Neutrino Oscillations

– current status and prospects

of accelerator-based long-baseline experiment

Atsuko K. Ichikawa, *Tohoku University*

The way we distinguish neutrinos - It is two sides of coins-

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.

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.

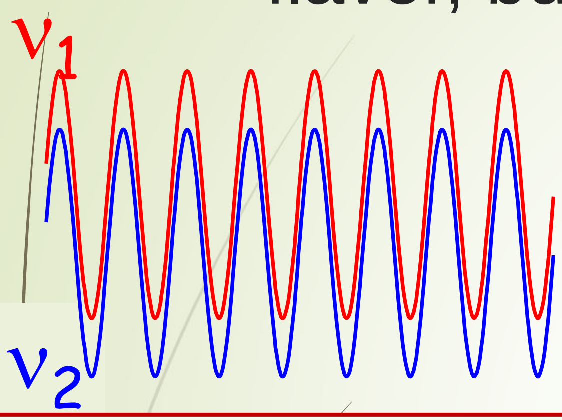
IF NEUTRINOS HAVE MASSES, there is no need for three types to be mass eigenstates.

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

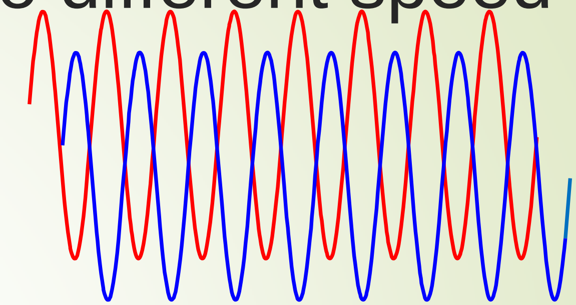
Same thing is happening for quarks. (e.g. Cabibbo angle)

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

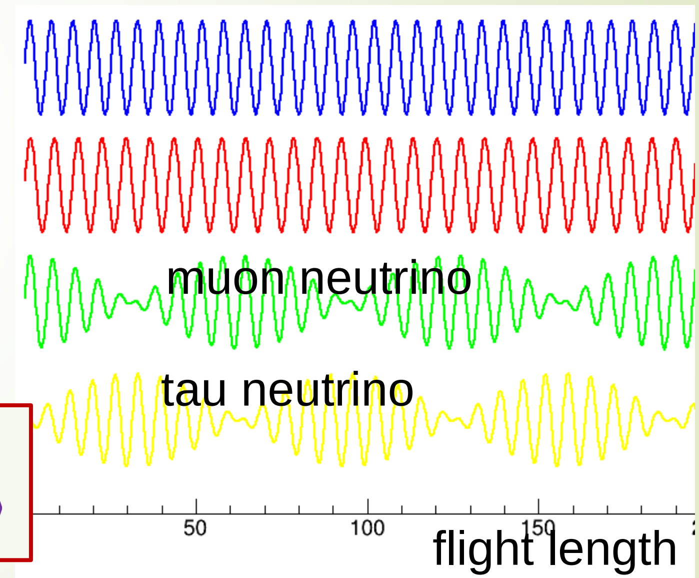


Traveling distance L



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

Neutrino Oscillation!

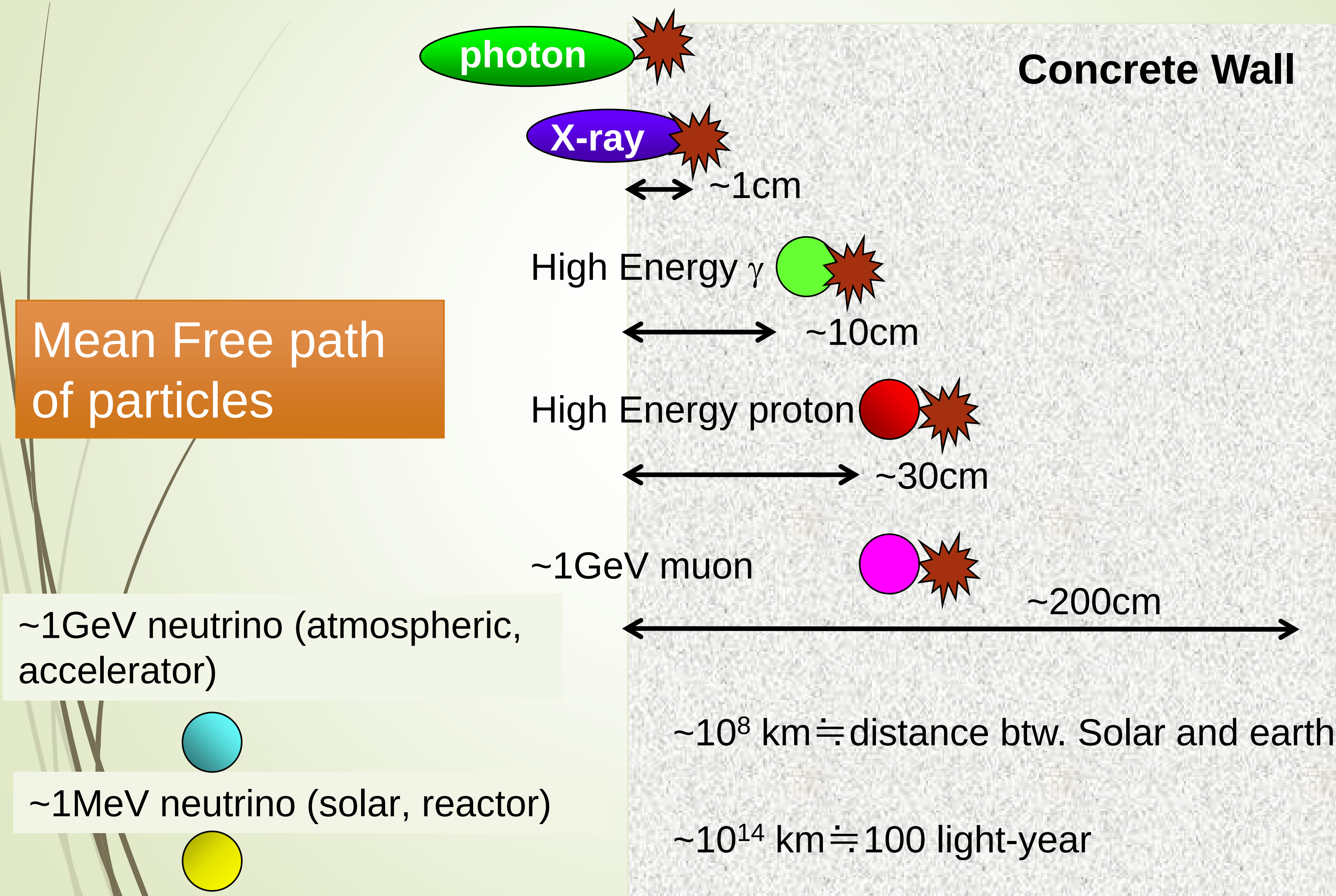


$$|\nu_1\rangle e^{-i\frac{m_1^2}{2E}L}\cos\theta + |\nu_2\rangle e^{-i\frac{m_1^2}{2E}L}\sin\theta \Rightarrow |\nu_\beta\rangle$$

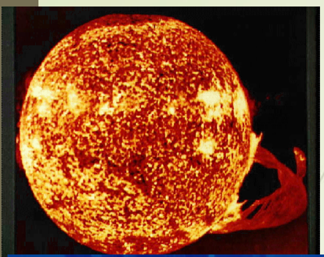
$$P(\nu_\alpha \rightarrow \nu_\beta) = \left|\langle \nu_\beta | \nu_\alpha \rangle\right|^2 = \sin^2 2\theta \sin^2(\Delta m^2 \frac{L}{4E})$$

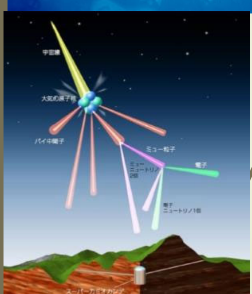
Neutrinos DO interact, but ....

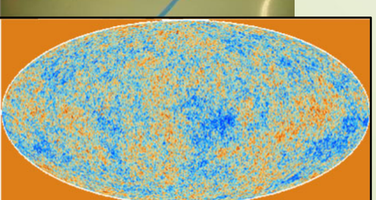
Mean Free path of particles



What we know about neutrino mass







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

- ✓ Solar and reactor neutrino

$$\Delta m_{21}^2 \equiv m_2^2 - m_1^2 = 7.53 \times 10^{-5}\ eV^2$$

- ✓ atmospheric, accelerator and reactor neutrino

$$|\Delta m_{32}^2| \equiv |m_3^2 - m_2^2| = 2.5 \times 10^{-3}\ eV^2$$

- ✓ Cosmic microwave background and Baryon Acoustic oscillations

$$\sum_j m_j < 0.180\ eV\ (95\%\ \text{CL})$$

↓

- ✓ If $m_1 < m_2 < m_3$ (normal mass order)

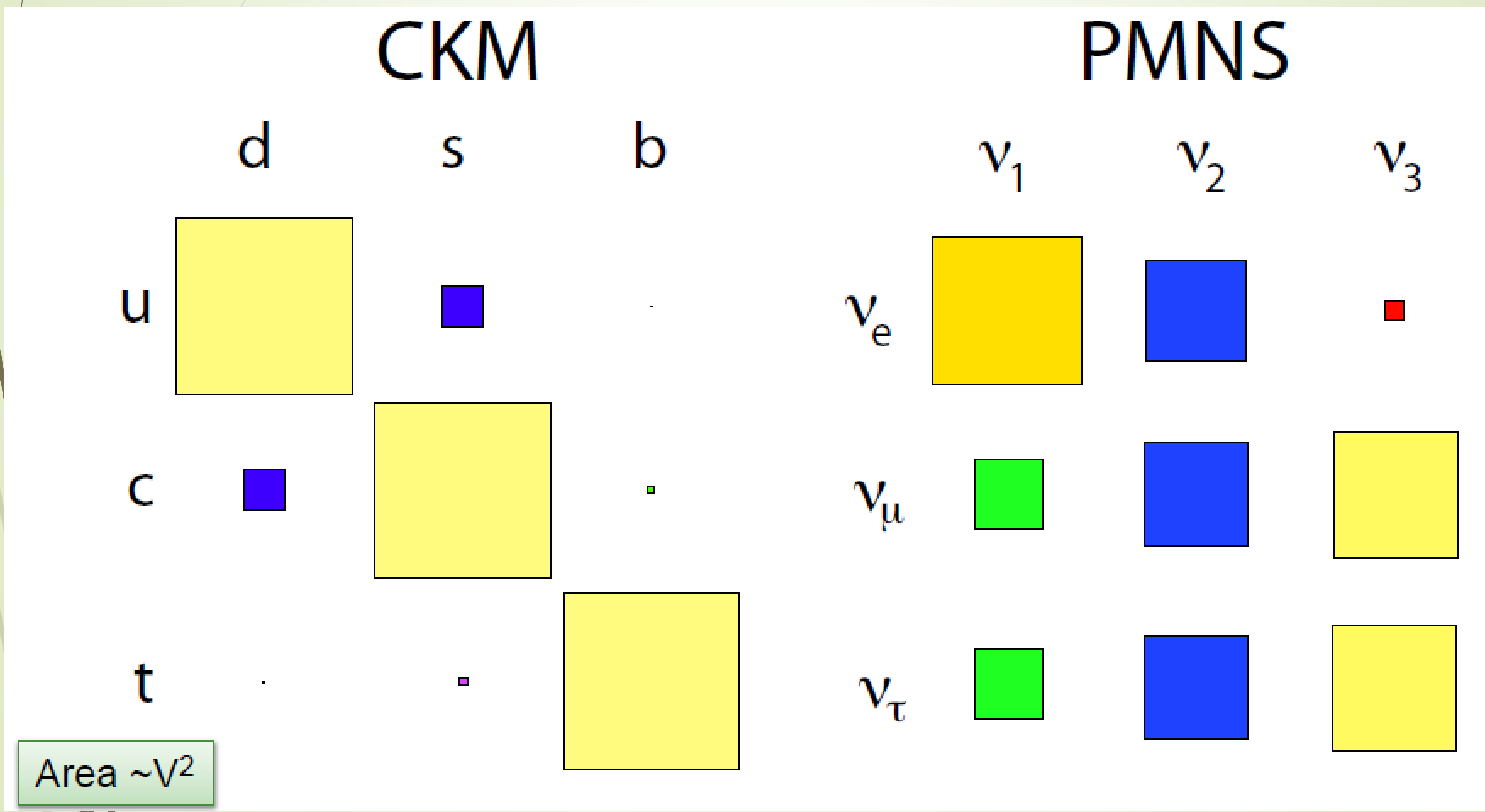
$$m_1 = 0\sim54\text{meV}, m_2 = 9\sim55\text{meV}, m_3 = 51\sim74\ \text{meV}$$

- ✓ If $m_3 < m_1 < m_2$ (inverted mass order)

$$m_1 = 50\sim72\text{meV}, m_2 = 57\sim67\text{meV}, m_3 = 0\sim45\text{meV}$$

And,

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



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

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

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

And GUT generally prefer normal mass ordering.

Important feature of mixing btw. Flavor and Mass in Three Generations

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

Kobayashi-Maskawa theory

Mixing with >= 3 types can have imaginary components.

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

Change the phase of the wavefunction oppositely for particle and antiparticle.
⇒ **CP violation!**

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

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

There is one big mystery :

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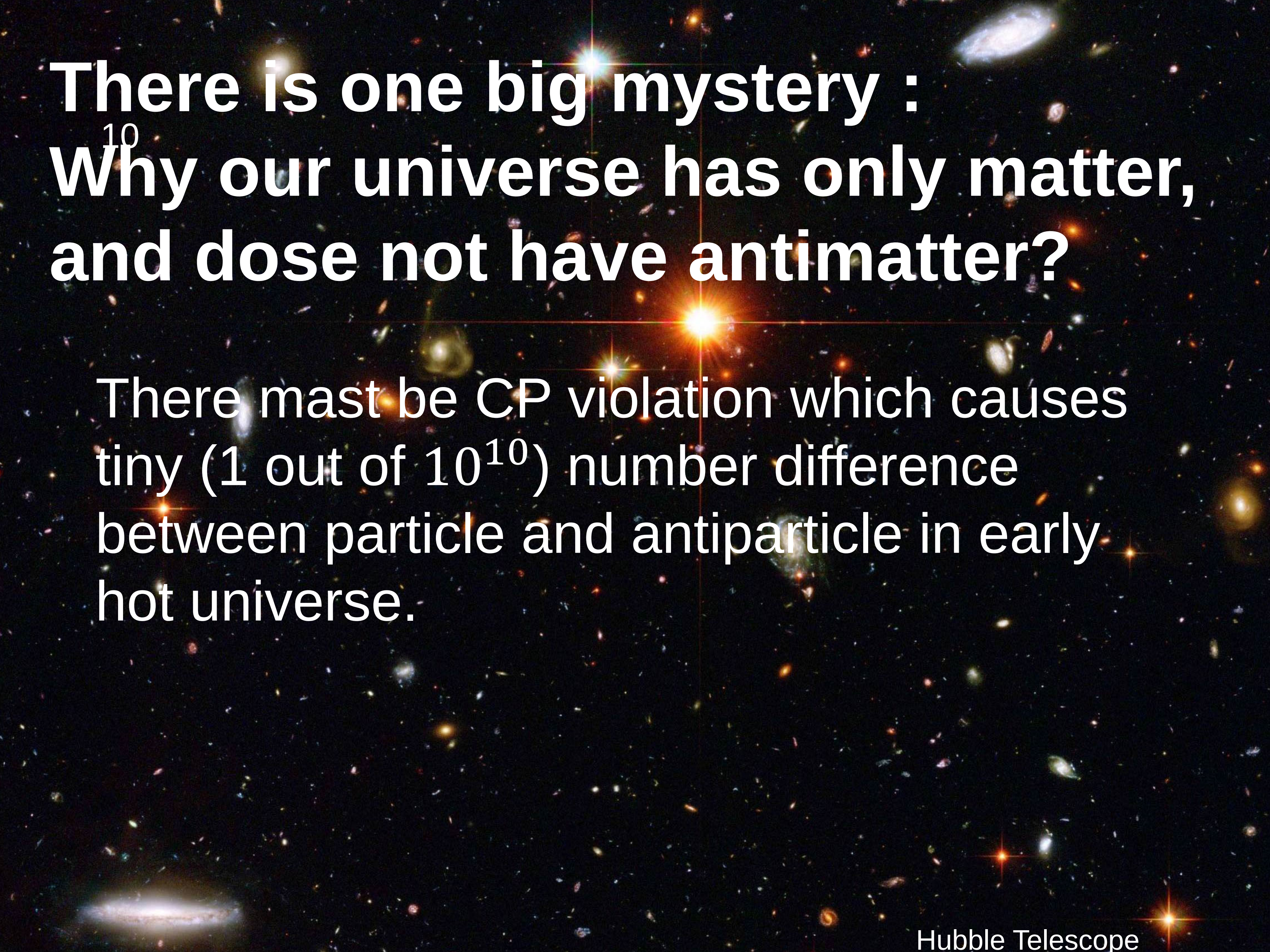
Why our universe has only matter, and dose not have antimatter?

