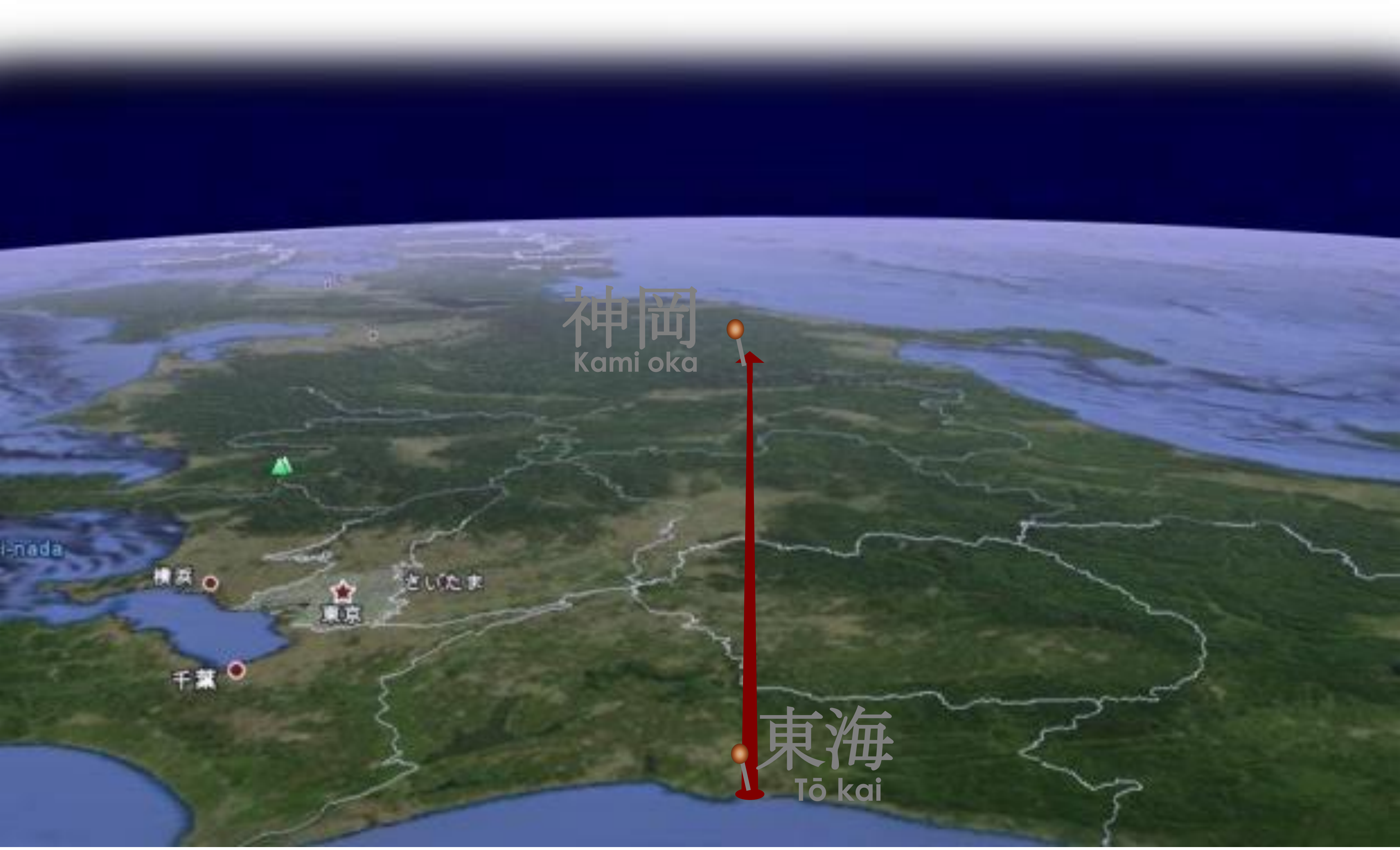
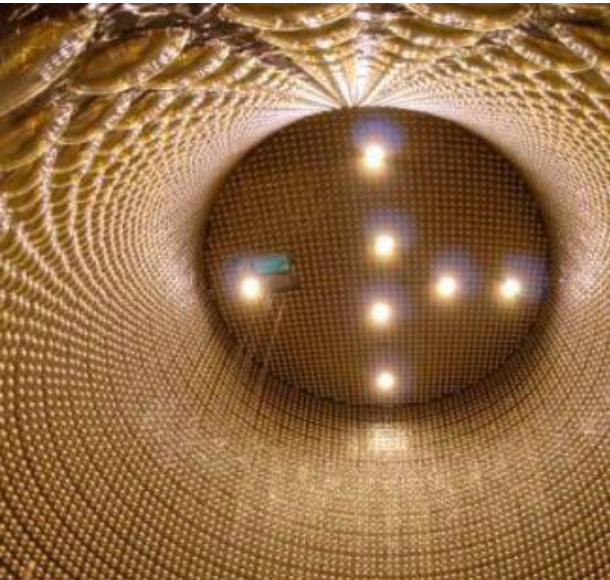
T2K, T2K-II and HyperK





Idea of T2K was born 1999-2001 hep-ex/0106019 combining:

-- existing SuperKamiokande detector (50kton W.Č., 22.5 kton fiducial)

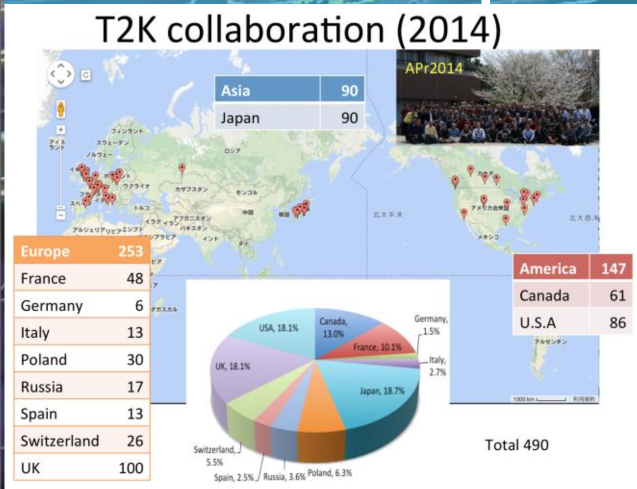
-- JAERI-KEK Japanese Proton Accelerator Research Complex (JPARC) at TOKAI including a high power, 0.75MW/30GeV Proton Synchrotron neutrino beam from pion decay $\pi^+ \rightarrow \mu^+ \nu_\mu$

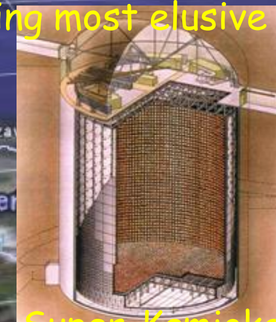
-- baseline 295 km ➔ neutrino energy for first maximum is ~650 MeV achievable by pion-decay beam at 2.5 degrees off-axis

T2K Long Baseline Neutrino Oscillation Experiment

Attack fundamental questions of nature, eg,
- How matter (us) was created in the Universe
- What is the ultimate law to govern extreme microscopic world

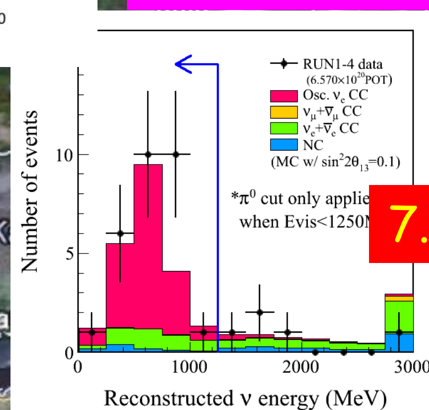
through exploring most elusive elementally particle called "neutrino"





40m$^{\phi}$x40m^{H}
50kt Water Cherenkov det.

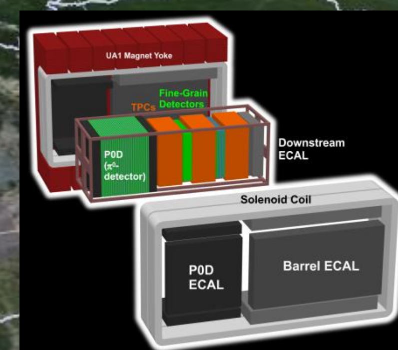
Discovery of appearance of electron neutrino



7.3σ

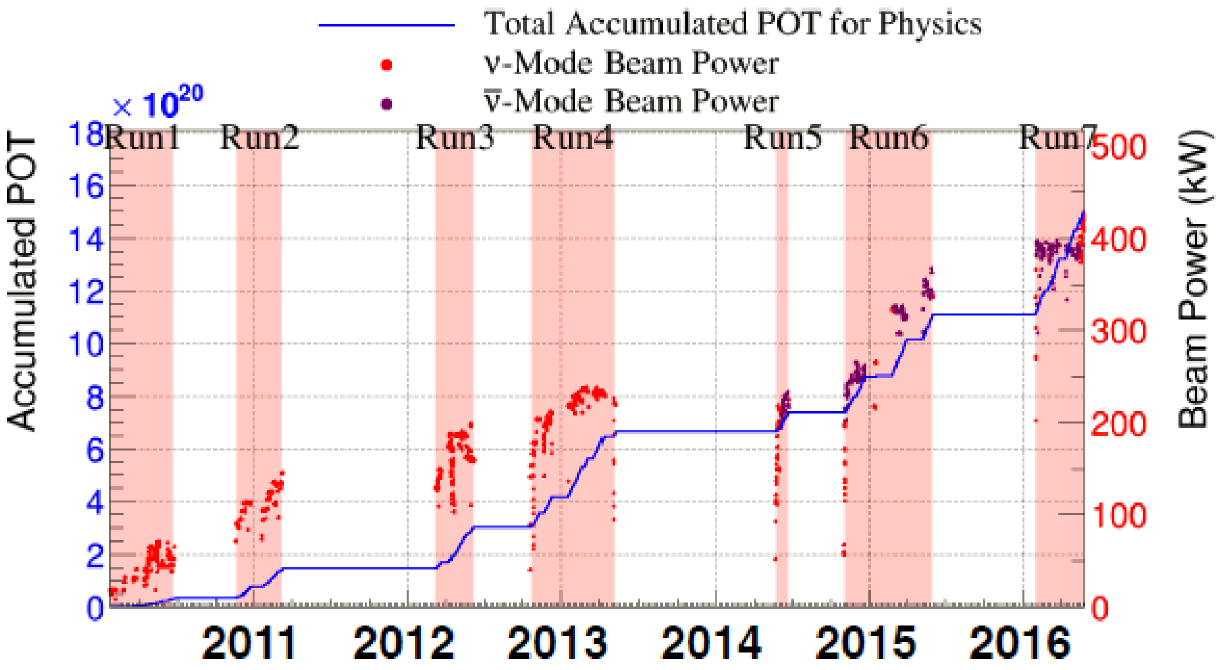
Muon neutrino beam
295km

Near neutrino detect



- T2K collaboration ~500 collaborators from 59 institutions, 11 countries
- Funded in FY2004, Started measurements in 2010
- First discovery of ν_e appearance in ν_μ beam
- Best measurement of ν_μ disappearance
- Opens the door for CP violation measurements
  - Could be the key to matter in the universe!

