Masse e Oscillazioni dei Neutrini Lezione IV

Corso di Fisica Nucleare e Subnucleare III

Lucio Ludovici 11 dicembre 2008

Programma

1. Richiami sull'equazione di Dirac, proiezioni chirali, equazione di Weyl.

2. Chiralità ed elicità. Neutrini di Majorana. Decadimento doppio β.

3. Massa di Dirac e di Majorana.   Meccanismo dell'altalena (see-saw).

4. Matrice di mescolamento per tre famiglie.   Fasi di Dirac e di Majorana. Oscillazioni nel vuoto per tre famiglie.   Violazione di CP.

5.Caso limite di due famiglie.   Formule approssimate: one mass dominance. Interpretazione del plot Δm^2 vs $\sin^2 2\theta$. Valore sperimentale dei parametri della matrice di mixing.

6. Oscillazioni nella materia, meccanismo MSW.

7. Gli esperimenti. I raggi cosmici. Le oscillazioni dei neutrini atmosferici. Super-Kamiokande.   K2K. Le oscillazioni dei neutrini solari: Homestake, SNO. Esperimenti ai reattori. Prospettive future.

Dalla teoria agli esperimenti

Nel 1934 la sezione d'urto neutrino-nucleone è calcolata essere dell'ordine di 10^{-44} cm^2 per neutrini di qualche MeV, cioè 19 ordini di grandezza più piccola della sezione d'urto fotone-protone a energie corrispondenti.

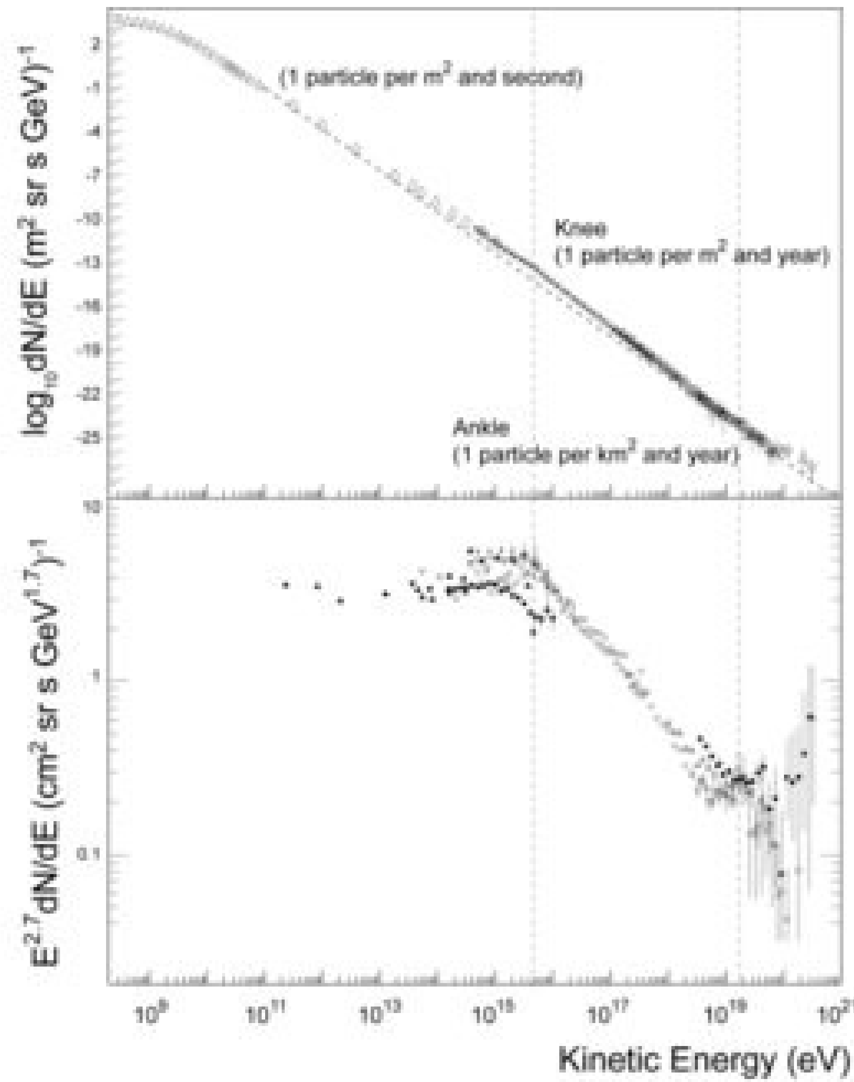
“ [...] there is no practically possible way of observing the neutrino”

The “Neutrino”
H.A. Bethe, R.E. Peierls,
Nature 133 (1934) 532

Fisica dei neutrini e oscillazioni

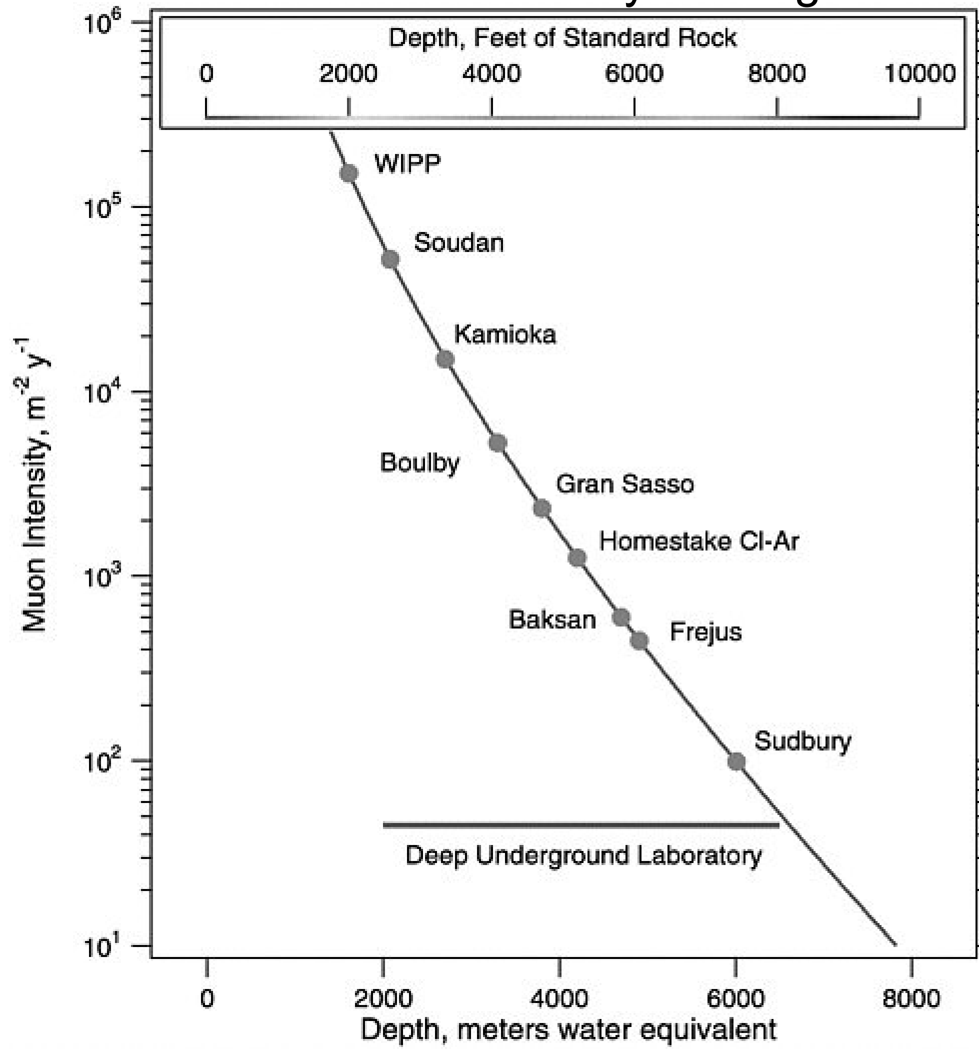
1930	ν existence postulated	Pauli
1934	ν interaction theory and name	Fermi
1938	Solar ν flux calculation	Bethe
1946	Idea of ν chlorine detector	Pontecorvo
1956	ν interactions observed	Reines & Cowan
1957	Idea of ν oscillation	Pontecorvo
1958	Left-handed ν	Goldhaber
1962	2 ν's, ν_μ ,ν_e	Lederman, Schwartz & Steinberger
1968	Solar neutrino deficit	Davis
1973	ν NC interactions observed	Gargamelle
1975	τ and the third ν	Perl
1986	Solar deficit again, atmospheric(?)	Kamiokande
1987	ν from SN1987A	Kamiokande, IMB
1989	3 light neutrino families	LEP Collaborations
1991	Solar deficit again	Gallex, SAGE
1998	Atmospheric ν oscillation	Super-Kamiokande
2002	Solar ν oscillation confirmed	SNO, KamLand
2005	Atmospheric ν oscillation confirmed	K2K

Cosmic rays flux



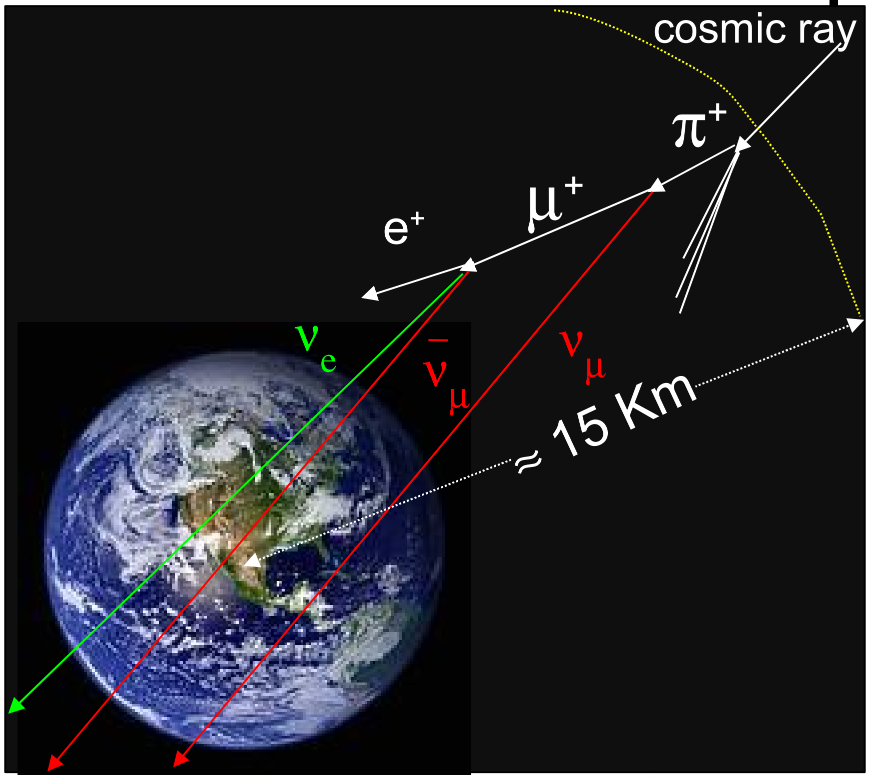
CR Induced muon flux

Standard rock density: 2.65 g/cm^3



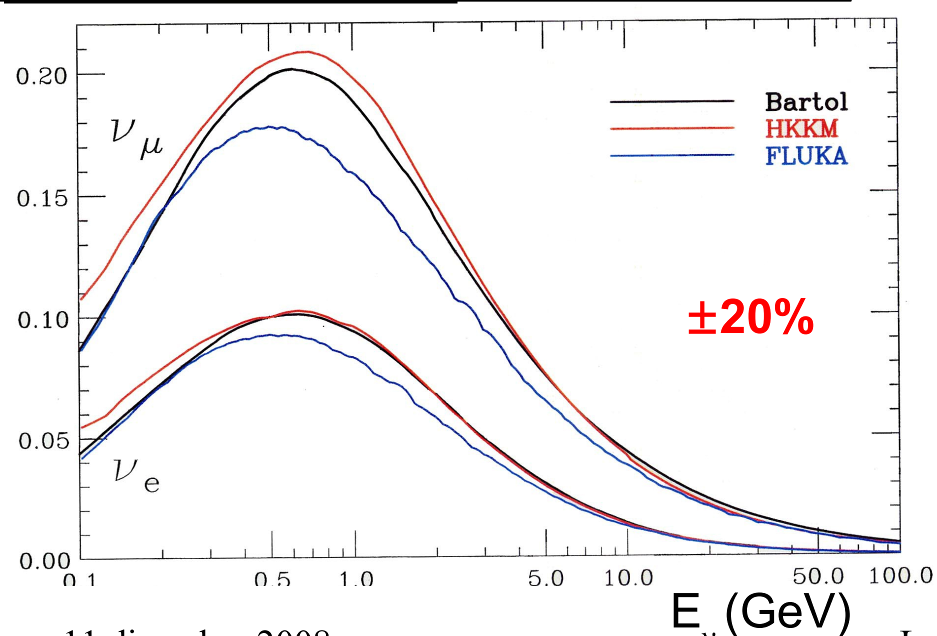
At 12,000 MWE (meter water equivalent) deep underground muon from neutrino interactions ~ cosmic ray induced muons

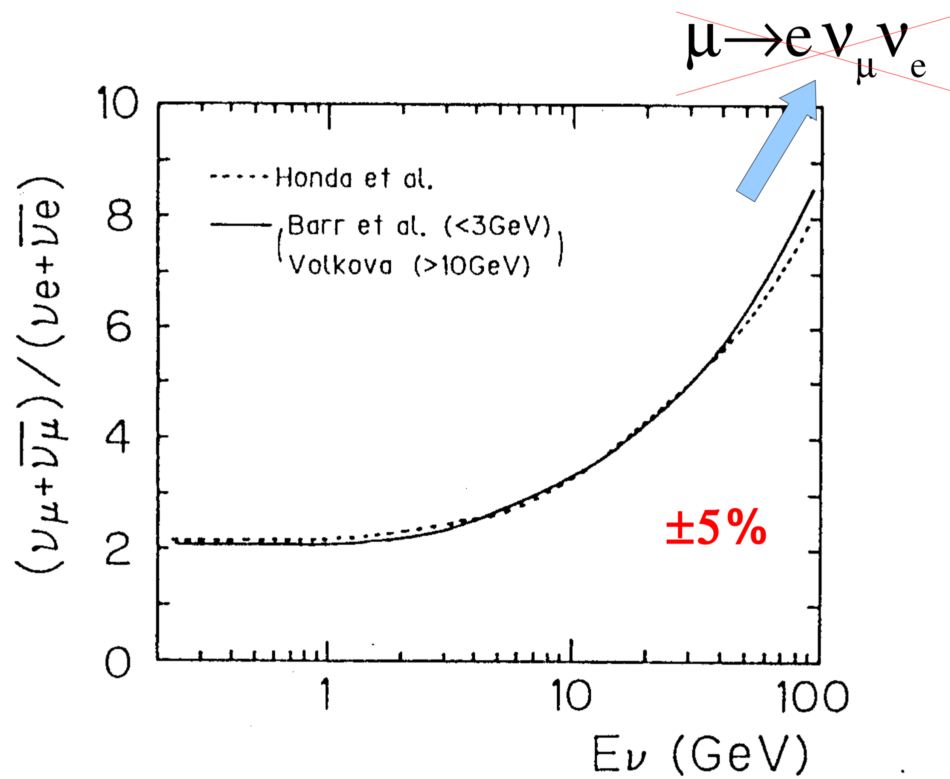
Atmospheric neutrinos



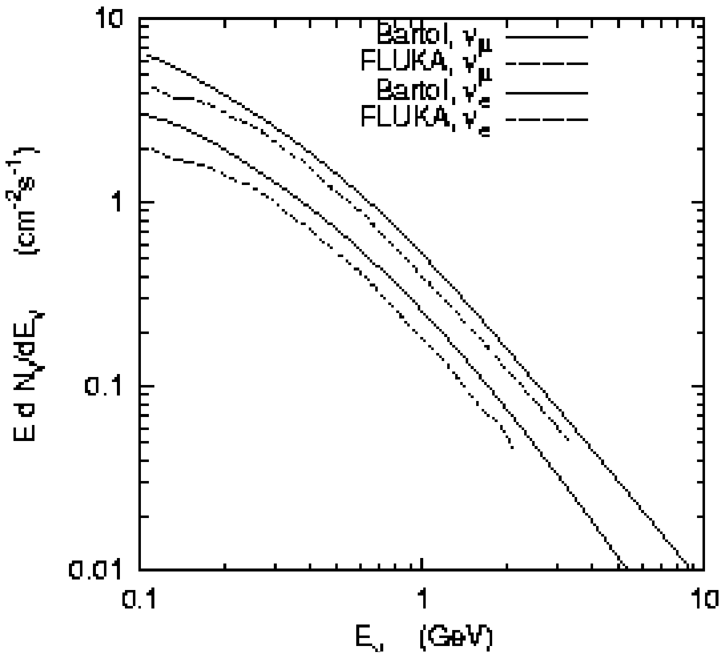
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\quad \hookrightarrow e^+ \bar{\nu}_\mu \nu_e$$
$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$
$$\quad \hookrightarrow e^- \nu_\mu \bar{\nu}_e$$

