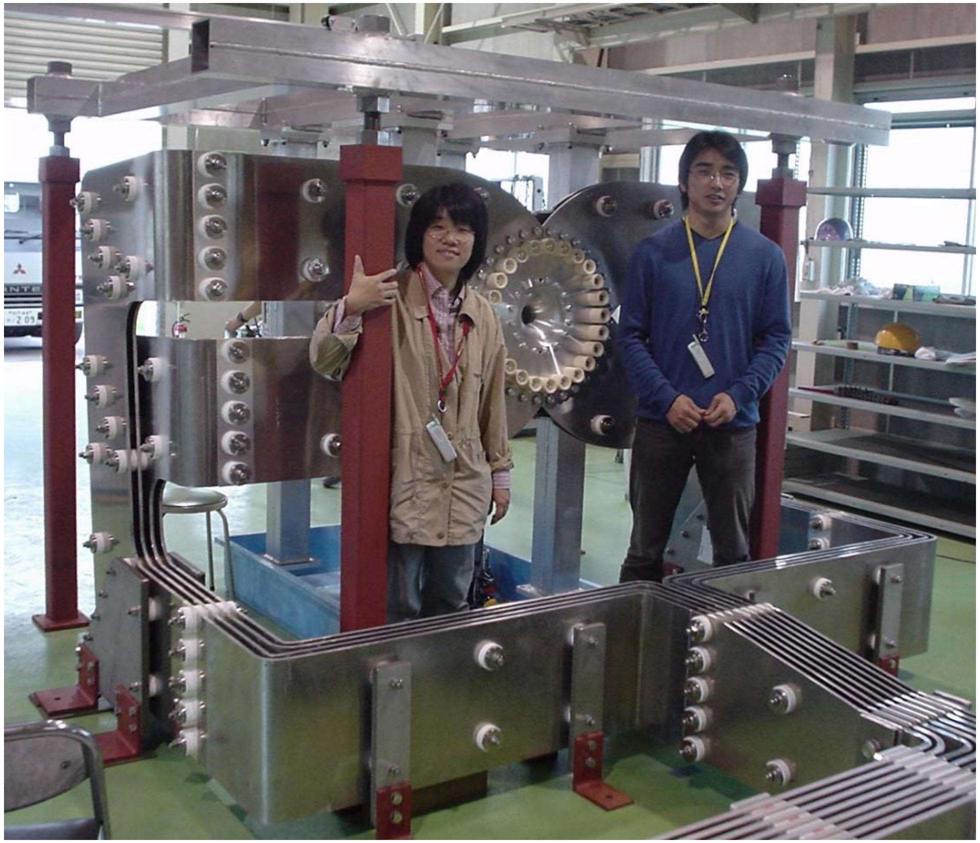
EXPLORING PARTICLE-ANTIPARTICLE ASYMMETRY IN NEUTRINO OSCILLATION

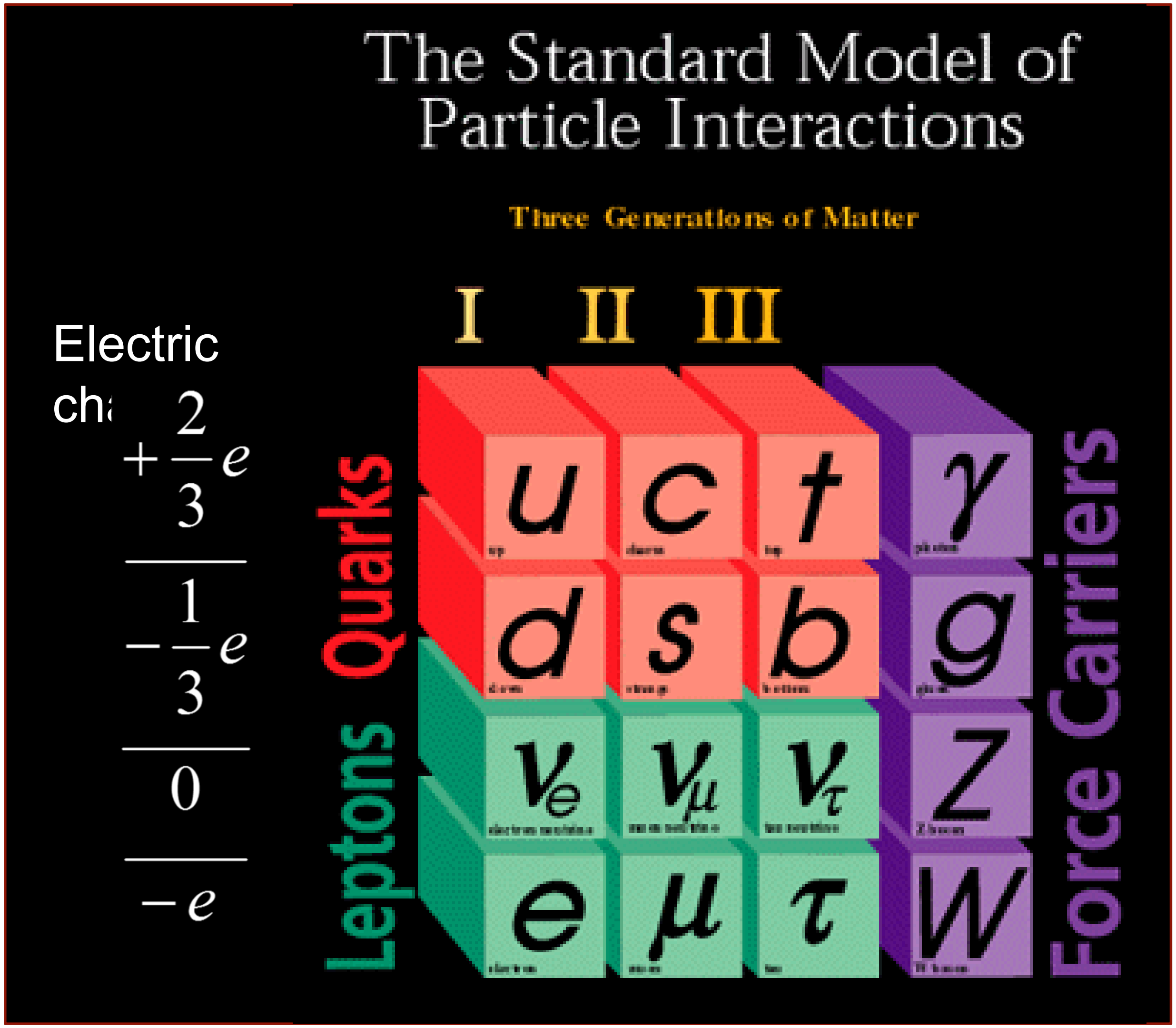
Atsuko K. Ichikawa, *Kyoto University*

INTRODUCTION OF MYSELF

- Got PhD by detecting doubly-strange nuclei using emulsion
- After that, working on accelerator-based long-baseline neutrino oscillation experiments in Japan, especially on neutrino production, neutrino detector in accelerator-site and analysis.
- Recently, started a high-pressure Xenon gas project for double-beta decay search



CONSTITUENTS OF THIS WORLD



How can we distinguish btw.

- u, c and t
- d, s and b
- ν_e, ν_μ and ν_τ
- e, μ and τ

Same spin, same charge…

Only by mass!
Except for ν's.

+α (Higgs, dark matter, dark energy…..?)

Fig. from FNAL home page

HOW CAN WE DISTINGUISH NEUTRINOS?
- IT IS TWO SIDES OF COINS-

Neutrinos do interact with matter and

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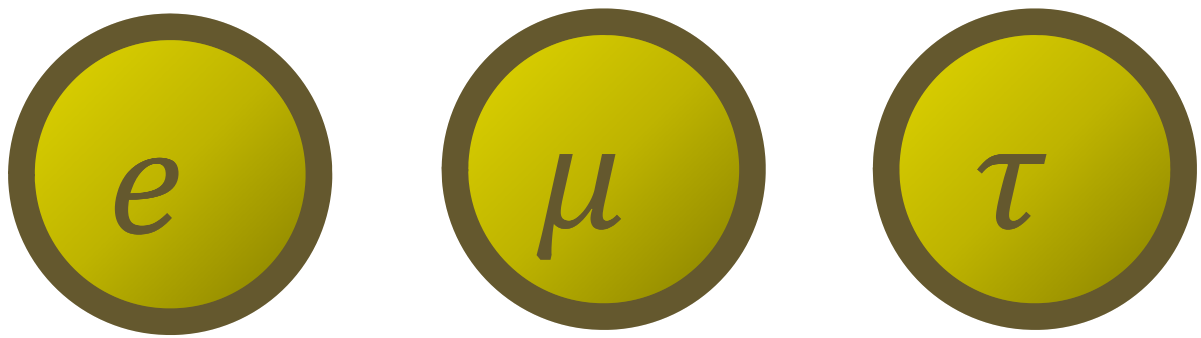
Neutrinos do interact with matter and



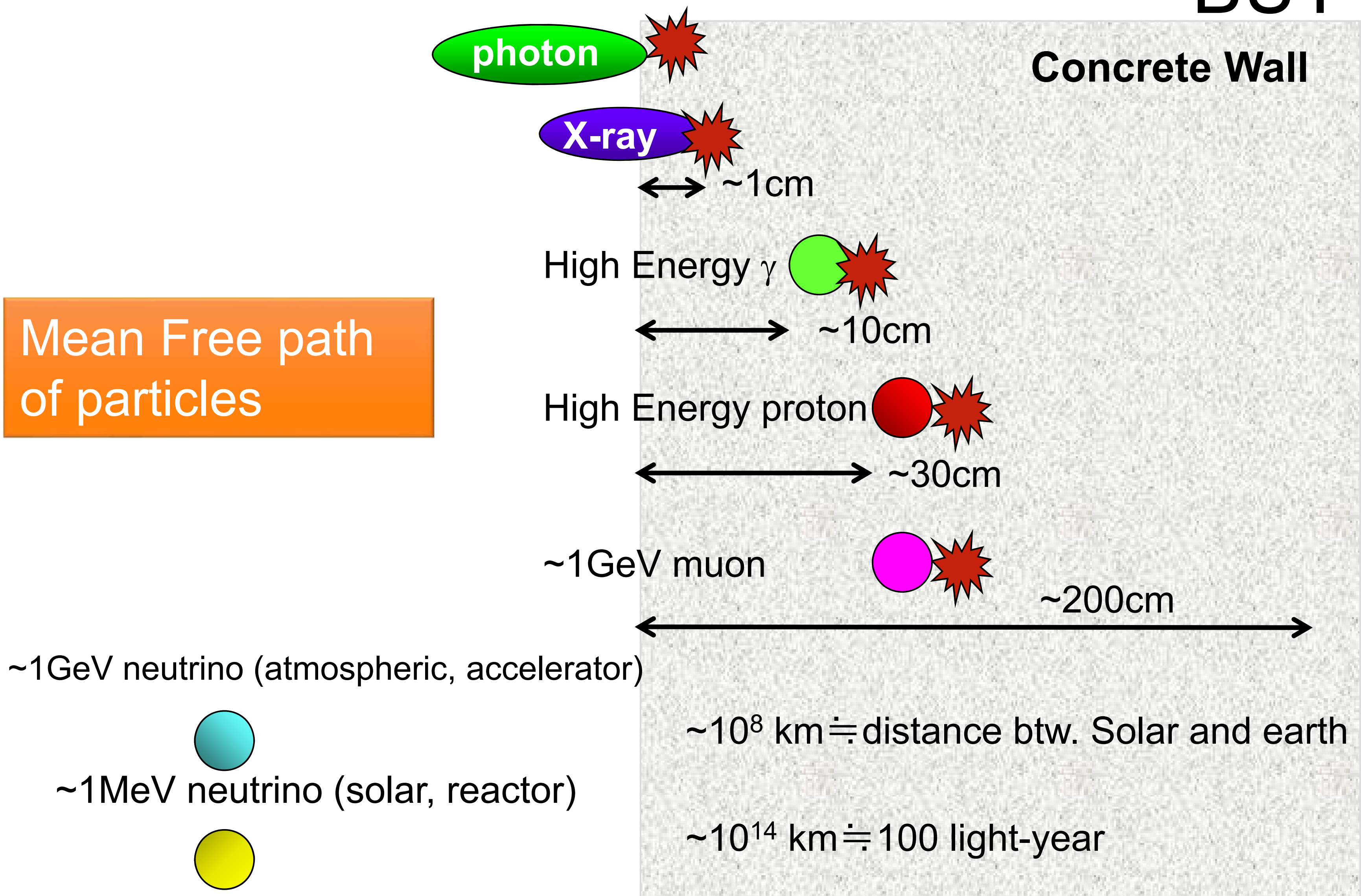
- **An electron neutrino** changes to **an electron**.
- **A muon neutrino** changes to **a muon**.
- **A tau neutrino** changes to **a tau**.

We call this categorization ‘flavor’.

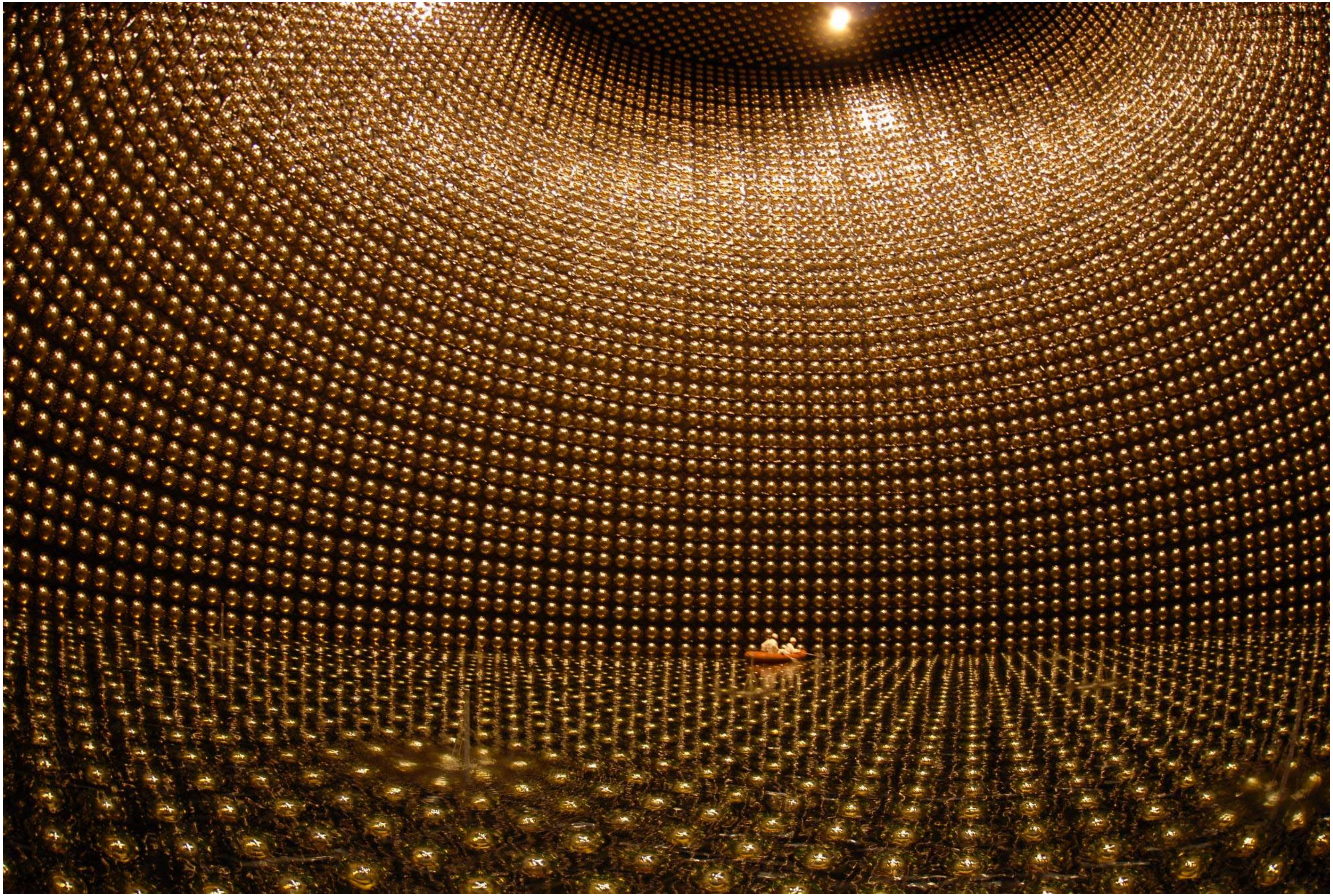
And it was believed that electron neutrino only changes to electron, never into muon nor tau before the neutrino oscillation was found.

NEUTRINOS DO INTERACT, BUT ….

