Neutrinos and Nuclei

Plan of lectures:

- Introduction, neutrino mass and oscillations
- Double beta decay
- Neutrinos and supernovae
- Neutrino interactions and cross sections

Petr Vogel, Caltech

NNPSS-TSI-Lecture 1

A brief history of neutrino physics:

1930: Pauli proposes existence of neutrinos in order to save the laws of energy and angular momentum conservation.

1953: Reines and Cowan show that neutrinos are real particles. (1995 Nobel prize for Reines)

1962: Danby *et al.* show that ν_μ and ν_e are distinct particles (1988 Nobel prize for Lederman, Schwartz and Steinberger)

1970: Davis solar neutrino experiment begins; measured flux is only ~1/3 of expected (2002 Nobel prize for Davis).

1975: The third lepton, τ, discovered (1995 Nobel prize for Perl).

1993-2006: LEP experiments establish that $N_\nu = 2.984 \pm 0.008$.

1980-present: Experiments with atmospheric, solar, reactor, and accelerator neutrinos show that neutrinos have a tiny but finite mass and are strongly mixed. (2002 Nobel prize for Koshiba).

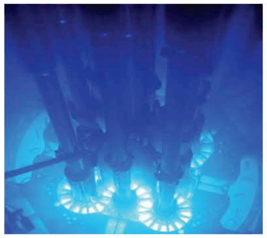
Discovery of neutrino mass and mixing represents the first and until now the only indication for ``physics beyond the Standard Model".

Why experiments with neutrinos are so difficult?

Estimate of the cross section:
Take n -> p + e^- + $\bar{\nu}$ and consider $\bar{\nu}$ + p -> n + e^+
At low (~MeV) energies the cross section can depend only on E
(the energy of the neutrino or positron).
Hence $\sigma \sim G_F^2 E^2 (hc)^2$. $G_F = 1.17 \times 10^{-11}$ MeV^{-2}, hc = 2×10^{-11}MeV cm
Thus $\sigma \sim 10^{-44}$ cm^2 (as in Bethe and Peierls in 1934)

Reminder: Nuclei have R ~ a few x 10^{-13} cm, nucleon
Size is ~ 10^{-13} cm $\equiv$ 1 fm. Hence typical cross sections
are $\sigma \sim \pi R^2 \sim 10^{-24}$ cm^2 $\equiv$ barn. The low energy weak
cross sections are ~20 orders of magnitude smaller.

Track record of neutrino observations:

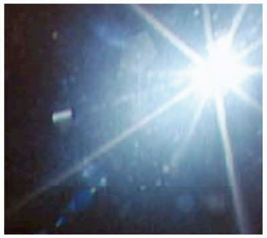


Neutrinos from reactors.

Detected (1950s)

Neutrinos from supernovae.

Detected (1980s)



Neutrinos from the sun.

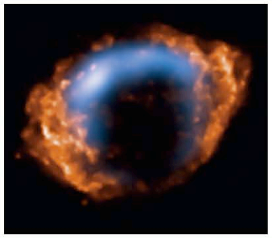
Detected (1960s)

Neutrinos from the Earth.

Detected (2000s)

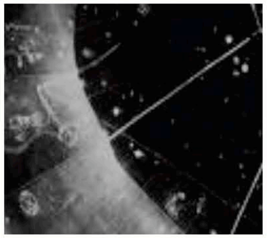
Neutrinos from the atmosphere.

Detected (1960s)



Neutrinos from galactic sources.

Not yet (but close!)



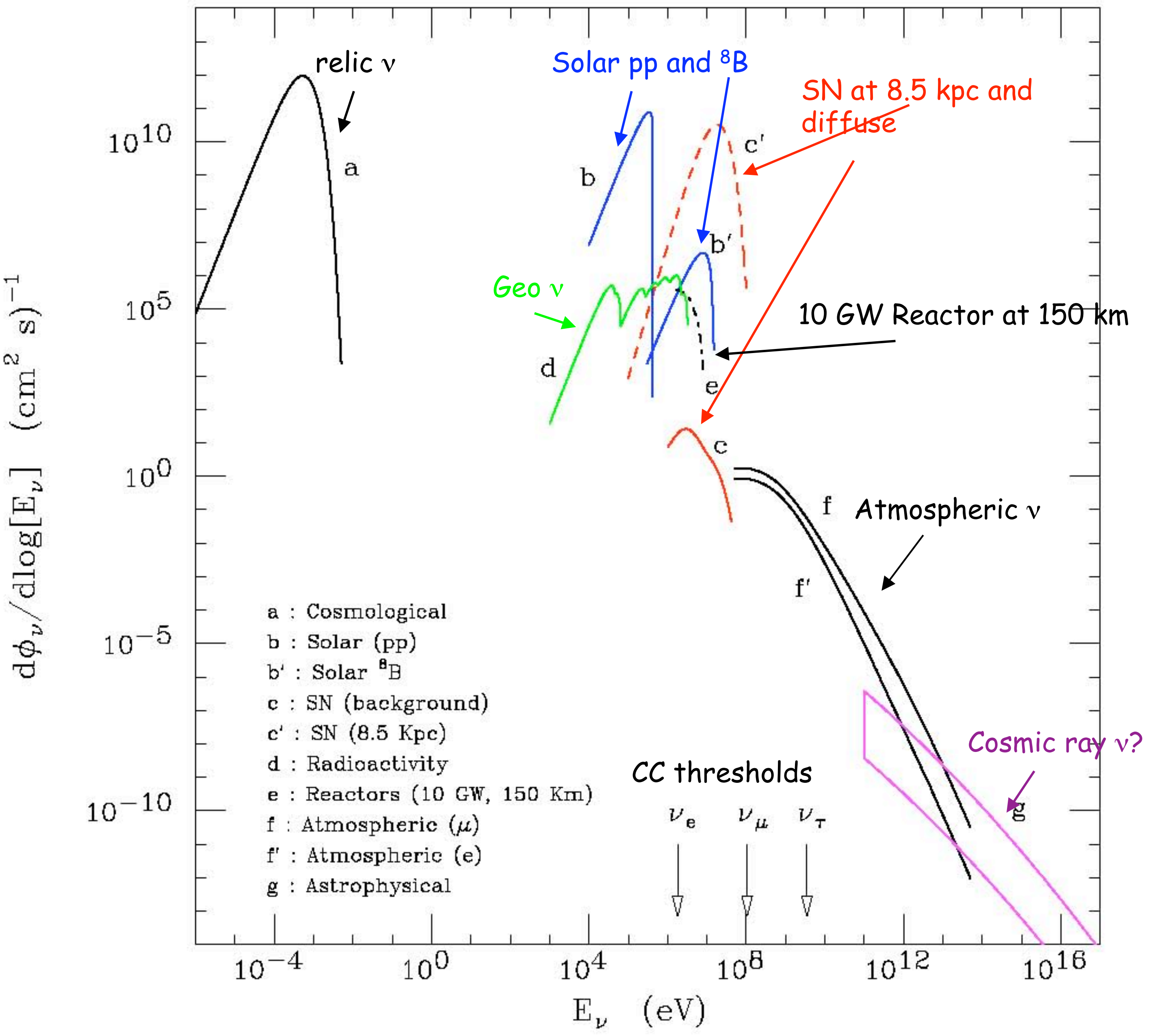
Neutrinos from accelerators.

Created & detected (1960s)

Neutrinos from the Big Bang.

Not even close...

Overview of neutrino sources and fluxes (20 orders of magnitude in energy and flux)

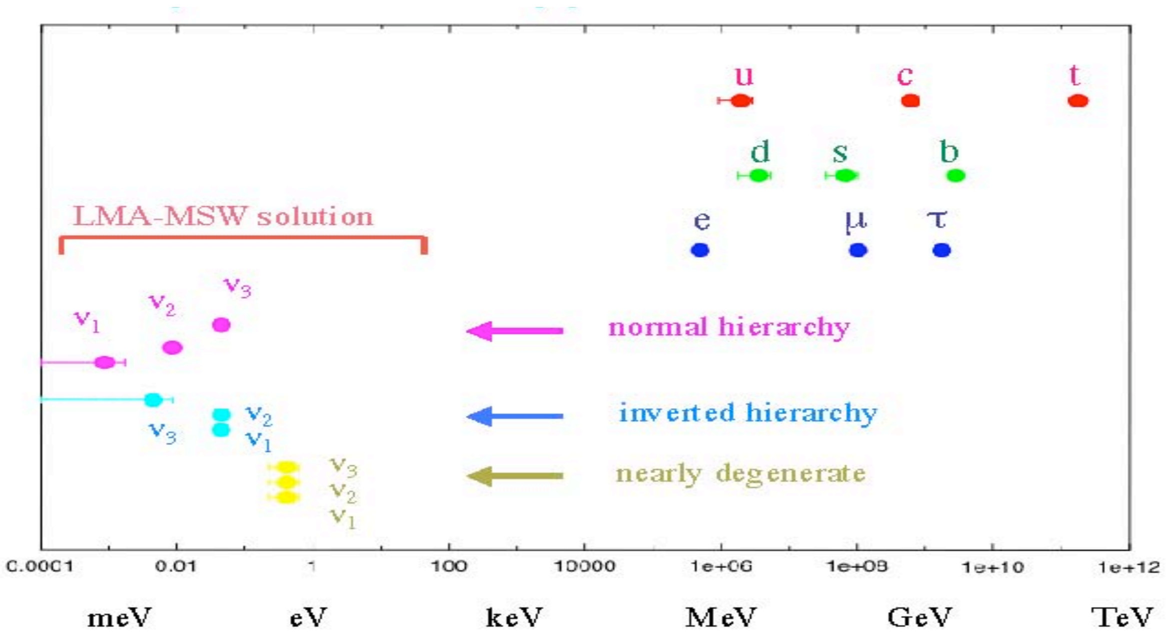


Slide by P.Lipari

Standard Model of Electroweak interactions postulates that all neutrinos are exactly massless. As a consequence, the individual lepton flavors are conserved, i.e. processes like $\mu \to e + \gamma$ and also $\nu_\mu + n \to e^- + p$ etc. are strictly forbidden.

However, more recent discoveries challenge this postulate and show that neutrinos are massive (albeit much lighter than other fermions) and that the individual lepton numbers are not conserved.

Description of these phenomena will be the main topic of these lectures. It is hoped that the pattern of neutrino masses and mixing that is emerging will offer a glimpse into the fundamental source of particle masses and the role of flavor.



Even though we do not know as yet the exact values (or pattern) of neutrino masses, we **do know** that they are $\sim 10^6$ times lighter than other fermions.

Oscillation phenomenology-quantum mechanical interference

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

$$|\nu_\mu\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

States with a definite flavor, ν_e, ν_μ, are superpositions of states ν_1, ν_2 with definite mass which propagate simply as plane waves.

$$|\nu(t)\rangle = e^{-iE_1t}\,\cos\theta|\nu_1\rangle + e^{-iE_2t}\,\sin\theta|\nu_2\rangle$$

Propagation of a beam that began as ν_e.

$$E_2 - E_1 \cong (m_2^2 - m_1^2)/2p = \Delta m^2/2p$$

Phase difference for ultrarelativistic neutrinos

$$|\langle\nu_e|\nu(t)\rangle|^2 = 1 - \sin^2 2\theta\,\sin^2(\pi L/L_{osc})$$
$$|\langle\nu_\mu|\nu(t)\rangle|^2 = \sin^2 2\theta\,\sin^2(\pi L/L_{osc})$$

When the beam $\nu(t)$ is projected onto $|\nu_e\rangle$ or $|\nu_\mu\rangle$ at $L = t$ the resulting probability is an oscillating function of L.

Where $L_{osc} = 4\pi p/\Delta m^2 = 4\pi E_\nu/\Delta m^2$

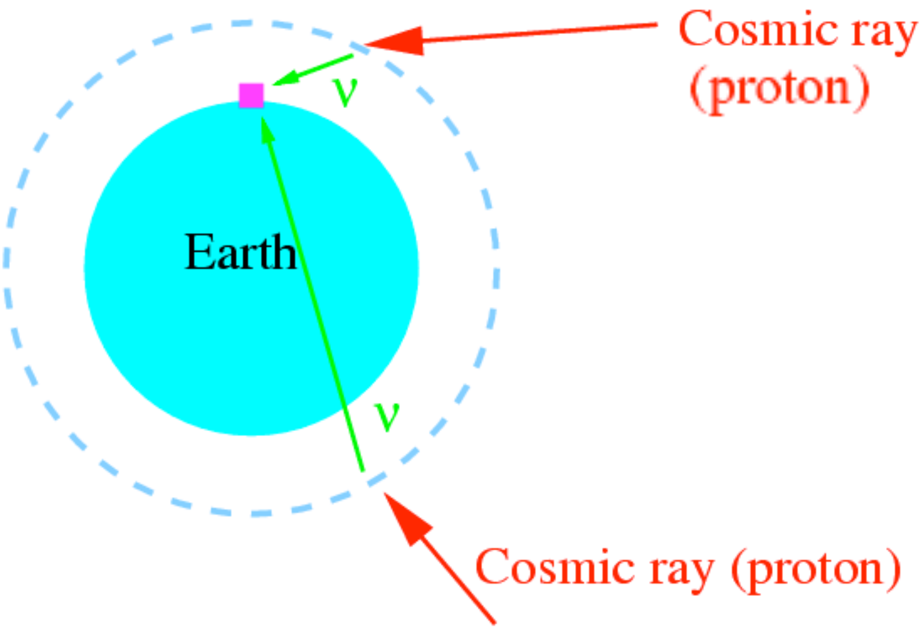
$E_\nu = 1$ GeV, $\Delta m^2 = 10^{-3}$ eV^2, $L = 1240$ km — Atmospheric neutrinos, long baseline accelerator experiments

$E_\nu = 1$ MeV, $\Delta m^2 = 10^{-3}$ eV^2, $L = 1.2$ km — Reactor searches for θ_{13}

$E_\nu = 1$ MeV, $\Delta m^2 = 10^{-5}$ eV^2, $L = 125$ km — Solar neutrinos, reactor verification of the solar neutrino oscillations.

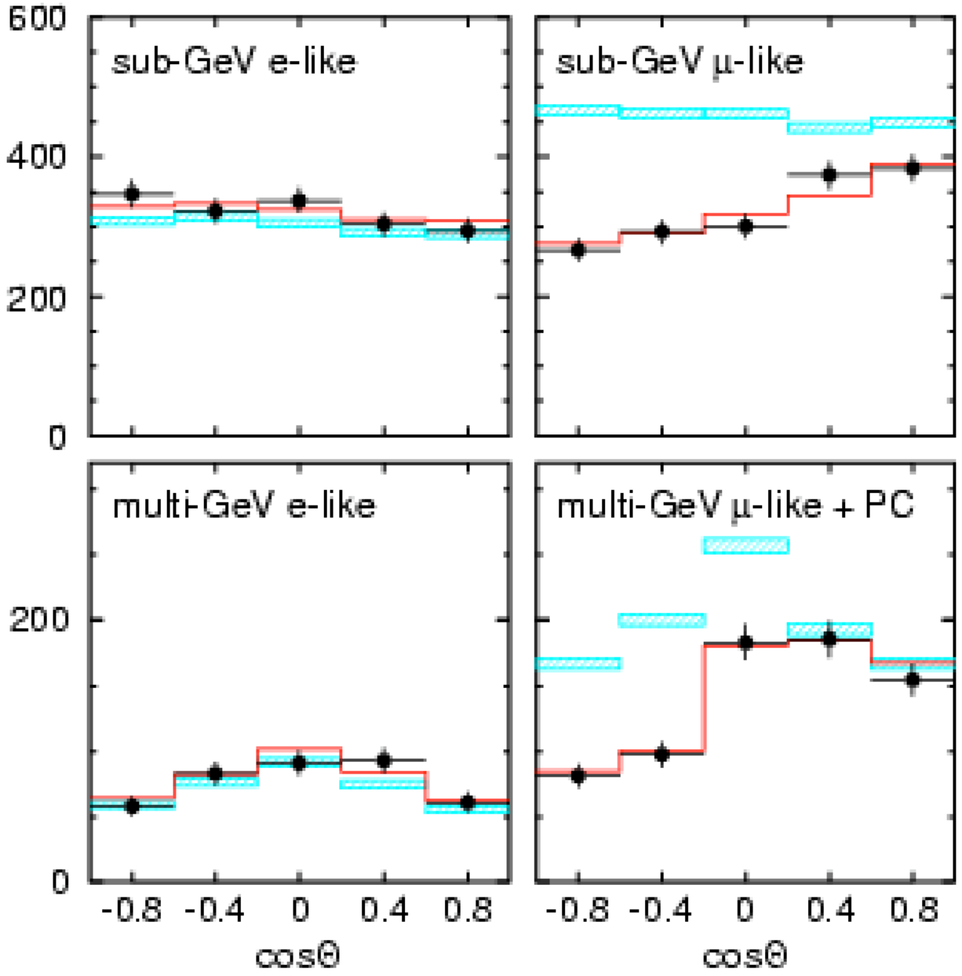
Super – Kamiokande
Atmospheric Neutrino Oscillations

Dependence on the zenith angle, i.e. on the path length. Blue - no oscillations, red - with oscillations. Fit: $\sin^2 2\theta \sim 1$, $\Delta m^2 \sim 2.5\mathrm{x}10^{-3}$ eV^2.

