Quest for physics of neutrino mixing

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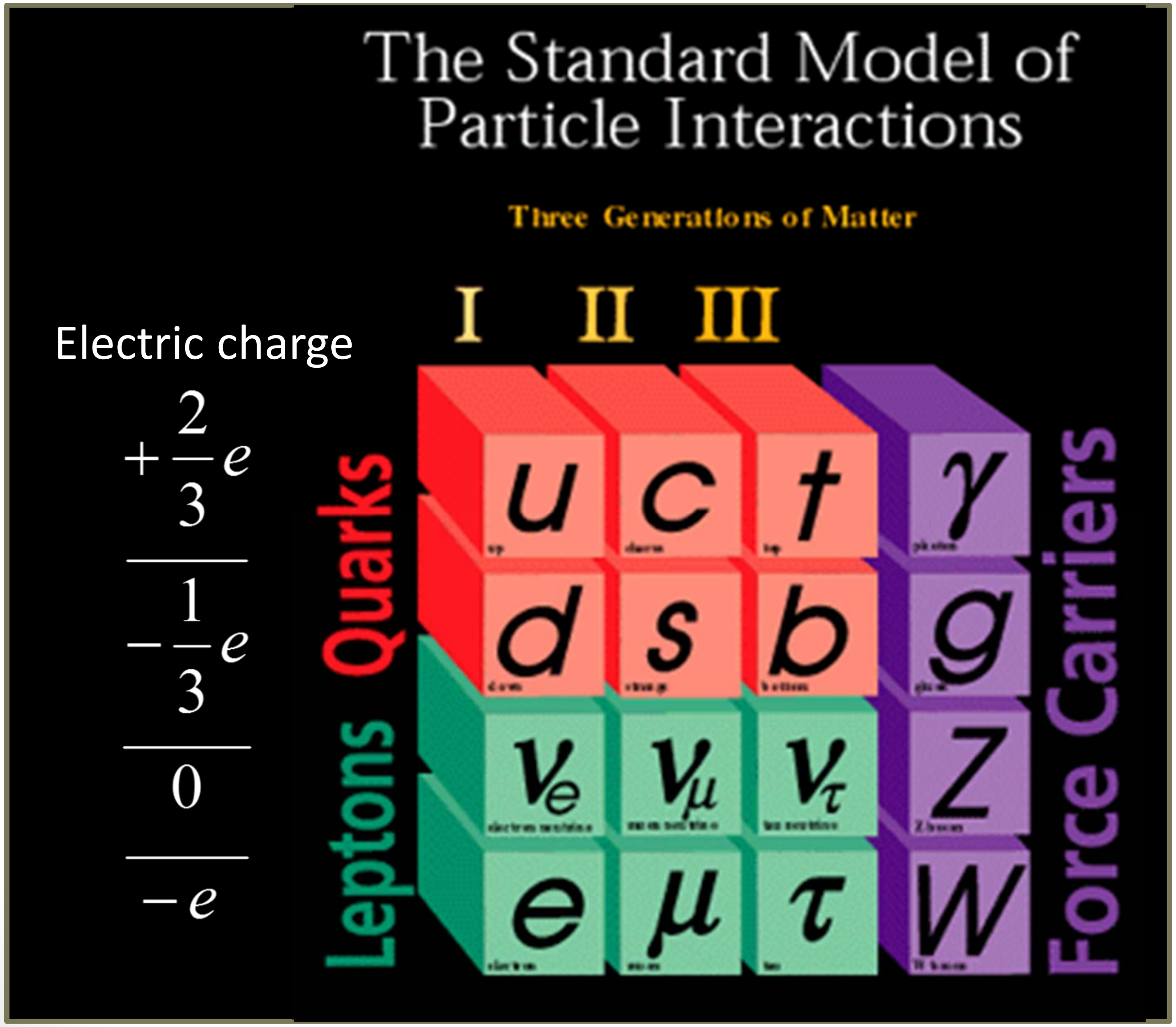
Constituents of This World



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

Fig. from FNAL home page

How can we distinguish btw.

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

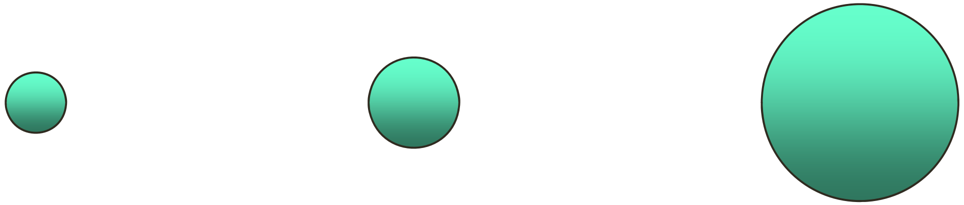
Same spin, same charge…

Only by mass!
Except for ν's.

Mixing btw. Flavor and Mass

We know that there are three types of charged lepton.

Distinguishable only via mass.



electron (0.5MeV) muon(110MeV) tau (1776MeV)

Then, we found that there are three types neutrino.
Distinguishable via interaction w/ matter.

- The one which create electron $\rightarrow$ electron neutrino (ν_e)
- The one which create muon $\rightarrow$ muon neutrino (ν_μ)
- The one which create tau $\rightarrow$ tau neutrino (ν_τ)

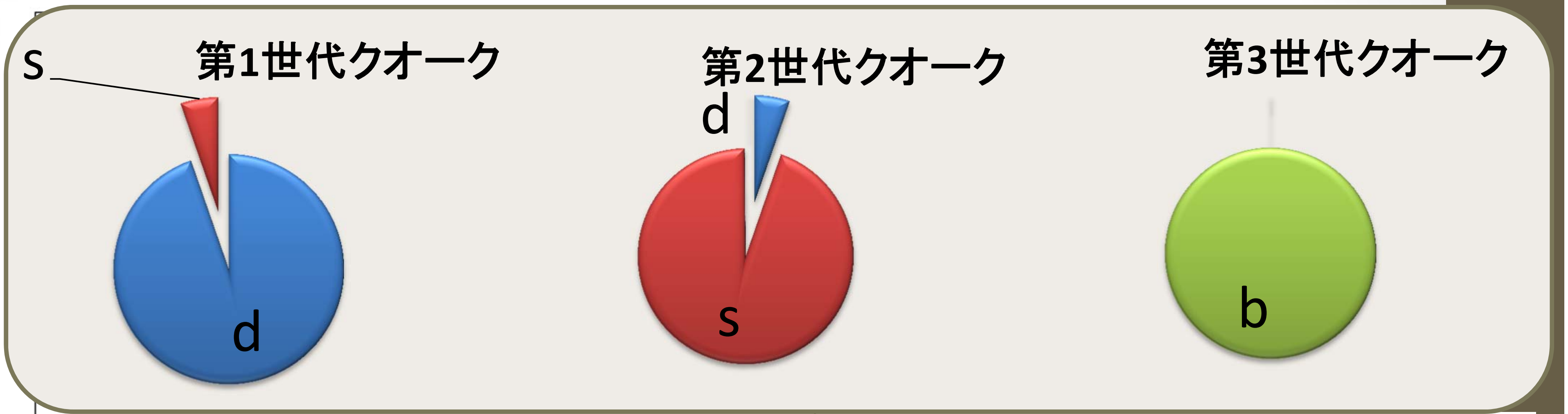
There is no need for them to be mass eigen states.

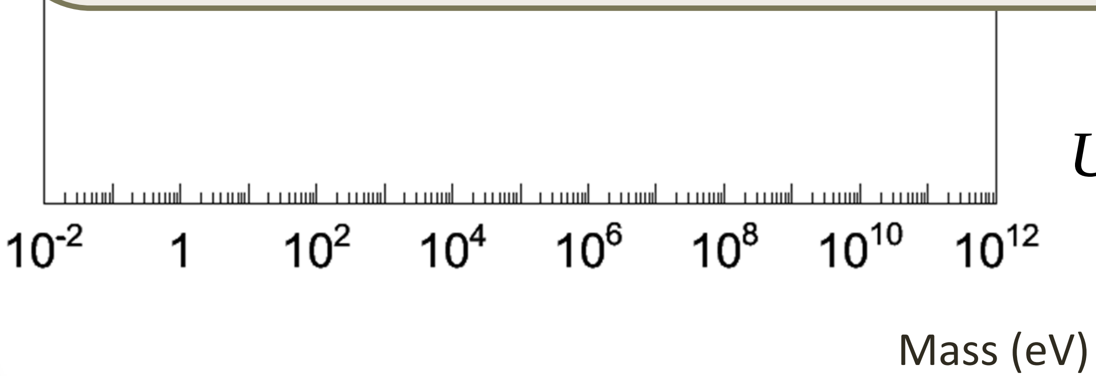
- $|\nu_e\rangle = a|\nu_1\rangle + b|\nu_2\rangle + c|\nu_3\rangle$ ν_1, ν_2, ν_3 : mass eigen states

Same thing can happen for quarks.

- Partner of |up> quark = a|down> + b|strange> + c|bottom>

Quark Flavor(≅generation) and Mass



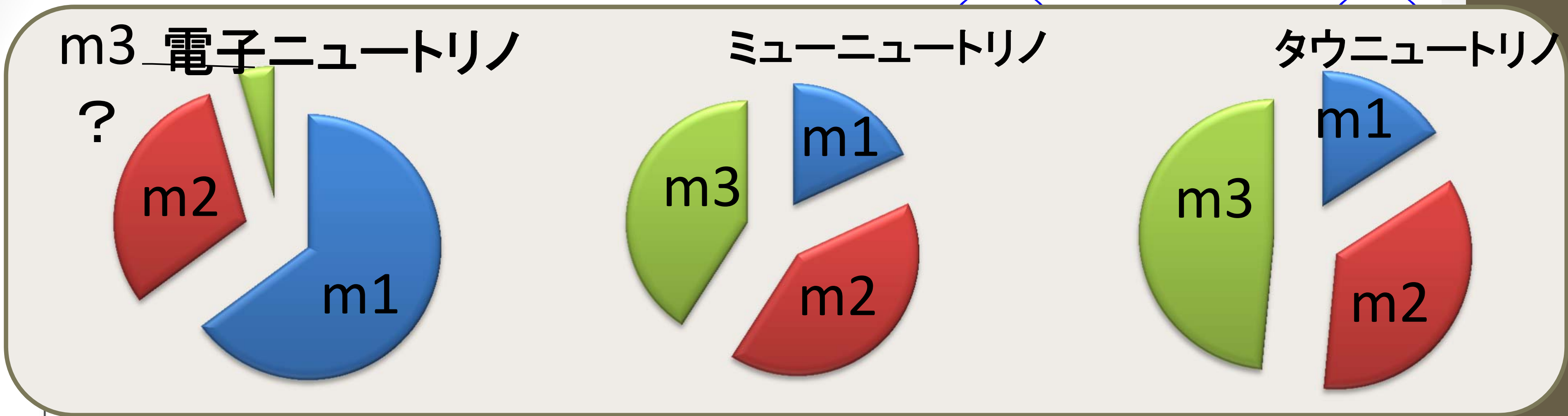


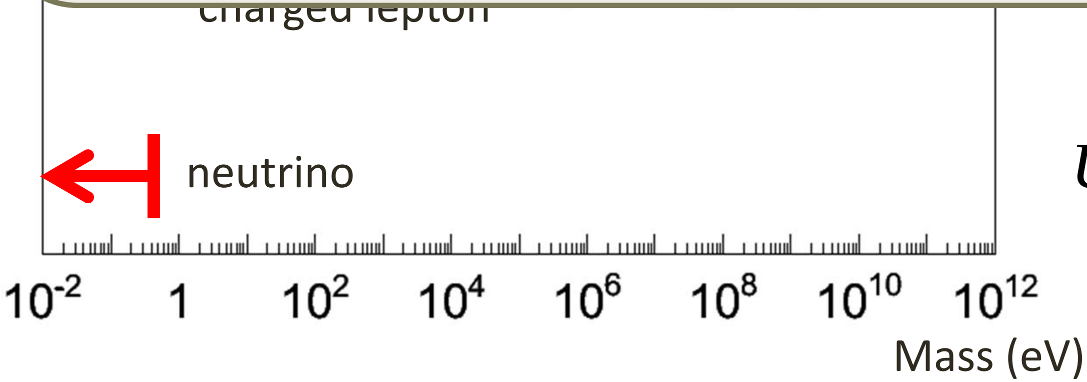
$$U_{CKM} \approx \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