Mean Free path of particles



SUPER-KAMIOKANDE



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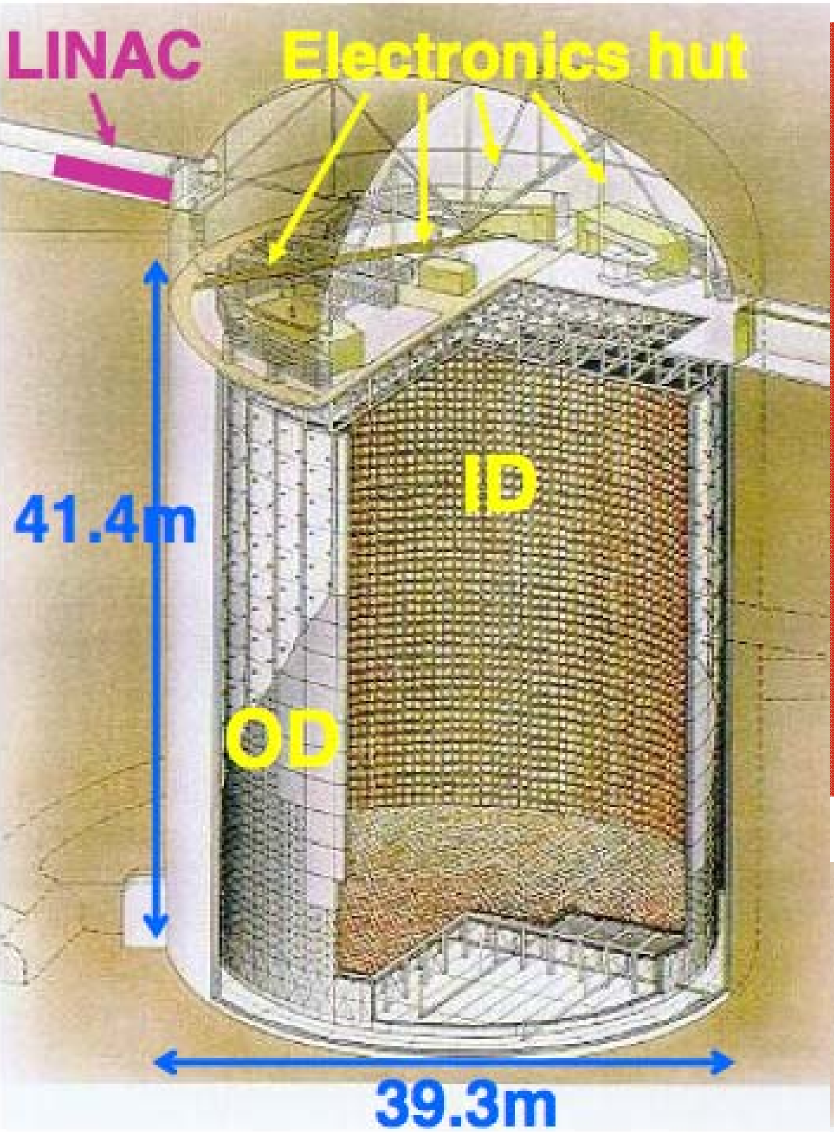
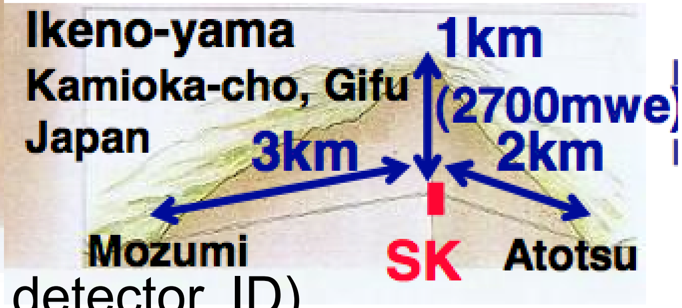
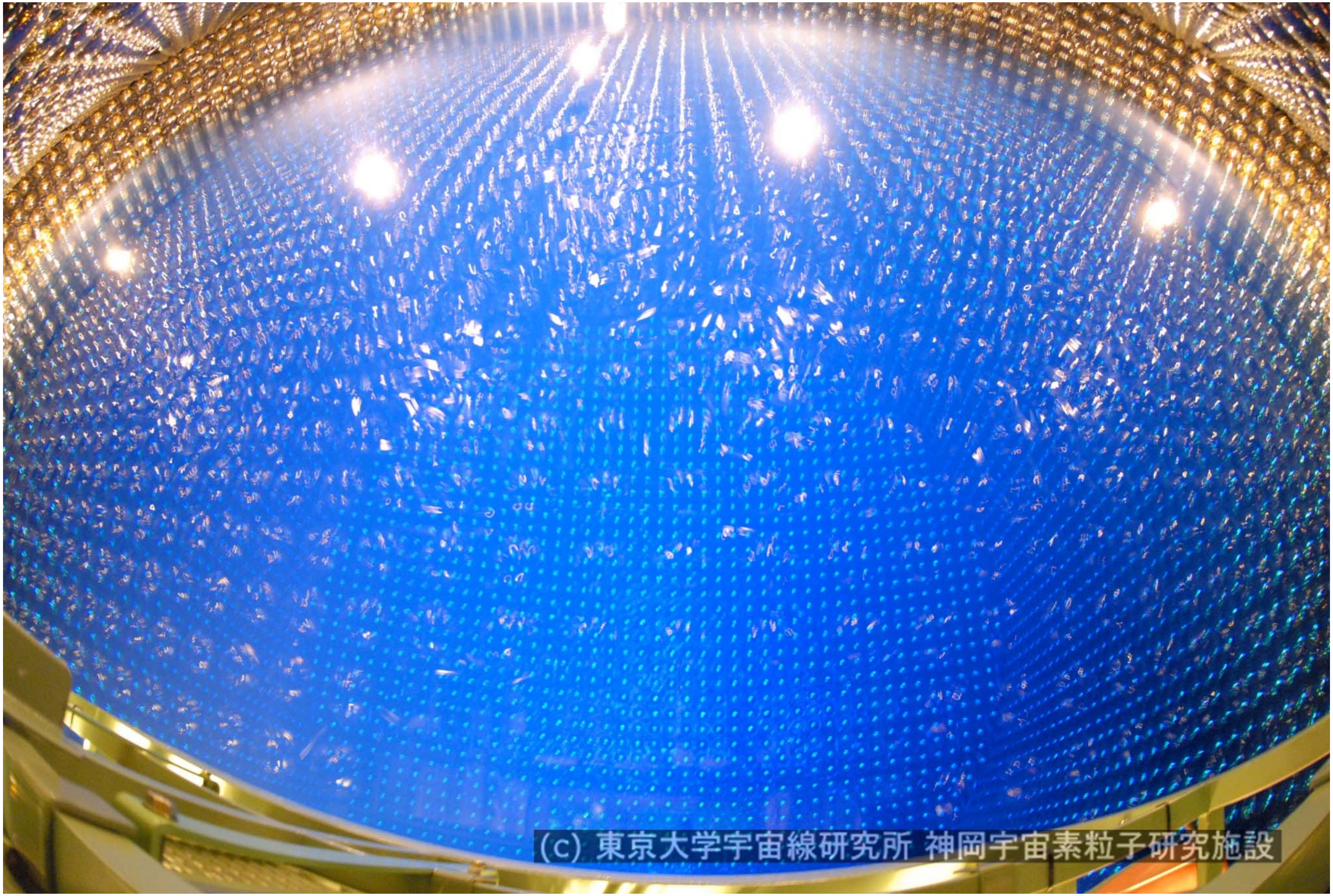


- Since April 1996
- Water Cherenkov detector w/ fiducial volume 22.5kton
- Detector performance is well-matched at sub GeV
  - **Excellent performance for single particle event**
  - **Good e-like(shower ring) / μ-like separation** ***(next page)***

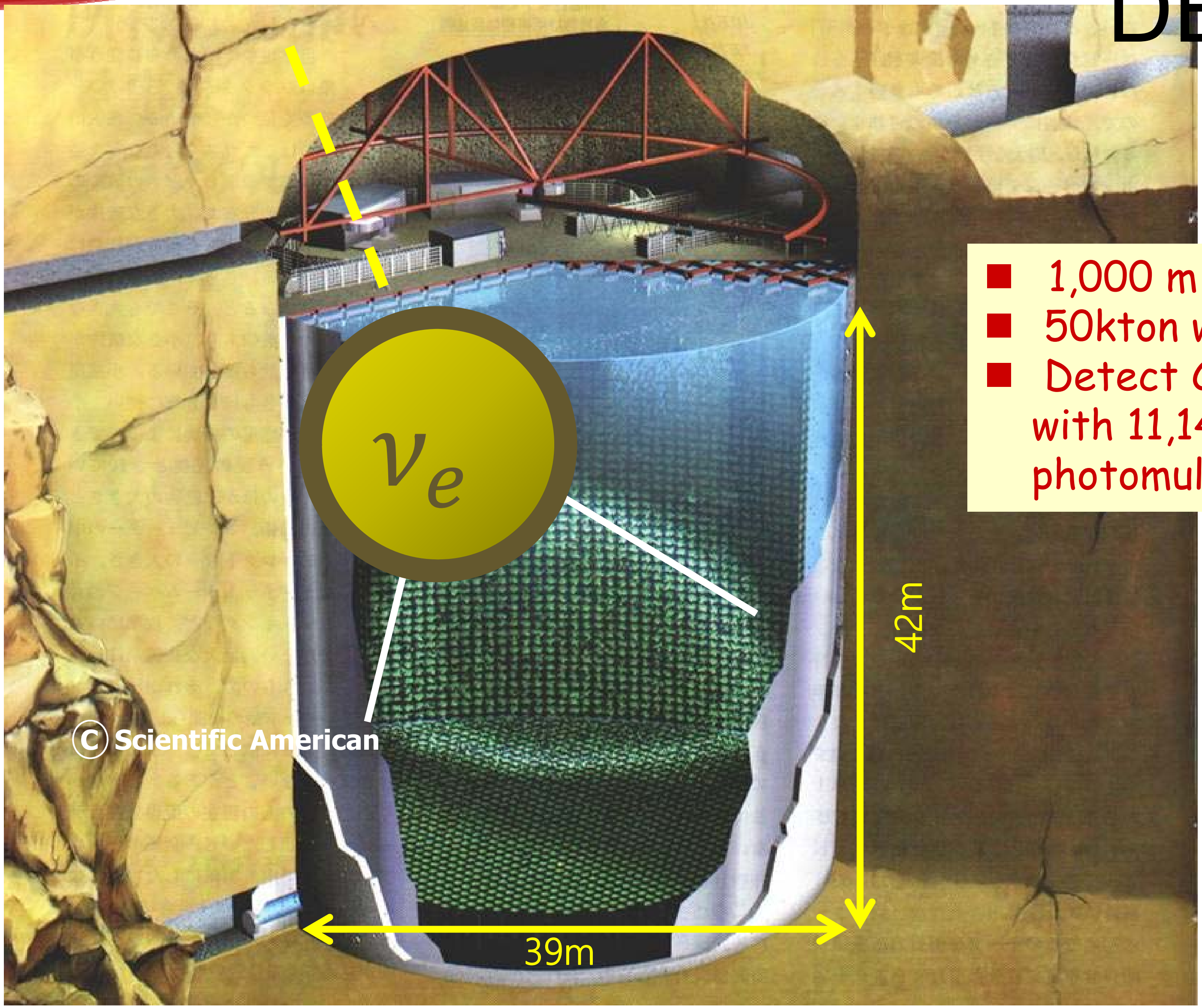


~11000 x 20inch PMTs (inner detector, ID)

SUPER-KAMIOKANDE

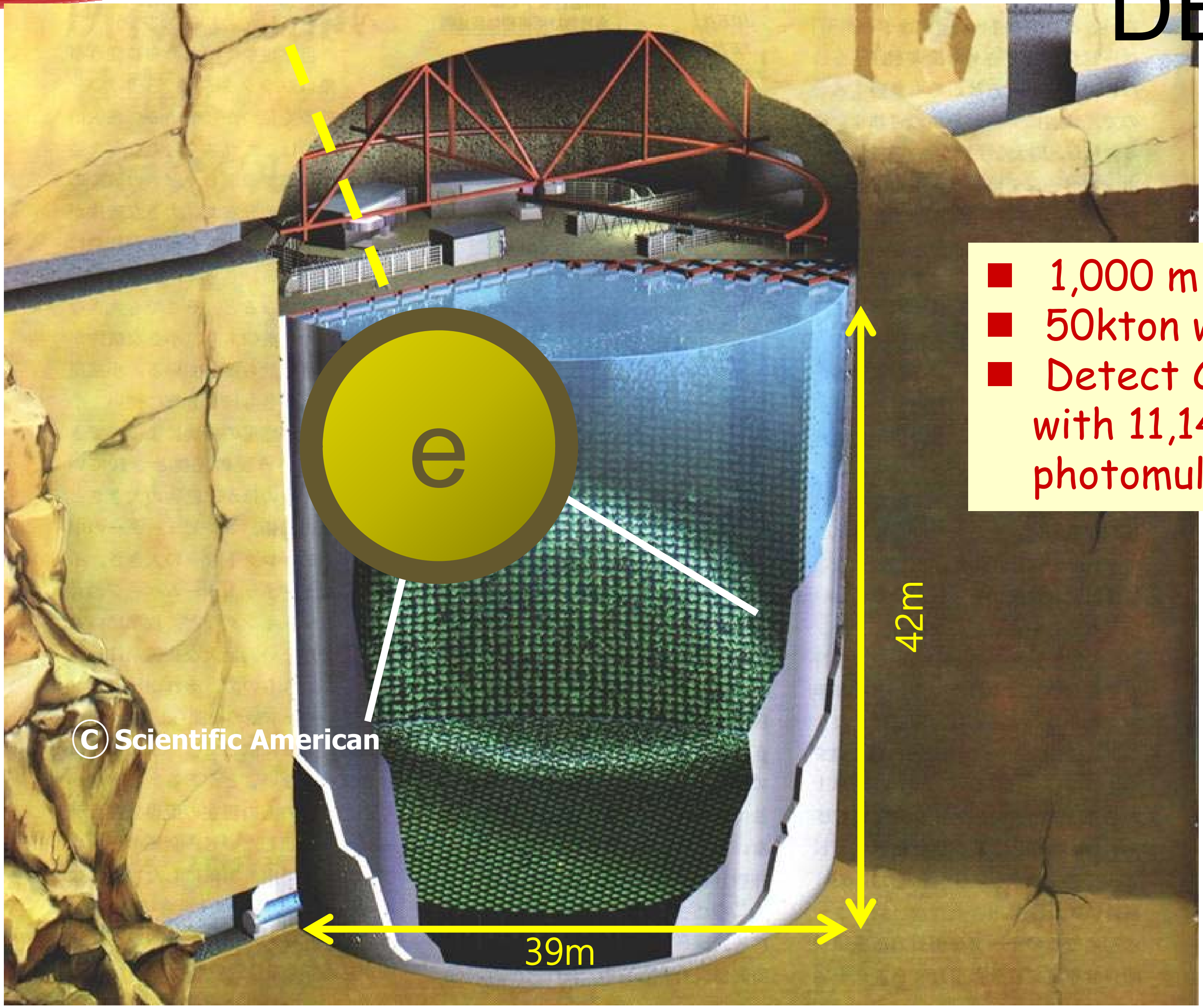


SUPER KAMIOKANDE DETECTOR



- 1,000 m underground
- 50kton water tank
- Detect Cherenkov photons with 11,146 20 inch photomultiplier tubes

SUPER KAMIOKANDE DETECTOR



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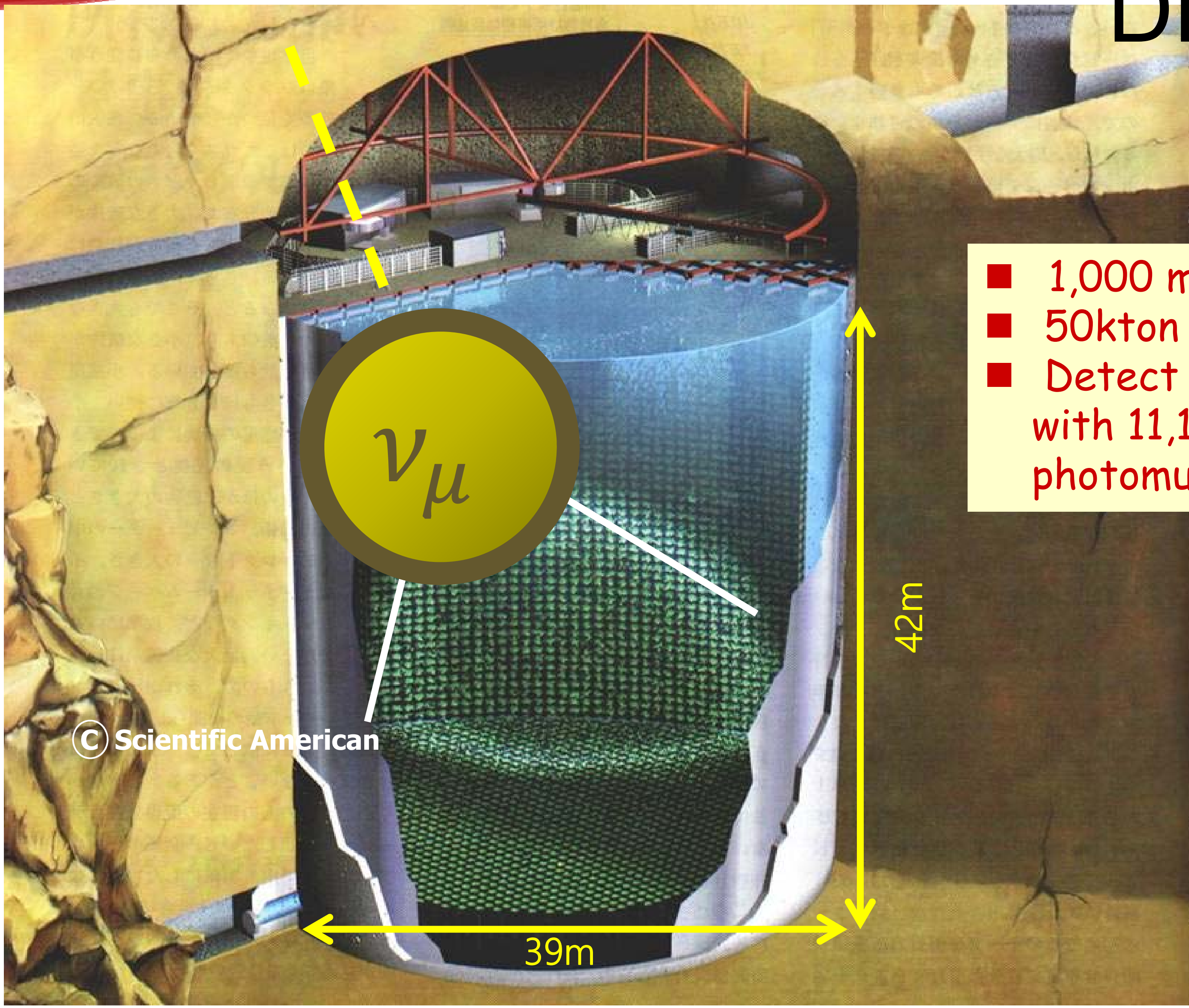

