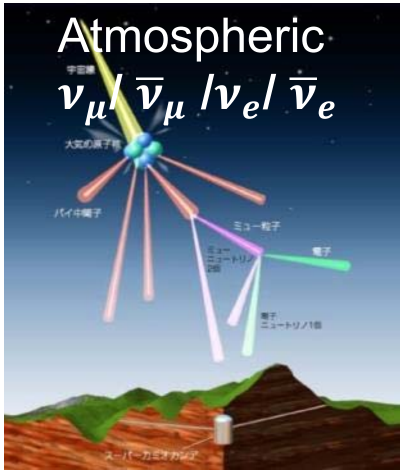
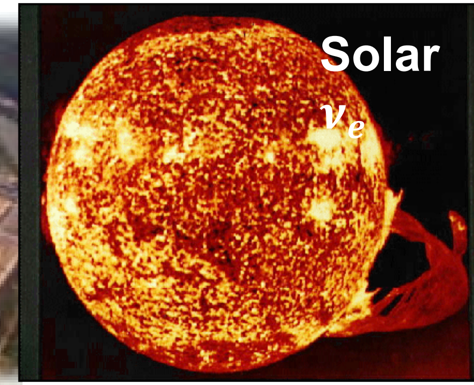
PROSPECT OF LONG BASELINE NEUTRINO OSCILLATION EXPERIMENTS

A.K.Ichikiawa, Kyoto University

What we know about neutrino mass





Three mass values: m_1, m_2, m_3

- $\Delta m^2_{21} \equiv m_2^2 - m_1^2 = 7.53 \times 10^{-5}\ eV^2$
- $\Delta m^2_{32} \equiv m_3^2 - m_2^2 = 2.51 \times 10^{-3}\ eV^2$

  or $-2.56 \times 10^{-3}\ eV^2$

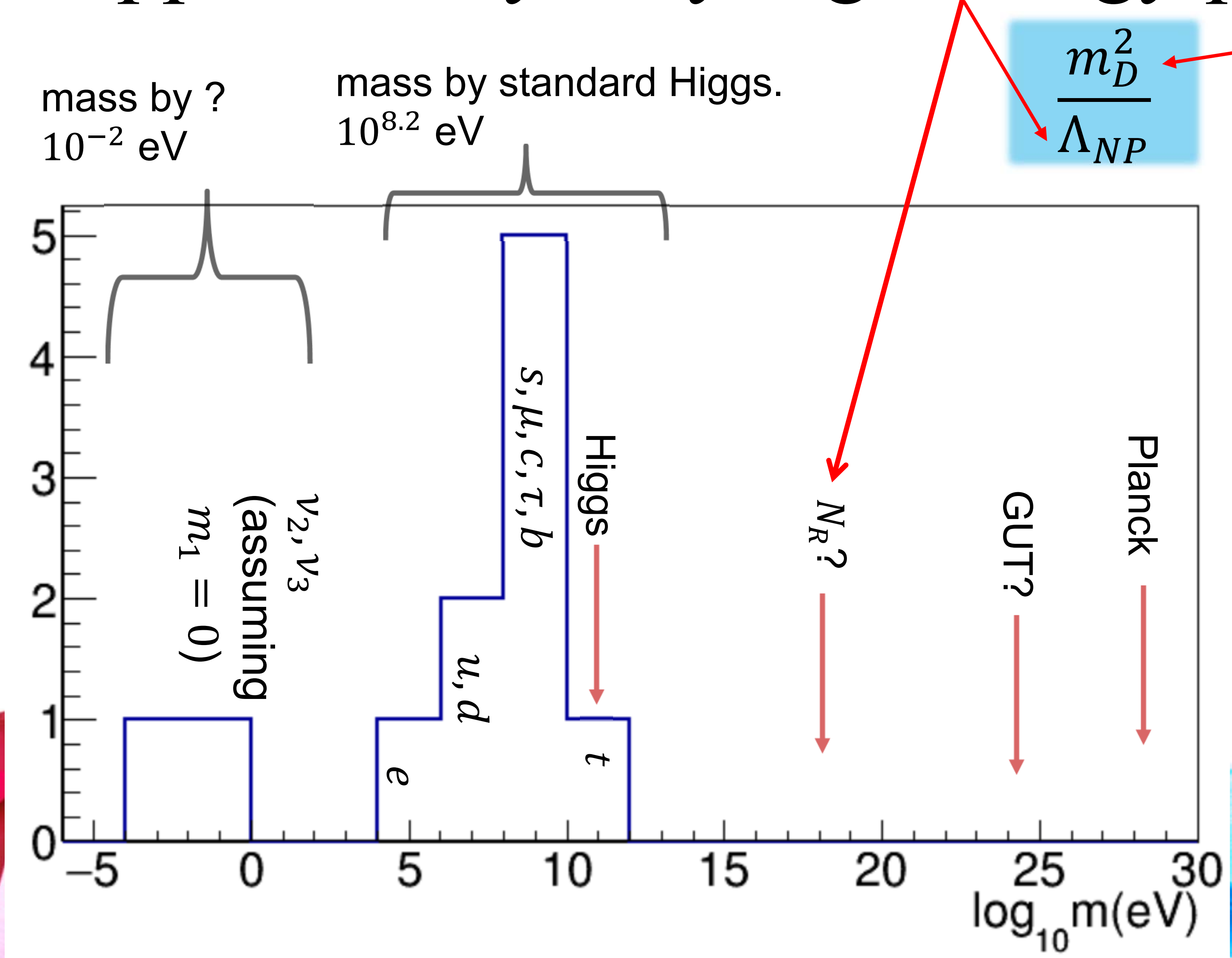
- Cosmological observations

  $\sum_j m_j < 0.12\ eV$ (95% CL)

  ↓

- If $m_1 \ll m_2 \ll m_3$, $m_2 \sim 9\mathrm{meV}, m_3 \sim 50\ \mathrm{meV}$

Neutrino mass is suppressed by very high energy physics?



Mixing between flavor and mass

Flavor eigenstates Mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix}$$

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

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

What we know about mixing

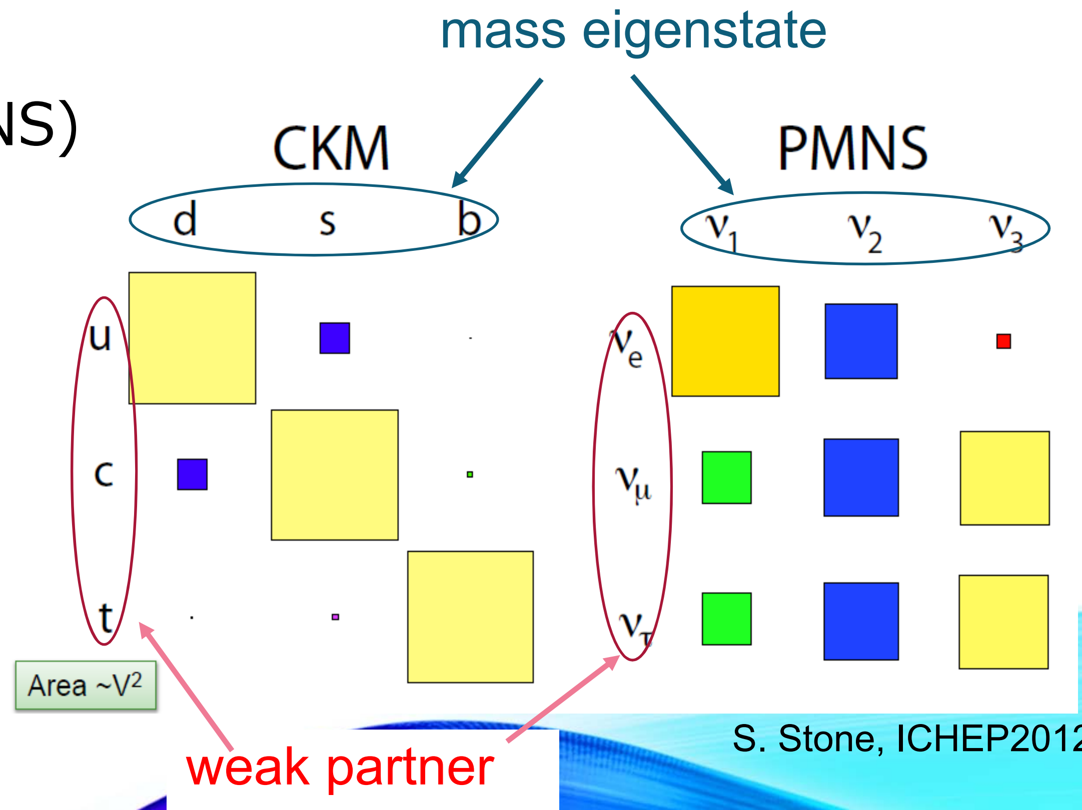
quark mixing matrix (CKM)

$$\begin{pmatrix} 0.9742 & 0.2243 & 0.0039 \\ 0.218 & 0.997 & 0.042 \\ 0.0081 & 0.04 & 1.02 \end{pmatrix}$$

lepton mixing matrix (PMNS)

$$\begin{pmatrix} 0.82 & 0.55 & 0.146 \\ -0.469 & 0.51 & 0.71 \\ 0.32 & -0.66 & 0.70 \end{pmatrix}$$

* smallest digits correspond to the current precision



S. Stone, ICHEP2012

Dirac CP phase, source of CPV

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

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

- Quark case $\delta_{CP}^{CKM} \sim 60° \sim 70°$
  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. : $J_{CP} \equiv Im\left(U_{\mu 3} U_{e3}^* U_{e2} U_{\mu 2}^*\right)$

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

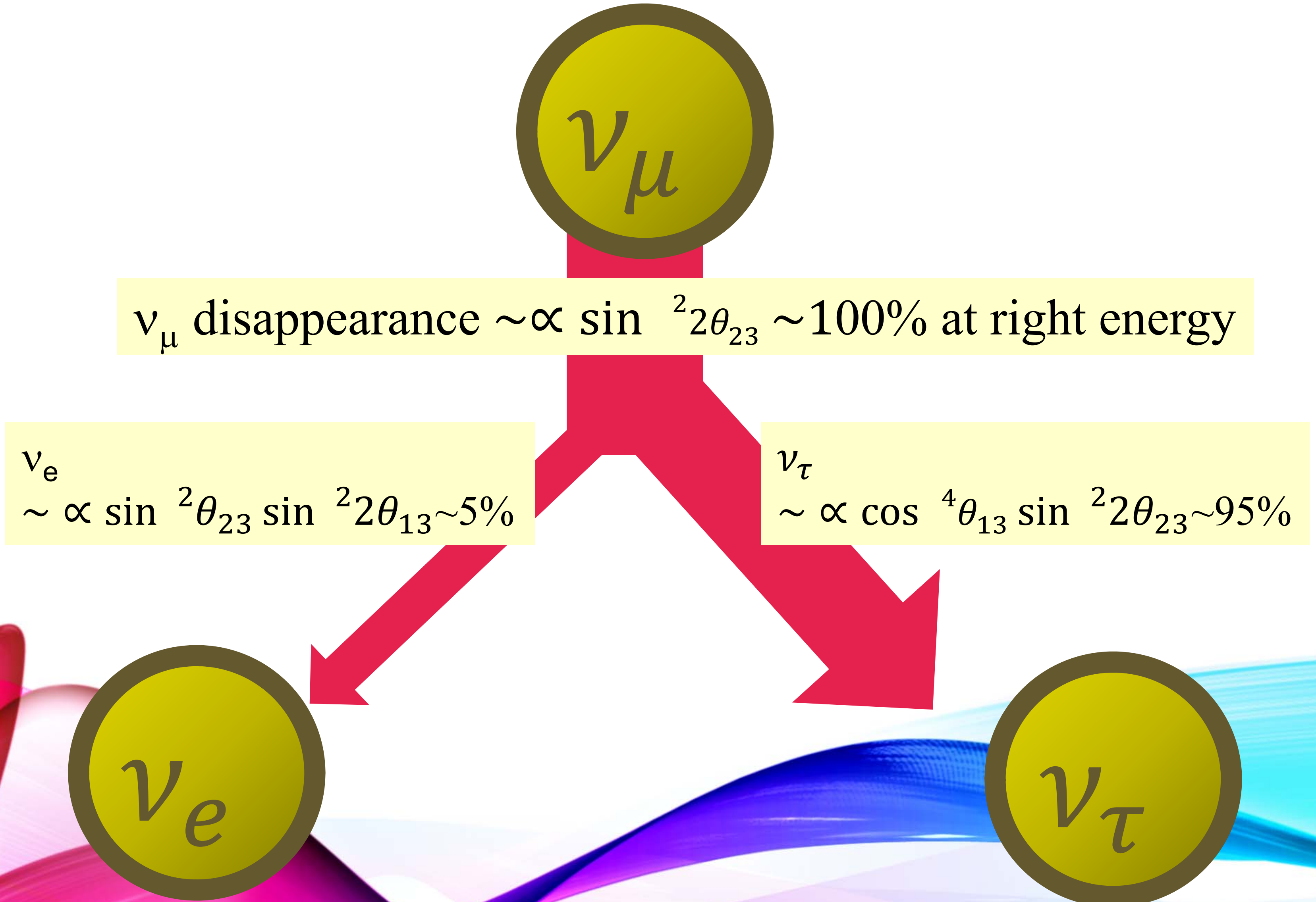
$$J_{CP}^{PMNS} \approx 0.033 \sin\delta_{CP}$$

Leptonic CPV can be much larger than Quark's

δ_{CP}^{PMNS} may or may not be the source of matter dominant universe,

but can be large enough to create our Universe matter-antimatter asymmetry.

