Part II

Measuring neutrino parameters

Solar Neutrinos

$4p + 2e^- \rightarrow {}^4He + 2\nu_e + 26.73$ MeV

electron neutrinos are produced

Adiabatic conversion

$F = 6\ 10^{10}\ cm^{-2}\ c^{-1}$

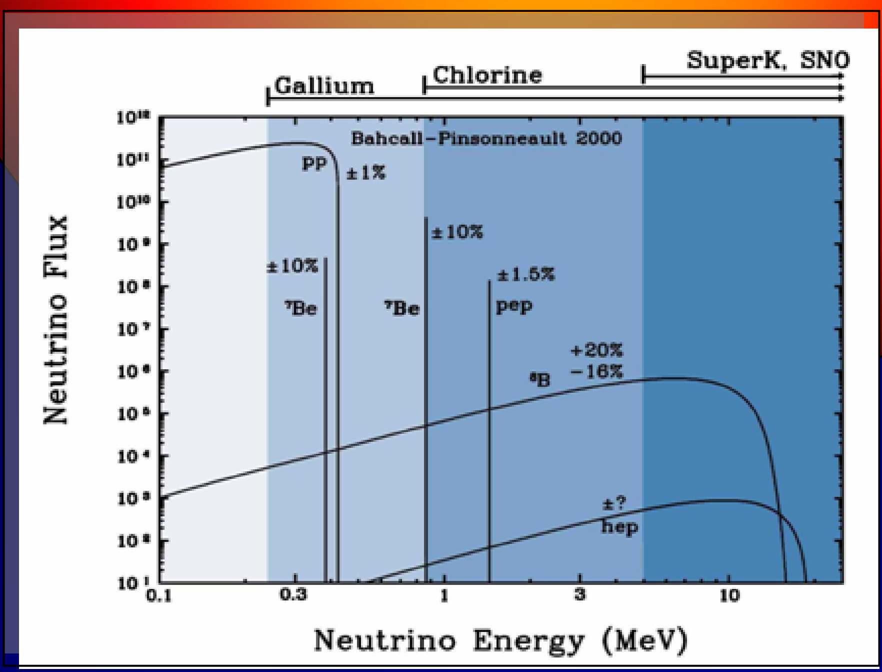
total flux at the Earth

J.N. Bahcall

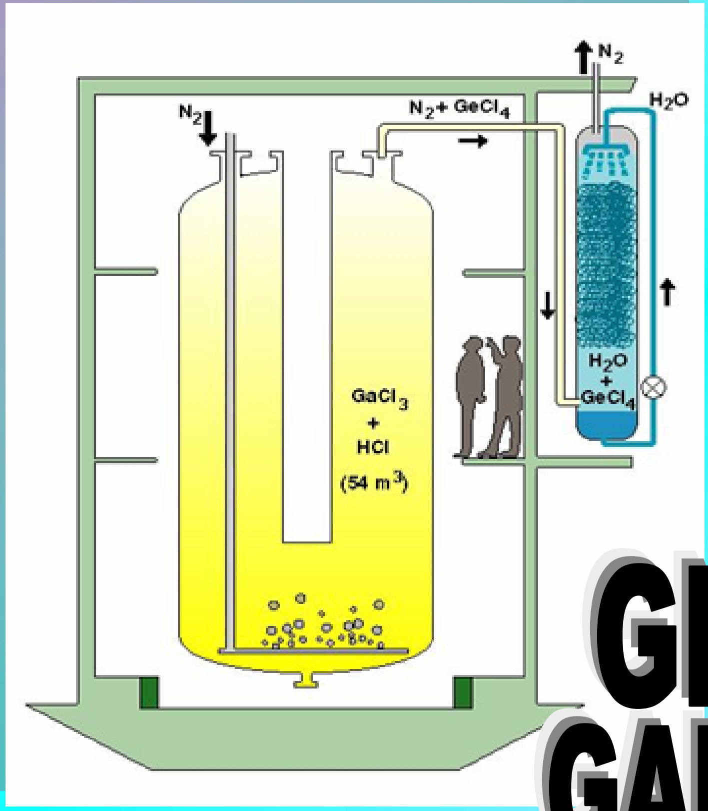
ν

Oscillations in matter of the Earth

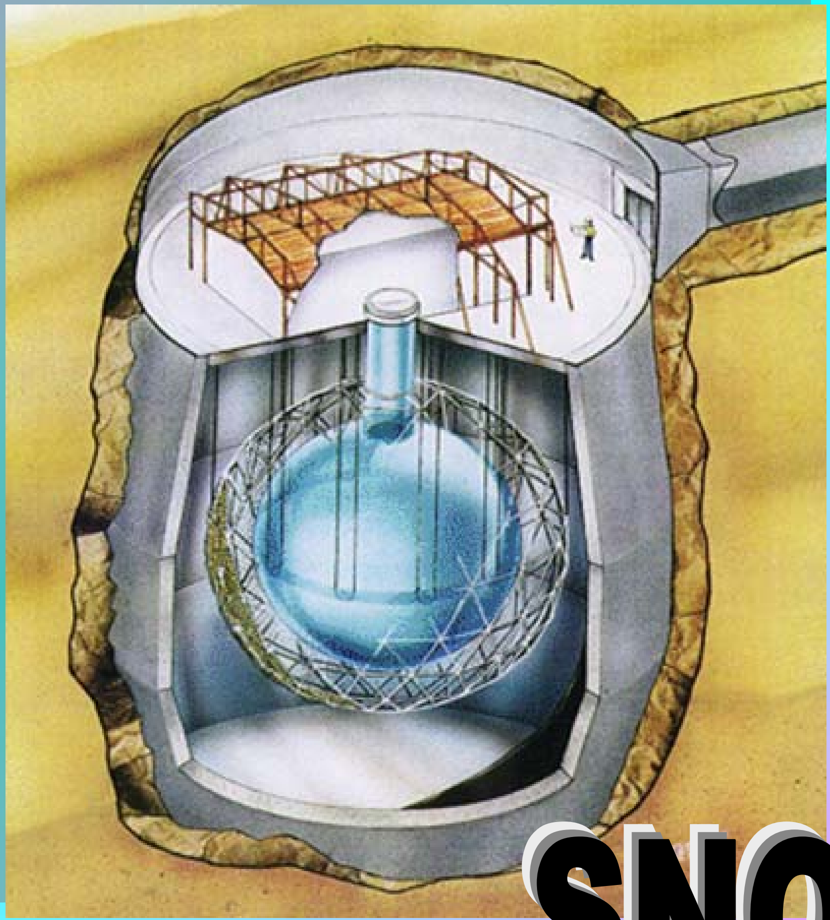
ρ : (150 $\Rightarrow$ 0) g/cc



Homestake
Kamiokande
SAGE

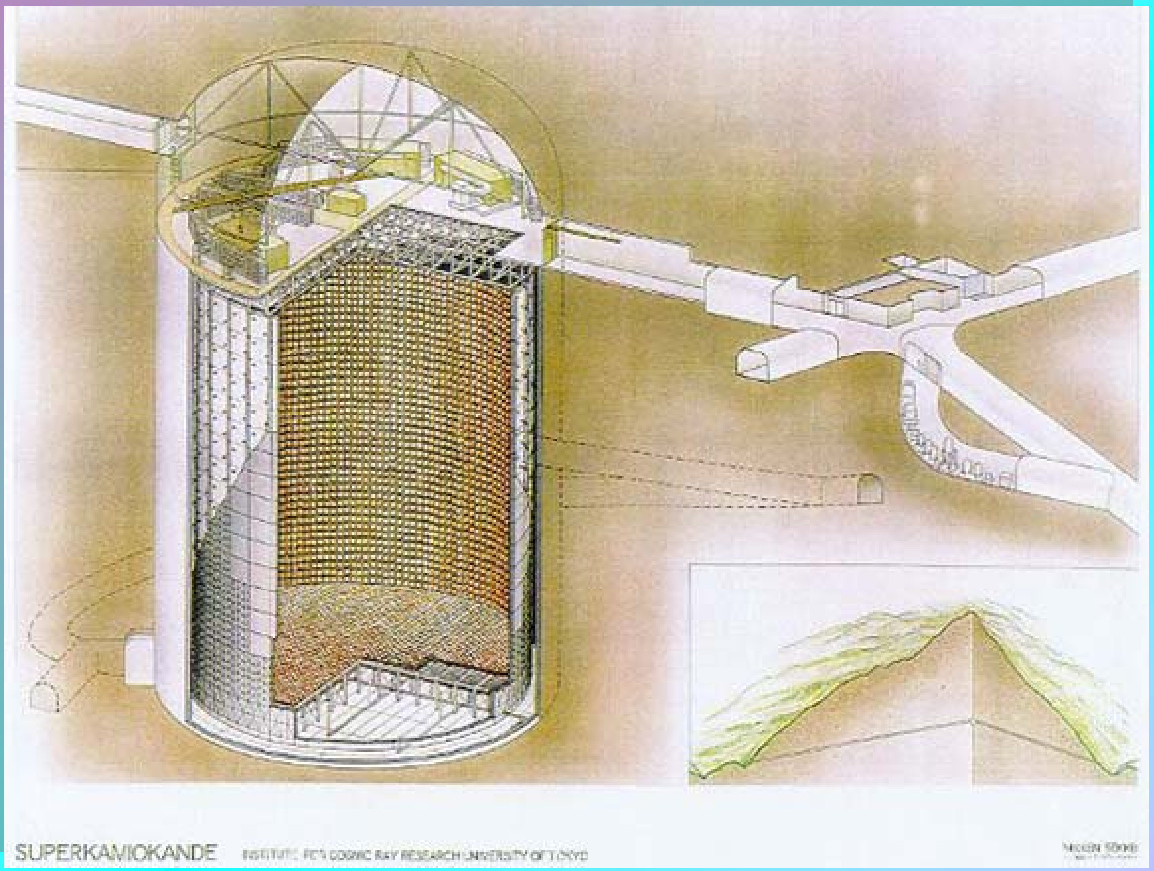


GNO
GALLEX



SNO
SuperKamiokande

SuperKamiokande



Water
Cherenkov detector

$\nu \; e \; \rightarrow \nu \; e$

Experiments and data

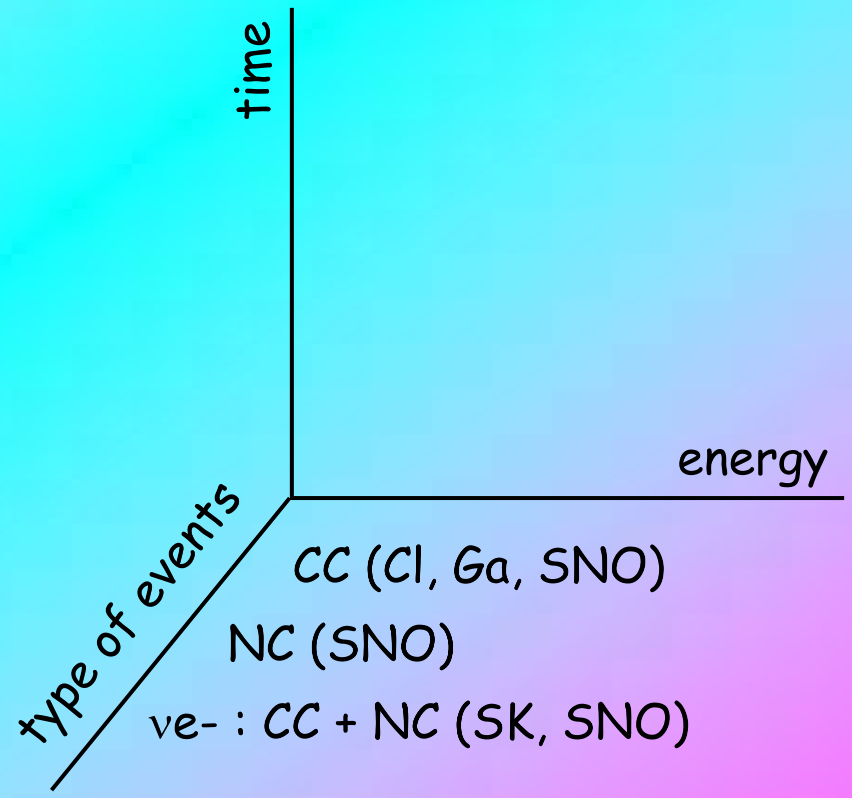
Homestake

SAGE

Gallex, GNO

SuperKamiokande

SNO



Evidence of conversion

1). Deficit of signals in all experiments

2). Indirect evidence of the spectrum distortion - dependence of the suppression factor on energy:

Low energies (Ga): R ~ 0.5 - 0.6

High energies (Cl, SNO, SK): R ~ 0.3

LMA MSW solution

3). CC/NC ~ 0.34

No statistically significant

- distortion of the boron neutrino spectrum (at E > 5 MeV) in SK, SNO
- day-night effect
- time variations apart from annual variations (due to eccentricity of the Earth orbit)

Physics of conversion

1. Adiabaticity

Adiabaticity parameter

$$\gamma(x) = \frac{l_m(x)}{4\pi h(x)} \sim 10^{-4}$$

l_m - oscillation length in matter;
h – height of the density profile

- Corrections are γ^2
- Also relevant for oscillation in the Earth where affect $\sim \gamma$

2. Loss of coherence

3. Oscillations in the matter of the Earth

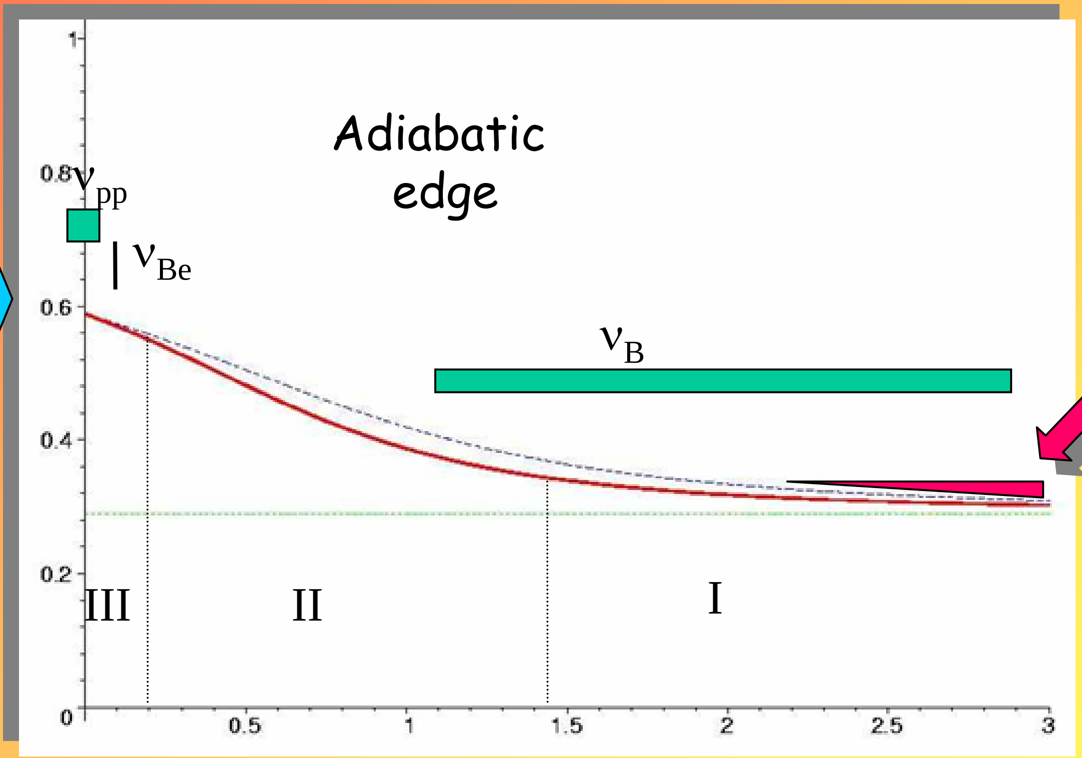
Physical picture

LMA MSW: profile of the effect

Synthetic solution

Survival probability

$1 - 0.5\sin^2 2\theta$



Earth matter effect

$\sin^2\theta$

$l_\nu / l_0 \sim E$

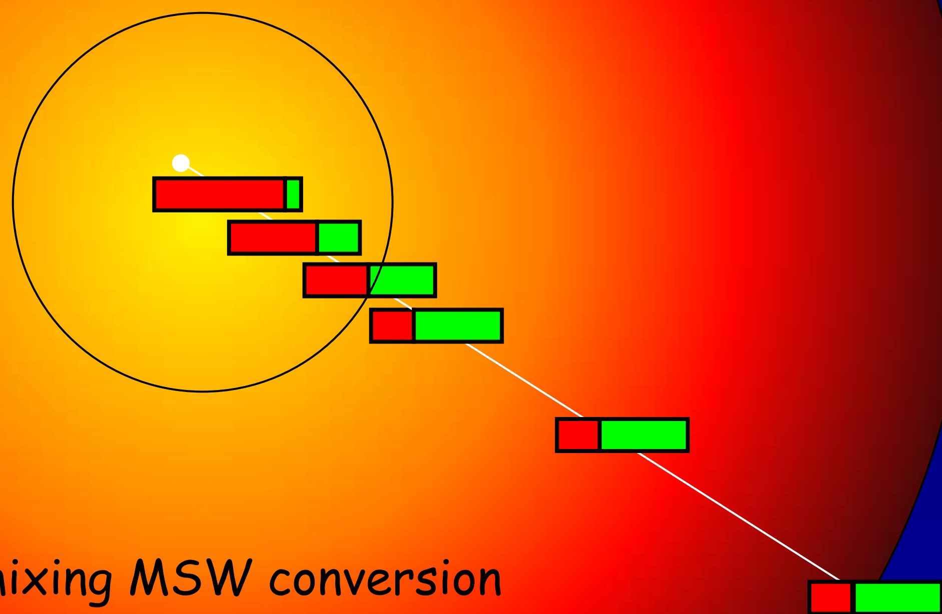
Averaged oscillations with small matter effect

Conversion + oscillations

Conversion with small oscillation effect

Non-oscillatory transition

Solar neutrinos



E = 10 MeV

Resonance layer:

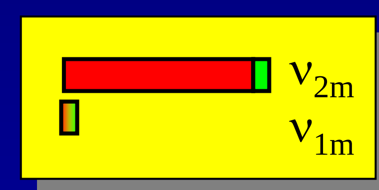
$n_R\, Y_e = 20$ g/cc

$R_R = 0.24\, R_{sun}$

In the production point:

$\sin^2\theta_m^0 = 0.94$

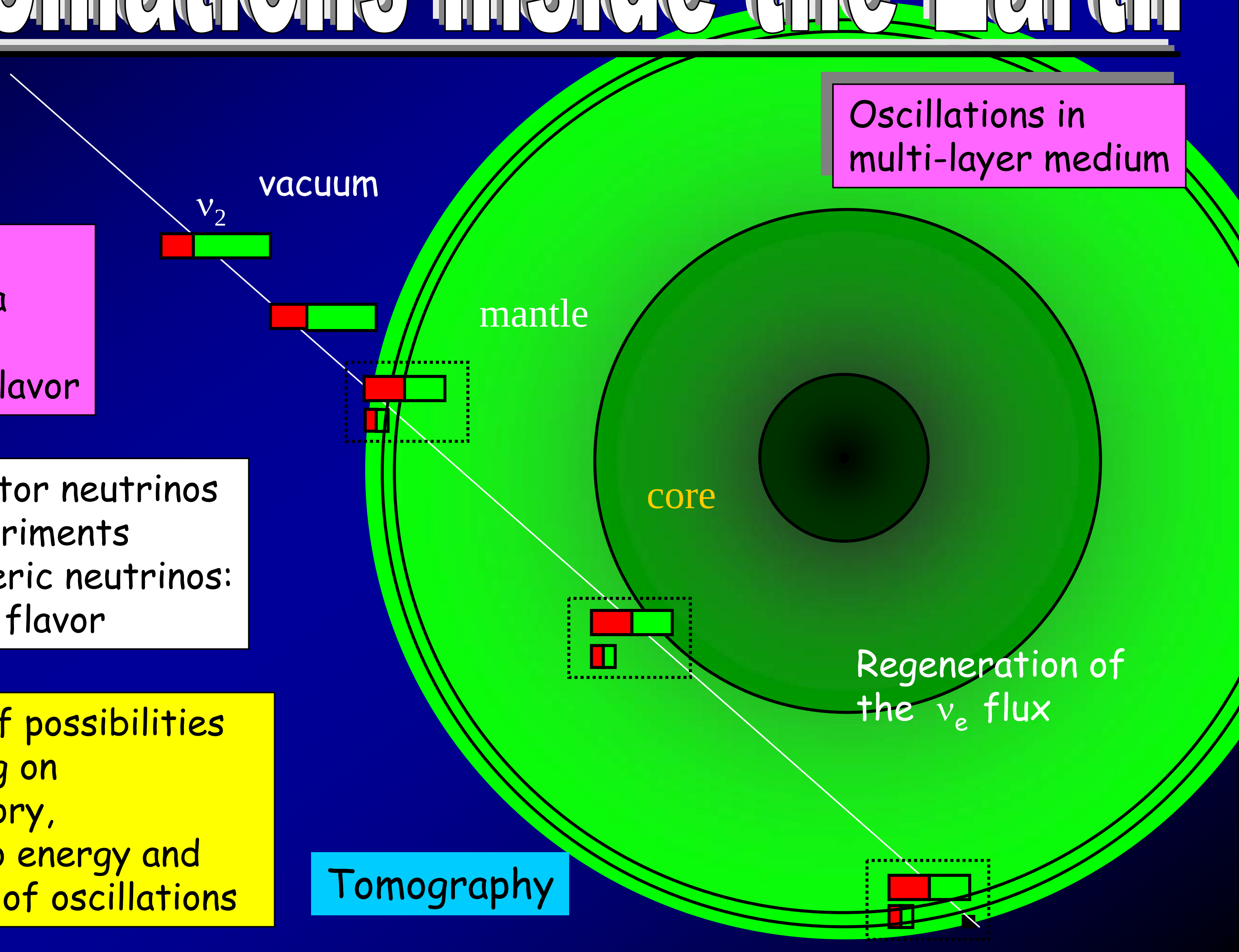
$\cos^2\theta_m^0 = 0.06$



Large mixing MSW conversion provides the solution of the solar neutrino problem (Homestake, Kam...)