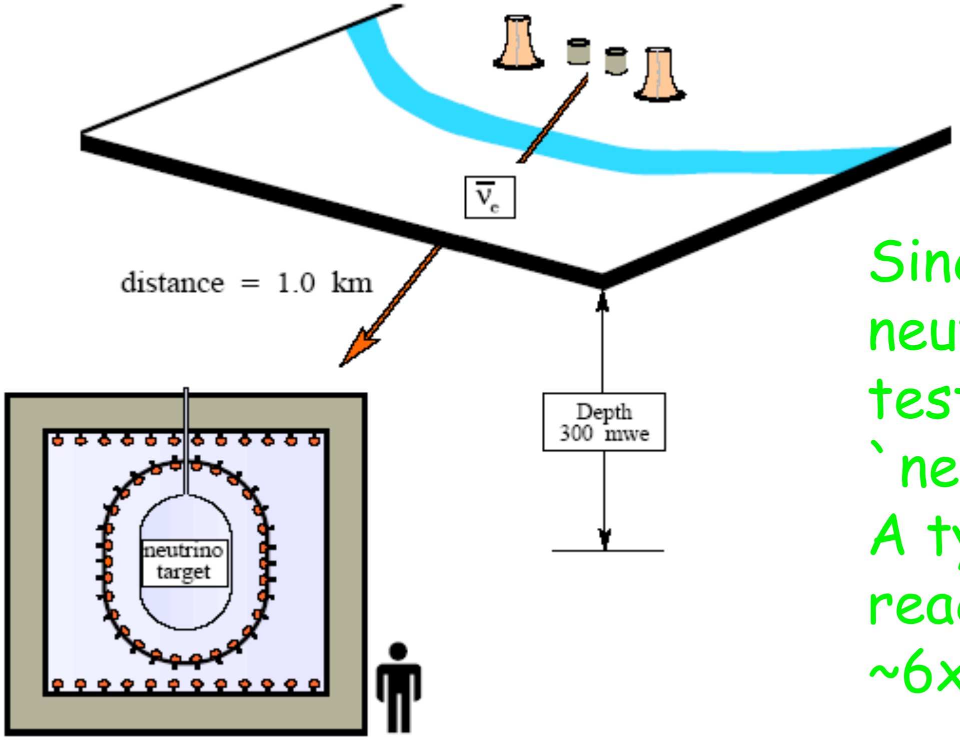


ν_μ oscillate, presumably into ν_τ,
ν_e is not affected.

This finding now confirmed by accelerator experiments K2K and MINOS.



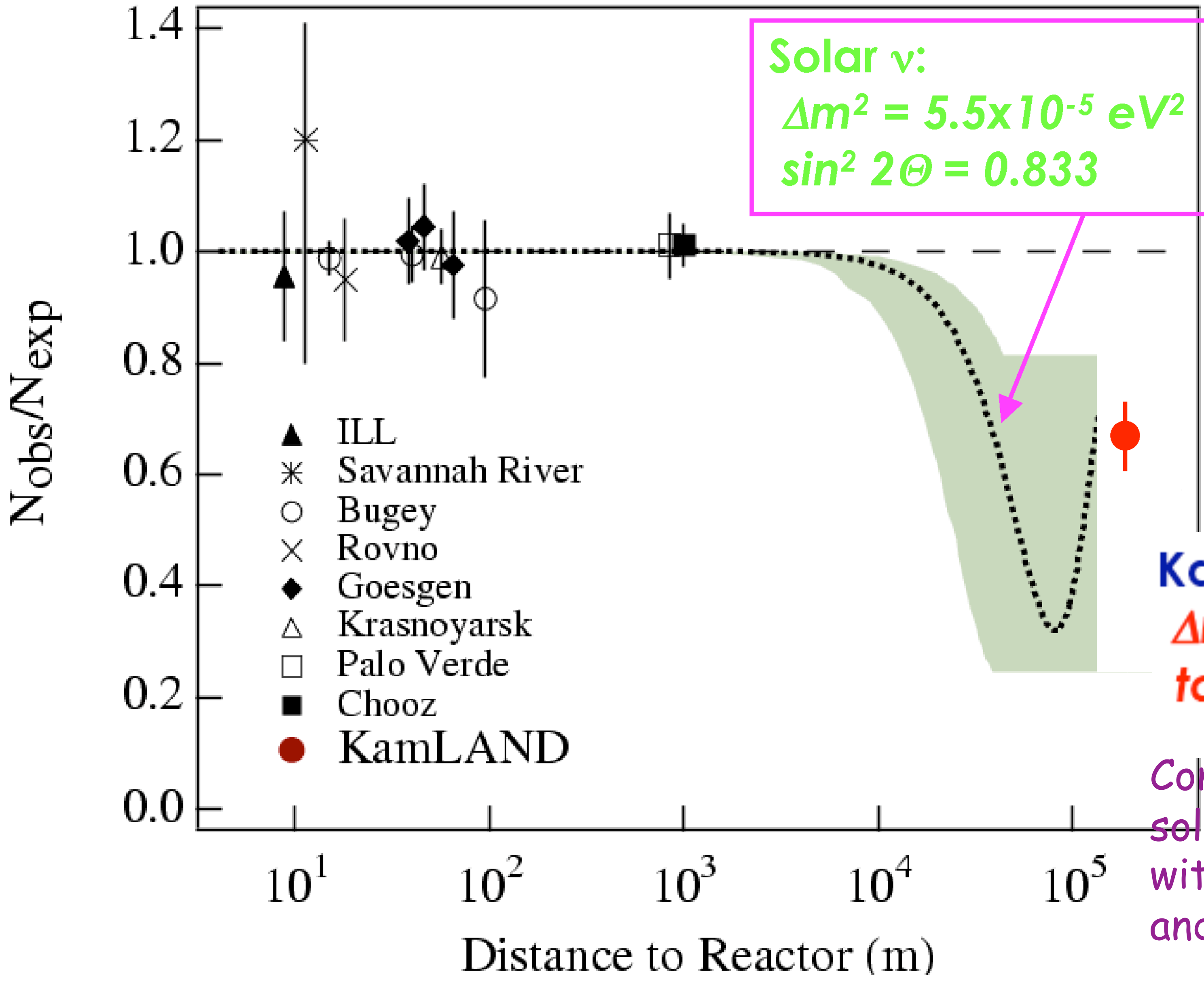
Reactor Neutrino Experiments



Since only few MeV neutrinos are involved, test of the `neutrino disappearance'
A typical 3 GW_{th} power reactor produces $\sim 6\times10^{20} \underline{\nu}_e\ s^{-1}$

- $\bar{\nu}_e$ from n-rich fission products
- detection via inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$)
- Measure flux and energy spectrum
- Variety of distances L= 10-1000 m **+ ~180 km (Kamland)**

Ratio of Measured and Expected $\overline{\nu}_e$ Flux from Reactor Neutrino Experiments



Solar ν:

$\Delta m^2 = 5.5 \times 10^{-5}\ \mathrm{eV}^2$

$\sin^2 2\Theta = 0.833$

G.Fogli et al., PR D66, 010001-406, (2002)

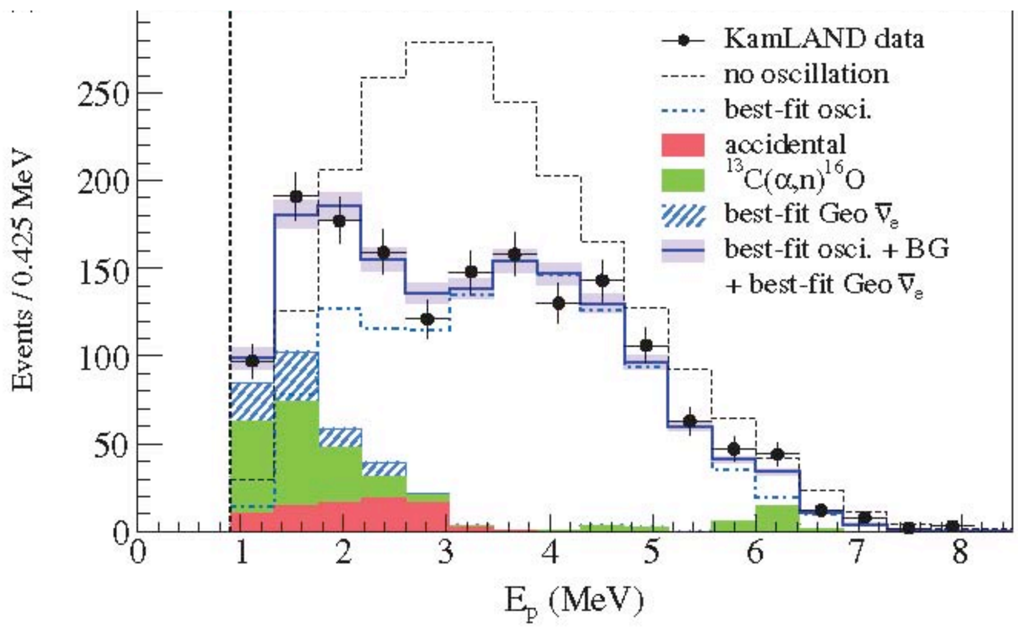
KamLAND best fit :

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

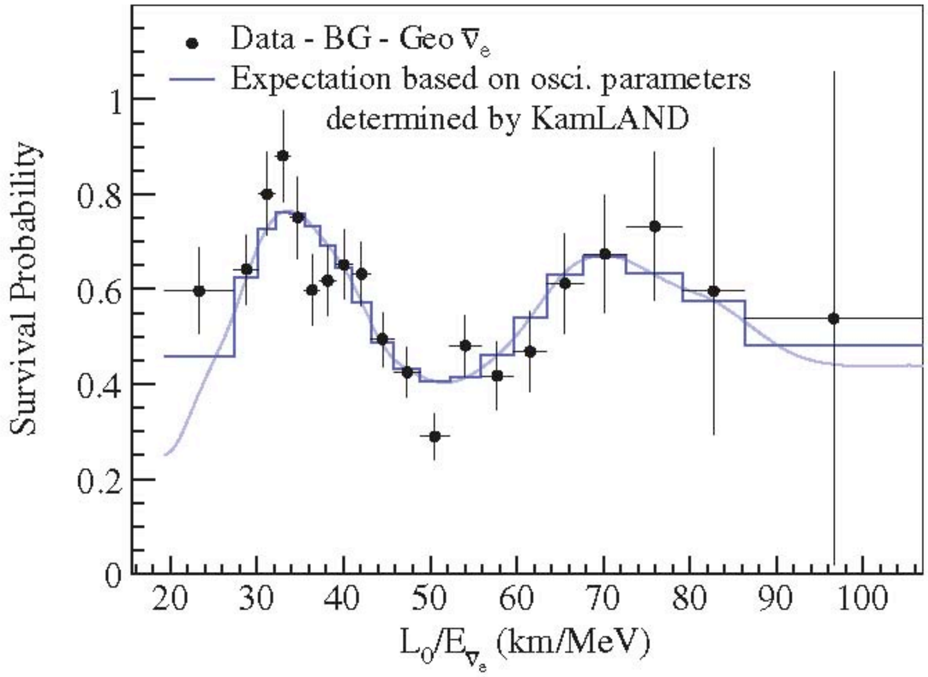
$\tan^2\theta = 0.45$

Confirmation of the solar neutrino result, without matter effects and with antineutrinos

Kamland convincingly shows that $\bar{\nu}_e$ disappear and that the spectrum is distorted in a way only compatible with oscillations.



There are fewer events than expected and the shape is significantly different



Even though there is no well defined distance (40 reactors) ~80% of the flux originates from L_0 = 180 km. One can see that neutrinos indeed oscillate.

See PRL100, 221803(2008)

Oscillation of solar neutrinos:

Effect of matter on neutrino propagation

That is a preposterous idea; the mean free path is too long $\lambda = 1/N\sigma$,
N = number density ~ $N_0\rho \sim 10^{24}$ cm^{-3}, σ = cross section ~ 10^{-43} cm^2
for low energy neutrinos , thus, $\lambda \sim 10^{19}$ cm ~ 10 light years.

The σ is so small because it is ~ G_F^2. But interaction energy with matter is ~ G_F and might affect the relative phase of states that are not energy eigenstates.

In matter the phase e^{-iEt}, where $E \sim p + m^2/2p$ should be replaced by **$E + \langle H_{eff} \rangle$**, where $\langle H_{eff} \rangle$ represents the expectation value of the weak interaction between the neutrinos and the constituents of matter.

