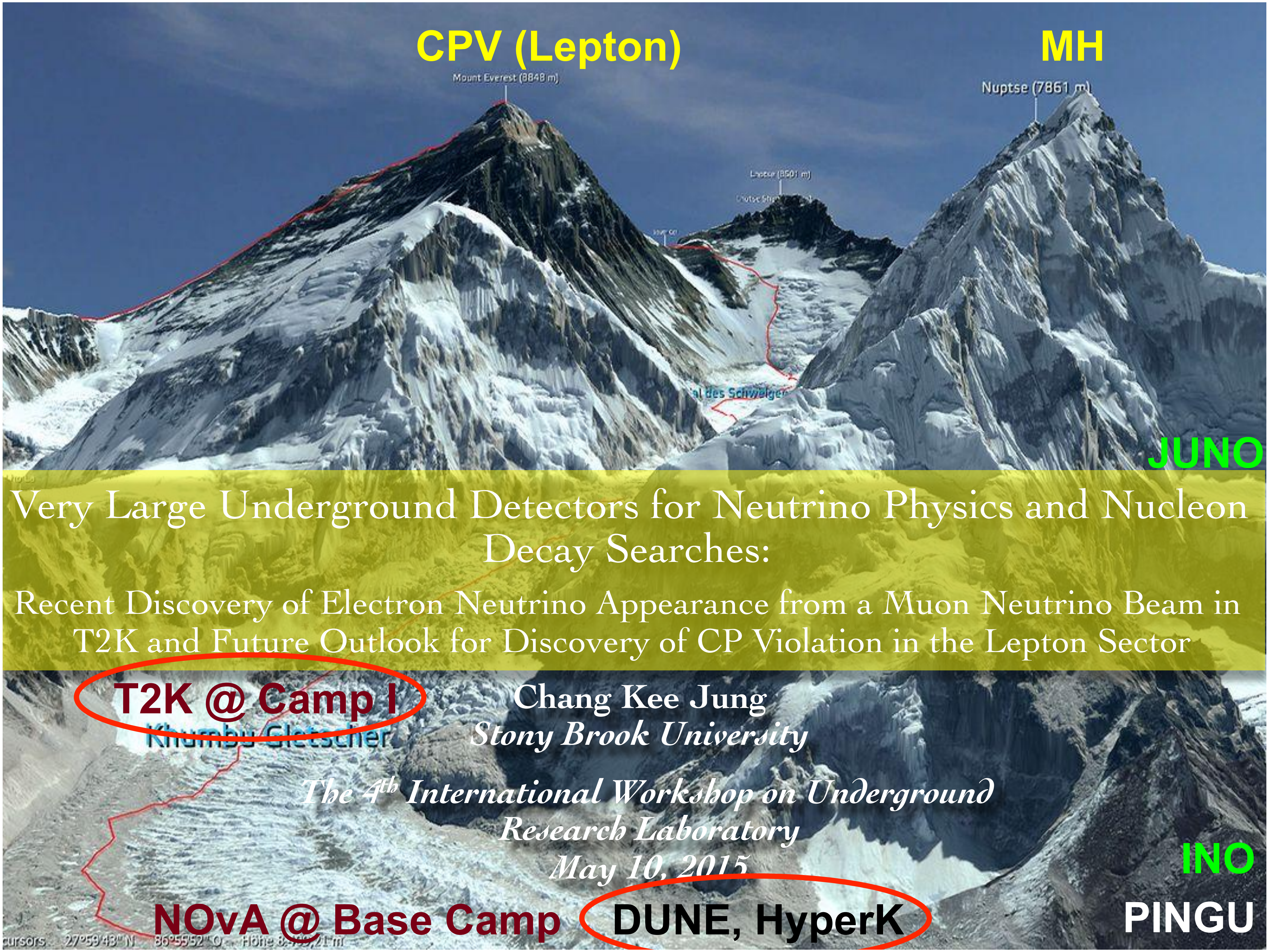


CPV (Lepton)
MH
Mount Everest (8848 m)
Nuptse (7861 m)
JUNO
Very Large Underground Detectors for Neutrino Physics and Nucleon Decay Searches:
Recent Discovery of Electron Neutrino Appearance from a Muon Neutrino Beam in T2K and Future Outlook for Discovery of CP Violation in the Lepton Sector
T2K @ Camp I
Khumbu Gletscher
Chang Kee Jung
Stony Brook University
The 4th International Workshop on Underground Research Laboratory
May 10, 2015
INO
NOvA @ Base Camp
DUNE, HyperK
PINGU

Building Blocks of the Universe

Elementary Particles In the Standard Model

only candidates to be Majorana particles among matter field particles

Interactions

	Strong (gluon)	EM (γ)	Weak (W, Z)	Gravitation (graviton)
anti- Quarks				
u $\bar{u}$ c $\bar{c}$ t $\bar{t}$ / d $\bar{d}$ s $\bar{s}$ b $\bar{b}$	yes	yes	yes	yes
anti- Leptons				
e e^+ μ μ^+ τ τ^+	no	yes	yes	yes
ν_e $\bar{\nu}_e$ ν_μ $\bar{\nu}_\mu$ ν_τ $\bar{\nu}_\tau$	no	no	yes	yes

Grand Unified Theory (GUT)

Unified Electroweak

Superstring Theory

Massless Neutrinos

Higgs Particle

Holy Grail of the Standard Model: Discovered at LHC

Matter/Anti-Matter Asymmetry in the Universe and Baryogenesis/Leptogenesis

B >> 0 at t = 13.8 Gy

B = 0 at t ~ 0

# of antiparticles = # of particles

Andrei Sakharov

Sakharov's 3 Conditions:

1) At least one baryon number violating process e.g. sphaleron process
2) C (Charge) and CP (Charge-Parity) violation
3) Interactions outside of thermal equilibrium

➔ The observed CP violations in the quark sector are not enough to explain the large asymmetry

Leptogenesis to the rescue!!!

➔ Search for CP violation in the lepton sector

Grand Physics Goals with the Very Large Underground Particle Physics Detectors

1) Discovery of CP Violation in the Lepton Sector
   i.e. $P(\nu_\mu \rightarrow \nu_e) \neq P(\text{anti } \nu_\mu \rightarrow \text{anti } \nu_e)$

2) Discovery of Proton Decay (baryon number violation)
   - Predicted by Grand Unification Theories
   - Only direct experimental access to 10^{16} GeV scale

3) Detection of Neutrinos from Core-collapsing Supernova
   - 99% of the energy is released in the form of neutrino in ~10 s period
   - Galactic supernova

Large Underground Proton Decay/Neutrino Detectors

These detectors were inspired by the GUTs for proton decay searches

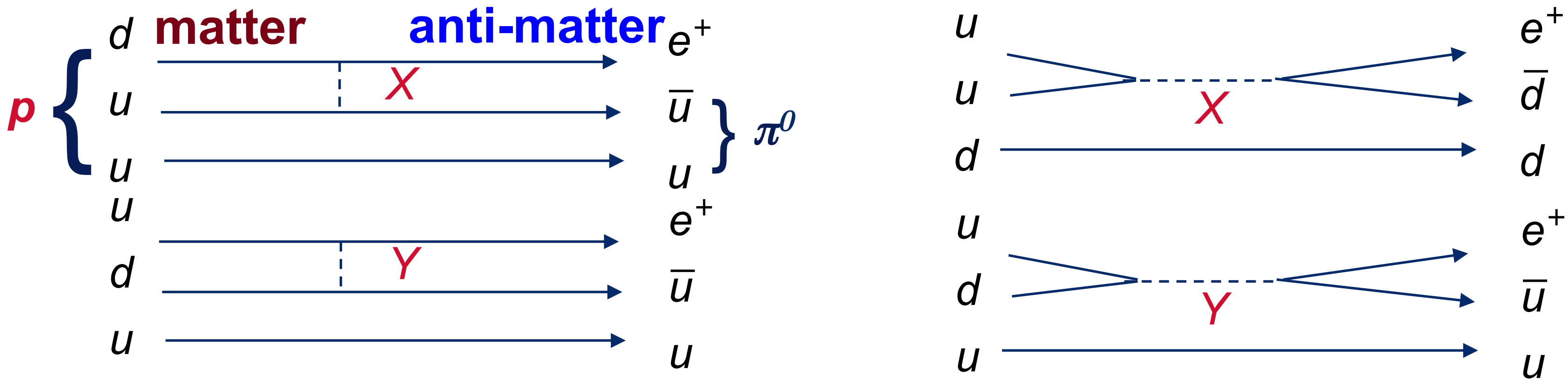
→ Went underground to avoid cosmic rays (muons)