There mast be CP violation which causes tiny (1 out of 10^{10}) number difference between particle and antiparticle in early hot universe.



Hubble Telescope

Origin of Matter-Antimatter asymmetry in Universe?

- Quark : $\delta_{CP}^{CKM} \sim 60° \sim 70°$

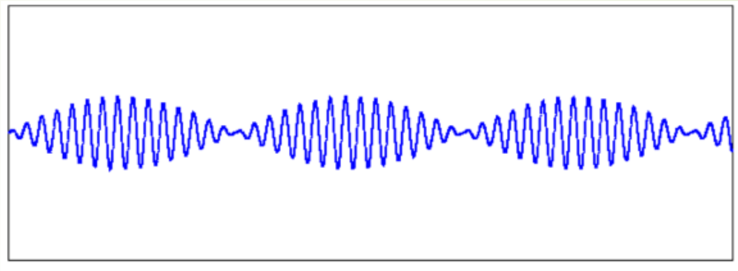
  looks large, but cannot explain matter-dominant universe.
- Strong CP $\theta < 10^{-10}$
- Lepton case $\delta_{CP}^{MNS} \sim ?$
- δ_{CP} is dependent on definition.

  Jarlskog Invariant shows size of CP violation effect.

  $$J_{CP} \equiv Im\left(U_{\mu 3} U_{e3}^{*} U_{e2} U_{\mu 2}^{*}\right) = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta_{CP}$$
- Quark $\boldsymbol{J_{CP}^{CKM} \approx 3 \times 10^{-5}}$
- Lepton $\boldsymbol{J_{CP}^{PMNS} \approx 0.033\, sin\, \delta_{CP}}$
- CPV in neutrino can be much larger than Quark's
- There are a number of theoretical models which explain the matter-antimatter asymmetry in universe by **this** CPV.

Neutrino oscillation of three states

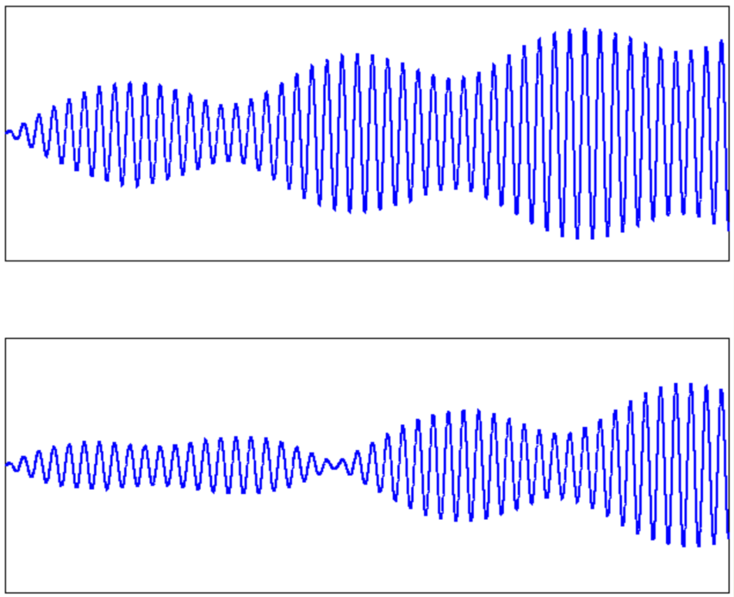
Two neutrinos case



Three neutrinos case

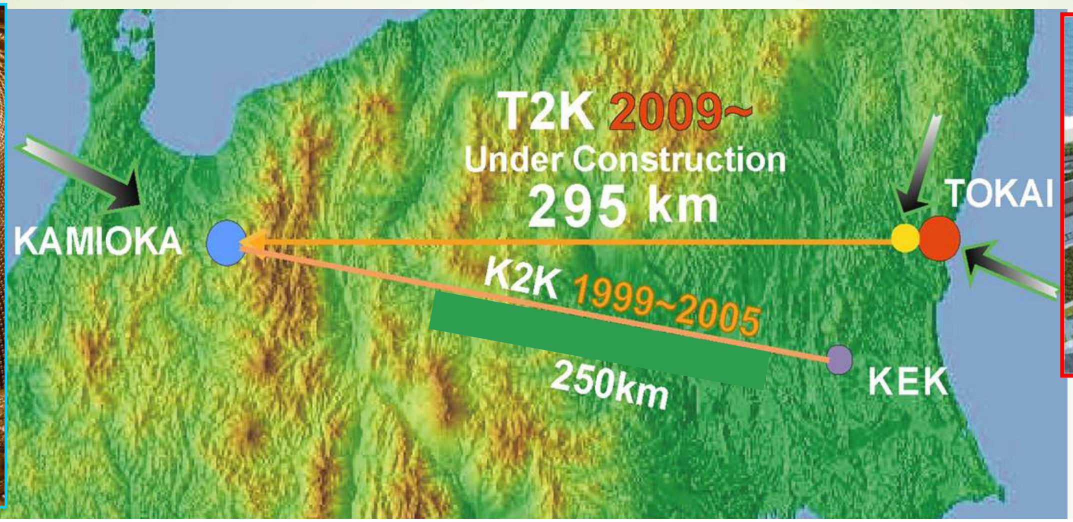
neutrino

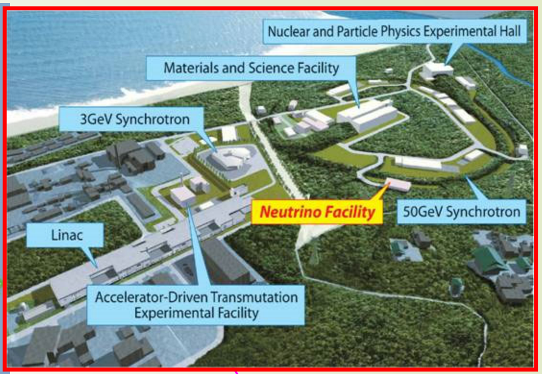
antineutrino



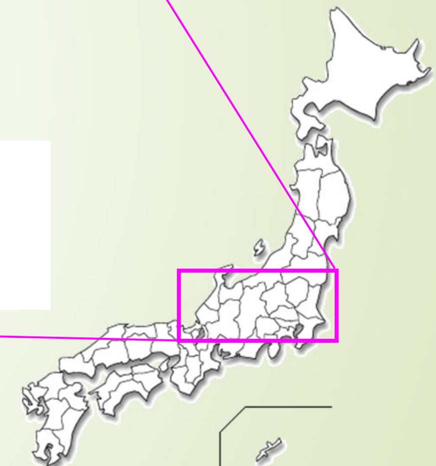
Depending on the value of δ_{CP}, neutrino and antineutrino oscillate differently!

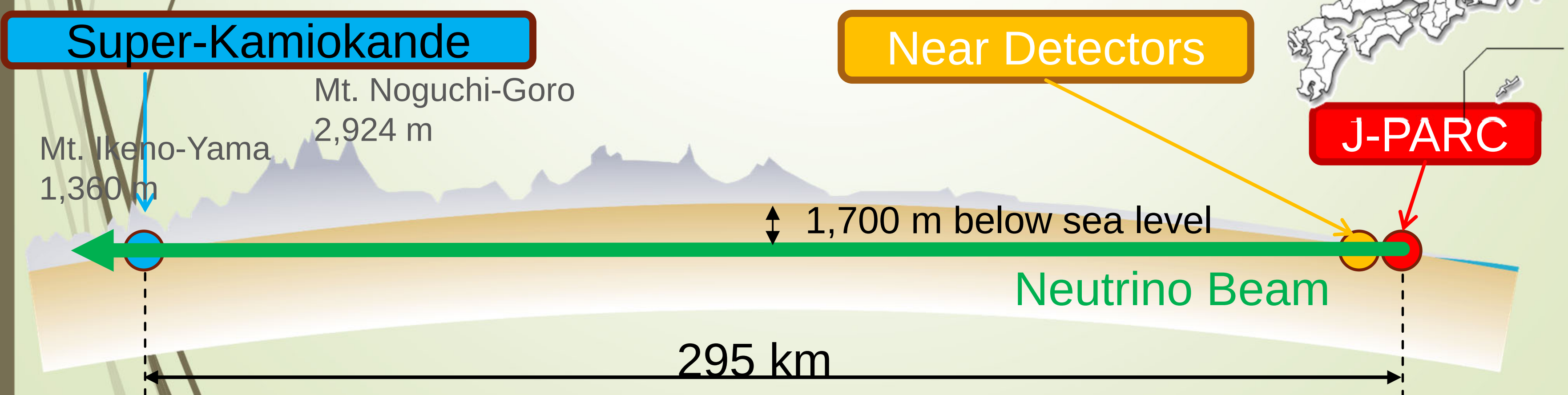
T2K (Tokai to Kamioka) Long Baseline experiment



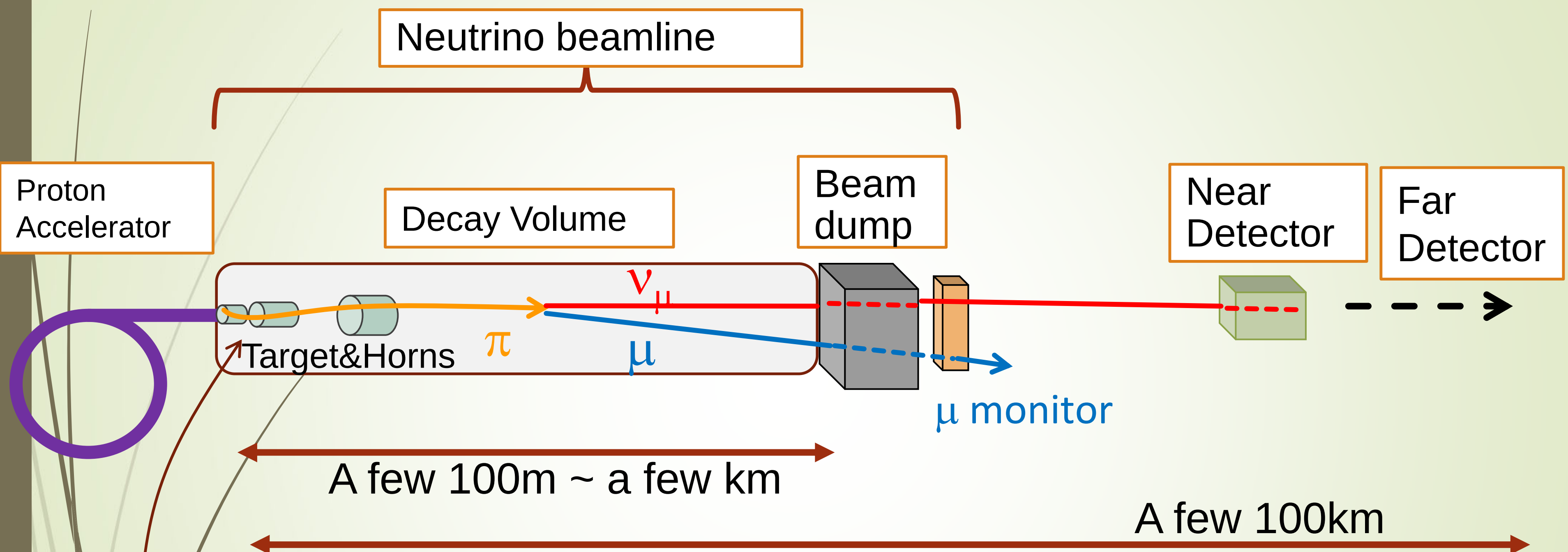


~1ν/cm^2/s at T2K Far detector(295km away) @750kW proton beam power)





