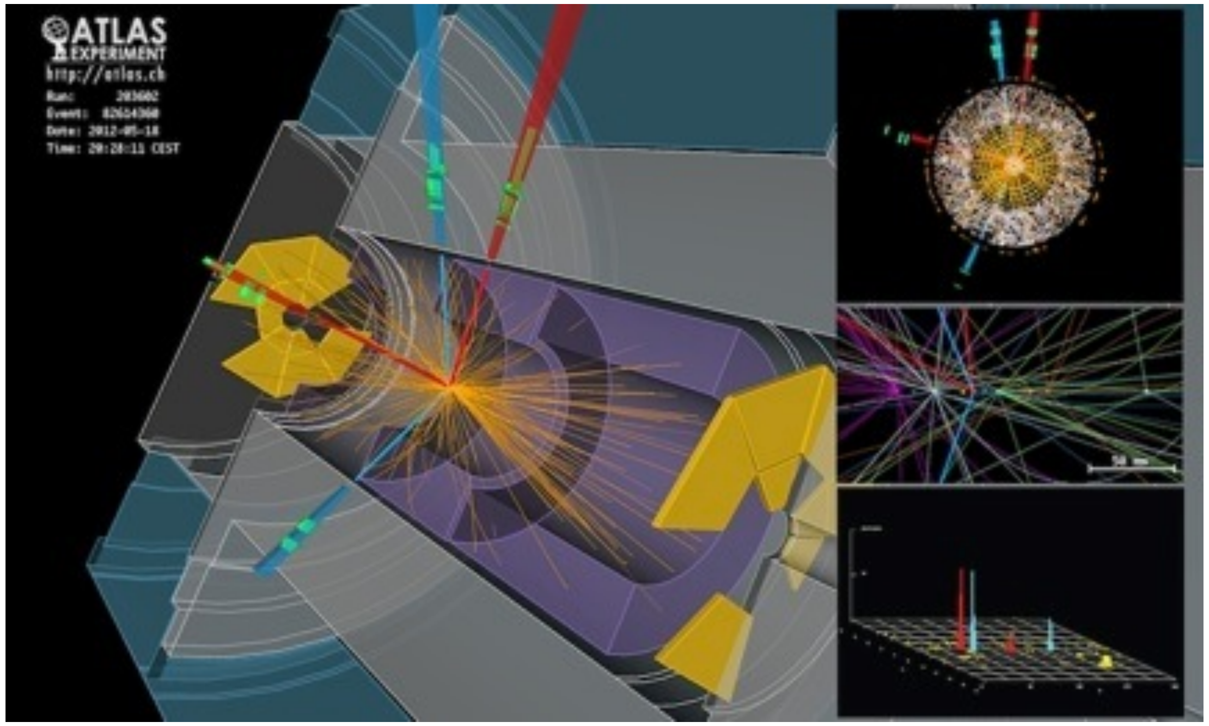
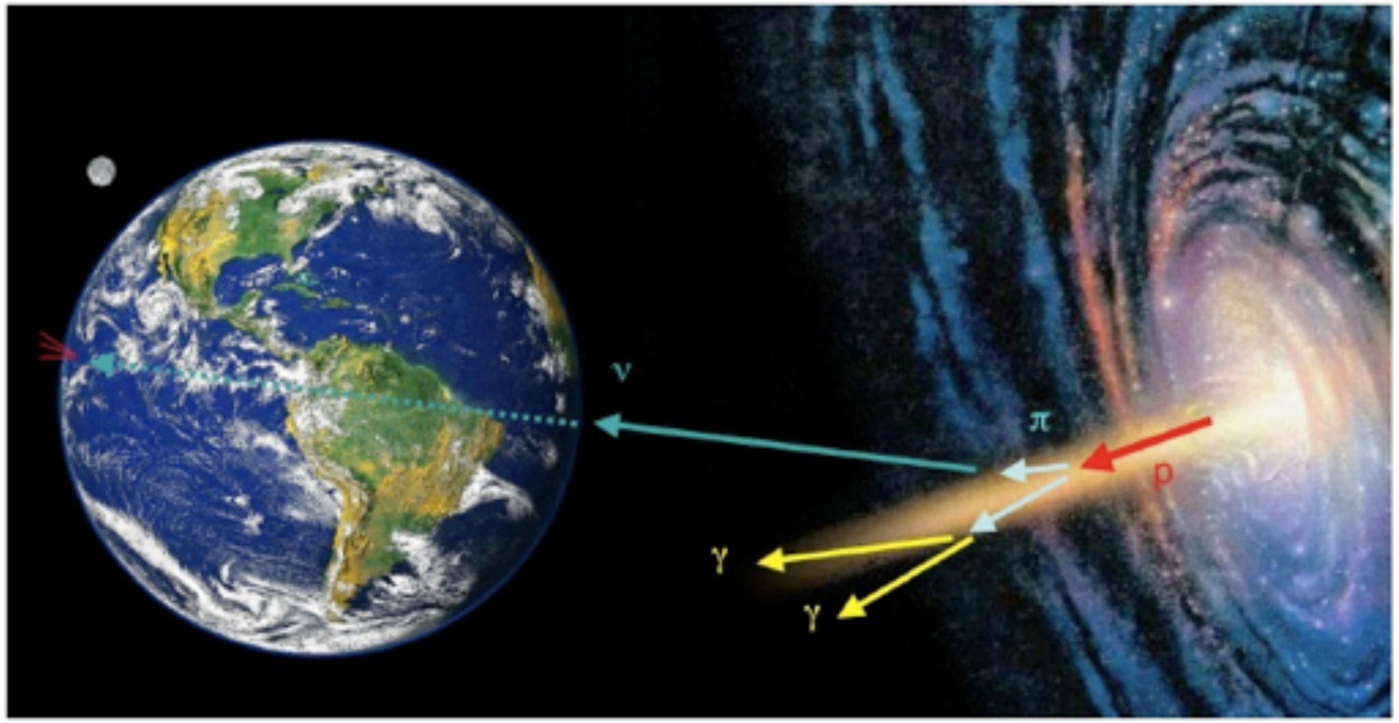
Particle Physics with
Accelerators and Natural Sources





08. Neutrino Oscillations with Manmade Sources

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Overview

- Neutrino Oscillation Recap
- Neutrino Experiments & Sources
- Reactor Experiments
- Accelerator Experiments
- Bonus Feature: Faster than light neutrinos?

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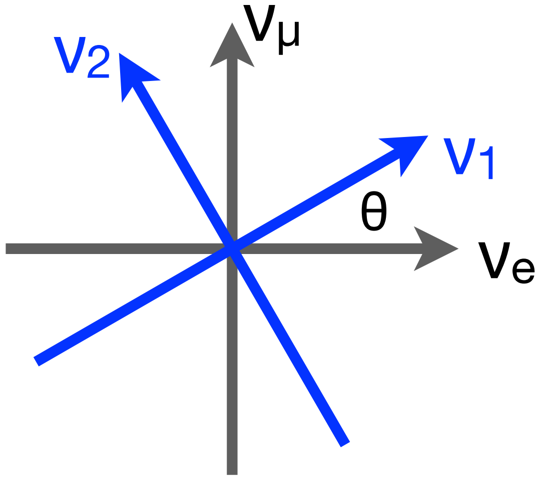
Neutrino Oscillation Intro / Recap

Neutrino Oscillation Formalism: Basics

- Neutrinos have to have mass to be able to oscillate!
  - Mass eigenstates are not the same as flavor eigenstates

- Example: A world with two neutrino types:
  - The eigenstates of the weak interaction ν_μ und ν_e are not identical to the mass eigenstates ν_1 und ν_2



$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- The eigenstates of the weak interaction ν_μ und ν_e (which we can observe and identify) are mixes of the mass eigenstates:

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

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

Neutrino Oscillation Formalism: 2 Neutrinos

- The time evolution in vacuum is given by the mass eigenstates (Schrödinger Eq):

$$|\nu_\mu(t)\rangle \;=\; -sin\theta\,(|\nu_1\rangle\; e^{-iE_1 t}) \,+\, cos\theta\,(|\nu_2\rangle\; e^{-iE_2 t})$$

$$E_i \;=\; \sqrt{p^2 + m_i^2} \;\approx\; p + \frac{m_i^2}{2p} \;\approx\; E + \frac{m_i^2}{2E}$$

- If the two mass eigenstates have different masses the relative composition changes over time, a ν_μ can transform into a ν_e!
- The oscillation property is:

$$P(\nu_\mu \rightarrow \nu_e) \;=\; |\,\langle \nu_e | \nu_\mu(t)\rangle\,|^2$$

- The transition probability as a function of distance and neutrino energy is:

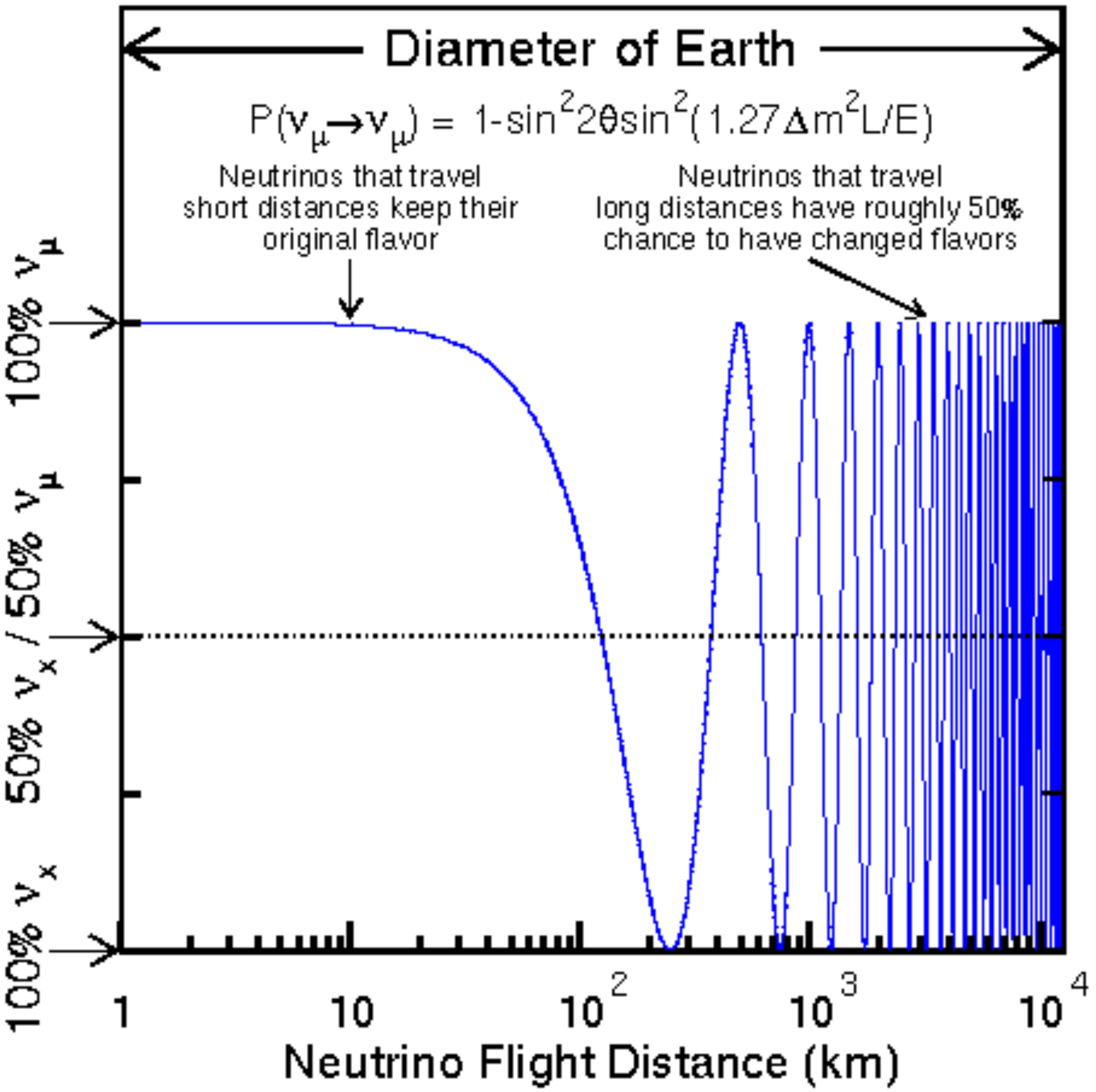
$$P(\nu_\mu \leftrightarrow \nu_e) \;=\; sin^2 2\theta\, sin^2\left(\frac{\Delta m^2 L}{4E}\right) \;=\; sin^2 2\theta\, sin^2\left(1.27\,\frac{\Delta m^2}{\mathrm{eV}^2}\,\frac{L/\mathrm{m}}{E/MeV}\right)$$

$$\Delta m^2 \;=\; m_1^2 - m_2^2$$

Neutrino Oscillations: Flavor vs Distance

- Neutrino oscillations as a function of distance

$$\Delta m^2 = 0.005\,\mathrm{eV}^2\ ,\ sin^2 2\theta = 1\ ,\ E = 1\,\mathrm{GeV}$$



Oscillation length:

$$L_{osc} = \frac{4\pi \cdot E}{\Delta m^2}$$

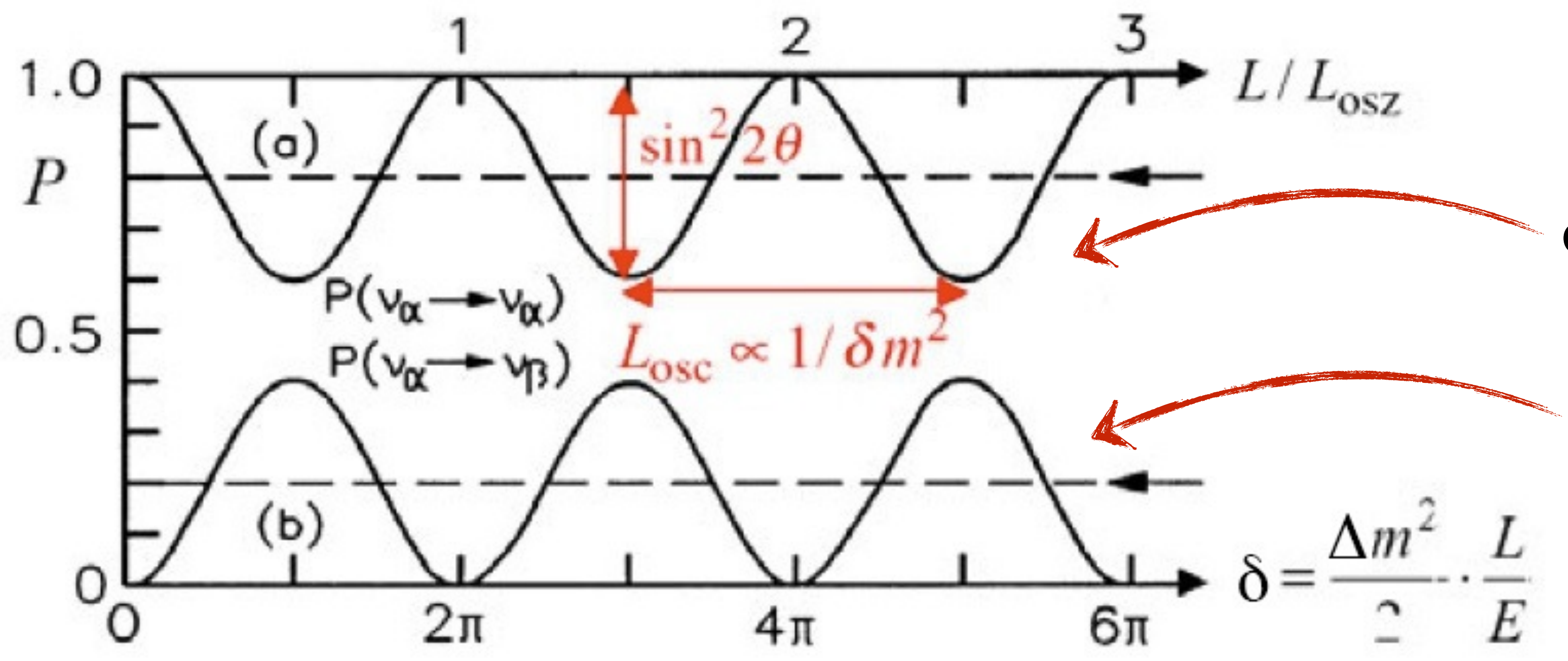
$$L_{osc}/m = \frac{2{,}5 \cdot E/MeV}{\Delta m^2/eV}$$

here:

$$L_{osc} = 500\ km$$

Neutrino Oscillations: Mixing Angle

- The influence of the mixing angle:



two classes of measurements:

disappearance

appearance

- The mixing angle determines the amplitude (the maximum level of transformation), the mass difference determines the speed of the oscillation

Neutrino Oscillation Formalism: The 3 ν Case

- Described by a 3 x 3 matrix (Pontecorvo-Maki-Nakagawa-Sakata-Matrix PMNS):
  - 3 angels and one CP violating phase
- analogous to the CKM matrix in the quark case

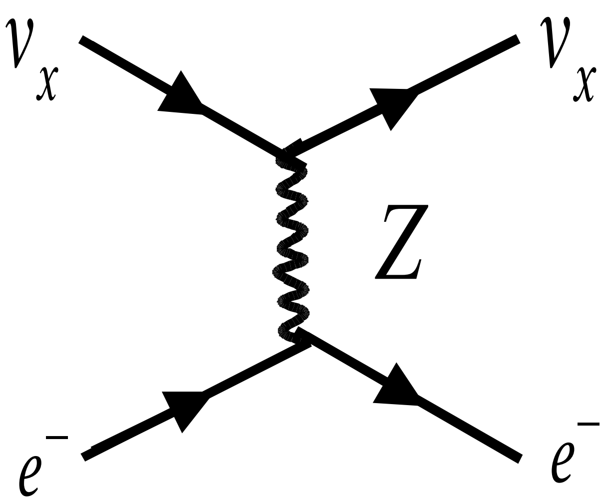
$$U_{MNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

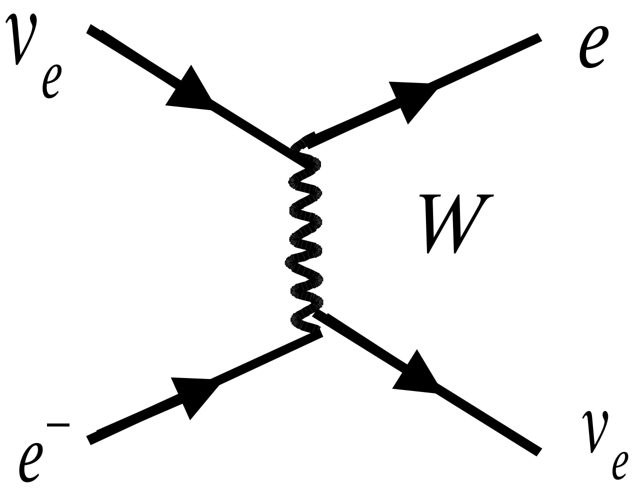
CP violation connected to Θ13

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

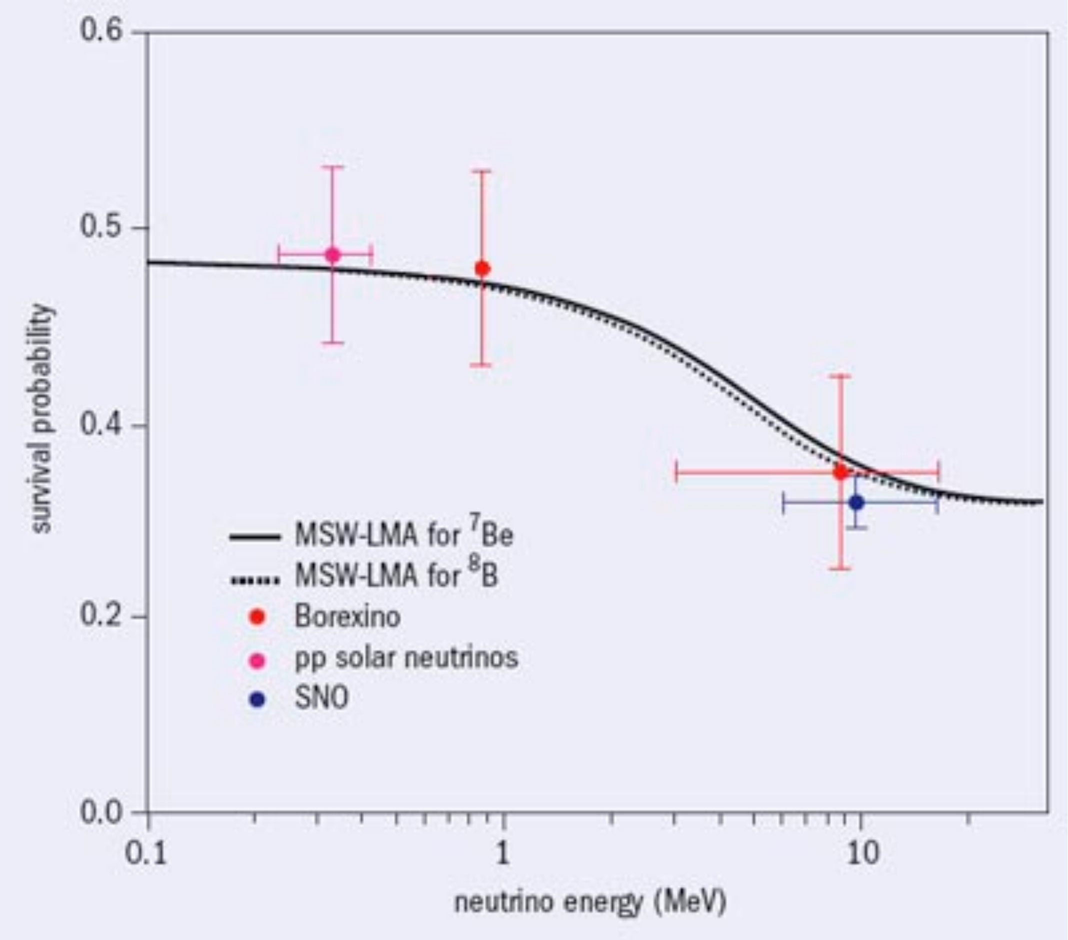
Neutrinos in Matter

- Electron neutrinos have additional reaction possibilities in matter:





- Elastic forward scattering - introduces a change in effective mass (energy dependent!), and thus changed oscillation patterns - electron neutrinos further suppressed by interaction in matter in the sun: MSW (Mikheyev, Smirnov, Wolfenstein) effect



