Hyper-Kamiokande

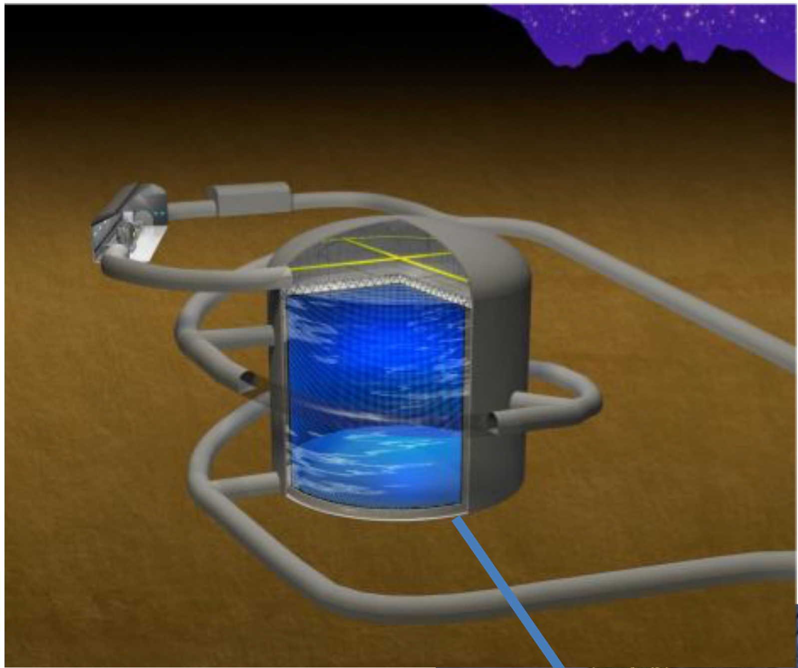
- Introduction
- Far Detector Design
- Neutrino Astrophysics & Proton Decay
- Beam and Near Detectors
- CP Violation, Mass Hierarchy & Mixing Angles
- Construction Schedule & 2nd Detector in Korea

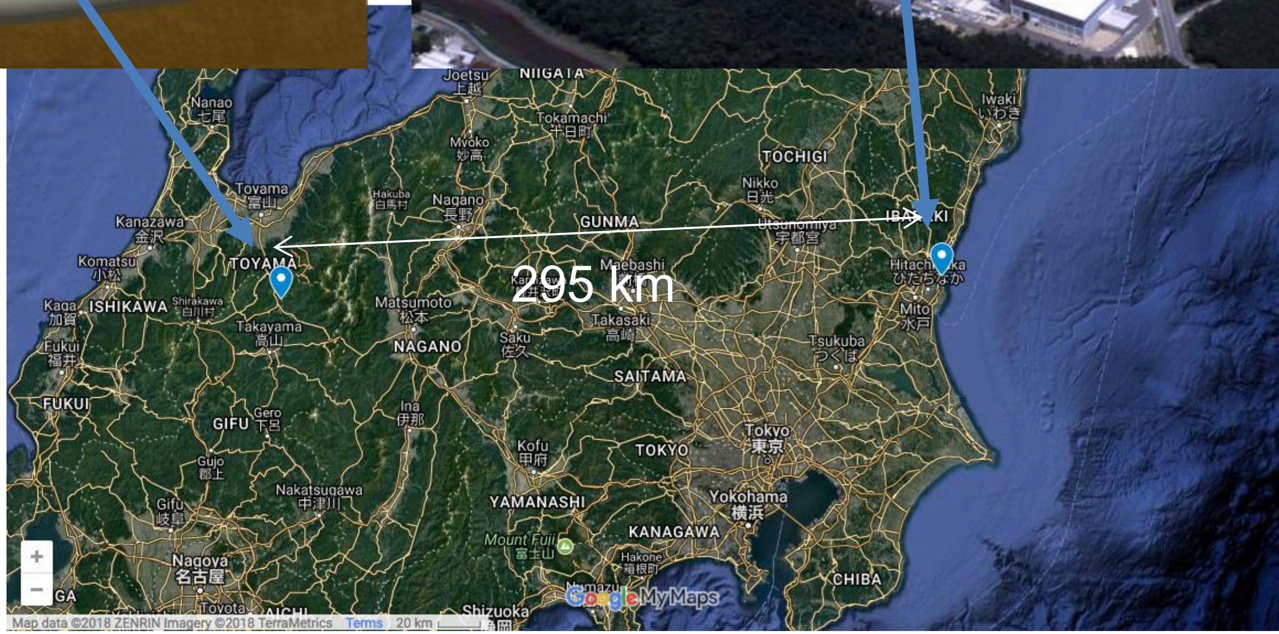
Steve Playfer
NuPhys2019, London, 18th December 2019

Hyper-K Proto-collaboration Sept. 2019 ~350 Collaborators from 17 countries

Hyper-Kamiokande

Design Report **arXiv:1805.04163**





Far Detector
(Kamioka)

Design is
being finalised

Technical Report
in preparation

Beam &
Near
Detectors
(JPARC)

Conceptual
Design Report
in preparation

Hyper-K Far Detector

8x larger than Super-K (will be largest man-made cavern in the world)
Location 8km south of Super-K

- A 260kton tank of pure water
- Inner Detector 216kt

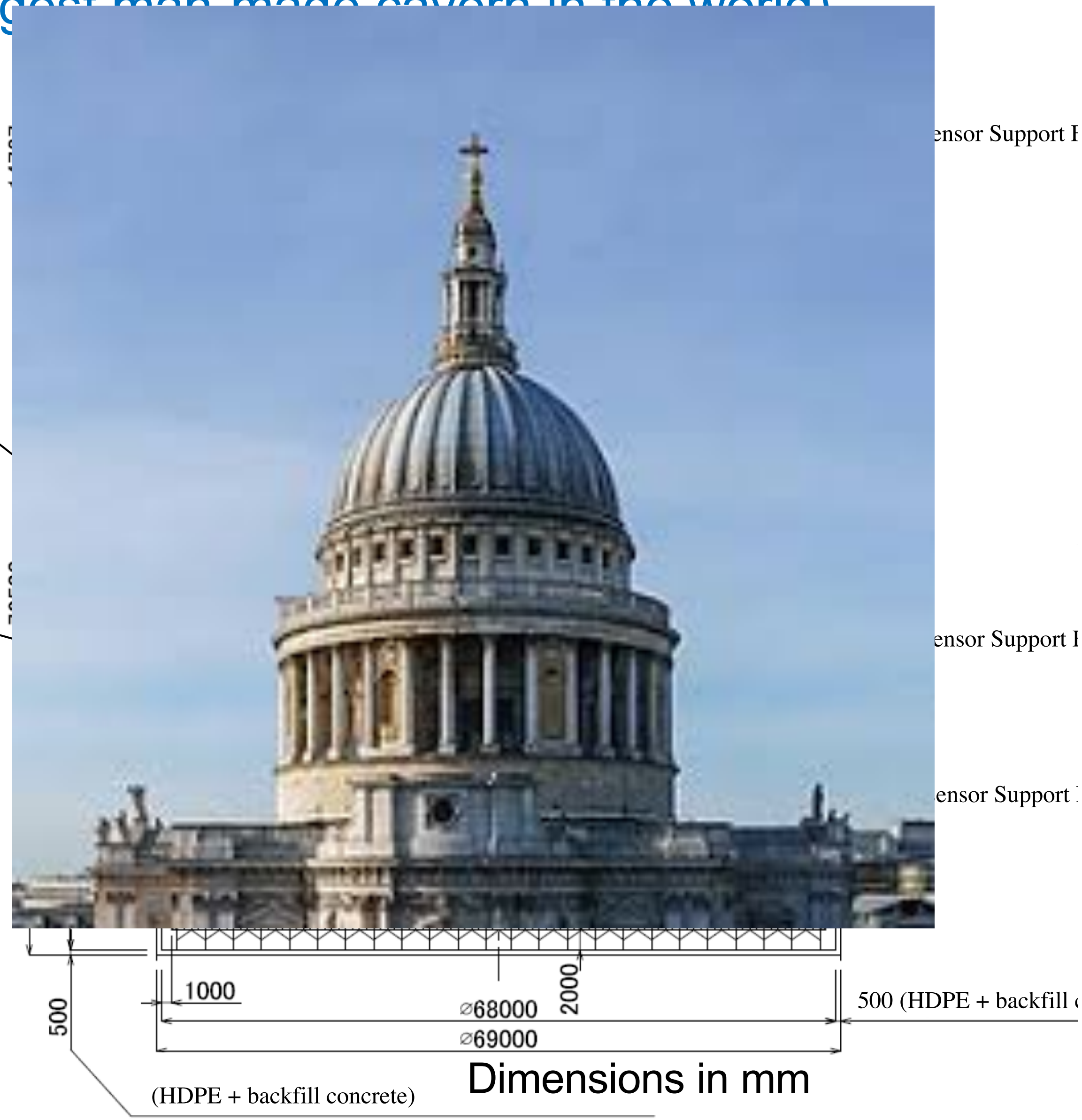
Fiducial volume ~200kt
Up to 40% photosensor coverage
(40k 20” PMTs)

- Outer Detector veto region

1m to 2m thick (~13k 3” PMTs)

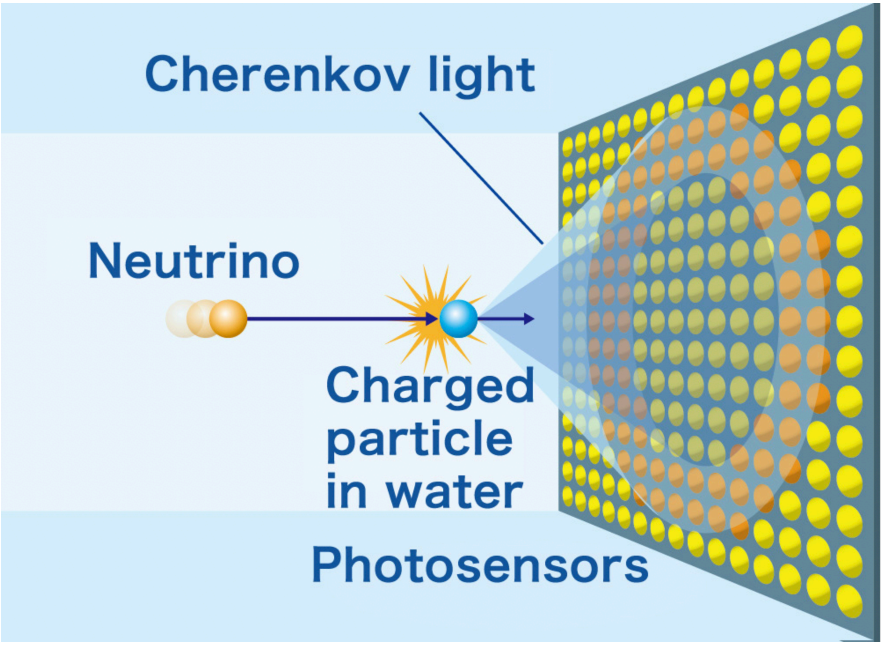
- Japanese budget request 2019 covers cavern excavation, tank, water system and half the photosensors.