It turned out these detectors were well suited for studies of neutrinos mainly because their large masses

Proton Decay in SU(5)
By Georgi and Glashow (1974)

- Decay mechanisms

  dominated by the dimension=6 op. gauge boson mediated decays



$(X^{\pm 4/3}, Y^{\pm 1/3}$: new gauge bosons)

- Predictions

$$\tau/B\ (p \rightarrow e^+\pi^0) = 4 \times 10^{29\pm1.7}\ \text{years},\ B\ (p \rightarrow e^+\pi^0) \approx 40 \sim 60\ \%$$

- Experimental Results

$$\tau/B\ (p \rightarrow e^+\pi^0) > 1.2 \times 10^{33}\ \text{yrs (IMB (+Frejus) Lower Limit @90\% C.L.)}$$

1.3×10^{34} yrs (current SuperK Lower Limit @90% C.L.)

➔ Complete exclusion of minimal SU(5) model

Neutrinos from the Type II-a Core-collapse Supernovae

- Produced by the neutralization process at the core
- Observed for the first time in 1987 (SN1987a): a total of 20 events by two detectors (IMB and Kamiokande) in about 10 second period of time
- Galactic Supernova (@10 kpc)
  - Tens of thousands neutrino events in DUNE and hundreds of thousands events in Hyper-Kamiokande

→Detailed study of supernova mechanism

→Possible direct observation of a blackhole formation

Supernova 1987a

Large Magellanic Cloud

2-flavour Neutrino Oscillation in Vacuum

weak eigenstates

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

mass eigenstates

Survival Probability

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

Oscillation Probability

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

$\Rightarrow \Delta m^2 (\equiv m_1^2 - m_2^2)$ *and* $\sin^2(2\theta)$ *are oscillation parameters given by the nature*

$\Rightarrow$ *L(source to observer distance) and E(neutrino energy) are exerimental parameters*

$$\left(\frac{\Delta m^2 L}{4E}\right) \Rightarrow \left(1.27\frac{\Delta m^2 L}{E}\right) \quad with \quad \begin{pmatrix} \Delta m^2 \; in\, eV^2 \\ L\, in\, km \\ E\, in\, GeV \end{pmatrix}$$

$$P_{\nu \text{-->} \nu'} = \sin^2 2\theta \sin^2 (1.27\, \Delta m^2\, L/E)$$

Note that for neutrino oscillation to occur at least one neutrino must have mass

➔ Recall in the SM, neutrino has no mass

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Lepton Mixing Matrix (a la CKM matrix)

weak eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathrm{U}_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

mass eigenstates

1 Dirac Phase ⇒ CPV

Three Angles

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

$\mathrm{c}_{ij} = \cos(\theta_{ij}),\ \ \mathrm{s}_{ij} = \sin(\theta_{ij})$

atm/accelerator **accelerator/reactor** **solar/reactor**

Current Status of Neutrino Oscillation Parameter Measurements

- Remarkable progress!
- All mixing angles are now known
  - $\theta_{12} = 33.9^o \pm 1.0^o$
  - $\theta_{13} = 8.7^o \pm 0.4^o$
  - $\theta_{23} = 45^o \pm 6^o$ (90% C.L.)
    → largest uncertainty

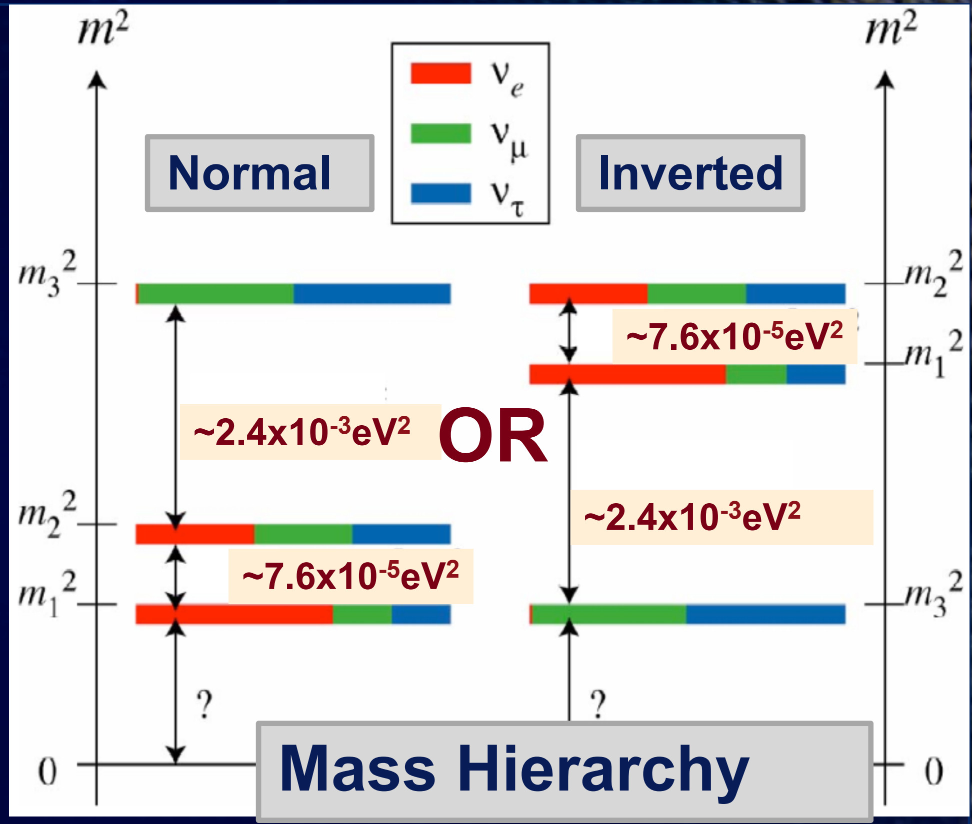
All three angles are non-zero and relatively large

→ allows exploration of CPV in the lepton sector

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

$\propto$ leading term + …
+ term($\sin\theta_{12} \sin\theta_{23} \sin\theta_{13} \sin\delta_{CP}$)

Why is nature so kind to us?