Pointer 36° 23'41.59" N 139° 11'54.71" E elev 665 m Streaming 100%



27 May 2016
POT total: 1.510×10^{21}

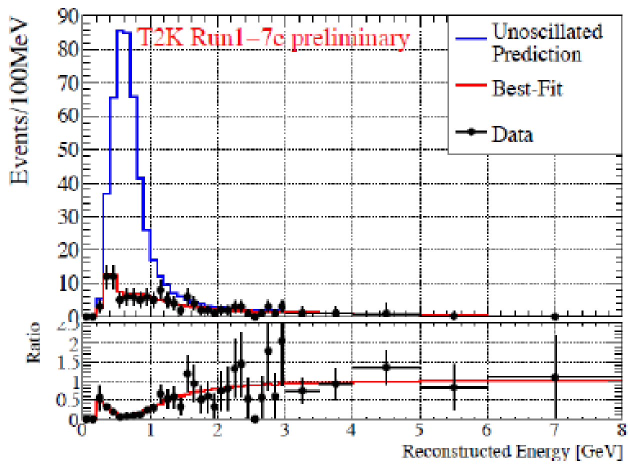
ν-mode POT: 7.57×10^{20} (50.14%)
ν̄-mode POT: 7.53×10^{20} (49.86%)

(POT = Proton on target)

Steady improvements since start in 2010 … and many interruptions
earthquake+ tsunami (2011), safety incident in hadron hall (2013-14)
now running at 450kW average beam 2.6 sec. rep. rate.
Planned improvements: beam feedbacks and optics → 600MW
upgrade of power supply and RF system → rep rate to 1.15 s.
Aim towards 1.3 MW by early 2020's

T2K fit to $\nu_\mu \rightarrow \nu_\mu$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_\mu}$ disappearance

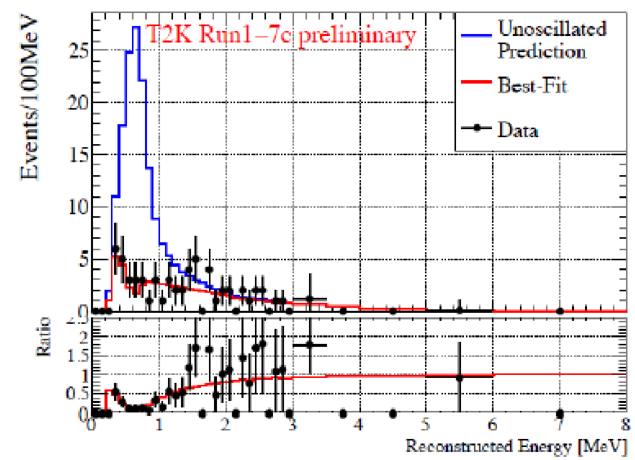
Neutrino



$$\Delta m^2_{32} = [2.34, 2.75] \times 10^{-3} eV^2 (NH) \text{ at } 90\% \text{ CL}$$

$$\sin^2\theta_{23} = [0.42, 0.61] (NH) \text{ at } 90\% \text{ CL}$$

Antineutrino



$$\Delta \overline{m}^2_{32} = [2.16, 3.02] \times 10^{-3} eV^2 (NH) \text{ at } 90\% \text{ CL}$$

$$\sin^2\overline{\theta}_{23} = [0.32, 0.70] (NH) \text{ at } 90\% \text{ CL}$$

Neutrino and antineutrino parameters are consistent

No evidence of CPT violation, NSI, etc

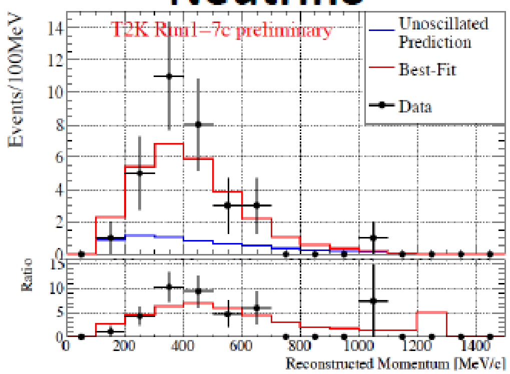
T2K fit to $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ appearance

Predictions:

ν_e: 19.6 events (NH, $\delta_{CP} = \pi/2$) to 28.7 events (NH, $\delta_{CP} = -\pi/2$)

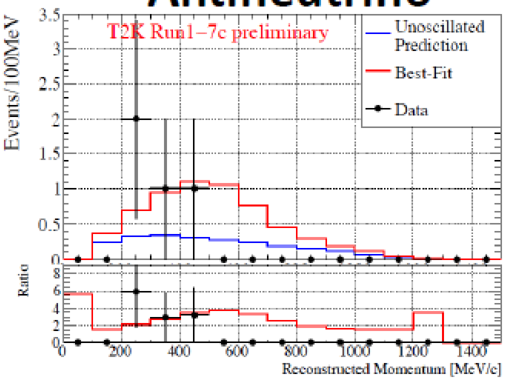
$\overline{\nu_e}$: 7.7 events (NH, $\delta_{CP} = \pi/2$) to 6.0 events (NH, $\delta_{CP} = -\pi/2$)

Neutrino



Observed 32 events

Antineutrino



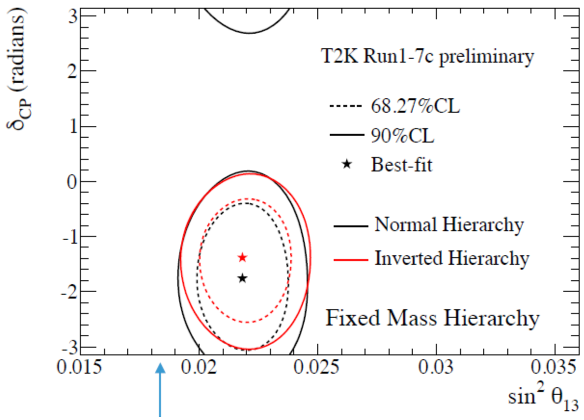
Observed 4 events

Excess of ν_e events above prediction favors NH and $\delta_{CP} = -\pi/2$ ($3\pi/2$)

Deficit of $\bar{\nu}_e$ events below prediction favors NH and $\delta_{CP} = -\pi/2$ ($3\pi/2$)

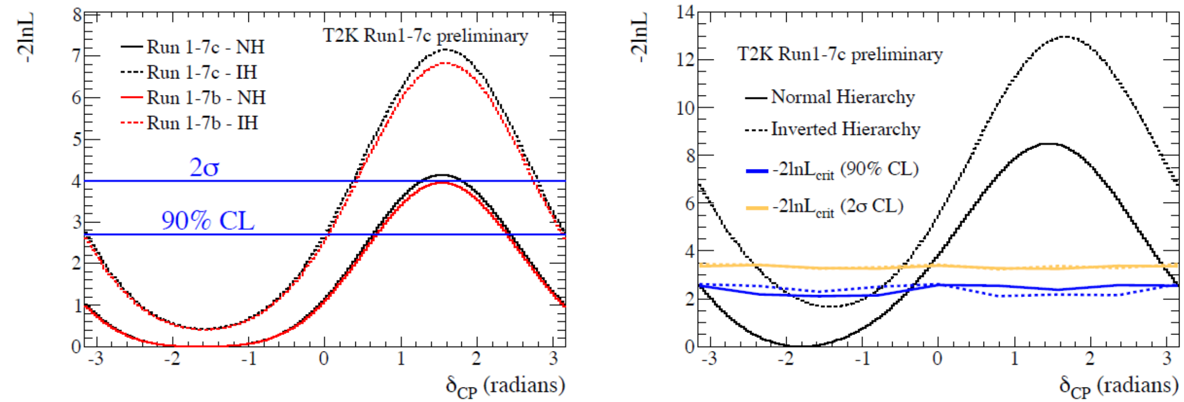
θ_{13} and δ_{cp}

T2K Result with Reactor Constraint
($sin^2 2\theta_{13} = 0.085 \pm 0.005$)



