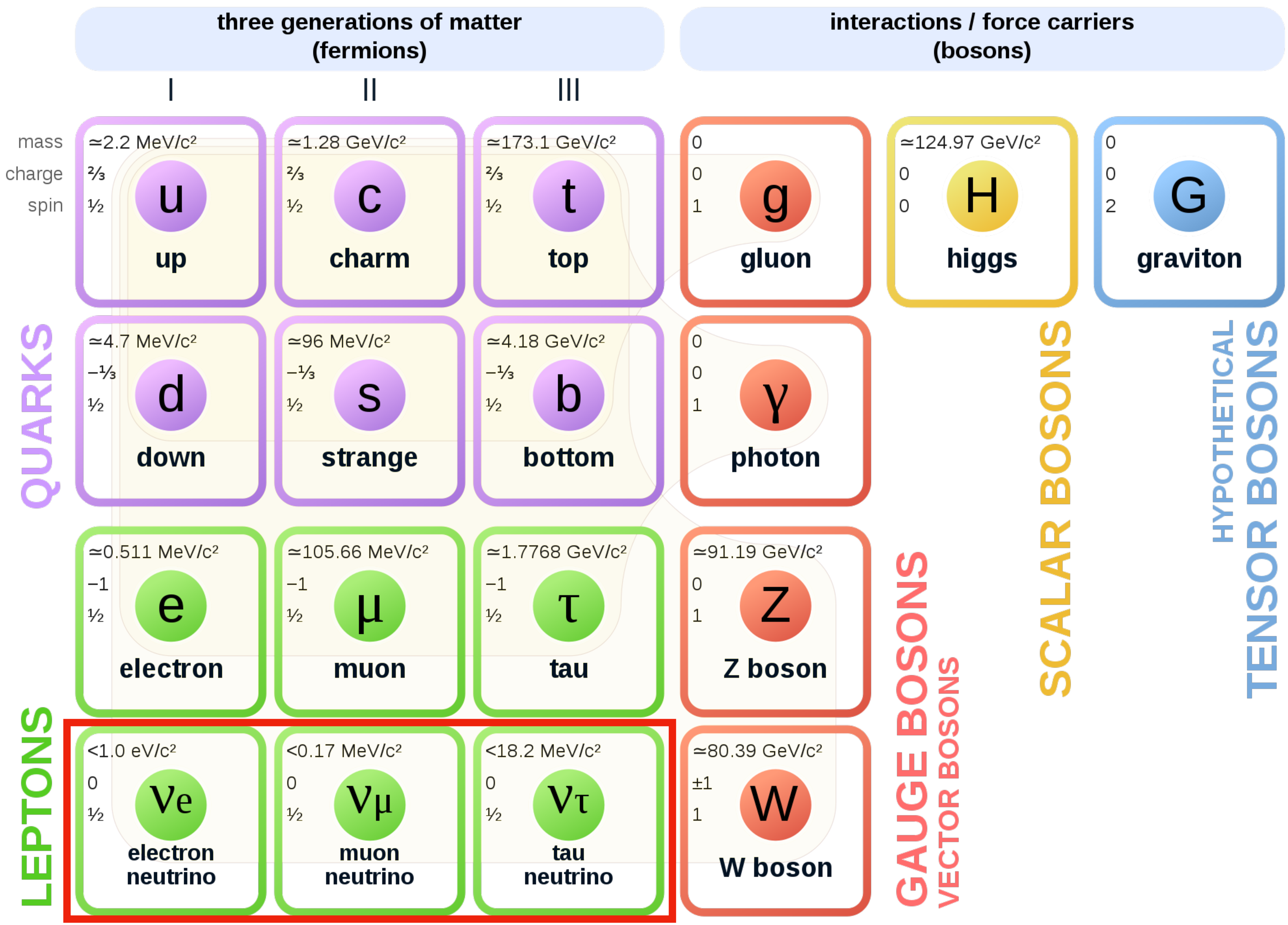
Neutrino Physics

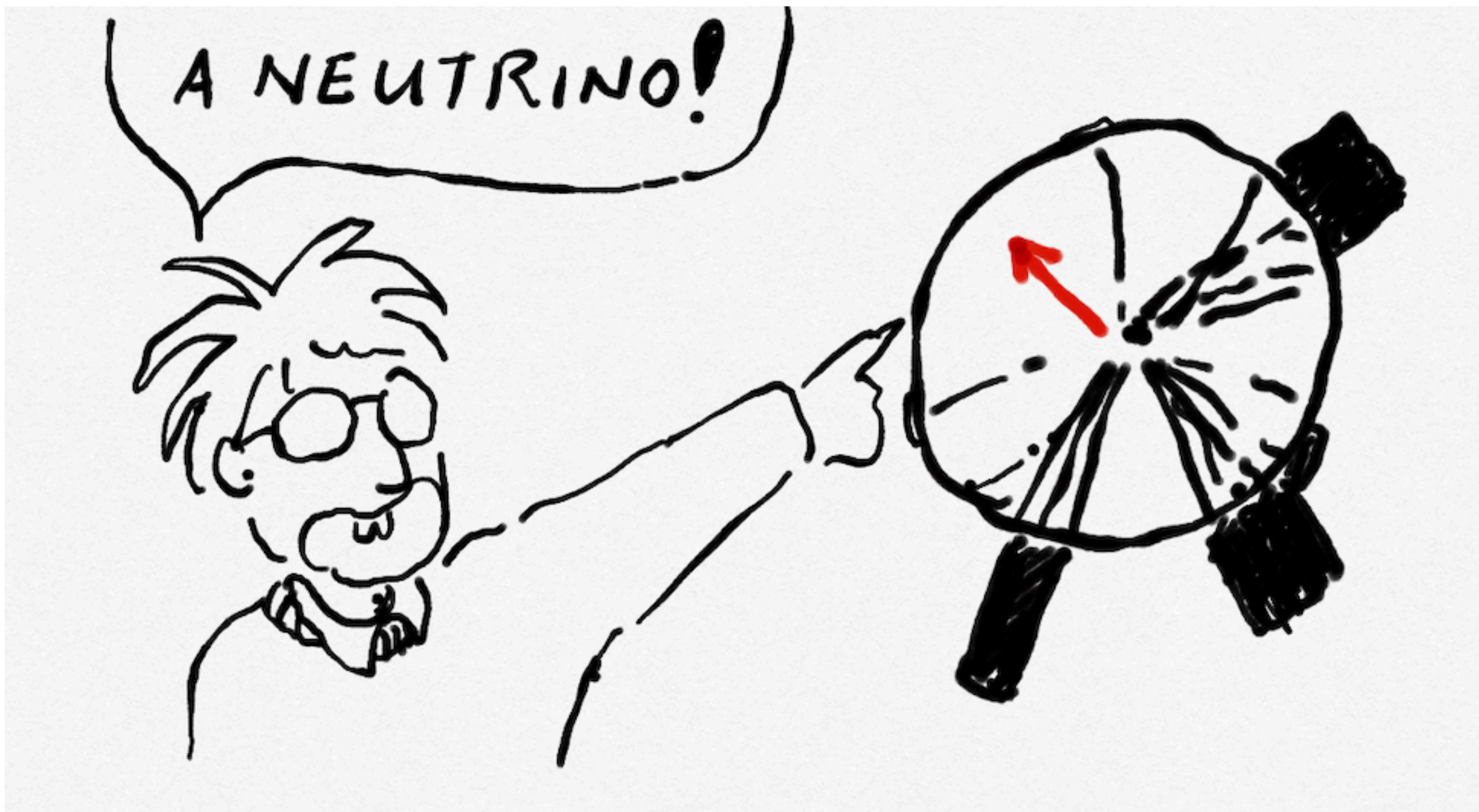
and other underground physics

Hyunsoo Kim (Sejong Univ.)

Standard Model of Elementary Particles and Gravity



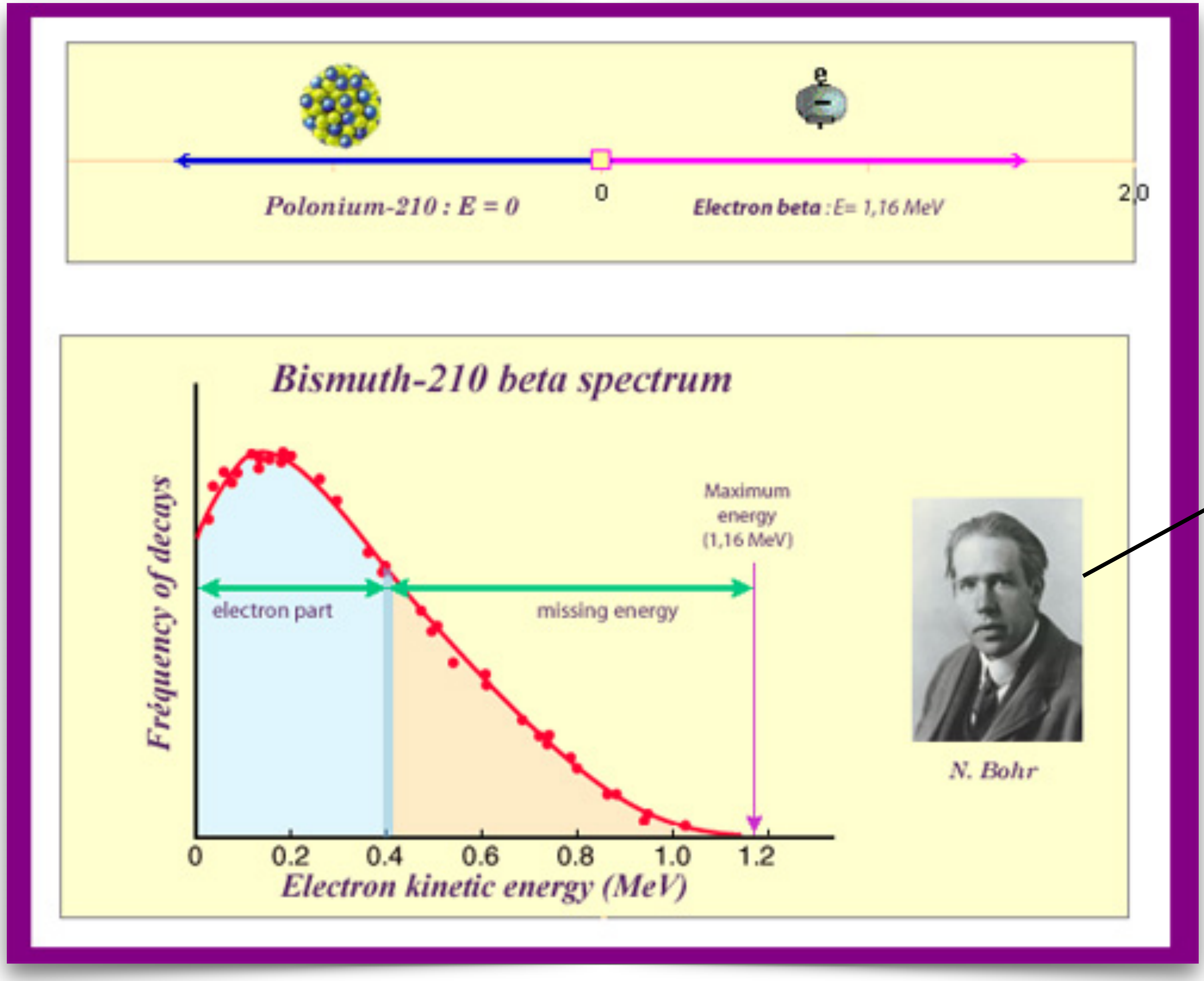
Neutrinos to Collider Physicists?



Neutrinos are more than the missing E_T.

The Beginning

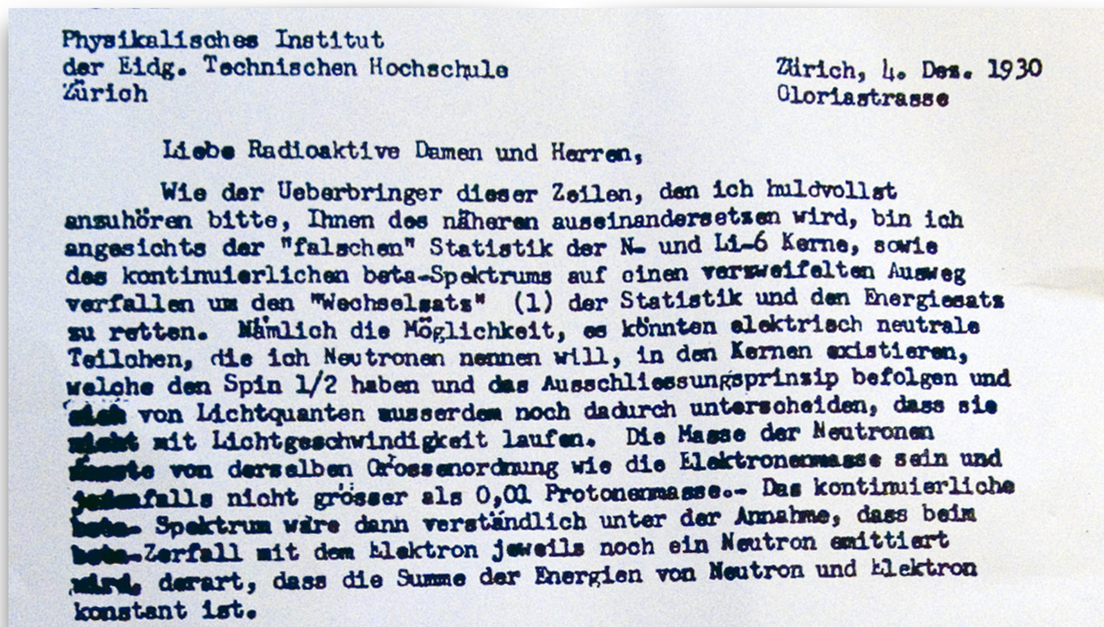
β-decay puzzle (1930s)



The law of energy conservation is held only in a statistical sense…

The Beginning

- Pauli's proposal for a new particle



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei **electrically neutral** particles, that I wish to call neutrons, which have **spin 1/2 and obey the exclusion principle** and which further differ from light quanta in that **they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass** and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

....

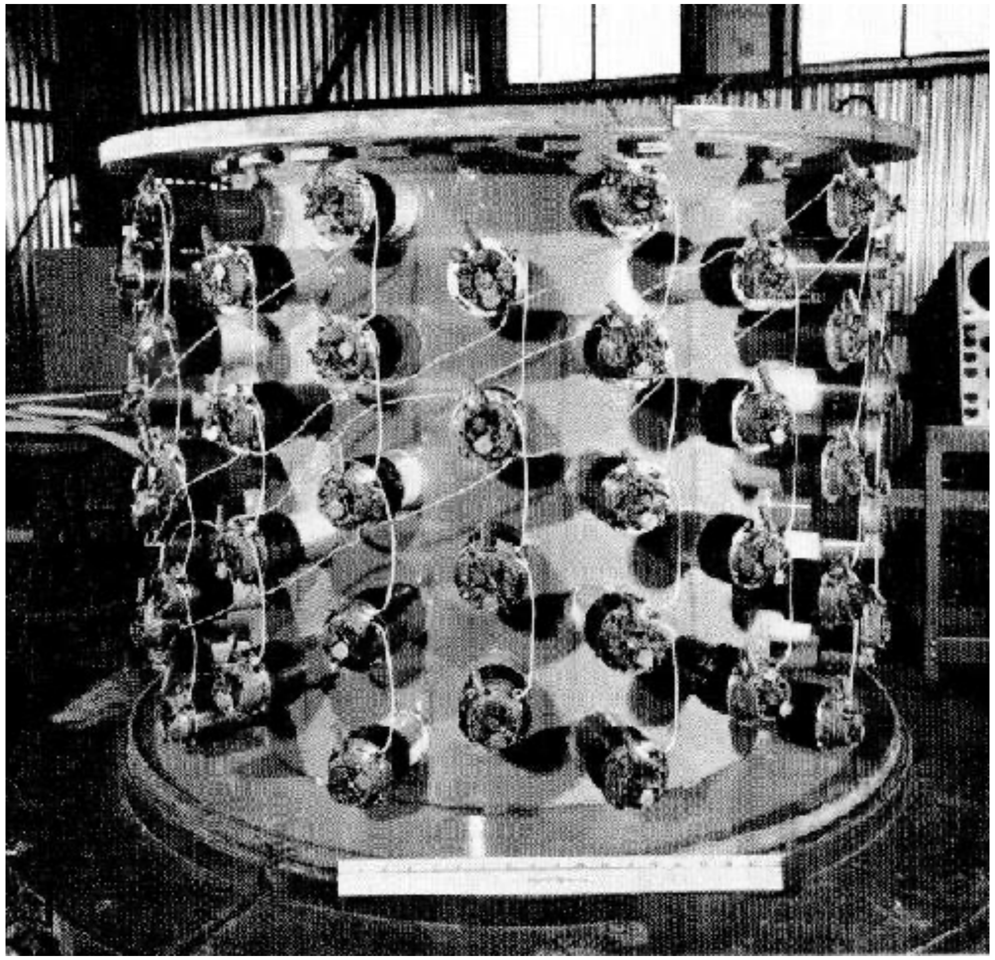
Your humble servant,

W. Pauli

The Discovery of Electron Neutrinos

- observed ~25 years later in 1956 by a group led by Cowan and Reines
- antineutrinos from a nuclear reactor at the Savannah River Plant in South Carolina
- a "target" consisting of cadmium chloride dissolved in water, surrounded by large detectors filled with a liquid scintillator
- inverse beta decay, in which a proton captures an antineutrino. $\bar{\nu}_e + p \rightarrow e^+ + n$

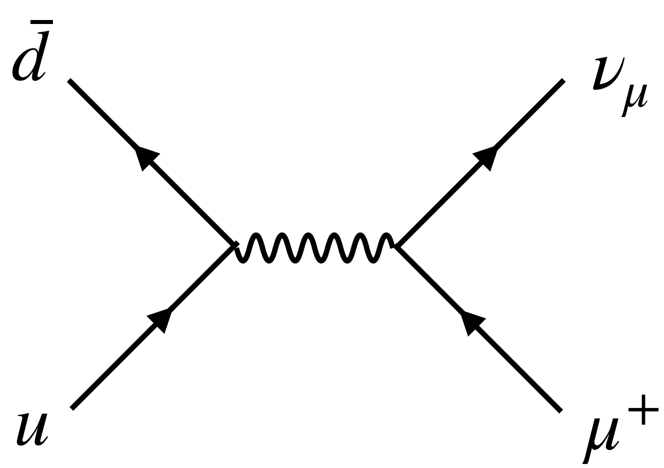
$$n + ^{108}\mathrm{Cd} \rightarrow ^{109m}\mathrm{Cd} \rightarrow ^{109}\mathrm{Cd} + \gamma$$



https://neutrino-history.in2p3.fr/experimental-discovery/

The Discovery of Muon Neutrino

- Discovered in1962 by Lederman, Schwartz, and Steinberger
- Used a detector consisting of spark chambers and scintillators
- This new neutrino is produced together with the muon in the decay of a pion.



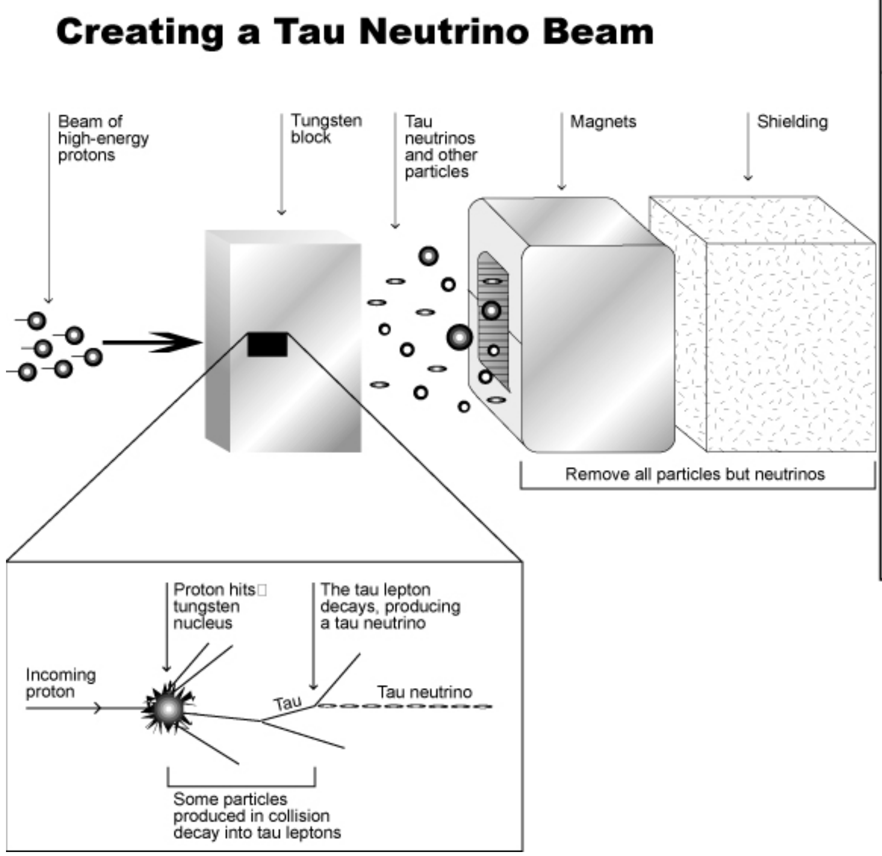
Melvin Schwartz standing next to spark chamber.

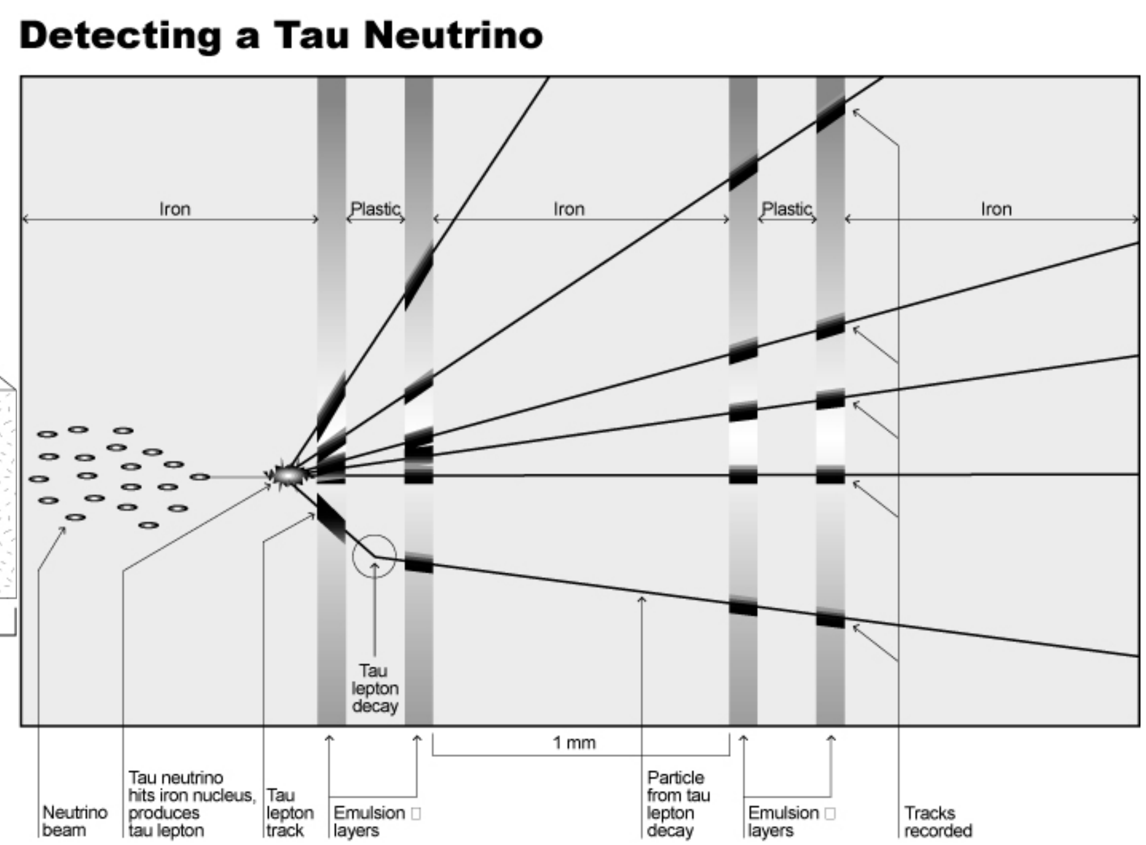
https://www.bnl.gov/bnlweb/history/nobel/1988.php

The Discovery of Tau Neutrino

- Tau lepton discovered in 1975 implying the existence of tau neutrinos.
- Tau neutrino discovered in 2000 by Donut experiment.

  Neutrino beam interacting with target produced tau leptons.





Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.

https://news.fnal.gov/2000/07/physicists-find-first-direct-evidence-tau-neutrino-fermilab/signal/

Three types of light neutrinos

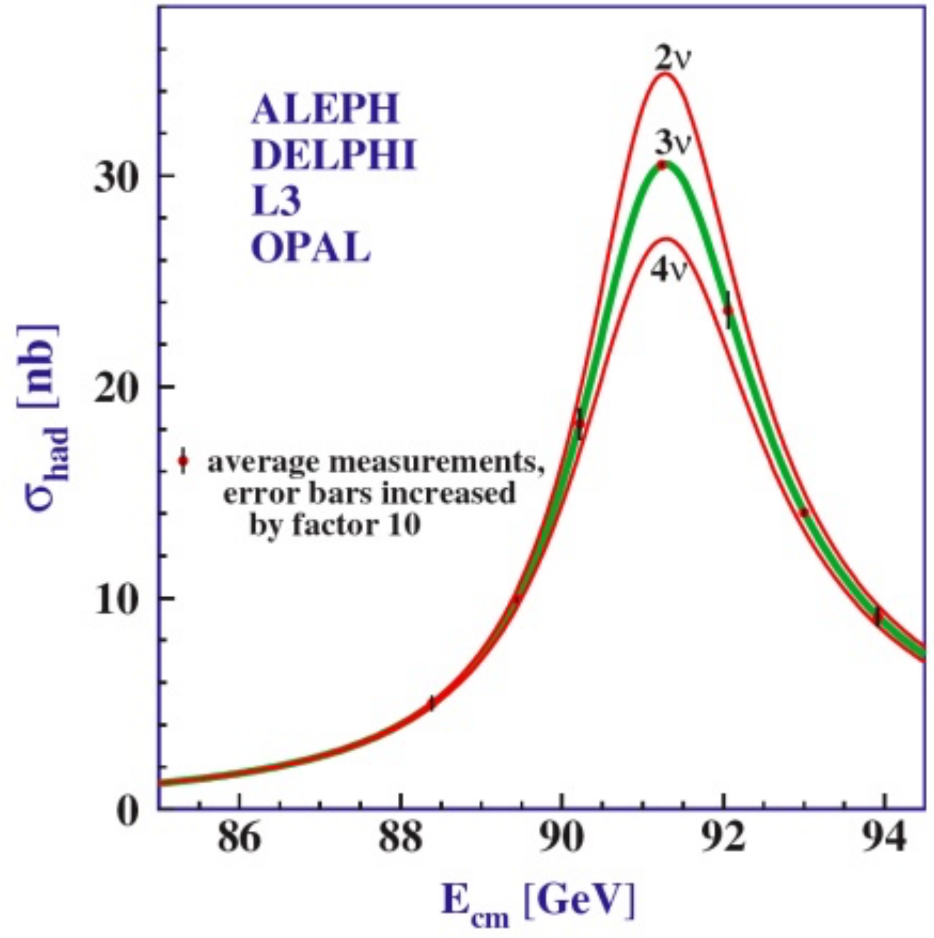
- Z width measured at LEP experiments showed that there are three types of neutrinos participating in the weak interaction.

$$N_\nu = 2.92 \pm 0.05$$

- Using LEP-SLC Bhabha cross section calculation for corrections

$$N_\nu = 2.9963 \pm 0.0074$$

- N_ν is also constrained by astrophysical data pointing at three types of neutrinos.