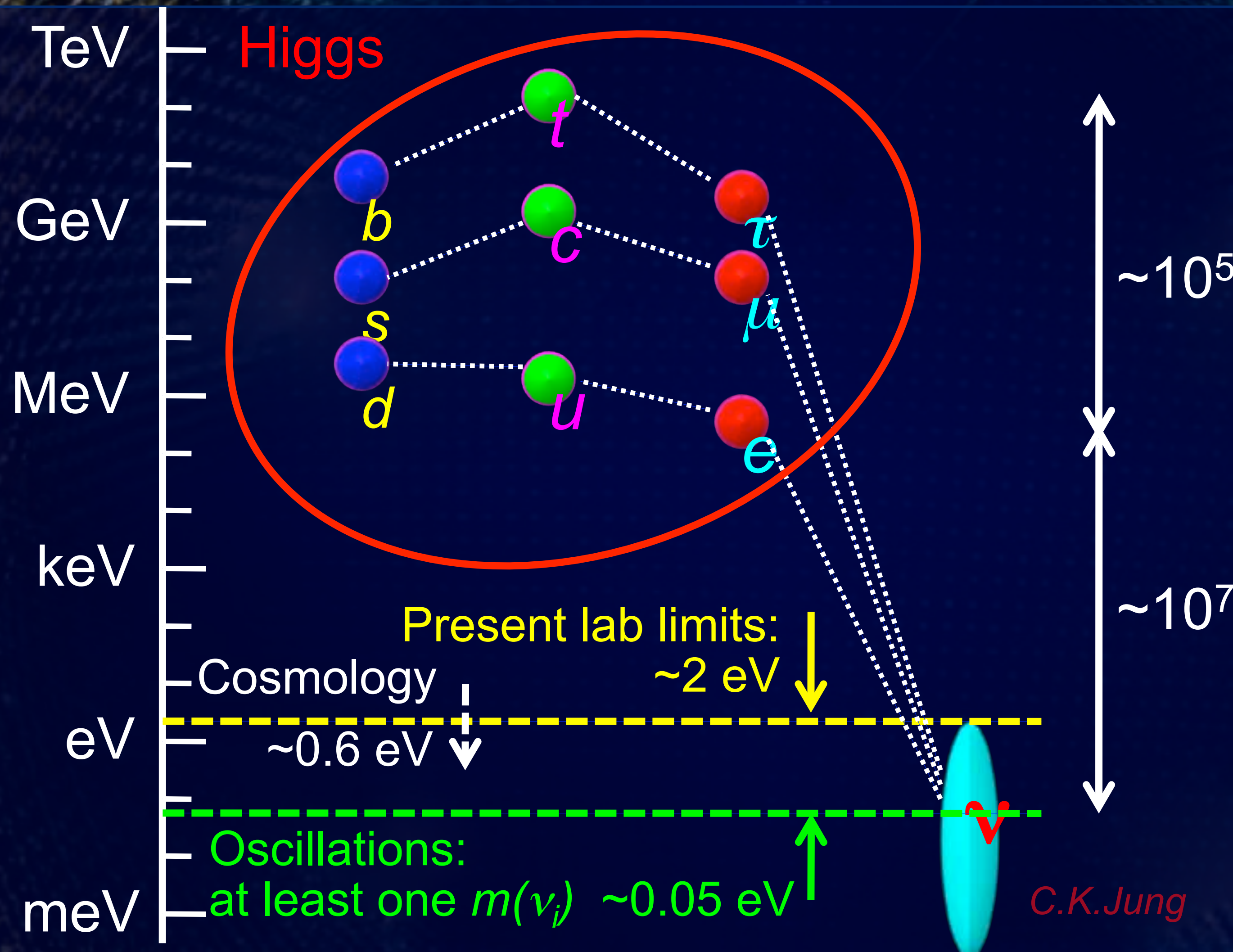


Critical for the ν-less double-β decay searches that would determine the Majorana-nature of ν

Remaining Unknown Neutrino Properties

- θ_{23}> 45°, = 45° (maximal)   or < 45°
  → maximal mixing may indicate a profound hidden symmetry
- δ_{CP} (≠ 0, i.e. CPV?)
- Mass ordering (NH or IH?)
- Is PMNS matrix correct description of the lepton sector?
- Any sterile ν
- Absolute m_ν
- Dirac/Majorana

Spin ½ Matter Field Particle Mass Spectrum



Are neutrino masses suppressed by new physics at very high energy?

$m(\nu_i) = m^2_{Di} / M$

Seesaw in SO(10)

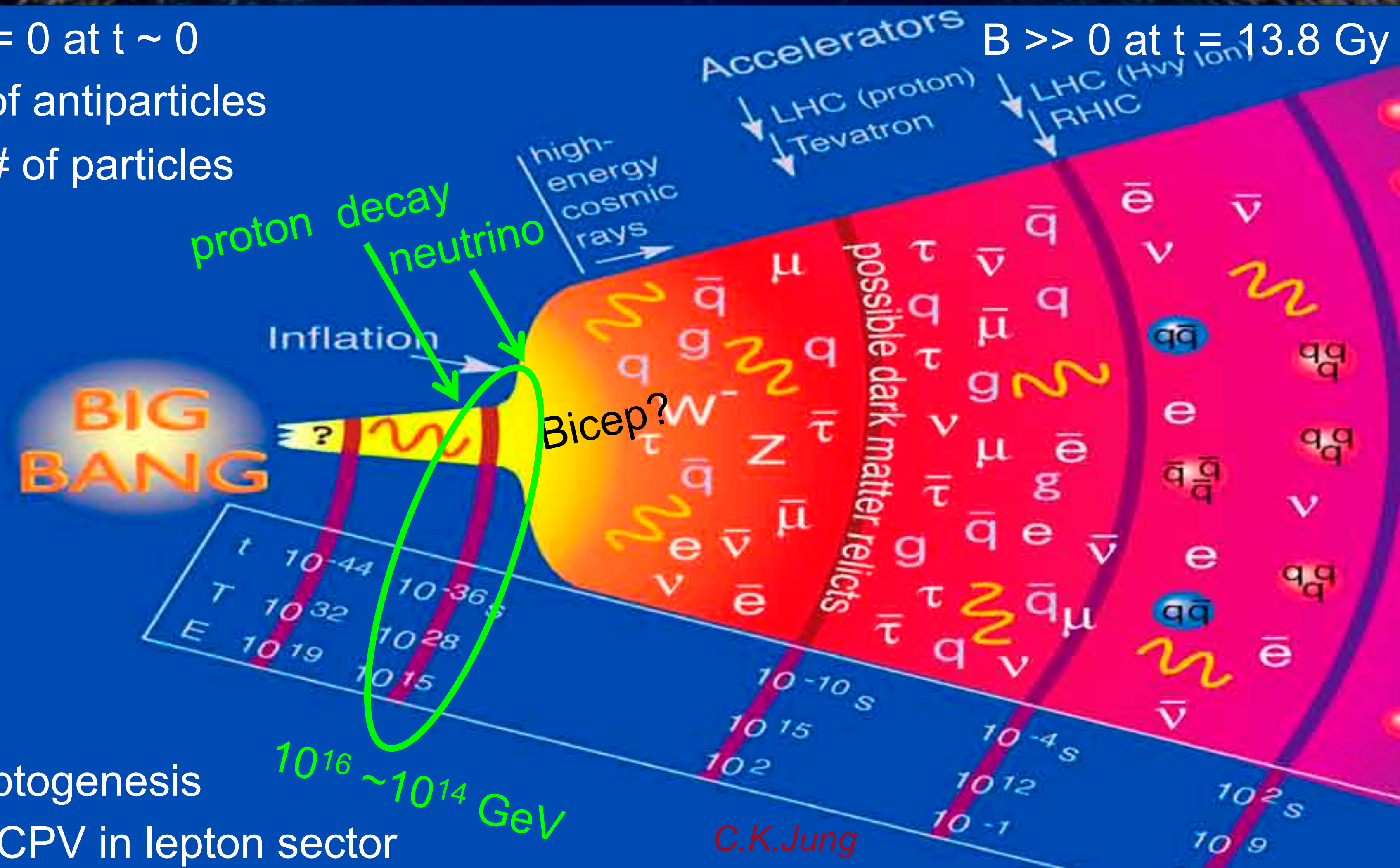
Nucleon decay and Neutrino Experiments: Probing the earliest time and the highest energies

