

# **Rozdział 6**

**Oscylacje neutrin słonecznych  
i atmosferycznych.**

**Eksperymenty Superkamiokande,  
SNO i inne.**

**Macierz mieszania Maki-Nakagawy-  
Sakaty (MNS)**

# Kilka interesujących faktów

Każdy człowiek wysyła dziennie około 340 milionów neutrin (z rozpadu  $^{40}\text{K}$ )

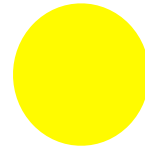
W każdym  $\text{cm}^3$  wszechświata znajduje się około 330 neutrin reliktowych (z Wielkiego Wybuchu)

Każdy  $\text{cm}^2$  powierzchni ziemi wysyła około 6 milionów neutrin na sekundę

Na każdy  $\text{cm}^2$  powierzchni ziemi pada w ciągu sekundy około 70 miliardów neutrin ze Słońca

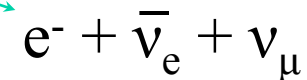
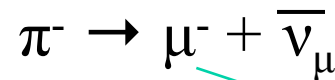
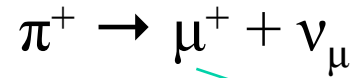
Standardowa elektrownia jądrowa wysyła w ciągu sekundy około  $5 \cdot 10^{20}$  neutrin

# 1. Neutrina słoneczne



$\nu_e$

# 2. Neutrina atmosferyczne



# 3. Neutrina z akceleratorów

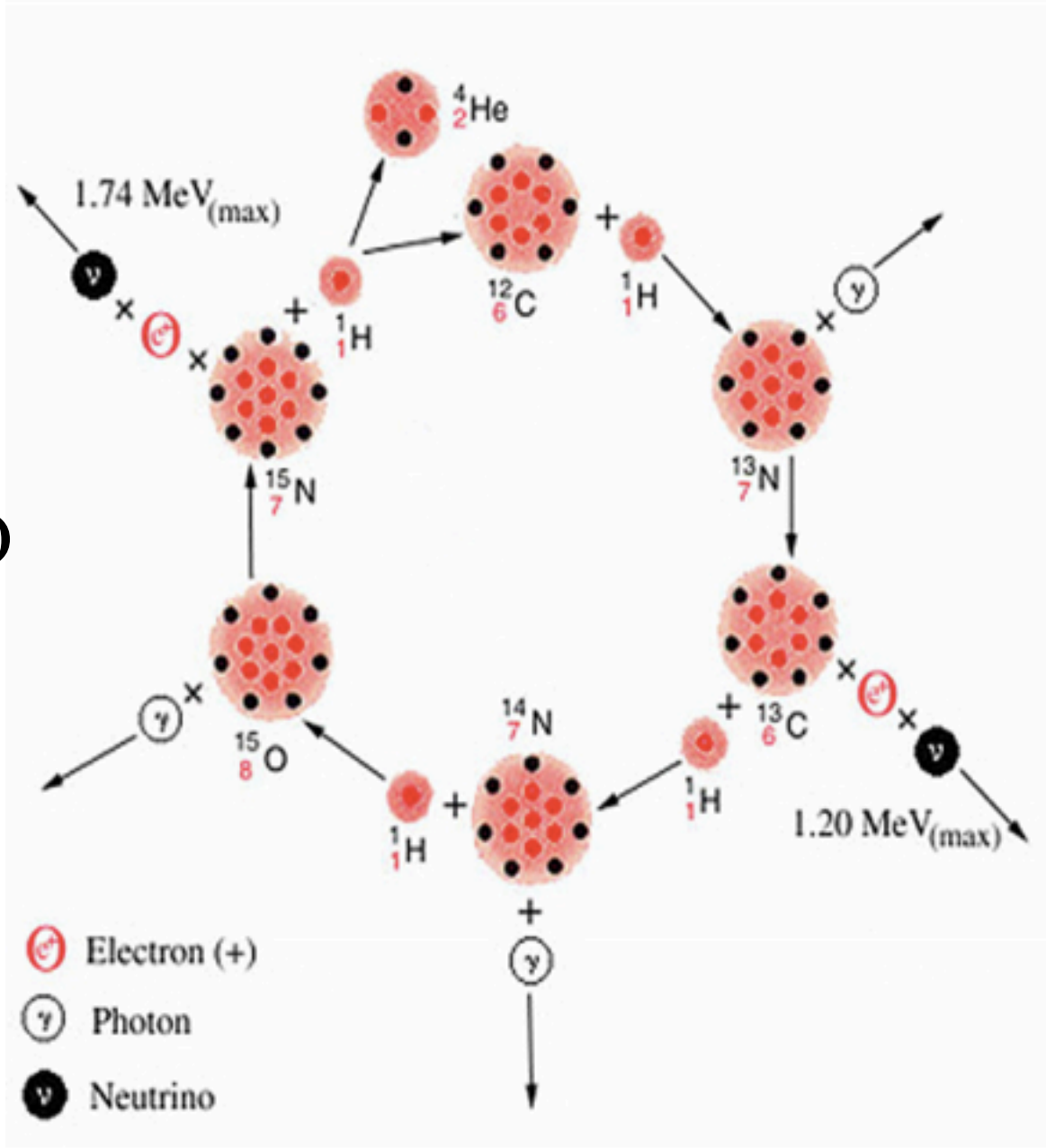
$\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$

# 4. Neutrina z reaktorów

$\bar{\nu}_e$

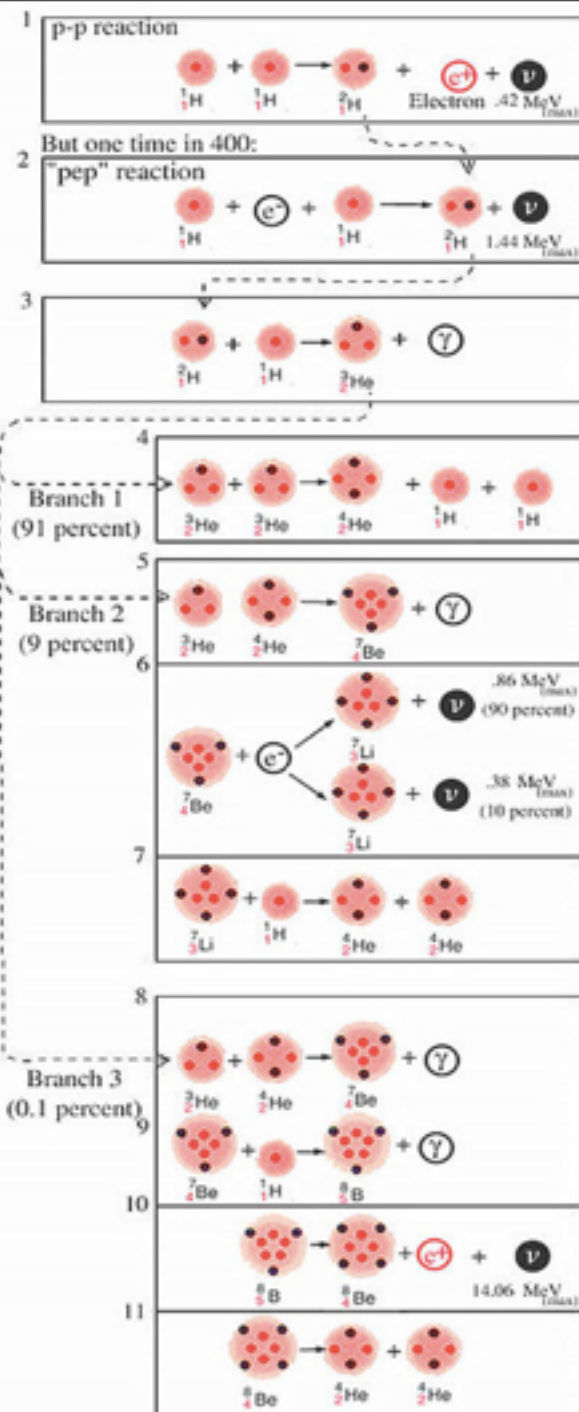
# 5. Neutrina z wybuchów Supernowych (SN 1987A)

# Neutrina słoneczne



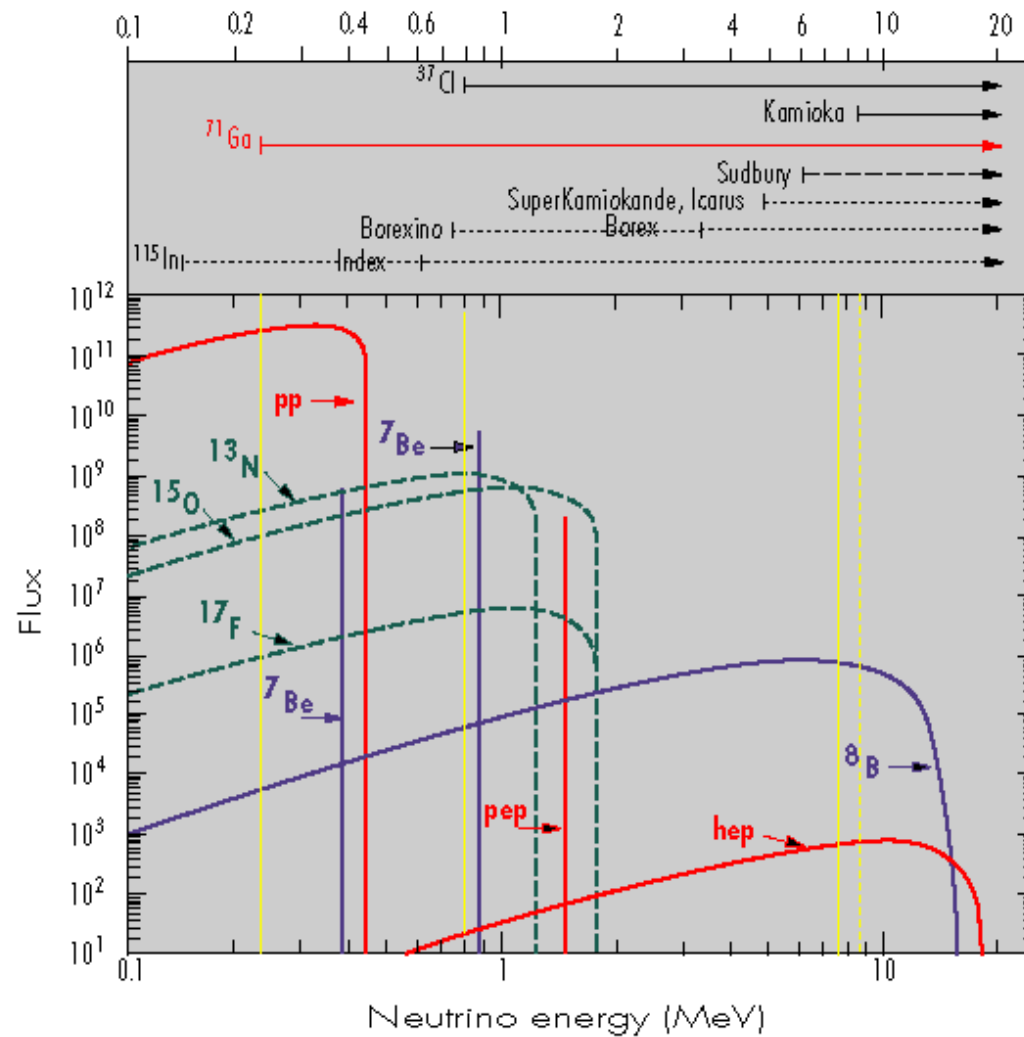
Cykl CNO

# Neutrino słoneczne

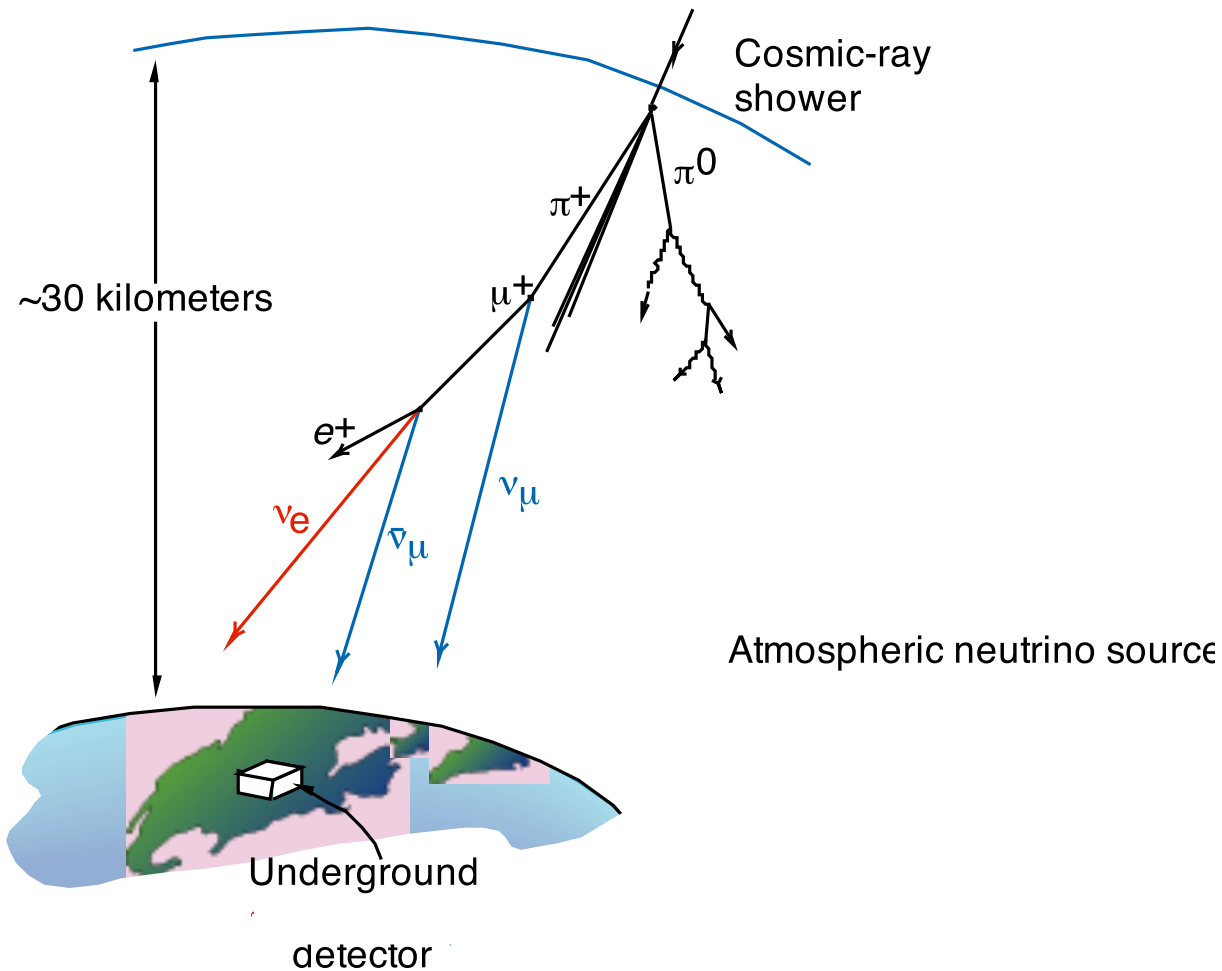


## Cykl p-p

# Widmo energii neutrin słonecznych

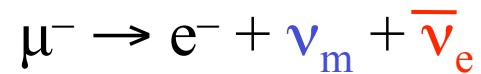
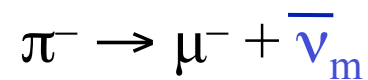
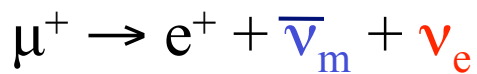
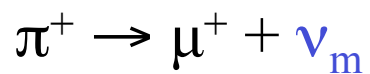


