XII MEXICAN WORKSHOP
ON PARTICLES
AND FIELDS

Neutrino Oscillation (and Mass) Experiments

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XII Mexican Workshop on Particles and Fields
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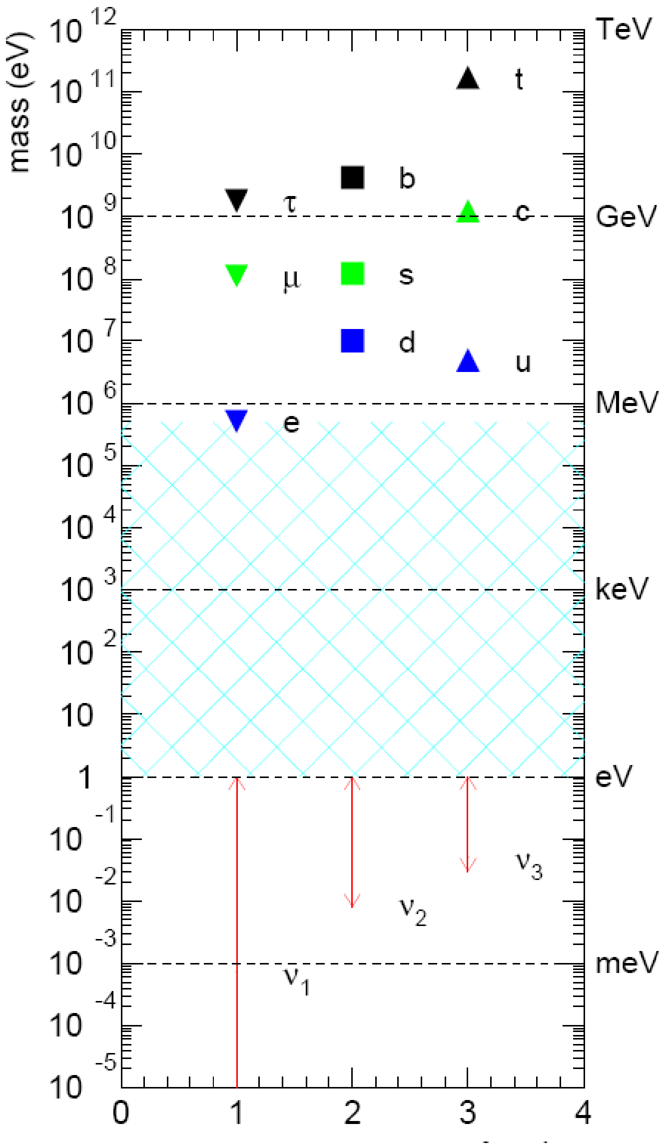
Outline

- Introduction
- Neutrino Absolute Mass Measurement
  - Direct mass measurements
  - Double beta decay
  - Cosmological constraints
- Current Results for Neutrino Oscillations
  - Solar neutrinos
  - Atmospheric Neutrinos
  - LSND / MiniBooNE
- Near Term Neutrino Oscillation Results
  - T2K and Nova
- Future Oscillation Experiment Plans
  - Hyper-K and LBNE
- Conclusion

Neutrinos in the Standard Model

- Neutrinos are the only fundamental fermions with no electric charge
- Neutrinos are left-handed (Antineutrinos are right-handed) since only (V-A) interactions
- Neutrinos are massless
- Lepton number is conserved $\Rightarrow$ No neutrino flavor mixing



We now know:

1. **Neutrinos have tiny masses**
2. **The neutrino flavor mix**

Current Major Neutrino Questions

- What are their masses?
  - Neutrinos have extremely tiny masses. Why?
  - But important contributors to how the universe works.

- Are there more than three types of neutrinos (electron, muon, and tau neutrino)?
  - Could there be new “sterile” type neutrino partners?
  - Are these “sterile” neutrinos the reason that neutrinos are different?

- Neutrinos can change from one type to another
  - What is the pattern (and explanation) of these mixings?
  - Could this hold the key to the “matter-antimatter” asymmetry in the universe?

- Are neutrinos a new type of matter particle where the particle and antiparticle are the same? (Are neutrinos Majorana fermions?)

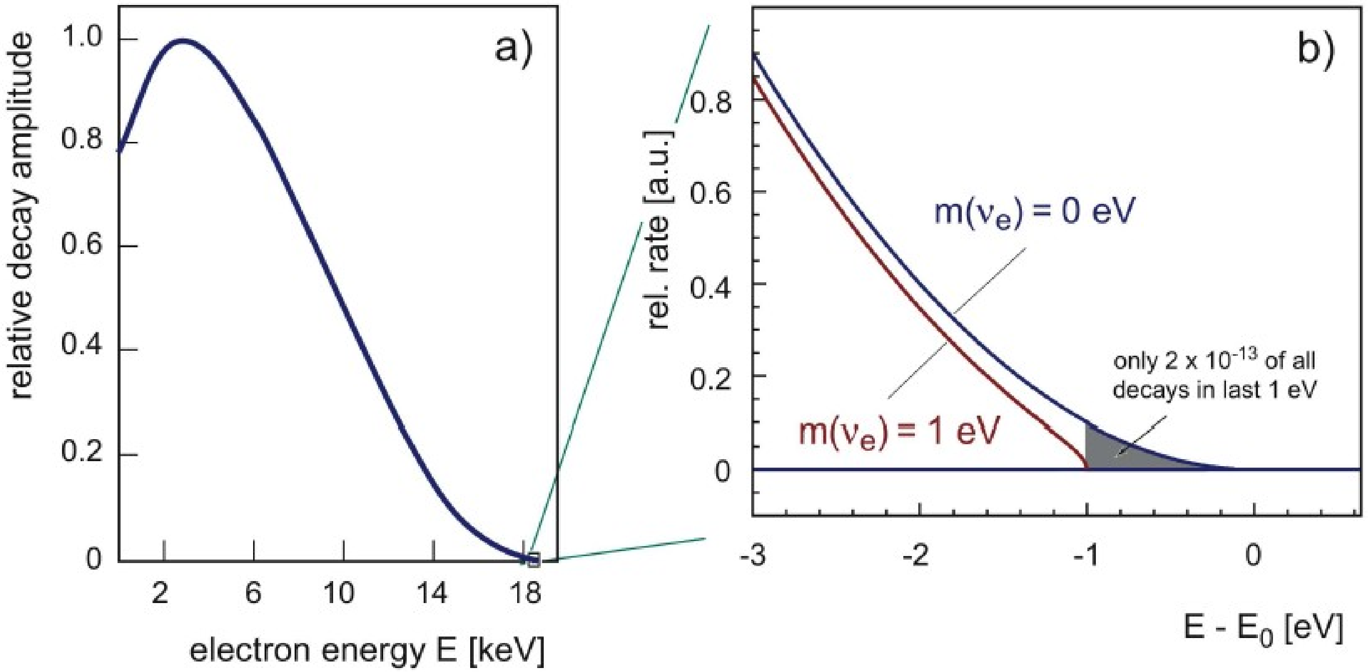
Absolute Mass Scale Determinations

Tritium β decay	$m_{\nu_e} = \left(\sum_i \lvert U_{ei}\rvert^2 m_i^2\right)^{1/2}$ $\rightarrow [c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$
Neutrinoless double beta decay	$m_{ee} = \left\lvert \sum_i U_{ei}^2 m_i \right\rvert$ $\rightarrow \lvert c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \rvert$
Cosmology	$\sim \sum_i m_i$

ν_e Mass Measurements (Tritium β-decay Searches)

- Search for a distortion in the shape of the β-decay spectrum in the end-point region.

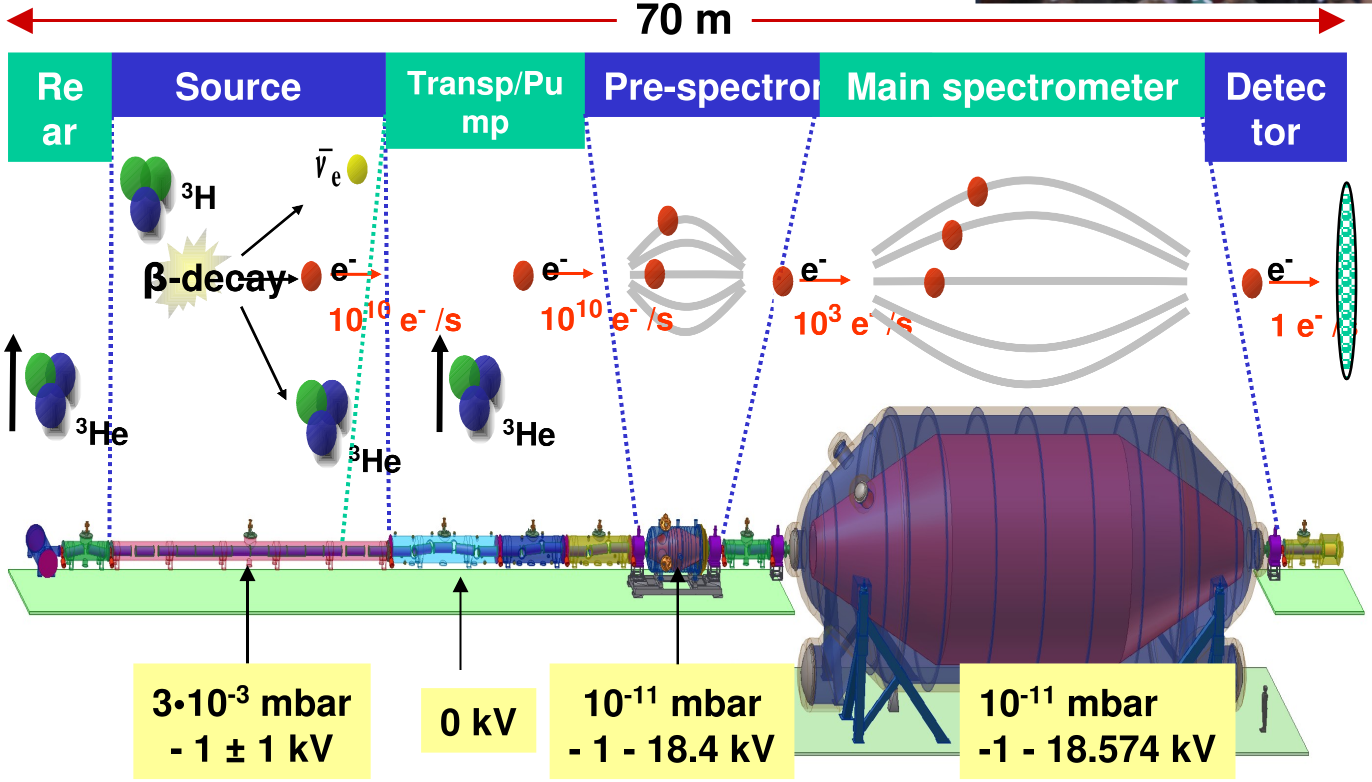
$$^3H \rightarrow {}^3He + \nu_e + e^-$$



Current limit: $m_\nu < 2.2$ eV @ 95% CL (Mainz group 2000)

Next Generation KATRIN Experiment

KATRIN
Karlsruhe Tritium Neutrino Experiment



70 m

Rear

Source

Transp/Pump

Pre-spectro

Main spectrometer

Detector

^3H

$\bar{\nu}_e$

β-decay

e^-

10^{10} e^-/s

^3He

^3He

^3He

e^-

10^{10} e^-/s

e^-

10^3 e^-/s

e^-

1 e^- /

$3 \cdot 10^{-3}$ mbar
-1 ± 1 kV

0 kV

10^{-11} mbar
$-1 - 18.4$ kV

10^{-11} mbar
$-1 - 18.574$ kV

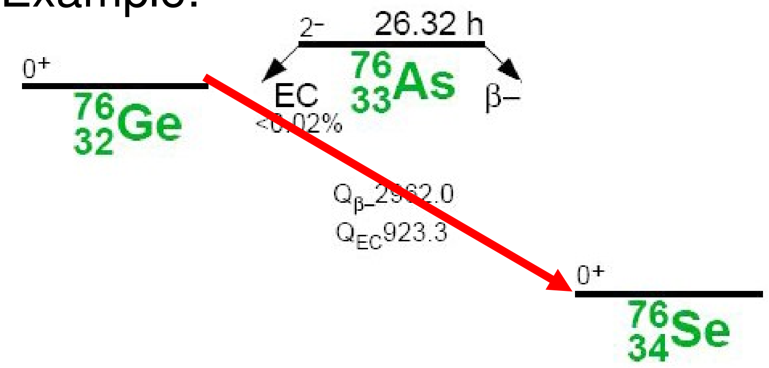
discovery potential:
$m_\nu = 0.35$eV (5σ)
$m_\nu = 0.3$eV (3σ)

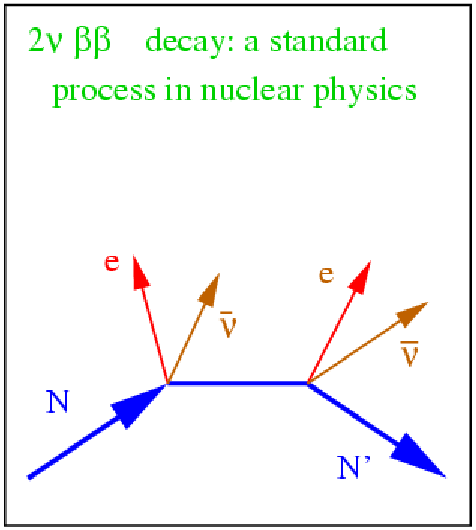
sensitivity:
$m_\nu < 0.2$eV (90%CL)

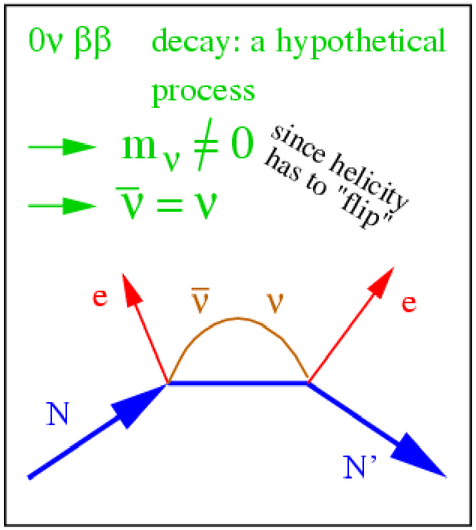
Double Beta Decay

- Some nuclei are stable against singe beta decay and so only decay with double beta decay
- 2νββ can always occur for these nuclei
  ⇒ but if the neutrino is Majorana, the 0νββ can also occur

Example:



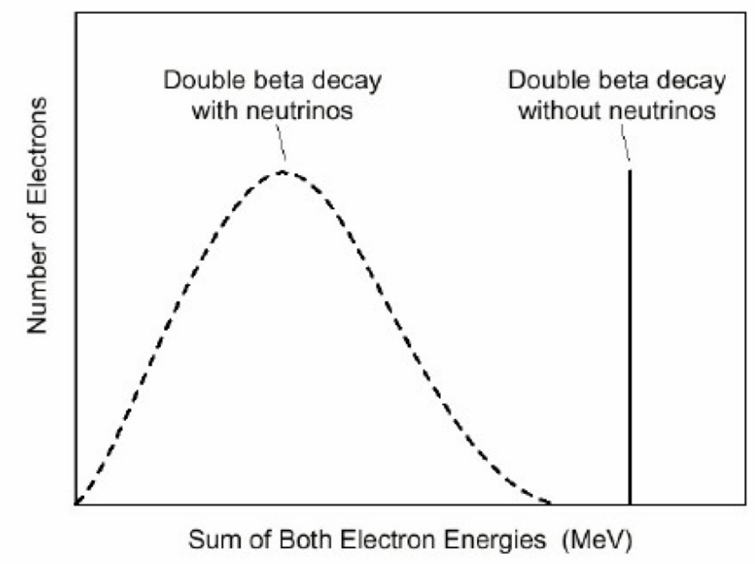

2ν ββ decay: a standard process in nuclear physics


0ν ββ decay: a hypothetical process

→ $m_\nu \neq 0$

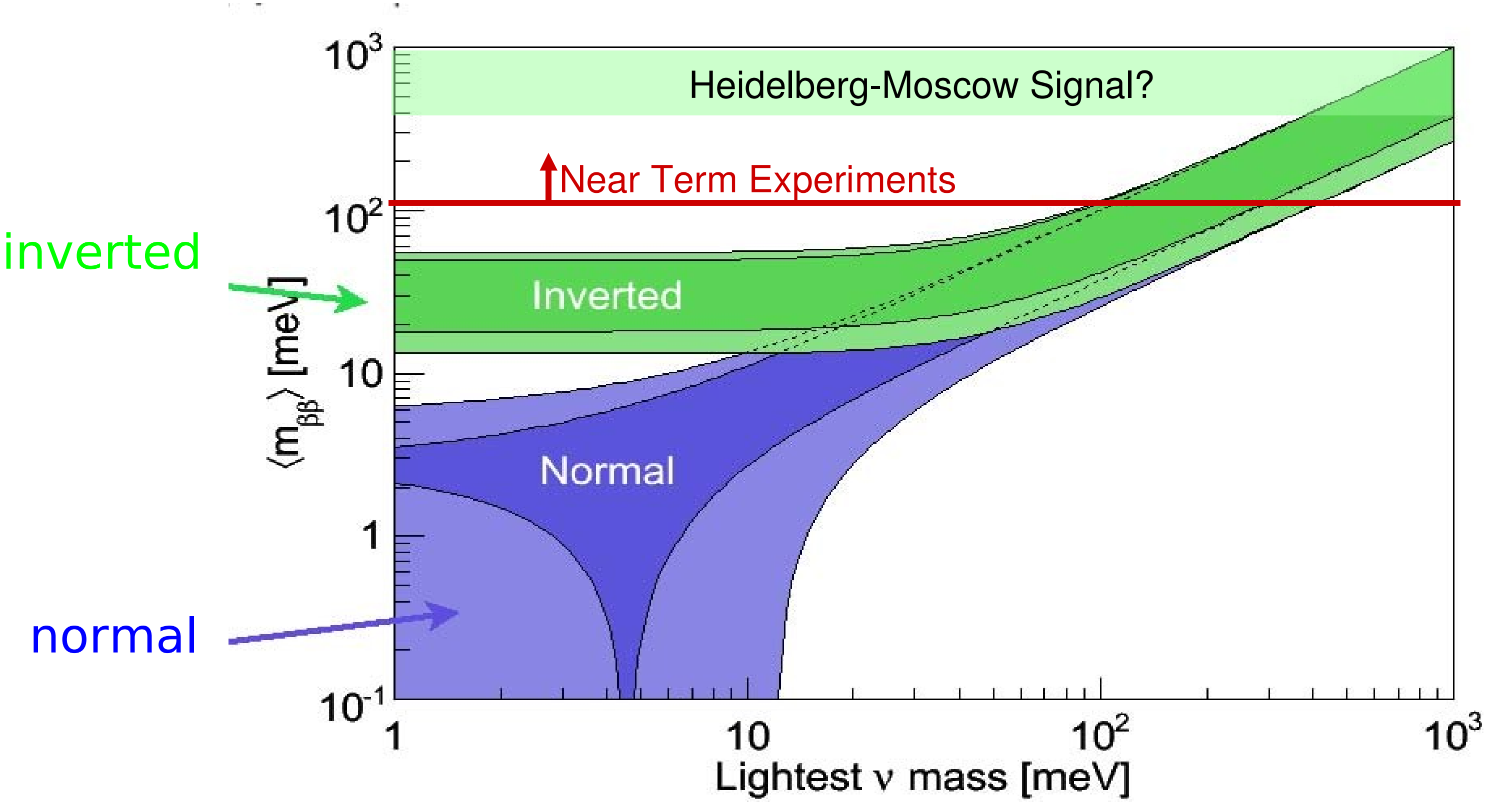
→ $\bar{\nu} = \nu$

since helicity has to "flip"



Double Beta Decay Measurement Interpretations

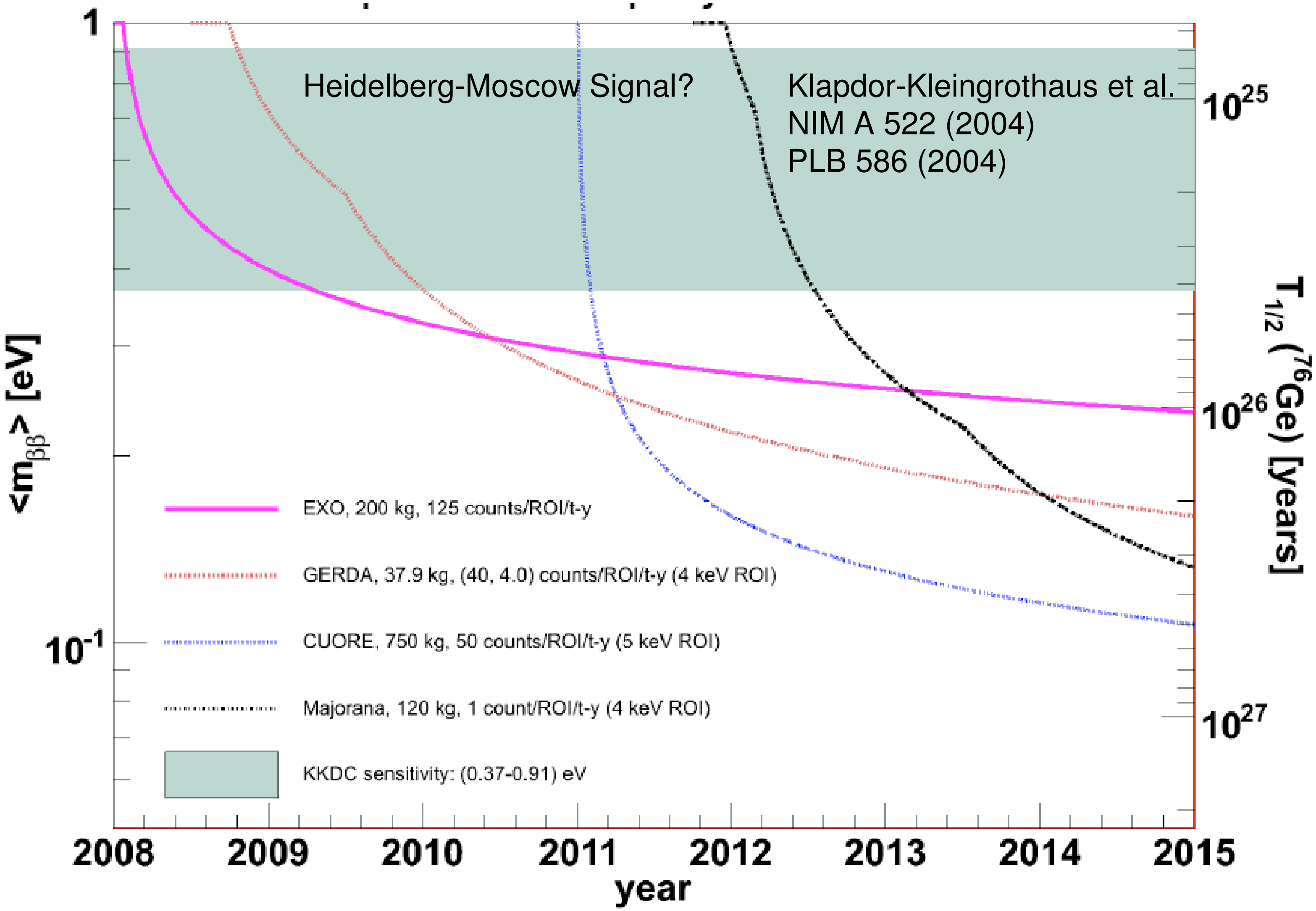
$$\left\langle m_{\beta\beta} \right\rangle = \left| \quad {}_{i} \left| U_{ei} \right|^{2} e^{i\alpha_i}\, m_i \right|$$



$\langle m_{\beta\beta} \rangle$ also gives information on absolute mass scale of neutrinos

- If detect 0ν2β decay ⇒ Neutrinos are Majoranna particles
- If know inverted hierarchy and do not detect 0ν2β decay with sensitivity of > 10 meV (0.01 eV) ⇒ Neutrinos are not Majoranna particles
- If normal hierarchy and do not detect 0ν2β decay ⇒ Cannot determine if neutrinos are Majoranna or not

Projected Sensitivity of Various 2-β Experiments

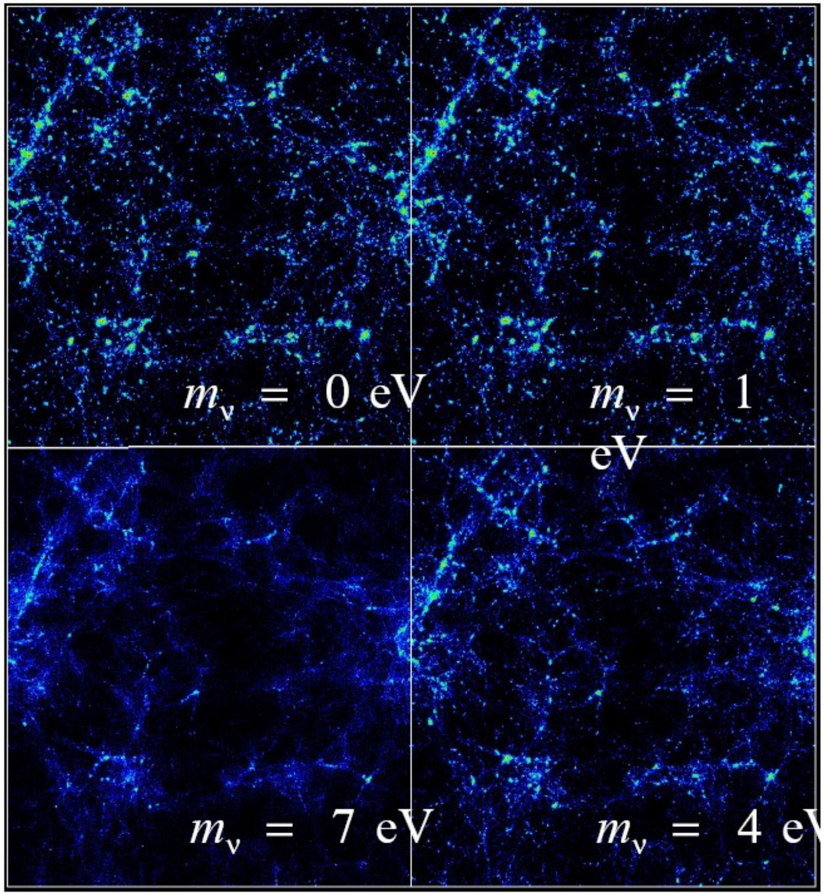


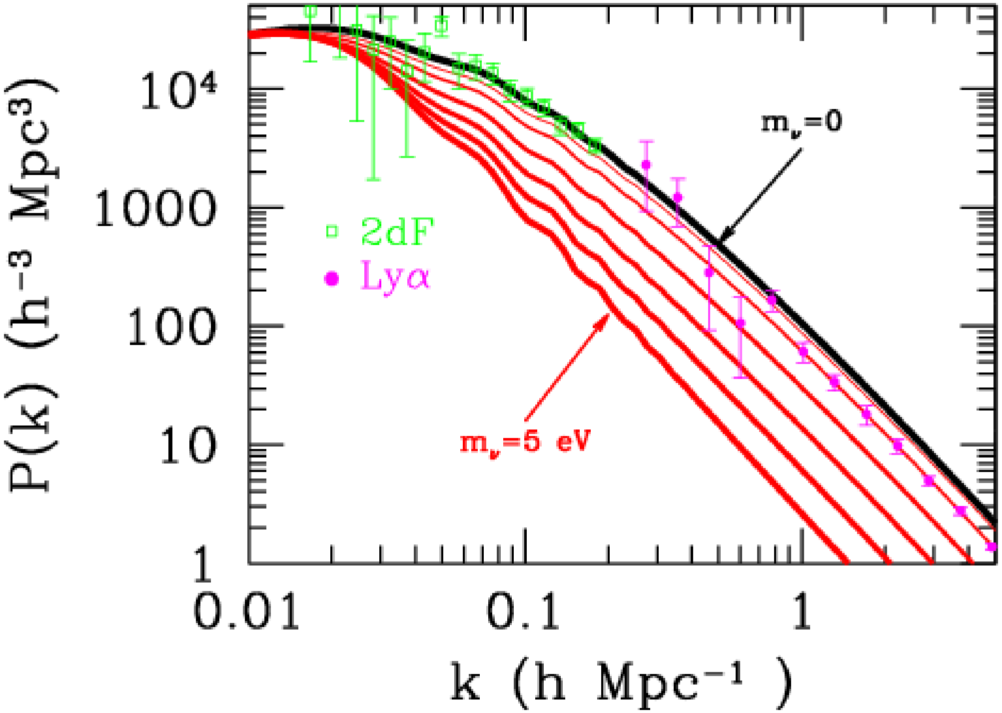
These projected timescales are a few years old

Cosmological Neutrino Mass Limits

- Density fluctuations are affected by neutrino mass in the early universe
  - Highly model dependent
    - *What data is used*
    - *Cosmological model and set of parameters*
    - *Assumed properties of the big bang neutrinos*

Limits sum of neutrino masses: $\Sigma m\nu < 0.7 eV$





Neutrino Oscillations

The observation of neutrino oscillations where one type of neutrino can change (oscillate) into another type implies:

- Neutrinos have mass

and

- Lepton number (electron, muon, tau) is not conserved ($\nu_e \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_\tau$, $\nu_e \rightarrow \nu_\tau$)

- The phenomena comes about because the mass and flavor states are different as parameterized by a mixing matrix

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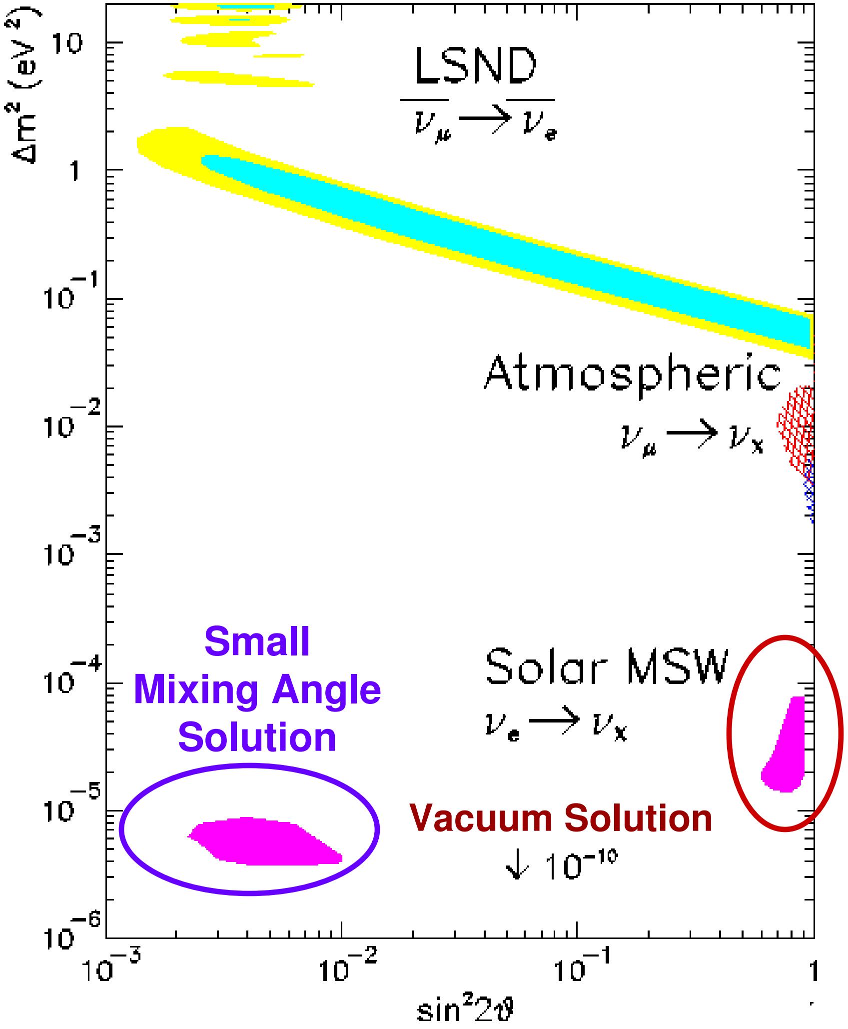
- Two types of oscillation searches: $P_{Osc} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 L / E\right)$
  - ***Appearance Experiment:***

    Look for appearance of ν_e or ν_τ in a pure ν_μ beam vs. L and E
    - Need to know the backgrounds
  - ***Disappearance Experiment:***

    Look for a change in $\nu_{e/\mu}$ flux as a function of L and E
    - Need to know the flux/and cross sections

Three Signal Regions (Mid 1990's)