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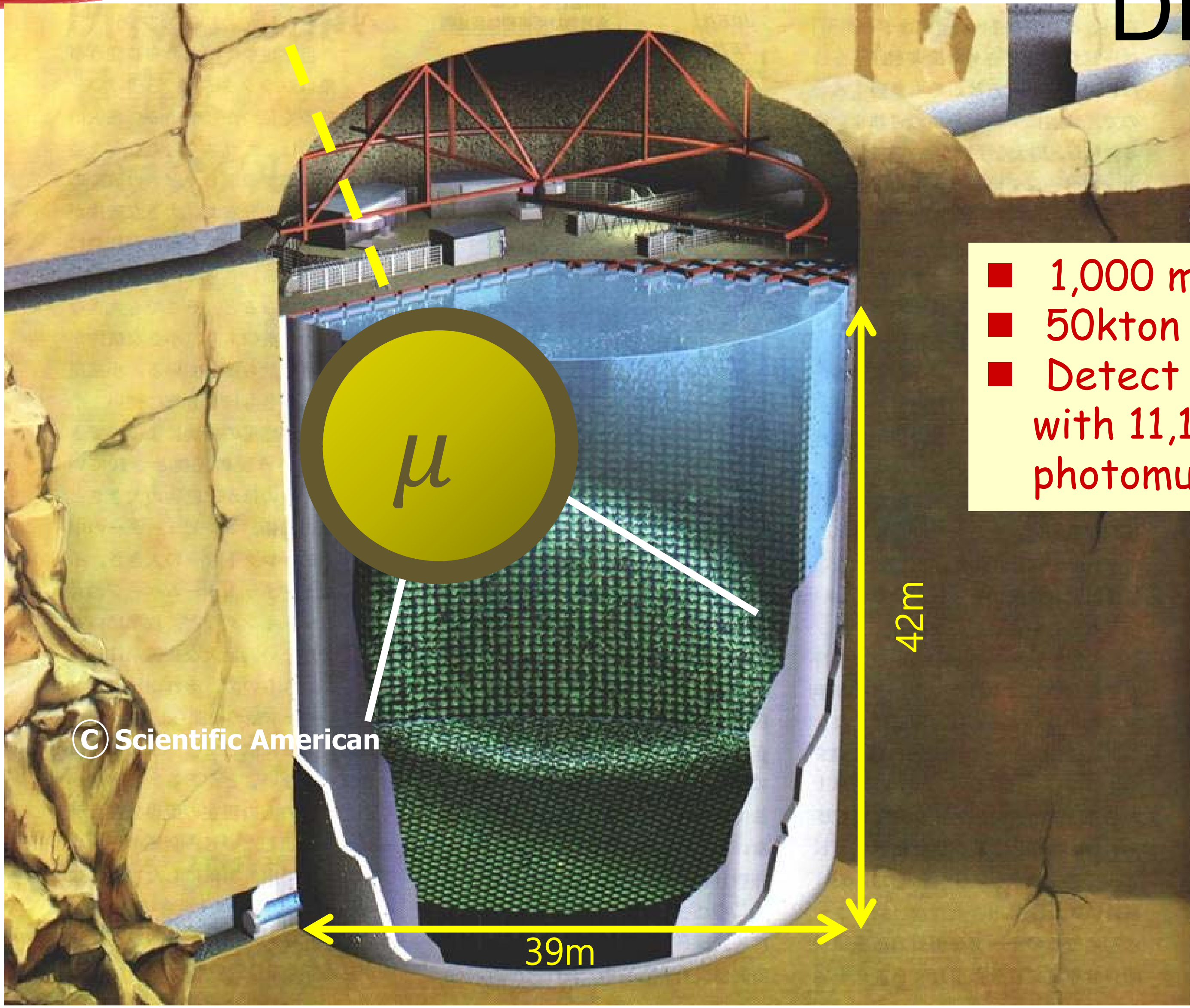
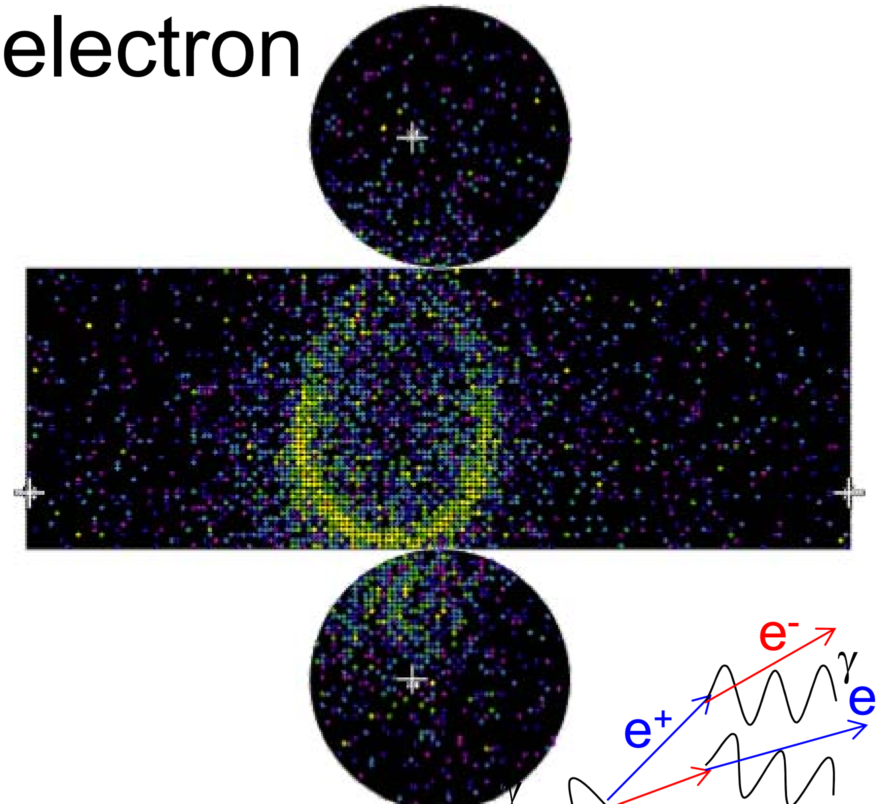
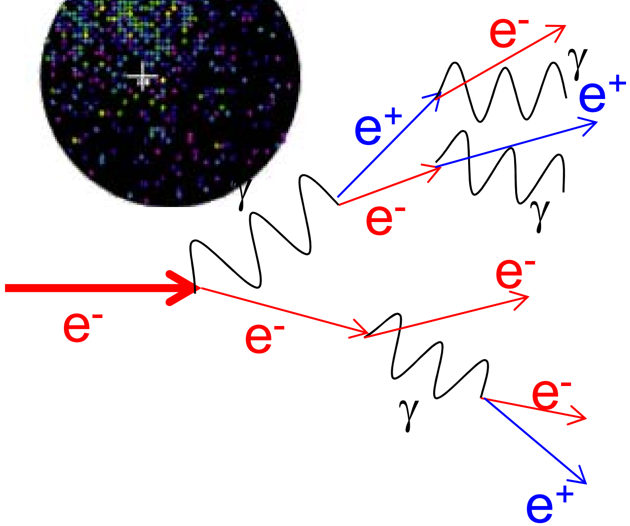


- 1,000 m underground
- 50kton water tank
- Detect Cherenkov photons with 11,146 20 inch photomultiplier tubes

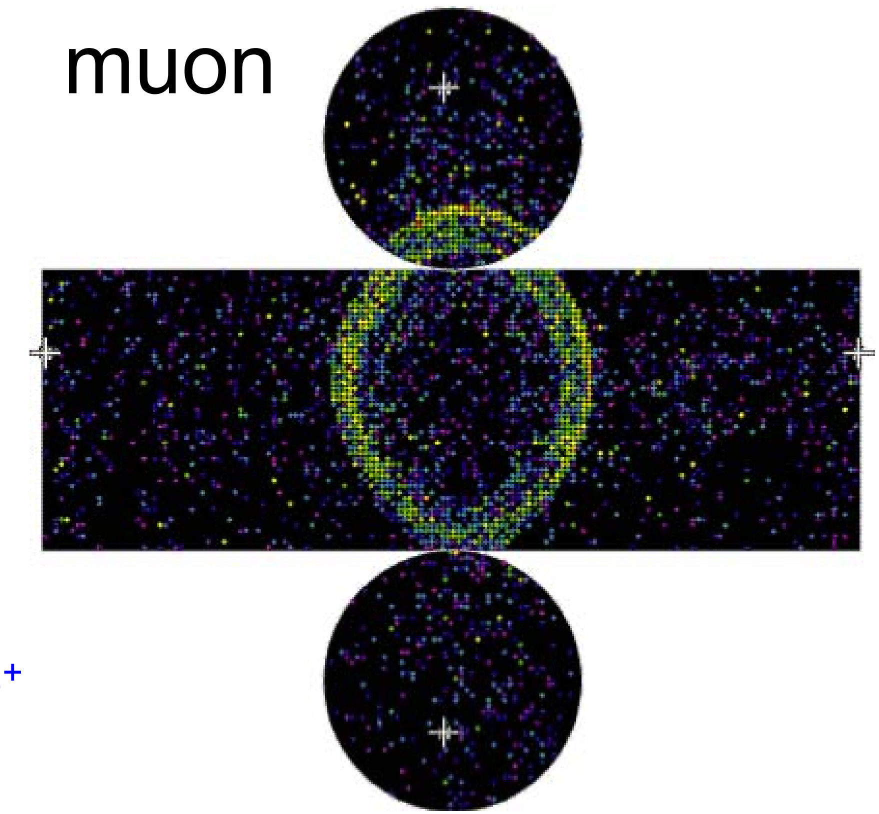
THEY CAN BE DISTINGUISHED.

electron



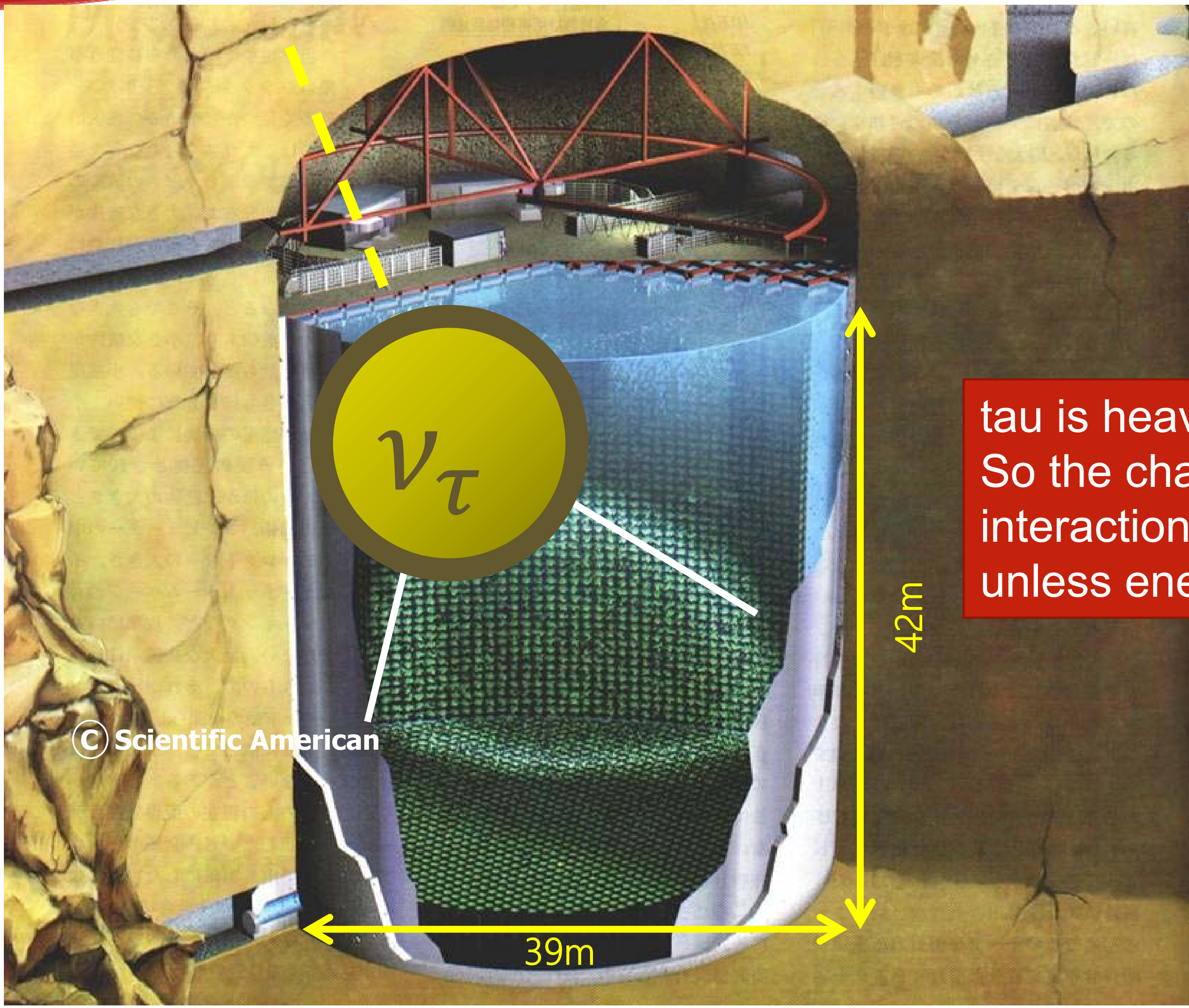


muon



SK MC event display

TAU NEUTRINO….



tau is heavy.
So the charged current interaction dose not occur unless energy > ~ 3.5 GeV.

MIXING BTW. FLAVOR AND MASS

We know that there are three types of charged lepton (e, μ, τ), distinguishable only via mass.

Then, we found that there are three types of neutrinos, distinguishable via interaction w/ matter.

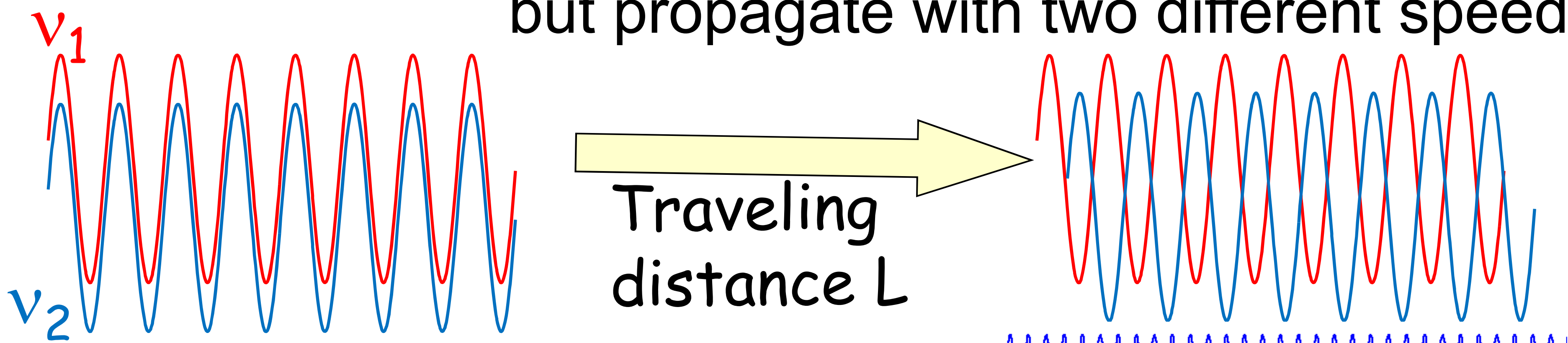
IF NEUTRINOS HAVE MASSES, there is no need for three types to be mass eigenstates.

$|\nu_e\rangle = a|\nu_1\rangle + b|\nu_2\rangle + c|\nu_3\rangle$, ν_1, ν_2, ν_3 : mass eigenstates

Same thing is happening for quarks. (e.g. Cabibbo angle)

Partner of $|up\rangle$ quark $= a|down\rangle + b|strange\rangle + c|bottom\rangle$

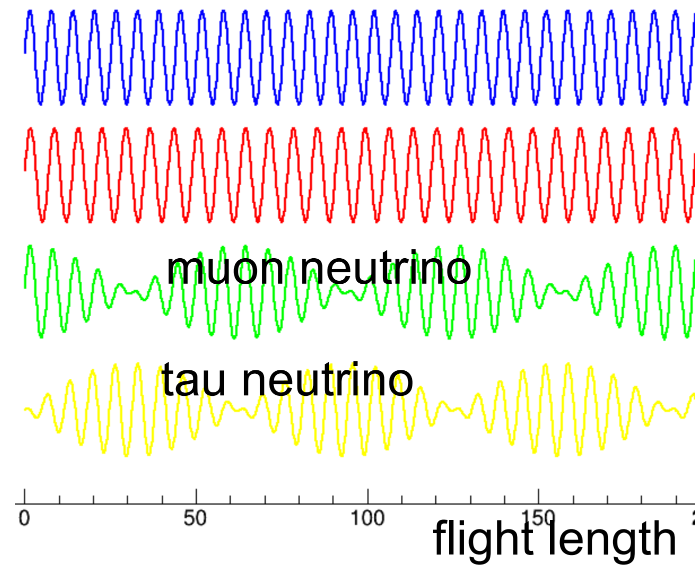
Then,
a neutrino is produced as an eigenstate of one flavor,
but propagate with two different speed



$|\nu_\alpha\rangle = |\nu_1\rangle\cos\theta + |\nu_2\rangle\sin\theta, \quad \alpha = e, \mu, \tau$

Neutrino Oscillation!