Thus in matter schematically $E_{eff} = E_0 + m^2/2E_0 + 2^{1/2} G_F N_e$

This term is present
only for ν_e and has a
minus sign for $\bar{\nu}_e$

All neutrinos interact equally through Z^0 exchange (NC) with electrons and quarks

Electron neutrinos interact with electrons by Z^0 and W^{+-} exchange

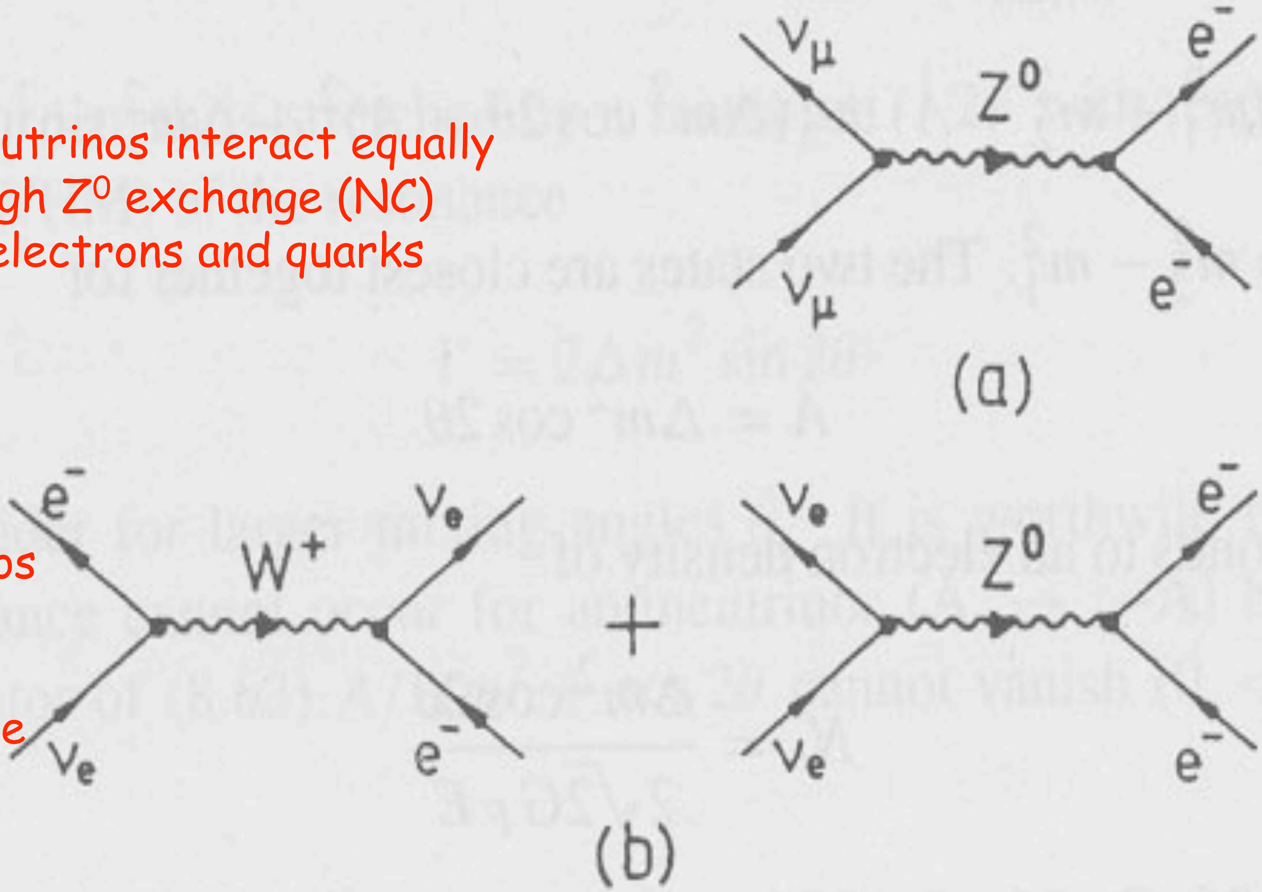


Figure 10.16. Origin of the Mikheyev–Smirnov–Wolfenstein effect. Whereas weak NC interactions are possible for all neutrino flavours, only the ν_e also has the possibility of interacting via charged weak currents.

The matter oscillation length is therefore

$L_0 = 2\pi/2^{1/2}G_F N_e = 1.7\times10^7$ (meters)$/Y_e\rho$(g cm^{-3}) $Y_e = Z/A$ (electron fraction)

L_0 is independent of energy. For typical densities on Earth L_0 ~ Earth diameter so matter effects are small.However, in Sun or other astrophysical objects they are decisive.

So, we can have two kinds of neutrino oscillations, **vacuum and matter**. To see which of them dominates, compare the two oscillation lengths:

$$L_{osc}/L_0 = 2^{3/2}G_F N_e\, E_\nu/\Delta m^2$$
$$= 0.22[E_\nu(\text{MeV})][\rho Y_e(100\text{g cm}^{-3})][7\times10^{-5}/\Delta m^2(\text{eV}^2)]$$

If this ratio is >> 1 matter oscillations dominate, if it is <1, vacuum oscillations dominate.

A bit of formalism: In matter, for the simplified case of two neutrino flavors, we have to diagonalize *H* in the flavor basis that contains $V= 2^{1/2}G_FN_e$ and $\xi= L_{osc}/L_0$. The hamiltonian matrix can be transformed into the form of vacuum oscillations by introducing the effective mixing angle θ_m and effective oscillation length $L_m = L_{osc} \sin2\theta_m/\sin2\theta$

$$
\begin{aligned}
H &= H_{\text{vacuum}} + H_{\text{matter}} \\
&= \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} m_1^2/2E & 0 \\ 0 & m_2^2/2E \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} + \begin{pmatrix} V & 0 \\ 0 & 0 \end{pmatrix} \\
&= \frac{\Delta m^2}{4E} \begin{pmatrix} -\cos 2\theta + \xi & \sin 2\theta \\ \sin 2\theta & \cos 2\theta - \xi \end{pmatrix} \\
&= \frac{(\Delta m^2)_m}{4E} \begin{pmatrix} -\cos 2\theta_m & \sin 2\theta_m \\ \sin 2\theta_m & \cos 2\theta_m \end{pmatrix} \qquad (1.13)
\end{aligned}
$$

For constant density case there can be three distinct regimes:

1) Low density, $L_0 >> |L_{osc}|$: matter has little effect on oscillations

3) High density, $L_0 << |L_{osc}|$: $\nu_e \to \nu_H$ and oscillations are suppressed (since the amplitude ~ $\sin^2 2\theta_m$, where θ_m is the effective mixing angle in matter.

3) Resonance, when $2^{3/2} E G_F N_e \to \Delta m^2 \cos 2\theta_v$ ($L_{osc} = L_0 \cos 2\theta v$): in that case the oscillations are enhanced since $\theta_m \to \pi/4$ independently of θ_v. Note that the resonance condition depends on the sign of Δm^2, and whether ν or ν are involved.

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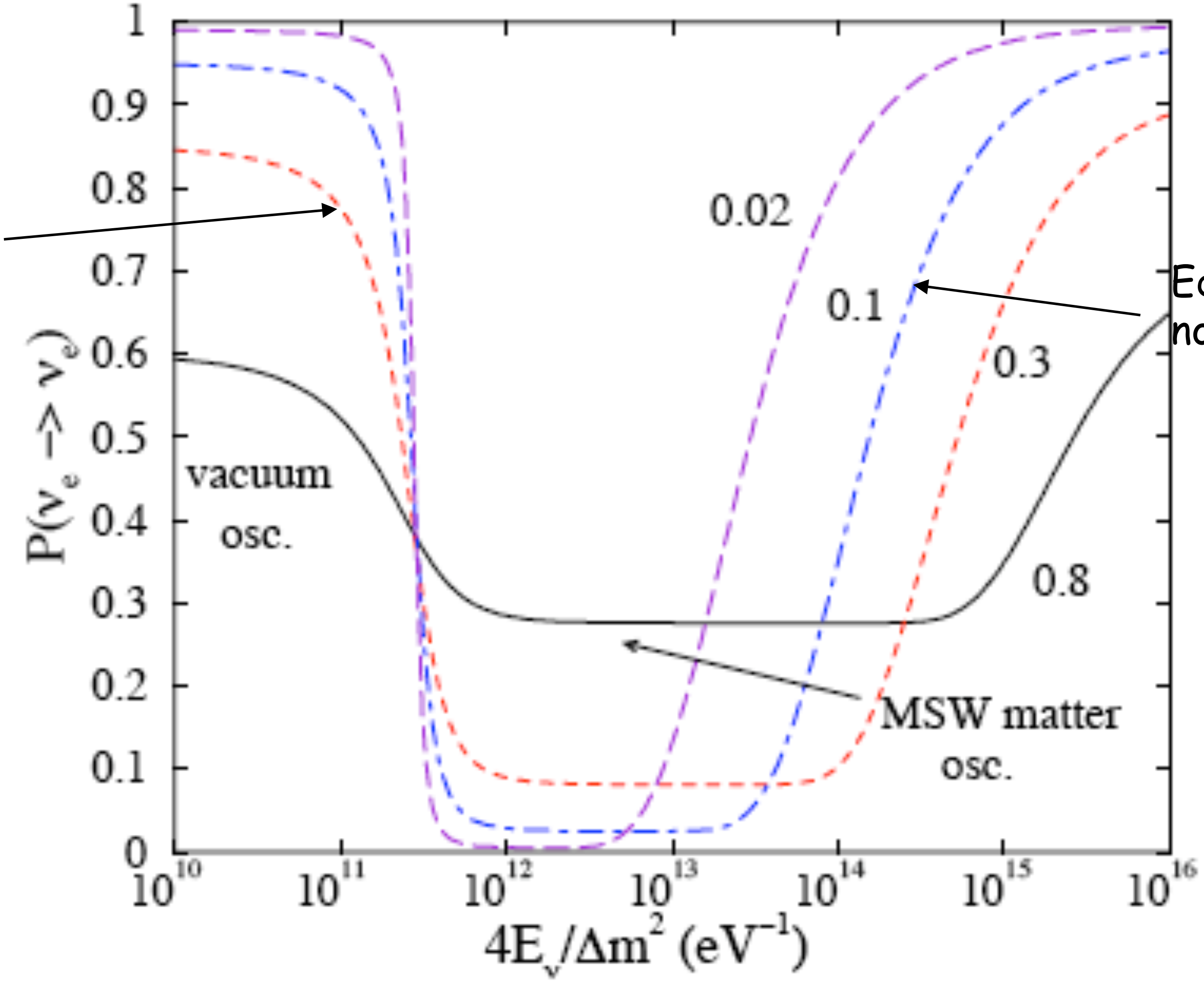
The most interesting case is the case of neutrinos propagating through an object of varying density (e.g. the Sun) from the high density regime to the low density regime.

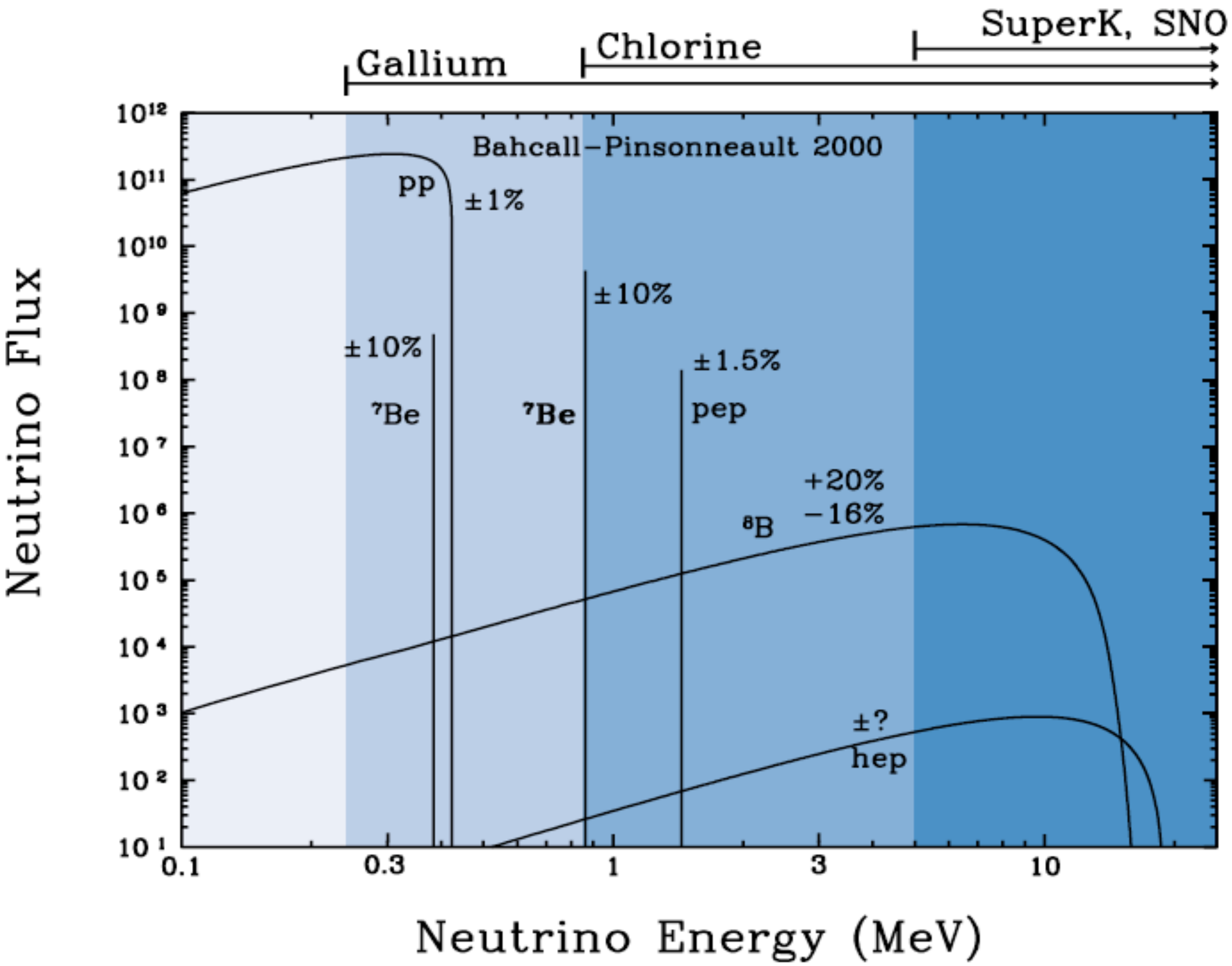


Edges of matter effects

Edges of nonadiabacity

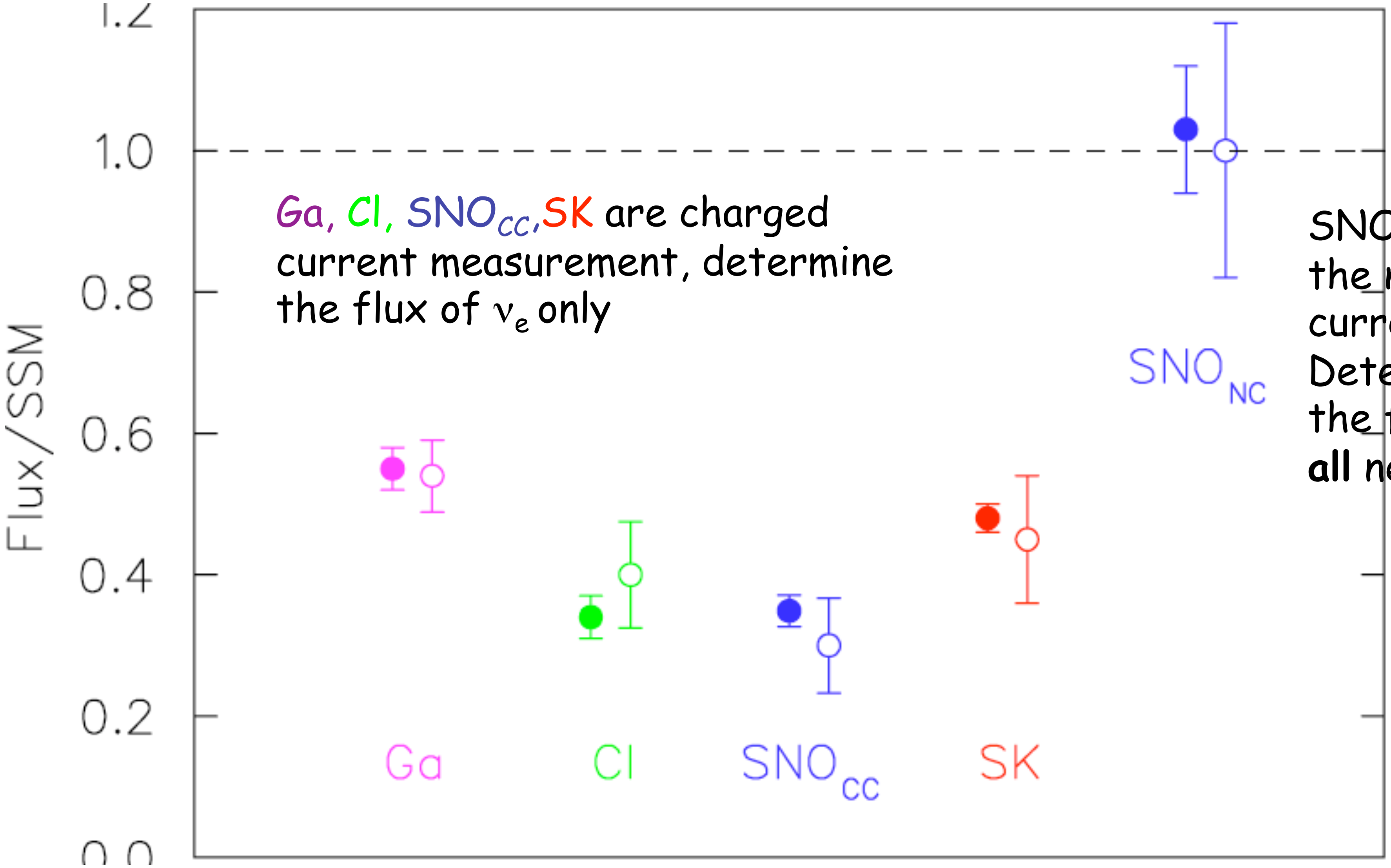
Schematic illustration of the survival probability of ν_e created at the solar center. Curves are labelled by the corresponding $\sin^2 2\theta$ values.