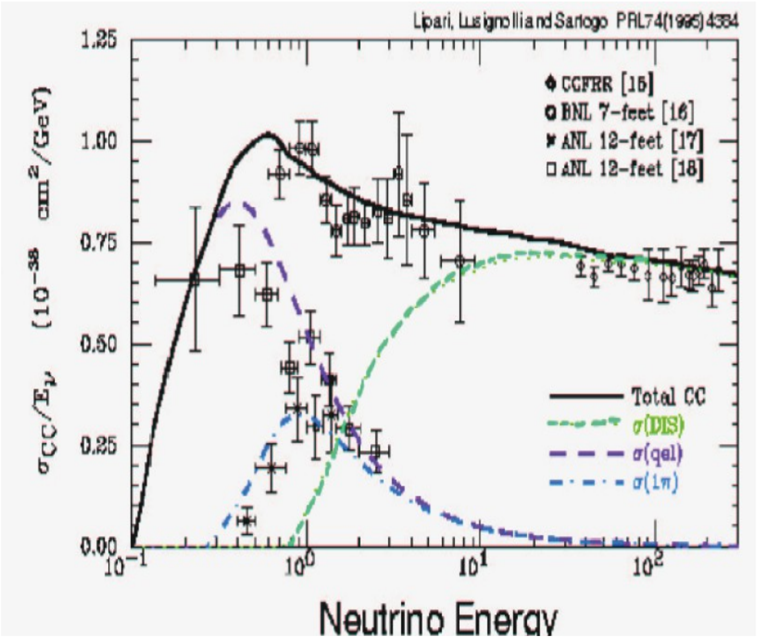
$$R(E) = \frac{(\nu_\mu + \bar{\nu}_\mu)}{(\nu_e + \bar{\nu}_e)} \xrightarrow[E \lessapprox 1\,\mathrm{GeV}]{} 2$$





Back of envelope calculation of atmospheric neutrino events in 1 kt detector





Flux	$\Phi \sim 2\ cm^{-2}\ s^{-1}$
Cross-section	$\sigma \sim 0.5\ 10^{-38}\ cm^2$
Target mass	$M \sim 6\ 10^{32}$ nucleons/1kt
Z/A	$I \sim ½$
Time	$T \sim 3.15\ 10^7$ s/year

$N_{inter} = \Phi(cm^{-2}\ s^{-1}) \cdot \sigma(10^{-38}\ cm^2) \cdot M(\text{nucleons/1kt}) \cdot I \cdot T(\text{s/year}) \sim 100$ events/kt/year

νμ/νe Ratio (of Ratios)

Kamioka mines (3000t)

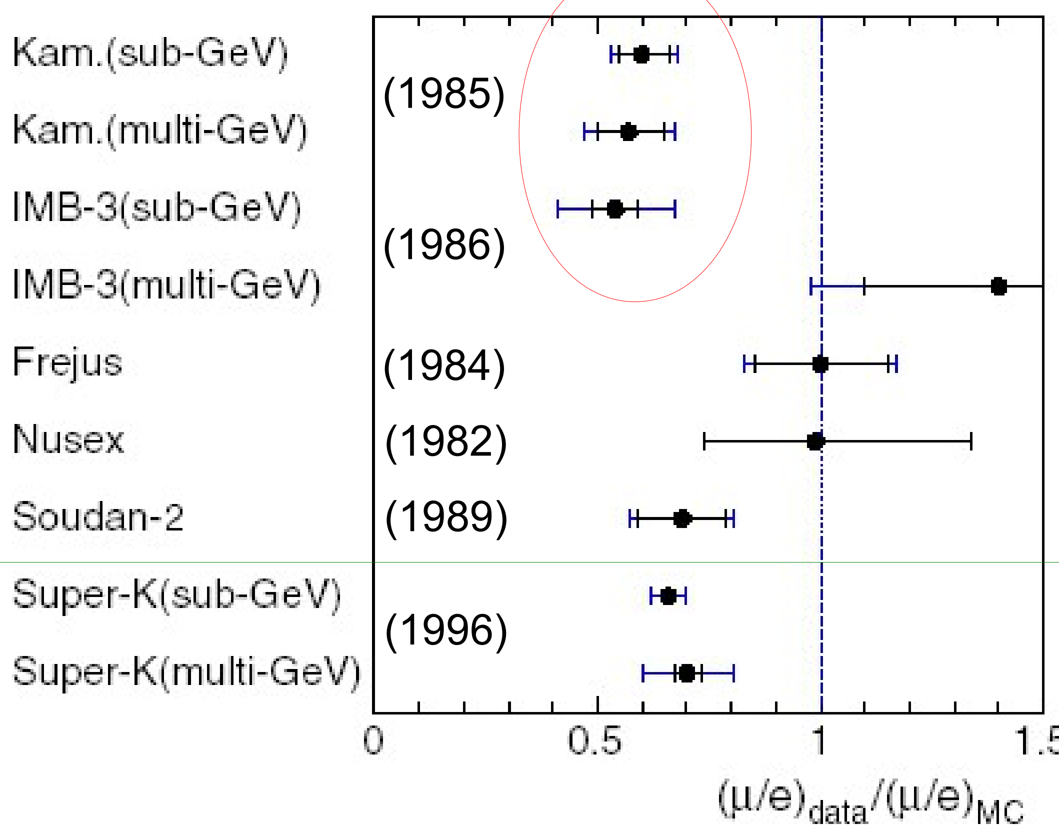
Morton salt mines (8000t)

Frejus (900t)

Mont Blanc (150t)

Soudan mines(960t)

Kamioka mines (50,000t)



Prime (contrastanti) indicazioni

Confermate da SuperKamiokande (1998)

Phys.Rev.Lett.81:2016-2019,1998
hep-ex/9806038

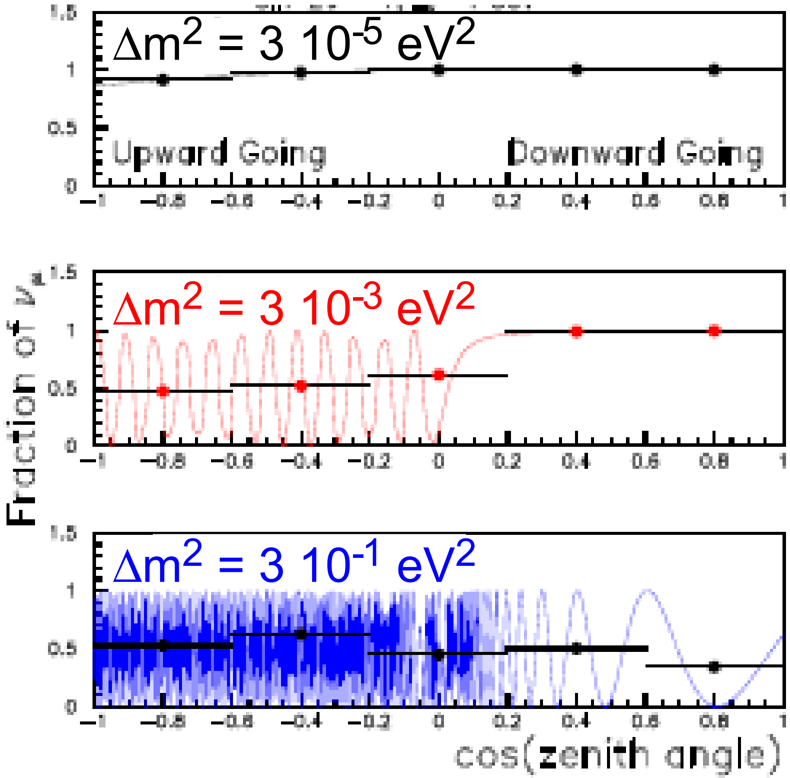
Prima indicazione del deficit di νμ dal rapporto νμ/νe (Kamiokande)

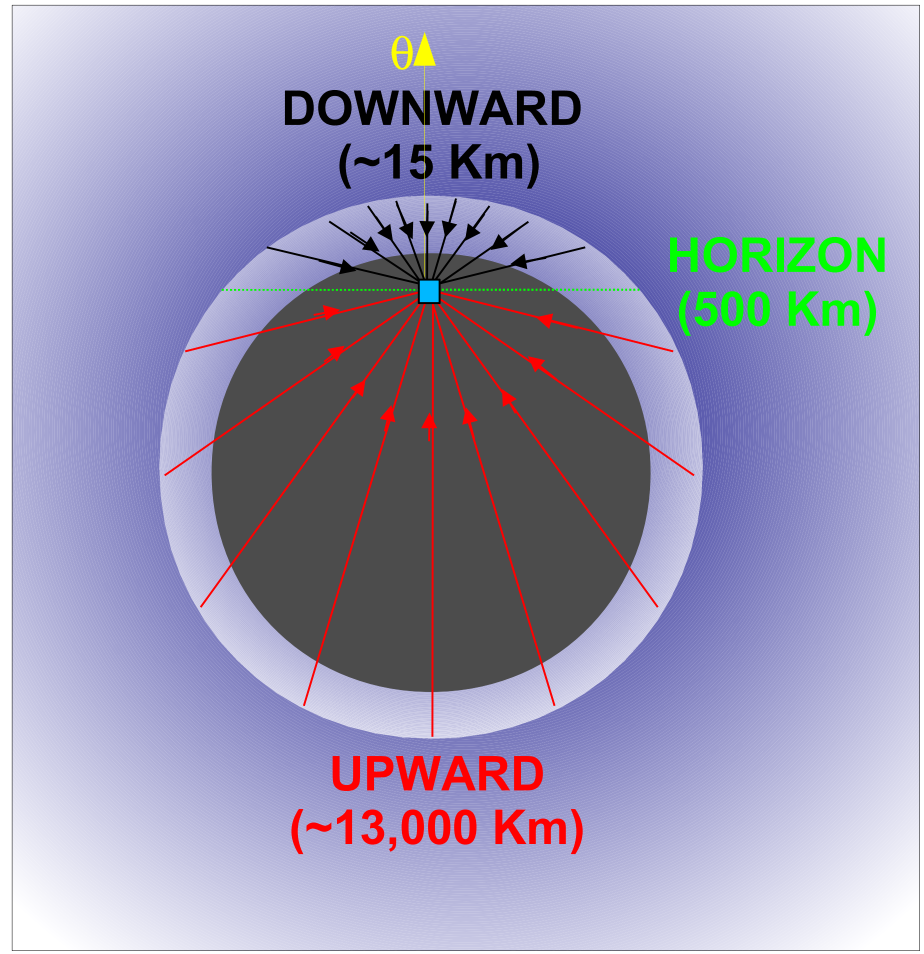
Indicazioni contrastanti negli anni '80

Osservazione dell'asimmetria up-down (Super-Kamiokande, 1998)

L/E dei neutrini atmosferici

$\sin^2 2\theta = 1$ E= 1 GeV



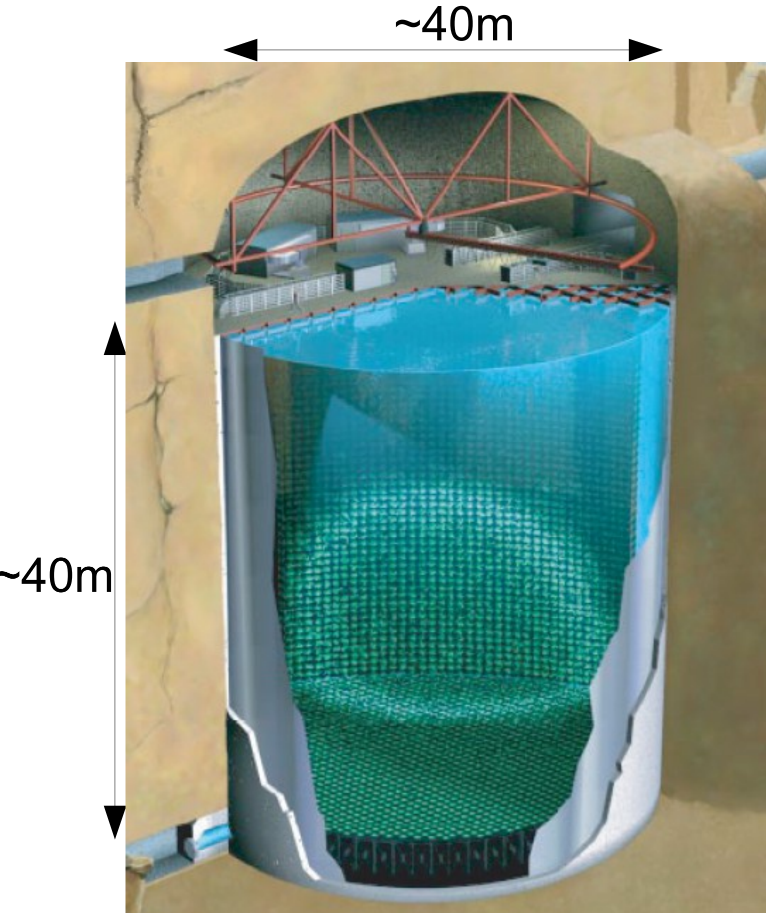


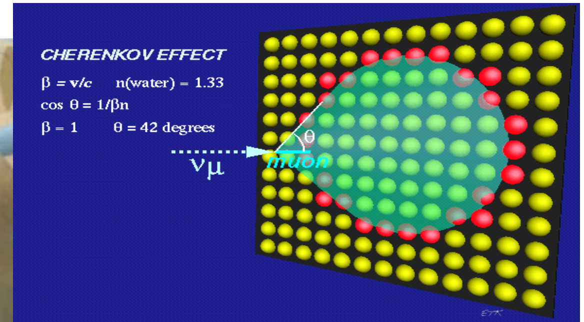
Ampio intervallo di L/E:

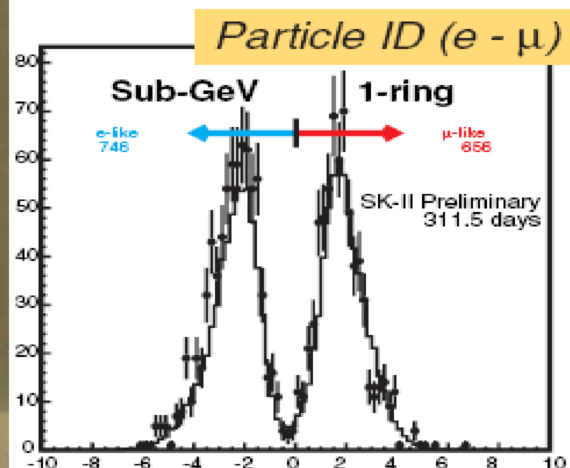
E~0.2 →100 GeV

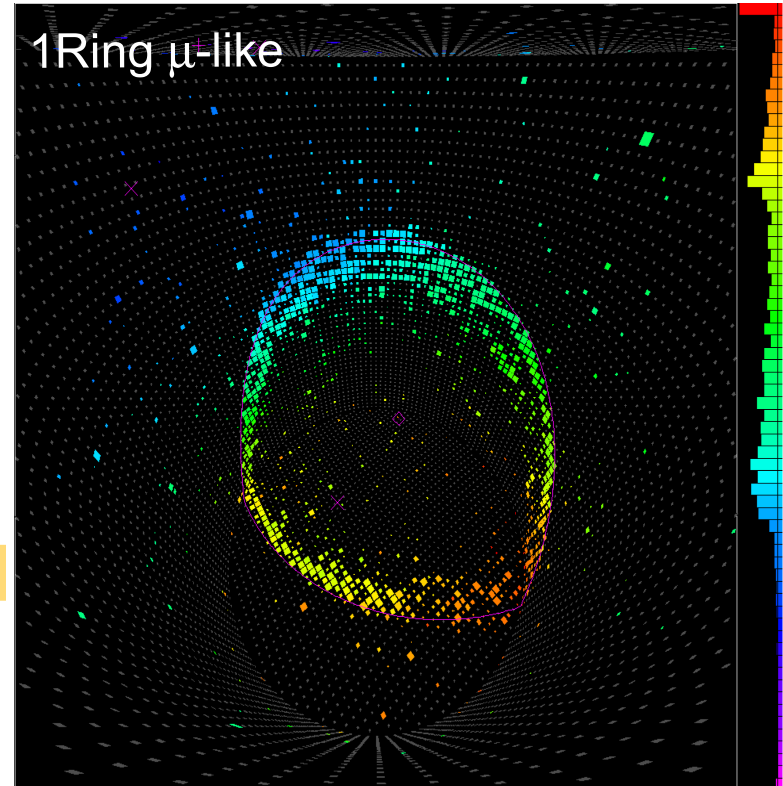
L~15 →13,000 Km

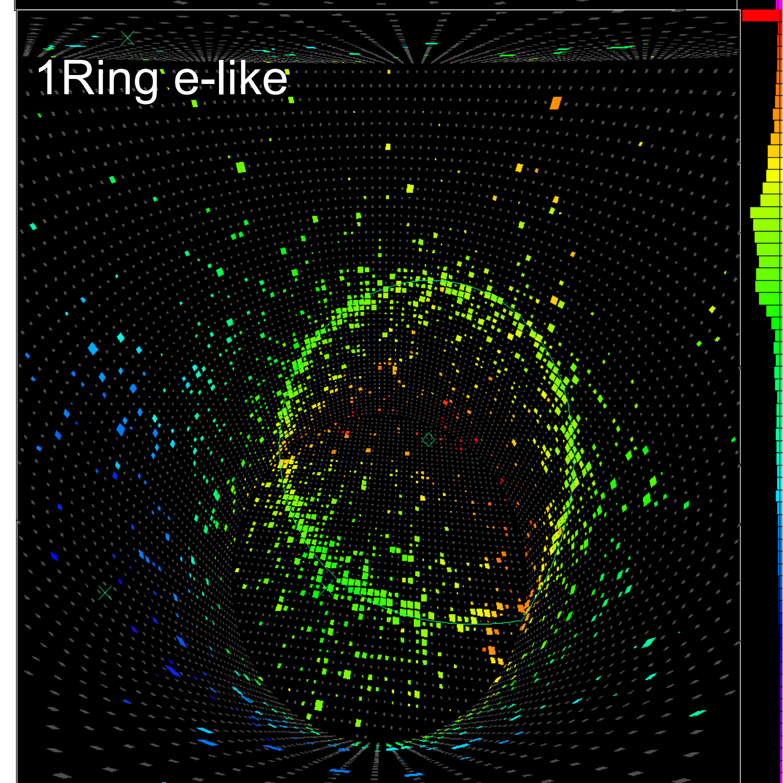
Super-Kamiokande



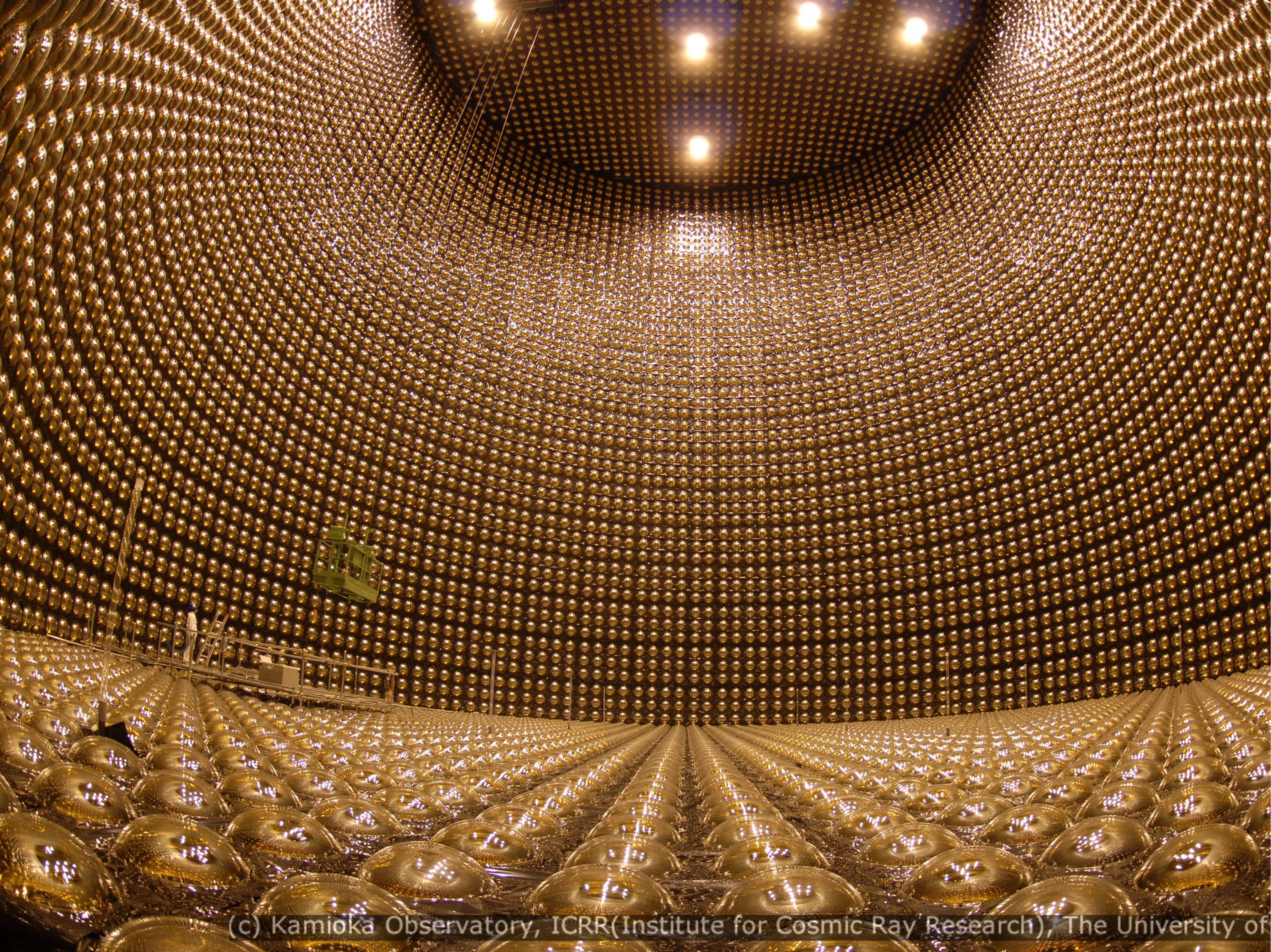






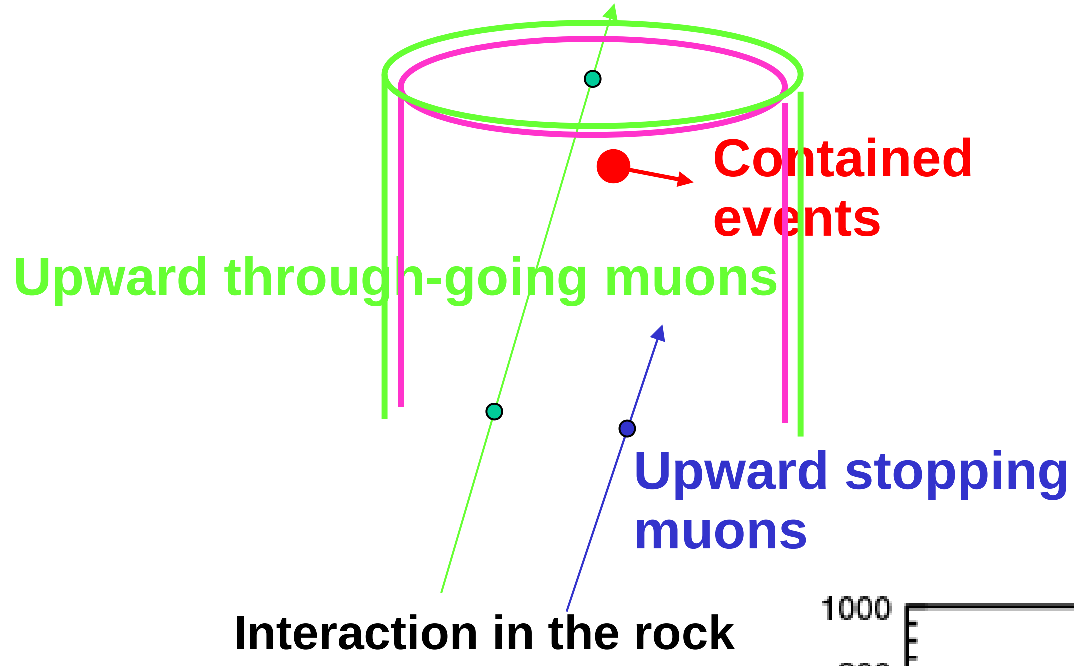


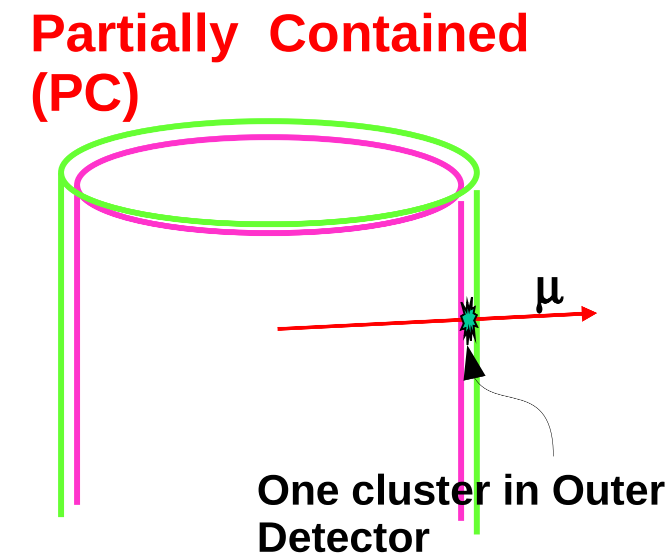
50,000 ton water Cherenkov detector
22.5 kton fiducial volume
1000 m underground (2700 m.w.e.)
11,146 20-inch PMTs for inner detector
1,885 8-inch PMTs for outer detector

