Hyper-Kamiokande Project

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INR, Moscow

On behalf of the Hyper-Kamiokande Proto-Collaboration

NOW 2018
Rosa Marina, Ostuni, Italy
11 September 2018

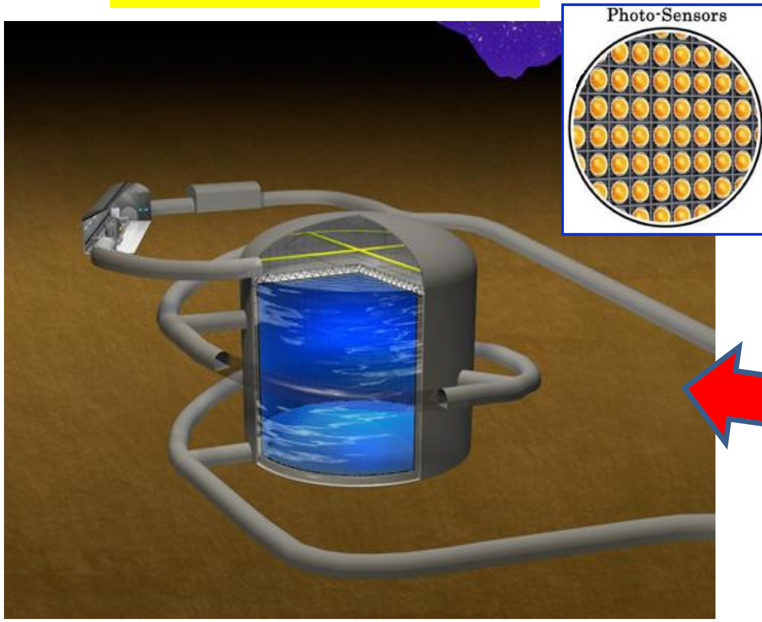
Collaboration

Hyper-Kamiokande proto-collaboration

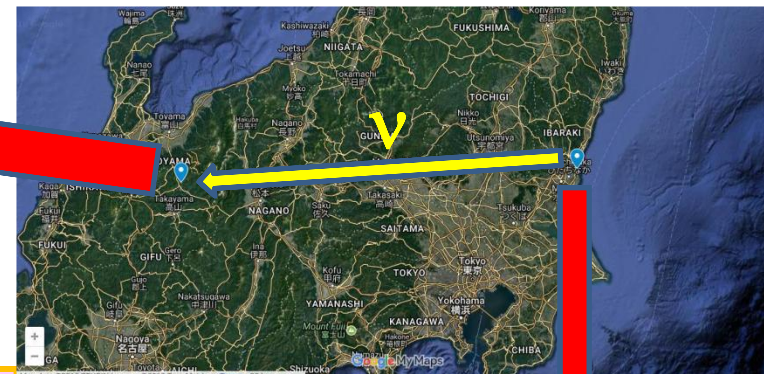
- International proto-collaboration was formed in 2015
- 15 countries, 73 institutes, ～300 members
- 2 host institutes: U-Tokyo/ICRR & KEK/IPNS

Hyper-Kamiokande Project

Hyper-K water tank



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

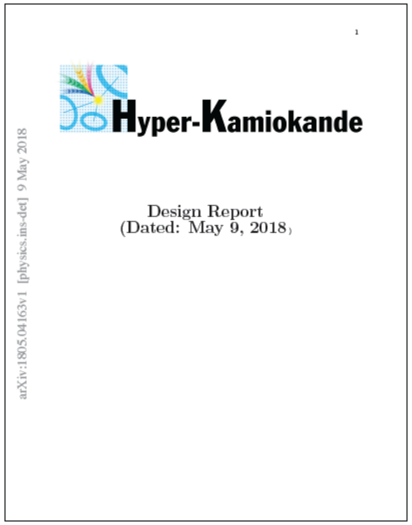


J-PARC

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

Documentation


Hyper-Kamiokande

Design Report
(Dated: May 9, 2018)

arXiv:1805.04163v1 [physics.ins-det] 9 May 2018

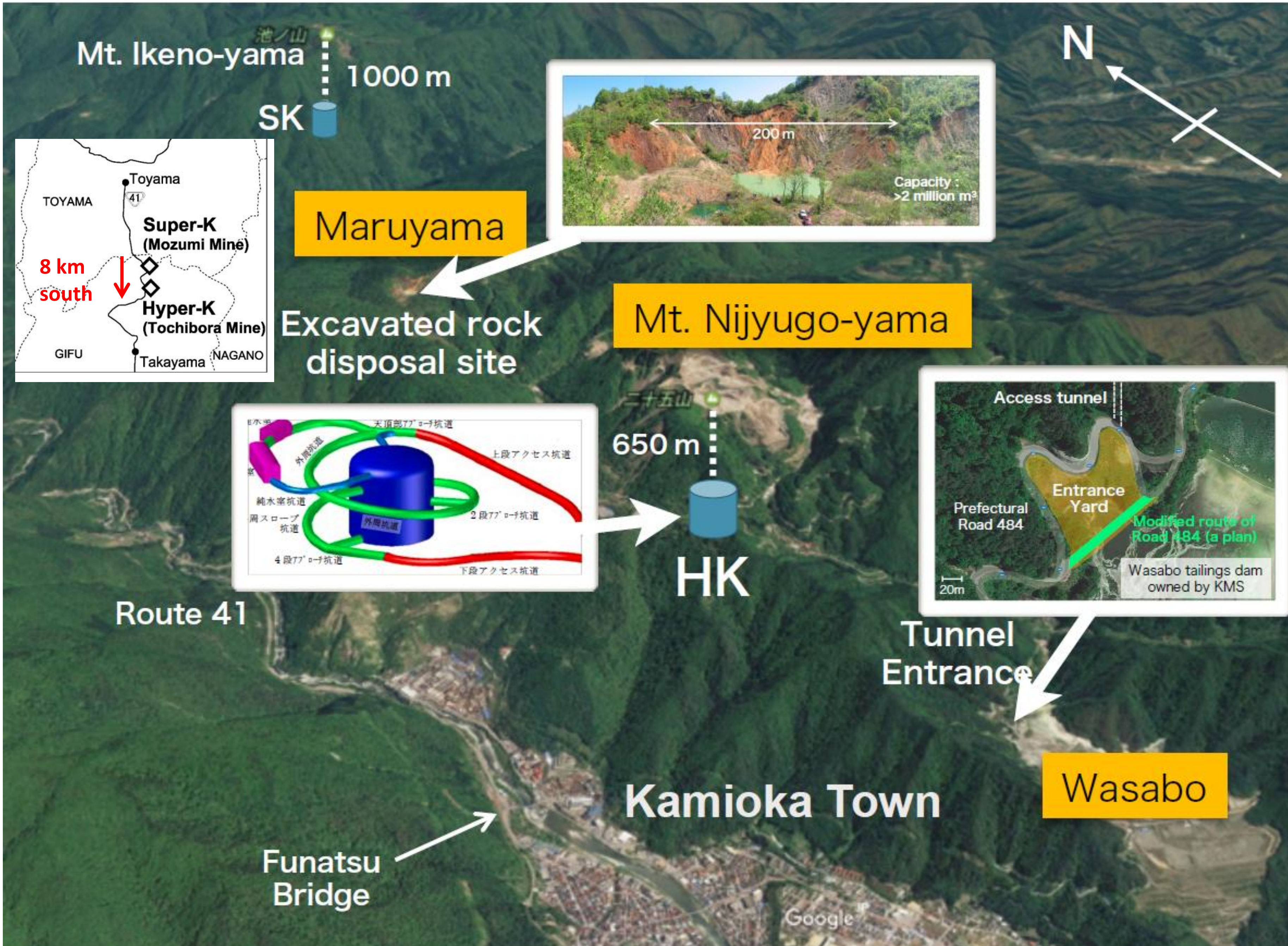
K. Abe et al. (Hyper-Kamiokande Collaboration),
Hyper-Kamiokande Design Report, arXiV:1805.04163

K. Abe et al. (Hyper-Kamiokande Collaboration), **Physics potentials with the Second Hyper-Kamiokande detector in Korea**, PTEP 2018(2018) 6, 063C01

K. Abe et al. (Hyper-Kamiokande Working Group),
A Long Baseline Neutrino Oscillation Experiment Using J-PARC Neutrino Beam and Hyper-Kamiokande,
arXiv:1412.4673 [physics.ins-det]

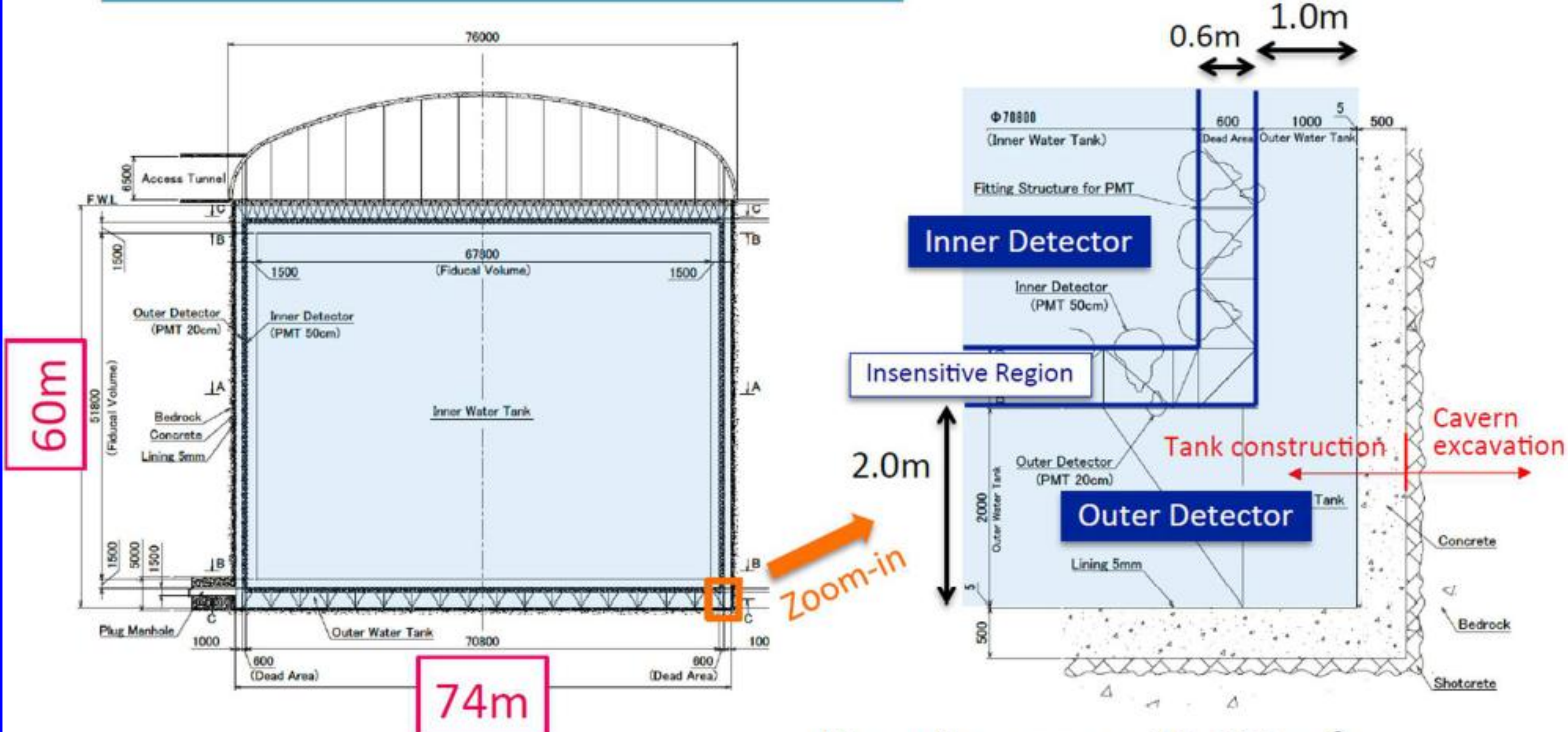
K. Abe et al. **Letter of Intent: The Hyper-Kamiokande Experiment**,
arXiv:1109.3262 [hep-ex]

