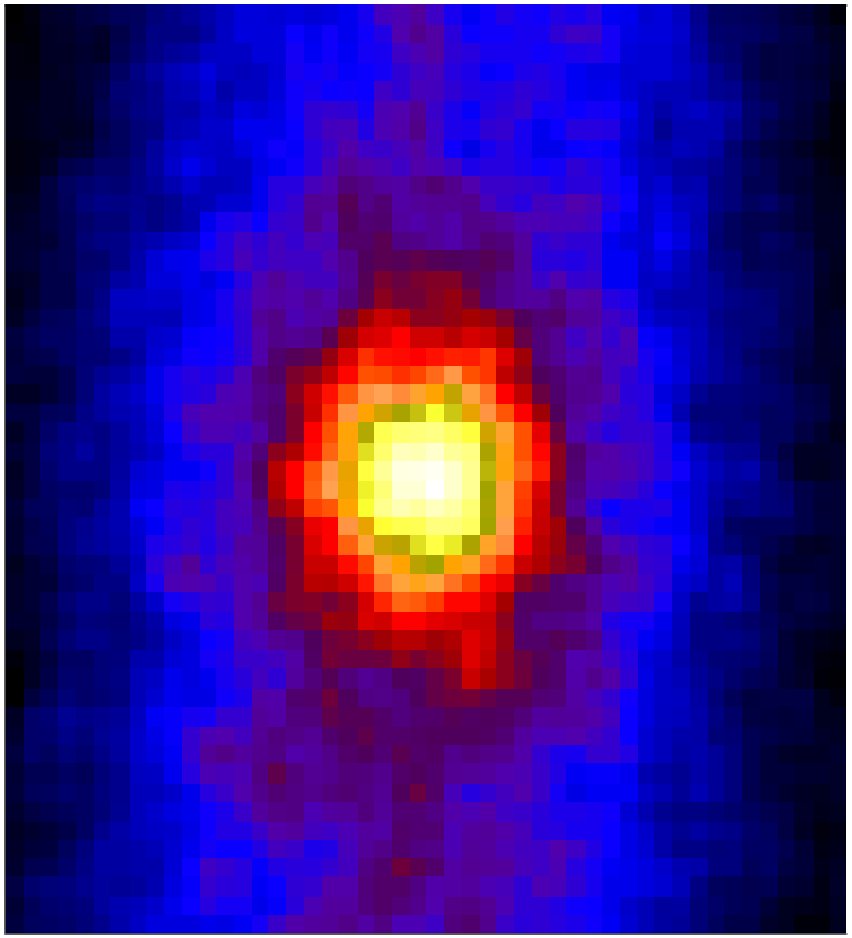
The neutrino oscillation industry

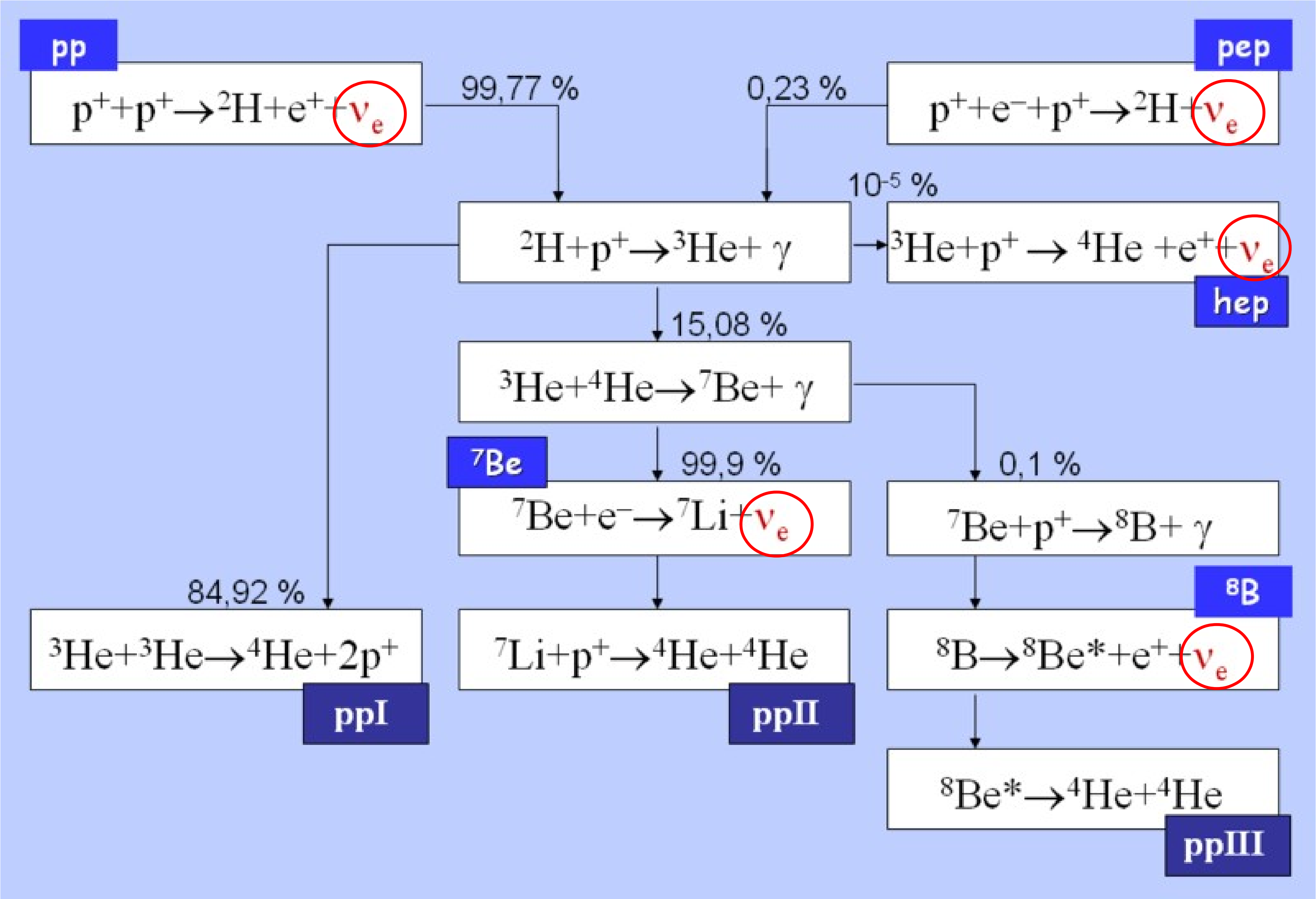
Solar Neutrinos

SuperK : Solar neutrino-gram

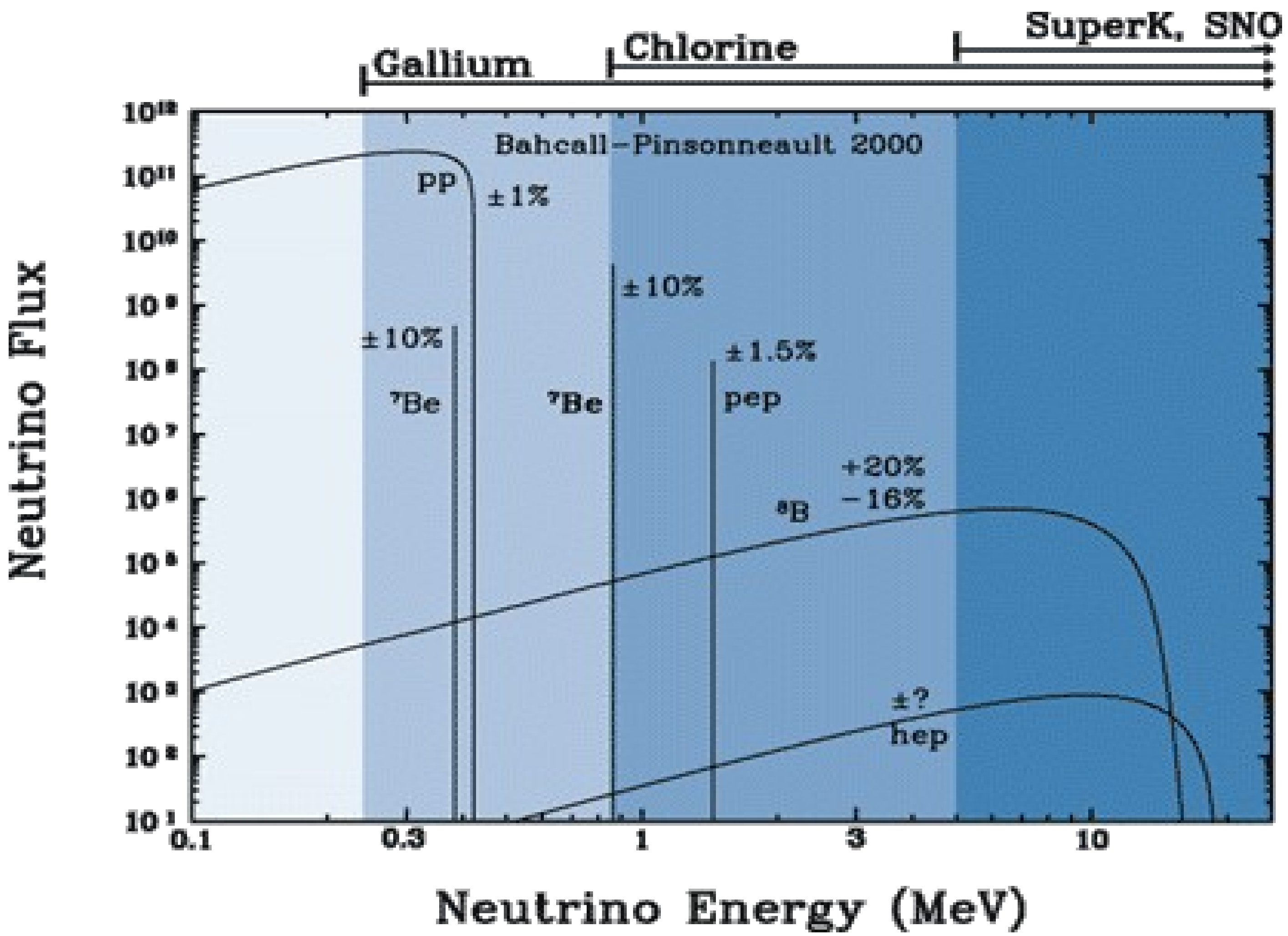


- Light from the solar core takes a million years to reach the surface
- Fusion processes generate electron neutrinos which take 2s to leave
- Solar neutrinos are a direct probe of the solar core
- Roughly 4.0×10^{10} solar ν_e per cm^2 per second on earth

Solar neutrino generation

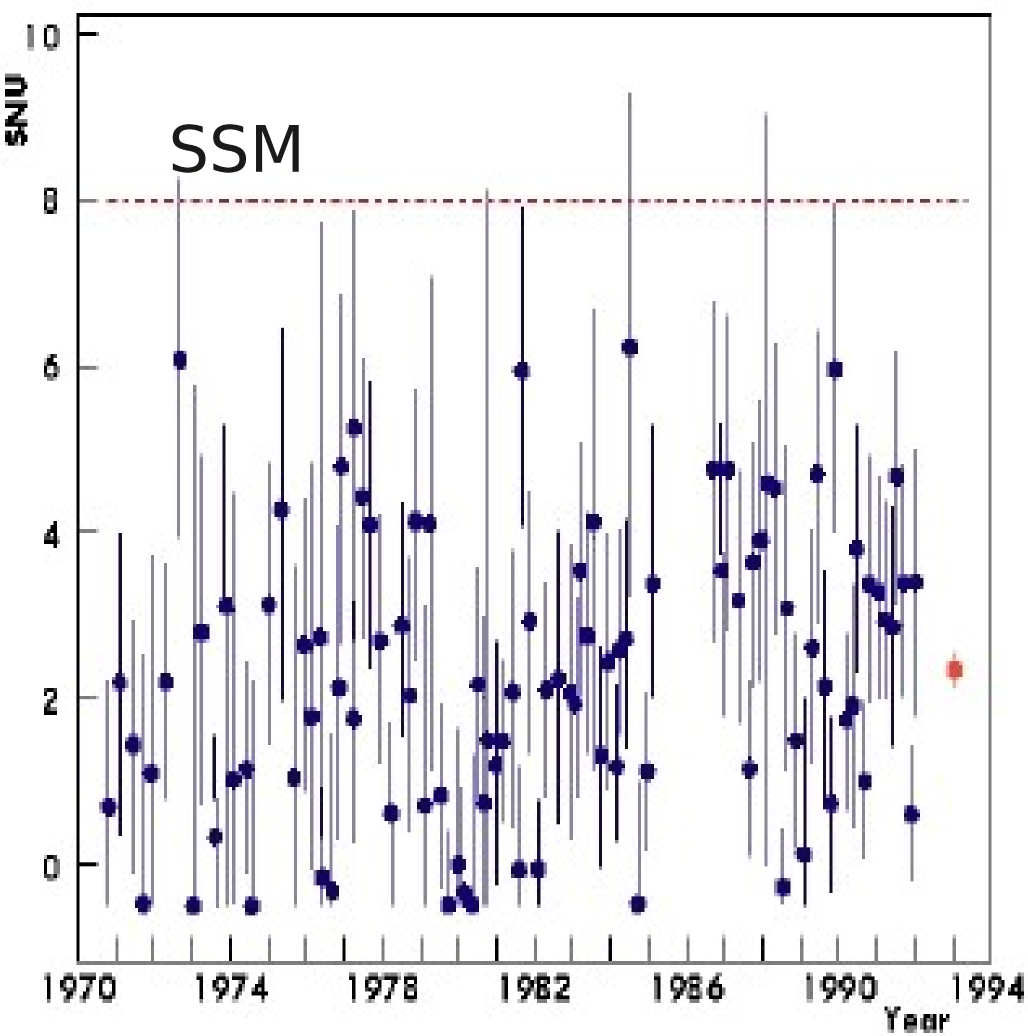


Solar Neutrino Flux



As predicted by Bahcall's Solar model

The Solar Neutrino Problem - Homestake



1 SNU = 1 interaction per 10^{36} atoms per second

Homestake sensitive to ^{8}B and ^{7}Be *electron neutrinos*

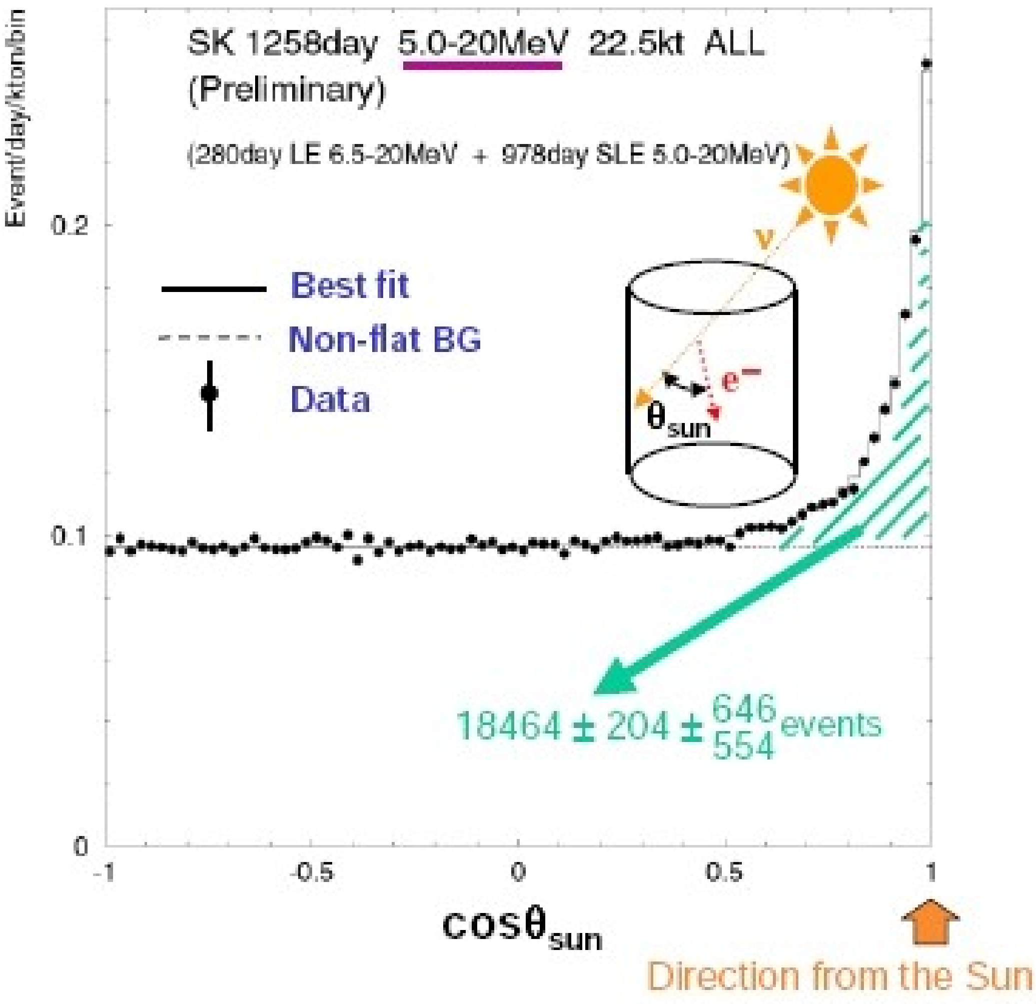
E_{ν} > 800 keV

Observe 1/3 of the expected number of solar neutrinos

Something wrong with
the experiment?
the SSM?
the neutrinos?

(Super)Kamiokande

1987 – Kamiokande : 1000 phototubes, 5000 tons of water
1997 – SuperKamiokande : 11000 PMT, 50000 tons of water



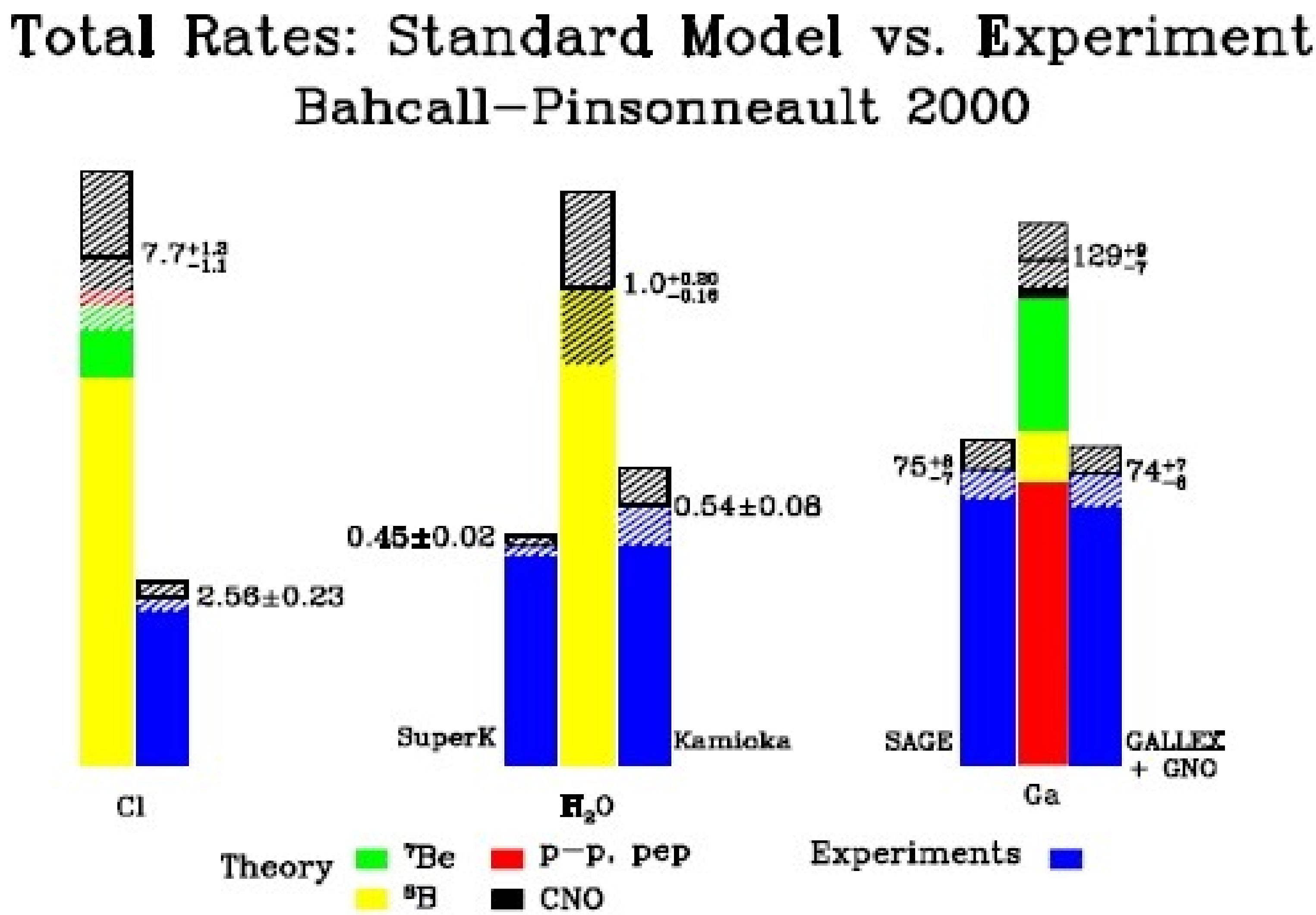
SuperK can only observe the ^{8}B flux (> 5 MeV)

$$\frac{Data}{SSM} = 0.451 \pm 0.017$$

Confirmation that
it wasn't just Homestake

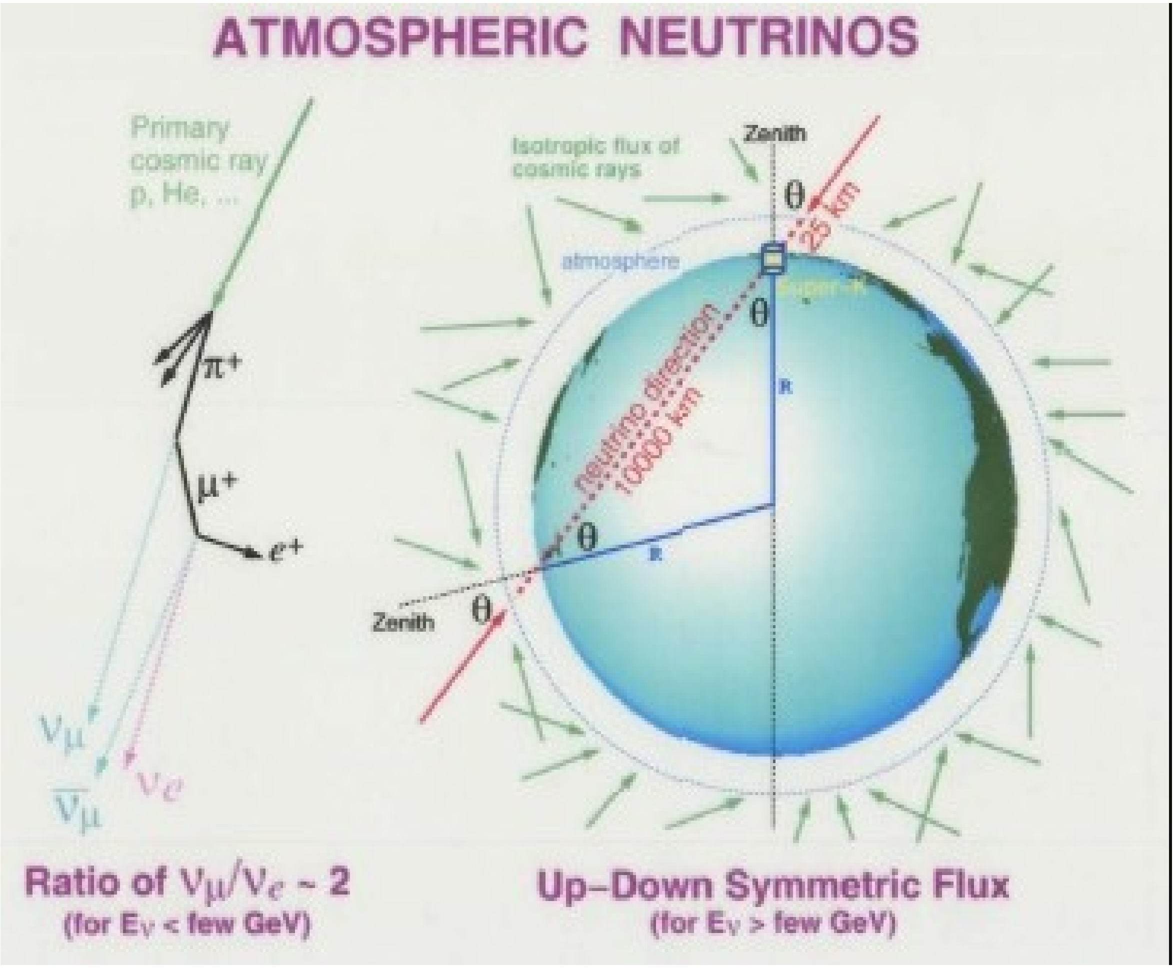
SuperK only sensitive to ν_e

Experimental summary



Atmospheric Neutrinos

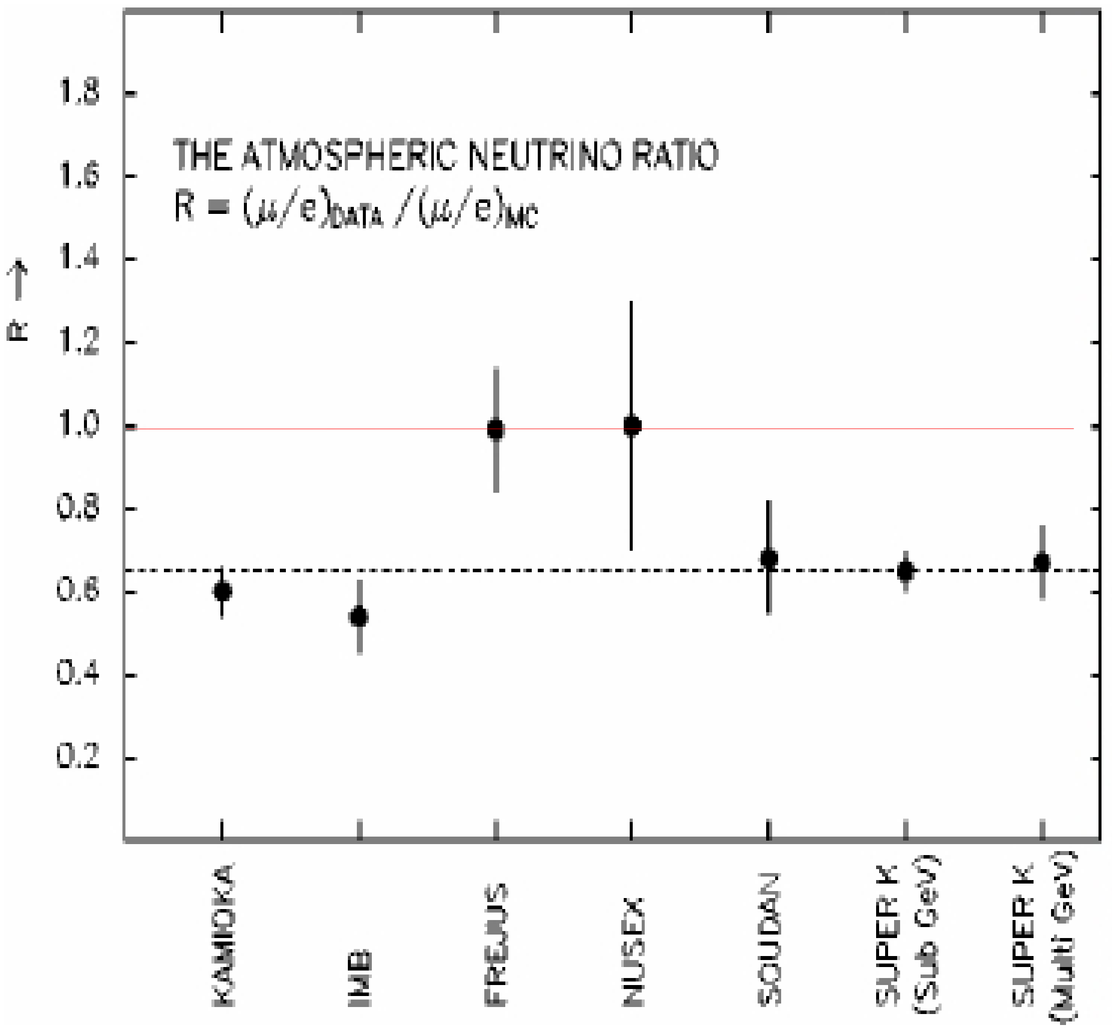
Neutrinos produced from cosmic rays interactions in the atmosphere



- Flux modelled using
  - Measured primary flux
  - Cross sections from accelerators
  - Includes geomagnetic effects
  - Absolute flux only known to 20-30%

$$\delta(R)=\delta\left(\frac{\nu_\mu+\overline{\nu}_\mu}{\nu_e+\overline{\nu}_e}\right)\sim 5\%$$

Atmospheric Neutrino Problem



Study of atmospheric neutrinos started in the early 1980's

Background for proton decay experiments.