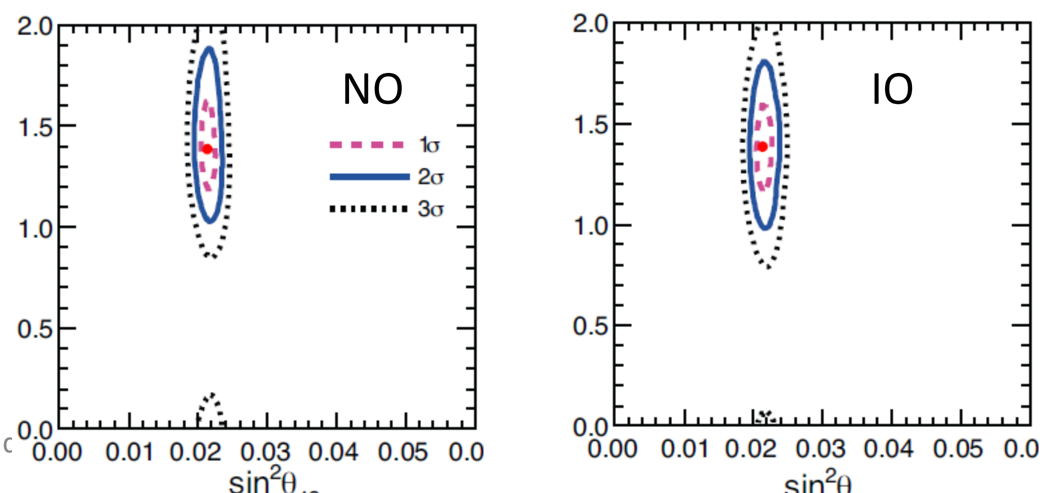
- T2K result with reactor constraint ($\sin^2 2\theta_{13} = 0.085 \pm 0.005$)

Sensitivity (Simulation) **Measurement (Data)**



$$\delta_{cp} = [-3.13, -0.39](NH), [-2.09, -0.74]\ (IH)\ \text{at } 90\%\ \text{CL}$$

Similar (but less significant) effects seen in NOvA and SuperK)
➔ 2.5 σ CP violation.
average by Marrone (neutrino2016)
Regardless of Hierarchy



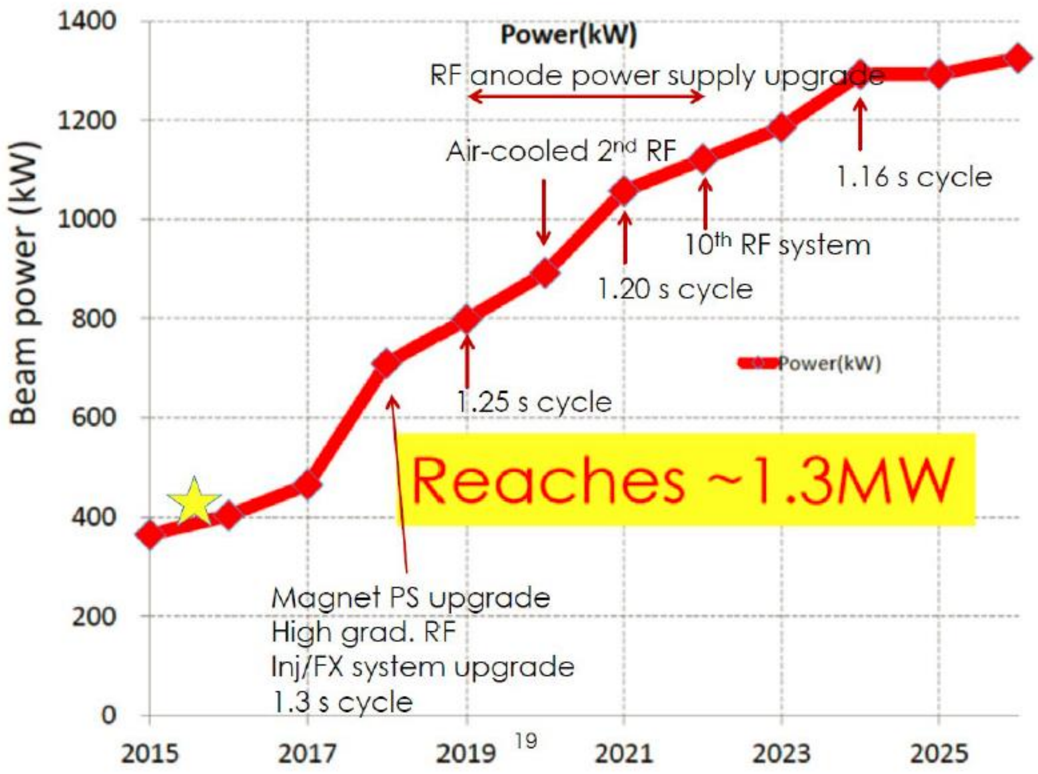
Power upgrade plan of MR

FX: The high rep. rate scheme is adopted to achieve the design beam intensity, 750 kW.
Rep. rate will be increased from ~ 0.4 Hz to ~1 Hz by replacing magnet PS's and RF cavities.
SX: After replacement of stainless steel ducts to titanium ducts to reduce residual radiation dose, 50 kW operation for users will be started. Beam power will be gradually increased toward 100 kW carefully watching the residual activity. Local shields will also be installed if necessary.

JFY	2014	2015	2016	2017	2018	2019
Event	Li. current 30 -> 50 mA		New PS Buildings →			
FX [kW] (study/trial) SX [kW] (study/trial)	240-320 -	>320 24~50	~400 >50	>400 50~100	~750 ~100	>750 100
Period of magnet PS New magnet PS	2.48 s R&D →	Low cost R&D →	Mass production →		1.3 s	
Present RF system High gradient rf system	Manufacture, installation & test →					
Ring collimators	Back to JFY2012 (2kW)	Add. colli. C,D	Add. colli. E,F			
Injection system FX system	Kicker PS improvement, Septa manufacture /test → Kicker PS improvement, LF & HF septa manufacture /test →					
SX collimator / Local shields			Local shields →			
Ti ducts and SX devices with Ti chamber	Beam ducts	ESS				

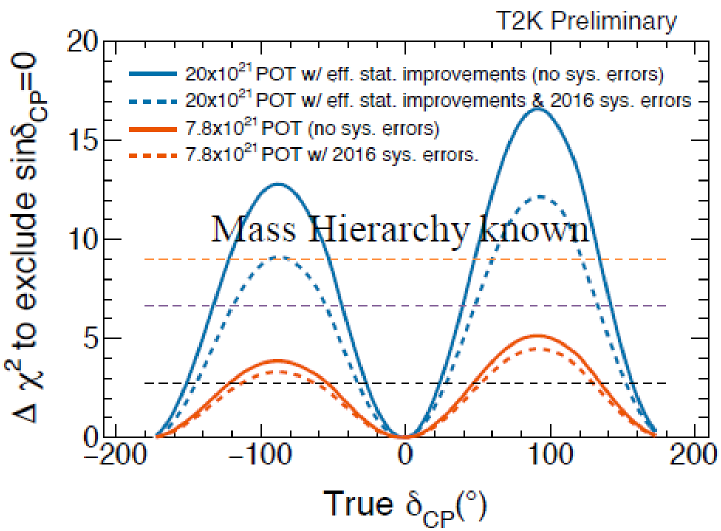
Expect O(1MW by 2019)
original beam request:
5 yrs @750kW

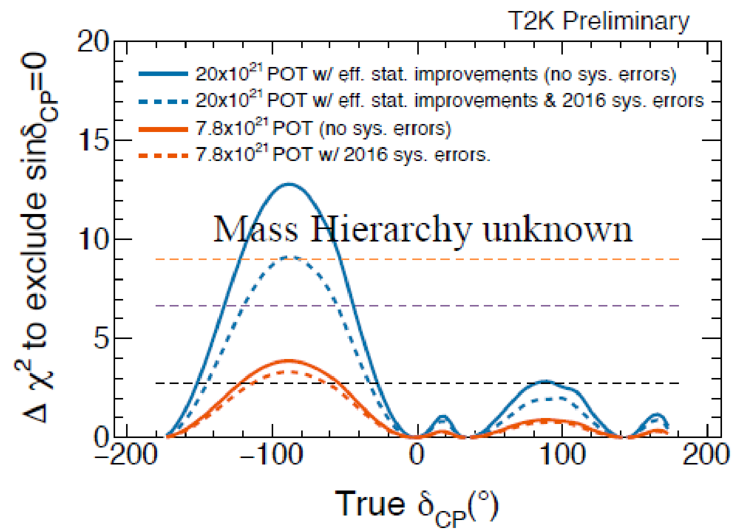
Timeline toward MW beam

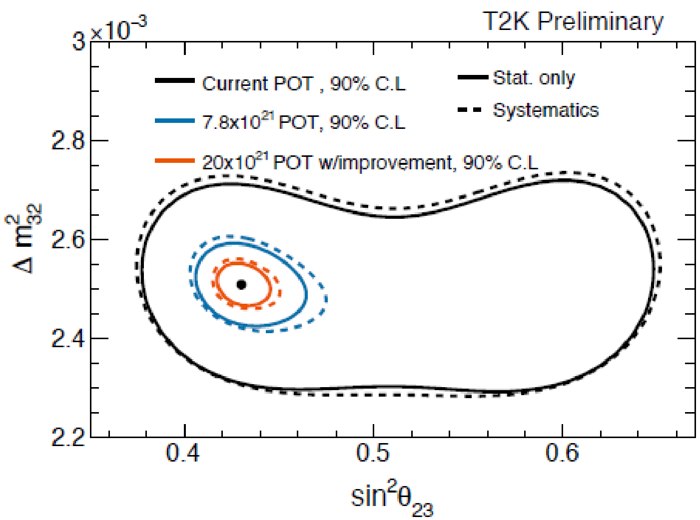


Realizing 1.3MW operation before 2025

Physics Potential of T2K-II







- ~50% increase in effective POT
- ~3σ sensitivity to δ_{cp}
- Precise measurement of θ_{23}
  - resolution of 1.7%

Systematic Error Type	1Re Neutrino Mode	1Re Antineutrino Mode
Far Detector Model	2.39%	3.09%
Final State/Secondary Interactions	2.50%	2.46%
Extrapolation from Near Detector	2.88%	3.22%
ν_e(bar)/ν_μ(bar)	2.65%	1.50%
NC1γ	1.44%	2.95%
Other	0.16%	0.33%
Total	6.86%	7.39%

Uncertainty at the 6-7% level. Need reduction to ~3% for Hyper-K.

