Particle Physics: Neutrinos – part I

José I. Crespo-Anadón

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Columbia University Science Honors Program

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

NEVIS LABORATORIES

Course Policies

Attendance

Up to four absences
Send email notifications of all absences to shpattendance@columbia.edu.

Please, no cell phones

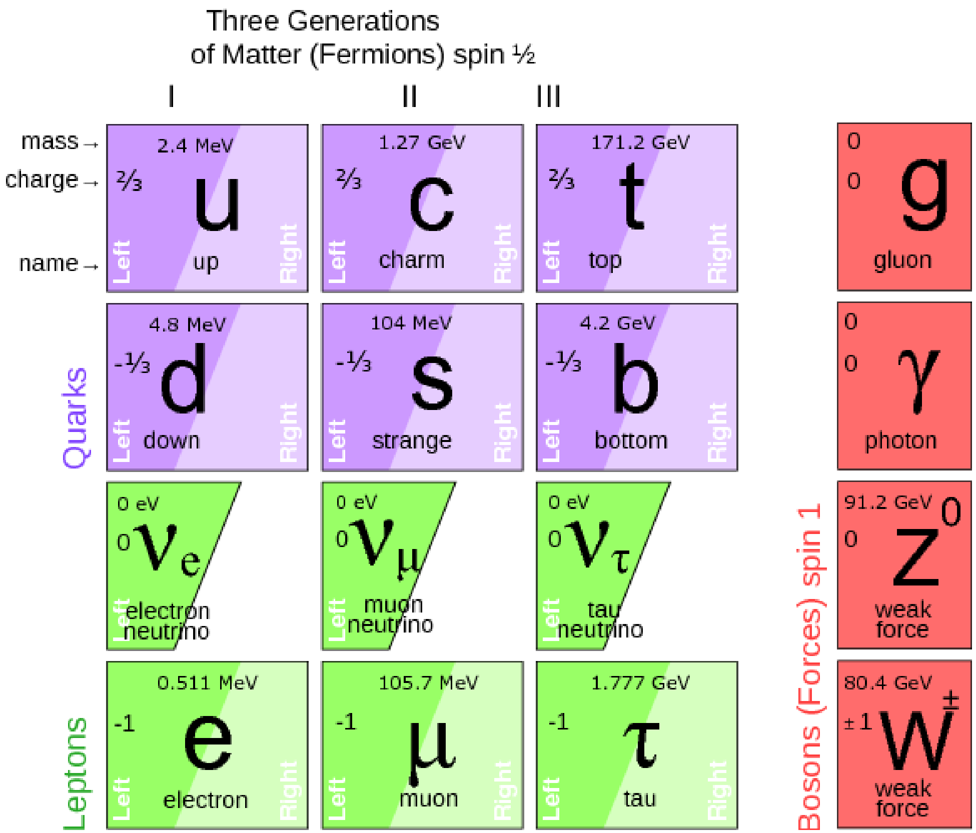
Please, ask questions!

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

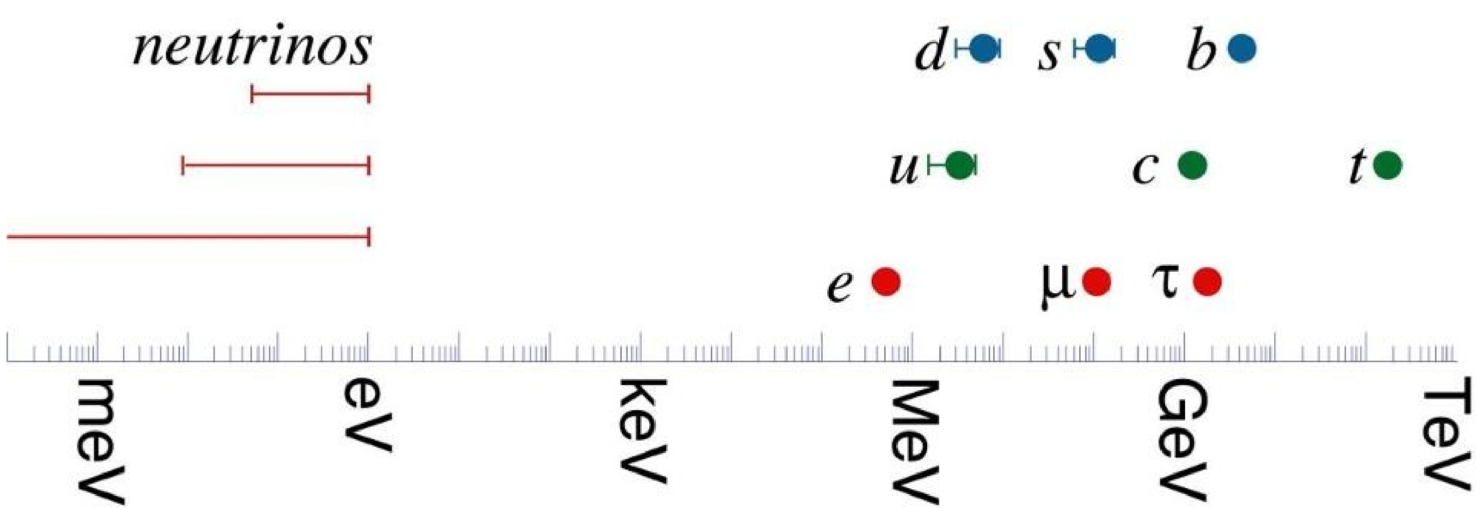
Schedule

1. ~~Introduction (Inês)~~
2. ~~History of Particle Physics (José)~~
3. ~~Special Relativity (José)~~
4. ~~Quantum Mechanics (Inês)~~
5. ~~Experimental Methods (Cris)~~
6. ~~The Standard Model – Overview (Cris)~~
7. ~~The Standard Model – Limitations (Cris)~~
8. **Neutrinos – part I (José)**
9. **Neutrinos – part II (José)**
10. LHC and Experiments (Inês)
11. The Higgs Boson and Beyond (Inês)
12. Particle Cosmology (Cris)

Neutrinos in the Standard Model



- 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 (2-neutrino example)

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

Flavor eigenstates **Mass eigenstates**

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

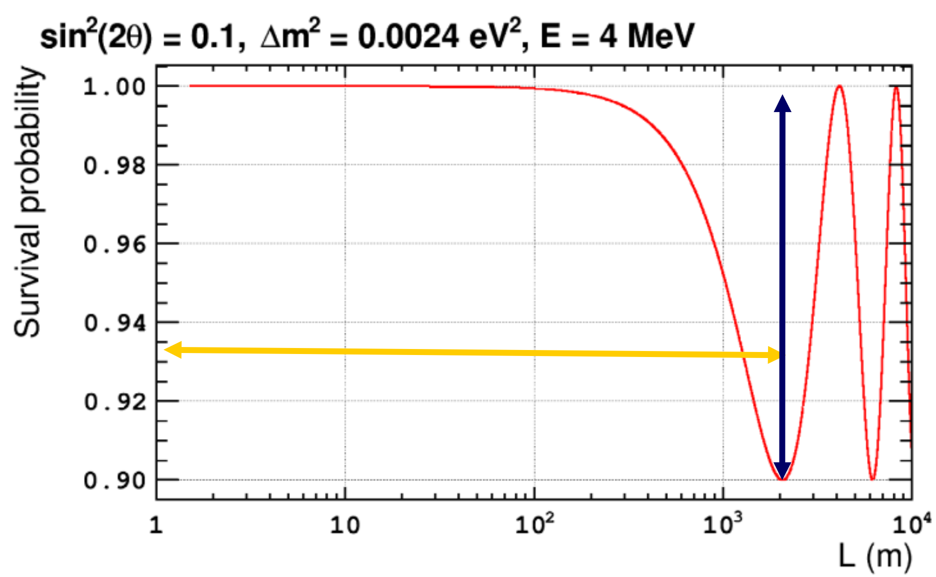
- **Transition** probability (derivation in blackboard):

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

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

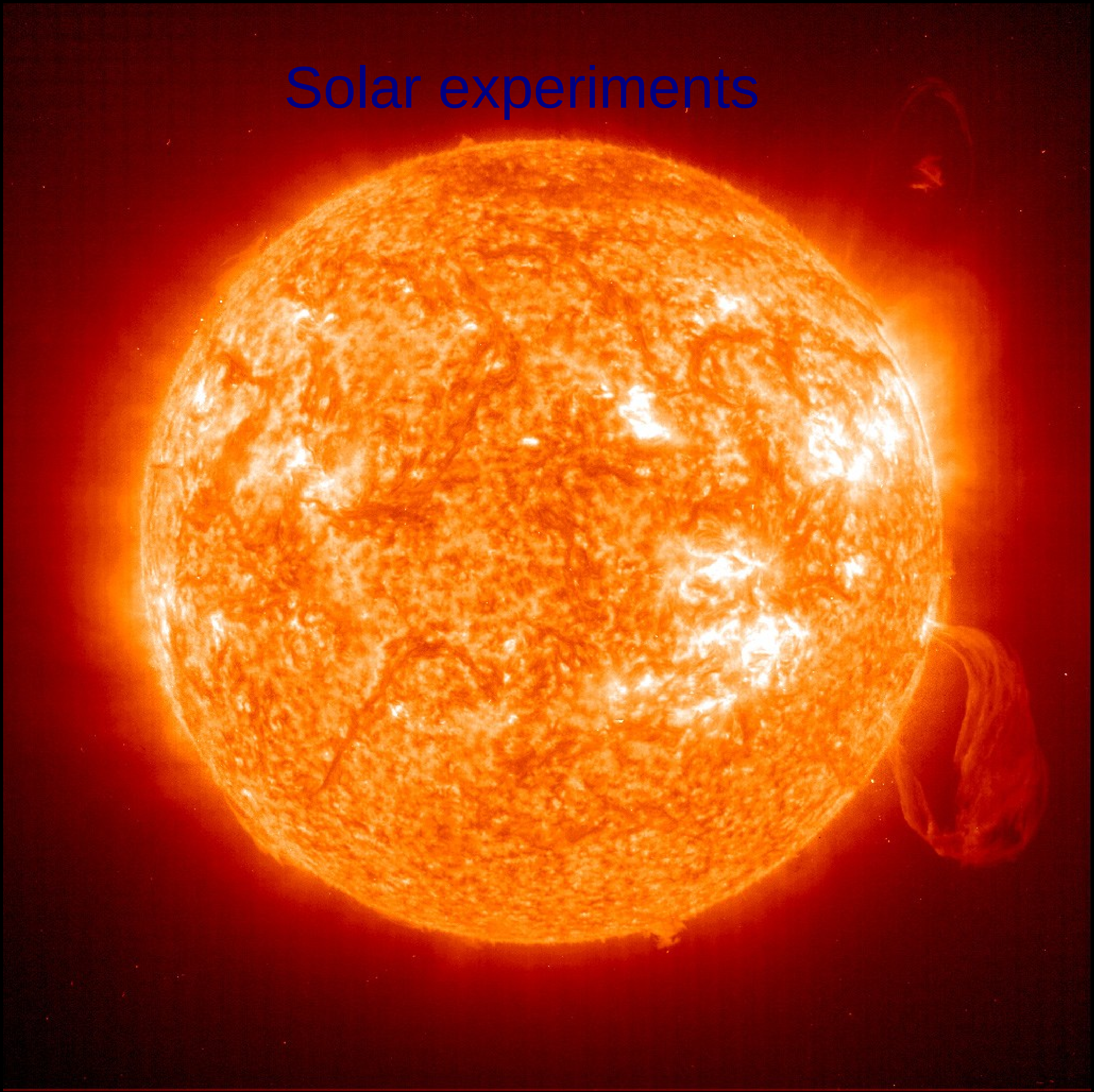
Reactor & Long-baseline accelerator experiments

Solar & KamLAND experiments

- CP violation only possible if all three angles are not zero.

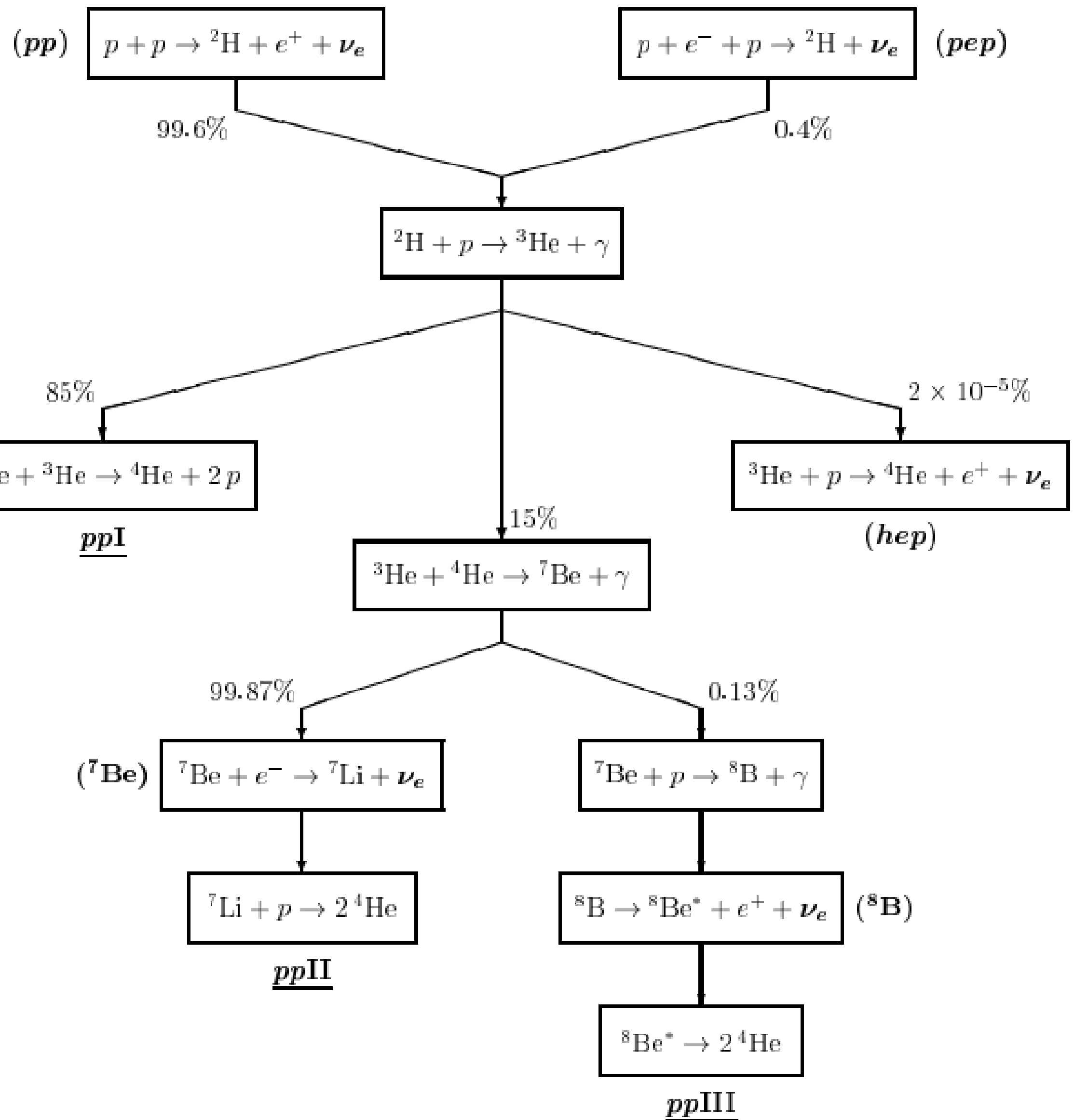
Measurement of θ_{12} and Δm^2_{21}

Solar experiments



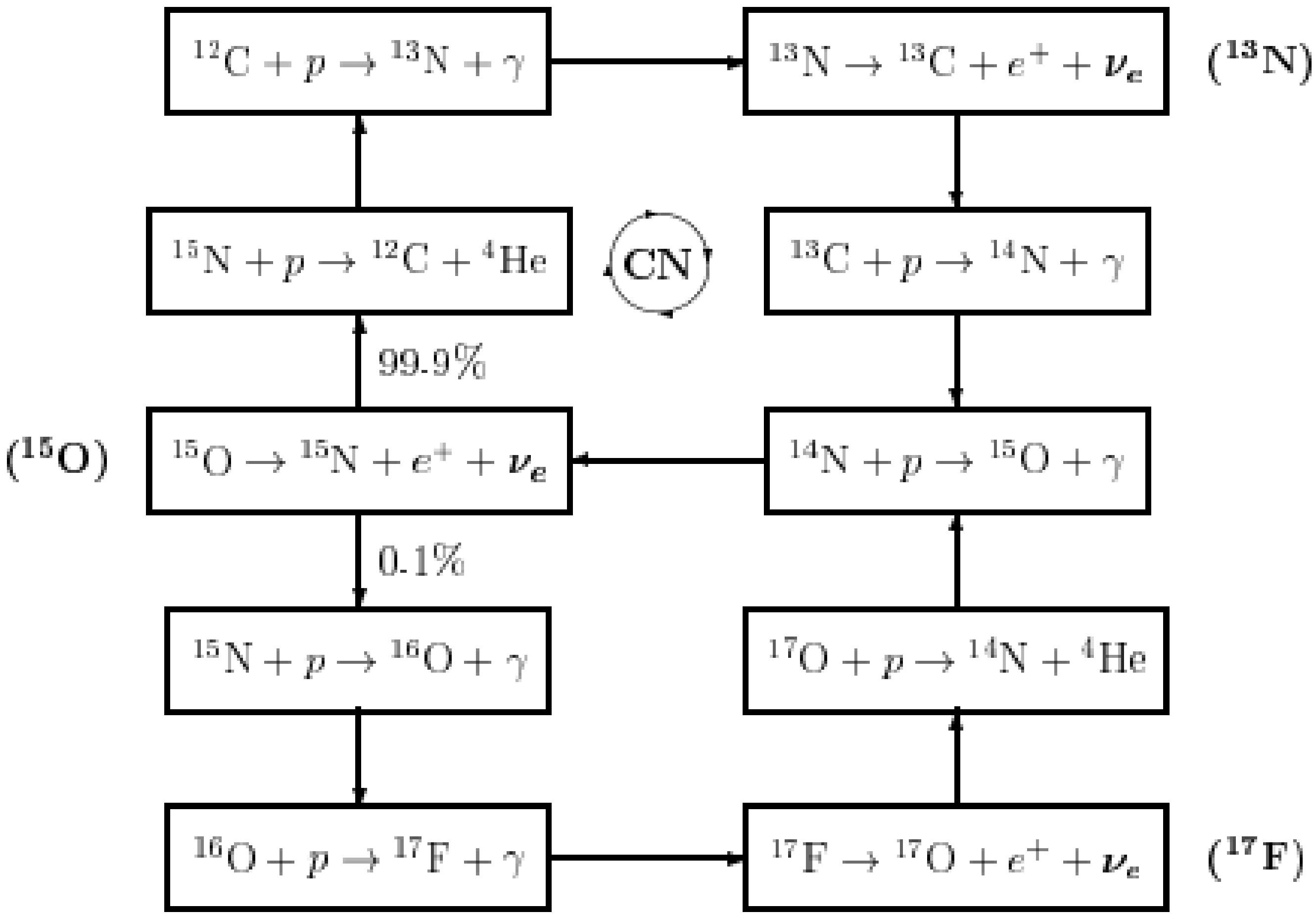
Solar neutrinos: pp chain

- 98.4% of Sun's fusion energy.