“Today's background is tomorrow's signal”

Neutrino Flavour Oscillations

Mixing

CKM Mechanism

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L , \begin{pmatrix} c \\ s' \end{pmatrix}_L$$

$$d' = d\cos\theta_c + s\sin\theta_c$$
$$s' = -d\sin\theta_c + s\cos\theta_c$$

In the quark sector, the flavour eigenstates (those states which couple to the W/Z) are not identical to the mass eigenstates (those states which are solutions of the Dirac equation)

Weak states →

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 0.97 & 0.23 & 0.003 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 0.99 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

← Mass states

Mixing

CKM Mechanism

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L$$

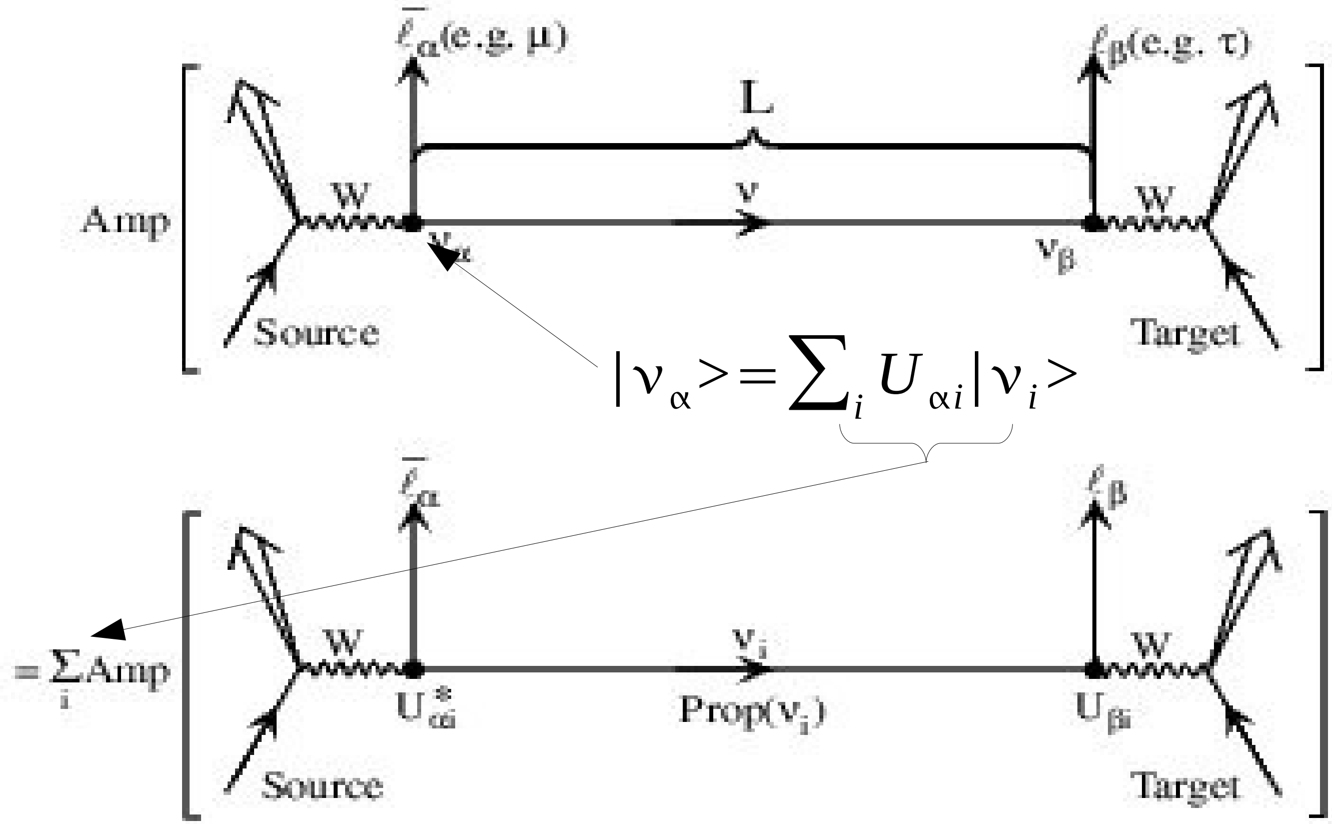
$$d' = d\cos\theta_c + s\sin\theta_c$$
$$s' = -d\sin\theta_c + s\cos\theta_c$$

In the quark sector, the flavour eigenstates (those states which couple to the W/Z) are not identical to the mass eigenstates (those states which are solutions of the Dirac equation)

Weak states →
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$
← Mass states

Unitary mixing matrix

Neutrino Oscillations



$$Amp(\nu_\alpha \rightarrow \nu_\beta) \propto \sum_i U^*_{\alpha i} \, \mathrm{Prop}(\nu_i) \, U_{\beta i}$$

If we can't resolve the individual mass states then the amplitude involves a <u>coherent</u> superposition of ν_i states

$$Prob(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U_{\alpha i}^{*} U_{\beta i} U_{\alpha j} U_{\beta j}^{*}) \sin^2(\Delta m_{ij}^2 \frac{L}{4E})$$
$$+ 2\sum_{i>j} \Im(U_{\alpha i}^{*} U_{\beta i} U_{\alpha j} U_{\beta j}^{*}) \sin(\Delta m_{ij}^2 \frac{L}{2E})$$

- If $\Delta m_{ij}^2 = 0$ then neutrinos don't oscillate
- Oscillation depends on $|\Delta m^2|$ - absolute masses, or mass patterns cannot be determined.
- If there is no mixing (If $U_{\alpha i} = 0$) neutrinos don't oscillate
- One can detect flavour change in 2 ways : start with ν_α and look for ν_β (appearance) or start with ν_α and see if any disappears (disappearance)
- Flavour change oscillates with L/E. L and E are chosen by the experimenter to maximise sensitivity to a given Δm^2
- Flavour change doesn't alter total neutrino flux – it just redistributes it amongst different flavours (unitarity)

Two flavour oscillations

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \Rightarrow U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

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

$P(\nu_\alpha \rightarrow \nu_\beta)$: Appearance Probability

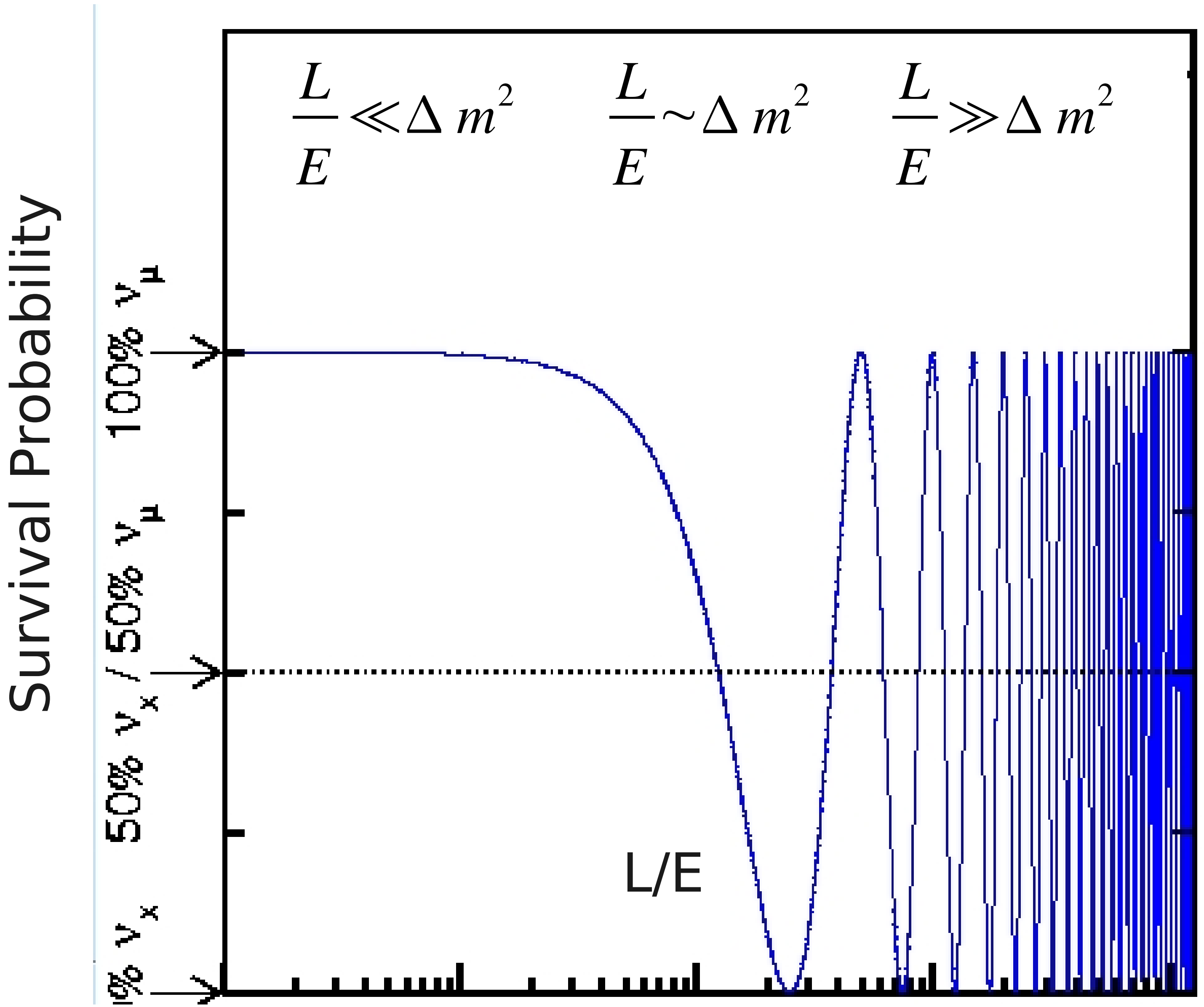
$P(\nu_\alpha \rightarrow \nu_\alpha)$: Survival Probability

$$P(\nu_\alpha \rightarrow \nu_\beta) = -4 (U_{\alpha 1} U_{\beta 1} U_{\alpha 2} U_{\beta 2}) \sin^2(\Delta m_{ij}^2 \frac{L}{4E})$$

$$. = \sin^2(2\theta) \sin^2(1.27 \Delta m^2 (eV^2) \frac{L(km)}{E(GeV)})$$

(changing to useful units)

$$P(\nu_\alpha(0)\rightarrow\nu_\alpha(x))=1-\sin^2(2\theta)\sin^2\left(1.27\,\Delta m^2\frac{(L/km)}{(E/GeV)}\right)$$



Sensitivity

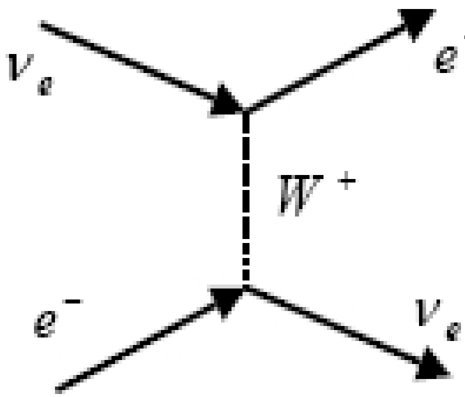
	E_ν (MeV)	L (m)	$\Delta m^2 (eV^2)$
Supernovae	<100	$>10^{19}$	10^{-19} - 10^{-20}
Solar	<14	10^{11}	10^{-10}
Atmospheric	>100	10^{4} - 10^{7}	10^{-4}
Reactor	<10	$<10^{6}$	10^{-5}
Accelerator with short baseline	>100	10^{3}	10^{-1}
Accelerator with long baseline	>100	$<10^{6}$	10^{-3}

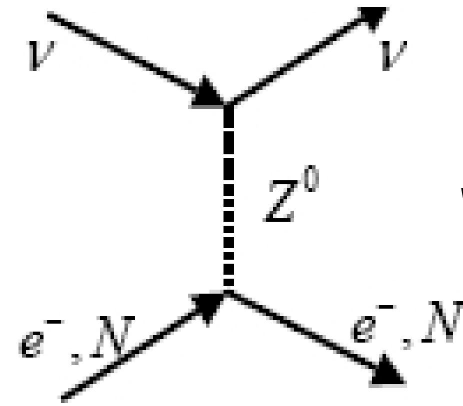
Oscillations in Matter (MSW Effect)

Electrons exist in standard matter – μ/τ do not. Electron neutrinos travelling in matter can experience an extra charged current interaction that other flavours cannot.

$$V_W = \sqrt{2}\, G_F N_e$$

Interaction Potential





$$V_Z = -\frac{\sqrt{2}}{2} G_F N_n$$

Oscillation probabilites are now function of $\theta_M, \Delta m_M^2$

$$\Delta m_M^2 = \Delta m_V^2 \sqrt{\sin^2(2\theta) + (\cos 2\theta - \zeta)^2}$$

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - \zeta)^2}$$

$$\zeta = \frac{2\sqrt{2}\, G_F N_e E}{\Delta m_V^2}$$

Implications

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - \zeta)^2} \qquad \zeta = \frac{2\sqrt{2}\, G_F N_e E}{\Delta m^2_{Vac}}$$

- If Δm^2_{Vac} = 0 or matter is very dense, $\zeta = \infty$ and $\theta_m = 0$
- Similarly, if $\theta=0$, then $\theta_M = 0$
- If there is no matter, then $\zeta = 0$ and we have vacuum mixing
- At a particular electron density, dependent on Δm^2,

$$\zeta = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2} = cos2\theta \;\Rightarrow\; \sin^2 2\theta_M = 1$$

Even if the vacuum mixing angle is tiny, there is a density for which the matter mixing is large

Mass heirarchy

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - \zeta)^2} \qquad \zeta = \frac{2\sqrt{2}\,G_F N_e E}{\Delta m_V^2}$$

If mass of ν_1 < mass of ν_2, $\Delta m^2 = m_1^2 - m_2^2 < 0$

$$\zeta = -\frac{2\sqrt{2}\,G_F N_e E}{\left|\Delta m^2\right|} \rightarrow \sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (cos2\theta + \zeta)^2}$$

Positive definite – no resonance

If mass of ν_1 > mass of ν_2, $\Delta m^2 = m_1^2 - m_2^2 > 0$

$$\zeta = \frac{2\sqrt{2}\,G_F N_e E}{\left|\Delta m^2\right|} \rightarrow \sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (cos2\theta - \zeta)^2}$$

Three Flavour Oscillation

The three flavour case is more complicated, but no different

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

$$Prob(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} \frac{L}{4E})$$

$$+ 2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} \frac{L}{2E})$$

Oscillation parameters

$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}=\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

2 independent Δm^2

$$Prob(\nu_\alpha \rightarrow \nu_\beta)=\delta_{\alpha\beta}-4\sum_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(\Delta m^2_{ij}\frac{L}{4E})$$

$$+2\sum_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin(\Delta m^2_{ij}\frac{L}{2E})$$

Oscillation parameters

$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}=\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Three angles

$$Prob(\nu_\alpha \rightarrow \nu_\beta)=\delta_{\alpha\beta}-4\sum_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(\Delta m^2_{ij}\frac{L}{4E})$$

$$+2\sum_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin(\Delta m^2_{ij}\frac{L}{2E})$$

Oscillation parameters

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

CP violating phase

$$Prob(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re (U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 (\Delta m^2_{ij} \frac{L}{4E})$$

$$+ 2 \sum_{i>j} \Im (U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin (\Delta m^2_{ij} \frac{L}{2E})$$

Explaining the solar data

Testing oscillation hypothesis

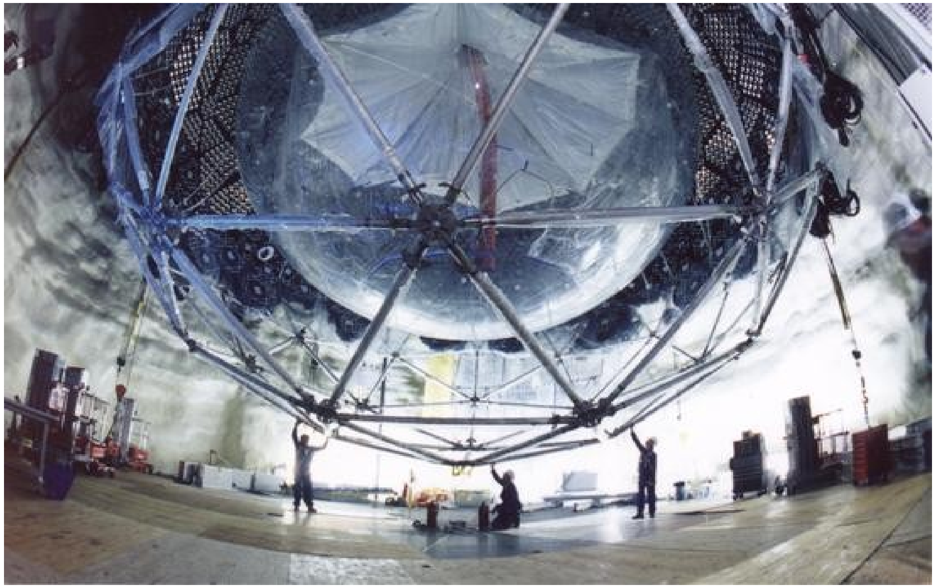
Solar neutrino problem

n_e from sun would change to n_μ or n_τ . However these have too little energy to interact via the charged current, and all the detectors are only sensitive to charge current interactions.

Non-n_e component would effectively disappear, reducing the apparent n_e flux.

Proof : Neutral current event rate shouldn't change.

Sudbury Neutrino Observatory



1000 tonnes of $D_2 0$

6500 tons of $H_2 0$

Viewed by 10,000 PMTS

In a salt mine 2km underground
in Sudbury, Canada

SNO

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

Produces Cherenkov Light Cone in D_2O

- Q = 1.445 MeV
- good measurement of ν_e energy spectrum
- some directional info $\propto$ (1 – 1/3 cosθ)
- ν_e only

ν_e

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

n captures on deuteron

$^2H(n, \gamma)^3H$

Observe 6.25 MeV γ

- Q = 2.22 MeV
- measures total ^8B ν flux from the Sun
- equal cross section for all ν types

$\nu_e + \nu_\mu + \nu_\tau$

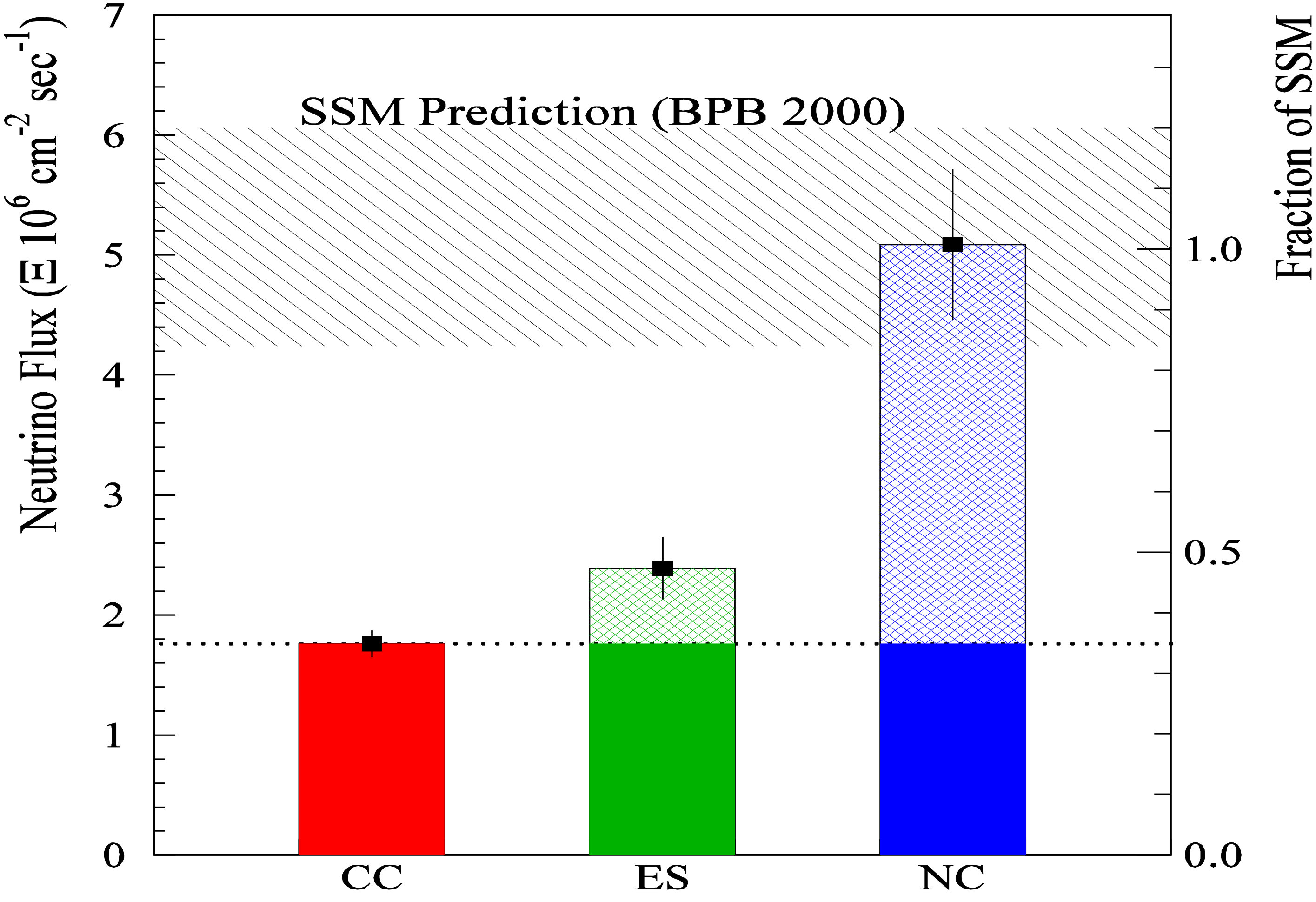
ES $\nu_x + e^- \rightarrow \nu_x + e^-$

Produces Cherenkov Light Cone in D_2O

- low statistics
- mainly sensitive to ν_e, some ν_μ and ν_τ
- strong directional sensitivity

$\nu_e + 0.15*(\nu_\mu + \nu_\tau)$

SNO Results



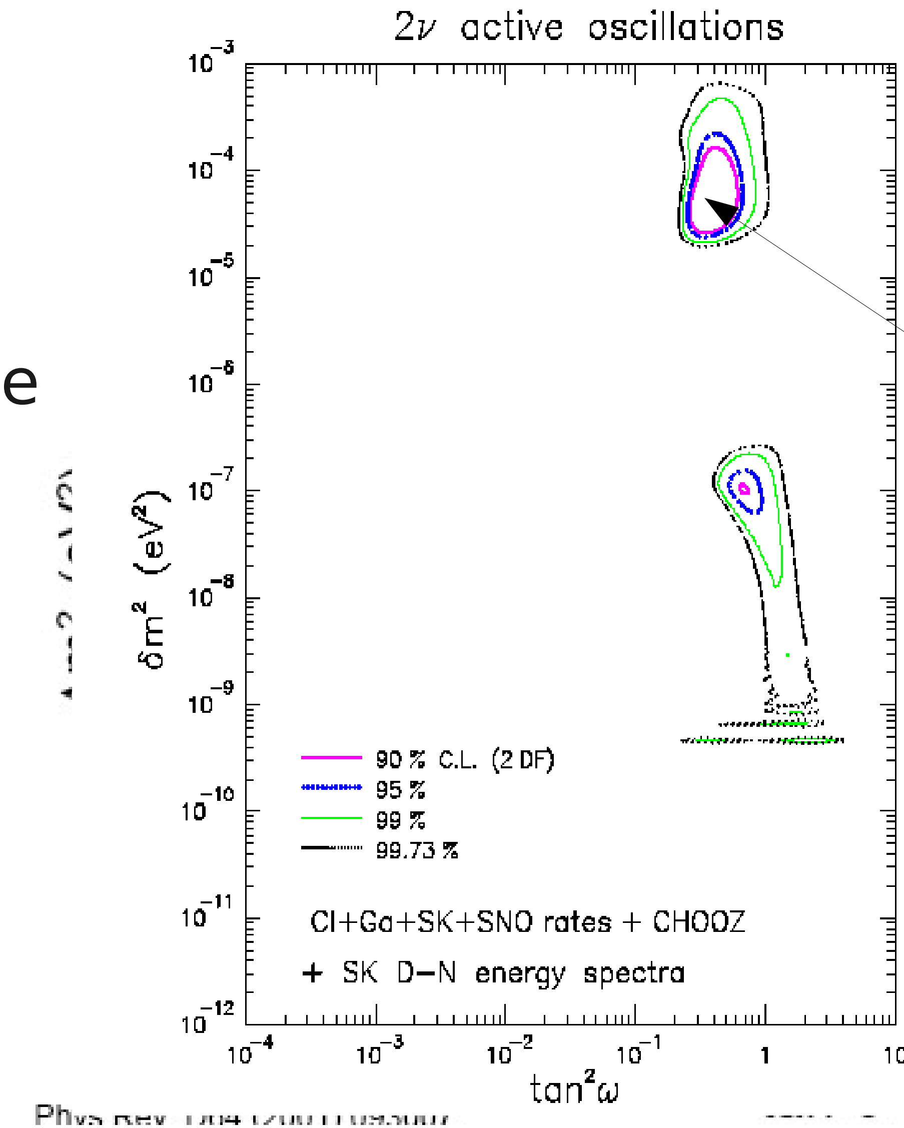
5.3 σ appearance of $\nu_{\mu\tau}$ in a ν_e beam

Roughly 70% of ν_e oscillates away

Adding SNO to the mix

The data shows that the solar oscillations come mostly from the MSW effect.

The neutrinos have oscillated before they get to the solar surface.



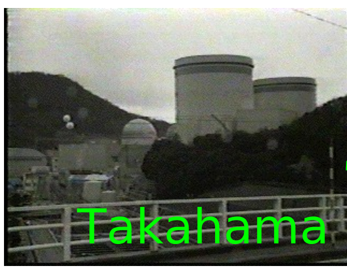
$$\theta_{e\mu} = 32.5^{\circ} \pm 2.4^{\circ}$$

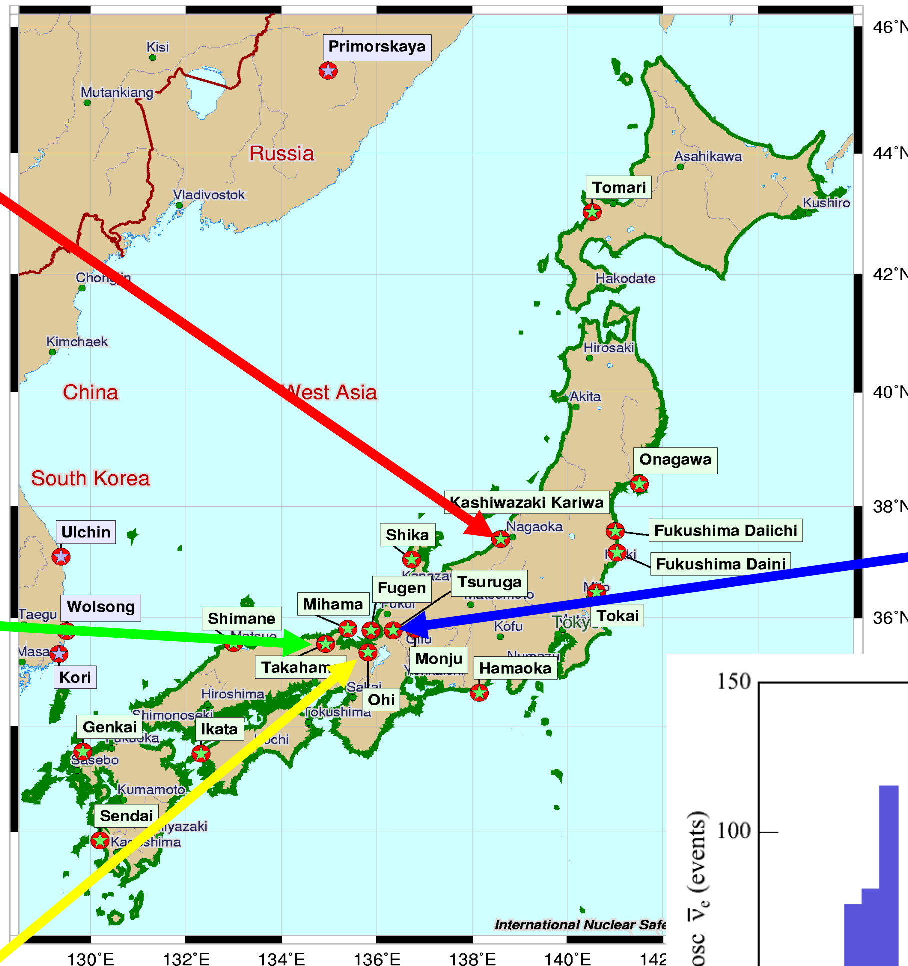
$$\Delta m^2_{12} = +7.1 \times 10^{-5}\, eV^2$$

Transition mostly

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

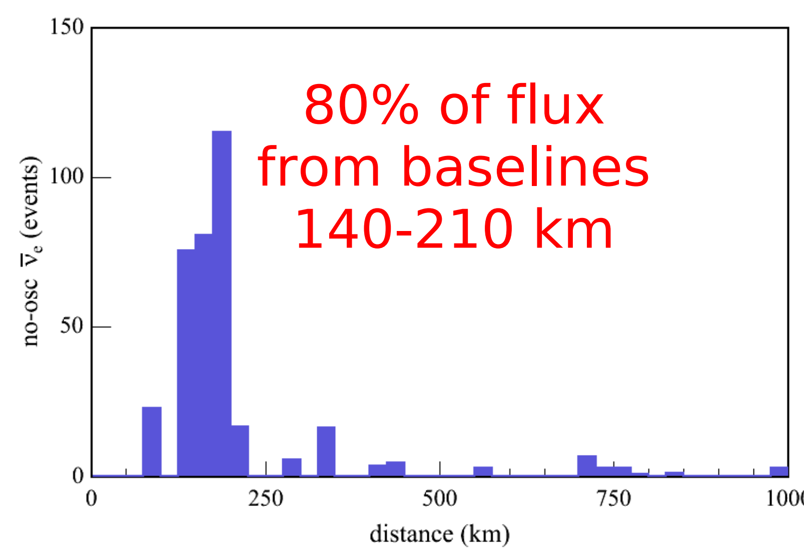
KamLAND



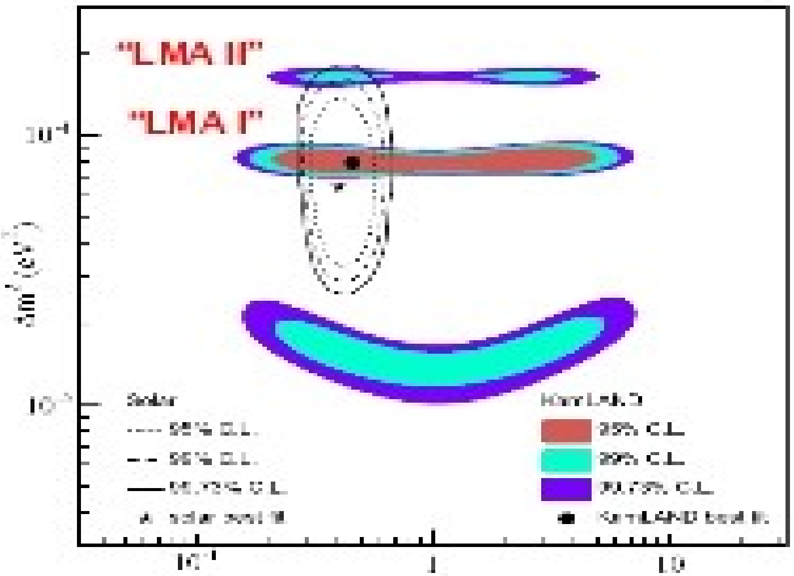


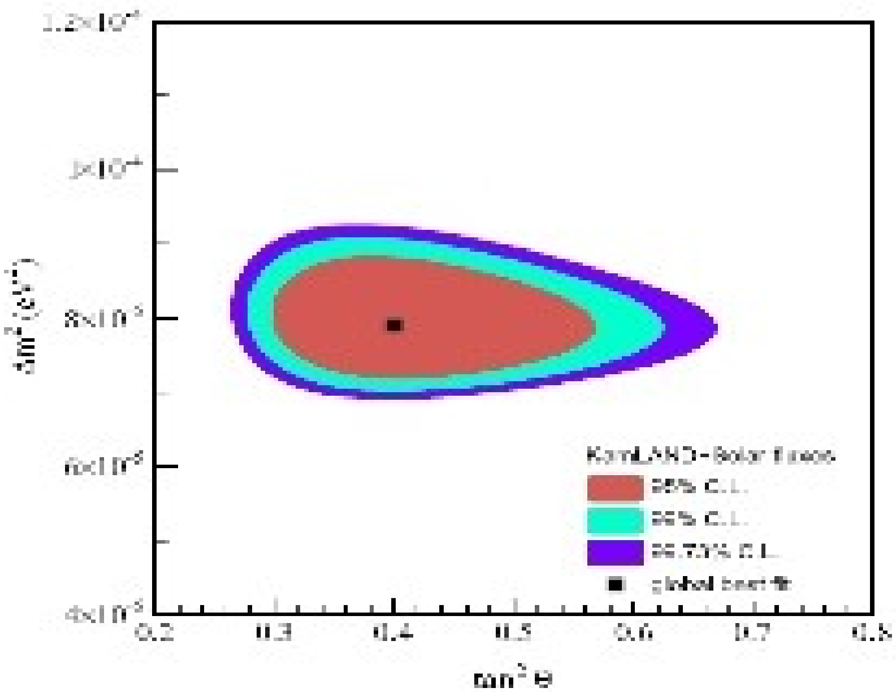
KamLAND uses the entire Japanese nuclear power industry as a long-baseline source

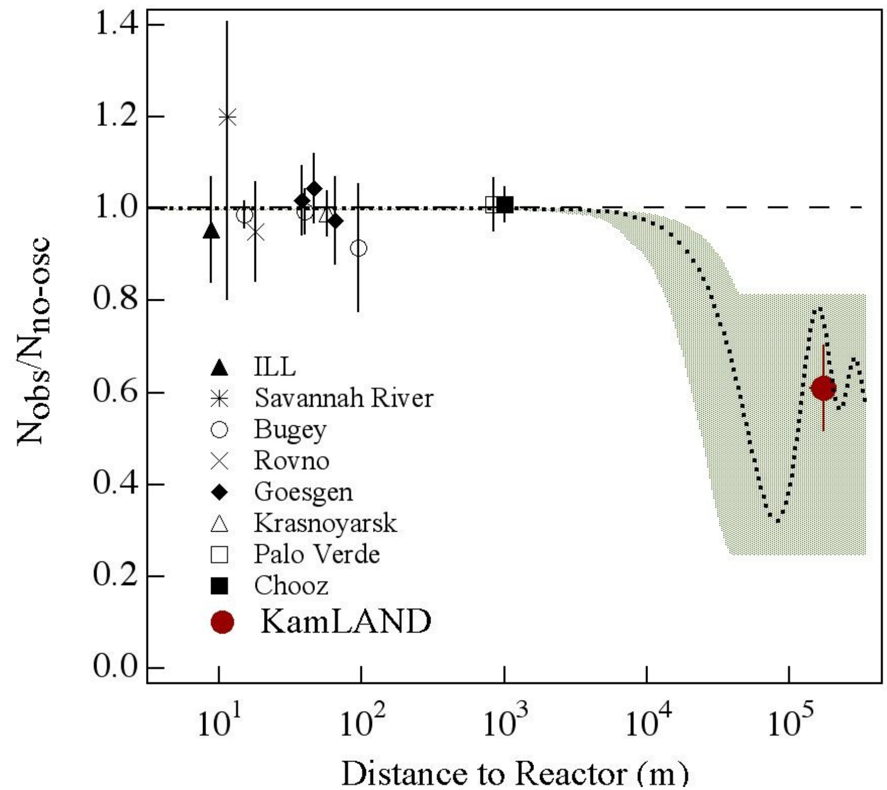
KamLAND @ Kamioka



KamLAND



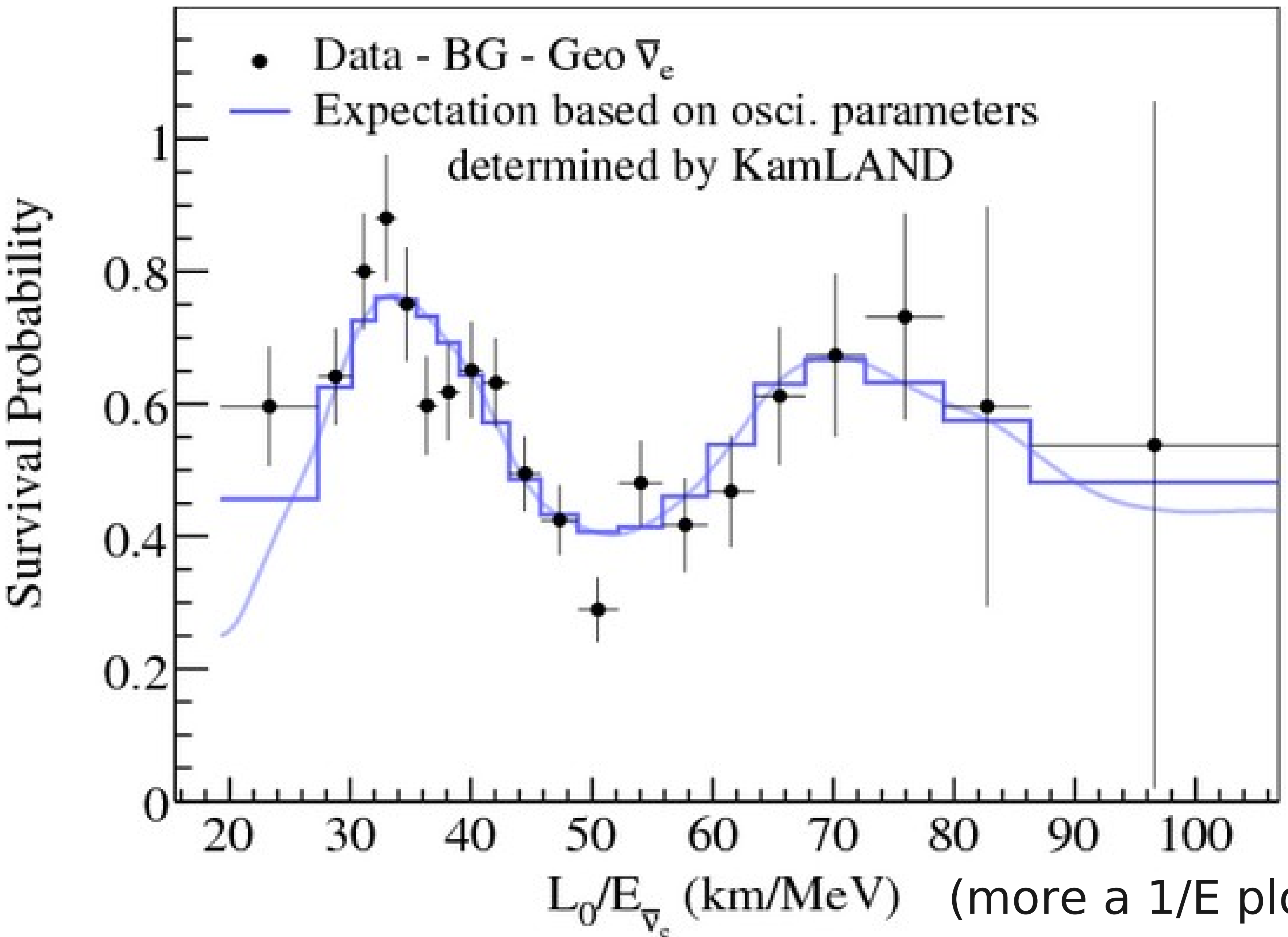




$$\Delta m_{12}^2 = +7.9 \pm 0.5 \times 10^{-5} eV^2$$

$$\tan^2(\theta) = 0.4 \pm 0.09$$

An oscillation!