Expected fluxes of solar neutrinos (Bahcall)



Components of the ν_e flux (no oscillations) and ranges of the solar neutrino detection experiments are indicated. Note the extreme log Scale.

Summary of results: Ratio of the observed/expected flux



Ga, Cl, SNO$_{CC}$, SK are charged current measurement, determine the flux of ν_e only

SNO$_{NC}$ is the neutral current. Determines the flux of **all** neutrinos

Note: The Cl and SNO$_{cc}$ are below ~0.3. Ratio below 0.5 is impossible for two flavor vacuum oscillations. This is a clear indication of matter effects.

By combining the charged and neutral current events, SNO was able to show convincingly that the solar ν_e were transformed into another active neutrino flavor.

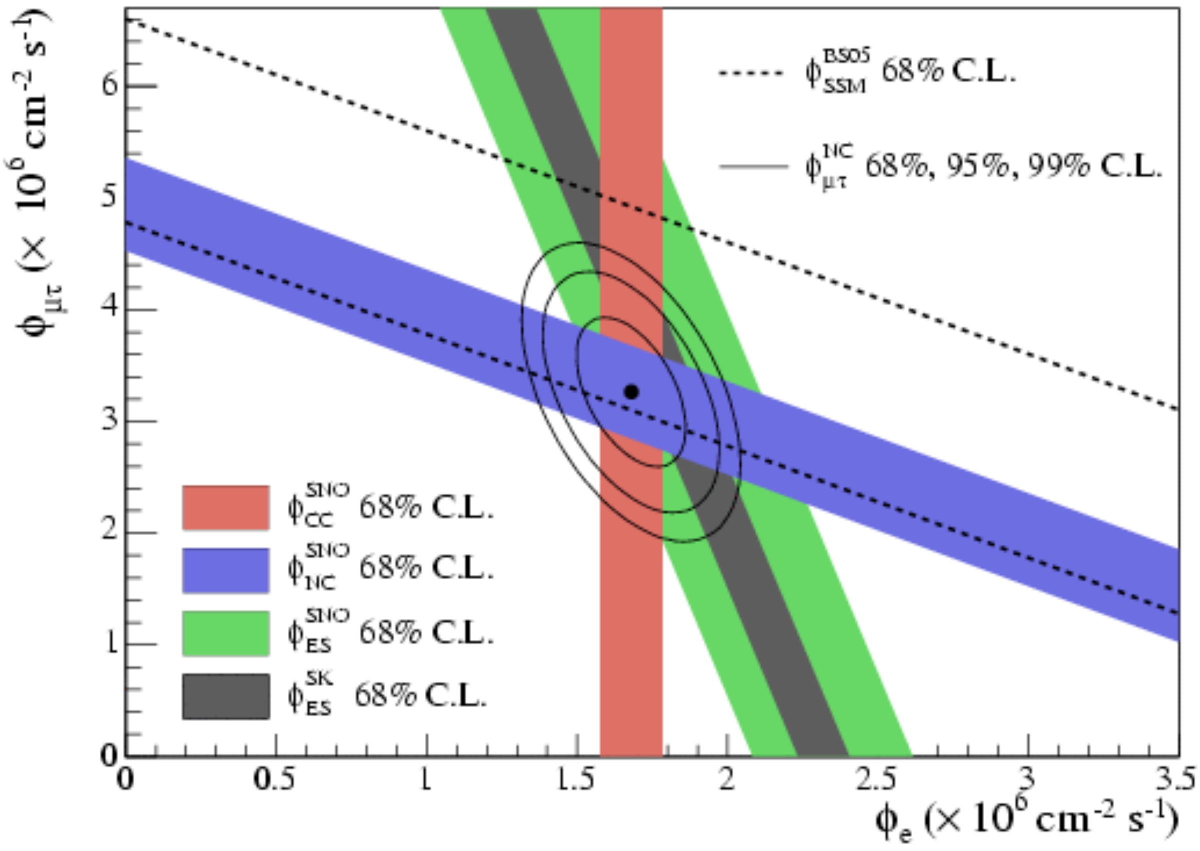
$$\phi_{CC} = 1.68 \;{}^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

$$\phi_{NC} = 4.94 \;{}^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

$$\phi_{ES} = 2.35 \;{}^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$$

(Fluxes Φ in units of 10^6 cm^{-2}s^{-1})
Shown are the SNO results from the 391 day salt phase.



Summary of the positive evidence:

1) ν_μ oscillate into ν_τ with $|\Delta m^2| \sim 2.4 \times 10^{-3}$ eV^2 and nearly maximum mixing angle (near 45^0). The sign of Δm^2 remains unknown.

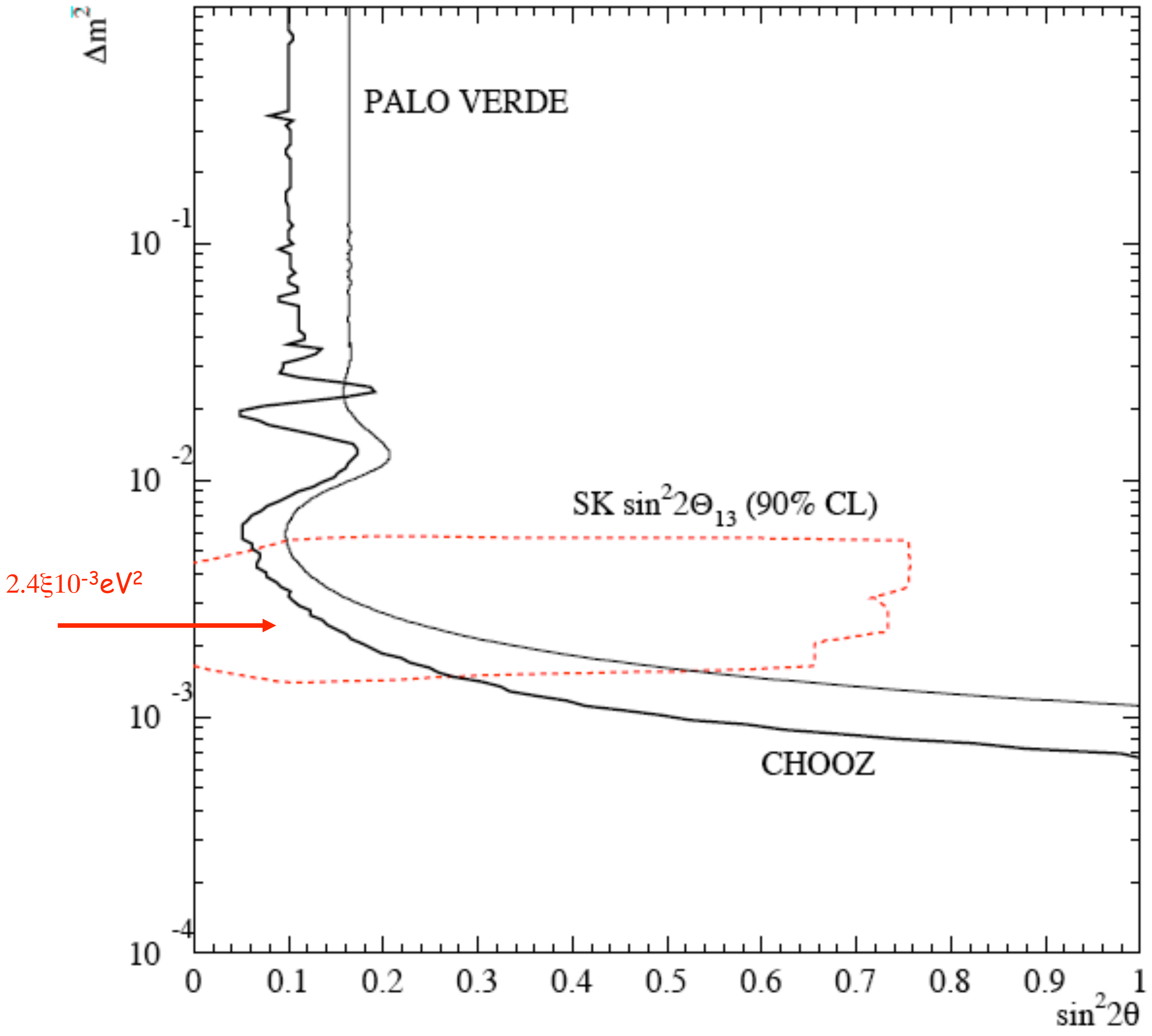
2) ν_e oscillate into another active flavor with $\Delta m^2 \sim 8 \times 10^{-5}$ eV^2 and a large but not maximum mixing angle ($\theta_{12} \sim 32^0$). Because of the matter effects in the Sun, the sign of Δm^2 is fixed (> 0 by convention, ν_e are dominantly the lighter of the two).

3) But we do not know whether ν_e are affected by oscillations with $|\Delta m^2| \sim 2.4 \times 10^{-3}$ eV^2 . If that effect exists, it is small because the angle θ_{13} is small.

What about the corresponding mixing angle θ_{13}?

We have argued that the determination of the ν_e component of atmospheric neutrino flux does not give very useful information on the angle θ_{13}. The most natural way of determining that angle is to look for the ν_e disappearance (or appearance) at distances corresponding to Δm^2_{atmos}.

Two such experiments with reactor antineutrinos, CHOOZ and Palo Verde were done in late nineties when it was unclear whether the atmospheric neutrinos involve $\nu_\mu \to \nu_\tau$, or $\nu_\mu \to \nu_e$.
The characteristic distance is ~ km, and no effect was seen.
Hence these result constrain θ_{13} from above to rather small value.



$2.4\xi 10^{-3}$eV^2

Constraints on θ_{13} from the Chooz and Palo Verde reactor experiments. The region to the right of the curves is excluded.

Note that the maximum $\sin^2\theta_{13}$ value depends on the so far poorly determined Δm_{31}^2 value.

Global fits give $\sin^2\theta_{13} = 0.9_{-0.9}^{+2.3} \times 10^{-2}$ at 95% CL, consistent with vanishing θ_{13}.

Present status of our knowledge of oscillation parameters or what do we know?

Neutrino Oscillation Parameters Determined From Various Experiments (2003)

Parameter	Value $\pm 1\sigma$	Reference	Comment
Δm^2_{12}	$7.1^{+1.2}_{-0.6} \times 10^{-5}$ eV^2	[72]	$(7.59 \pm 0.21) \times 10^{-5}$ eV^2 (2008)
θ_{12}	$32.5^{\circ}{}^{+2.4}_{-2.3}$	[72]	For $\theta_{13} = 0$ $34.4^0 \pm 1.6^0$(2008)
Δm^2_{32}	$2.0^{+0.6}_{-0.4} \times 10^{-3}$ eV^2	[62]	$(2.43 \pm 0.13) \times 10^{-3}$ eV^2 (2009)
$\sin^2 2\theta_{23}$	> 0.94	[62]	For $\theta_{13} = 0$
$\sin^2 2\theta_{13}$	< 0.11	[64]	For $\Delta m^2_{atm} = 2 \times 10^{-3}$ eV^2

The mixing matrix therefore, as of now, looks like this (error bars not shown):

$$U = \begin{array}{c|ccc|} & \nu_1 & \nu_2 & \nu_3 \\ e & 0.82 & 0.56 & 0.0(0.15) \\ \mu & -0.42 & 0.61 & 0.67 \\ \tau & 0.38 & -0.56 & 0.74 \end{array}$$

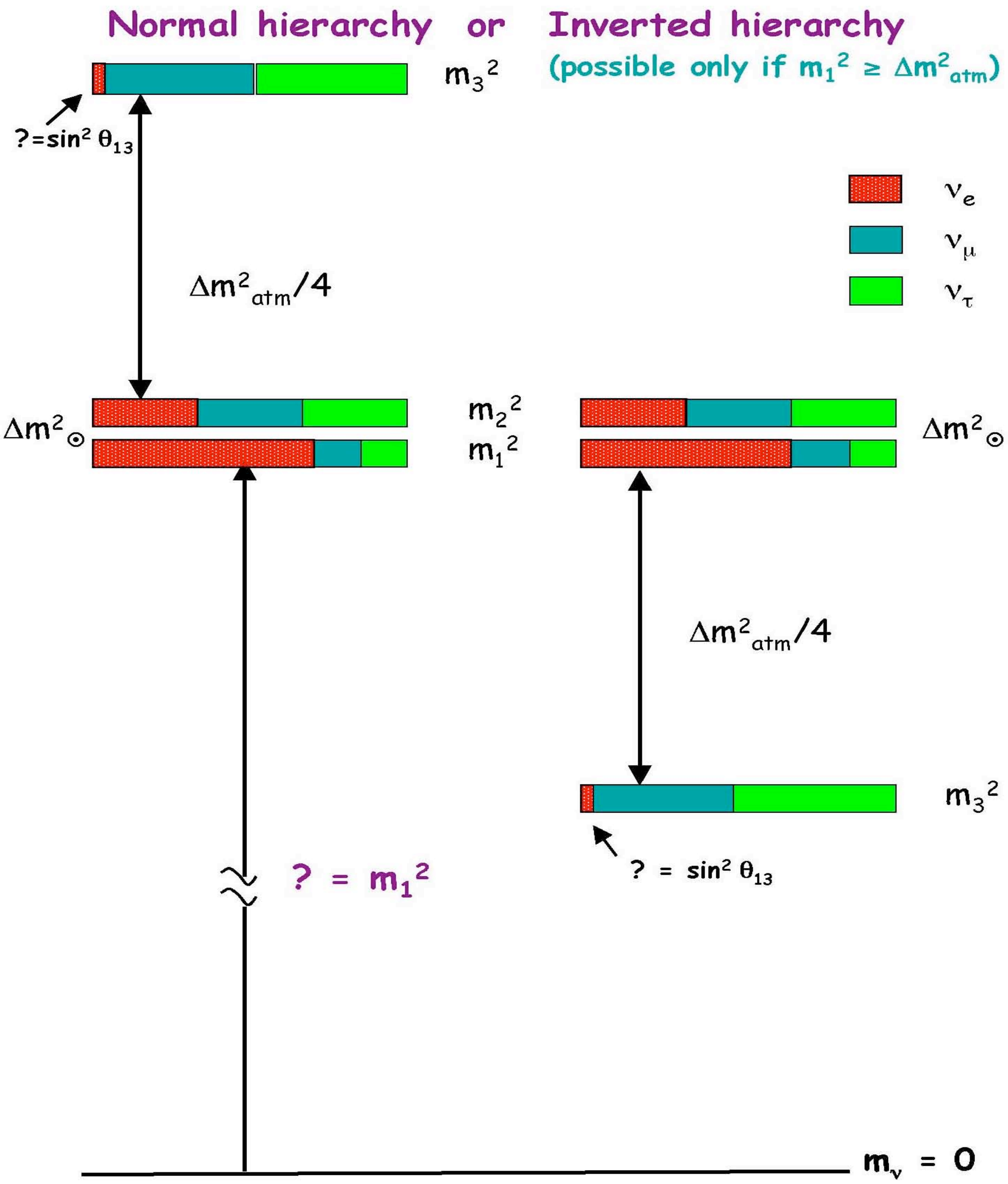
Here the first entry is for $\theta_{13} = 0$ and the (second) for $\theta_{13} = 0.15$, i.e. the maximum allowed value. (The possible deviation of θ_{23} from 45^0 is neglected as well as error bars on all mixing angles, also, the CP phase δ is assumed to vanish.)