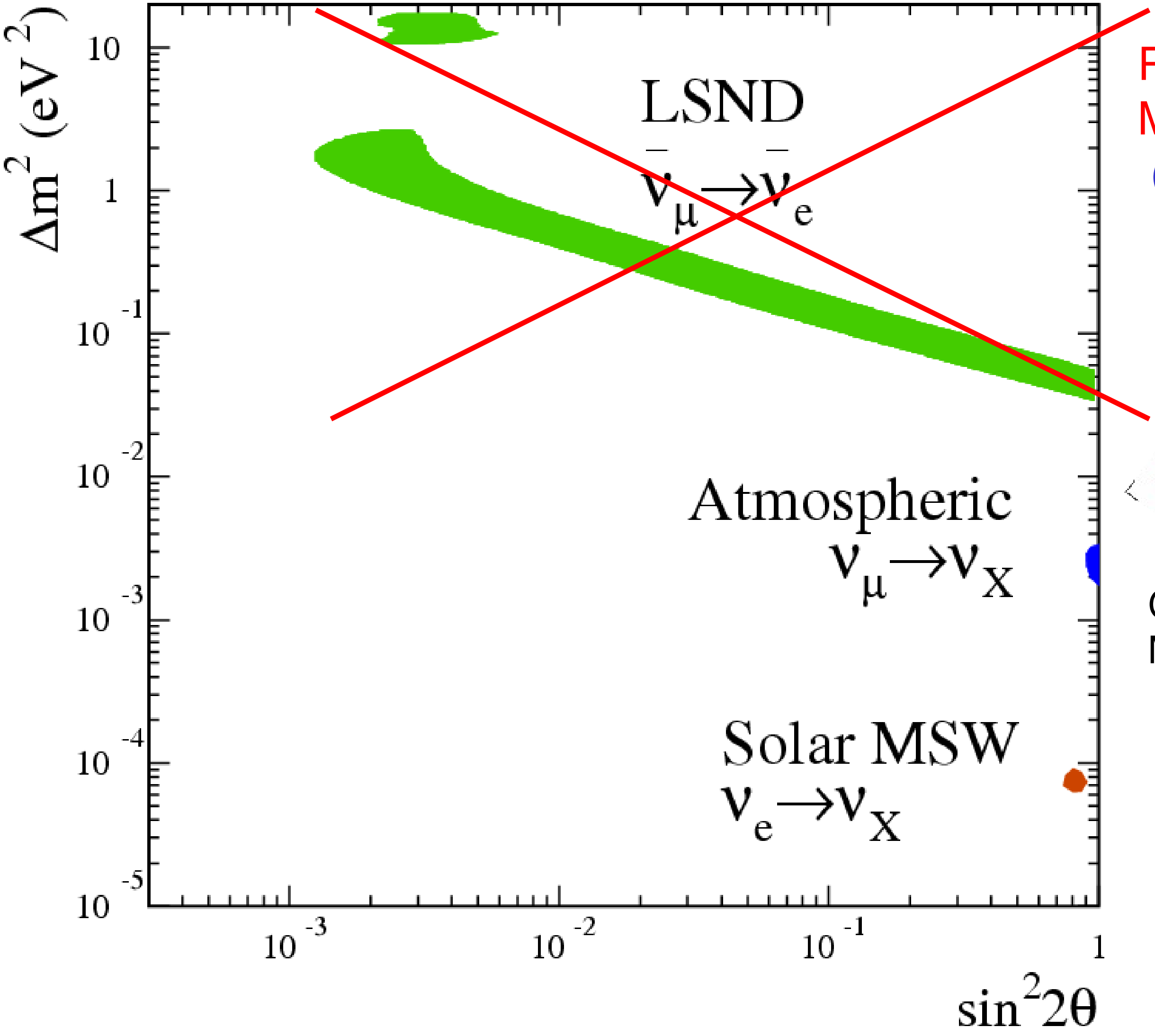


Small Mixing Angle Solution

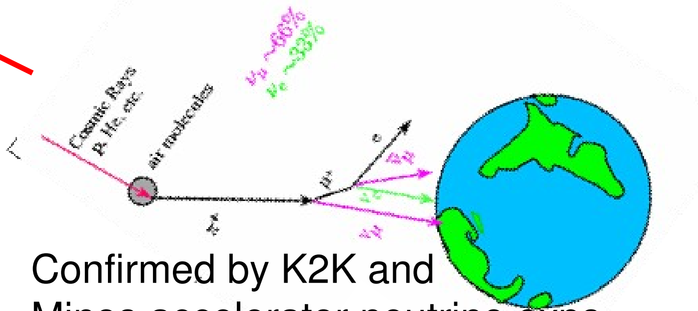
Vacuum Solution
↓ 10^{-10}

Large Mixing Angle Solution

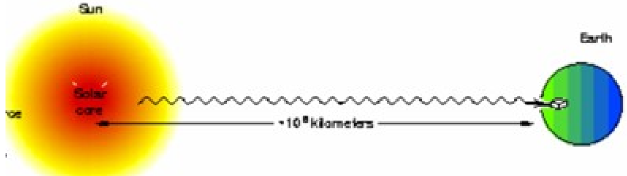
Current Oscillation Summary



Ruled out by MiniBooNE (almost)
($\bar{\nu}$ running; low-E excess)



Confirmed by K2K and Minos accelerator neutrino exps



Confirmed by Kamland reactor neutrino exp

Oscillations Parameterized by 3x3 Unitary Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} Flavor \\ Eigenstate \end{pmatrix} = (Mixing\ Matrix) \begin{pmatrix} Mass \\ Eigenstate \end{pmatrix}$$

Three mass splittings: $\Delta m_{12}^2 = m_1^2 - m_2^2$, $\Delta m_{23}^2 = m_2^2 - m_3^2$, $\Delta m_{31}^2 = m_3^2 - m_1^2$

But only two are independent since only three masses

If δ 0, then have CP violation $P(\nu_\mu \quad \nu_e) \quad P(\bar{\nu}_\mu \quad \bar{\nu}_e)$

solar atmospheric

Current Measurements: $\Delta m_{12}^2 = 8 \quad 10^{-5}$ eV^2 , $\Delta m_{13}^2 \quad \Delta m_{23}^2 =¿2.5 \quad 10^{-3}$ eV^2

$$U = \begin{matrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{matrix} \quad \begin{matrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{matrix} \quad \begin{matrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{matrix}$$

3-mixing angles

Solar: θ_{12} ~ 33°

Little mixing angle, θ_{13}
$\sin^2 2\theta_{13} < 0.14$ at 90% CL
(or $\theta_{13} < 11°$) and δ = ??

Atmospheric: θ_{23} ~ 45°

CP Violation in Neutrino Oscillations

- Disappearance measurements cannot see CP violation effect

$$P\left(\nu_\mu \to \nu_\mu\right) = P\left(\bar{\nu}_\mu \to \bar{\nu}_\mu\right)$$

- Very, very hard to see CP violation effects in exclusive (appearance) measurements.
  - Only can see CP violation effects if an experiment is sensitive to oscillations involving all three types of neutrinos.

$$P\left(\nu_\mu \to \nu_e\right) - P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right) = 4\,\mathrm{Im}\left(U_{\mu 1} U^*_{e1} U^*_{\mu 3} U_{e3}\right)\left(s_{12} + s_{23} + s_{31}\right)$$

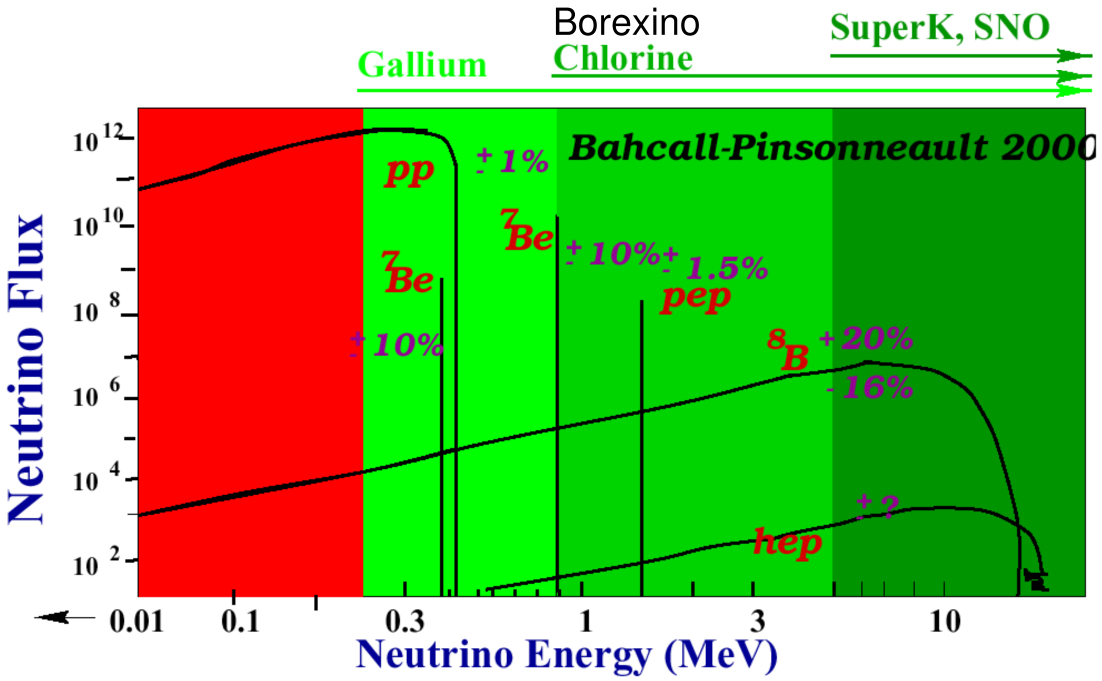
where $s_{ij} = \sin\left(\delta m^2_{ij}\, L/2E\right)$ and $\delta m^2_{ij} = m^2_i - m^2_j$

⇒ **To see CP violation must be sensitive to all three neutrino oscillations**

i.e. the hardest is usually the lowest (solar neutrino)

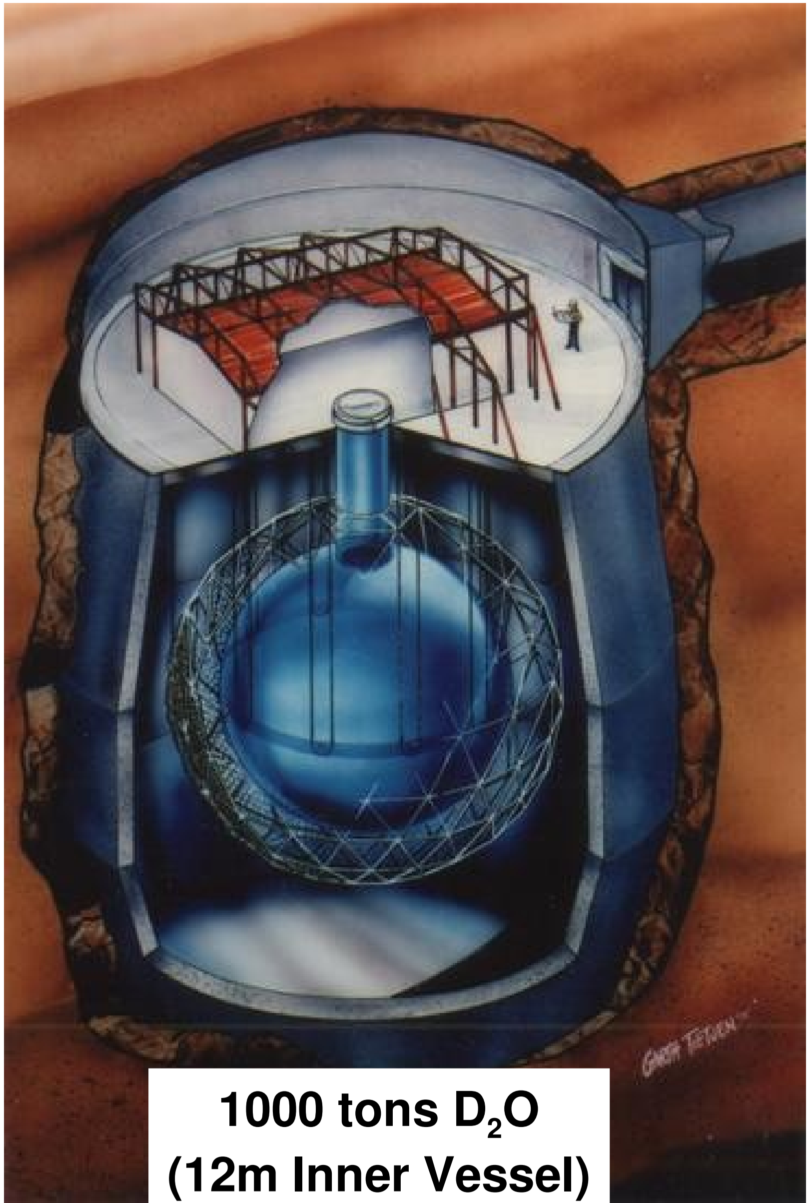
$\Delta m^2_{12} = 8 \times 10^{-5}$ eV^2

Solar Neutrino Experiments – Phenomenology Well Understood

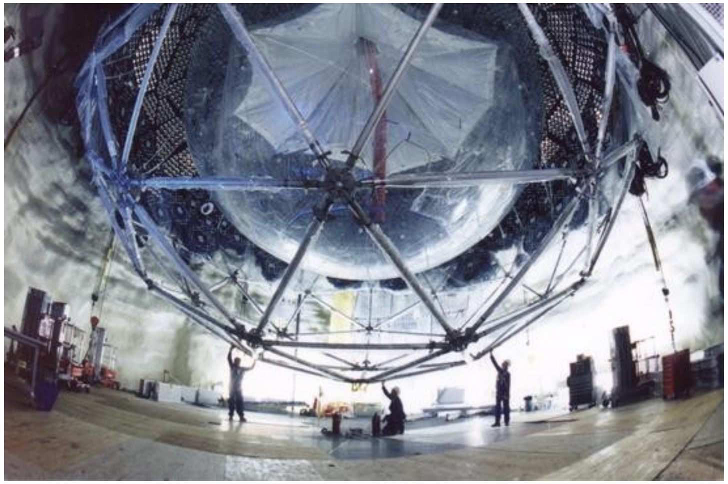


Rate measurement	Reaction	Obs / Theory
Homestake (US)	$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$	0.34 ± 0.04
SAGE (Russia)	$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$	0.59 ± 0.06
Gallex+GNO (Italy)	$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$	0.58 ± 0.05
Super-K (Japan) H_2O	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.46 ± 0.02
SNO (Canada) D_2O	$\nu_e + d \rightarrow p + p + e^-$	0.35 ± 0.03
BOREXINO	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.56 ± 0.08

Sudbury Neutrino Observatory (SNO)



1000 tons D_2O
(12m Inner Vessel)



- Advantages of Heavy vs Light Water
  - $\nu_x + d \rightarrow \nu_x + n + p$ (D_2O)
  - $\nu_e + d \rightarrow p + p + e^-$ (D_2O)
  - $\nu_x + e^- \rightarrow \nu_x + e^-$ (H_2O or D_2O)
  - Cross section $\propto (E_{cm})^2 = s$
    - $s = 2\, m_{target}\, E_\nu$
      $\Rightarrow s_N/s_{e-} = M_p/M_e \approx 2000$
  - But x5 more electrons in H_2O than n's

SNO (1kton) 8.1 CC events/day
SuperK (22ktons) 25 events/day

Neutrino Reactions in SNO

CC

$$\nu_e + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^-$$

- pure ν_e measurement

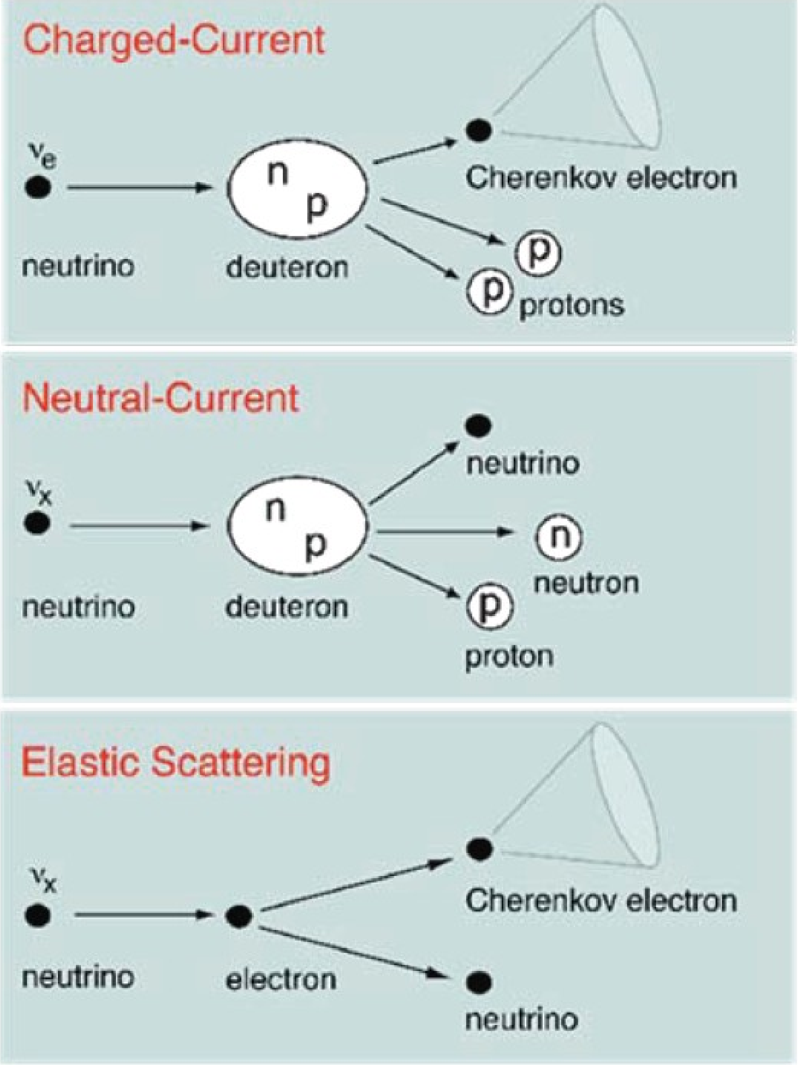
NC

$$\nu_x + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{n} + \nu_x$$

- measures total ^{8}B ν flux from the Sun
- equal cross section for all active ν flavors

ES

$$\nu_x + \mathrm{e}^- \rightarrow \nu_x + \mathrm{e}^-$$



Three Phases for neutron capture:

- On Deuterium
- On Salt
- Using ^{3}He Counters

SNO Physics

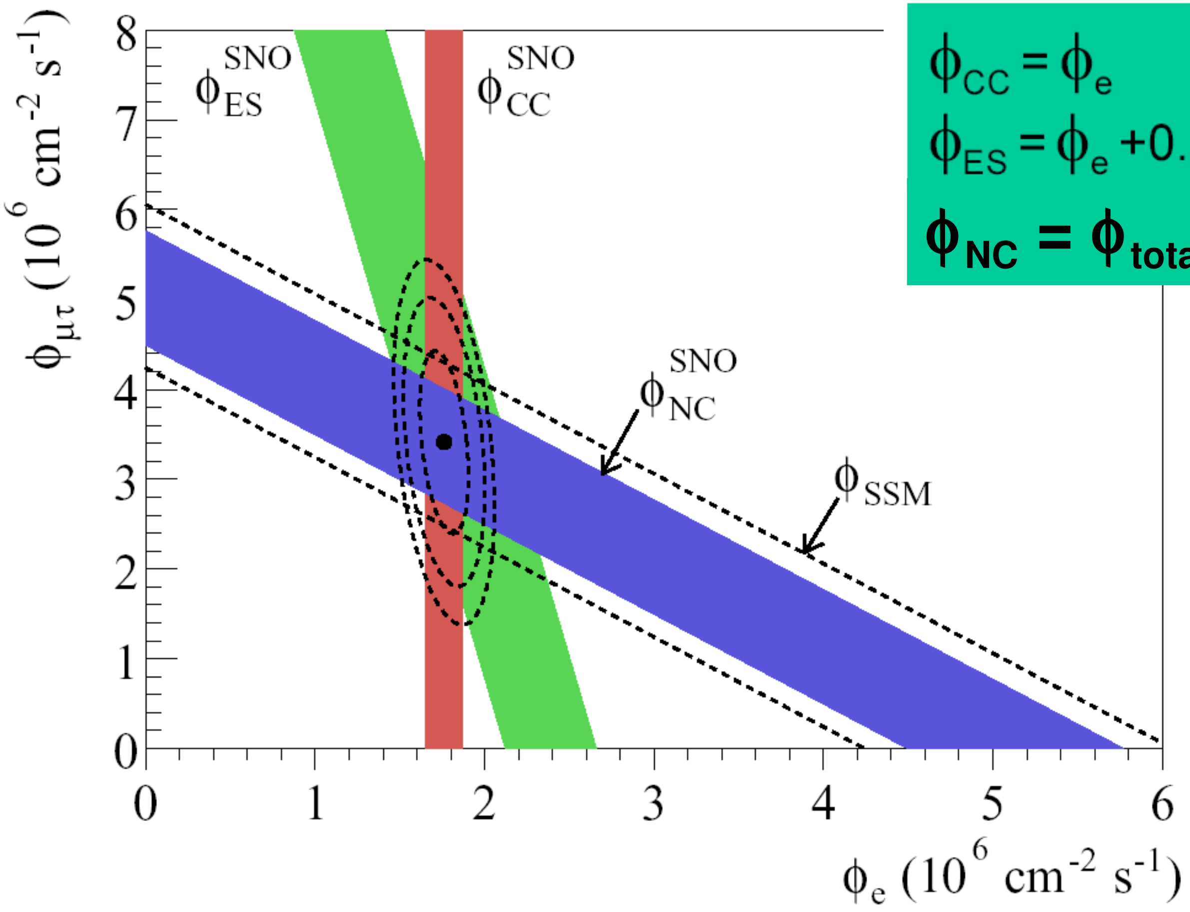
- First measurement of the total flux of ^{8}Be neutrinos:

$\phi_{total}(^8Be) = 5.21 \pm 0.47 \times 10^6\ cm^{-2}s^{-1}$

- Agrees well with solar models:

$\phi_{total}(^8Be) = 5.05 \pm 1.00 \times 10^6\ cm^{-2}s^{-1}$

⇒ Solar Oscillations not totally to sterile neutrinos



$\phi_{CC} = \phi_e$

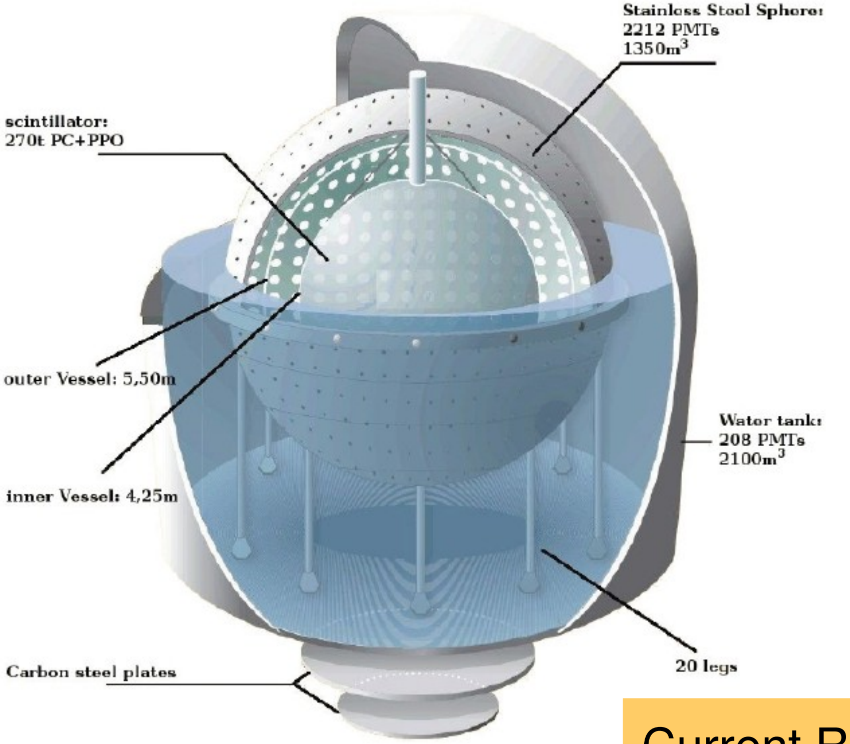
$\phi_{ES} = \phi_e + 0.154\ \phi_{\mu.\tau}$

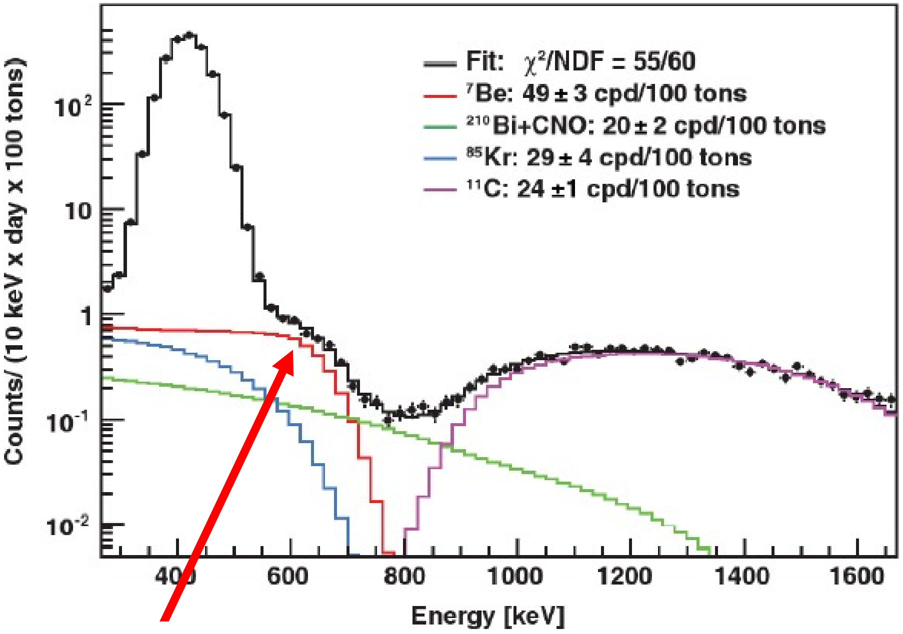
$\boldsymbol{\phi_{NC} = \phi_{total} = \phi_e + \phi_{\mu,\tau}}$

Borexino – Real Time Measurement of ^{7}Be

- Neutrino-Electron scattering at Low energy ⇒ ^{7}Be neutrinos
- Liquid scintillator neutrino target (~100t fiducial mass)
- Main issue is radioactive contamination
  - Need to use very “clean” material
  - Reduce cosmic muons

$$\nu_{x,e} + e^- \rightarrow \nu_{x,e} + e^-$$





^{7}Be Neutrinos

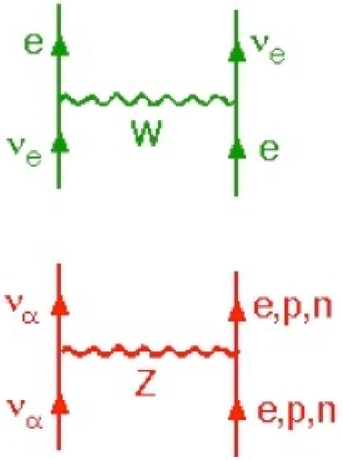
Current Result: $49 \pm 3_{stat} \pm 4_{syst}$ Counts/day/100 tons

Obs/SSM = 0.56 ± 0.08

Matter Effects in the Sun

Comes about due to interactions with the electron plasma in the sun
⇒ Which makes ν_e propagation different from $\nu_{\mu/\tau}$ interactions

Coherent Forward Scattering:



Wolfenstein '78

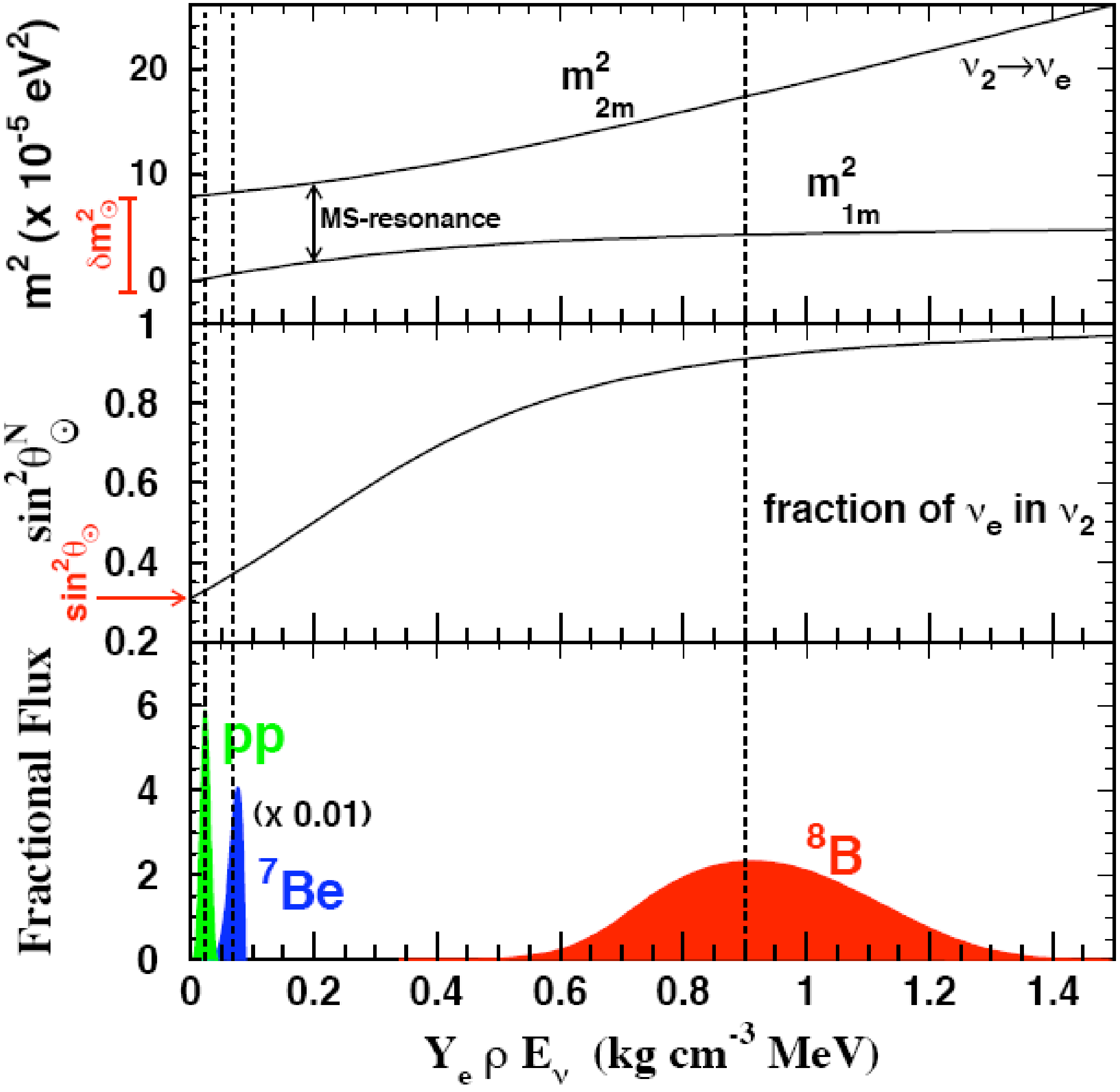
These matter effects change masses and mixings of the neutrino eigenstates

$$\sin^2\theta_\odot^N = \frac{1}{2}\left\{1 + \frac{(A - \delta m_\odot^2 \cos 2\theta_\odot)}{\sqrt{(\delta m_\odot^2 \cos 2\theta_\odot - A)^2 + (\delta m_\odot^2 \sin 2\theta_\odot)^2}}\right\}$$

$$\delta m_N^2 = \sqrt{(\delta m_\odot^2 \cos 2\theta_\odot - A)^2 + (\delta m_\odot^2 \sin 2\theta_\odot)^2}$$

$$A \equiv 2\sqrt{2} G_F (Y_e \rho / M_n) E_\nu$$

Matter Effects in the Sun



hep-ph/0601198

In Vacuum

$$\delta m^2_\odot = 8.0 \pm 0.4 \times 10^{-5}\ eV^2$$

$$\sin^2\theta_\odot = 0.31 \pm 0.03$$

(**pp** and ^{7}**Be** are quasi-vacuum osc.)

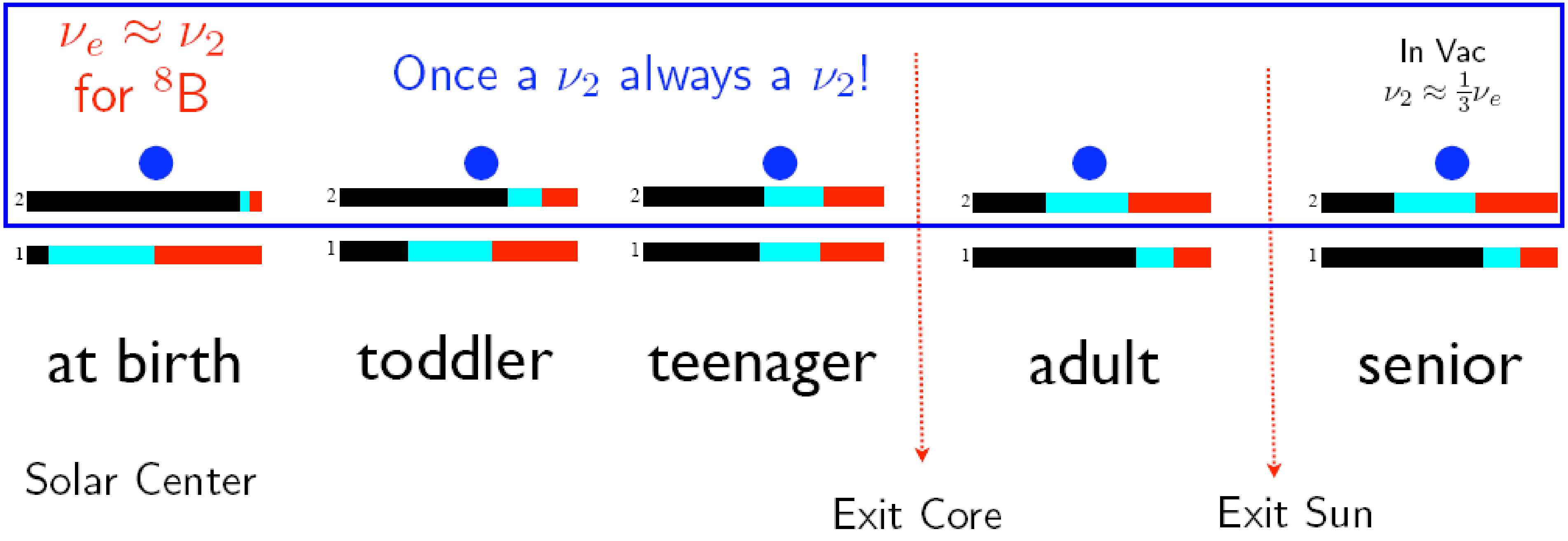
Whereas for ^{8}B
at center of Sun

$$\delta m^2_N = 14 \times 10^{-5}\ eV^2$$

$$\sin^2\theta^N_\odot = 0.91$$

From Stephen Parke
(See PRD 74 (2006) 13006)

Life of a Boron-8 Solar Neutrino:



$\nu_e \approx \nu_2$
for ^{8}B

Once a ν_2 always a ν_2!