Dominant errors: electron (anti)neutrino cross section, near-to-far extrapolation of event rates, far detector modeling

Improvements on three fronts:

near detector acceptance

enery response (E^{rec} vs E^{true})

fake CP violation from (ν_e/ν_μ) / $(\bar{\nu}_e/\bar{\nu}_\mu)$

aim at larger samples of electron neutrinos

Magnetic and non-magnetic detectors

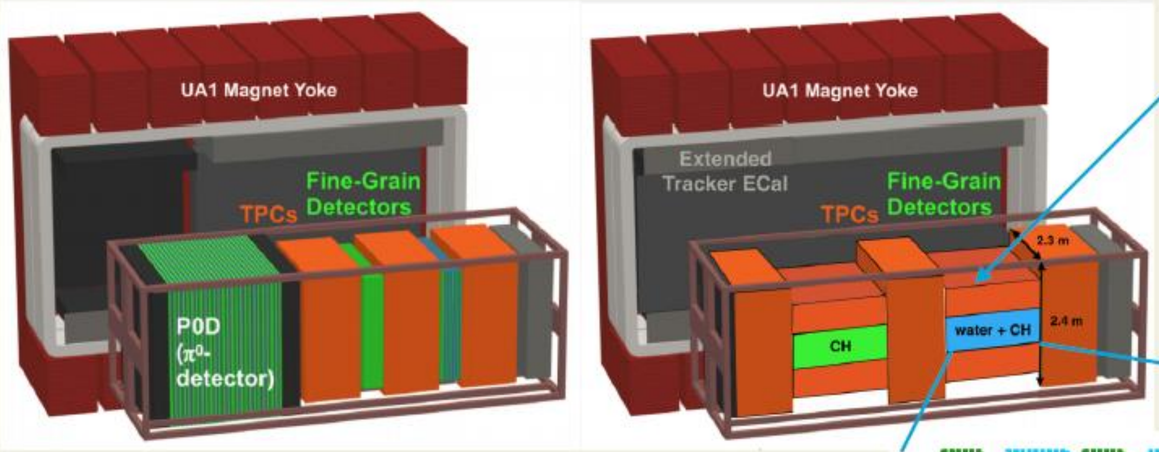
Near detector upgrade for T2K-II

Near and intermediate detectors for Hyper-K are being developed to control flux and cross-section systematic errors

Will continue using the INGRID on -axis and magnetized ND280 detectors

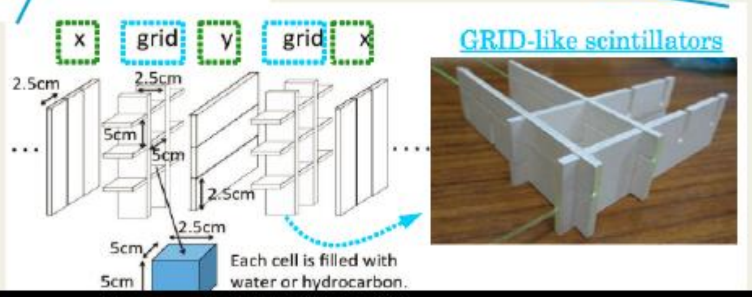
Work within T2K to upgrade ND280 detector

Current ND280 Detectors **Concept for Upgrade**



TPC reconfiguration for high angle track reconstruction

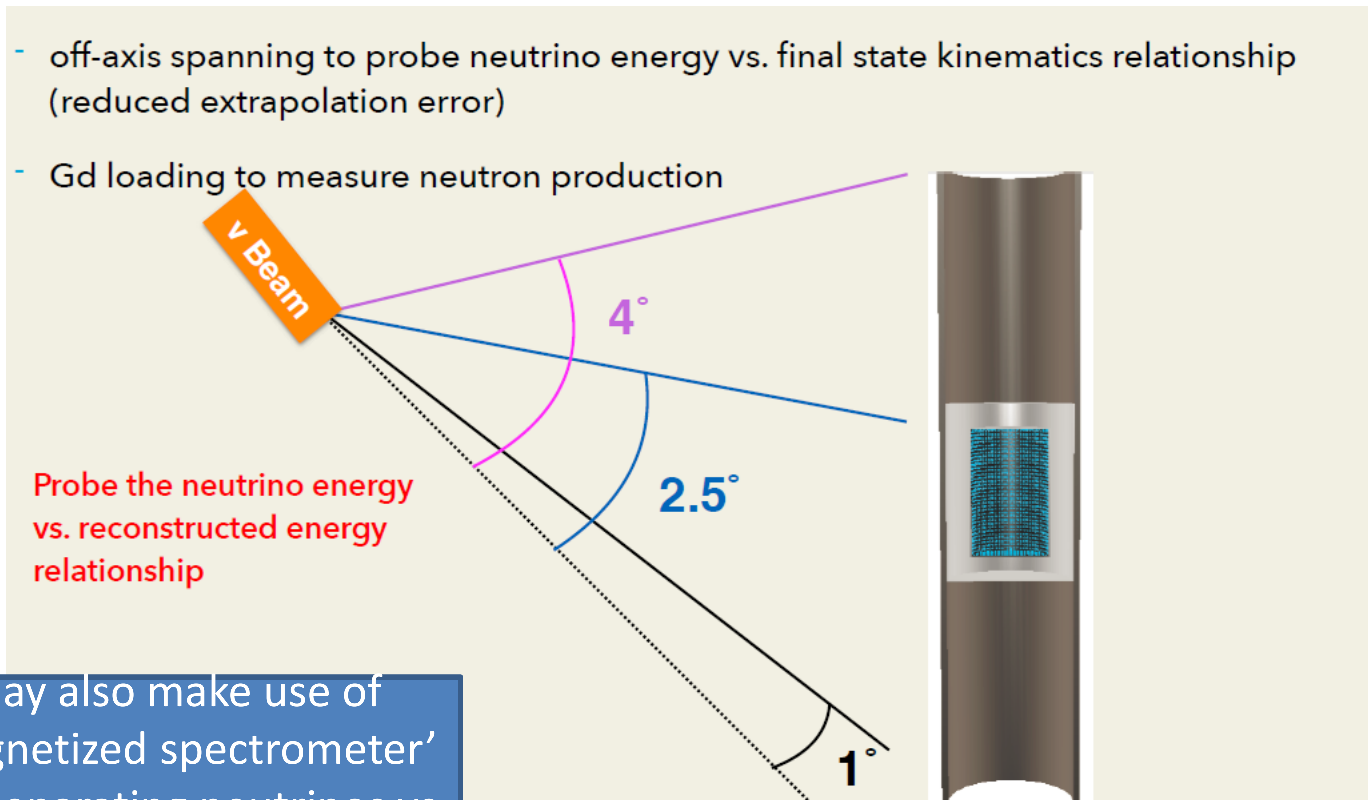
Potential upgrade for tracking target is WAGASCI tracker



Testing the energy response of the near and far detector system

Energy response is biased by

- -- energy absorbed in nuclei
- -- missing reconstructed particles (below Cherenkov threshold)
- -- need monochromatic neutrino beam (but we dont have that)
  - ➔ can make one using off-axis neutrino kinematics



May also make use of 'Magnetized spectrometer' for separating neutrinos vs antineutrinos (Baby-MIND

T2K = Tokai to KamioKa neutrino experiment

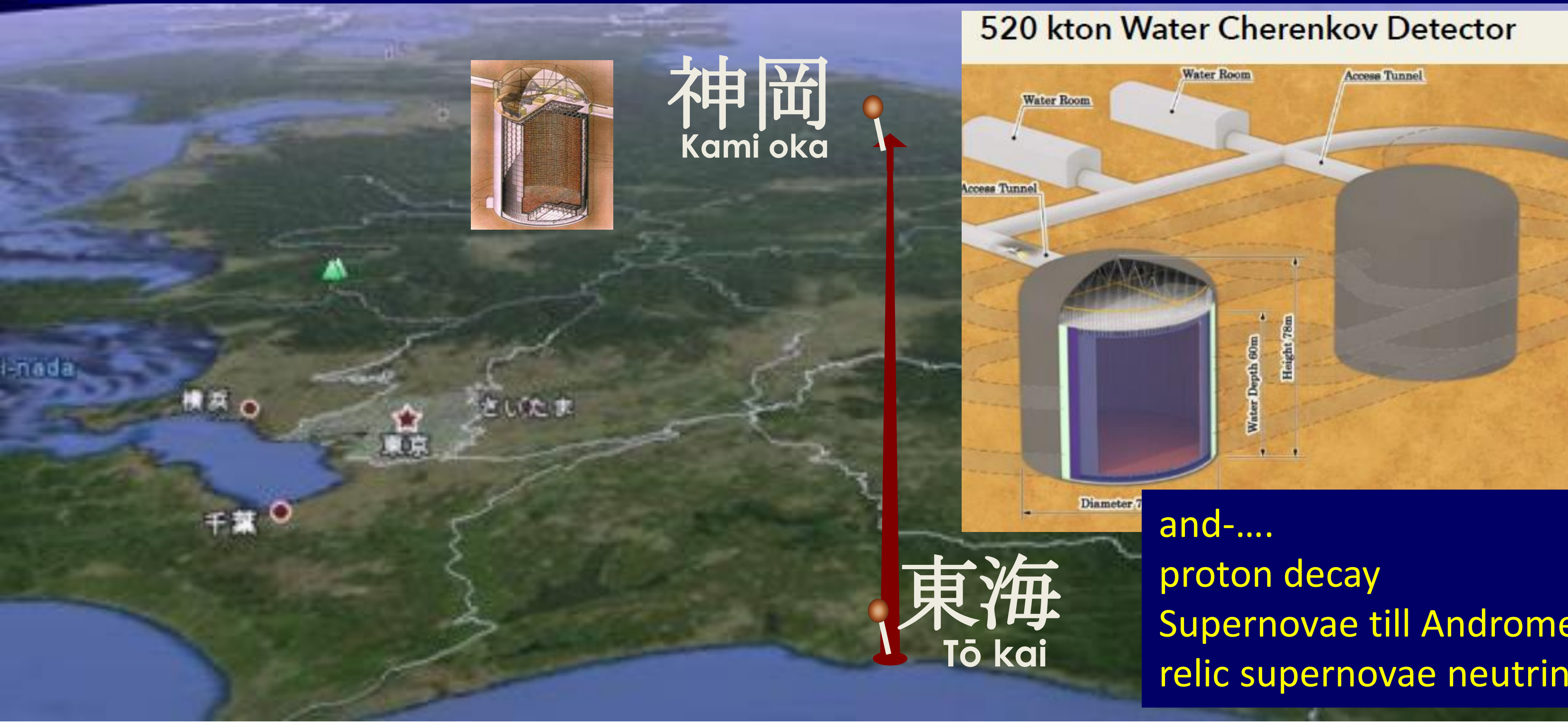
2015 Breakthrough prize for discovery of $\nu_\mu \rightarrow \nu_e$ Oscillation

