ГиперКамиоканде и DUNE

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ИЯИ РАН

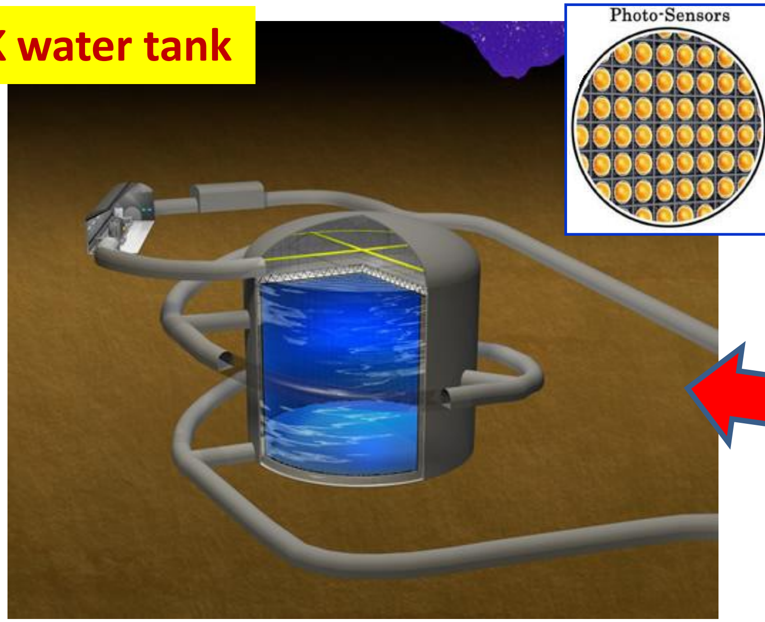
Ученый Совет ИЯИ РАН
18 октября 2018

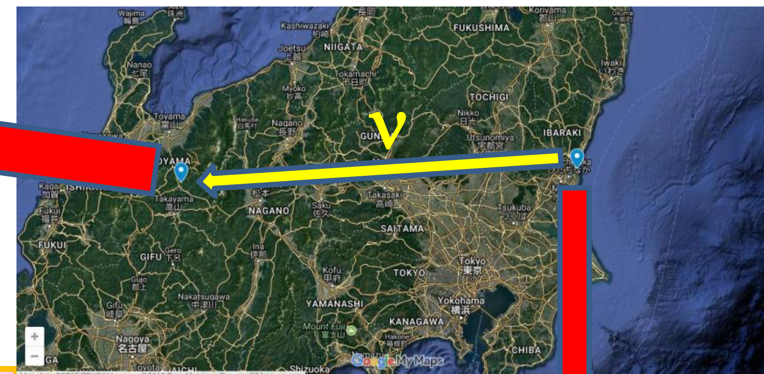
Hyper-Kamiokande Project

12countries
> 350 collaborators

Main goals:
- **Search for CP violation**
- **Proton decay**
- **Neutrino astrophysics**

Hyper-K water tank

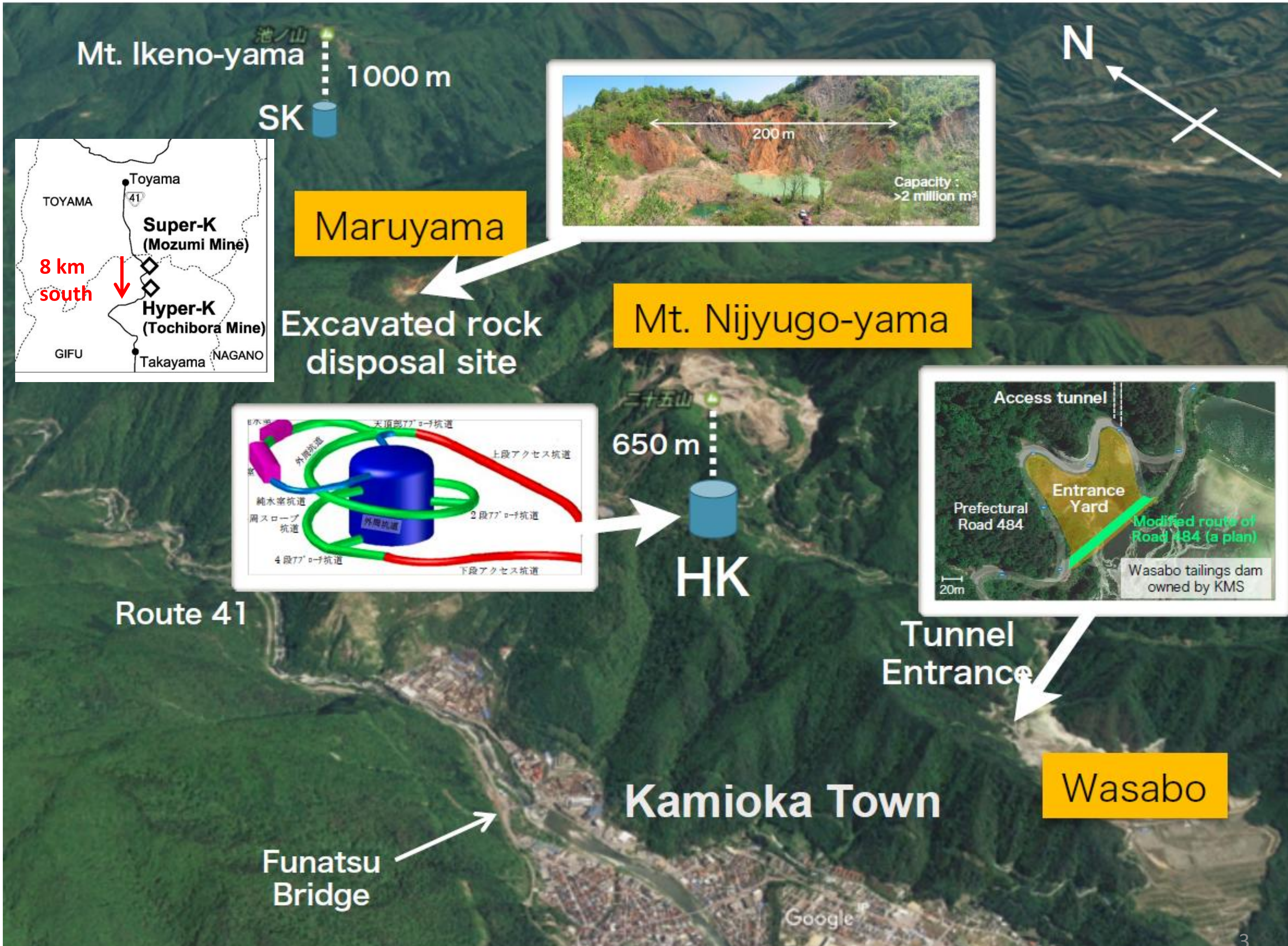




Water tank

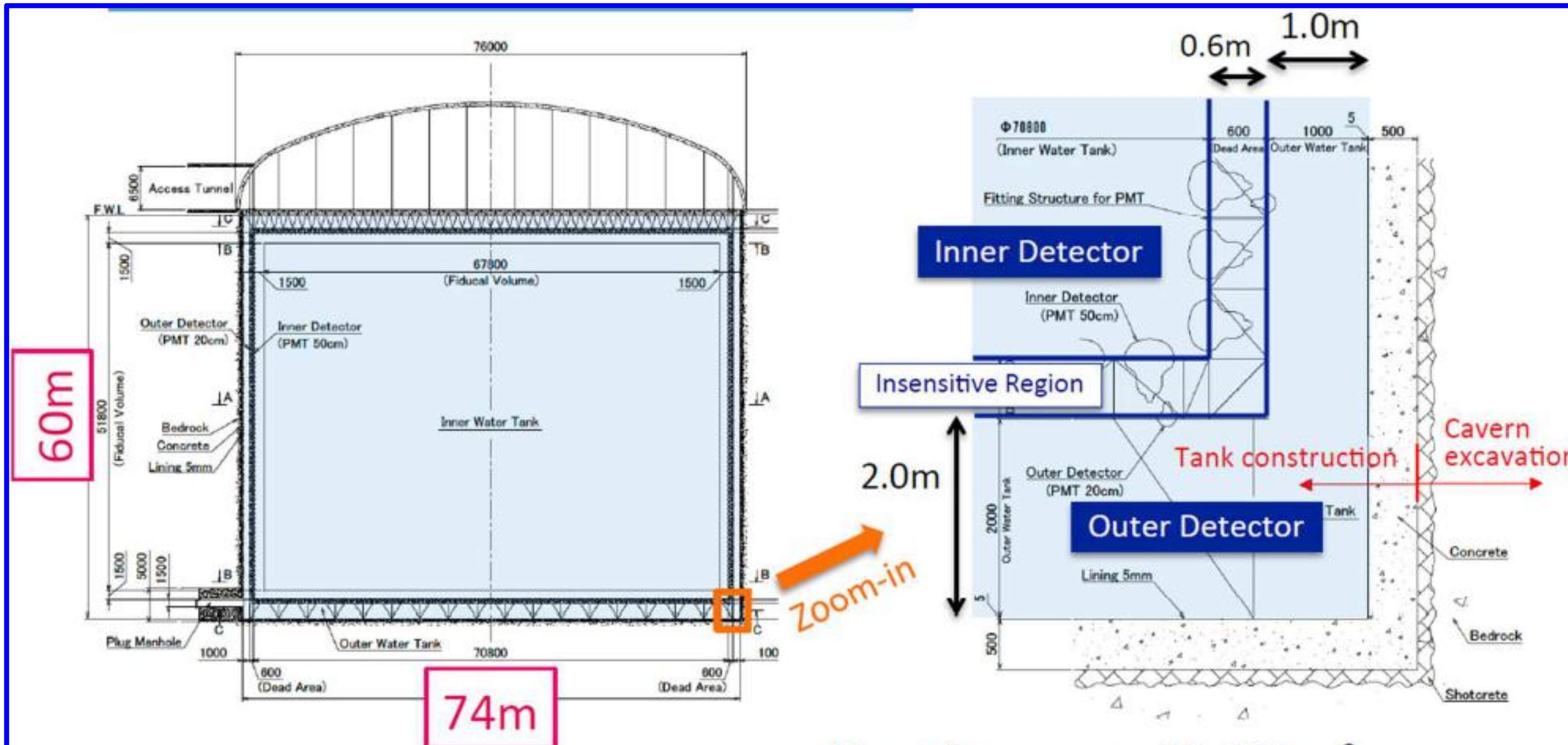
60 m(H)x74m(D)
Total volume 260 kt
Fiducial volume 190 kt ~10xSuper-K
40000 50 cm ID PMTs PMT coverage 40%
6700 20 cm OD PMT's
Photon sensitivity ~2 times better than Super-K
Construction of 2nd tank in Korea
(1-3 deg off axis, 2nd oscill. maximum) is under study

J-PARC



Mt. Ikeno-yama
1000 m
SK
N
200 m
Capacity : >2 million m³
Toyama
TOYAMA
41
Super-K
(Mozumi Mine)
8 km south
Hyper-K
(Tochibora Mine)
GIFU
Takayama
NAGANO
Maruyama
Excavated rock disposal site
Mt. Nijyugo-yama
天頂部ｱﾌﾟﾛｰﾁ坑道
外周坑道
上段アクセス坑道
純水室坑道
スロープ坑道
2段ｱﾌﾟﾛｰﾁ坑道
4段ｱﾌﾟﾛｰﾁ坑道
下段アクセス坑道
650 m
HK
Access tunnel
Entrance Yard
Prefectural Road 484
Modified route of Road 484 (a plan)
Wasabo tailings dam owned by KMS
20m
Route 41
Tunnel Entrance
Wasabo
Kamioka Town
Funatsu Bridge
Google

Water tank



Total : 258.1 kt/tank

Inner Detector : 215.7 kt/tank

Fiducial Volume: 187.0 kt/tank

ID surface area : 20,063 m^2

1 ID-PMT/0.5m^2 (40% coverage)

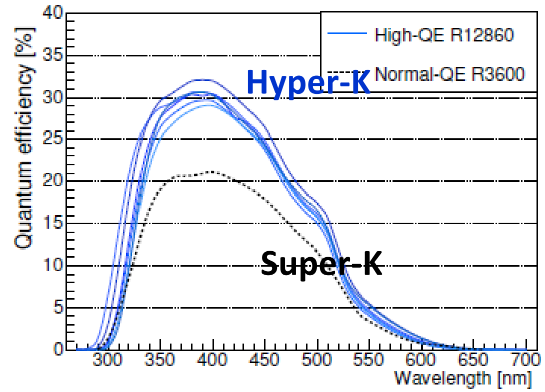
→ ~40,000 ID-PMTs/tank

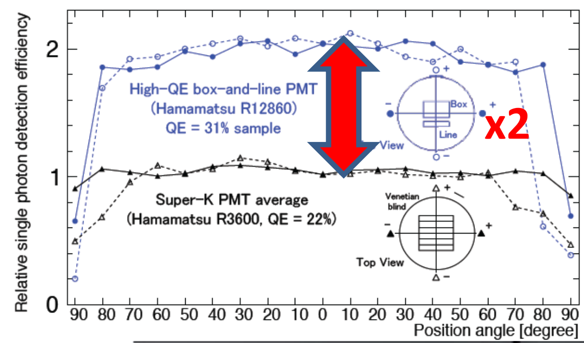
~6,700 OD-PMTs/tank

Photosensors

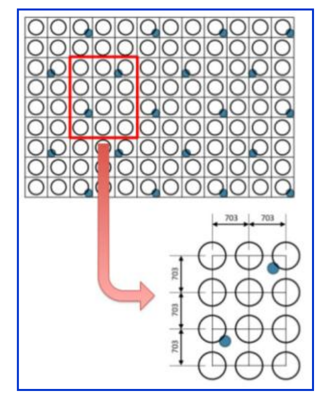
Hamamatsu R12860-HQE
B&L 50 cm PMT

40000 PMTs
40% photocoverage



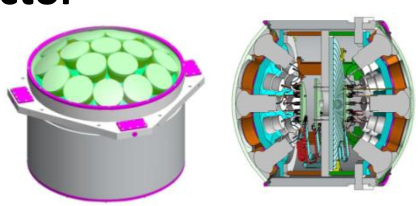


1 p.e.
time resolution 1.1. ns
charge resolution 35%



Hamamatsu R5912-HQE
B&L 20 cm PMT

Other 50-cm candidates:
- **Hybrid Photo-Detector**
- **MCP PMT**
- **Multi-PMT**