Oscillations peculiar to the long baseline experiment



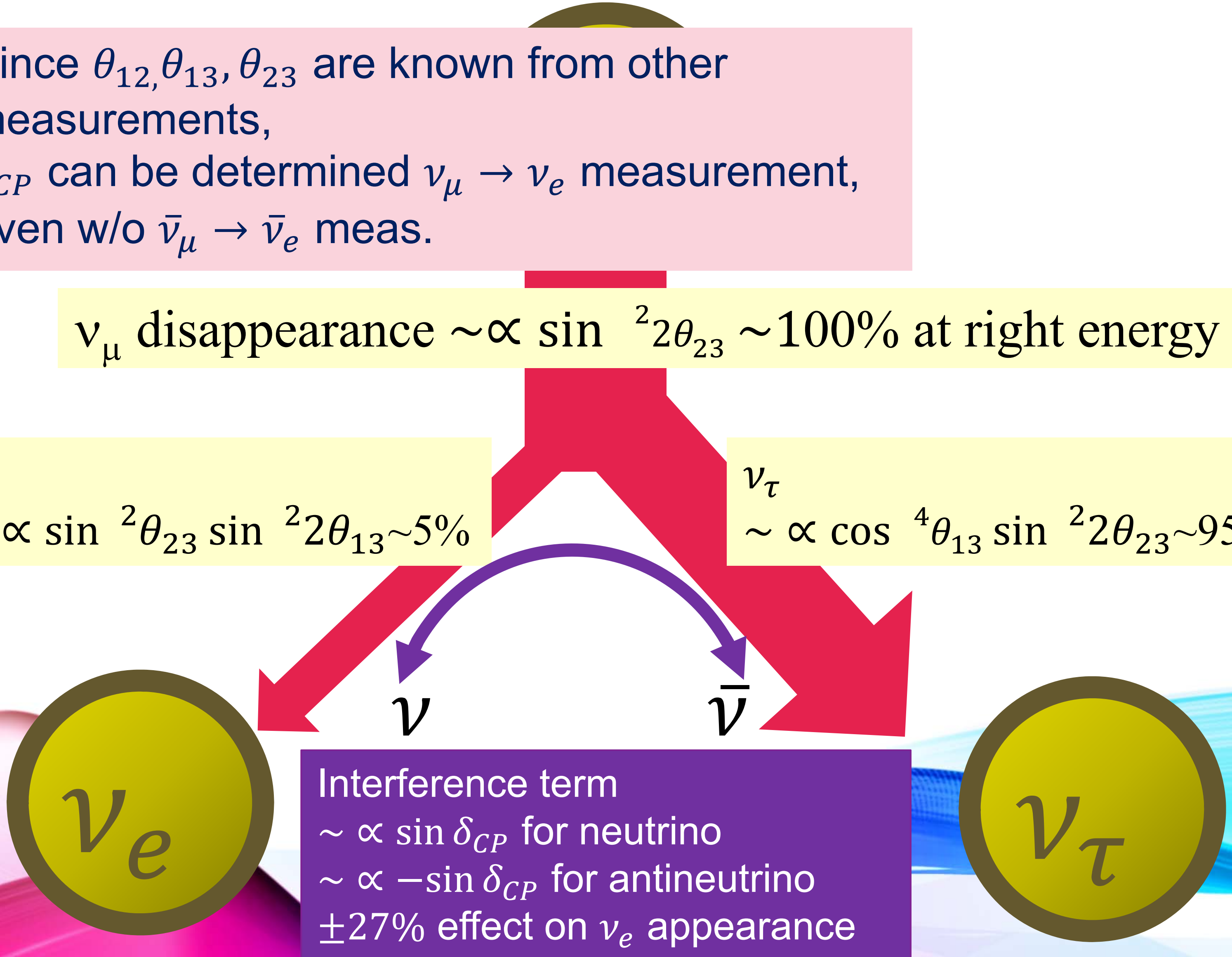
Oscillations peculiar to the long baseline experiment

Since $\theta_{12}, \theta_{13}, \theta_{23}$ are known from other measurements,
δ_{CP} can be determined $\nu_\mu \rightarrow \nu_e$ measurement,
even w/o $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ meas.

ν_μ disappearance $\sim\propto \sin^2 2\theta_{23}$ ~100% at right energy

ν_e
$\sim \propto \sin^2\theta_{23} \sin^2 2\theta_{13} \sim 5\%$

ν_τ
$\sim \propto \cos^4\theta_{13} \sin^2 2\theta_{23} \sim 95\%$

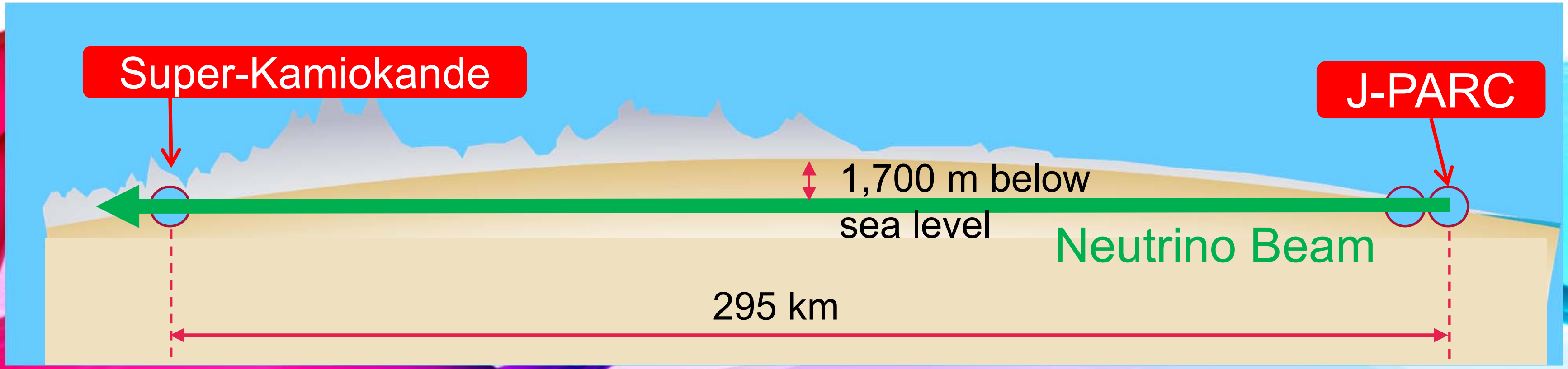


Interference term
$\sim \propto \sin\delta_{CP}$ for neutrino
$\sim \propto -\sin\delta_{CP}$ for antineutrino
$\pm 27\%$ effect on ν_e appearance

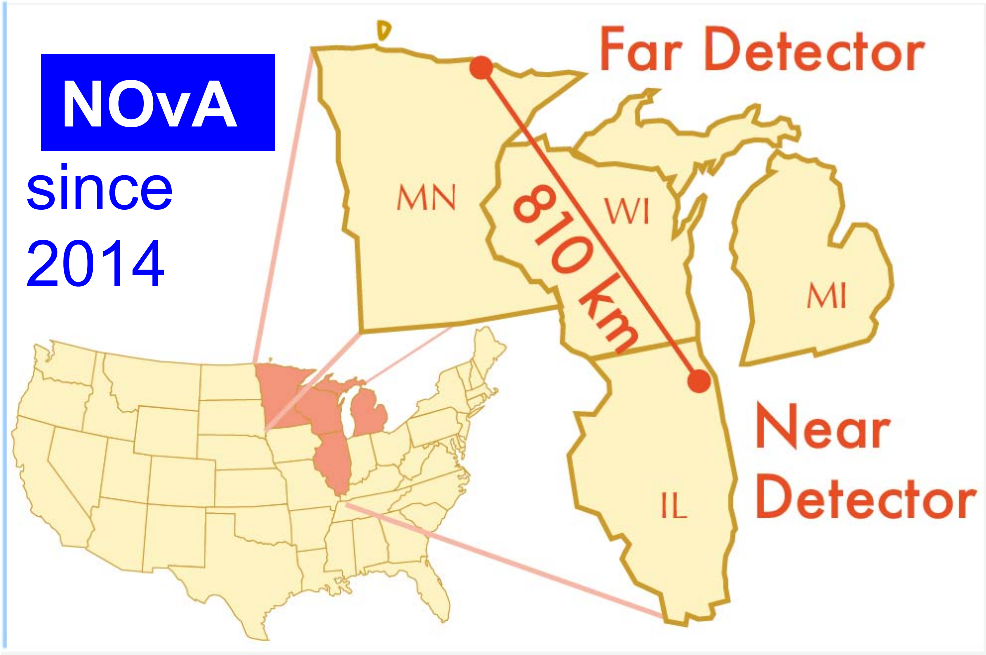
Some complexity from matter effect

"Earth is not symmetric about flavor nor CP"

- Neutrino feels potential from matter → affect oscillation
  - Difference between ν_e and ν_μ/ν_τ
  - Difference between ν and anti-ν
    - oscillation prob. is different for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$!
- Effect is opposite depending on mass order
  normal($m_1 < m_2 < m_3$) vs inverted($m_3 < m_1 < m_2$)
- Matter effect is larger for higher-E or Longer L
  Good synergy between US and Japan experiments!

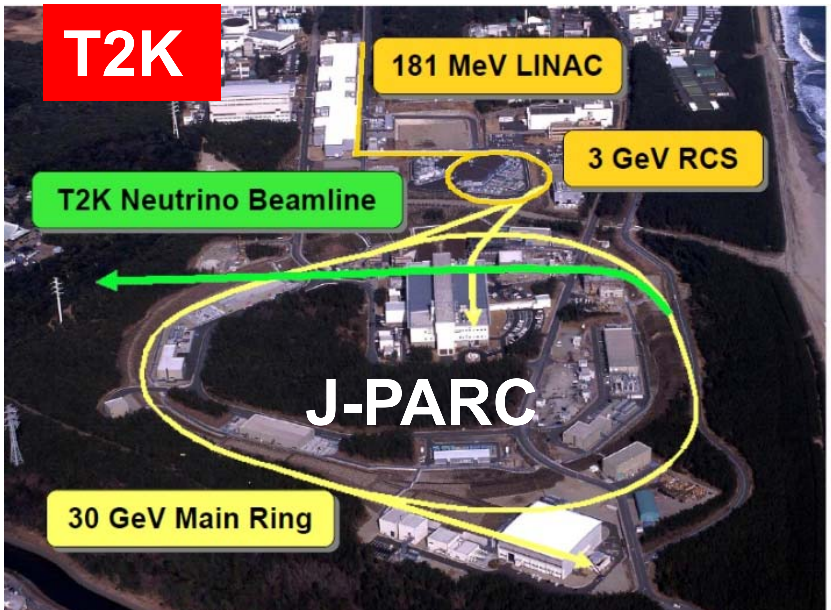


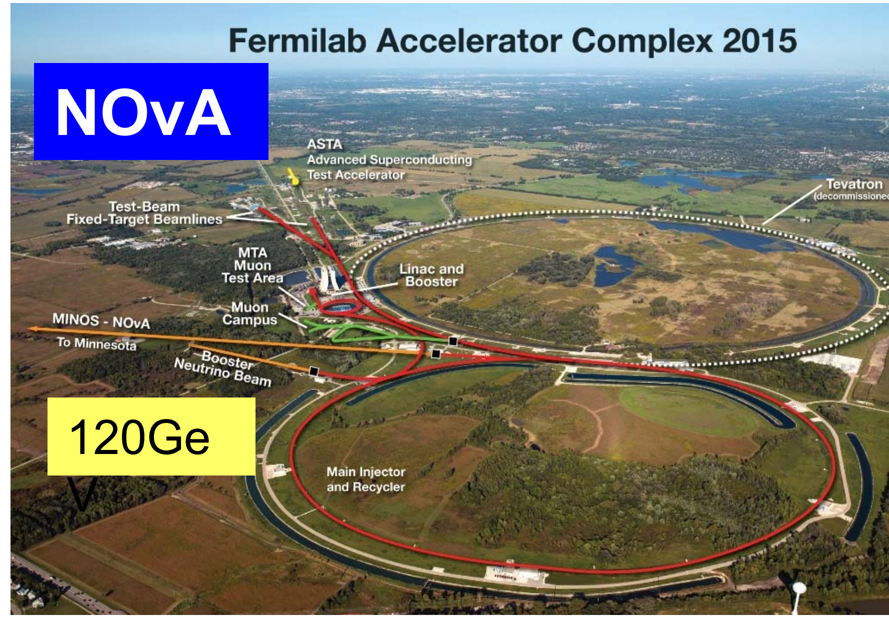
Running Accelerator long baseline experiments T2K and NOvA