Neutrinos by the number

Charge neutral (electric, strong)

Interact only via weak interactions

spin 1/2

Very, very light ($m_{\nu_e} < 0.8\ \mathrm{eV}$)

Left-handed (right-handed for anti-particles)

Three flavors (so far)

Abundant ($7 \times 10^{10}\ /(\mathrm{cm}^2 \cdot \mathrm{s})$) on Earth

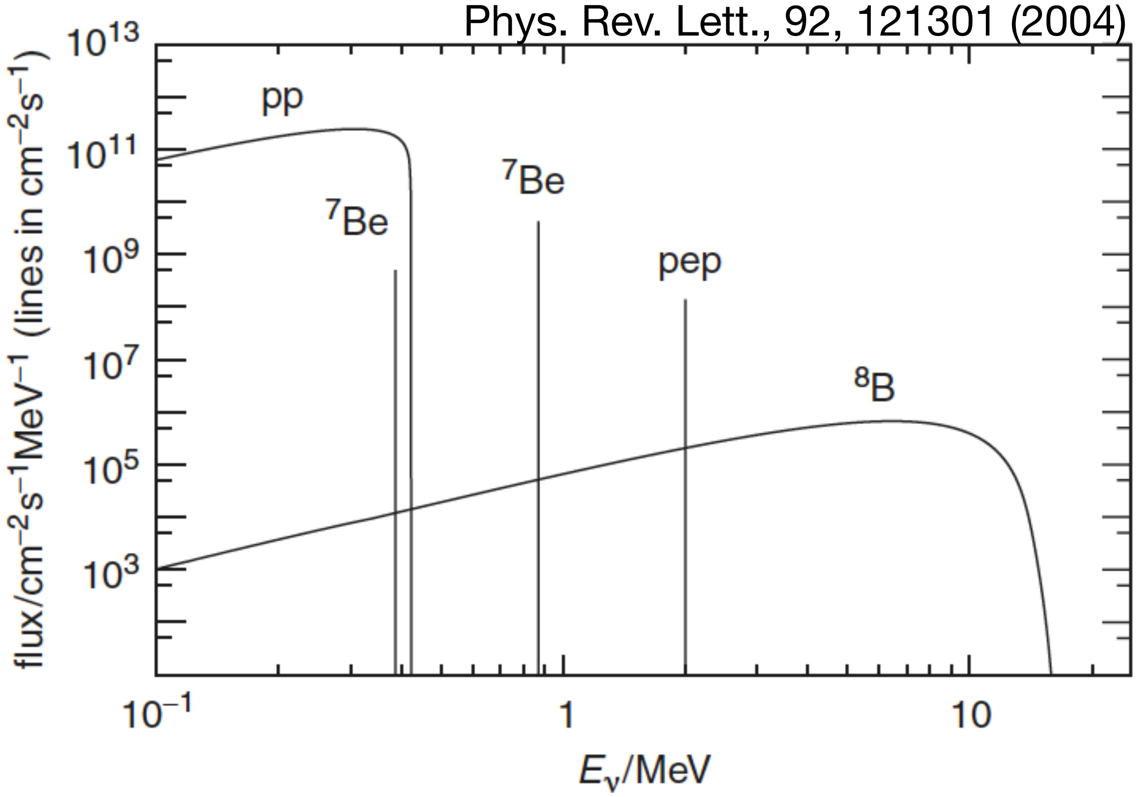
Changes flavors

Evidence of Neutrino flavor chage

- In late 1960s, Davis and Bahcall's experiment measured flux of neutrinos from the Sun.
  - Number of detected electron neutrinos coming from the Sun is 1/3 of that expected from the Sun's luminosity. (The solar neutrino problem)
  - The deficit was confirmed by many subsequent experiments including Kamiokande and SNO experiments.
- Deficit of up-going muon neutrinos measured Super Kamiokande experiment compared to the expectation.
  - SNO experiment measured ^{8}B neutrinos (10 MeV) and found that the total number of neutrinos of all flavors consistent with expectation of ^{8}B neutrinos.

Solar Neutrino Experiments

Phys. Rev. Lett., 92, 121301 (2004)



$$p + p \to D + e^+ + \nu_e$$

$$^7\text{Be} + e^- \to {}^7\text{Li} + \nu_e$$

$$p + e^- + p \to {}^2\text{H} + \nu_e$$

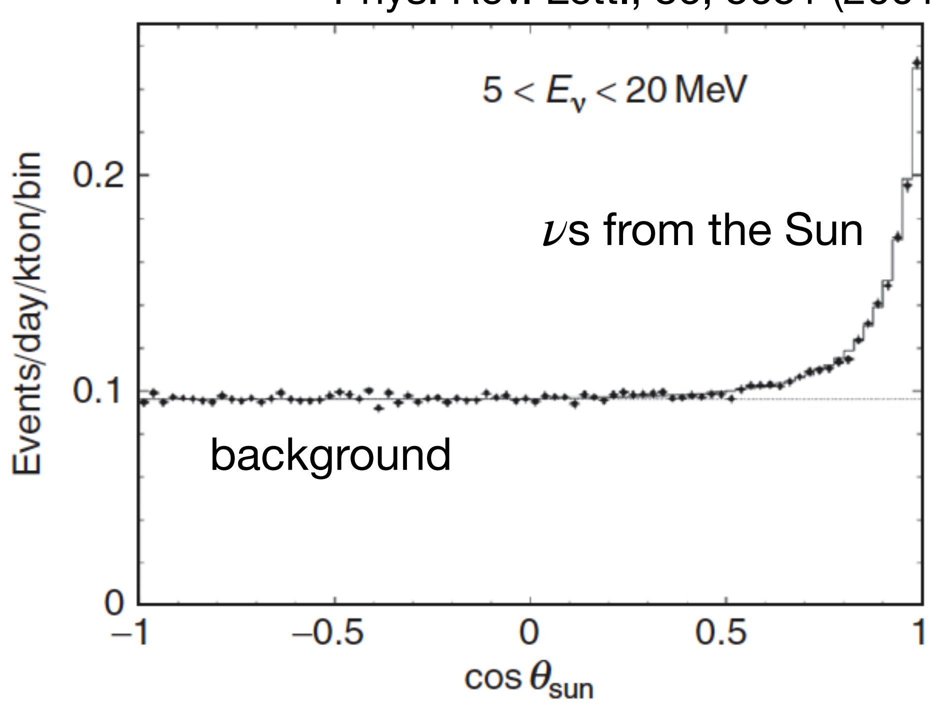
$$^8_5\text{B} \to {}^8_4\text{Be}^* + e^+ + \nu_e$$

produce only electron neutrinos

Homestake experiment

$$\nu_e + {}^{37}\text{Cl} \to {}^{37}\text{Ar} + e^-$$

Phys. Rev. Lett., 86, 5651 (2001)



A 20 year experiment using a tank of chlorine found only a 1/3 of expected rate. (The solar neutrino problem.)

Same for the Kamiokande experiment

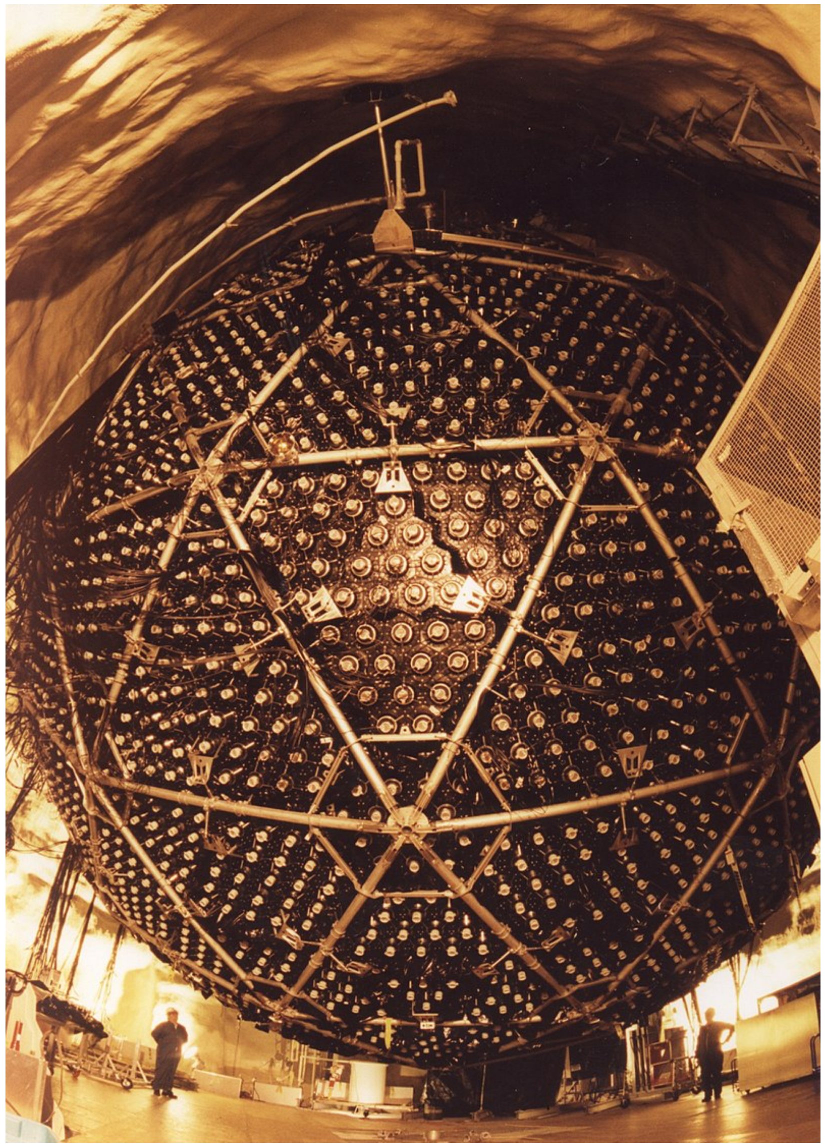
SNO experiment

- A 1 kton heavy water Cherenkov detector
- Can detect electron neutrinos (CC) and neutrinos of all flavors (NC)

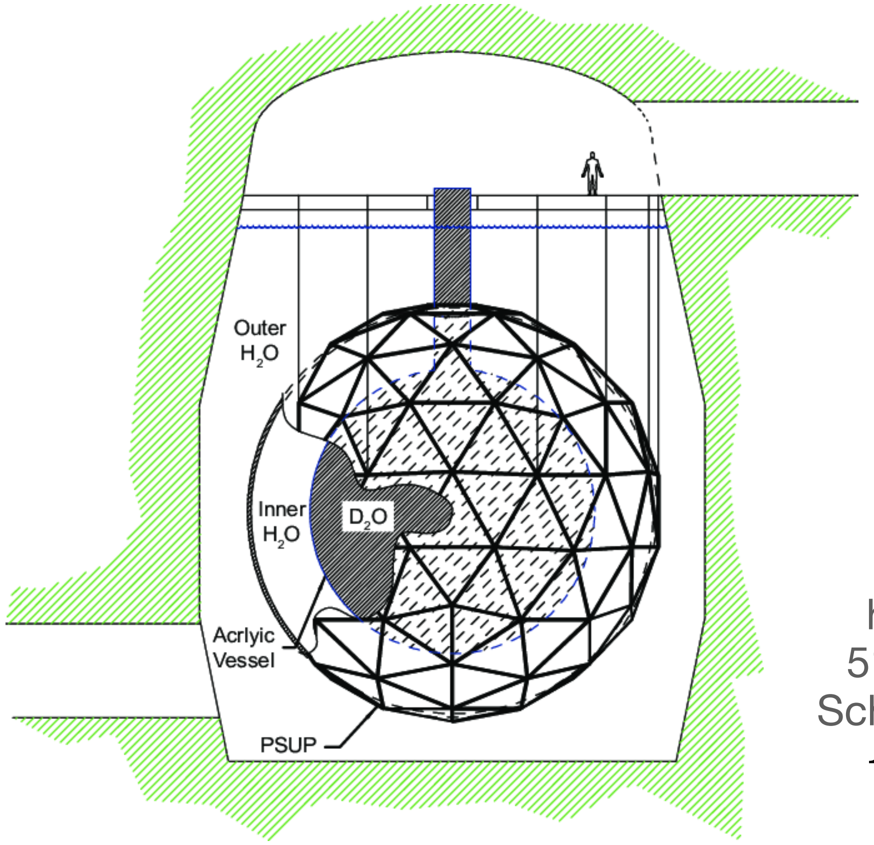
$$\nu_e + \mathrm{d} \rightarrow p + p + e^- \quad \text{(CC)}$$

$$\nu_x + \mathrm{d} \rightarrow n + p + \nu_x \quad \text{(NC)}$$

- Significant deficit in the CC/NC ratio indicates that the Sun's electron neutrinos were changing to one of other two types.



By (Courtesy of SNO) - (Courtesy of SNO), CC BY-SA 4.0, https://en.wikipedia.org/w/index.php?curid=56786015

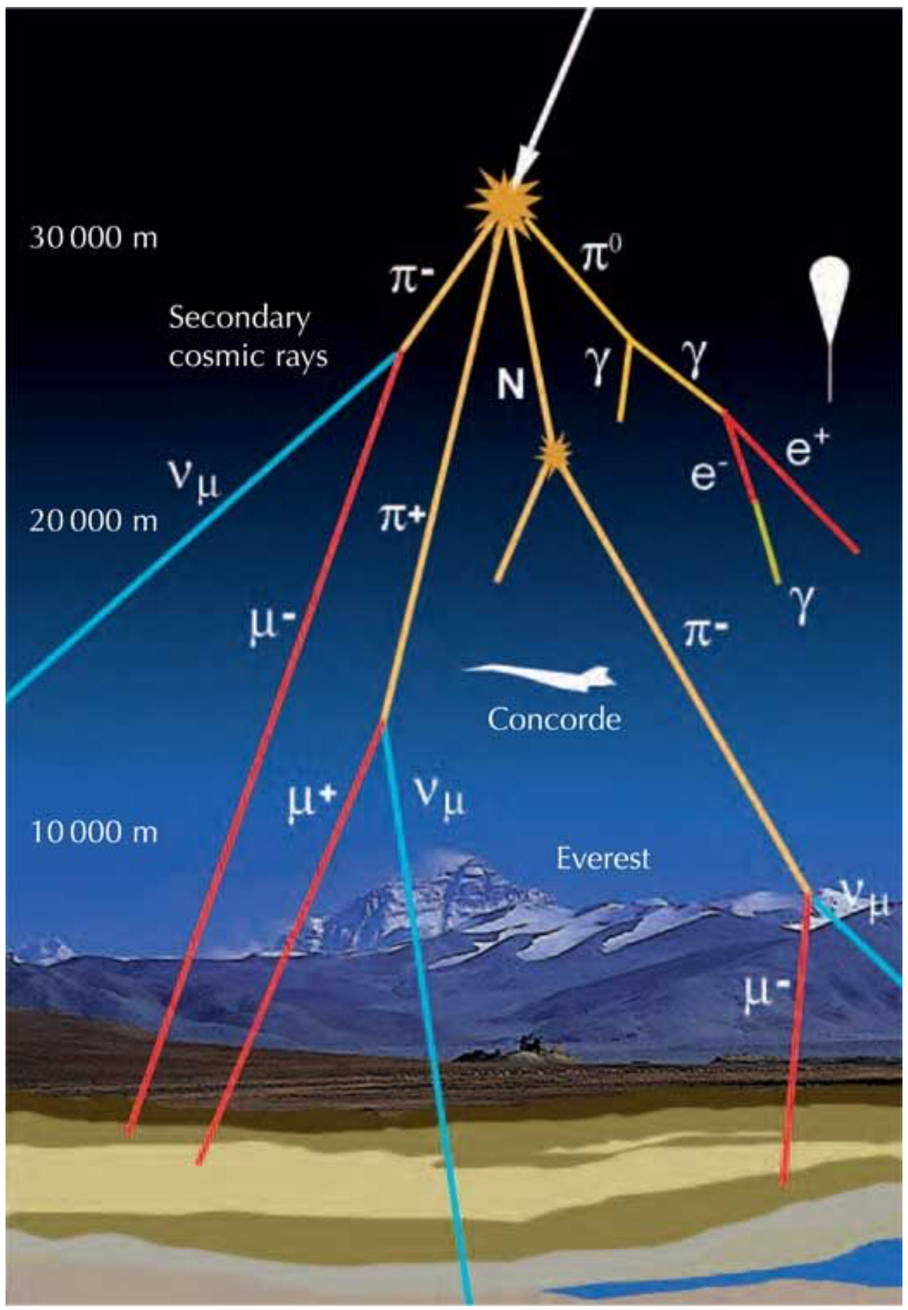


https://www.researchgate.net/profile/Awp-Poon/publication/51936565/figure/fig1/AS:669021166923776@1536518484174/Schematic-diagram-of-the-SNO-detector-We-used-a-coordinate-system-with-the-center-of-the.png

Atmospheric Neutrinos

Up to 10^{20} GeV cosmic rays interact in the upper atmosphere of the Earth.

Mostly interact hadronically giving showers of mainly pions.



$$\pi^+ \to \mu^+\nu_\mu,\ \mu^+ \to e^+\nu_e\bar{\nu}_\mu$$

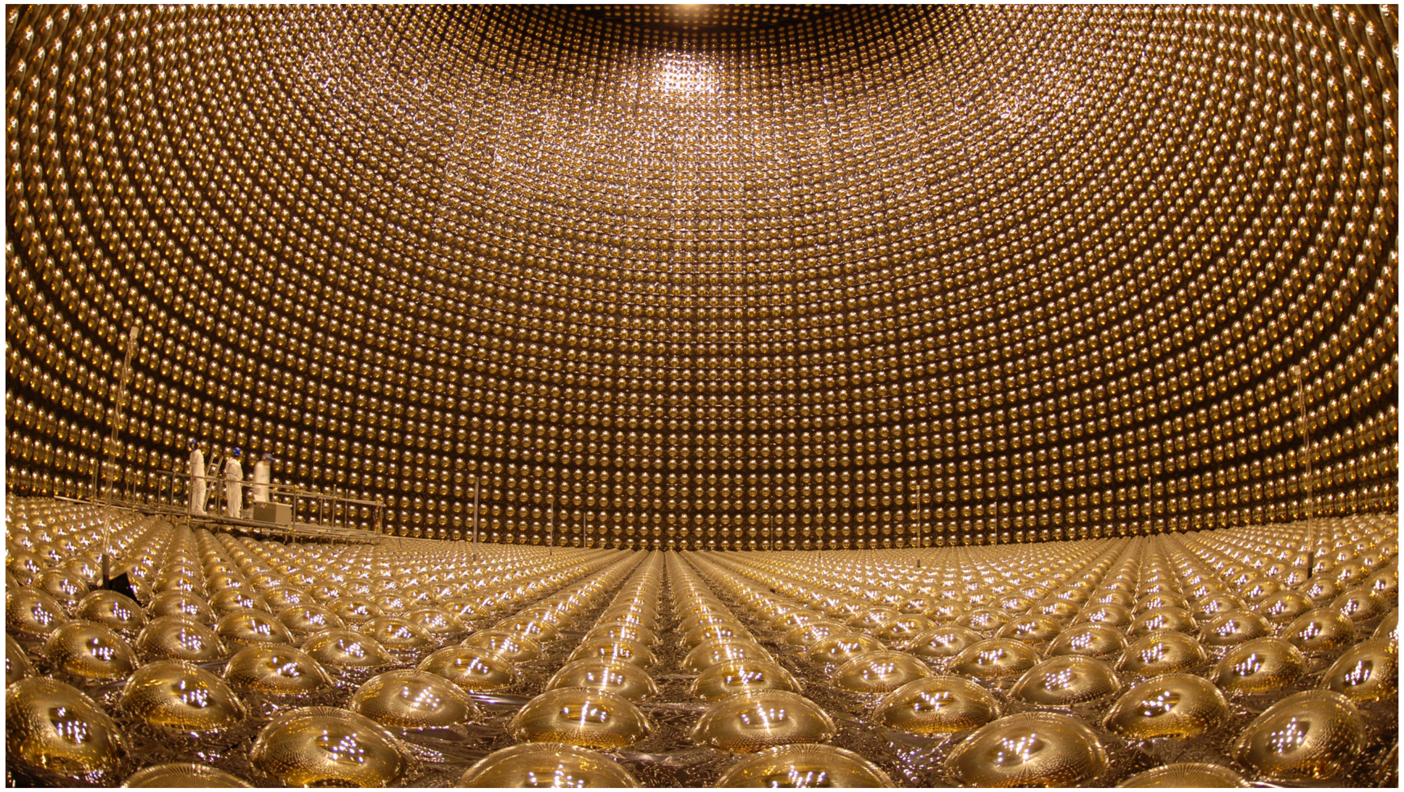
$$\pi^- \to \mu^-\bar{\nu}_\mu,\ \mu^- \to e^-\bar{\nu}_e\nu_\mu$$

Typical energy: $E_\nu \sim 1\ \mathrm{GeV}$

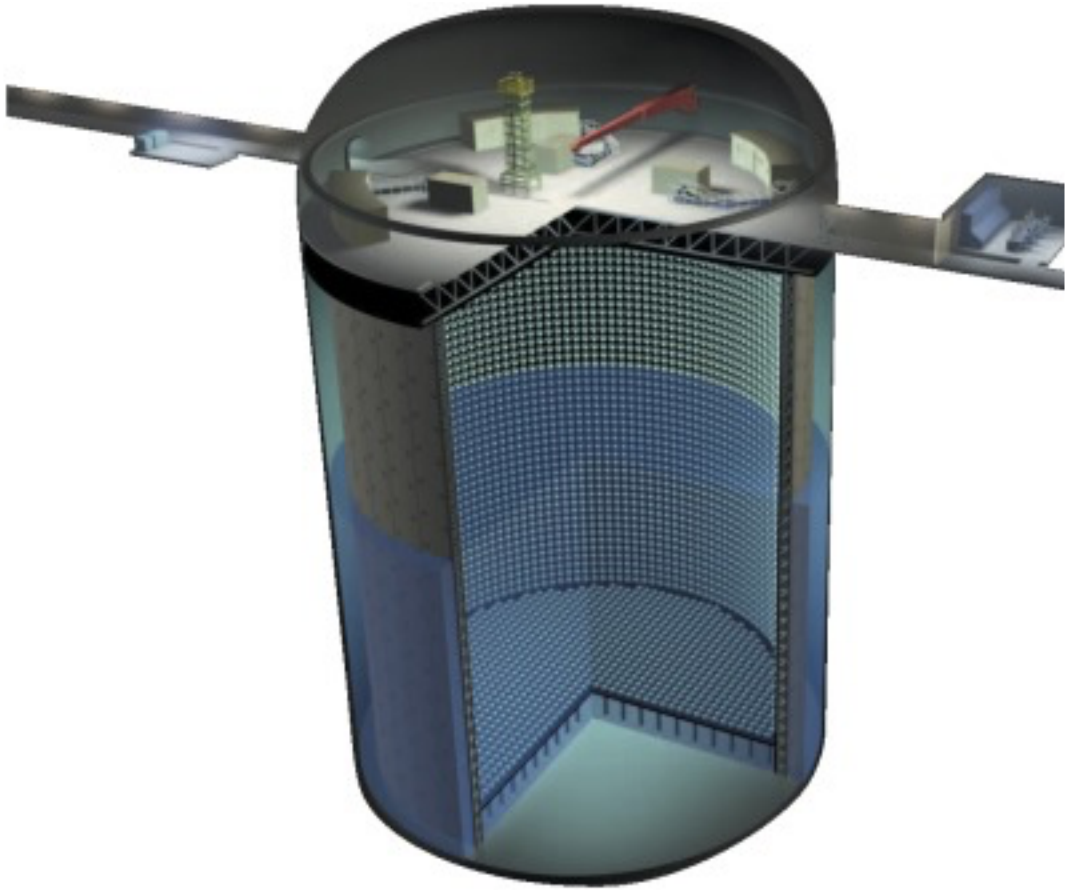
Expect $\dfrac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} \approx 2$

Observe a lower ratio with deficit of ν_μ/ν_e coming from below the horizon, i.e. large distance from production point on other side of the Earth

Super-Kamiokande Experiment

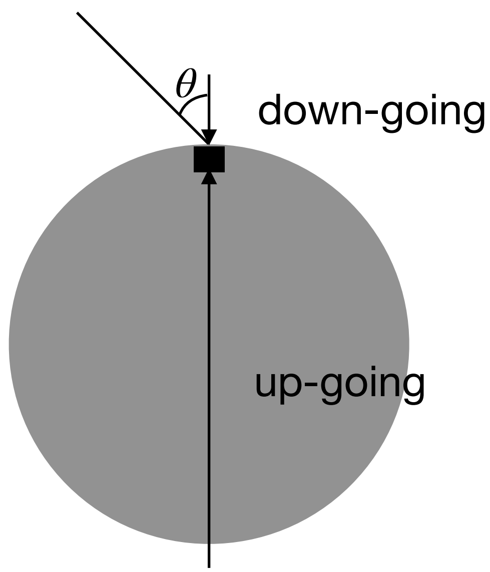


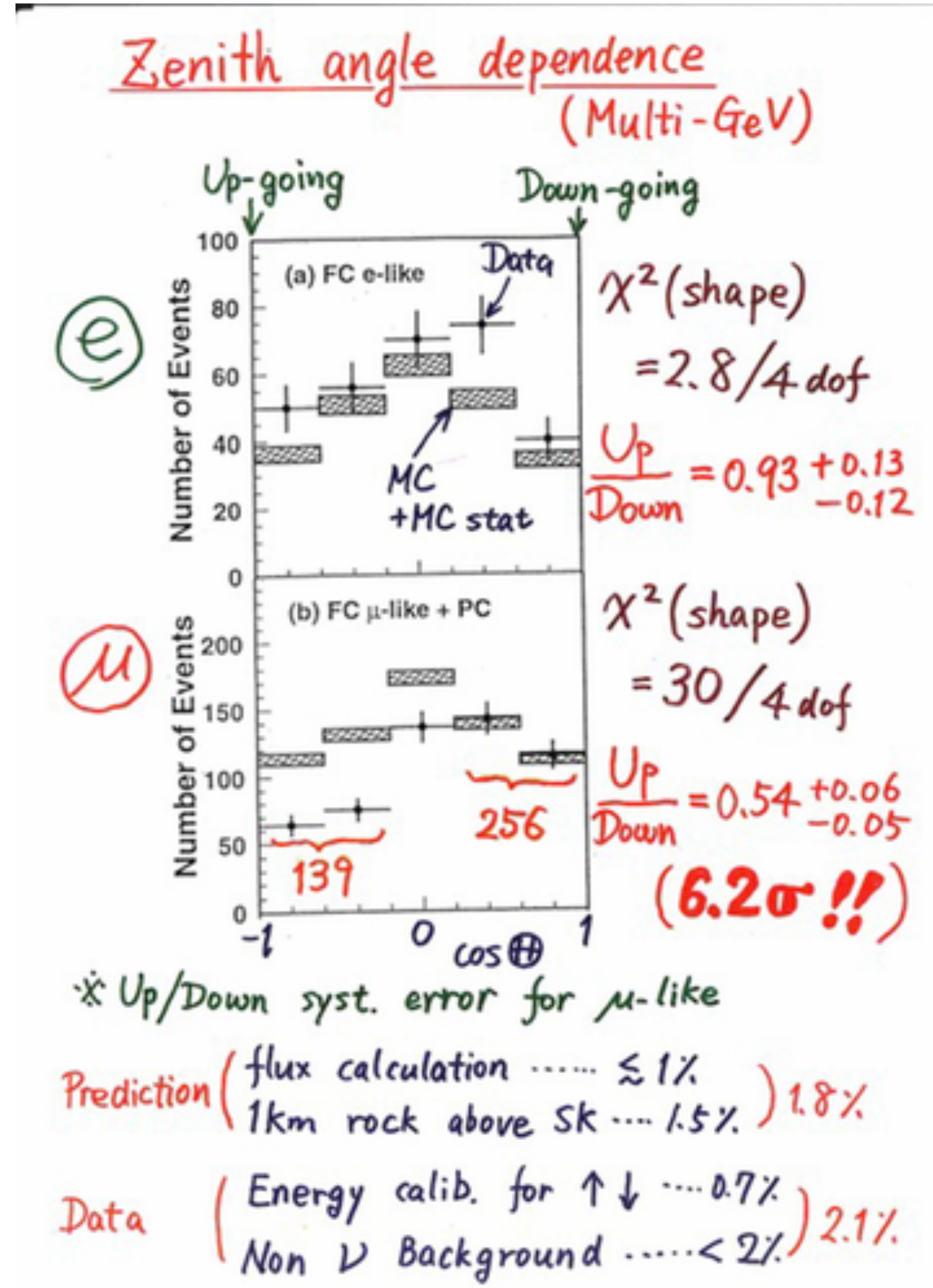
- 50 kton water Cherenkov detector
- 40 m in height, 40 m in diameter
- 13000 PMTs
- Identify ν_e and ν_μ interactions using Cherenkov rings



Super-Kamiokande Experiment

- Typical energy: ~ 1 GeV ($\gg E_\nu^{\rm solar}$)
- Neutrinos coming from above travel ~20 km
- Neutrinos coming from below travel ~13000 km





- ν_e prediction agrees well with data
- consistent with a strong evidence for ν_μ disappearance
- Oscillation of $\nu_\mu \to \nu_\tau$, where ν_τs are not detected.

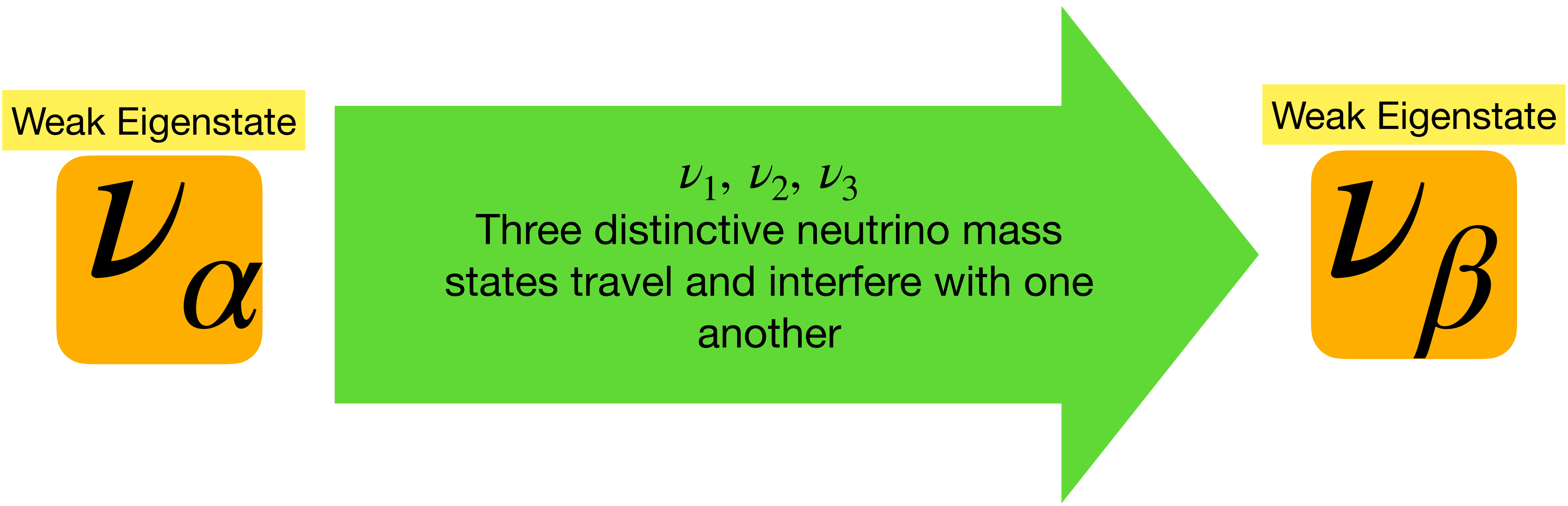
Neutrino Oscillations

Neutrino Flavor/Mass Eigenstates

We cannot detect the neutrinos directly but through weak interactions. Hence, for example, ν_e is a neutrino state that is produced with an electron. Or charged current interactions of the state ν_e produce an electron.