Neutrino Oscillations: Status

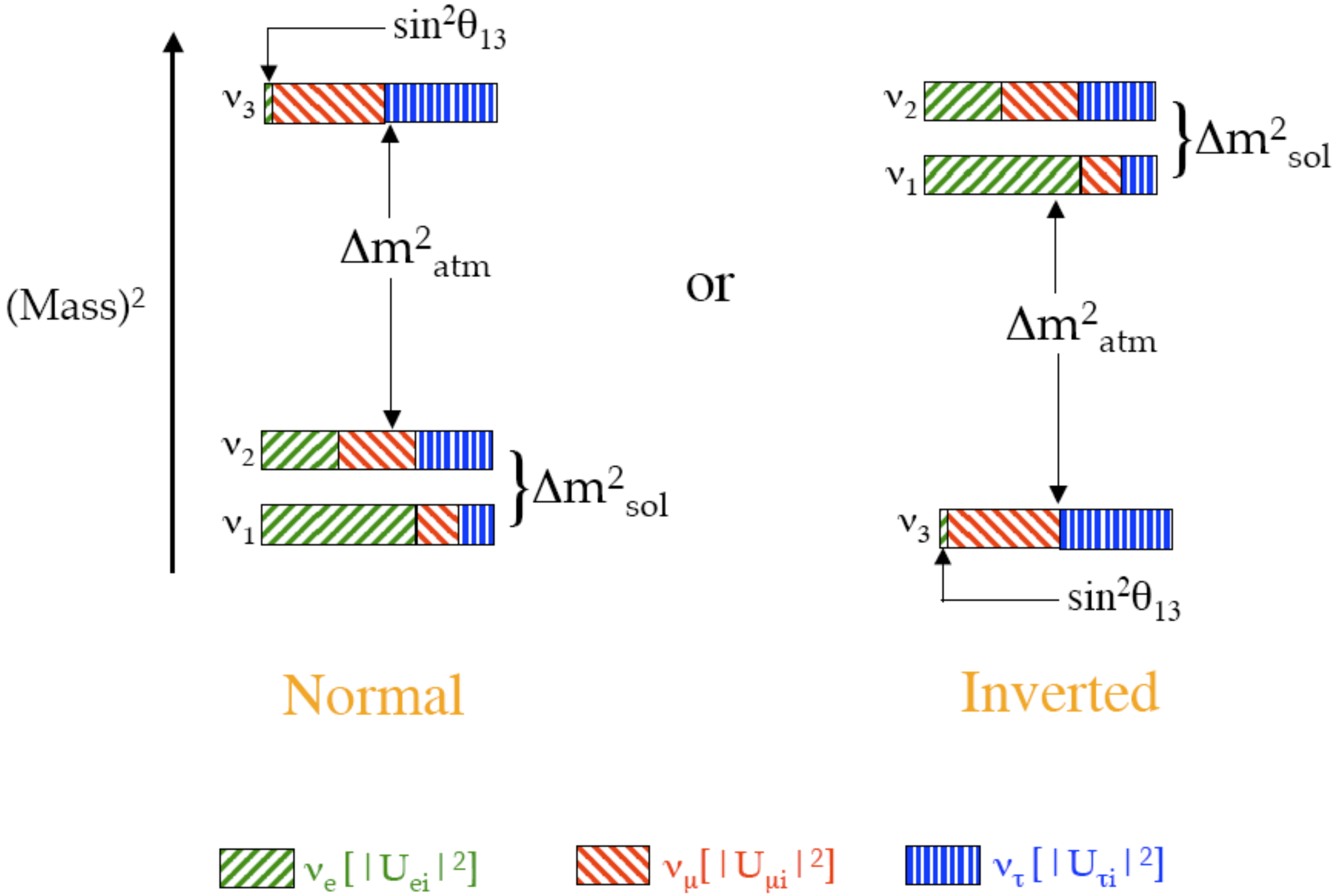
- Two distinct types of oscillations (with quite different mass splittings) have been observed:
  - Solar - disappearance of ν_e, $\Delta m^2 \sim 7.6 \times 10^{-5}$ eV^2
  - Atmospheric - disappearance of ν_μ, $\Delta m^2 \sim 2.4 \times 10^{-3}$ eV^2
- Choice of convention: small splitting between ν_1 and ν_2, big between ν_1/ν_2 and ν_3
- The data tell us: mixing between ν_1 and ν_3 is small
  - In solar oscillations, we observe $\nu_1 \rightarrow \nu_2$ oscillations, ν_1 has to have a big ν_e component
  - In atmospheric oscillations, we observe $\nu_2 \rightarrow \nu_3$, with maximal mixing: ν_3 is (almost) a 50-50 mixture of ν_τ and ν_μ

solar/ reactor

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

atmospheric/ accelerator

Neutrino Oscillations: Current Picture



Δm^2_{sol} ~ 7.6 x 10^{-5} eV^2

Δm^2_{atm} ~ 2.4 x 10^{-3} eV^2

One neutrino has to have a mass of at least ~ 0.05 eV!

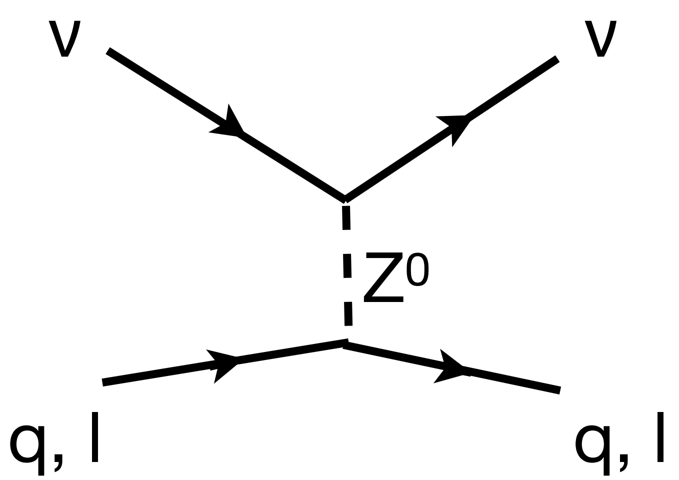
Solar and atmospheric oscillations probe two of the three mixing angles - the 3rd (smallest) needs “laboratory” experiments

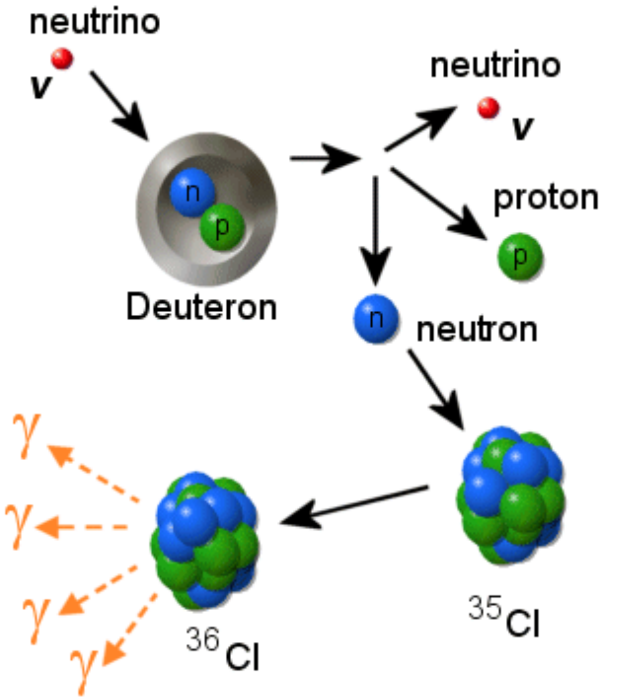
- Absolute masses and hierarchy not known yet! Two possible arrangements...

Neutrino Experiments & Sources - Overview

Neutrino Detection: Interaction Basics

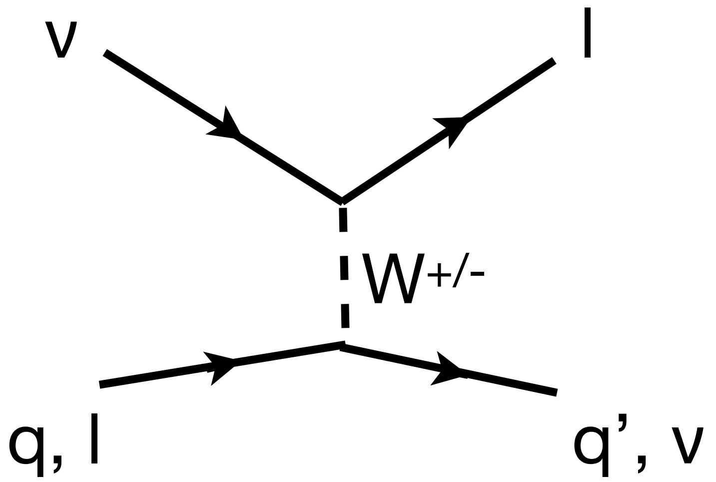
- Neutral current

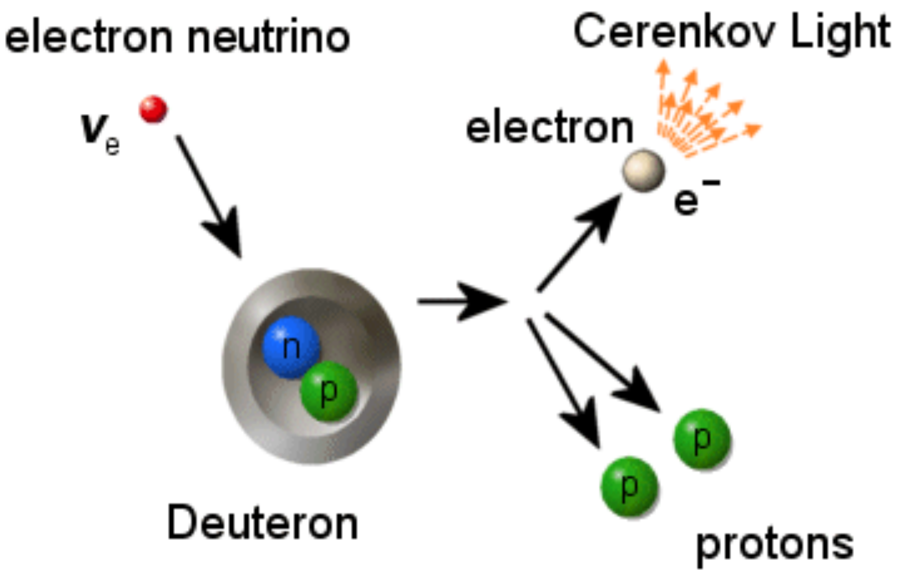




SNO

- Charged current



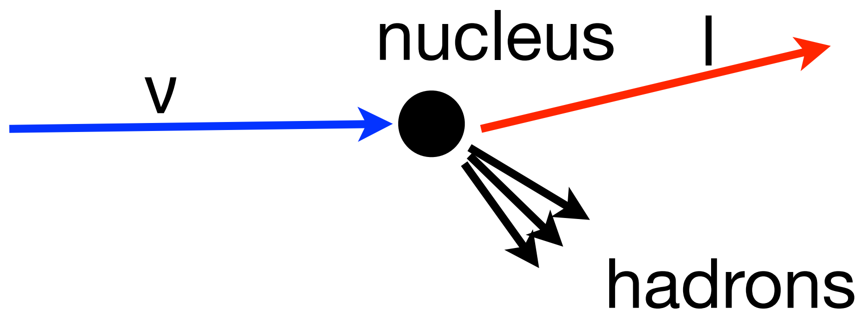


SNO

In general: neutrino cross sections are proportional to the neutrino energy!

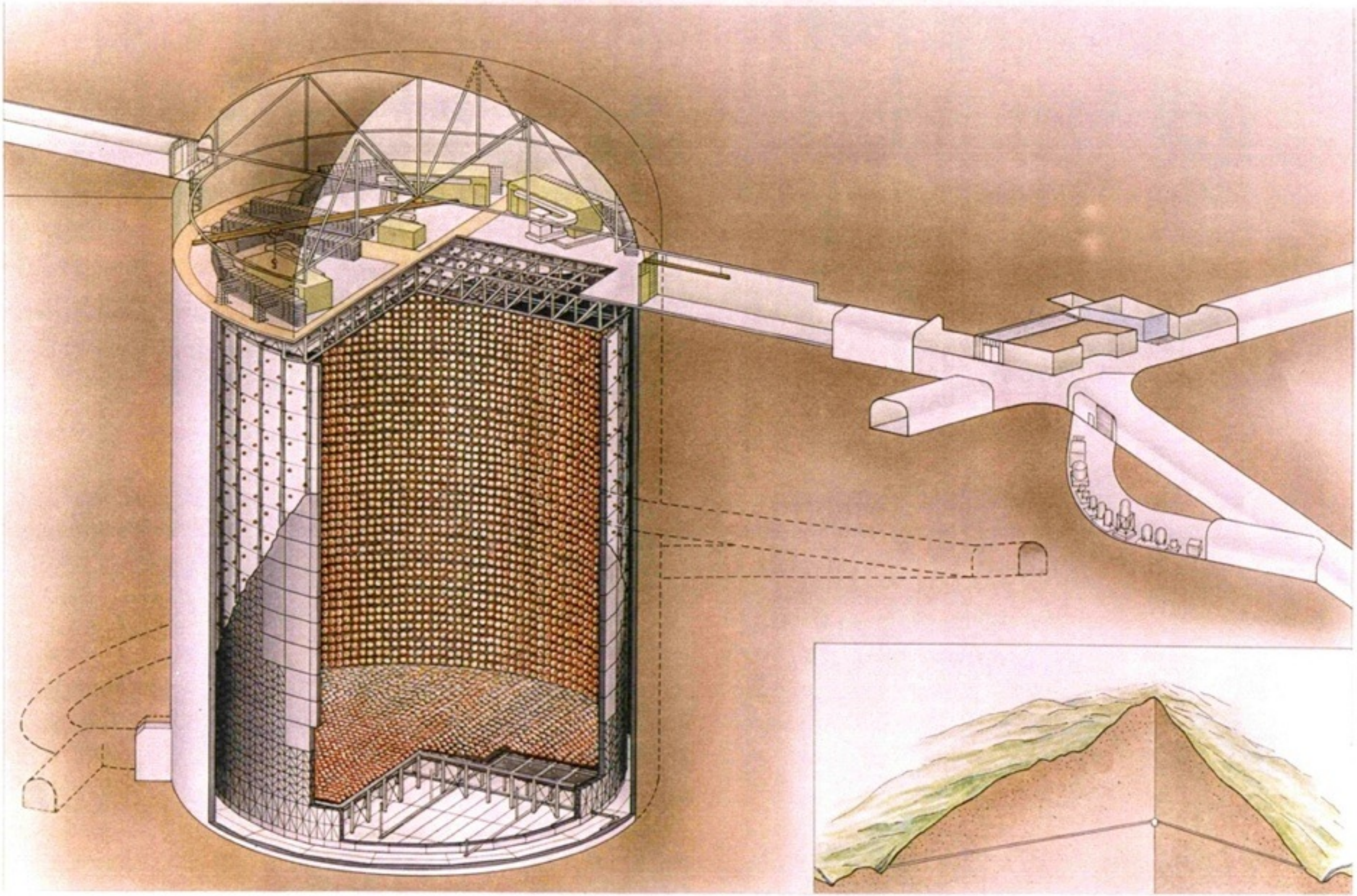
Neutrino Detectors: Example SuperKamiokande

- Neutrinos produce their corresponding leptons via charged current interaction

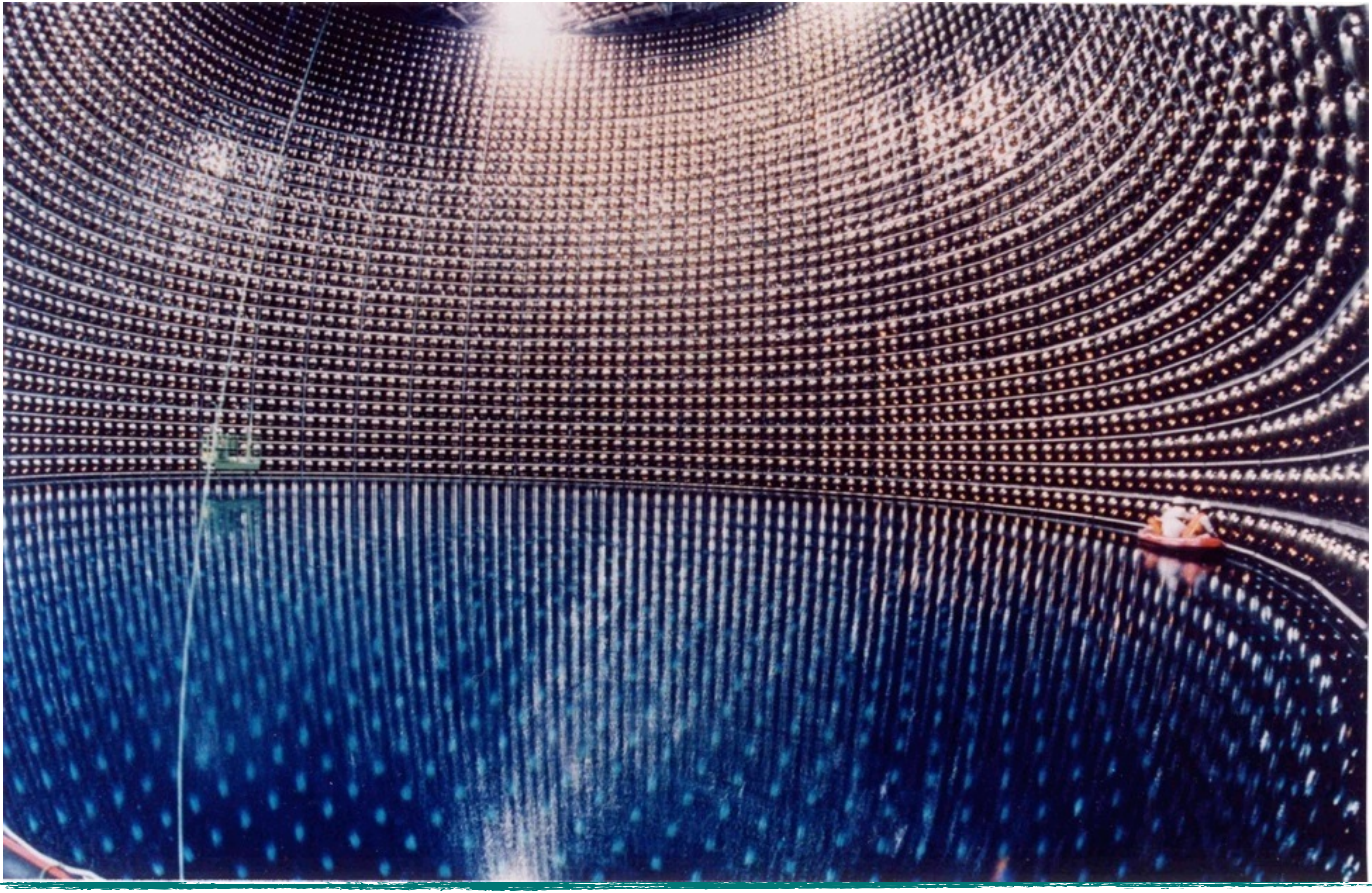


  - High energy threshold for τ - production due to high mass (1.777 GeV), thus only detection of electrons and muons
- Production of Cherenkov light of charged leptons in water (index of refraction 1.33)
  - Detection of Cherenkov light:
    - Light distribution enables particle identification (μ or e)
    - Amount of light enables measurement of track length, with that also energy and direction determination of the original neutrino

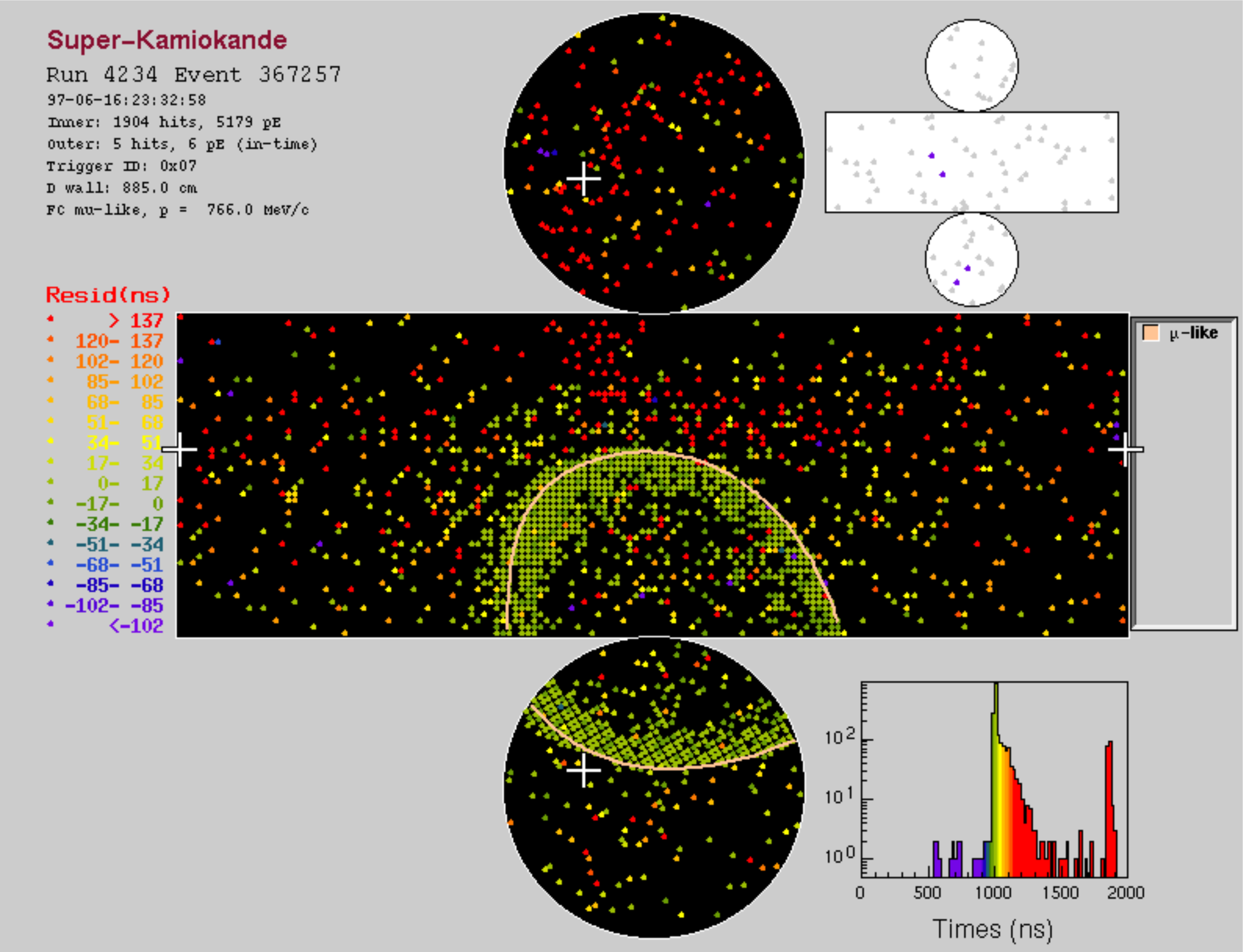
Neutrino Detectors: Example SuperKamiokande



Neutrino Detectors: Example SuperKamiokande



SuperKamiokande Measurements



Super-Kamiokande

Run 4234 Event 367257

97-06-16:23:32:58

Inner: 1904 hits, 5179 pE

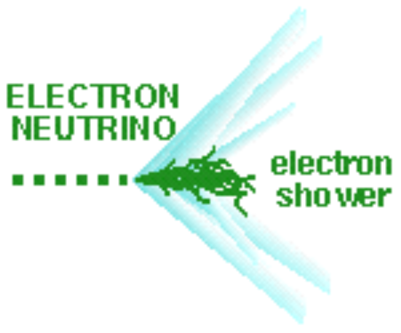
Outer: 5 hits, 6 pE (in-time)