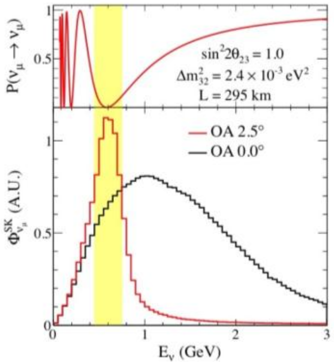


Tokai-to-Hyper-K (T2HK)

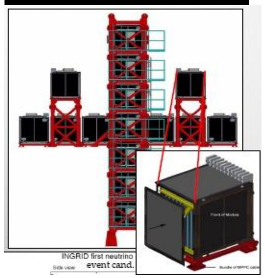
Hyper-K

J-PARC

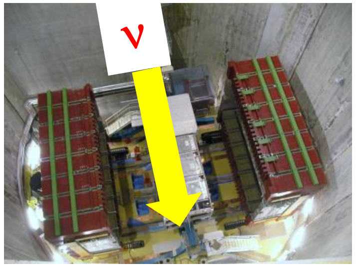
Off-axis neutrino beam



Neutrino monitor INGRID



Off-axis near neutrino detector



Near neutrino detector at 280 m from target

Decay tunnel

Horn

Target

Neutrino beam elements

J-PARC neutrino beam

2.5°off-axis, peak energy 600 MeV (oscillation maximum), current beam power 485 kW

Physics

Accelerator neutrinos

- **search for CP violation**
- **precise measurement of oscillation parameters**

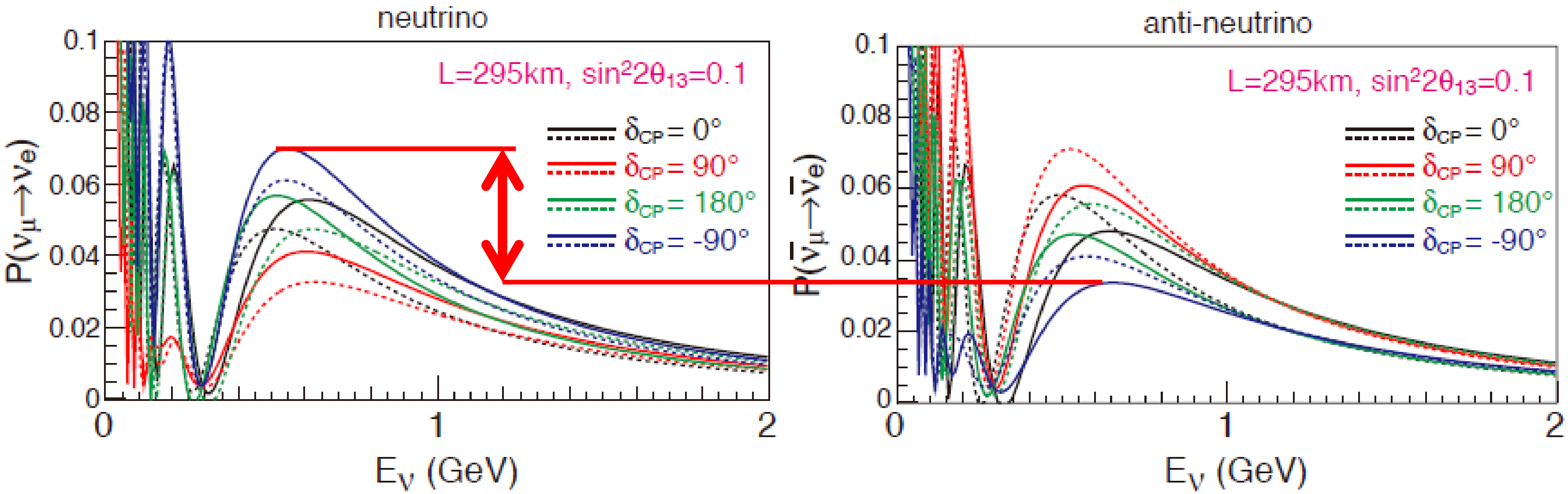
Atmospheric and solar neutrinos

- **mass hierarchy**
- **θ_{23} octant**

Nucleon decays

Neutrino astronomy and astrophysics

Search for CP violation

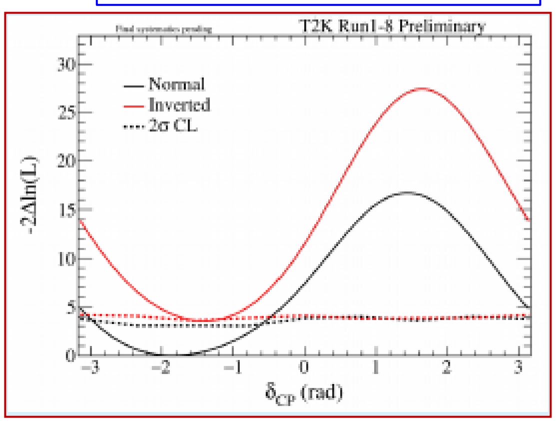


$$L = 295\,\text{km},\ \sin^2 2\theta_{13} = 0.1,\ \sin^2 2\theta_{23} = 1.0,\ \delta_{CP} = -90°$$

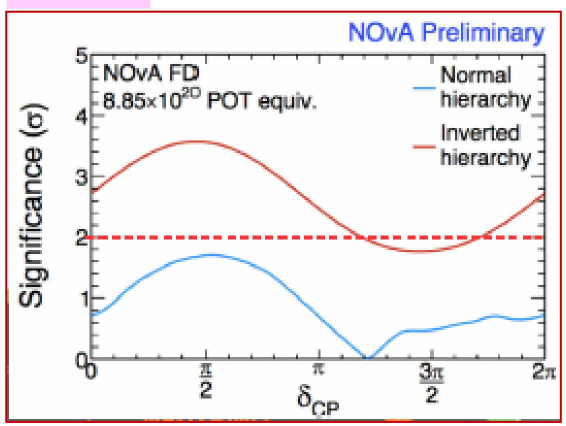
E = 0.6 GeV, $\Delta m^2_{32} L/4E \approx 1$

T2K

Hint on maximal CP violation, $\delta \sim -\pi/2$, $\delta = 0$ excluded at 2σ



NOvA



$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

T2HK

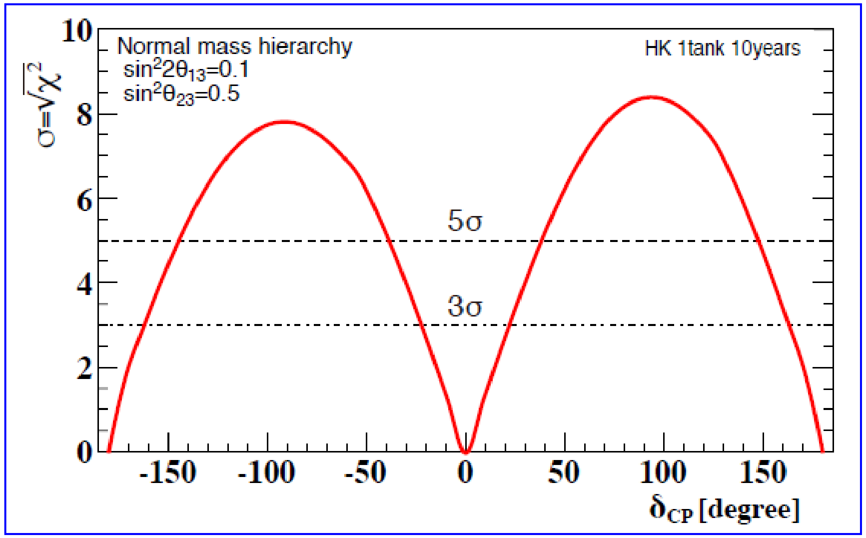
for $\delta = -\pi/2$

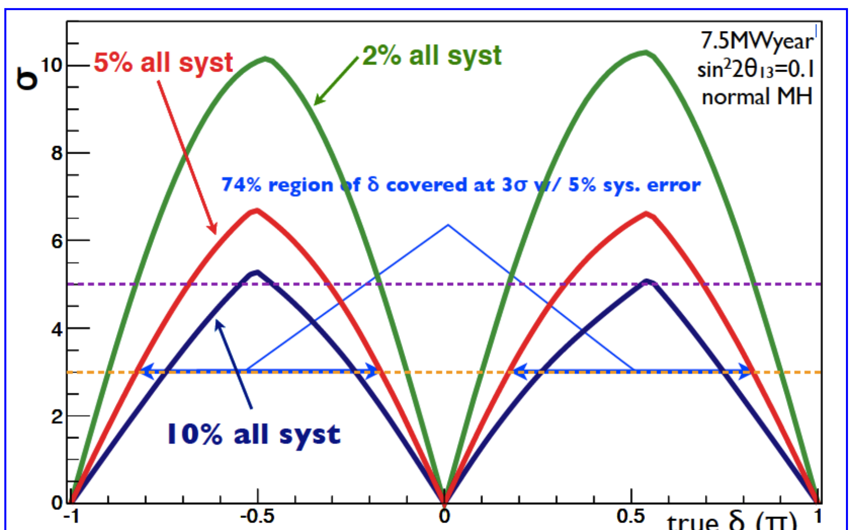
→**CP violation effect $A_{CP} \sim 28\%$**

→**matter effect ~8%**

Sensitivity to CP

$\nu : \bar{\nu} = 1:3$ $\sin^2 2\theta_{13} = 0.1$





Integrated beam power 1.3 MW x 10^8 s

$\rightarrow$ 2.7 x 10^{22} POT with 30 GeV proton beam

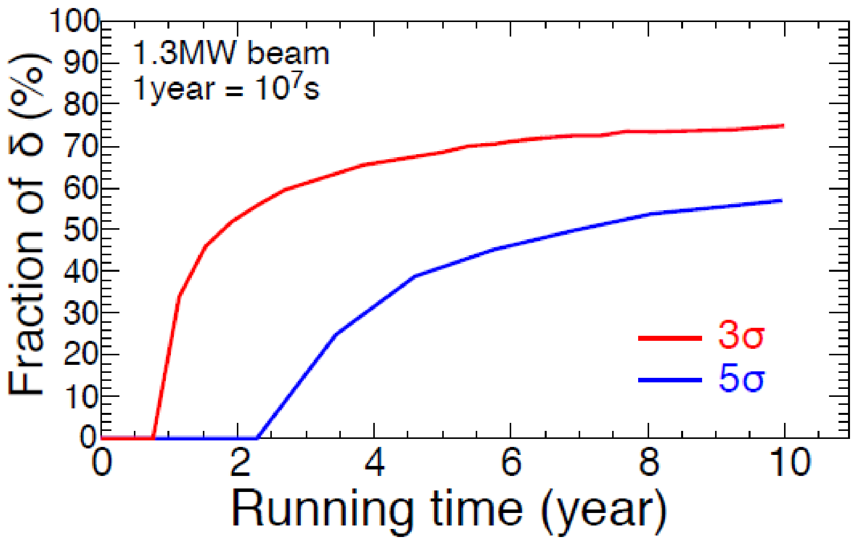
T2HK: uncertainties of expected number events

$\nu_\mu \rightarrow \nu_e$	3.2%
$\nu_\mu \rightarrow \nu_\mu$	3.6%
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.9%
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	3.6%

T2K systematic uncertainties 5-6 %

Exclusion of δ=0 at 8σ (for δ= -π/2)
5σ (3σ) significance for 57 (80)%
of possible δ values

