Particle Physics: Neutrinos – part I

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Week 8: November 10, 2017
Columbia University Science Honors Program

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

NEVIS LABORATORIES

Course policies

- **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!**

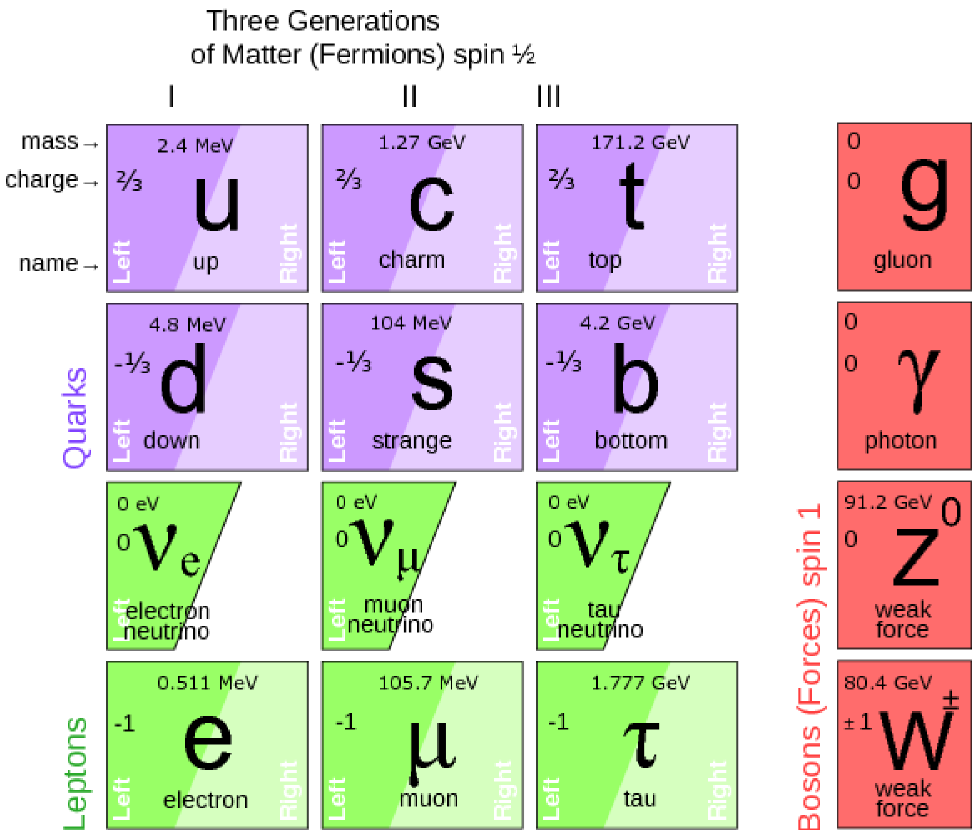
- Lecture materials

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

Schedule

Month	Day	Lecture	Teacher
September	16	Introduction	José
	23	History of Particle Physics	José
	30	No classes -- Yom Kippur	-
October	7	Special Relativity	Inês
	14	Quantum Mechanics	Inês
	21	Experimental Methods	Cris
	28	The Standard Model - Overview	Cris
November	4	The Standard Model - Limitations	Cris
	11	Neutrino Theory	José
	18	Neutrino Experiment	José
	25	No classes -- Thanksgiving	-
December	2	LHC and Experiments	Inês
	9	The Higgs Boson and Beyond	Inês
	16	Particle Cosmology	Cris

Neutrinos in the Standard Model



- **Only weak interaction.**

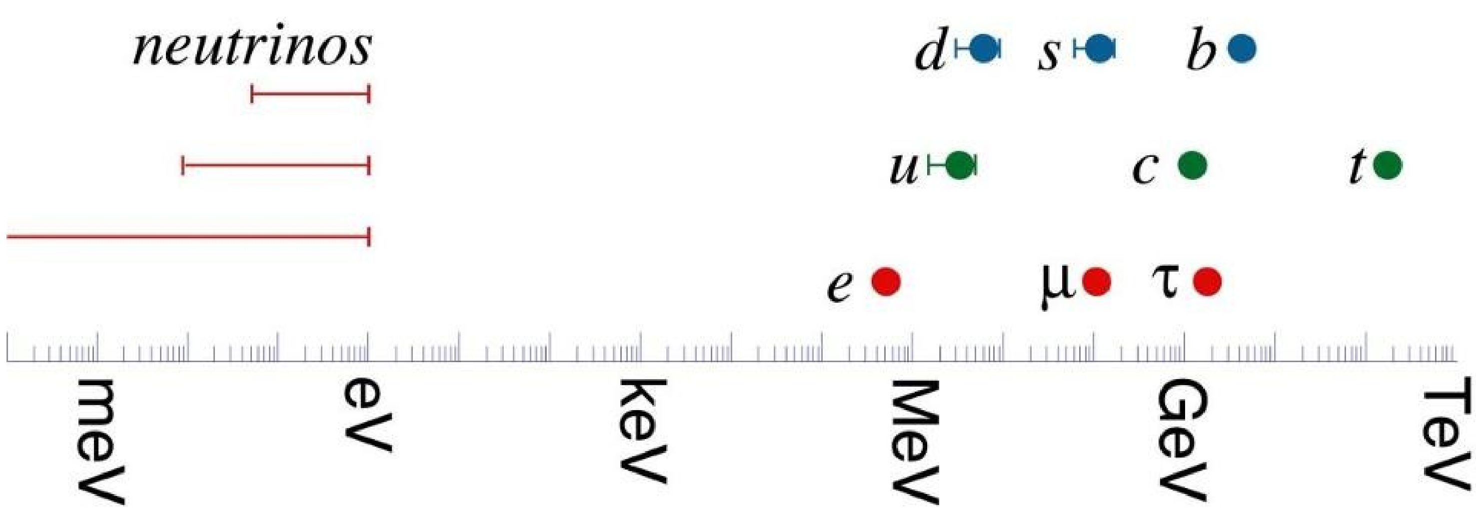
  Only left-handed neutrinos (and right-handed antineutrinos) in the Standard Model.

- 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*):

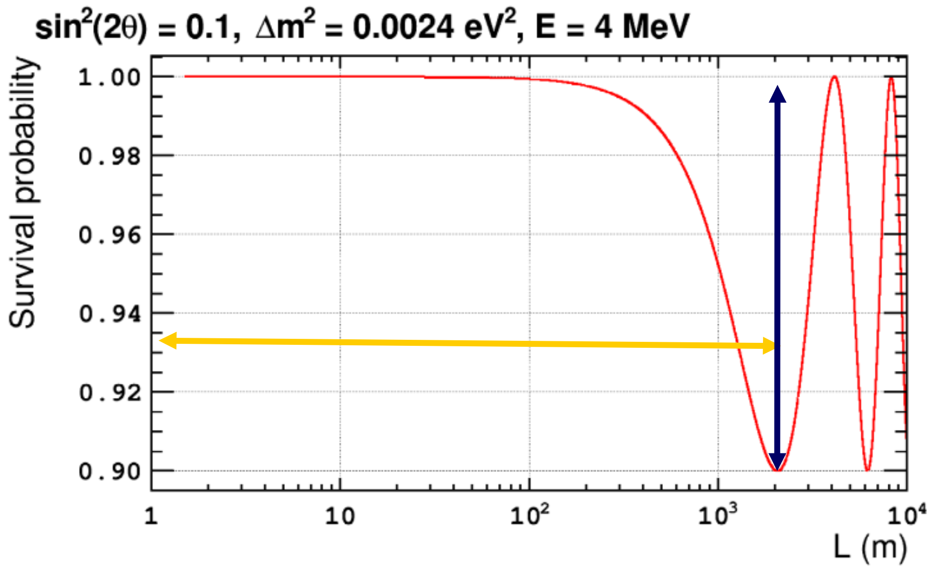
$$P^{2\nu}_{lx\,(l\neq x)}(L,E) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

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

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

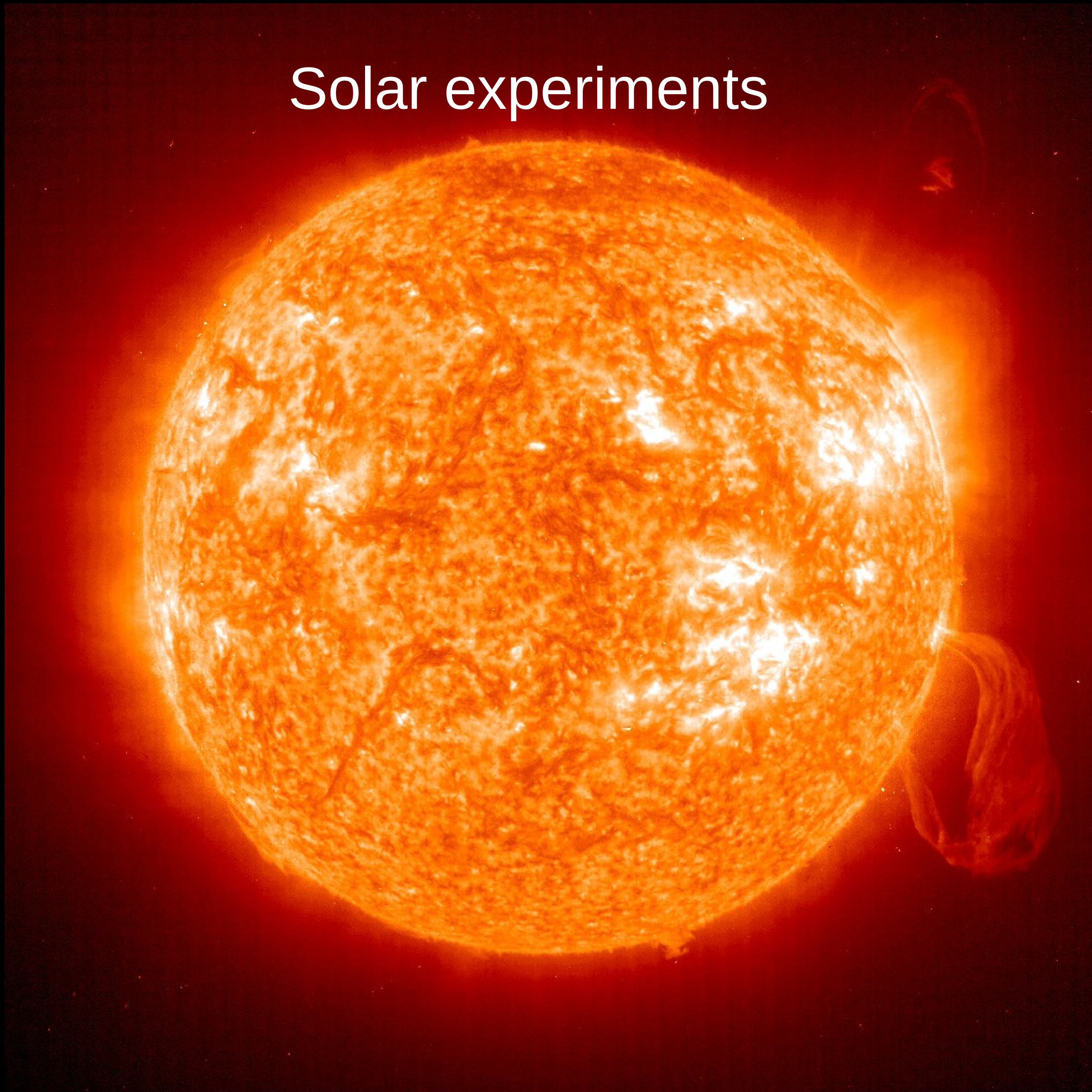
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13} e^{-i\delta} \\ & 1 & \\ -s_{13} e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} &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