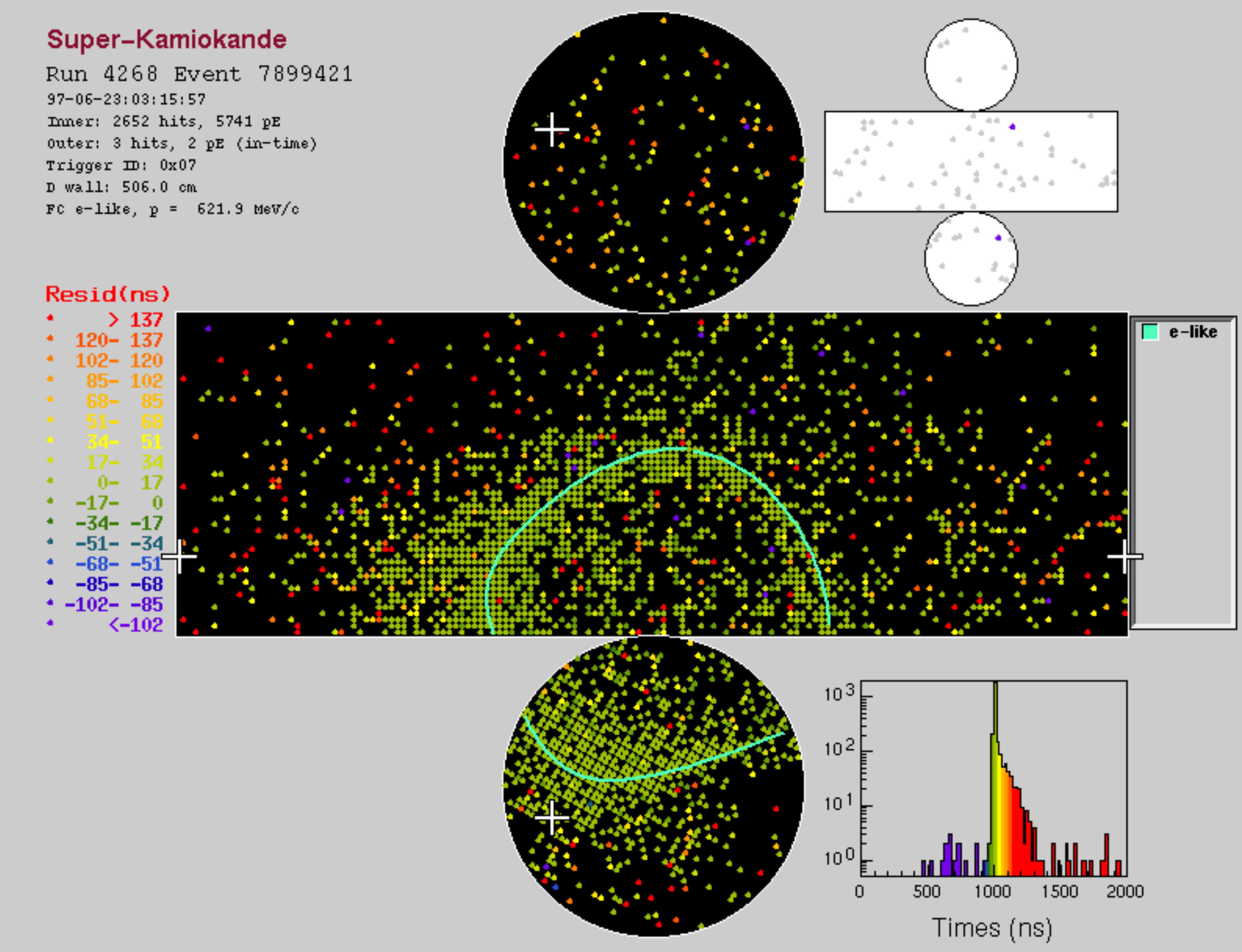
Trigger ID: 0x07

D wall: 885.0 cm

FC mu-like, p = 766.0 MeV/c

SuperKamiokande Measurements





Super-Kamiokande

Run 4268 Event 7899421

97-06-23:03:15:57

Inner: 2652 hits, 5741 pE

Outer: 3 hits, 2 pE (in-time)

Trigger ID: 0x07

D wall: 506.0 cm

FC e-like, p = 621.9 MeV/c

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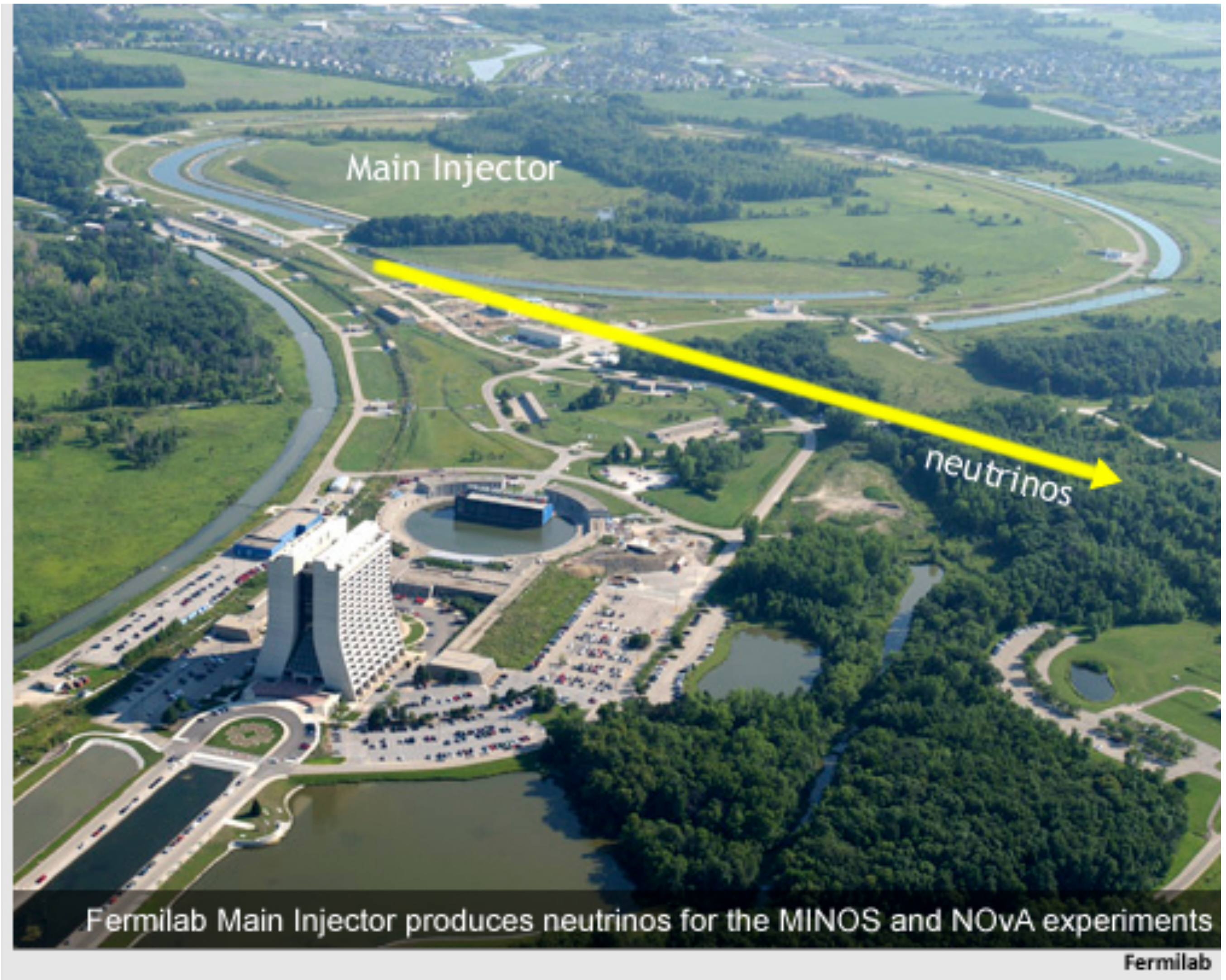
Manmade Neutrino Sources & Experiments

- Two main sources for neutrinos used for oscillation experiments:

nuclear power reactors

high energy accelerators



Fermilab Main Injector produces neutrinos for the MINOS and NOvA experiments

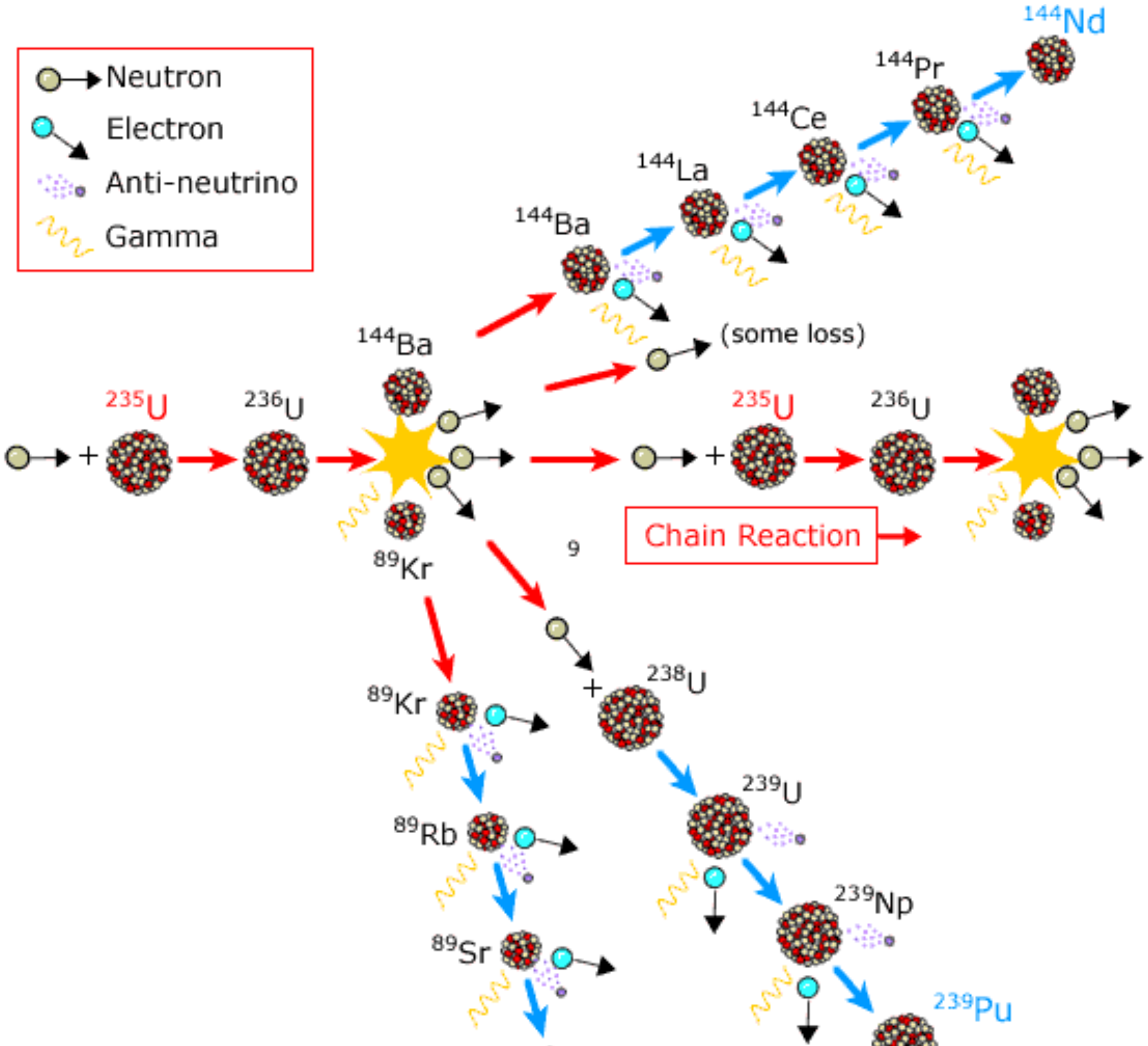
Fermilab

- Measurement strategy: Measure neutrino flux (possibly flavor - separated) at a certain distance from the source - ideally at a “near” and “far” location to observe oscillation pattern

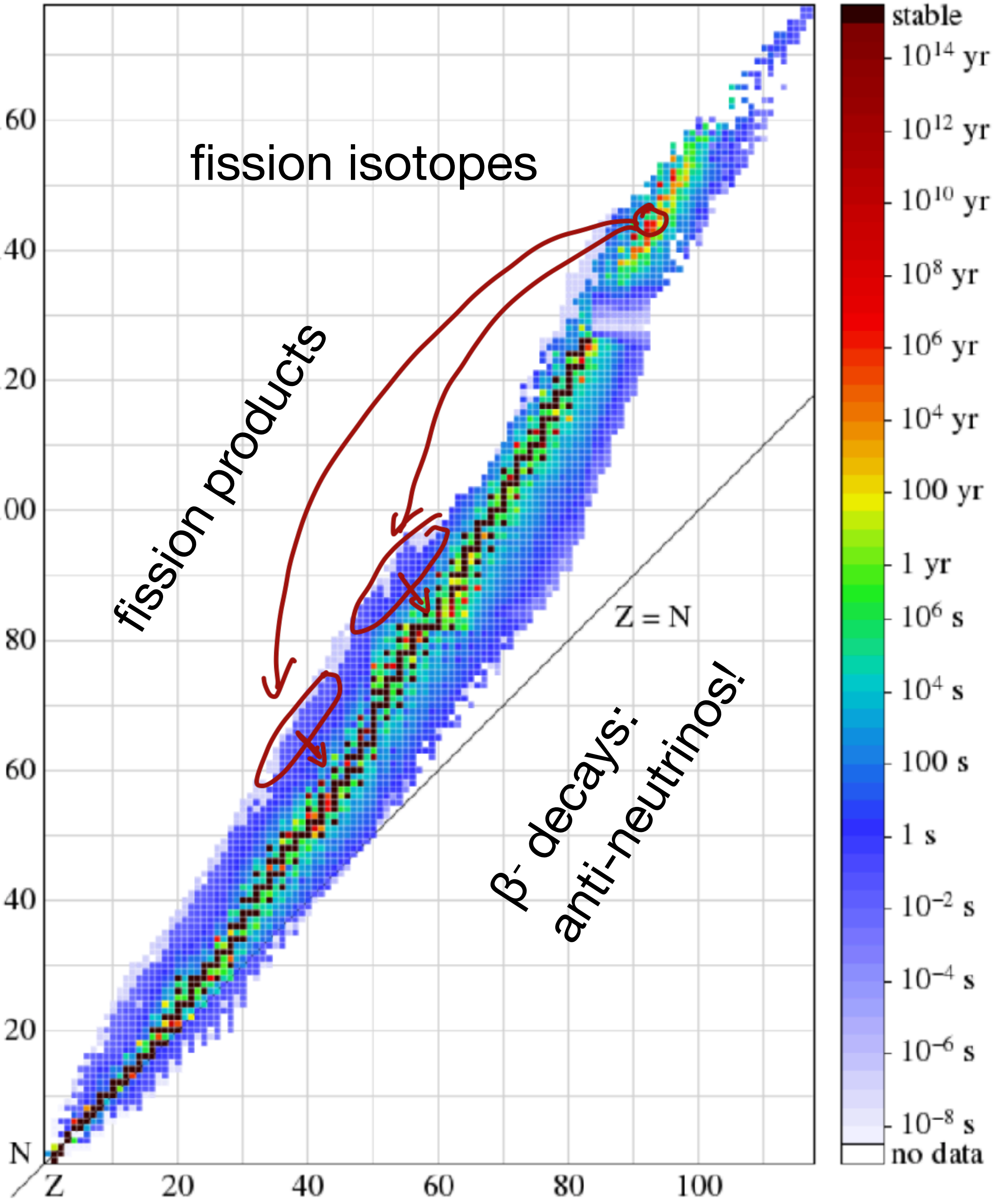
Reactor Experiments

Reactor Neutrinos

- A rich spectrum of anti-electron neutrinos - Energies in the MeV range



source: nobelprize.org

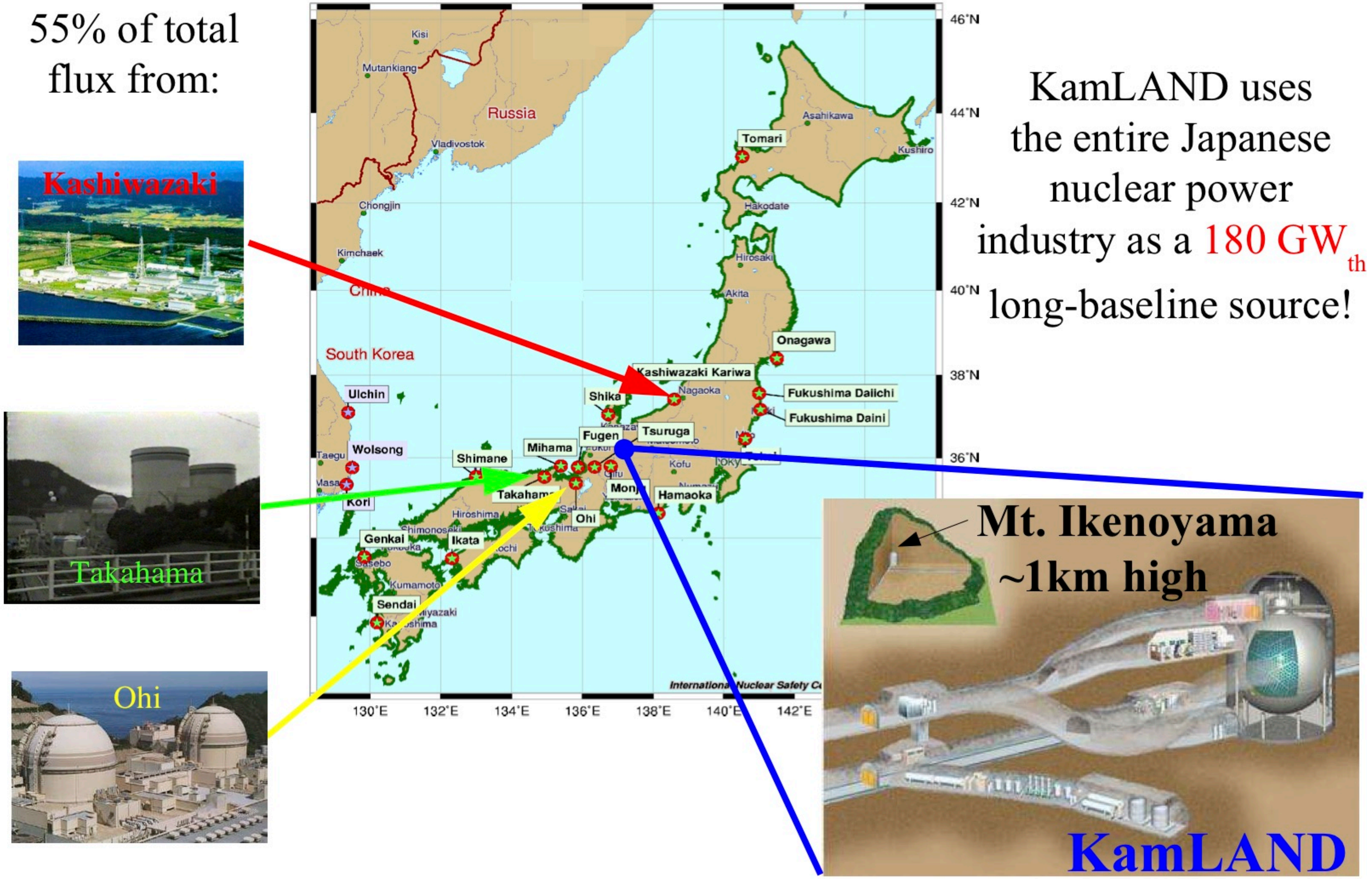


source: wikipedia.org

KamLAND: Using Reactors to prove Solar Oscillations

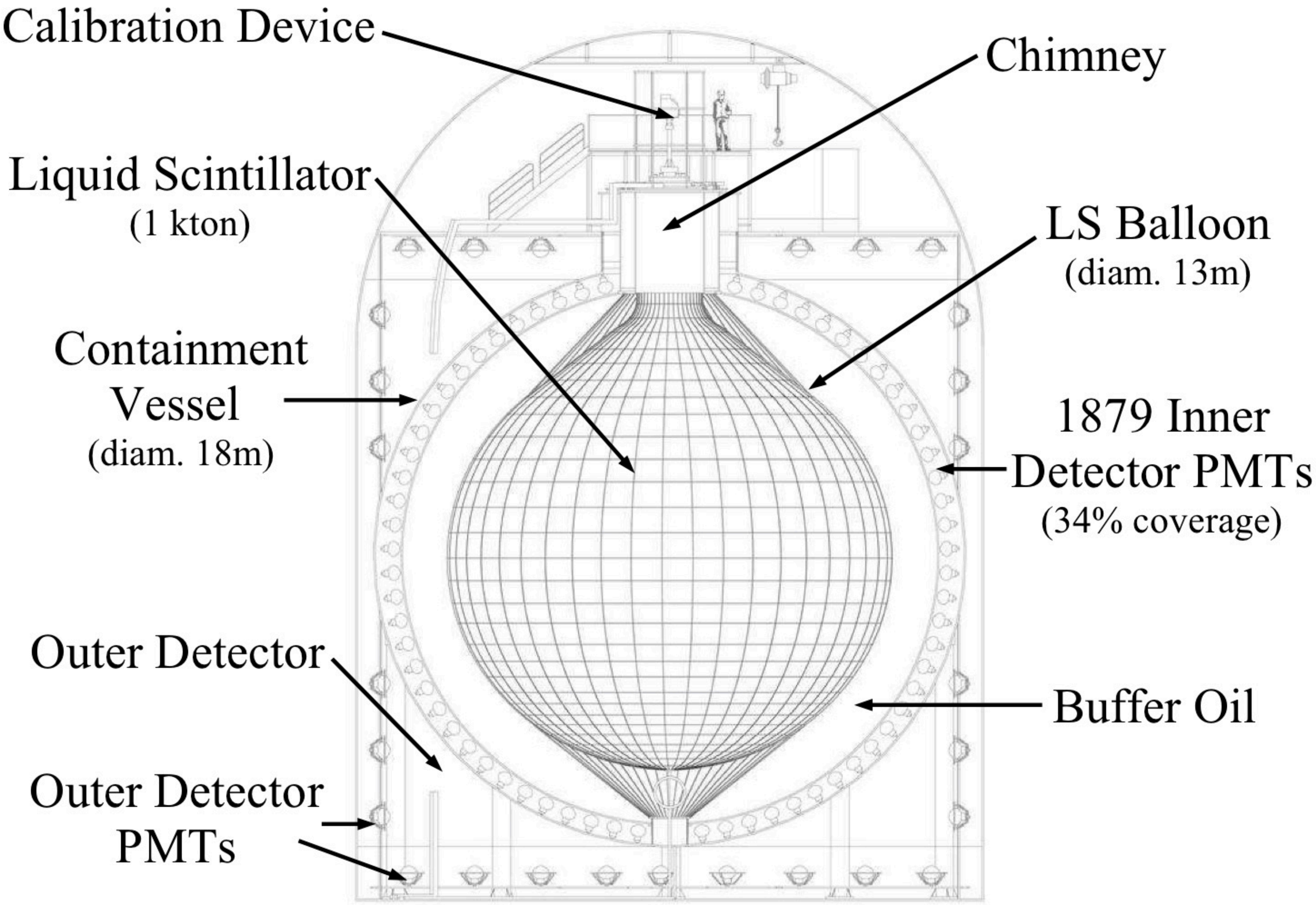
- For few MeV Neutrinos and “Large Mixing Angle” solution of solar observations: Need a baseline of ~ 100 km

55% of total flux from:



KamLAND uses the entire Japanese nuclear power industry as a 180 GW$_{\mathrm{th}}$ long-baseline source!