B = 0 at t ~ 0

# of antiparticles

= # of particles

B >> 0 at t = 13.8 Gy



Leptogenesis

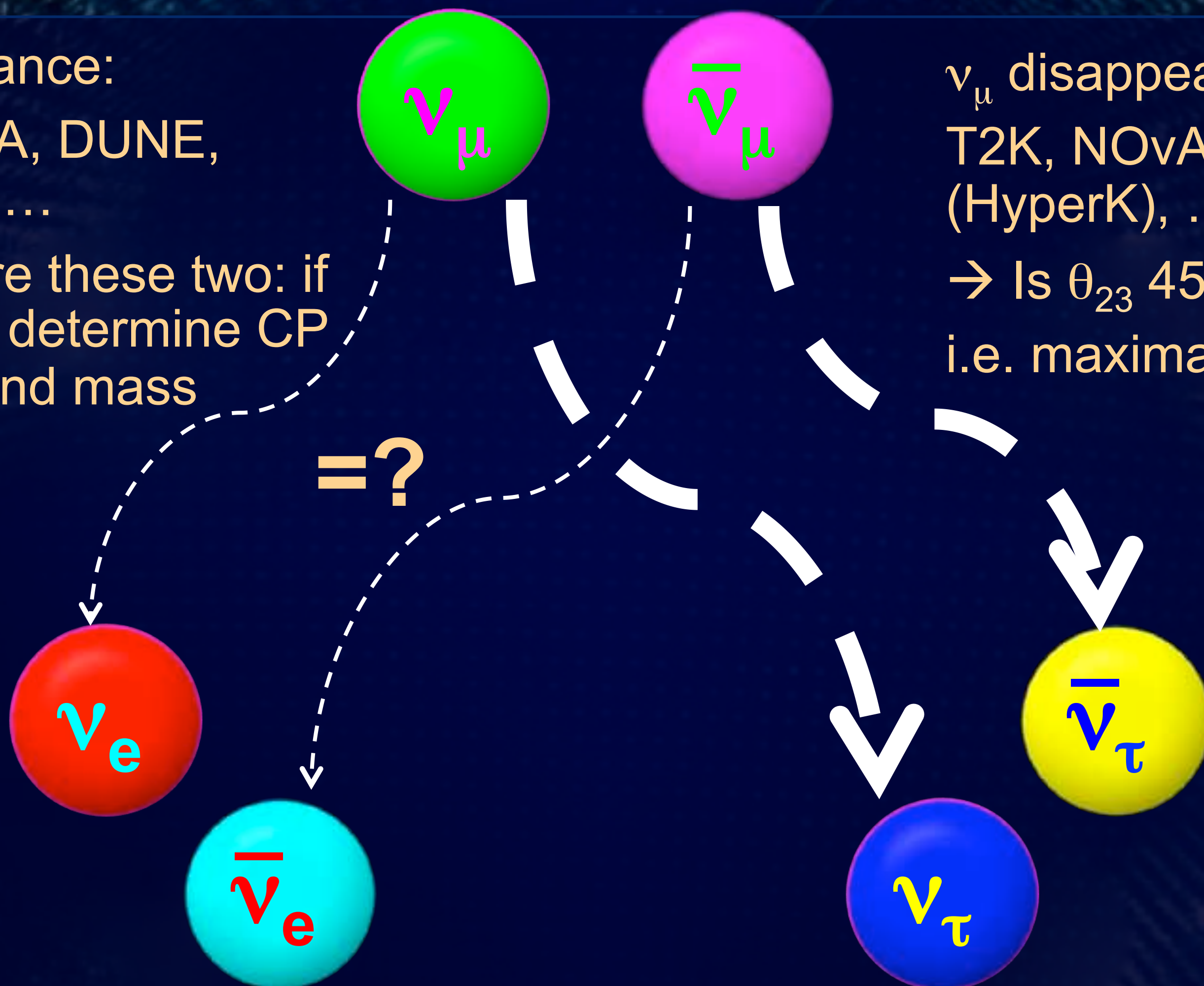
→ CPV in lepton sector

Physics Goals of Long Baseline Accelerator Based Neutrino Oscillation Experiments

ν_e appearance:

T2K, NOvA, DUNE, (HyperK), …

→ compare these two: if not equal, determine CP violation and mass ordering



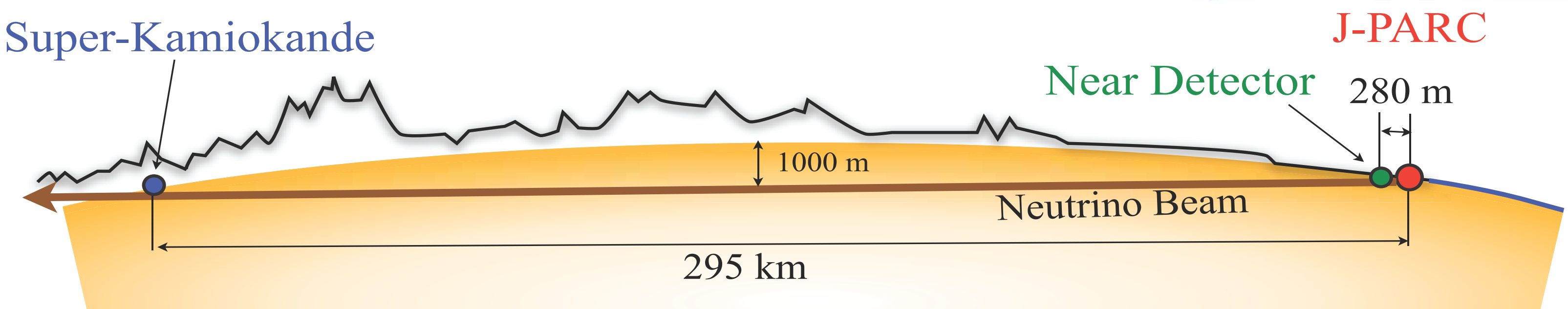
ν_μ disappearance:

T2K, NOvA, DUNE, (HyperK), …

→ Is θ_{23} 45^o ?

i.e. maximal mixing?

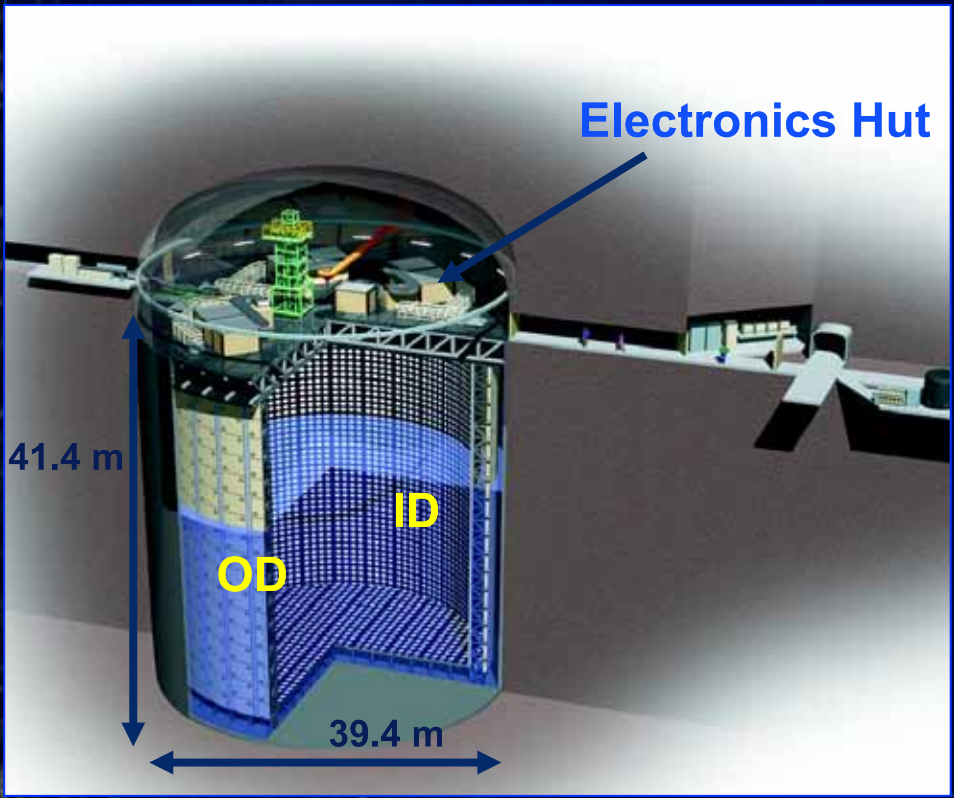
The T2K (Tokai to Kamioka) Experiment
(http://t2k-experiment.org/)