Cabbibo-Kobayashi-Maskawa matrix

- ✓ All are believed to be given mass by Higgs, but O(5) different.
- ✓ Relation btw. mass eigen states and weak eigen states is suggestive (close to diagonal)

Lepton Flavor(≅generation) and Mass



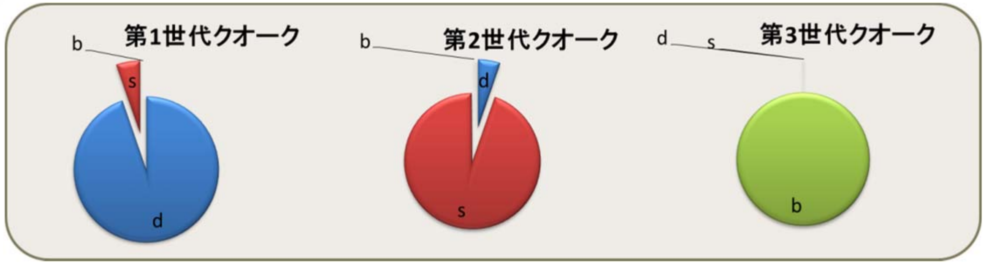


$$U_{MNS} \approx \begin{pmatrix} 0.8 & 0.55 & < 0.21 \\ -0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

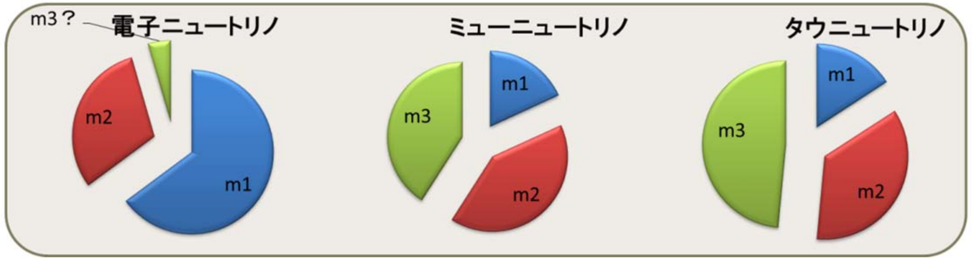
Maki-Nakagawa-Sakata matrix

- ✓O(11) difference. (O(6) w/ electron)
- ✓Relation btw. mass eigen states and weak eigen states is further suggestive (Large mixing).

Links among Hierarchies



$$U_{CKM} \approx \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$



$$U_{MNS} \approx \begin{pmatrix} 0.8 & 0.55 & < 0.21 \\ -0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

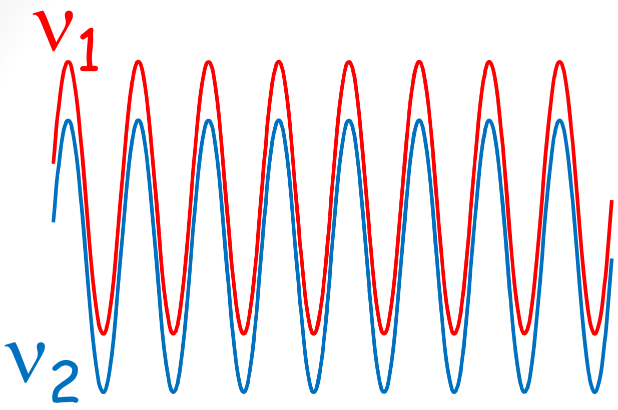
Assuming some symmetry among quarks and leptons, some models predict

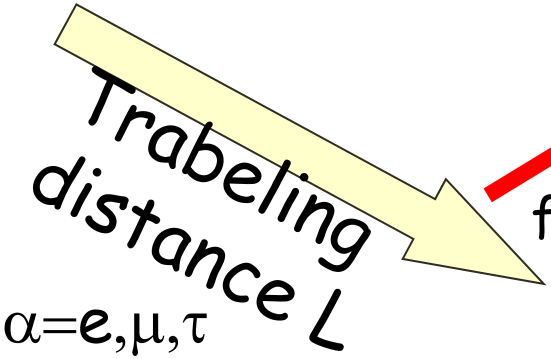
$$U_{CKM} \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

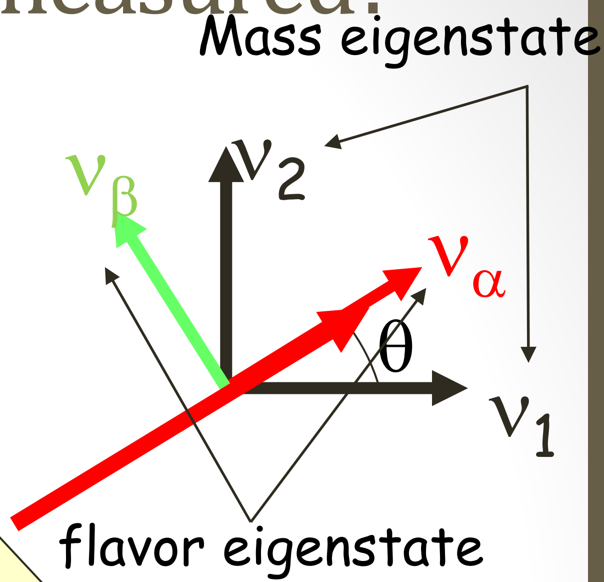
$$U_{MNS} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \\ \sqrt{1/6} & -\sqrt{1/3} & \sqrt{1/2} \end{pmatrix} = \begin{pmatrix} 0.816 & 0.577 & 0 \\ -0.408 & 0.577 & 0.707 \\ 0.408 & -0.577 & 0.707 \end{pmatrix}$$

How is lepton mixing matrix measured?

Neutrino Oscillation

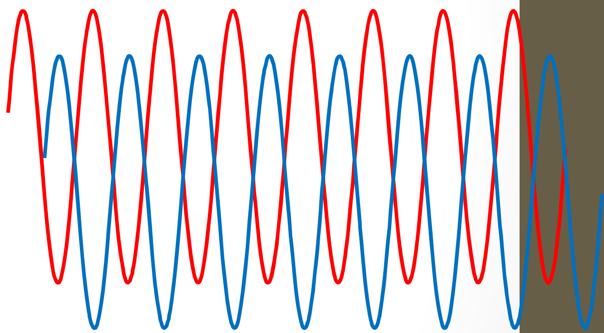






$|\nu_\alpha\rangle = |\nu_1\rangle\cos\theta + |\nu_2\rangle\sin\theta, \quad \alpha = e, \mu, \tau$

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



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

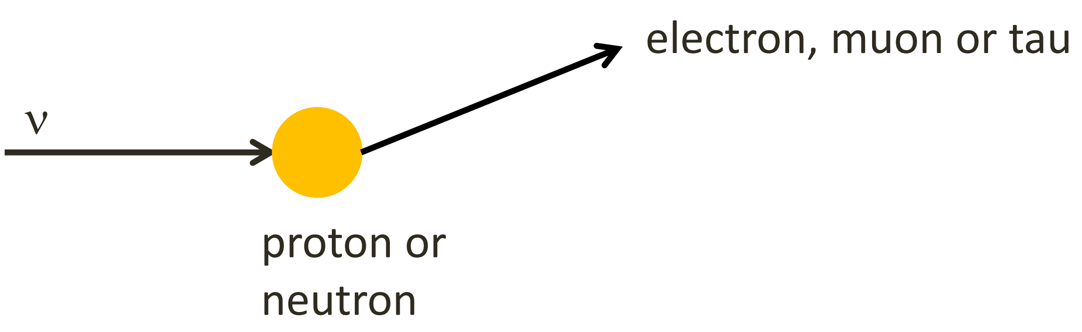
Appearance or Disappearance

Neutrino flavor is tagged via charged current (CC) interaction.

- The one which create electron $\rightarrow$ electron neutrino (ν_e) : $E_{threshold}$ >0 MeV
- The one which create muon $\rightarrow$ muon neutrino (ν_μ) : $E_{threshold}$ > 100 MeV
- The one which create tau $\rightarrow$ tau neutrino (ν_τ) : $E_{threshold}$ > 3.5 GeV

At $E < E_{threshold}$,

that flavor is not observed and recognized as **disappearance**.