Components of the Long Baseline Neutrino Experiment

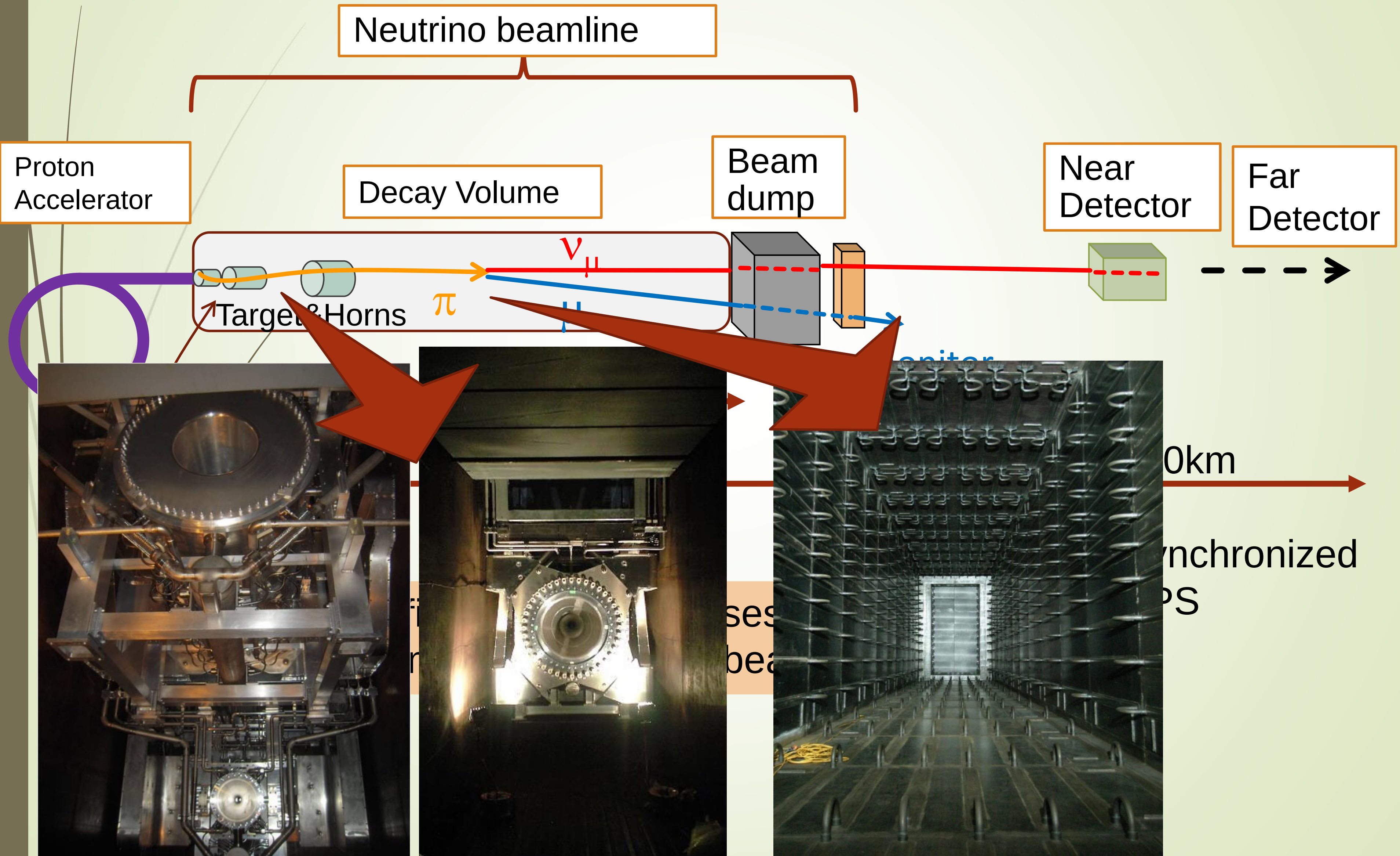


Toroidal magnetic field by `horn' focuses

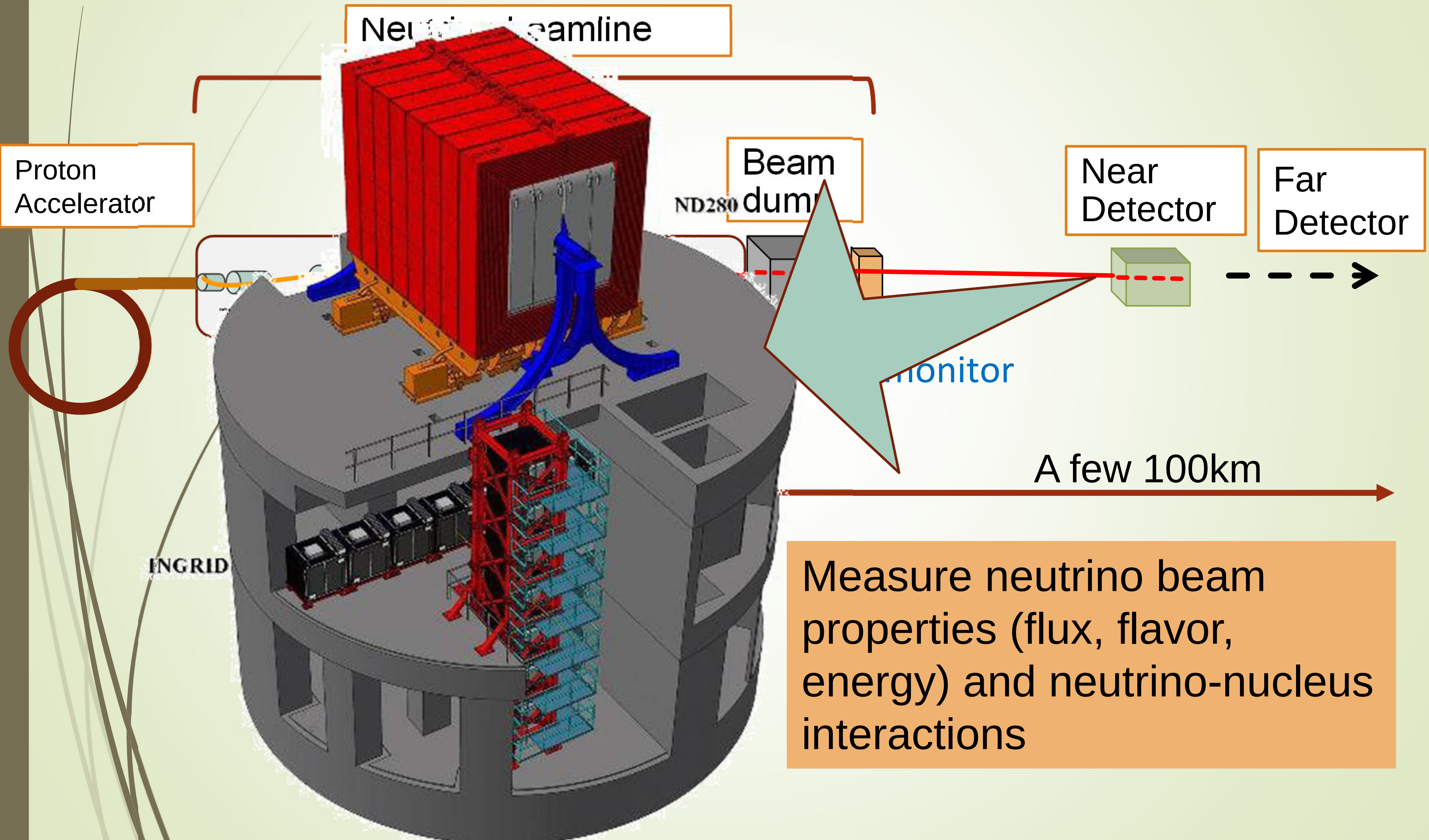
$\pi^+ \rightarrow \nu_\mu$ beam or $\pi^- \rightarrow \bar{\nu}_\mu$ beam

timing synchronized using GPS

Components of the Long Baseline Neutrino Experiment

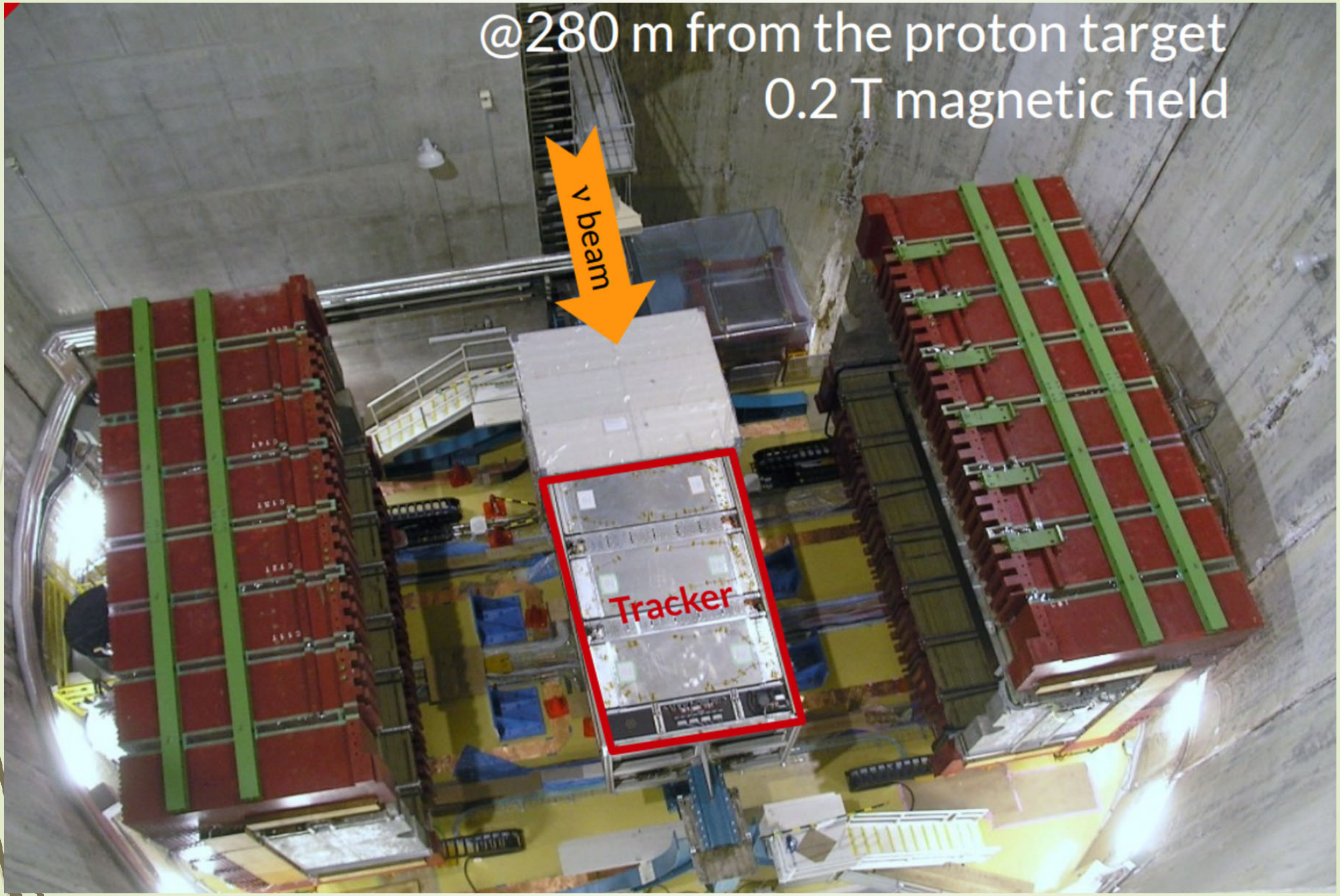


Components of the Long Baseline Neutrino Experiment

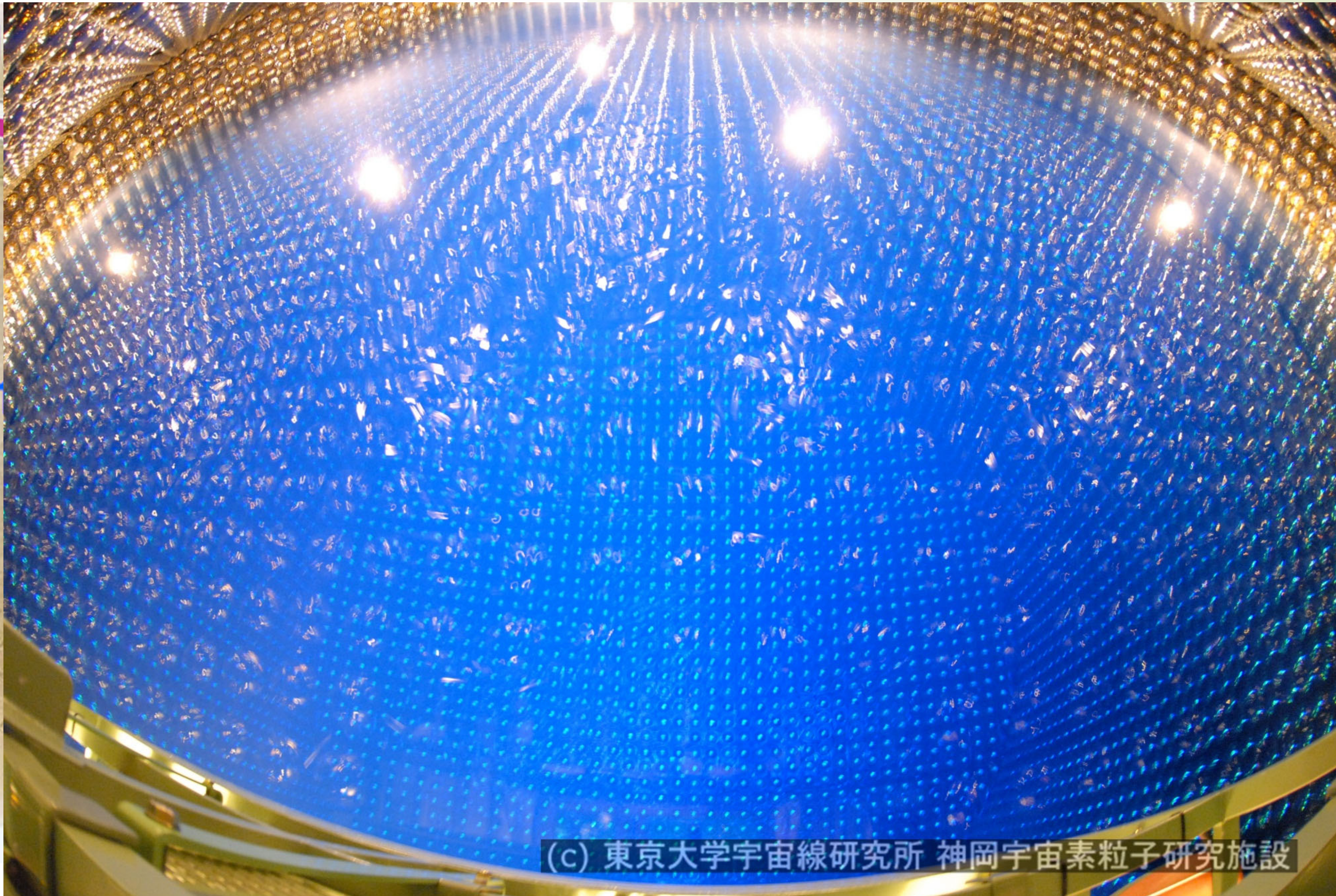


Measure neutrino beam properties (flux, flavor, energy) and neutrino-nucleus interactions

