HyperKamiokande

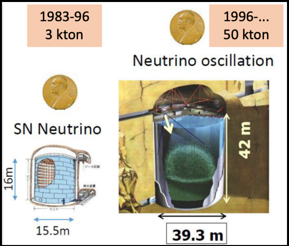
Federico Nova

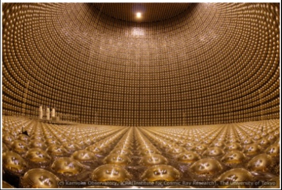
CNNP 2020

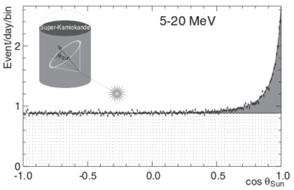
Outline:

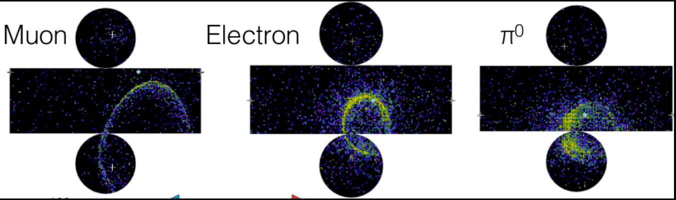
1. detector
2. physics program

Kamiokande family









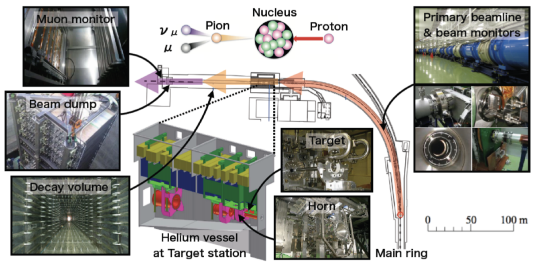
- id
- vertex
- direction
- energy

HyperKamiokande detector

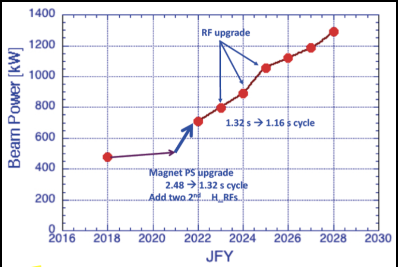
	SuperKamiokande	HyperKamiokande
site	Mozumi	Tochibora
ID PMTs	11k (50 cm)	40k (50 cm)
photo-coverage	40%	40% $\times$ 2 single p.e. efficiency
OD PMTs	2k (20 cm)	15k (7.5 cm)
mass (fiducial mass)	50 kton (22.5 kton)	260 kton (188 kton)

- $8\times$ SK fiducial volume
- improved photo-sensors
- project approved January 2020
- begin construction April 2020

J-PARC neutrino beamline

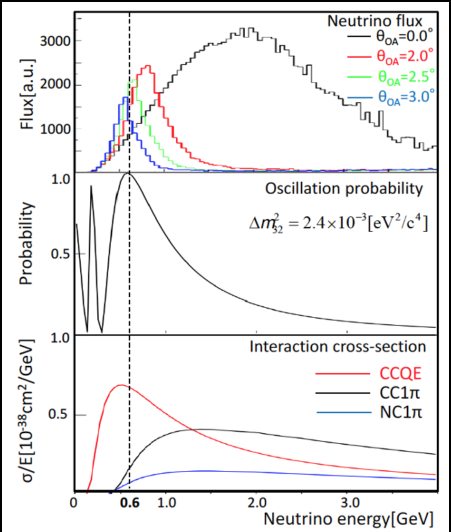


- narrow-band neutrino beam ($E \approx 600$ MeV)
- beam power to reach 1.3 MW
  - upgrade main ring (power supply, RF)
  - increase repetition rate (2.48 $\rightarrow$ 1.16 sec/cycle), keep same dynamic stress on window and target
  - increased statistics at HK



Near detector (280 m downstream)

- essential to tune fits and reduce systematics
- measure cross-sections and monitor flux before oscillations
- interaction dominated by CCQE
  - $\rightarrow$ single ring
  - $\rightarrow$ kinematic reconstruction of E_ν
- interaction rates uncertainty 3%
  - $\rightarrow$ systematic errors $5-6\%$ in T2K
  - must be reduced to 3% for HK

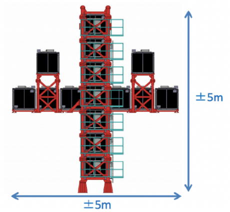


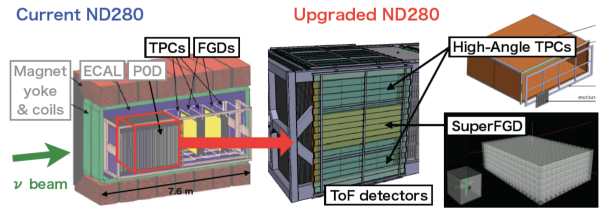
Near detector (280 m downstream)

- INGRID
  - on-axis
  - Fe + scintillator
  - very sensitive to beam direction (0.3 mrad already achieved in T2K)