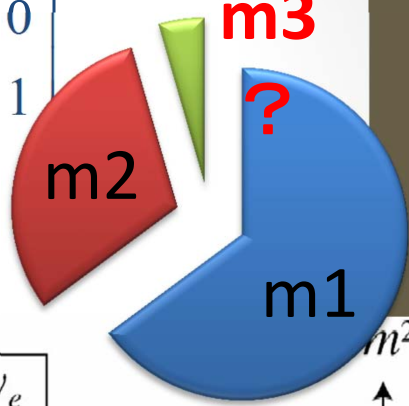
What we knew before 2

KEY to understand the origin of matter dominant universe

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

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

電子ニュートリノ



$$\theta_{12} = 34.4° \pm 1.3°$$

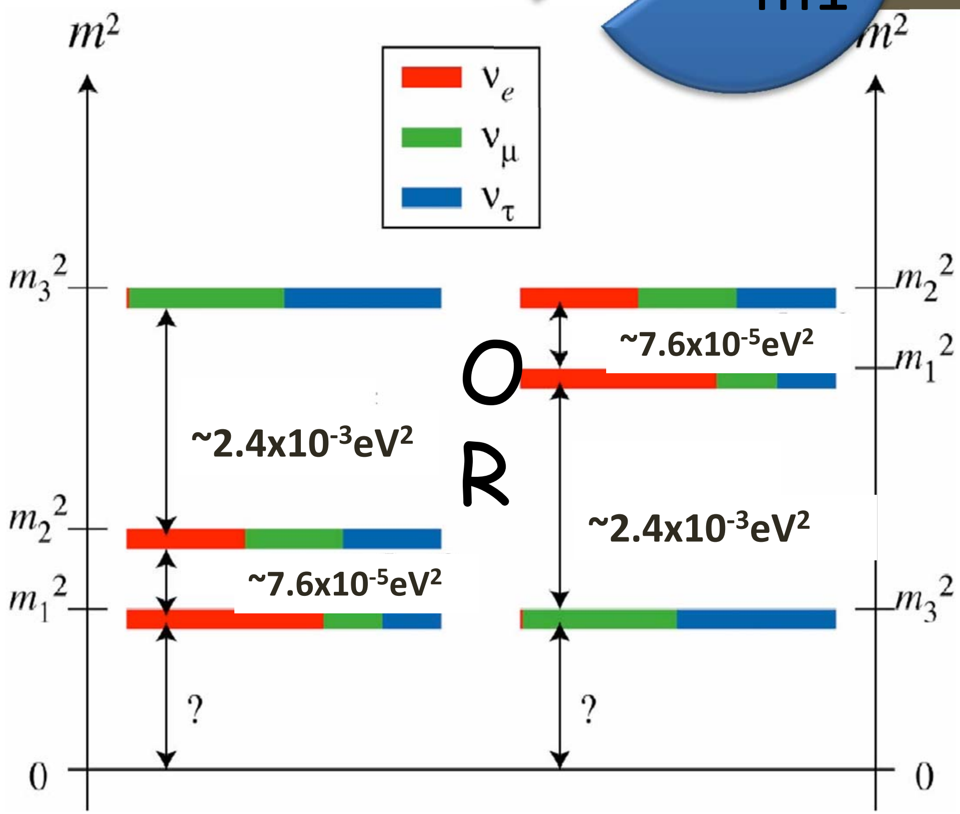
$$\theta_{23} = 45° \pm 8° \quad (90\%CL)$$

$$\theta_{13} \leq 12° \quad (90\%CL)$$

KEY to understand the origin of quark and lepton

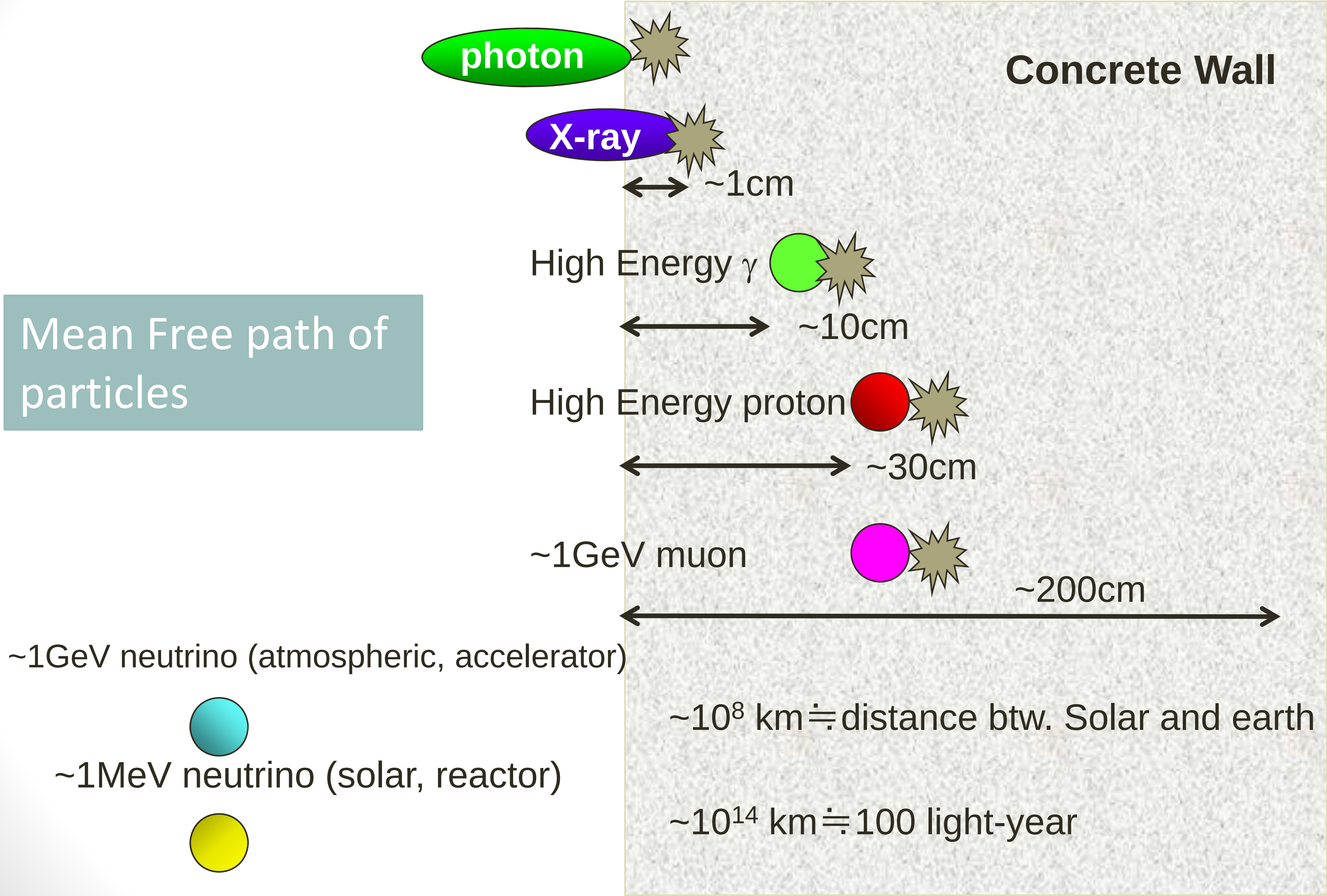
$$U_{MNS} \approx \begin{pmatrix} 0.8 & 0.55 & < 0.21 \\ -0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

δ=?

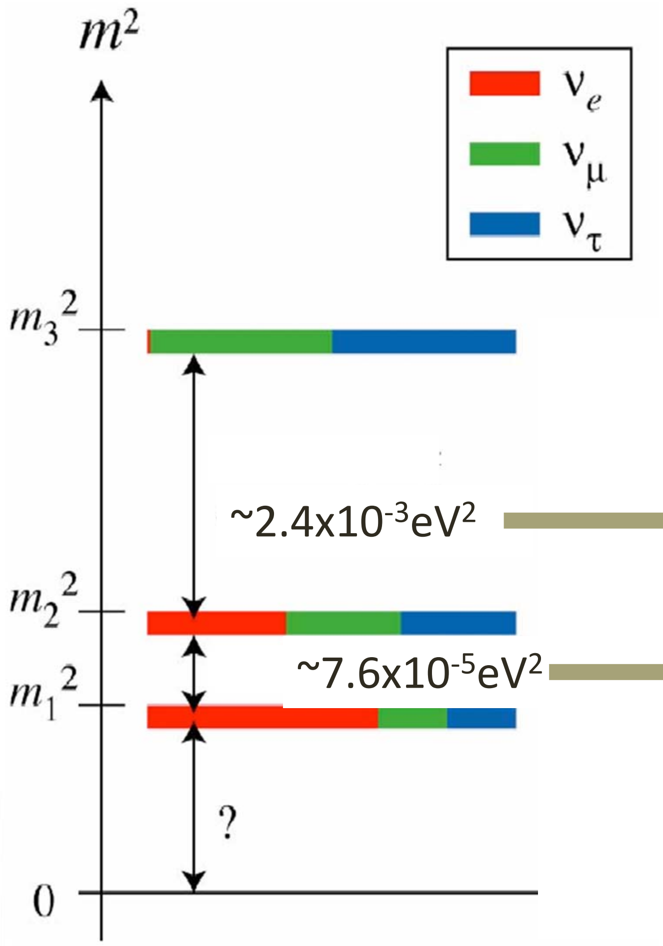


Why it takes so long time to just determine a few parameters???

Difficulty - Neutrino is so weak-



Difficulty
- Oscillate across long distance-

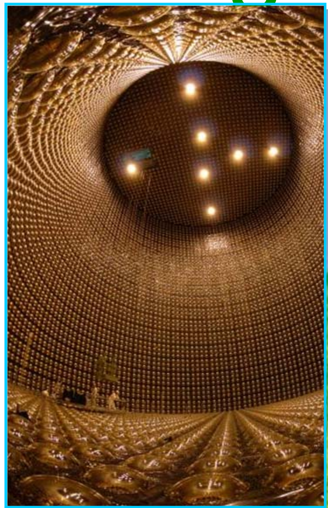


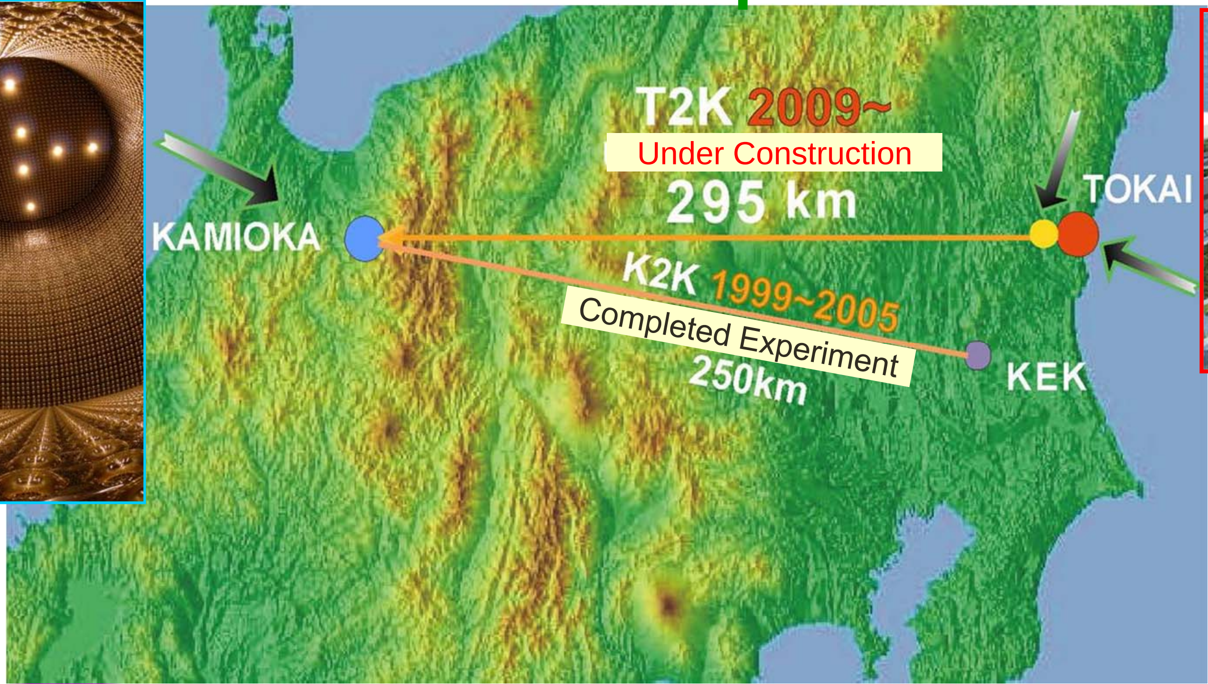
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