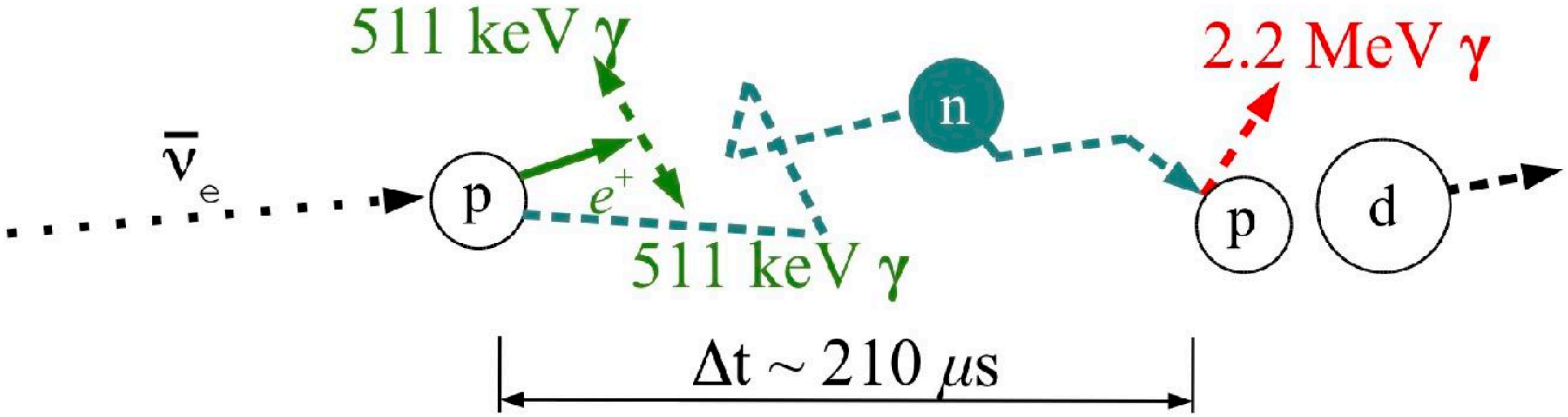
The KamLAND Experiment



The KamLAND Experiment

- Neutrino detection in KamLAND (and other reactor experiments):

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

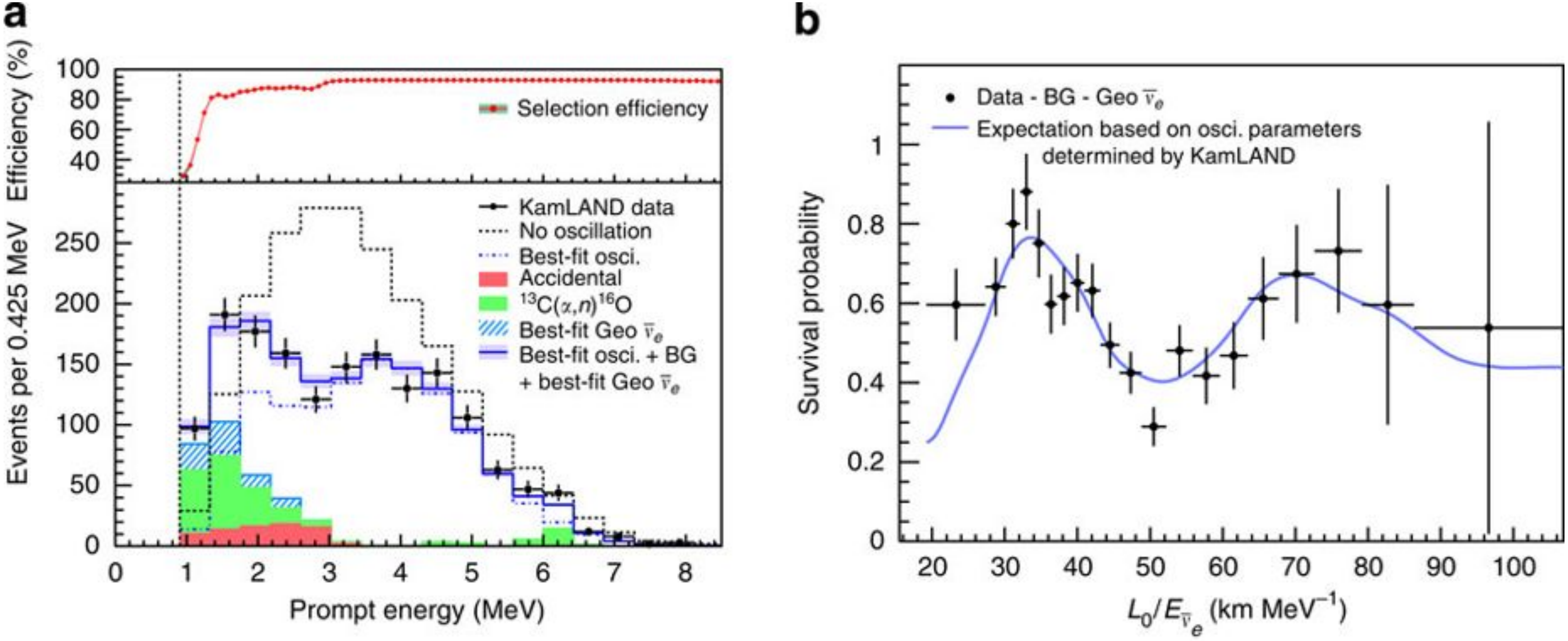


- Two-component signature:
  - Prompt signal: Ionisation energy from e^+, annihilation photons
  - Delayed signal: Photon from neutron capture

Universal feature: Only electron (anti-) neutrinos can be detected in CC reactions - Energy threshold for muon neutrinos > 105 MeV:
Reactor experiments are **disappearance experiments**

KamLAND: Proving Solar Oscillations

- Observed clear oscillation signal



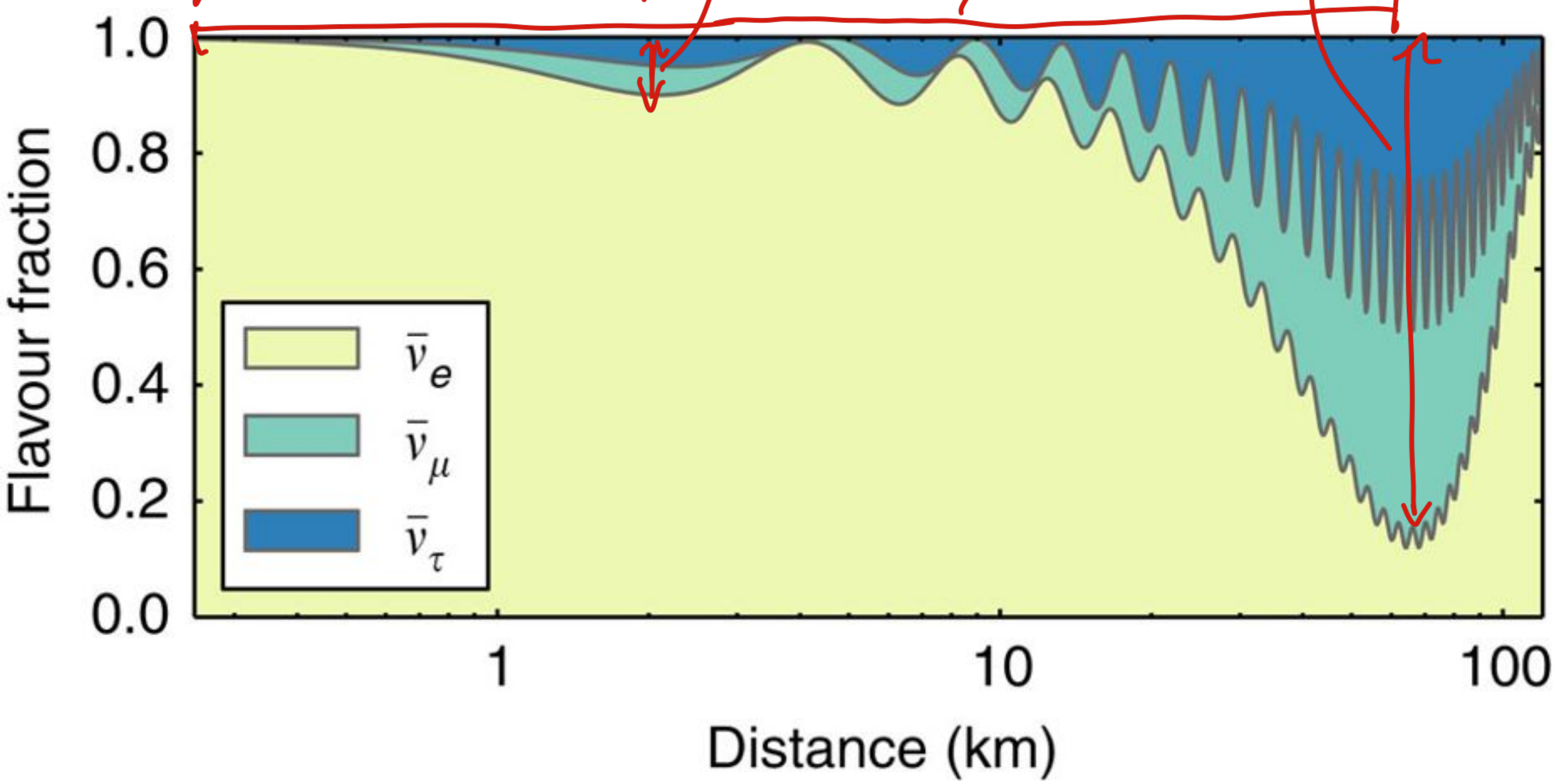
- Consistent with large mixing angle solution for solar observations

together with SNO:

$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$ (34.4 degrees) $\Delta m^2_{21} = 7.59^{+0.21}_{-0.21}\times 10^{-5}\,\mathrm{eV}^2$

Going beyond the leading Oscillation

- Oscillations of reactor (and solar) neutrinos are dominated by the 1->2 transition - but that is not all:



frequency given by Δm^2_{13}

Amplitude given by θ_{13}

frequency given by Δm^2_{12}

amplitude given by θ_{12} and MSW

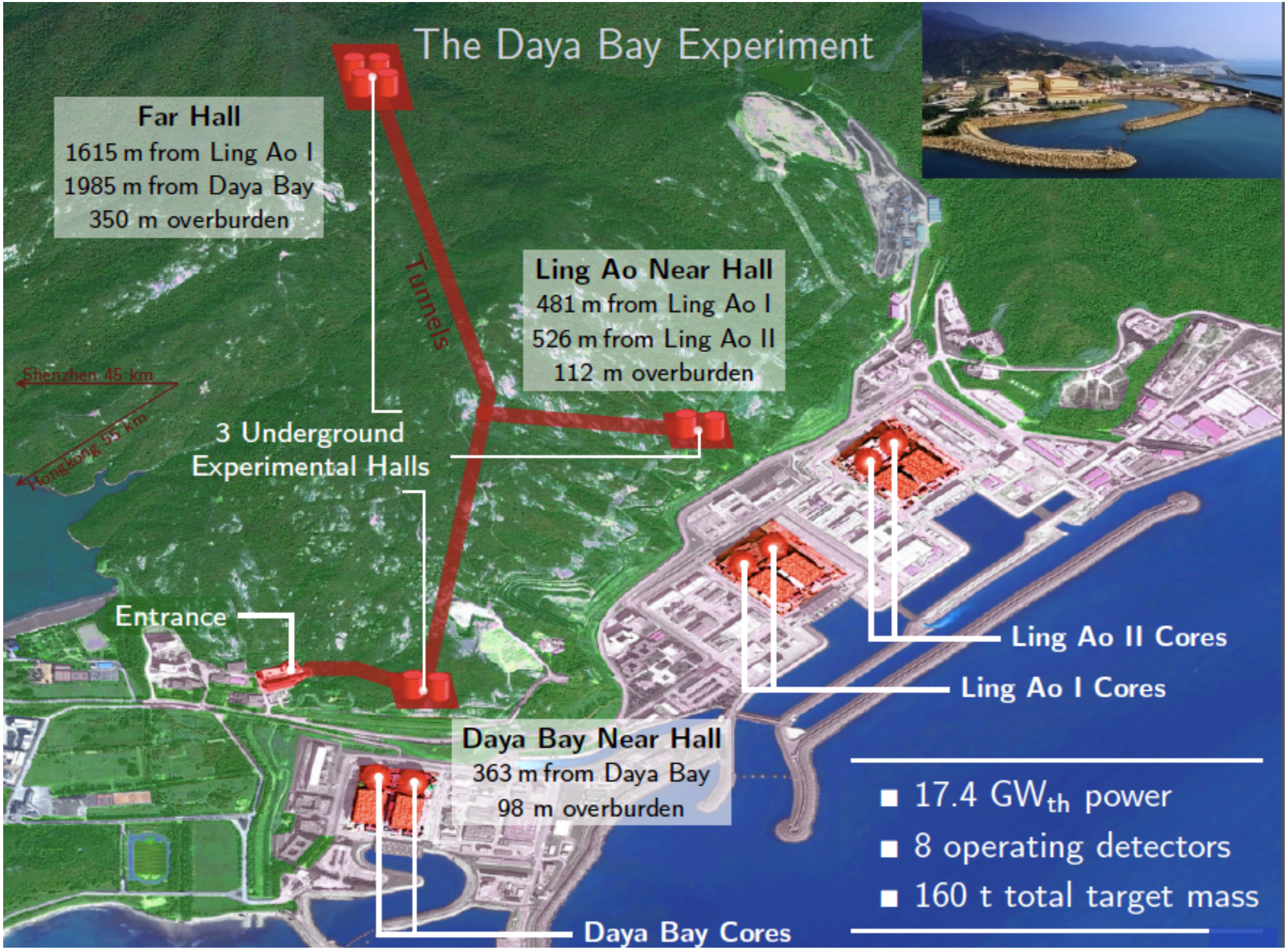
slow (dominant) oscillation: given by Δm^2_{12}

fast (sub-dominant) oscillation: given by Δm^2_{13} (~ Δm^2_{23})

~ factor 32 in oscillation speed

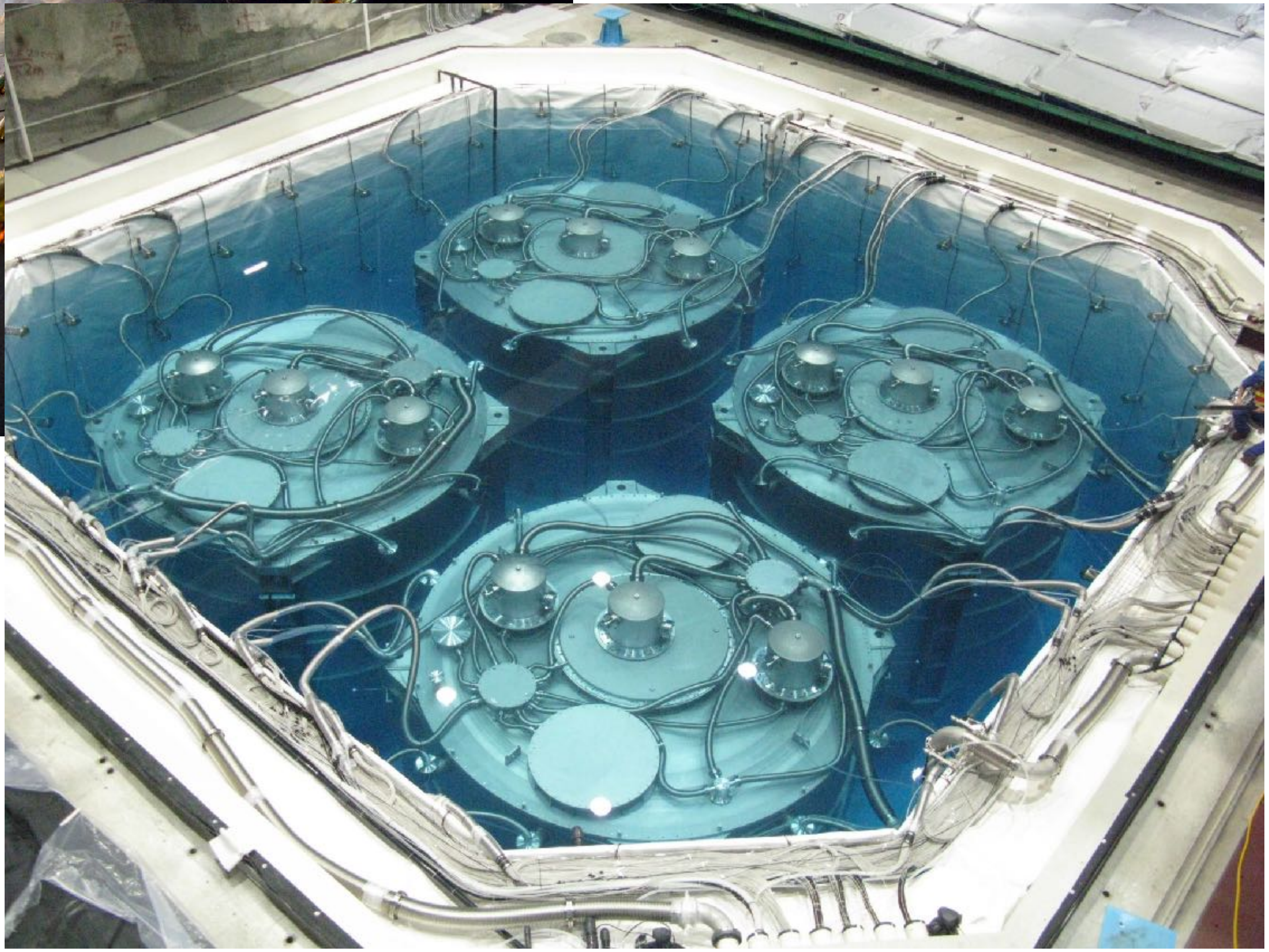
Illustrated for mono-energetic anti-electron neutrinos with E = 4 MeV

Daya Bay: Measuring Θ_{13}



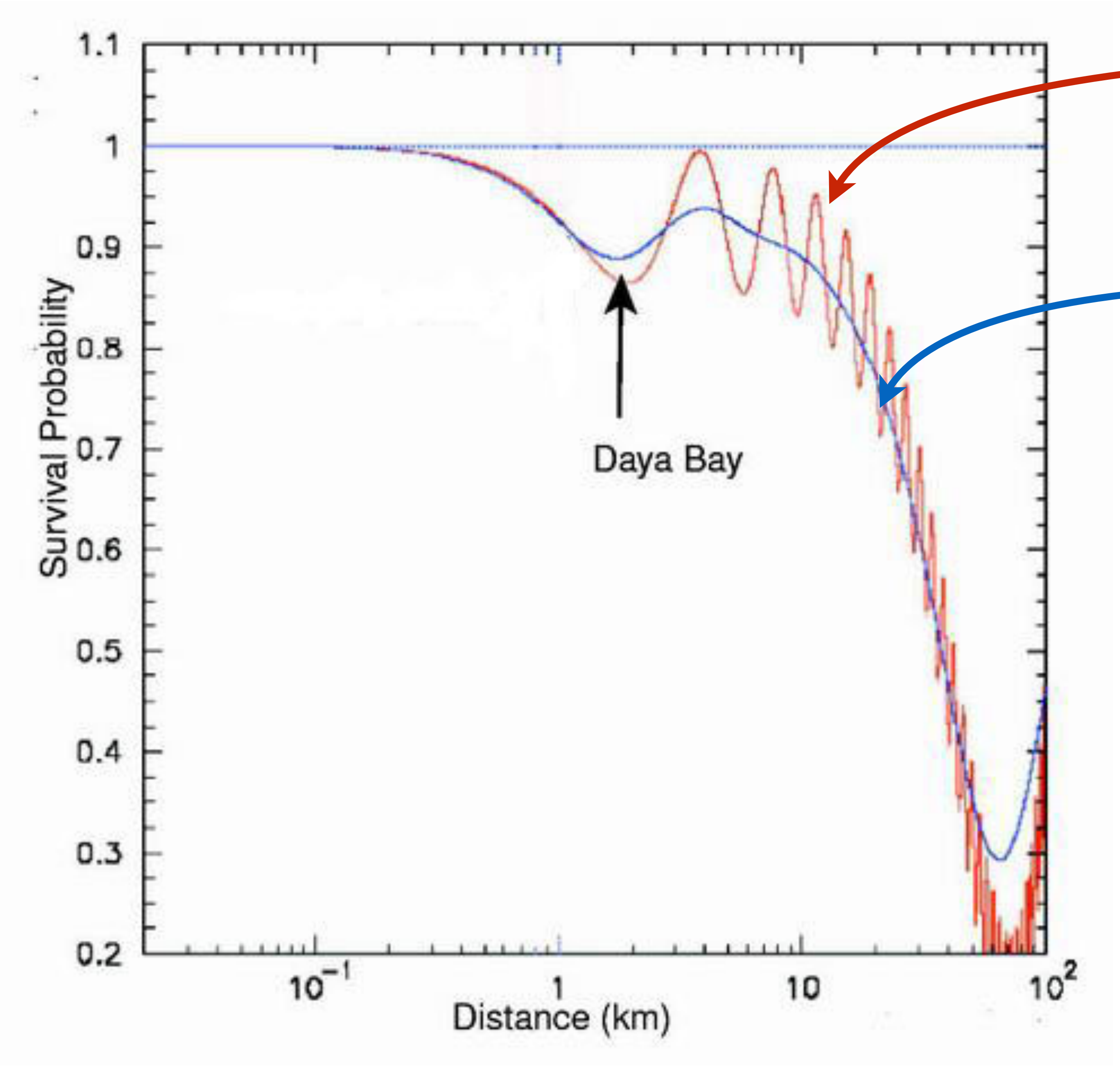
- 17.4 $\mathrm{GW_{th}}$ power
- 8 operating detectors
- 160 t total target mass

Daya Bay: Detectors



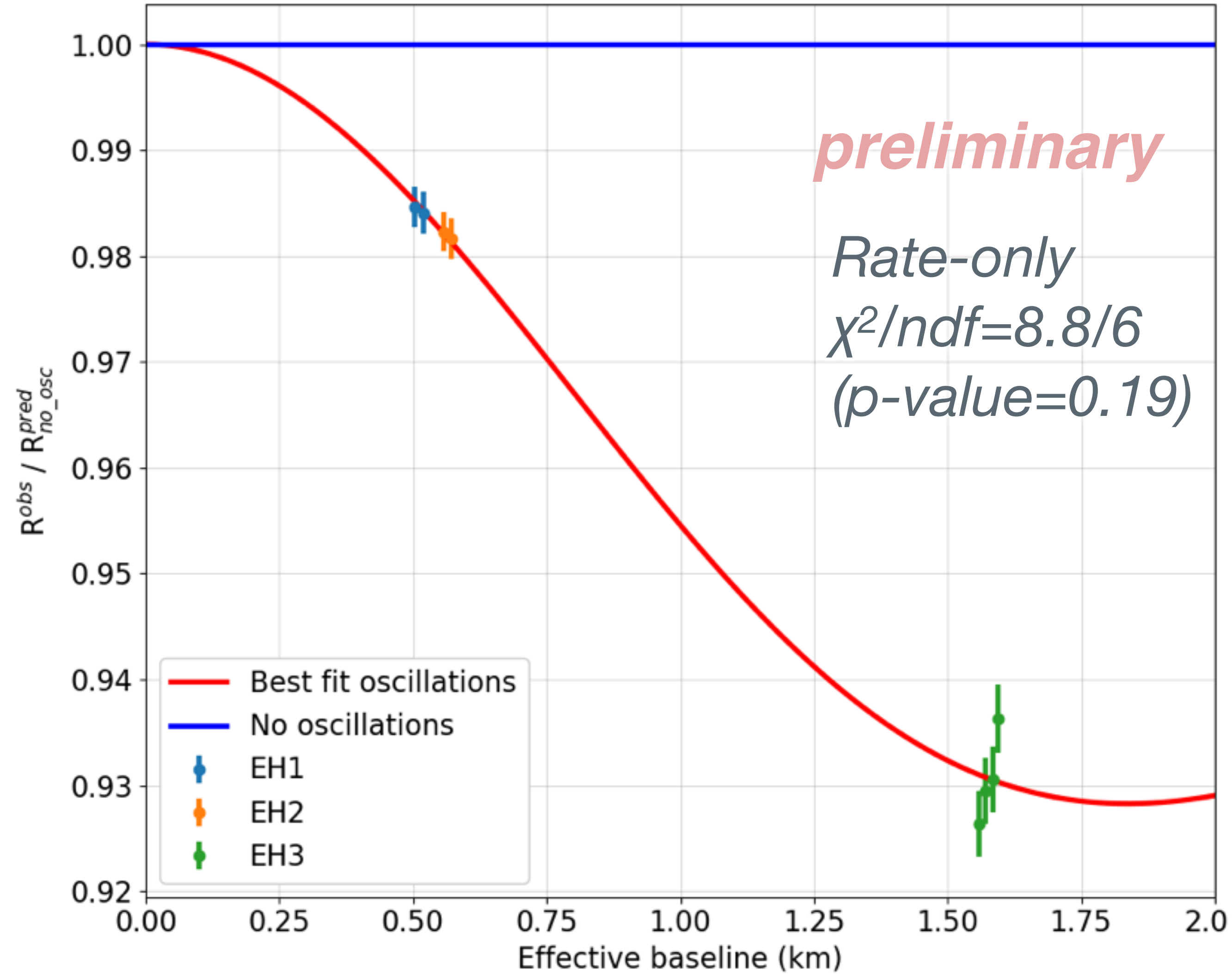
- Liquid scintillator detectors (20t)
    - Gd doped to improve neutron capture for secondary signal
- Water-based veto