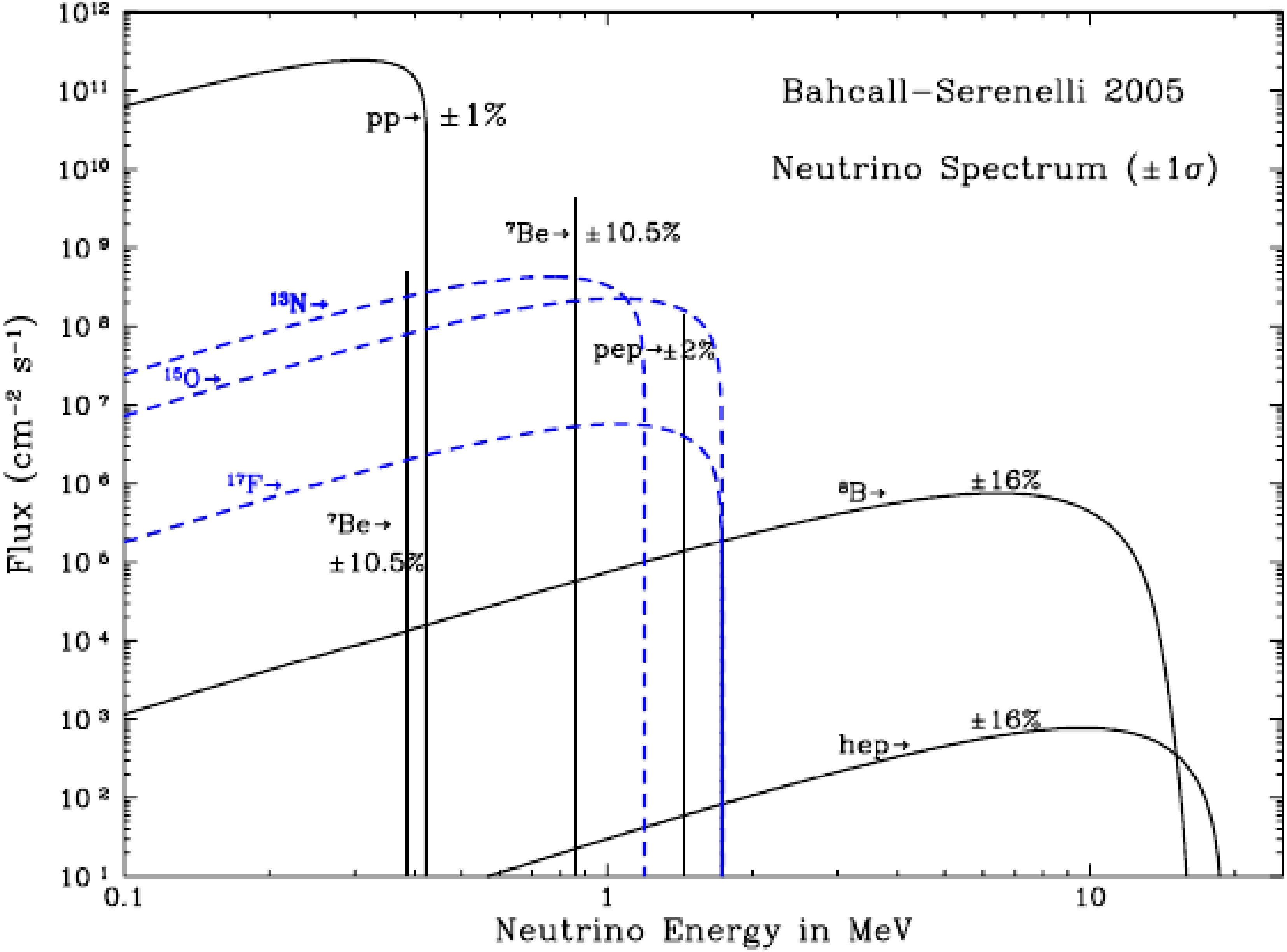


Solar neutrinos: CNO cycle

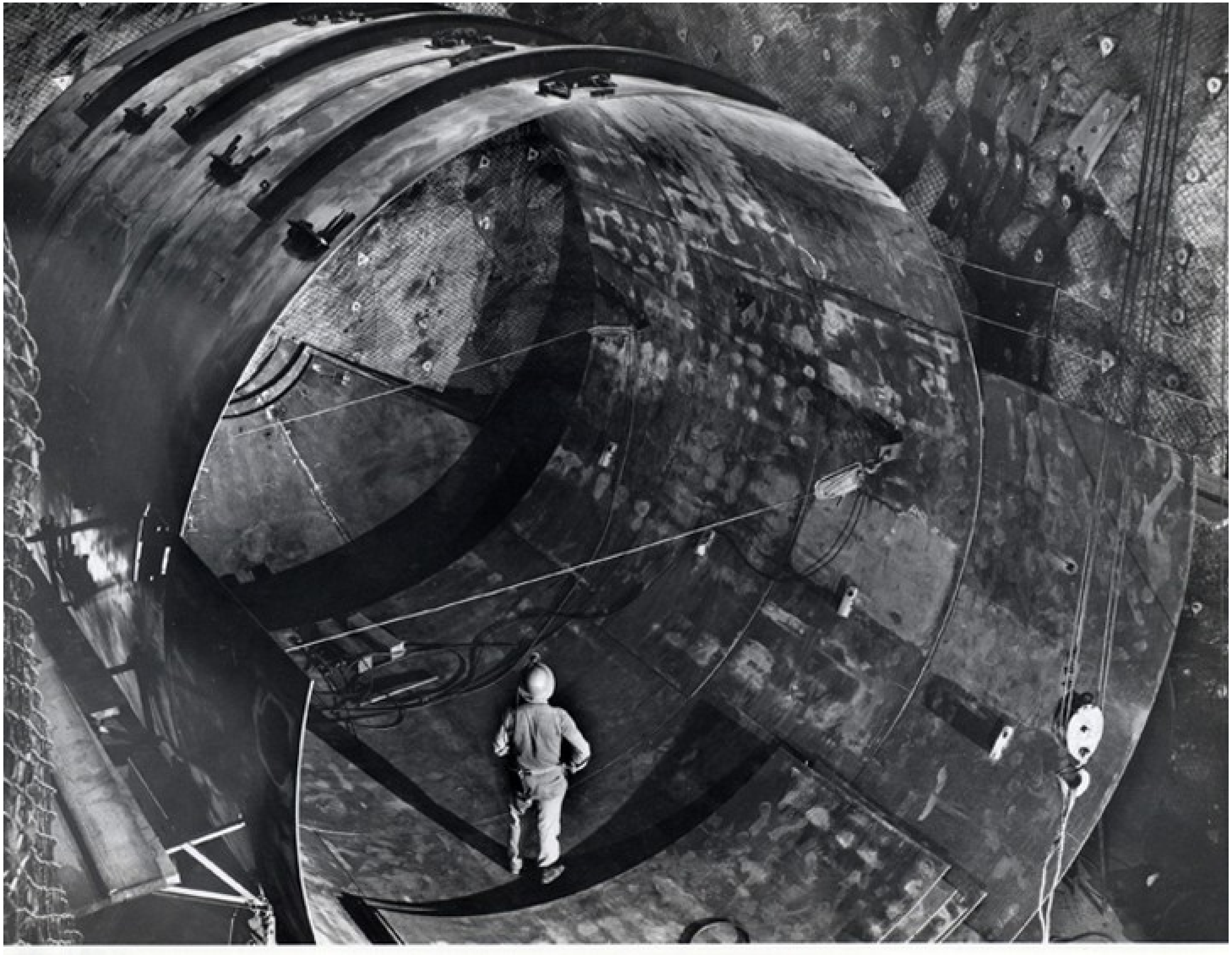
- 1.6% of Sun's fusion energy.



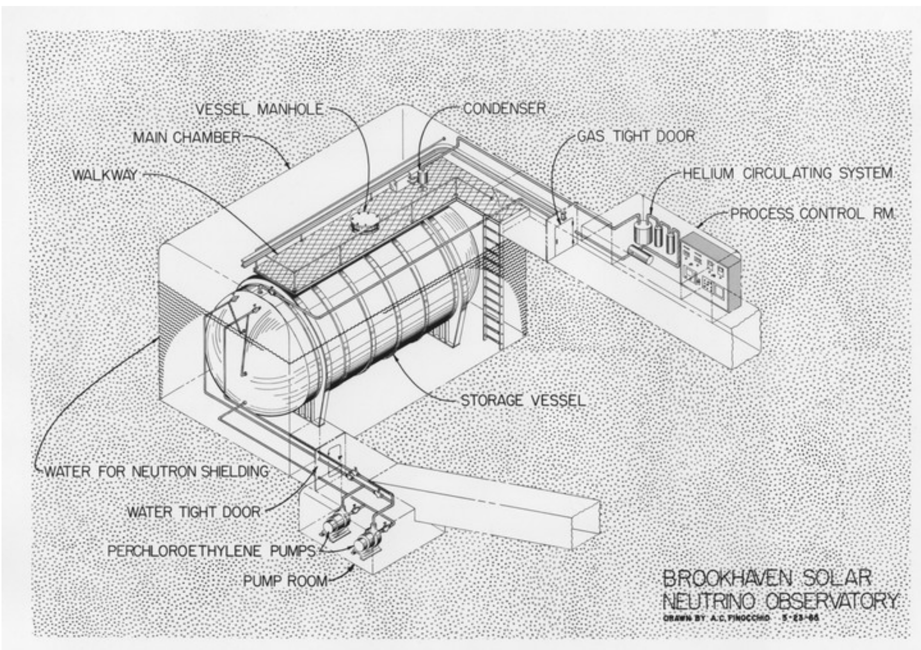
Solar neutrinos: energy spectrum



Homestake experiment



Homestake experiment



- Detection of solar neutrinos using the reaction:

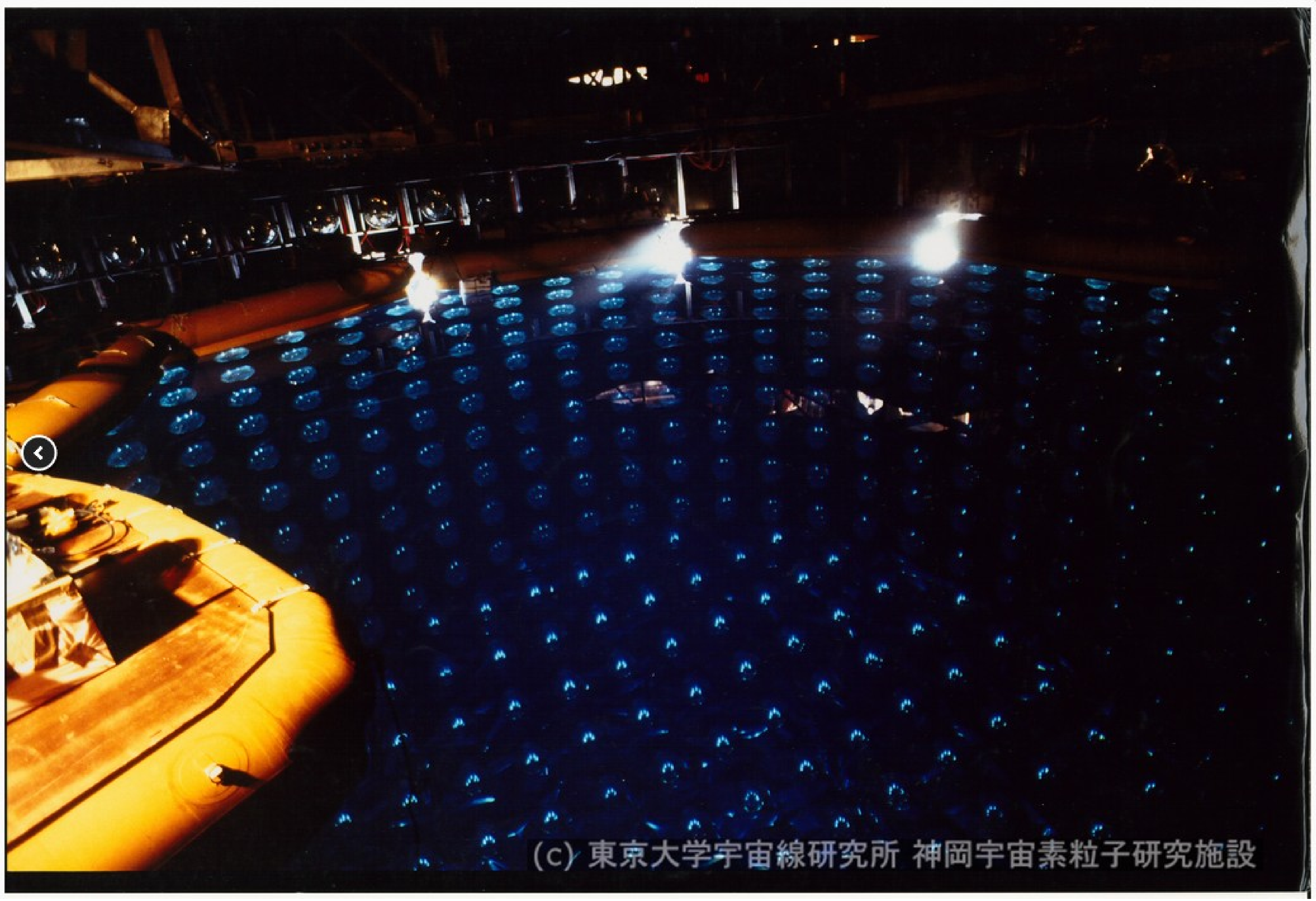
$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$$

- Ratio of observed to predicted:

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

- Missing neutrinos!