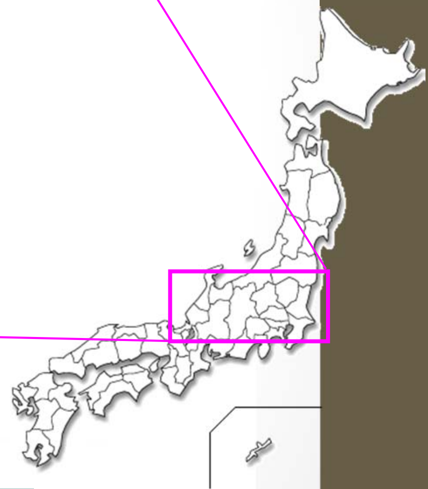
~300 km @ Eν=700 MeV

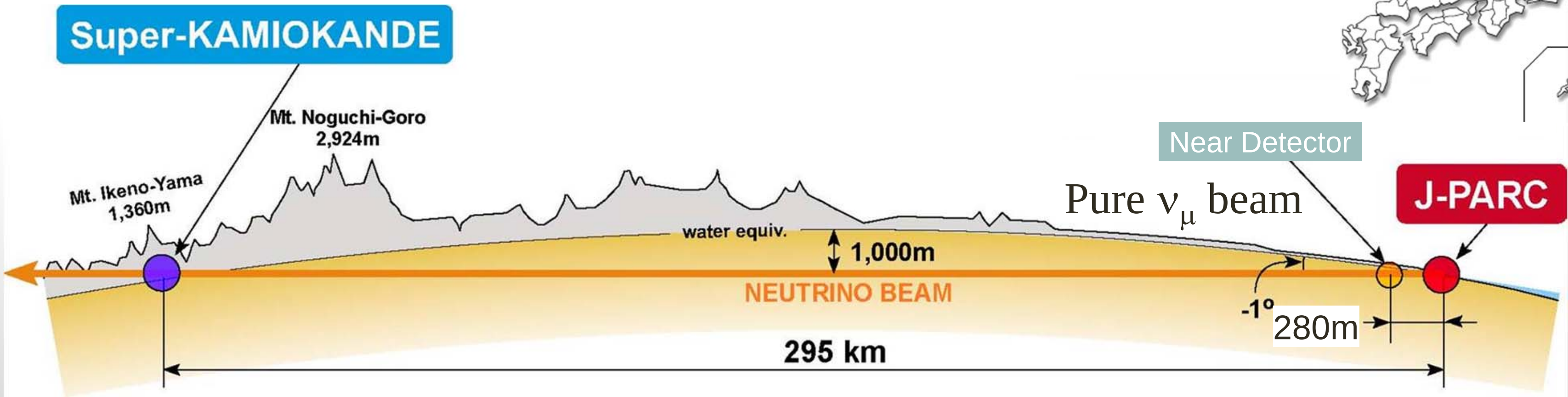
~50 km @ Eν=3 MeV

T2K (Tokai to Kamioka)
Long Baseline ν experiment









Why it takes so long time to just determine a few parameters???

Because we need

a strong Neutrino Source

and

a Large Neutrino Detector

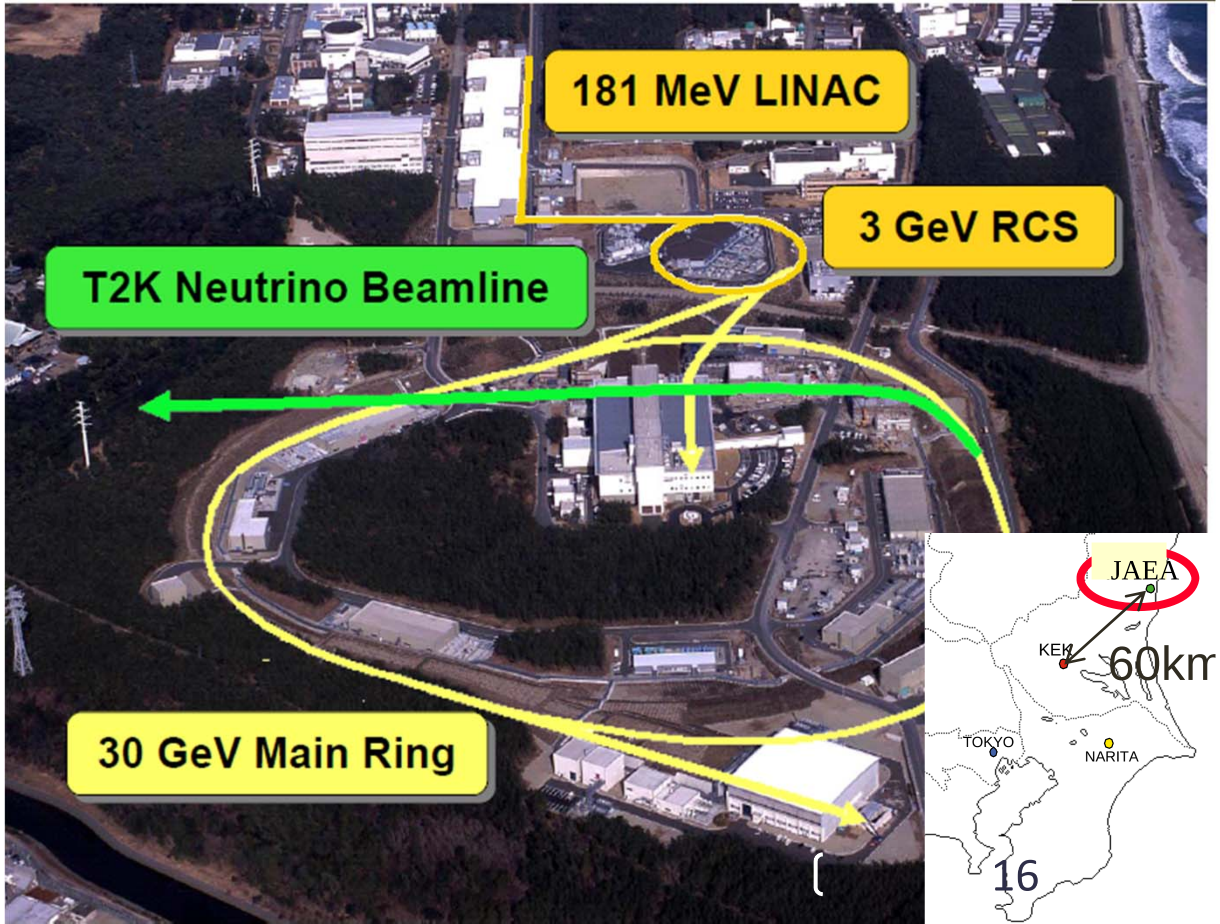
Neutrino Source

Accelerator

J-PARC Japan Proton Accelerator Research Complex

- Located in Tokai-village
- Completed in 2009
- Design goal
  - RCS: 1MW
  - MR: 750kW

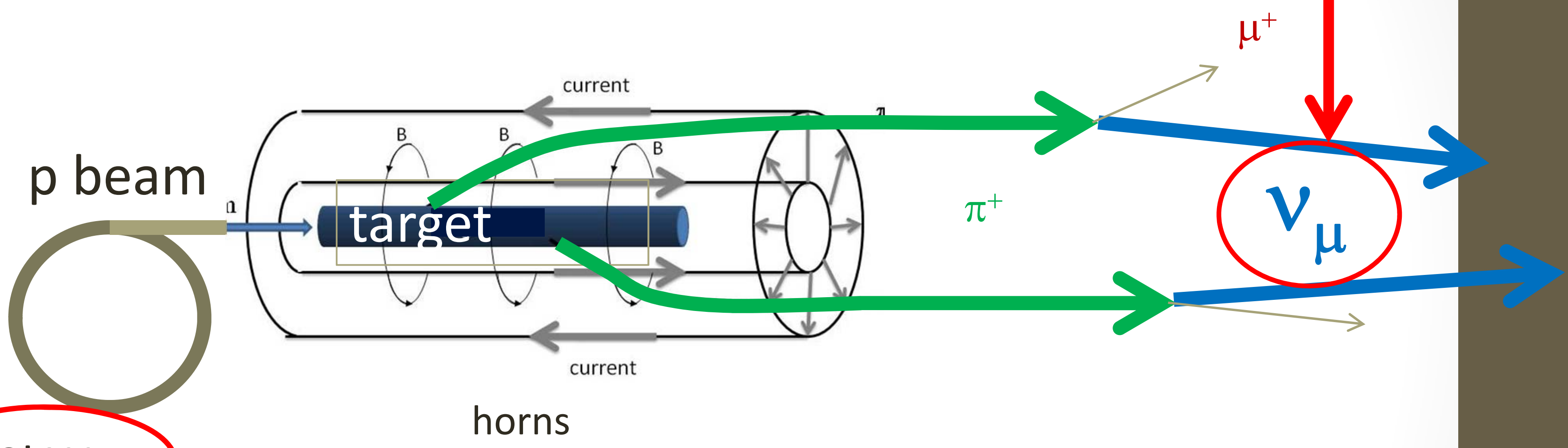
Beam power!



Joint project of KEK & Japan Atomic Energy Agency (JAEA)

Accelerator

This ν_μ may oscillate to
ν_τ (disappearance) via θ_{23}
or ν_e (appearance) via θ_{13}
after traveling 295km.



750kW proton synchrotron

Energy carried by beam!

10^{14}~10^{15} ν/s
~$1\nu/cm^2/s$ at T2K Far detector(295km away)
(@750kW proton beam power)

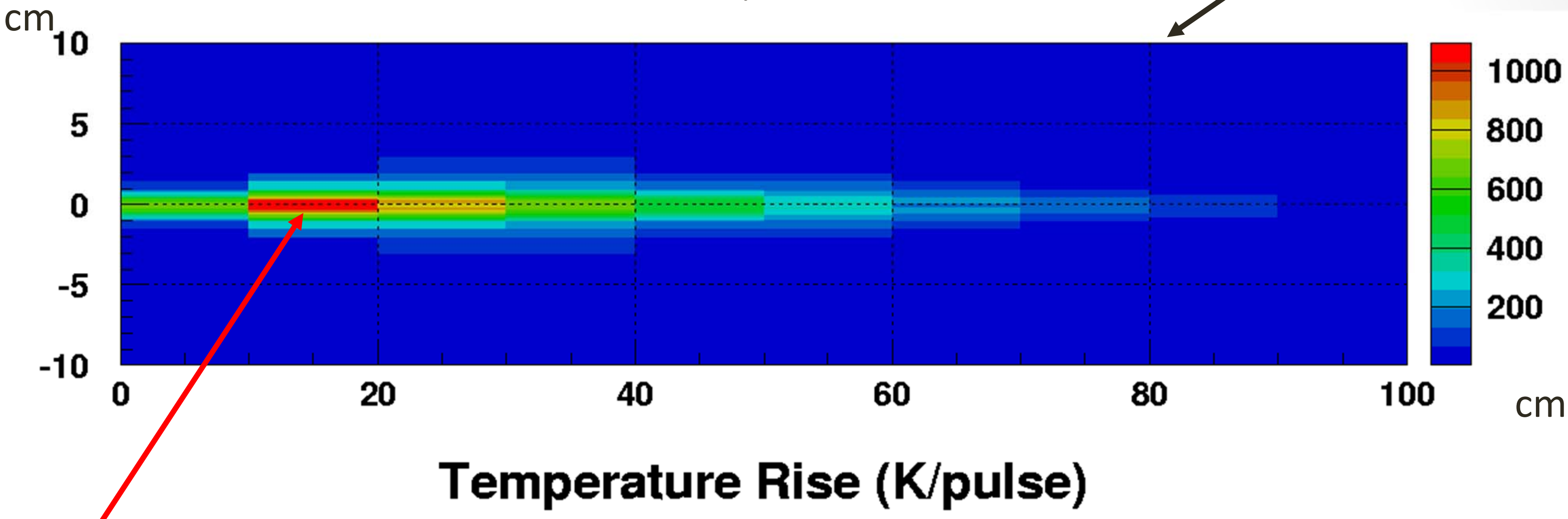
50 GeV 0.75 MW beam !