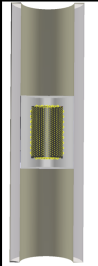
ND280 (ECAL, P0D, TPCs, FGDs)

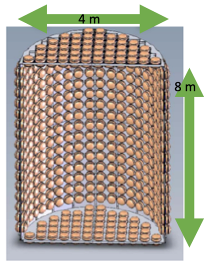
- magnetized detectors to identify wrong-sign ν (important for $\bar{\nu}$ mode where cross-section is $\frac{1}{3}$)
- new: TOF detectors, high-angle TPCs, scintillator superFGD
- upgrade for finer granularity and wider solid angle

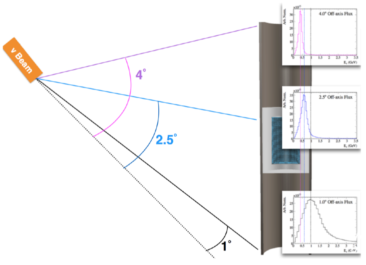




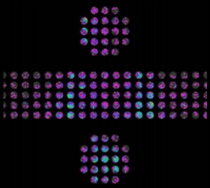
Intermediate water-Cerenkov detector



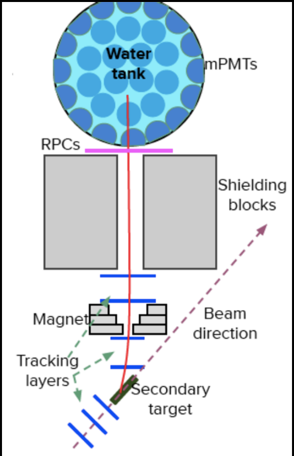




- a new intermediate detector
- 1 kton movable detector
- 1-2 km downstream ($\rightarrow$ point source as $L_\pi = 50$ cm)
- 50 m run height, sample different off-axis angles (2.5° in HK)
- match the flux between near and far detectors
- measure intrinsic ν_e and NC background
- direct measurement of ν_e cross-section (main systematic in $\delta_{\rm CP}$)
- vertex uncertainty: 2 cm
- 0.6 ns TTS from 3" PMTs (480 mPMTs)



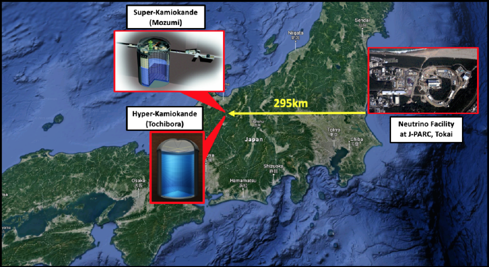
Intermediate water-Cerenkov detector



IWCD test beam experiment

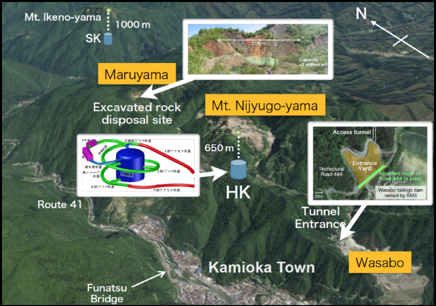
- to be run at CERN 2021-22
- PS test beam area selected
- Cerenkov cylinder, $H = 3.4$ m, $2R = 3.7$ m, 132 mPMT's
- test detector in beam of $p^{\pm}, e^{\pm}, \pi^{\pm}, \mu^{\pm}, n$
- low momentum (0.1-1 GeV) from decay
- motivation: proper modeling of detector response (ex. π scattering, secondary n)

HyperKamiokande far detector site



same choices as T2K:

- 295 km baseline
- $2.5°$ off-axis angle

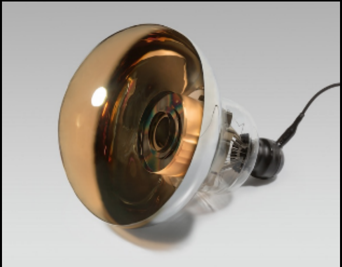


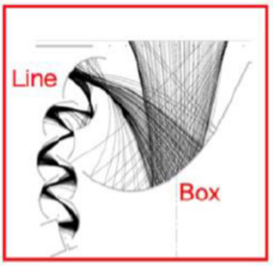
Photosensors: baseline choice

requirements:

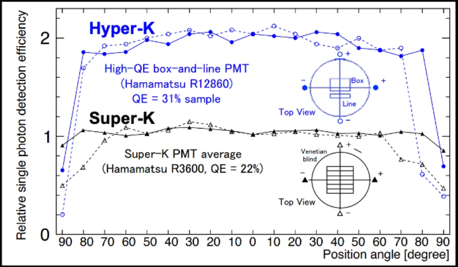
- wide dynamic range
- high charge resolutions
- high detection efficiency
- ns time resolution (15 cm vertex)
- low background (low radioactivity glass)
- clear photon counting
- high rate tolerance
- pressure-resistant acrylic cover