Kamiokande



Kamiokande

- Detection of solar neutrinos using the reaction:

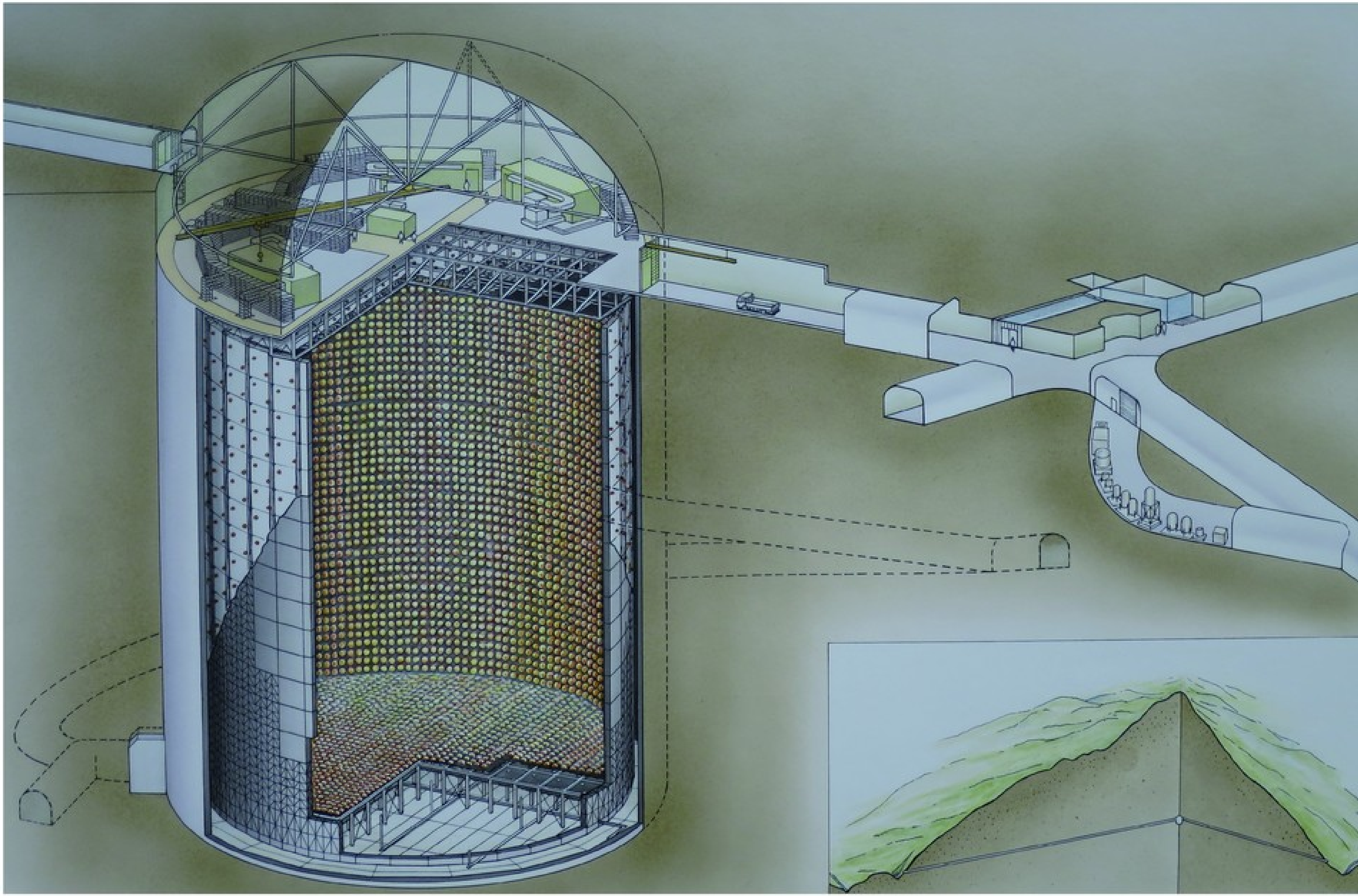
$$\nu_l + e^- \rightarrow \nu_l + e^-$$

- Ratio of observed to predicted:

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

- Missing neutrinos again!

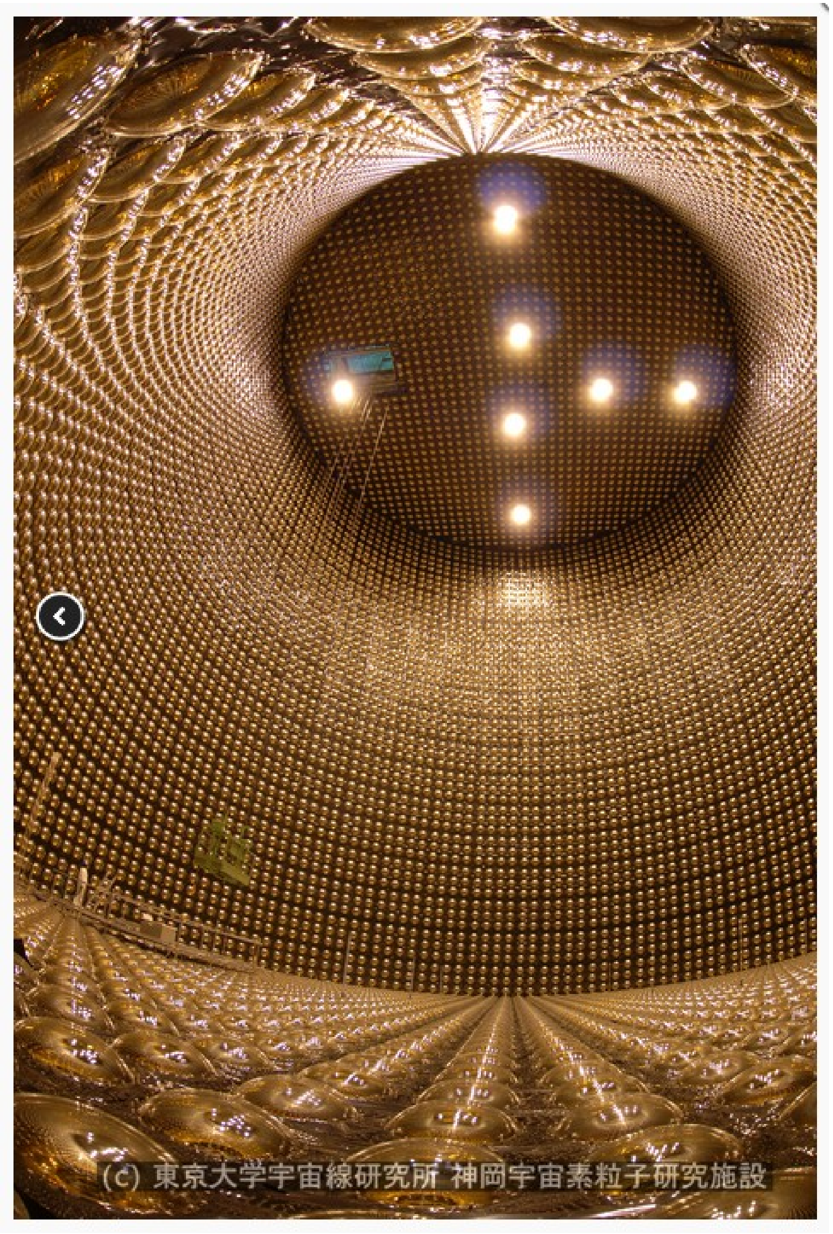
Super-Kamiokande



SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

NIKKEN SEKKEI

Super-Kamiokande



- Detection of solar neutrinos using the reaction:

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

- Ratio of observed to predicted:

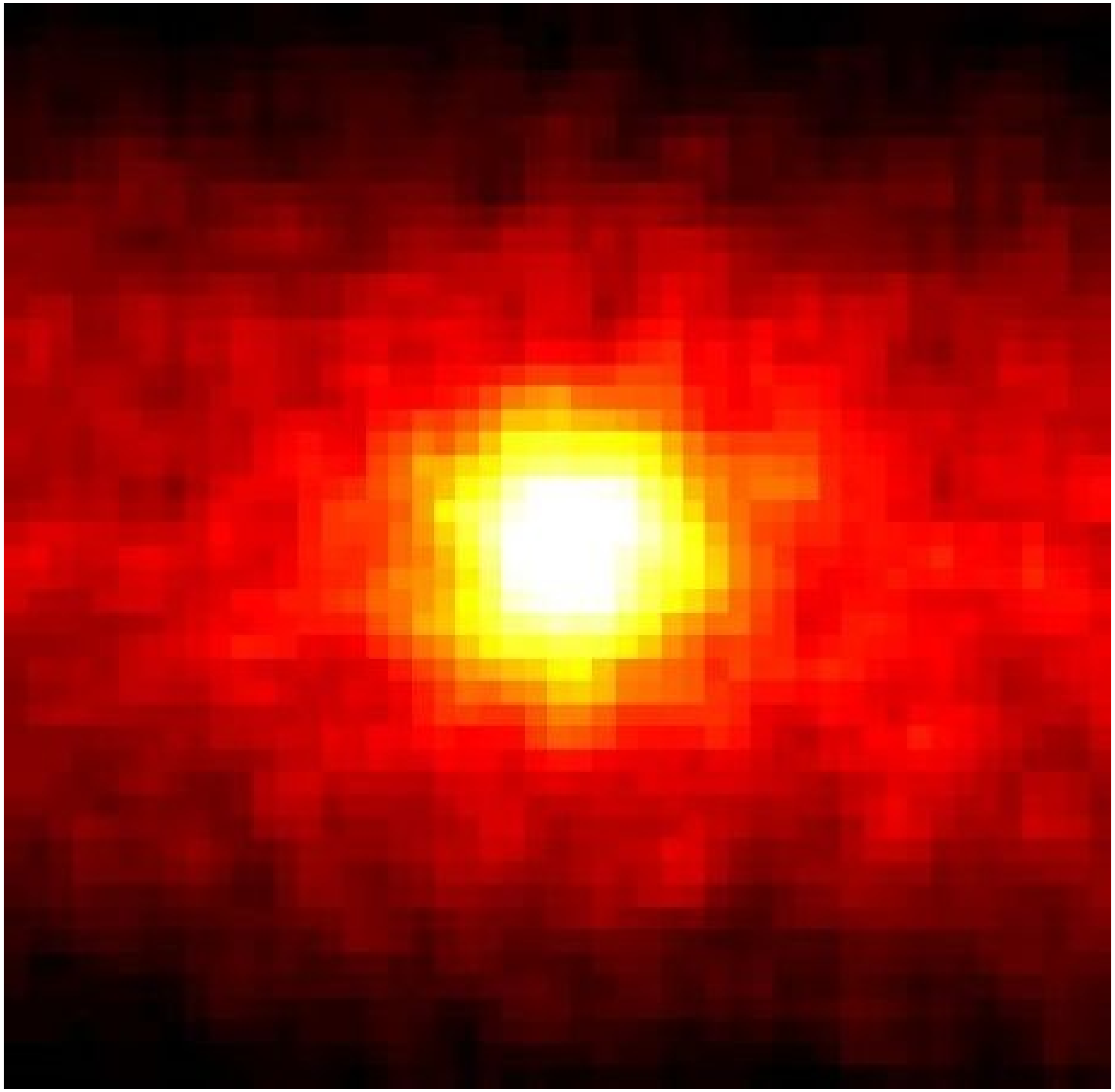
$$\frac{\Phi_{\mathrm{SK-I}}}{\Phi_{\mathrm{SSM}}} = 0.406 \pm 0.014$$

- Improved result over Kamiokande, neutrinos still missing!

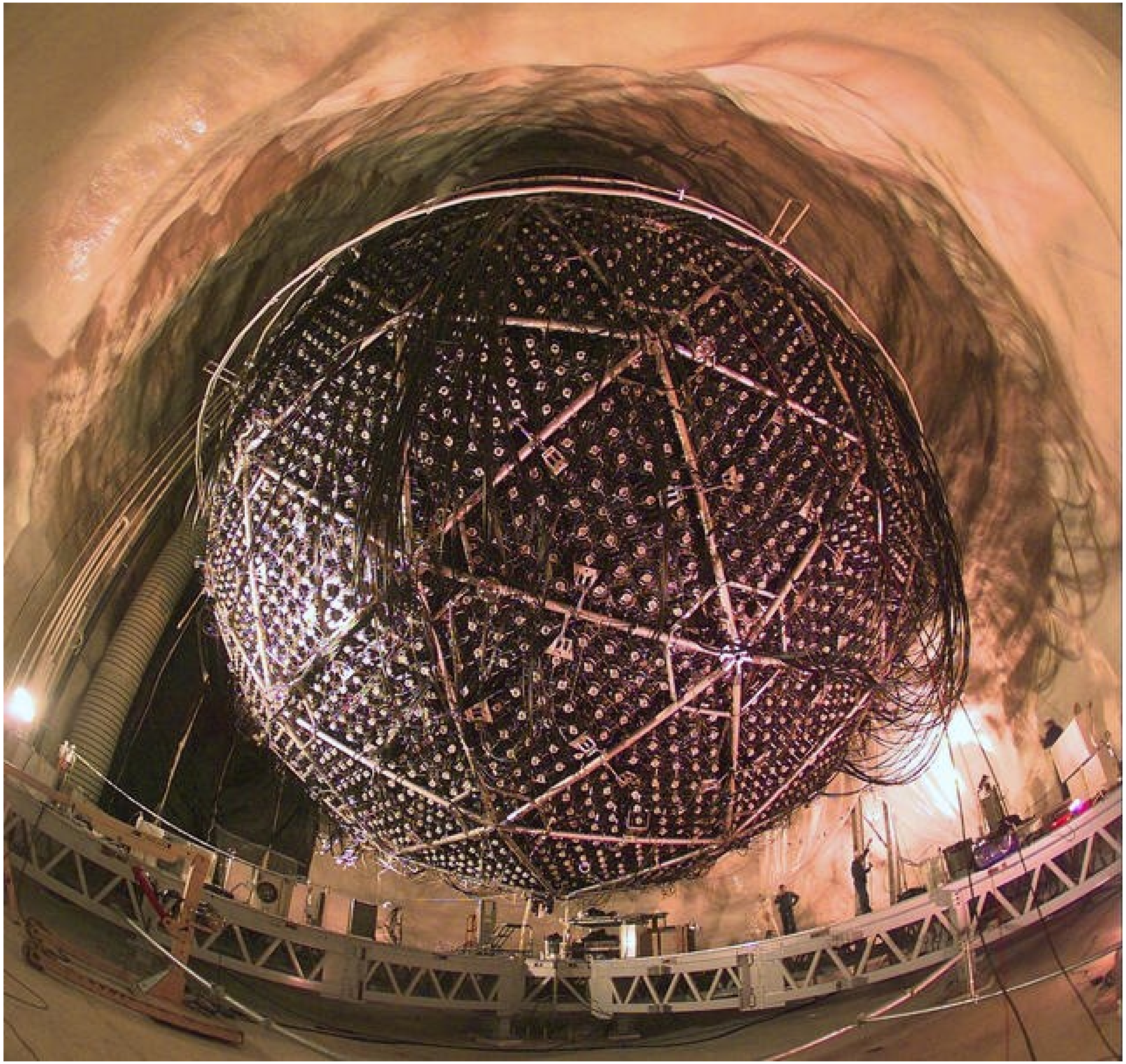
Super-Kamiokande

Super-Kamiokande

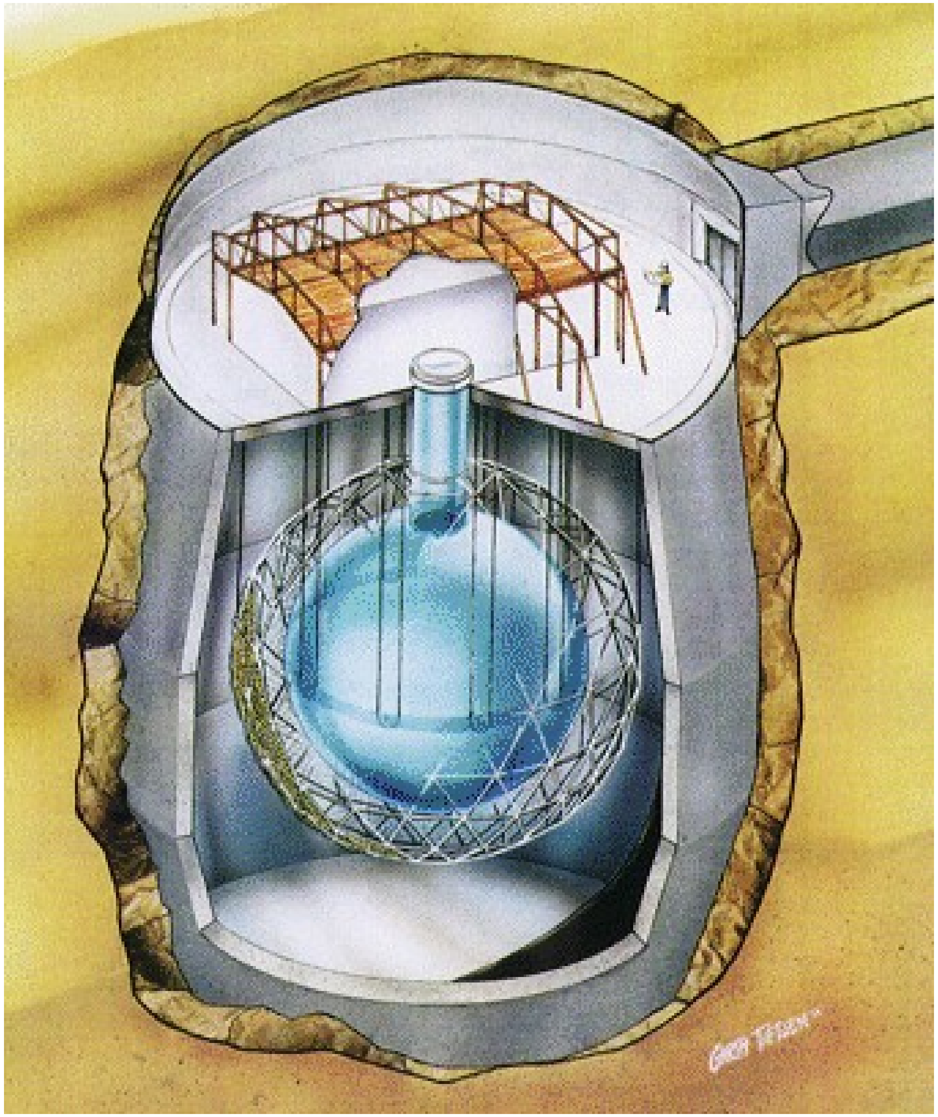
- NEUTRINOGRAPHY of the Sun. 500 days exposure!