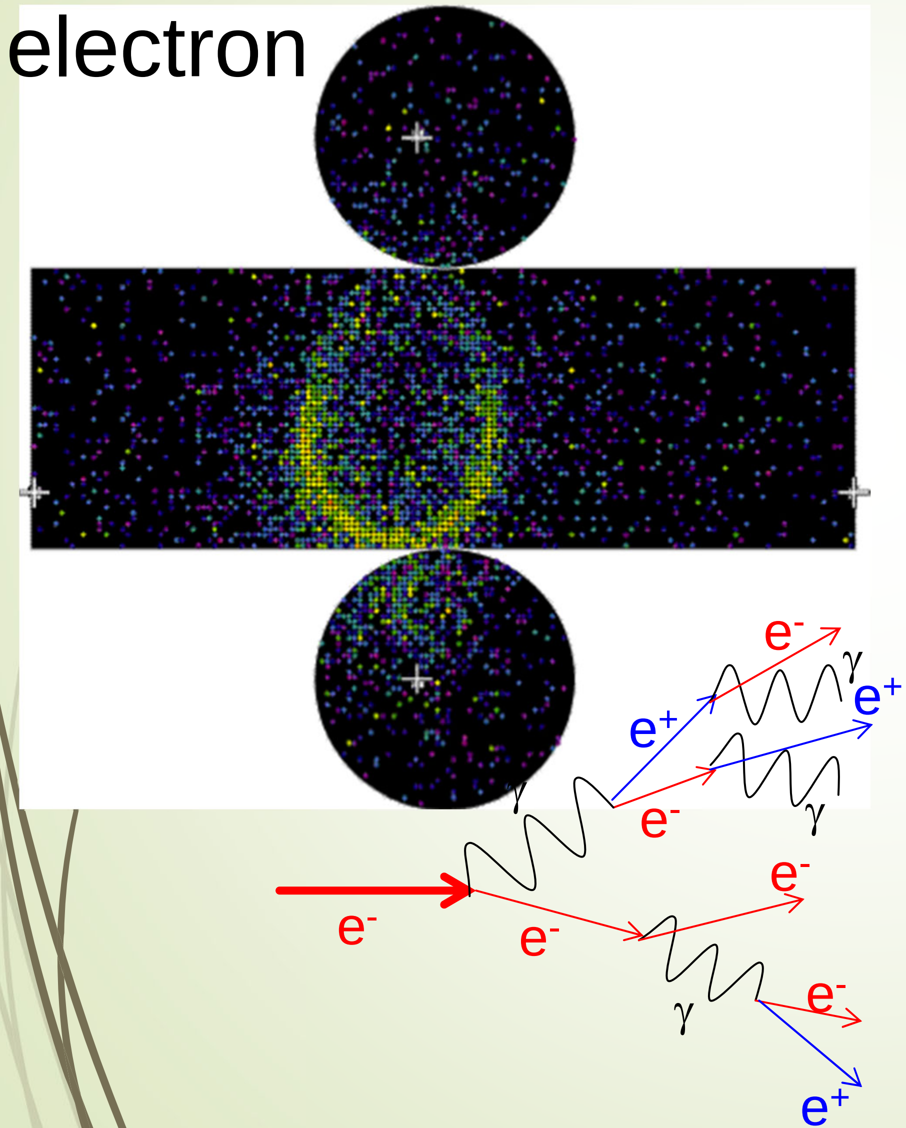
Off-axis near detector: ND280

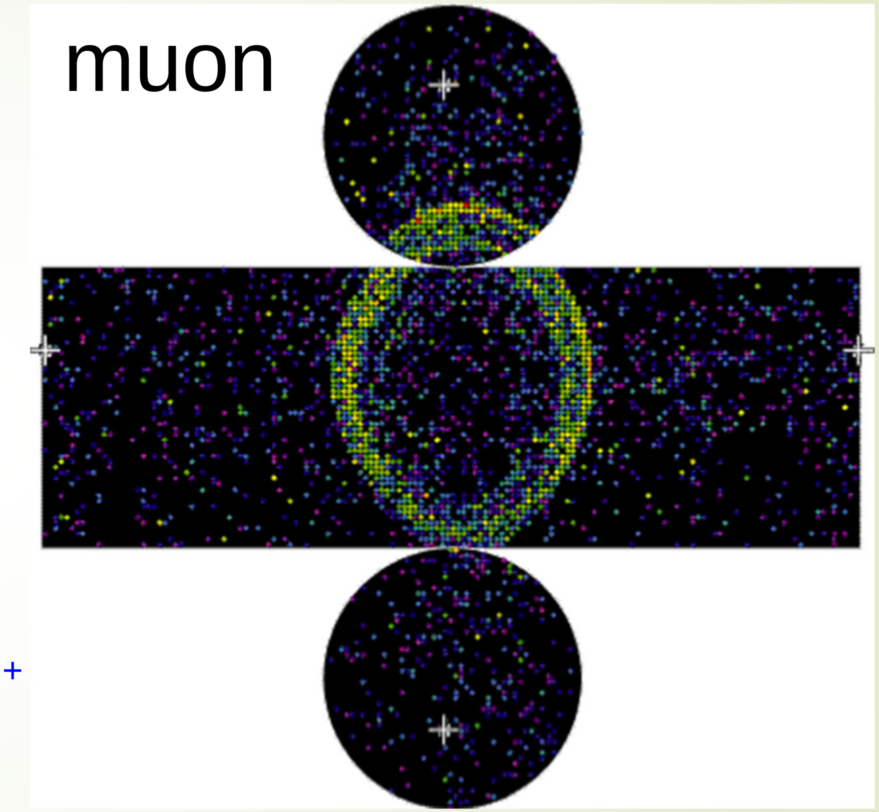


Super Kamiokande



SK can be distinguish electron and muon

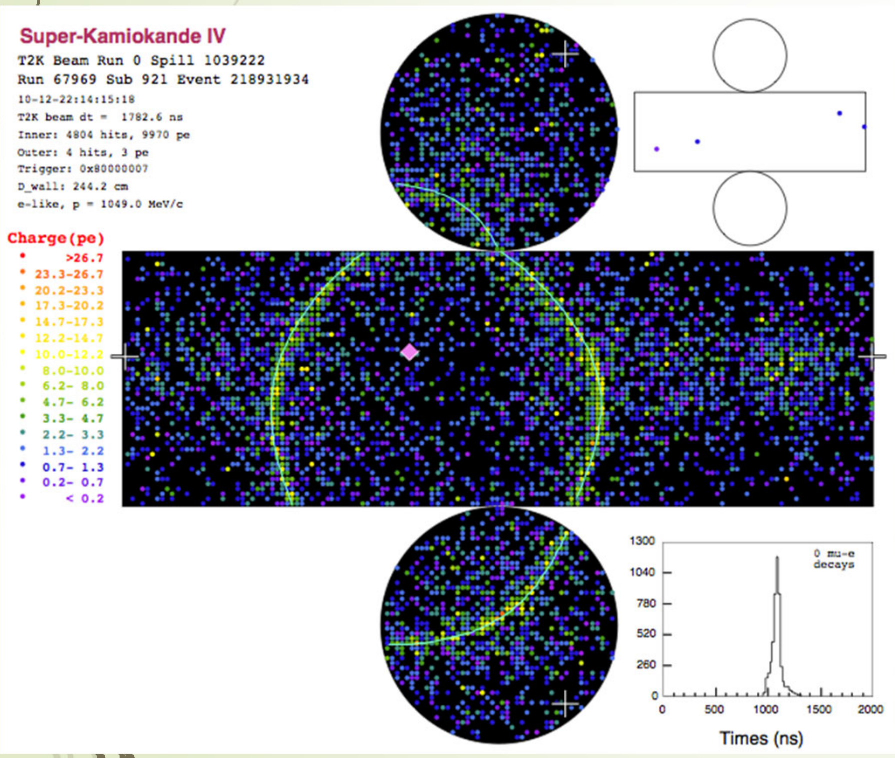




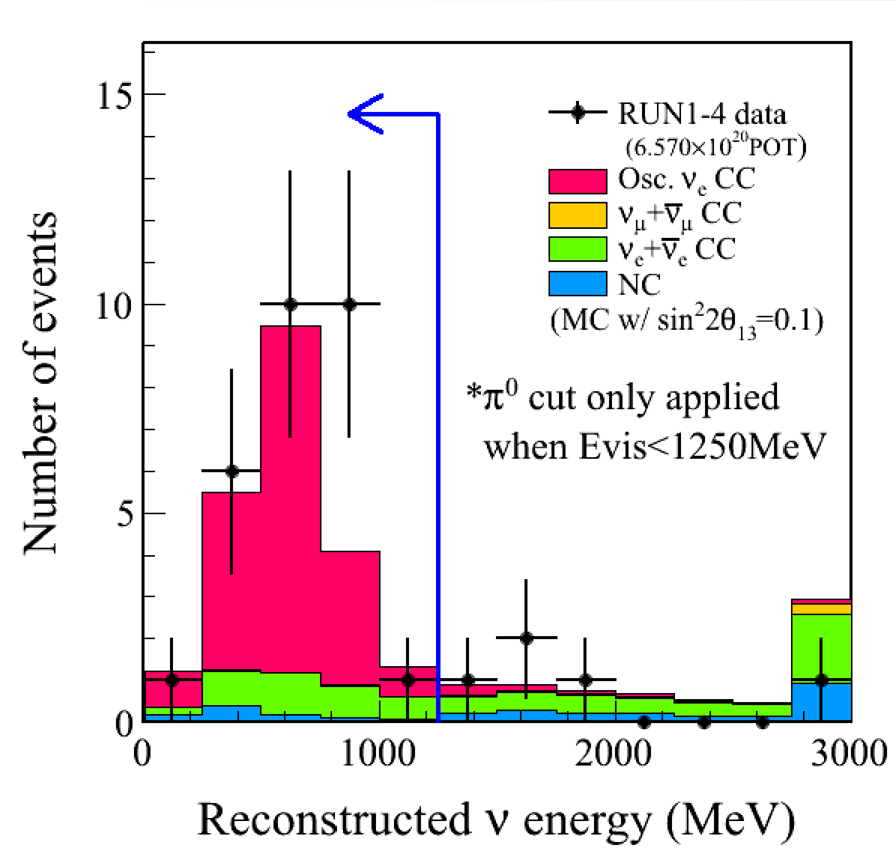
SK MC event display

ν_e appearance

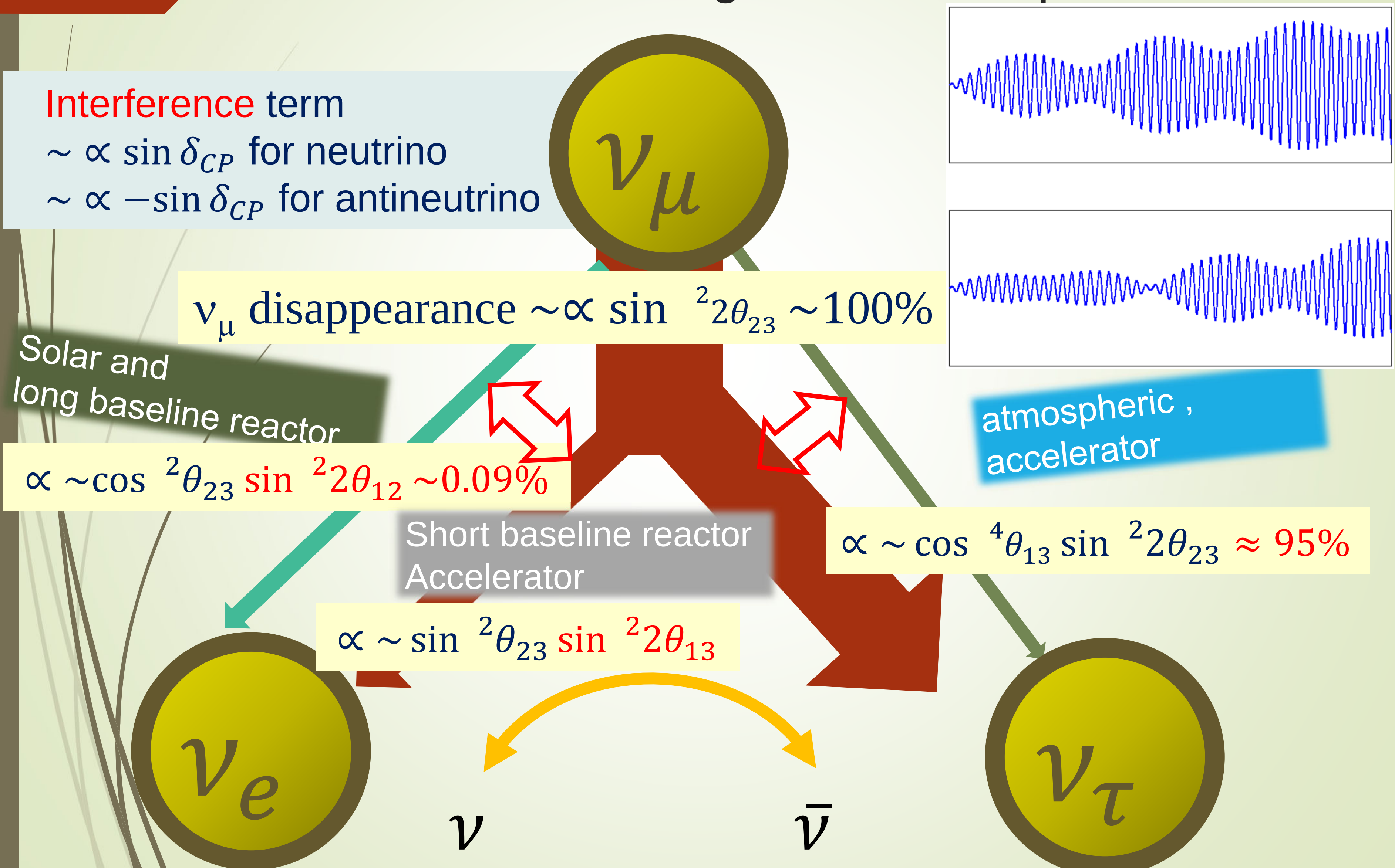
2013 T2K observed 28 events over 4.9bkgs 7.3σ significance.
Also first confirmation of ‘appearance’ w/ >5σ significance.



Example of ν_e candidate event

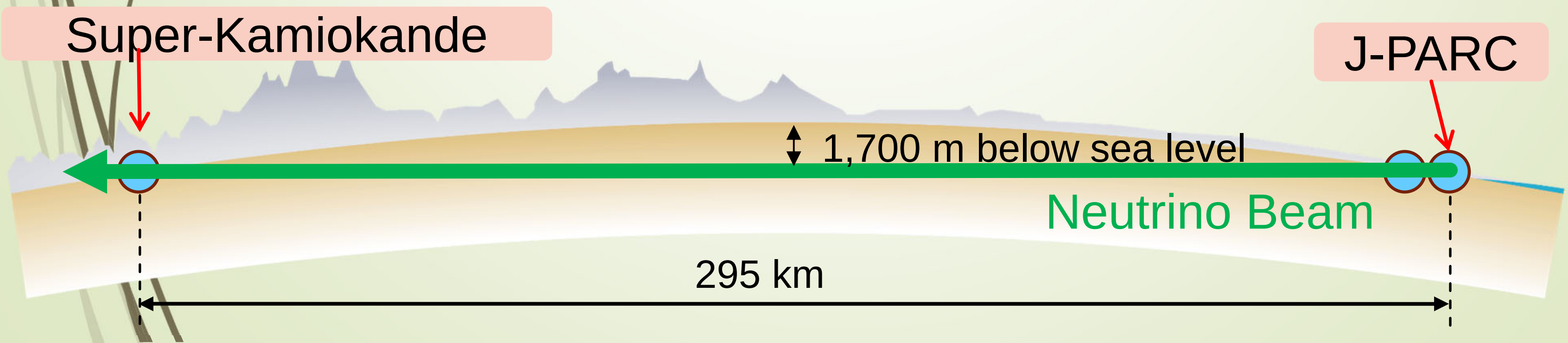


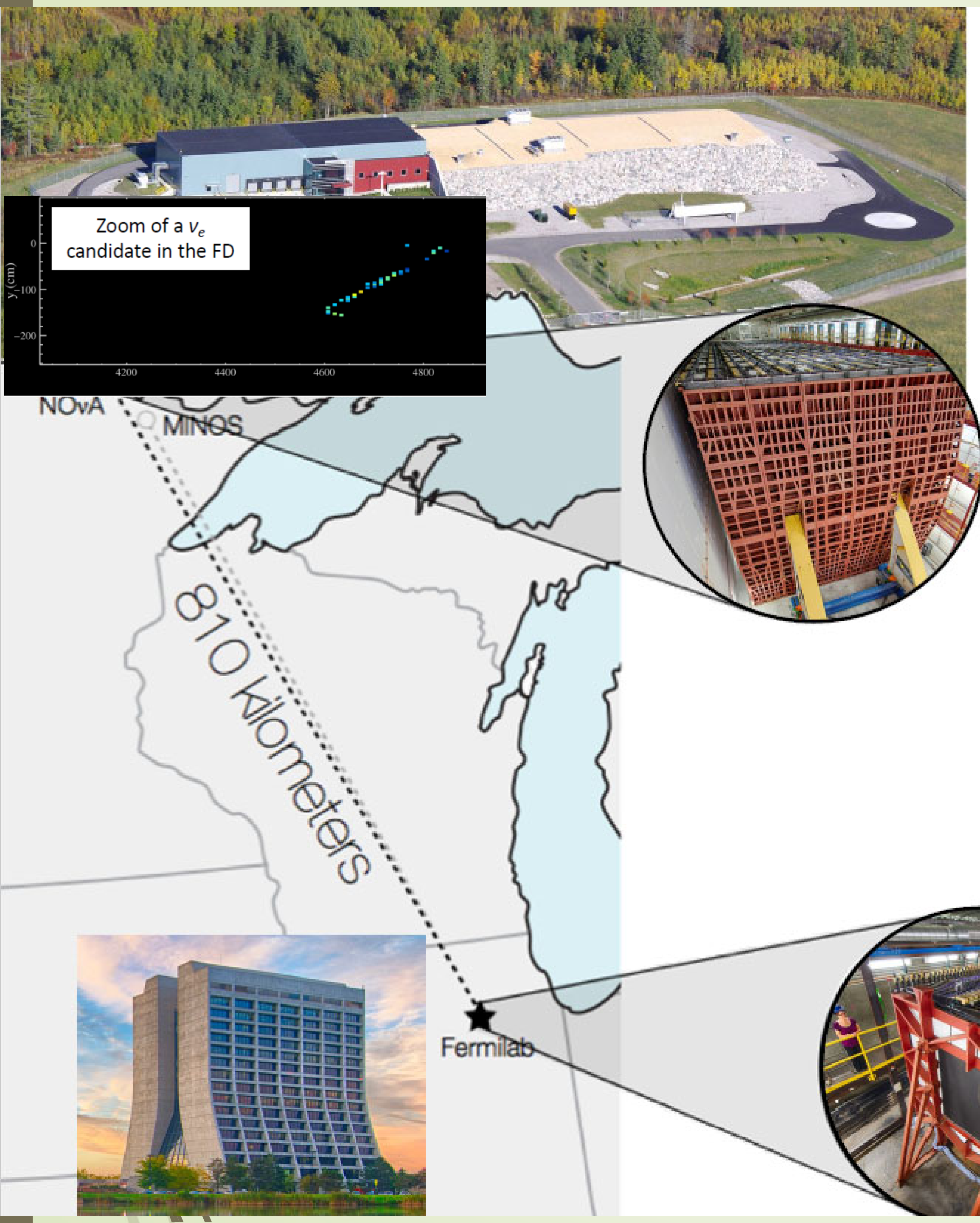
Oscillations peculiar to the Acc.-based long baseline experiment



Some complexity from matter effect "Earth is not symmetric about flavor nor CP"

- Neutrino feels potential from matter → affect oscillation
  - Difference between ν_e and ν_μ/ν_τ
    - No muon nor tau inside Earth
  - Difference between ν and anti-ν
    - No antimatter inside Earth
    - oscillation prob. is different for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$!
- Matter effect is larger for higher E or Longer L
- Effect is opposite depending on mass order
  - normal order $m_1 < m_2 < m_3$ vs inverted order $m_3 < m_1 < m_2$