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!**

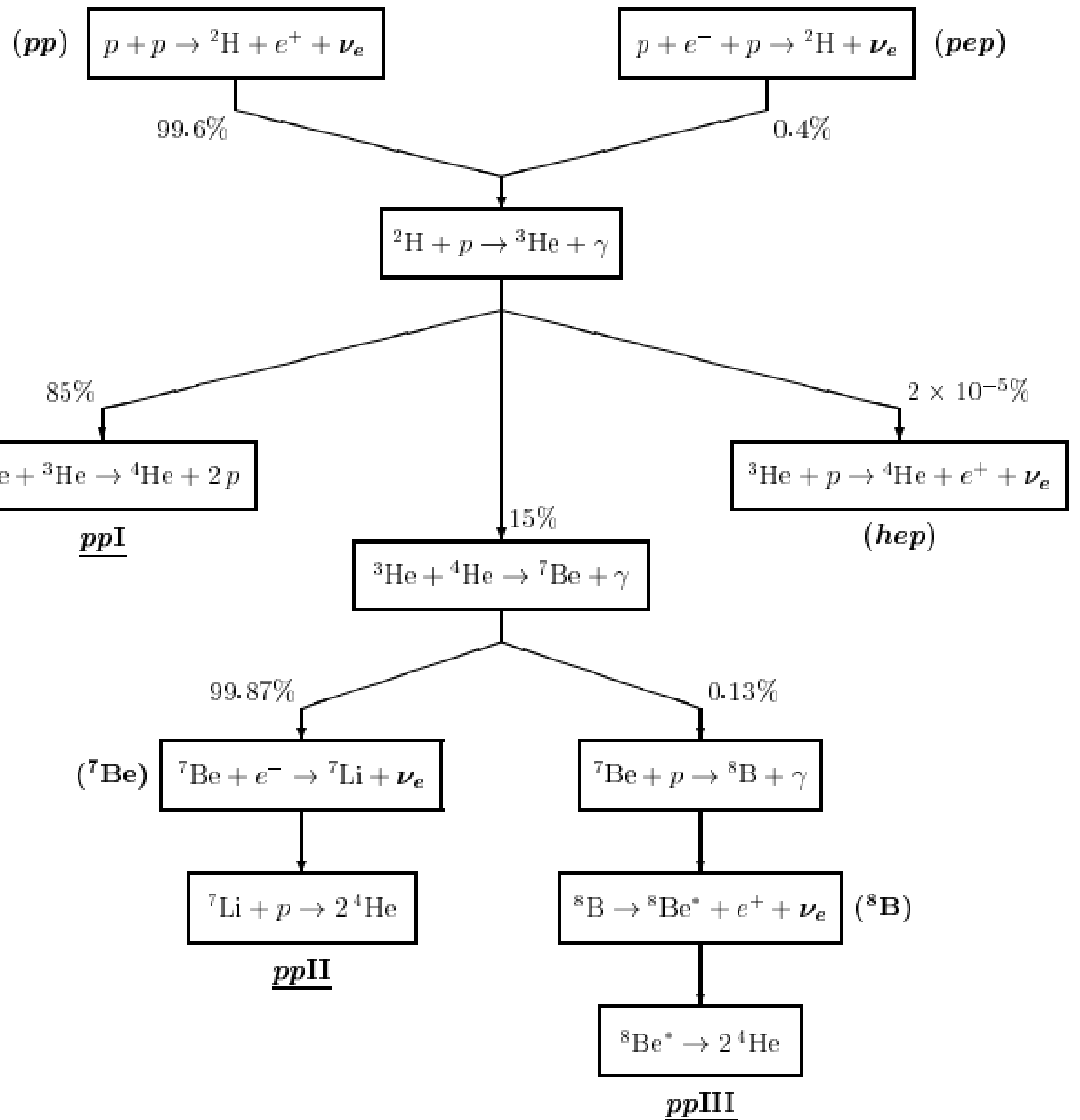
Measurement of θ_{12} and Δm^2_{21}

Solar experiments



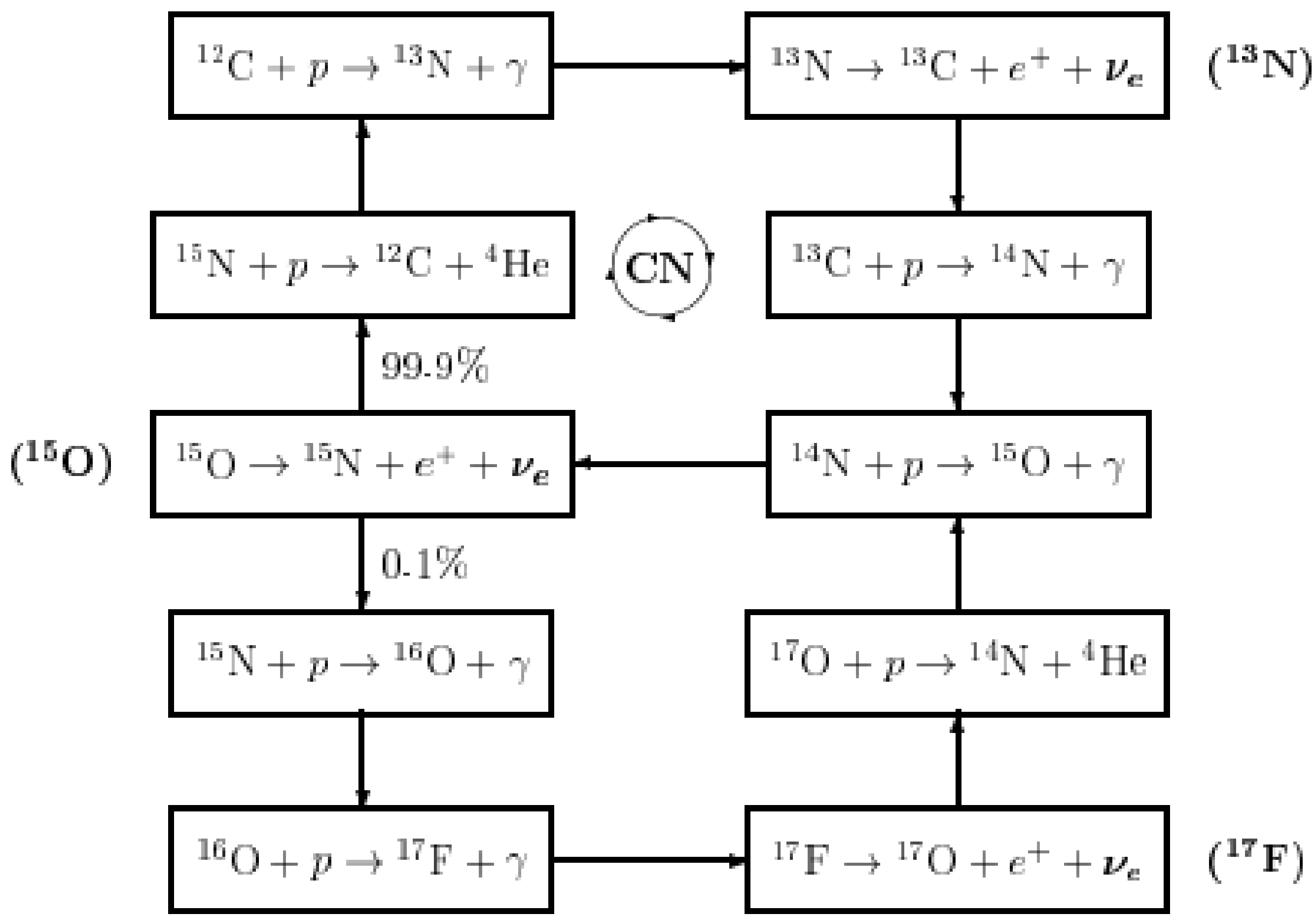
Solar neutrinos: pp chain

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

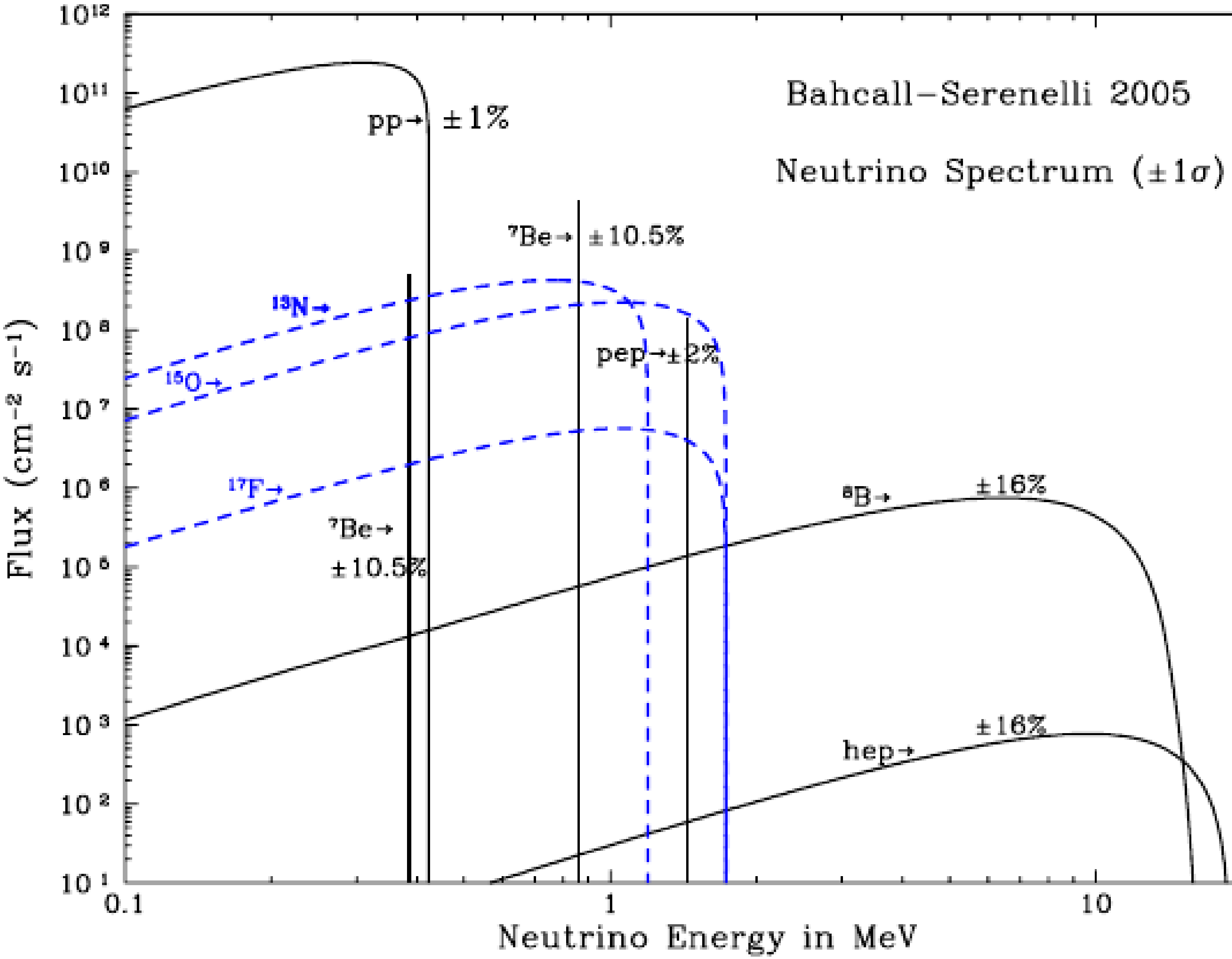


Solar neutrinos: CNO cycle

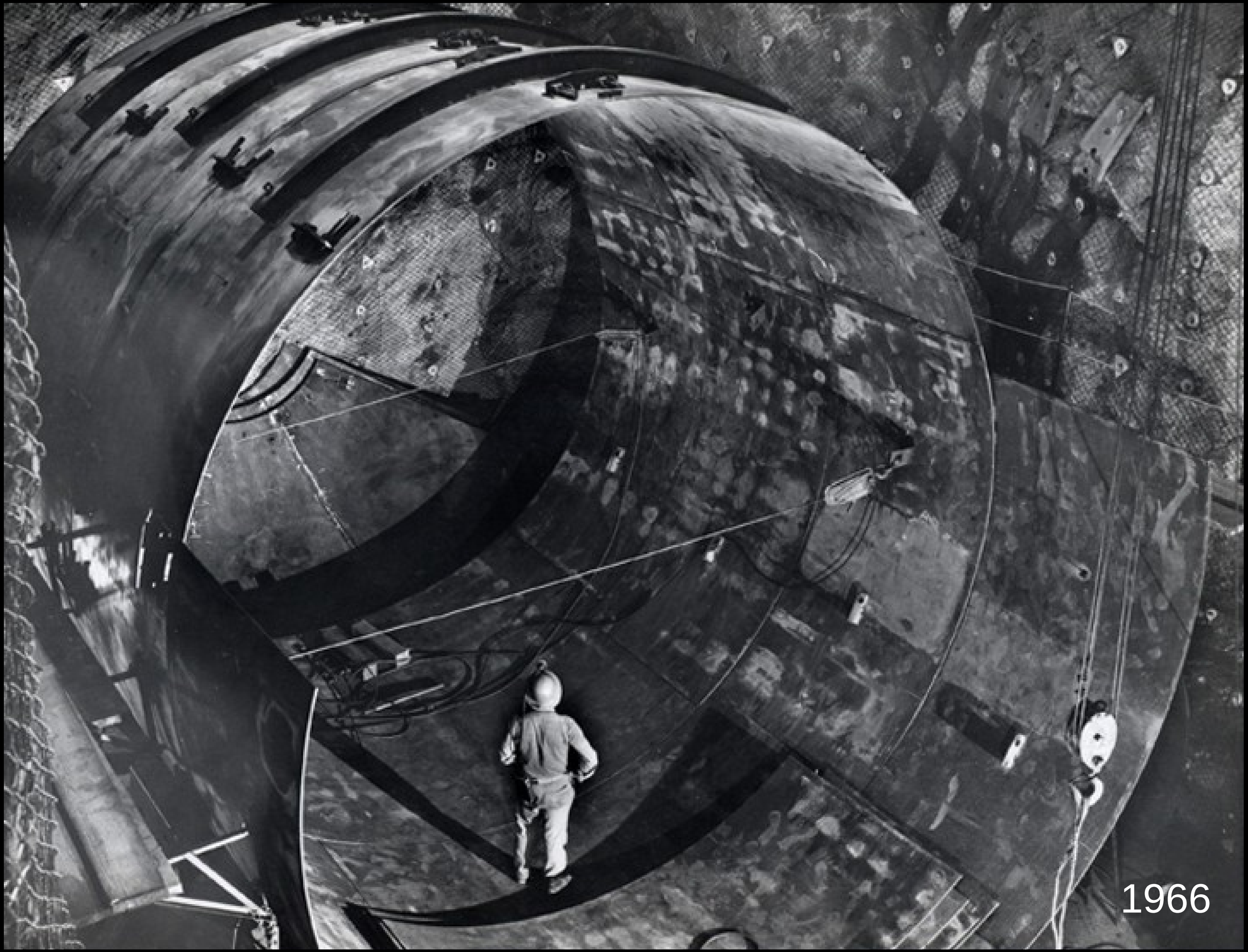
- CNO cycle produces 1.6% of Sun's fusion energy. It also produces **electron neutrinos**.



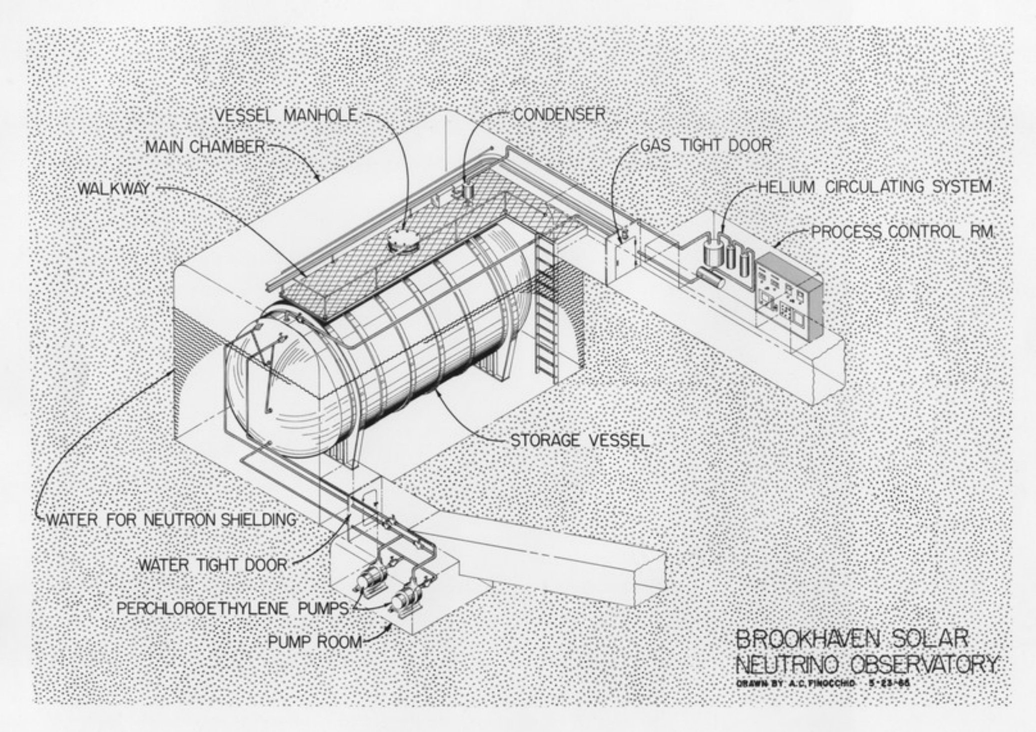
Solar neutrinos: energy spectrum



Homestake experiment (1970 - 1994)



Homestake experiment



- Detection of solar neutrinos using the reaction:

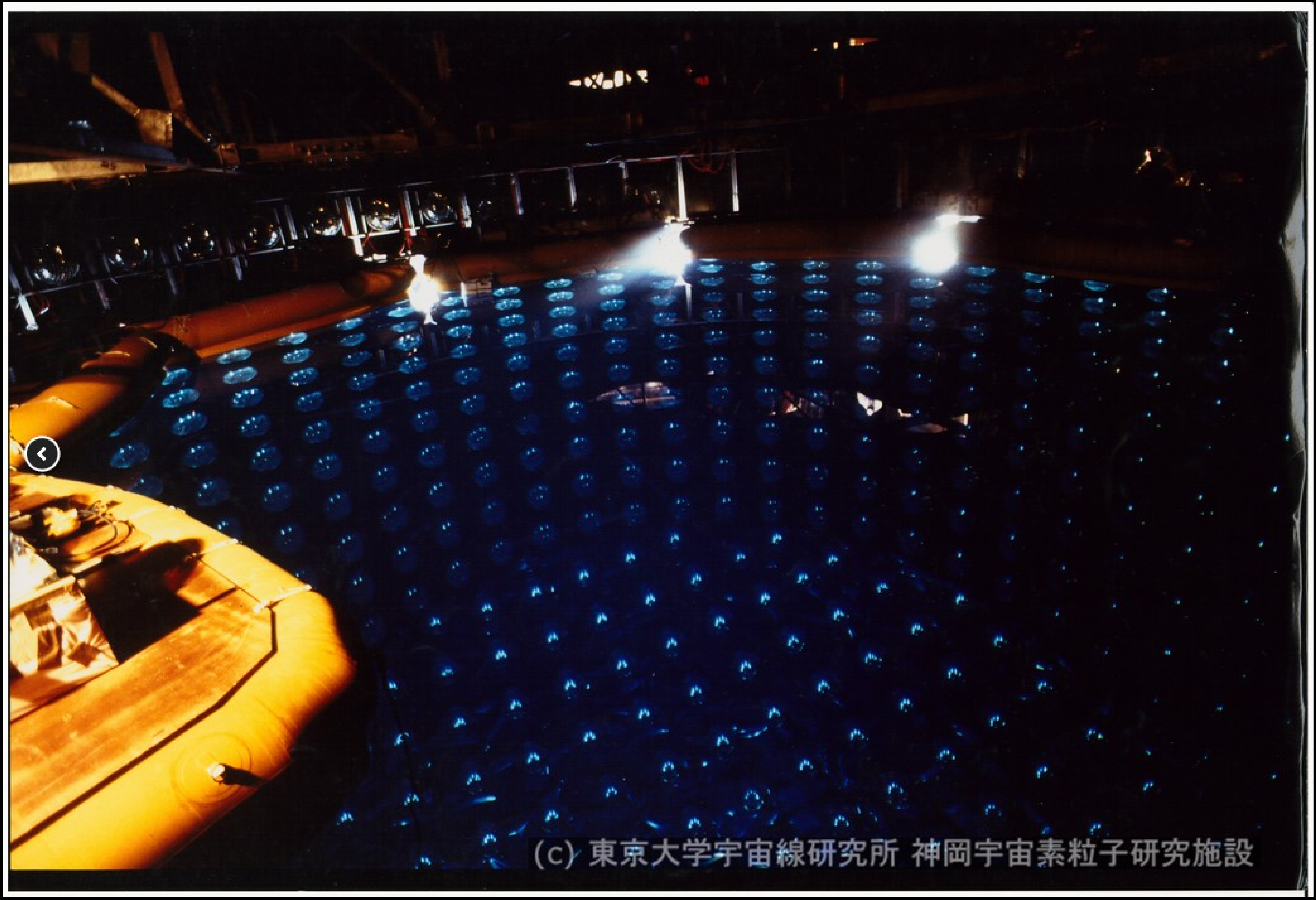
$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$$

- Radiochemical detector.
- Ratio of observed to predicted:

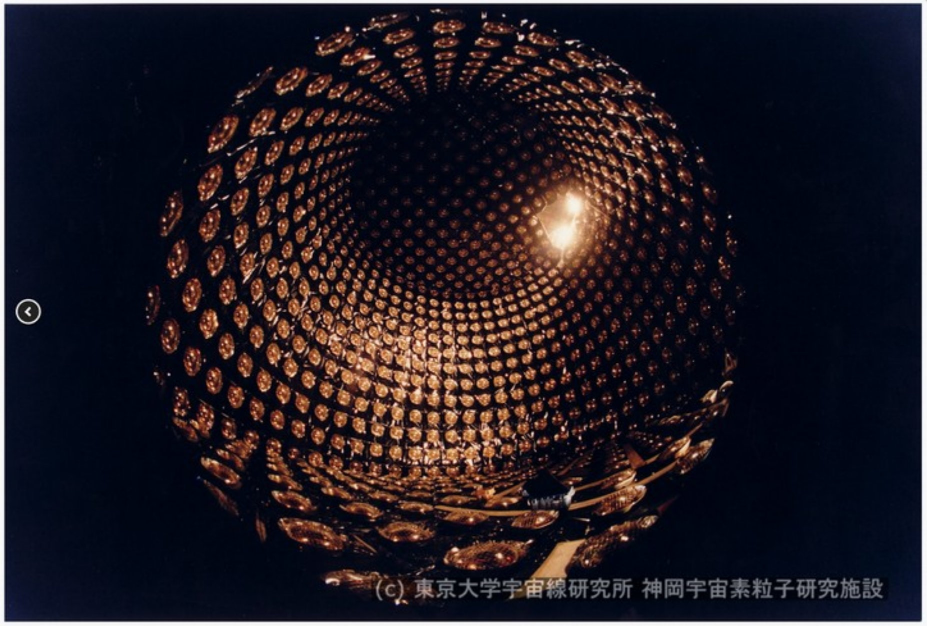
$$\frac{R_{\mathrm{Cl}}}{R_{\mathrm{SSM}}} = 0.301 \pm 0.027$$

- **Missing neutrinos!**

Kamiokande (1983 - 1996)



Kamiokande



- Detection of solar neutrinos using the reaction:

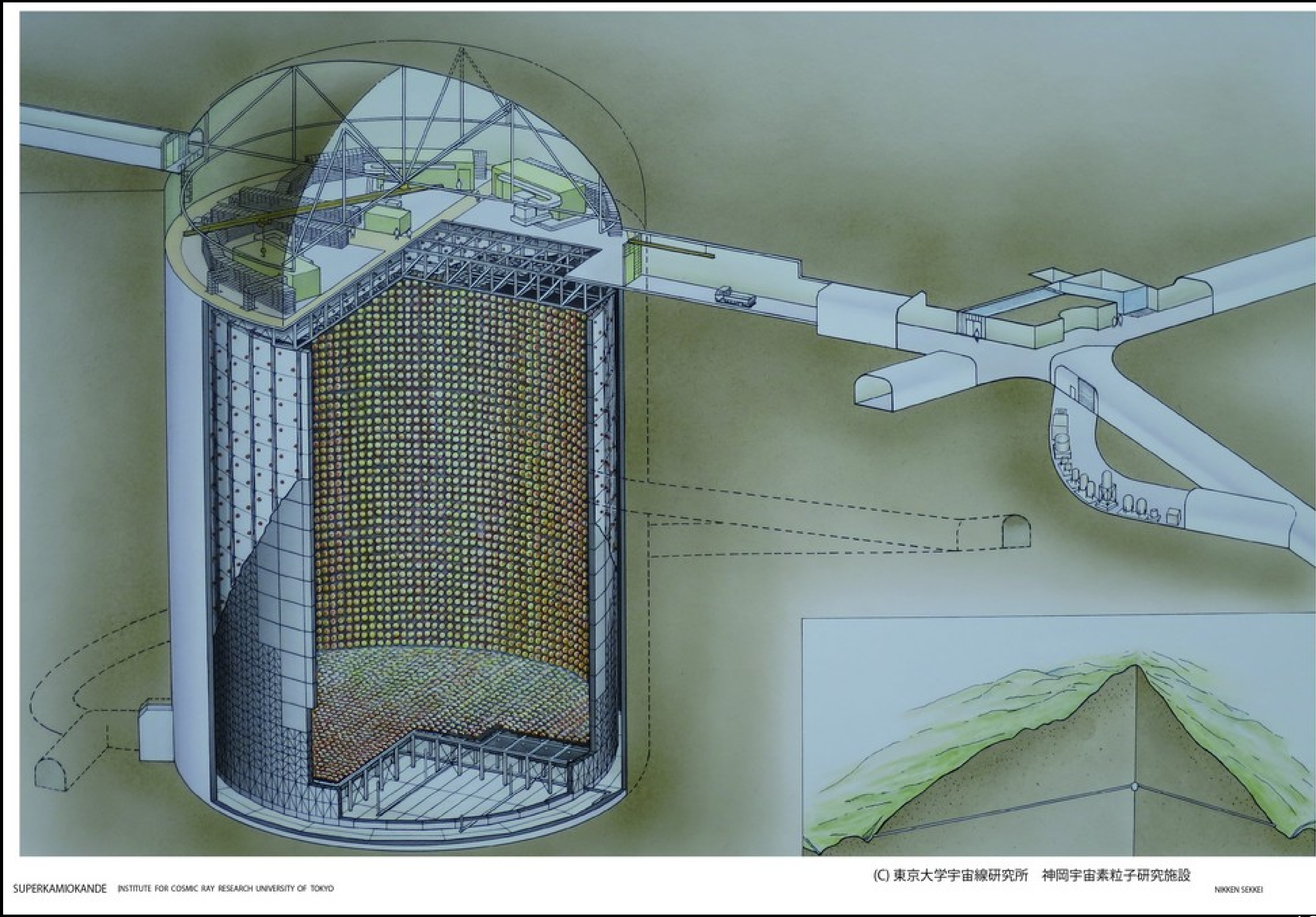
$$\nu_l + e^- \rightarrow \nu_l + e^-$$

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

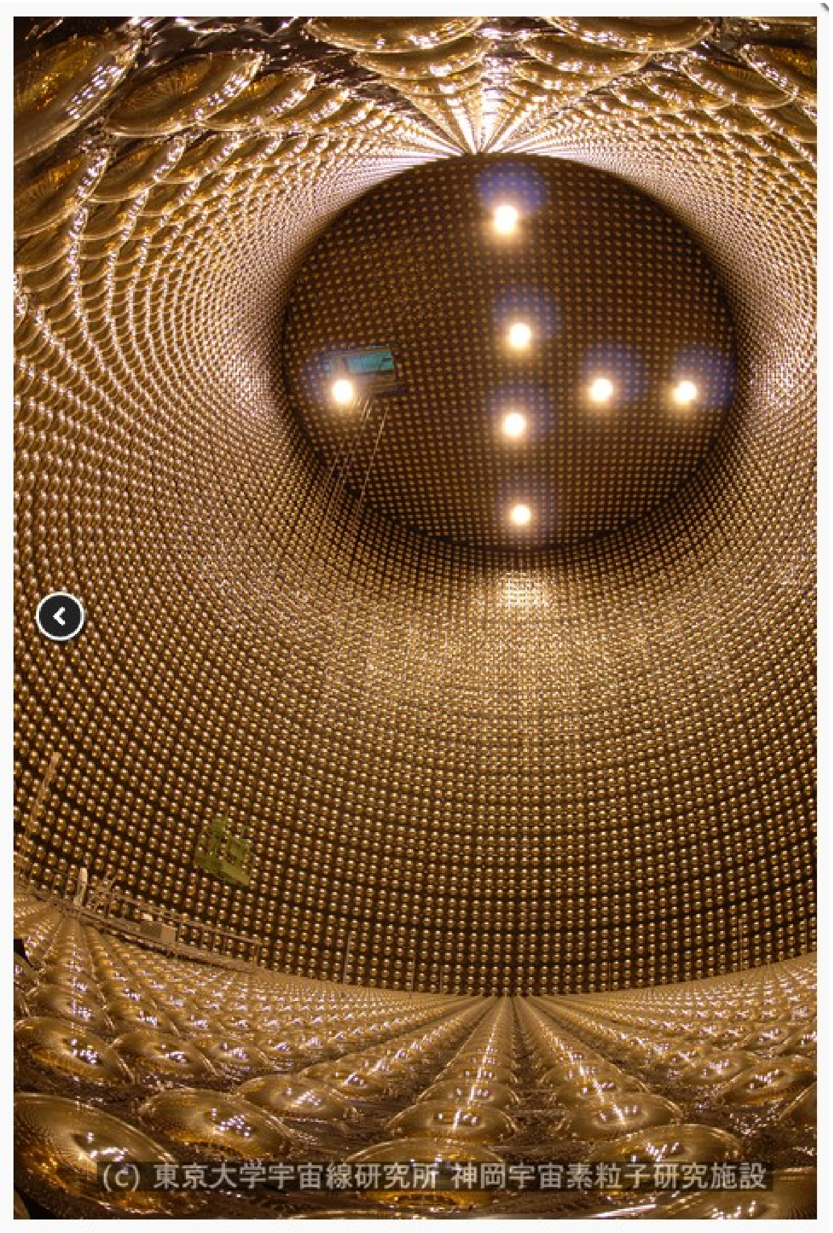
$$\frac{\Phi_{\text{Kamiokande}}}{\Phi_{\text{SSM}}} = 0.484 \pm 0.066.$$

- **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:

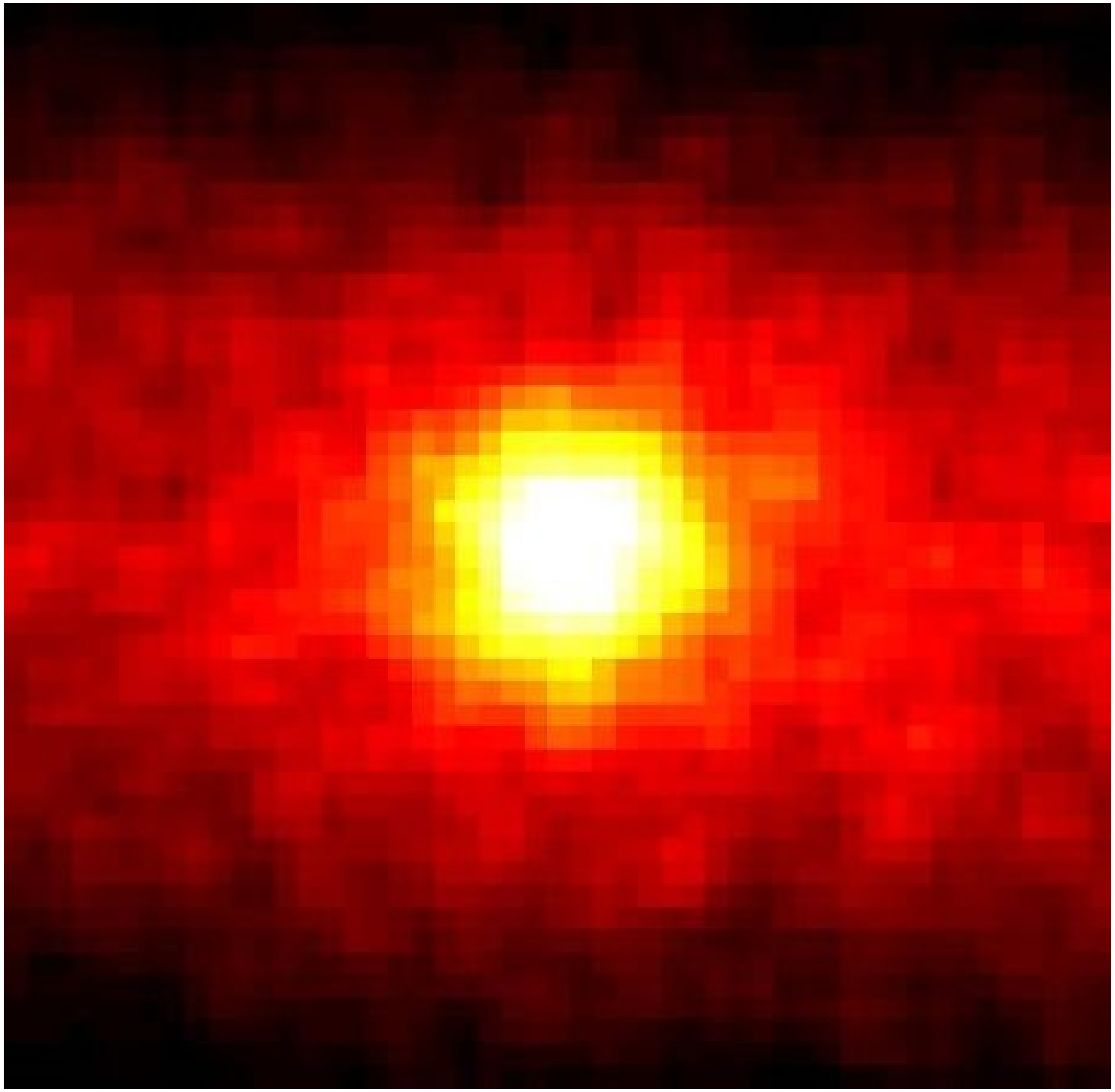
$$\frac{\Phi_{\mathrm{SK-I}}}{\Phi_{\mathrm{SSM}}} = 0.406 \pm 0.014$$

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

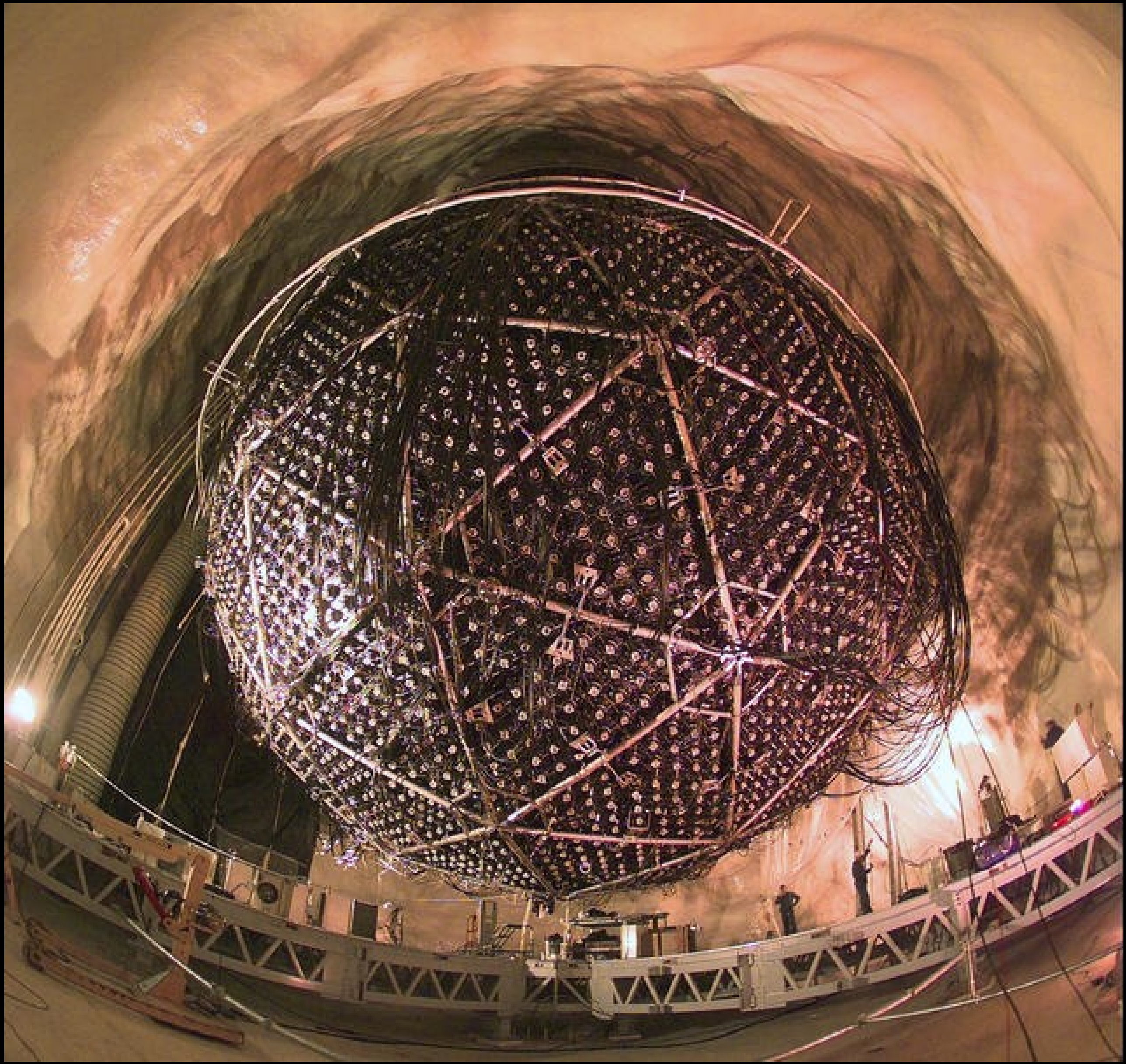
Super-Kamiokande

Super-Kamiokande

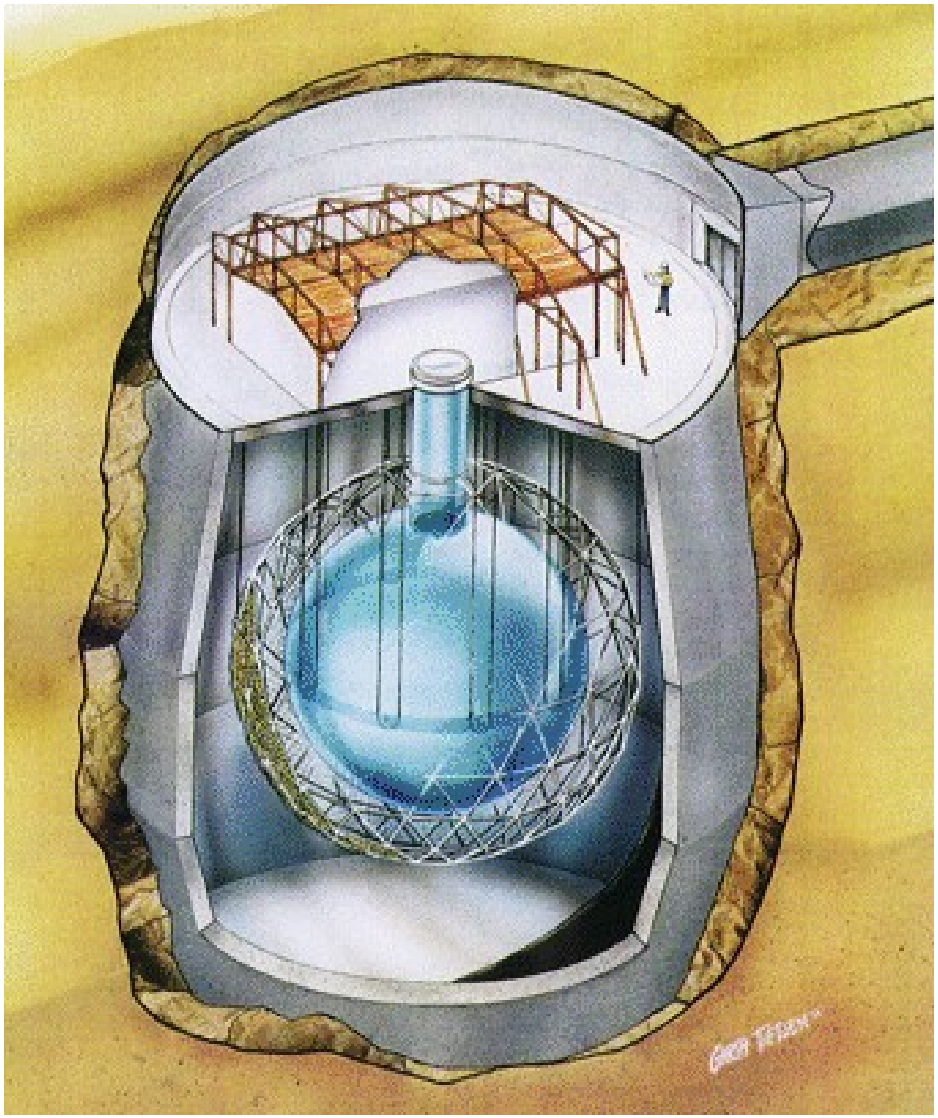
- **NEUTRINOGRAPHY** of the Sun. 500 days exposure!



SNO (1999 - 2006)



SNO



- Detection of solar neutrinos using the reactions:

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

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

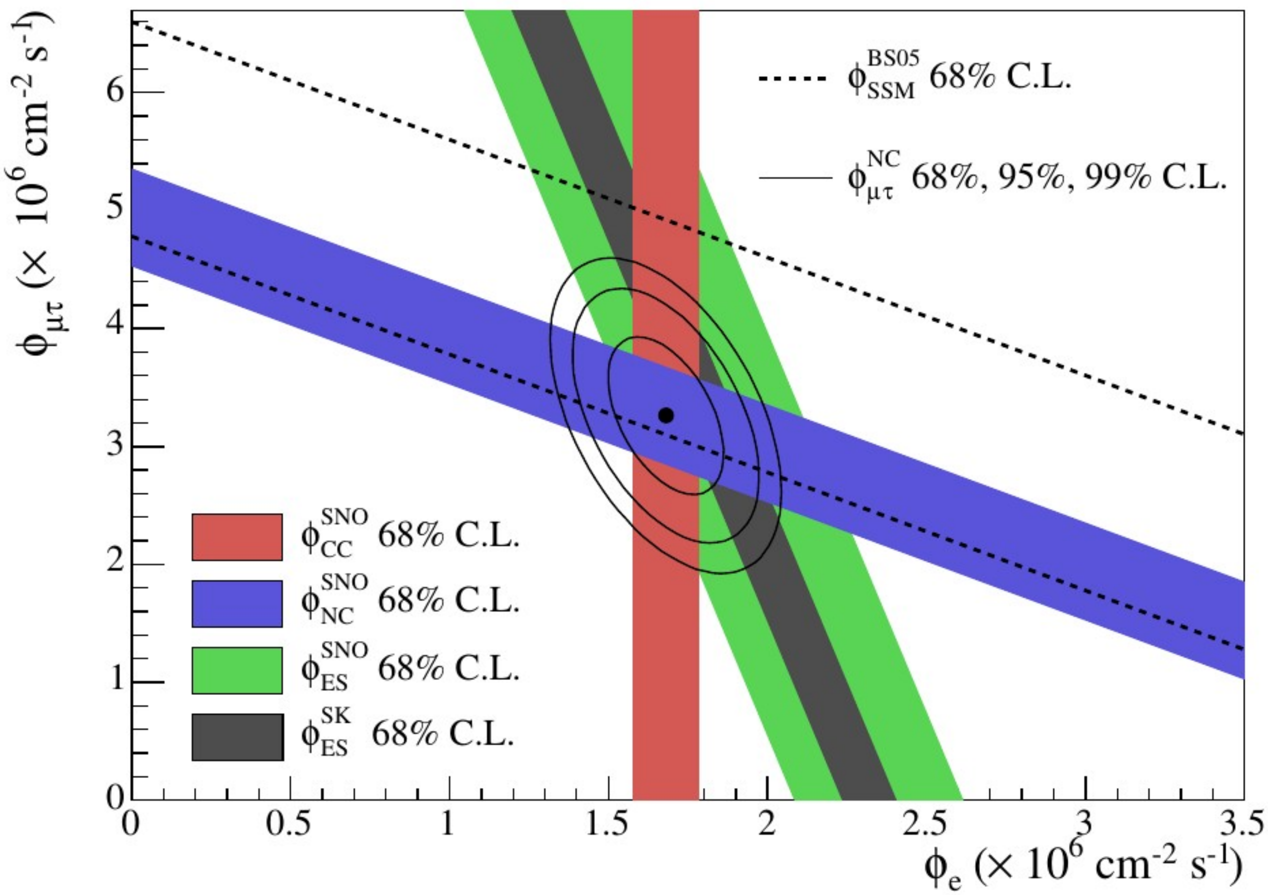
$$\frac{\Phi_{\mathrm{SNO}}^{\mathrm{ES}}}{\Phi_{\mathrm{SSM}}} = 0.406 \pm 0.046$$
$$\frac{\Phi_{\mathrm{SNO}}^{\mathrm{CC}}}{\Phi_{\mathrm{SSM}}} = 0.290 \pm 0.017$$
$$\frac{\Phi_{\mathrm{SNO}}^{\mathrm{NC}}}{\Phi_{\mathrm{SSM}}} = 0.853 \pm 0.075$$

