delta m_{13}^2}{4E} L\right)$$

- this means that $\sin\theta_{13} = |U_{e3}|$ can be directly measured, for instance in a reactor neutrino experiment with a long baseline (L ~ 1000 km) - since at this distance the reactor anti-neutrino oscillations driven by Δm_{sol}^2 are negligible
- One reactor experiment (CHOOZ) found no evidence for anti-neutrino disappearance so far, with an upper limit of:

$$\sin^2 2\theta_{13} < 0.19$$

Global interpretation of results

- The θ_{13} mixing angle can also be measured in accelerator neutrino oscillation experiments with conventional neutrino beams, using $\nu_\mu \rightarrow \nu_e$ appearance.

- For instance, the K2K experiment searched for the $\nu_\mu \rightarrow \nu_e$ appearance signal, but no evidence was found. Using only the dominant term in the probability of $\nu_\mu \rightarrow \nu_e$ appearance:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right) \sim \frac{1}{2}\sin^2 2\theta_{13} \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

- they set an upper limit of

$$\sin^2 2\theta_{13} < 0.26$$

- at the K2K measurement of $\Delta m^2 = 2.8 \times 10^{-3} eV^2$

- Even though this is less significant than the CHOOZ limit, it is the first result obtained from an accelerator ν_e appearance experiment (T2K should be able to improve upon this)

How about the mixing angles?

- The Pontecorvo-Maki-Nakagawa-Sakata-Matrix can be parameterized as:

δ_{CP}, α_1, α_2 : CP-violating phases
α_1, α_2 : only for Majorana neutrinos

$$U_{MNSP} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

$\alpha_1/2$ $\alpha_2/2$

Data from atmospheric ν's and accelerators
$\theta_{23} \approx 45$ deg
$\theta_{23} \approx \pi/4$

Future data from reactors and accelerators
$\theta_{13} = ?$
$\theta_{13} < \pi/13$

Data from solar and reactor neutrinos
$\theta_{12} \approx 34$ deg
$\theta_{12} \approx \pi/5.4$

Double beta decay

- The size of CP violation effects depends on the magnitude of the currently unknown, small value of θ_{13} and on the Dirac phase δ_{CP}:

$$J_{CP} \cong \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta_{CP}$$

End