Oscillations inside the Earth

Oscillations in multi-layer medium



Solar and supernova neutrinos
mass → flavor

Accelerator neutrinos
LBL experiments
atmospheric neutrinos:
flavor → flavor

Variety of possibilities depending on
- trajectory,
- neutrino energy and
- channel of oscillations

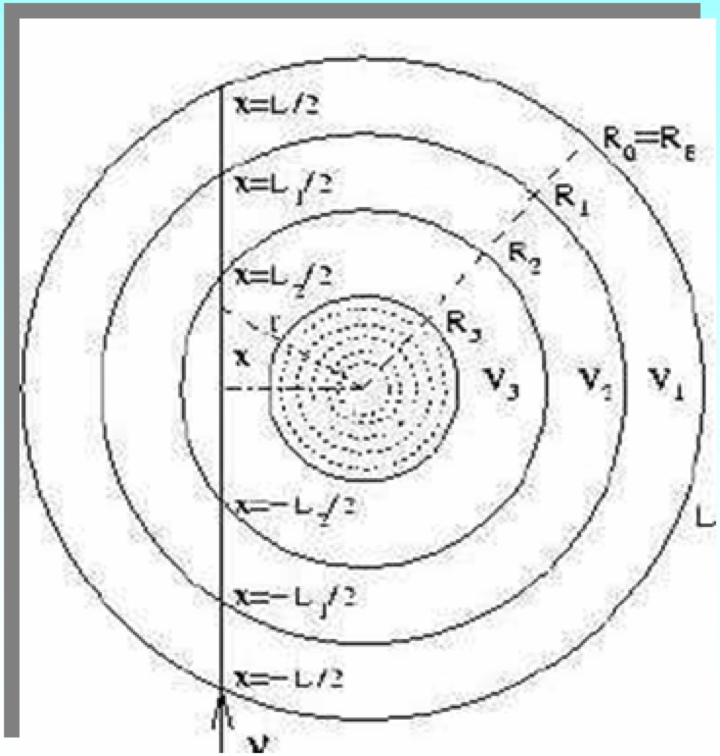
Tomography

Oscillations inside the Earth

1). Incoherent fluxes of ν_1 and ν_2 arrive at the surface of the Earth

2). In matter the mass states oscillate

3). the mass-to-flavor transitions, e.g. $\nu_2 \rightarrow \nu_e$ are relevant



Regeneration factor: $P_{2e} = \sin^2\theta + f_{reg}$

$$P_{ee} = 0.5[1 + \cos 2\theta_m^0 \cos 2\theta] - \cos 2\theta_m^0 f_{reg}$$

4). The oscillations proceed in the weak matter regime:

$$\varepsilon(x) = \frac{2EV(x)}{\Delta m^2} \ll 1$$

Regeneration factor

$f_{reg} = P_{2e} - \sin^2\theta$

$$P(\nu_2 \to \nu_e) = |\langle\nu_e|\, U(\theta_{mR})\, S(x_0 \to x_f)\, U^+(\theta_{mR})\, U(\theta)\, |\nu_2\rangle|^2$$

θ_{mR} - mixing angle at the surface of the Earth

Adiabatic perturbation theory

Liao Wei, P de Holanda, A.S.

$$f_{reg} = \varepsilon(R) \sin^2 2\theta \sin^2 [\Phi^m(x_0 \to x_f)/2] + \sin 2\theta\, \mathrm{Re}\{c(x_0 \to x_f)\}$$

amplitude of jump probability

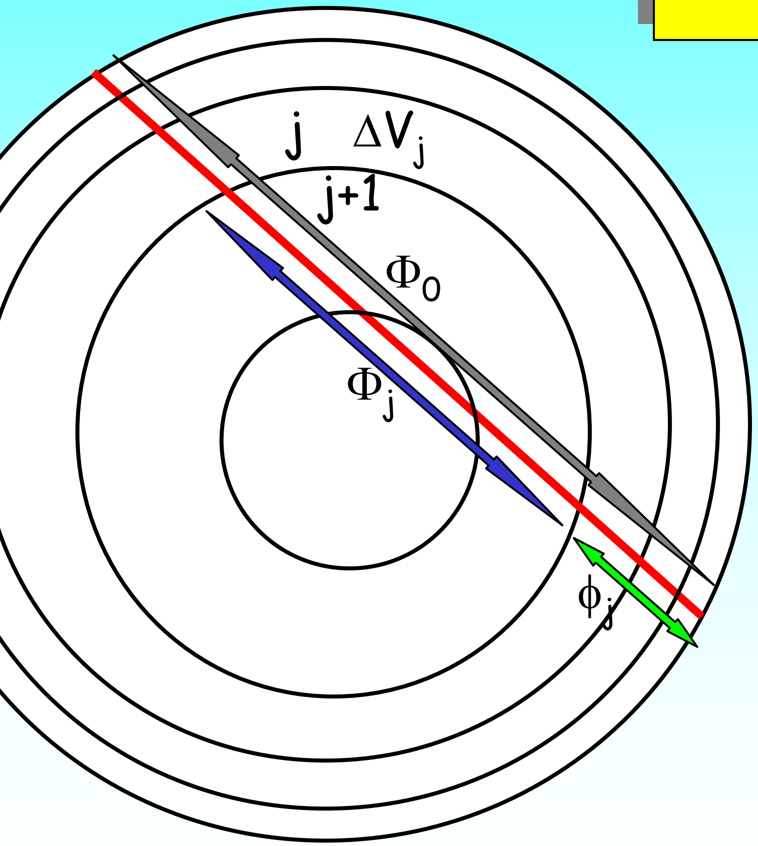
$$\varepsilon(R) = \frac{2EV(R)}{\Delta m^2}$$

- If adiabaticity is realized, the regeneration depends on the potential V(R) at the surface and on the total adiabatic phase

- Non-adiabatic conversion appears as the interference term and therefore - linearly (in contrast to conversion in the Sun)

Analytic result

$$f_{reg} = \frac{2E\sin^2 2\theta}{\Delta m^2}\,\sin\Phi_0/2\;\Sigma_{j=0\,\ldots n-1}\;\Delta V_j\,\sin\Phi_j/2$$

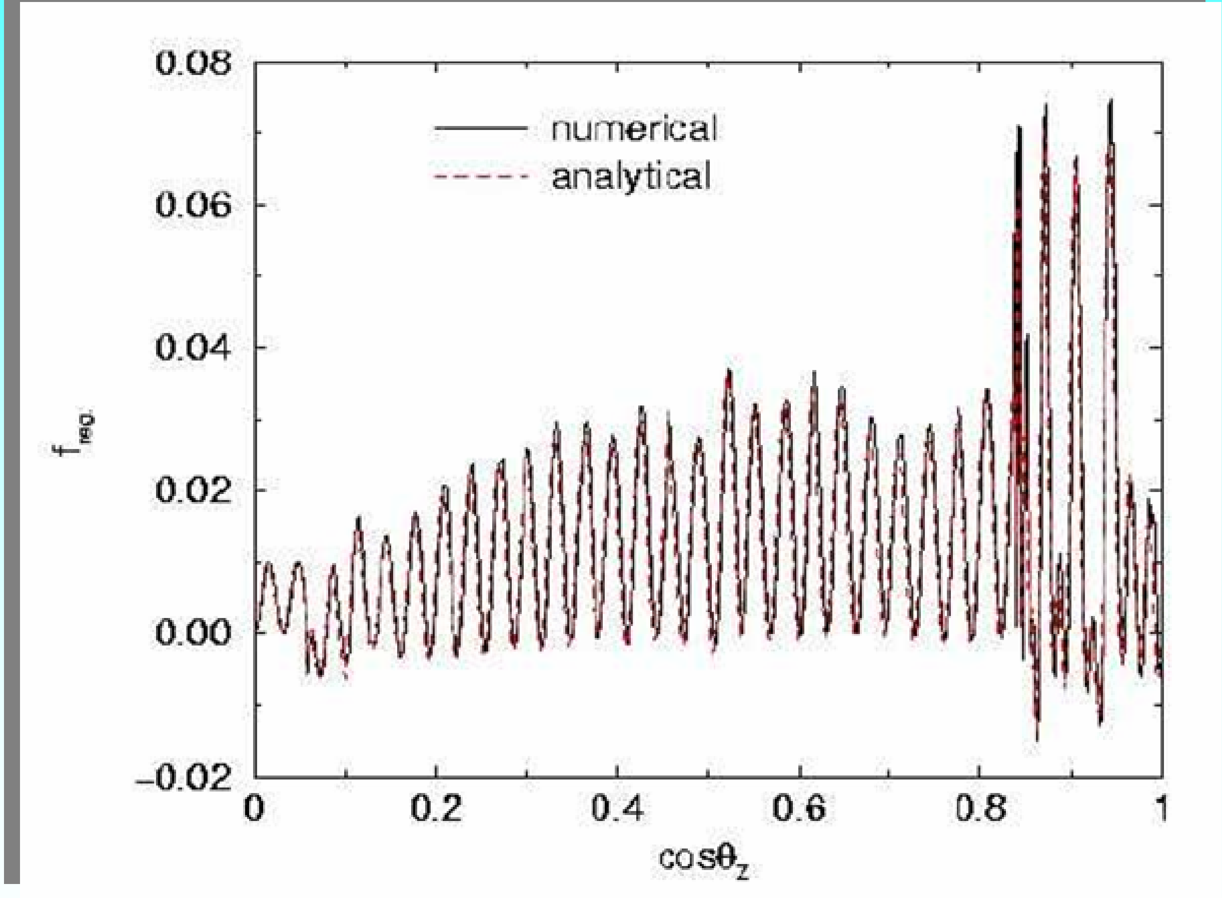


Defining $\boxed{\phi_j = 0.5(\Phi_0 - \Phi_j)}$

$$f_{reg} = \frac{2E\sin^2 2\theta}{\Delta m^2}\times$$
$$\Sigma_{j=0\,\ldots n-1}\;\Delta V_j[\sin^2\Phi_0/2\,\cos\phi_j\; - \;0.5\,\sin\Phi_0\,\sin\phi_j]$$

If ϕ_j is large - averaging effect.
This happens for remote structures, e.g. core

Analytic vs. numerical results



A. Ioanissian, A.S.

Regeneration factor as function of the zenith angle
E = 10 MeV, $\Delta m^2 = 6\ 10^{-5}\ eV^2$, $\tan^2\theta = 0.4$

Attenuation effect

Important for the oscillation tomography of the Earth
with solar and atmospheric neutrinos

Related to finite energy resolution of detectors
→ integration (averaging) over the energy
resolution intervals

Neutrino microscopes

Integral formula

$P_{2e} = \sin^2\theta + f_{reg}$

ε - perturbation theory

Regeneration factor

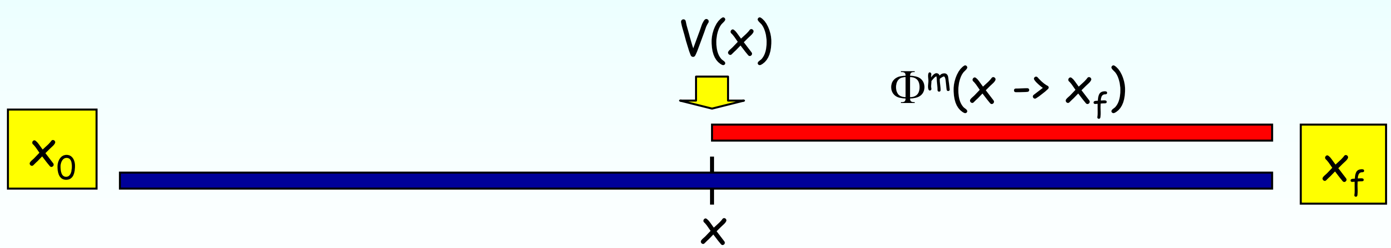
$$f_{reg} = 0.5 \sin^2 2\theta \int_{x_0}^{x_f} dx\, V(x) \sin \Phi^m(x \to x_f)$$

A. Ioannisian, A.S.

Explicitly:

$$f_{reg} = 0.5 \sin^2 2\theta \int_{x_0}^{x_f} dx\, V(x) \sin\left(\frac{\Delta m^2}{2E} \int_{x}^{x_f} dy \sqrt{\left(\cos 2\theta - \frac{2EV(y)}{\Delta m^2}\right)^2 - \sin^2 2\theta} \right)$$

Integration limits:



The phase is integrated from a given point to the final point

Sensitivity to density profile

For mass-to-flavor transition $V(x)$ is integrated with $\sin \Phi^m(d)$

$d = x_f - x$ the distance from structure to the detector

larger d → larger $\Phi^m(d)$ → stronger averaging effects → weaker sensitivity to structure of density profile

Integration with the energy resolution function $R(E, E')$:

$$\overline{f_{reg}} = \int dE' \; R(E, E')\, f_{reg}(E')$$

The effect of averaging:

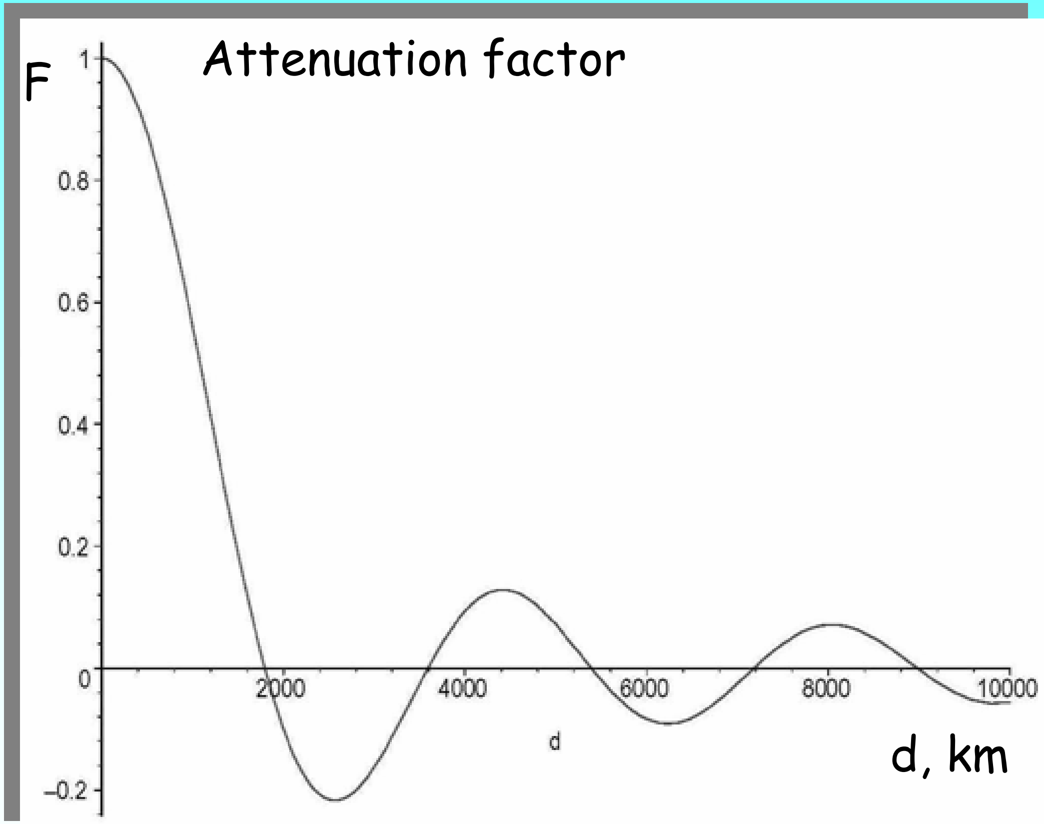
$$\overline{f_{reg}} = 0.5 \sin^2 2\theta \int_{x_0}^{x_f} dx\, V(x)\;\; F(x_f - x) \sin \Phi^m(x \to x_f)$$

averaging factor

For box-like $R(E, E')$ with width ΔE:

$$F(d) = \frac{l_\nu \; E}{\pi \; d \; \Delta E} \sin\left(\frac{\pi \; d \; \Delta E}{l_\nu \; E}\right)$$

Attenuation effect



The width of the first peak

$d < l_\nu E/\Delta E$

l_ν is the oscillation length

The sensitivity to remote structures is suppressed:

- Effect of the core of the Earth is suppressed
- Small structures at the surface can produce stronger effect
- The better the energy resolution, the deeper penetration