SNO

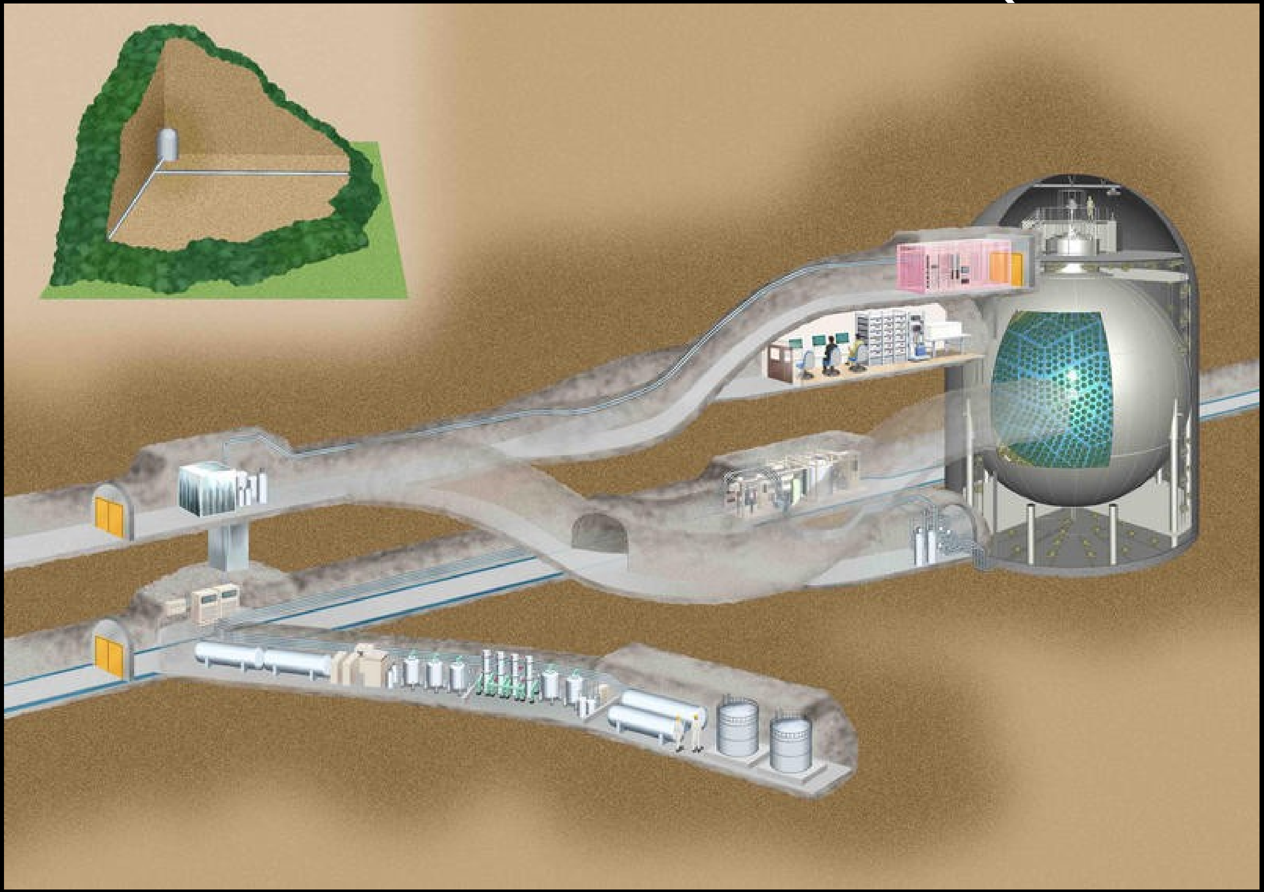
$$\Phi^{\nu_e}_{\rm SNO} + r^{\rm ES}\,\Phi^{\nu_{\mu,\tau}}_{\rm SNO} = \Phi^{\rm ES}_{\rm SNO} \qquad r^{\rm ES} \equiv \sigma^{\rm ES}_{\nu_{\mu,\tau}}/\sigma^{\rm ES}_{\nu_e} \approx 0.1553$$

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

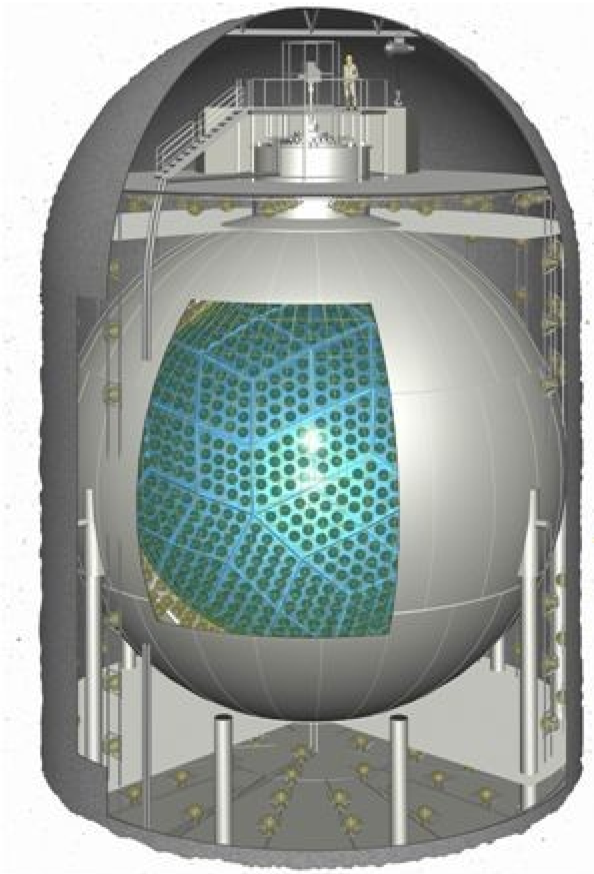
$$\Phi^{\nu_e}_{\rm SNO} + \Phi^{\nu_{\mu,\tau}}_{\rm SNO} = \Phi^{\rm NC}_{\rm SNO}$$

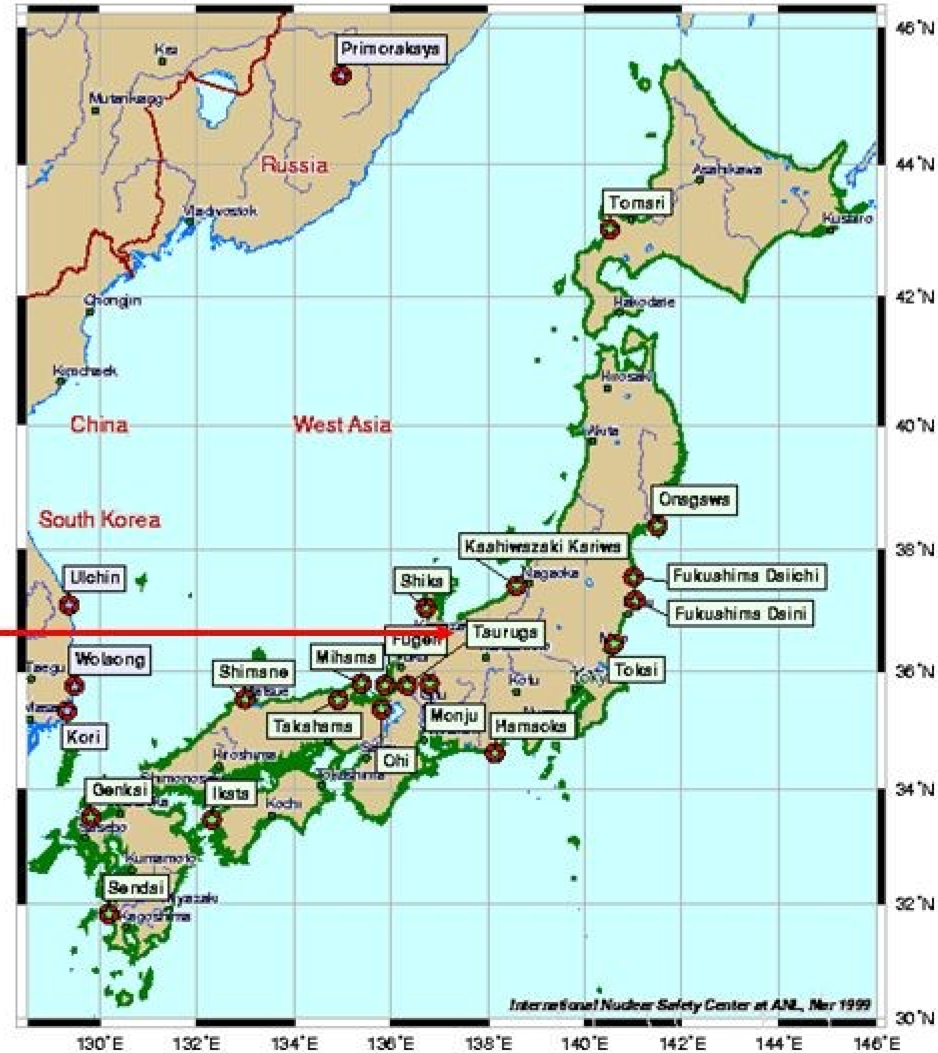


KamLAND (2002 - 2011)



KamLAND



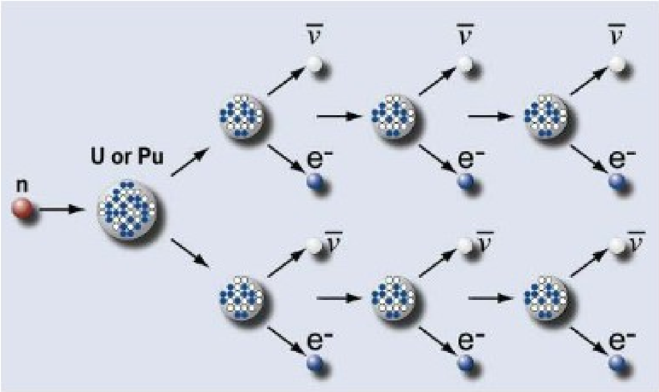

Russia
Primorskaya
Vladivostok
Chongjin
China
West Asia
South Korea
Ulchin
Wolsong
Kori
Genkai
Sendai
Shimane
Ikata
Mihama
Takahama
Ohi
Fugen
Shika
Tsuruga
Monju
Hamaoka
Tokai
Fukushima Daiichi
Fukushima Daini
Onagawa
Tomari
Hiroshima
Kochi
Nagaoka
Hakodate
Asahikawa
46°N
44°N
42°N
40°N
38°N
36°N
34°N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

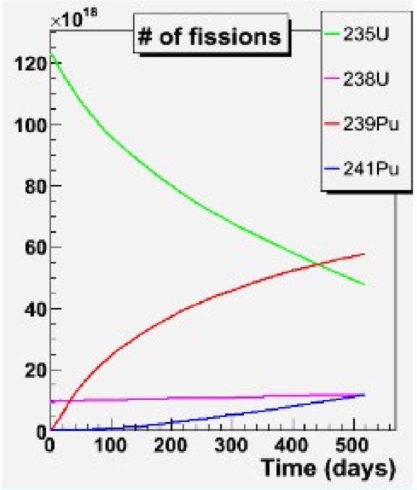
$\overline{\nu}_e$ production at nuclear reactors

- 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.





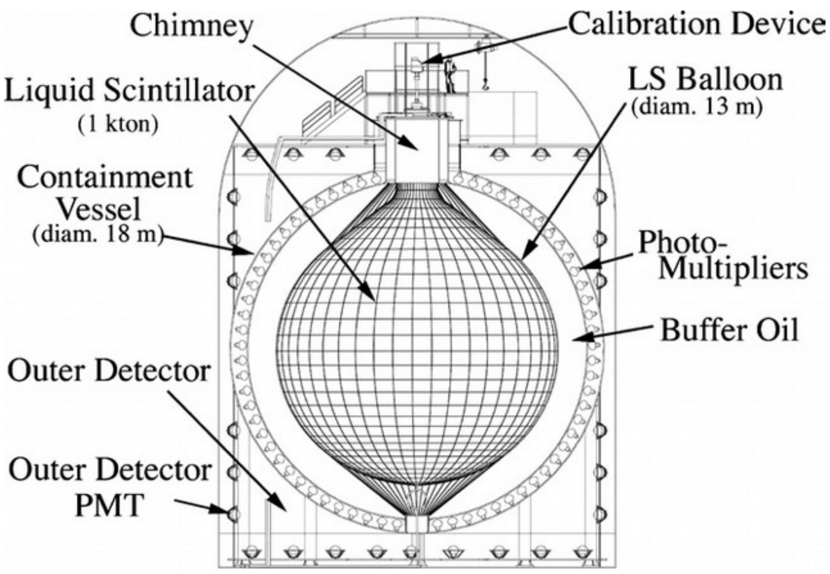
- Nuclear power plants: greatest man-made antineutrino source.
- Need to consider nuclear fuel evolution.

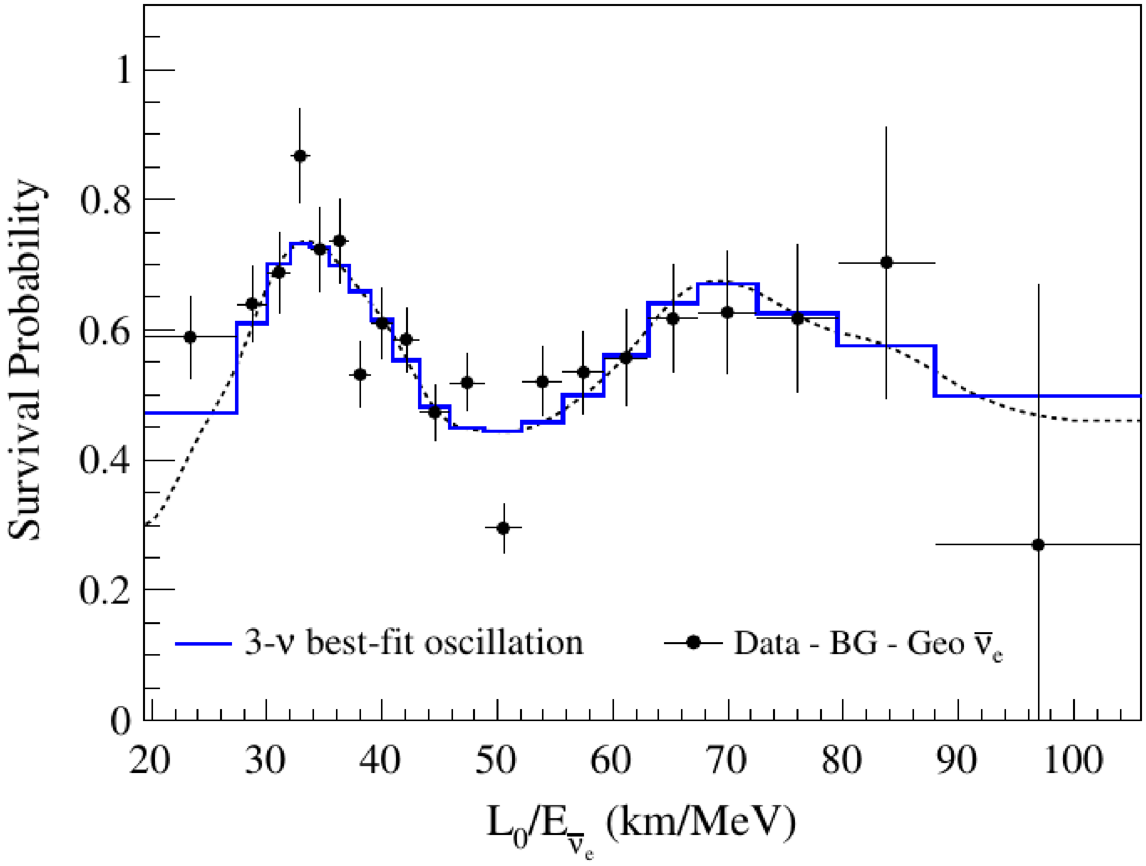
KamLAND

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

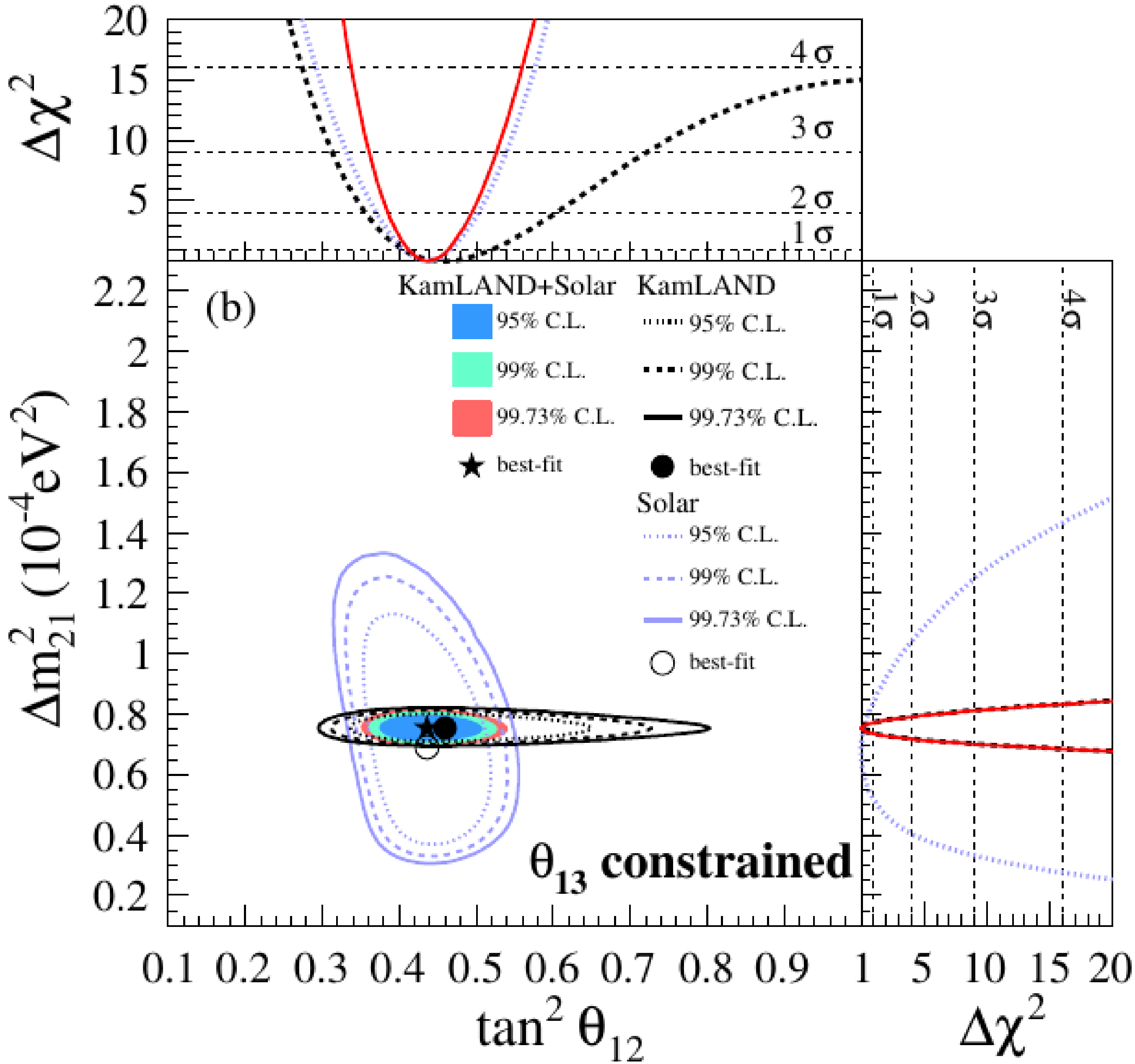
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

- Liquid scintillator detector.