Hyper-Kamiokande web page: http://www.hyperk.org/



Mt. Ikeno-yama
1000 m
SK
N
200 m
Capacity : >2 million m³
Maruyama
Toyama
TOYAMA
41
Super-K
(Mozumi Mine)
8 km south
Hyper-K
(Tochibora Mine)
GIFU
Takayama
NAGANO
Excavated rock disposal site
Mt. Nijyugo-yama
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



ID surface area : 20,063 m^2

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

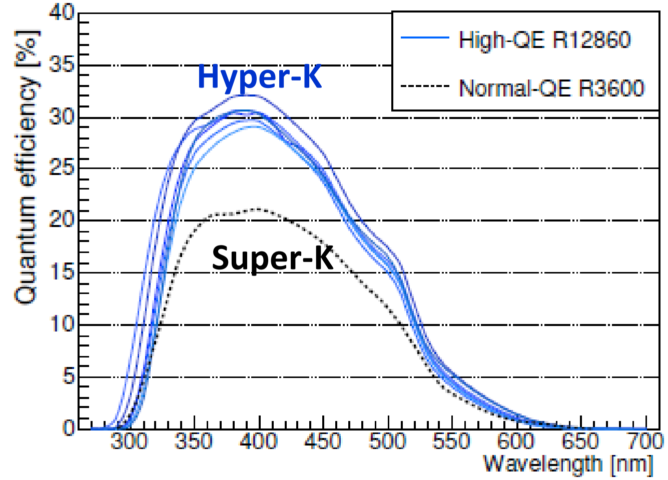
→ ~40,000 ID-PMTs/tank

~6,700 OD-PMTs/tank

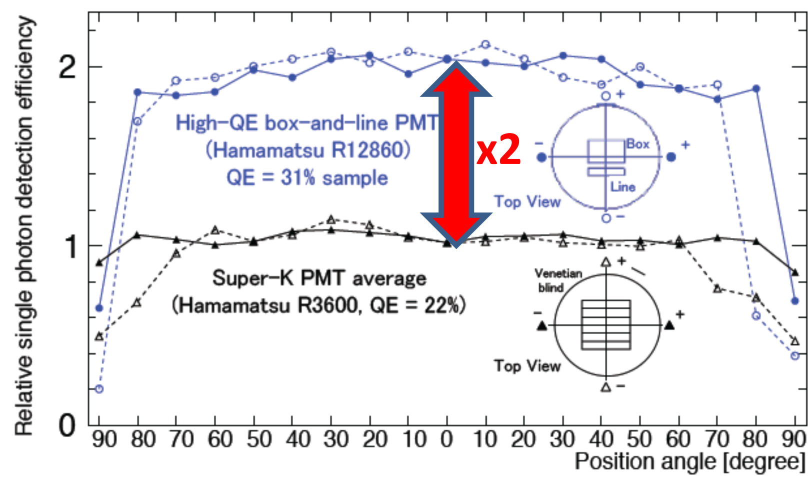
Total	:	258.1 kt/tank
Inner Detector	:	215.7 kt/tank
Fiducial Volume	:	187.0 kt/tank

Photosensors: ID

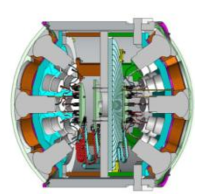
Hamamatsu R12860-HQE
B&L 50 cm PMT



40000 PMTs
40% photocoverage



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



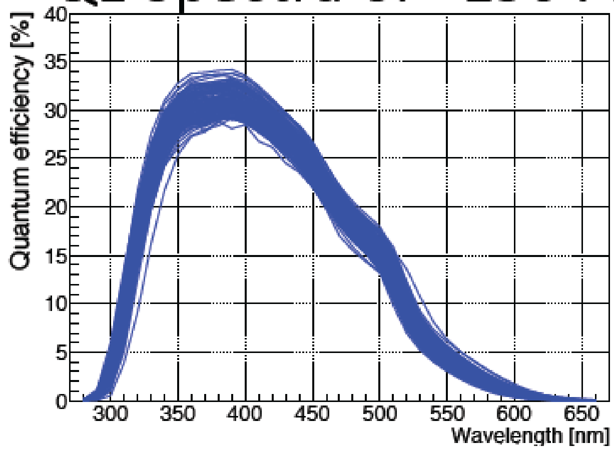
1 p.e. → time resolution 1.1. ns,
→ charge resolution 35%

Photosensors

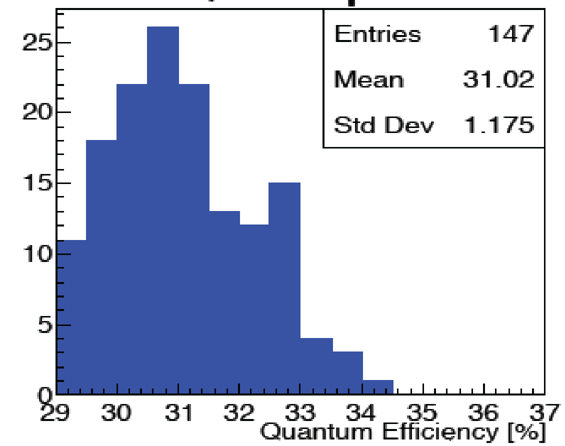
Y.Nishimura, talk at NEPTUNE2018

150 Box&Line 50 cm PMTs were manufactured
- all PMTs were tested at high pressure water ≤0.95 Mpa
- no damages were found

QE Spectra of ~150 PMTs



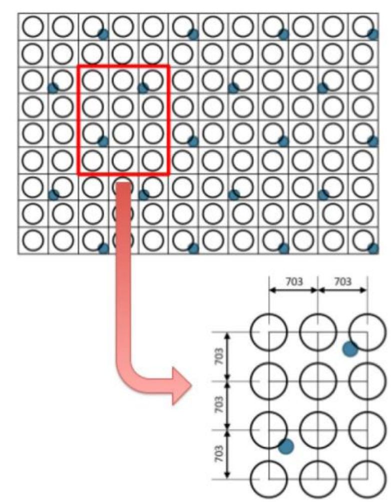
QE at peak



OD PMTs

6700 PMTs
1% photocoverage
OD water thickness
1m barrel, 2 m top and bottom

Hamamatsu R5912-HQE
B&L 20 cm PMT



Parameters of Hyper-K

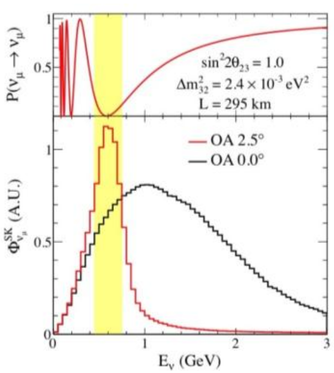
	Kamiokande	Super-K	Hyper-K
Depth	1,000 m	1,000 m	650 m
Dimensions of water tank			
diameter	15.6 m ϕ	39 m ϕ	74 m ϕ
height	16 m	42 m	60 m
Total volume	4.5 kton	50 kton	258 kton
Fiducial volume	0.68 kton	22.5 kton	187 kton
Outer detector thickness	$\sim$ 1.5 m	$\sim$ 2 m	1 $\sim$ 2 m
Number of PMTs			
inner detector (ID)	948 (50 cm ϕ)	11,129 (50 cm ϕ)	40,000 (50 cm ϕ)
outer detector (OD)	123 (50 cm ϕ)	1,885 (20 cm ϕ)	6,700 (20 cm ϕ)
Photo-sensitive coverage	20%	40%	40%
Single-photon detection efficiency of ID PMT	unknown	12%	24%
Single-photon timing resolution of ID PMT	$\sim$ 4 nsec	2-3 nsec	1 nsec

Tokai-to-Hyper-K (T2HK)

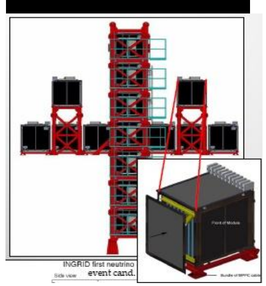
Hyper-K

J-PARC

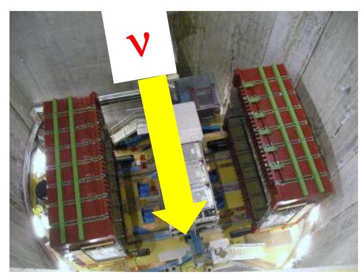
Off-axis neutrino beam



Neutrino monitor INGRID



Off-axis near neutrino detector



Near neutrino detector at 280 m from target

Decay tunnel

Horn

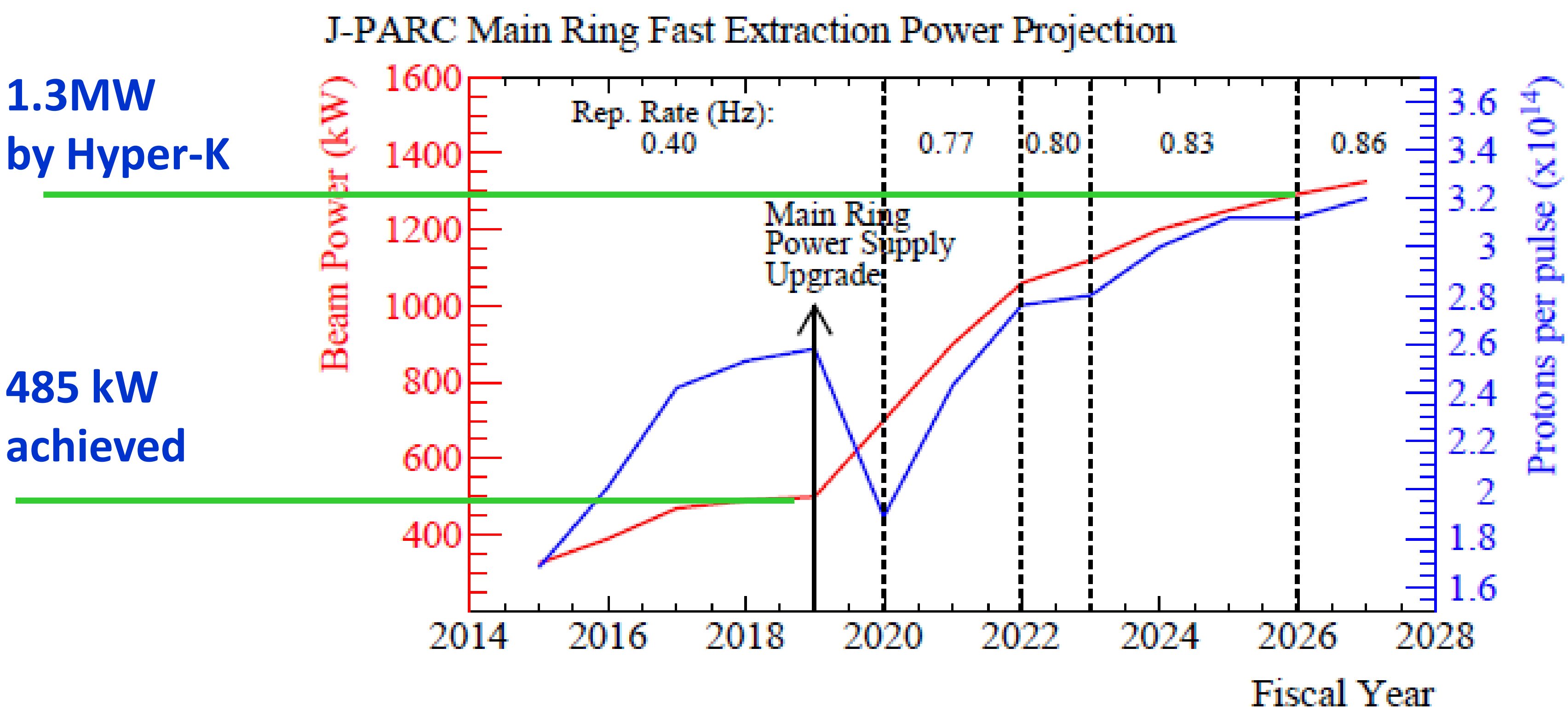
Target

Neutrino beam elements

J-PARC neutrino beam

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

J-PARC upgrade



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

arXiv: 1606.08114; 1412.3086

arXiv:1609.04111

E61: Movable Water Cherenkov detector

Inner diameter 8 m

Inner detector height 6-8 m

Multi-PMTs

Load detector with $Gd_2(SO_4)_3$

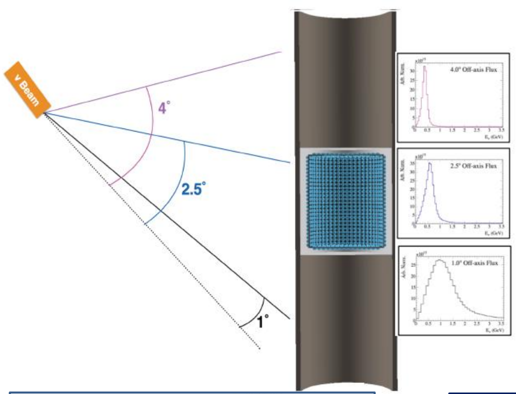
to enhance neutron detection

New upstream tracker:

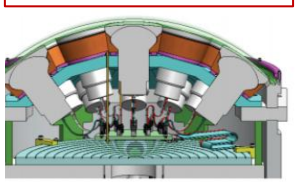
Two Horizontal TPC

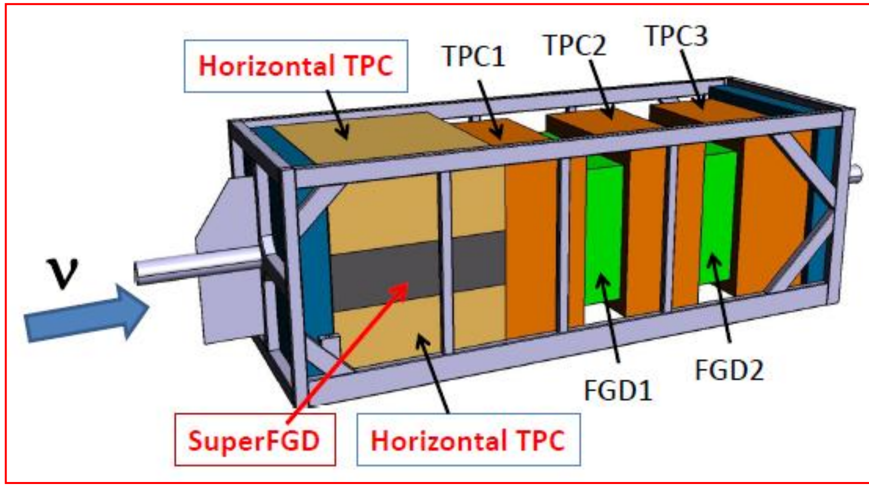
One 3D fine-grained scintillator target SuperFGD

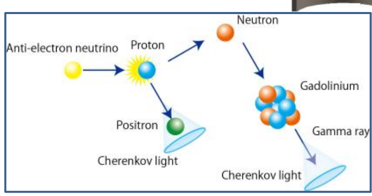
TOF system around new tracker



Multi-PMT Module

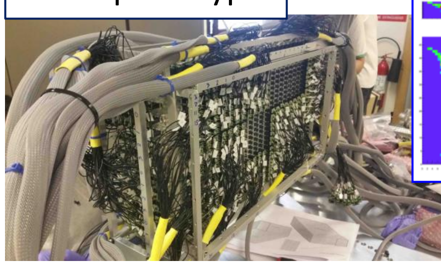




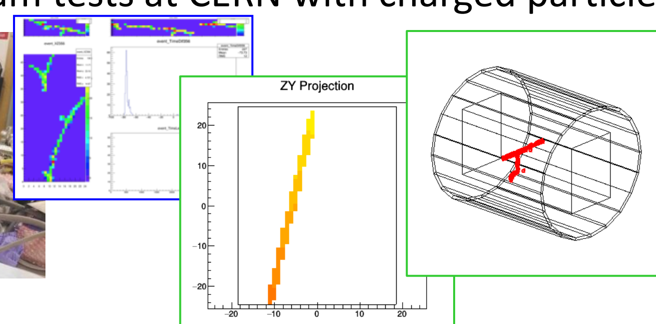


Measurement of neutron mutiplicity to understand Gd n-capture signal in Super-K and Hyper-K

SFGD prototype



Beam tests at CERN with charged particles



TPC prototype

Physics

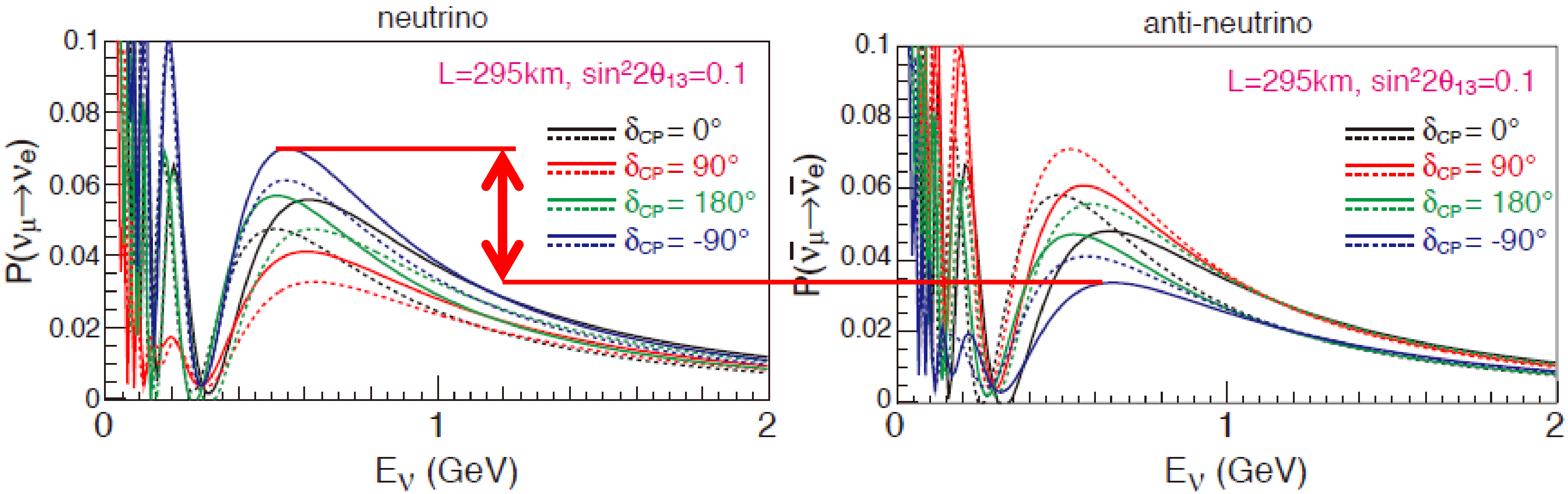
Accelerator neutrinos
- **search for CP violation**
- **precise measurement of oscillation parameters**

Atmospheric and solar neutrinos
- **mass hierarchy**
- **octant**

Nucleon decays

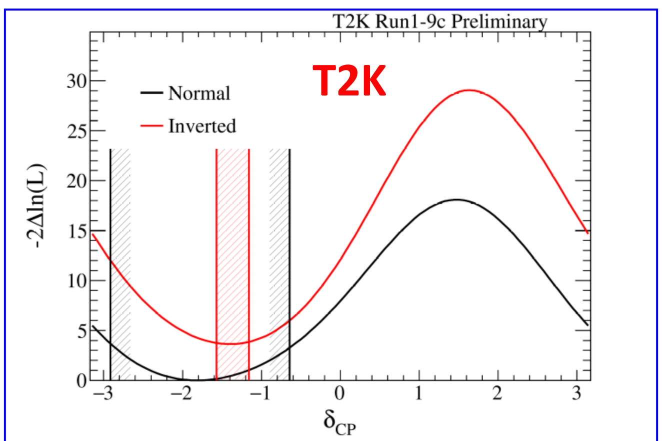
Neutrino astronomy and astrophysics

Search for CP violation



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

Hint on maximal CP violation, $\delta \sim -\pi/2$



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

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

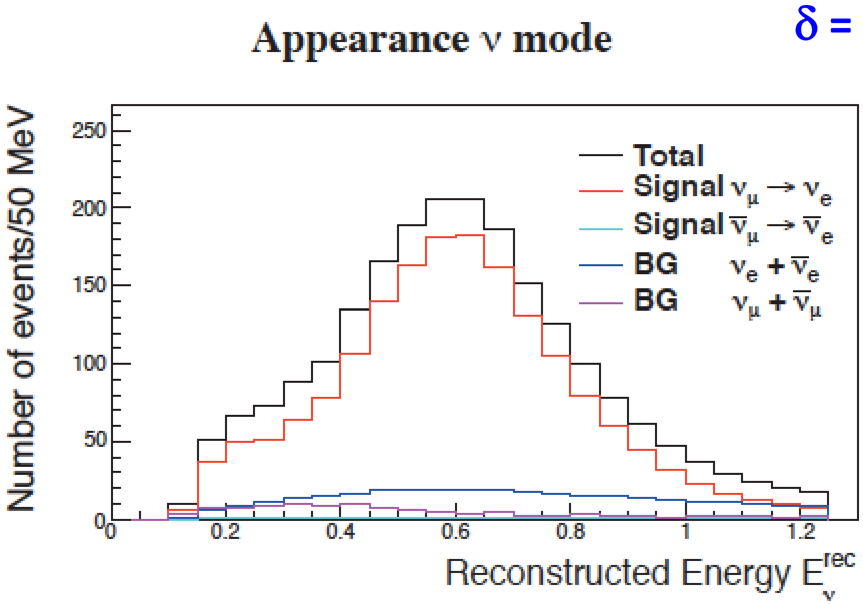
For $\delta = -\pi/2$

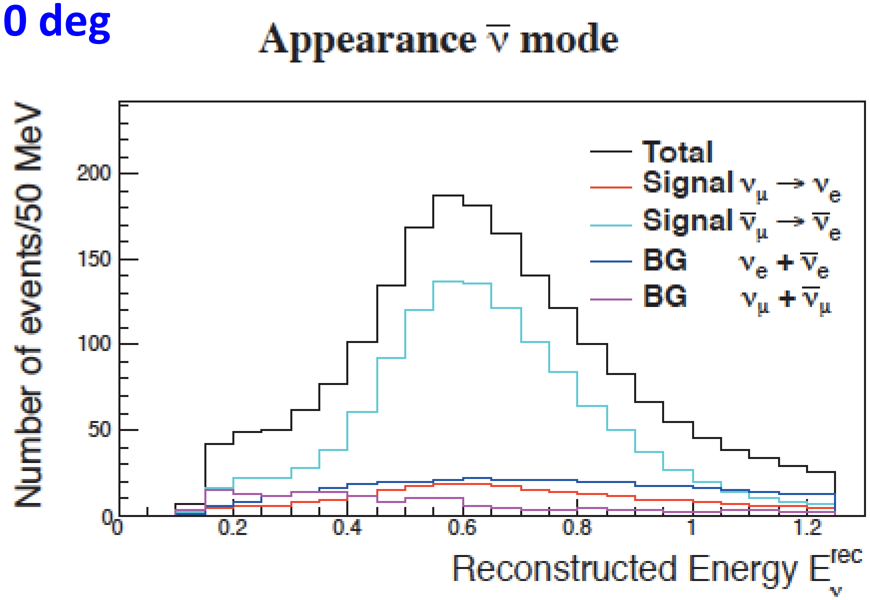
→ **CP violation effect $A_{CP} \sim 28\%$, matter effect ~8%**