The Daya Bay Oscillation Signal



hypothetical signal with monoenergetic neutrinos

expected signal taking energy spectrum into account



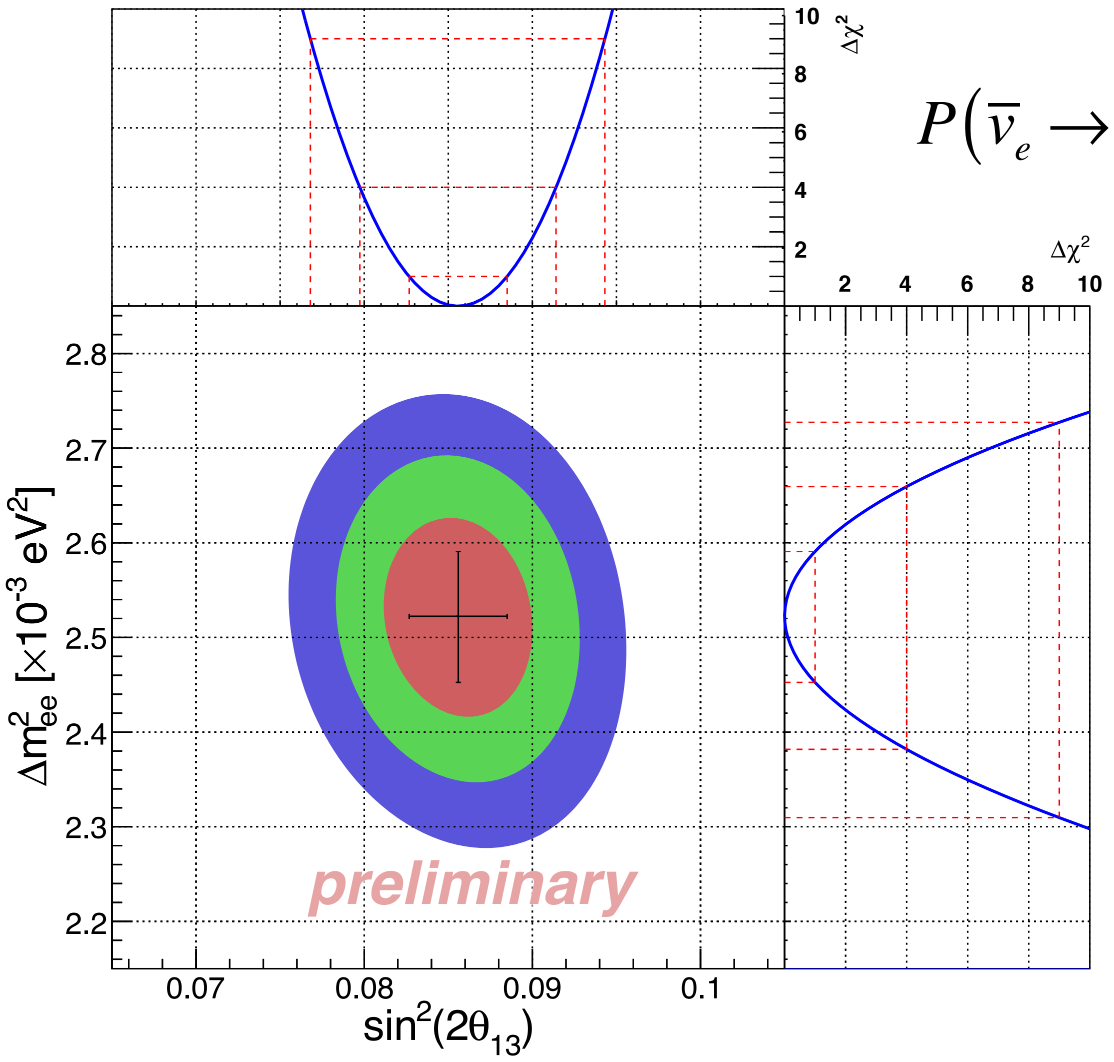
Rate-only
$\chi^2/ndf=8.8/6$
(p-value=0.19)

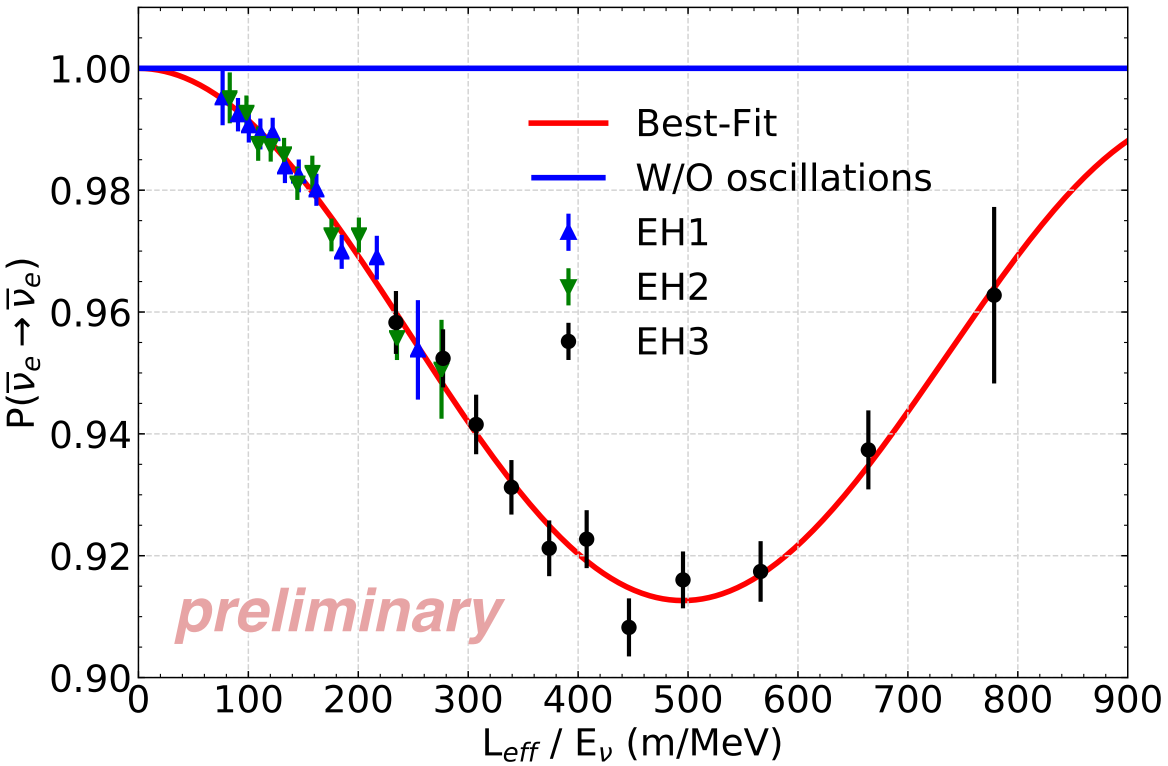
The Daya Bay Result

- Measure $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ to **3.4%** and **2.8%** respectively

effective mass splitting

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{1.267 \boxed{\Delta m^2_{ee}} L}{E} - \text{solar term}$$





results with 1958 days →

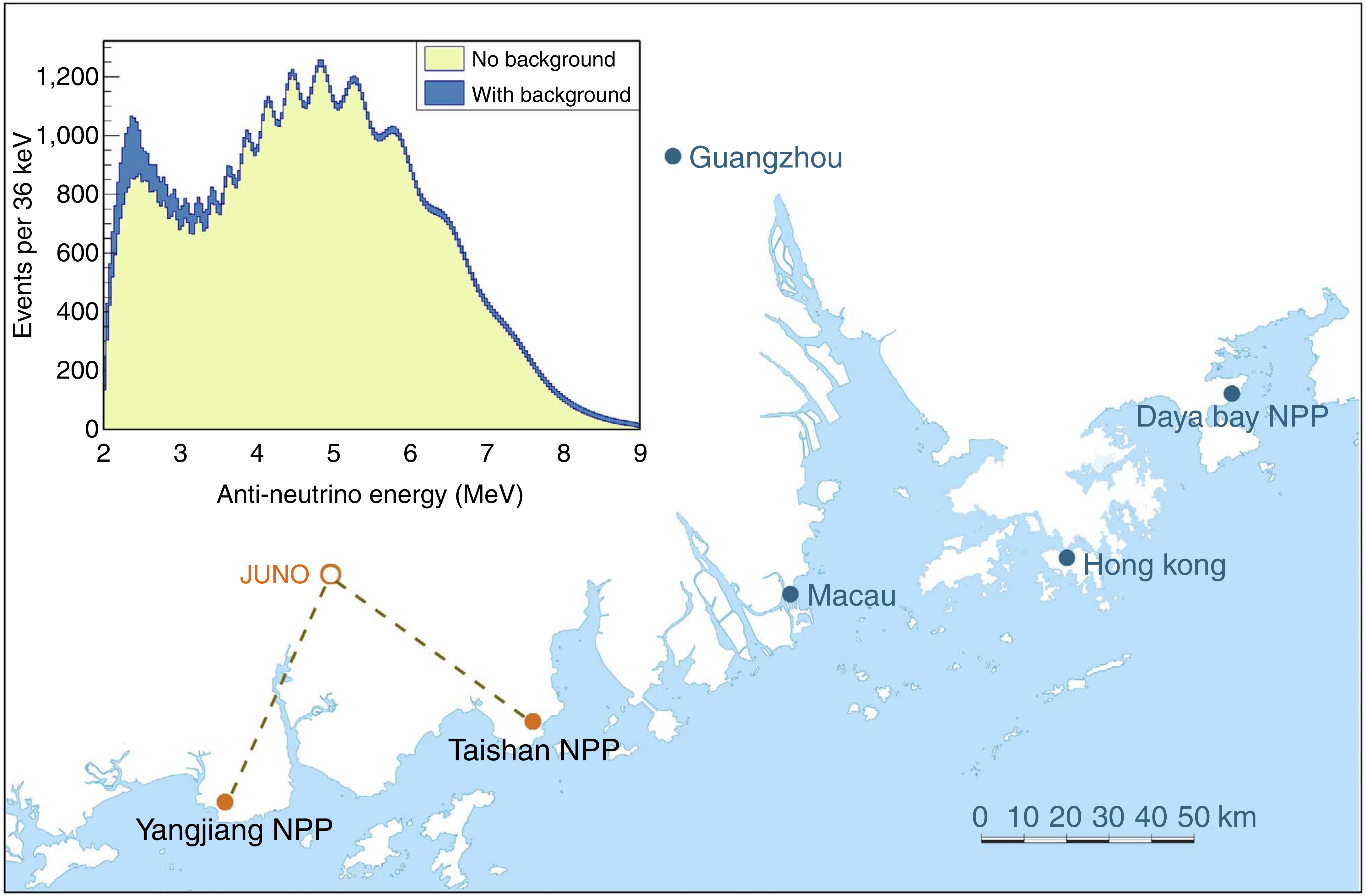
$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3} \text{ eV}^2$$

The statistical uncertainty contributes about 60% (50%) of the total θ_{13} (Δm^2_{ee}) uncertainty.

Daya Bay is not alone: Other experiments: Double Chooz (France), RENO (Korea)

The Next Generation of Reactor Experiments



- JUNO: Measure the mass ordering of neutrinos

Accelerator Experiments

Neutrinos at Accelerators

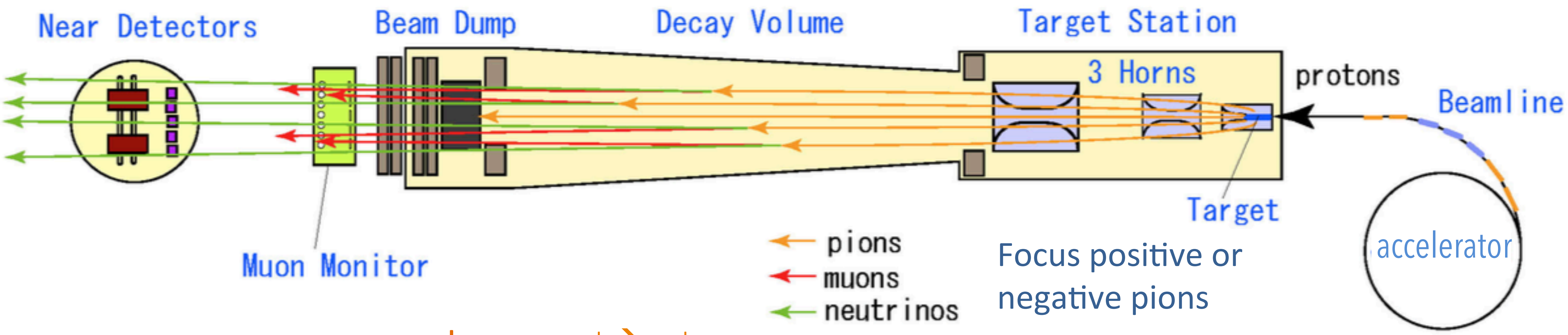
- Neutrino production:
    - Analogous to air showers: hadronic showers on impact of highly energetic protons on production target
    - Production of pions, kaons that decay in a decay tunnel:

$$\pi^-, K^- \rightarrow \mu^- + \bar{\nu}_\mu$$

    - Tunnel not long enough for substantial decay of muons: Essentially pure ν_μ beam

- There have been many different experiments with accelerator neutrinos
    - Study of the weak interaction
    - Measurement of the quark composition of nuclei
    - Discovery of the ν_τ
    - Confirmation of atmospheric measurements
    - Evidence for non-zero θ_{13}
    - First hints for CP violation

Making a Neutrino Beam

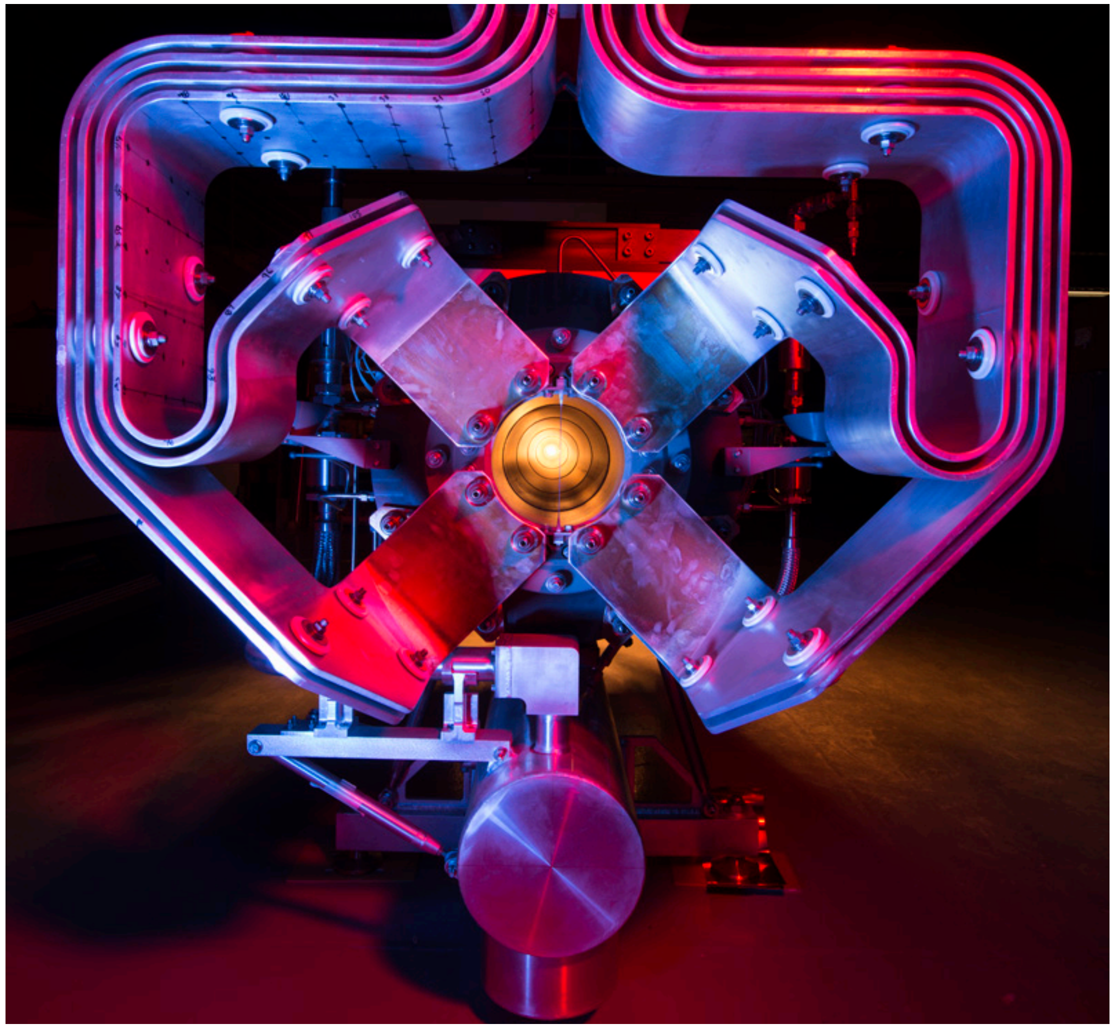


Focus positive or negative pions

ν beam: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\overline{\nu}$ beam: $\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$

- Pions focused by specialized magnet systems:
  “Neutrino Horns”

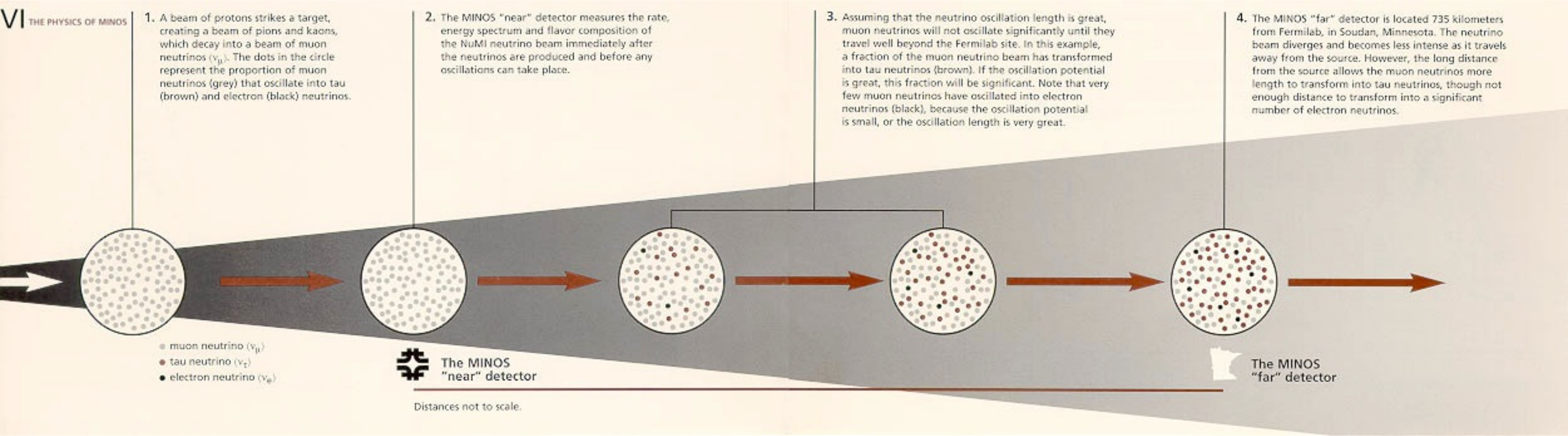


Long Baseline Experiments

- Neutrino beam produced with accelerator
- Reference measurement with a “Near Detector”
- Detection of neutrinos in a “Far Detector”

▸ Choice of distance and energy depends the region of the mixing matrix that can be probed

The composition of the beam changes from source to detector
From a pure ν_μ beam to a mixture of ν_μ , ν_τ and a few ν_e ($\theta_{13} \neq 0$)



VI THE PHYSICS OF MINOS

1. A beam of protons strikes a target, creating a beam of pions and kaons, which decay into a beam of muon neutrinos (ν_μ). The dots in the circle represent the proportion of muon neutrinos (grey) that oscillate into tau (brown) and electron (black) neutrinos.

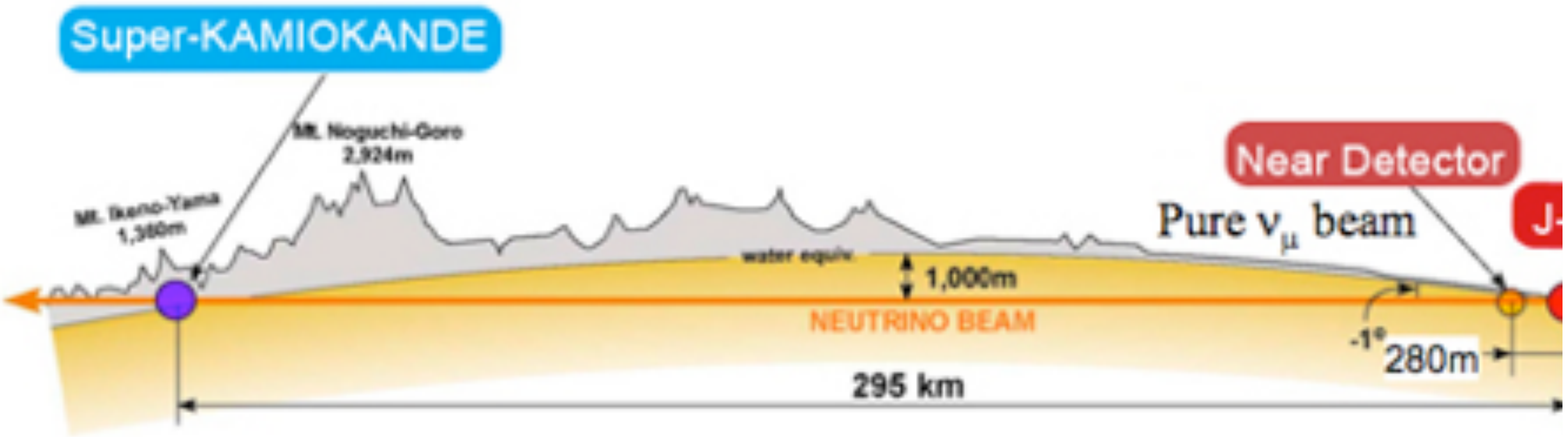
2. The MINOS "near" detector measures the rate, energy spectrum and flavor composition of the NuMI neutrino beam immediately after the neutrinos are produced and before any oscillations can take place.

3. Assuming that the neutrino oscillation length is great, muon neutrinos will not oscillate significantly until they travel well beyond the Fermilab site. In this example, a fraction of the muon neutrino beam has transformed into tau neutrinos (brown). If the oscillation potential is great, this fraction will be significant. Note that very few muon neutrinos have oscillated into electron neutrinos (black), because the oscillation potential is small, or the oscillation length is very great.

4. The MINOS "far" detector is located 735 kilometers from Fermilab, in Soudan, Minnesota. The neutrino beam diverges and becomes less intense as it travels away from the source. However, the long distance from the source allows the muon neutrinos more length to transform into tau neutrinos, though not enough distance to transform into a significant number of electron neutrinos.