# Neutrina atmosferyczne

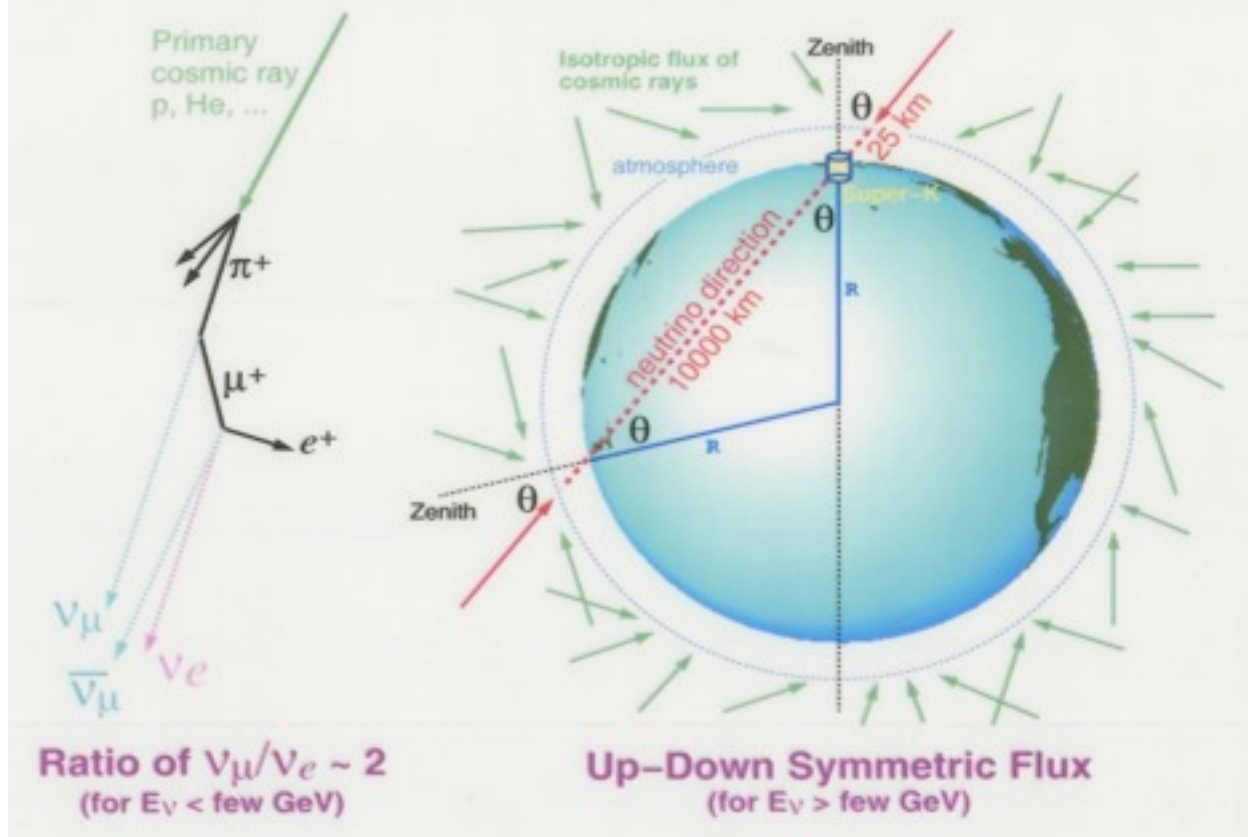


Obserwacje

$$\frac{\nu_\mu}{\nu_e} \neq 2$$



# ATMOSPHERIC NEUTRINOS



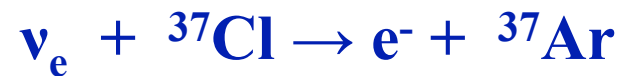


# Homestake



Raymond Davis  
(zbieranie danych 1968-1995)

zbiornik 680 000 litrów  $C_2Cl_4$   
(na głębokości 1500 m)



(próg 0,814 MeV)

Jednostka strumienia neutrin słonecznych na Ziemi  
SNU (Solar Neutrino Unit) = 1 wychwyty na s na  $10^{36}$  atomów tarczy

# Eksperymenty z galem



SAGE (Soviet-American Gallium Experiment)  
50 ton ciekłego galu

GALLEX (Gallium Experiment) 1992-1997  
(od 1998 r. GNO – Gallium Neutrino Observatory)

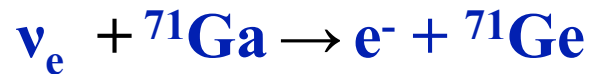
GaCl<sub>3</sub> w Gran Sasso

# Wyniki eksperymentów radiochemicznych

Homestake



$2,56 \pm 0,23$  SNU (SSM:  $8,1 \pm 1,3$ )



GALLEX

$77,5 \pm 6,2 \pm 4,5$  SNU (SSM:  $126 \pm 10$ )

GNO

$62,9 \pm 5,5 \pm 2,5$

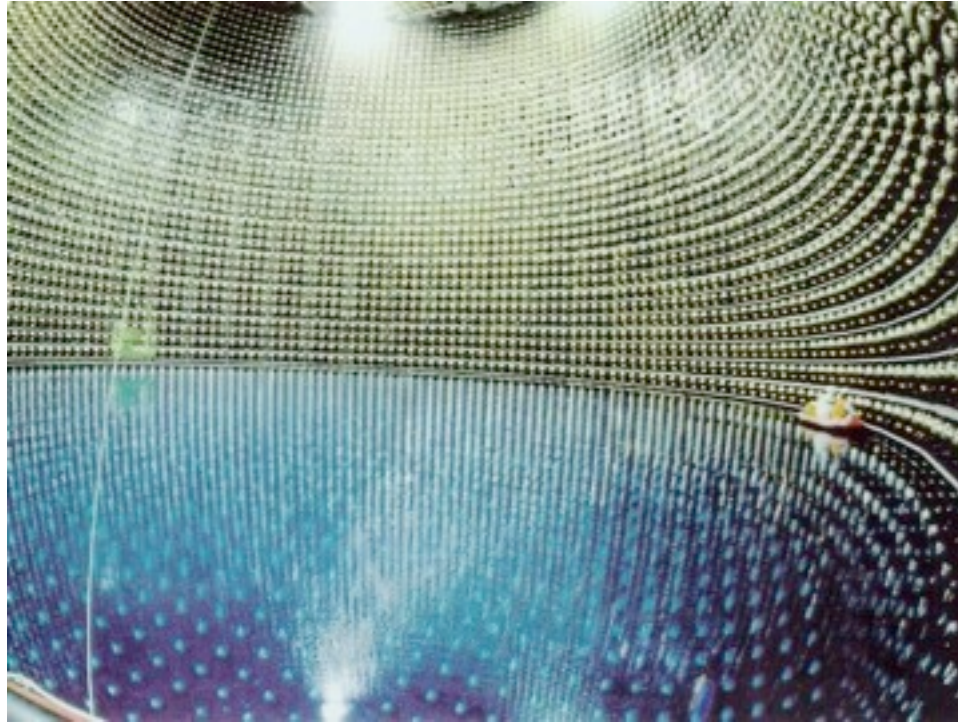
GNO + GALLEX

$69,3 \pm 4,1 \pm 3,6$

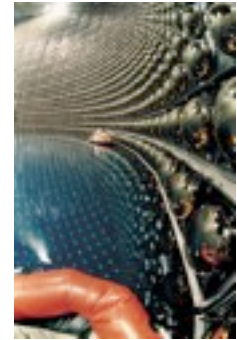
SAGE

$70,8 \pm 5,3 \pm 3,7$

# Superkamiokande



(Kamiokande od 1987 r.)



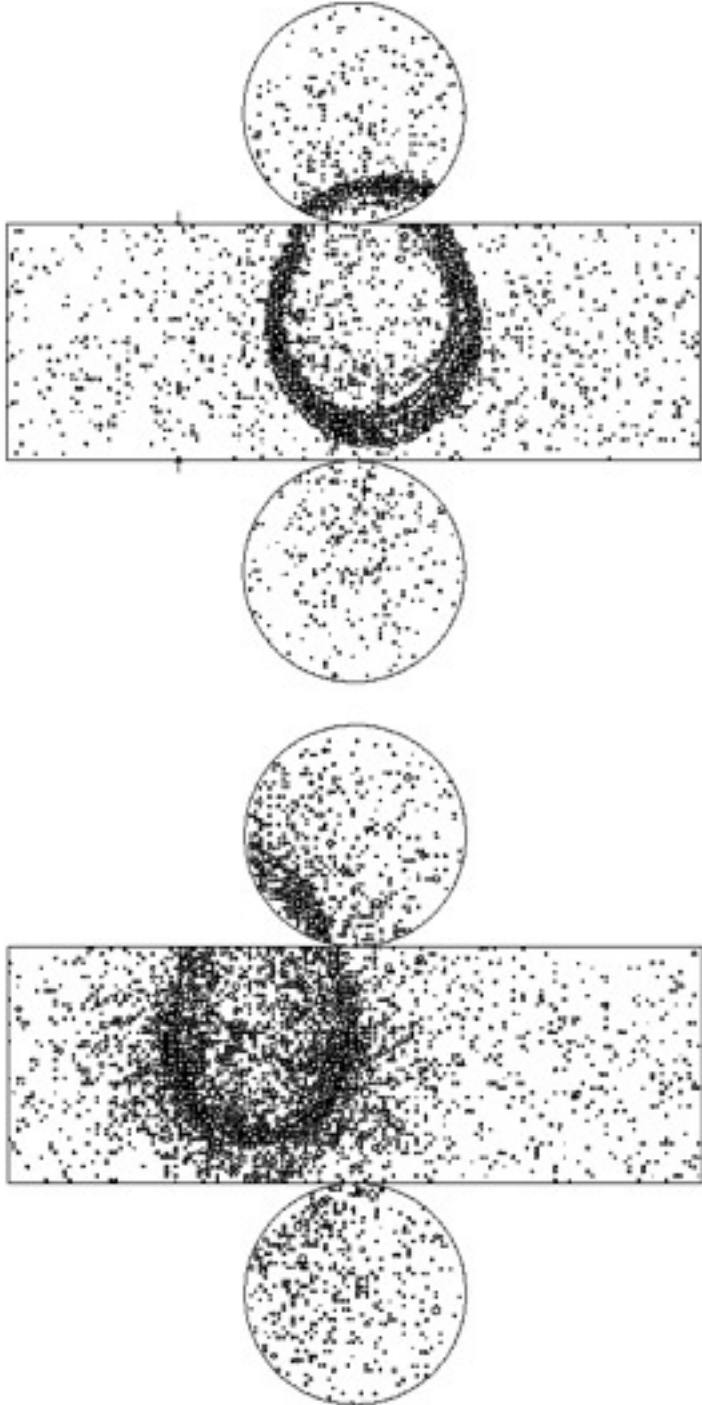
**Głównie**



próg ok. 5 MeV

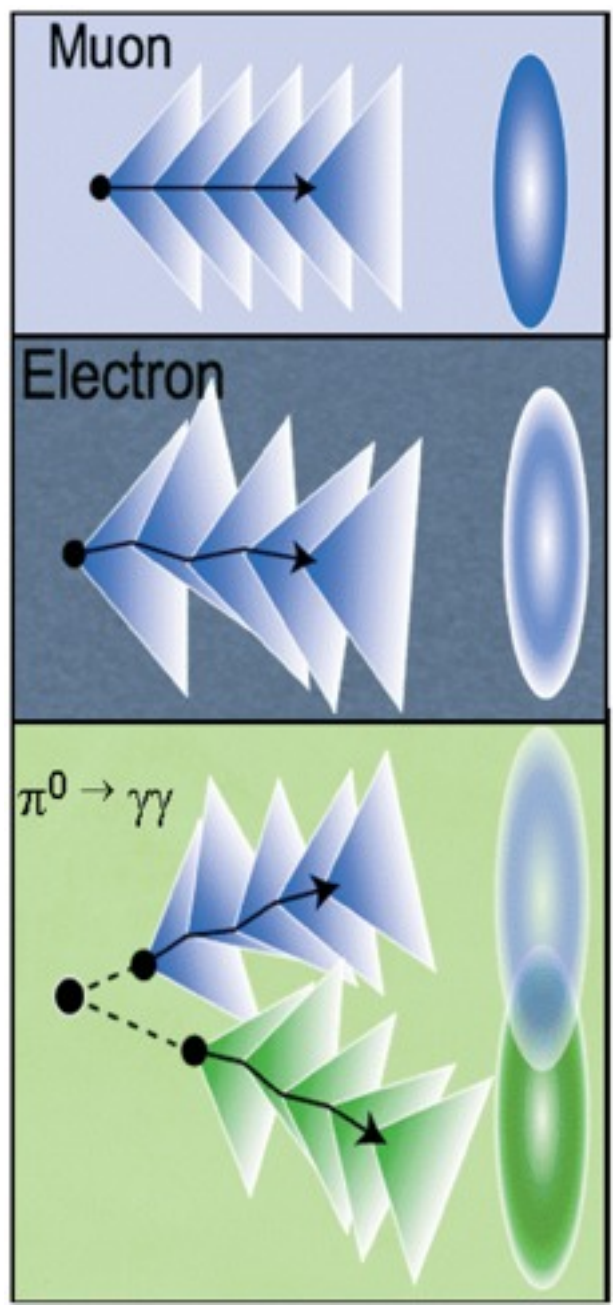
$$s(\nu_{\mu\tau} + e^- \rightarrow \nu_{\mu\tau} + e^-) \cong 0,15 \sigma(\nu_e + e^- \rightarrow \nu_e + e^-)$$