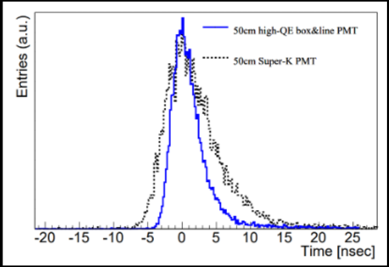
baseline choice: 50 cm Hamamatsu high-efficiency QE B&L PMT

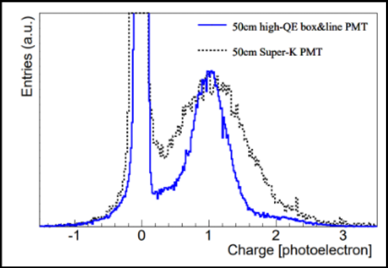




Photosensors: baseline choice

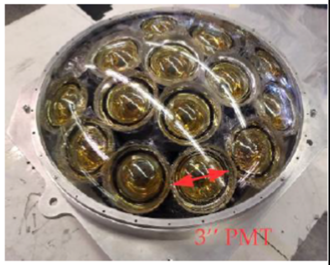


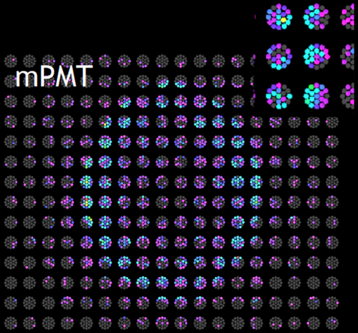




- wrt SK: 2× single p.e. efficiency
- 2× increased charge (35%, 50% in SK) and time resolution (1.1 ns transit time spread, 2.1 ns in SK)
- 2× increased pressure resistance (80 m water depth)
- 4 kHz dark rate
- 140 HK PMTs installed in SK, ready to produce

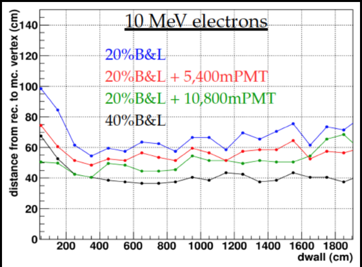
Photosensor alternative: mPMT

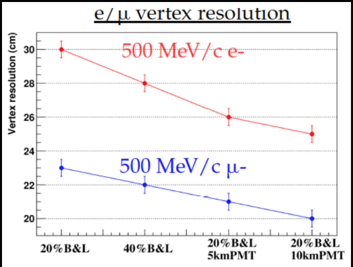




- concept from KM3NeT, international contribution
- module with 19 3" PMTs (economical)
- directional sensitivity
- local coincidences
- less magnetic field sensitivity
- final design early 2020

Photosensor alternative: mPMT





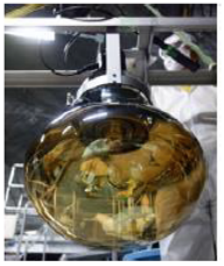
- finer granularity ($\rightarrow$ better vertex resolution near detector edges, enhanced event reconstruction for multi-ring events)
- better timing resolution (0.6 ns TTS, $2\times$ better than B&L)
- $+10\%$ fiducial volume, lower systematic uncertainties, decrease energy threshold 4.5 $\rightarrow$ 3.5 MeV (solar upturn, MSW effect)
- adopted for IWCD

Photosensor alternative: MCP PMT and HPD

MCP PMT 50 cm

- experience in JUNO
- R&D for HK

Hamamatsu HPD, 50 cm

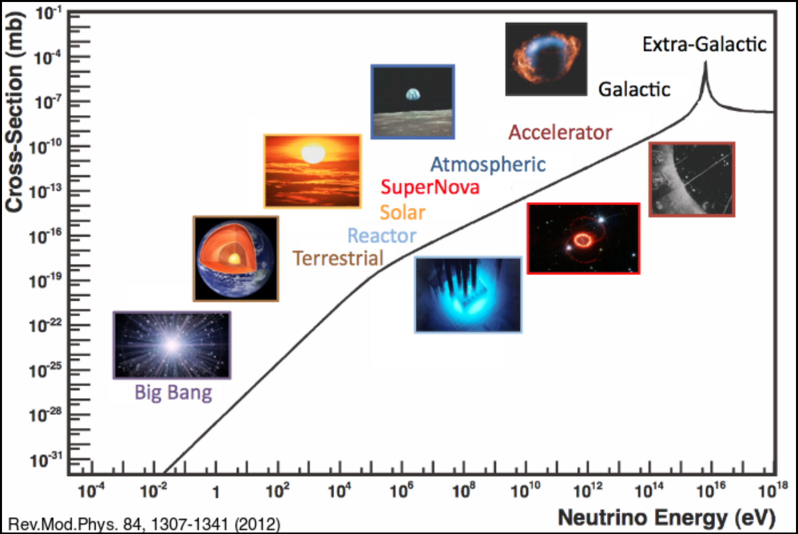


- hybrid photodetector (with avalanche diode)
- better charge resolution
- need R&D for mass production