SNO



SNO



- Detection of solar neutrinos using the reaction:

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

- Ratio of observed to predicted:

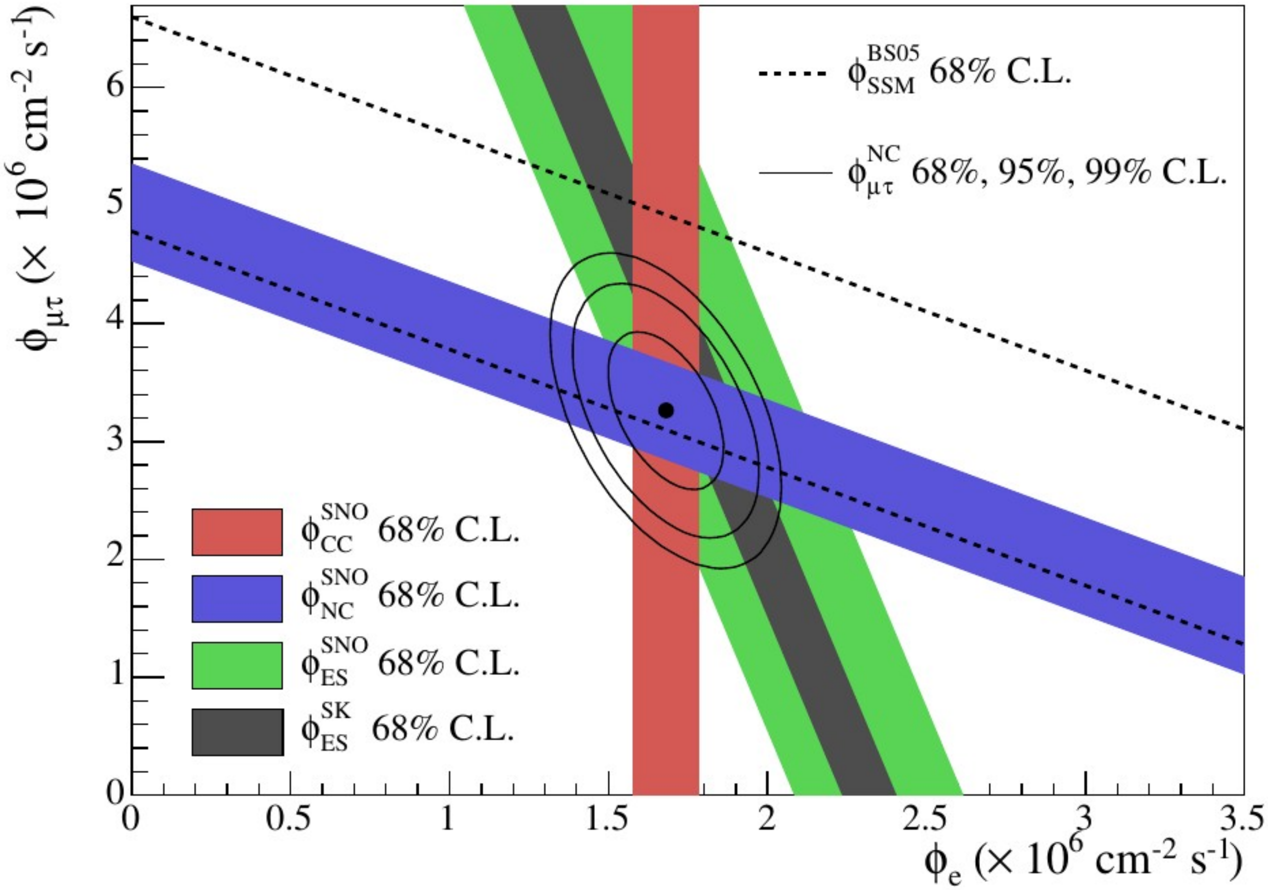
$$\frac{\Phi_{\mathrm{SNO}}^{\mathrm{ES}}}{\Phi_{\mathrm{SSM}}} = 0.406 \pm 0.046$$
$$\frac{\Phi_{\mathrm{SNO}}^{\mathrm{CC}}}{\Phi_{\mathrm{SSM}}} = 0.290 \pm 0.017$$
$$\frac{\Phi_{\mathrm{SNO}}^{\mathrm{NC}}}{\Phi_{\mathrm{SSM}}} = 0.853 \pm 0.075$$

SNO

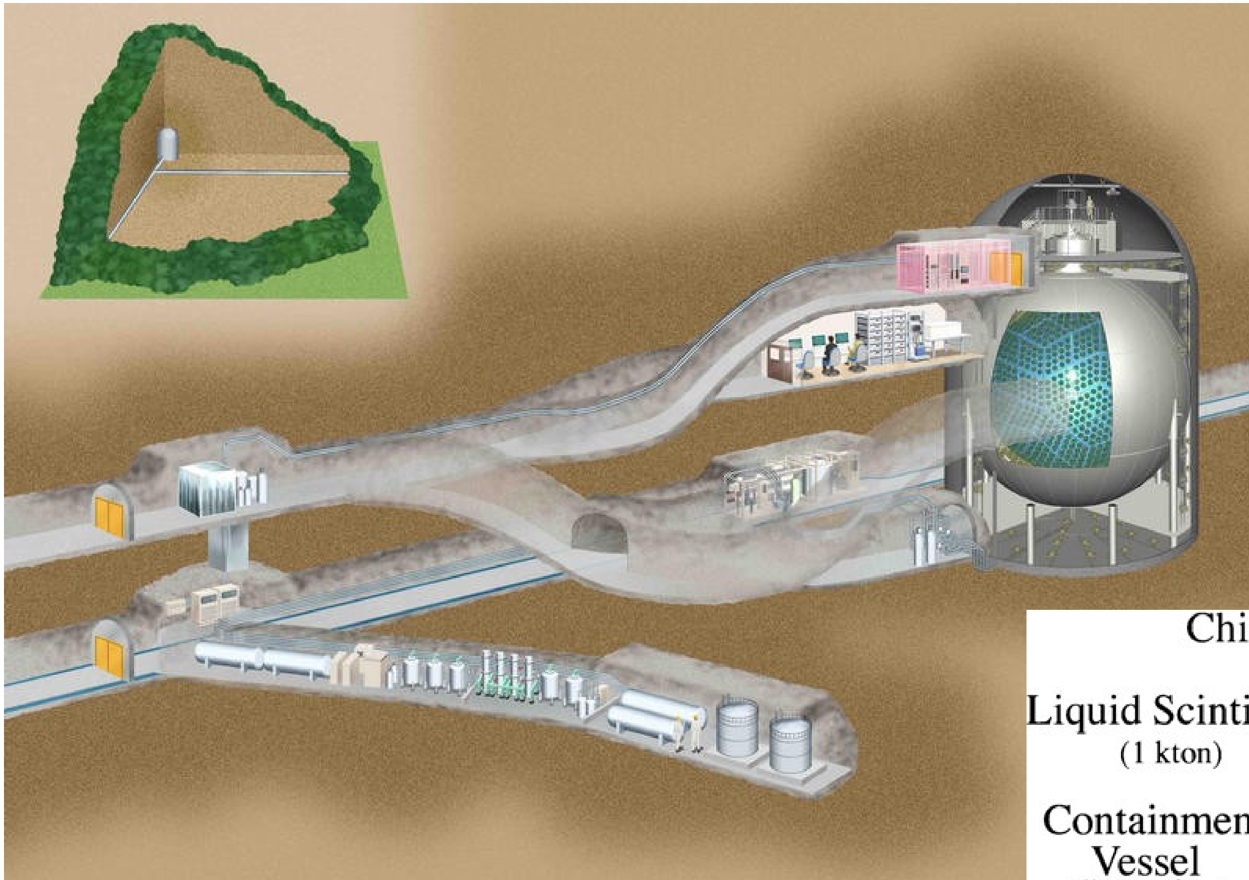
$$\Phi^{\nu_e}_{\rm SNO} + r^{\rm ES}\,\Phi^{\nu_{\mu,\tau}}_{\rm SNO} = \Phi^{\rm ES}_{\rm SNO} \qquad r^{\rm ES} \equiv \sigma^{\rm ES}_{\nu_{\mu,\tau}}/\sigma^{\rm ES}_{\nu_e} \approx 0.1553$$

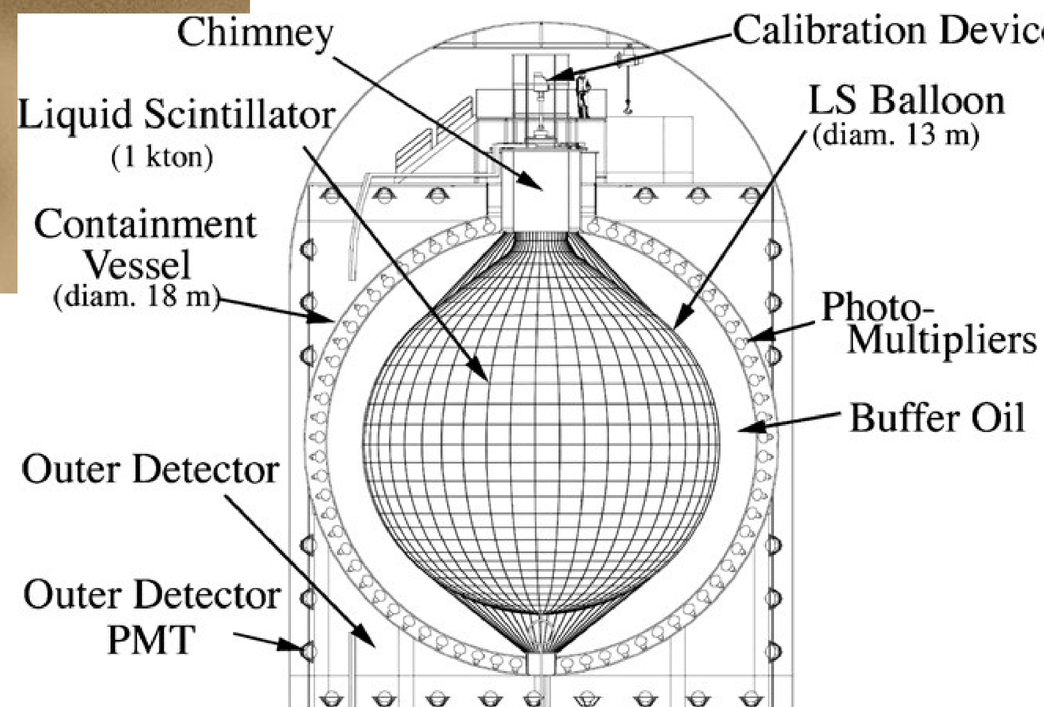
$$\Phi^{\nu_e}_{\rm SNO} = \Phi^{\rm CC}_{\rm SNO}$$

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

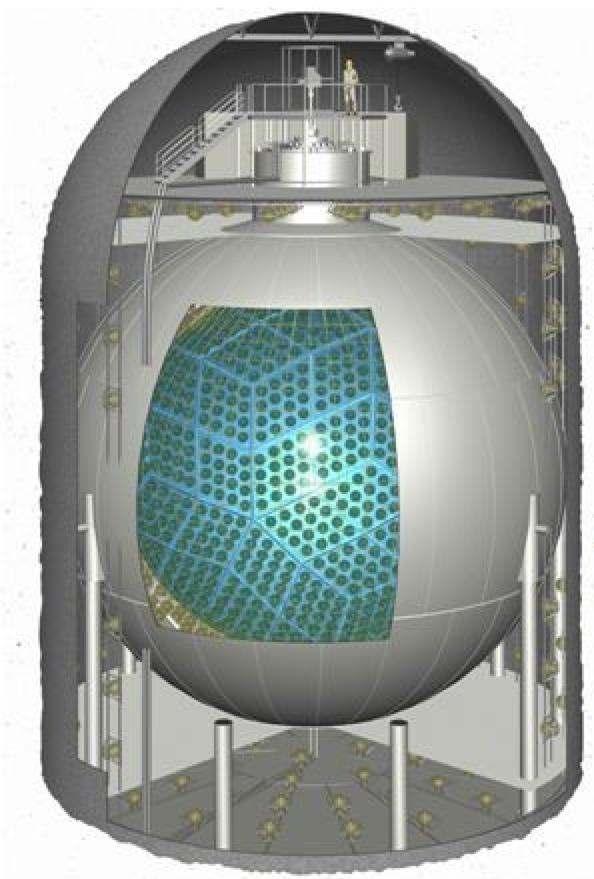


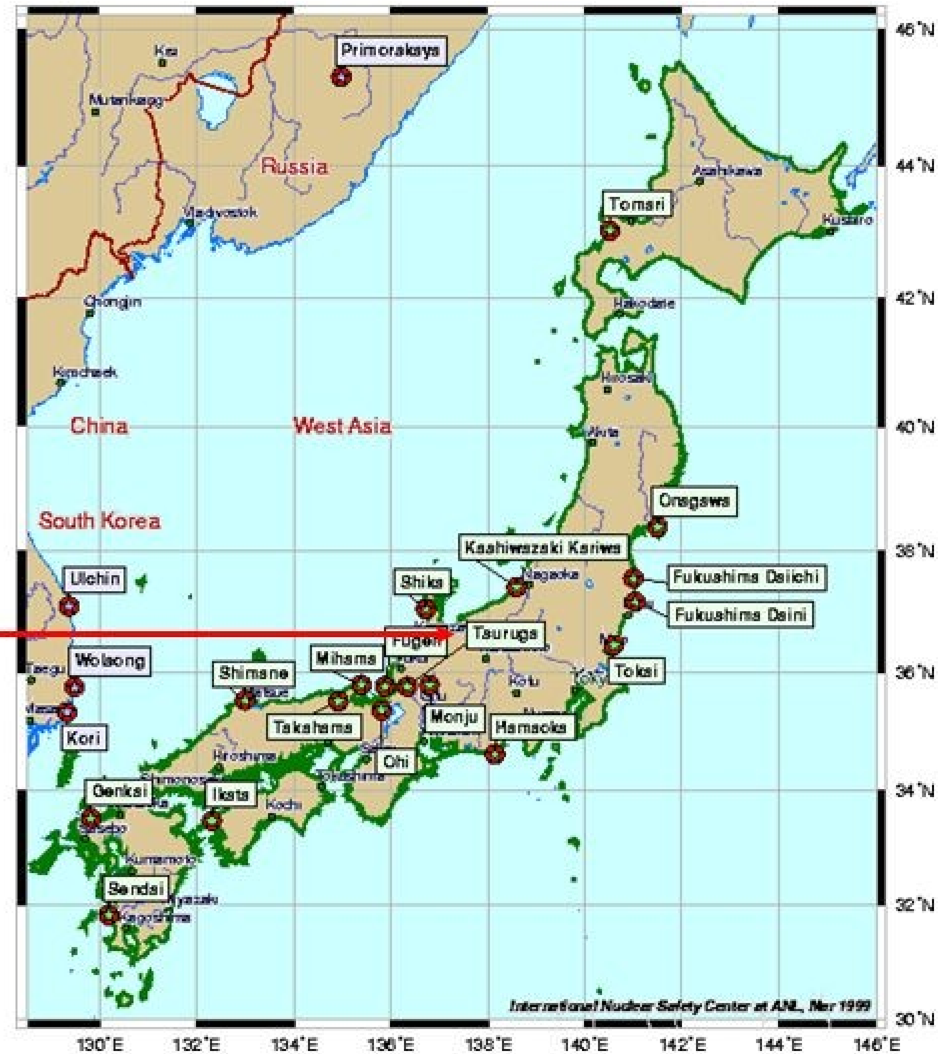
KamLAND




Chimney
Calibration Device
Liquid Scintillator
(1 kton)
LS Balloon
(diam. 13 m)
Containment
Vessel
(diam. 18 m)
Photo-
Multipliers
Buffer Oil
Outer Detector
Outer Detector
PMT

KamLAND

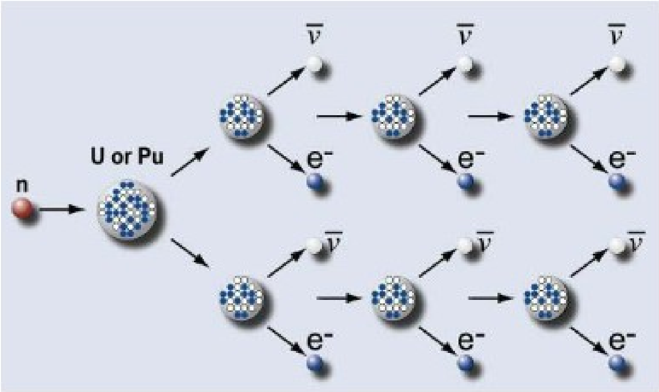



Primorskaya
Russia
Tomari
China
West Asia
South Korea
Onagawa
Kashiwazaki Kariwa
Shika
Fukushima Daiichi
Fukushima Daini
Ulchin
Tsuruga
Fugen
Wolsong
Mihama
Shimane
Tokai
Monju
Takahama
Hamaoka
Kori
Ohi
Genkai
Ikata
Sendai
International Nuclear Safety Center at ANL, Mar 1999
46°N
44°N
42°N
40°N
38°N
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