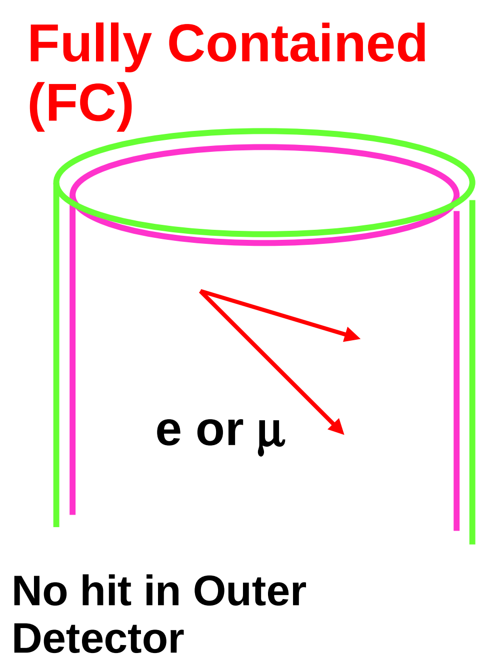

(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of

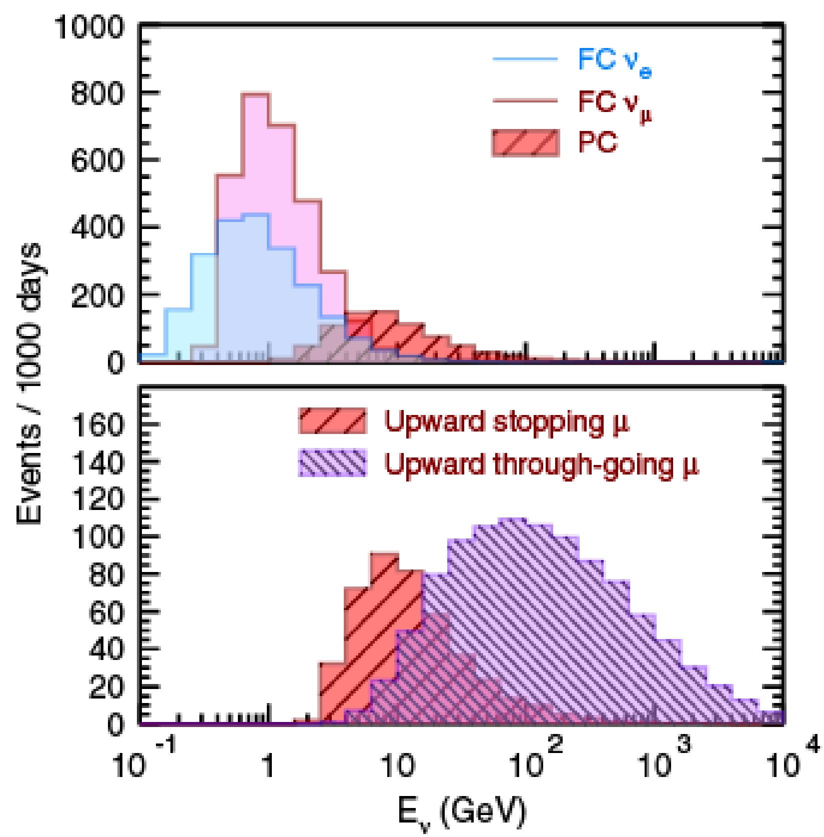
20" PMT by Hamamatsu Photonics

Detection of Atmospheric Neutrinos

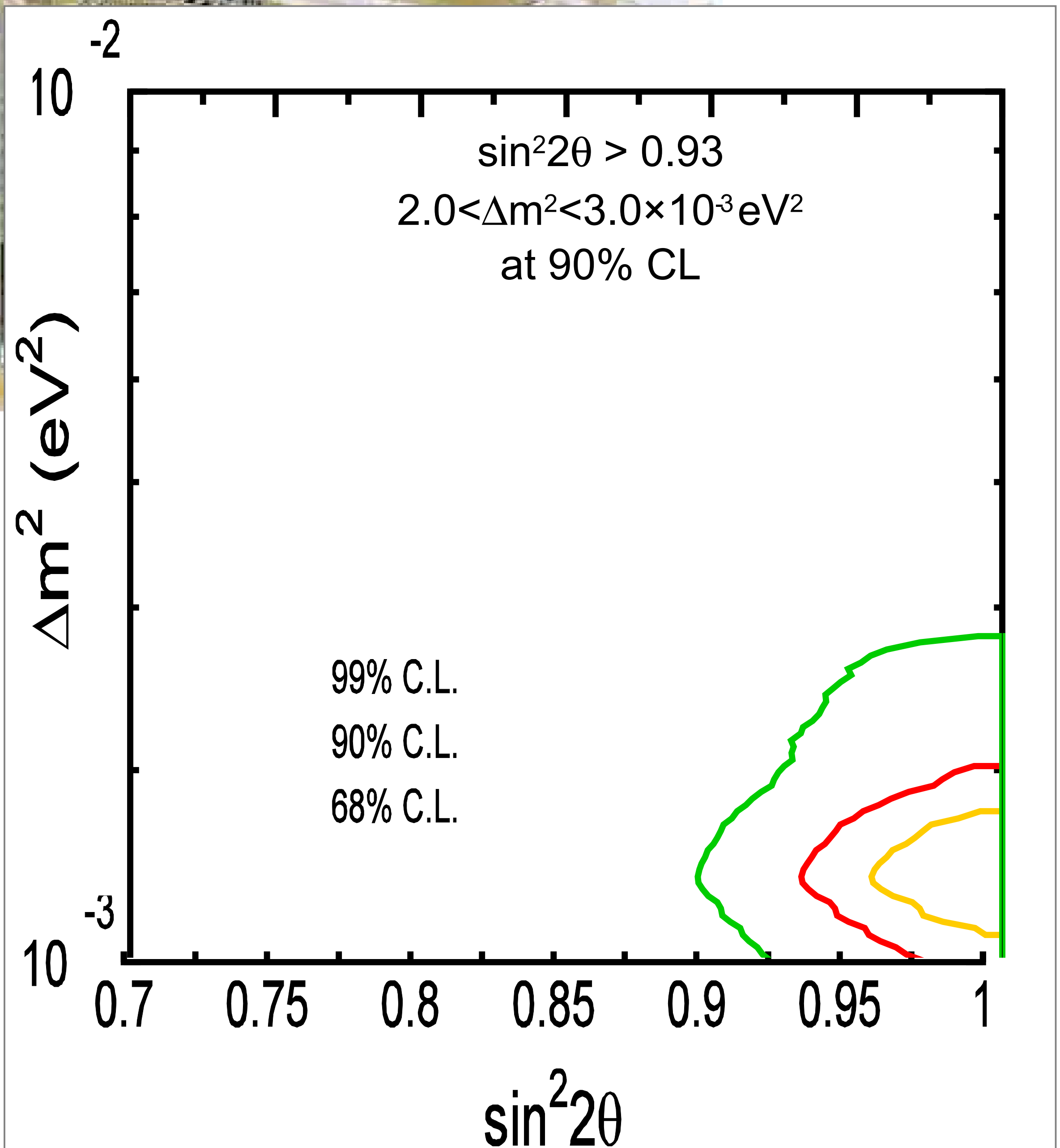


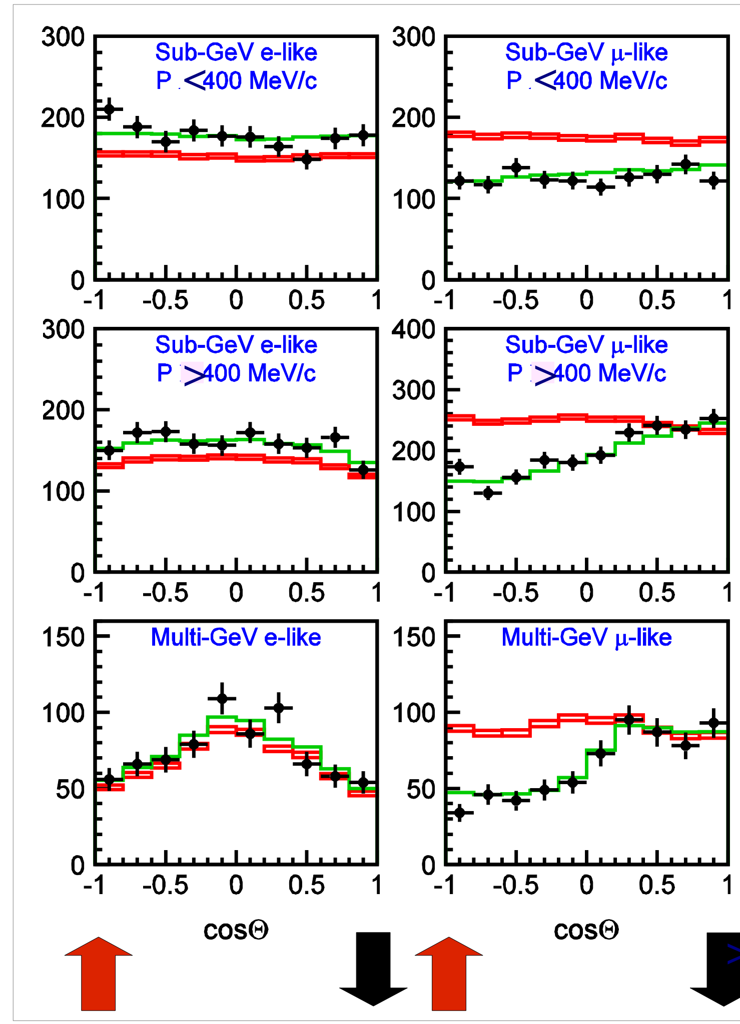






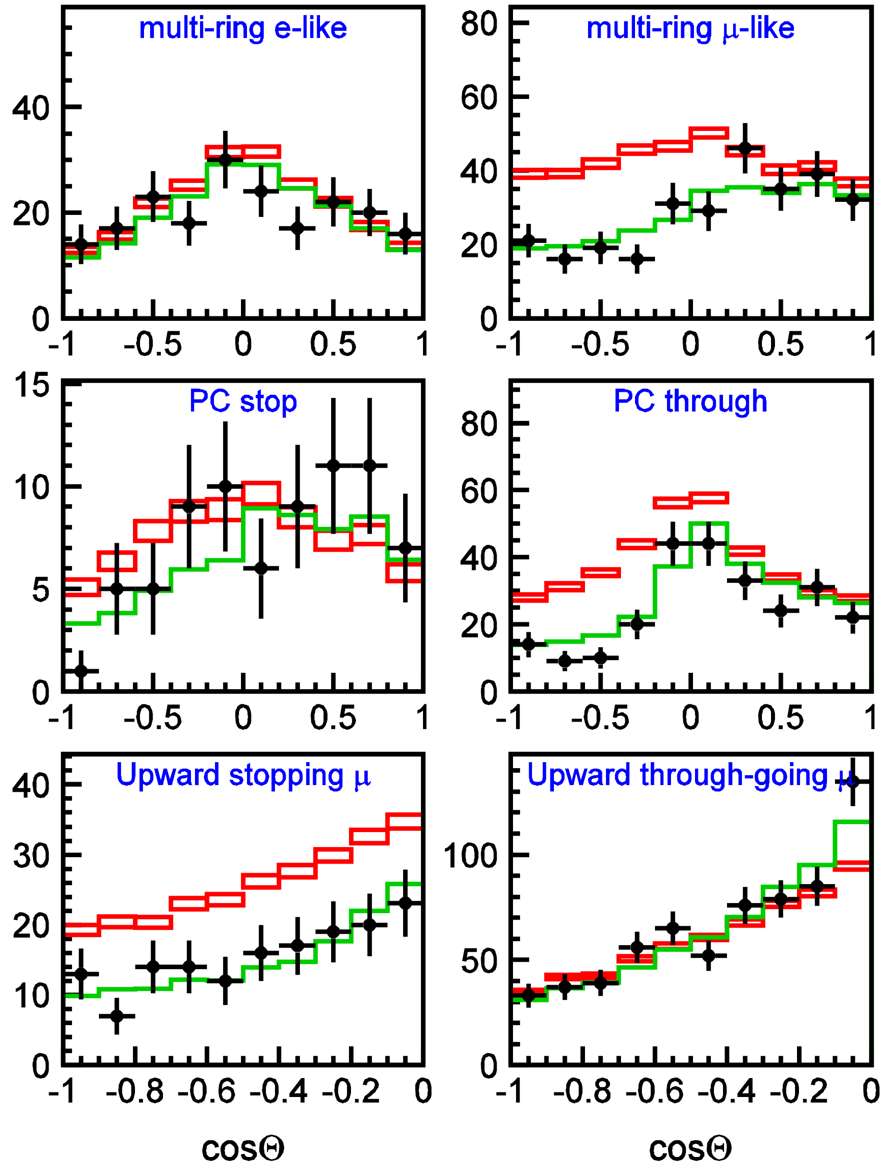
Zenith angle dependence





More Super-Kamiokande samples of atmospheric neutrinos

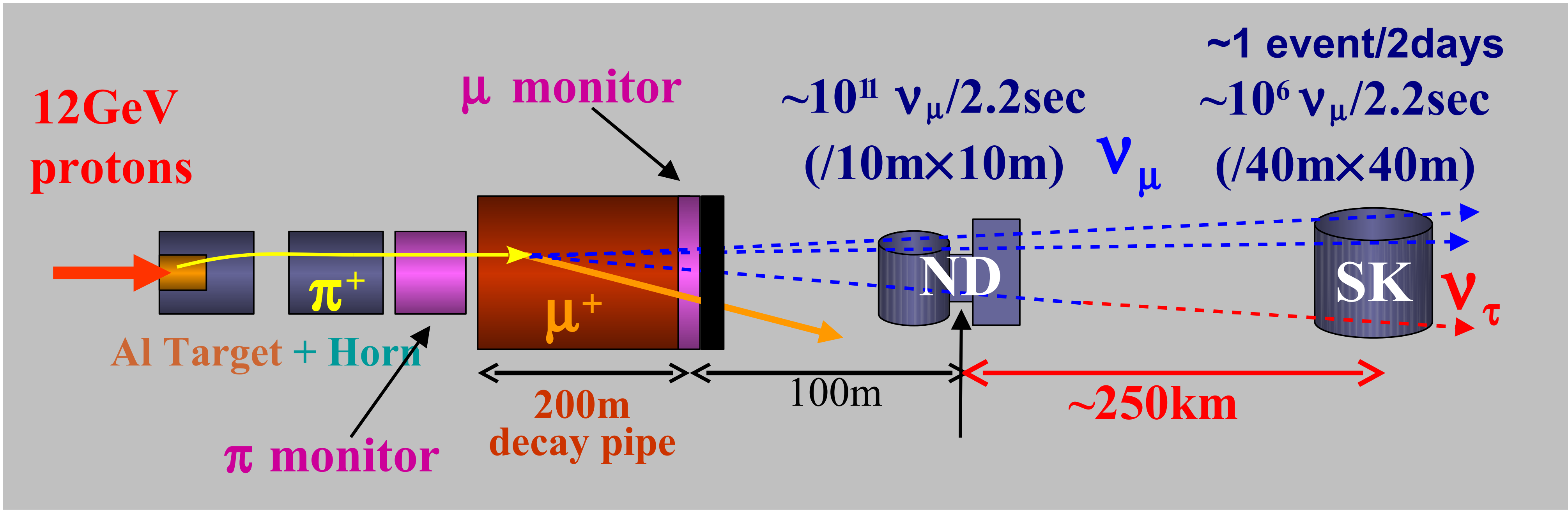
SK-II



Long Baseline per confermare le oscillazioni dei neutrini atmosferici ad un acceleratore

Che distanza? Quale energia ?

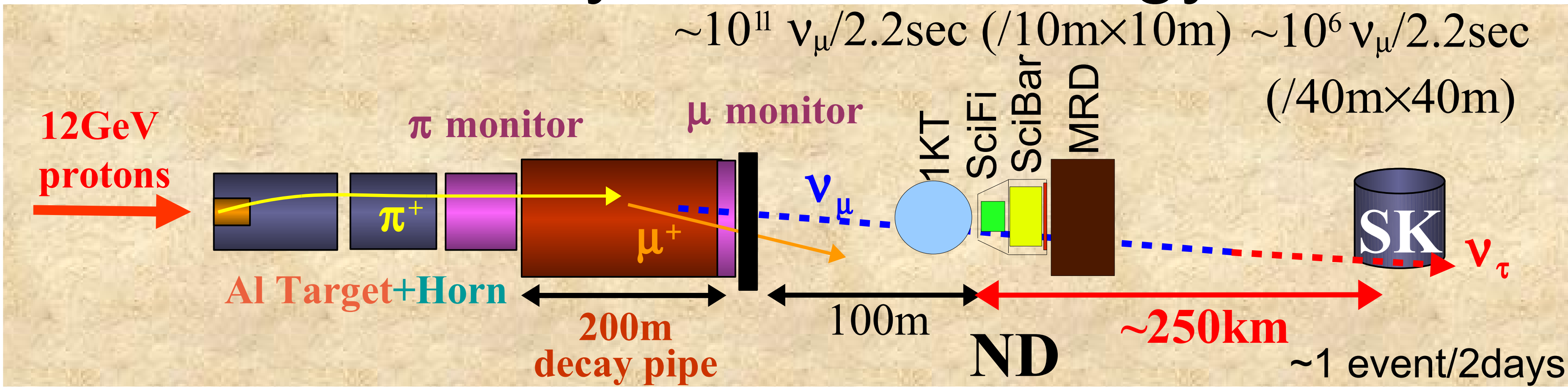
K2K Conceptual Layout



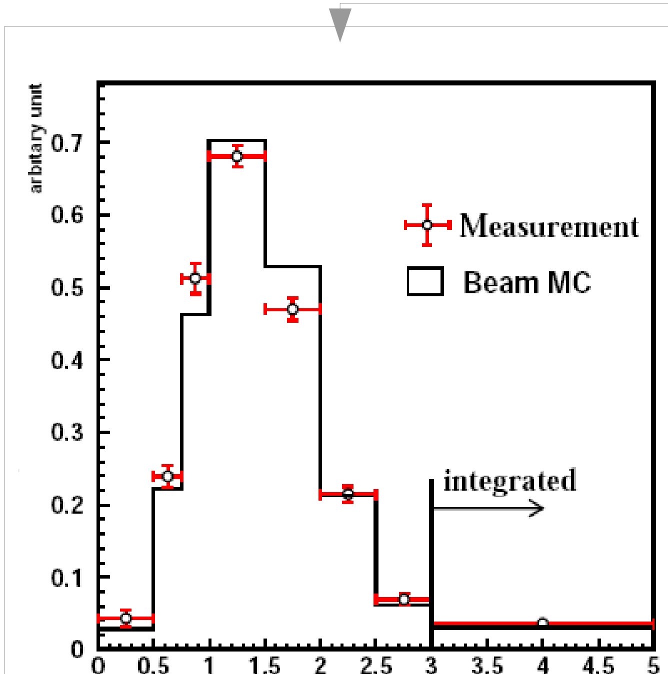
Signature of neutrino oscillation

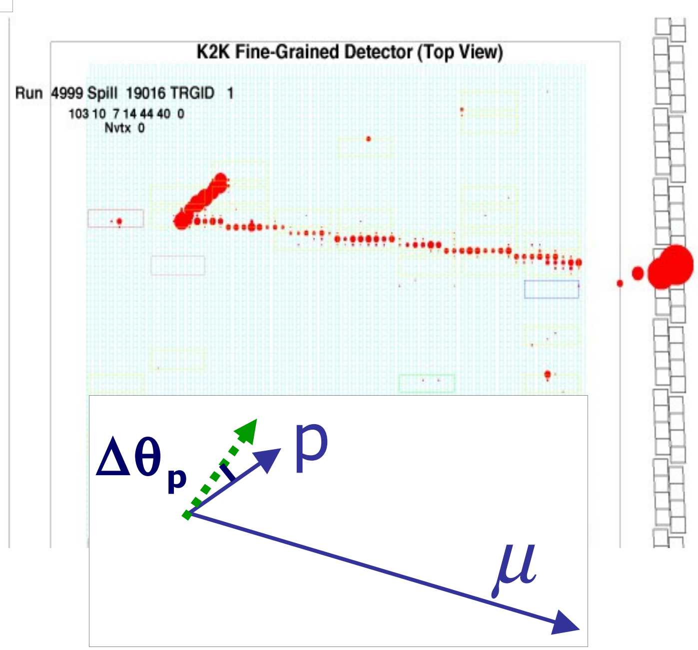
1. Reduction of ν_μ events
2. Distortion of ν_μ energy spectrum