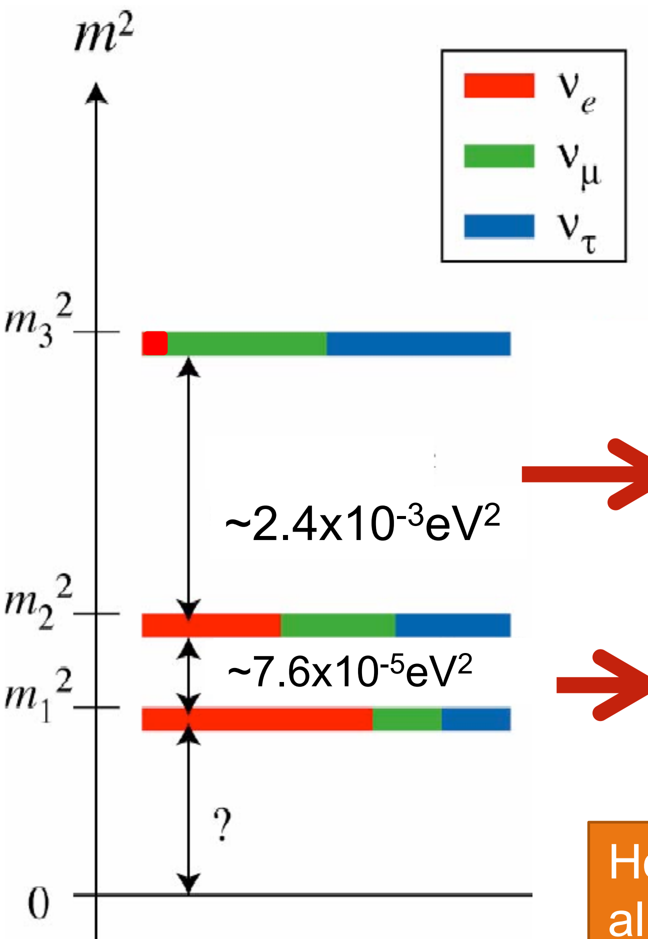
$$|\nu_1\rangle e^{-i\frac{m_1^2}{2E}L}\cos\theta + |\nu_2\rangle e^{-i\frac{m_2^2}{2E}L}\sin\theta \Rightarrow |\nu_\beta\rangle$$



$$P(\nu_\alpha \to \nu_\beta) = \left|\langle \nu_\beta | \nu_\alpha \rangle\right|^2 = \sin^2 2\theta \sin^2\left(\Delta m^2 \frac{L}{4E}\right)$$

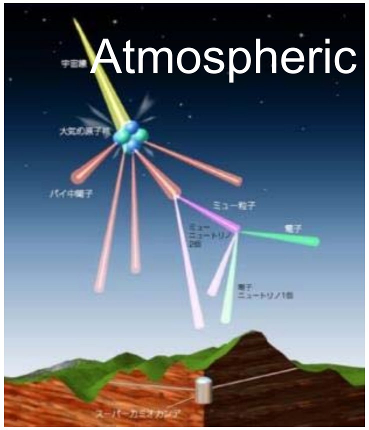
OSCILLATE ACROSS LOOOOONG DISTANCE

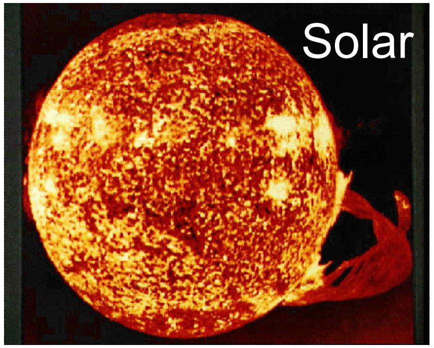
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$



~300 km @ Eν=700 MeV

~50 km @ Eν=3 MeV



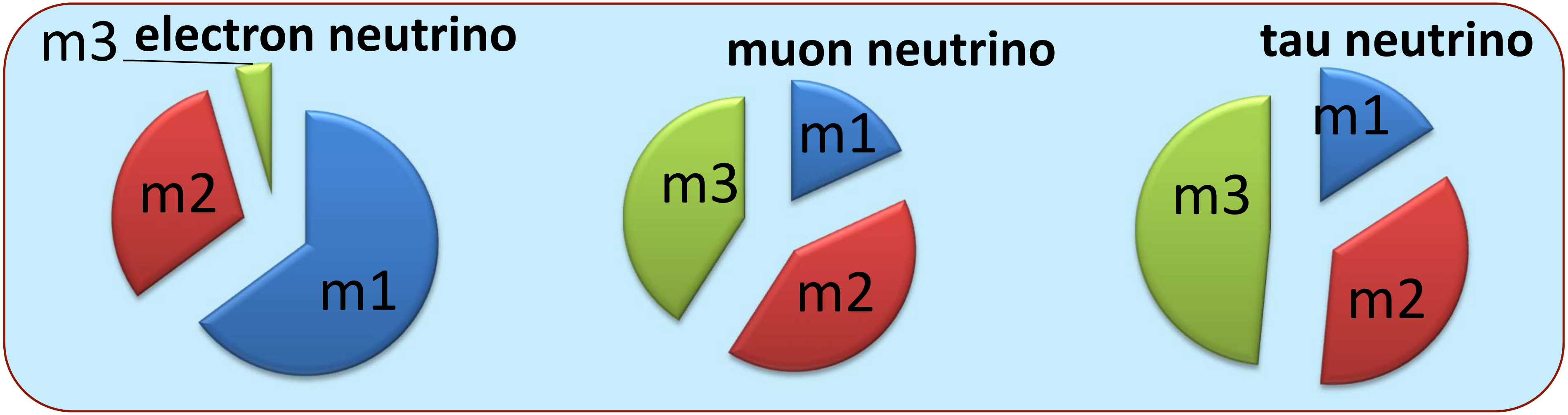


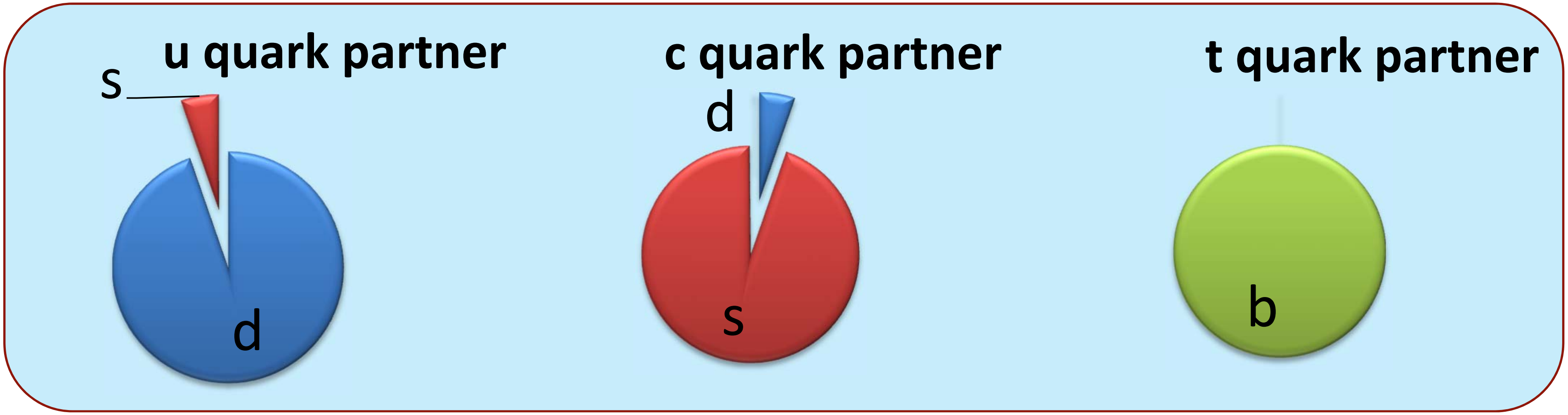
However, in other words, nature allows oscillations corresponding to three Δm^2's happen in Earth Scale

$m_3^2 \gg m_2^2 > m_1^2$ case

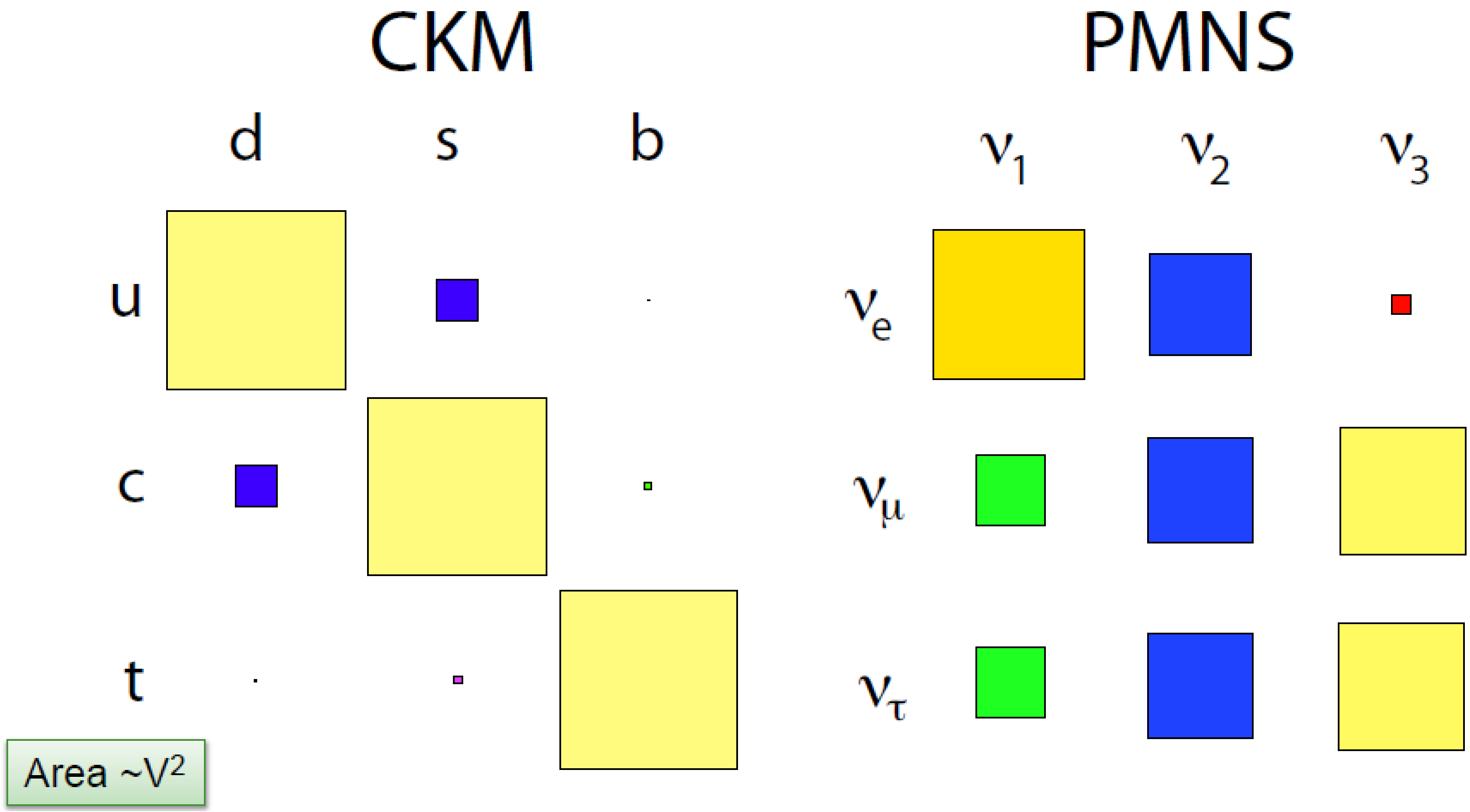
$m_2^2 > m_1^2 > m_3^2$ could be also possible

AND WE FOUND,


m3
electron neutrino
m2
m1
muon neutrino
m3
m1
m2
tau neutrino
m1
m3
m2


s
u quark partner
d
c quark partner
d
s
t quark partner
b

$$\begin{pmatrix} \text{flavor}_1 \\ \text{flavor}_2 \\ \text{flavor}_3 \end{pmatrix} = U_{3\times3} \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix}$$



S. Stone, ICHEP2012

DO THEY MEAN SOMETHING?

$$\begin{pmatrix} \text{flavor}_1 \\ \text{flavor}_2 \\ \text{flavor}_3 \end{pmatrix} = U_{3\times3} \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix}$$

quark

$$U_{CKM} \approx \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 1.01 & 0.04 \\ 0.008 & 0.04 & 0.89 \end{pmatrix}$$

lepton

$$U_{PMNS} \approx \begin{pmatrix} 0.82 & 0.55 & 0.16 \\ -0.49 & 0.52 & 0.55 \\ 0.20 & -0.65 & 0.70 \end{pmatrix}$$

Assuming some symmetry among quarks and leptons, some models predict

$$U_{CKM} \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$U_{MNS} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \\ \sqrt{1/6} & -\sqrt{1/3} & \sqrt{1/2} \end{pmatrix} = \begin{pmatrix} 0.816 & 0.577 & 0 \\ -0.408 & 0.577 & 0.707 \\ 0.408 & -0.577 & 0.707 \end{pmatrix}$$

MIXING BTW. FLAVOR AND MASS

$$\begin{pmatrix} \text{flavor}_1 \\ \text{flavor}_2 \\ \text{flavor}_3 \end{pmatrix} = U_{3\times 3} \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix}$$

Kobayashi-Maskawa theory

Mixing with >= 3 types can have imaginary components.

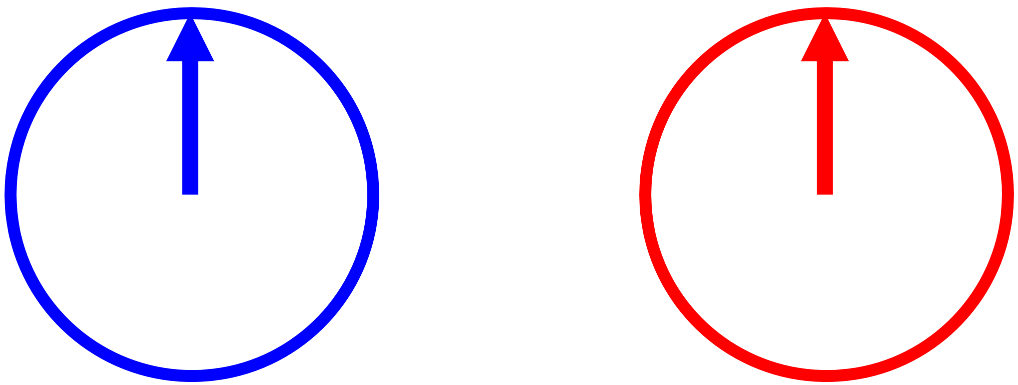
In case of 3 generations, **one CP phase**.

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

ANTI-PARTICLE

- Reverse the rotation of the clock i.e.phase of wavefunction → particle behaves like oppositely-charged particle.



$e^{-i\{(E+eV)t-(\vec{p}+eA)\cdot\vec{x}\}}$ vs. $e^{i\{(E-eV)t-(-\vec{p}-eA)\cdot\vec{x}\}}$

MIXING BTW. FLAVOR AND MASS

$$\begin{pmatrix} \text{flavor}_1 \\ \text{flavor}_2 \\ \text{flavor}_3 \end{pmatrix} = U_{3\times 3} \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix}$$

CKM (quark sector) δ~60°
PMNS (lepton sector) δ~?

Kobayashi-Maskawa theory

Mixing with > 3 generation can have imaginary components, which introduce different behavior between particle and anti-particle=**CP violation**.

In case of 3 generations, **one CP phase**.

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

LEPTONIC CPV CAN BE MUCH LARGER THAN QUARK'S

$\delta_{CP}^{CKM} \sim 60° \sim 70°$ looks large, but cannot explain matter-dominant universe.

δ_{CP} is dependent on definition.

Jarlskog Invariant : independent of definition. show the size of CP violation effect.

$$J_{CP} \equiv Im\left(U_{\mu 3} U_{e3}^* U_{e2} U_{\mu 2}^*\right) = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta_{CP}$$

$$J_{CP}^{CKM} \approx 3 \times 10^{-5}$$

$$J_{CP}^{PMNS} \approx 0.03 \sin \delta_{CP}$$

PDG2015 "NEUTRINOMASS,MIXING, AND OSCILLATIONS"

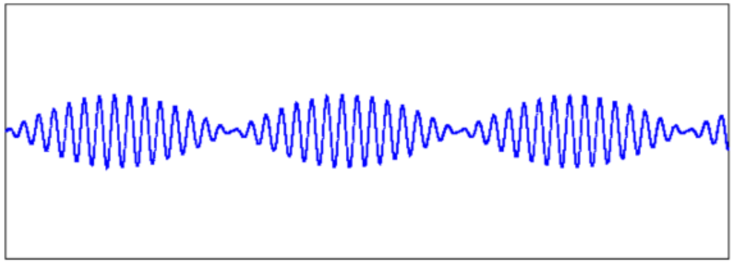
A value of $|\sin\theta_{13}\sin\delta| \gtrsim 0.09$, and thus $\sin\theta_{13} \gtrsim 0.09$, is a necessary condition for a successful "flavoured" leptogenesis with hierarchical heavy Majorana neutrinos when the CP violation required for the generation of the matter-antimatter asymmetry of the Universe is provided entirely by the Dirac CP violating phase in the neutrino mixing matrix [191]. This condition is comfortably compatible both with the measured value of $\sin^2\theta_{13}$ and with the best fit value of $\delta \cong 3\pi/2$.

$$|\sin\theta_{13}\sin\delta| \geq 0.09 \rightarrow |\sin\delta| \geq 0.58$$

If we find that $|\sin\delta| \geq 0.58$, we can, at least, say that there exists CPV which is as large as to produce matter-dominant universe.