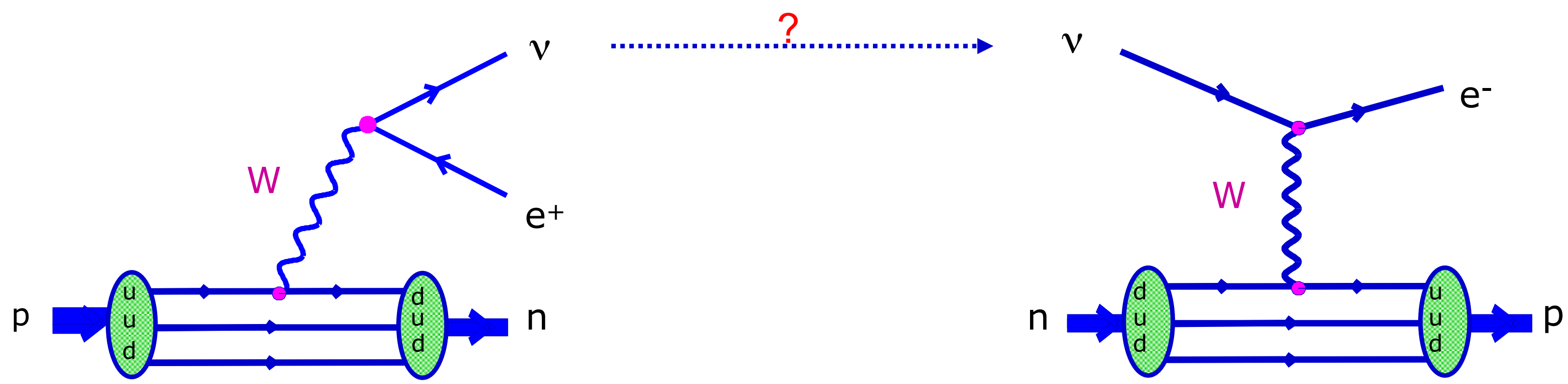
ν_e, ν_μ, ν_τ = weak (flavor) eigenstates

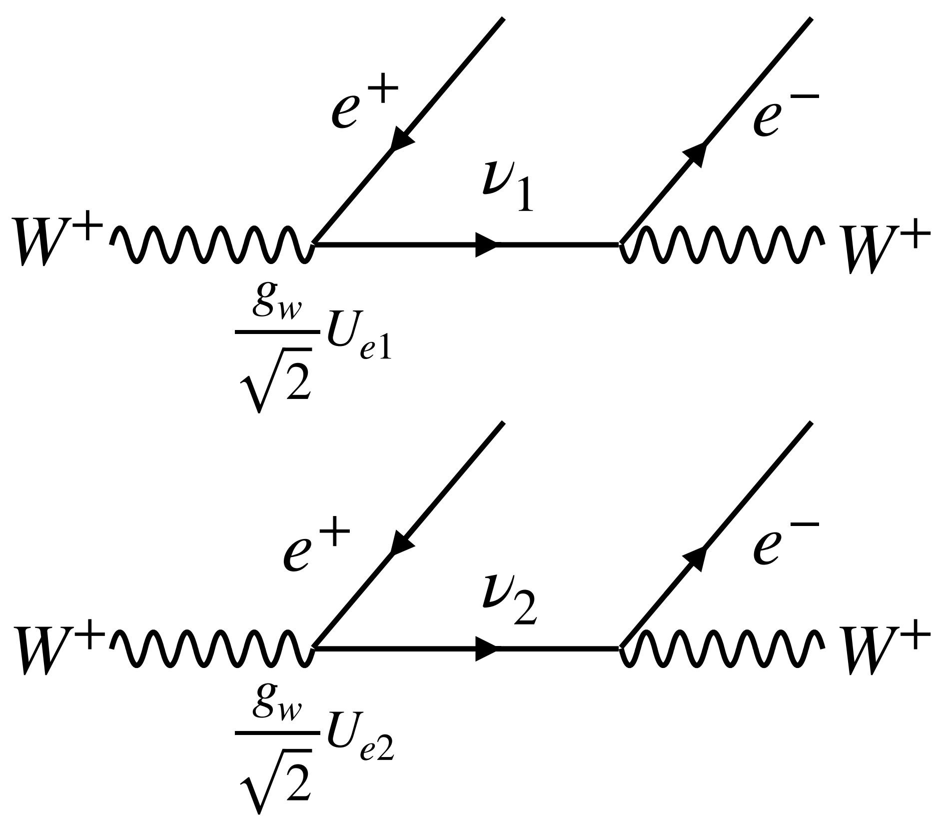
ν_1, ν_2, ν_3 = mass (physical) eigenstates



Neutrino Flavor/Mass Eigenstates

Suppose there are two mass eigenstates and we have below interactions





We cannot know which mass eigenstate (ν_1, ν_2) is involved in the interaction.

In QM, treat as coherent state of ν_1 and ν_2

$$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2$$

ν_e =wave function of the state produced along with an electron in weak interaction (weak eigenstate).

Neutrino Oscillations

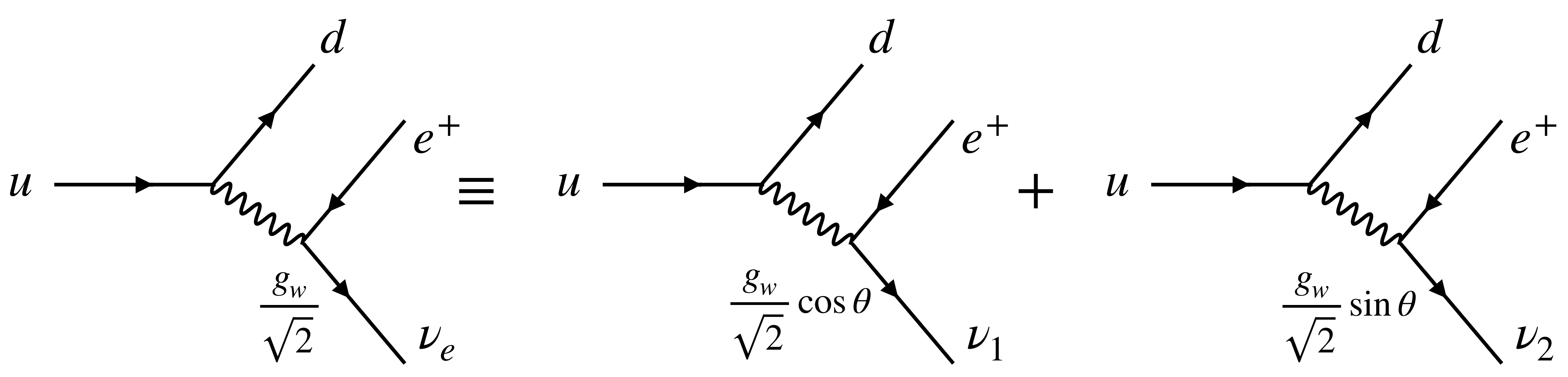
Neutrinos are produced and interact as weak eigenstates ν_e, ν_μ.

The weak eigenstates as coherent linear combinations of the fundamental mass eigenstates ν_1, ν_2.

The weak and mass eigenstates are related by the unitary 2x2 matrix.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_e = \cos\theta \nu_1 + \sin\theta \nu_2$$



Neutrino Oscillations

We can invert the previous equation to get

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

The mass eigenstates are the free particle solutions to the wave-equation and will be taken to propagate as plane waves.

$$|\nu_1(t)\rangle = e^{i(\overrightarrow{p}_1 \cdot \overrightarrow{x} - E_1 t)} |\nu_1(0)\rangle$$

$$|\nu_2(t)\rangle = e^{i(\overrightarrow{p}_2 \cdot \overrightarrow{x} - E_2 t)} |\nu_2(0)\rangle$$

Suppose at $t = 0$, a neutrino is produced as a pure ν_e state

$$|\psi(0)\rangle = |\nu_e\rangle = \cos\theta |\nu_1\rangle + \sin\theta |\nu_2\rangle$$

Neutrino Oscillations

Assume the neutrino is propagating along the z direction.

The wave function evolves over time evolution of mass eigenstates

$$|\psi(t)\rangle = |\nu_e(t)\rangle = \cos\theta|\nu_1\rangle e^{-ip_1x} + \sin\theta|\nu_2\rangle e^{-ip_2x}$$

where $\quad px = Et - |\overrightarrow{p}|z \quad (\overrightarrow{p} // \overrightarrow{x})$

Assume the neutrino interacts with a detector at a distance L and at time T

$$\phi \equiv ET - |\overrightarrow{p}|L$$

Then

$$\begin{aligned}|\psi(L,T)\rangle &= \cos\theta|\nu_1\rangle e^{-i\phi_1} + \sin\theta|\nu_2\rangle e^{-i\phi_2} \\ &= \cos\theta\left(\cos\theta|\nu_e\rangle - \sin\theta|\nu_\mu\rangle\right)e^{-i\phi_1} + \sin\theta\left(\sin\theta|\nu_e\rangle + \cos\theta|\nu_\mu\rangle\right)e^{-i\phi_2} \\ &= \left(\cos^2\theta e^{-i\phi_1} + \sin^2\theta e^{-i\phi_2}\right)|\nu_e\rangle + \sin\theta\cos\theta\left(-e^{-i\phi_1} + e^{-i\phi_2}\right)|\nu_\mu\rangle\end{aligned}$$

Neutrino Oscillations

$$|\psi(L,T)\rangle = \left(\cos^2\theta e^{-i\phi_1} + \sin^2\theta e^{-i\phi_2}\right)|\nu_e\rangle + \sin\theta\cos\theta\left(-e^{-i\phi_1} + e^{-i\phi_2}\right)|\nu_\mu\rangle$$

If $m_1 = m_2$, mass eigenstates are in phase, i.e. $\phi_1 = \phi_2 \rightarrow \; |\psi(L,T)\rangle = |\nu_e\rangle$.
No flavor change. Will produce an electron in a weak interaction.

If $m_1 \neq m_2$, no longer in a pure $|\nu_e\rangle$ state

The probability of having $|\nu_\mu\rangle$ is

$$P(\nu_e \rightarrow \nu_\mu) = \left|\langle\nu_\mu|\psi(L,T)\rangle\right|^2 = \sin^2\theta\cos^2\theta\left(-e^{-i\phi_1} + e^{-i\phi_2}\right)\left(-e^{i\phi_1} + e^{i\phi_2}\right)$$

$$= \frac{1}{4}\sin^2 2\theta\left(2 - 2\cos(\phi_1 - \phi_2)\right)$$

$$= \sin^2 2\theta \sin^2\left(\frac{\phi_1 - \phi_2}{2}\right)$$

Neutrino Oscillations

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left(\frac{\phi_1 - \phi_2}{2}\right)$$

The phase difference is

$$\phi_1 - \phi_2 = E_1 T - p_1 L - \left(E_2 T - p_2 L\right)$$

$$= (E_1 - E_2)T - (|p_1| - |p_2|)L \qquad\qquad p = p_1 = p_2$$

$$= \left[(p^2 + m_1^2)^{1/2} - (p^2 + m_2^2)^{1/2}\right] cT \qquad\qquad cT = L$$

$$= p\left[\left(1 + \frac{m_1^2}{p^2}\right)^{1/2} - \left(1 + \frac{m_2^2}{p^2}\right)^{1/2}\right] L \approx \frac{m_1^2 - m_2^2}{2p} L \qquad\qquad m \ll p$$

Neutrino Oscillations

If $E \gg m$

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left(\frac{\phi_1 - \phi_2}{2}\right)$$

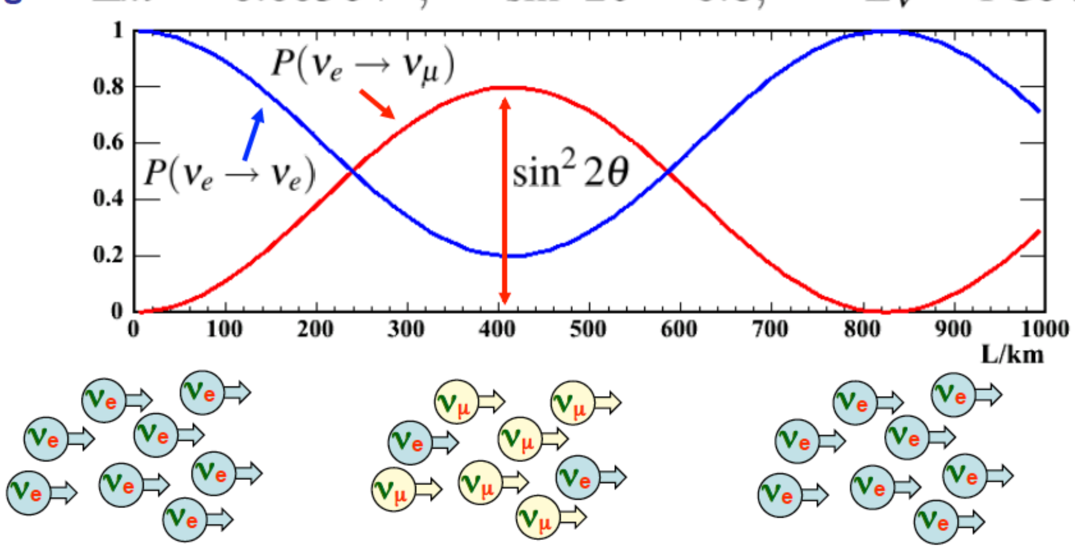
$$= \sin^2 2\theta \sin^2\left(\frac{m_1^2 - m_2^2}{4p} L\right) \qquad E \gg m \to E \approx p$$

$$= \sin^2 2\theta \sin^2\left(\frac{\Delta m_{21}^2}{4E} L\right) \qquad \Delta m_{21}^2 = m_2^2 - m_1^2$$

if $\Delta m_{21}^2 = 0$, no oscillation

$$P(\nu_e \to \nu_e) = 1 - P(\nu_e \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m_{21}^2}{4E} L\right)$$

- e.g. $\Delta m^2 = 0.003\,\mathrm{eV}^2, \quad \sin^2 2\theta = 0.8, \quad E_\nu = 1\,\mathrm{GeV}$



$$\lambda_{\text{osc}} = \frac{4\pi E}{\Delta m^2}$$

Neutrino Oscillations

In realistic units

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2_{21}}{E}L\right)$$

L in km, Δm^2 in eV², and E in GeV

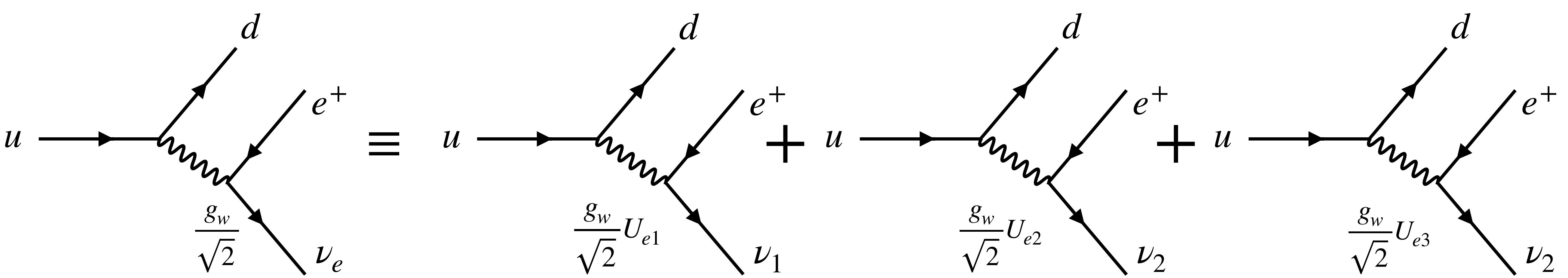
$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2_{21}}{E}L\right)$$

Homework: Derive the constant 1.27

Three flavor Neutrino Mixing

Simple to extend this treatment to three generation of neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



This 3x3 unitary matrix U is known as Pontecorvo-Maki-Nakakawa-Saki Matrix (PMNS matrix)

$$UU^\dagger = U^\dagger U = I$$

Three flavor Neutrino Mixing

From the unitarity of the matrix

$$UU^\dagger = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} U^*_{e1} & U^*_{\mu1} & U^*_{\tau1} \\ U^*_{e2} & U^*_{\mu2} & U^*_{\tau2} \\ U^*_{e3} & U^*_{\mu3} & U^*_{\tau3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

We get nine relations:

$$U_{e1}U^*_{e1} + U_{e2}U^*_{e2} + U_{e3}U^*_{e3} = 1$$
$$U_{e1}U^*_{\mu1} + U_{e2}U^*_{\mu2} + U_{e3}U^*_{\mu3} = 0$$
$$U_{e1}U^*_{\tau1} + U_{e2}U^*_{\tau2} + U_{e3}U^*_{\tau3} = 0$$
$$\vdots$$

i.e. $U_{\alpha1}U^*_{\beta1} + U_{\alpha2}U^*_{\beta2} + U_{\alpha3}U^*_{\beta3} = \delta_{\alpha\beta} \quad (\alpha, \beta = e, \mu, \tau)$

PMNS Matrix

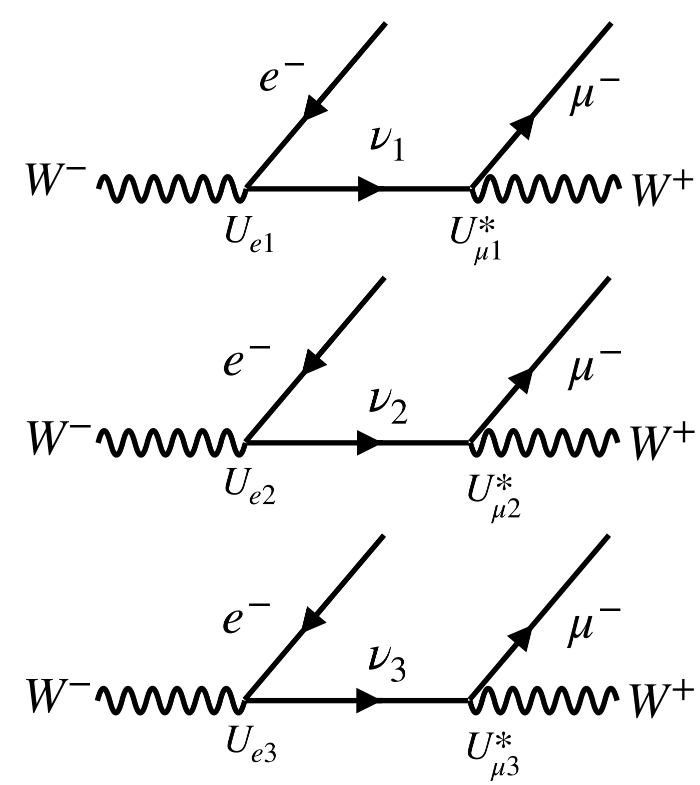
$$|\psi(L)\rangle = \sum_{i=1}^{3} U_{ei}^{*} |\nu_i\rangle e^{-i\phi_i} \quad \text{where } \phi_i = p_i x = E_i t - |\vec{p}_i| L = (E_i - |\vec{p}_i|)L \approx \frac{m_i^2}{2E_i} L$$

$$= \sum_{i=1}^{3} U_{ei}^{*} \left(U_{ei} |\nu_e\rangle + U_{\mu i} |\nu_\mu\rangle + U_{\tau i} |\nu_\tau\rangle \right) e^{-i\phi_i}$$

$$= \sum_{i=1}^{3} \left[U_{ei}^{*} U_{ei} e^{-i\phi_i} |\nu_e\rangle + U_{ei}^{*} U_{\mu i} e^{-i\phi_i} |\nu_\mu\rangle + U_{ei}^{*} U_{\tau i} e^{-i\phi_i} |\nu_\tau\rangle \right]$$

Therefore,

$$P(\nu_e \to \nu_\mu) = \left| \langle \nu_\mu | \psi(L) \rangle \right|^2 = \left| \sum_{i=1}^{3} U_{ei}^{*} U_{\mu i} e^{-i\phi_i} \right|^2$$



PMNS Matrix

$$P(\nu_e \to \nu_\mu) = \left|\langle \nu_\mu | \psi(L)\rangle\right|^2 = \left|\sum_{i=1}^{3} U^*_{ei} U_{\mu i} e^{-i\phi_i}\right|^2$$

$$|z_1 + z_2 + z_3|^2 = |z_1|^2 + |z_2|^2 + |z_3|^2 + 2\mathrm{Re}[z_1 z_2^* + z_2 z_3^* + z_3 z_1^*]$$

$$U^*_{e1}U_{\mu 1} + U^*_{e2}U_{\mu 2} + U^*_{e3}U_{\mu 3} = 0$$

$$|U^*_{e1}U_{\mu 1} + U^*_{e2}U_{\mu 2} + U^*_{e3}U_{\mu 3}|^2 = |U^*_{e1}U_{\mu 1}|^2 + |U^*_{e1}U_{\mu 1}|^2 + |U^*_{e1}U_{\mu 1}|^2$$
$$+2\mathrm{Re}[U^*_{e1}U_{\mu 1}U_{e2}U^*_{\mu 2} + U^*_{e1}U_{\mu 1}U_{e3}U^*_{\mu 3} + U^*_{e2}U_{\mu 2}U_{e3}U^*_{\mu 3}] = 0$$

$$P(\nu_e \to \nu_\mu) = |U^*_{e1}U_{\mu 1}|^2 + |U^*_{e2}U_{\mu 2}|^2 + |U^*_{e3}U_{\mu 3}|^2$$
$$+2\mathrm{Re}[U^*_{e1}U_{\mu 1}U_{e2}U^*_{\mu 2}(e^{-i(\phi_1-\phi_2)} - 1)]$$
$$+2\mathrm{Re}[U^*_{e1}U_{\mu 1}U_{e3}U^*_{\mu 3}(e^{-i(\phi_1-\phi_3)} - 1)]$$
$$+2\mathrm{Re}[U^*_{e2}U_{\mu 2}U_{e3}U^*_{\mu 3}(e^{-i(\phi_2-\phi_3)} - 1)]$$

PMNS Matrix

Because of the unitarity of PMNS matrix

$$U_{e1}^* U_{\mu 1} + U_{e2}^* U_{\mu 2} + U_{e3}^* U_{\mu 3} = 0$$

$$P(\nu_e \to \nu_\mu) = \left| \sum_{i=1}^{3} U_{ei}^* U_{\mu i} e^{-i\phi_i} \right|^2 = 0$$ if $\phi_i = 0$, i.e. no mass differences, no oscillation.

The survival probability is

$$P(\nu_e \to \nu_e) = \left| \sum_{i=1}^{3} U_{ei}^* U_{ei} e^{-i\phi_i} \right|^2$$

Using the unitarity relation $|U_{e1}U_{e1}^* + U_{e2}U_{e2}^* + U_{e3}U_{e3}^*|^2 = 1$

$$\begin{aligned} P(\nu_e \to \nu_e) = 1 &+ 2|U_{e1}|^2 |U_{e2}|^2 \left(\cos(\phi_1 - \phi_2) - 1\right) \\ &+ 2|U_{e1}|^2 |U_{e3}|^2 \left(\cos(\phi_1 - \phi_3) - 1\right) \\ &+ 2|U_{e2}|^2 |U_{e3}|^2 \left(\cos(\phi_2 - \phi_3) - 1\right) \end{aligned}$$

PMNS Matrix

$$\cos(\phi_2 - \phi_1) - 1 = -2\sin^2\left(\frac{\phi_2 - \phi_1}{2}\right) \qquad \phi_i \approx \frac{m_i^2}{2E}L$$

Phase of i at $z = L$

$$= -2\sin^2\left(\frac{m_2^2 - m_1^2}{4E}L\right)$$

$$\Delta_{21} = \frac{m_2^2 - m_1^2}{4E}L = \frac{\Delta m_{21}^2}{4E}L$$

$$\begin{aligned} P(\nu_e \to \nu_e) = 1 - & \ 4|U_{e1}|^2|U_{e2}|^2\sin^2\Delta_{21} \\ - & \ 4|U_{e1}|^2|U_{e3}|^2\sin^2\Delta_{31} \\ - & \ 4|U_{e2}|^2|U_{e3}|^2\sin^2\Delta_{32} \end{aligned}$$

$$\Delta_{21} = 1.27\frac{\Delta m_{21}^2(\text{eV}^2)L(\text{km})}{E(\text{GeV})} \qquad \lambda_{\text{osc}}(\text{km}) = 2.47\frac{E(\text{GeV})}{\Delta m^2(\text{eV}^2)}$$

PMNS Matrix

neglecting CP violating term, i.e. real PMNS matrix,

$$P(\nu_e \to \nu_\mu) = -4U_{e1}U_{\mu1}U_{e2}U_{\mu2}\sin^2\Delta_{21} - 4U_{e1}U_{\mu1}U_{e3}U_{\mu3}\sin^2\Delta_{31} - 4U_{e2}U_{\mu2}U_{e3}U_{\mu3}\sin^2\Delta_{32}$$

with $\Delta_{ij} = \frac{m_i^2 - m_j^2}{4E}L = \frac{\Delta m_{ij}^2}{4E}L$

Using $|\Delta_{32}^2| \approx |\Delta_{31}^2|$

$$P(\nu_e \to \nu_\mu) = -4U_{e1}U_{\mu1}U_{e2}U_{\mu2}\sin^2\Delta_{21} - 4(U_{e1}U_{\mu1} + U_{e2}U_{\mu2})U_{e3}U_{\mu3}\sin^2\Delta_{32}$$

Realising $U_{e1}U_{\mu1}^* + U_{e2}U_{\mu2}^* + U_{e3}U_{\mu3}^* = 0$

$$P(\nu_e \to \nu_\mu) = -4U_{e1}U_{\mu1}U_{e2}U_{\mu2}\sin^2\Delta_{21} - 4U_{e3}^2U_{\mu3}^2\sin^2\Delta_{32}$$

PMNS Matrix

neglecting CP violating term, i.e. real PMNS matrix, and using $|\Delta^2_{32}| \approx |\Delta^2_{31}|$

$$P(\nu_e \to \nu_e) = 1 - 4|U_{e1}|^2|U_{e2}|^2 \sin^2\Delta_{21} - 4|U_{e1}|^2|U_{e3}|^2 \sin^2\Delta_{31} - 4|U_{e2}|^2|U_{e3}|^2 \sin^2\Delta_{32}$$

$$\approx 1 - 4|U_{e1}|^2|U_{e2}|^2 \sin^2\Delta_{21} - 4(|U_{e1}|^2| + |U_{e2}|^2)|U_{e3}|^2 \sin^2\Delta_{32}$$

Realising $|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1$

$$P(\nu_e \to \nu_e) \approx 1 - 4|U_{e1}|^2|U_{e2}|^2 \sin^2\Delta_{21} - 4(1 - |U_{e3}|^2)|U_{e3}|^2 \sin^2\Delta_{32}$$

Summarizing

$$P(\nu_\alpha \to \nu_\alpha) \approx 1 - 4U^2_{\alpha1}U^2_{\alpha2} \sin^2\Delta_{21} - 4(1 - U^2_{\alpha3})U^2_{\alpha3} \sin^2\Delta_{32} \qquad (\alpha, \beta = e, \mu, \tau)$$

$$P(\nu_\alpha \to \nu_\beta) = P(\nu_\beta \to \nu_\alpha) \approx -4U_{\alpha1}U_{\beta1}U_{\alpha2}U_{\beta2} \sin^2\Delta_{21} - 4U^2_{\alpha3}U^2_{\beta3} \sin^2\Delta_{32} \qquad (\alpha \neq \beta)$$

solar $\lambda_{21} = \dfrac{4\pi E}{\Delta m^2_{21}}$

$\lambda_{32} = \dfrac{4\pi E}{\Delta m^2_{32}}$ atmospheric

PMNS Matrix

PMNS matrix is parametrized by three angles (θ_{12}, θ_{23}, θ_{13}) and one phase (δ_{CP})

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{“Atmospheric”}} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta_{\text{CP}}} & 0 & \cos\theta_{13} \end{pmatrix} \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{“Solar”}}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\text{CP}}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\text{CP}}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\text{CP}}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\text{CP}}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\text{CP}}} & c_{23}c_{13} \end{pmatrix}$$

$s_{ij} = \sin\theta_{ij}$

$c_{ij} = \cos\theta_{ij}$

Global fit results (Oct. 2021)

degrees

$\theta_{12} = 33.43^{\circ}{}^{+0.013^{\circ}}_{-0.012^{\circ}}$

$\theta_{23} = 49.2^{\circ}{}^{+1.0^{\circ}}_{-1.3^{\circ}}$

$\theta_{13} = 8.57^{\circ}{}^{+0.13^{\circ}}_{-0.12^{\circ}}$

$\delta_{\text{CP}} = 194^{\circ}{}^{+52^{\circ}}_{-25^{\circ}}$

with normal mass ordering from nufit.org

PMNS Matrix

PMNS Matrix

$$\begin{pmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{pmatrix} = \begin{pmatrix} 0.801 - 0.845 & 0.513 - 0.579 & 0.143 - 0.156 \\ 0.232 - 0.507 & 0.459 - 0.694 & 0.629 - 0.779 \\ 0.260 - 0.526 & 0.470 - 0.702 & 0.609 - 0.763 \end{pmatrix}$$

CKM Matrix

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 0.0080 \pm 0.0003 & 0.0388 \pm 0.0011 & 1.013 \pm 0.030 \end{bmatrix}.$$

Oscillation Parameters

$\|\Delta m_{21}\|^2 = \|m_2^2 - m_1^2\|$	θ_{12}	Solar and reactor neutrino experiments
$\|\Delta m_{32}\|^2 = \|m_3^2 - m_2^2\|$	θ_{23}	Atmospheric and beam neutrino experiments
	θ_{13}	Reactor neutrino experiments + future beam
	δ	Future beam experiments

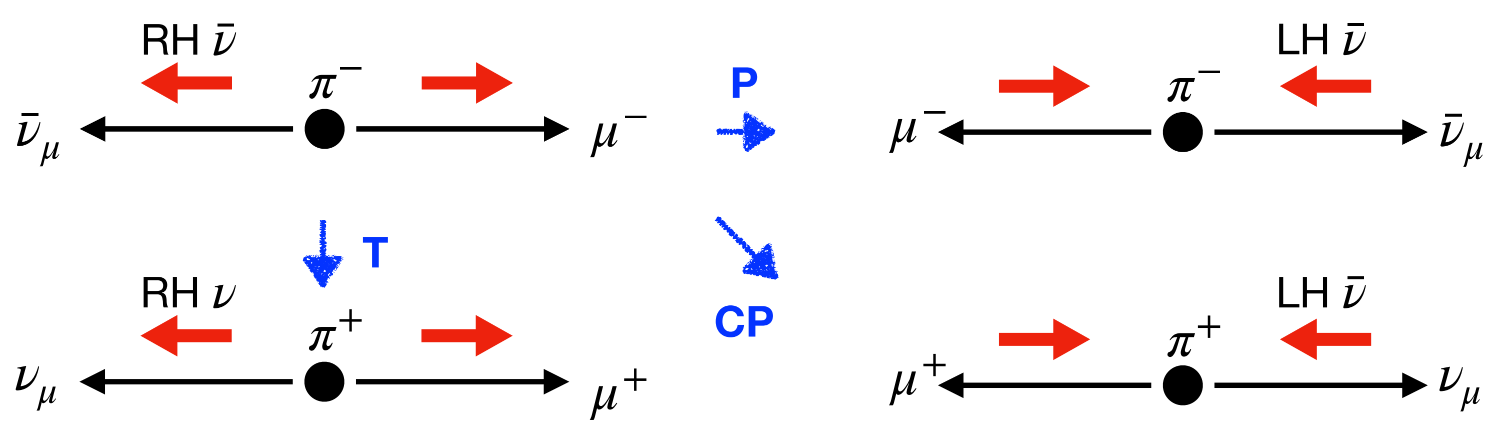
CP and CPT Symmetries in Weak Interaction

Parity (P): $\vec{r} \rightarrow -\vec{r}$

Time reversal (T): $t \rightarrow -t$

Charge conjugation (C): particle → anti-particle

Consider $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$ decay remembering that the neutrino is ultra-relativistic and only left-handed neutrinos and right-handed anti-neutrinos participate in weak interaction.