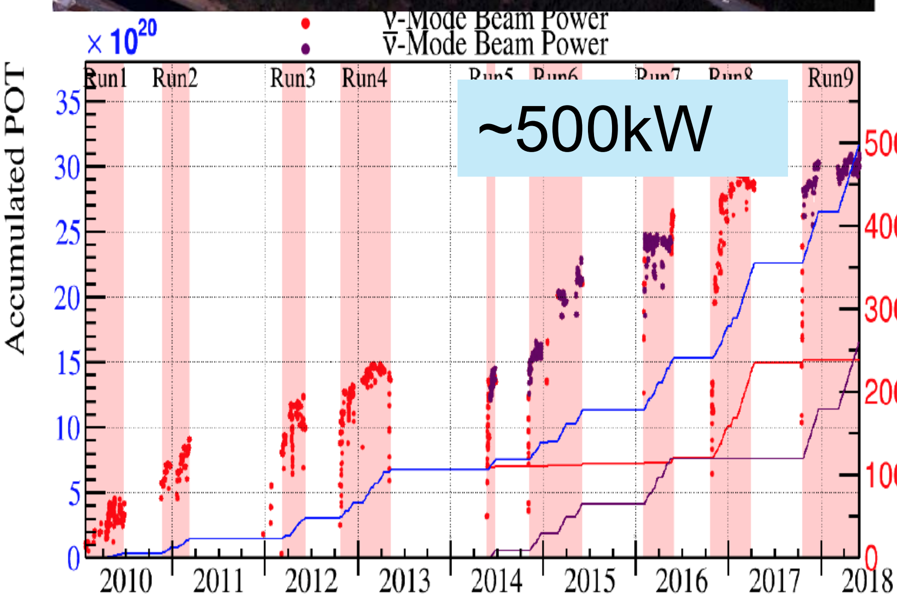


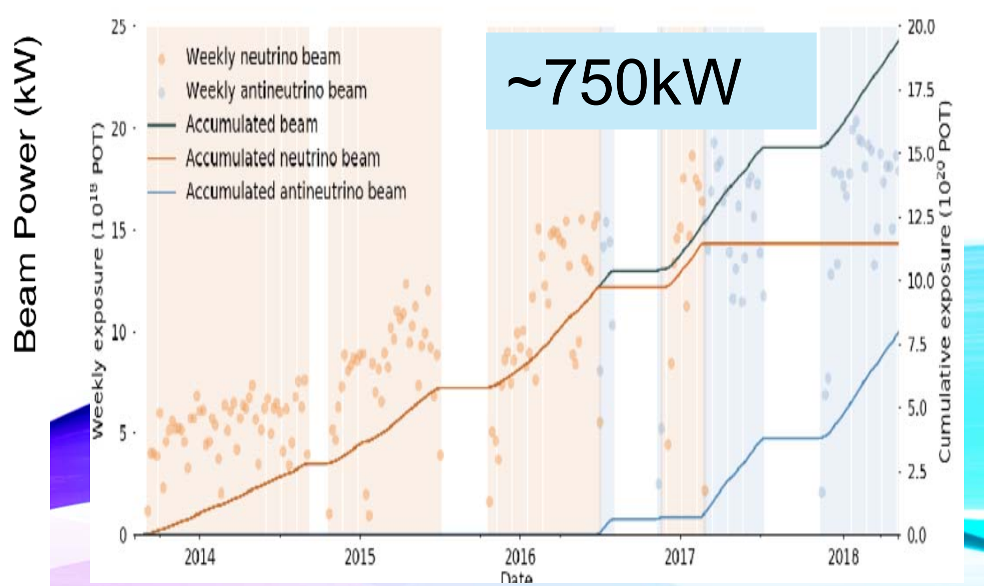
Matter effect ~10% for T2K and ~30% for NOvA
(Important to resolve degeneracies)

