

Particle Physics: Neutrinos – part I

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Week 8: March 24, 2018
Columbia University Science Honors Program



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 |
|----------|-----|--|---------|
| January | 27 | Introduction | Jose |
| February | 3 | History of Particle Physics | Jose |
| | 10 | Special Relativity | Jose |
| | 17 | Quantum Mechanics | Jose |
| | 24 | Experimental Methods | Cris |
| March | 3 | The Standard Model - Overview | Cris |
| | 10 | The Standard Model - Limitations | Cris |
| | 17 | No classes, Columbia University spring break | |
| | 24 | Neutrino Theory | Jose |
| | 31 | No classes, Easter and Passover weekend | |
| April | 7 | Neutrino Experiment | Cris |
| | 14 | LHC and Experiments | Ines |
| | 21 | No classes, SHP break | |
| | 28 | The Higgs Boson and Beyond | Ines |
| May | 5 | Particle Cosmology | Cris |

Neutrinos in the Standard Model

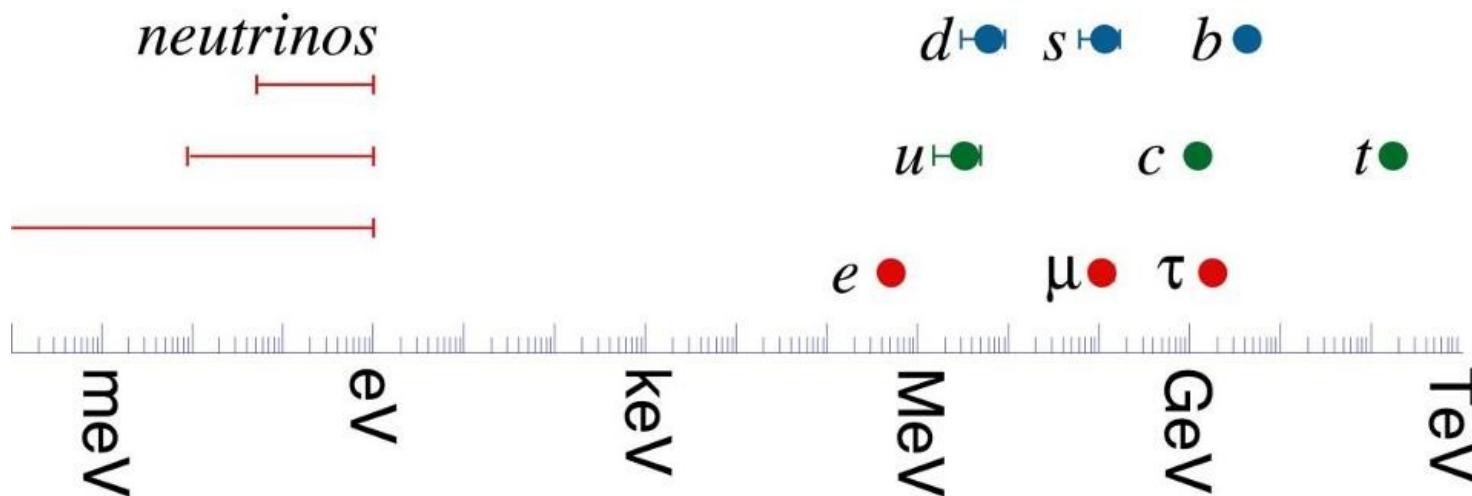
What is special about neutrinos
in the Standard Model?

Neutrinos in the Standard Model

| Three Generations of Matter (Fermions) spin $\frac{1}{2}$ | | | | | | | | |
|---|---------------------------|-------------------------|-------------------------|-------|----------|------------|------------|--|
| | I | II | III | | | | | |
| mass \rightarrow | 2.4 MeV | 1.27 GeV | 171.2 GeV | | | | | |
| charge \rightarrow | $\frac{2}{3}$ | $\frac{2}{3}$ | $\frac{2}{3}$ | | | | | |
| name \rightarrow | u | c | t | g | γ | Z | W $^+$ | |
| Quarks | Left up Right | Left charm Right | Left top Right | gluon | photon | weak force | weak force | |
| | d | s | b | | | | | |
| | Left down Right | Left strange Right | Left bottom Right | | | | | |
| Leptons | ν_e electron neutrino | ν_μ muon neutrino | ν_τ tau neutrino | | | | | |
| | Left e Right | Left muon Right | Left tau Right | | | | | |

Bosons (Forces) spin 1

- 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?



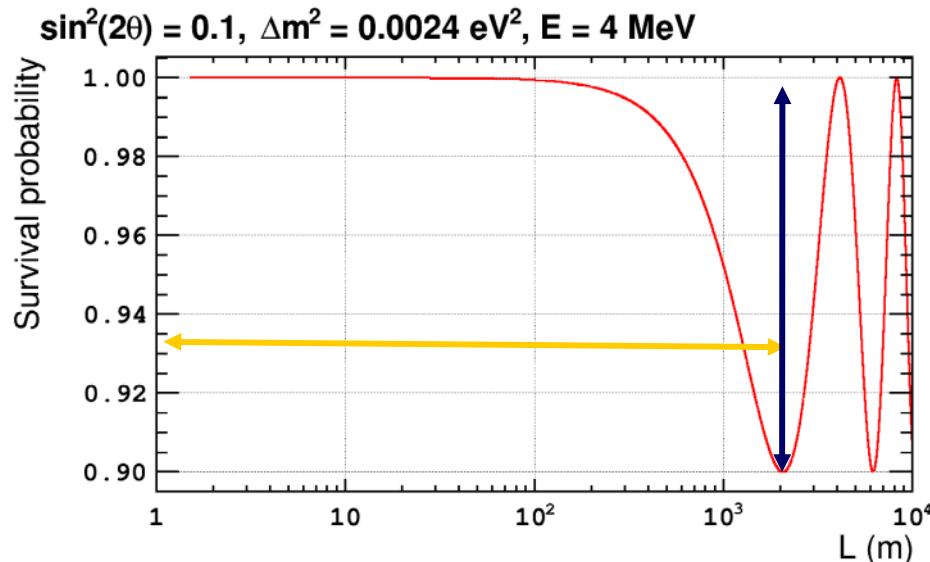
Neutrino oscillations (two-neutrino example)

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

$$\begin{array}{ccc}
 \text{Flavor eigenstates} & & \text{Mass eigenstates} \\
 \begin{pmatrix} |\nu_l\rangle \\ |\nu_x\rangle \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{pmatrix} \\
 & & \text{Mixing angle}
 \end{array}$$

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

Controlled by the experiment



- Survival probability:

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

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

3 neutrino mixing

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

PMNS matrix: U

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

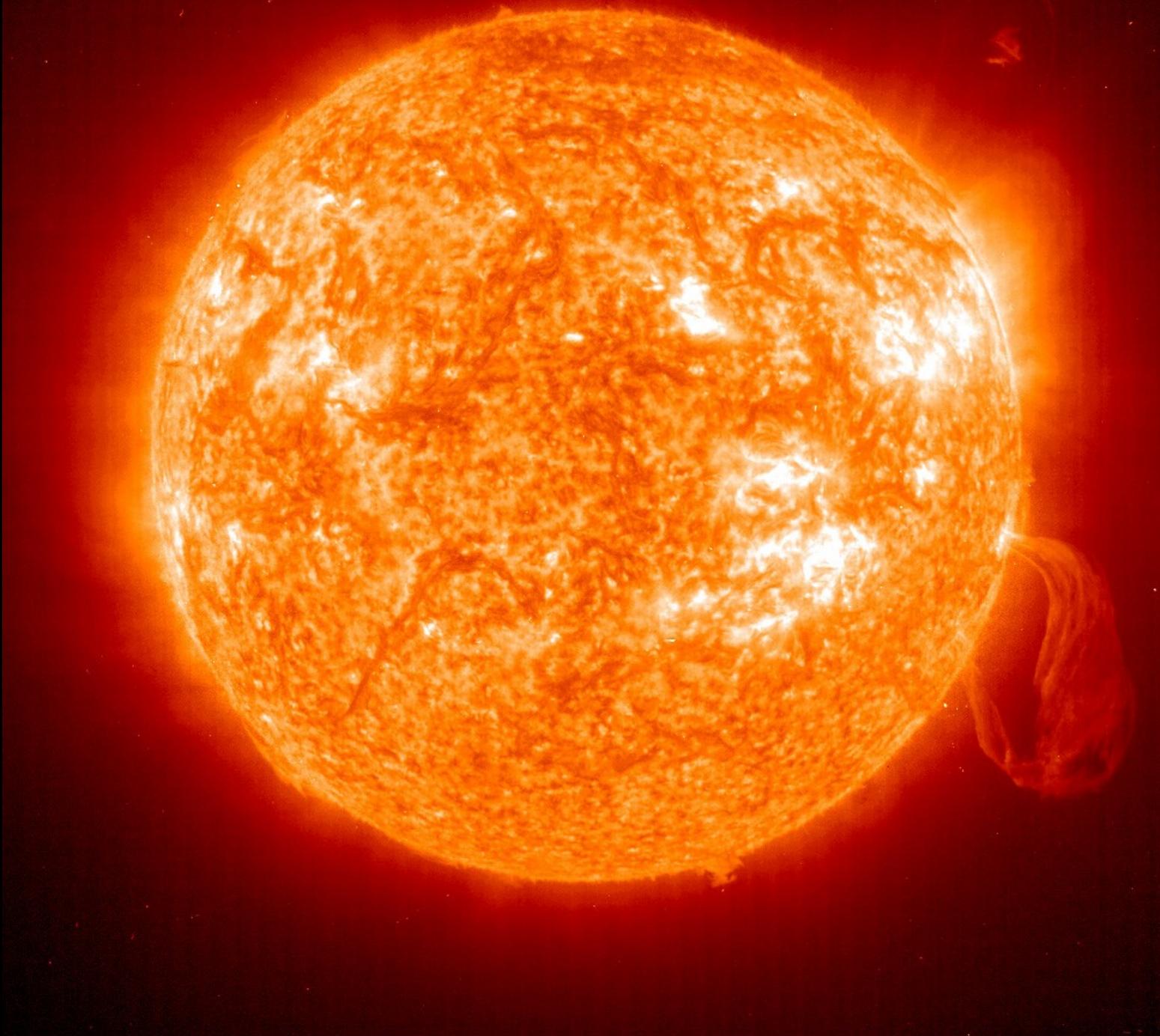
$c_{ij} = \cos \theta_{ij}, s_{ij} = \sin \theta_{ij}$

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 \rightarrow need to **measure them all!**