Residual radiation level

3.3E14 ppp (2.6MJ) in 5μs pulse

> 1000Sv/h

When this beam hits an iron block,



1100º

(cf. melting point 1536º)

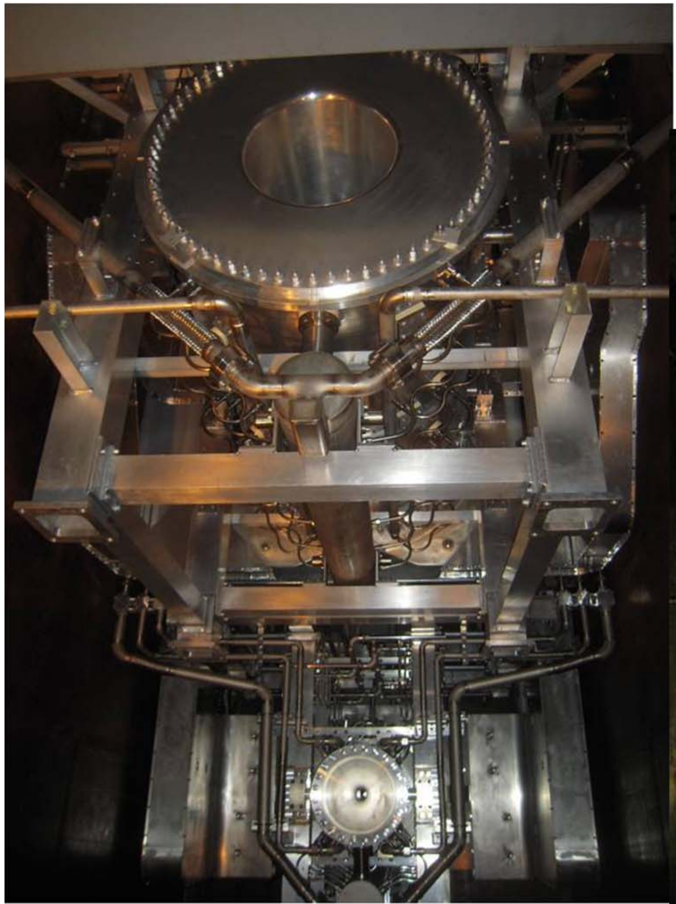
✓ Material heavier than iron would melt.

✓ Thermal shock stress $\approx E\alpha\Delta T \approx 3GPa$

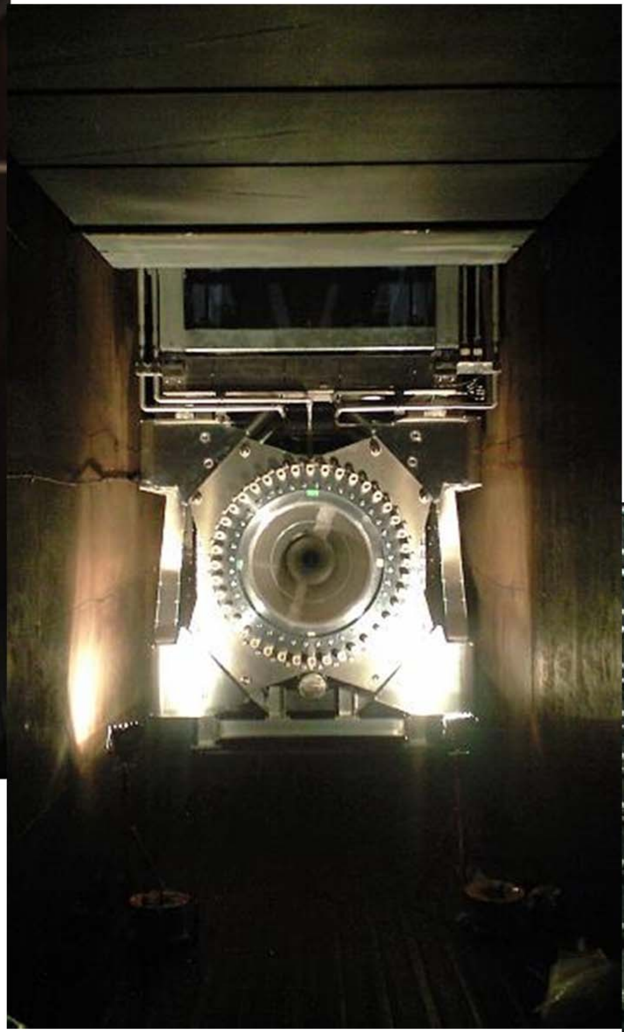
(cf. 耐力 ~300 MPa)

Material heavier than Ti might be destroyed.