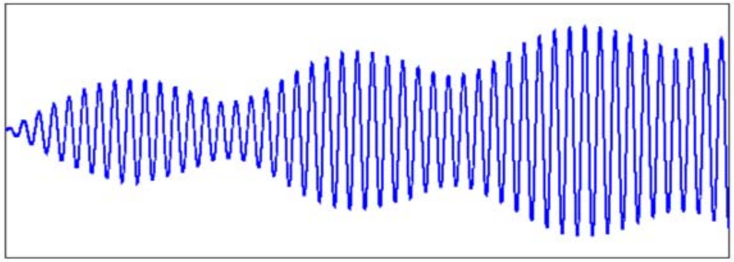
NEUTRINO OSCILLATION OF THREE STATES

Two neutrinos case

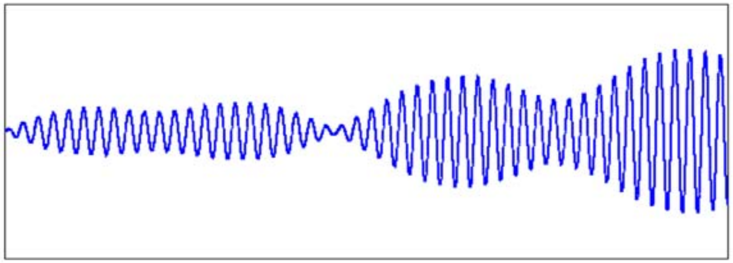


Three neutrinos case

neutrino



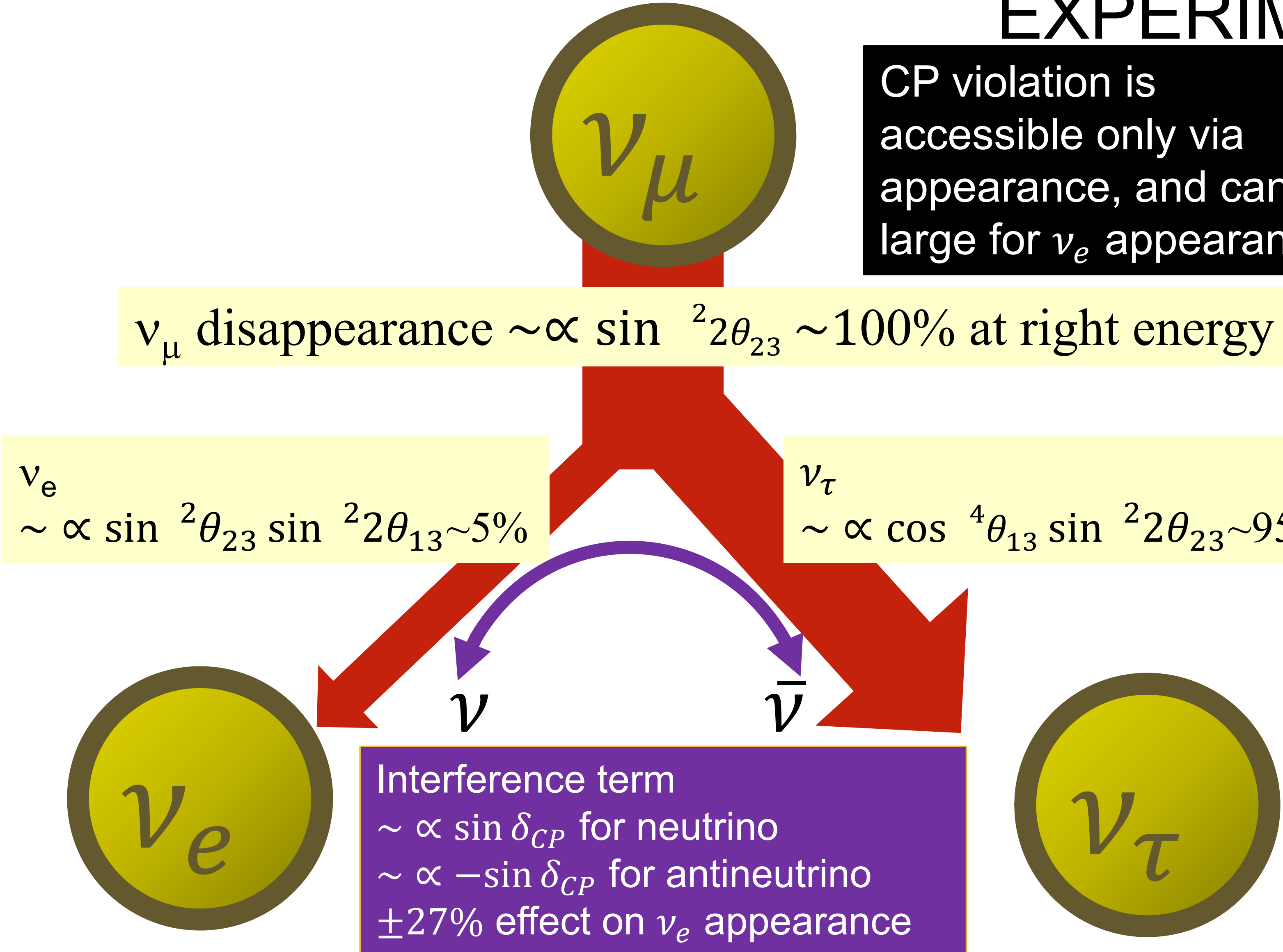
antineutrino



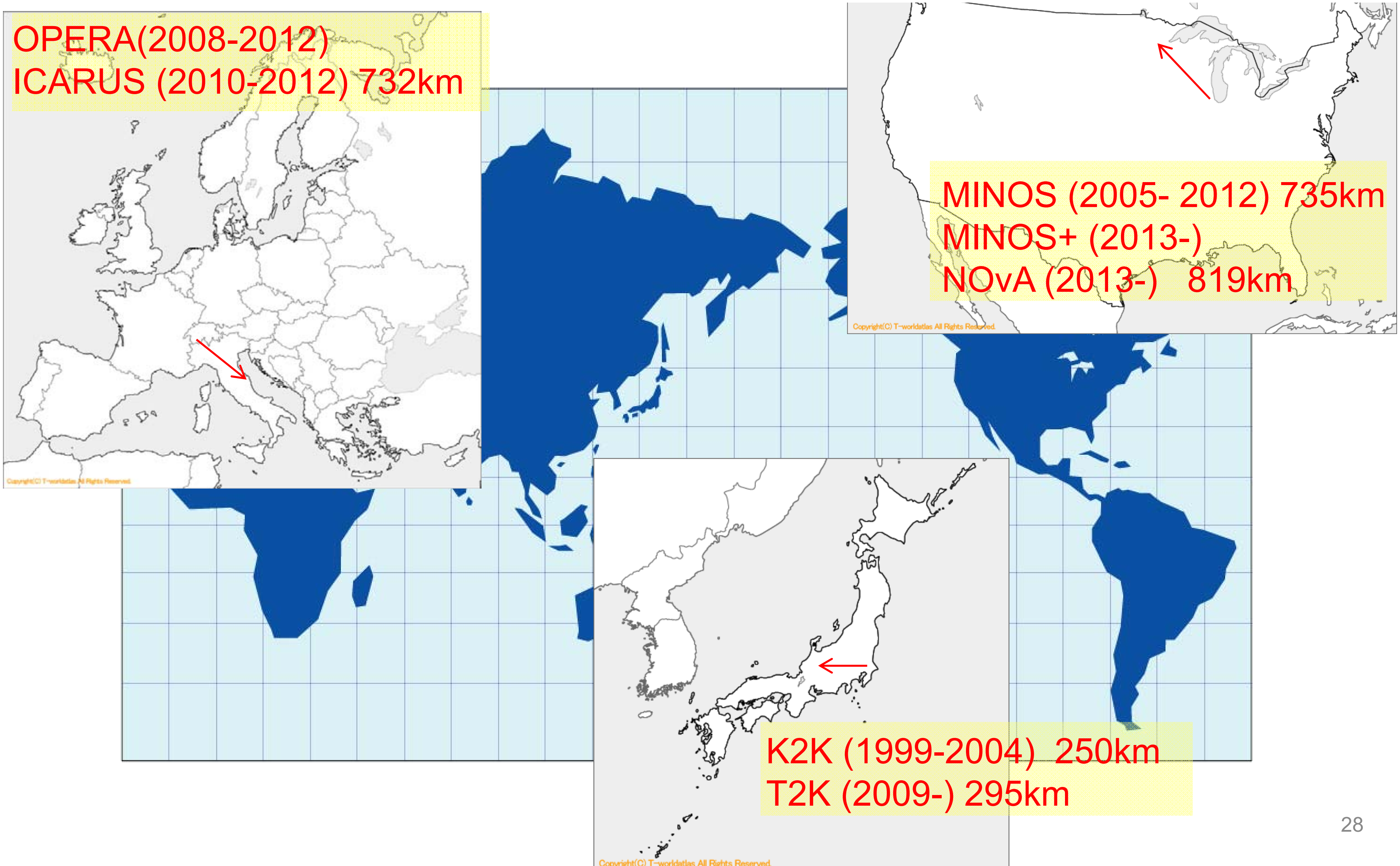
Depending on the value of δ_{CP}, neutrino and antineutrino oscillate differently!

OSCILLATIONS PECULIAR TO THE ACC.-BASED LONG BASELINE EXPERIMENT

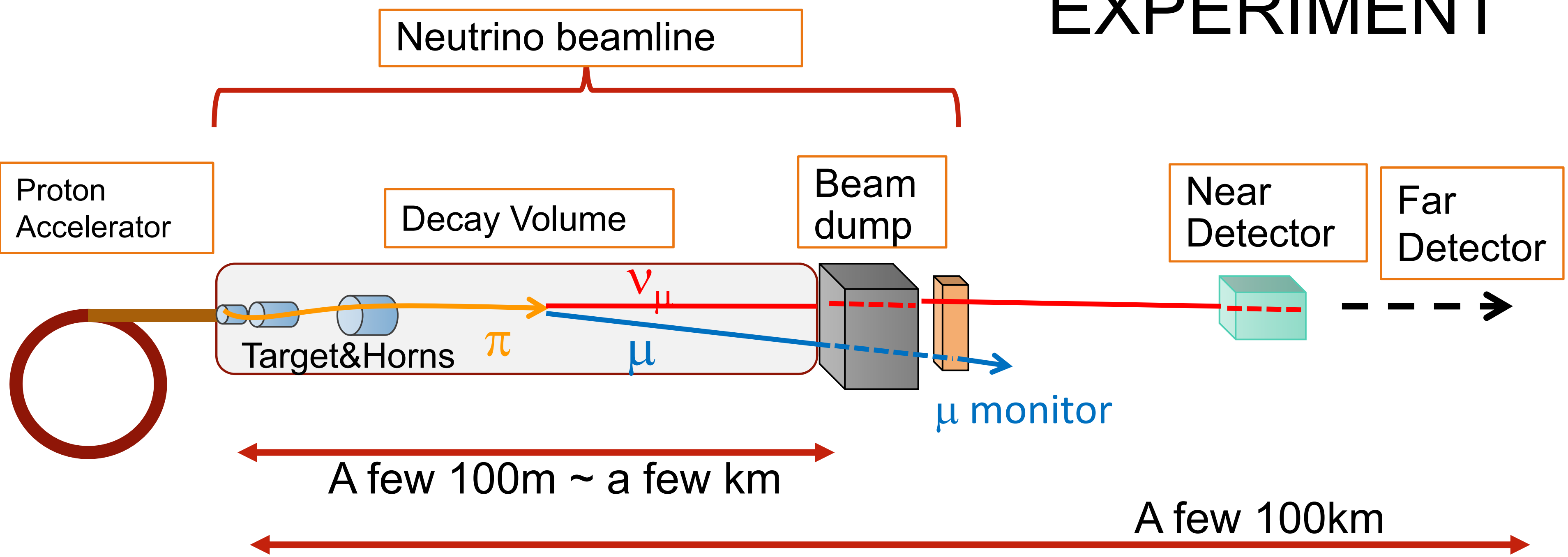
CP violation is accessible only via appearance, and can be large for ν_e appearance.



World Acc.-based Long baseline ν oscillation experiments



COMPONENTS OF THE LONG BASELINE NEUTRINO EXPERIMENT



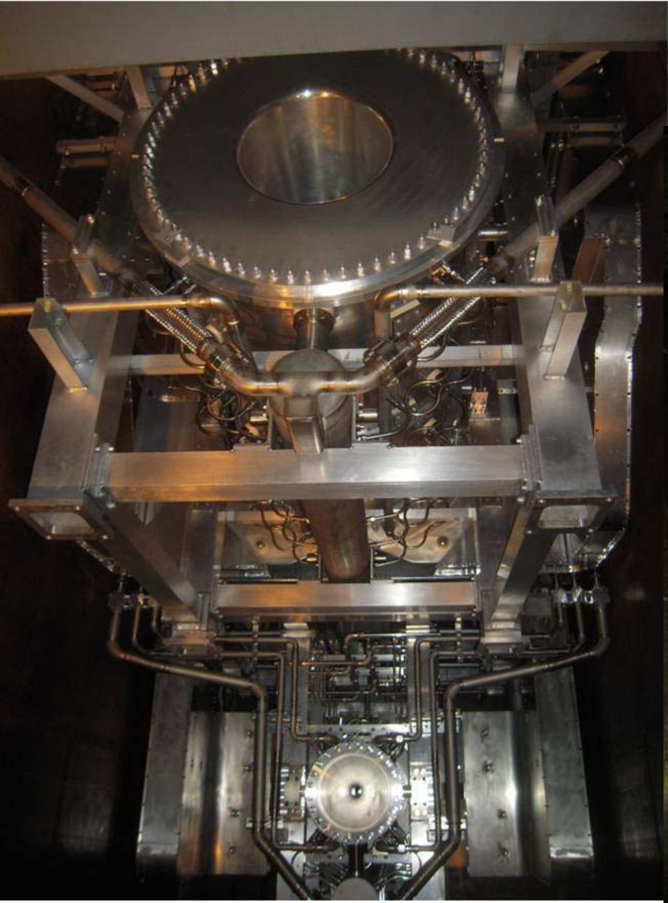
Toroidal magnetic field by `horn' focuses