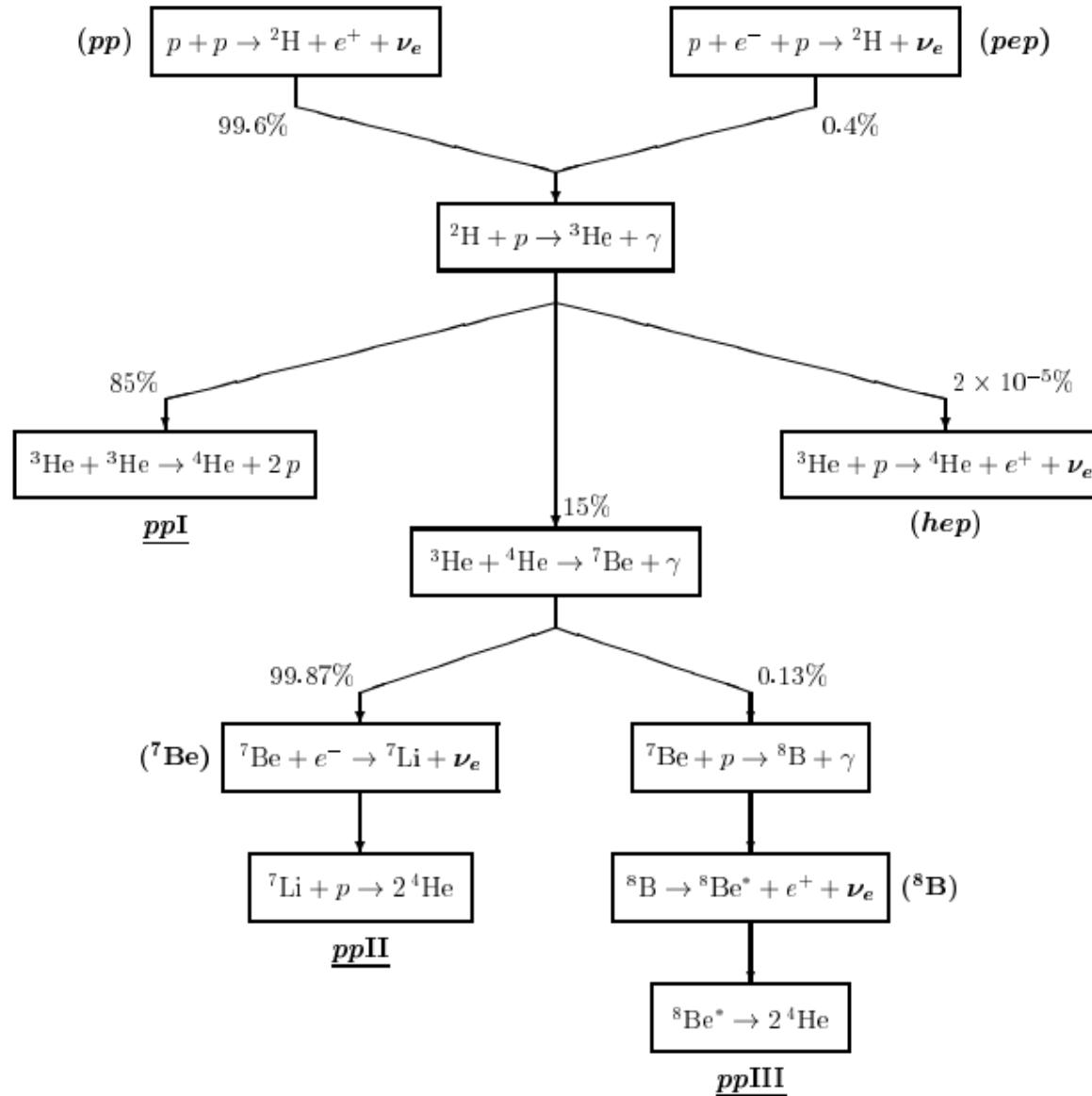
Measurement of θ_{12} and Δm^2_{21}

Solar experiments



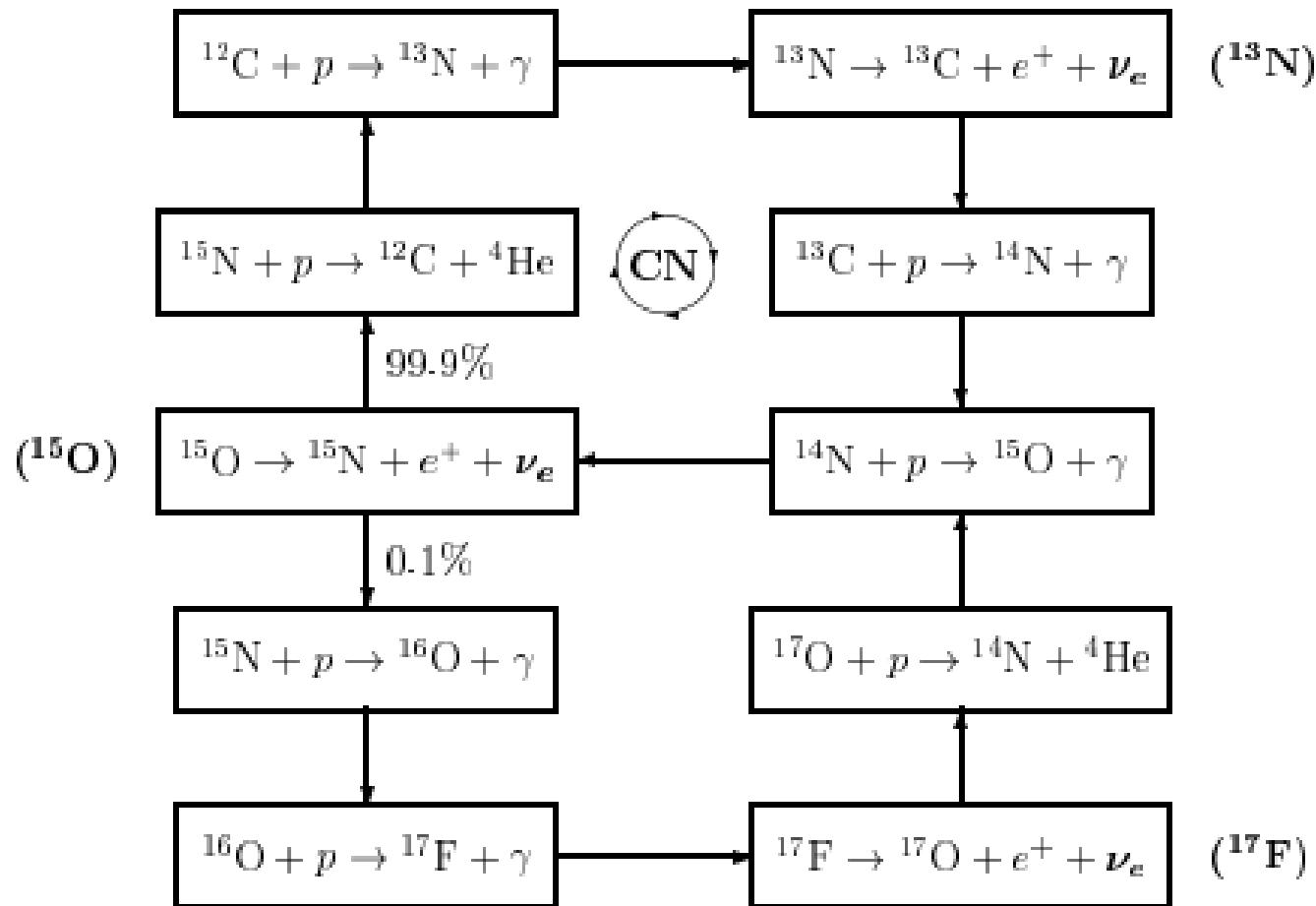
Solar neutrinos: pp chain

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

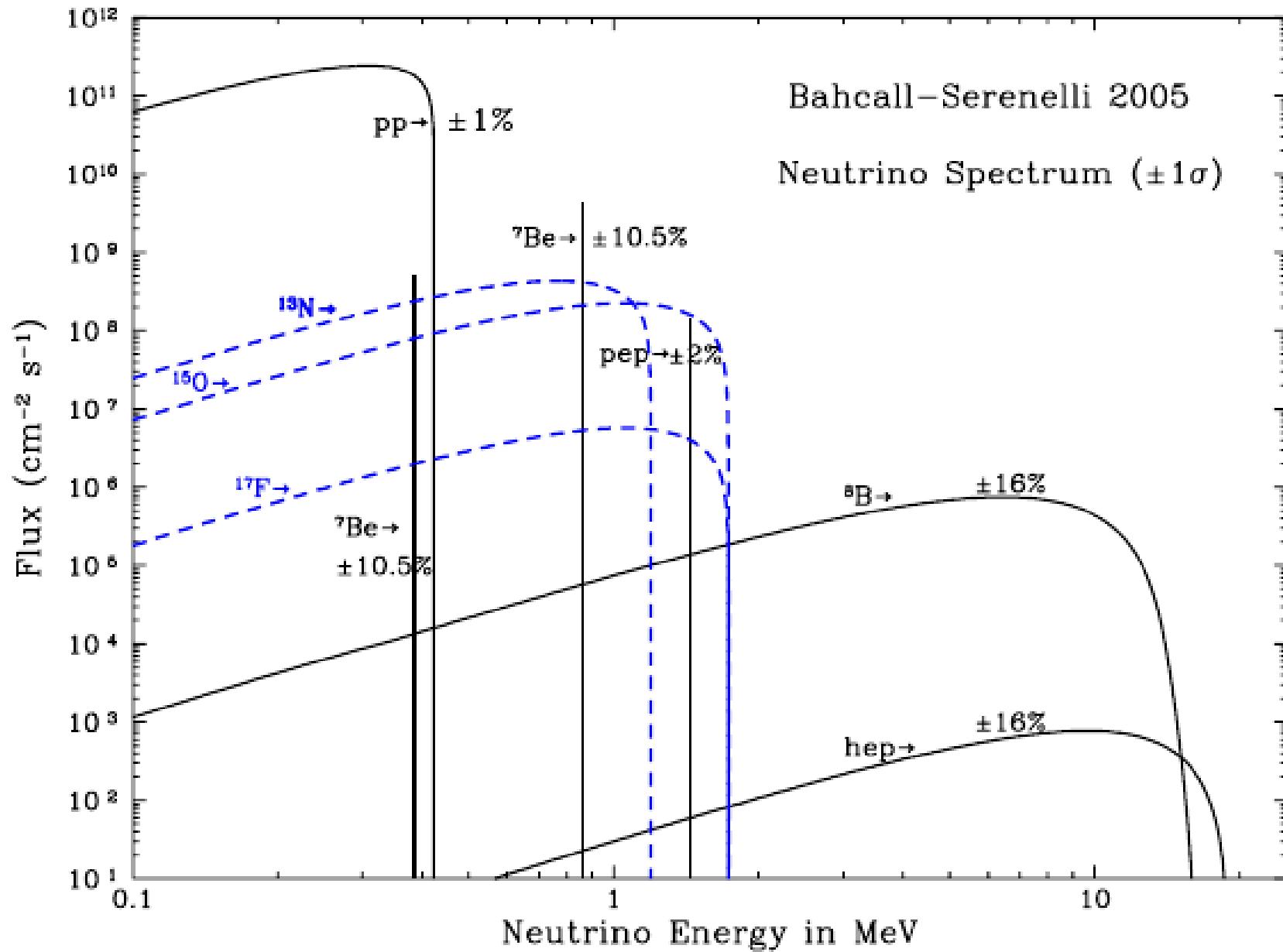


Solar neutrinos: CNO cycle

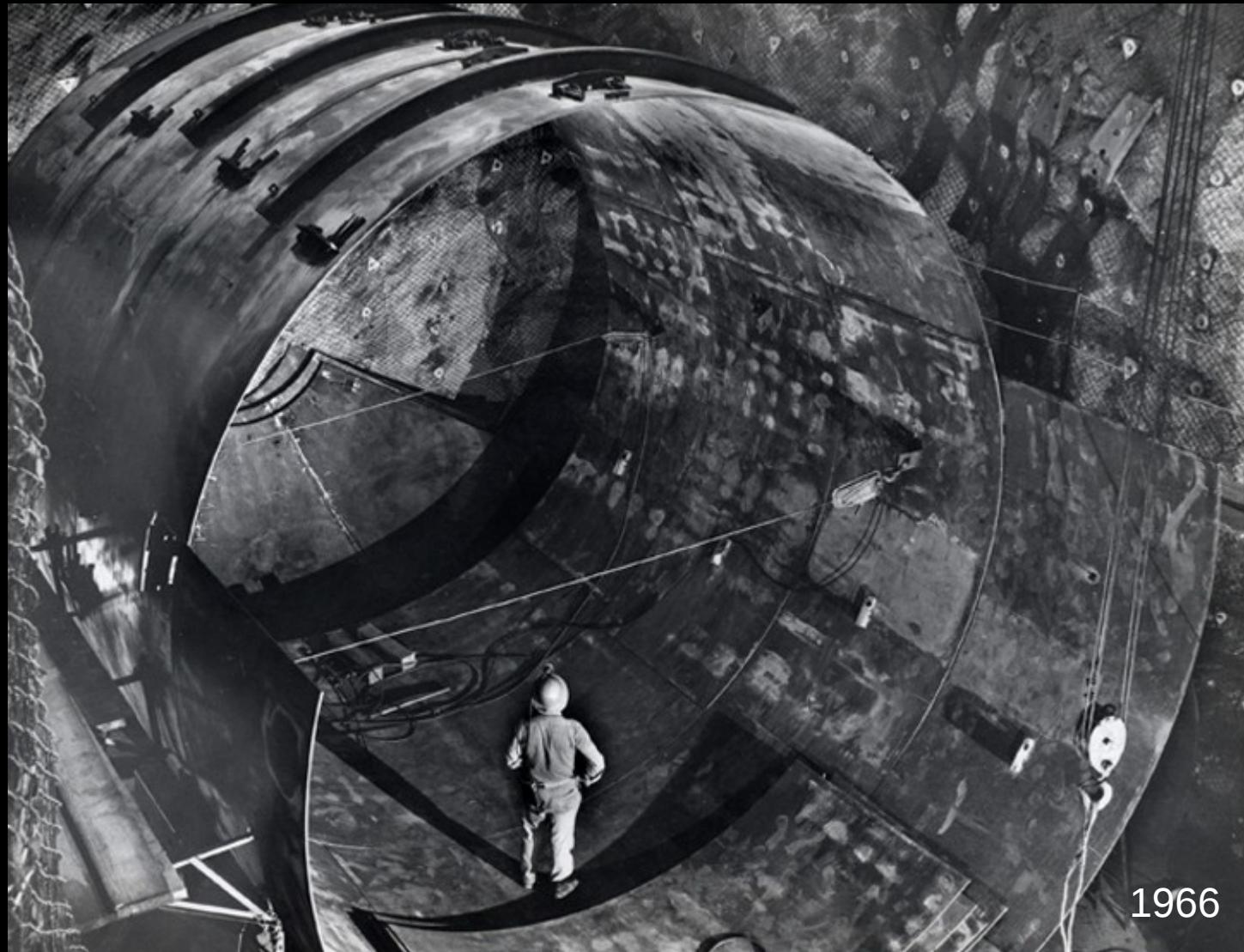
- CNO cycle produces 1.6% of Sun's fusion energy. It also produces **electron neutrinos**.



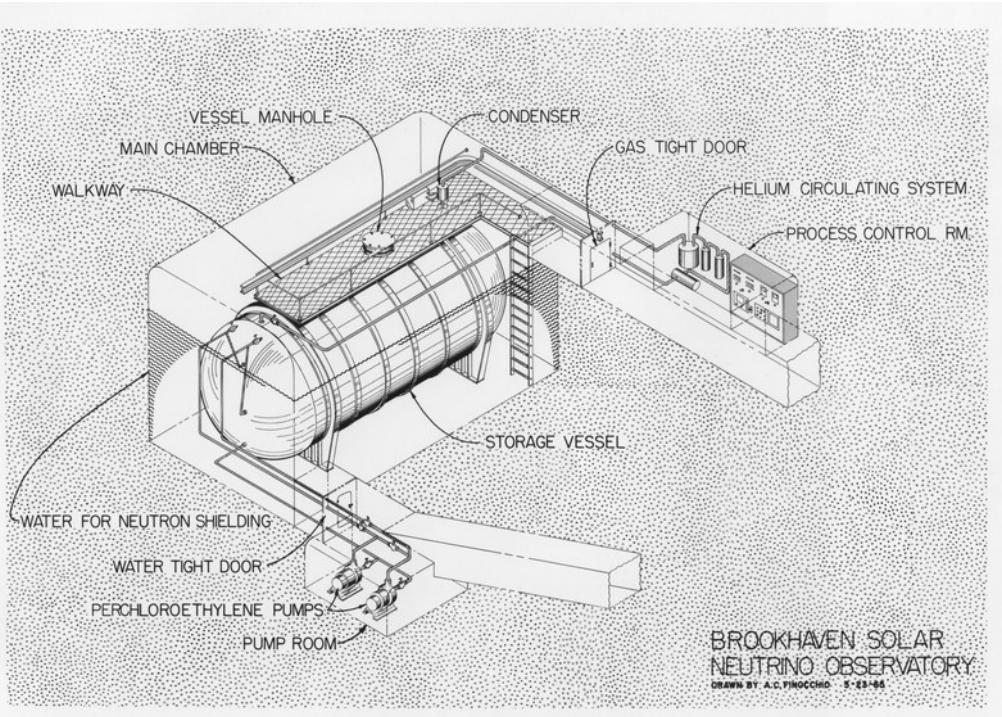
Solar neutrinos: energy spectrum



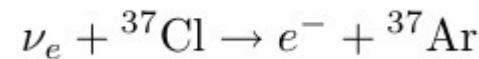
Homestake experiment (1970 - 1994)



Homestake experiment



- Detection of solar neutrinos using the reaction:

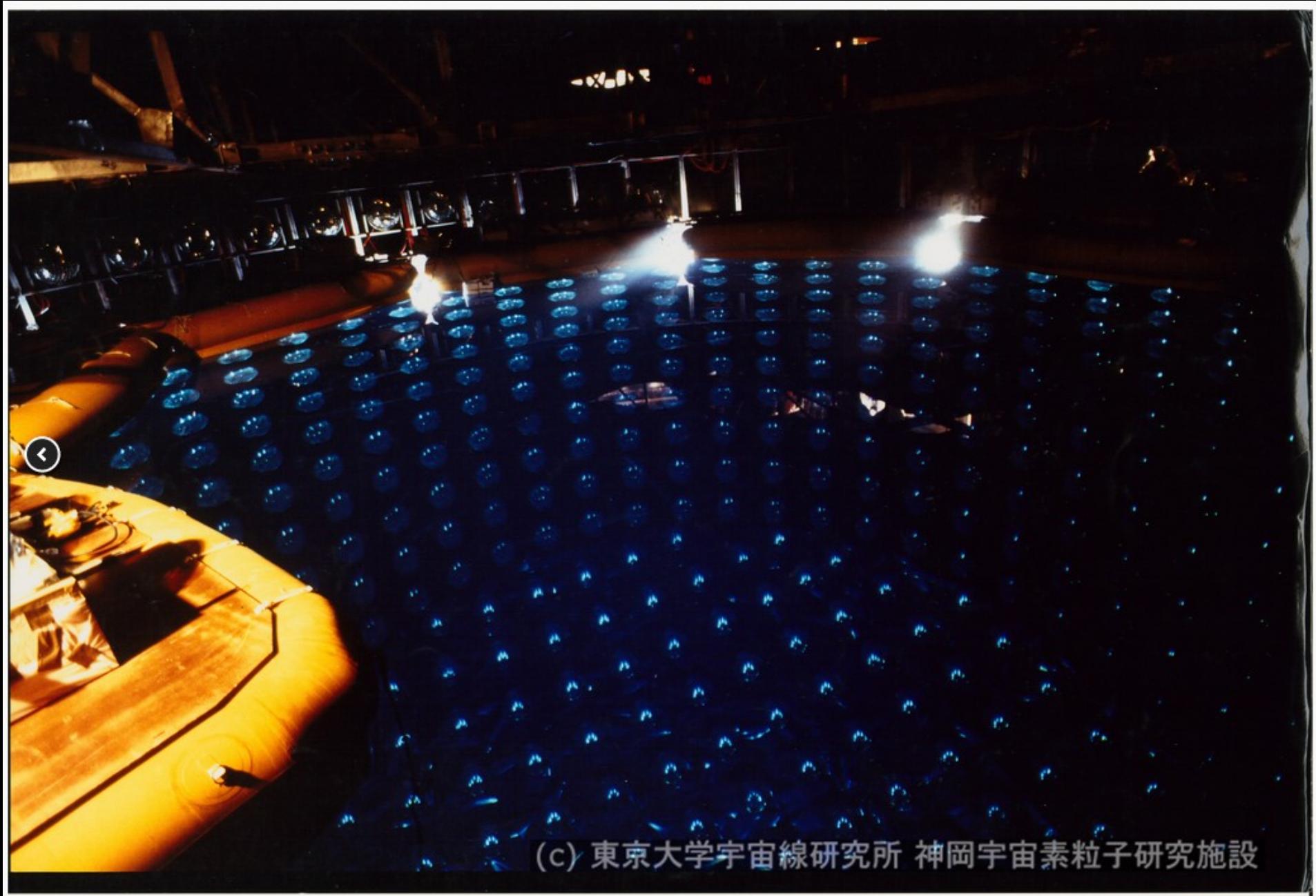


- Radiochemical detector.
- Ratio of observed to predicted:

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

- **Missing neutrinos!**

Kamiokande (1983 - 1996)



Kamiokande



- Detection of solar neutrinos using the reaction:

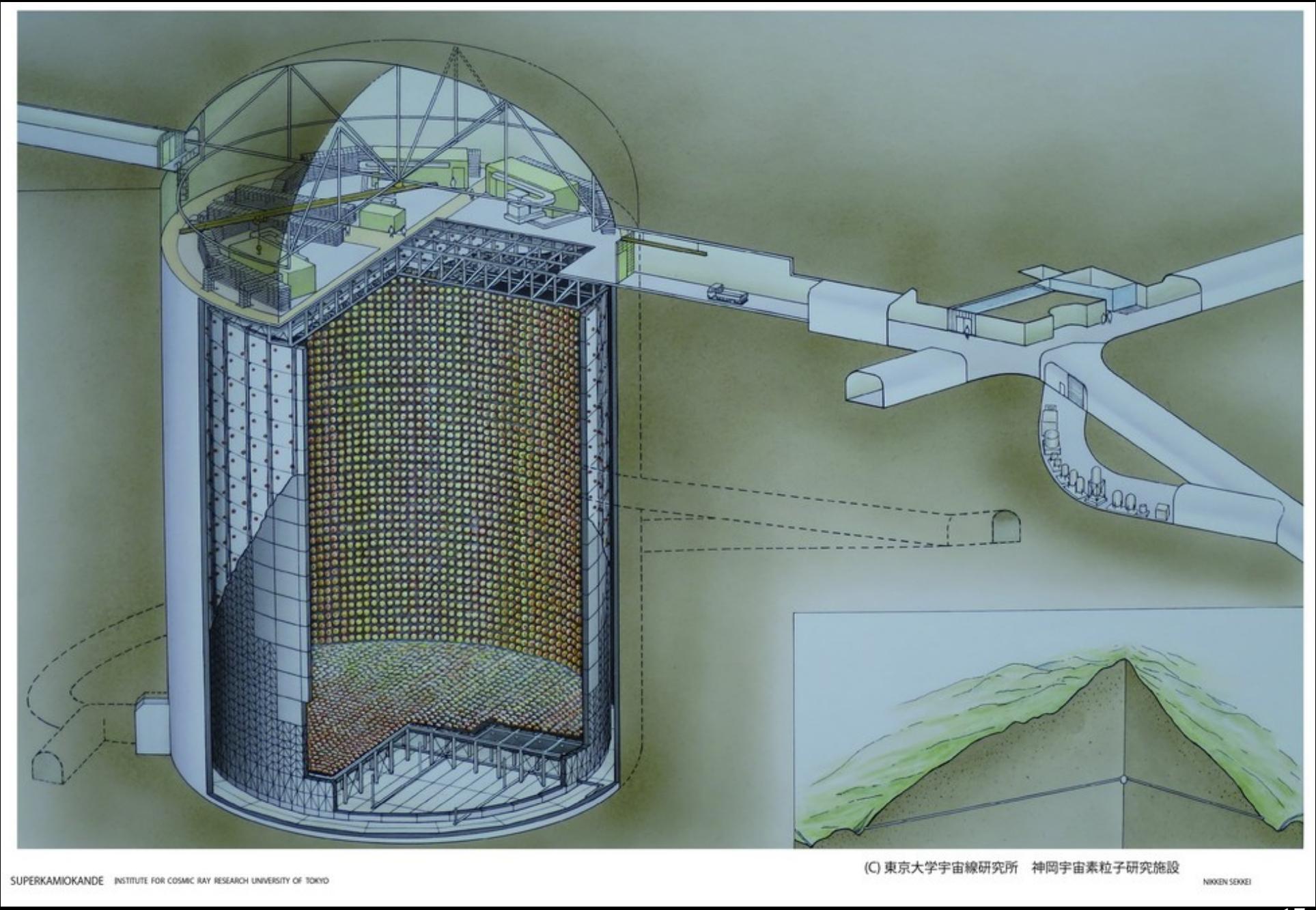


- Water Cherenkov detector.
- Ratio of observed to predicted:

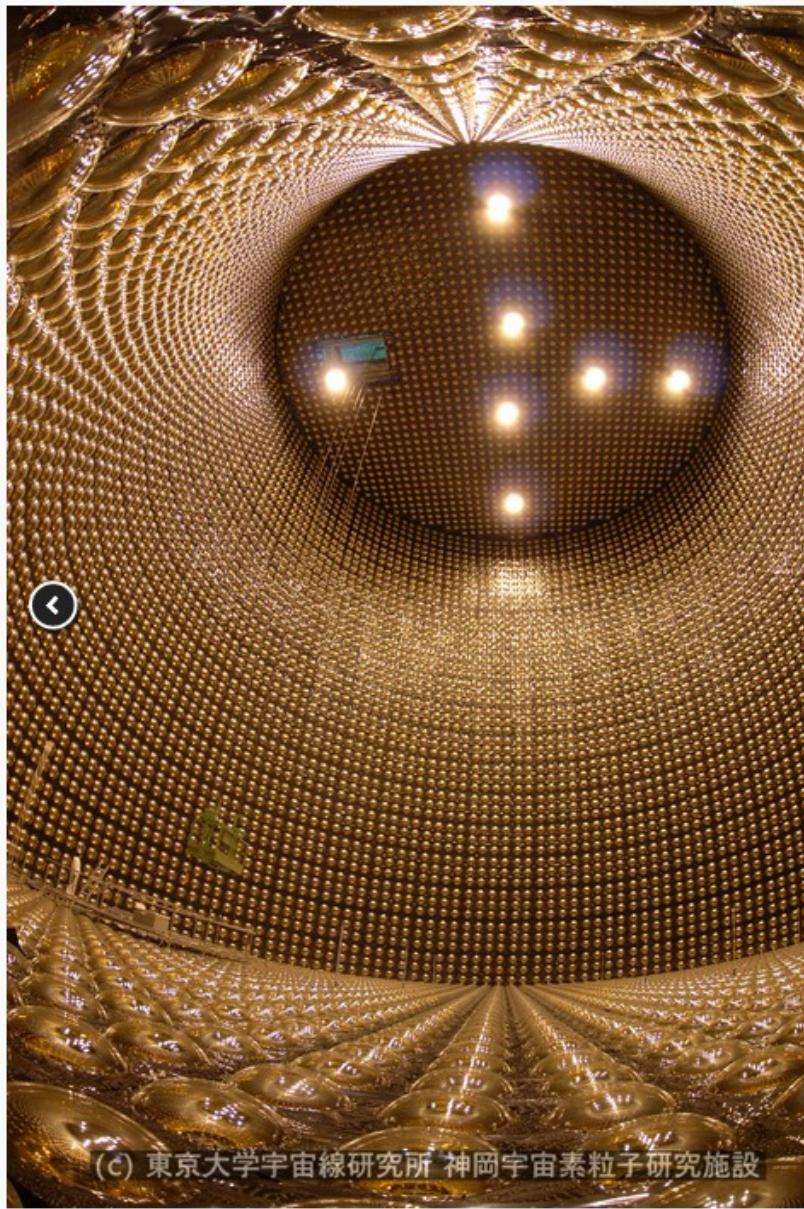
$$\frac{\Phi_{\text{Kamiokande}}}{\Phi_{\text{SSM}}} = 0.484 \pm 0.066.$$

- **Missing neutrinos again!**

Super-Kamiokande (since 1996)



Super-Kamiokande



- Detection of solar neutrinos using the reaction:



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

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

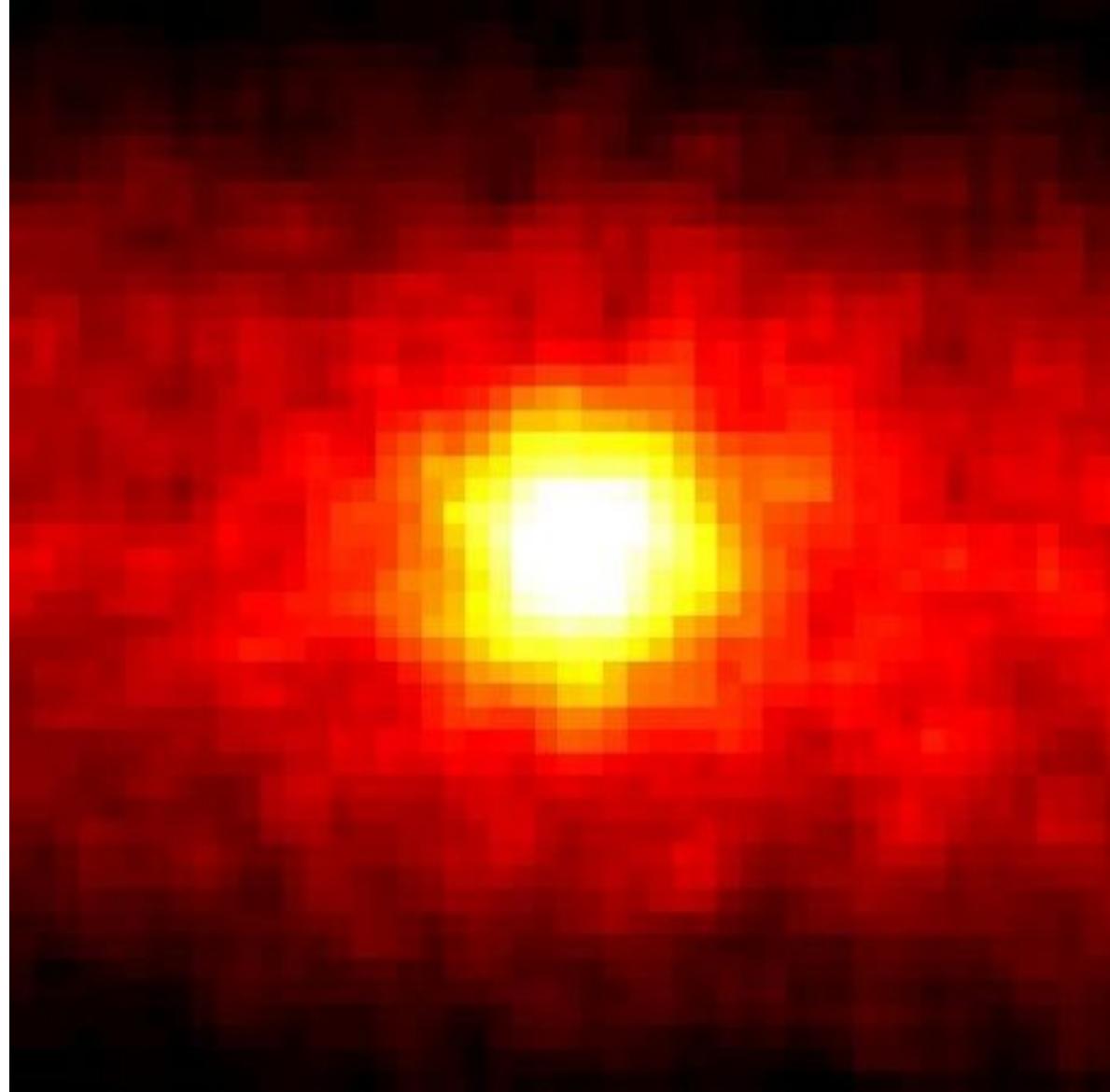
- **Improved result over Kamiokande, neutrinos still missing!**

Super-Kamiokande

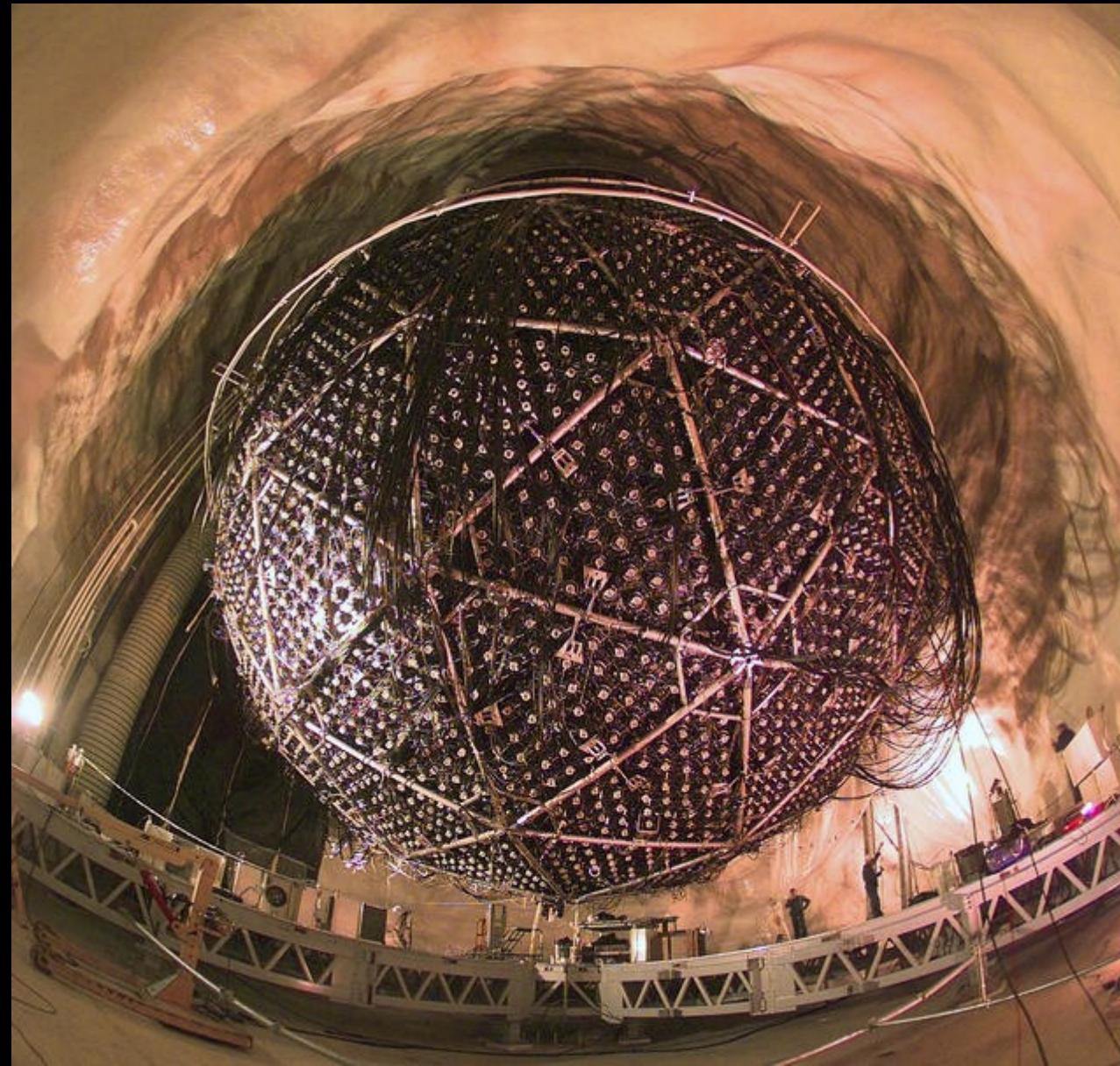


Super-Kamiokande

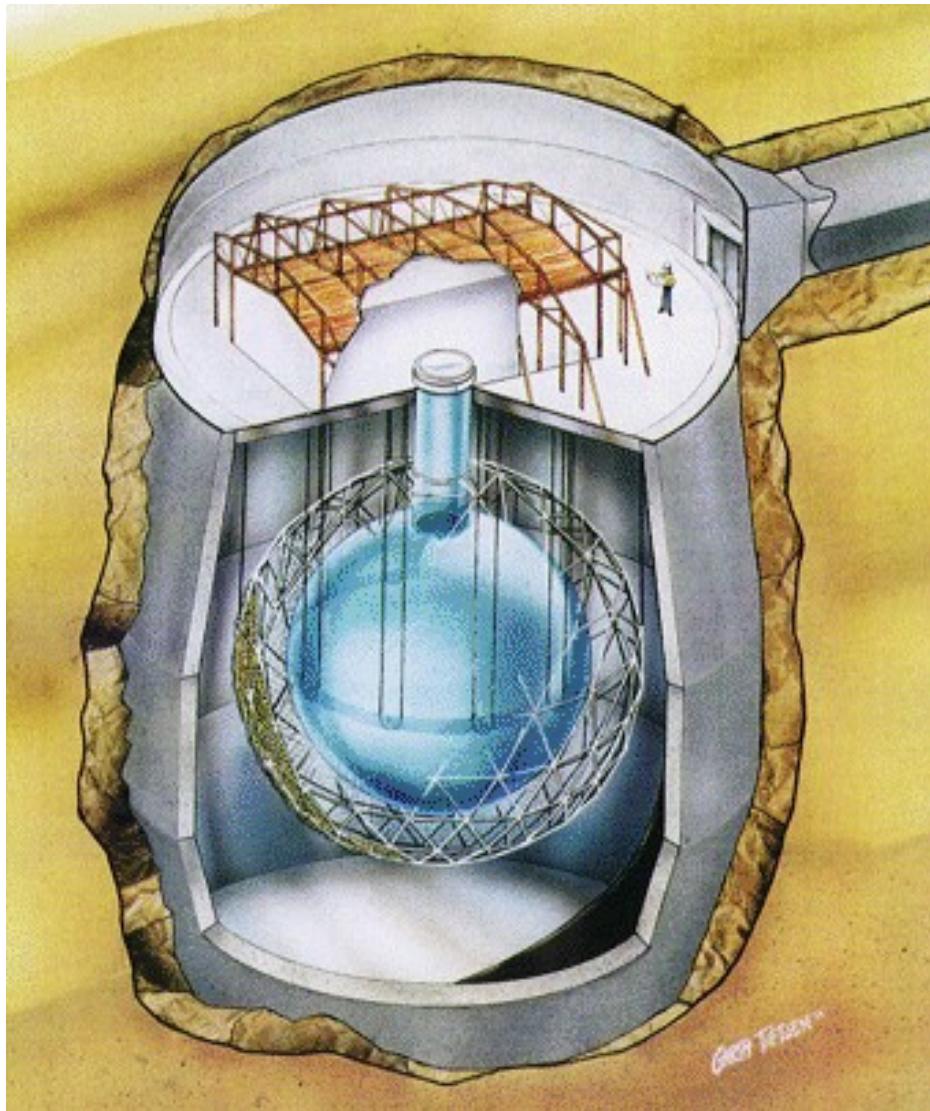
- **NEUTRINOGRAPHY** of the Sun. 500 days exposure!



SNO (1999 - 2006)



SNO



- Detection of solar neutrinos using the reactions:
$$\nu_l + e^- \rightarrow \nu_l + e^- \quad (\text{ES})$$
$$\nu_e + D \rightarrow e^- + p + p \quad (\text{CC})$$
$$\nu_l + D \rightarrow \nu_l + p + n \quad (\text{NC})$$
- Heavy Water Cherenkov detector.
- Ratio of observed to predicted:

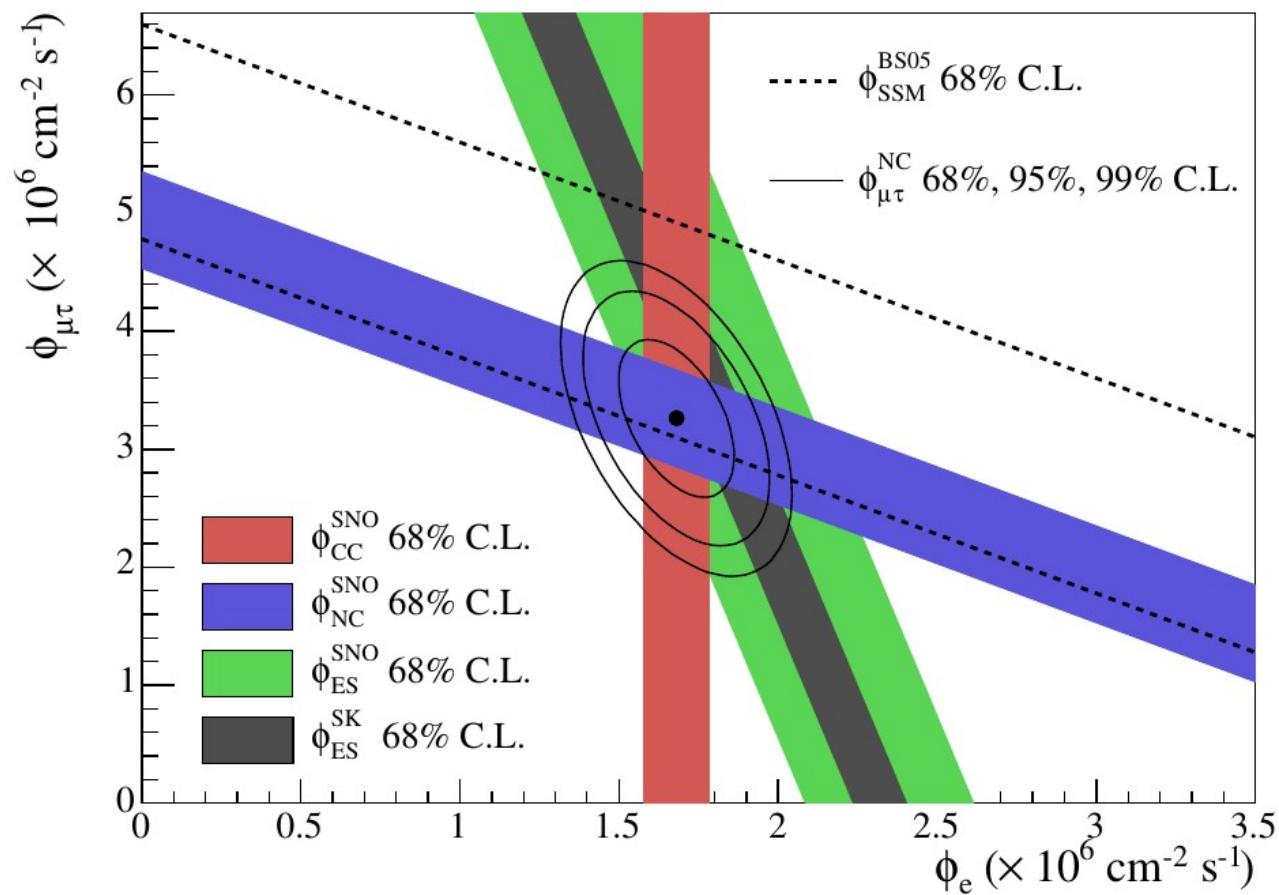
$$\frac{\Phi_{\text{SNO}}^{\text{ES}}}{\Phi_{\text{SSM}}} = 0.406 \pm 0.046$$