In Vac
$\nu_2 \approx \frac{1}{3}\nu_e$

at birth

toddler

teenager

adult

senior

Solar Center

Exit Core

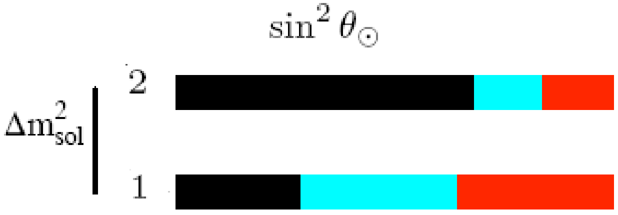
Exit Sun

ν_e ⬛ ν_μ 🟦 ν_τ 🟥

From Stephen Parke
(See PRD 74 (2006) 13006)

Solar Mass Hierarchy Also Determined From Matter Effects

If we chose the wrong mass hierarchy for the ν_1 and ν_2 , then:



$$\theta_\odot > \pi/4$$

ν_e ■ ν_μ 🟦 ν_τ 🟥

Solar matter effects put more of the neutrino into ν_2. This raises the survival probability above vacuum value since ν_2 has more ν_e.

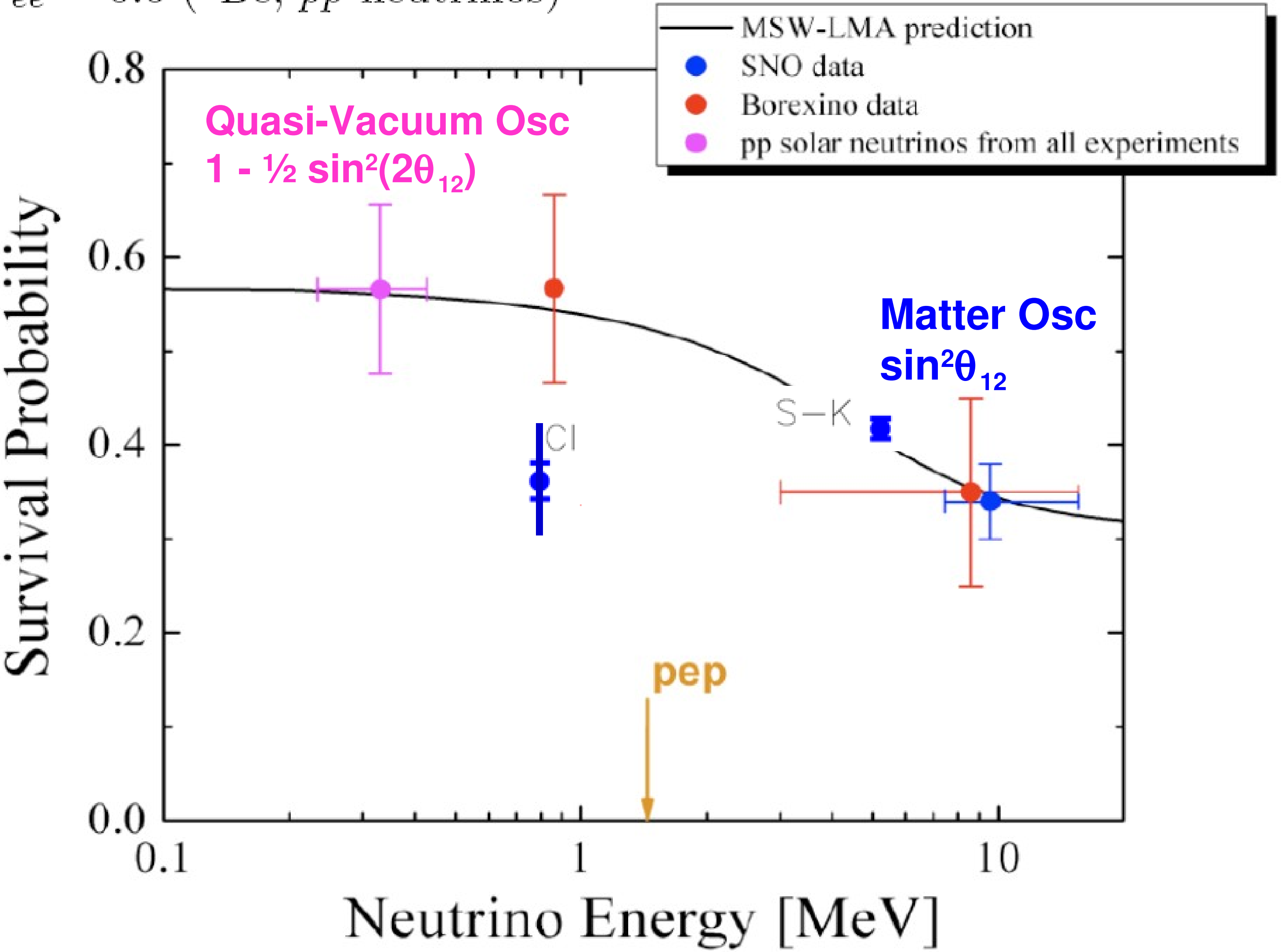
For this hierarchy $P_{ee}^{matter} \geq P_{ee}^{vac} \geq 1/2$

But $P_{ee}^{SNO} = 0.347 \pm 0.038 < 1/2$

This solar hierarchy EXCLUDED !!!.

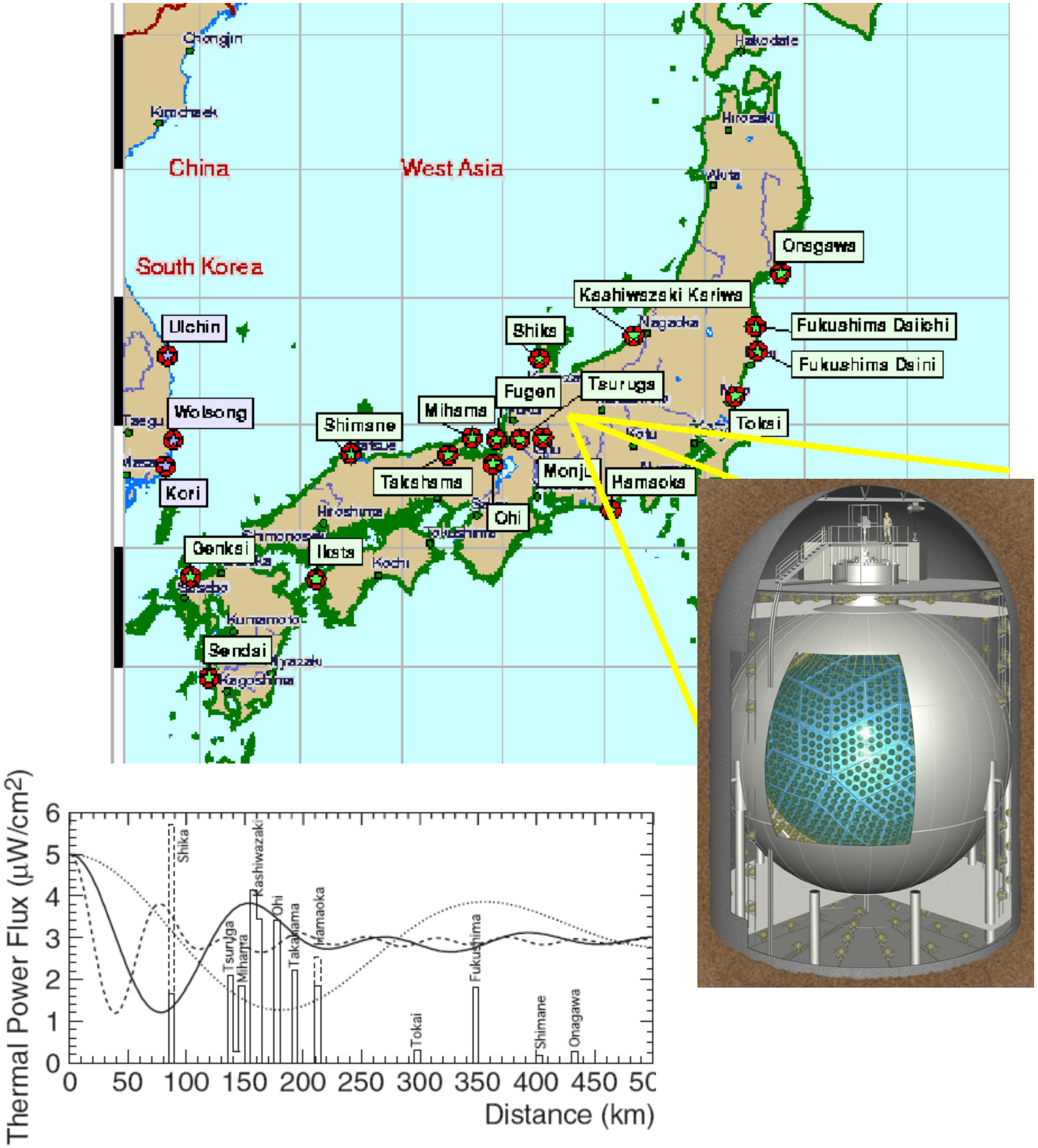
Transition from Vacuum to Matter Oscillations

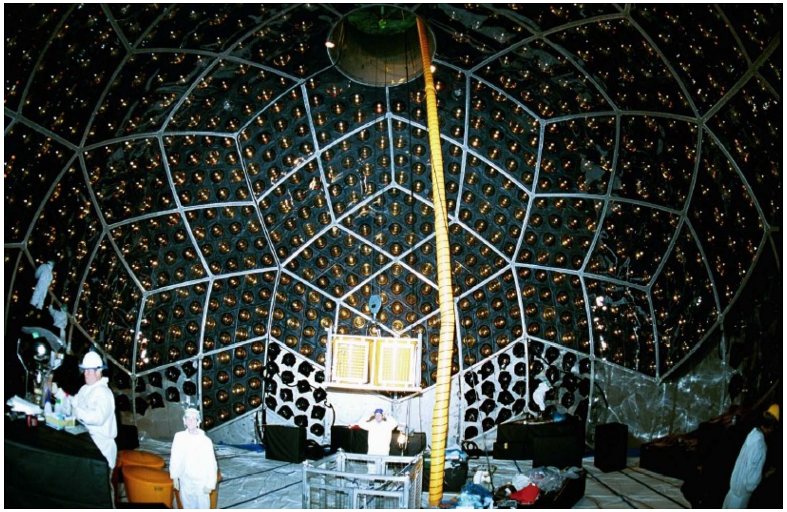
- $P_{ee} \sim 0.3$ (^{8}B neutrinos)
- $P_{ee} \sim 0.6$ (^{7}Be, pp neutrinos)



Kamland Reactor Exp.
(Probes for $\bar{\nu}_e$ Osc. In the Solar Region)

- Uses $\bar{\nu}_e$ from all the reactors in Japan
- 85% of signal events from:
  - Closest 60 GW of power
  - Distance range 140km-344 km with mean 180km
- KamLAND is a 1 kton liquid scintillator detector
  - 2000 photomultiplier tubes
  - 1 km underground





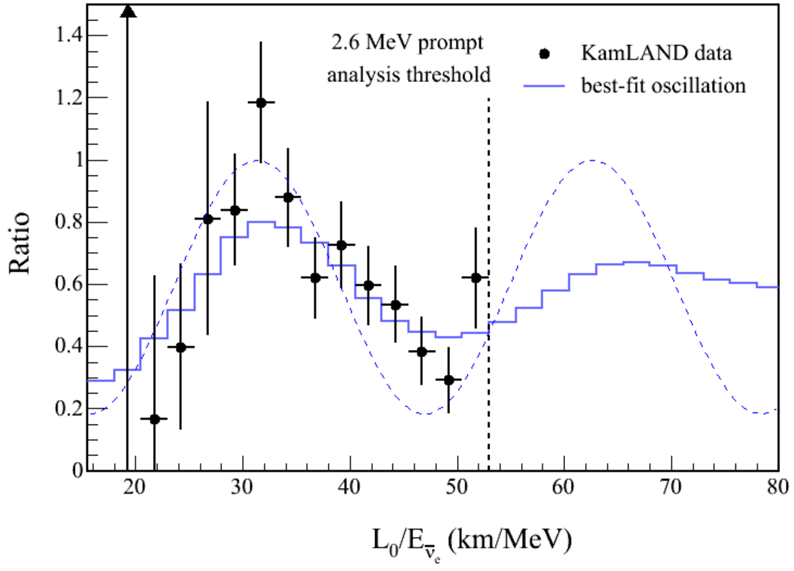
Kamland Neutrino Oscillation Measurements

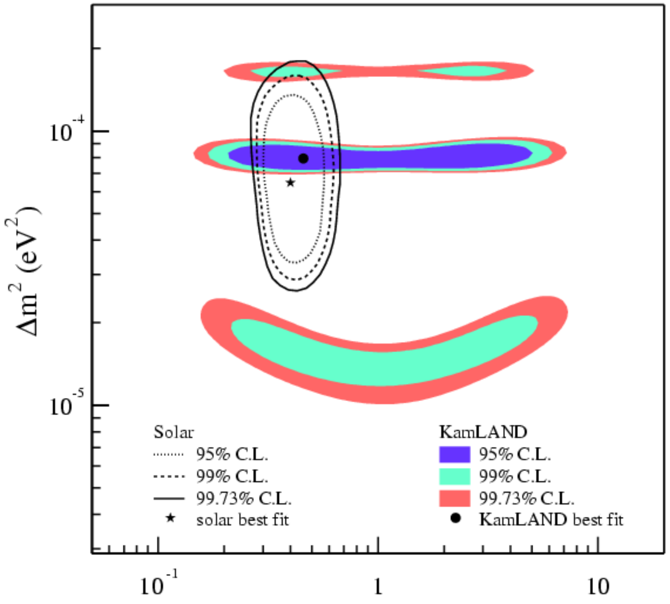
Distribution has L/E behavior expected for neutrino oscillations

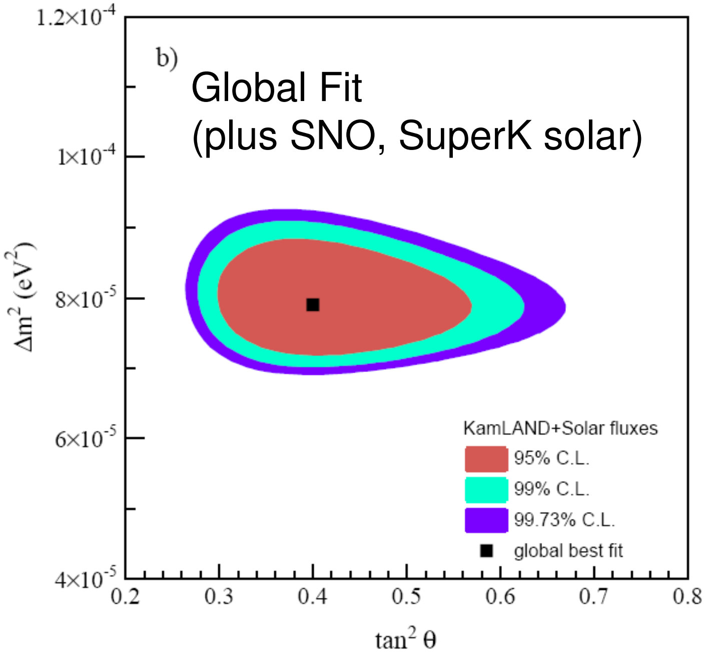
⇒ **KamLAND best fit :**

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

$\tan^2\theta = 0.45$







Global Fit
(plus SNO, SuperK solar)

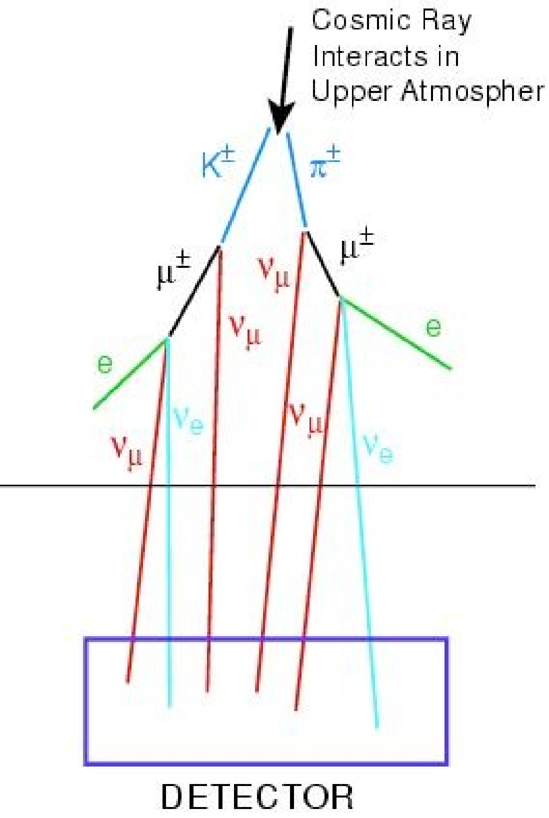
$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}$ eV^2

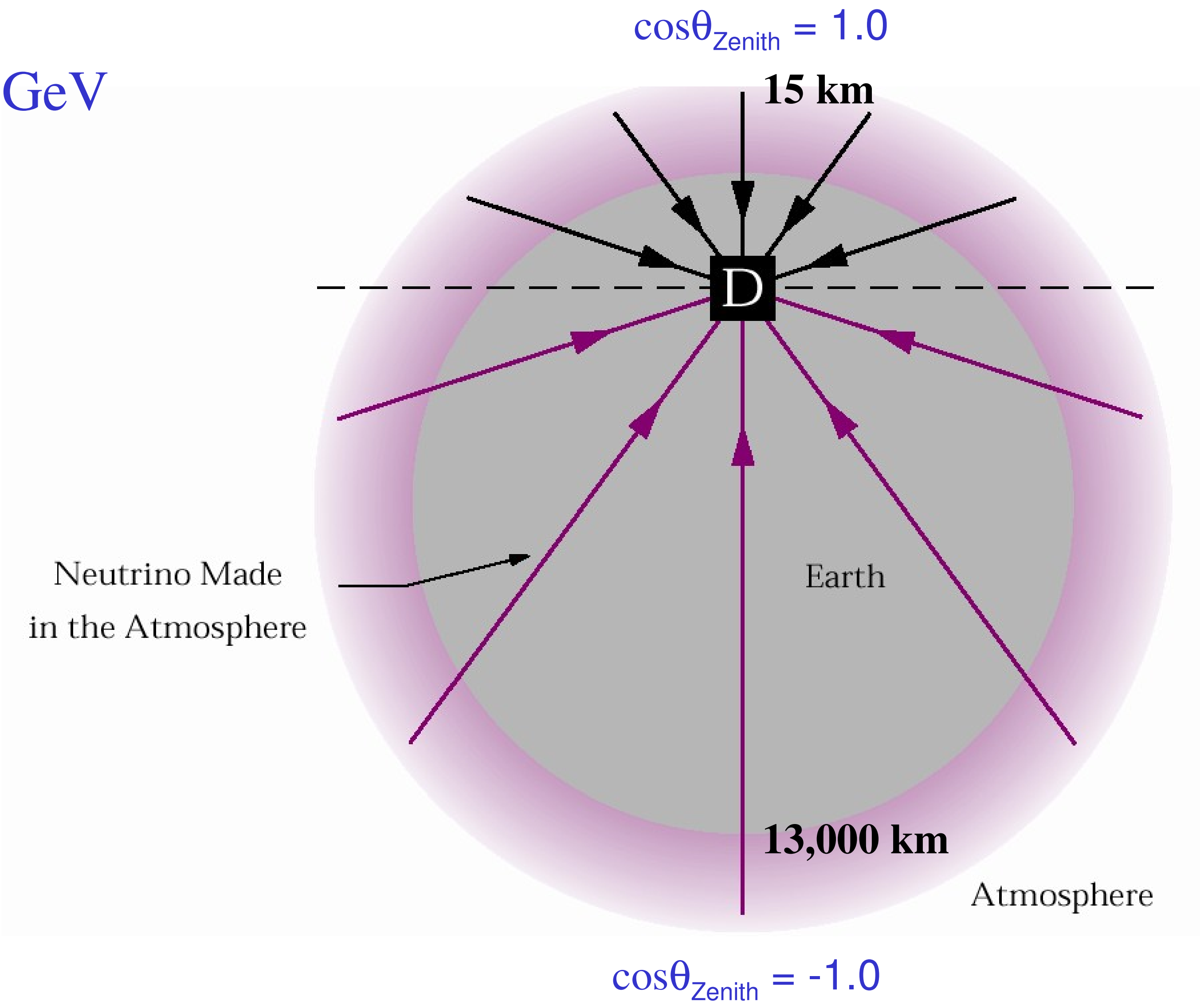
$\tan^2\theta = 0.40^{+0.10}_{-0.07}$

($\sin^2 2\theta_{12} = 0.82^{+0.07}_{-0.07}$)

Atmospheric Neutrino Studies

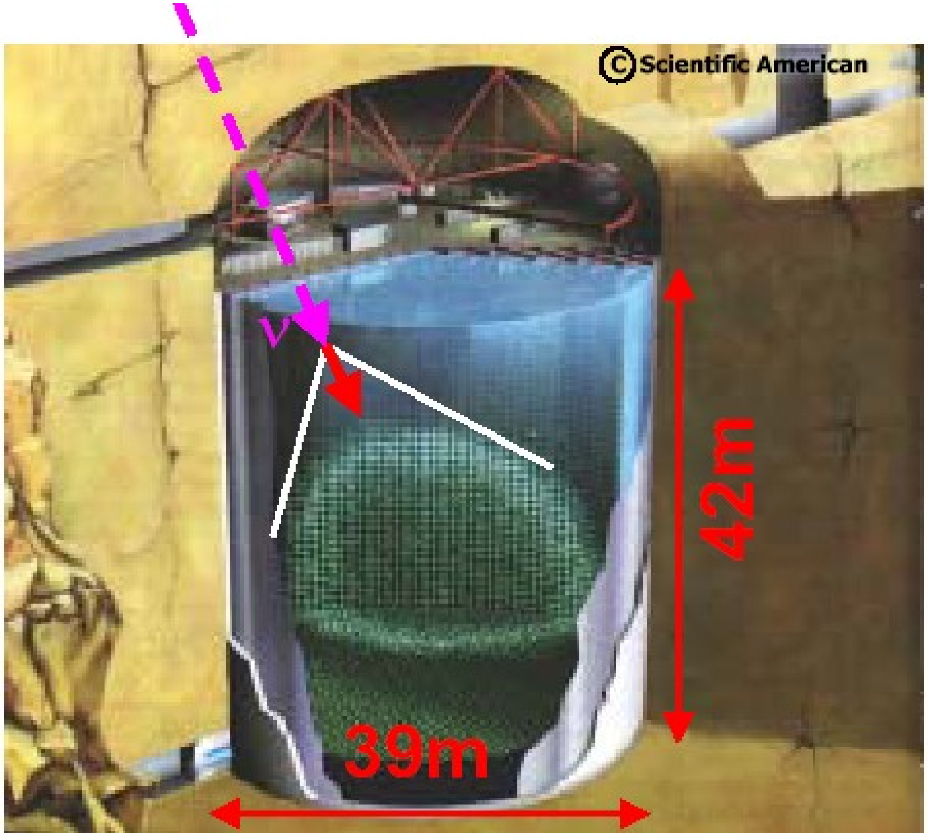
E_ν ~ 300 MeV - 2 GeV

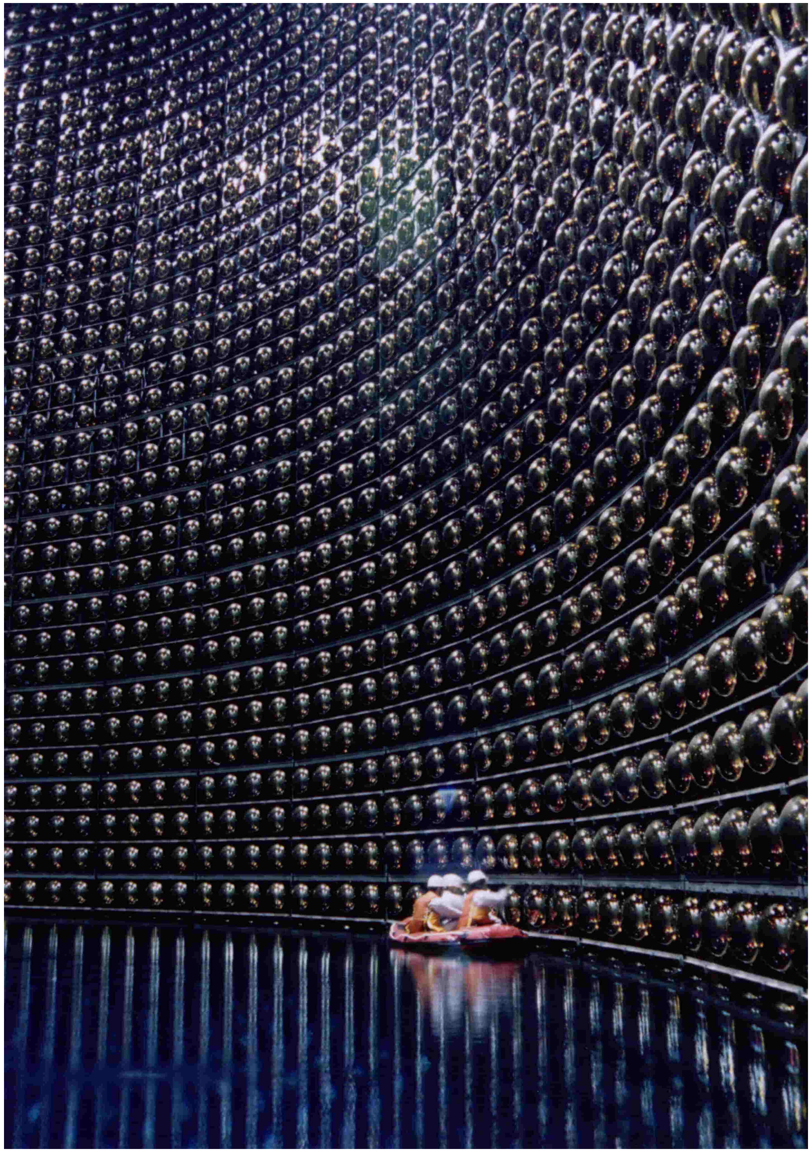




Super-Kamiokande (Super-K) Detector

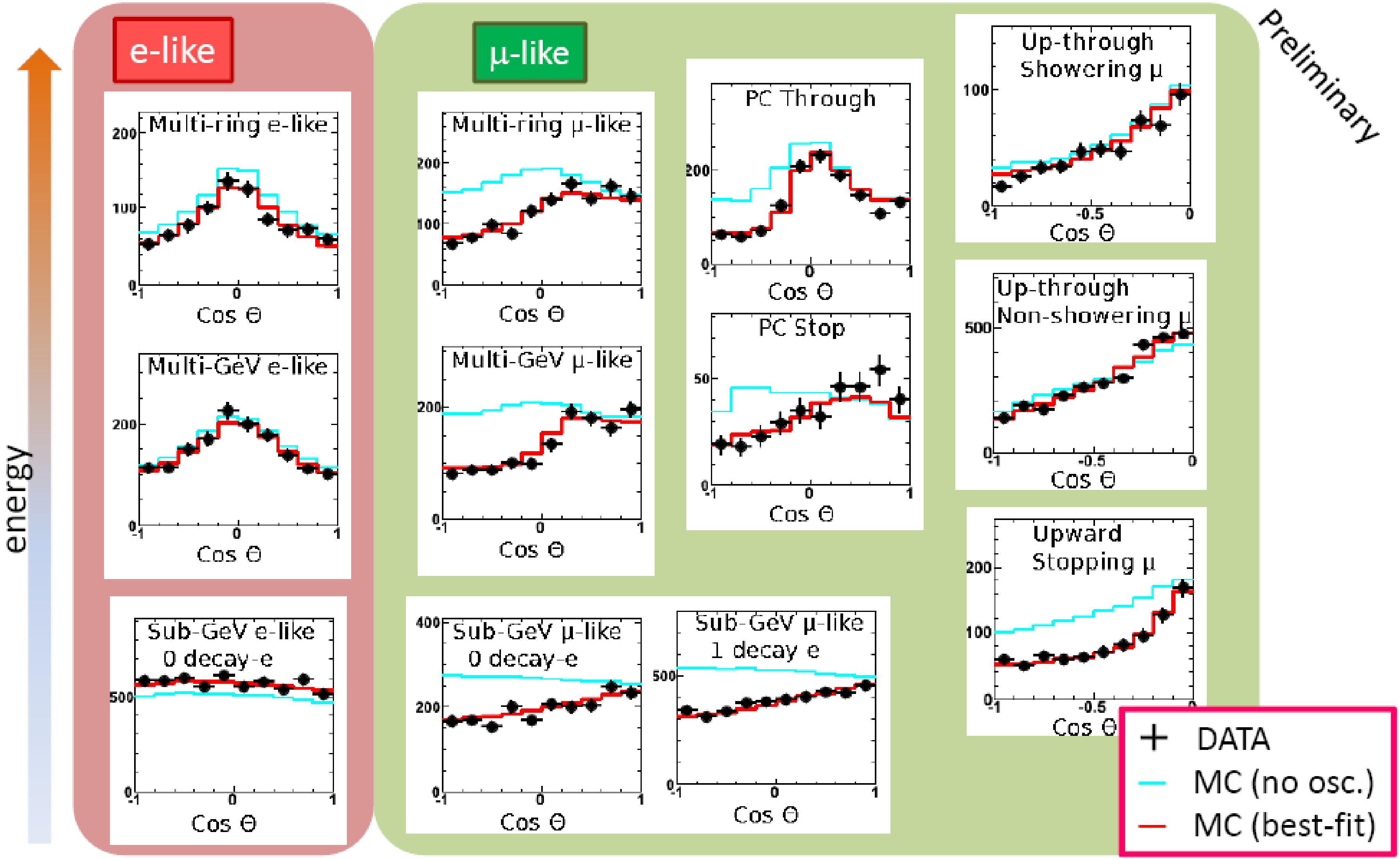
- 22.5 kton of ultra-pure water
- 11,150 20 inch phototubes
- Located in Kamioka mine at a depth of 1000m below the surface





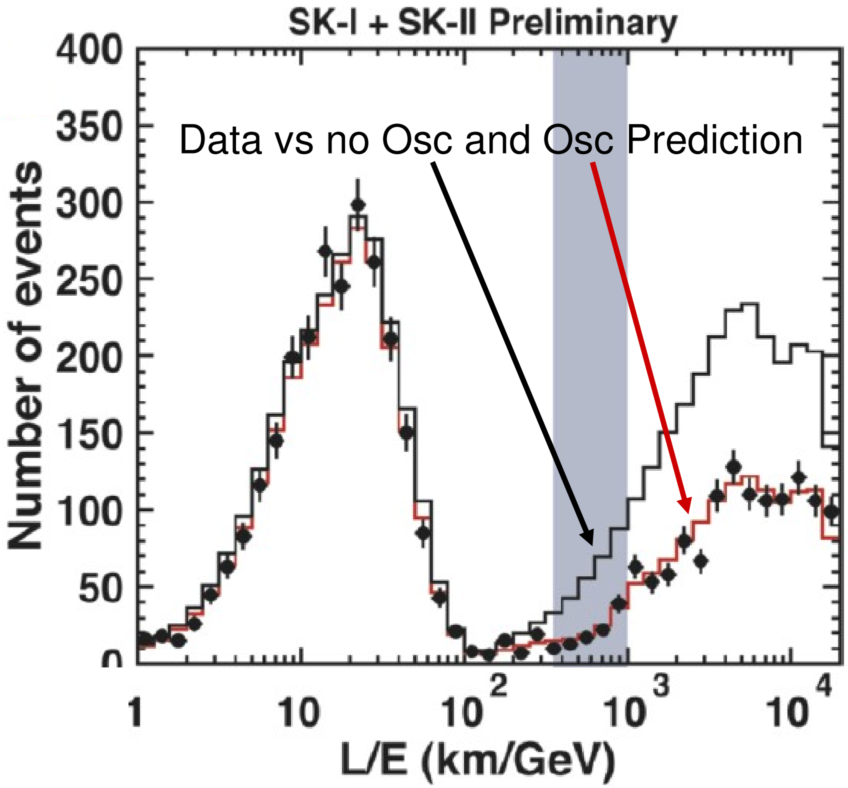
Atmospheric Neutrino Data from Super-K

Super-K-I+II+III (2806 days (173kton・yr) for FC+PC, 3109 days for up-μ)