50 000 litrów ultraczystej wody, 11146 fotopowielaczy na ścianach



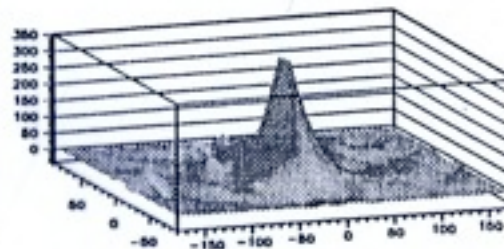
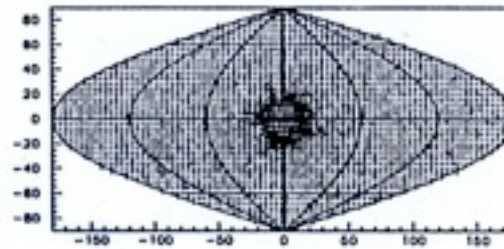
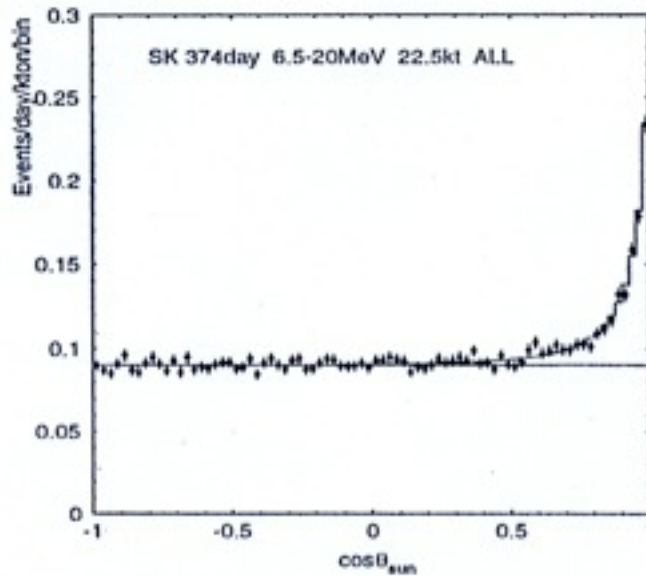
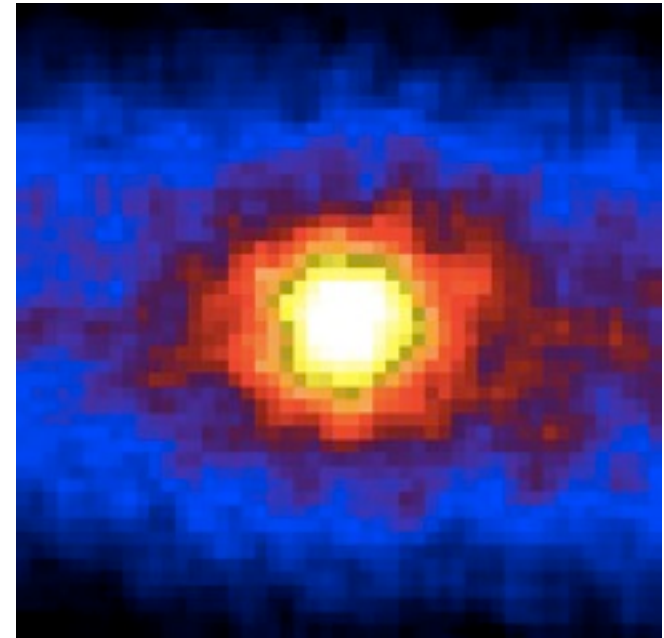
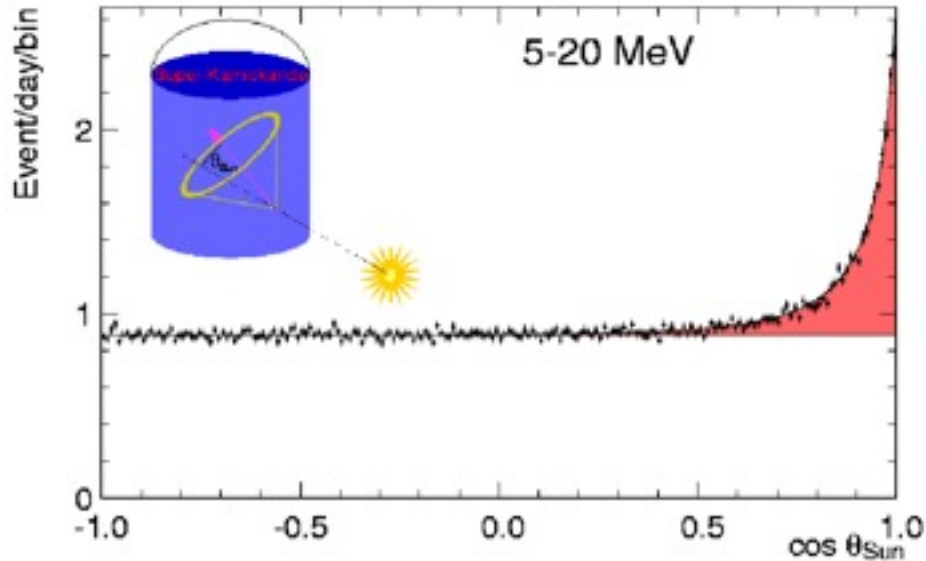
$\mu$ -like

e-like

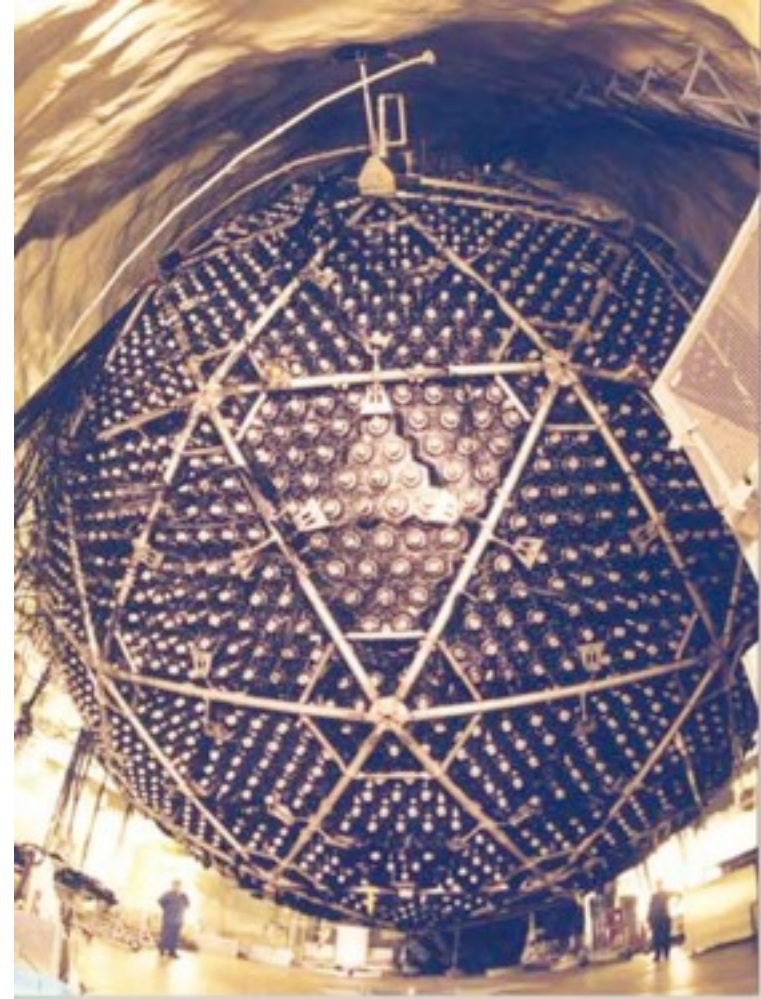
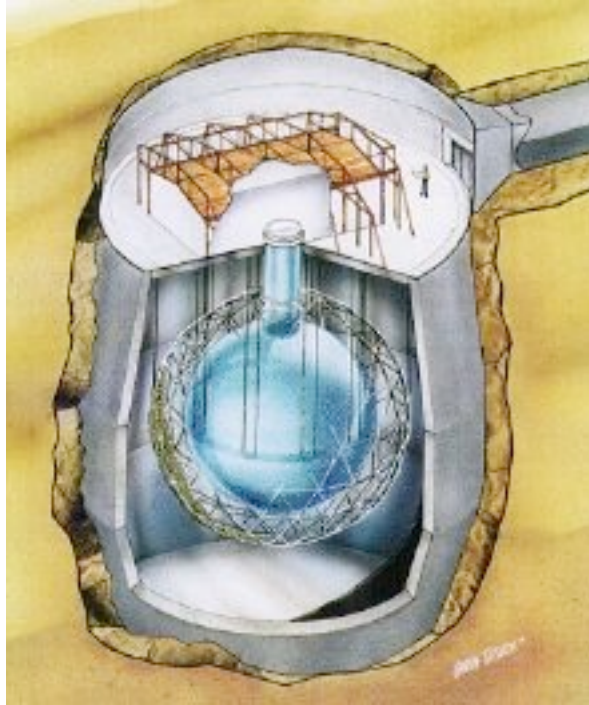




# Neutrina słoneczne w Superkamiokande



# Solar Neutrino Observatory (Sudbury)



1000 ton ciężkiej wody  
7000 ton zwykłej wody  
9456 fotopowielaczy

# Solar $\nu$ Interactions in SNO

## Elastic Scattering (ES) $\nu_x + e^- \rightarrow \nu_x + e^-$

- Directional sensitivity ( $e^-$  forward peaked)
- Cross-section for  $\nu_e$  is  $6.5 \times$  larger than for  $\nu_{\mu\tau}$

## Charged Current (CC) $\nu_e + d \rightarrow p + p + e^-$

- Some directional information ( $1 - \frac{1}{3} \cos \theta_{e\nu}$ )
- good  $E_\nu$  sensitivity ( $\nu_e$  spectrum)

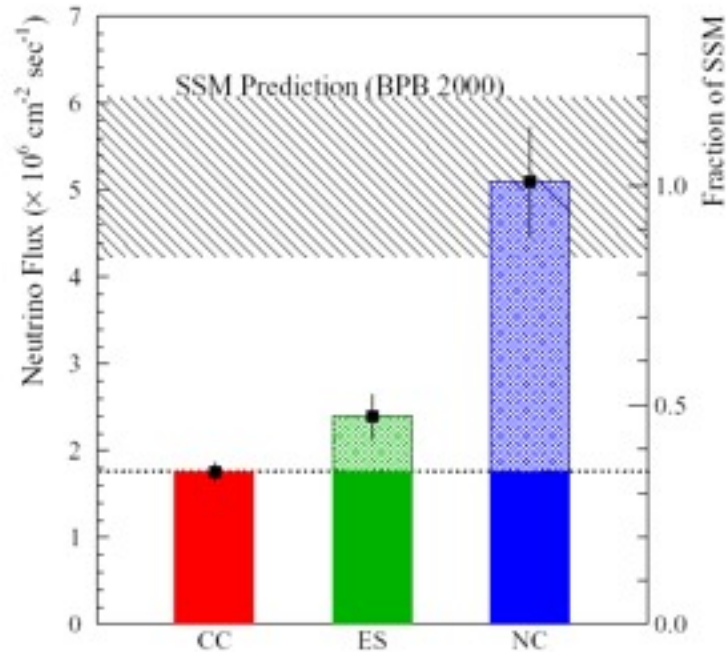
## Neutral Current (NC) $\nu_x + d \rightarrow n + p + \nu_x$

- Total flux of active neutrinos above 2.2 MeV
- Detect neutrons by  $n + d \rightarrow t + 6.25 \text{ MeV } \gamma$



## Measured SNO Fluxes

Assuming  $^8\text{B}$  energy spectrum ...



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

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

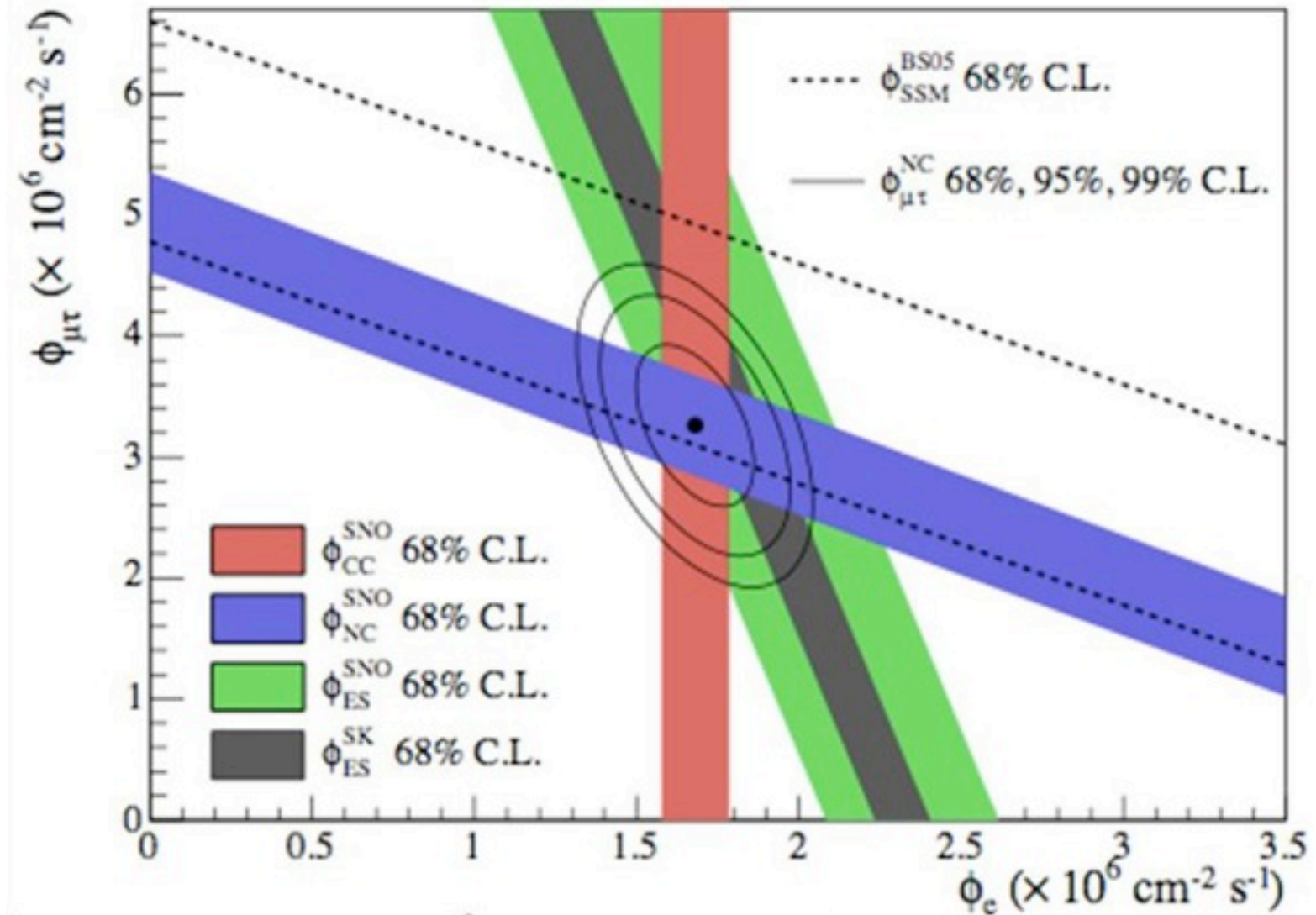
$$\phi_{ES} = 2.39^{+0.24}_{-0.23} \text{ (stat.)} \pm 0.12 \text{ (sys.)}$$

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

$$\phi_{CC} < \phi_{ES} < \phi_{NC}$$

NC flux in agreement with SSM prediction!