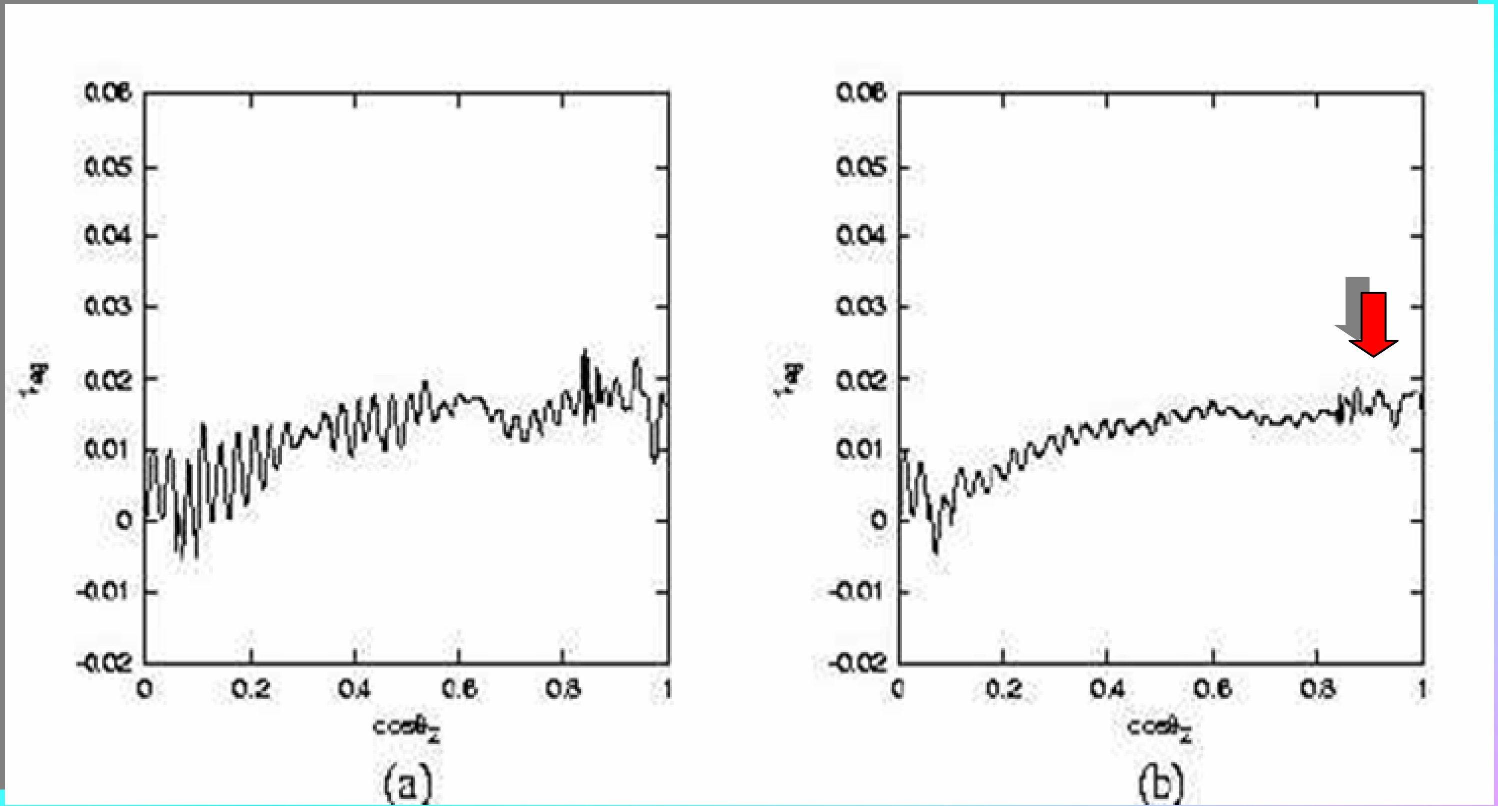
Attenuation length

$d = l_\nu E/\Delta E$ $\quad$ $d \sim 4\pi E\, E/\Delta E \Delta m^2$

	l_ν	$\Delta E/E$	d, km	Core
Solar neutrinos E = 10 MeV	300 km	10 - 20%	1500 - 3000	can not be seen
Supernova neutrinos E = 30 MeV	900 km	10%	9000	can be seen

l_ν is the oscillation length

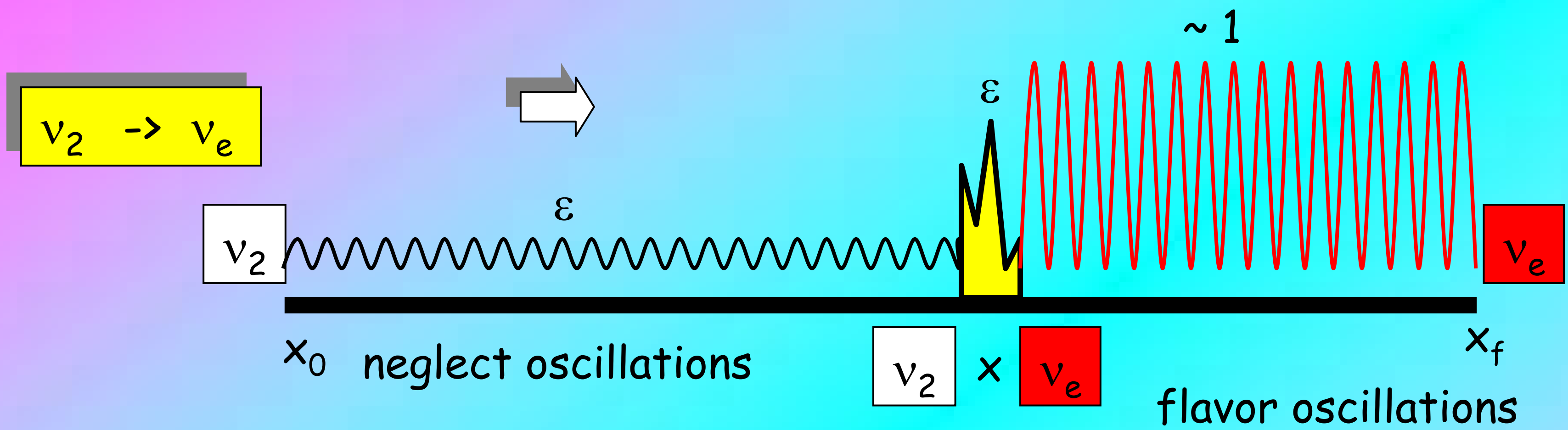
Averaging regeneration factor

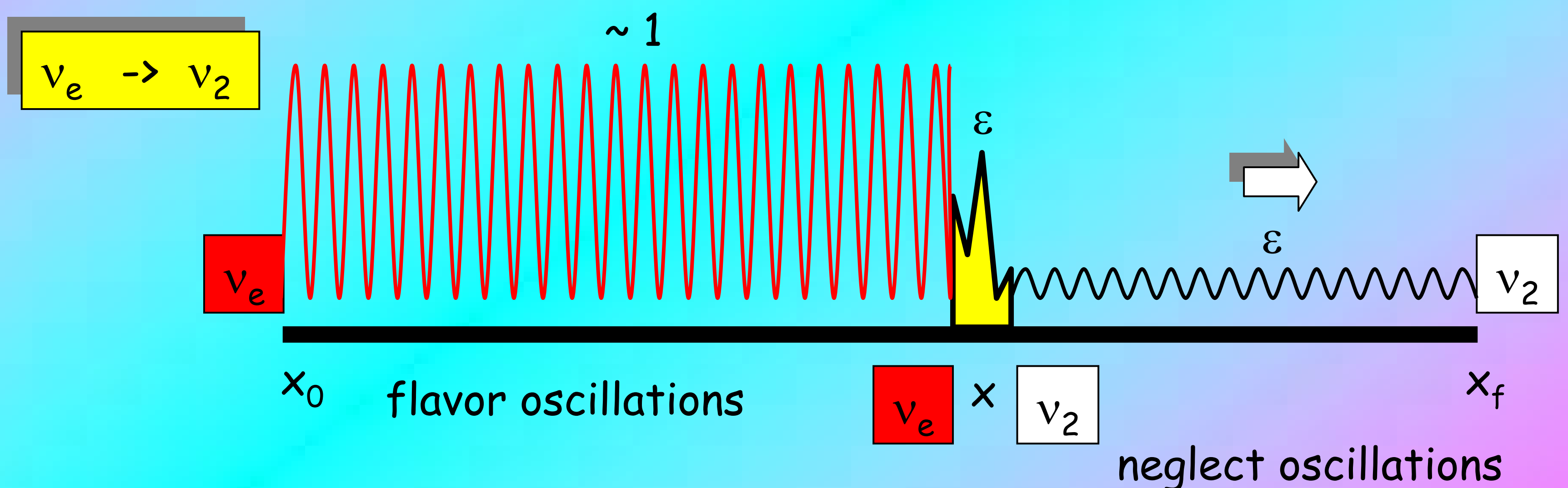


Regeneration factor averaged over the energy intervals
E = (9.5 - 10.5) MeV (a), and E = (8 - 10) MeV (b).

No enhancement for core crossing trajectories in spite of larger densities

In ε order



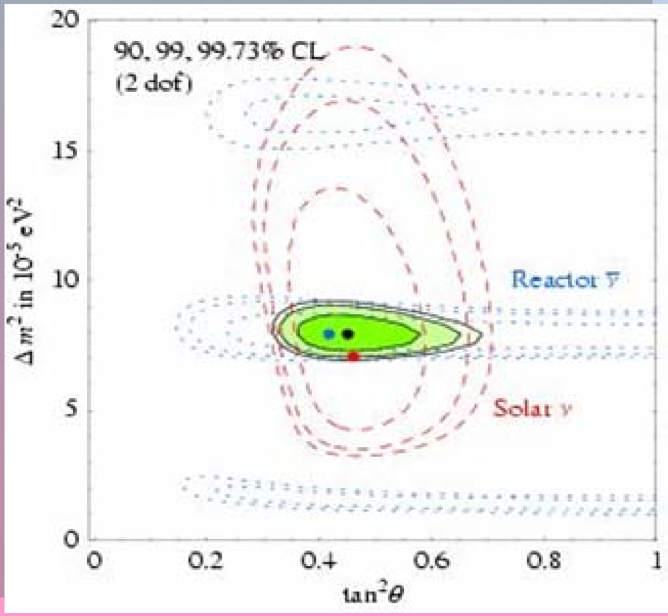


LMA MSW

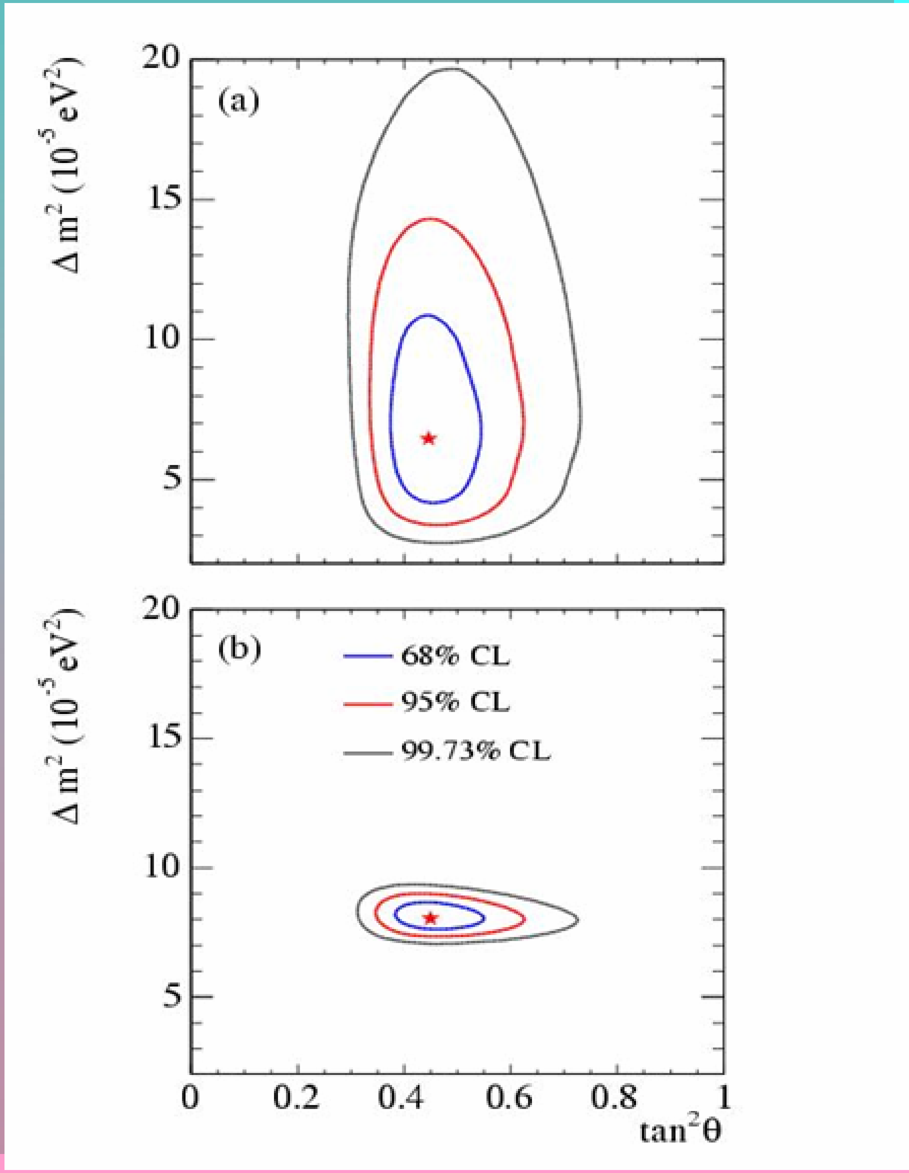
Global Solar: $\Delta m^2 = 6.5\ 10^{-5}\ eV^2$
$\tan^2\theta = 0.45\ _{-0.08}^{+0.09}$

Solar + KL: $\Delta m^2 = 7.9\ 10^{-5}\ eV^2$
$\tan^2\theta = 0.45$

A. Strumia, F. Vissani



SNO Collaboration



Stability of bfp

Status and perspectives

Expect new SNO data: phase-3 ^{3}He counters of neutrons

better identification of the NC events
-> better measurements of CC/NC ratio
-> better determination of θ_{13}

BOREXINO, KamLAND: measurements of fluxes in the intermediate energy range (Be neutrino flux)

SAGE calibration result: obs/exp = 0.79 +0.09/- 0.10

Lower cross-section – higher pp-flux
-> larger survival probability? Tension?

Monitoring of the solar neutrino flux
-> searches for time variations, periodicity

Analysis of data: periodicity

Solar models, abundance of heavy elements at the surface??
Boron neutrino cross-section

KamLAND

Kamioka
Large Anti-Neutrino Detector

- Reactor long baseline experiment
  150 - 210 km
  Liquid scintillation detector

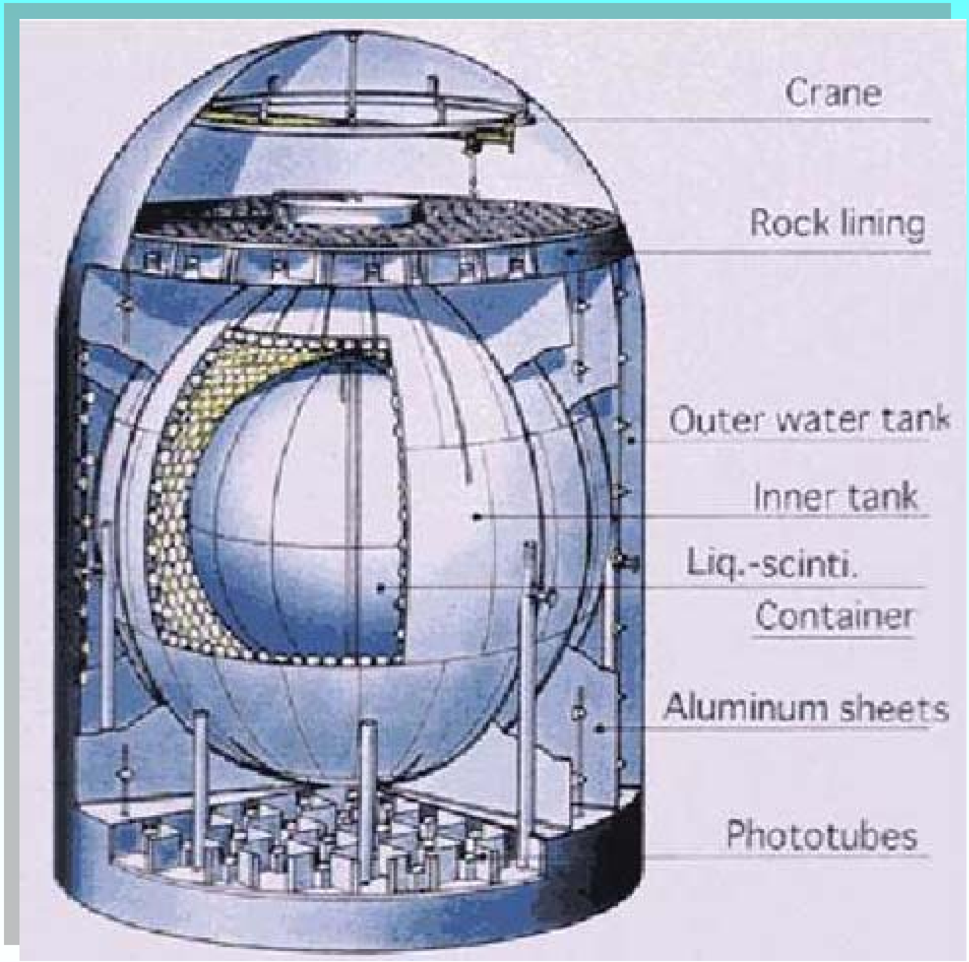
- $\bar{\nu}_e + p \dashrightarrow e^+ + n$

  $E_{pr} > 2.6$ MeV

- Data: total rate
  energy spectrum of events

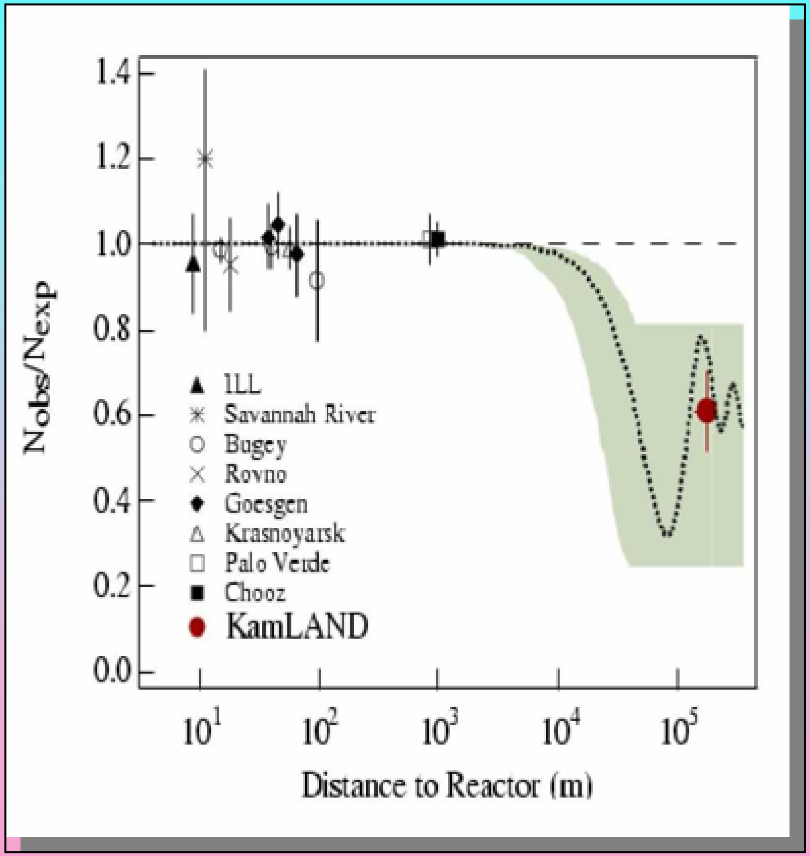
- LMA ⇨
  precise determination of
  the oscillation parameters
  10% accuracy

- Detection of the Geo-neutrinos
  $E_{pr} > 1.3$ MeV



1 kton of LS

KamLAND results



Δm^2 is determined from phase of oscillations (energy spectrum distortion)