2016 0.45 MW (proton+C-> neutrinos) beam → 50 ton SuperKamionande WC detector

2σ indication of CP violation

2016-2026 upgrades to reach 1.3 MW beam power → up to 4σ evidence for CP violation

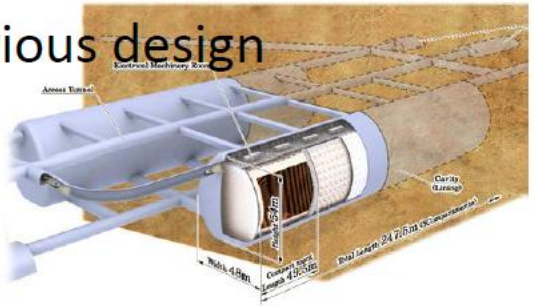
2016 300-600 kton HyperKamiokande WC detector → precise measurements (5-10°)

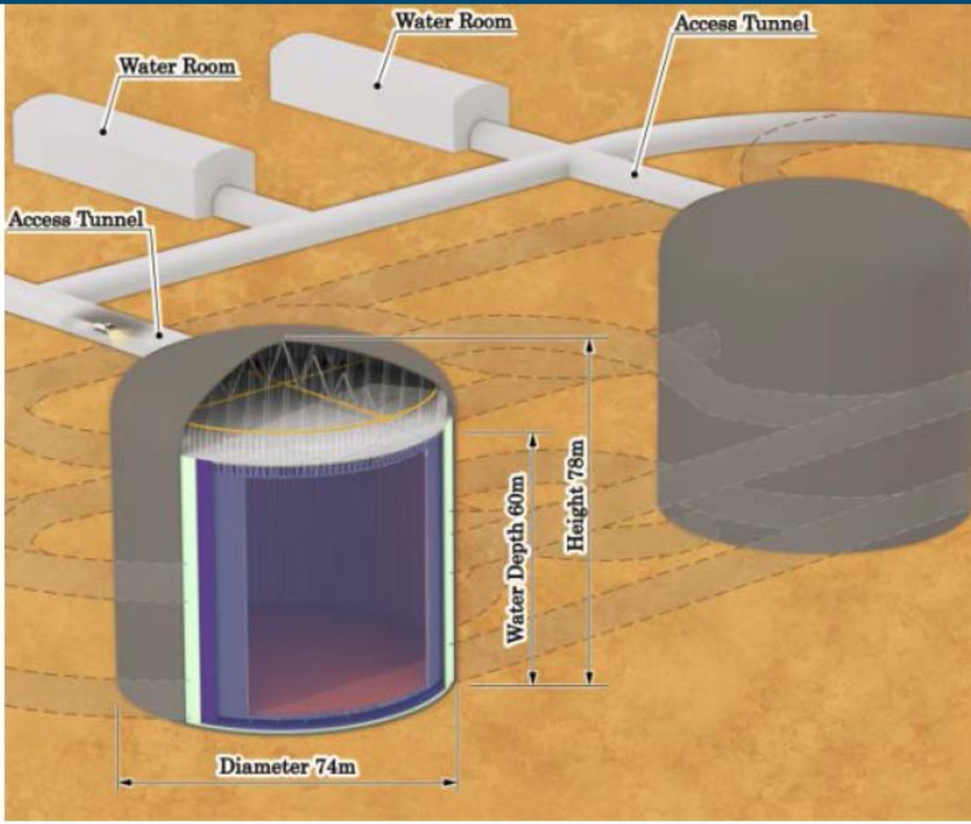


and-....
proton decay
Supernovae till Andromeda
relic supernovae neutrinos

Present design of Hyper-K

Previous design





✓ Super-K-like structure

✓ 2 tanks with staging

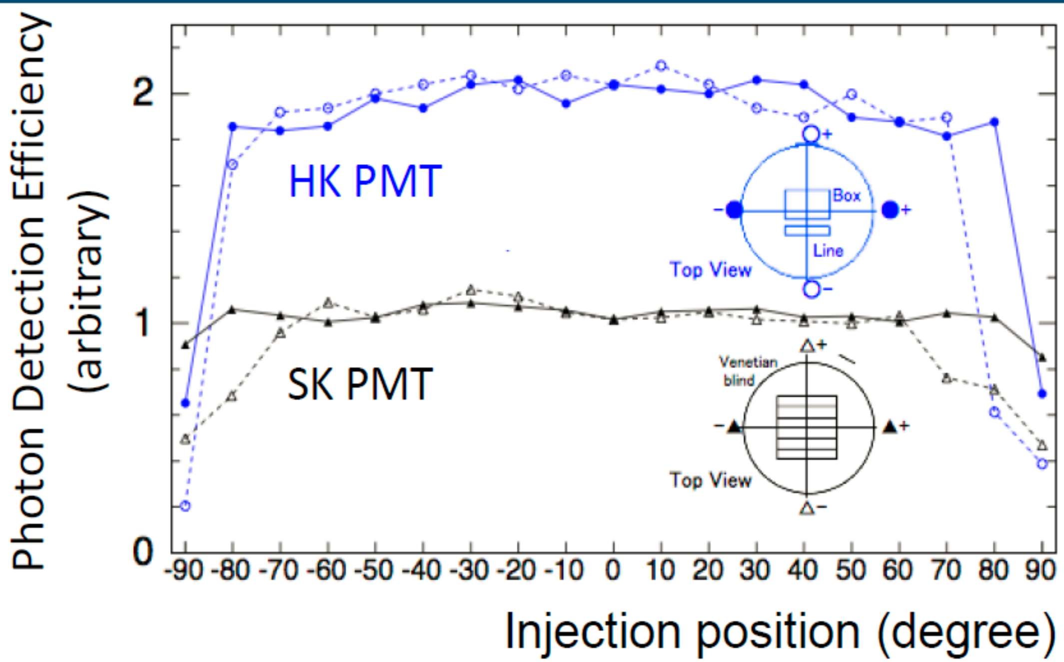
(2nd tank assumed to be ready 6 years later)

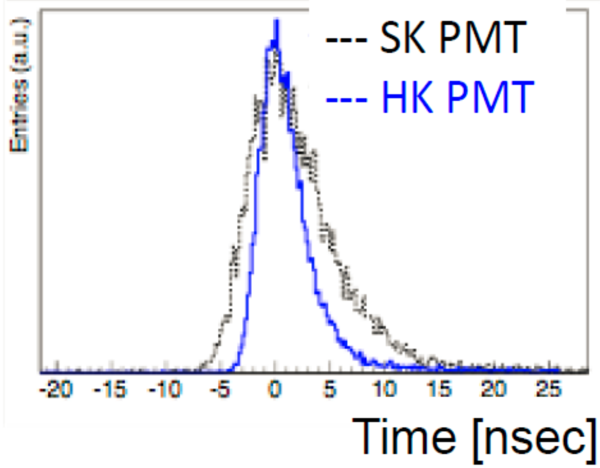
✓ 1 tank will be;

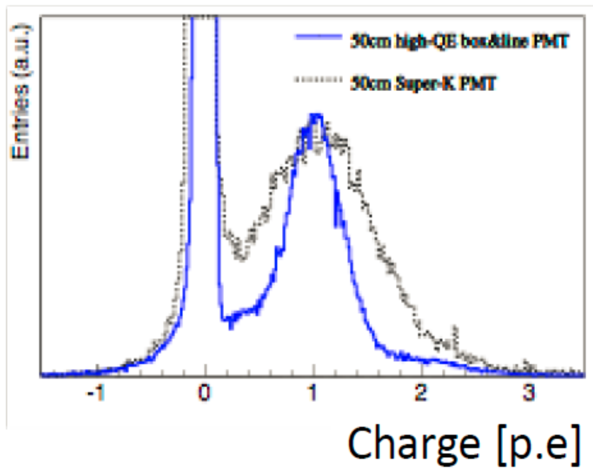
- 60m(H)×74m(D)
- Total volume: 260 kton
- Fiducial volume(FV): 190 kton
  ~10 x Super-K FV
- PMT coverage 40%, 40,000 ID-PMT, 6,700 OD-PMT

✓ The candidate site is ~8km south of SK (2.5 degree off axis beam, L=295km)

A highlight of the Hyper-K R&D: New 50cmϕ PMT







- ✓ Photon detection efficiency x 2,
- ✓ Timing & charge (@1 p.e.) resolution x 1/2
- ✓ (Pressure tolerance x 2 (>100m))

➔ Large impacts to physics

11

The HyperK physics list

-- PMNS matrix
- -- Mass Hierarchy
- -- CP violation and CP phase determination
- -- precision determination of theta_23

-- Beyond PMNS (unitarity, sterile neutrinos etc..)