$$\pi^+ \rightarrow \nu_\mu \text{ beam}$$

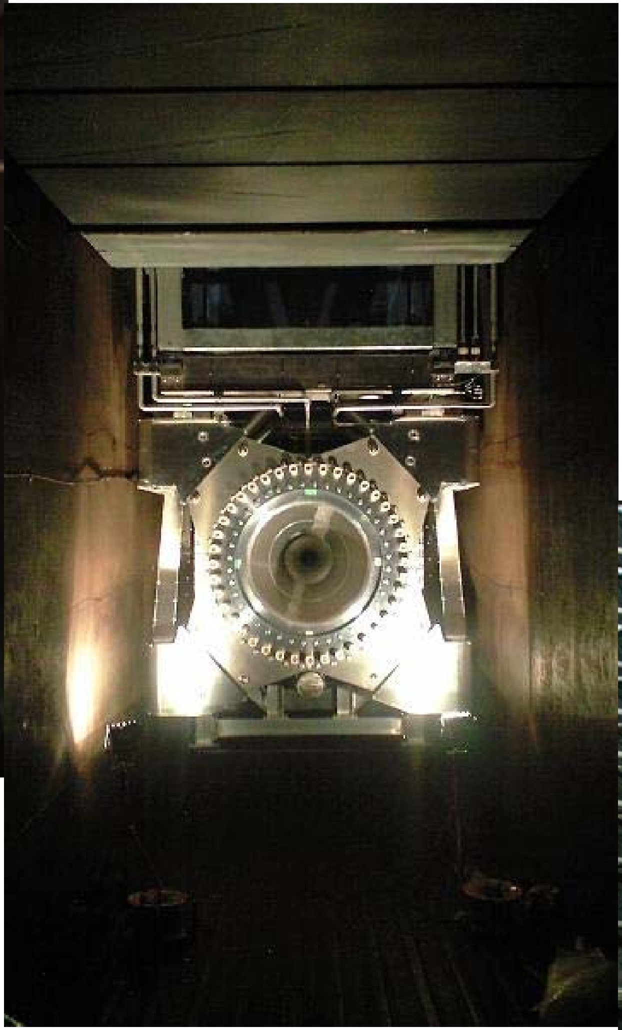
or

$$\pi^- \rightarrow \bar{\nu}_\mu \text{ beam}$$

timing synchronized using GPS



1st Horn & 2nd Horn

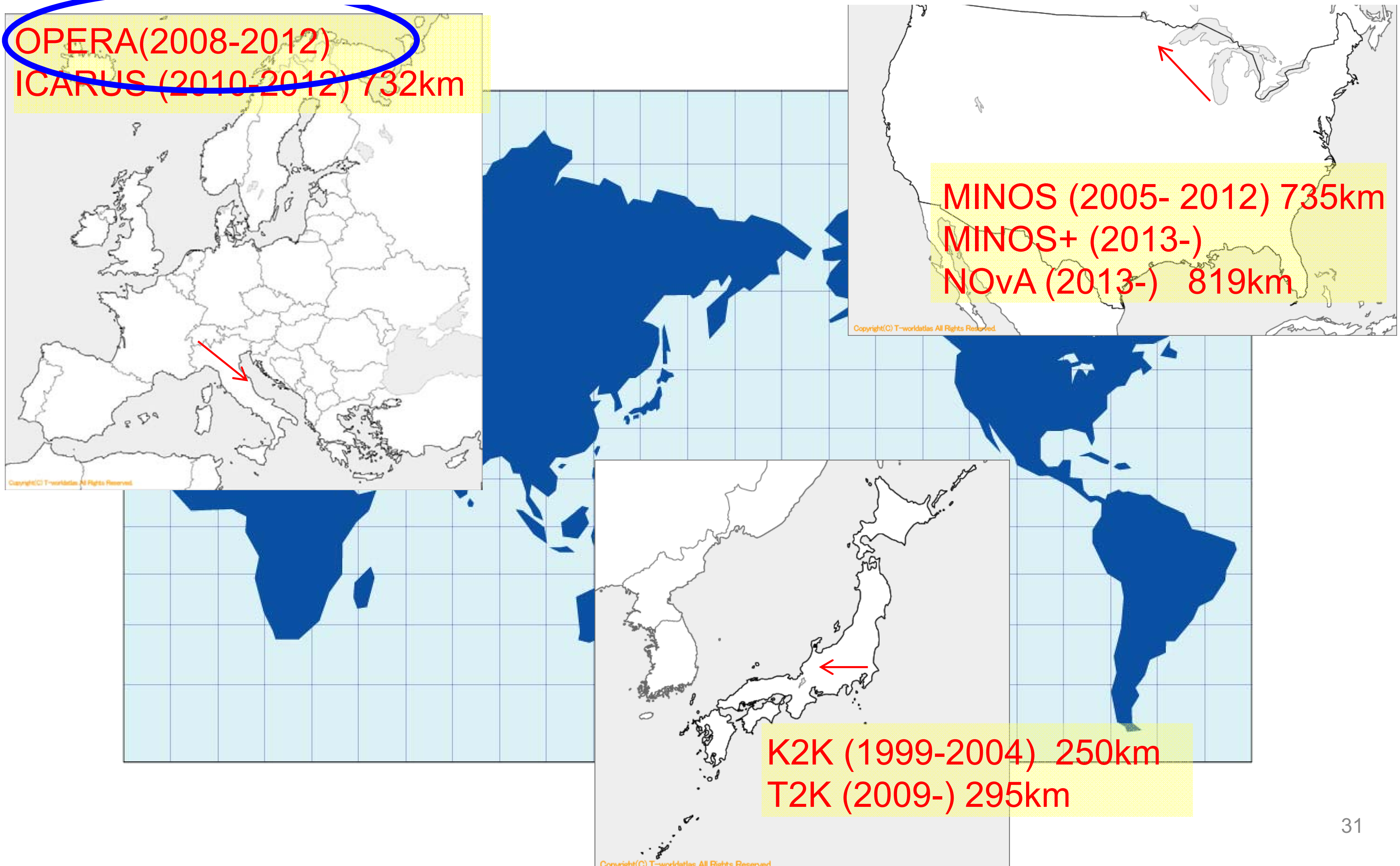


3rd Horn

Decay Volume

T2K

World Acc.-based Long baseline ν oscillation experiments

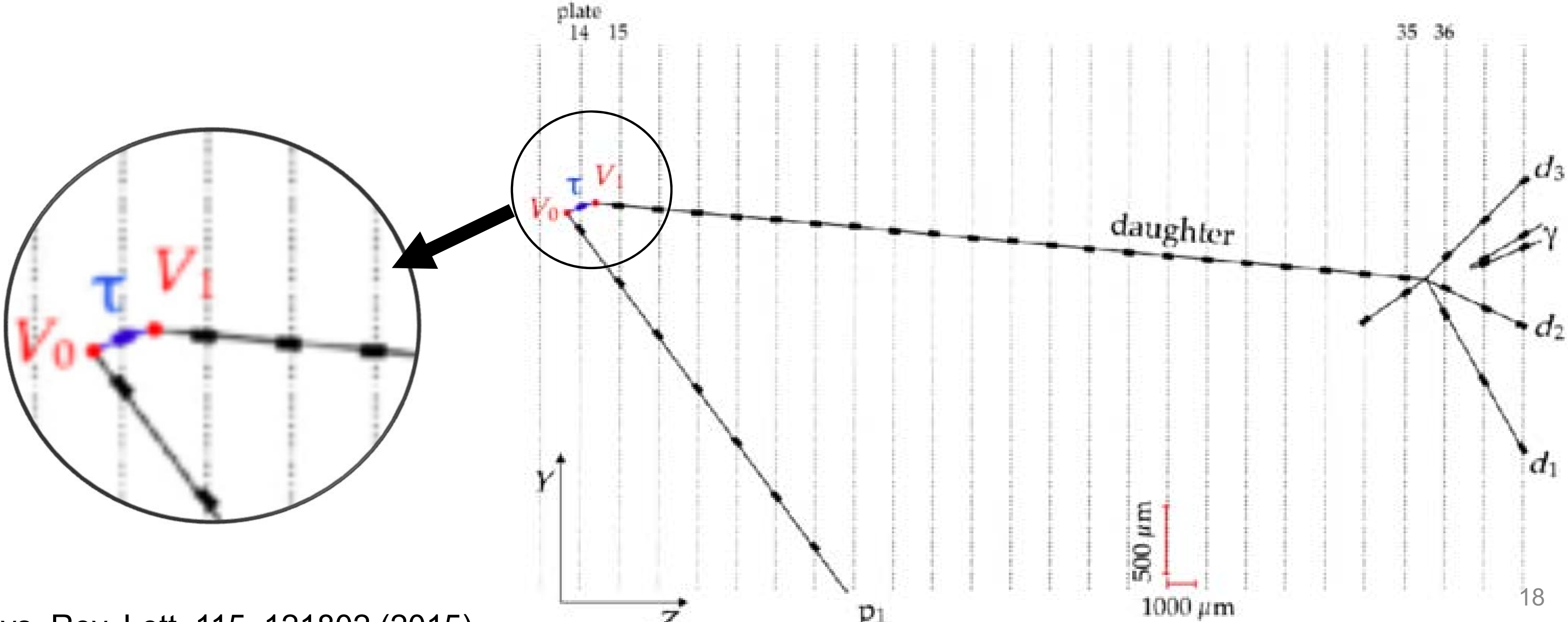


ν_τ APPEARANCE

3.8σ ν_τ appearance by Super-K atmospheric data *(Abe et al., PRL 110, 181802 (2013))* from a sample of enhanced τ-like events.

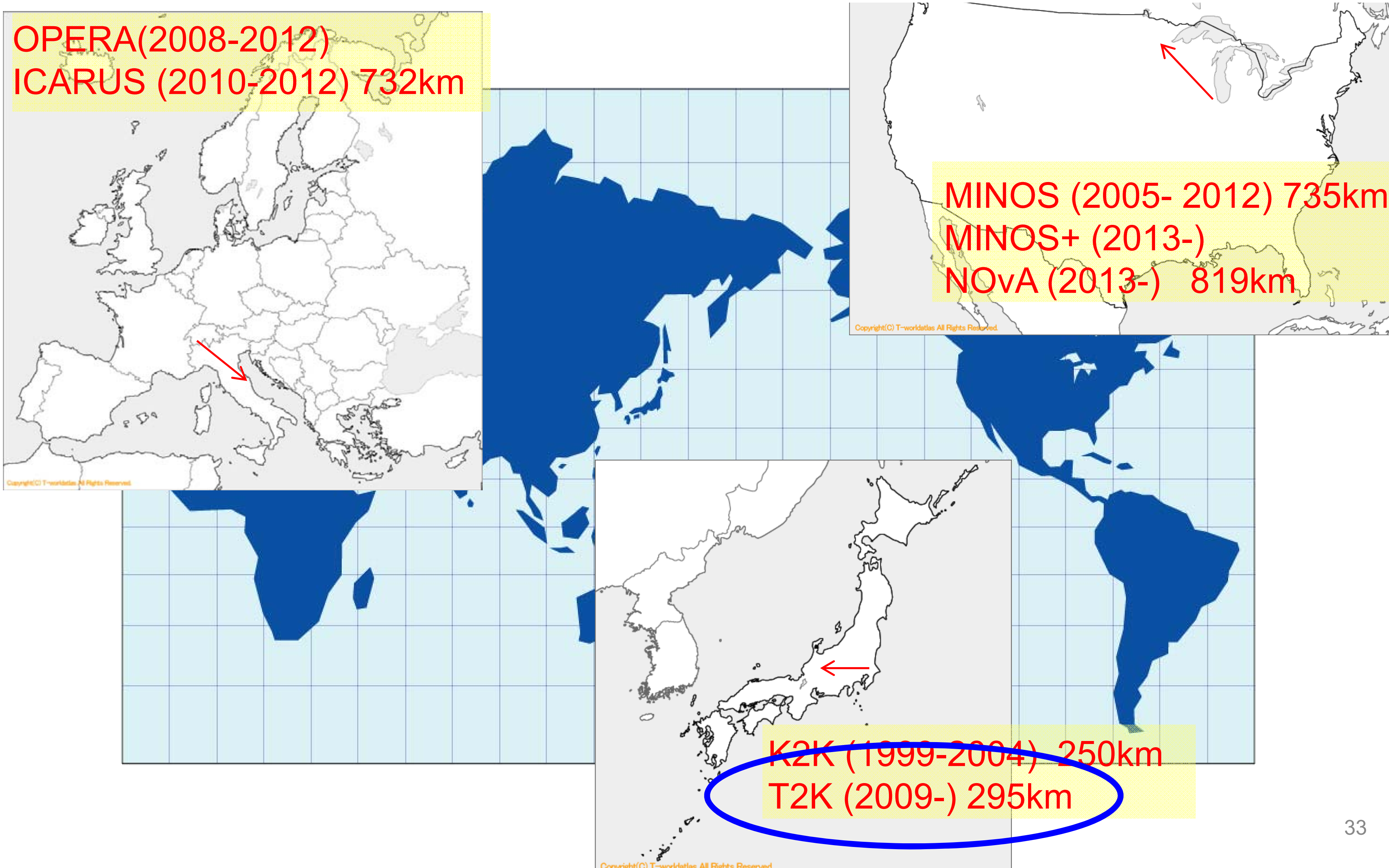
OPERA experiment, long baseline accelerator neutrino experiments. identifies τ production in event-by-event basis using nuclear emulsion.

5 events observed →confirmation by 5.1σ significance.



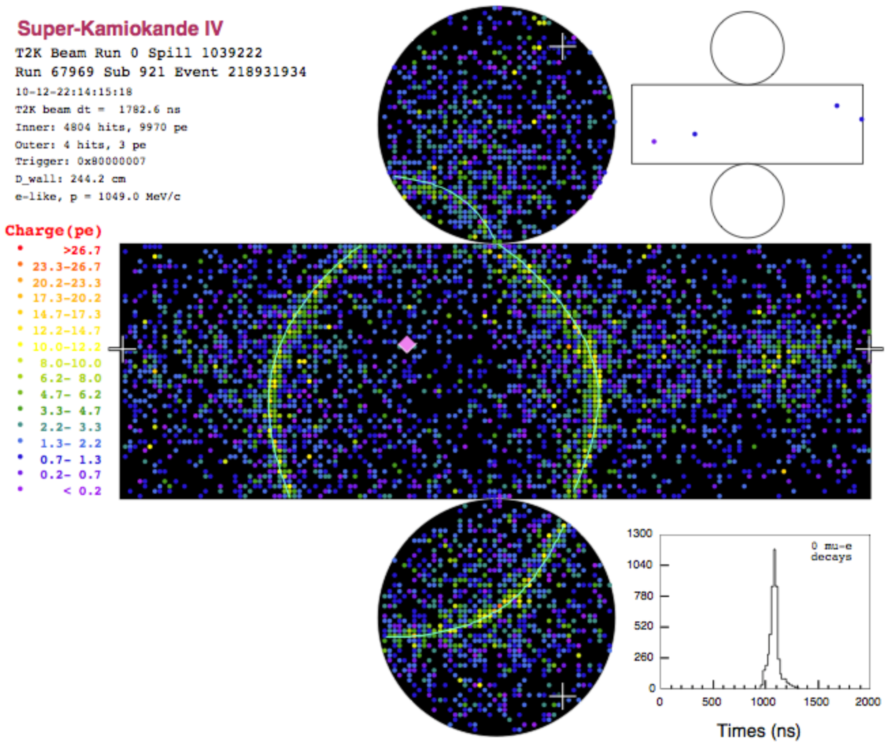
Phys. Rev. Lett. 115, 121802 (2015)

World Acc.-based Long baseline ν oscillation experiments

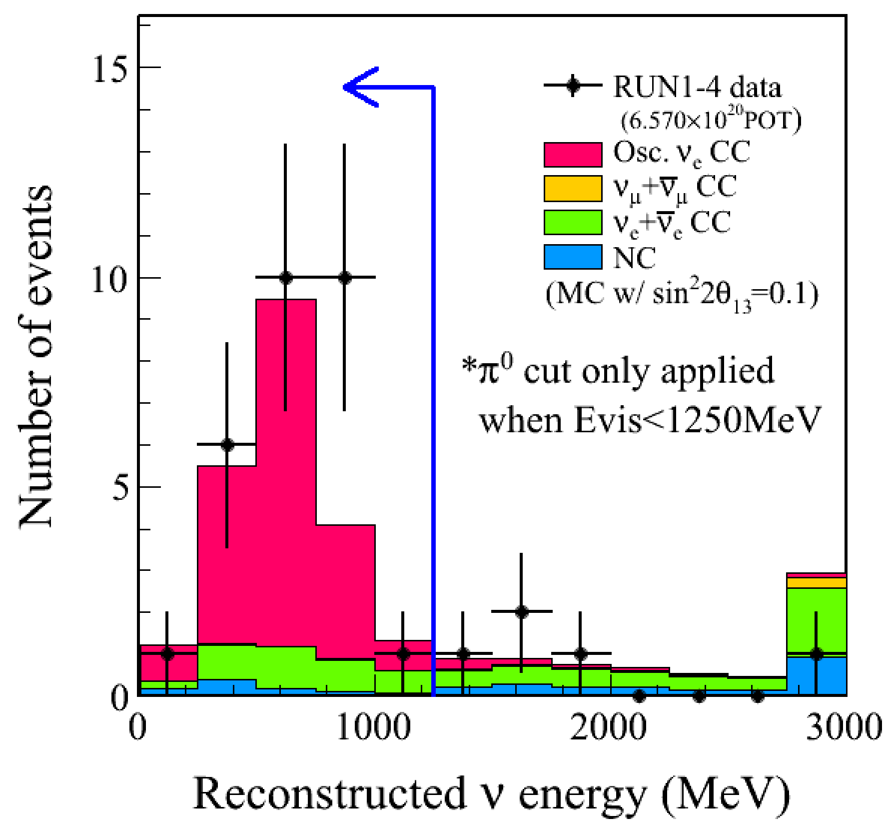


ν_e appearance

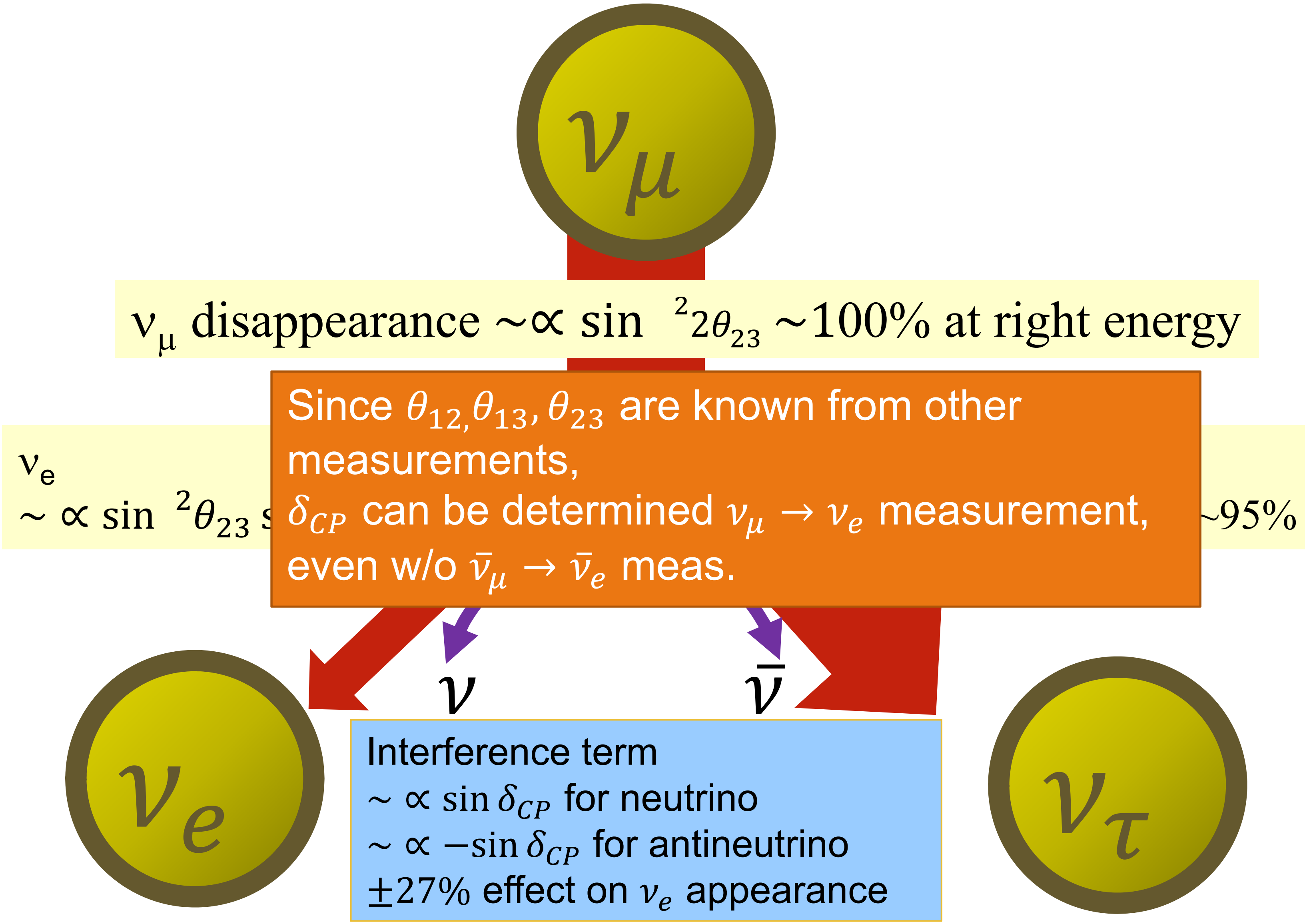
2011 T2K observed 6 events(1.5 bkgs). 2.5σ significance.
2013 T2K observed 28 events over 4.9bkgs 7.3σ significance.
Also first confirmation of ‘appearance’ w/ >5σ significance.



