Particle Physics: Neutrinos – part I

Edward Dunton

Week 8: November 10, 2018
Columbia University Science Honors Program

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

NEVIS LABORATORIES

Course policies

- Classes from 10:00 AM to 12:30 PM (10 min break at ~ 11:10 AM).
- **Attendance record counts.**
  - Up to four absences
  - Lateness or leaving early counts as half-absence
    - Send email notifications of all absences to shpattendance@columbia.edu
- Please, no cell phones during class
- **Please, ask questions!**
- Lecture materials + Research Opportunities + Resources to become a particle physicist

https://twiki.nevis.columbia.edu/twiki/bin/view/Main/ScienceHonorsProgram

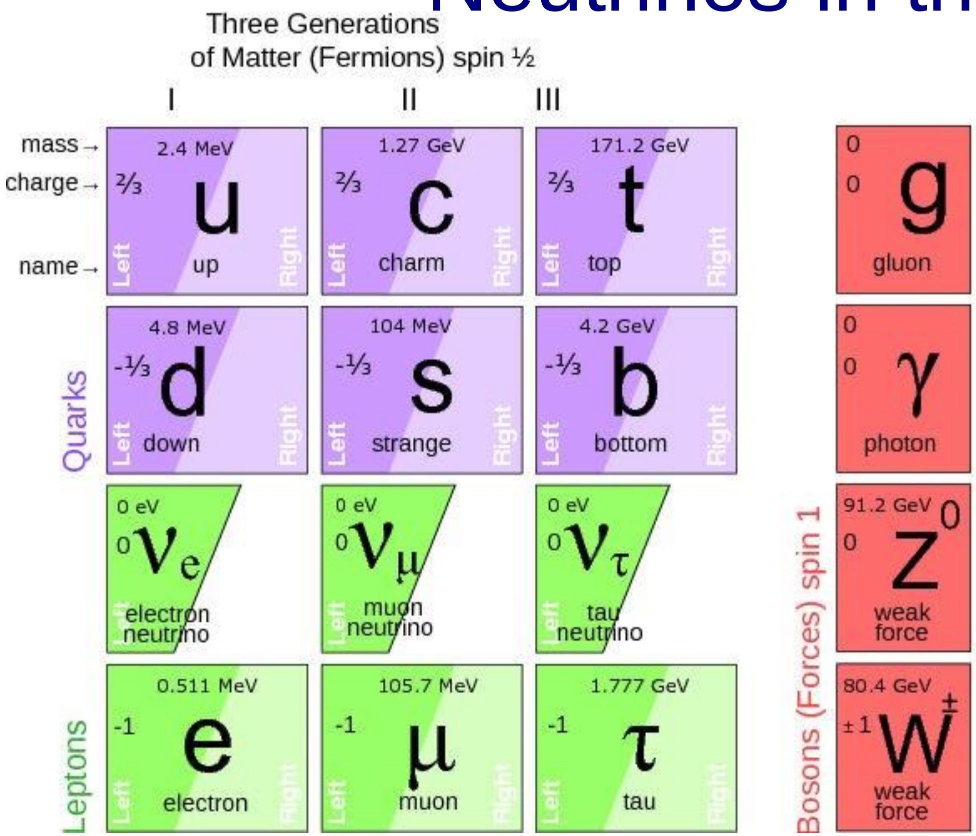
Schedule

Month	Day	Lecture	Teacher
~~September~~	~~22~~	~~Introduction~~	~~Yeon-jae~~
	~~29~~	~~History of Particle Physics~~	~~Yeon-jae~~
~~October~~	~~6~~	~~Special Relativity~~	~~Edward~~
	~~13~~	~~Quantum Mechanics~~	~~Edward~~
	~~20~~	~~Experimental Methods~~	~~Edward~~
	~~27~~	~~The Standard Model - Overview~~	~~Yeon-jae~~
~~November~~	~~3~~	~~The Standard Model - Limitations~~	~~Yeon-jae~~
	10	Neutrino Theory	Edward
	17	Neutrino Experiment	Edward
	24	No classes, SHP break	
December	1	LHC and Experiments	Yeon-jae
	8	The Higgs Boson and Beyond	Yeon-jae
	15	Particle Cosmology	Edward

Neutrinos in the Standard Model

What is special about neutrinos
in the Standard Model?

Neutrinos in the Standard Model



- **Only weak interaction.**

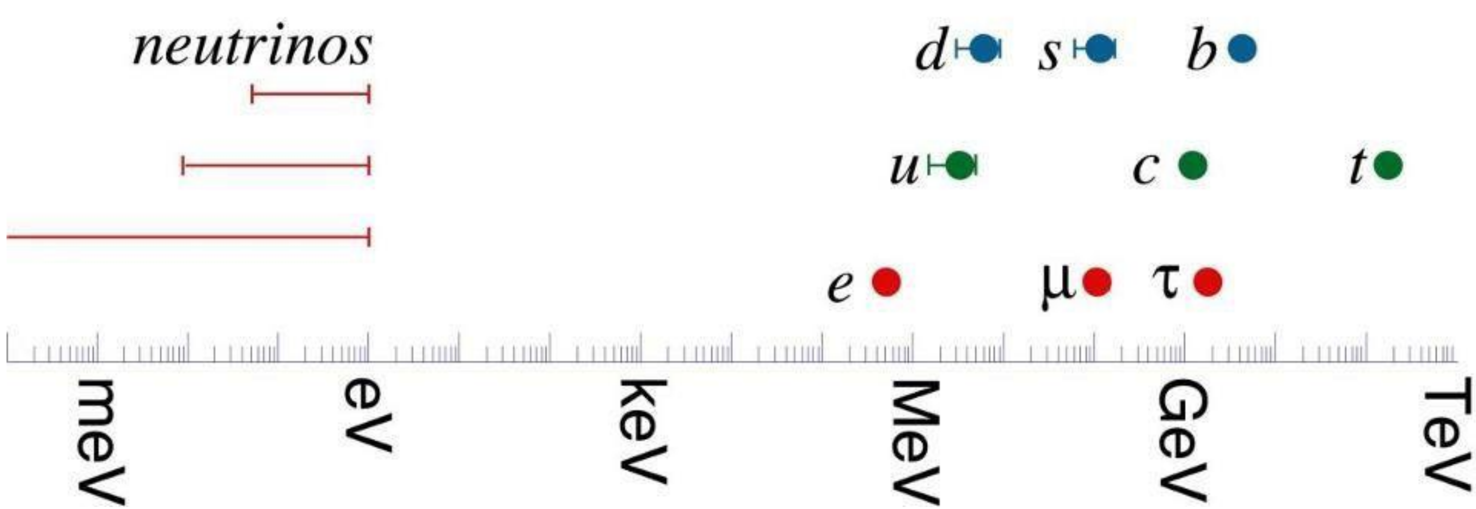
  Only left-handed neutrinos (and right-handed antineutrinos) in the Standard Model.

- Initially implemented as massless particles.

  Neutrino oscillations show neutrinos have mass!

- Why neutrino masses are so different from the other fermions?

  Are neutrinos acquiring mass through the same mechanism (Higgs) or from something else?



Neutrino oscillations (two-neutrino example)

- Consequence of **neutrino mixing** (**quantum superposition**, as in Schrödinger's cat): **the neutrinos that interact are not the same kind as the neutrinos that propagate.**
- Two-flavor approximation:

Flavor eigenstates **Mass eigenstates**

$$\begin{pmatrix} |\nu_l\rangle \\ |\nu_x\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{pmatrix}$$

Mixing angle

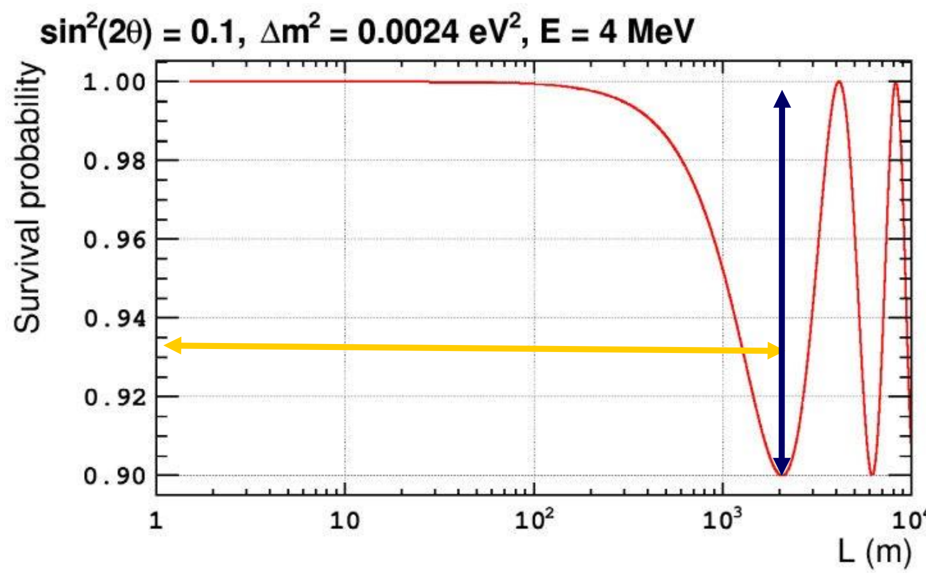
- **Transition** probability (*derivation in blackboard*):

$$P^{2\nu}_{lx\,(l\neq x)}(L,E) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Controlled by the experiment

- **Survival** probability:

$$P^{2\nu}_{ll}(L,E) = 1 - P_{lx\,(l\neq x)}(L,E)$$



- **Neutrino oscillation** implies **neutrinos are massive** and non-degenerated.

3 neutrino mixing

- **Flavor eigenstates (ν_e, ν_μ, ν_τ) ≠ mass eigenstates (ν_1, ν_2, ν_3).**
- Related by **Pontecorvo-Maki-Nakagawa-Sakata mixing matrix**: 3 neutrinos → 3 angles (θ_{12}, θ_{23}, θ_{13}) + 1 CP-violating phase (δ).

PMNS matrix: U

$c_{ij}=\cos\theta_{ij},\ s_{ij}=\sin\theta_{ij}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \begin{matrix} \rightarrow m_1 \\ \rightarrow m_2 \\ \rightarrow m_3 \end{matrix}$$

Atmospheric & Long-baseline accelerator experiments

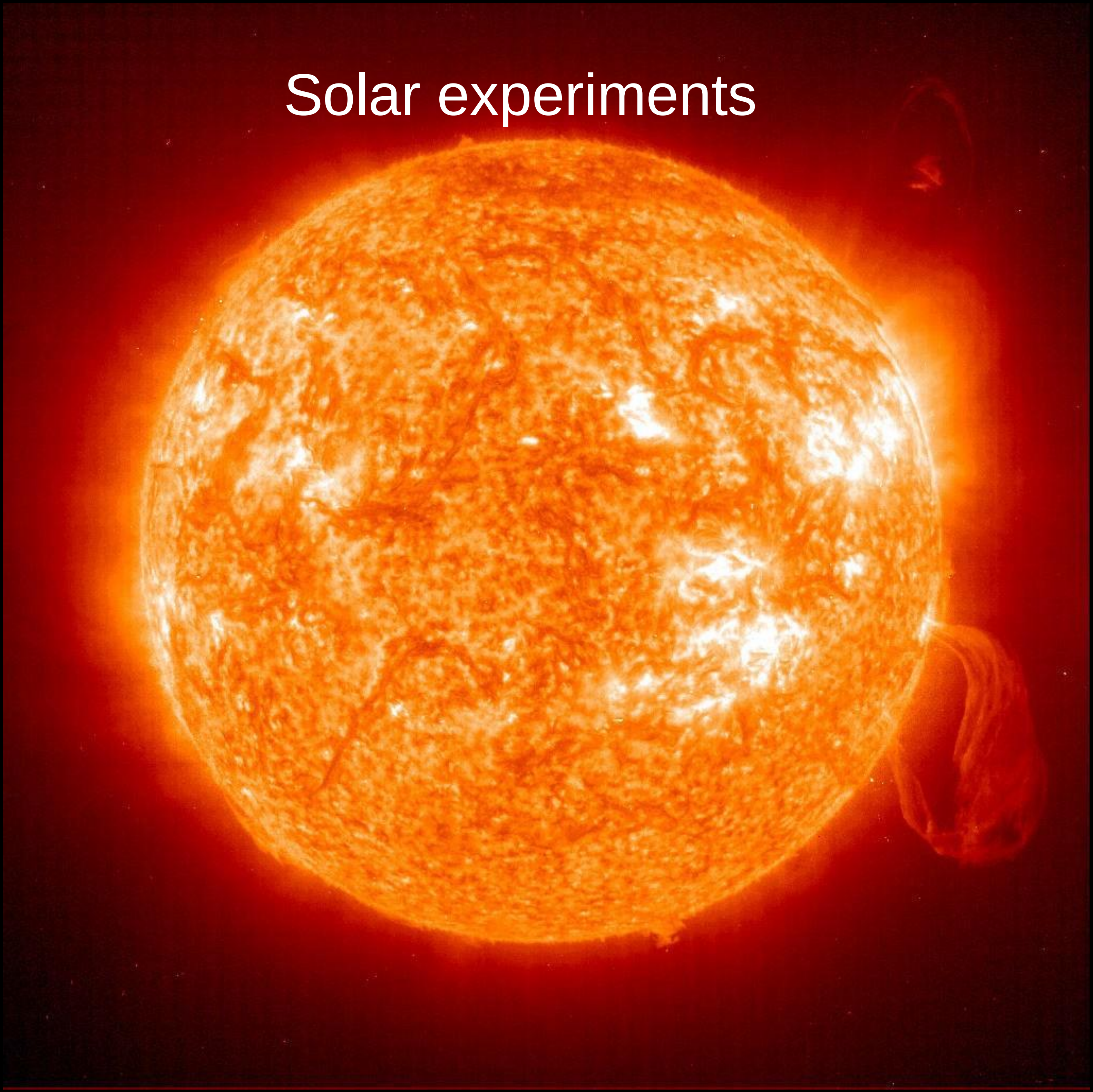
Reactor & Long-baseline accelerator experiments

Solar & KamLAND experiments

- CP-violating phase changes sign for antineutrinos: a **source of matter-antimatter different behavior!**
- CP violation only possible if all three angles are not zero → need to **measure them all!**

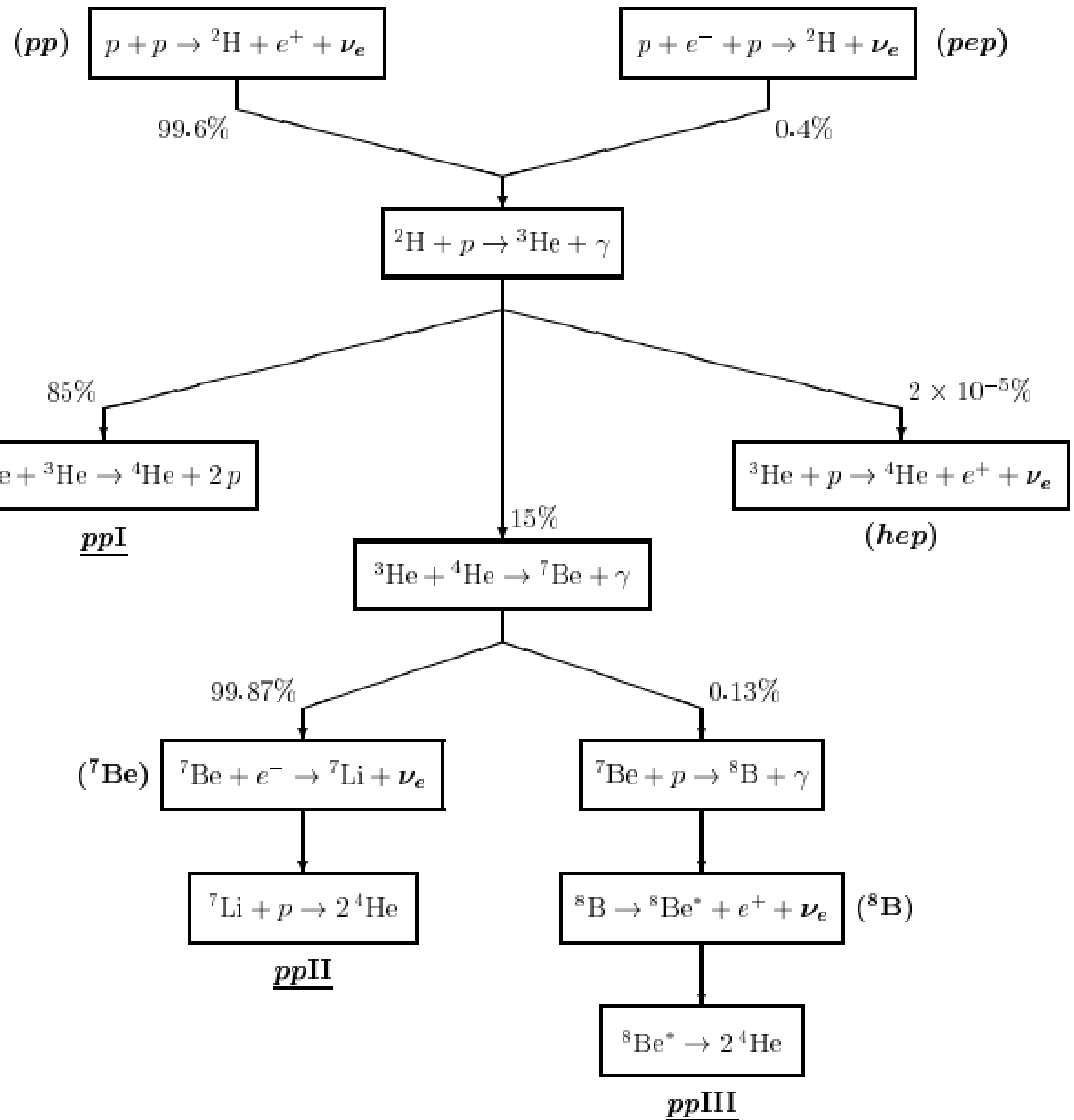
Measurement of θ_{12} and Δm^2_{21}

Solar experiments



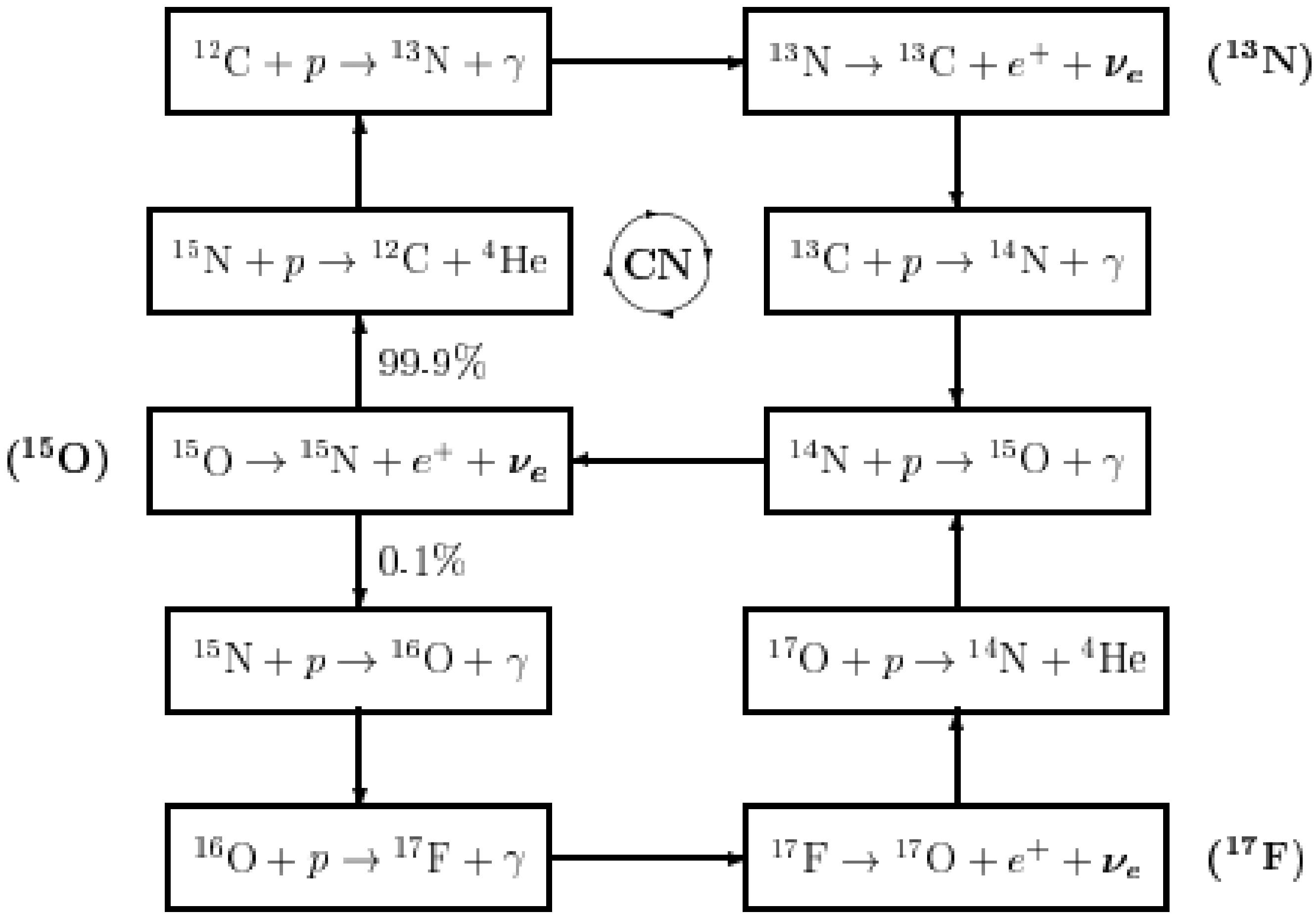
Solar neutrinos: pp chain

- pp chain produces 98.4% of Sun's fusion energy. It also produces **electron neutrinos**.

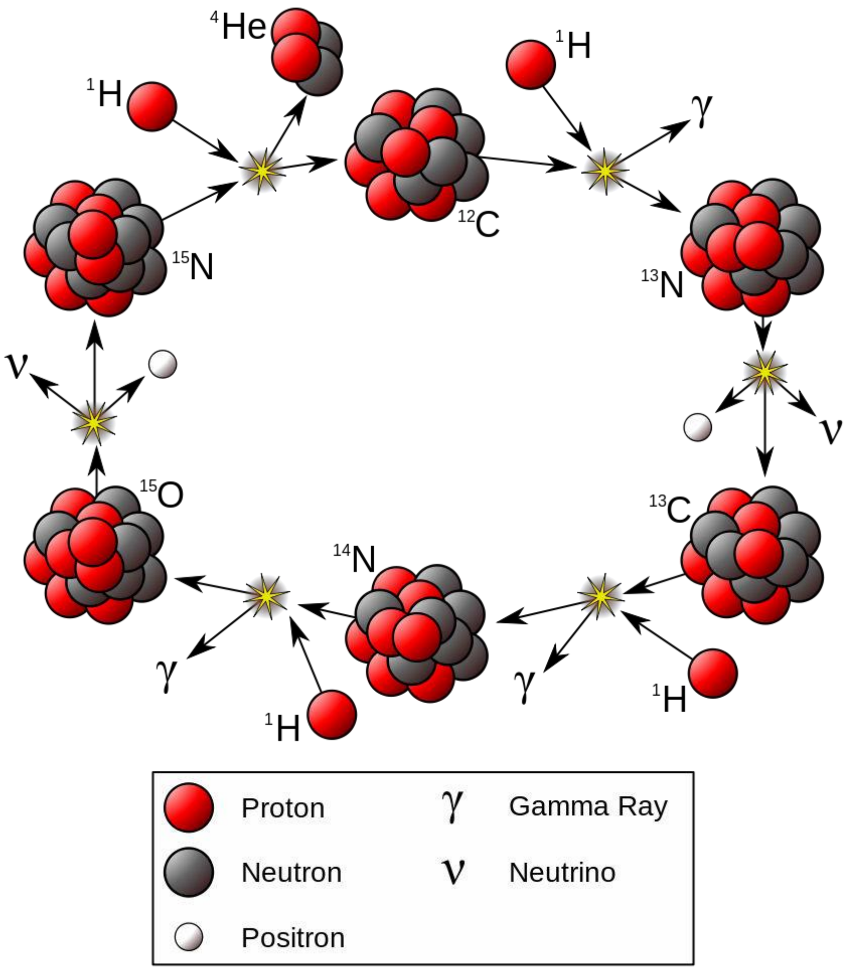


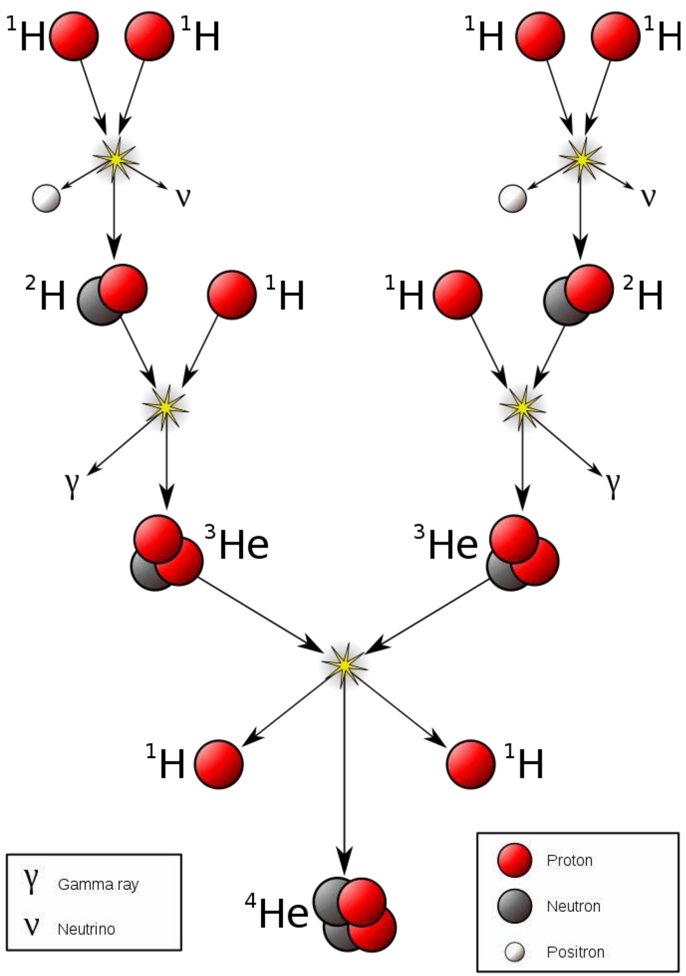
Solar neutrinos: CNO cycle

- CNO cycle produces 1.6% of Sun's fusion energy. It also produces **electron neutrinos**.

