Experimental Neutrino Physics

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The discovery of neutrino masses and mixings
is the one BSM physics discovery we've got.

ν mass & mixing: Only known window to new physics

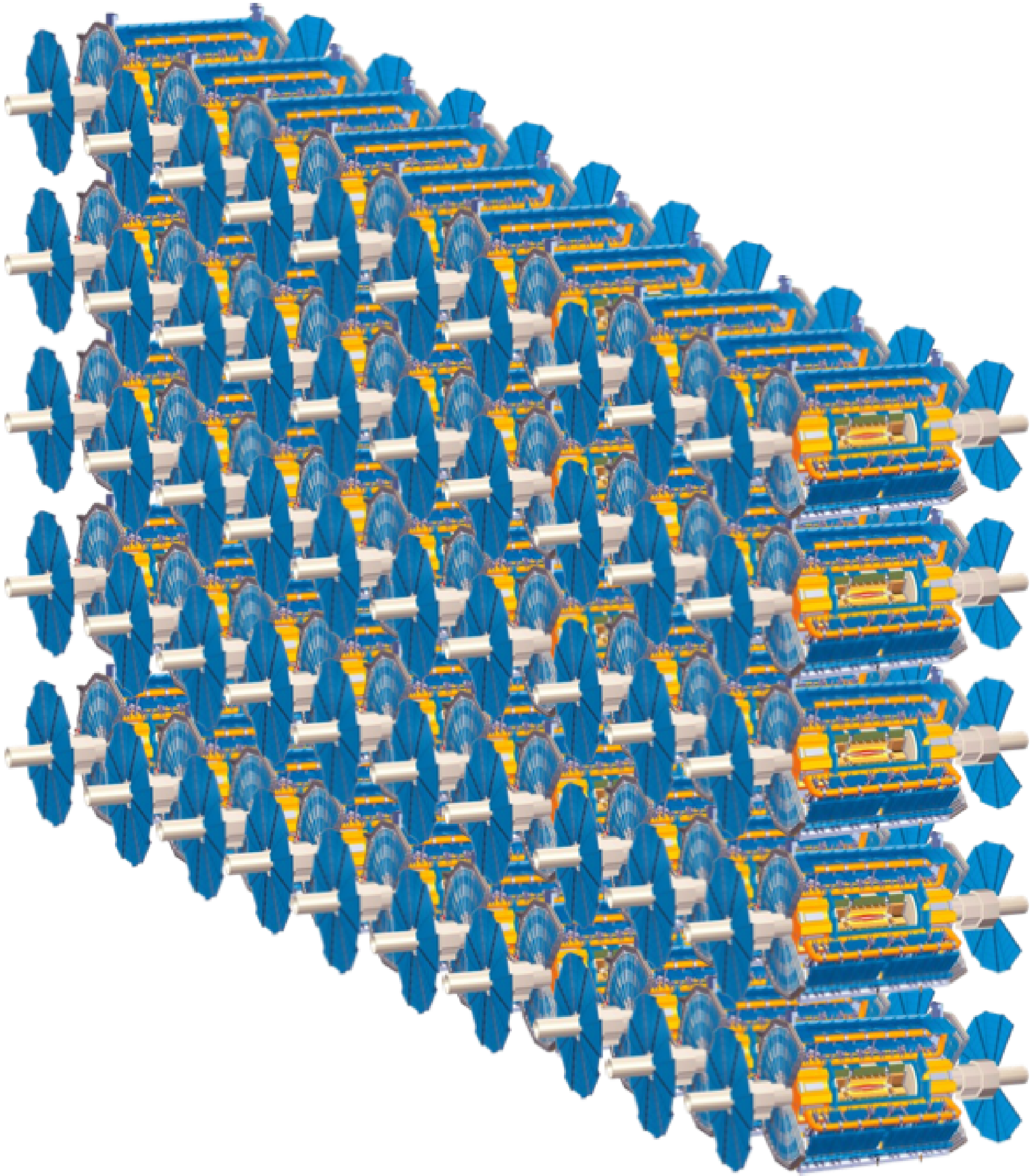
That new physics is not well understood:

- **What is the mass generation mechanism?**
  - Could the neutrino be a Majorana particle?
  - Why are the masses so small?
- **Does it explain flavour?**
  - Nearly (exactly?) maximal mixing observed: 'μ' and 'τ' flavour interchangeable in neutrino oscillations.
- **Does it provide a connection between the quark and lepton sectors?**
  - Why the corresponding mixing matrices are so different?
- **What are the implications for the universe we live in?**
  - Baryon asymmetry of the universe: CP violation + Majorana masses ingredients of the leptogenesis hypothesis.
  - Dark matter: Sterile neutrino is a candidate.

To explore that new physics
we are building
(or planning to build)
some of the
most spectacular physics experiments ever!

Have you been told about the *mighty* ATLAS detector in this school?

This is how many ATLAS detectors we would be able to stack up within Hyper-Kamiokande!



This lecture

- I will try to describe this remarkable discovery path we have taken and show some of the results that shaped our current understanding.

- I will also try to convey some of the enthousiasm in our field for the great new experiments we are now proposing or building and their mind-blowing physics sensitivity.

- My task of telling you all about 'Experimental Neutrino Physics' in an hour is an impossible one, so I had to be very selective.
  - The selection and relative emphasis is my own.
  - It is certainly biased (if nothing else, by the fact I know some areas better than others).
  - You have my apologies in advance if your favourite topic / experiment / result is overlooked.

Outline

- **Establishing the 3-flavour neutrino oscillation picture**
  - Resolving the solar neutrino problem
  - Resolving the atmoshperic neutrino anomaly
  - Global fit results & outstanding questions
  - Near future sensitivity of running experiments (-2020)
  - Future sensitivity (2020 and beyond)
- **Tensions in the 3-flavour scheme**

Production & Detection

Flavour eigenstates

- ν_e, ν_μ, ν_τ, ...

Interactions described by:

$\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}} j^{\mu}_{CC} W_\mu + h.c.$

Propagation

Mass eigenstates:

- ν_1, ν_2, ν_3, ...

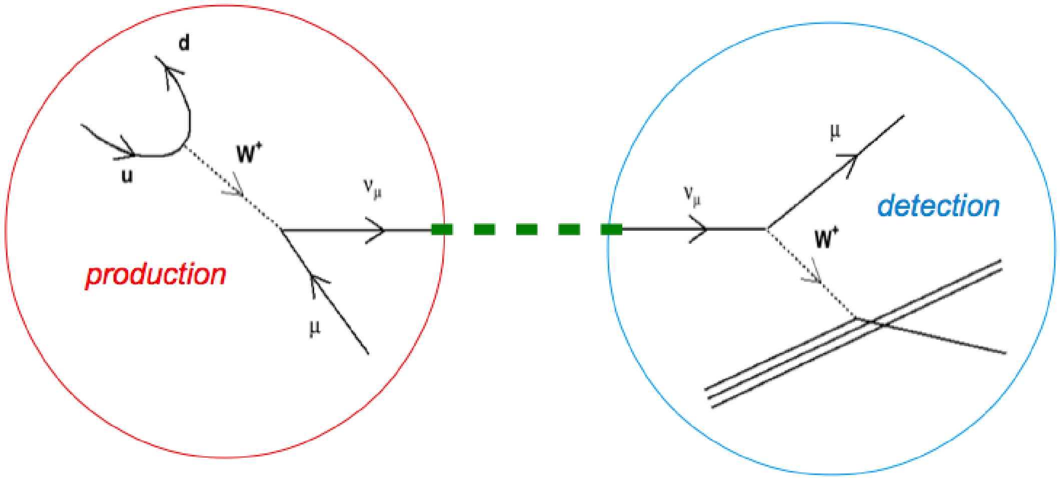
Described by plane waves:

$|\nu_i(L) >= e^{-im_i^2 L/2E} \cdot |\nu_i(0) >$

Each flavour eigenstate a superposition of mass eigenstates

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

A quantum-mechanical interference effect



A neutrino state that starts its life as particular flavour eigenstate (e.g. ν_μ) may be detected as a different flavour eigenstate (e.g. ν_e).

Just a quick reminder since that topic was covered in the theoretical neutrino lectures by Guido Altarelli

What do we measure in neutrino oscillation experiments?

Probability for $\nu_\alpha \rightarrow \nu_\beta$ $(\alpha, \beta : e, \mu, \tau)$ flavour oscillation:

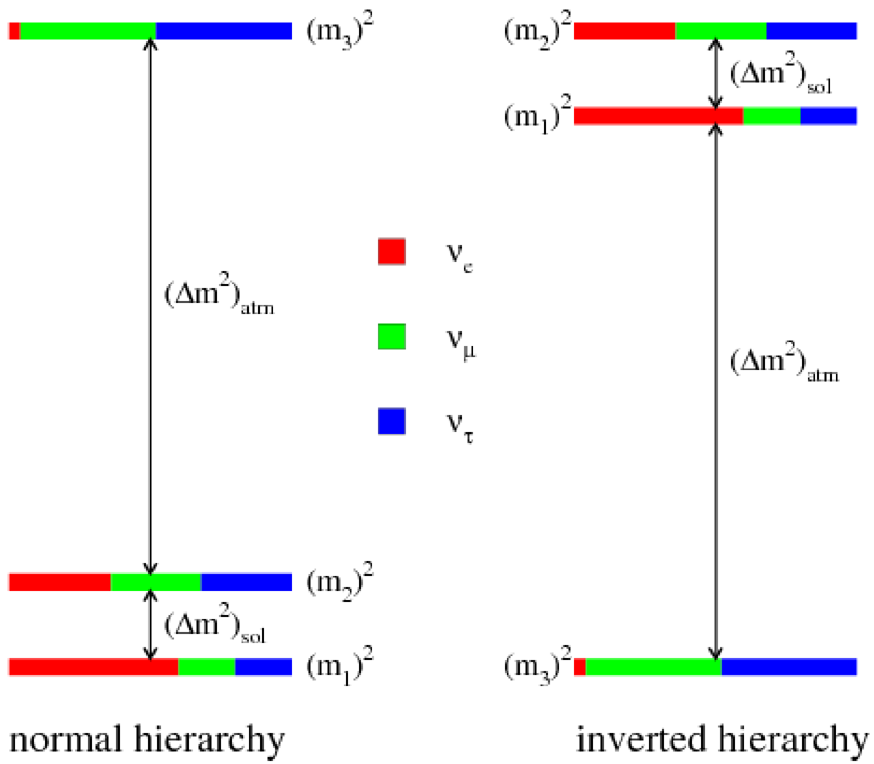
$$P_{\alpha\beta} = \delta_{\alpha\beta} \quad - \quad 4\sum_{i>j} Re[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}] sin^2(\frac{1}{4}\frac{L}{E}\Delta m^2_{ij})$$
$$+ \quad 2\sum_{i>j} Im[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}] sin(\frac{1}{2}\frac{L}{E}\Delta m^2_{ij})$$

Sensitivity to oscillations by tuning L/E (baseline to energy ratio)

For a purely phenomenological description of neutrino oscillations, assuming 3 active neutrinos, we need:

- Any 2 squared mass splittings (e.g. Δm^2_{21},Δm^2_{32})
- 3 mixing angles (θ_{12}, θ_{13}, θ_{23})
- 1 CP invariance violating phase (δ_{CP})

Two squared-mass splitting scales



As you have seen at the previous lectures, we have now observed oscillations at both squared-mass splitting scales

- **the "solar" splitting**

  $\Delta m^2_{21} \approx 7.5 \times 10^{-5}\ eV^2/c^4$

- **the "atmospheric" splitting**

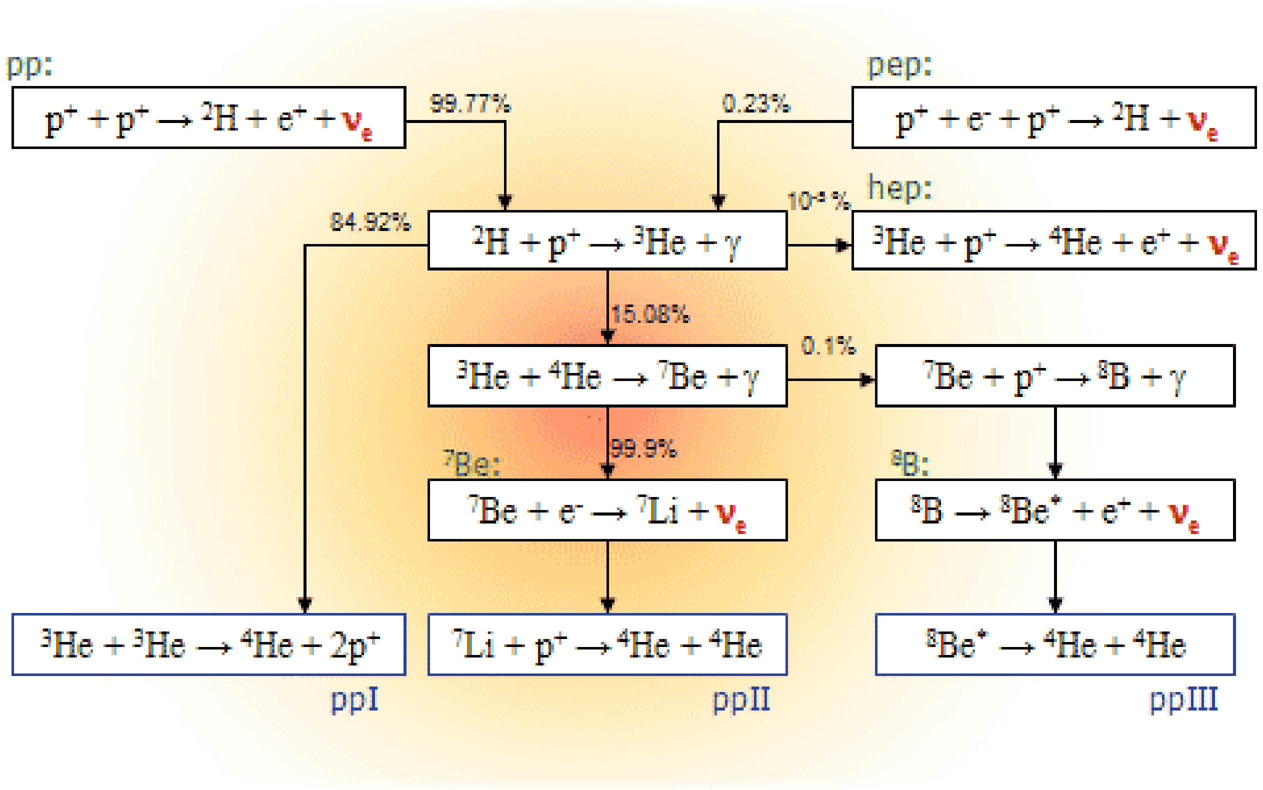
  $|\Delta m^2_{32}| \approx 2.5 \times 10^{-3}\ eV^2/c^4$

Oscillations at the solar squared-mass splitting:
Discovery, status and prospects

Energy production in the Sun: $4p \rightarrow He + 2e^{+} + 2\nu_e$ + **27 MeV**

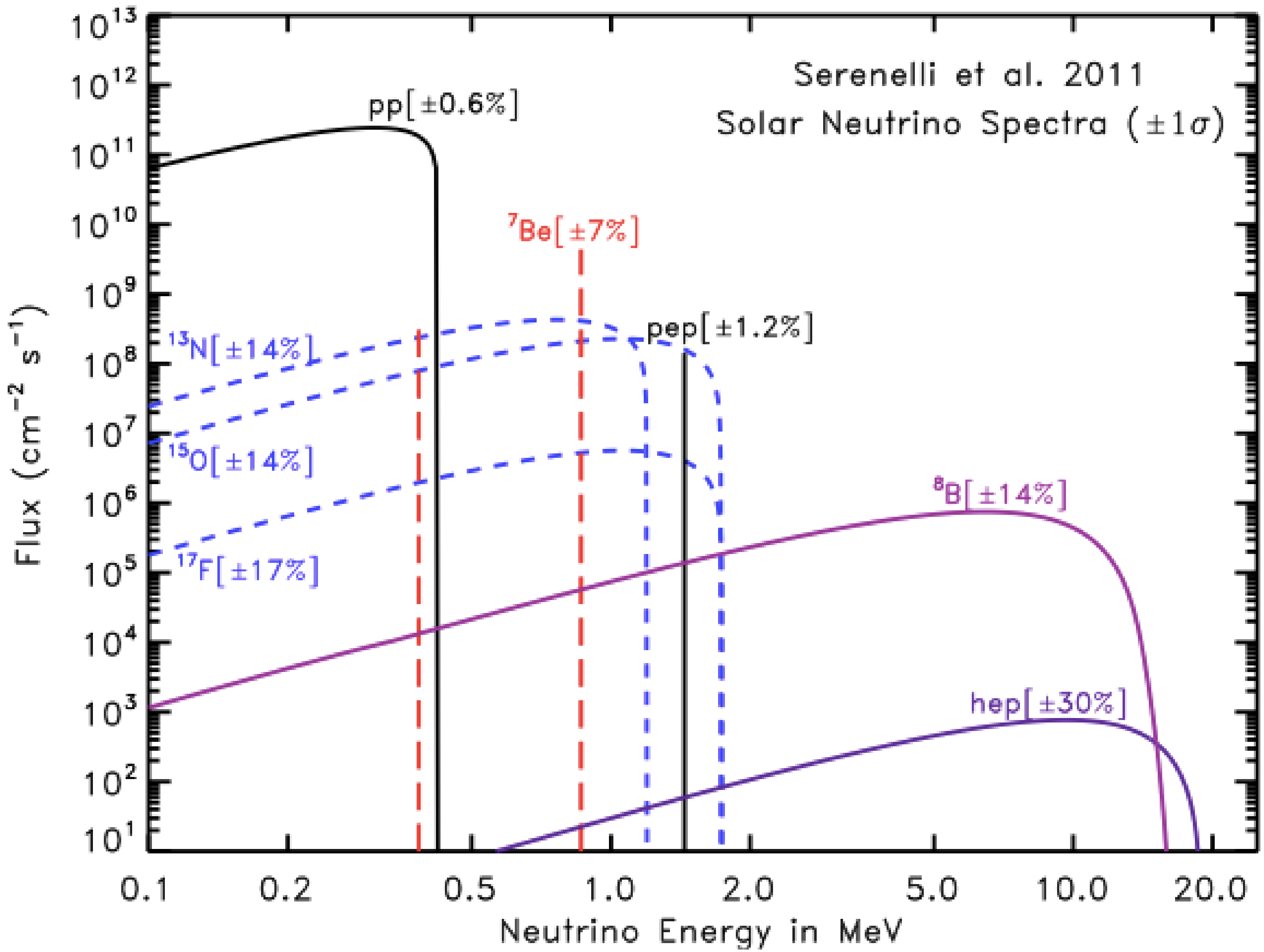
Solar neutrino flux in Earth: $\sim 6\times 10^{10}\ \nu_e/cm^2\ /sec$

(deduced from the solar luminosity $L_{sun} = 8.6\ \times 10^{11}$ MeV $/cm^2\ /$sec)



This proceeds via the chain reaction shown on the left (pp chain) The pp chain dominates for stars up to the Sun's size. The primary alternative is the CNO cycle which dominates in stars with mass $> M_{sun}$. In the Sun the CNO sycle contributes $\sim$1% of the produced energy.

Solar neutrino flux



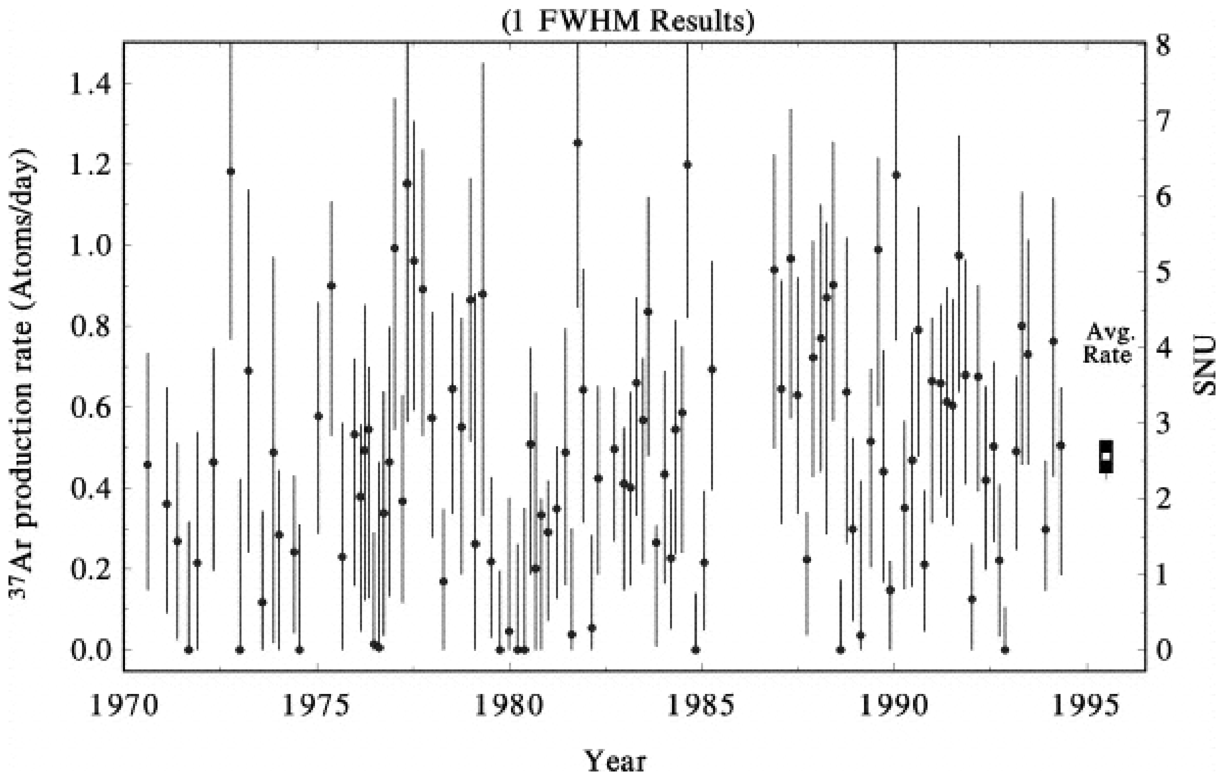
Detection of solar neutrinos: Homestake experiment

The Davis experiment (1969-99): Using 600 tonnes of C_2Cl_4 in vessel deep in the Homestake mine ($\sim$ 1.5 km) to shield the experiment from cosmic backgrounds.

- Detection: $\nu_e +^{37} Cl \rightarrow e^- +^{37} Ar$
- Energy threshold: 814 keV
  - Sensitive to the ^8B and ^7Be neutrinos of the pp chain
- Extract the ^{37}Ar ($\sim$monthly) and count the number of ^{37}Ar atoms
  - Using the EC reaction: $^{37}Ar + e^- \rightarrow^{37} Cl + \nu_e$
  - $\tau_{1/2} = 35$ days
  - Produces a 2.82 keV Auger e^-

Homestake results

Solar Standard Model (SSM) prediction for Homestake: 8.5 $\pm$ 1.8 SNU
(1 SNU $= 10^{-36}$ interactions per target atom per sec.)



Measured a flux of:
2.56 $\pm$ 0.23 SNU
($\sim$1 ^{37}Ar atom /2 days!)

$\sim$30% of the prediction!.

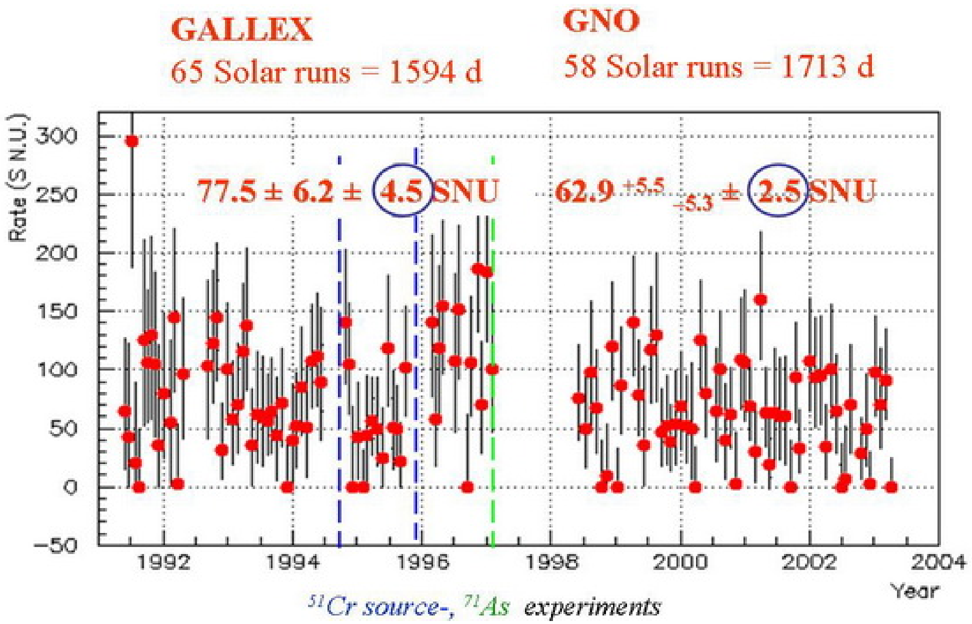
That deficit became known as the 'solar neutrino problem'

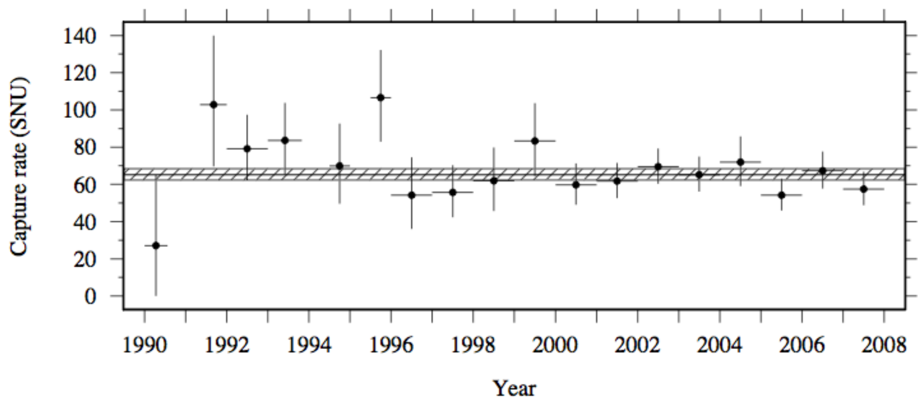
What was wrong??

- The experiment must be wrong
  - How confident are we in the knowledge of the efficiency extracting a dozen of ^{37}Ar atoms out of $\sim$600 tonnes of cleaning fluid?
- Or the theory must be wrong
  - The predicted flux has strong temperature dependence ($\Phi_\nu \propto T^m$)
    - For pp neutrinos, m=-1.1
    - ... but for ^7Be neutrinos, m=+10 (!)
    - ... and for ^8B neutrinos, m=+24 (!!)
  - A small change in temperature could change the ^7Be and ^8B flux significantly
- Or something must be wrong with the neutrino?

Solar neutrino detection by GALLEX/GNO and SAGE

Reducing the dependence on the SSM: Measure pp neutrinos.

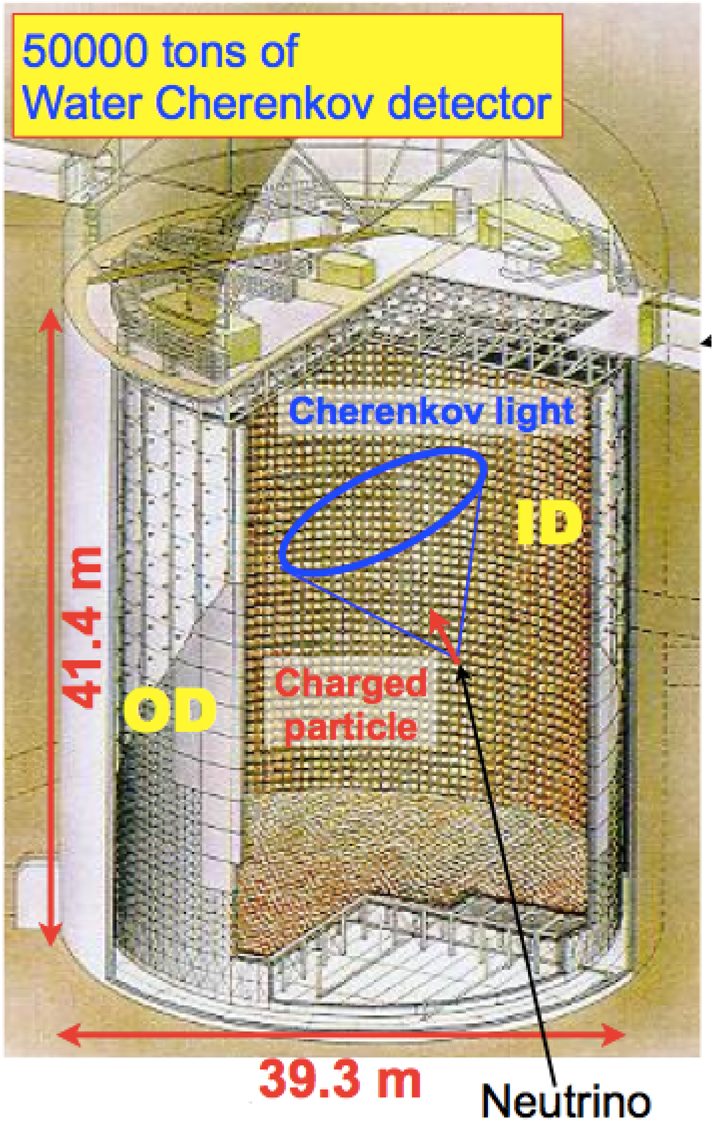




- New generation of Gallium radiochemical experiments
- Detection: $\nu_e +^{71} Ga \rightarrow e^- +^{71} Ge$
- Threshold: 233 keV
  - sensitive to pp
- 130 SNU ($\pm$12) predicted.
- Seeing around 50% of that.

[GALLEX: Phys.Lett.B 685 (2010) 47;
GNO: Phys.Lett. B 616 (2005) 174;
SAGE: Phys.Rev. C80 (2009) 015807]

Solar neutrino detection by (Super-)Kamiokande

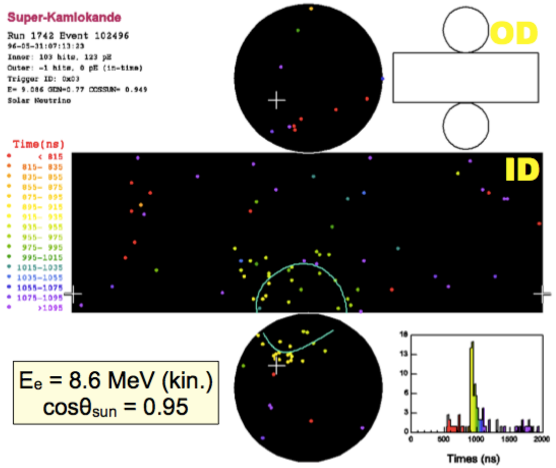


[Y.Koshio, Neutrino 2014, Boston]

Kamiokande (3 kt): 1983-96, 3 phases
Super-Kamiokande (50 kt): 1996-now, 4 phases

Phase	Period	Livetime (days)	Fiducial vol. (kton)	# of PMTs	Energy thr.(MeV)
SK-I	1996.4 ~ 2001.7	1496	22.5	11146 (40%)	4.5
SK-II	2002.10 ~ 2005.10	791		5182 (20%)	6.5
SK-III	2006.7 ~ 2008.8	548	22.5 (>5.5MeV) 13.3 (<5.5MeV)	11129 (40%)	4.5
SK-IV	2008.9 ~	1669	22.5 (>5.5MeV) 13.3 (4.5<E<5.5) 8.8 (<4.5MeV)		3.5

Typical event



Detection via $\nu + e^-$ elastic scattering: $\nu + e^- \rightarrow \nu + e^-$

Energy threshold: ~5 MeV. Sensitive to the ^8B neutrino flux component.

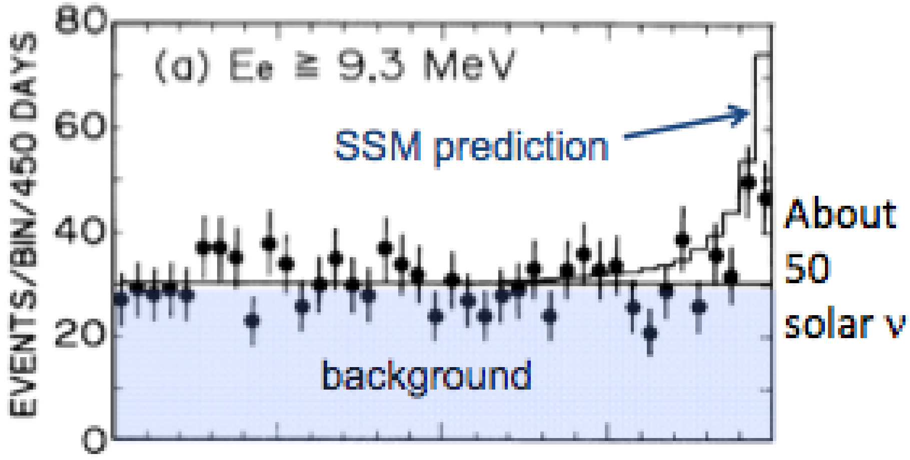
- Timing: Day/night asymmetry and seasonal variations
- Directionality
- Energy spectrum

SK-IV performance:

- 55 cm vertex resolution
- 23 degrees angular resolution
- 14% energy resolution

Solar neutrino detection by (Super-)Kamiokande

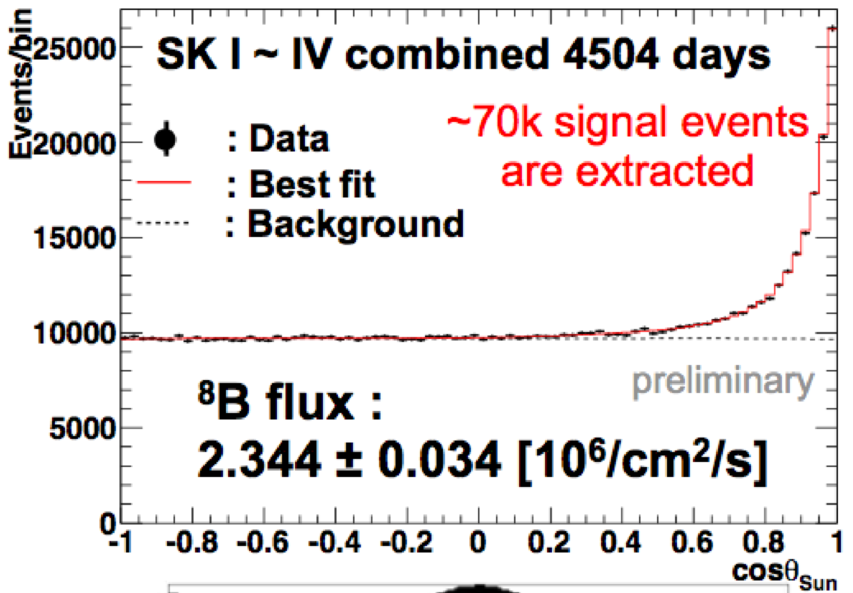
Initial Kamiokande result (1989):

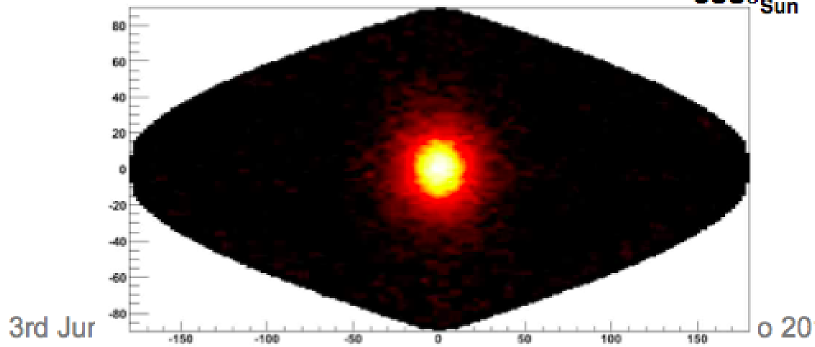


- Strong forward peak
  - Direct evidence of neutrino production at the solar core
- Observed deficit
  - $0.46 \pm 0.13(\mathrm{stat}) \pm 0.08(\mathrm{syst})$ of SSM prediction.

[PRL 63, 16 (1989)]

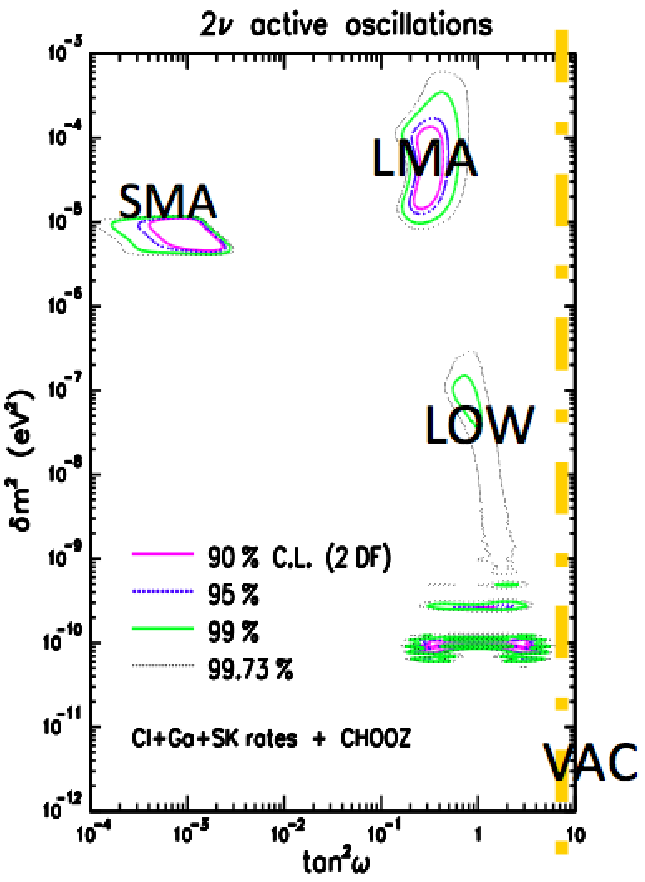
Latest Super-Kamiokande result:





[Y.Koshio, Neutrino 2014, Boston]

Solving the solar neutrino problem



But no smoking-gun signature.
Solar data fits preferred the Large Mixing Angle (LMA) solution, but other regions could not be ruled out.

