

# 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](mailto: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	<del>The Standard Model Overview</del>	Cris
	10	<del>The Standard Model Limitations</del>	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 →	2.4 MeV	1.27 GeV	171.2 GeV
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
name →	u up	c charm	t top
	Left Right	Left Right	Left Right
	d down	s strange	b bottom
	Left Right	Left Right	Left Right
	$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	$\nu_\tau$ tau neutrino
	Left Right	Left Right	Left Right
	e electron	$\mu$ muon	$\tau$ tau
	Left Right	Left Right	Left Right
	0.511 MeV	105.7 MeV	1.777 GeV
	-1	-1	-1

0	0	g gluon
0	0	$\gamma$ photon
91.2 GeV	0	Z <sup>0</sup> weak force
80.4 GeV	$\pm 1$	W <sup>±</sup> weak force

Bosons (Forces) spin 1

- Only weak interaction.

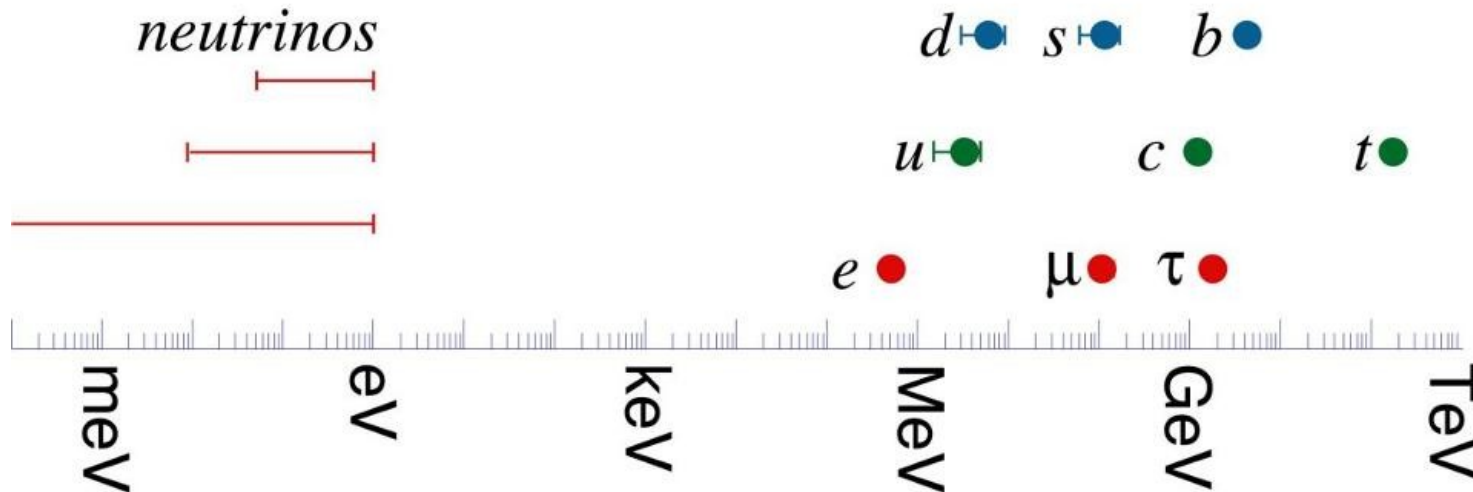
Only left-handed neutrinos (and right-handed antineutrinos) in the Standard Model.

- 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:

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*):

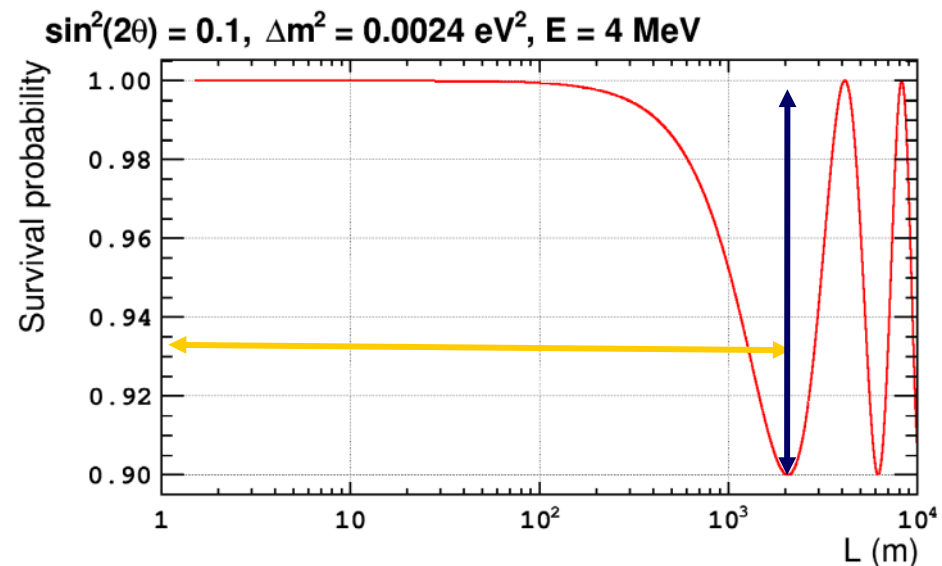
$$P_{lx(l \neq x)}^{2\nu}(L, E) = \boxed{\sin^2(2\theta)} \sin^2\left(\frac{\boxed{\Delta m^2 L}}{\boxed{4E}}\right)$$

Controlled by the experiment

- Survival** probability:

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

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



# 3 neutrino mixing

- **Flavor eigenstates ( $\nu_e, \nu_\mu, \nu_\tau$ )  $\neq$  mass eigenstates ( $\nu_1, \nu_2, \nu_3$ ).**
- Related by **Pontecorvo-Maki-Nakagawa-Sakata mixing matrix**:  
3 neutrinos  $\rightarrow$  3 angles ( $\theta_{12}, \theta_{23}, \theta_{13}$ ) + 1 CP-violating phase ( $\delta$ ).

PMNS matrix: U  $c_{ij} = \cos \theta_{ij}, s_{ij} = \sin \theta_{ij}$

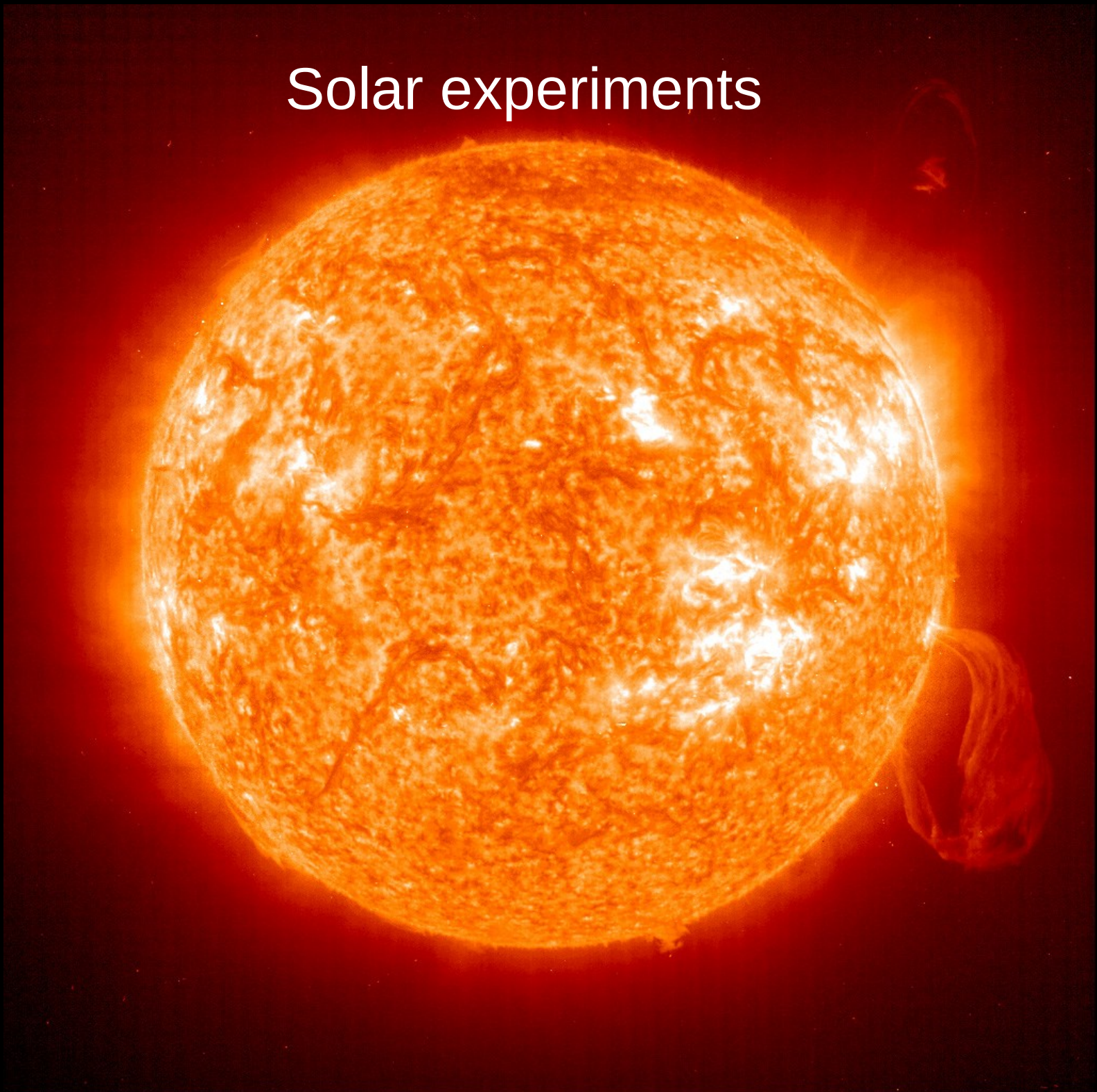
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric \& Long-baseline accelerator experiments}} \underbrace{\begin{pmatrix} c_{13} & & s_{13} e^{-i\delta} \\ & 1 & \\ -s_{13} e^{i\delta} & & c_{13} \end{pmatrix}}_{\text{Reactor \& Long-baseline accelerator experiments}} \underbrace{\begin{pmatrix} c_{12} & s_{12} \\ -s_{12} & c_{12} \\ & & 1 \end{pmatrix}}_{\text{Solar \& KamLAND experiments}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \rightarrow \begin{matrix} m_1 \\ m_2 \\ m_3 \end{matrix}$$

- 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  $\theta_{12}$  and  $\Delta m^2_{21}$