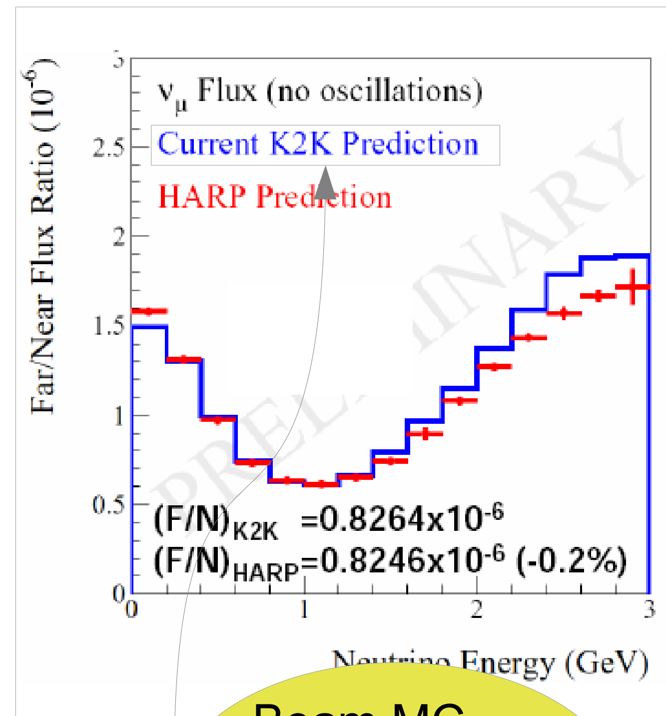
K2K Layout and Strategy



Combined (1KT,SciFi,SciBar) fit of Pμ,θμ distributions





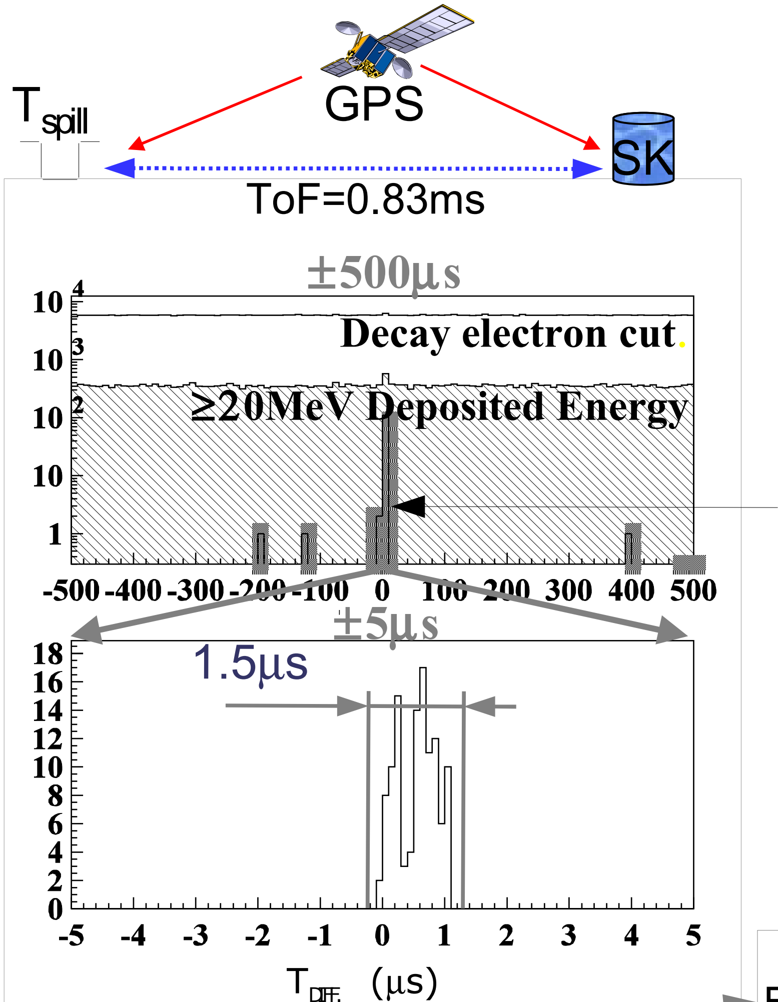


Near detector flux

Far detector flux

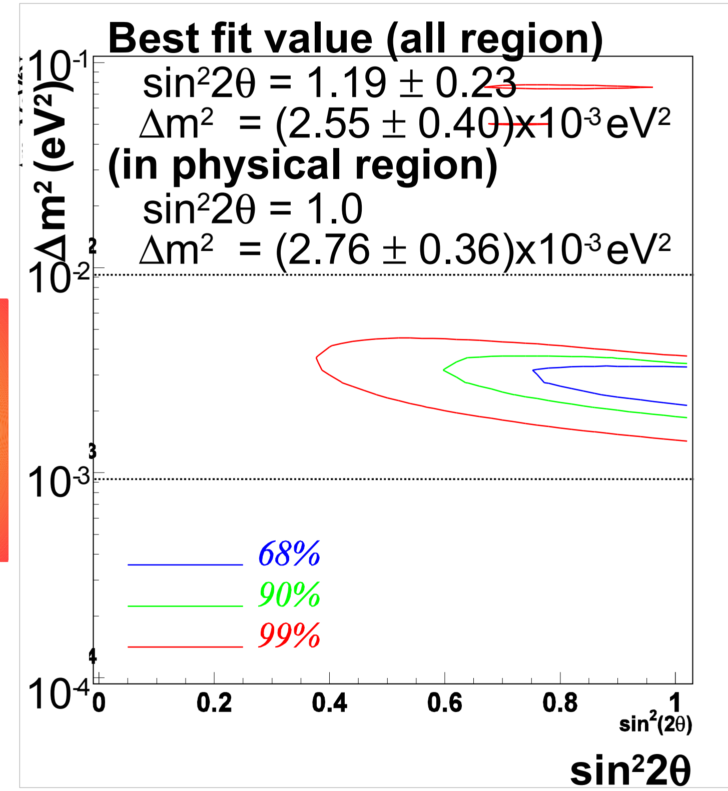
Beam MC
PIMON
Hadronic models
Hadropr. exp.

K2K Result



No Activity in Outer Detector
Event Vertex in Fiducial Volume
More than 30MeV Deposited Energy

No Oscillation 0.003% 4.2σ

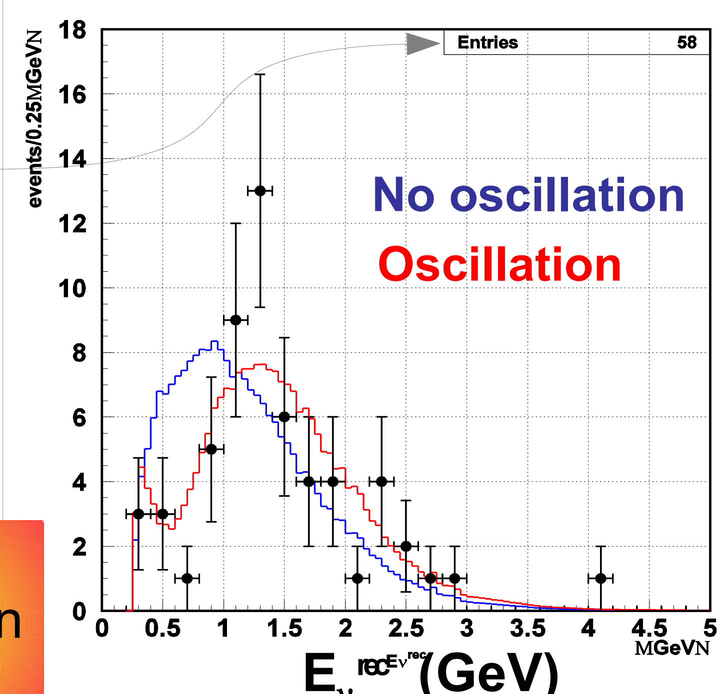


$$E_\nu^{rec} = \frac{(m_N-V)E_\mu - m_\mu^2/2 + m_N V - V^2/2}{(m_N-V) - E_\mu + p_\mu \cos\theta_\mu}$$

K2K	DATA	MC
FC 22.5kt	**112**	**155.9**
1-Ring	**67**	**99.0**
1-R μ-like	**58**	**90.8**
1-R e-like	**9**	**8.2**
Multi Ring	**45**	**56.8**

+11.5 (7.4%)
-10.2 (6.5%)

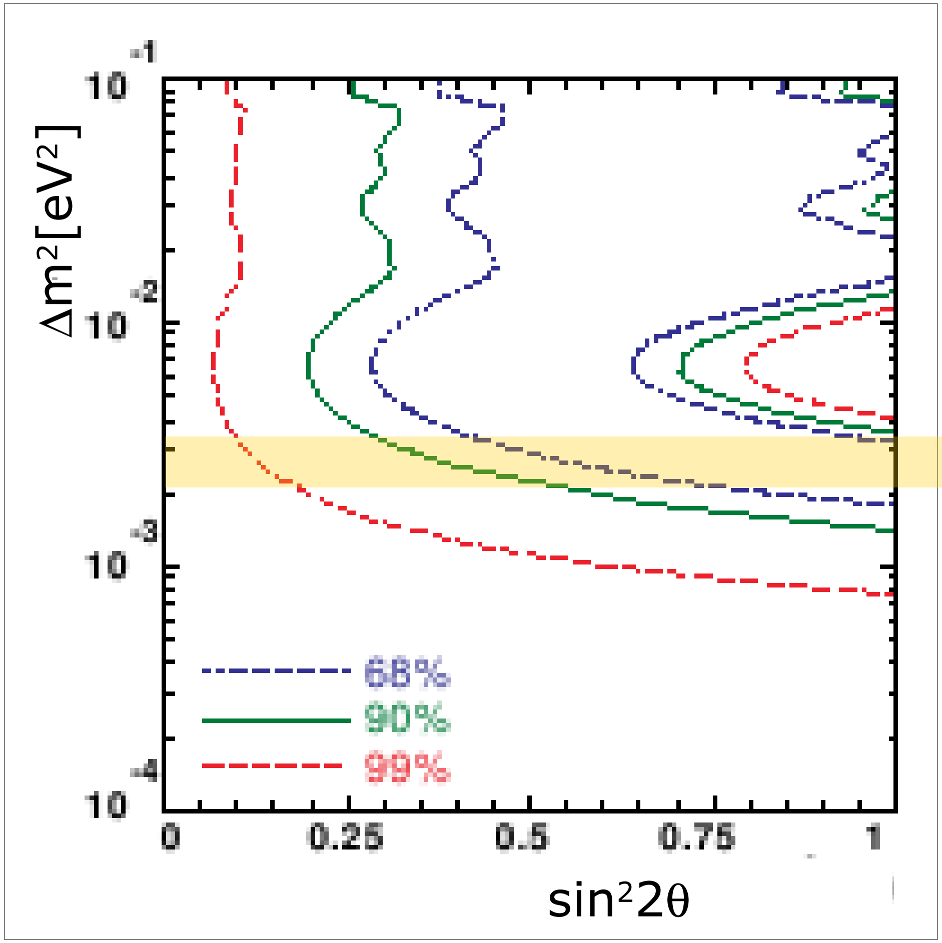
Absolute Deficit 3.1σ



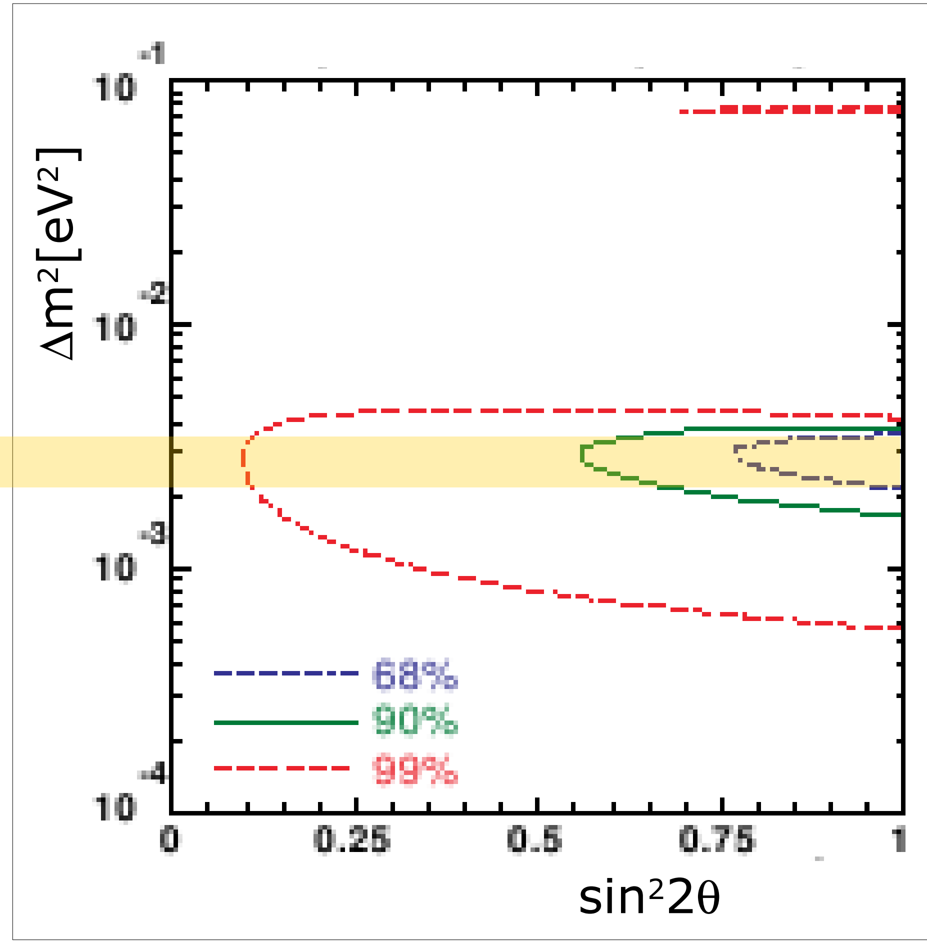
Shape Distortion 2.8σ

Disappearance & Shape

ABSOLUTE DEFICIT

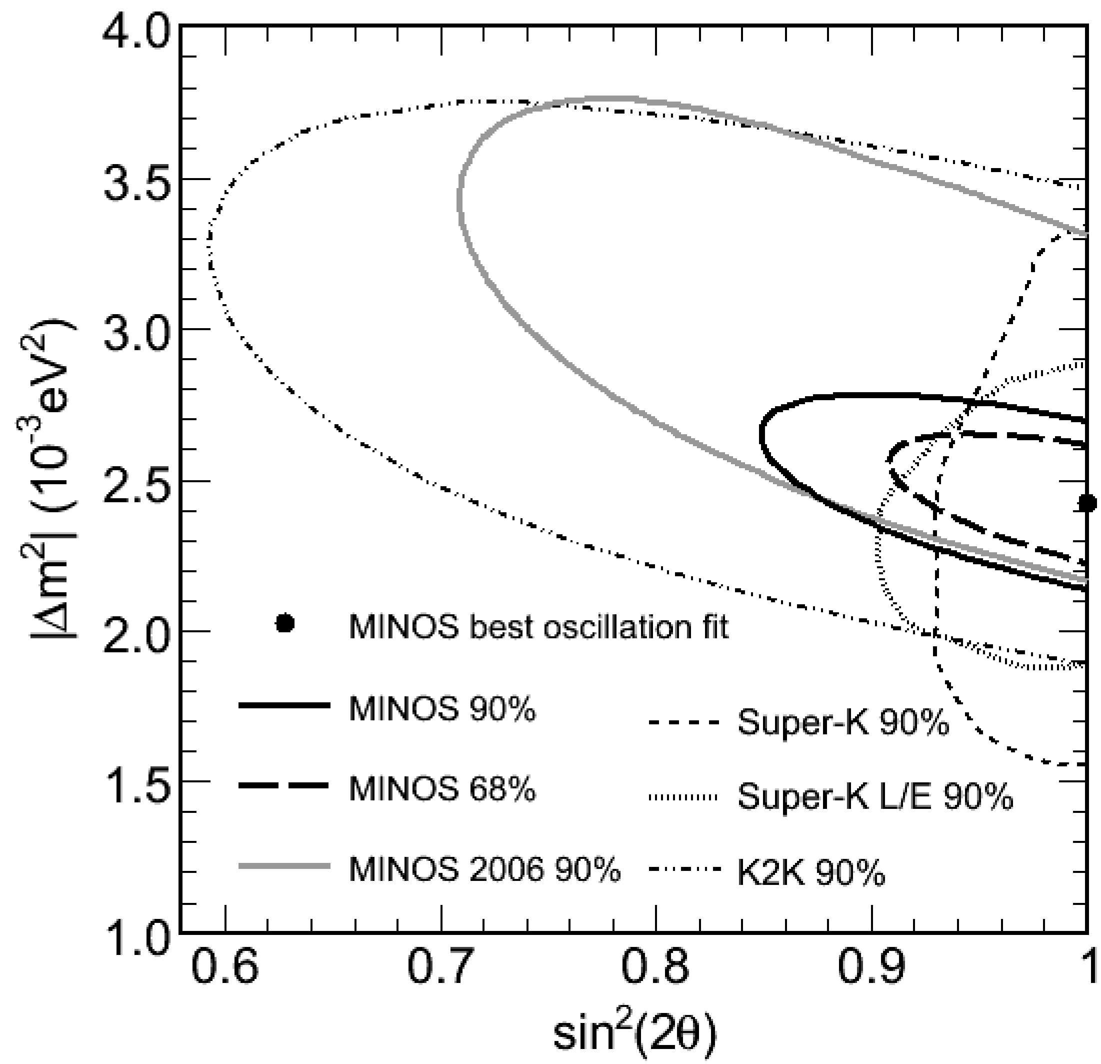


ENERGY SPECTRUM DISTORTION



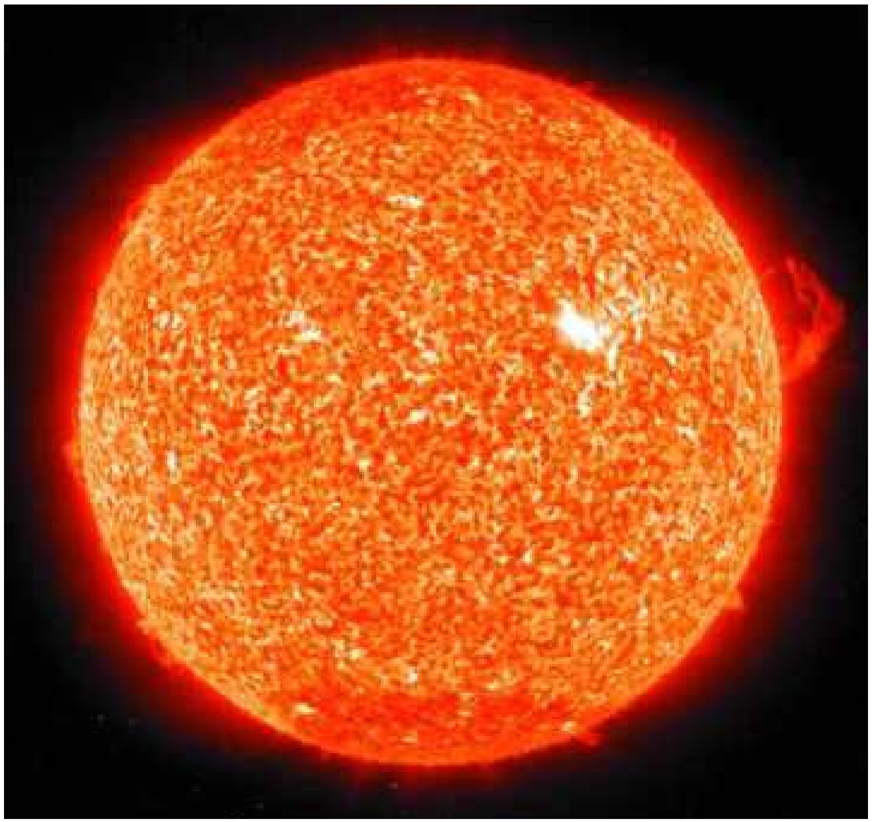
Allowed regions from ν_μ disappearance and distortion of E_ν spectrum are consistents