A heavy water experiment was proposed, able to **measure both** the:

- **CC rate** (ν_e flux), and
- **NC rate** (ν_e+ν_μ+ν_τ flux)

and establish conclusively (independently of solar model calculations) the existence of solar neutrino flavour oscillations.

VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

Direct Approach to Resolve the Solar-Neutrino Problem

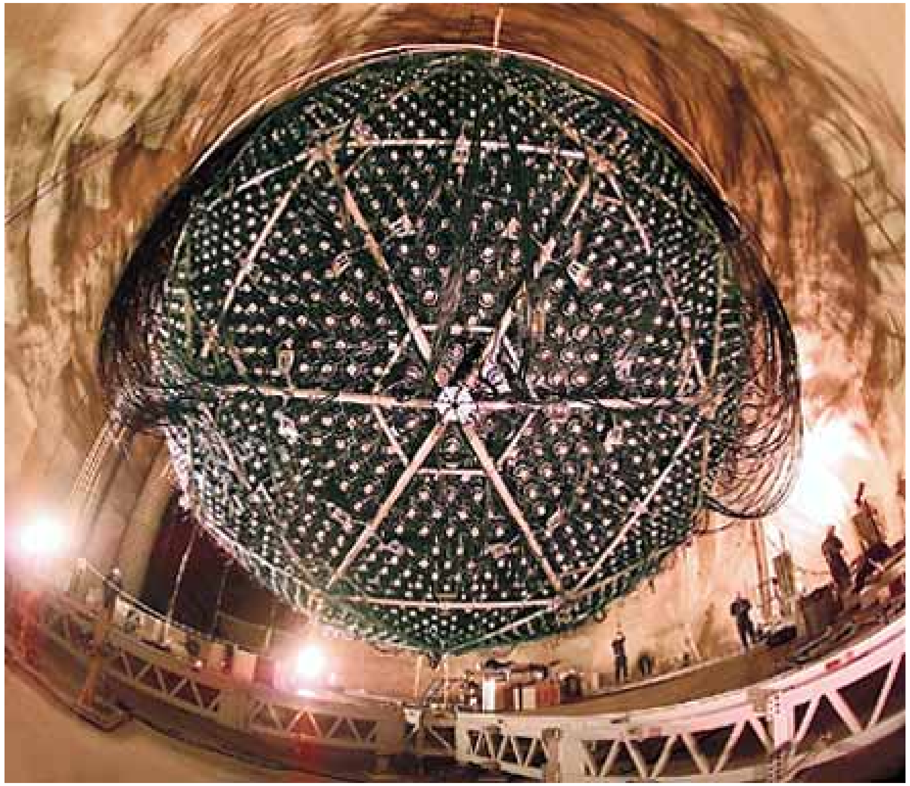
Herbert H. Chen
Department of Physics, University of California, Irvine, California 92717
(Received 27 June 1985)

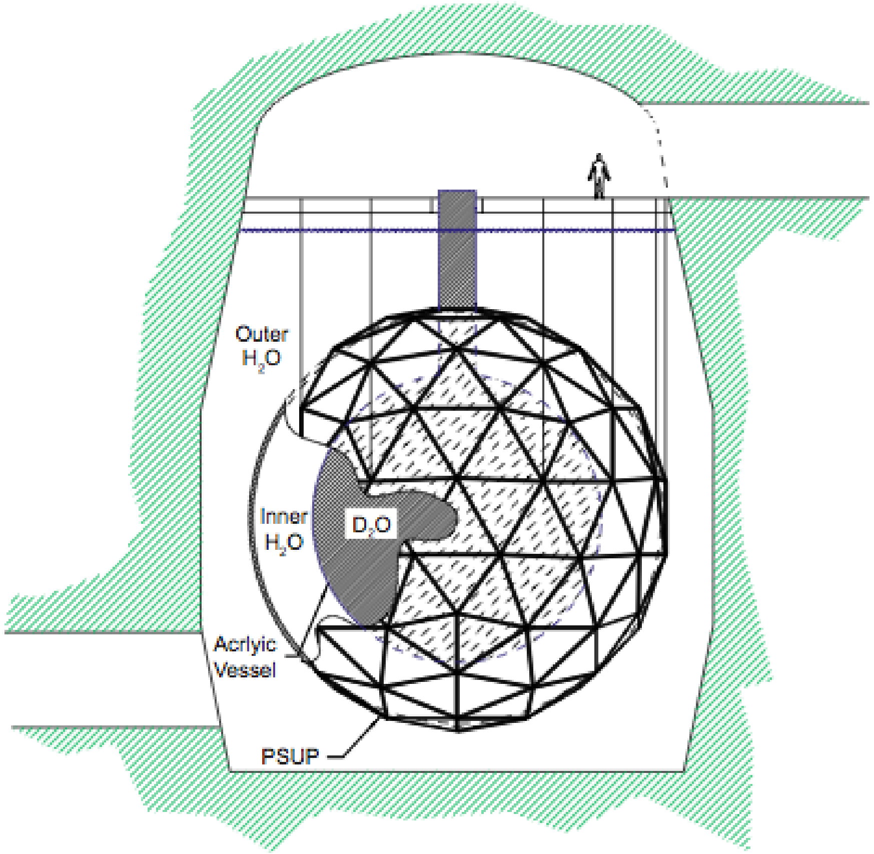
A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu + d \to \nu + p + n$ and the charged-current reaction $\nu_e + d \to e^- + p + p$, is suggested for this purpose.

PACS numbers: 96.60.Kx, 14.60.Gh

[H.Chen, Phys.Rev.Lett. 55 (1985) 1534]

SNO (Sudbury Neutrino Observatory) located 2km underground at the Sudbury nickel mine in Canada: 1,000 tonnes of heavy water in acrylic vessel of 6 m radius, surrounded by 6,500 tonnes of normal water. Instrumented with 9,438 photomultipliers (54% photocathode coverage).



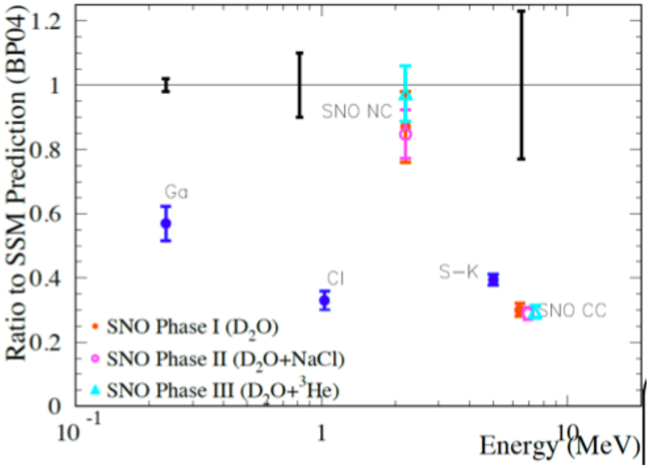


The SNO experiment - Neutrino detection mechanisms

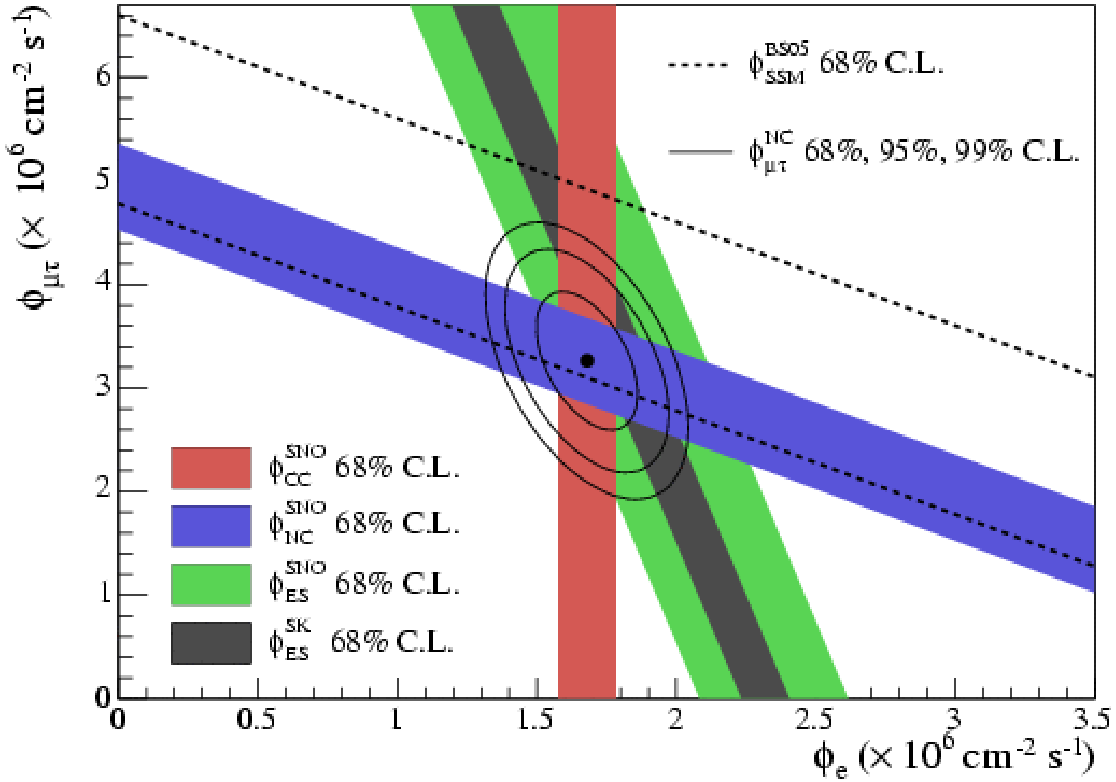
- CC ($\nu_e + d \rightarrow e^- + p + p$) -1.44 MeV
  - Sensitive only to ν_e
- NC ($\nu + d \rightarrow \nu + p + n$) -2.22 MeV
  - **Phase 1** (Nov 99 - May 01): **Pure heavy water**
    - Neutrons detected via n+d $\rightarrow$ t+γ (6.3 MeV), $\sigma = 0.52$ mb
    - Using the Cherenkov light of e^- from the Compton scattering of γ
  - **Phase 2** (Jul 01 - Sep 03): **Salt phase** (2 tonnes of NaCl)
    - Neutrons detected via n+$^{35}Cl \rightarrow {}^{36}Cl + \gamma's$ (8.6 MeV), $\sigma = 0.44$ b
  - **Phase 3** (Nov 04 - Nov 06): **NCD phase** (36 ^{3}He proport. counters)
    - Neutrons detected directly via n+$^3He \rightarrow$ p+t, σ=5333 barns
    - No statistical separation, breaks correlations with CC rate measurement
- $\nu + e^-$ elastic ($\nu + e^- \rightarrow \nu + e^-$) $\leftarrow$ As in Super-K
  - Sensitive to all neutrino flavours
  - Cross-section for ν_e about 6 times larger than that of ν_μ or ν_τ.

Backgrounds mainly from the radioactive decay chains of U and Th

The SNO results



$\Phi_{SNO}^{CC} = (1.76 \pm 0.06\ (\text{stat}) \pm 0.09\ (\text{syst})) \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$
$\Phi_{SNO}^{NC} = (5.09 \pm 0.44\ (\text{stat}) \pm 0.46\ (\text{syst})) \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$
$\Phi_{SNO}^{ES} = (2.39 \pm 0.24\ (\text{stat}) \pm 0.12\ (\text{syst})) \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$



- Total ν flux from NC rate in agreement with SSM for ^8B ν's (Φ_{SSM}=(5.05 +1.01 -0.81) $\times$ 10^6 cm^{-2} s^{-1})
- ν_e flux from CC rate much smaller (oscillations!)
- Flux from ES rate larger than flux from CC (some contributions from (ν_μ+ν_τ) and consistent with SuperK.

Phase 1: [PRL 87 (2001) 071301; PRL 89 (2002) 011301; PRL 89 (2002) 011302; PRC 75 (2007) 045502], Phase 2: [PRL 92 (2004) 181301; PRC 72 (2005) 055502], Phase 3: [PRL 101 (2008) 111301], Combined:[PRC 88 (2013) 025501]

Explanation of solar experiment results

The solar results favour the large mixing angle MSW solution.
(with $\theta_{12} \approx 33^o$ and $\Delta m^2_{21} \approx 5 \times 10^{-5}$ eV^2/c^4)

You must have seen at your theory lectures that due to coherent forward scattering, ν_e's propagating in matter feel a potential that ν_μ's and ν_τ's do not.

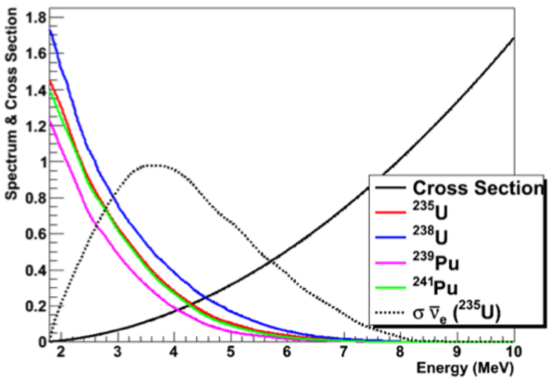
The oscillation probability is modified by matter effects ($x = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2}$):

$$sin2\theta_{\mathbf{m}} = \frac{sin2\theta}{\sqrt{sin^2 2\theta + (cos2\theta - x)^2}}, \quad cos2\theta_{\mathbf{m}} = \frac{cos2\theta - x}{\sqrt{sin^2 2\theta + (cos2\theta - x)^2}}$$

[Wolfenstein, PRD17 (1978) 2369; Mikheyev and Smirnov, Sov. J. Nucl. Phys. 42 (1985) 913]

- For a neutrino created in the dense solar core $\theta_m \to \pi/2$.
- If $\theta < \pi/4$ in vacuum, the composition of the weak eigenstates is reversed.
- ν_e is mostly ν_1 in vacuum, but mostly ν_2 in the dense solar core.
- Remains in this state as it travels in regions of lower density (if density changes slowly).

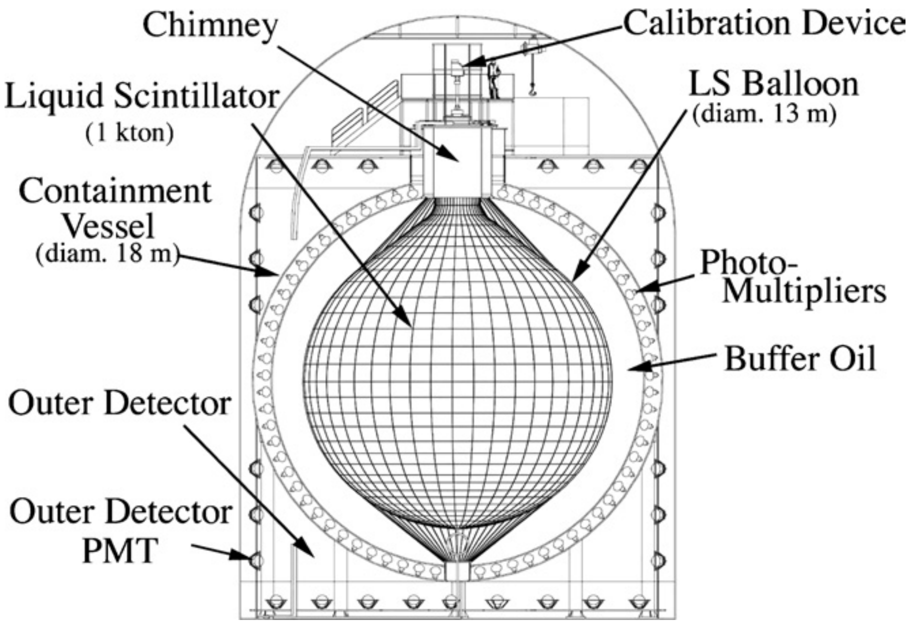
Confirmation with man-made neutrinos: KamLAND

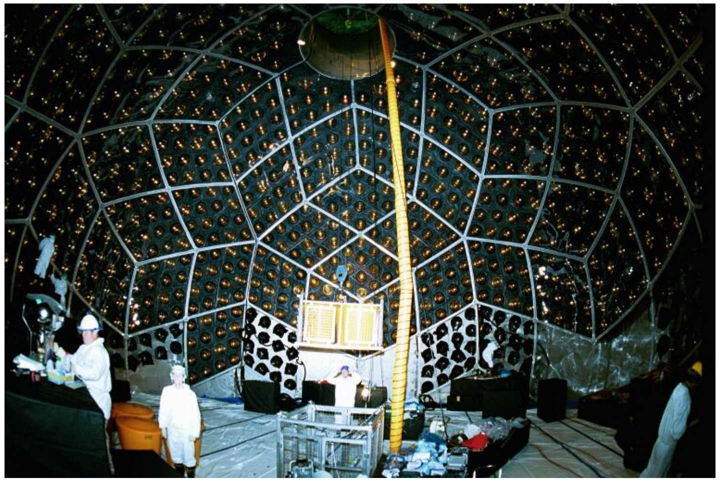


[plot from Qian and Wang, arXiv:1405.7217]

- **Using neutrinos from nuclear reactors**
  - 68 GW_{th} of nuclear power (20% of the world's nuclear power) were available before the Tohoku earthquake.
  - $\sim$80% within 140-210 km from the Kamioka mine ($< L > \sim$ 180 km)
- **Reactors are sources of a pure and isotropic flux of $\bar{\nu}_e$**
  - On average, 6 $\bar{\nu}_e$ per fission along the decay chain of all fission products.
  - A 1 GW_{th} reactor emits 2 $\times 10^{20}$ $\bar{\nu}_e$ /sec.
  - Main $\bar{\nu}_e$ sources: ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu.
- **$\bar{\nu}_e$ detection:**
  - Prompt e^+ signal ($\bar{\nu}_e + p \rightarrow e^+ + n$)
  - Followed (within 200 μs) by a correlated signal from neutron capture ($n + p \rightarrow d + \gamma$ (2.2 eV))
- **$\bar{\nu}_e$ energy reconstruction:** $E_\nu = T_e + 1.8 MeV$

The KamLAND experiment

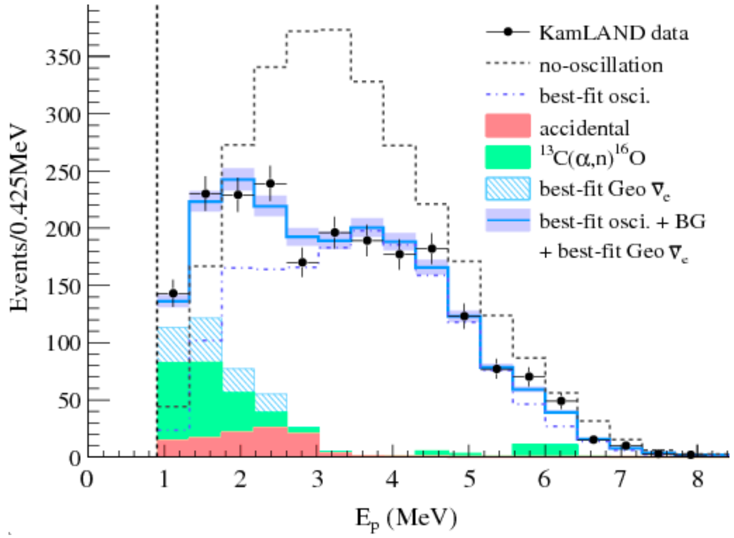




Detector:

- 1,000 tonnes of liquid scintillator in a 13 m diameter nylon balloon
- Within 18 m diameter stainless steel vessel, filled with mineral oil to shield the target region from external radiation
- Viewed by 1879 (554 20" and 1325 17") photomultipliers
- Surrounded by Water Cherenkov detector to absorb γ, n and tag cosmic μ
- In 2700 m.w.e depth

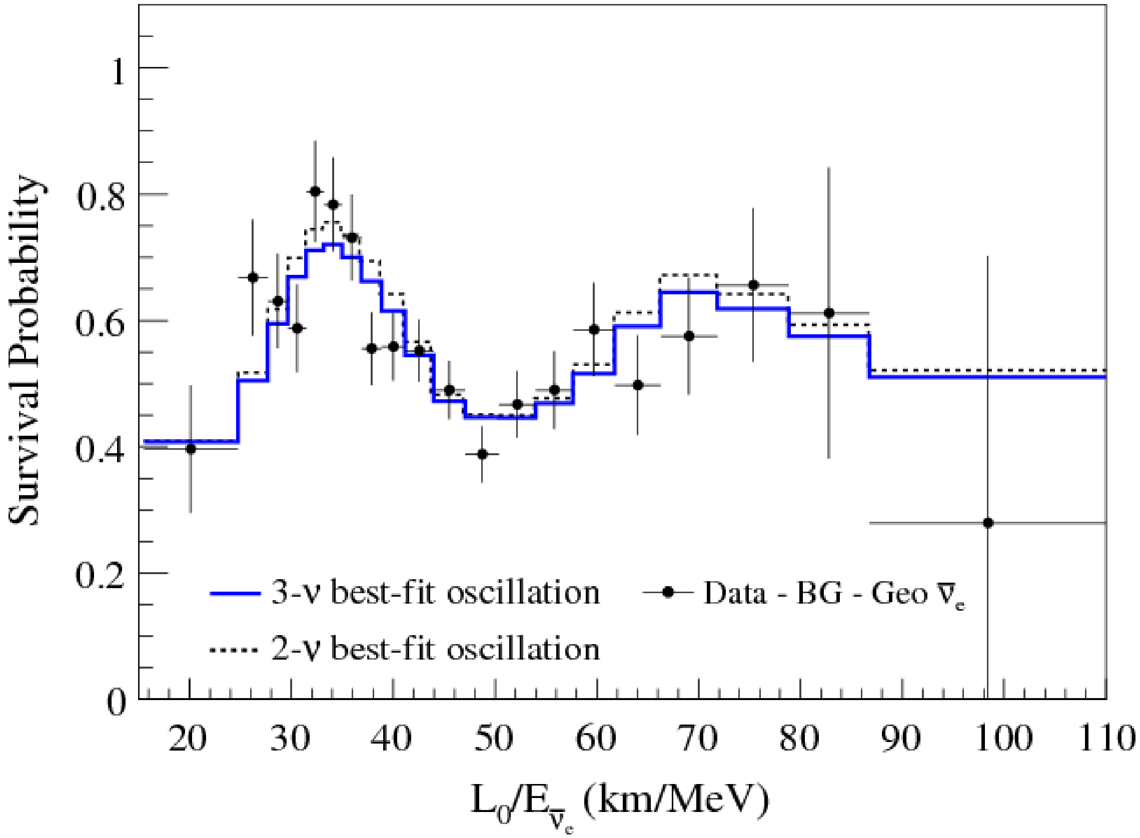
KamLAND saw $\bar{\nu}_e$ disappearance and energy spectrum distortion ($>5\sigma$).



Backgrounds:

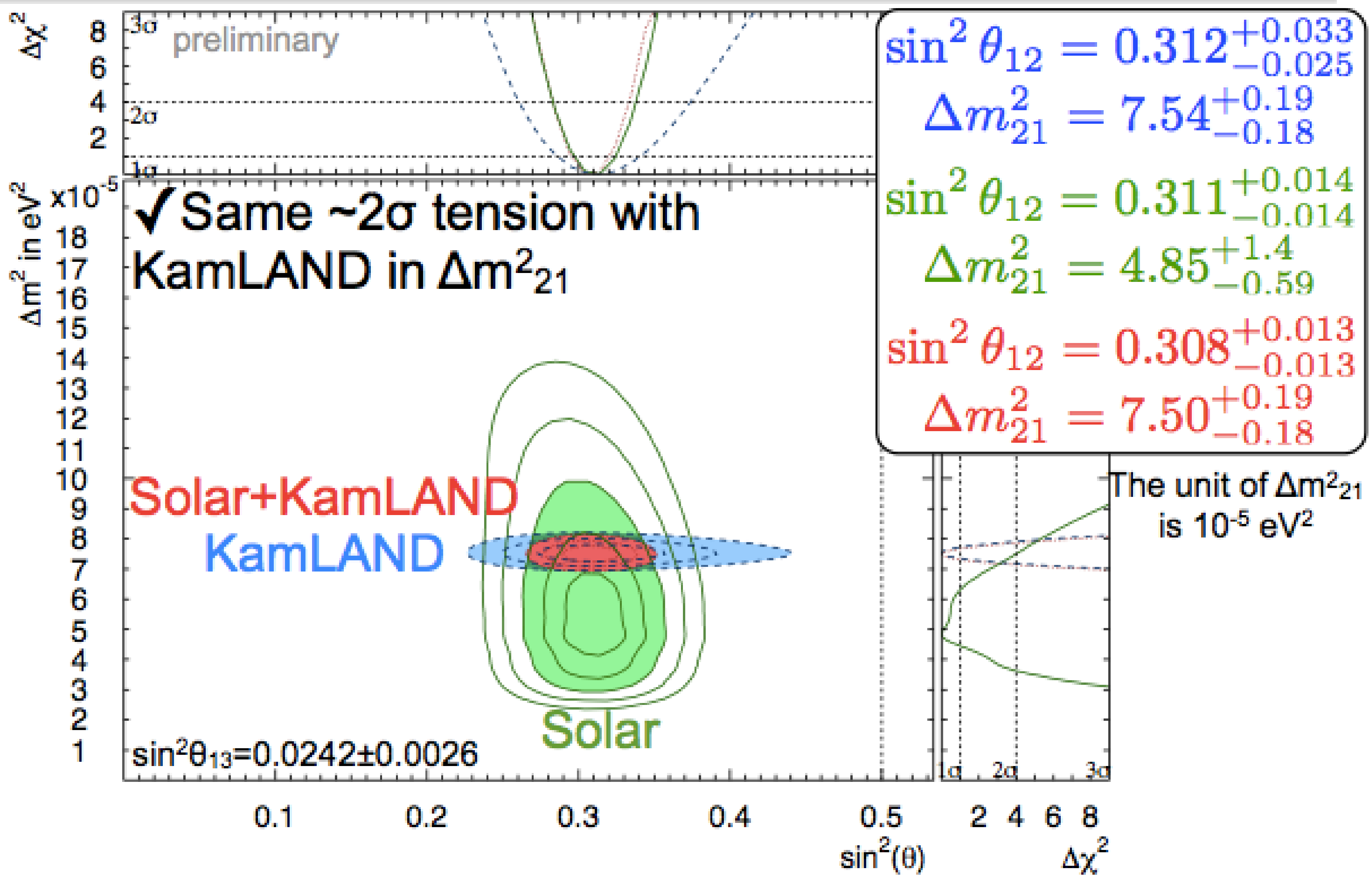
- Accidental
- Terrestrial neutrinos (from ^{238}U and ^{232}Th in the Earth crust and mantle)
- **Correlated**: Fast neutrons, α decays ^{13}C(α,n)$^{16}O*$ and ^{9}Li and ^{8}He spallation products

Smoking-gun signature for neutrino oscillations!



[Abe et al., Phys.Rev.Lett. 100 (2008) 221803]

Oscillation analysis of KamLAND+solar results

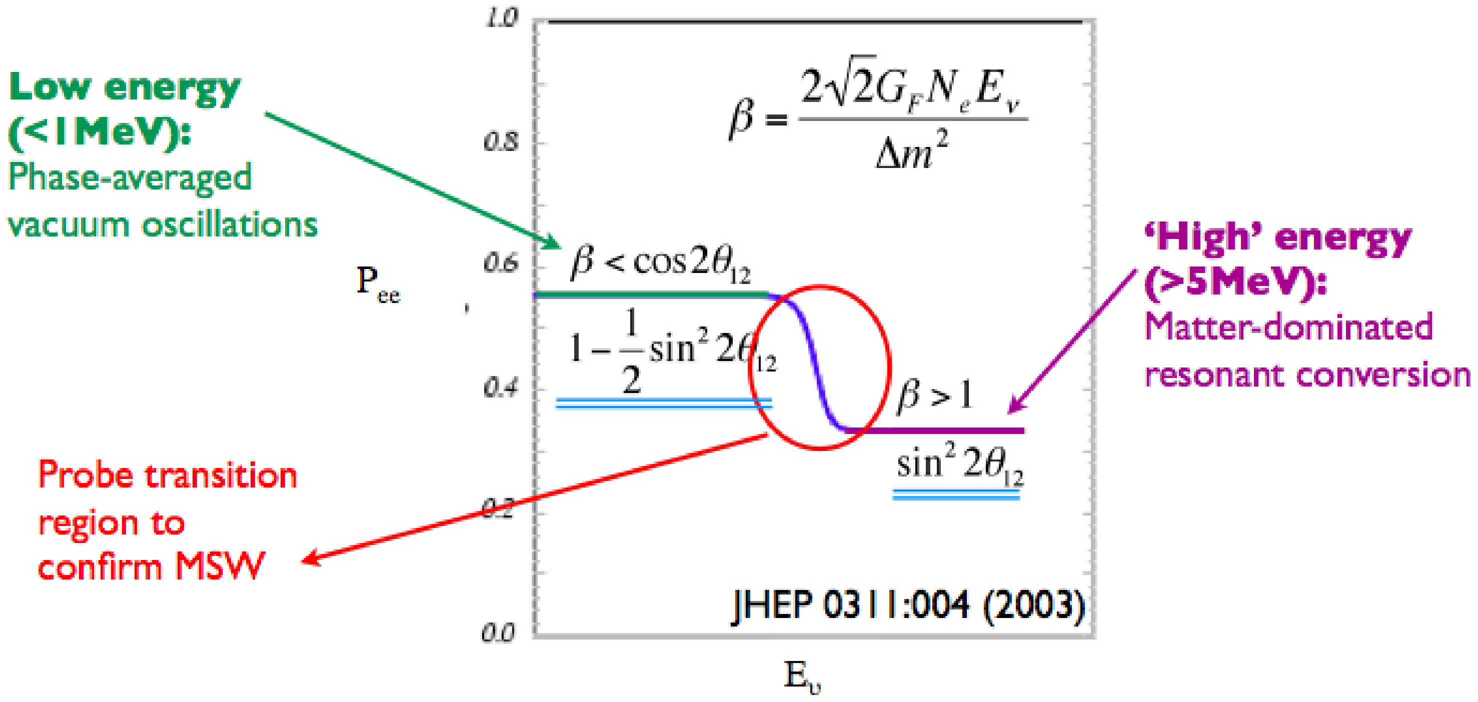


Future prospects: Probing the transition region

Precision oscillation measurements and a probe of the transition region to

- confirm MSW and
- search for non-standard neutrino physics.

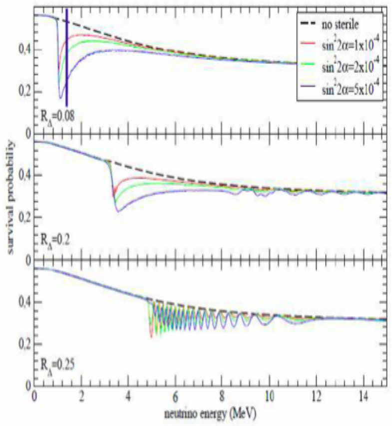
Measuring low energy solar neurinos is also important in order to improve the SSM model.



[schematic by O.Gann, Neutrino 2014 conference, Boston]

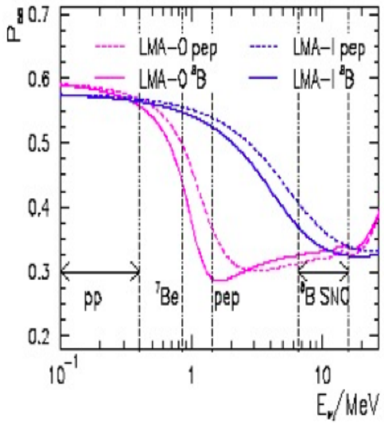
Future prospects: Probing the transition region

Sterile ν



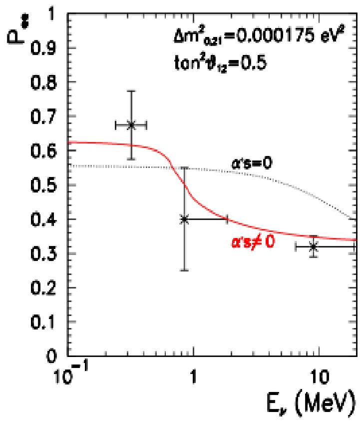
[Phys.Rev.D 83 (2011)]

FCNC



[Phys.Lett.B 594 (2004)]

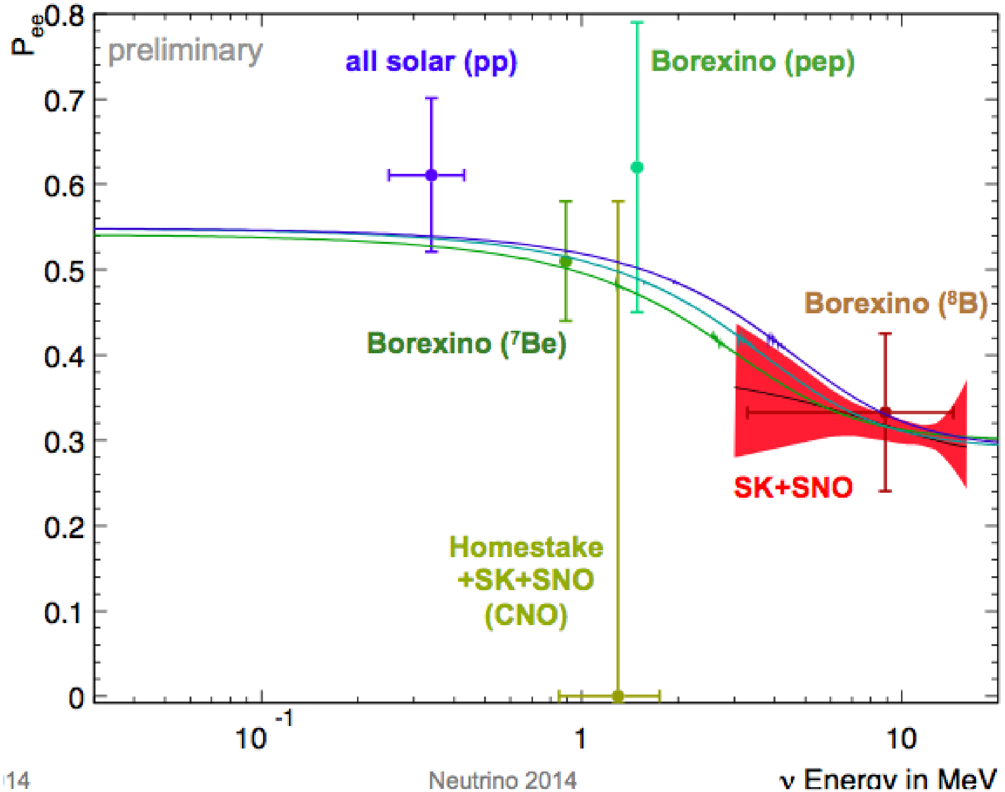
Mass-varying ν



[Phys.Rept. 460 (2008) 1-129]

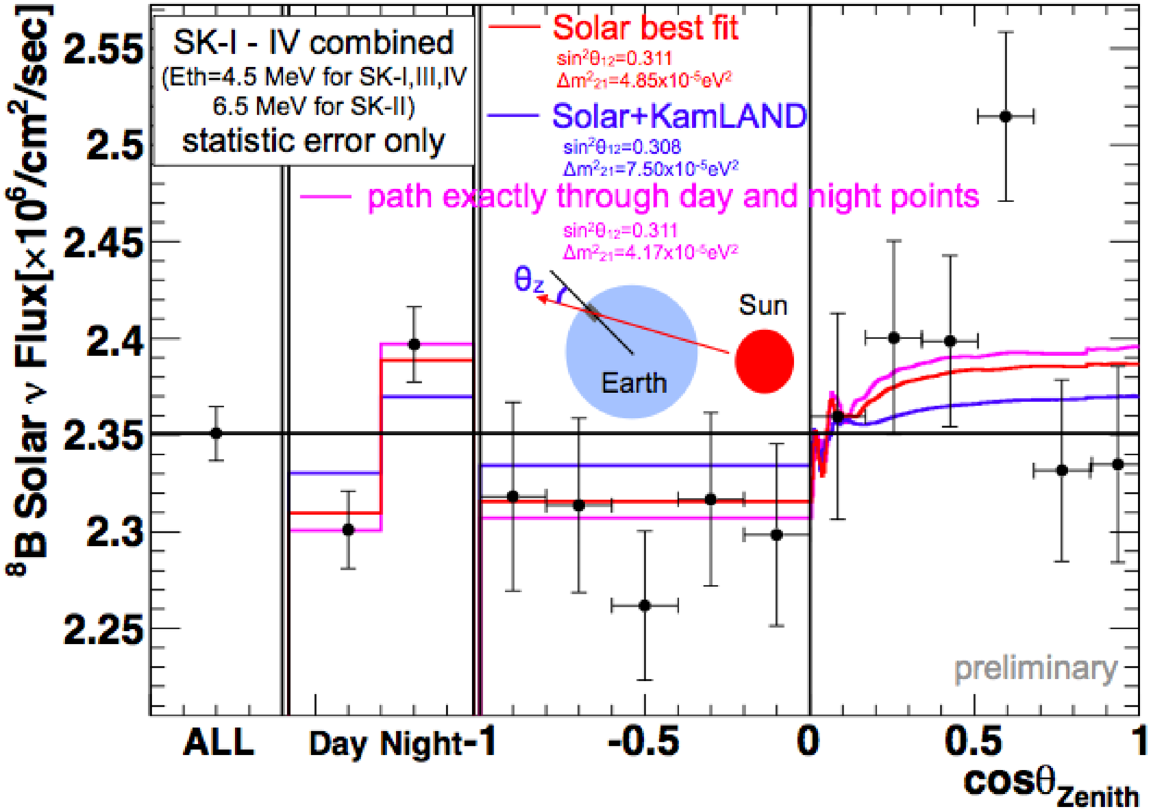
[Plots from O.Gann, Neutrino 2014 conference, Boston]

The transition region provides a sensitive probe of new physics



[Y.Koshio, Neutrino 2014, Boston]

Future prospects: Confirming MSW



[Phys.Rev.Lett. 112 (2014) 091805]

Direct test of matter effects.

Day-night difference in the solar neutrino flux.