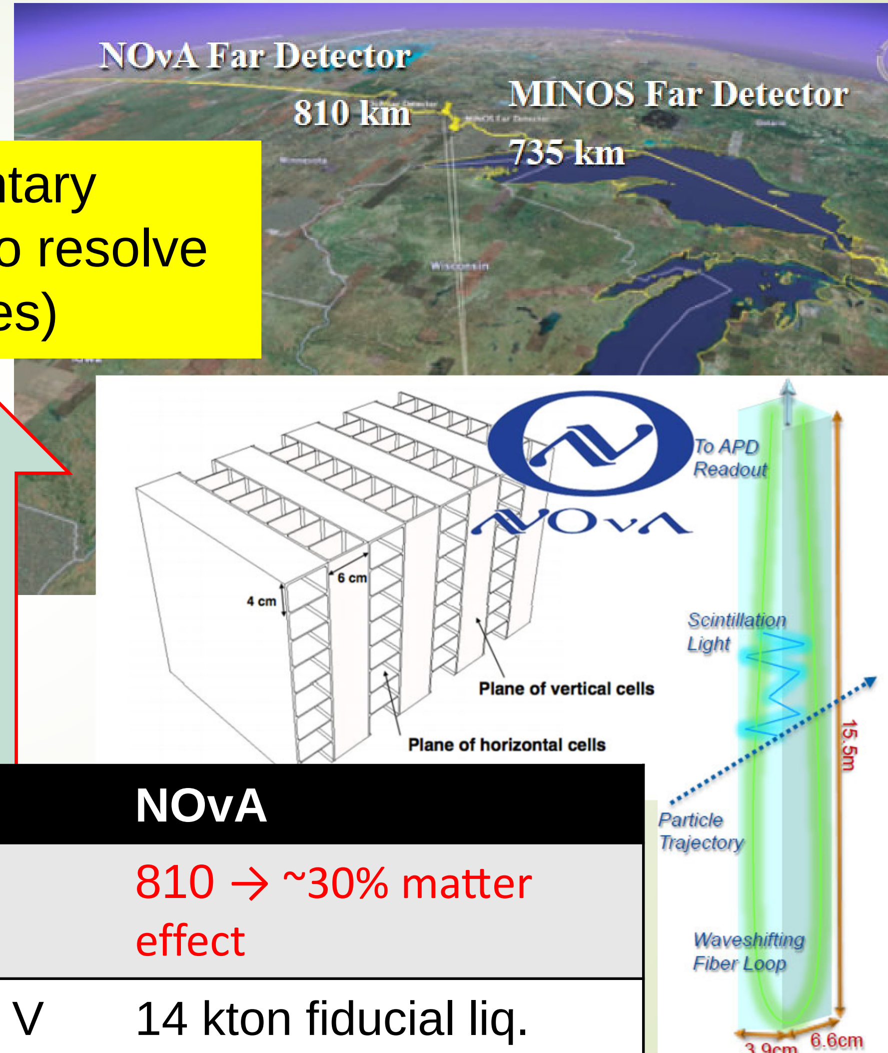


The NOvA Experiment

- Long-baseline neutrino oscillation experiment
- NuMI beam: ν_μ or $\bar{\nu}_\mu$
- 2 functionally identical, tracking calorimeter detectors
  - Near: 300 T underground
  - Far: 14 kT on the surface
  - Placed off-axis to produce a narrow-band spectrum
- 810 km baseline
  - Longest baseline of current experiments.

Slide from A.Himmel, neutrino2020

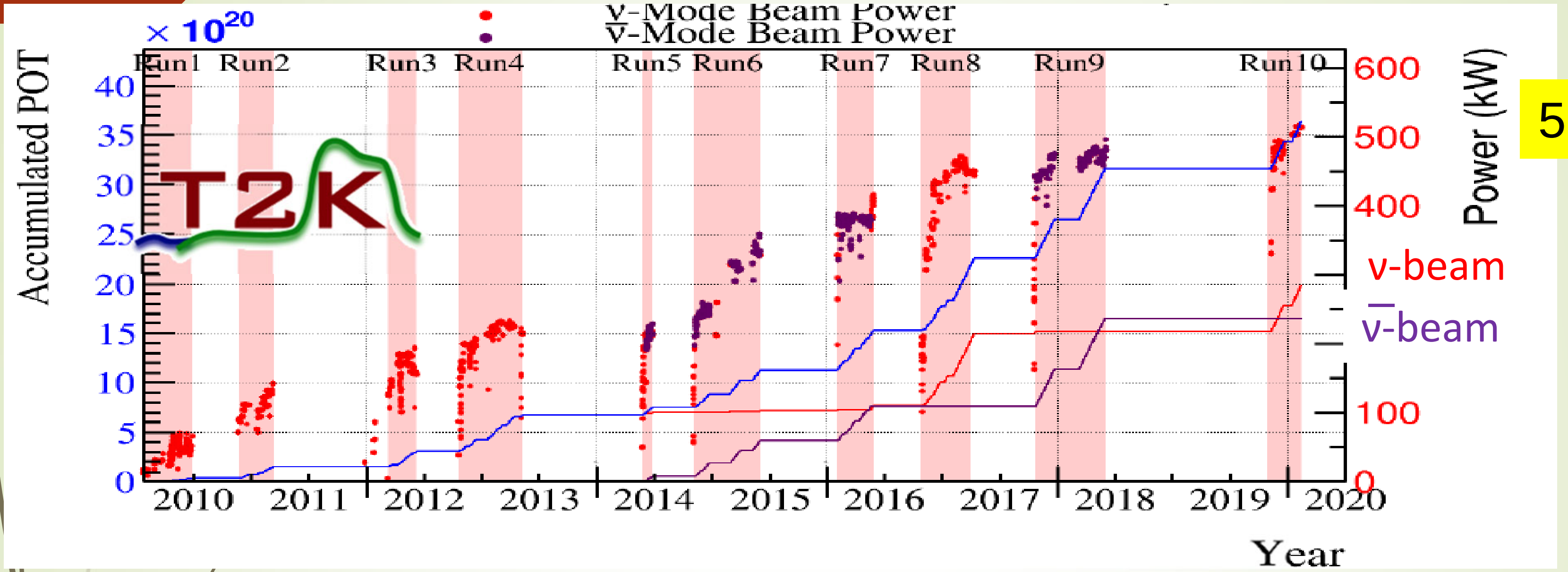
Running Accelerator-based long baseline experiments : T2K and NOvA



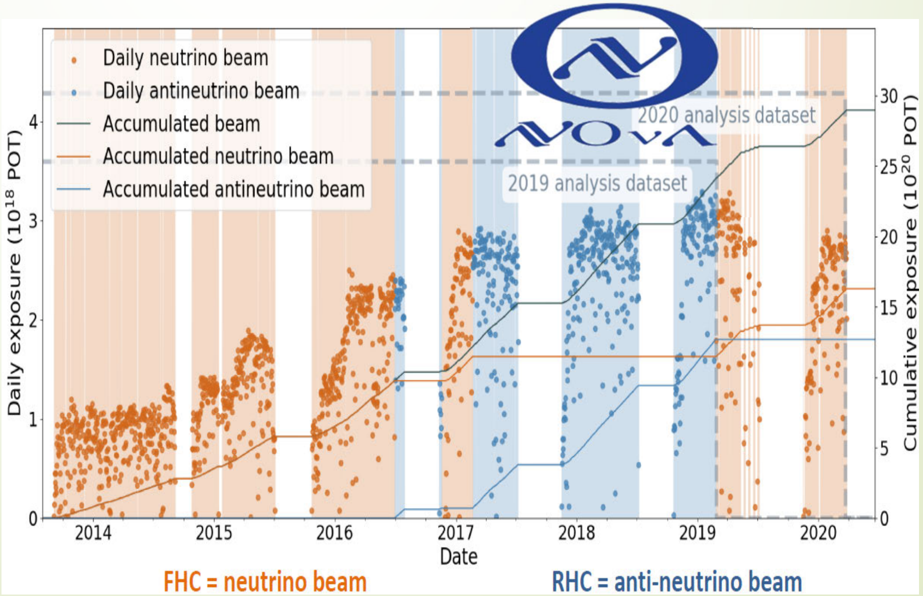
Complementary (Important to resolve degeneracies)

	T2K	NOvA
L(km)	295 → ~10% matter effect	810 → ~30% matter effect
detector	Super-K (22.5+ fid. V water Cherenkov)	14 kton fiducial liq. Scintillator (6cm pitch)
period	2009~	2014~

Data accumulation



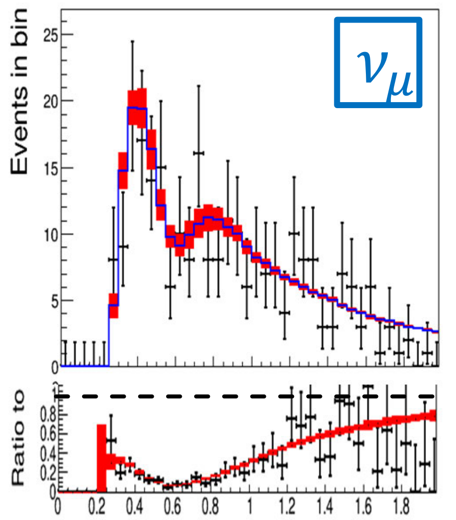
520 kW



750 kW

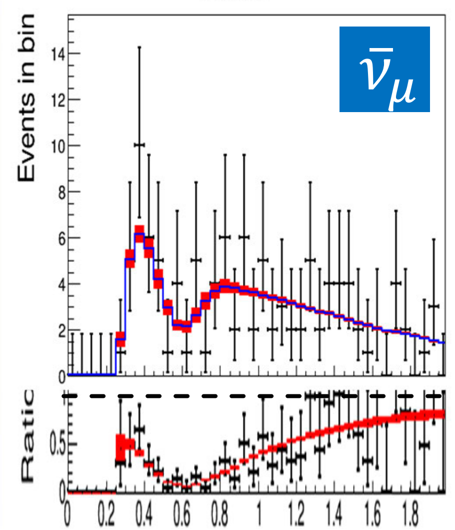
Muon neutrino disappearance

T2K Run1-10 Preliminary



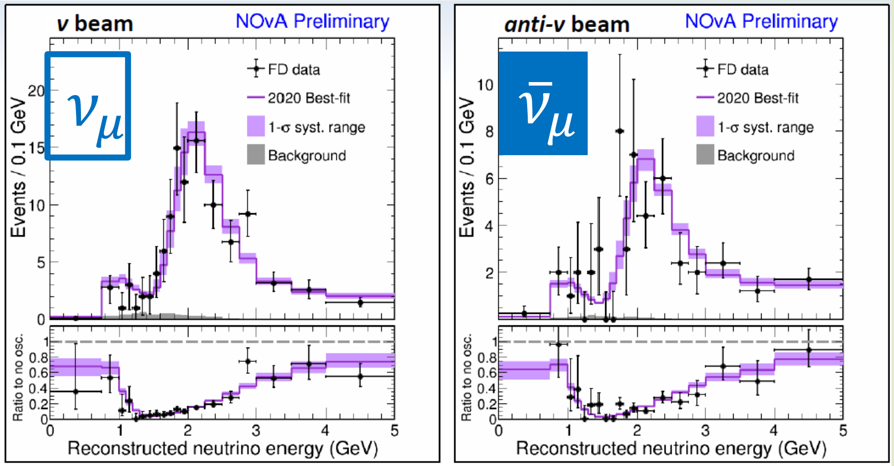
Reconstructed Neutrino Energy[GeV]
318 events

T2K Run1-10 Preliminary



Reconstructed Neutrino Energy[GeV]
137 events

M. Baird, ICHEP2020

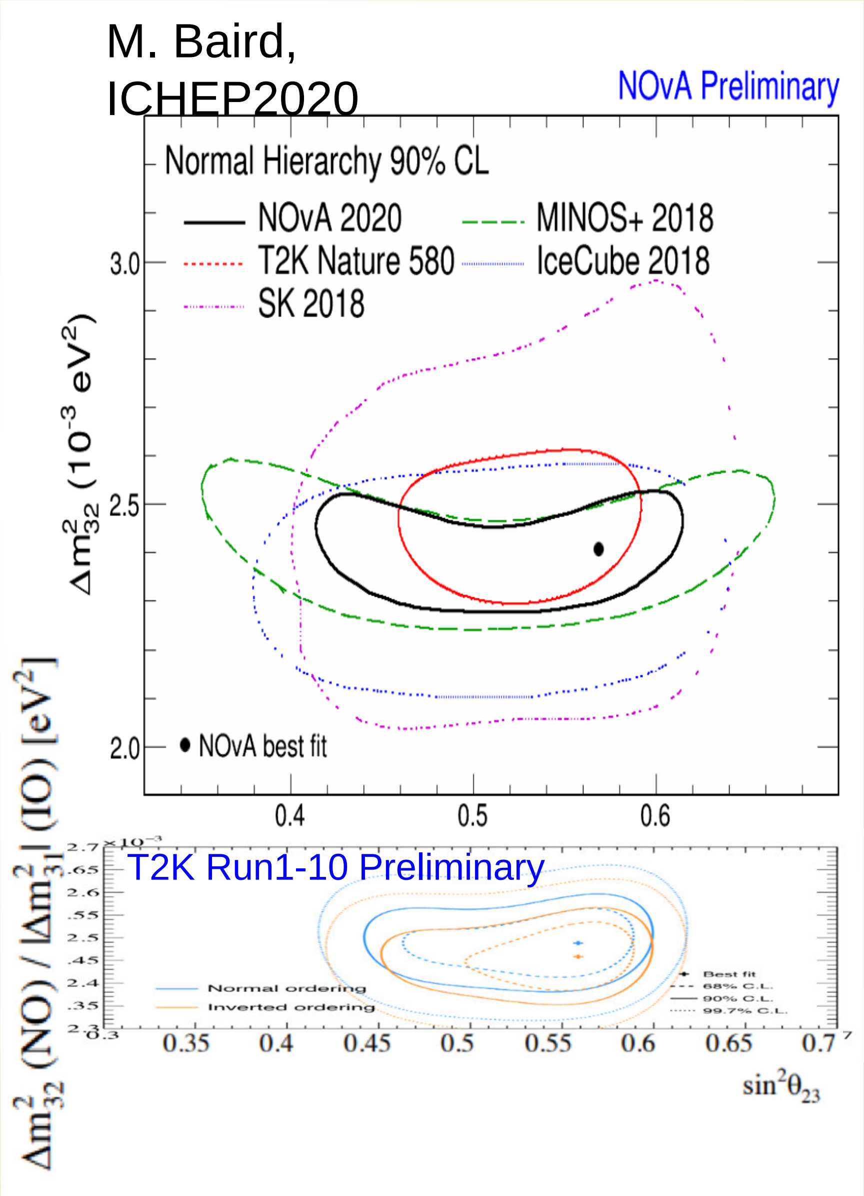


Observed: 211 events
Prediction: 222 ± 23 (8.2 bkg)

Observed: 105 events
Prediction: 105 ± 10 (2.1 bkg)

$$P_{\mu \to \mu} \approx 1 - \sin^2 2\theta_{23} \sin^2 \left(1.27 \Delta m^2 L / E_\nu\right)$$