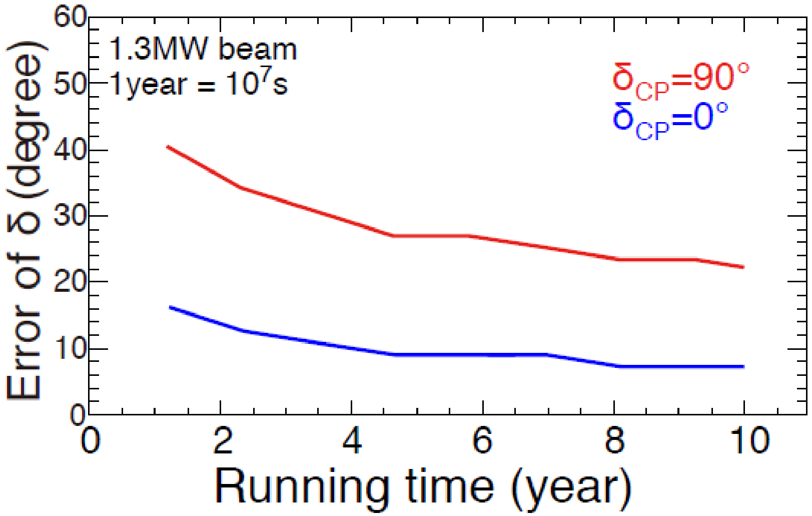
Prospects for δ measurements

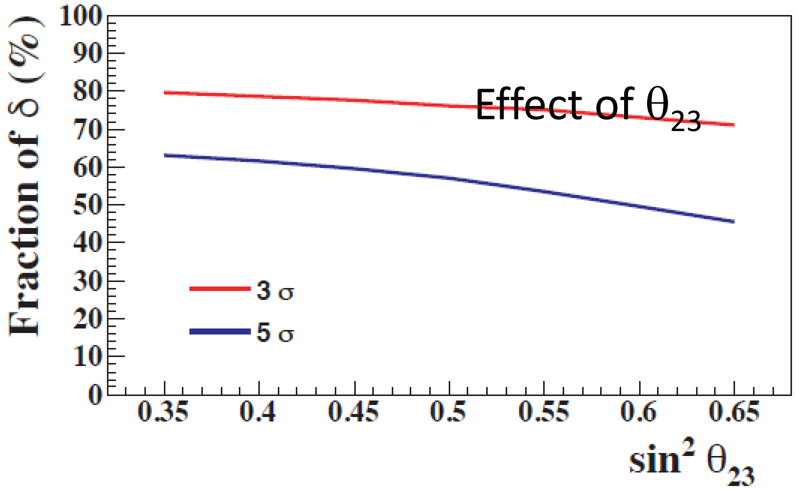


Measurement of δ

δ = 90 deg σ = 23 deg

δ = 0 deg σ = 7 deg

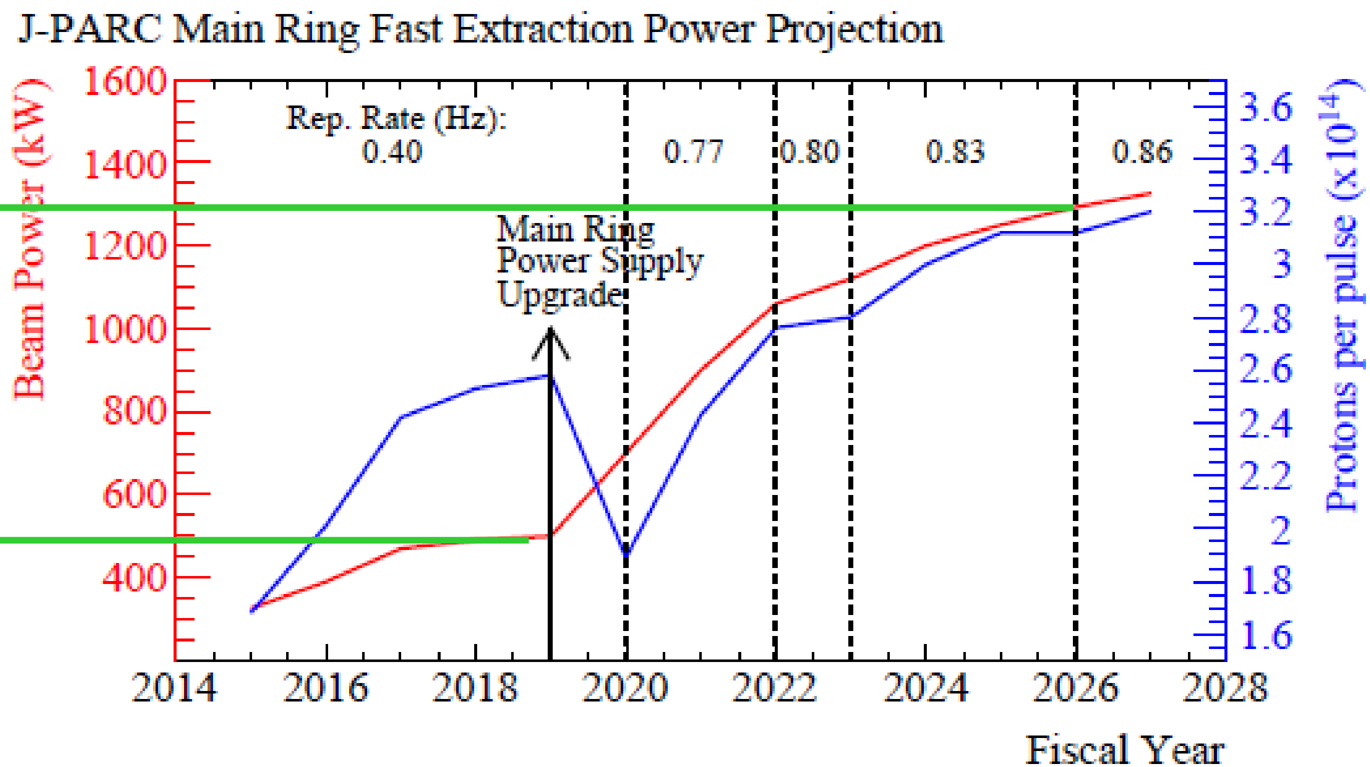




J-PARC upgrade

1.3MW by Hyper-K

485 kW achieved



J-PARC 30 GeV main ring
→ 750 kW (cycle 1.3 s) - 2020
→ 1.3 MW (cycle 1.16 s) - 2026
Narrow-band neutrino beam, peak energy 600 MeV

ND280 upgrade

- Reduction of systematics

- Cross sections

arXiv: 1606.08114; 1412.3086

E61: Movable Water Cherenkov detector

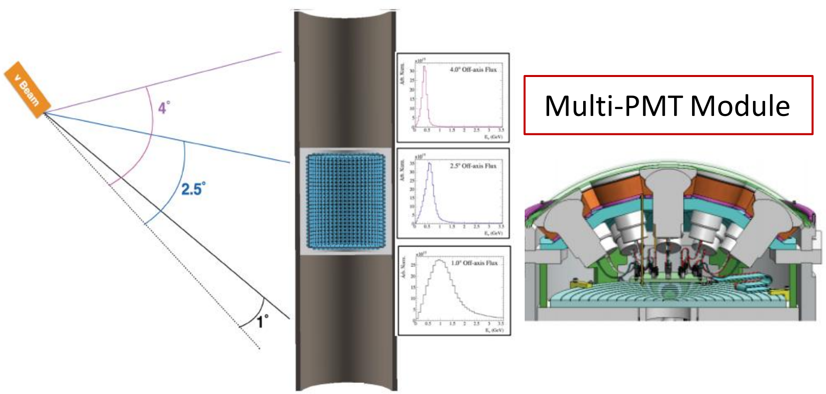
Inner diameter 8 m

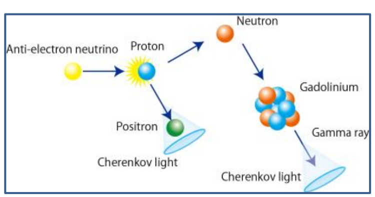
Inner detector height 6-8 m

Multi-PMTs

Load detector with $Gd_2(SO_4)_3$

to enhance neutron detection





Measurement of neutron mutiplicity to understand Gd n-capture signal in Super-K and Hyper-K

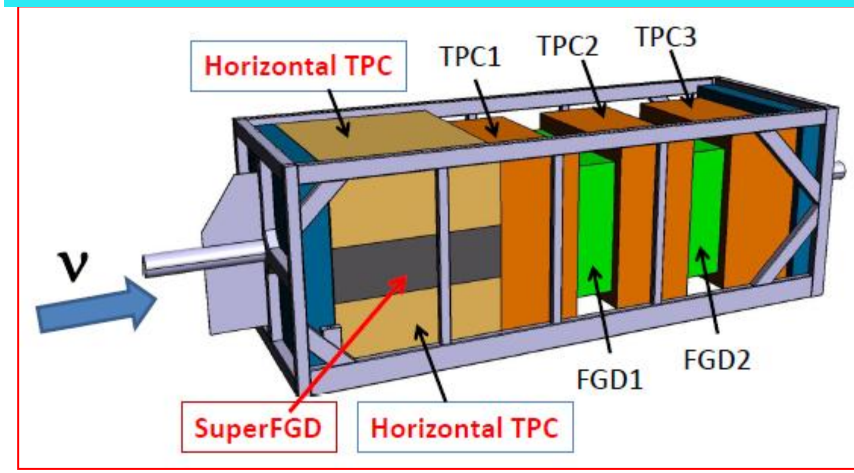
arXiv:1609.04111

New upstream tracker:

Two Horizontal TPCs

One 3D fine-grained scintillator target SuperFGD

TOF system around new tracker



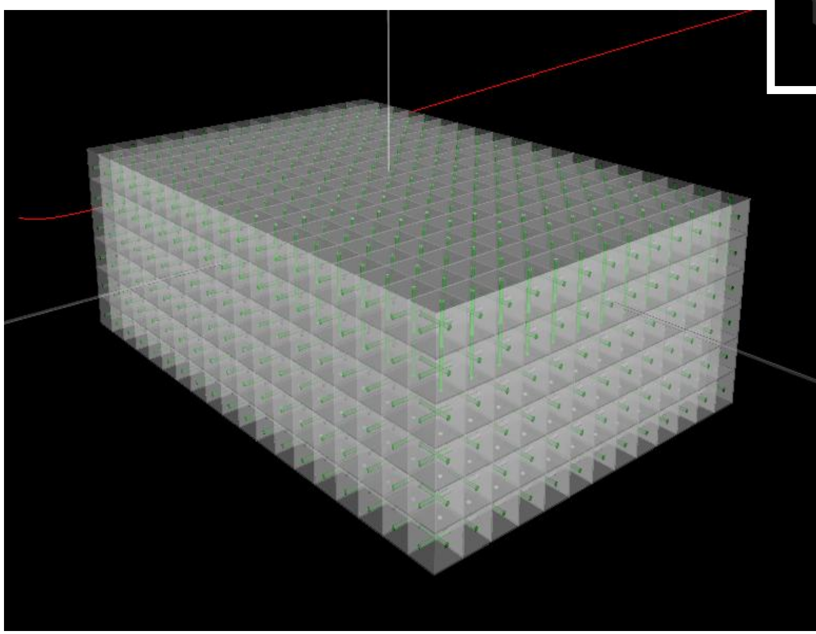
3D highly granular scintillator detector (SuperFGD):

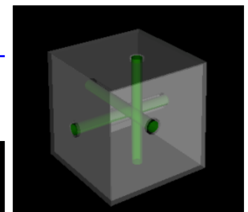
- precise measurement of neutrino energy;
- cover full solid angle and low momentum for charged particles from neutrino interactions;
- measure electron neutrino cross sections;
- measure nuclear effects in neutrino interactions
- reduce systematic uncertainties to 3-4% level in oscillation measurements

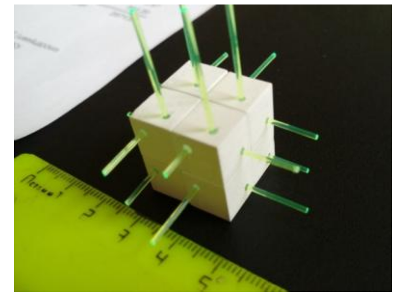
SuperFGD

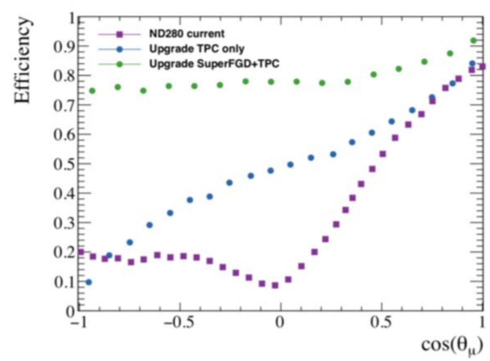
- Volume 200 x 200 x 60 cm^3
- **2 x 10^6** scintillator cubes , 1 x 1 x 1 cm^3
- Each cube has 3 holes, diameter 1.5 mm
- 3D (x,y,z) WLS readout
- About 60000 readout WLS/MPPC channels
- Total active weight about 2 t

Fully active, highly granular, 4π scintillator neutrino detector with 3D WLS/MPPC readout