The weak interaction violates parity conservation. It also violates charge conjugation symmetry but appears to be invariant under combined effect of C and P.

CP and CPT Symmetries in Weak Interaction

CP transformation

RH particle ⟷ RH anti-particle

LH particle ⟷ LH anti-particle

If weak interaction is CP invariant, expect

$$\Gamma(\pi^+ \to \mu^+\nu_\mu) = \Gamma(\pi^- \to \mu^-\bar{\nu}_\mu)$$

Lorentz invariant QFT can be shown to be invariant under CPT transformation.

Particles and their anti-particles have identical masses, lifetimes, magnetic moments, etc.

$$\frac{m_{K_0} - m_{\bar{K}_0}}{m_{K_0}} < 6 \times 10^{-19}$$

If we are to believe CPT holds:

If CP invariance holds ⟷ time reversal symmetry

If CP is violated ⟷ time reversal symmetry is violated

To account for excess of matter over anti-matter requires CP violation in particle physics and it can arise in the weak interaction…

CP Violation

$$P(\nu_e \to \nu_\mu) = |U_{e1}^* U_{\mu1}|^2 + |U_{e2}^* U_{\mu2}|^2 + |U_{e3}^* U_{\mu3}|^2$$
$$+2\mathrm{Re}[U_{e1}^* U_{\mu1} U_{e2} U_{\mu2}^* (e^{-i(\phi_1-\phi_2)} - 1)]$$
$$+2\mathrm{Re}[U_{e1}^* U_{\mu1} U_{e3} U_{\mu3}^* (e^{-i(\phi_1-\phi_3)} - 1)]$$
$$+2\mathrm{Re}[U_{e2}^* U_{\mu2} U_{e3} U_{\mu3}^* (e^{-i(\phi_2-\phi_3)} - 1)]$$

Time reversal

$$P(\nu_\mu \to \nu_e) = |U_{\mu1}^* U_{e1}|^2 + |U_{\mu2}^* U_{e2}|^2 + |U_{\mu3}^* U_{e3}|^2$$
$$+2\mathrm{Re}[U_{\mu1}^* U_{e1} U_{\mu2} U_{e2}^* (e^{-i(\phi_1-\phi_2)} - 1)]$$
$$+2\mathrm{Re}[U_{\mu1}^* U_{e1} U_{\mu3} U_{e3}^* (e^{-i(\phi_1-\phi_3)} - 1)]$$
$$+2\mathrm{Re}[U_{\mu2}^* U_{e2} U_{\mu3} U_{e3}^* (e^{-i(\phi_2-\phi_3)} - 1)]$$

elements of PMNS are complex conjugate

↓

Unless the elements are real, the time reversal symmetry does not necessarily hold true.

$$P(\nu_e \to \nu_\mu) \neq P(\nu_\mu \to \nu_e)$$

CP Violation

If the weak interaction is CPT symmetric

T	$\nu_e \rightarrow \nu_\mu$	$\rightarrow$	$\nu_\mu \rightarrow \nu_e$
CP	$\nu_e \rightarrow \nu_\mu$	$\rightarrow$	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$
CPT	$\nu_e \rightarrow \nu_\mu$	$\rightarrow$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

If the weak interaction is CPT symmetric

$$P(\nu_e \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

$$P(\nu_\mu \rightarrow \nu_e) = P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$$

If PMNS matrix is not purely real (Time reversal)

$$P(\nu_e \rightarrow \nu_\mu) \neq P(\nu_\mu \rightarrow \nu_e)$$

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\nu_e \rightarrow \nu_\mu)$$

CP Violation

$$\nu_e \to \nu_\mu \quad \overset{CP}{\to} \quad \bar{\nu}_e \to \bar{\nu}_\mu$$

$$P(\nu_e \to \nu_\mu) = |U_{e1}^* U_{\mu 1}|^2 + |U_{e2}^* U_{\mu 2}|^2 + |U_{e3}^* U_{\mu 3}|^2$$
$$+2\text{Re}[U_{e1}^* U_{\mu 1} U_{e2} U_{\mu 2}^* (e^{-i(\phi_1 - \phi_2)} - 1)]$$
$$+2\text{Re}[U_{e1}^* U_{\mu 1} U_{e3} U_{\mu 3}^* (e^{-i(\phi_1 - \phi_3)} - 1)]$$
$$+2\text{Re}[U_{e2}^* U_{\mu 2} U_{e3} U_{\mu 3}^* (e^{-i(\phi_2 - \phi_3)} - 1)]$$

$$P(\bar{\nu}_e \to \bar{\nu}_\mu) = |U_{e1} U_{\mu 1}^*|^2 + |U_{e2} U_{\mu 2}^*|^2 + |U_{e3} U_{\mu 3}^*|^2$$
$$+2\text{Re}[U_{e1} U_{\mu 1}^* U_{e2}^* U_{\mu 2} (e^{i(\phi_2 - \phi_1)} - 1)]$$
$$+2\text{Re}[U_{e1} U_{\mu 1}^* U_{e3}^* U_{\mu 3} (e^{i(\phi_3 - \phi_1)} - 1)]$$
$$+2\text{Re}[U_{e2} U_{\mu 2}^* U_{e3}^* U_{\mu 3} (e^{i(\phi_3 - \phi_2)} - 1)]$$

Neutrino Mass and Hierarchy

- From the recent tritium decay experiment $m_{\nu_e} < 0.8\ \text{eV}\ \ @90\,\%\,\text{CL}$
- From recent cosmological measurements of the large-scale structure of the Universe, it can be deduced that $\sum m_{\nu_i} < \text{few eV}$
- The current hypothesis for this large difference between the neutrino masses and other particles are known as Seesaw mechanism.
- Introducing Majorana mass M

$$\mathscr{L}_{DM} = -\frac{1}{2}\left[m_D\bar{\nu}_L\nu_R + m_D\bar{\nu}^c_R\nu^c_L + M\bar{\nu}^c_R\nu_R\right] + h.c.$$

If $m_D \ll M$, then $m_\nu \approx \frac{m_D^2}{M}$ and $m_N \approx M$

$$m_D \sim \mathcal{O}(1\ \text{GeV})$$

Neutrino Mass and Hierarchy

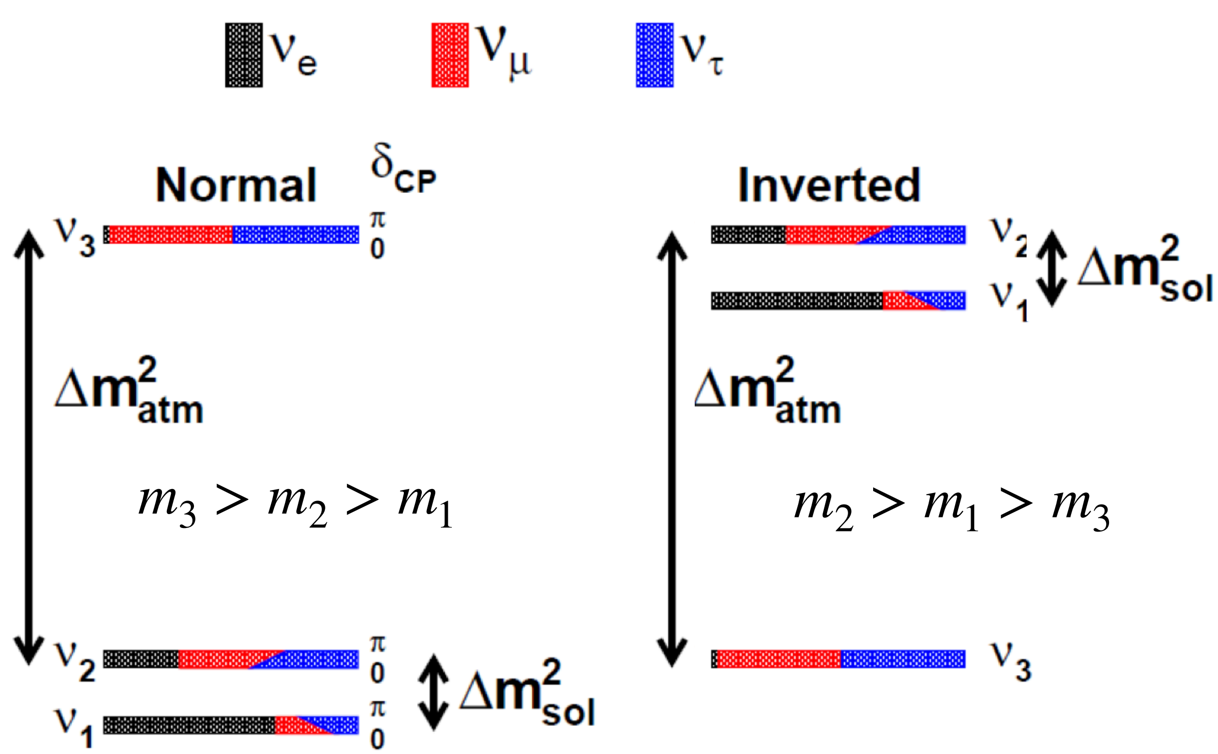
So far, cannot determine the absolute neutrino masses, but

$$|\Delta m_{ij}^2| \equiv |m_i^2 - m_j^2|$$

atmospheric neutrino oscillations: $|\Delta m^2|_{\rm atm} \sim 2.5 \times 10^{-3}\ {\rm eV}^2$

solar neutrino oscillations: $|\Delta m^2|_{\rm sol} \sim 7.6 \times 10^{-5}\ {\rm eV}^2$

The mass ordering of ν_1 and ν_2 was determined by matter effects in the interior of the sun by the SNO experiment



$$\Delta m_{21}^2 \sim 7.6 \times 10^{-5}\ {\rm eV}^2$$

$$|\Delta m_{31}^2| \sim 2.5 \times 10^{-3}\ {\rm eV}^2$$

$$|\Delta m_{31}^2| \approx |\Delta m_{32}^2|$$

Current data favours normal hierarchy

Neutrino Masses

Neutrino oscillations require non-zero neutrino masses.

But we can determine only the mass squared differences through the oscillations.

No direct measure of neutrino masses.

$$m_\nu(e) < 0.8 \text{ eV } @90\,\%\,\text{CL}$$ (KATRIN Exp.)

$$m_\nu(\mu) < 0.17 \text{ MeV } @90\,\%\,\text{CL}$$

$$m_\nu(\tau) < 18.2 \text{ MeV } @90\,\%\,\text{CL}$$

The cosmological evolution constrains

$$\sum_i m_i < \text{few eV } @90\,\%\,\text{CL}$$

The next generation neutrino experiments (T2HK, DUNE) would focus on the mass hierarchy and CP violation (δ_{CP}).

Sterile Neutrinos

Possible to have additional massive neutrinos that are right handed and do not take part in weak interactions.

In experiments, assume a simplest case, ν_4 at an eV scale (3+1 model).

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Can be detected through mixing with active neutrinos.

It is expected to be massive (compare to active neutrinos), the detectors reside near the neutrino sources

Sterile Neutrinos

Approximate to a two flavor problem

Reactor experiment: disappearance experiment

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{14} \sin^2\left(1.27\,\frac{\Delta m^2_{41} L}{E}\right)$$

Accelerator experiment

From unitarity: $\sum_{i=1}^{3} U_{ei}U_{\mu i} = -\,U_{e4}U_{\mu 4}$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{14} \sin^2\left(1.27\,\frac{\Delta m^2_{41} L}{E}\right)$$

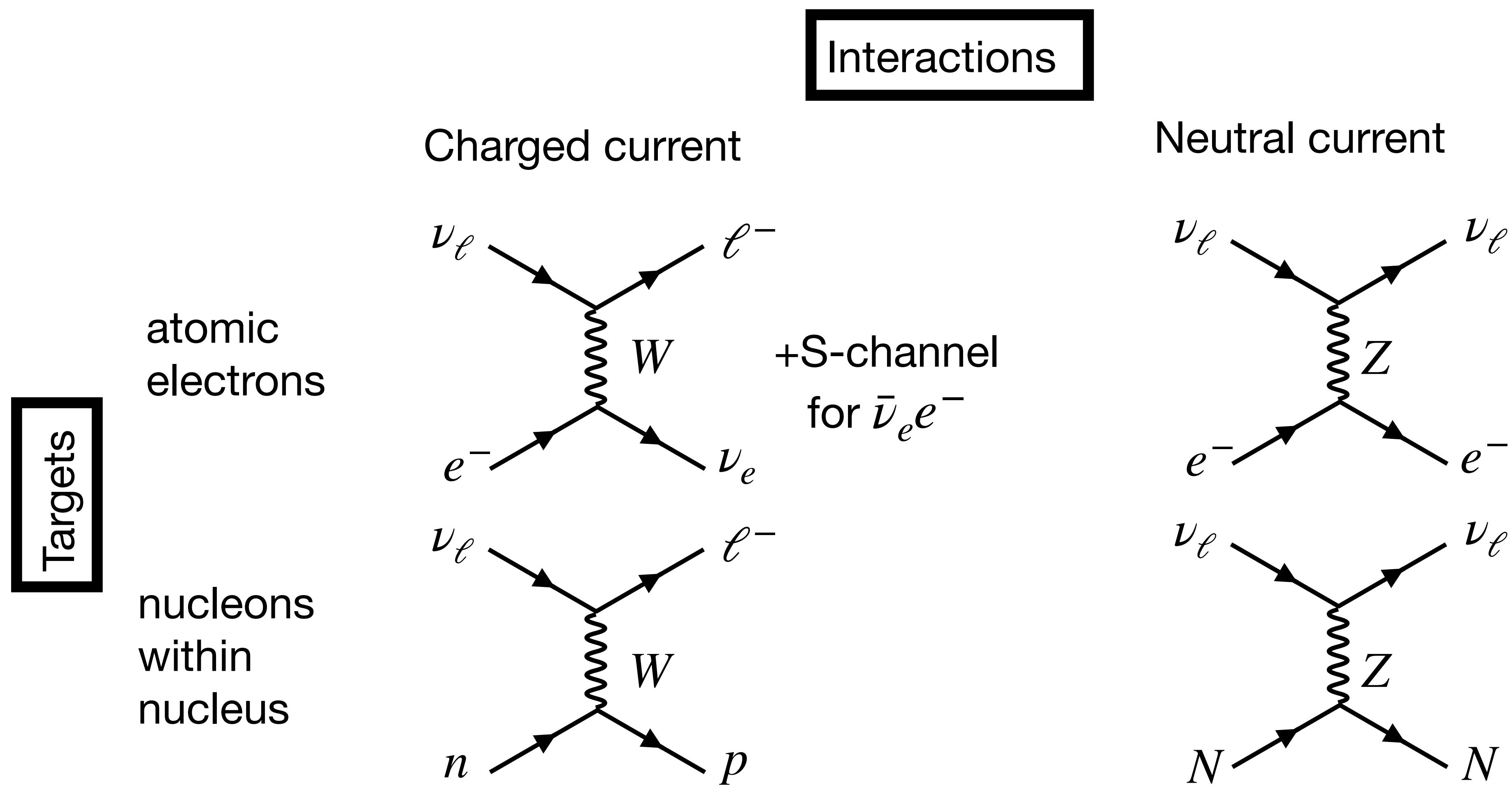
Matter Effect

- When propagating through media, neutrinos undergo weak interactions with primarily electrons.
  - all ν's interact p, n, and e^- equally through NC interactions
  - only ν_e interacts with e^- through CC interaction
- This intrinsic asymmetry among ν flavors modifies the vacuum oscillation patterns.
- ν_e appearance is enhanced for normal hierarchy ($m_1 < m_3$) but suppressed for inverted hierarchy ($m_1 > m_3$)

Neutrino Experiments

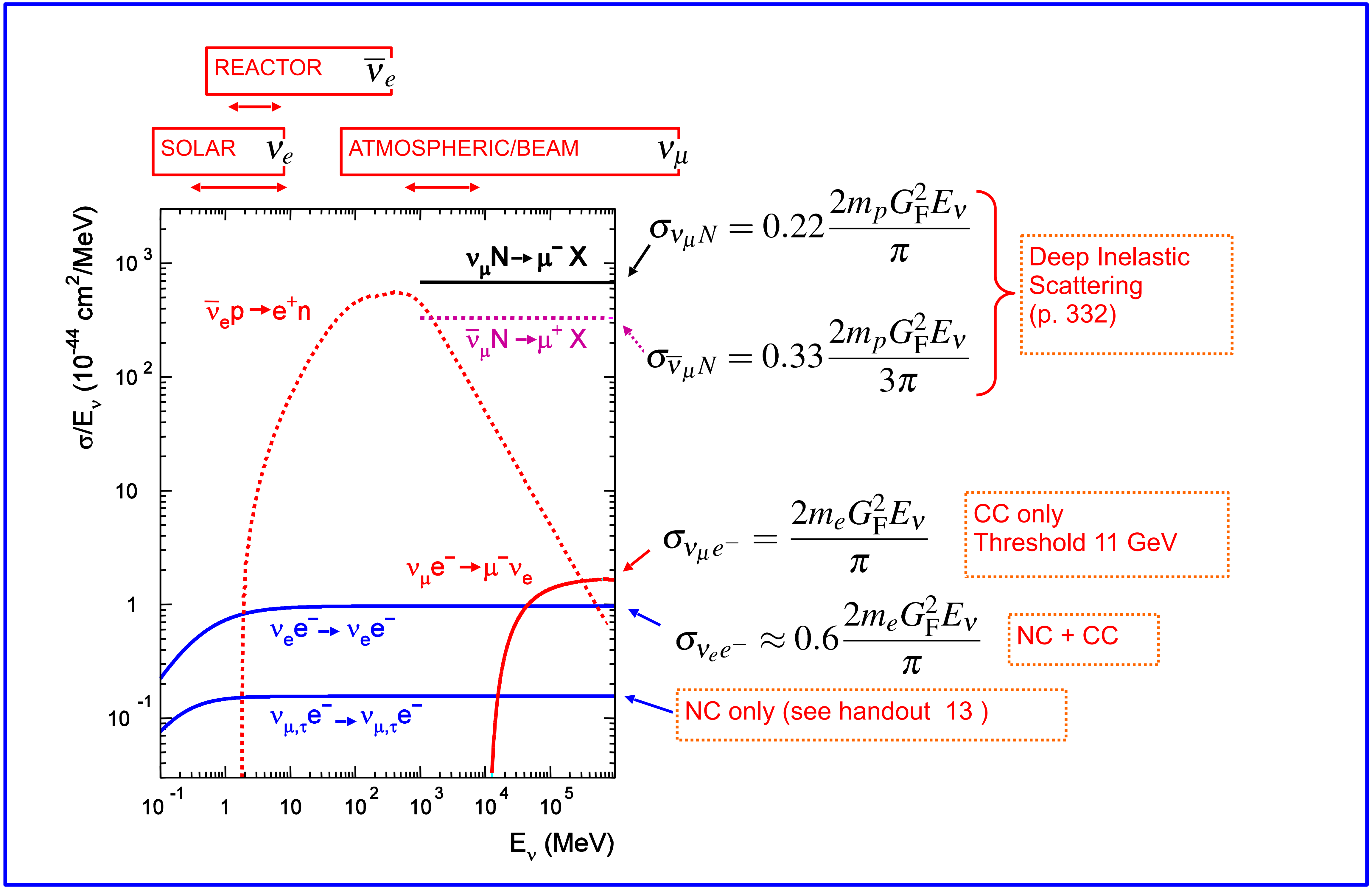
Neutrino Interactions

How do we “detect” neutrinos?



- An appearance signal can be observed if the interaction is kinematically allowed.
- Charged-current neutrino interactions are allowed if the centre-of-mass energy is sufficient to produce a charged lepton and the final state hadronic system.

Neutrino Interactions



from M. Thomson's Lecture

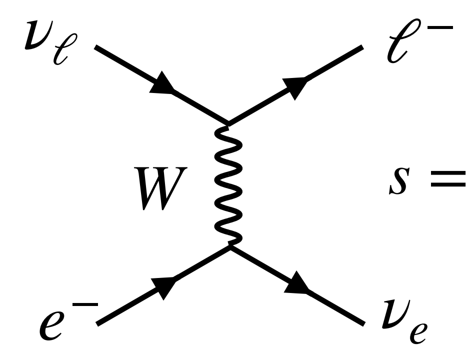
Interaction Thresholds

Neutrino detection depends on the energy and flavor of neutrinos

Charged current interactions on electrons "at rest" (atomic electrons)

$$p_\nu = (E_\nu, 0, 0, E_\nu)$$

$$p_e = (m_e, 0, 0, 0)$$



$$s = (p_\nu + p_e)^2 = (E_\nu + m_e)^2 - E_\nu^2 > m_\ell^2$$

For the interactions to occur $E_\nu > \frac{m_e}{2}\left[\left(\frac{m_\ell}{m_e}\right)^2 - 1\right]$

Solar neutrinos $E_\nu \sim 1\ \mathrm{MeV}$

Atmospheric neutrinos $E_\nu \sim 1\ \mathrm{GeV}$

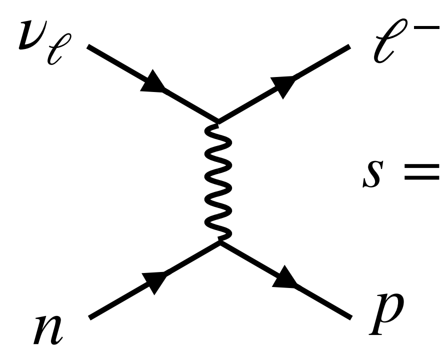
$$E_{\nu_e} > 0 \qquad E_{\nu_\mu} > 11\ \mathrm{GeV} \qquad E_{\nu_\tau} > 3090\ \mathrm{GeV}$$

Interaction Thresholds

- Charged current interactions on nucleons

$$p_\nu = (E_\nu, 0, 0, E_\nu)$$

$$p_n = (m_n, 0, 0, 0)$$



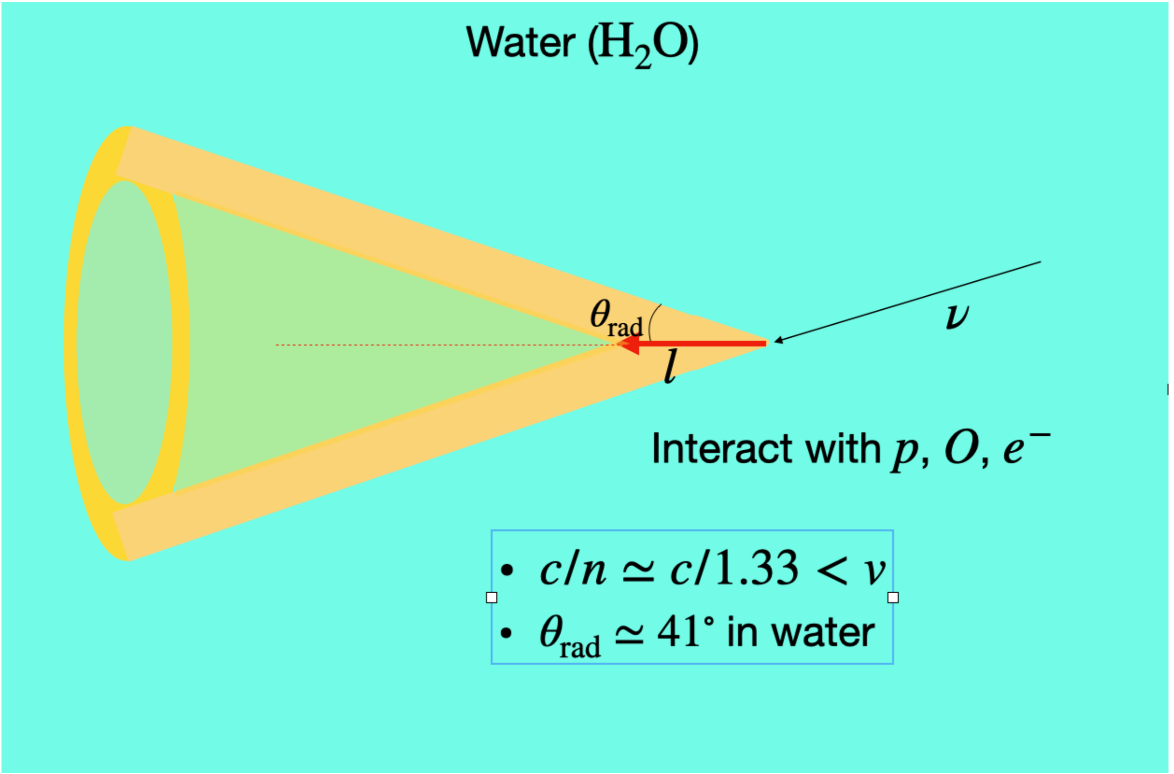
$$s = (p_\nu + p_n)^2 = (E_\nu + m_n)^2 - E_\nu^2 > (m_\ell + m_p)^2$$

For the interactions to occur $E_\nu > \dfrac{(m_p^2 - m_n^2) + m_\ell^2 + 2m_p m_\ell}{2m_n}$

$E_{\nu_e} > 0$ $\quad$ $E_{\nu_\mu} > 110$ MeV $\quad$ $E_{\nu_\tau} > 3.5$ GeV

Disappearance experiment of neutrino oscillations for low energy neutrinos.

Cherenkov Radiation



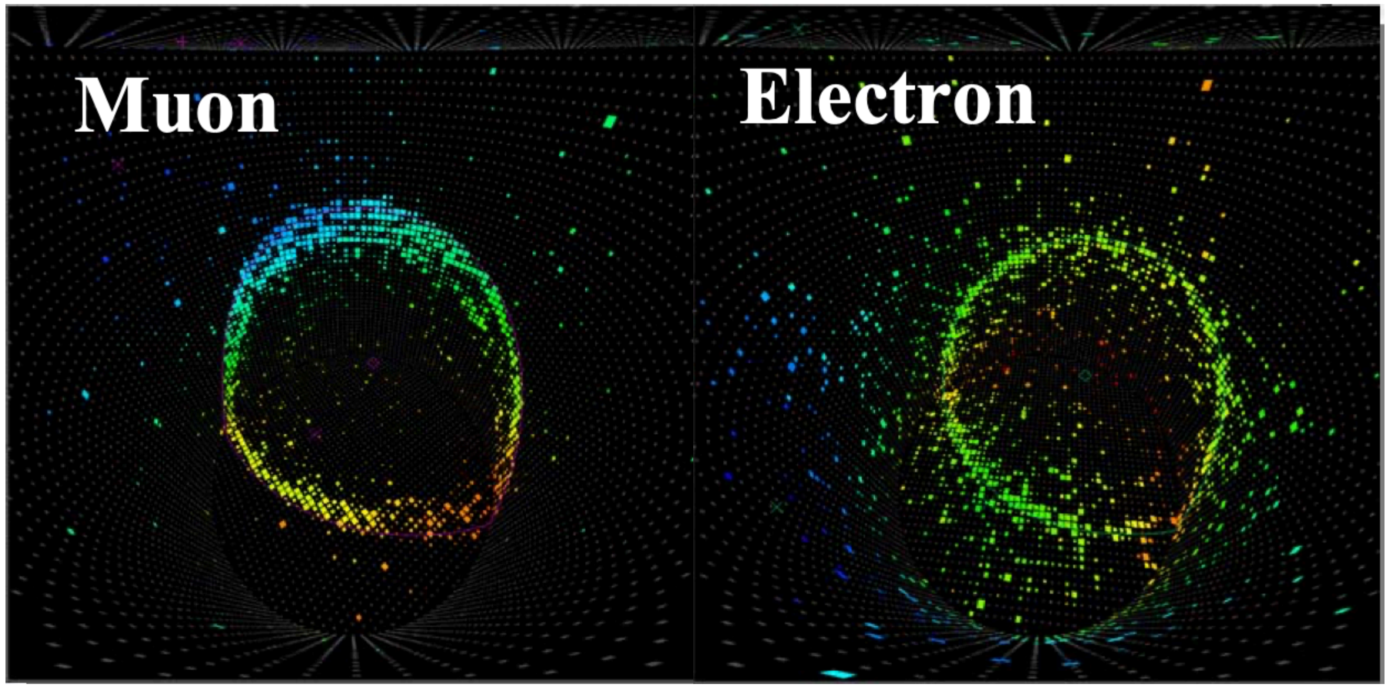
- When a charged particle is moving in a medium at $v > c/n$, where n is the index of refraction of medium, Cherenkov radiation occurs.
- Light sensors (PMTs) detect the photons.