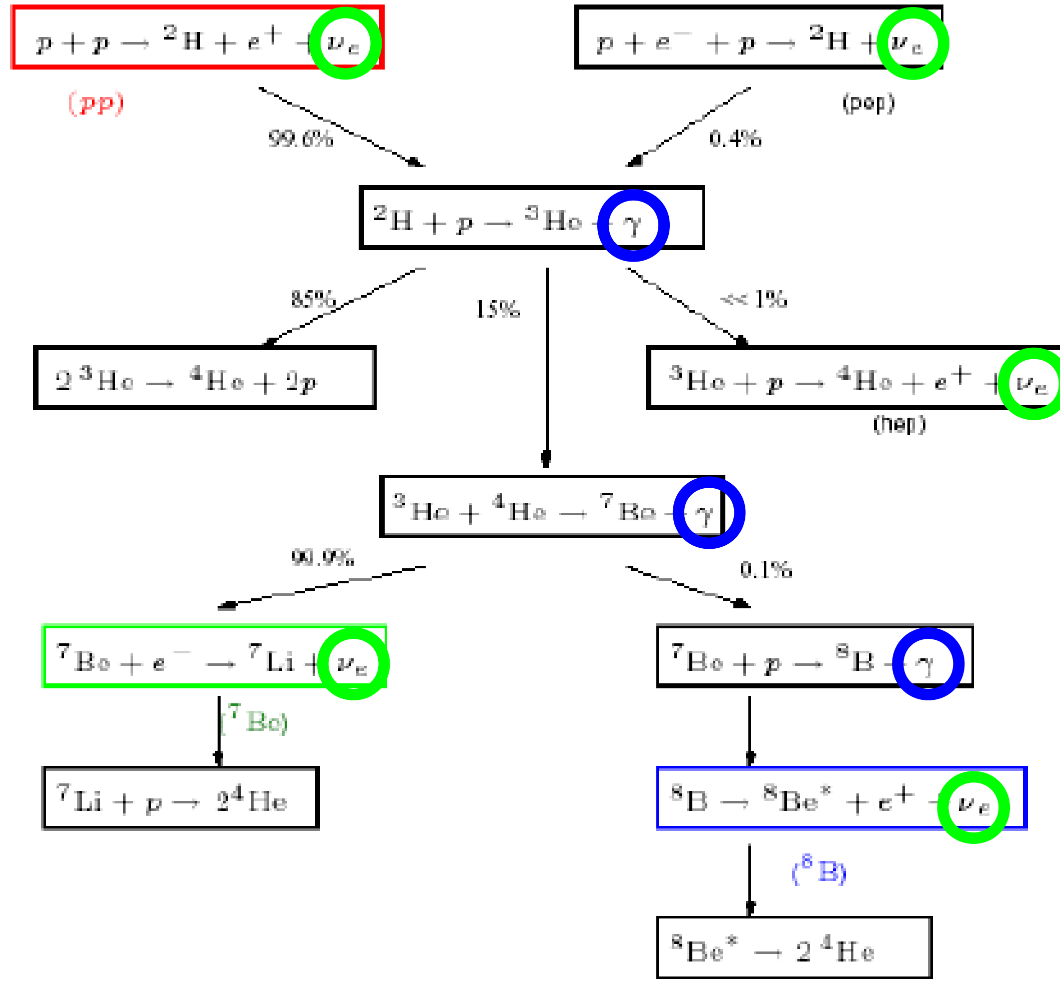
Minos (Fermilab→Soudan)



Neutrino from the Sun

The Standard Solar Model (SSM) predicts the power radiated by the Sun from fusion reactions in its core





98.5% of the Sun power comes from the pp reaction: $4\,p \to 4He + 2e^+ + 2\nu_e + 26.7$ MeV

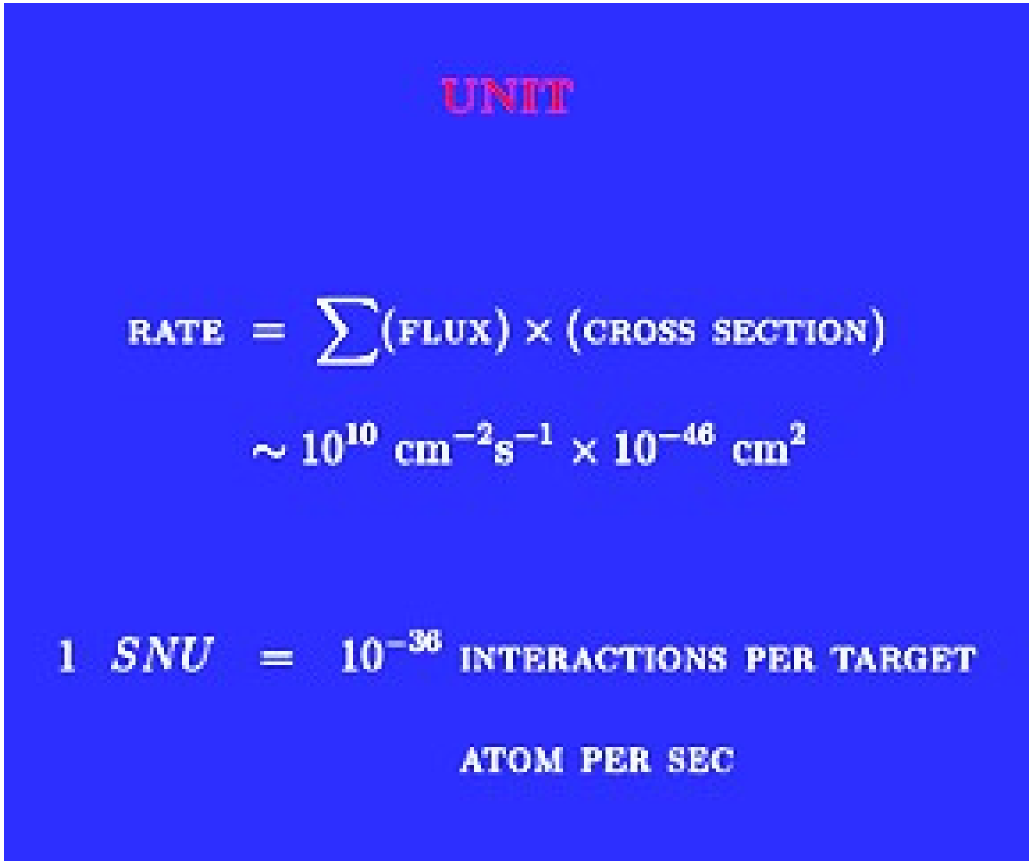
$L_\odot = 3.9\ 10^{26}\ Js^{-1}$

$D = 1.5\ 10^{11}$ m

$Q = 26.7$ MeV $= 4.3\ 10^{-12}$ J

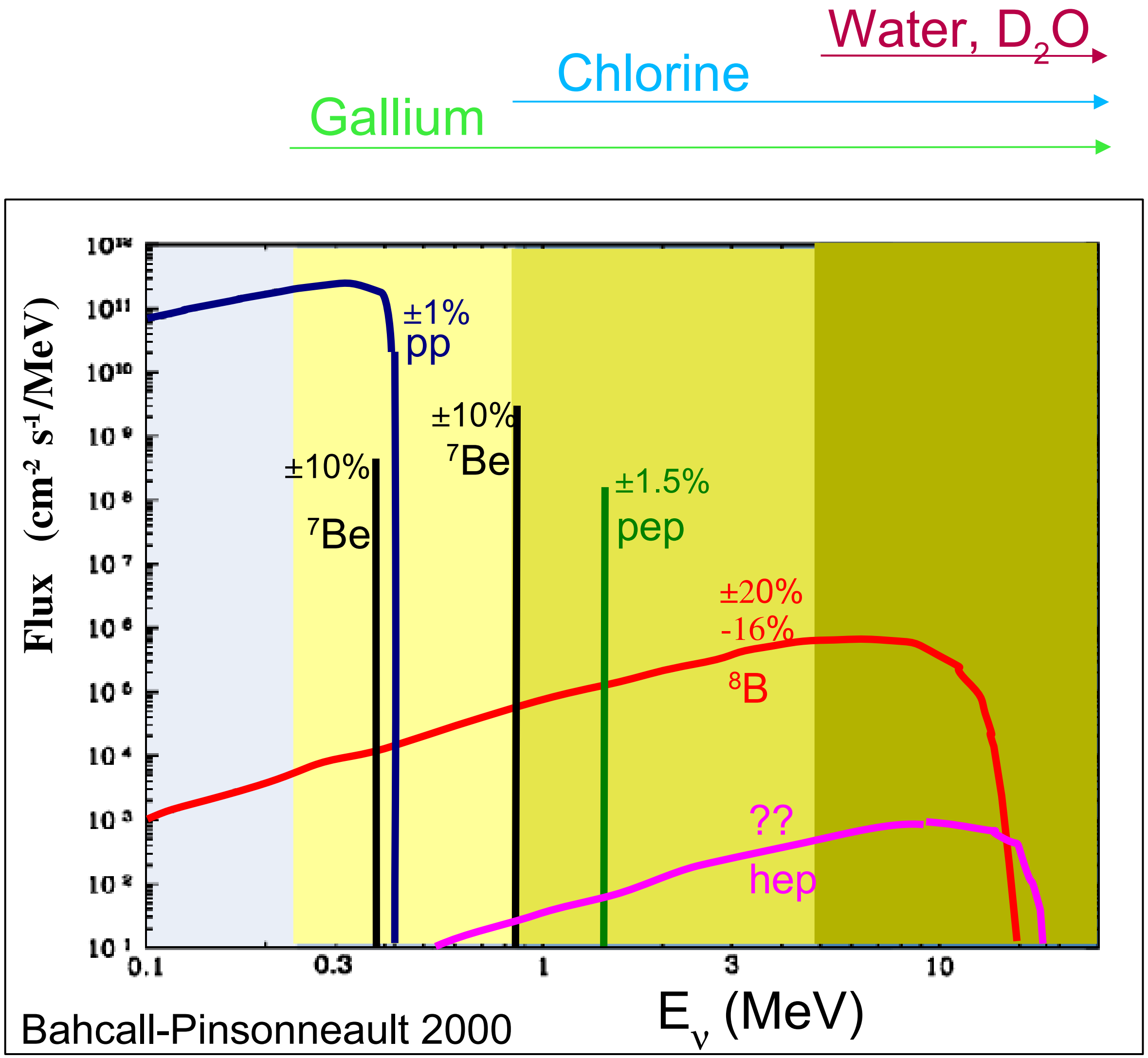
$$\Phi_\odot = 2L_\odot / Q \bullet (1/4\pi D^2) \approx 6.5\ 10^{10}\ cm^{-2}\ s^{-1}$$

SNU – Solar Neutrino Unit



Per avere 1 interazione al giorno sono necessari O(1030) nuclei bersaglio, cioè O(106) mol, rivelatori di masse dell'ordine del kt

Spettro dei neutrini solari



Chlorine

Homestake

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

Gallium

SAGE, Gallex,GNO

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

Water

Kamiokande, SuperK

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

D_2O

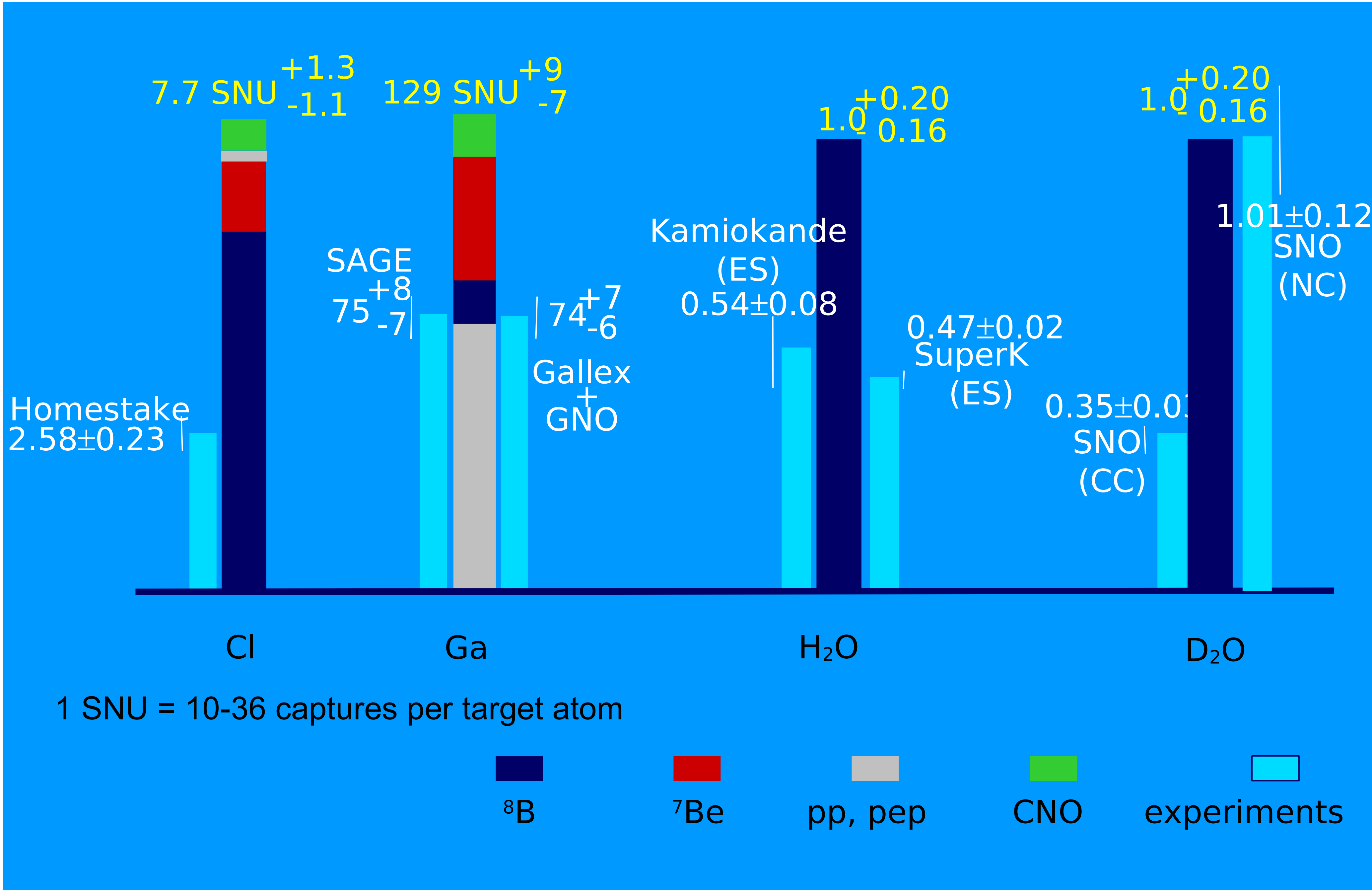
SNO

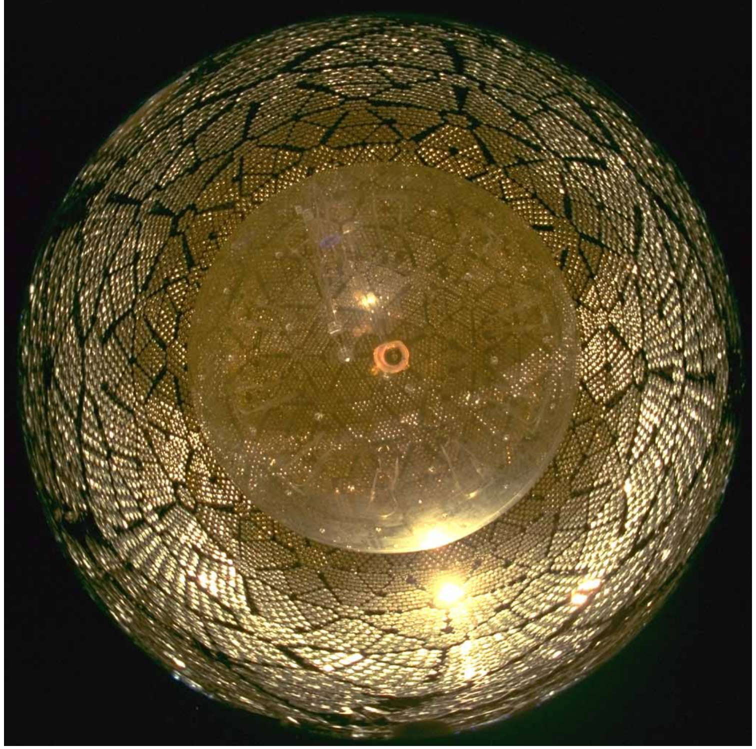
$\nu_x + e^- \rightarrow \nu_x + e^-$ (ES)