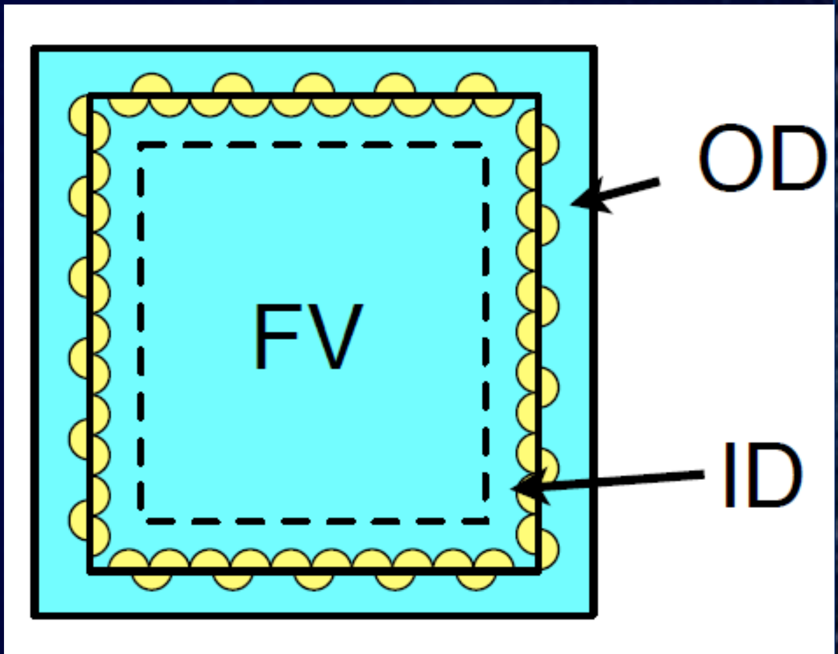


"The T2K Experiment", K. Abe, et al., Nucl. Instr. and Meth. A **659**, 106 (2011)

The Far Detector: Super-Kamiokande

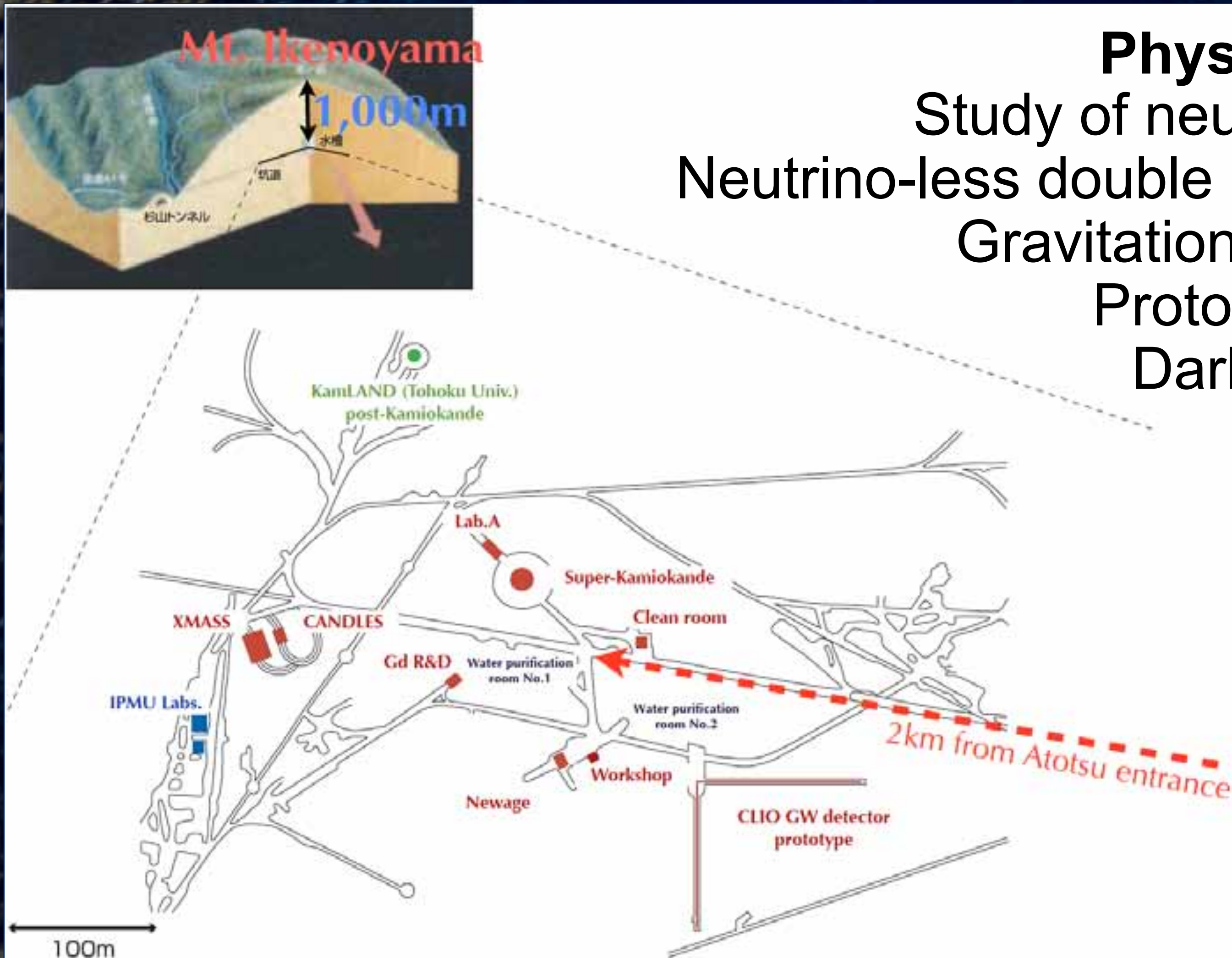
50 kton Water Cherenkov Detector
- Inner Detector (ID) w/ 11,000 20" PMTs
- Outer Detector (OD) w/ 1,840 8" PMTs
- 40% Photocathode coverage





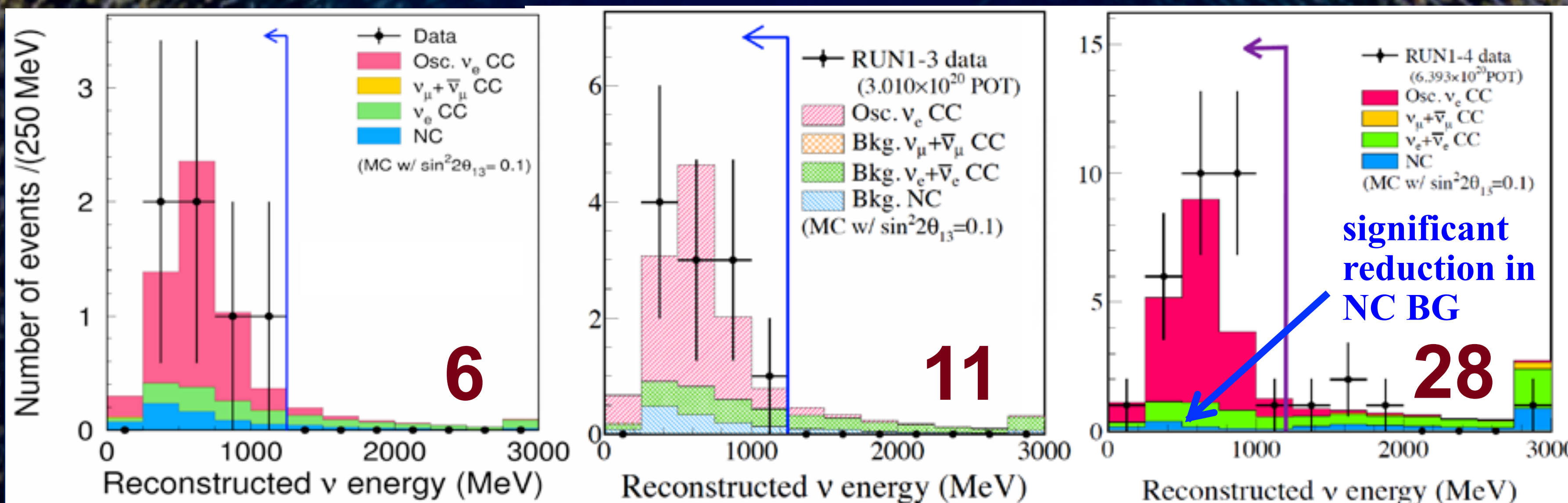
Fully Contained (FC) events
FCFV events for analysis