$$\frac{\Phi_{\text{SNO}}^{\text{CC}}}{\Phi_{\text{SSM}}} = 0.290 \pm 0.017$$

$$\frac{\Phi_{\text{SNO}}^{\text{NC}}}{\Phi_{\text{SSM}}} = 0.853 \pm 0.075$$

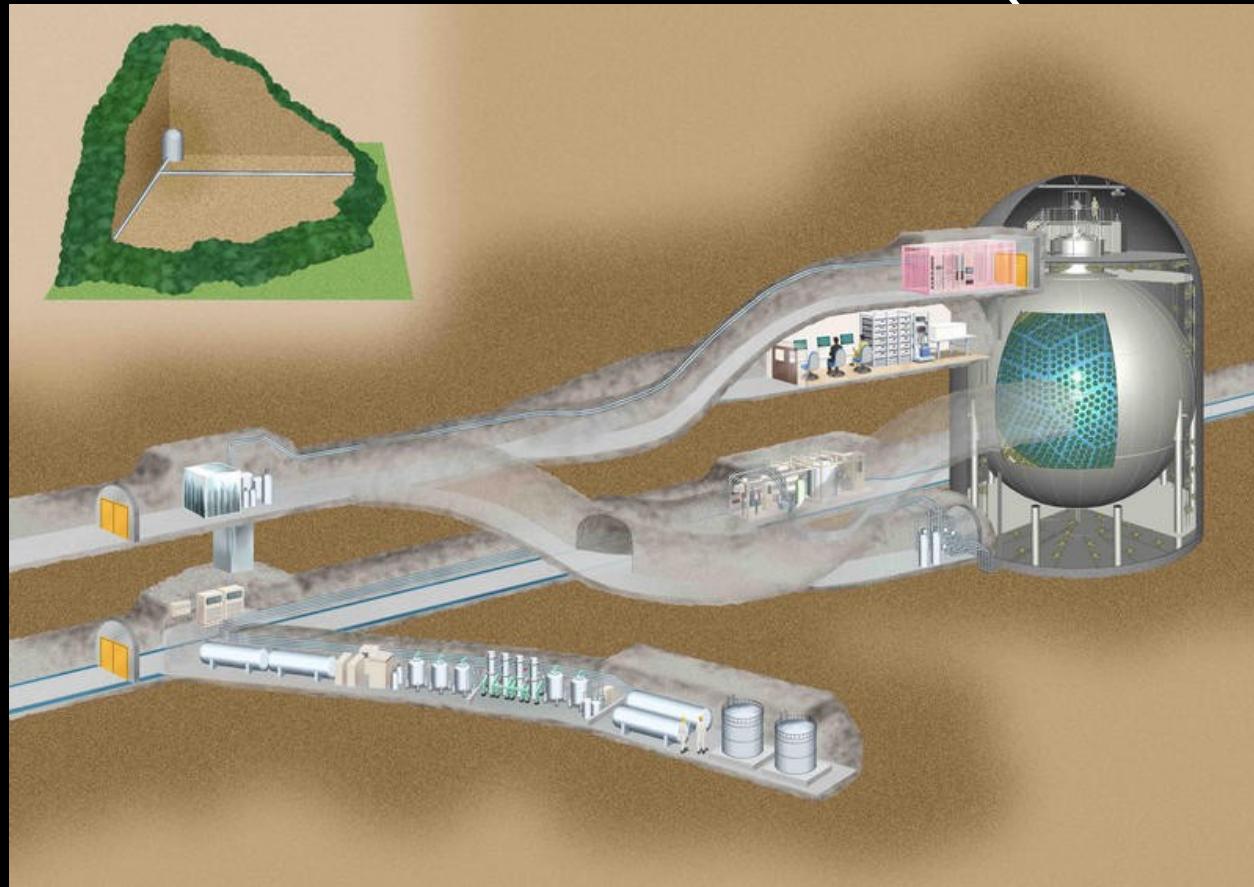
SNO

$$\begin{aligned}
 \Phi_{\text{SNO}}^{\nu_e} + r^{\text{ES}} \Phi_{\text{SNO}}^{\nu_{\mu, \tau}} &= \Phi_{\text{SNO}}^{\text{ES}} & r^{\text{ES}} \equiv \sigma_{\nu_{\mu, \tau}}^{\text{ES}} / \sigma_{\nu_e}^{\text{ES}} \approx 0.1553 \\
 \Phi_{\text{SNO}}^{\nu_e} &= \Phi_{\text{SNO}}^{\text{CC}} \\
 \Phi_{\text{SNO}}^{\nu_e} + \Phi_{\text{SNO}}^{\nu_{\mu, \tau}} &= \Phi_{\text{SNO}}^{\text{NC}}
 \end{aligned}$$



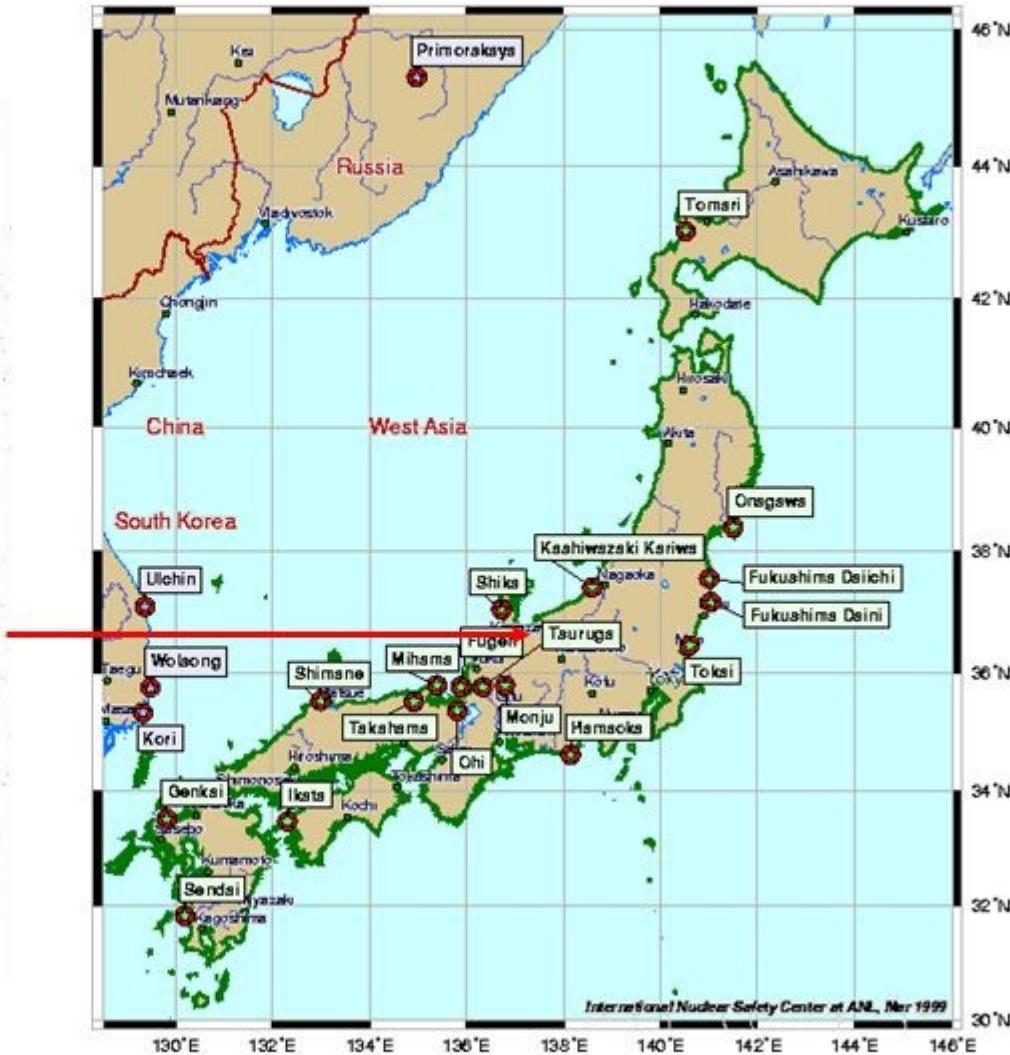
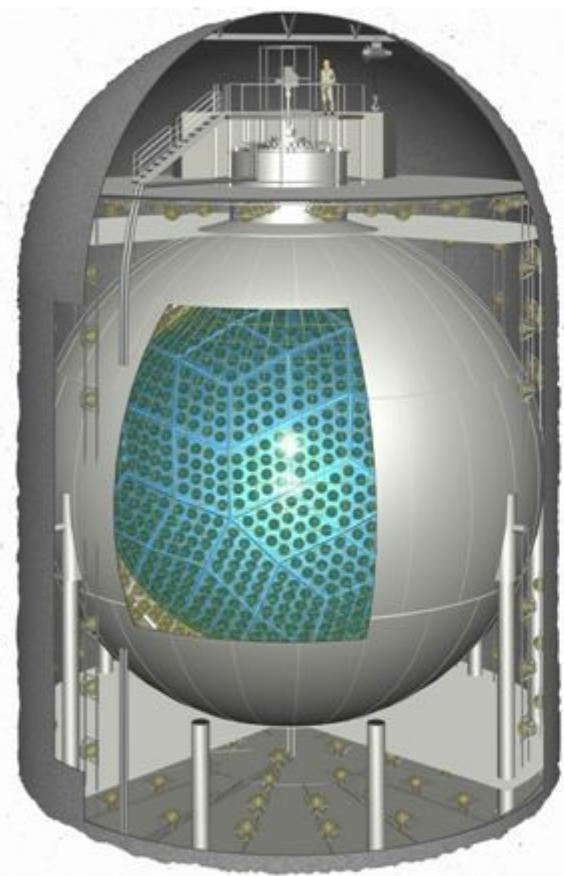
Additional material

KamLAND (2002 - 2011)





KamLAND

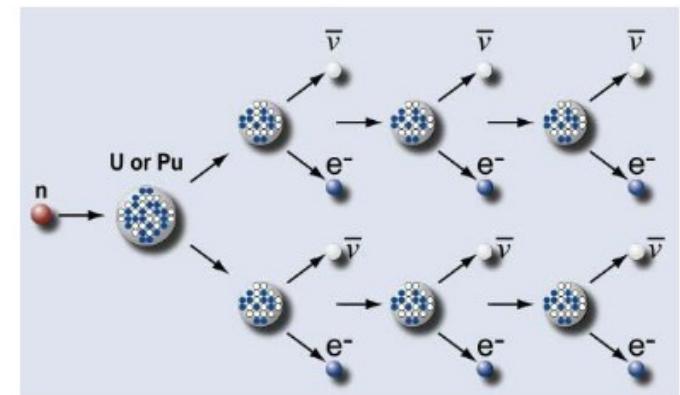


$\bar{\nu}_e$ production at nuclear reactors

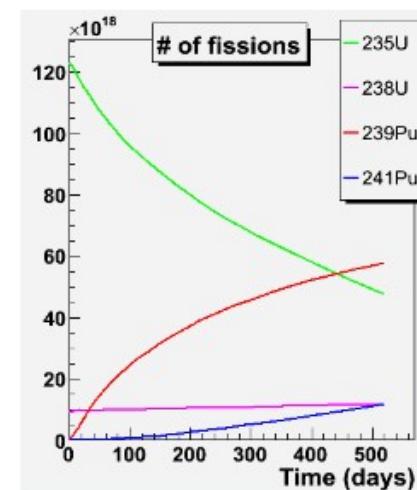
- Fission of nuclear fuel (^{235}U , ^{238}U , ^{239}Pu , ^{241}Pu) produces neutron rich fission products.
- β^- decay of fission products:



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

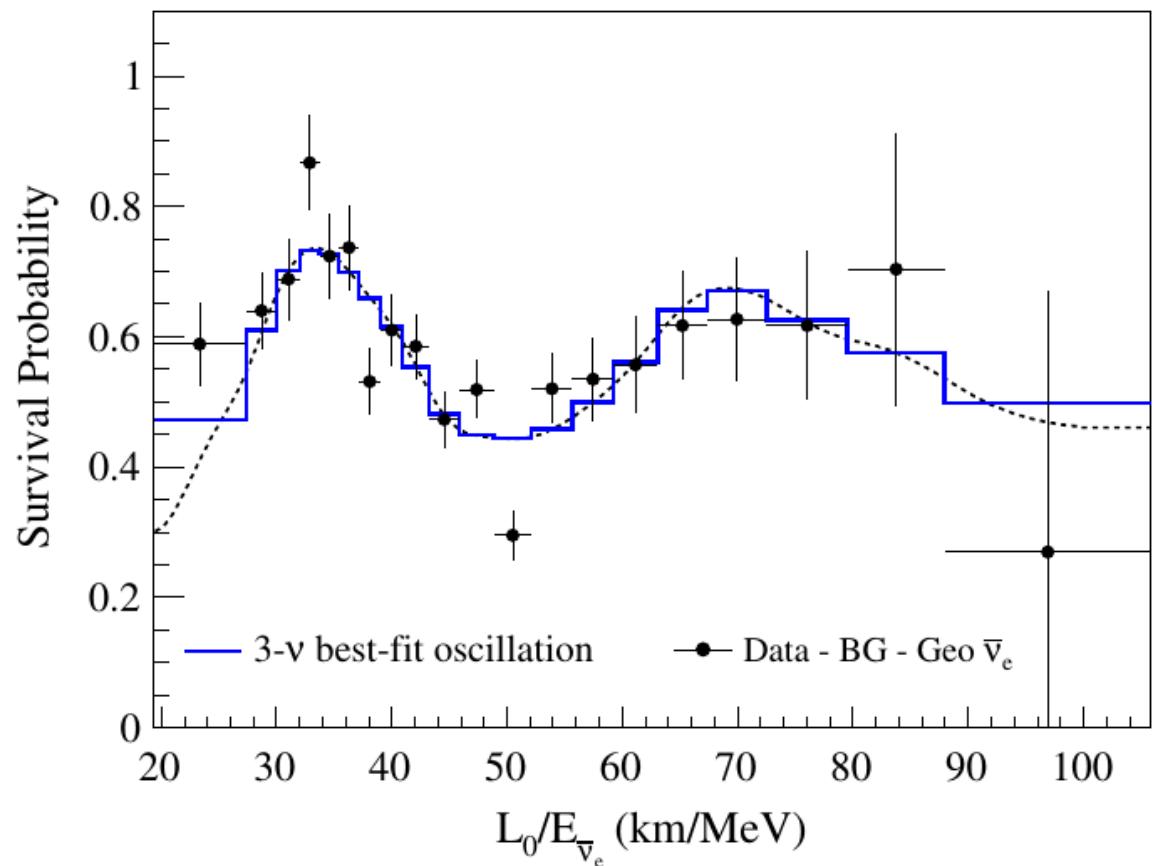
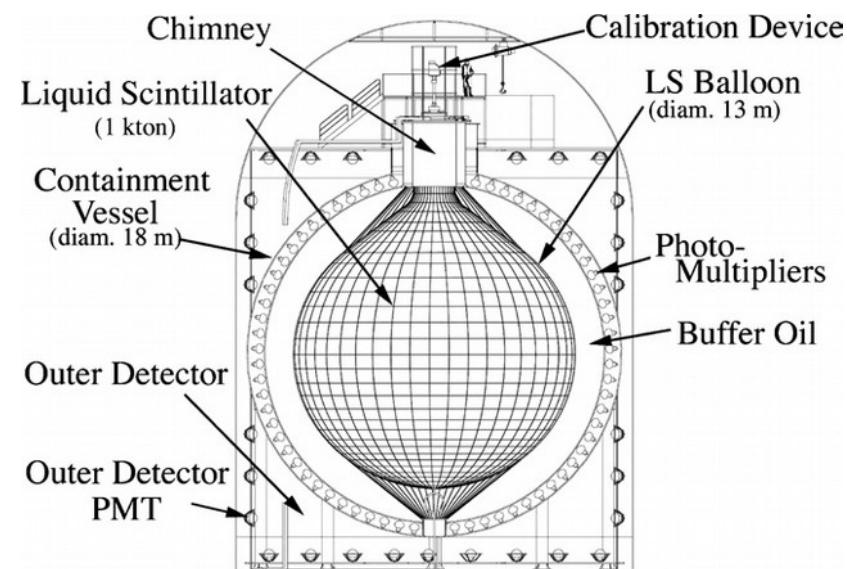


- Nuclear power plants: greatest man-made antineutrino source.
- Need to consider nuclear fuel evolution.

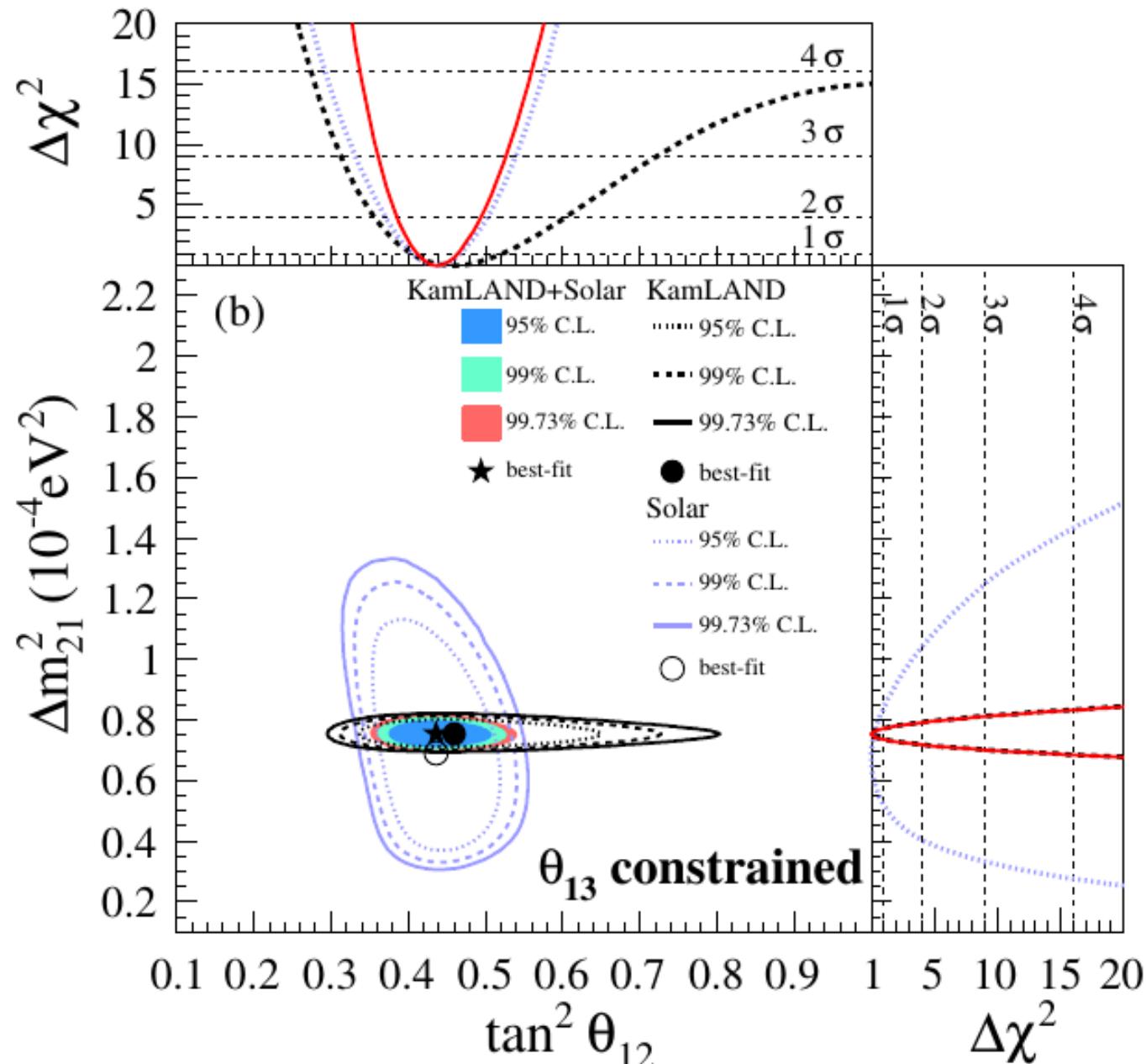


KamLAND

- Detection of reactor neutrinos using the inverse beta-decay reaction:
$$\bar{\nu}_e + p \rightarrow e^+ + n$$
- Liquid scintillator detector.