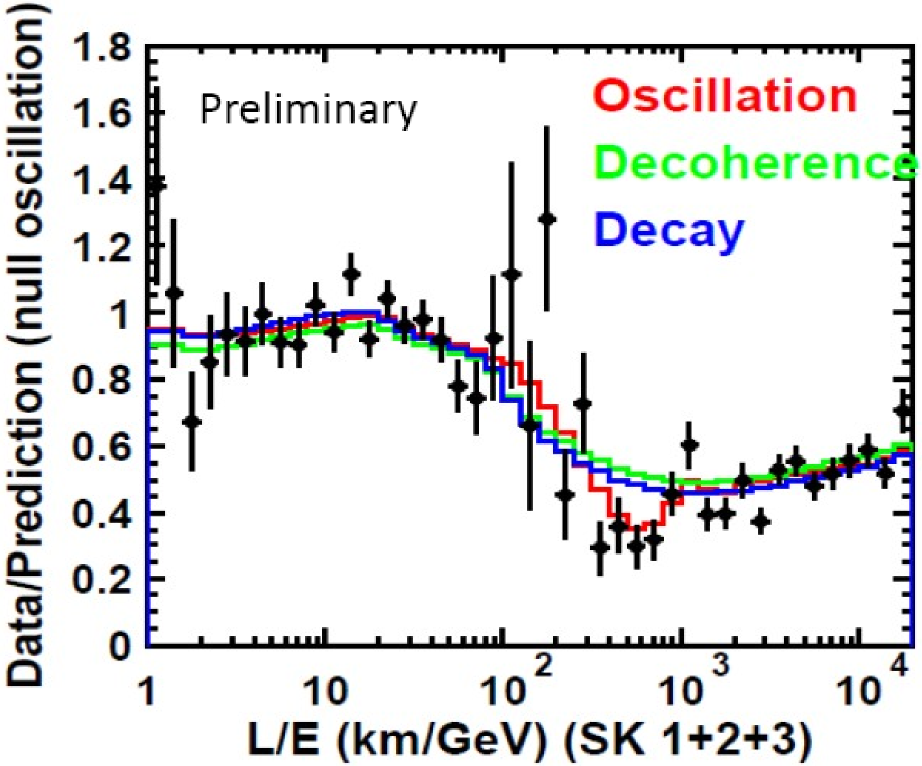


Atmospheric Oscillation Results vs L/E Osc Behaviior

$$P_{osc} = \sin^2(2\theta)\,\sin^2(1.27\Delta m^2 L/E)$$



Data vs no Osc and Osc Prediction



$\sin^2 2\theta_{23} > 0.92$ @ 90% CL

$1.9 \times 10^{-3}\ \mathrm{eV}^2 < \Delta m^2 < 3.0 \times 10^{-3}\ \mathrm{eV}^2$

Inconsistent with:

Neutrino decay (4.4σ)

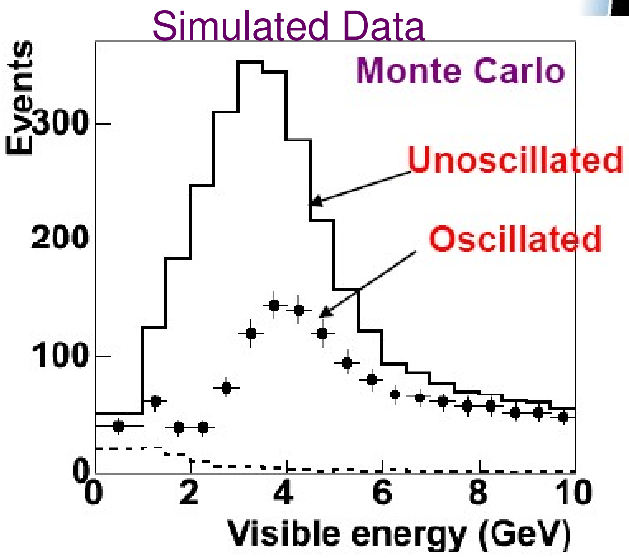
Neutrino decoherence (5.4σ)

MINOS Accelerator Oscillation Experiment at Fermilab

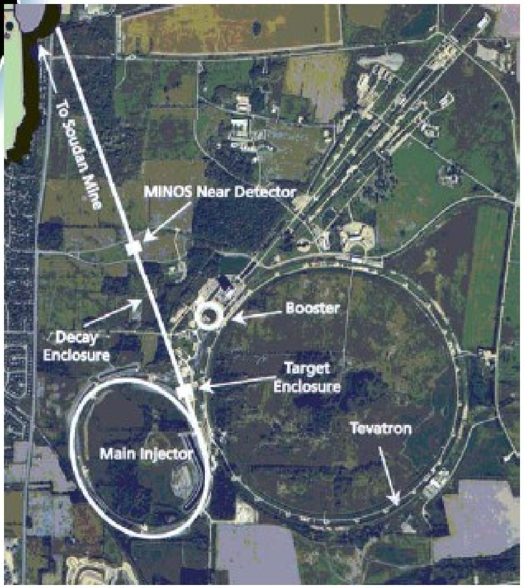
A,Habig, July 2

5.4 kton MINOS far detector

1 kton near detector

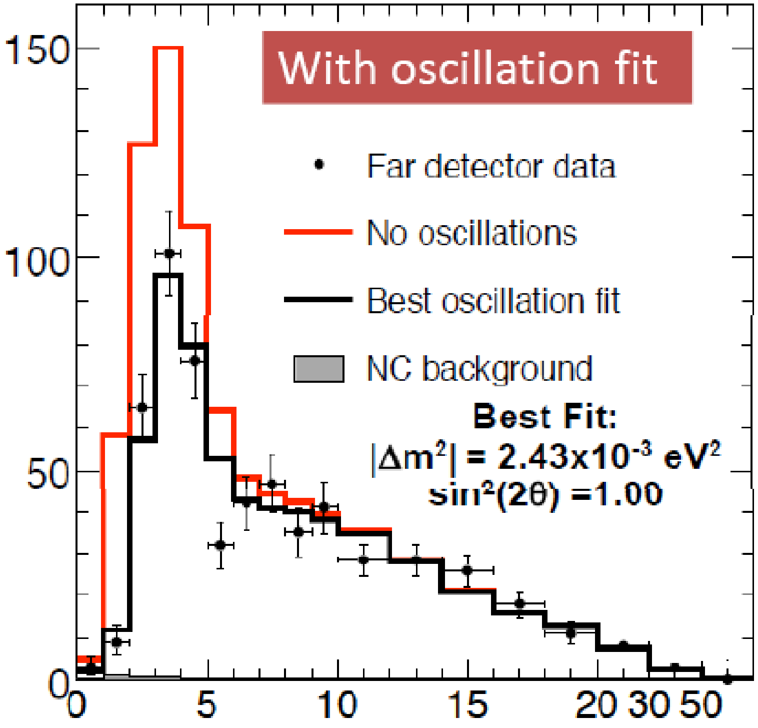


NuMI
beam line

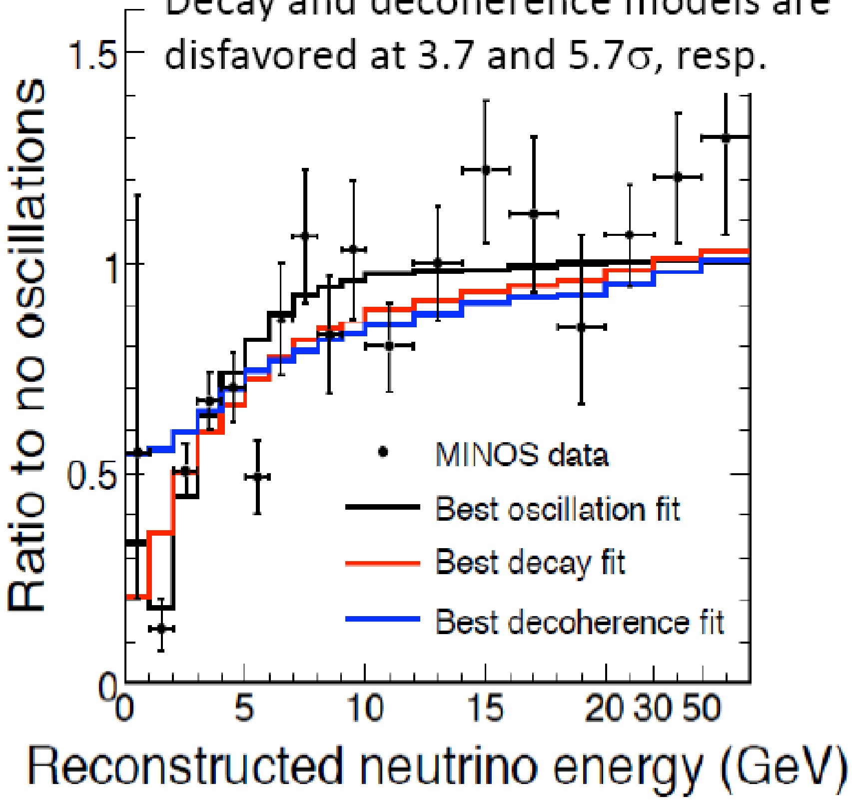


MINOS ν_μ Disappearance Results

848 CC ν_μ candidates ⇐⇒ 1065±60(syst) no-osc. prediction



With oscillation fit



Decay and decoherence models are disfavored at 3.7 and 5.7σ, resp.

$$\Delta m^2_{23} = 2.43 \pm 0.13 \times 10^{-3}\,\mathrm{eV}^2$$

(5% accuracy, MINOS)

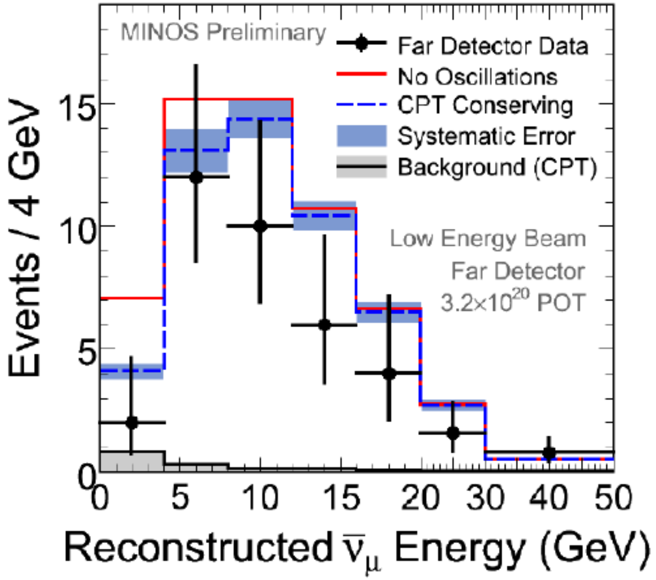
PRL 101 (2008) 131802

(hep-ex/0806.2273)

1st “Pure” $\bar{\nu}_\mu$ Disappearance Results from MINOS

- CPT invariance requires that $\bar{\nu}_\mu$ and ν_μ disappearance should be the same
- MINOS is first longbaseline experiment that can separate $\bar{\nu}_\mu$ and ν_μ interactions using the sign of the outgoing muon.
  - For the standard ν_μ running, 6.4% of CC interactions from $\bar{\nu}_\mu$ with 82% efficiency and 97% purity.

⇒ Can search for $\bar{\nu}_\mu$ disappearance!

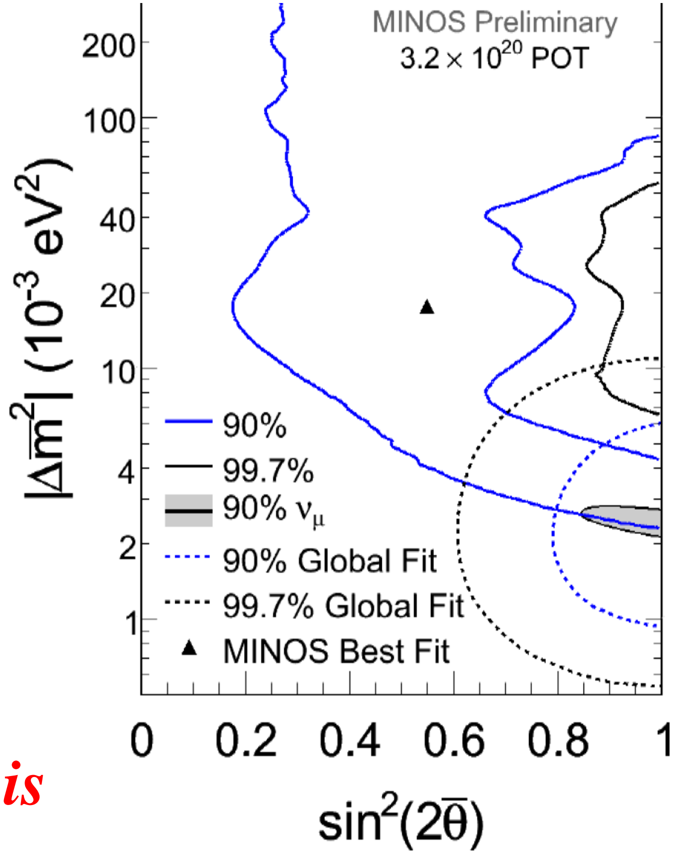


Results: 42 events observed

Expect: No osc: $65 \pm 8_{stat} \pm 4_{syst}$

CPT conserving: $58 \pm 8_{stat} \pm 4_{syst}$

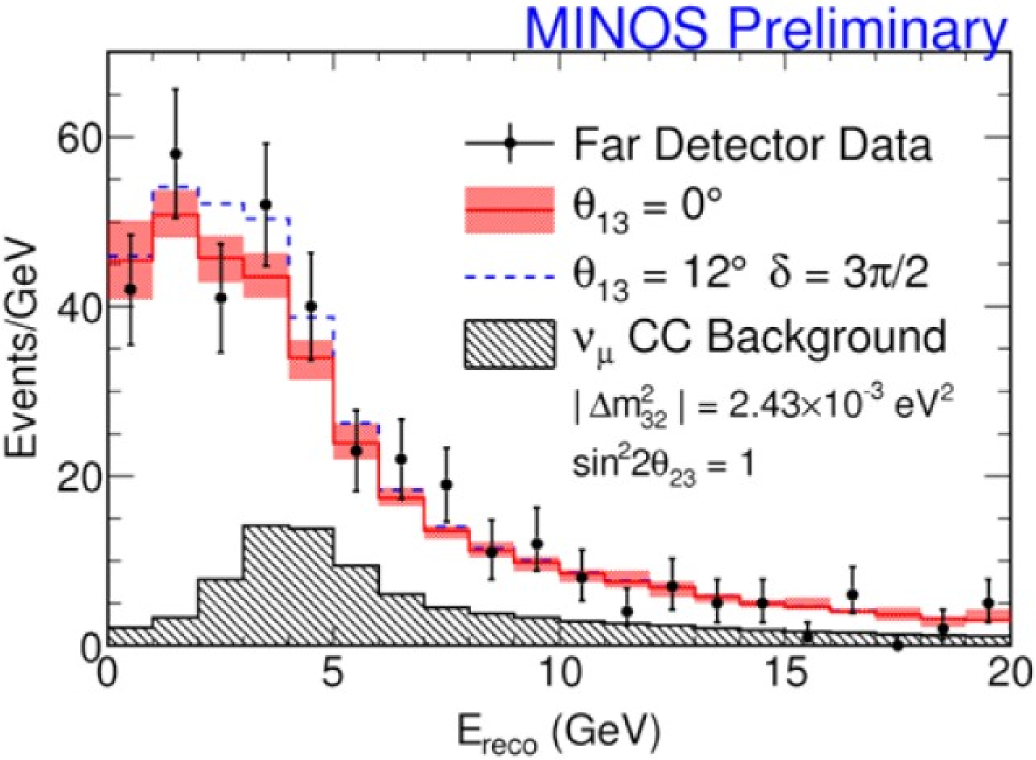
$\bar{\nu}_\mu$ and ν_μ Compatible within statistical uncertainties



Next: Running $\bar{\nu}_\mu$ currently to check this

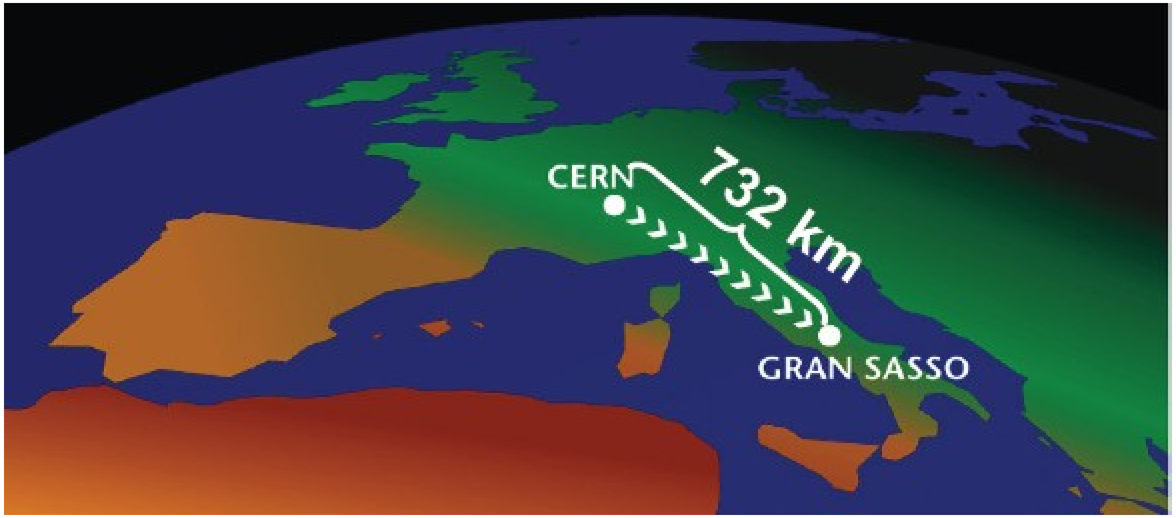
MINOS Search for Oscillations to Sterile Neutrinos

- “Atmospheric region” oscillations from $\nu_\mu \rightarrow \nu_\tau$ but ν_τ energy is below threshold to produce τ leptons $\Rightarrow$ only ν_τ NC interactions $\Rightarrow$ NC rate in near and far detector should be the same
- If $\nu_\mu \rightarrow \nu_{\mathrm{sterile}}$ then NC rate should be less in far detector



Data are consistent with no NC deficit at FD and thus with no sterile neutrino mixing

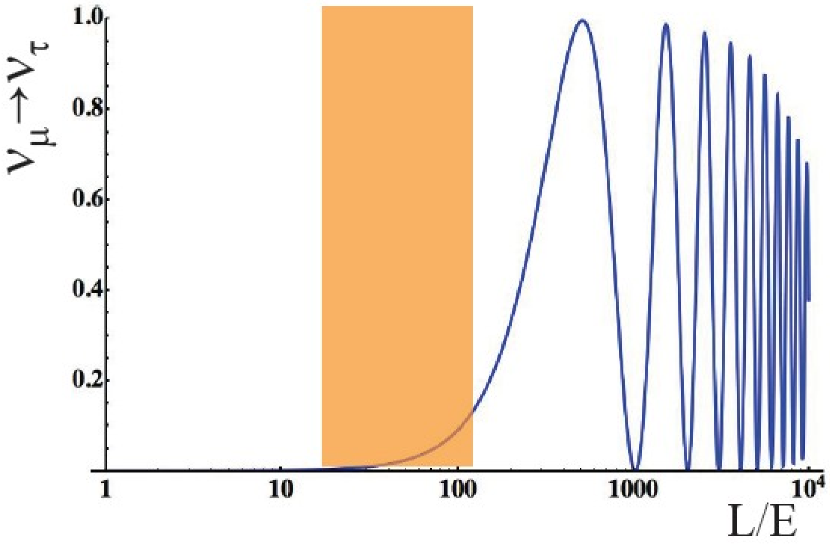
OPERA and ICARUS: ν_τ Appearance Search



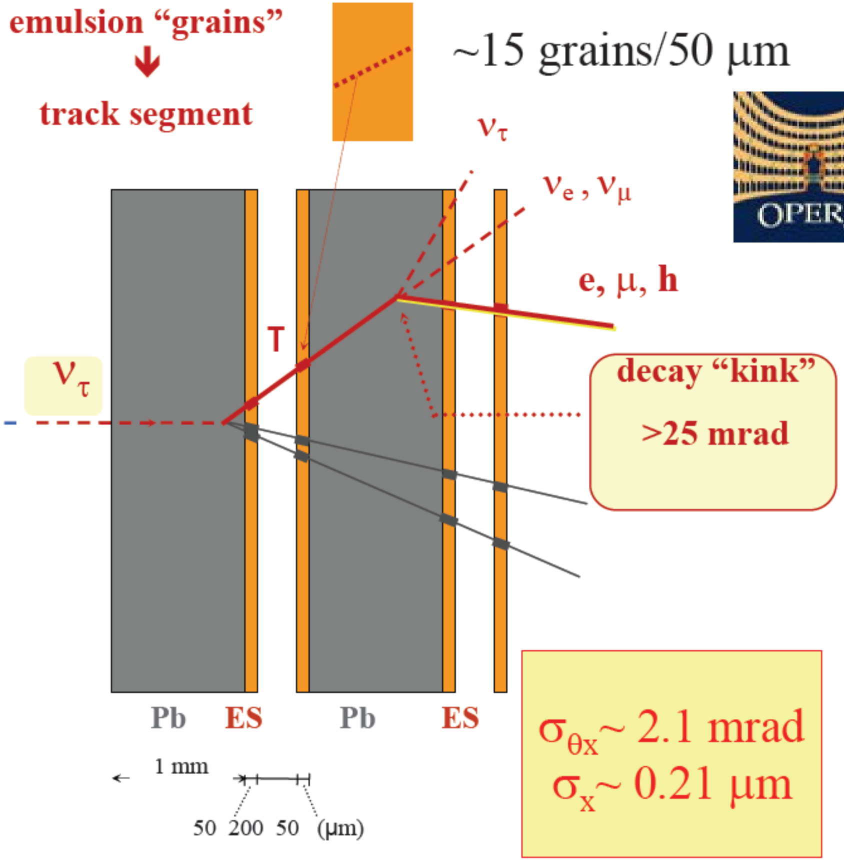
- Uses 400 GeV protons to produce neutrino beam $\langle E_\nu \rangle \approx$ 17 GeV

∀ $\langle E_\nu \rangle$ above threshold to produce τ leptons from ν_τ

∀ $\langle L/E \rangle \approx 43$ so oscillation probability for Δm^2_{atm} is small



OPERA: Nuclear Emulsion plus Lead

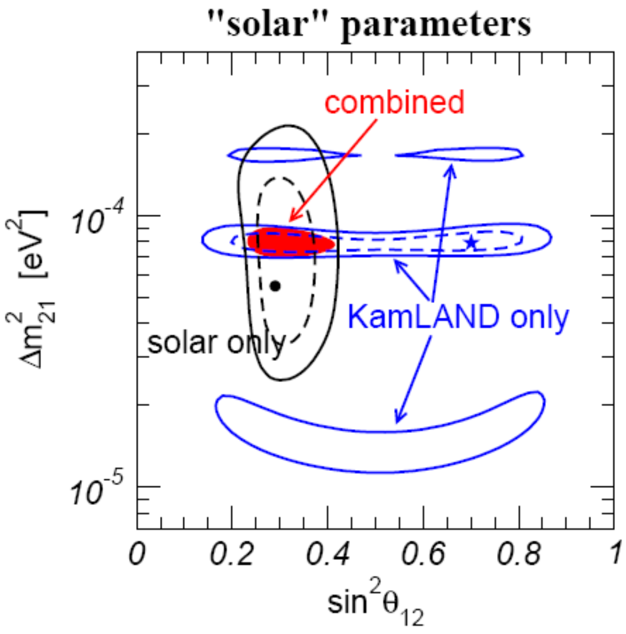


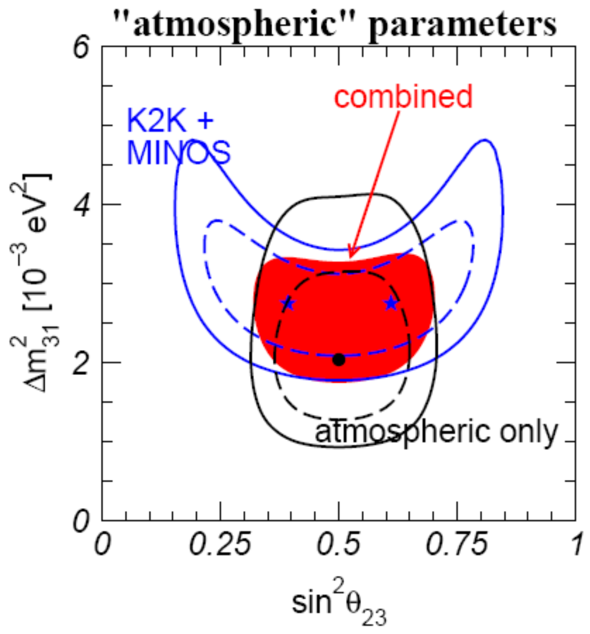
- Scintillator Strips isolate emulsion brick with an event
- Robot then picks out brick to be scanned.
- Currently running since 2007
- Expect about 15 ν_τ events in 5 years

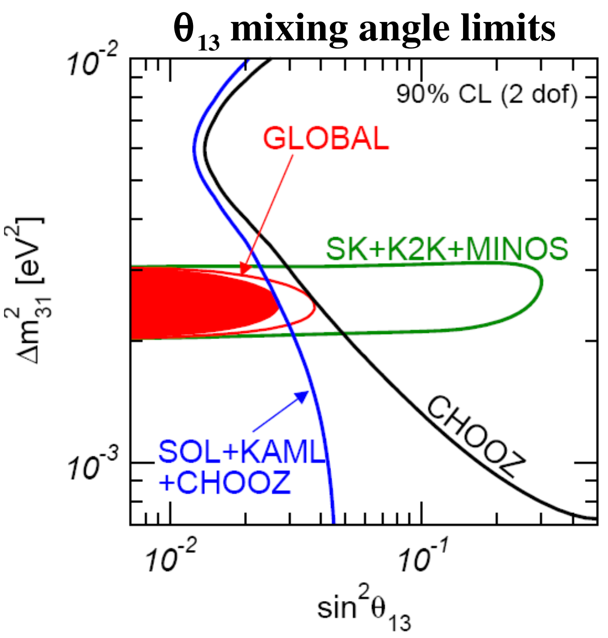
ICARUS: Liquid Argon TPC 600 Tons

- Will use kinematic reconstruction to isolate ν_τ-events.
- 1st event expected by end of 2009

Current Global Fits to Solar, Atmospheric, Accelerator, and Reactor Data

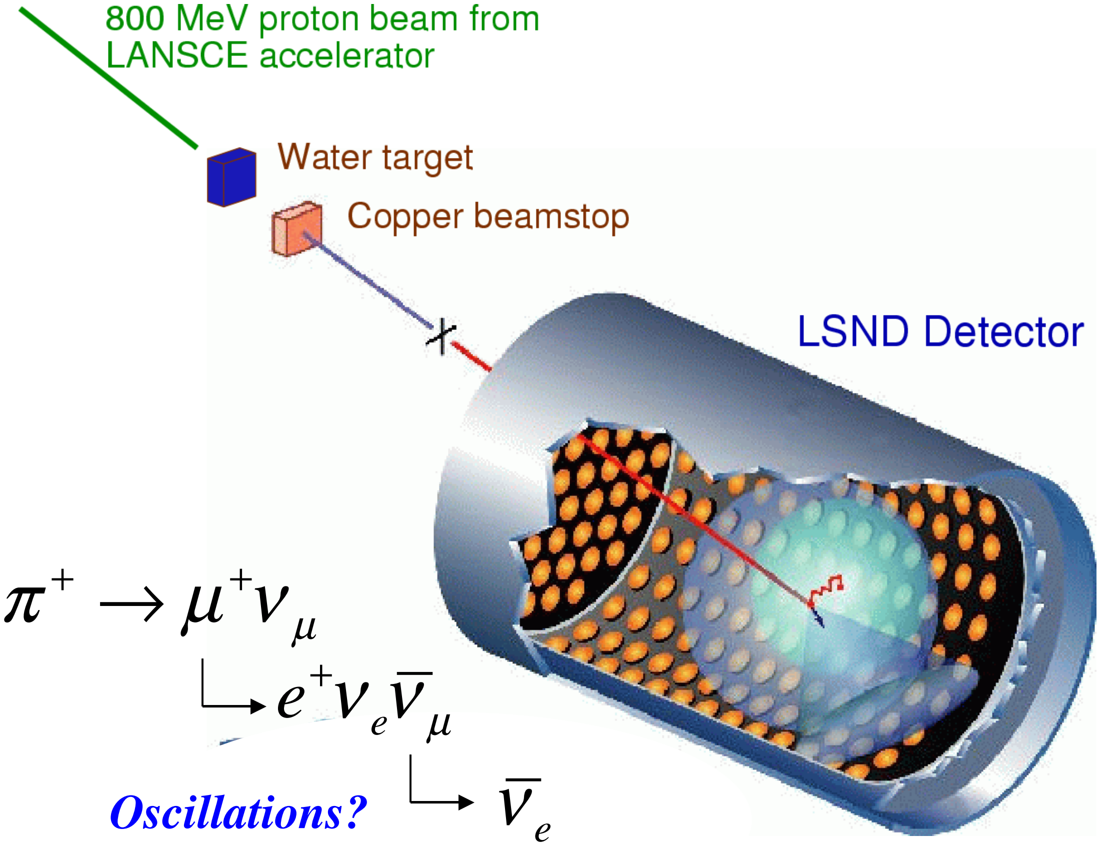






Parameter	Best fit	2σ	3σ
Δm^2_{21} (10^{-5}eV^2)	7.6	7.3–8.1	7.1–8.3
$\lvert\Delta m^2_{31}\rvert$ (10^{-3}eV^2)	2.4	2.1–2.7	2.0–2.8
$\sin^2\theta_{12}$	0.32	0.28–0.37	0.26–0.40
$\sin^2\theta_{23}$	0.50	0.38–0.63	0.34–0.67
$\sin^2\theta_{13}$	0.007	≤ 0.033	≤ 0.050

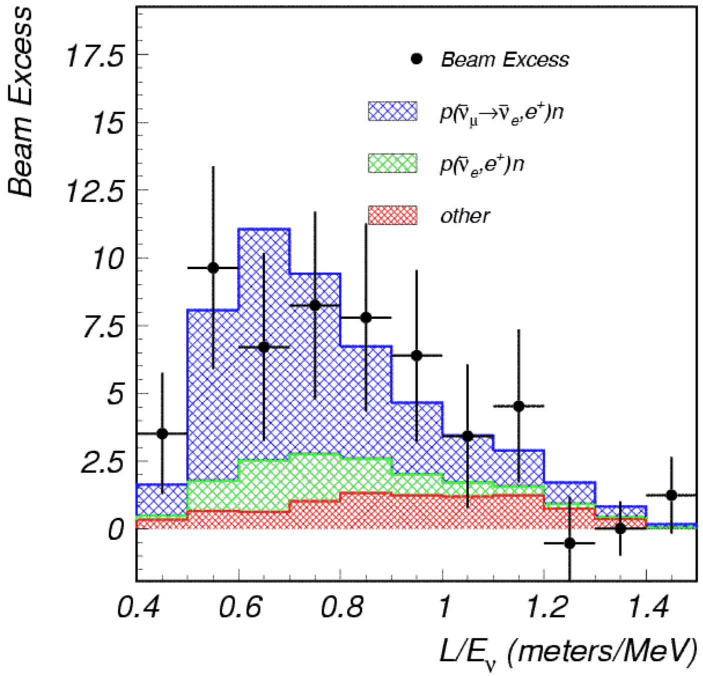
The Fly in the Ointment – “La mosca en la sopa”
The LSND Anomaly



$$\pi^{+} \rightarrow \mu^{+} \nu_{\mu}$$

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

Oscillations? $\rightarrow \bar{\nu}_{e}$



Saw an excess of:
87.9 ± 22.4 ± 6.0 events.

With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

3.8 σ evidence for oscillation.