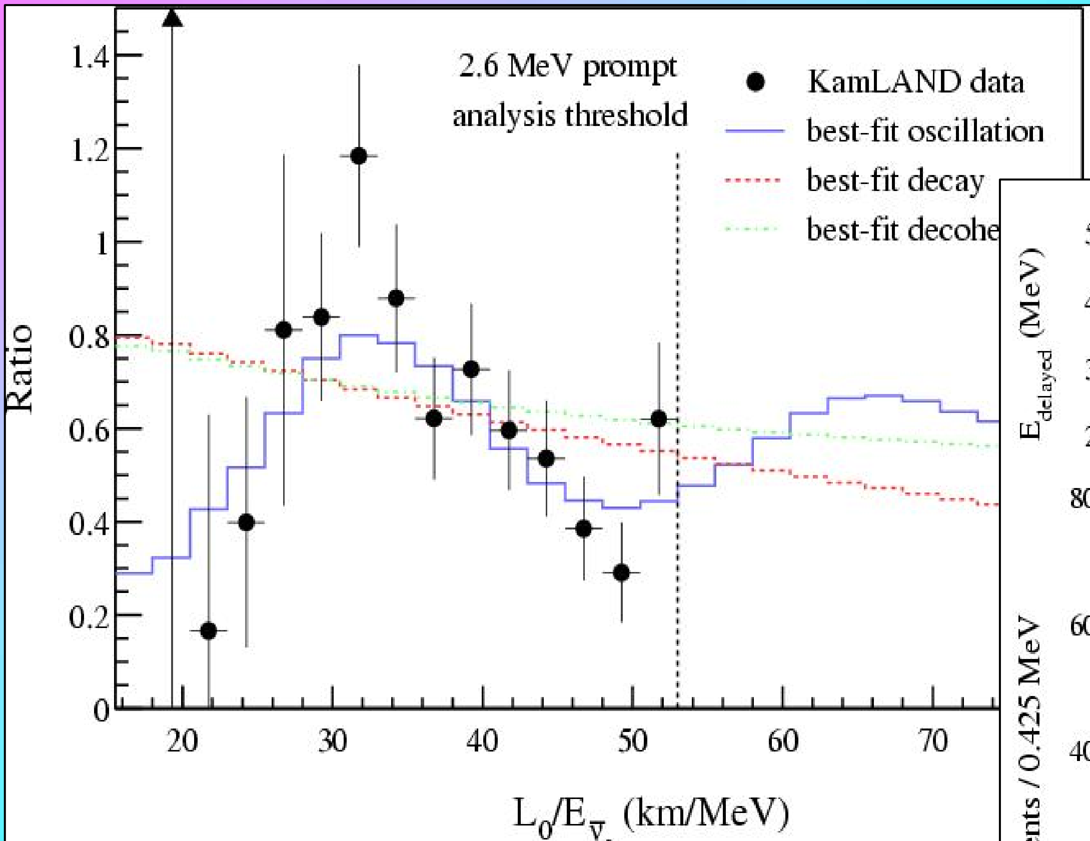
According to LMA the range of Δm^2 is restricted

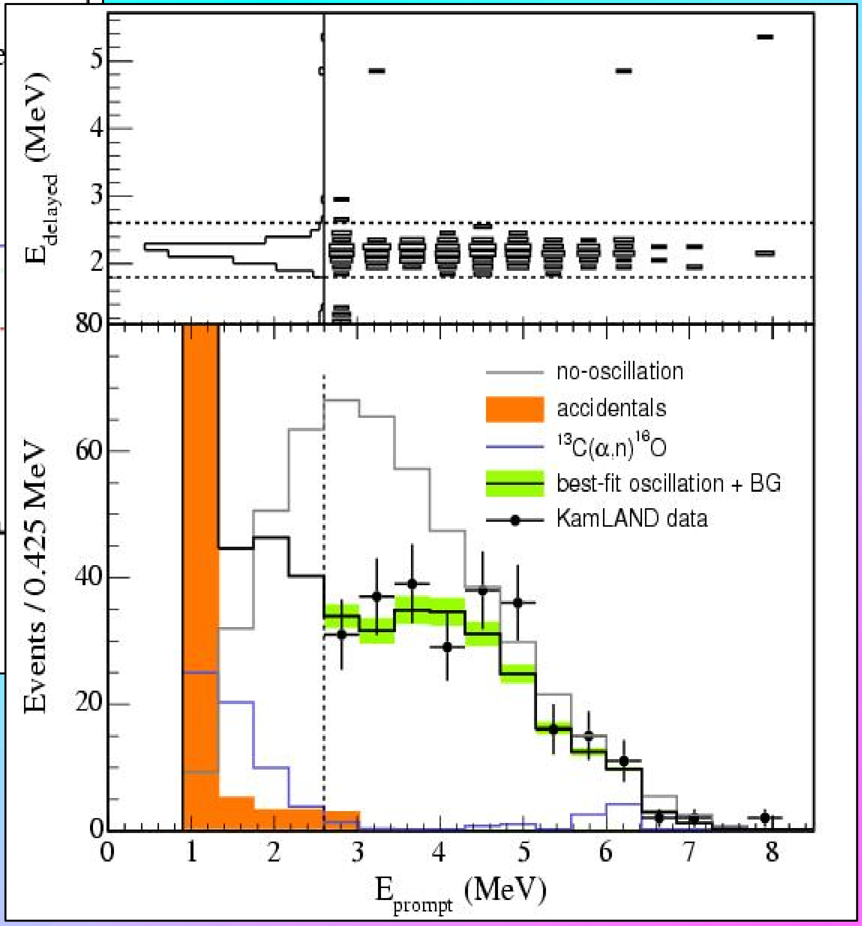
-from above - by spectrum distortion (up turn)

- from below by increasing day-night asymmetry

No dependence on phase

KamLAND results





PRL 94, 081801 (2005)

Testing Theory of oscillations

Solar neutrinos

- Adiabatic conversion (MSW)
- Matter effect dominates (at least in the HE part)
- Non-oscillatory transition, or averaging of oscillations

⇒ the oscillation phase is irrelevant

Adiabatic conversion formula

KamLAND

- Vacuum oscillations
- Matter effect is very small
- Oscillation phase is crucial for observed effect

Vacuum oscillations formula

Δm^2, θ

Coincidence of these parameters determined from the solar neutrino data and from KamLAND results testifies for the correctness of the theory (phase of oscillations, matter potential, etc..)

Testing the MSW effect in the Sun

SK+SNO:

$\langle P_{ee} \rangle = 0.34 +/- 0.12\ (3\sigma)$

$\langle P_{ee} \rangle < 0.46\ (3\sigma)$

2ν - vacuum oscillations:

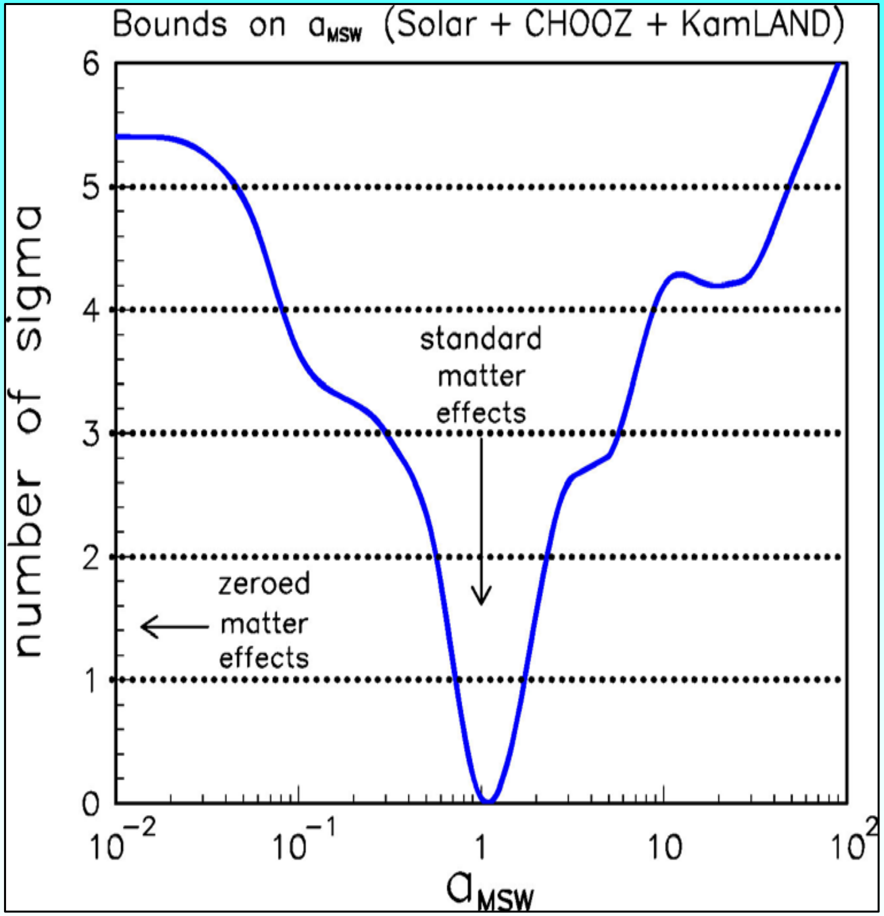
$\langle P_{ee} \rangle > 0.5$

$V \to a_{MSW}\ V$

free parameter

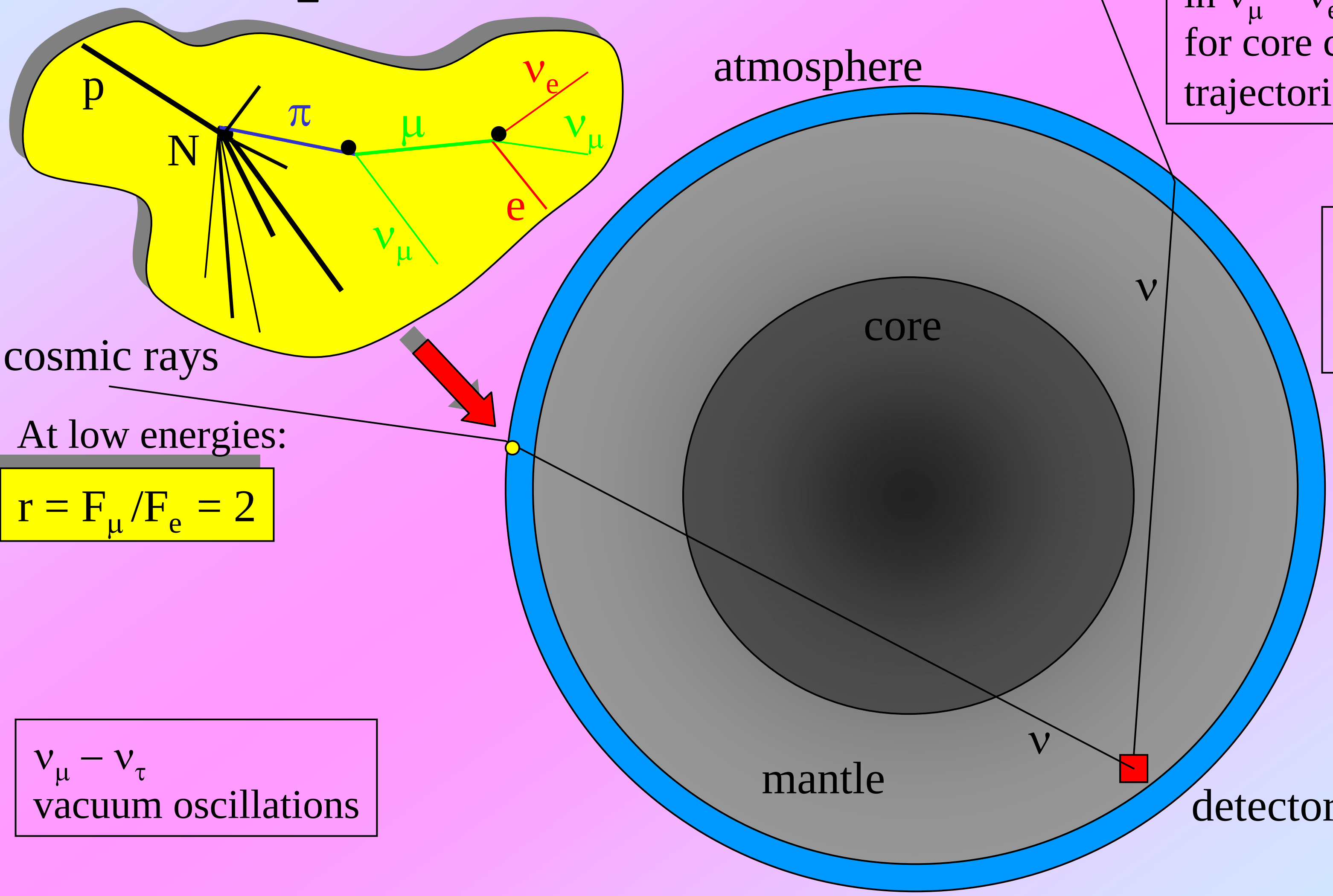
Global analysis of solar and reactor (KamLAND+CHOOZ) data with Δm_{12}^2, $\sin^2\theta_{12}$, a_{MSW} unconstrained:

G. L. Fogli, E. Lisi, A. Marrone, A. Palazzo, A. M. Rotunno, hep-ph/0506307



Notice: in the best fit point $a_{MSW} > 1$ reflects mismatch of the b.f. values from solar and KamLAND analysis

Atmospheric neutrinos



Parametric effects in $\nu_\mu - \nu_e$ oscillations for core crossing trajectories

$\nu_\mu - \nu_e$ oscillations in matter

At low energies:

$r = F_\mu / F_e = 2$

$\nu_\mu - \nu_\tau$
vacuum oscillations

Experiments and data

SuperKamiokande

MACRO

SOUDAN

MINOS

Evidence of oscillations

Appearance of τ-like events

Zenith angle distribution of μ-like events

L/E-dependence

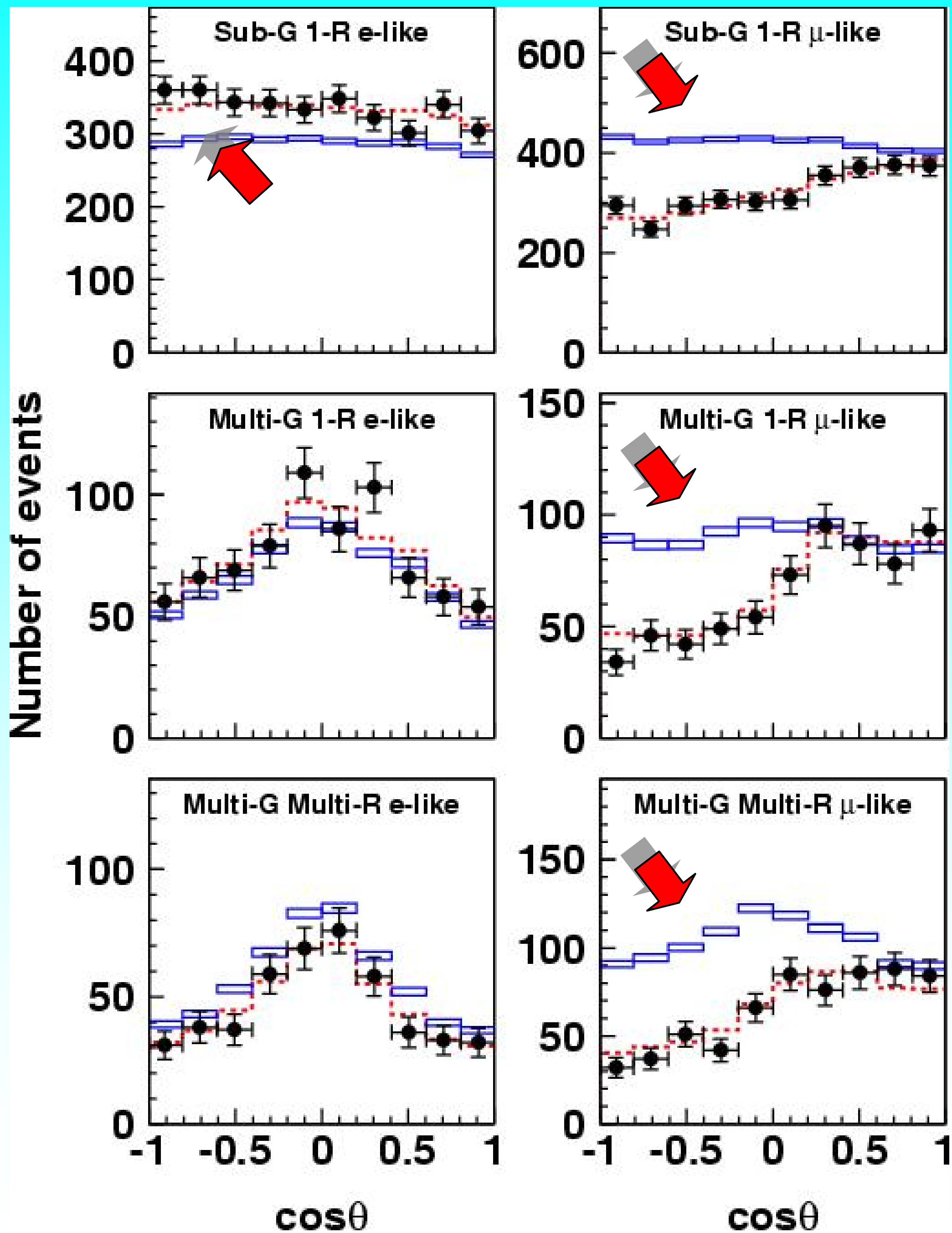
Up-down asymmetry

$\nu_\mu - \nu_\tau$

Ratio of numbers of μ-like to e-like events

Zenith angle distribution

SuperKamiokande
hep-ex/0604011



Deficit

and excess

mu/e-ratio

$$R = \frac{(\mu/e)_{data}}{(\mu/e)_{MC}}$$

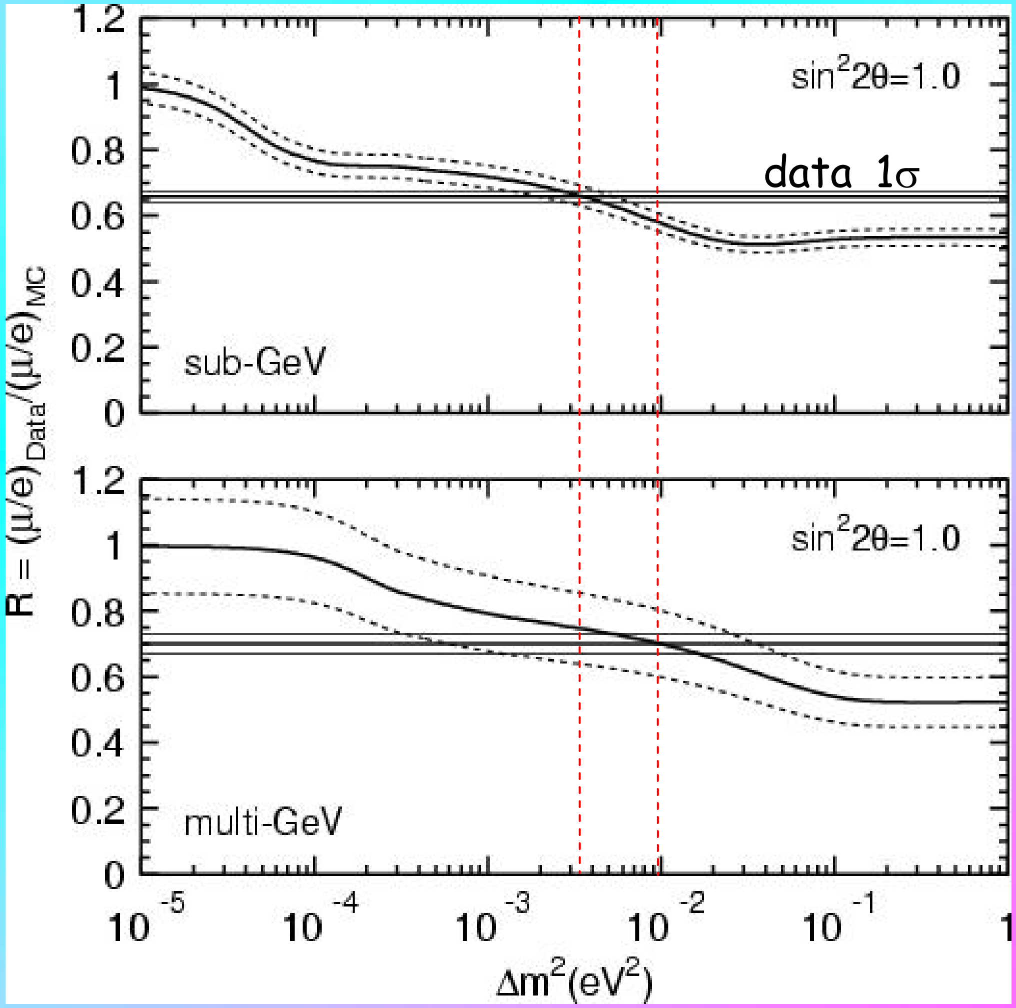
$R \sim 1 - \sin^2 2\theta \, \langle \sin^2 \phi/2 \rangle_z$