Pros:

- Energy measurement
- Direction measurement
- Particle ID
- Low cost (PMTs are not…)

Cons:

- Low energy limit
- No tracking



http://www.slac.stanford.edu/econf/C040802/lec_notes/Casper/Casper.pdf

Scintillation

- Passing charged particle excites atom/molecules along its path
- When de-excitation happens photons are emitted.
- Inorganic (crystals) and organic scintillators

Pros:

- More photons than Cherenkov radiation
- Low energy particle sensitivity.
- “Fast” response (compared to TPC)

Cons:

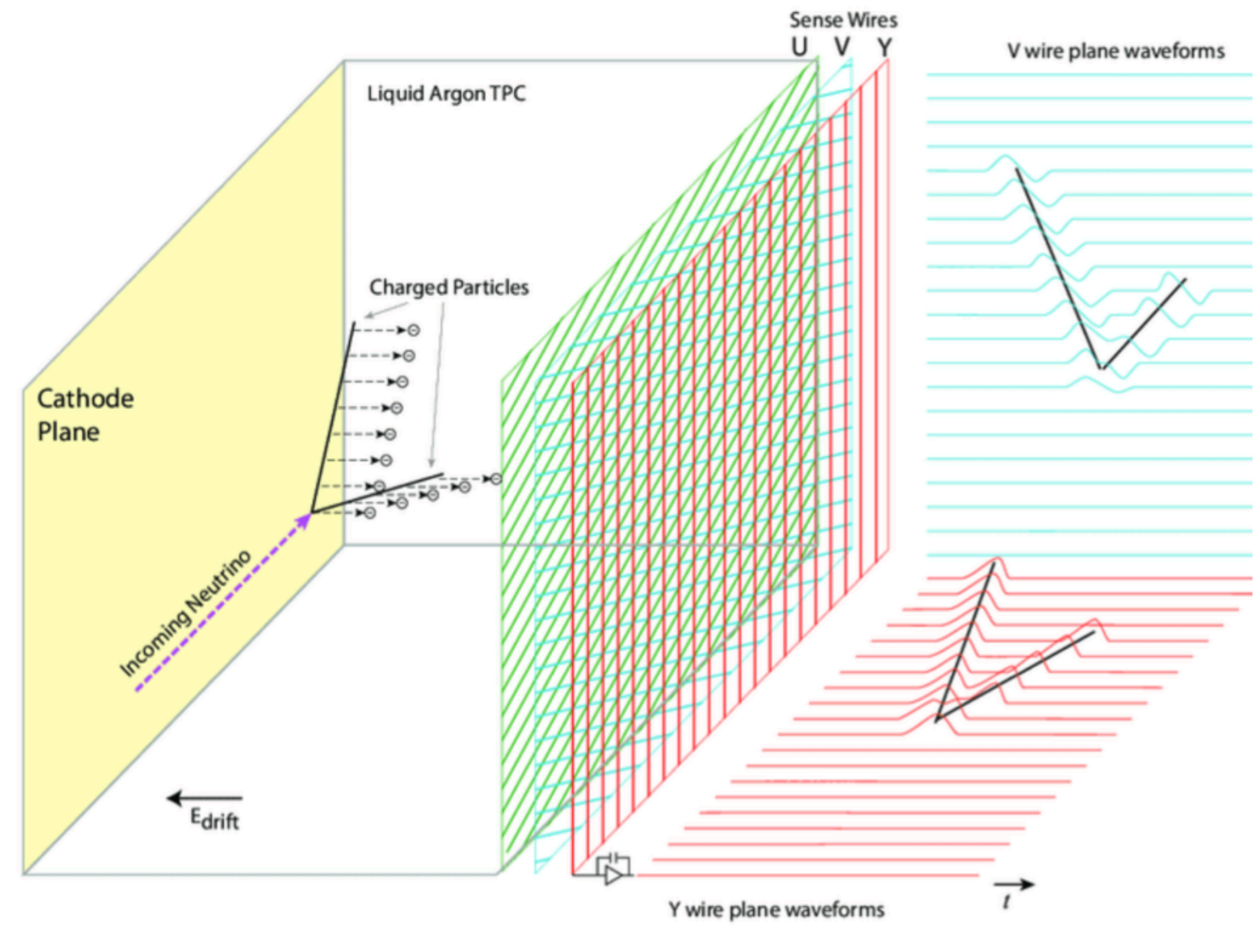
- No tracking
- No directional sensitivity

Ionization

- Charged particles produced in neutrino interactions ionize the medium atoms/molecules.
- Ionization electrons in electric field drift toward anode plane.
- Sense wires detect incoming charge

Pros:
- Tracking
- Low energy particle sensitivity

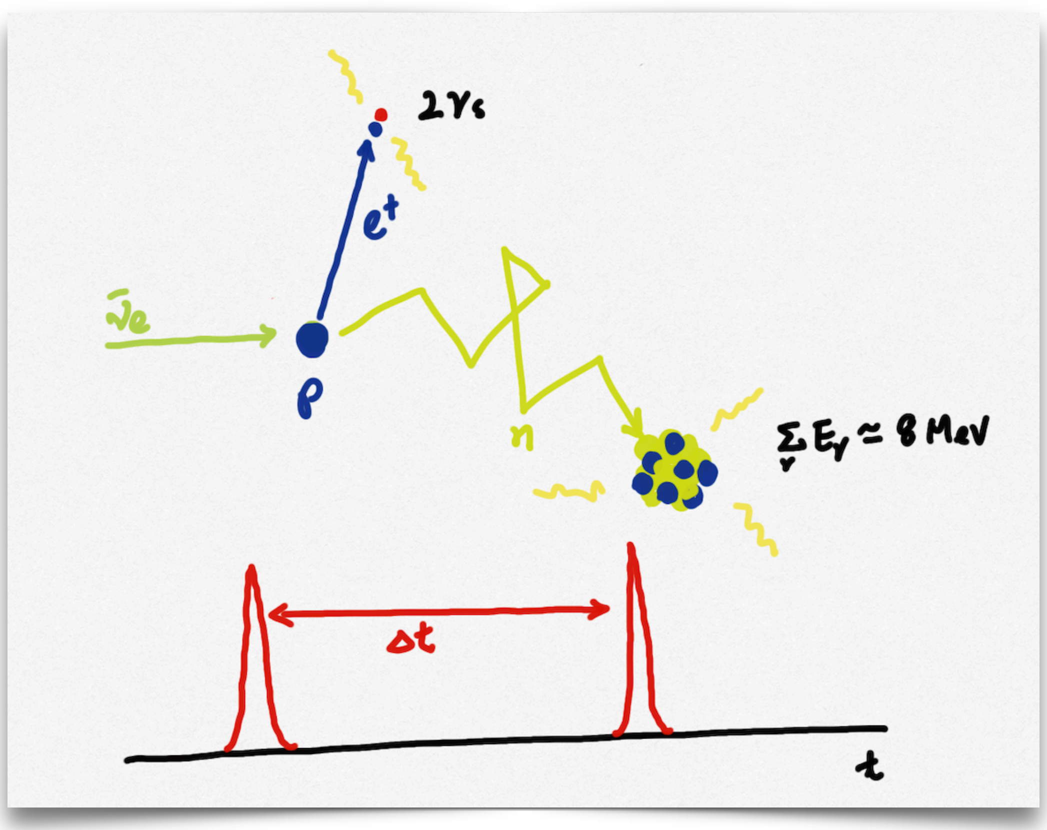
Cons:
- Expensive to build & maintain for cryogenic detector

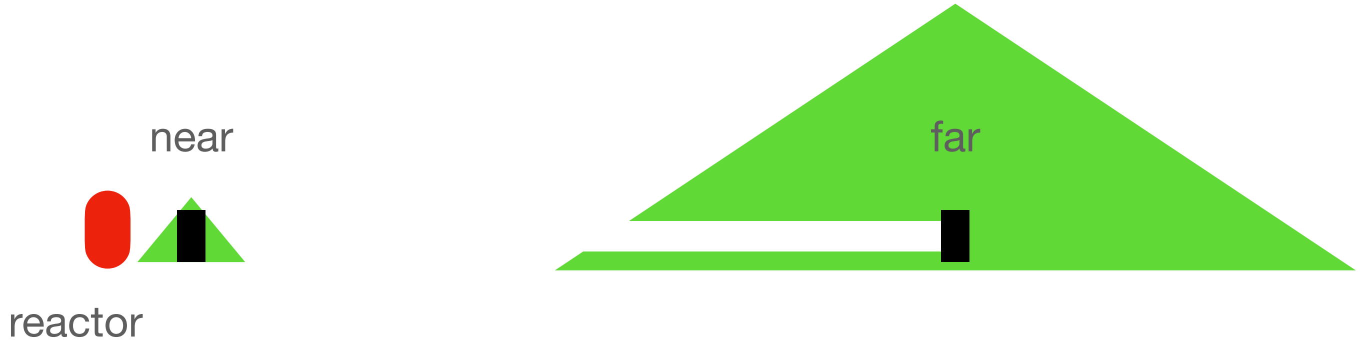


LArTPC arXiv:1612.05824

Reactor Neutrino Experiments

- $\bar{\nu}_e$ disappearance experiments: $P(\bar{\nu}_e \to \bar{\nu}_e)$
- To measure $\sin 2\theta_{13}$ and $|\Delta m^2_{31}|$.
- $\sim 6\ \bar{\nu}_e/\text{fission}\ (<10\ \text{MeV}). \to 2 \times 10^{20}\ \bar{\nu}_e/\text{GW}_\text{th}\ \text{s}$
- "Two identical" detectors (near and far)
- Use inverse beta decay ($\bar{\nu}_e + p \to e^+ + n$)
- Liquid scintillator doped with Gd for enhanced neutron signal.





Reactor Neutrino Experiments

- The electron (anti)neutrino survival probability is

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - 4U_{e1}^2 U_{e2}^2 \sin^2 \Delta_{21} - 4(1 - U_{e3}^2)U_{e3}^2 \sin^2 \Delta_{32}$$

$$= 1 - 4(c_{12}c_{13})^2(s_{12}c_{13})^2 \sin^2 \Delta_{21} - 4(1 - s_{13}^2)s_{13}^2 \sin^2 \Delta_{32}$$

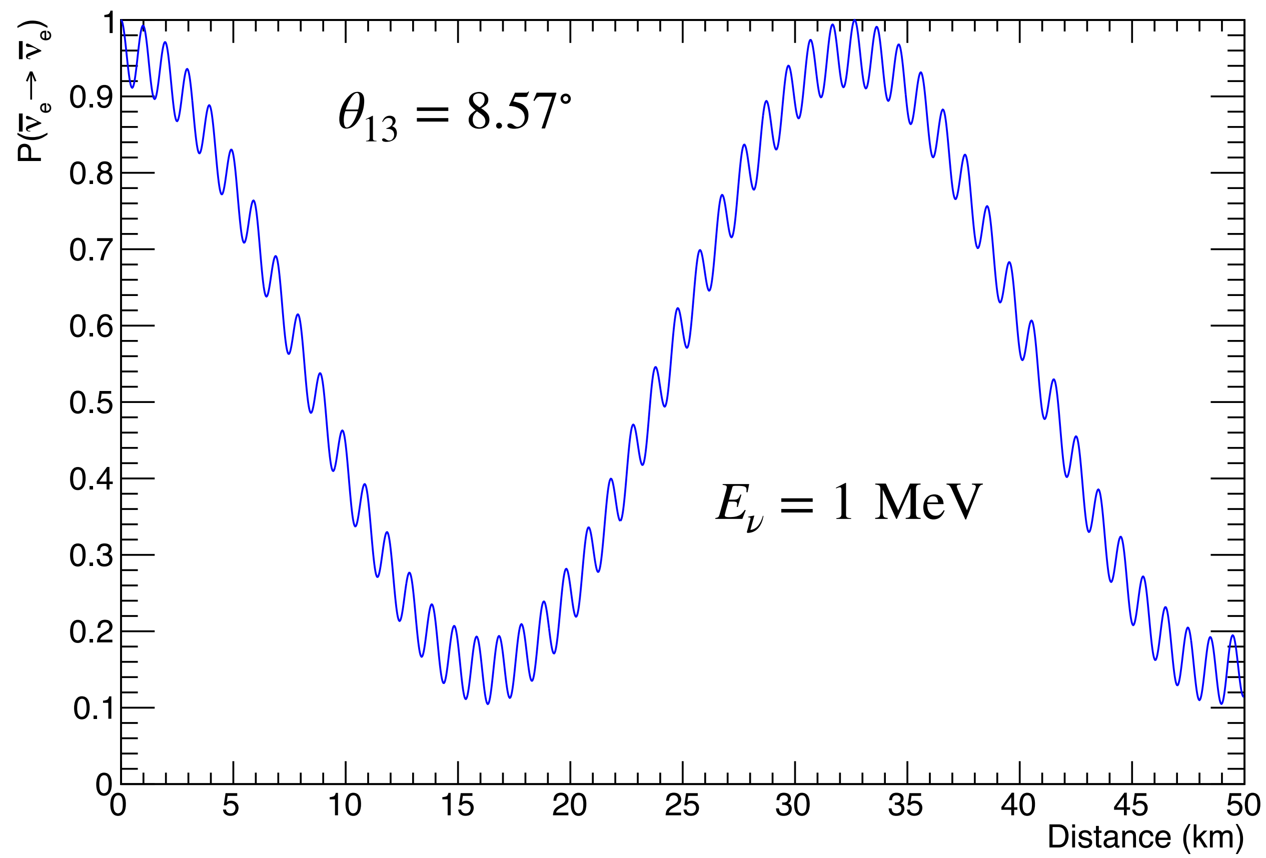
$$= 1 - c_{13}^4(2c_{12}s_{12})^2 \sin^2 \Delta_{21} - 4c_{13}^2 s_{13}^2 \sin^2 \Delta_{32}$$

$$= 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} - \sin^2 2\theta_{13} \sin^2 \Delta_{32}$$

$$\lambda_{\text{osc}} = 2.47 \frac{E \text{ (GeV)}}{\Delta m^2 \text{ (eV}^2)}$$

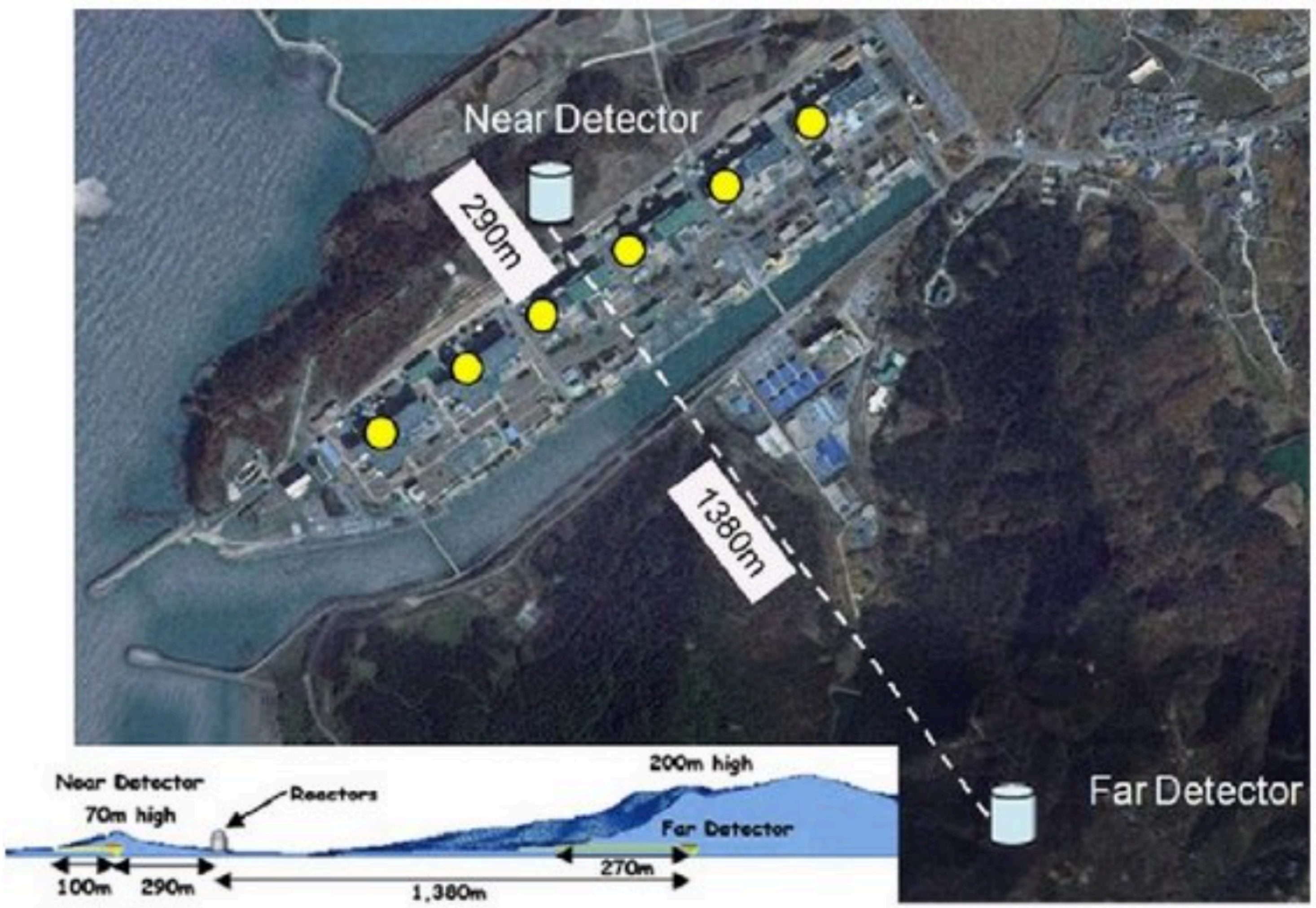
$$\lambda_{21} \approx 30 \text{ km}$$

$$\lambda_{32} \approx 1 \text{ km}$$

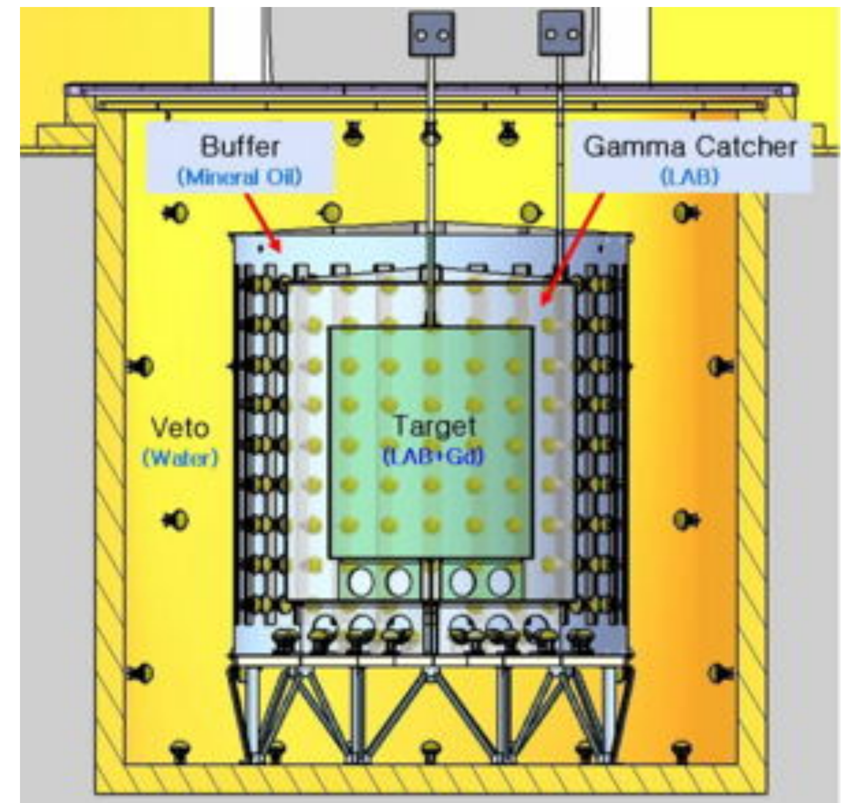


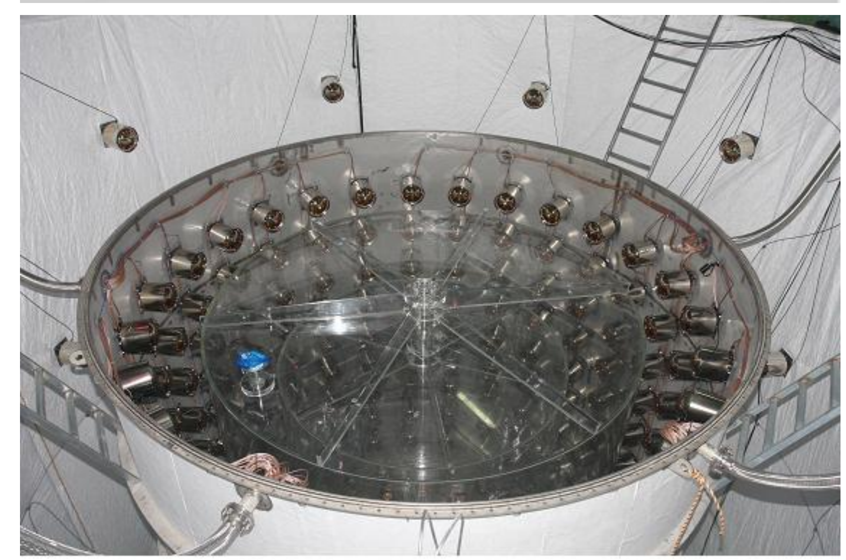
RENO

- Using Yeonggwang Hanbit reactors
- Six reactors each with 2.8 GW_{th}



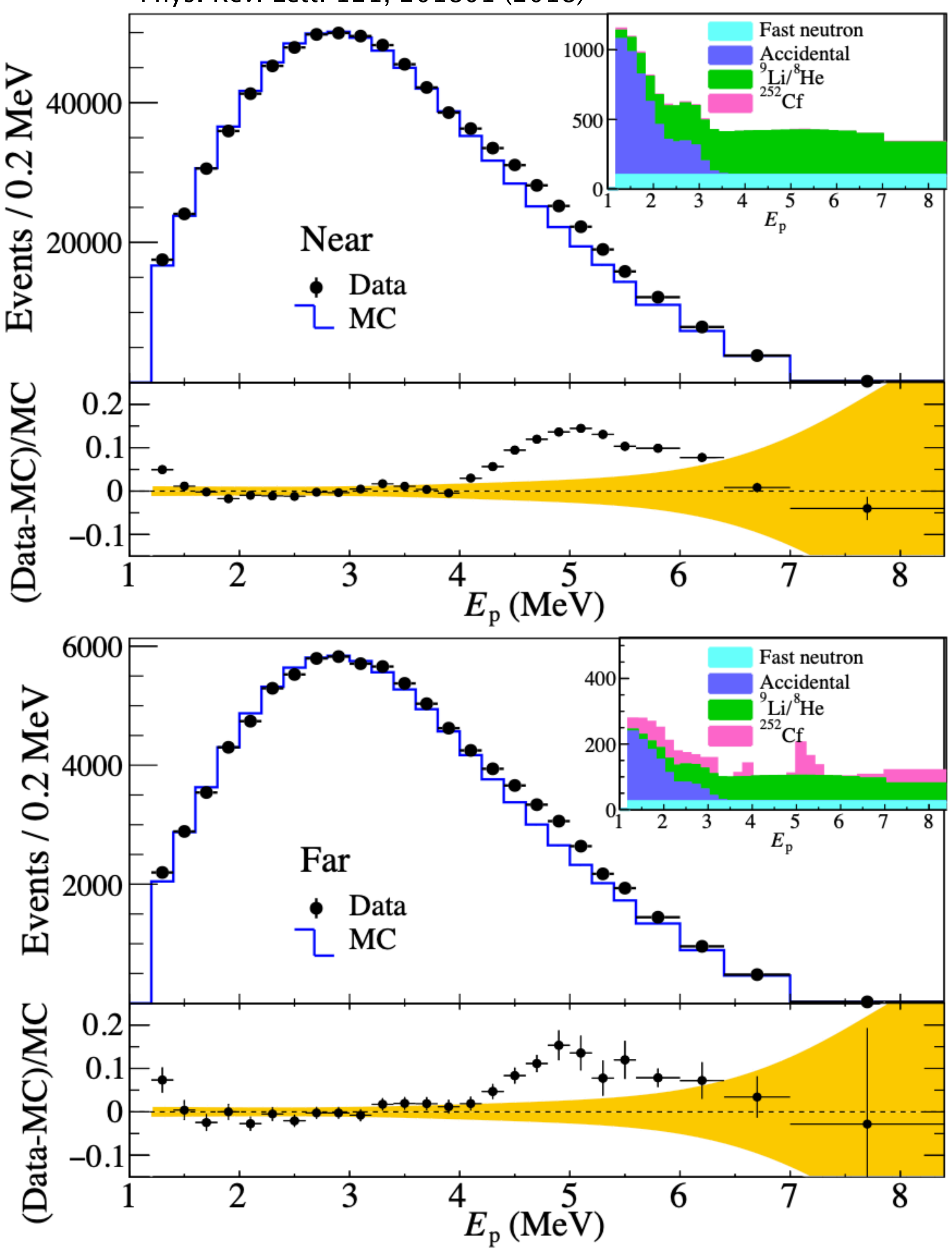
- Detectors filled with Gd loaded liquid scintillator (15.4 t)





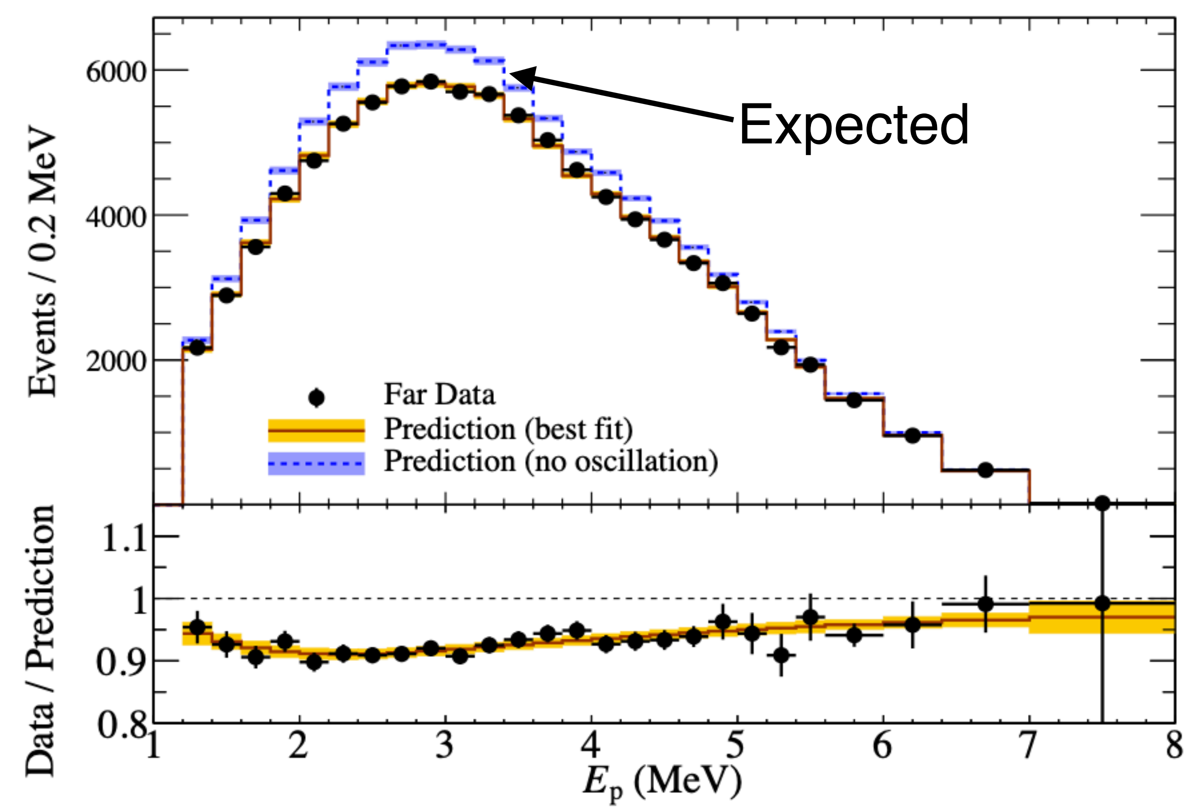
RENO

Phys. Rev. Lett. 121, 201801 (2018)



Data and expectation with an oscillation assumption agree well except “5 MeV” bump.