International contributions are needed for more photosensors!



Photosensors – 20” PMTs

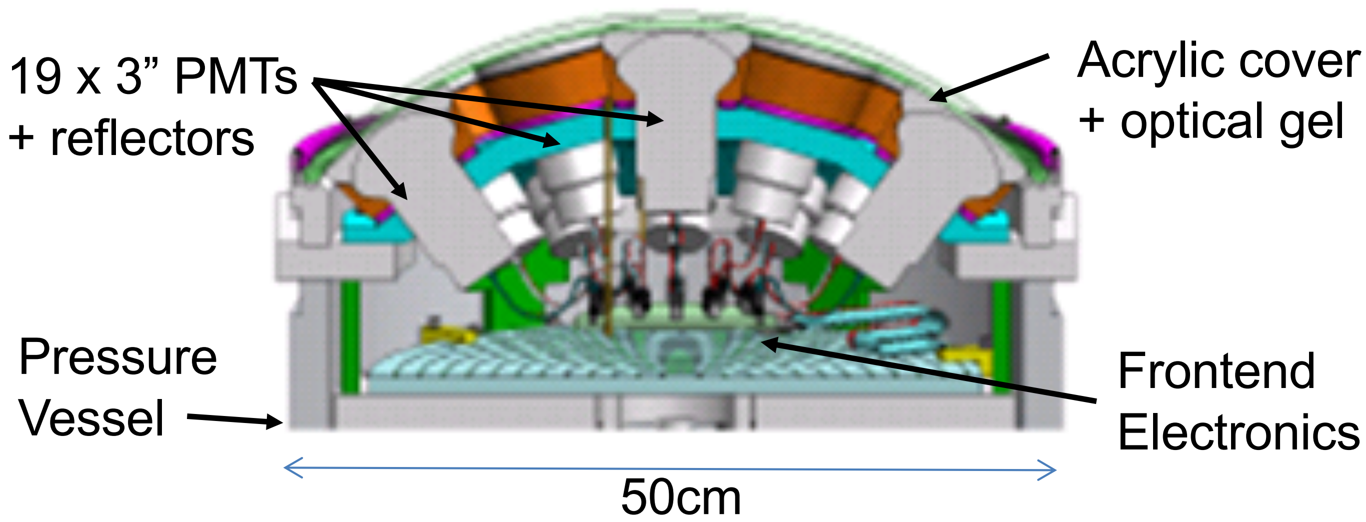
These are either Hamamatsu B&L or NNVT MCP-PMT



- Quantum efficiency 30% at 390nm (x1.4 compared to Super-K)
- Collection efficiency 95% at 10^7 gain (x1.3 compared to Super-K)
- Transit time spread 2.7ns for 1p.e.
- Charge resolution 27% for 1p.e.
- Dark count rate 8.5kHz → 5.7kHz (in past 2 years) → 4kHz?

Photosensors - mPMT Modules

We are considering adding ~5,000 multi-PMT modules

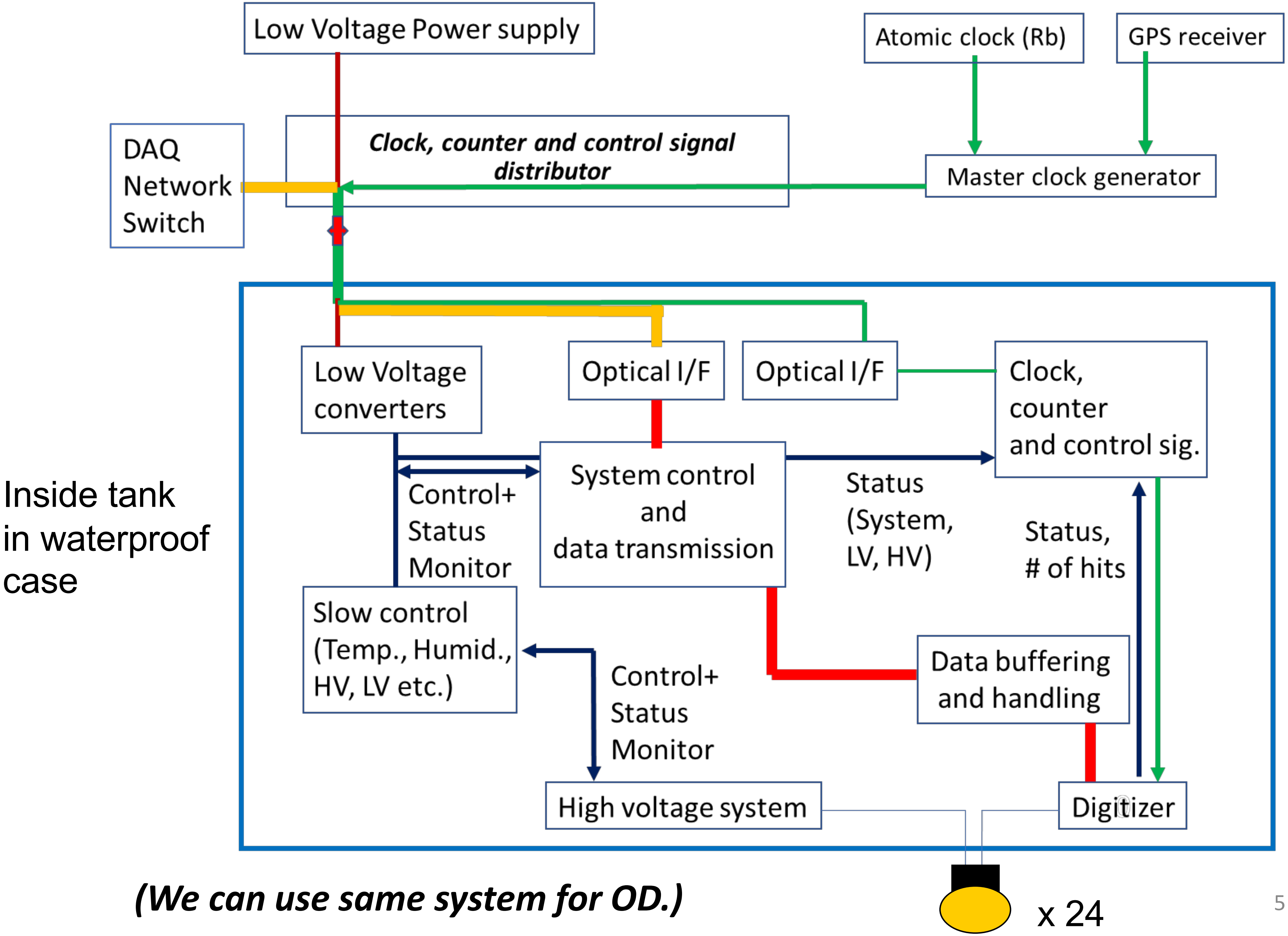


- 3” PMTs are Hamamatsu R14374 or ETEL D794KFL or HZC XP82B20
- Collection efficiency 45% due to packing fraction of PMTs
- Dark count rate 100-300Hz/PMT
- Transit time spread 1.3ns for 1p.e.

Improved spatial accuracy, timing, dynamic range, lower dark rate?