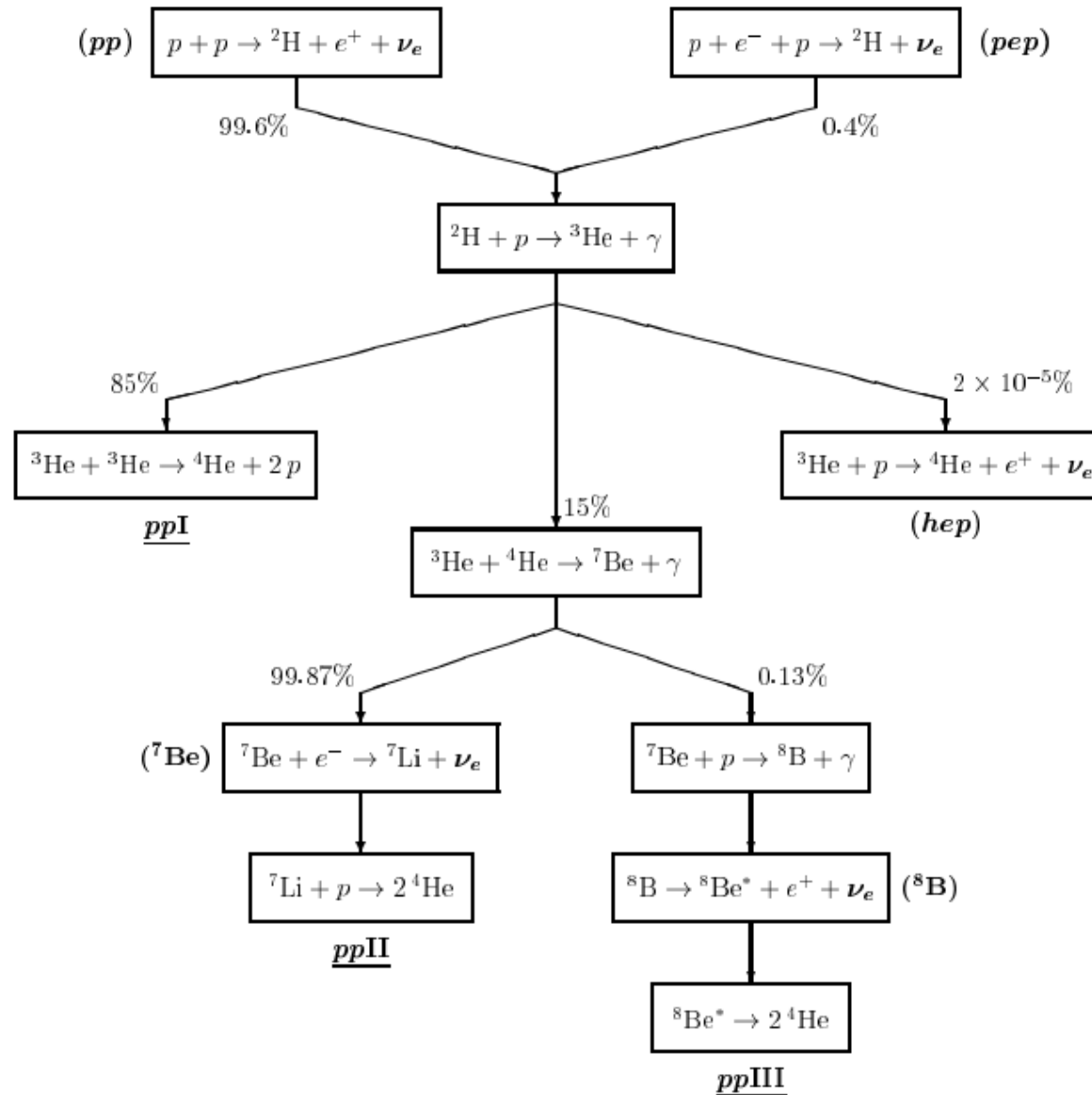


# Solar experiments



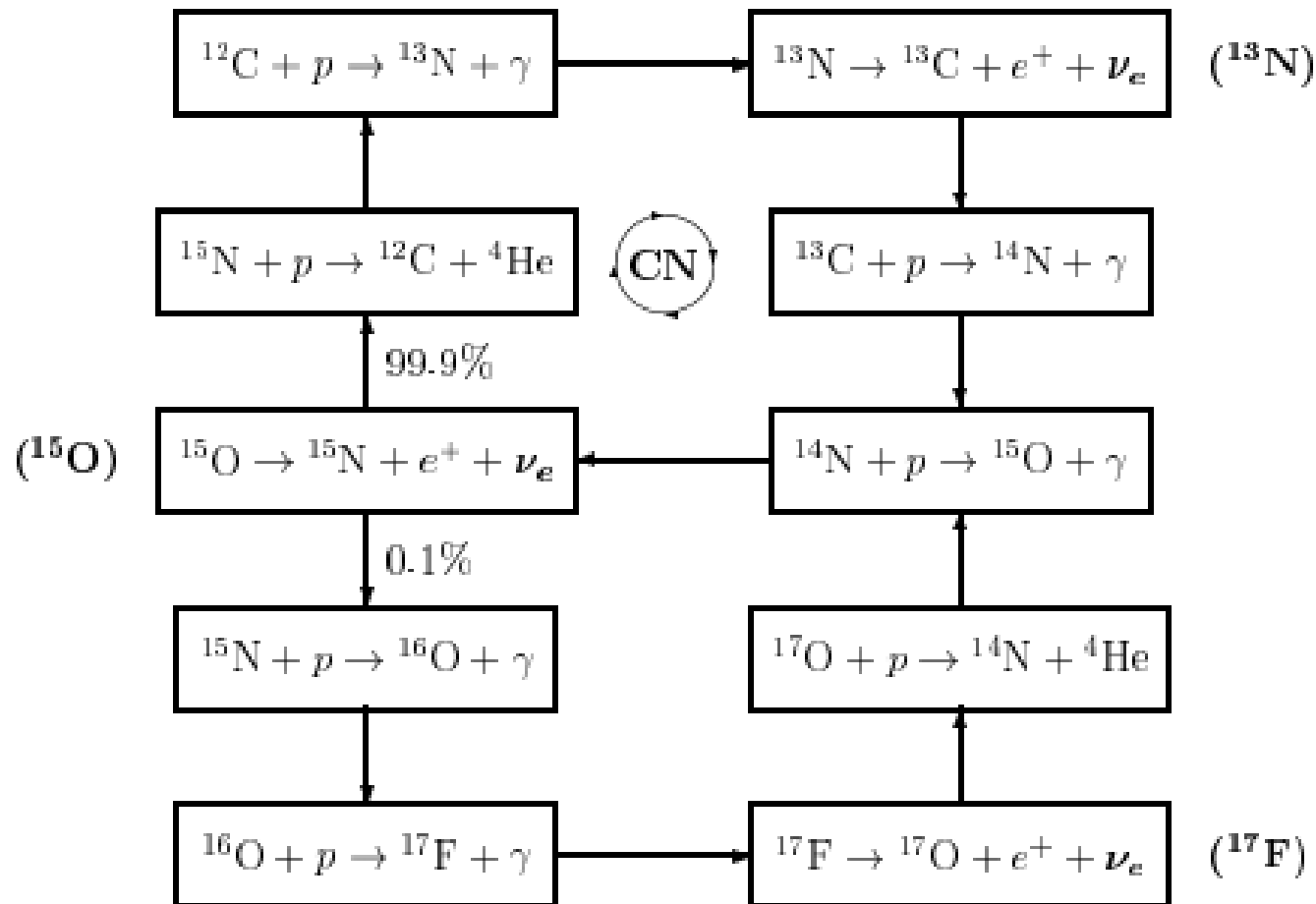
# Solar neutrinos: pp chain

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

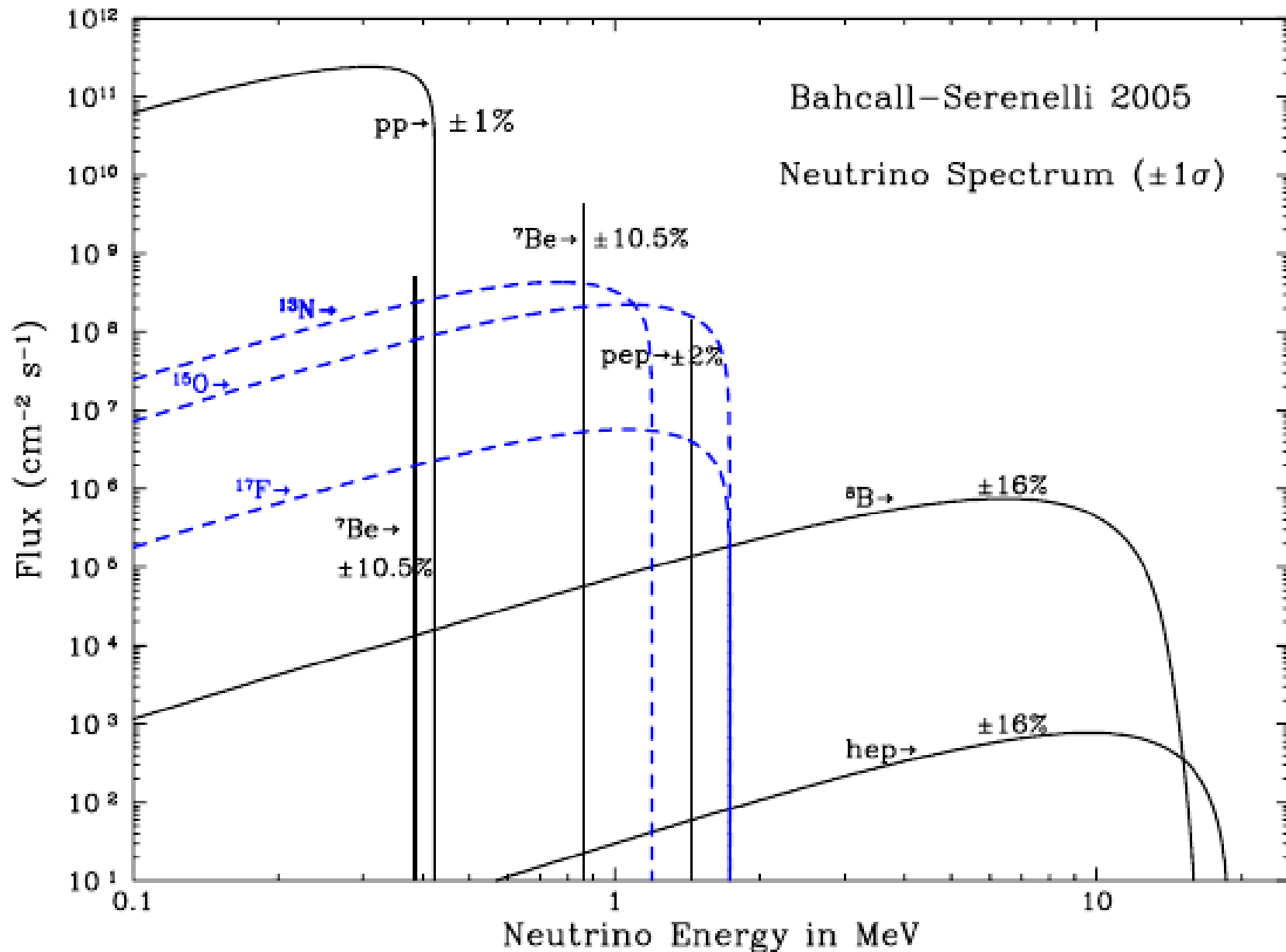


# Solar neutrinos: CNO cycle

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

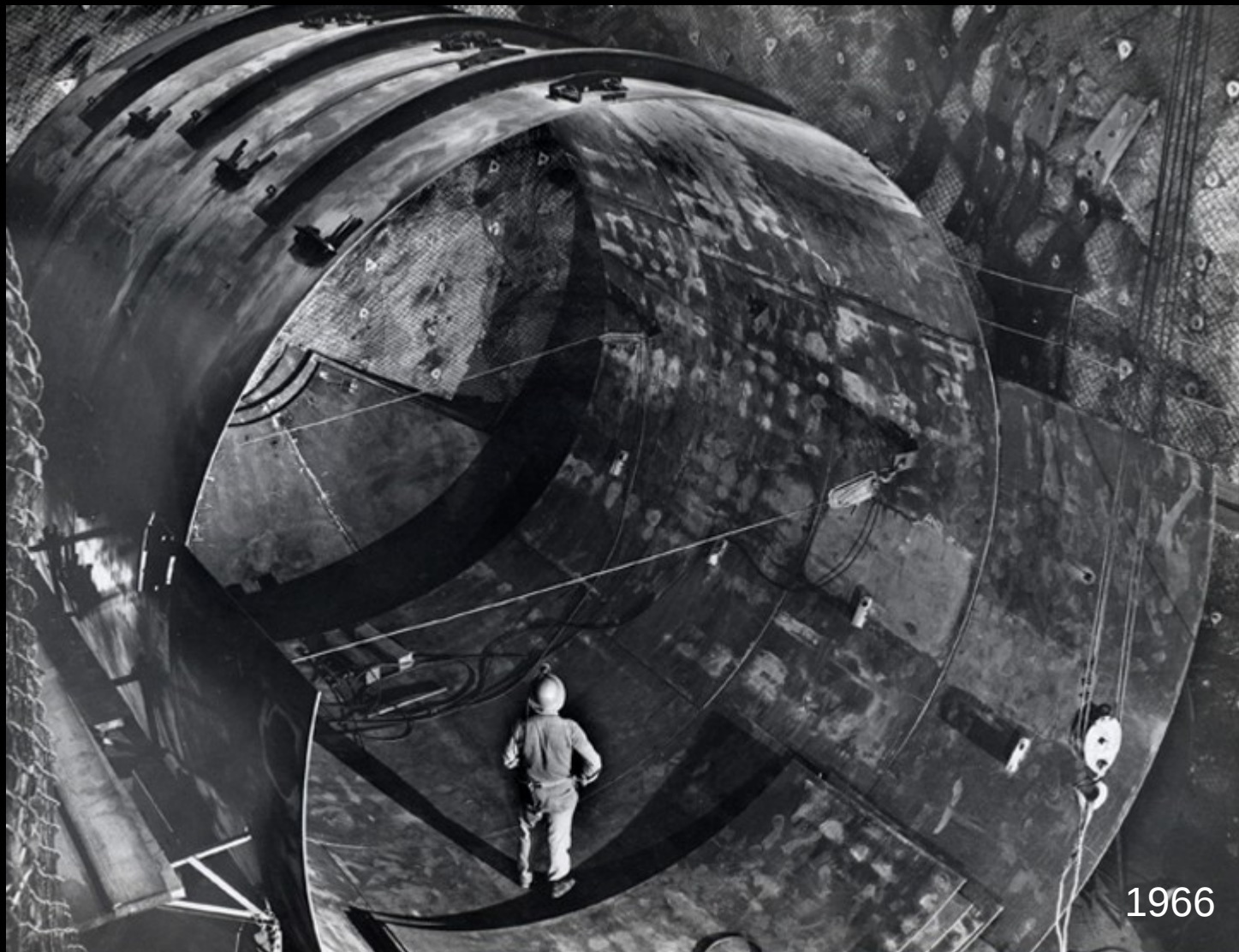


# Solar neutrinos: energy spectrum

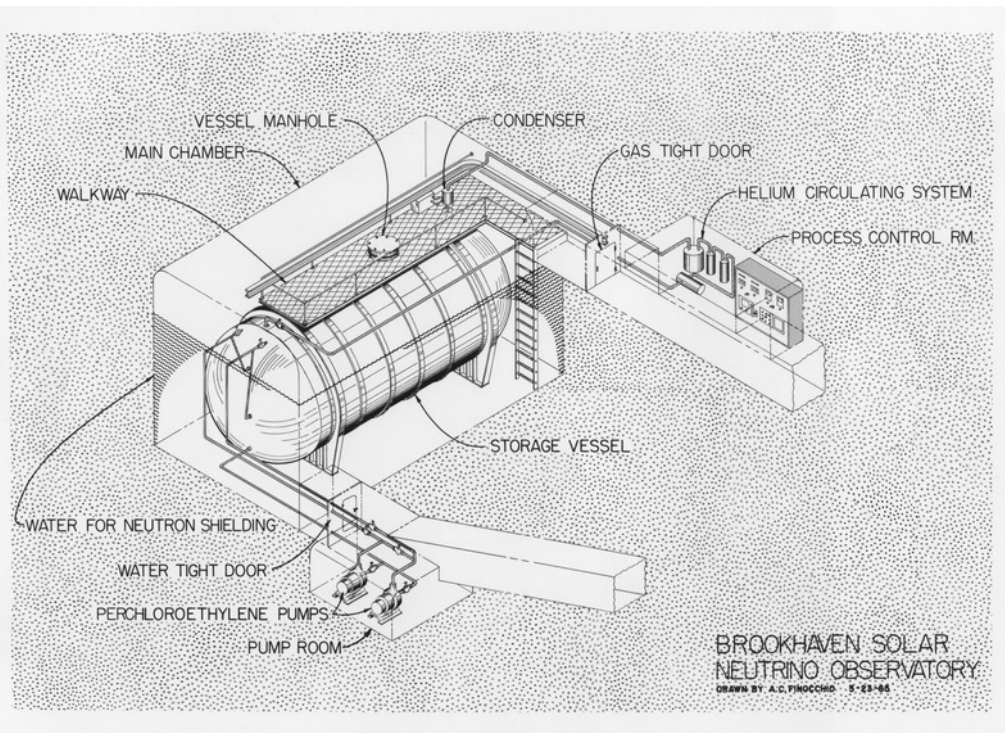




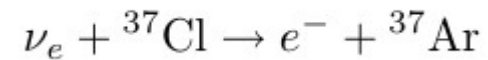
# Homestake experiment (1970 - 1994)



# Homestake experiment



- Detection of solar neutrinos using the reaction:



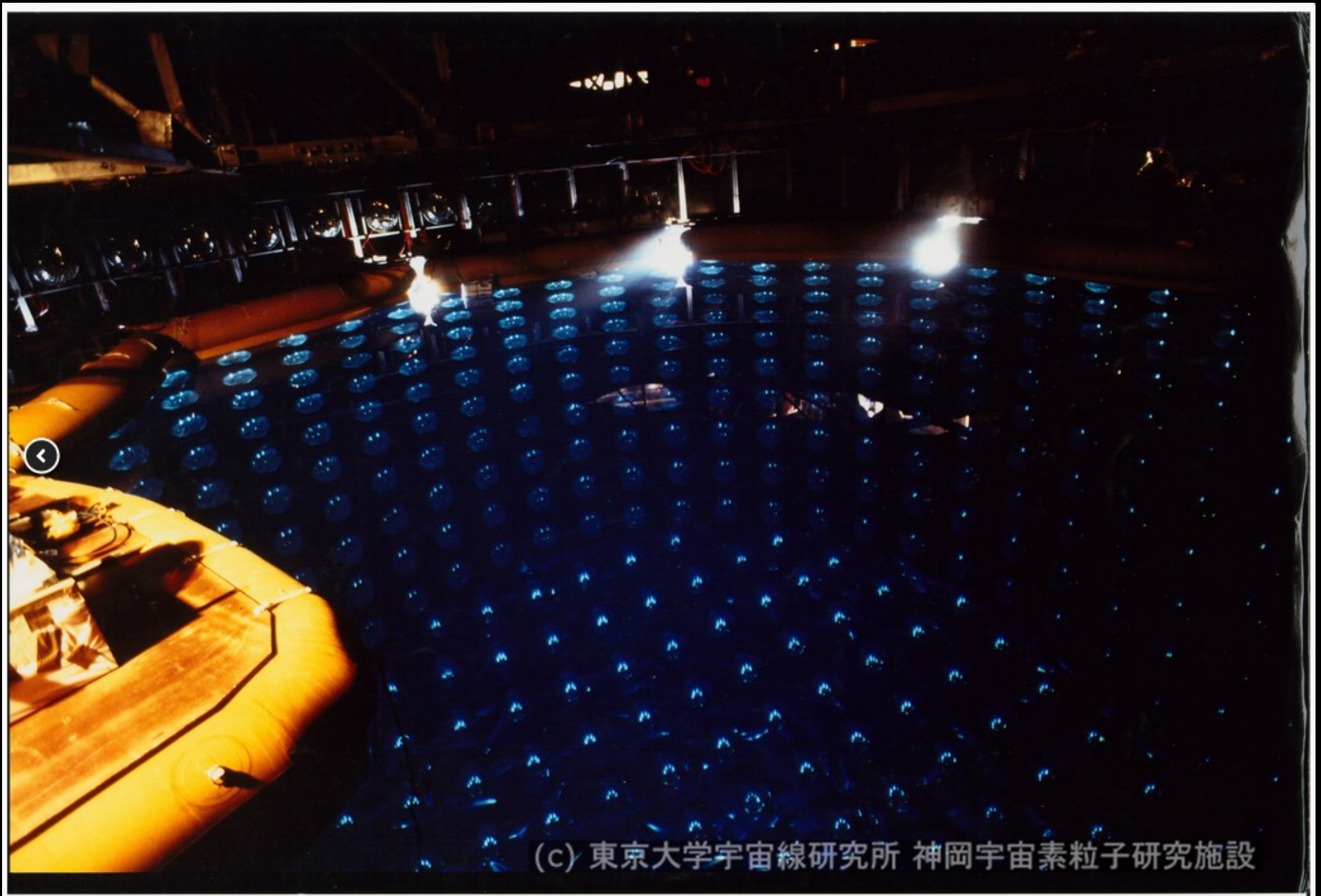
- Radiochemical detector.
- Ratio of observed to predicted:

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

- **Missing neutrinos!**

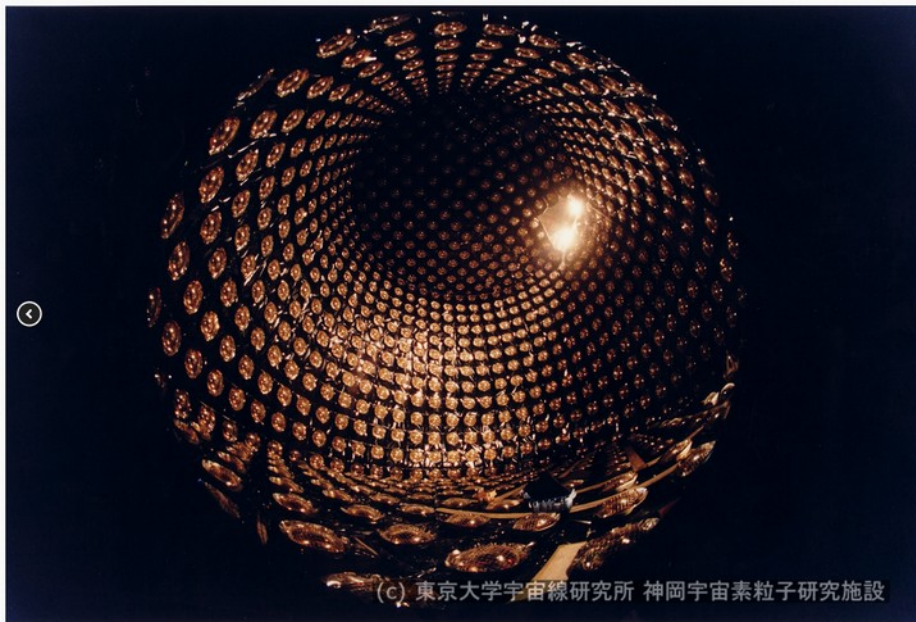


# Kamiokande (1983 - 1996)

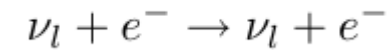


(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設

# Kamiokande



- Detection of solar neutrinos using the reaction:



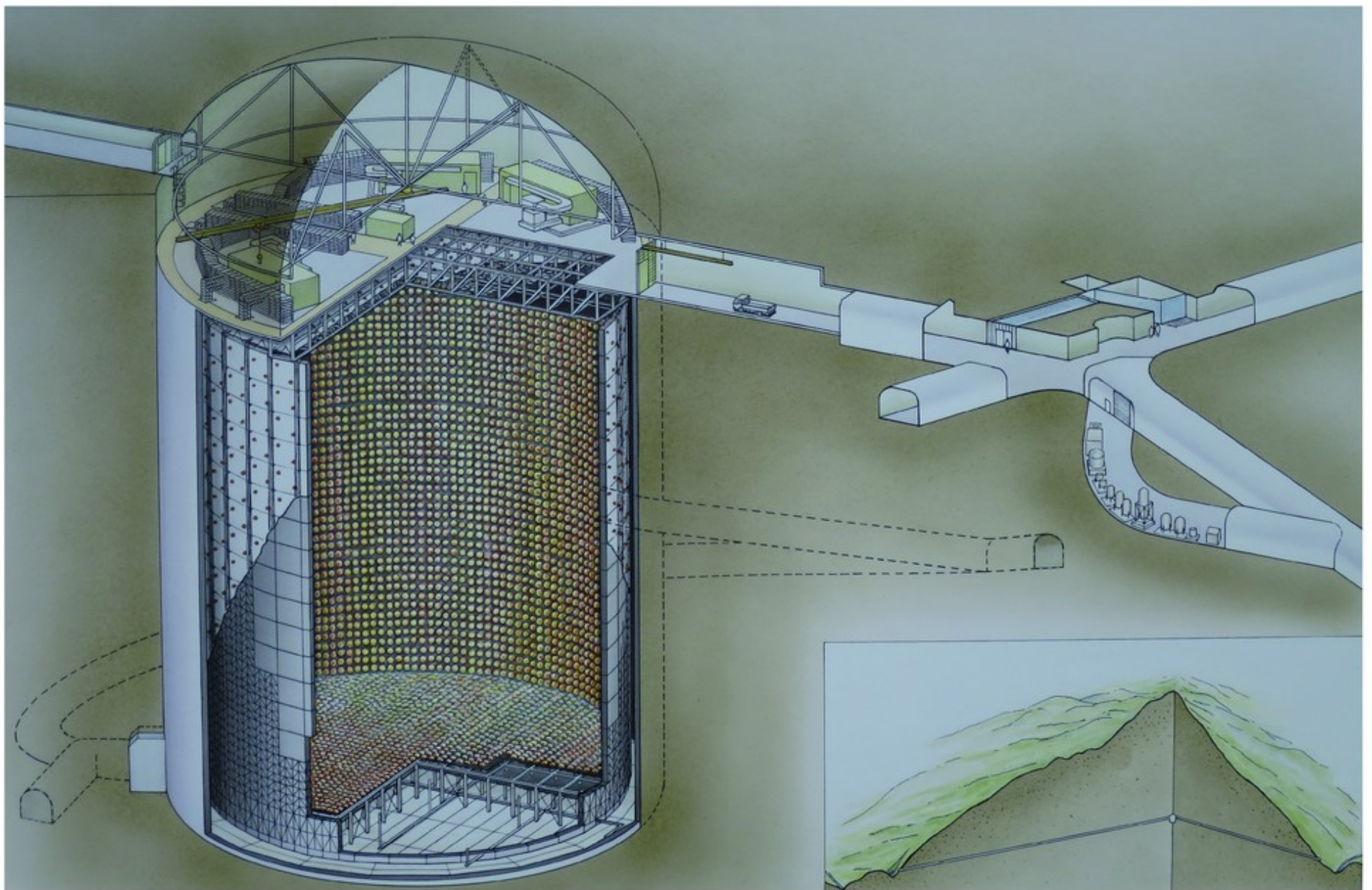
- Water Cherenkov detector.
- Ratio of observed to predicted:

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

- **Missing neutrinos again!**

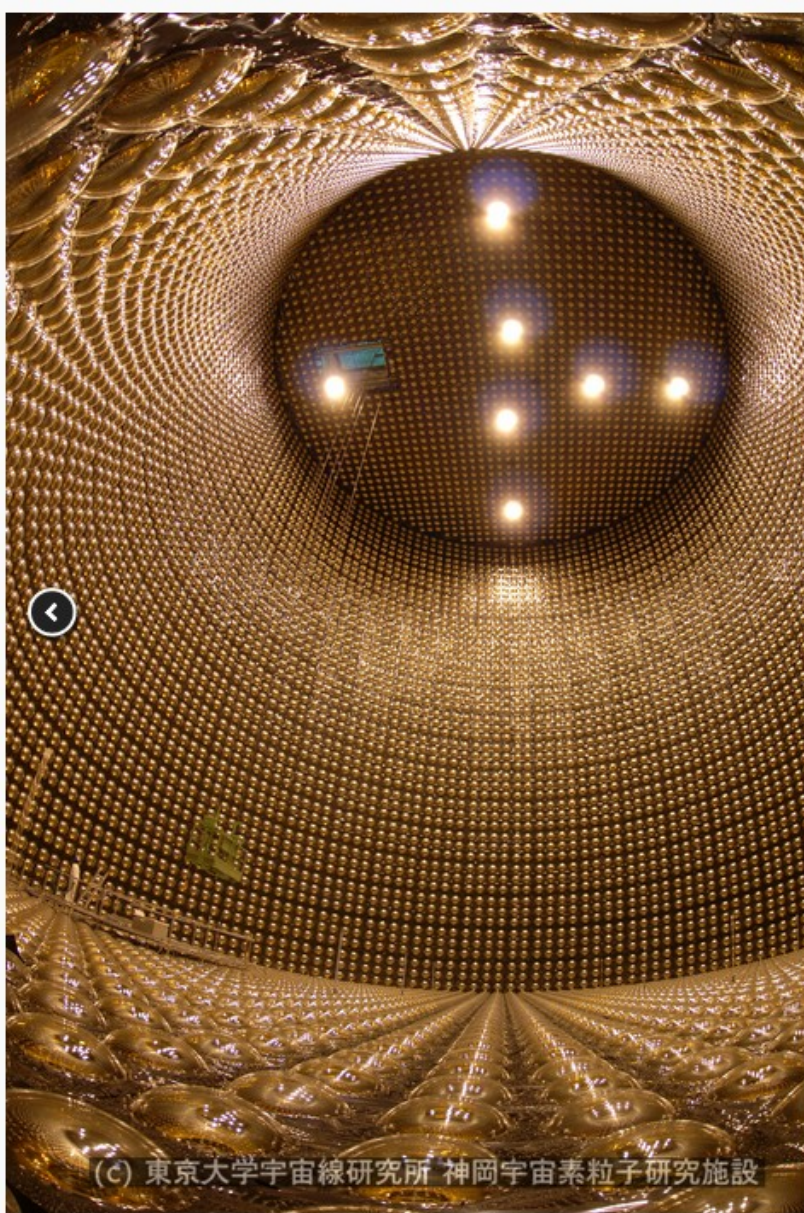


# Super-Kamiokande (since 1996)

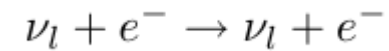




# Super-Kamiokande



- 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!**

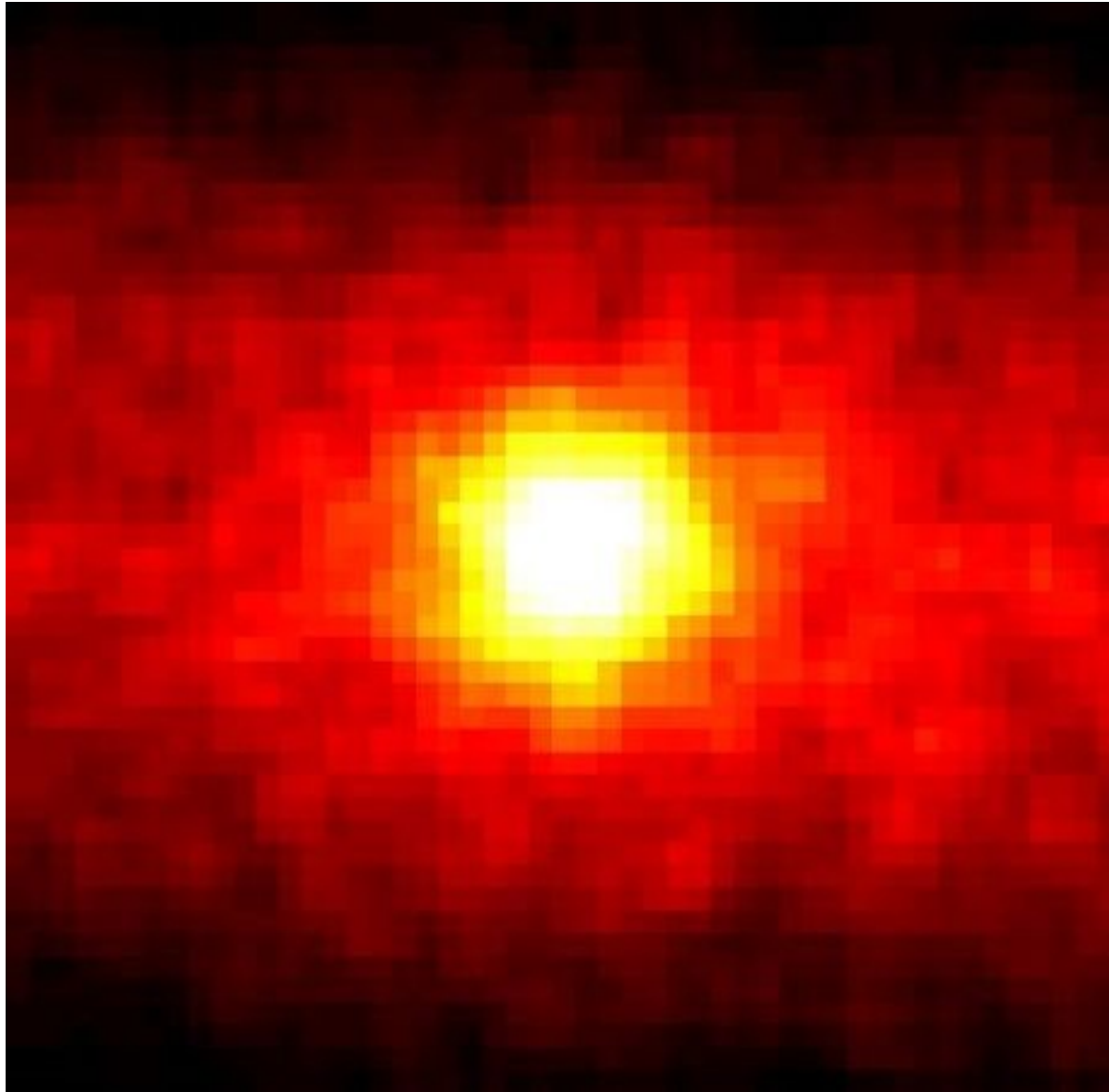
# Super-Kamiokande



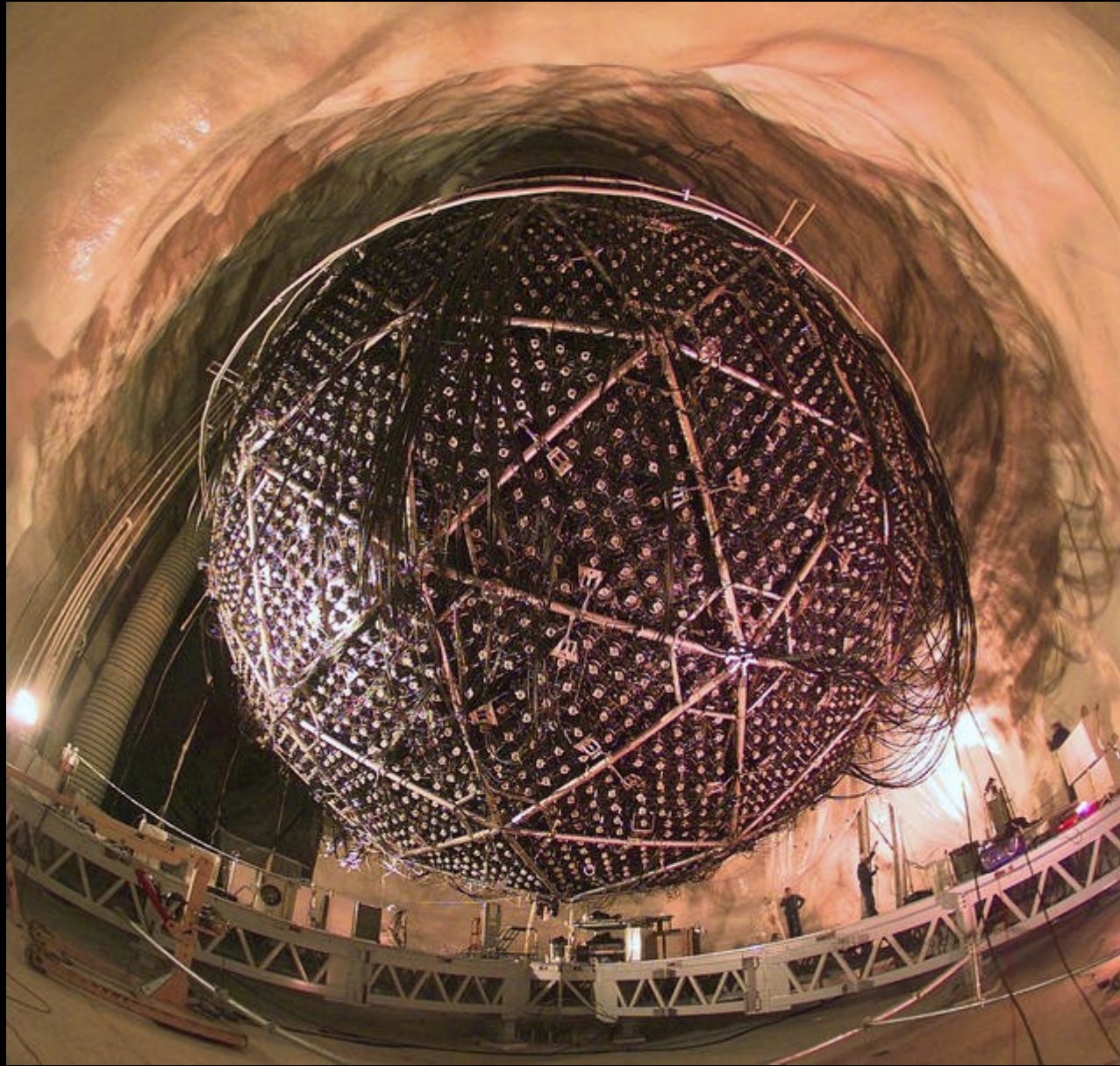


# Super-Kamiokande

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

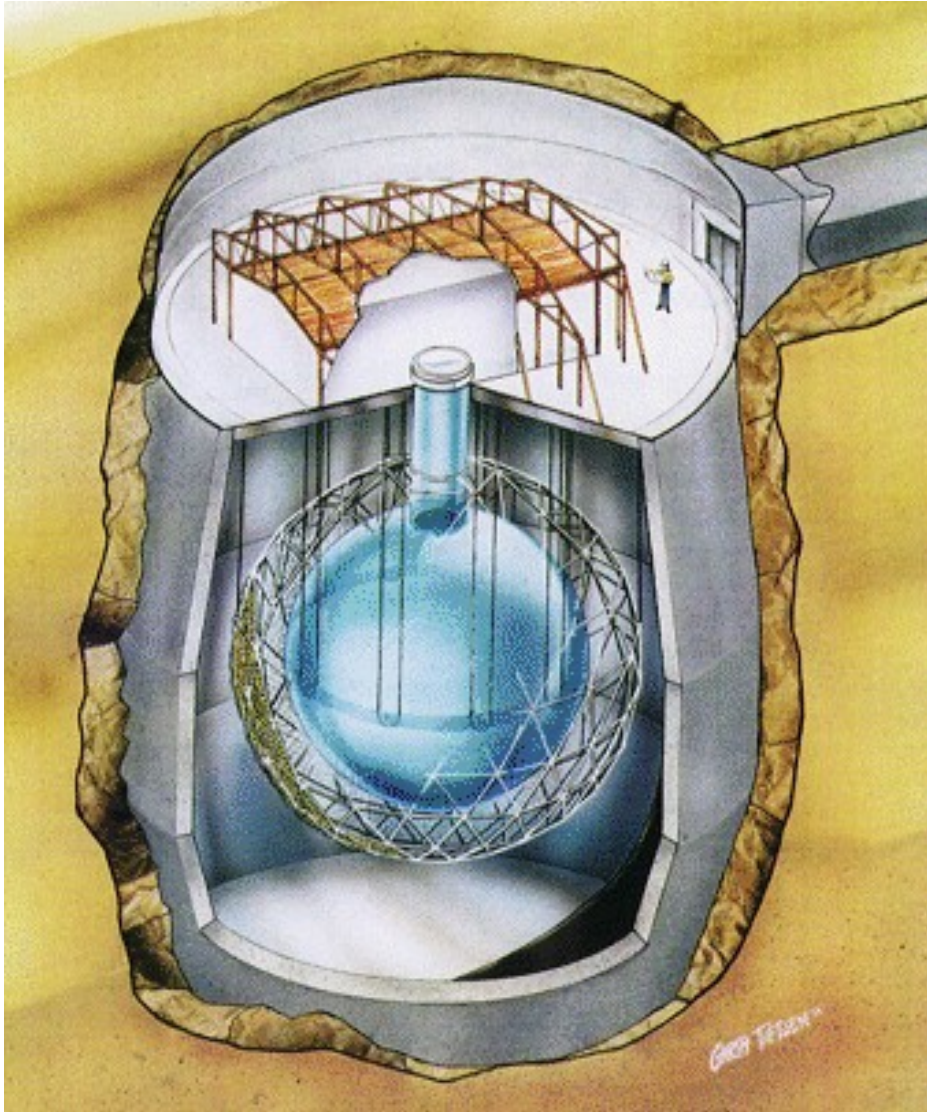


# SNO (1999 - 2006)

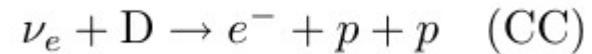
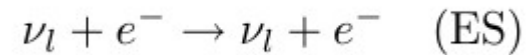




# SNO



- Detection of solar neutrinos using the reactions:



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

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

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

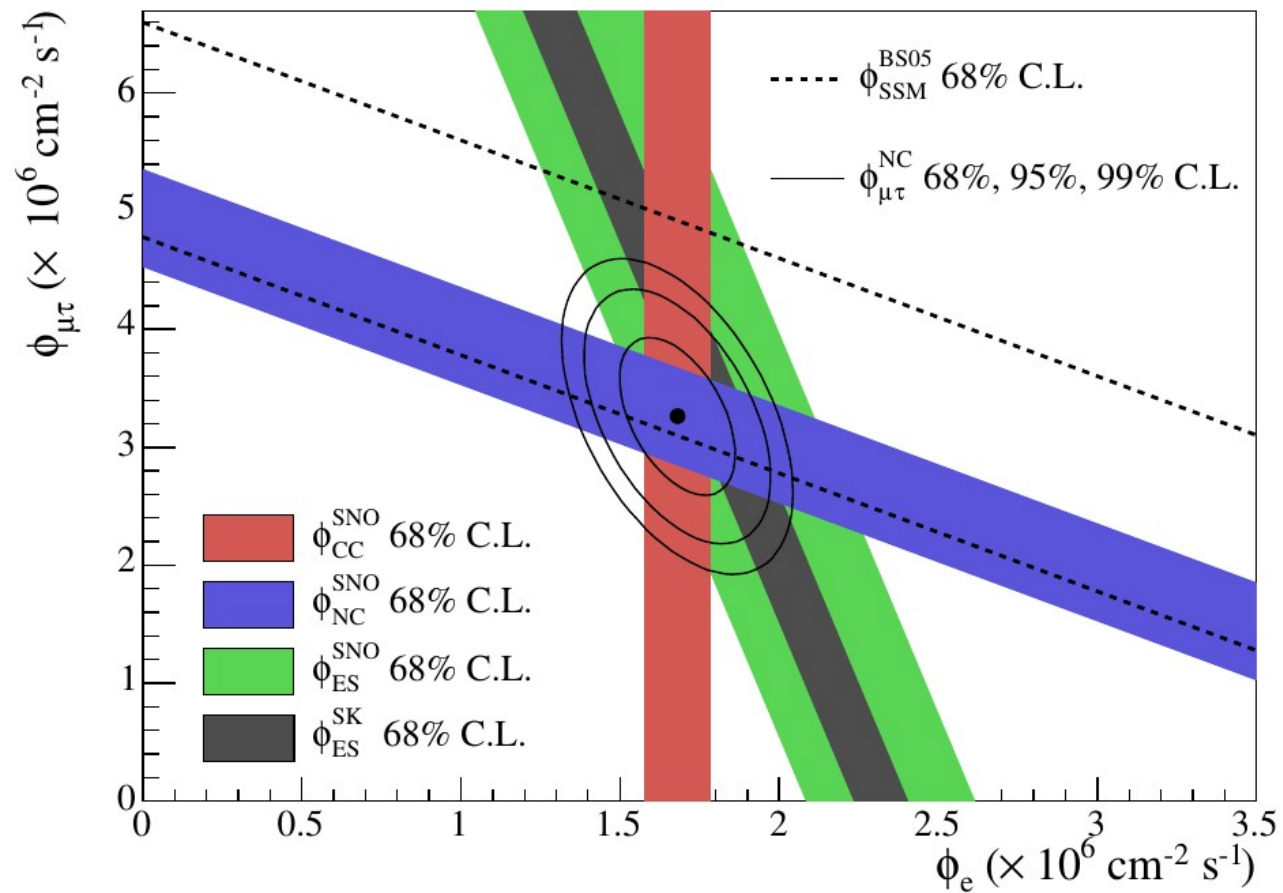
$$\frac{\Phi_{\text{SNO}}^{\text{NC}}}{\Phi_{\text{SSM}}} = 0.853 \pm 0.075$$