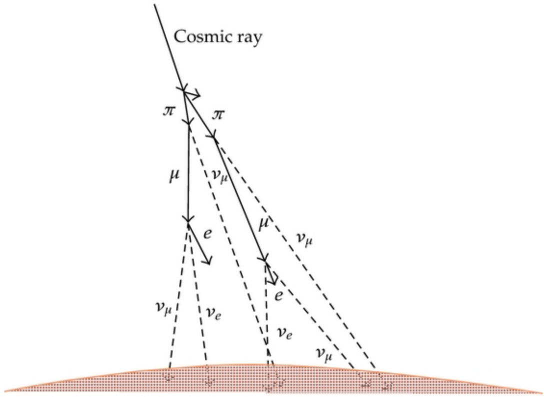
Super-K observes the difference between the average day and night rates over the average of the two rates to be:

(-3.2 $\pm$1.1 (stat) $\pm$0.5(syst))%

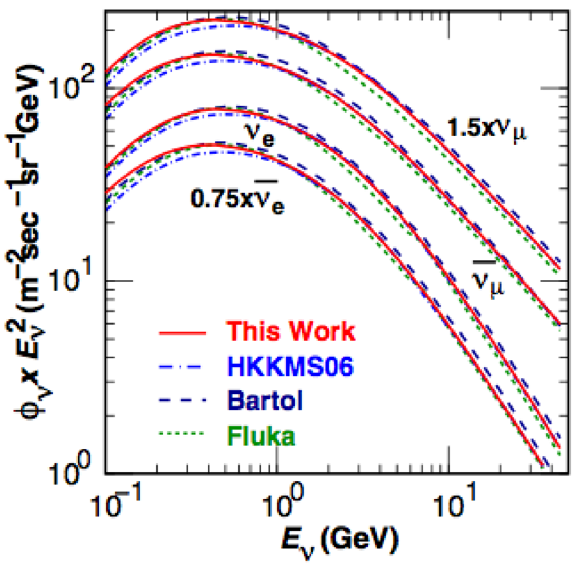
which deviates from 0 by 2.7σ

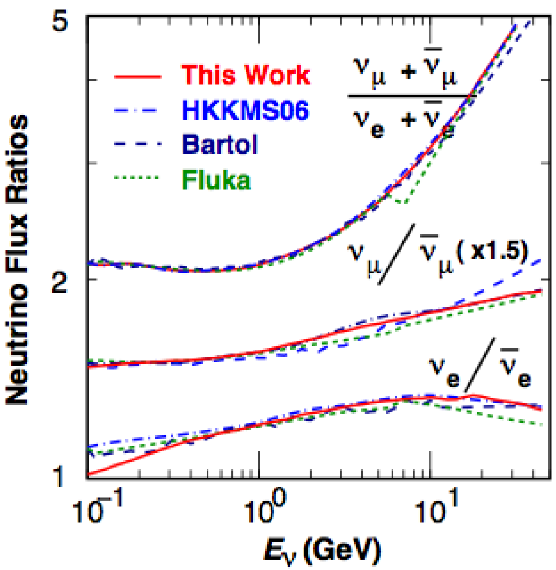
Oscillations at the atmospheric squared-mass splitting: Discovery, status and prospects

Neutrinos produced from interactions of cosmic rays with the atmosphere.



- Neutrinos energies from ∼100 MeV to more than ∼100 TeV
- Flight paths from ∼10 km to ∼13,000 km

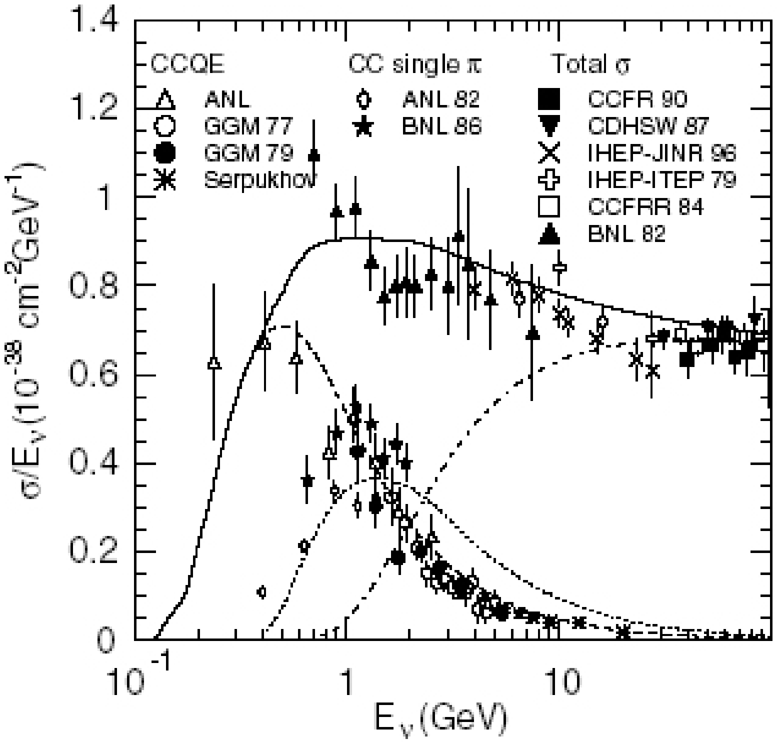


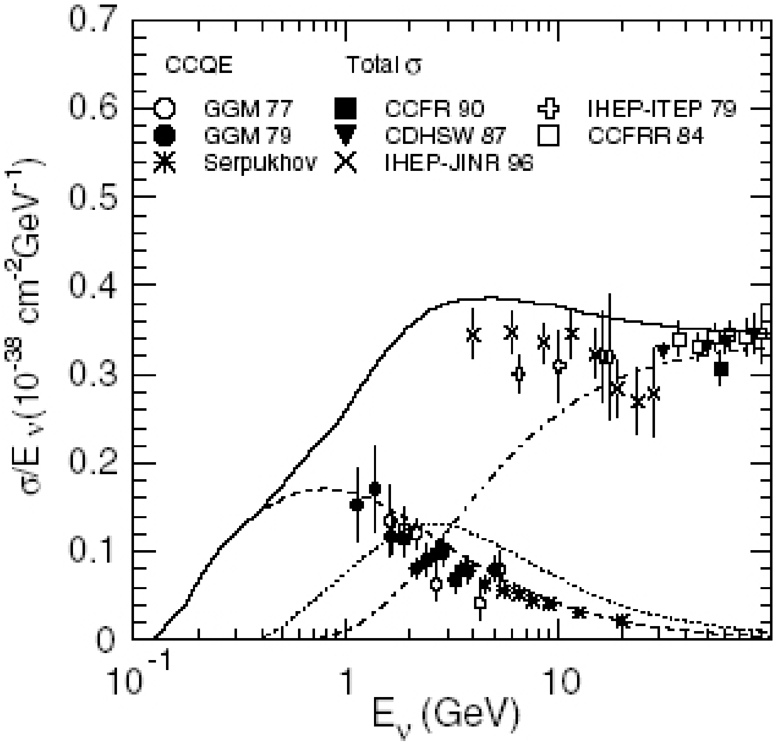


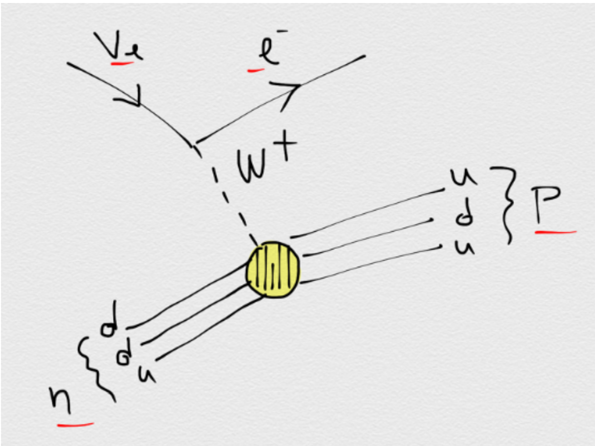
Flux characteristics:

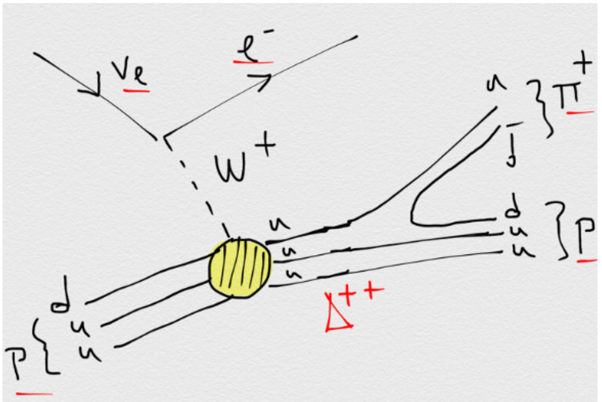
- ∼10% uncertainties <10 GeV, much higher at higher energy
- Up/down symmetric above a few GeV
- ν_μ/ν_e ratio accurately known (∼3% in the ∼few GeV range)
- $\nu/\bar{\nu}$ ratio also accurately known

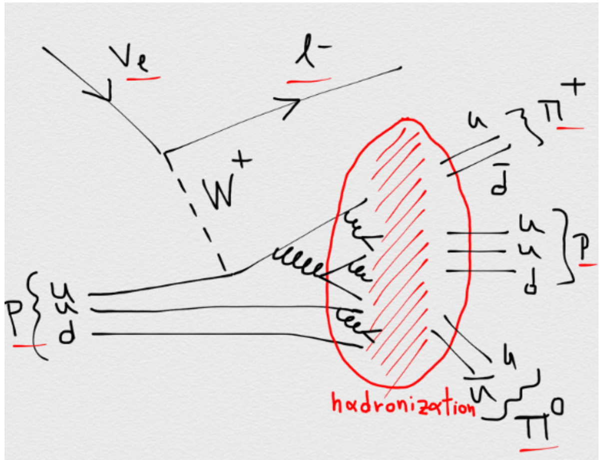
Neutrino interactions in the ~GeV energy range











Detection of atmospheric neutrinos

- First atmospheric neutrino detection in 1965 nearly simultaneously by 2 experiments.
- In the East Rand gold mine (3.2 km depth) in South Africa using a liquid scintillator detector [Reines et al, Phys.Rev.Lett. 15 (1965) 429
- In the Kolar Gold Field mine (2.4 km depth) using a plastic scintillator detector [Achar et al, Phys.Lett. 18 (1965) 196
- Primary motivation to investigate weak interactions at high energies.
- Predicted/Observed = 1.6 ± 0.4 [Crouch et al, Phys.Rev. D18 (1978) 2239

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Cosmic-ray muon fluxes deep underground: Intensity vs depth, and the neutrino-induced component

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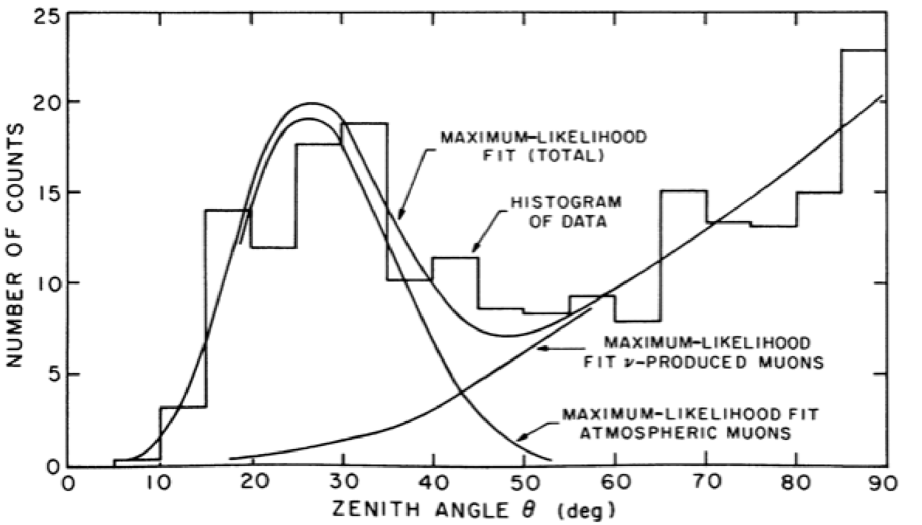
(Received 3 March 1978; revised manuscript received 12 September 1978)

The angular distribution of muons observed deep underground (10788 ft, or 8.89×10^5 g cm^{-2} standard rock) has been measured with a 174-m^2 liquid scintillation detector in conjunction with 48384 neon flash tubes. The data are fitted by a curve giving the vertical intensity of muons vs vertical depth h_0 as $I_{\mu}(h_0) = A \exp(-h_0/\lambda) + I_{\nu\mu}^{(v)}$, where $A = (2.26 \pm 0.16) \times 10^{-6}$ cm^{-2} sec^{-1} sr^{-1}, and $\gamma = (7.58 \pm 0.09) \times 10^4$ g cm^{-2}. The constant term, representing the measured depth-independent flux of muons produced in the surrounding rock by interactions of cosmic-ray neutrinos generated in the earth's atmosphere, has the value $I_{\nu\mu}^{(v)} = (2.23 \pm 0.20) \times 10^{-13}$ cm^{-2}sec^{-1}sr^{-1}. This observed flux is in fair agreement with that predicted assuming a cosmic-ray neutrino flux which is a composite of several theoretical estimates. Thus the flux of muons from extraterrestrial neutrinos is $< 10^{-13}$ cm^{-2} sec^{-1}sr^{-1}.

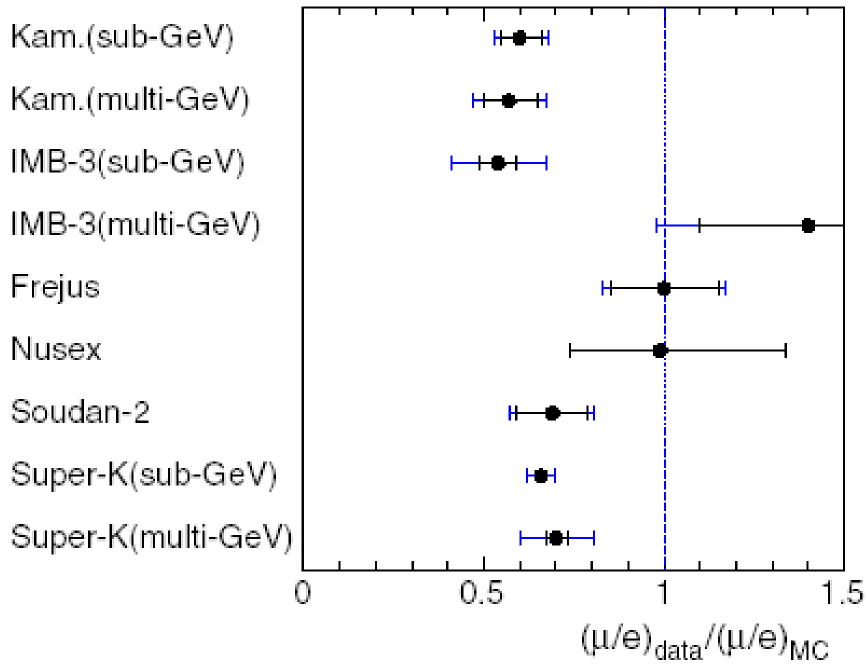


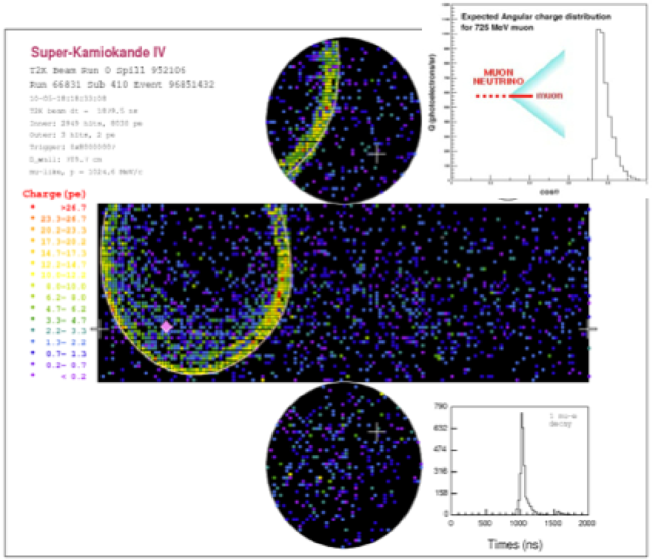
Atmospheric neutrinos as background to proton decay

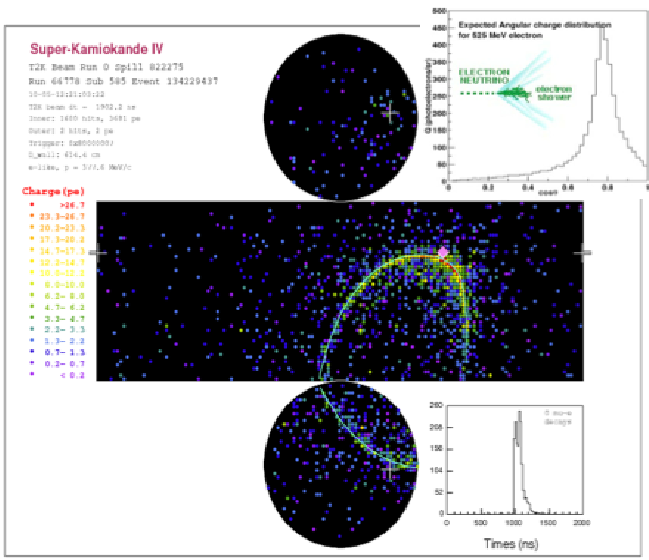
- In the 80's the interest for atmospheric neutrinos was revived.
- Grand Unified Theories (GUTs) predicted that the proton might be unstable and several experimental searches (using fine-grained tracking or water Cherenkov detectors) were conducted [IMB, Kamiokande, Soudan, NUSEX]
- Interactions of atmospheric neutrinos were a background to proton decay searches, so atmospheric neutrinos were studied.

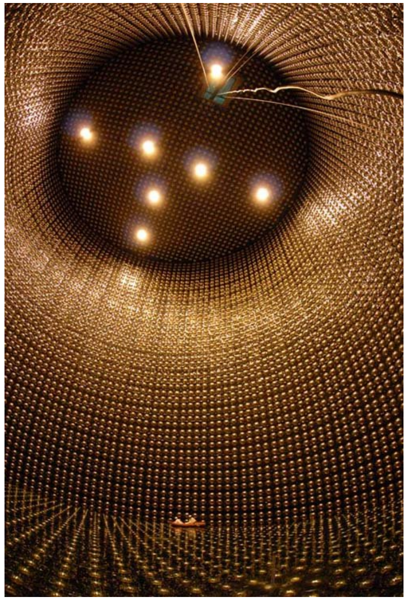
These studies found the ν_μ/ν_e ratio to be significantly lower than expected (with good accuracy).

This was puzzling and became known as the *atmospheric neutrino anomaly.*







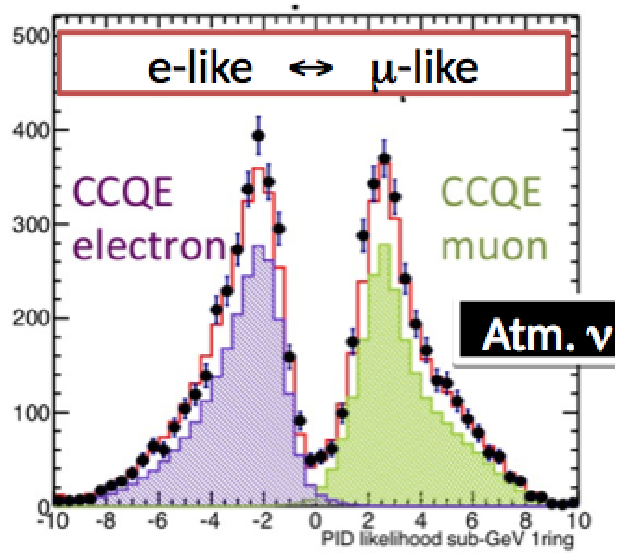


Cherenkov cone opening angle: $cos\theta = 1/\beta n$

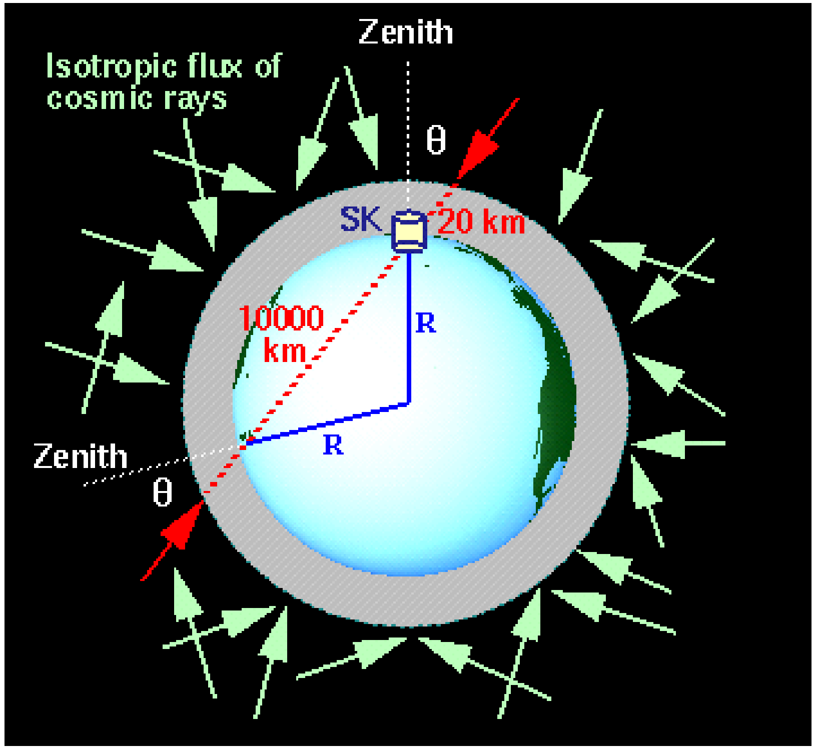
In water (refractive index n=1.33) and for a highly relativistic particle: $\theta = 42$ degrees

μ-like and e-like event topologies identified based on the Cherenov ring pattern.

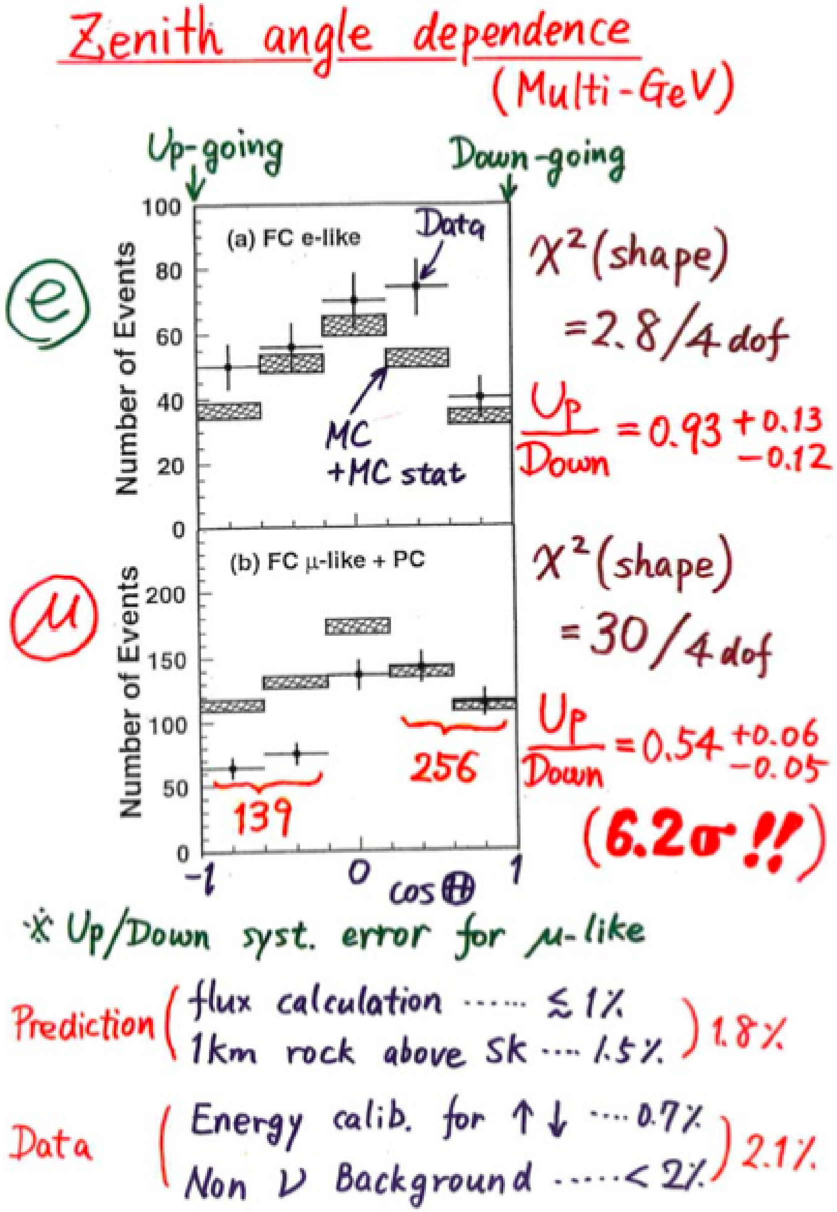
Mis-ID probability below 1GeV/c is <1%.



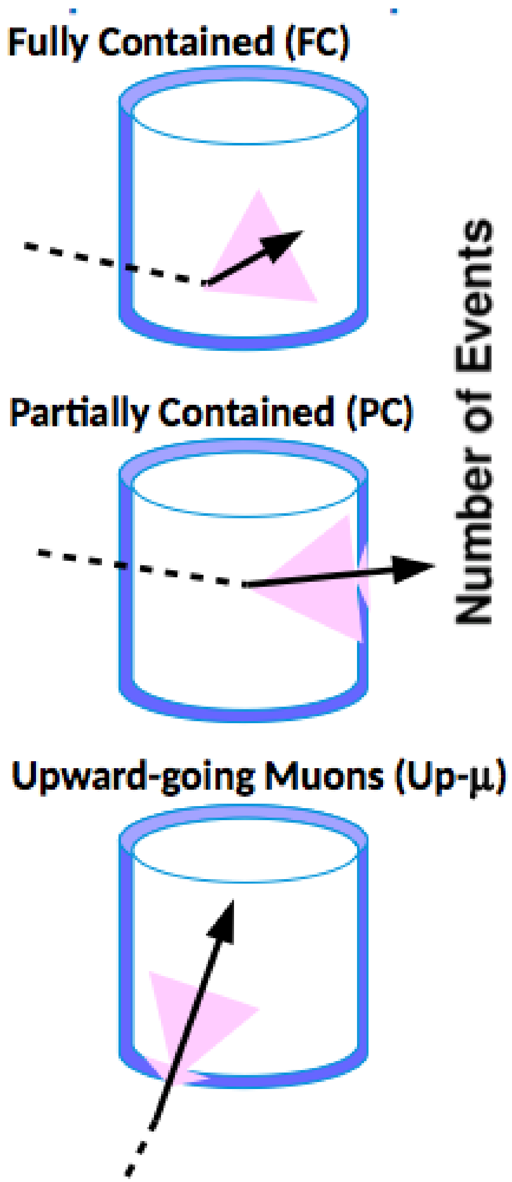
SK atmospheric neutrino measurement (1998)



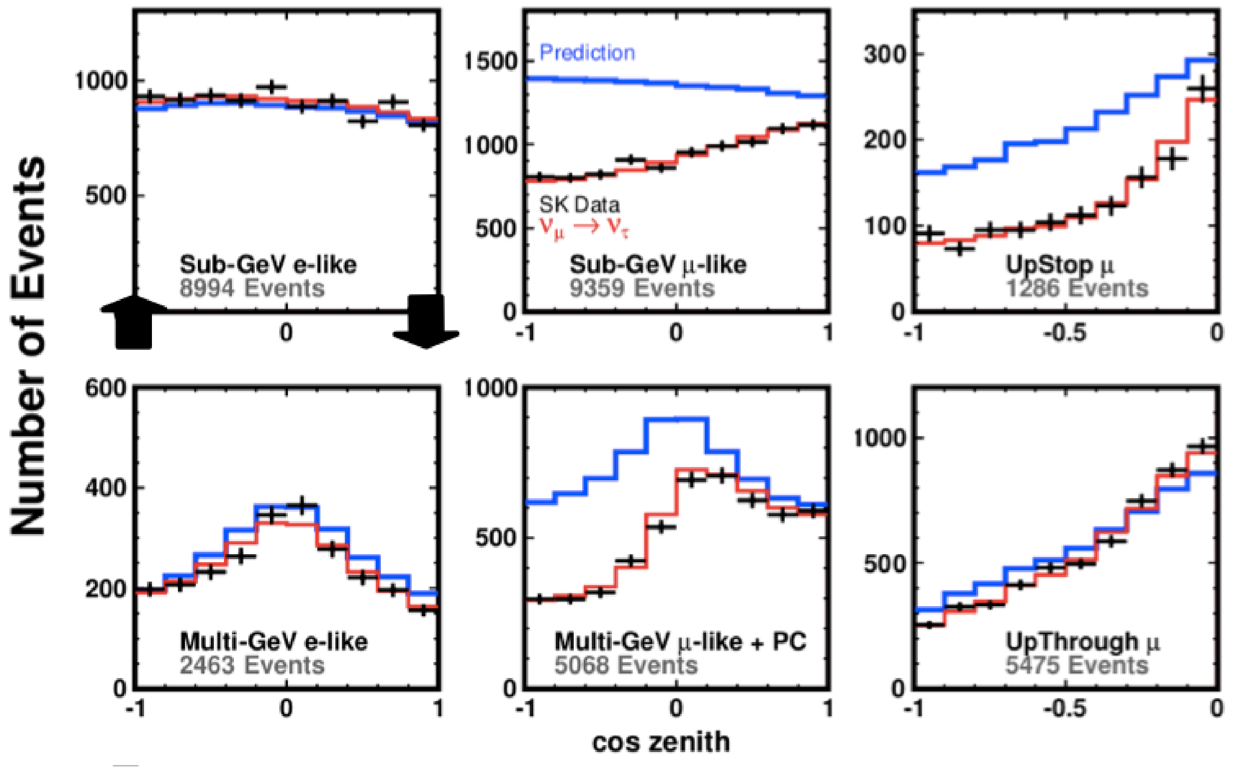
For downward-going neutrinos the flight length is ~20 km whereas for upward-going ones is ~ 13,000 km.
For $\Delta m^2 \sim 10^{-3}$ eV^2/c^4 the oscillation length is of the order of few hundred km, then for upward-going neutrinos the oscillation effect is averaged out.
The up/down ratio is ~ 1 - 0.5 · $sin^2 2\theta_{23}$



SK atmospheric neutrino measurement (2014)



19 analysis samples analysis included in latest analysis
Due to the wide range of energies and baselines and the high statistics, atmospheric neutrinos are a fantastic tool complementing the accelerator searches $\rightarrow$ sensitivity to subleading effects.

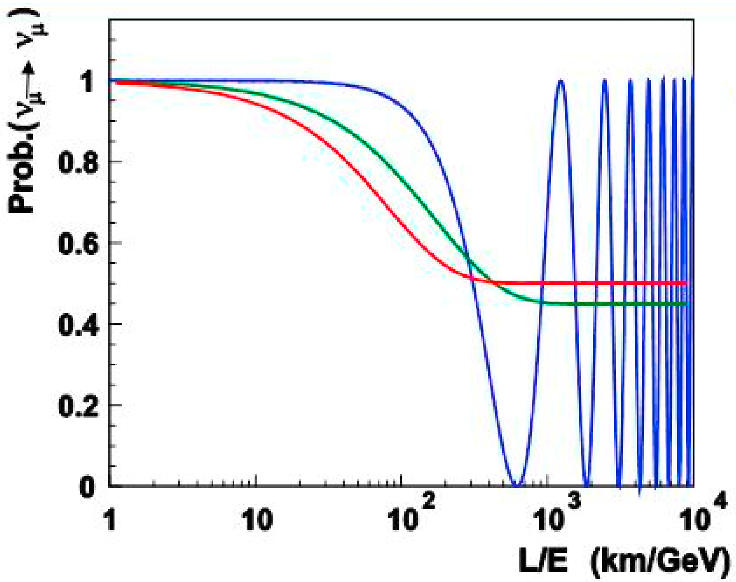


[Wendell, Neutrino 2014 conference, Boston]

SK atmospheric neutrino L/E analysis

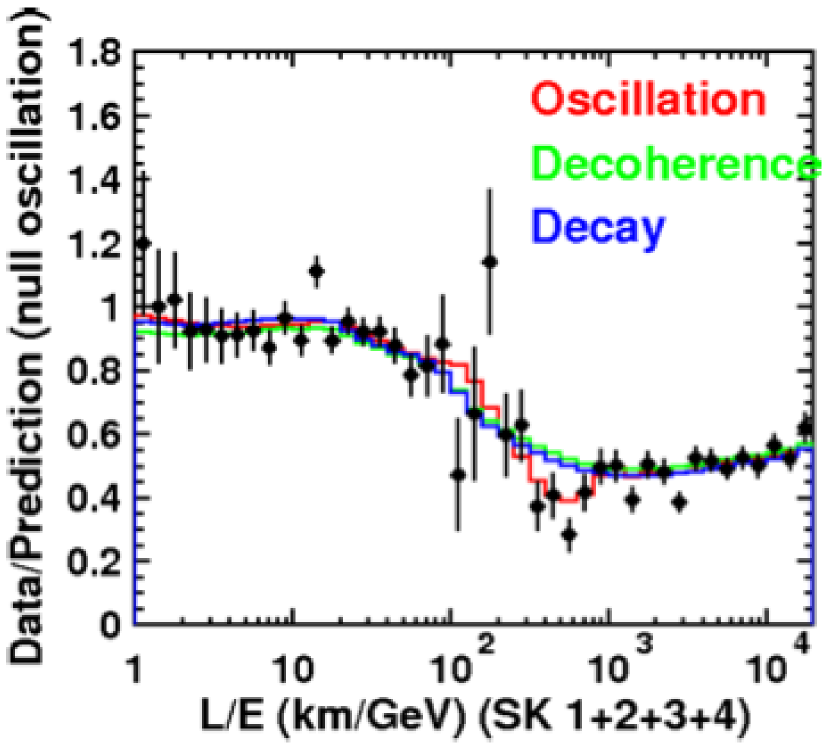
Neutrino oscillations ($\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\tau$) describe the atmospheric data well.
However, alternative models were also proposed.

The smoking-gun signature for neutrino oscillations is ..., well, oscillations.
To be confident for the observation of oscillations we need to see wiggles.



[oscillations] [decoherence] [decay]

3903 days of SK atmospheric data.
Decay (decoherence) disfavoured at 4σ (4.8σ).



[Wendell, Neutrino 2014 conference, Boston]

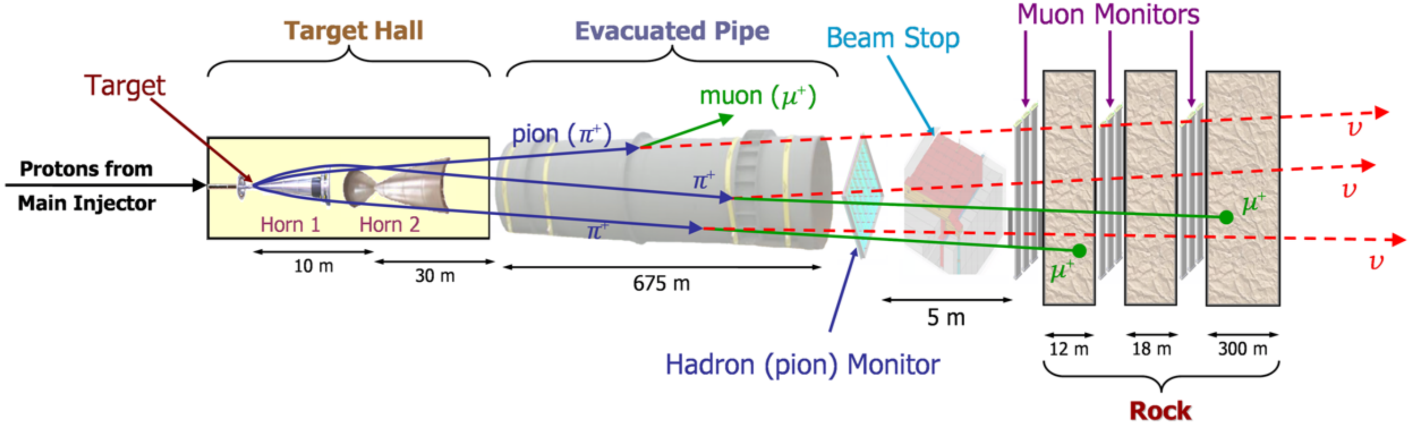
Confirmation with accelerator neutrinos: K2K and MINOS

- The atmospheric neutrino result was *very* convincing
- The data suggested $\overset{(-)}{\nu}_\mu$ oscillations with
  - nearly maximal mixing ($\theta_{23} \approx 45^o$), and
  - $|\Delta m^2_{32}| \approx 2.5 \times 10^{-3} eV^2/c^4$.

- But **confirmation** and, subsequently, **precision measurements** were needed in a **controlled environment with a man-made beam**
- The measured value of $|\Delta m^2_{32}|$ suggested an appropriate baseline
  - L (km) $\approx \frac{\pi}{2 \cdot 1.267} \cdot \frac{E_\nu (GeV)}{|\Delta m^2_{32}|(eV^2/c^4)}$, for $E_\nu = 1$ GeV $\rightarrow$ L $\approx$ 500 km!

- **Challenging experiments**!
  Because, besides the technical difficulties making of a ν beam and pointing it several hundreds of km away to a massive underground detector, we
  - didn't know how to estimate the neutrino flux to better than $\sim$20%
  - didn't understand (as we later found out) few-GeV neutrino scattering off nuclear targets to better than $\sim$20%

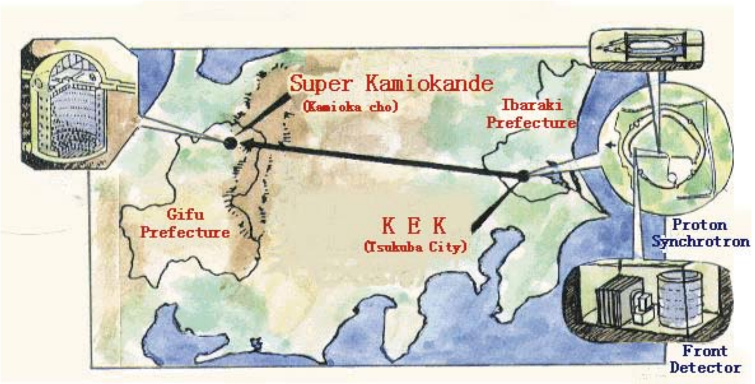
How to make a (conventional) neutrino beam



Where do our ν's come from?