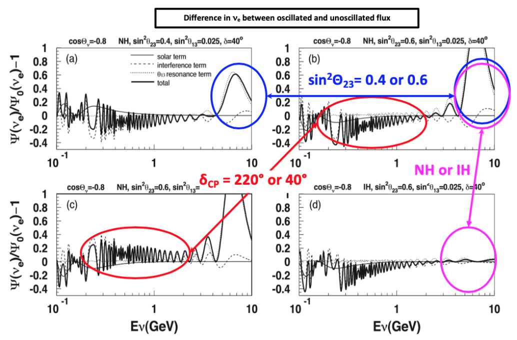
HyperK may adopt hybrid system

- ID: 20" B&L + mPMT/MCP/etc.
- OD: 3" or 8" PMTs + WLS plate

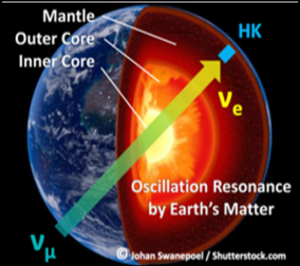
Very wide physics program



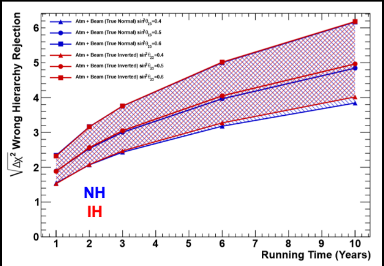
Atmospheric neutrinos

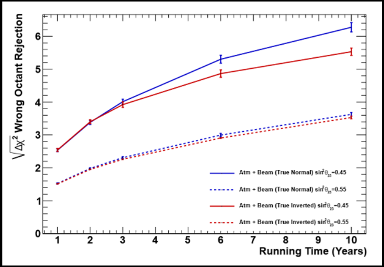


- wide energy range (peak below 1 GeV) and long travel distance
- precision mixing parameters
- ν_e flux enhanced depending on hierarchy, θ_{23} and δ_{CP}



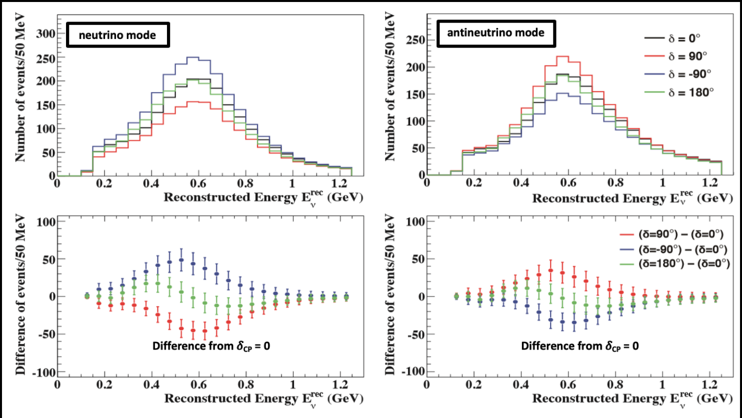
Mass hierarchy and octant sensitivity





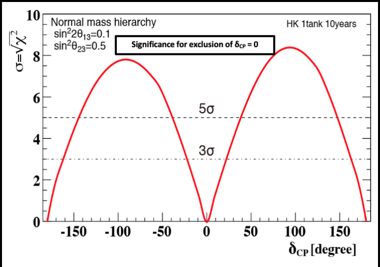
- earth matter effect for ν's passing through core allow measurement of δ_{CP}, mass hierarchy and θ_{23} octant
- measure mass ordering at 3σ for all values of θ_{23}
- determine octant at 3σ for $|\theta_{23} - 45°| \geq 2°$

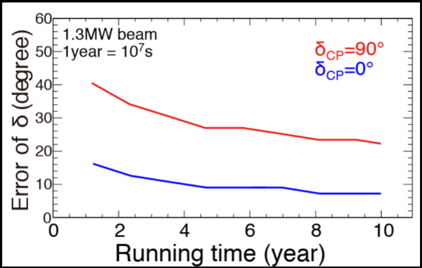
beam: CP violation



- ν_e appearance in ν_μ beam
- T2K disfavour CP conservation ($\delta = 0, \pi$) at $\sim 3\sigma$ level
- effect of $\delta_{\rm CP}$ clearly seen in reconstructed spectra (10 years, NH)

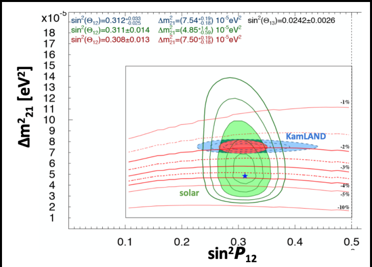
beam: CP violation

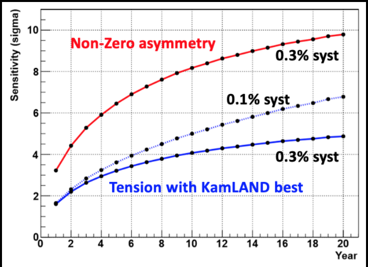


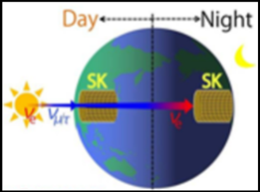


- assume 1 tank, 10 years exposure (1600 neutrino events, 1200 anti-neutrino events), normal ordering, 3-4% systematic uncertainty
- exclude $\sin\delta_{CP} = 0$ with $> 3\sigma$ for 76% of range
- measure δ_{CP} with $\pm(7^\circ, 22^\circ)$ for $\sin\delta_{CP} = (0, 1)$