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





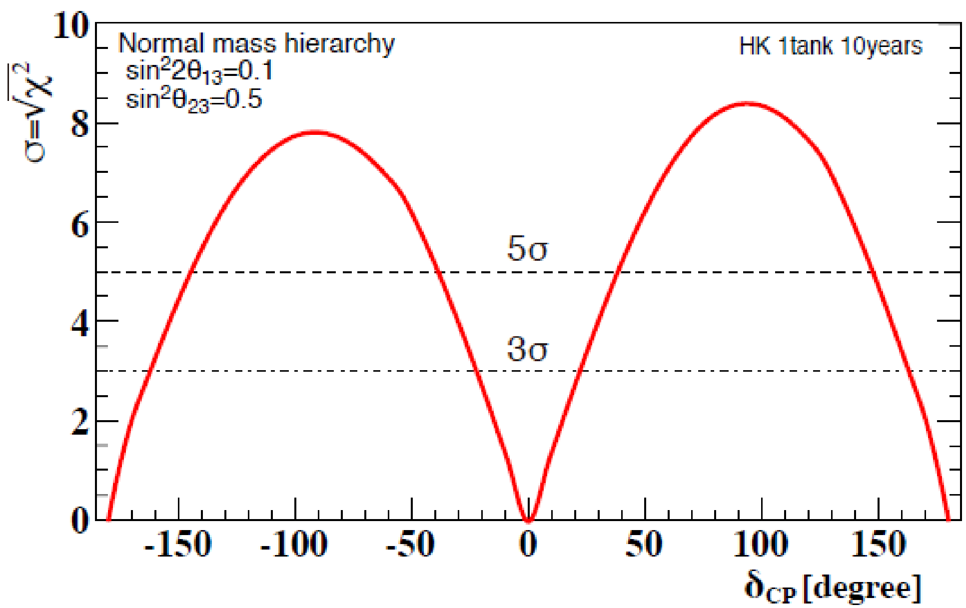
δ = 0 deg	Appearance signal	Wrong sign	Beam ν_e background	NC background
ν mode	1643	15	259	134
anti-ν mode	1183	206	317	196

Sensitivity to CP

Integrated beam power 1.3 MW x 10^8 s

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

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



Hyper-K: 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 %

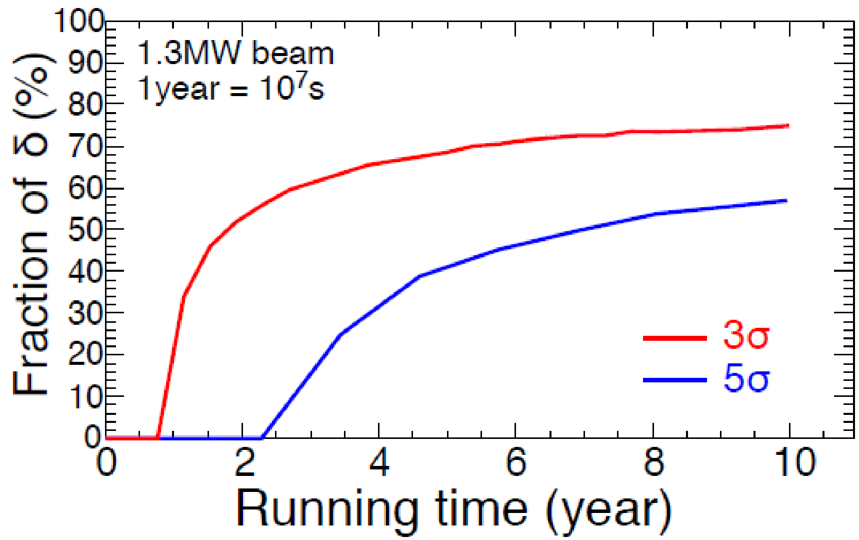
Exclusion of δ=0 at 8σ (for δ= -π/2)
5σ (3σ) significance for 57 (80)% of possible δ values

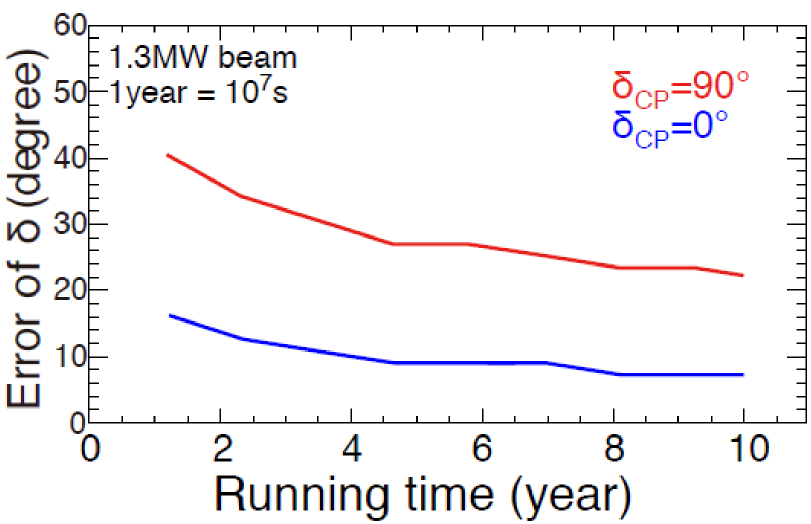
Prospects for δ measurements

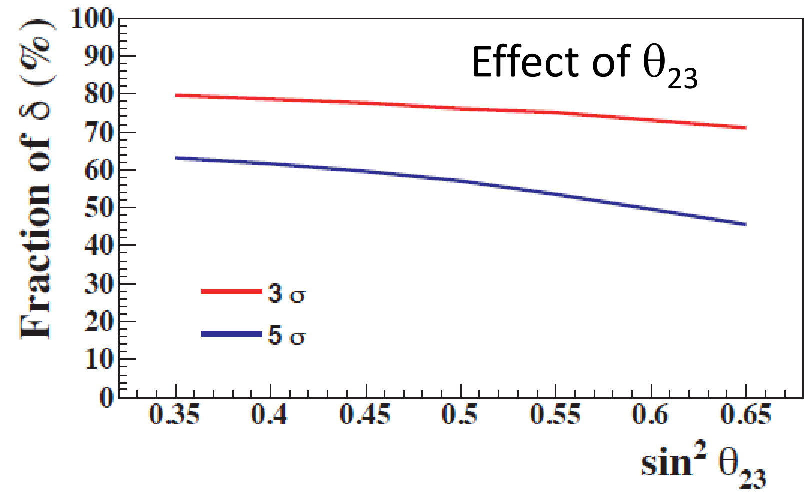
Measurement of δ

δ = 90 deg   σ = 23 deg

δ = 0 deg   σ = 7 deg







CPV Significance

arXiv:1805.04163

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

$\nu : \bar{\nu} = 1:3$

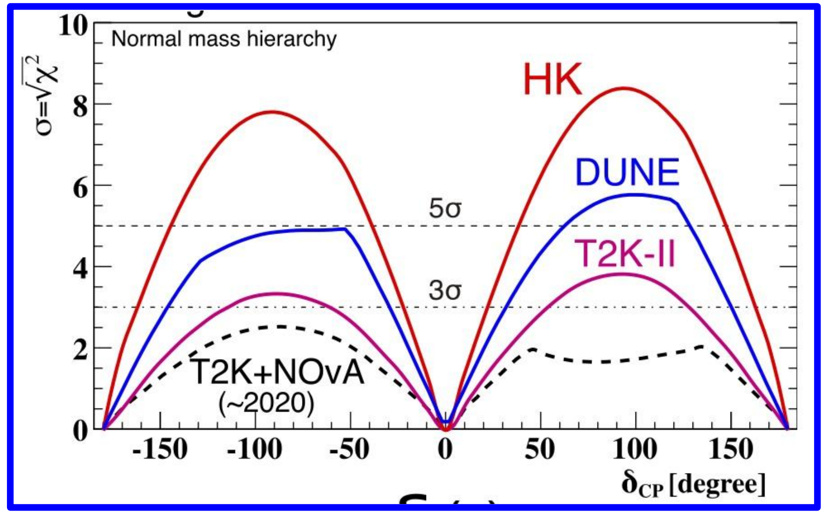
- CPV (δ = -90 deg, 5σ)
  → 1.3MW x 4 years

arXiv:1807.10334

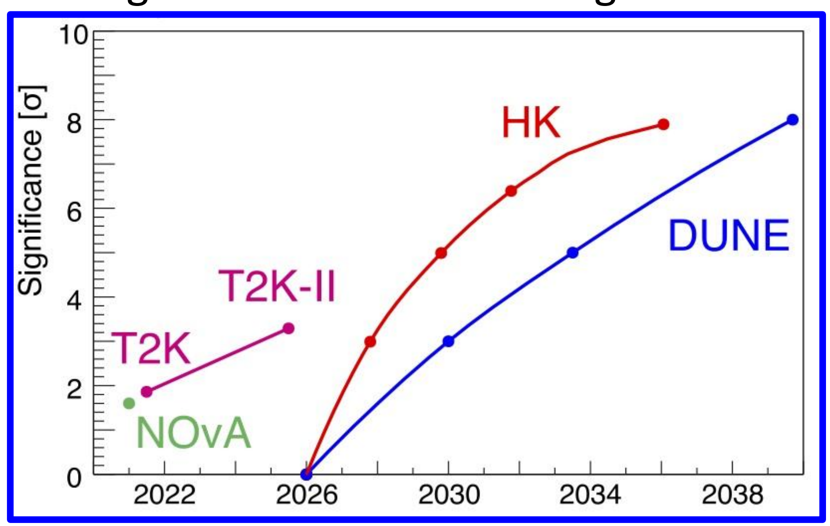
DUNE
- Staging plan
- Normal hierarchy
  $\nu : \bar{\nu} = 50\% : 50\%$
- CPV (δ = -90 deg, 5σ) 253 kt·MW·year
  → 6.5 years