Kamioka (Underground) Observatory Layout



Physics Programs:
Study of neutrino oscillation
Neutrino-less double β-decay search
Gravitational wave search
Proton decay search
Dark matter search

T2K Reconstructed E_ν Spectrum of the Final Selected Events



Year	2011	2012	2013
POT (10^{20})	1.43	3.01	6.57
$N_{\nu_e}^{\text{obs.}}$	6	11	28
$N_{\text{BG}}^{\text{exp}}$	1.5 ± 0.3	3.3 ± 0.4	4.92 ± 0.55
$\sin^2 2\theta_{13}$(T2K)	0.11	$0.088^{+0.049}_{-0.033}$	$0.140^{+0.038}_{-0.032}$
Significance	2.5σ	3.1σ	7.3σ
Systematic Error (%) on $N_{\text{tot}}^{\text{exp}}$	17.5	9.9	8.8

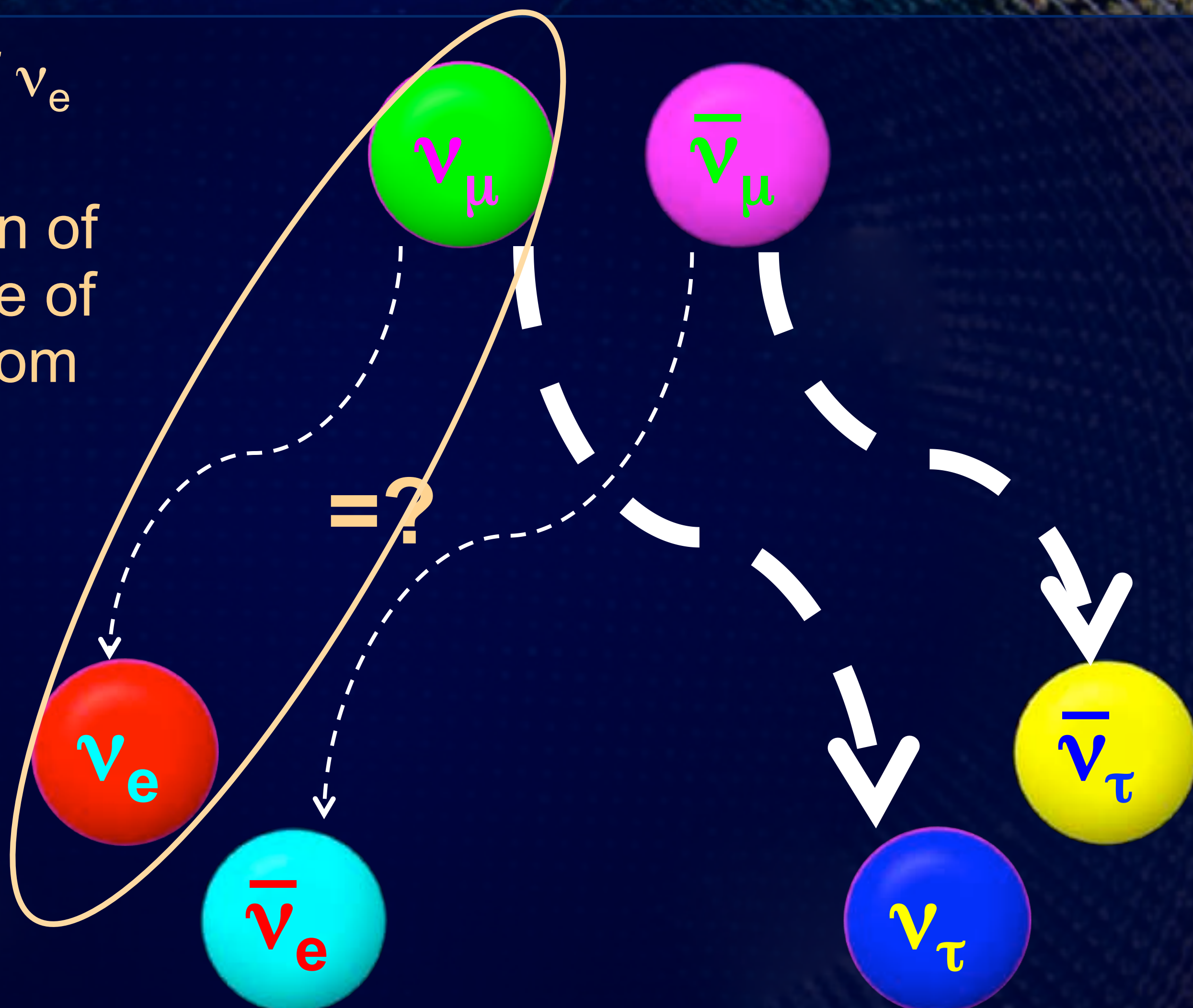
- θ_{13}= 0 is excluded at 7.3σ level of significance

→ Discovery of ν_e appearance from a ν_μ beam!

Physics Goals of Long Baseline Accelerator Based Neutrino Oscillation Experiments

T2K's discovery of ν_e appearance:

→ First observation of explicit appearance of a neutrino flavor from a different flavor neutrino beam



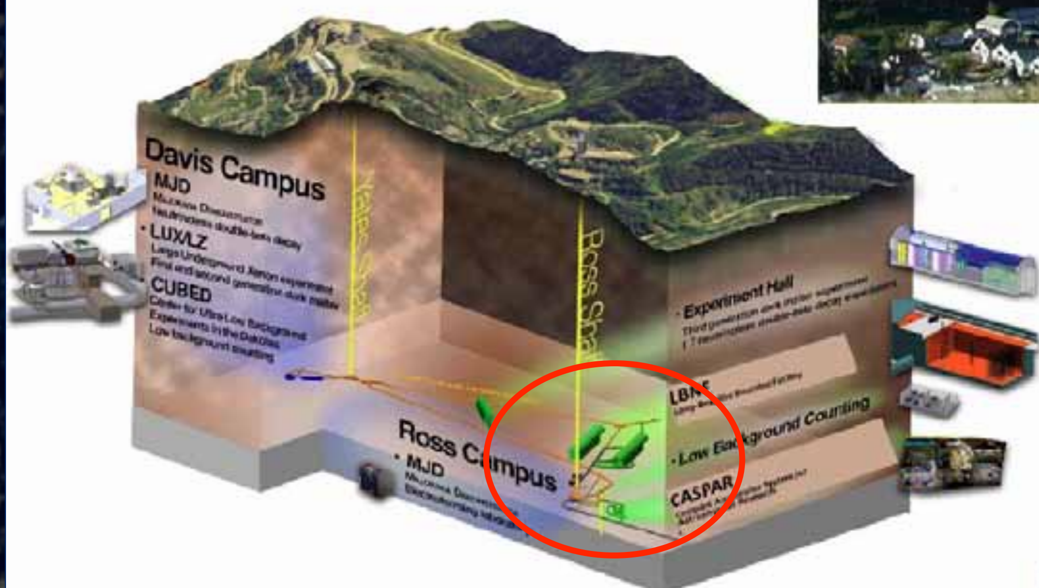
LBNE, LBNO, DUNE/LBNF and Hyper-Kamiokande

DUNE Far Detector Deep Underground at SURF, South Dakota

Experimental facility operated by the State of South Dakota.