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

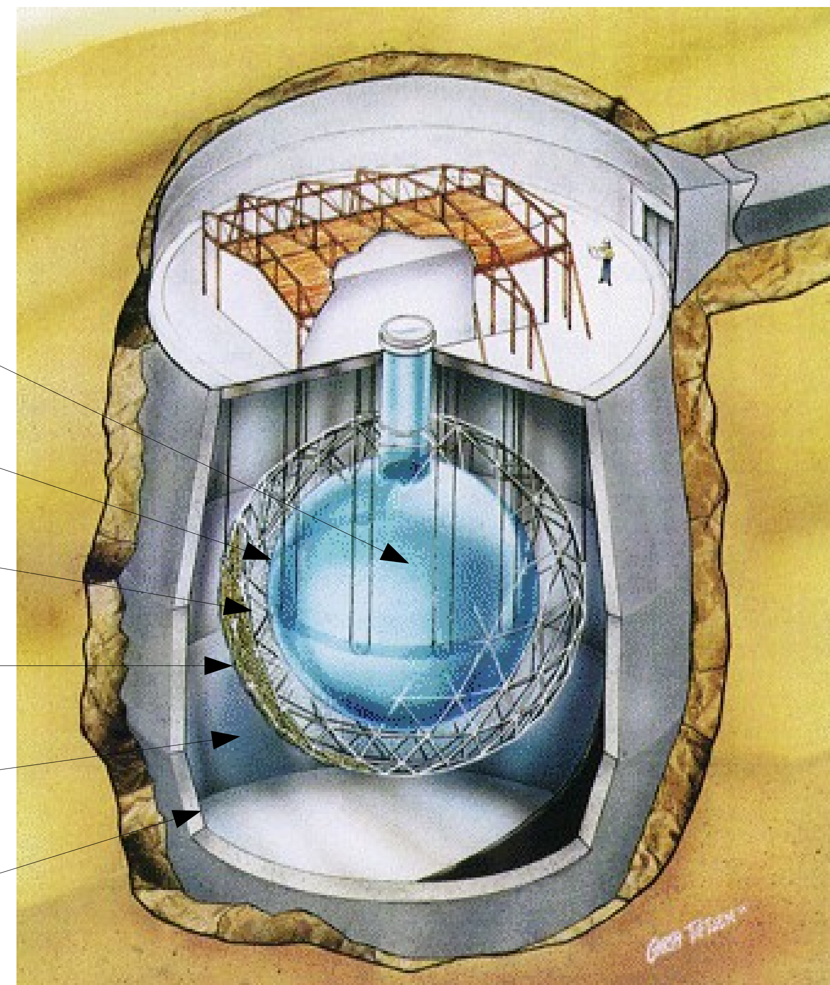
$\nu_x + d \rightarrow n + p + \nu_x$ (NC)

Misure del flusso dei neutrini solari





Sudbury Neutrino Observatory (SNO)



1000 tonnes D_2O

12 m Diameter Acrylic Vessel

1700 tonnes Inner Buffer H_2O

9500 PMTs, 60% coverage

5300 tonnes Outer Shield H_2O

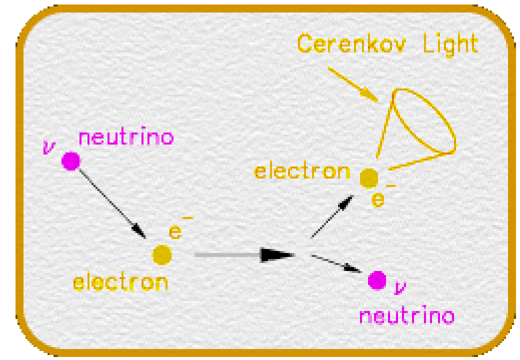
Urylon Liner and Radon Seal

Neutrino interactions in SNO

ES

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

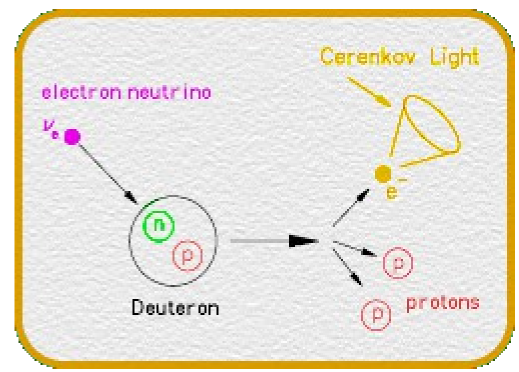
- In SNO (D_2O) as in SK (H_2O)
- Mainly ν_e but also ν_μ,ν_τ (1:6)
- Strong Θ_ν sensitivity



CC

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

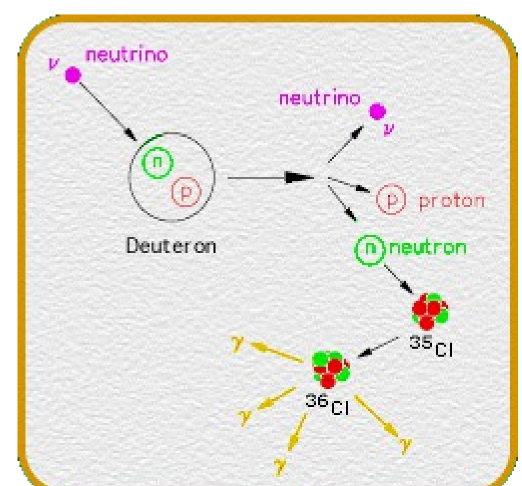
- Good energy measurement
- ν_e only
- Weak directionality: $\propto 1-1/3\cos(\Theta_\nu)$



NC

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

- Equally sensitive to all ν
- Measure the total ^8B flux



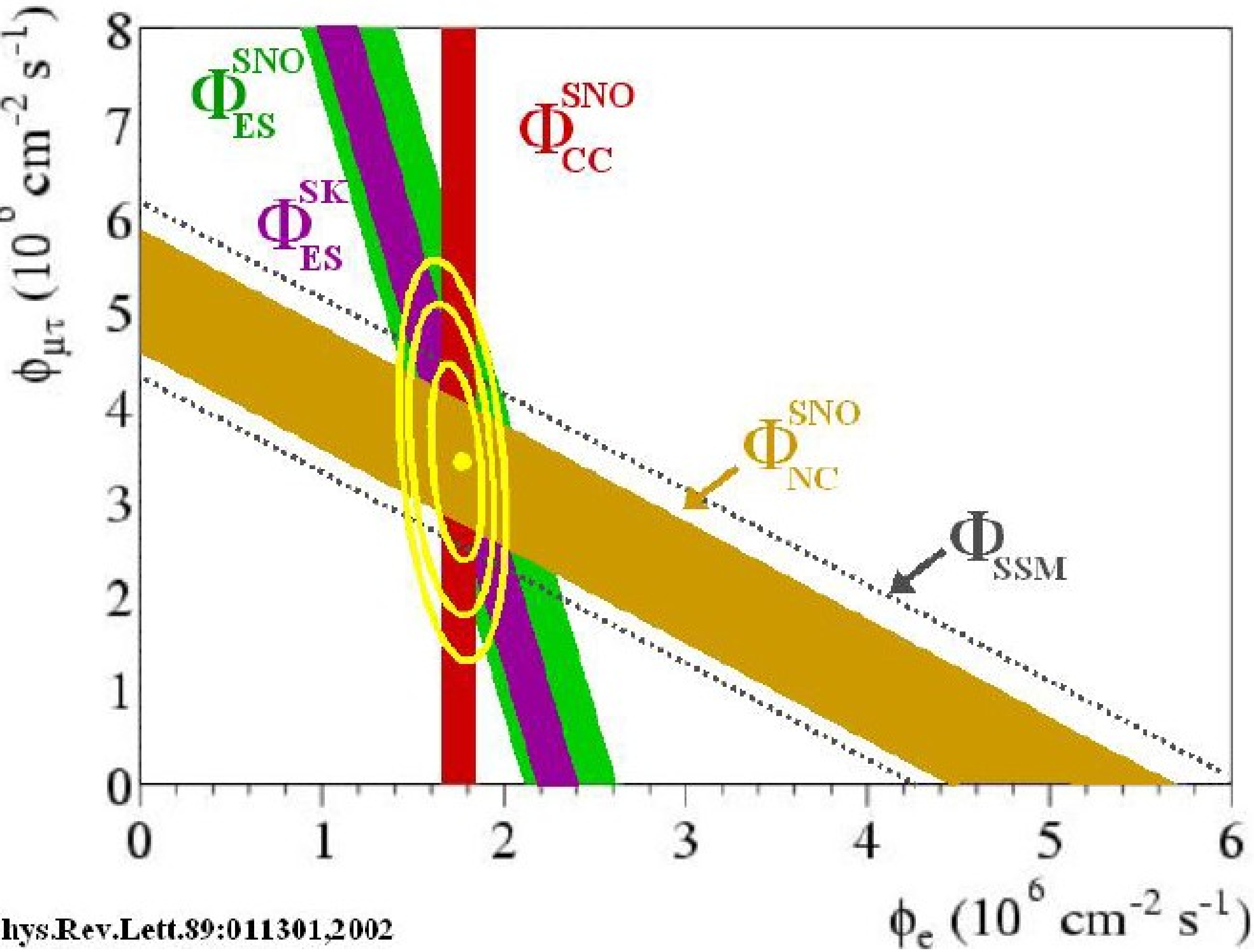
SNO: total flux as expected from SSM

- NC rate as expected from SSM (all neutrinos)
- CC rate (only ν_e) is 0.31 SSM
- ES rate is consistent with Super-Kamiokande and oscillation into ν_μ,ν_τ

$$\Phi_{CC} = 1.59^{+0.10}_{-0.11} \cdot 10^{-6} cm^{-2} s{-1}$$

$$\Phi_{ES} = 2.21^{+0.33}_{-0.28} \cdot 10^{-6} cm^{-2} s{-1}$$

$$\Phi_{ES} = 5.21 \pm 0.47 \cdot 10^{-6} cm^{-2} s{-1}$$



Phys.Rev.Lett.89:011301,2002

Neutrino differents from ν_e coming from the Sun ! (2002)

Oscillazioni con anti-neutrini da reattore

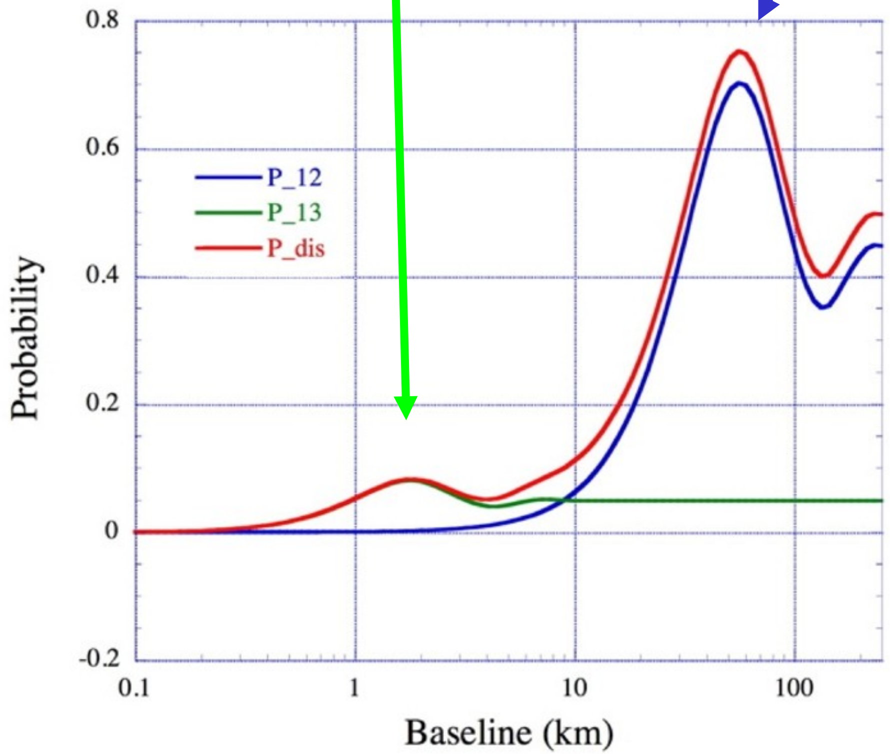
Probabilità di sparizione

$$P_{dis} \approx \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{\Delta m^2_{13} L}{4E_\nu}\right) + \cos^4\theta_{13} \cdot \sin^2 2\theta_{12} \cdot \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)$$

Small oscillation (due to θ_{13})
< 2 km

Large oscillation (due to θ_{12})
> 50 km

Osc. prob. (integrated over E_ν) vs distance



$\bar{\nu}_e$ disappearance at short baseline(~2 km): unambiguous measurement of θ_{13}

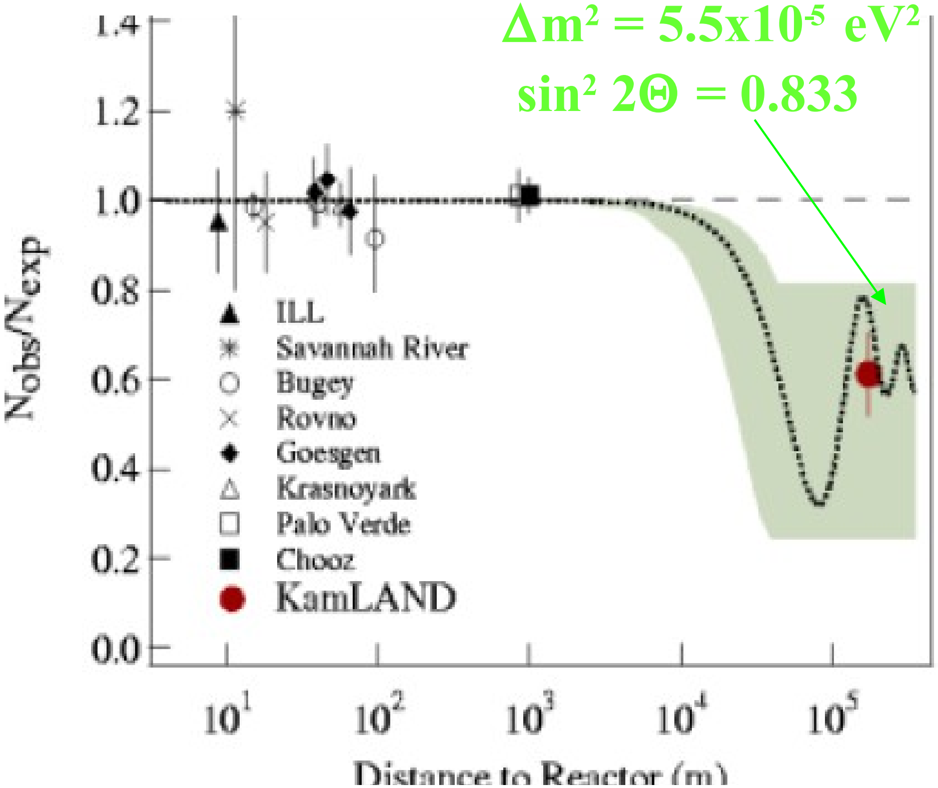
$\sin^2 2\theta_{13} = 0.1$
$\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2
$\sin^2 2\theta_{12} = 0.825$
$\Delta m^2_{21} = 8.2 \times 10^{-5}$ eV^2