Running Accelerator long baseline experiments T2K and NOvA

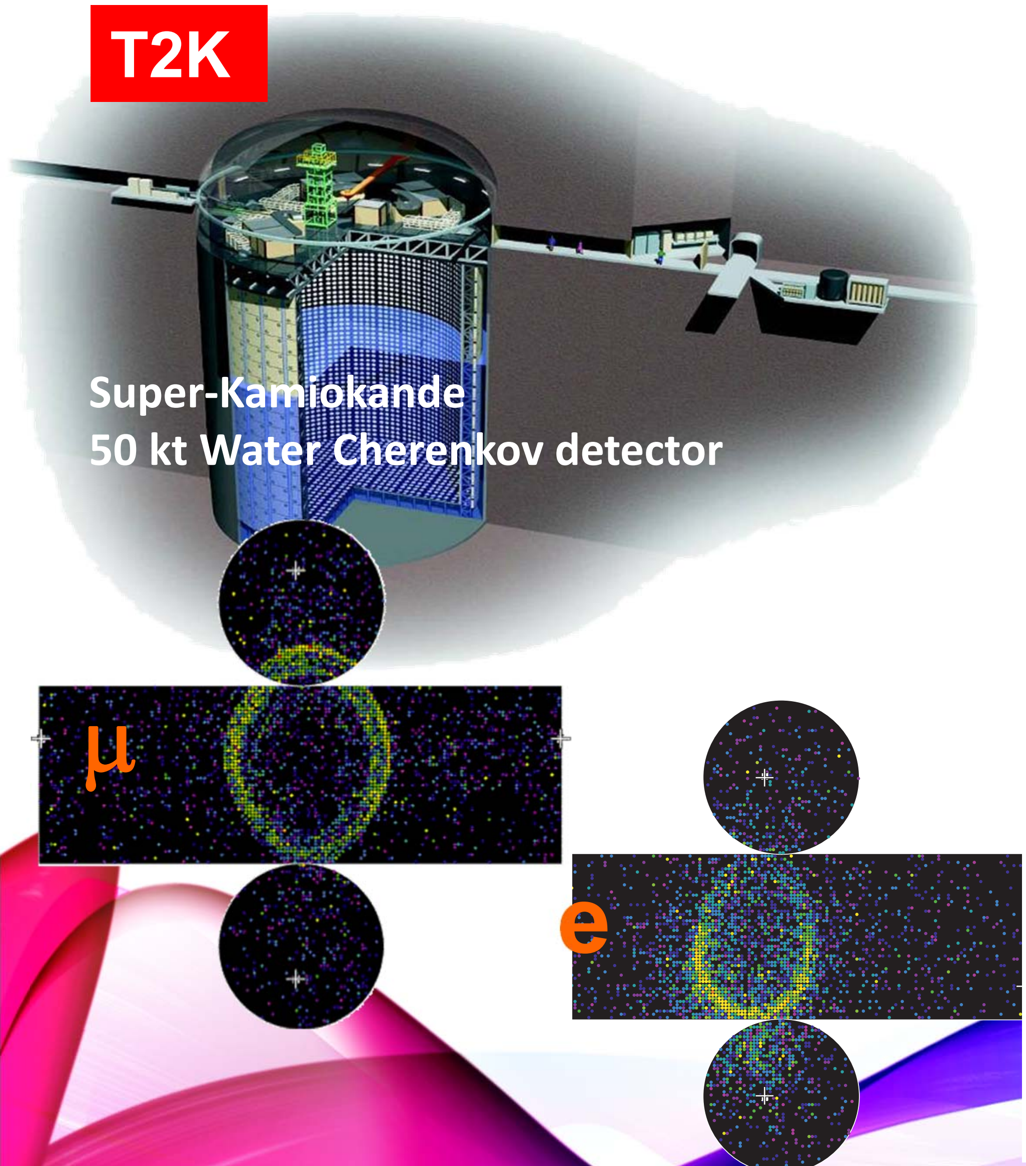


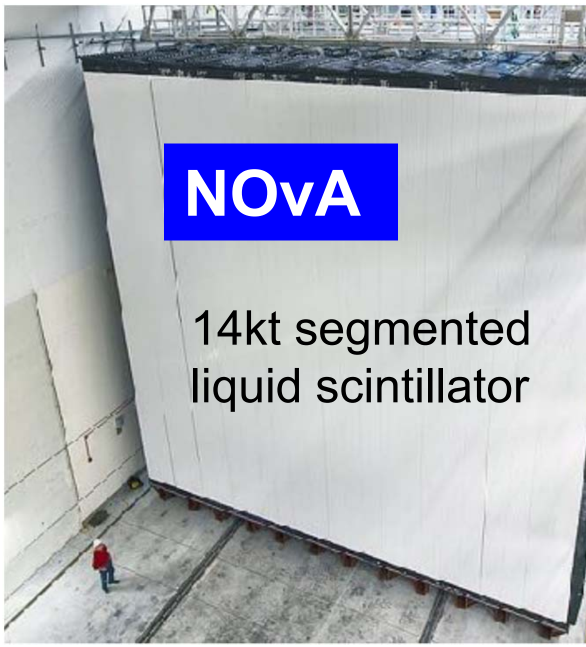


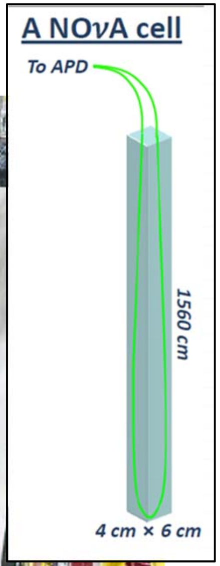


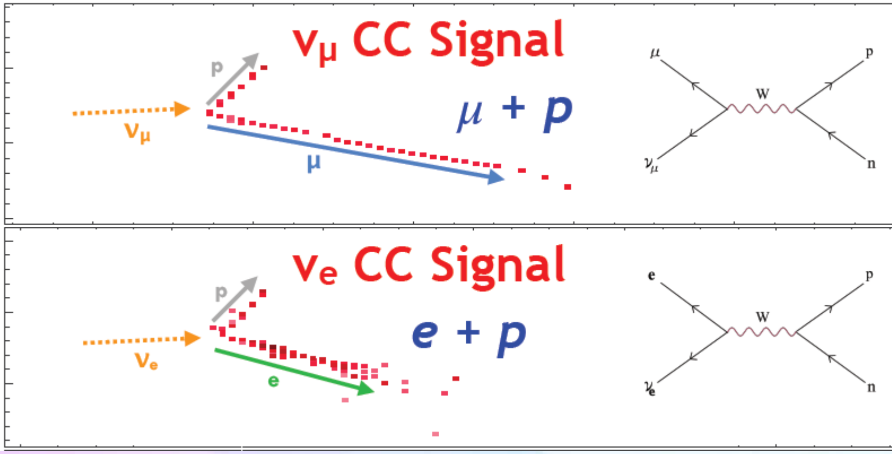


Running Accelerator long baseline experiments T2K and NOvA

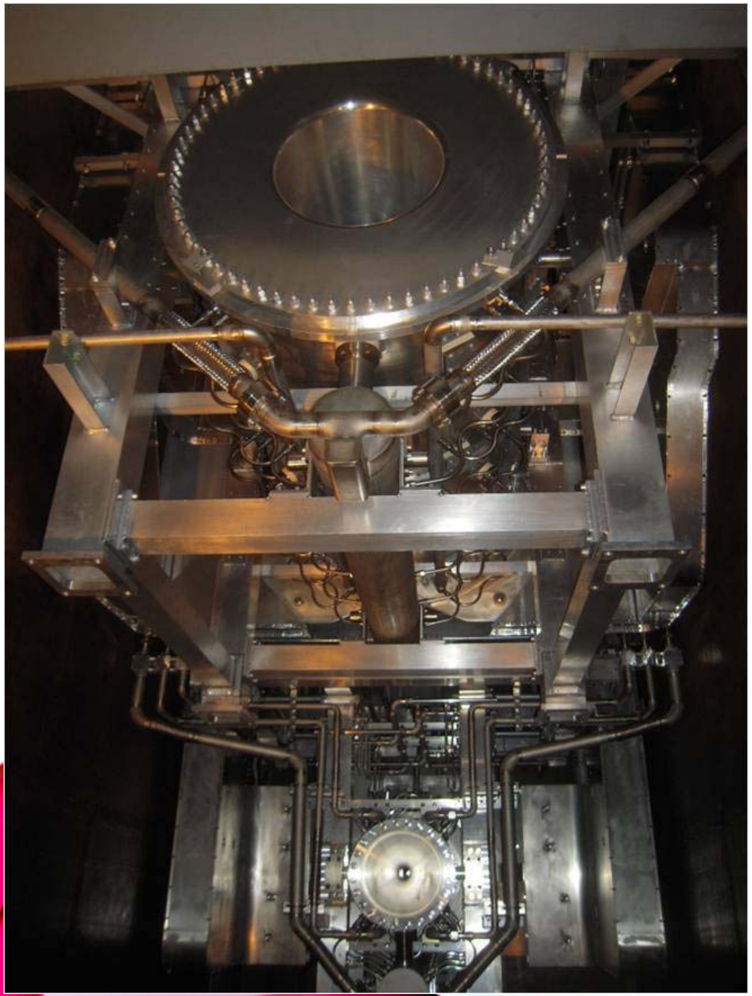








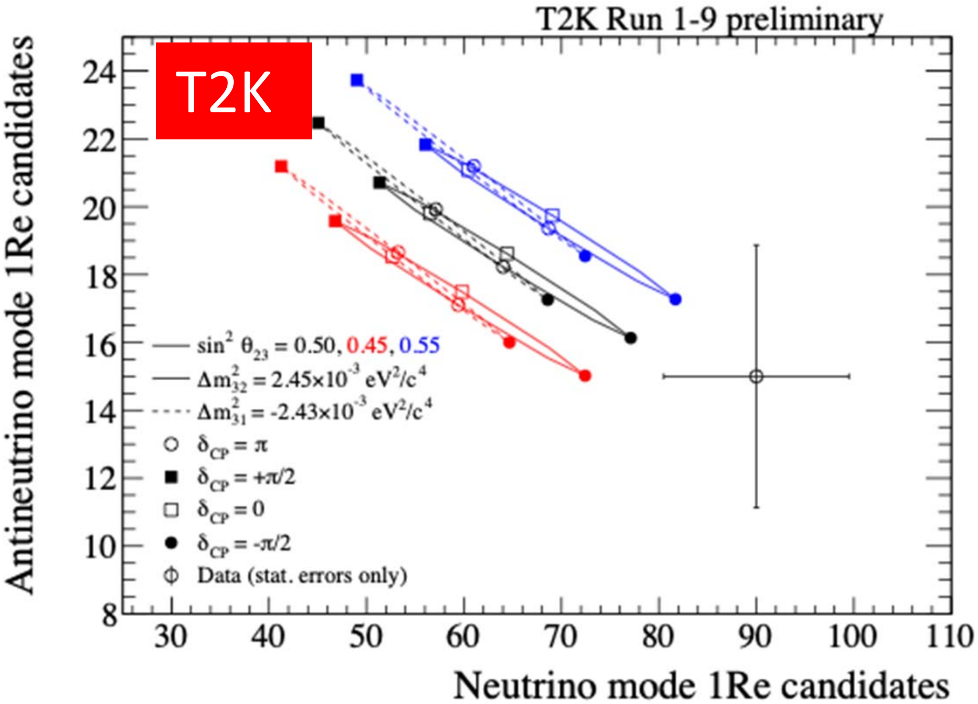
US Contributions to T2K

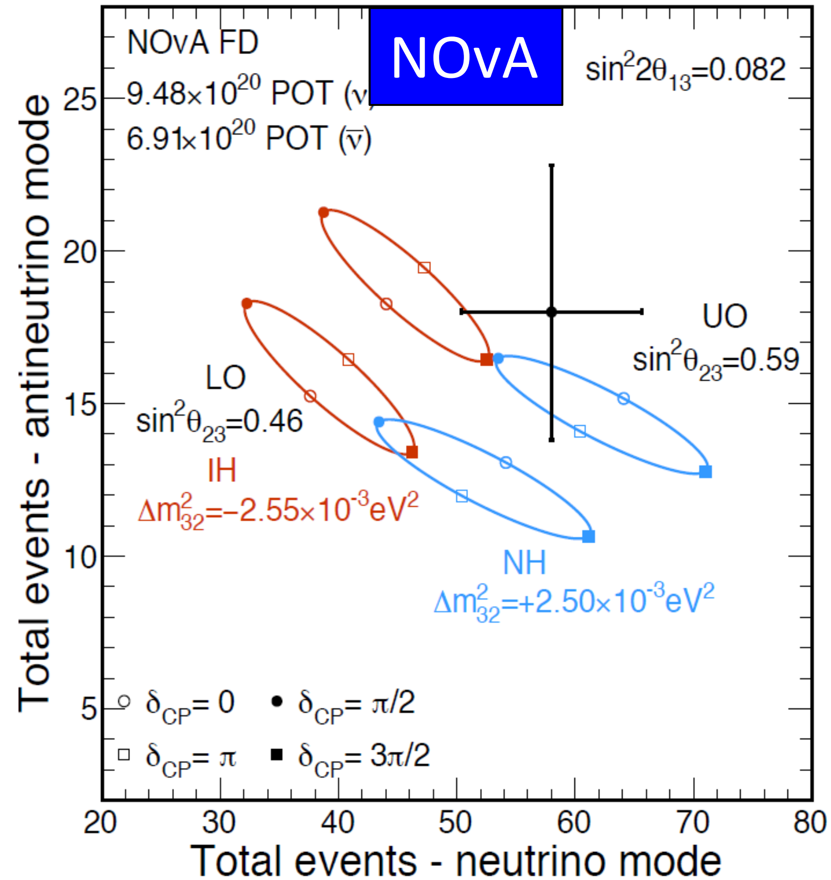


- **Many advices on neutrino beamline from FNAL NuMI**
- Electromagnetic horns
- GPS system
- P0D in near detector complex
- neutrino flux, interaction and cross section analysis
- Brand-new reconstruction software at Super-K
- Various oscillation analyses
- Various key leadership positions

etc. etc.

$\bar{\nu}_e$ v.s. ν_e in 2018





T2K : more ν, less anti-ν than expected → large CP violation?

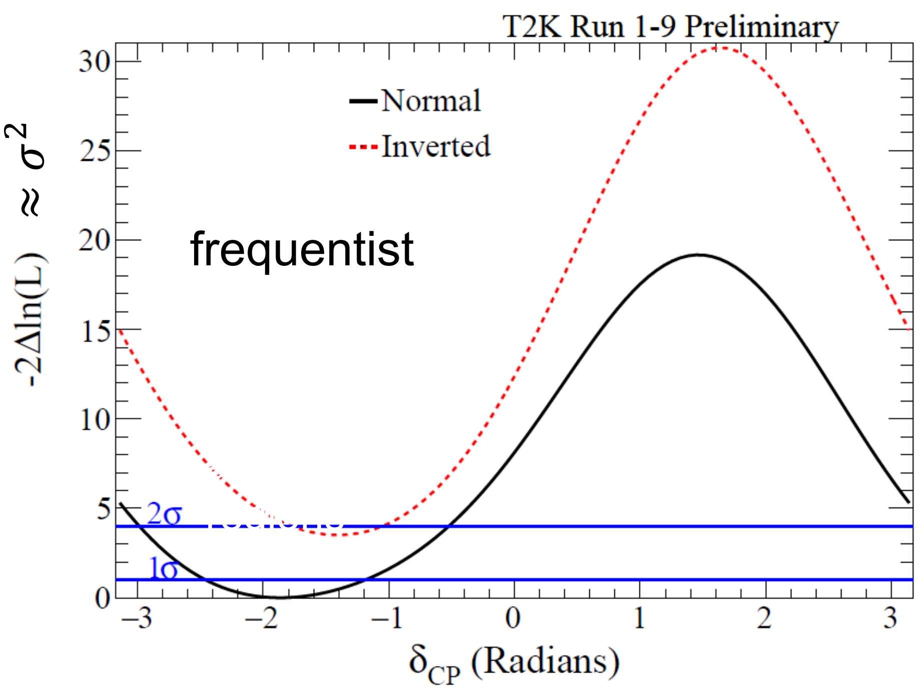
NOvA : $\theta_{23} > 45°$?

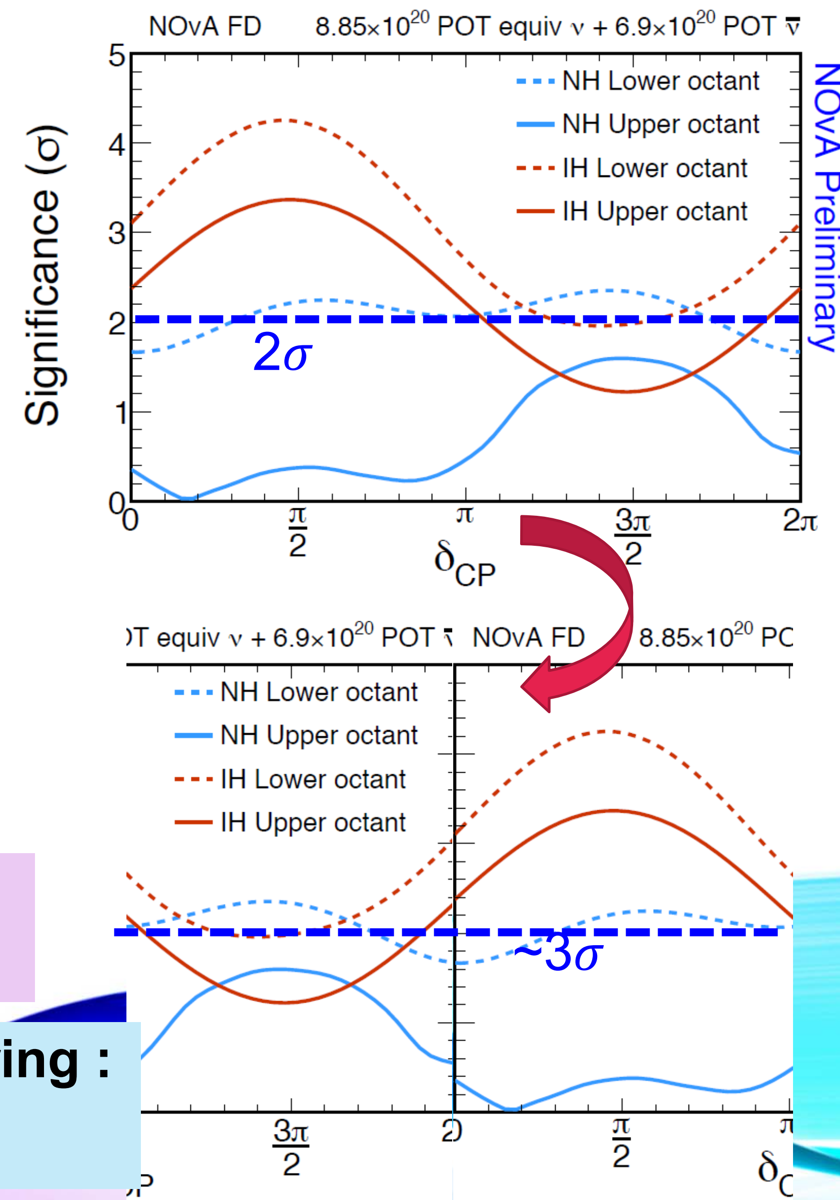
Hint of large CP violation by T2K

NOvA

T2K

$\Delta\chi^2$ v.s. δ_{CP}





T2K CP conserving case($\delta_{CP} = 0, \pi$) is disfavored by >2σ (95%) C.L.

T2K posterior probability for mass ordering :

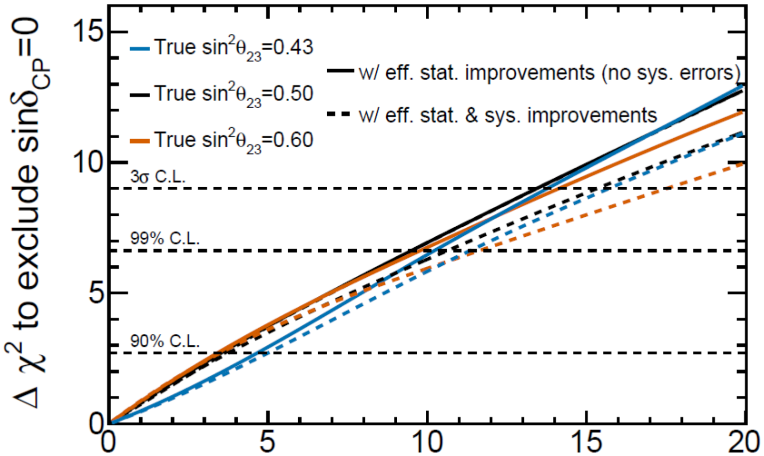
Normal 89%, Inverted 11%

T2K and NOvA future prospects

Both experiments are proposing extensions.