# SNO

$$\Phi_{\text{SNO}}^{\nu_e} + r^{\text{ES}} \Phi_{\text{SNO}}^{\nu_{\mu,\tau}} = \Phi_{\text{SNO}}^{\text{ES}} \quad \underline{r^{\text{ES}}} \equiv \sigma_{\nu_{\mu,\tau}}^{\text{ES}} / \sigma_{\nu_e}^{\text{ES}} \approx 0.1553.$$

$$\Phi_{\text{SNO}}^{\nu_e} = \Phi_{\text{SNO}}^{\text{CC}}$$

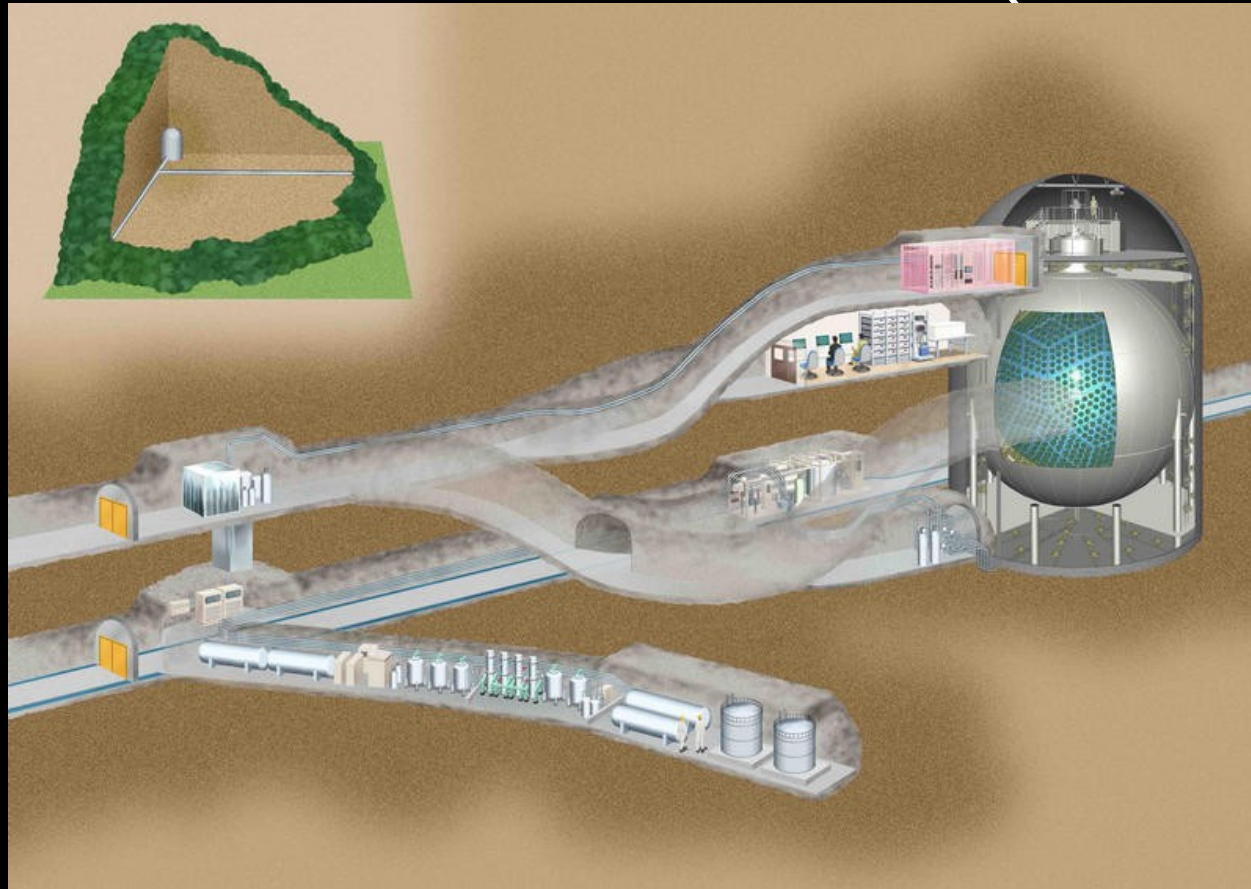
$$\Phi_{\text{SNO}}^{\nu_e} + \Phi_{\text{SNO}}^{\nu_{\mu,\tau}} = \Phi_{\text{SNO}}^{\text{NC}}$$



Additional material

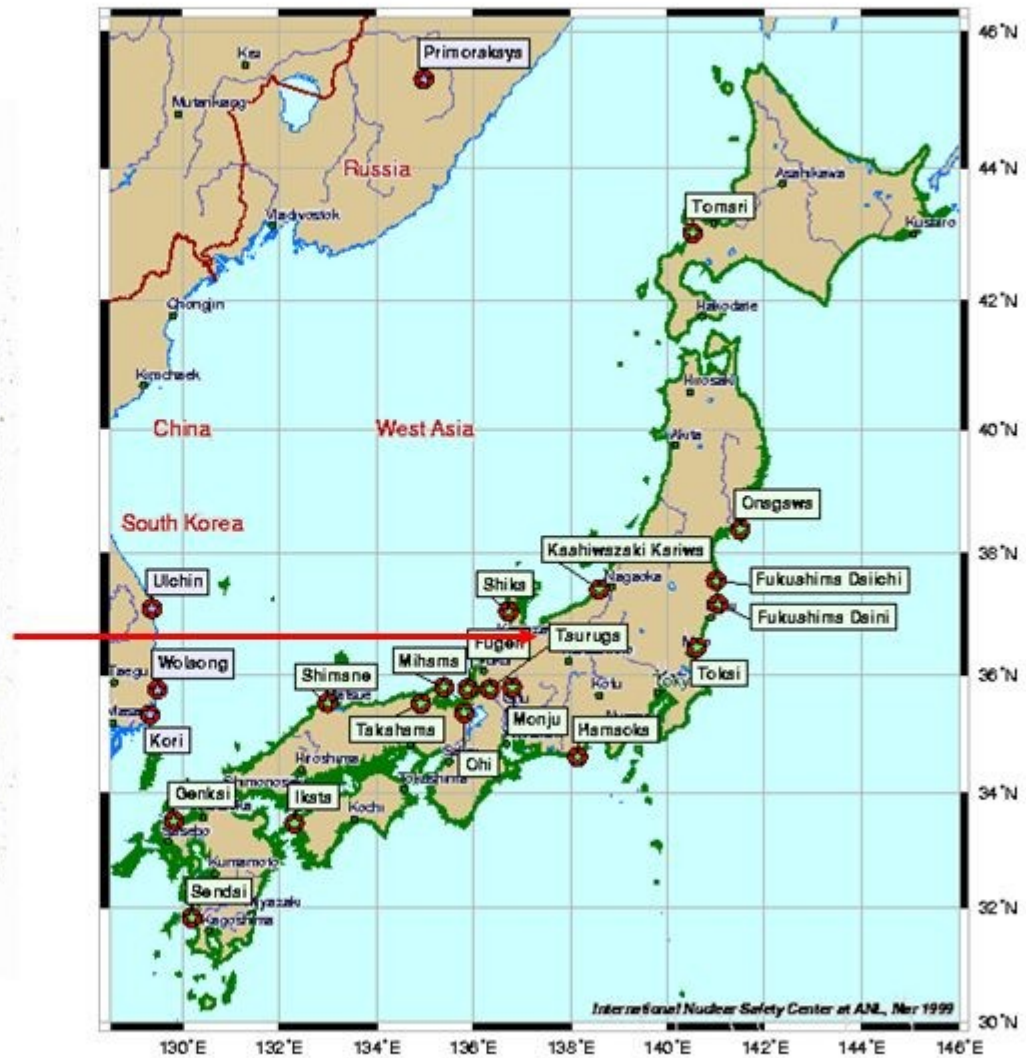
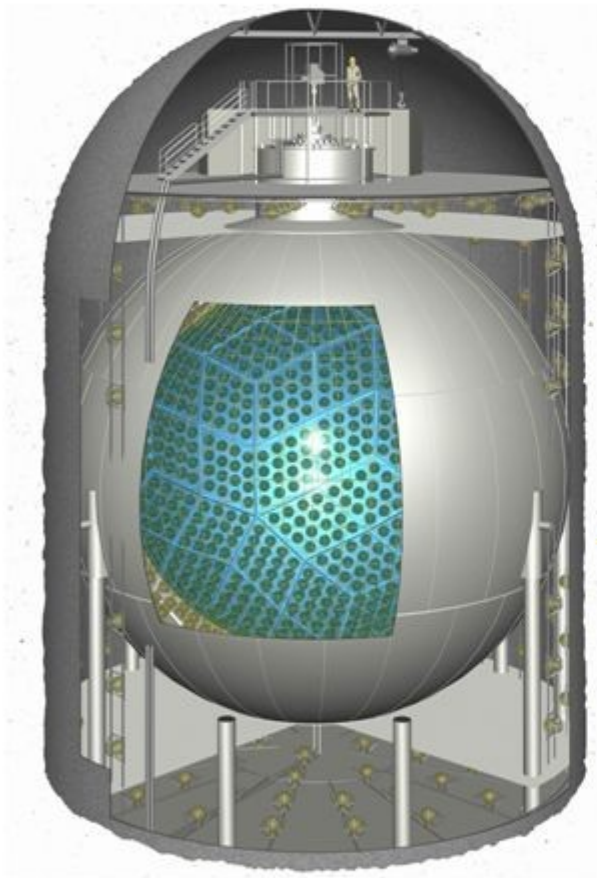


# KamLAND (2002 - 2011)





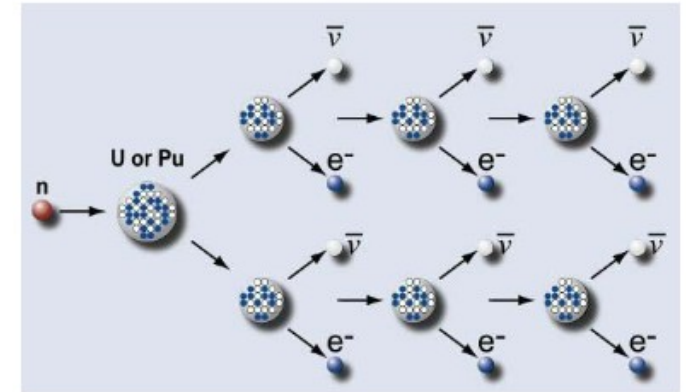
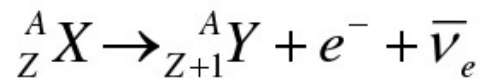
# KamLAND



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

- Fission of nuclear fuel ( $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{241}\text{Pu}$ ) produces neutron rich fission products.

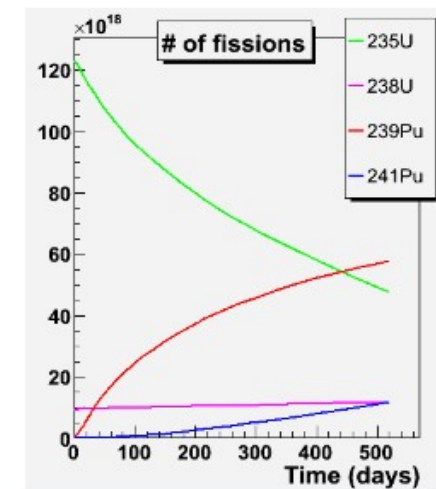
- $\beta^-$  decay of fission products:



- Average per fission:

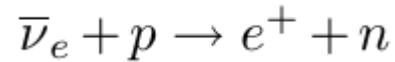
- 200 MeV released.
- 6 antineutrinos.

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

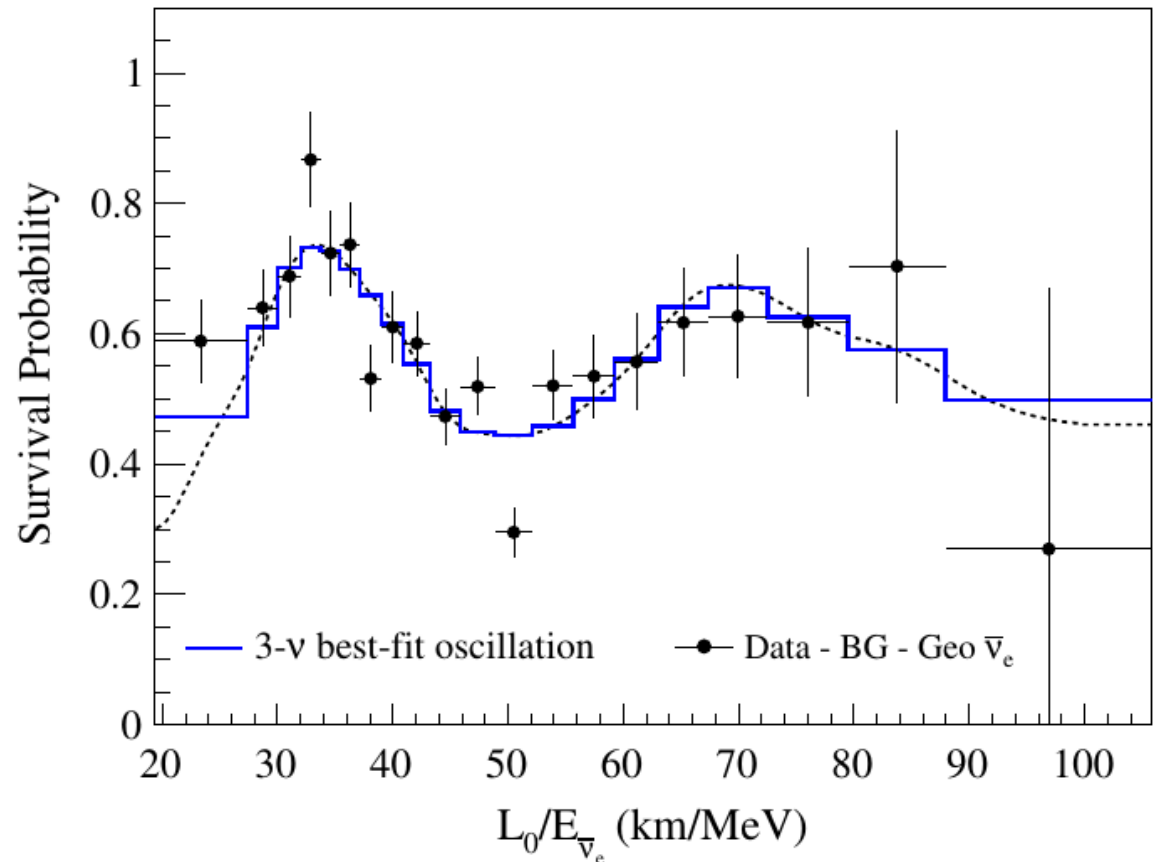
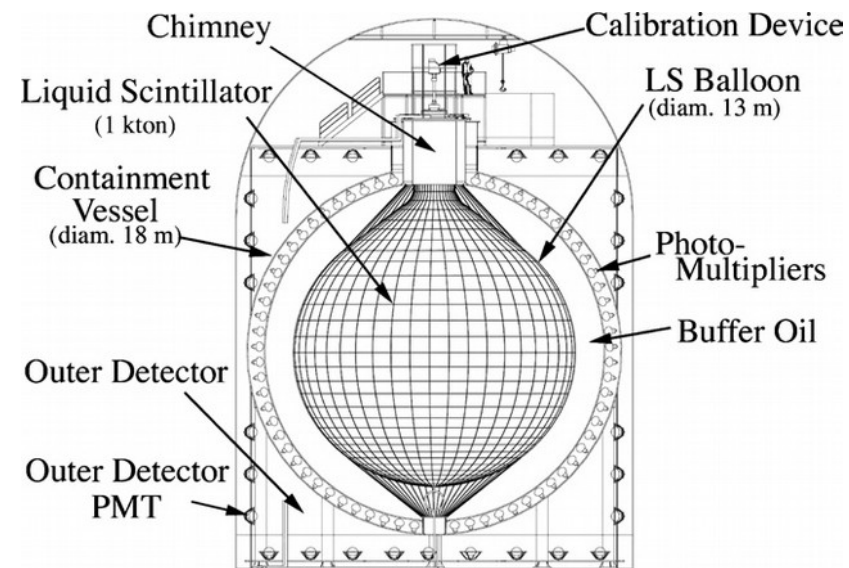


# KamLAND

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

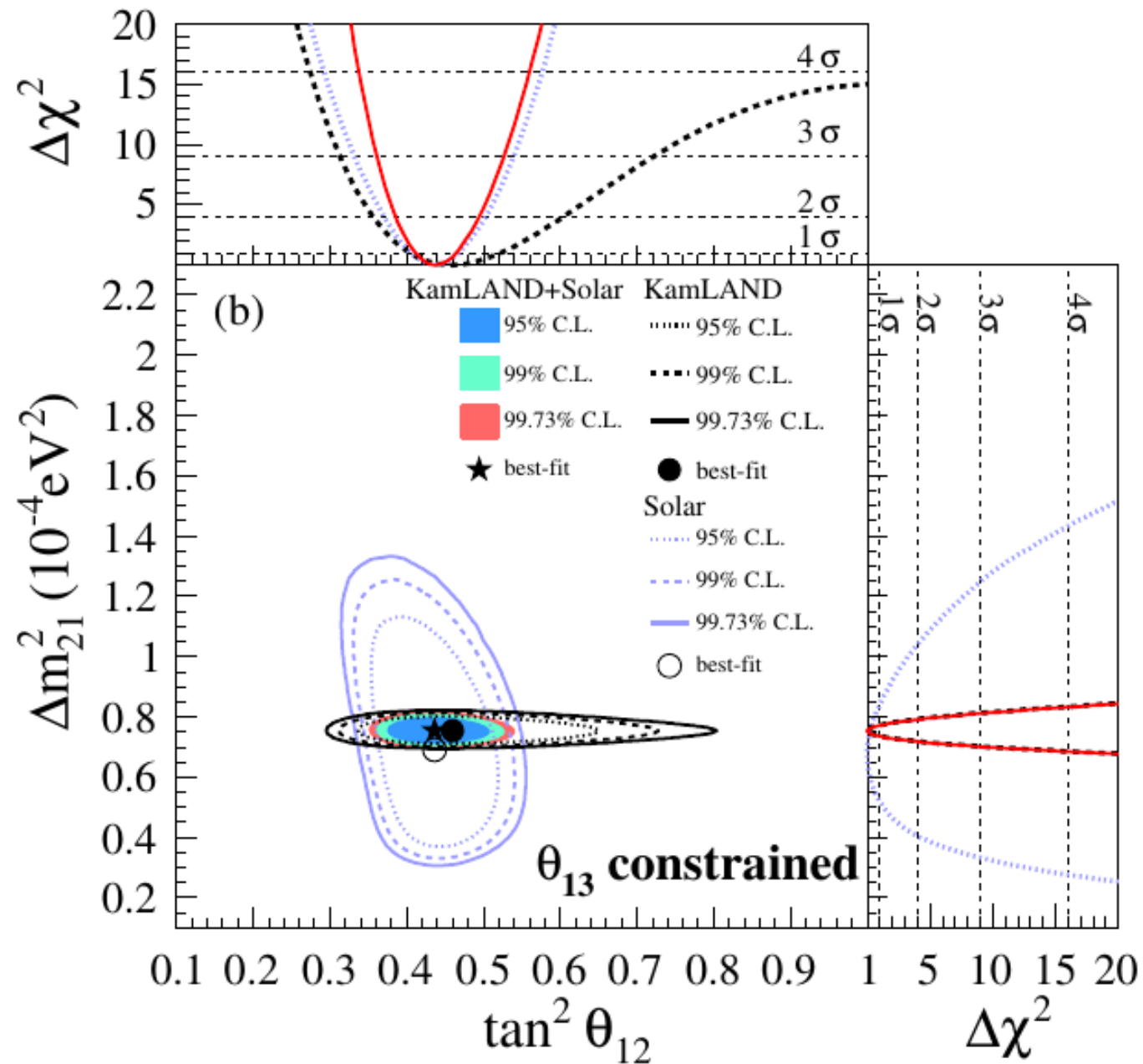


- Liquid scintillator detector.