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

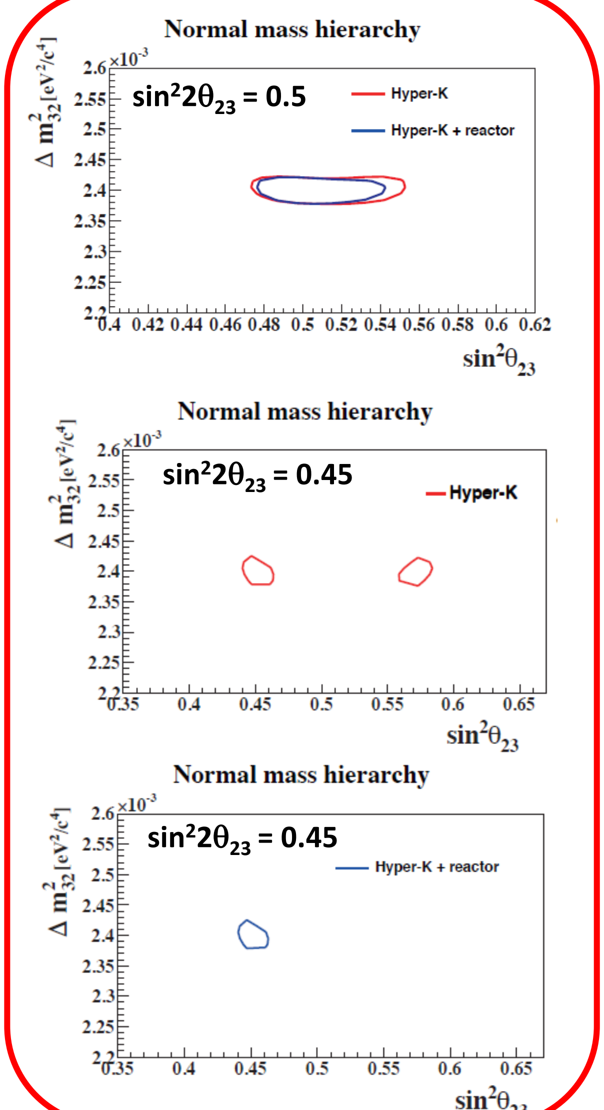
Significance for δ = 0 exclusion



Significance for δ = -90 deg



Measurement of Δm^2_{32} and θ_{23}

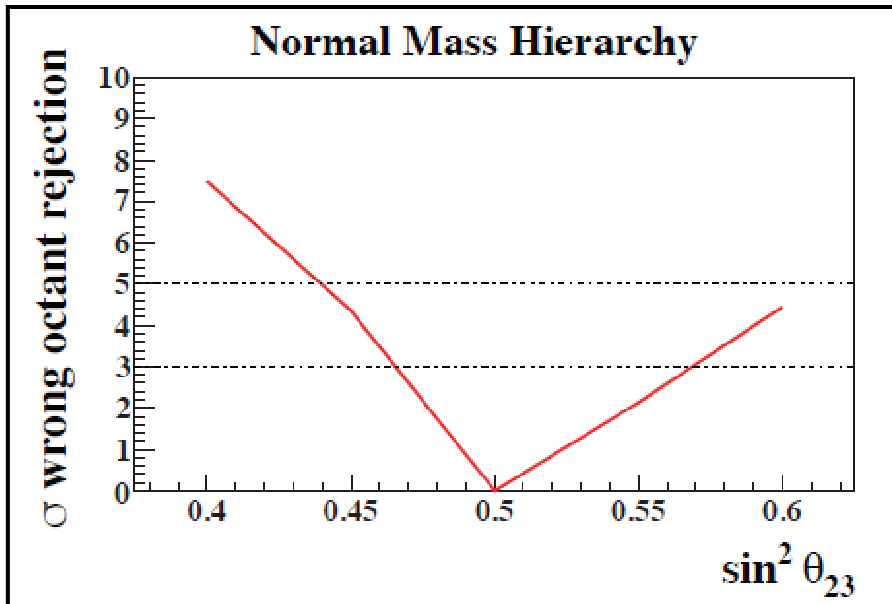


Joint ν_μ and ν_e analysis
→ precision measurements of oscillation parameters

Expected 1σ uncertainty with reactor θ_{13}

True $\sin^2\theta_{23}$	0.45		0.50		0.55	
Parameter	Δm^2_{32} (eV²)	$\sin^2\theta_{23}$	Δm^2_{32} (eV²)	$\sin^2\theta_{23}$	Δm^2_{32} (eV²)	$\sin^2\theta_{23}$
NH	1.4×10^{-5}	0.006	1.4×10^{-5}	0.017	1.5×10^{-5}	0.009
IH	1.5×10^{-5}	0.006	1.4×10^{-5}	0.017	1.5×10^{-5}	0.009

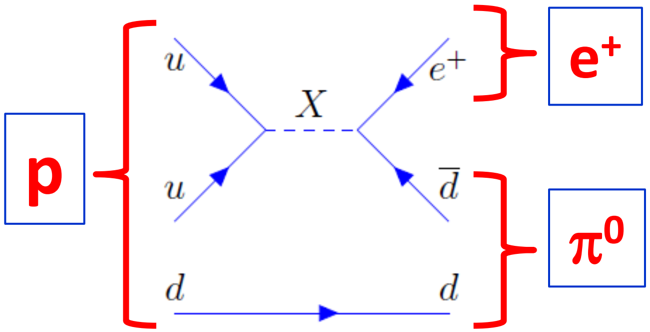
Expected significance for wrong octant rejection

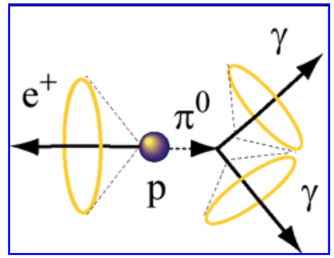


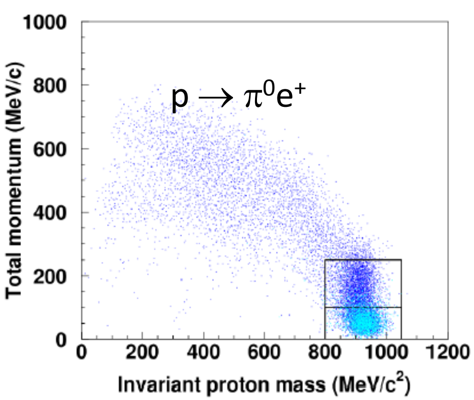
Proton Decay: $p \to \pi^0 e^+$

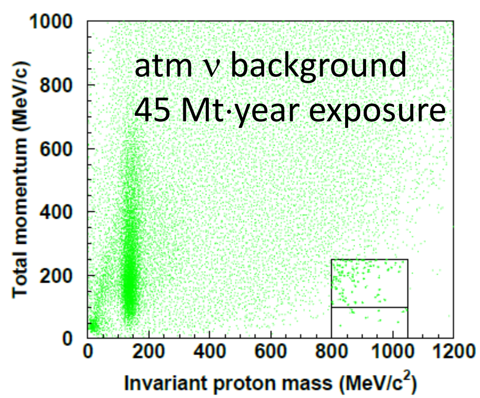
GUT predicts this process through gage bosons

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



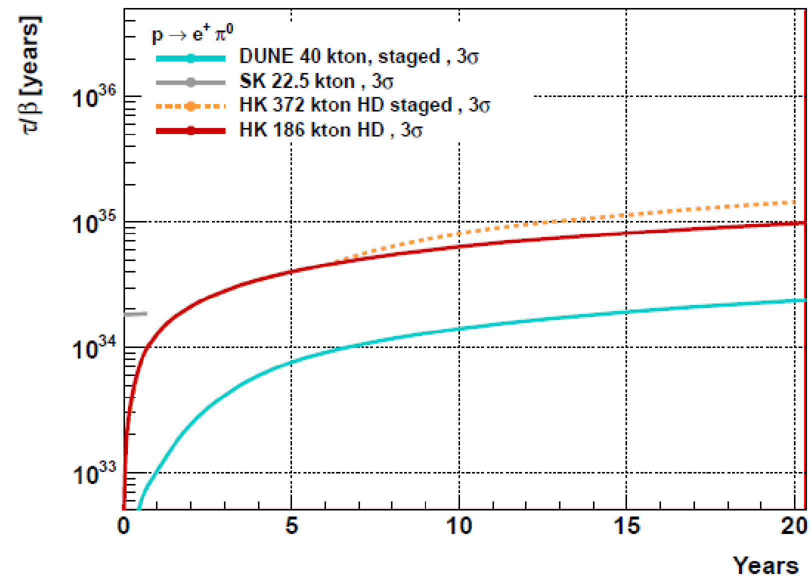






0.06 bkg events/Mt·year in free proton bin
0.62 bkg events/Mt·year in bound proton bin

3σ discovery potential



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

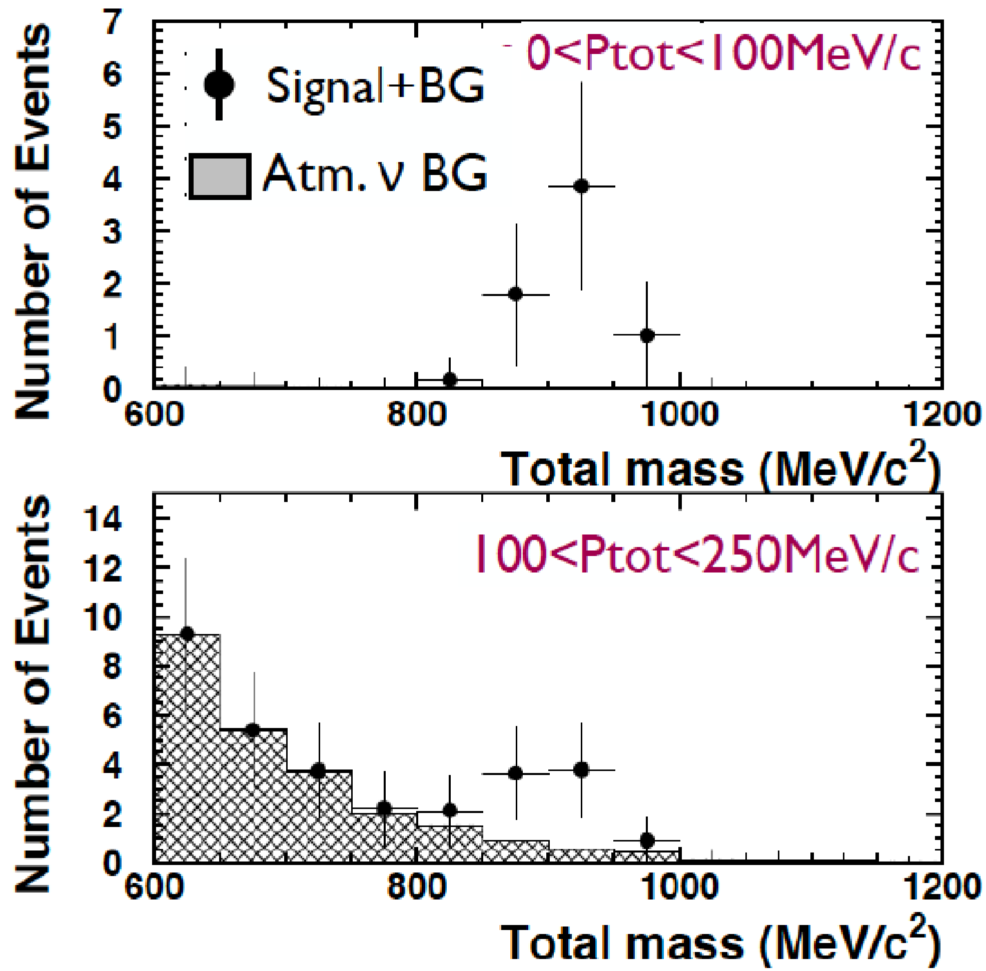
$p \rightarrow e^{+}\pi^{0}$ events

1 tank, 10 year exposure

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

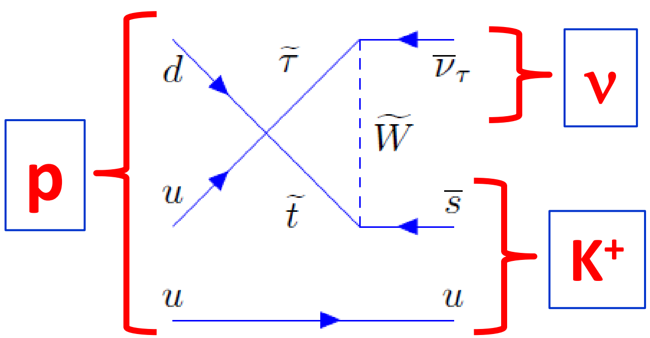
Free proton bin

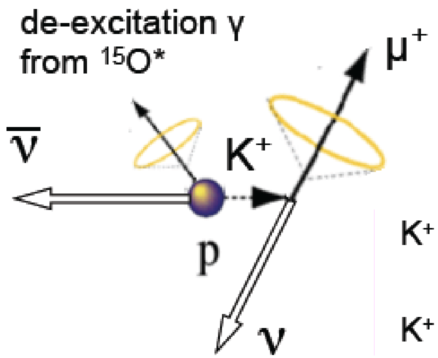
Bound proton bin



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

Supersymmetric GUTs





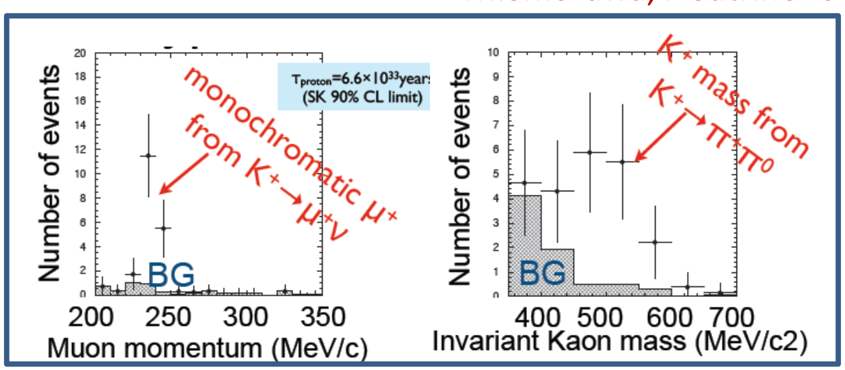
K+ - invisible,
signatures by decay particles