T2K

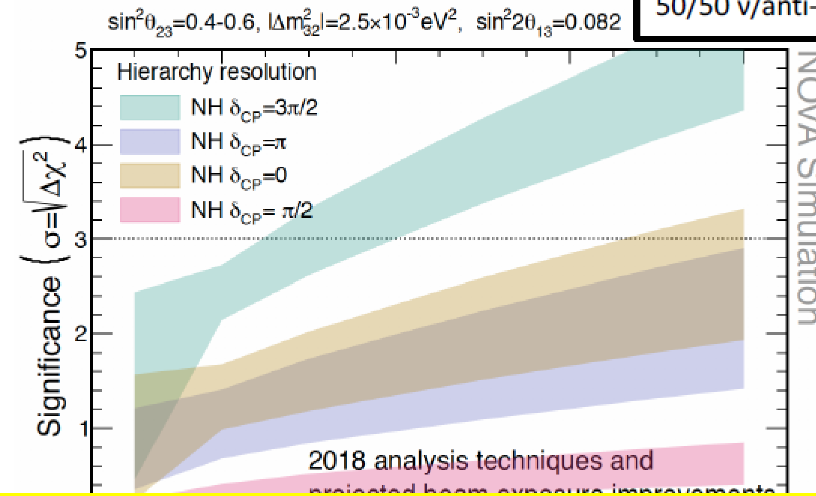
CPV sensitivity



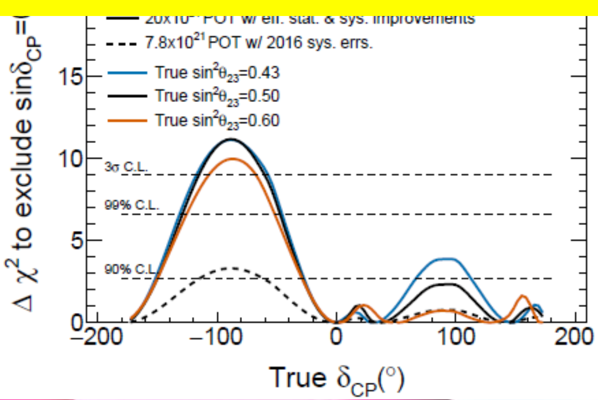
NOvA

mass hierarchy sensitivity

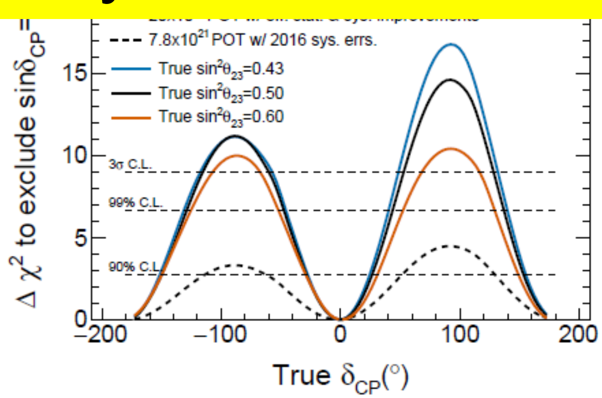
50/50 ν/anti-ν



T2K and/or NOvA may show CPV and mass order by 3σ.

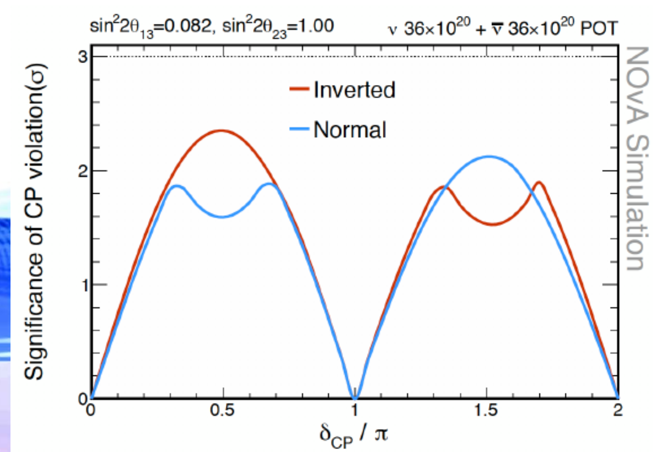


Mass order unknown



Mass order known

CPV sensitivity

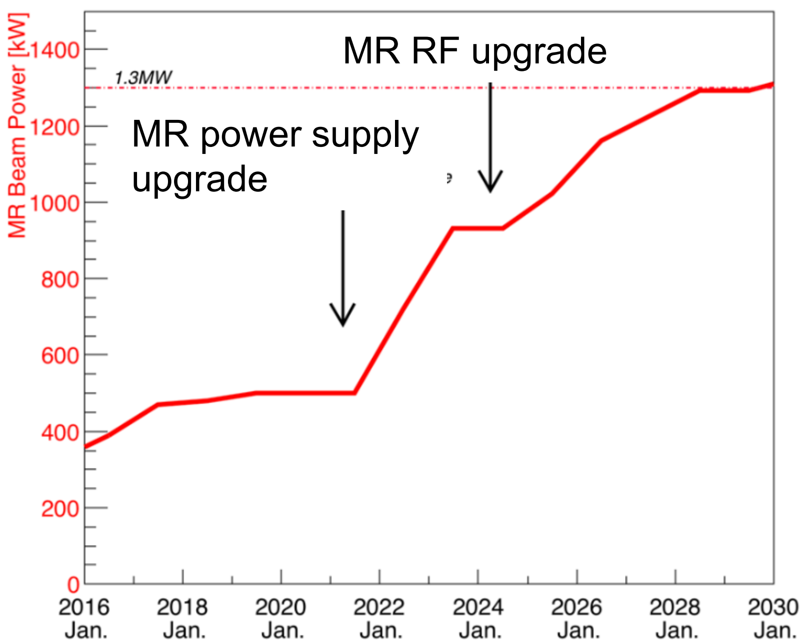


NOvA plan and T2K Upgrades plan

T2K

- Beam power 500 kW → 750 kW → 1.1 MW → 1.3 MW
- Near detector upgrades to reduce systematic error

T2K-II Target POT (Protons-On-Target)



NOvA

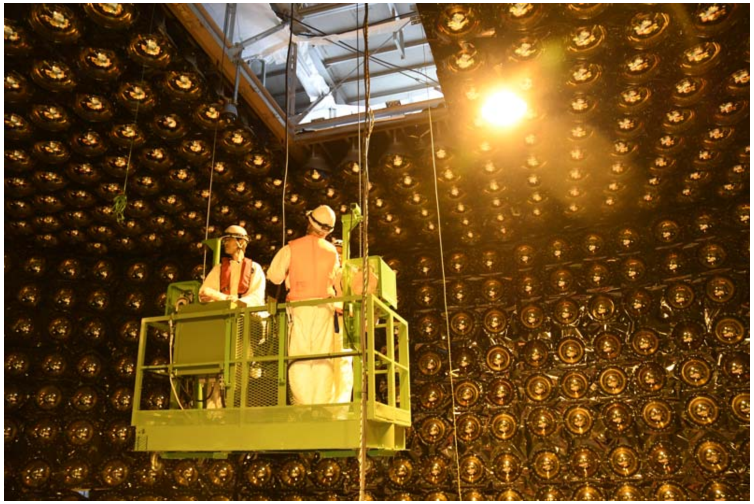
Accelerator and beamline improvement: 750 kW → 900+ kW

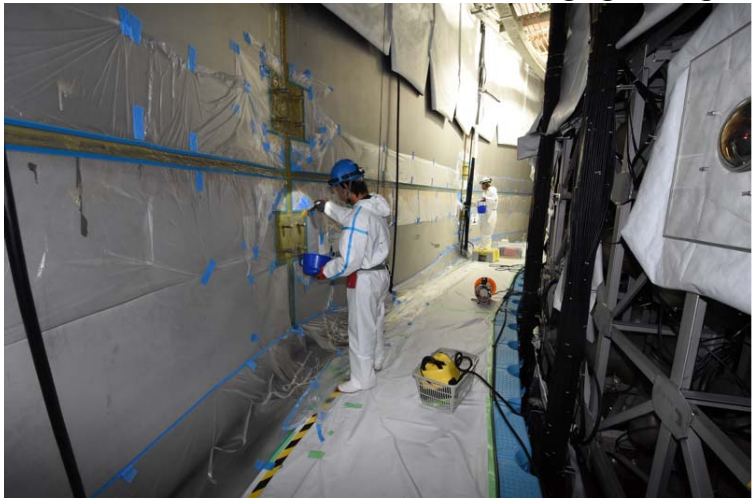
- ✓ high-power target in summer 2019
- ✓ Booster work as part of PIP-II over the next 1~3 years (Schedule TBD).

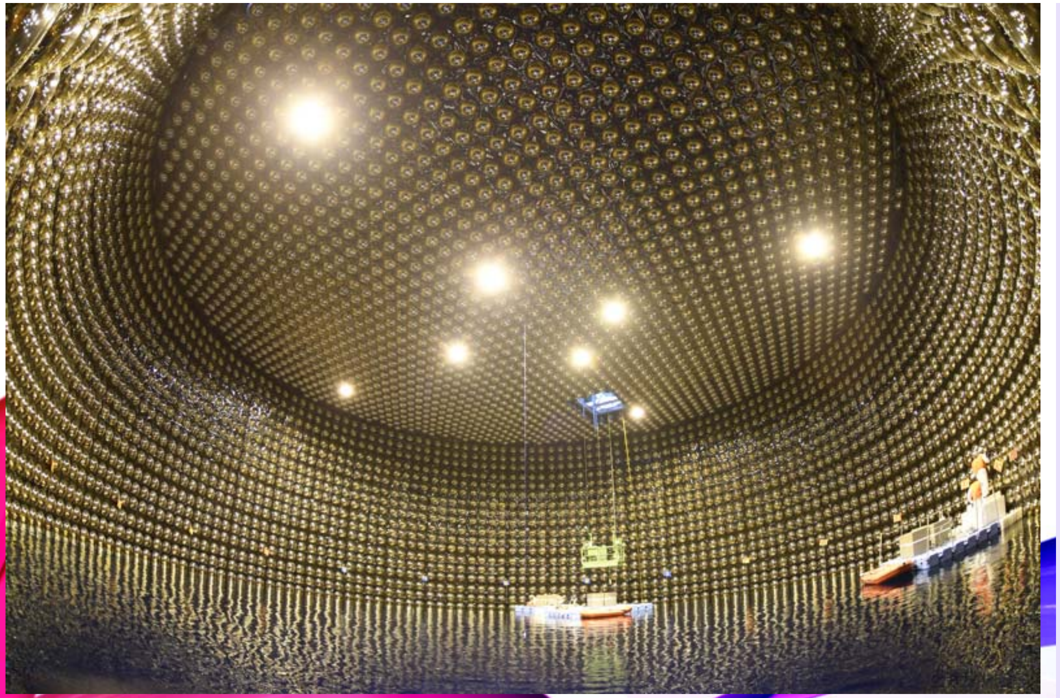
Run to 2025

SK-Gd

-dissolve Gd to SK water for neutron tagging -



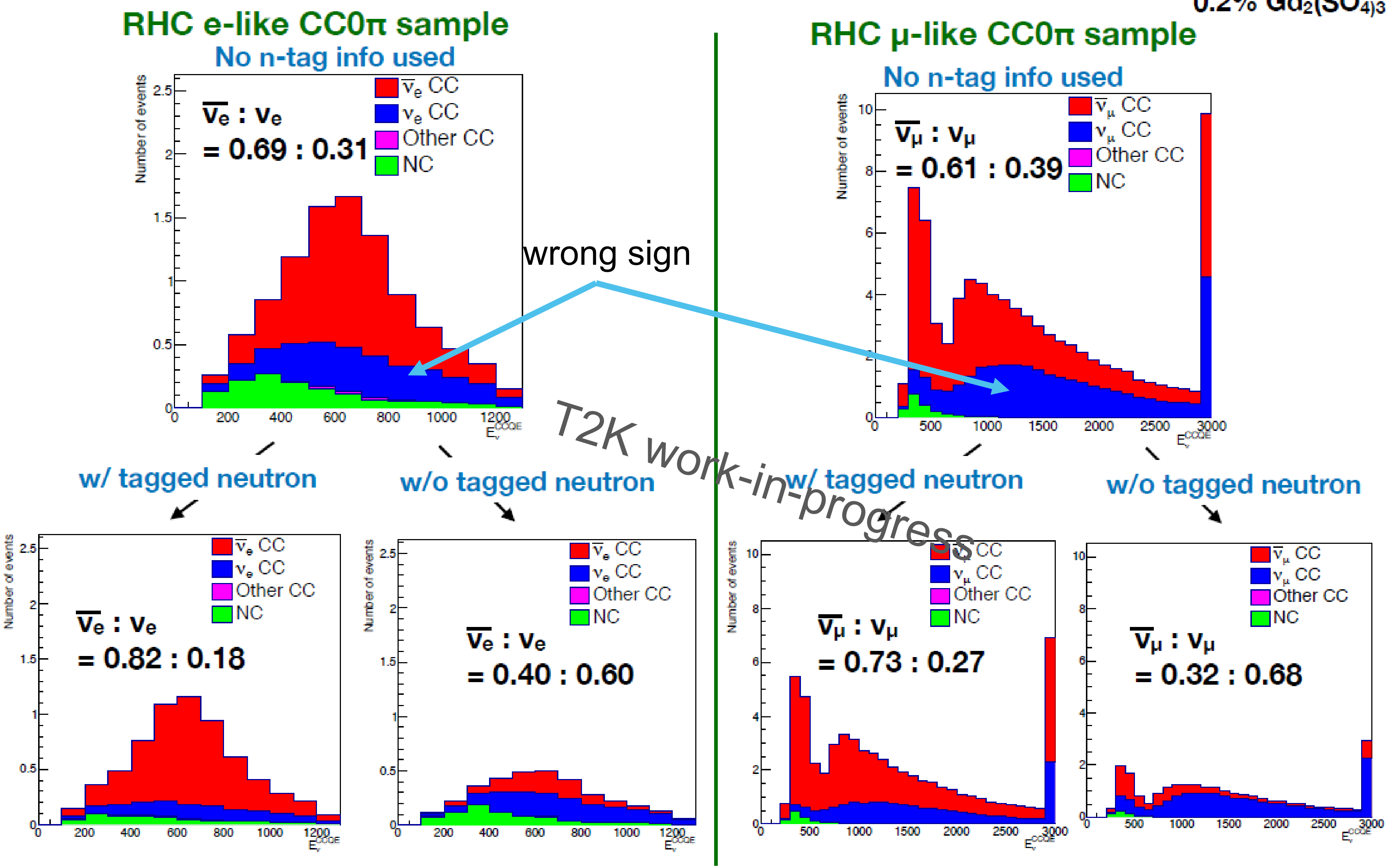




- 0.2% loading of $Gd_2(SO_4)_3$
- Supernova Relic, Signal = $\bar{\nu}_e + p \rightarrow e^+ + n$
- Reduce background by neutrino tagging with Gadolinium
- SK tank was opened in June 2018 for the first time in 12 years.
- 0.02% loading will happen in JFY2019