Reactor oscillation experiments

Several generations of short baseline reactor experiments have set upper limits

Chooz (France) set limits on $\bar{\nu}_e \rightarrow \bar{\nu}_e$ at <E>~6MeV, L~1Km

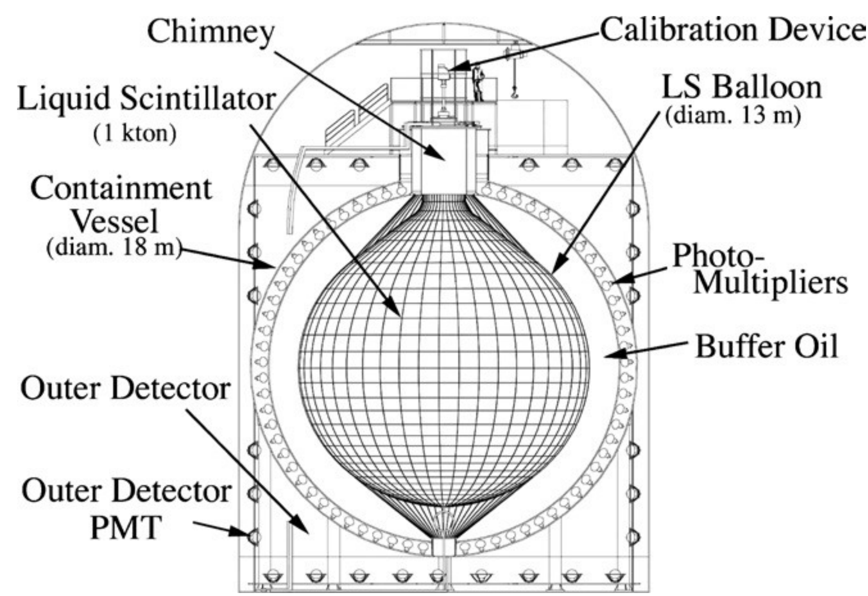
$\sin^2 2\theta_{13} < 0.17$ for large Δm^2_{13} and $\Delta m^2_{13} < 8 \cdot 10^{-4}$ for maximal mixing



Kamland in Kamioka mine (Japan), first long baseline reactor experiment

Sensitive to many reactors with <L>~175Km

Observed/Expected = 0.611 ± 0.085 ± 0.041

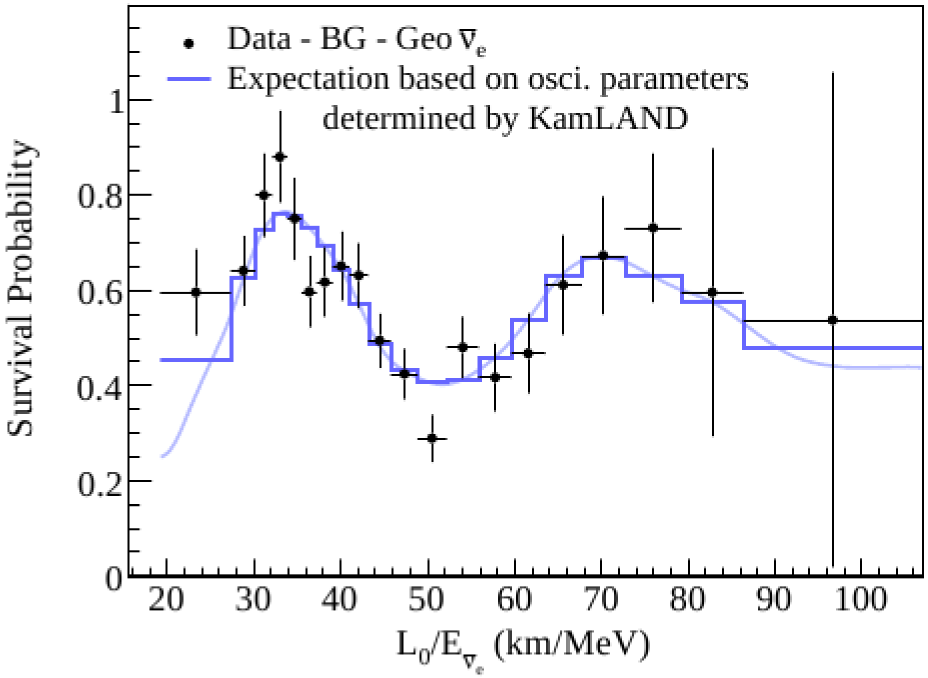


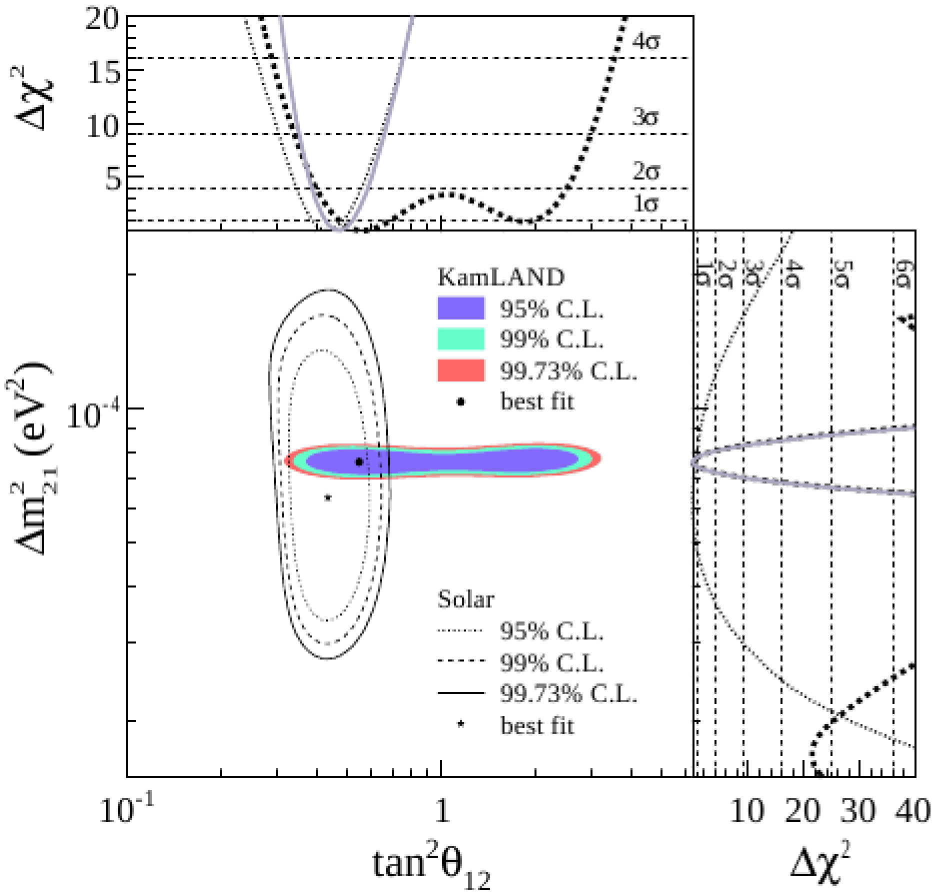
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = \cos^4\theta_{13}\left[1 - \sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{12} L}{4E_\nu}\right]$$

$$\Delta m^2_{12} = 7.58^{+0.14}_{-0.13} \pm 0.15 \cdot 10^{-5} eV^2$$

$$\tan^2\theta_{12} = 0.56^{+0.10+0.10}_{-0.07-0.06} \longrightarrow \theta_{12} = 36.8°$$

Kamland results (2008)

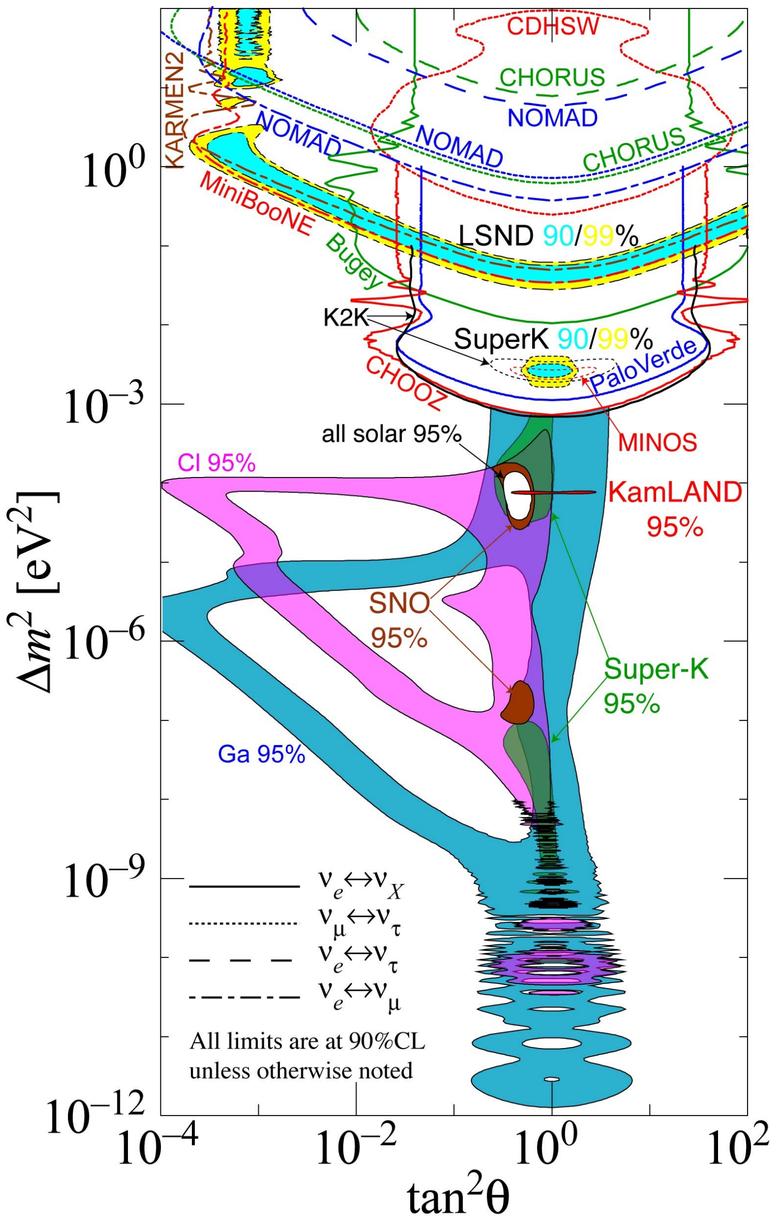




Best oscillation fit simultaneously to Kamland and solar neutrino data:

$$\Delta m^2_{21} = 7.59^{+0.21}_{-0.21} \times 10^{-5}\,\mathrm{eV}^2 \text{ and } \tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

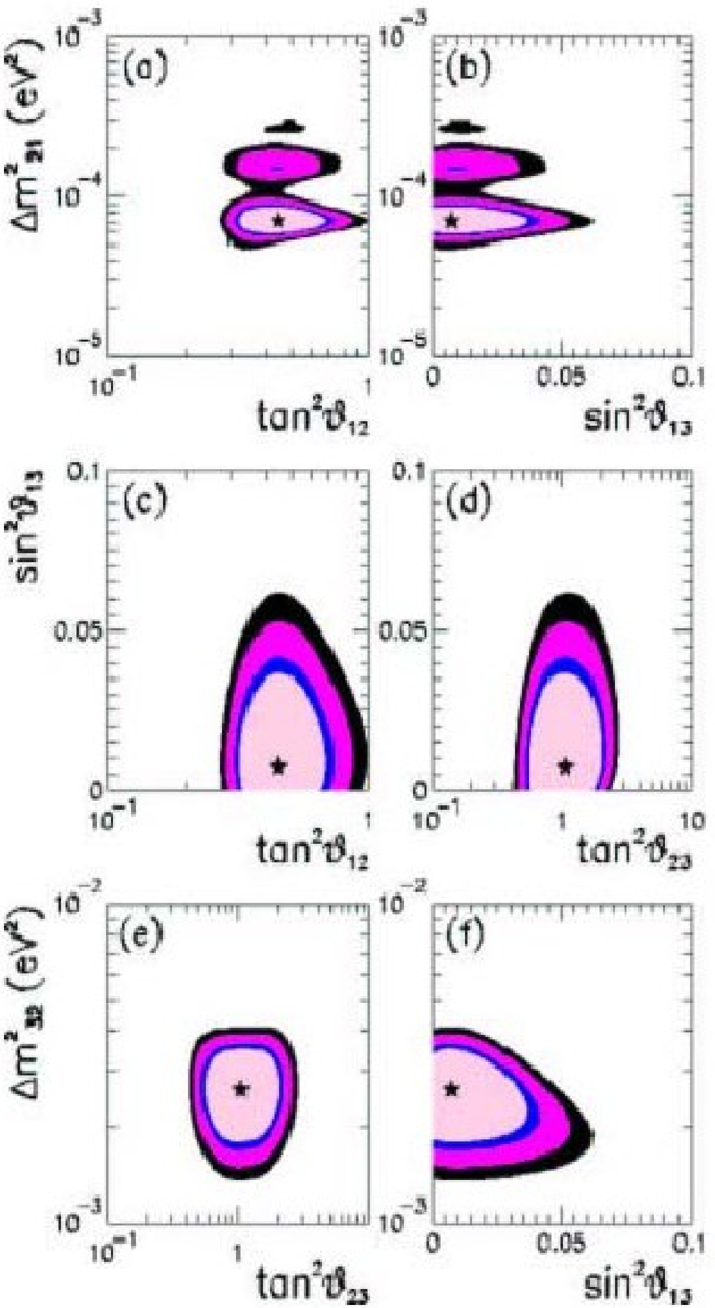
Oscillation data overview



http://hitoshi.berkeley.edu/neutrino

Decades of experimental and theoretical efforts !

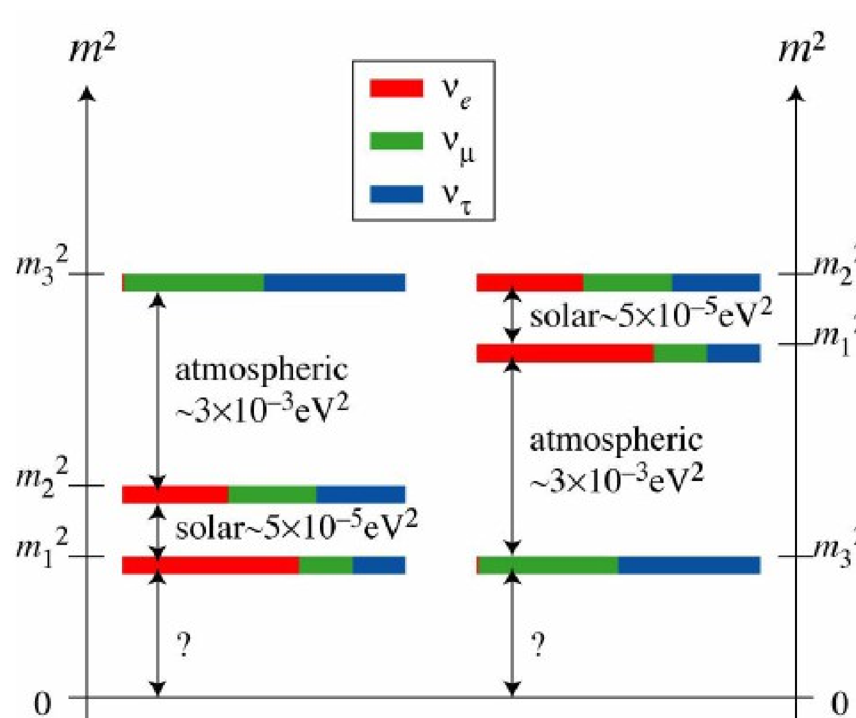
Global fits to oscillation data



A coherent and consistent global picture emerged.

Global fit of neutrino oscillation experiments gives θ_{12} θ_{23} Δm^2_{12} Δm^2_{23}

Still unknown θ_{13},(hints it might be just below the present limit) mass hierarchy, CP δ violation phase



Compiti a casa per i prossimi O(20) anni

- Quanto vale il terzo angolo di mixing θ_{13} ?
- Ci sono neutrini sterili ?
- I neutrini sono fermioni di Dirac o di Majorana ?
- Nei leptoni c'è violazione di CP ?
- E' la leptogenesi l'origine dell'asimmetria materia/antimateria ?
- Quali sono le proprietà elettromagnetiche dei neutrini ?
- Osserveremo mai i neutrini “relic” del Big Bang ?
- Saremo sorpresi da risultati inattesi ?

This is the end ?

“There is nothing new to be discovered in physics now.
All that remains is more and more precise measurement.”

Kelvin, c. 1900