(more a 1/E plot)

Mixing matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Solar sector

$$\theta_{e\mu} = 32.5^{\circ} \pm 2.4^{\circ}$$

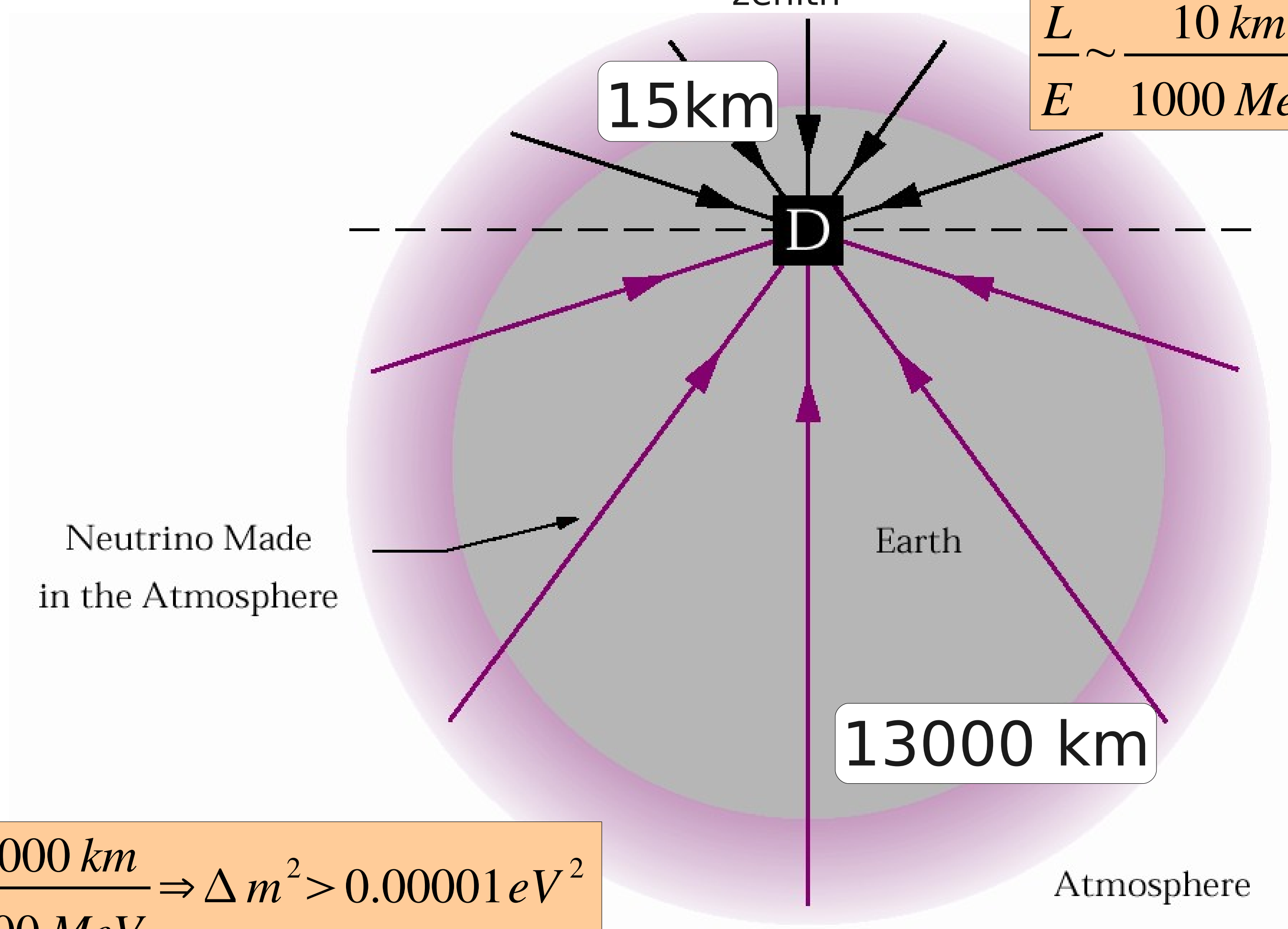
$$\Delta m_{12}^{2} = +7.9 \times 10^{-5} eV^{2}$$

Explaining the atmospheric data

Cosmic Labs

$\cos\theta_{zenith} = 1.0$

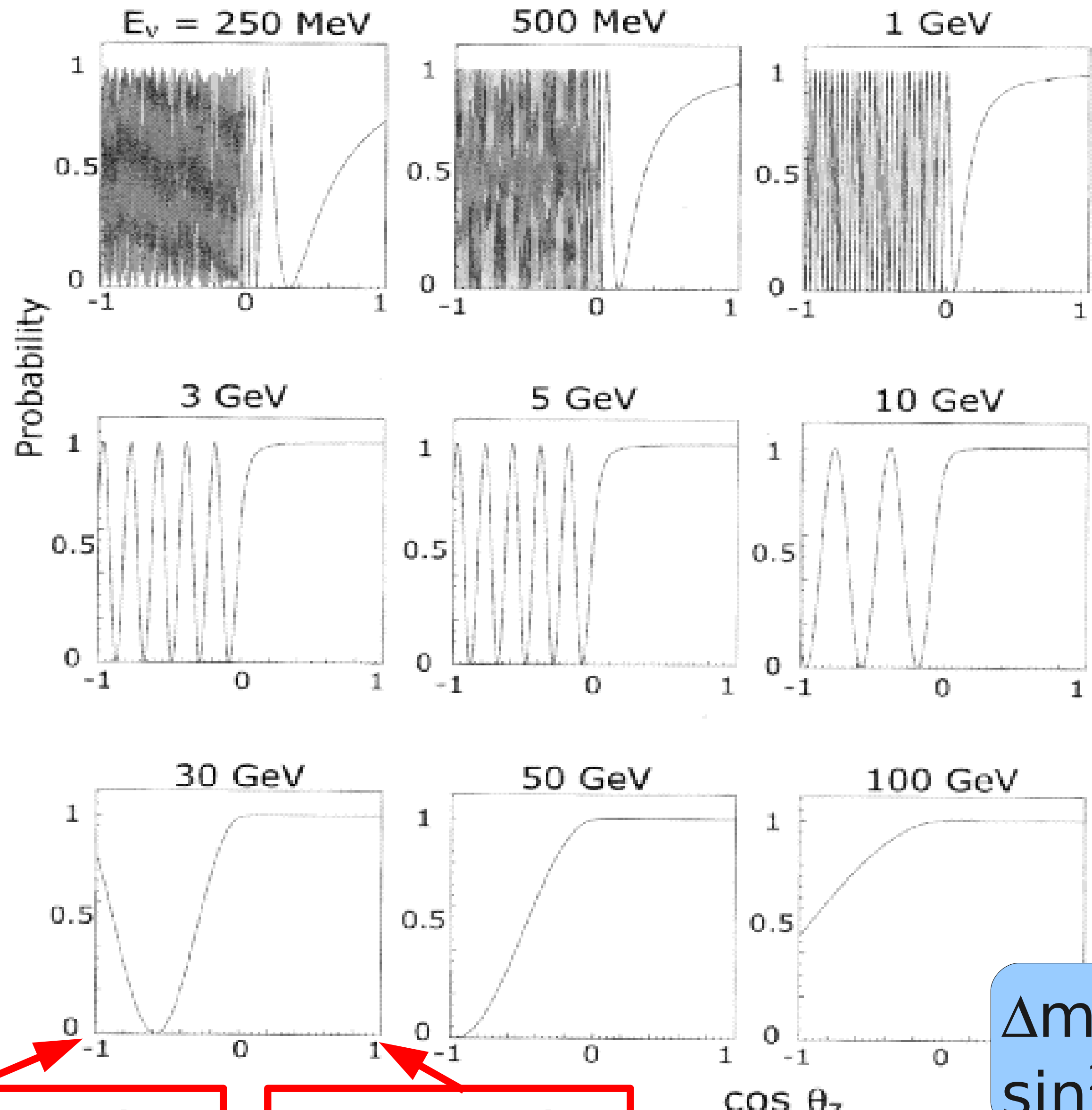
$$\frac{L}{E} \sim \frac{10\,km}{1000\,MeV} \Rightarrow \Delta m^2 > 0.01\,eV^2$$



$$\frac{L}{E} \sim \frac{10000\,km}{1000\,MeV} \Rightarrow \Delta m^2 > 0.00001\,eV^2$$

$\cos\theta_{zenith} = -1.0$

Survival Probability



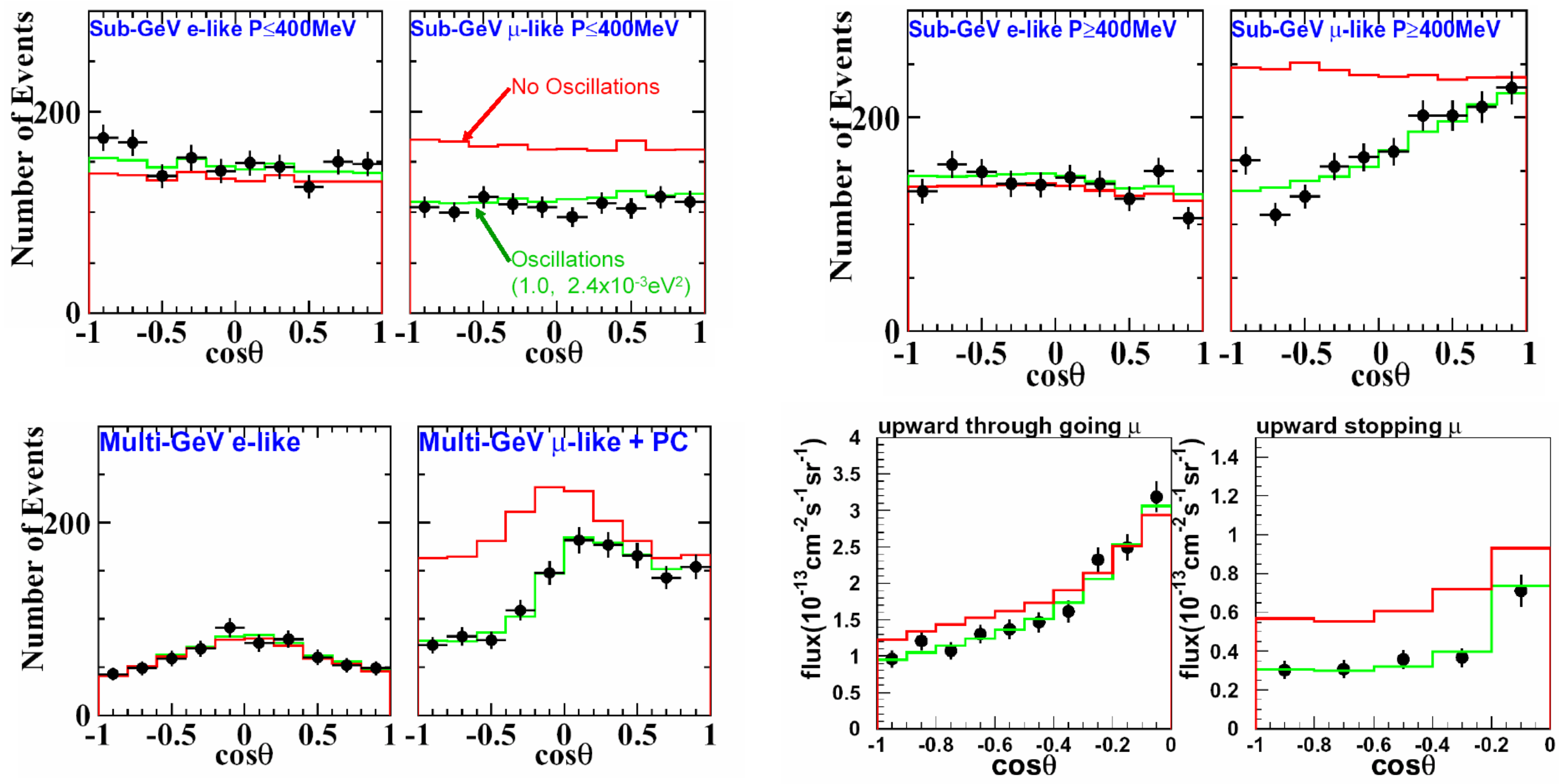
Up-coming

Down going

$\Delta m^2 = 5\text{x}10^{-3}\ eV^2$
$\sin^2 2\theta = 1.0$

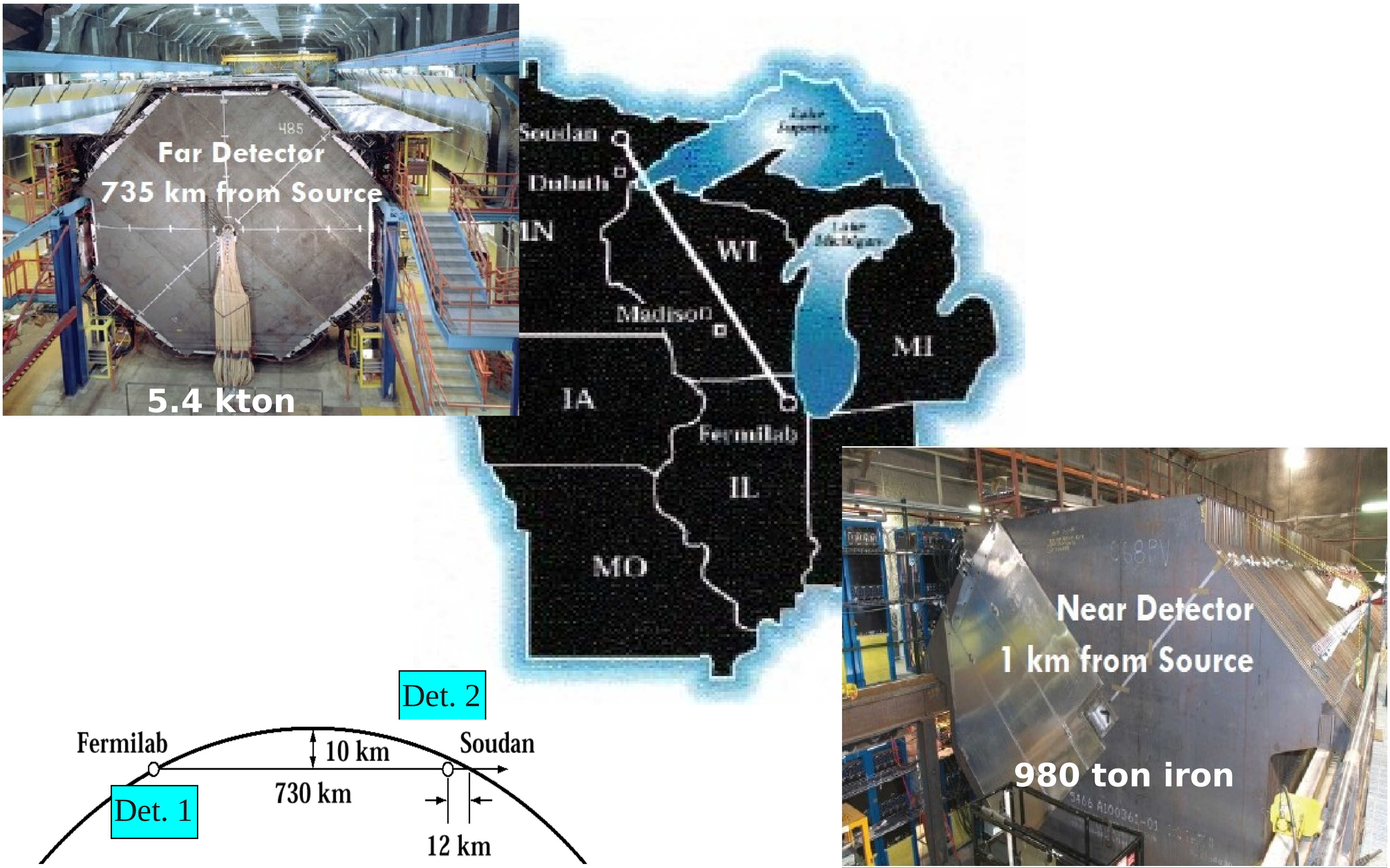
Super-Kamiokande

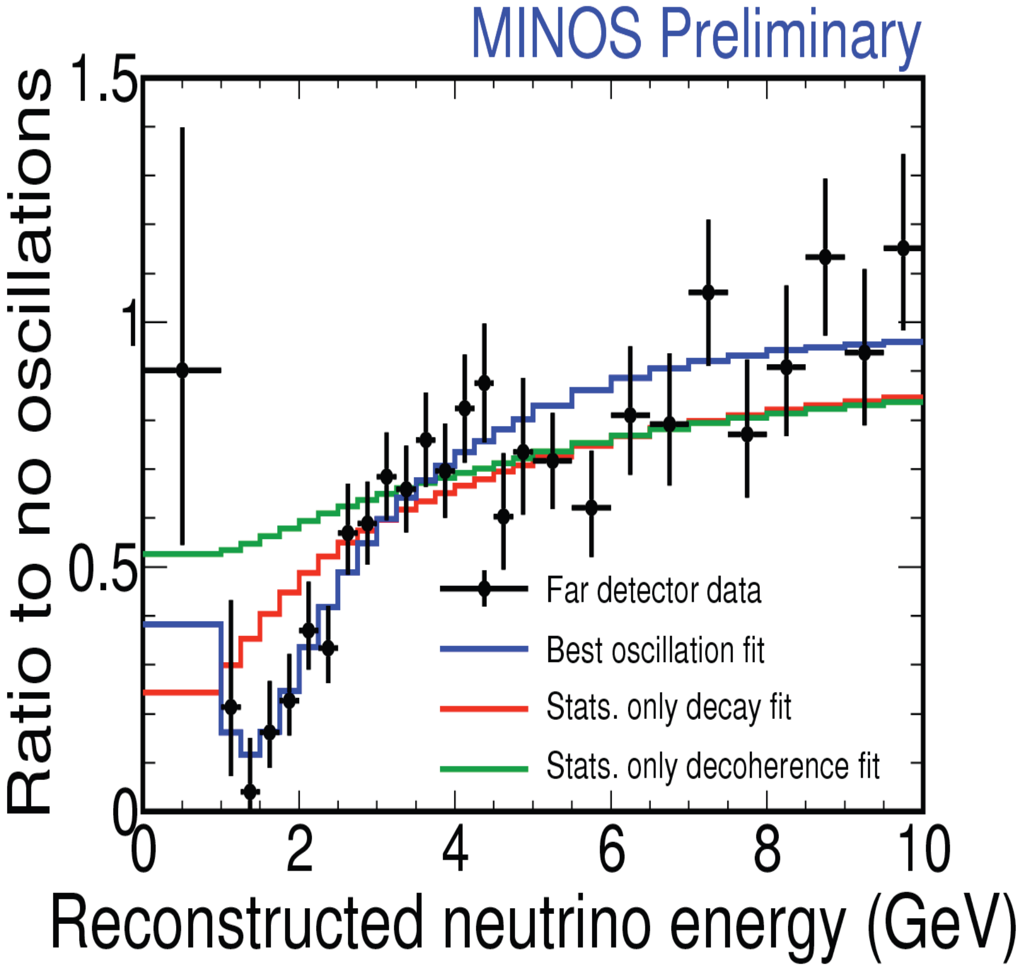
SuperK has both energy and direction information

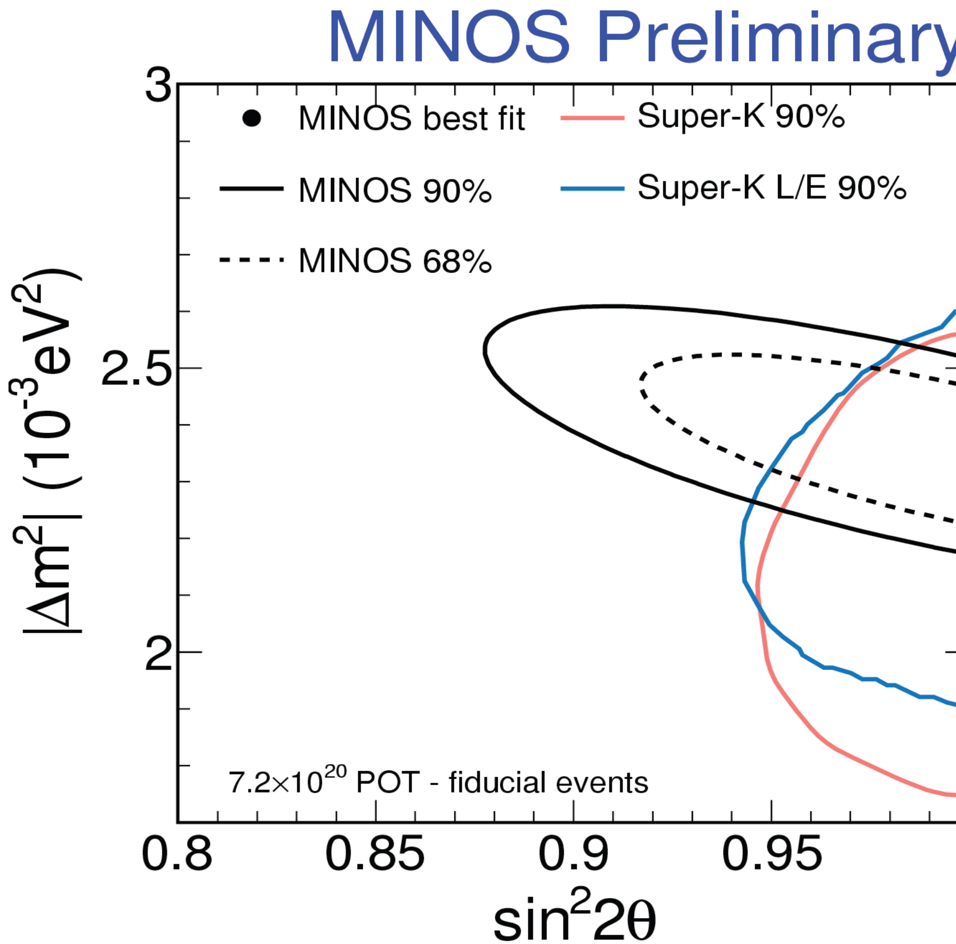


Sees disappearance of ν_μ but NOT into ν_e – almost total $\nu_\mu \rightarrow \nu_\tau$ oscillations?

MINOS verification







$$\frac{\#\,events\,observed}{\#\,events\,expected} = P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(\Delta m^2 L 4 E)$$

$$\Delta m^2 = 2.35^{+0.11}_{-0.08} \times 10^{-3}\, eV^2$$

$$\sin^2(2\theta) > 0.91 (@ 90\ CL)$$

Mixing matrix

$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}=\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Solar sector : $n_{\mu} \rightarrow n_{e}$

$$\theta_{e\mu}=32.5^{o}\pm 2.4^{o}$$

$$\Delta m_{12}^{2}=+7.9\times 10^{-5}eV^{2}$$

Atmospheric sector

$n_{\mu} \rightarrow n_{\tau}$

$$\theta_{\mu\tau}=45.0^{o}\pm 2.4^{o}$$

$$\Delta m_{23}^{2}=\left|2.35\times 10^{-3}\right|eV^{2}$$

Mixing matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

And this sector?

Probabilities

For Atmospheric L/E and δ = 0

$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2(1.27\Delta m^2_{23}\frac{L}{E})$$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2(1.27\Delta m^2_{23}\frac{L}{E})$$

$$P(\nu_e \to \nu_\tau) = \sin^2 2\theta_{13}\cos^2\theta_{23}\sin^2(1.27\Delta m^2_{23}\frac{L}{E})$$

For Solar L/E and δ = 0

$$P(\nu_e \to \nu_{\mu,\tau}) = \cos^2\theta_{13}\sin^2 2\theta_{12}\sin^2(1.27\Delta m^2_{12}\frac{L}{E}) + 0.5\sin^2\theta_{13}$$

If $\theta_{13} = 0$

For Atmospheric L/E and $\delta = 0$

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta_{23} \sin^2(1.27\Delta m_{23}^2 \frac{L}{E})$$

$$P(\nu_\mu \rightarrow \nu_e) = P(\nu_e \rightarrow \nu_\tau) = 0$$

For Solar L/E and $\delta = 0$

$$P(\nu_e \rightarrow \nu_{\mu,\tau}) = \sin^2 2\theta_{12} \sin^2(1.27\Delta m_{12}^2 \frac{L}{E})$$

θ_{13} couples the atmospheric and solar sectors. So what is it?

How do we get to θ_{13}?