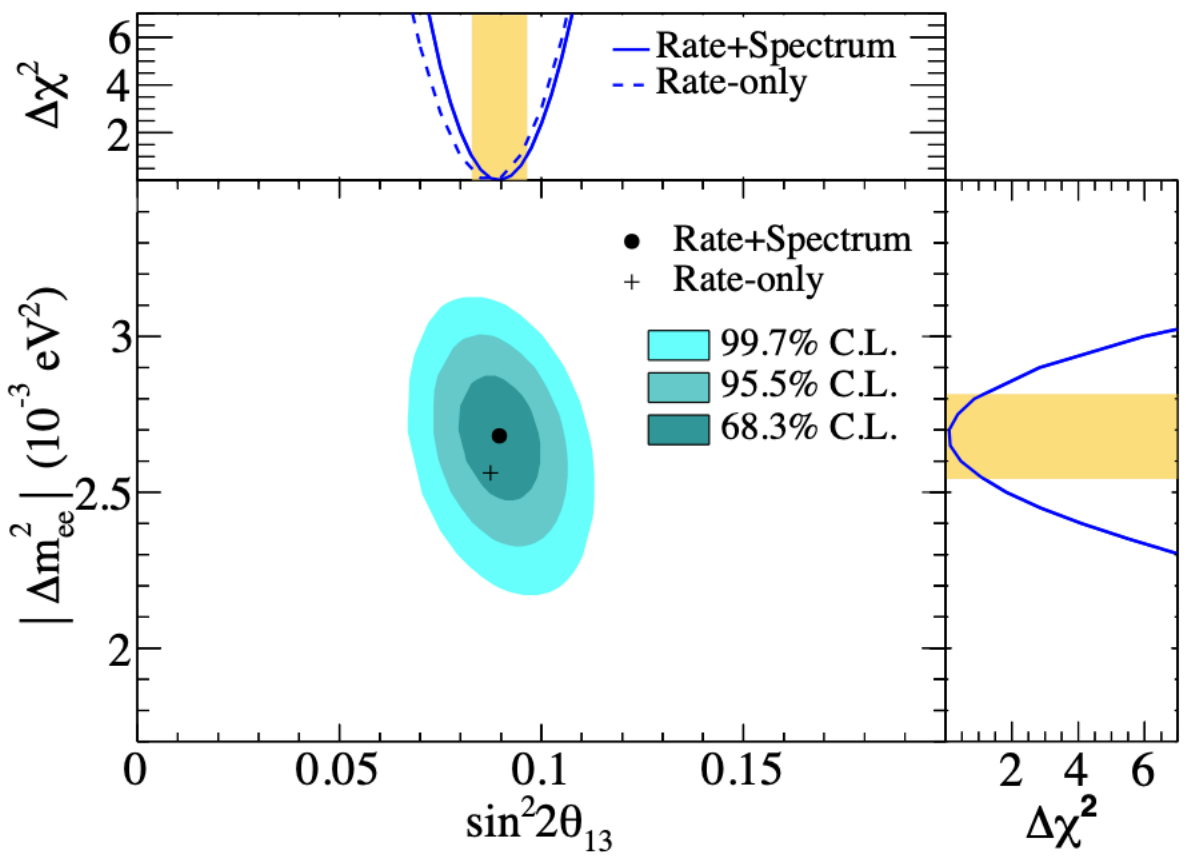
Phys. Rev. Lett. 121, 201801 (2018)



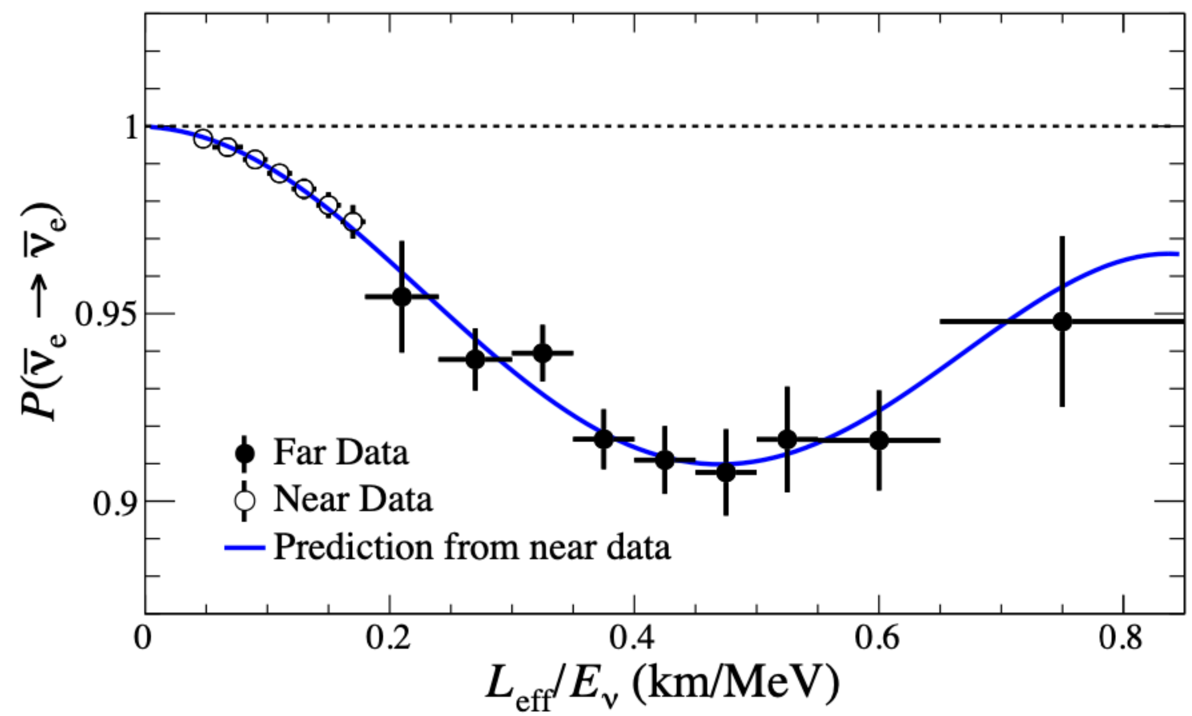
Comparison of far data and to near data with no oscillation assumption.

RENO

Phys. Rev. Lett. 121, 201801 (2018)



Phys. Rev. Lett. 121, 201801 (2018)



$$\sin^2 2\theta_{13} = 0.0896 \pm 0.0048(\text{stat.}) \pm 0.0047(\text{syst.})$$

$$\Delta m^2_{32} = (2.63 \pm 0.14) \times 10^{-3}\ \text{eV}^2$$

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{32}$$

with $\Delta_{ij} = \dfrac{m_i^2 - m_j^2}{4E} L = \dfrac{\Delta m^2_{ij}}{4E} L$

similar experiments: Daya Bay and Double Chooz

KamLAND Experiment

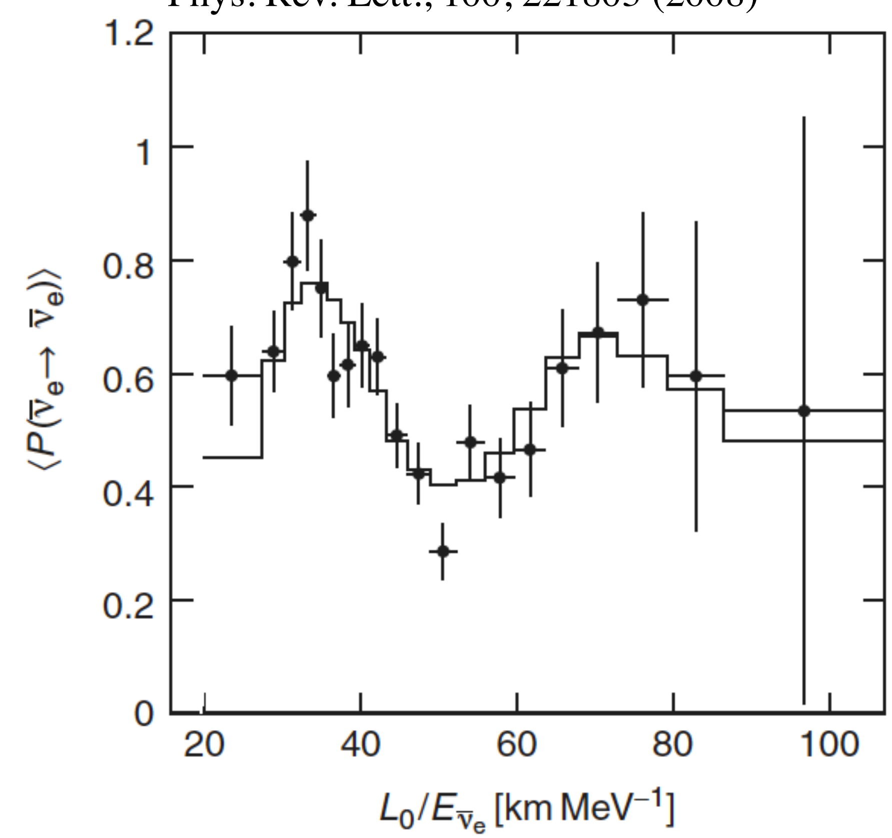
- Detected $\bar{\nu}_e$s from number of reactors located at distances in the range of 130~240 km
- A large volume of liquid scintillator with 1800 PMTs
- Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$
- Multiple $\bar{\nu}_e$ sources at various distances and not enough energy resolution

$$\langle \sin \Delta_{32} \rangle = 1/2$$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} - \sin^2 2\theta_{13} \sin^2 \Delta_{32}$$

$$\approx \cos^4 \theta_{13} \left[1 - \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m^2_{21} L}{4E} \right) \right]$$

Phys. Rev. Lett., 100, 221803 (2008)

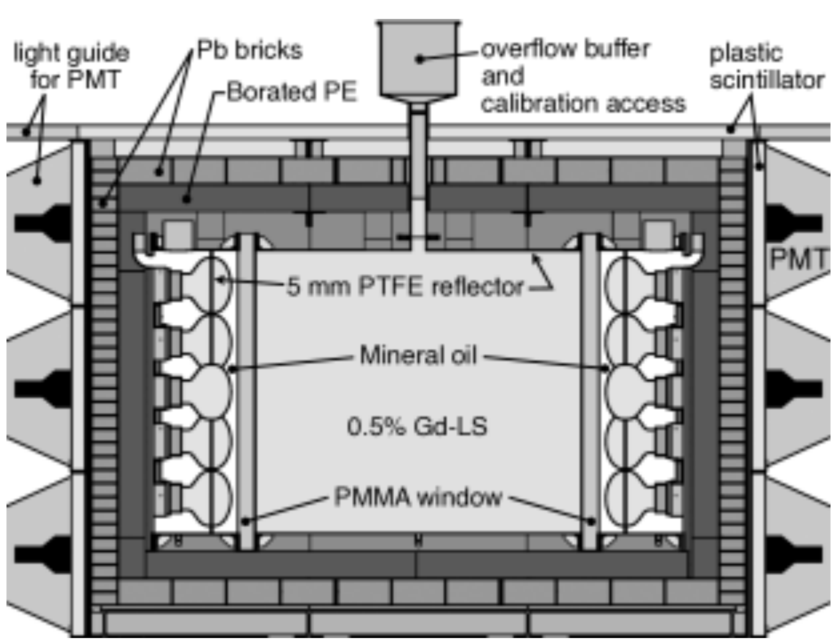


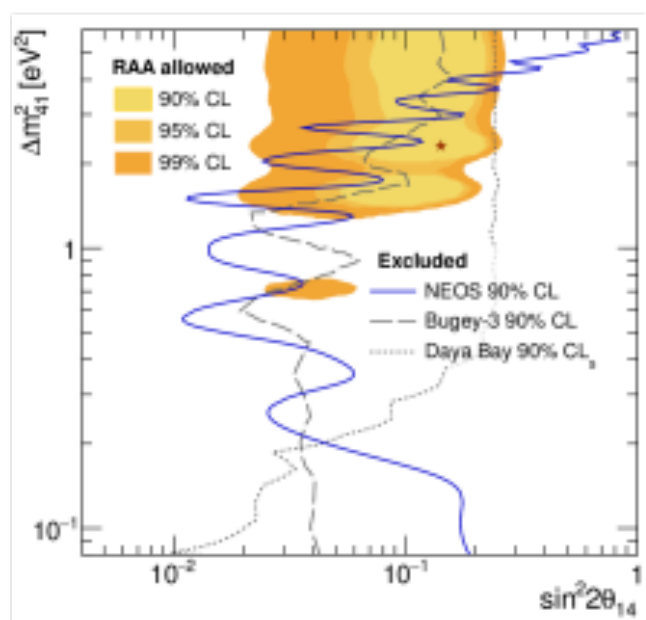
NEOS

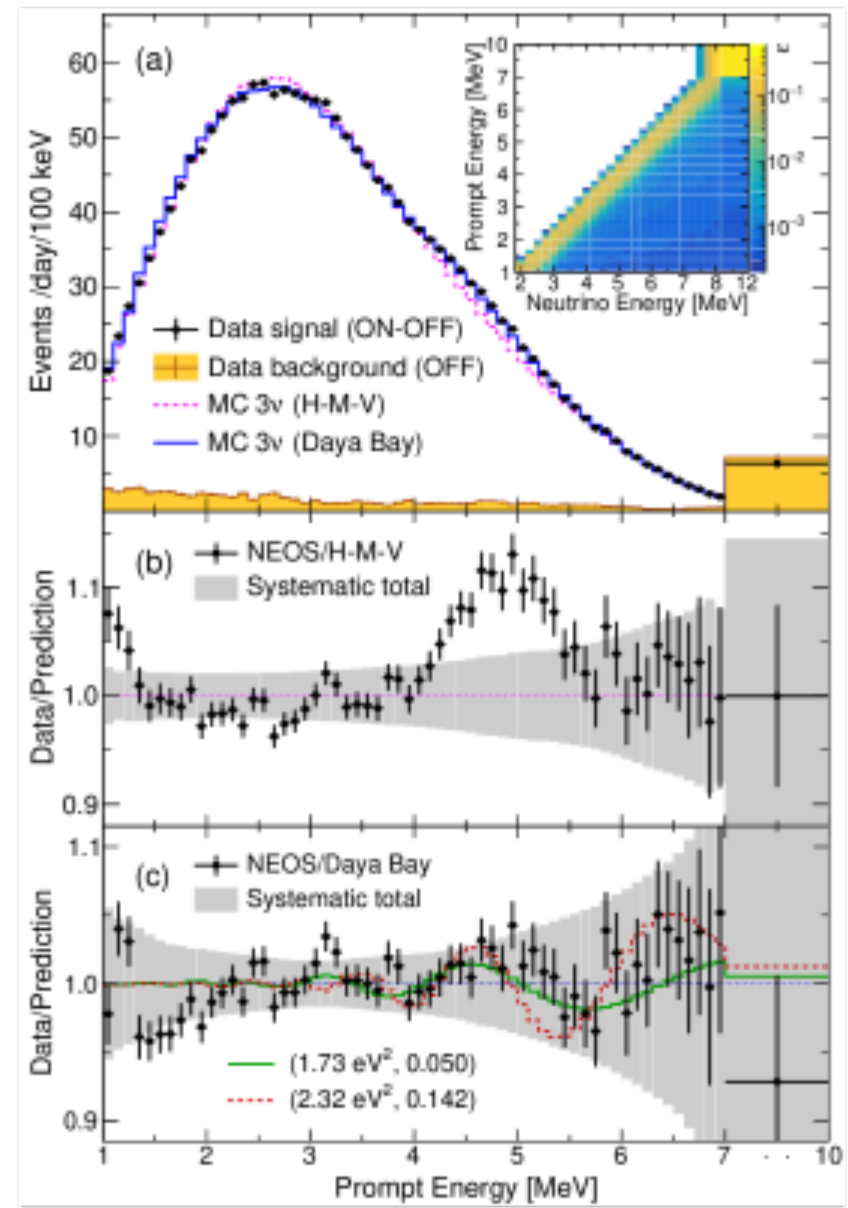
- A very short baseline reactor neutrino experiment for sterile neutrino search.
- If Δm^2 is "large," then the 1st oscillation minimum happens near the reactor.

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{14} \sin^2 \Delta_{41}$$

$$\text{with } \Delta_{41} = \frac{\Delta m^2_{41}}{4E} L$$







Phys. Rev. Lett.118.121802

Accelerator Based Experiment

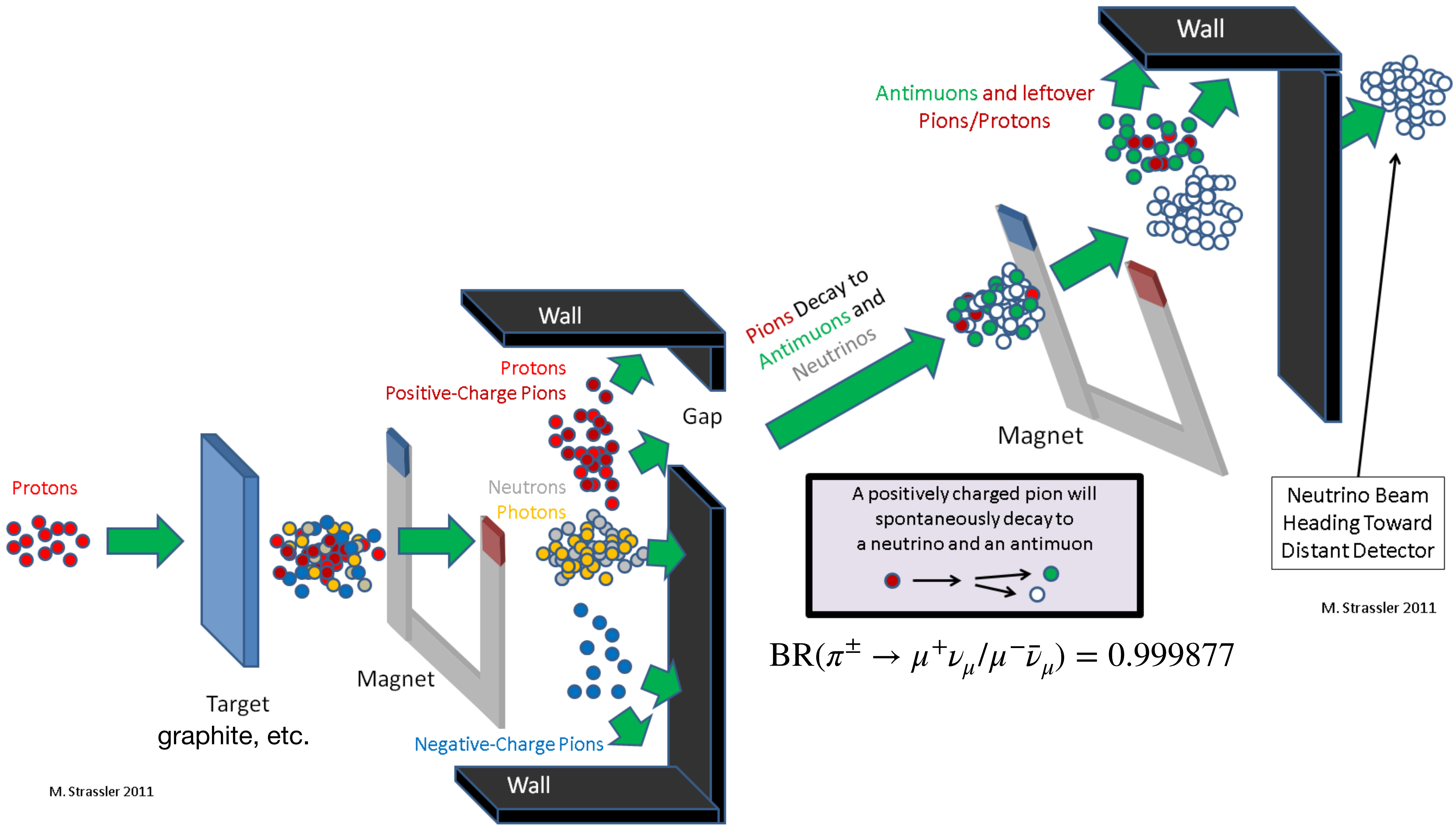
Long baseline

- Using intense neutrino beam: can have more control than other sources
- Two detectors: one near the beam source and the other at hundreds km away
- Measure the ratio of the neutrino energy spectrum in far detector to that in near detector
- Partial cancellation of systematic uncertainties
- MINOS, T2K, T2HK, DUNE
- what to measure….θ_{12}, θ_{13}, Δm^2, $\delta_{\rm CP}$

“Short” Baseline

- Sterile neutrino search

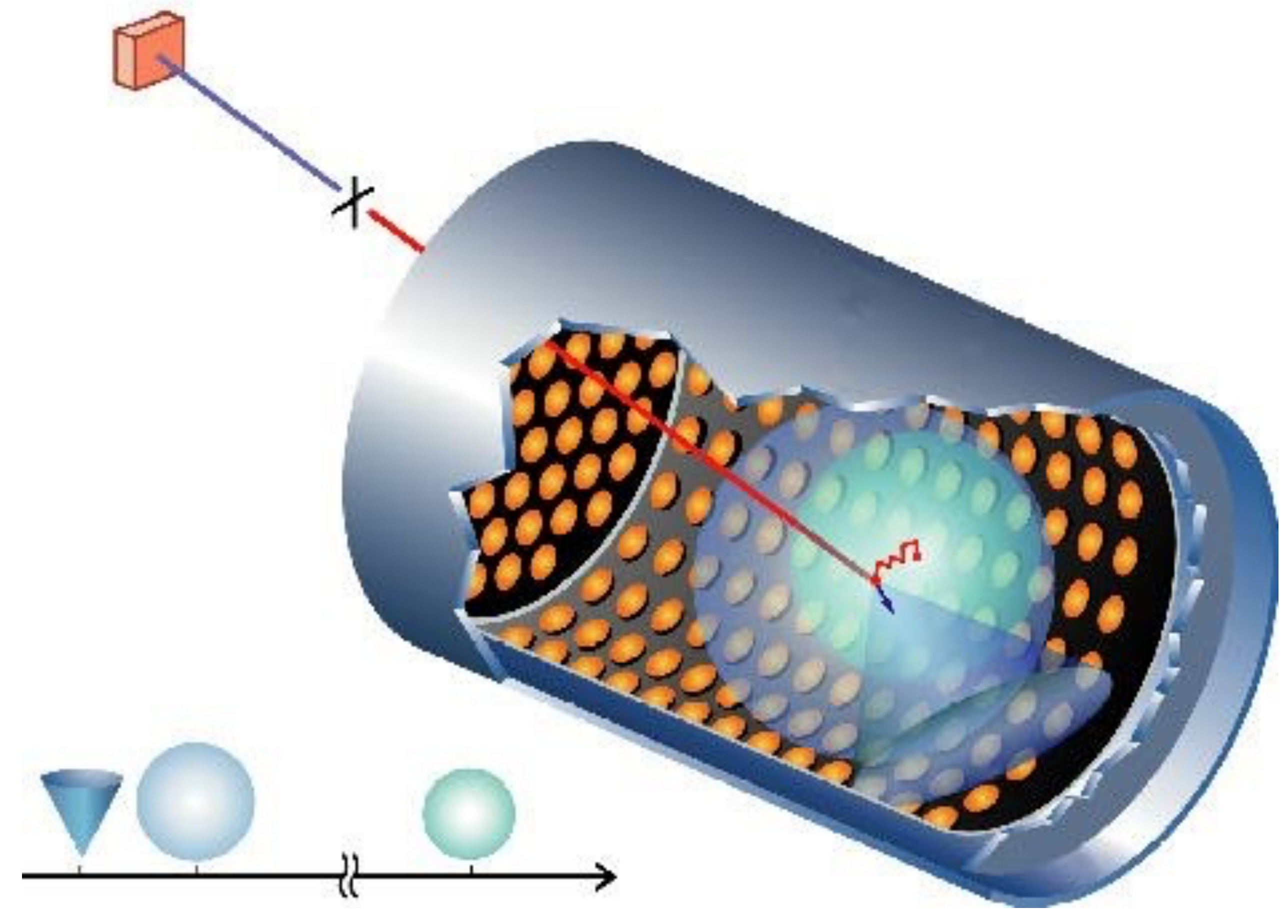
How to make neutrino beams



$$BR(\pi^{\pm} \to \mu^{+}\nu_{\mu}/\mu^{-}\bar{\nu}_{\mu}) = 0.999877$$

LSND Experiment

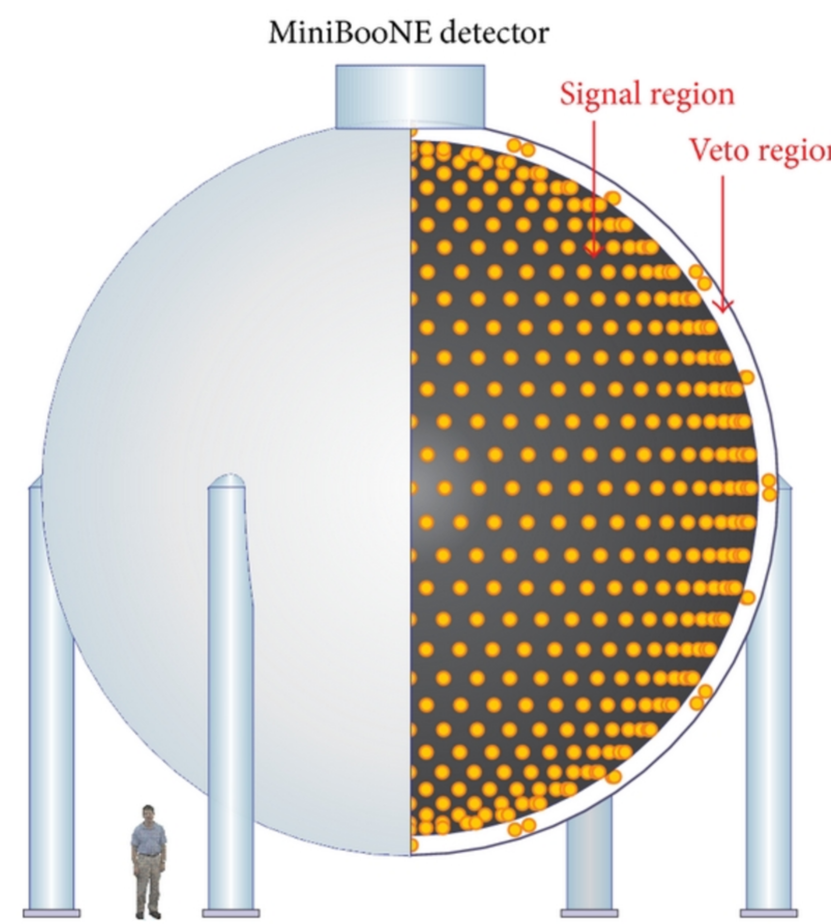
- "Short" baseline experiment: 30 m from the proton beam dump.
  - Sterile neutrino search: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance experiment.
- Liquid Scintillator Neutrino Detector
- 798 MeV proton beam with $\nu_\mu/\bar{\nu}_\mu$ at L/E ~ 1 m/MeV to probe $\Delta m^2 \sim 1$ eV^2.
- 9 observed and 2.1 ± 0.3 background expected.
- sterile neutrinos?



https://sciencesprings.wordpress.com/2015/10/06/from-nova-sterile-neutrinos-the-ghost-particles-ghost-july-2014-old-but-worth-it-for-the-details/lsnd-experiment/

MiniBooNE Experiment

- "Short" baseline experiment: 541 m from the beryllium target
- To confirm the LSND result : $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance experiment.
- ~800 tons of mineral oil Cherenkov/Scintillator detector
- 400-600 MeV $\nu_\mu/\bar{\nu}_\mu$



https://static-01.hindawi.com/articles/ahep/volume-2013/439532/figures/439532.fig.009.jpg

MINOS/+ Experiments

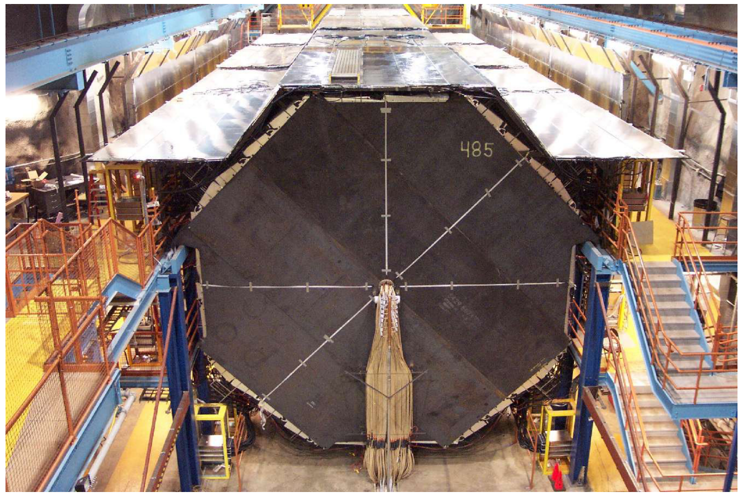
- Long baseline neutrino experiment:
- 1-10 GeV neutrino beam
- Steel-plastic scintillator sandwich
- Near at 1 km, far at 734 km
  - CC ν_μ disappearance channel has sensitivity to Δm^2_{32} and θ_{23}, and θ_{14} and Δm^2_{41}.

$$P(\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)) \approx 1 - \sin^2 2\theta_{23} \cos^2 2\theta_{24} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \sin^2 2\theta_{24} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