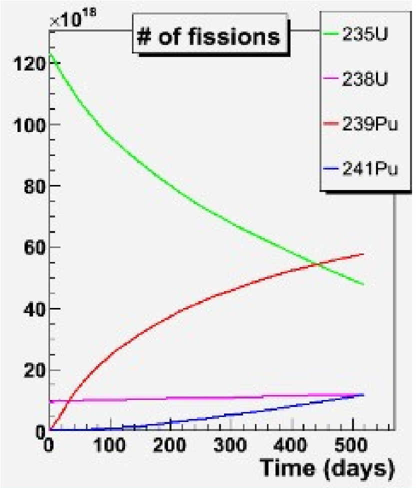
$\overline{\nu}_e$ production at nuclear reactors

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

$$^A_ZX \rightarrow {}^A_{Z+1}Y + e^- + \overline{\nu}_e$$



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

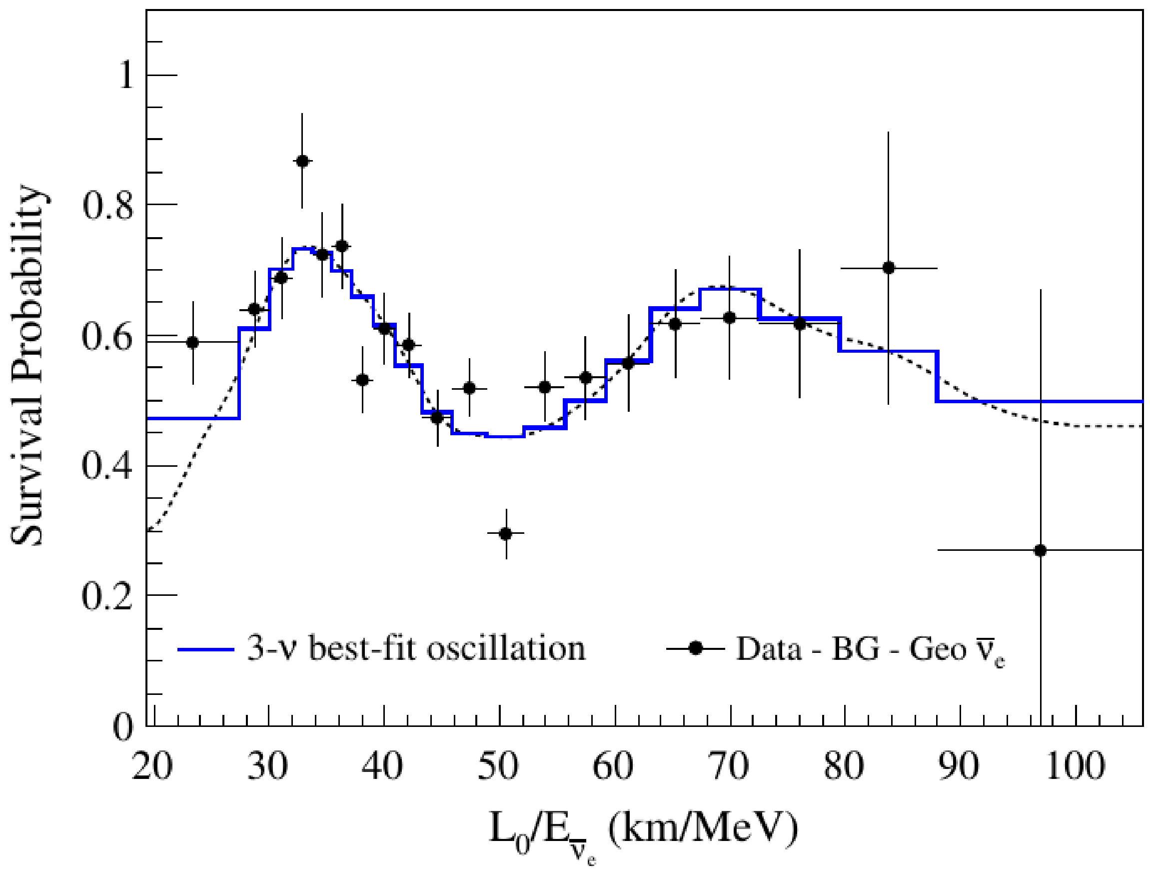


- Nuclear power plants: greatest man-made antineutrino source.
- Need to consider nuclear fuel evolution.