Δm^2_{32} vs. $\sin^2\theta_{23}$
plot sizes are changed to give same scale



Δm^2_{32} vs. $\sin^2\theta_{23}$

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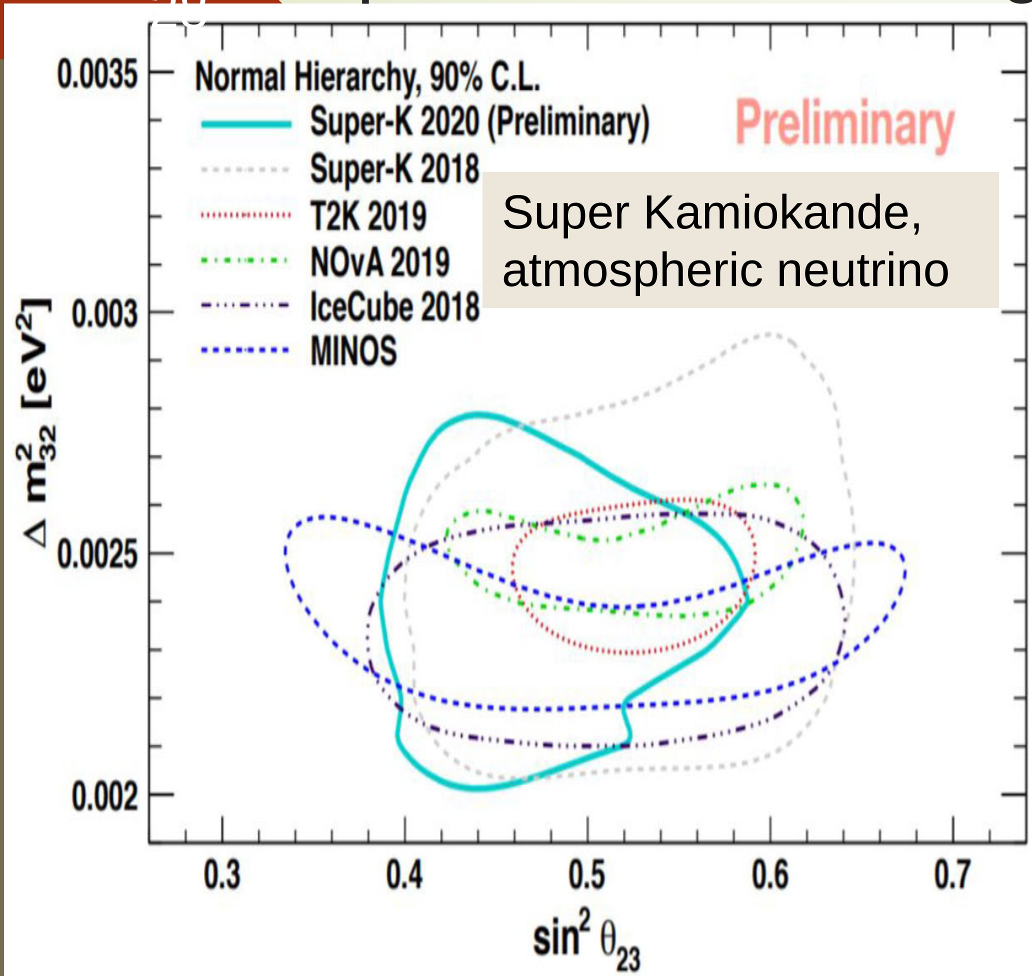
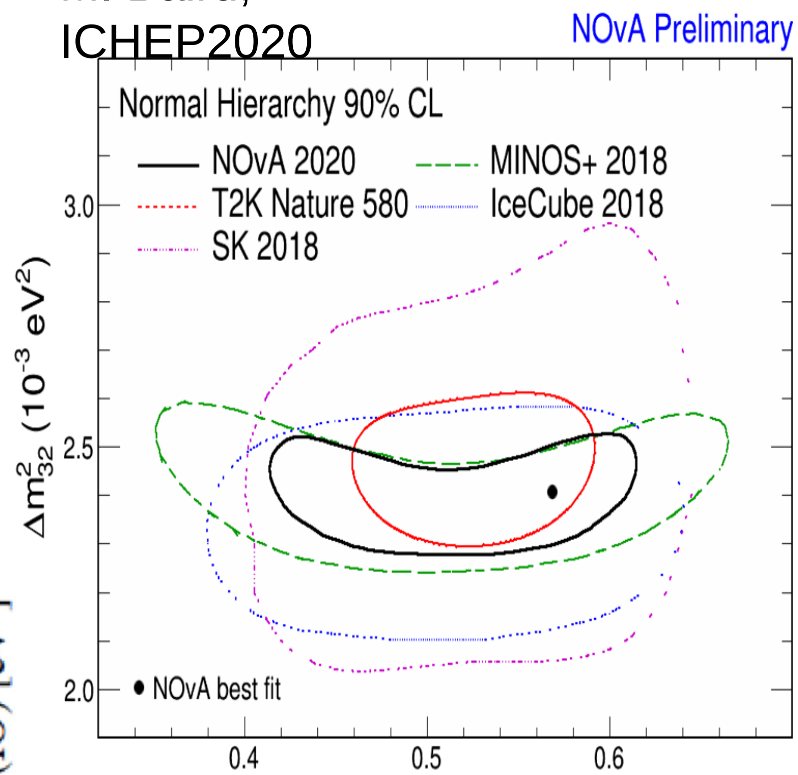
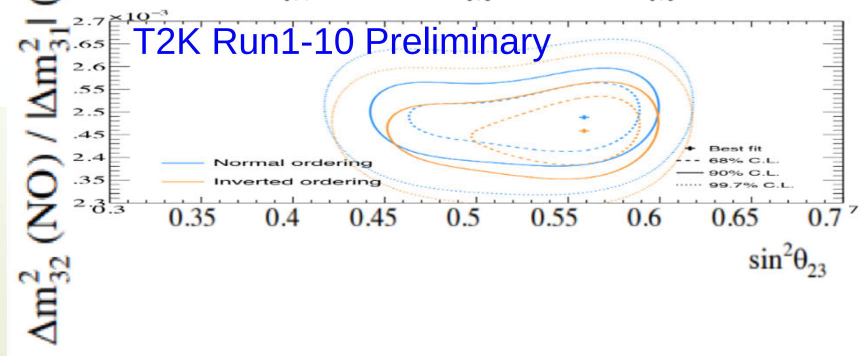


V. Takhistov, ICHEP2020

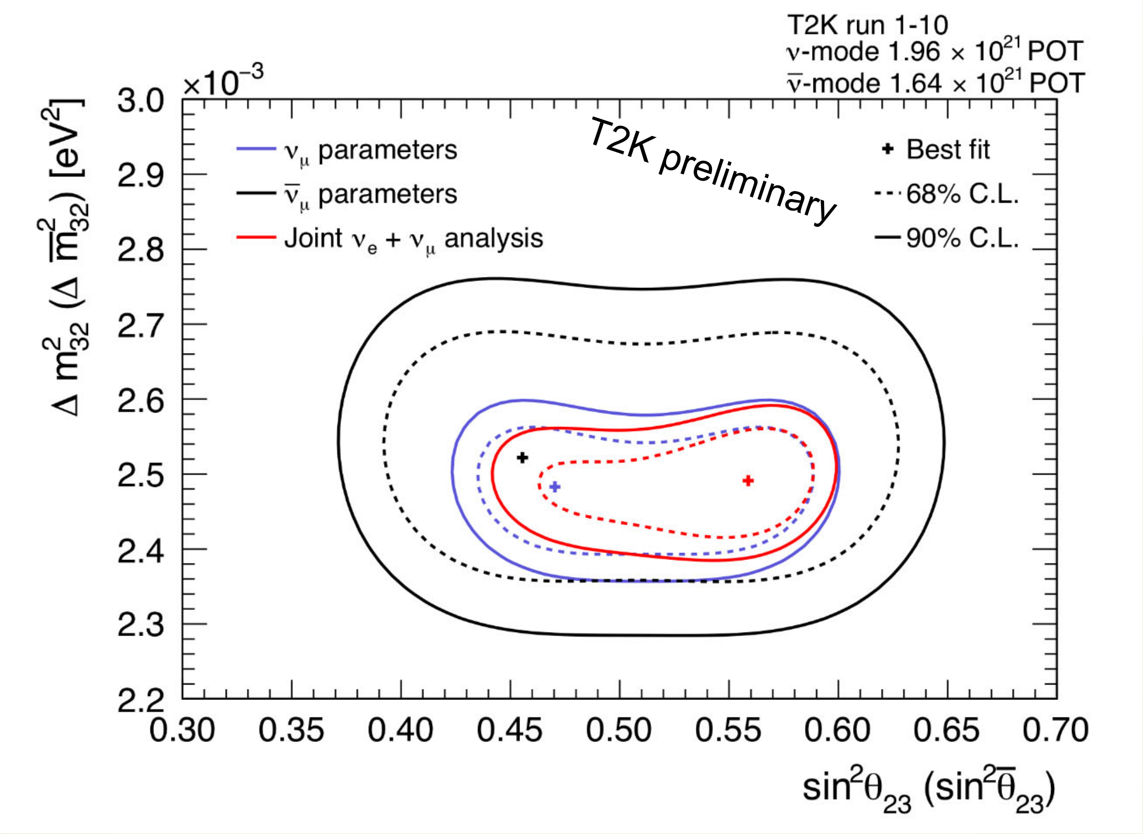
M. Baird, ICHEP2020



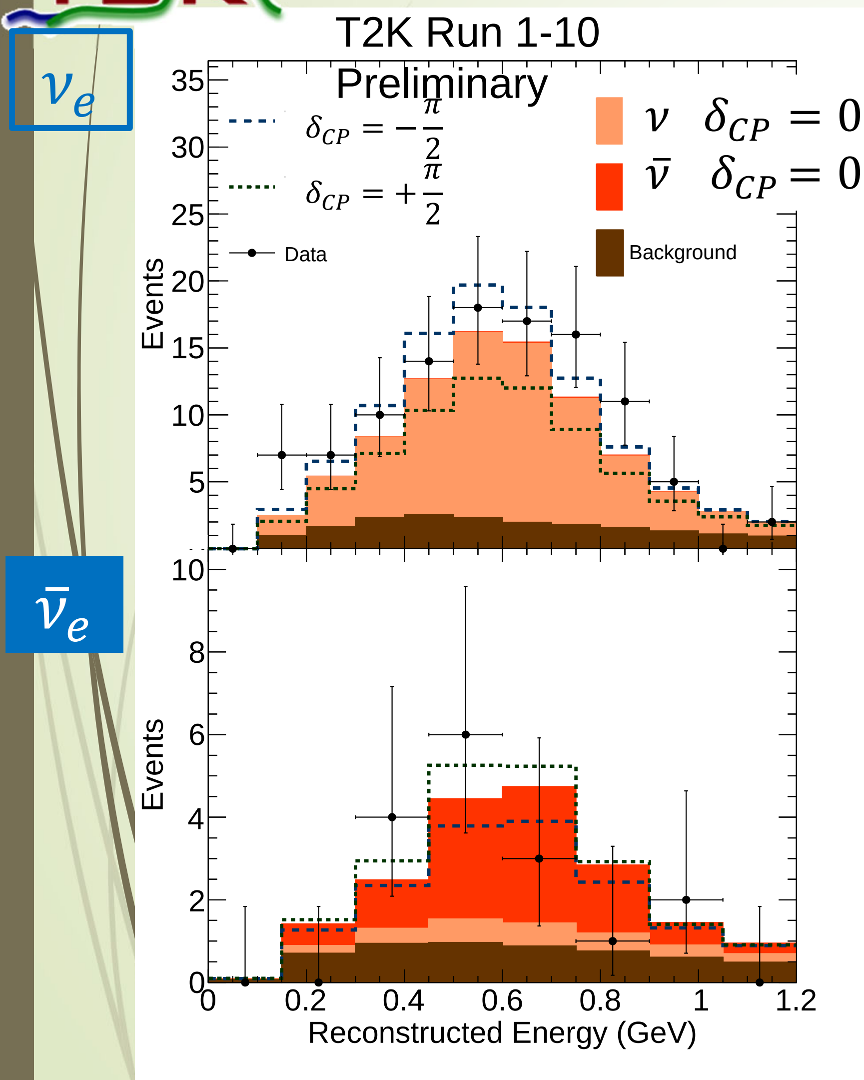


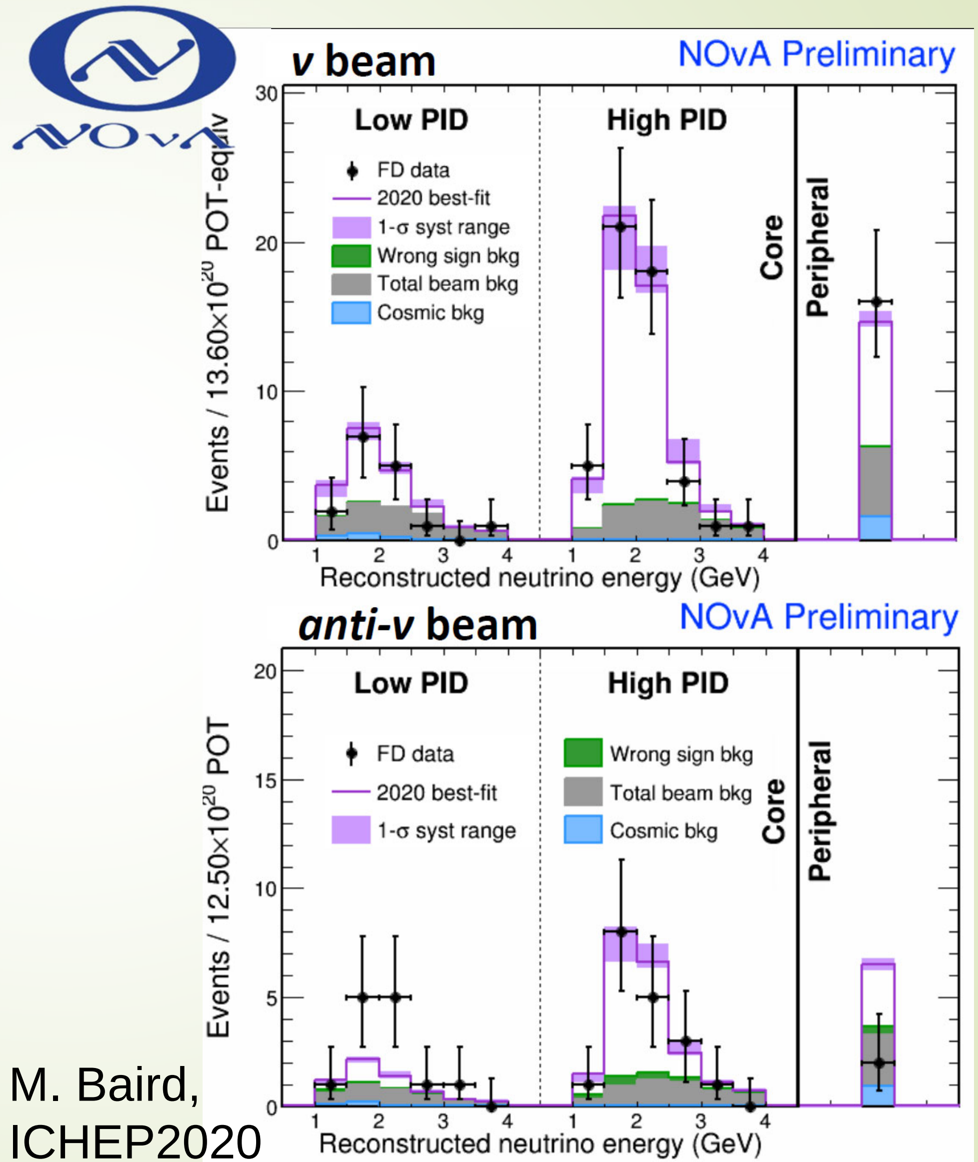
muon disappearance ν vs. $\bar{\nu}$

- CPV appears only for appearance.
- If disappearance is different between ν vs. $\bar{\nu}$, that violates CPT
- This is unlikely to happen, but ν mass may be related to physics at ~10^{14} GeV, so worth to check!