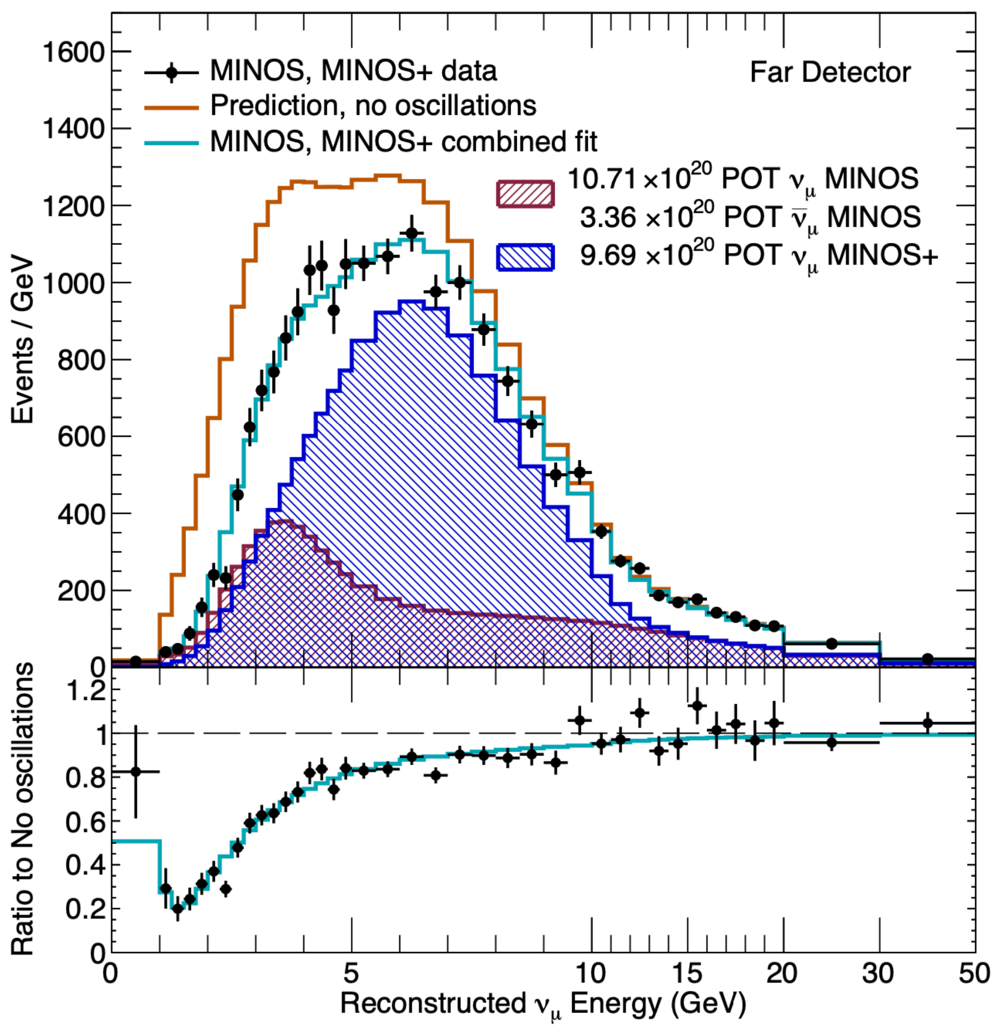
  - The NC sample has sensitivity to θ_{34}, θ_{24}, and Δm^2_{41}

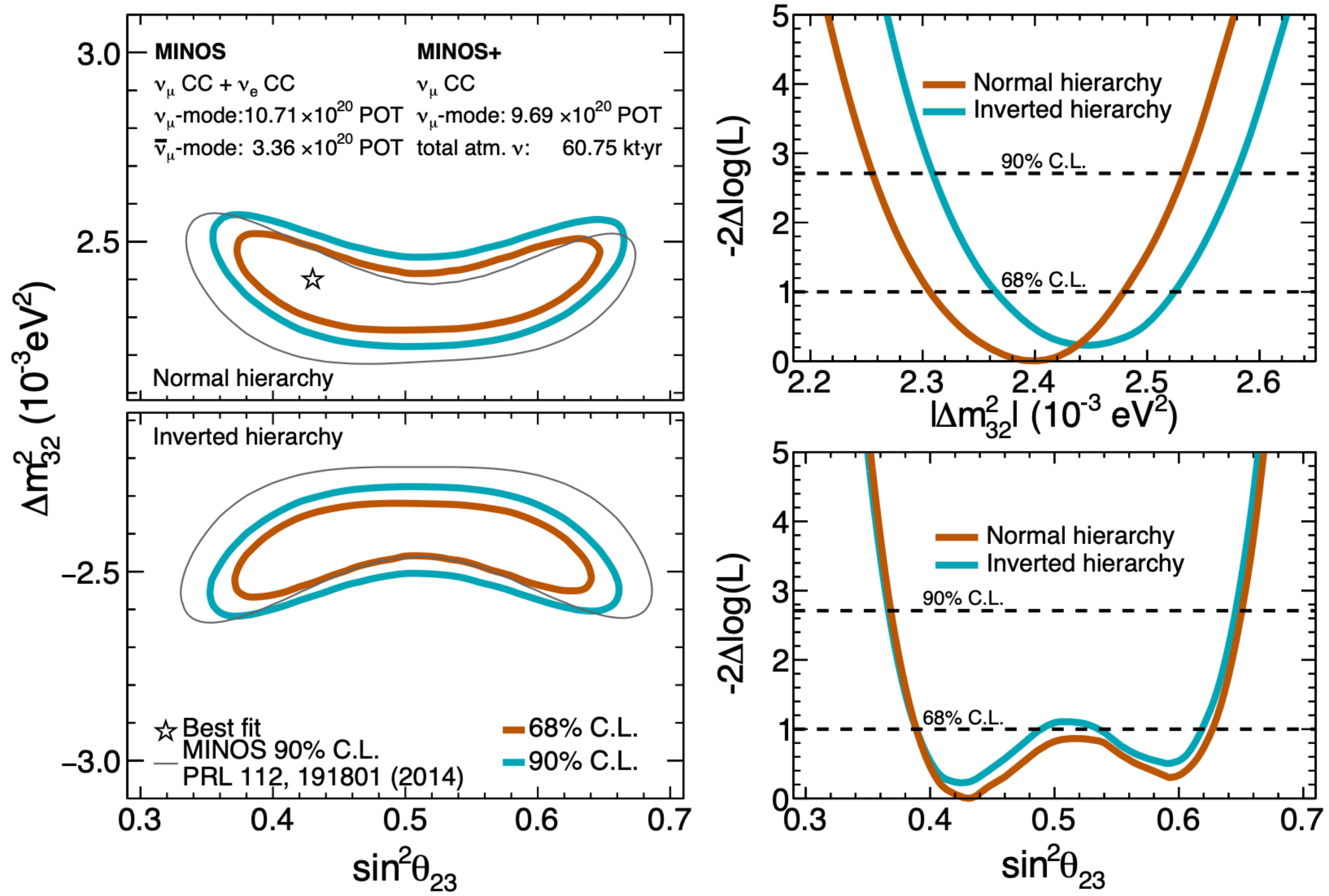
$$P_{\rm NC} = 1 - P(\nu_\mu \to \nu_s) \approx 1 - \cos^4\theta_{14} \cos^2\theta_{34} \sin^2 2\theta_{24} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

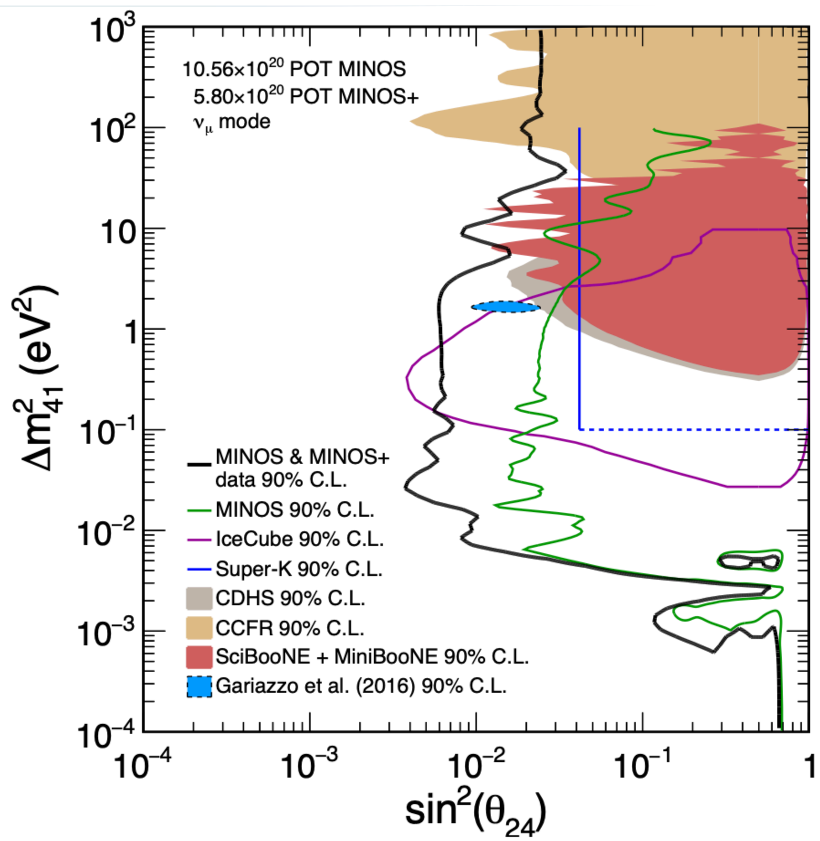
https://www.hep.ucl.ac.uk/minos/



MINOS Experiment

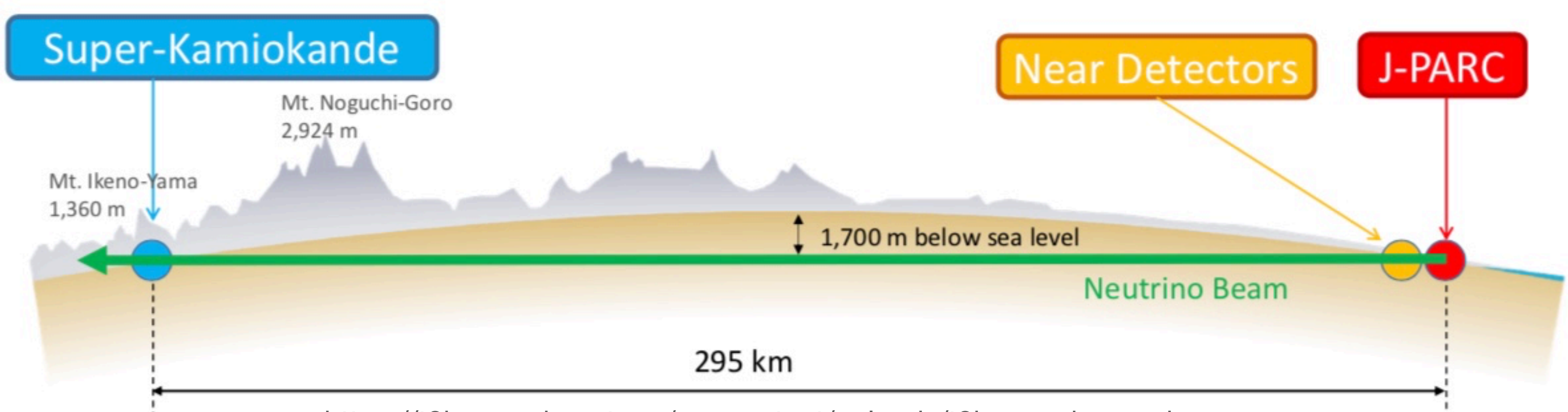






T2K Experiment

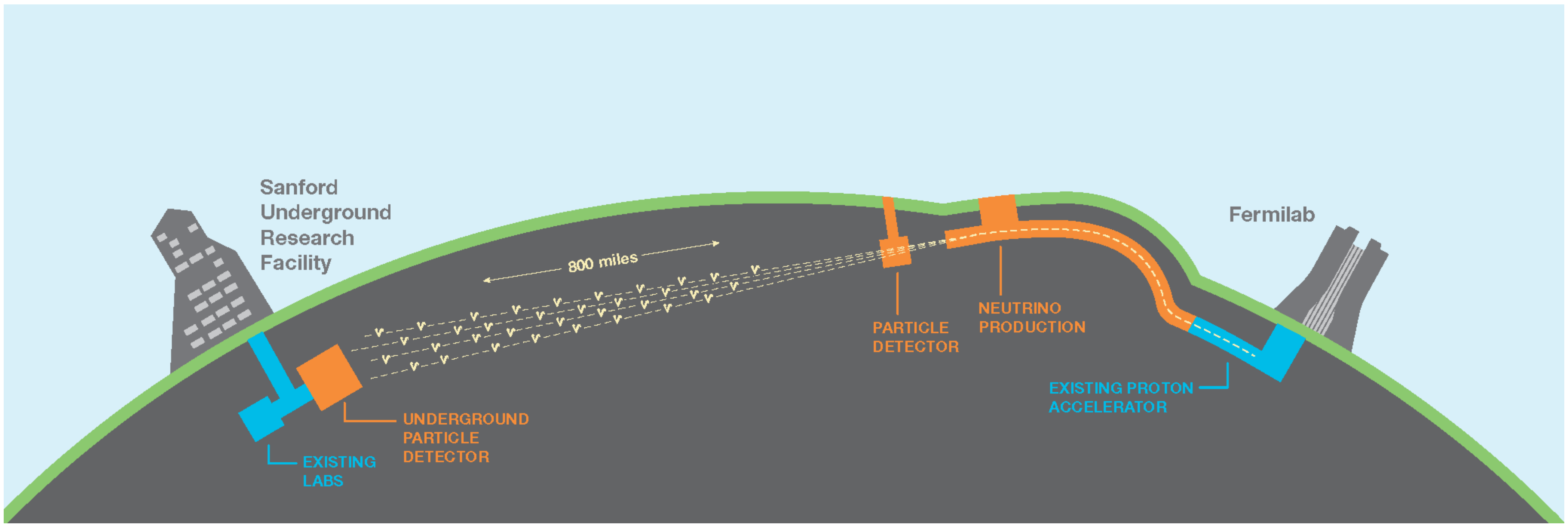
- ~50 kton water Cherenkov detector @295 km from the beam source
- 600 MeV peaked neutrino beam
- Detectors sitting at 2.5 degree off-axis: better defined beam energy
- Taking data since 2014
- First to show $\nu_\mu \rightarrow \nu_e : \theta_{13} \neq 0$
- Mass effect is not as pronounced as NOvA experiment due to the relatively short baseline



https://t2k-experiment.org/wp-content/uploads/t2k-overview-en.jpg

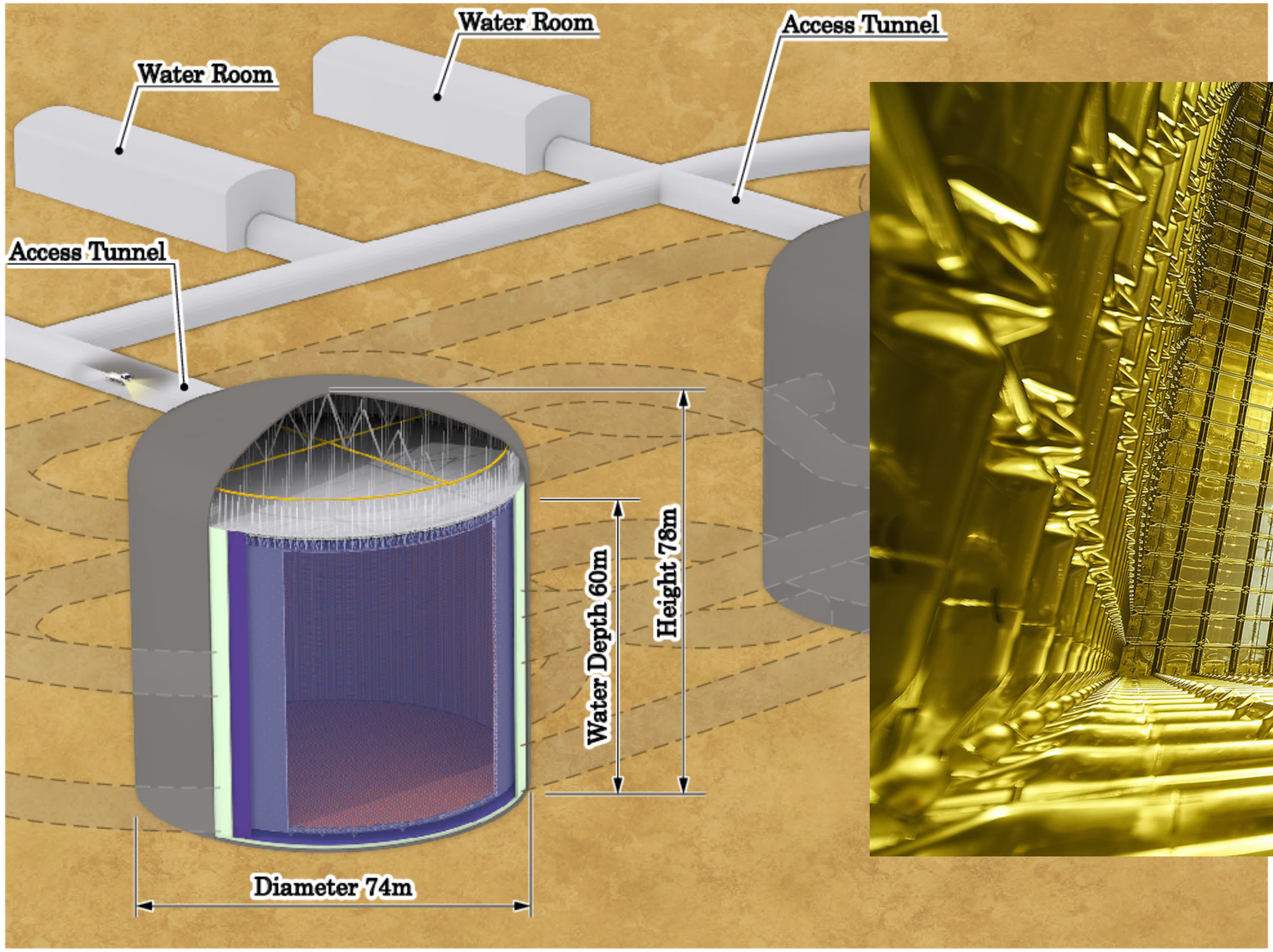
Future Long Baseline Neutrino Beam Exps.

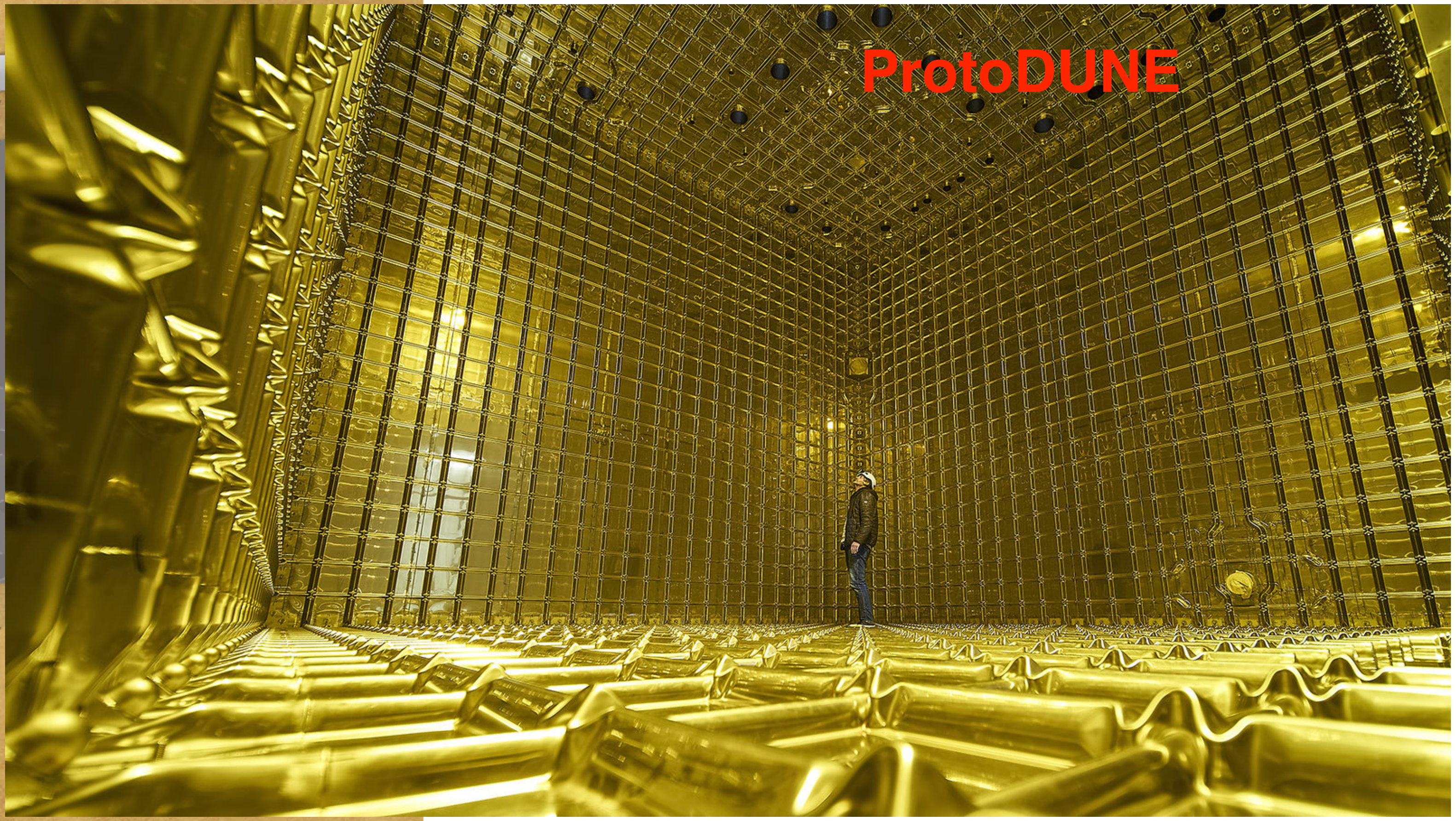
Send an intense beam of neutrinos created by accelerator down ~300 km (T2HK) and ~1300 km (DUNE).



- An investigation of neutrino oscillations to test CP violation in the lepton sector
- Determine the ordering of the neutrino masses
- Search for neutrinos beyond the currently known three
- Study supernovae and the formation of a neutron star or black hole
- Search for proton decay

T2HK(K)/DUNE Experiments



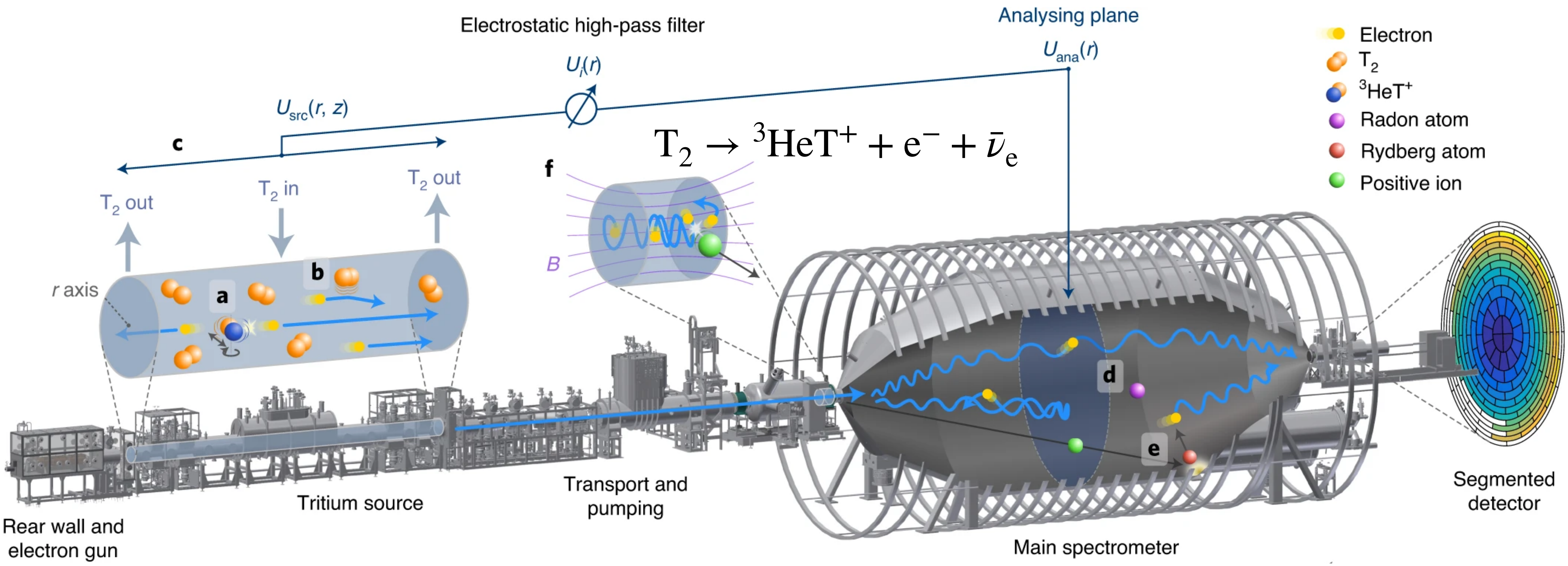


- Water Cherenkov Detector
- 260,000 tons of water
- Proposal to put another detector in Korea

- Liquid Ar time projection detector
- Total of 68,000 tons of Liquid Ar.

Direct Neutrino Mass Measurement Exp.: KATRIN

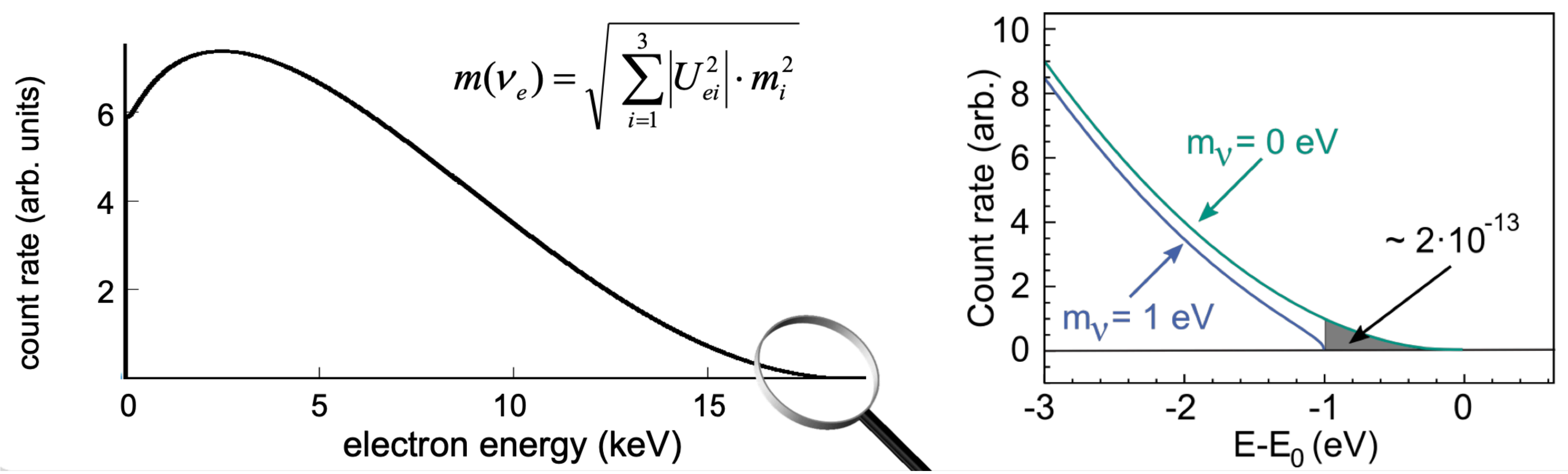
$$T_2 \rightarrow {}^3\mathrm{HeT}^+ + e^- + \bar{\nu}_e$$



A precision electron spectrometer

KATRIN Experiment

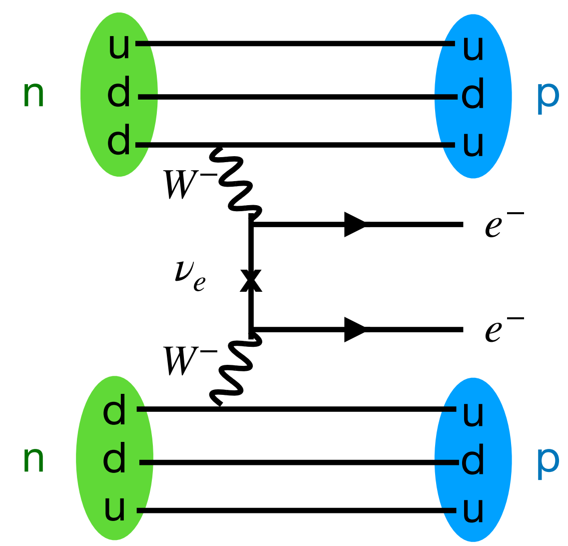
$$\frac{\mathrm{d}\Gamma_i}{\mathrm{d}E} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_i^2} \cdot F(E,Z) \cdot \theta(E_0 - E - m_i)$$



$$m_\nu < 0.8\ \mathrm{MeV} \quad @90\,\%\ \mathrm{CL}$$

Neutrinoless Double Beta Decay

If neutrinos are Majorana particle, a neutrino is its own anti-particle. Possible to have neutrinoless double beta decay ($0\nu\beta\beta$). For light Majorana neutrinos, the electrons carry almost all decay energy.