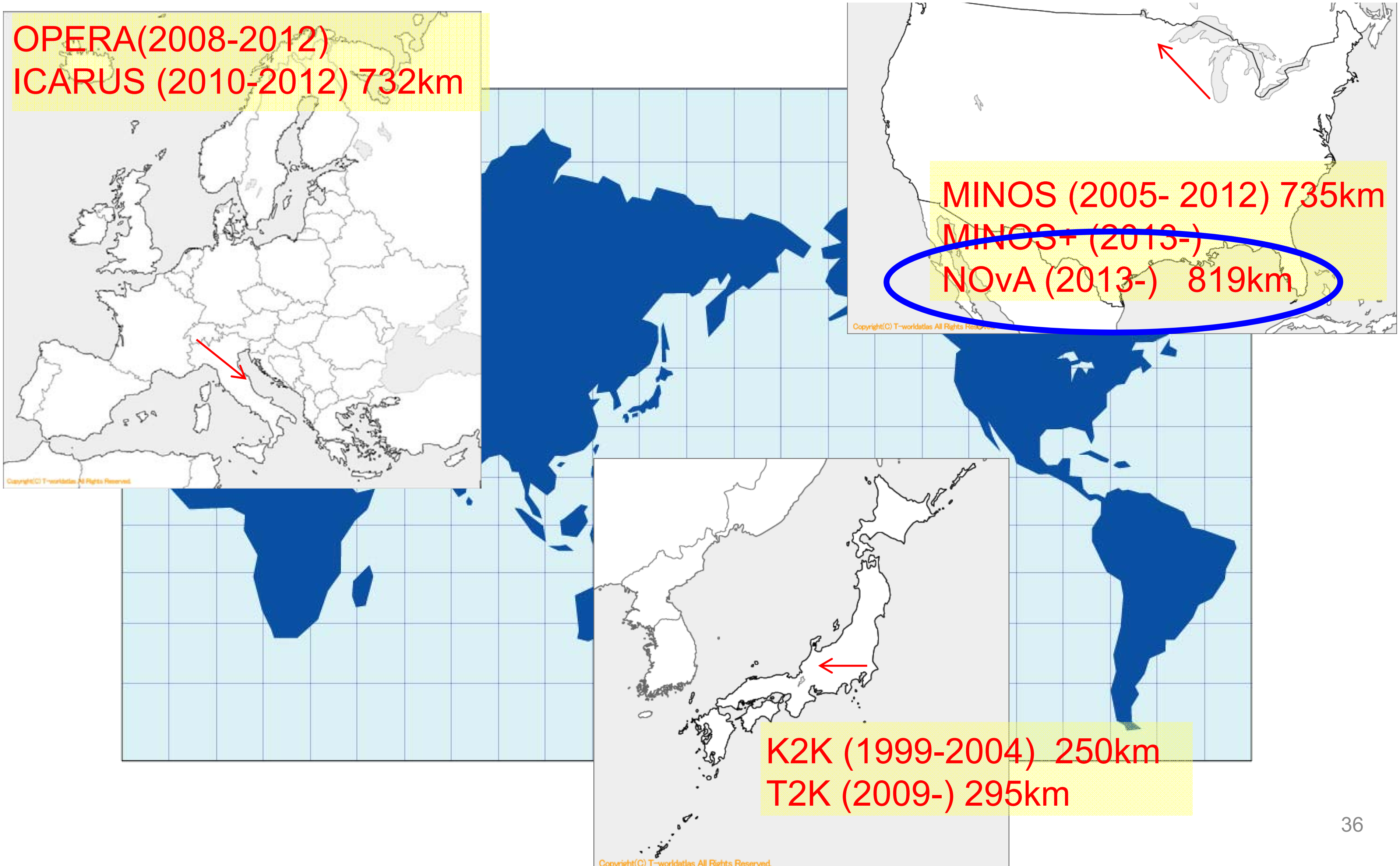
Example of ν_e candidate event



OSCILLATIONS PECULIAR TO THE LONG BASELINE EXPERIMENT

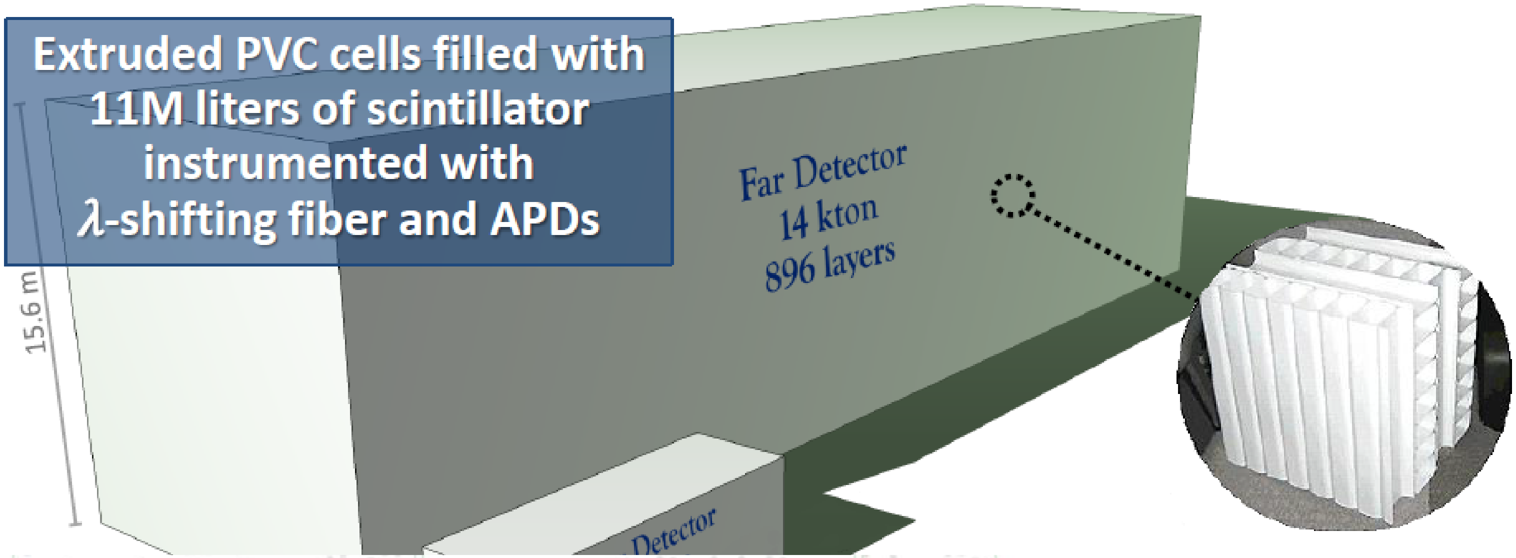


World Acc.-based Long baseline ν oscillation experiments

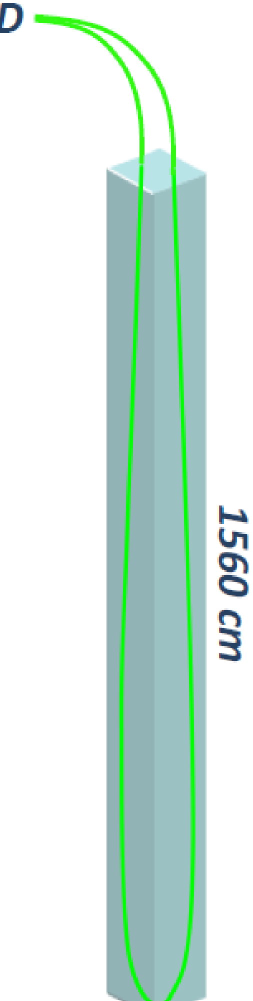


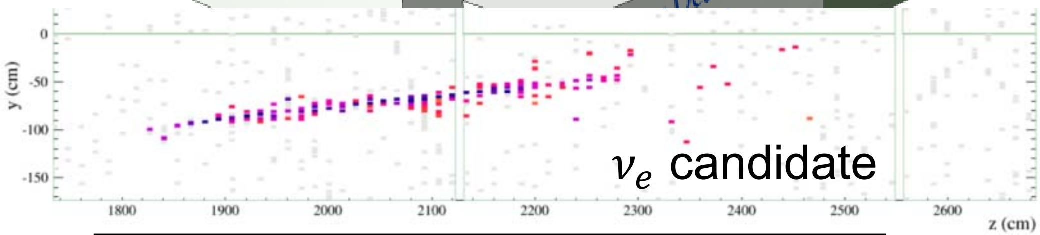
NOνA detectors

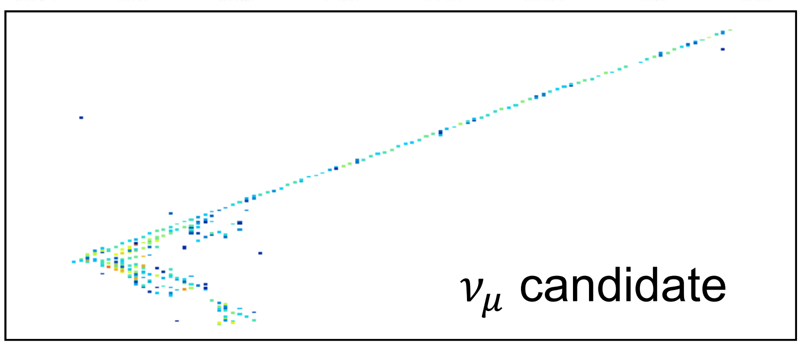
Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs



A NOνA cell







Far detector:

14-kton, fine-grained, low-Z, highly-active tracking calorimeter
→ *344,000 channels*

Near detector:

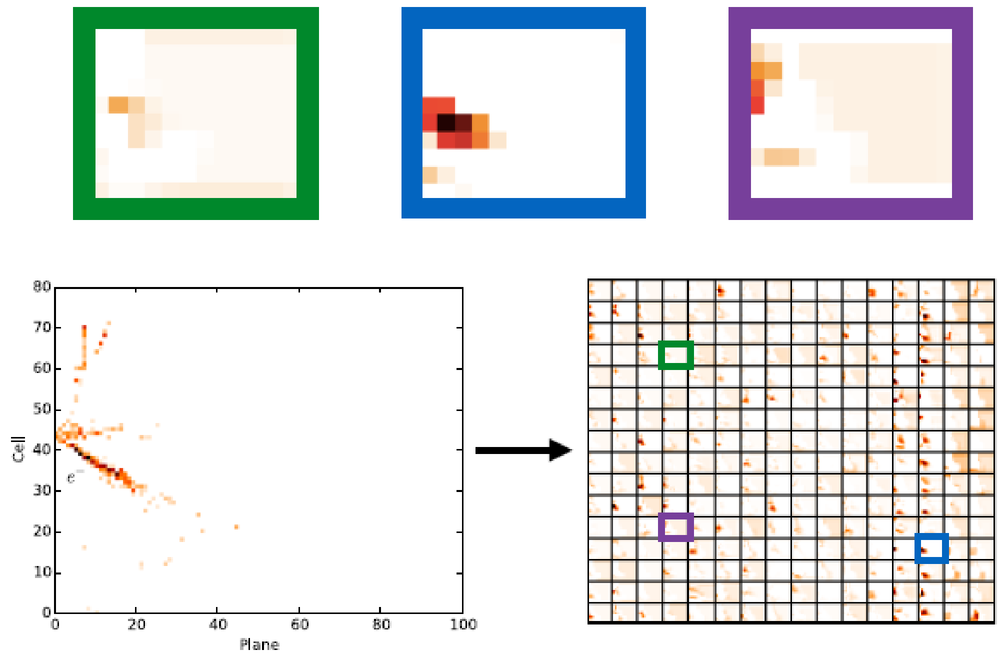
0.3-kton version of the same
→ *18,000 channels*

DEEP LEARNING!

Improved Event Selection

- This analysis features a new event selection technique based on ideas from computer vision and deep learning

- Calibrated hit maps are inputs to Convolutional Visual Network (CVN)
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event