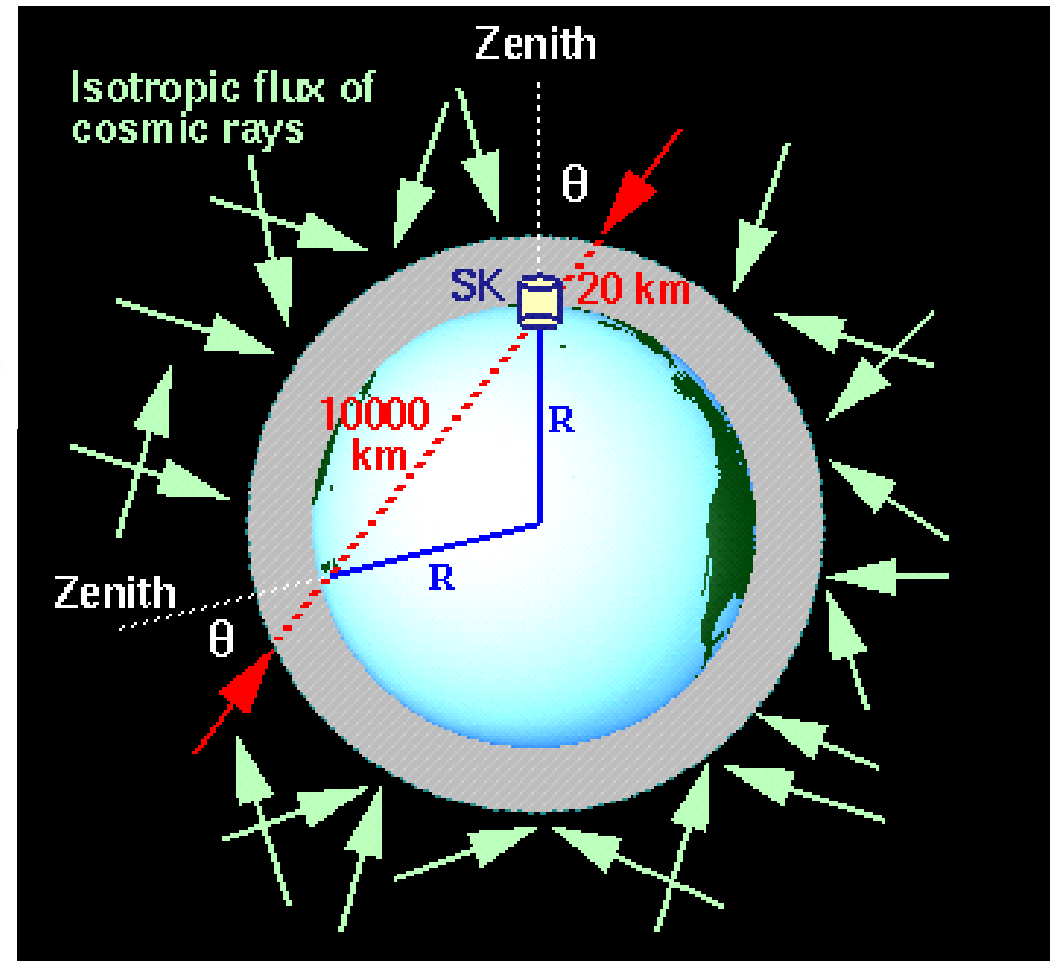
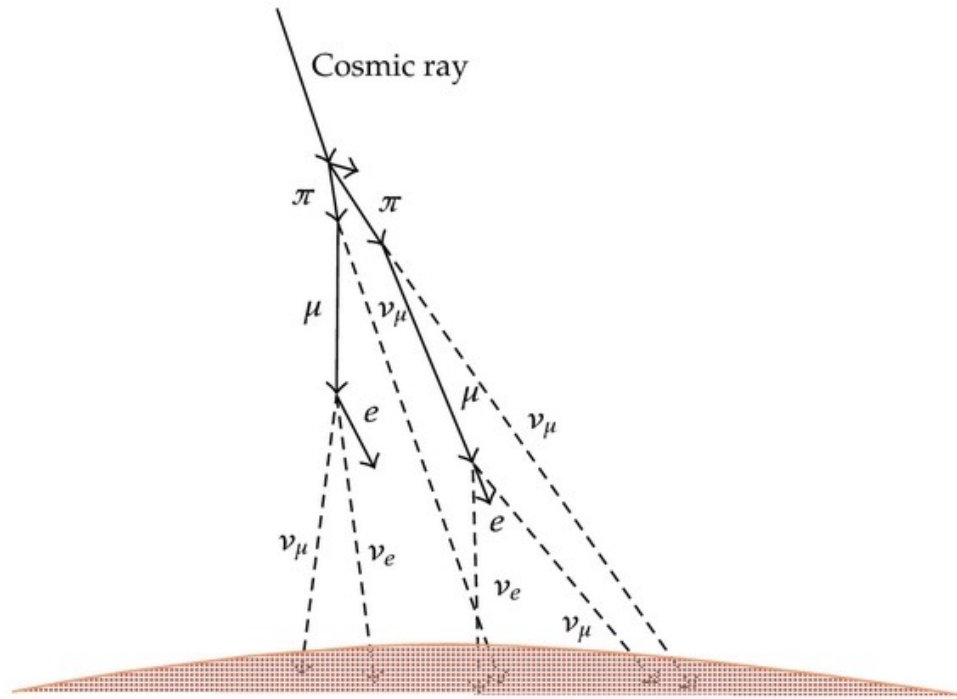


# Solar + KamLAND results

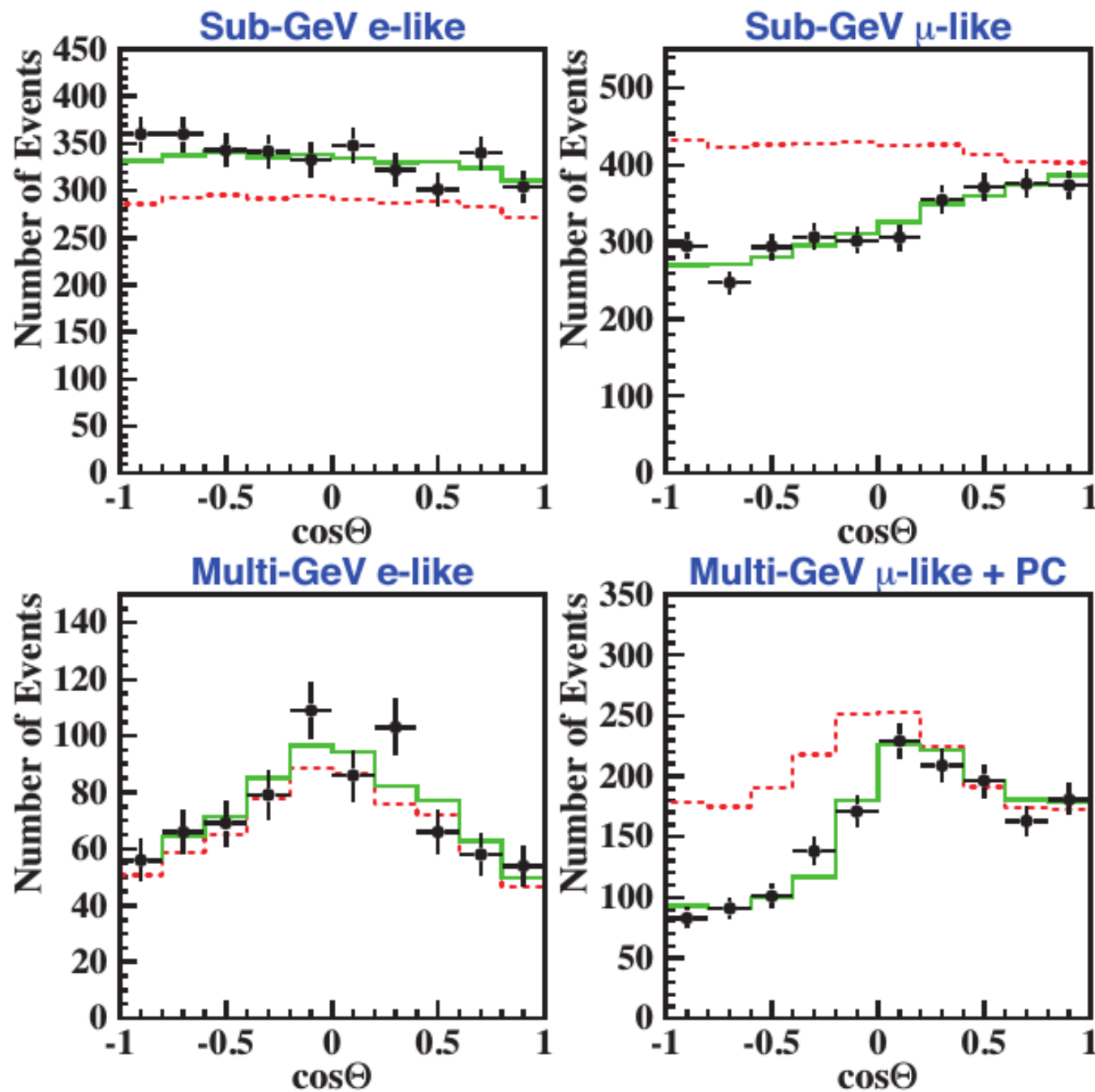
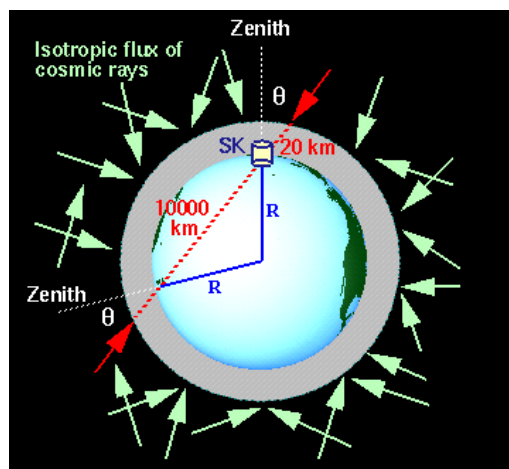


Measurement of  $\theta_{23}$  and  $\Delta m^2_{\text{atm}}$

# Atmospheric neutrinos

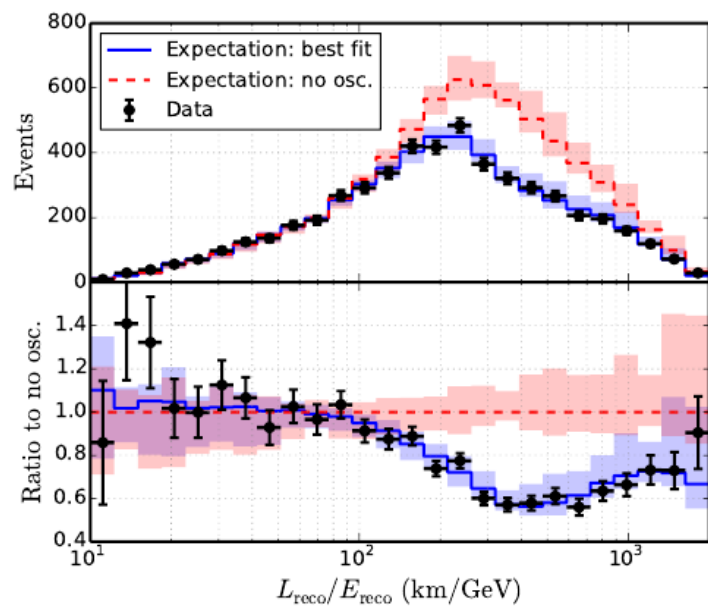
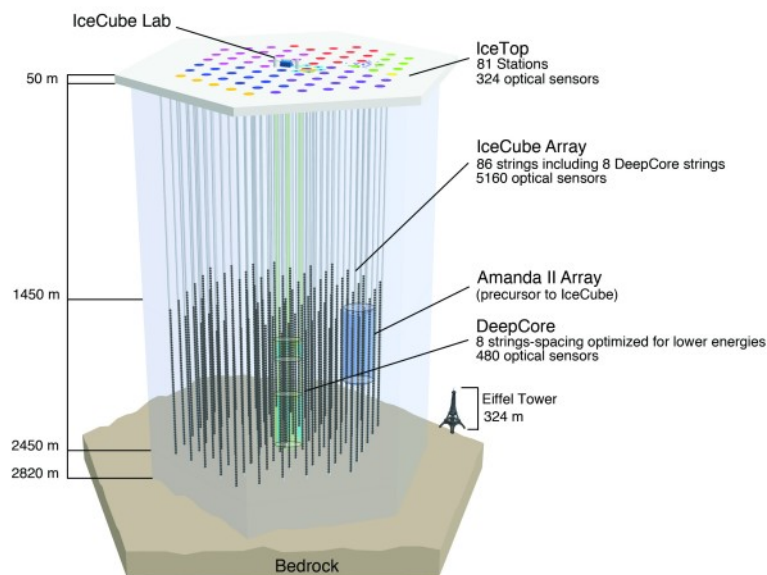


# Super-Kamiokande results

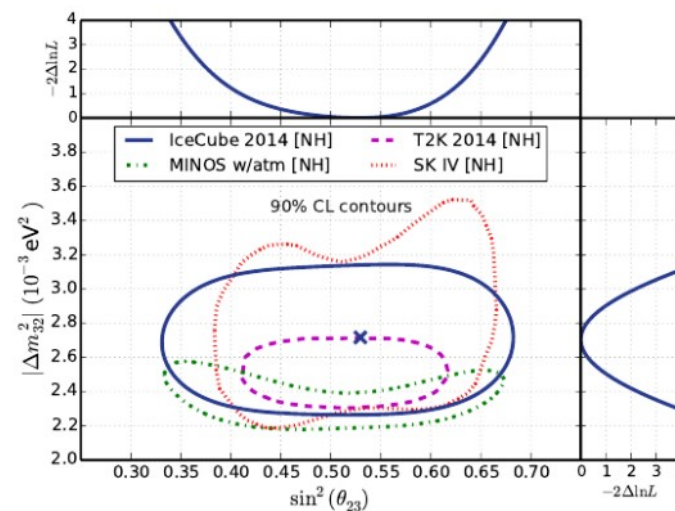
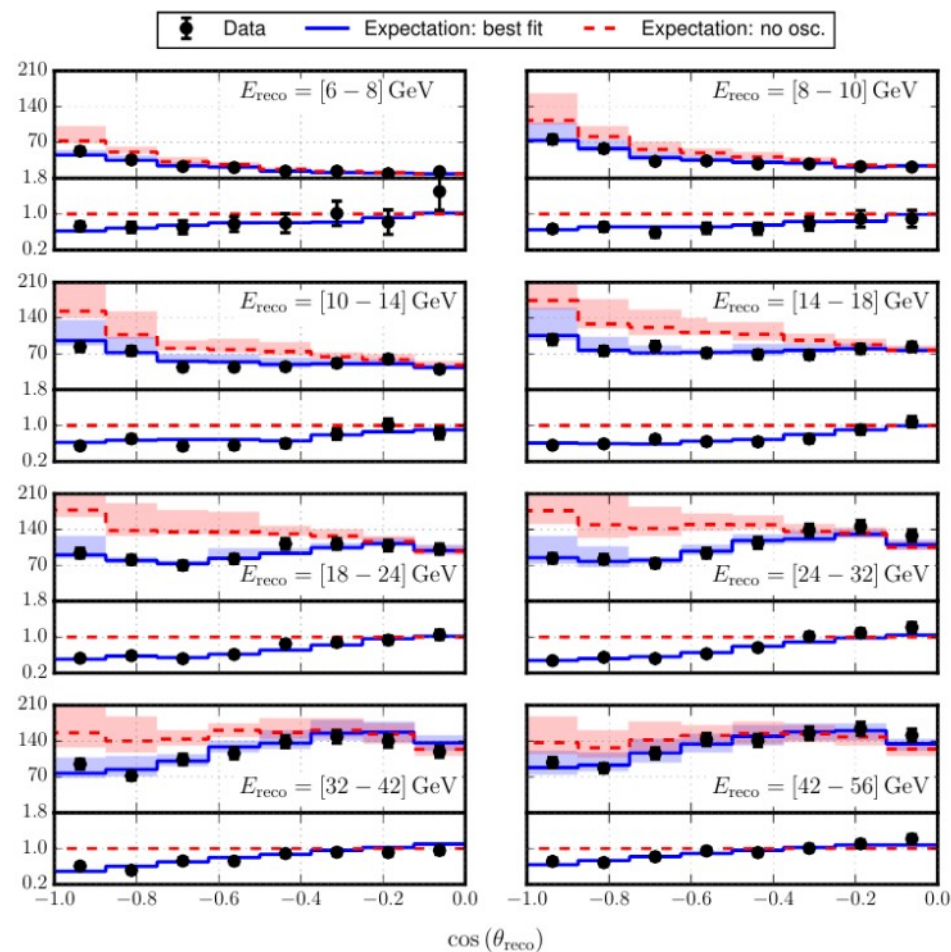