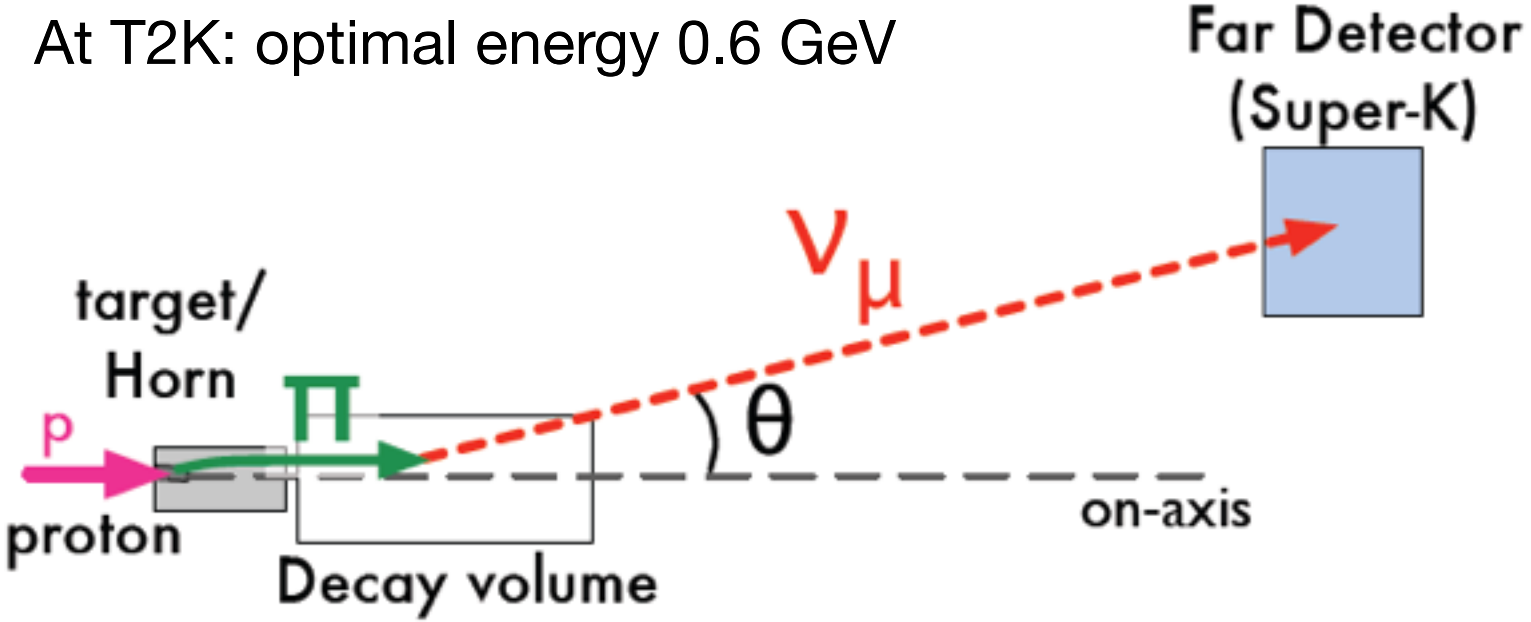
T2K: Neutrino Beam to SuperK

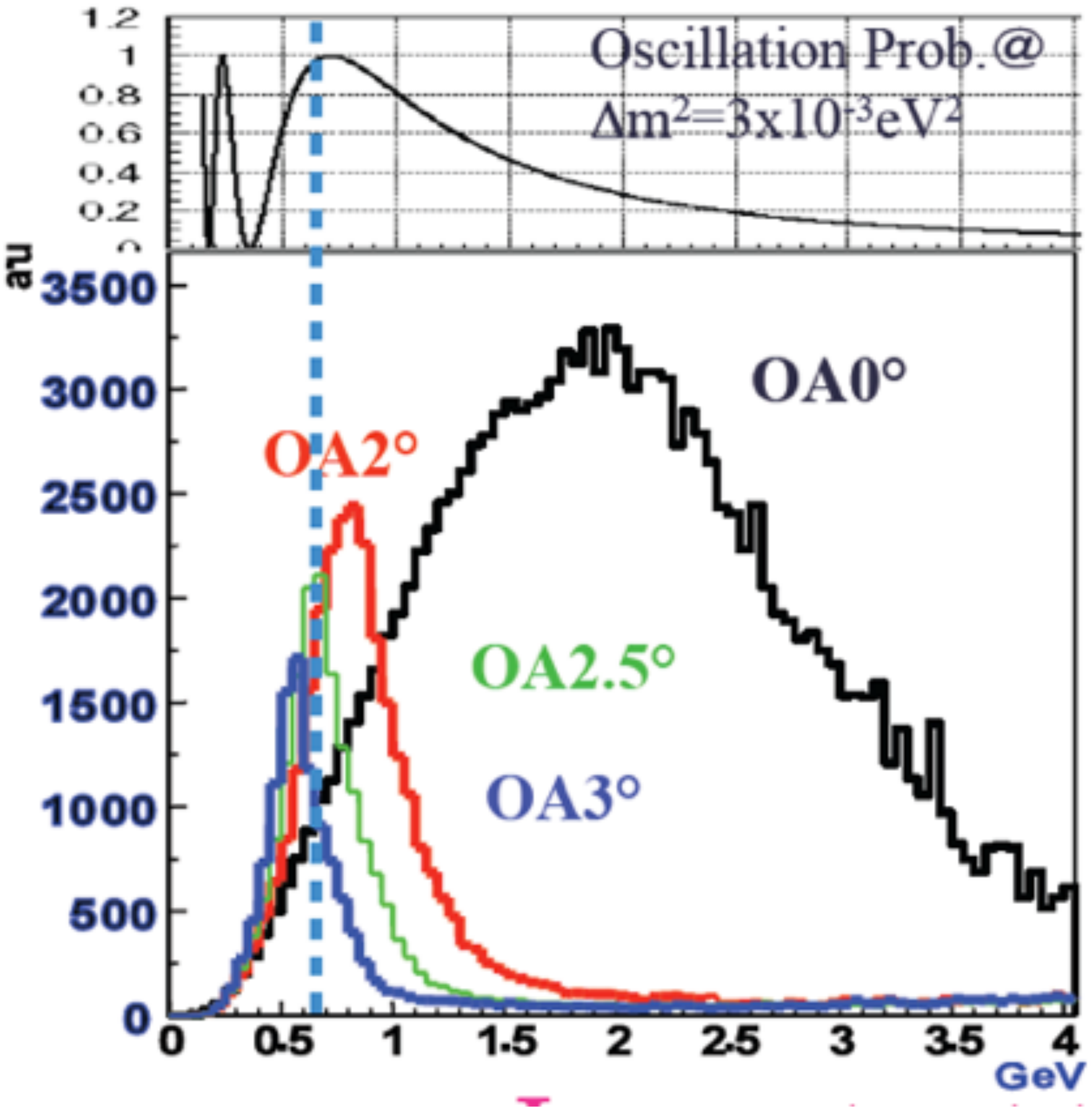
- Goal: precise measurement of atmosph. oscillation, θ_{13}, possible CP violation
- Runs since 2010 (with 1 year down time due to Tohoku Earthquake)



T2K is an “off-axis”- Beam: Aims not directly at the far detector -results in sharper energy distribution

At T2K: optimal energy 0.6 GeV

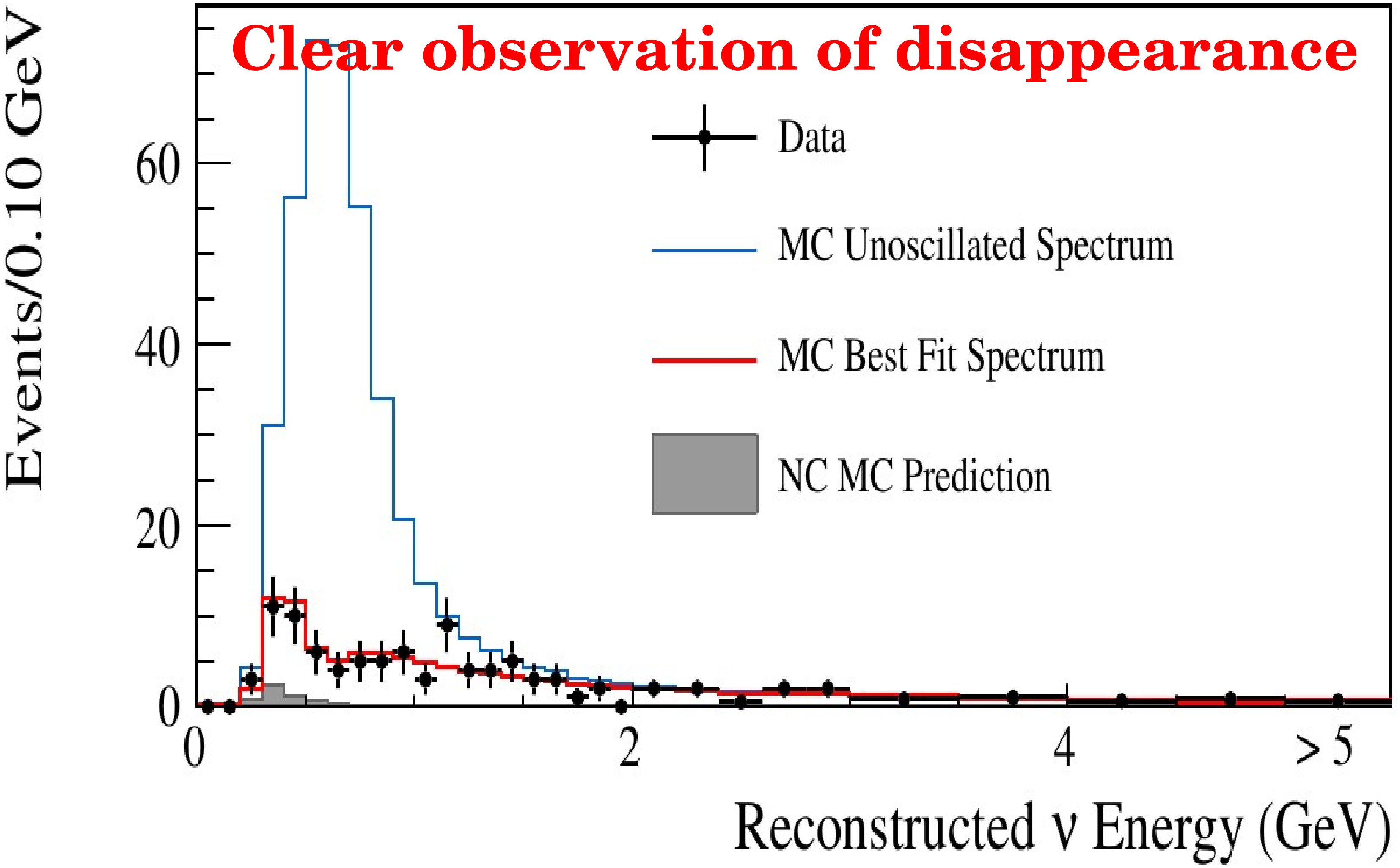




Ken Sakashita, KEK Seminar

T2K: The Choice of the Right Energy / Baseline

- Almost complete disappearance of ν_μ:

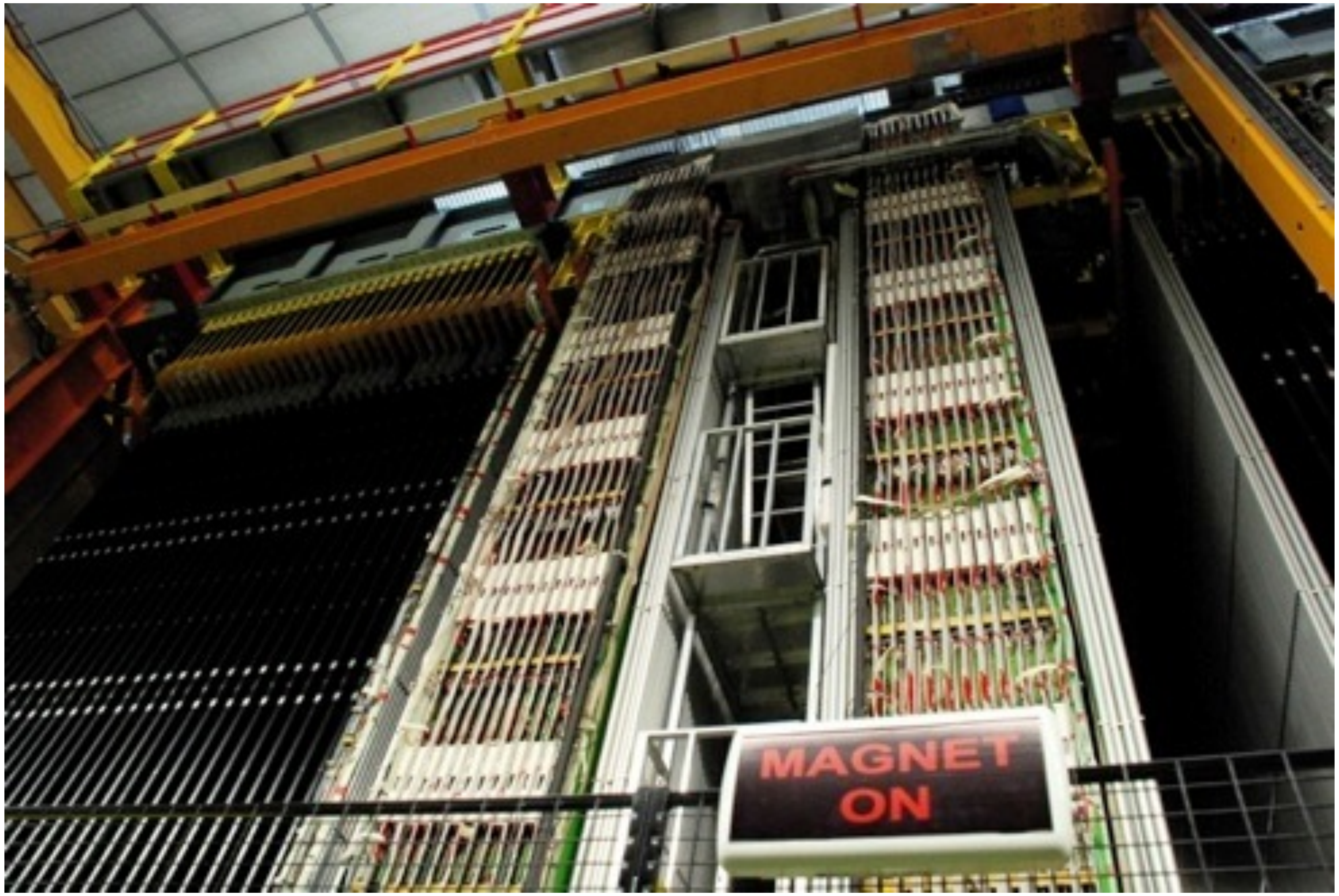


Also optimal for a measurement of θ_{13}!

=> Observations fit very well with measurements of atmospheric neutrinos

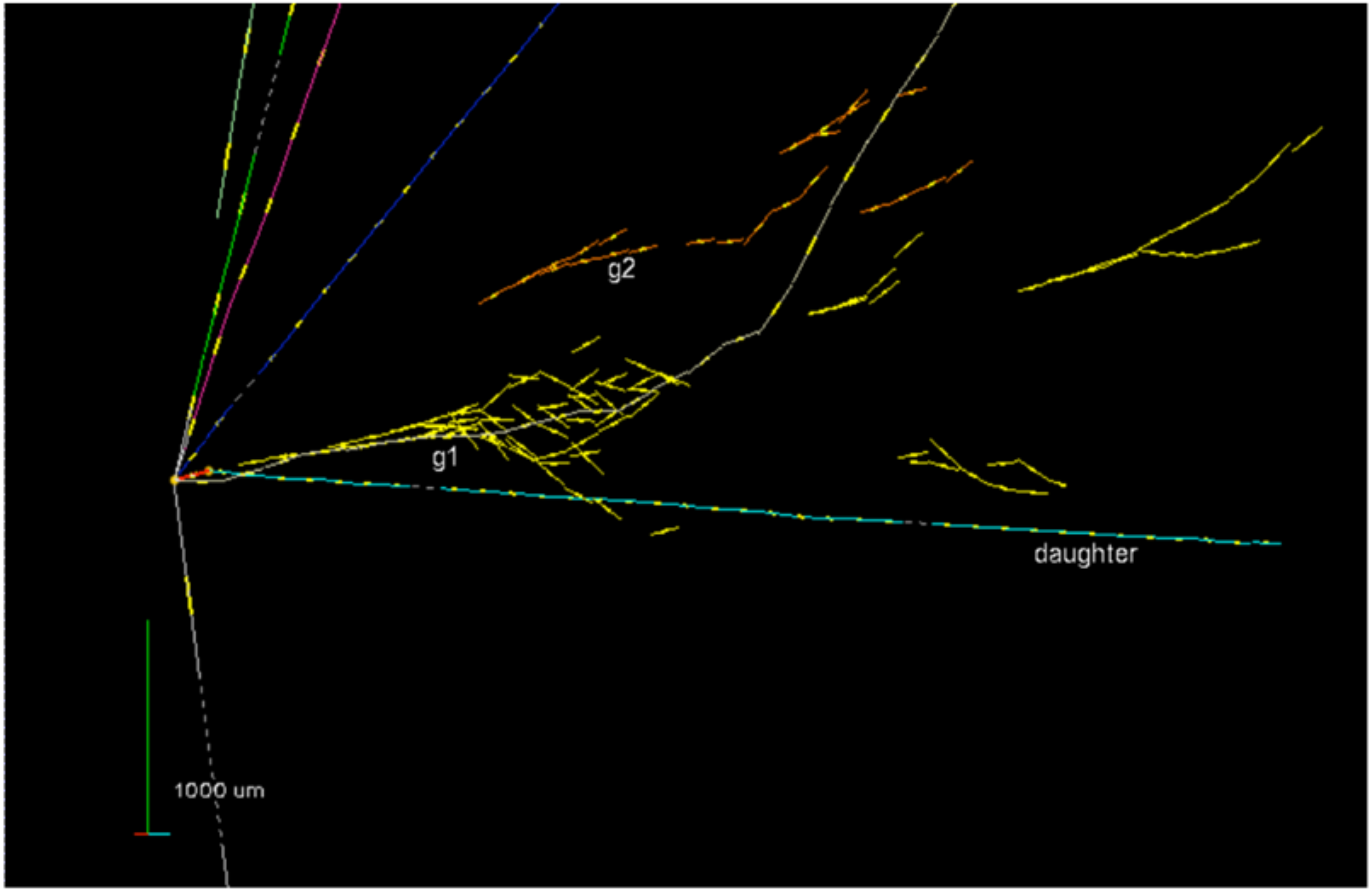
CNGS / Opera: Confirmation of ν_μ -> ν_τ Oscillation

- One of the goals: Direct observation of oscillations of ν_μ to ν_τ in a ν_μ Long Baseline Beam (CERN → Gran Sasso)



- Magnetic spectrometer for track and energy reconstruction, in between blocks of photo emulsion for precise reconstruction of tracks at the interaction vertex
  - If an interesting event is observed in the spectrometer, the corresponding block is extracted and examined

CNGS / Opera: Confirmation of ν_μ -> ν_τ



In total 4 additional ν_τ have been observed - “5 -sigma discovery”: matches expectations

ν_τ produces τ, fast decay into μ and vs

➯ Proof, that the atmospheric oscillation is $\nu_\mu \rightarrow \nu_\tau$

OPERA Press Release, 31.05.2010

Measuring Θ_{13} at Accelerators

- θ_{13} describes $\nu_1 \rightarrow \nu_3$ oscillations: Squared mass differences (almost) as in the atmospheric case, but transitions involving ν_e (large ν_e component in ν_1!)
  - With a ν_μ beam, θ_{13} is accessible through the subdominant oscillation from ν_μ to ν_e (the dominant oscillation is ν_μ to ν_τ)

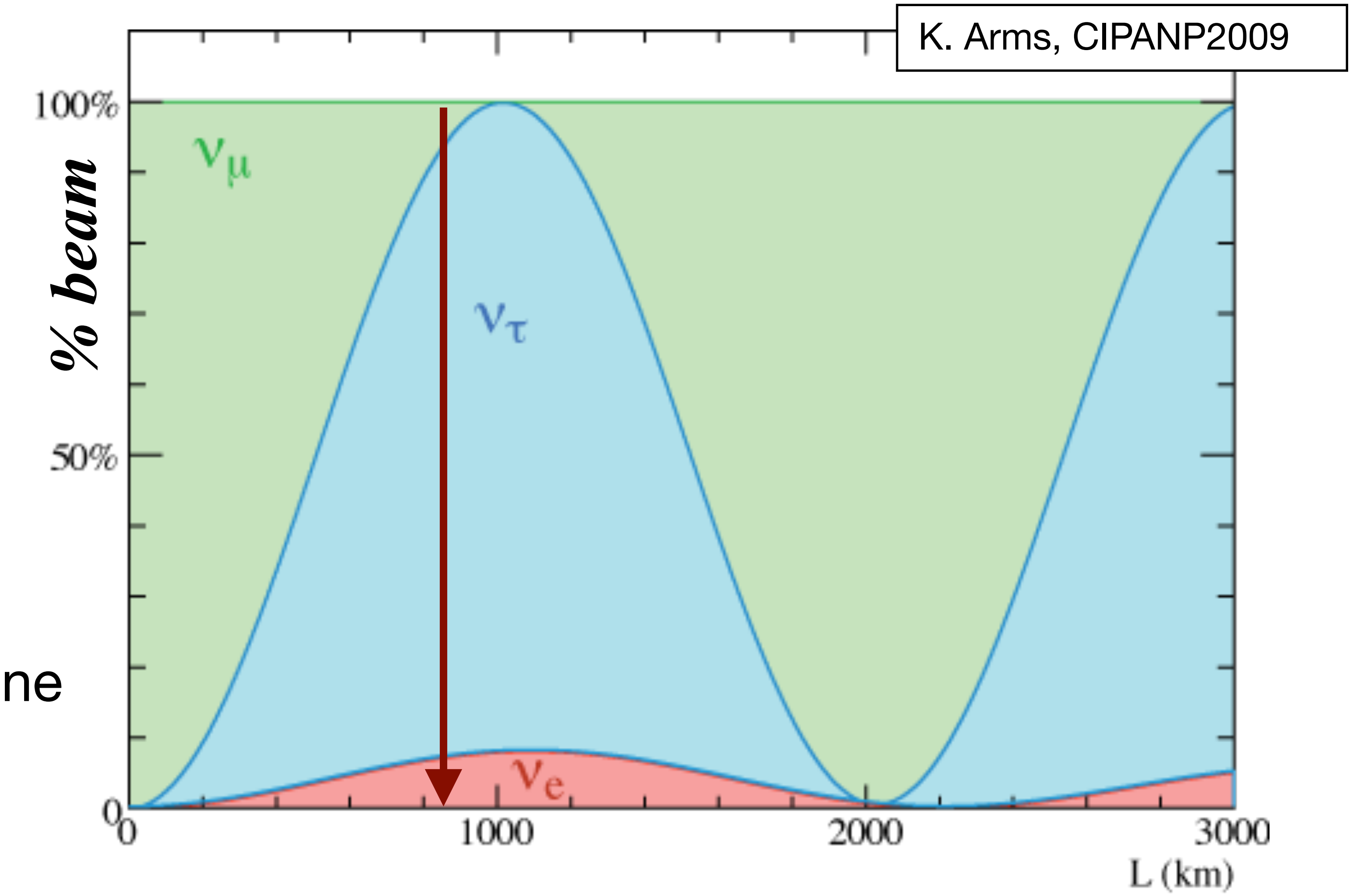
Oscillation probability: $$P(\nu_\mu \leftrightarrow \nu_e) \approx sin^2 2\theta_{13} \, sin^2\theta_{23} \, sin^2 \left(\frac{\Delta m_{13}^2 L}{4E}\right)$$