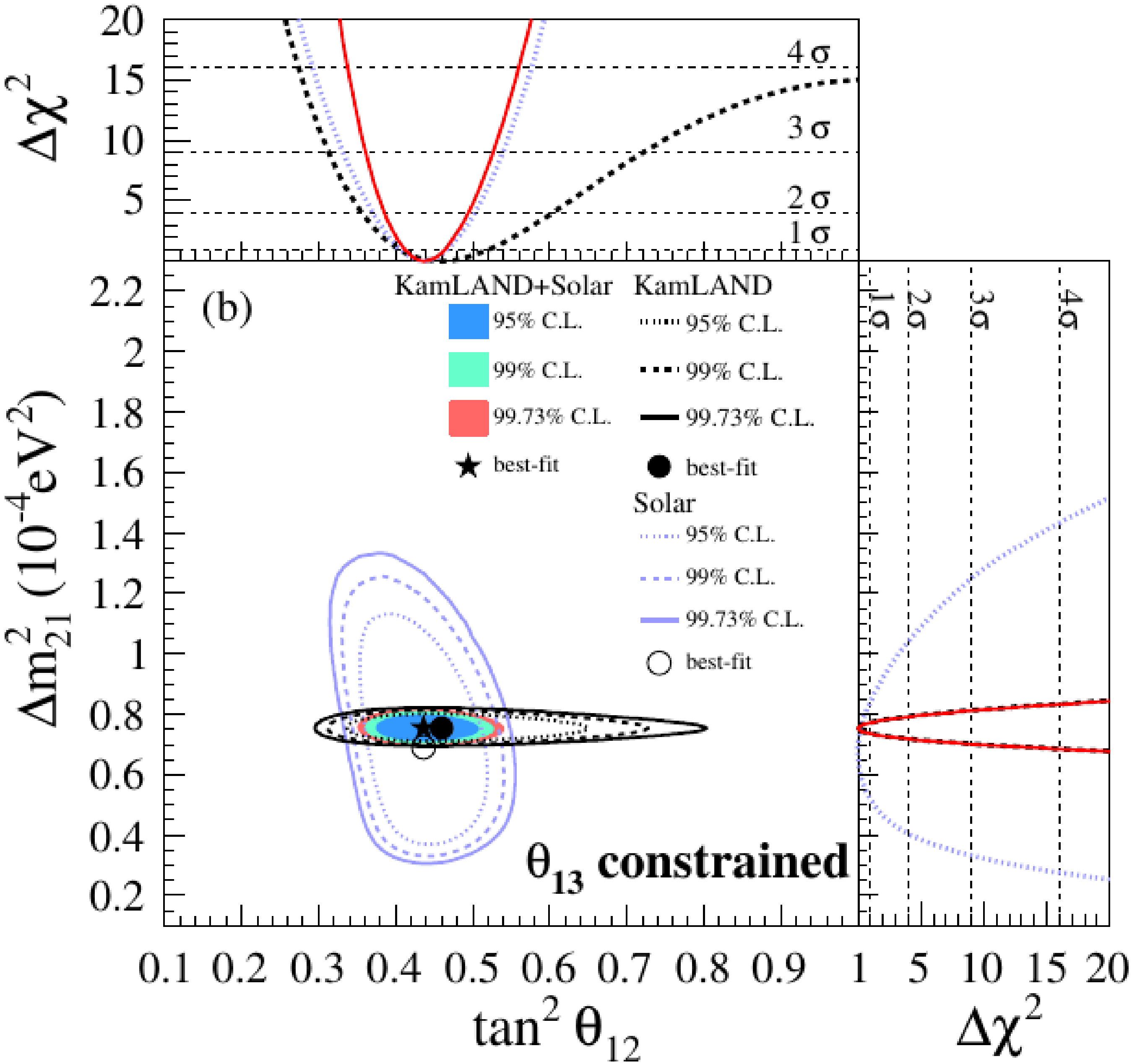
KamLAND

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

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

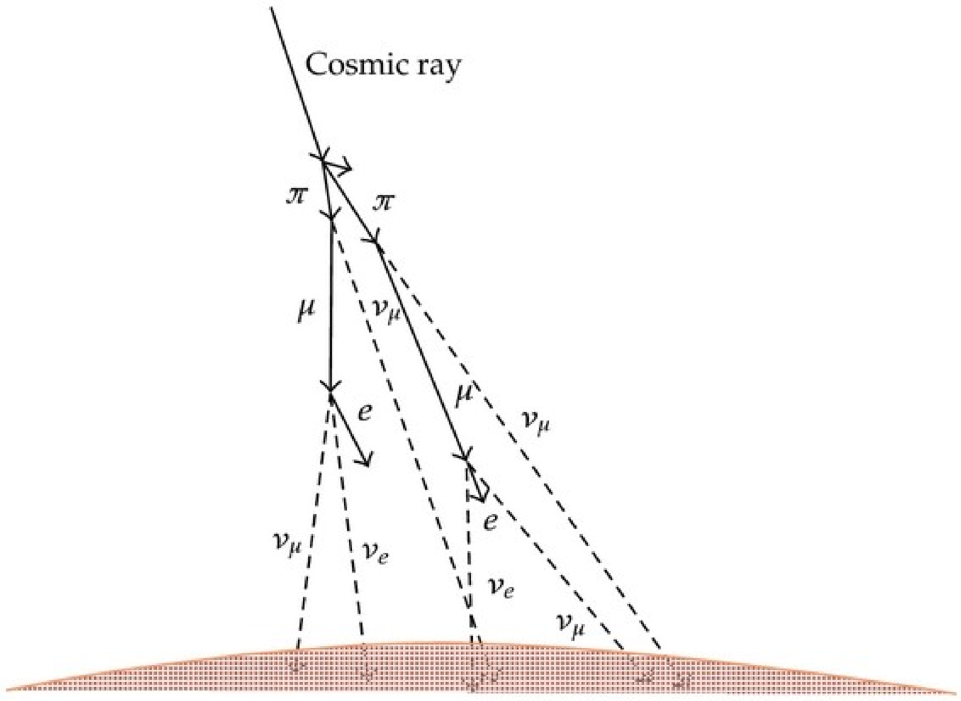


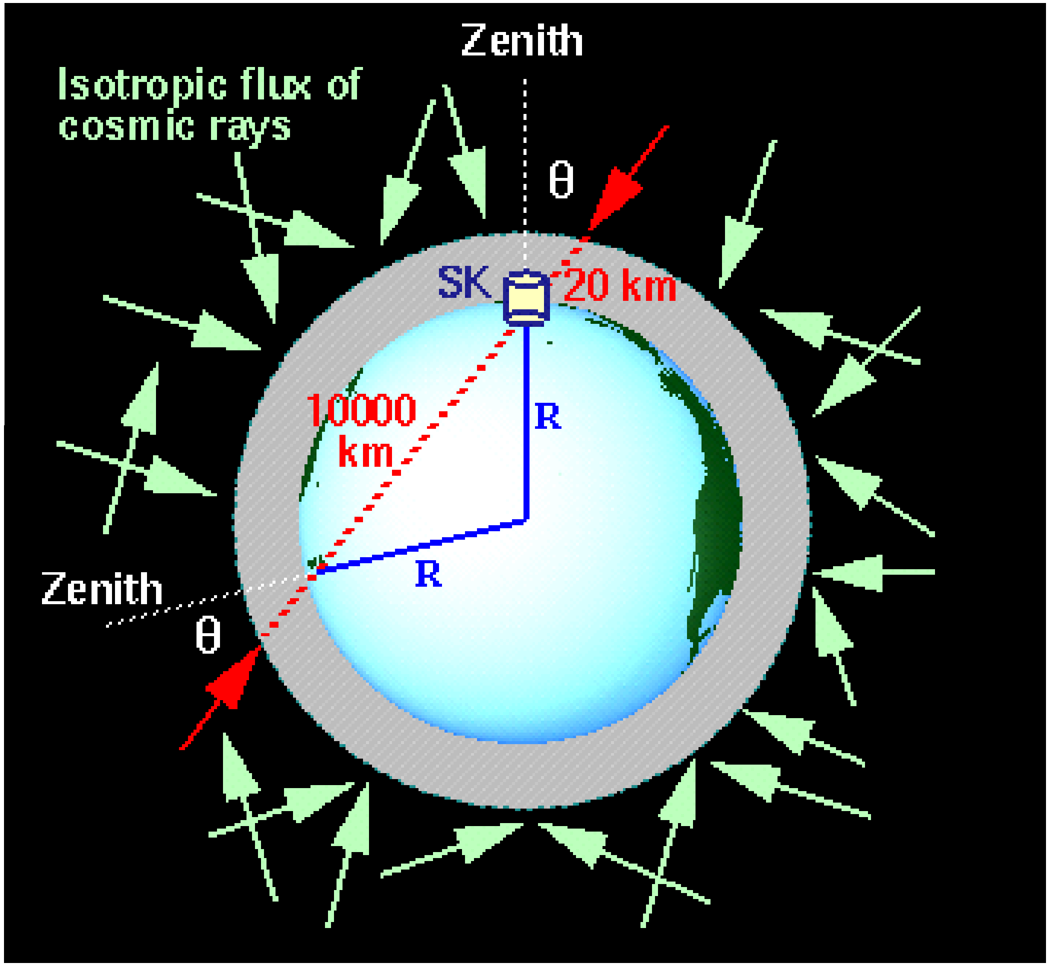
Solar + KamLAND results



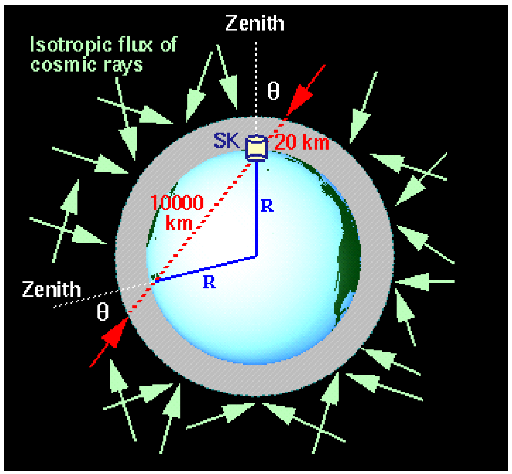
Measurement of θ_{23} and Δm^2_{atm}

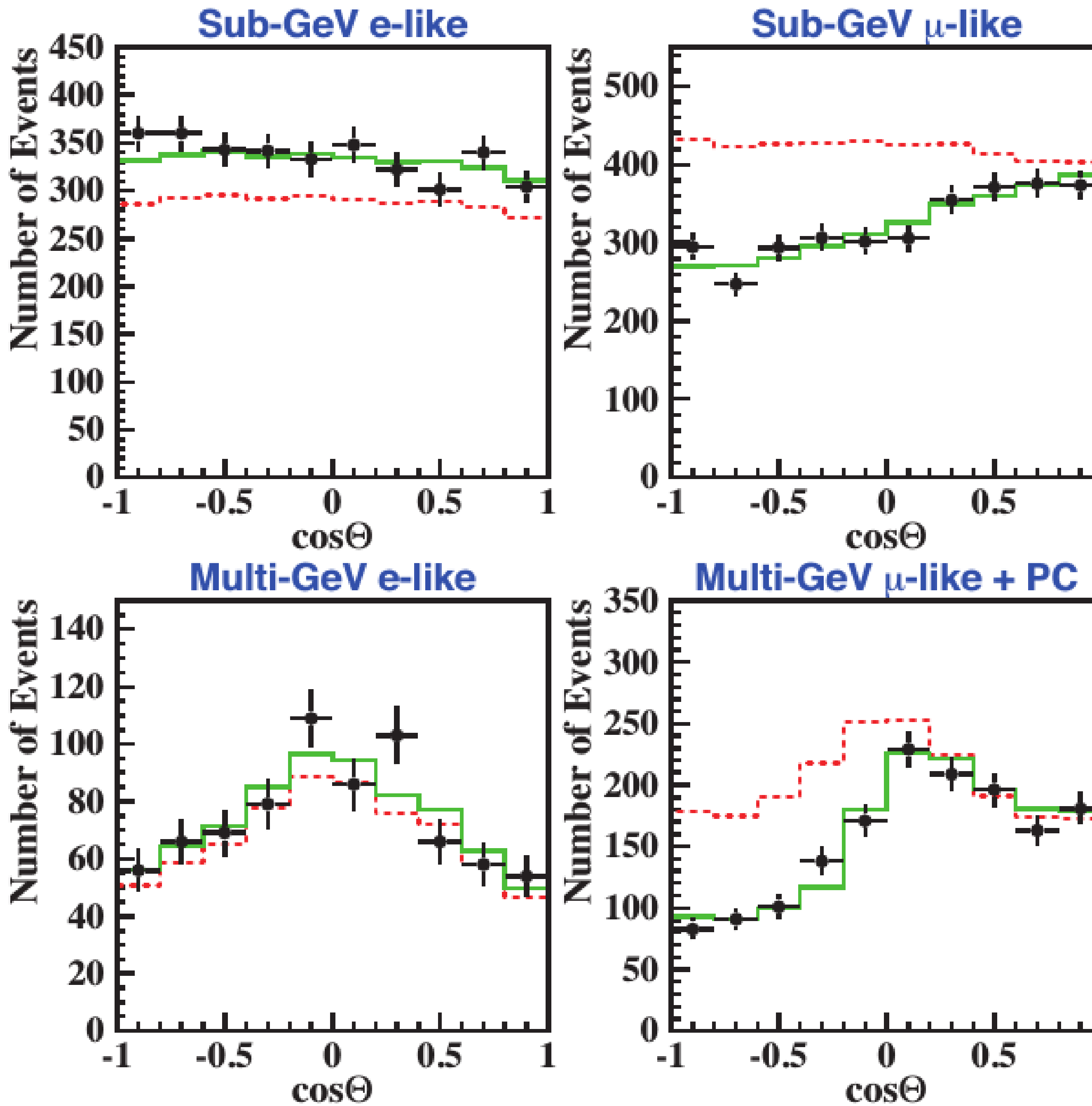
Atmospheric neutrinos



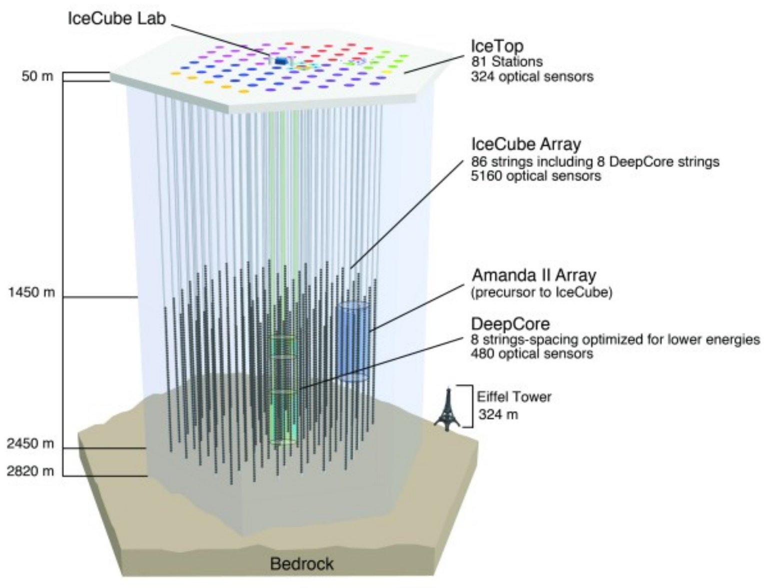


Super-Kamiokande results

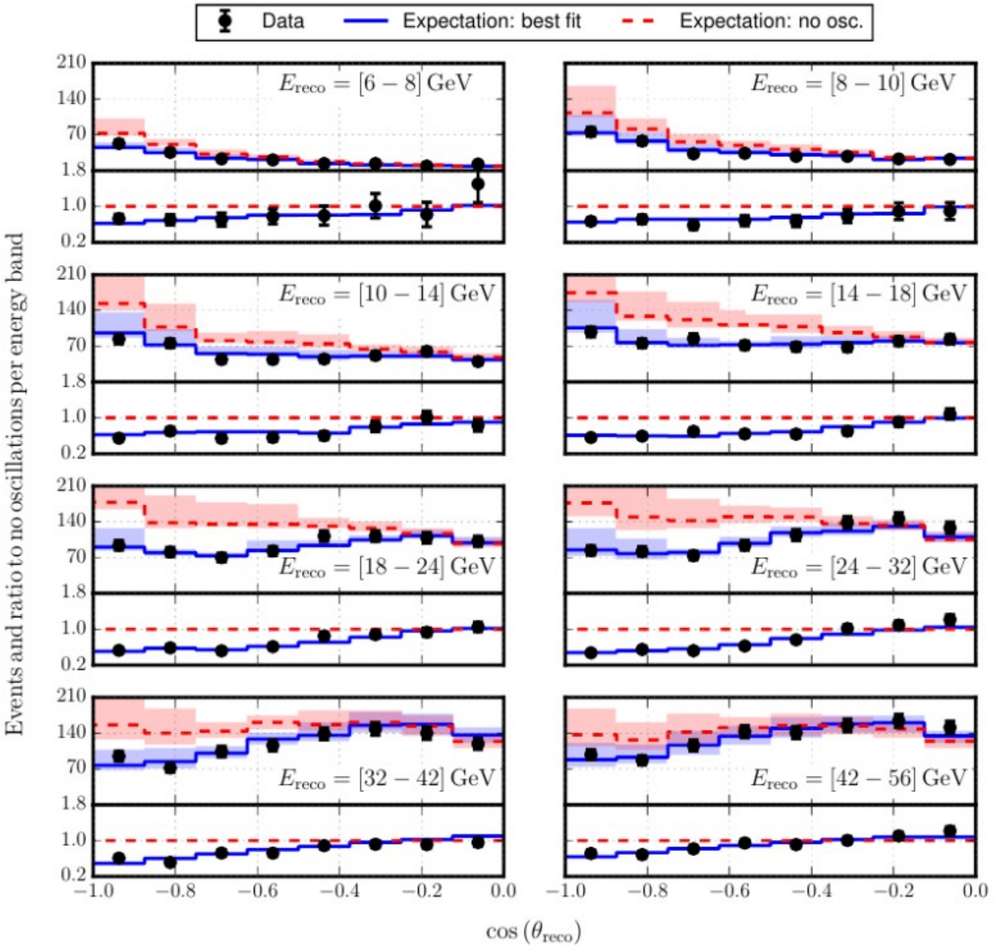




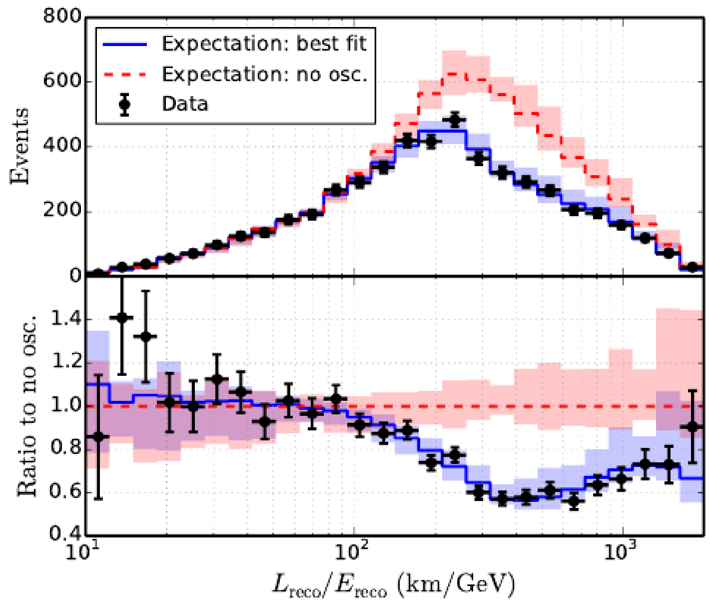
IceCube



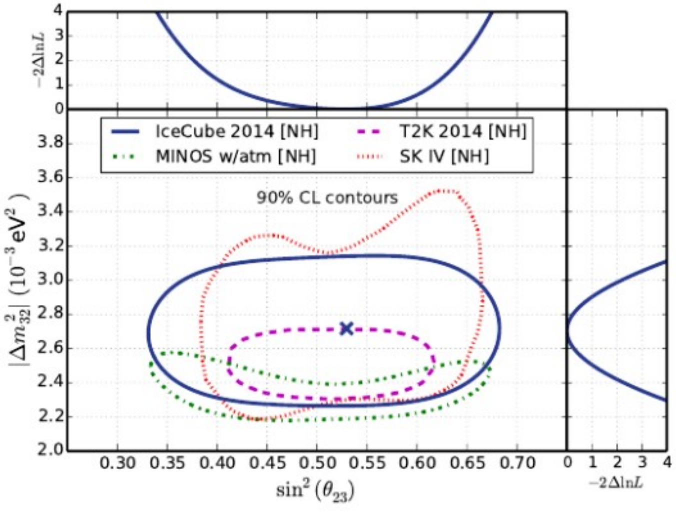
IceCube Lab
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
Amanda II Array
(precursor to IceCube)
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m
Bedrock



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
$\cos(\theta_{reco})$

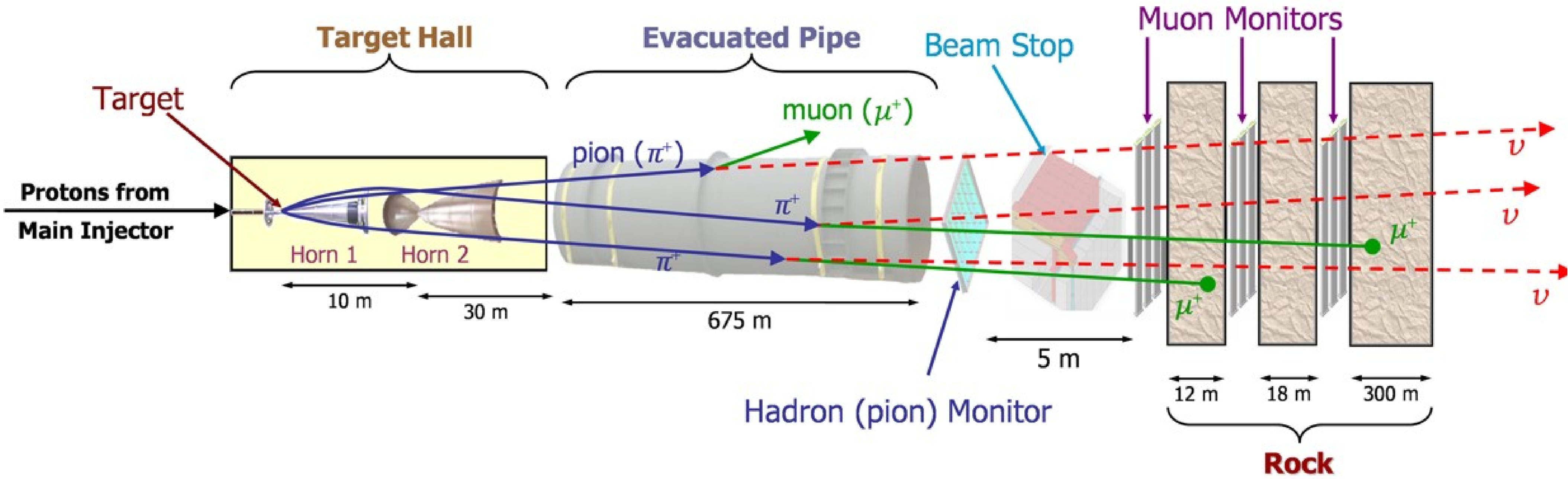


Expectation: best fit
Expectation: no osc.
Data
Events
Ratio to no osc.
L_{reco}/E_{reco} (km/GeV)

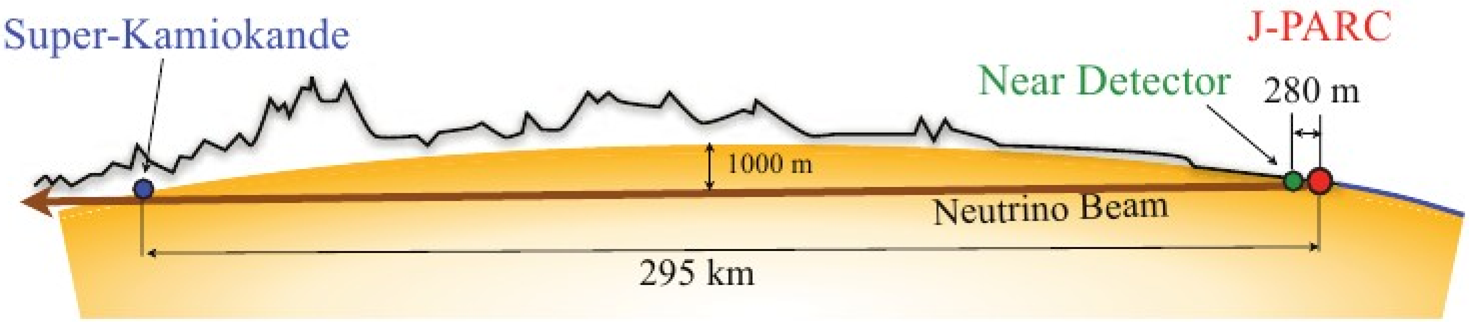


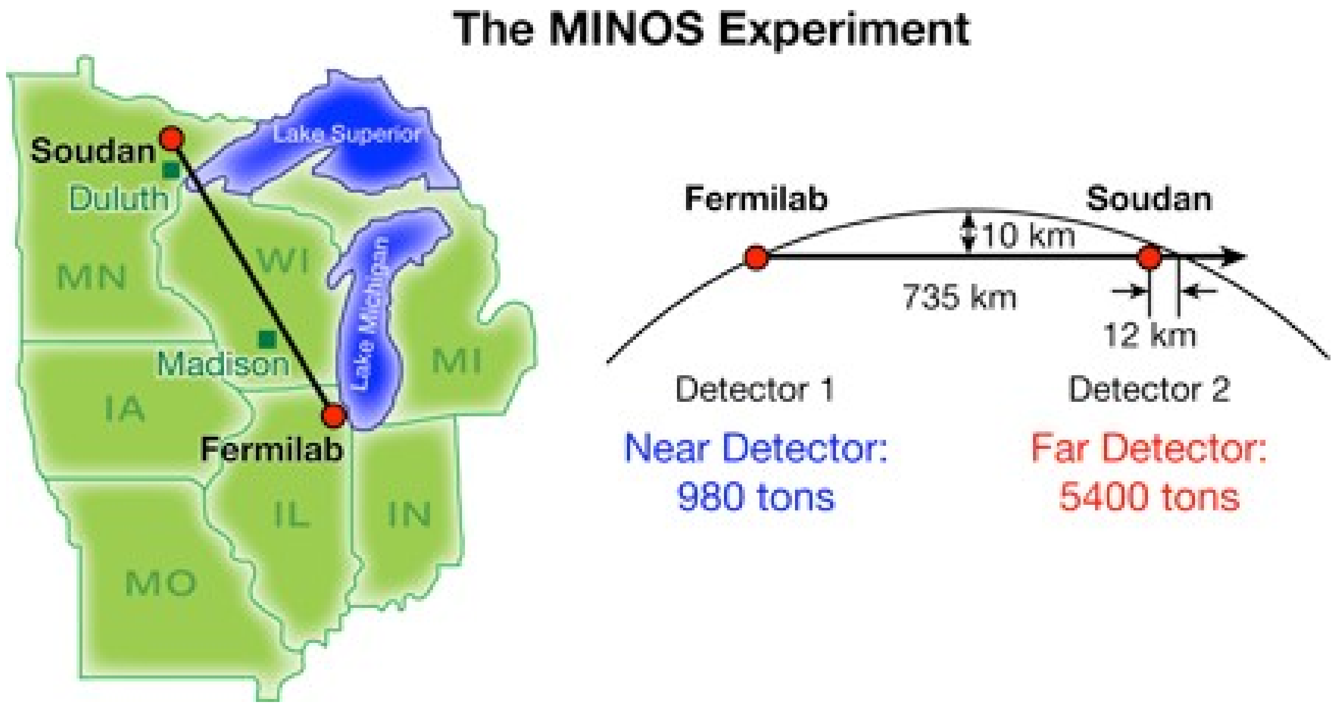
IceCube 2014 [NH]
T2K 2014 [NH]
MINOS w/atm [NH]
SK IV [NH]
90% CL contours
$|\Delta m^2_{32}|$ $(10^{-3}$ eV$^2)$
$\sin^2(\theta_{23})$
$-2\Delta\ln L$