Cost comparison mPMT $8k, 20” PMT + cover + electronics $5k

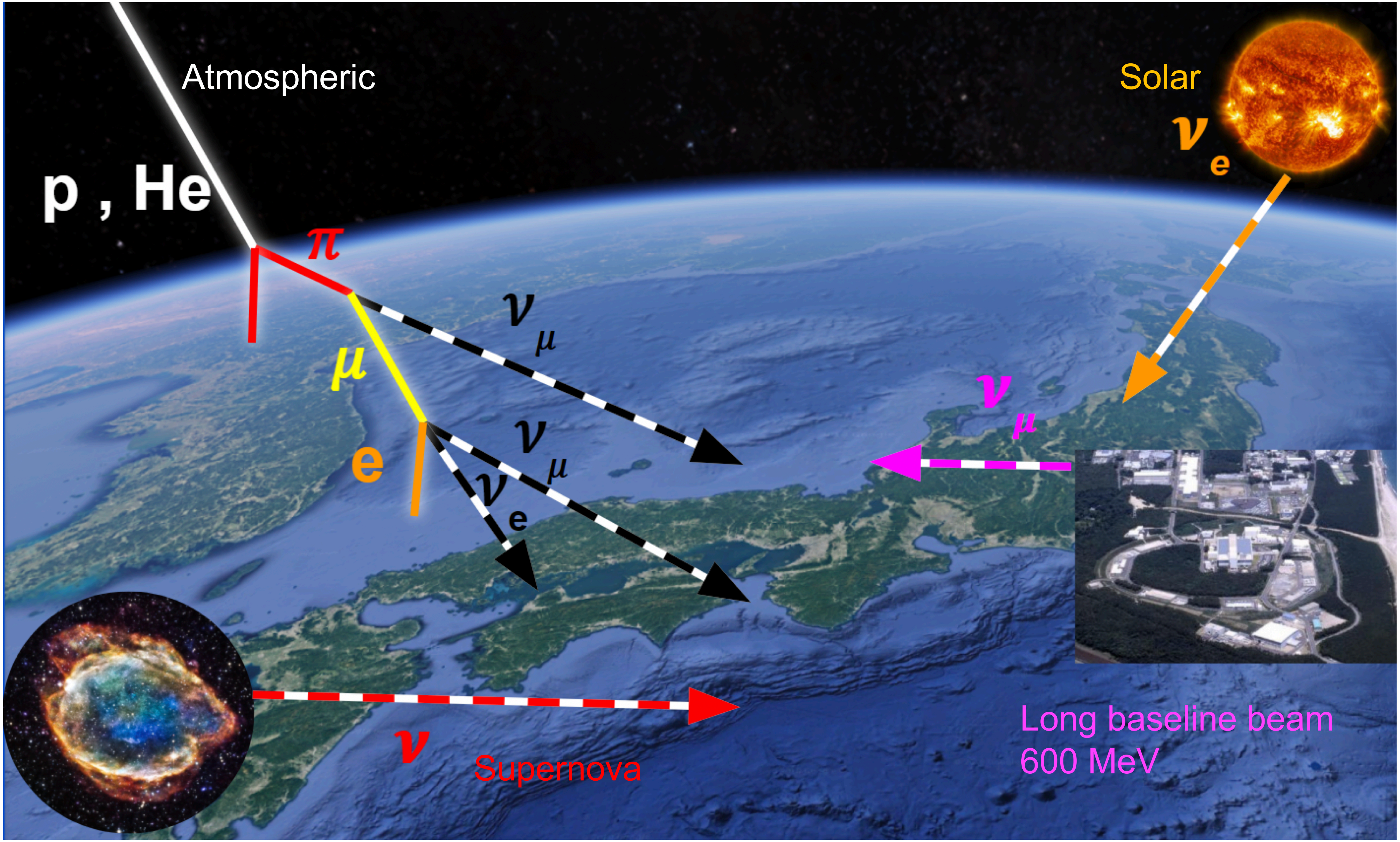
Block diagram (20inch PMT readout electronics)



(We can use same system for OD.)

Steve Playfer, NuPhys2019, London

A broad neutrino physics programme…
Energy range 4 MeV to 100 GeV



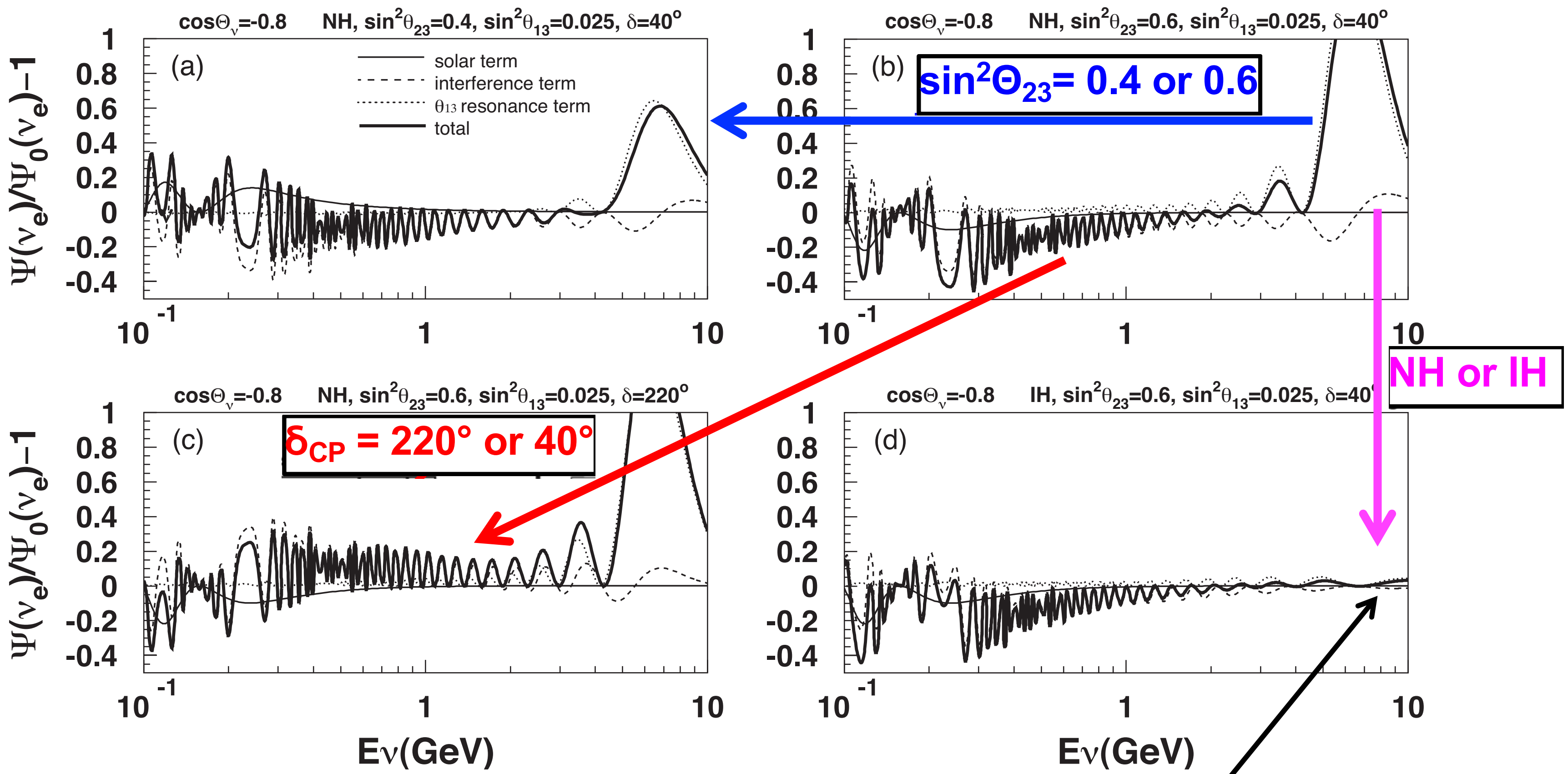
… and proton decay

Upward-going atmospheric neutrinos

Oscillations are sensitive to mass hierarchy, θ_{23} octant and δ_{CP}

Cos θ = –0.8

Difference in nue between oscillated and unoscillated flux

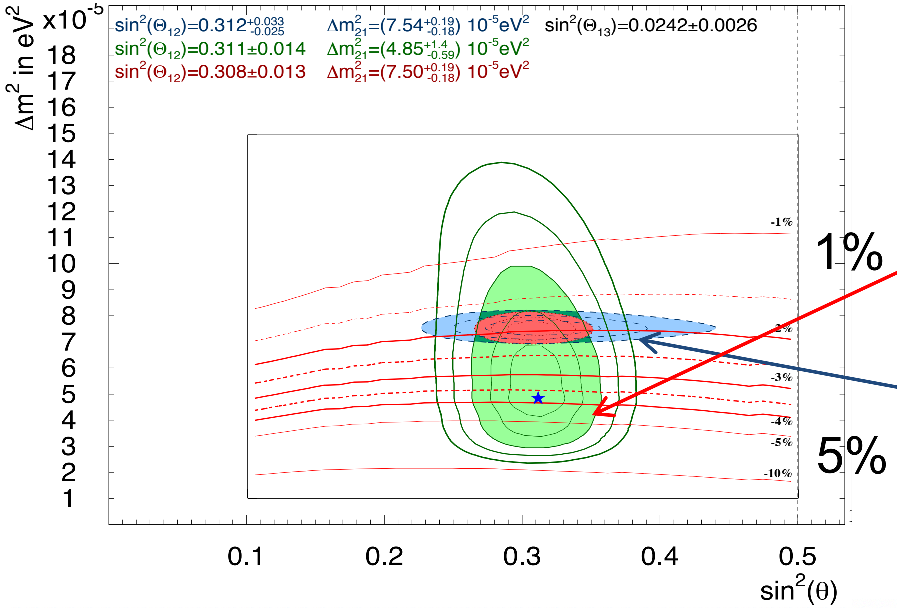


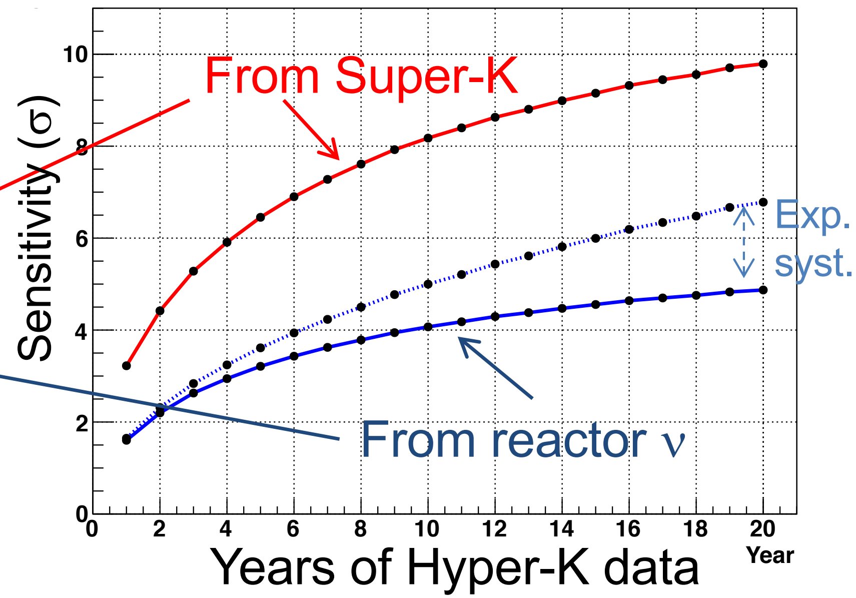
This is just for electron neutrinos! For antineutrinos the MSW peak is suppressed in NH