-- Astrophysical neutrinos
- -- SuperNovae signals
- -- solar neutrinos

-- proton decay
- -- e+ π^0 and other 1st family decays
- -- decays with Kaons

Main actors in the global scene

T2K,T2KII, SK-Gd, NOvA, JUNO/RENO50, PINGU, ORCA, DUNE

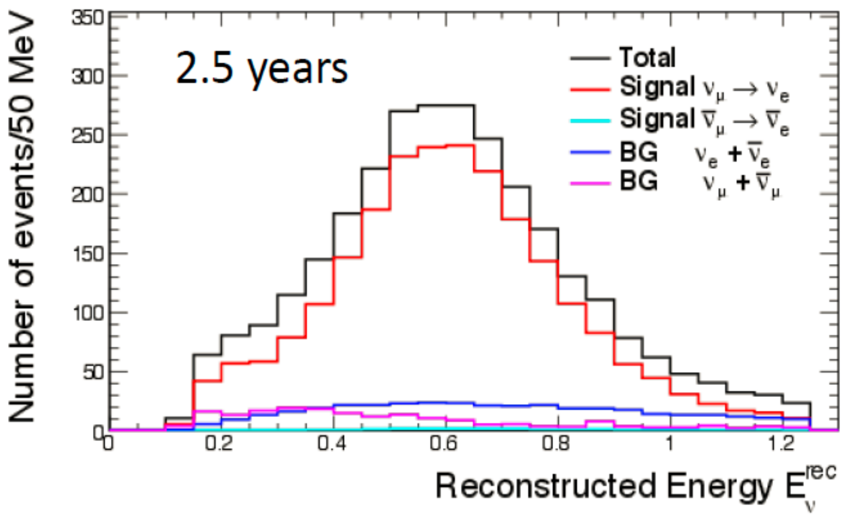
A very large program for the LSND eV region (will not discuss here) and towards future (SHIP, FCC…)

SK-Gd, JUNO/RENO50, DUNE
JUNO/RENO50

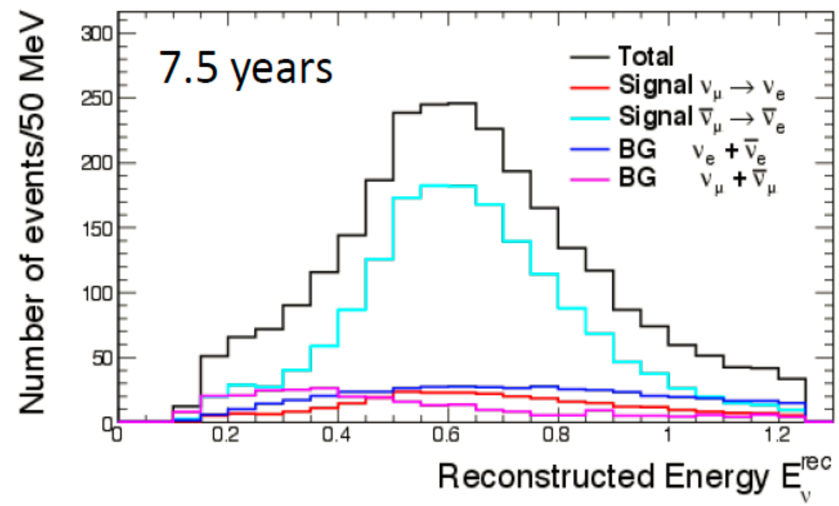
JUNO/RENO50, DUNE

Expected number of events (10 years)

Appearance ν mode



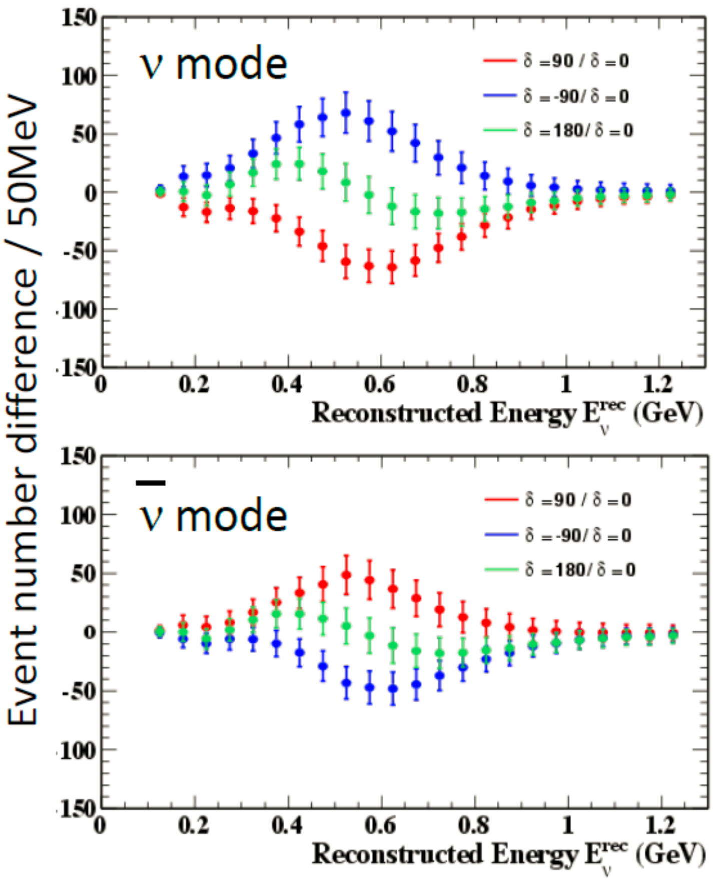
Appearance $\bar{\nu}$ mode

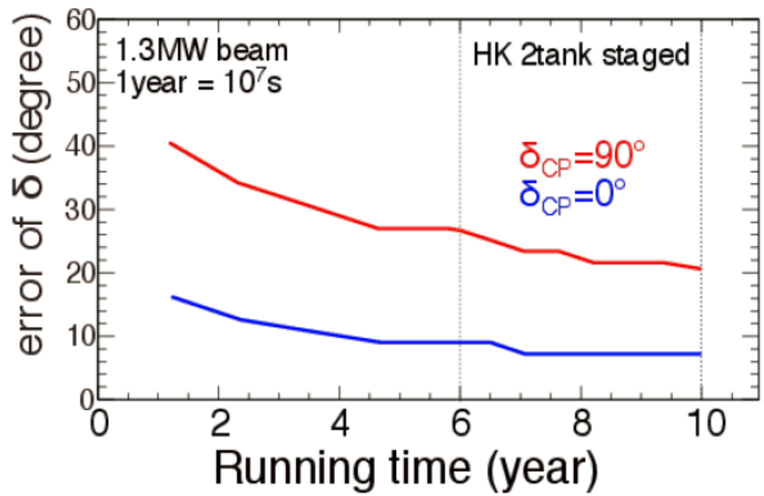


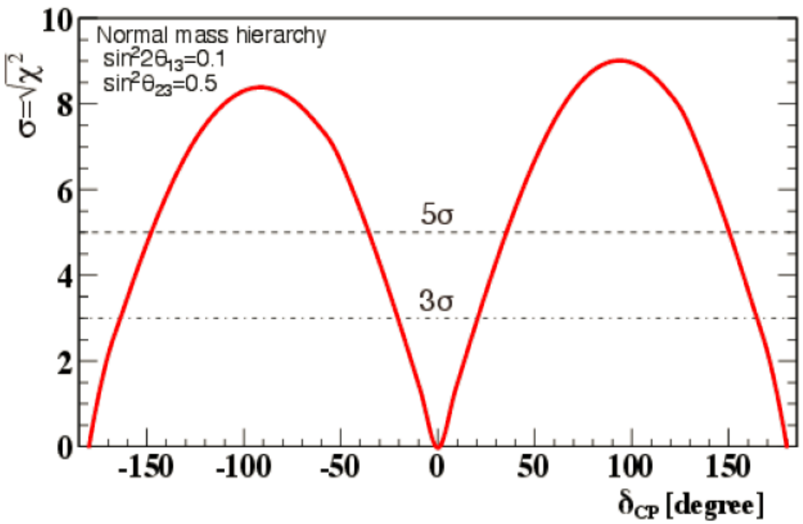
	Signal ($\nu_\mu \to \nu_e$ CC)	Wrong sign appearance	ν_μ, $\bar{\nu}_\mu$ CC	Beam ν_e, $\bar{\nu}_e$ contamination	NC
ν beam (δ_{CP}=0)	2300	21	10	362	188
$\bar{\nu}$ beam (δ_{CP}=0)	1656	289	6	444	274