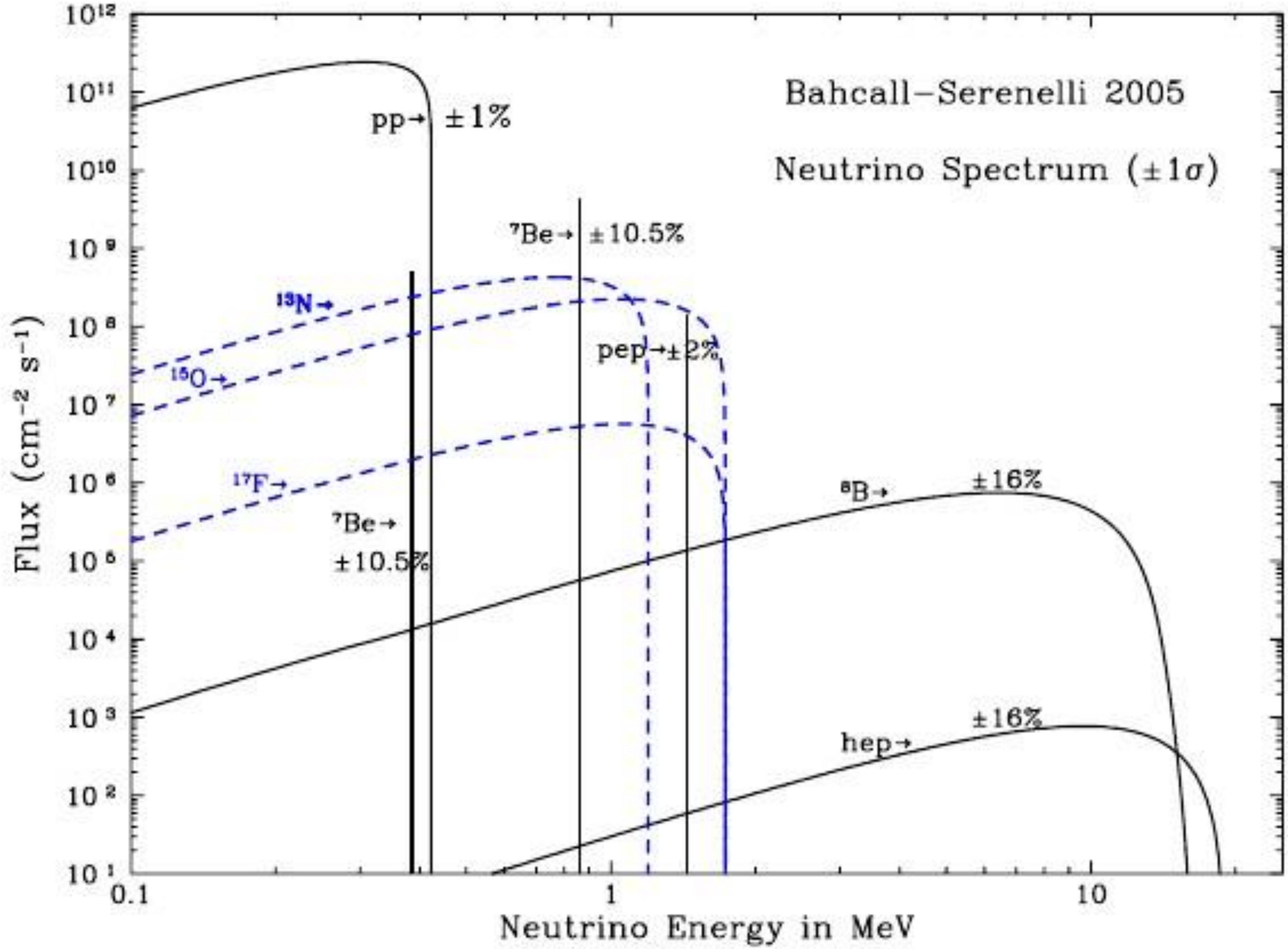


Solar neutrinos: pp chain and CNO cycle Illustrations

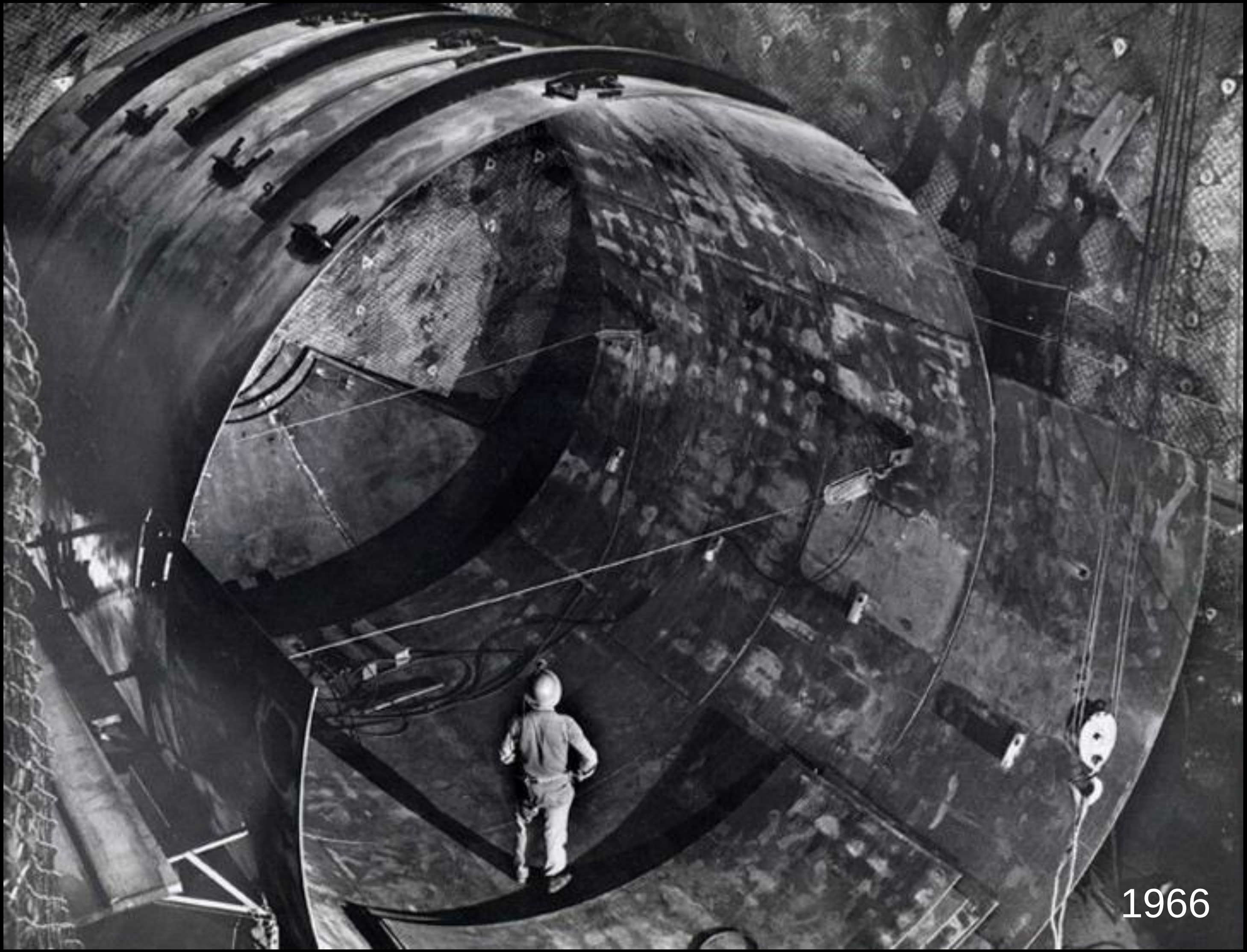




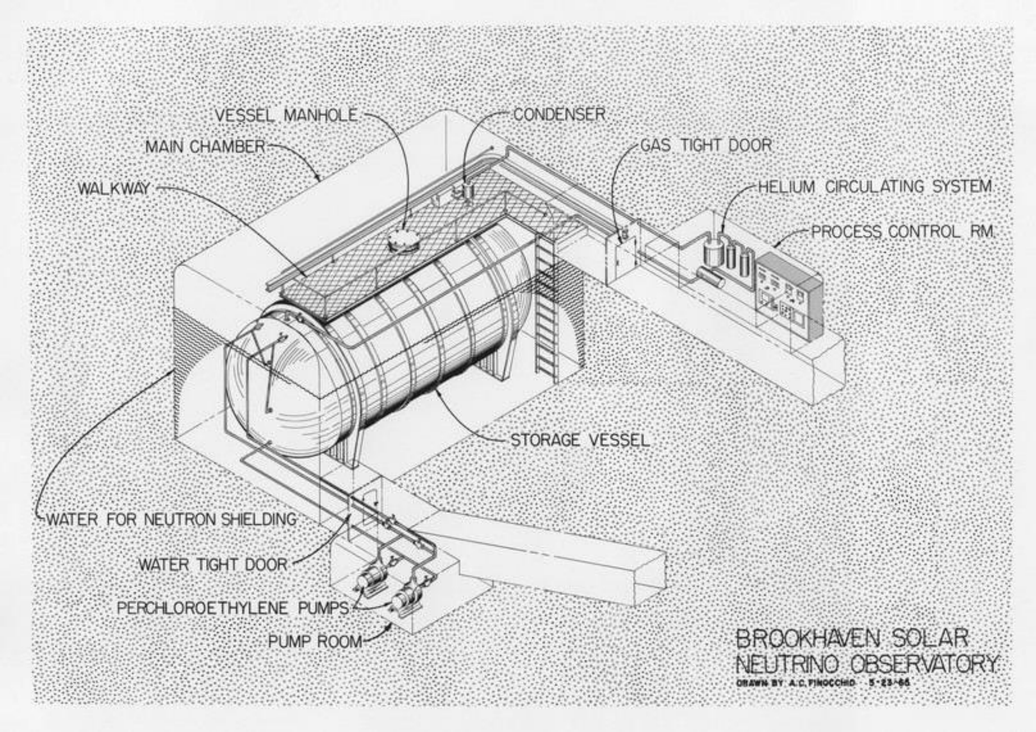
Solar neutrinos: energy spectrum



Homestake experiment (1970 - 1994)



Homestake experiment



- In the late 1960s Ray Davis and John Bahcall set up an experiment to try to detect these solar neutrinos.
- Detection of solar neutrinos using the reaction:

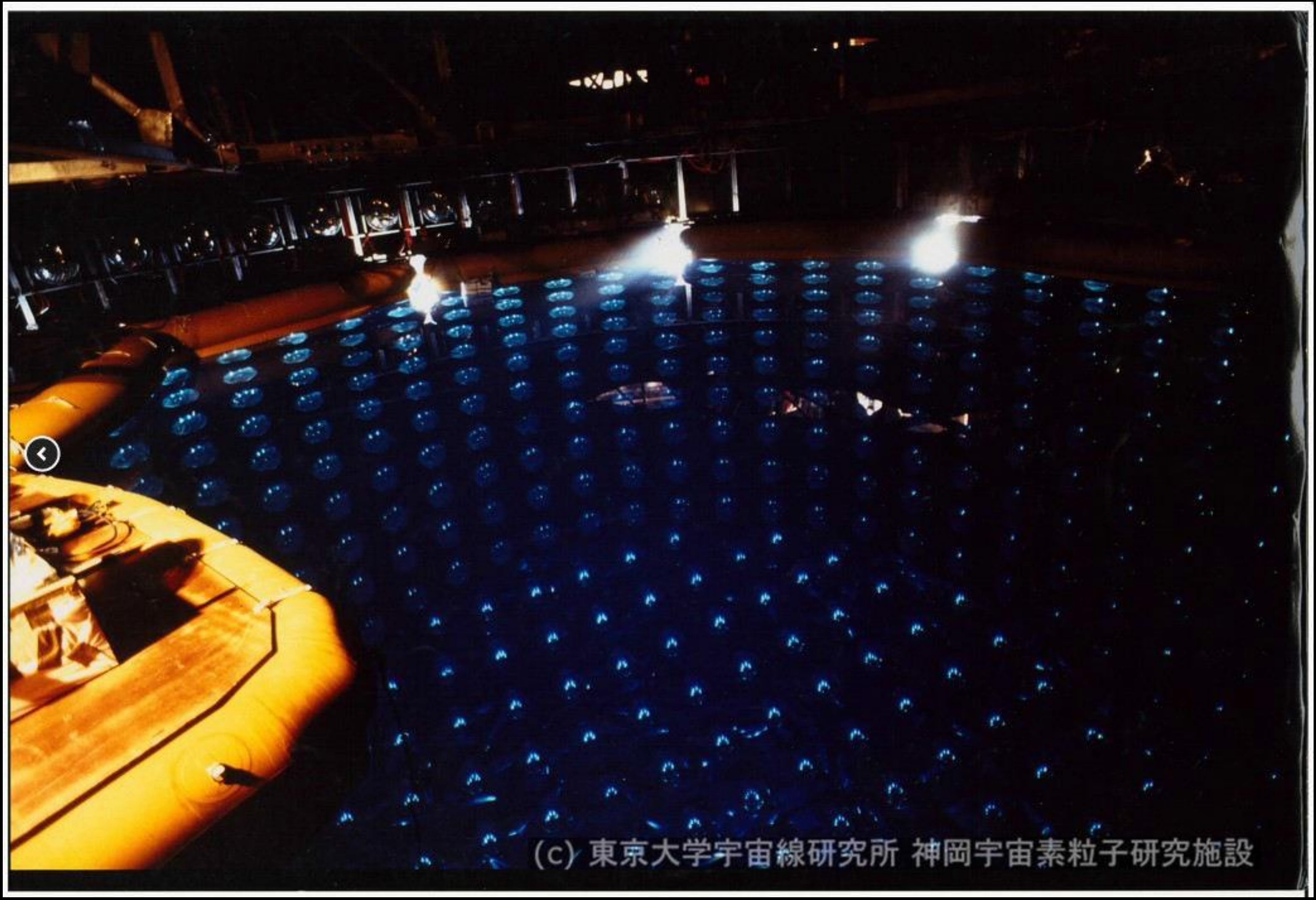
$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$$

- Radiochemical detector.
- Ratio of observed to predicted:

$$\frac{R_{\mathrm{Cl}}}{R_{\mathrm{SSM}}} = 0.301 \pm 0.027$$

- **Missing neutrinos!**

Kamiokande (1983 - 1996)



Kamiokande

- Detection of solar neutrinos using the reaction:

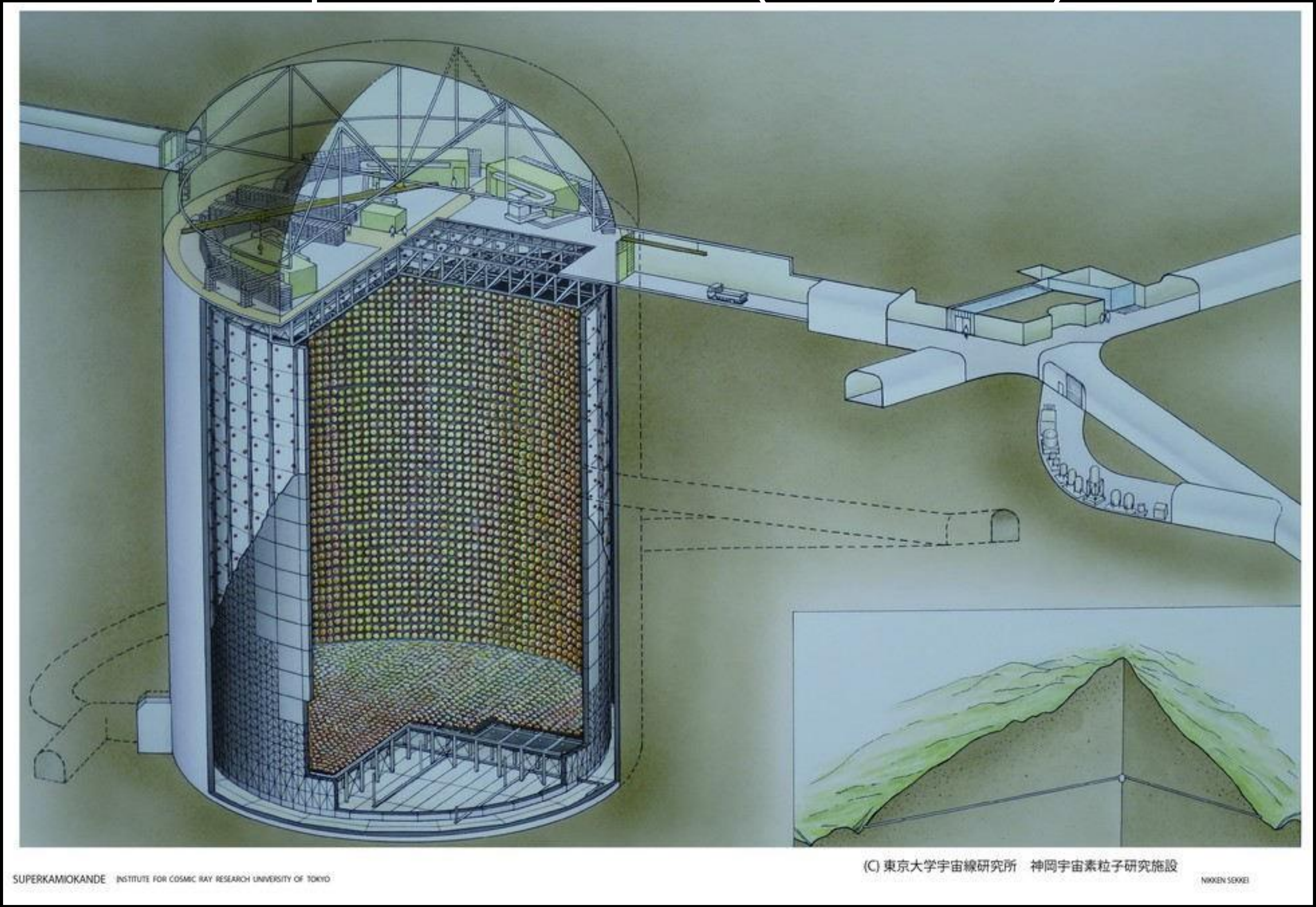
$$\nu_l + e^- \to \nu_l + e^-$$

- Water Cherenkov detector.
- Ratio of observed to predicted:

$$\frac{\Phi_{\text{Kamiokande}}}{\Phi_{\text{SSM}}} = 0.484 \pm 0.066.$$

- **Missing neutrinos again!**

Super-Kamiokande (since 1996)



Super-Kamiokande

- Detection of solar neutrinos using the reaction:

$$\nu_l + e^- \rightarrow \nu_l + e^-$$

- Water Cherenkov detector.
- Ratio of observed to predicted:

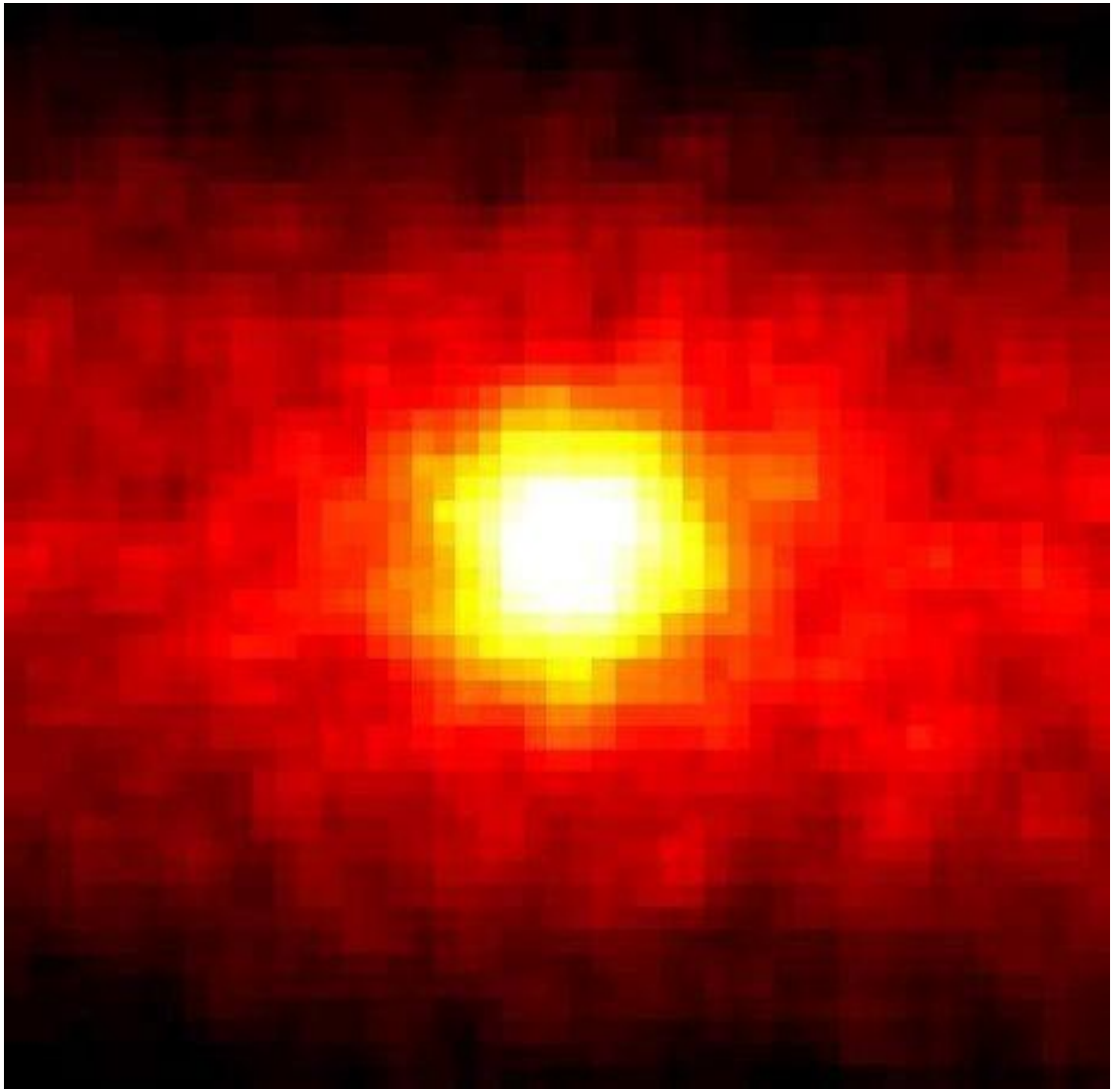
$$\frac{\Phi_{\mathrm{SK-I}}}{\Phi_{\mathrm{SSM}}} = 0.406 \pm 0.014$$

- **Improved result over Kamiokande, neutrinos still missing!**

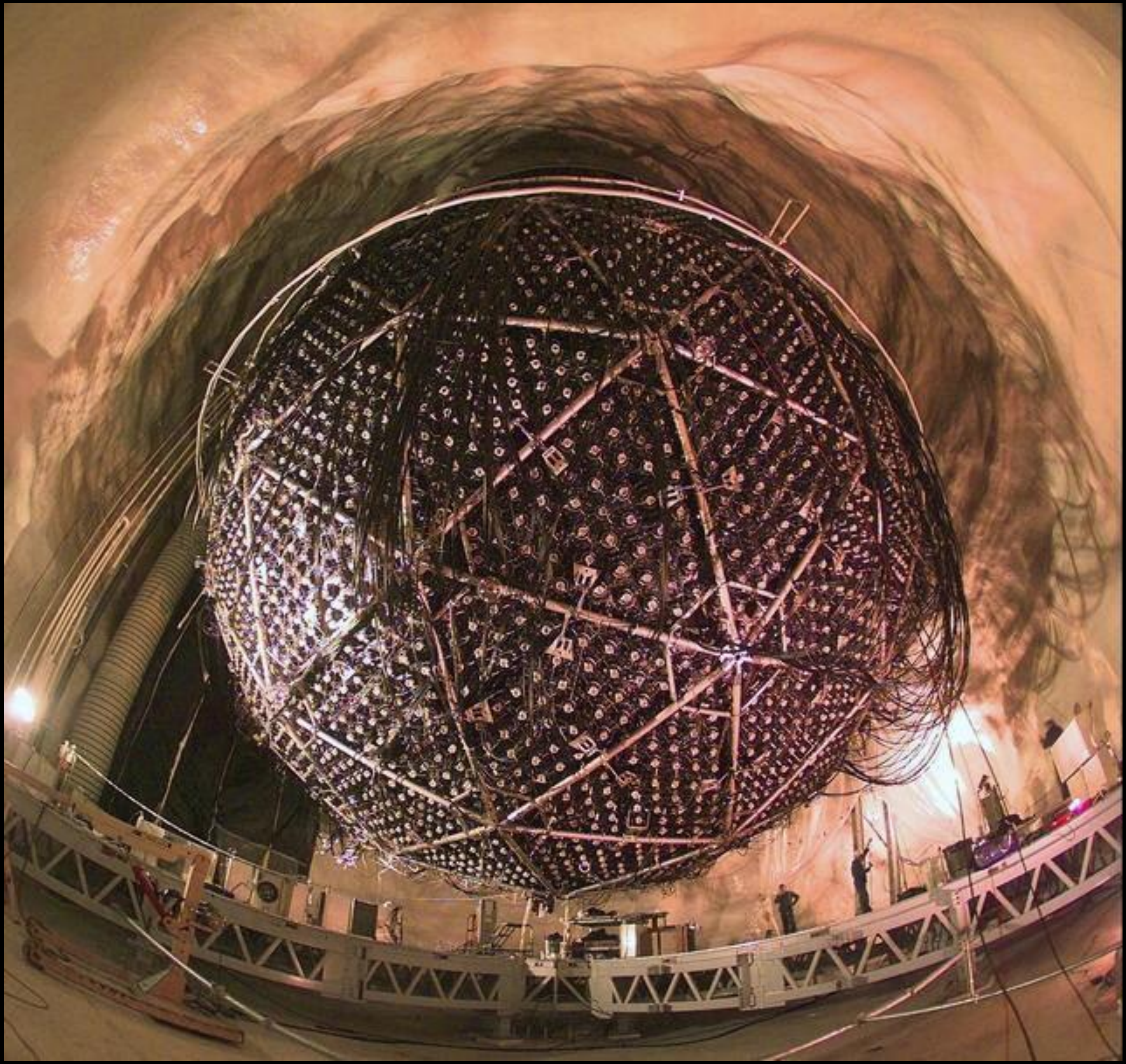
Super-Kamiokande

Super-Kamiokande

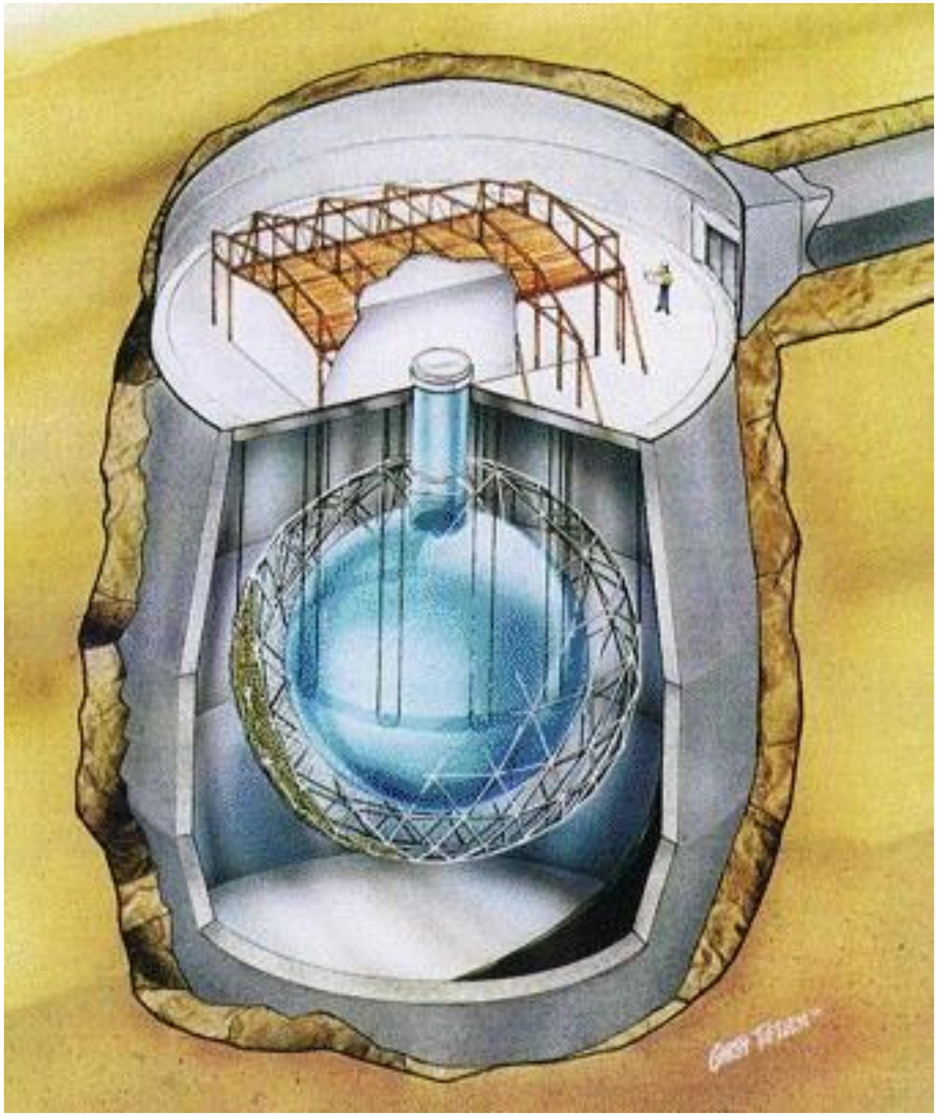
- **NEUTRINOGRAPHY** of the Sun. 500 days exposure!