Accelerator neutrinos

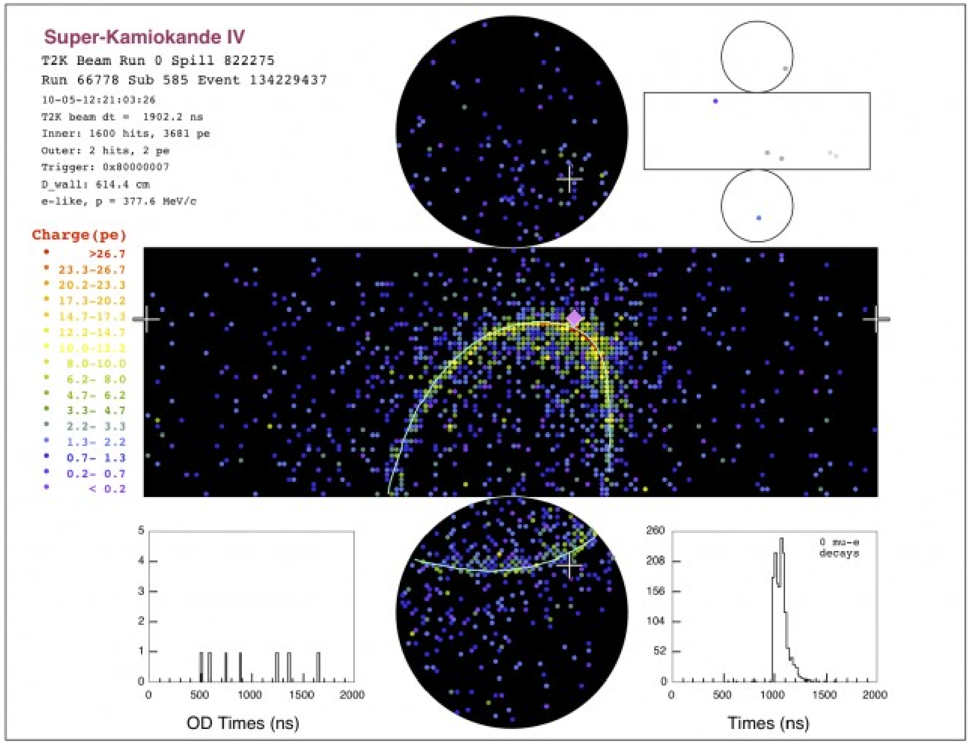


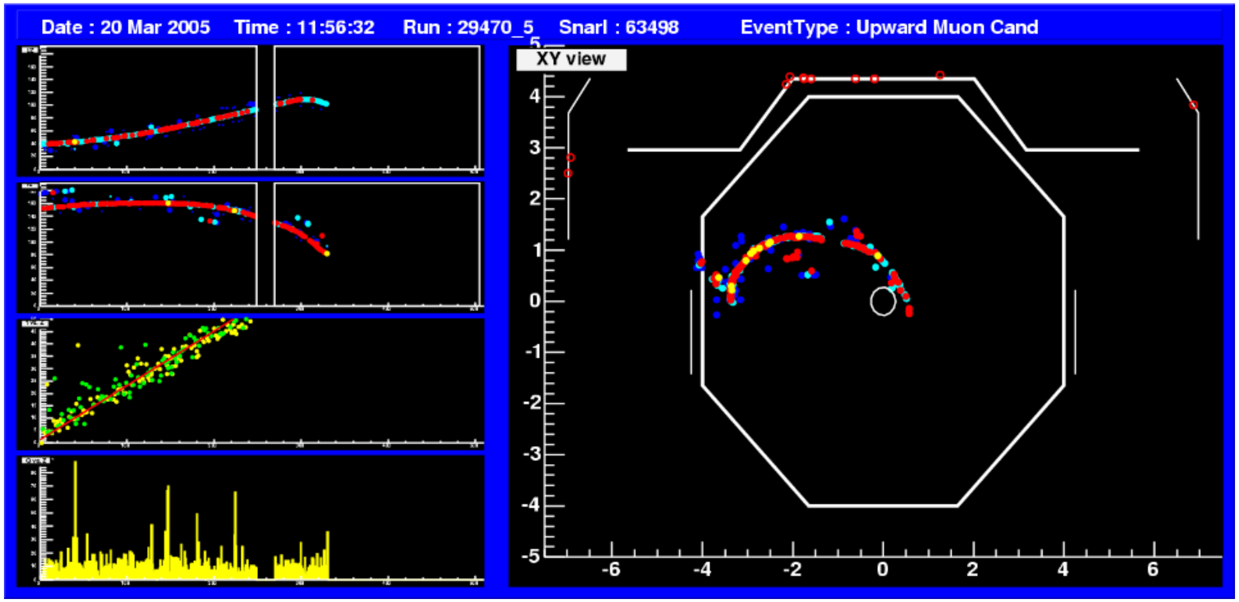
T2K & MINOS experiments



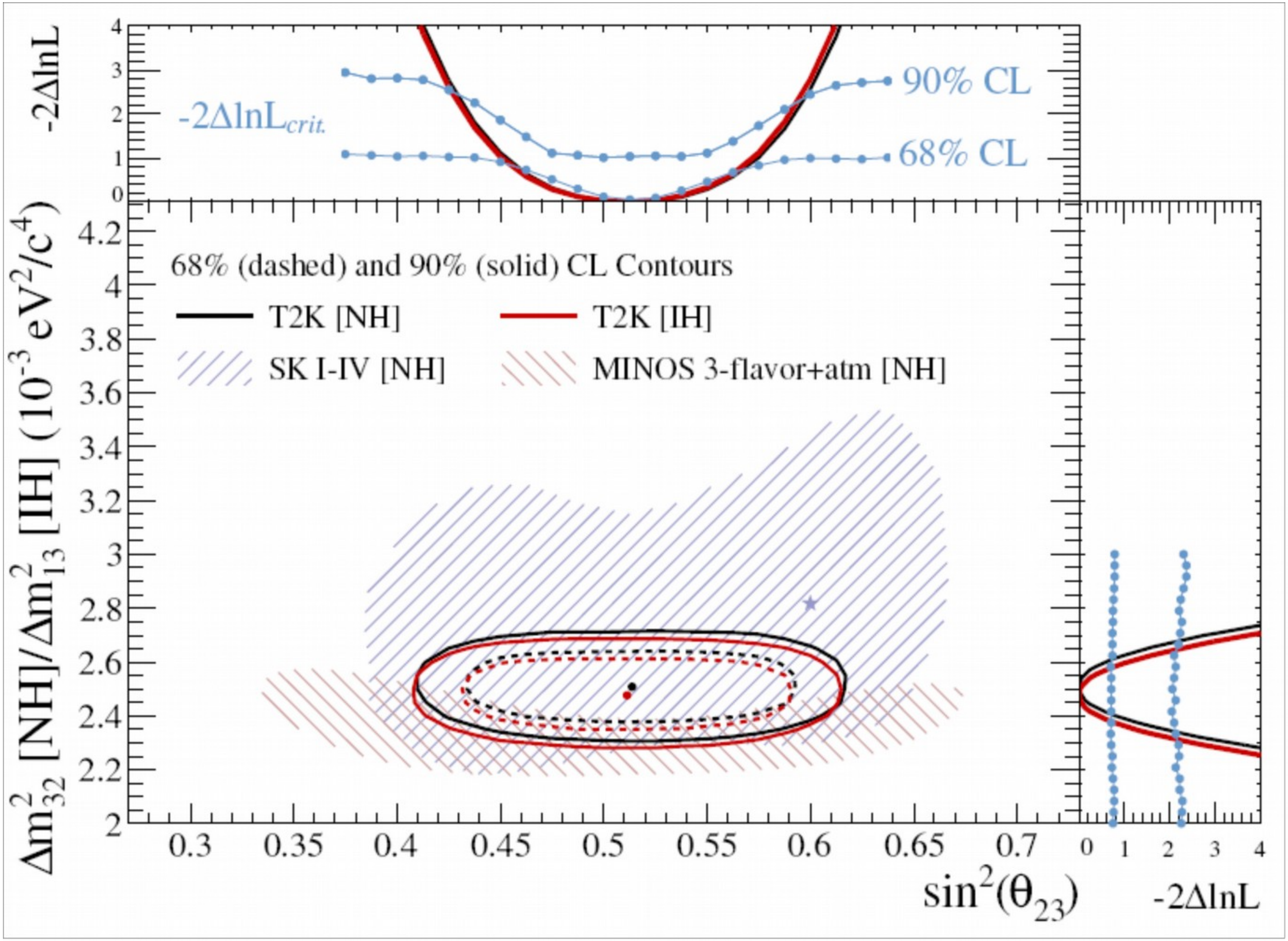


T2K & MINOS experiments

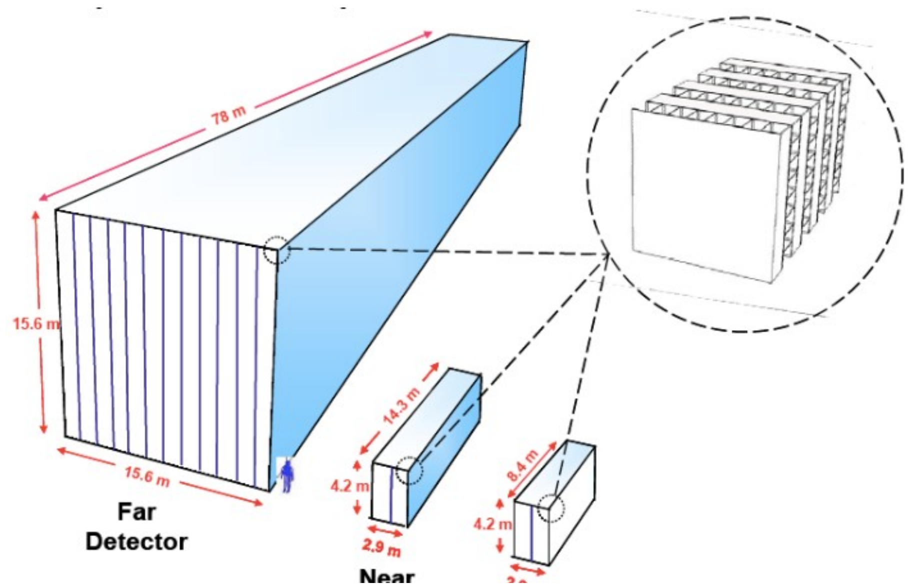


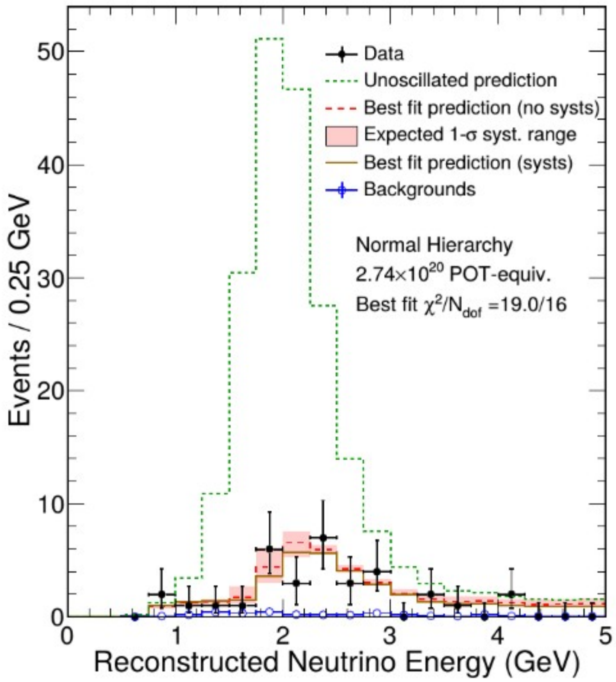


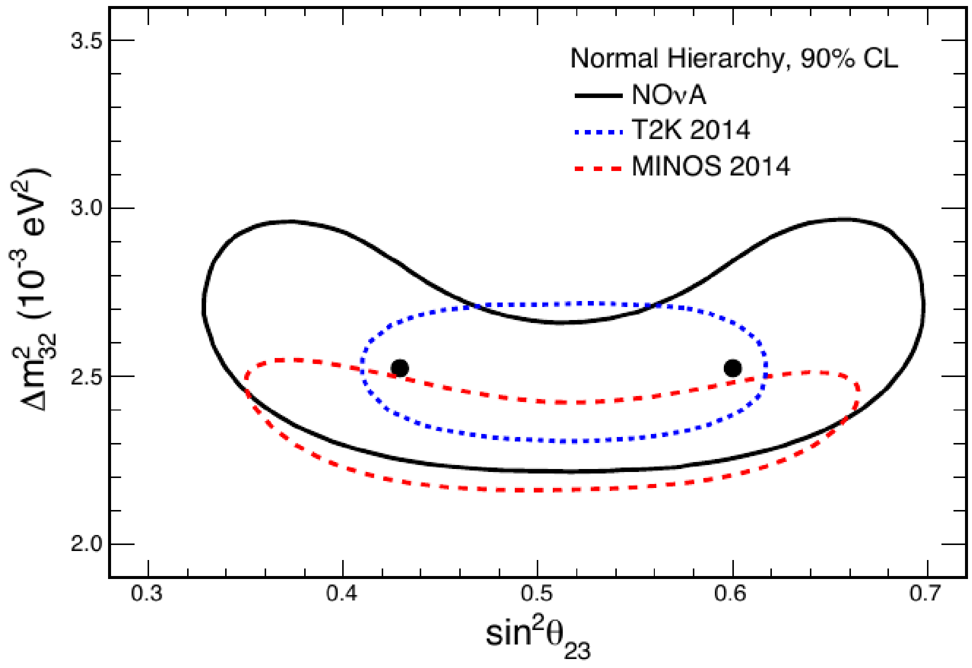
SK (atm) & T2K & MINOS



NOvA

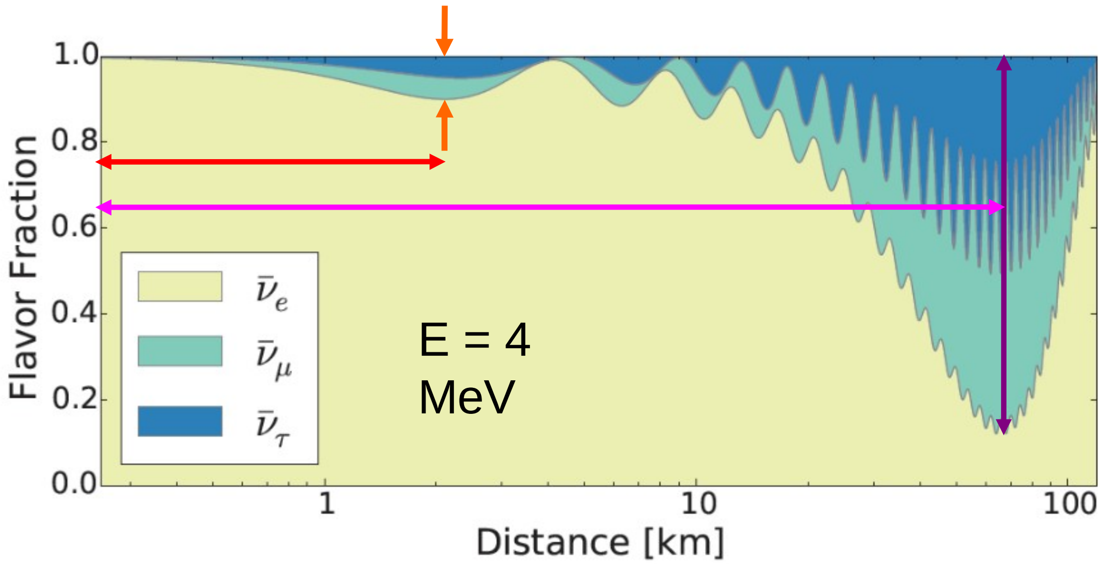

78 m
15.6 m
15.6 m
Far
Detector
14.3 m
4.2 m
2.9 m
Near
8.4 m
4.2 m


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)


Normal Hierarchy, 90% CL
NOνA
T2K 2014
MINOS 2014
Δm²_32 (10^-3 eV²)
sin²θ_23

Measurement of θ_{13}

Measurement of θ_{13} with reactors



$$P_{ee}(L,E) =$$

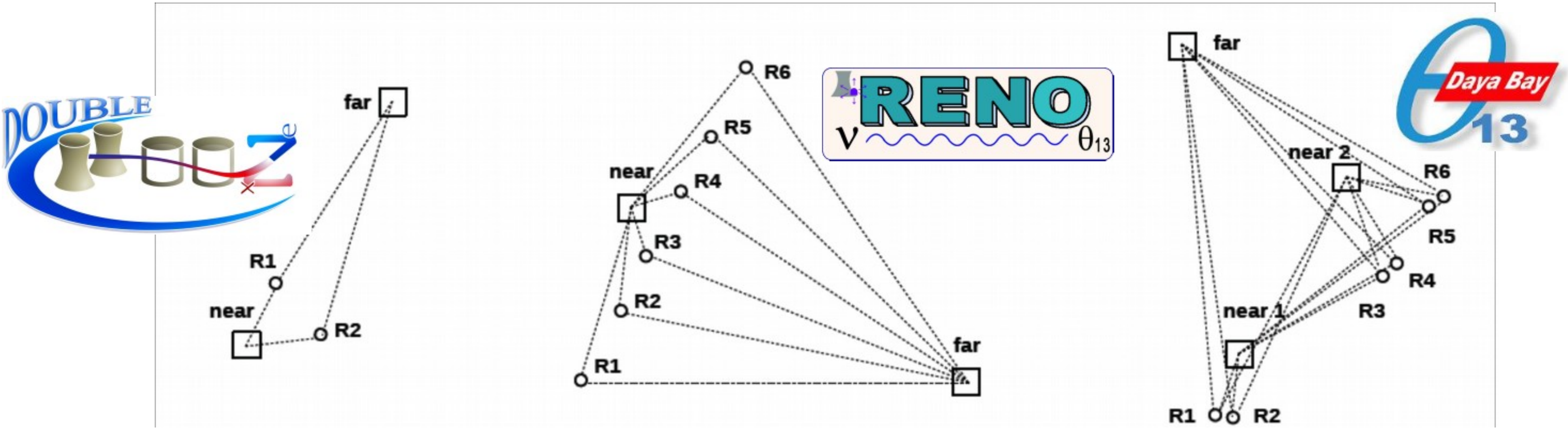
$$P_{ee}(L,E) = 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