oscillation phase factor integrated over zenith angle

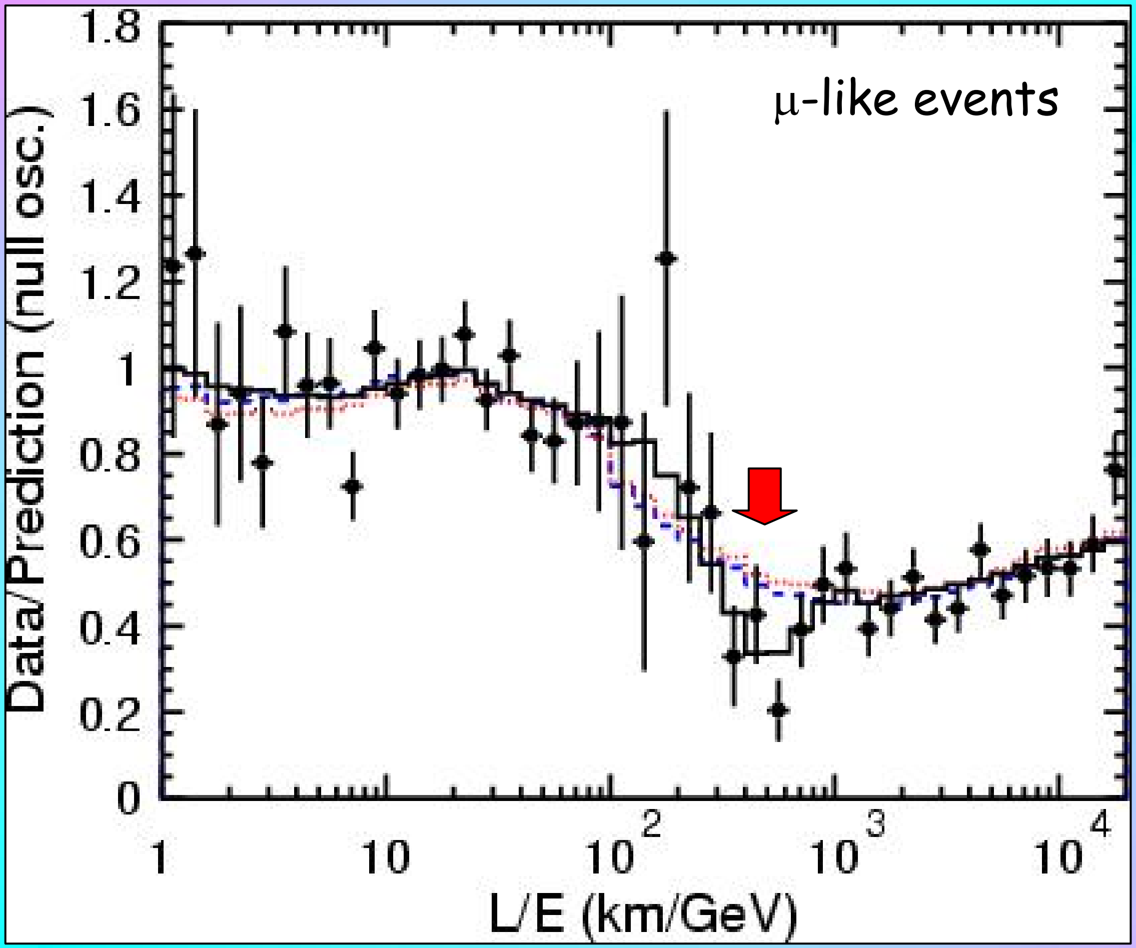
(decreases with energy)

for multi-GeV:
$\langle \sin^2 \phi/2 \rangle_z \sim 0.25 - 0.30$

from data $\sin^2 2\theta \sim 1$



L/E dependence



In the first oscillation maximum (dip): $\phi = \pi$

$\Delta m^2 = 2\pi\ E/L$

data: $L/E \sim 500$ km/GeV

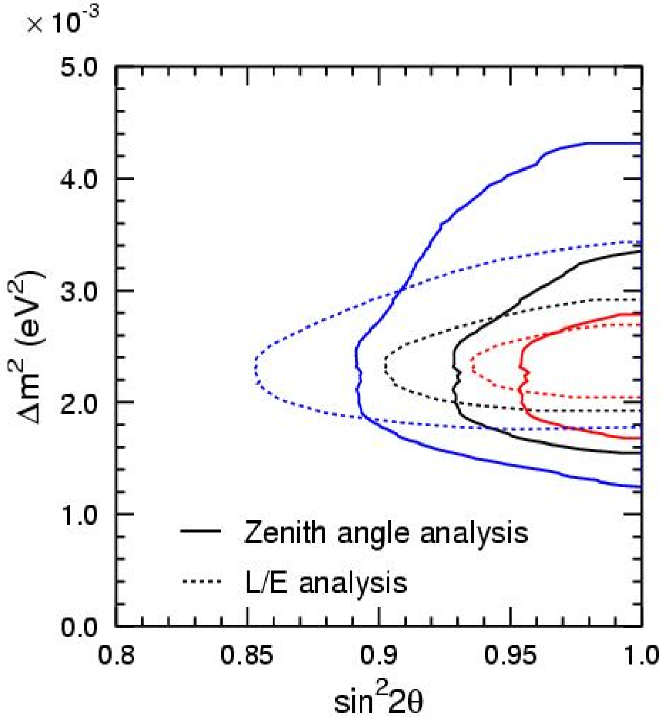
$\Delta m^2 \sim 2.5\ 10^{-3}\ eV^2$

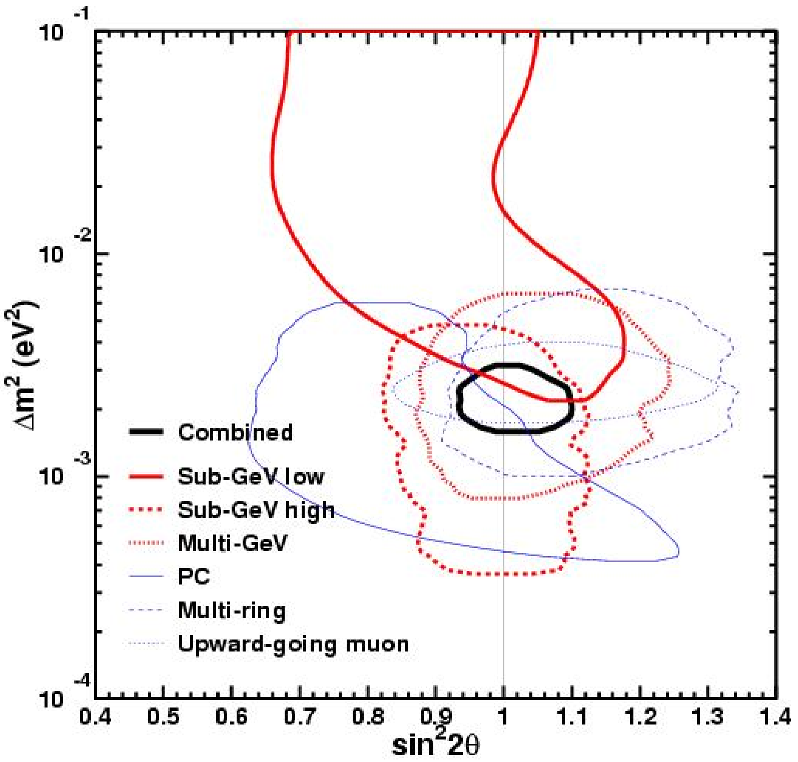
Super-Kamiokande
PRL, 93 101801 (2004)

Oscillation parameters

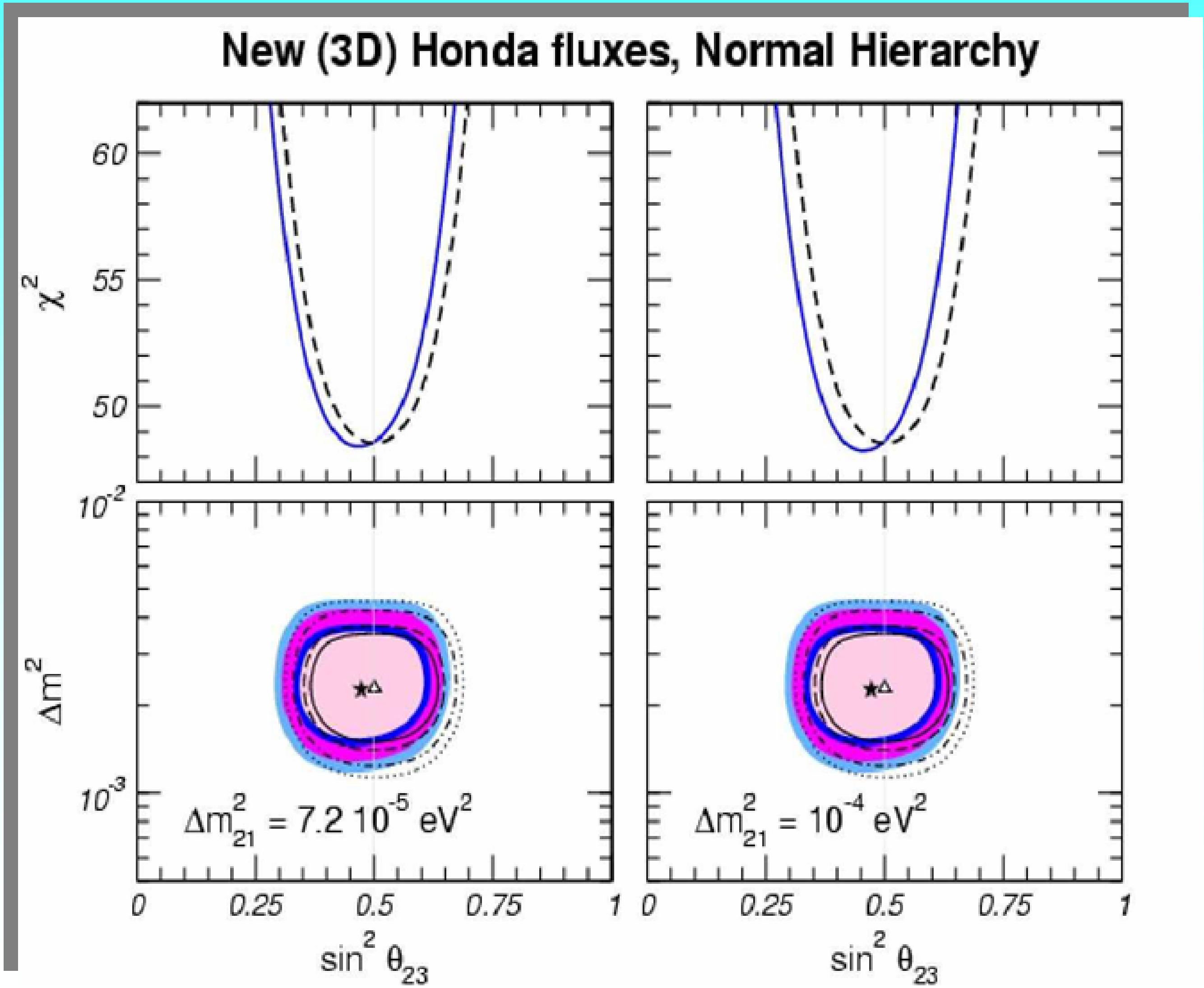
Super-Kamiokande
hep-ex/0501064

$1.5\times10^{-3} < \Delta m^2 < 3.4\times10^{-3}$ eV^2
$0.92 < \sin^2 2\theta$ at 90% C.L.





Deviation of 2-3 mixing from maximal



$\Delta m^2 = 0$

$\Delta m^2 \neq 0$

$\sin^2\theta_{23} = 0.45 - 0.47$

M. C. Gonzalez-Garcia
M. Maltoni, A.S.

Status and perspectives

Still complete 3ν analysis of the atmospheric neutrino data should be done by the experimental collaboration (SK)

Physics potential of future detectors (next generation experiments)

Rich source:

- various flavors ν_ε and ν_μ
- neutrinos and antineutrinos
- huge interval of energies: E ~ 0.1 – 10^4 GeV

``Variable baseline'':

L ~ 10 – 10^4 km (zenith angles)
sensitivity to both Δm^2
opens a possibility (in principle) to establish the CP violation

Drawback:

- small statistics
- uncertainties in the predicted fluxes

Physics and Detectors

- determination of mass hierarchy
- 1-3 mixing
- deviation of 2-3 mixing from maximal (and quadrant)
- CP violation
- Earth tomography

■ INO – Indian Neutrino observatory

50 kton iron calorimenter

■ HyperKamiokande

0.5 Megaton whater Cherenkov detectors

■ Underwater detectors NEMO, ANTARES

■ Icecube (1000 Mton)

■ TITAND (Totally Immersible Tank Assaying Nuclear Decay)

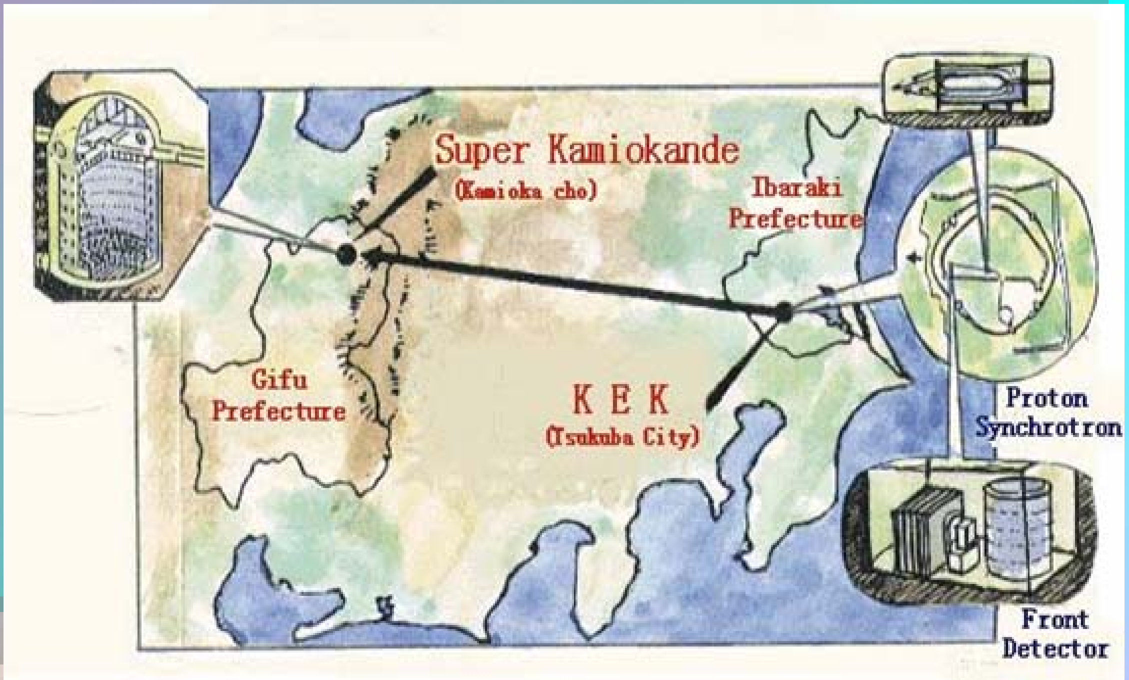
2 Mt and more

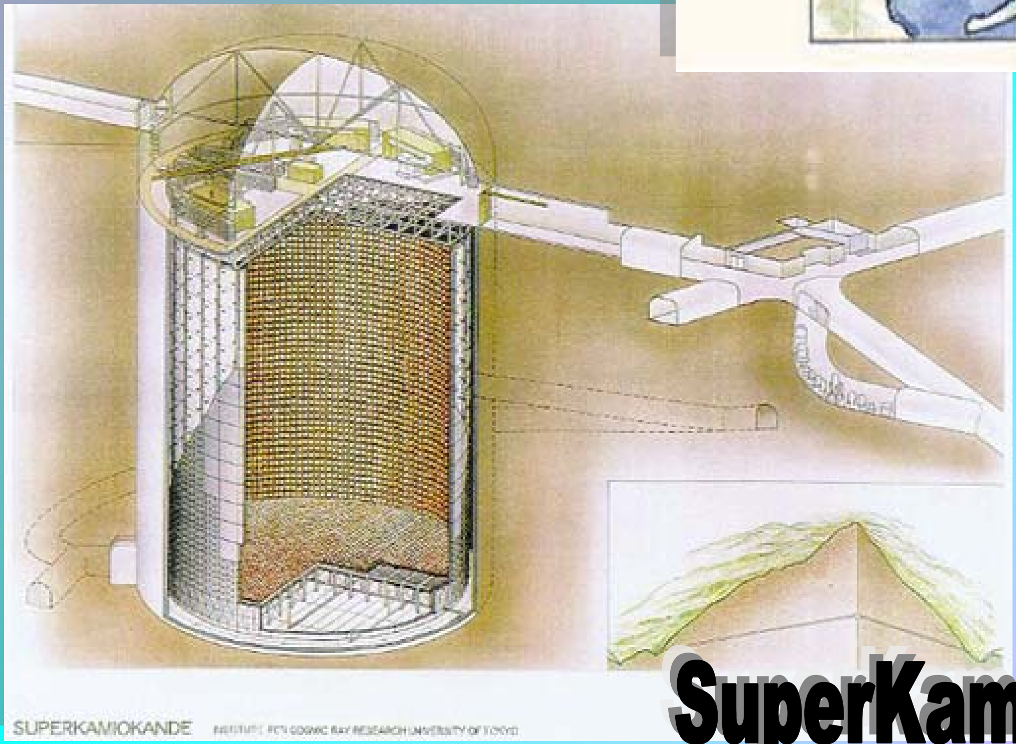
Y. Suzuki..