SNO (1999 - 2006)



SNO



- Detection of solar neutrinos using the reactions:

$$\nu_l + e^- \rightarrow \nu_l + e^- \quad \text{(ES)}$$
$$\nu_e + \text{D} \rightarrow e^- + p + p \quad \text{(CC)}$$
$$\nu_l + \text{D} \rightarrow \nu_l + p + n \quad \text{(NC)}$$

- Heavy Water Cherenkov detector.
- Ratio of observed to predicted:

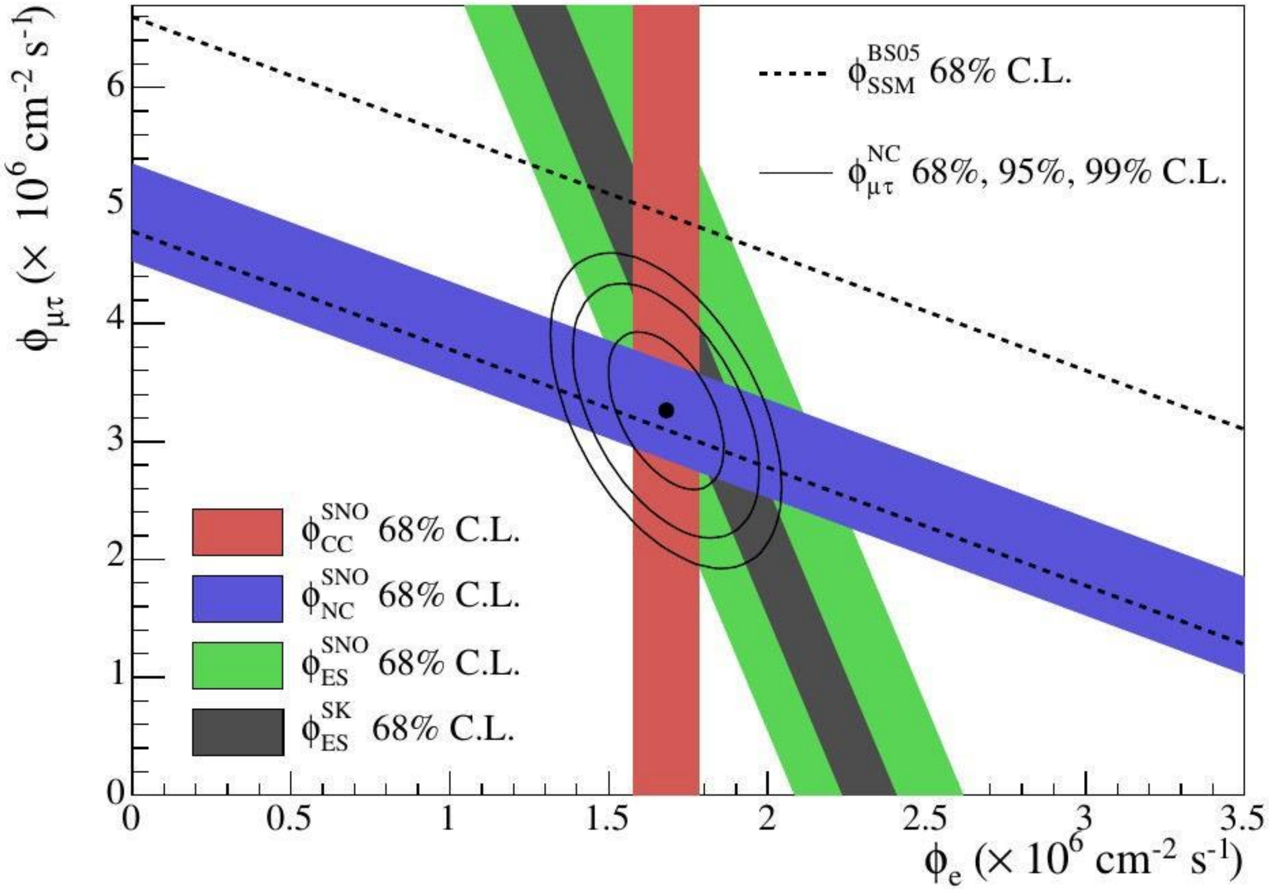
$$\frac{\Phi^{\text{ES}}_{\text{SNO}}}{\Phi_{\text{SSM}}} = 0.406 \pm 0.046$$
$$\frac{\Phi^{\text{CC}}_{\text{SNO}}}{\Phi_{\text{SSM}}} = 0.290 \pm 0.017$$
$$\frac{\Phi^{\text{NC}}_{\text{SNO}}}{\Phi_{\text{SSM}}} = 0.853 \pm 0.075$$

SNO

$$\Phi^{\nu_e}_{\text{SNO}} + r^{\text{ES}}\,\Phi^{\nu_{\mu,\tau}}_{\text{SNO}} = \Phi^{\text{ES}}_{\text{SNO}} \qquad r^{\text{ES}} \equiv \sigma^{\text{ES}}_{\nu_{\mu,\tau}}/\sigma^{\text{ES}}_{\nu_e} \approx 0.1553$$

$$\Phi^{\nu_e}_{\text{SNO}} = \Phi^{\text{CC}}_{\text{SNO}}$$

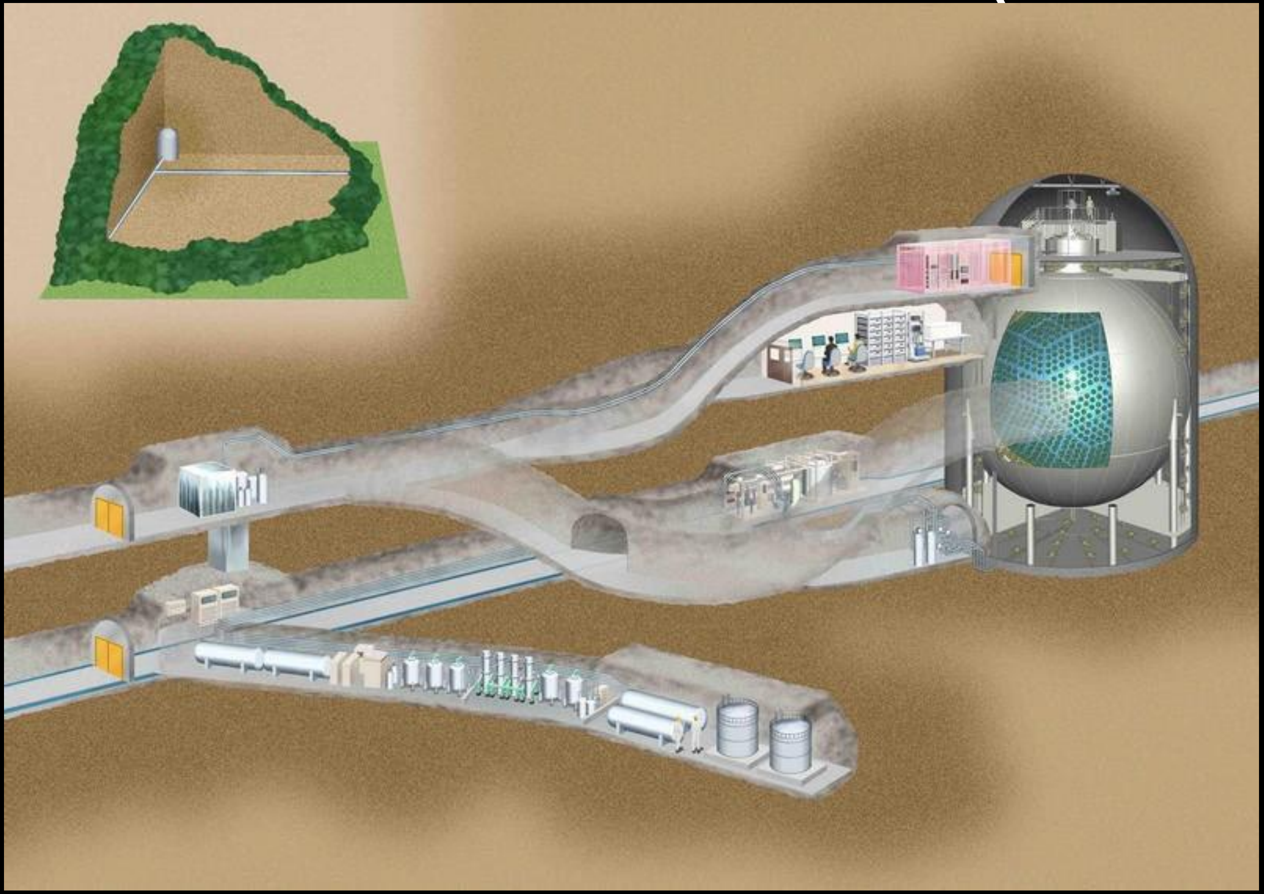
$$\Phi^{\nu_e}_{\text{SNO}} + \Phi^{\nu_{\mu,\tau}}_{\text{SNO}} = \Phi^{\text{NC}}_{\text{SNO}}$$



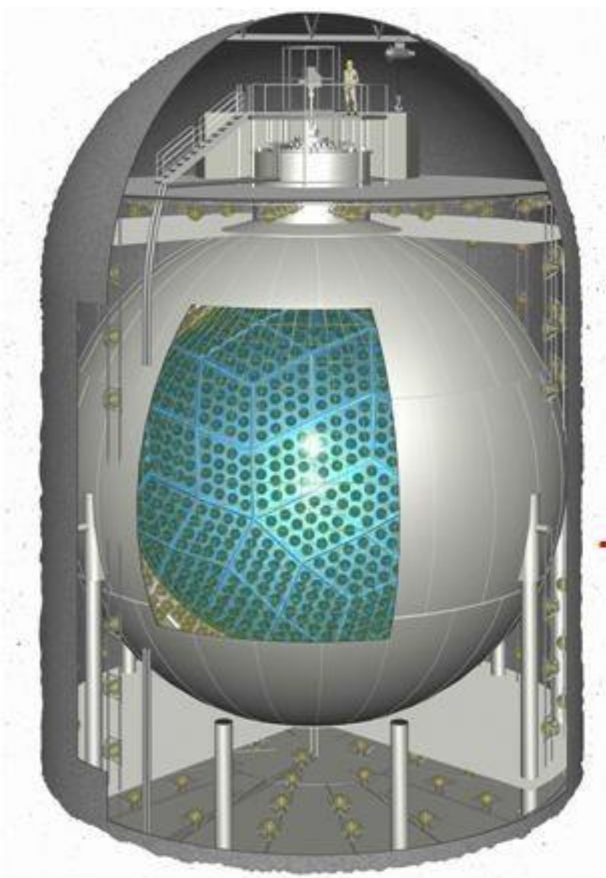
- The SNO results (along with Super-K for atmospheric neutrinos) led to a Nobel prize in 2015.

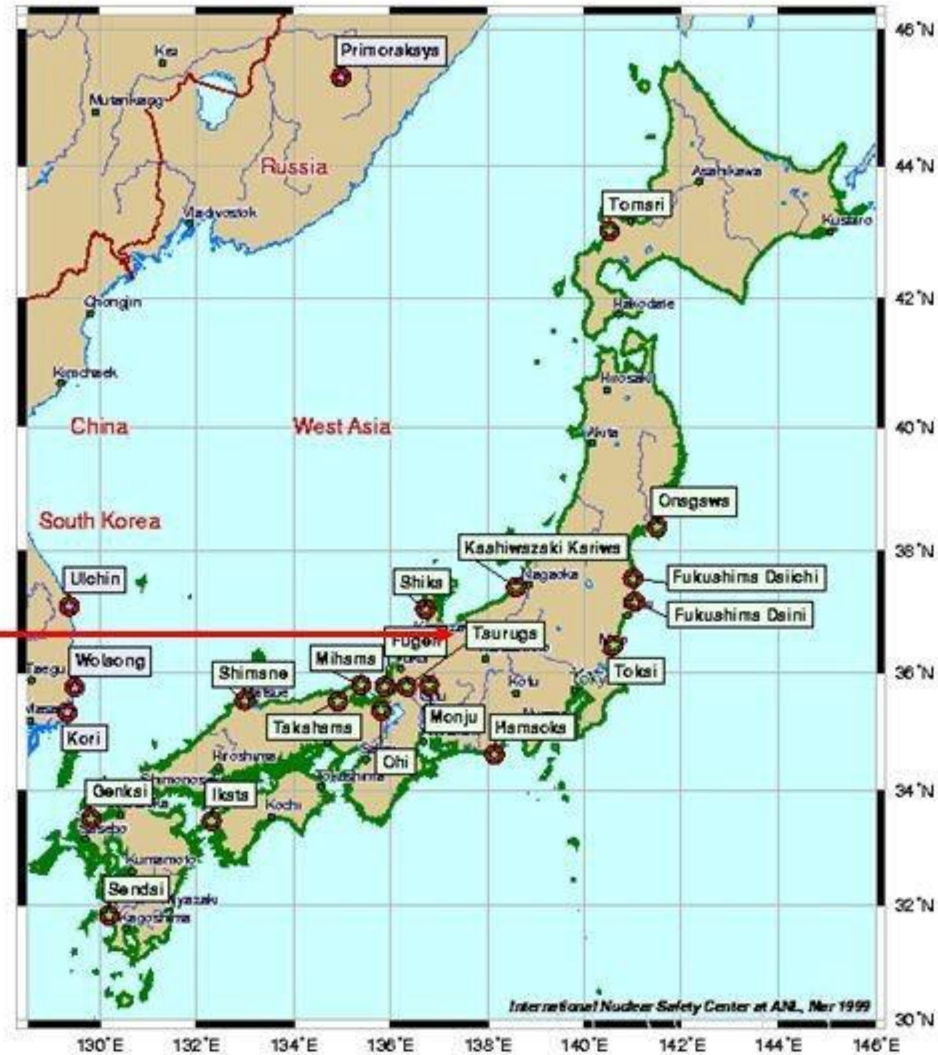
Additional material:
Reactor Experiments

KamLAND (2002 - 2011)



KamLAND



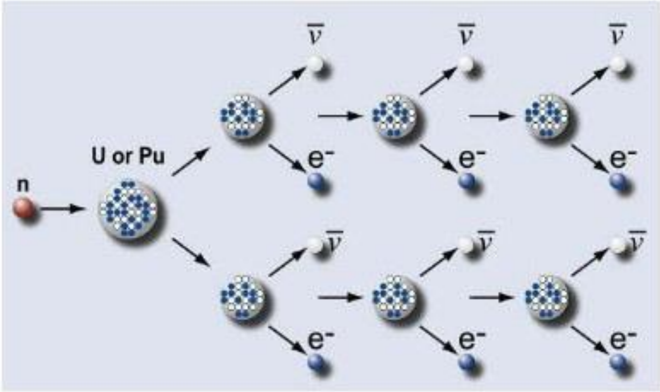

Primorskaya
Russia
Vladivostok
Chongjin
China
West Asia
South Korea
Tomari
Asahikawa
Kushiro
Hakodate
Hirosaki
Akita
Onagawa
Kashiwazaki Kariwa
Niigata
Shika
Fukushima Daiichi
Fukushima Daini
Tsuruga
Fugen
Tokai
Ulchin
Wolsong
Shimane
Mihama
Takahama
Monju
Hamaoka
Ohi
Kori
Hiroshima
Genkai
Ikata
Kochi
Sendai
Kumamoto
Kagoshima
International Nuclear Safety Center at ANL, Mar 1999
46°N
44°N
42°N
40°N
38°N
36°N
34°N
32°N
30°N
130°E
132°E
134°E
136°E
138°E
140°E
142°E
144°E
146°E

$\overline{\nu}_e$ production at nuclear reactors

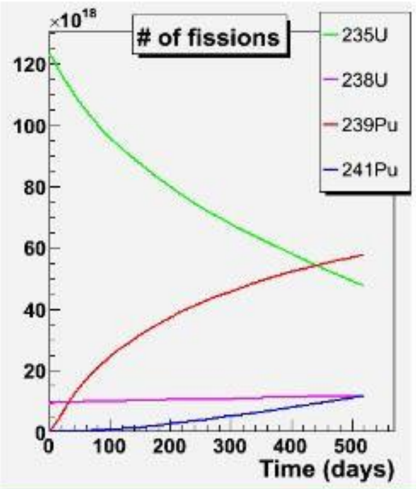
- Fission of nuclear fuel (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu) produces neutron rich fission products.
- β^- decay of fission products:

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \overline{\nu}_{e} $$

- Average per fission:
  - 200 MeV released.
  - 6 antineutrinos.



- Nuclear power plants: greatest man-made antineutrino source.
- Need to consider nuclear fuel evolution.

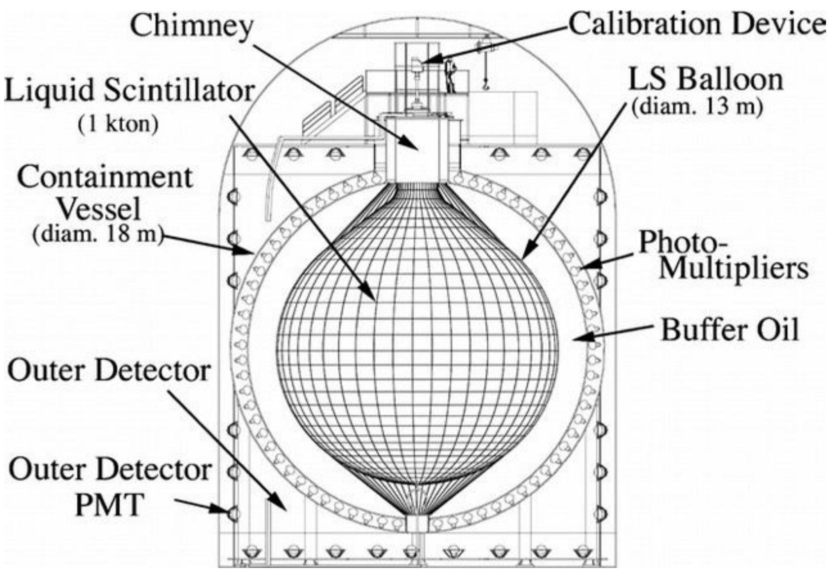


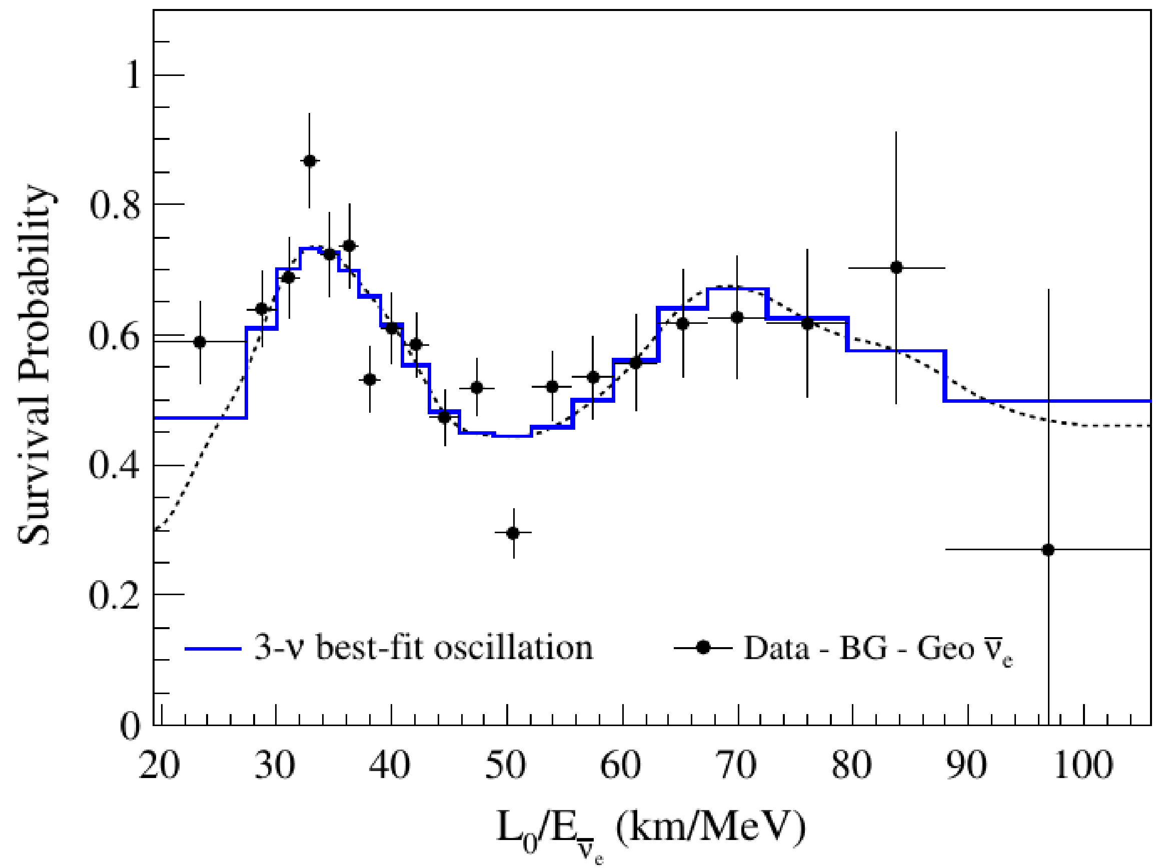
KamLAND

- Detection of reactor neutrinos using the inverse beta-decay reaction:

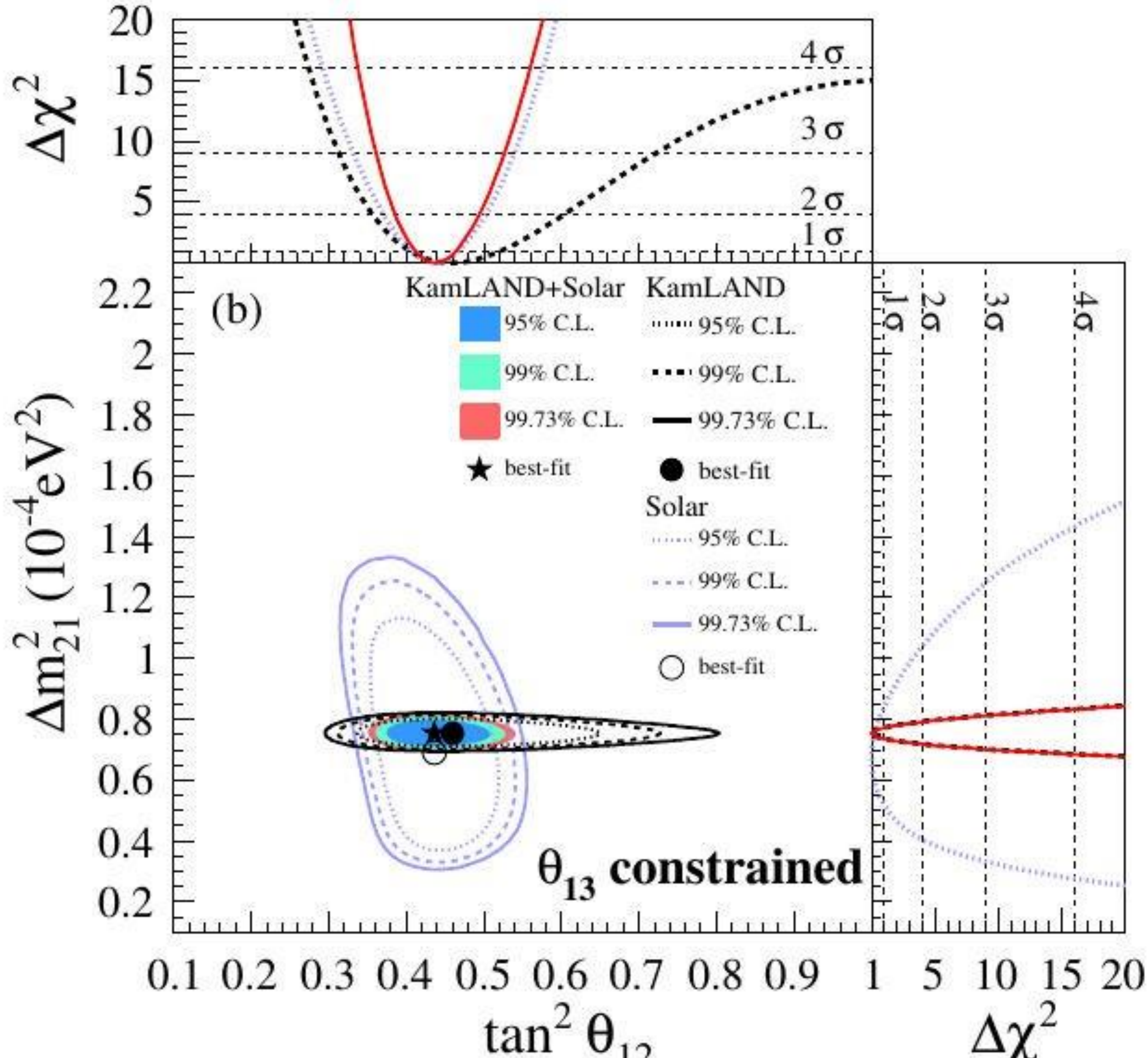
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

- Liquid scintillator detector.