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

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

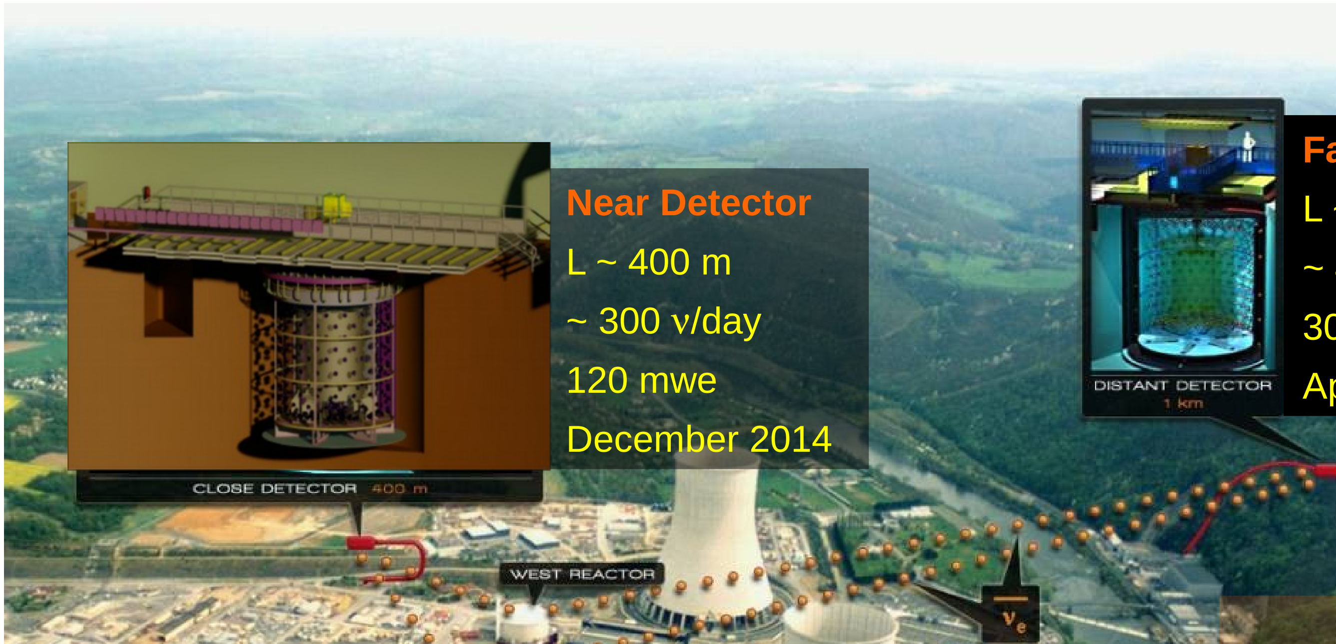
Measurement of θ_{13} with two-detector reactor experiments

- Antineutrinos detected by inverse β-decay: on Gd-loaded liquid scintillator calorimeters. $\overline{\nu}_e + p \rightarrow e^+ + n$
- Reactor prediction and the antineutrino detection systematics 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

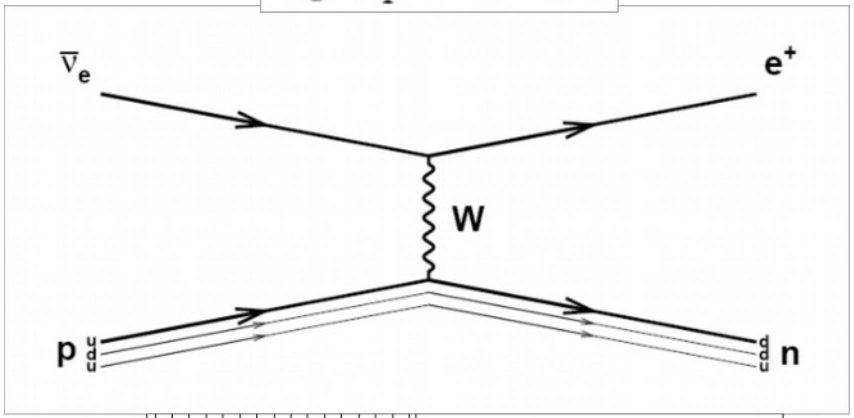
Far Detector
L ~ 1050 m
~ 40 ν/day
300 mwe
April 2011

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

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

Electron antineutrino detection

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



Inverse Beta Decay (IBD):

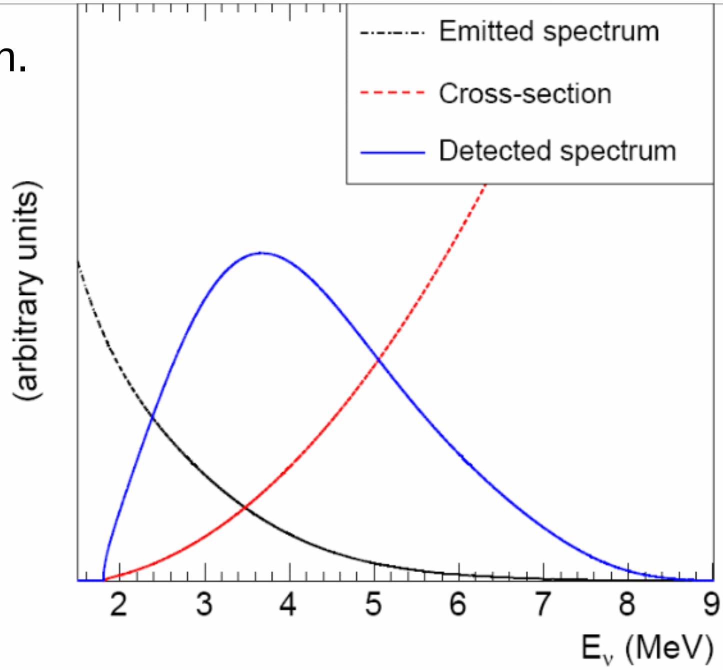
- Reaction threshold: $E_\nu \geq 1.806$ MeV.
- Disappearance experiment.
- Well known cross-section (0.2%).
- Coincidence of 2 signals: background suppression.

Prompt signal:

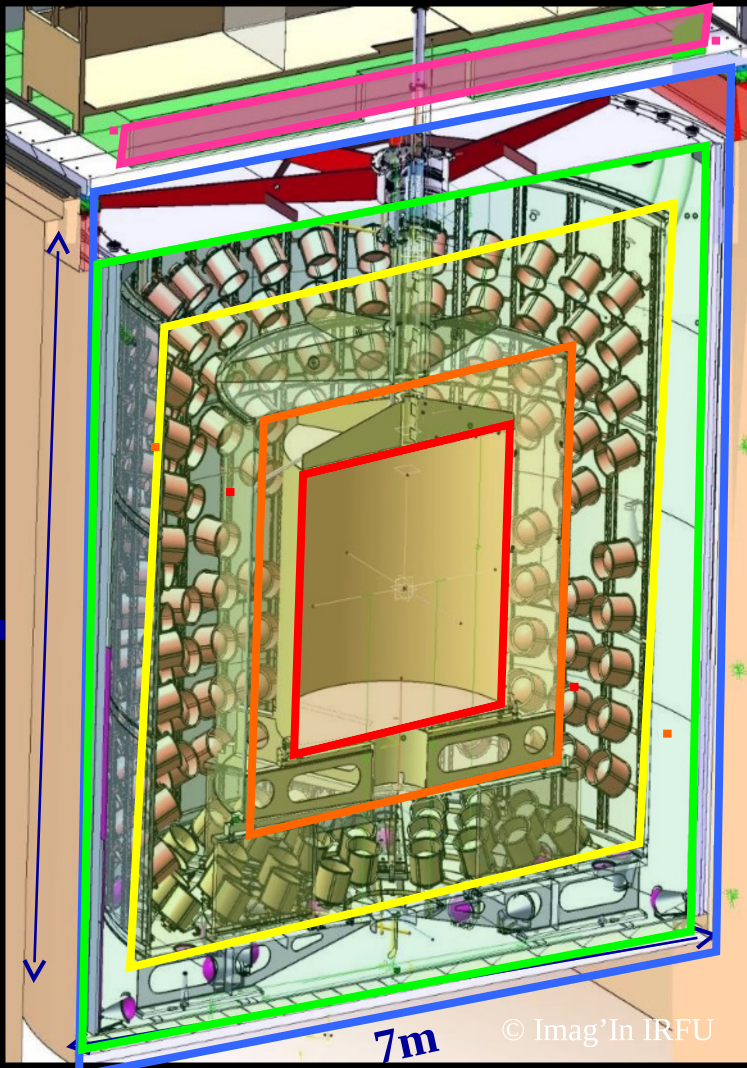
- Positron kinetic energy + γ's from annihilation.
- $E_{prompt} \approx E_\nu - 0.782$ MeV
- $E_{prompt} \sim 1 - 9$ MeV

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.

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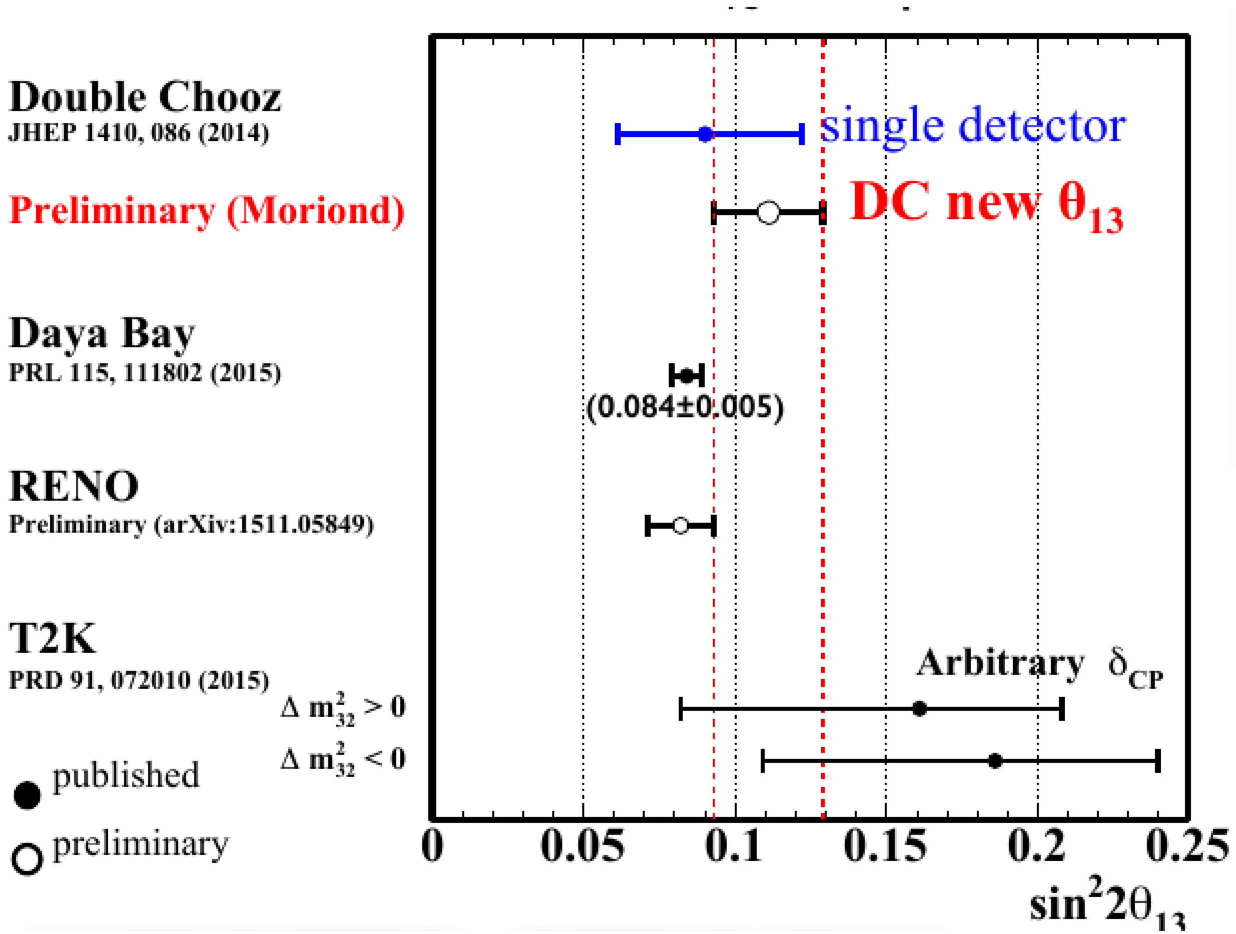
Latests measurements of θ_{13}

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

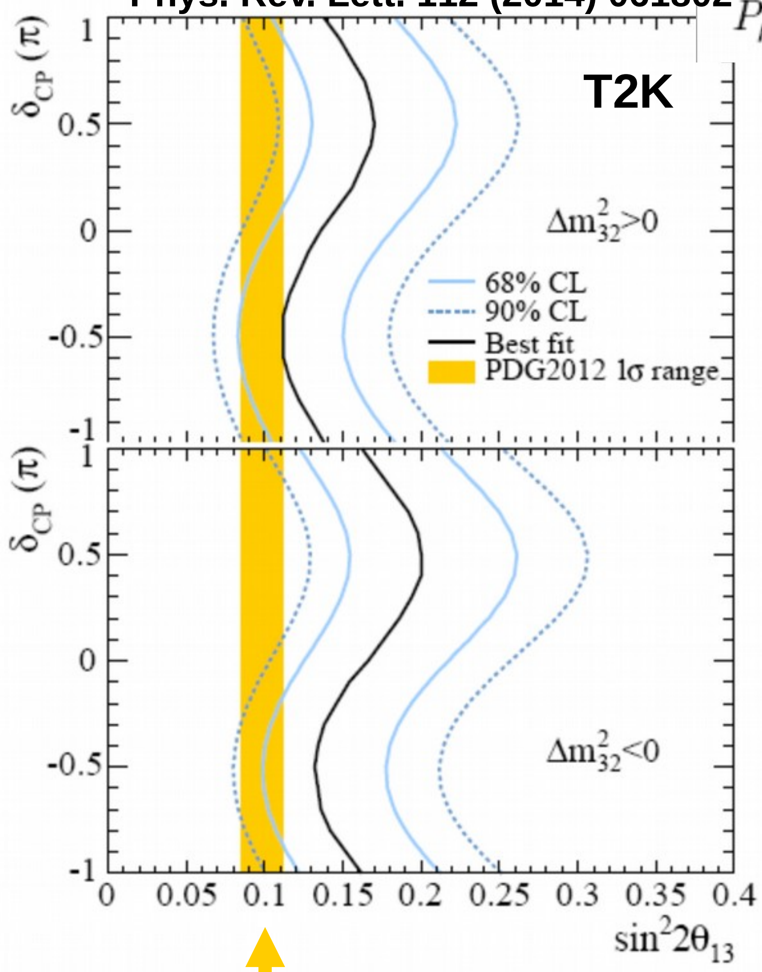


A. Cabrera, FNAL seminar 03/25/2016

First glimpse of δ

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

Phys. Rev. Lett. 112 (2014) 061802



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

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

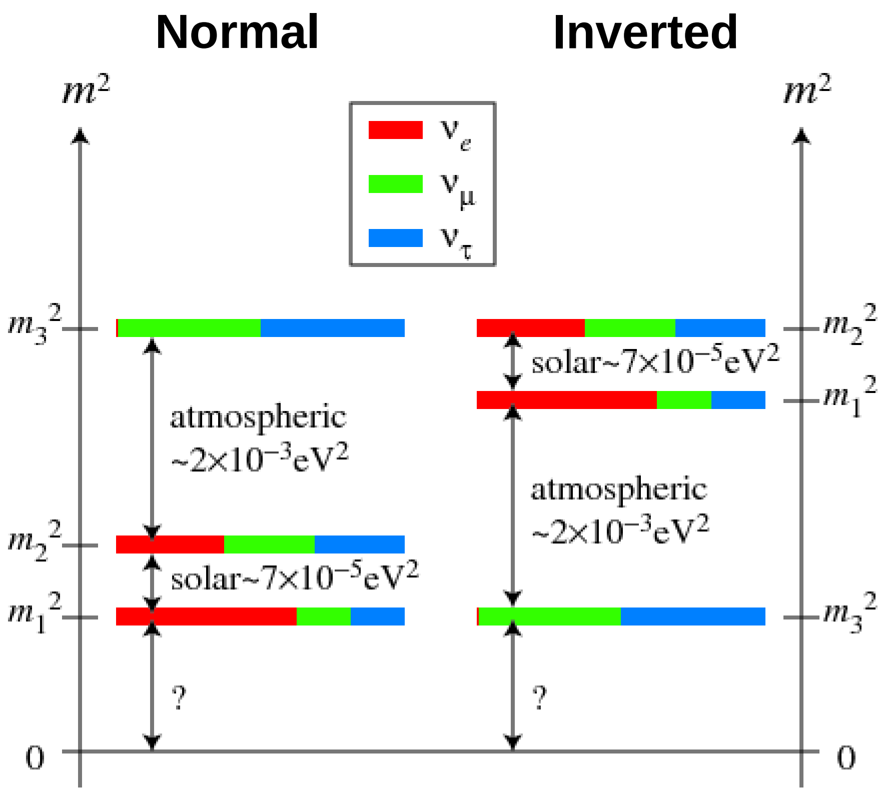
$$\Delta \equiv \frac{\Delta m^2_{32} L}{4E}$$

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

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

3 neutrinos: mass hierarchy

- 2 squared-mass differences
- But which is on top of which?
- The Solar + KamLAND experiments show that 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.