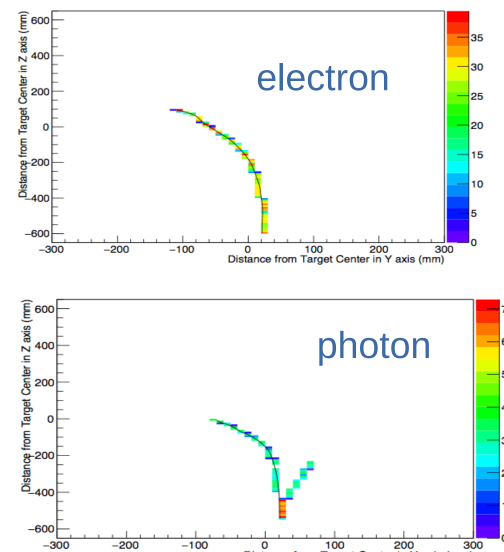








MC simulation



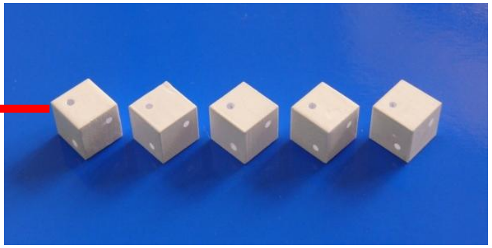
Technology

Cubes are manufactured at Uniplast, Vladimir

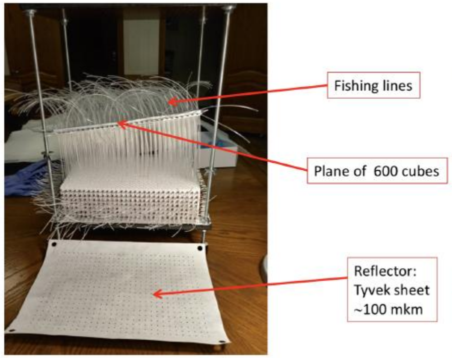
Extrusion → injection molding

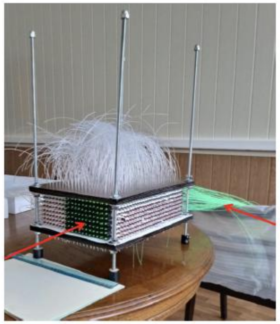
New machine for injection molding was bought and commissioned at Uniplast in July 2018

Precision: each side ≤ 30 μm



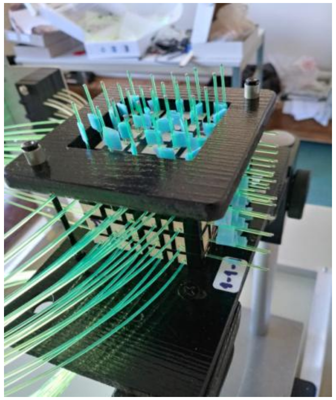
Assembly, mechanics, tests, fibers, photosensors .... at INR



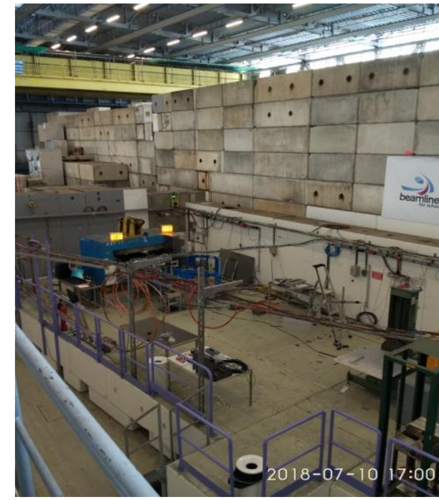


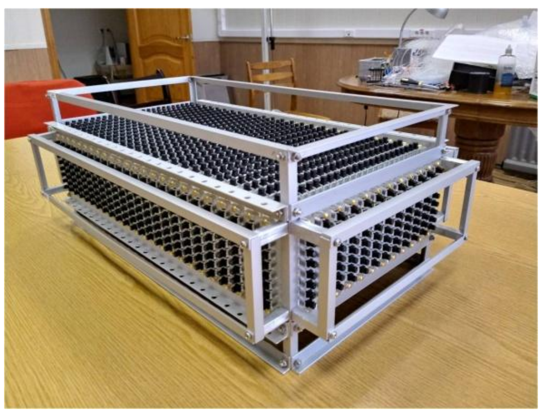
Beam tests at CERN

T9 channel at CERN: muons, pions, protons, electrons 0.5 – 5.0 GeV



-First **small prototype**:
-125 cubes, 75 readout channels
- Beam test October 2017



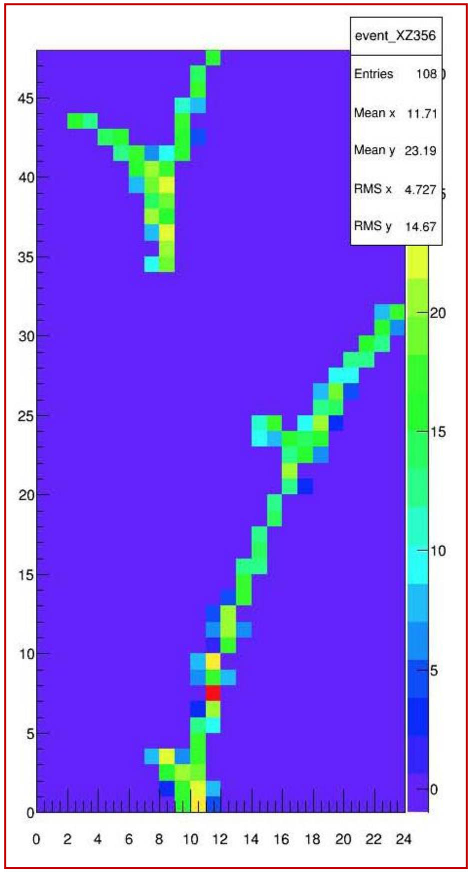


Large prototype
Length 48 cm
Width 24 cm
Height 8 cm
9216 cubes, each 1x1x1 cm^3
1728 Y11 WLS fibers, 1 mm diameter
Readout: 1728 MPPC's
2 beam tests:
June-July 2018
August-September 2018

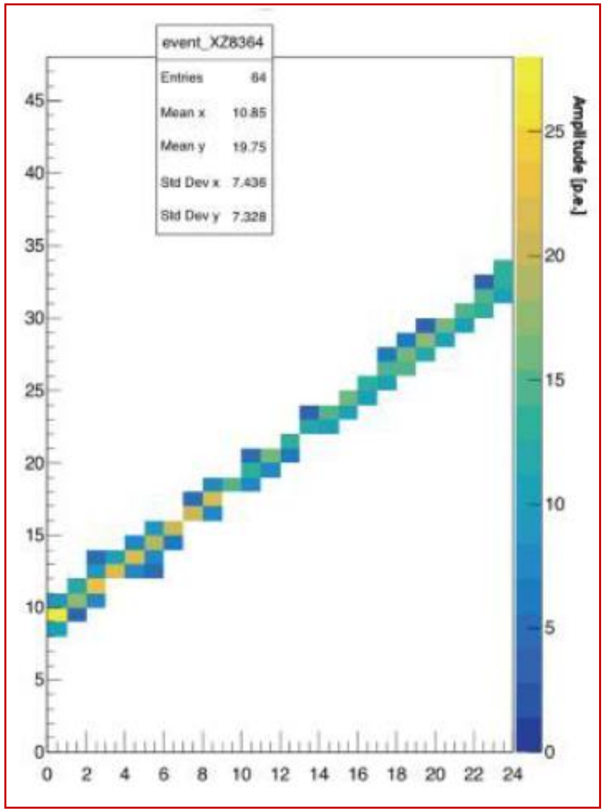
Beam events

Top views

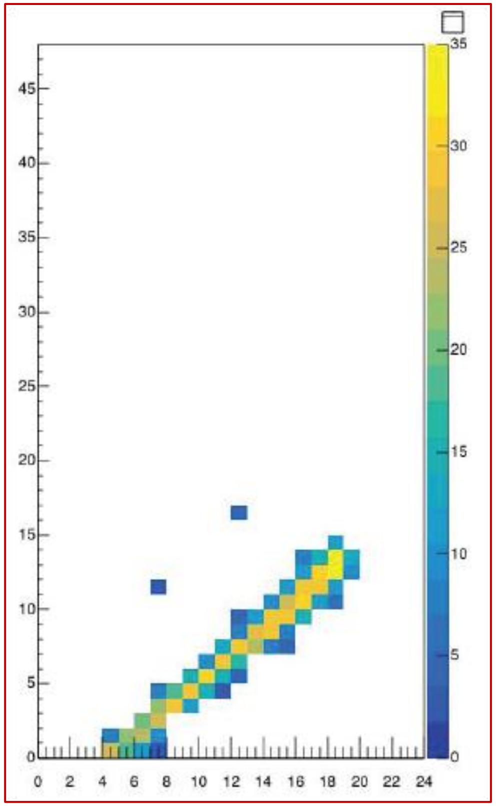
Positron, 1 GeV, B = 0.2 T



Muon, 5 GeV, 45 deg

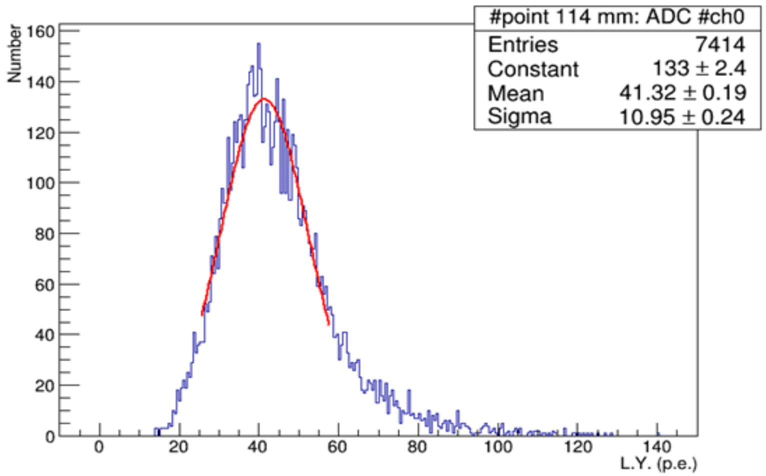


Stopped proton, 0.5 GeV, 45 deg

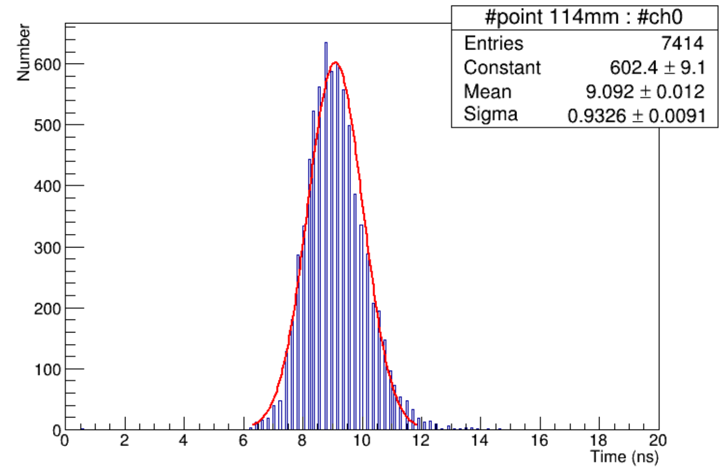


Results

MIP: Light yield per fiber



MIP: time resolution per fiber



Light yield of 1 cube/1 fiber **42 p.e./MIP**
Light yield of 1 cube/2 fibers **80 p.e./MIP**
Time resolution **(σ)**
- 1 fiber: **0.92 ns**
- 1 cube/2 fibers: **0.68 ns**
- 2 cubes/4 fibers: **0.48 ns**
- 3 cubes/6 fibers: **0.39 ns**

Schedule for SuperGFD

Manufacturing of detector elements	01.2019 - 12.2020
Assembly	10.2020 – 09.2021
Tests	07.2021 – 09.2021
Installation into ND280 pit	10.2021

Participants :
INR; KEK, U.Tokyo, U.Kyoto; U.Geneva, CERN;
Ecole polytechnique, Saclay; Uppsala;
NCBJ,Warsaw; LSU, Stony Brook

Status of Hyper-K and T2HK

Official statement, 12 September 2018

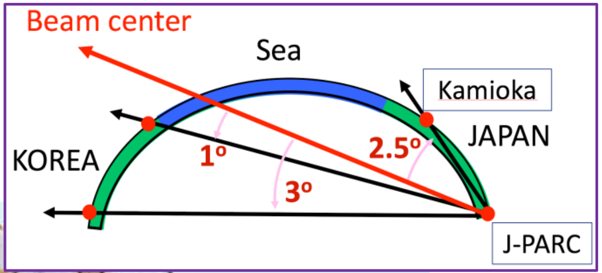
- **Seed funding for Hyper-Kamiokande construction was allocated within MEXT 2019 budget**