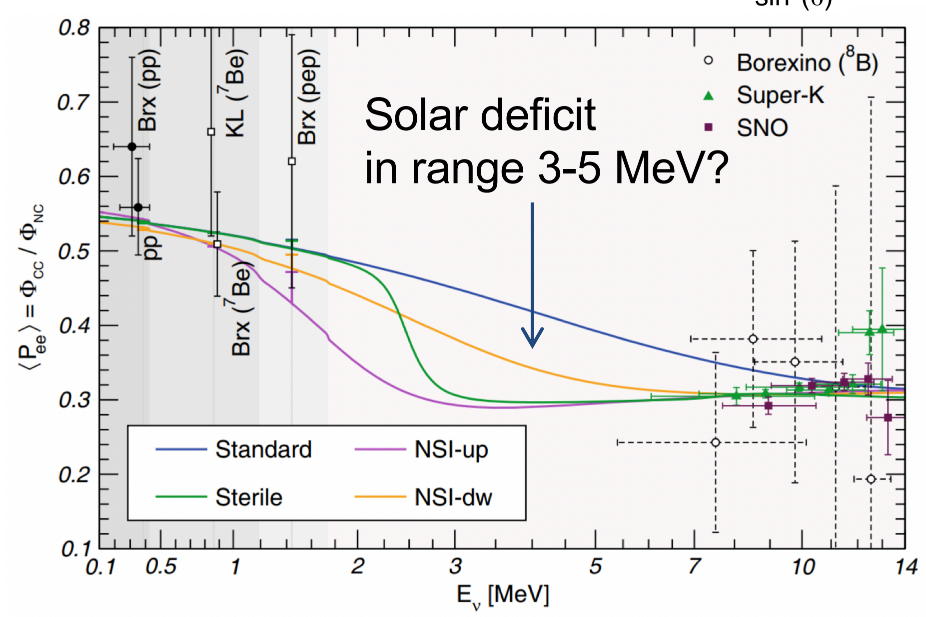
Solar Neutrinos

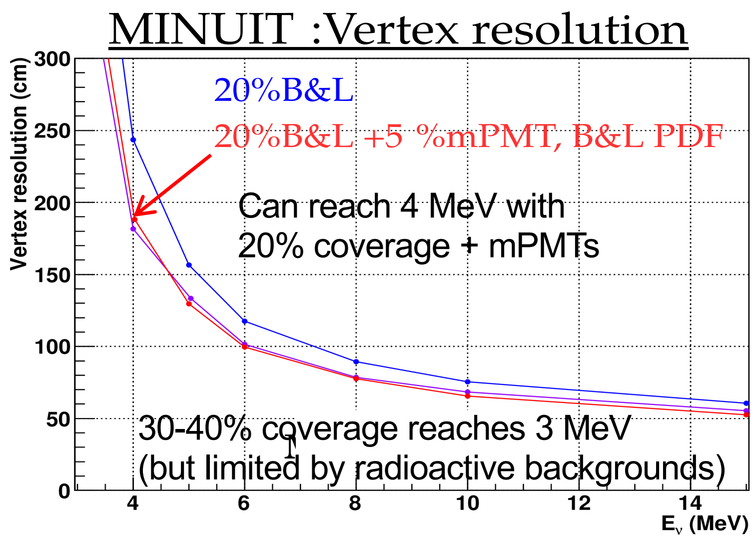
Day/night asymmetry depends on $1/\Delta m_{21}^2$

Expected to be a few %





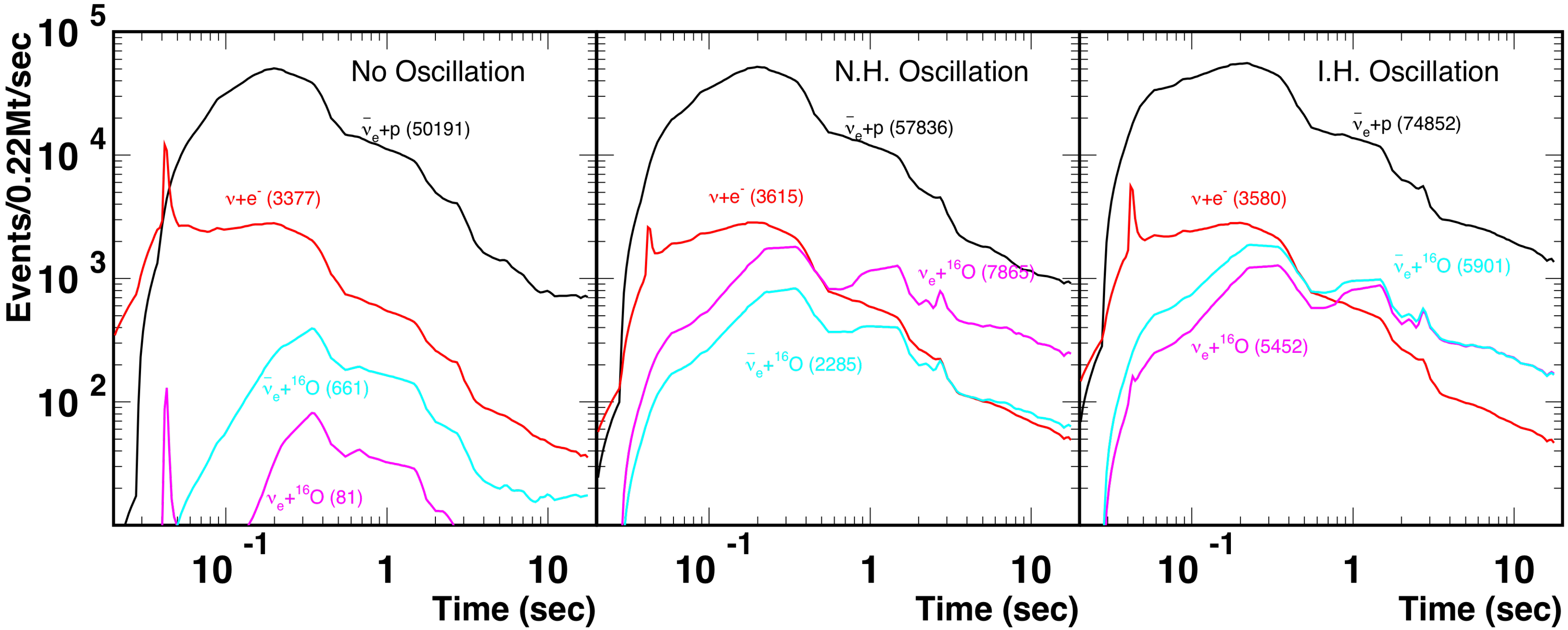




Supernova Neutrinos

SN at 10kpc expect 50-100k events in 20s. Betelgeuse would give MHz!

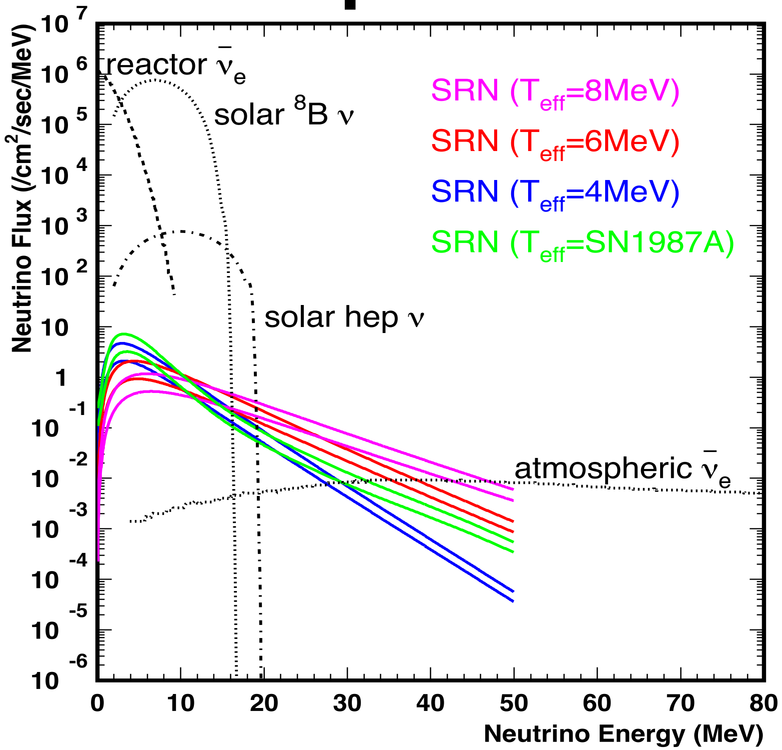
Expect ~10 events from SN in M31 (Andromeda)