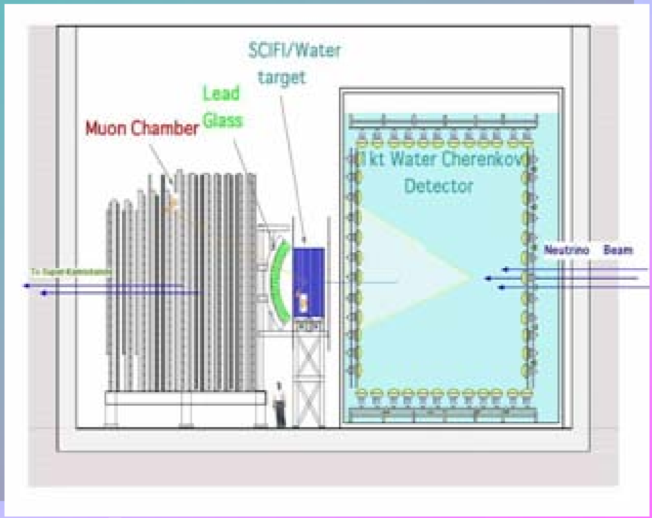
K2K

KEK to Kamioka

$\nu_\mu \rightarrow \nu_\mu$



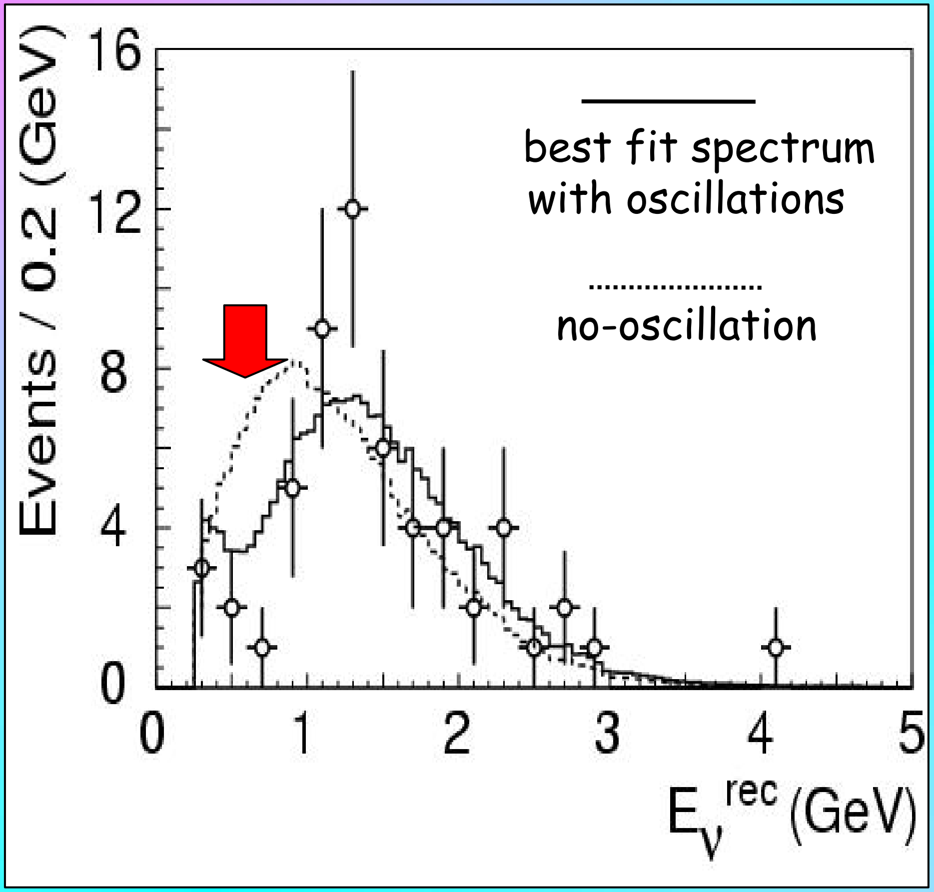




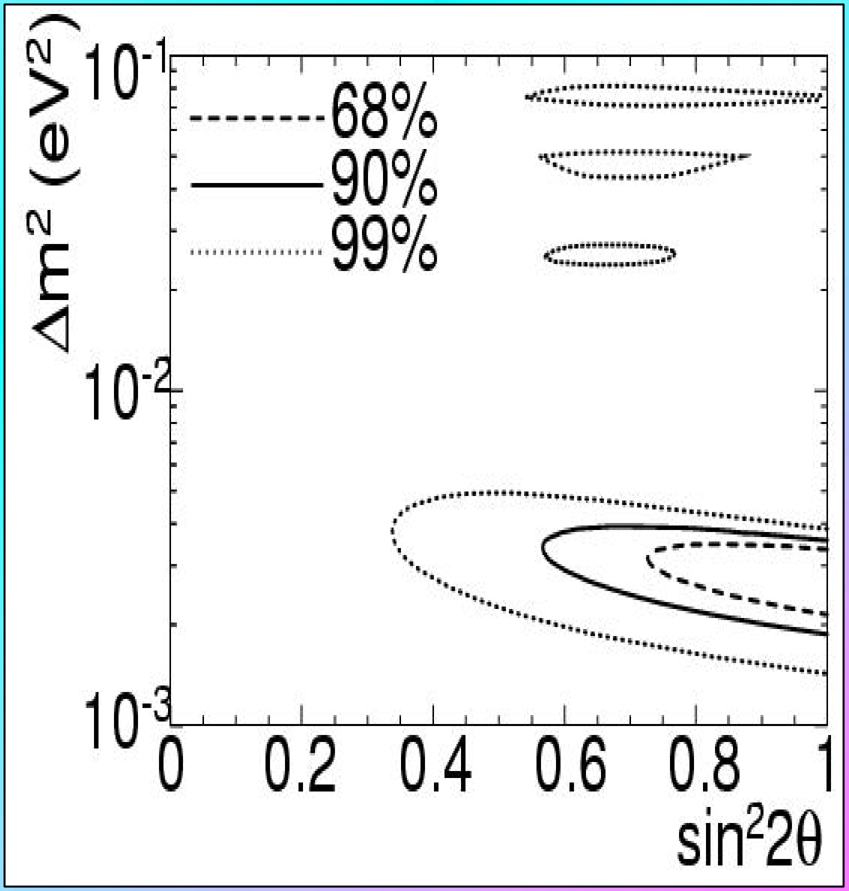
SuperKamiokande

K2K results

107 events observed
151 +12/-10 -expected



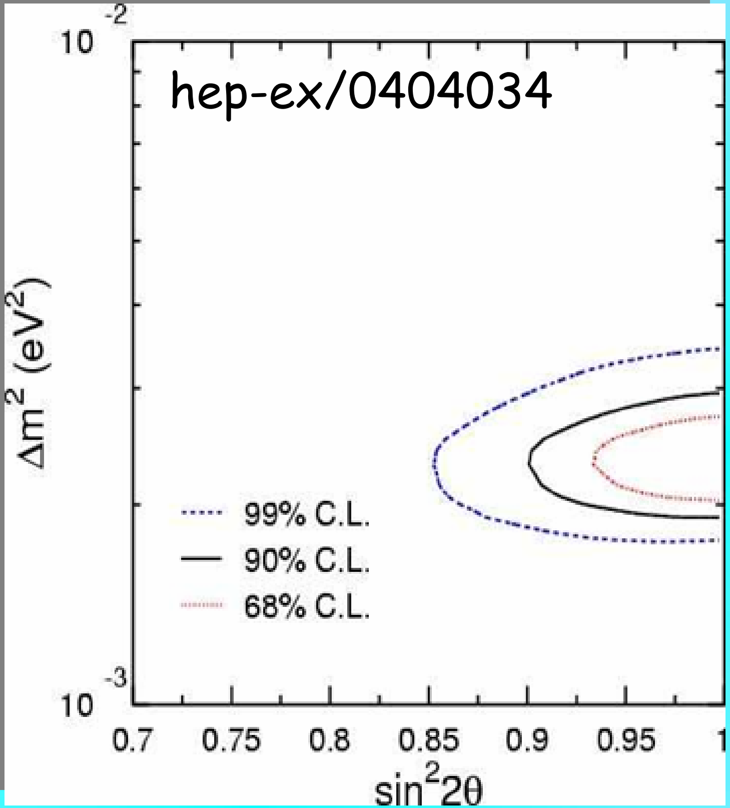
Normalized (57 events) reconstructed neutrino energy spectra



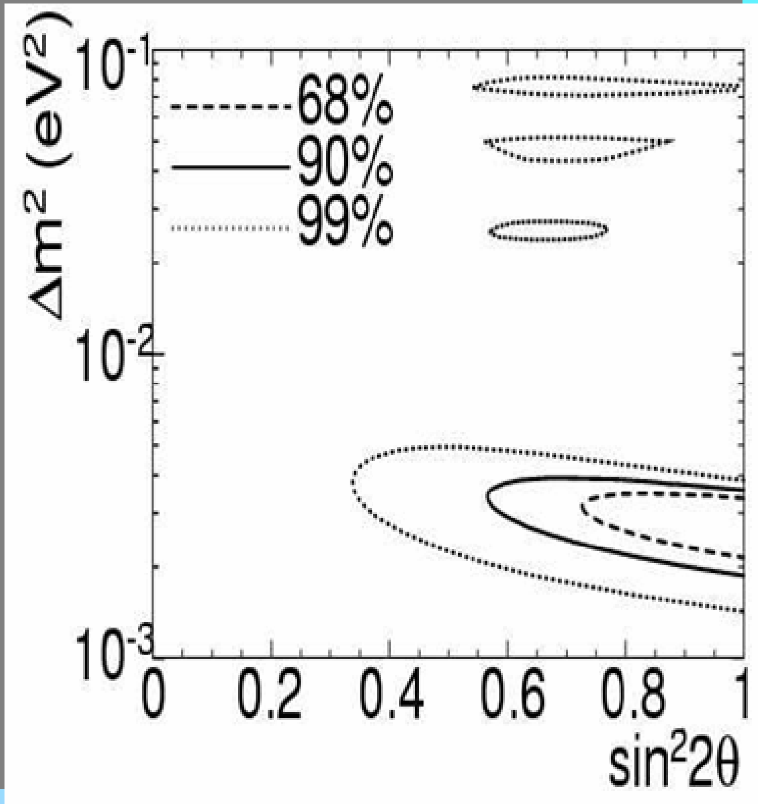
Allowed regions of parameters

2-3 masses and mixing

SuperKamiokande (atmospheric)



K2K hep-ex/0411038



$\Delta m_{23}^2 = (2.4\ \ +0.6/-0.5\ )\ 10^{-3}$, eV^2

$\Delta m_{23}^2 = (1.9\ \ -\ \ 3.6\ )\ 10^{-3}$, eV^2

90 % C.L.

$\sin^2 2\theta_{23} = 1.0$

90 % C.L.

MINOS

Main Injector Neutrino
Oscillation Search

LBL: Fermilab – SOUDAN mine

Near detector (1km):
1 kton

Far detector (735 km)
5400 t, steel,
sampling calorimeter

Beam: 120 GeV protons
2.5 10^{20} p/year
-> 1- 10 GeV neutrinos

MINOS results

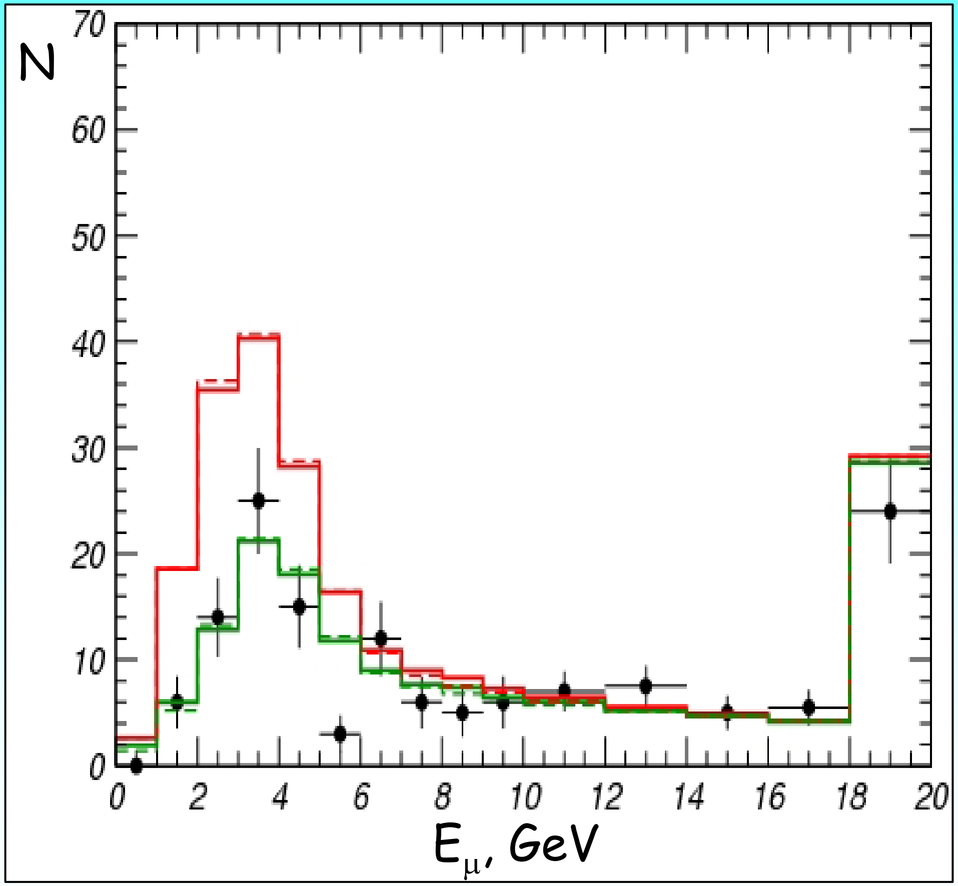
Expected: 177 +/- 11 events
Observed: 92 events

CC events induced by ν_μ

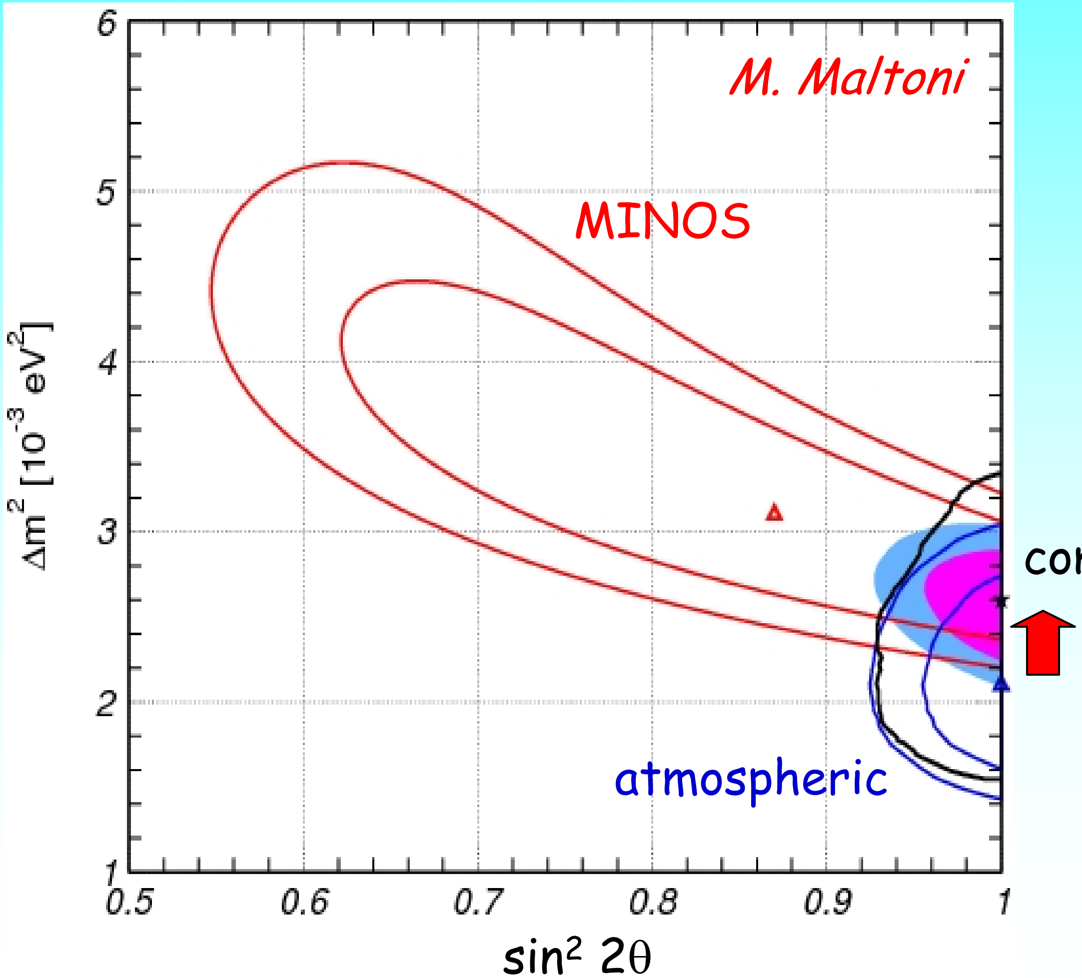
b.f.:
$\Delta m^2 = 3.1 \ 10^{-3}$ eV^2

The first oscillation minimum:
E = 1.8 GeV

Second minimum: E = 5.4 GeV



Combined analysis



Allowed regions at 68% and 90% C.L.

b.f.:

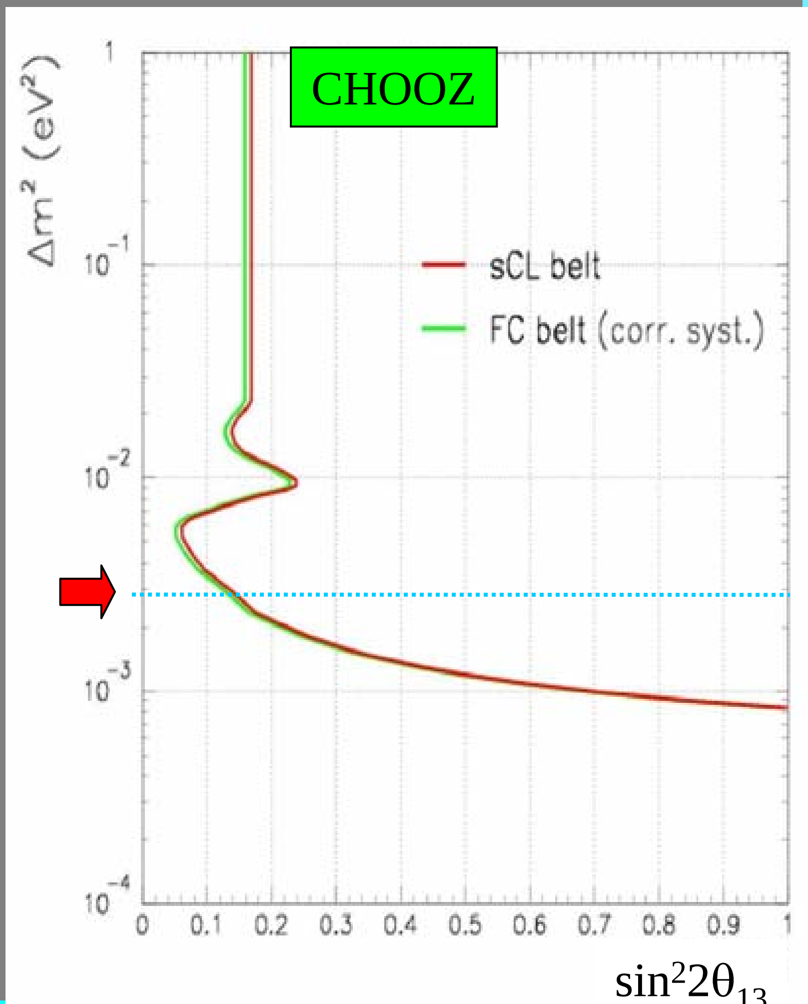
$\Delta m^2 = 2.6 \ 10^{-3} \ eV^2$

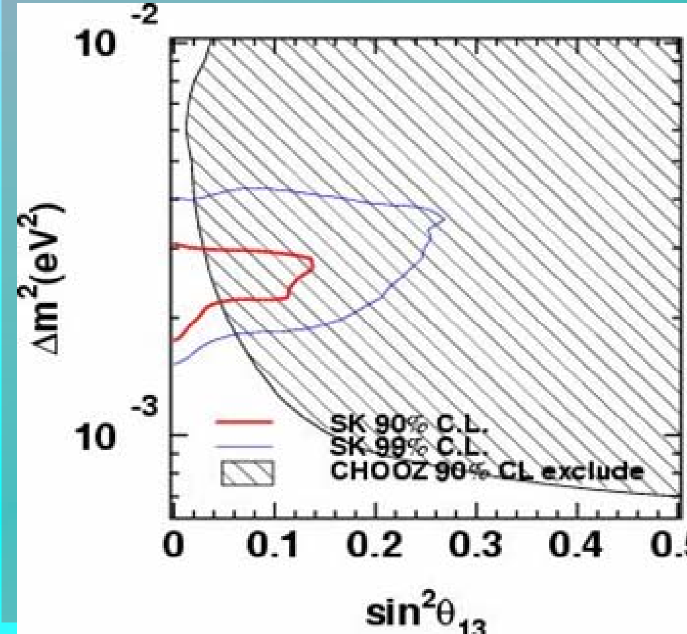
MINOS has not produced shift from maximal mixing in the global fit