Note that the second column ν_2 looks like a constant made of $1/\sqrt{3} = 0.58$, i.e. as if ν_2 is maximally mixed. The μ and τ lines are almost identical suggesting another symmetry.

In fact, the neutrino mixing matrix resembles the tri-bimaximal matrix, which can be a convenient zeroth order term of expansions. (Compared to the empirical matrix above the the last line and last column were multiplied by -1)

$$U = \begin{array}{c|ccc|} & \nu_1 & \nu_2 & \nu_3 \\ e & (2/3)^{1/2} & (1/3)^{1/2} & 0 \\ \mu & -(1/6)^{1/2} & (1/3)^{1/2} & -(1/2)^{1/2} \\ \tau & -(1/6)^{1/2} & (1/3)^{1/2} & (1/2)^{1/2} \end{array}$$

Many papers exist trying to find the reasons for such apparent symmetry as well as using the small expansion parameter $\Delta m^2_{sol}/\Delta m^2_{atm} \sim 1/30$.



The status of the present knowledge of the neutrino oscillation phenomena.

These quantities are unknown at present:

a) The mass m_1

b) The angle θ_{13}

c) Whether the normal or inverted hierarchy is realized.

d) Most importantly, we do not know whether neutrinos are Dirac or Majorana fermions. Need $0\nu\beta\beta$ decay to decide this question.

Fly in the ointment: The LSND Experiment (1993-98)

$\pi^+ \to \mu^+ \nu_\mu$

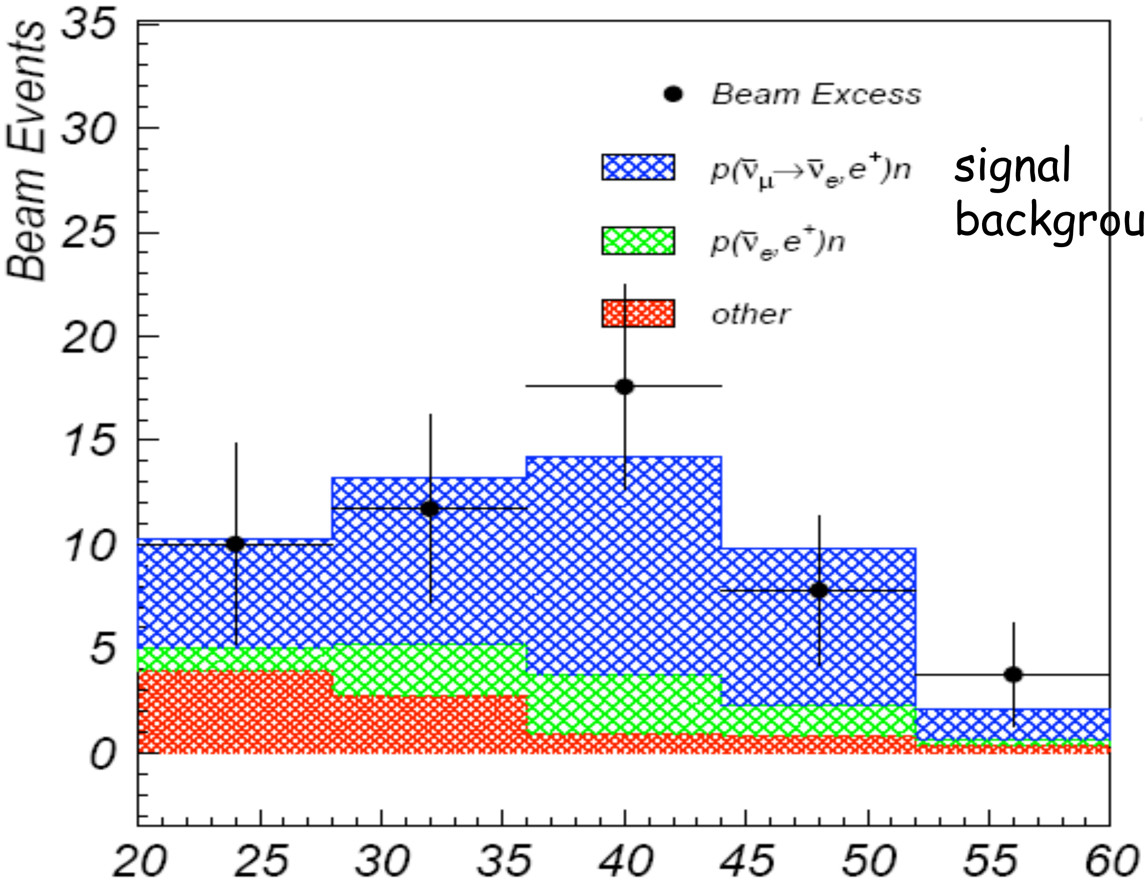
$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$

Oscillations? $\hookrightarrow \boxed{\bar{\nu}_e}$

Decay at rest (DAR)

$\boxed{\bar{\nu}_e p \to e^+ n}$ detect prompt e track, $20 < E_e < 60$ MeV

There were no (essentially) ν_e in the neutrino beam, baseline = 30m



signal

backgrounds

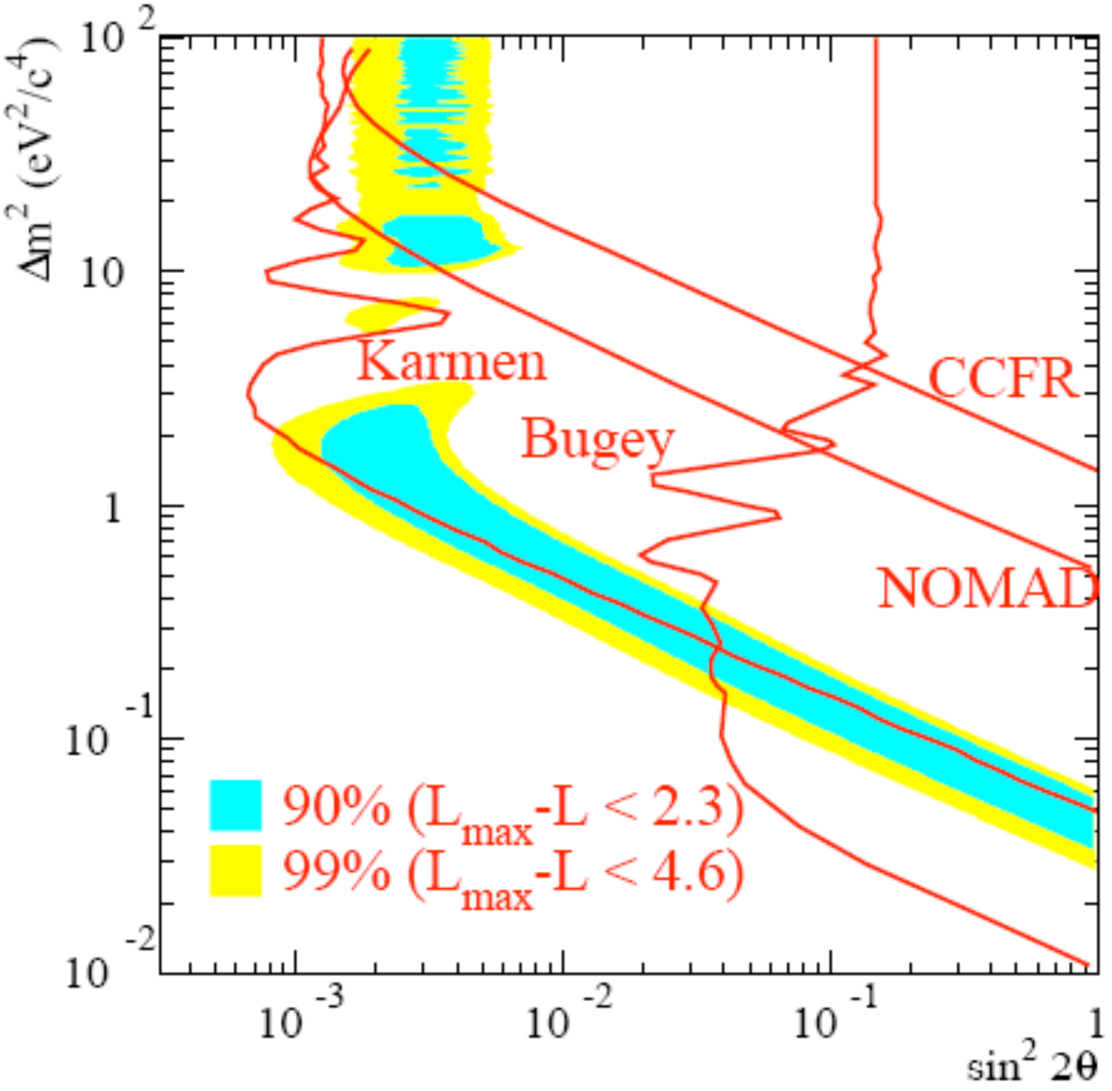
Excess events:

$87.9 \pm 22.4 \pm 6.0\ \bar{\nu}_e p \to e^+ n$ events

Oscillation probability:

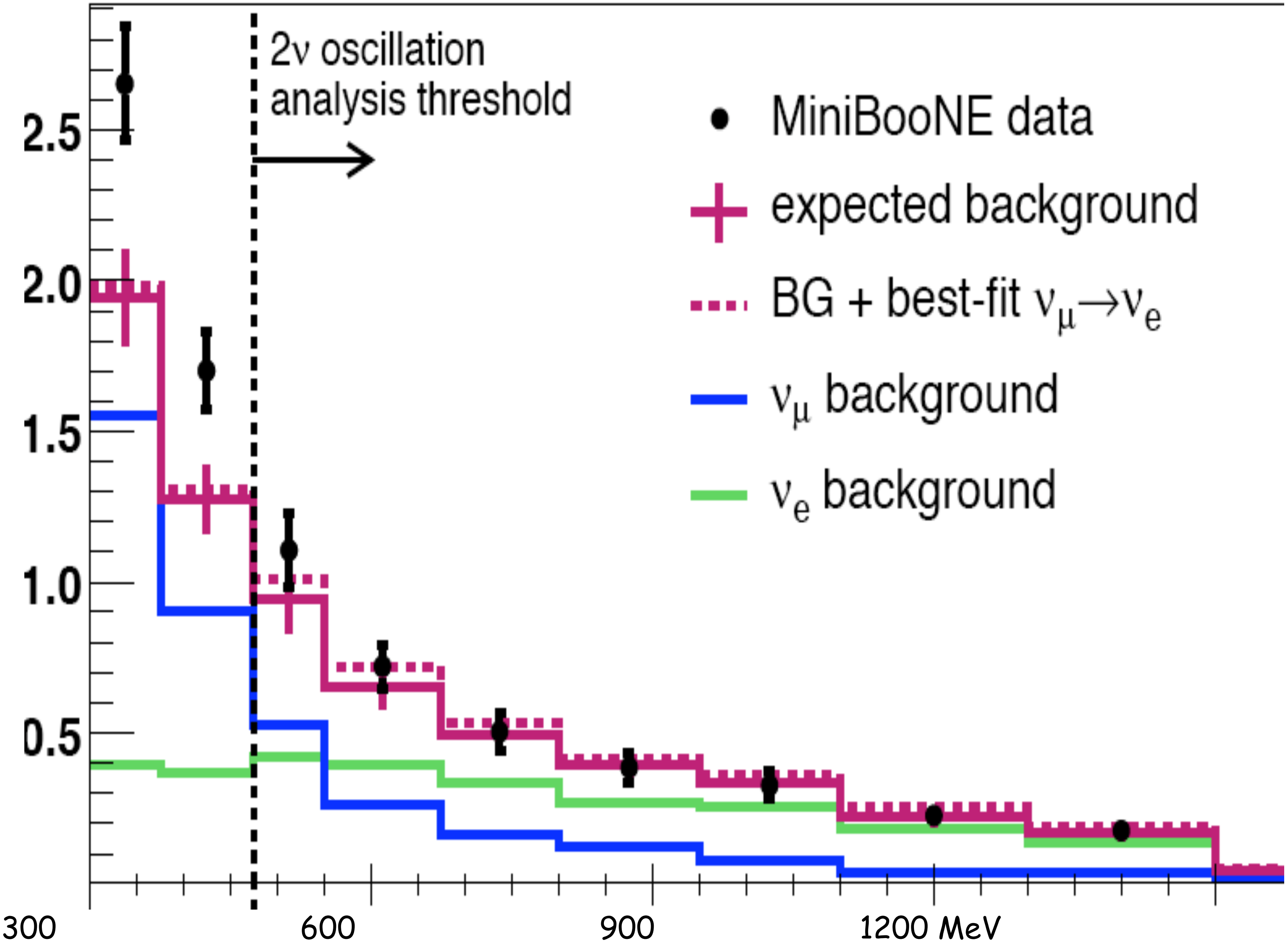
$(0.264 \pm 0.067 \pm 0.045)\%$

For LSND L(m)/E(MeV) ~ 1 so the simple oscillation picture requires that $\Delta m^2 \sim 1$ eV^2, clearly not compatible with the 3 neutrino picture with solar and atmospheric Δm^2. Hence at least one sterile neutrino is required.



To test this hypothesis the MiniBoone experiment at Fermilab used similar L/E but E = 500-1500 MeV (See Phys.Rev.Lett.**98**,231801)

MiniBoone data above the previously chosen threshold of 475 MeV are compatible with background. LSND oscillation signal not observed. However, an anomaly at lower energies observed.



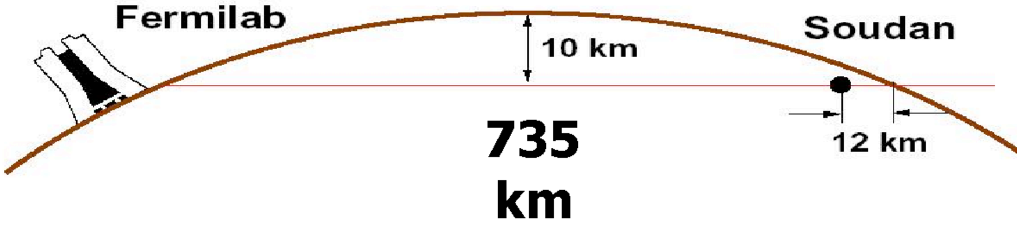
Experimental goals for near future

1. Determine the mixing angle θ_{13}
2. Resolve the mass hierarchy (sign of Δm^2_{atm})
3. Determine the Dirac CP phase δ
4. Determine how close is θ_{23} to 45^0
5. Determine the absolute mass scale

In order to solve the problems 1.-4. it is necessary to go beyond the 2 flavor picture and observe `subdominant' oscillations, suppressed by one of the small parameters, $\sin^2 2\theta_{13}$ or $\Delta m^2_{sol}/\Delta m^2_{atm}$.
The mass hierarchy can be resolved by matter effects.
The CP violation is proportional to the product (Jarlskog invariant)
$\sin^2 2\theta_{13} \sin^2 2\theta_{12} \sin^2 2\theta_{23} \sin^2 \Delta m^2_{21} L/E_\nu \sin^2 \Delta m^2_{31} L/E_\nu \sin^2 \Delta m^2_{32} L/E_\nu \sin\delta$

MINOS experiment:

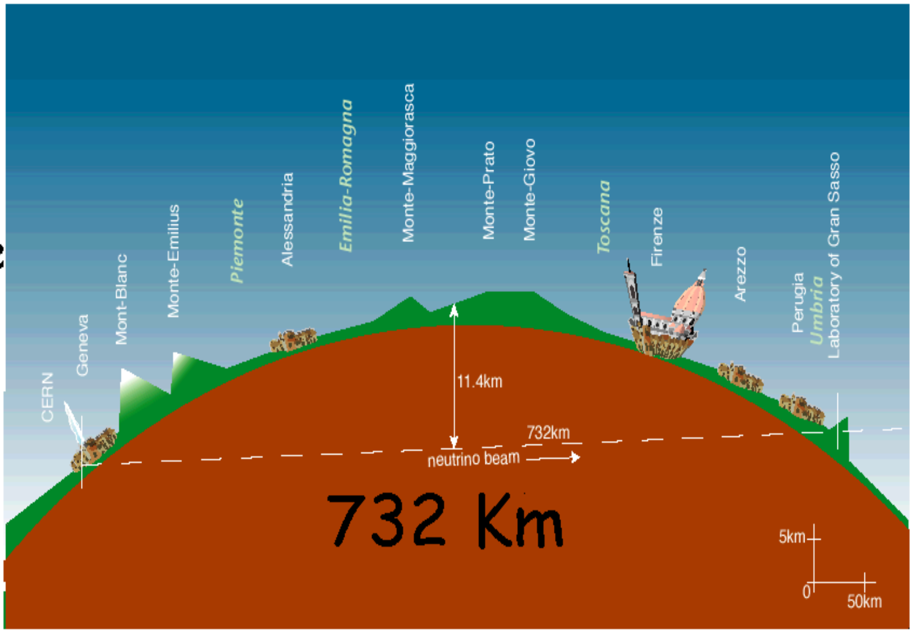
- Running since 3/2005. Results so far: $|\Delta m^2_{23}| = 2.38^{+0.20}_{-0.16} \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} > 0.87$ (68%CL), and $(v-c)/c = (5.1 \pm 2.9) \times 10^{-5}$.