$\nu_\mu \to \nu_e$ oscillations with atmospheric L/E

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(1.27\Delta m^2_{23} \frac{L}{E})$$

$\nu_e \to \nu_x$ disappearance oscillations with atmospheric L/E

$$P(\nu_e \to \nu_x) = \sin^2(2\theta_{13}) \sin^2(1.27\Delta m^2_{23} \frac{L}{E})$$

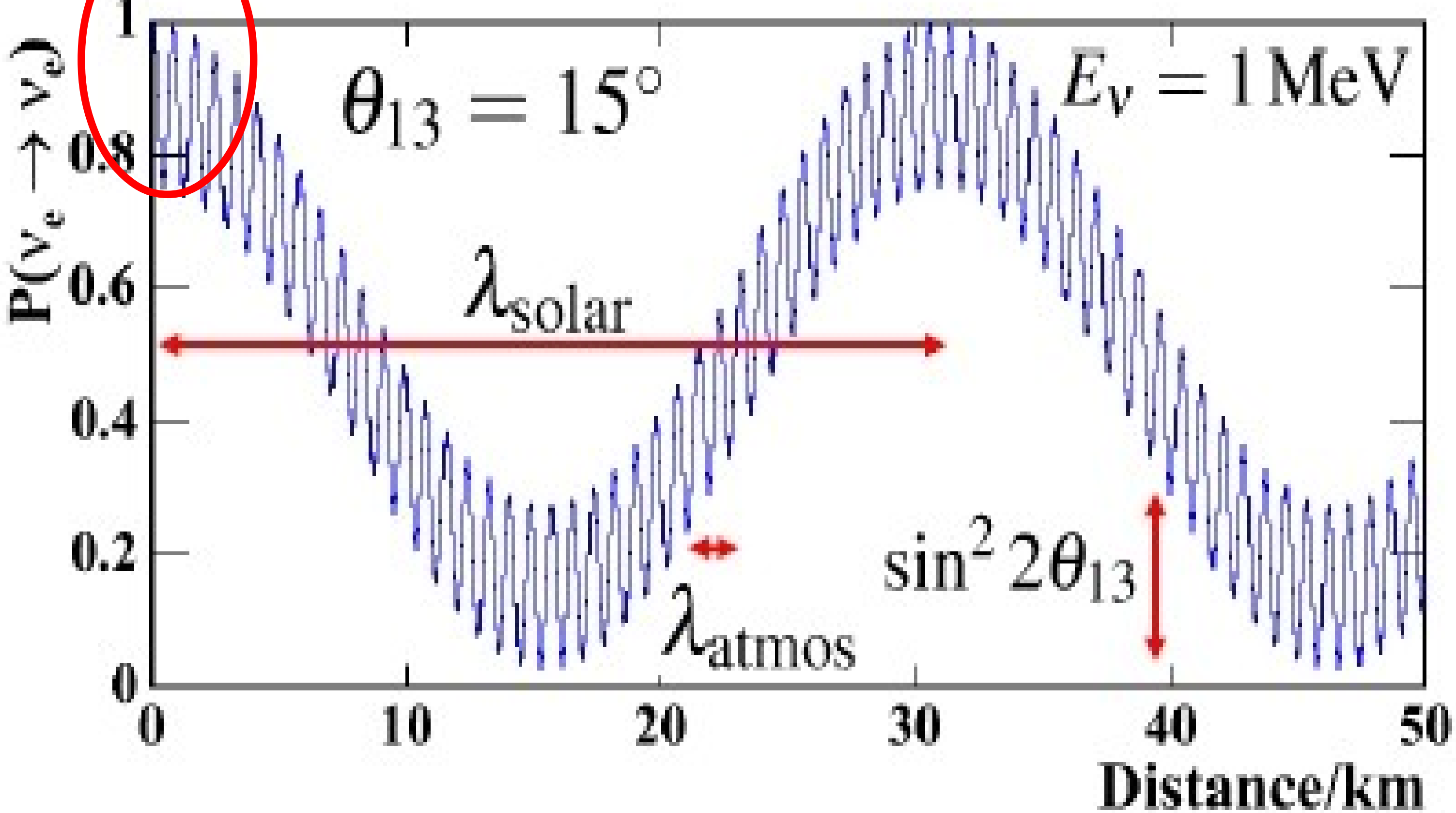
$\overline{\nu}_e \to \overline{\nu}_x$ disappearance oscillations with atmospheric L/E

$$P(\nu_e \to \nu_x) \overset{\hat{C}\hat{P}\hat{T}}{=} P(\overline{\nu}_e \to \overline{\nu}_x)$$

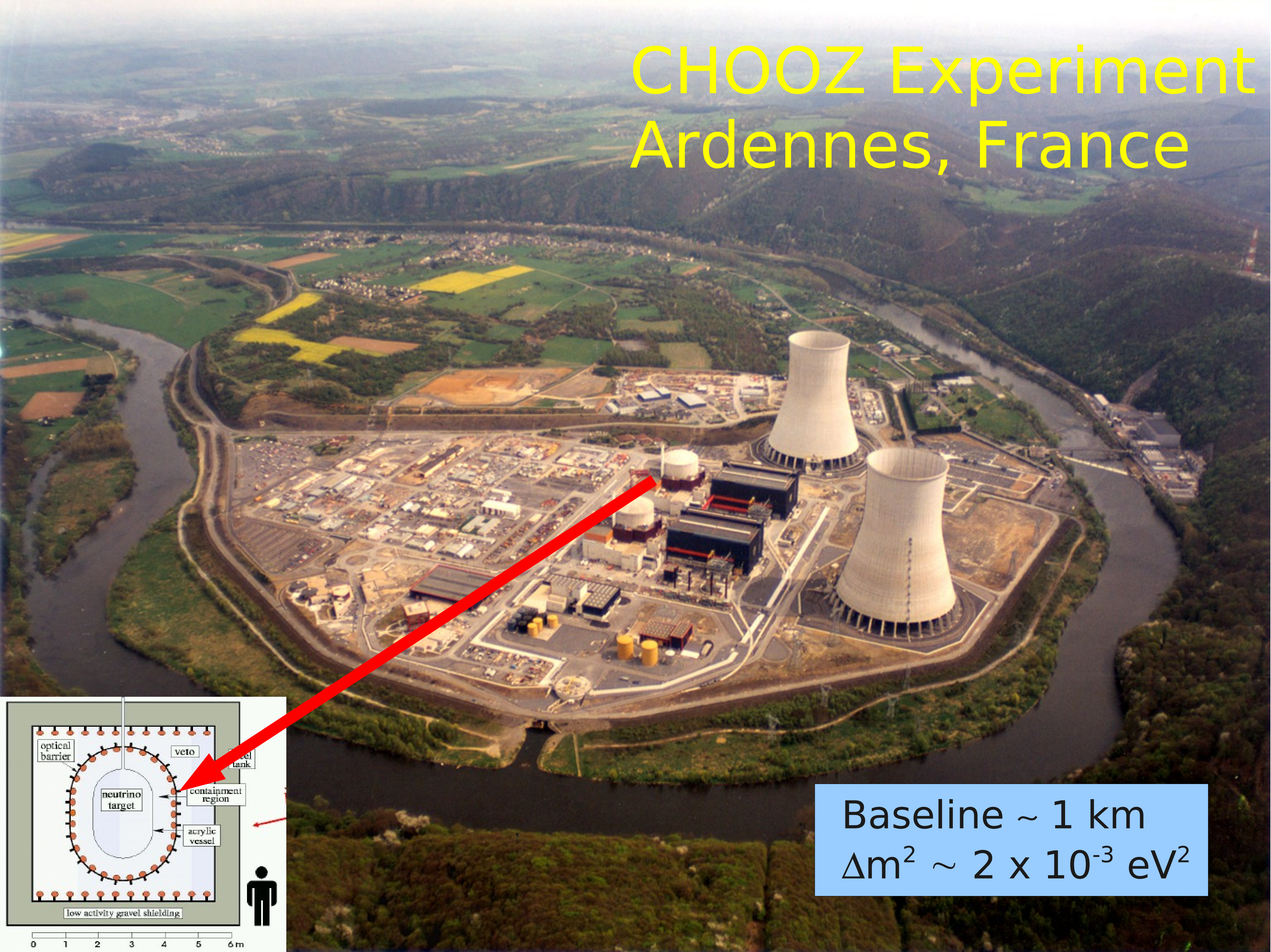
Reactor Experiments

$$P(\nu_e \rightarrow \nu_e) = 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(1.27 \Delta m^2_{12} \frac{L}{E})$$

$$- \sin^2(2\theta_{13}) \sin^2(1.27 \Delta m^2_{23} \frac{L}{E})$$

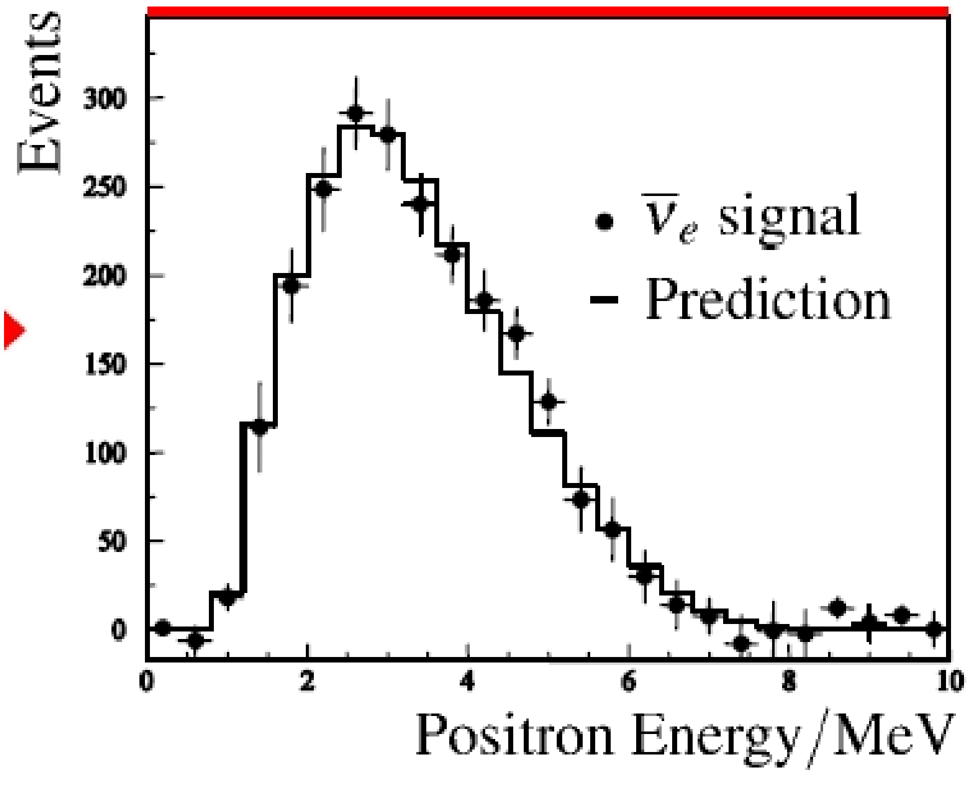


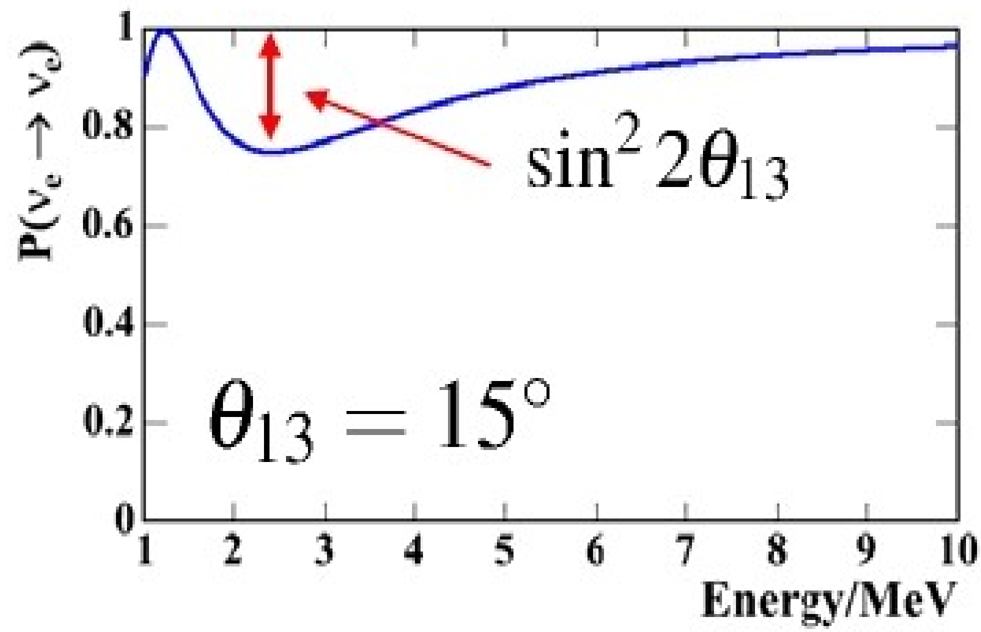
CHOOZ Experiment
Ardennes, France



Baseline ~ 1 km
$\Delta m^2 \sim 2 \times 10^{-3}\ eV^2$

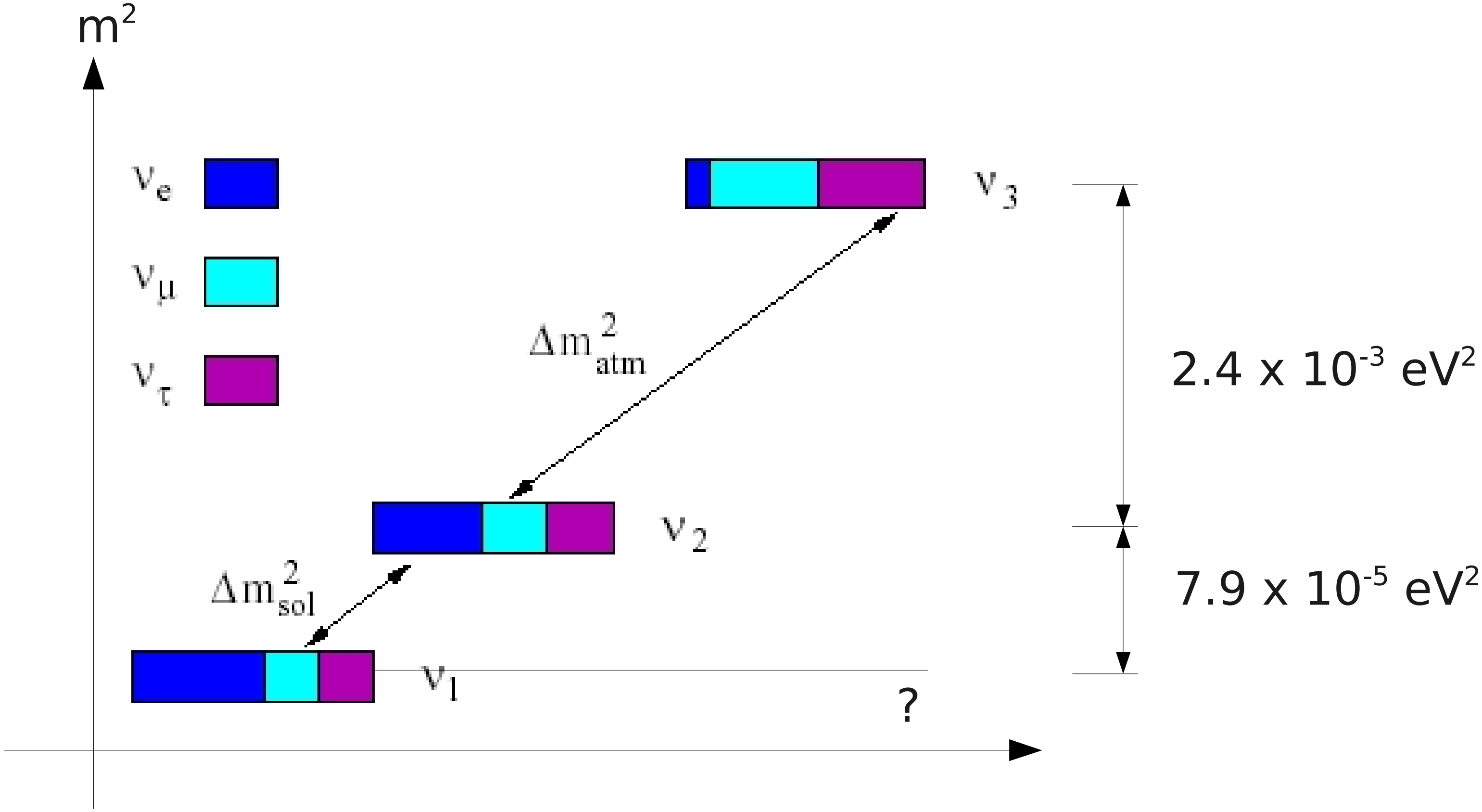
$$R = \frac{N_{observed}}{N_{expected}} = 1.01 \pm 2.8\,\%(stat) \pm 2.7\,\%(sys)$$





$$\sin^2(2\,\theta_{13}) < 0.12 - 0.2 \;\Rightarrow\; \theta_{13} < 10\,deg$$

This is what we know...



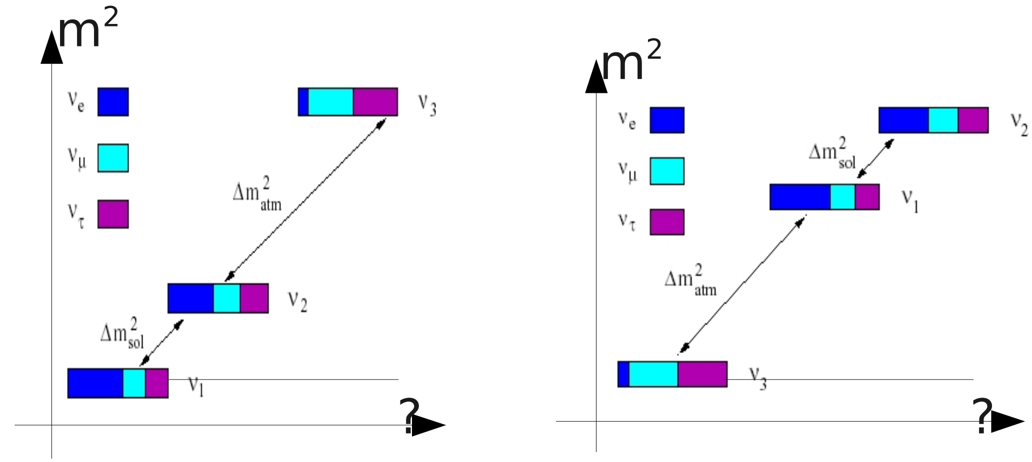
$$U_{MNSP} = \begin{pmatrix} 0.8 & 0.5 & \epsilon \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Some elements only known to 30-50%

This is what we want to know…

$$\begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

Value of θ_{13} Value of δ



Normal or inverted?

$$U_{MNSP} = \begin{pmatrix} 0.8 & 0.5 & \epsilon \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \Leftrightarrow U_{CKM} = \begin{pmatrix} 0.975 & 0.222 & 0.004 \\ 0.221 & 0.97 & 0.04 \\ 0.01 & 0.04 & 0.999 \end{pmatrix}$$

Majorana?

Better estimates of the oscillation parameters using accelerators

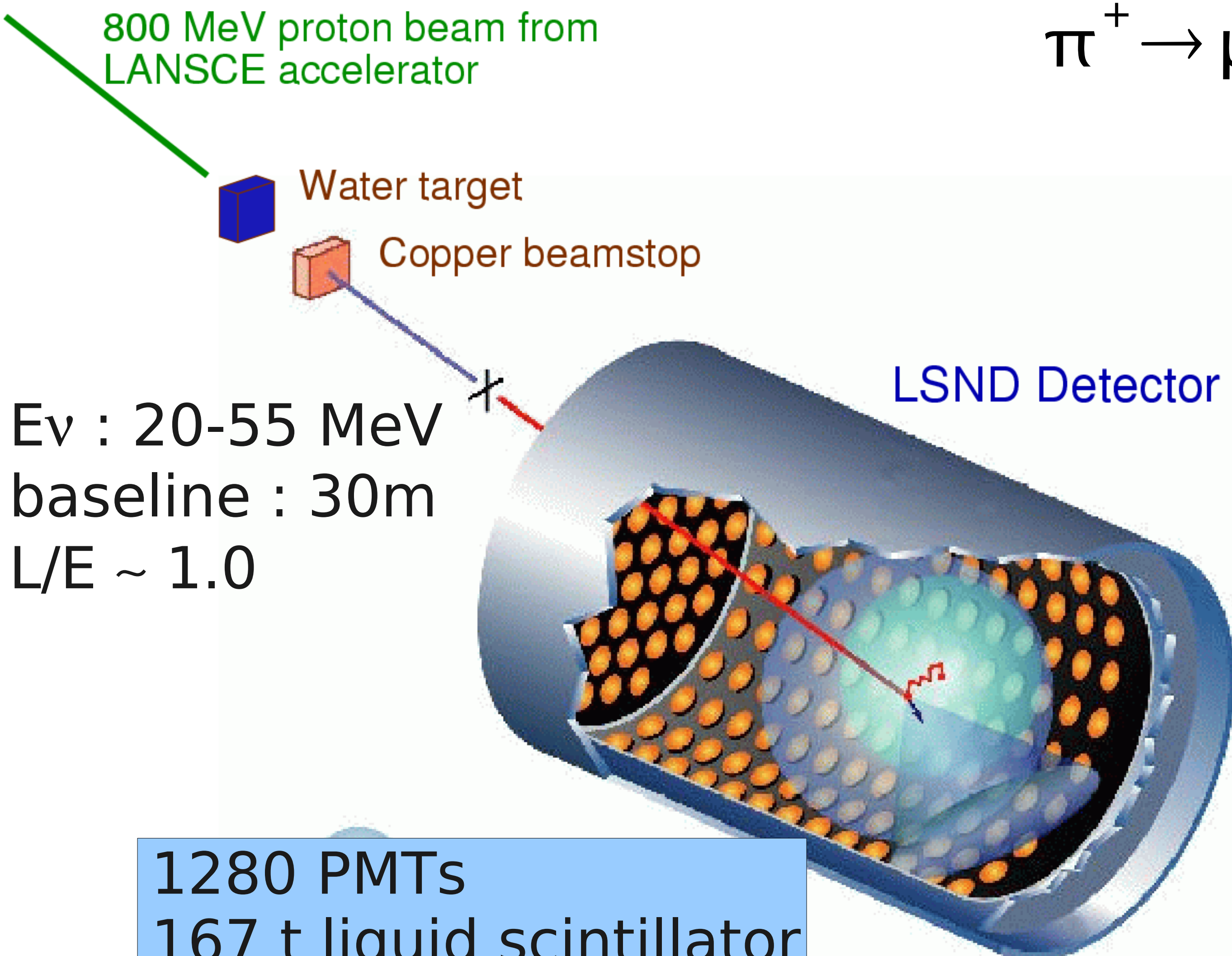
Is the atmospheric mixing angle maximal?

The next 20 years

Measurement	Method	Experiments	Why?	When
$\lvert\Delta m_{23}^2\rvert$	ν_μ Disapp.	MINOS	More precise Estimates	Now
θ_{23}	ν_μ Disapp.	T2K, NovA	Is it maximal?	2012
θ_{13}	ν_e Appear.	T2K, NovA	Equal to 0? Can't measure δ_{CP} if it is	2012
	Anti-ν_e Disapp.	Reactor		2012
Sgn(Δm_{23}^2) δ_{CP}	ν_e / anti-ν_e	T2KK, neutrino Factory, ???	Unification, GUT Lepton asymmetry	2025?

A spanner in the works

The LSND experiment was the first accelerator experiment to report a positive appearance signal



Eν : 20-55 MeV
baseline : 30m
L/E ~ 1.0

1280 PMTs
167 t liquid scintillator

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \overline{\nu}_\mu$$
$$\Updownarrow$$
$$\overline{\nu}_e$$

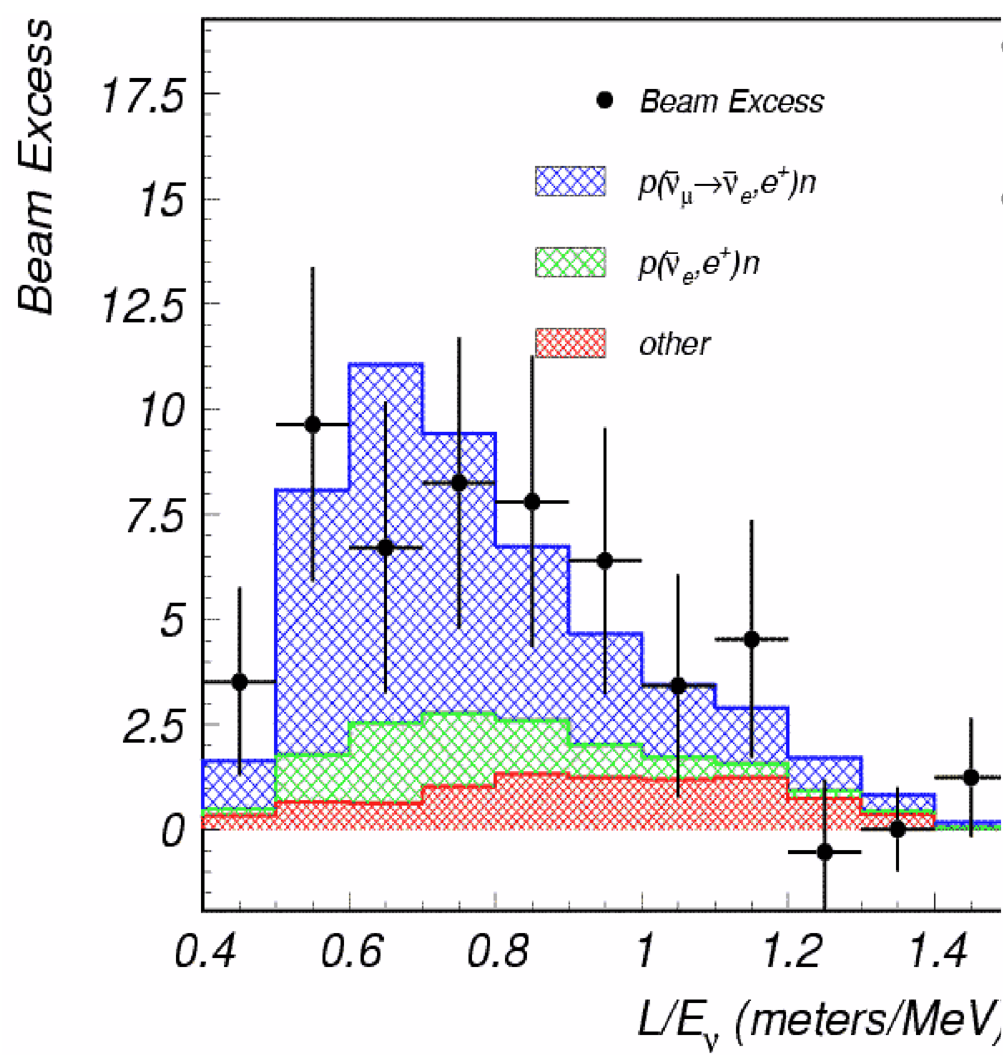
$$\overline{\nu}_e p \rightarrow e^+ n$$
20-60 MeV

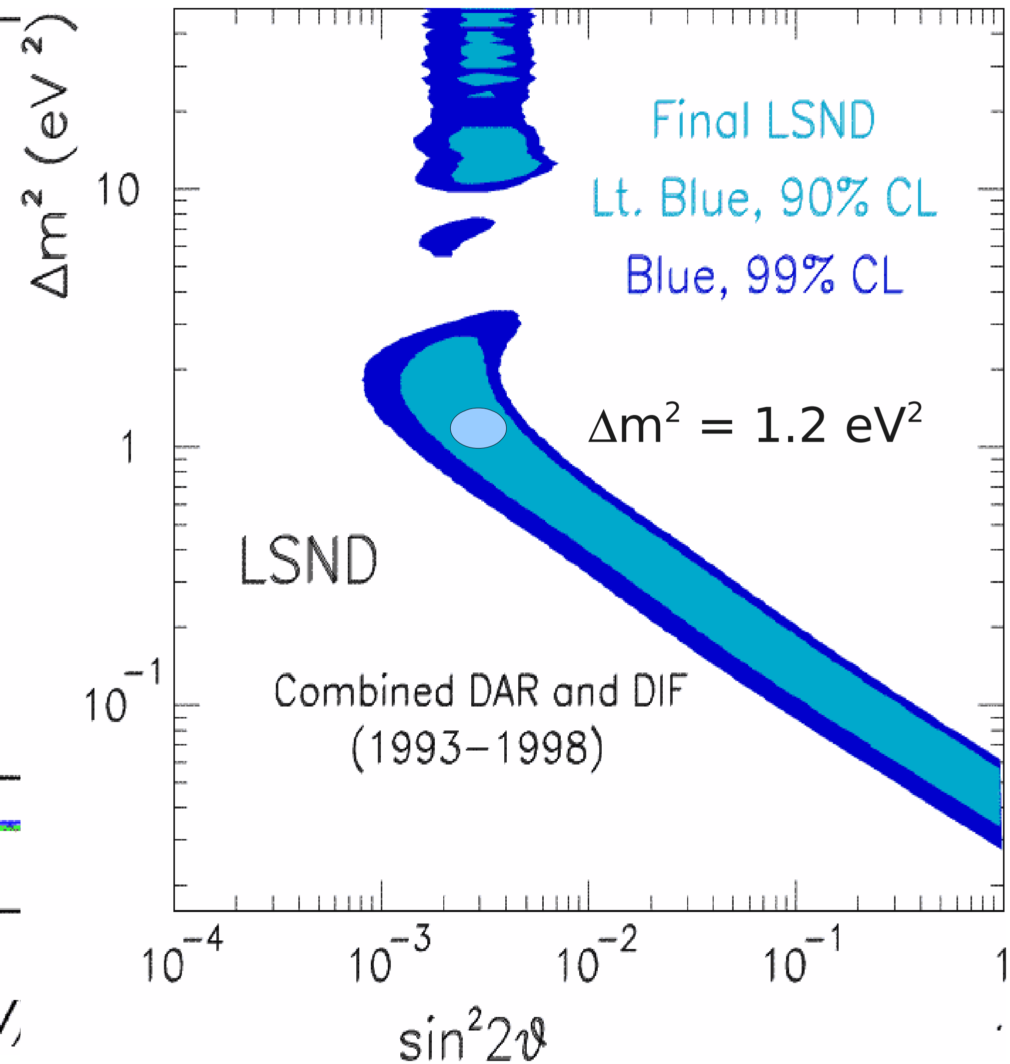
$$n\, p \rightarrow \gamma\, d$$
2.2 MeV

LSND Result (1997)

87.9 ± 22.4 ± 6 excess events from $\overline{n}_{\mu} \rightarrow \overline{n}_{e}$

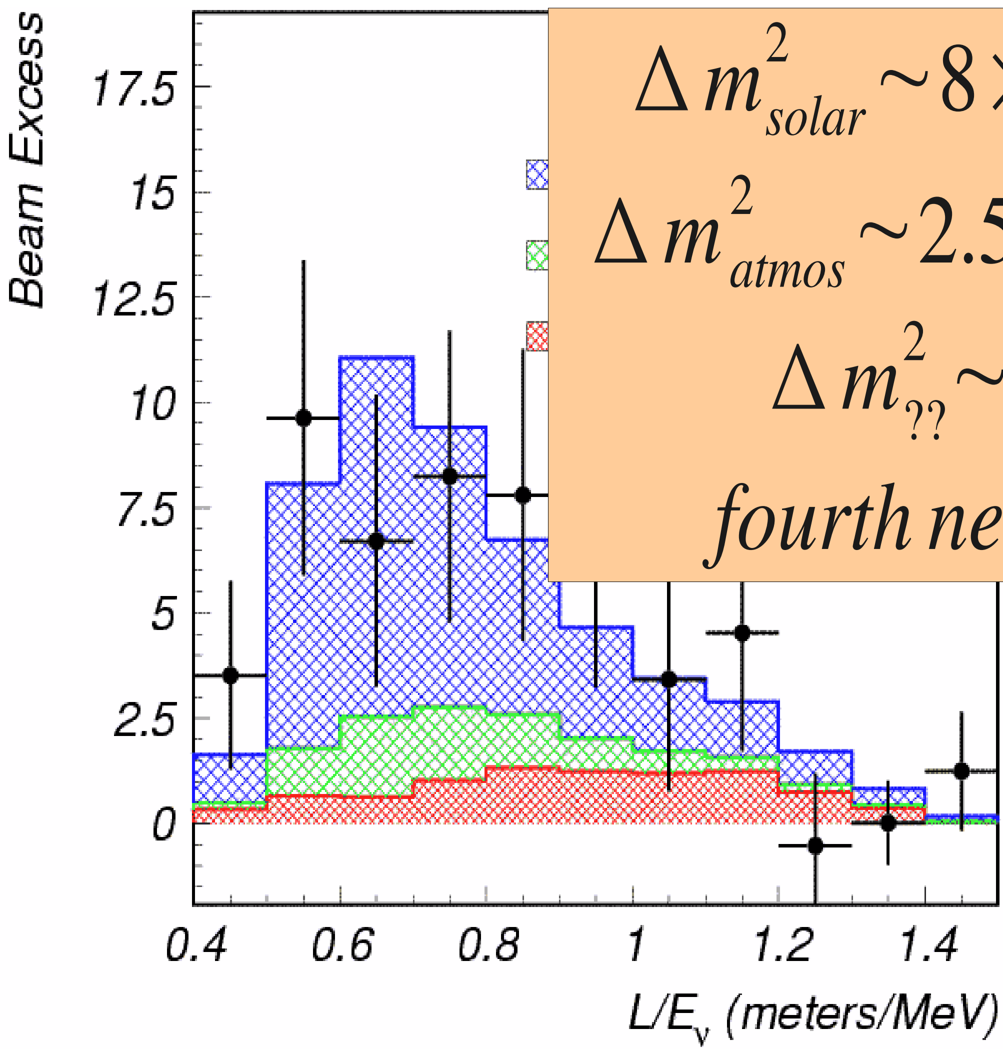
3.3 σ evidence for oscillations





LSND Result

87.9 ± 22.4 ± 6 excess events

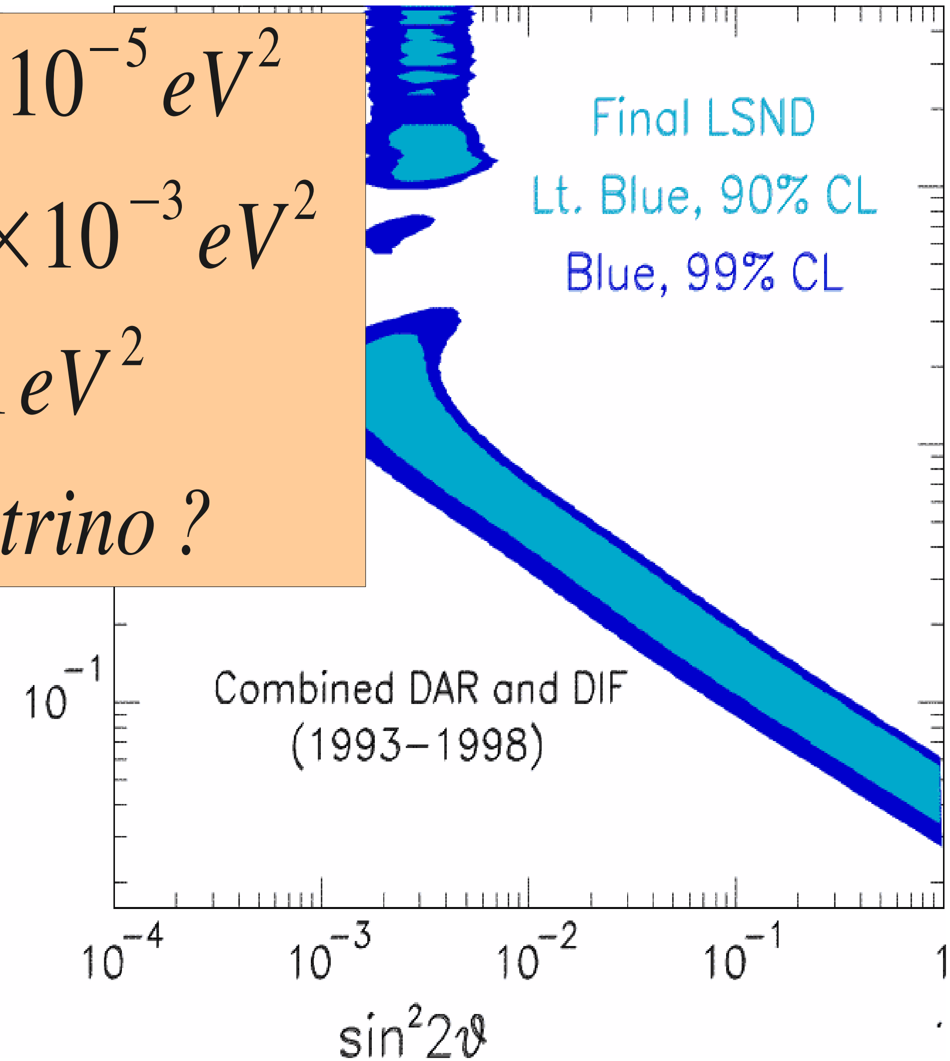


$$\Delta m^2_{solar} \sim 8\times10^{-5}\, eV^2$$

$$\Delta m^2_{atmos} \sim 2.5\times10^{-3}\, eV^2$$

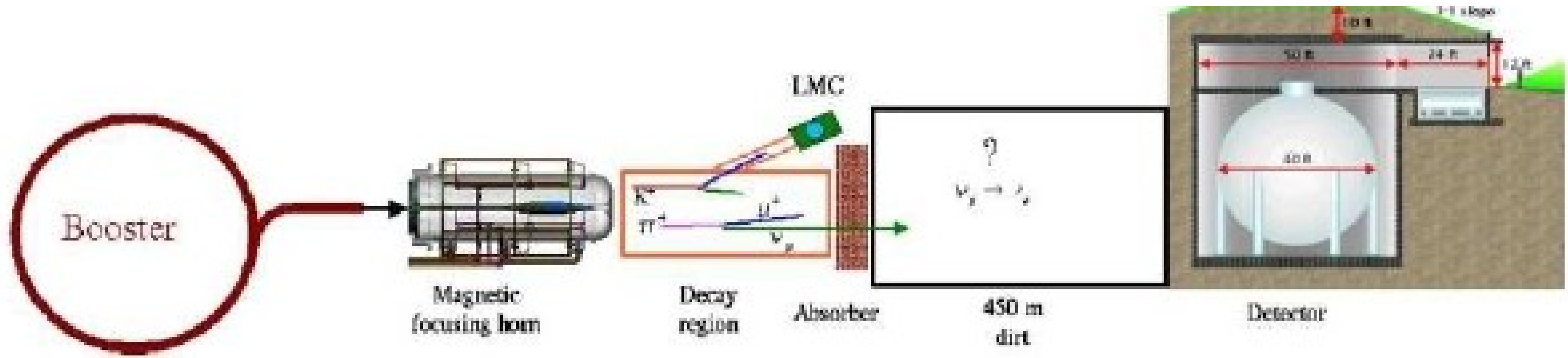
$$\Delta m^2_{??} \sim 1\, eV^2$$

fourth neutrino ?