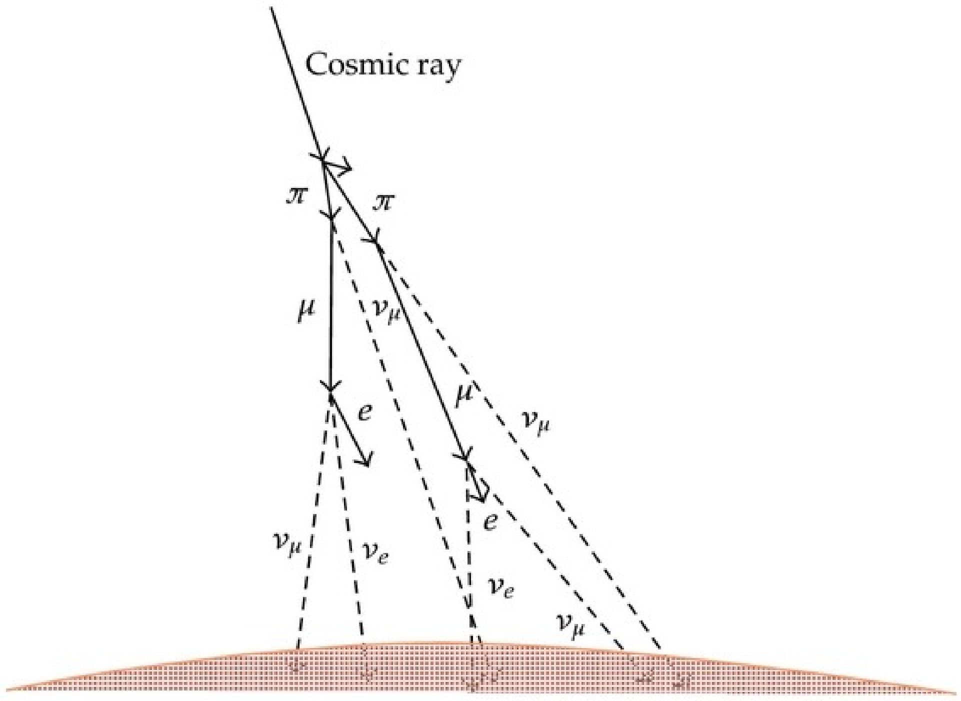


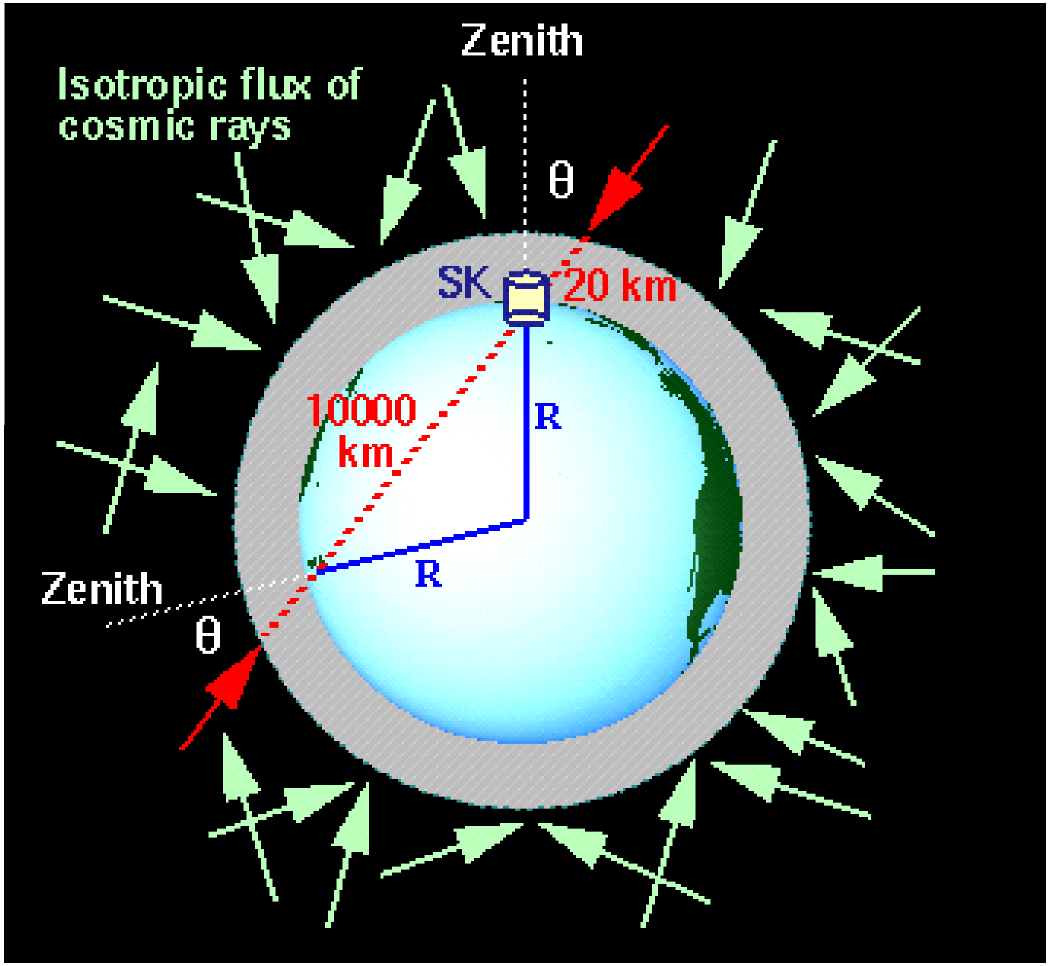
Solar + KamLAND results



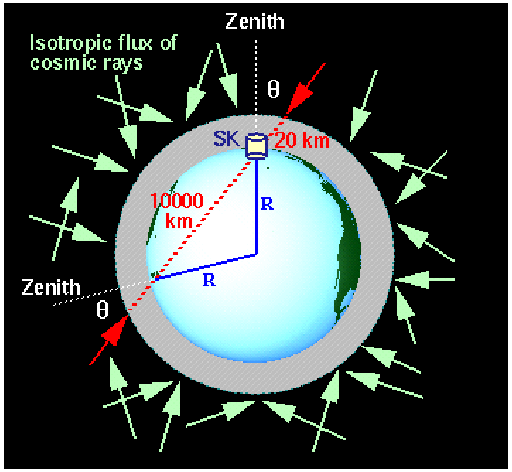
Measurement of θ_{23} and Δm^2_{atm}

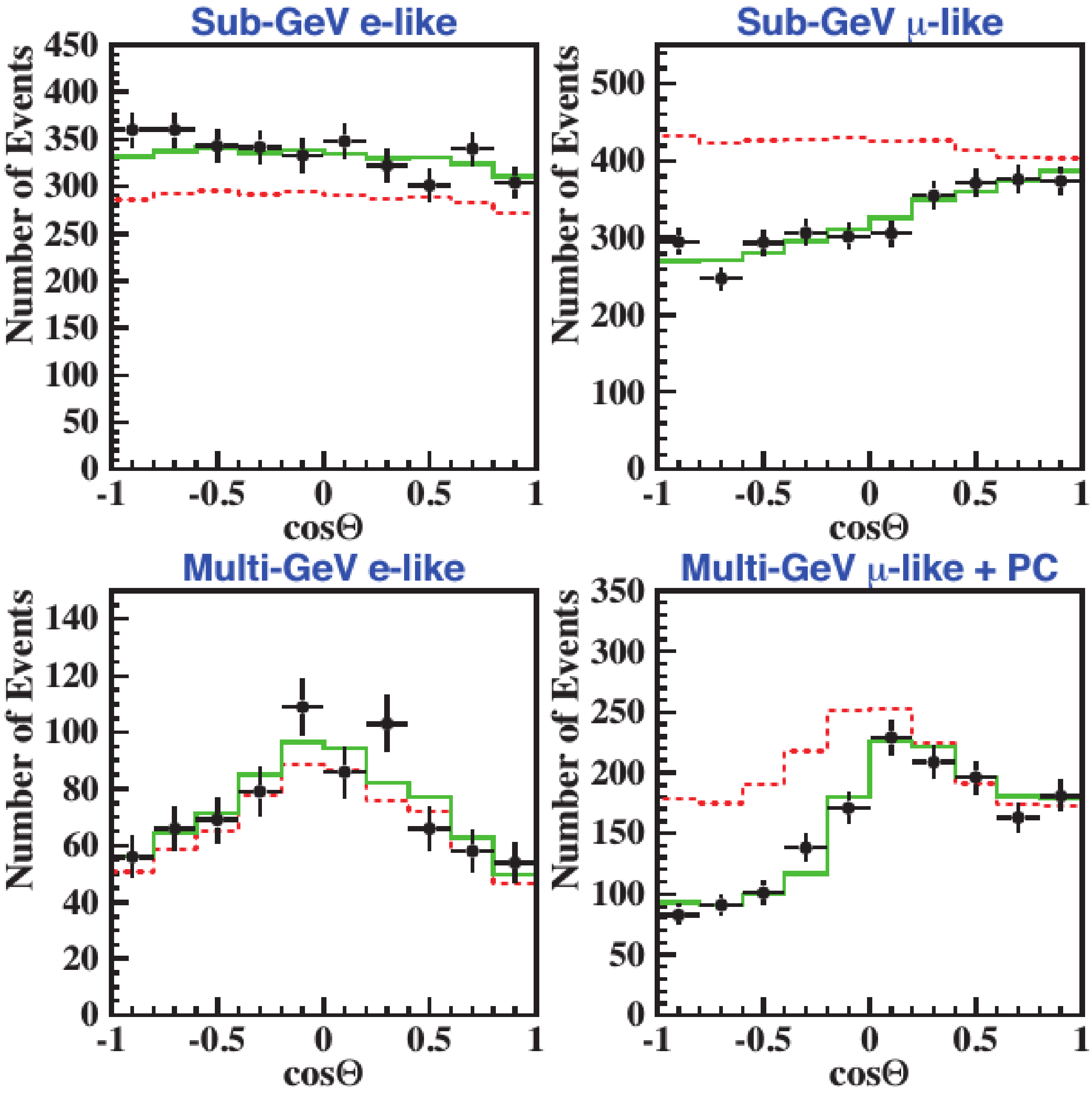
Atmospheric neutrinos



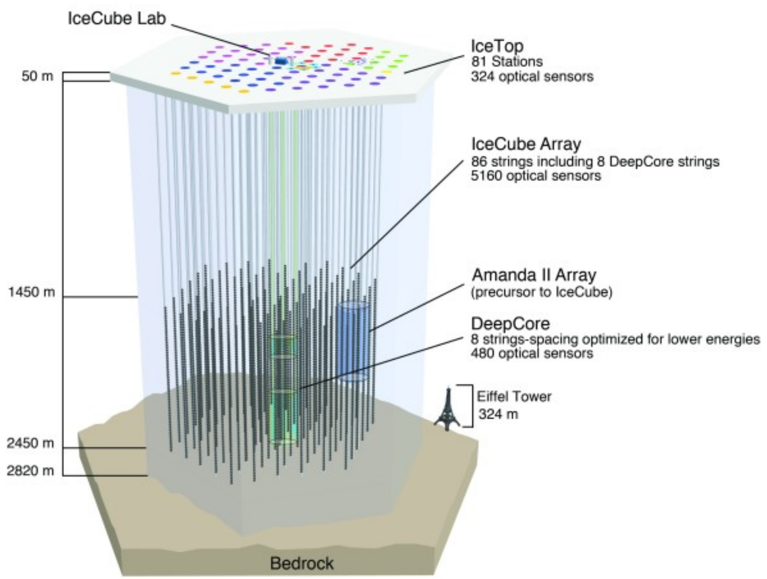


Super-Kamiokande results

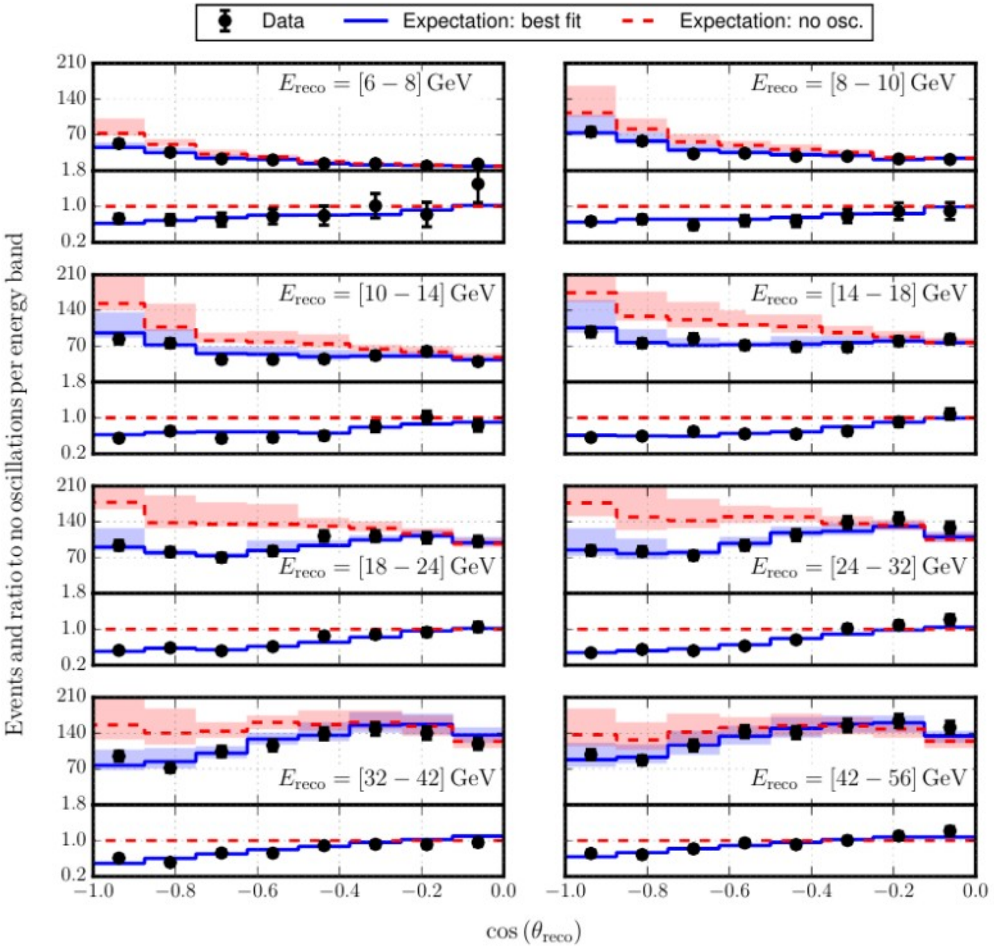




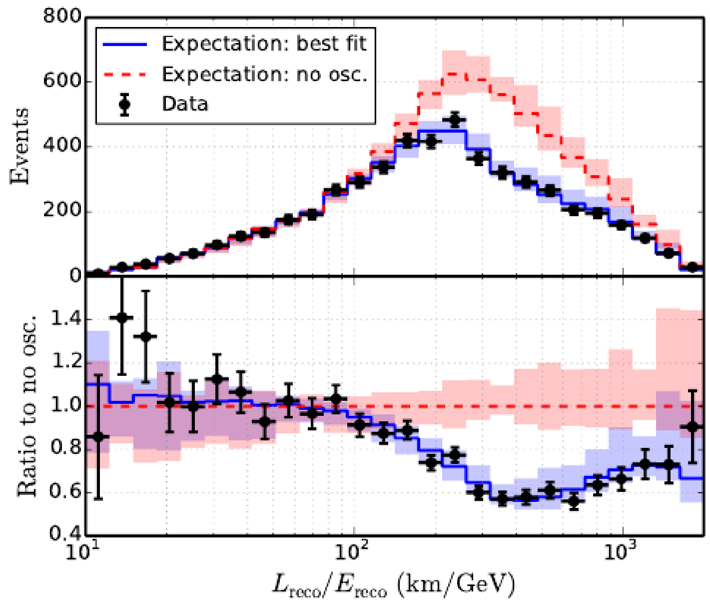
IceCube



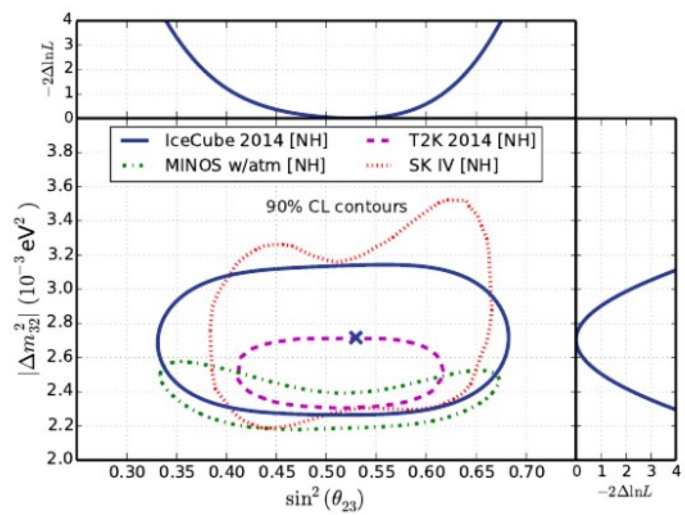
IceCube Lab
IceTop
81 Stations
324 optical sensors
50 m
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
Amanda II Array
(precursor to IceCube)
1450 m
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
Bedrock



Data
Expectation: best fit
Expectation: no osc.
Events and ratio to no oscillations per energy band
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
$\cos(\theta_{reco})$

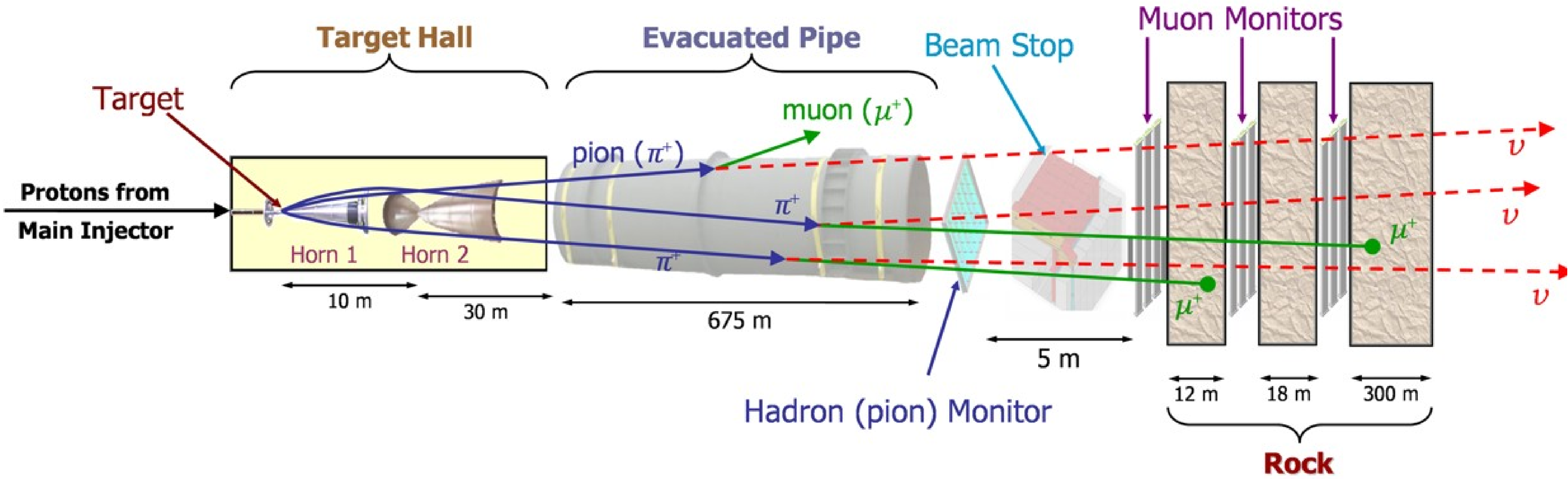


Expectation: best fit
Expectation: no osc.
Data
Events
Ratio to no osc.
L_{reco}/E_{reco} (km/GeV)