Current experiments:

- LUX (dark matter)
- Majorana ($0\nu\beta\beta$)
- Several smaller experiments



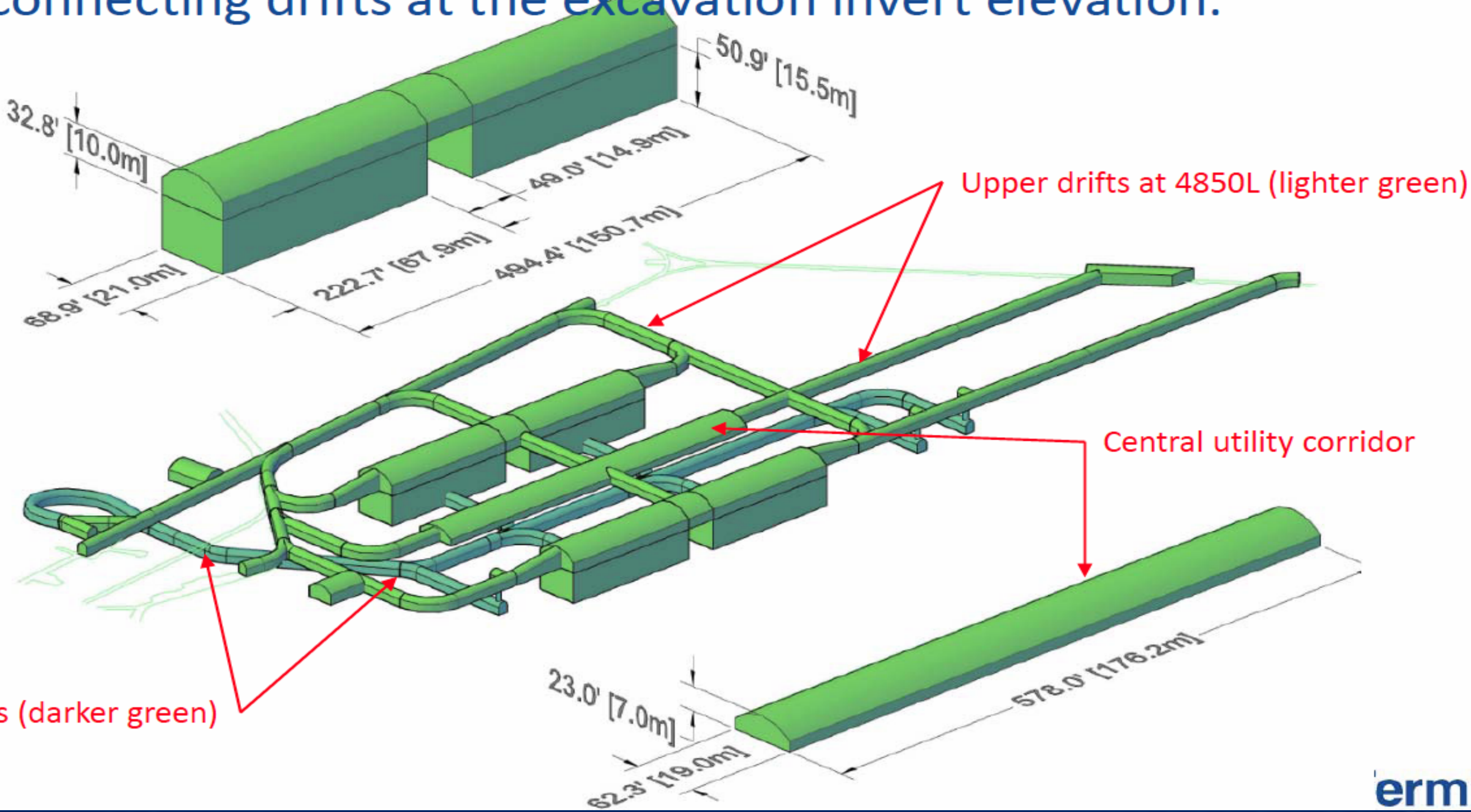
Future home of:

- LZ (G2 dark matter experiment)
- CASPAR (Compact Accelerator System for Astrophysical Research)
- DUNE-LBNF

Fermilab

LBNF Cavern Configuration for the DUNE Far Detector

Four LAr detector caverns, one central utility corridor, a series of connecting drifts at the 4850L (upper elevation), another series of lower connecting drifts at the excavation invert elevation.



LBNF Steel-supported Cryostat Design for DUNE

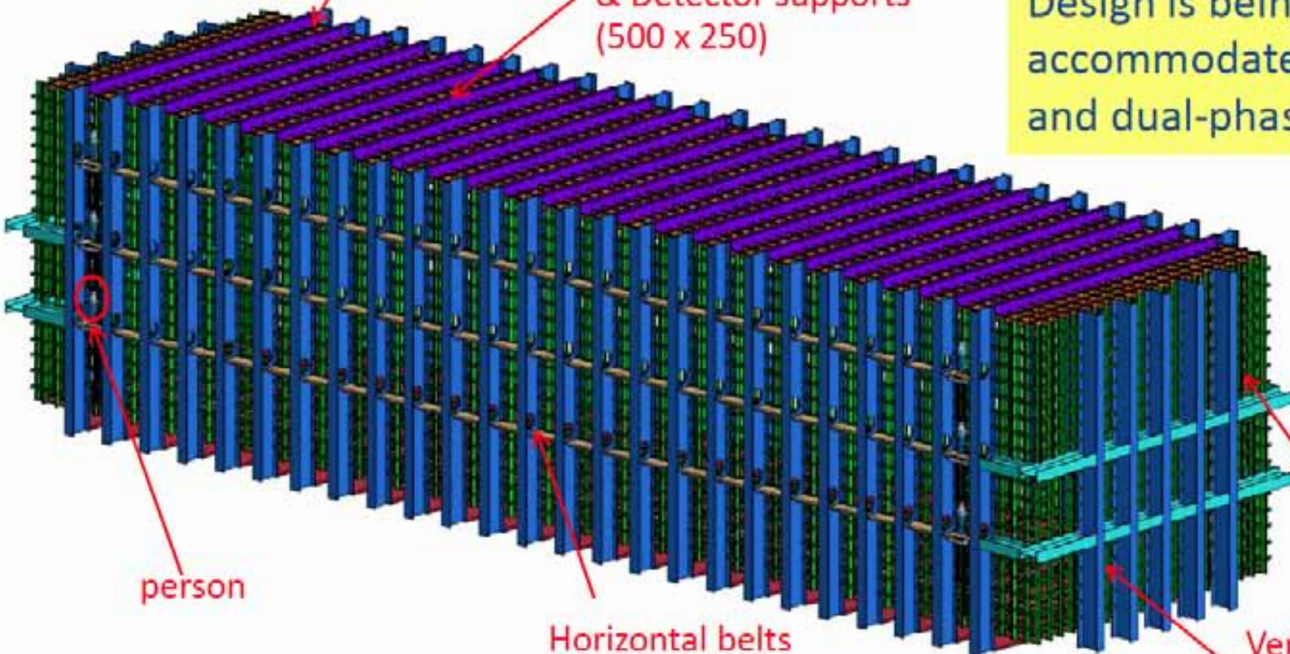
Steel-Frame Cryostat

Inner dimension (liquid+gas):