Electron neutrino appearance



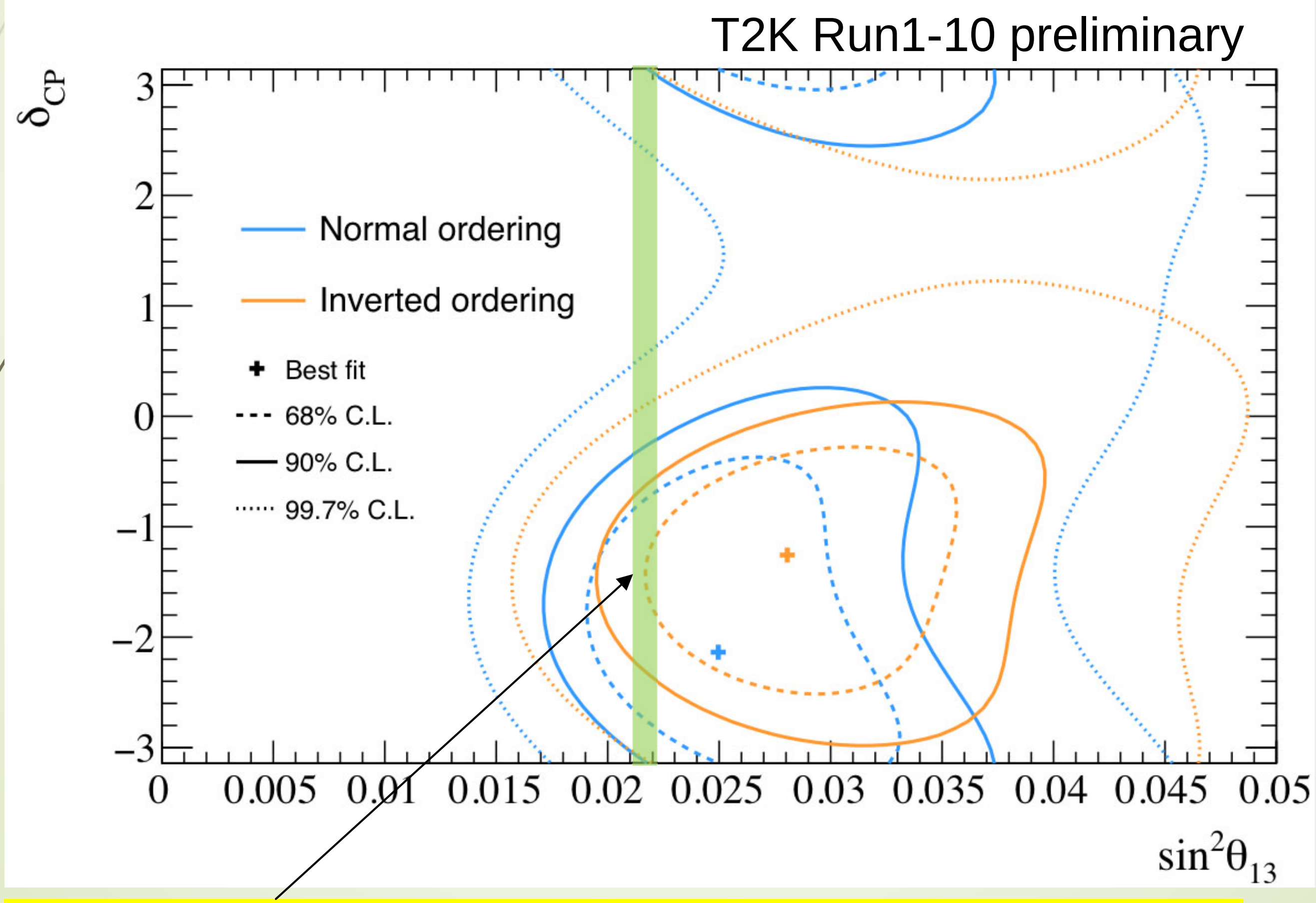


M. Baird, ICHEP2020

>4σ evidence of $\bar{\nu}_e$ appearance

Allowed region w/o reactor $\sin^2\theta_{13}$

$$P(\nu_\mu \to \nu_e) \fallingdotseq \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\Phi_{31} - \sin 2\theta_{12} \sin 2\theta_{23} \cos\theta_{13} \sin 2\theta_{13} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$

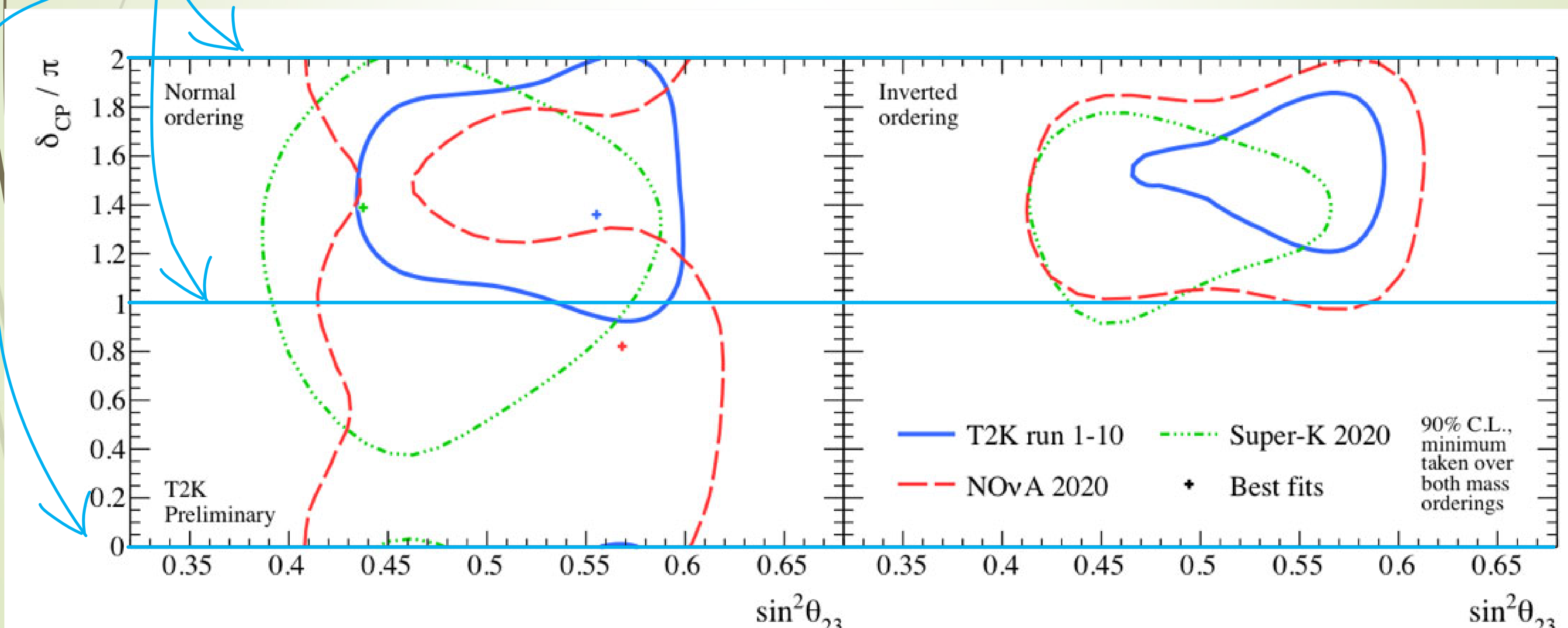


Reactor measurement (JUNO, RENO, DoubleChooz)

δ_{CP} vs. $\sin^2\theta_{23}$ allowed region w/ reactor constraint

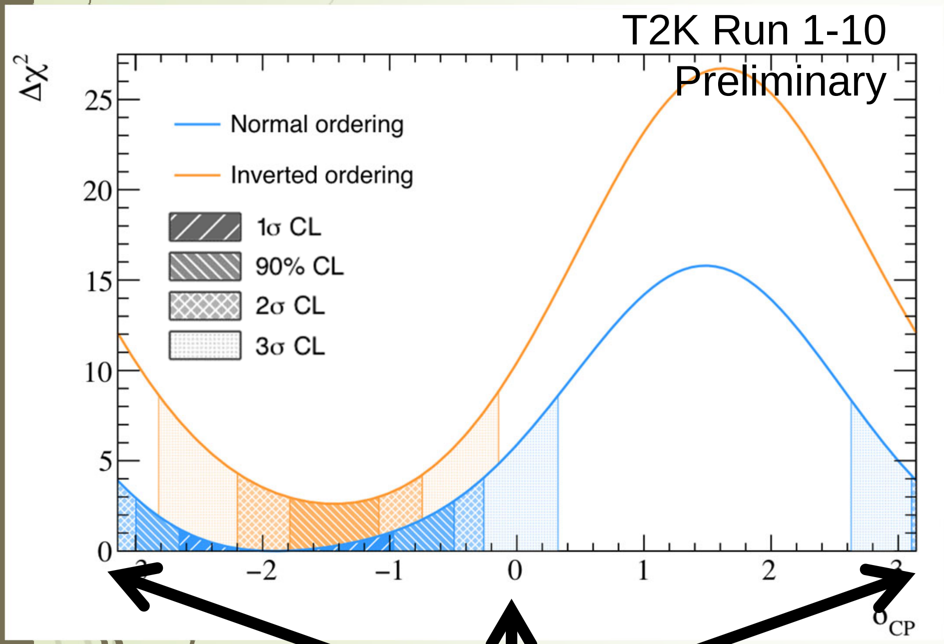
$$P(\nu_\mu \to \nu_e) \fallingdotseq \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \Phi_{31} - \sin 2\theta_{12} \sin 2\theta_{23} \cos\theta_{13} \sin 2\theta_{13} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$

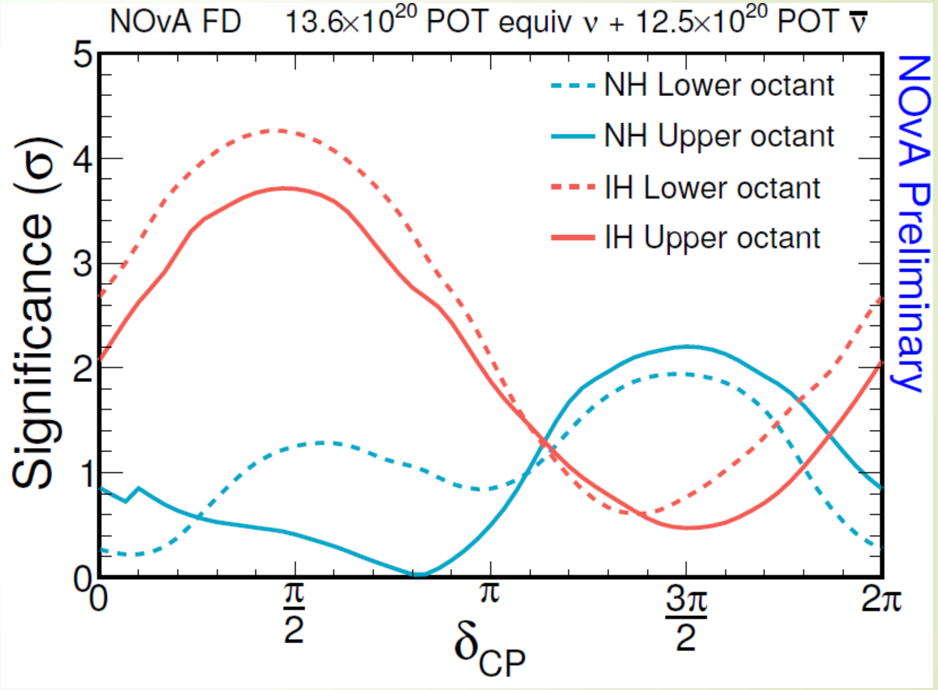
CP is conserved on these lines.



δ_{CP}

L. Munteanu, ICHEP2020



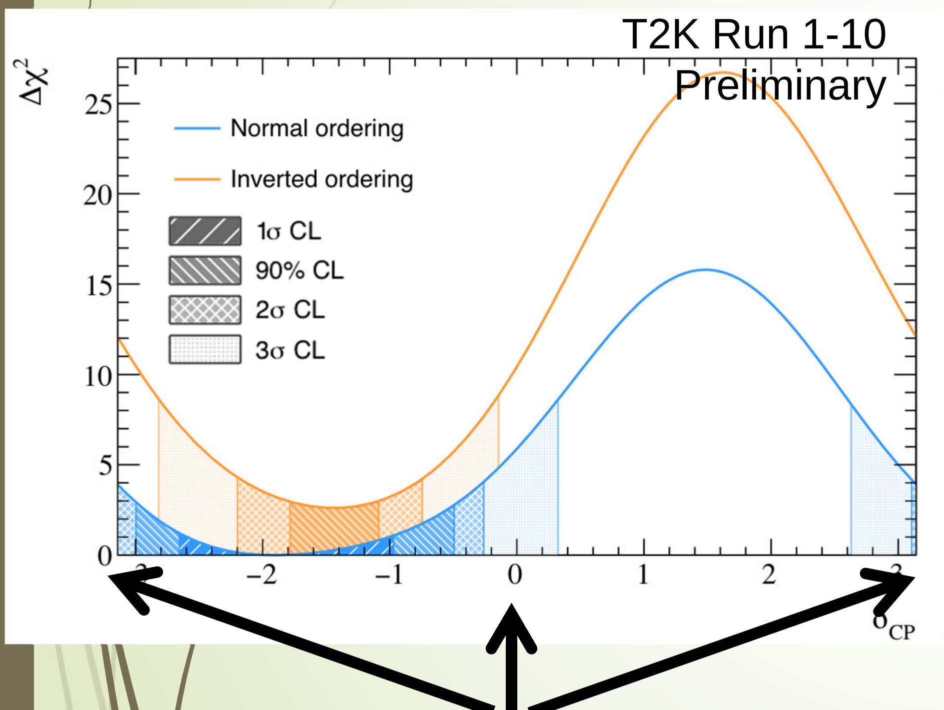


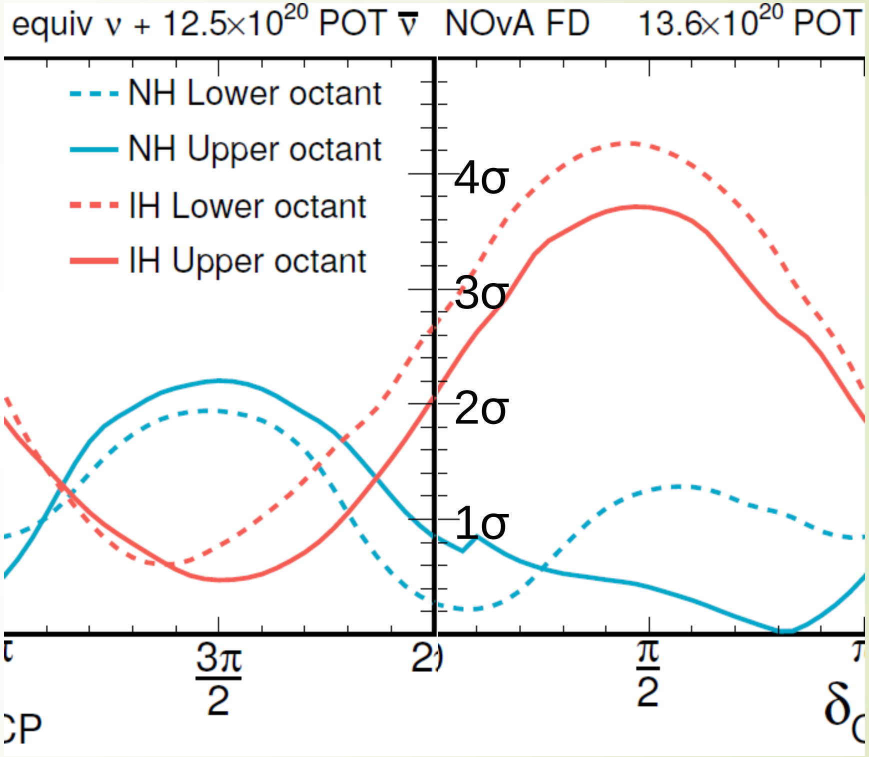
no CPV

T2K disfavors CP conserving case at $\lesssim 2\sigma$ (95%) C.L.