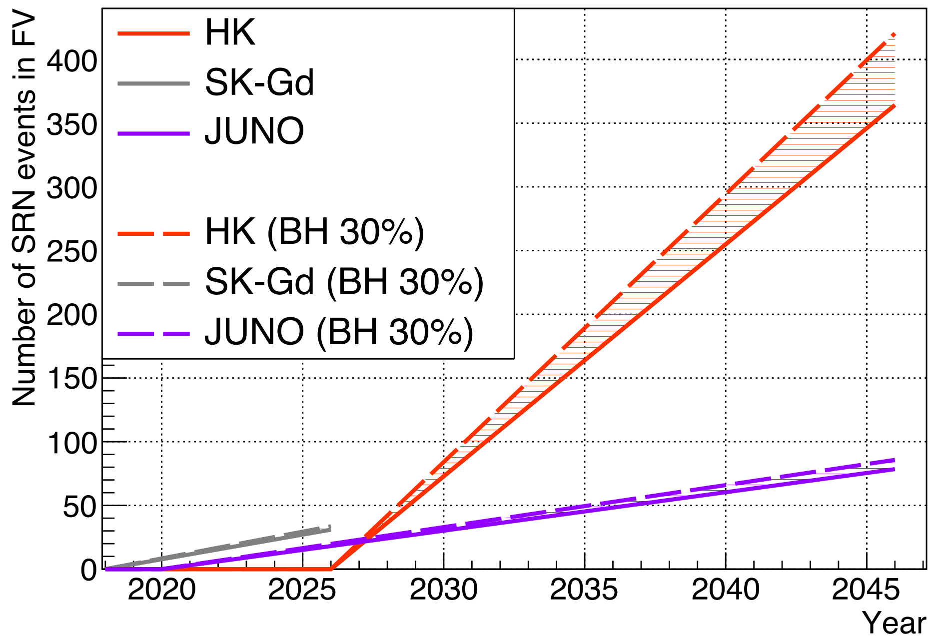


Inverse beta decay of anti-ν_e on p gives flavour, energy and direction from e^+ (and n)

$\nu+e^-$ scattering also gives energy and direction. Initial spike is sensitive to oscillations.

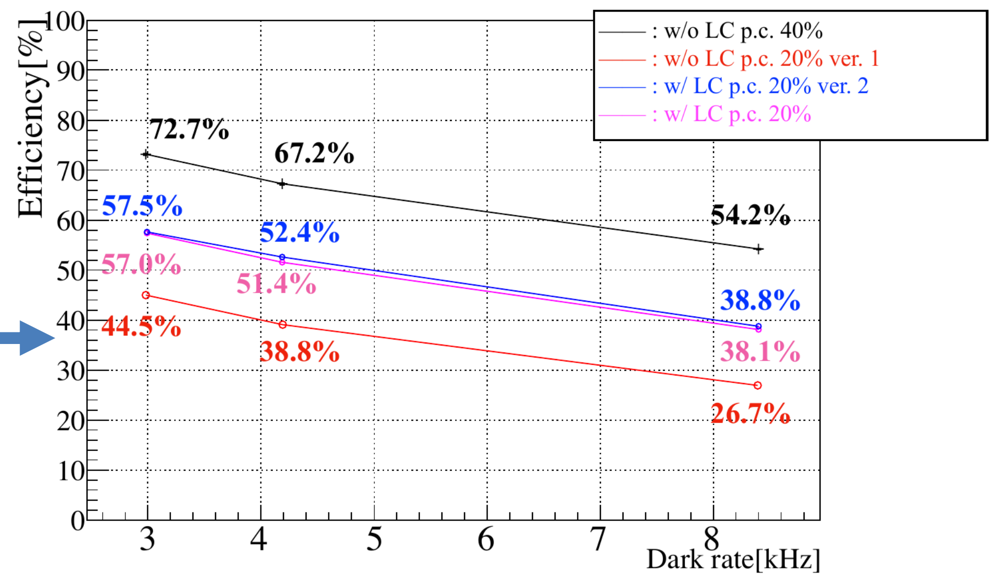
Supernova Relic Neutrinos





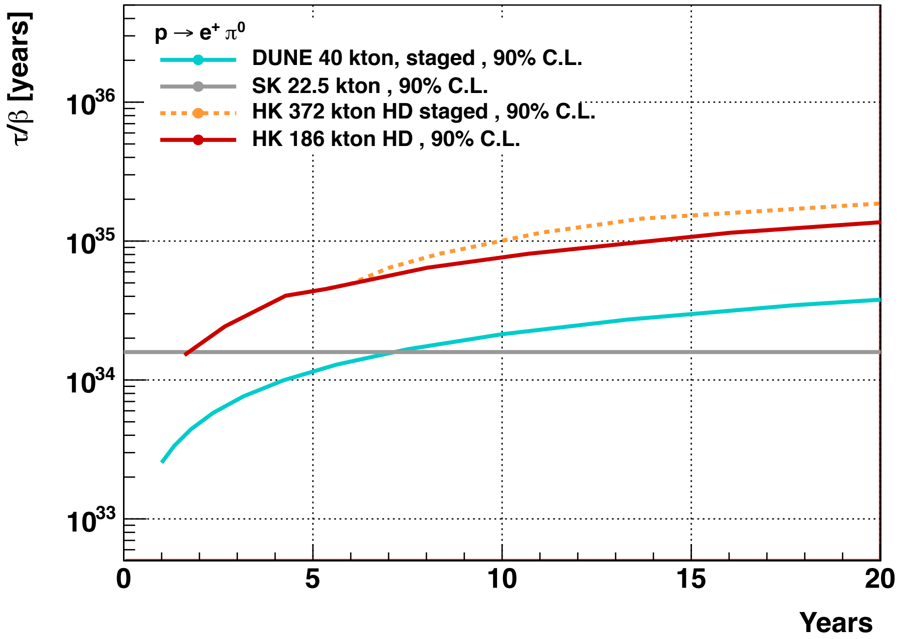
15-40 MeV anti-ν_e from ancient SN detected by inverse β–decay

Neutron-tag crucial to reduce backgrounds
n-tag with capture on H is 30-70% efficient
(depends on dark rate and photocoverage)



n-tag with capture on Gd is >80% efficient
(with a much lower mistag rate)

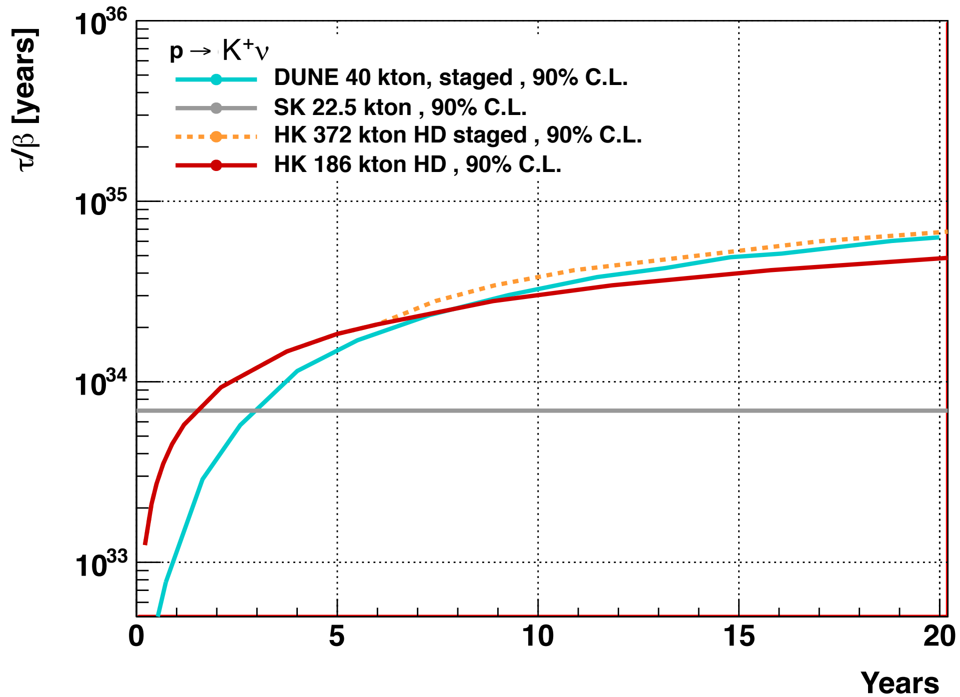
Proton Decay



We can improve limit on decay to $e^{+}\pi^{0}$ from 10^{34} to 10^{35} years

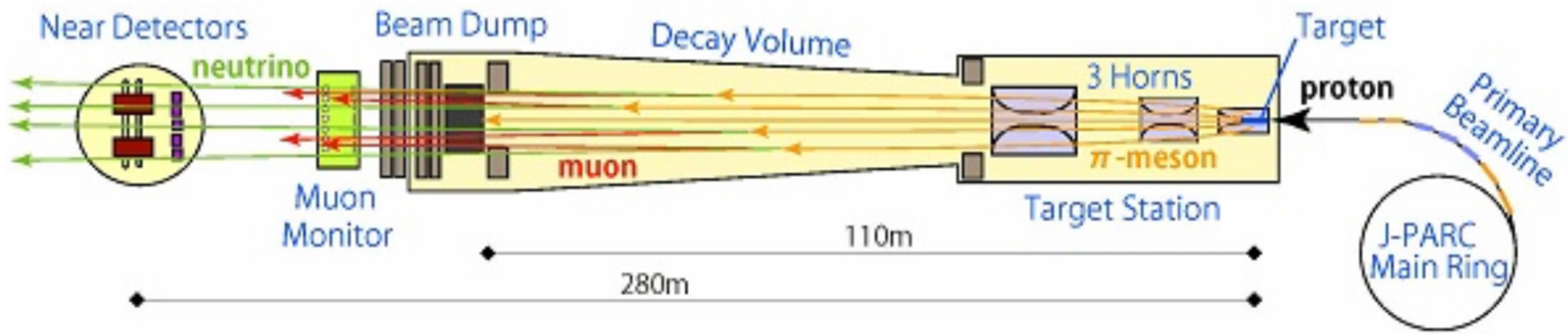
We may eventually run into background from atmospheric ν
but neutron tags help reduce this.