$\pi^+ \rightarrow \nu_\mu + \mu^+$
$\pi^- \rightarrow \bar{\nu}_\mu + \mu^-$
$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$
$\mu^- \rightarrow \bar{\nu}_e + \nu_\mu + e^-$
$K^+ \rightarrow \nu_\mu + \mu^+$
$K^+ \rightarrow \nu_e + \pi^0 + e^+$
$K^+ \rightarrow \nu_\mu + \pi^0 + \mu^+$
$K^- \rightarrow \bar{\nu}_\mu + \mu^-$
$K^- \rightarrow \bar{\nu}_e + \pi^0 + e^-$
$K^- \rightarrow \bar{\nu}_\mu + \pi^0 + \mu^-$
$K_L^0 \rightarrow \bar{\nu}_\mu + \pi^+ + \mu^-$
$K_L^0 \rightarrow \nu_\mu + \pi^- + \mu^+$
$K_L^0 \rightarrow \bar{\nu}_e + \pi^+ + e^-$
$K_L^0 \rightarrow \nu_e + \pi^- + e^+$

Confirmation with accelerator neutrinos

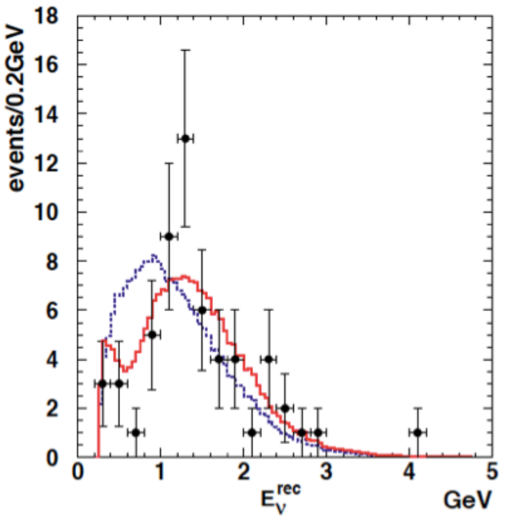


- K2K (KEK to Kamioka, 250km), 06/1999-11/2004
- Using a ν_μ beam made at the KEK 12-GeV proton synchrotron (peak $E_\nu \approx 1$ GeV)
- Used 50-kt Super-K as far detector
- Near detectors at ~300m from the target: 1kt water Cherenkov + fine-grained tracking detectors

- MINOS (FNAL to Soudan, 735 km), 2/2005- (now MINOS+)
- Using a $\overset{(-)}{\nu}_\mu$ beam made at the 120-GeV Main Injector at FNAL (several beam configurations: peak $E_\nu \approx 3.5$-8 GeV)
- 5.4 kt steel-scintillator magnetized tracking calorimeter 0.7km underground
- 1-kt steel-scintillator magnetized tracking calorimeter near detector, ~1km the from source and 100m underground

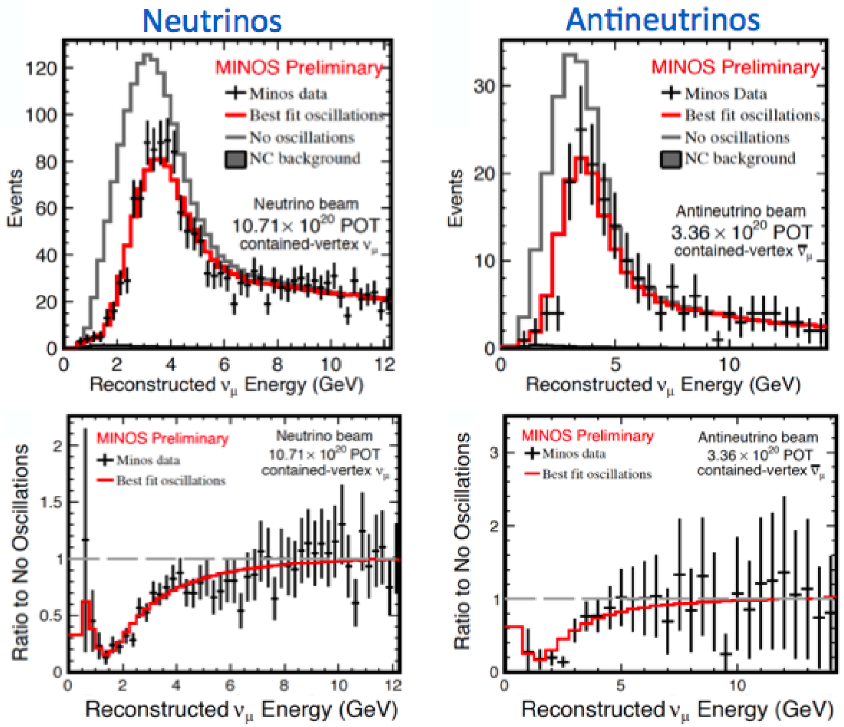
K2K and MINOS $\overset{(-)}{\nu}_\mu$ disappearance results

- **K2K:** Analyzed 0.92×10^{20} POT.
- $158.1^{+9.2}_{8.6}$ events were expected with no oscillations, but only 112 were seen.
- Out of those events, the energy could be reconstructed for 58 1-ring μ-like events and energy distrortions were seen.
- No oscillation excluded at 4.3σ.



[PRD 74 (2006), 072003]

- **MINOS:** Analyzed 10.71×10^{20} POT in a ν_μ beam and 3.36×10^{20} POT in a $\bar{\nu}_\mu$-enhanced beam
- Jointly with atmospheric ν sample (48.67 kt·yr)
- High statistics / precision measurements (oscillation contours to be shown later)



[Sousa, Neutrino 2014, Boston]

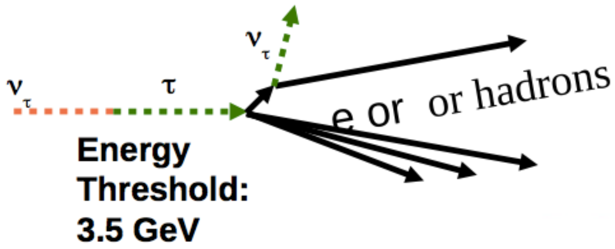
So, ν_μ's oscillate away. But what do they oscillate to?

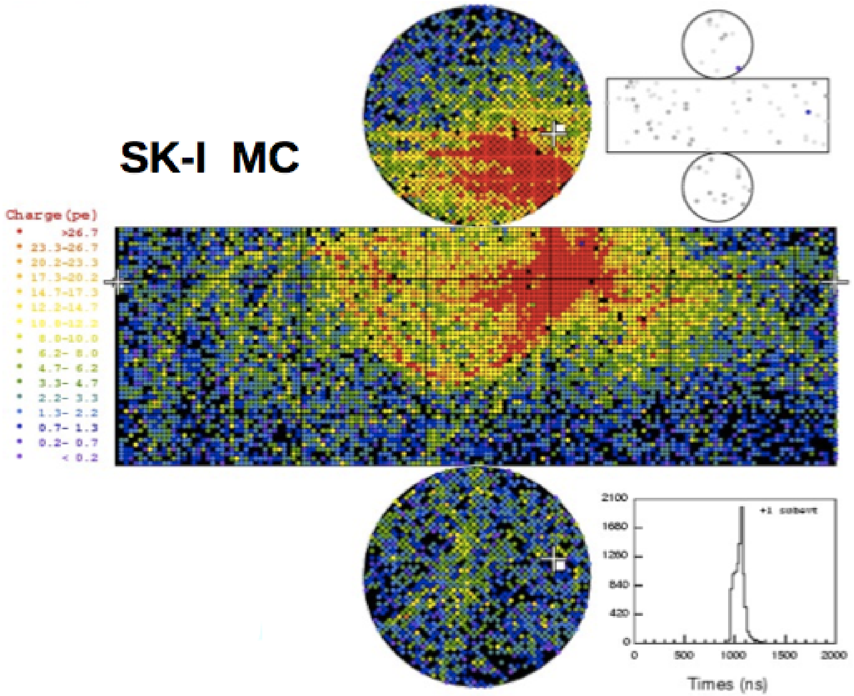
We knew for the Super-Kamiokande atmospheric measurement that $\nu_\mu \to \nu_e$ was not the dominant mode.

This leaves two obvious possibilities:

- $\nu_\mu \to \nu_\tau$
- $\nu_\mu \to \nu_{sterile}$

- Expecting $\sim$ 1 (atmospheric) ν_τ CC event per kt*year
- τ typically decays to hadrons (BR: $\sim$65%) close to the primary interaction vertex ($<$ 1 mm)
- Complicated event topologies with several particles above Cherenkov threshold
- Difficult to separate from NC events on an event-by-event basis.
- But the number of ν_τ induced by ν_μ oscillations could be calculated statistically.

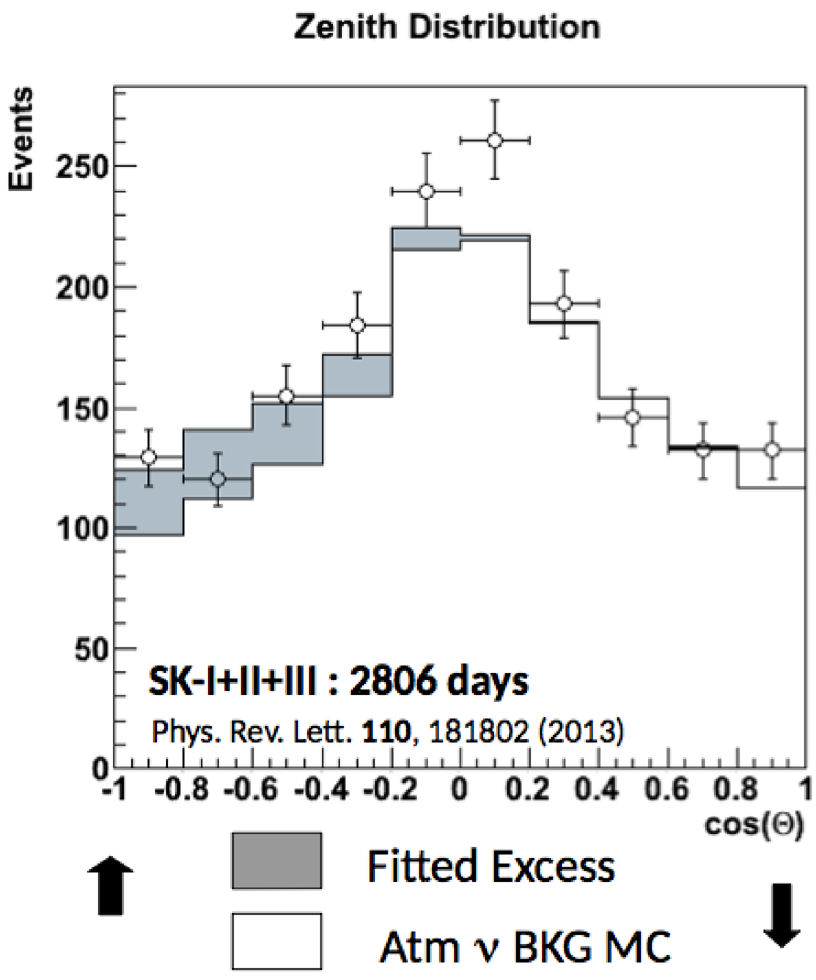




ν_τ event at SK (MC):

[Wendell, Neutrino 2014 conference, Boston]

Search for ν_τ at Super-Kamiokande



Neutrino-induced → Upward-going

Statistical search for ν_τ CC-like events using an exposure of 2,806 days

SK observed an event excess of:
180.1 $\pm$ 44.3(stat) +17.8 -15.2 (syst)

The significance of this excess is 3.8σ

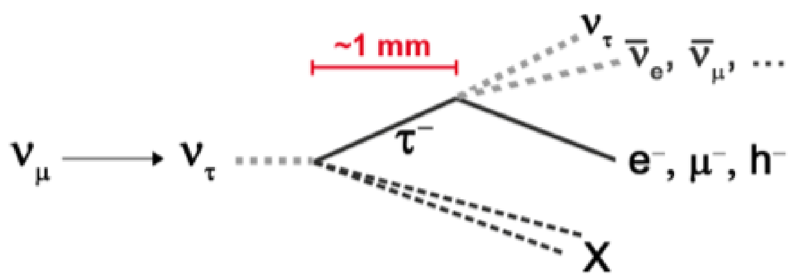
[Wendell, Neutrino 2014 conference, Boston]

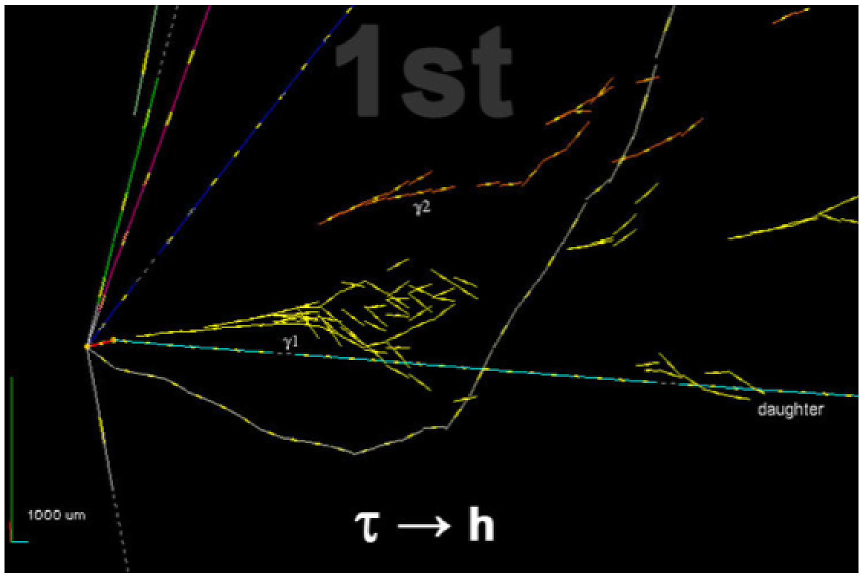
The atmospheric sample at Super-Kamiokande provides also a strong constraint on $\nu_\mu \rightarrow \nu_{sterile}$ oscillations by studying NC-enriched and upgoing μ samples.

Direct search for ν_τ CC interactions at OPERA

μm-scale resolution emulsion detector + electronic spectrometer in Gran Sasso (3,800 mwe), at the CERN CNGS ν_μ beam ($< E_\nu > \approx 17$ GeV) (2008-12)

ν_τ CC interactions identified from the characteristic τ decay kink





- L/$< E_\nu > \approx 43$ km/GeV: $P(\nu_\mu \to \nu_e) \approx 1\%$ (ν_τ CC threshold = 3.5 GeV)
- Exposure of 1.797×10^{20} POT
- 4 ν_τ CC events observed (expected background = 0.23)
- ν_τ appearance significance: 4.2σ

τ decay channel	Signal (exp.) $\Delta m^2_{23} = 2.32\,\mathrm{meV}^2$	Total BG (exp.)	Data (obs.)
$\tau \to h$	0.41 ± 0.08	0.033 ± 0.006	2
$\tau \to 3h$	0.57 ± 0.11	0.155 ± 0.030	1
$\tau \to \mu$	0.52 ± 0.10	0.018 ± 0.007	1
$\tau \to e$	0.62 ± 0.12	0.027 ± 0.005	0
Total	2.11 ± 0.42	0.233 ± 0.041	4

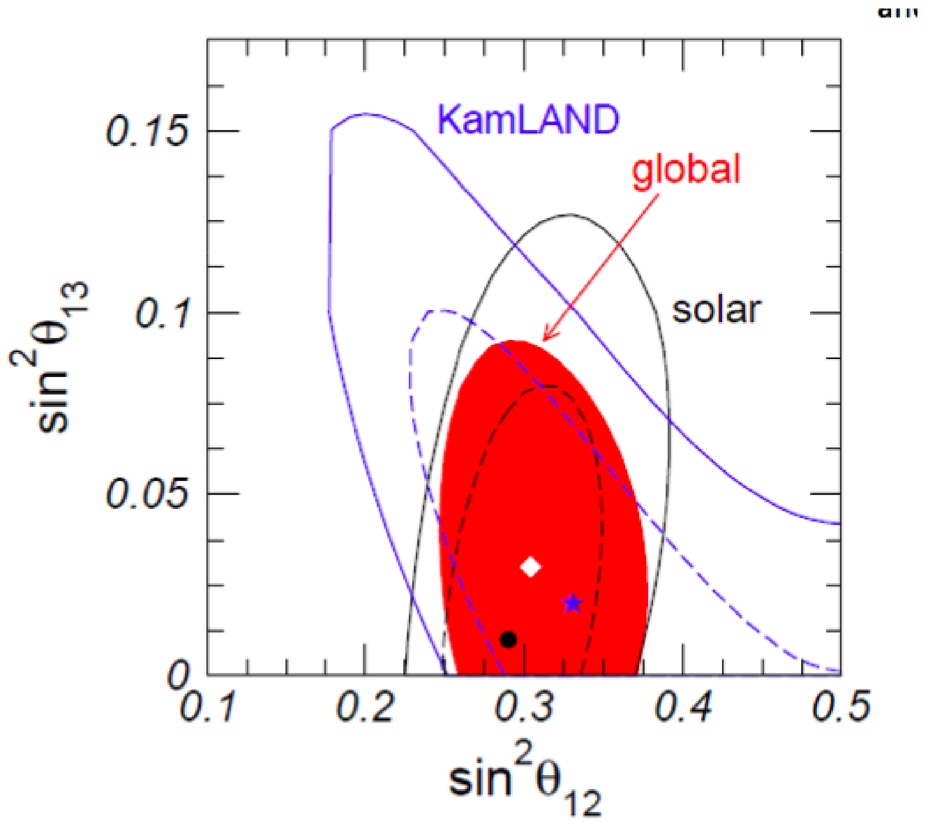
[Hollnagel, PANIC 2014 conference, Hamburg]

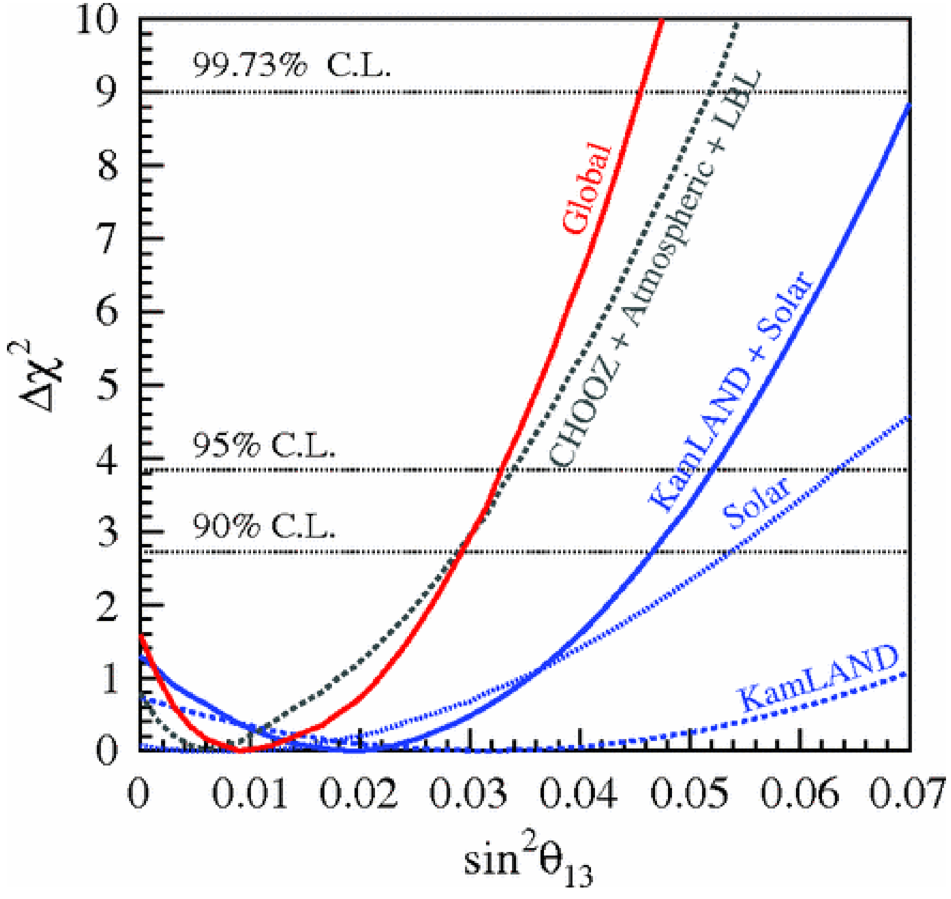
So ν_μ's oscillate predominantly to ν_τ

How about sub-dominant $\nu_\mu \to \nu_e$ oscillations

Initial hints for non-zero θ_{13}

For $\theta_{13}=0$, a small tension existed between the solar and KamLAND values of θ_{12} (KamLAND favoured larger values).





[Phys. Rev. D 83, 052002 (2011)] and others

2 experimental strategies to measuring θ_{13}

- $\bar{\nu}_e$ **disappearance at short-baseline reactor experiments**

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - sin^2 2\theta_{13} \cdot sin^2(\frac{\Delta m^2_{ee} L}{4E_\nu}) + (solar\ term)$$

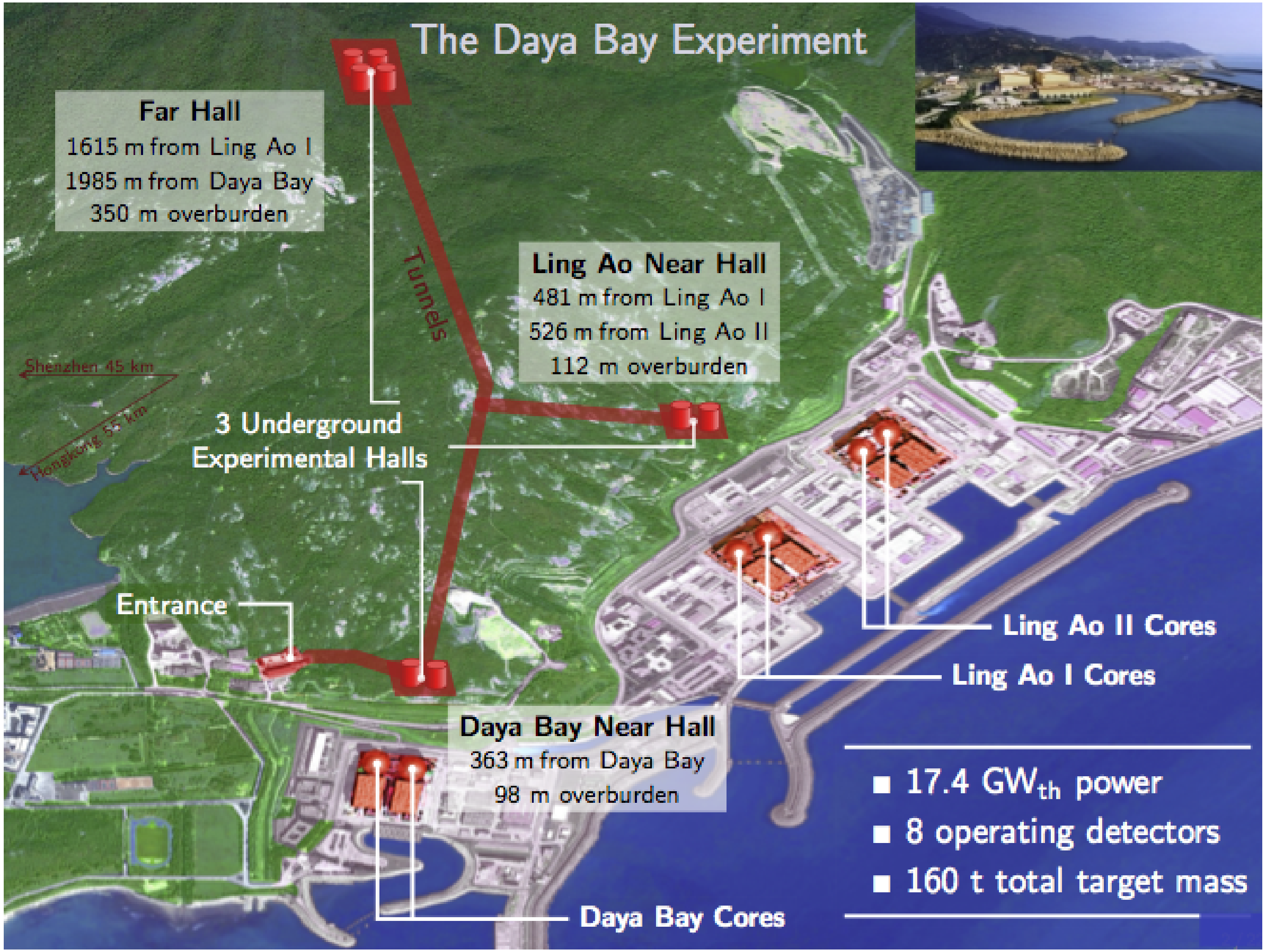
- $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ **appearance in long-baseline accelerator experiments**

$$\begin{aligned} P(\nu_\mu \to \nu_e) \quad = \quad & sin^2\theta_{23} \cdot sin^2 2\theta_{13} \cdot sin^2(\frac{\Delta m^2_{32} L}{4E_\nu}) \\ & - \frac{sin2\theta_{12} \cdot sin2\theta_{23} \cdot sin^2 2\theta_{13}}{2 sin\theta_{13}} \cdot sin^2(\frac{\Delta m^2_{21} L}{4E_\nu}) \cdot sin^2(\frac{\Delta m^2_{32} L}{4E_\nu}) \cdot sin\delta \\ & +(CP\ even\ term) + (matter\ effect\ term) + (solar\ term) \end{aligned}$$

Running SBL reactor experiments

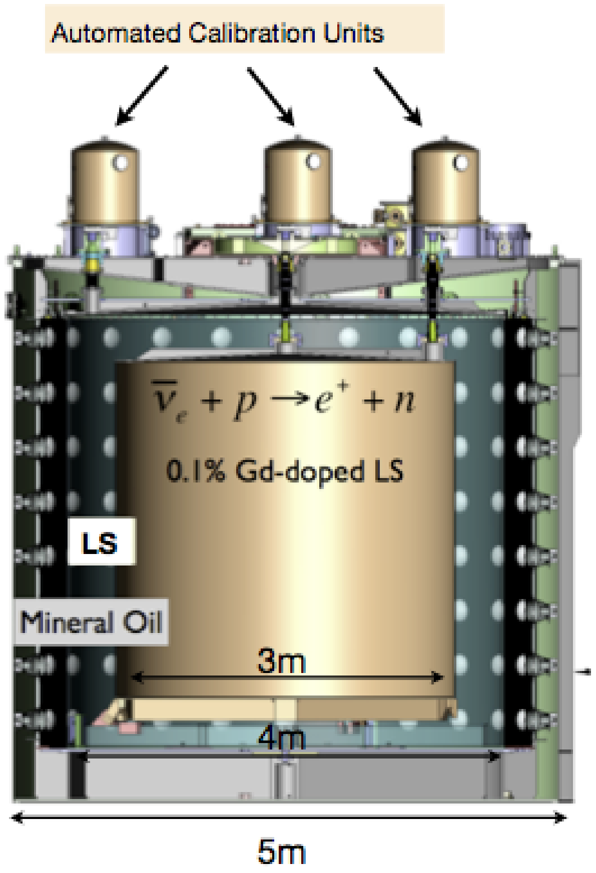
- **Daya Bay**, South China (6: 12/2011-07/2012, 8: 10/2012-now)
    - Reactors: 6 cores, 17.6 GW_{th} total
    - Far detector: 4 functionally identical far detectors $\times$ 20 tonnes target mass each (80 tonnes total mass), 1615 - 1985 m from cores
    - Near detector: 4 functionally identical near detectors $\times$ 20 tonnes target mass each, 363-526 m from cores
- **RENO**, South Korea (08/2011-)
    - Reactors: 6 cores, 16.4 GW_{th} total
    - Far detector: 16.5 tonnes target mass, 290 m from cores
    - Near detector: 16.5 tonnes target mass, 1380 m from cores
- Double CHOOZ, France
    - Reactors: 2 cores, 8.7 GW_{th} total
    - Far detector: 8.2 tonnes target mass, 1067 m from cores
    - Near detector: 8.2 tonnes target mass, 410 m from cores (no data-taking with near detector yet)

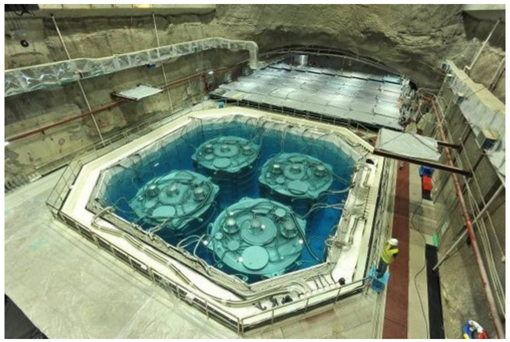
The Daya Bay experiment (others similar)



[Chao Zang, Neutrino 2014, Boston]

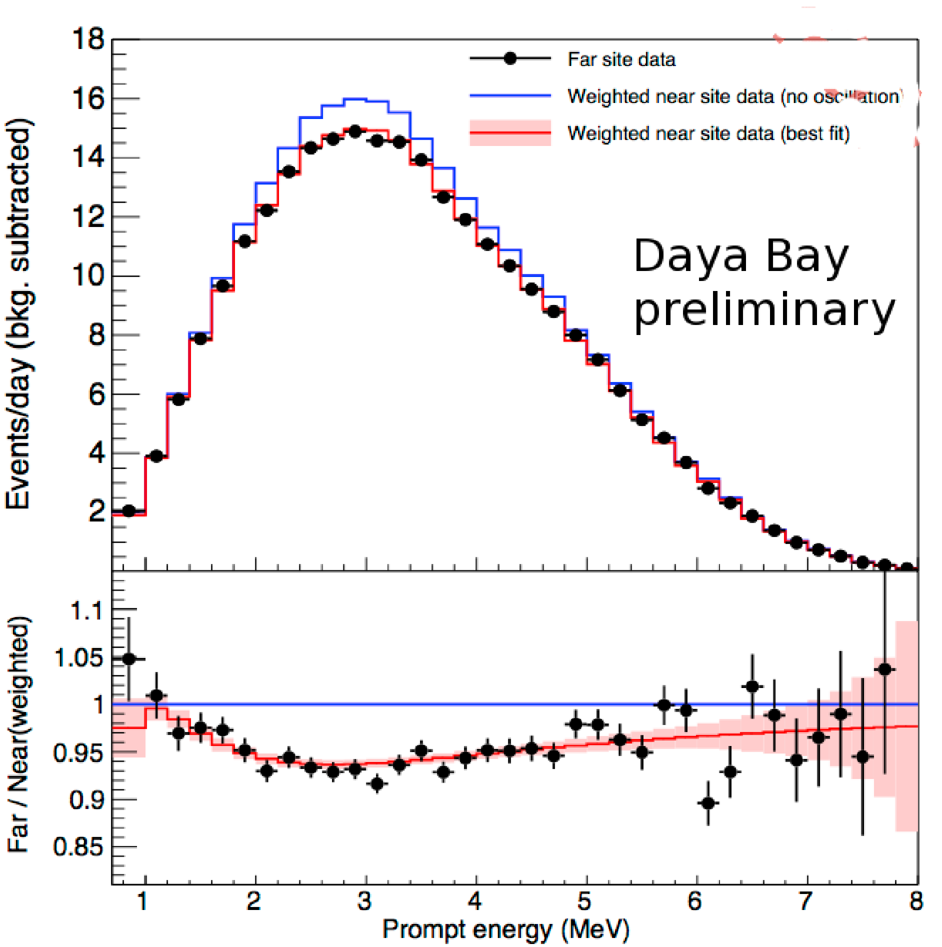
The Daya Bay experiment (others similar)

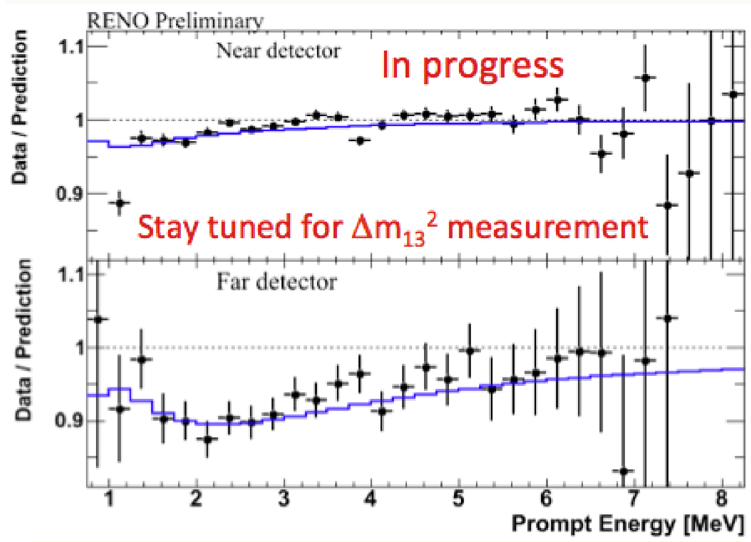


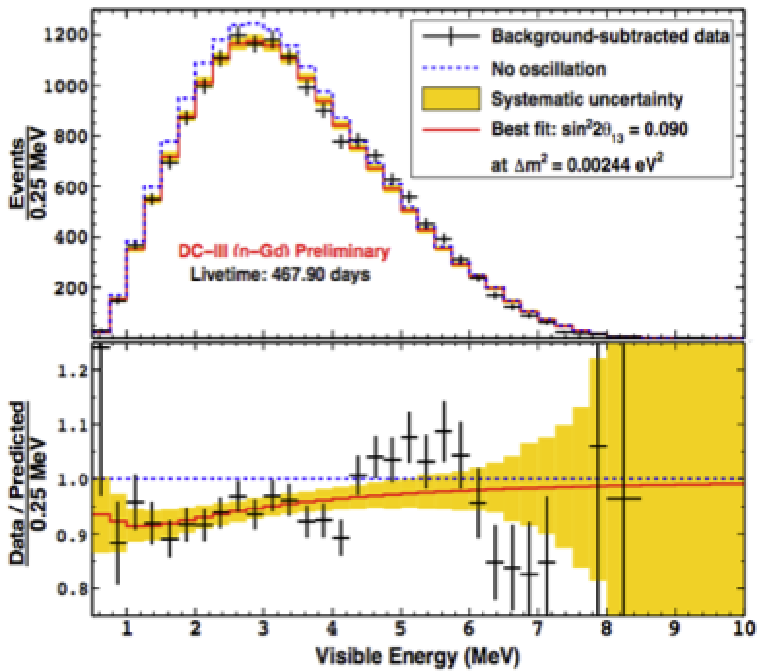


- Three cylindrical zone design:
  - **Inner**: 20 tonnes of Gd-doped (0.1% in weight) liquid scintillator
  - **Middle**: 22 tonnes of liquid scintillator
  - **Outer**: 40 tonnes of mineral oil
- 192 8" photosensors installed in each detector (8% photo-cathode coverage)
- Each detector placed within high purity water to further reduce background
- Water pools divided in optically separated regions (inner and outer) and instrumented with photo-sensors.
- Backgrounds: accidental, fast neutrons, ^{9}Li and ^{8}He spallation products, internal radioactivity and correlated background from Am-C calibration source

SBL reactor experiment results

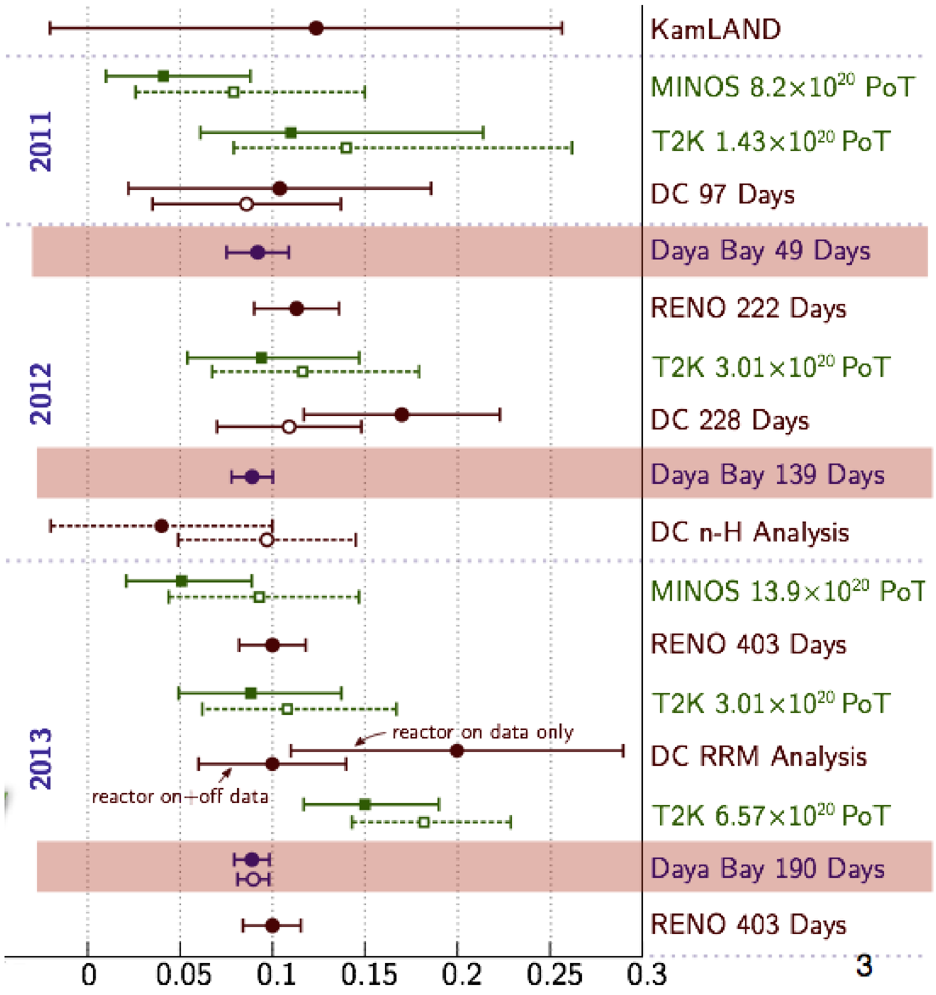






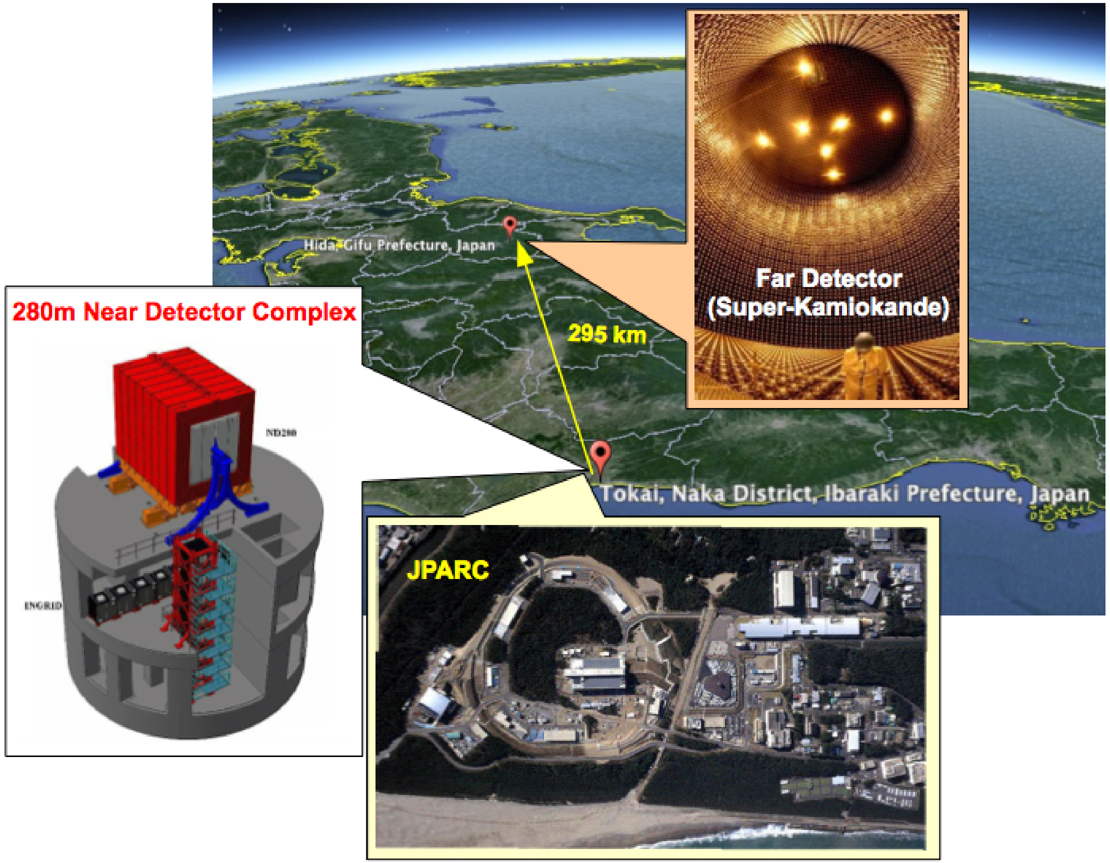
[plots from Chao Zang, Seon-Hee Seo and De Kerret, Neutrino 2014, Boston]