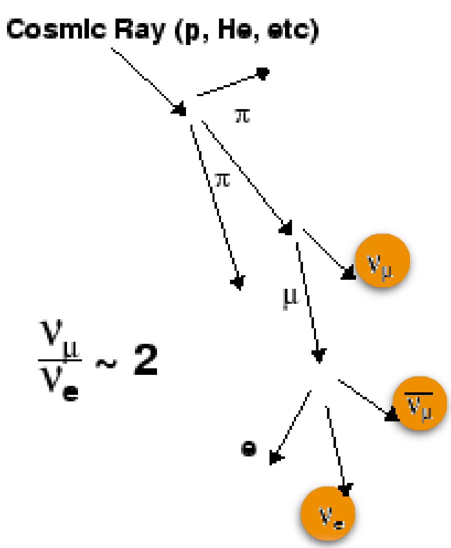
Solar + KamLAND results

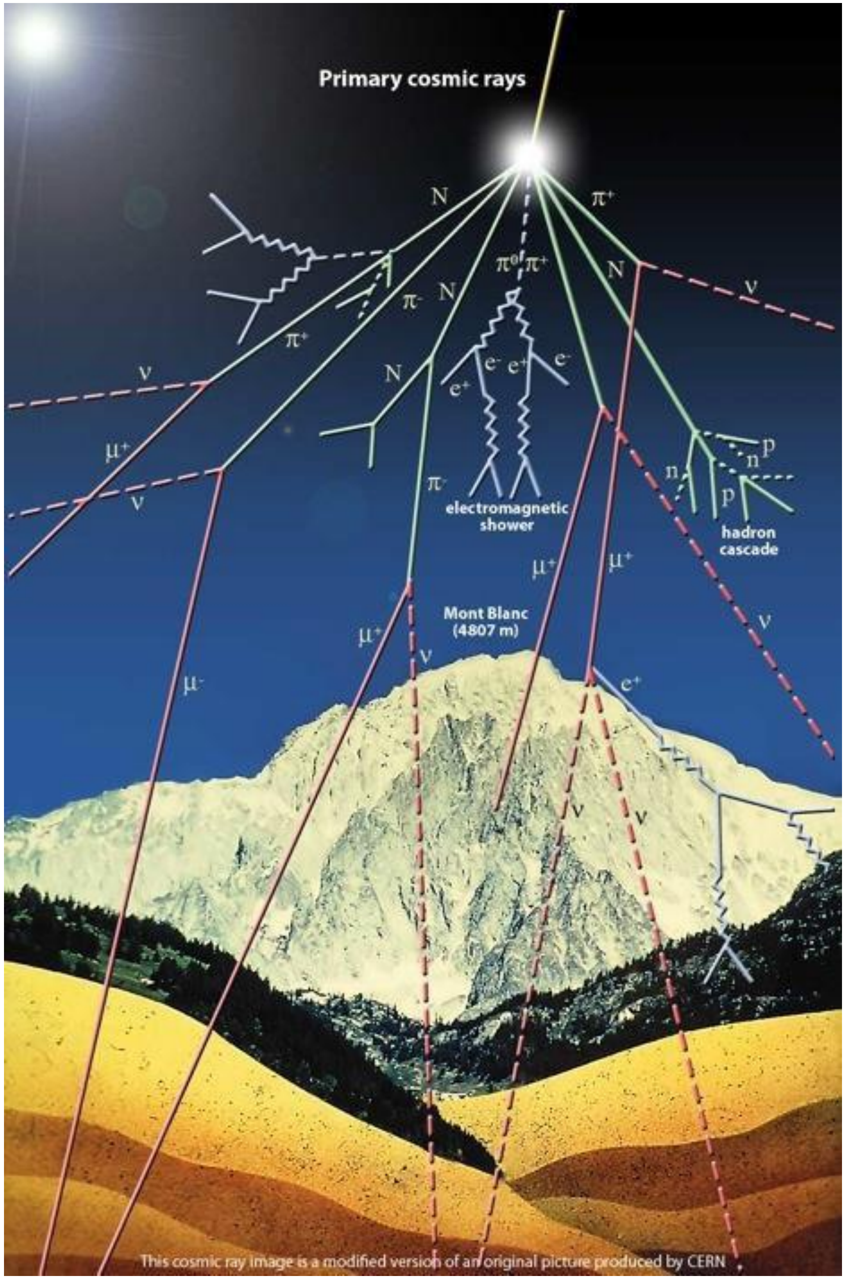


Measurement of θ_{23} and Δm^2_{atm}

NEUTRINOS FROM THE ATMOSPHERE

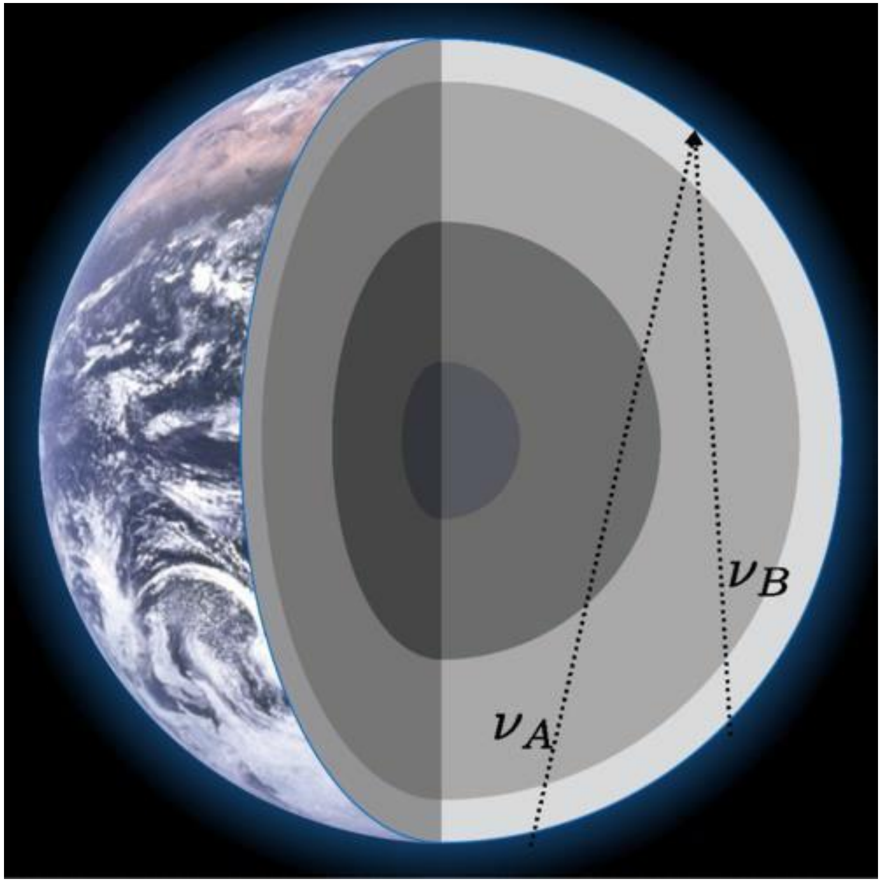
- The Earth is constantly being bombarded by cosmic rays (mostly protons) with astrophysical origin.
- These interact strongly with nuclei in the atmosphere, producing showers of hadrons.
- Unstable hadrons eventually decay to the lightest meson, π, which decays weakly, producing neutrinos!





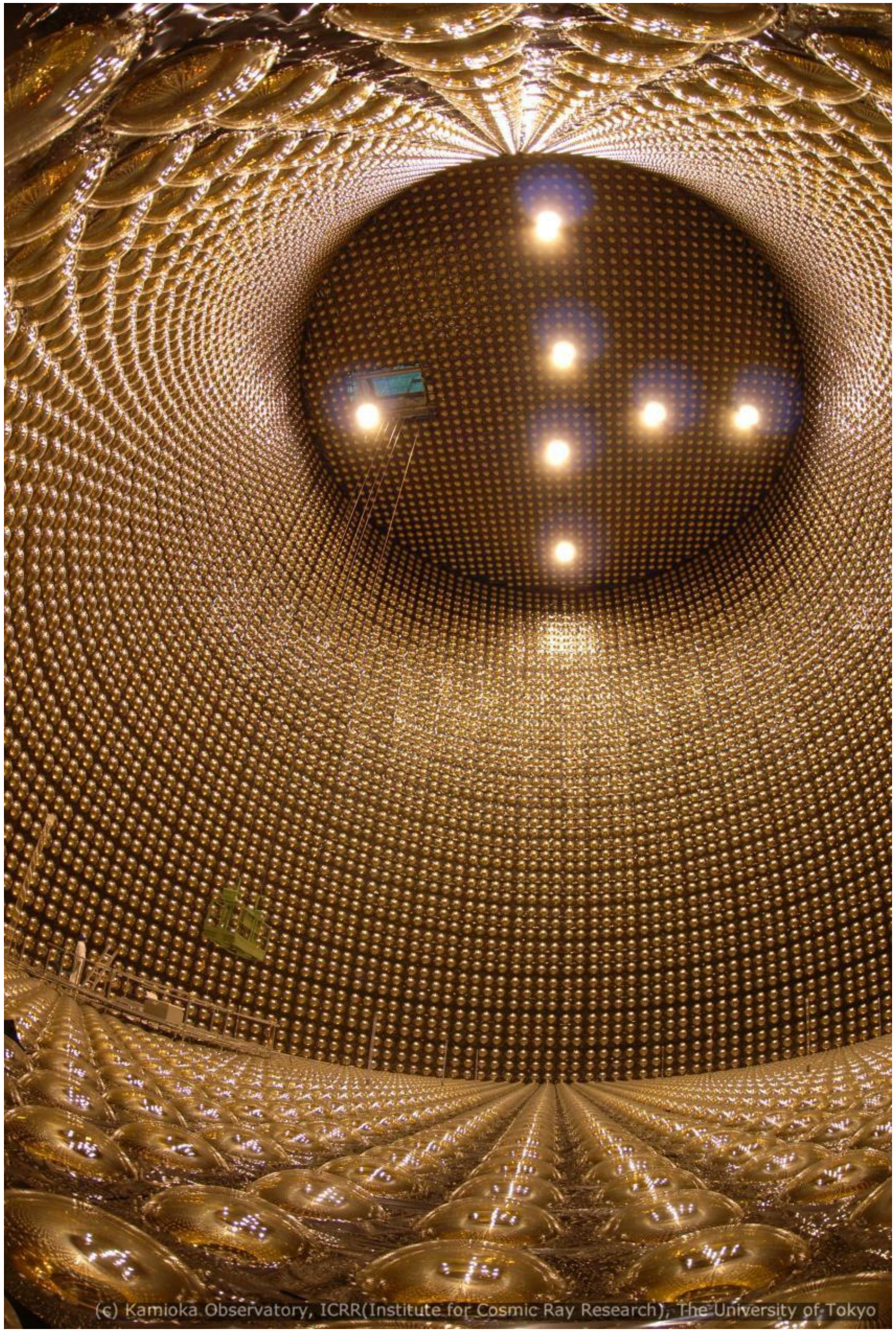
ATMOSPHERIC NEUTRINO OSCILLATIONS

- Naïvely expect 2-to-1 ratio of muon to electron neutrinos.
- However, neutrinos produced on the "far" side of the earth travel thousands of kilometres before they reach a detector.
  - So, they oscillate!
- Comparing the number of neutrinos hitting the detector from the "top" (short L) to those coming from the "bottom" (long L) gives a direct measurement of atmospheric neutrino oscillations.

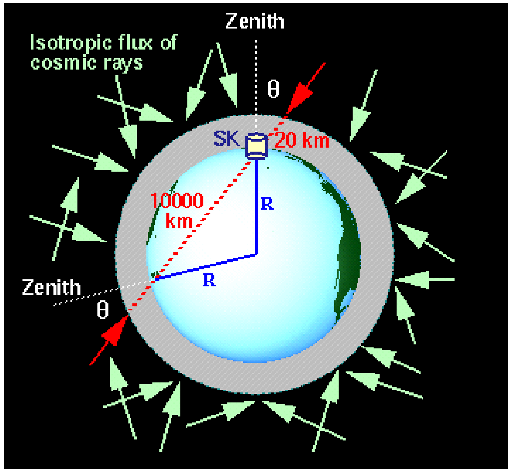


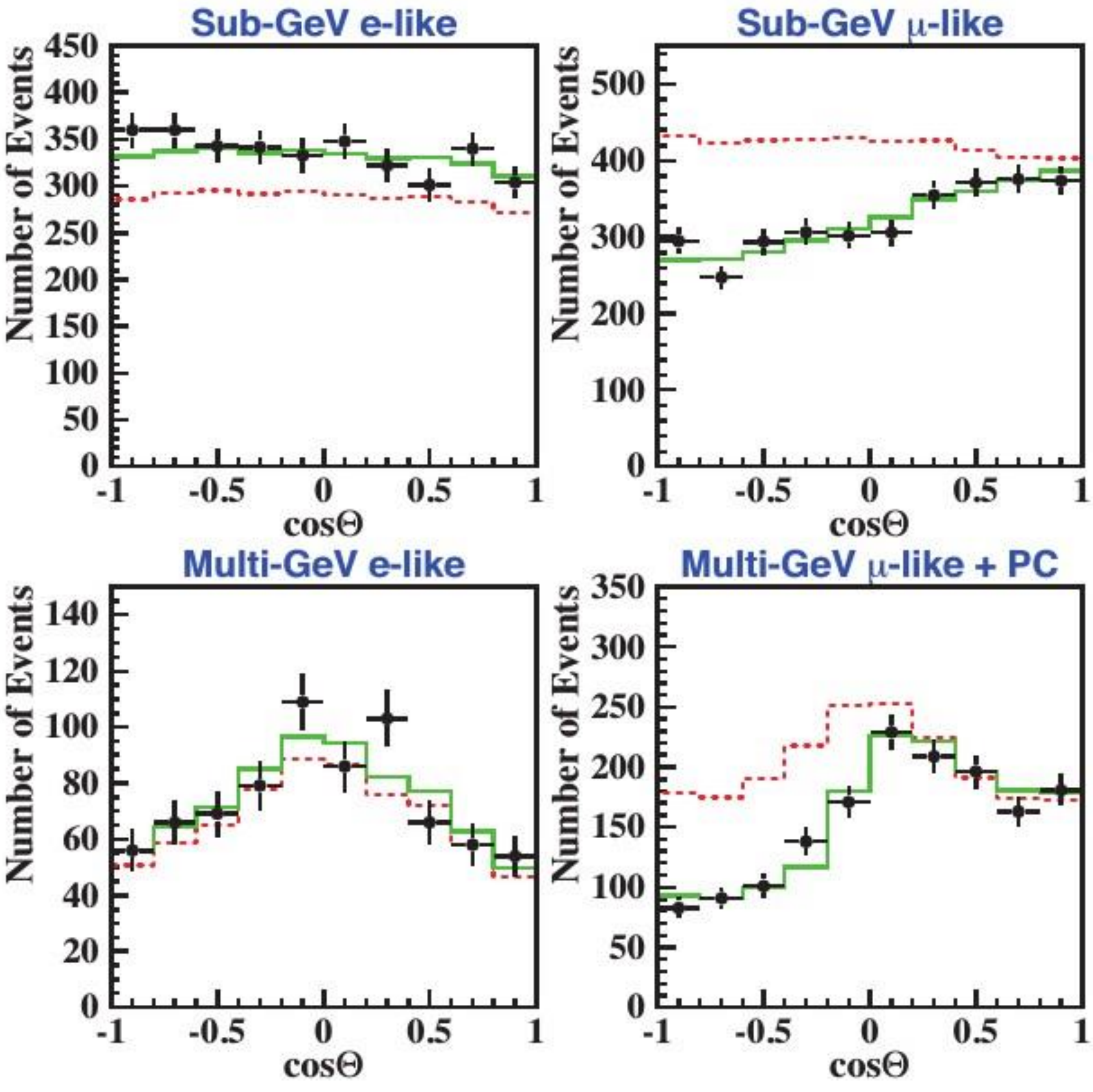
SUPER-KAMIOKANDE

- The Super-Kamiokande experiment was designed to unambiguously observe oscillations in atmospheric neutrinos.
  - Following hints from its predecessor, Kamiokande.
- A tank containing 50 kilo-tons of ultra-pure water is instrumented with 11000 photo sensors to detect Cherenkov radiation emitted by relativistic charged particles.
- Excellent particle identification and directionality.
  - Crucial for oscillation measurement.



Super-Kamiokande results

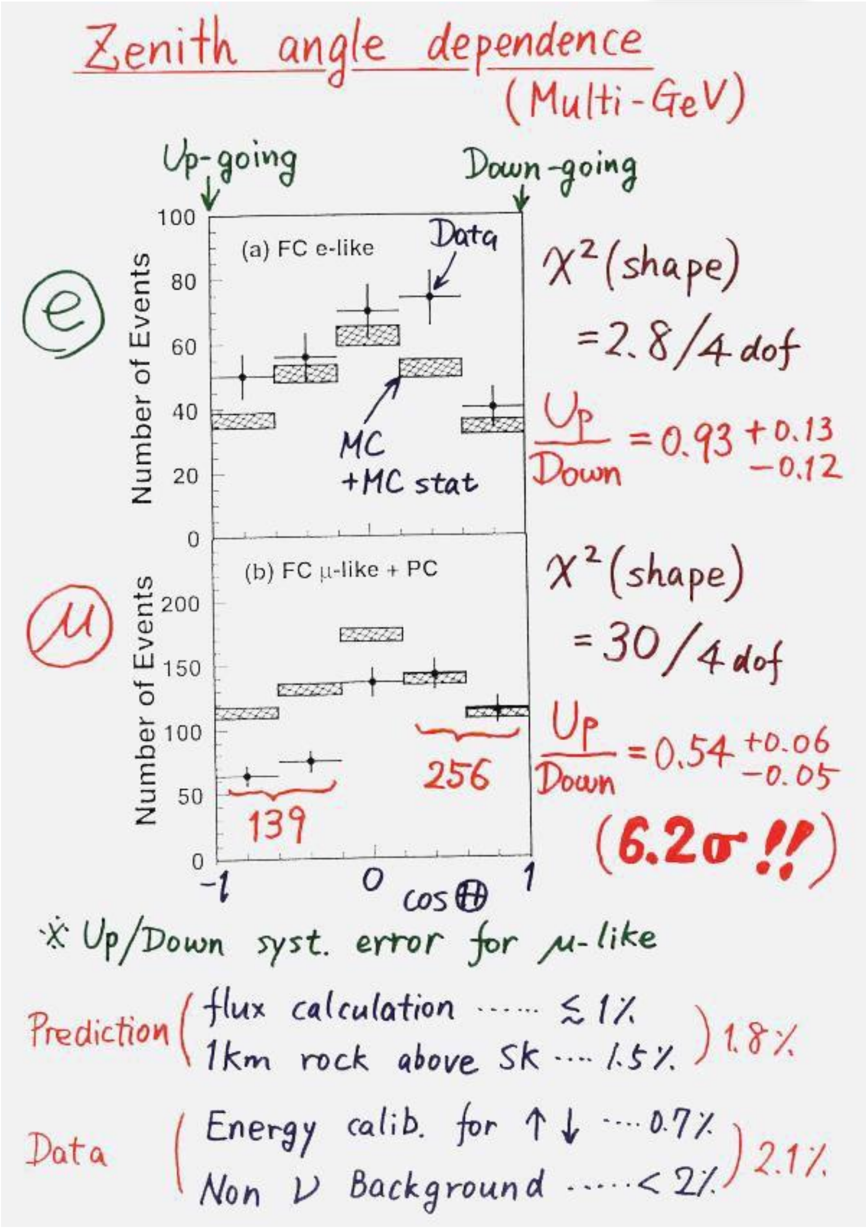




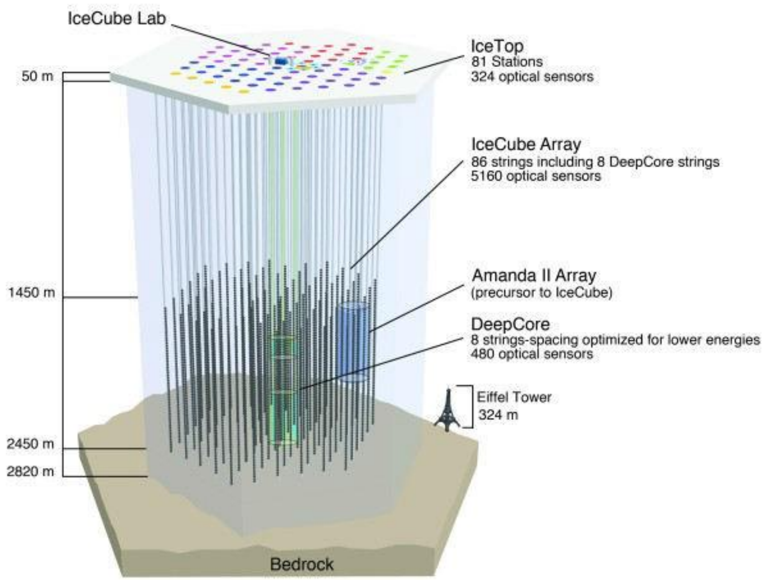
SUPER-K FIRST RESULTS

2015

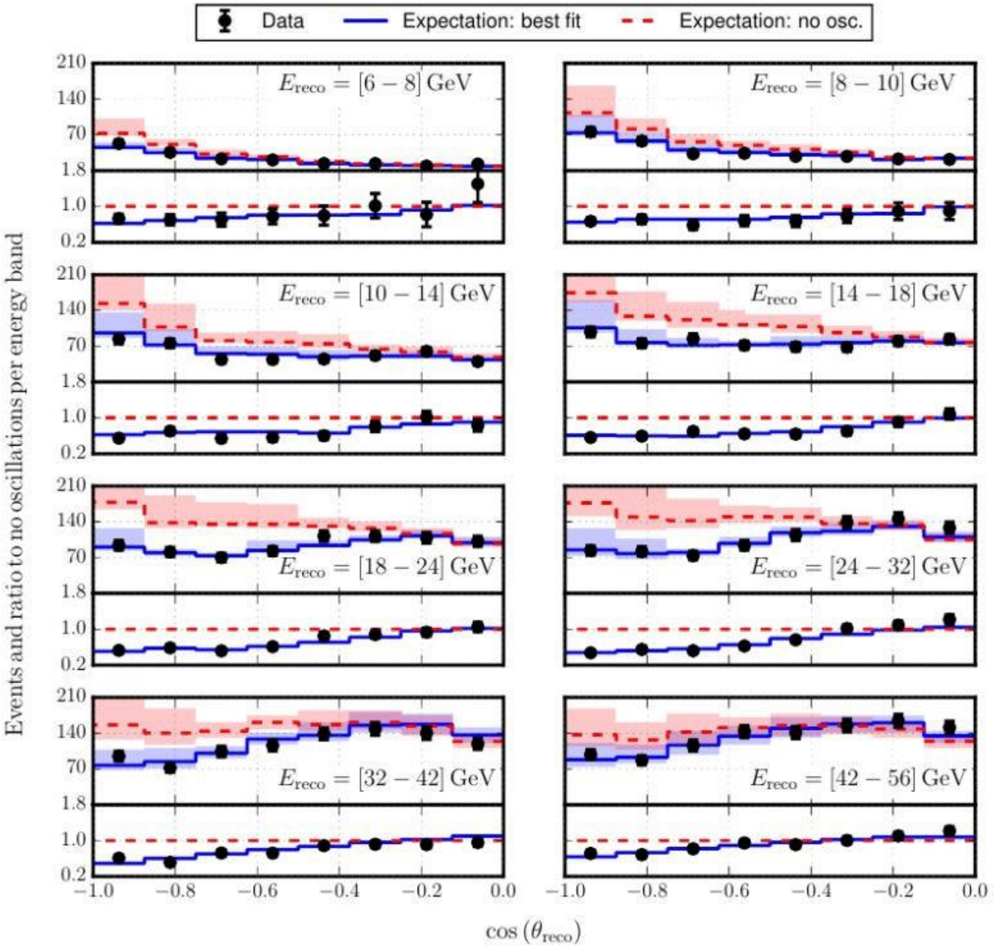
- Super-Kamiokande announced its discovery of oscillations in atmospheric neutrinos in 1998.
- A clear deficit of “up-going” muon neutrinos was observed in the data.
  - Muon neutrinos are oscillating into tau neutrinos, which are not detected.
- Effect not seen in electron neutrinos.
  - Muon neutrino to electron neutrino oscillations are sub-dominant at this L/E.