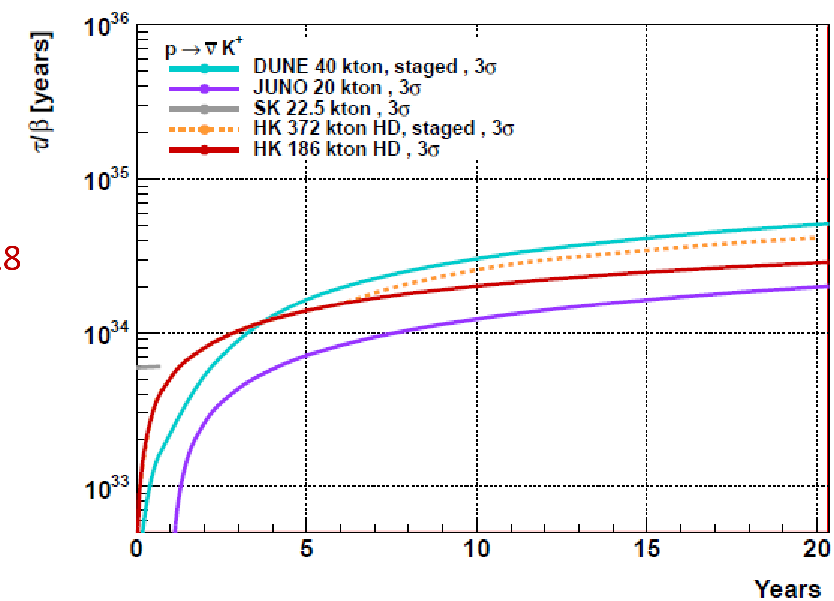
$K^+ \rightarrow \mu^+ \nu$ (64%)	236 MeV/c μ^+ + decay e^+ de-excitation γ from $^{16}O^*$ (6 MeV)
$K^+ \rightarrow \pi^+ \pi^0$ (21%)	205 MeV/c π^+ + π^0 back-to-back

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

1 tank, 10 year exposure

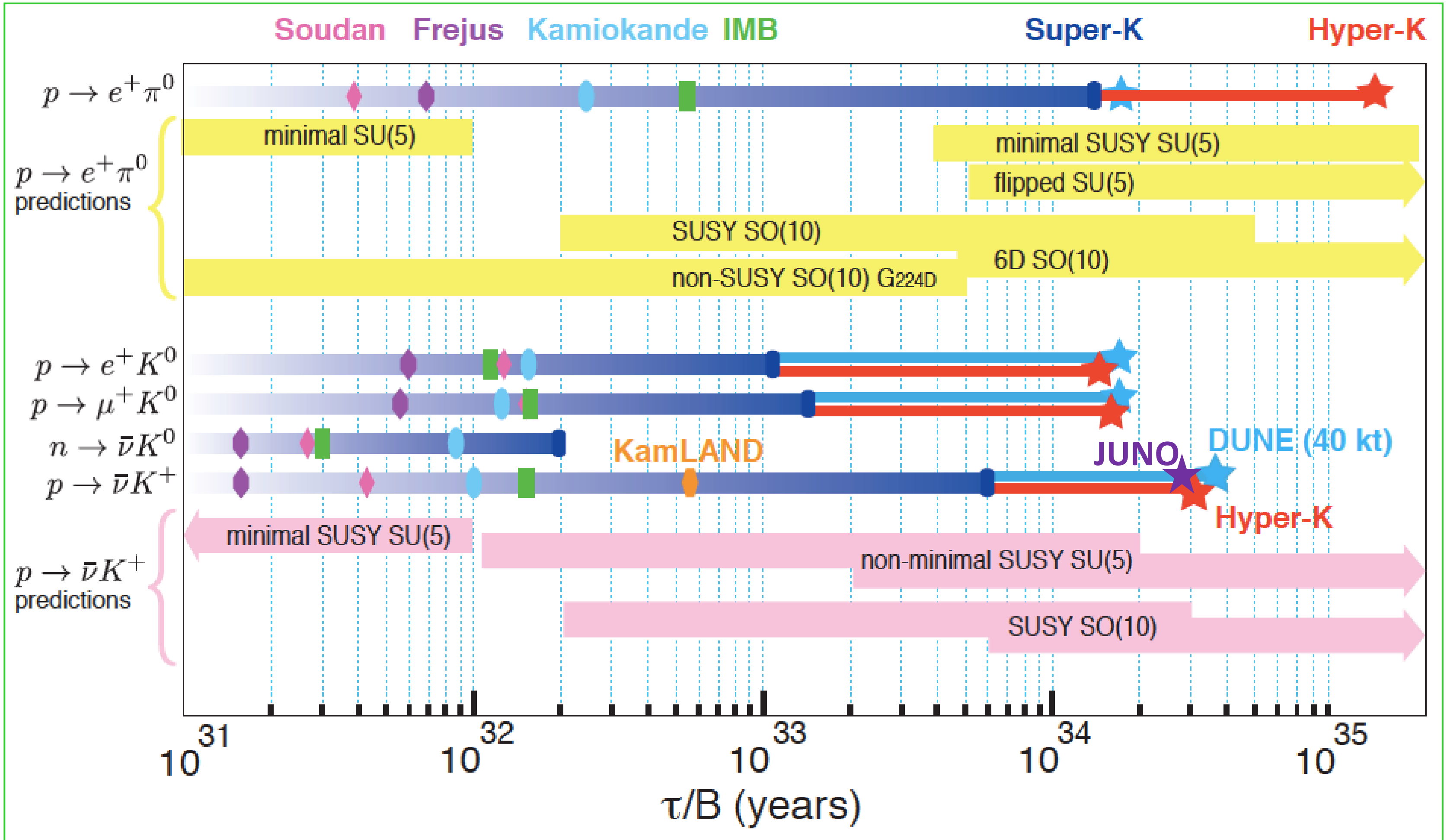
M.Shiozawa, Neutrino2018





Nucleon Decay sensitivities

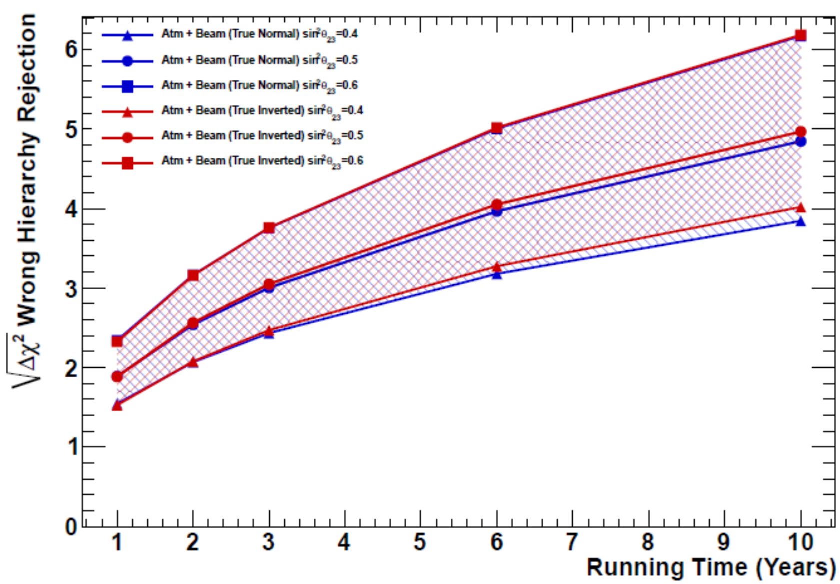
Hyper-K 3σ discovery potential



Atmospheric Neutrinos

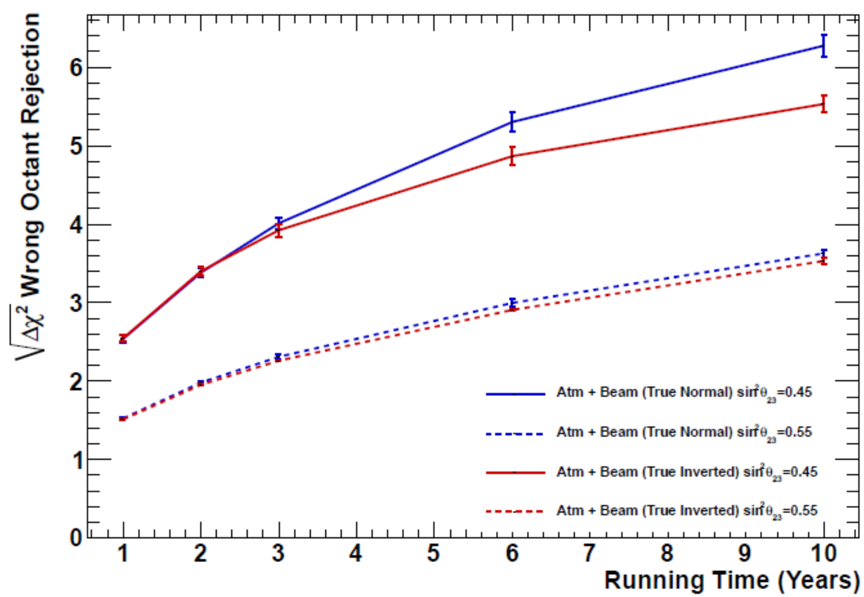
Joint analysis of atmospheric and accelerator neutrinos