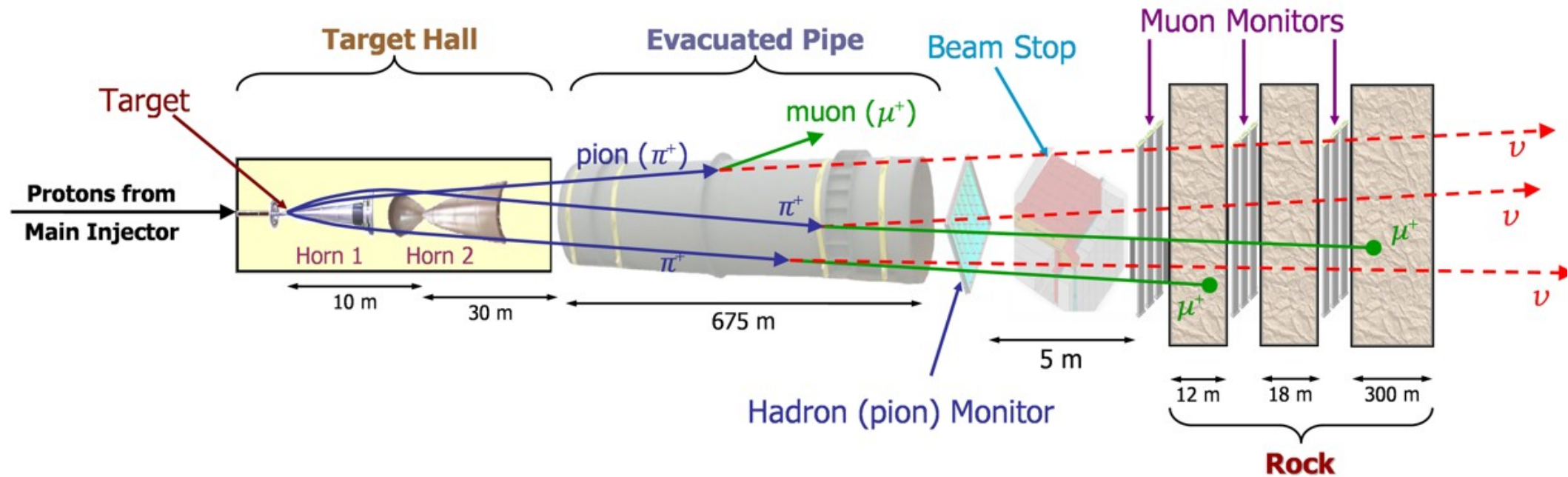
# IceCube



Events and ratio to no oscillations per energy band

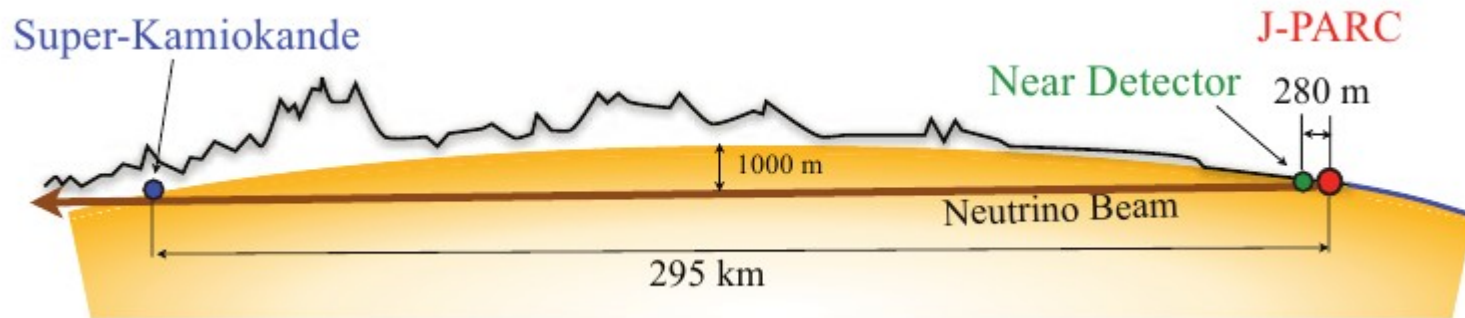


# Accelerator neutrinos

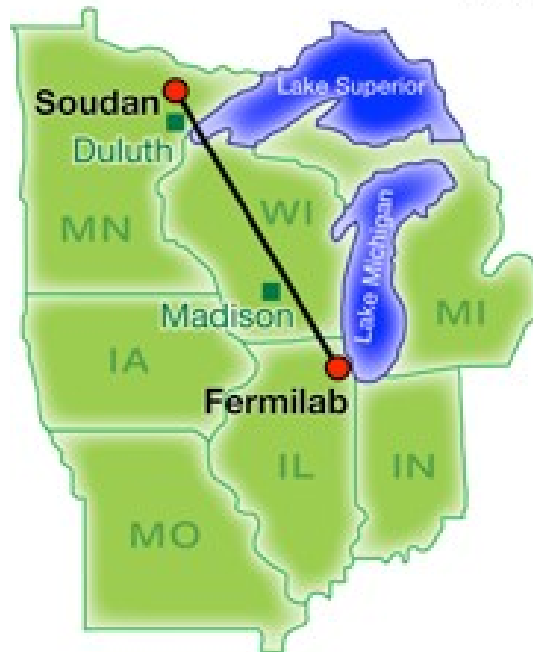


[https://www.youtube.com/watch?v=U\\_xWDWKq1CM](https://www.youtube.com/watch?v=U_xWDWKq1CM)

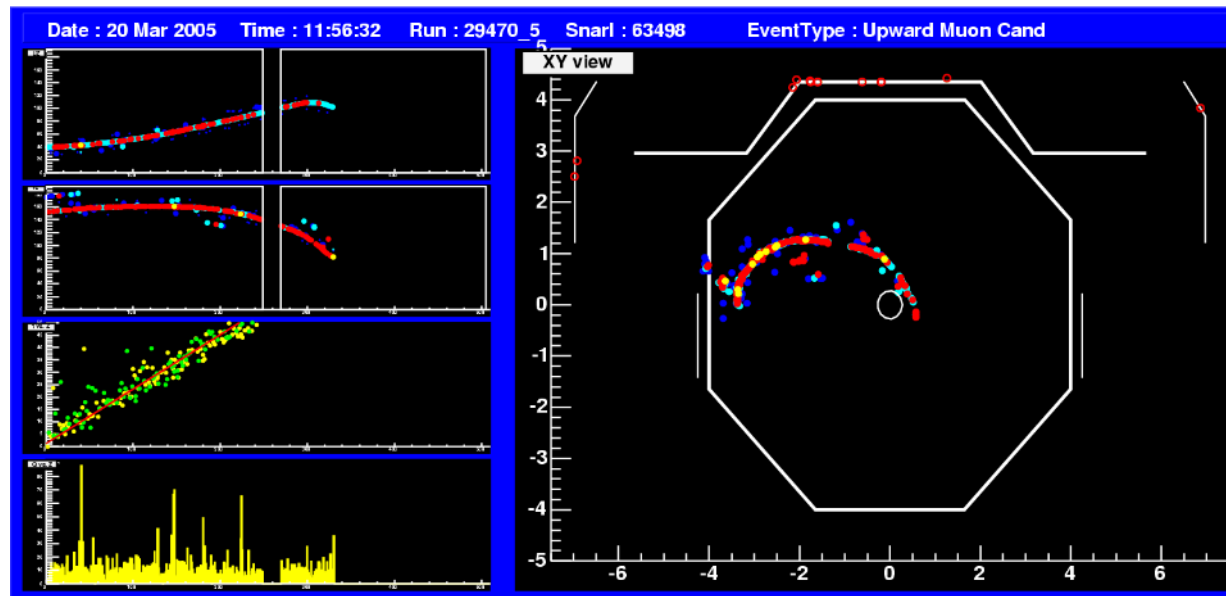
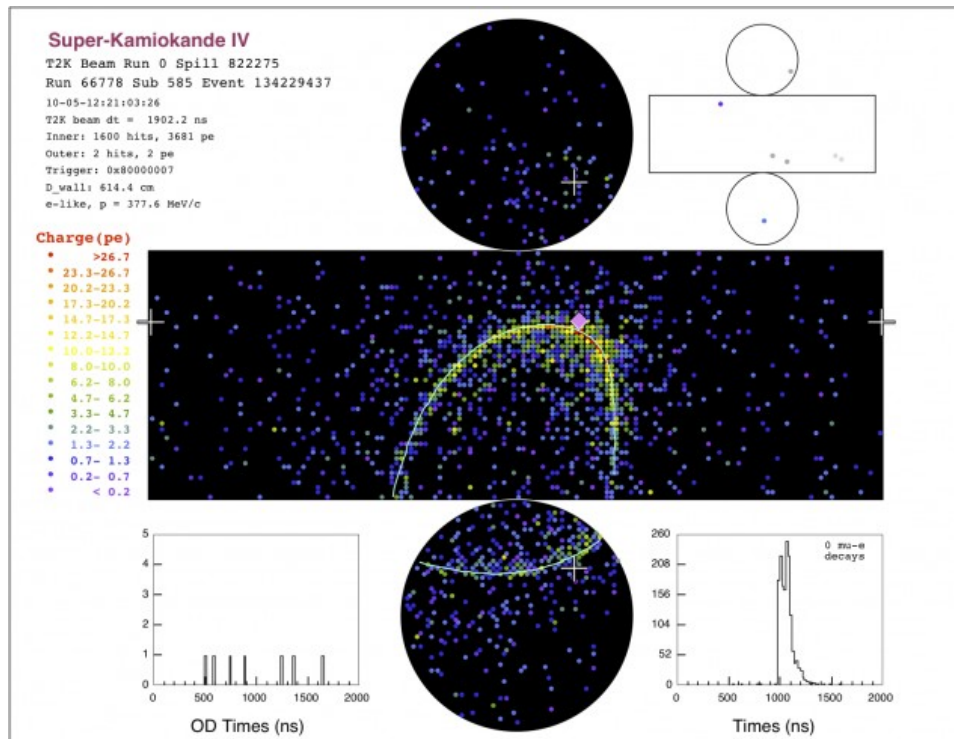
# T2K & MINOS experiments



## The MINOS Experiment

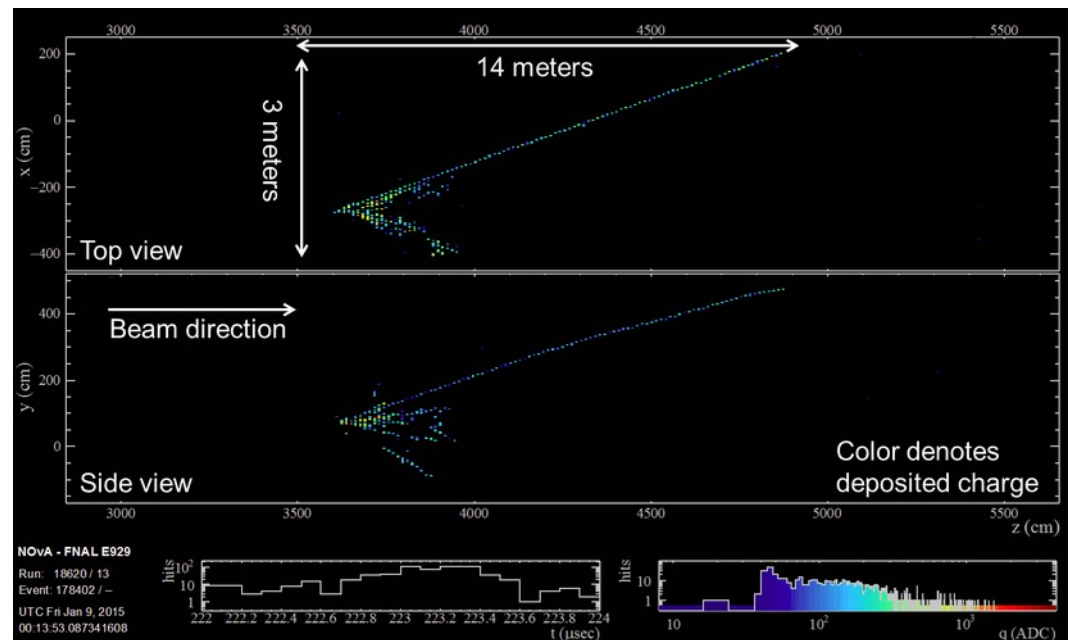
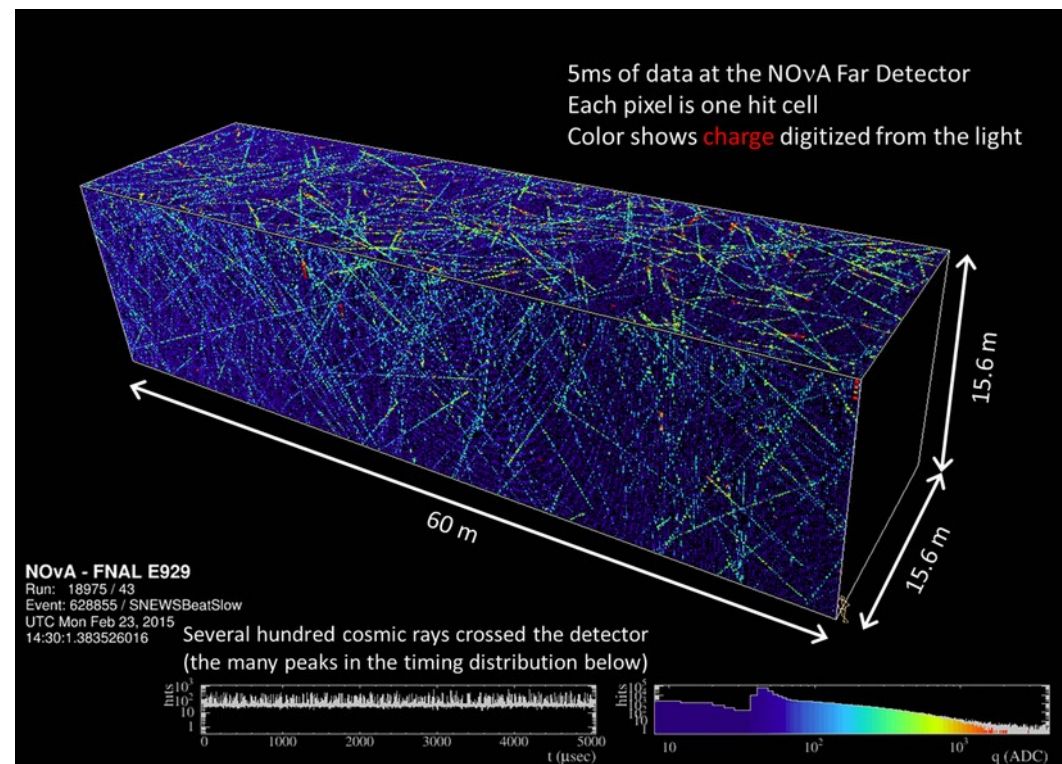
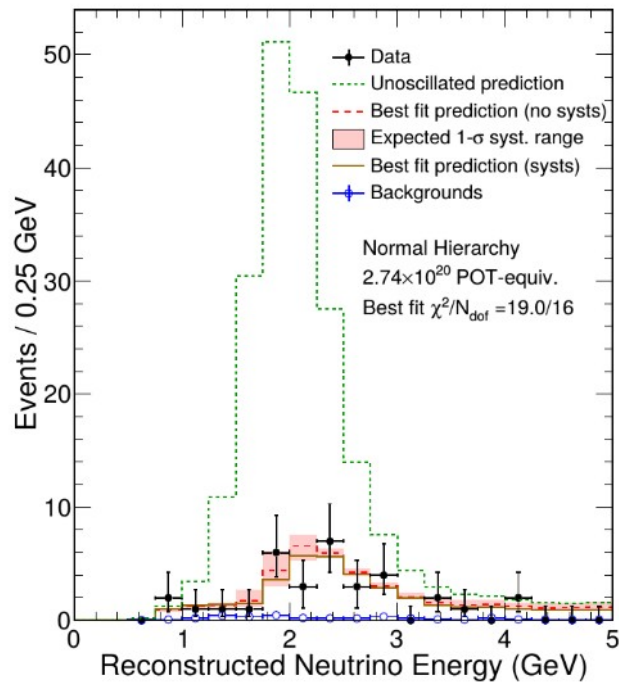
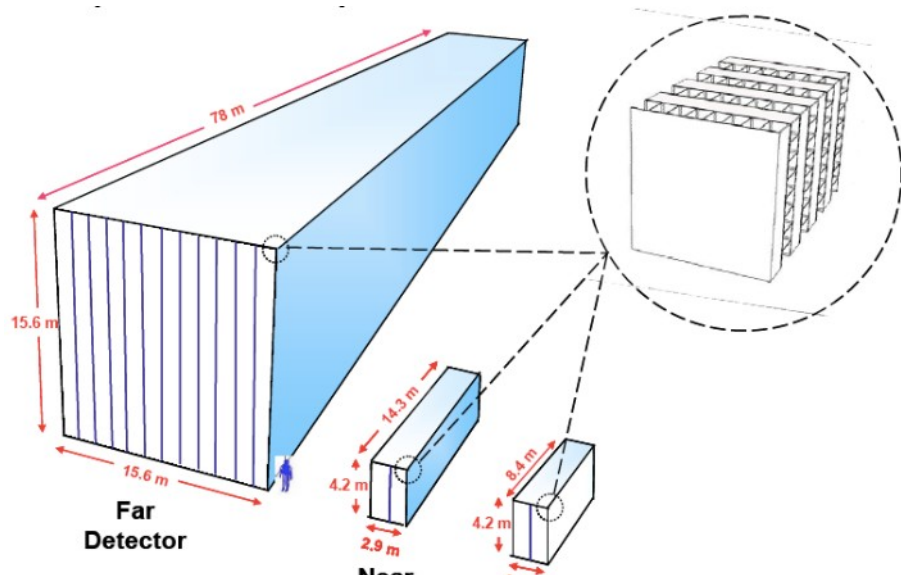