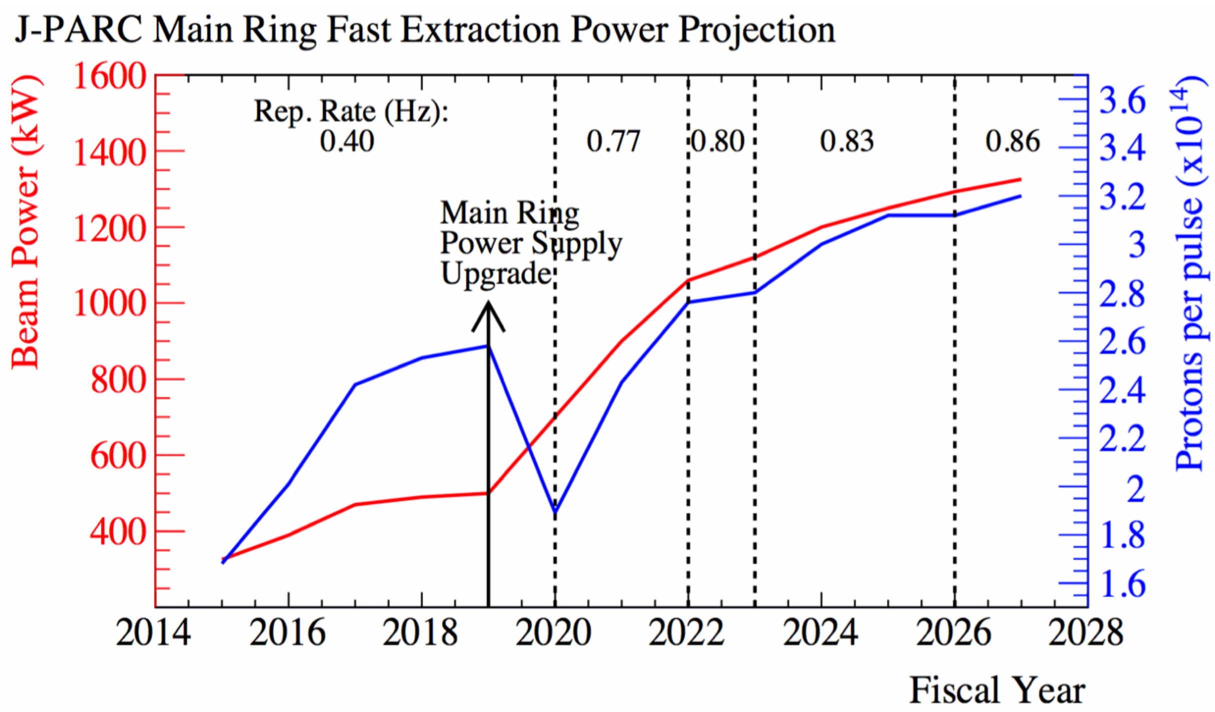
Can also improve limit on decay to $K^{+}\nu$
but the signature for this is harder
and there is atmospheric ν background.



K^{+} is below water Cherenkov threshold
Detect K^{+} decay to 236 MeV/c μ^{+}
in coincidence with 6.3 MeV γ
from $^{15}N^{*}$ decay (after p decays in ^{16}O)

J-PARC Beam





Off-axis 2.5degrees

E_ν = 600 MeV (peak)

1.3MW beam power

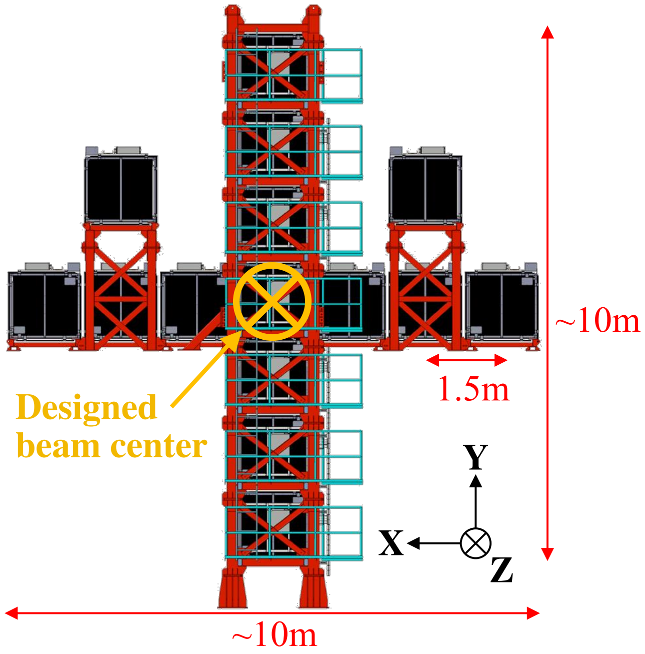
Being upgraded for T2K

Will be available at start of Hyper-K

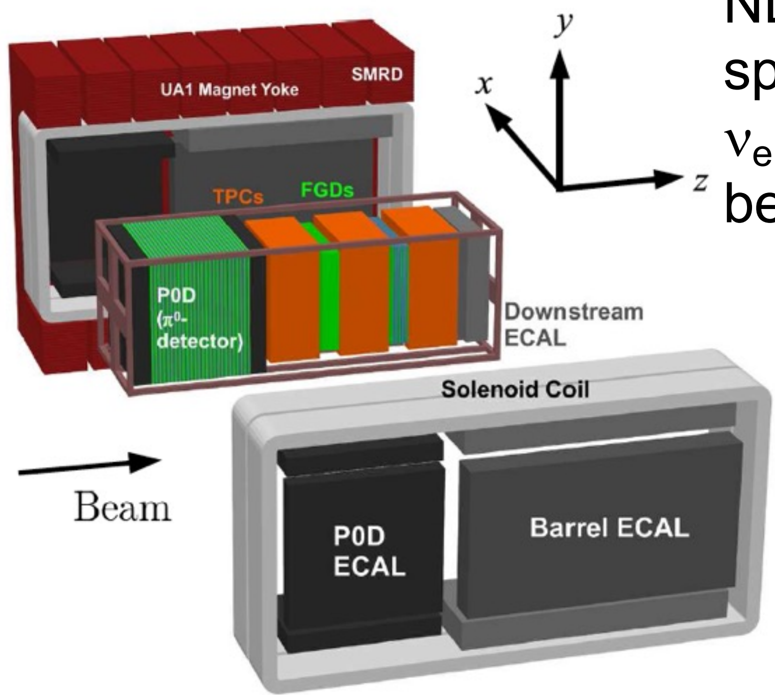
Further upgrades?

Near Detectors at 280m

INGRID monitors beam position



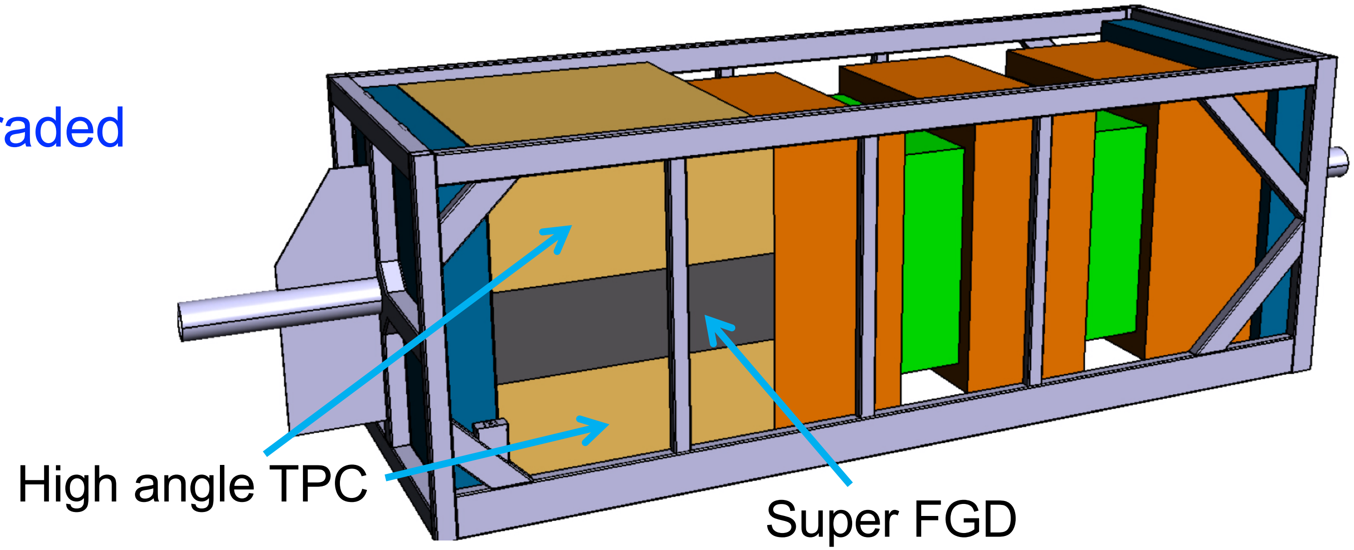
ND280 magnetic spectrometer for ν_e and wrong sign beam components



ND280 is being upgraded for T2K in 2021

Will be available at start of Hyper-K

Further upgrades?