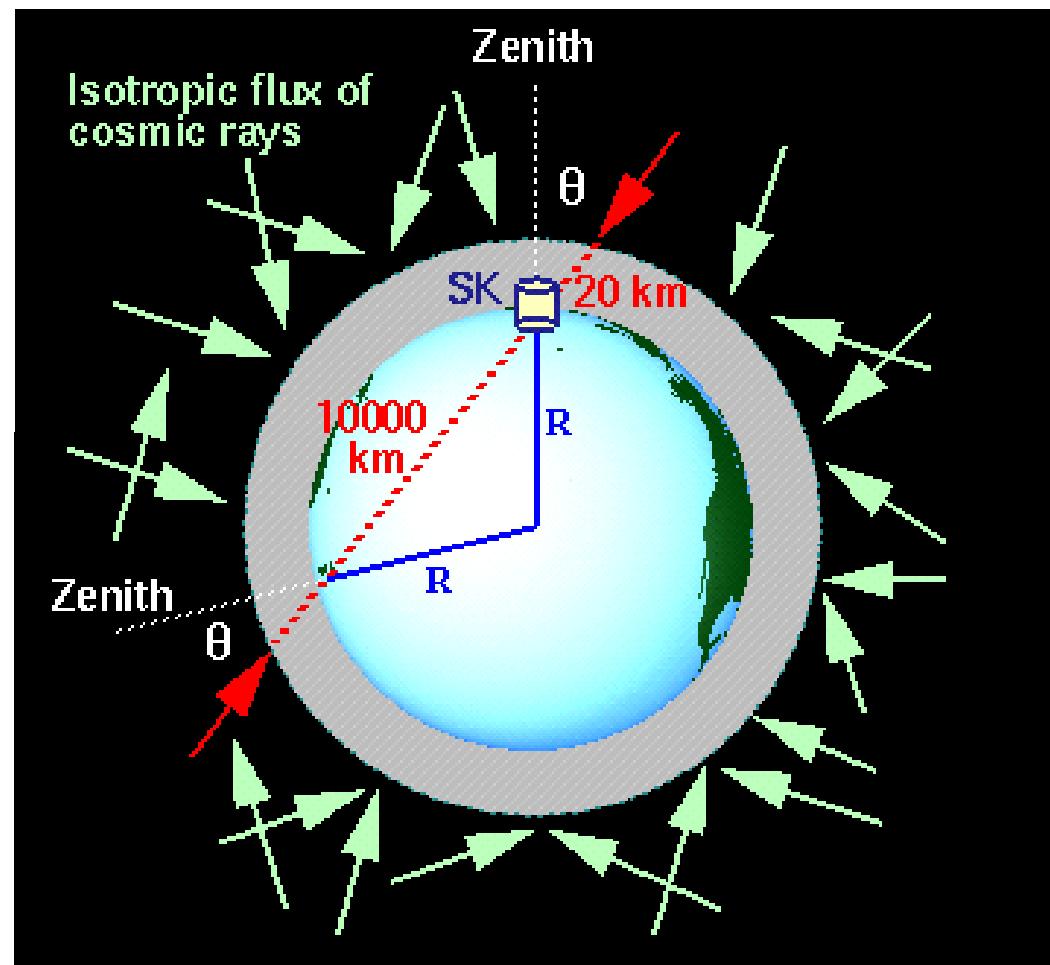
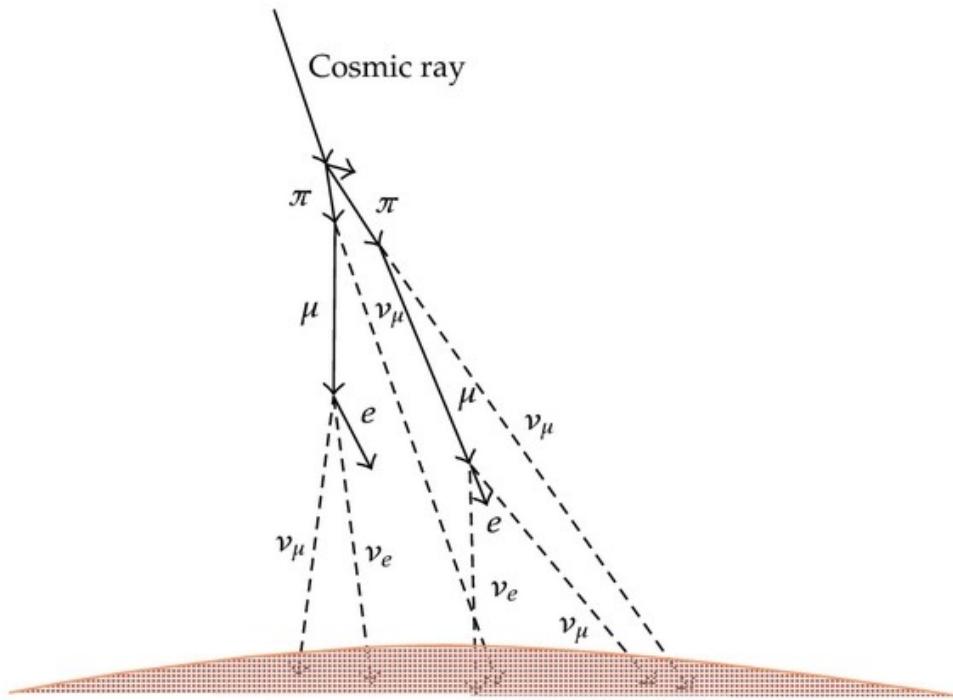


Solar + KamLAND results

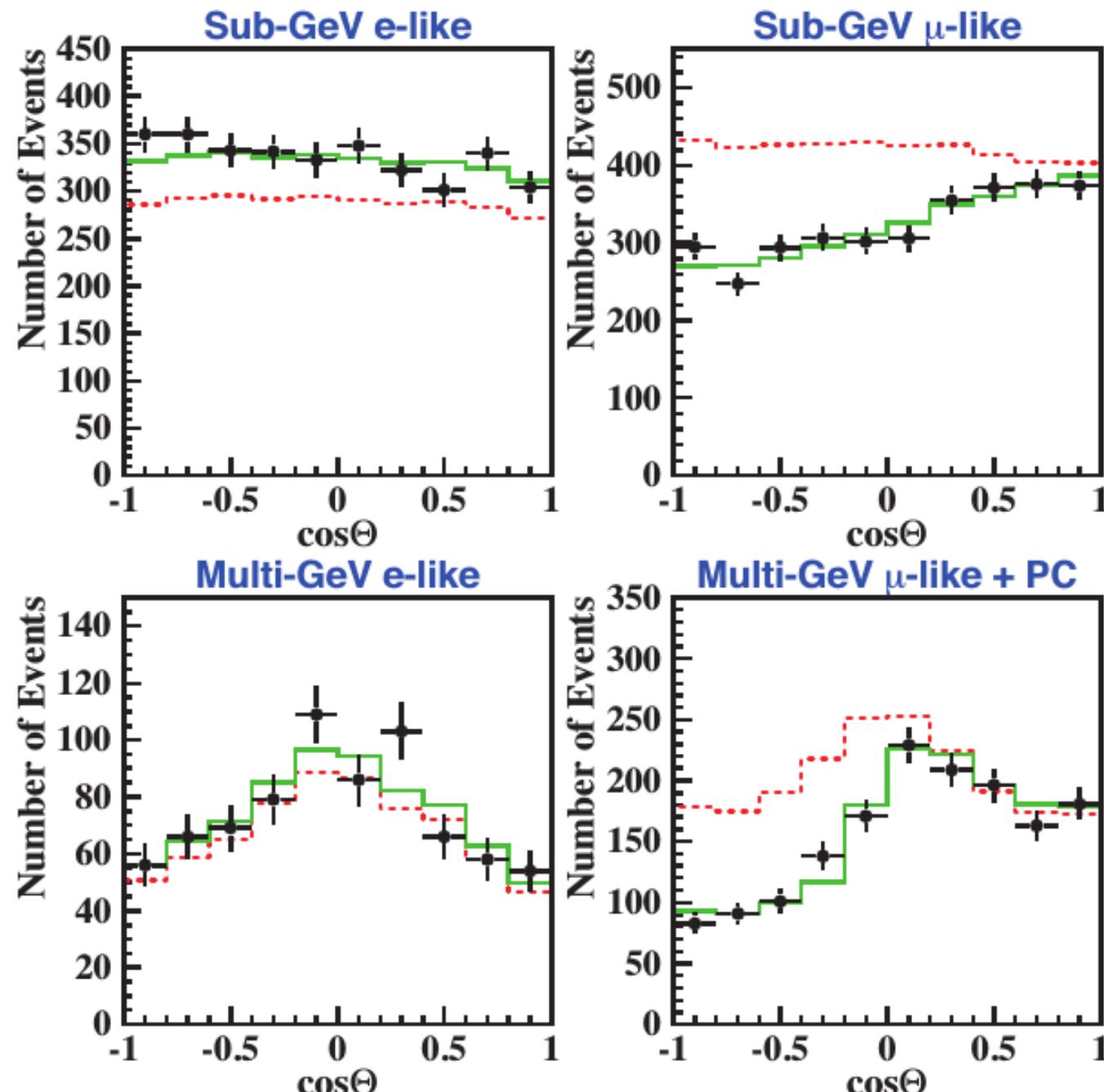
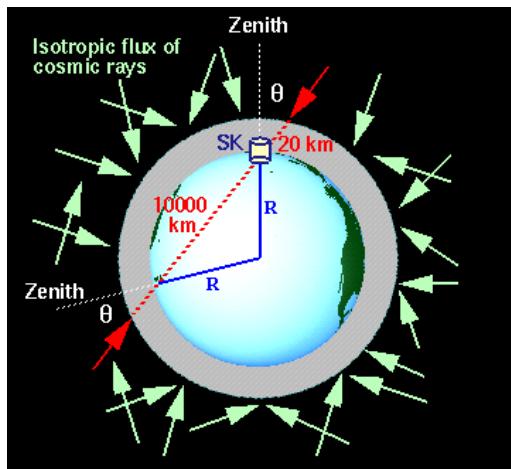


Measurement of θ_{23} and Δm^2_{atm}

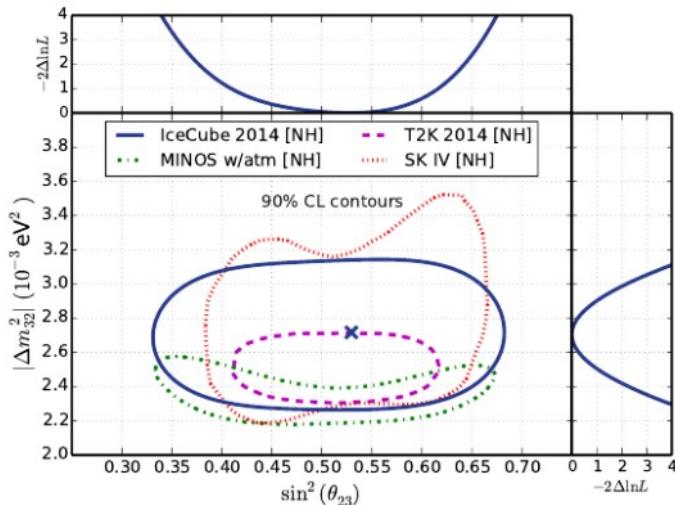
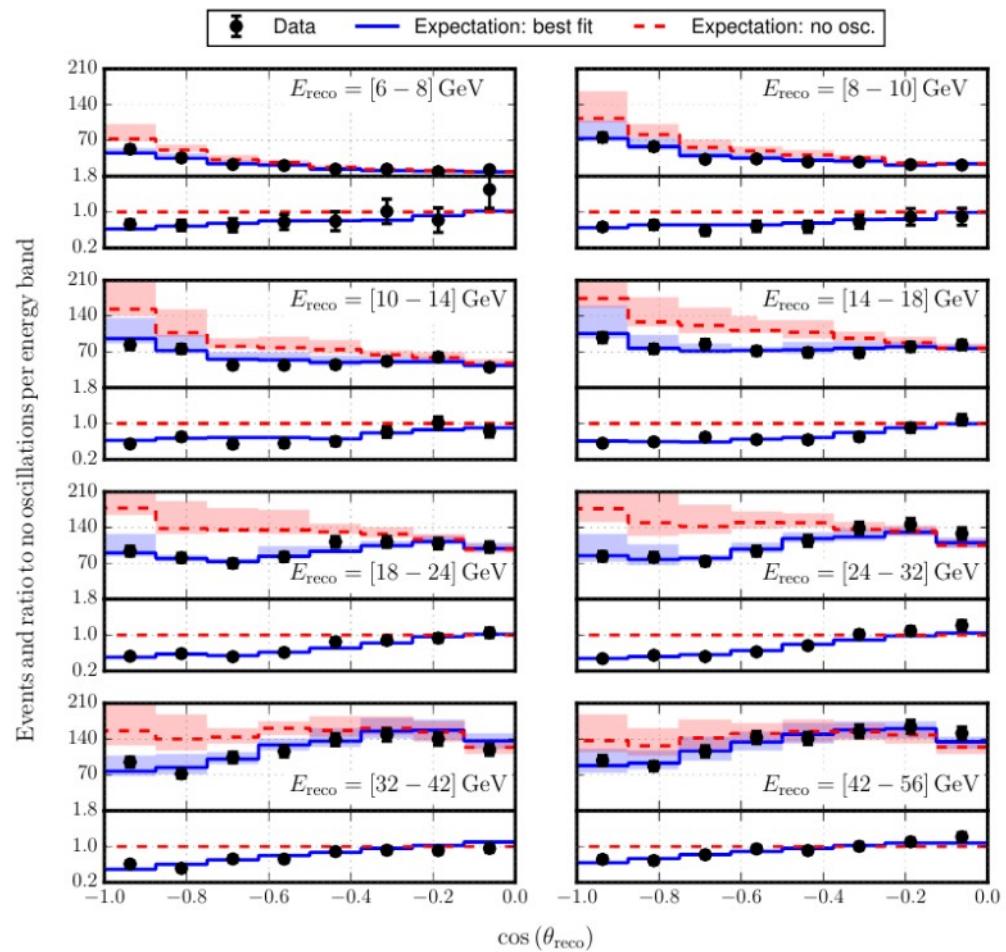
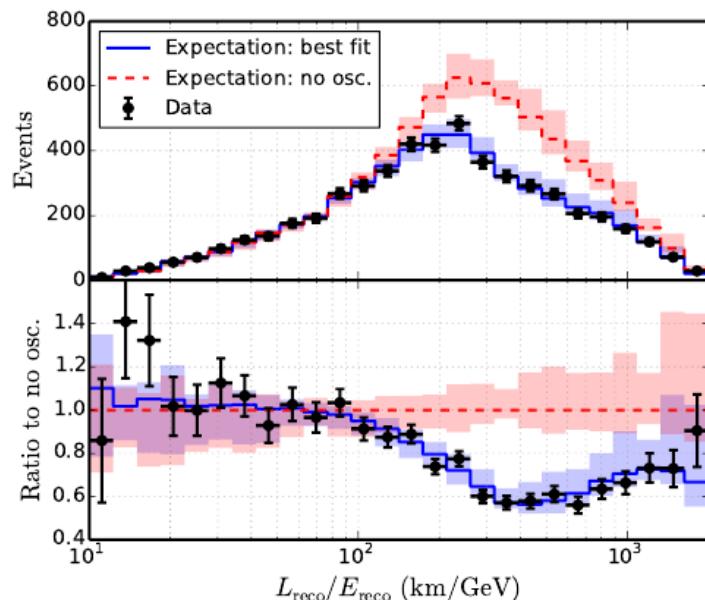
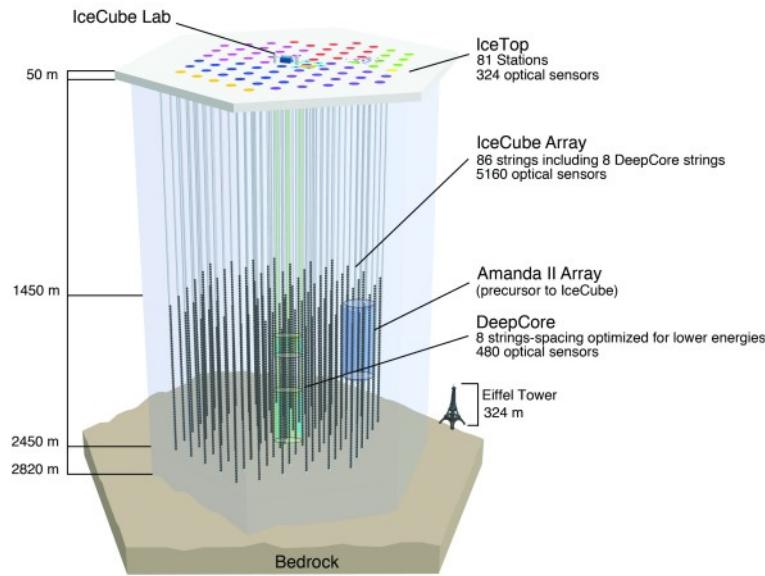
Atmospheric neutrinos