# T2K & MINOS experiments

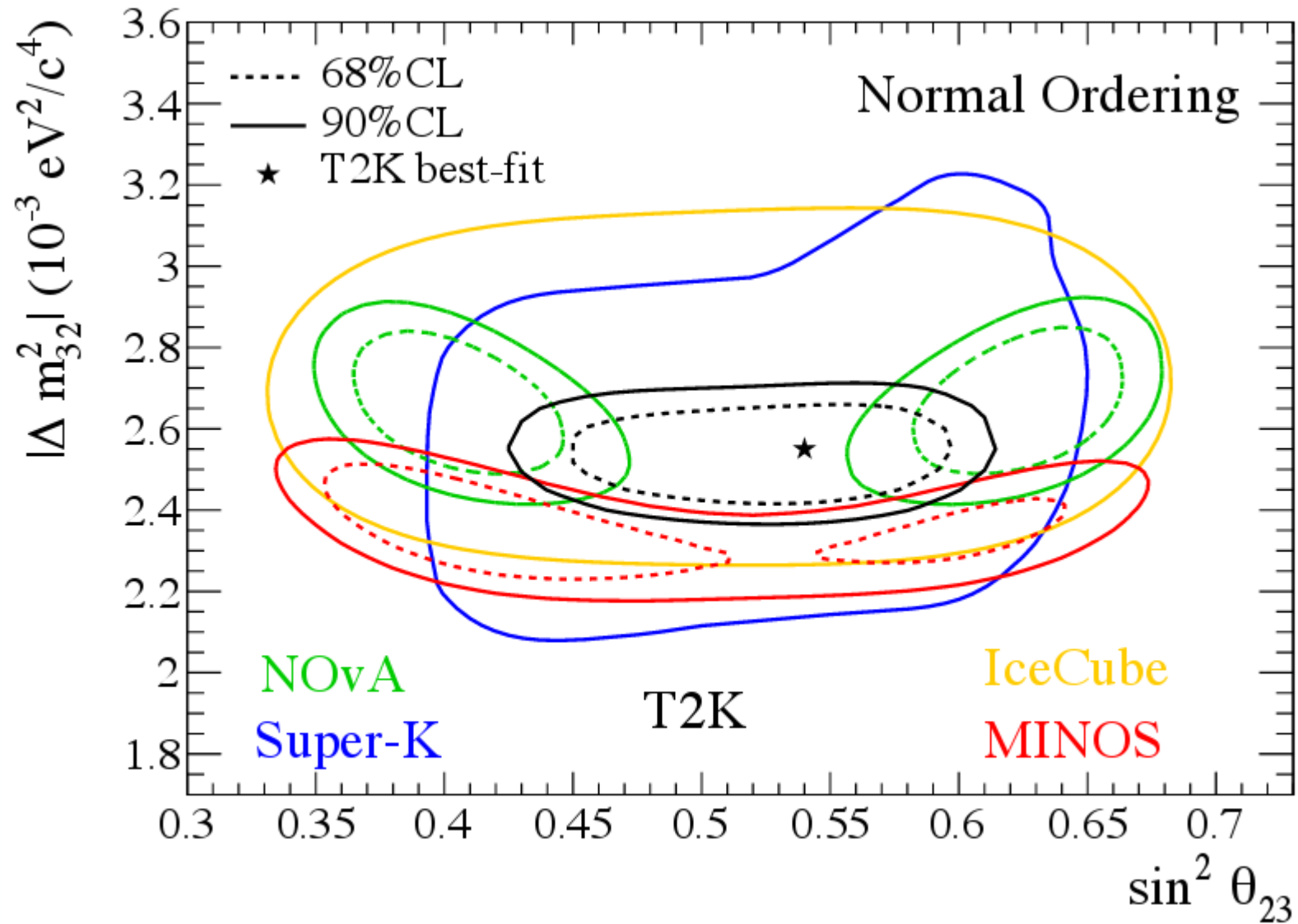




# NOvA

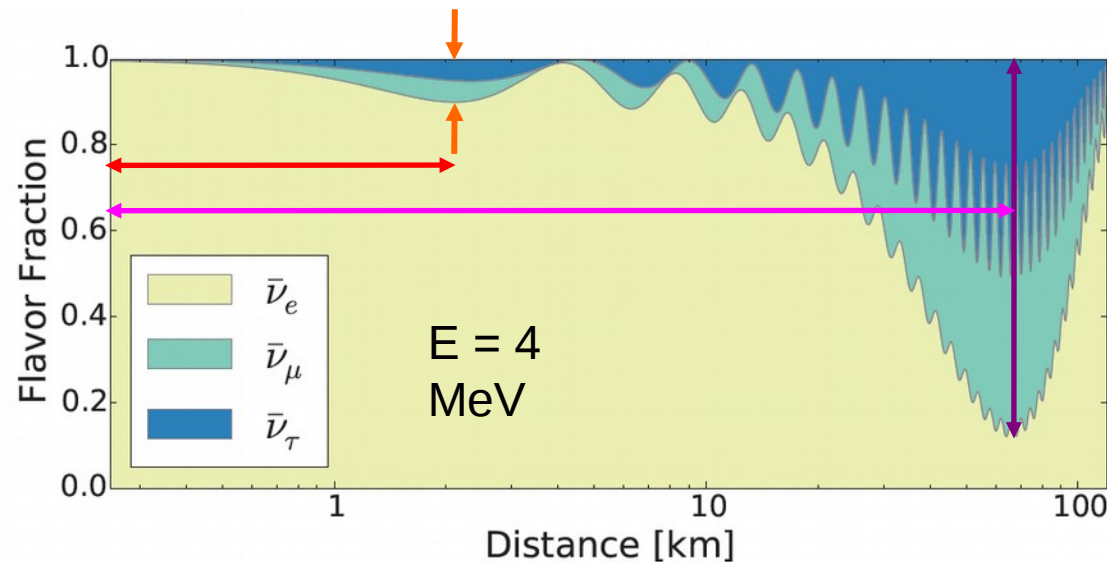


# SK (atm), T2K, MINOS, IceCube (atm), NOvA



# Measurement of $\theta_{13}$

# Measurement of $\theta_{13}$ with reactors



$$\begin{aligned}
 P_{ee}(L, E) &= \\
 &= 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right) \\
 &\quad - \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) \\
 &\quad - \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)
 \end{aligned}$$

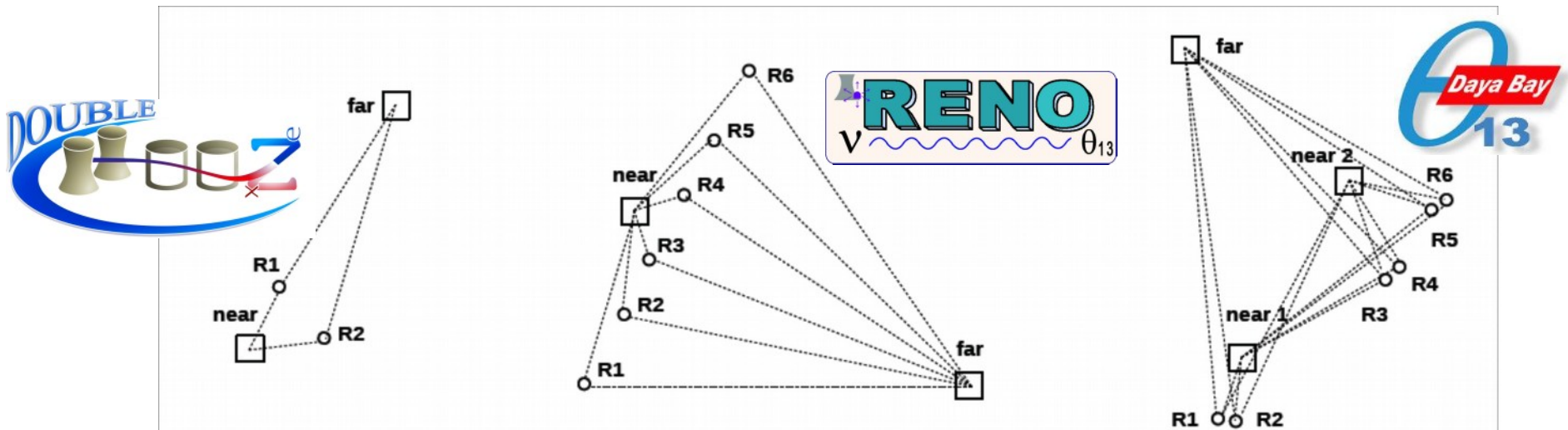
- For baselines of  $\sim 1$  km, the probability can be approximated by:

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



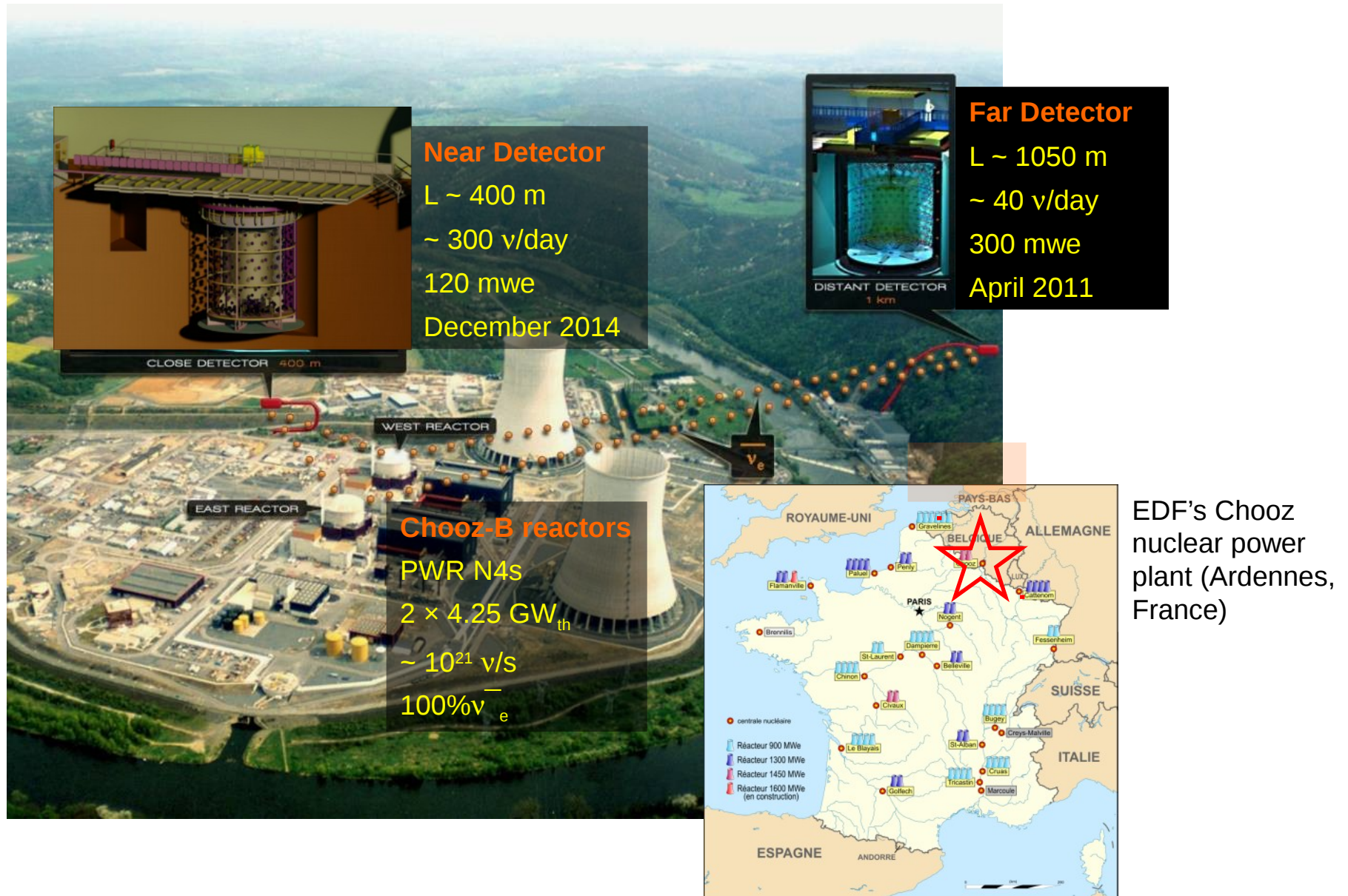
# Measurement of $\theta_{13}$ with two-detector reactor experiments

- Antineutrinos detected by inverse  $\beta$ -decay:  $\bar{\nu}_e + p \rightarrow e^+ + n$  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 <sub>th</sub> )	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



# Electron antineutrino detection

## Inverse Beta Decay (IBD):

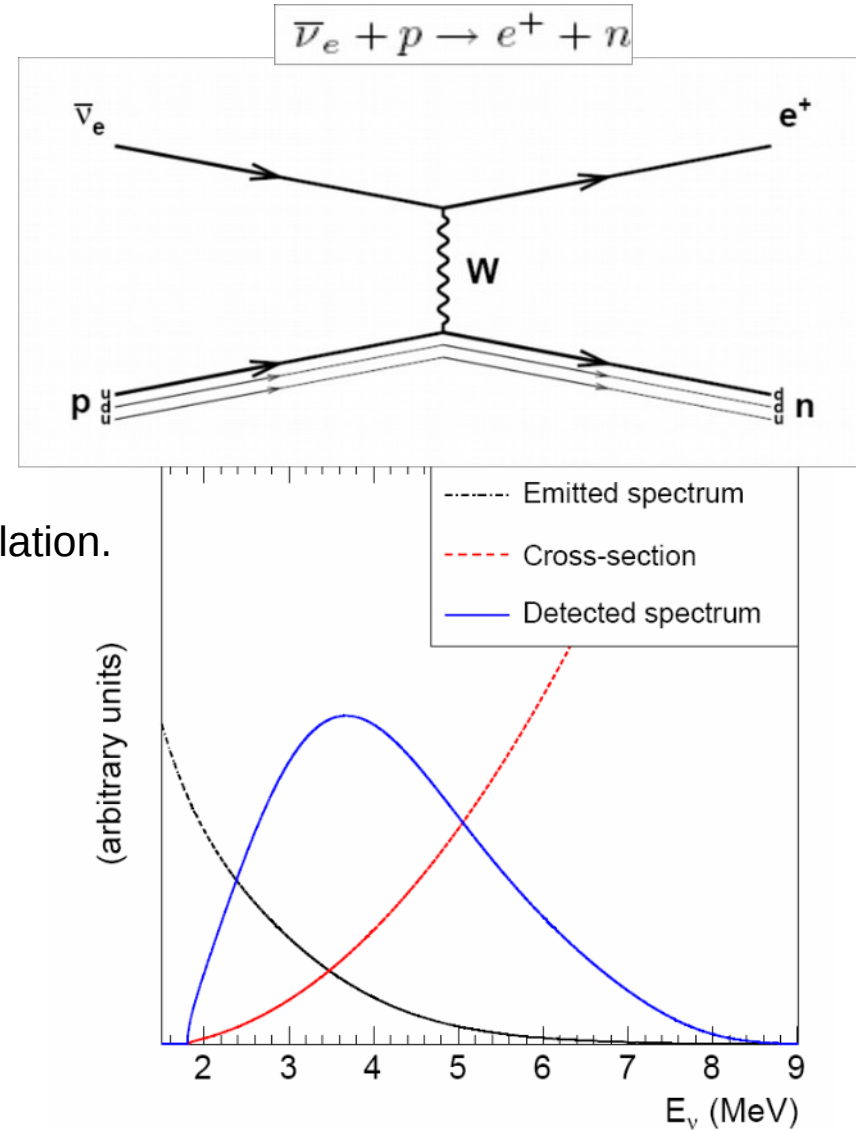
- Reaction threshold:  $E_\nu \geq 1.806$  MeV.
- Disappearance experiment.
- Well known cross-section (0.2%).
- Coincidence of 2 signals: background suppression.