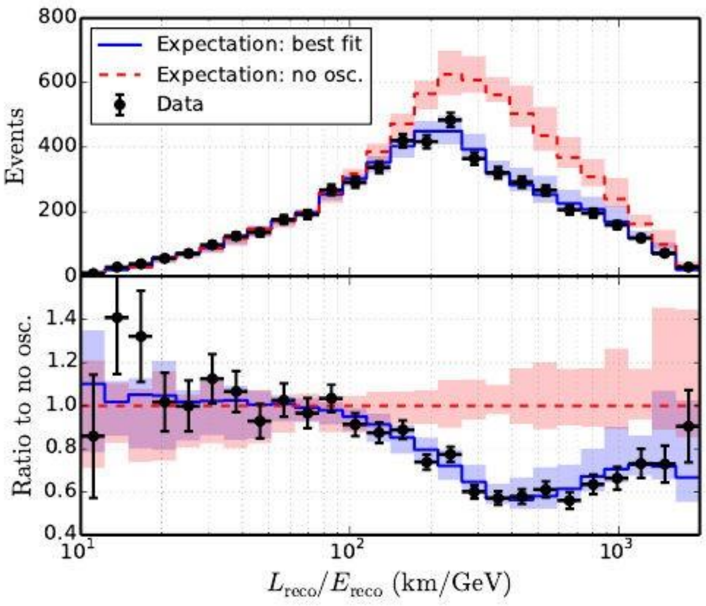
IceCube



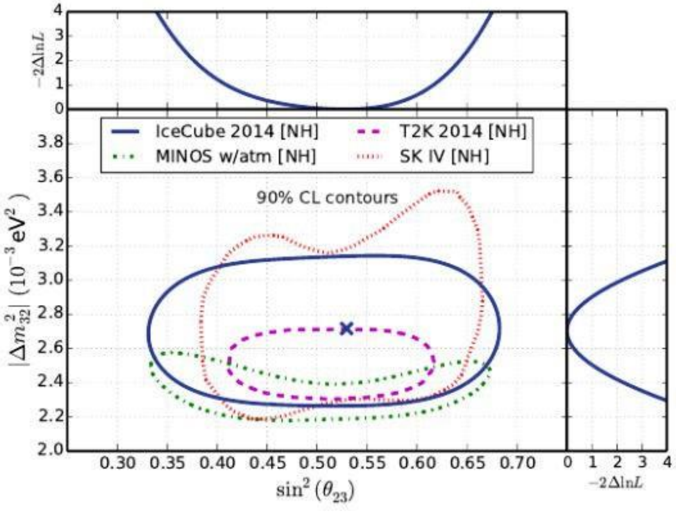
IceCube Lab
IceTop
81 Stations
324 optical sensors
50 m
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
1450 m
Amanda II Array
(precursor to IceCube)
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
Bedrock



Data
Expectation: best fit
Expectation: no osc.
$E_{reco} = [6-8]$ GeV
$E_{reco} = [8-10]$ GeV
$E_{reco} = [10-14]$ GeV
$E_{reco} = [14-18]$ GeV
$E_{reco} = [18-24]$ GeV
$E_{reco} = [24-32]$ GeV
$E_{reco} = [32-42]$ GeV
$E_{reco} = [42-56]$ GeV
Events and ratio to no oscillations per energy band
$\cos(\theta_{reco})$



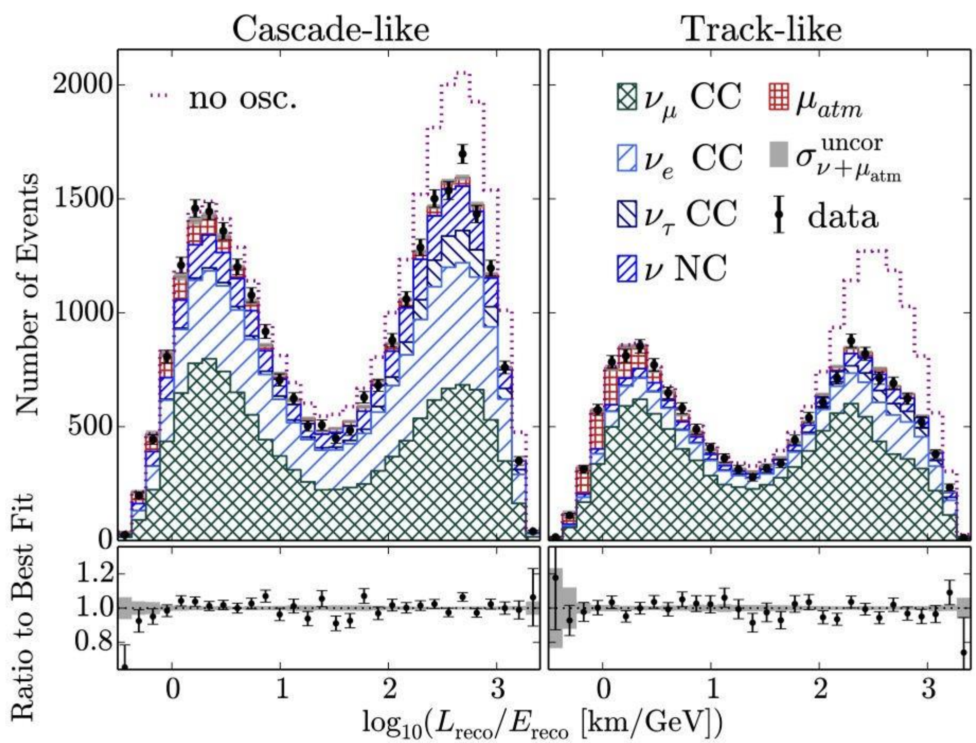
Expectation: best fit
Expectation: no osc.
Data
Events
Ratio to no osc.
L_{reco}/E_{reco} (km/GeV)

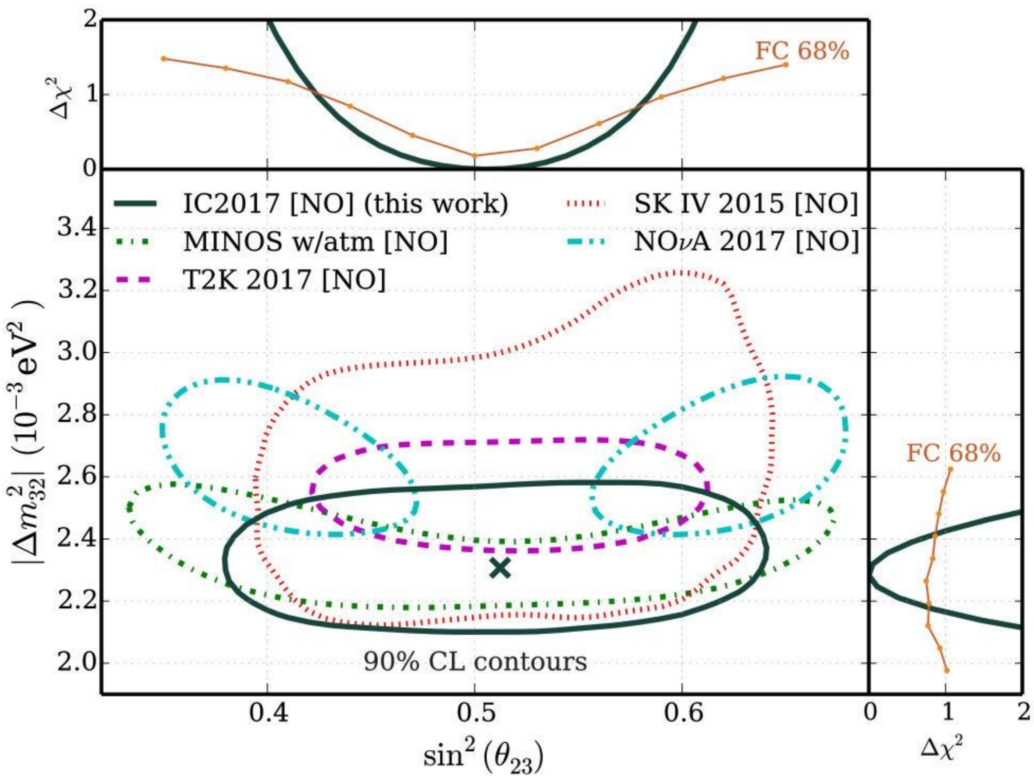


IceCube 2014 [NH]
T2K 2014 [NH]
MINOS w/atm [NH]
SK IV [NH]
90% CL contours
$-2\Delta\ln L$
$|\Delta m^2_{32}|$ (10^{-3} eV^2)
$\sin^2(\theta_{23})$

ICECUBE ATMOSPHERIC NEUTRINOS

- Icecube sees atmospheric neutrino oscillations **consistent** with the Super-K results.





- Note $\Delta m^2 \sim 10^{-3}$, 100 times larger than solar mass splitting!
- Also, the mixing angle is **very** large – it looks like mixing is **maximal** or close…

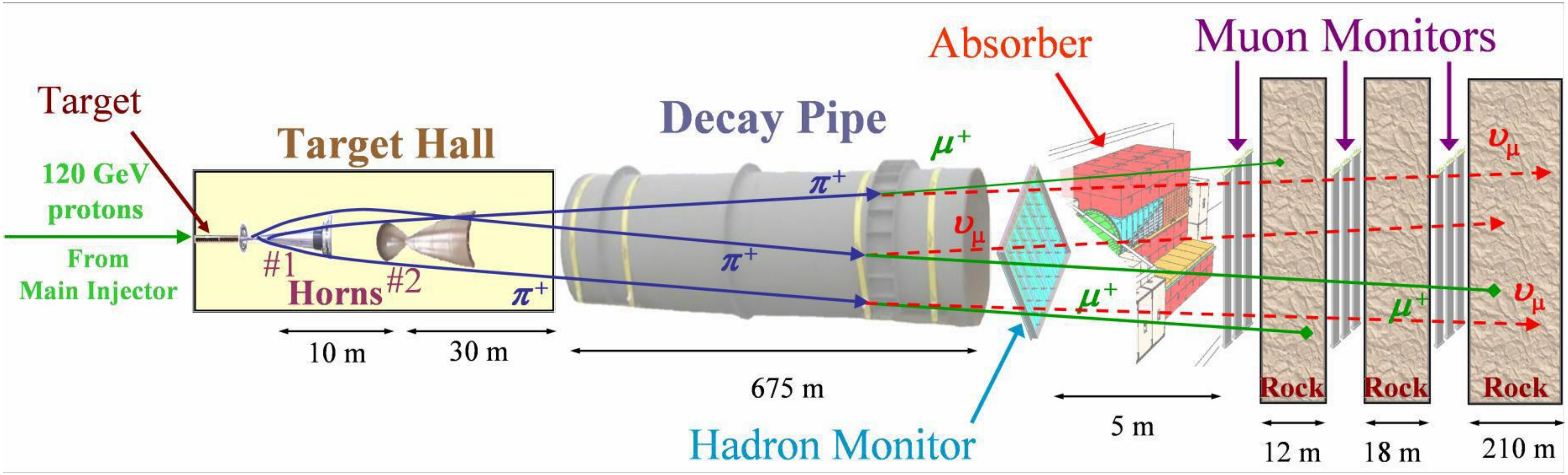
NEUTRINO BEAMS

- So far, looked at experiments that use pre-existing neutrino sources.
  - Either natural: Sun, cosmic rays impinging on the atmosphere.
  - Or artificial: commercial nuclear reactors – electricity is paid for, but neutrinos are free!
- But we've been producing neutrino beams since the 60s.
- We can confirm neutrino oscillations using a well controlled neutrino source.
- Long baseline neutrino experiments:
  - Produce very intense muon neutrino beam
  - Point it at very large detector very far away.
  - Use well controlled beam energy, direction and timing to make very precise measurements.
    - Including searching for electron neutrino appearance from a muon neutrino beam.
      - Needs non-zero θ_{13}

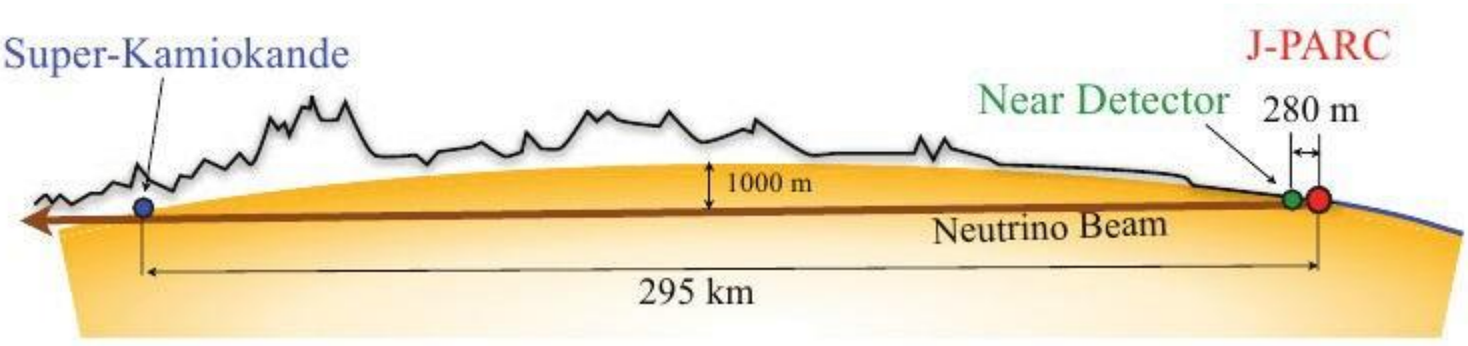
PRODUCING A NEUTRINO BEAM

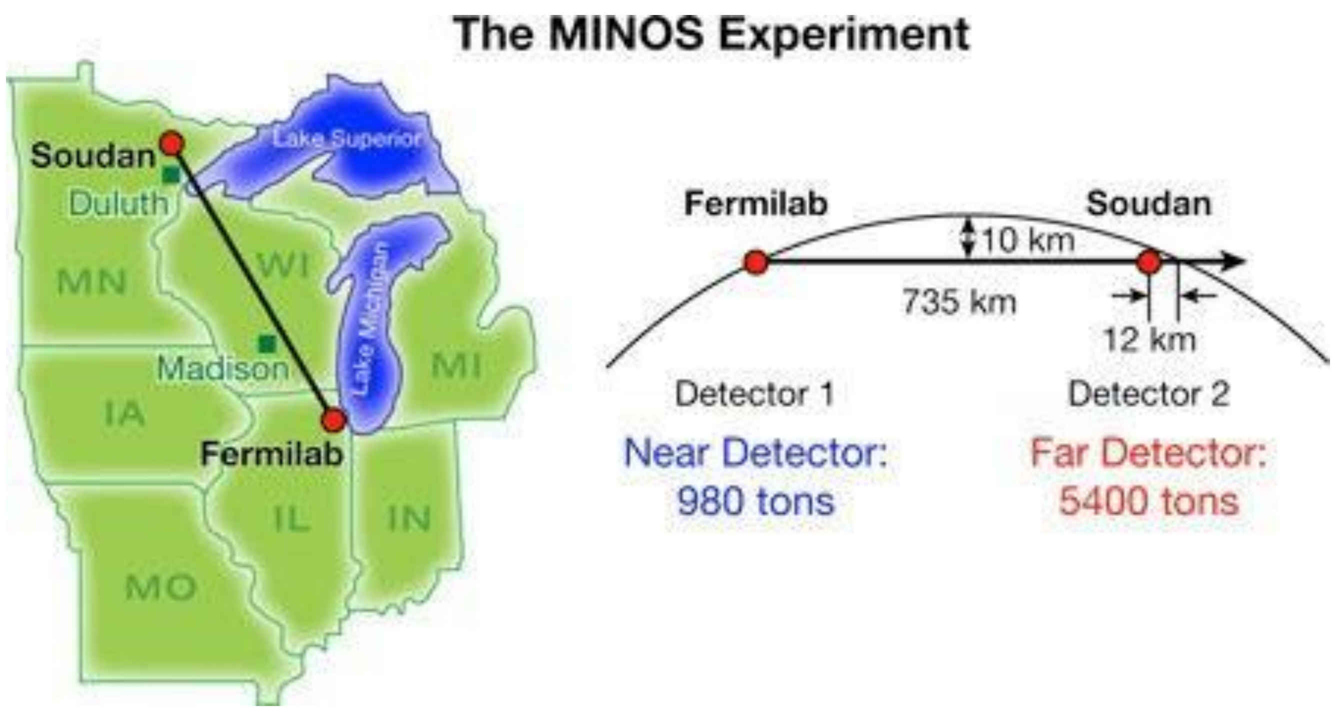
- https://www.youtube.com/watch?v=U_xWDWKq1CM

1. Accelerate protons and aim them at a target.
2. Focus the resulting pions using magnetic horns.
   - Can focus positive or negative pions to give neutrinos or anti-neutrinos.
3. Allow pions to decay in empty volume, producing neutrinos and muons.
4. Absorb the muons, and neutrinos will go through.

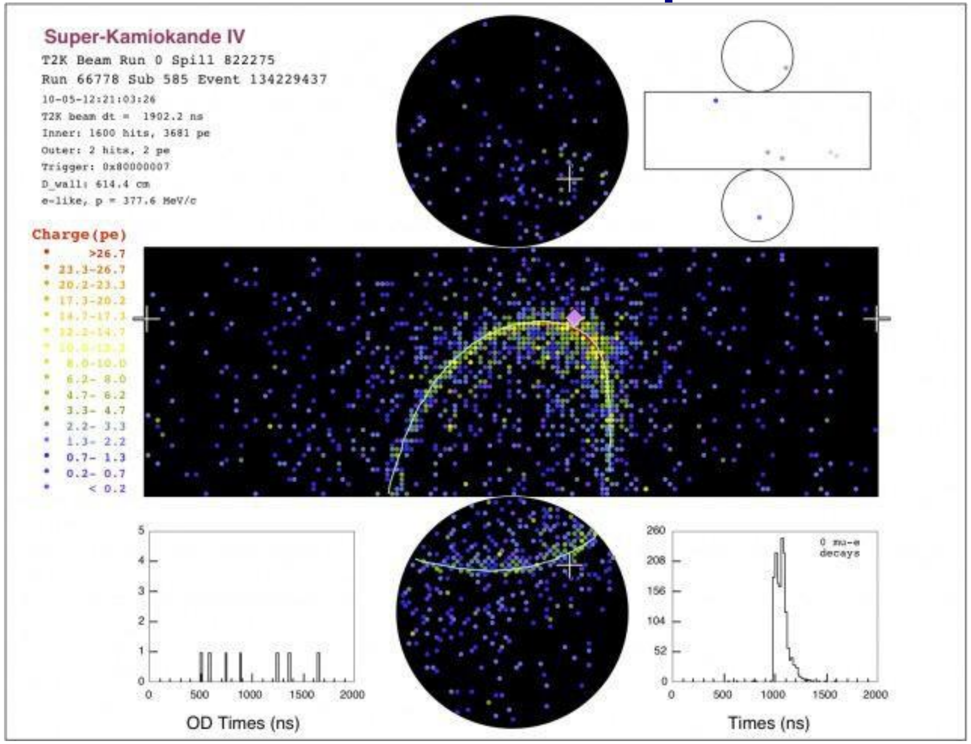


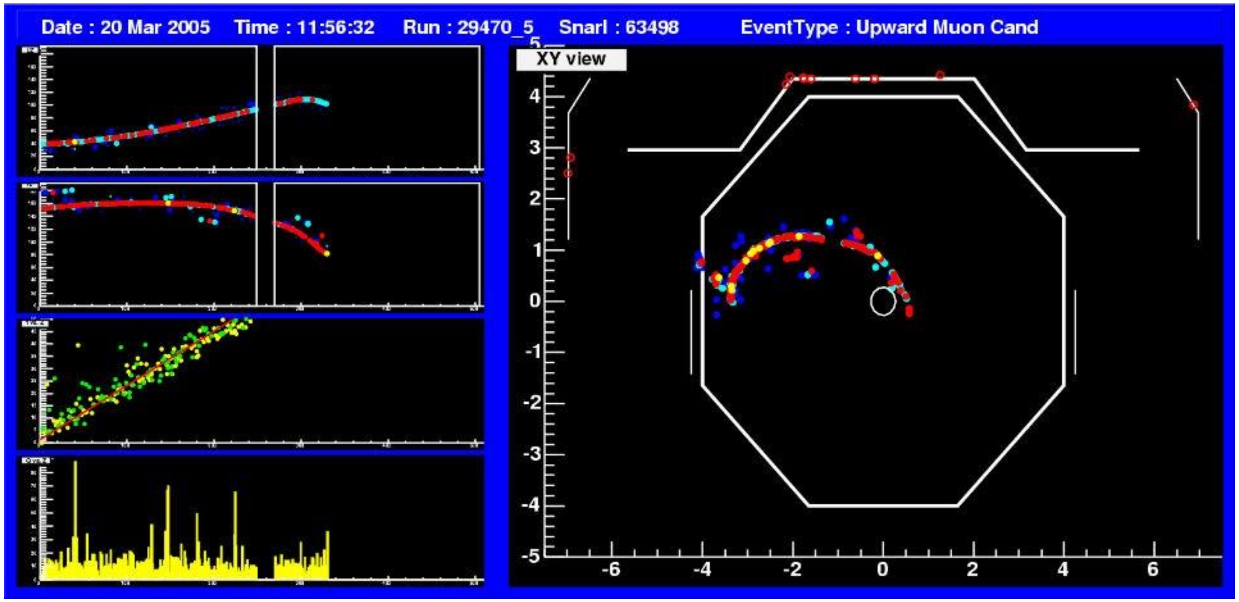
T2K & MINOS experiments



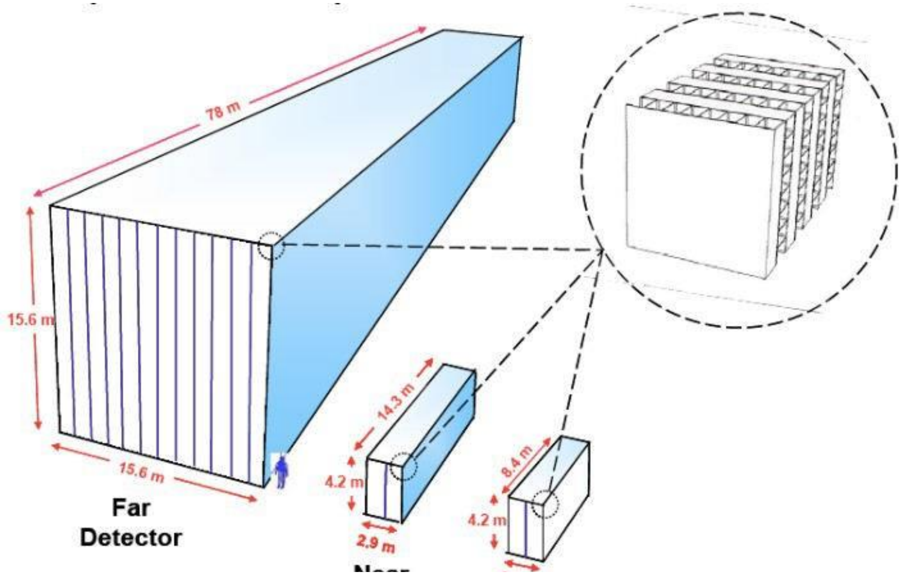


T2K & MINOS experiments

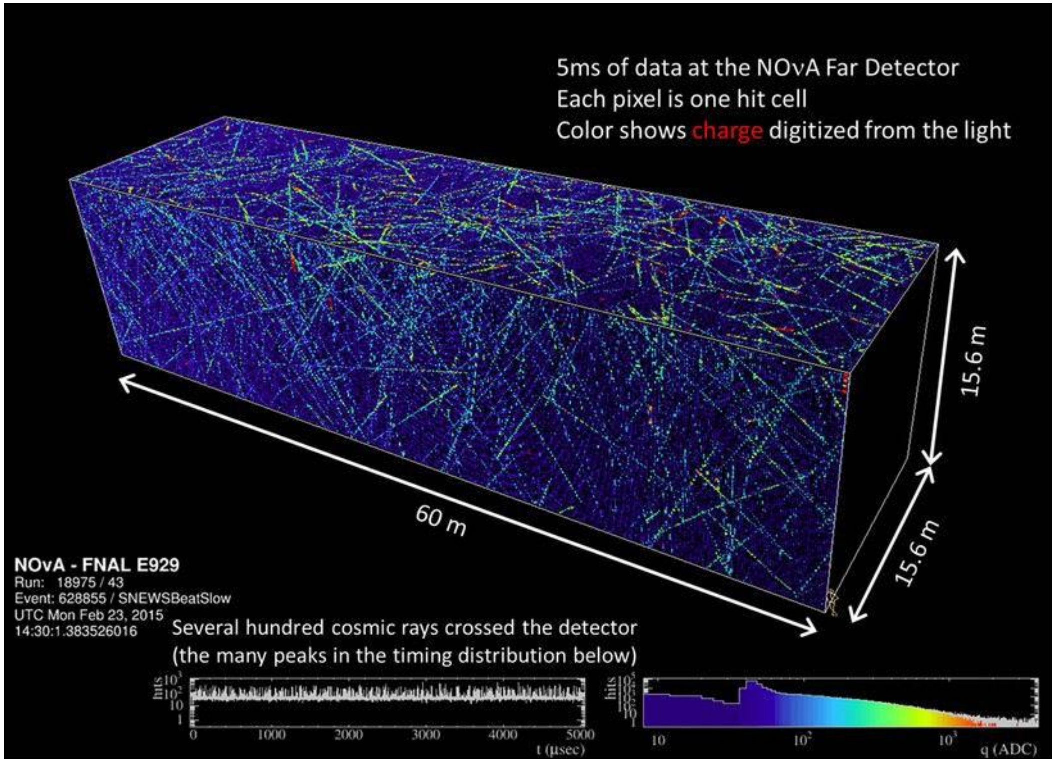




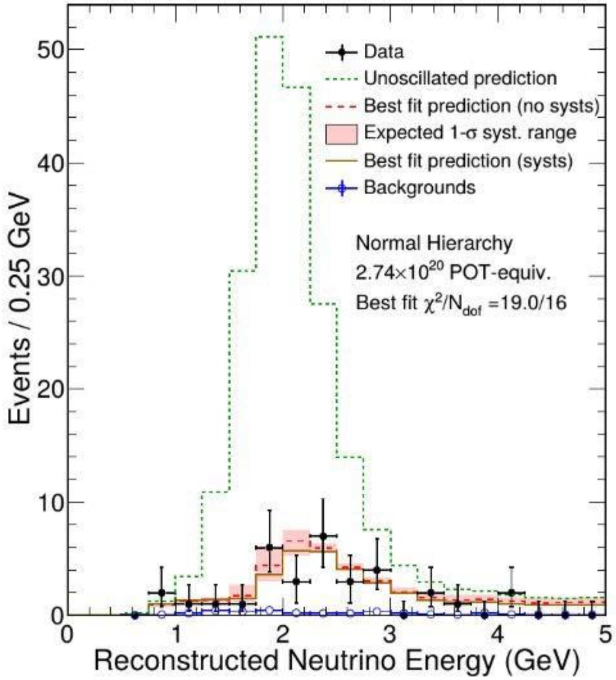
NOvA



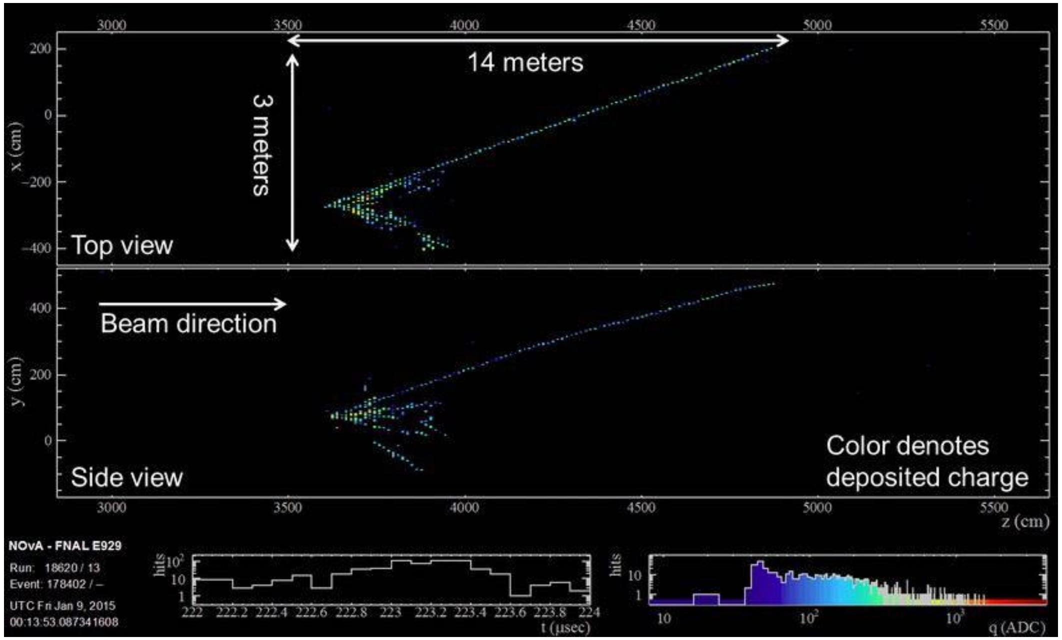
78 m
15.6 m
15.6 m
Far
Detector
14.3 m
4.2 m
2.9 m
8.4 m
4.2 m