θ_{13} measurement evolution



- Following solar+KamLAND hints, the accelerator experiments, and T2K in particular, produced good evidence for a non-zero θ_{13}
- But once the reactor experiments turned-up, the game was over
- The Daya Bay result in particular left everybody in awe, with 5.2σ evidence of non-zero θ_{13} after less than 2 months of data-taking [Phys.Rev.Lett. 108 (2012) 171803]
- RENO followed just 2 weeks later with 4.9σ evidence of non-zero θ_{13} (222 days)
- Currently, from Daya Bay alone, $\sin^2 2\theta_{13} = 0.084 \pm 0.005$ ($\sim$6% precision)!
- This is, of course, excellent news for T2K and NOvA

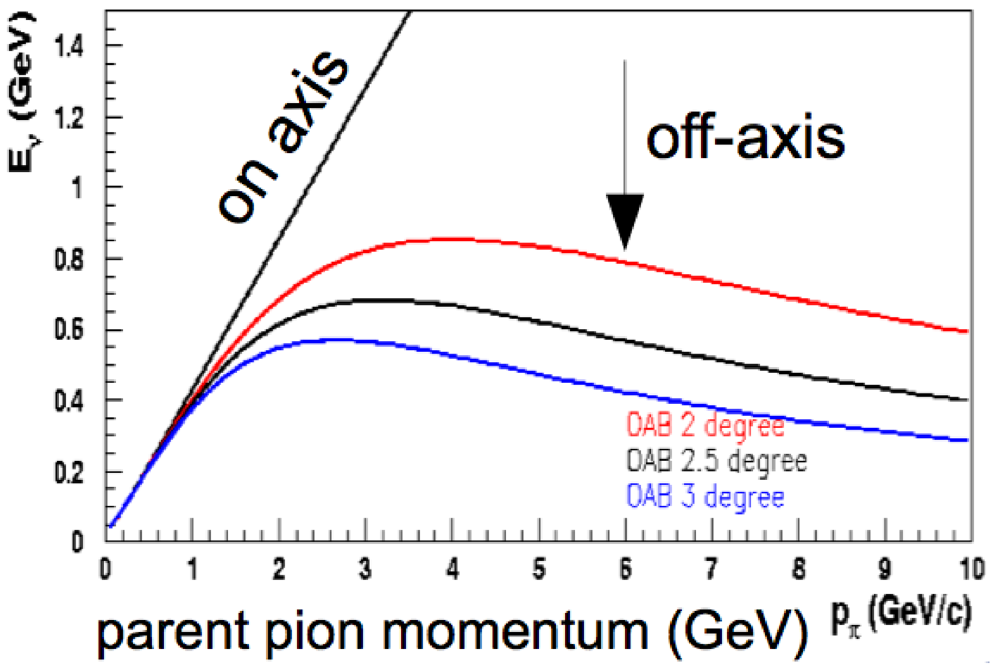
The T2K experiment

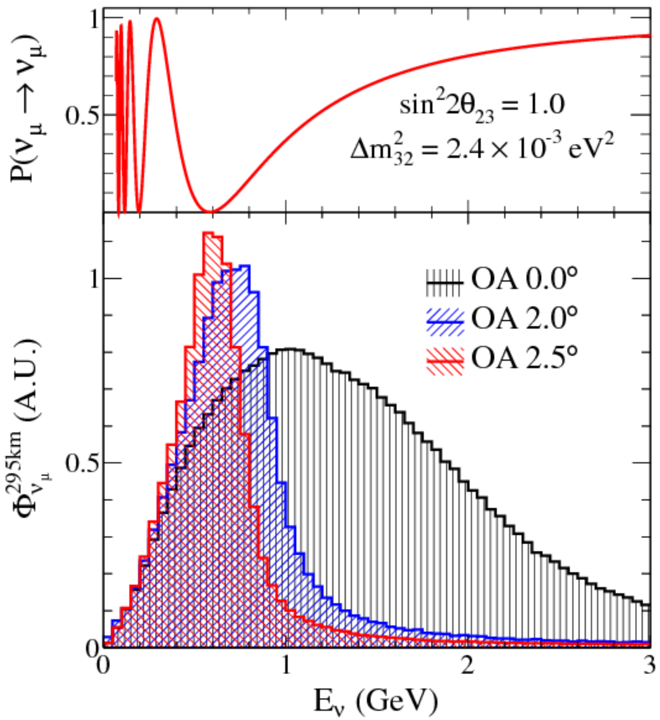


- Pure ν_μ beam.
- Produced using the 30-GeV proton beam at J-PARC
- Design power of 750 kW (230 kW achieved to date)
- Near detectors: on-axis and off-axis at 280 m to monitor and constrain flux characteristics and interaction rates.
- Far detector: SuperK 50-kton (22.5 kton fiducial) water Cherenkov detector, 2.5 degrees off-axis, 295 km away.
- Neutrino flux at SuperK peaked at $\sim$0.6 GeV.
- L/E tuned to the 'atmospheric' Δm^2 ($\sim 2.4\times10^{-3}$ eV^2/c^4).

Going *off-axis*

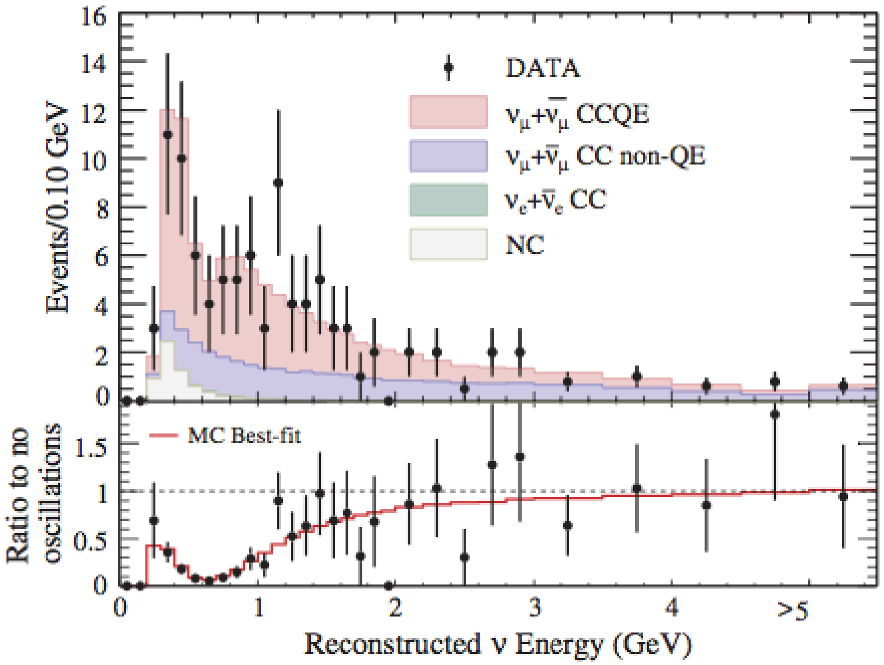
T2K is the first accelerator experiment employing the off-axis trick.
Exploits kinematical properties of pion decay to create a narrow-band neutrino beam peaked at an energy chosen so as to maximize the oscillation probability at the SuperK location.

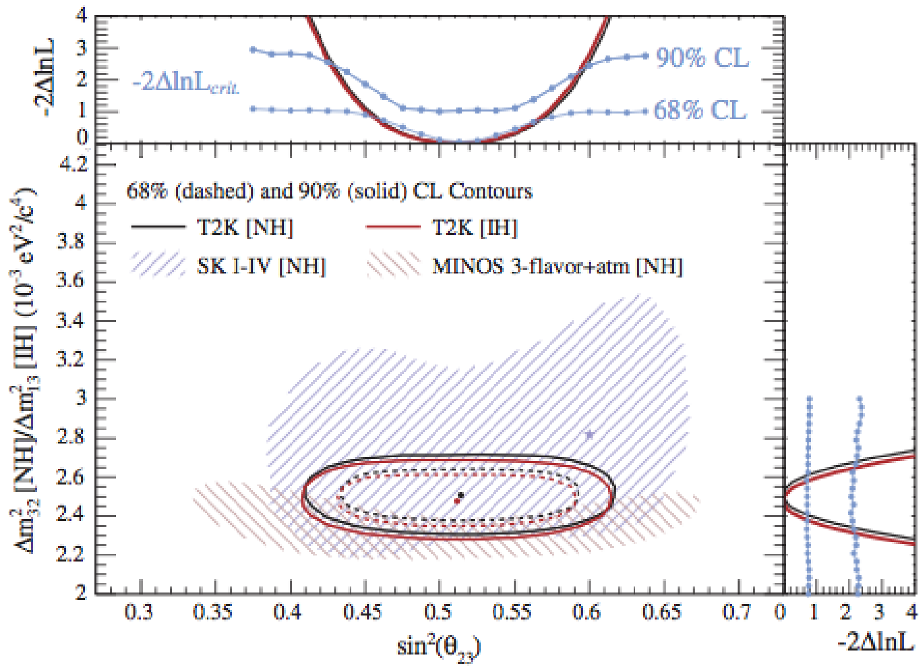




T2K ν_μ disappearance

446.0 ± 22.5 (syst.) single-ring μ-like events expected in absence of oscillations but only 120 events were observed (Run 1-4: 6.57×10^{20} POT, $\sim$ first 10% of the final exposure). The observed deficit is strongly energy-dependent.

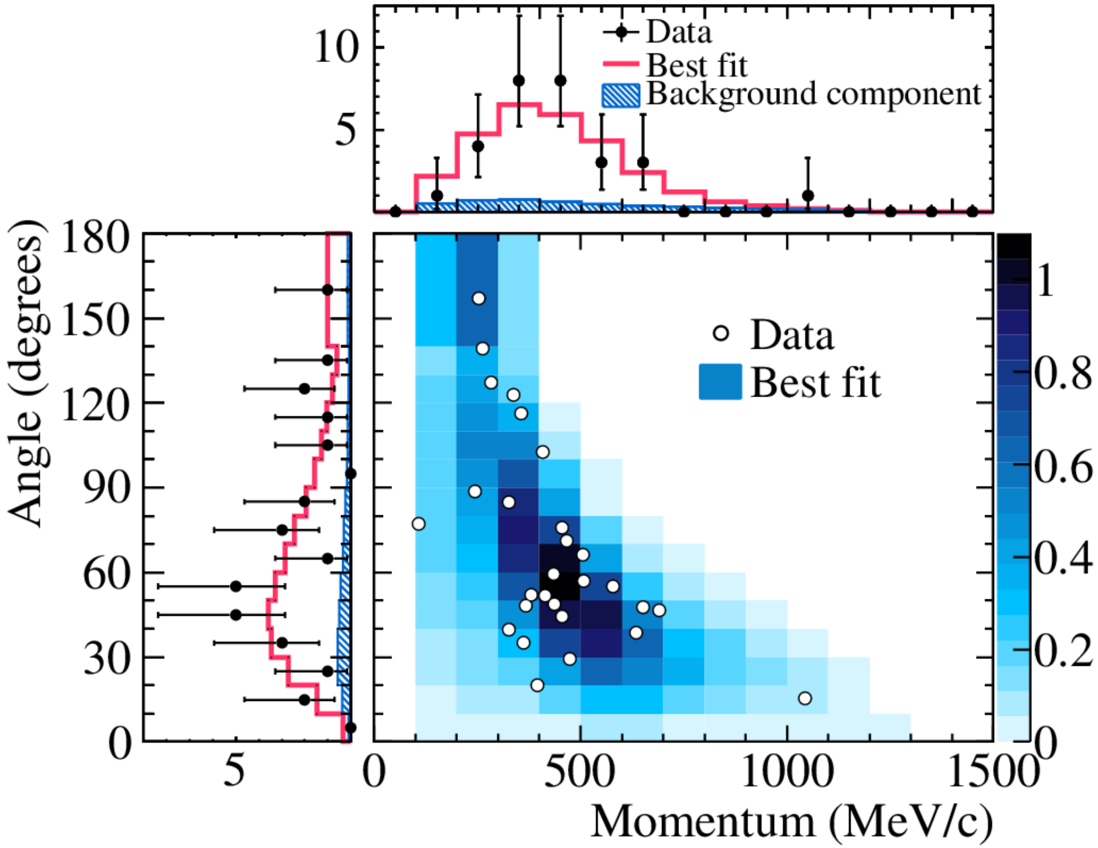




- The dramatic energy dependent deficit allows T2K to place very stringent constraints on ν_μ disappearance parameters.
- NH: $|\Delta m^2_{32}| = (2.51 \pm 0.10) \times 10^{-3} eV^2/c^4$ and $\sin^2\theta_{23} = 0.514 \, ^{+0.055}_{-0.056}$
- Some tension with the MINOS results.

T2K ν_e appearance

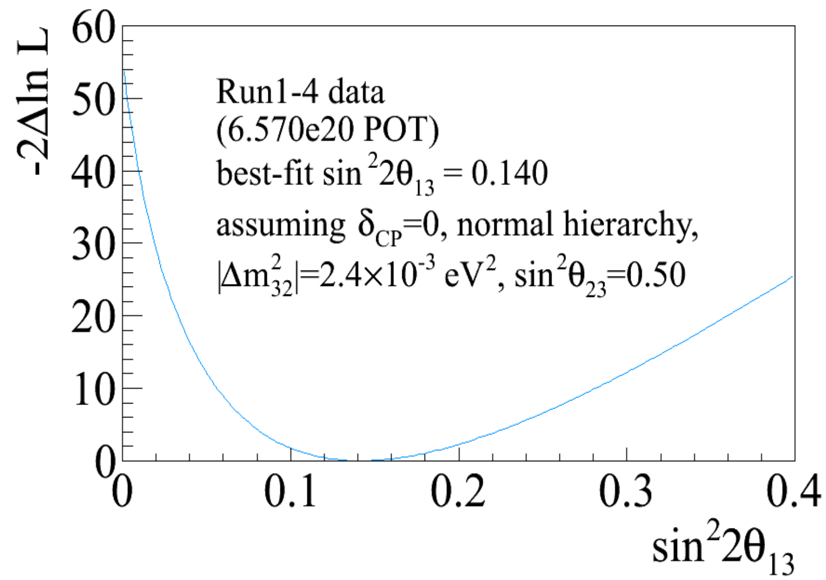
28 1-ring e-like events were observed, with an expected background of 4.92 $\pm$ 0.55 (syst) events. The significance of the excess is 7.3σ (first ever observation of an explicit appearance signal).

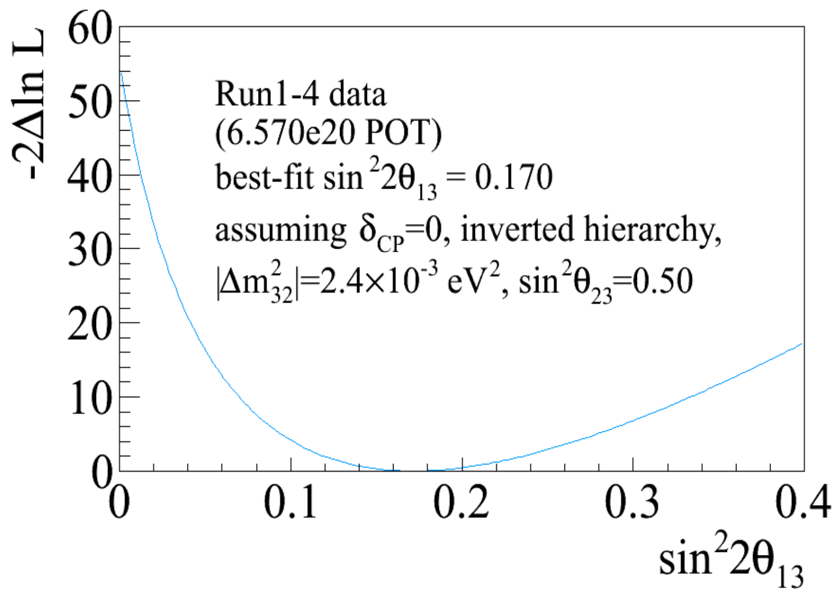


Event category	The predicted number of events $\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	4.92	21.56
ν_e signal	0.40	17.30
ν_e background	3.37	3.12
ν_μ background	0.94	0.94
$\bar{\nu}_\mu$ background	0.05	0.05
$\bar{\nu}_e$ background	0.16	0.15

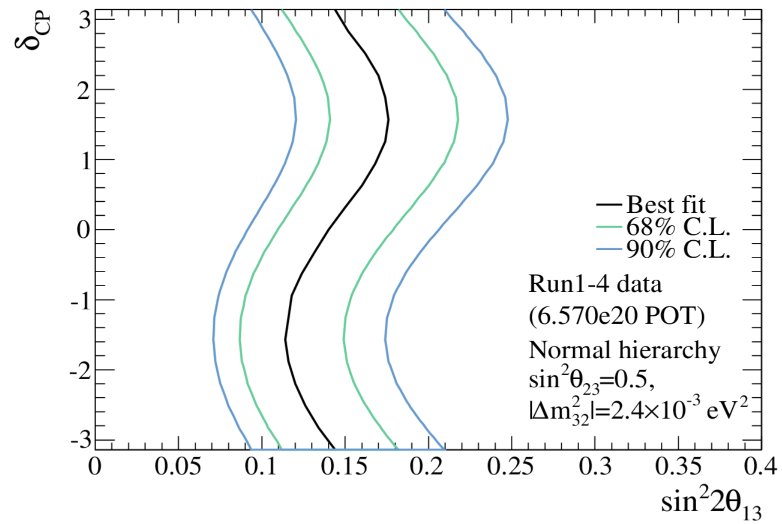
Best fit value of $\sin^2 2\theta_{13}$ (for $\delta_{CP} = 0$, $|\Delta m^2_{32}| = 2.4\times10^{-3} eV^2/c^4$ and $\sin^2\theta_{23} = 0.5$):

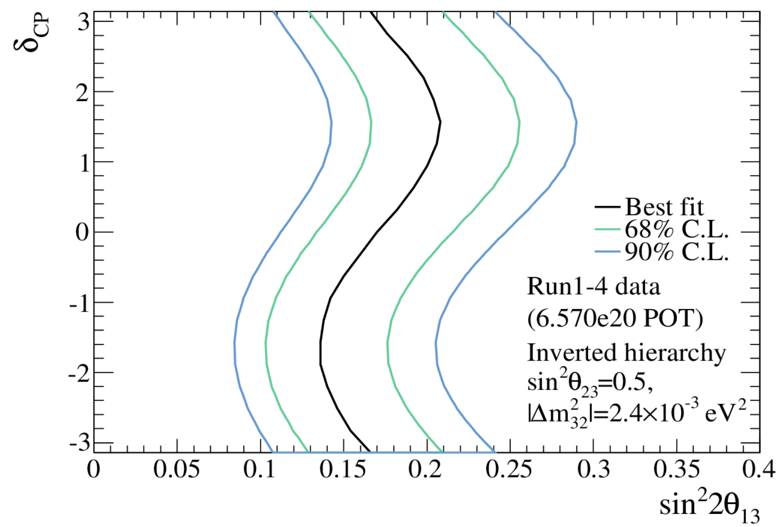
- $\sin^2 2\theta_{13} = 0.14$ (Normal)
- $\sin^2 2\theta_{13} = 0.17$ (Inverted)



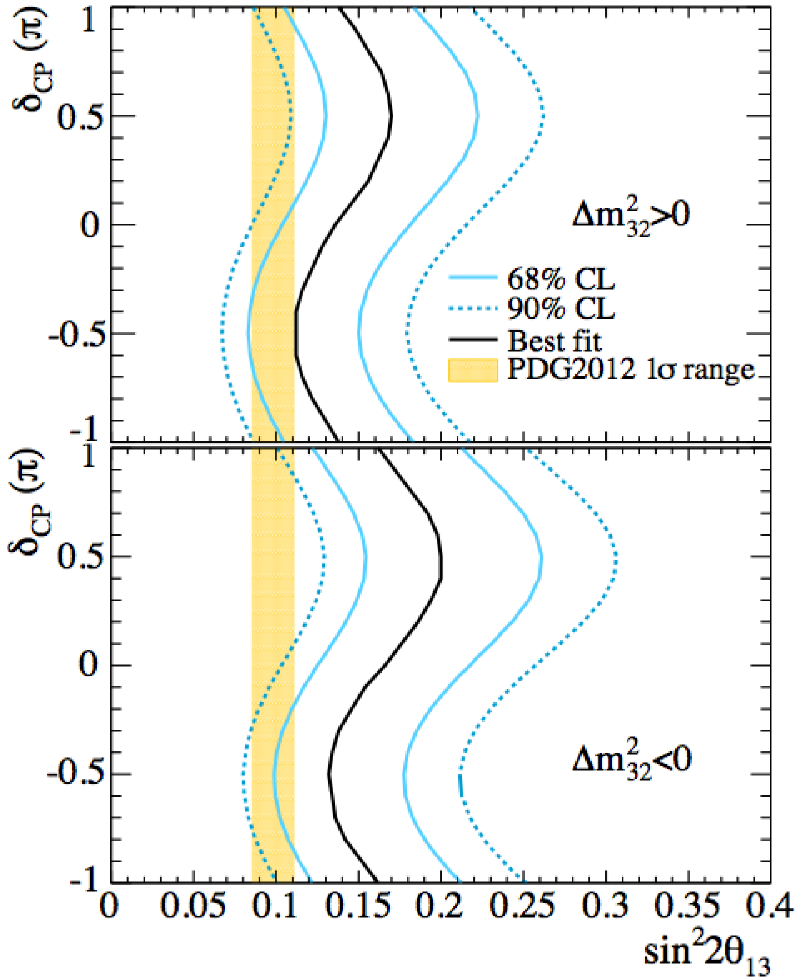


θ_{13} limit has a weak dependence on δ_{CP}
(note: 'raster scan' plots shown below)

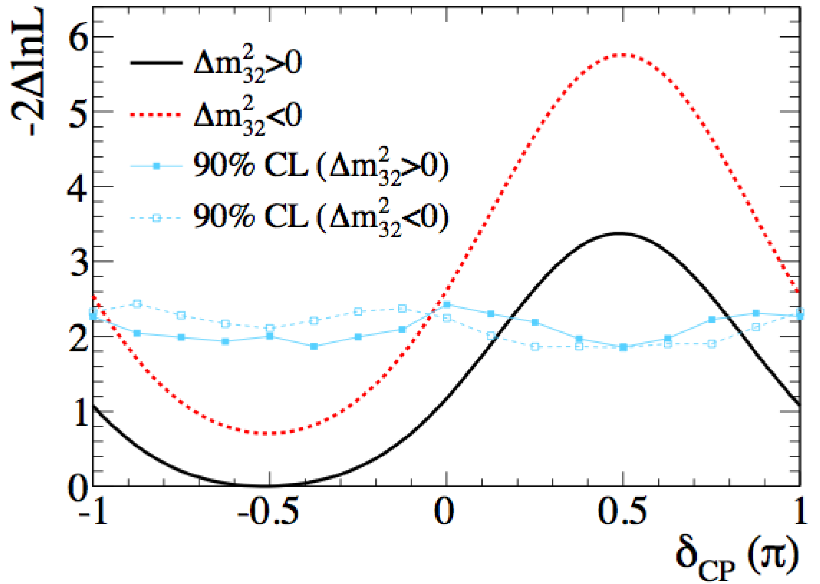




First constraint on δ_{CP}



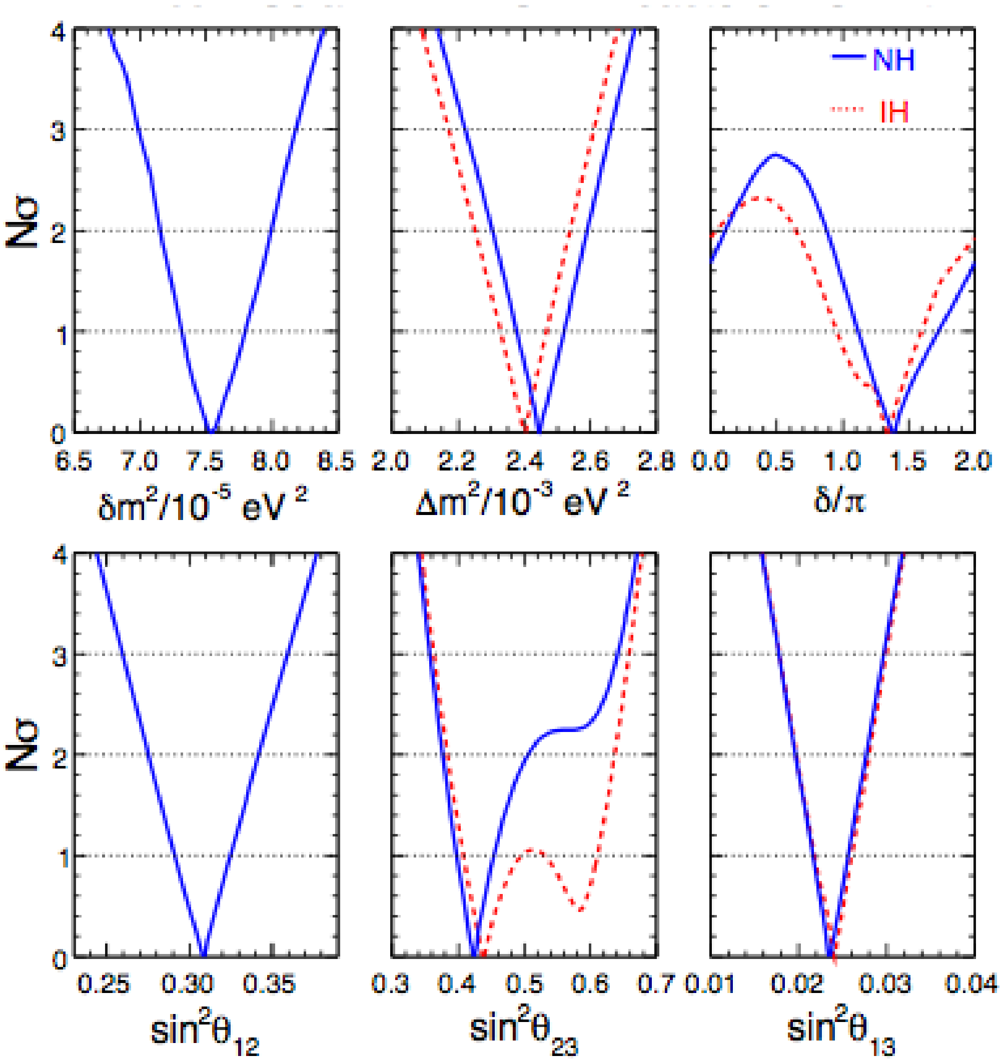
- The T2K appearance contour depends on the values of $|\Delta m^2_{32}|$ and θ_{32}. These parameters were marginalized using the T2K disappearance measurement (left).
- Difference in reactor ($\bar{\nu}_e$ disappearance) and T2K ($\nu_\mu \to \nu_e$ appearance) best-fit values of θ_{13}.
- Using the precise reactor value of θ_{13} (PDG12: 0.098 $\pm$ 0.013) we can start constraining δ_{CP}.



$sin^2\theta_{23}$ and Δm^2_{32} were varied in the fit using the constraint from the T2K ν_μ disappearance measurement (with Run 1-3 data).

Global fit results, unresolved questions, future prospects

3-Flavour Oscillations: The current picture



Parameter	Best fit	1σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.08	2.91 – 3.25
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.44	2.38 – 2.52
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.40	2.33 – 2.47
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	2.16 – 2.56
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.39	2.18 – 2.60
$\sin^2\theta_{23}/10^{-1}$ (NH)	4.25	3.98 – 4.54
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.37	4.08 – 4.96 $\oplus$ 5.31 – 6.10
δ/π (NH)	1.39	1.12 – 1.72
δ/π (IH)	1.35	0.96 – 1.59

F.Capozzi, G.L.Fogli, E.Lisi, A.Marrone, D.Montanino, and A.Palazzo, Status of three-neutrino oscillation parameters, circa 2013, arXiv:1312.2878

Unresolved questions

Next *deep questions* to address with oscillation experiments:

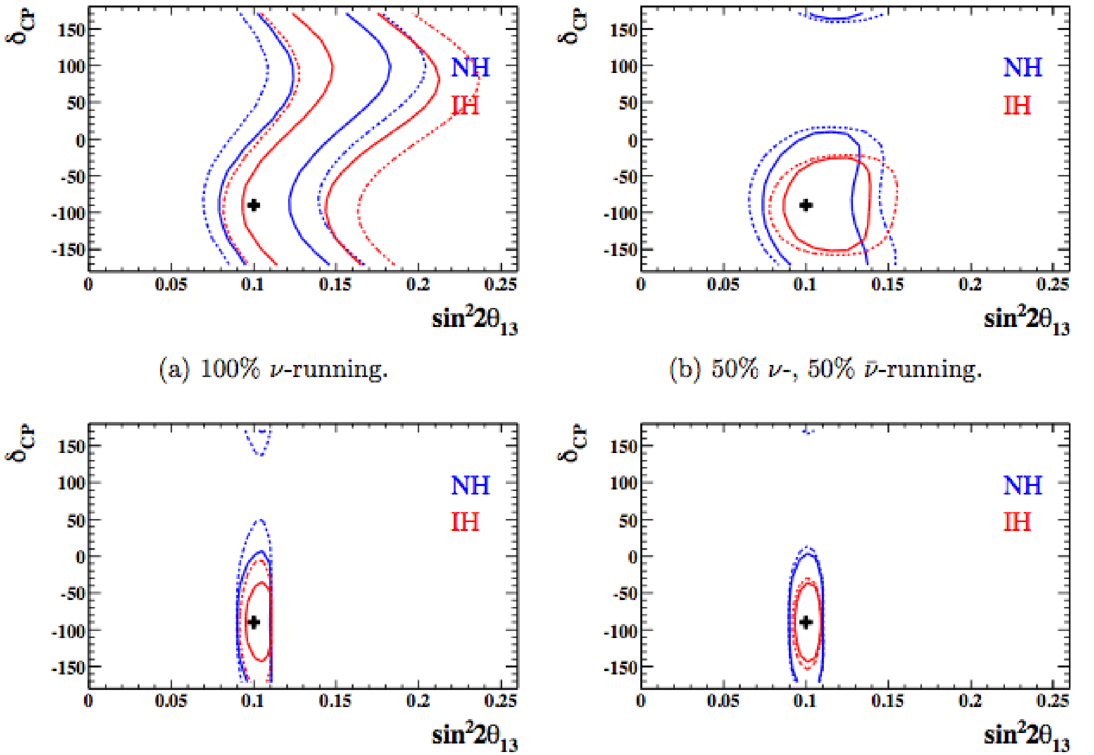
- What is the mass hierarchy?
- Is θ_{23} maximal?
  - If not, what is the θ_{23} octant?
- **Do neutrinos violate CP invariance?**
- **Is the PMNS matrix unitary?**

`‘A deep question is one where either a yes or no answer is interesting.’`

N.Bohr

Near-Future LBL Accelerator Expt Sensitivity (T2K)

T2K Future Sensitivity results from T2K report to 2013 J-PARC PAC. Publication in progress.



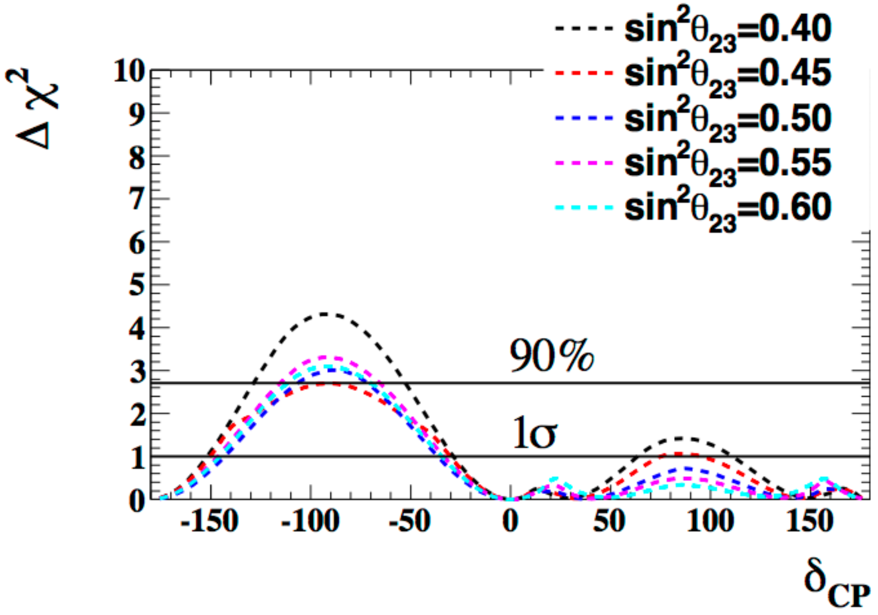
(a) 100% ν-running. (b) 50% ν-, 50% $\bar{\nu}$-running.

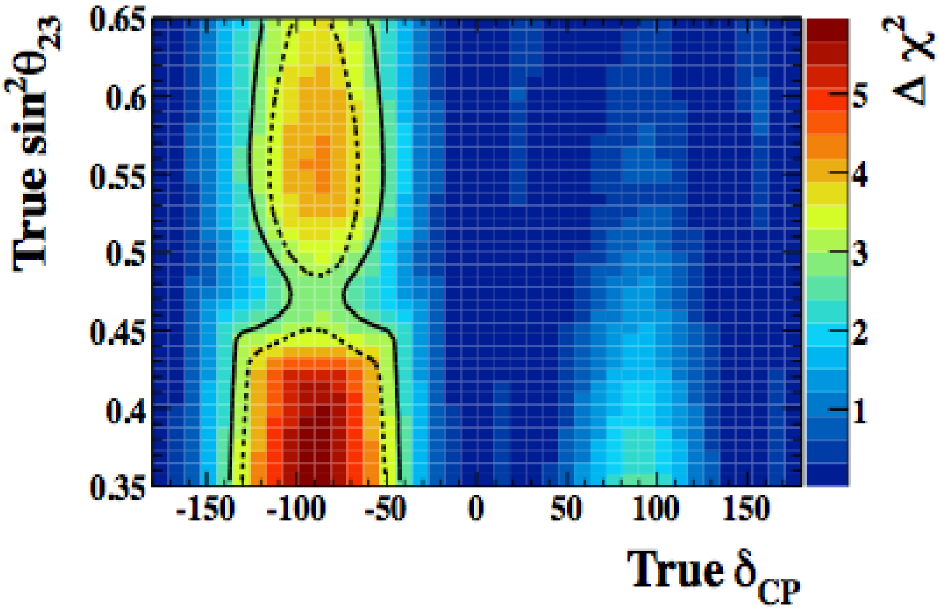
(c) 100% ν-running, with ultimate reactor constraint. (d) 50% ν-, 50% $\bar{\nu}$-running, with ultimate reactor constraint.

- Difference in δ_{CP} sensitivity with ν-enhanced and $\bar{\nu}$-enhanced beam running.
- Improved sensitivity with a combination of ν and $\bar{\nu}$ data.
- **$\sim$90% C.L. measurement for certain true values of δ_{CP}.**
- Similar δ_{CP} constraint with and without the reactor data: **Could start over-constraining the PMNS framework.**

90% C.L. intervals for true NH and true $\delta_{CP} = -\pi/2$, $sin^2 2\theta_{13}$=0.1, $sin^2\theta_{23}$=0.5, Δm^2_{32}=2.4$\times 10^{-3}$ eV^2/c^4.
Blue: Correct hierachy, Red: Incorrect hierarchy - Solid: Statistical errors only, Dashed: With 2012 systematics.
Assumed exposure: 7.8 $\times$ 10^{21} protons on target. Assumed ultimate reactor constraint: $\delta(sin^2 2\theta_{13})$=0.005.
Fully correlated ν and $\bar{\nu}$ systematic errors.