Intermediate Water Cherenkov

Located at 1-2km

Shaft is 50-100m deep

Tank diameter 10m, height 8m
moves up and down shaft
using buoyancy (pit water)

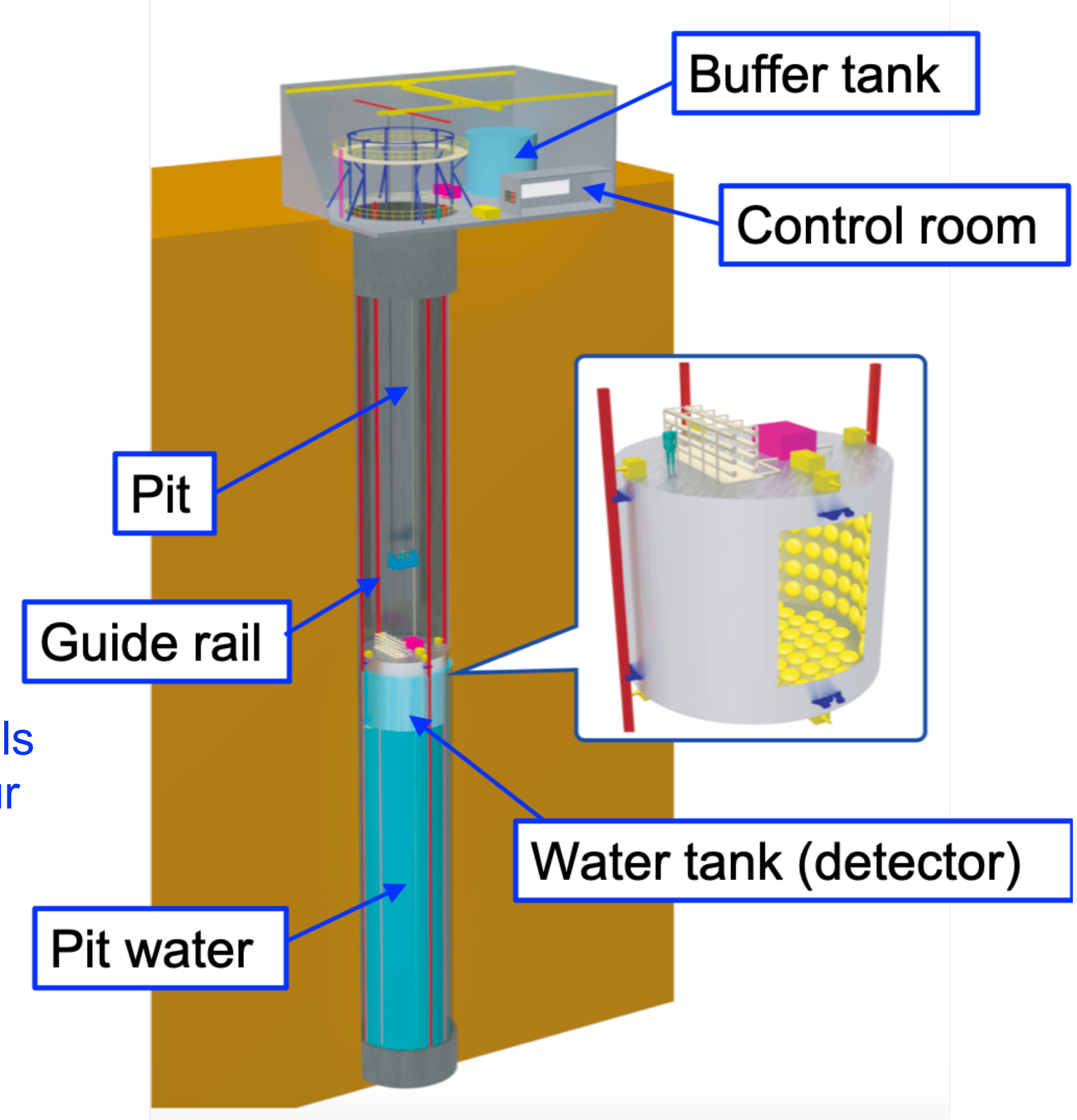
Spans off-axis angles 1 to 4°

Detector has 480 mPMTs

Measures water Cherenkov signals
as function of ν energy and flavour

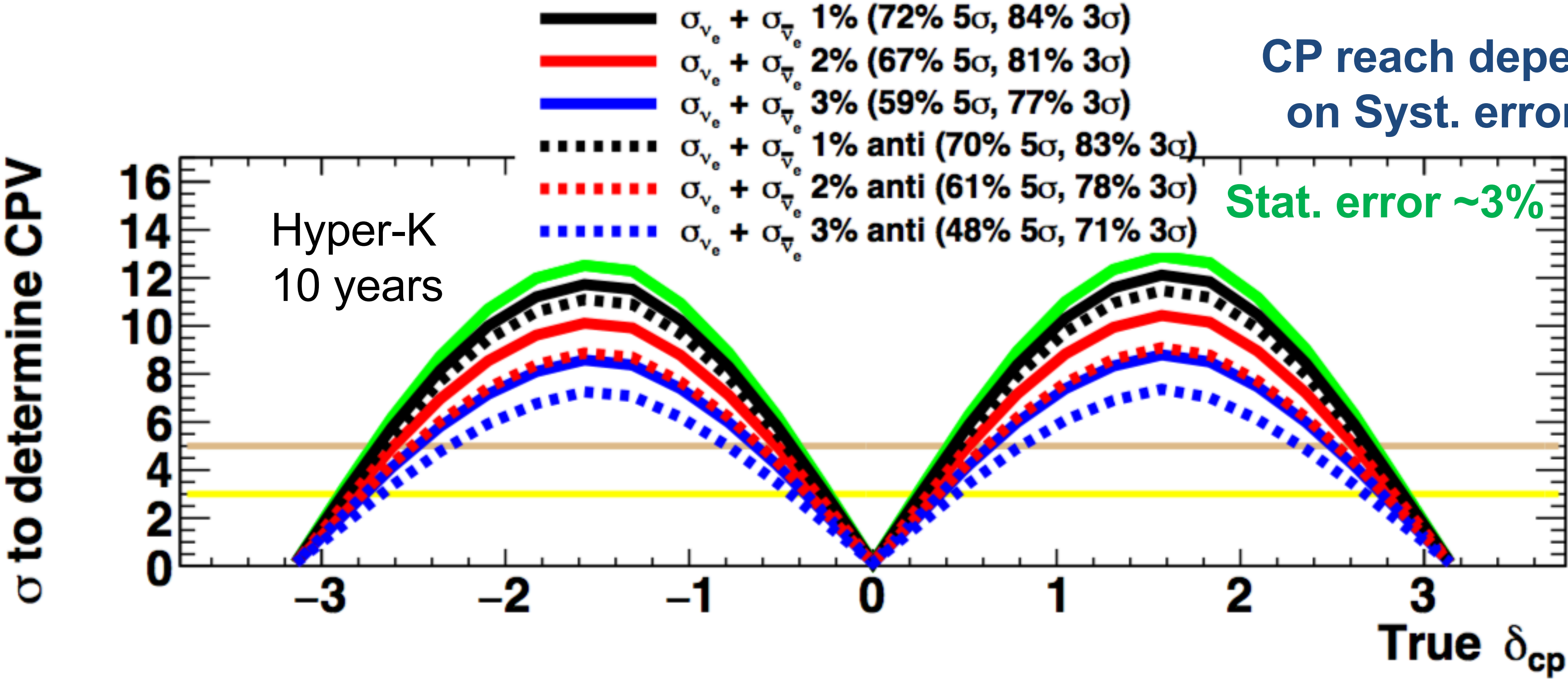
Determines ν cross-sections

A new detector for Hyper-K
Planned to be ready in 2026



Systematics aimed for by Hyper-K

HK design report arXiv:1805.04163		Flux & ND-constrained cross section	ND-independent cross section	Far detector	Total
ν mode	Appearance	3.0%	0.5%	0.7%	3.2%
	Disappearance	3.3%	0.9%	1.0%	3.6%
$\bar{\nu}$ mode	Appearance	3.2%	1.5%	1.5%	3.9%
	Disappearance	3.3%	0.9%	1.1%	3.6%



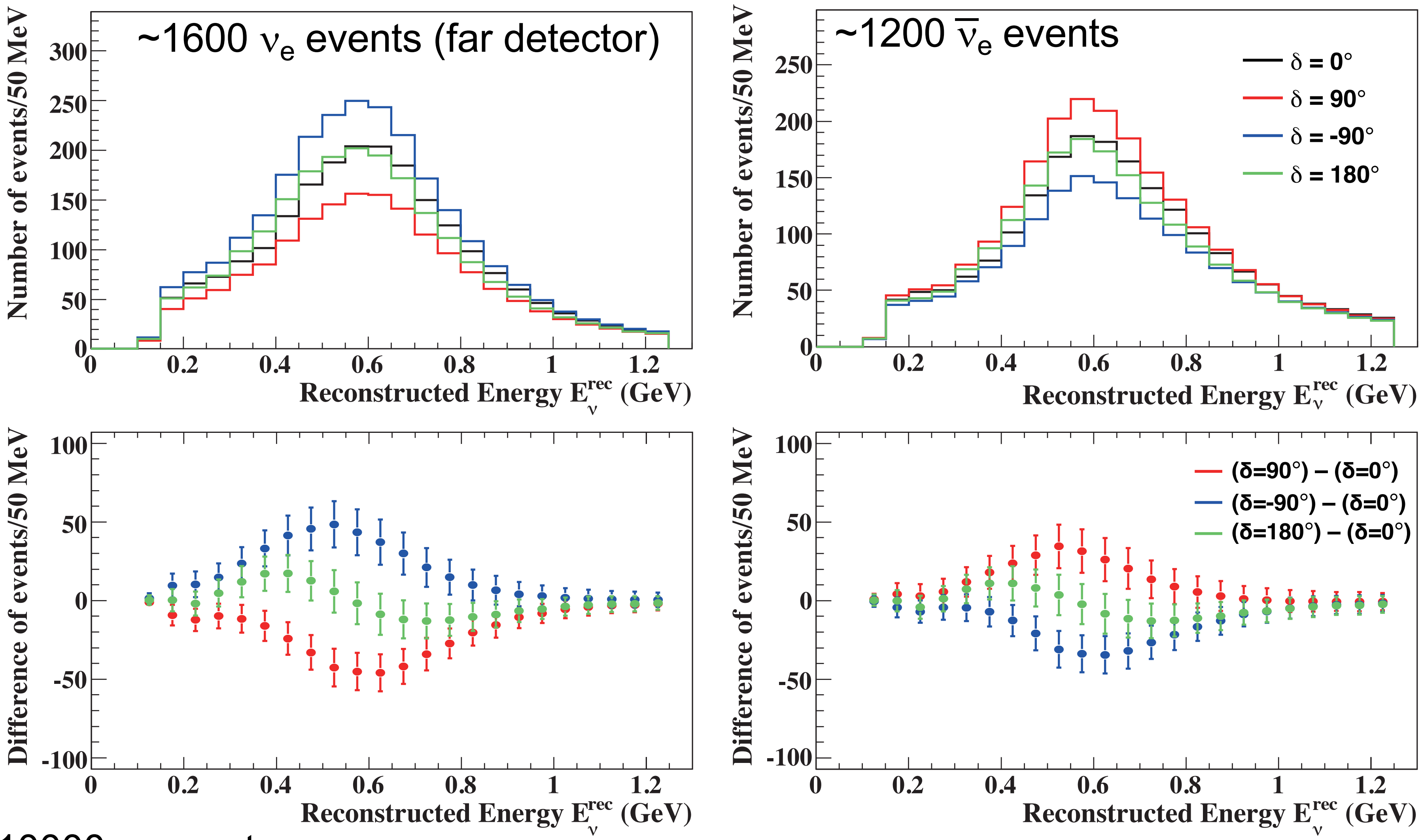
CP reach depends on Syst. errors!