Sensitivity to mass hierarchy



1 Hyper-K tank
3σ rejection of wrong hierarchy
with 10 year data

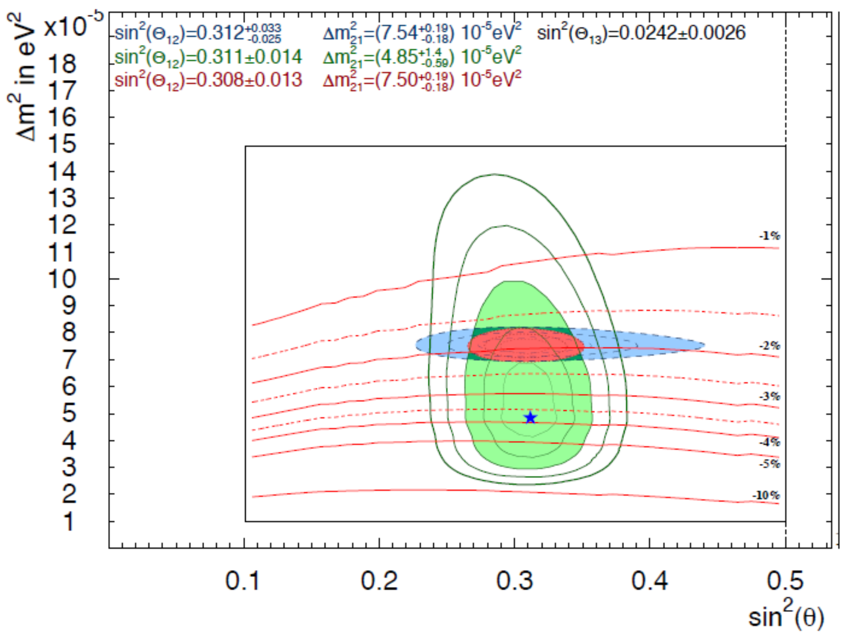
Octant sensitivity



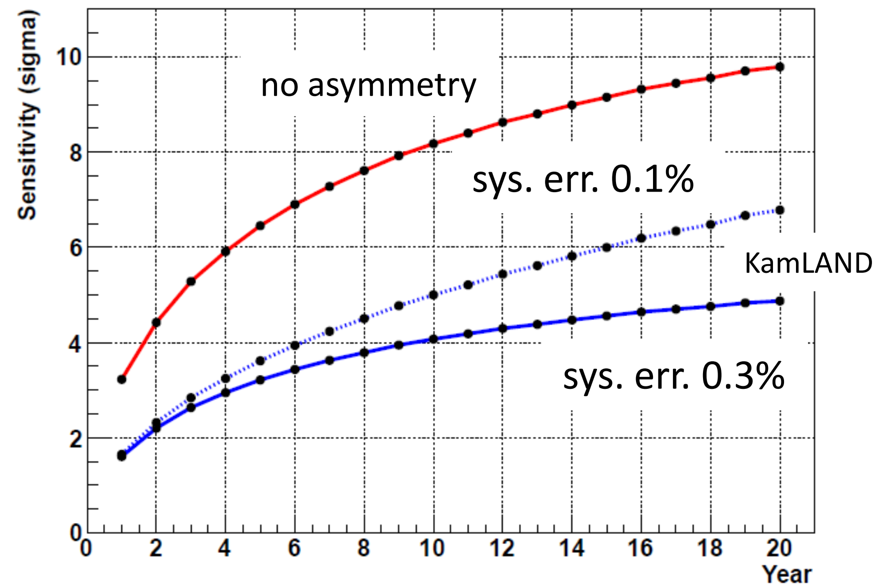
1 Hyper-K tank
can resolve octant at 3σ,
for $|45^0 - \theta_{23}| \geq 2.3$ deg

Solar Neutrinos

Allowed parameter regions
KamLAND: blue
Solar: green
Combined: red
Contours: expected day-night asymmetry



Hyper-K sensitivity to day-night asymmetry observation



Hyper-K
Energy threshold 6.5 MeV
Systematic error (goal) 0.3%

Supernova Burst Neutrino

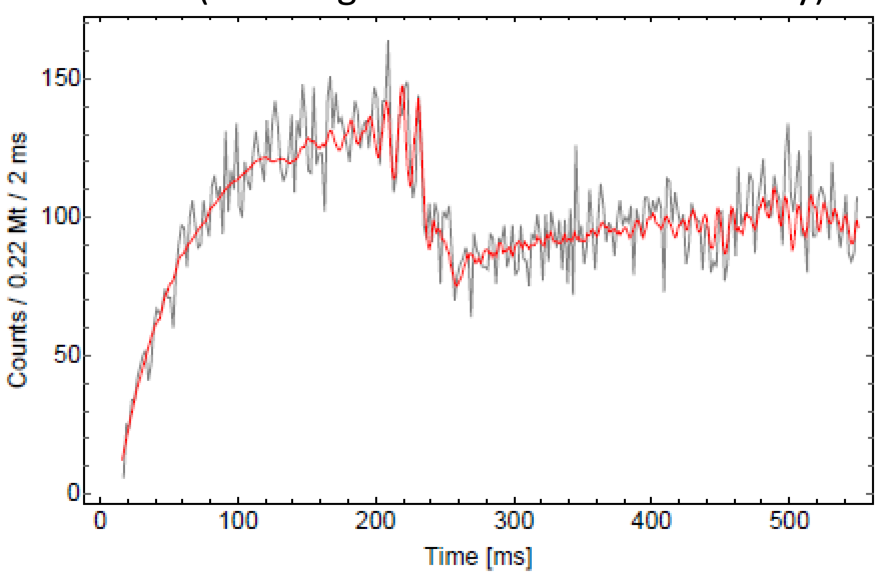
Main reaction in Hyper-K

$$\bar{\nu}_e + p \rightarrow n + e^{+}, \text{threshold} \sim 3\,\text{MeV}$$

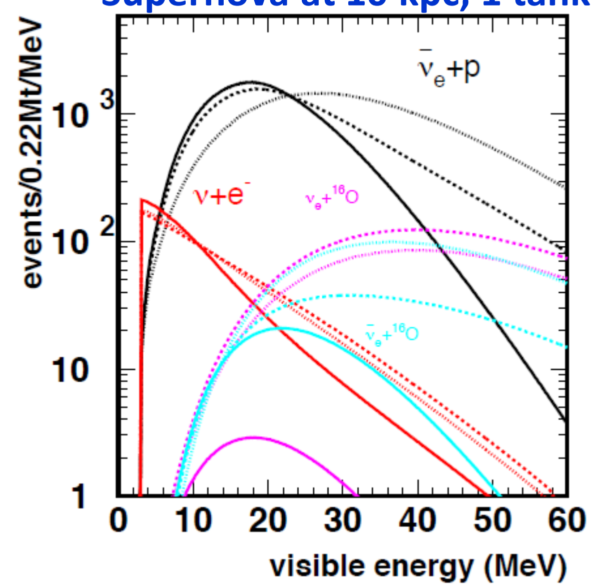
DUNE primarily detects ν_e

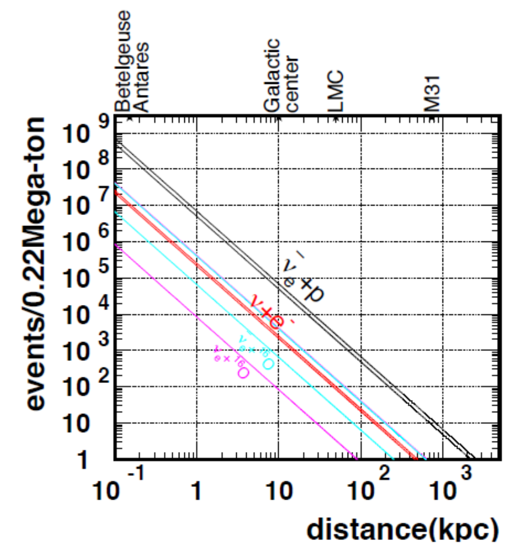
Hyper-K will detect
- 50-80 k events for 10 kpc Supernova
- 2-3 k events for LMC (location of SN1987a)

Detection rate modulation due to
SASI (standing accretion shock instability)



Supernova at 10 kpc, 1 tank

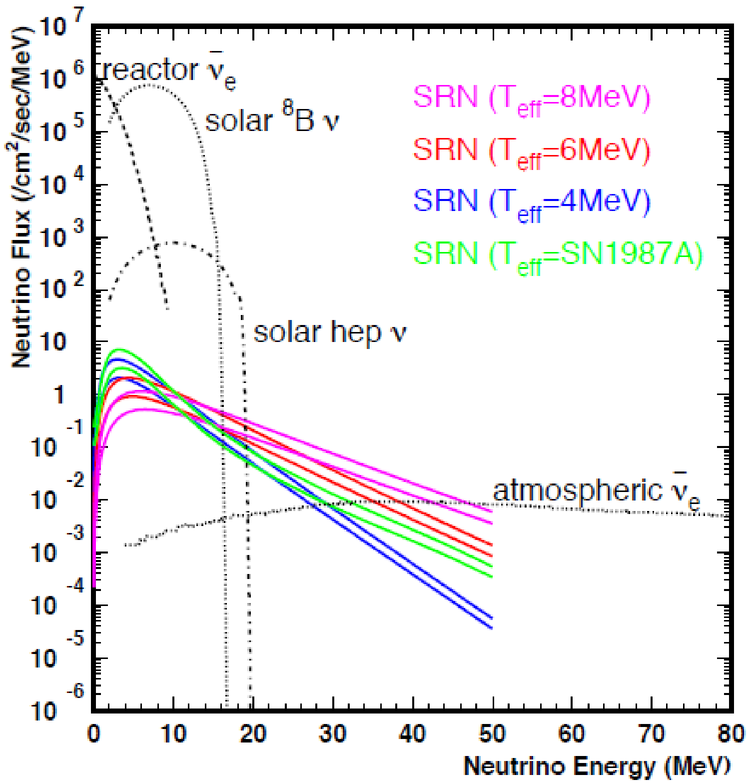


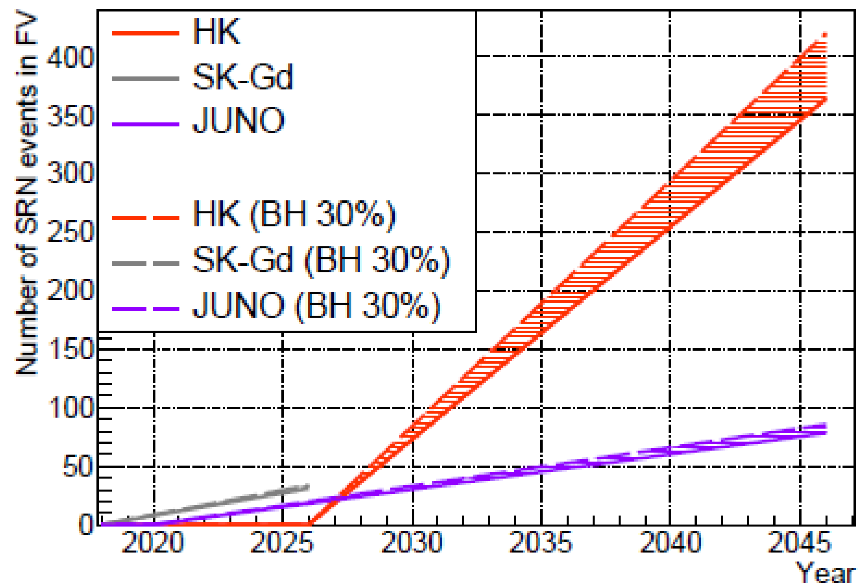


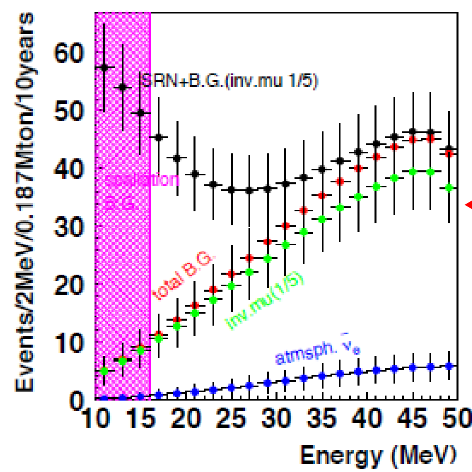
Supernova Relic Neutrino

Hyper-K will measure the SRN spectrum
- → formation of black holes
- → formation of stars, their metallicity