Solar neutrinos

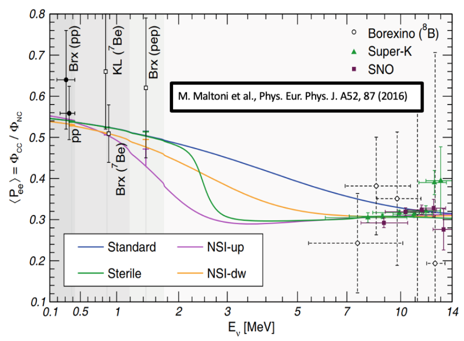


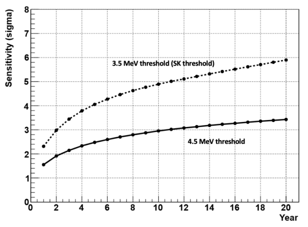




- day/night asymmetry
- regeneration of ν_e due to earth matter effect $\rightarrow$ higher ν_e flux at night
- 2σ tension between solar experiments and KamLAND

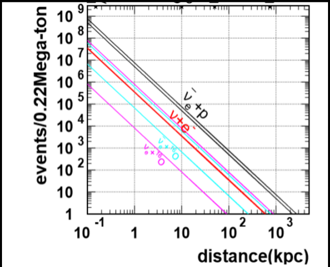
Solar neutrinos

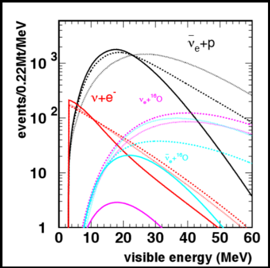




- solar neutrinos up-turn: increase in low-energy survival probability
- $> 3\sigma$ measurement of spectrum up-turn

Supernovae neutrinos: $\bar{\nu}_e + p^+ \rightarrow e^+ + n$

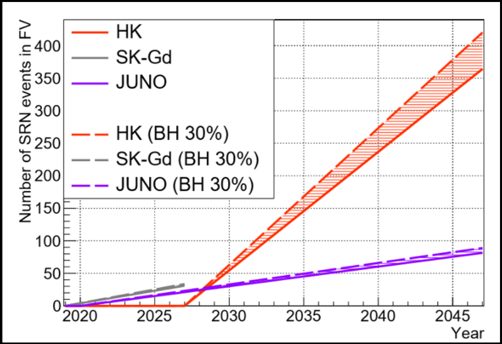




SN location	n events/tank
galactic centre (10 kpc)	70k
SN1987a (50 kpc)	3k
Andromeda (0.8 Mpc)	10

- first and only detection of supernova neutrinos SN1987a (11 ± 8 events @ 50 kpc)
- 50-80k events for a 10 kpc supernova $\rightarrow$ neutrino properties, SN mechanism
- sensitive to 1 Mpc (Andromeda)
- 1° pointing for SN alert

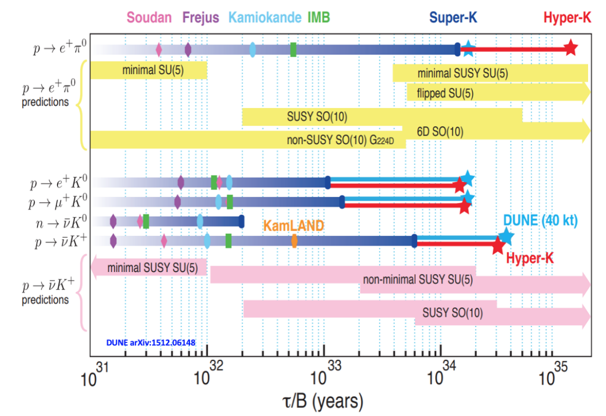
Supernovae relic neutrinos



- neutrinos from all SN since the beginning of the universe
- relevant for star metallicity and black-hole formation
- SK-Gd (march 2020!) will have improved neutron tagging and can detect SRN at 10-20 MeV
- HK will measure SRN in 16-30 MeV (window limited by backgrounds: spallation and atmospheric neutrinos)

also: dark matter annihilation in the sun $\rightarrow$ neutrinos!