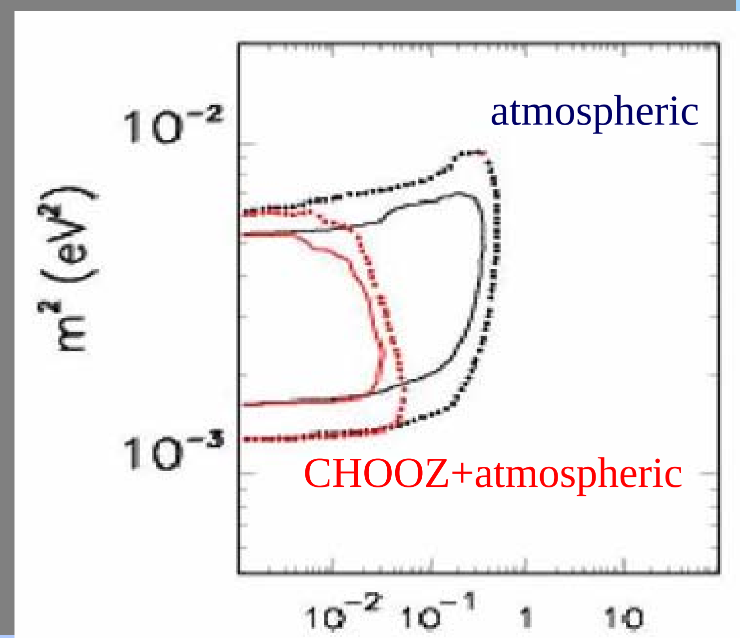
1-3 mixing: effects and bounds

U_e3

$$U_{e3} = \sin\theta_{13}\, e^{-i\delta} = \langle \nu_e \,|\, \nu_3 \rangle$$





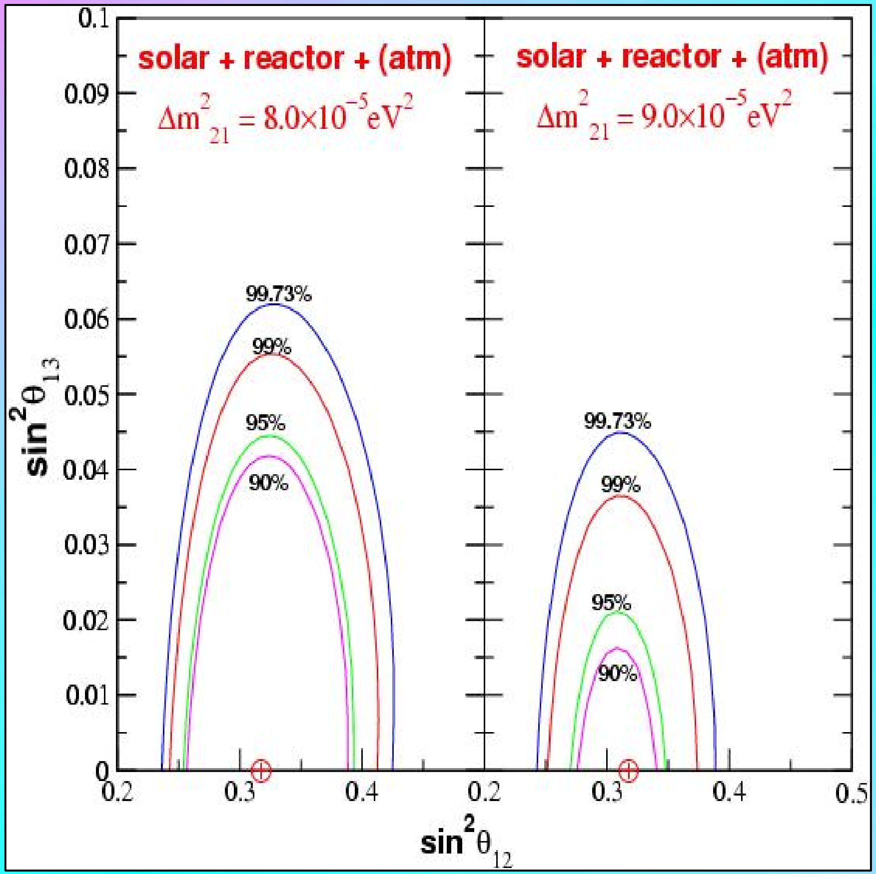


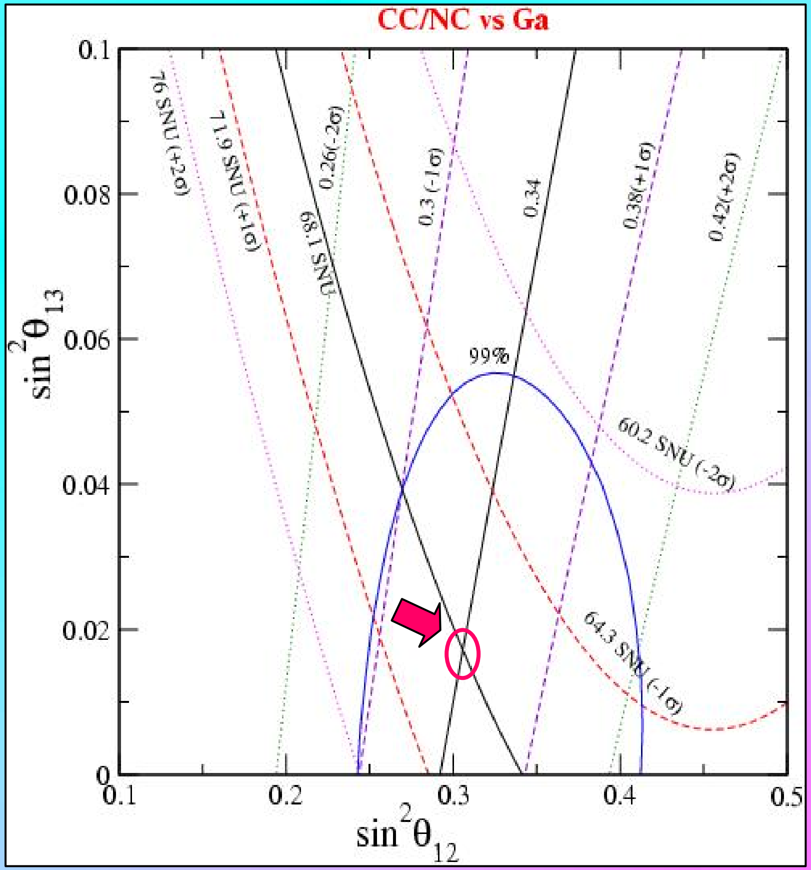
$\tan^2\theta_{13}$

Theta 1-3

Solar neutrinos: degeneracy of 1-2 and 1-3 mixing

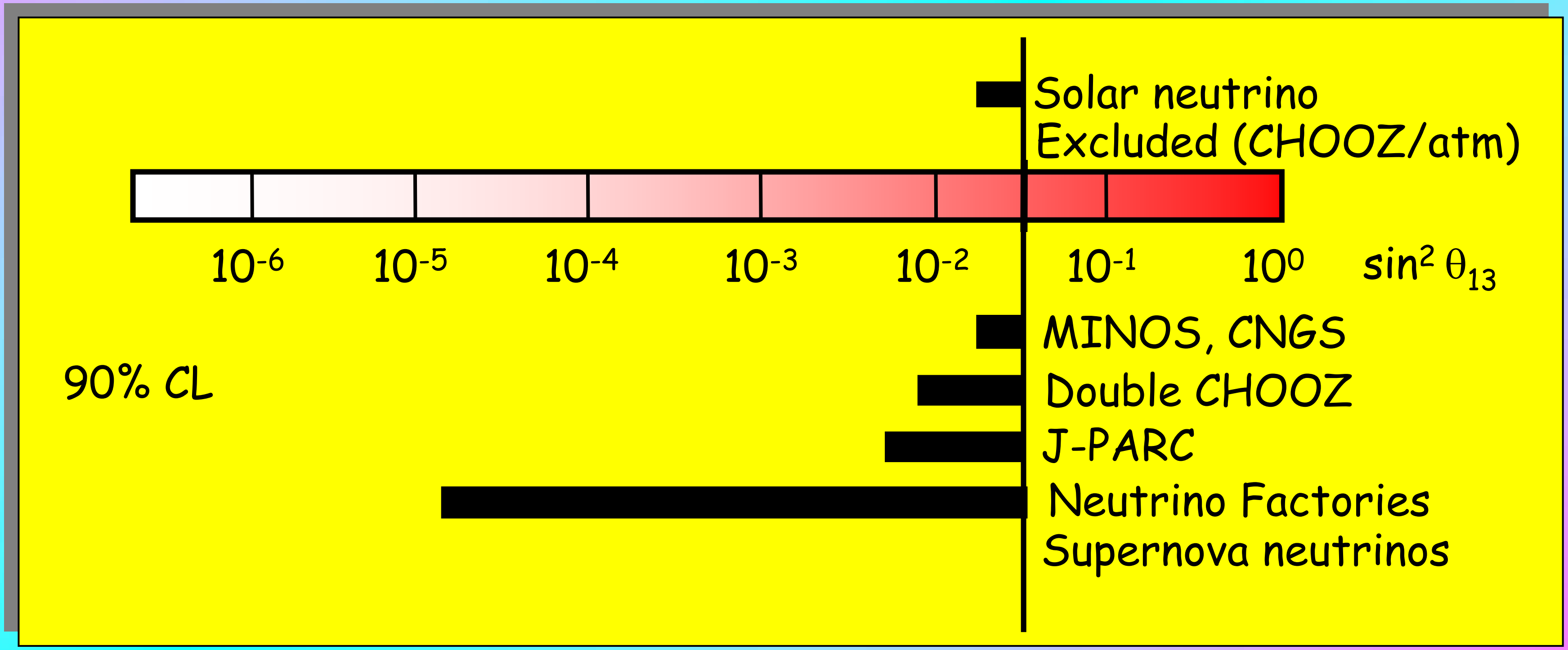
S. Goswami, A.S.





$\sin^2\theta_{13}$ = 0.017+/- 0.26

Sensitivity to 1-3 mixing

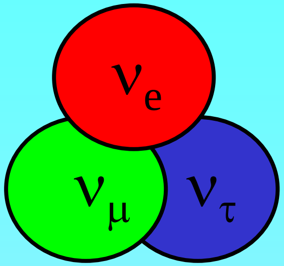


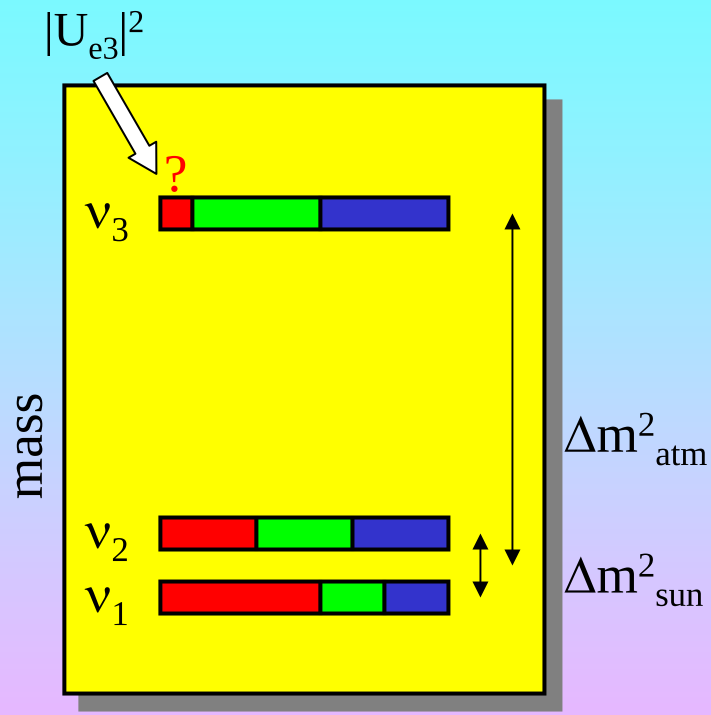
Plausible values of paremeters

No new physics apart from 3 massive and mixed neutrinos

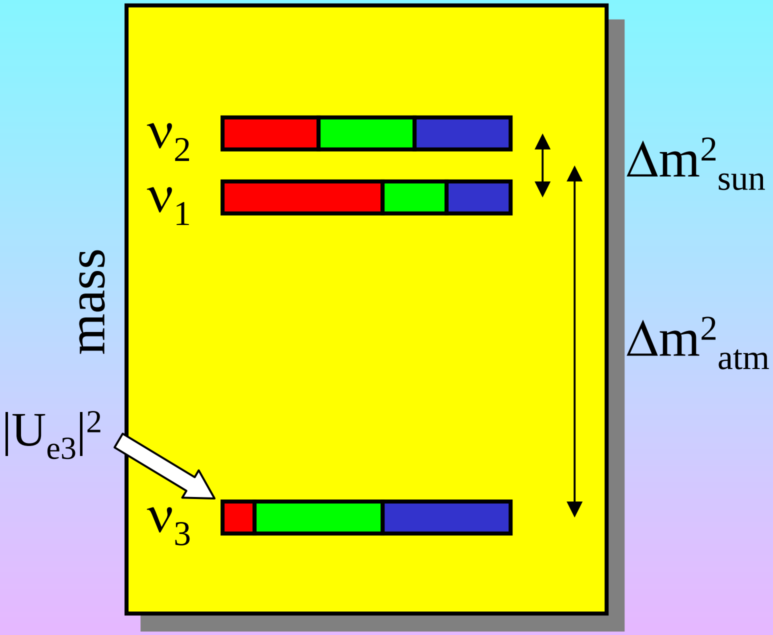
	S-V	Bari	
Δm_{12}^2	$8.0\ 10^{-5}$ eV^2	$7.9\ 10^{-5}$ eV^2	
$\sin^2\theta_{12}$	0.310	0.314	
Δm_{23}^2	$2.5\ 10^{-3}$ eV^2	$2.4\ 10^{-3}$ eV^2	
$\sin^2\theta_{23}$	0.50	0.44	
$\sin^2\theta_{13}$	0.00 [< 0.013]	0.009 [< 0.020]	[1σ]

Mass spectrum and mixing





Normal mass hierarchy (ordering)



Inverted mass hierarchy (ordering)

- Type of mass spectrum: with Hierarchy, Ordering, Degeneracy ➡ absolute mass scale
- Type of the mass hierarchy: Normal, Inverted
- U_{e3} = ?

A Yu Smirnov

Beyond standard picture

LSND

Large Scintillator Neutrino Detector

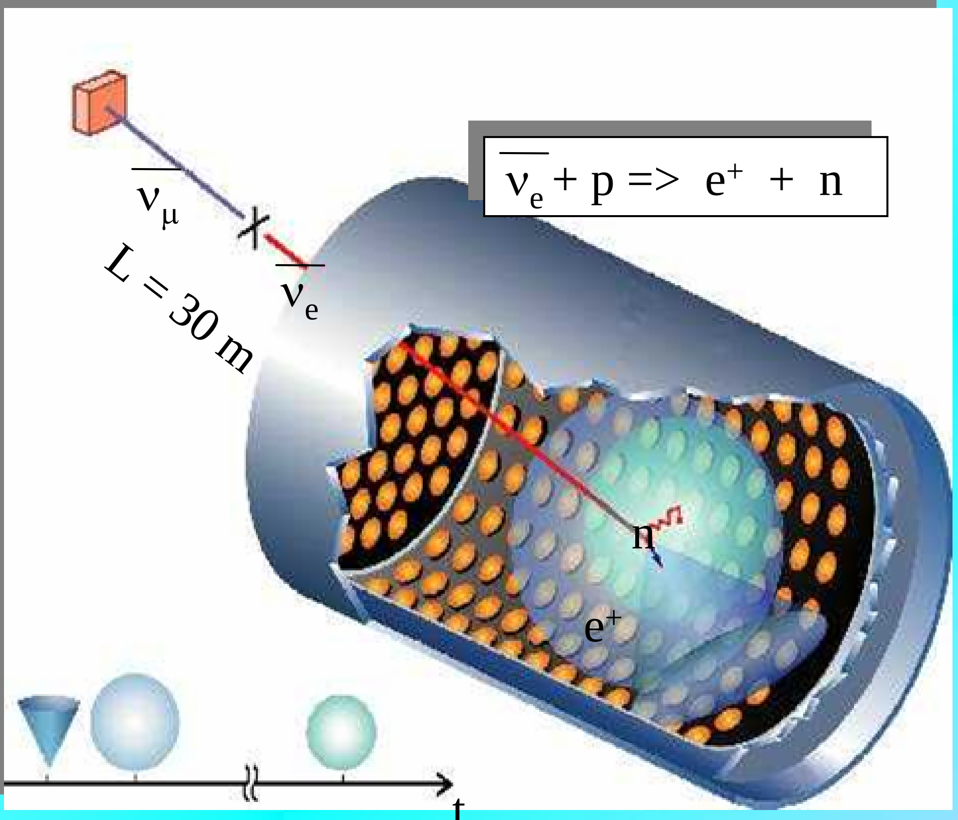
Los Alamos Meson Physics Facility

$p \longrightarrow$

$\pi^+ \longrightarrow \mu^+ + \nu_\mu$

$\longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$

decay at rest



Cherenkov cone + scintillations

200 t mineral oil scintillator

$\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$

P = (2.64 +/- 0.67 +/- 0.45) 10^{-3}

Oscillations?

$\Delta m^2 > 0.2$ eV^2

Beyond ``standard" picture:

- new sector,
- new symmetry

LSND

Ultimate oscillation anomaly?

CPT-violation

G. Barenboim,
L. Borissov, J. Lykken

Disfavored by atmospheric neutrino data, no compatibility of LSND and all-but LSND data below 3σ-level

M.C. Gonzalez-Garcia,
M. Maltoni, T. Schwetz

Sterile neutrino (3 + 1)-scheme (3 + 2) ?