Neutron tag impact on T2K

10^{21} POT
0.2% $Gd_2(SO_4)_3$

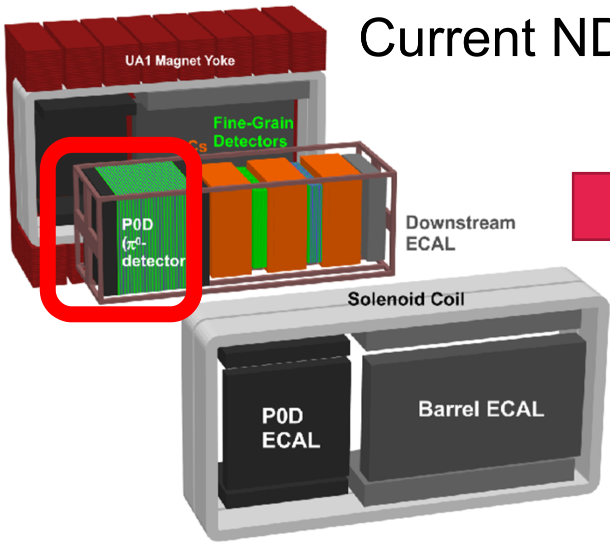


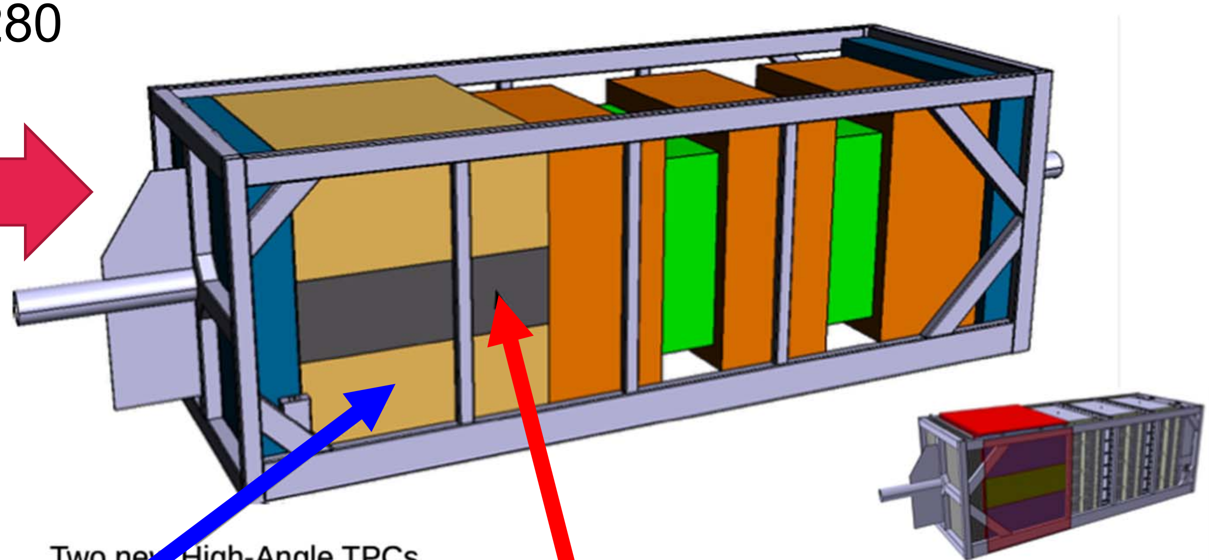
Powerful discrimination of wrong-sign background expected

T2K

ND280 upgrade

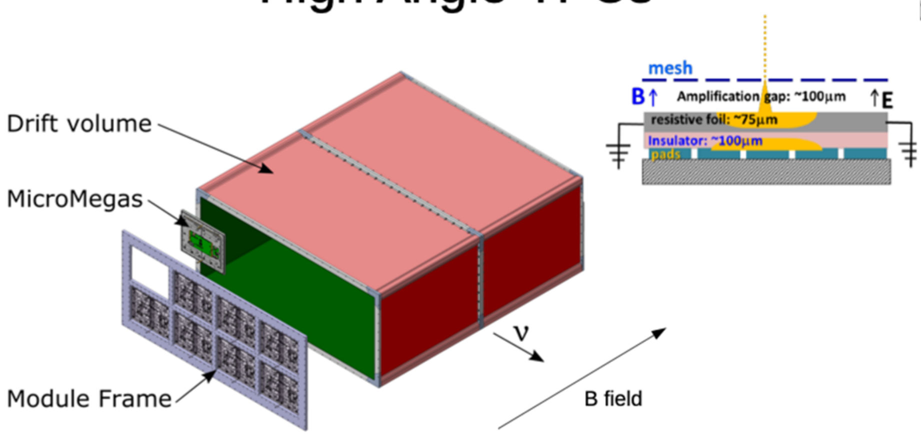
Current ND280





Two new High-Angle TPCs

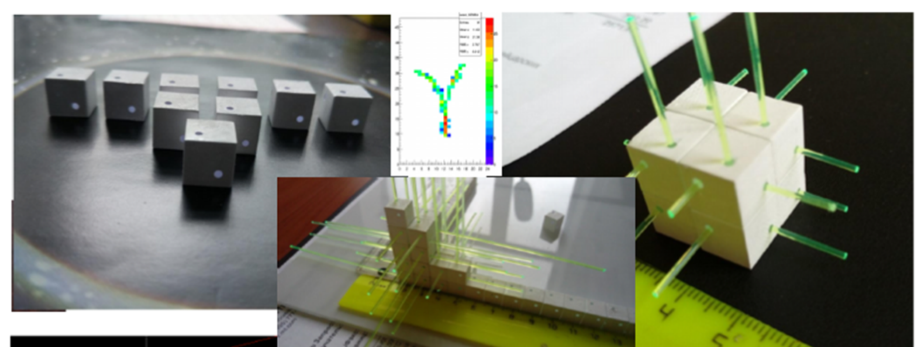
High Angle-TPCs

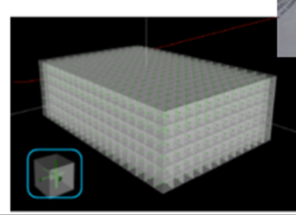


- Atmospheric pressure TPC using the same gas mixture as the present TPC
- Main difference with the existing TPC: thin field cage, resistive Micromegas
- Large overlap with the TPC group
- Benefiting from ILC TPC developments and RD51

Super-FGD

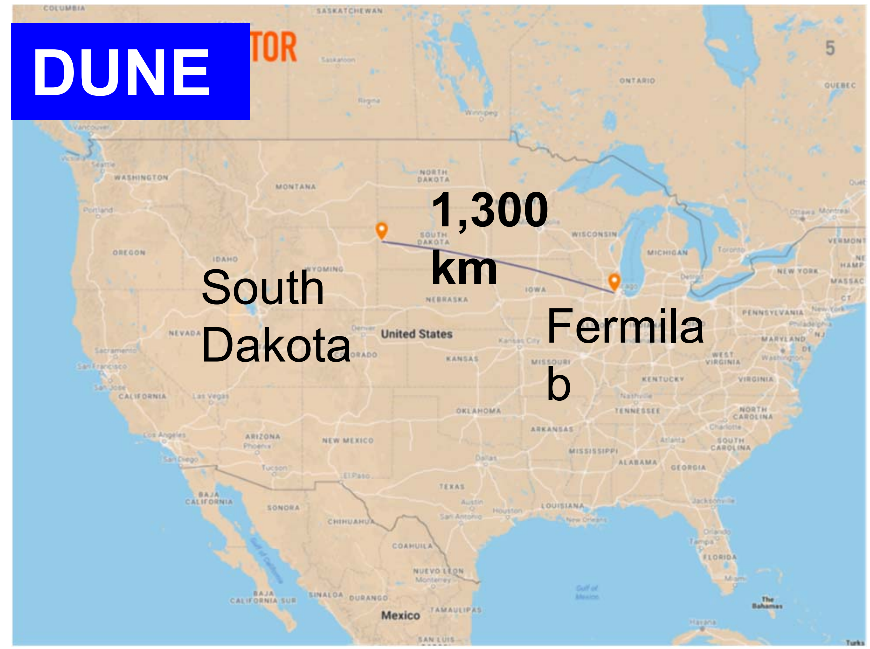
arXiv:1707.01785





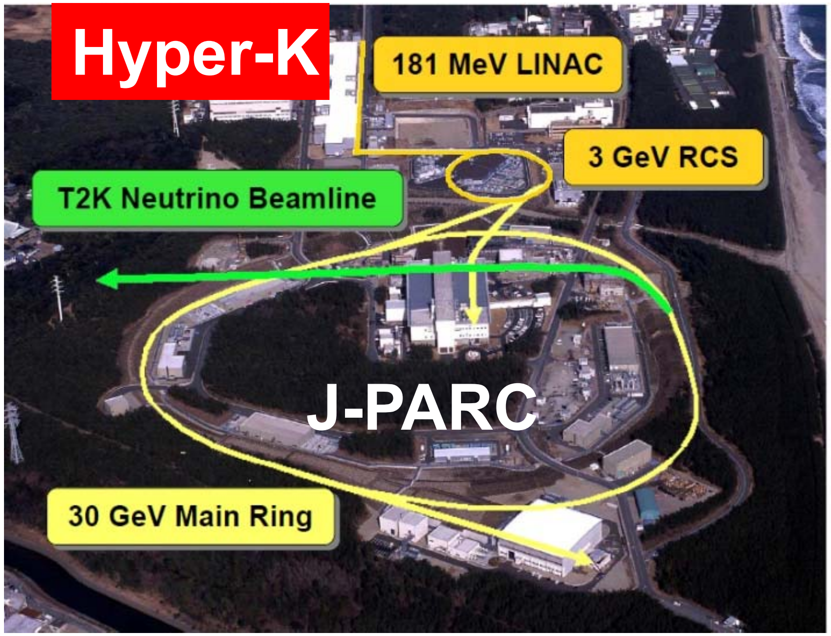
1x1x1 cm^3 plastic scintillator cubes with 3 fibers readout along x, y, z
Detailed (3 2-D projections) and highly segmented view of the interaction
Successful tests of prototypes
Good tracking, PID, timing

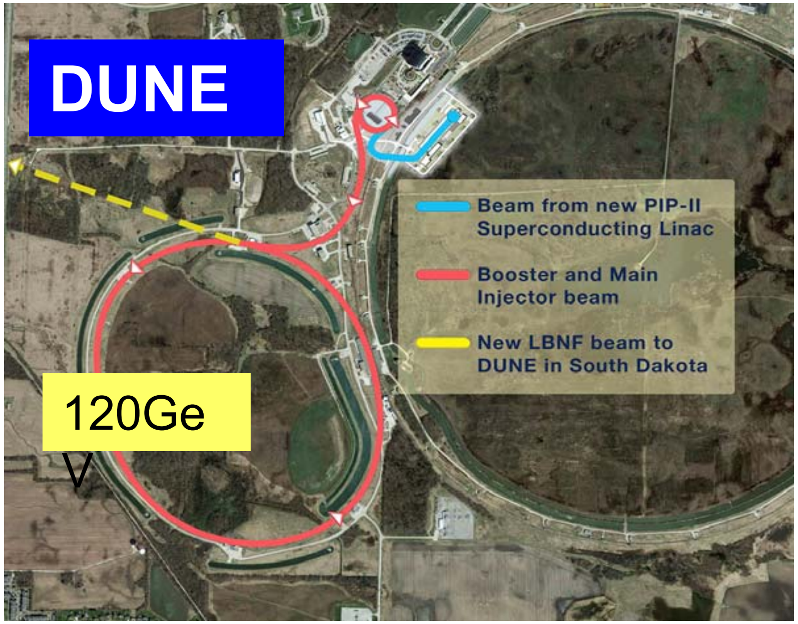
Next generation Accelerator long baseline experiments
Hyper-Kamiokande and DUNE