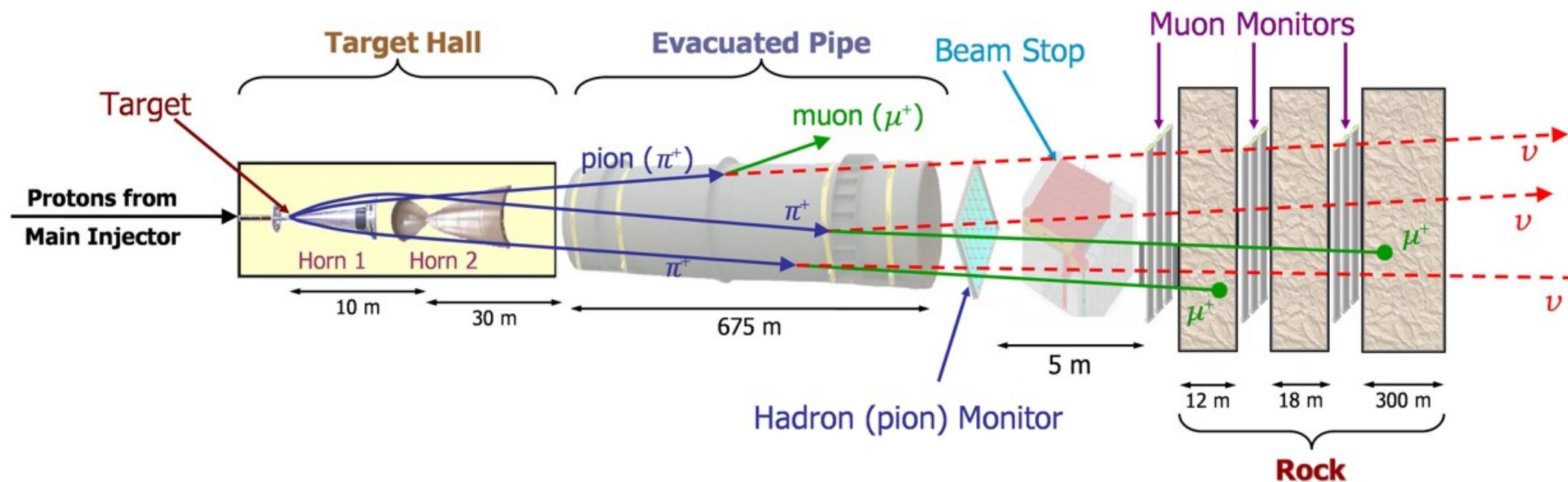
Super-Kamiokande results



IceCube

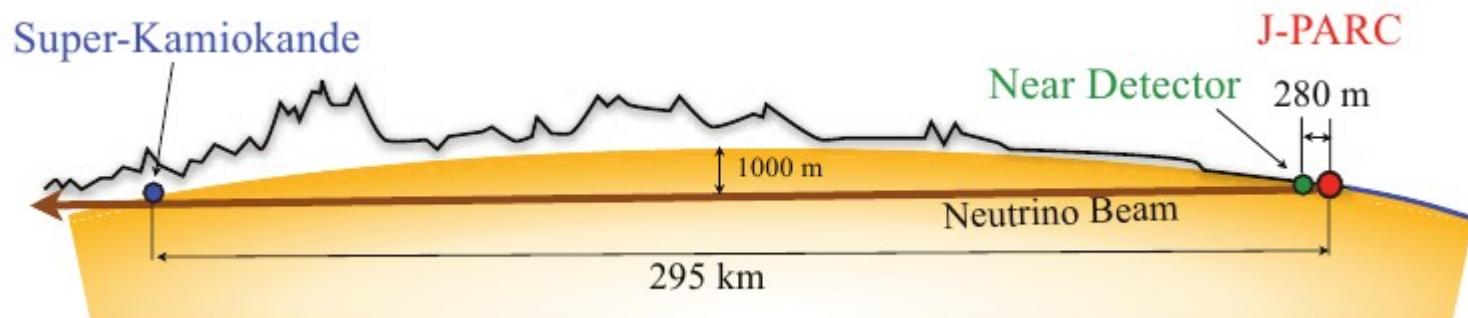


Accelerator neutrinos

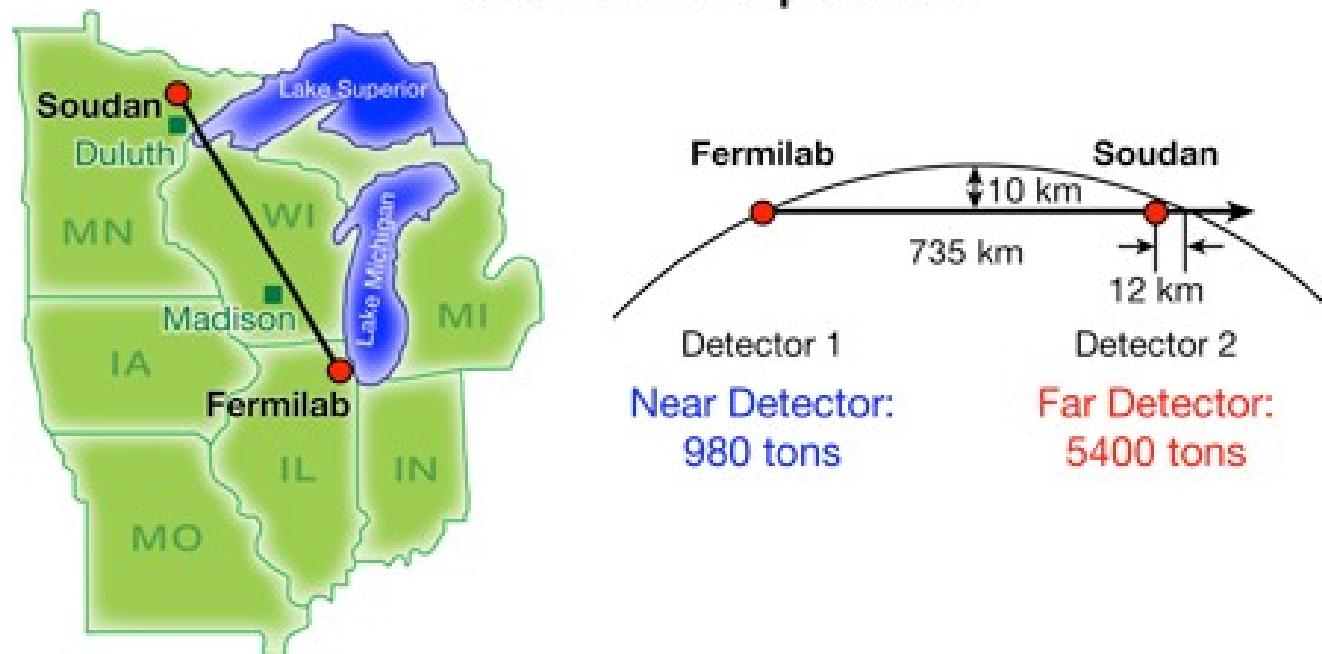


https://www.youtube.com/watch?v=U_xWDWKq1CM

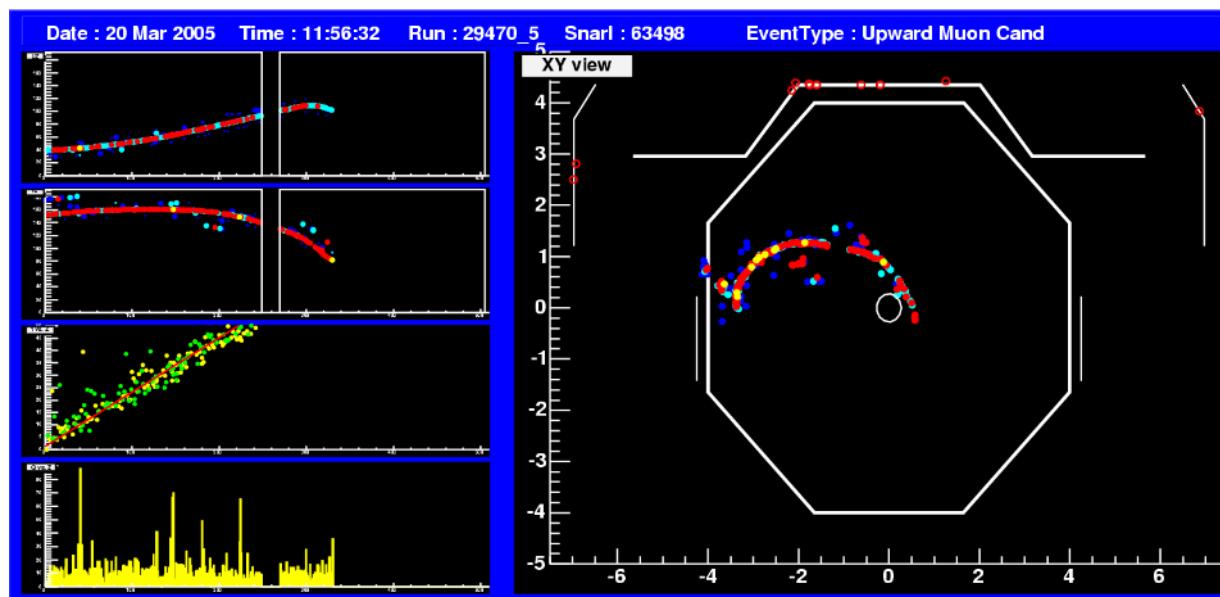
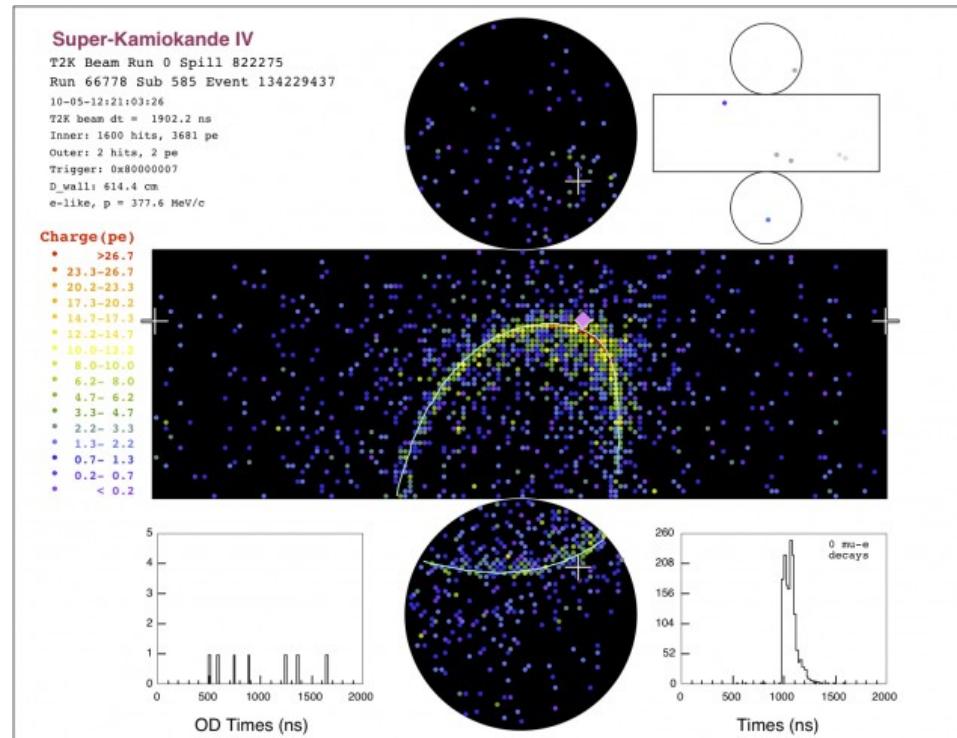
T2K & MINOS experiments



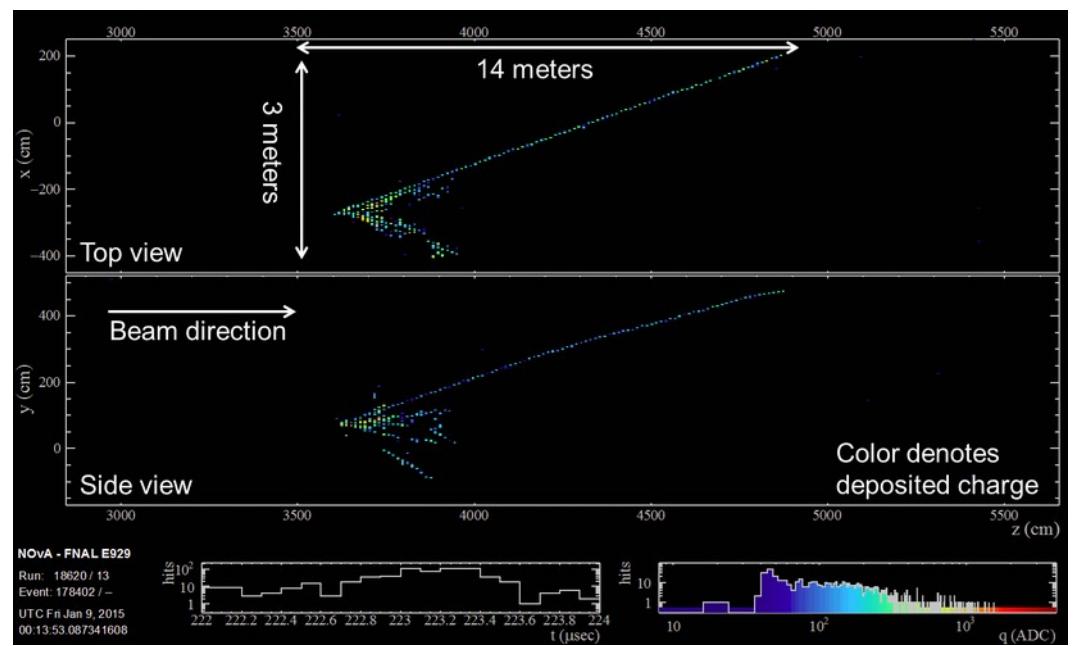
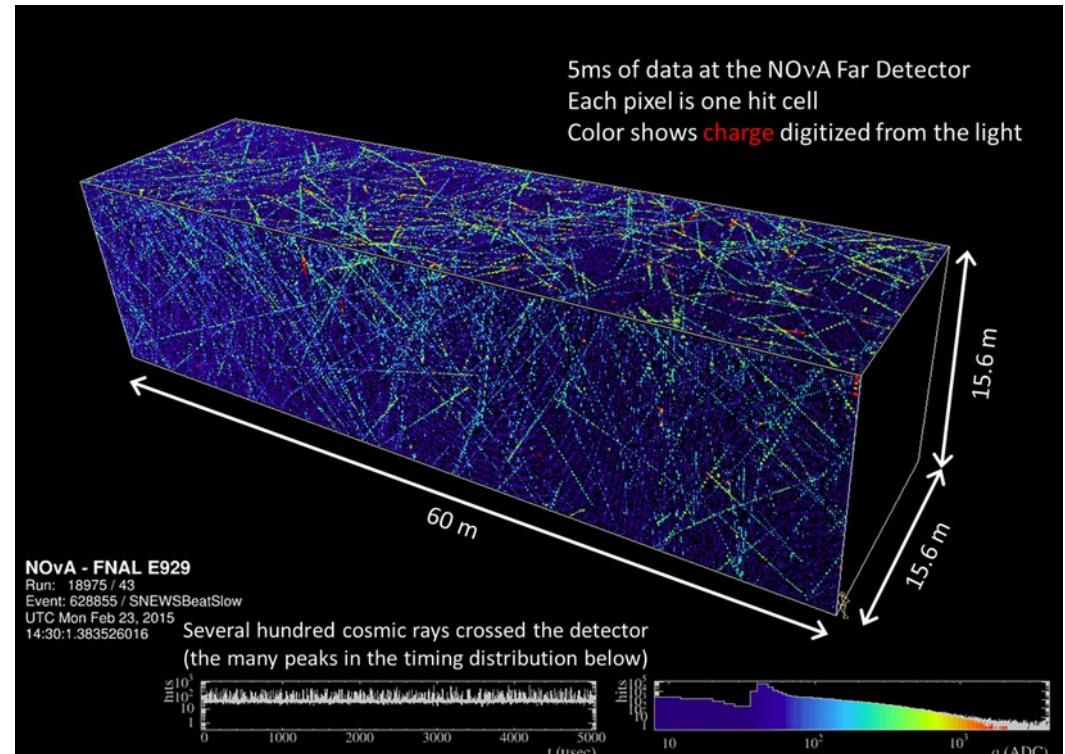
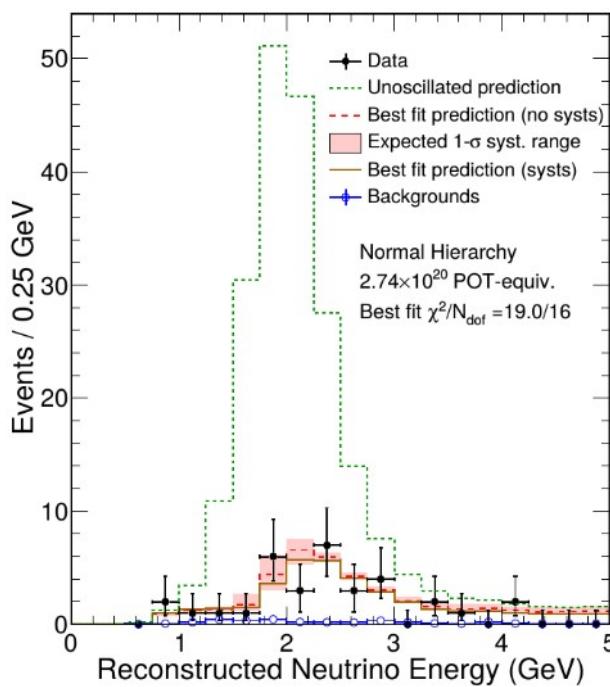
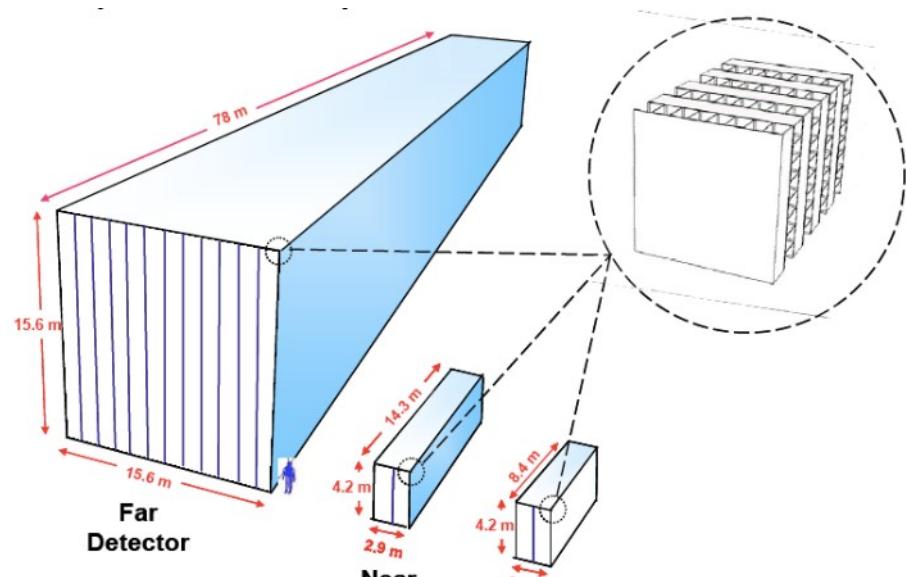
The MINOS Experiment