δ_{CP} sensitivity

Difference from δ_{CP}=0

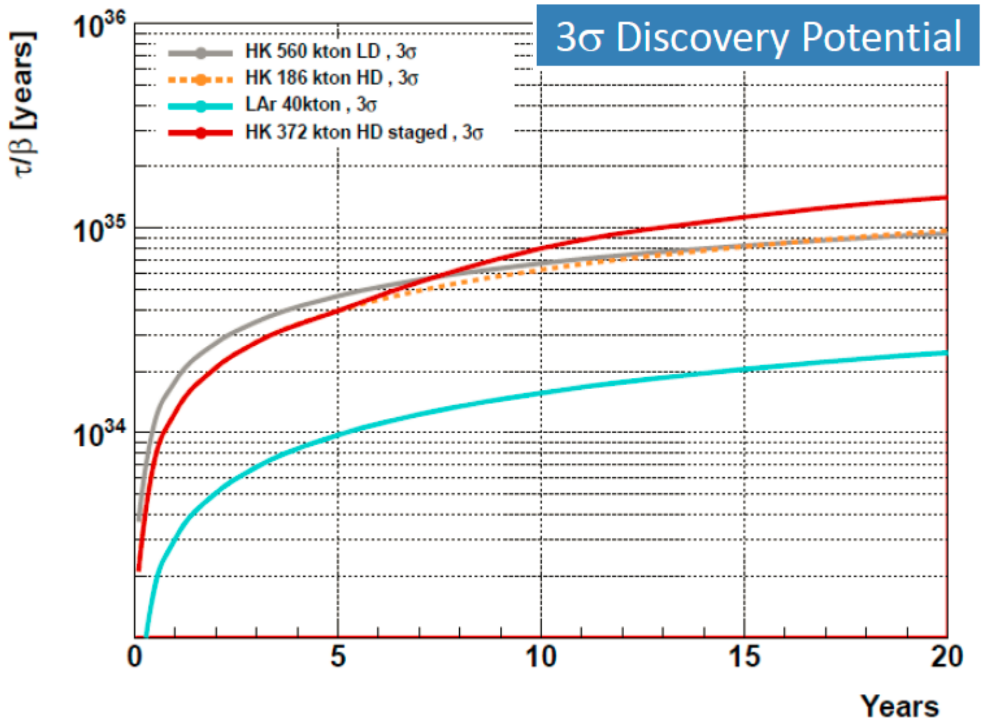


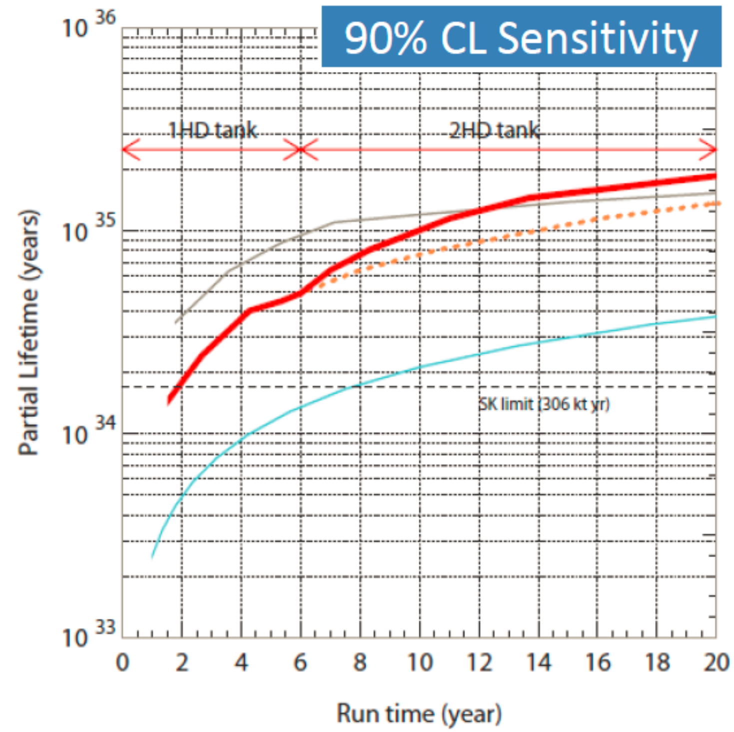




Proton decay

$P \rightarrow e^+ \pi^0$: sensitivity

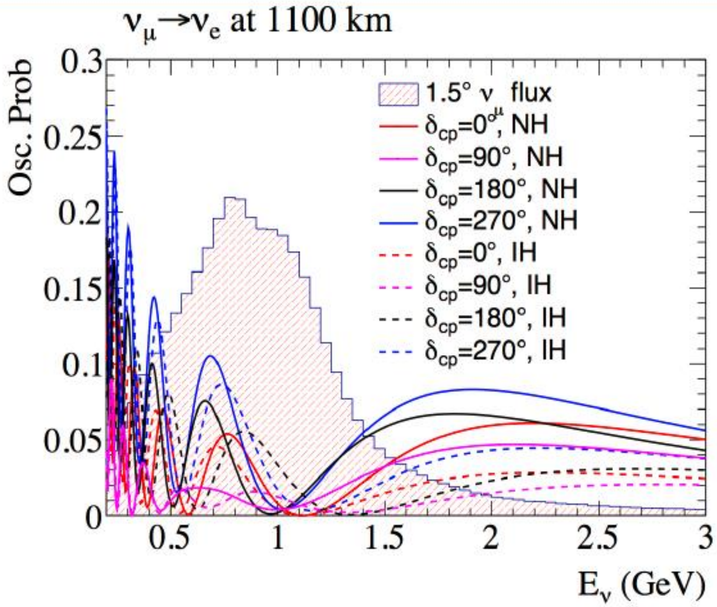


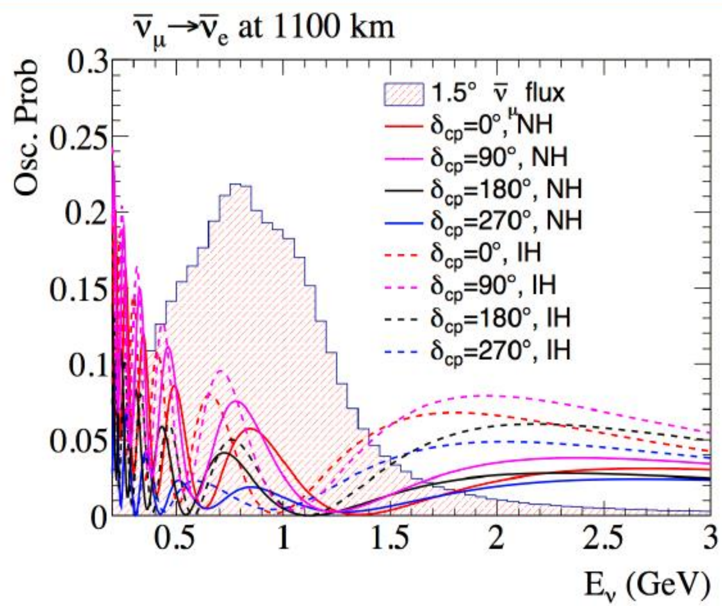


- ✓ > 1×10^{35} years after 2.7 Mton yr (90%CL) or 3σ discovery with 4.0 Mtonyr.
- ✓ If proton lifetime is near the current Super-K limit of 1.7×10^{34} years Hyper-K will observe a positive signal at 8.9σ in 2.7 Mtonyr exposure.

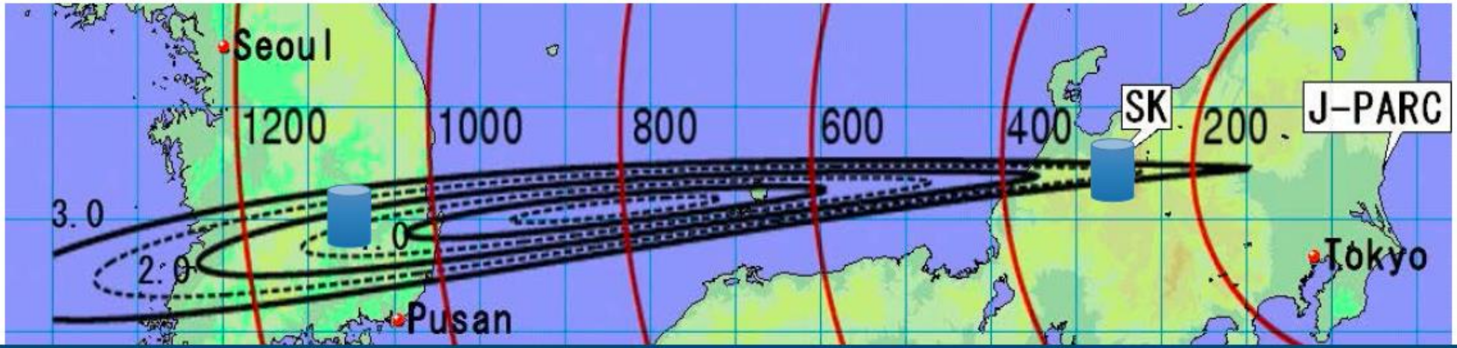
(Lines for the liquid argon experiment have been generated based on numbers in the literature (efficiency: 45% bkg: 1 event/Mtonyr).)

2^{nd} Hyper-K detector in Korea ?





Phys.Rev.D72:033003,2005
Phys.Lett.B637:266-273,2006
Phys. Rev. D81, 093001, 2010



- The 2^{nd} HK tank can be located some other place.
- About 10 years ago, this possibility was discussed.
- Now this possibility is revisited...

The players Mass Ordering

Experiment	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Accelerator LBL																									
T2K																									
T2K-II										}2-4σ															
NOvA																									
Atmospheric																									
PINGU										3σ															
ORCA										3σ															
SK-Gd																									
INO(?)																									
Reactor 20km																									
JUNO										3-4σ															
RENO 50	?	?	?	?	?	?	?	?	?	?				3-4σ											
Accelerator LBL-II																									
HYPER-K																3.5-5σ									
DUNE																**5-15σ**									