Both experiments are aiming to start around 2026.
Matter effect ~10% for T2HK and ~45% for DUNE

Next generation Accelerator long baseline experiments Hyper-Kamiokande and DUNE

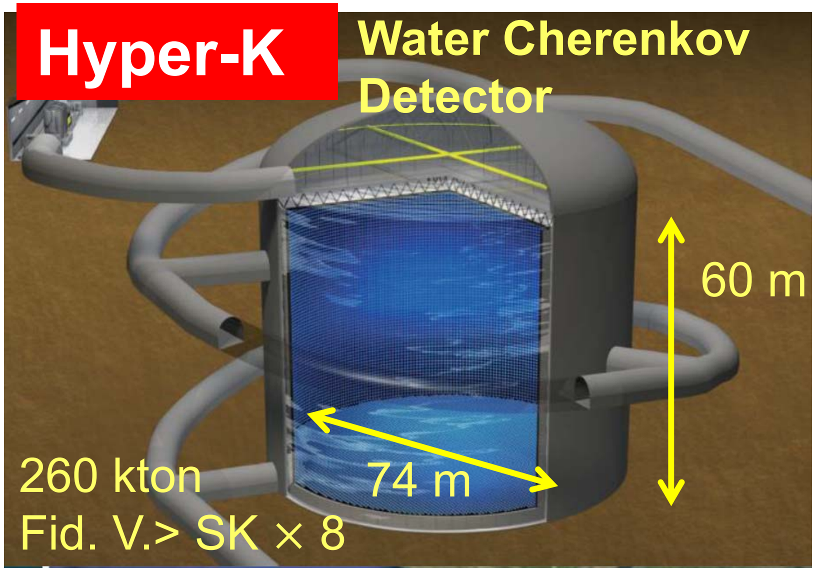


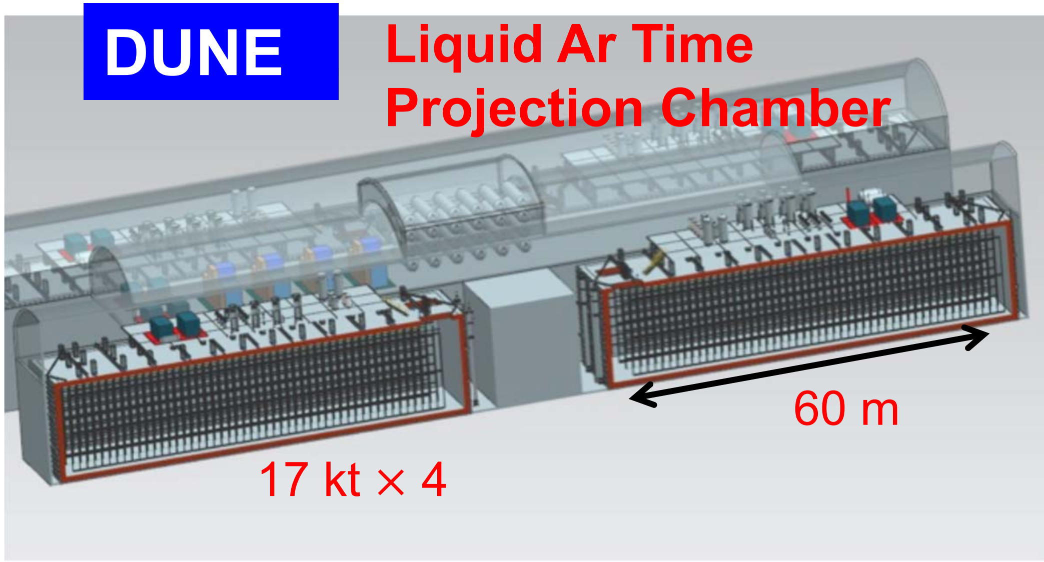


current(~500 kW)
→ 1.3 MW by upgrading RF etc.

current(~700 kW)
→ 1.2 MW by upgrading LINAC etc.
(→ 2.4 MW)

Next generation Accelerator long baseline experiments Hyper-Kamiokande and DUNE





Multipurpose

- Acc. long baseline neutrino oscillation
- atmospheric neutrino
- Solar neutrino
- Supernovae neutrino
- proton decay

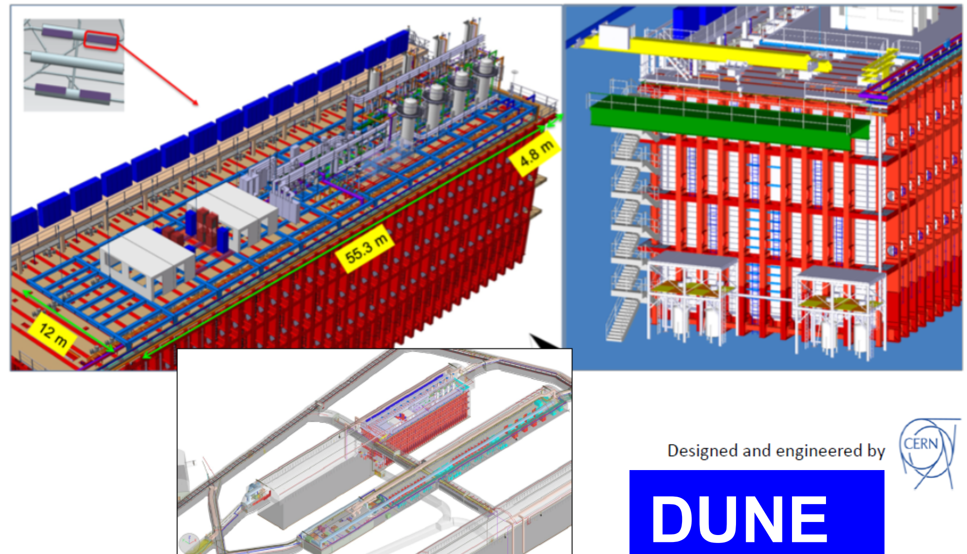
etc.

Cutting Edge technologies of next generation experiments

Hyper-K

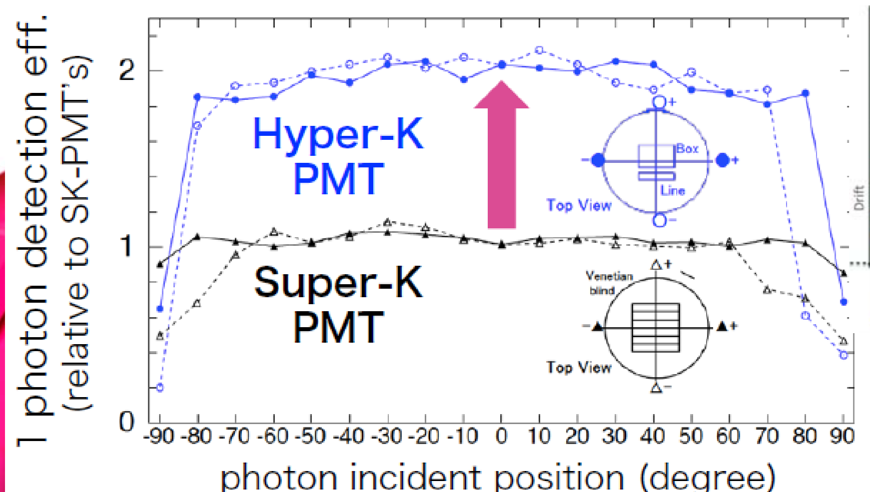
New 50cm PMT
- ×2 efficiency
- × 2 timing resolution
- × 2 pressure tolerance

Basic module is a 10 kt fiducial mass (17 kt total) liquid argon TPC

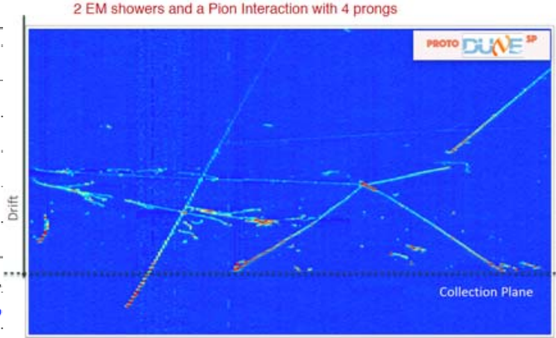


Designed and engineered by CERN

DUNE



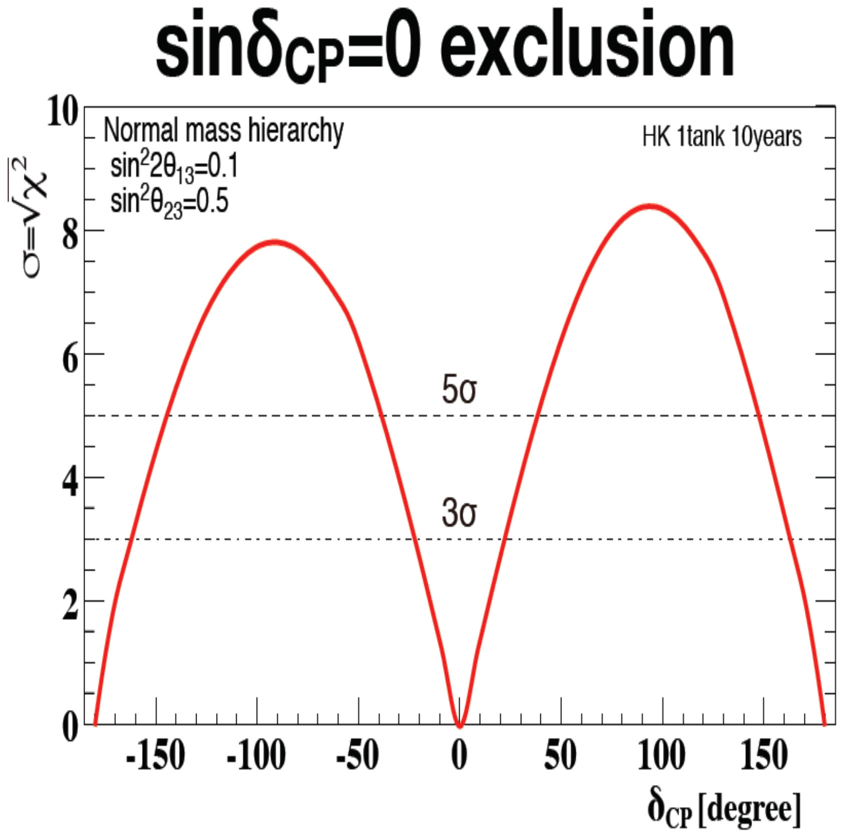
2 EM showers and a Pion Interaction with 4 prongs



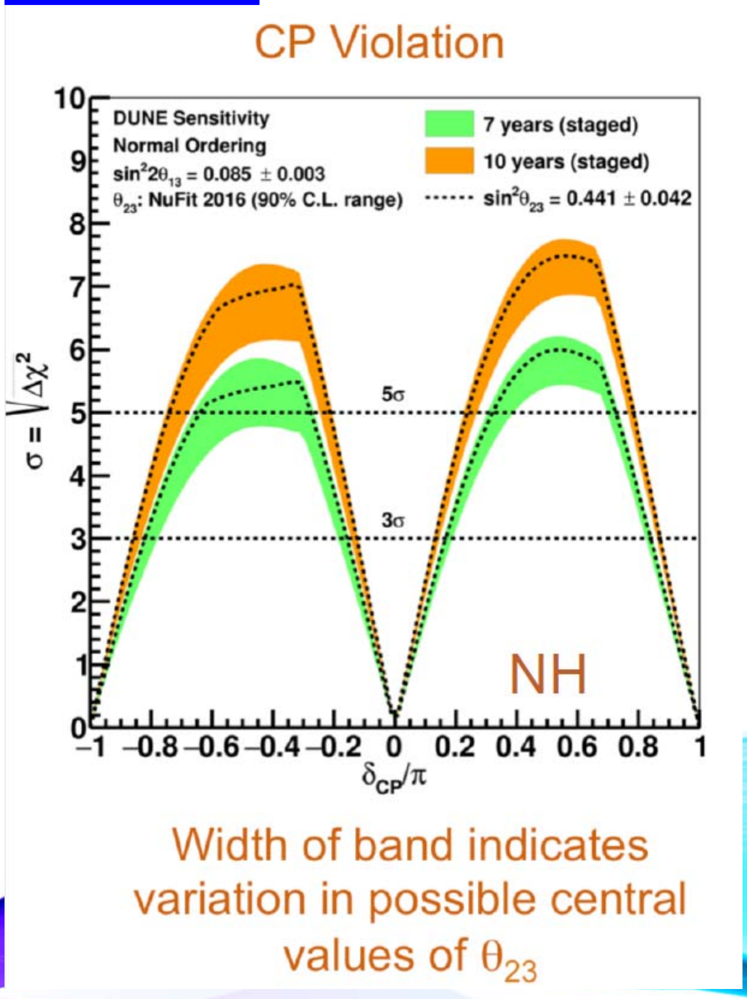
Large commercial-scale cryostat
single-phase/double-phase options
Thin photon sensor for 127nm scintillation