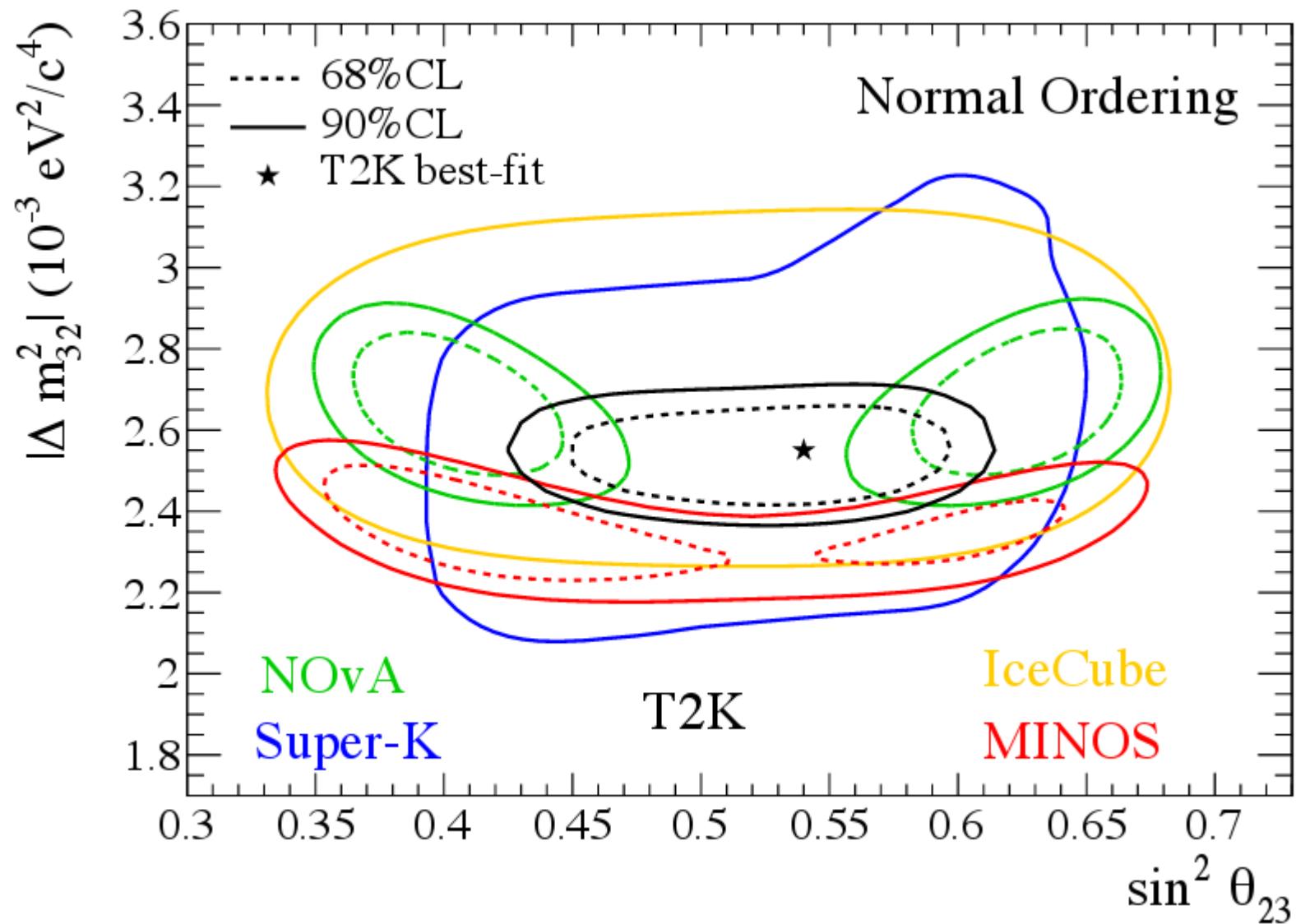
T2K & MINOS experiments



NOvA

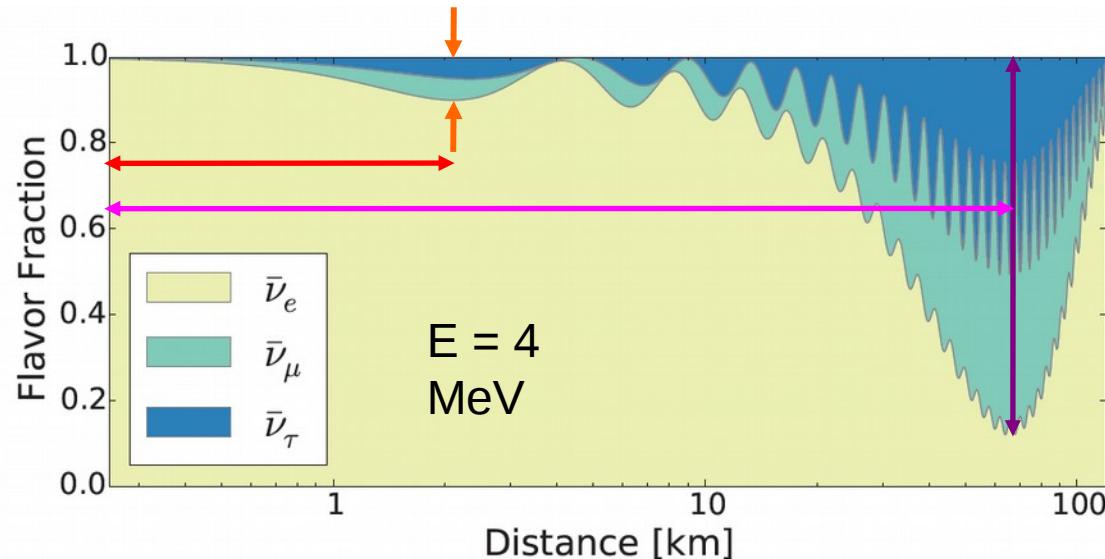


SK (atm), T2K, MINOS, IceCube (atm), NOvA



Measurement of θ_{13}

Measurement of θ_{13} with reactors



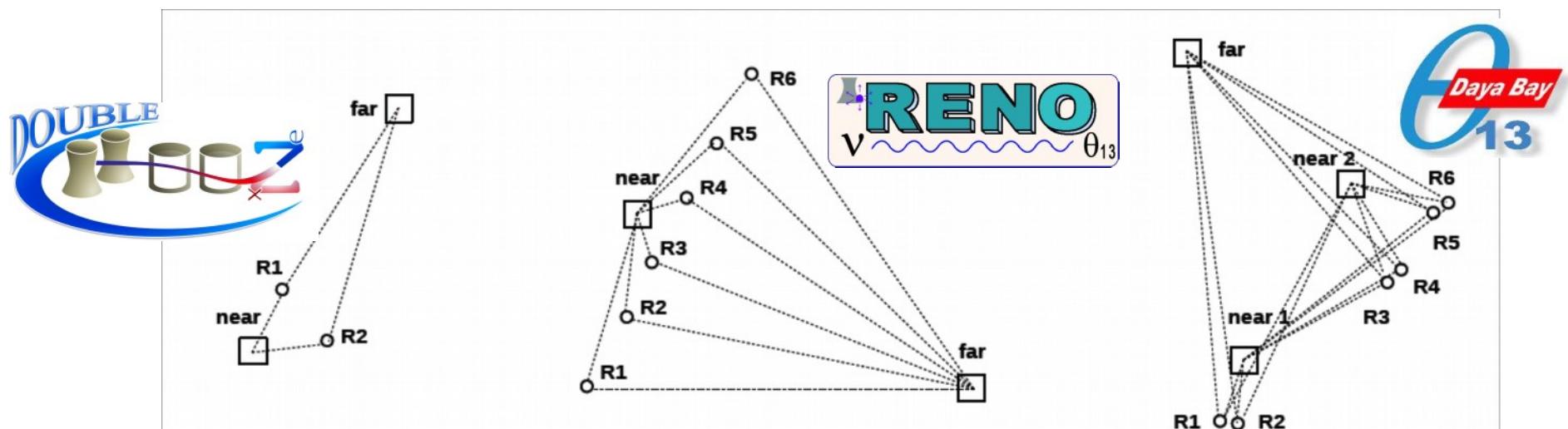
$$\begin{aligned}
 P_{ee}(L, E) &= \\
 &= 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m^2_2 L}{4E}\right) \\
 &\quad - \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_3 L}{4E}\right) \\
 &\quad - \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)
 \end{aligned}$$

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

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

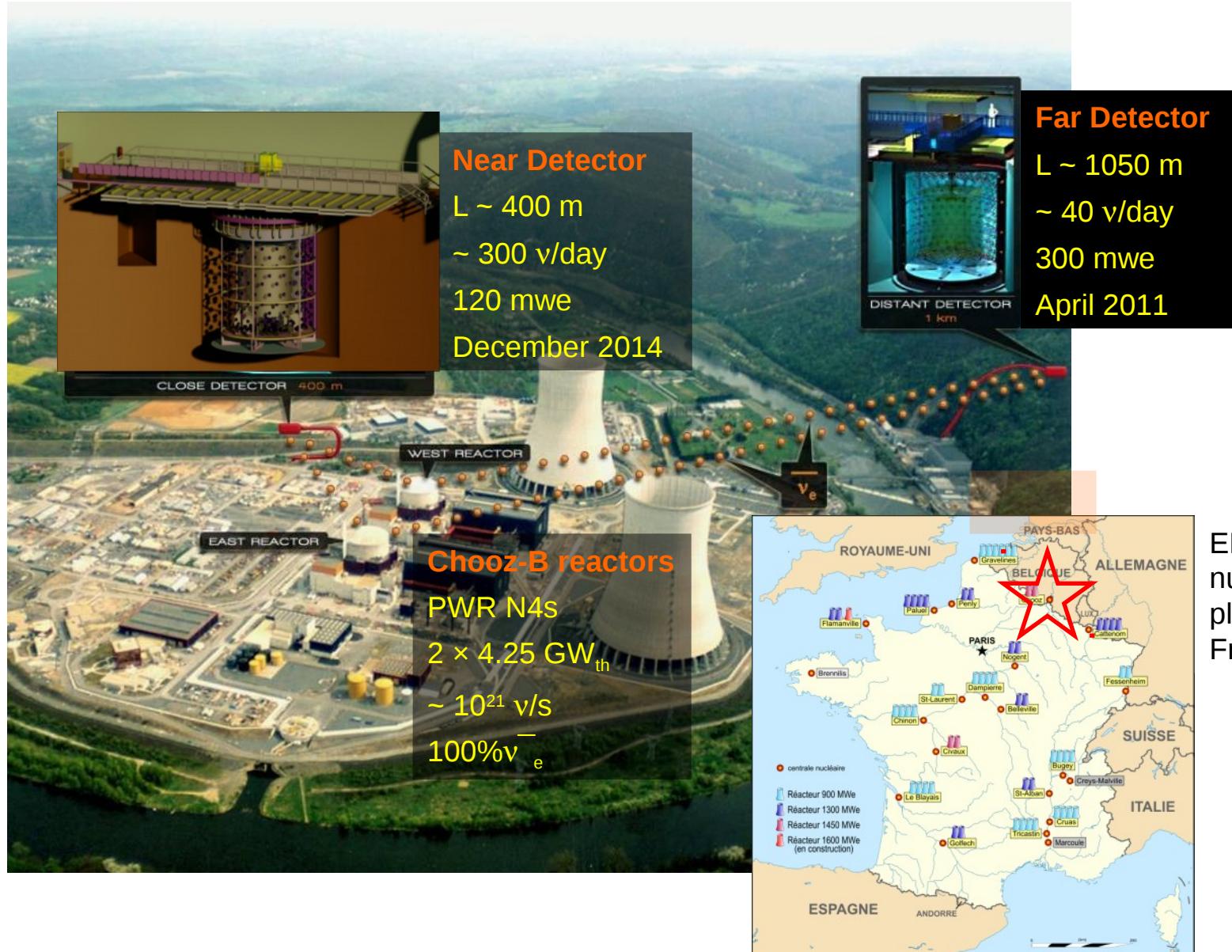
Measurement of θ_{13} with two-detector reactor experiments

- Antineutrinos detected by inverse β -decay:
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) \times 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



Electron antineutrino detection

Inverse Beta Decay (IBD):

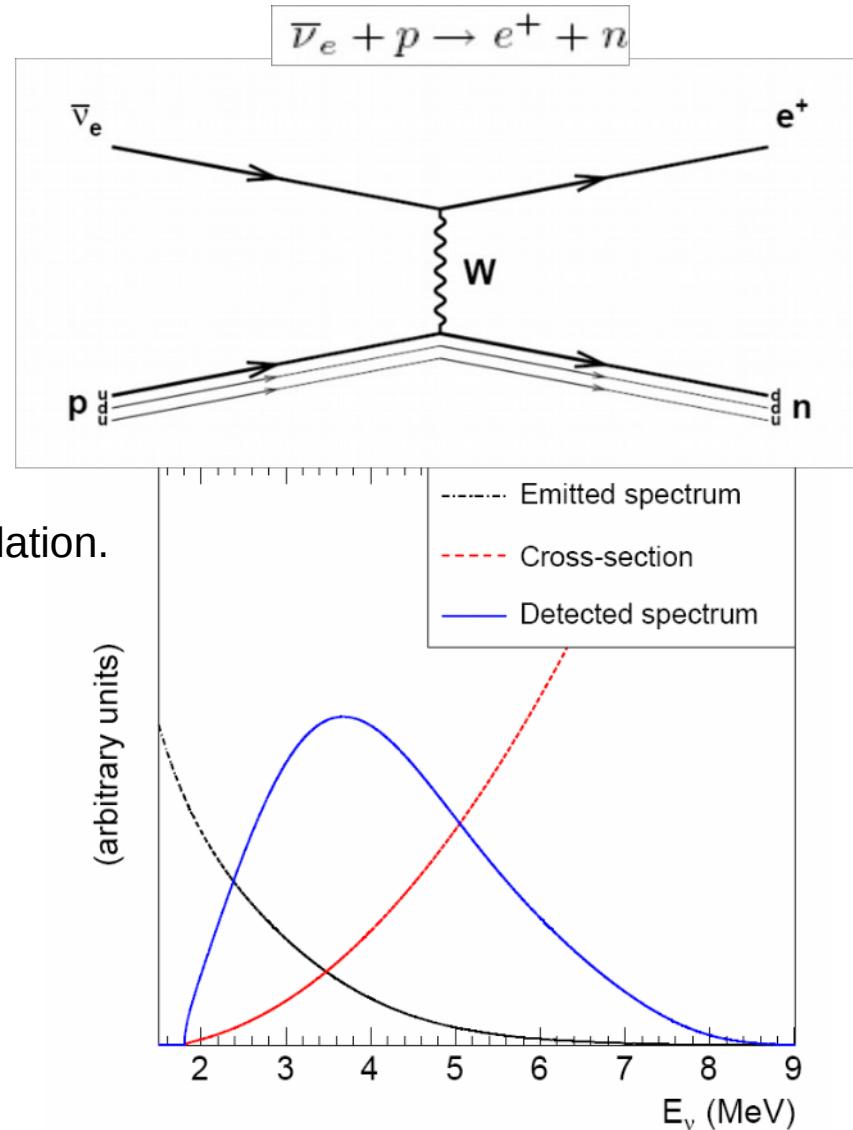
- Reaction threshold: $E_\nu \geq 1.806$ MeV.
- Disappearance experiment.
- Well known cross-section (0.2%).
- Coincidence of 2 signals: background suppression.