δ_{CP}

L. Munteanu, ICHEP2020





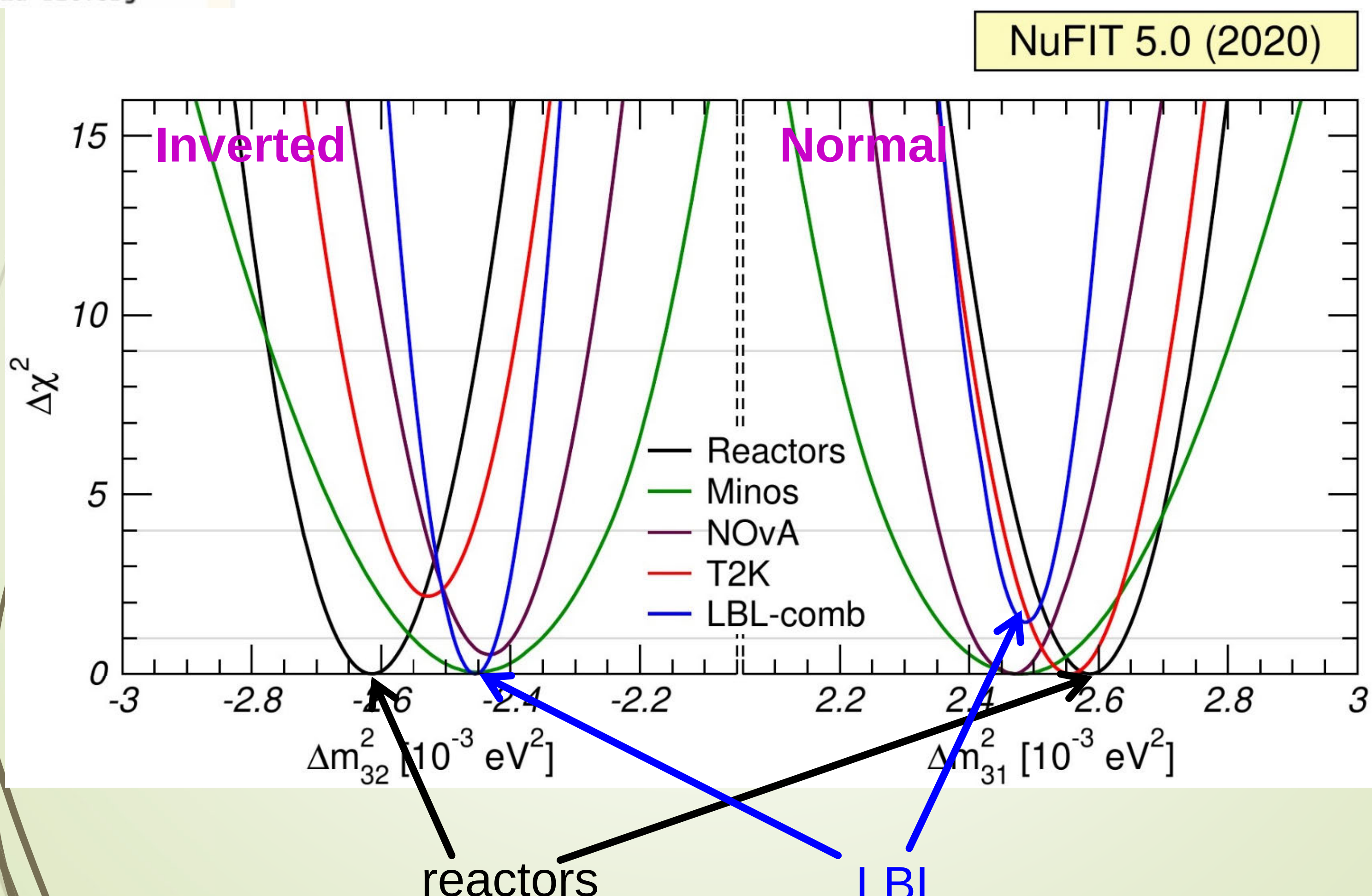
T2K disfavors CP conserving case at $\lesssim 2\sigma$ (95%) C.L.

Global Fit

www.nu-fit.org

Home

v5.0: Three-neutrino fit based on data available in July 2020



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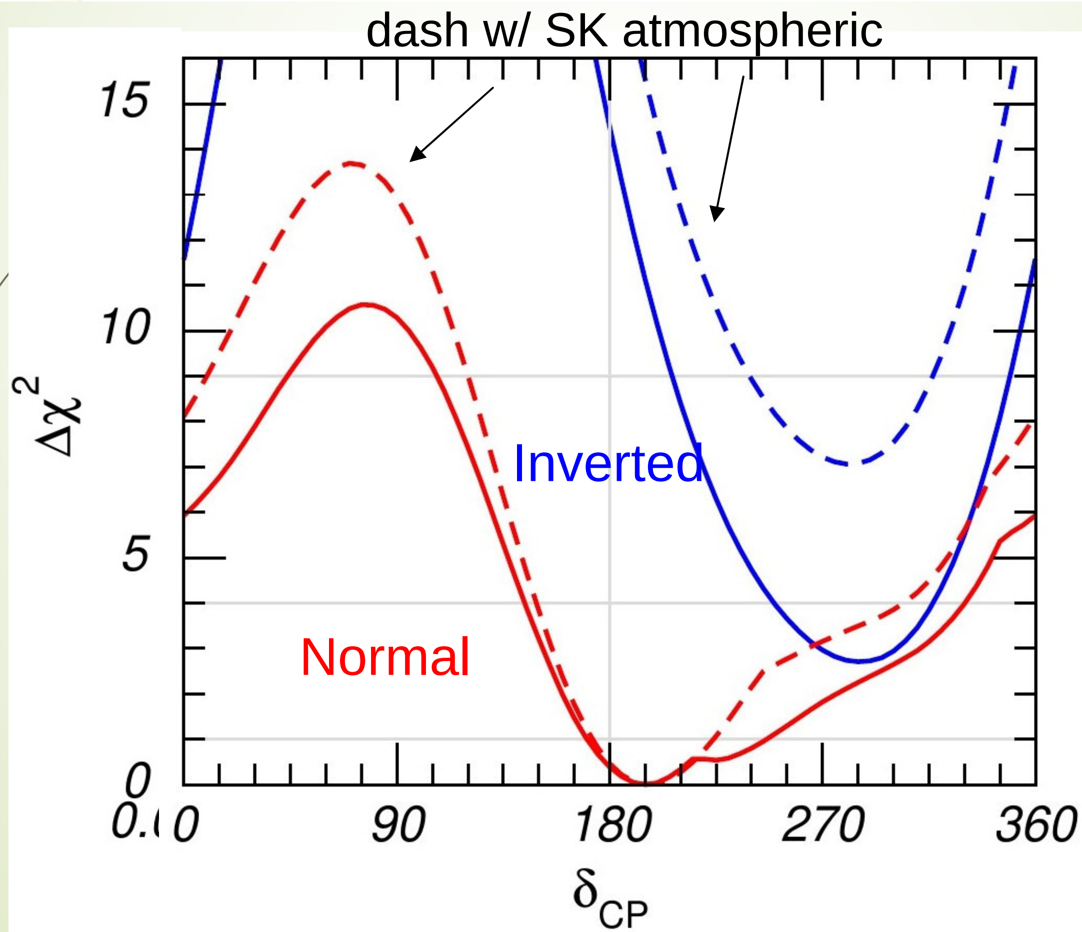


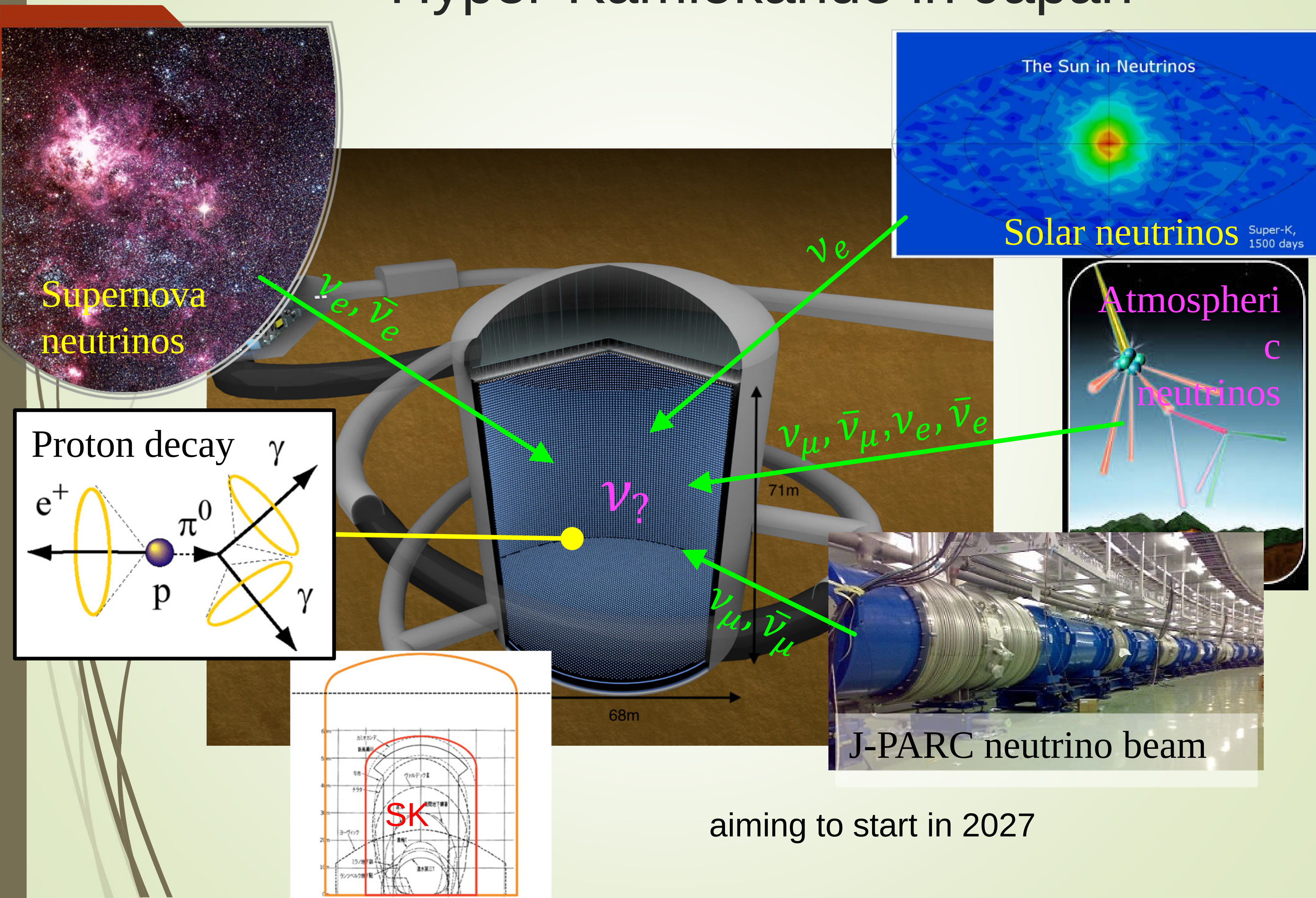
Prospect

NOvA and T2K will continue data taking a few years

- Beam intensity improvement
- T2K will upgrade near detector and far detector
- NOvA will have a test beam experiment

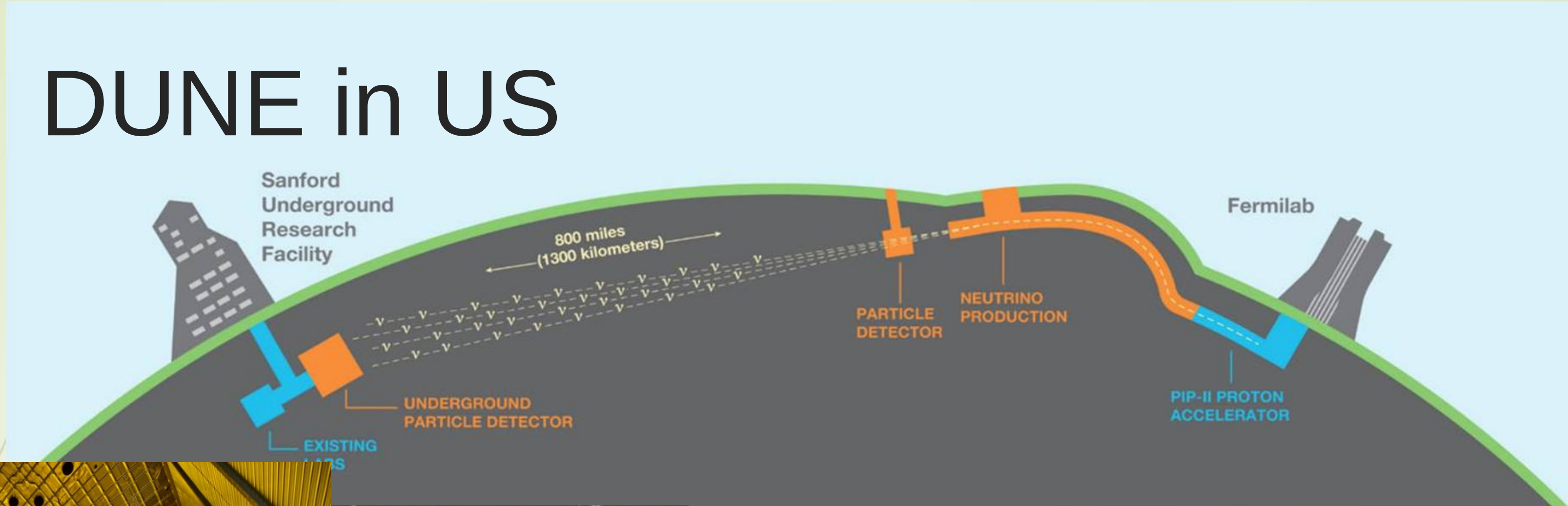
If $\delta_{CP} \sim -\frac{\pi}{2}$, CPV may be confirmed at $\sim 3\sigma$ C.L.

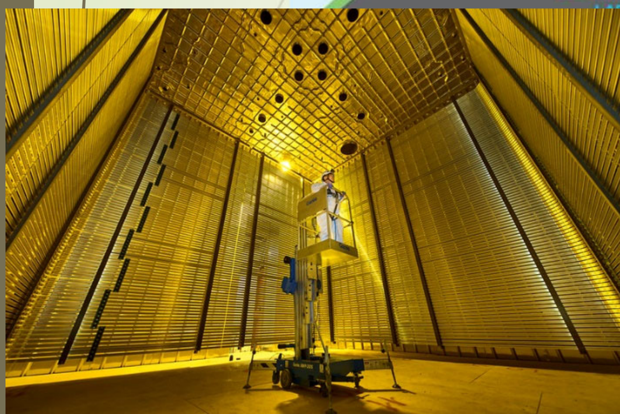
Hyper-Kamiokande in Japan

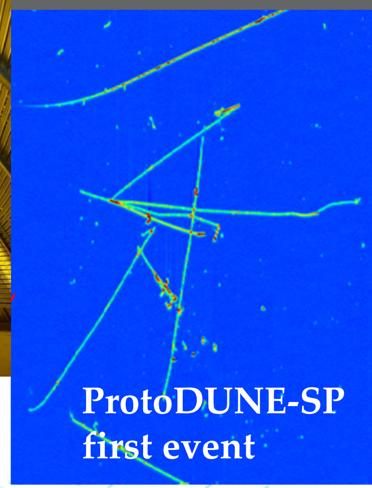


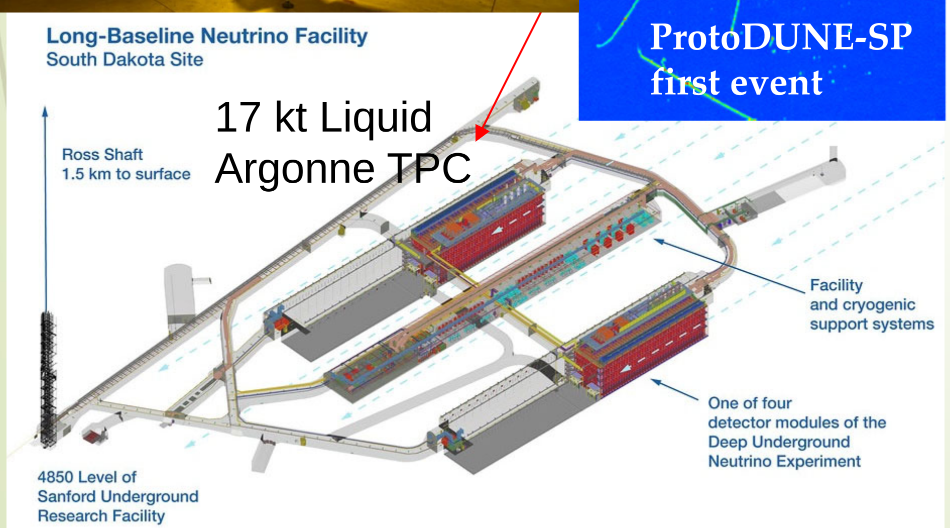
aiming to start in 2027

DUNE in US









60-120 GeV Proton beam
1.2 MW, upgradable to 2.4 MW
in late 2020's

- CP Violation
- Neutrino Mass Hierarchy
- Precision measurements of neutrino oscillation parameters
- Supernova & Astrophysics
- Nucleon Decay
- BSM searches

Summary

- CP violation in the quark sector is too small to explain our matter universe
- Large mixing in the lepton sector allow large CP violation
- CPV is accessible by accelerator long-baseline neutrino oscillation experiments
- T2K may be seeing CPV, present significance $(\lesssim)2.5\sigma$
  - very large CPV?
- T2K and NOvA experiment will prove with up to 3σ sensitivity in coming years
  - w/ hardware & analysis upgrades
- Hyper-K and DUNE will explore CPV with > 5σ sensitivity and **determine its size**.