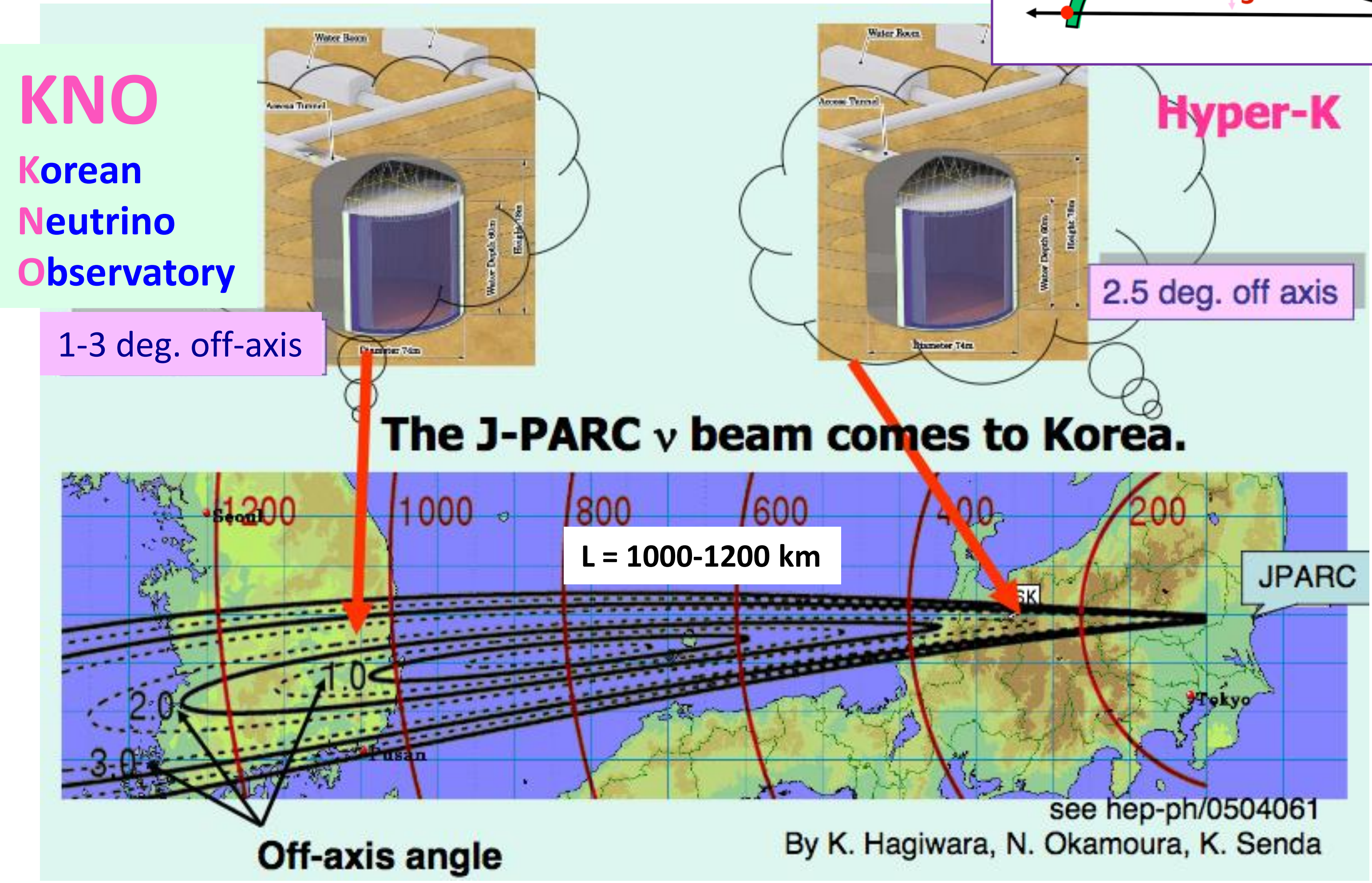
- **The University of Tokyo pledges to ensure construction of Hyper-Kamiokande in April 2020**

T2HKK

2nd Hyper-K detector in Korea

T2HKK = Tokai-to(2)-HK-to-Korea





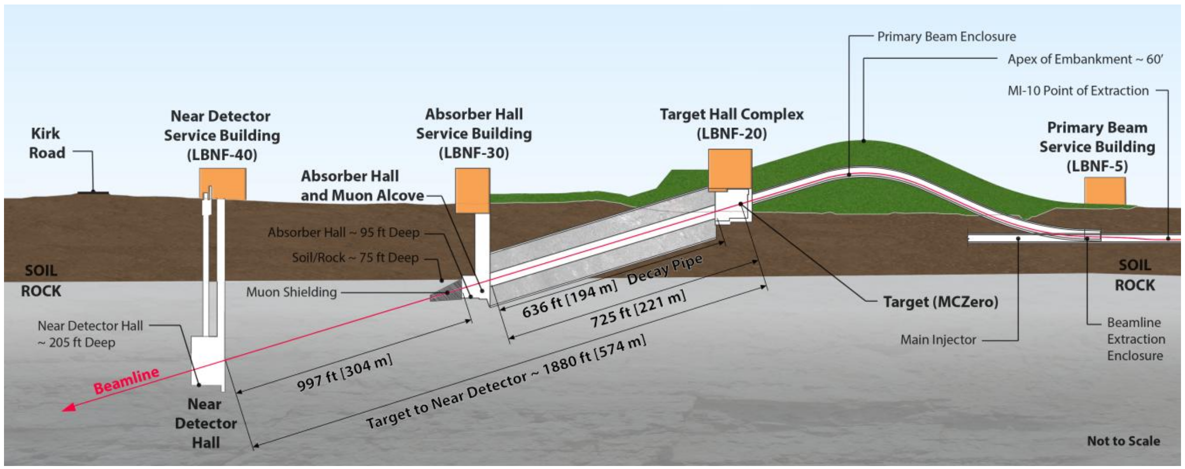
LBNF/DUNE project

Flagship FNAL project

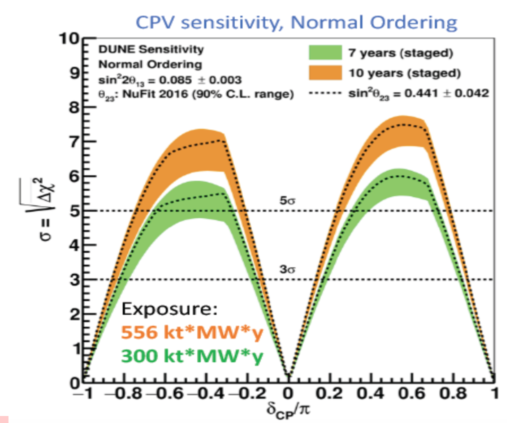
Main goals: **- discovery of CP violation in leptonic sector**
- neutrino mass hierarchy at >5σ level
- neutrino astronomy
- proton decay search

30 countries
161 institutions
> 1000 collaborators

E_p = 60-120 GeV
Beam power 1.2 -> 2.4 MW
On axis neutrino beam
Eν ~ 1- 6 GeV
L=1300 km from FNAL to SURF, S.Dakota

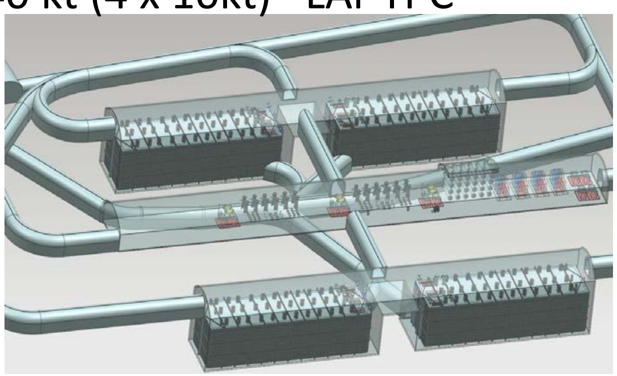


Sensitivity to CP violation



Far detector 40 kt (4 x 10kt) LAr TPC

Single
and
Dual
phase
detectors



2021 – installation of 1st far detector
2024 – 2 modules operational
2026 – deliver neutrino beam

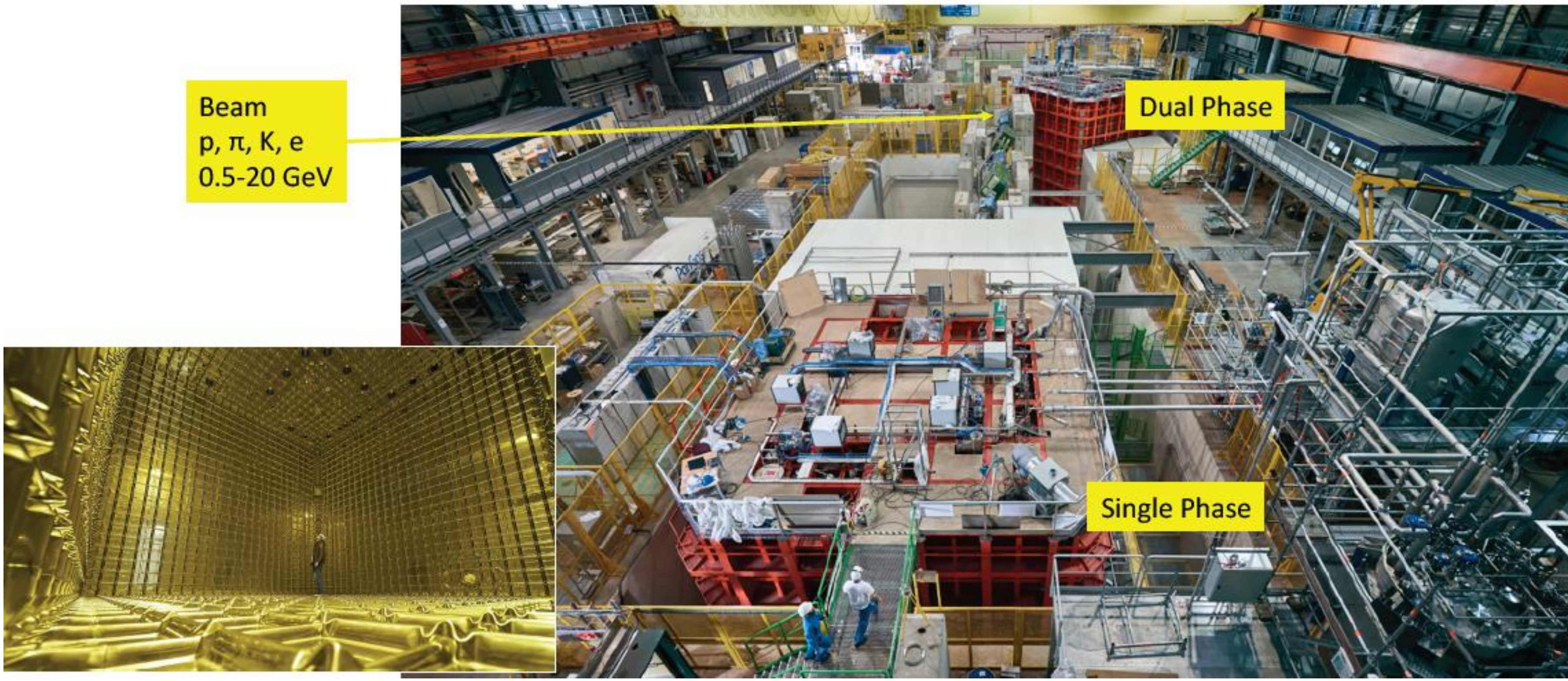
Detector prototyping

Detector R&D of LAr detectors within the CERN neutrino platform

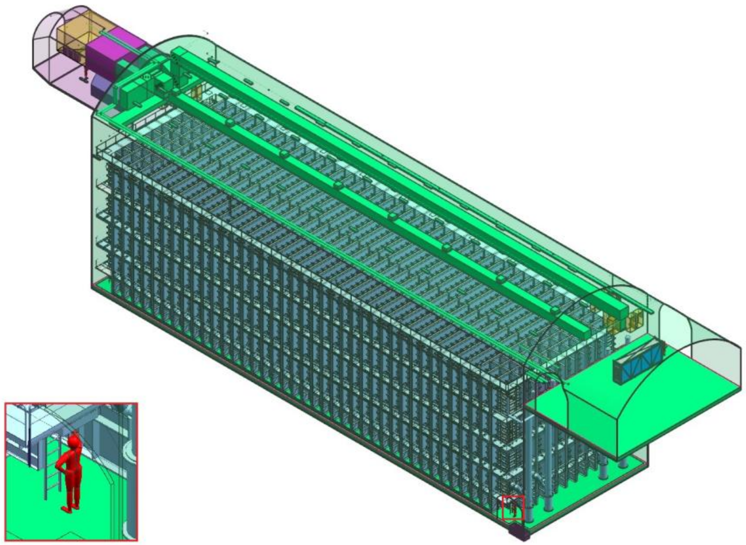
start in 2016

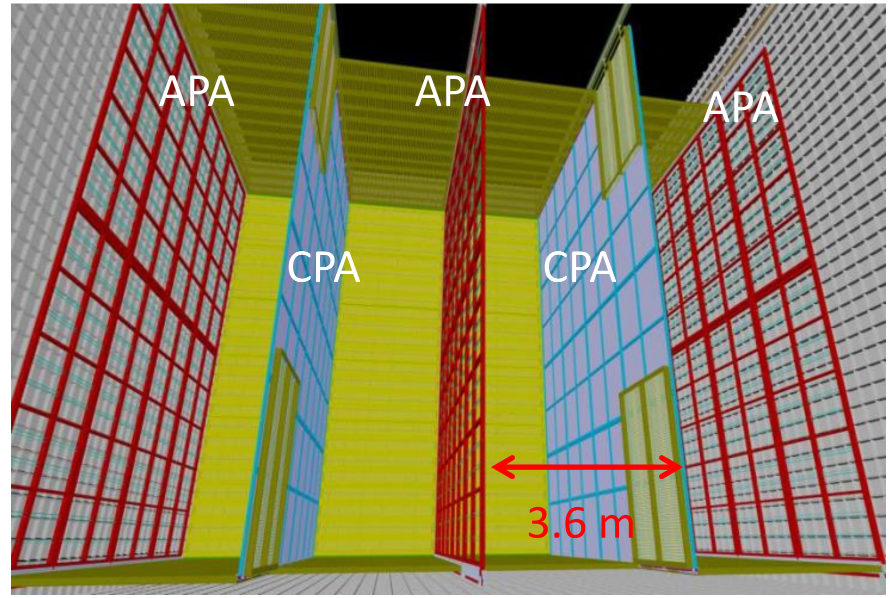
beam in 2018

Both prototypes are installed at CERN, in a dedicated extension of the North Area