# Wyniki Solar Neutrino Observatory



Aphelion



2005-07-05  
152.10 million km  
31.46 arc-mins  
Altitude @ 73.87°

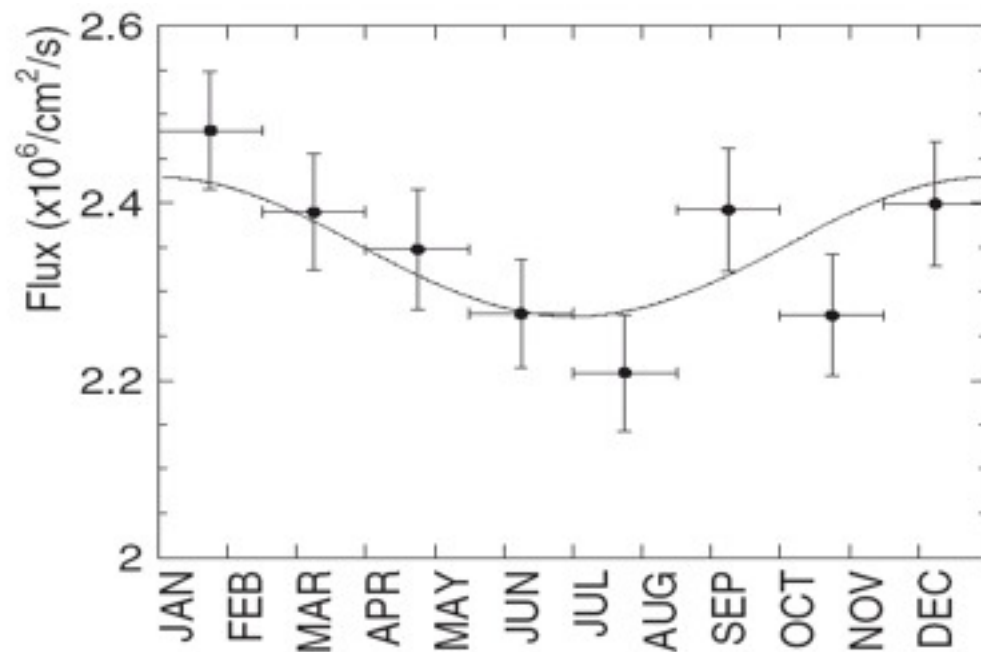
Perihelion



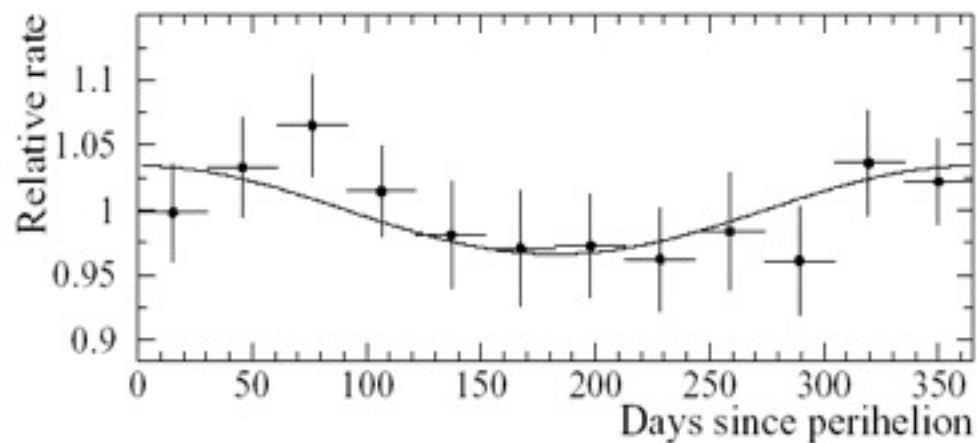
2005-01-02  
147.10 million km  
32.53 arc-mins  
Altitude @ 28.84°

# Zmiany strumienia neutrin spowodowane eliptycznością orbity Ziemi

SuperKamiokande



Solar Neutrino Observatory

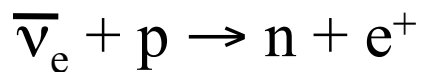


# Eksperymenty akceleratorowe i reaktorowe

Produkcja wiązki neutrin mionowych przez rozpady  $\pi \rightarrow \mu \rightarrow \nu$

„*disappearance experiments*” detekcja  $\nu_{\mu}$   
„*appearance experiments*” detekcja  $\nu_e, \nu_{\tau}$  } w różnych odległościach

Detekcja  $\bar{\nu}_e$  w różnych odległościach od reaktora (reaktorów)



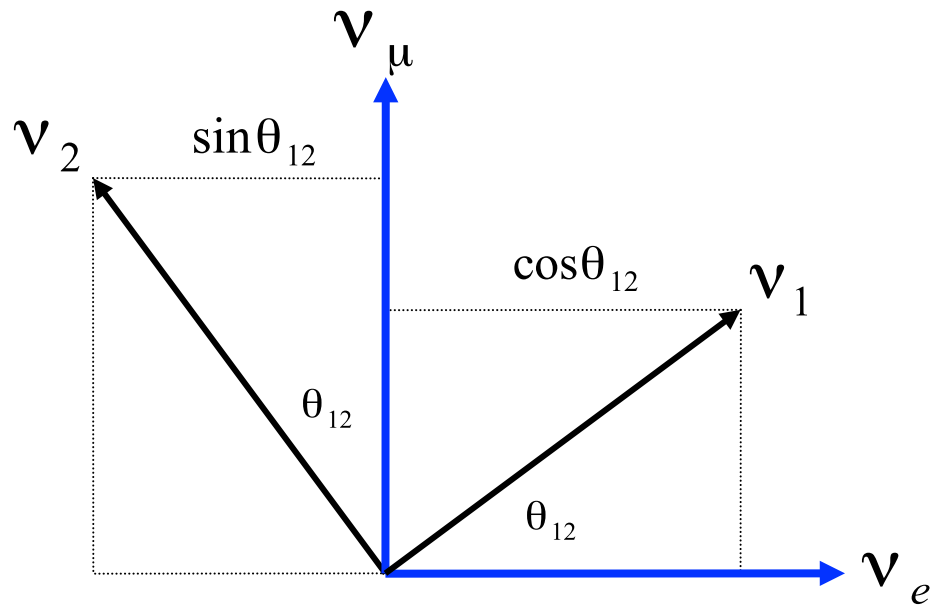
„*disappearance experiments*”

**Table 13.1:** Sensitivity of different oscillation experiments.

Source	Type of $\nu$	$\bar{E}$ [MeV]	$L$ [km]	$\min(\Delta m^2)$ [eV <sup>2</sup> ]
Reactor	$\bar{\nu}_e$	$\sim 1$	1	$\sim 10^{-3}$
Reactor	$\bar{\nu}_e$	$\sim 1$	100	$\sim 10^{-5}$
Accelerator	$\nu_\mu, \bar{\nu}_\mu$	$\sim 10^3$	1	$\sim 1$
Accelerator	$\nu_\mu, \bar{\nu}_\mu$	$\sim 10^3$	1000	$\sim 10^{-3}$
Atmospheric $\nu$ 's	$\nu_{\mu,e}, \bar{\nu}_{\mu,e}$	$\sim 10^3$	$10^4$	$\sim 10^{-4}$
Sun	$\nu_e$	$\sim 1$	$1.5 \times 10^8$	$\sim 10^{11}$

PDG 2010

# Mieszanie 2 neutrin



$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} \\ -\sin\theta_{12} & \cos\theta_{12} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$|v_{\mu}(0)\rangle = |v_m\rangle = -\sin\theta |v_1\rangle + \cos\theta |v_2\rangle$$

$$|v_{\mu}(t)\rangle = -\sin\theta \exp(-i(E_1/\hbar)t) |v_1\rangle \\ + \cos\theta \exp(-i(E_2/\hbar)t) |v_2\rangle$$

$$[\hbar = c = 1] \quad E = (p^2 + m^2)^{1/2} \approx p + m^2/2p, \\ \Delta m^2 = m_1^2 - m_2^2, \quad t = L/c$$

$$|v_{\mu}(t)\rangle = \exp[-i t (p + m_1^2/2E_v)] \times \\ \times [-\sin\theta |v_1\rangle + \cos\theta |v_2\rangle \exp(i \Delta m^2 t/2E_v)]$$

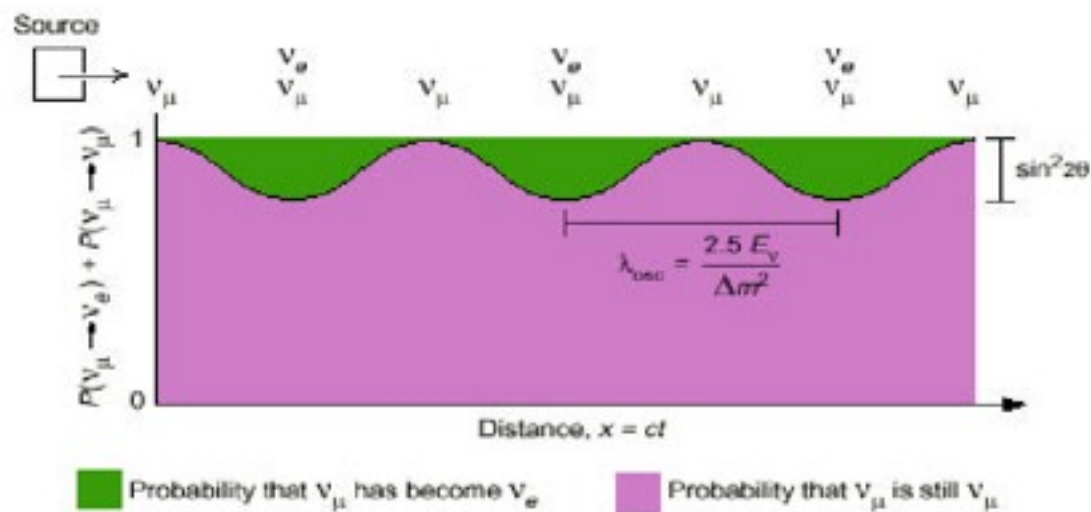
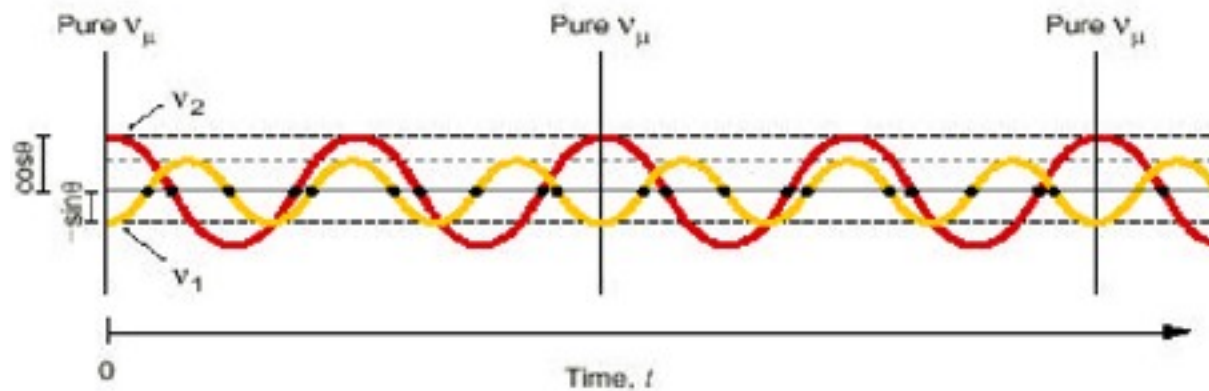


$$\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) &= |\cos \theta \sin \theta (1 - \exp(i \Delta m^2 t / 2E_\nu))|^2 = \\
&= \sin^2 2\theta \sin^2(\Delta m^2 L / 4E_\nu) = \\
&= \sin^2 2\theta \sin^2(1,27 \Delta m^2 L / E_\nu) = \\
&= \sin^2 2\theta \sin^2(p L / l_{\text{osc}})
\end{aligned}$$

$$\lambda_{\text{osc}} = \pi E_\nu / 1,27 \Delta m^2 \approx 2,5 E_\nu / \Delta m^2$$

[współczynnik 1,27 jeśli  $\Delta m^2$  w  $(\text{eV})^2$ ,  $L$  w m (**km**),  $E_n$  w MeV (**GeV**),  $\hbar c = 197 \text{ MeV fm}$ ]

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1,27 \Delta m^2 L / E_\nu)$$



# Mieszanie 3 neutrin

$$\begin{pmatrix} \mathbf{v}_e \\ \mathbf{v}_\mu \\ \mathbf{v}_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \mathbf{v}_1 \\ \mathbf{v}_2 \\ \mathbf{v}_3 \end{pmatrix}$$

$$U_{12} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = U_{12}U_{13}U_{23}$$

$$U_{13} = \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} \\ 0 & 1 & 0 \\ -\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}$$

Macierz **Maki-Nakagawy-Sakaty**

$$U_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

[W bardziej ogólnej postaci jeszcze jeden parametr: faza – jak w macierzy CKM]

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{j>i} U_{\alpha i} U_{\beta i} U_{\alpha i}^* U_{\beta i}^* \sin^2(\pi x / \lambda_{ij})$$

$$\lambda_{ij} = \pi E_\nu / 1,27 \Delta m_{ij}^2 \approx 2,5 E_\nu / \Delta m_{ij}^2$$