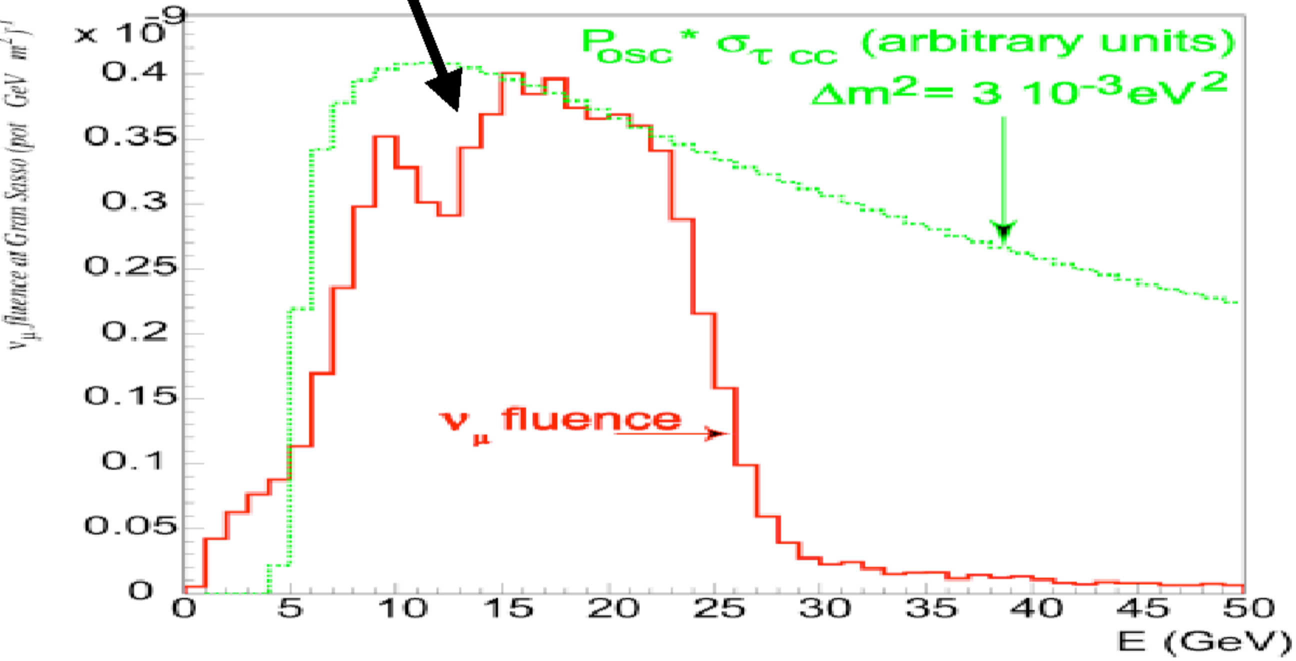
OPERA: at Gran Sasso

- Provide an unambiguous evidence for $\nu_\mu \to \nu_\tau$ scillations in the region of atmospheric eutrinos by looking for ν_τ appearance in a pure $_\mu$ beam

- Search for the subleading $\nu_\mu \to \nu_e$ scillations (measurement of Θ_{13})



Given the distance (732 Km):
ν_μ flux optimized for the maximal number of ν_τ charged current



$<E\nu_\mu>$	17 GeV
$(\nu_e+\overline{\nu}_e)/\nu_\mu$	0.87%
$\overline{\nu}_\mu$ / ν_μ	2.1%
ν_τ prompt	negligible

<L/E> = 43 Km/GeV :

« off peak »

OPERA: 6200 ν_μ CC+NC /year

19 ν_τ CC/year (@ 2 10^{-3} eV^2)

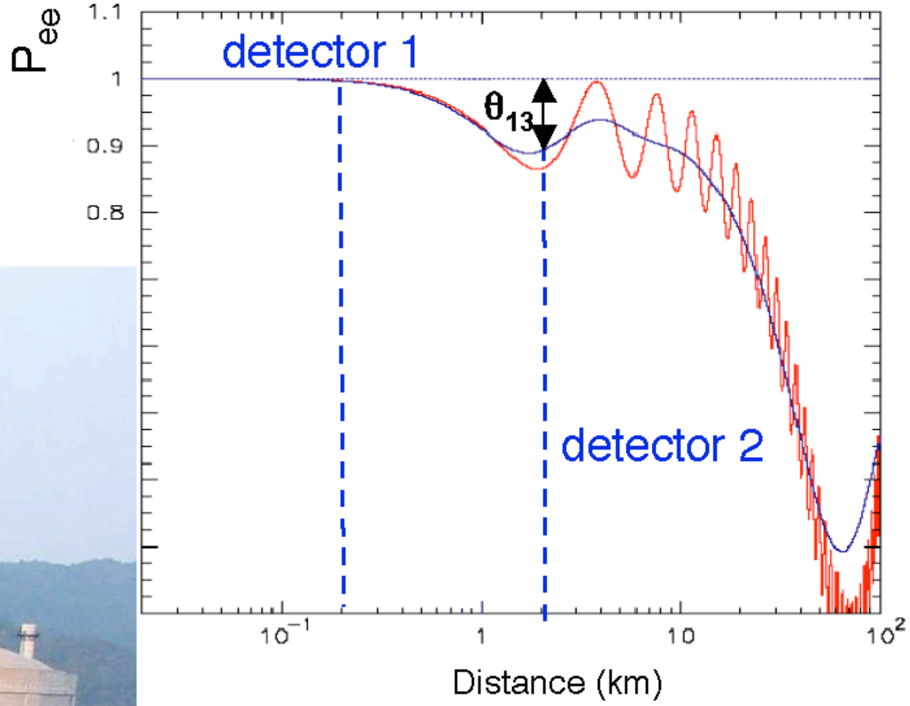
Determining θ_{13} with reactor neutrinos:

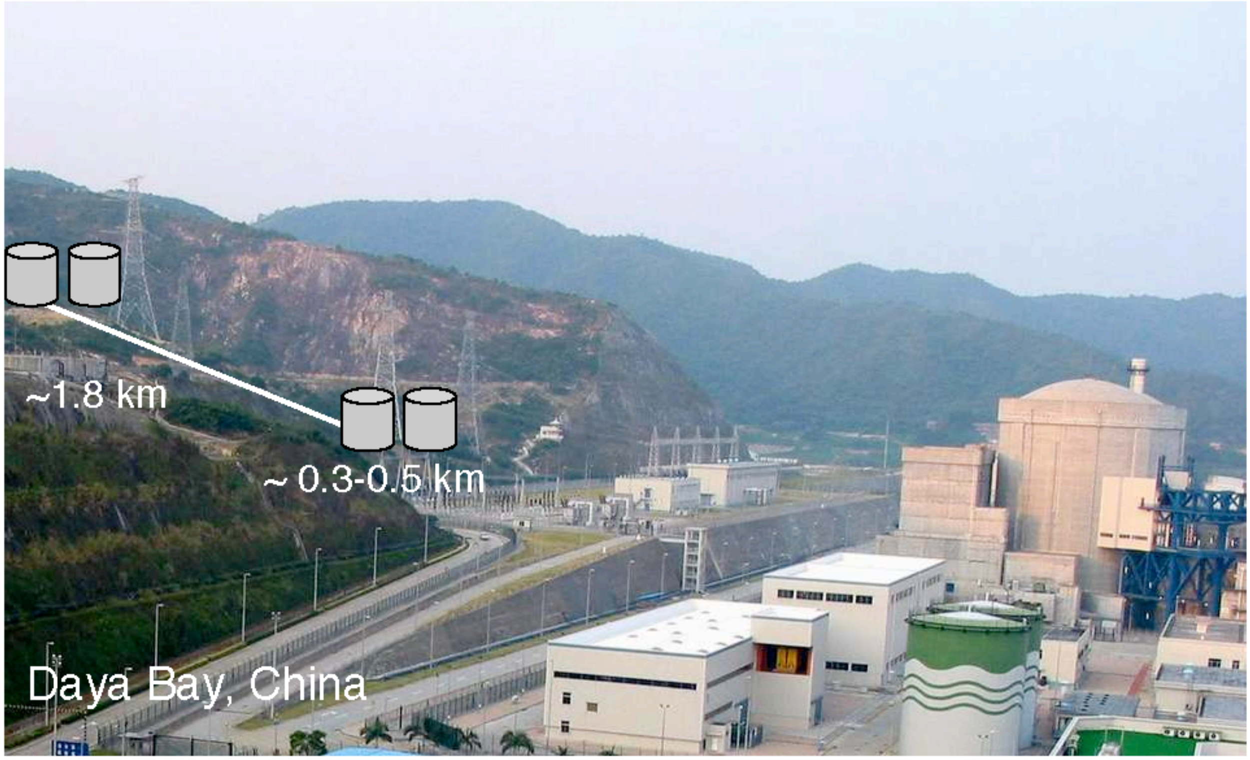
$\bar{\nu}_e$ survival probability with two oscillation lengths