5ms of data at the NOvA Far Detector
Each pixel is one hit cell
Color shows charge digitized from the light
60 m
15.6 m
15.6 m
NOvA - FNAL E929
Run: 18975 / 43
Event: 628855 / SNEWSBeatSlow
UTC Mon Feb 23, 2015
14:30:1.383526016
Several hundred cosmic rays crossed the detector
(the many peaks in the timing distribution below)
t (μsec)
q (ADC)



Data
Unoscillated prediction
Best fit prediction (no systs)
Expected 1-σ syst. range
Best fit prediction (systs)
Backgrounds
Normal Hierarchy
2.74×10^20 POT-equiv.
Best fit χ²/N_dof =19.0/16
Events / 0.25 GeV
Reconstructed Neutrino Energy (GeV)

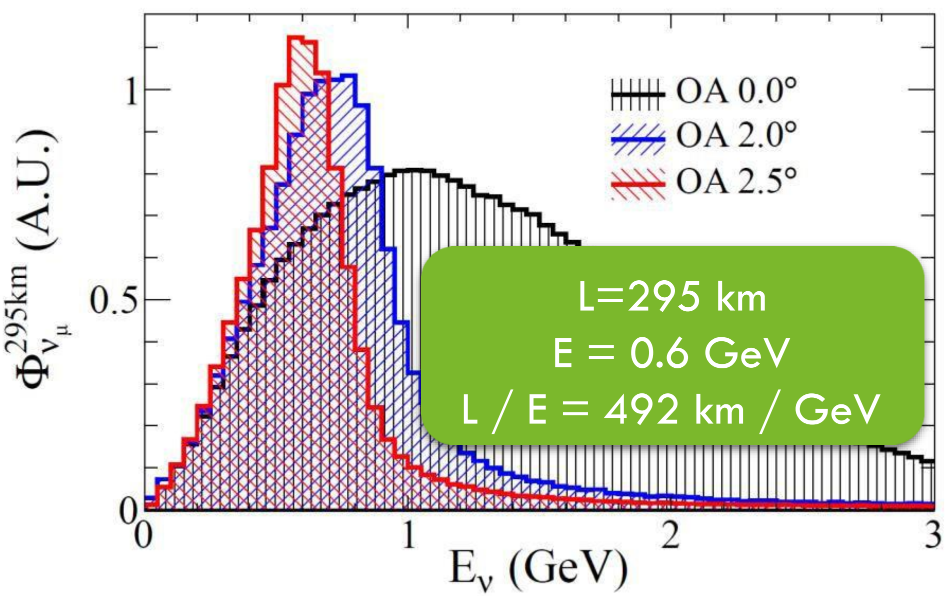


14 meters
3 meters
Top view
Beam direction
Side view
Color denotes
deposited charge
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
t (μsec)
q (ADC)

THE OFF-AXIS TRICK

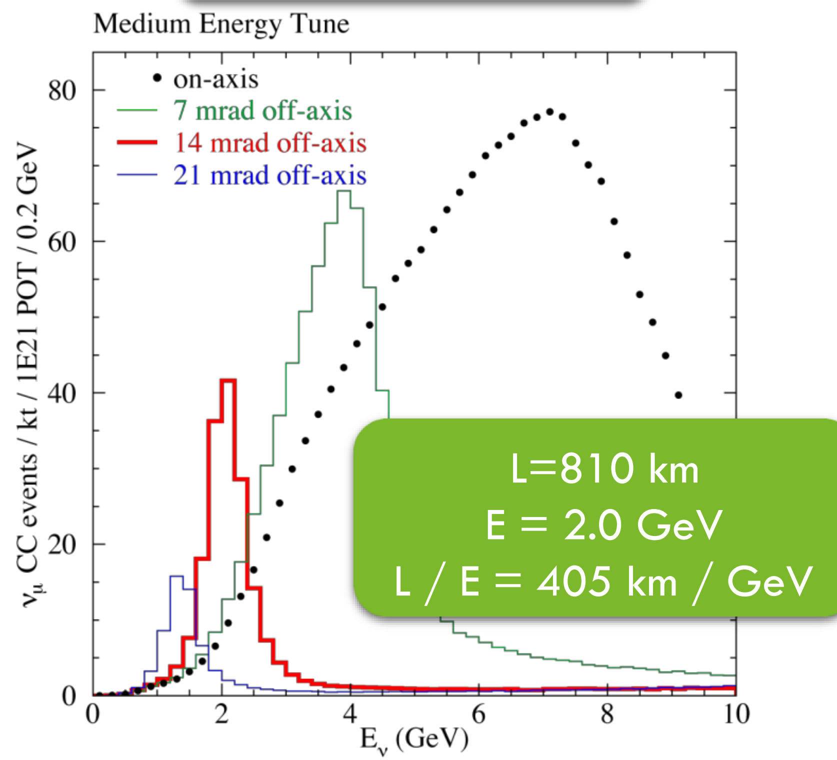
- Both NOvA and T2K use the "off-axis trick".
- Don't place the detector right in front of the neutrino beam, but a little to the side.
- Neutrinos that leave the decay pipe at a high angle have a more well defined energy.
  - Can tune L / E very precisely!

T2K



L=295 km
E = 0.6 GeV
L / E = 492 km / GeV

NOvA

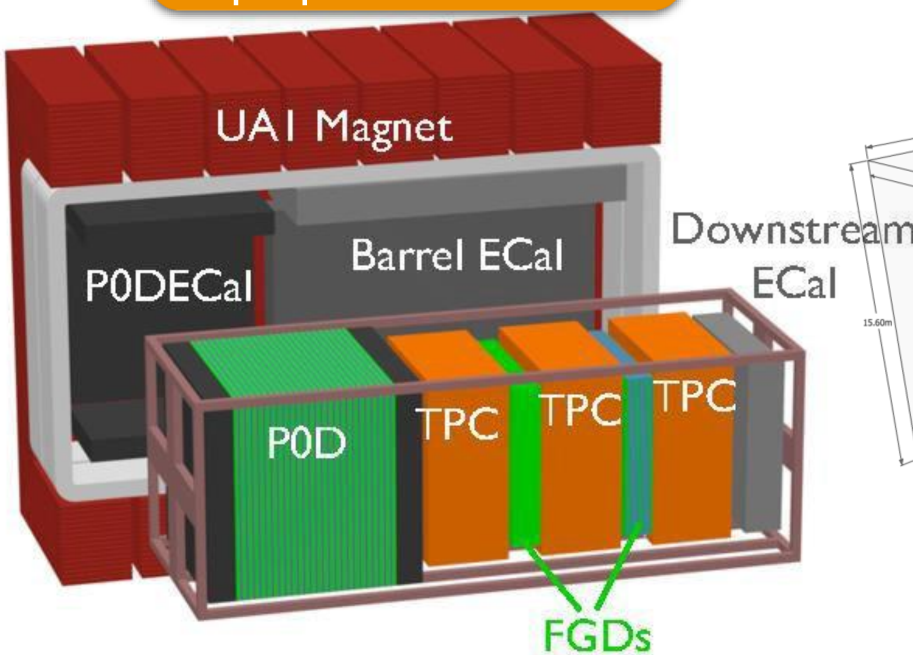


L=810 km
E = 2.0 GeV
L / E = 405 km / GeV

NEAR DETECTORS

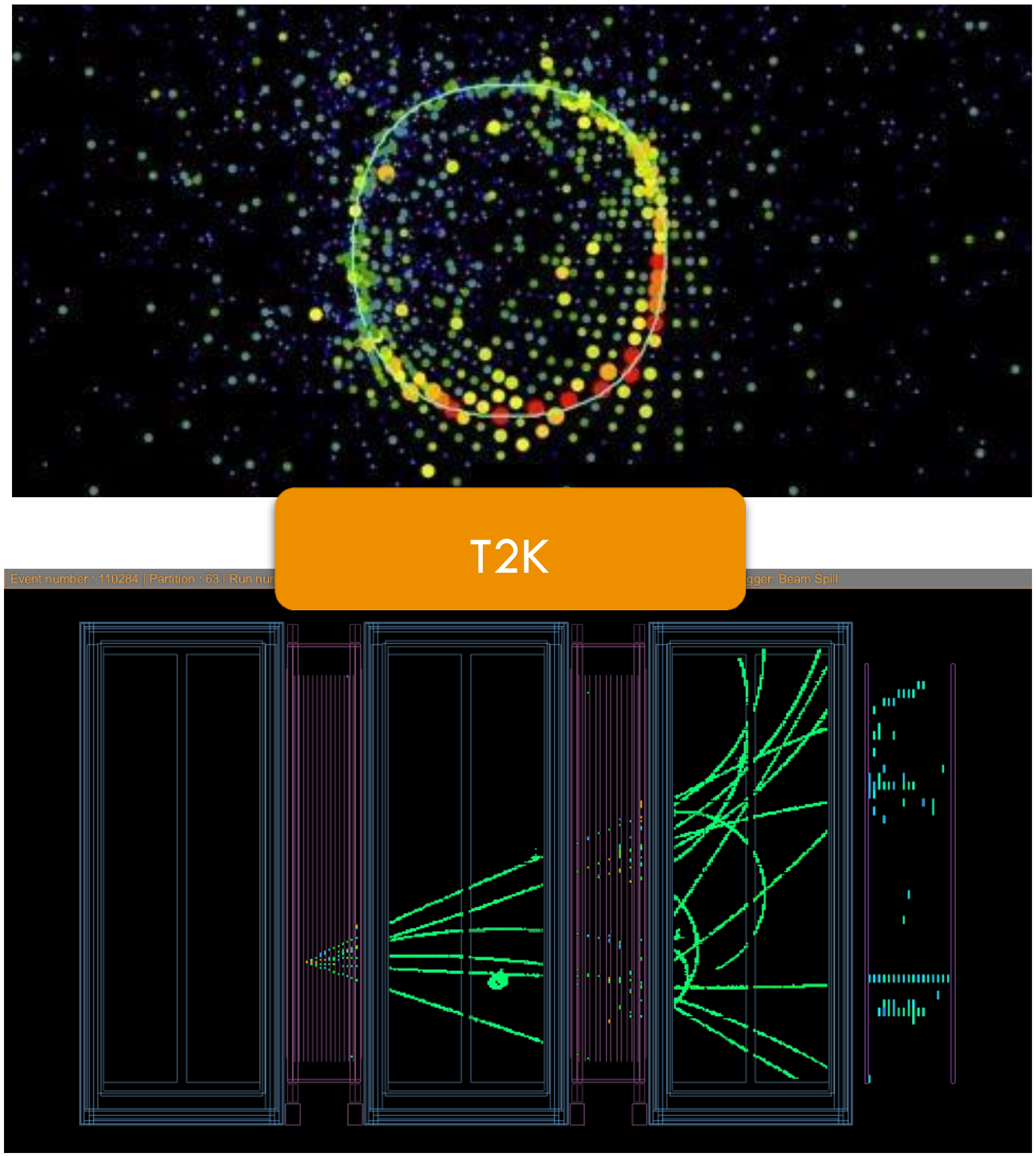
- Want to characterise the neutrino beam as well as possible before any oscillations.
- Place neutrino detectors near the neutrino production point.
- Use data from these detectors to measure neutrino cross sections.

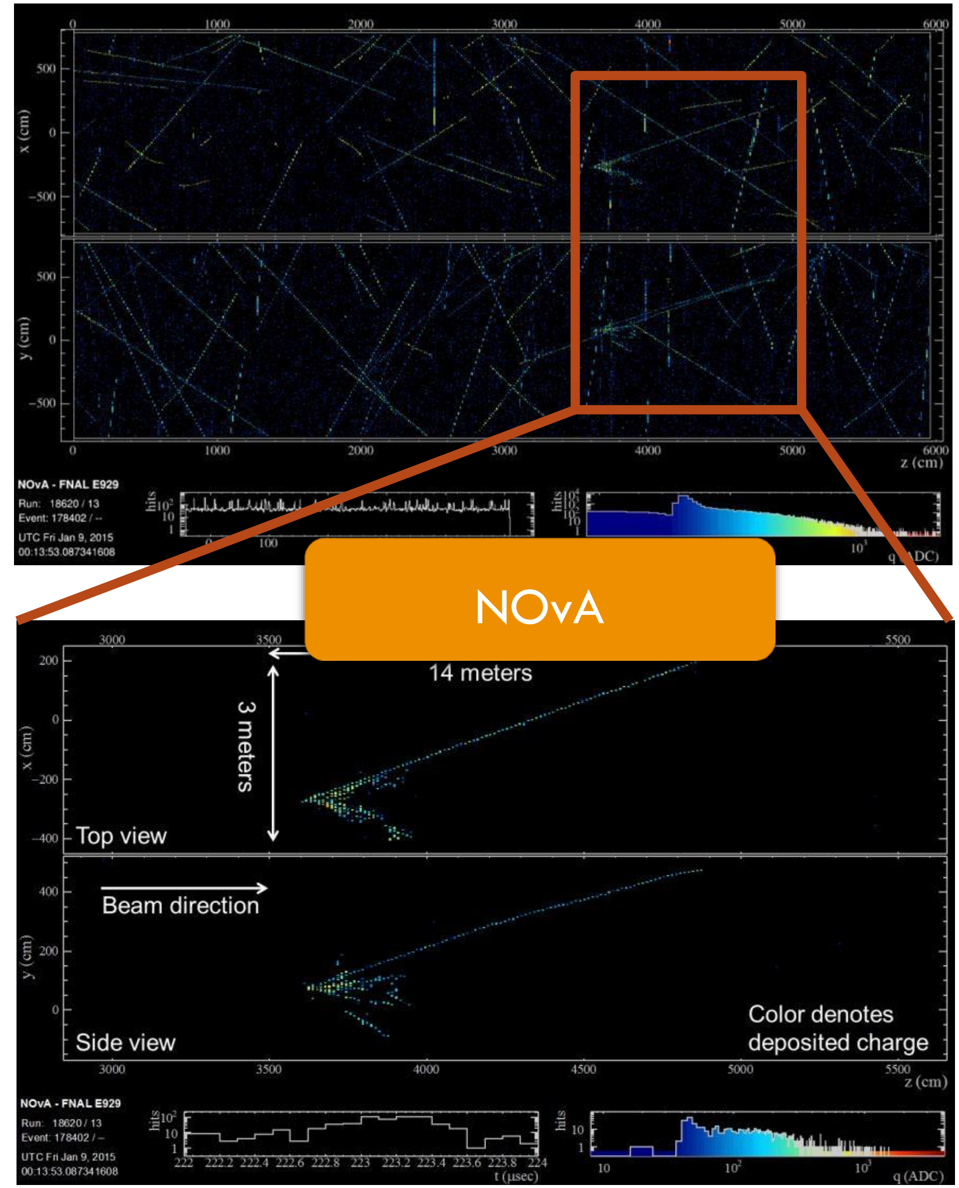
T2K:
Complex of general purpose detectors



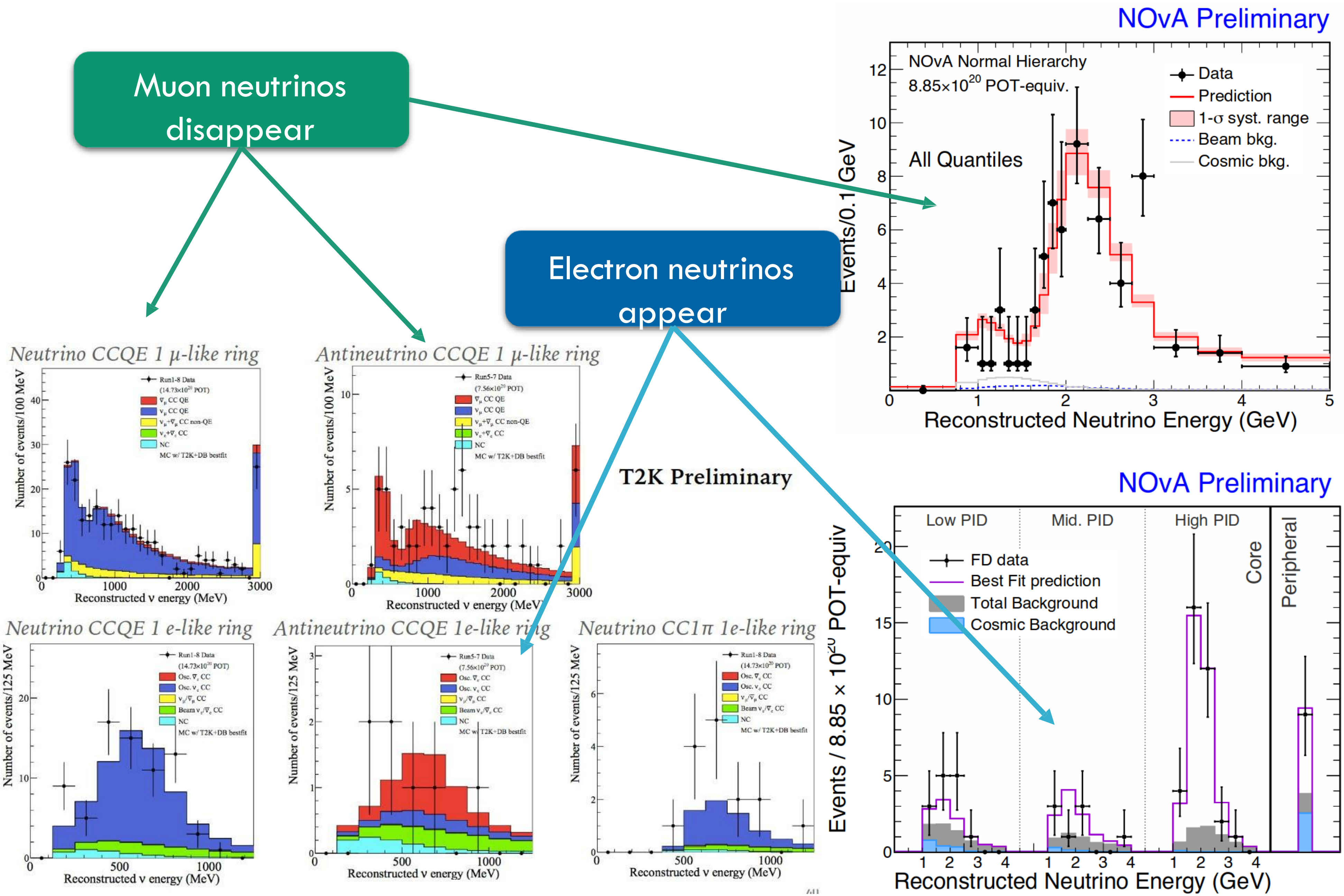
NOvA:
Miniaturized version of far detector