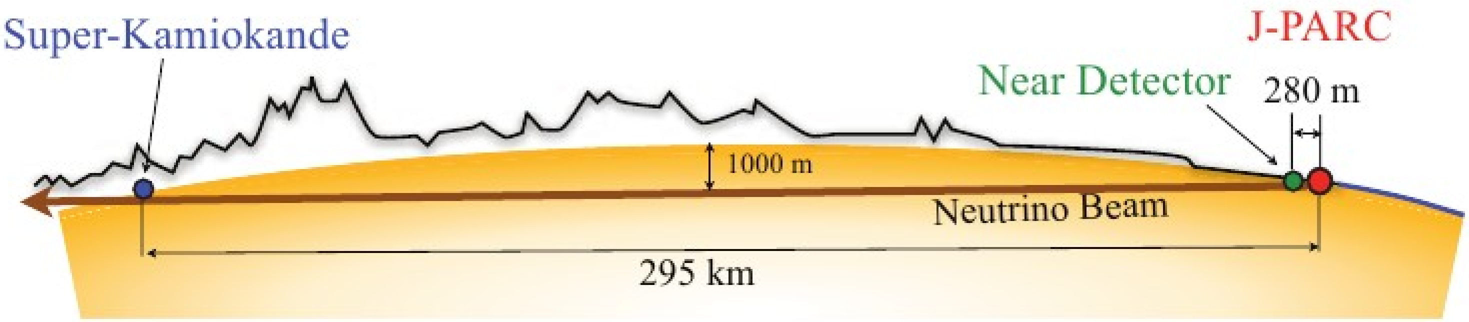
IceCube 2014 [NH]
T2K 2014 [NH]
MINOS w/atm [NH]
SK IV [NH]
90% CL contours
$|\Delta m^2_{32}|$ (10^{-3} eV^2)
$\sin^2(\theta_{23})$
$-2\Delta\ln L$

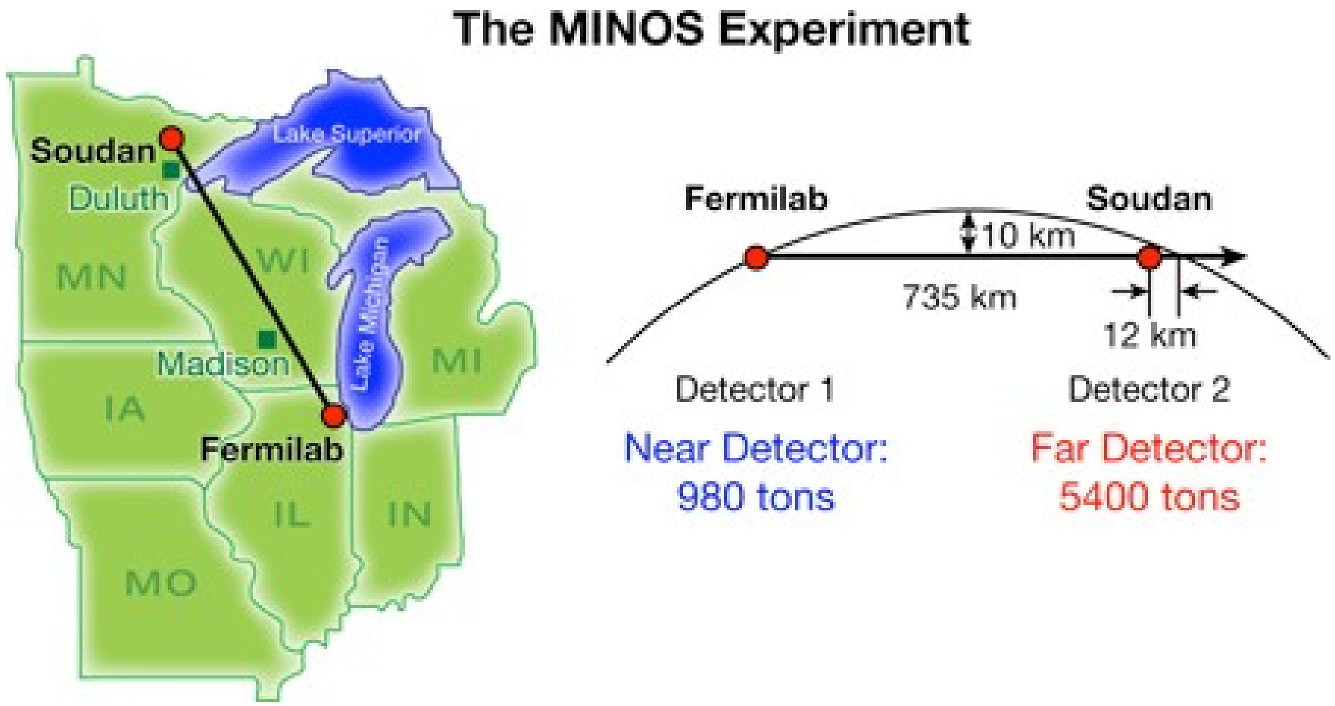
Accelerator neutrinos



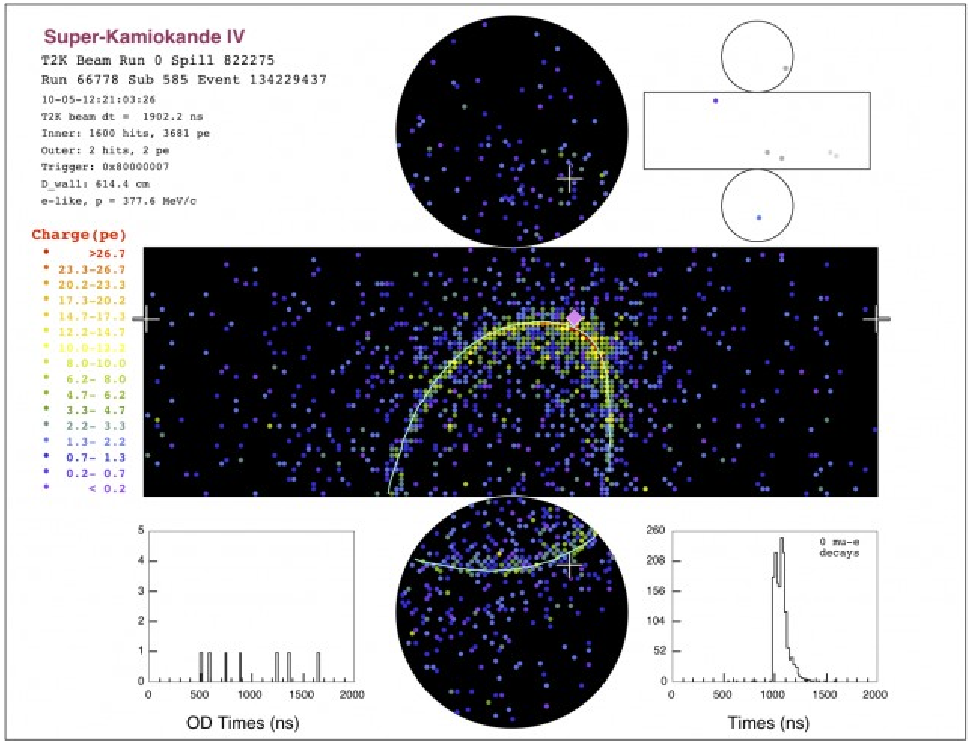
https://www.youtube.com/watch?v=U_xWDWKq1CM