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

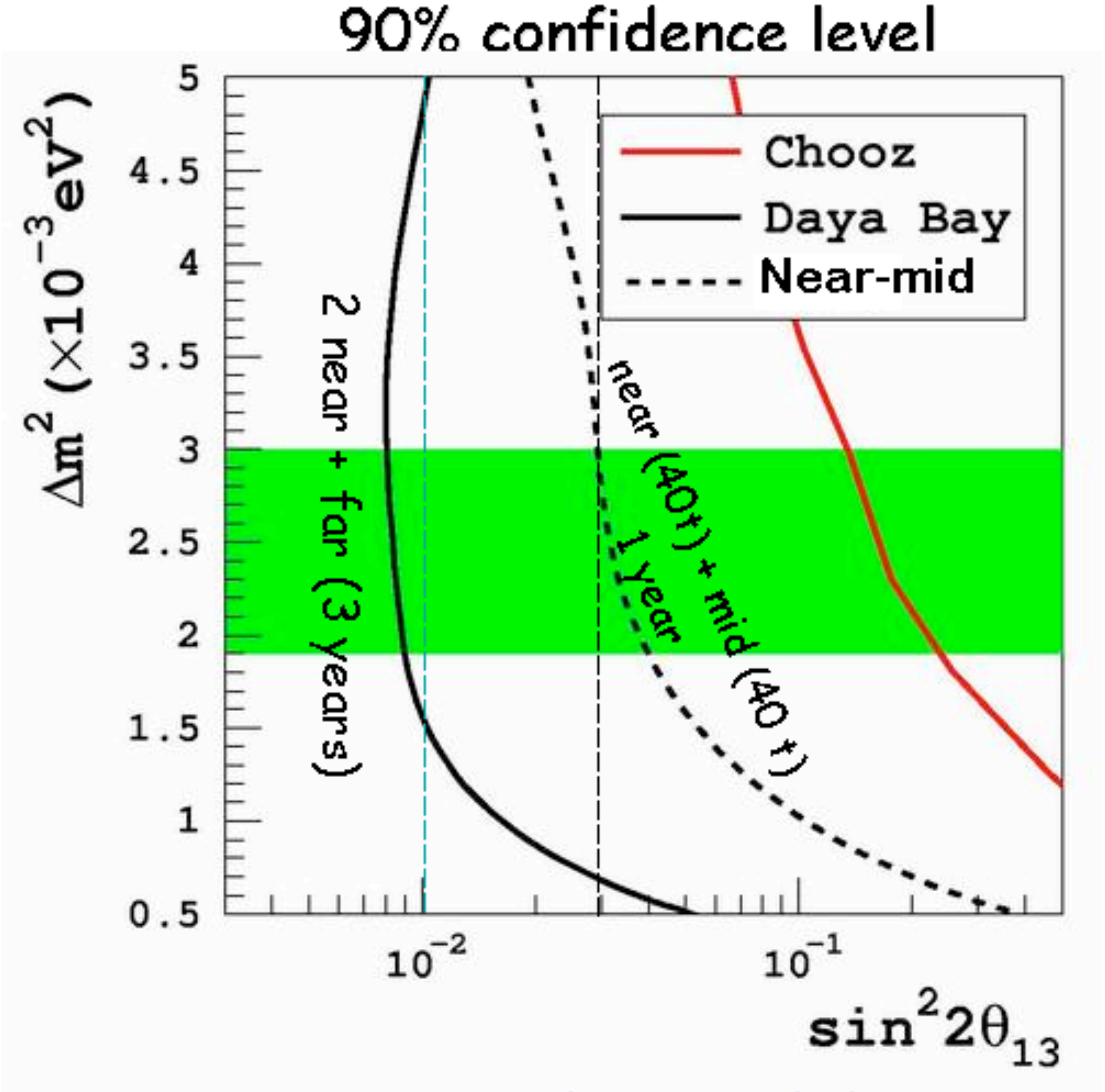
Neutrinos

$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$





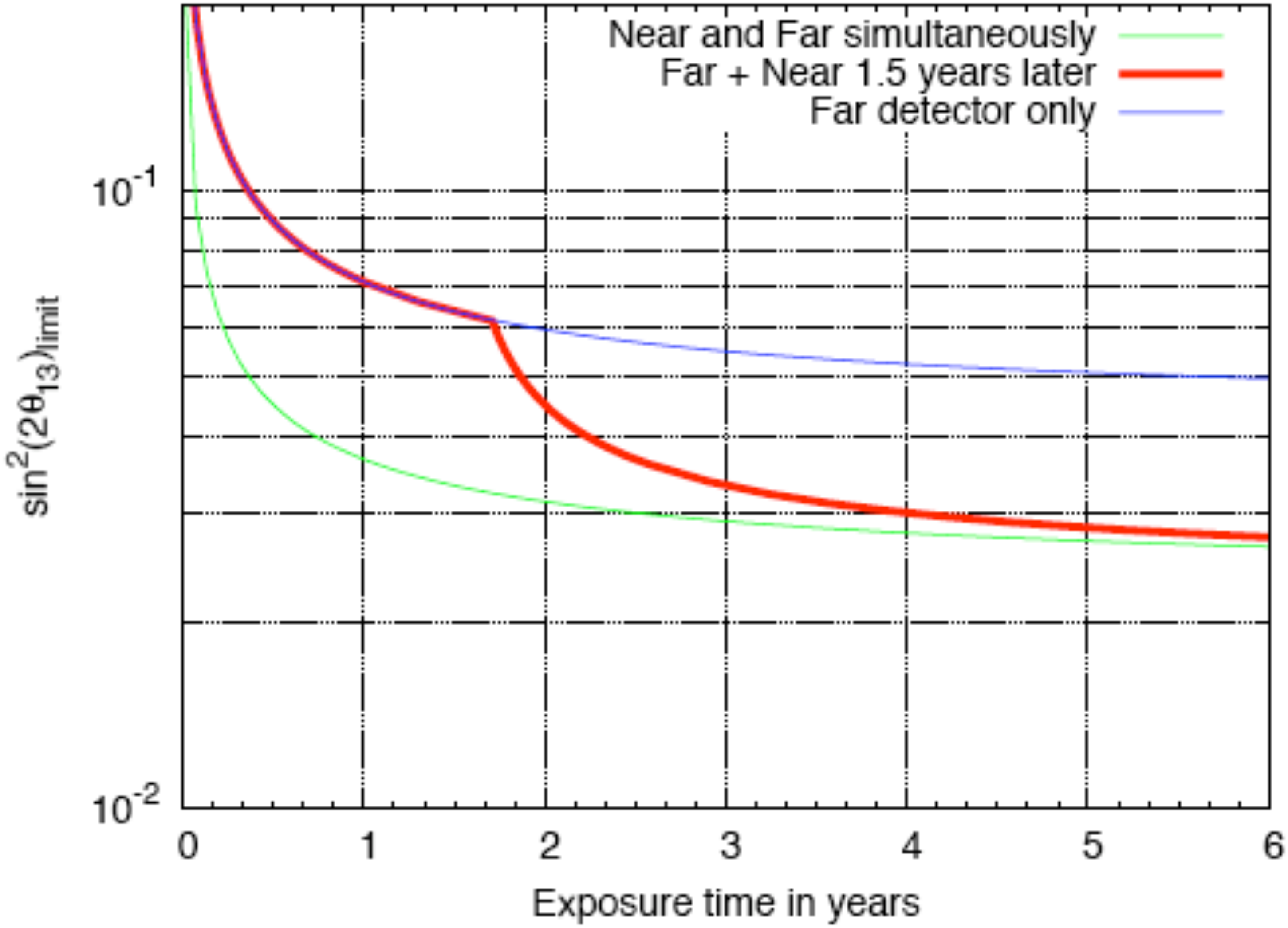
Pure measurement of θ_{13}.



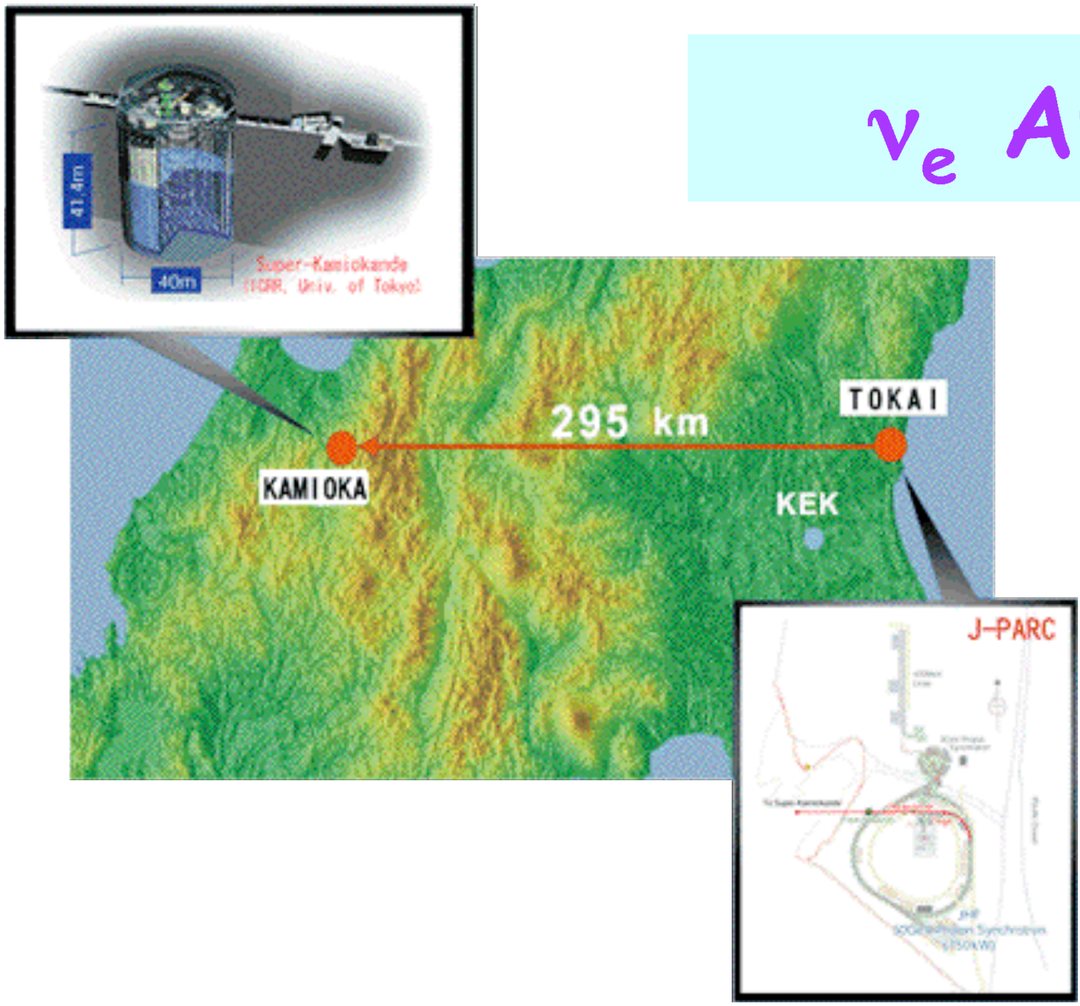
Projected sensitivity of the Daya-Bay experiment (ultimately to $\sin^2 2\theta_{13} \sim 0.01$)

- Use rate and spectral shape
- input relative detector systematic error of 0.2%

Double Chooz experiment: projected sensitivity $\sin^2 2\theta_{13} = 0.03$.



ν_e Appearance in a ν_μ beam



T2K- *From Tokai To Kamioka*

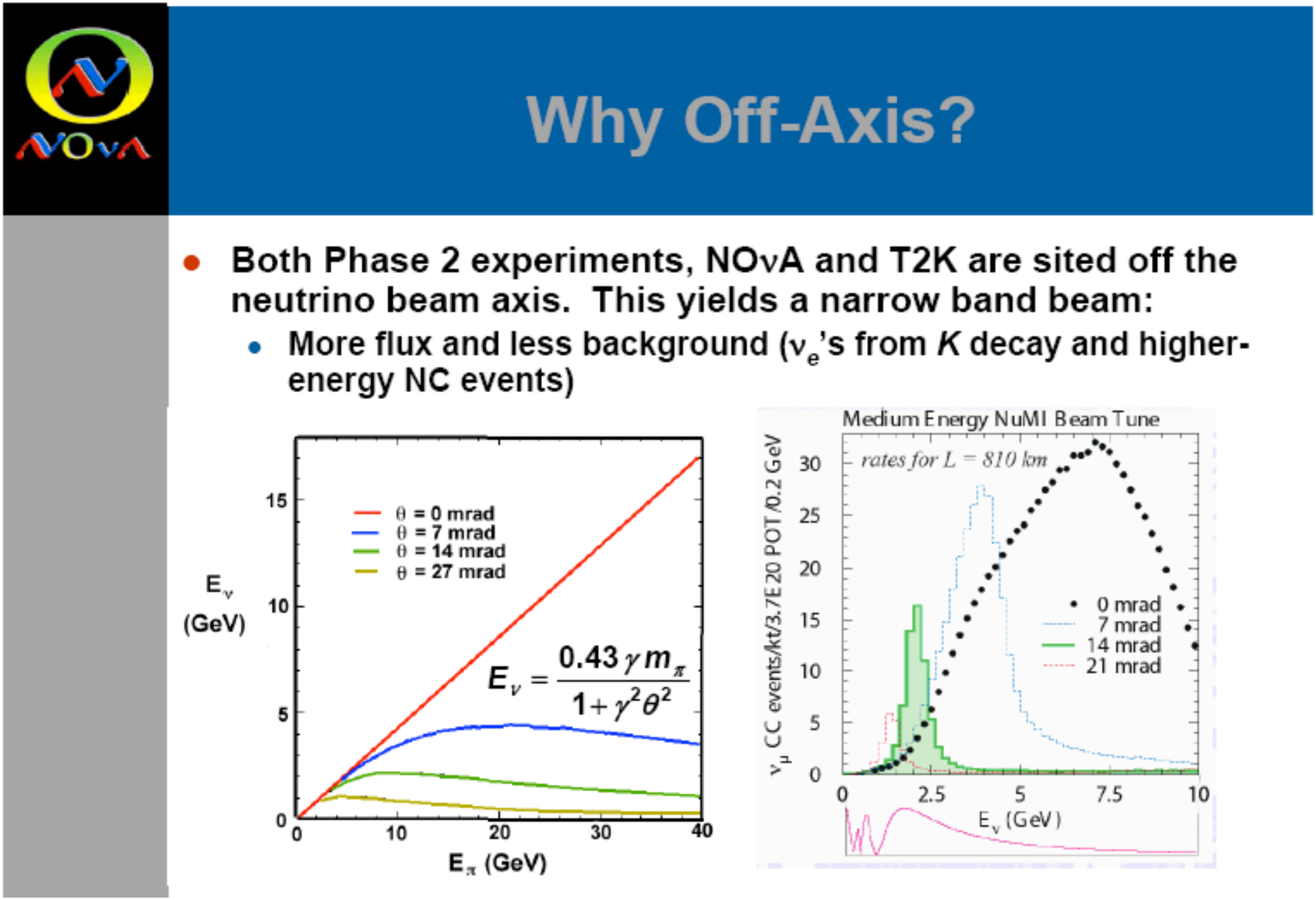
Mass hierarchy (+/-)

CP violation

matter

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} \\
& + 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin \Delta_{31} [\cos \Delta_{32} \cos \delta - \sin \Delta_{32} \sin \delta] \sin \Delta_{21} \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21} \\
& + 4c_{13}^2 s_{12}^2 [c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta] \sin^2 \Delta_{21} \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \frac{aL}{4E_\nu} \sin \Delta_{31} \left[\cos \Delta_{32} - \frac{\sin \Delta_{31}}{\Delta_{31}} \right] .
\end{aligned}
$$

NOνA experiment at Ash River, 810 km from FermiLab

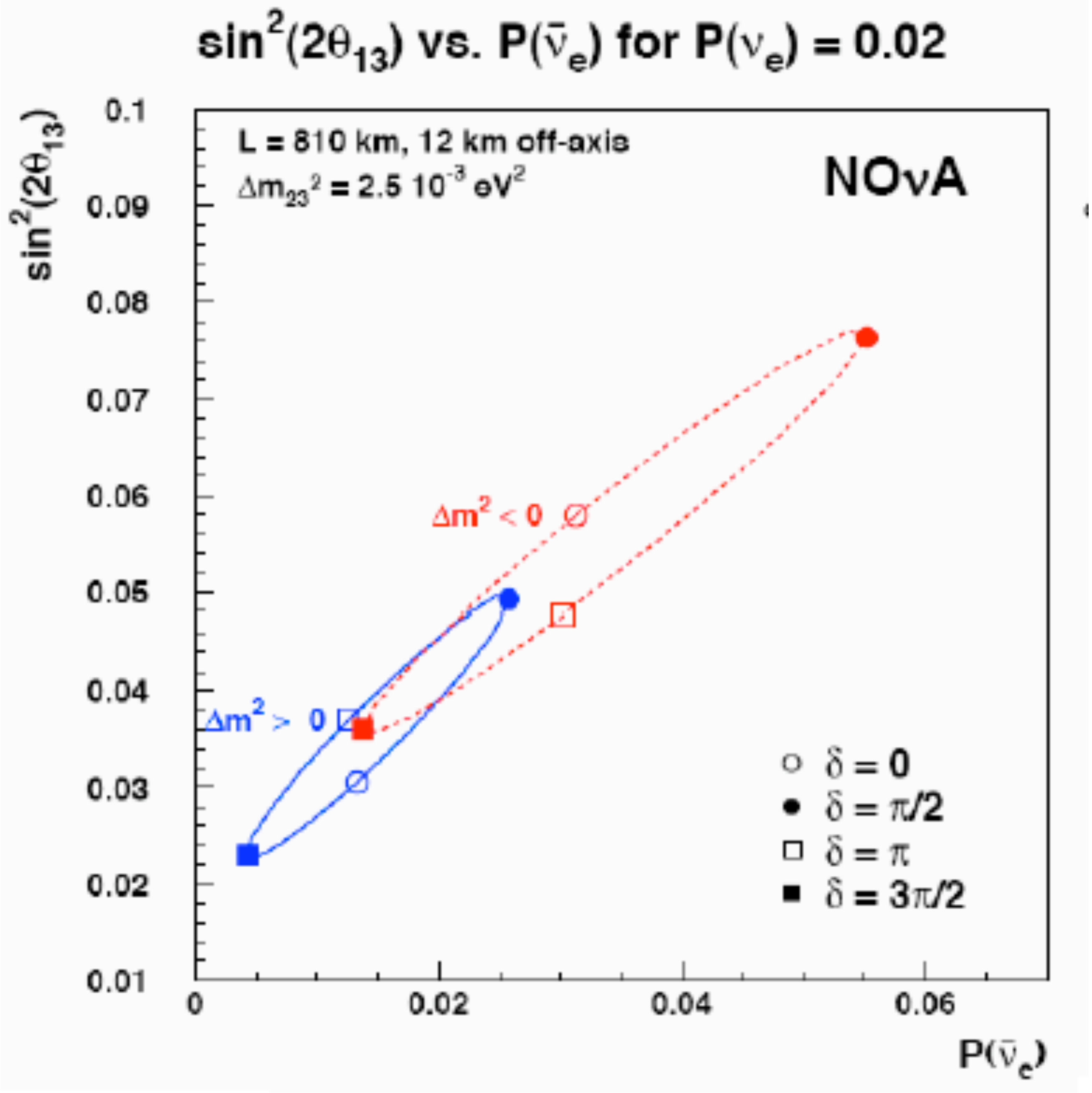


Why Off-Axis?