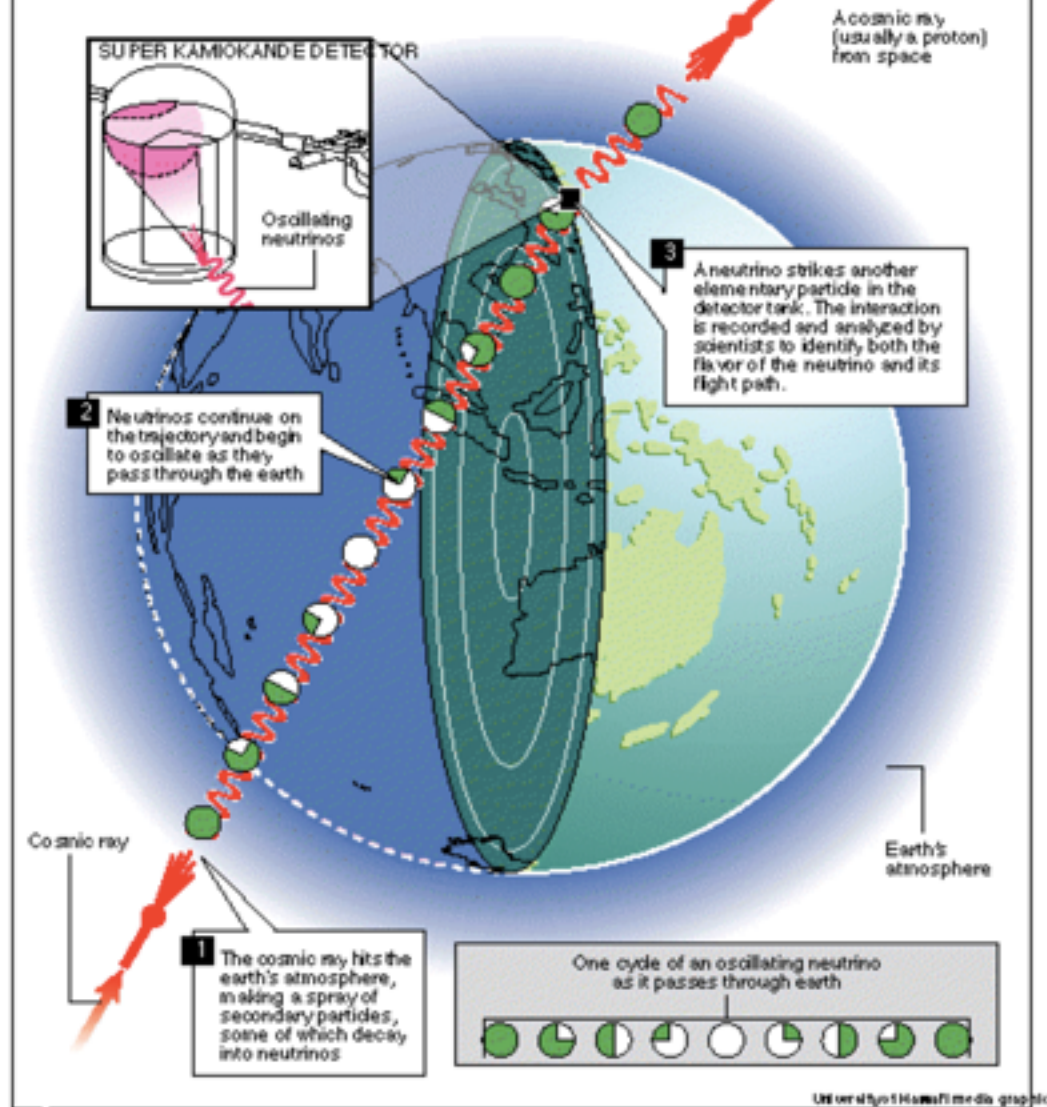
$$P(\nu_\mu \rightarrow \nu_\mu) = 4 U_{e1} U_{\mu1} U_{e2} U_{\mu2} \sin^2(\pi L / \lambda_{12}) +$$

$$+ 4 U_{e1} U_{\mu1} U_{e3} U_{\mu3} \sin^2(\pi L / \lambda_{13}) +$$

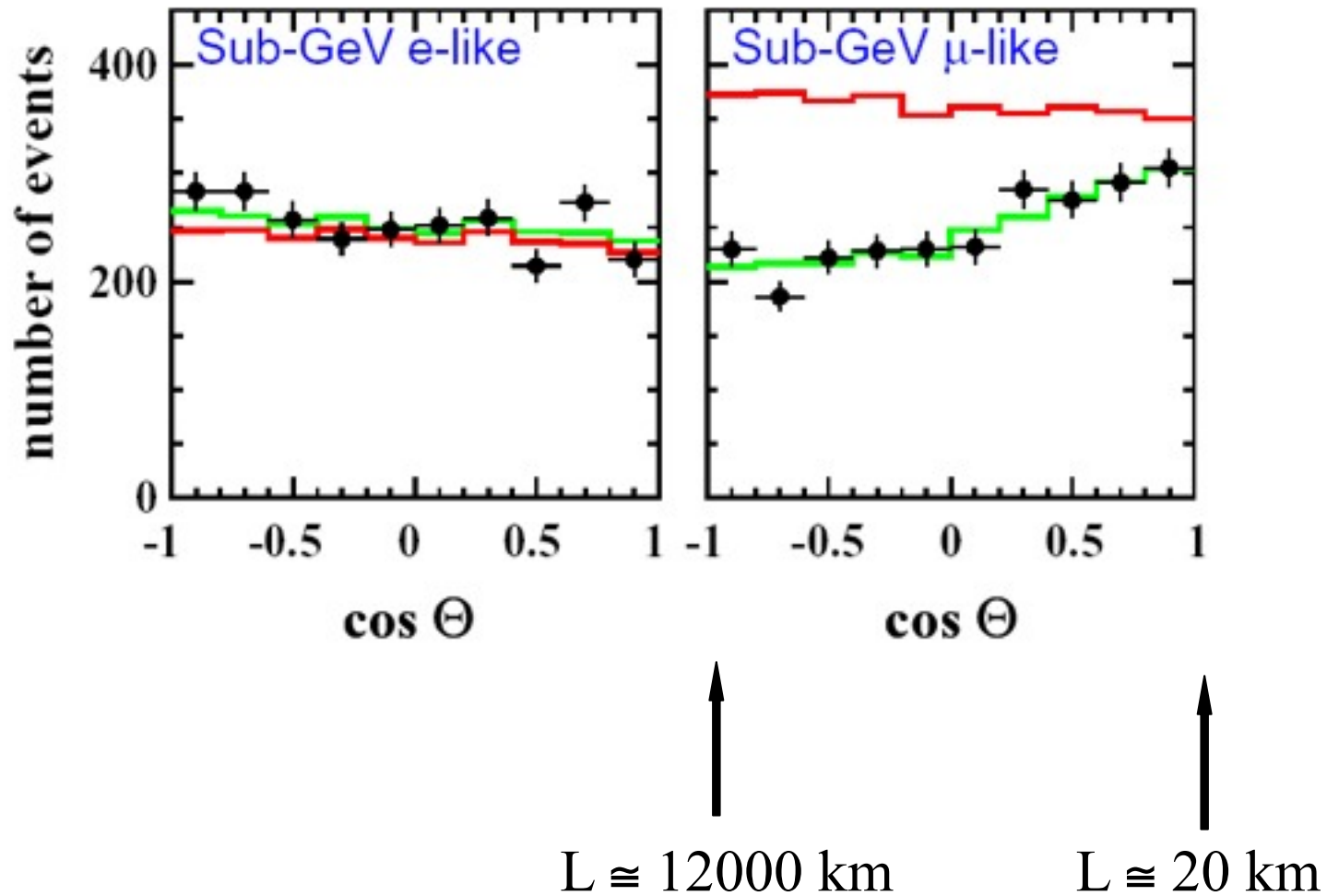
$$+ 4 U_{e2} U_{\mu2} U_{e3} U_{\mu3} \sin^2(\pi L / \lambda_{23})$$

## Discovering Mass

The farther neutrinos travel, the more time they have to oscillate. By comparing the ratio of flavors of neutrinos coming "up" through the Earth to those coming from overhead, physicists determined that neutrinos oscillate, which neutrinos can only do if they have mass.

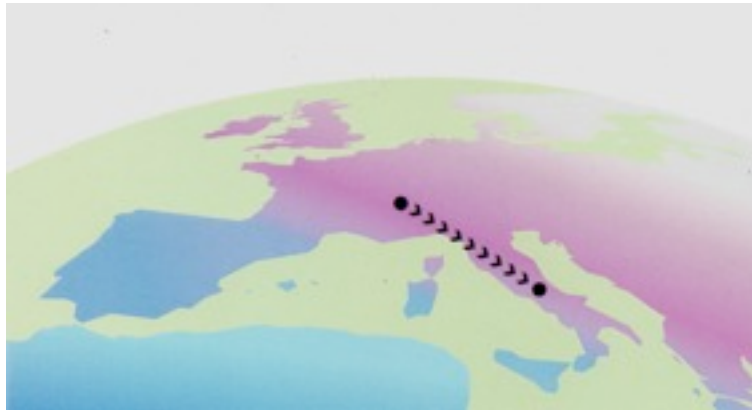


# Przykładowe wyniki dotyczące neutrin atmosferycznych (Superkamiokande)

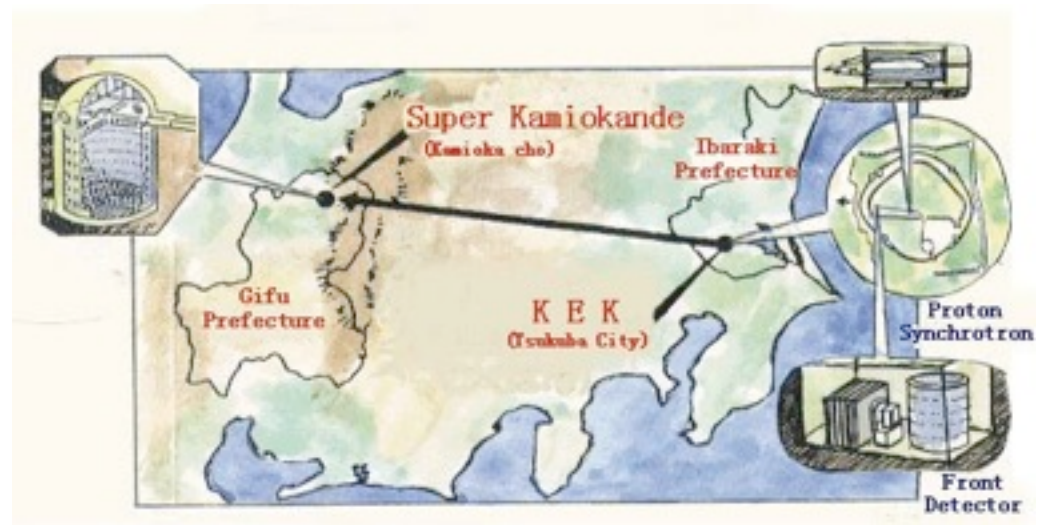




Minos



CERN-GS



K2K experiment



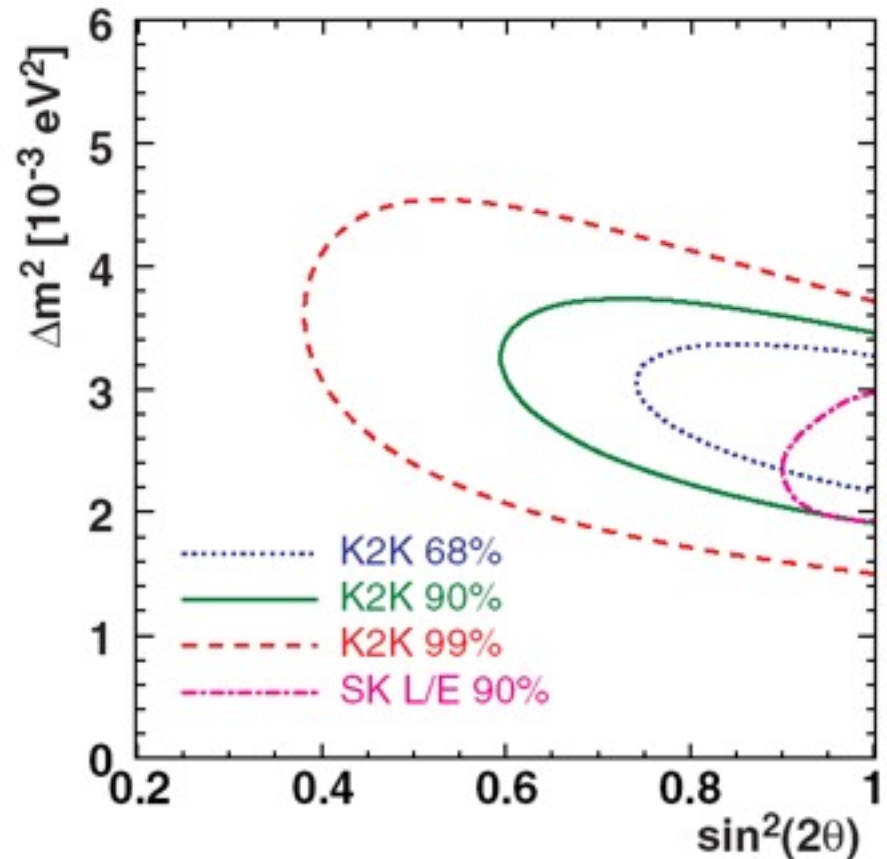
# Eksperyment K2K

[M. H. Ahn et al., Phys. Rev. D74, 072003 (2006)]

Detektor bliski (300 m):  
1 kton H<sub>2</sub>O licznik Czerenkowa  
Detektor daleki (250 km)  
Superkamiokande