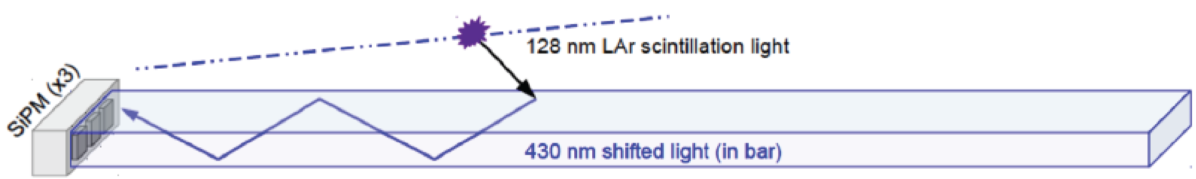


Single Phase TPC



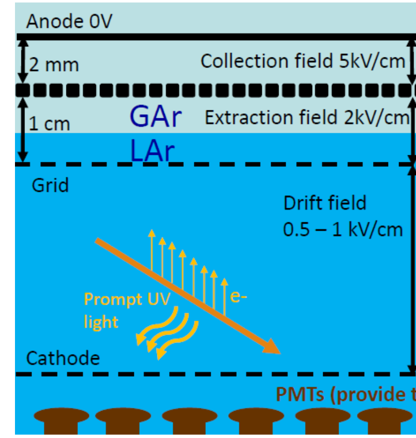


1st 10 kt module of DUNE - single-phase TPC
6m x 2.3 m anode and cathode planes 3.6 m spacing
Photon detectors – light guides + SiPMs embedded in APAs

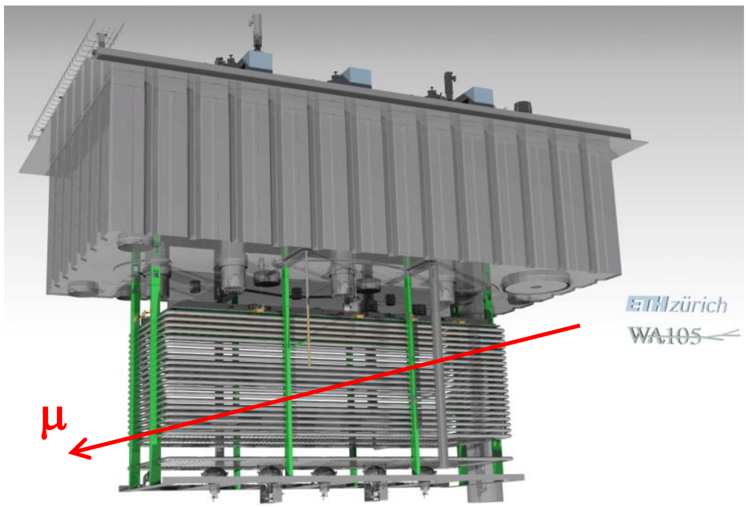


Dual Phase TPC

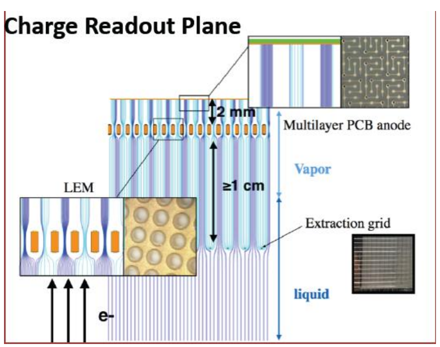
NP02: WA105 (DP demonstrator + ProtoDUNE DP)