Proton decay

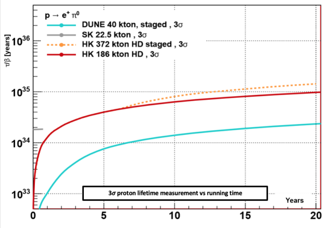


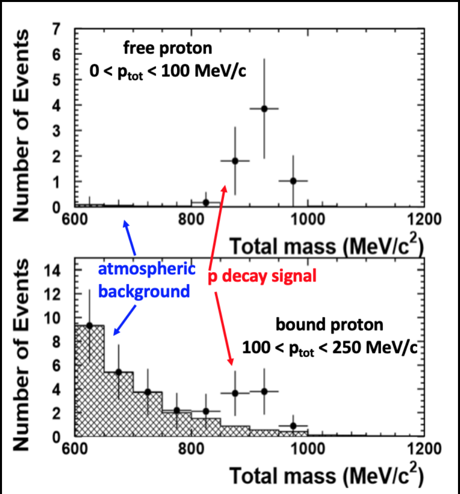
- predicted by many GUT models
- particles have less than $\frac{m_p c^2}{2} = 500$ MeV
- water Cerenkov sensitive to many decay modes
- suppress backgrounds with improved neutron tagging
- reach 10^{35} y lifetime

Proton decay: $p^+ \rightarrow e^+ + \pi^0$

golden channel

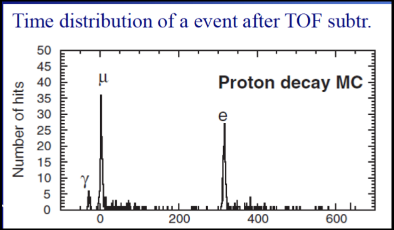
- favoured by many GUTs
- can see all products
- background-free search thanks to neutron tagging ($n + p^+ \rightarrow d + \gamma$, $E_\gamma = 2.2$ MeV)
- 3σ discovery potential

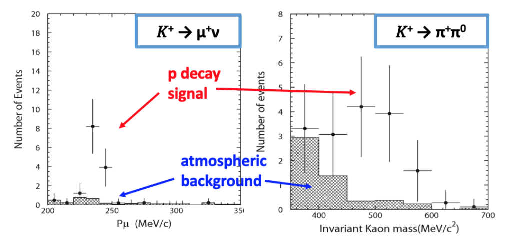


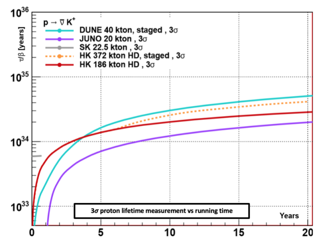


Proton decay: $p^+ \to \bar{\nu} + K^+$

- favoured by SUSY GUT
- K^+ below Cerenkov threshold (visible in DUNE), detect via decay $K^+ \to \mu^+ + \nu$ (64%) or $K^+ \to \pi^+ + \pi^0$ (21%)
- prompt gamma de-excitation, followed by μ^+ from K^+ decay (12 ns) and e^+ from μ^+ decay (2 ms)
- 3σ discovery

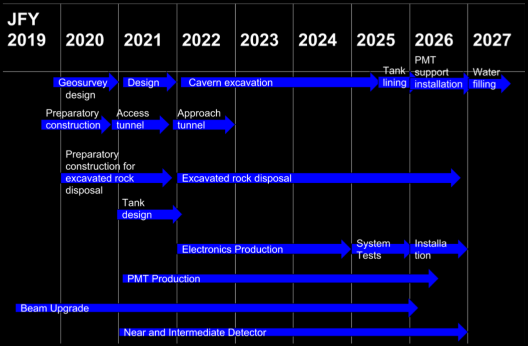


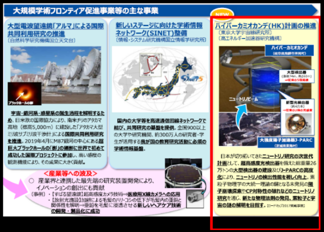




many other modes improved by 1 order

Timeline





- design report released 2018
- construction announced in 2018 by University of Tokyo
- project approved in Japan (MEXT budget announcement 2019)
- begin construction April 2020
- data taking 2027

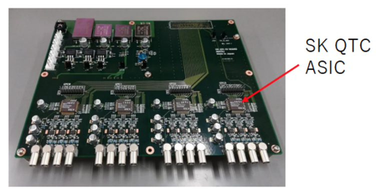
Summary

- HyperKamiokande is the next-generation neutrino experiment
  - $8\times$ larger than SK
  - improved photo-sensors
  - upgraded 1.3 MW beam
  - intermediate water Cerenkov to reduce systematic errors
- rich physics program
  - precise neutrino oscillation: δ_{CP}, mass ordering
  - astrophysics: solar neutrinos, supernovae etc.
  - new physics: proton decay, dark matter ...
- construction starts 2020, data taking 2027

Back-up slides

Electronics

- electronics timing resolution < PMT TTS
- frontend electronics and HV module in water
- timing delivered by GPS
- communication via fiber (200 m)
- large buffer for SN burst
- prototype developed with: SK QTC ASIC (charge to time), FPGA TDC 4GHz
- electronics resolution: 0.2 ns at 1 p.e., 10% charge resolution at 1 p.e., 2000 p.e. range with 1% linearity



mPMT electronics:

- 0.4 ns for 1 p.e., 0.1 ns for larger pulses
- charge resolution: 0.05 to 25 p.e.
- power consumption: 3-4 W/mPMT for HK (driven by water circulation requirements), 5-10 W/mPMT for IWCD

Systematic errors

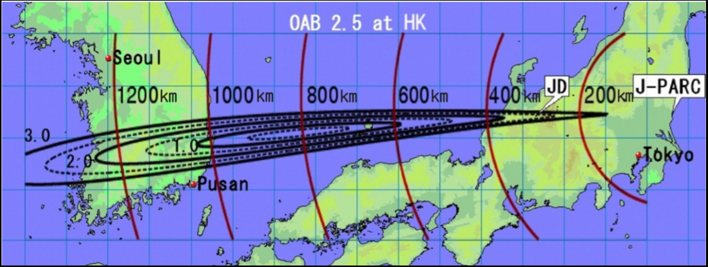
- statistical error will be 3% in HK
- require 3% systematic error on interaction rates (through upgraded ND280 and IWCD)

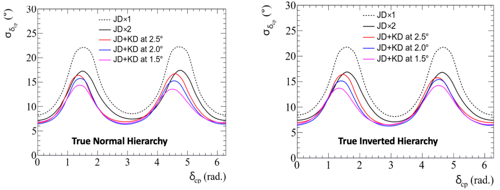
Source of uncertainty	ν_μ CC	ν_e CC	$\bar{\nu}_\mu$ CC	$\bar{\nu}_e$ CC
Flux and common cross sections				
(w/o ND280 constraint)	10.8%	10.9%	11.9%	12.4%
(w/ ND280 constraint)	2.8%	2.9%	3.3%	3.2%
Unconstrained cross sections	0.8%	3.0%	0.8%	3.3%
SK	3.9%	2.4%	3.3%	3.1%
FSI + SI(+ PN)	1.5%	2.5%	2.1%	2.5%
Total				
(w/o ND280 constraint)	11.9%	12.2%	13.0%	13.4%
(w/ ND280 constraint)	5.1%	5.4%	5.2%	6.2%

Systematic Source	Required Precision	For Which Measurement	Detector	Achievable Precision
$\sigma(\nu_e)/\sigma(\nu_\mu)$	3-5%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim0$, θ_{23} precision at $\sin(\theta_{23})\sim0.5$	IWCD	3.5-5%
$\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	3-5%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim0$, θ_{23} precision at $\sin(\theta_{23})\sim0.5$	IWCD	4-7%
Wrong-sign background normalization	9%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim0$	ND280	TBD (expect <9%)
Intrinsic ν_e,$\bar{\nu}_e$ and NC backgrounds	3-4%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim0$	IWCD	2.3% (neutrino)
Normalization of non-QE with E_ν>0.7 GeV	5%	θ_{23} precision at $\sin(\theta_{23})\neq0.5$	IWCD	5% (neutrino)
Normalization of non-QE with all energies	5%	δ_{cp} precision at $\sin(\delta_{cp})\sim0$ Δm^2_{32} precision	IWCD, ND280*	5% (IWCD neutrino) <4% (N280 neutrino) <7% (ND280 antineutrino)

Systematic Source	Required Precision	For Which Measurement	Detector	Achievable Precision
Beam Direction	0.6 mrad (4 MeV shift)	δ_{cp} precision at $\sin(\delta_{cp})\sim0$ Δm^2_{32} precision	INGRID	<0.3 mrad (<2 MeV)
Removal (binding) energy	4 MeV*	δ_{cp} precision at $\sin(\delta_{cp})\sim0$ Δm^2_{32} precision	IWCD, ND280	2.6 MeV (IWCD on O) ~1 MeV (ND280 on C)**
High angle measurement (cosθ<0.2)	4%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim0$	IWCD, ND280	<4% statistical precision in both detectors
Beam rate monitoring	~1% per day	General monitoring of beam quality	INGRID	<0.5% per day for neutrinos and antineutrinos
Neutron Multiplicity	TBD	Atmospheric neutrino Nucleon decay	IWCD, ND280	<5% IWCD <4% ND280
$\mu\pi^0$ cross section & neutron multiplicity	TBD	$e\pi^0$ proton decay	IWCD	TBD