Obserwacja (VII 1999 – XI 2004)  
**112 events**

Przewidywanie (bez oscylacji)  
**158 ± 9 events**





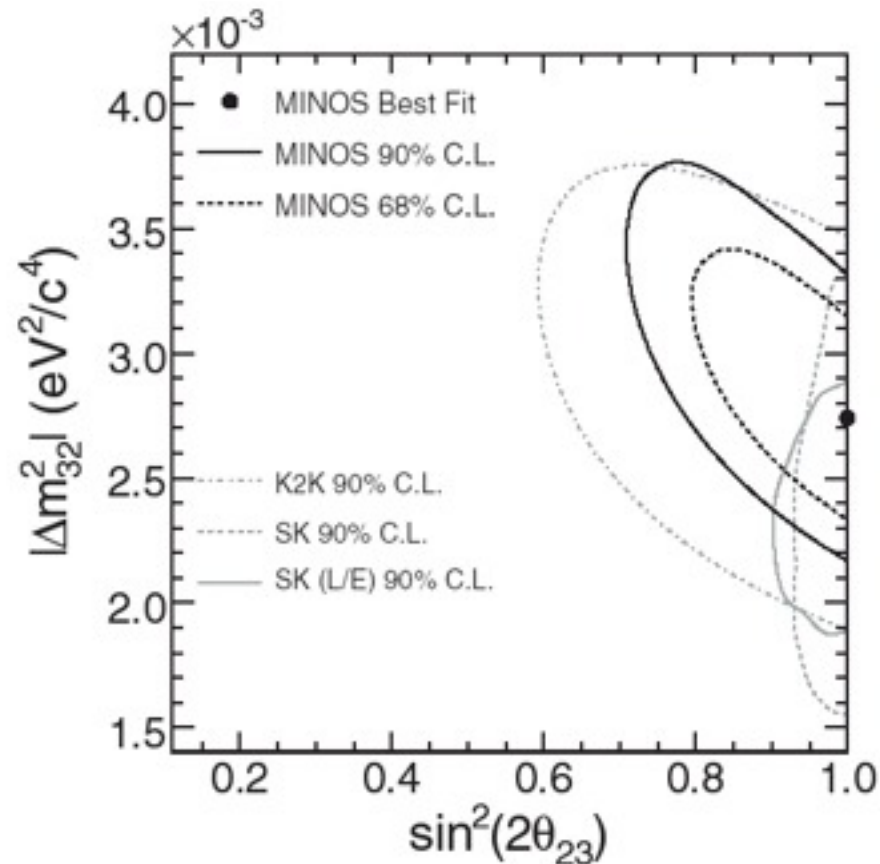
# MINOS

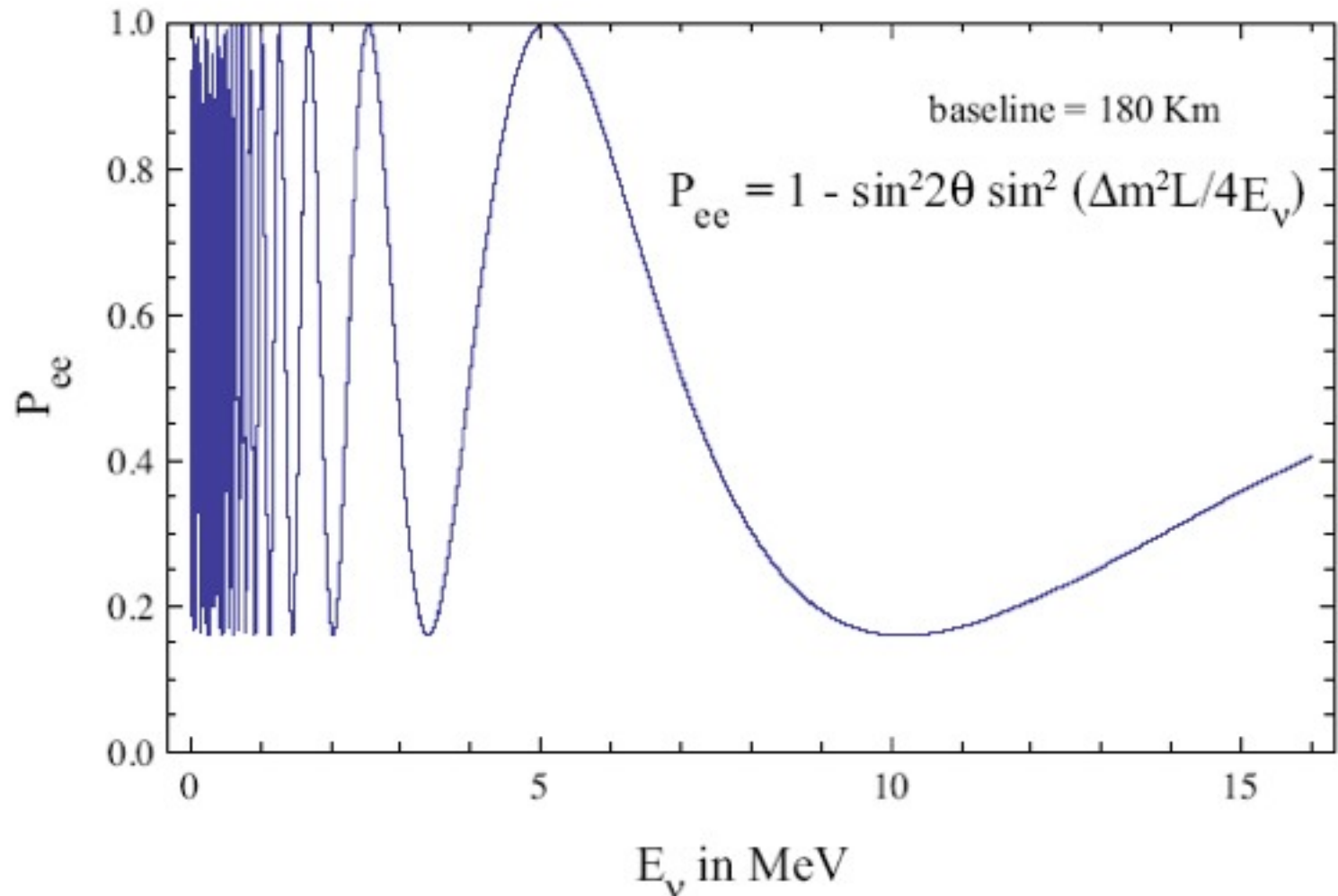
[D. G. Michael et al., Phys. Rev. Lett. 97, 191801 (2006)]

Detektor bliski: 1 km (Fermilab)  
Detektor daleki: 735 km (Soudan)

Obserwacja:  
**215 events**

Przewidywanie (bez oscylacji):  
 **$336 \pm 14$  events**

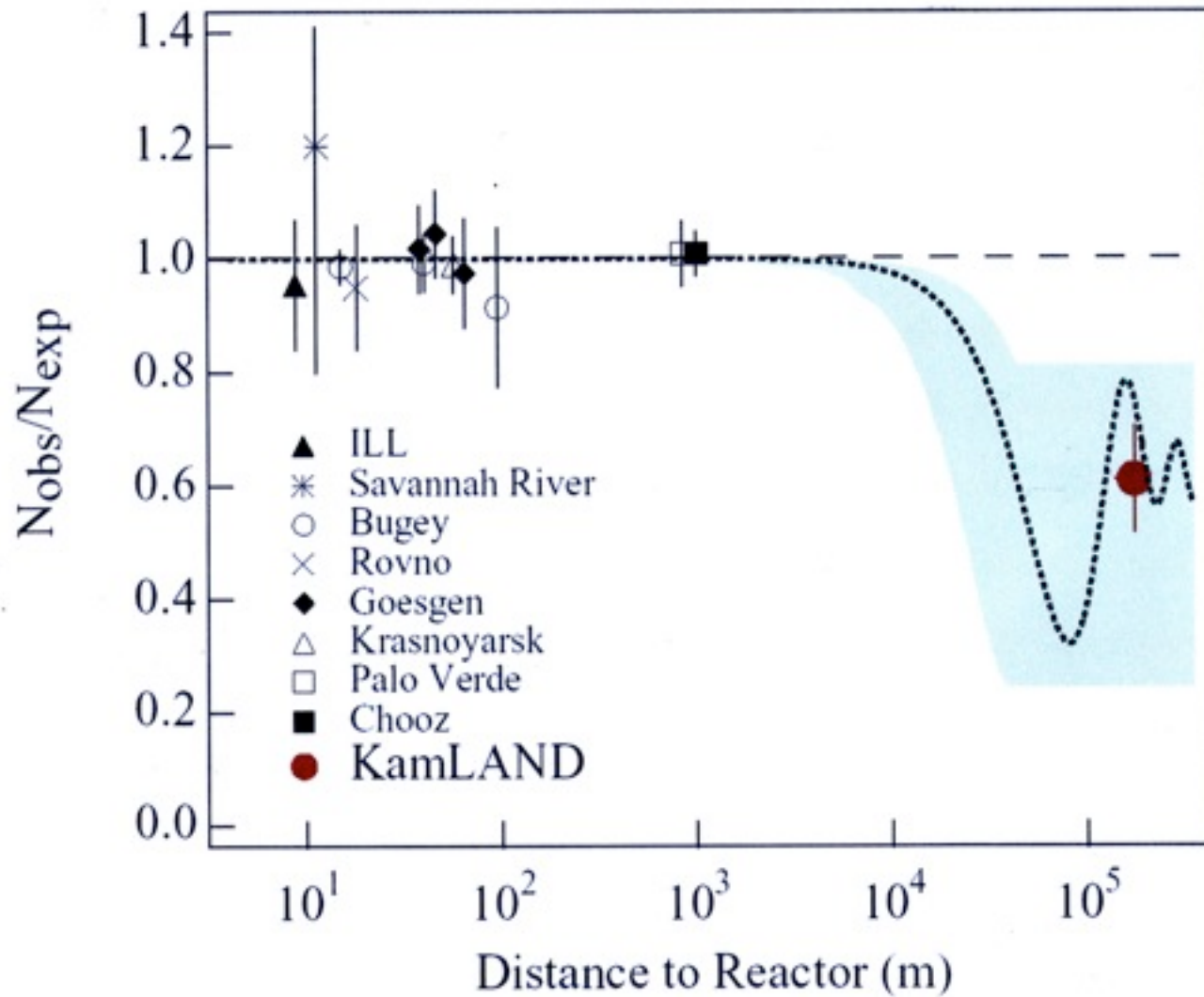




**Figure 13.1:** The  $\nu_e$  ( $\bar{\nu}_e$ ) survival probability  $P(\nu_e \rightarrow \nu_e) = P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ , Eq. (13.30), as a function of the neutrino energy for  $L = 180$  km,  $\Delta m^2 = 7.0 \times 10^{-5}$  eV<sup>2</sup> and  $\sin^2 2\theta = 0.84$  (from [48]).

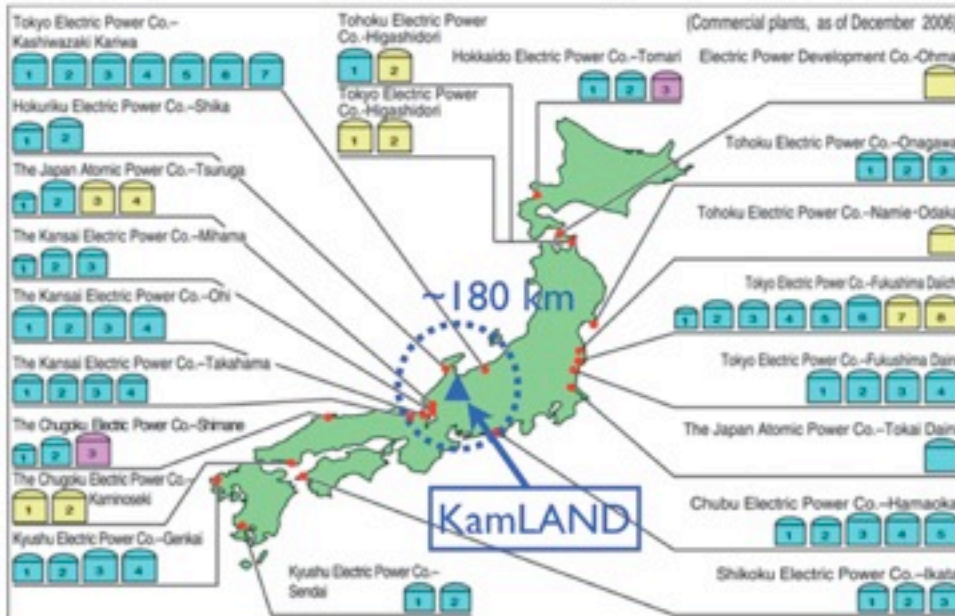
# KAMLAND experiment

(K. Eguchi et al., Phys. Rev. Lett. 90, 021802 (2003))



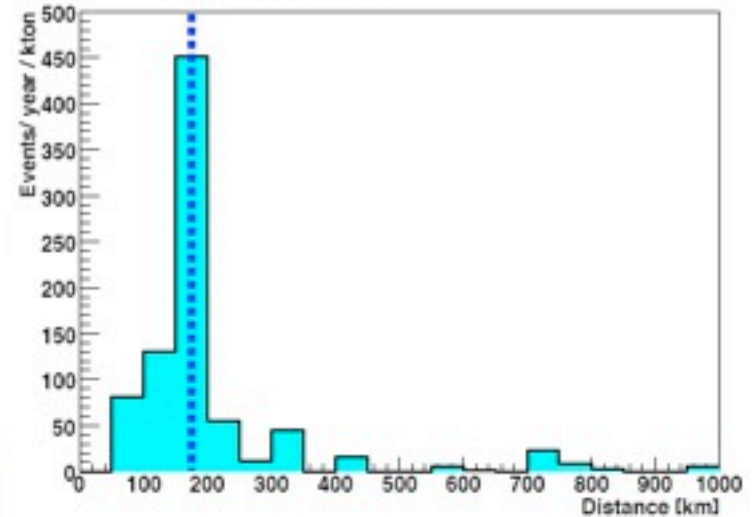
# KAMLAND II

Nuclear Power Plants in Japan



World reactors + Research reactors : 0.96%  
 Korean reactors : 3.2%

Effective baseline  
 ~180 km

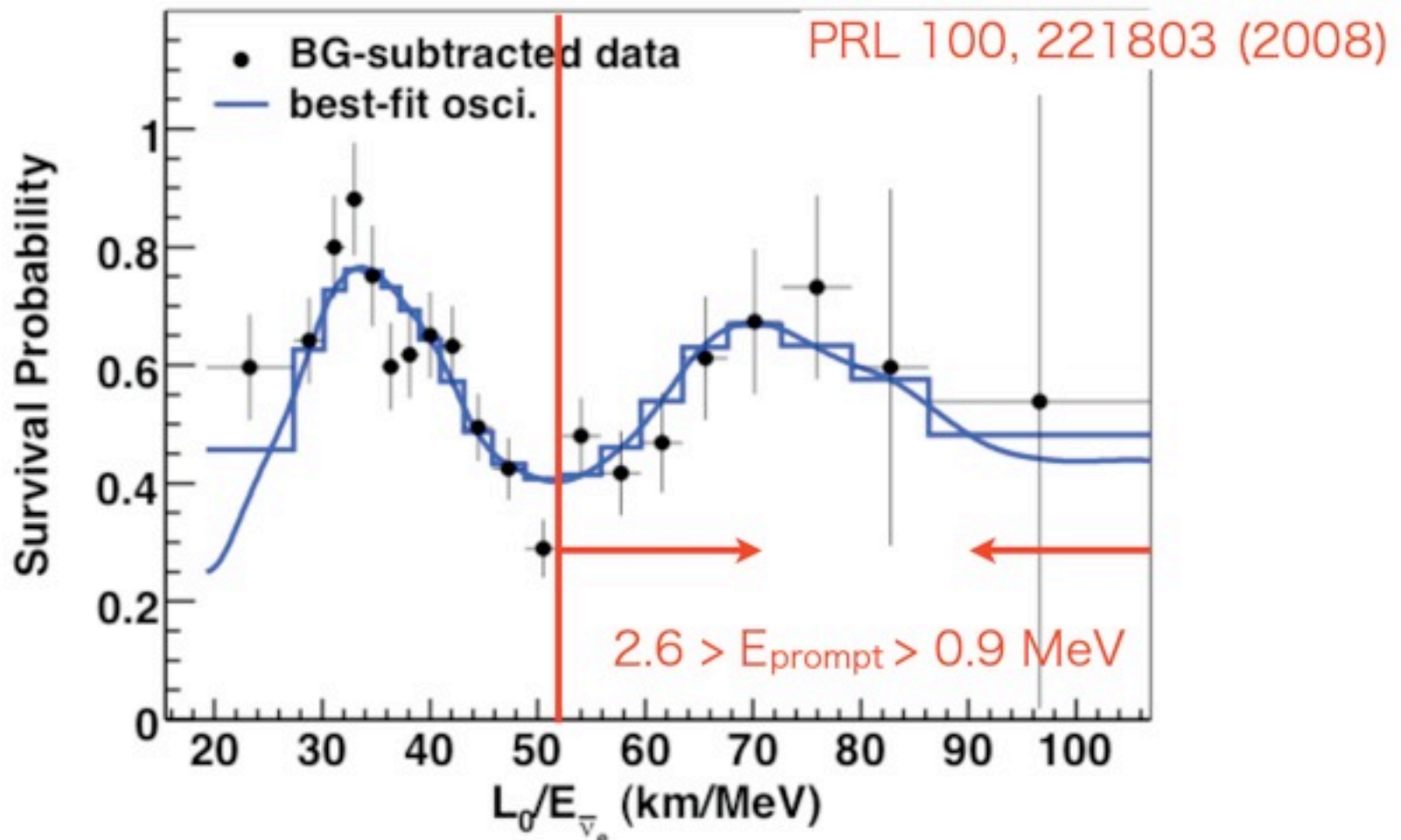


- 55 nuclear power reactor units in Japan
- 70 GW (7% of world total) is generated at 130~220 km distance from KamLAND
- well-known anti-neutrino energy spectra