T2K AND NOVA NEUTRINO EVENTS





T2K AND NOVA DATA

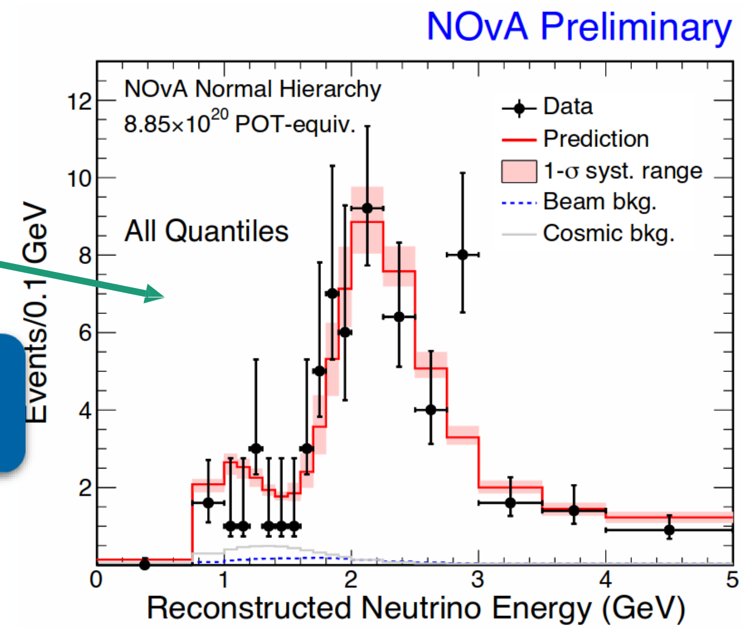


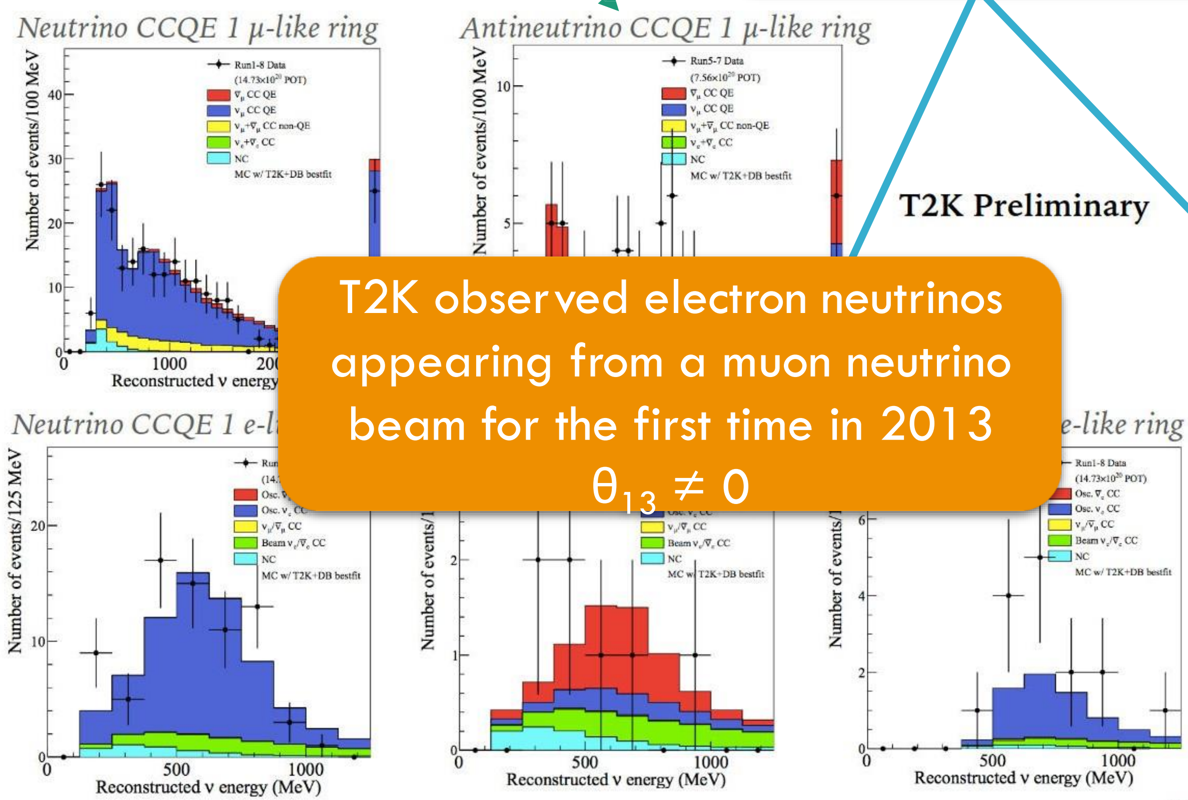
T2K AND NOVA DATA

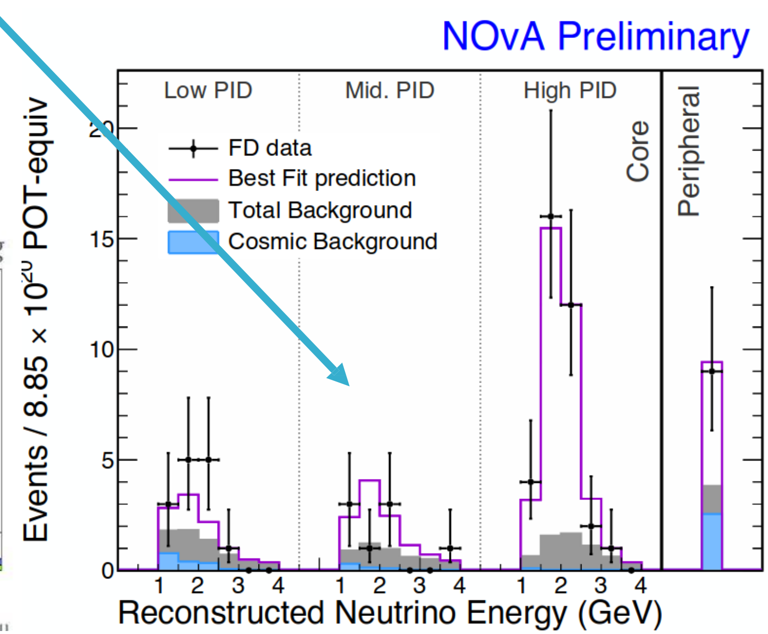
Muon neutrinos disappear

Electron neutrinos appear

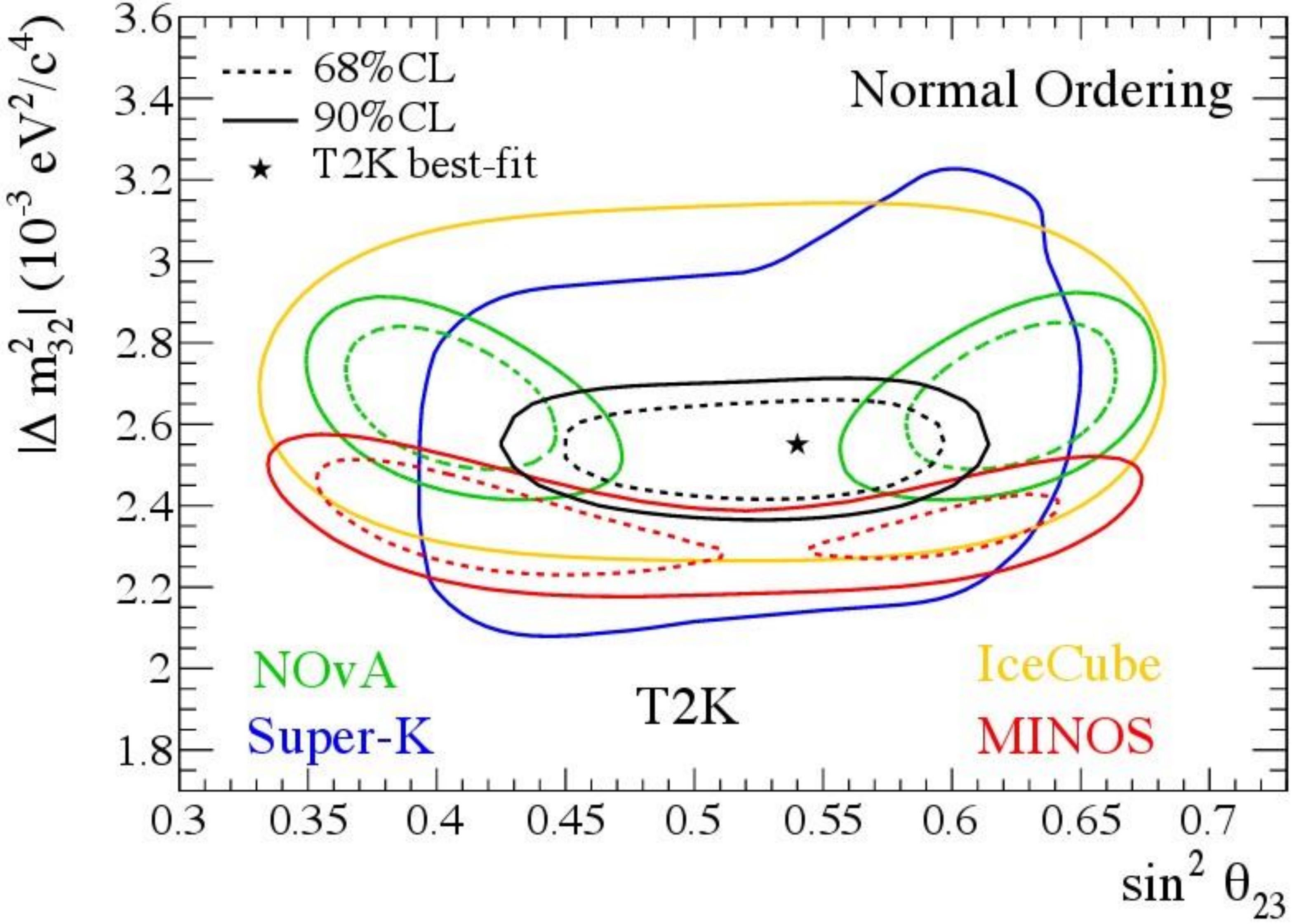
T2K observed electron neutrinos appearing from a muon neutrino beam for the first time in 2013
$\theta_{13} \neq 0$





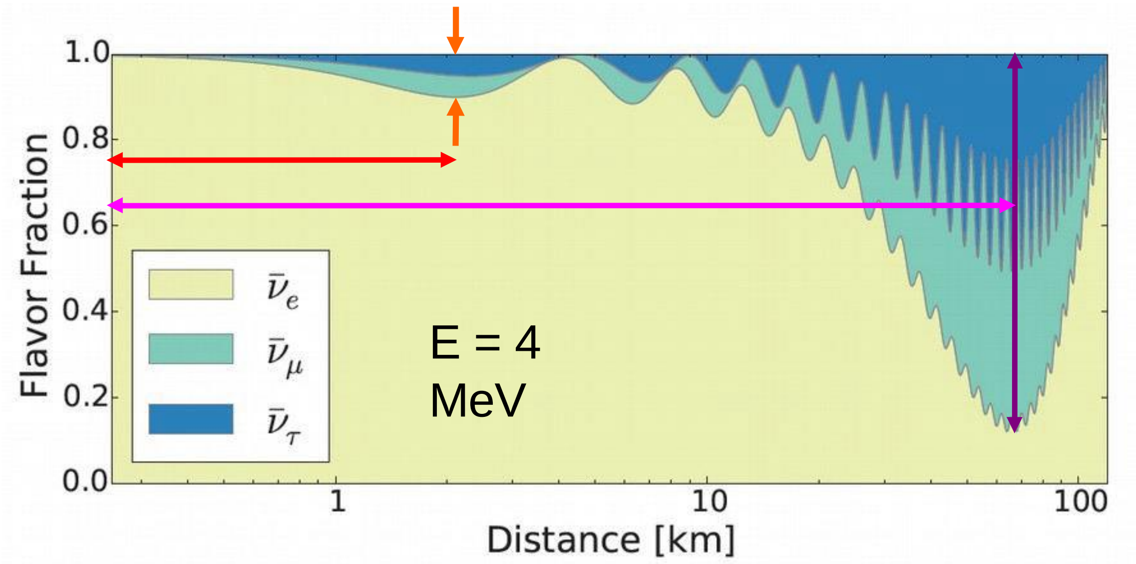


SK (atm), T2K, MINOS, IceCube (atm), NOvA



Measurement of θ_{13}

Measurement of θ_{13} with reactors



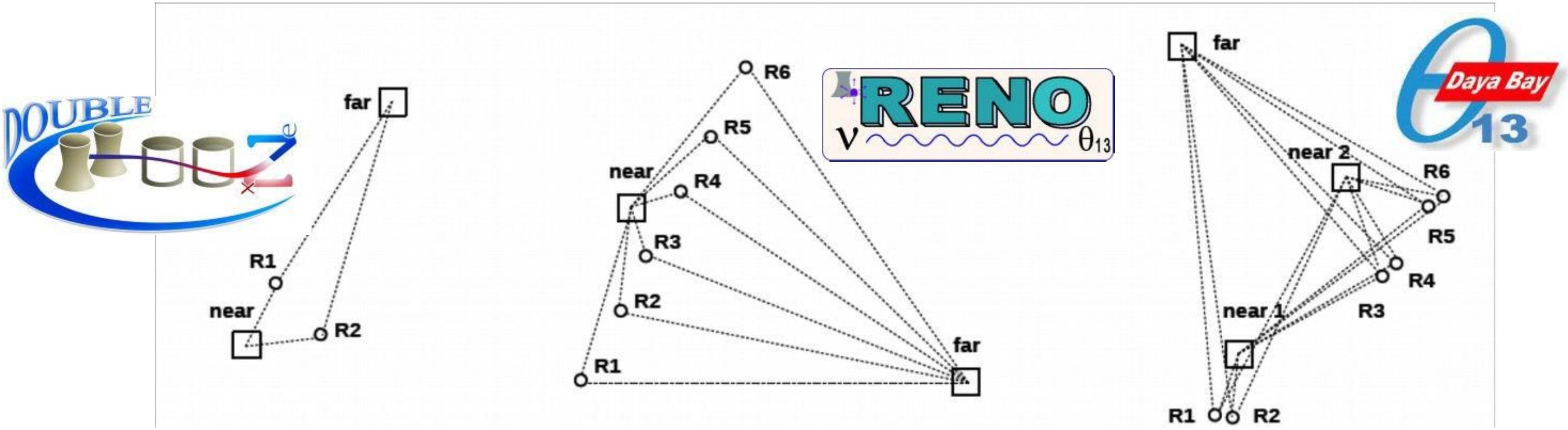
$$P_{ee}(L,E) = 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right) - \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) - \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)$$

- For baselines of ~ 1 km, the probability can be approximated by:

$$P_{ee}(L,E) \simeq 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$
$$\approx 1 - \sin^2(2\theta_{13})\sin^2\left(1.27\frac{\Delta m^2_{31}[\mathrm{eV}^2]L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)$$

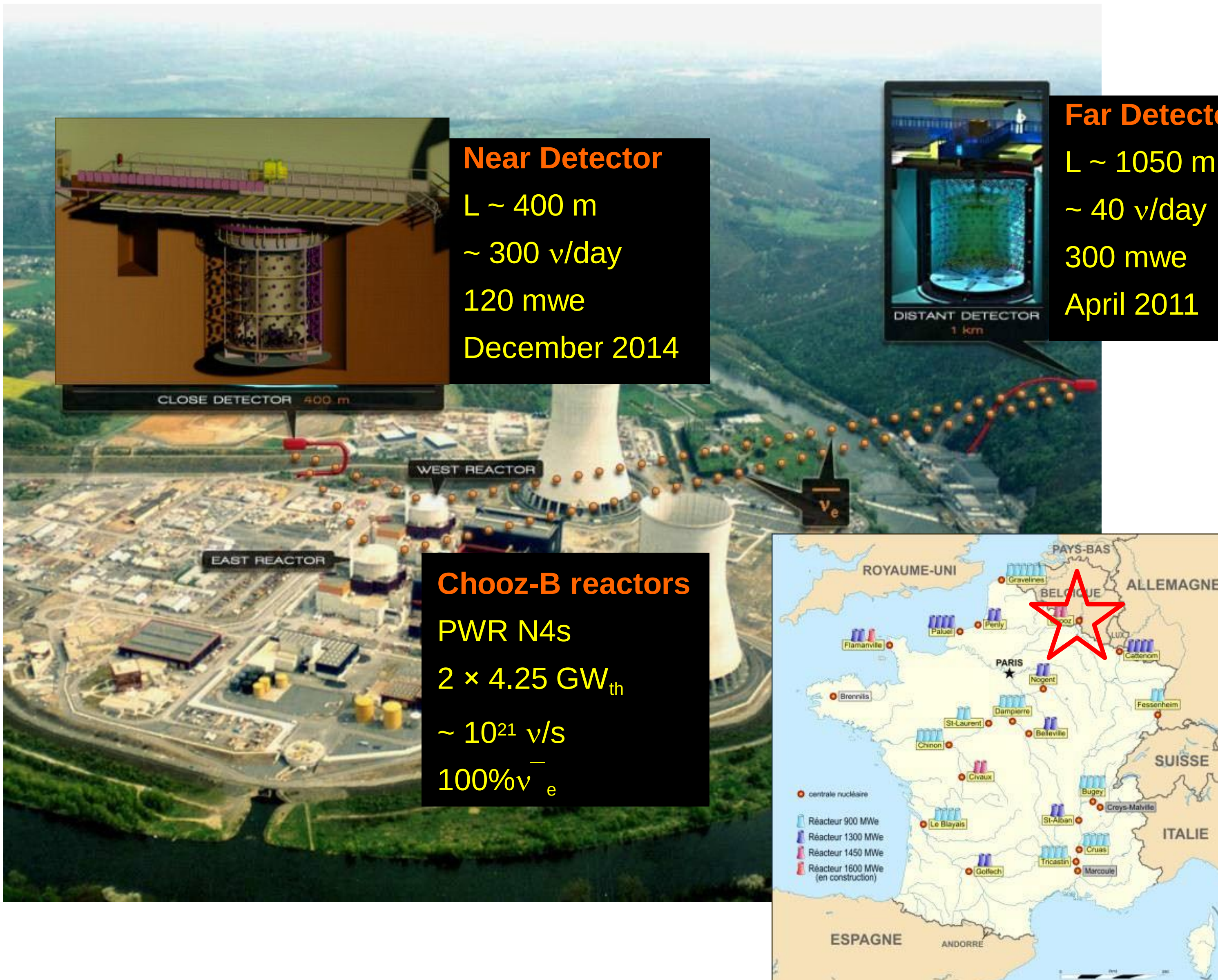
Measurement of θ_{13} with two-detector reactor experiments

- Antineutrinos detected by inverse β-decay: $\overline{\nu}_e + p \rightarrow e^+ + n$
  on Gd-loaded liquid scintillator calorimeters.
- Reactor prediction and the antineutrino detection systematic uncertainties can be reduced if **two identical detectors**, one near and one far from the reactors, are built.



Experiment	Reactor power (GW_{th})	Distance (m) Near / Far	Depth (mwe) Near / Far	Target mass (ton) × detectors
Double Chooz	8.5	400 / 1050	120 / 300	8 × 2
Daya Bay	17.4	470, 576 / 1648	260 / 860	20 × 8
RENO	16.5	294 / 1383	120 / 450	16 × 2

Double Chooz: a two-detector experiment



Near Detector
L ~ 400 m
~ 300 ν/day
120 mwe
December 2014

Far Detector
L ~ 1050 m
~ 40 ν/day
300 mwe
April 2011

Chooz-B reactors
PWR N4s
2×4.25 GW_{th}
~ 10^{21} ν/s
100% $\bar{\nu}_e$

nuclear power plant (Ardennes, France)

Electron antineutrino detection

Inverse Beta Decay (IBD):

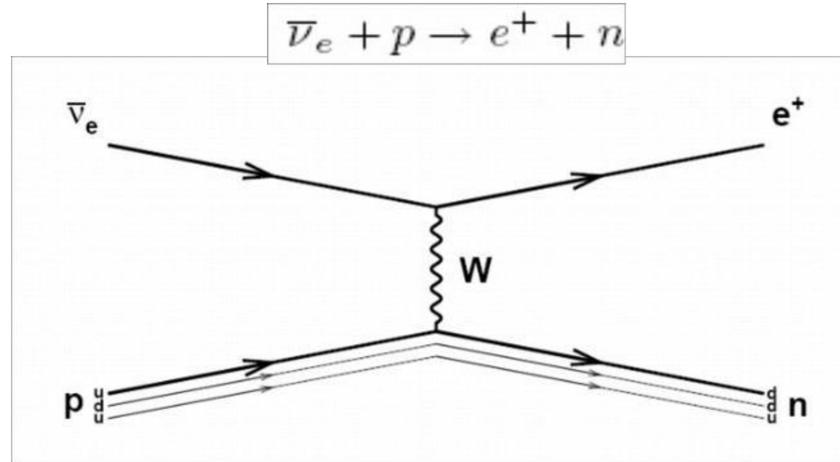
- Reaction threshold: $E_\nu \geq 1.806$ MeV.
- Disappearance experiment.
- Well known cross-section (0.2%).
- Coincidence of 2 signals: background suppression.

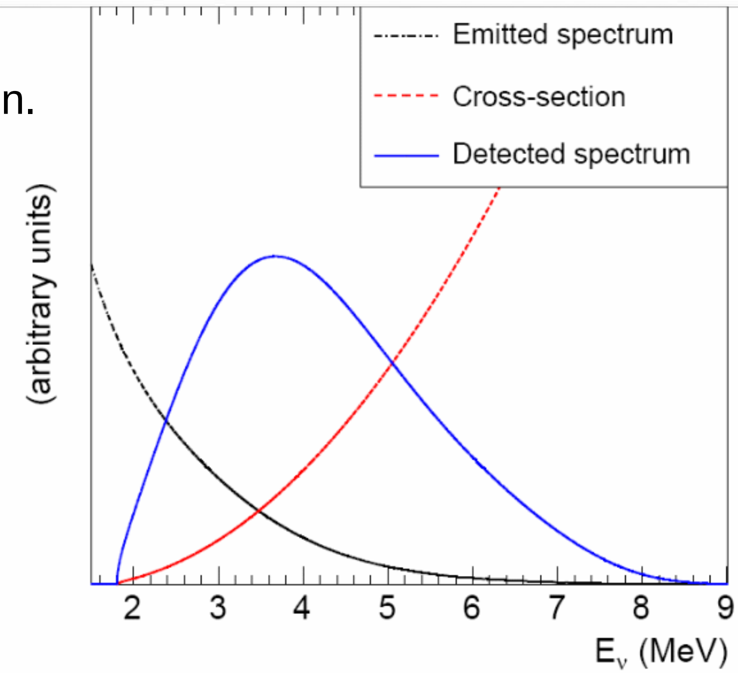
Prompt signal:

- Positron kinetic energy + γ's from annihilation.
- $E_{prompt} \approx E_\nu - 0.782$ MeV
- $E_{prompt} \sim 1 - 9$ MeV

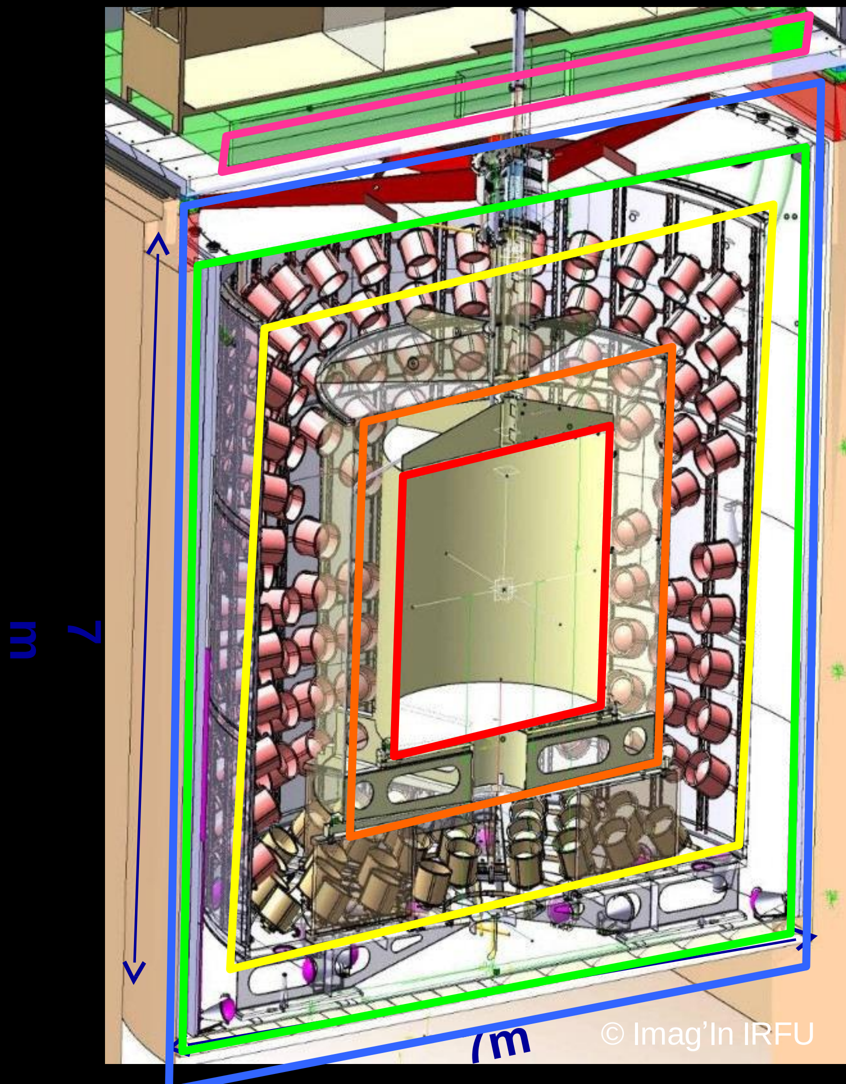
Delayed signal:

- γ's from radiative neutron capture.
- **Gd:** $\Delta T \sim 30$ μs, $E_{delayed} \sim 8$ MeV.
- **H:** $\Delta T \sim 200$ μs, $E_{delayed} = 2.22$ MeV.





The Double Chooz Far Detector



Inner Detector:

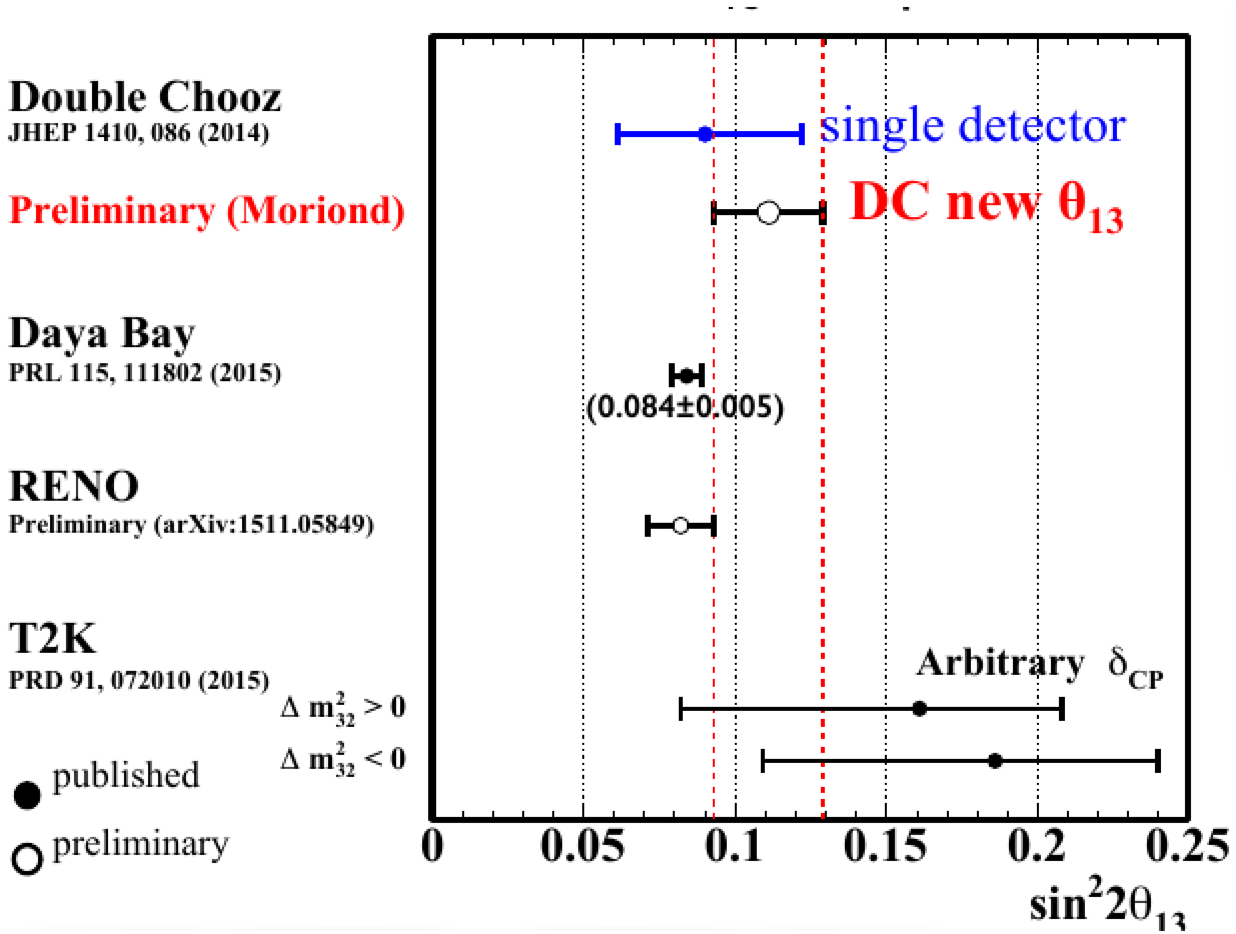
- **Neutrino Target:** acrylic vessel (8 mm) with 10.3 m^3 **Gd-loaded** (1 g/l) **liquid scintillator**.
- **Gamma-Catcher:** acrylic (12 mm) vessel with 22.5 m^3 of **liquid scintillator**.
- **Buffer:** stainless steel (3 mm) vessel supporting **390 10" PMTs**, with 110 m^3 of **non-scintillating mineral oil**.

Outer Detector:

- **Inner Veto:** steel (10 mm) vessel supporting **78 8" PMTs**, with 90 m^3 of **liquid scintillator**.
- **Shielding:** 15 cm **steel**.
- **Outer Veto:** **plastic scintillator** strips.