Prompt signal:

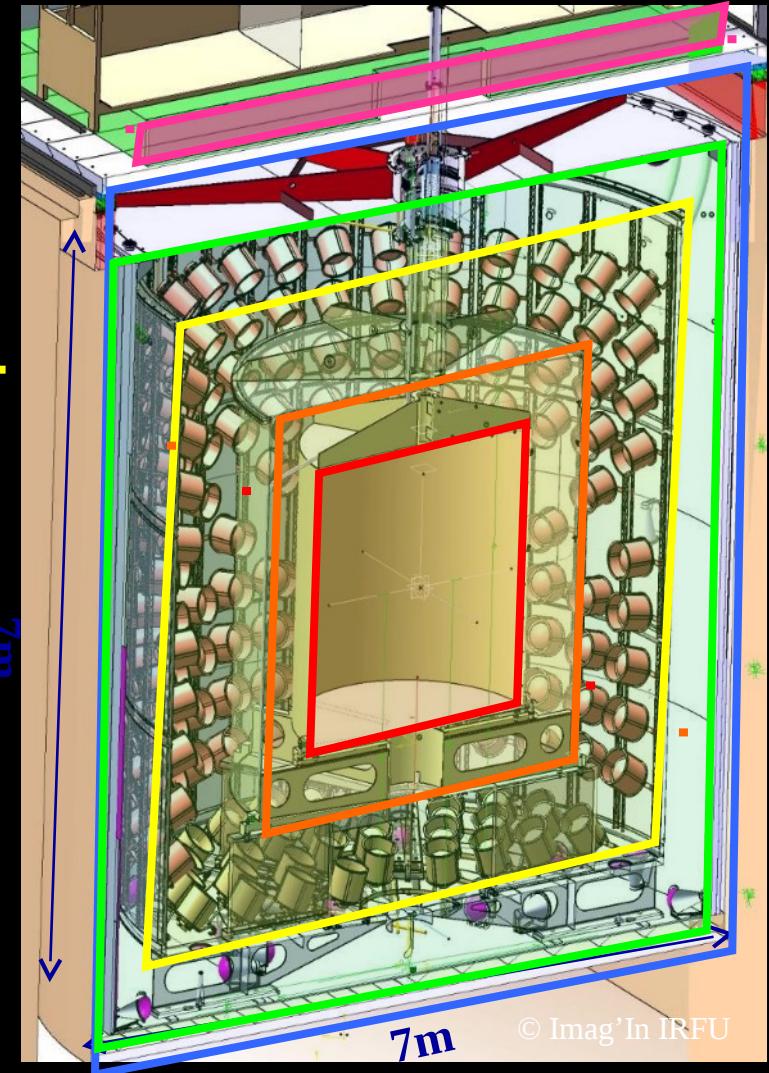
- Positron kinetic energy + γ 's from annihilation.
- $E_{\text{prompt}} \approx E_\nu - 0.782$ MeV
- $E_{\text{prompt}} \sim 1 - 9$ MeV

Delayed signal:

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

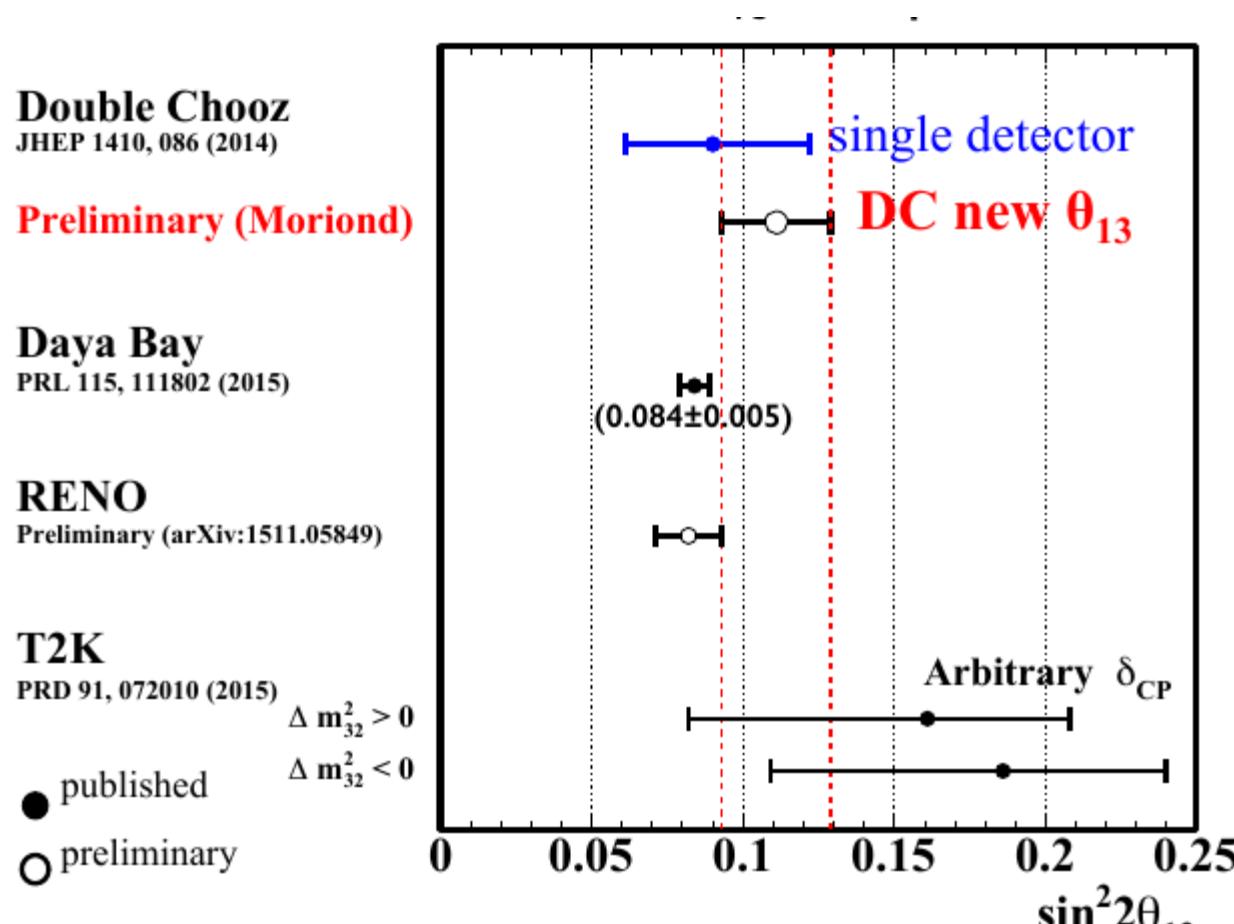
Outer Detector:

- **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.

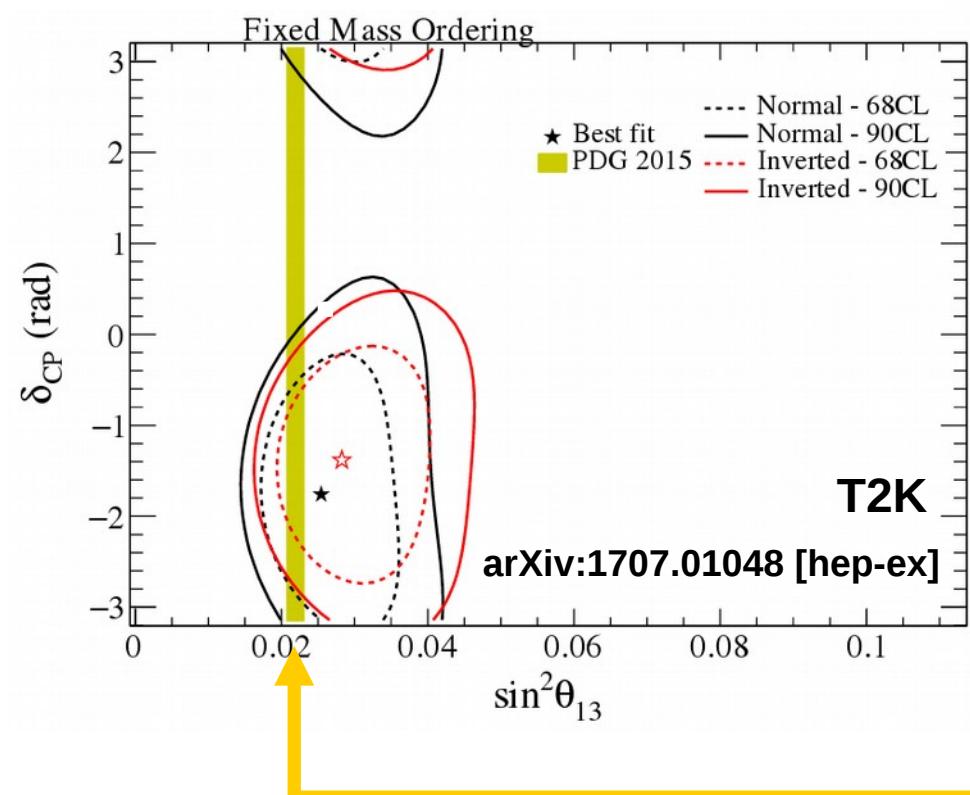


A. Cabrera, FNAL seminar 03/25/2016

First glimpse of δ

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

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



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

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

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

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

$$\begin{pmatrix} v_e \\ v_\mu \\ v_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13} e^{-i\delta} \\ -s_{13} e^{i\delta} & 1 & \\ & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix} \rightarrow \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix}$$

PMNS matrix: U

$c_{ij} = \cos \theta_{ij}$, $s_{ij} = \sin \theta_{ij}$
 $\Delta m_{jk}^2 \equiv m_j^2 - m_k^2$

Atmospheric &
 Long-baseline accelerator
 experiments

Reactor & Long-baseline
 accelerator experiments

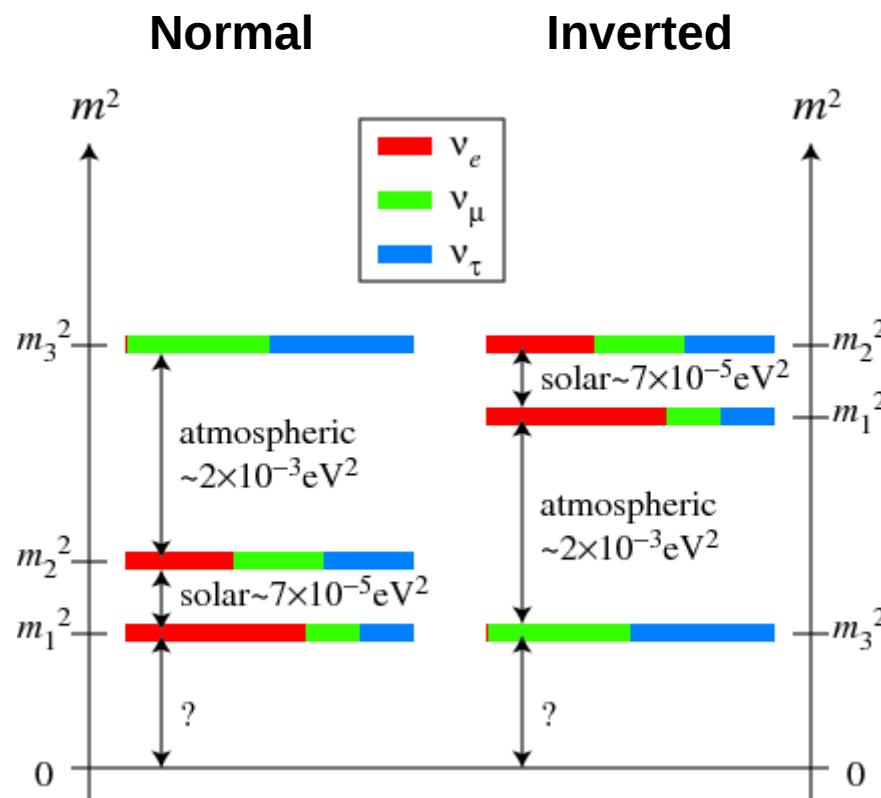
Solar &
 KamLAND
 experiments

- 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?

$$\begin{array}{c} U_{\text{CKM}} \\ \parallel \\ \begin{bmatrix} u & & \\ & c & \\ & & t \end{bmatrix} \begin{bmatrix} d & s & b \end{bmatrix} \end{array} \quad \begin{array}{c} U_{\text{PMNS}} \\ \parallel \\ \begin{bmatrix} v_e & & \\ v_\mu & & \\ v_\tau & & \end{bmatrix} \begin{bmatrix} v_1 & v_2 & v_3 \end{bmatrix} \end{array}$$

3 neutrinos: mass ordering

- 3 mass eigenstates \rightarrow **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:



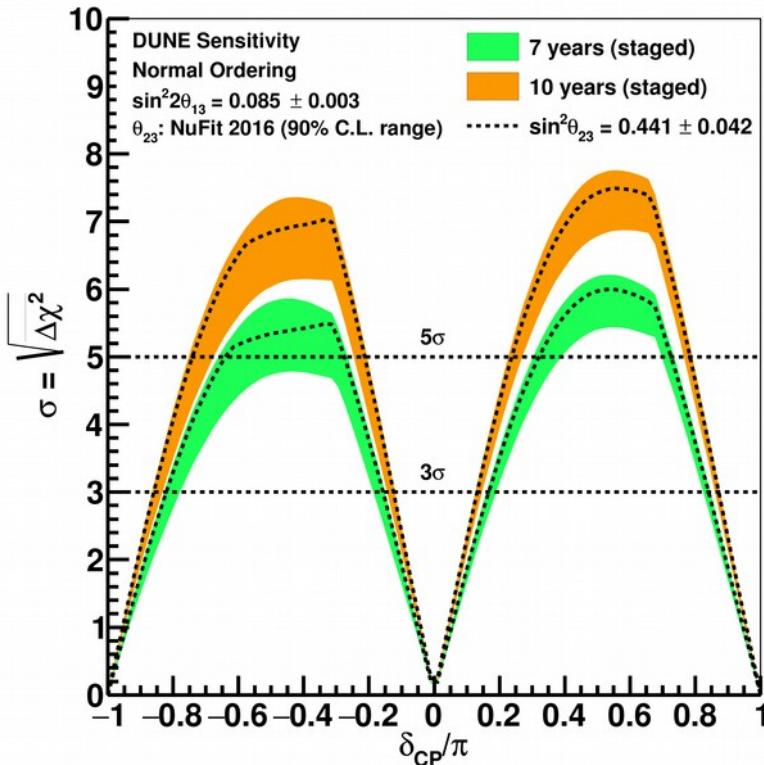
Future: δ and mass hierarchy

- 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.

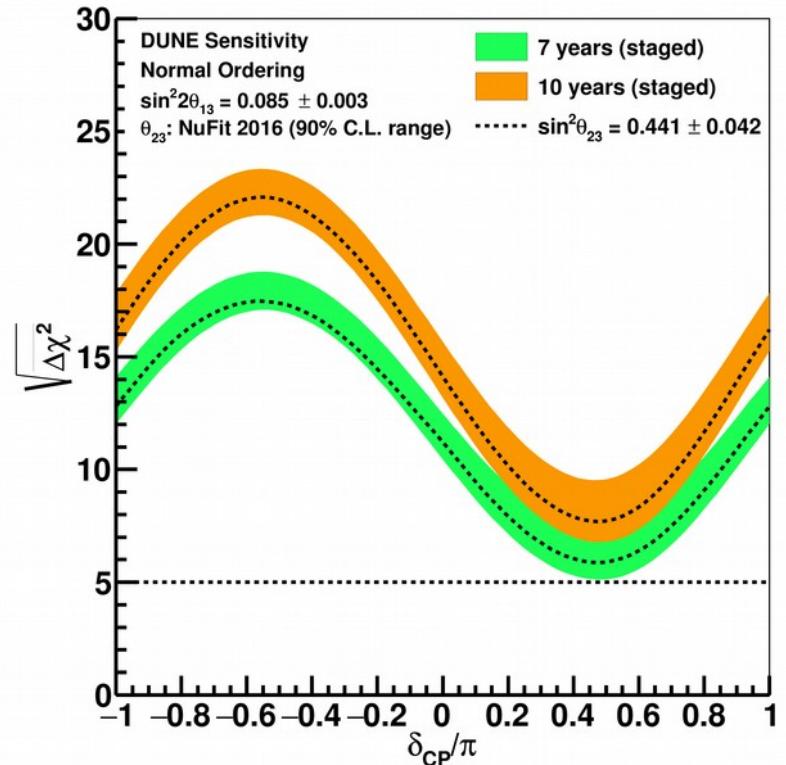


Neutrino beam expected by 2026.

CP Violation Sensitivity

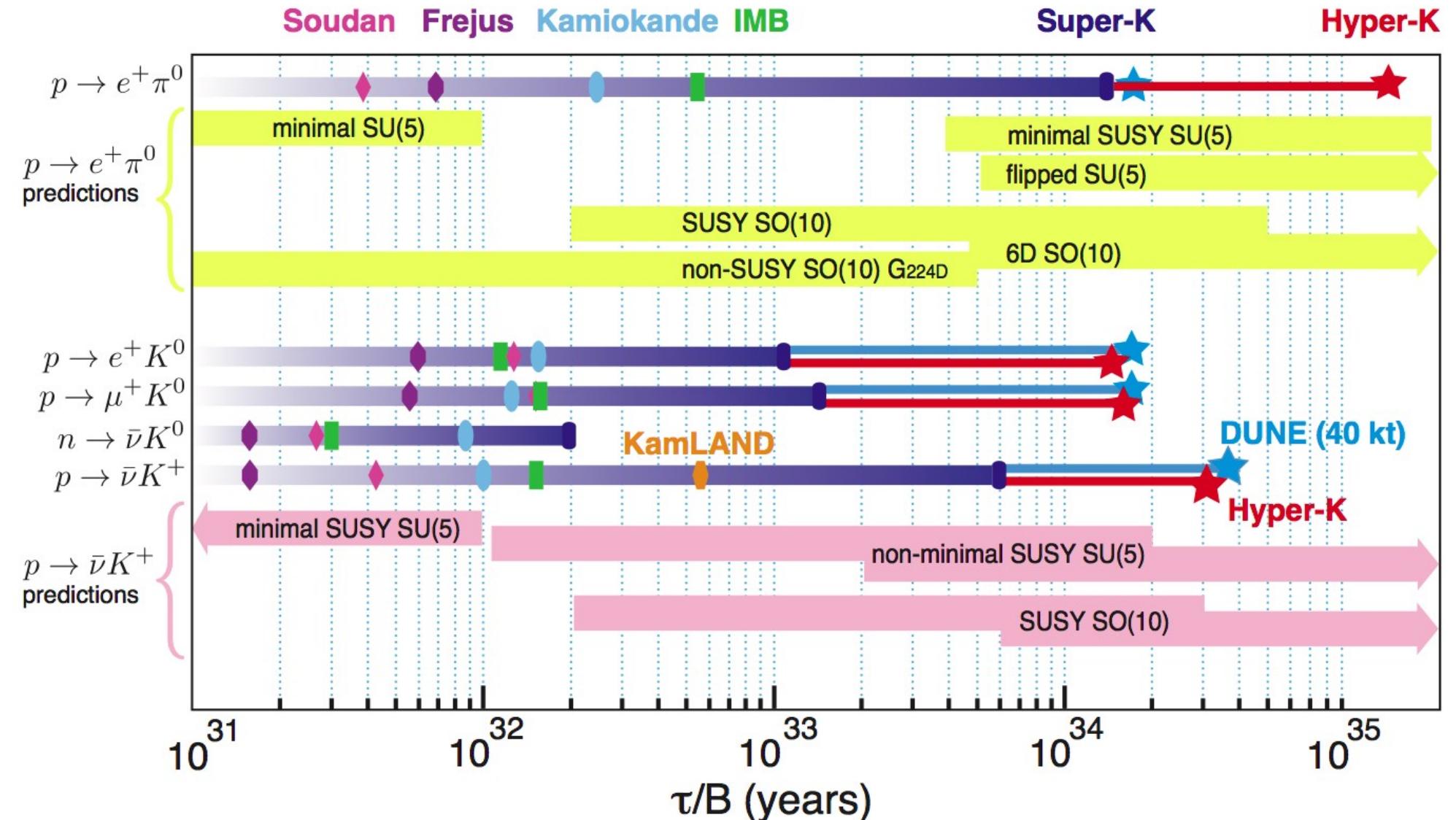


Mass Hierarchy Sensitivity



- > 5 σ measurement of CP-violating phase if CP violation is close to maximal.
 - > 3 σ measurement for 65% of δ range.
- > 5 σ 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