S.Horiuchi et al. PRD 79 (1990) 083013





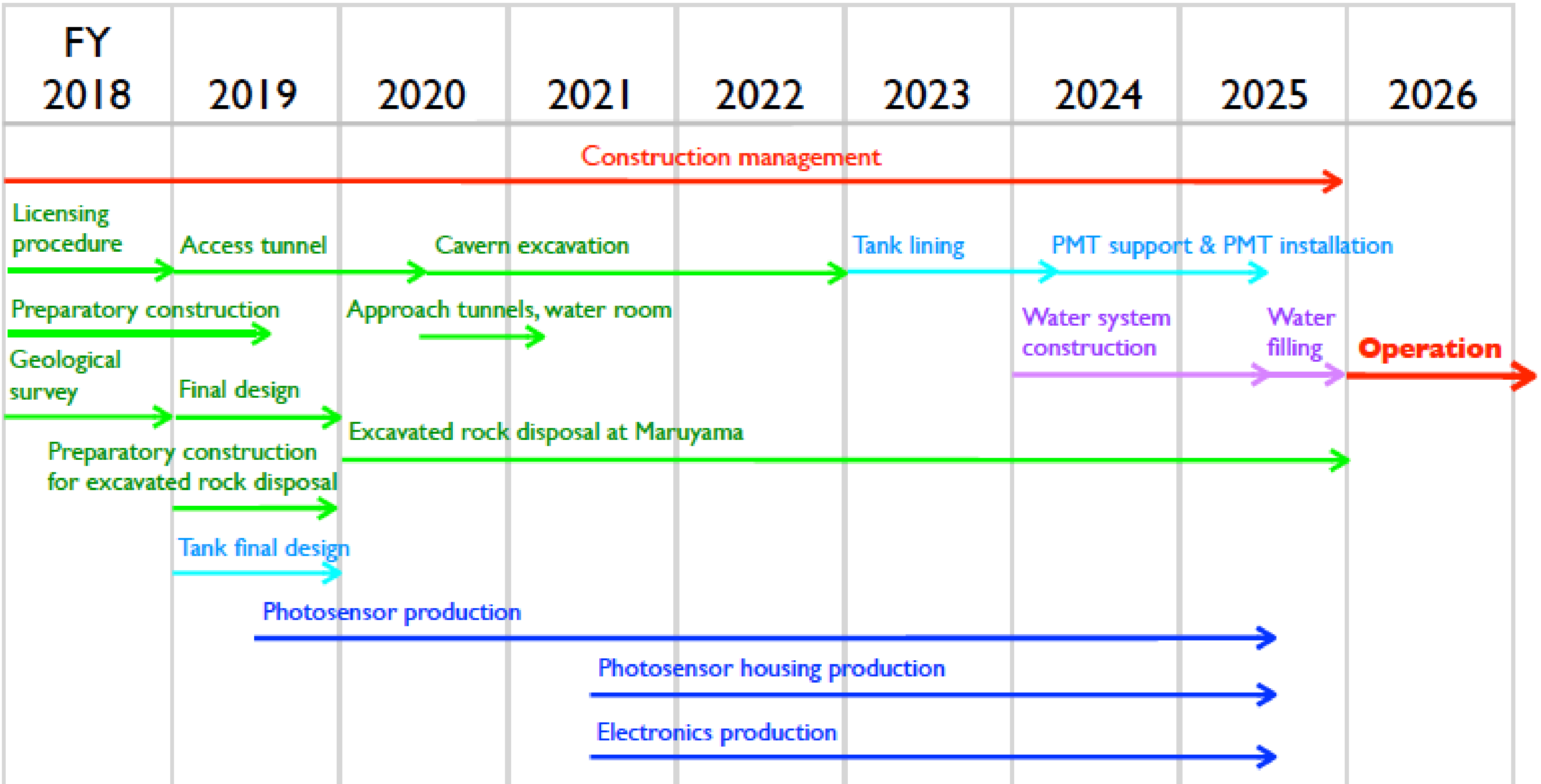


Energy spectrum of SRN
- 10 years of exposure
- neutron tagging efficiency 67%

Status

- International Hyper-Kamiokande proto-collaboration is formed
- Two host institutions: U Tokyo/ICRR and KEK/IPNS
- U Tokyo has created a new institution for Hyper-K construction: Next generation Neutrino Science Organization (NNSO)
- Hyper-Kamiokande is the list of the Japanese Ministry of Education, Culture, Sports, Science (MEXT) 2017 Roadmap as one of 7 large projects
- Hyper-Kamiokande is awaiting final approval by Japanese Government soon

Hyper-K timeline

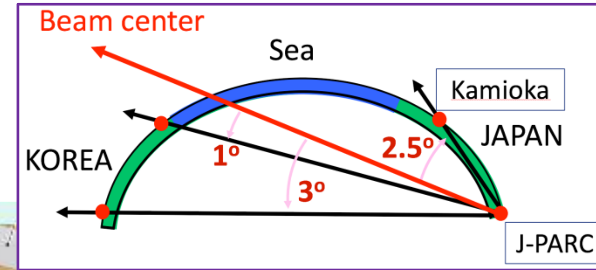


Assuming that Hyper-K budget is approved in 2018

T2HKK

2nd Hyper-K detector in Korea

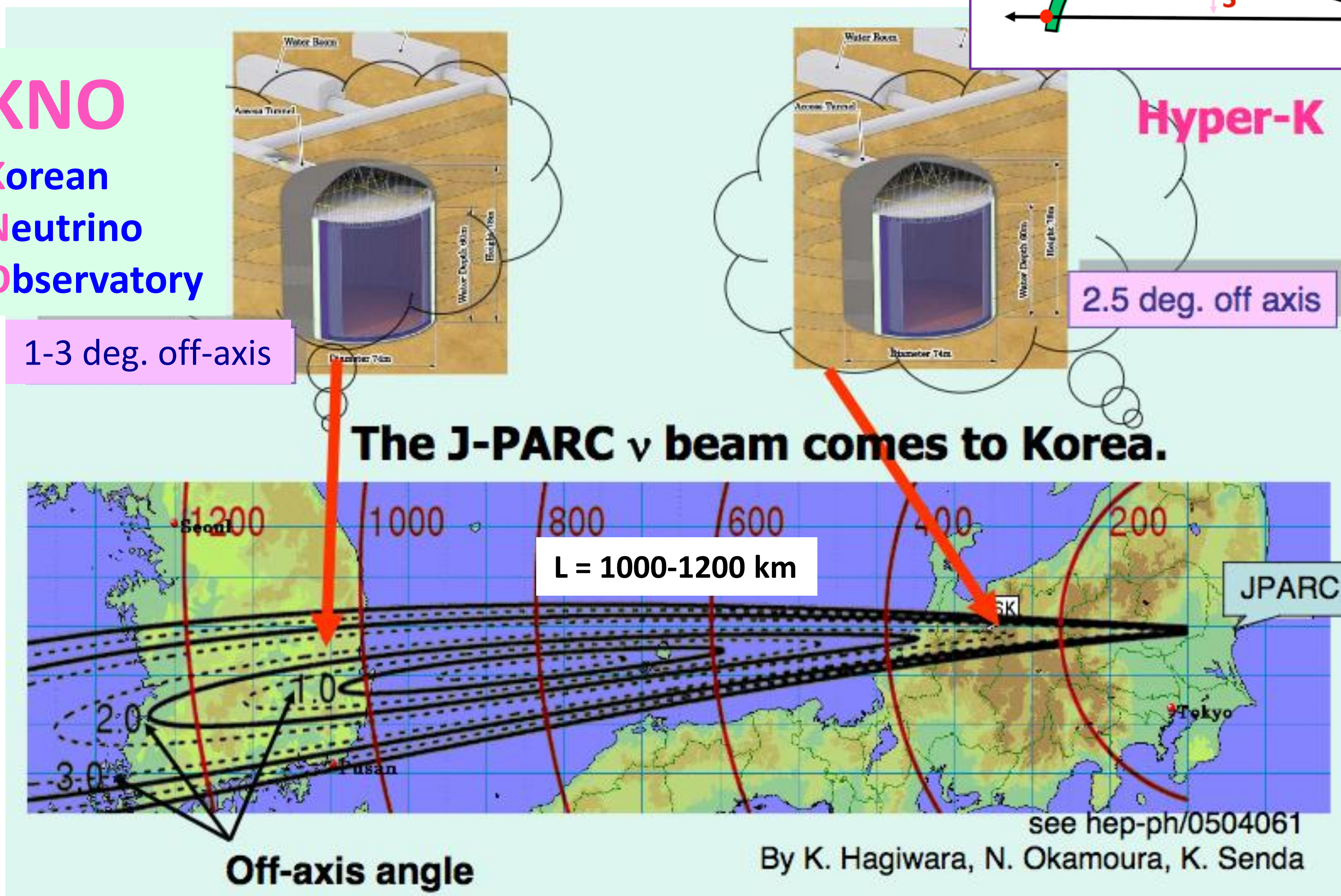
T2HKK = Tokai-to(2)-HK-to-Korea



KNO

Korean
Neutrino
Observatory

1-3 deg. off-axis



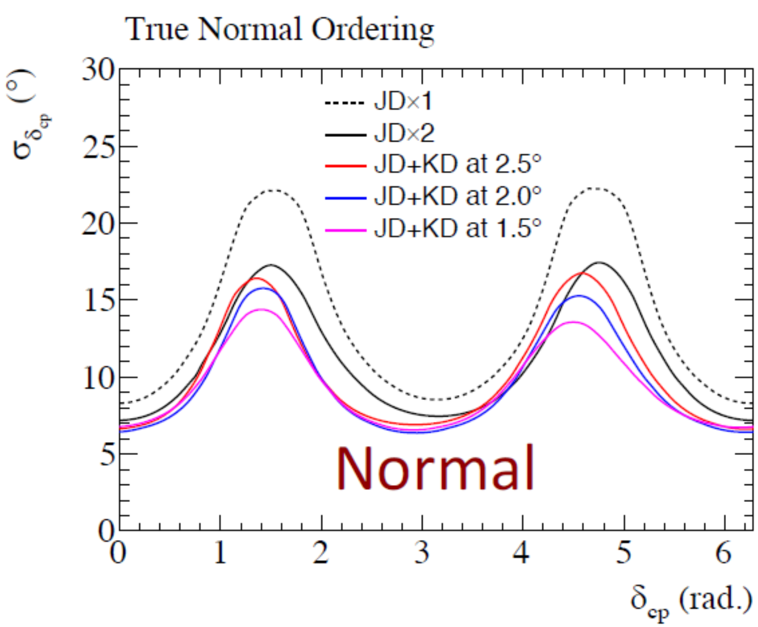
T2HKK: δ precision

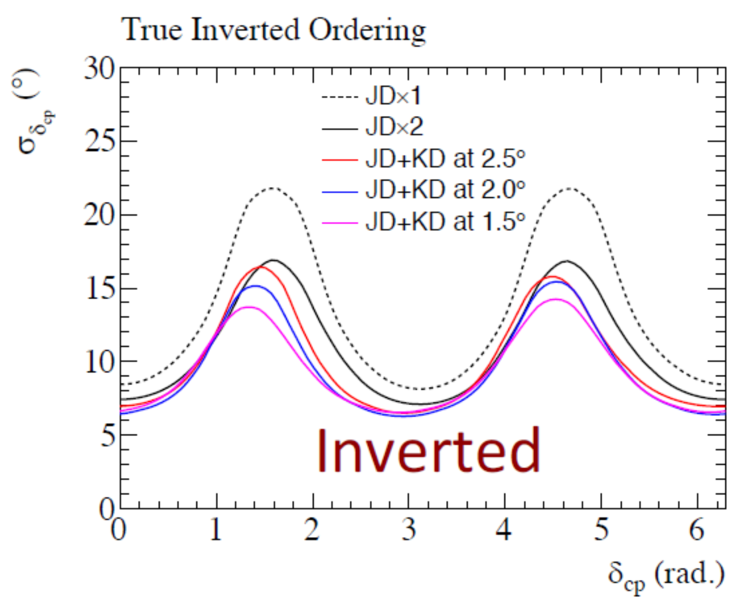
T2HKK : study oscillations at 1st and 2nd oscillation maxima

→ better sensitivity to mass hierarchy

→ better sensitivity to CP violation

arXiv:1611.06118





JD x 1:	**HK 1 tank, Japan**	**σ(δ) = 22 deg**
JD x 2:	**HK 2 tanks, Japan**	**σ(δ) = 17 deg**
JD + KD:	**HK 1tank (Japan + HK 1 tank (Korea)**	**σ(δ) = 13-14 deg**

Summary

Hyper-Kamiokande will be the major next generation neutrino experiment

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**

Hyper-Kamiokande
- **included in the MEXT Roadmap-2017**
- **will be built using Super-K and T2K experience**
- **start with one 260 kt detector**
- **open for new ideas and collaborators**
- **awating the final approval**