O. Peres, A.S.
M. Sorel, J. Conrad, M. Shaevitz

Non-standard Interactions

K.Babu, S Pakvasa

Disfavored by a new analysis of KARMEN collaboration

CPT + (3+1)

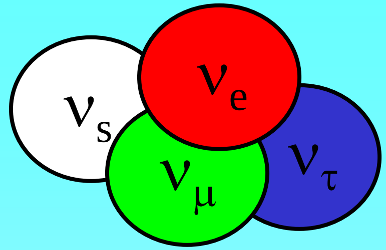
Decaying sterile neutrino

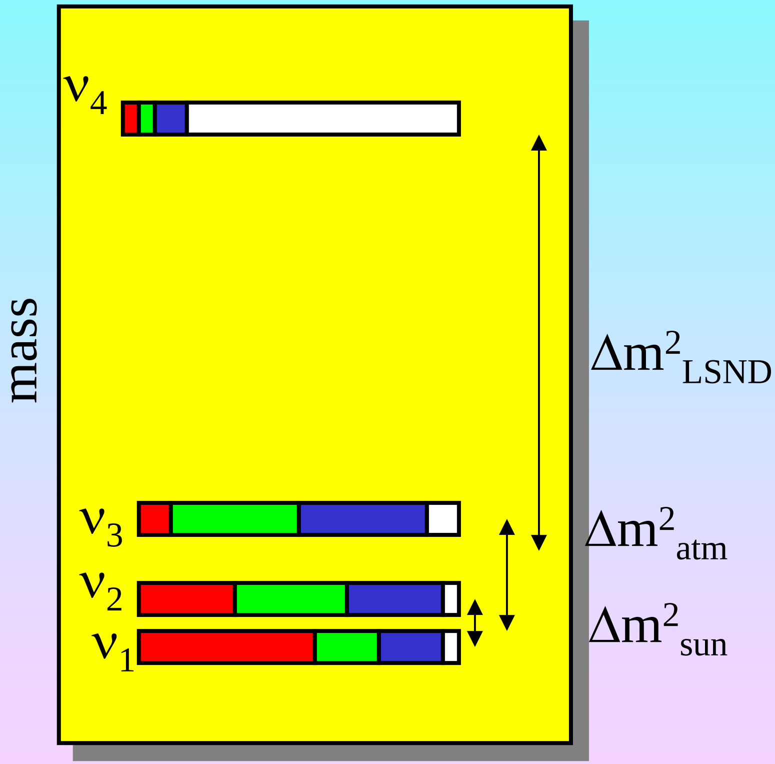
S. Palomares-Ruiz, S. Pascoli,
T.Schwetz

MaVaN

R.Fardon, A. E. Nelson,
N. Weiner

(3 + 1) scheme





1-3 subsystem of levels is frozen

The problem is

$$P \sim |U_{e4}|^2 \; |U_{\mu 4}|^2$$

Restricted by short baseline experiments CHOOZ, CDHS, NOMAD

2 - 3σ below the observed probability

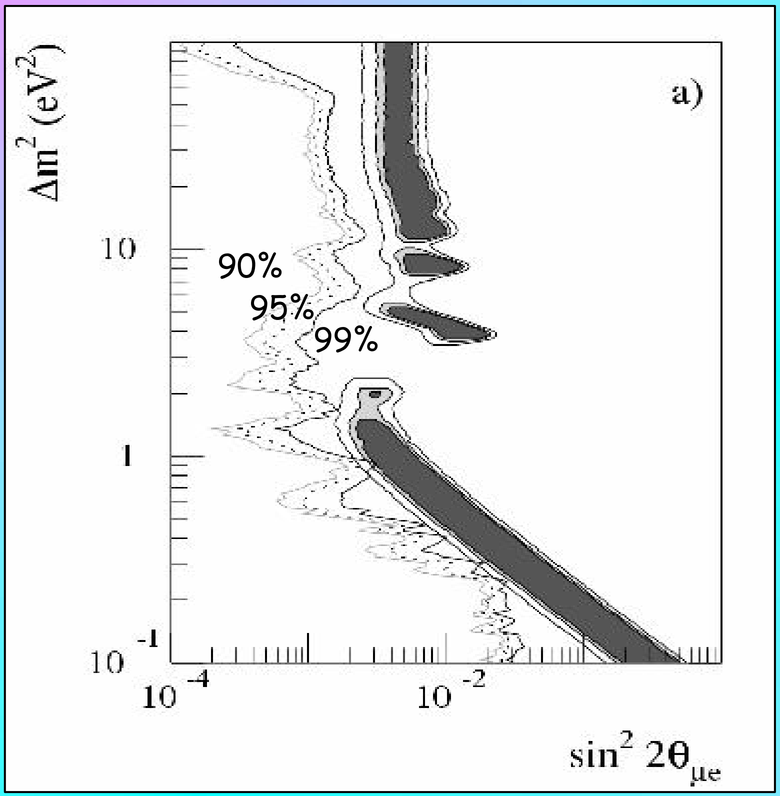
Generic possibility of interest even independently of the LSND result

Generation of large mixing of active neutrinos due to small mixing with sterile state

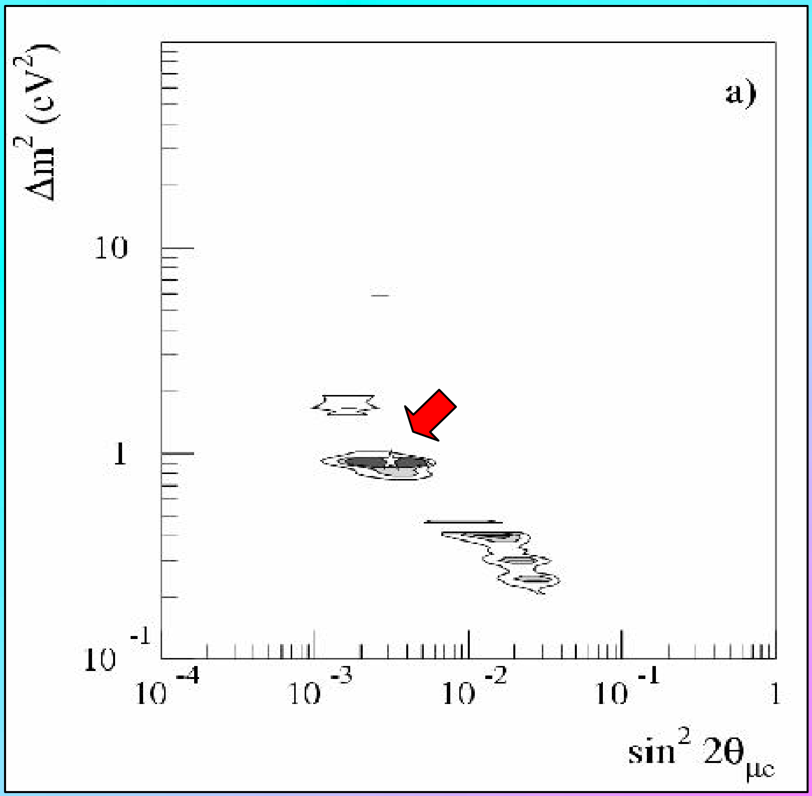
Produces uncertainty in interpretation of results

(3+1) - fit

hep-ex/0407027

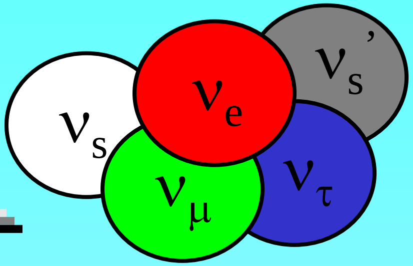


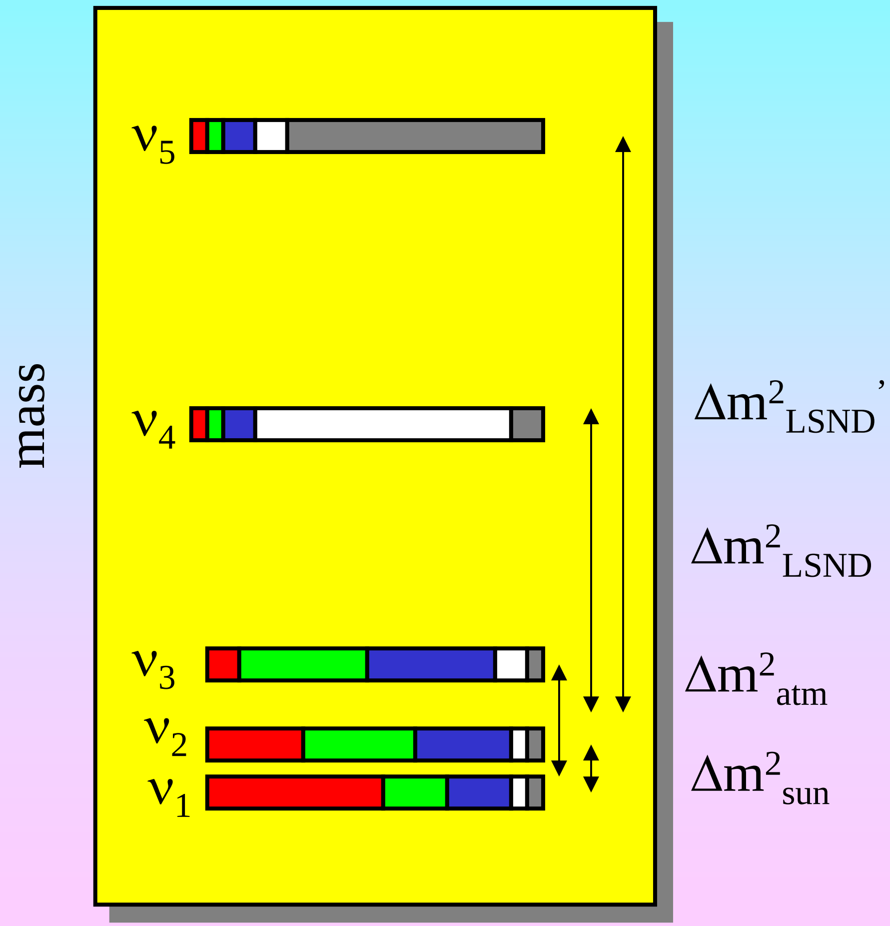
Compatibility of short baseline
Experiments and LSND datasets



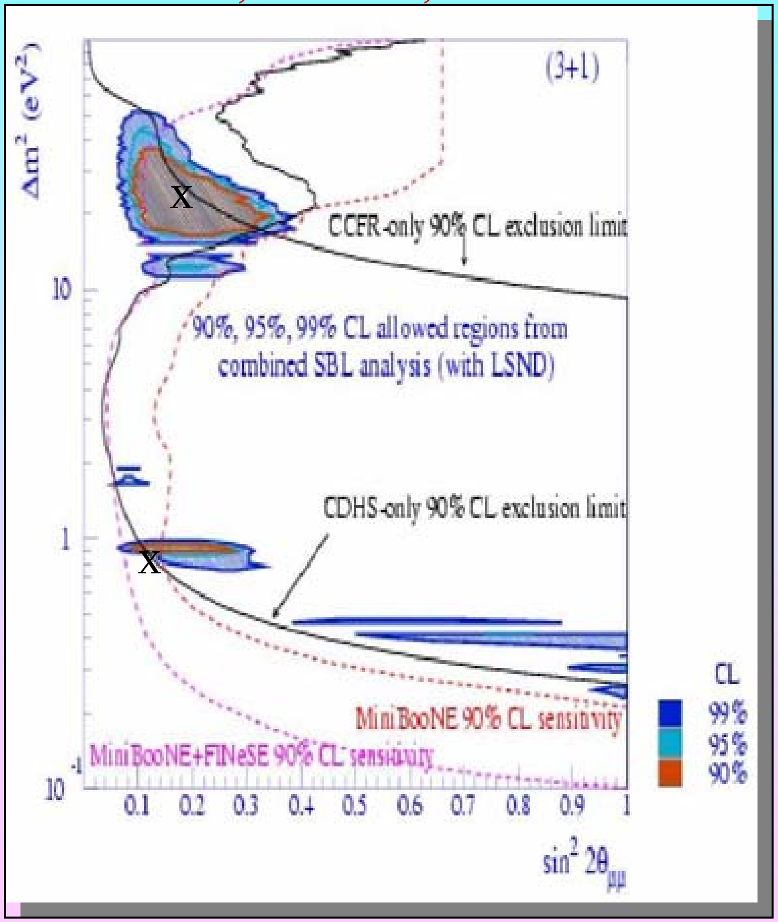
Allowed regions from combined fit of
LSND and short baseline experiments

(3+2) scheme





M. Sorel, J. Conrad, M. Shaevitz



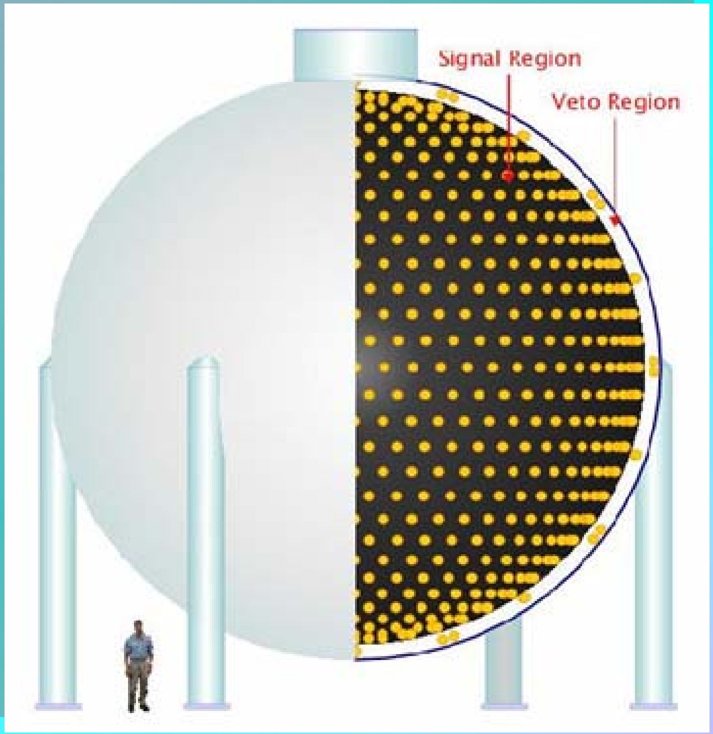
FINeSE

MiniBooNE

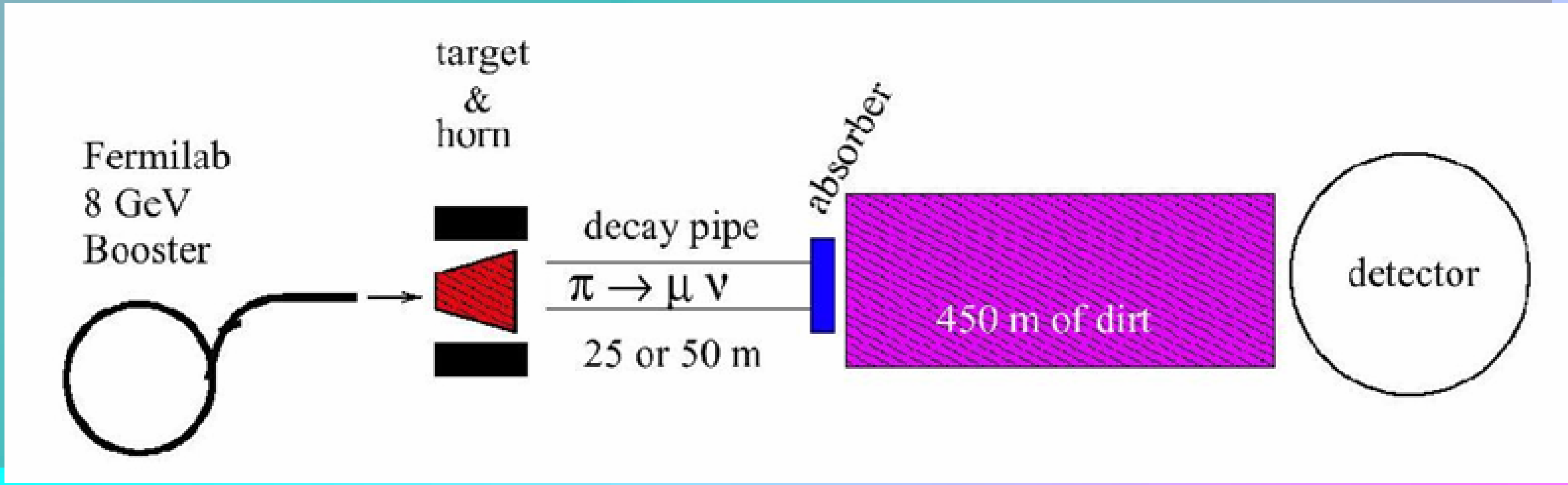
Search for ν_e appearance

12 m diameter tank

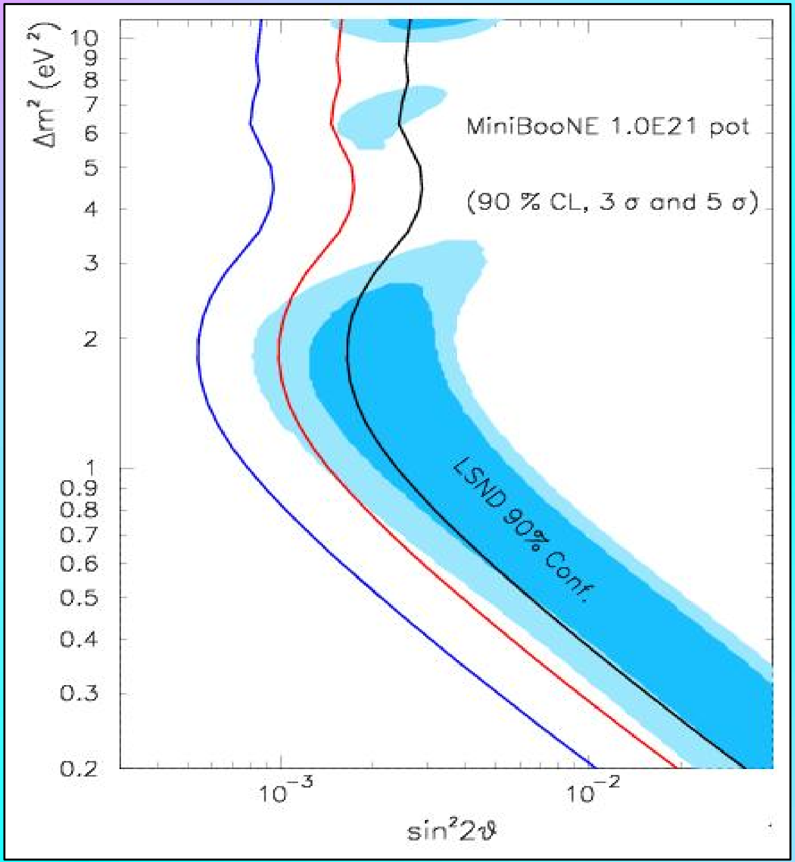
450 t (mineral oil)
1280 PMT

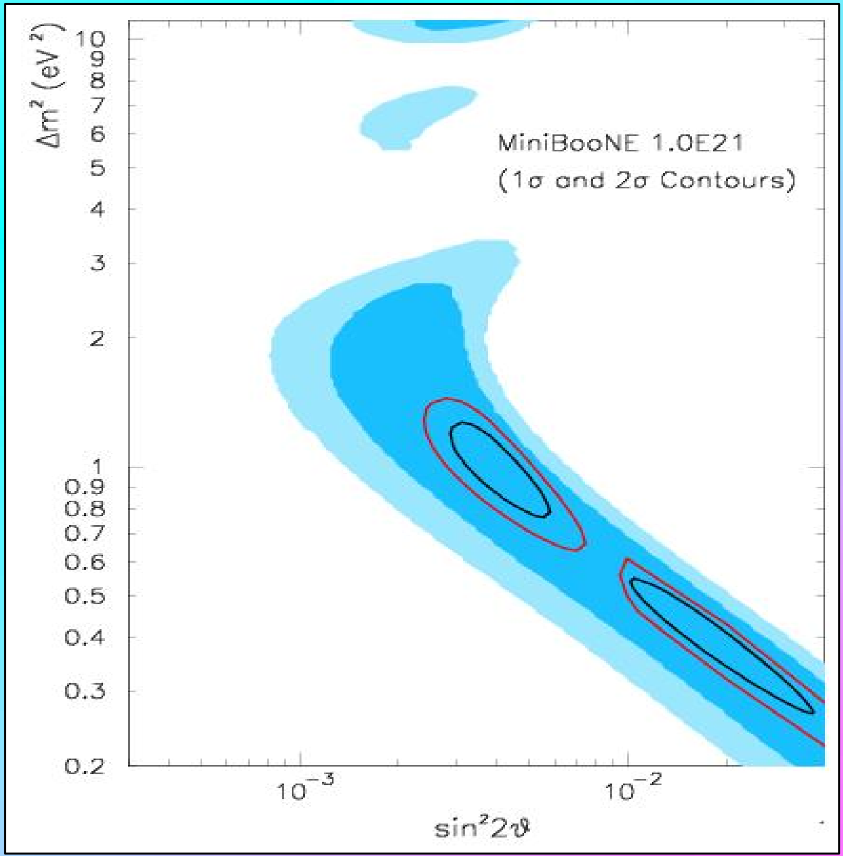


L = 541 m, $\langle E_\nu \rangle \sim$ 800 MeV



MiniBooNE sensitivity





M.H. Shaevitz

Empirical relations

Koide relation

$$\frac{m_e + m_\mu + m_\tau}{(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2} = 2/3$$

Y. Koide, Lett. Nuov. Cim. 34 (1982), 201

with accuracy 10^{-5}

$$\tan\theta_C = \sqrt{3}\,\frac{\sqrt{m_\mu} - \sqrt{m_e}}{2\sqrt{m_\tau} - \sqrt{m_\mu} - \sqrt{m_e}}$$

Both relations can be reproduced if

$$m_i = m_0(z_i + z_0)^2$$

$$\Sigma_i z_i = 0$$

$$z_0 = \sqrt{\Sigma_i z_i^2/3}$$

C A Brannen

Neutrinos

Another representation which is closely connected to circulant symmetry

Summary

Consistent picture: interpretation of all * the results in terms of vacuum mixing of three massive neutrinos

LSND ?

Two effects are important for the interpretation (at the present level of accuracy):
vacuum oscillations, adiabatic conversion (MSW)

Still unknown parameters → future
Phenomenological and experimental studies

Other effects if exist
- sub-leading contributions

Next level, sub-leading effects -
require more involved study

Strong difference of quark and lepton mixing patterns

Furthermore:
- particular neutrino symmetries
- tri-bimaximal mixing
- quark-lepton complementarity?

New puzzle?
Real or
Accidental?