✓ Cooling power and radiation shield 12GeV PS x 100



1st Horn & 2nd Horn

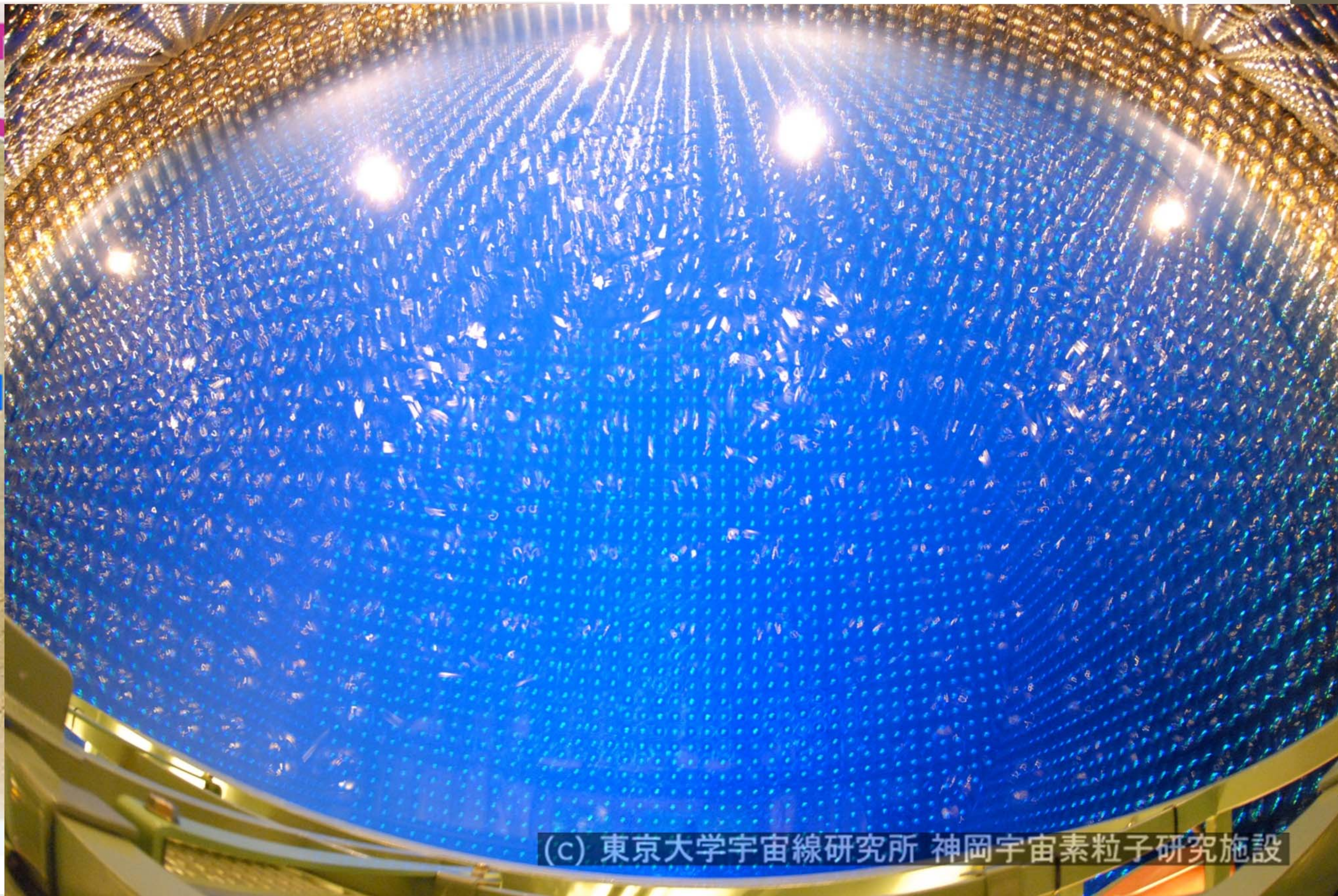


3rd Horn

Decay Volume

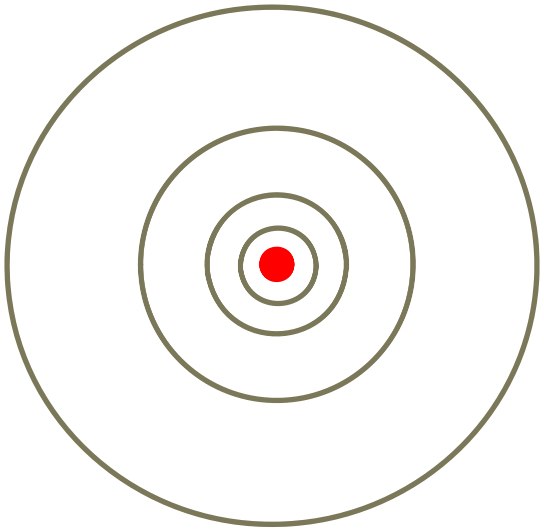
Neutrino Detector

Super-Kamiokande

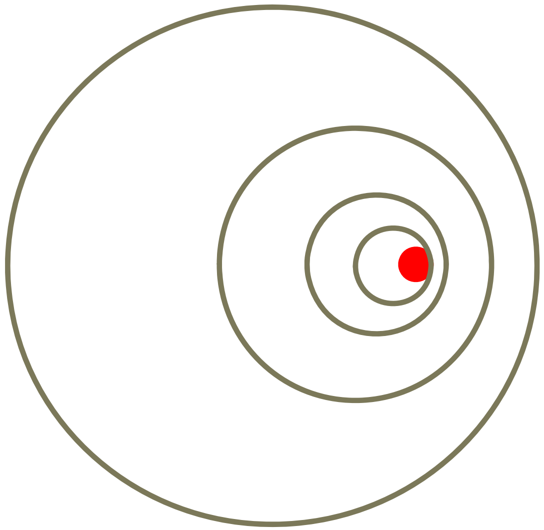


Cherenkov radiation

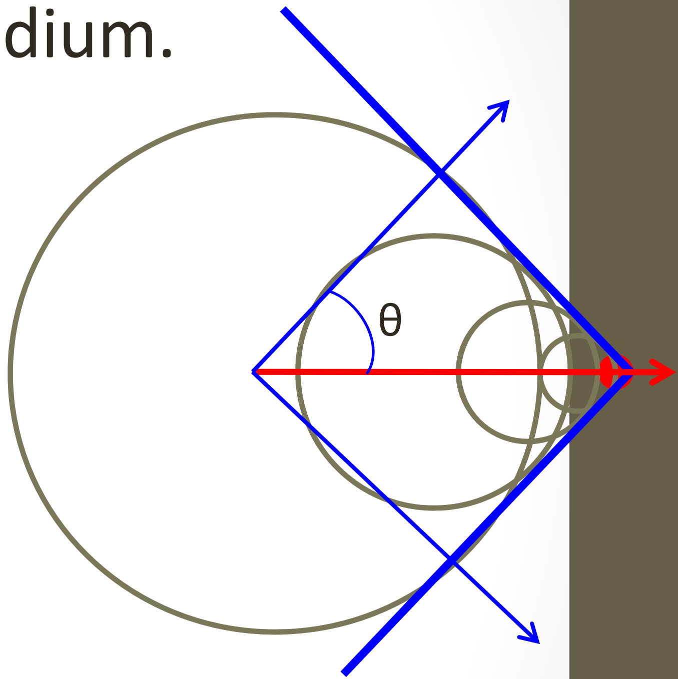
Photons are emitted when charged particle travel faster than the light velocity in medium.



静止した荷電粒子が作る
静電場

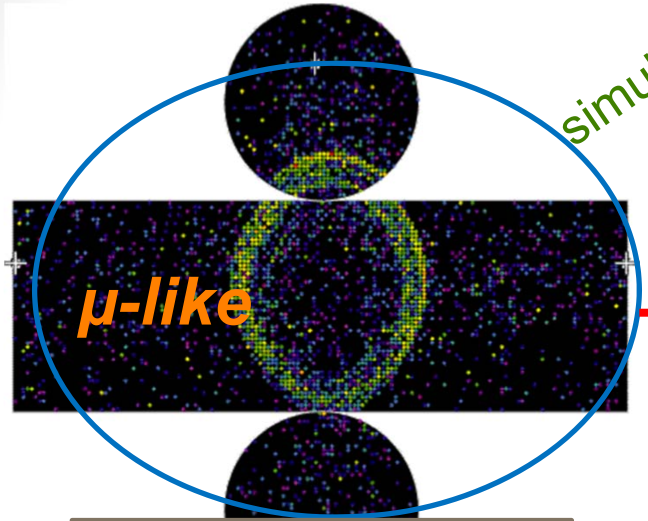


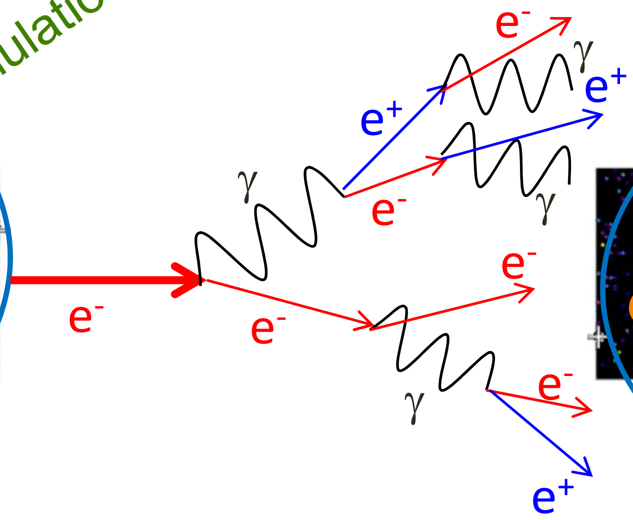
ゆっくりと動く荷電粒子が作る電場
電場の変化は、光速で伝わっていく

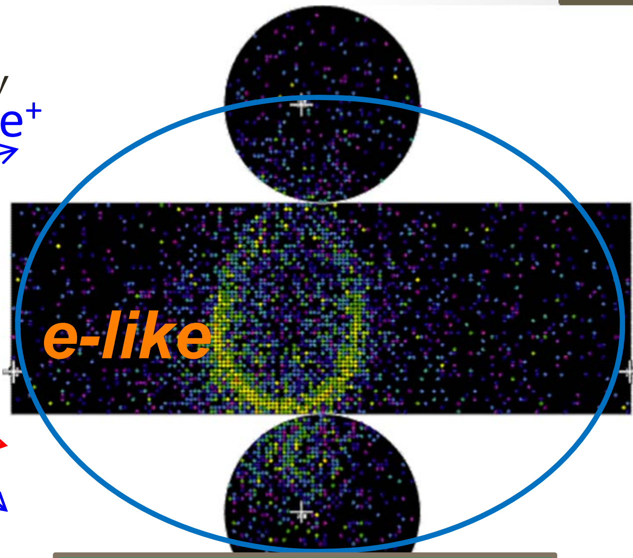


光速(c/n)より速く動く荷電粒子が作る電場
衝撃面が形成される

Detection at Super-K

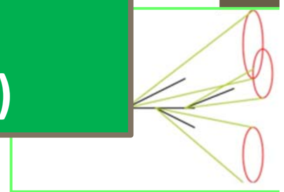


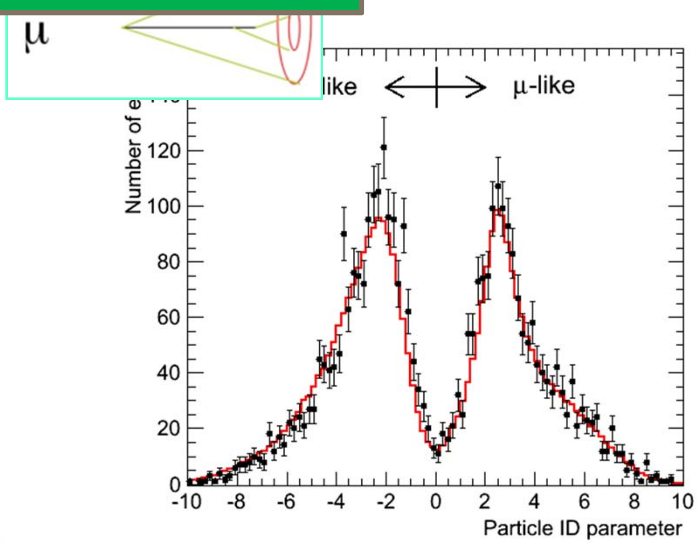




Signal for θ_{23}
(ν_μ disappearance)

Signal for θ_{13}
(ν_e appearance)



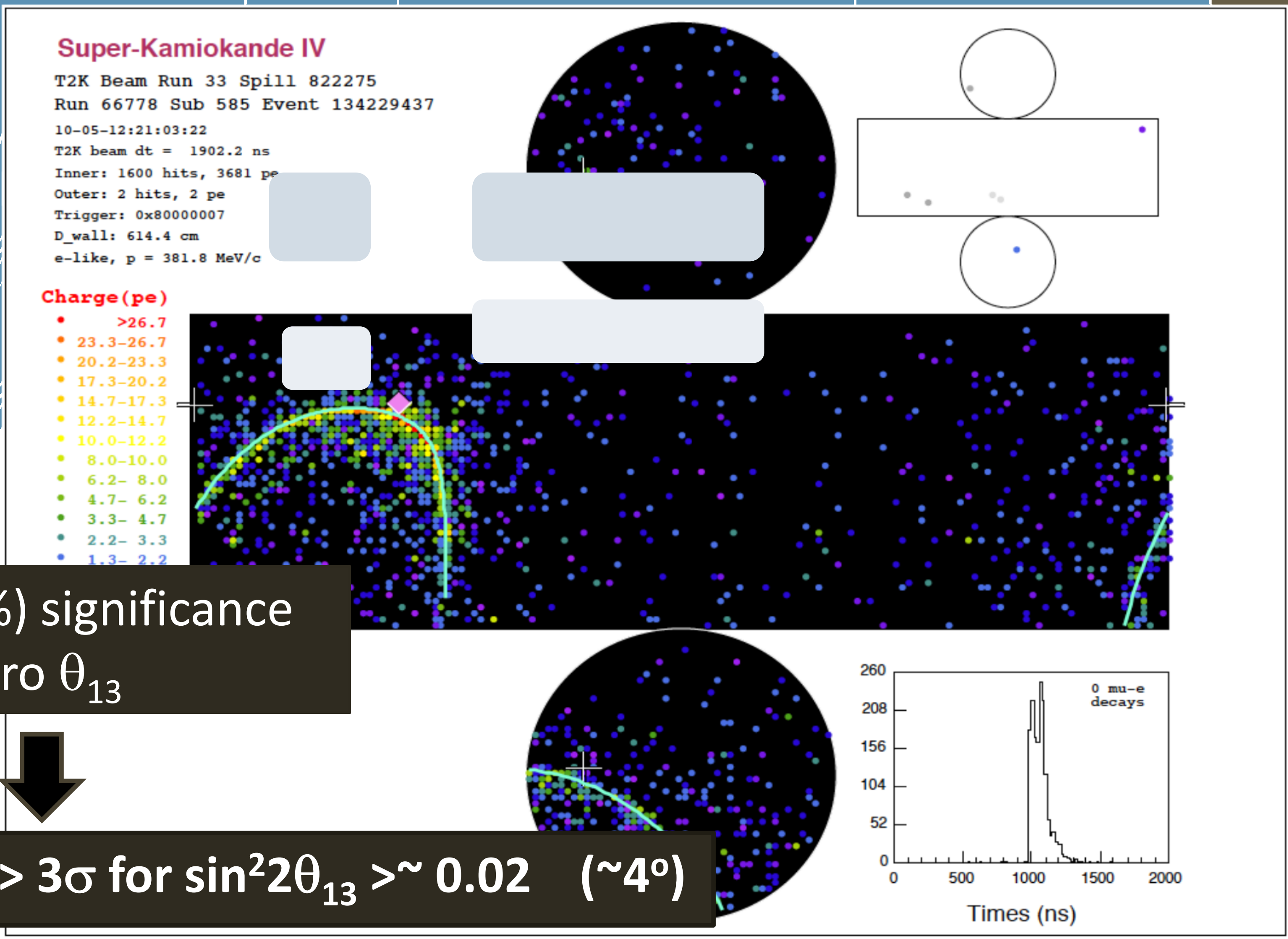


99% Back ground
rejection is necessary.