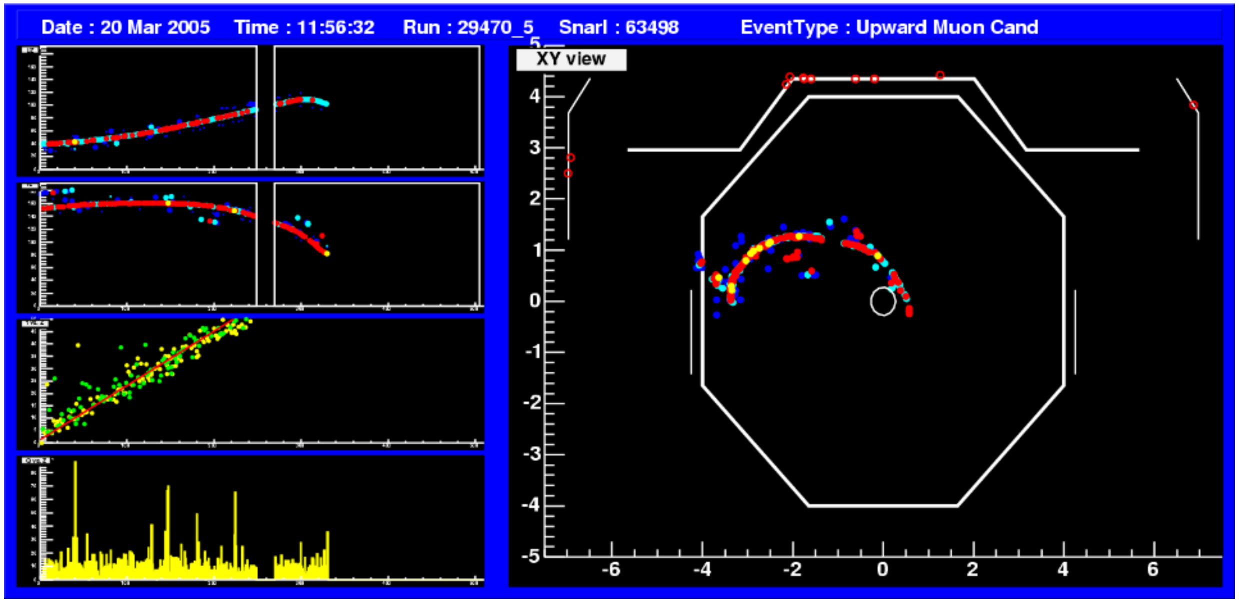
T2K & MINOS experiments



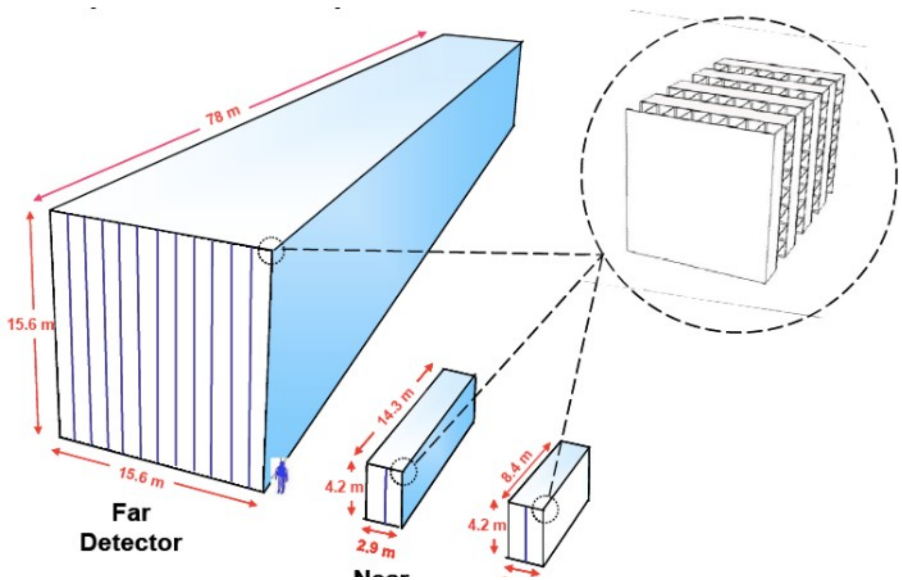


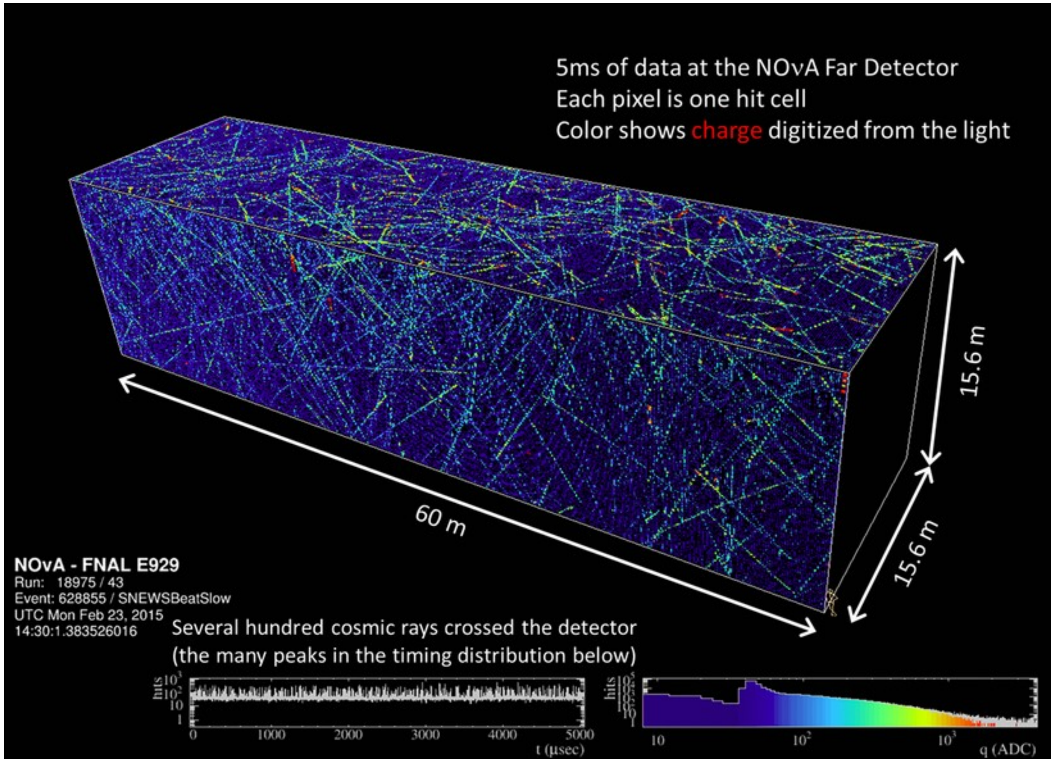
T2K & MINOS experiments

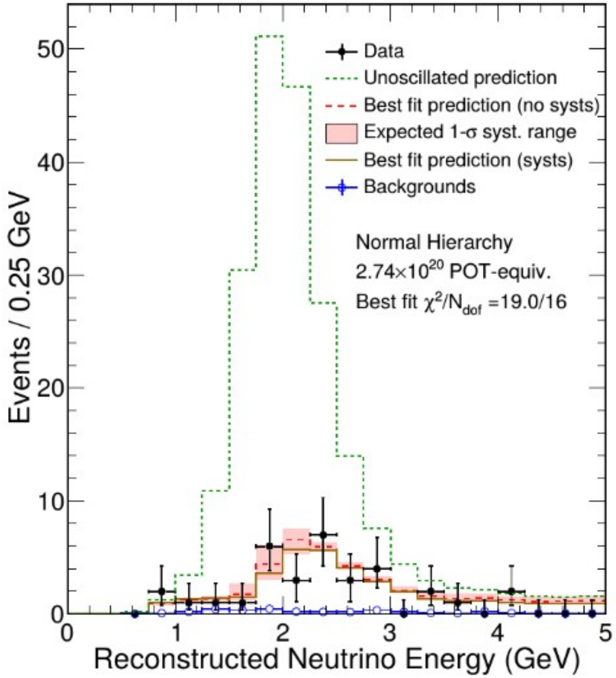


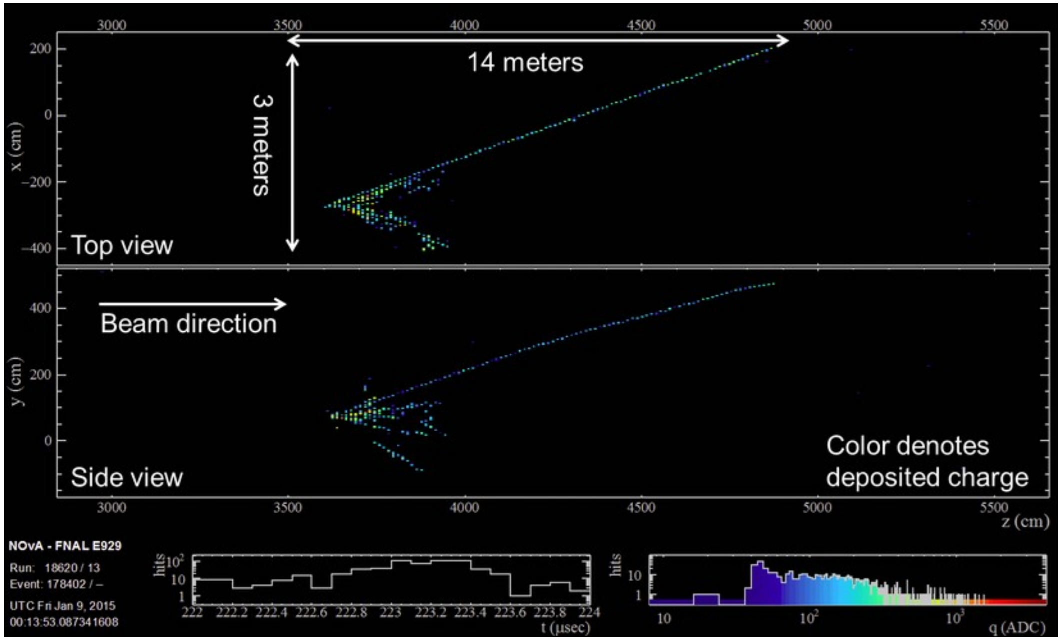


NOvA

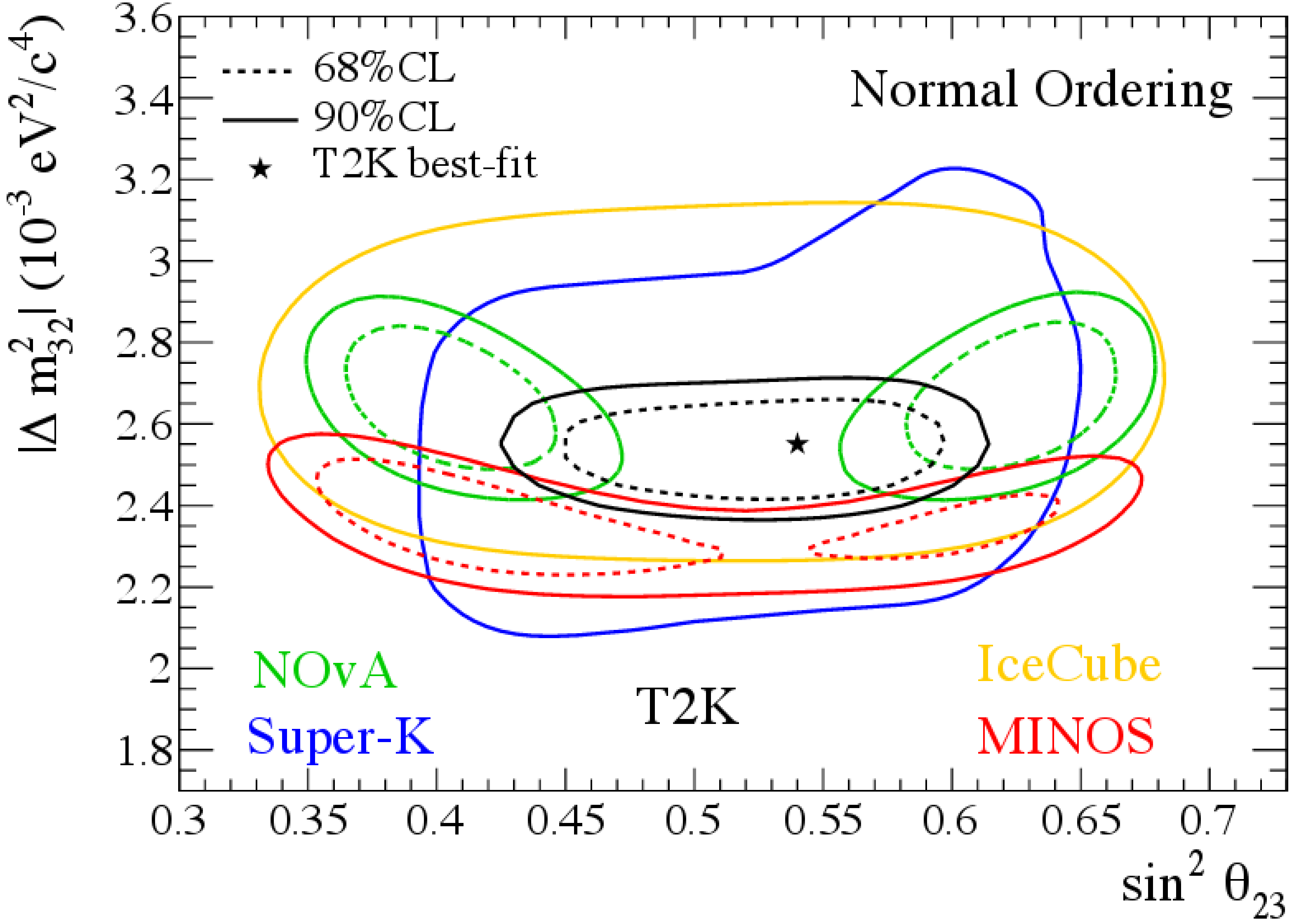

78 m
15.6 m
15.6 m
14.3 m
4.2 m
2.9 m
8.4 m
4.2 m
Far Detector


5ms of data at the NOvA Far Detector
Each pixel is one hit cell
Color shows charge digitized from the light
15.6 m
60 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)

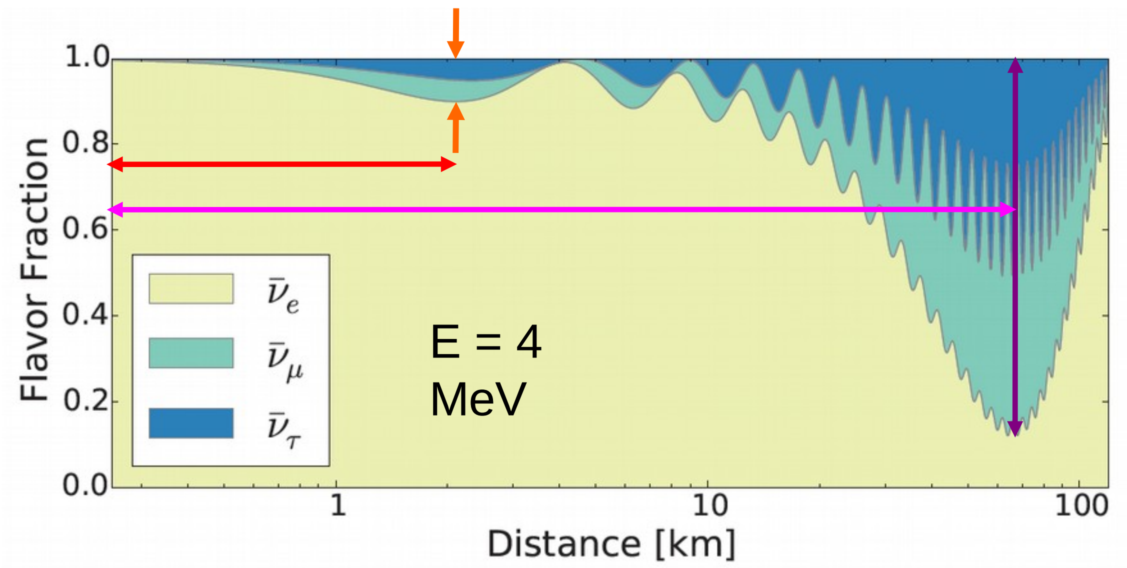

14 meters
3 meters
Top view
Beam direction
Side view
Color denotes deposited charge
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
t (μsec)
q (ADC)

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



Measurement of θ_{13}

Measurement of θ_{13} with reactors



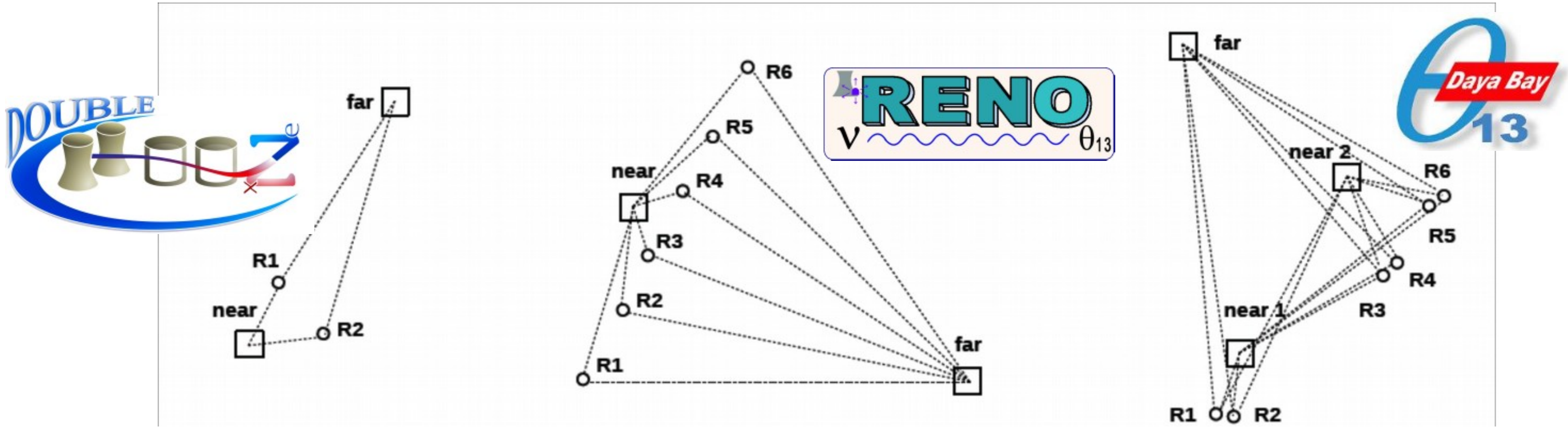
$$P_{ee}(L,E) =$$
$$= 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

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

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

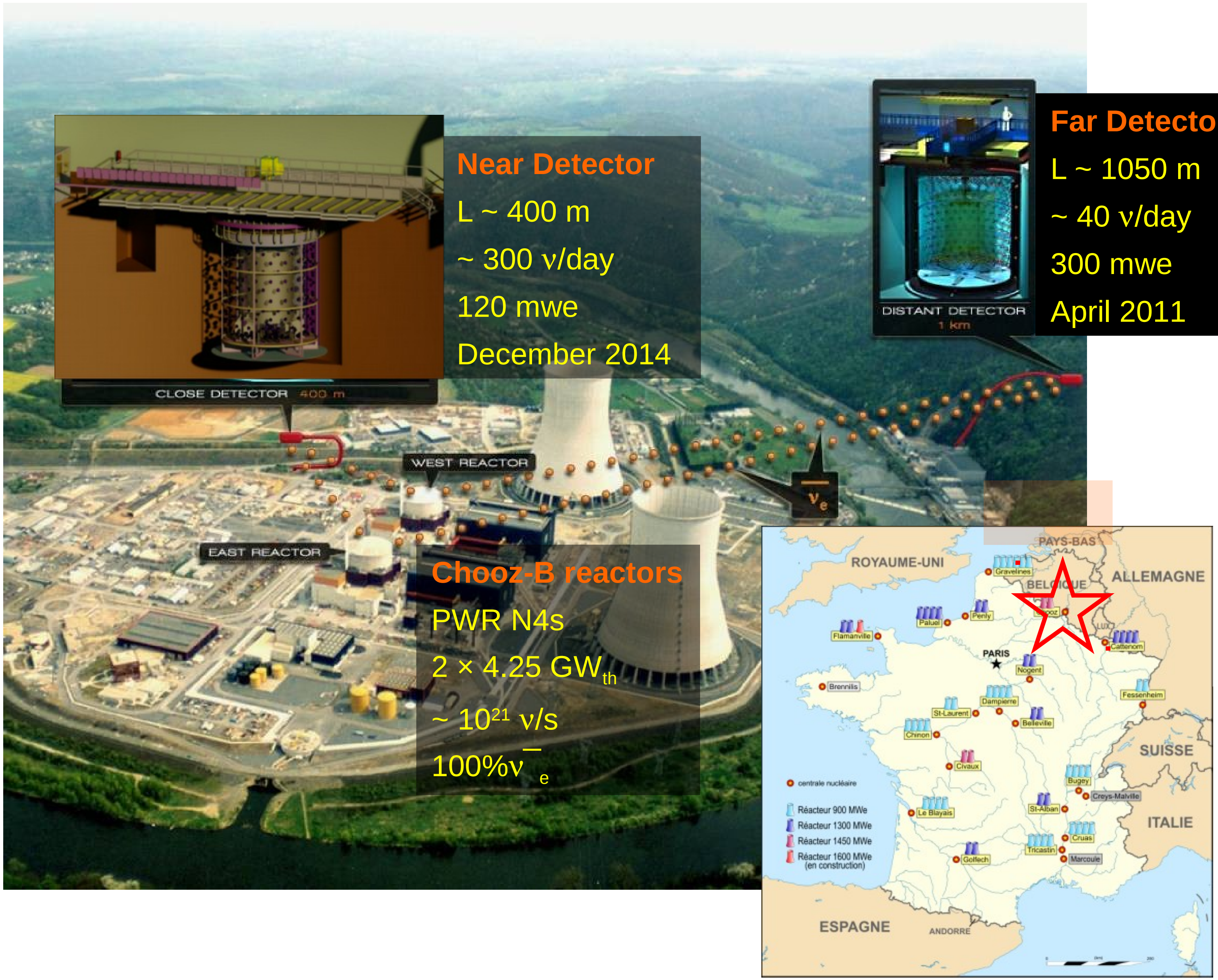
Measurement of θ_{13} with two-detector reactor experiments

- 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

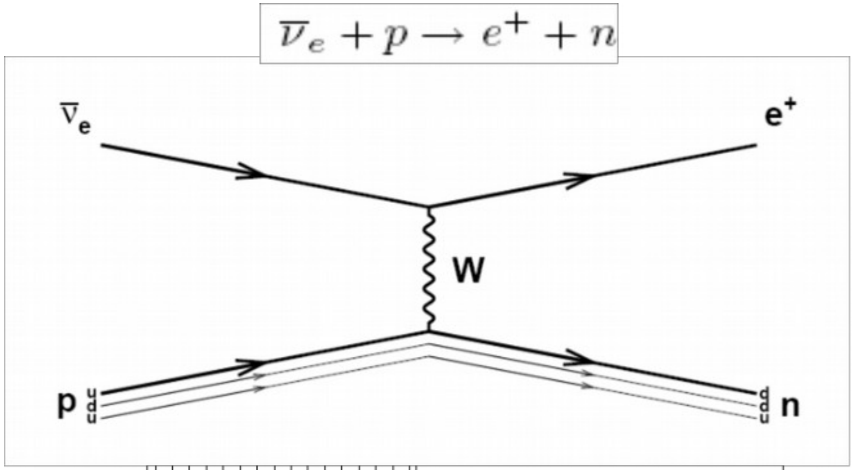
Chooz-B reactors
PWR N4s
2 × 4.25 GW_{th}
~ 10^{21} ν/s
100% $\bar{\nu}_e$

EDF's Chooz nuclear power plant (Ardennes, France)

Electron antineutrino detection

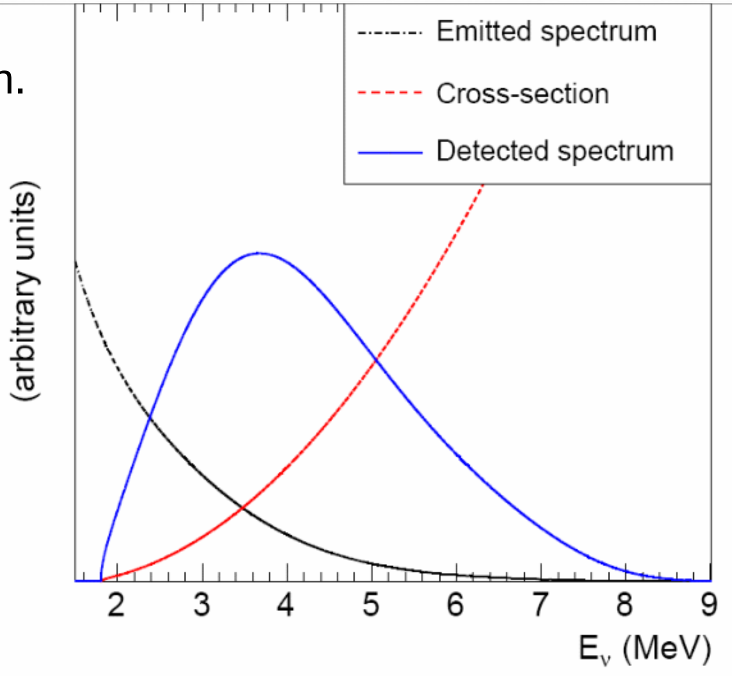
Inverse Beta Decay (IBD):

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



Prompt signal:

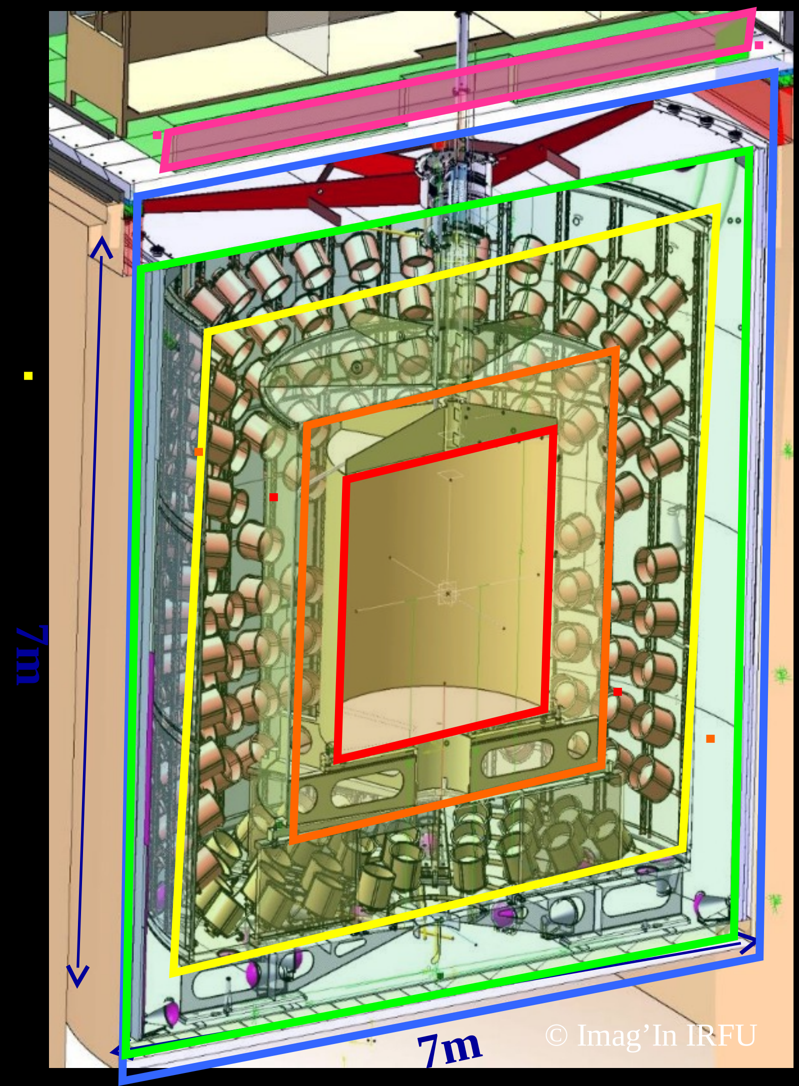
- Positron kinetic energy + γ's from annihilation.
- $E_{prompt} \approx E_\nu - 0.782$ MeV
- $E_{prompt} \sim 1 - 9$ MeV



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:

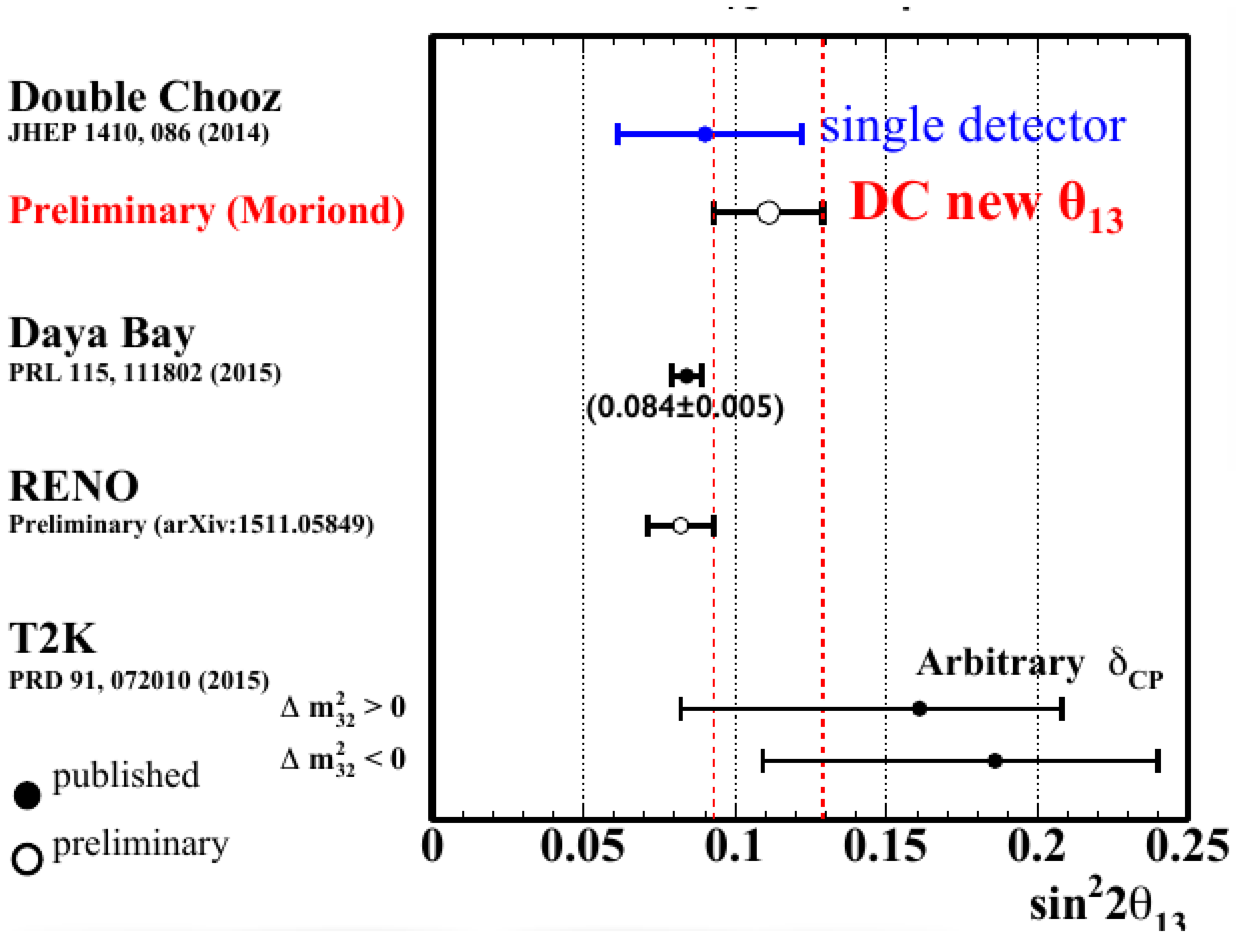
- **Neutrino Target:** acrylic vessel (8 mm) with 10.3 m^3 **Gd-loaded** (1 g/l) **liquid scintillator**.
- **Gamma-Catcher:** acrylic (12 mm) vessel with 22.5 m^3 of **liquid scintillator**.
- **Buffer:** stainless steel (3 mm) vessel supporting **390 10" PMTs**, with 110 m^3 of **non-scintillating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

First glimpse of δ

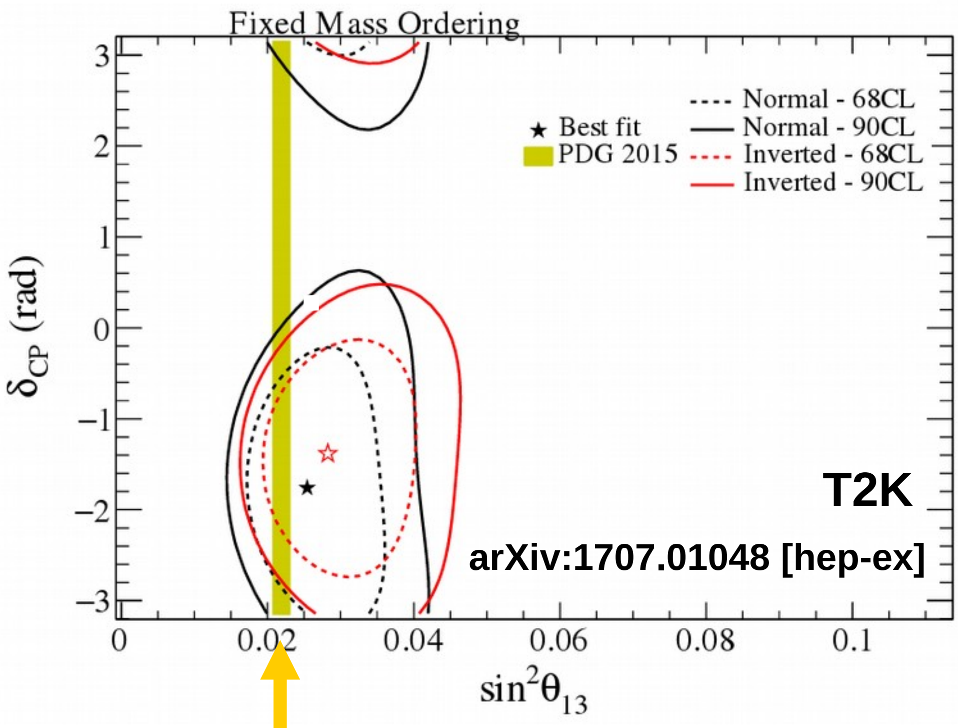
- $\nu_\mu \to \nu_e$ depends on the mass hierarchy and CP-violating phase.

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

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

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

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



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

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

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1&&\\ &c_{23}&s_{23}\\ &-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&&s_{13}e^{-i\delta}\\ &1&\\ -s_{13}e^{i\delta}&&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&\\ -s_{12}&c_{12}&\\ &&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \begin{matrix}\rightarrow \mathrm{m}_1\\ \rightarrow \mathrm{m}_2\\ \rightarrow \mathrm{m}_3\end{matrix}$$

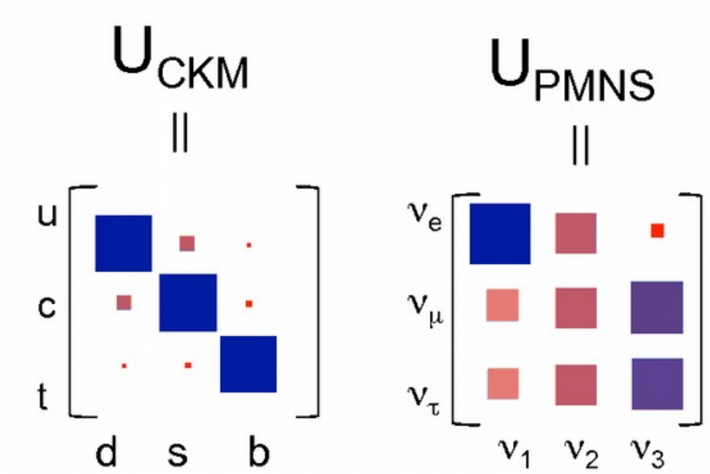
Atmospheric & Long-baseline accelerator experiments

Reactor & Long-baseline accelerator experiments

Solar & KamLAND experiments

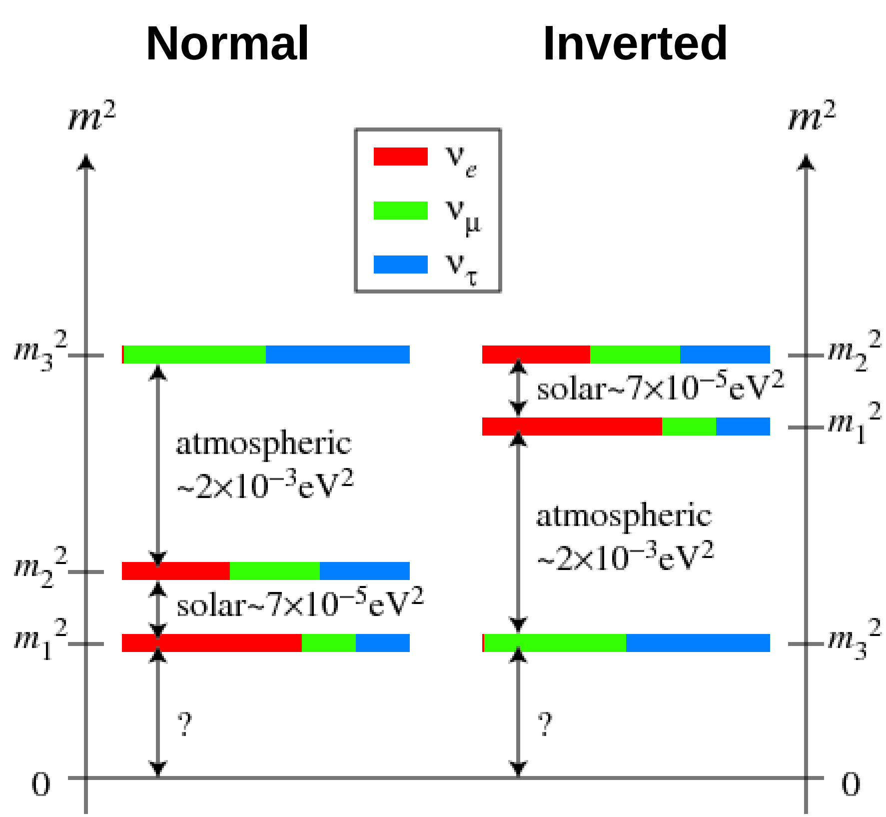
$$\Delta m^2_{jk} \equiv m^2_j - m^2_k$$

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



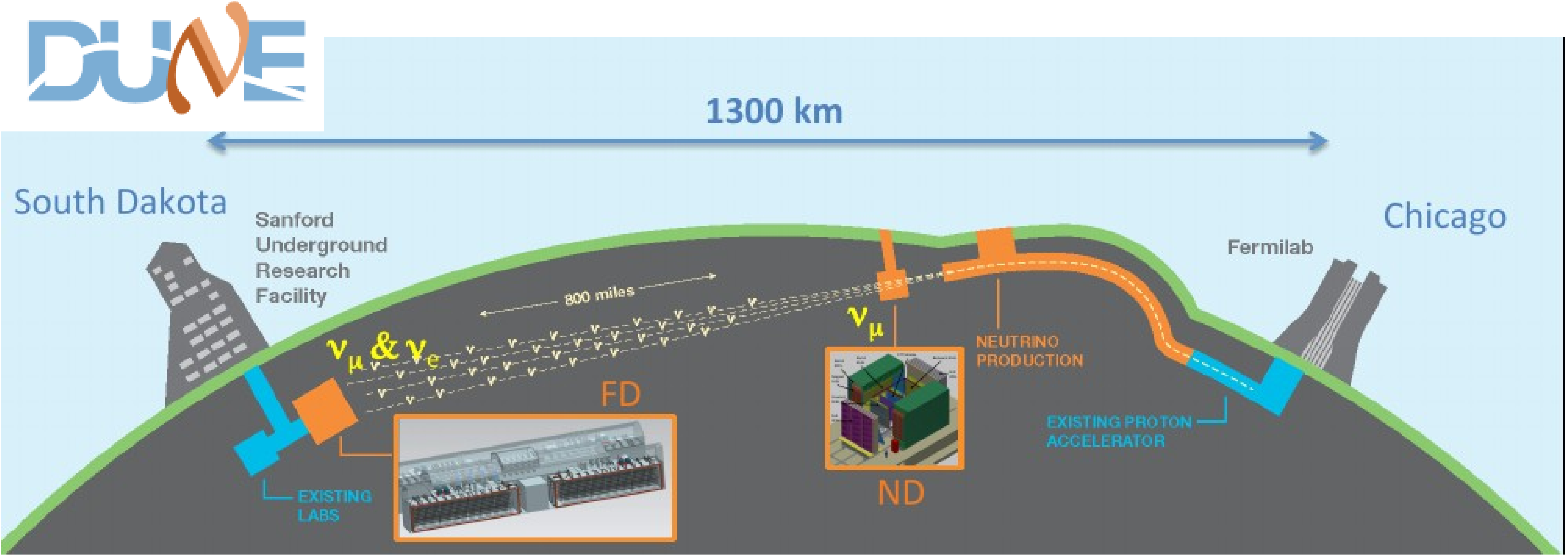
3 neutrinos: mass ordering

- 3 mass eigenstates → **2 independent squared-mass differences:** $\Delta m_{32}^2 + \Delta m_{21}^2 = \Delta m_{31}^2$
- 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:



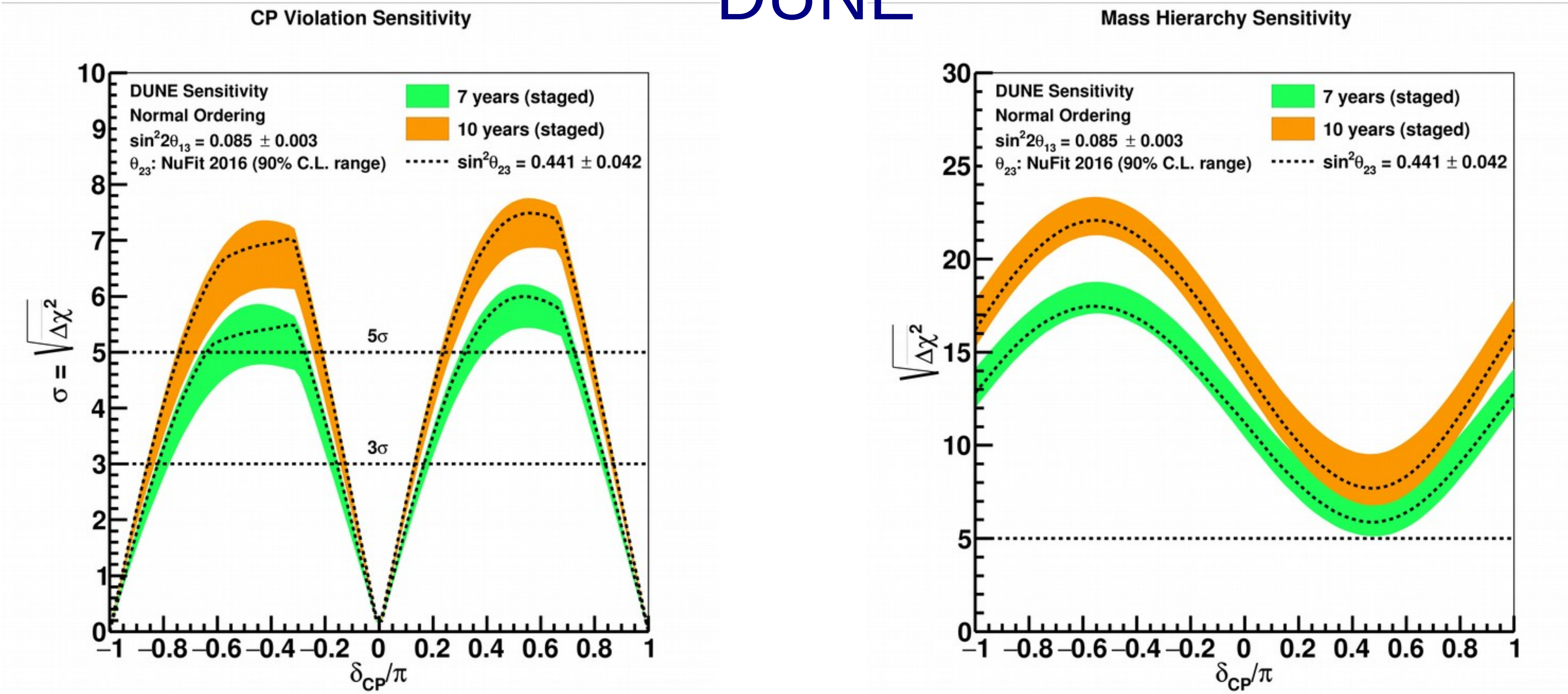
Future: δ and mass hierarchy

- 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.



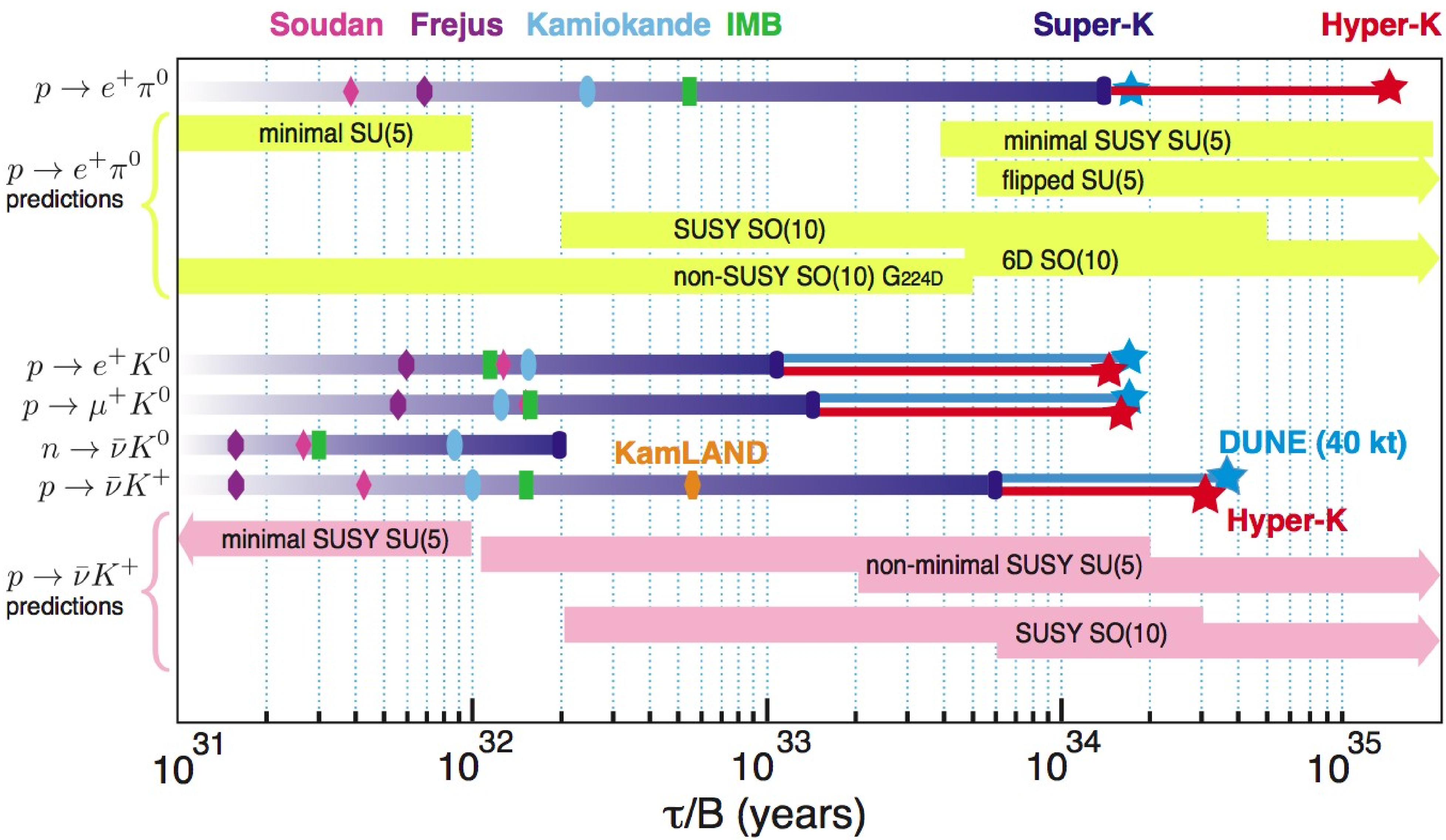
Neutrino beam expected by 2026.

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