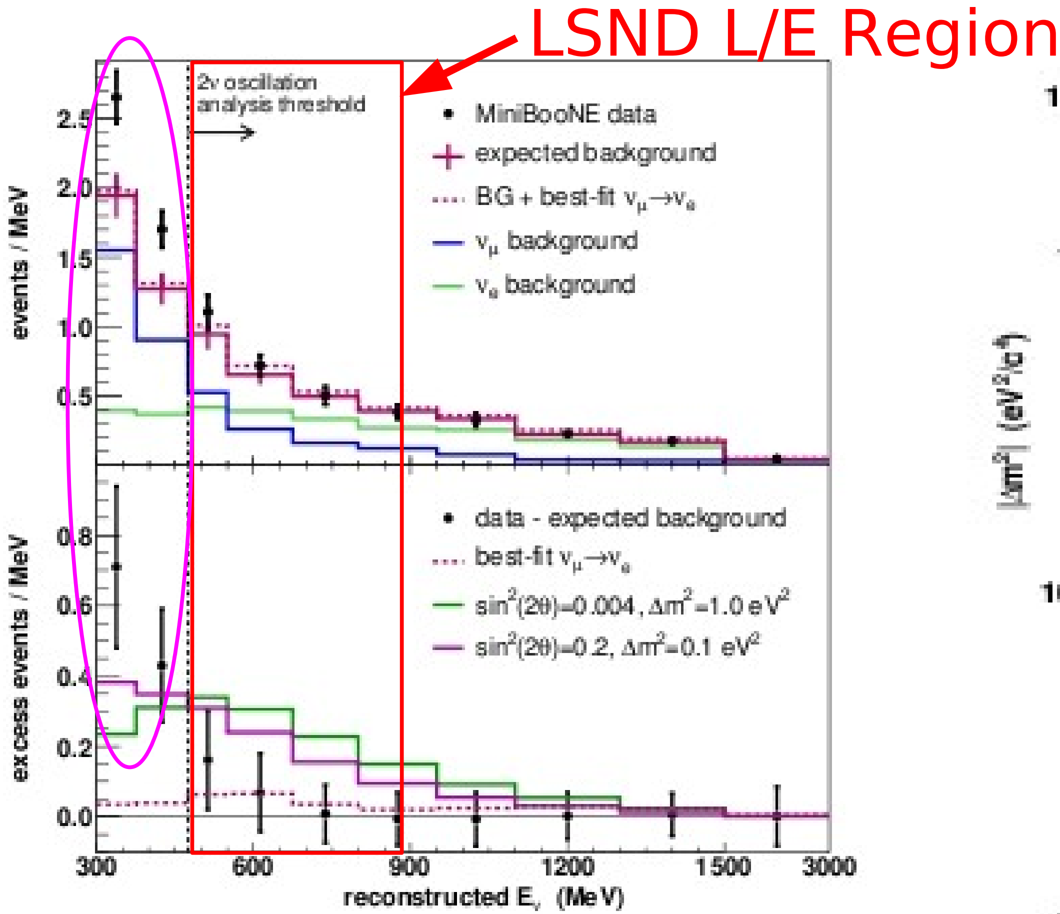


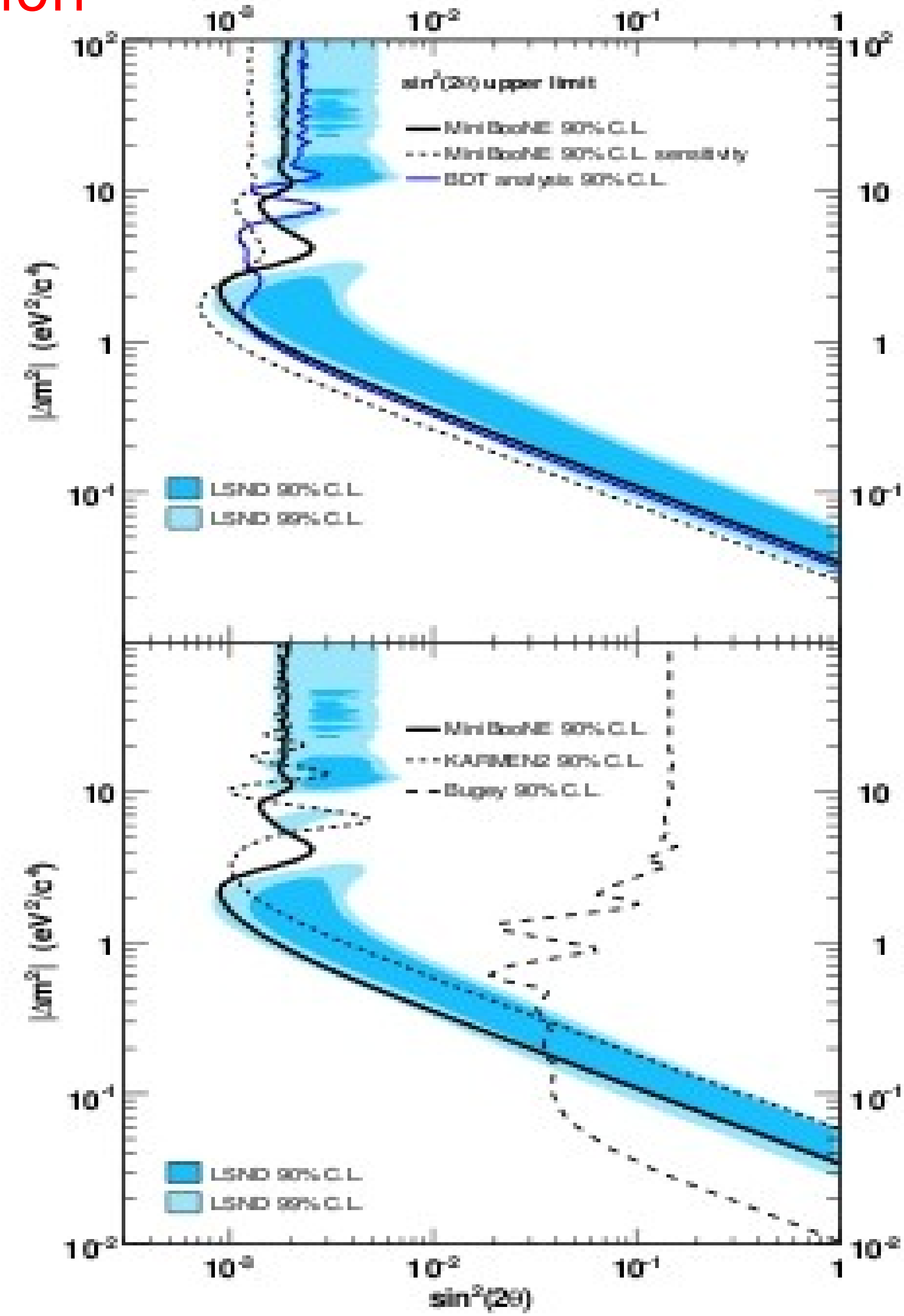
MiniBooNE

Currently running since 2002 at Fermilab



- Average neutrino energy ≈ 1 GeV
- L/E the same as LSND
- Same technology as LSND
- Different energy = different event types = different systematics
- Looks for $\nu_\mu \rightarrow \nu_e$ oscillations ← $= \overline{\nu}_e \rightarrow \overline{\nu}_\mu$ if CPT symmetry holds



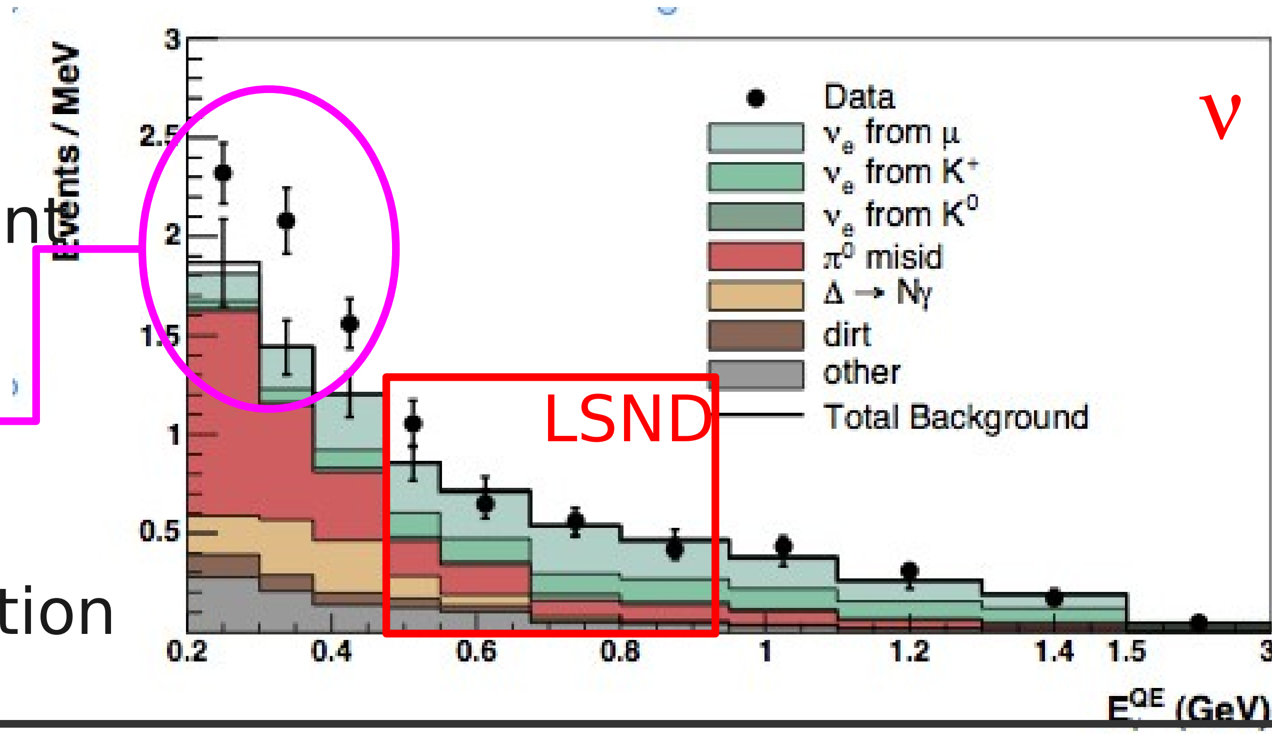


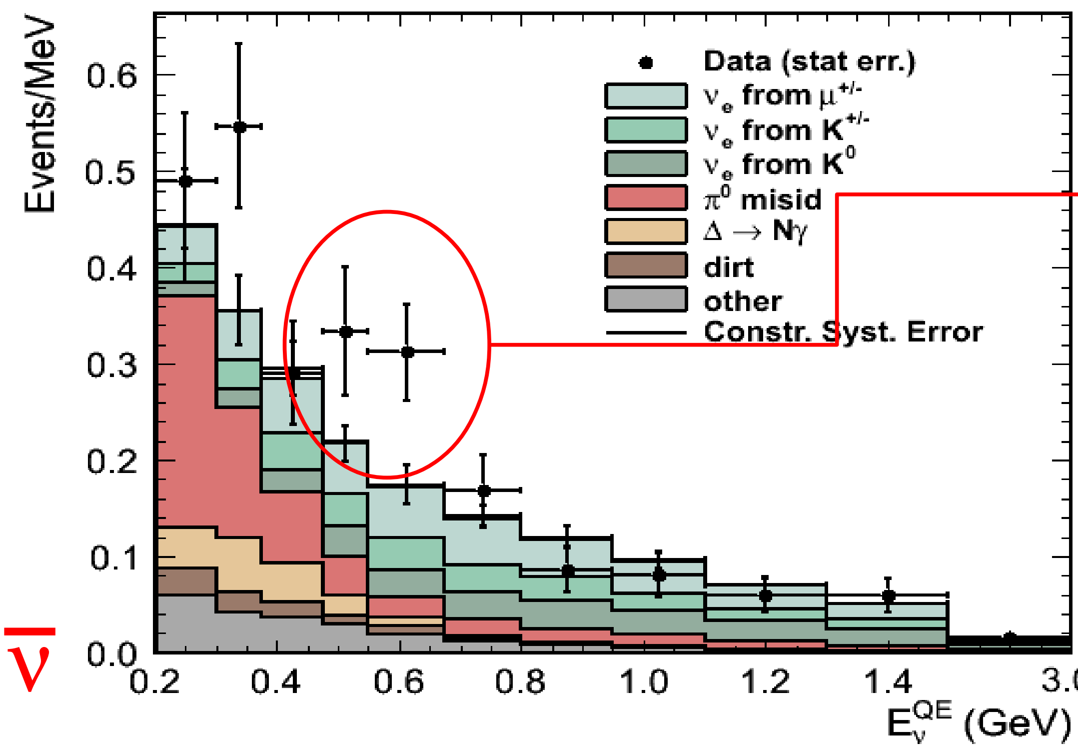
- 2009 analysis
- No excess of ν_e events in signal region (E>450 MeV)
- Unknown excess of events at low energy

New analysis in 2010, with better background treatment

excess still there for neutrinos at 3 σ

But not LSND oscillation

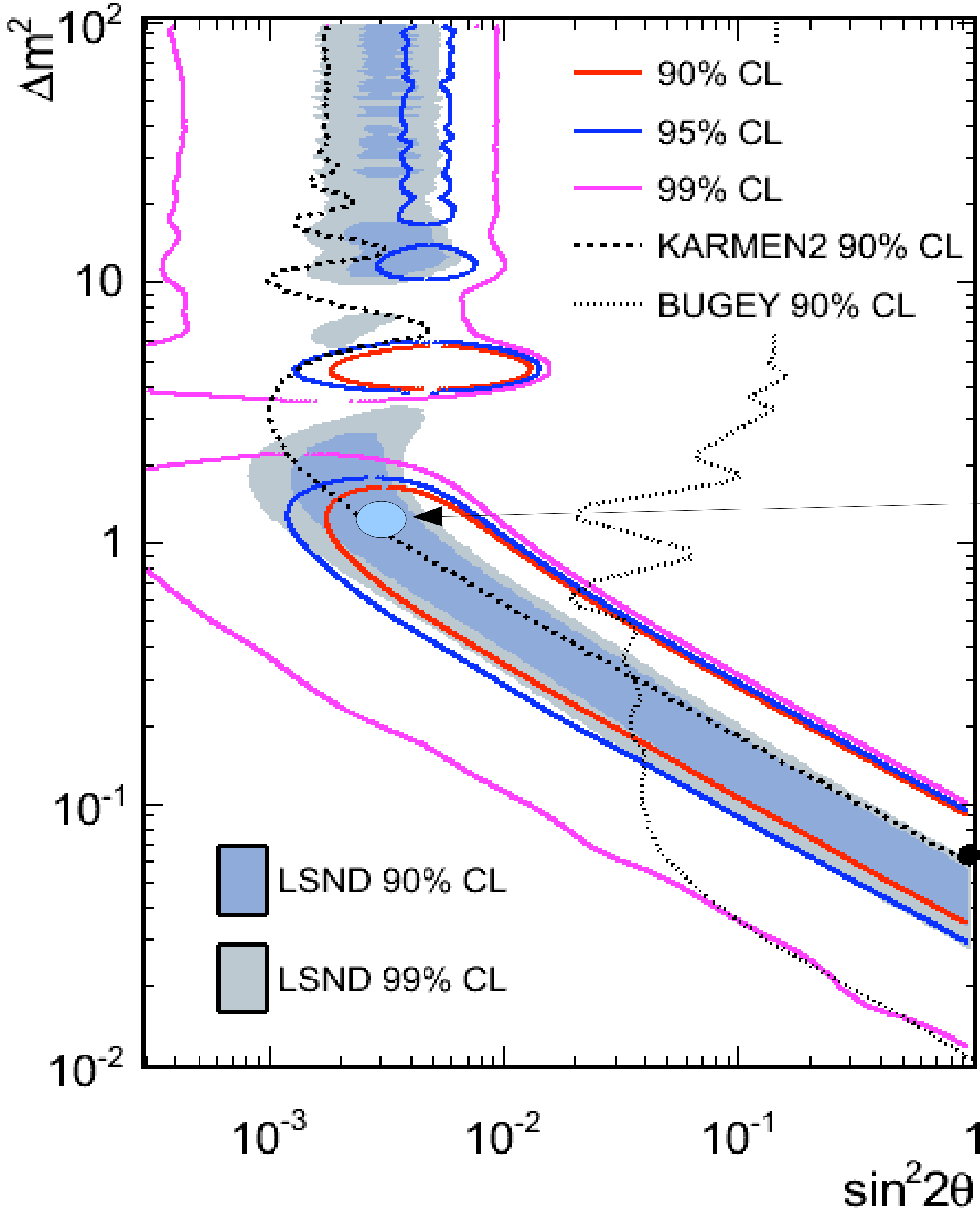




But there is a possible signal for antineutrino running

But only about 1.3 σ significance

Very small excess below 475 MeV



No oscillation excluded at 99% confidence

LSND

$\left(0.064\, eV^2, 0.96\right)$

Summary

- LSND reports a 3 σ excess of antineutrino events probing a $\Delta m^2 \approx 1.0$ eV^2

- miniBooNE reports a 1.5 σ excess of antineutrino events probing a $\Delta m^2 \approx 1.0$ eV^2

- miniBooNE reports a 3 σ excess of neutrino events probing a $\Delta m^2 \approx 0.3$ eV^2

- Antineutrino result suggests the existence of at least one sterile (remember the Z^0 result - we know that there are 3 active light neutrinos) neutrino taking part in the oscillation process

- Neutrino result can only be modeled (badly) by an extra two sterile neutrinos plus significant CP violation

Decaying sterile neutrinos?

Lorentz violation?

CPT Violation?

Extra dimensions?

No bleedin' idea

Wait for more data

3-Neutrino Mixing

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric sector

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

$$\theta_{e\mu} = 45.0^\circ \pm 2.4^\circ$$

$$\Delta m_{23}^2 = |2.8 \times 10^{-3}| eV^2$$

13 Sector

Link between solar and atmos. Sector

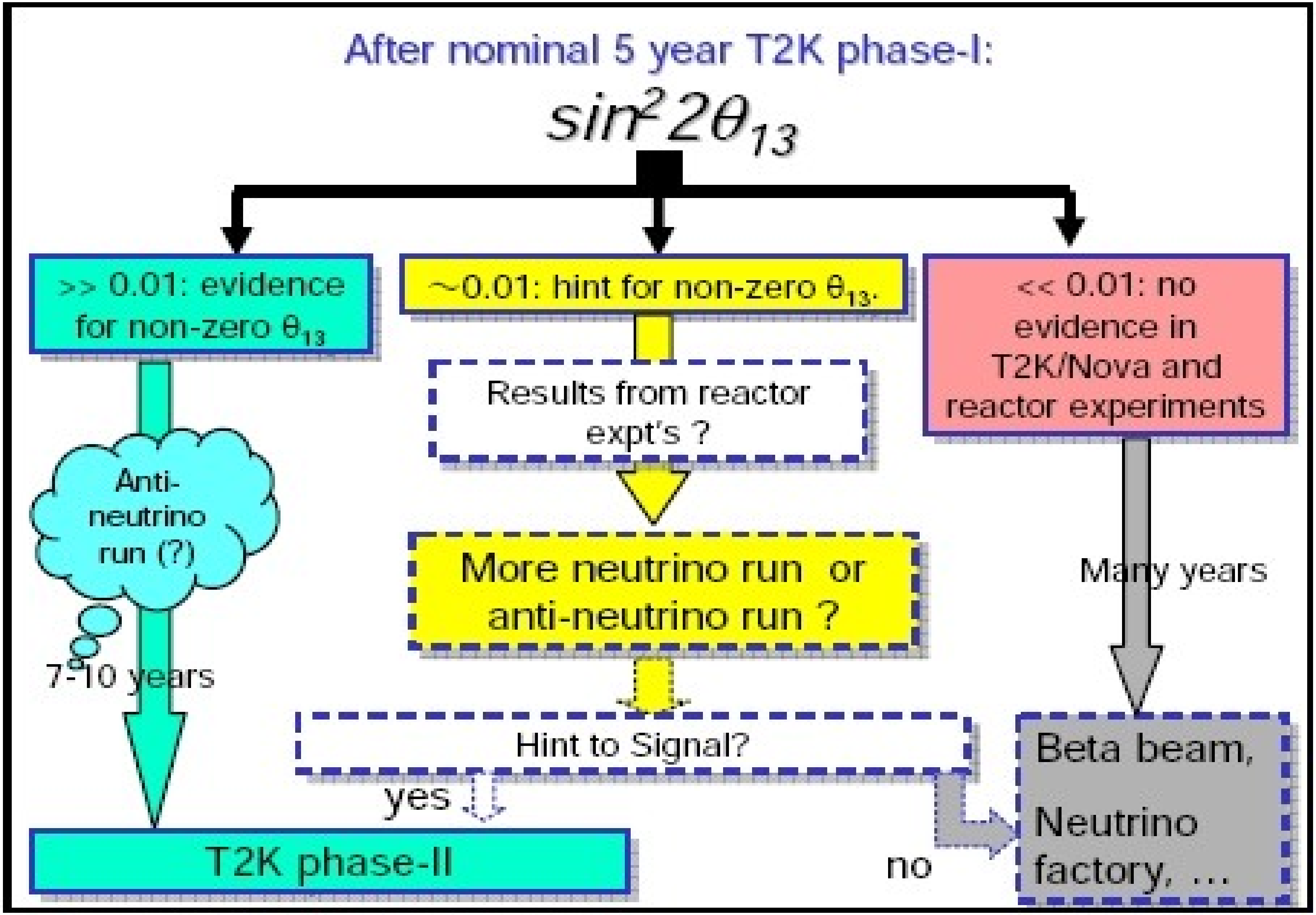
$$\theta_{13} < 10^\circ$$

Solar sector

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

$$\theta_{e\mu} = 32.5^\circ \pm 2.4^\circ$$

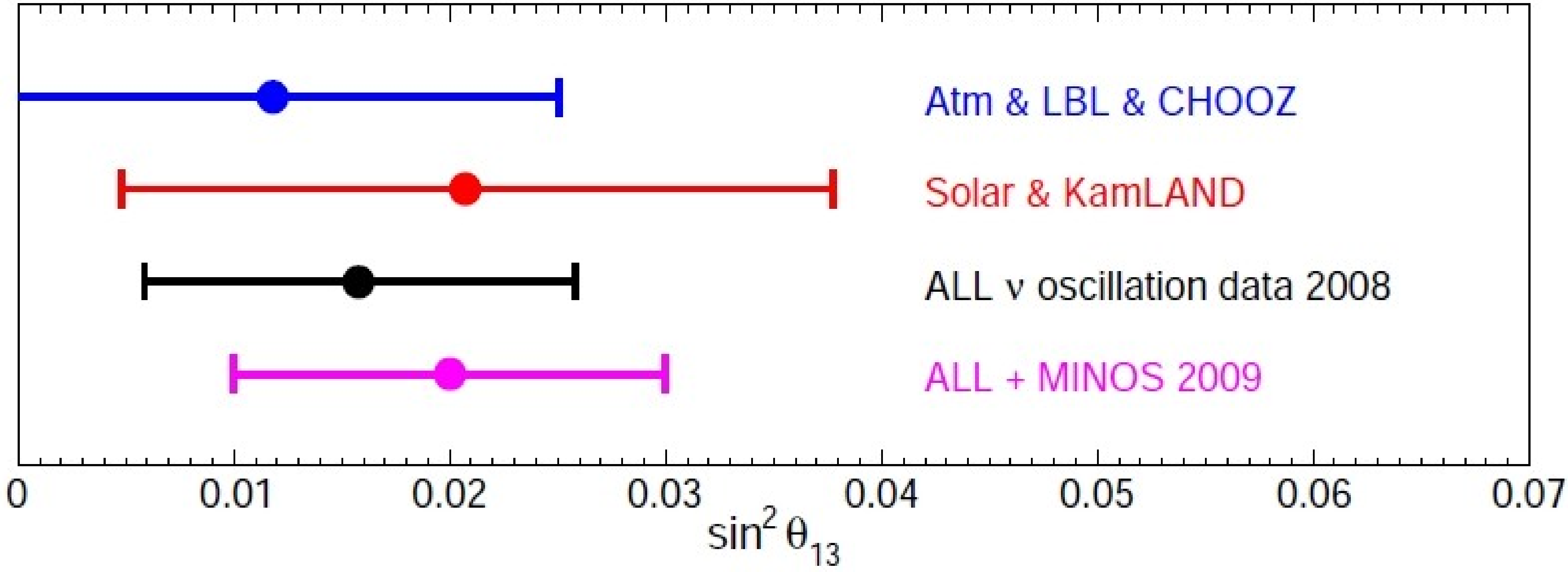
$$\Delta m_{12}^2 = +7.1 \times 10^{-5} eV^2$$



θ_{13} determines the next 15-30 years or so of the field

How large is it?

Fogli et al -
arXiv:0905.3549



$$\sin^2(\theta_{13}) = 0.02 \pm 0.01 \Rightarrow \theta_{13} = 8^o \pm 3^o$$ CHOOZ limit : $\theta_{13} < 10^o$

Real or accidental? Need more data...

How do we get to θ_{13}?

$\nu_\mu \rightarrow \nu_e$ oscillations with atmospheric L/E

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

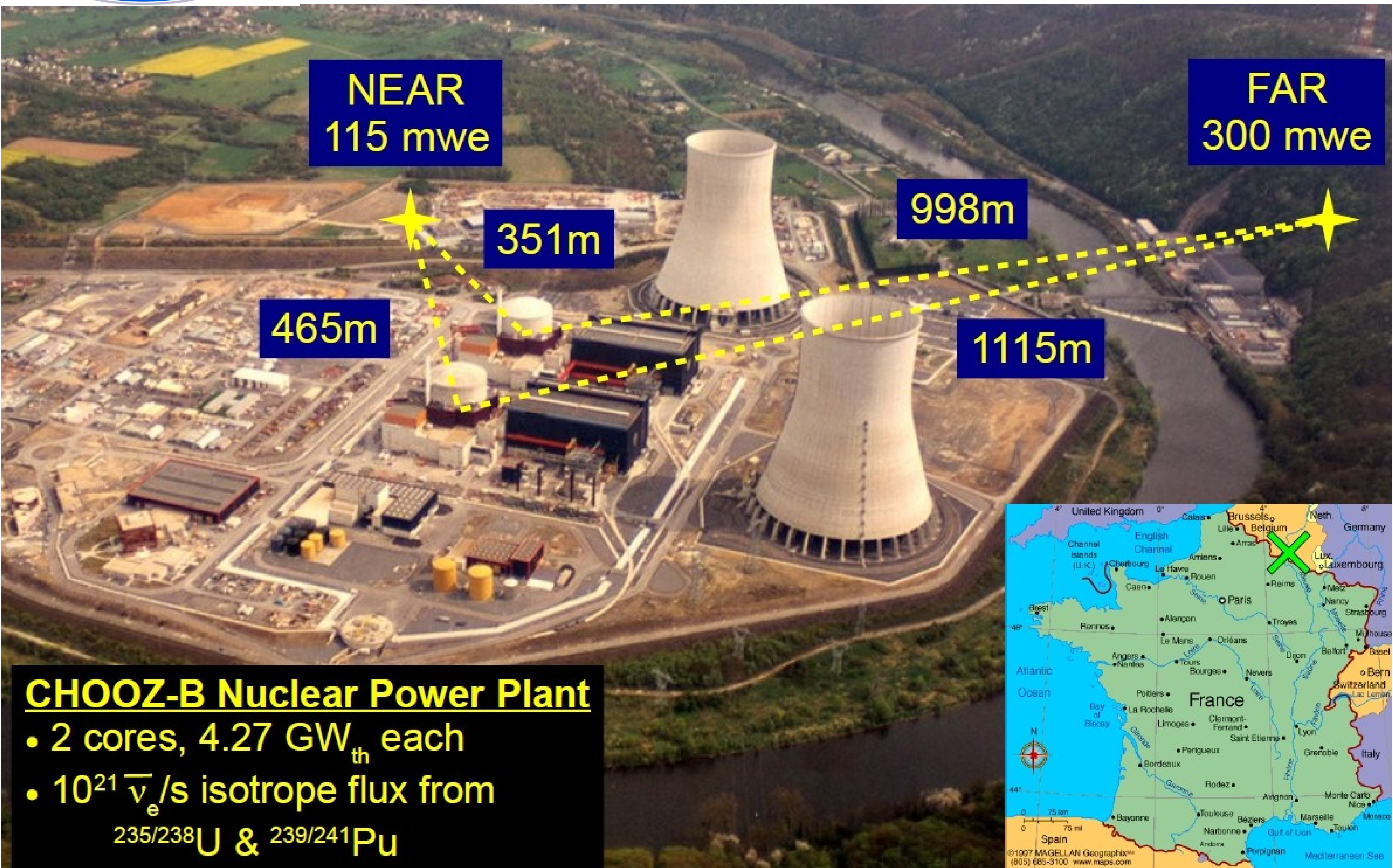
$\nu_e \rightarrow \nu_x$ disappearance oscillations with atmospheric L/E

$$P(\nu_e \rightarrow \nu_x) = \sin^2(2\theta_{13}) \sin^2(1.27 \Delta m^2_{23} \frac{L}{E})$$

$\overline{\nu}_e \rightarrow \overline{\nu}_x$ disappearance oscillations with atmospheric L/E

$$P(\nu_e \rightarrow \nu_x) \overset{\hat{C}\hat{P}\hat{T}}{=} P(\overline{\nu}_e \rightarrow \overline{\nu}_x)$$