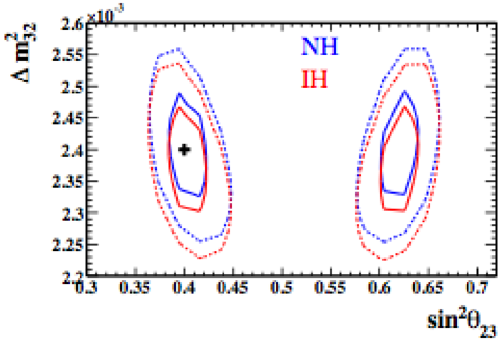
Sensitivity to δ_{CP} depends strongly on its true value.
Plots below show the calculated $\Delta\chi^2$ **for the** $sin(\delta_{CP}) = 0$ **hypothesis** for different values of δ_{CP} and θ_{23}.



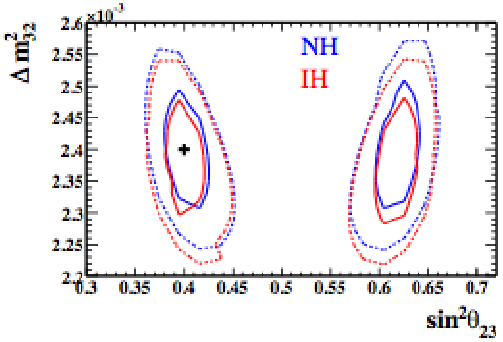


True: NH, $sin^2 2\theta_{13}$=0.1, Δm^2_{32}=2.4×10^{-3} eV^2/c^4.
Solid: Statistical errors only, Dashed: With 2012 systematics.
Assumed exposure: 7.8 × 10^{21} protons on target. Assumed ultimate reactor constraint: $\delta(sin^2 2\theta_{13})$=0.005.
Assumed a ν:$\bar{\nu}$ = 1:1 running scenario with fully correlated systematic errors.

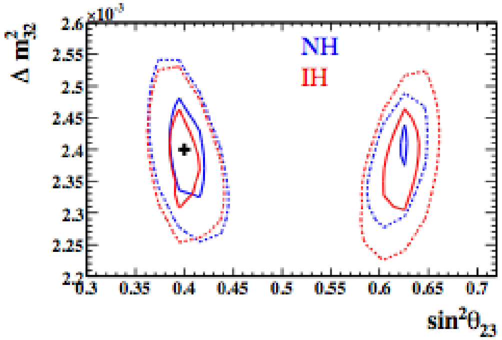
Near-Future LBL Accelerator Expt Sensitivity (T2K)



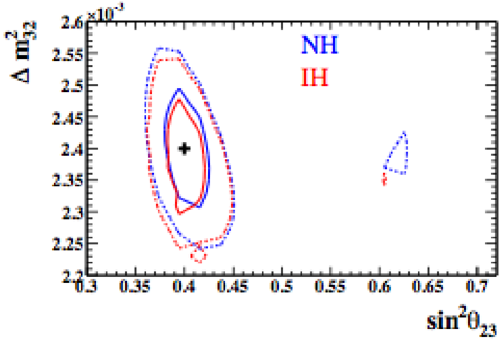
(a) 100% ν-running.



(b) 50% ν-, 50% $\bar{\nu}$-running.



(c) 100% ν-running, with ultimate reactor error.

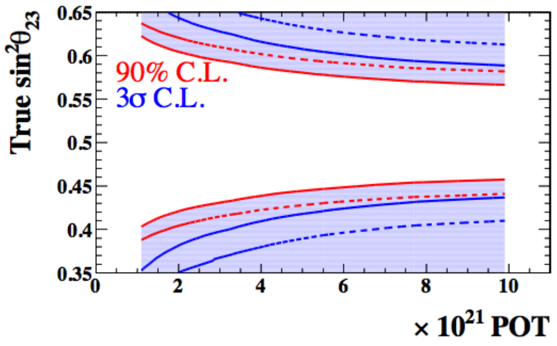


(d) 50% ν-, 50% $\bar{\nu}$-running, with ultimate reactor error.

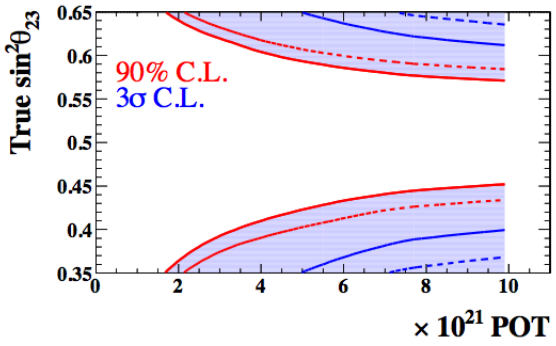
- Added power from combining ν and $\bar{\nu}$ data compensates for loss of statistics in $\bar{\nu}$-enhanced beam mode. There is no effect on the disappearance measurement using T2K data alone.
- Combination of T2K ν and $\bar{\nu}$ data and reactor data could allow us to resolve the θ_{23} octant.

90% C.L. intervals for true NH and true Δm^2_{32}=2.4$\times 10^{-3}$ eV^2/c^4, $sin^2\theta_{23}$=0.4, $\delta_{CP} = 0$ and $sin^2 2\theta_{13}$=0.1.
Blue: Correct hierachy, Red: Incorrect hierarchy - Solid: Statistical errors only, Dashed: With 2012 systematics.
Assumed exposure: 7.8 $\times$ 10^{21} protons on target. Assumed ultimate reactor constraint: $\delta(sin^2 2\theta_{13})$=0.005.
Fully correlated ν and $\bar{\nu}$ systematic errors.

Values of $sin^2\theta_{23}$ for which maximal mixing and the wrong octant can be rejected at the stated C.L.



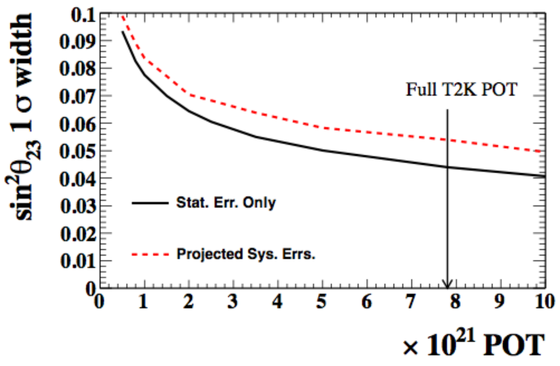
(a) $\theta_{23} \neq \pi/4$



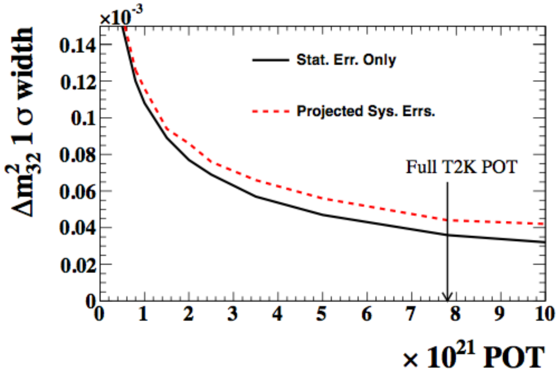
(b) θ_{23} Octant

θ_{23} octant could be determined at 90% C.L. if $|\theta_{23} - 45^o| > 4^o$.

1σ err for $sin^2\theta_{23}$ and Δm^2_{32} as function of T2K exposure.



(b) 50% ν, 50% $\bar{\nu}$-running.



$\delta(sin^2\theta_{23}) \simeq 0.045\ (2.6^o)$

$\delta(\Delta m^2_{32}) \simeq 4\times10^{-5}\ eV^2/c^4$

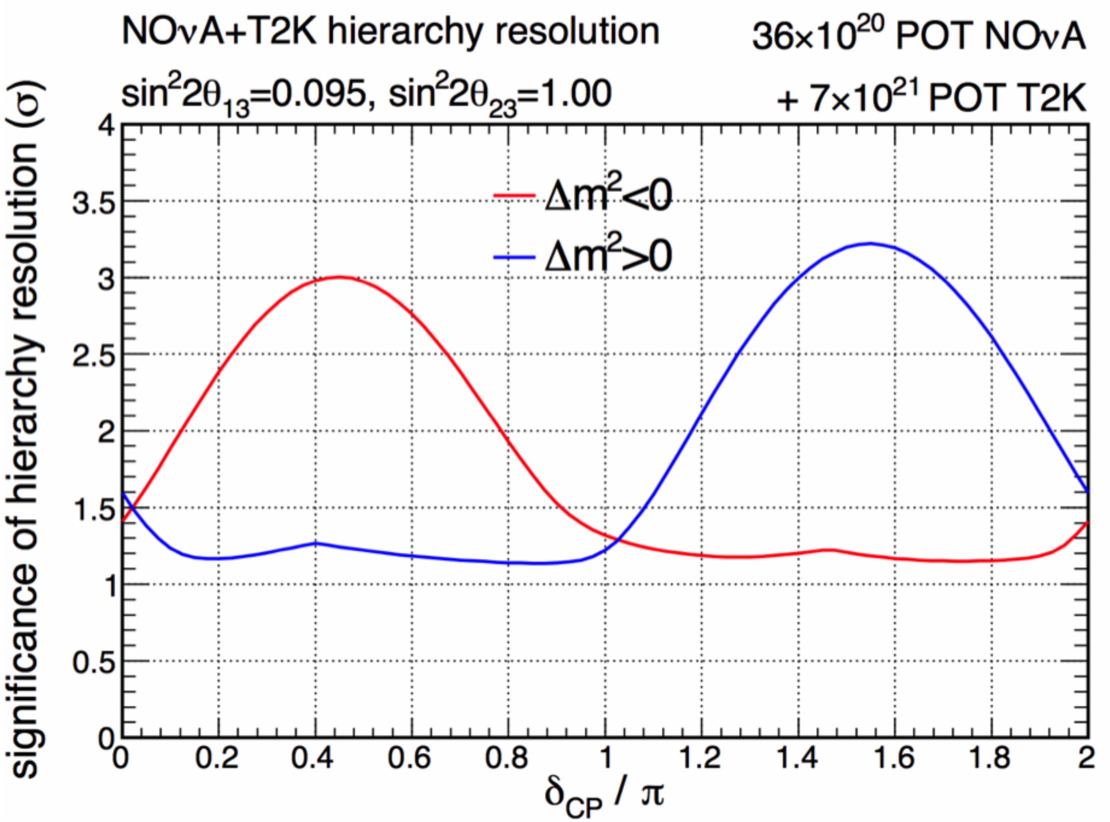
---

2 left plots:
True: NH, $\delta_{CP} = 0$, $sin^2 2\theta_{13}$=0.1, Δm^2_{32}=$2.4\times10^{-3}\ eV^2/c^4$.
Solid: Statistical errors only, Dashed: With 2012 systematics.

2 right plots:
True: NH, $\delta_{CP} = 0$, $sin^2 2\theta_{13}$=0.1, $sin^2\theta_{23}$=0.5, Δm^2_{32}=$2.4\times10^{-3}\ eV^2/c^4$.
Solid: Statistical errors only, Dashed: With projected systematics.

All plots:
Assumed a ν:$\bar{\nu}$ = 1:1 running scenario with fully correlated systematic errors.
Assumed ultimate reactor constraint: $\delta(sin^2 2\theta_{13})$=0.005.

NOvA, which is quite complementary to T2K has also started taking data quite recently.



[Andrew Norman, Neutrino 2014 conference, Boston]

LBL Accelerator Oscillation in the next decade

T2K+NOvA could establish that $sin(\delta_{CP}) \neq 0$, the MH and θ_{23} octant at up to 3σ.

... if we are lucky with the true values of oscillation parameters.

Note:
The actual observed significance can be much better than the projected sensitivity

- For the latest T2K ν_e appearance result, the observed significance was 7.3σ whereas the projected sensitivity was 5.3σ.

... of course, actual observed significance can also be worst than the projected sensitivity.

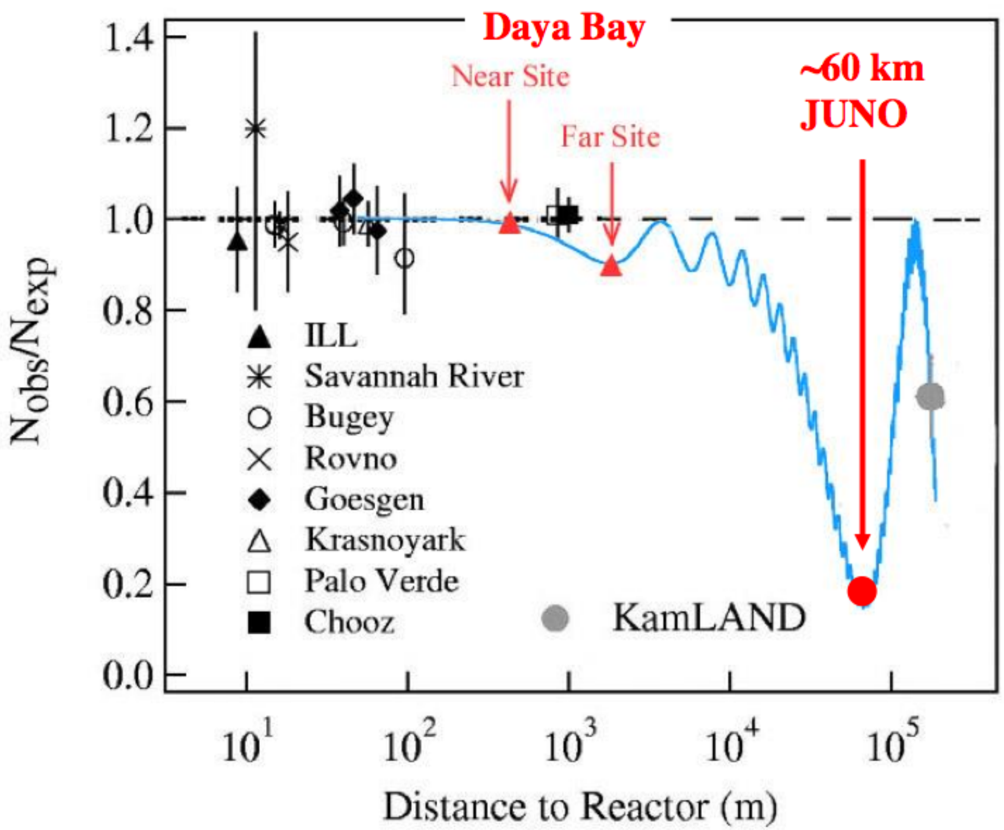
A new generation of experiments is needed to extend our sensitivity to:

- neutrino CP violation
- neutrino mass hierarchy
- deviations from the 3-flavour paradigm

The level of investment necessary to realize a next generation experiment requires that we design experiments with proven and **compelling sensitivity**.

Future long-baseline reactor experiments

LBL reactor experiment with a very large liquid scintillator detector:
Can observe simultaneously the wiggles from oscillations at the solar and atmospheric squared-mass splittings.



Primary goals:

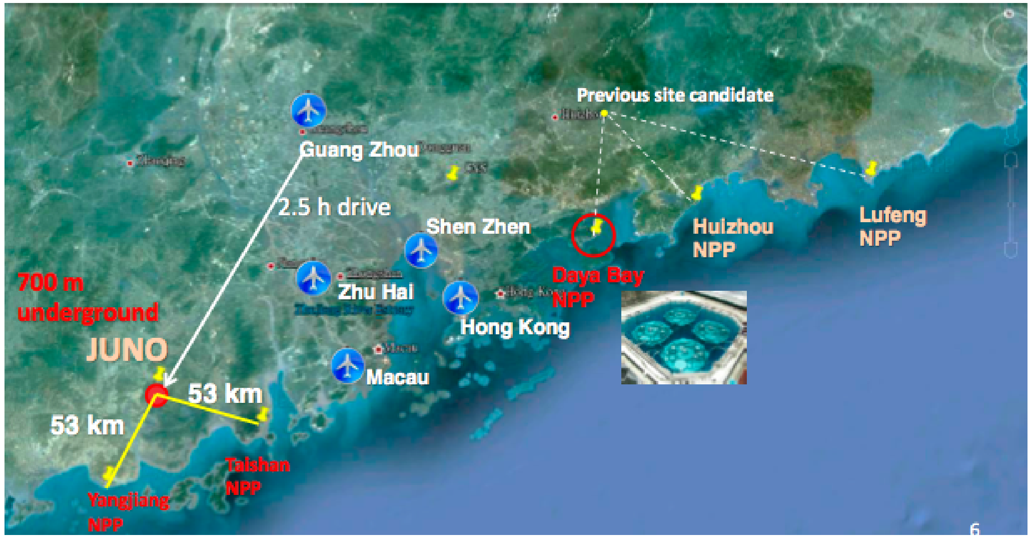
- Determination of the mass hierarchy
- Precision measurements of Δm^2_{31}, Δm^2_{21}, θ_{12}

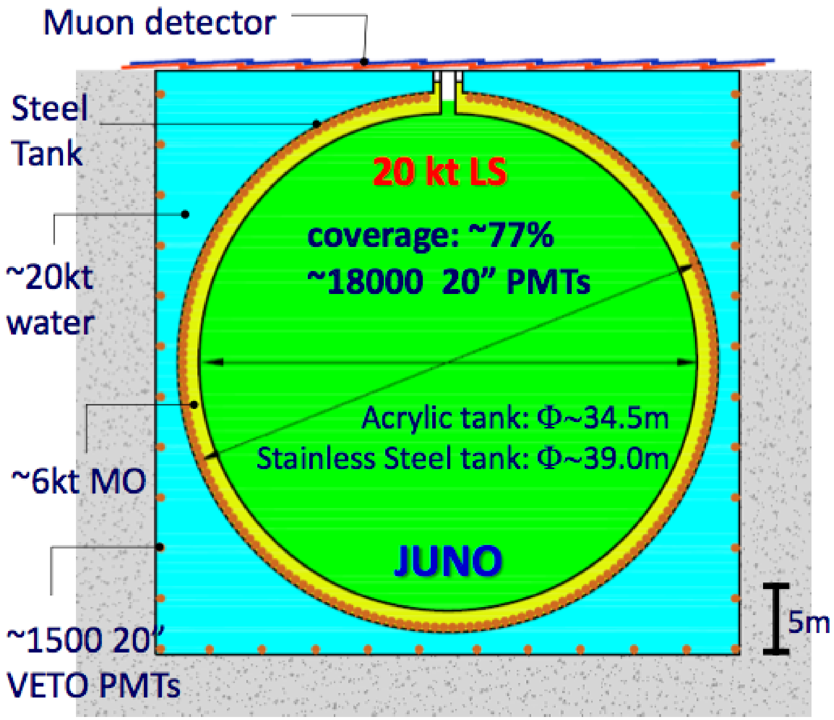
Such a large detector would also develop a rich physics programme:

- Supernova neutrinos
- Solar neutrinos
- Atmospehric neutrinos
- Geo-neutrinos
- Sterile neutrinos

JUNO (Jiangmen Underground Neutrino Observatory) in China: A 20 kt liquid scintillator detector observing $\bar{\nu}_e$ from 2 reactor complexes (Taishan and Yangjiang) with an average baseline of 52.5 km (0.25 km RMS). The combined power of the power plants is 35.8 GW [Phys. Rev. D 88, 013008 (2013)].

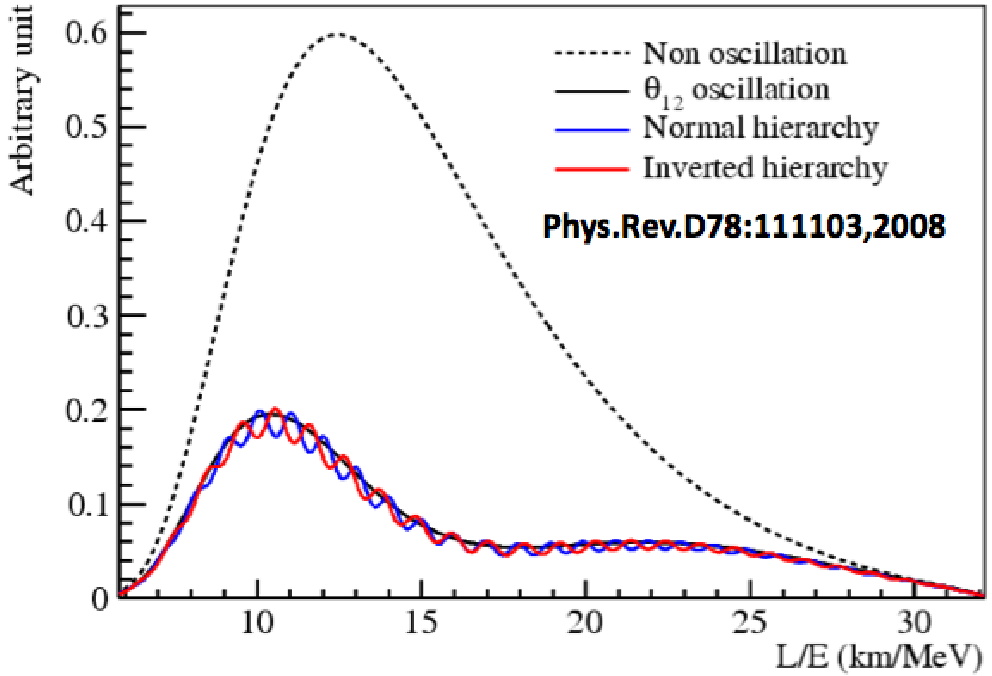
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



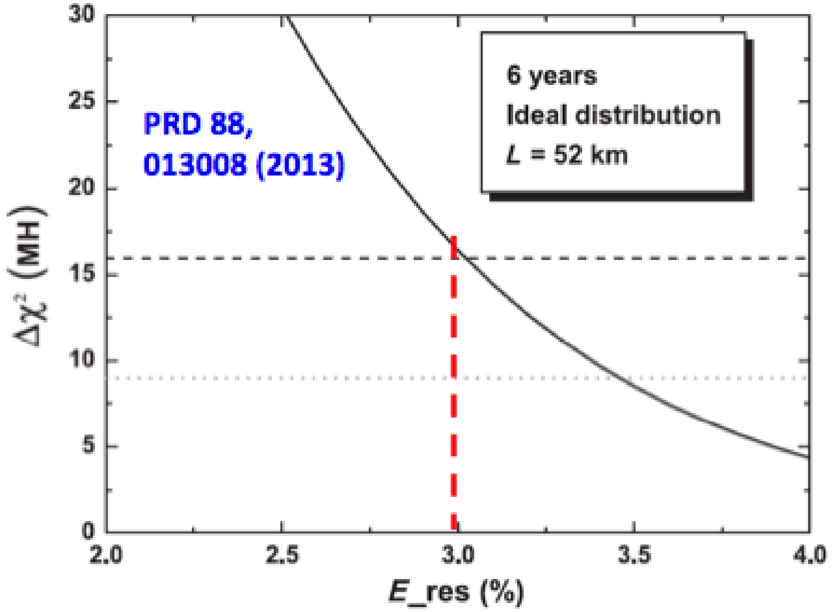


A similar experiment (RENO-50) is proposed in S.Korea.

Energy resolution would be critical for the MH determination.

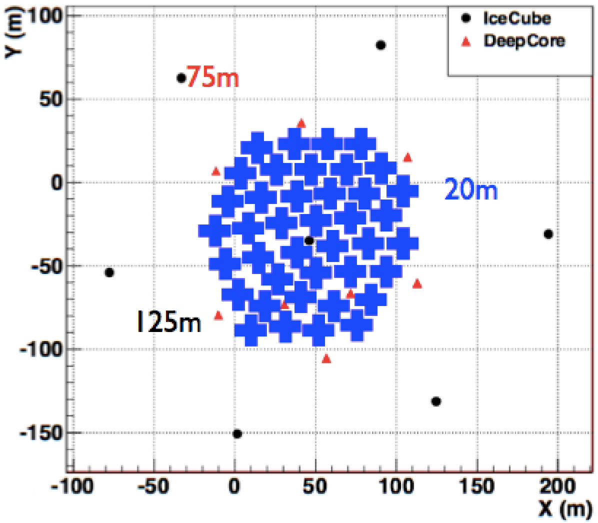


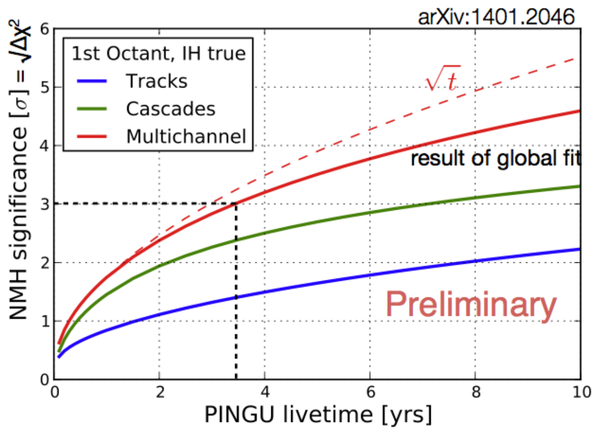
JUNO is aiming for $3\%/\sqrt{E}$ energy resolution



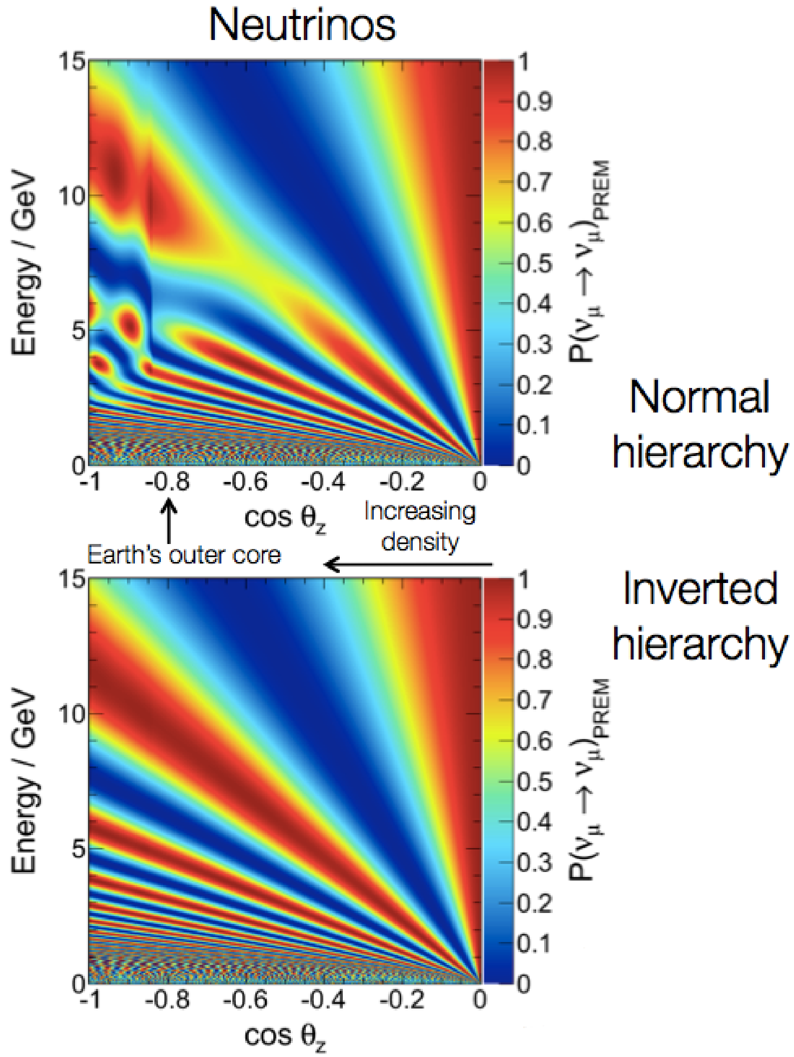
PINGU (Precision IceCube Next Generation Upgrade) [arXiv:1401.2046]:
In-fill array for IceCube
(40 strings, 20m spacing, 3-5m DOM spacing)

IceCube-DeepCore-PINGU top view





$\sim$20% difference in $\overset{(-)}{\nu}_\mu$ due to matter effects



[Grant, Neutrino 2014, Boston]

Main approaches for future LBL accelerator experiments

Few-10kt LAr detector in wide-band beam

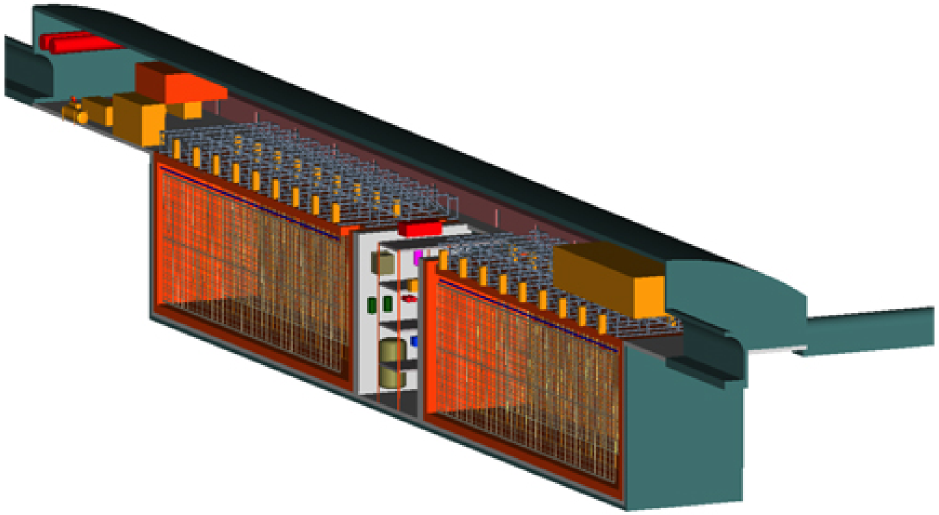
- Bubble-chamber-like imaging but not well known technology
- Relatively dense material $\rightarrow$ secondary re-interactions complicating event topologies
- Technology allows reconstruction of multi-particle event topologies and calorimetric energy reconstruction.
- Can work in high-E_ν wide-band beams
- Wide band and good energy resolution $\rightarrow$ rich spectral information (e.g. redundancy in δ_{CP} measurements, discrimination between δ_{CP}=0 or π, increased sensitivity to exotic physics scenarios).
- High E_ν $\rightarrow$ Very long baseline
- Very long baseline $\rightarrow$ Matter effects
- Matter effects $\rightarrow$ Sensitivity to MH (as well as δ_{CP}) with beam neutrinos

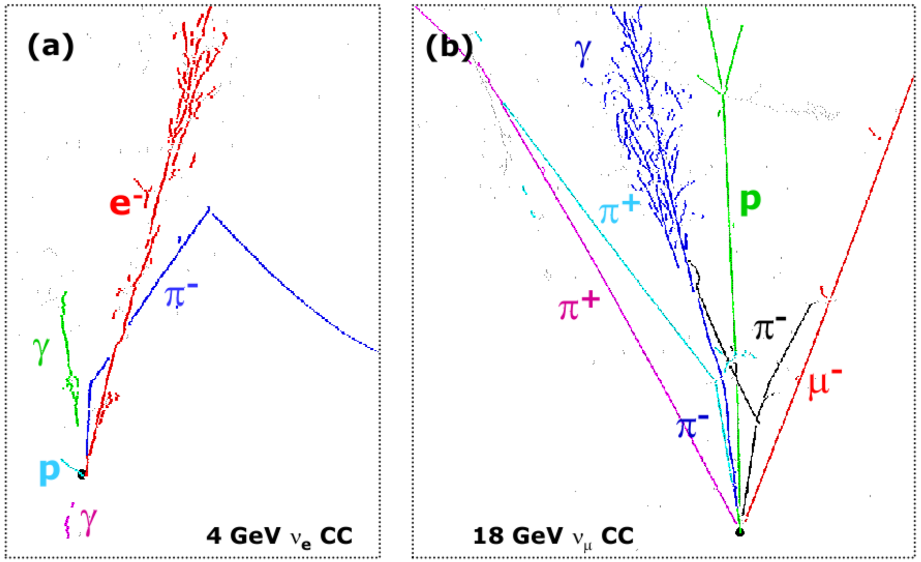
$\sim$1-Mt water Ckv detector in narrow-band beam

- Very well-known detector technology.
- Excellent detection capabilities for charged leptons but largely blind to the details of the hadronic system.
- Golden oscillation analysis samples are CCQE-enhanced 1-ring e-like and 1-ring μ-like samples.
- Works best at relatively low-energy narrow-band beams
- Narrow band $\rightarrow$ limited spectral information
- Low energy $\rightarrow$ Not very long baseline
- Not very long baseline $\rightarrow$ No matter effects
- No matter effects $\rightarrow$ No MH sensitivity with beam ν's.
- Excellent δ_{CP} sensitivity comparing $\nu/\bar{\nu}$ running if MH is known
- But MH has to come from somewhere else (or atmospherics, $\sim 3\sigma$ in 10 yrs)

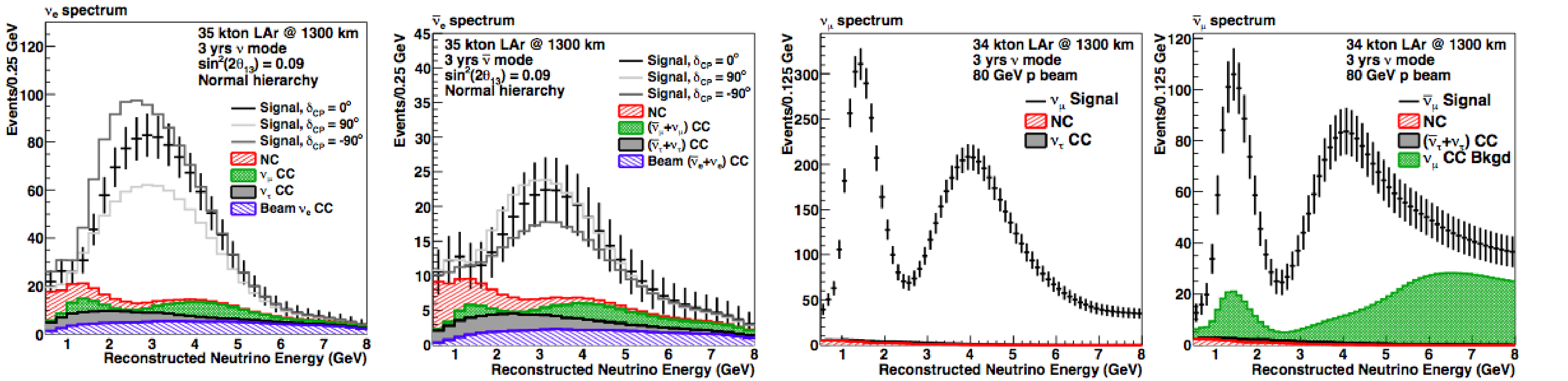
The LBNE(?) experiment

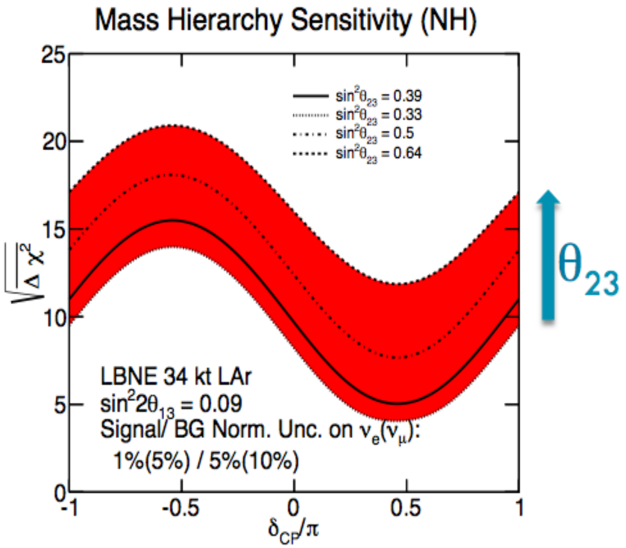
- Very long-baseline (Fermilab to SURF, 1300km) experiment in a wide-band beam
- Upgraded beam power (Fermilab PIP-II): 60-120 GeV protons 1.2 MW at startup (2.3 MW upgrade capability)
- Deep underground (SURF, 4850 ft)
- $>$35kt fiducial ($\sim$50kt total) liquid Argon TPC far detector. (baseline: single phase, based on ICARUS design, but with industrial cryostat and cold electronics)
- Highly capable near detectors $\sim$ 450 m from target
- (baseline: straw-tube tracker)
- Very rich physics program:
- Neutrino oscillations with accelerator, atmospheric and solar neutrinos
- Proton decay searches
- Neutrino astrophysics (supernova bursts, relic neutrinos, dark matter)