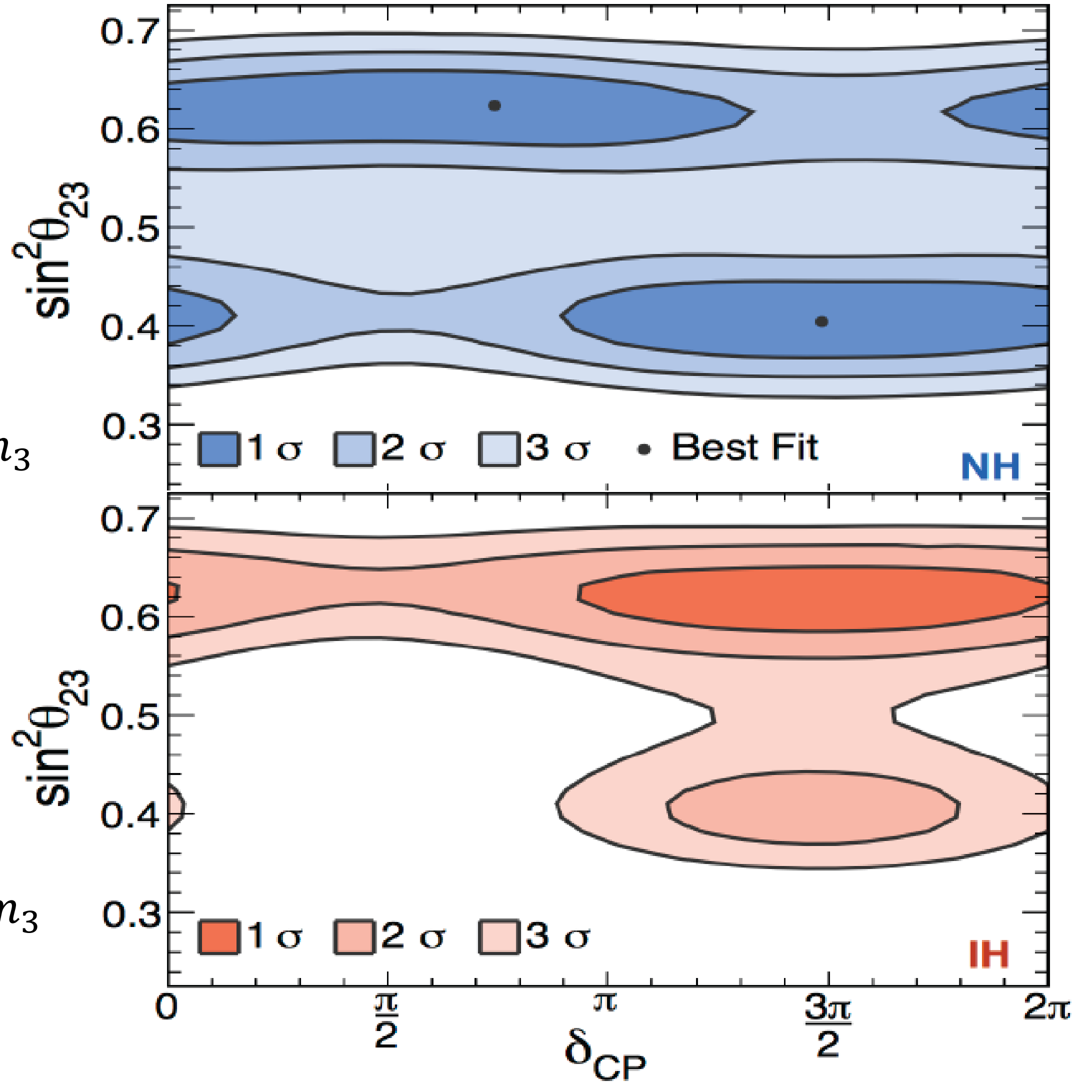


A. Aurisano et al., arXiv:1604.01444
Posters P1.028 by A. Radovic, P1.032 by F. Psihas and A. Himmel for more detail

NOvA

Based on neutrino data by 2016

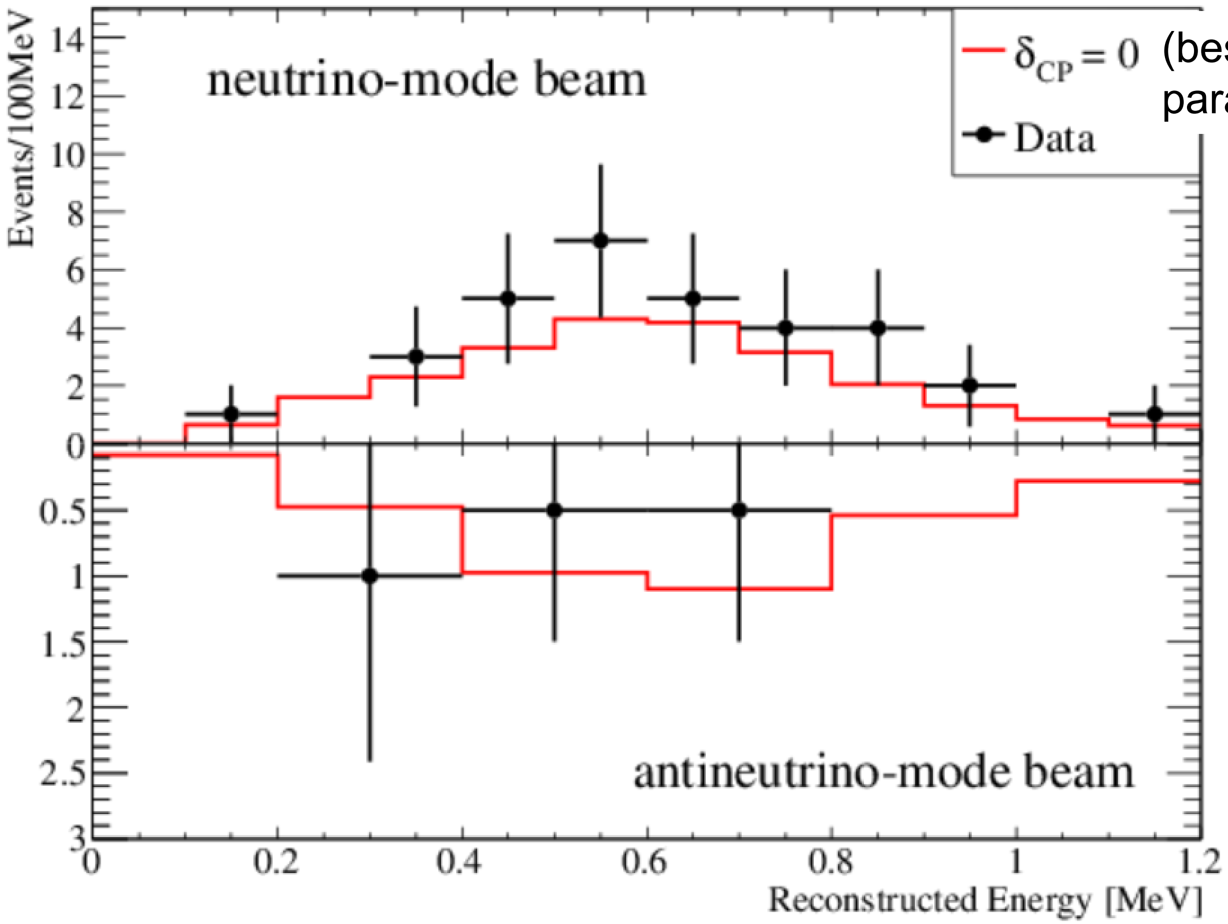
NH=$m_2 < m_3$



IH=$m_2 > m_3$

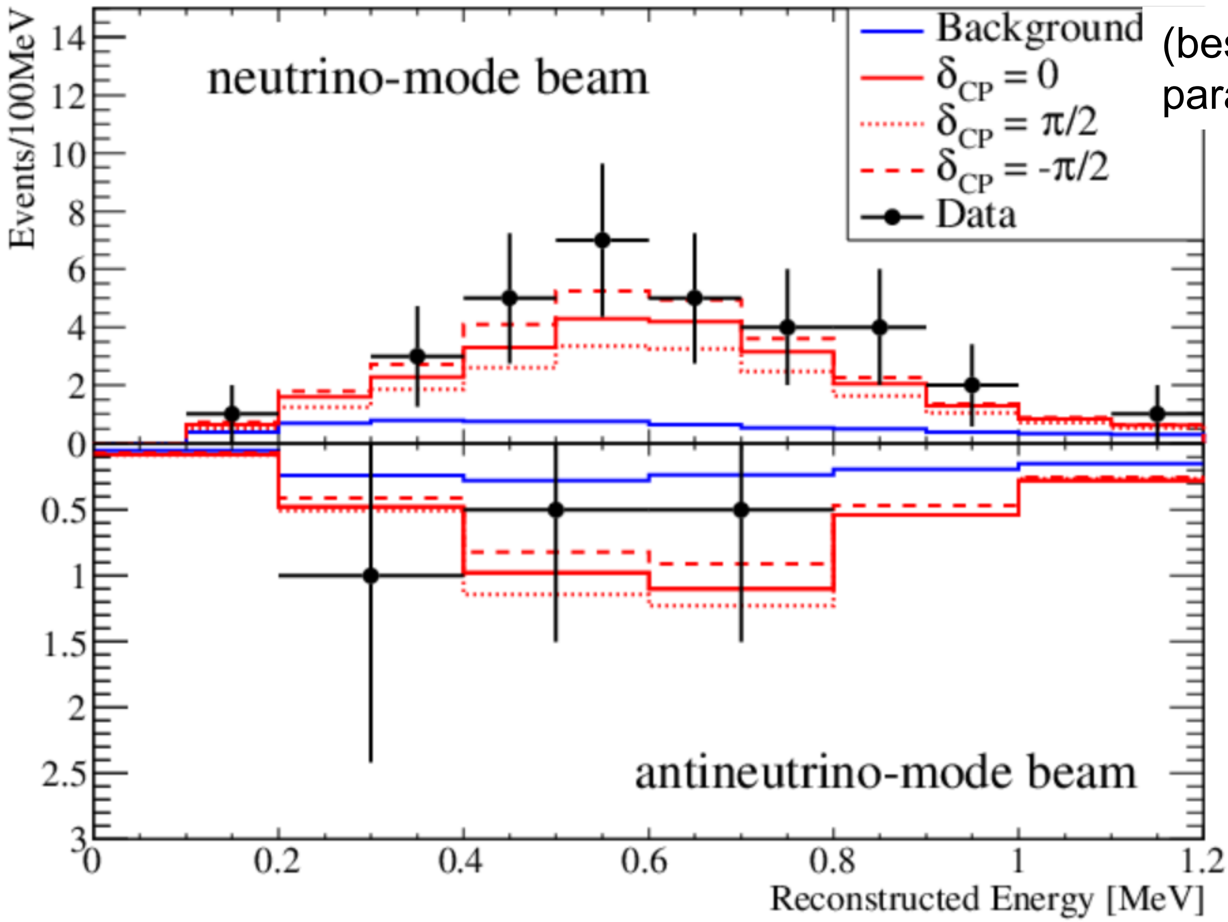
Now accumulating antineutrino data!

T2K HAS STARTED ANTINEUTRINO DATA TAKING IN 2013



(best fit for other parameters)

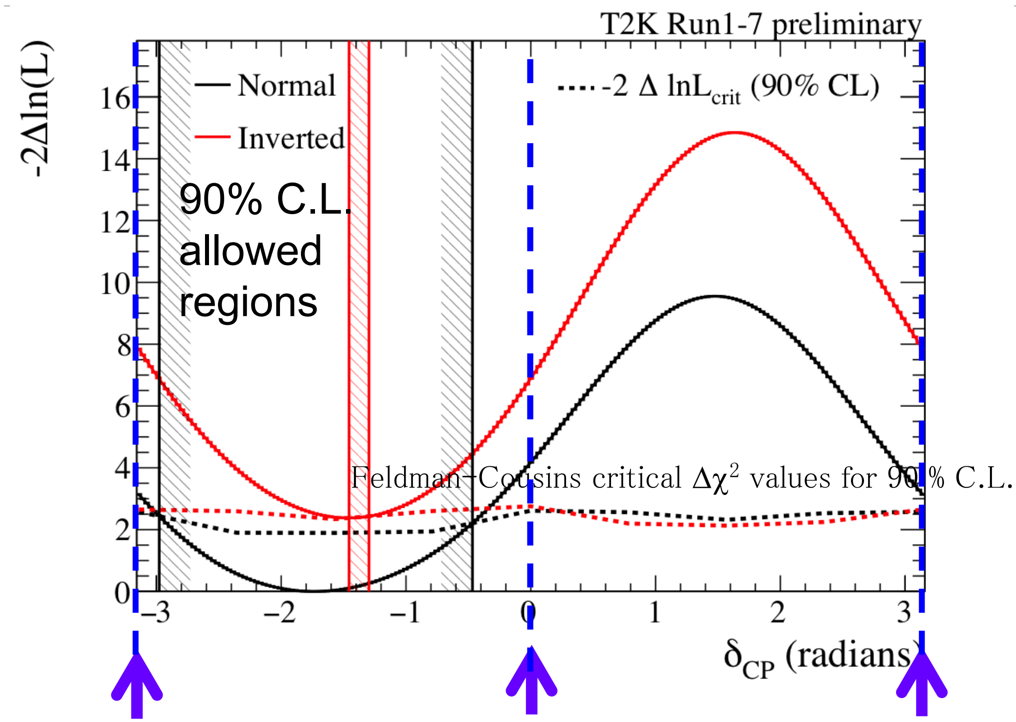
T2K ν_e AND $\bar{\nu}_e$ SELECTED EVENT DISTRIBUTIONS



(best fit for other parameters)

INDICATION OF CP VIOLATION???

$\Delta\chi^2$ v.s. δ_{CP}



no CPV

90% Confidence Interval:

Normal mass ordering	$(-171°, -27°)$
Inverted mass ordering	$(-84°, -73°)$

CP conserving case is disfavored by >90% C.L.

Need more statistics!
This year, we doubled neutrino-beam data. Results coming soon.

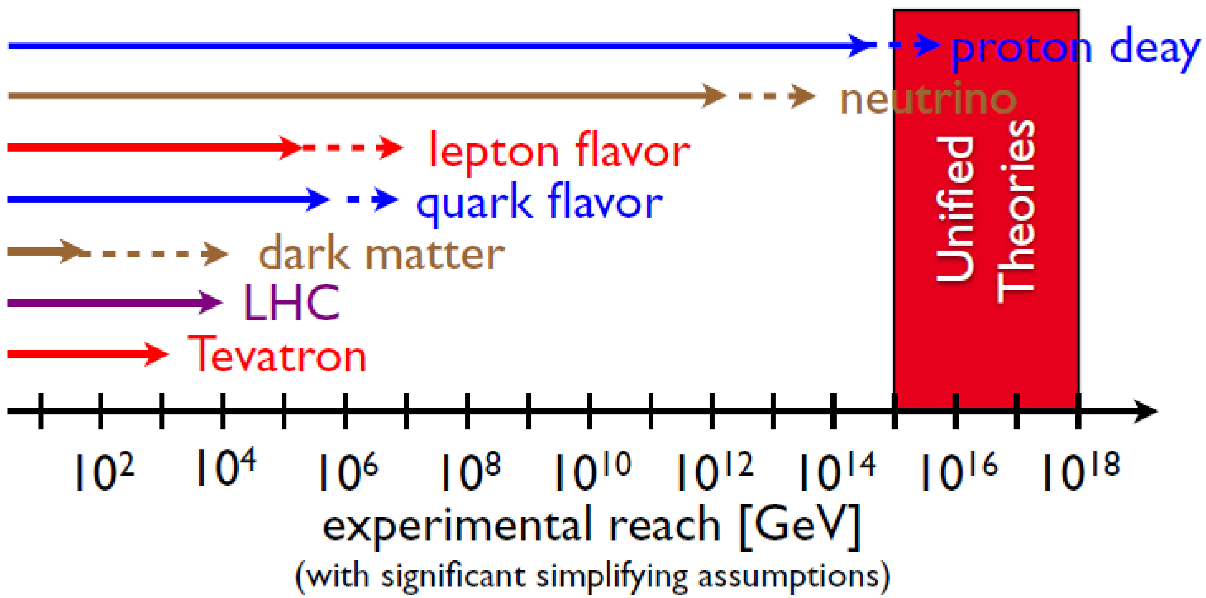
PROSPECT IN 10 YEARS

- **T2K**
  - beam power 350 kW → 900 kW by ~2021
  - CP violation may be indicated with >90% C.L. if it is maximally violated.
- **NOvA**
  - Mass ordering determination (~3σ)
  - CP violation may be indicated with >90% C.L. if it is maximally violated.
- **T2K-II**
  - Target Beam power 1.3 MW, near detector upgrade
  - x 3 times T2K POT in total by ~2026
  - CP violation can be observed with 3σ C.L. if it is maximally violated
  - (new collaborators are welcomed)

T2K-II Expected number of events (1:1 $\nu:\bar{\nu}$ running case)
ν_e sample : 455 evts$\pm$20% change depending on δ_{CP}
$\bar{\nu}_e$ sample : 129 evts$\pm$13% change depending on δ_{CP}

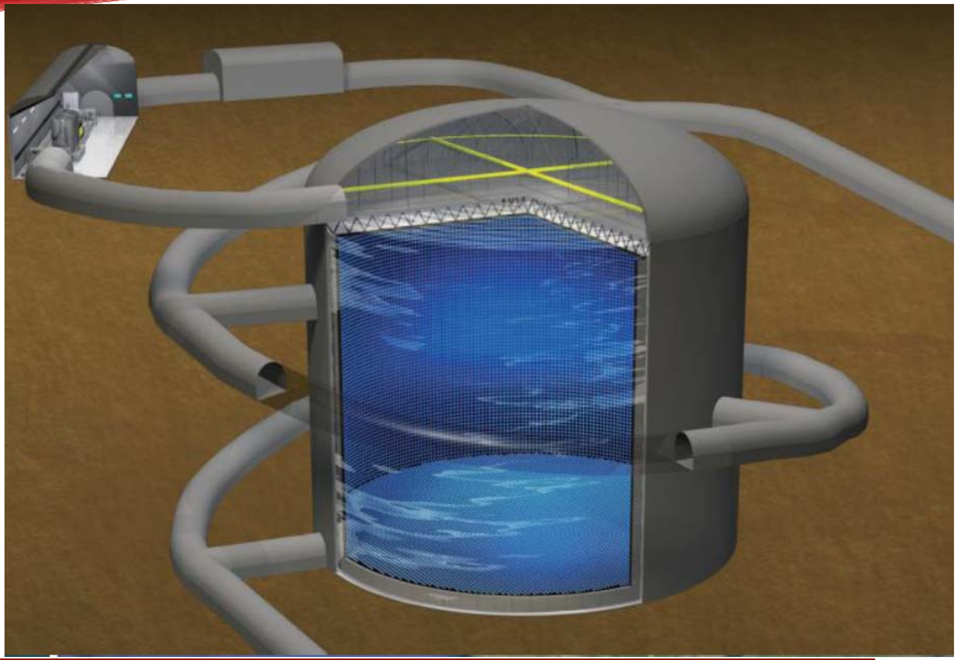
SURPRISE?

$K/B/\mu/\tau/n$ and LHC is searching TeV scale new physics. difficult with neutrinos because of low statistics.
However, extremely-small neutrino mass is possibly generated by Grand-unification Theory(GUT) scale physics ($m_\nu \sim \frac{m_D^2}{M_N}$ (m_D Dirac mass like quarks/charged leptons, $M_N \lesssim$GUTスケール). So m_ν scale measurement(=neutrino oscillation) may reveal surprising phenomenon from GUT scale physics



"Future Experimental Programs" H. Murayama Phys.Scripta T158 (2013) 014025

BEYOND 10 YEARS,

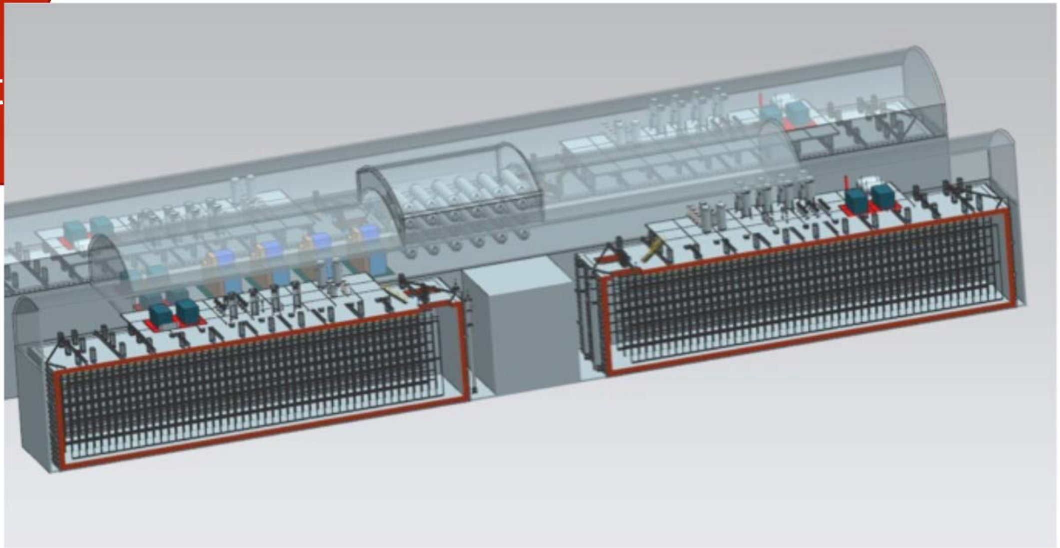


Hyper-Kamiokande
~1 Mton Water Cherenkov Detector at Kamioka,

CPV for wide range of δ_{CP}
ν's from Solar, Supernova, atmospheric
Proton decay, dark matter…

Liquid Ar technology established by ICARUS

In US, DUNE experiment, with 40kt liquid Ar TPC



SUMMARY

- Since the discovery of neutrino oscillation, understanding of 3 generation mixing has been steadily progressed.
  - Still we don't know why mass-flavor mixing is small in quark and large in lepton.
- Remaining known unknowns are: CP violation, mass ordering and maximal or non-maximal θ_{23}
  - They will be solved in 1~20 years by the accelerator long baseline experiments, reactor long baseline experiments and atmospheric measurements
- Our knowledge on the origin of the matter-dominant universe will be progressed by neutrino CP violation.
- It is likely that the tiny mass of neutrino originates from the physics in high energy (>10^{14} GeV) scales. Then, unknown unknown may be also found in the neutrino oscillations
- We are entering the era where precise comparison among measurements are possible like the quark sector.