Particle identification using
ring shape & opening angle

T2K accumulated 2% of planned data(ν_μ beam) before the earthquake

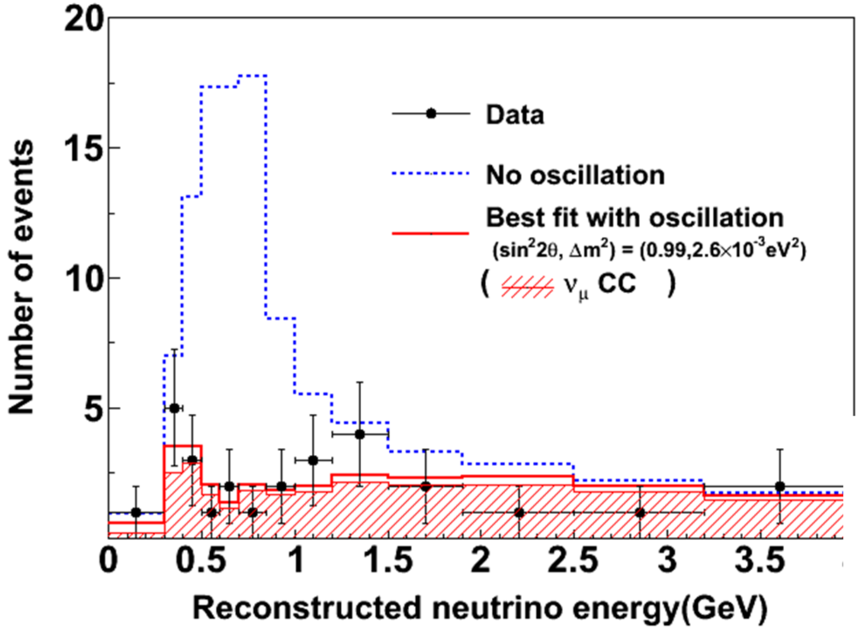
ν_μ –disap (θ_{23}) s
ν_e -dapp (θ_{13}) s



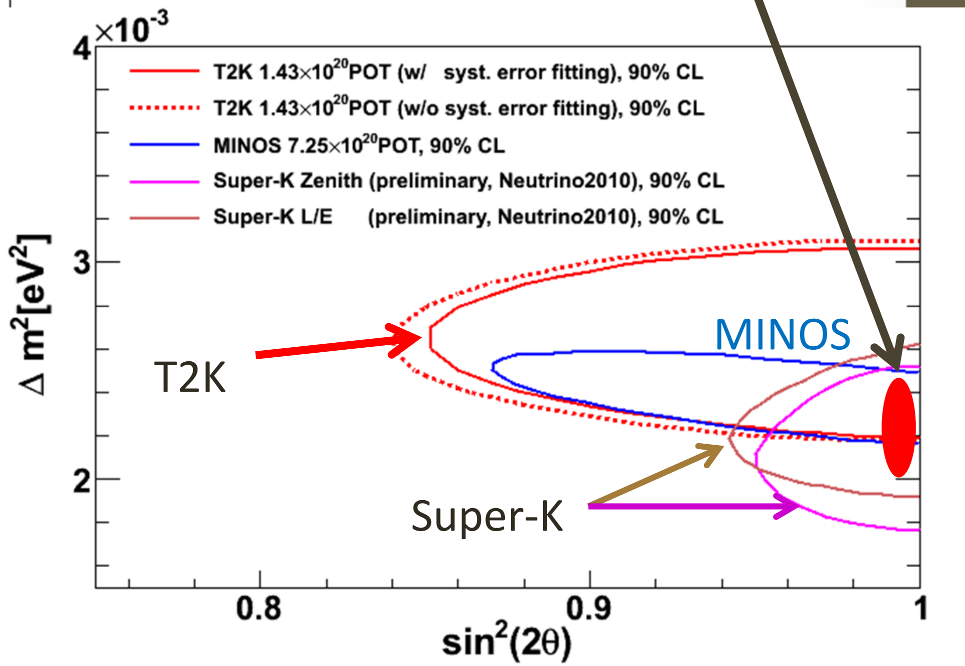
2.5σ (0.7%) significance for non-zero θ_{13}

T2K goal > 3σ for $\sin^2 2\theta_{13}$ >~ 0.02 (~4°)

T2K result θ_{23} and Δm^2_{23} (ν_μ disappearance)

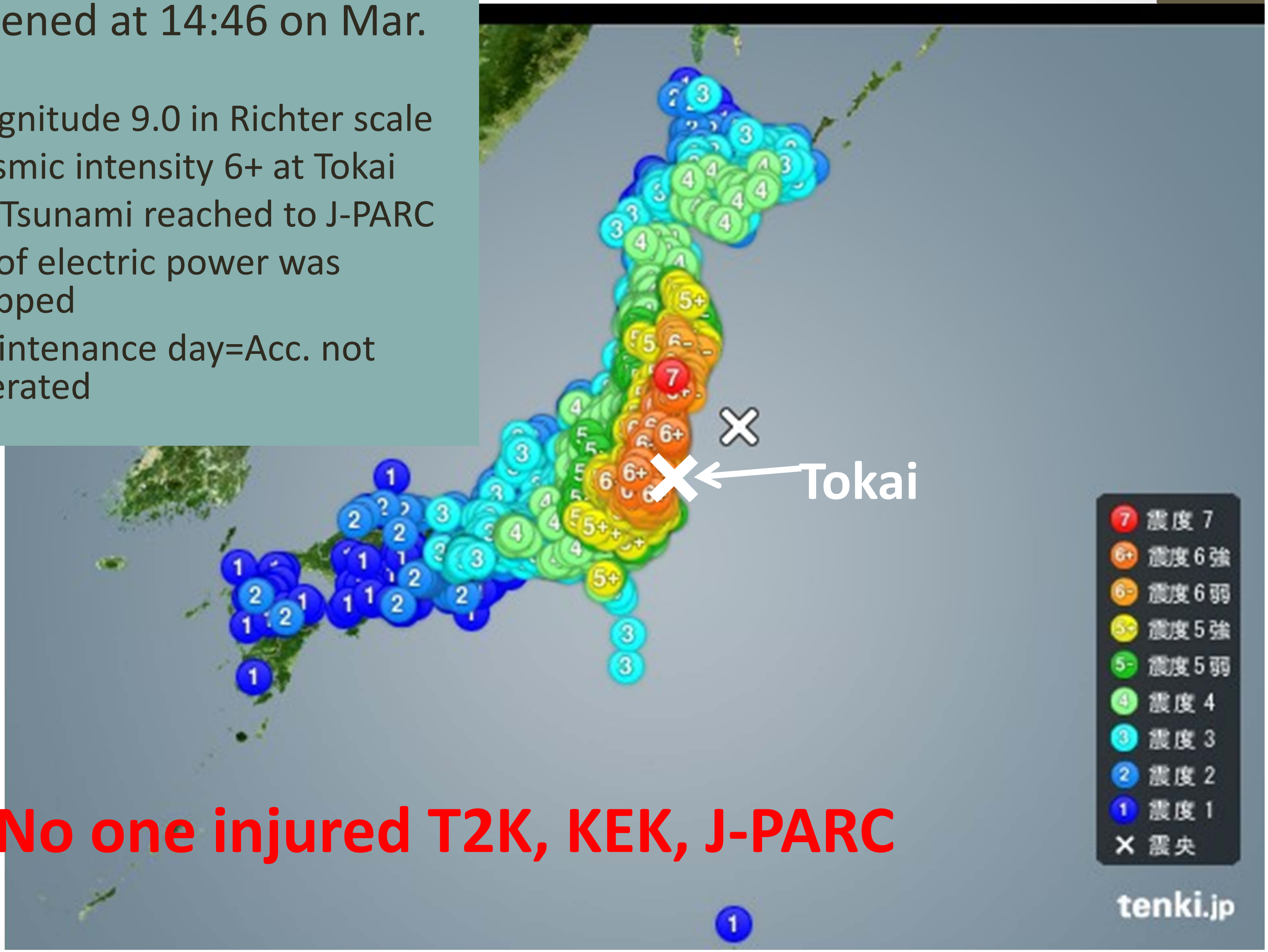


Goal : $\delta(\sin^2 2\theta_{23}) \sim 0.01$ ($\delta\theta \sim 3^o$)
$\delta(\Delta m^2_{23}) < 1 \times 10^{-4}$ [eV²]

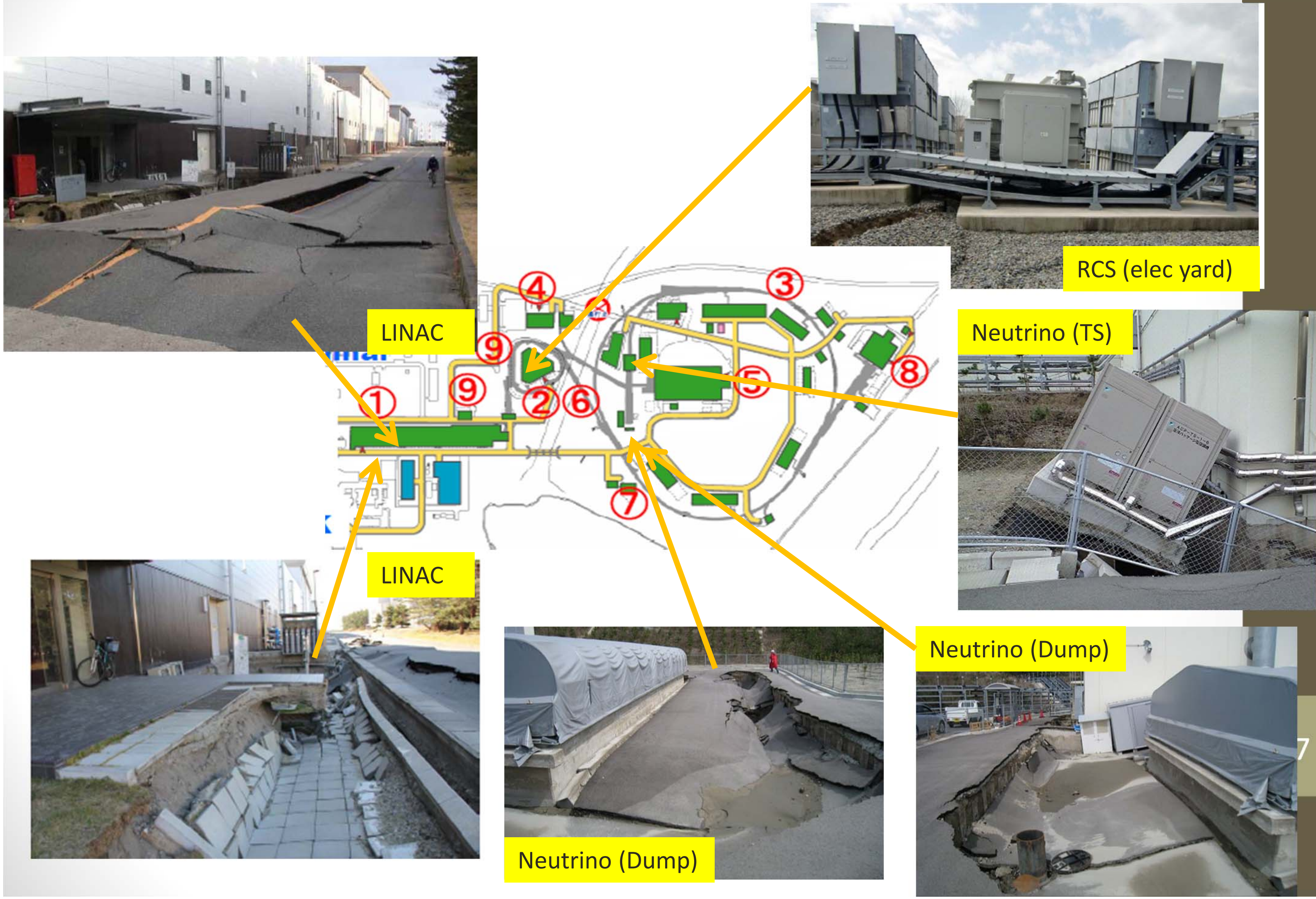


Earthquake on Mar. 11th

- Happened at 14:46 on Mar. 11th
  - Magnitude 9.0 in Richter scale
  - Seismic intensity 6+ at Tokai
  - No Tsunami reached to J-PARC
  - All of electric power was stopped
  - Maintenance day=Acc. not operated