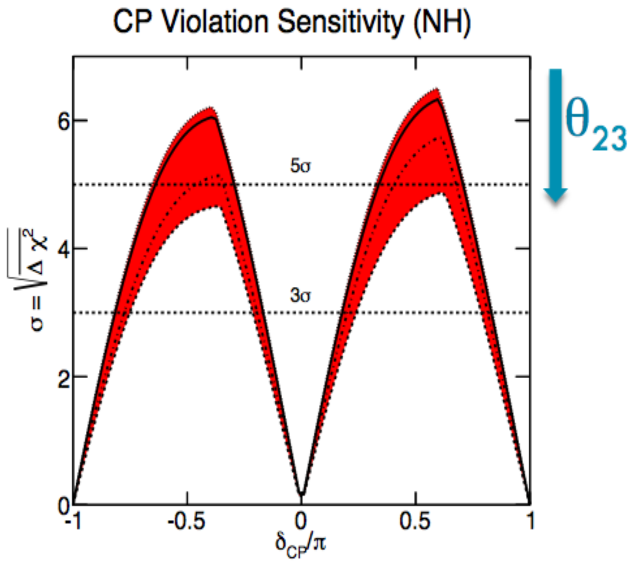


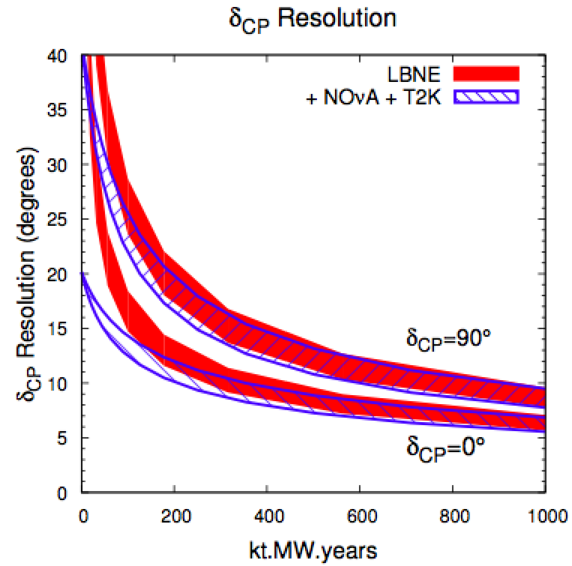


LBNE physics sensitivity





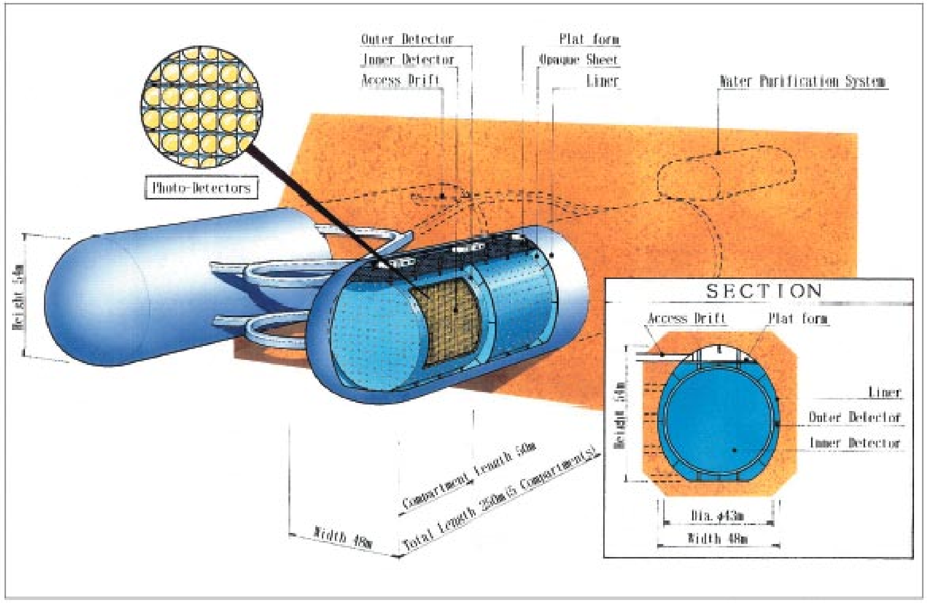




[Worcester, NOW 2014 conference]

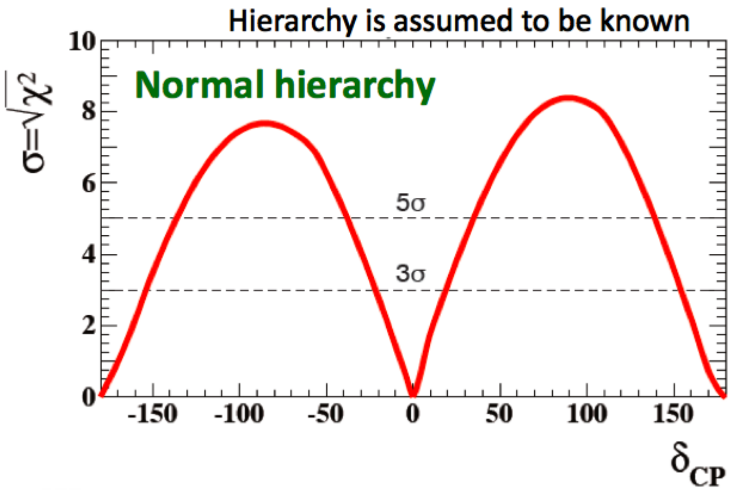
The Hyper-Kamiokande experiment

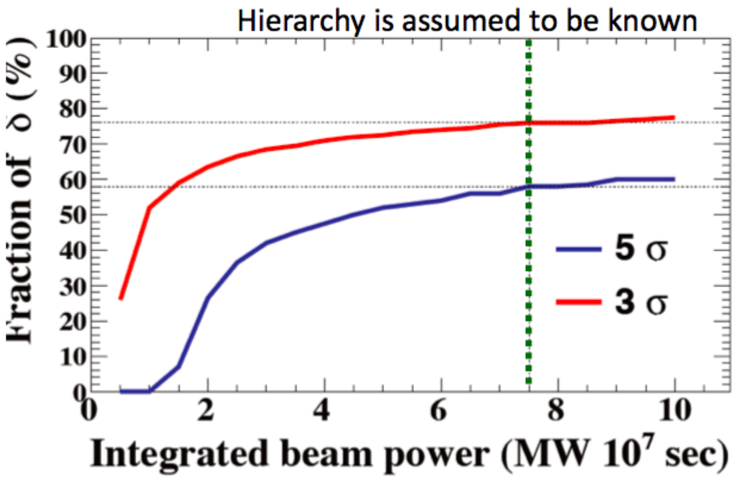
A natural extension of the T2K programme (Tokai to Kamioka, in J-PARC narrow band beam)



- 1 Mton water Cherenkov detector
- 0.560 Mton fiducial (25 $\times$ Super-K)
- In 10 compartments of 0.056 Mton each
- 2 tanks, each 48m $\times$ 54m $\times$ 250m !
- Inner detector: 99,000 20" PMTs
  - 20% photo-coverage
- Outer detector: 25,000 8" PMTs

- In upgraded J-PARC beam
  - 750 kW expected in next $\sim$3 yrs
  - $>$ 1MW under study
- Possible to construct the huge cavern needed with existing technology
  - Candidate site: Tochibora mine, same off-axis angle as Super-K
- Photo-sensor R&D ongoing
  - improve timing and QE
- Very rich physics program:
  - Neutrino oscillations with accelerator, atmospheric and solar neutrinos
  - Proton decay searches
  - Neutrino astrophysics



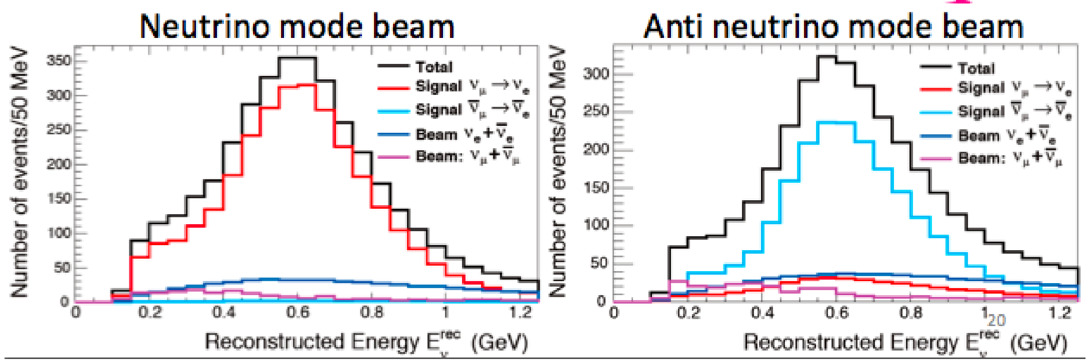


76% (58%) coverage at 3σ(5σ)

$\delta(\delta_{CP}) \approx 8^o - 19^o$

Assuming 7.5×10^7 MW*sec, $\nu : \bar{\nu} = 1 : 3$, T2K systematics

	Signal ($\nu\mu \to \nu e$ CC)	Wrong sign appearance	$\nu\mu/\bar{\nu}\mu$ CC	beam $\nu e/\bar{\nu}e$ contamination	NC
ν	3,016	28	11	523	172
$\bar{\nu}$	2,110	396	9	618	265



$sin^2 2\theta_{13}$=0.1, δ_{CP}=0, NH

[Hayato, Neutrino 2014 conference]

A taster of other physics capabilities:

- Will set 90% C.L limits of 1.3 $\times 10^{35}$ yrs (2.5 $\times 10^{34}$ yrs) for p $\rightarrow$ e π^0 (p $\rightarrow \nu K^+$)
- Will detect 200 solar neutrinos /day
- Will detect 200,000 supernova neutrinos if one blows up at the Galactic centre (10 kpc)

Tensions in the 3-active-neutrino scheme

Summary of tensions in the 3-active-neutrino scheme

Hints:

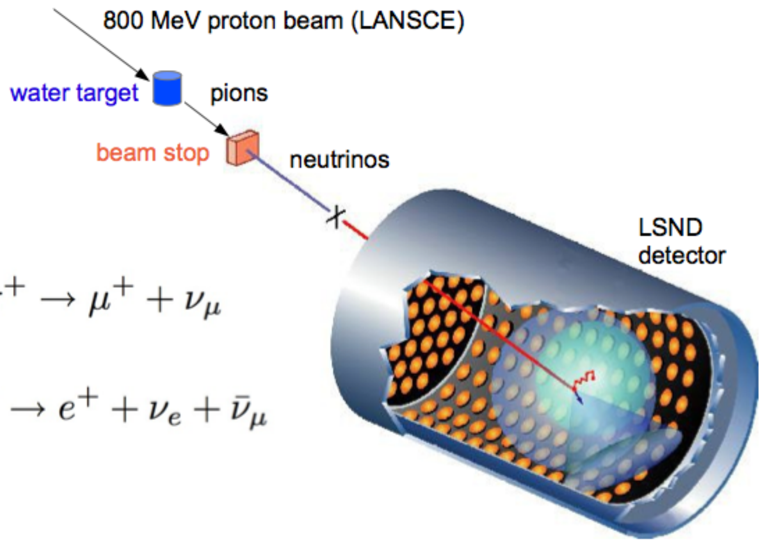
- **LSND anomaly**
  $\sim$50 MeV $\bar{\nu}_e$ appearance, $\sim 3.8\sigma$
- **MiniBooNE anomaly**
  $\sim$1 GeV ν_e and $\bar{\nu}_e$ appearance, $\sim 3.8\sigma$
- **Reactor anomaly**
  Few-MeV $\bar{\nu}_e$ disappearance, $\sim 3.0\sigma$
- **Gallium anomaly**
  Sub-MeV ν_e disappearance, $\sim 2.7\sigma$

Null results:

- KARMEN search for $\bar{\nu}_e$ appearance at $\sim$50 MeV
- OPERA and ICARUS searches for ν_e appearance at multi-GeV
- MiniBooNE searches for ν_μ and $\bar{\nu}_\mu$ disappearance at $\sim$1 GeV
- CDHS and MINOS searches for ν_μ disappearance at few-GeV

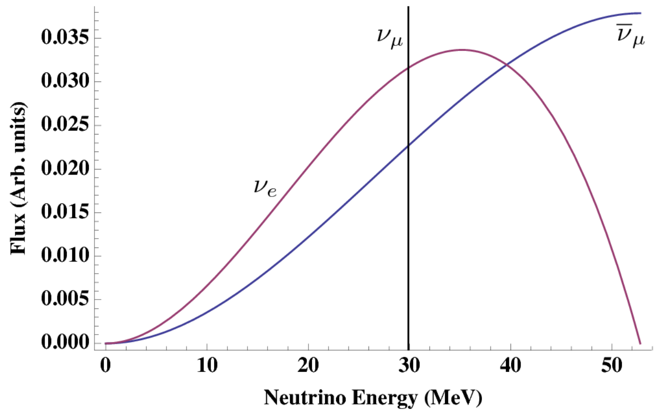
The LSND experiment

Liquid Scintillator Neutrino Detector (LSND) experiment (Los Alamos, 1993-1998) using a neutrino beam from π^+ decay at rest [Athanassopoulos et al., NIM A388 (1997) 149-172].



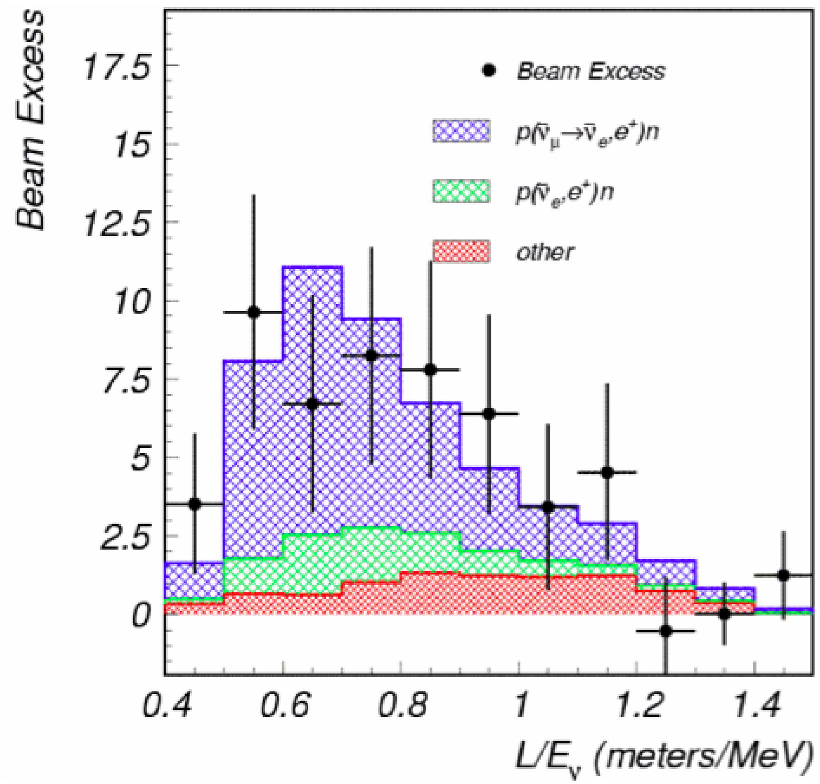
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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



- 0.8-MW 800-MeV p beam
- Copious amounts of pions produced in interactions with a water target
- π^+ come to rest and decay
- Only a small fraction of π^+ (3.4%) decayed in flight
- $\pi^-/\pi^+ \sim 1/8$ and most π^- (and μ^-) are absorbed before decaying.
- Flux shape determined simply from π, and μ decay and is well known.
- Homogenous mineral oil (167 tonnes) detector viewed by 1220 photomultiplier tubes (isotropic scintillation light + directional Cherenkov light cone)
- At a baseline of $\sim$30m (L/E $\sim$ 1m/MeV)
- $\bar{\nu}_e$ detection: Prompt e^+ signal ($\bar{\nu}_e$ + p $\rightarrow e^+$ + n) followed by a correlated signal from n capture (n + p $\rightarrow$ d + γ (2.2 eV))

$\sim$3.8σ $\bar{\nu}_e$ appearance in a beam of $\bar{\nu}_\mu$ from μ decay at rest (ν_μ energy $<$ 52.8 eV) at a baseline of $\sim$30 m (L/E $\sim$ 0.7 m/MeV)



Main backgrounds:

- μ^- decay at rest followed by $\bar{\nu}_e + \mathrm{p} \to e^+ + \mathrm{n}$
- π^- decay in flight followed by $\bar{\nu}_\mu + p \to \mu^+ + n$

$\bar{\nu}_e$ excess observed:

87.9 $\pm$ 22.4 (stat) $\pm$ 6 (syst)

Under a 2-ν mixing hypothesis:

$P(\bar{\nu}_\mu \to \bar{\nu}_e) = 0.264 \pm 0.067 \pm 0.045$ %

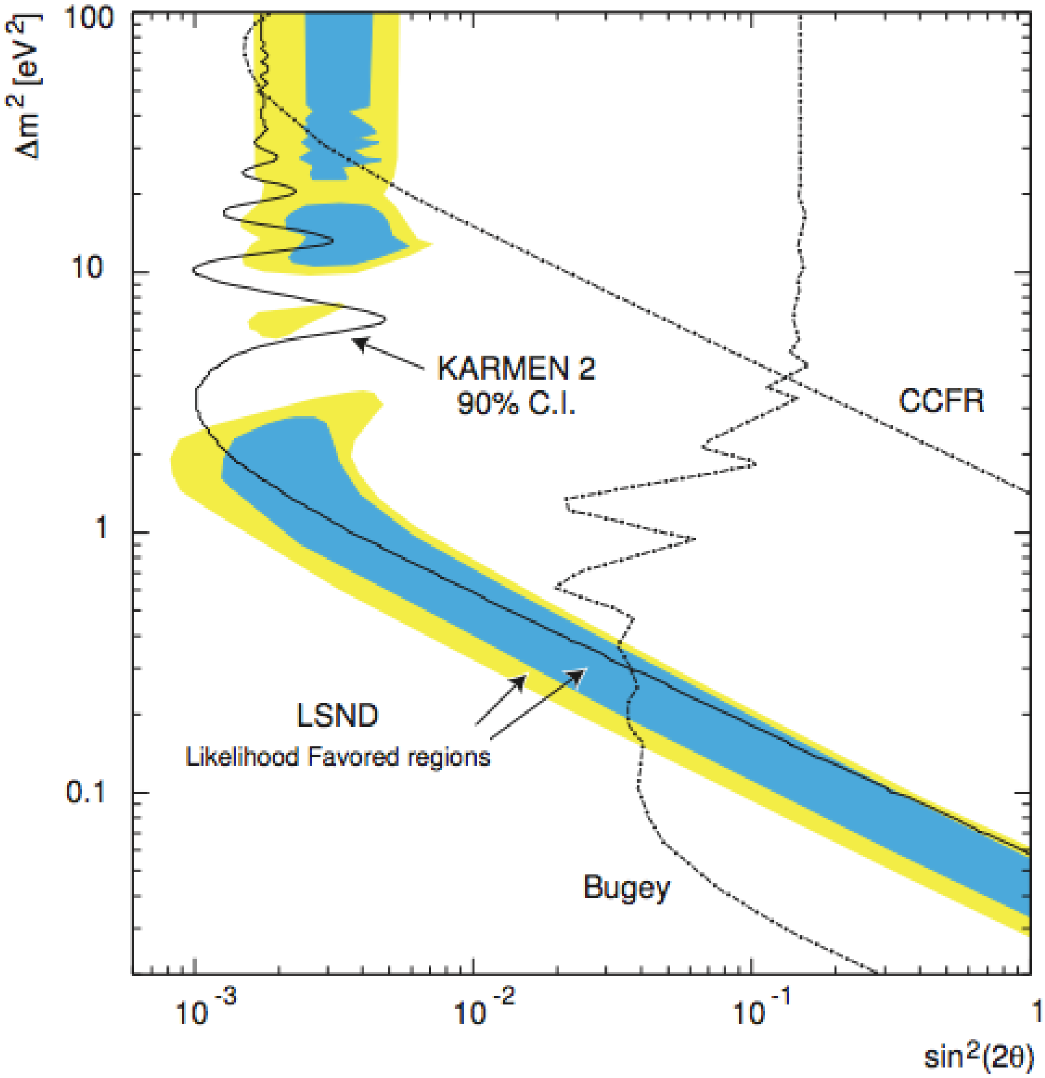
[Aguilar-Arevalo, RD64 (2001) 112007]

But no significant $\bar{\nu}_e$ excess seen in KARMEN

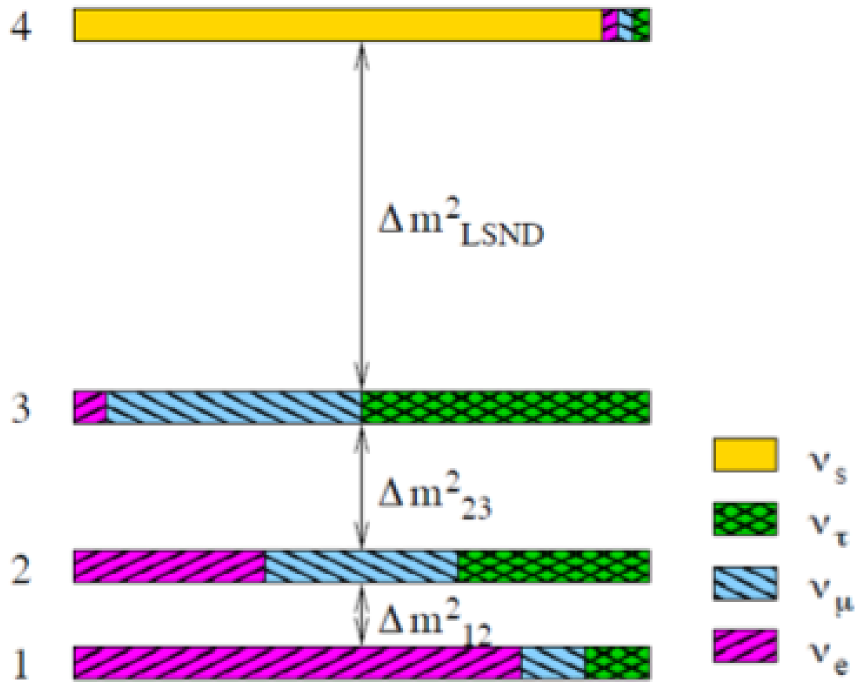
At the same time with LSND, a very similar experiment (KARMEN) using a segmented liquid scintillation calorimeter was run at the Rutherford Appleton Laboratory exploiting the distinct time structure of the ISIS source [Drexlin et al., NIM A289 (1990) 490-495].

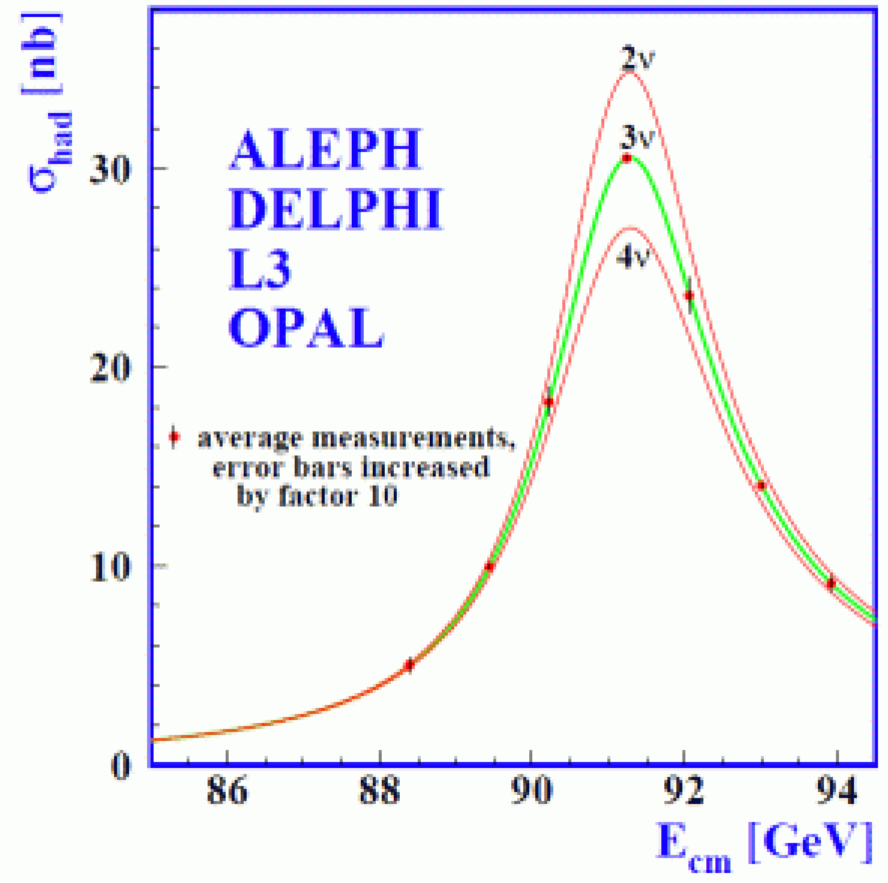
KARMEN found no evidence for a $\bar{\nu}_e$ excess [Armbruster et al., Phys.Rev. D65 (2002) 112001].

However the KARMEN and LSND results were not incompatible (under a 2-neutrino oscillation hypothesis).



A 4^{th} neutrino?

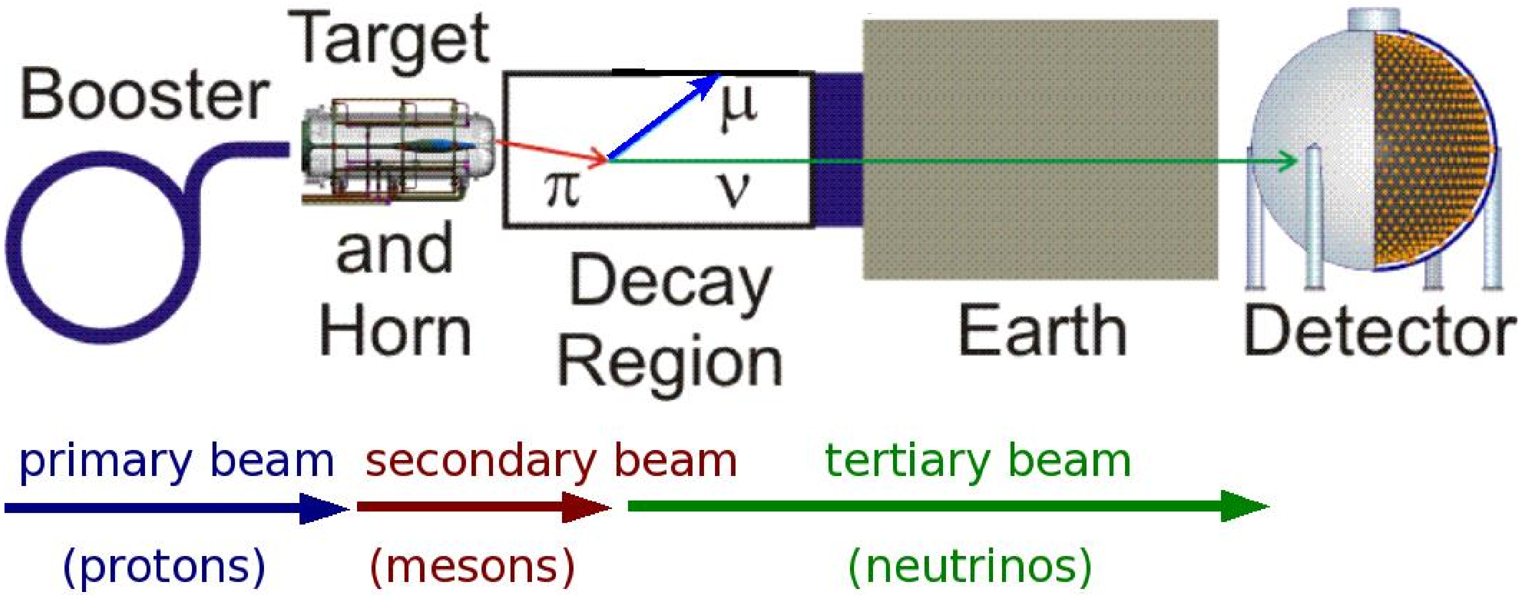




A 4^{th} light neutrino would have to be sterile

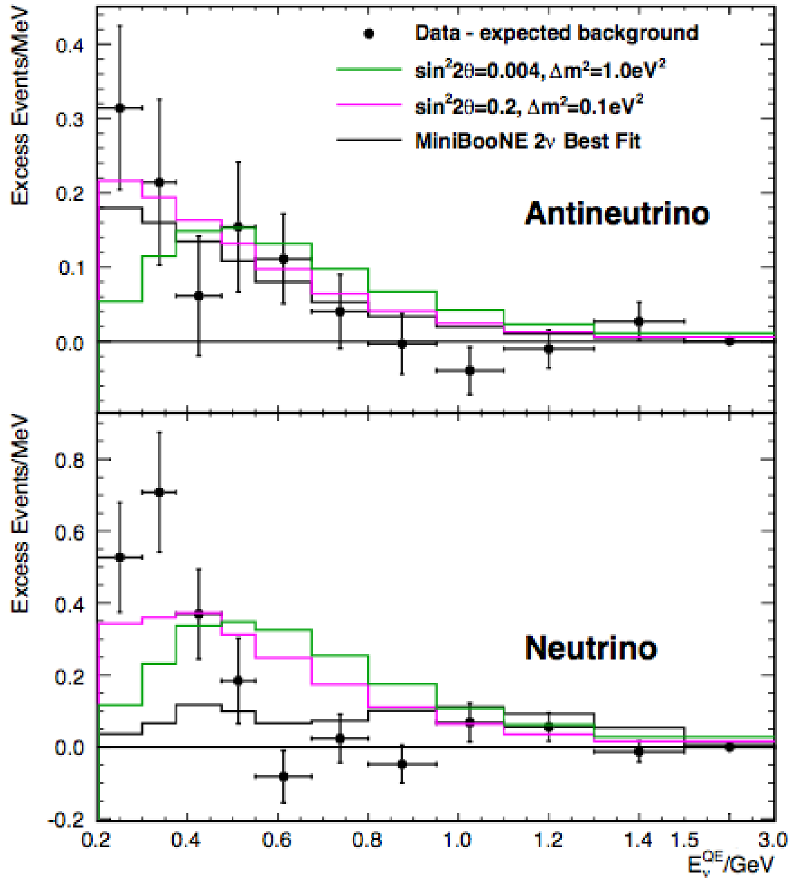
MiniBooNE experiment:

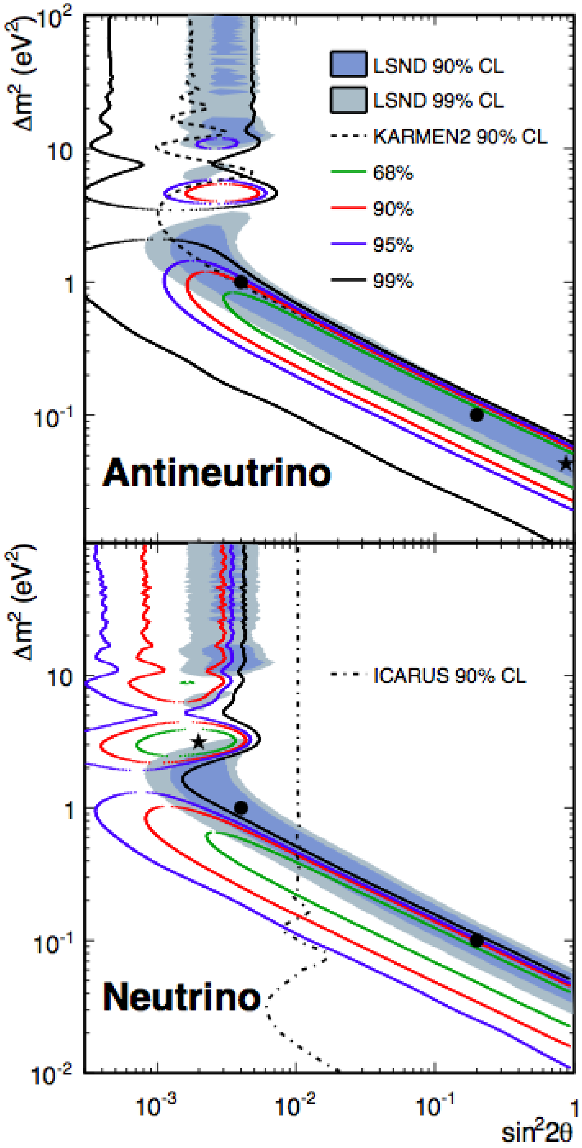
- Keeping the same L/E ratio, but perform an indpendent experiment at a different energy range, with different event signature / backgrounds and different systematics
- Detector: 800 tonnes of mineral oil instrumented with 1280 photosensors
- $\sim$500 m from the target, at the Booster neutrino beam at Fermilab



MiniBooNE results

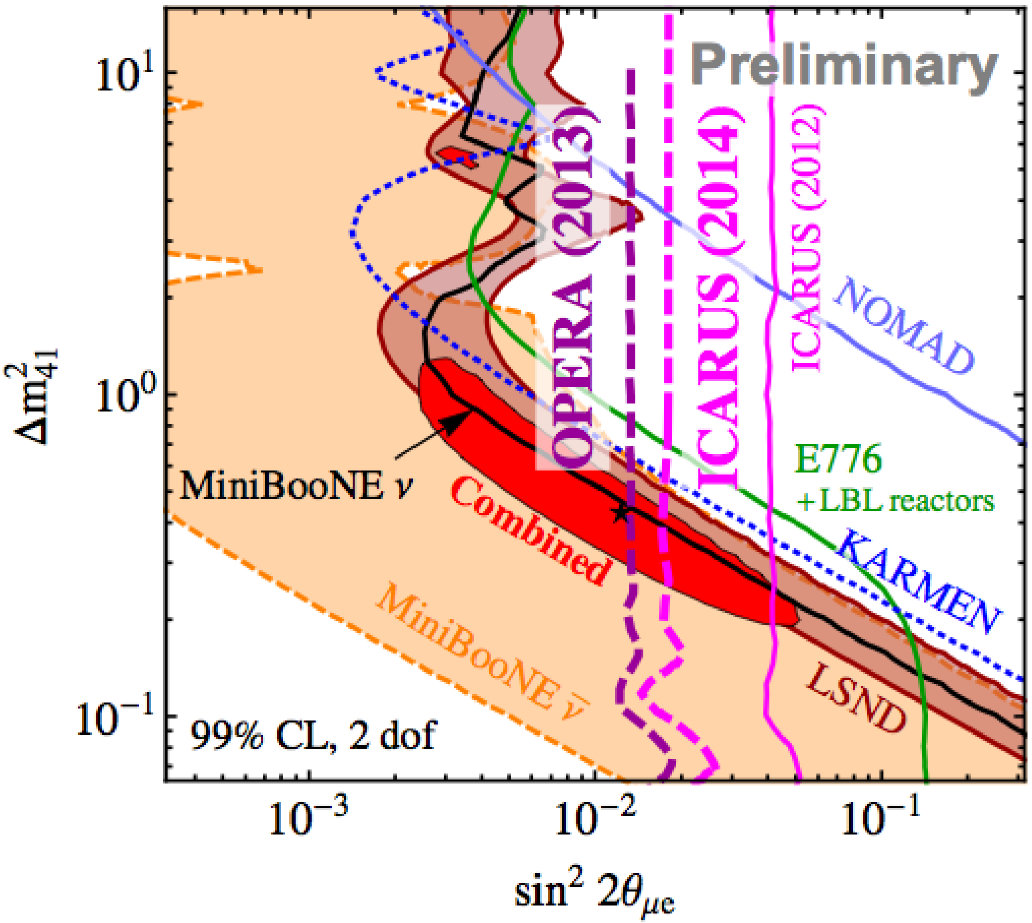
[Phys. Rev. Lett. 110, 161801 (2013)]





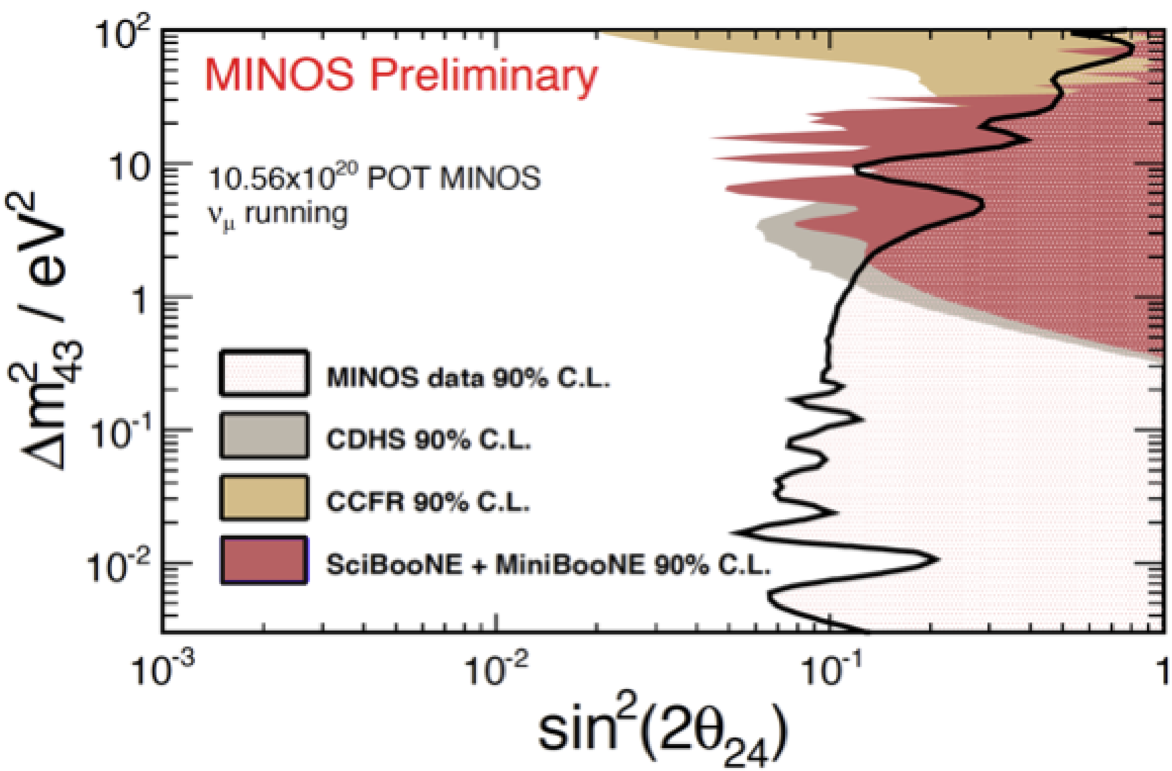
Multi-GeV ν_e and $\bar{\nu}_e$ appearance searches

- Recent results from the ICARUS and OPERA experiments at the CERN CNGS beam.
- No evidence for ν_e appearance in multi-GeV ν_μ beam.
- Cutting away at the LSND+MiniBooNE region.
- Global fit to appearance data still consistent with oscillations.



[Kopp, Neutrino 2014 conference, Boston].

ν_μ and $\bar{\nu}_\mu$ disappearance searches



[Sousa, Neutrino 2014 conference, Boston].