LSND in conjunction with the atmospheric and solar oscillation results needs more than 3 ν’s

⇒ Models developed with 2 sterile ν’s

or

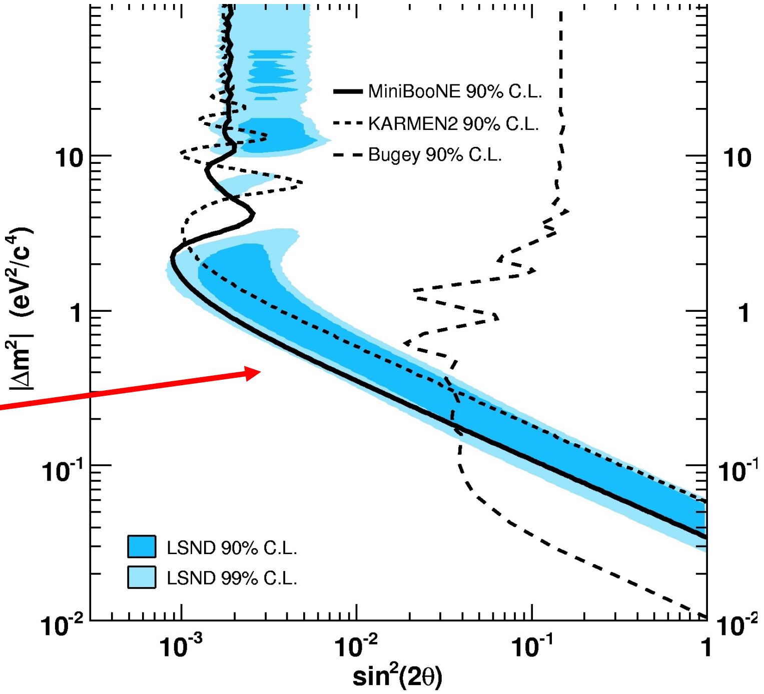
⇒ Other new physics models

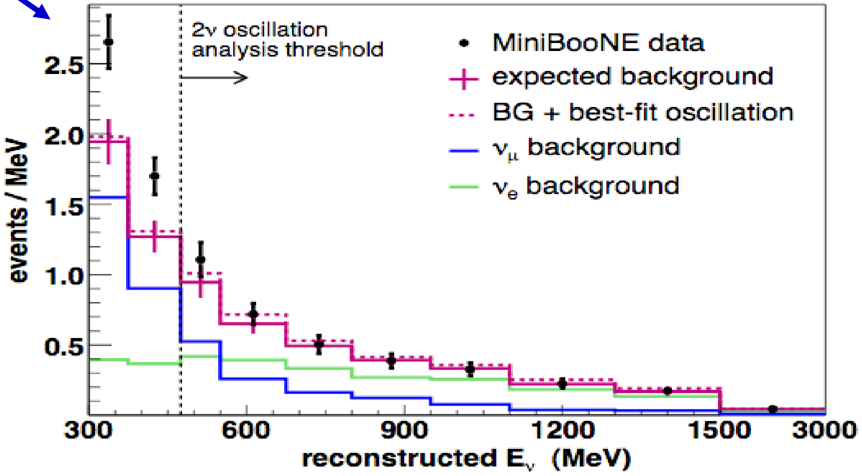
MiniBooNE $\nu_\mu \rightarrow \nu_e$ Appearance Search in LSND Region

- Method: Search for an excess of "ν_e" events over expectation
  $\Rightarrow$ Knowing expectation is key
  Use observed ν_μ events to constrain ν_e physics and background

- In analysis region between 475 < Eν < 3000 MeV, no evidence for oscillation in LSND region
  - Simple 2ν osc excluded at 98% CL

- Unexpected excess of events at low energy < 475 MeV





Phys. Rev. Lett. 98, 231801 (2007), arXiv:0704.1500 [hep-ex]

Also: "Unexplained Excess of Electron-Like Events from a 1 GeV ν Beam", PRL **102**, 101802 (2009)

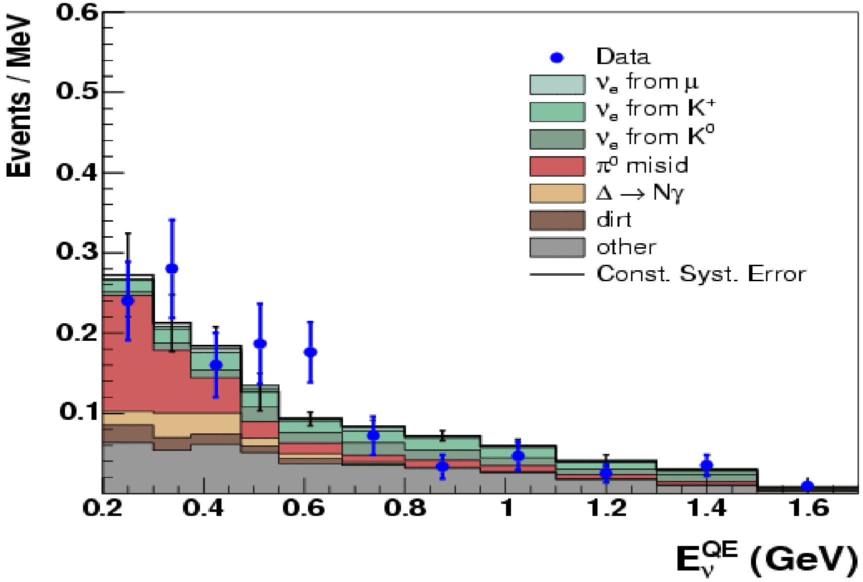
New MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ Appearance Results

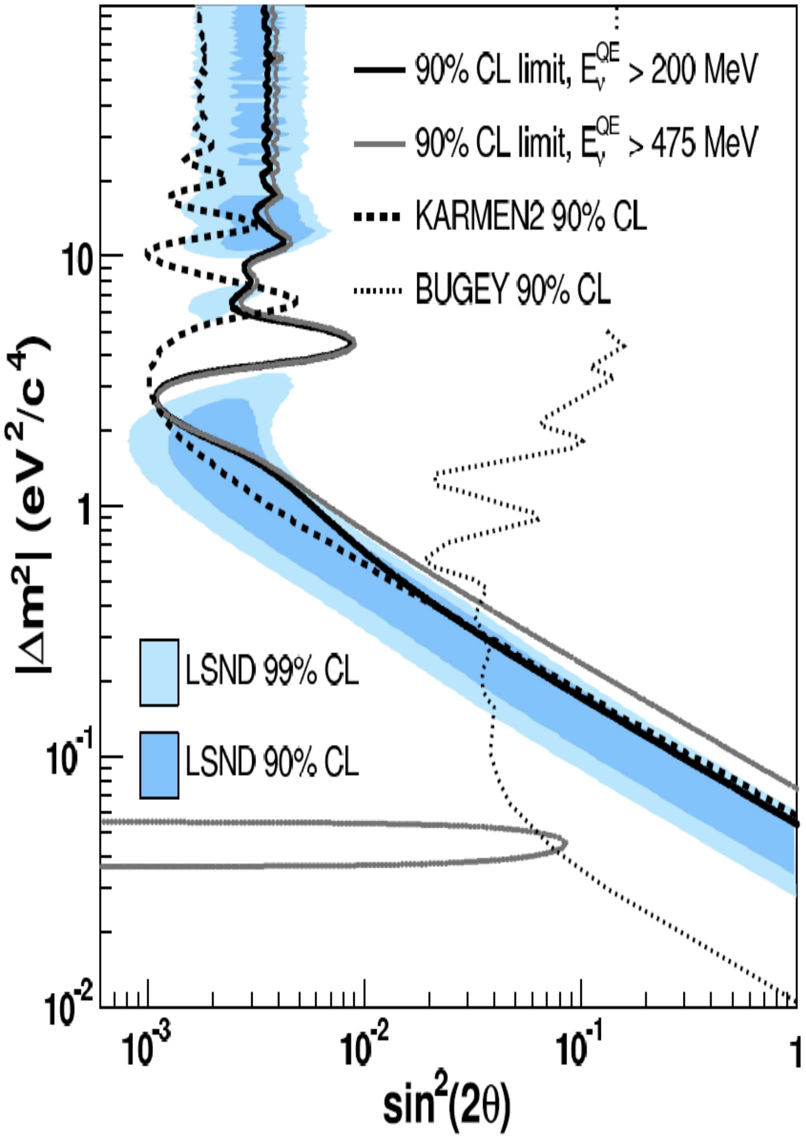
- The antineutrino search important because
  - Provides direct tests of LSND $\bar{\nu}$ appearance
  - More information on low-energy excess
- The backgrounds at low-energy are almost the same for the neutrino and antineutrino data samples.
- Antineutrino analysis is the same as the neutrino analysis.
- First antineutrino result has low statistics
  - 3.4×10^{20} POT giving about 100K event
  - Inconclusive wrt LSND

No indication of $\bar{\nu}$ data-MC excess:

200-475 MeV: -0.5 ± 11.7 events

475-1250 MeV: 3.2 ± 10.0 events

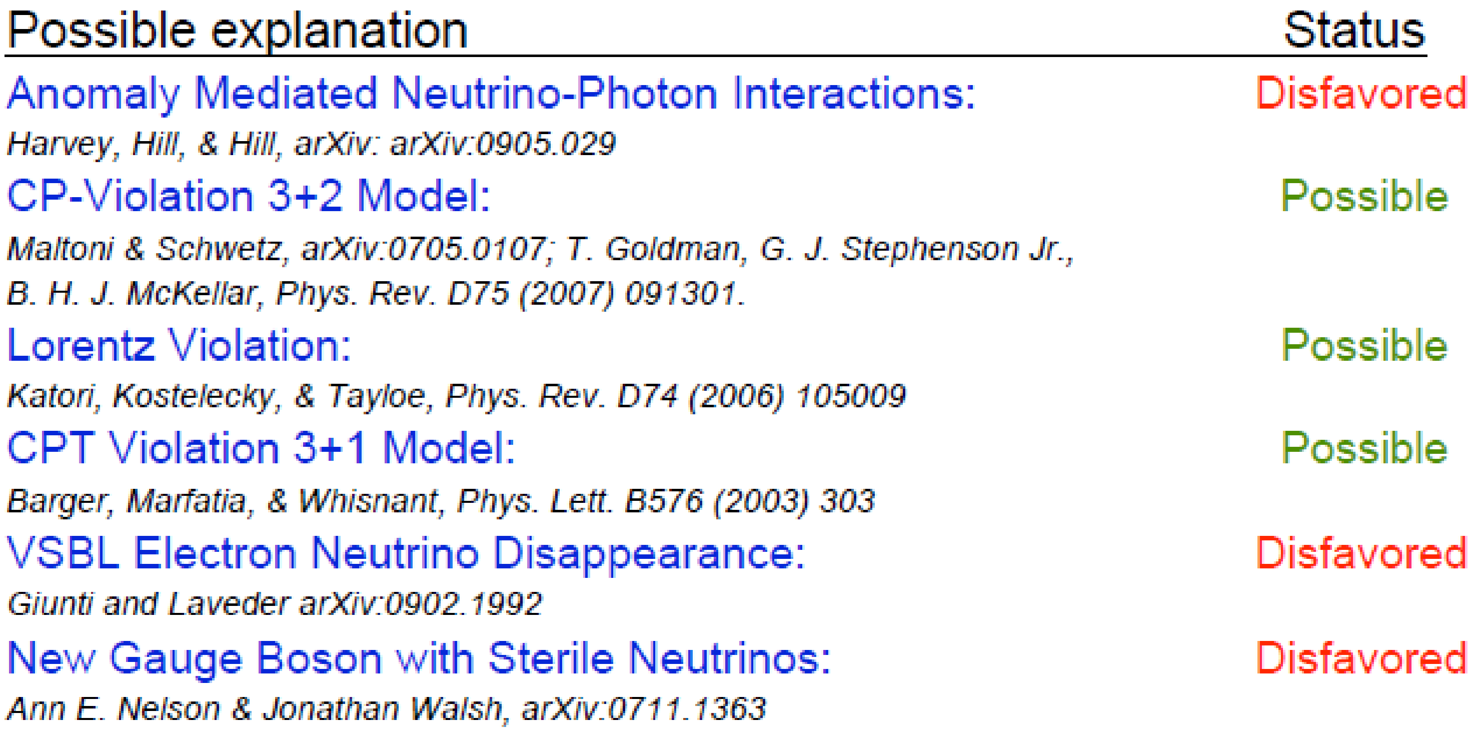




(arXiv:0904.1958)

Low Energy Excess Models

- Few standard model explanations and many new physics ideas
- Many models have equal effects in neutrinos and antineutrinos
  - ⇒ These models are “disfavored” by absence of $\bar{\nu}_e$ excess.

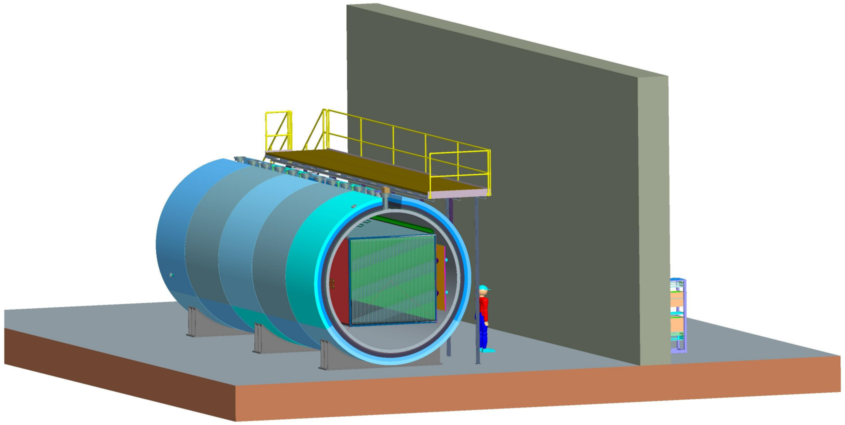


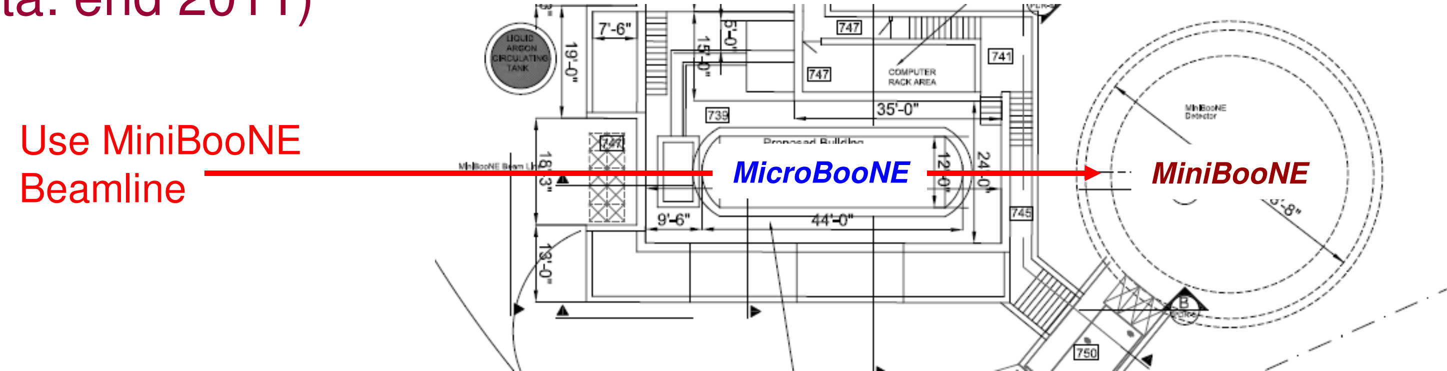
Possible explanation	Status
Anomaly Mediated Neutrino-Photon Interactions: *Harvey, Hill, & Hill, arXiv: arXiv:0905.029*	Disfavored
CP-Violation 3+2 Model: *Maltoni & Schwetz, arXiv:0705.0107; T. Goldman, G. J. Stephenson Jr., B. H. J. McKellar, Phys. Rev. D75 (2007) 091301.*	Possible
Lorentz Violation: *Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009*	Possible
CPT Violation 3+1 Model: *Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303*	Possible
VSBL Electron Neutrino Disappearance: *Giunti and Laveder arXiv:0902.1992*	Disfavored
New Gauge Boson with Sterile Neutrinos: *Ann E. Nelson & Jonathan Walsh, arXiv:0711.1363*	Disfavored

Future Plans and Prospects

- Will triple the MiniBooNE $\bar{\nu}$ data over the next 2 years
  ⇒ Allow better comparison of low-energy excess

- New MicroBooNE Experiment approved at Fermilab
  - Liquid Argon TPC detector which can address the low-energy excess:
    - – Reduced background levels
    - – Is excess due to single electron or photon events?
  - Approximately 70-ton fiducial volume detector, located near MiniBooNE (initial data: end 2011)





Use MiniBooNE Beamline

MicroBooNE

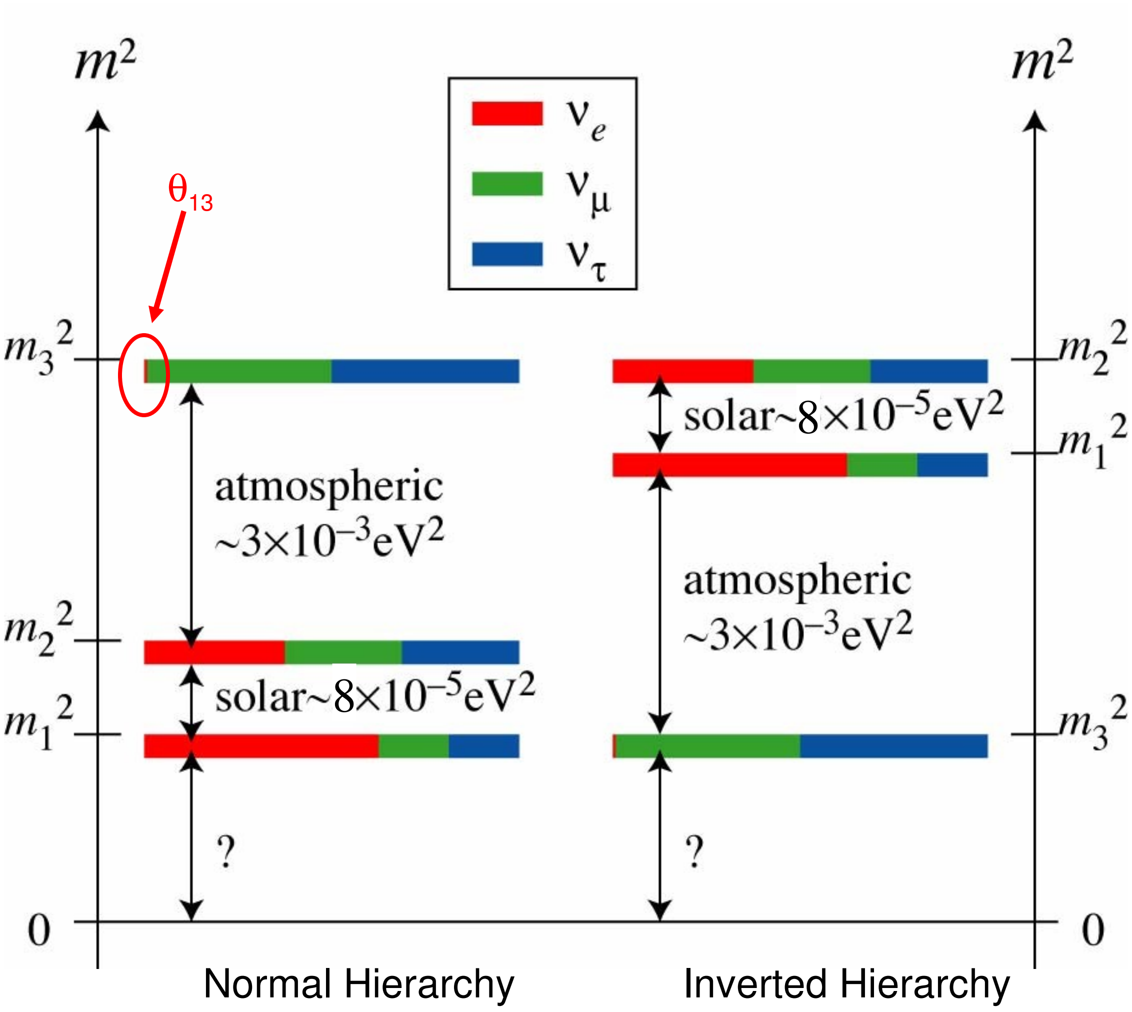
MiniBooNE

Big Questions in Neutrino Oscillations

- What is ν_e component in the ν_3 mass eigenstate? $\Rightarrow$ The size of the "little mixing angle", θ_{13} ?
  - Only know $\theta_{13}<11^0$

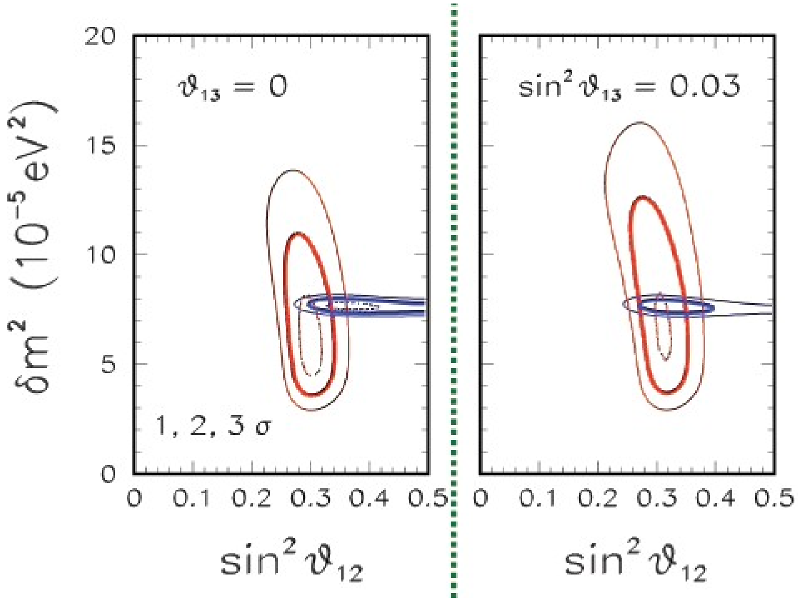
3. What is the mass hierarchy?
   - Is the solar pair the most massive or not?

4. Do neutrinos exhibit CP violation, i.e. is $\delta \neq 0$?



Some Current Hints of Non-zero θ_{13}

- 3ν analysis Atmospheric region from Super-K, K2K, and Chooz
  - Small excess of sub-GeV electron-like events if solar δm^2 included in the fit $\Rightarrow$ 1 sigma effect
- Solar and Kamland prefer a different value of θ_{12} unless $\theta_{13}>0$
  - 1.2 to 1.5 sigma effect
- MINOS sees a 1.5 sigma excess in ν_e appearance search



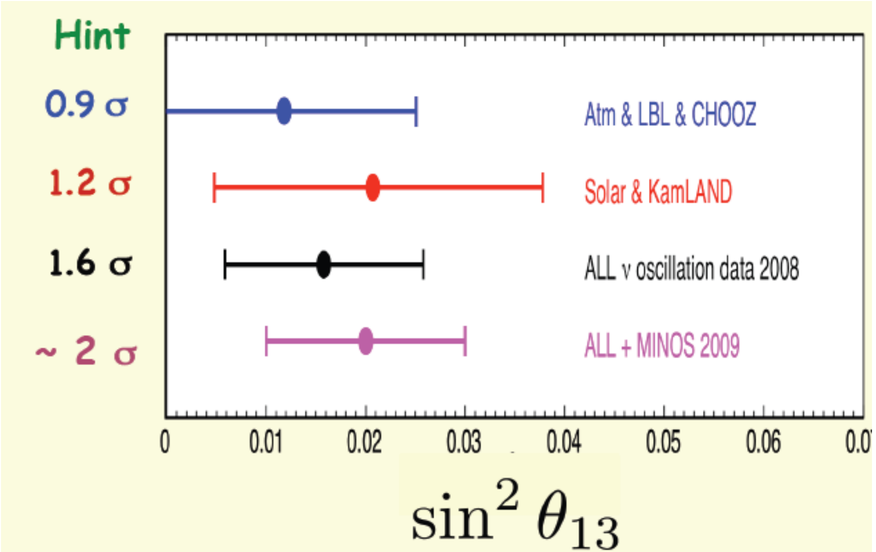
Solar (red) vs Kamland (blue)

Be careful, these are regions for $\sin^2\theta_{ij}$!!

$\sin^2\theta_{13} = 0.02 \;\Rightarrow\; \sin^2 2\theta_{13} = 0.08$

Cheat Sheet:

$U_{e3}^2 = \sin^2\theta_{13} \sim \frac{1}{2}\sin^2\theta_{\mu e} \sim 1/4 \sin^2 2\theta_{13}$



Fogli et al. hep-ph 0905.3549

The Search for the “Little Mixing Angle” (θ_{13}), CP Violation, and the Mass Hierarchy

Experimental Methods to Measure the “Little Mixing Angle”, θ_{13}

- Long-Baseline Accelerators: Appearance ($\nu_\mu \to \nu_e$) at $\Delta m^2 \approx 2.5 \times 10^{-3}$ eV^2
  - Look for appearance of ν_e in a pure ν_μ beam vs. L and E
    - Use near detector to measure background ν_e's (beam and misid)

NOνA:
$\langle E_\nu \rangle = 2.3$ GeV
$L = 810$ km

T2K:
$\langle E_\nu \rangle = 0.7$ GeV
$L = 295$ km

- Reactors: Disappearance ($\bar{\nu}_e \to \bar{\nu}_e$) at $\Delta m^2 \approx 2.5 \times 10^{-3}$ eV^2
  - Look for a change in $\bar{\nu}_e$ flux as a function of L and E
    - Look for a non- $1/r^2$ behavior of the ν_e rate
    - Use near detector to measure the un-oscillated flux

Double Chooz:
$\langle E_\nu \rangle = 3.5$ MeV
$L = 1100$ m

Long-Baseline Accelerator Appearance Experiments

- Oscillation probability complicated and dependent not only on θ$_{13}$ but also:
  - CP violation parameter (δ)
  - Mass hierarchy (sign of Δm$_{31}^2$)
  - Size of sin^{2}θ$_{23}$

$$\begin{aligned}
P(\nu_\mu \to \nu_e) &= 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\;(1-2S_{13}^2)\right) \\
&+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} (1-2S_{13}^2)
\end{aligned}$$

⇒ ***These extra dependencies are both a "curse" and a "blessing"***

Reactor Disappearance Experiments

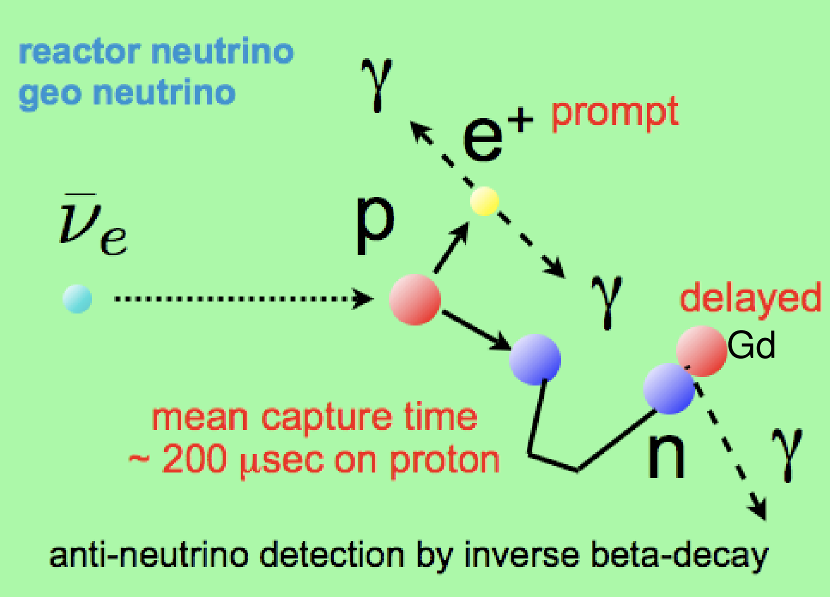
- Reactor disappearance measurements provide a straight forward method to measure θ$_{13}$ with no dependence on matter effects and CP violation

$$P(\bar{\nu}_e = \;\; \not\to \bar{\nu}_e) \quad 1 \quad \sin^2 2\theta_{13} \sin^2 + \frac{\Delta m_{13}^2 L}{4E} \qquad \textit{small terms}$$

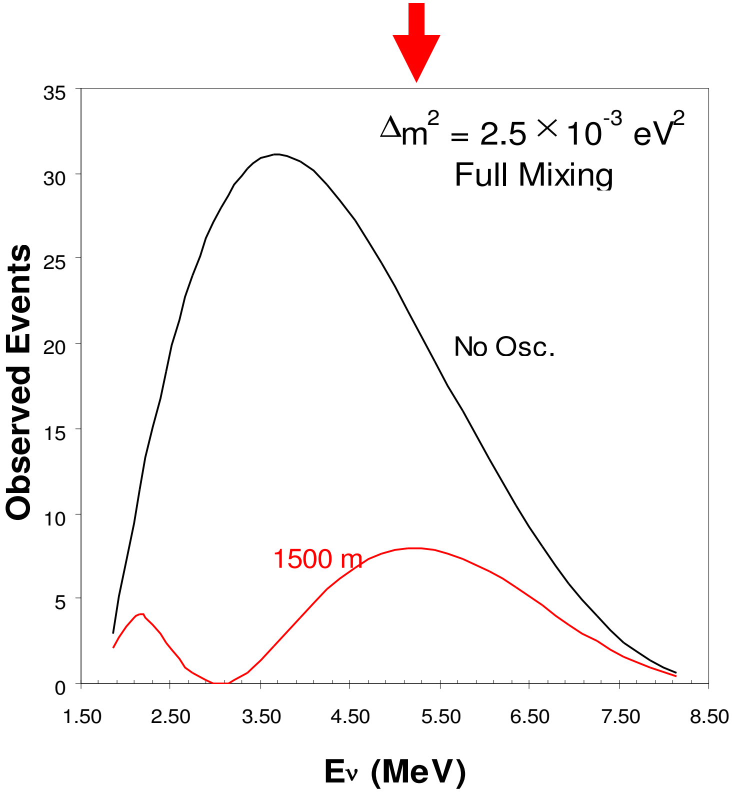
Reactor Neutrino Experiments

Reactor Measurements of θ_{13}

- Nuclear reactors are very intense sources of $\bar{\nu}_e$ with a well understood spectrum
  - 3 GW → 6×10^{20} $\bar{\nu}_e$/s
    700 events / yr / ton at 1500 m away
  - Reactor spectrum peaks at ~3.7 MeV
  - Oscillation Max. for $\Delta m^2 = 2.5\times10^{-3}$ eV^2 at L near 1500 m



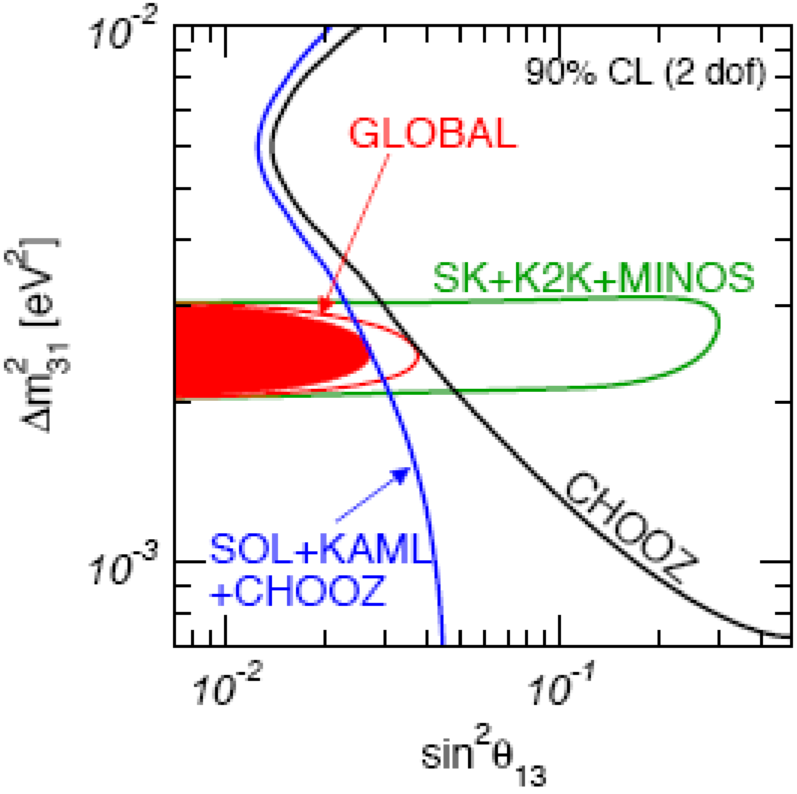
anti-neutrino detection by inverse beta-decay



- Disappearance Measurement:
  Look for small rate deviation from $1/r^2$ measured at near and far baselines
  - Counting Experiment
    - Compare events in near and far detector
  - Energy Shape Experiment
    - Compare energy spectrum in near and far detector

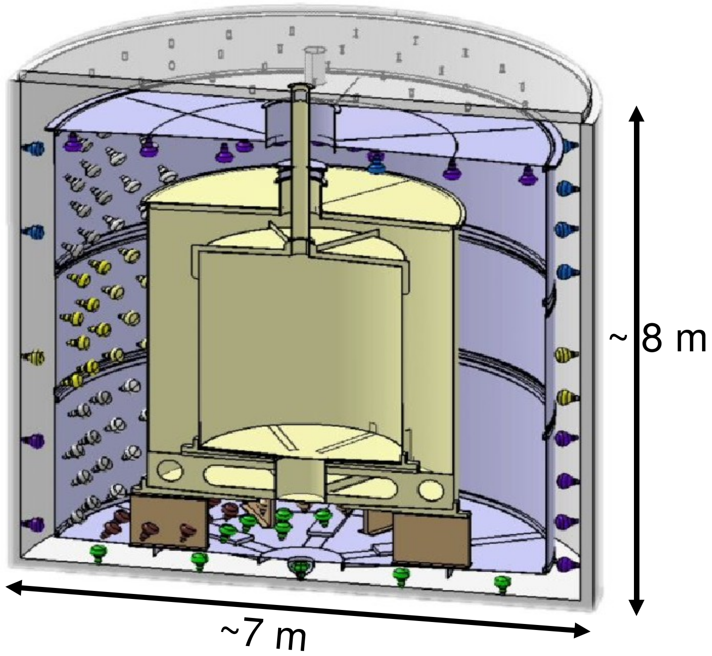
Current Limits on $\sin^2\theta_{13}$

Best current limit from:
CHOOZ (single detector experiment)
$\sin^2(2\theta_{13}) < 0.14$
$(\sin^2(\theta_{13}) < 0.035)$

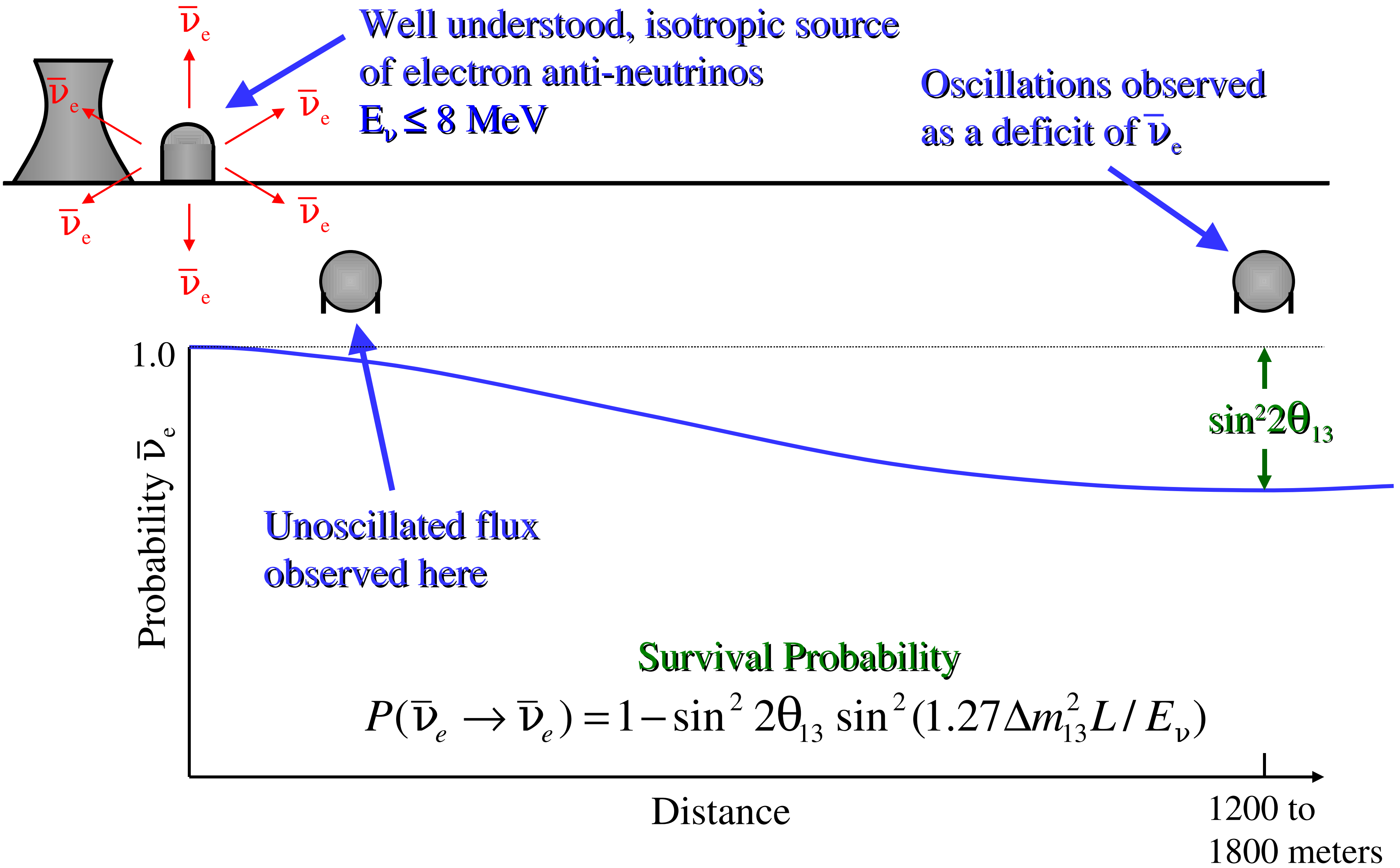


How to do better than previous reactor experiments?