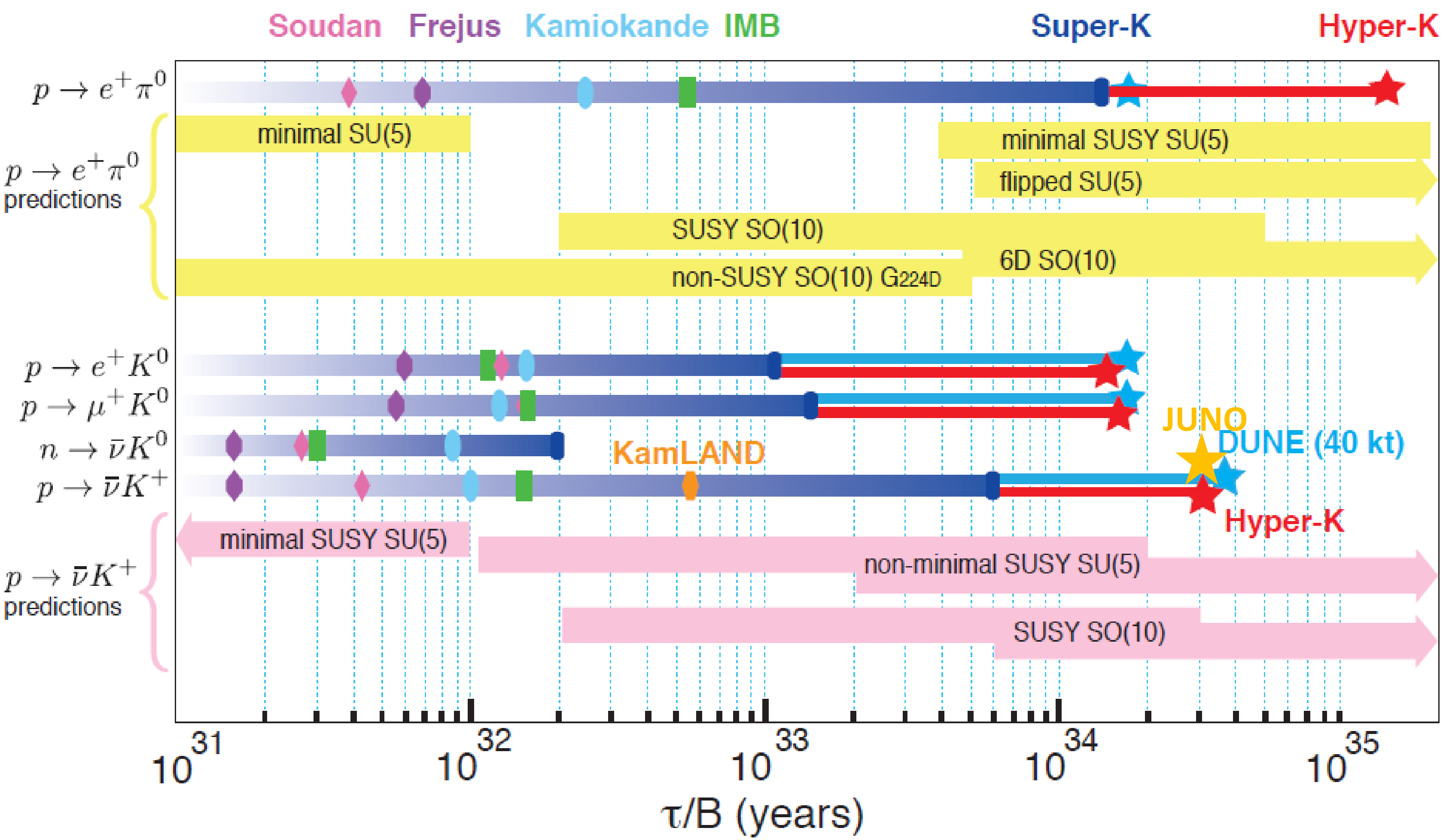
The players CP Violation fraction at 3σ /5σ /(1σ error at δ=0)

Experiment	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Accelerator LBL																									
T2K																									
T2K-II																									
NOvA																									
Atmospheric																									
PINGU																									
ORCA																									
SK-Gd																									
INO(?)																									
Reactor 20km																									
JUNO																									
RENO 50	?	?	?	?	?	?	?	?	?	?															
Accelerator LBL-II																									
HYPER-K																									
DUNE																									

40%/0/<20°

78%/62%/7°

75%/50%/7°



Soudan
Frejus
Kamiokande
IMB
Super-K
Hyper-K
$p \to e^+\pi^0$
$p \to e^+\pi^0$ predictions
minimal SU(5)
minimal SUSY SU(5)
flipped SU(5)
SUSY SO(10)
6D SO(10)
non-SUSY SO(10) G224D
$p \to e^+K^0$
$p \to \mu^+K^0$
$n \to \bar{\nu}K^0$
$p \to \bar{\nu}K^+$
KamLAND
JUNO
DUNE (40 kt)
Hyper-K
$p \to \bar{\nu}K^+$ predictions
minimal SUSY SU(5)
non-minimal SUSY SU(5)
SUSY SO(10)
10^{31}
10^{32}
10^{33}
10^{34}
10^{35}
τ/B (years)

CONCLUSIONS

The T2K (+NA61) experiment is extremely successful → discovery of $\nu_{\mu} \rightarrow \nu_{e}$ oscillation!
this opens the way towards CP violation.

JPARC accelerator improvements and prospects are now impressive.
Experiment is approved for another factor 5 more data .
It has requested an extension (T2K-II) for an additional 2.5 times more until 2025.
The upgrade program is first priority of JPARC/KEK
→ more precise parameters and possibly first 3-4 σ observation for CP Violation
this requires continued improvement of systematics!
Upgrade of near detector organized: magnetic detector + intermediate Water Cherenkov

HyperK is an upgrade by a further factor 10-20. It is highly placed on Japan road map.
-- It has been submitted to MEXT for approval
-- CDR has been published and reviewed favorably by the HK advisory committee.
-- Seeking approval towards the end of 2017 for a start of exploitation in 2026.

HYPERK is a highly competitive for the study of neutrino oscillations (discovery of CPV)
+ unparalleled program for proton decay, supernovae observations (near and relic)
and other astrophysical sources.

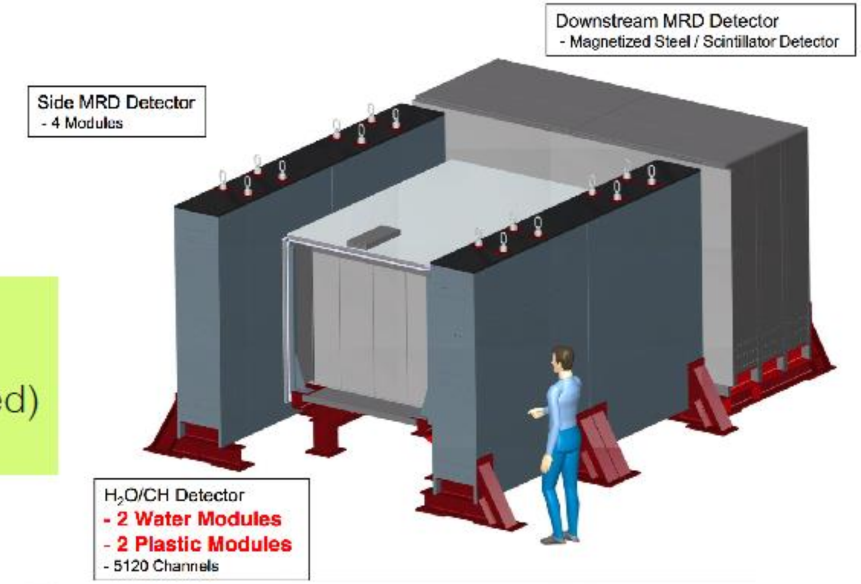
The complemetarity with NOvA, JUNO, Atmospheric programs PINGU and ORCA, and with DUNE, is compelling.

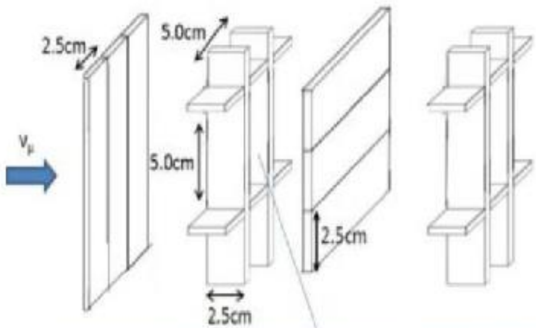
3% precision H_2O / CH x-section ratio

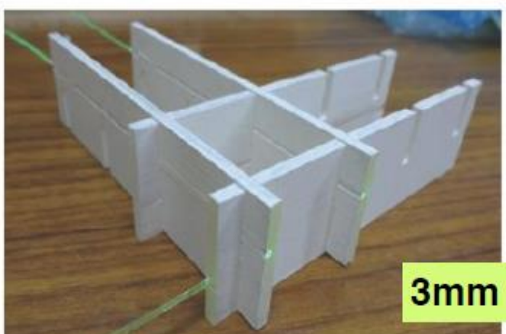
Wagasci

Wagasci collaboration

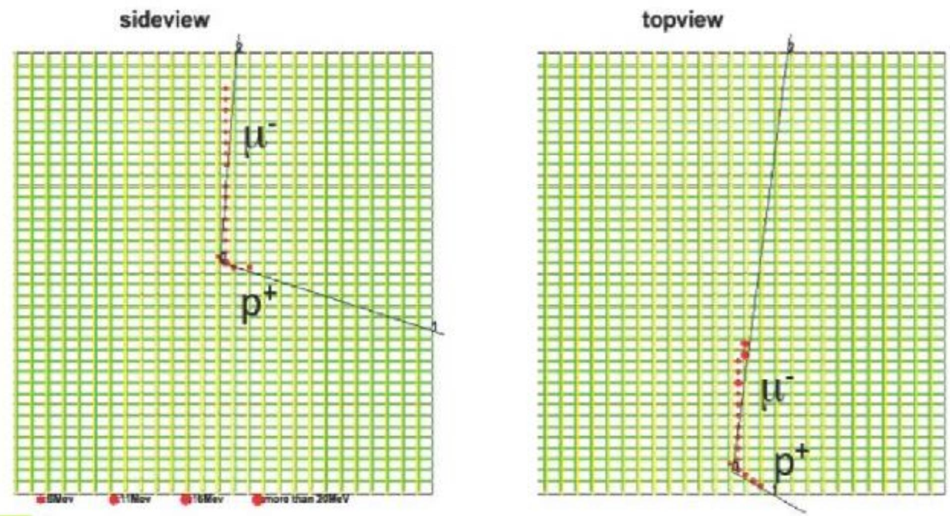
'The B2 experiment'
- 3D scintillator grid filled with water
- Side MRDs and end MRD (magnetized)
- Excellent phase space coverage







3mm thick



See talk on Tuesday