$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

$$\Gamma^{0\nu}_{\beta\beta} = \frac{1}{T^{0\nu}_{\beta\beta}} = G^{0\nu} \cdot \left| M^{0\nu} \right|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

Phase space factor

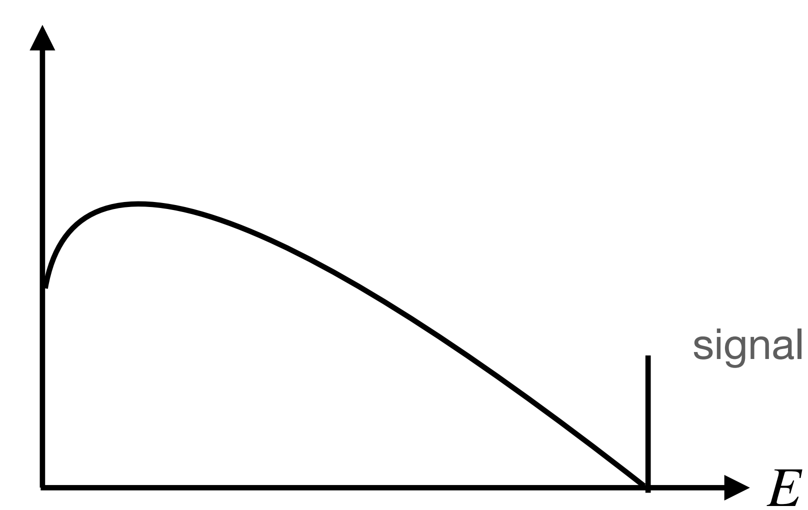
Nuclear matrix elements

Effective Majorana mass

$$\langle m_{\beta\beta} \rangle = \sum_i U_{ei} m_i$$

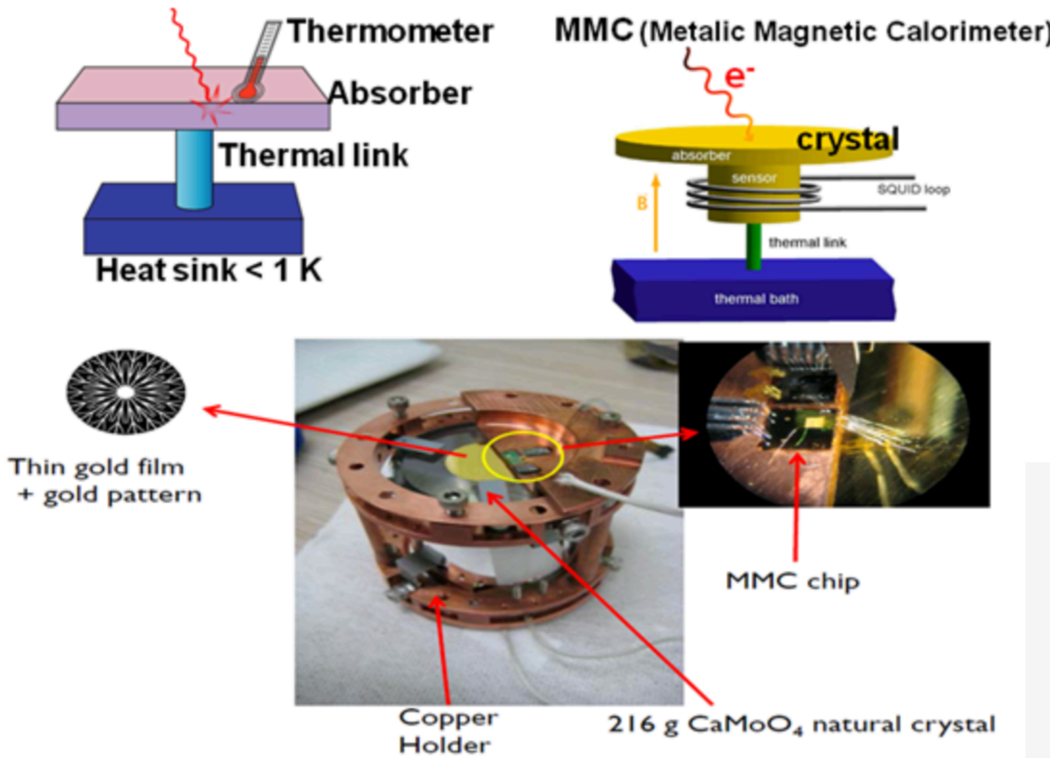
$0\nu\beta\beta$ Candidates: $^{48}\mathrm{Ca}$, $^{76}\mathrm{Ge}$, $^{82}\mathrm{Se}$, $^{96}\mathrm{Zr}$, $^{100}\mathrm{Mo}$, $^{116}\mathrm{Cd}$, $^{130}\mathrm{Te}$, $^{136}\mathrm{Xe}$, $^{150}\mathrm{Nd}$

Limits extends $T^{0\nu}_{\beta\beta} > 10^{22} \sim 10^{25}$ yrs .



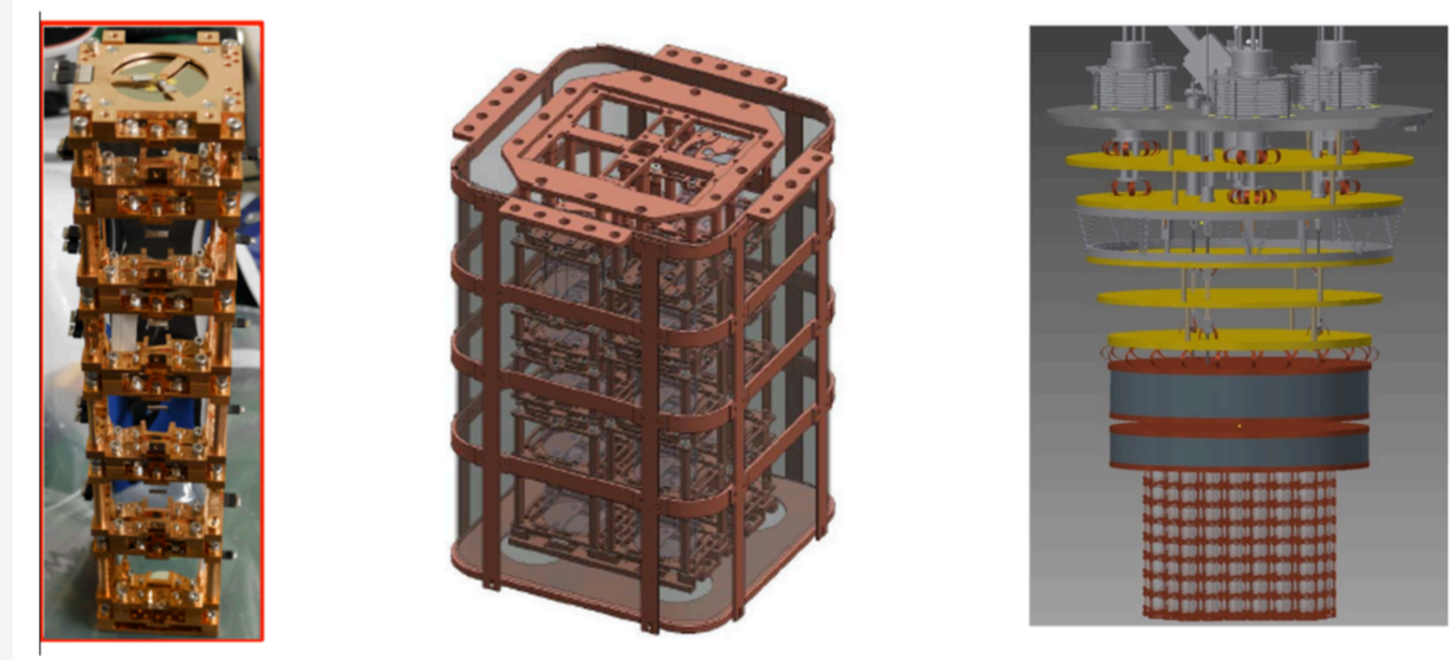
AMoRE

AMoRE (Advanced Mo Rare decay Experiment) in Korea uses ^{100}Mo crystals.



Heat (phonon) and light signal coincidence is used to remove noises.

Figure 8. Left: assembled tower of AMoRE-Pilot with six $CaMoO_4$ crystals (~1.9 kg in total). **Middle**: schematic design of the AMoRE-I configuration with 13 $CaMoO_4$ crystals and 5 Li_2MoO_4 crystals (~6 kg in total). **Right**: design of the AMoRE-II detector with ~400 molybdate crystals (~200 kg in total) beneath lead shields and cold plates. The figure is reprinted with permission from [64]. Creative Commons License CC BY 4.0.



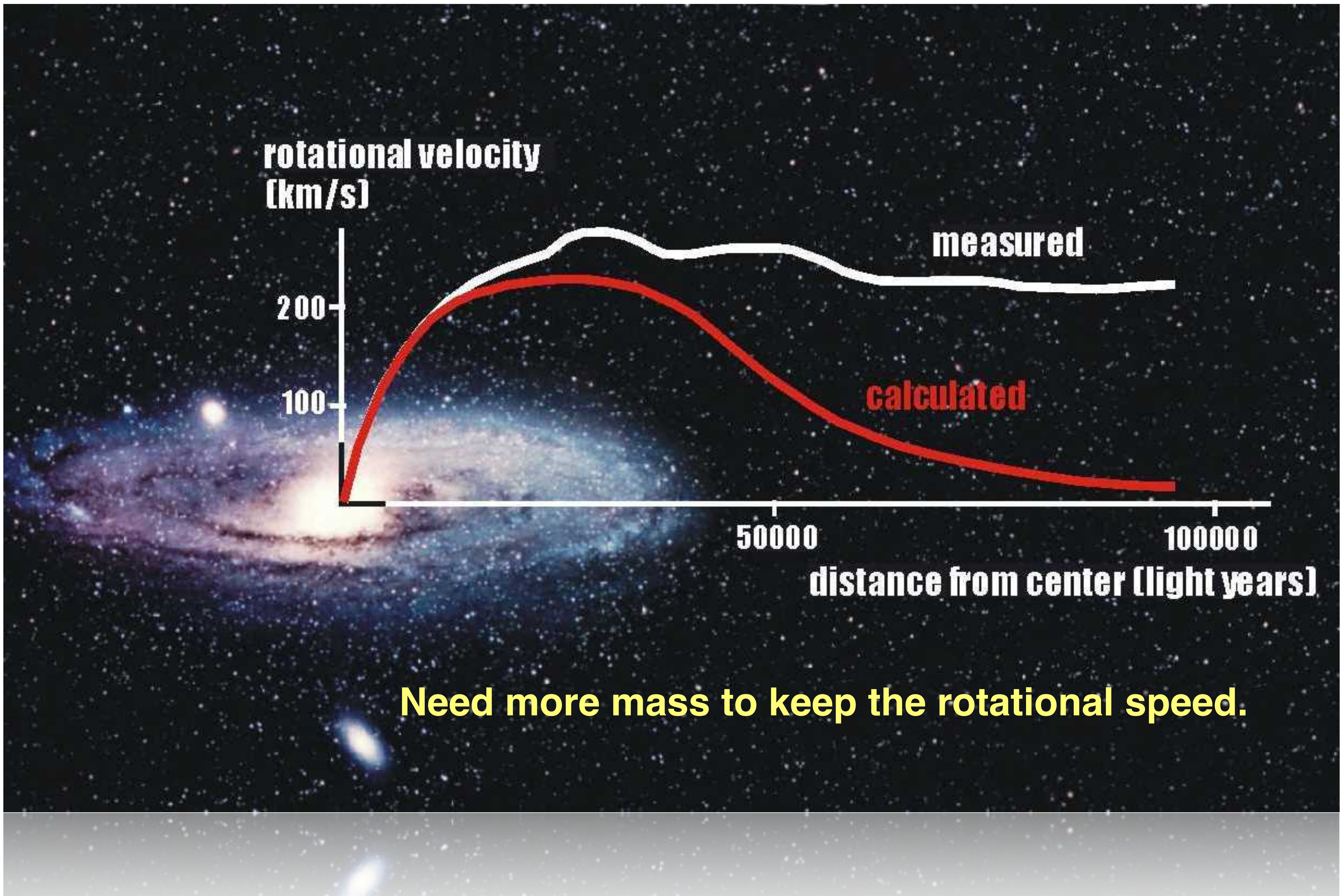
Three stages of the experiment

1. Pilot: total ~1.9 kg crystals
2. AMoRE-I: total ~6 kg crystals
3. AMoRE-II: total ~200 kg crystals

Dark Matter Searches

Dark Matter

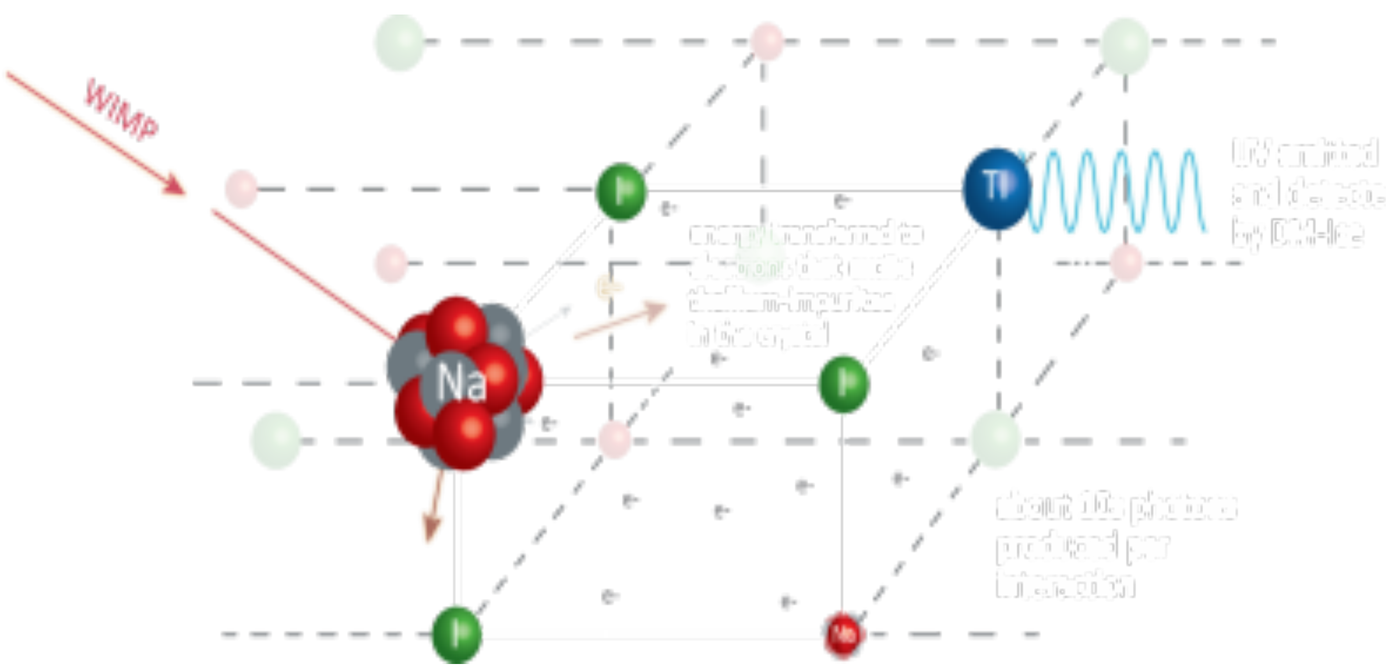
Observed rotational speed of galaxy is different from what we expect using visible mass.



DAMA/LIBRA experiment

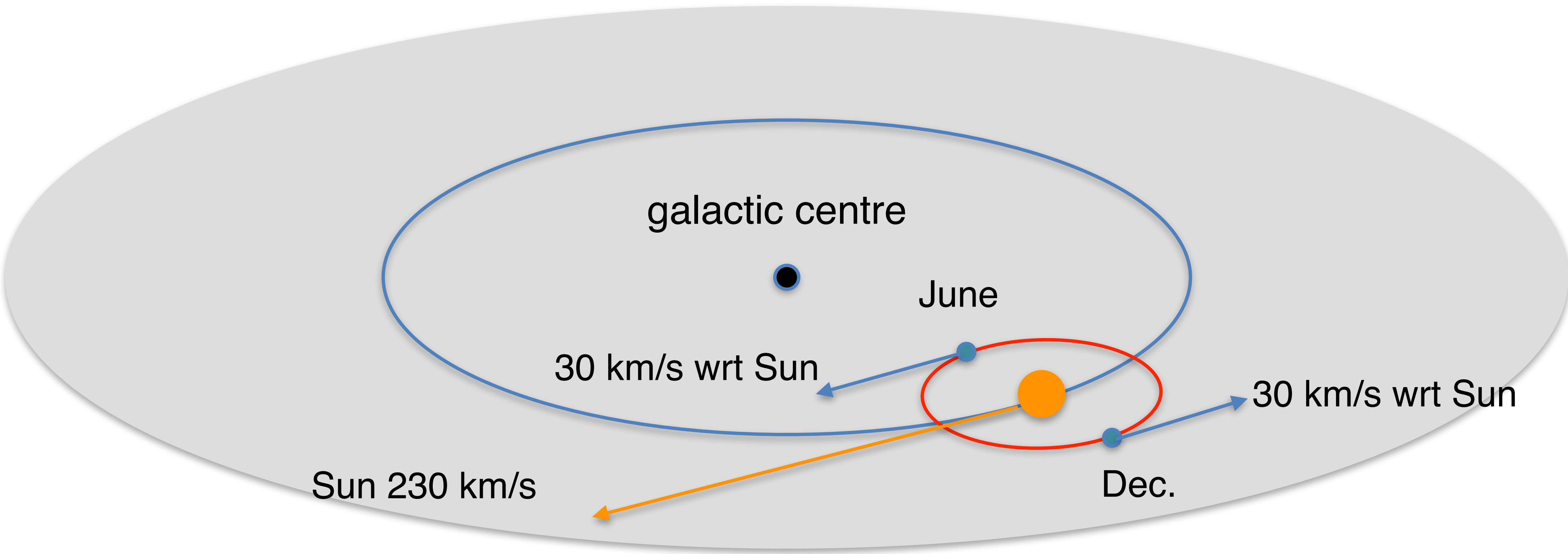
Located underground at Gran Sasso in Italy

Used scintillation detector made up of ~250 kg NaI(Tl) to detect dark matter particles in the galactic halo.



Detecting Dark Matter Particles

Solar system is moving in the dark matter halo.



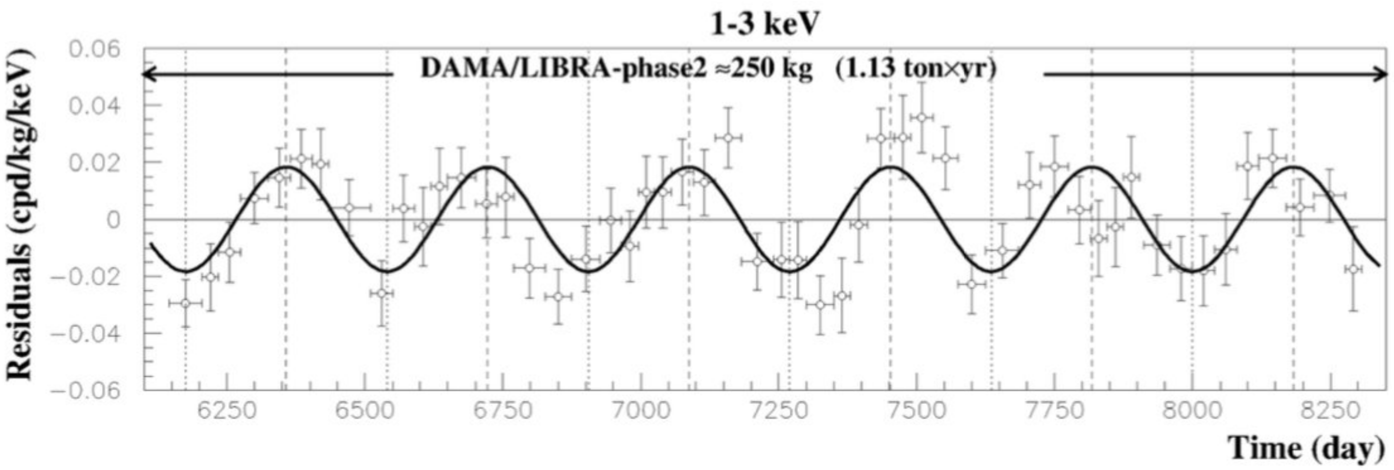
$S(t) = S_0 + S_m \cos[\omega(t - t_0)]$

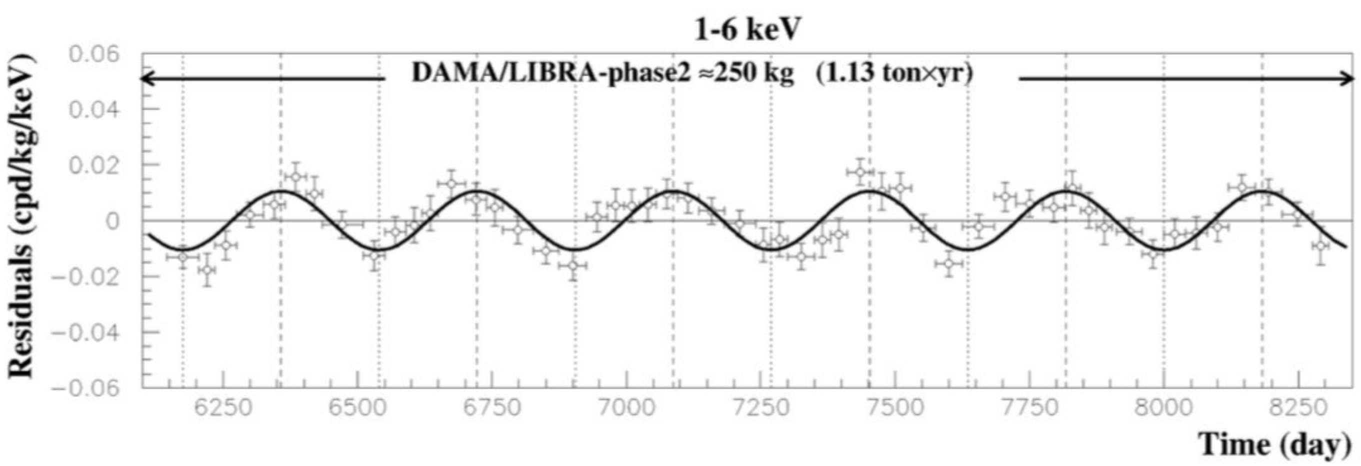
$\omega = 2\pi/T$

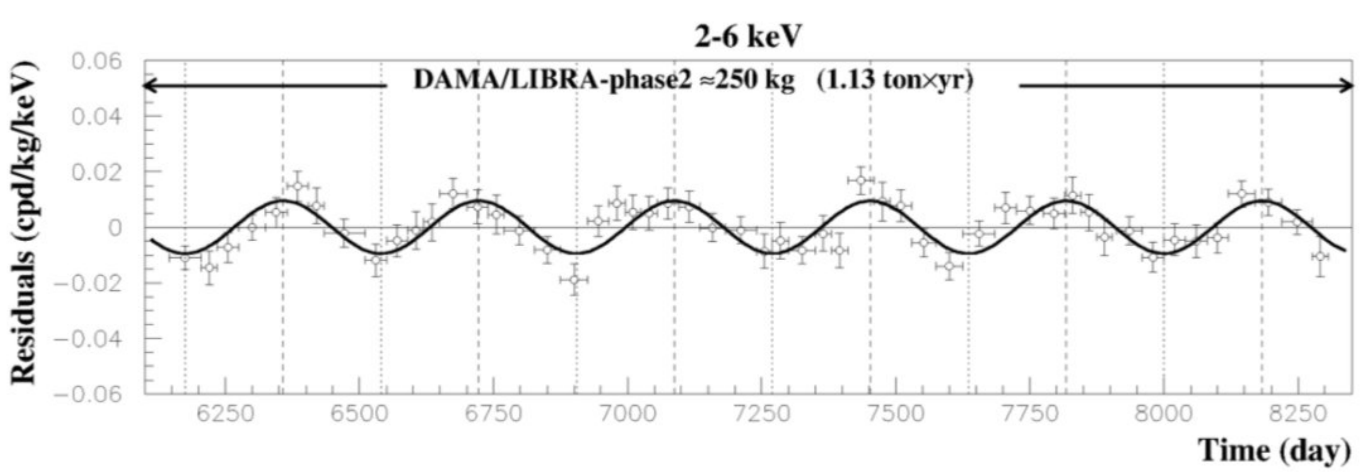
with $T = 1$ year

Expect annual modulation of signal rate

Results of DAMA/LIBRA phase 2







Solid lines

$$\text{Residual} = A\cos[\omega(t - t_0)]$$

$$t_0 = 152.5 \text{ days}$$

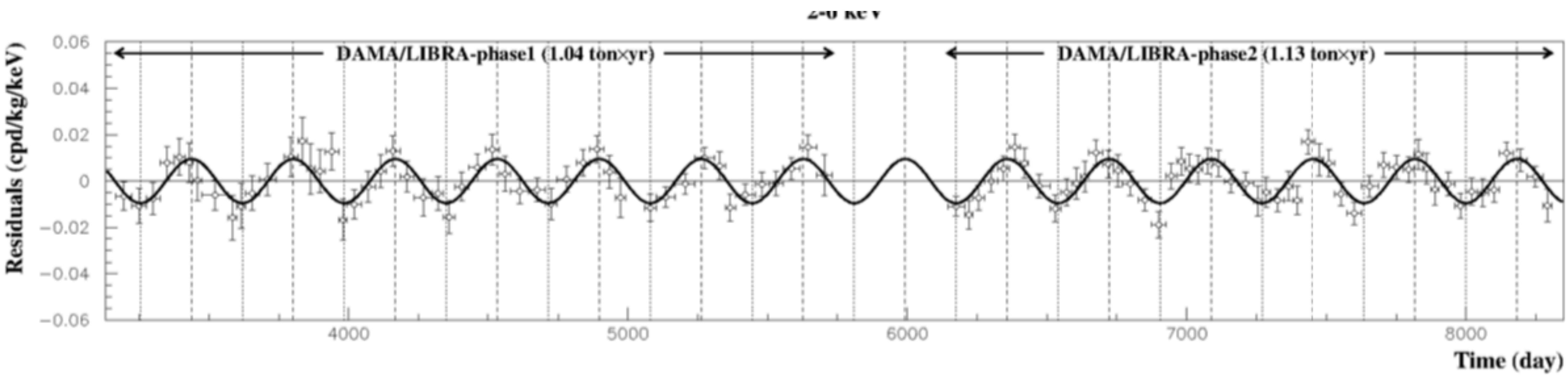
$$T = 1 \text{ year}$$

Absence of modulation? No

- 1-3 keV: $\chi^2/\text{dof}=127/52 \Rightarrow P(A=0) = 3\times10^{-8}$
- 1-6 keV: $\chi^2/\text{dof}=150/52 \Rightarrow P(A=0) = 2\times10^{-11}$
- 2-6 keV: $\chi^2/\text{dof}=116/52 \Rightarrow P(A=0) = 8\times10^{-7}$

Results favour the presence of annual modulation with proper features at a very very high confidence level..

Results of DAMA/LIBRA phase 1-2



Absence of modulation? No

- 2-6 keV: $\chi^2/\text{dof}=199.3/102 \Rightarrow P(A=0)=2.9\times10^{-8}$

Fit on DAMA/LIBRA-phase1+ DAMA/LIBRA-phase2

$A\cos[\omega(t-t_0)]$;
continuous lines: t_0 = 152.5 d, T = 1.00 y

2-6 keV

A=(0.0095±0.0008) cpd/kg/keV

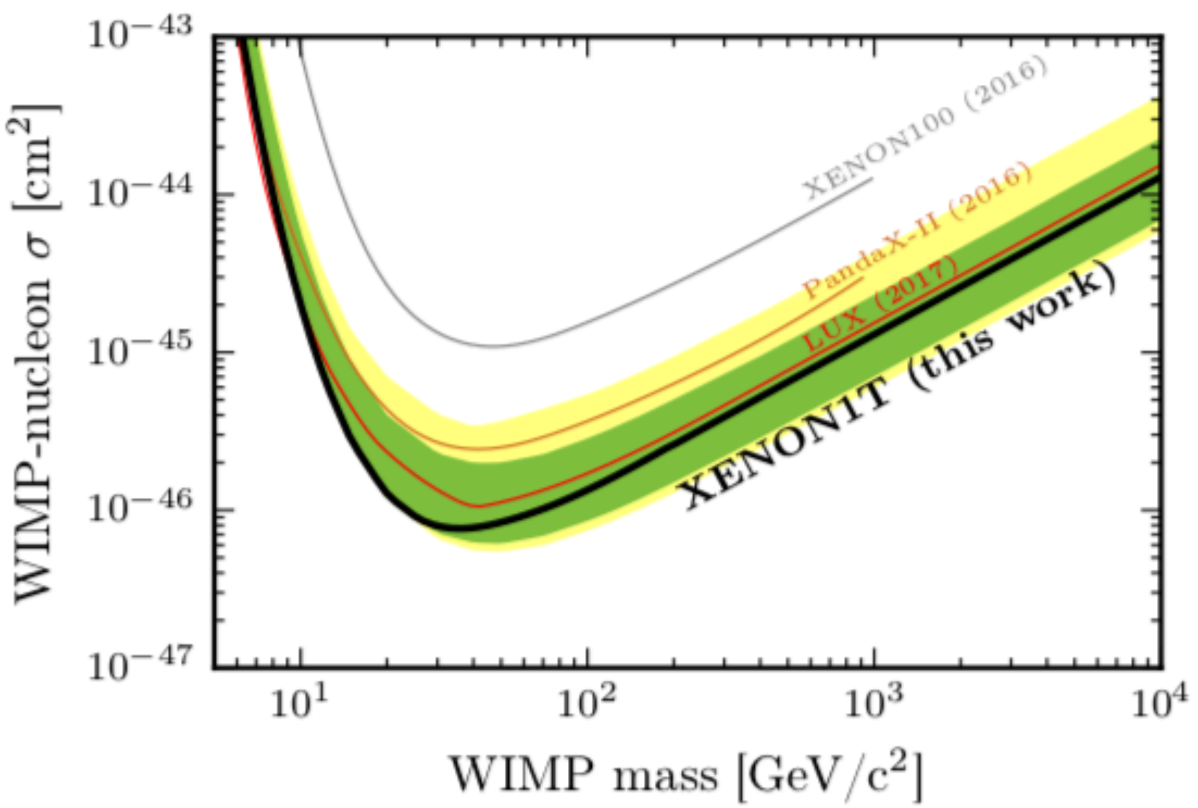
χ^2/dof = 71.8/101 **11.9σ C.L.**

Contradicting Results

- XMASS-I

  “We did not find any particular periodicity in the data…”

- XENON1T



Both experiments uses liquid xenon

COSINE-100, which uses NaI(TI), to directly compare to DAMA/LIBRA results.