Strongly suppressed compared to $\nu_\mu \rightarrow \nu_\tau$ oscillations: Looking for small effects!

length scale depends on ν energy here: shown for the NOvA experiment at FNAL

Important: Energy matched to baseline

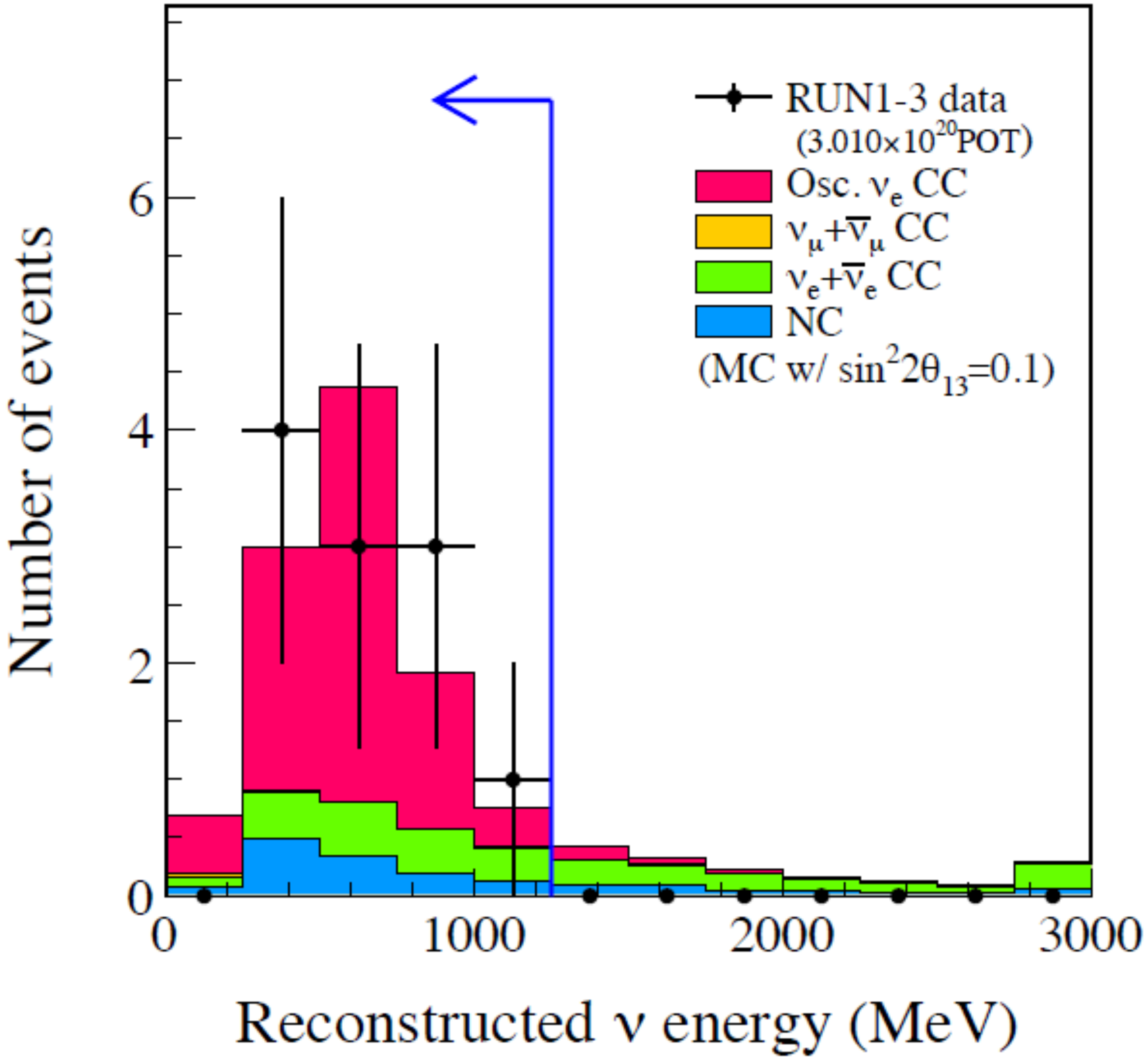
Narrow energy distribution

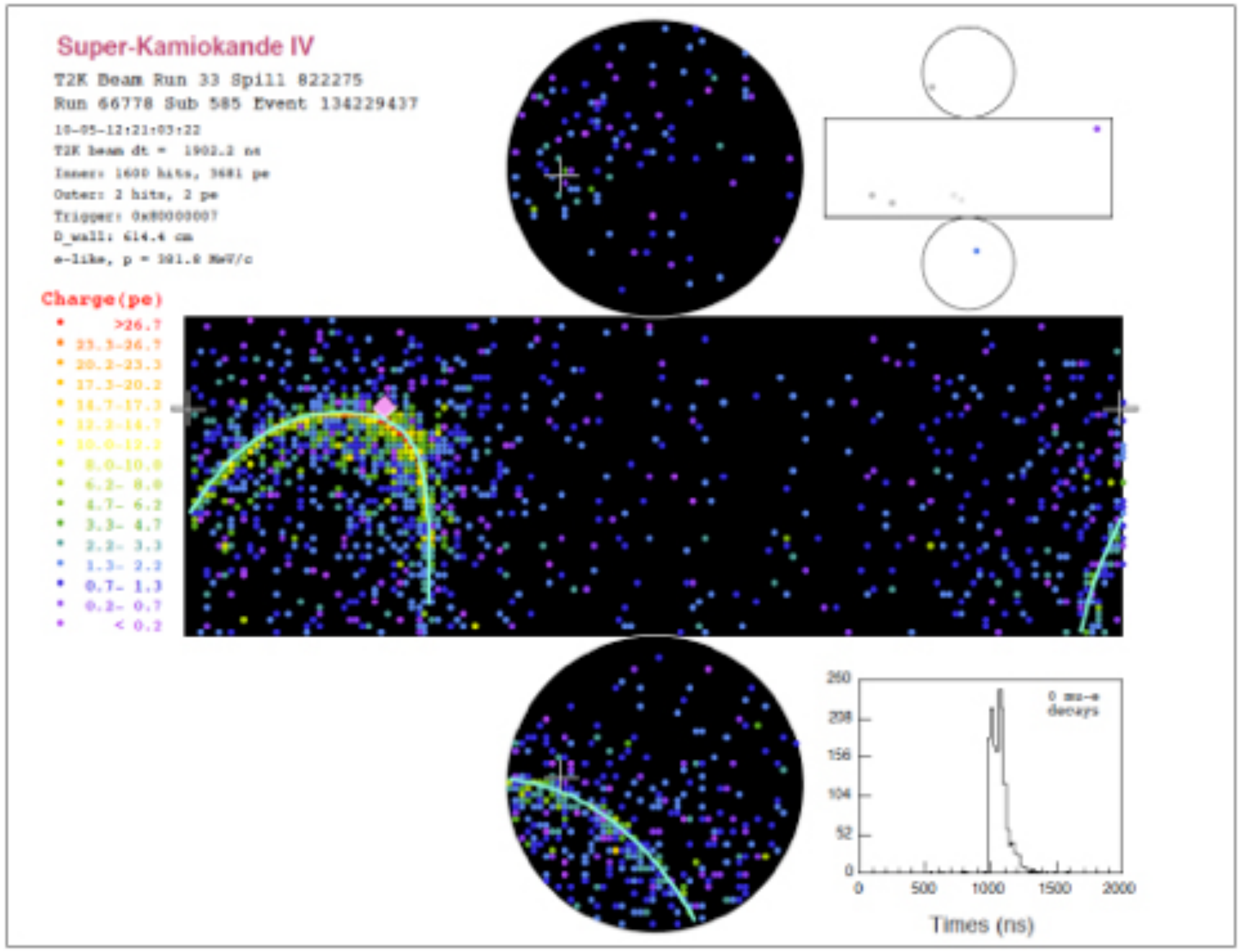

K. Arms, CIPANP2009

T2K Oscillation Results

- Observation of $\nu_\mu \rightarrow \nu_e$ oscillations :

11 events (3.2 σ that θ_{13} is not 0)





T2K was first - but best results currently from Daya Bay (see above)

Searching for CP Violation in the v - Sector

- CP Violation: A difference between matter and antimatter
- In the SM: Generated by the complex phase in the mixing matrix (Quarks, vs), if δ ≠ 0
    - Shows up in differences in oscillation behavior between neutrinos and anti-neutrinos!

Phys. Rev. D64 (2001) 053003

$$P(\nu_\mu \to \nu_e) \simeq \boxed{\sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}}$$

Leading term

CP violating

$$\boxed{-}\alpha \boxed{\sin\delta_{CP}} \times \sin^2 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

“+” for antineutrino

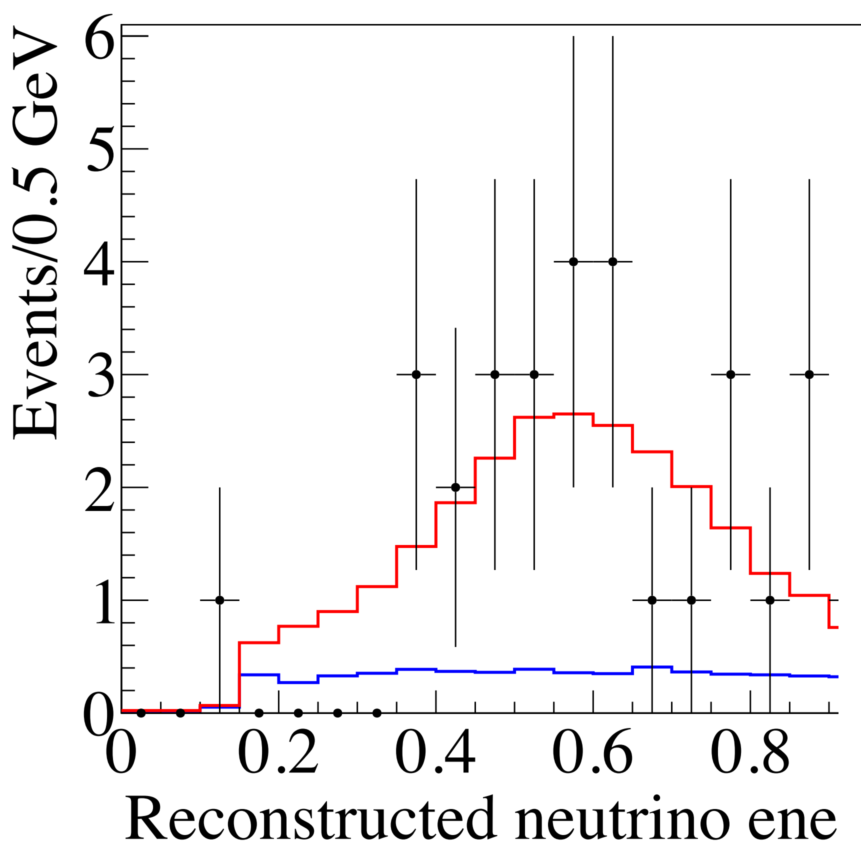
CP conserving

$$\alpha \boxed{\cos\delta_{CP}} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

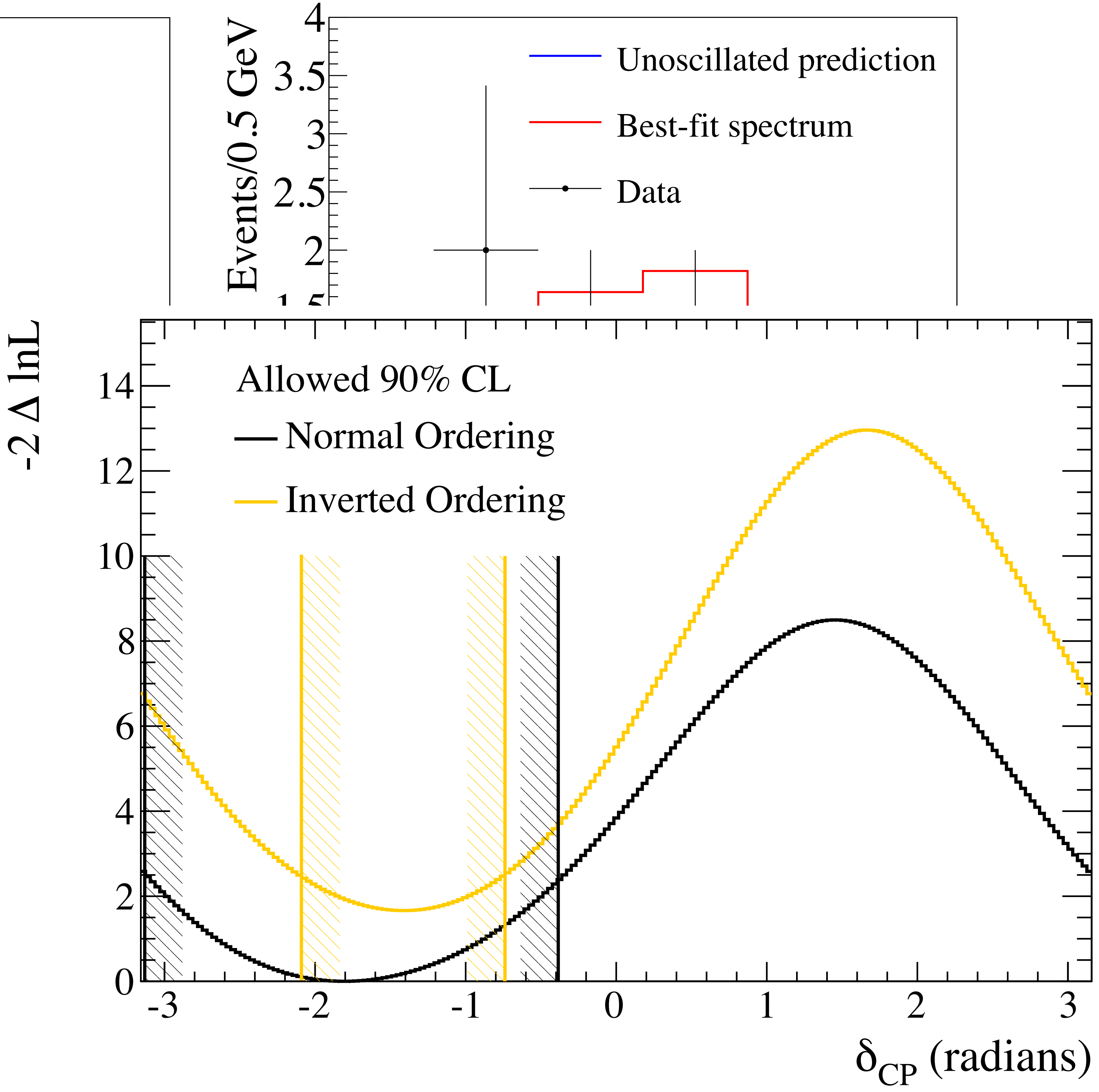
$$+ O(\alpha^2)$$

$$x = \frac{2\sqrt{(2)}G_F N_e E}{\Delta m^2_{31}} \qquad \alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \qquad \Delta = \frac{\Delta m^2_{31} L}{4E}$$

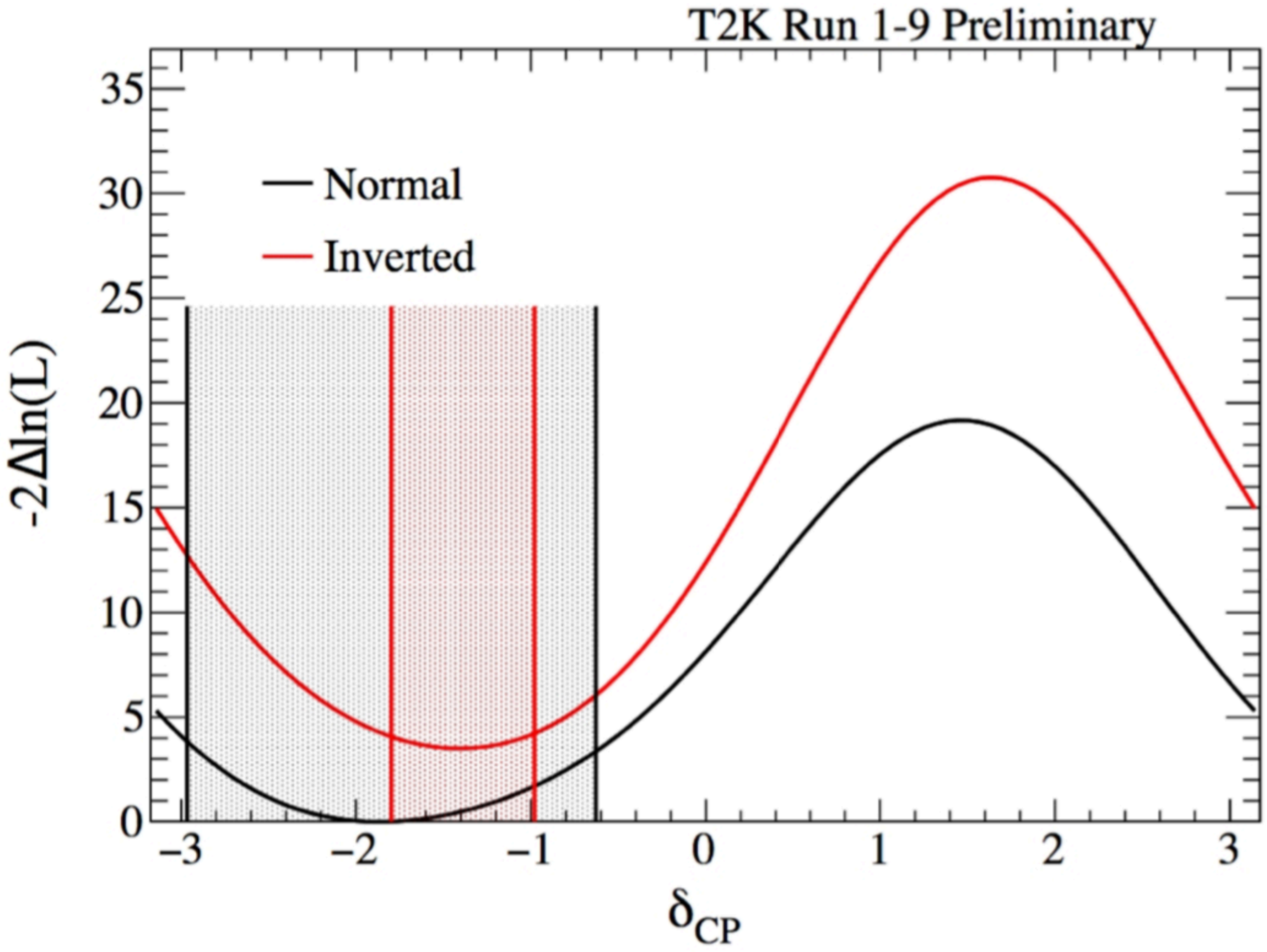
First Hints for CPV: T2K 2016



- Running both with neutrinos and anti-neutrinos: Observed less anti-ν_e than expected in any scenario: hints at maximal CP violation



T2K - More Data



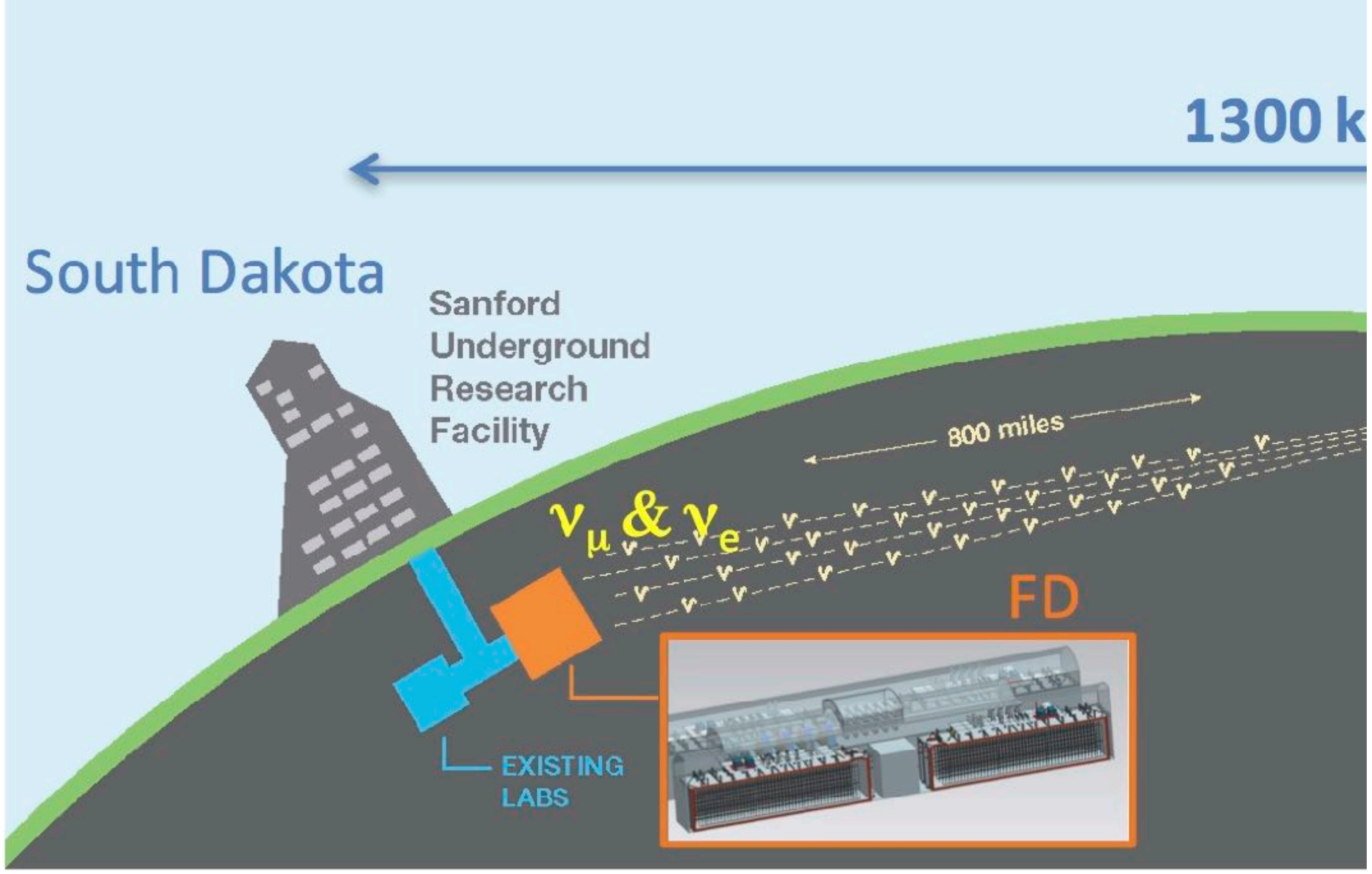
- Significance pointing towards CP violation firm up - strong dependence on mass ordering