Latests measurements of θ_{13}

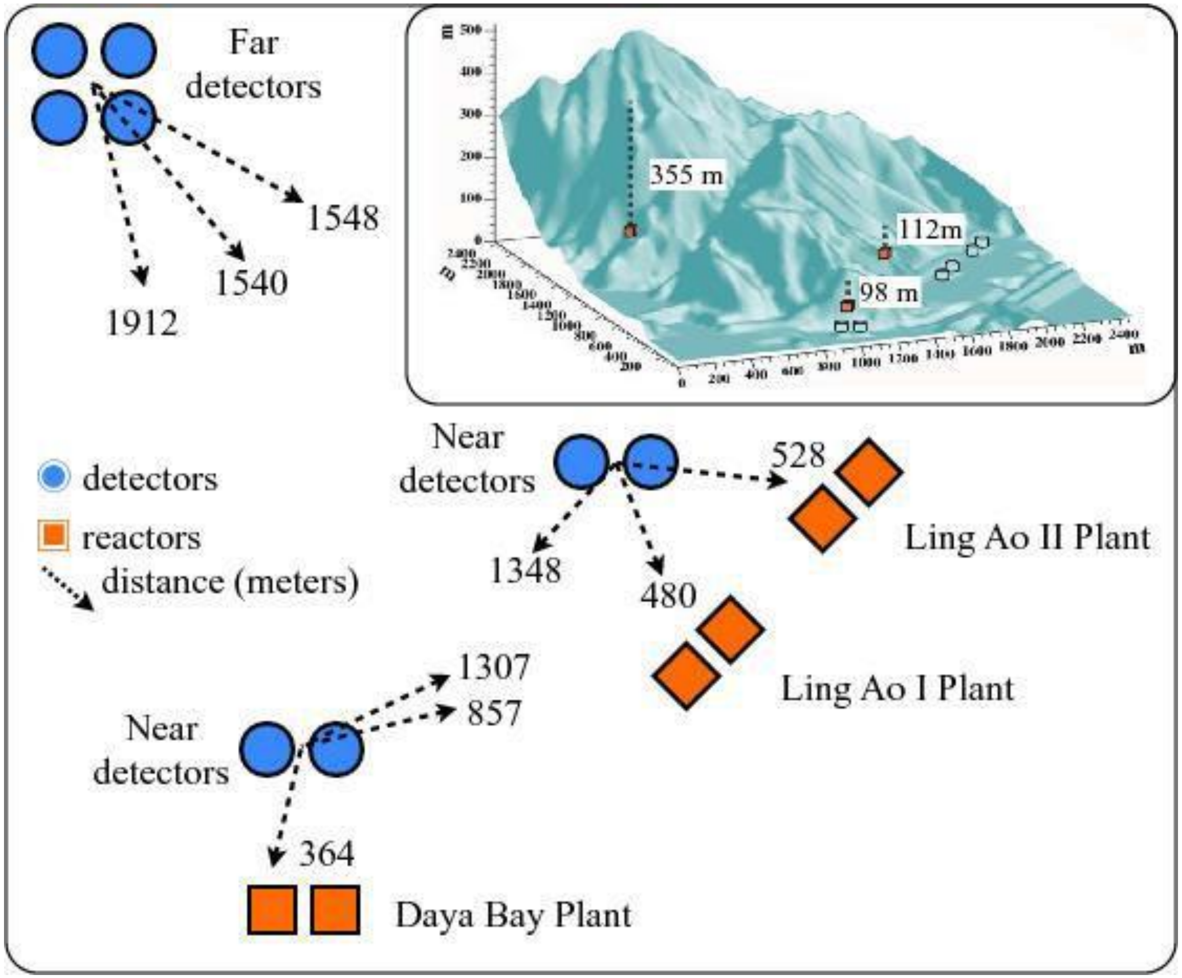
θ_{13} unknown until 2011. Huge progress in a few years.

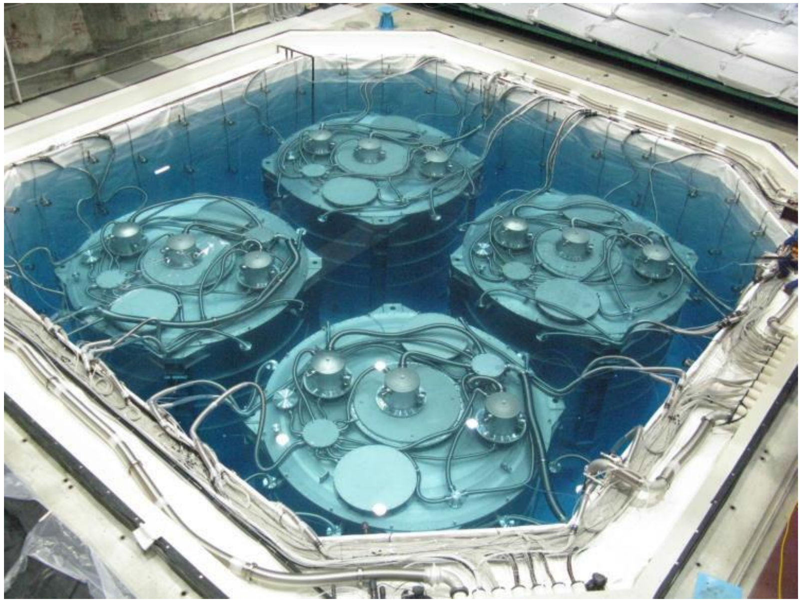


A. Cabrera, FNAL seminar 03/25/2016

SHORT(ER) BASELINE REACTOR EXPERIMENTS

- Daya Bay experiment, south China.
- L ~ 1.5 km; E ~ 1 MeV; Minimum $\Delta m^2 \sim 10^{-3}$ eV^2

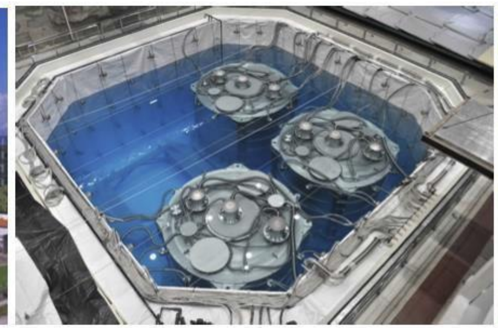
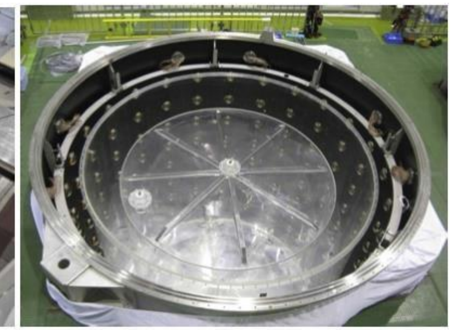




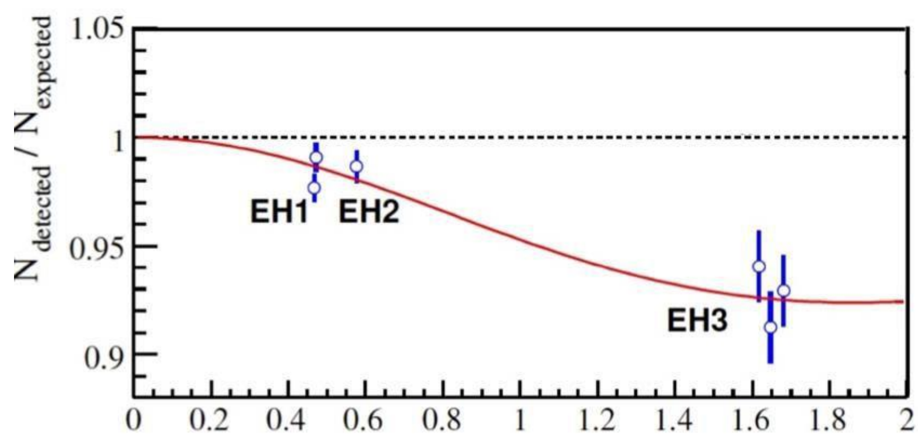
SHORT(ER) BASELINE REACTOR EXPERIMENTS

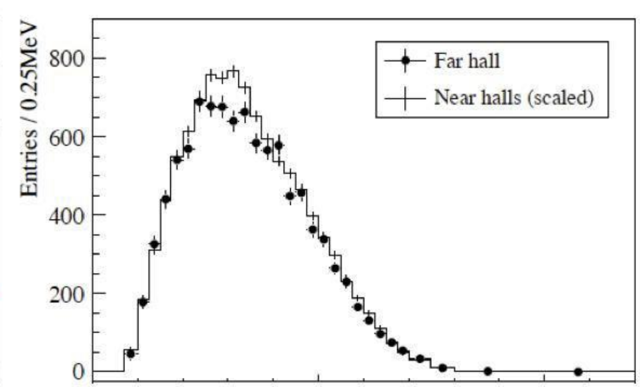
- In 2012, θ_{13} went from being the least well known of the mixing angles to the most precisely measured!

Observation of Electron Antineutrino Disappearance at Daya Bay

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$$

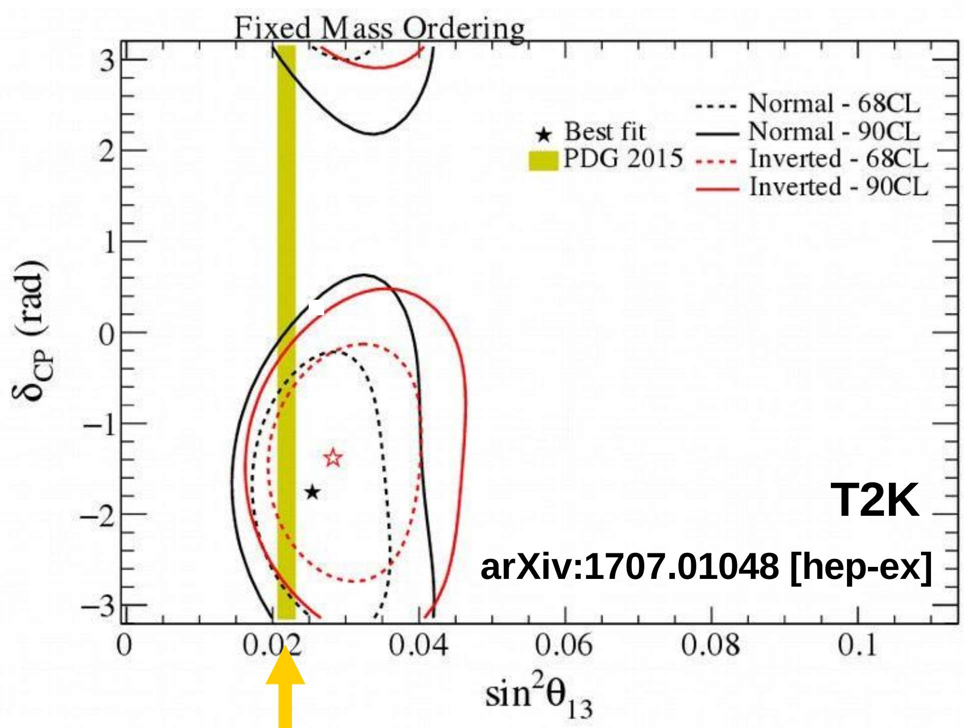




First glimpse of δ

- $\nu_\mu \rightarrow \nu_e$ depends on the mass hierarchy and CP-violating phase.

$$P_{\mu e}(L,E) = \frac{1}{(A-1)^2}\sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left[(A-1)\Delta\right]$$
$$\mp \frac{\alpha}{A(1-A)}\cos(\theta_{13})\sin(2\theta_{12})\sin(2\theta_{23})\sin(2\theta_{13})\times$$
$$\times \underline{\sin(\delta)}\sin(\Delta)\sin(A\Delta)\sin\left[(1-A)\Delta\right]$$
$$+ \frac{\alpha}{A(1-A)}\cos(\theta_{13})\sin(2\theta_{12})\sin(2\theta_{23})\sin(2\theta_{13})\times$$
$$\times \underline{\cos(\delta)}\cos(\Delta)\sin(A\Delta)\sin\left[(1-A)\Delta\right]$$
$$+ \frac{\alpha^2}{A^2}\cos^2(\theta_{23})\sin^2(2\theta_{12})\sin^2(A\Delta),$$



$$\alpha \equiv \Delta m^2_{21}/\Delta m^2_{32}$$

$$\Delta \equiv \frac{\Delta m^2_{32} L}{4E}$$

$$A \equiv 2\sqrt{2}G_F N_e \frac{E}{\Delta m^2_{32}}$$

Critical input: Using the θ_{13} from the reactor experiments, the mass hierarchy and the CP-violating phase can be studied.

3 neutrinos: mixing matrix

PMNS matrix: U

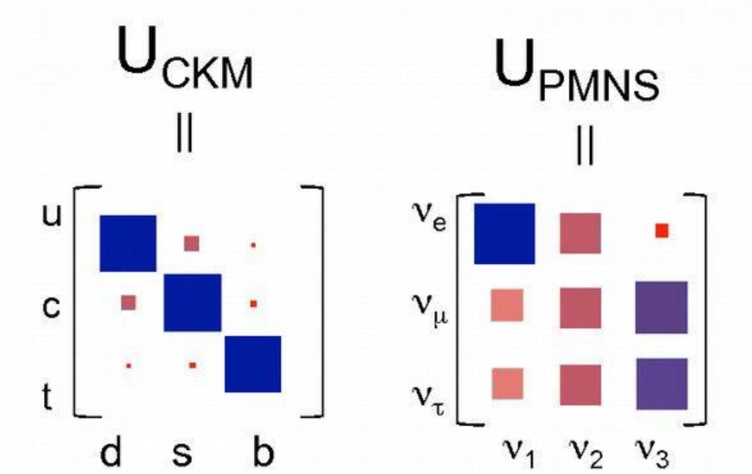
$c_{ij}=\cos\theta_{ij},\ s_{ij}=\sin\theta_{ij}$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & s_{13}e^{-i\delta}\\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}\begin{matrix}\rightarrow m_1\\ \rightarrow m_2\\ \rightarrow m_3\end{matrix}$$

Atmospheric & Long-baseline accelerator experiments | Reactor & Long-baseline accelerator experiments | Solar & KamLAND experiments

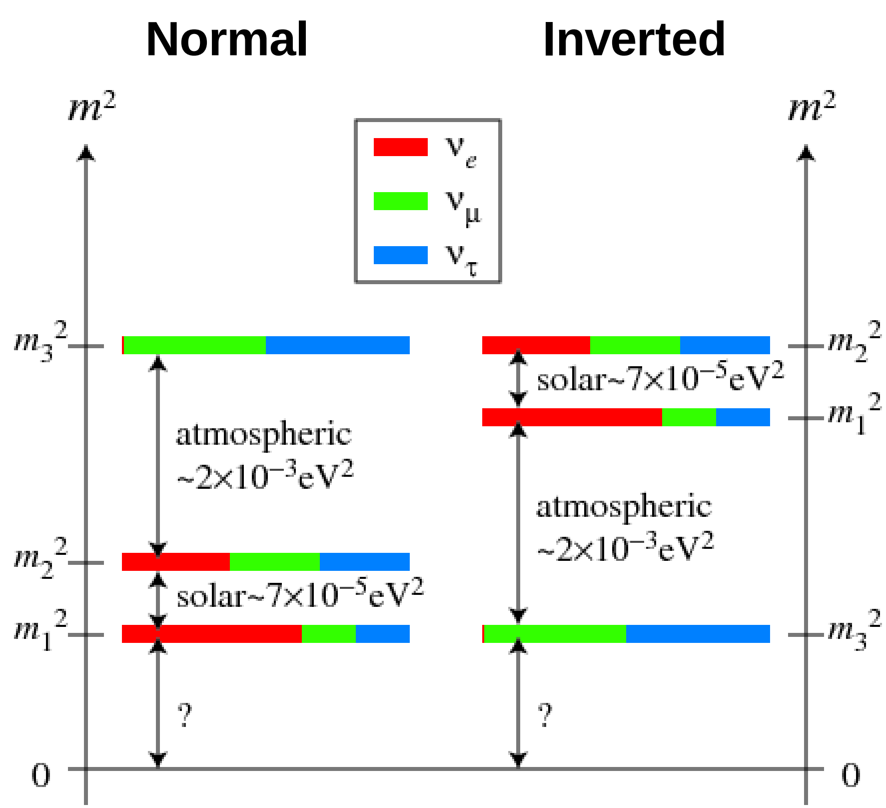
$$\Delta m_{jk}^2 \equiv m_j^2 - m_k^2$$

- **3 angles measured (mnemonic approximation):**
  - **$\theta_{12} \approx 34°$**
  - **$\theta_{23} \approx 45°$ (symmetry?)**
  - **$\theta_{13} \approx 9°$**
- **CP-violating phase δ?**
- Why so different from quark mixing?



3 neutrinos: mass ordering

- 3 mass eigenstates → **2 independent squared-mass differences:** $\Delta m^2_{32} + \Delta m^2_{21} = \Delta m^2_{31}$
- But which is on top of which?
- **Matter effects within the Sun show the mass eigenstate ν_2 is heavier than ν_1.**
- Which is the **lightest neutrino**? Two possibilities left:

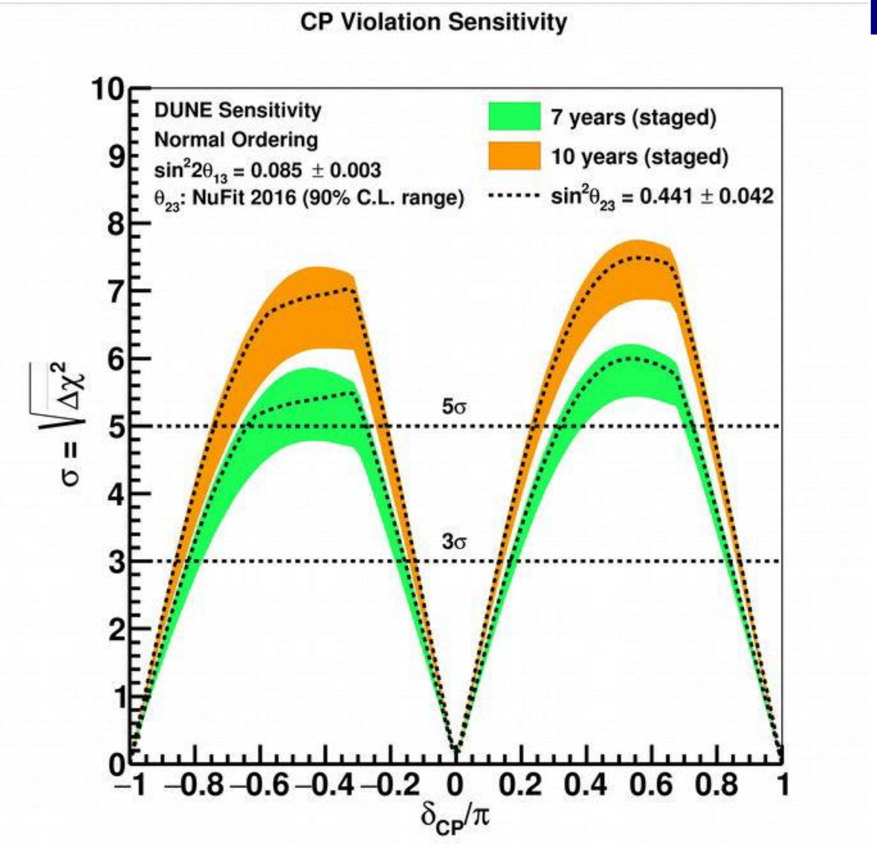


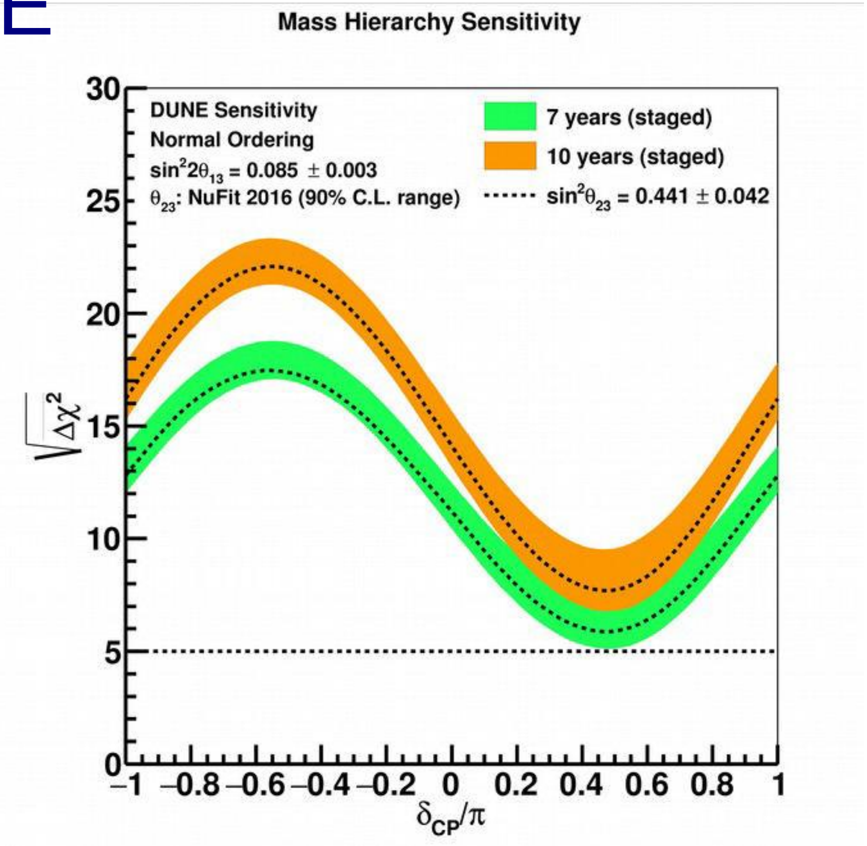
Future: δ and mass hierarchy

- Both CP-violating phase and the mass hierarchy can be measured in a long-baseline accelerator experiment.
- Need a long baseline and a broad-energy beam to disentangle CP violation caused by matter effects (Earth is made only from matter) from the intrinsic CP violation.

Neutrino beam expected by 2026.

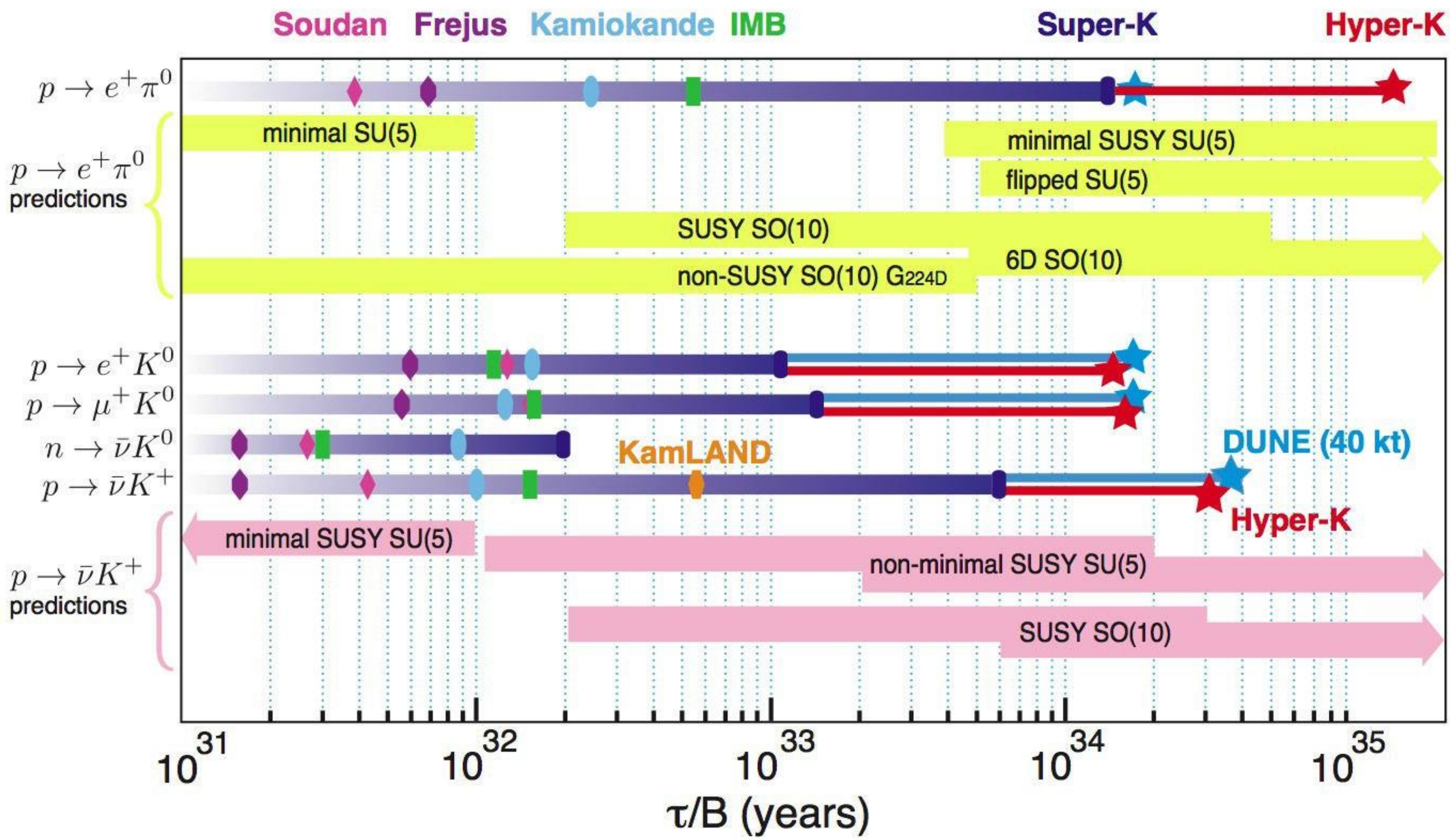
DUNE





- > 5σ measurement of CP-violating phase if CP violation is close to maximal.
  - > 3σ measurement for 65% of δ range.
- > 5σ determination of mass hierarchy for any value of CP-violating phase.
- 2017: Far Laboratory construction started.
- 2018: DUNE detector prototypes (protoDUNE) at CERN test beam.
- 2021: Far Detector installation begins.
- 2024: Beginning of Physics data taking.
- 2026: First neutrinos from Fermilab beam.

Proton decay at DUNE



Core-collapse supernova neutrinos at DUNE