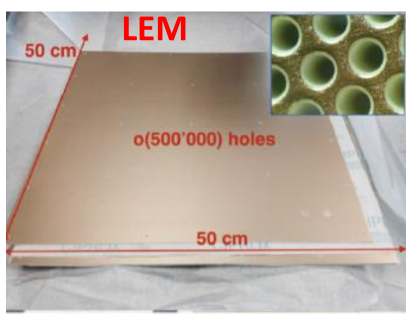


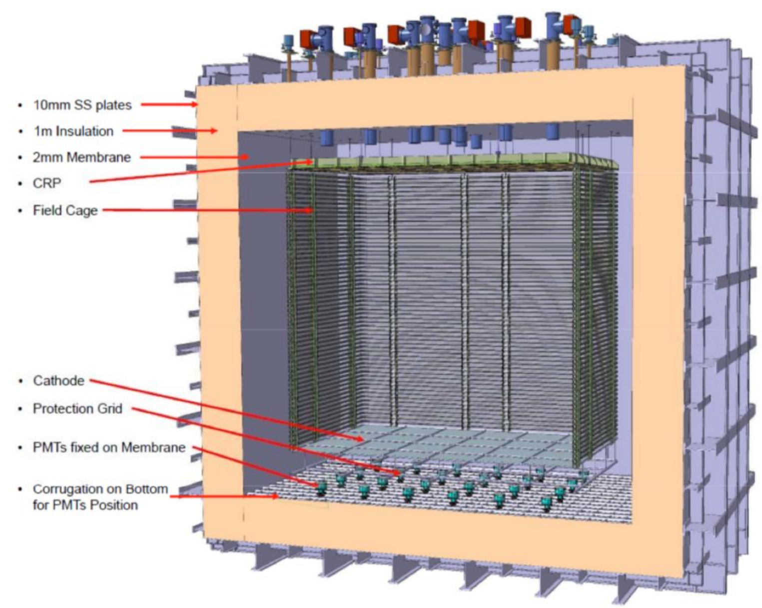
Demonstrator: 3x1x1 m^3 – 5 tons



ProtoDUNE DP:
6x6x6 m^3
300 tons active mass

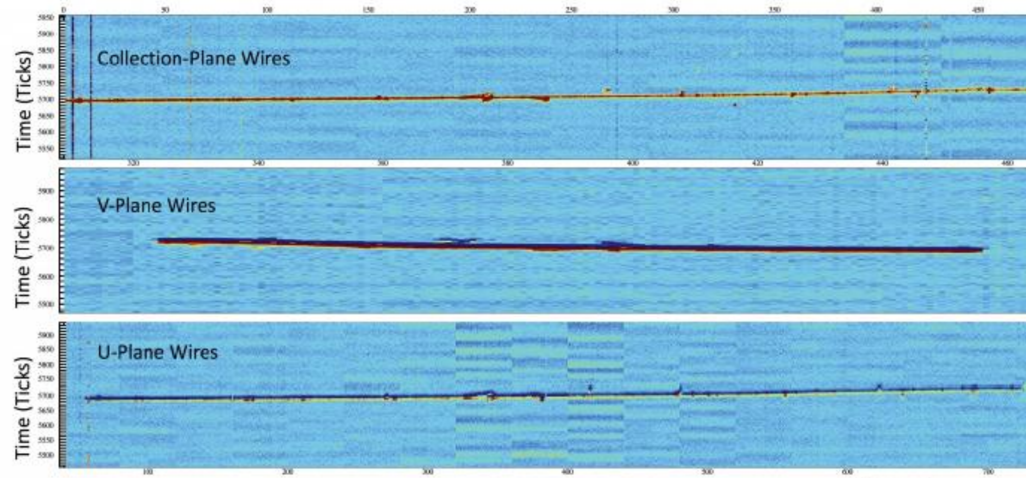


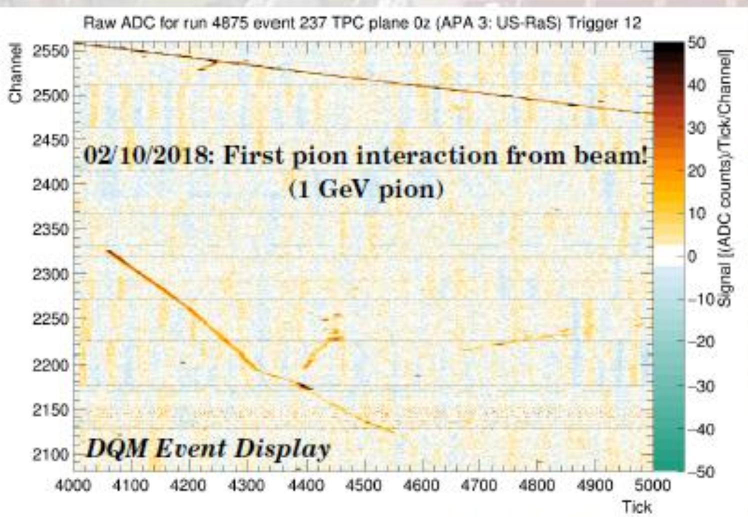


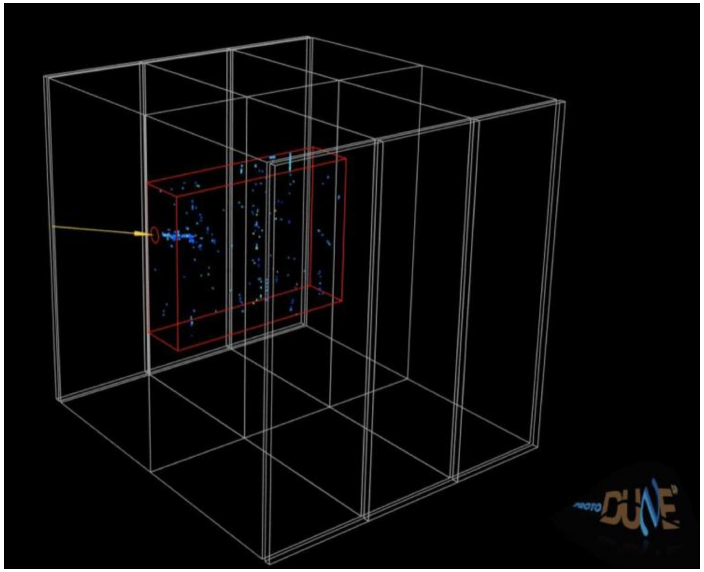


Measurements with test beam in 2018

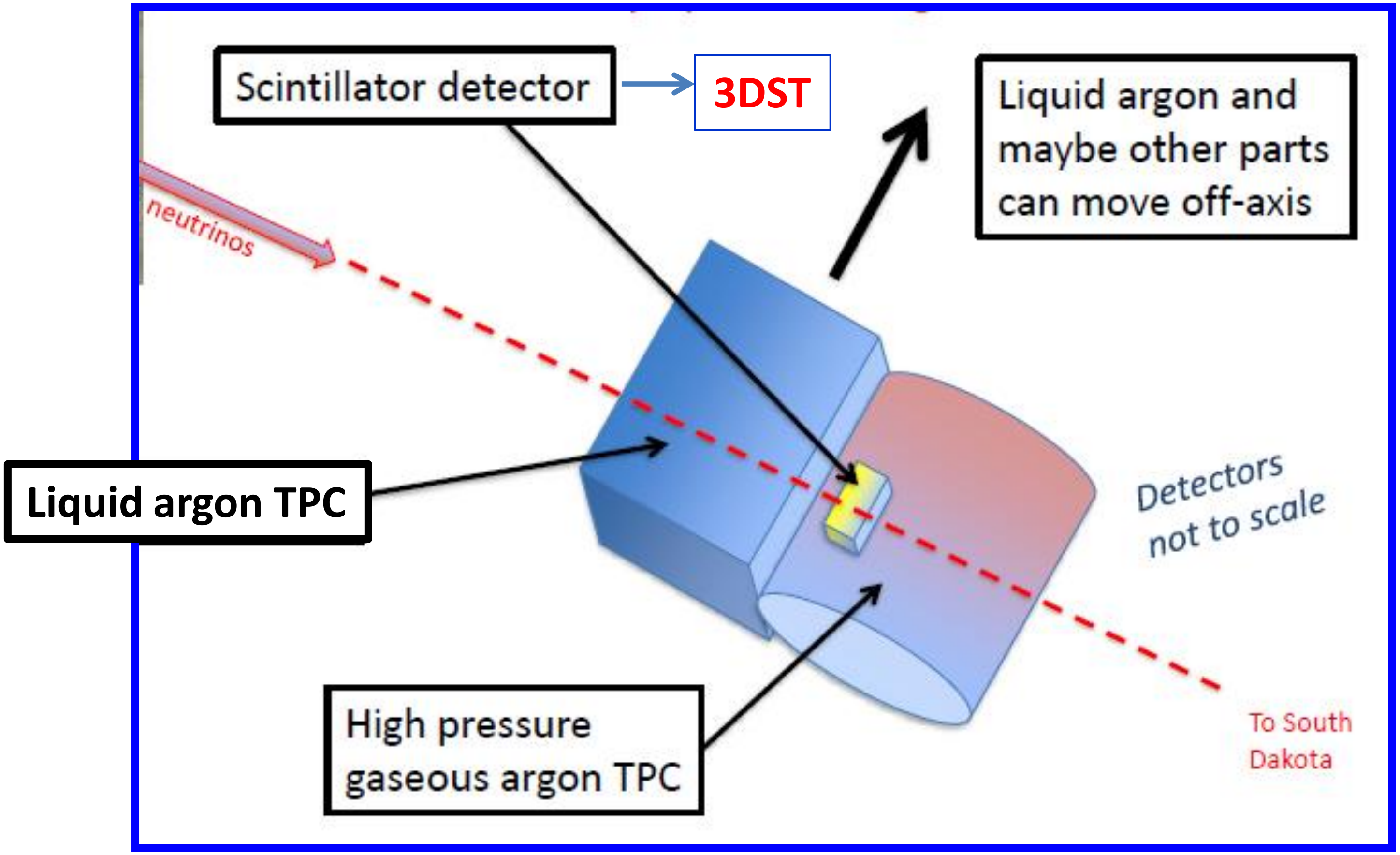
First events in SP TPC







DUNE Near Detector



Concept study

3DST:
A few ton segmented scintillator detector.
Similar to **SuperFGD**

T2HK and DUNE: CPV Significance

arXiv:1805.04163

Hyper-K
- Single tank
- Normal hierarchy
- Systematics 3-4%

  $\nu : \bar{\nu} = 1:3$
- CPV (δ = -90 deg, 5σ)

  $\rightarrow$ 1.3MW x 4 years

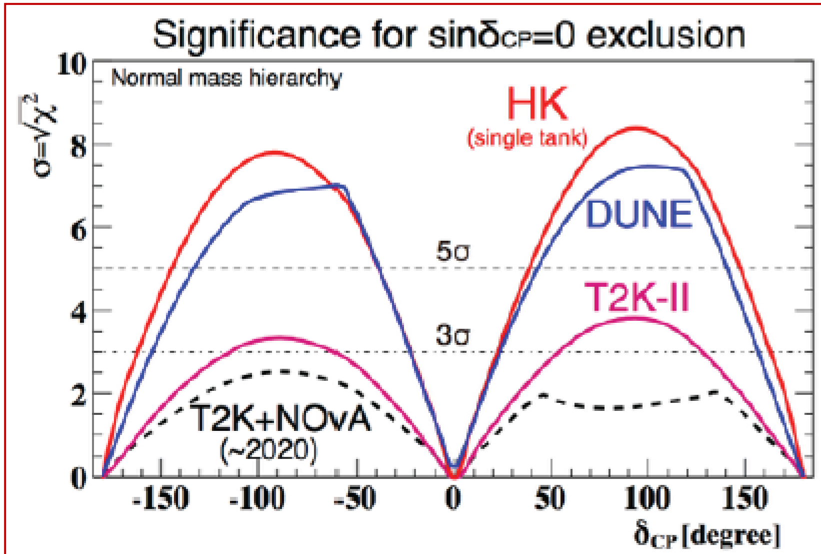
arXiv:1807.10334

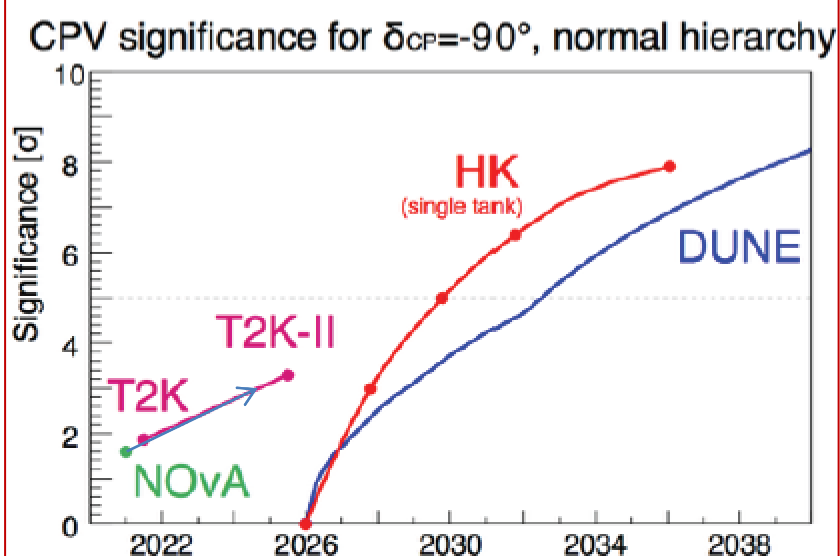
DUNE
- Staging plan
- Normal hierarchy

  $\nu : \bar{\nu} = 50\% : 50\%$
- CPV (δ = -90 deg, 5σ) 253 kt·MW·year

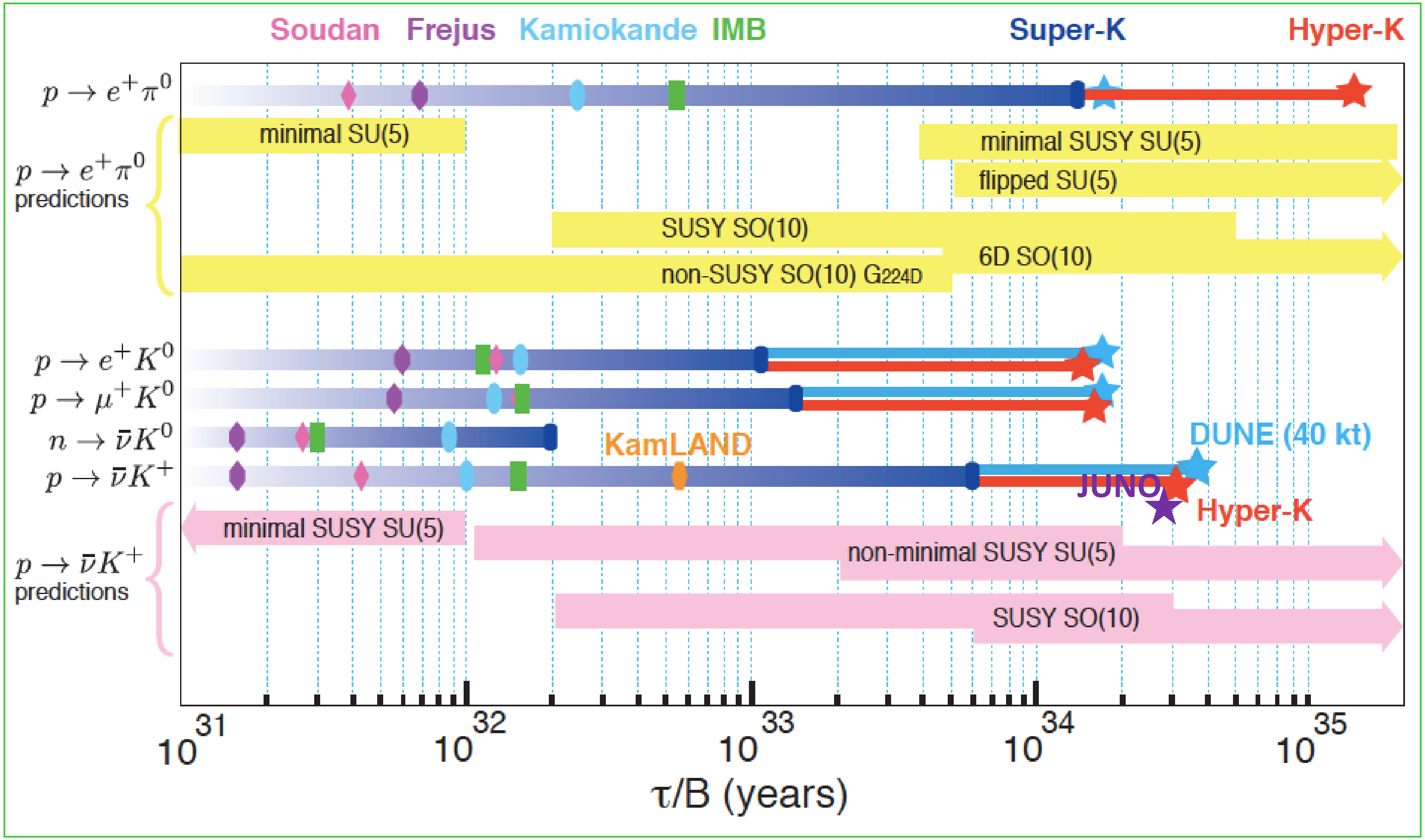
  $\rightarrow$ 6.5 years

Combination T2K-II and NOvA can reach 4.0-4.5σ for δ = -90 deg by 2026





Nucleon Decay sensitivities



Summary

Hyper-Kamiokande and DUNE - the major next generation neutrino experiments

Very broad physics program:

- **search for CP violation in neutrino oscillations**
- **proton decay**
- **rich program with atmospheric and solar neutrinos**
- **supernova neutrinos**
- **+ other interesting physics**