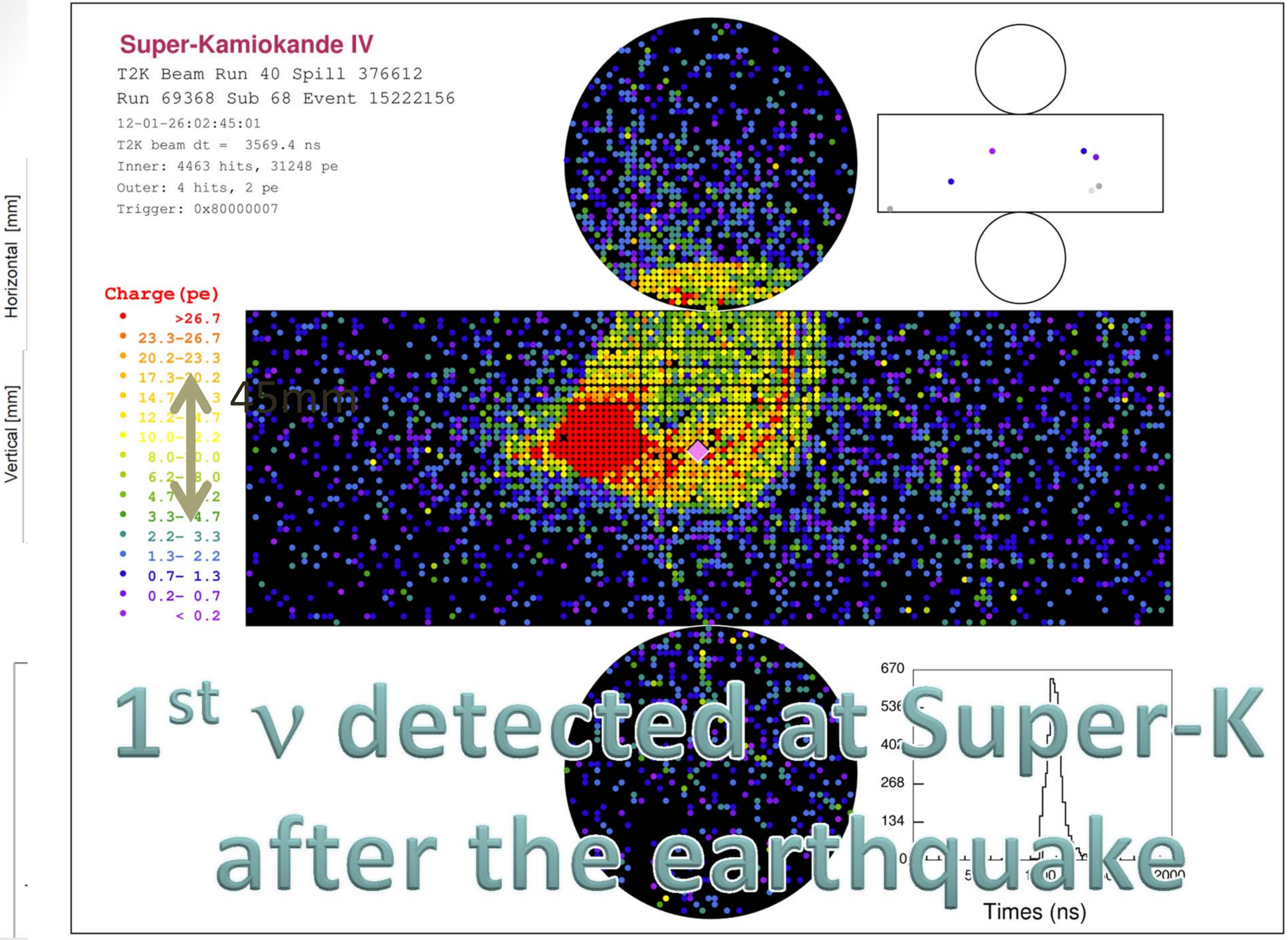


- **No one injured T2K, KEK, J-PARC**


LINAC
LINAC
RCS (elec yard)
Neutrino (TS)
Neutrino (Dump)
Neutrino (Dump)

Being rapidly repaired

1^{st} ν detected at Super-K after the earthquake



Next – CP violation and origin of matter dominant universe-

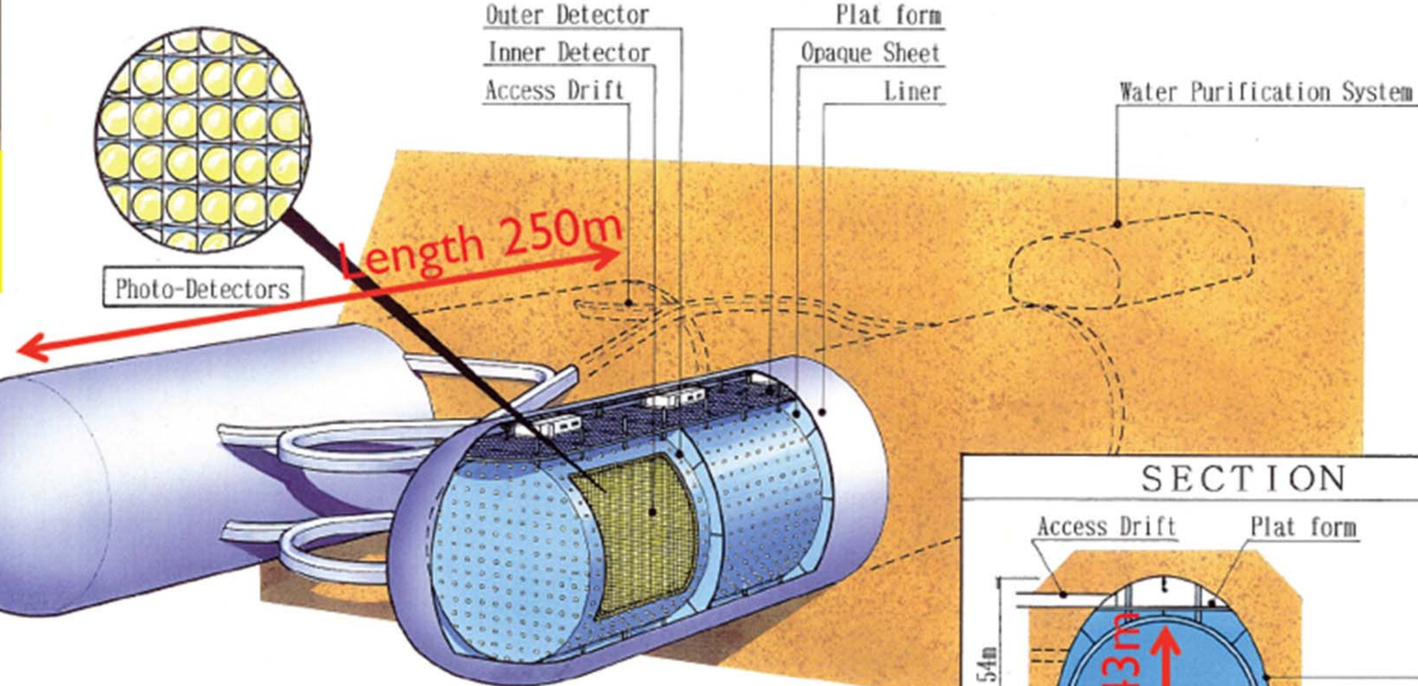
- CP violation
  - ✓ Fundamental understanding of the origin of lepton mass and mixing
  - ✓ First step to understand the matter dominant universe
- Mass hierarchy
  - ✓ Fundamental understanding of the origin of lepton mass and mixing
  - ✓ Inverted hierarchy is desirable for the discovery of neutrinoless double-beta decay $\rightarrow$ Proof Majorana neutrino and See-Saw mechanism

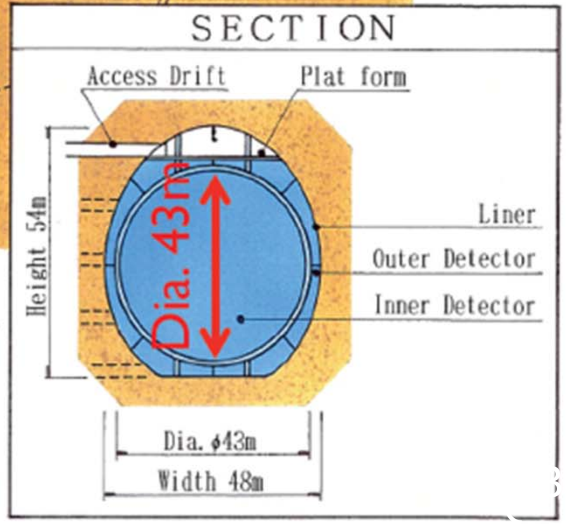
$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \approx \frac{\Delta m_{12}^2 L}{4E_\nu} \bullet \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \bullet \sin\delta$$

$$\approx 0.046 \times \frac{\sin\delta}{\sin\theta_{13}} \quad @\text{oscillation maximum}$$

Need >100 statistics

Hyper-Kamimokande project





Baseline design

- 1Mton total volume, twin cavity
- **~0.6Mton** fiducial volume
- Photo coverage 20% (1/2 x SK)
- 20 inch PMT x 102,000

Aiming to start ~2020

Summary

The mixing between flavor and mass can be a link among Hierarchies:
Current world and world at Grand Unified Scale (~10^{16} GeV?)

- How close to maximal mixing is θ_{23}?
- How small is θ_{13}?

T2K and reactor neutrino experiments start to answer.

CP violation in the lepton sector is a kind of 'required condition' for good-bet theories explaining our matter-dominant universe.

⇩

It is within our reach!

T2K goal > 3σ for $\sin^2 2\theta_{13}$ >~ 0.02 (~4^o)

$\delta(\sin^2 2\theta_{23}) \sim 0.01$ ($\delta\theta \sim 3^o$)

Hyper-K CP violation if δ(CP)>~20^o