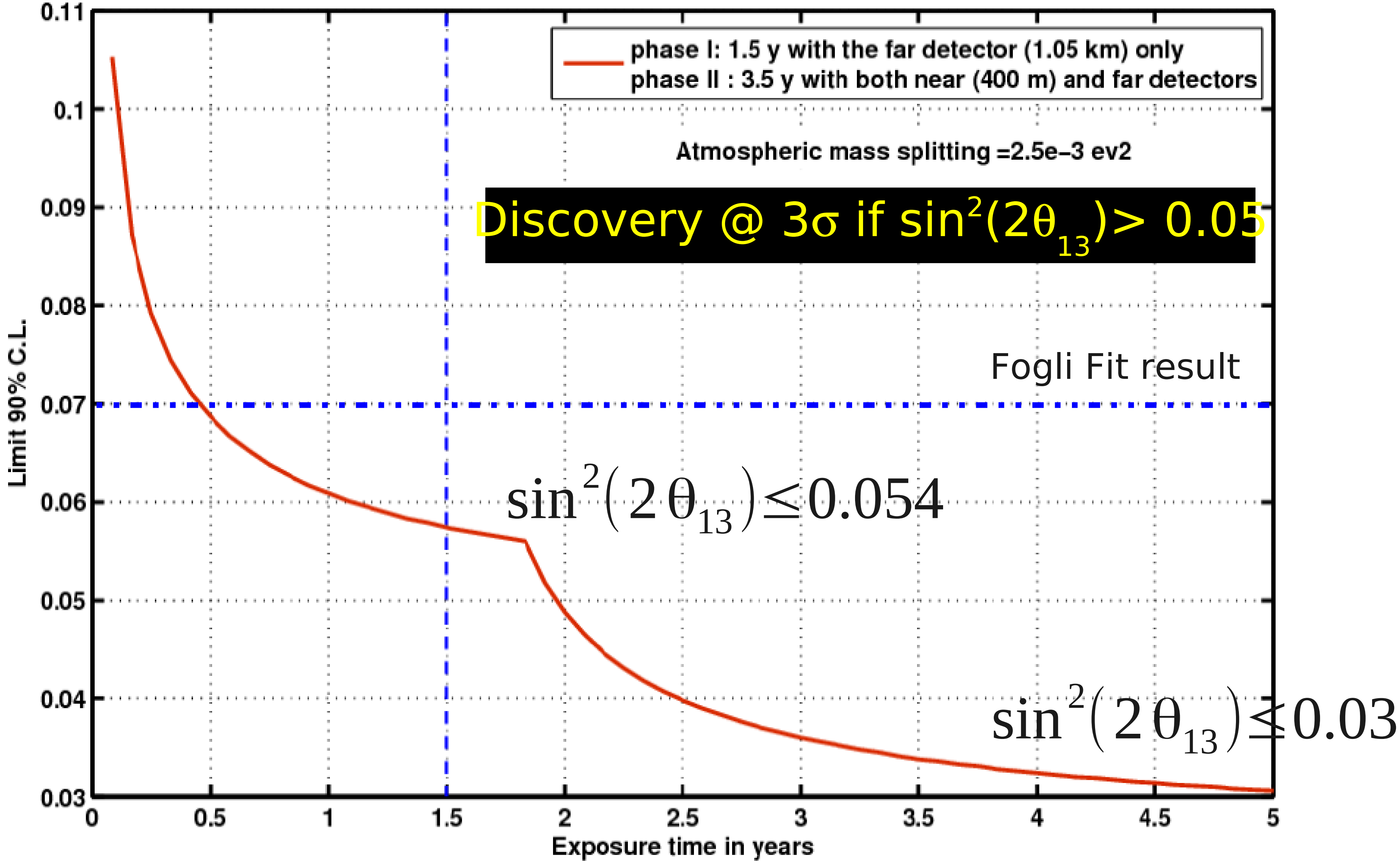
The experiment



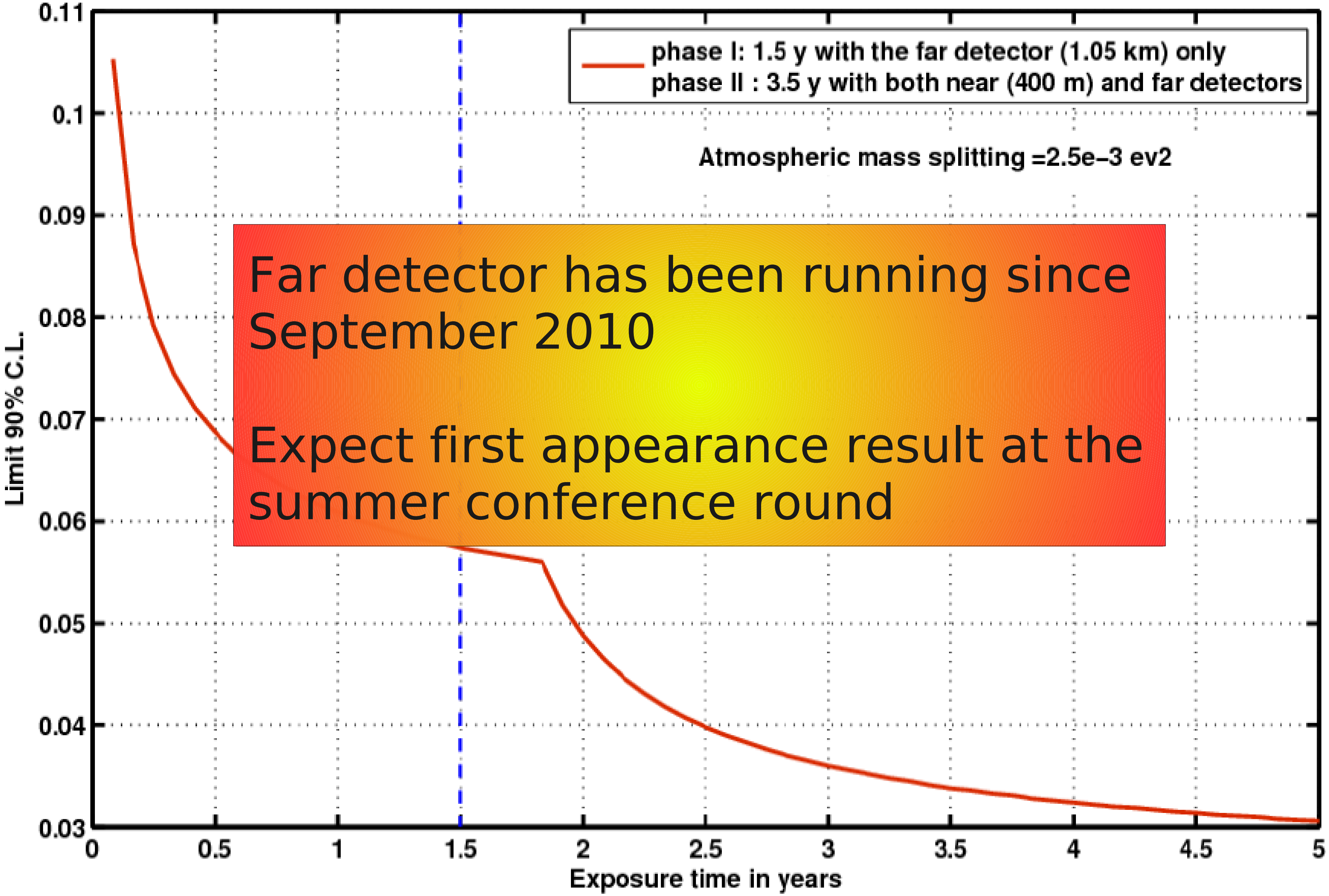
CHOOZ-B Nuclear Power Plant

- 2 cores, 4.27 GW_{th} each
- 10^{21} $\overline{\nu}_e$/s isotrope flux from $^{235/238}U$ & $^{239/241}Pu$

Sensitivity



Sensitivity



Far detector has been running since September 2010

Expect first appearance result at the summer conference round

How do we get to θ_{13}?

$\nu_\mu \rightarrow \nu_e$ oscillations with atmospheric L/E

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

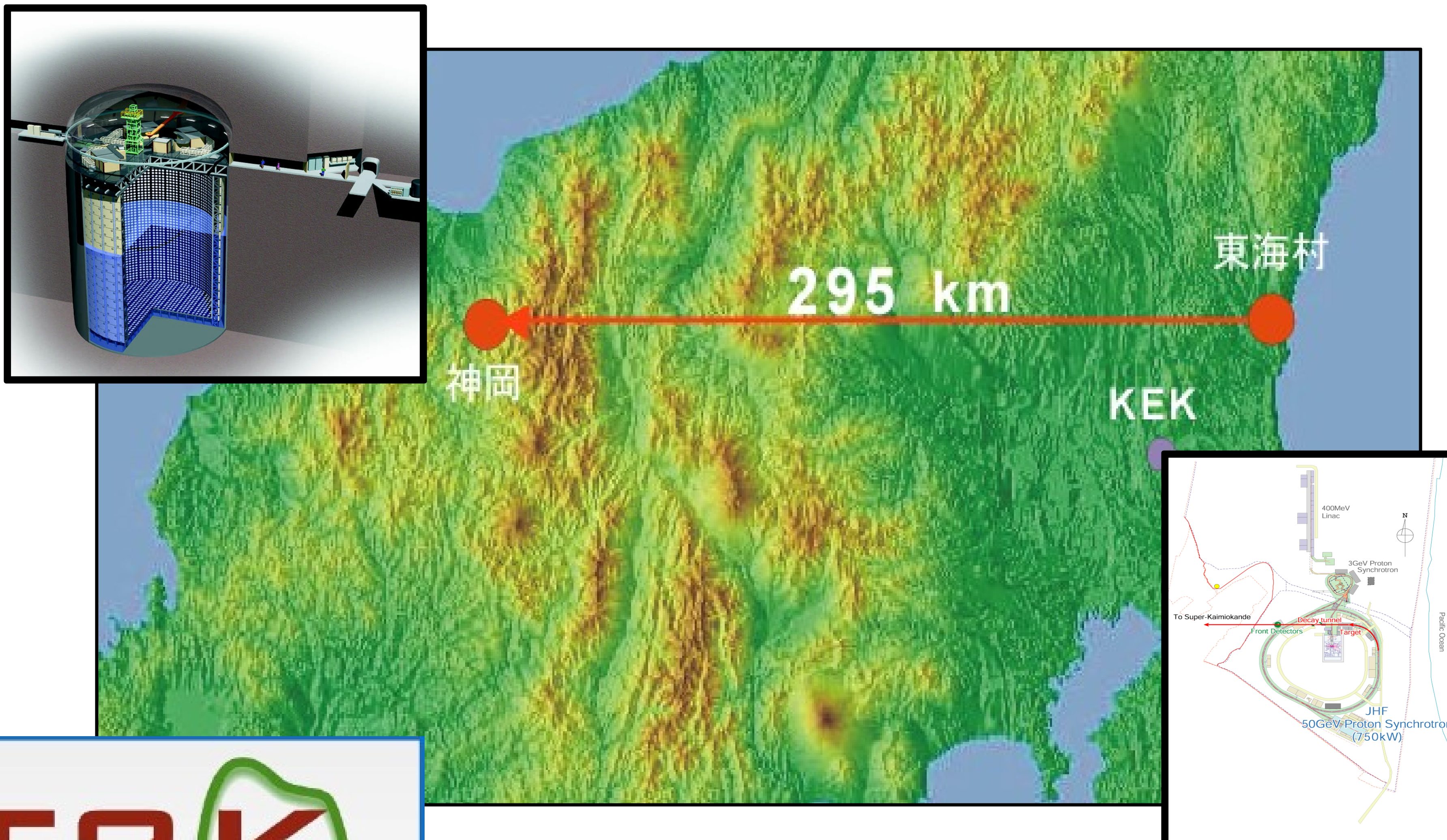
$\nu_e \rightarrow \nu_x$ disappearance oscillations with atmospheric L/E

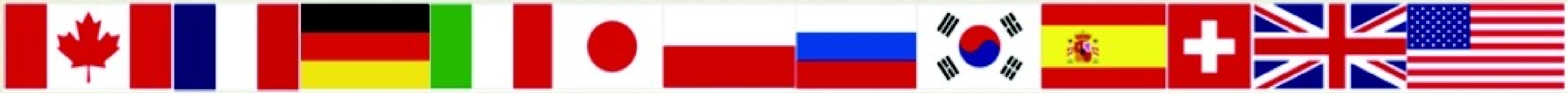
$$P(\nu_e \rightarrow \nu_x) = \sin^2 (2\theta_{13}) \sin^2 (1.27 \Delta m^2_{23} \frac{L}{E})$$

$\overline{\nu}_e \rightarrow \overline{\nu}_x$ disappearance oscillations with atmospheric L/E

$$P(\nu_e \rightarrow \nu_x) \overset{\hat{C}\hat{P}\hat{T}}{=} P(\overline{\nu}_e \rightarrow \overline{\nu}_x)$$

The T2K (Tokai-2-Kamioka) Experiment





~500 members, 61 Institutes, 12 countries

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U. B. Columbia
U. Regina
U. Toronto
U. Victoria
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
U. Aachen

Italy
INFN, U. Roma
INFN, U. Napoli
INFN, U. Padova
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Japan
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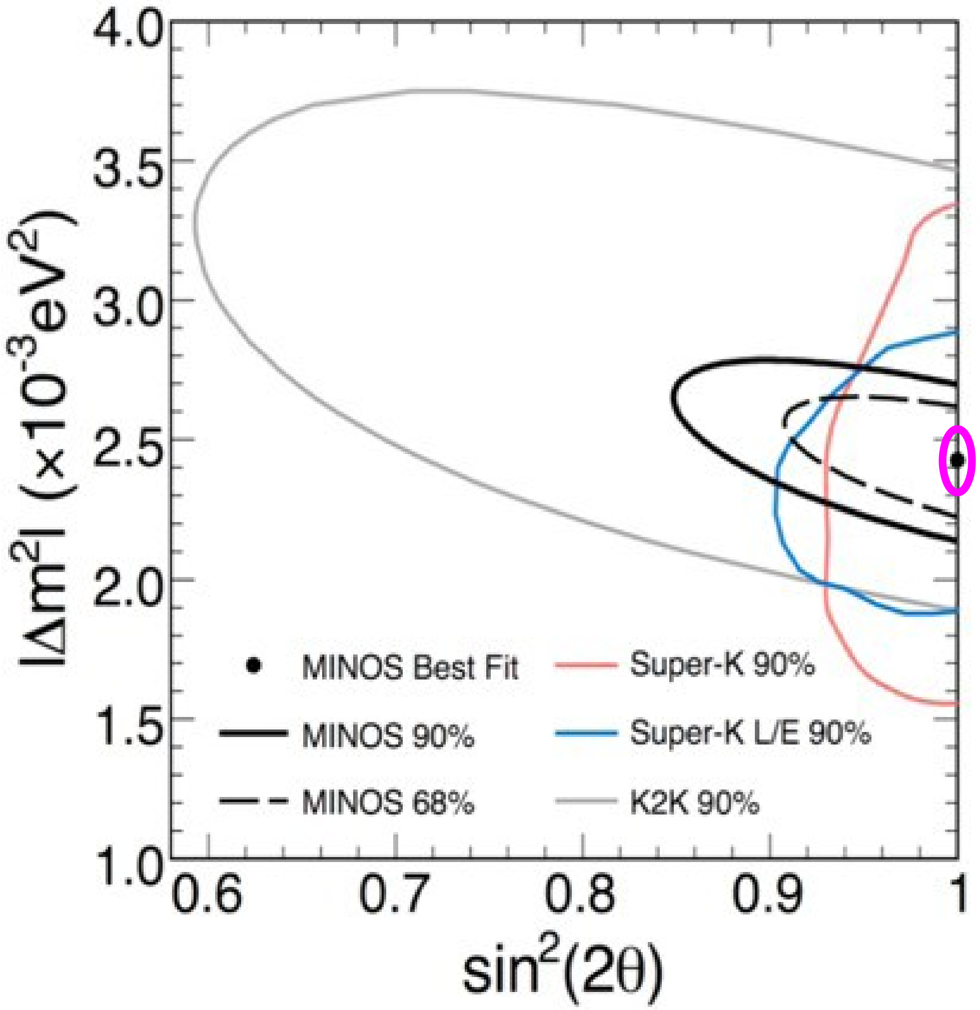
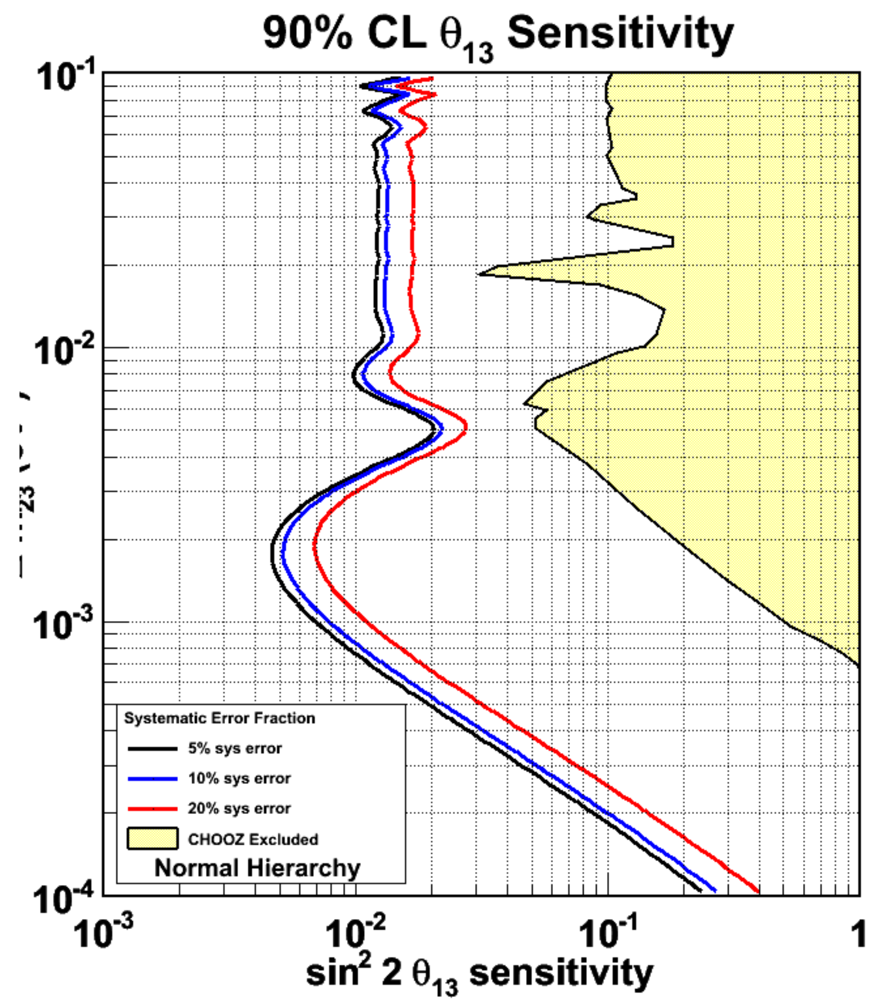
U. Washington

What can T2K do?



$$\delta\left(\sin^2\left(2\theta_{23}\right)\right) \sim 0.01$$
$$\delta\left(\Delta m_{23}^2\right) < 1\times10^{-4}\, eV^2$$

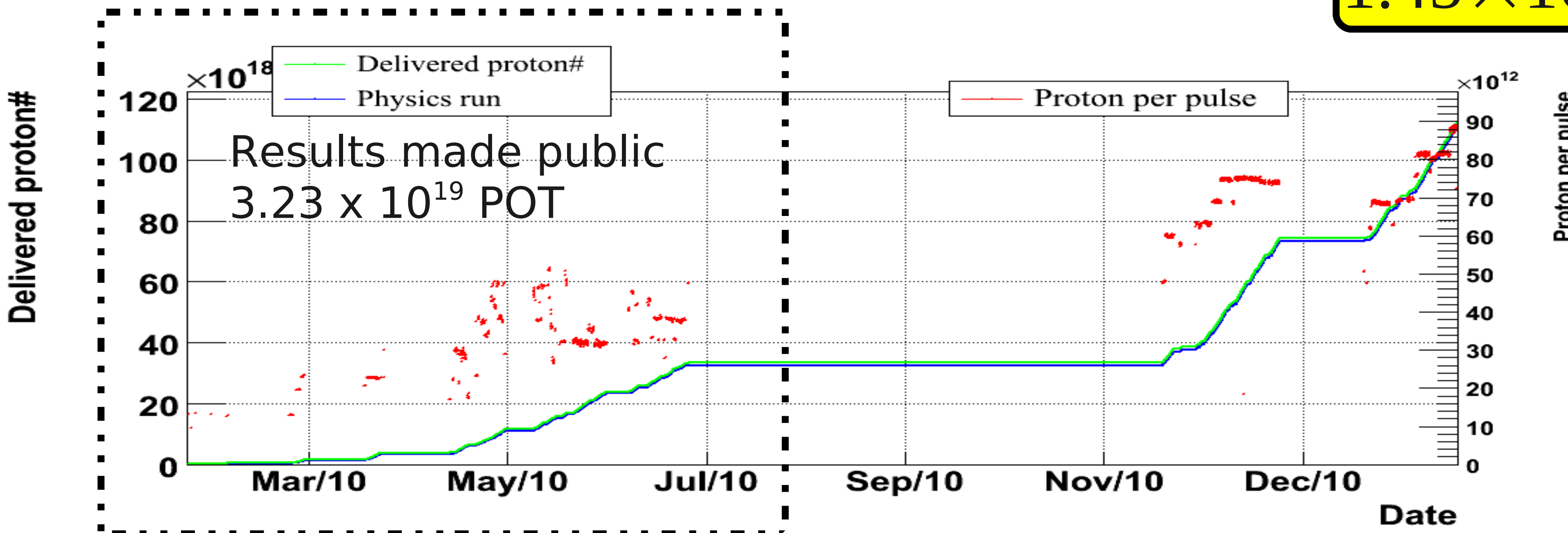
ν_e disappearance



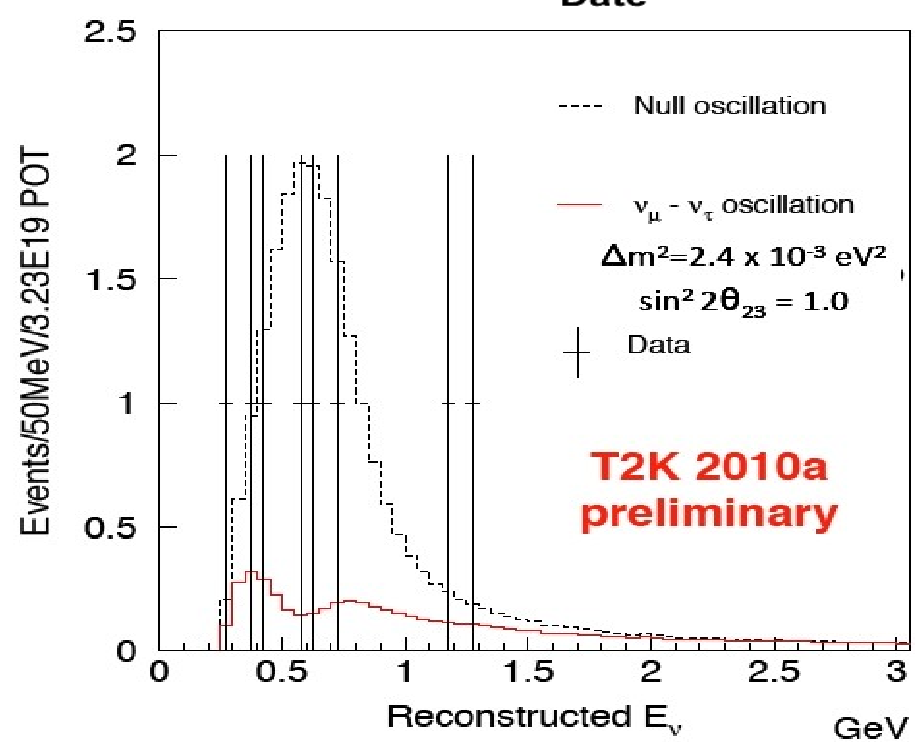
$\sin^2(2\theta_{13}) \sim 0.02$

Results to date

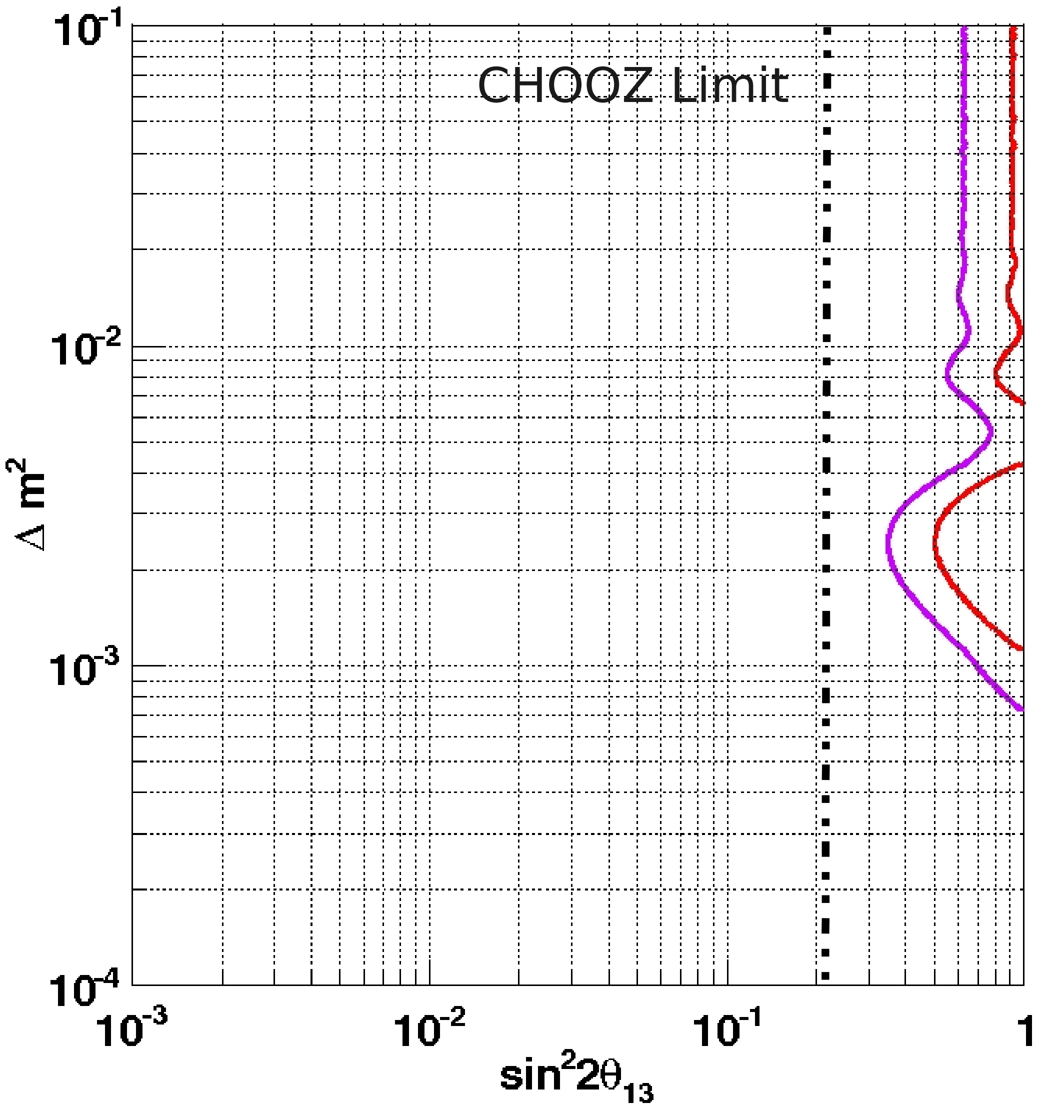
$1.45 \times 10^{20}\ POT$



- 8 n_{μ} events observed in SK
- 22.8 ± 1.3 events expected in the absence of oscillations
- 6.3 ± 1.0 events expected if
  - $\Delta m^2 = 2.4 \times 10^{-3}\ eV^2$
  - $\sin^2 2\theta_{23} = 1.0$



n_e Appearance



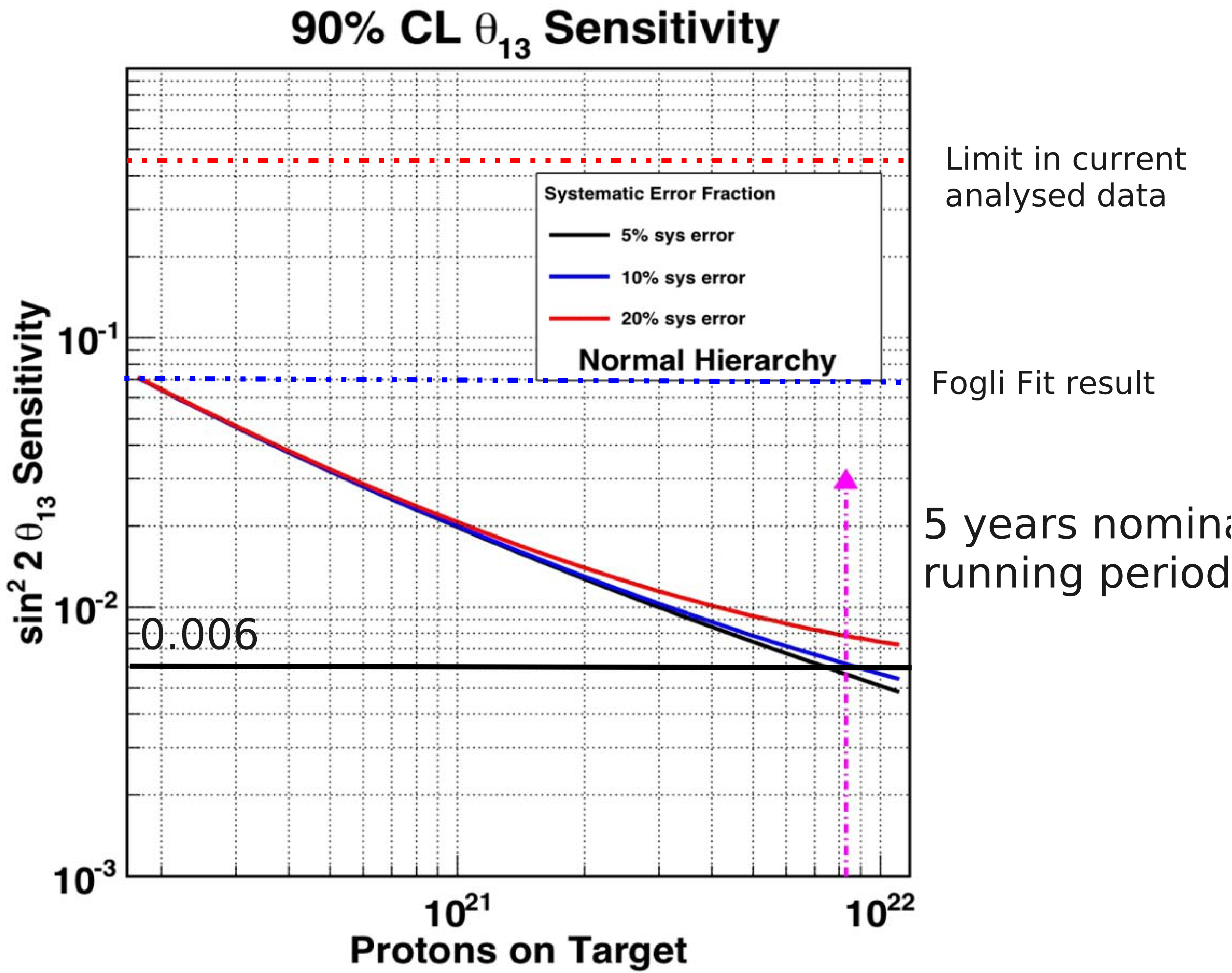
T2K-SK events	Data	MC		Acc. BG (12μs window)
		No oscillation	With oscillation and θ_{13}=0	
Fully-Contained	33	54.5	24.6	0.0094
Fiducial Volume, E_{vis} > 30MeV	23	36.8	16.7	0.0011
Single-ring e-like P_e>100MeV/c	2	1.5±0.7	1.3±0.6	-

$$\sin^2(2\theta_{13}) < 0.5 \, @ \, 90\ CL$$

$$\Delta m^2_{23} = 2.4 \times 10^{-3}\, eV^2$$

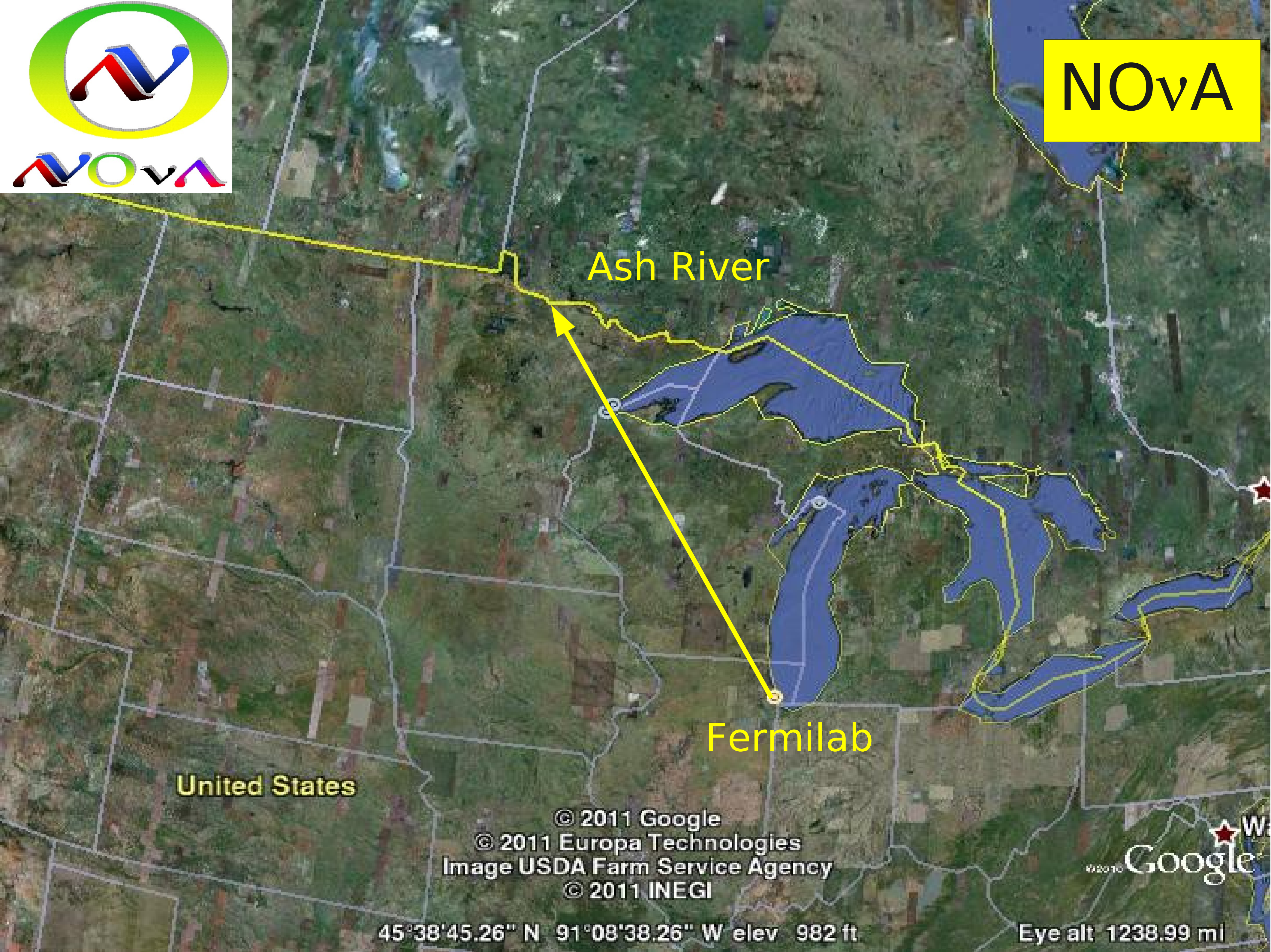
We have 4 times the amount of data released in the can which should push the limit down to about 0.1.