# KAMLAND II

$L_0/E$  oscillatory shape is clearly seen

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2 \left( 1.27 \Delta m^2 \frac{L_0}{E} \right) \quad \langle L_0 \rangle = 180 \text{ km}$$





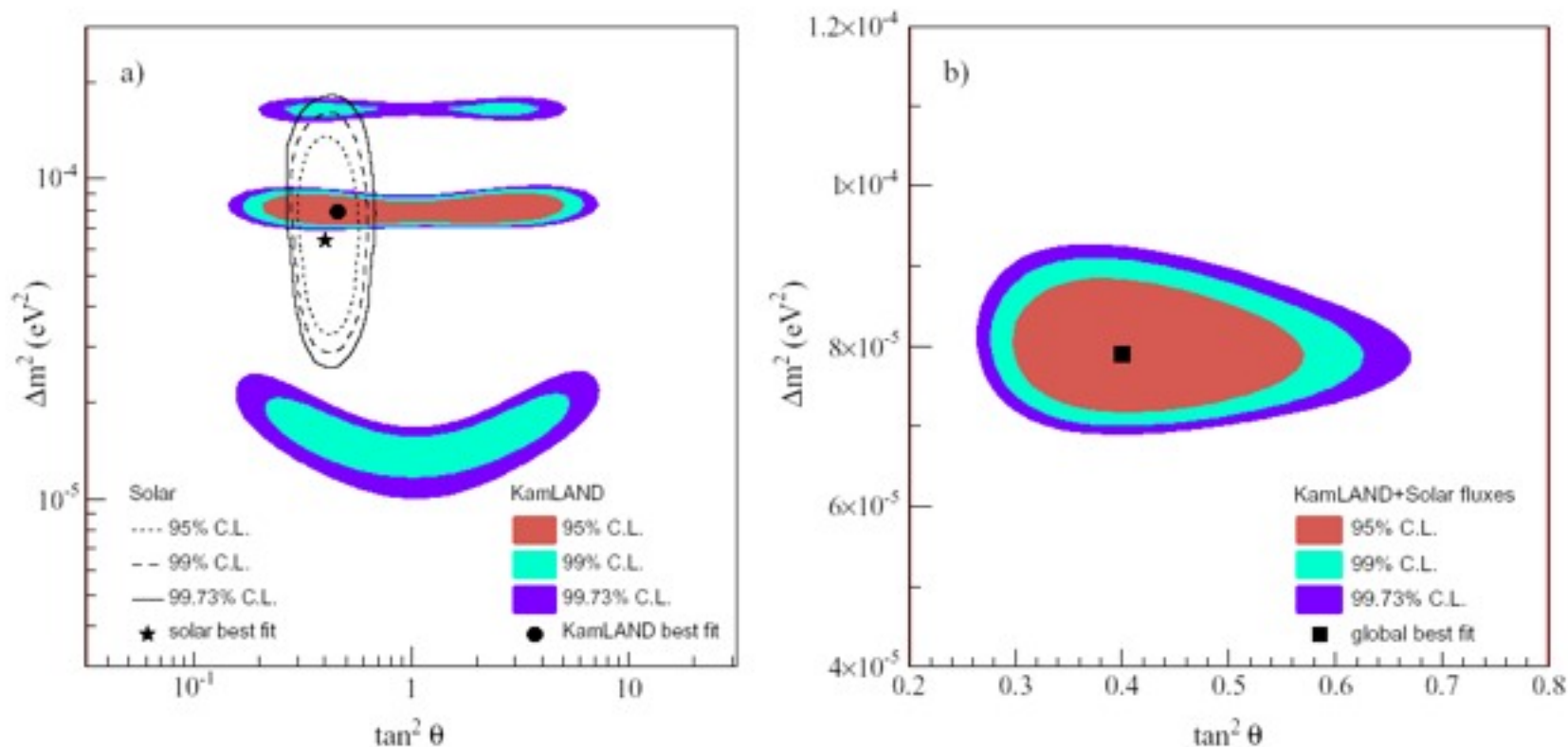


FIG. 4: (a) Neutrino oscillation parameter allowed region from KamLAND anti-neutrino data (shaded regions) and solar neutrino experiments (lines) [12]. (b) Result of a combined two-neutrino oscillation analysis of KamLAND and the observed solar neutrino fluxes under the assumption of CPT invariance. The fit gives  $\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5} \text{ eV}^2$  and  $\tan^2 \theta = 0.40^{+0.10}_{-0.07}$  including the allowed 1-sigma parameter range.

T. Araki et al. Phys. Rev. Lett. 94, 081801 (2005)

# SNO Wrzesień 2003

$$\Phi_{\text{CC}}^{\text{SNO}} = 1.59_{-0.07}^{+0.08} (\text{stat})_{-0.08}^{+0.06} (\text{syst})$$

$$\Phi_{\text{ES}}^{\text{SNO}} = 2.21_{-0.26}^{+0.31} (\text{stat})_{-0.26}^{+0.31} (\text{syst})$$

$$\Phi_{\text{NC}}^{\text{SNO}} = 5.21 \pm 0.27 (\text{stat}) \pm 0.38 (\text{syst})$$

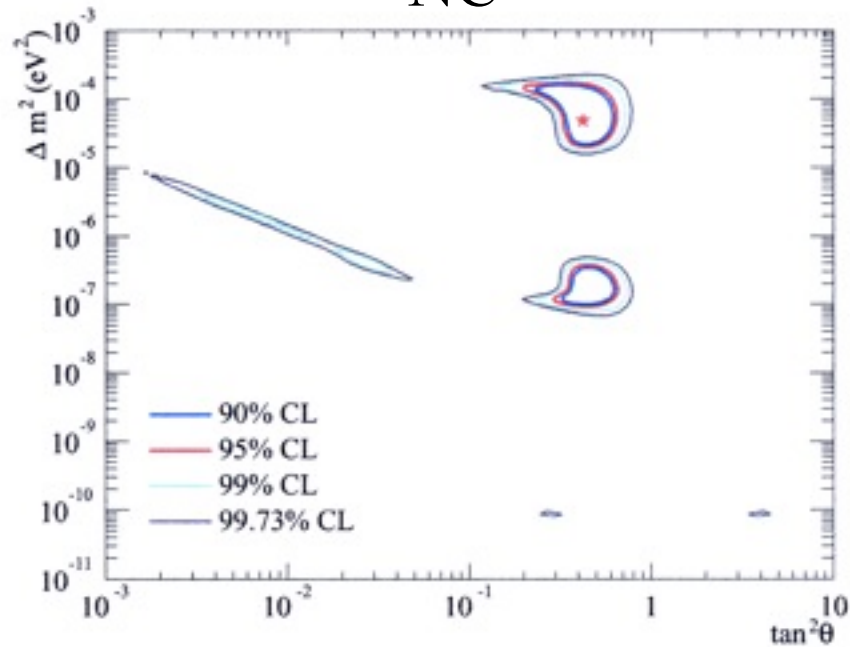


FIG. 4: SNO-only neutrino oscillation contours, including pure D<sub>2</sub>O day and night spectra, salt CC, NC, ES fluxes, with <sup>8</sup>B flux free and hep flux fixed. The best-fit point is  $\Delta m^2 = 4.7 \times 10^{-5}$ ,  $\tan^2 \theta = 0.43$ ,  $f_B = 1.03$ , with  $\chi^2/\text{d.o.f.} = 26.2/34$ .

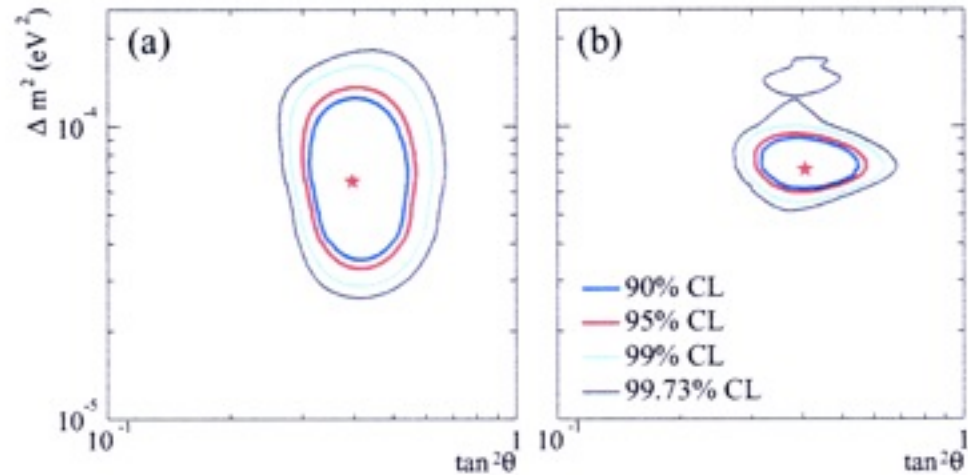
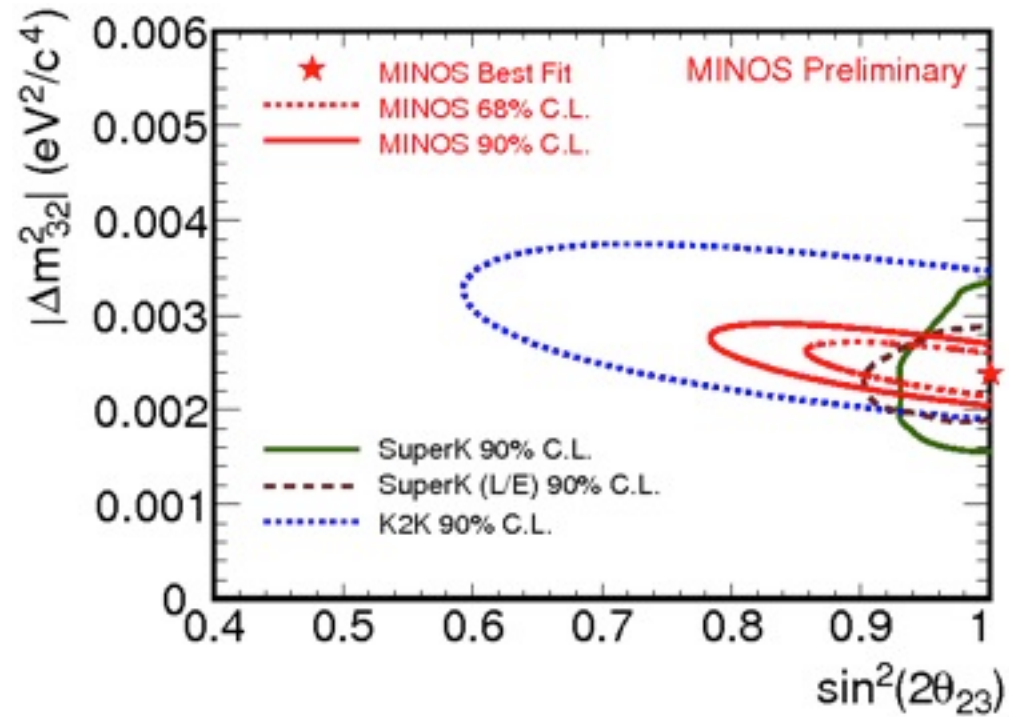
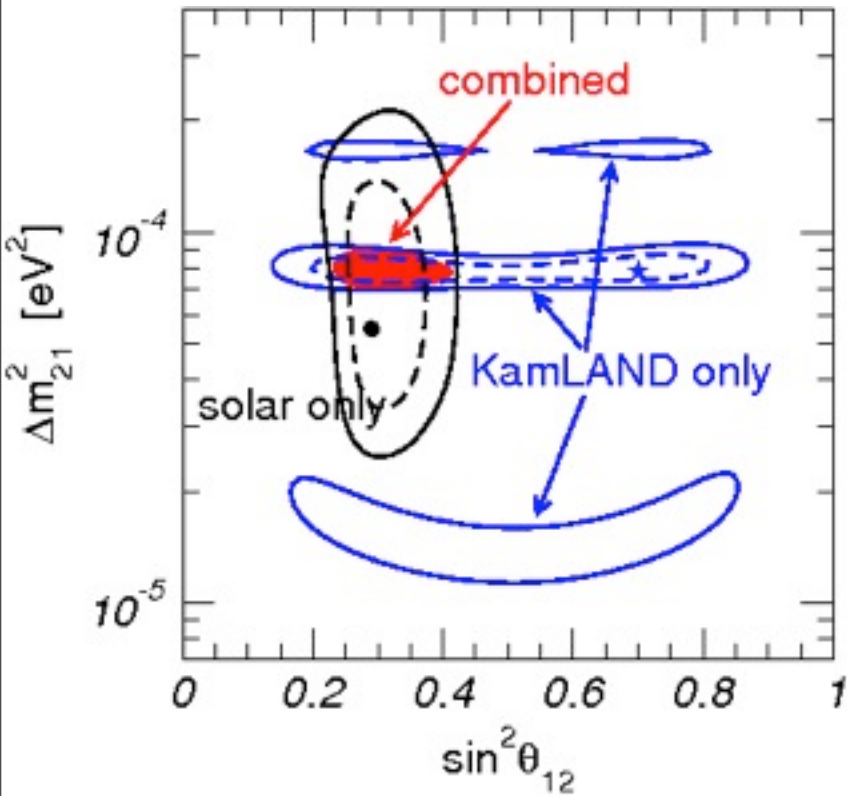


FIG. 5: Global neutrino oscillation contours. (a) Solar global: D<sub>2</sub>O day and night spectra, salt CC, NC, ES fluxes, SK, Cl, Ga. The best-fit point is  $\Delta m^2 = 6.5 \times 10^{-5}$ ,  $\tan^2 \theta = 0.40$ ,  $f_B = 1.04$ , with  $\chi^2/\text{d.o.f.} = 70.2/81$ . (b) Solar global + KamLAND. The best-fit point is  $\Delta m^2 = 7.1 \times 10^{-5}$ ,  $\tan^2 \theta = 0.41$ ,  $f_B = 1.02$ . In both (a) and (b) the <sup>8</sup>B flux is free and the hep flux is fixed.