Next generation Accelerator long baseline experiments
Hyper-Kamiokande and DUNE

Hyper-K



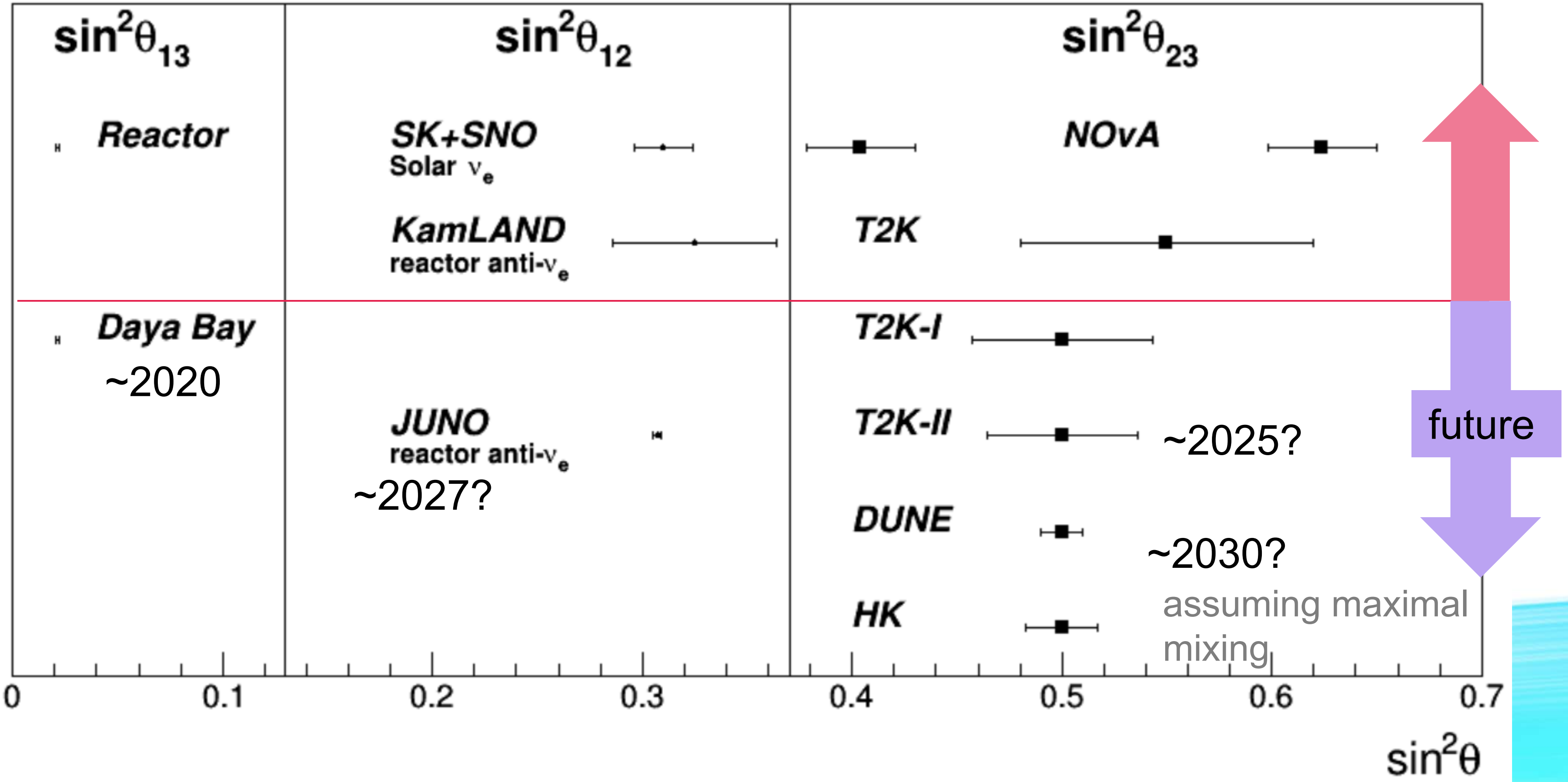
DUNE



Prospect of mixing angle determination
High precision and redundant measurements

* may not be precise comparison

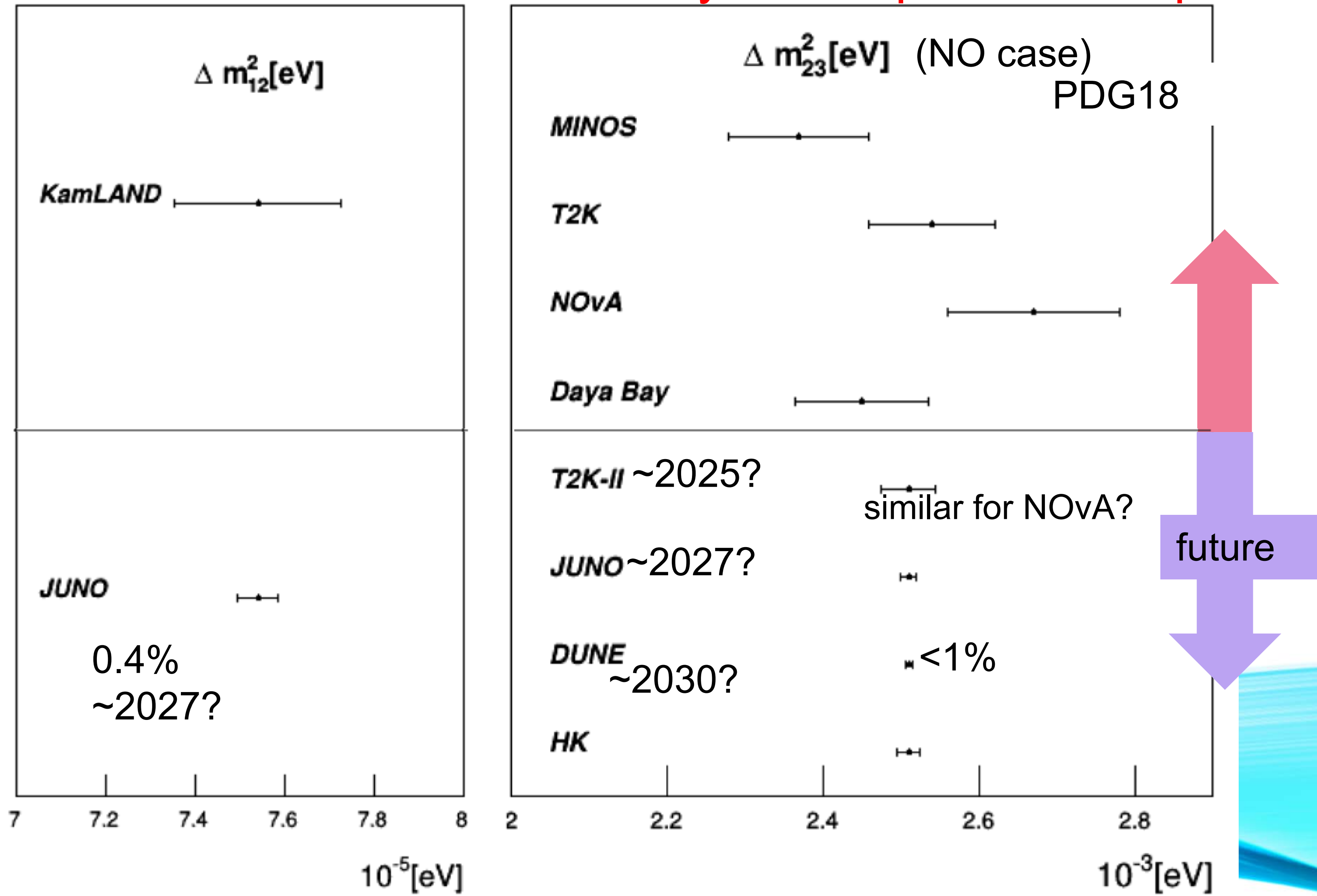
PDG18



Ploted $\sin^2\theta$ to see the size of mixing

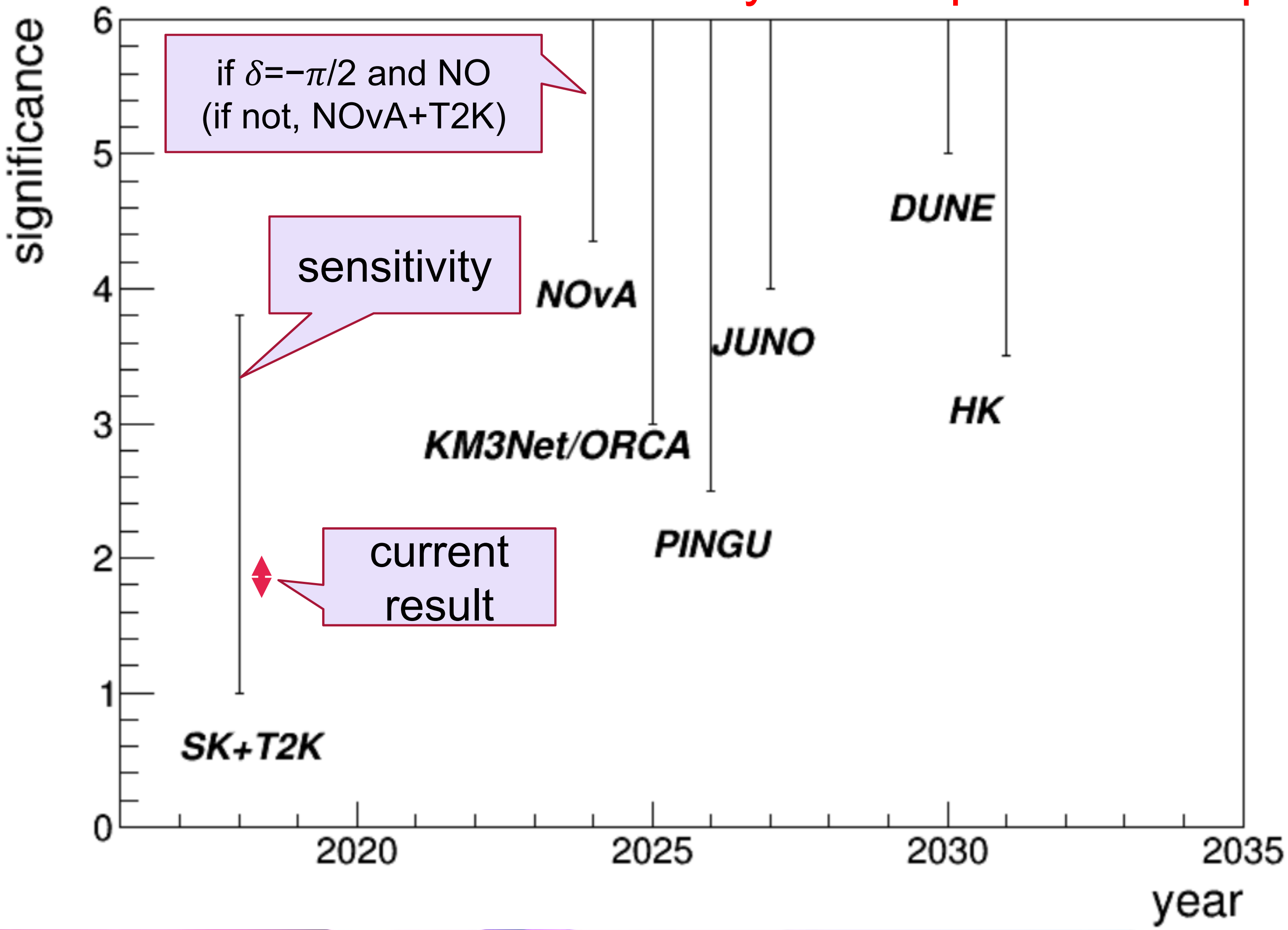
Prospect of Δm^2 determination
High precision and redundant measurements

* may not be precise comparison



Prospect of Mass Ordering determination

* may not be precise comparison



Summary

- Mixing in the lepton sector has been established by neutrinos from atmospheric, Solar, reactor and accelerator.
- Remaining's are CP-violation phase and mass ordering
  - ✓ T2K 2σ confidence interval $-170° < \delta_{CP} < -36°$, CP conserving case ($\delta_{CP} = 0°, 180°$) is outside.
  - ✓ Normal mass ordering is preferred by $\gtrsim$ 90%
  - ✓ NOvA (combined w/ T2K) may resolve mass orderin g at 3σ before the next generation experiments.
- Next generation experiments will fully explore CP-violation phase, mass ordering, and also start exploring beyond the three-generation mixing.
  - ✓ Hyper-Kamiokande, DUNE etc.