- ⇒ **Reduce systematic uncertainties due to reactor flux and detector**
- ⇒ **Larger detectors**
- ⇒ **Reduce and control backgrounds**
- ⇒ **Use Near/Far Detectors**



Two Detector Reactor Experiment



Well understood, isotropic source
of electron anti-neutrinos
$E_\nu \leq 8$ MeV

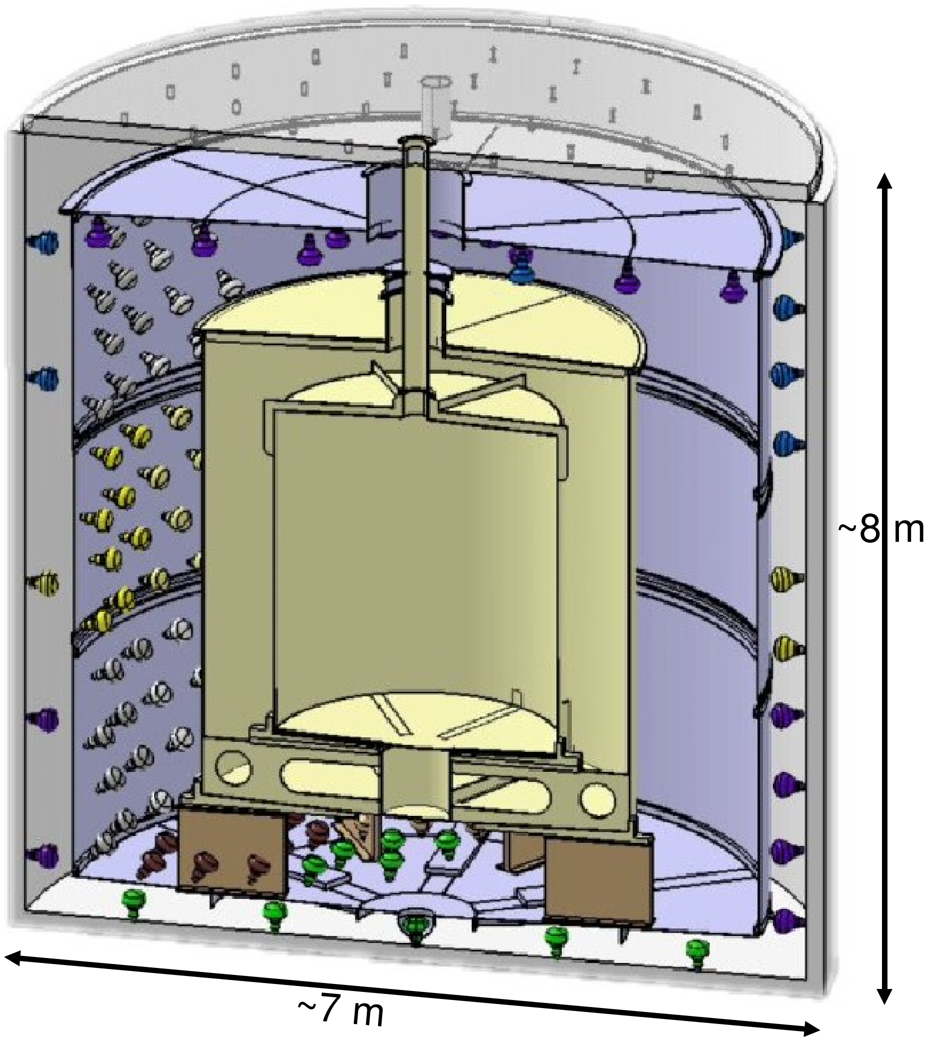
Oscillations observed
as a deficit of $\bar{\nu}_e$

Unoscillated flux
observed here

Survival Probability

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2(1.27 \Delta m^2_{13} L / E_\nu)$$

Improved Detector Design



- Multi-layer, high efficiency veto system

- Homogenous Volume

- Viewed by PMT's
  Coverage of 10% or better

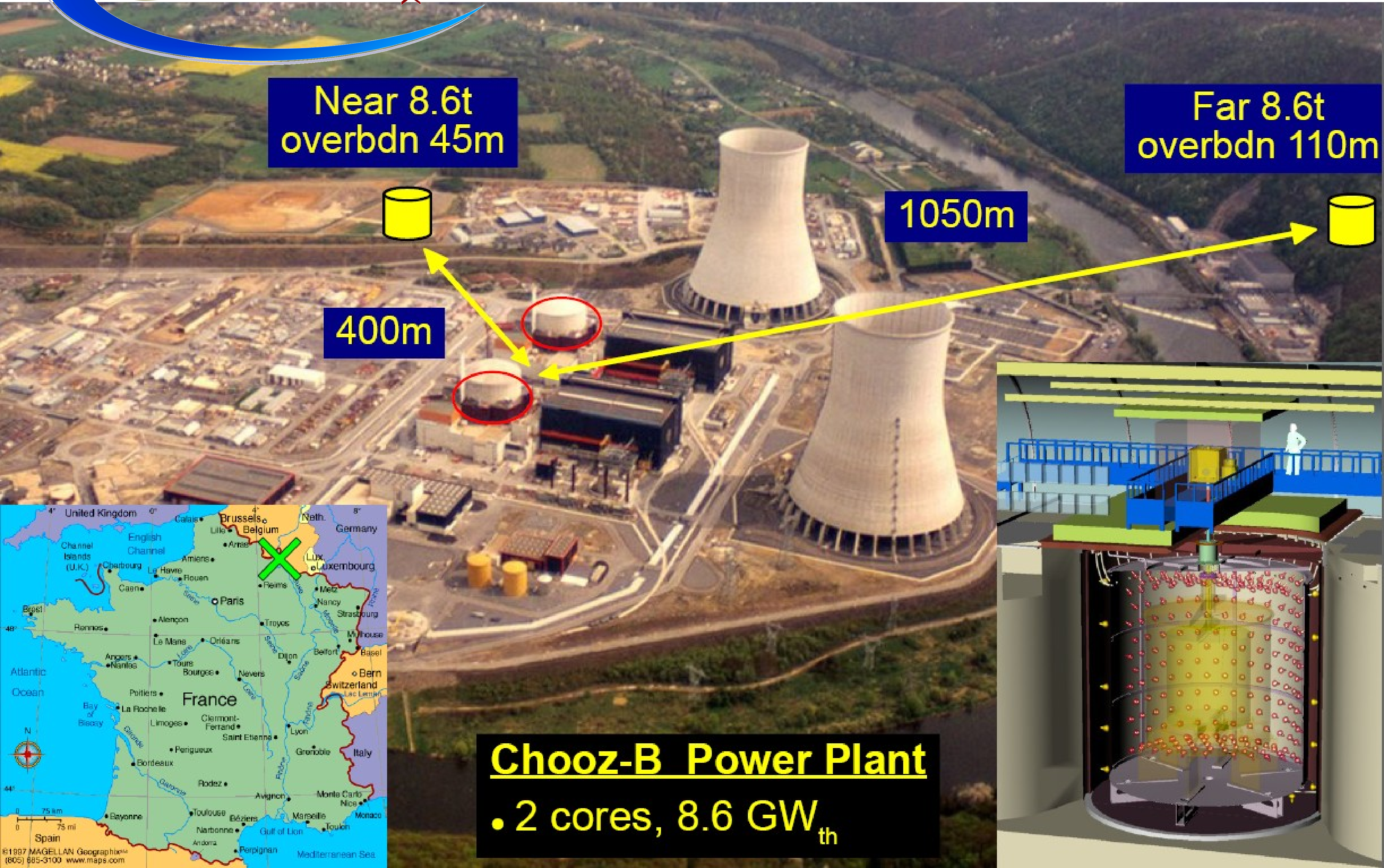
- Gadolinium Loaded, Liquid Scintillator Target (10 – 20 tons)
  Enhances neutron capture

- Extra scintillator region to capture gammas that might leak

  out from Gd target region

- Pure Mineral Oil Buffer
  To shield the scintillator from radioactivity in the PMT glass

Double Chooz Reactor Experiment in Ardennes, France



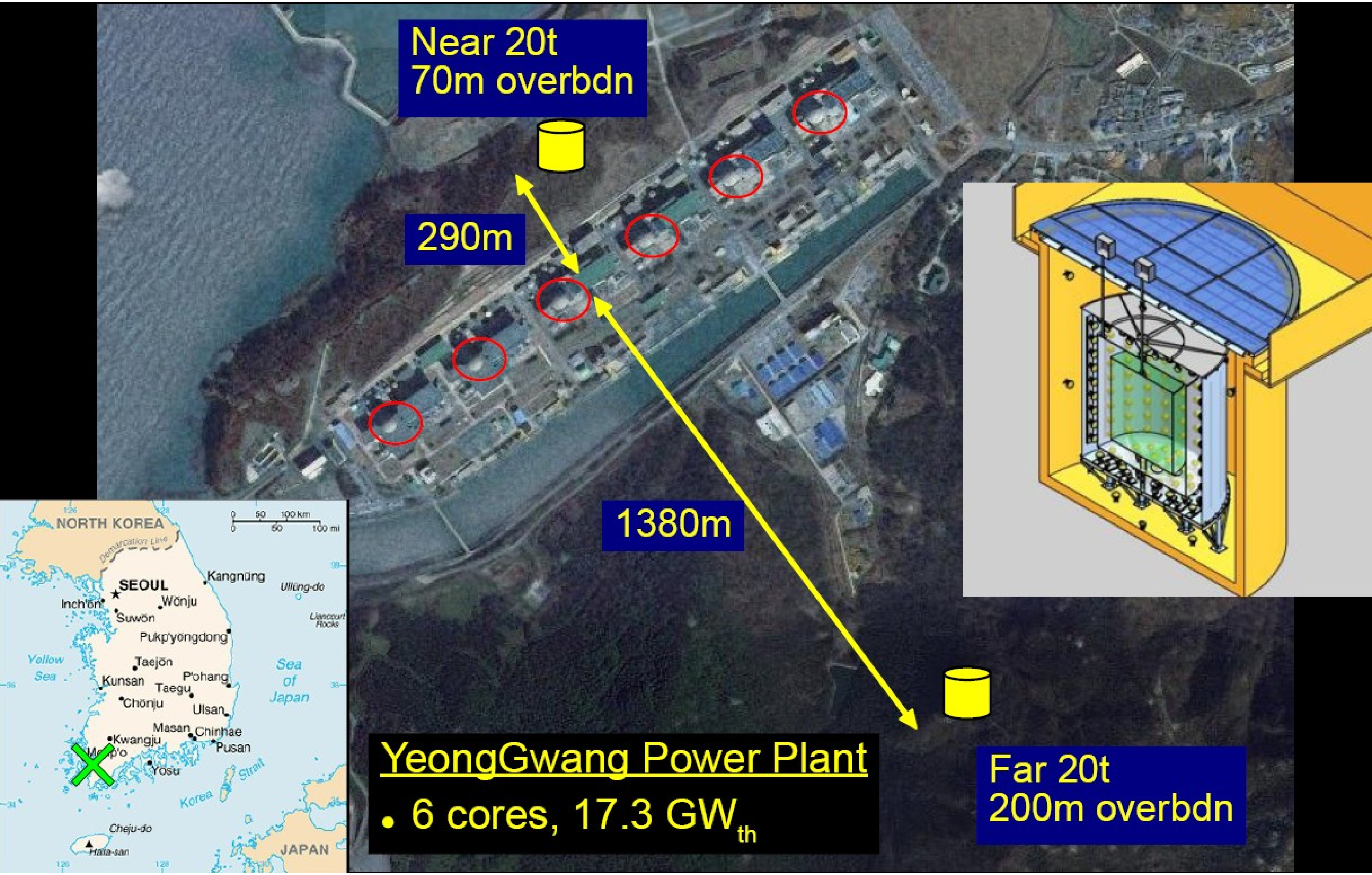
Chooz-B Power Plant

- 2 cores, 8.6 GW_{th}

Systematic uncertainties

		Chooz	Double-Chooz	
Reactor-induced	ν flux and σ	1.9 %	<0.1 %	Two ''identical'' detectors, Low bkg
	Reactor power	0.7 %	<0.1 %	
	Energy per fission	0.6 %	<0.1 %	
Detector - induced	Solid angle	0.3 %	<0.1 %	Distance measured @ 10 cm + monitor core barycenter
	Volume	0.3 %	0.2 %	Precise control of detector filling
	Density	0.3 %	<0.1 %	Accurate T control (near/far)
	H/C ratio & Gd concentration	1.2 %	<0.1 %	Same scintillator batch + Stability
	Spatial effects	1.0 %	<0.1 %	Identical detectors and monitoring
	Live time	-----	0.25 %	Special electronic systems and monitoring
Analysis	From 7 to 3 cuts	1.5 %	0.2 - 0.3 %	Simplified cuts due to detector design
	Total	**2.7 %**	**< 0.6 %**	

Reactor Experiment for Neutrino Oscillations at YoungGwang in Korea



Near 20t
70m overbdn

290m

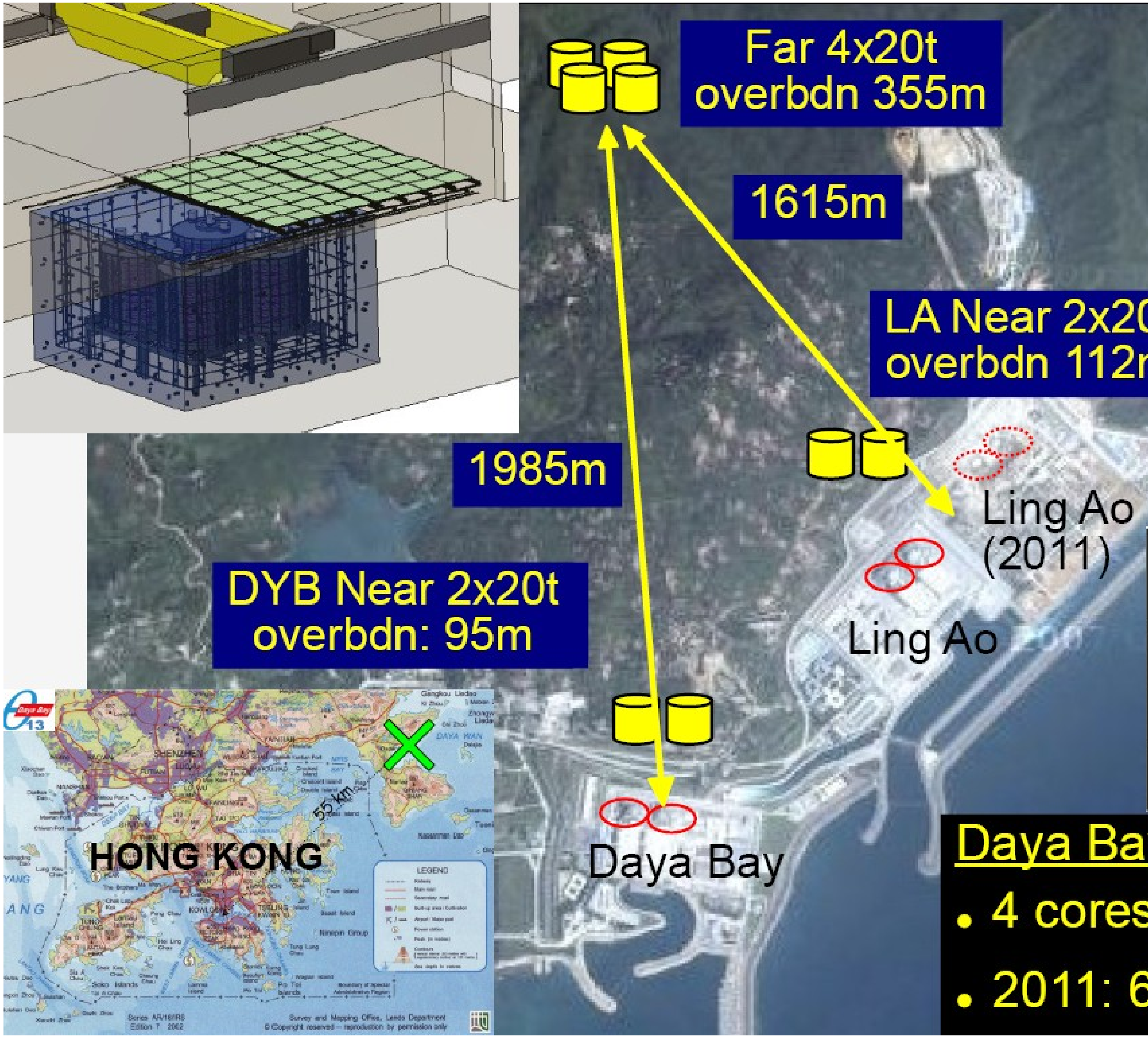
1380m

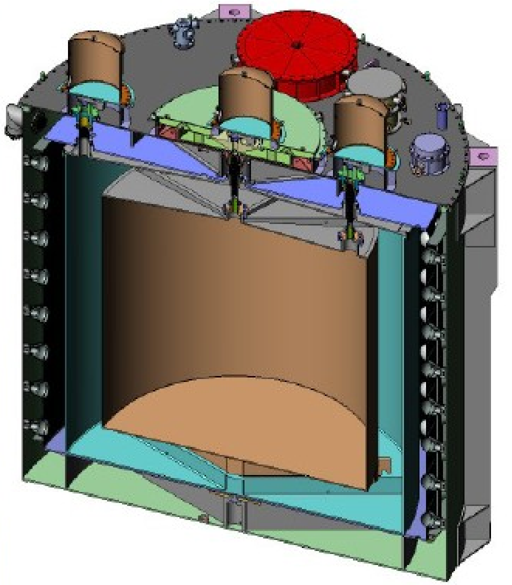
YeongGwang Power Plant

- 6 cores, 17.3 GW_{th}

Far 20t
200m overbdn

Daya Bay Experiment



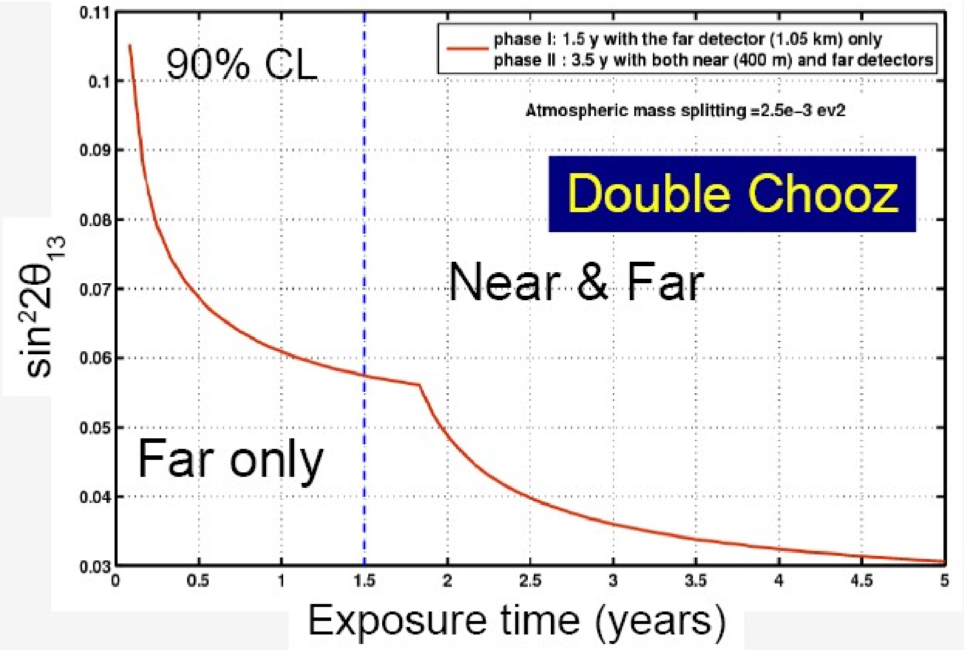


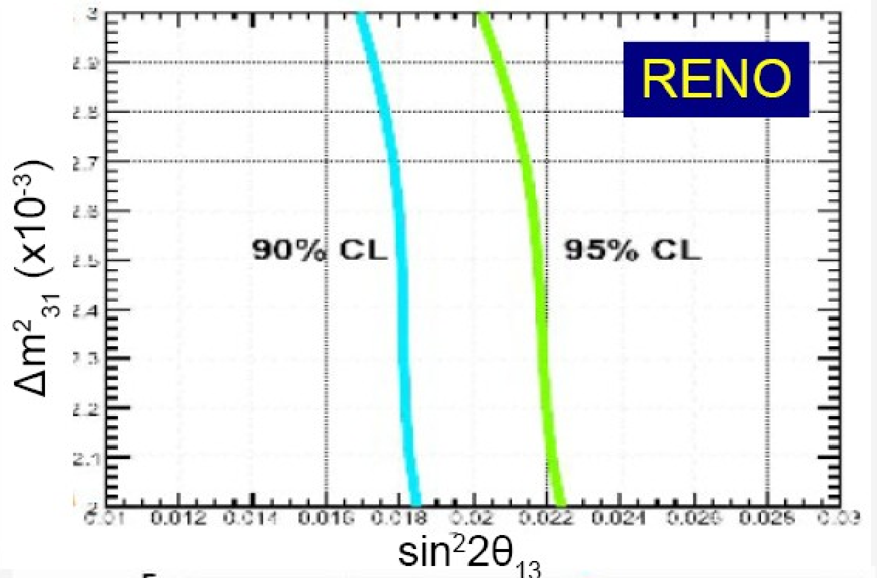
	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985
LA	857	481	1618
LA II	1307	526	1613

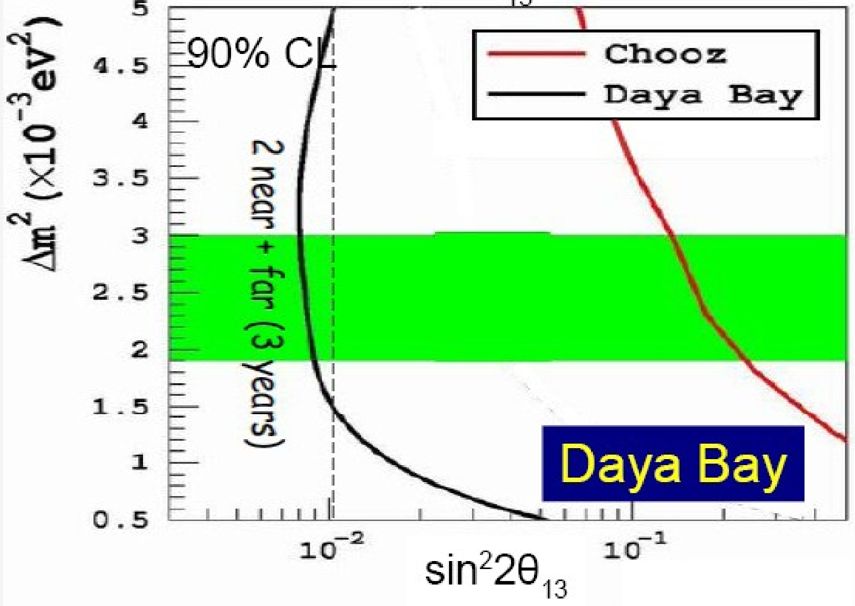
Daya Bay/Ling Ao Power Plant

- 4 cores, 11.6 GW_{th}
- 2011: 6 cores, 17.4 GW_{th}

Expected Sensitivities







Expt	σ_{stat} [%]	σ_{syst} rel. [%]	$\sin^2 2\theta_{13} >$ (90% CL)
Double Chooz	0.5	0.6	0.03
RENO	0.3	0.5	0.02
Daya Bay	0.2	0.4	0.01

Longbaseline ν_e Appearance Experiments

Long-Baseline Accelerator Appearance

- Oscillation probability dependent not only on mixing angles but also:
  - CP violation parameter (δ)
  - Mass hierarchy (sign of Δm_{31}^2)
  - Size of $\sin^2\theta_{23}$ (as opposed to the measured $\sin^2 2\theta_{23}$)
- These are both complications and an opportunity to measure these parameters
  - Use information from other oscillation measurements: reactors, solar/atmospheric/accelerator disappearance
  - Use combinations of appearance measurements for neutrinos and antinuetrinos at different baselines to determine CP δ and mass hierarchy

Ambiguities and Correlations in Appearance Measurements

Expansion to second order in α and Δ

$$P_{long-baseline} \simeq \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\Delta$$
$$\mp \alpha \sin 2\theta_{13} \sin\delta_{CP} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3\Delta$$
$$+ \alpha \sin 2\theta_{13} \cos\delta_{CP} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \sin^2\Delta$$
$$+ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2\Delta$$

Mass Hierarchy

CP Violation

with $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{23}$ and $\Delta \equiv \Delta m^2_{31} L/(4E_\nu)$

Ambiguities due to:

Measured by Atmos

= Need $\sin^2\theta_{23}$ $\frac{1- \sqrt{1\ \ \sin^2 2\theta_{23}}}{2}$, not $\sin^2 2\theta_{23}$

Δ Sign of m^2_{31} Overall shifts

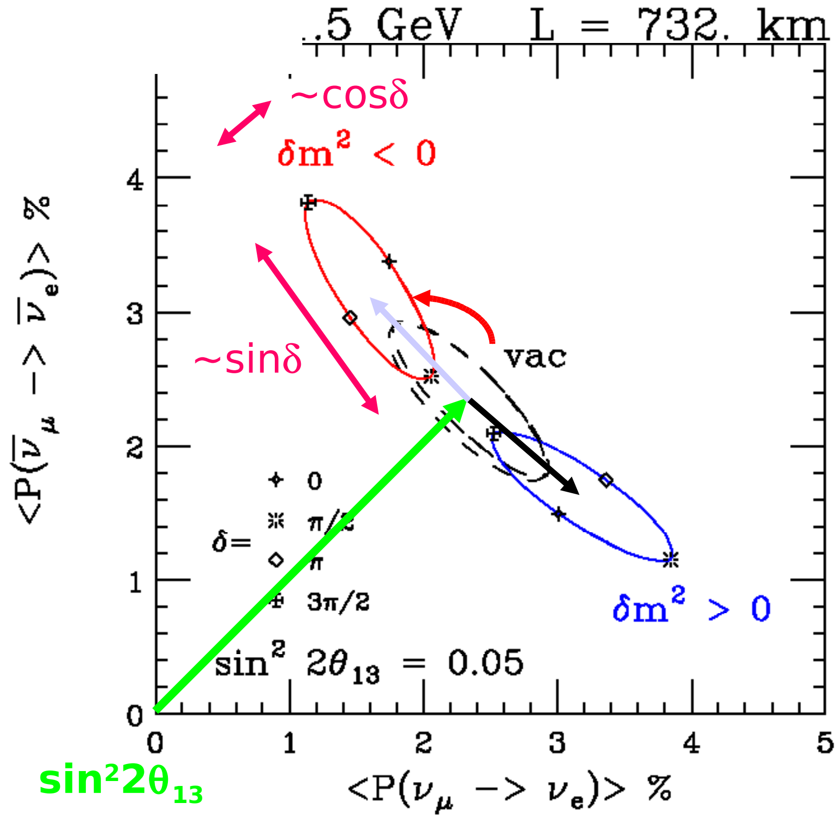
Correlations:

CP violation phase δ Ellipse Regions

Δ Interference with subdominant m^2_{12} terms

Matter Effects:

$$P_{e\mu} = \sin^2 2\theta_M \sin^2\left(\frac{\Delta_M L}{2}\right)$$
$$\Delta_M = \sqrt{(A - \Delta\cos 2\theta)^2 + \Delta^2 \sin^2 2\theta}$$
$$A = \pm\sqrt{2}G_F N_e \text{ (+ for neutrinos, − for antineutrinos)}$$



Minakata and Nunokawa, hep-ph/0108085

The “Curse” and the “Blessing”

Oscillation probability vs δ_{CP} for T2K and Nova

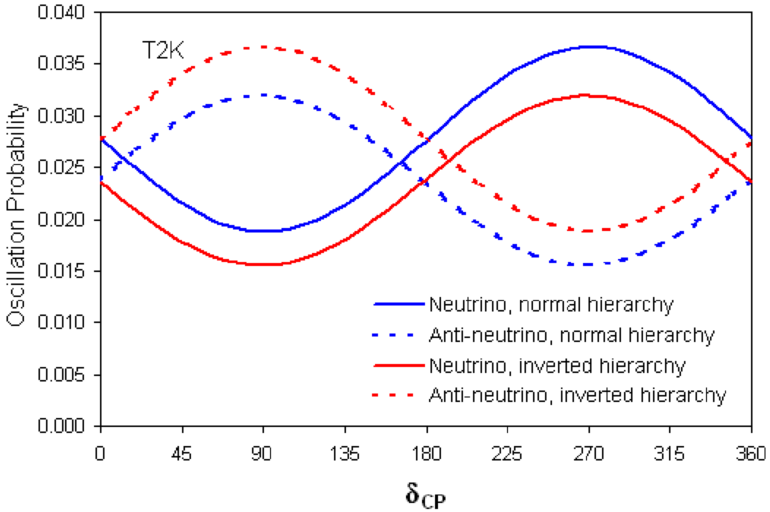
($\Delta m^2 = 2.5\text{x}10^{-3}\ \text{eV}^2$, $\sin^2 2\theta_{13} = 0.05$)

Blue: normal hierarchy

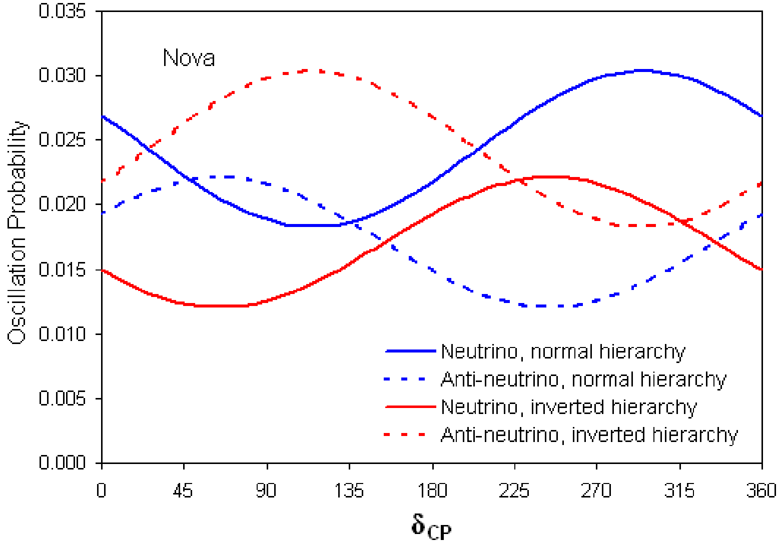
Red: inverted hierarchy

Solid: neutrino

Dashed: antineutrino



T2K:
Small matter effects

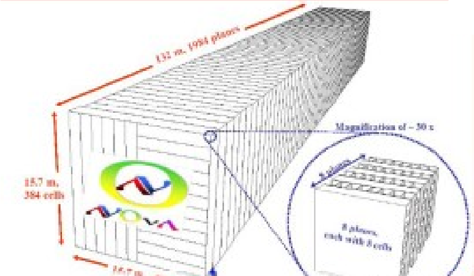


Nova:
Large matter effects

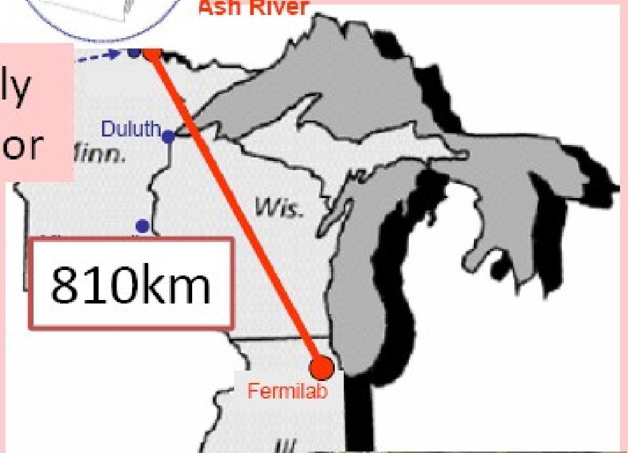
Upcoming Longbaseline Experiment: T2K and Nova

Improved Beams and Near/Far Detectors
Much Higher Intensity

NOνA
(~2013 -)