Expect release of this data by summer.


90% CL θ_{13} Sensitivity
Limit in current analysed data
Systematic Error Fraction
5% sys error
10% sys error
20% sys error
Normal Hierarchy
Fogli Fit result
5 years nomina
running period
0.006
$\sin^2 2\theta_{13}$ Sensitivity
10^{-1}
10^{-2}
10^{-3}
10^{21}
10^{22}
Protons on Target

Earthquake

- Subsidence at the LINAC building
- But the near detector seems to be superficially OK
- The accelerator magnets may need realignment but the ring seems to be also OK
- Japanese build for earthquakes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Ash River
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United States
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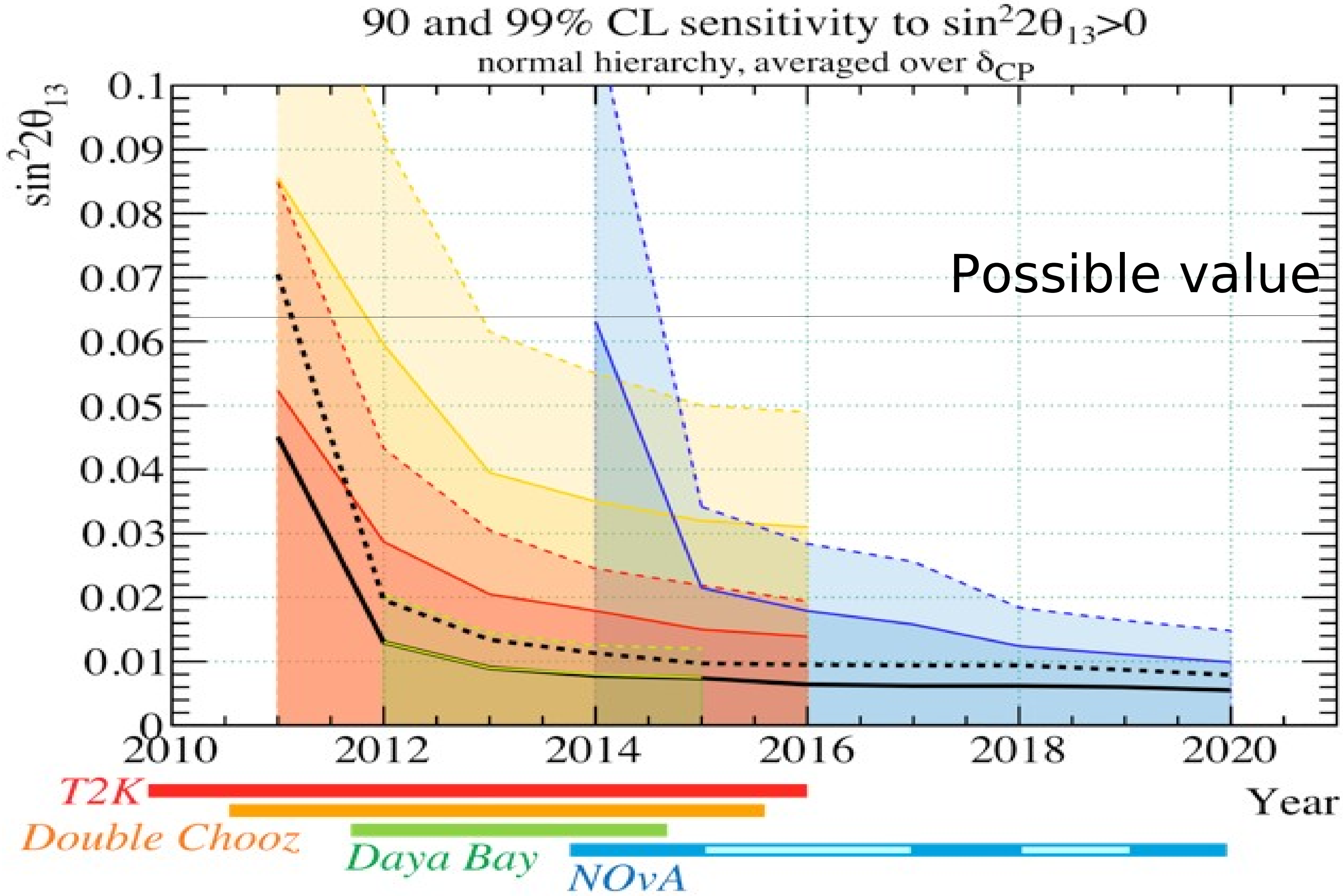
Image USDA Farm Service Agency
© 2011 INEGI
45°38'45.26" N 91°08'38.26" W elev 982 ft
Eye alt 1238.99 mi
Google



Only NOvA can measure matter effect to get the mass heirarchy.

Probably need a combination of NOvA, T2K and the reactors to fully disentangle the parameter space.

Summary - Near Future

- If θ_{13} is large (> 6^o) we should have an indication and
  possibly a measurement by the end of this year
- If θ_{13} is > 2^o we should know in 3 years
- If θ_{13} is less than 2^o we will have to think about what to do

Summary - Near Future

- If θ_{13} is large (> 6^o) we should have an indication and
  possibly a measurement by the end of this year
- If θ_{13} is > 2^o we should know in 3 years
- If θ_{13} is less than 2^o we will have to think about what to do

Eu possible Strategies for Future Accelerator υ Physics

NEu2012 Network

Neutrinos for Europe in2012

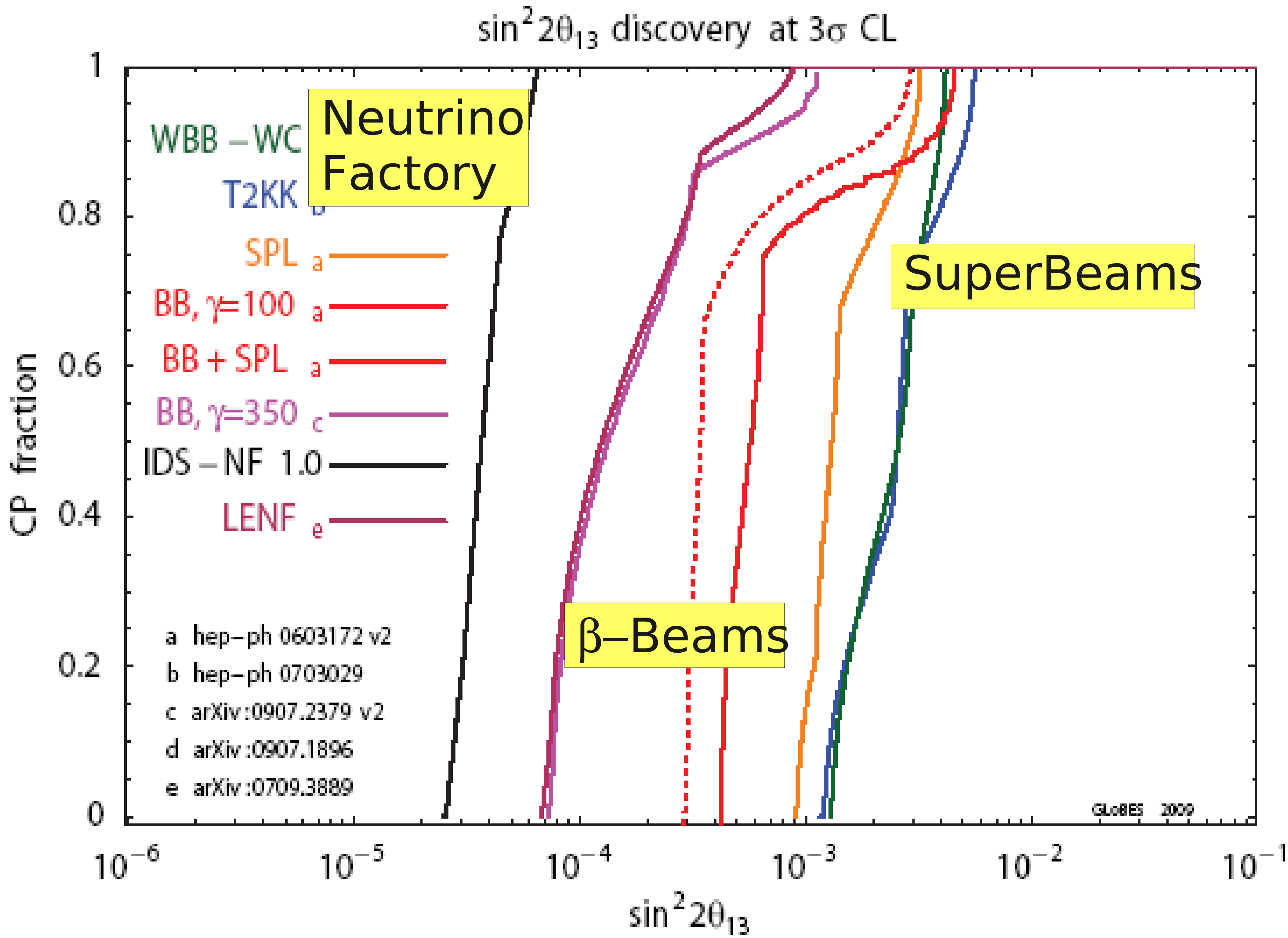
EUROnu Design Study (beams)

LAGUNA Design Study (sites)

CERN Council Strategy Document dixit, July 2006

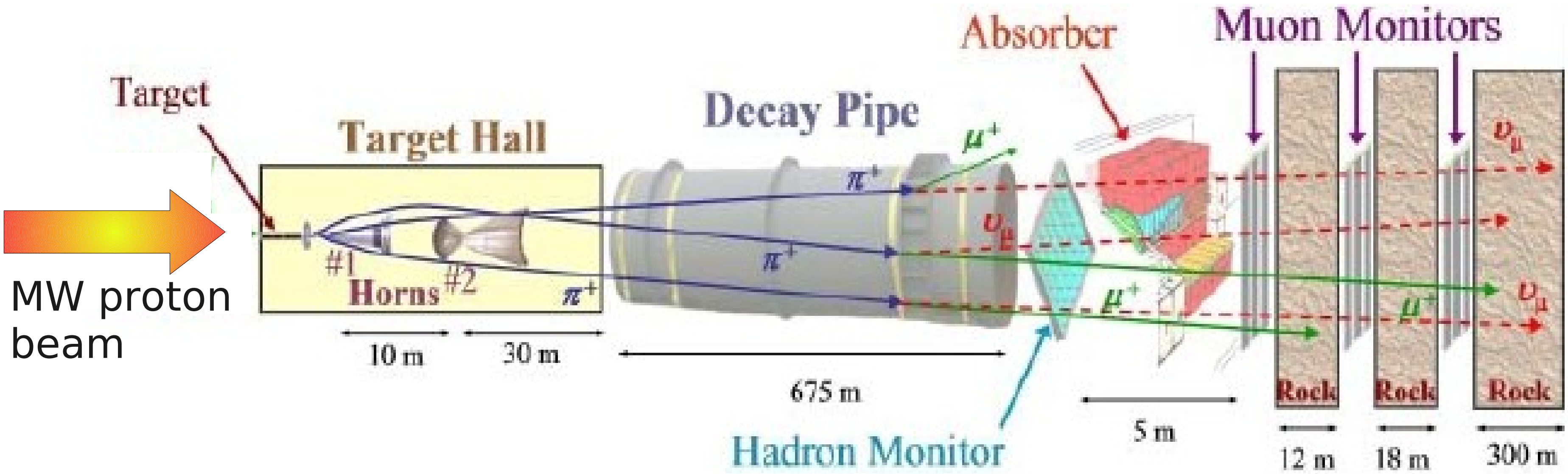
...... *be in position to define the optimal neutrino program*
.... *in around 2012*

Including Neutrino Factory International Design Study



sin²2θ13 discovery at 3σ CL
Neutrino Factory
SuperBeams
β–Beams
WBB – WC
T2KK b
SPL a
BB, γ=100 a
BB + SPL a
BB, γ=350 c
IDS – NF 1.0
LENF e
a hep–ph 0603172 v2
b hep–ph 0703029
c arXiv:0907.2379 v2
d arXiv:0907.1896
e arXiv:0709.3889
GLoBES 2009
CP fraction
1
0.8
0.6
0.4
0.2
0
10⁻⁶
10⁻⁵
10⁻⁴
10⁻³
10⁻²
10⁻¹
sin²2θ13

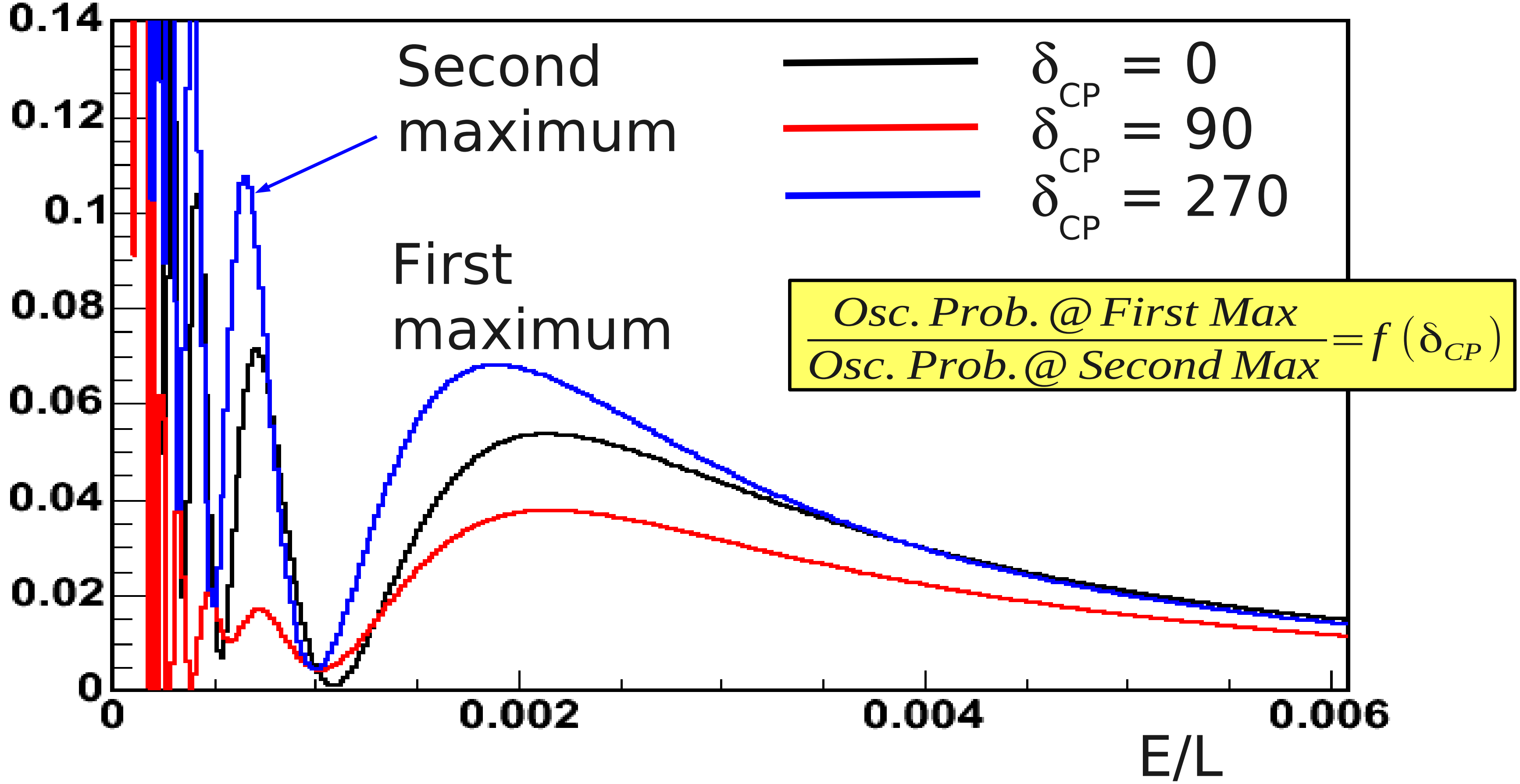
SuperBeams



- Conventional neutrino beam with a MW proton beam (T2K has the most intense beam - 750 kW)
- Challenge to proton source (so-called proton driver)
- Challenge to the targetry - MW pulse would vaporise the target

CP Violation redux

$\nu_\mu \rightarrow \nu_e$ oscillation probability



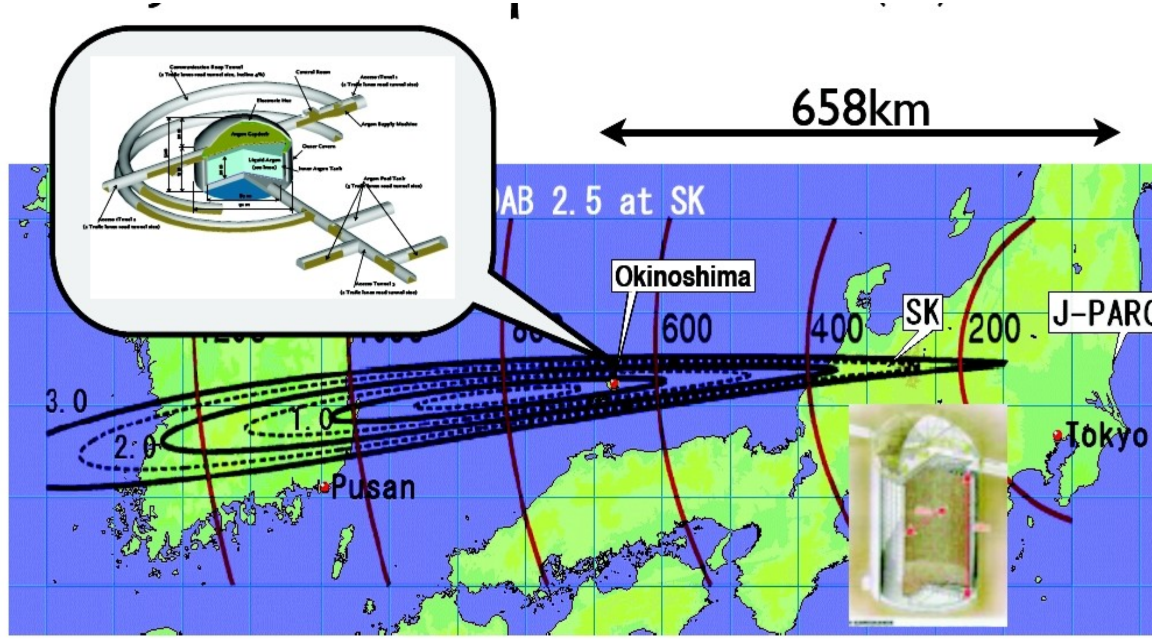
Could study CPV using a superbeam and an experiment sensitive to both maxima using only a neutrino beam.

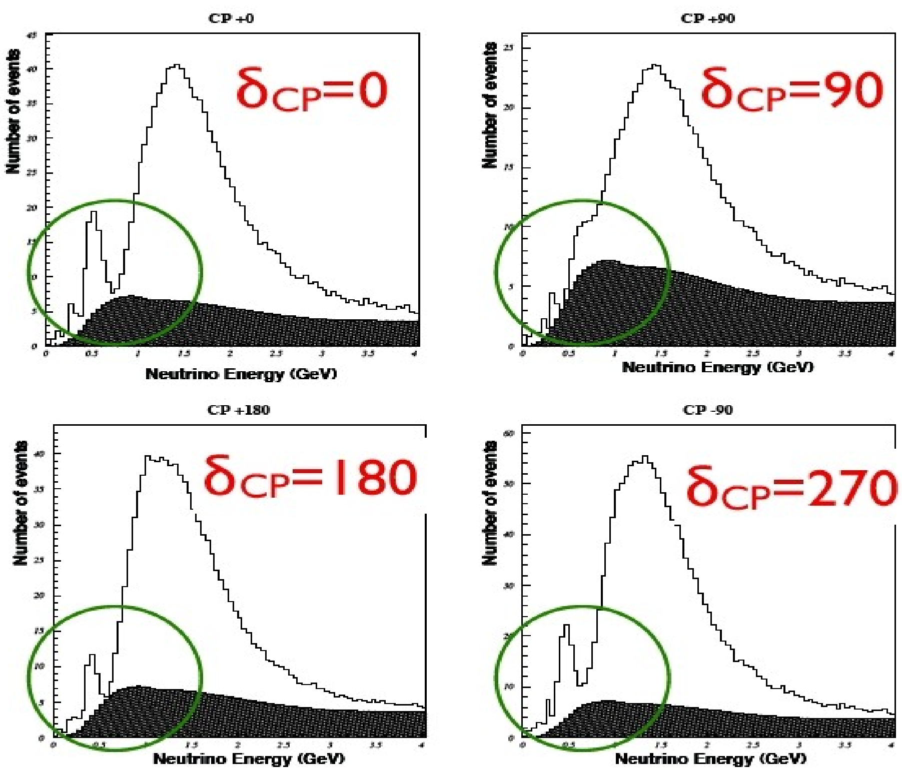
Future VLBL Experiments

High power beam and very large detectors at the second maxi

	current	*plan*	*under discussion*
J-PARC/KEK	~0.05MW	0.75 MW	4MW
	T2K (θ_{13})		JPARC-to-somewhere (CPV, hierarchy, θ_{13})
	22.5kton W.C. (SK)		540kton W.C. or 100kton LArTPC
FNAL	~0.3MW NuMI/MINOS (ν_μ disapp.)	0.7 MW NOvA (θ_{13}, hierarchy) 14kton Liquid Scint.	~2MW (Project-X) FNAL-to-DUSEL (CPV, hierarchy, θ_{13}) ~300kton W.C. and/or ~50kton LArTPC
CERN	~0.3MW CNGS/OPERA (ν_τ app.)	0.4MW	2MW(HP-PS2) ~ 4MW(HP-SPL) 130~2300km site (CPV, hierarchy, θ_{13}) ~500kton W.C. or ~100kton LArTPC or ~50kton LiquidScint.

OA Beam
L = 660 km
500 MeV @ 2^{nd} Max





$\sin^2 2\theta_{13}$=0.03 & varying CP phase

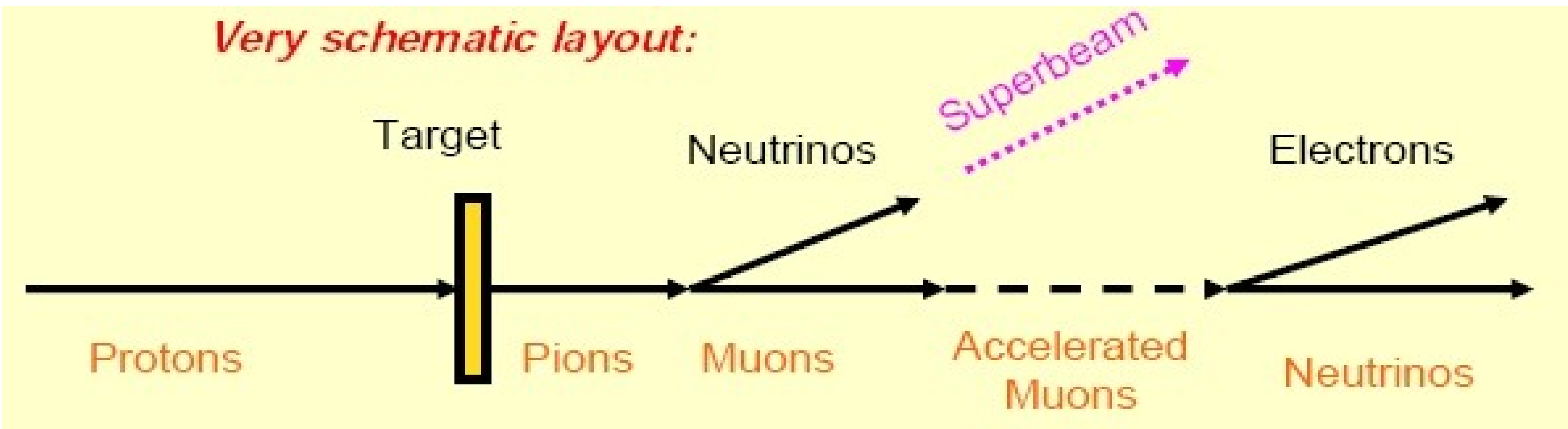
- ν only run
- Can detect CP Violation at 3 sigma significance if $\sin^2(2\theta_{13})>0.02$

SuperBeam Summary

- Future Superbeam facilities will look for CPV and mass heirarchy measurements using Very Long Baseline experiments
- Could be built now - upgrade of the existing beams (J-PARC, NUMI) and new main detector
- Competitive CPV discovery potential down to $\theta_{13} > 2$ degrees
- a lot of R&D already done. Detector is on the cutting edge, but could be build soon with more work.
- Cost on the order of £4 million.
- What we'll go for if θ_{13} is large.