# Porównanie wyników eksperymentów





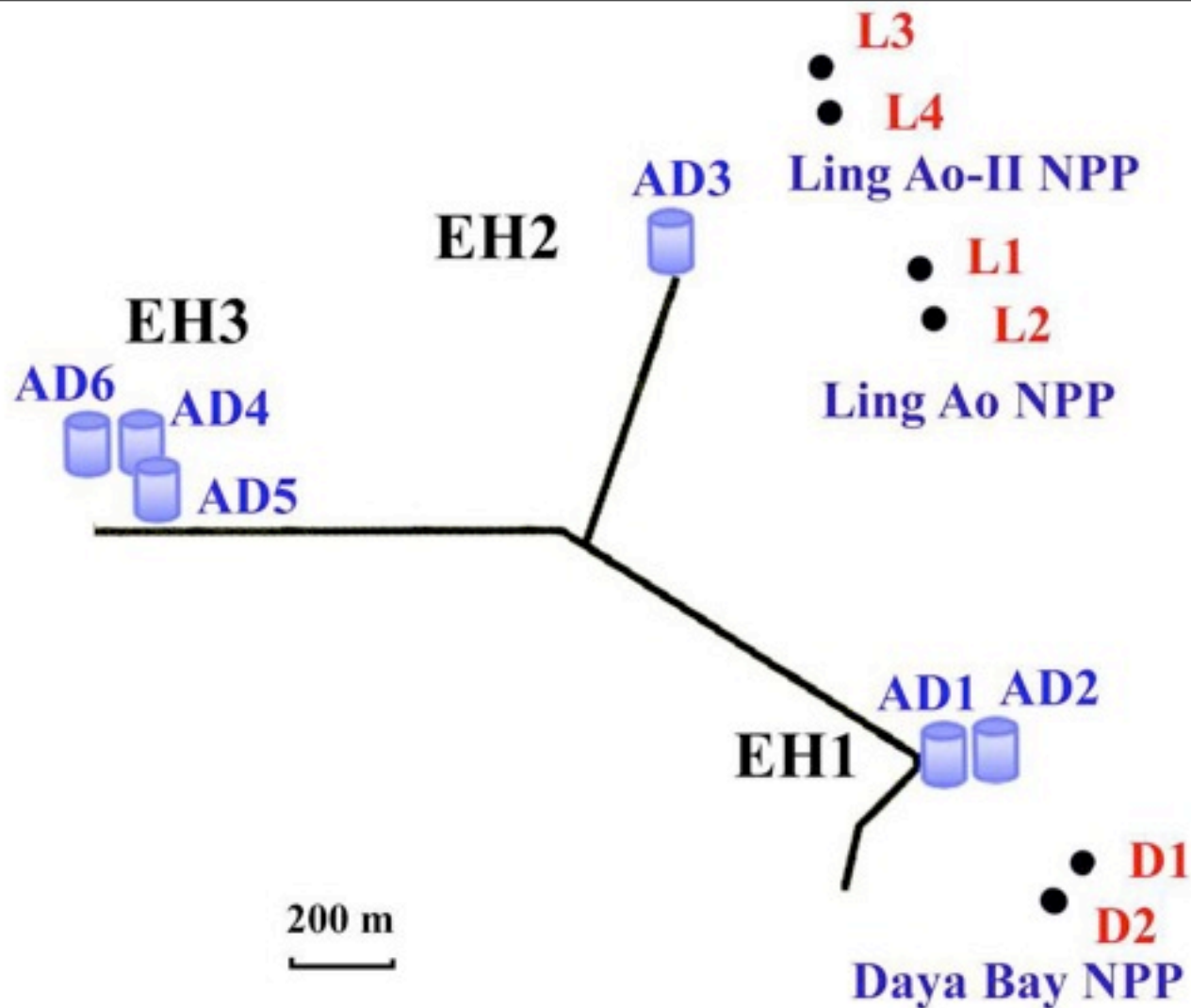


FIG. 1. Layout of the Daya Bay experiment. The dots represent reactors, labeled as D1, D2, L1, L2, L3 and L4. Six ADs, AD1–AD6, are installed in three EHs.

# Daya Bay (marzec 2012)

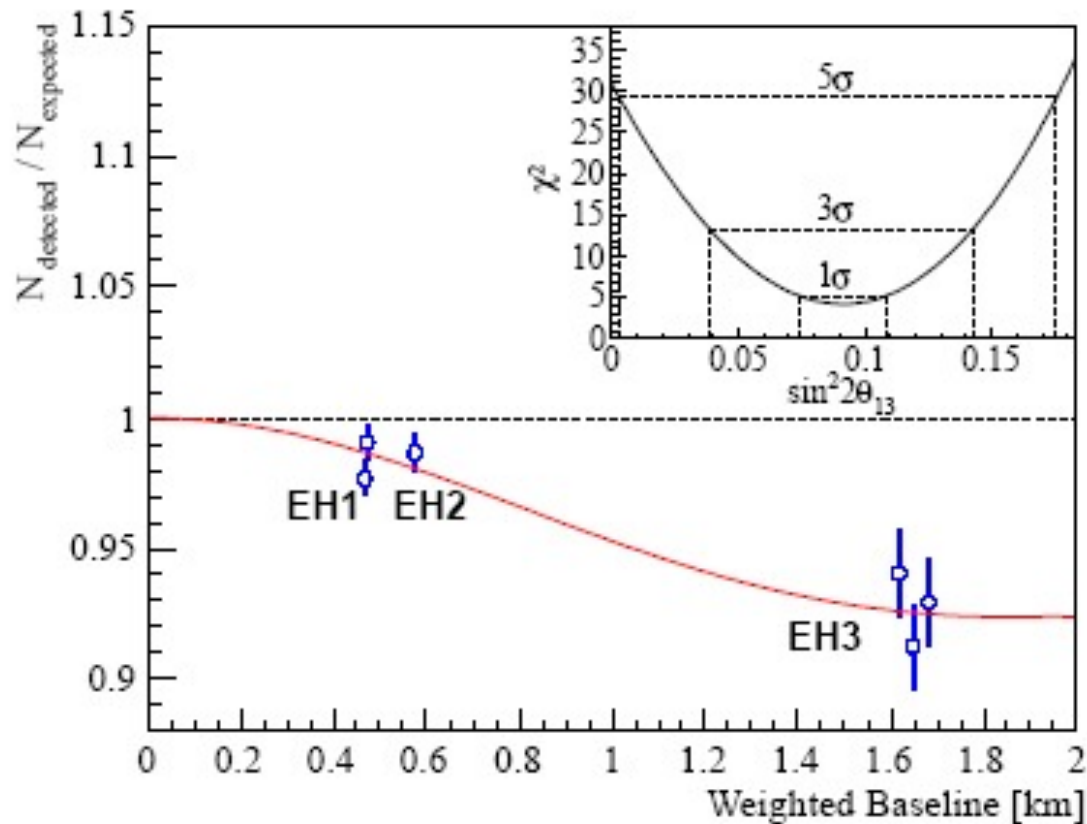


FIG. 4. Ratio of measured versus expected signal in each detector, assuming no oscillation. The expected signal is corrected with the best-fit normalization parameter. Reactor and survey data were used to compute the flux-weighted average baselines. The oscillation survival probability at the best-fit value is given by the smooth curve. The AD4 and AD6 data points are displaced by -30 and +30 m for visual clarity. The  $\chi^2$  versus  $\sin^2 2\theta_{13}$  is shown in the inset.

$$U_{12} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

słoneczne, Kamland

$$\sin^2\theta_{12} = 0.304^{+0.022}_{-0.016}, \quad \Delta m_{21}^2 = 7.65^{+0.23}_{-0.20} \times 10^{-5} \text{ eV}^2$$

$$U_{13} = \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} \\ 0 & 1 & 0 \\ -\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}$$

Daya Bay

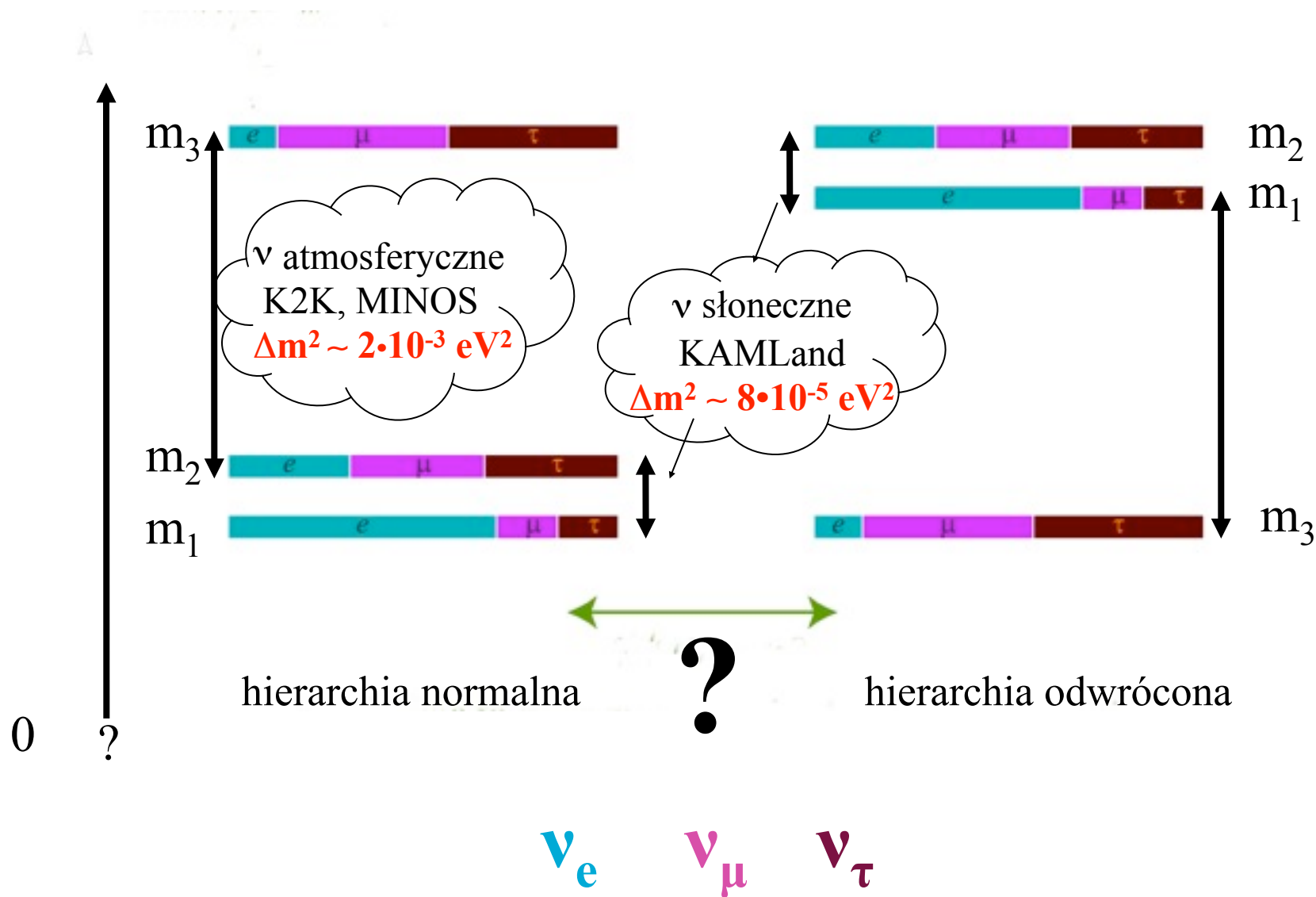
$$\sin^2 2\theta_{13} \approx 0.092 \pm 0.016_{\text{stat}} \pm 0.005_{\text{sys}}$$

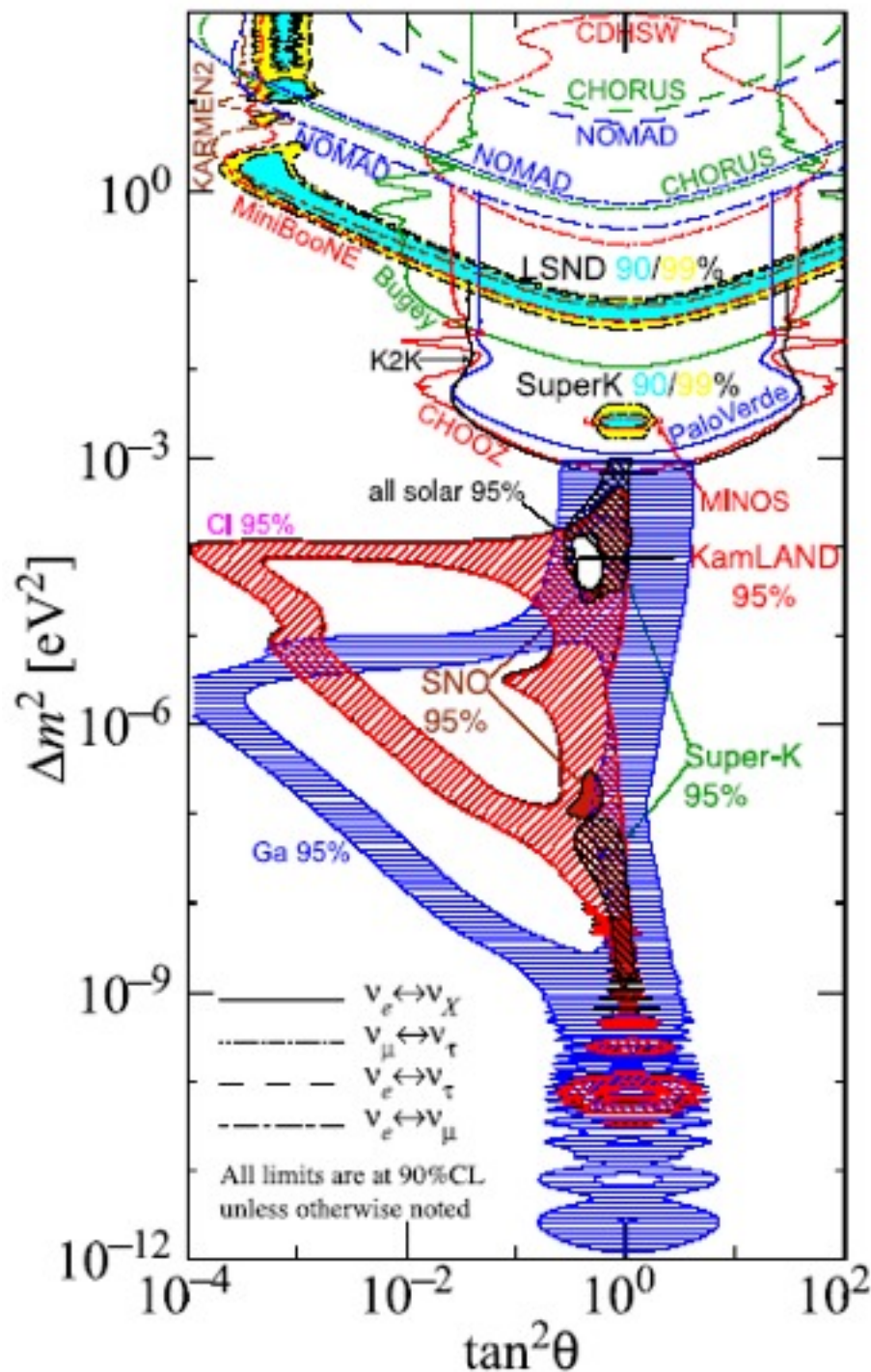
$$U_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

atmosferyczne, K2K, Minos

$$\sin^2\theta_{23} = 0.50^{+0.07}_{-0.06}, \quad |\Delta m_{31}^2| = 2.40^{+0.12}_{-0.11} \times 10^{-3} \text{ eV}^2$$

# Co wiemy o mieszaniu neutrin





PDG 2010

# Wiele innych eksperymentów neutrinowych

**T2K**

**Borexino**

**MiniBoone**

**Opera**

**Nova**

**IceCube**

**Antares**

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