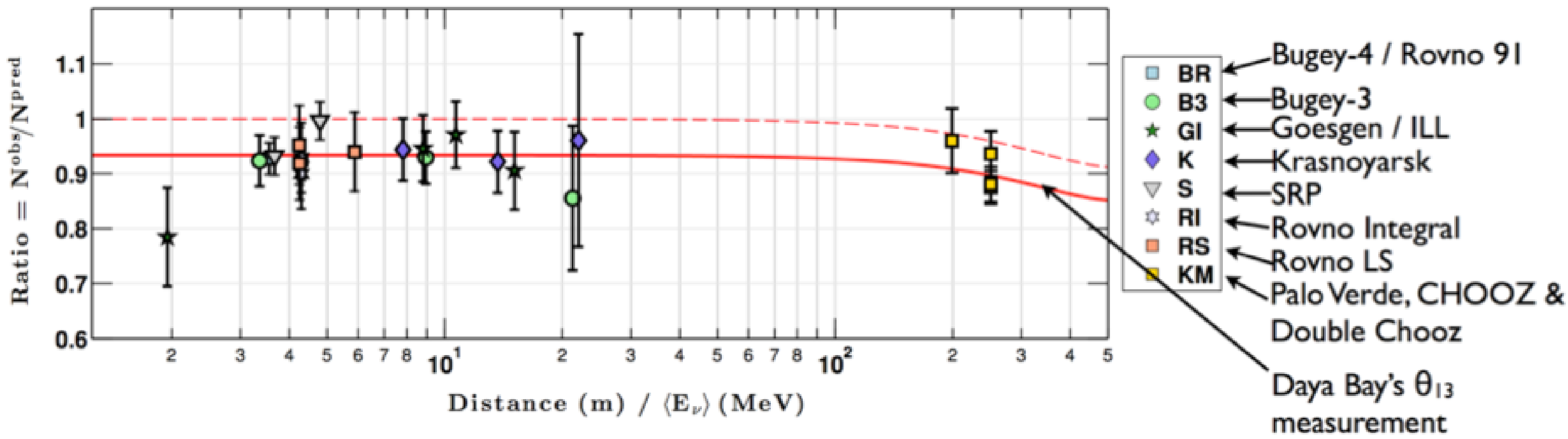
Negative results by several experiments using both ν_μ and $\bar{\nu}_\mu$ beams at a wide range of energies

- MINOS
- MiniBooNE + SciBooNE
- CDHS
- CCFR

The reactor anomaly

Recent re-evaluation of the predicted reactor neutrino flux (+3.5%), accounting of long-lived isotopes (+1%) and new measurements of the neutron lifetime impacting the inverse beta decay cross-section (+1.5%).

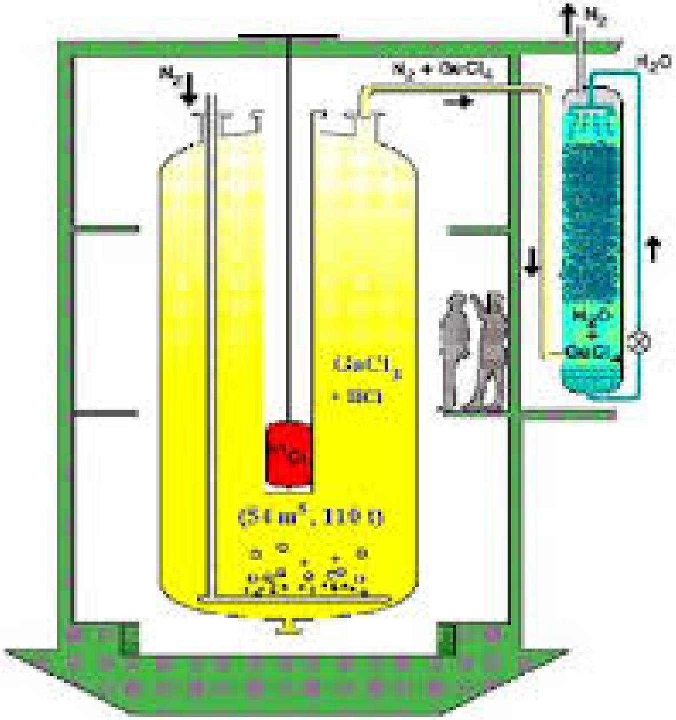
Experimental results now sitting about 3σ lower than predictions.



Mention et al., Phys. Rev. D 83 073006 (2011); Mueller et al., Phys. Rev. C 83, 054615 (2011); P. Huber, Phys. Rev. C 84, 024617 (2011); Hayes et al, Phys. Rev Le1. 112,202501 (2014)

The Gallium anomaly

- Tests of (the detection efficiency of the) GALLEX and SAGE radiochemical solar neutrino detectors
- Neutrino detection via $\nu_e + {}^{71}\text{Ga} \rightarrow e^- + {}^{71}\text{Ge}$
- 4 runs using intense (0.6 - 2 MCi) radioactive (electron capture) ν_e sources (^{51}Cr (750 keV) and ^{37}Ar (810 keV))
- GALLEX: ^{51}Cr, $< L >$=1.9m.
- SAGE: ^{51}Cr and ^{37}Ar, $< L >$=0.6m.



The Gallium anomaly

A deficit was observed:

Experiment	Run	Source	Ratio (measured/predicted)
GALLEX	1	^{51}Cr	0.953 ± 0.11
GALLEX	2	^{51}Cr	$0.812^{+0.10}_{-0.11}$
SAGE	1	^{51}Cr	0.95 ± 0.12
SAGE	2	^{37}Ar	$0.791^{+0.084}_{-0.078}$

Combined ratio $R = 0.86 \pm 0.05$ [Giunti and Laveder, Phys.Rev. C83 (2011) 065504]

- The deficit depends on the cross-section value for the $\nu_e + {}^{71}\text{Ga} \rightarrow e^- + {}^{71}\text{Ge}$ process.
- The cross-section for the transition from the ground state of ^{71}Ga to the ground state of ^{71}Ge is known precisely from the electron capture decay rate of ^{71}Ge.
- However, ν_e from the sources used at GALLEX and SAGE may be absorbed by ^{71}Ga with transitions to excited states of ^{71}Ge (175 keV, 500 keV)
    - Inferred from: $p + {}^{71}\text{Ga} \rightarrow n + {}^{71}\text{Ge}$.
    - Supported by recent data [Frekers et al.,Phys.Lett. B706 (2011) 134-138]

Sterile neutrino phenomenology

- $\overset{(-)}{\nu}_e$ **disappearance**

$$P(\overset{(-)}{\nu}_e \nrightarrow \overset{(-)}{\nu}_e) = 1 - sin^2(2\theta_{ee}) \cdot sin^2(\frac{\Delta m^2_{41}}{4E_\nu}), \; sin^2(2\theta_{ee}) = |U_{e4}|^2 \cdot (1 - |U_{e4}|^2)$$

- $\overset{(-)}{\nu}_\mu$ **disappearance**

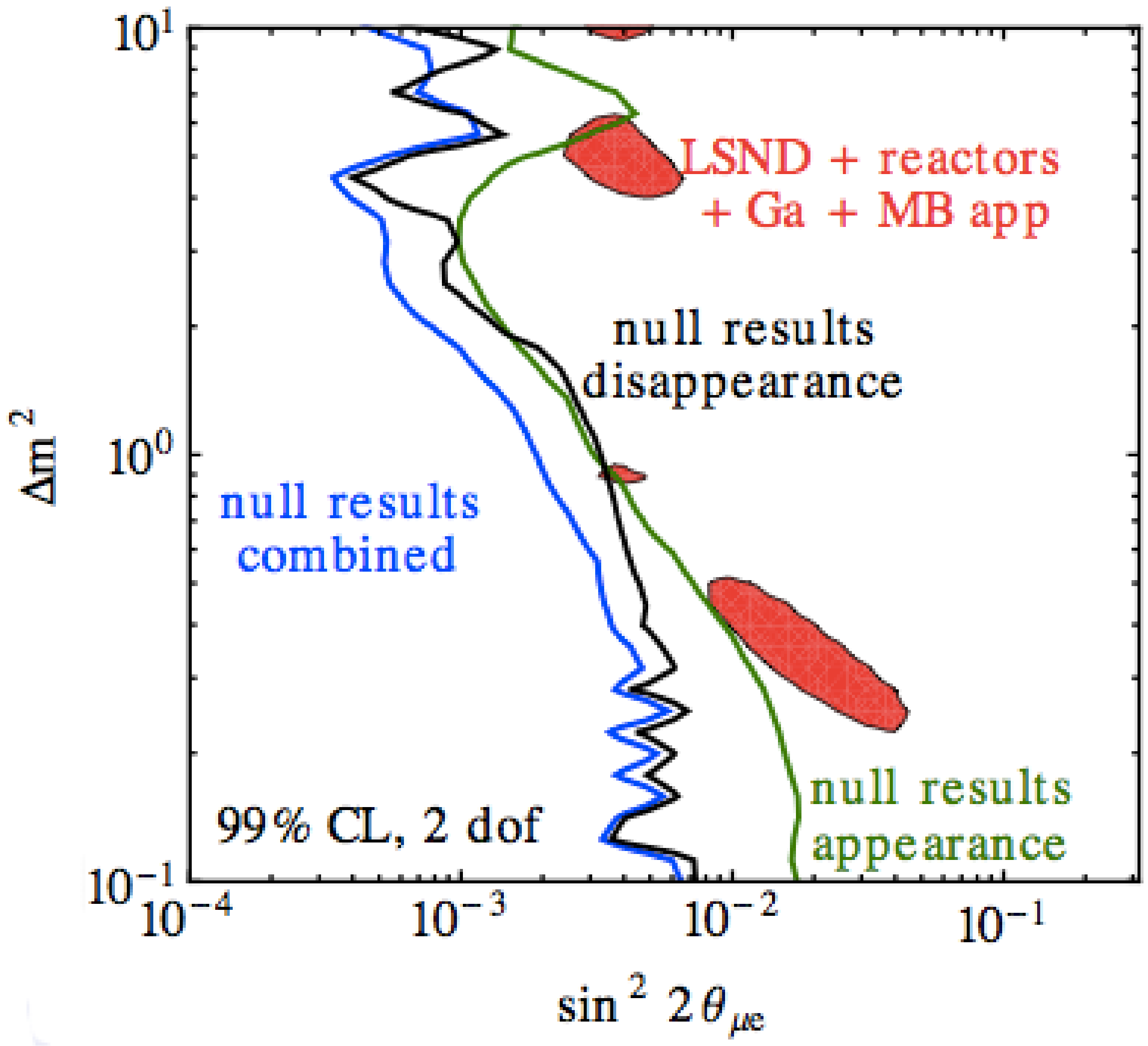
$$P(\overset{(-)}{\nu}_\mu \nrightarrow \overset{(-)}{\nu}_\mu) = 1 - sin^2(2\theta_{\mu\mu}) \cdot sin^2(\frac{\Delta m^2_{41}}{4E_\nu}), \; sin^2(2\theta_{\mu\mu}) = |U_{e4}|^2 \cdot (1 - |U_{\mu 4}|^2)$$

- $\overset{(-)}{\nu}_e$ **appearance in** $\overset{(-)}{\nu}_\mu$ **beam**

$$P(\overset{(-)}{\nu}_\mu \nrightarrow \overset{(-)}{\nu}_e) = 1 - sin^2(2\theta_{\mu e}) \cdot sin^2(\frac{\Delta m^2_{41}}{4E_\nu}), \; sin^2(2\theta_{\mu e}) = \frac{1}{4} sin^2(2\theta_{ee}) \cdot sin^2(2\theta_{\mu\mu})$$

Relation between appearance and disappearance channels:
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance requires $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_e$ disappearance.

Global sterile neutrino fits



We saw ν_e disappearance and $\nu_\mu \to \nu_e$ appearance but no ν_μ disappearance

Severe tension between datasets in a 3+1 framework

Tension relieved somewhat with more complex models, but...

However the implications are just too important to ignore.

[Kopp, Machado, Maltoni and Schwetz, JHEP 1305 (2013) 050]

Summary of tensions in the 3-active-neutrino scheme

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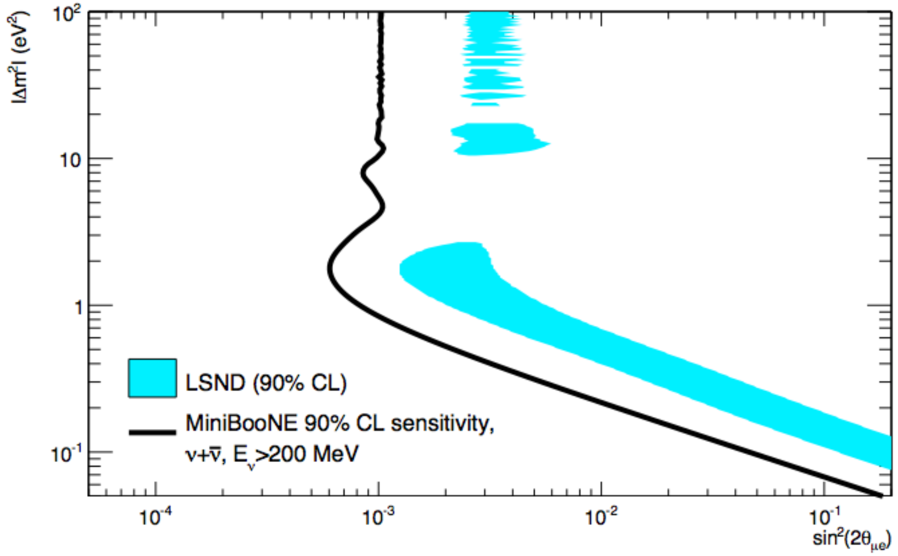
- MiniBooNE searches for ν_μ and $\bar{\nu}_\mu$ disappearance at $\sim$1 GeV
- CDHS and MINOS searches for ν_μ disappearance at few-GeV

Need more data!

Where did MiniBooNE went wrong?

What was MiniBooNE's sensitivity*?

*The *actual* experimental sensitivity achieved (not from the proposal)



From MiniBooNE data release:
http://www-boone.fnal.gov/for_physicists/data_release/nue_nuebar_2012/

This sensitivity is not good enough to be definitive!!

[Spitz, Neutrino 2014 conference, Boston]

- But, remember that MiniBooNE was going to provide the data to resolve the LSND anomaly (which is now known as the LSND + MiniBooNE anomaly)
- MiniBooNE had enough sensitivity to exclude the eV-scale sterile hypothesis if it didn't see anything
- But MiniBooNE saw something, and it didn't have the redundancy of information to claim discovery or understand the unknown systematic effect

To address the question of the
potential existence of eV-scale sterile neutrino
we need data from experiments
with **compelling [*]** sensitivity

[*] The definition of *compelling* is subjective. In my view, $\sim\mathbf{10}\sigma$ **exclusion** of the allowed range is needed by proposals likely to produce the data to settle the issue. Such proposals exist.

Future sterile neutrino searches

- Accelerator facilities
- Source experiments
- Reactor experiments

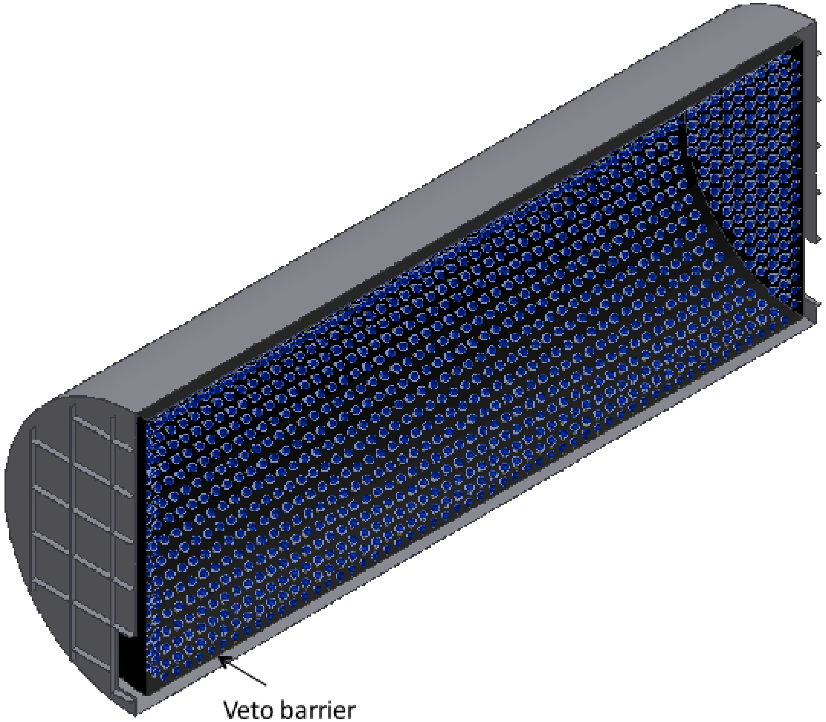
Future accelerator based projects

- π,μ **decay at rest**
  - OscSNS, JPARC MLF
- **Isotope decay at rest**
  - IsoDAR@KamLAND
- π,**K decay in flight**
  - LAr1-ND, MicroBooNE, ICARUS@FNAL
- μ **decay in flight**
  - νStorm

Future accelerator-based projects: π DAR neutrinos

Try to solve the LSND anomaly with an improved LSND-style experiment: OscSNS [The OscSNS White Paper, arXiv:1307.7097]

- Proposed experiment using the 1.4-MW 1-GeV proton beam at the Oak Ridge Spallation Neutron Source.
- 2.2×10^{23} protons/yr $\rightarrow$ 2.8×10^{22} ν/yr
- Short-pulses (695 ns) $\rightarrow$ reduced cosmic-ray bkg and to separate neutrinos from π^+ and μ^+ decay.
- Cylindrical detector 60 m away from the beam stop, filled with 886 tonnes (450 tonnes fiducial) mineral oil and instrumented with 350 8-inch photomultiplier tubes (25% coverage).

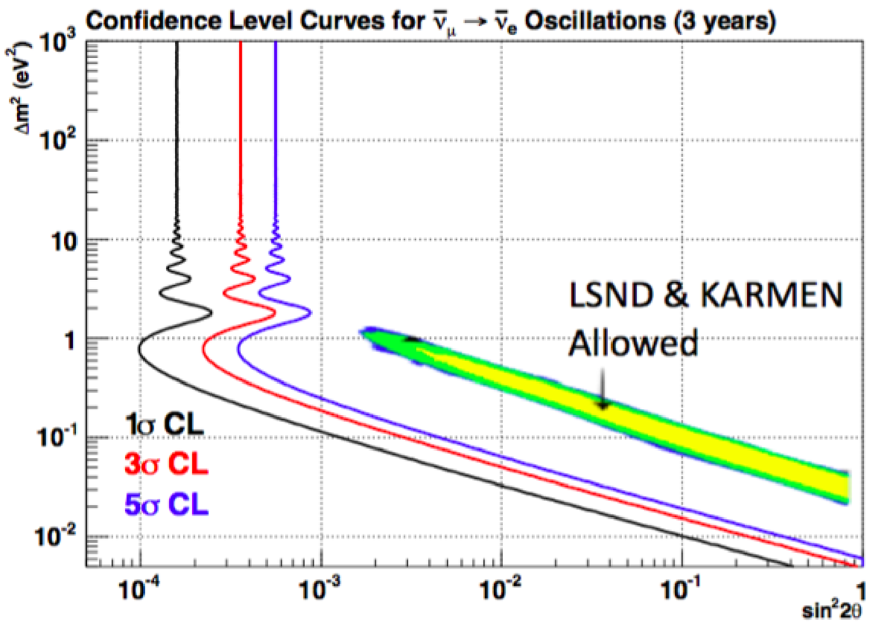


Similar experiment is being proposed at J-PARC (Japan) [Harada et al, arXiv:1310.1437]

Future accelerator-based projects: π DAR neutrinos

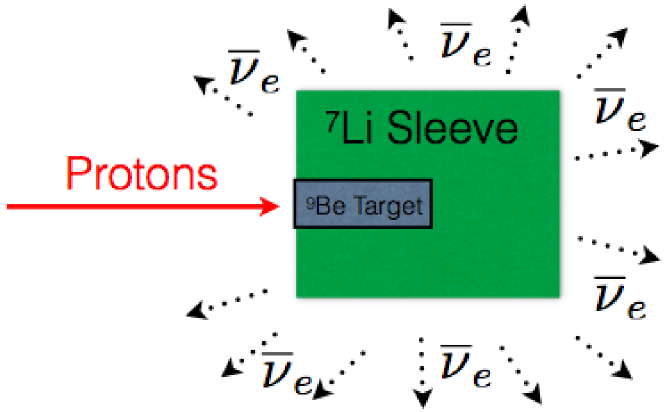
Try to solve the LSND anomaly with an improved LSND-style experiment: OscSNS [The OscSNS White Paper, arXiv:1307.7097]

- $\bar{\nu}_\mu \to \bar{\nu}_e$
  Prompt e^+ signal ($\bar{\nu}_e + p \to e^+ + n$) followed by a correlated signal from n capture ($n + p \to d + \gamma$ (2.2 eV))
- $\nu_\mu \to \nu_e$
  Monoenergetic 12.5 MeV e^-
  ($\nu_e +^{12} C \to e^- +^{12} N$) followed by e^+
  from the β-decay of ^{12}N.
- ν_μ **disappearance**
  15.11 MeV γ from $\nu_\mu C \to \nu_\mu C^*$
- ν_e **disappearance**
  $\nu_e +^{12} C \to e^- +^{12} N$ followed by e^+
  from the β-decay of ^{12}N.



Future accelerator-based projects: Isotope DAR neutrinos

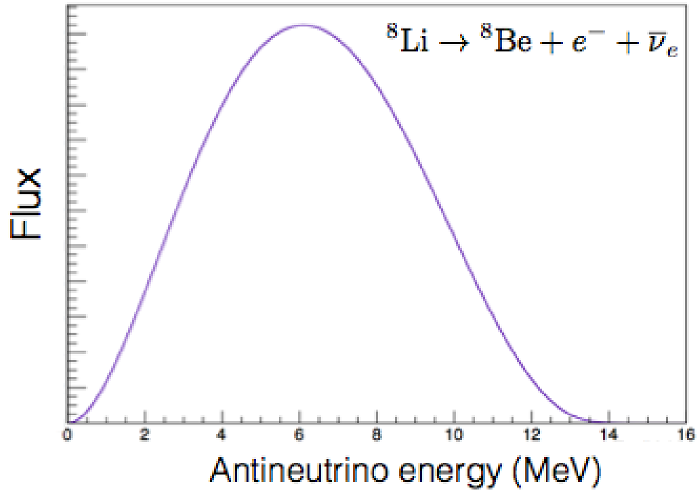
IsoDAR experiment:
Injector cyclotron setup + kton-scale scintillator-based detector

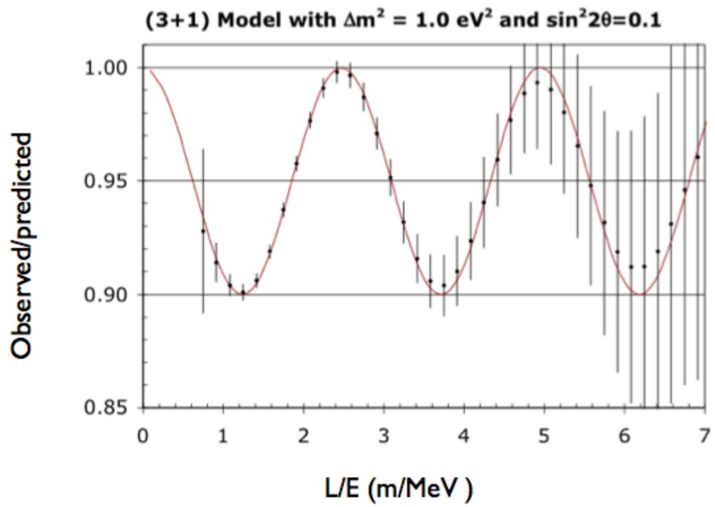


$$p + {}^9\mathrm{Be} \to {}^8\mathrm{Li} + 2p$$

$$p + {}^9\mathrm{Be} \to {}^9\mathrm{B} + n$$
$$n + {}^7\mathrm{Li} \to {}^8\mathrm{Li} + \gamma$$

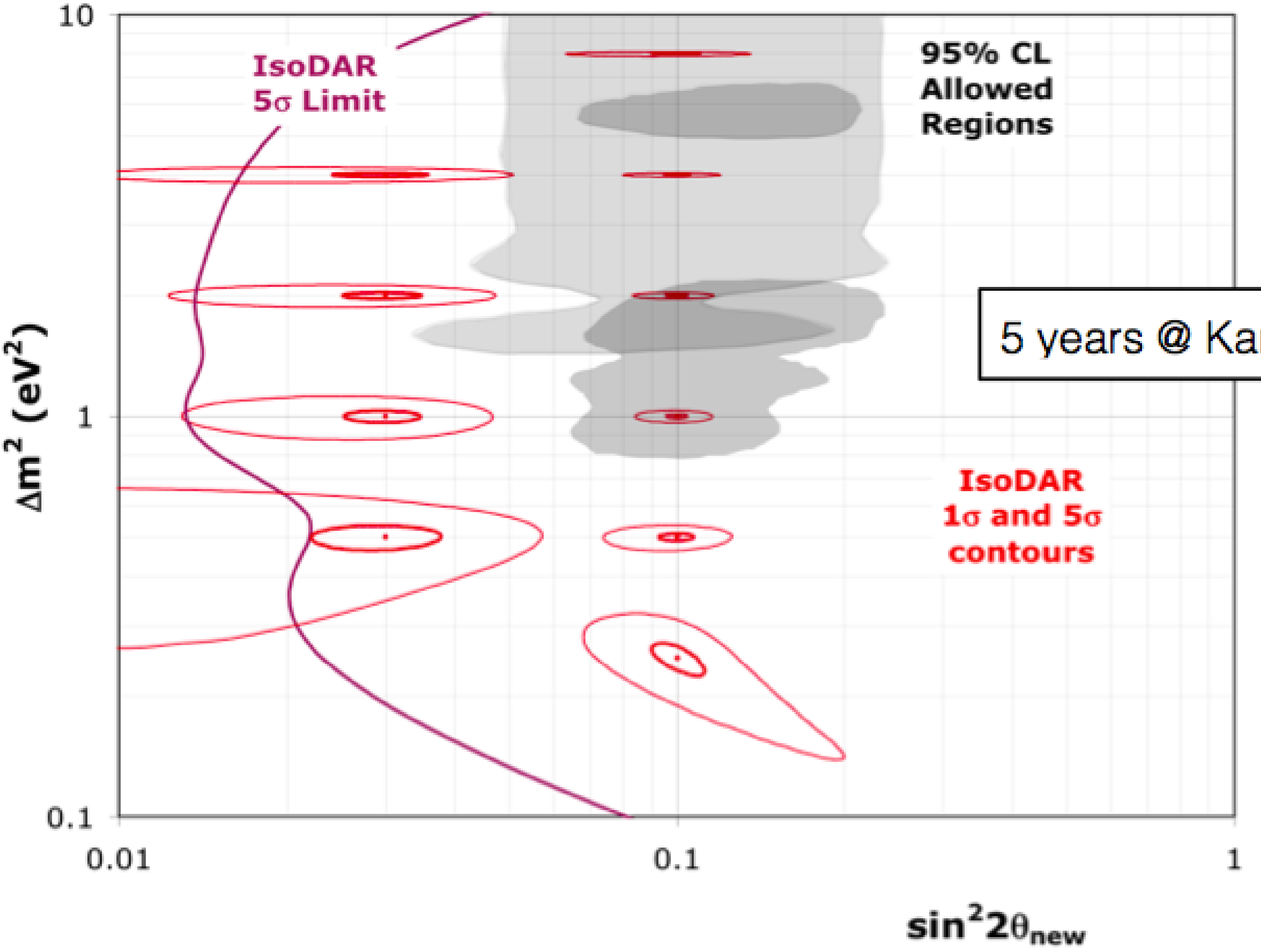
$$^8\mathrm{Li} \to {}^8\mathrm{Be} + e^- + \overline{\nu}_e$$





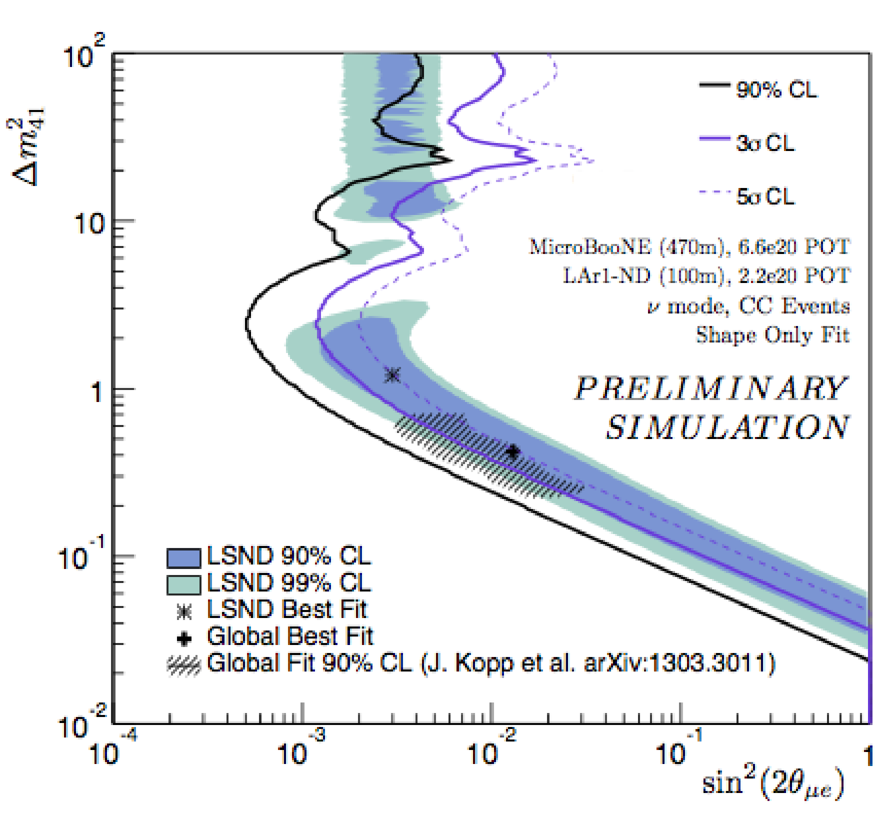
[adapted from J.Spitz, Neutrino 2014, Boston]

Future accelerator-based projects: Isotope DAR neutrinos



5 years @ KamLAND

Future accelerator-based projects: π,K DIF neutrinos



[Camilleri, CETUP*14]

LAr1-ND [FERMILAB-PROPOSAL-1053]

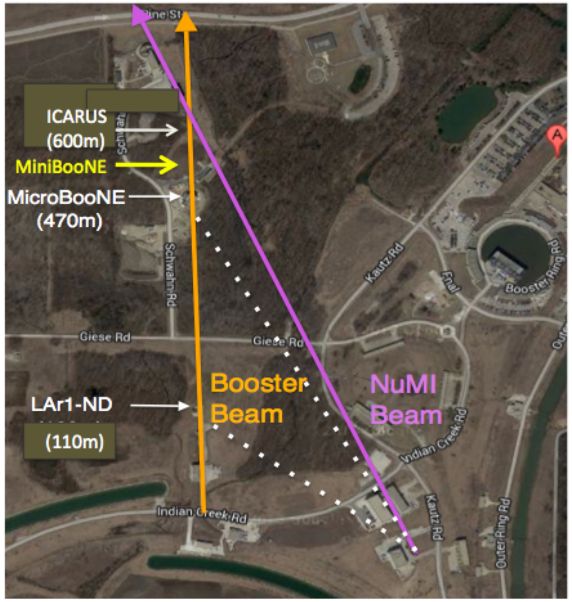
MicroBooNE [FERMILAB-PROPOSAL-0974]

and refurbished ICARUS in the Booster neutrino beam

ICARUS: L=600m
476t Active volume TPC

MicroBooNE: L=470m
89t Active volume TPC

LAr1-ND: L=110m
82t Active volume TPC

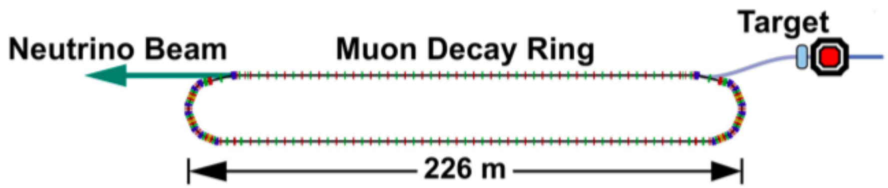


Similar proposal in Europe using the CERN SPS beam [J.Phys.Conf.Ser. 460 (2013) 012014]

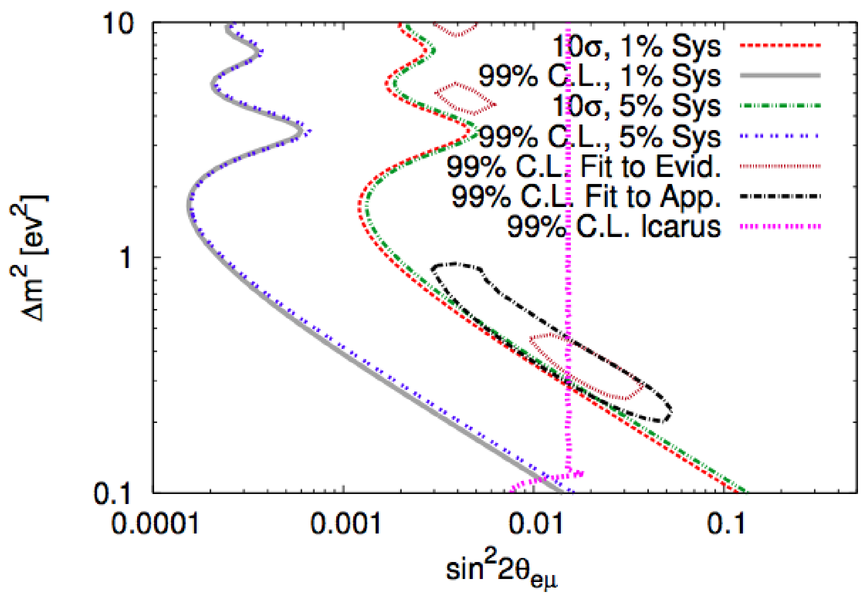
Future accelerator-based projects: μ DIF neutrinos

Entry-level neutrino factory
[FERMILAB-PROPOSAL-1028]:

- ν_e and ν_μ beam from the decay of a stored muon beam
- Injecting 5 GeV pions into a muon storage ring
- Straight section of the ring is 185 m
- Pions that do not decay prior to first bent are removed
- Ring circulated muons with momenta of 3.8 GeV/c ($\pm$10% momentum acceptance)
- 2×10^{18} usefull muon decays (in the straight towards the detector) per 10^{21} protons on target.



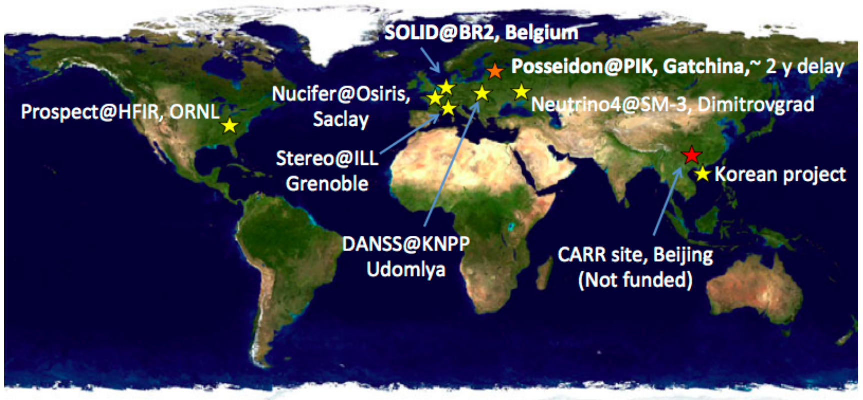
10σ sensitivity to the LSND+MiniBooNE anomaly
"with conservative systematics"



[Phys.Rev. D89 (2014) 071301]

Future reactor projects

- New experiments, at very short baselines, close to a single (research) reactor core
- Challenging environment: Very short baseline (reactor backgrounds) and shallow depths (cosmic backgrounds).



	Gd	^{6}Li	Highly Segmented	Moving detector	2 det.
Nucifer (FRA)	■				
Poseidon (RU)	■				
Stéréo (FRA)	■			■	
Neutrino 4 (RU)	■			■	
Hanaro (KO)	◣	◥	■	■	
DANSS (RU)	■		■		
Prospect (USA)	◣	◥	■		■
SoLid (UK)		■	■		

	P_{th} (MW)	M_{target} (tons)	L (m)	Depth (m.w.e.)
Nucifer (FRA)	70	0.8	7	13
Poseidon (RU)	100	~ 3	5-8	~ 15
Stéréo (FRA)	57	1.75	8.8-11.2	18
Neutrino 4 (RU)	100	1.5	6-12	~ 10
Hanaro (KO)	30-2800	~ 1	6	few
DANSS (RU)	3000	0.9	9.7-12.2	50
Prospect (USA)	85	1 & 10	7-18	few
SoLid (UK)	45-80	2.9	6-8	10

[schematics from David Lhuillier, Neutrino 2014 conference, Boston]

Future neutrino source projects

Technique	Detector	Sources	Reaction	Activity	Reference
Large Liquid scintillator detectors	SOX (Borexino)	^{51}Cr,	$\nu+e \rightarrow \nu+e$	10MCi	*JHEP08(2013)038,*
		^{144}Ce-^{144}Pr	$\nu+p \rightarrow e^{+}+n$	100kCi	*Phys. Rev. Lett. 107, 201801 (2011)*
	KamLAND	^{8}Li (ISODAR)	$\bar{\nu}+p \rightarrow e^{+}+n$	8.2 x 10^{14} ν/sec	*arXiV:1205.4419, arXiV:1310.3857*
		^{144}Ce(CeLAND)	$\bar{\nu}+p \rightarrow e^{+}+n$	100kCi	arXiv:1312.0896
	Daya-Bay	^{144}Ce-^{144}Pr	$\bar{\nu}+p \rightarrow e^{+}+n$	500kCi	*arXiV:1109.6036*
	LENS	^{51}Cr	$\nu+^{115}In \rightarrow ^{115}Sn^{*}+e$	10MCi	*Phys.Rev.D75 093006(2007)*
	JUNO	^{8}Li (ISODAR)	$\bar{\nu}+p \rightarrow e^{+}+n$	8.2 x 10^{14} ν/sec	*arXiV:1310.3857*
Radiochemical	BEST	^{51}Cr	$\nu+^{70}Ga \rightarrow ^{71}Ge+e$	3MCi	arXiV:1204.5379
Bolometers	Richochet	^{37}Ar	$\nu+N \rightarrow \nu+N$	5MCi	Phys. Rev. D85, 013009, (2012)

[Barbara Caccianiga, Neutrino 2014 conference, Boston]

Summary

- I gave you a rushed tour of several experimental results that helped build the current picture of 3-flavour neutrino oscillations
  - and several results that threaten to prove that picture inadequate.
- Historically, neutrino physics was led by the experiment and it was **full of surprises**
  - The neutrino is just the weirdest particle there is.
- I am absolutely certain that there are more neutrino surprises waiting to be discovered.
- Neutrino experiments with tremendous physics sensitivity are planned for the near future
- **So let's be surprised again!**