Detector (Far and Near) R&D and upgrade in progress → good results

Experiments are expected to start data taking in 2026

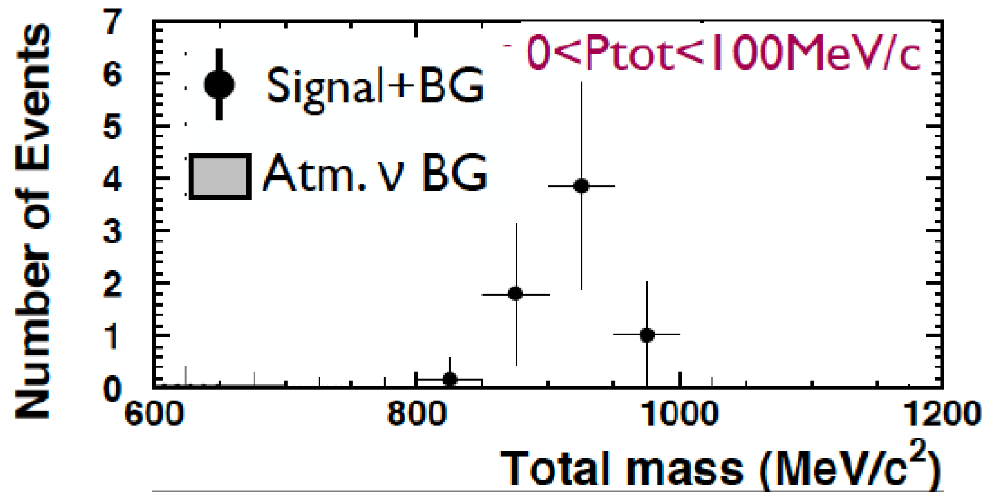
Backup slides

$p \to e^+\pi^0$ events

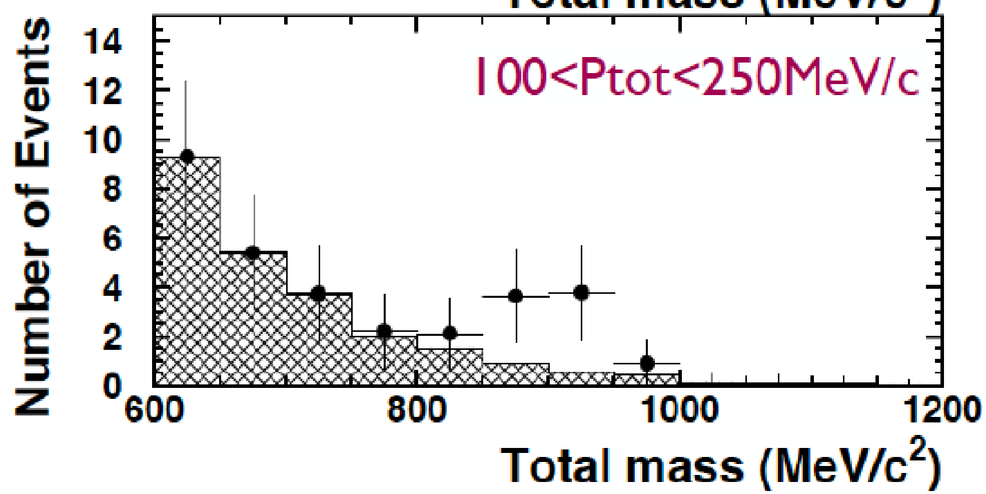
Hyper K, 1 tank, 10 year exposure

Assumed proton lifetime
$\tau_p/Br = 1.7 \times 10^{34}$ years

Free proton bin



Bound proton bin

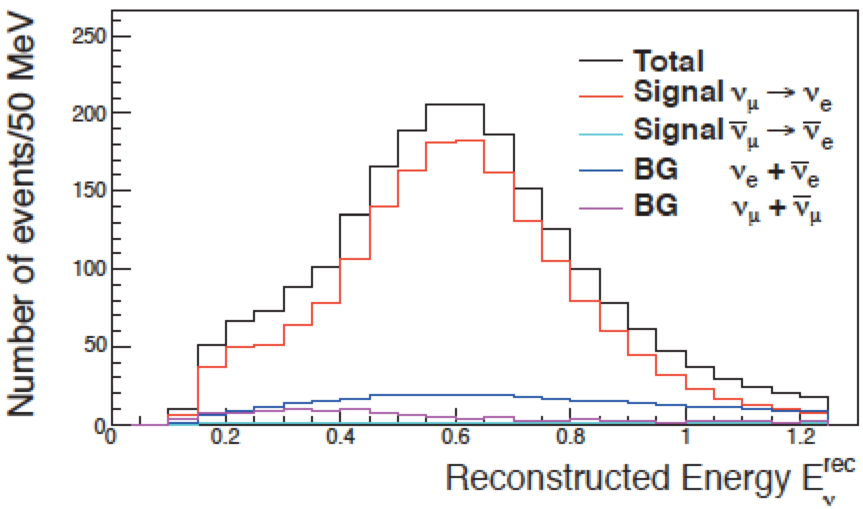


ν_e and $\bar{\nu}_e$ events

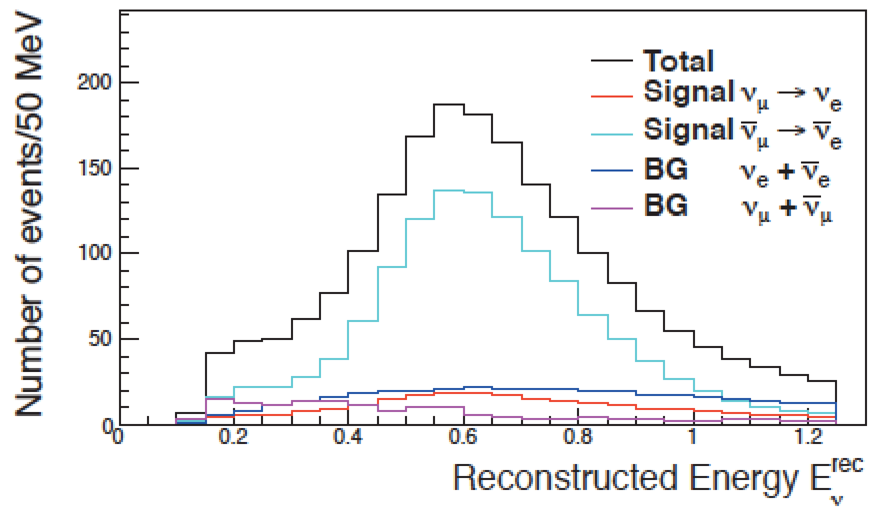
1 Hyper-K tank , 1.3MW, 10×10^7sec, ν : anti-ν = 1:3 , $\sin^2 2\theta_{13}$ = 0.1

δ = 0 deg

Appearance ν mode



Appearance $\bar{\nu}$ mode



δ = 0 deg	Appearance signal	Wrong sign	Beam ν_e background	NC background
ν mode	1643	15	259	134
anti-ν mode	1183	206	317	196

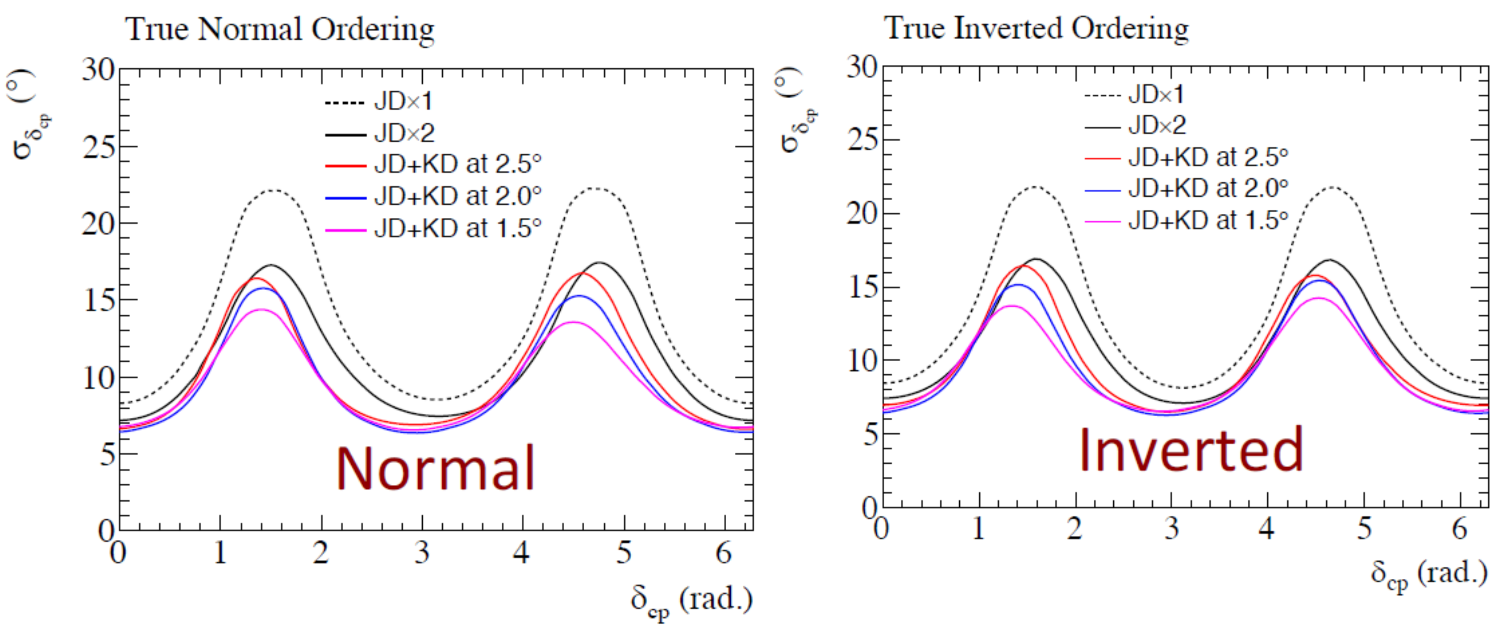
T2HKK: δ precision

T2HKK : study oscillations at 1st and 2nd oscillation maxima

$\rightarrow$ better sensitivity to mass hierarchy

$\rightarrow$ better sensitivity to CP violation

arXiv:1611.06118



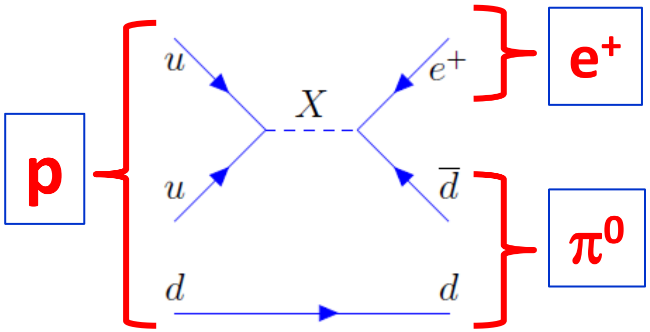
JD x 1:	**HK 1 tank, Japan**	**$\sigma(\delta)$ = 22 deg**
JD x 2:	**HK 2 tanks, Japan**	**$\sigma(\delta)$ = 17 deg**
JD + KD:	**HK 1tank (Japan + HK 1 tank (Korea)**	**$\sigma(\delta)$ = 13-14 deg**

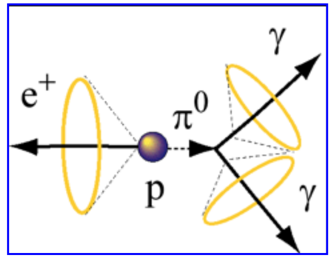
Proton Decay: $p \to \pi^0 e^+$

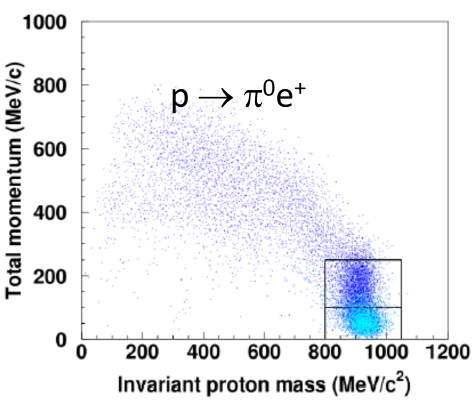
HyperK

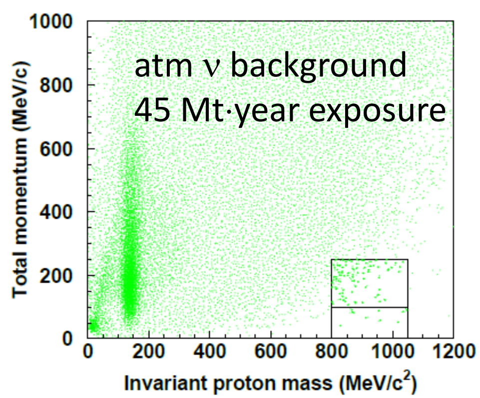
GUT predicts this process through gage bosons

$$\Gamma(p \to e^+\pi^0) \sim \frac{1}{M_X^4} \qquad \tau_p \sim M_X^4 / m_p^5$$



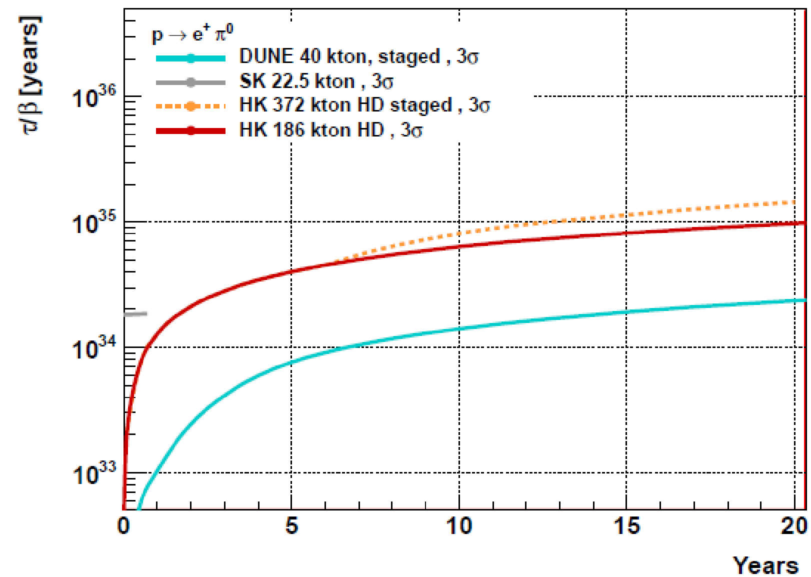






0.06 bkg events/Mt·year in free proton bin
0.62 bkg events/Mt·year in bound proton bin

3σ discovery potential

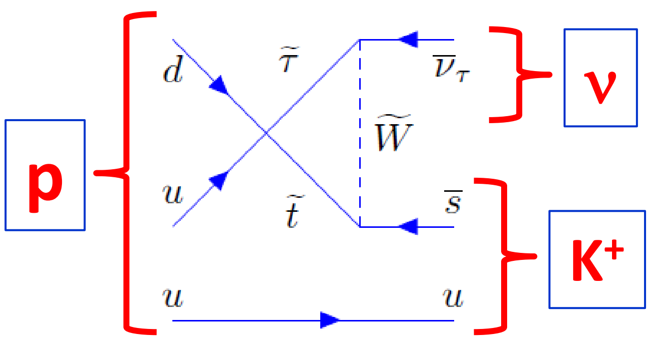


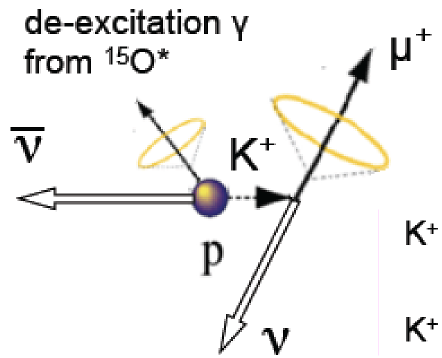
Neutron tagging
($n+p \to d+\gamma$, E_γ=2.2MeV)
helps to reduce background

Proton Decay: $p \rightarrow \bar{\nu} K^+$

HyperK

Supersymmetric GUTs





K+ - invisible,
signatures by decay particles

$K^+ \rightarrow \mu^+ \nu$ (64%)	236 MeV/c μ^+ + decay e^+ de-excitation γ from $^{16}O^*$ (6 MeV)
$K^+ \rightarrow \pi^+ \pi^0$ (21%)	205 MeV/c π^+ + π^0 back-to-back

Assumed proton lifetime
$\tau_p/Br = 6.6 \times 10^{33}$ years

1 tank, 10 year exposure

M.Shiozawa, Neutrino2018