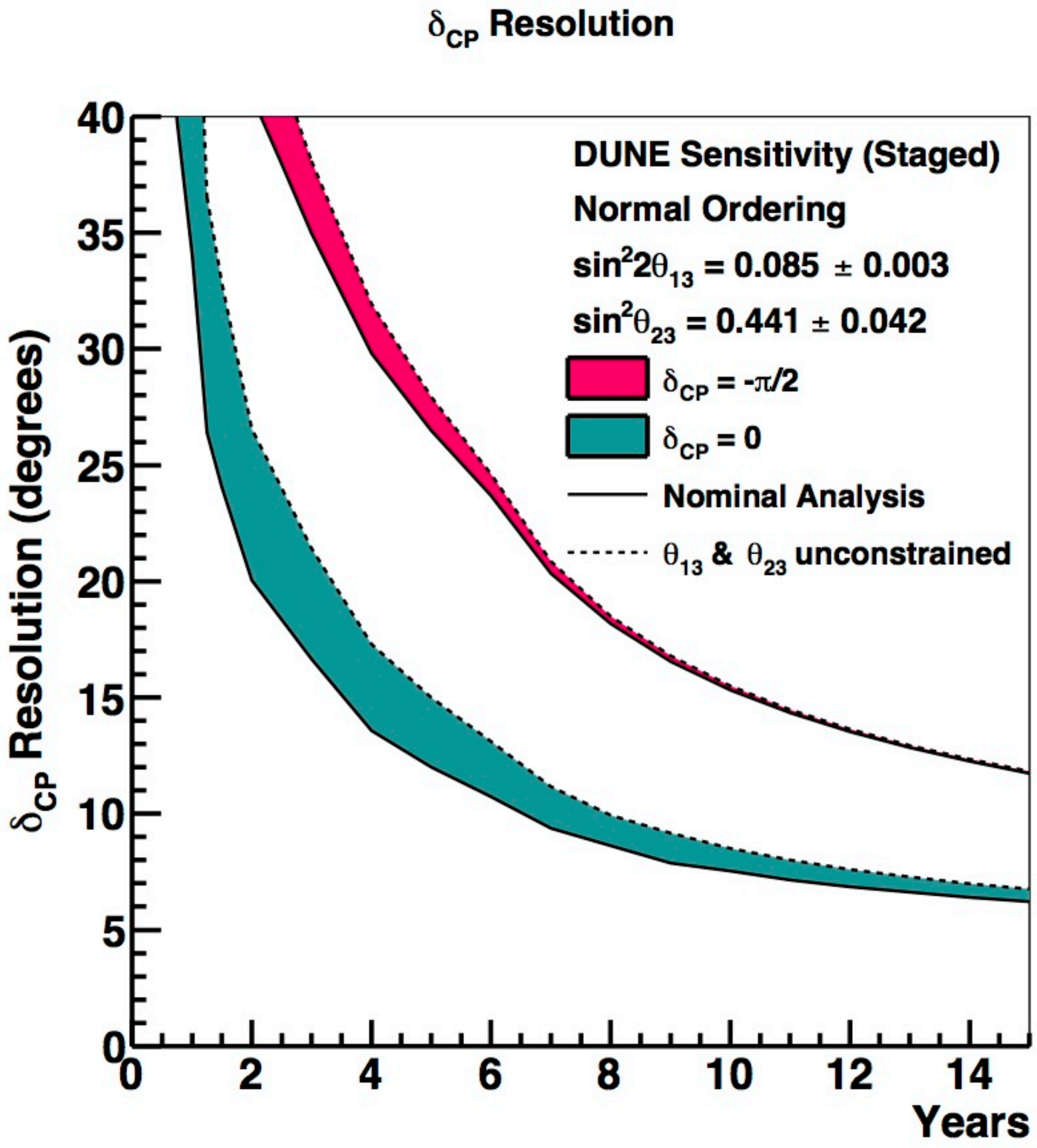
- Normal Hierarchy preferred (posterior probability: 89%)
- CP-conserving values excluded at 2σ level

- Best fit: δ_{CP} = -1.885 for NH, -1.382 for IH
- ±1σ range: [-2.460, -1.187] for NH, [-1.930, -0.907] for IH

Future Measurements of CP Violation

- The “next big thing” in neutrino physics - with future experiments to make definitive measurements





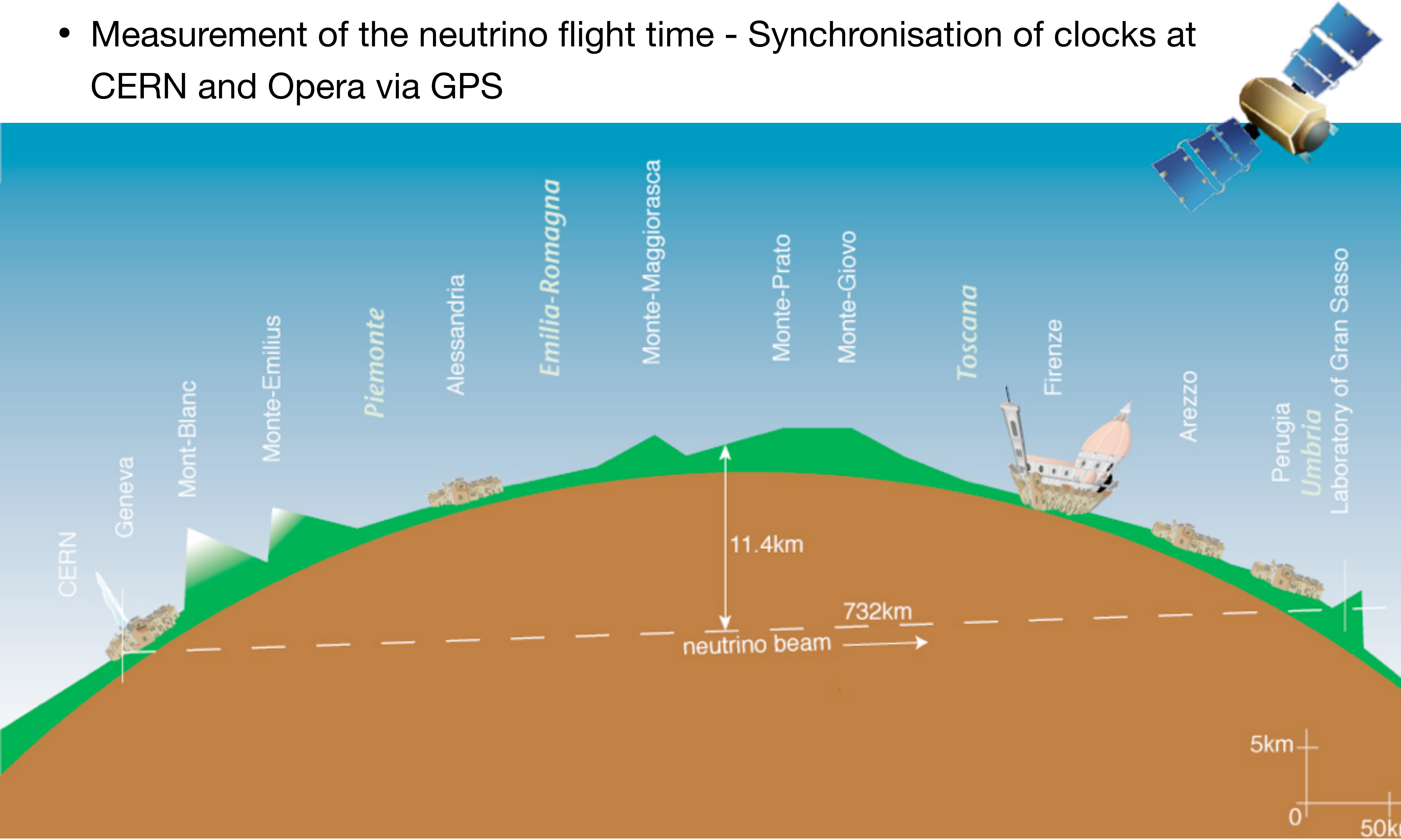
- DUNE at Fermilab - to start taking data in
  - x4 higher mean energy than T2K: longe
- Also in discussion T2HK: Much larger wat from Tokai, same baseline as T2K

Bonus Feature: Faster than light Neutrinos?

… if you are interested and have time.

Now History: Neutrino Speed

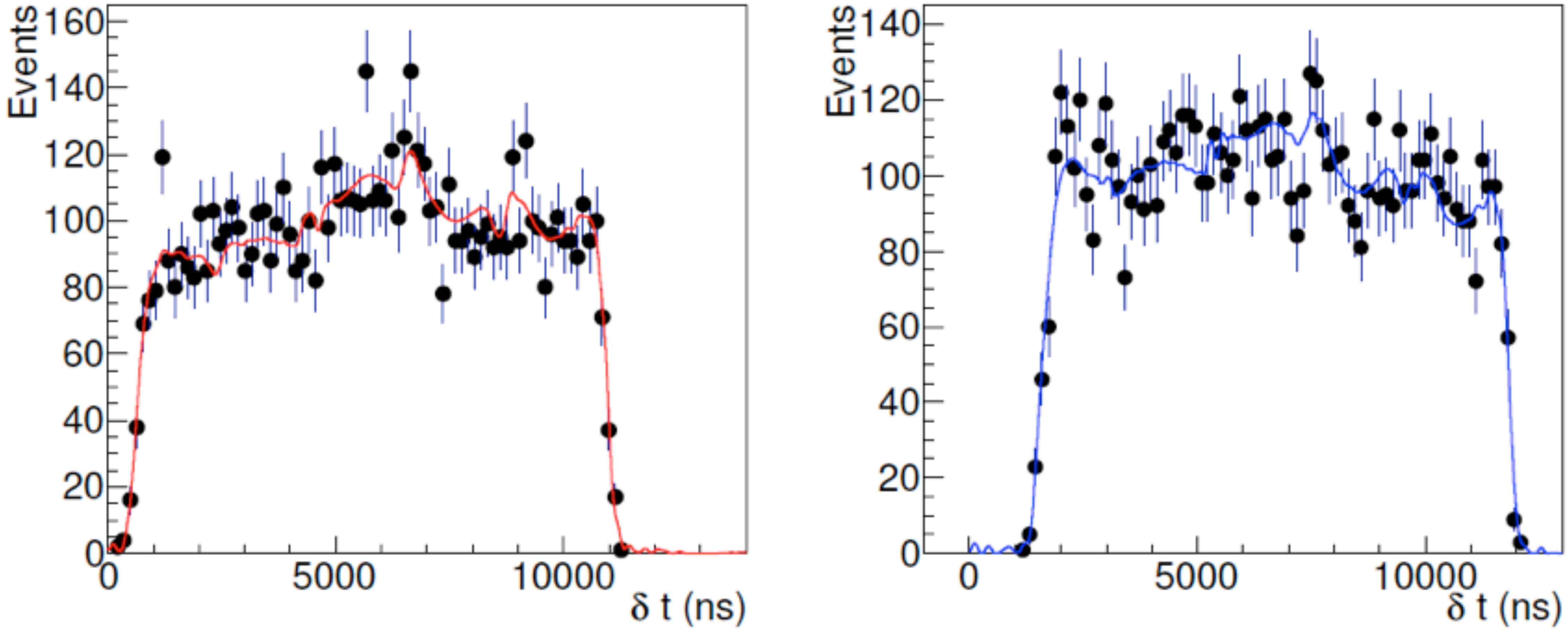
- Measurement of the neutrino flight time - Synchronisation of clocks at CERN and Opera via GPS



First Attempt - Spectacular Result

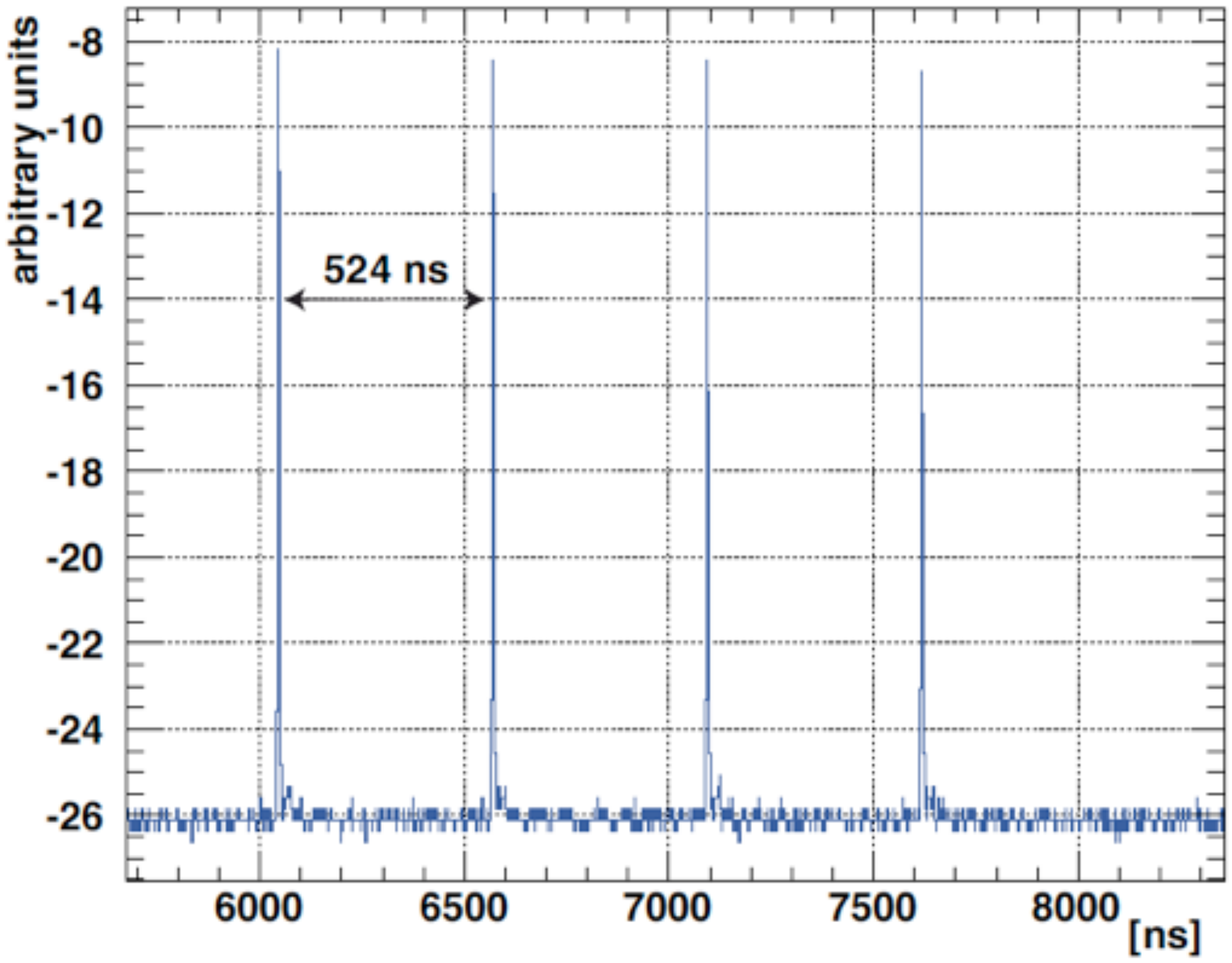
- September 2011: Opera observes, that the neutrinos are 60 ns too fast (with an uncertainties of 10 ns).

Technique: "edges" of the neutrino distribution in Opera, relative to the proton pulse -at CERN - statistical method, possible uncertainties from beam focusing (time structure of the neutrino pulse)



The Confirmation

- New measurements with pulsed beam, beam pulses 3 ns FWHM - direct measurement of flight time!



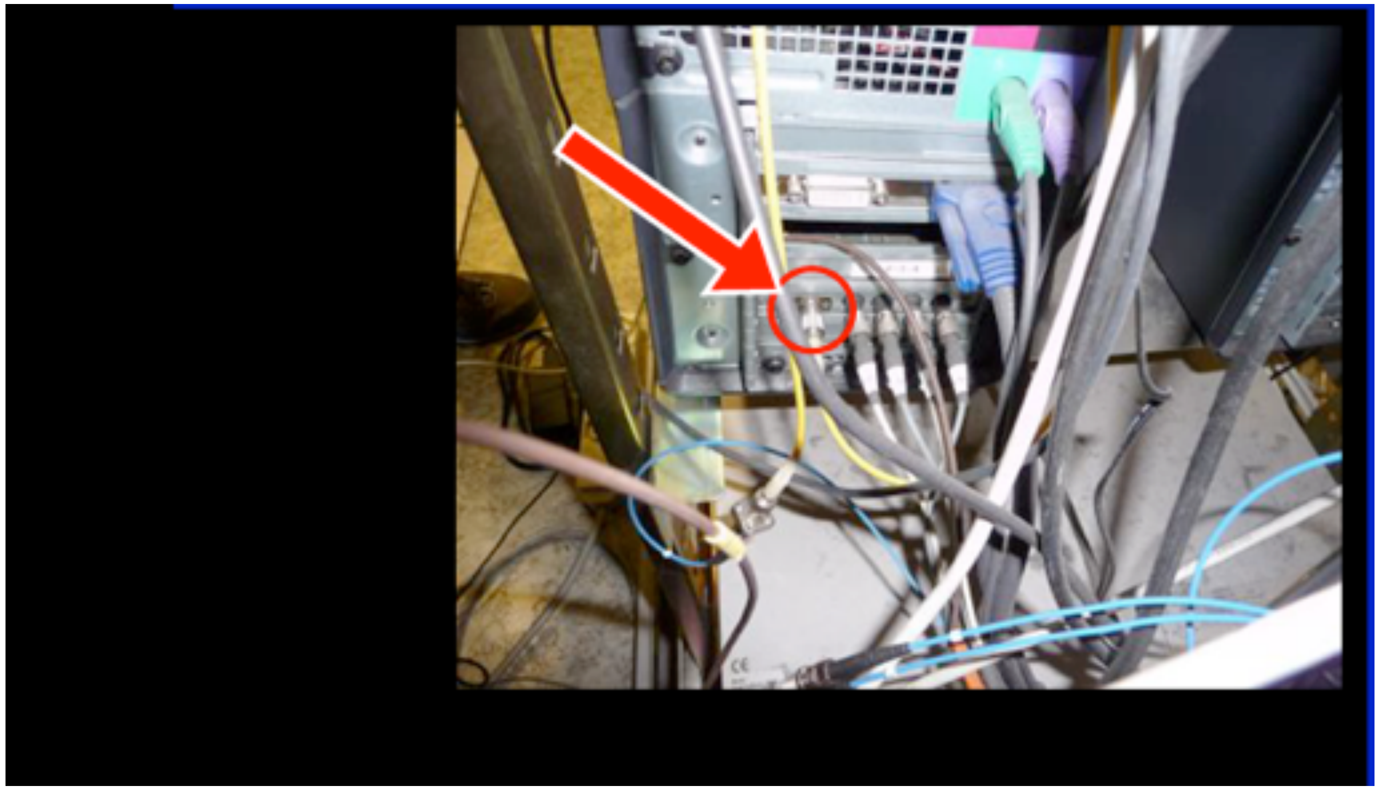
Confirms original results: beam structure as cause excluded

Uncertainty now only 4 ns (for a “signal” of 60 ns)

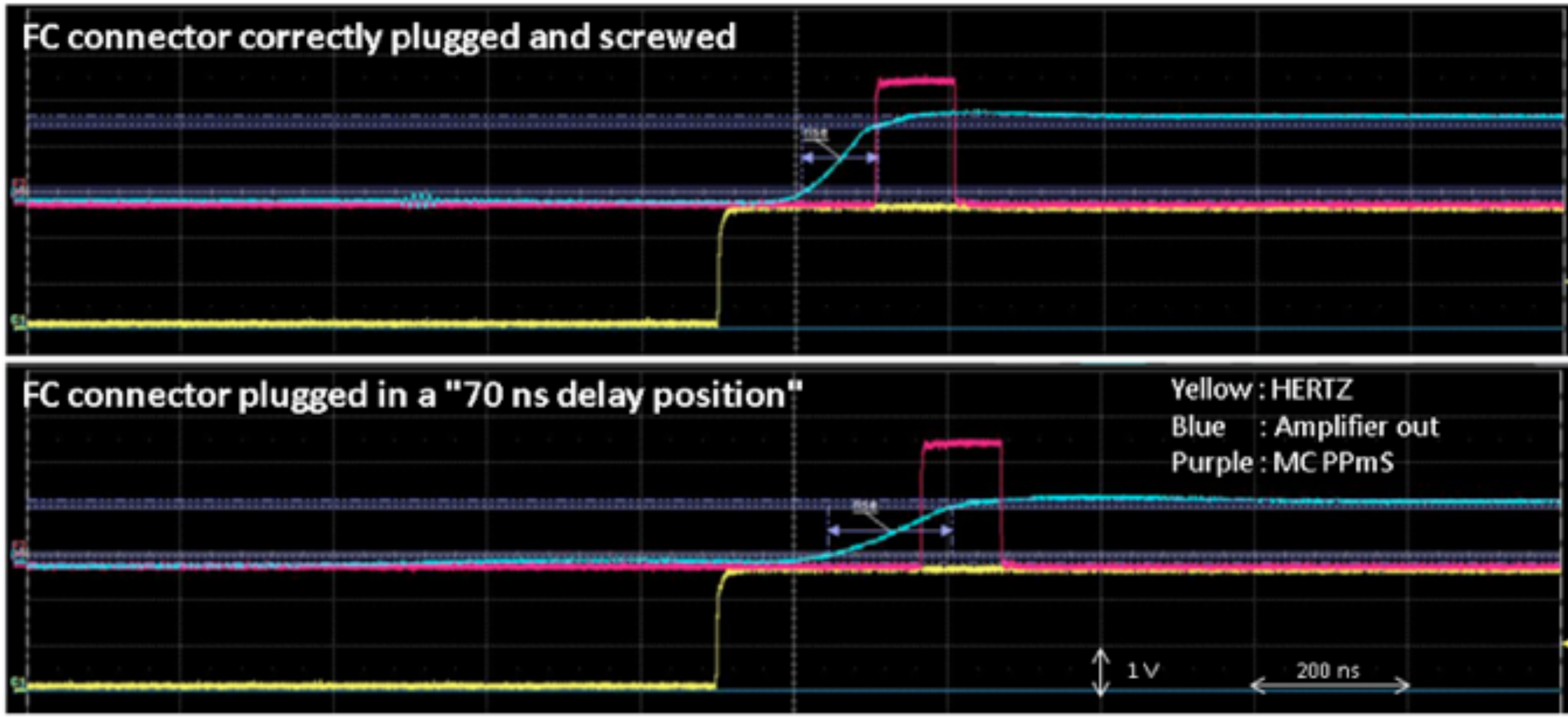
... but N.B.: There are corrections of 40 µs for signal running times in the electronics!

The Resolution

- As most had expected - It was a measurement error: An optical fiber of the timing system was not correctly plugged in - Resulted in a slower signal rise on the corresponding photo diode, the clock is a bit later due to later passing of threshold, voila...



Now: The time of flight is bang on, within a few ns!



Summary

- Neutrino experiments using reactor and accelerator neutrinos have
  - confirmed the observations with solar and atmospheric neutrinos with high precision
  - made a precise measurement of the third mixing angle Θ_{13}
  - provided first indications for a non-zero CP violating phase
- Upcoming experiments will
  - determine the neutrino mass ordering (JUNO + DUNE)
  - discover and measure CP violation in the neutrino sector if it exists (DUNE, HyperK)

Next Lecture: 01.07., “Precision Experiments with low-energy accelerators”, F. Simon

Lecture Overview

29.04.	Introduction & Recap: Particle Physics & Experiments	*F. Simon*
06.05.	Dark Matter axions and ALPs: Where do they come from?	*B. Majorovits*
13.05.	Axions and ALPs detection	*B. Majorovits*
20.05.	Dark Matter WIMPs - origin and searches	*B. Majorovits*
27.05.	Precision Tests of the Standard Model	*F. Simon*
03.06.	Neutrinos: Freeze out, cosmological implications, structure formation	*B. Majorovits*
	Pentecost	
17.06.	Natural Neutrino Sources: What can we learn from them?	*B. Majorovits*
24.06.	Neutrino Oscillations with Manmade Sources	*F. Simon*
01.07.	Precision Experiments with low-energy accelerators	*F. Simon*
08.07.	Neutrinoless Double Beta Decay	*B. Majorovits*
15.07.	Gravitational Waves	*F. Simon*
22.07.	Physics with Flavor: Top and Bottom	*F. Simon*