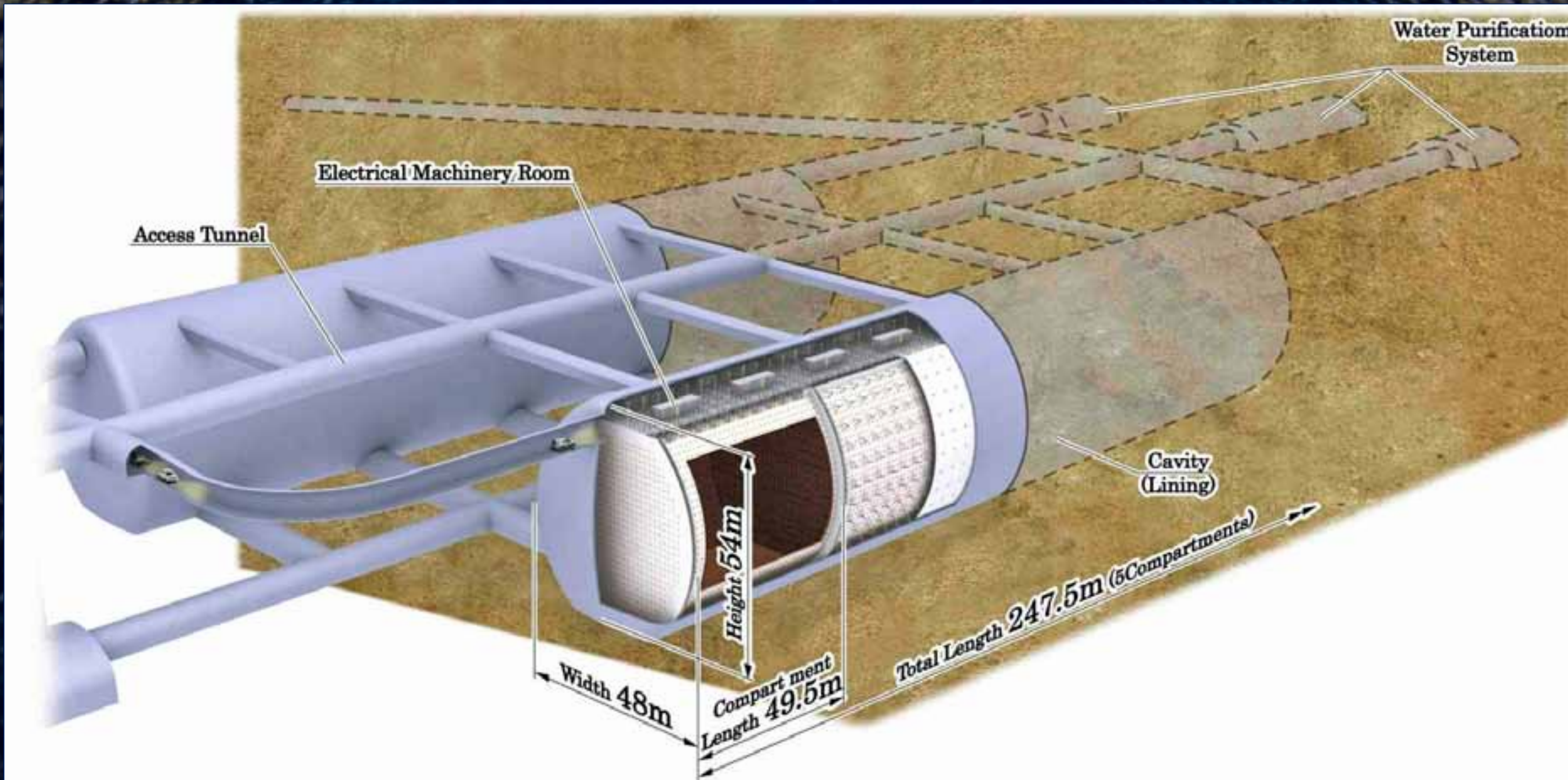
- L = 62.00 m
- W = 15.10 m
- H = 14.00 m

LAr = 17'432 tons (95% liquid)

Design is being developed to accommodate both single- and dual-phase detectors.



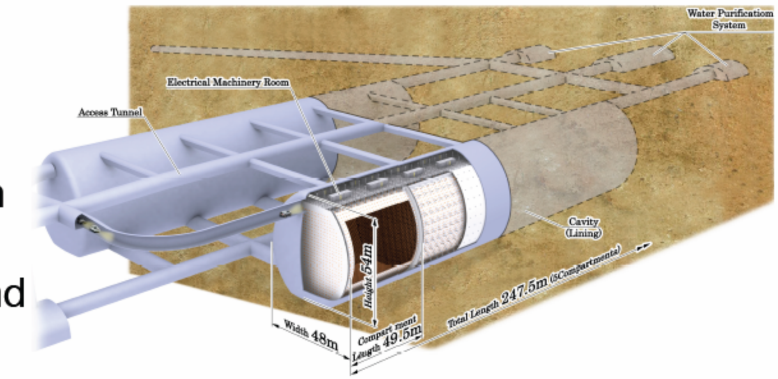
Hyper-Kamiokande
(Go Really Big!)

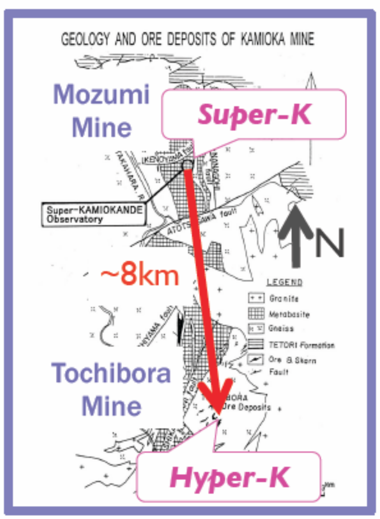


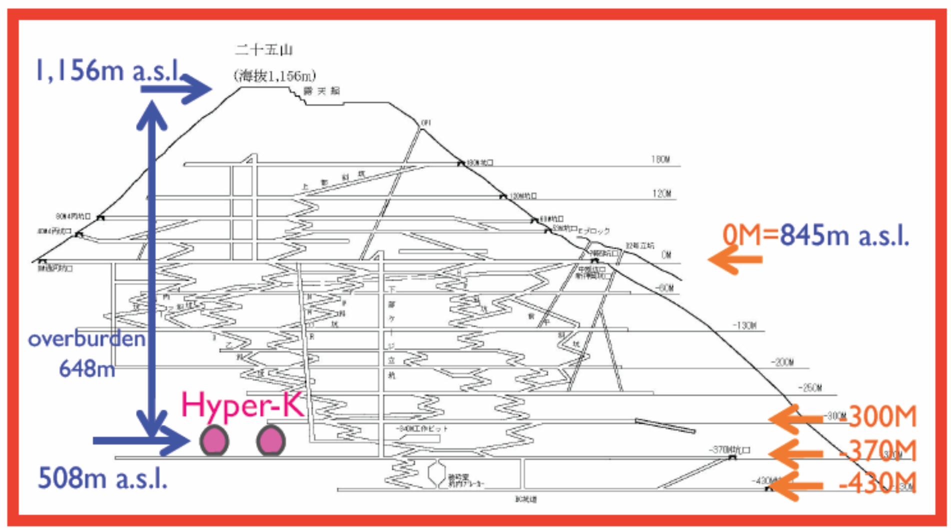
A new 1 Mton underground water Cherenkov detector near Super-Kamiokande is being proposed

Hyper-Kamiokande Candidate Site

- ✦ 8km south from Super-K
  - ✦ same T2K beam off-axis angle
- ✦ 2.6km horizontal drive from entrance
- ✦ under the peak of Nijuugo-yama
  - ✦ 648m of rock or 1,750 m.w.e. overburden
  - ✦ 508m above sea level
- ✦ dominated by Hornblende Biotite Gneiss and Migmatite
- ✦ 2.3km from waste rock disposal place
- ✦ 13,000 m^3/day or 1megaton/80days natural water







Conclusions

- **“Observation of ν_e appearance from a ν_μ beam”** has now been made
  - This opens the door to study CPV in neutrinos
  - Next generation experiments should follow in order to ensure the discoveries
- A new international collaboration (DUNE) has been formed
  - 768 members, 144 institutions (65 US and 79 non-US) from 26 countries
  - DOE CD-1 “Refresh” Review in July 2015
- A proposal for Hyper-Kamiokande is being prepared as well
- Particle/nuclear physics underground labs are now at a matured stage
  - Many labs around the world w/ more to come → getting bigger!
- Neutrino oscillation (i.e. the existence of massive neutrino states) is the only phenomena beyond the SM observed in laboratory venue today
- Measurement of CPV will provide critical experimental input to our understanding of the matter–antimatter asymmetry in the universe

The End