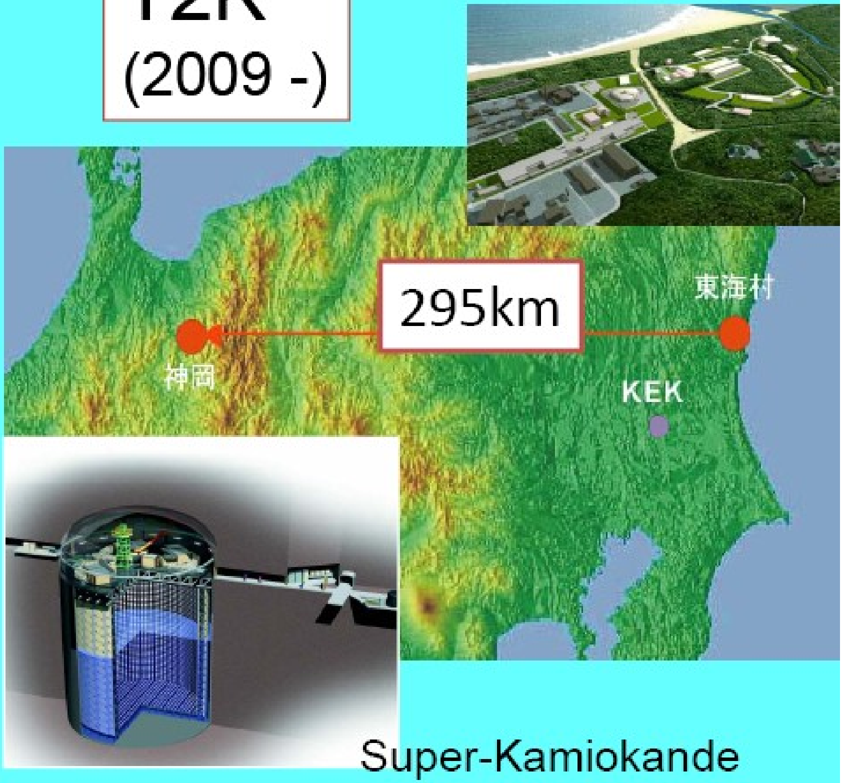
15 kton totally active detector



NuMI beam intensity upgrade to 700 kW

T2K
(2009 -)

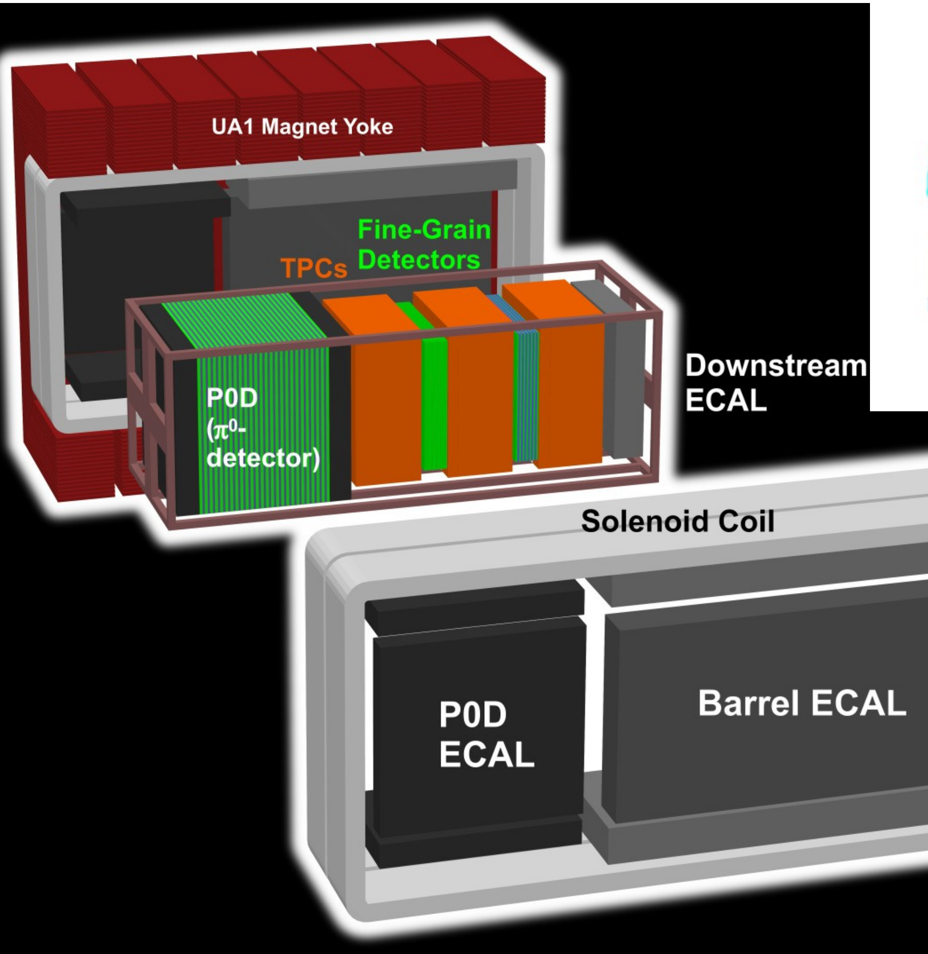
J-PARC
(750kW design)

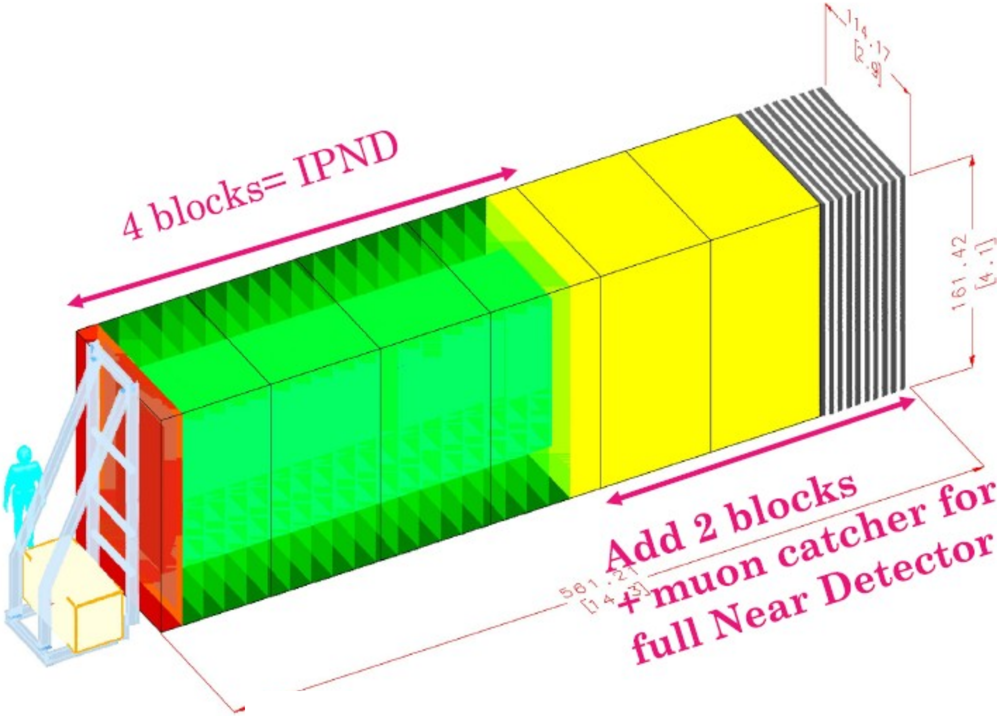


Super-Kamiokande
(22.5 kton fid. vol)

Use Near Detectors to Measure Beam Flux and Backgrounds

T2K Near Detector



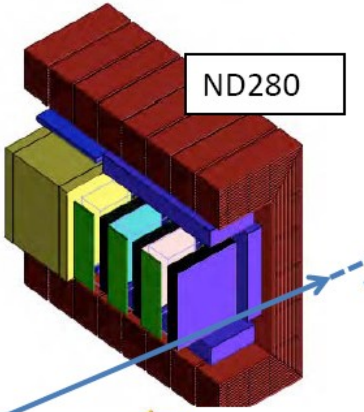


NOνA Near Detector

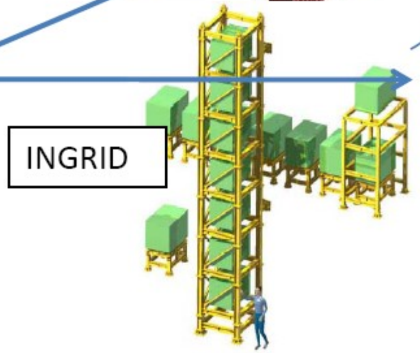
T2K Experiment

JParc
ν beam-line

30 GeV protons



ND280



INGRID

θ_{OA} off-axis angle= 2.5°

SK

22.5 kt water cerenkov

295 km

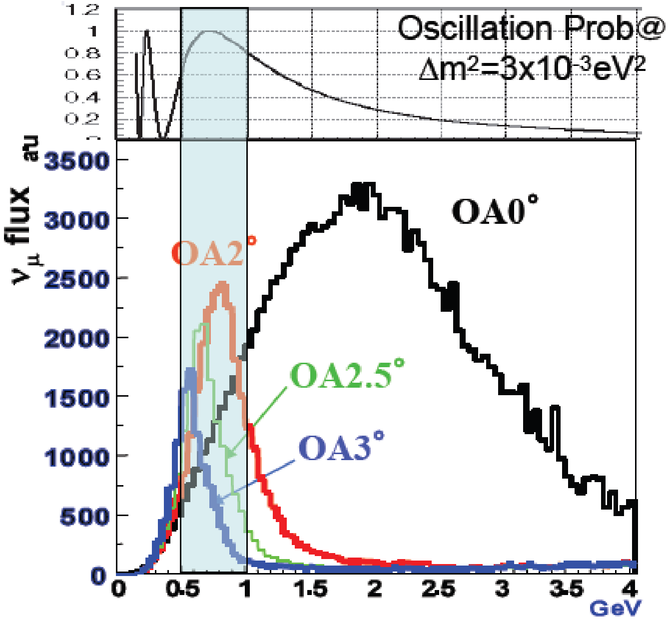
Statistics at SK

(OAB 2.5 deg, 1 yr, 22.5 kt)

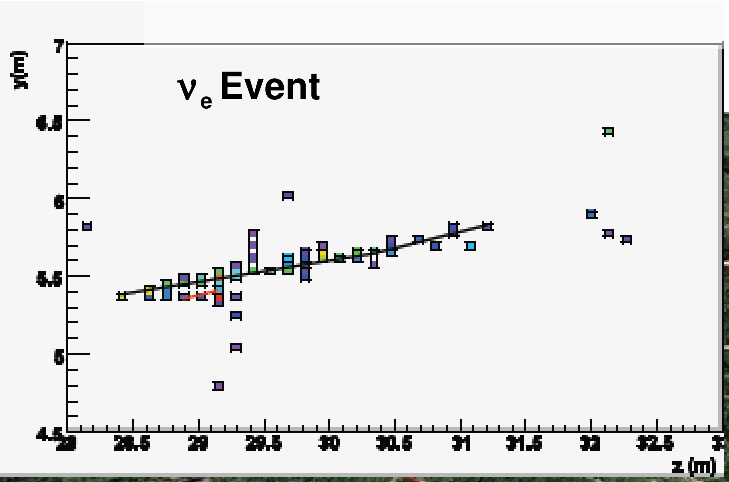
~ 2200 ν_μ tot

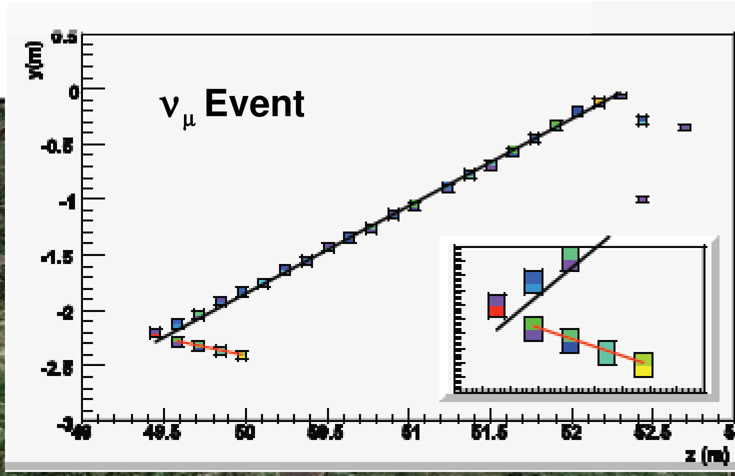
~ 1600 ν_μ CC

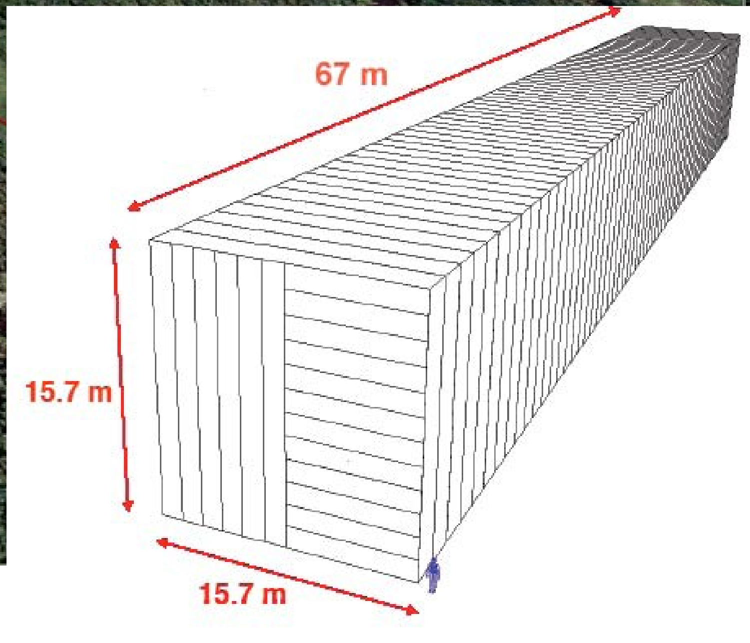
ν_e ~0.4% at ν_μ peak



NOvA Experiment in Minnesota







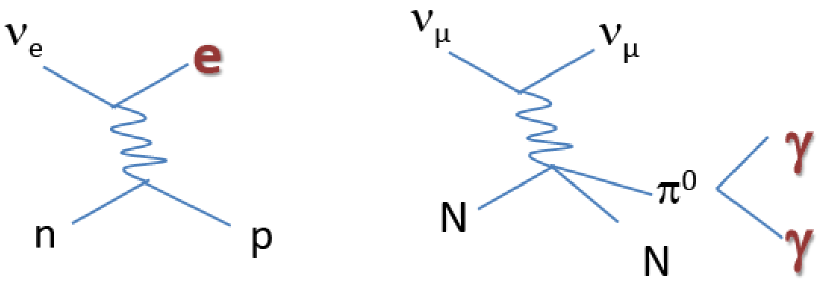
Main Backgrounds For Appearance Experiments

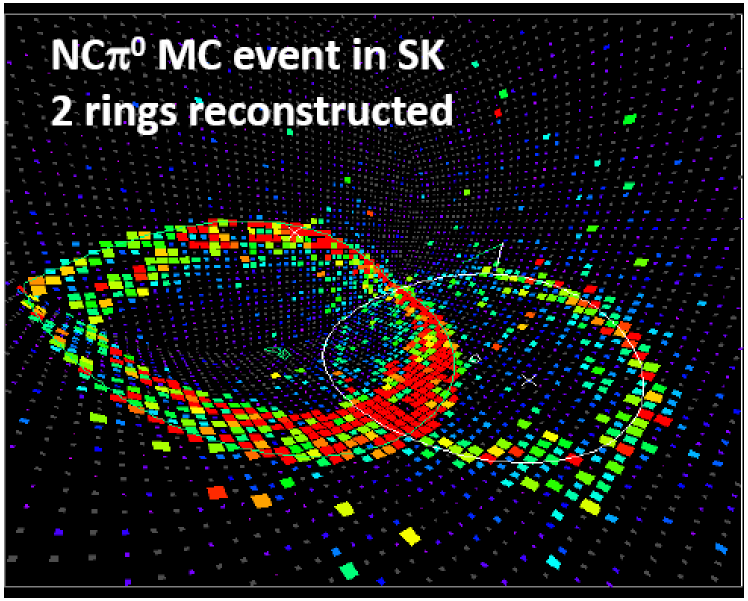
•for ν_e appearance

Measure θ_{13}

-beam ν_e

-NCπ^0 events




NCπ^0 MC event in SK

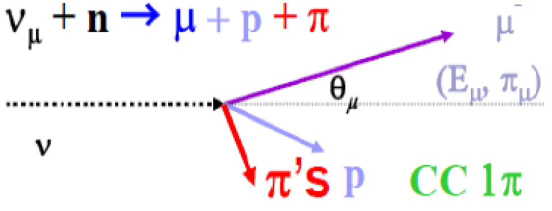
2 rings reconstructed

•for ν_μ disappearance (muon energy measurement)

Measure θ_{23}

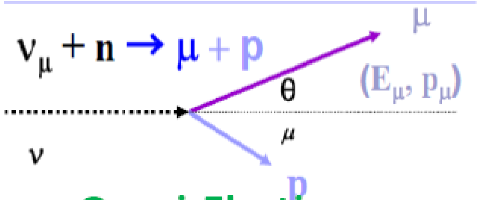
-inelastic processes

$\nu_\mu + n \rightarrow \mu + p + \pi$



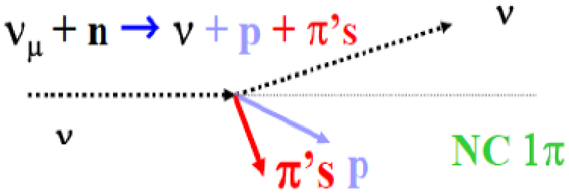
CC 1π

$\nu_\mu + n \rightarrow \mu + p$

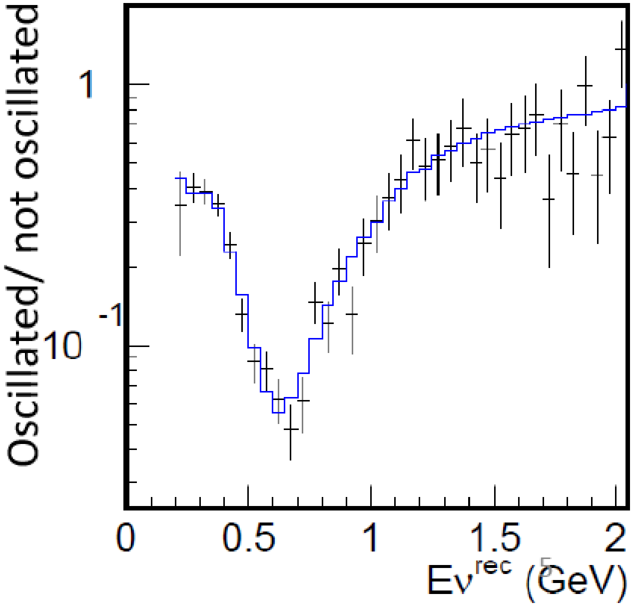


Quasi-Elastic process

$\nu_\mu + n \rightarrow \nu + p + \pi\text{'s}$

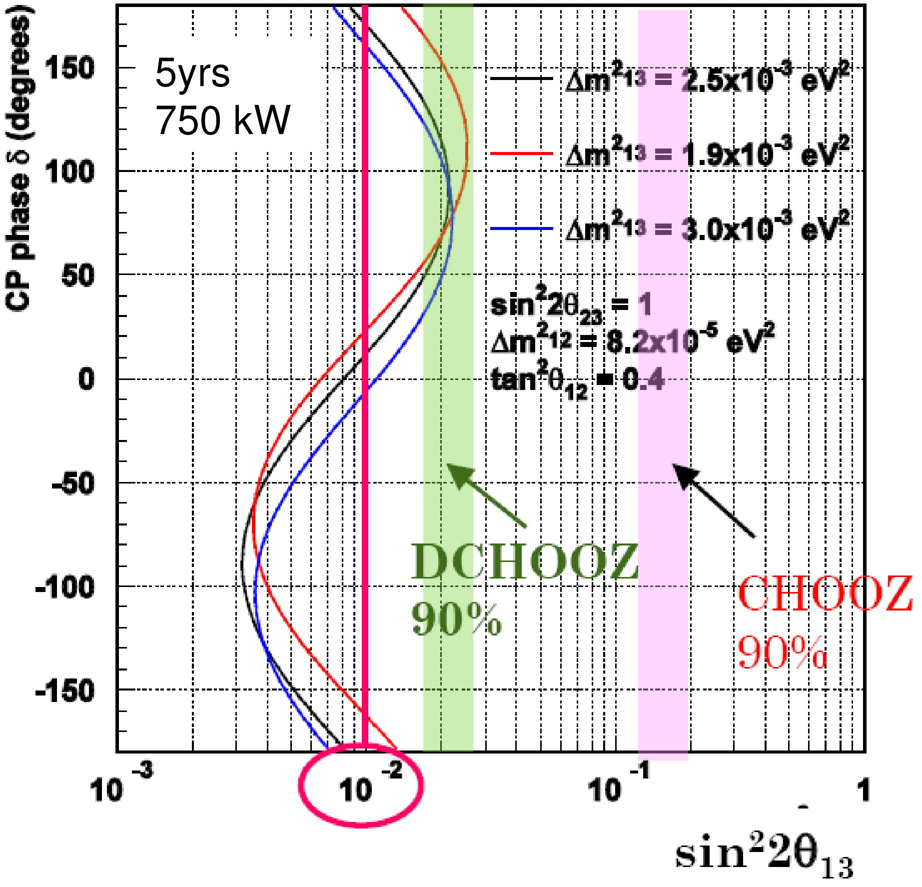


NC 1π

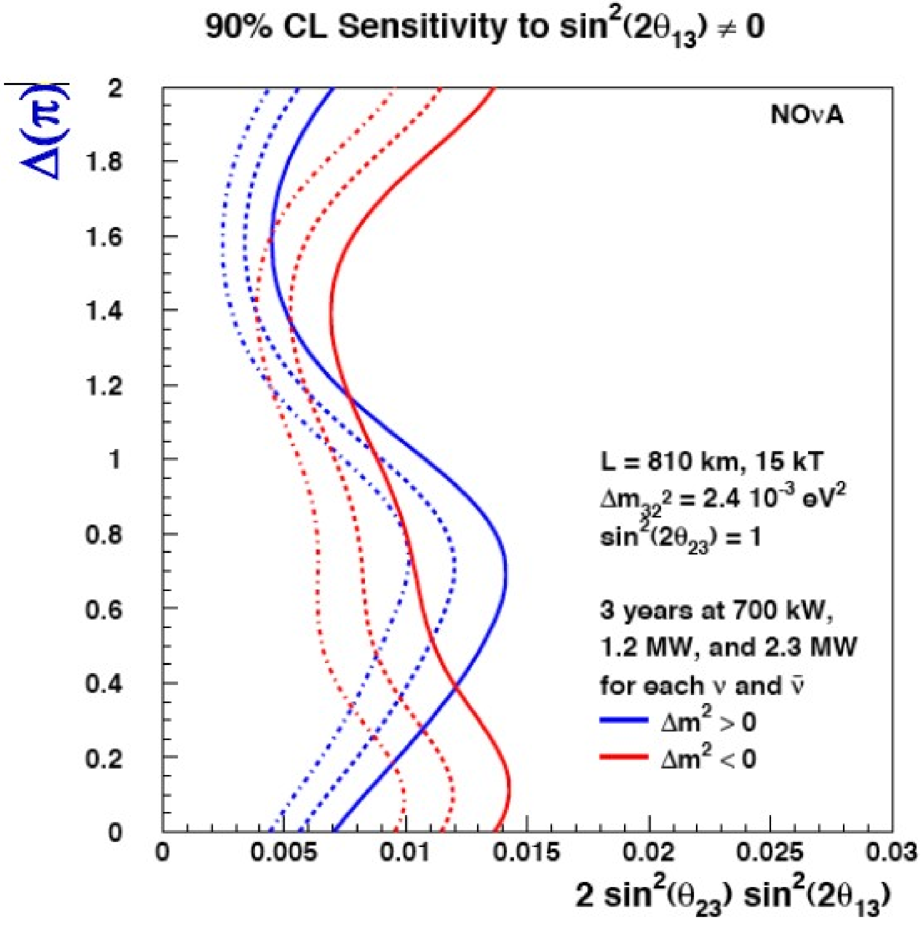


Expected Sensitivity to θ_{13}

T2K



NOνA



Experiments sensitive to $\sin^2(2\theta_{13}) > 0.008$

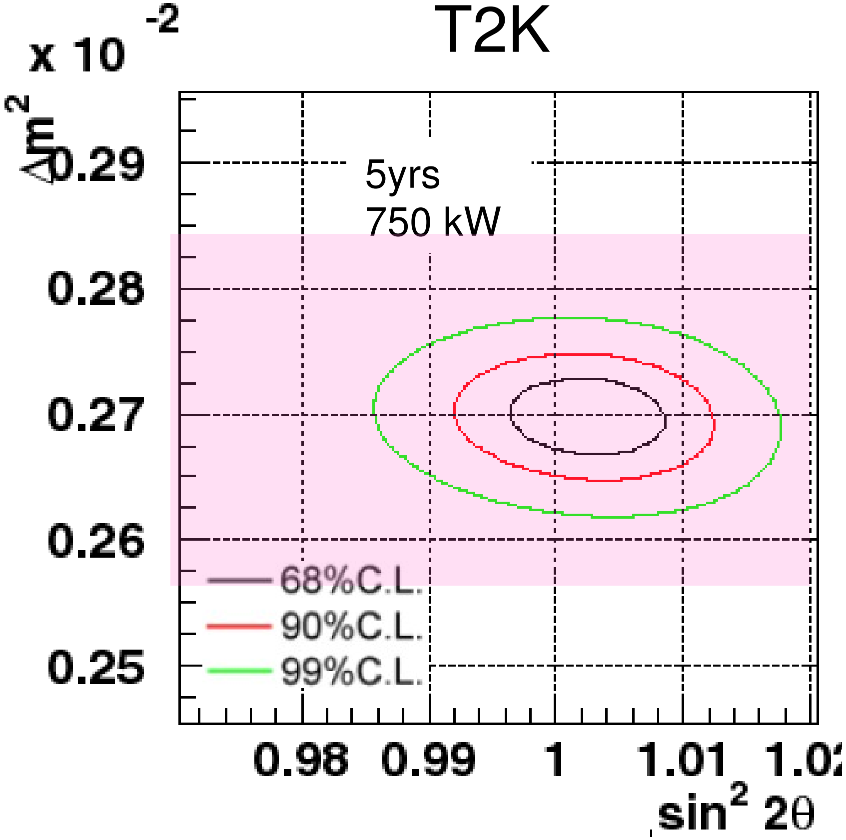
Better Measurements of θ_{23} and Δm^2_{23}

Current Measurements:

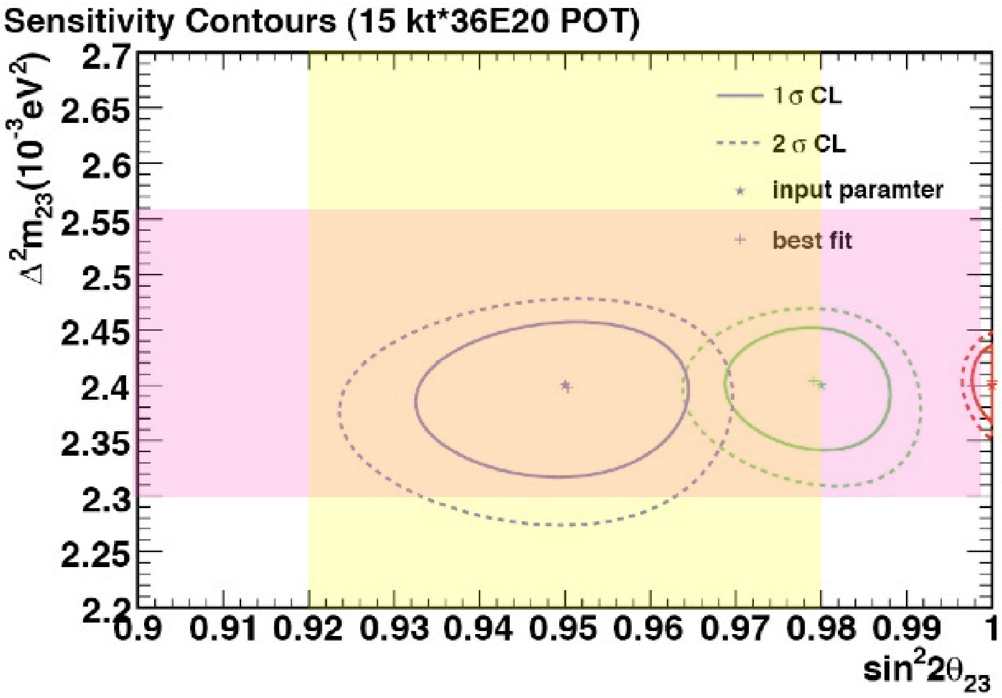
$\Delta m^2 = 2.43 \pm 0.13 \times 10^{-3}$ eV^2 → Improvements by x3 to x5

$\sin^2(2\theta_{23}) = 1.00 \pm 0.03$

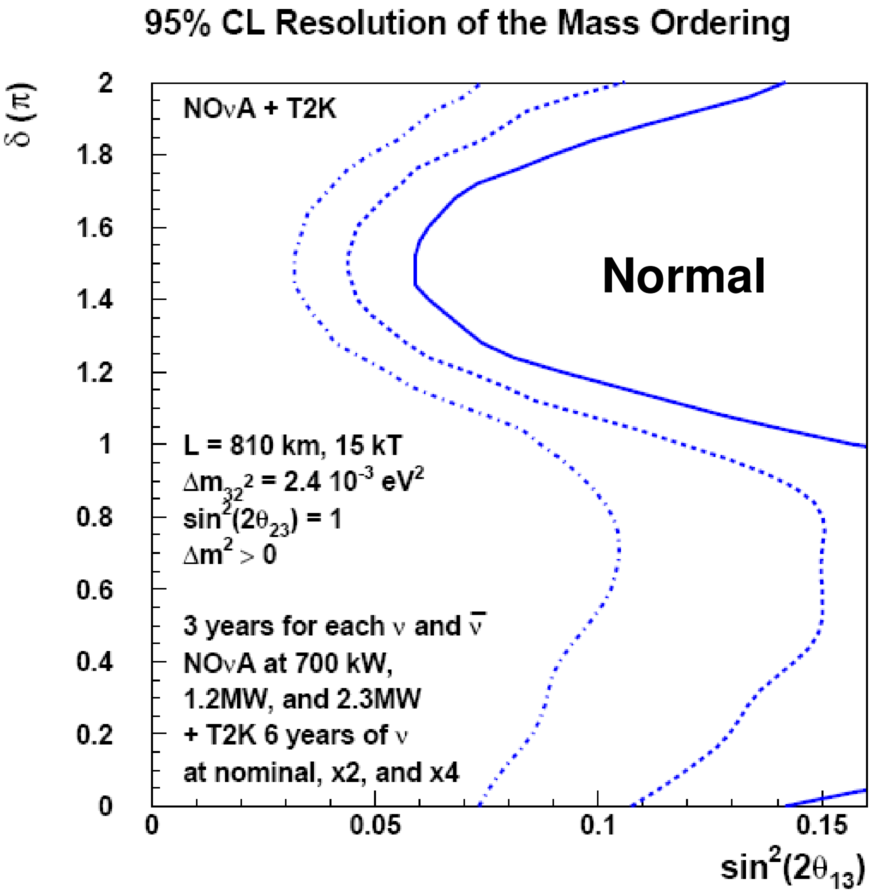
T2K

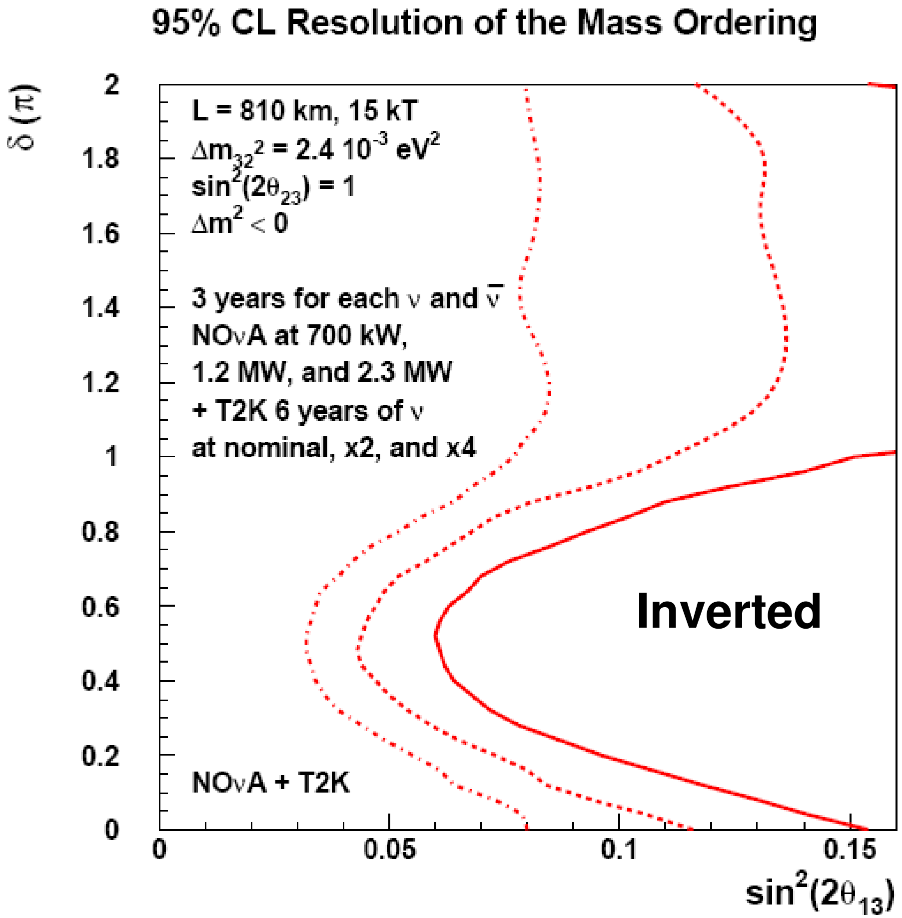


NOνA

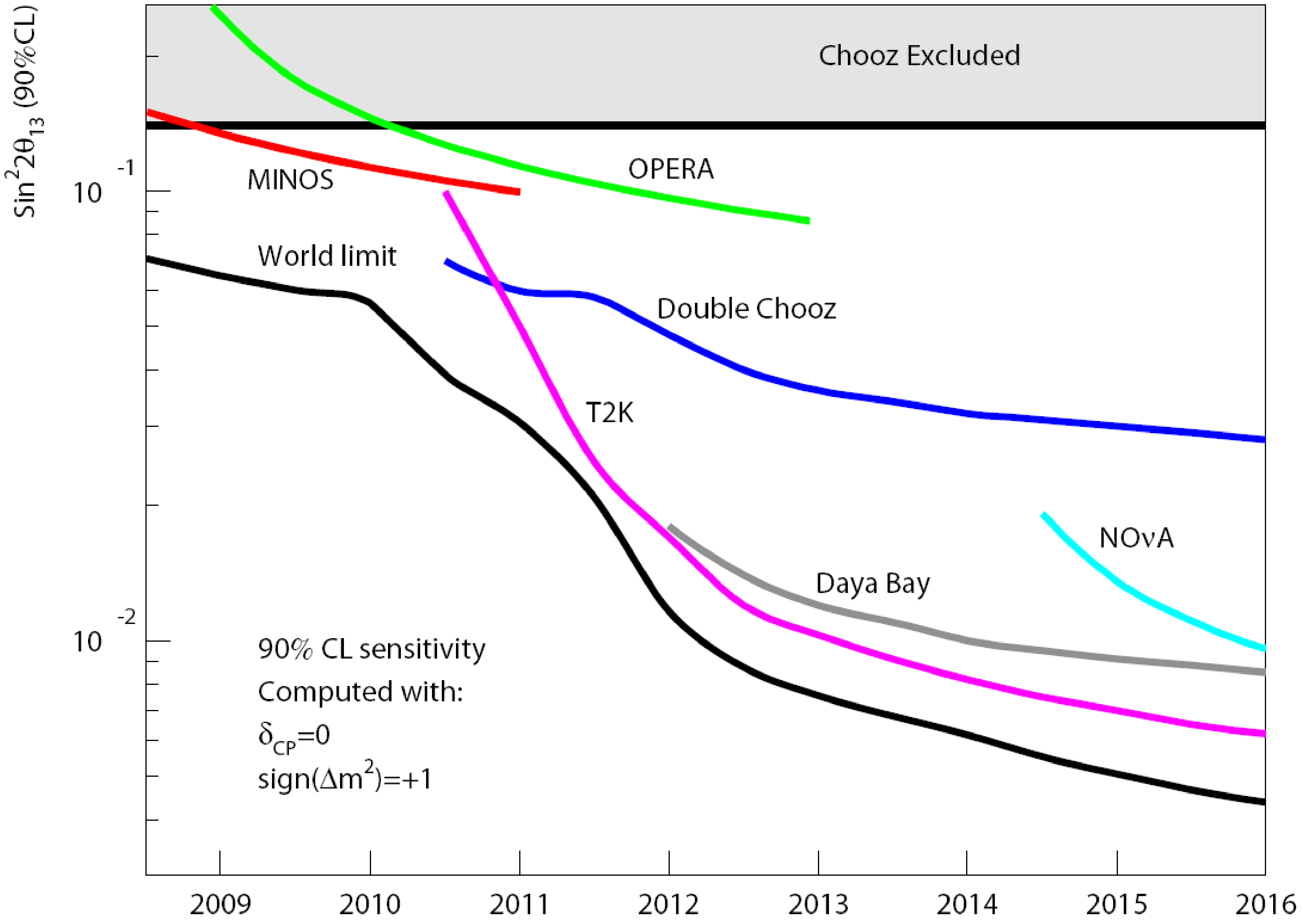


NOvA + T2K Has Some Sensitivity to Mass Hierarchy (sign Δm^2_{23})