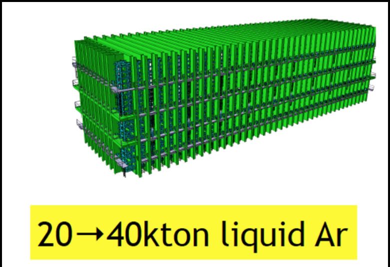
Second tank in Korea



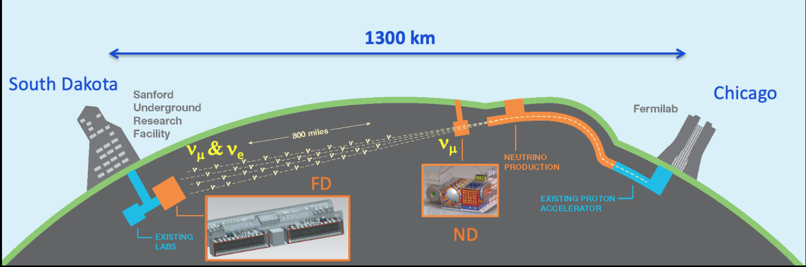


- 1100 km
- 2nd oscillation maximum
- higher precision on δ_{CP}

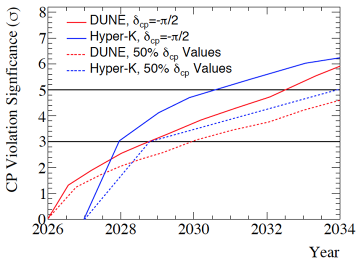
HyperK and DUNE

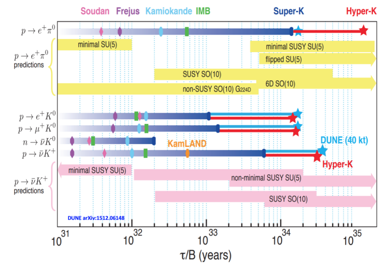


- HK: 188 kton water, 1.3 MW beam
- DUNE: 20 $\rightarrow$ 40 kton liquid Ar, $1.2 \rightarrow 2.4$ MW beam



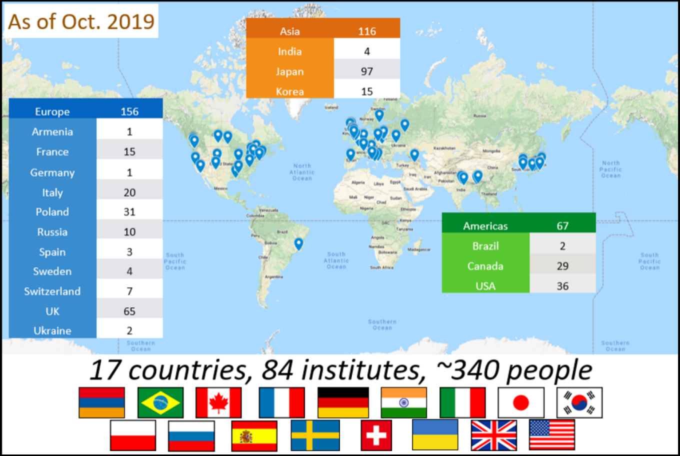
HyperK and DUNE





- similar sensitivities for δ_{CP}
- similar sensitivities for proton decay
  - DUNE has excellent event reconstruction, high efficiency, low backgrounds, golden $p^+ \to \bar{\nu} + K^+$
  - HK has larger volume and covers several decay modes, golden $p^+ \to e^+ + \pi^0$
- supernovae
  - DUNE observes $\nu_e \to$ time and flavour profile of collapse
  - HK has larger mass (188 kton vs 20/40 kton fiducial mass)

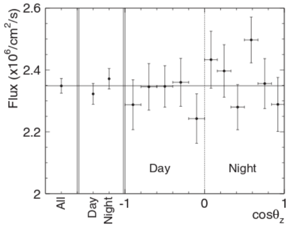
HyperKamiokande protocollaboration

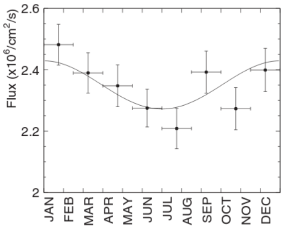


SuperK results on solar and atmospheric neutrinos

- measured 45% flux of electron neutrinos w.r.t. no oscillation
- same flux by day and by night $\Longrightarrow$ no matter effect in Earth
- seasonal modulation due to Earth orbit eccentricity, consistent with no vacuum oscillation $\Longrightarrow$ matter effect in Sun

$$\nu_e \leftrightarrow \frac{\nu_\mu - \nu_\tau}{\sqrt{2}} \quad \text{(sun)},$$
$$\theta_{12} = 0.59 = 34^\circ$$
$$m_2^2 - m_1^2 = 0.75 \cdot 10^{-4} \left(\frac{\text{eV}}{c^2}\right)^2$$





- detect neutrinos of $10^{-1} - 10^5$ GeV
- asymmetry $\frac{\phi_{\text{up}} - \phi_{\text{down}}}{\phi_{\text{up}} + \phi_{\text{down}}} = -0.3$ for ν_μ (no asymmetry for ν_e)
- ratio $\frac{\phi_{\text{up}}}{\phi_{\text{down}}} = 0.6$ for ν_μ and 1 for ν_e $\Longrightarrow$ ν_μ disappear, not into ν_e
- no matter effect $\Longrightarrow$ no oscillation to sterile neutrinos
- 2015 nobel prize

$$\nu_\mu \leftrightarrow \nu_\tau \quad \text{(vacuum)}$$
$$\theta_{23} = 0.79 = 45^\circ$$
$$|m_3^2 - m_2^2| = 2.4 \cdot 10^{-3} \left(\frac{\text{eV}}{c^2}\right)^2$$