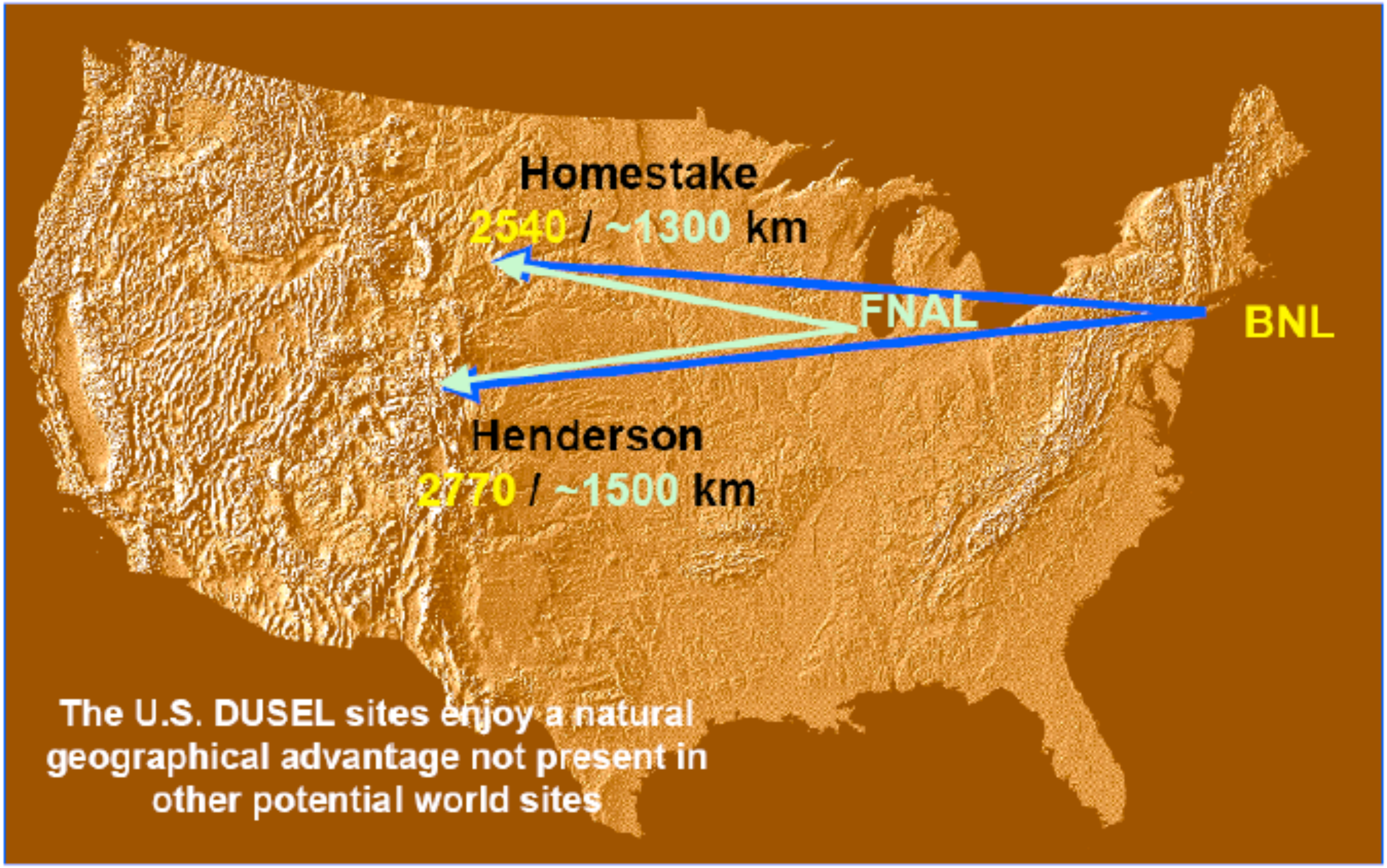
- **Both Phase 2 experiments, NOνA and T2K are sited off the neutrino beam axis. This yields a narrow band beam:**
  - **More flux and less background (ν_e's from *K* decay and higher-energy NC events)**

$$E_\nu = \frac{0.43\,\gamma m_\pi}{1+\gamma^2\theta^2}$$

Parameter degeneracy: There are several solutions with different Θ_{13}, sign of hierarchy, CP phase δ giving the same $P(\nu_\mu \to \nu_e)$



Super Neutrino Beam to DUSEL Candidate Sites



DUSEL = Deep Underground Science and Engineering Laboratory

The Homestake (South Dakota) site now chosen and the FNAL beam

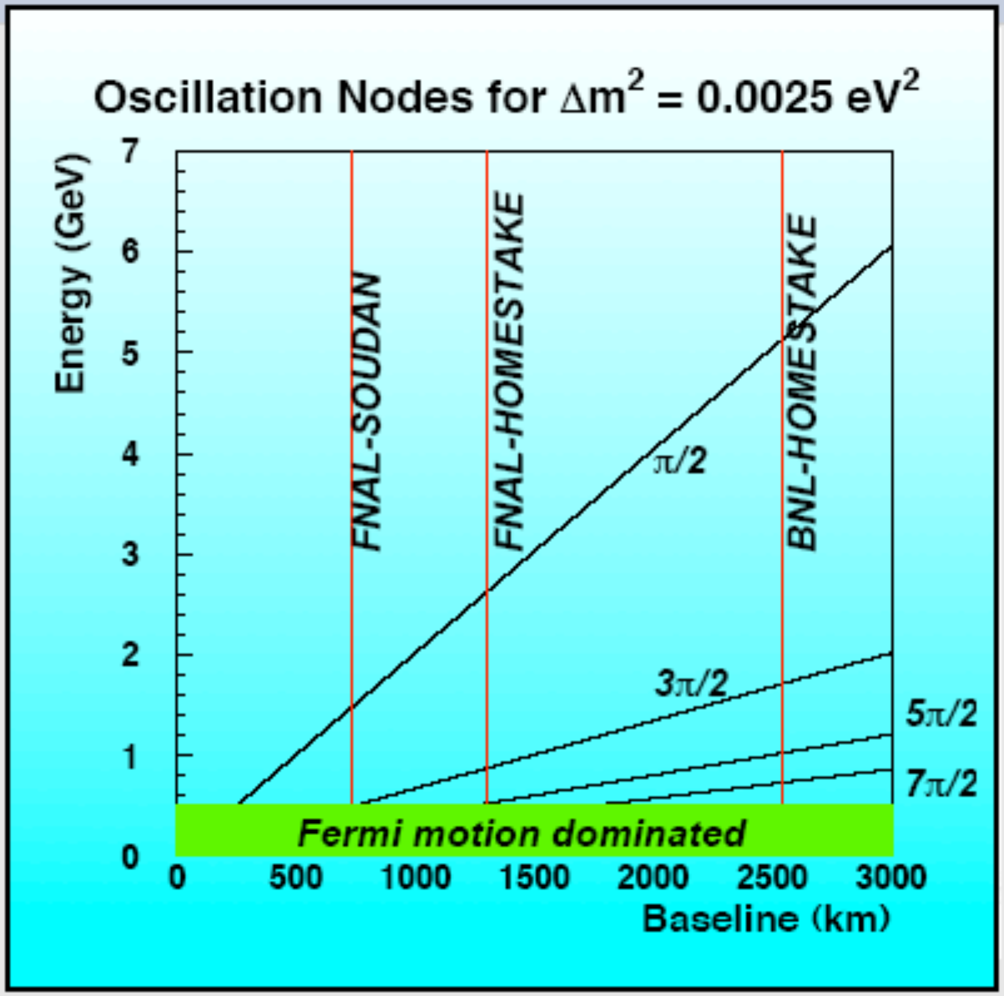
Why Very Long Baseline?

observe multiple nodes in oscillation pattern

☞ less dependent on flux normalization

neutrino travels larger distance through earth

larger matter effects



flux ~ L^{-2}: lower statistics

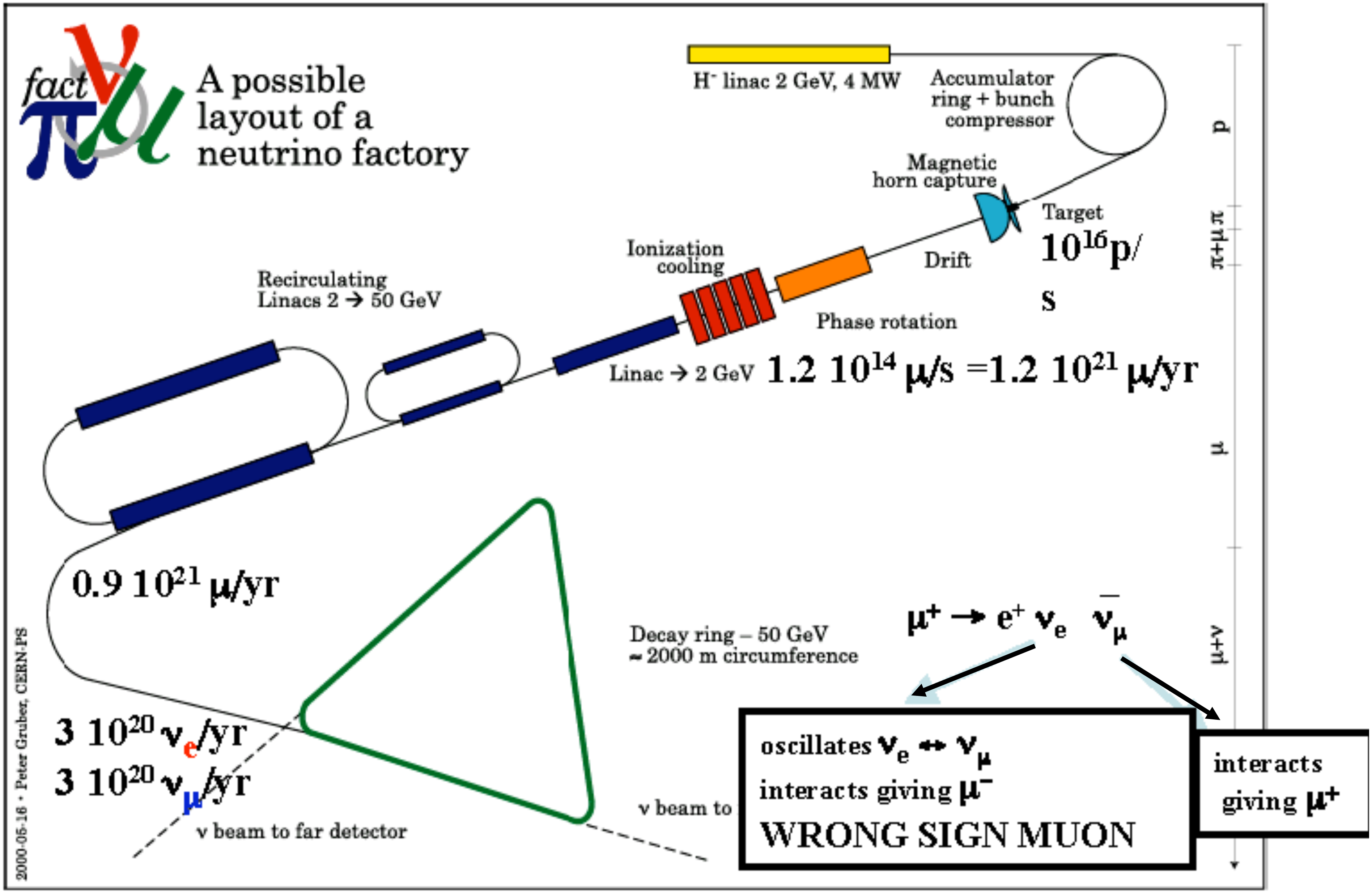
but: CP asymmetry ~ L

sensitivity to δ_{CP} independent of distance!

better S:B

(Marciano hep-ph/0108181)

Neutrino Factory -- CERN layout



10^{16} p/s

$1.2\ 10^{14}\ \mu/s = 1.2\ 10^{21}\ \mu/yr$

$0.9\ 10^{21}\ \mu/yr$

$3\ 10^{20}\ \nu_e/yr$

$3\ 10^{20}\ \nu_\mu/yr$

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

oscillates $\nu_e \leftrightarrow \nu_\mu$

interacts giving μ^-

WRONG SIGN MUON

interacts giving μ^+

The appearance of wrong sign muon represents golden measurement

Beta Beams

guaranteed pure ν_e or $\overline{\nu}_e$ beams

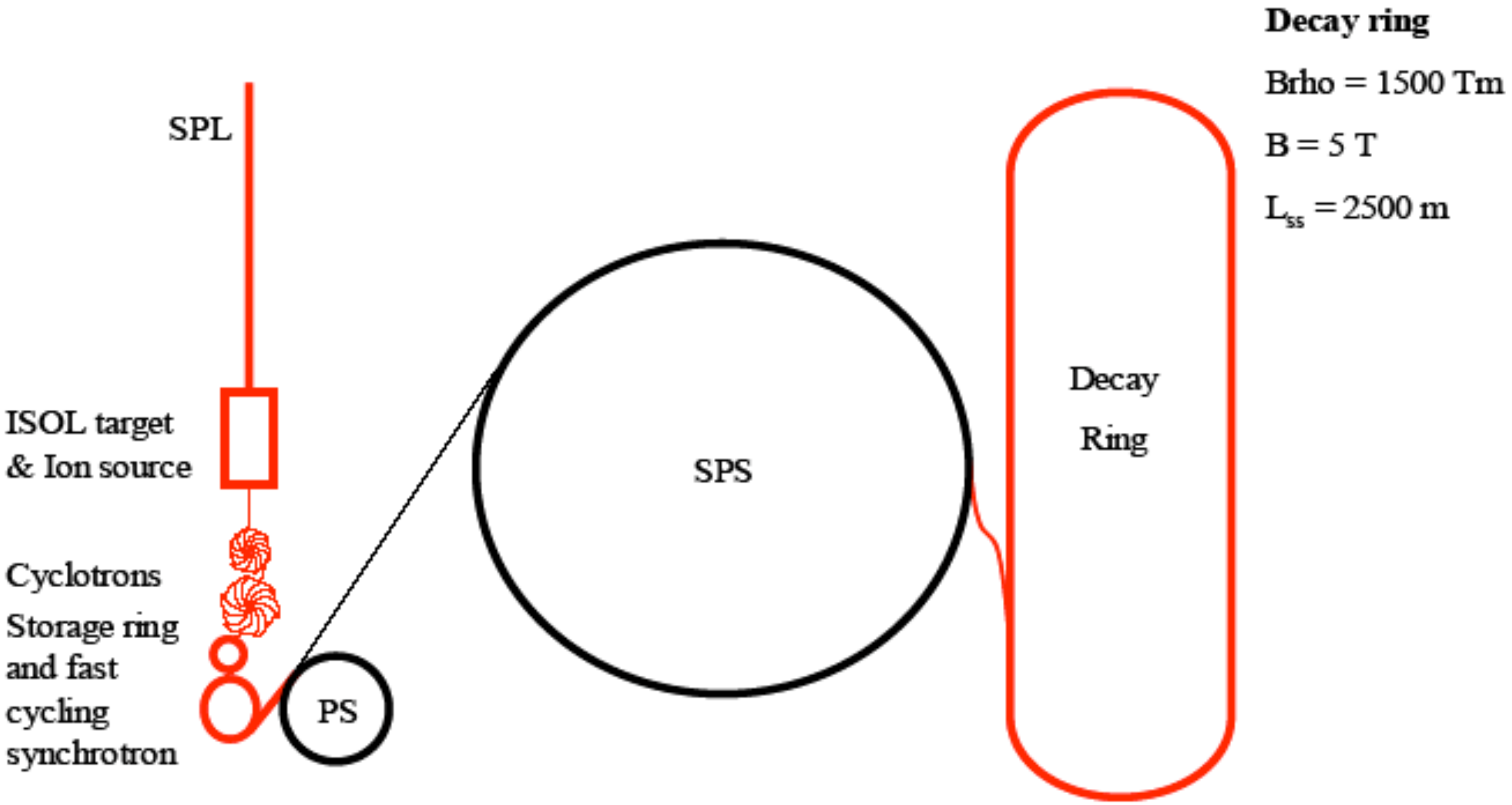


Figure 1: The CERN baseline scenario

The accelerated ions could be ^{6}He ($T_{1/2}$ = 0.8s, Q = 3.5MeV, β^-, $\gamma \sim 150$) and ^{18}Ne ($T_{1/2}$ = 1.7s,Q = 4.4 MeV, β^+, $\gamma \sim 60$) with ~10^{18} decays/year

Summary:

- The evidence for ν oscillations and thus for the nonvanishing neutrino mass is beyond reasonable doubt.
- Several parameters (angles and Δm^2) are determined with good accuracy, but some are still missing.
- Experiments designed to furnish the missing information are either running or will run soon.
- The pattern of mixing angles and masses is quite different than the somewhat analogous CKM matrix and masses of quarks.
- Some approximate symmetries (tri-bimaximal mixing) are present; their significance is not yet clear.
- It is hoped that the study of neutrino intrinsic properties will eventually lead to the formulation of the generalized Standard Model and to a better understanding of the origin of mass of elementary fermions.