## Prompt signal:

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

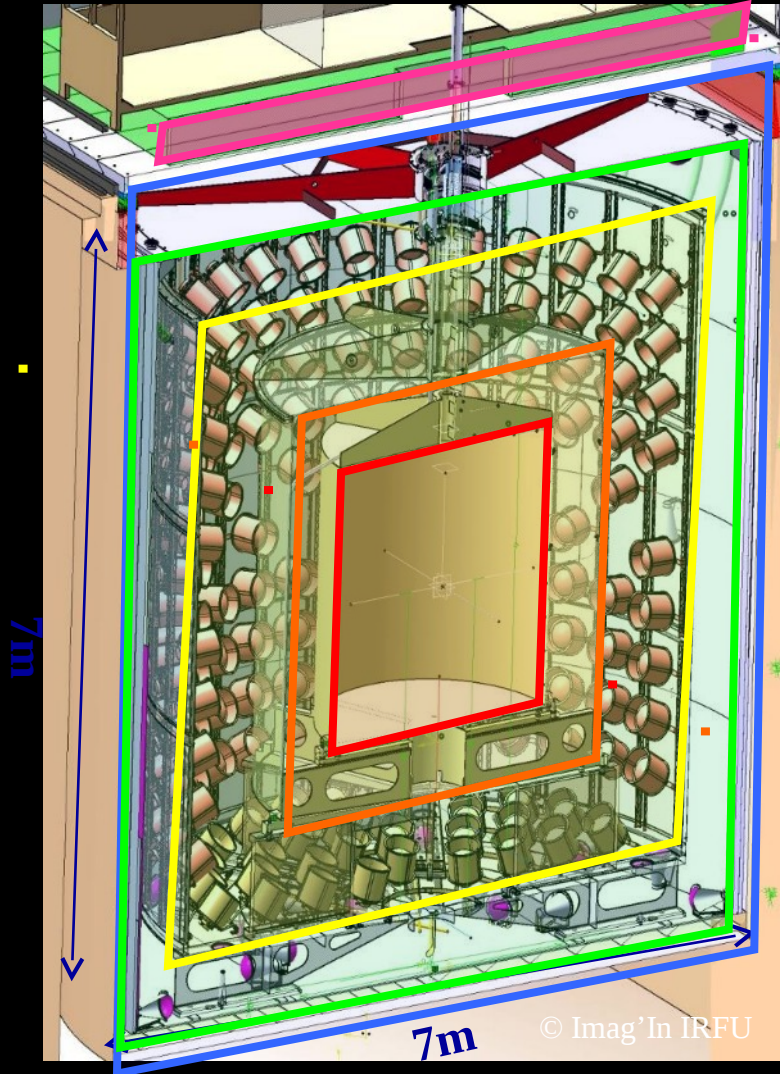
## Delayed signal:

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





# The Double Chooz Far Detector



## Inner Detector:

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

## Outer Detector:

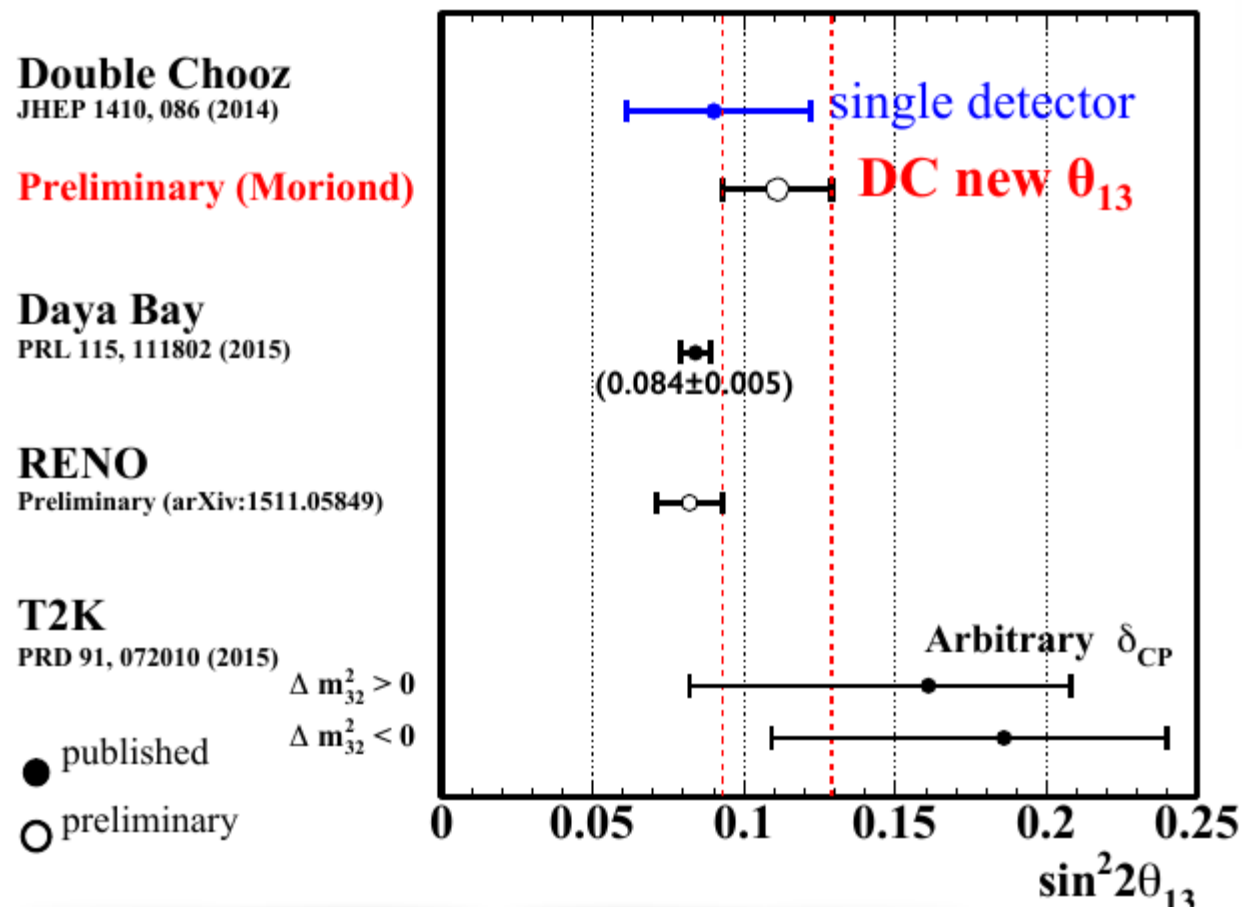
- **Inner Veto:** steel (10 mm) vessel supporting 78 8" PMTs, with 90 m<sup>3</sup> of liquid scintillator.
- **Shielding:** 15 cm steel.
- **Outer Veto:** plastic scintillator strips.





# Latests measurements of $\theta_{13}$

$\theta_{13}$  unknown until 2011. Huge progress in a few years.



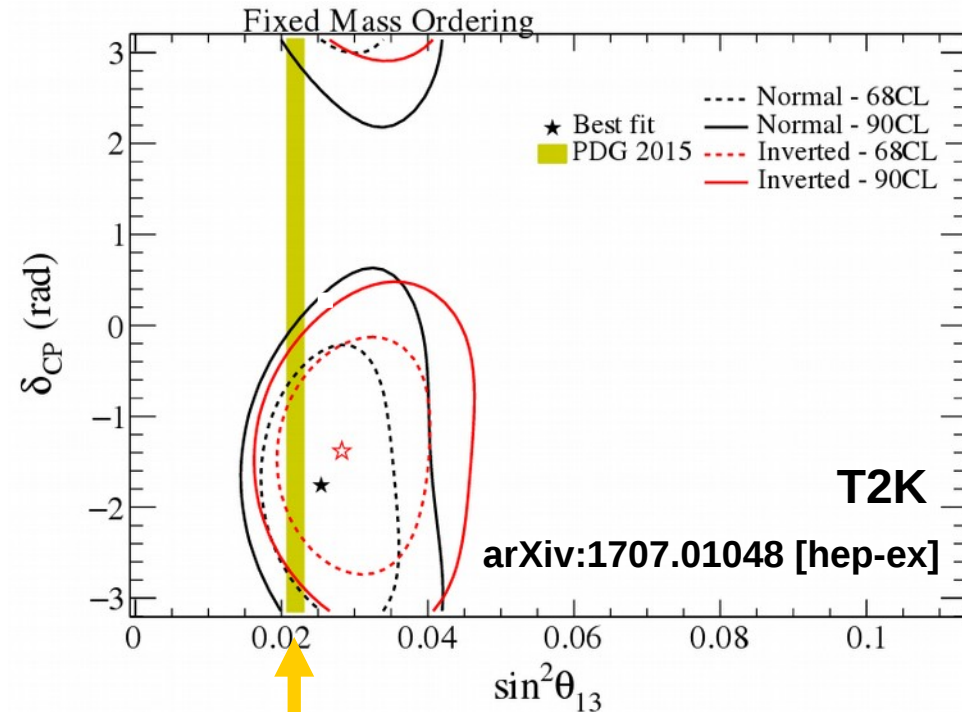
A. Cabrera, FNAL seminar 03/25/2016



# First glimpse of $\delta$

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

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



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

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

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

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

# 3 neutrinos: mixing matrix

PMNS matrix: U

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

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

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

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  $\delta$ ?

- Why so different from quark mixing?

$U_{\text{CKM}}$   
 $\parallel$   

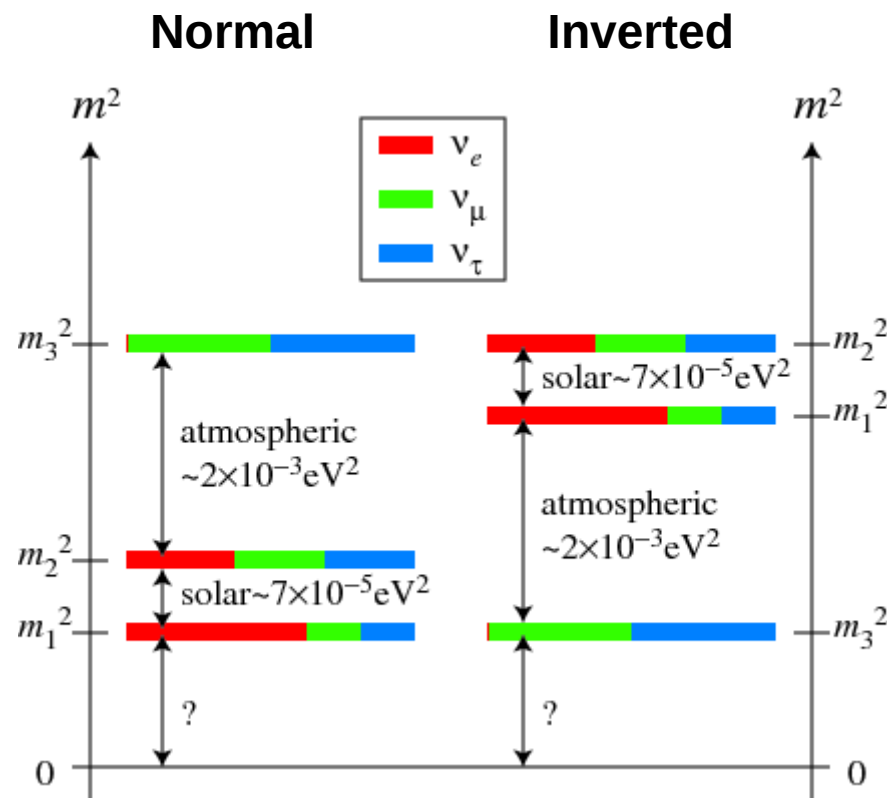
$$\begin{matrix} u \\ c \\ t \end{matrix} \begin{bmatrix} \text{blue} & \text{red} & \text{red} \\ \text{red} & \text{blue} & \text{red} \\ \text{red} & \text{red} & \text{blue} \end{bmatrix} \begin{matrix} d \\ s \\ b \end{matrix}$$

$U_{\text{PMNS}}$   
 $\parallel$   

$$\begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \begin{bmatrix} \text{blue} & \text{red} & \text{red} \\ \text{red} & \text{red} & \text{blue} \\ \text{red} & \text{red} & \text{blue} \end{bmatrix} \begin{matrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{matrix}$$

# 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  $\nu_2$  is heavier than  $\nu_1$ .**
- Which is the **lightest neutrino**? Two possibilities left:



# Future: $\delta$ 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.

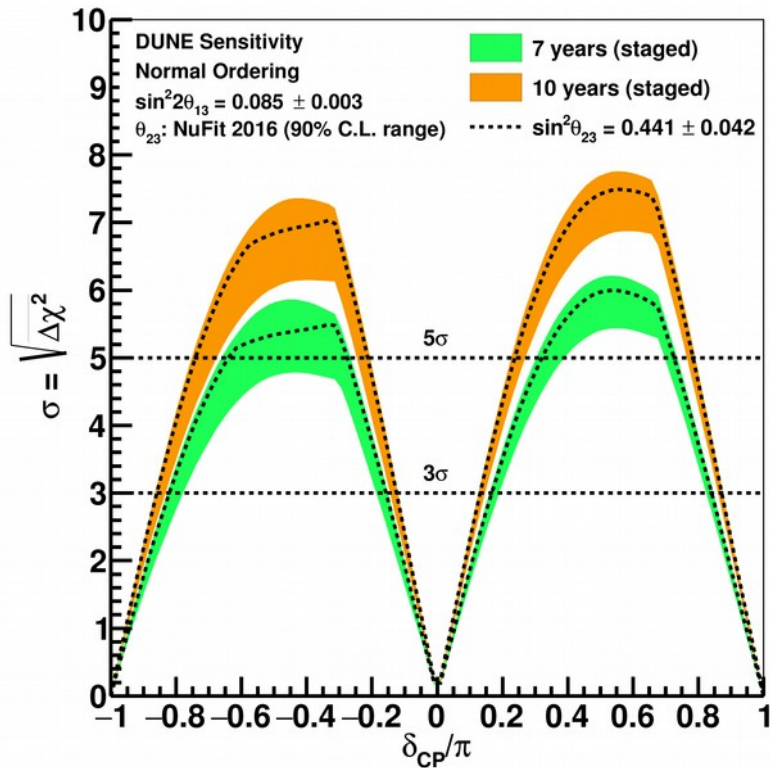


Neutrino beam expected by 2026.

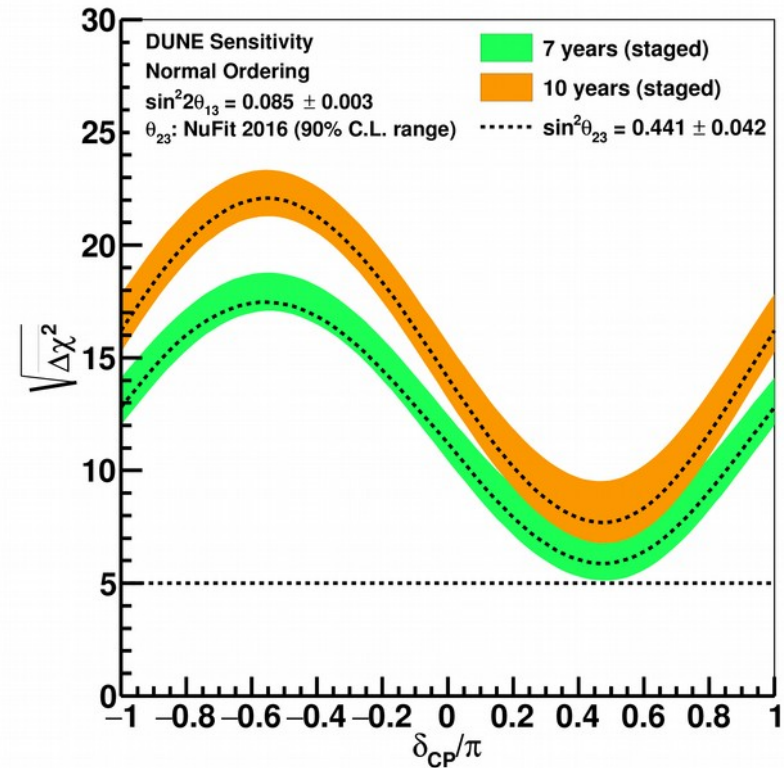


# DUNE

CP Violation Sensitivity

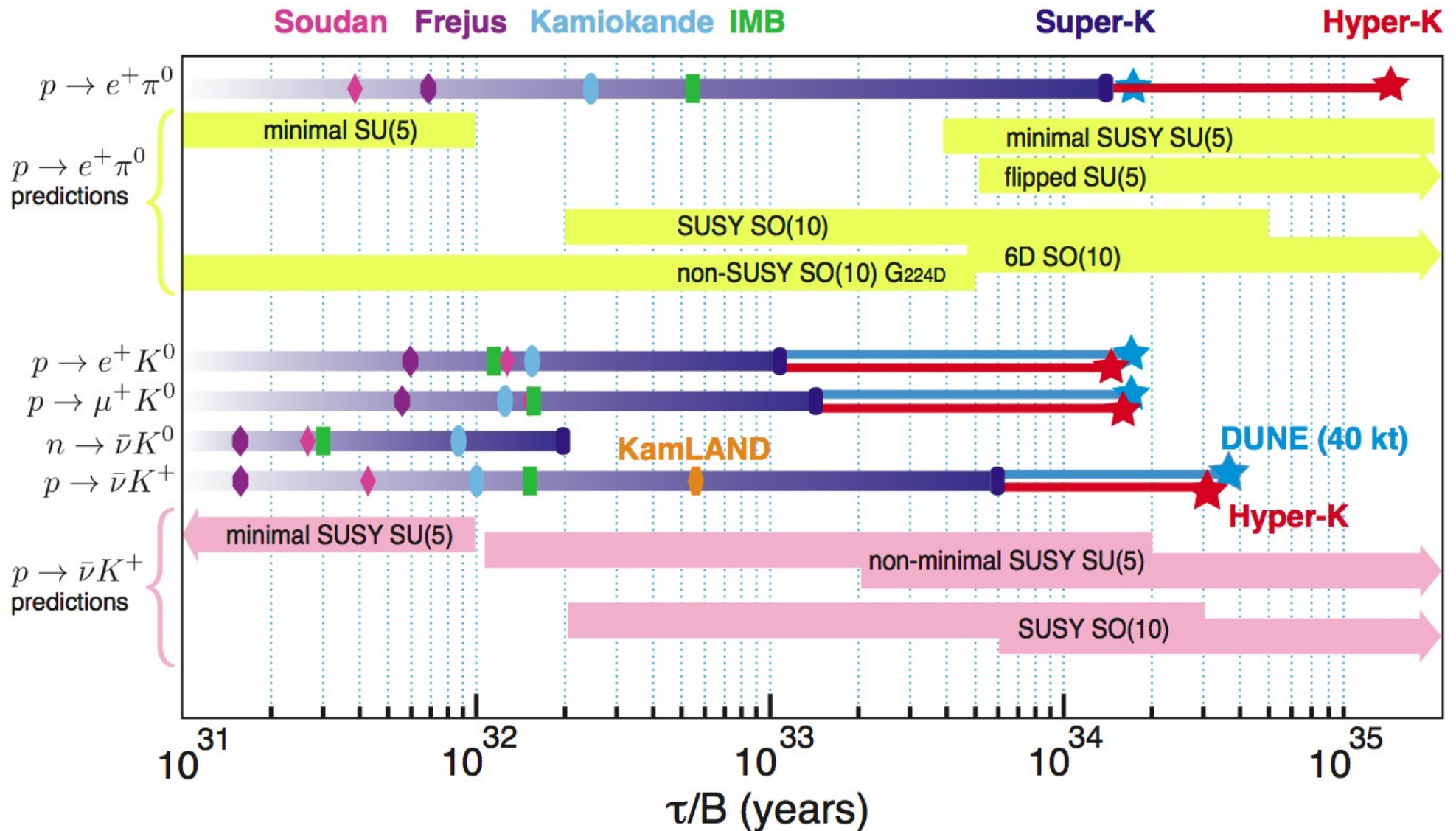


Mass Hierarchy Sensitivity



- > 5 $\sigma$  measurement of CP-violating phase if CP violation is close to maximal.
  - > 3 $\sigma$  measurement for 65% of  $\delta$  range.
- > 5 $\sigma$  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