Neutrino Factories

In a conventional beam the neutrinos from pion decay
In a neutrino factory the neutrinos come from muon decay

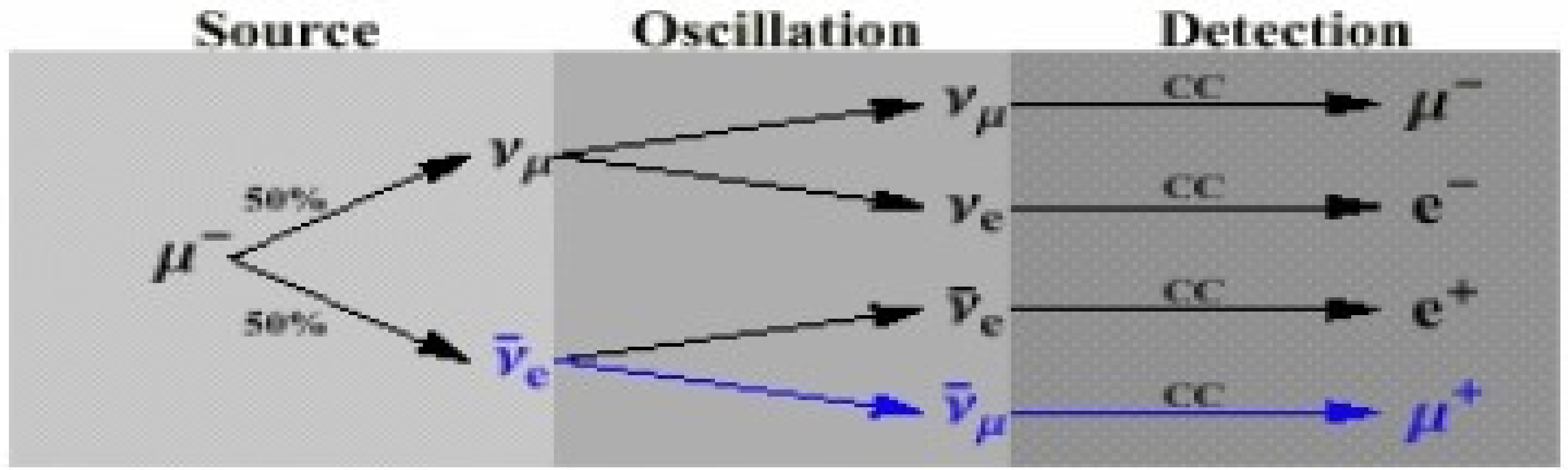


$$\mu^- \rightarrow \nu_\mu \overline{\nu}_e e^-$$

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

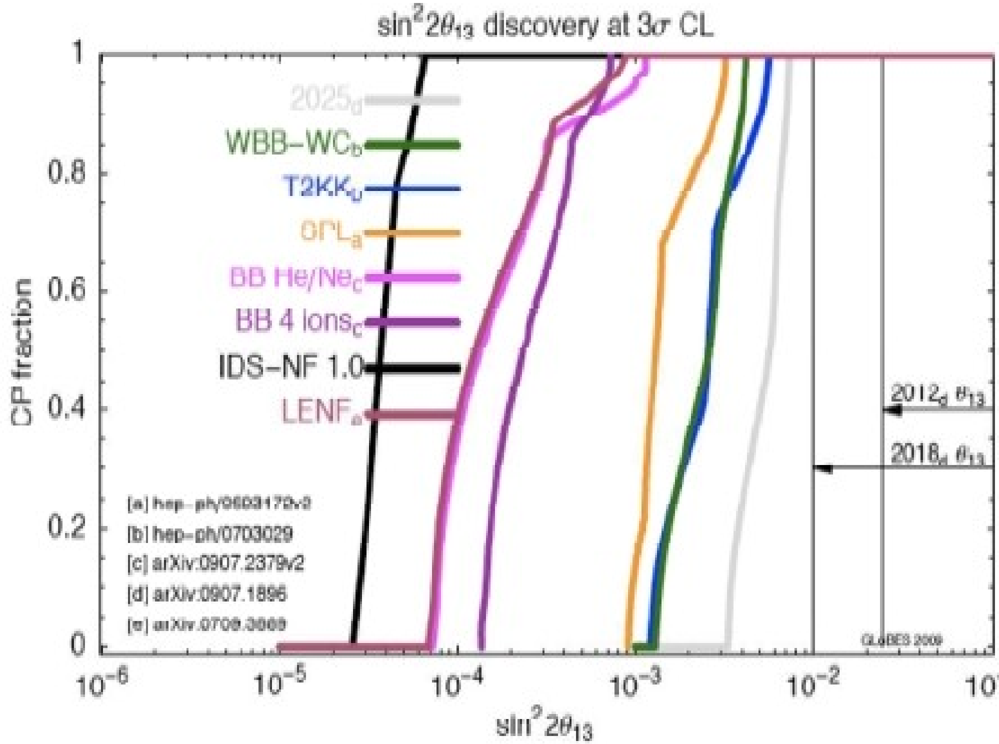
Beam is very clean
50% n_μ, $\overline{n}_e$
Extremely high flux
Precise and predictable energy spectrum

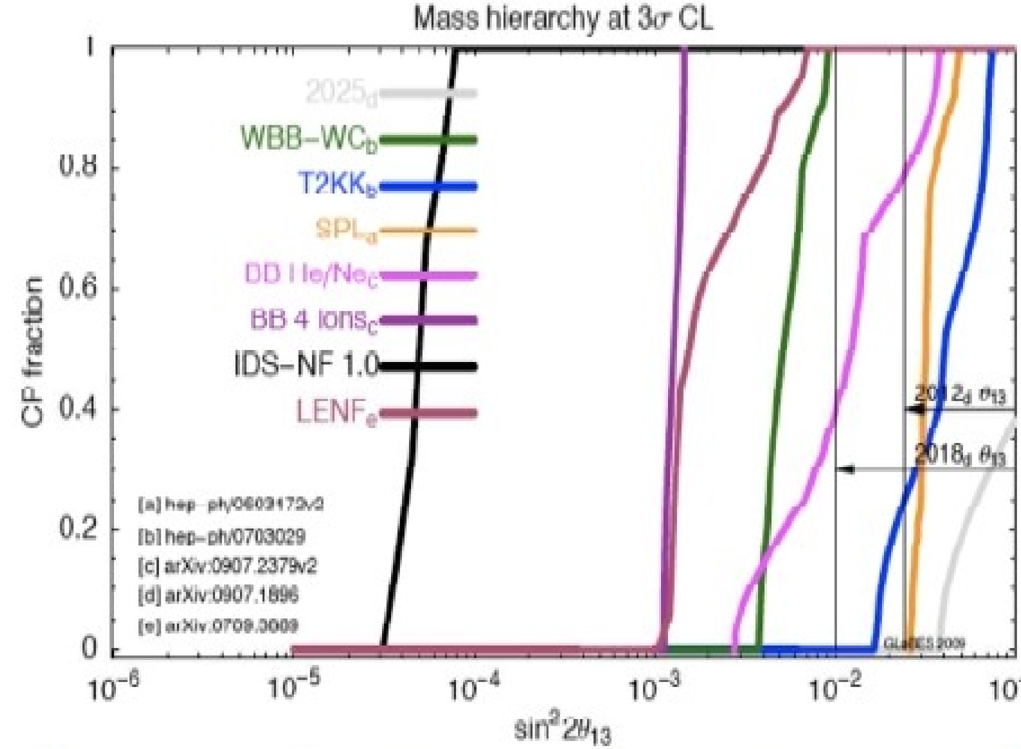
Neutrino Factory Oscillation

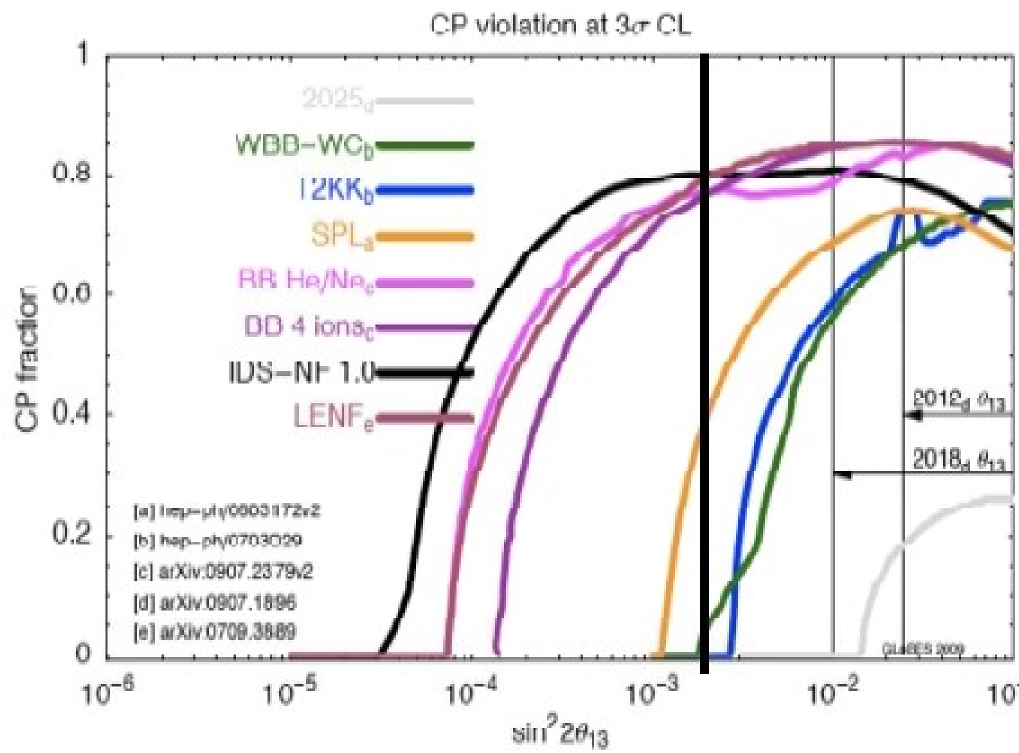


Golden channel

- No background from other neutrino flavours
- But this requires the charge of the final state lepton to be known
- Need to magnetise the far detector

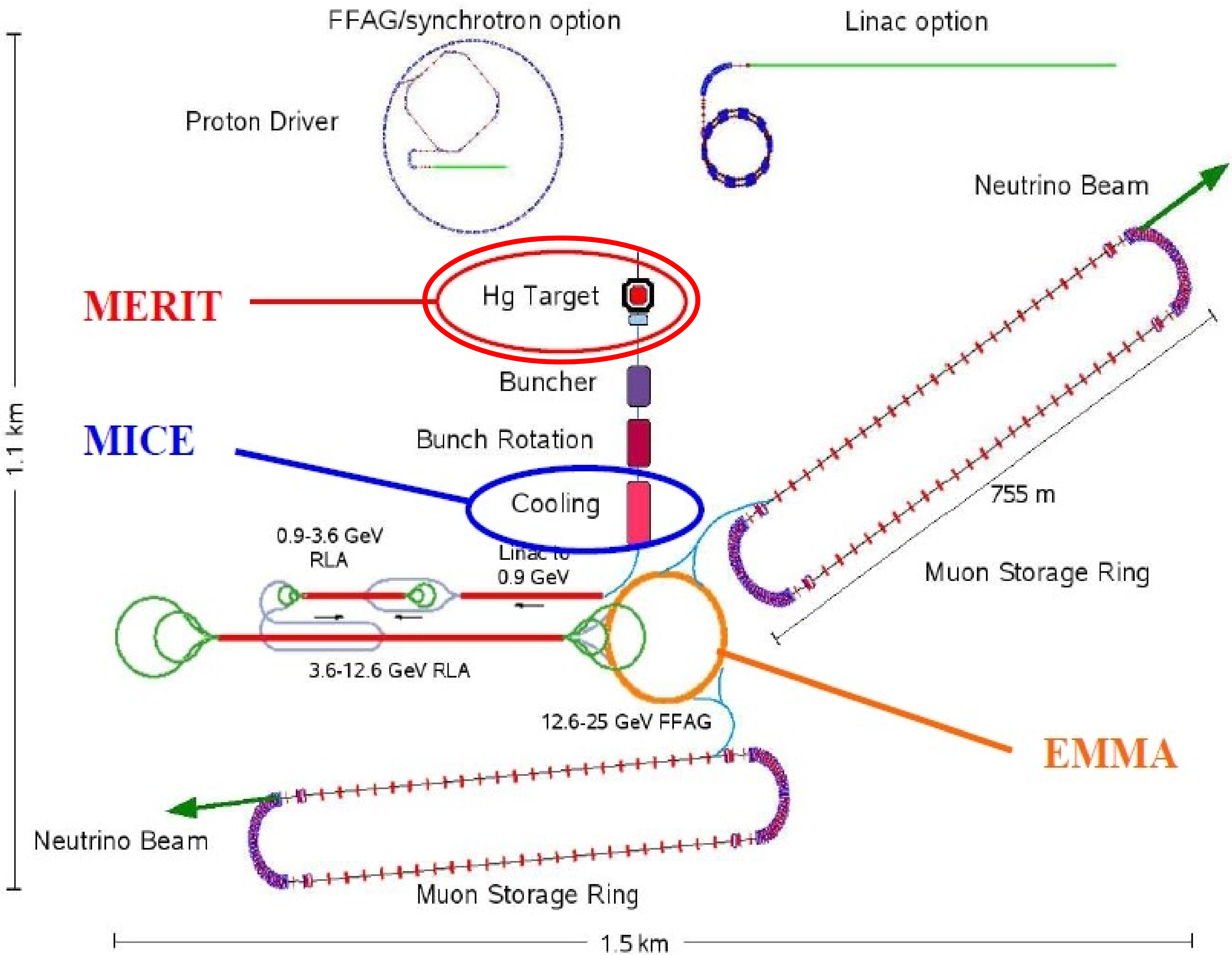






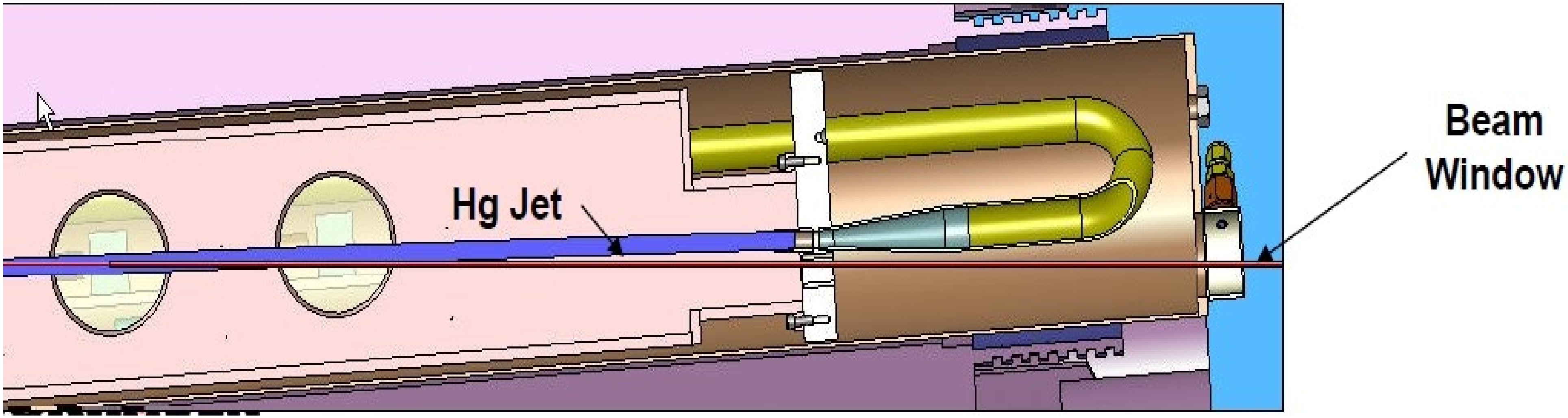
- **Neutrino Factory outperforms other options:**
  - **Larger discovery reach**
- **Competitors (large θ_{13}):**
  - **Beta beam:**
    - **But requires large Ne flux, high-γ, and/or 4-ions**
  - **Low energy Neutrino Factory:**
    - **See later, but, reduced redundancy/flexibility**

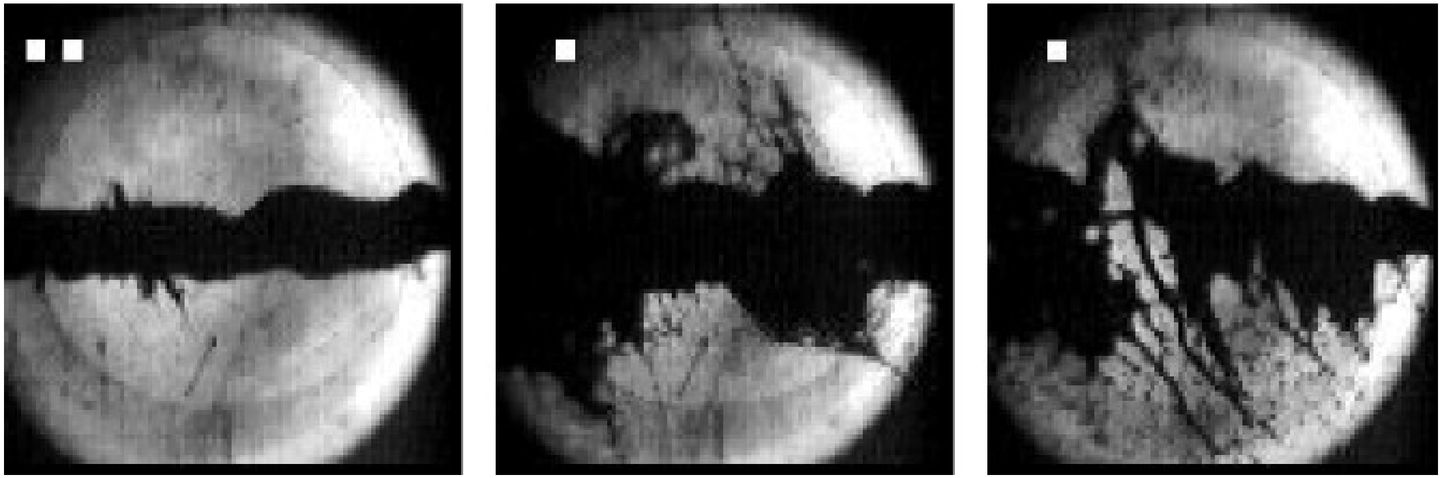
EUROnu: 1005.3146v1



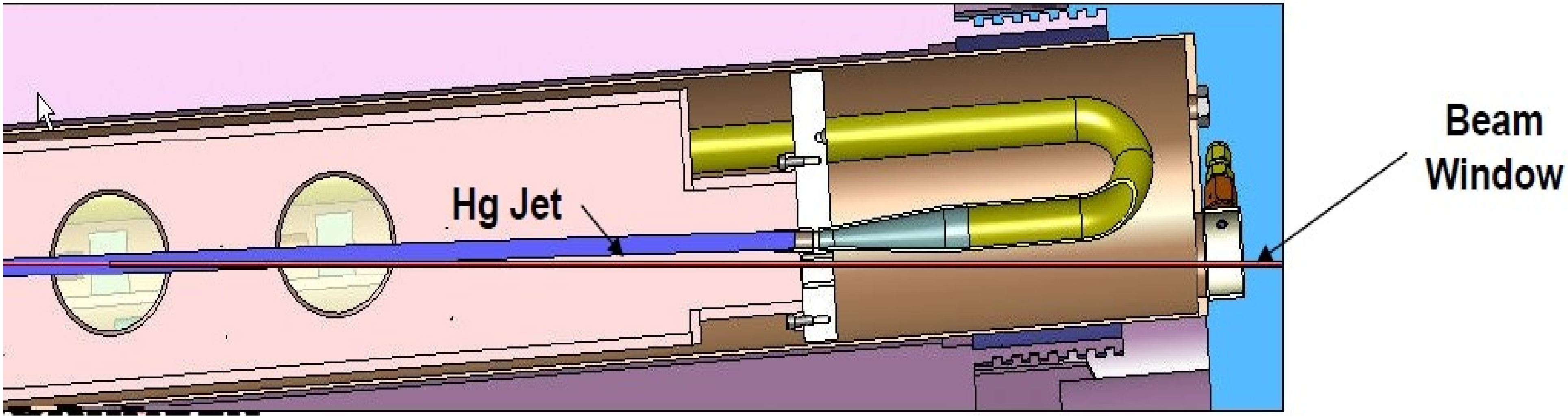
FFAG/synchrotron option
Linac option
Proton Driver
Neutrino Beam
MERIT
Hg Target
Buncher
MICE
Bunch Rotation
Cooling
755 m
0.9-3.6 GeV
RLA
Linac to
0.9 GeV
Muon Storage Ring
3.6-12.6 GeV RLA
12.6-25 GeV FFAG
EMMA
Neutrino Beam
Muon Storage Ring
1.1 km
1.5 km

Targetry – MERIT Experiment

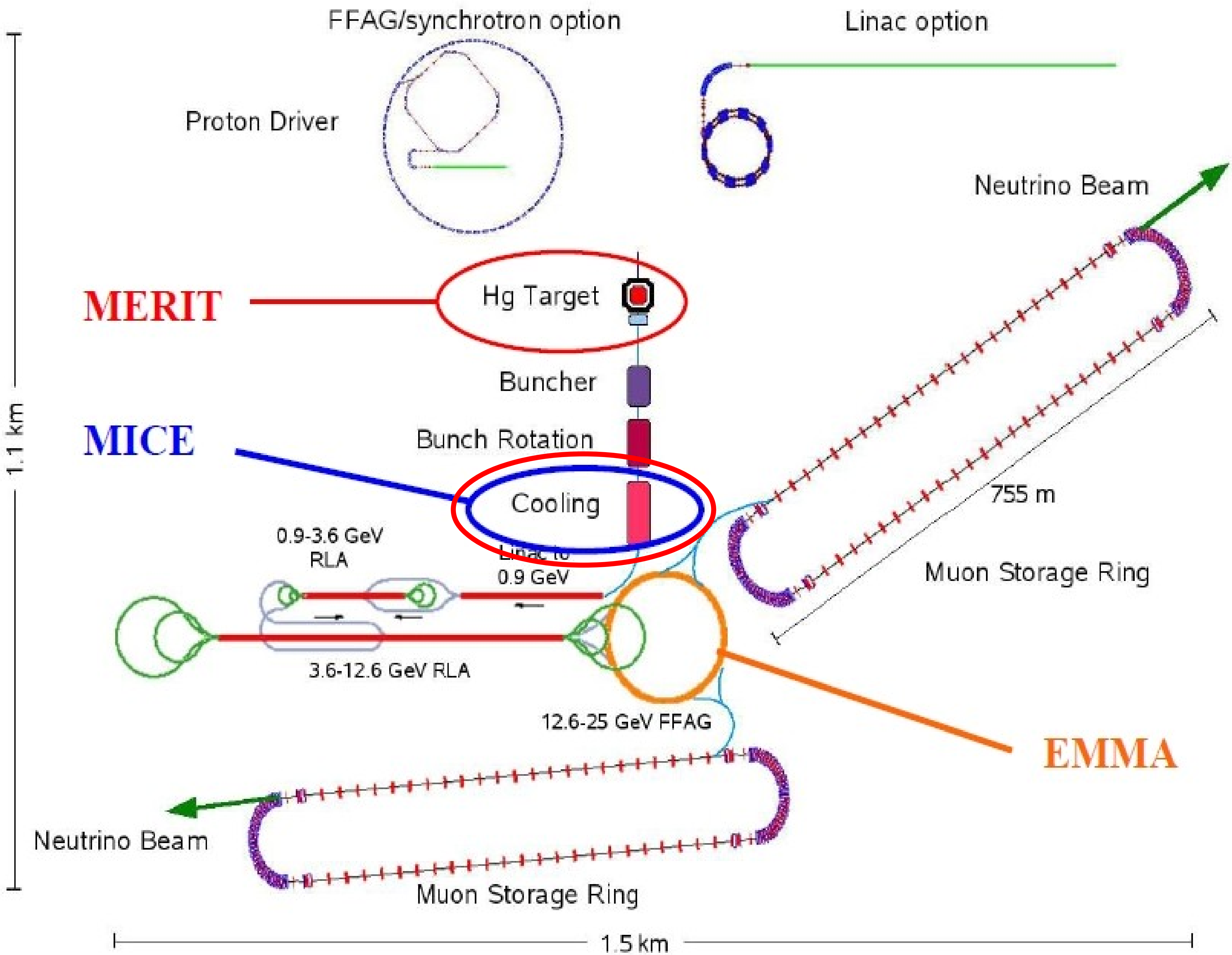




Targetry – MERIT Experiment



Other ideas out there : supercooled tungsten ring
tungsten powder jet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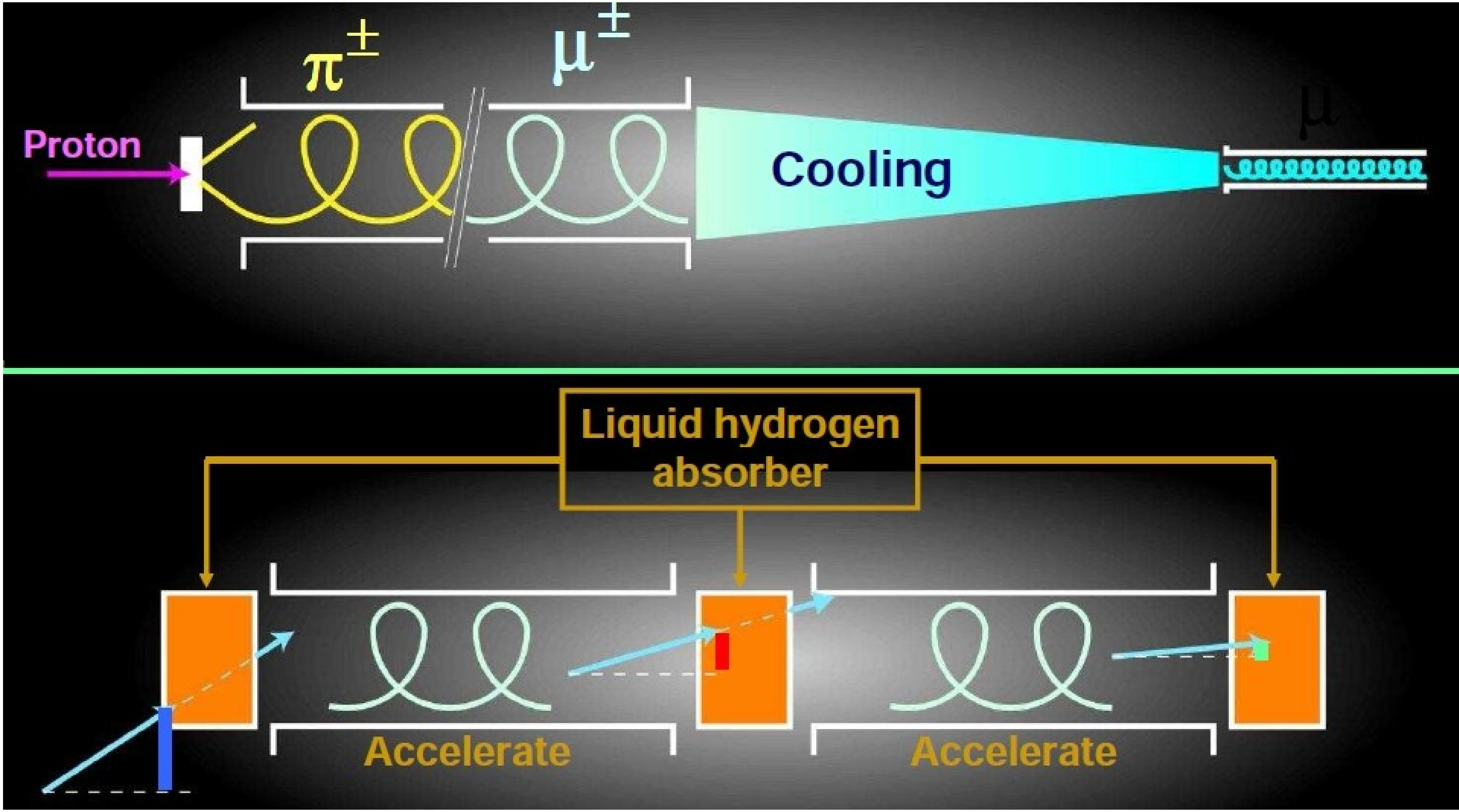
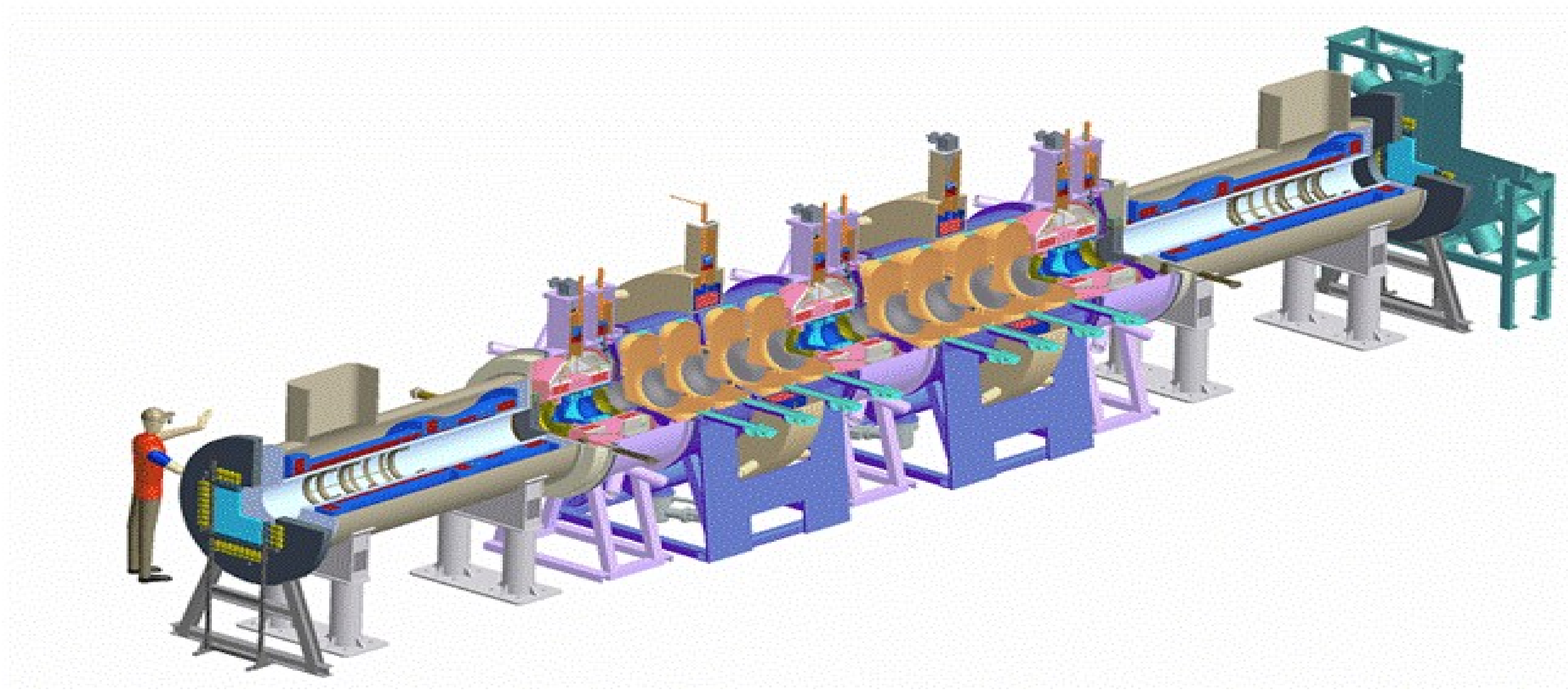
Muon Storage Ring
1.1 km
1.5 km

Muon Cooling



MICE

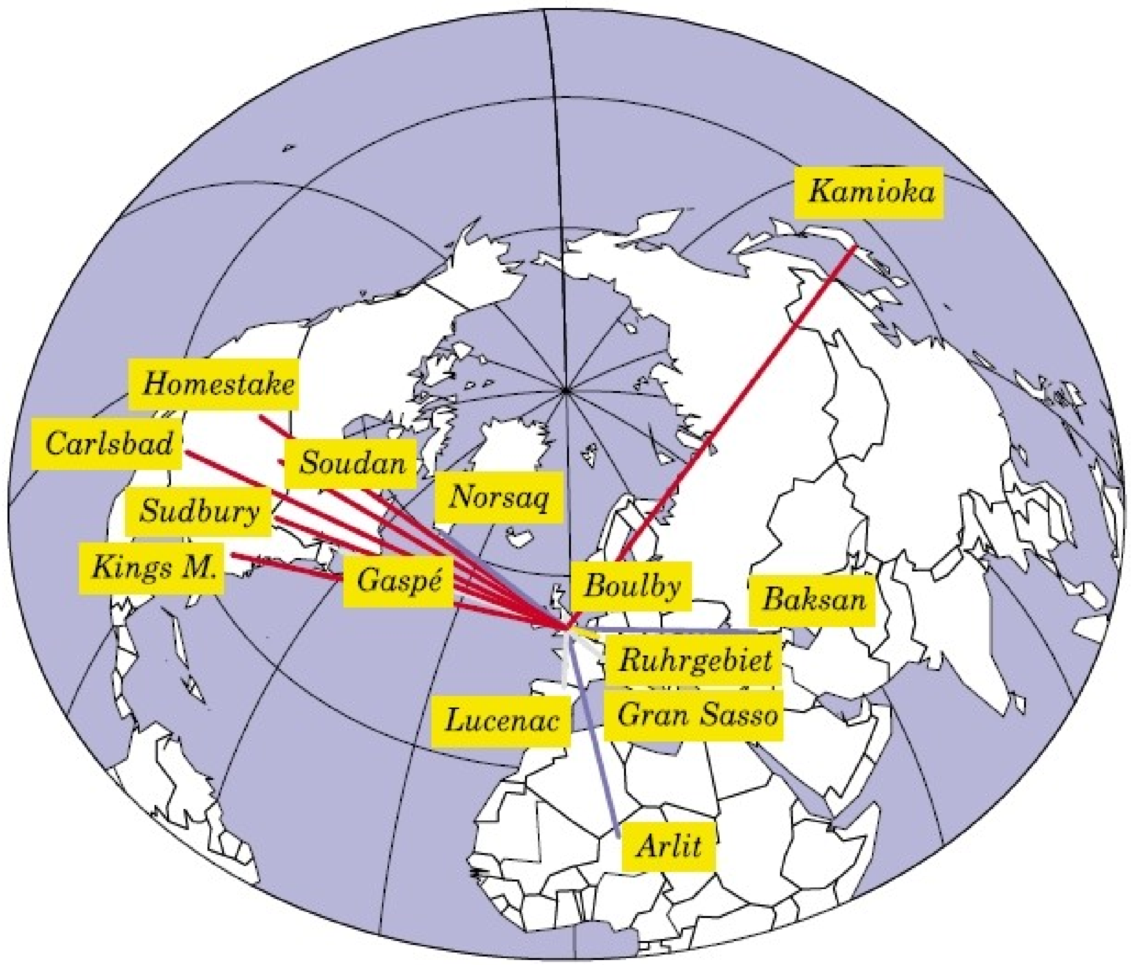


Muon Ionisation Cooling Experiment @ Rutherford Labs in Ox

Detectors

Physics sensitivity prefers two 50 kton (mass of the Titanic) detectors around 4000 km from the beam, and around 7500 km from the beam

Arlit:	3636
Baskan:	3366
Boulby:	229
Carlsbad:	7293
Essen:	565
Gaspe:	4264
GranSasso:	1514
Homestake:	6655
Kamioka:	8621
KingsMountain:	6095
Lucenac:	1002
Norsaq:	2788
Soudan:	5925
Sudbury:	5548



Neutrino Factory Summary

- Best discovery potential and sensitivity from all options
- Couldn't be built now. If we decided to build one it, and it's detectors, wouldn't be ready until 2025 or so.
- Only choice if $\theta_{13} < 1^{o}$
- Design study underway and the problems are being
- •addressed by demonstrator experiments
- Cost on the order of £3 billion (LHC cost £3 billion; 2008 bank bailout was £ 50 billion, although that wasn't cash in hand)
- Can we do this now? No.
- Wait for next θ_{13} measurement

Concluding Remarks

We have gone through a lot but I can easily fill another 15 hours of lectures.

The neutrino is : light, neutral, left-handed (chiral) and almost left-handed (helicity). It is generated purely in weak interactions (which is why it is chiral). It is generated by many sources : the Big Bang, astrophysical events, supernova, the sun, cosmic rays, radioactive decays, and countless other sources. We can generate them in reactors and accelerators. Their cross sections are tiny and we need big detectors to look at them. They mix and oscillate.

They may be the reason that we are here at all.

But…what is their mass? Why is it so small? Why are the mixing parameters so odd? Still lots of questions remain. We have a 20 year plan for trying to deal with them.

The first thing we need to do is determine the size of θ_{13}.

In words

Because ν_e can suffer an extra interaction it picks up an effective mass that is slightly different from its vacuum mass. From another point of view, the extra interaction gives the ν_e an apparent inertia with respect to the other neutrinos.

Think of this in much the same way as phonons in crystals which have "effective" masses arising from interactions with the crystal lattice

Matter presents an effective refractive index for ν_e

This inertia is felt by some linear combination of the mass eigenstates, and hence passed to the other flavours. Oscillations still happen, but now with a different effective mass splitting