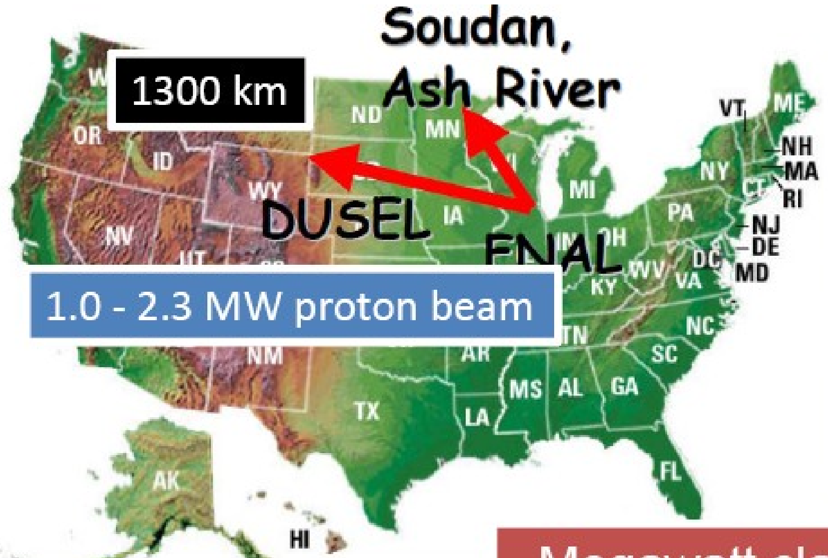


Sensitivity Estimates for θ_{13} vs Time



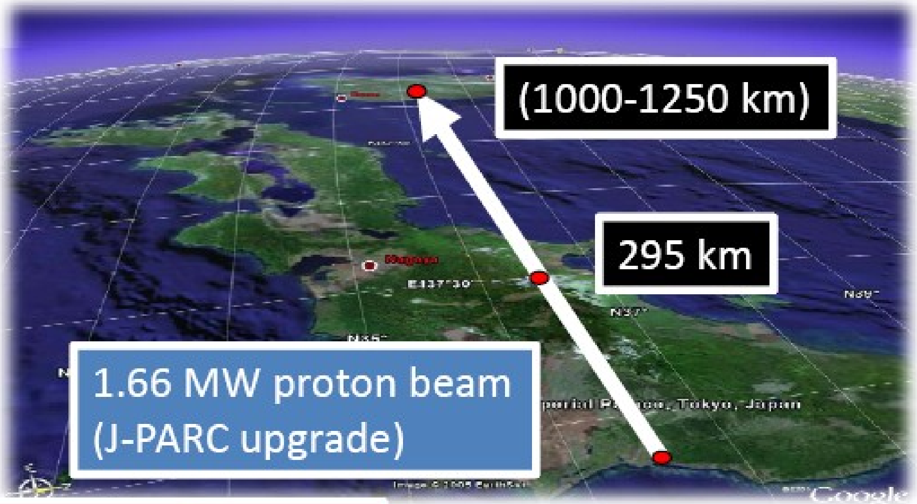
From Mauro Mezzetto NT 2009

Future Longbaseline Experiments



1300 km

1.0 - 2.3 MW proton beam

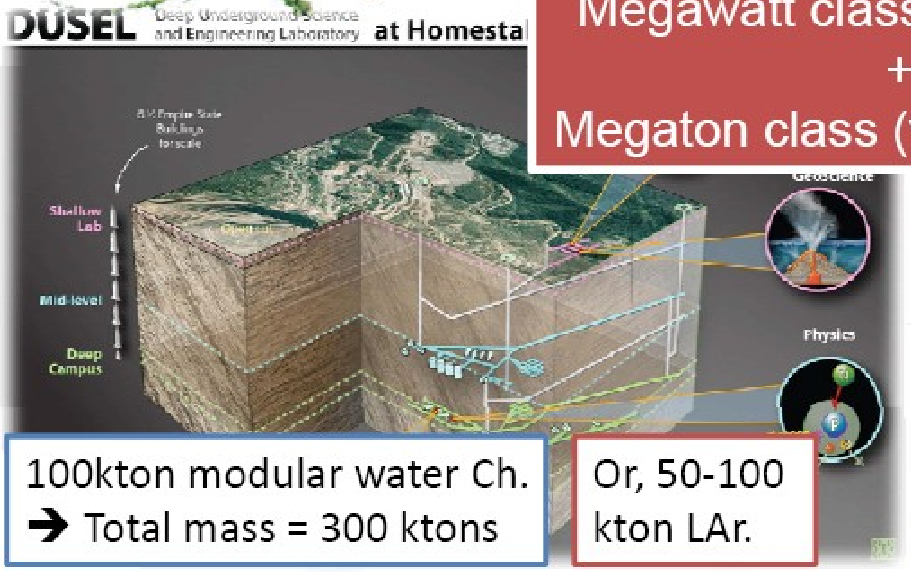


(1000-1250 km)

295 km

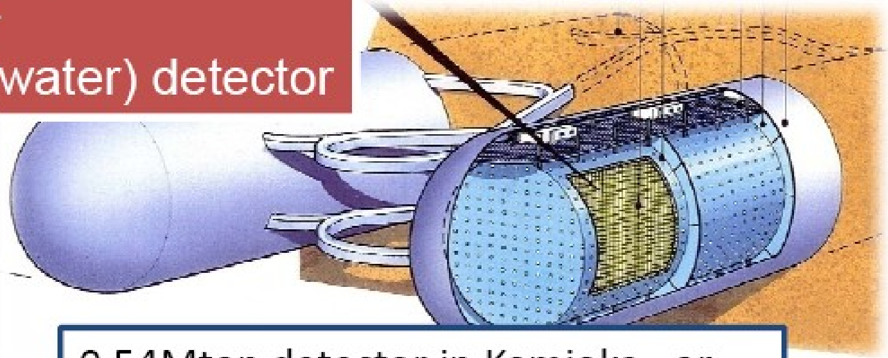
1.66 MW proton beam
(J-PARC upgrade)

Megawatt class super-beam
+
Megaton class (water) detector



100kton modular water Ch.
➔ Total mass = 300 ktons

Or, 50-100
kton LAr.



0.54Mton detector in Kamioka, or
0.27 Mton water Cherenkov detector
in Kamioka and Korea.

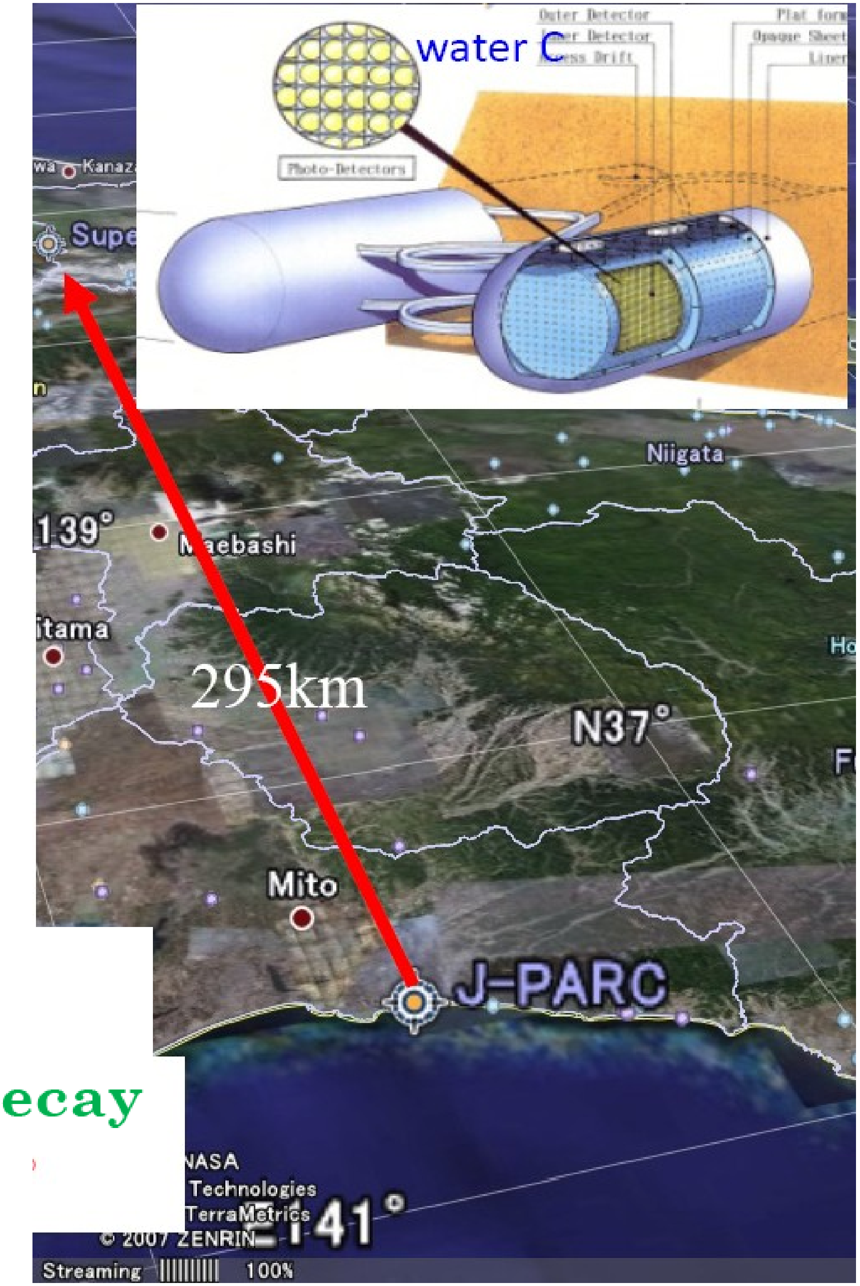
Hyper-K Experiment

J-PARC Upgrade
KEK Roadmap
→1.7MW

Best Optimization

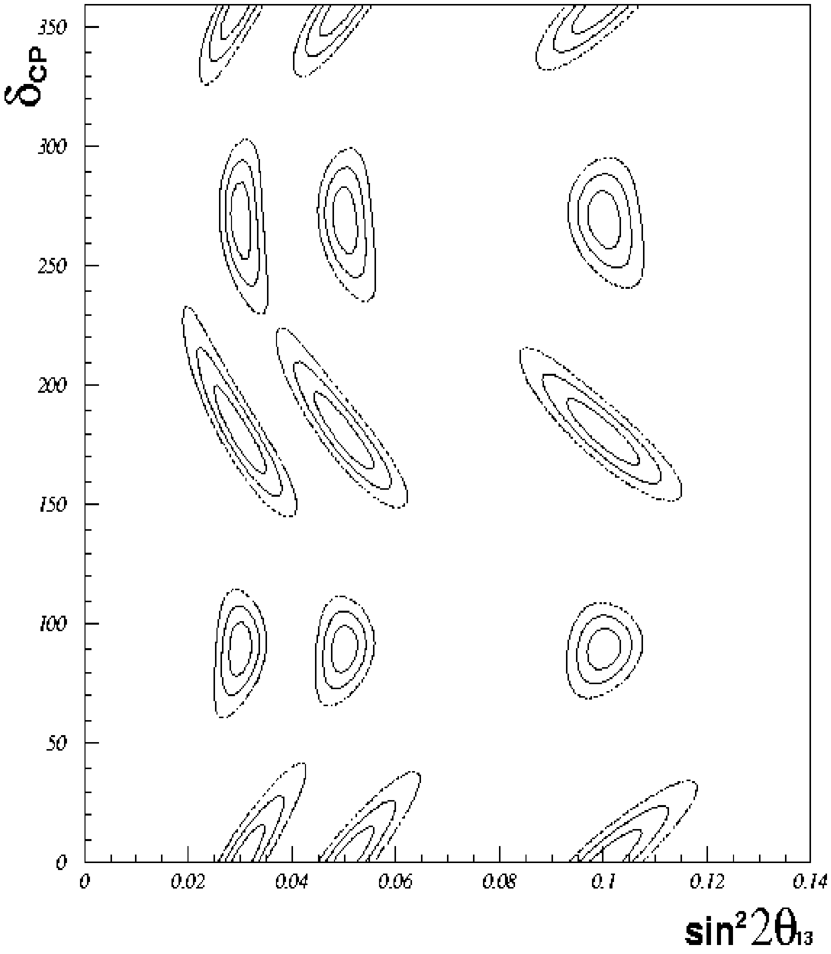
Huge ν detector
- Water Cherenkov (500 kton)
- Lq. Ar TPC
  O(~100k)ton

GUT
Proton Decay

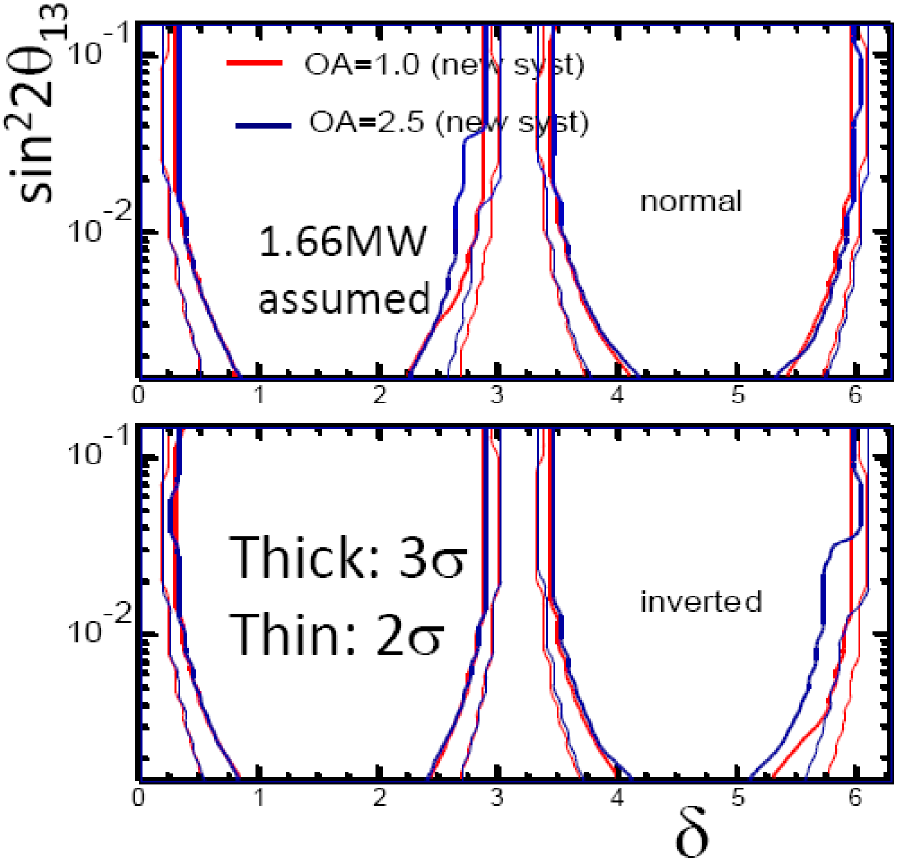


Hyper-K CP Violation Sensitivities

100 kton Liquid Argon Detector



J-PARC to Kamioka + Korea



1.66MW assumed

Thick: 3σ

Thin: 2σ

Long Baseline Neutrino Experiment at DUSEL (LBNE)

DUSEL Deep Underground Science and Engineering Laboratory

Homestake mine
South Dakota

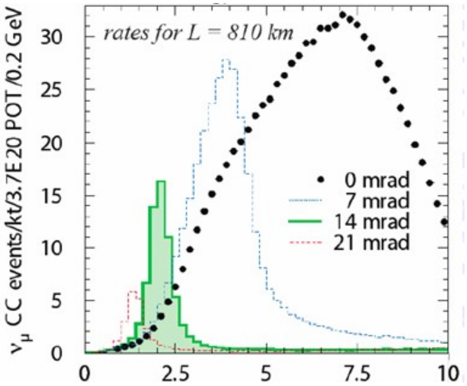
Two detector technologies:
-Water Cherenkov (WC)
-Liquid Argon (LAr)

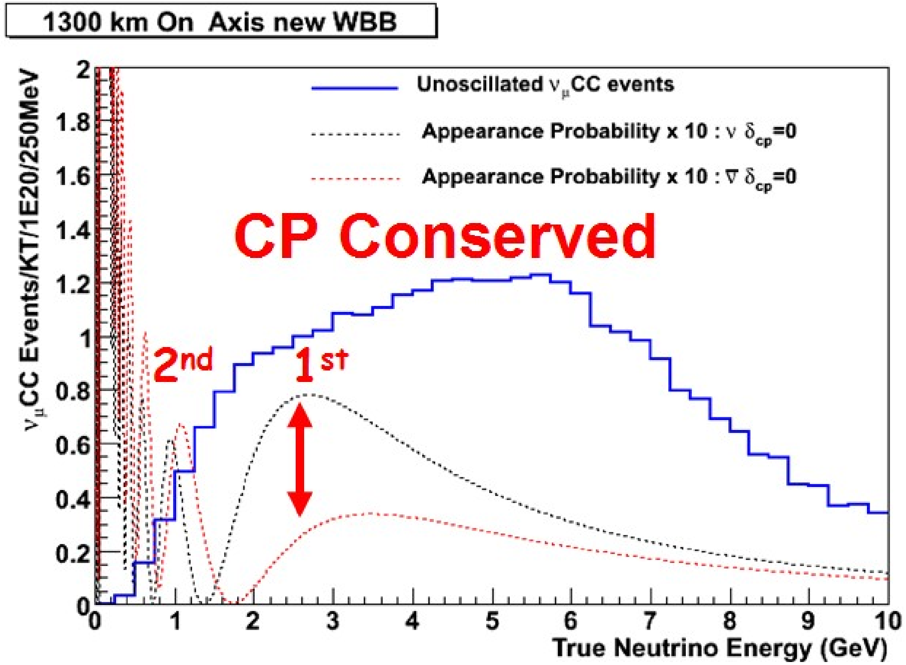
- Beam Requirements:
  - Large neutrino flux covering 1st and 2nd oscillation max points (0.8 and 2.4 GeV)
  - High purity ν_μ flux with little ν_e contamination
  - Minimize flux with energy above 5 GeV that causes background

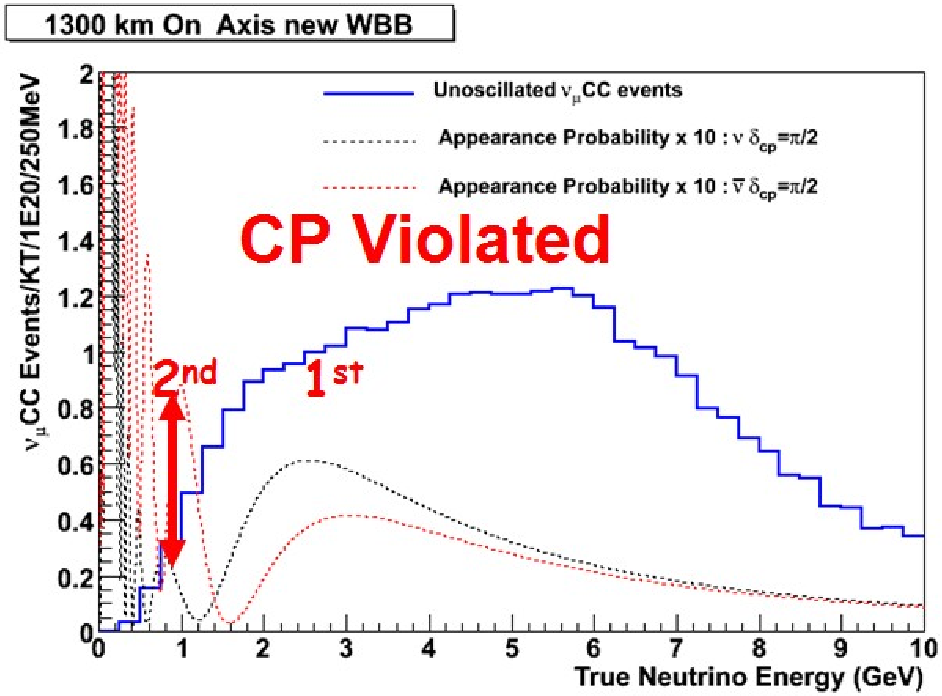
⇒ Run at reduced energy 90 ± 30 GeV but then less flux

On-axis Beam May Be Better for DUSEL Exp

- On-axis beam spans large energy region that allows one to measure the oscillation probability at both the first and second maximum ($\sin^2(1.27\Delta m^2 L/E)$)





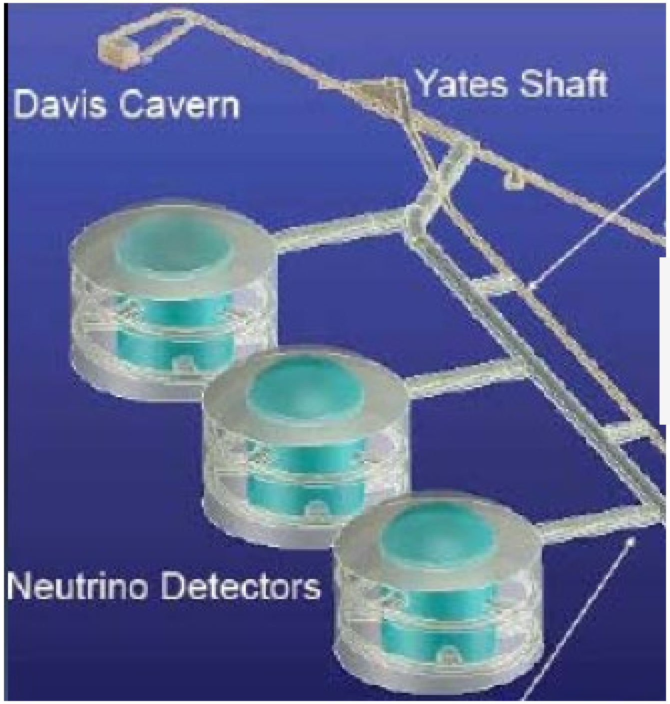


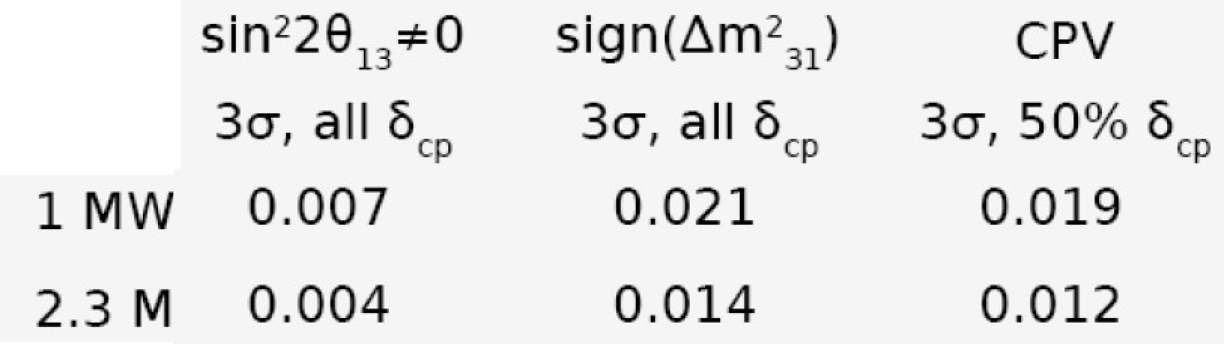
1st Maximum : Gives the neutrino mass hierarchy

2nd Maximum : Sensitive to CP Violation effects

DUSEL LBNE Experiment and Expectations

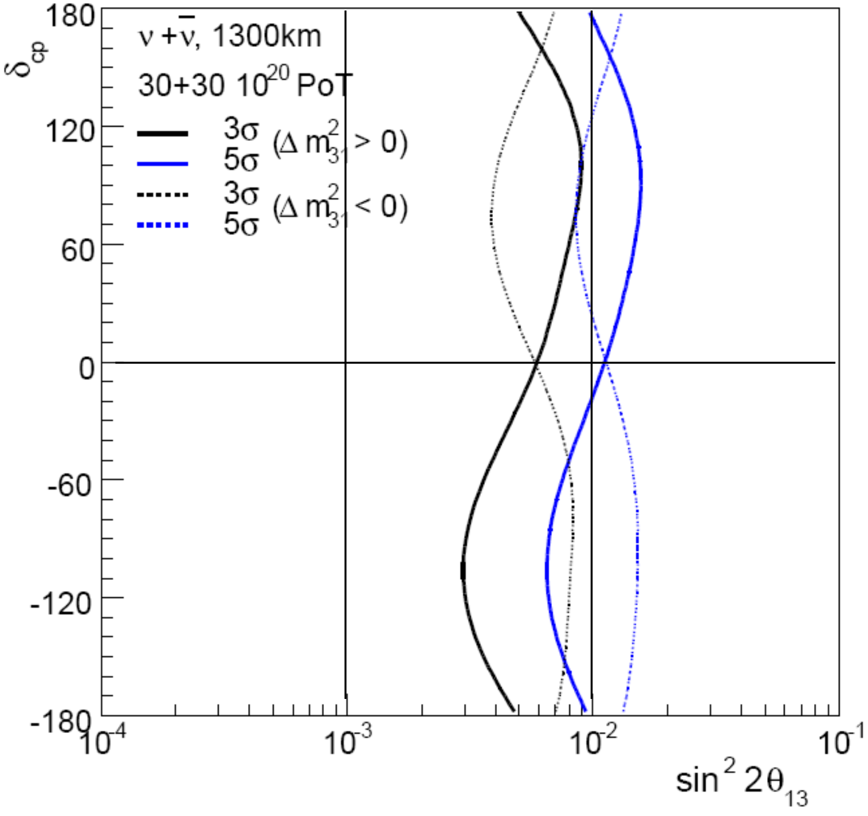
- Baseline experiment:
  - Three 100 kton fiducial “water Cherenkov” detectors (Each 5 times Super-K)
  - 1 MegaWatt (2.3 MW) 120 GeV beam with plug to reduce high E_ν
  - 3 yrs ν + 3 yrs $\bar{\nu}$ of data

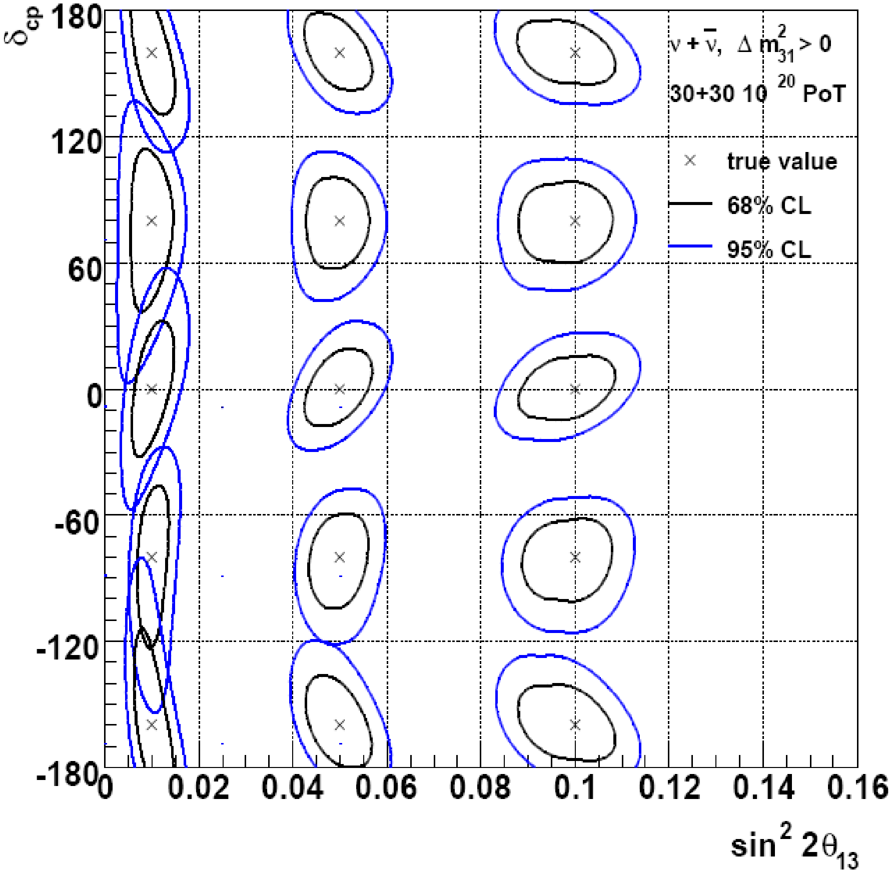




	$\sin^2 2\theta_{13} \neq 0$ 3σ, all δ_{cp}	sign(Δm^2_{31}) 3σ, all δ_{cp}	CPV 3σ, 50% δ_{cp}
1 MW	0.007	0.021	0.019
2.3 M	0.004	0.014	0.012

LBNE Sensitivity (3 yr ν and 3 yr $\bar{\nu}$)





Final Comments

- Reactor and longbaseline experiments will be soon providing new information on θ_{13}
  - θ_{13} is a important physics parameter for modeling ν mixing
  - θ_{13} is key for planning future long-baseline experiments to measure CP violation and the mass hierarchy
    - If $\sin^2 2\theta_{13}$ is > ~0.03, T2K and Nova can make important measurements
    - If $\sin^2 2\theta_{13}$ is < ~0.01, need other techniques to access the physics (1st,2nd max. measurements; Superbeam exps, Neutrino Factory….)

- Longbaseline experiments are more complicated but have the promise to give information on the mass hierarchy and CP violation
  - T2K and Nova could give some early hints of these parameters
  - Next generation superbeams will be necessary to make quantitative measurements

- There is a strong ongoing program of oscillation experiments and serious plans for taking the next step to superbeams

  ⇒ Exciting times for neutrino physics