Stat. error ~3%

Hyper-K long baseline (10 years)

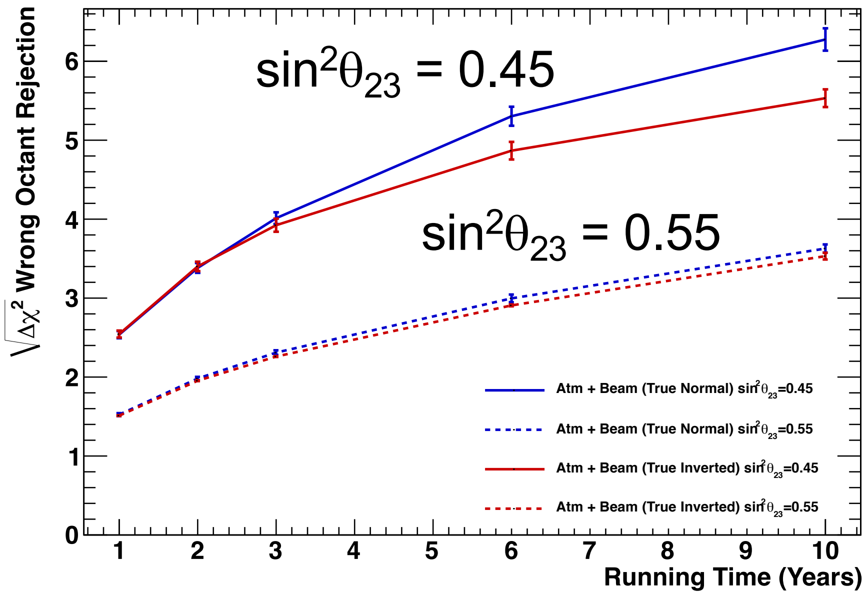
Assumes Normal Hierarchy, beam $\nu : \bar{\nu} = 1 : 3$

Neutrino mode: appearance **Antineutrino mode: appearance**

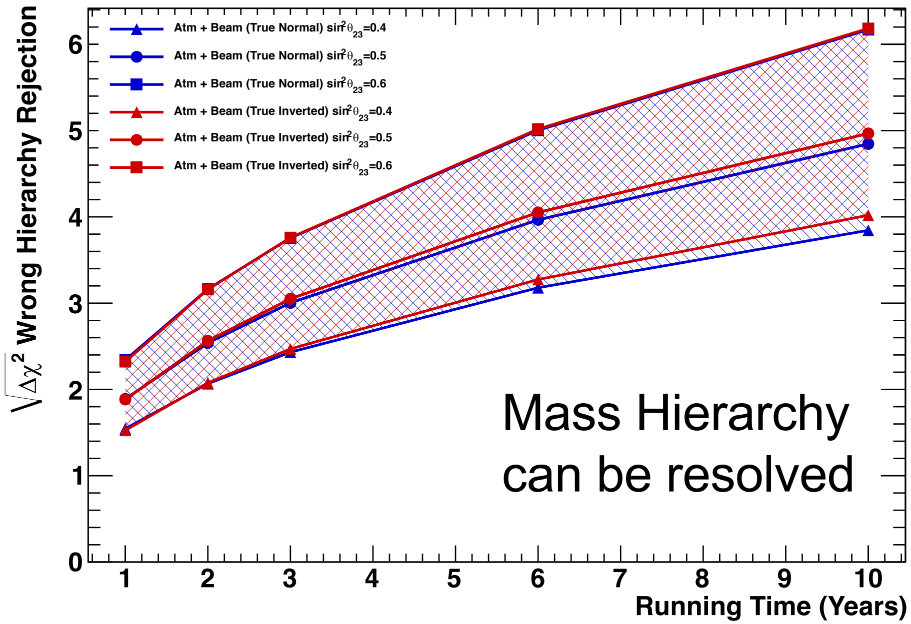


~10000 ν_μ events

Long baseline beam + atmospheric ν

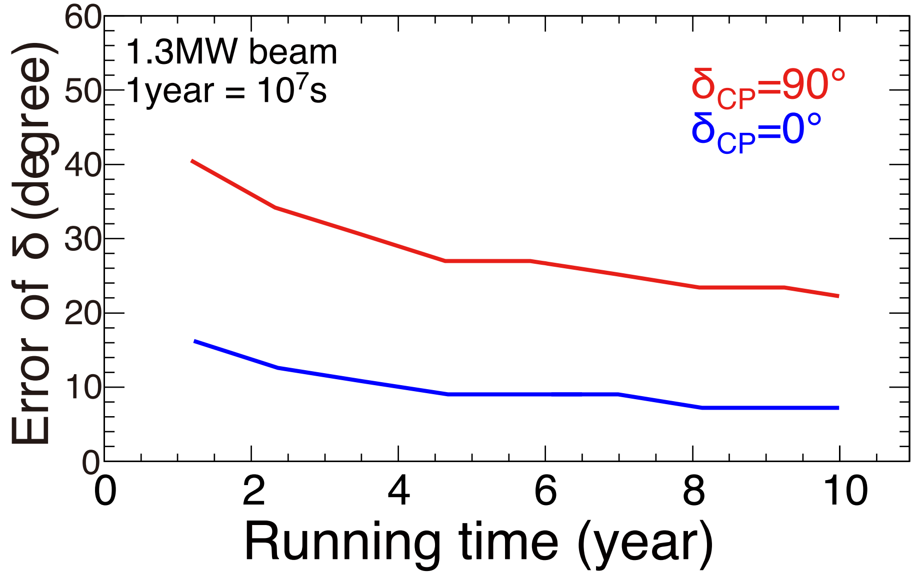


Octant of θ_{23} can be resolved for $\sin^2\theta_{23}$ < 0.45 or $\sin^2\theta_{23}$ > 0.55



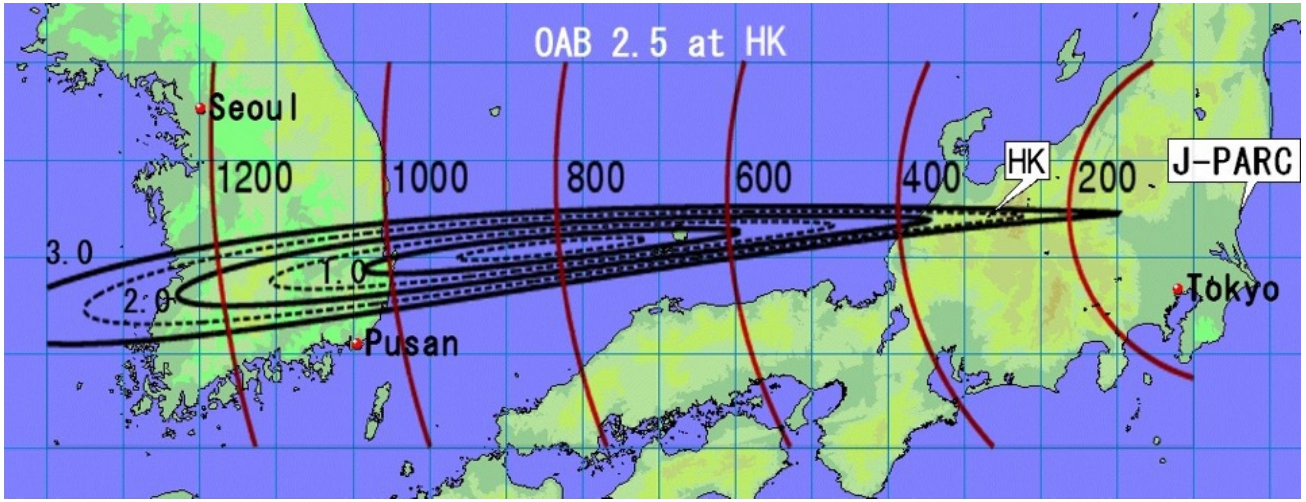
CP violation can be measured at 3σ (5σ) over 75% (60%) of the full range of δ_{CP}

Error on δ_{CP} = 0 ($\pi/2$) is 7° (20°)



Second Detector in Korea

arXiv:1611.06118v3
PTEP (2018) 6,063C01



Baseline 1100km
At 2nd maximum (750 MeV)
At 1st maximum (2 GeV)

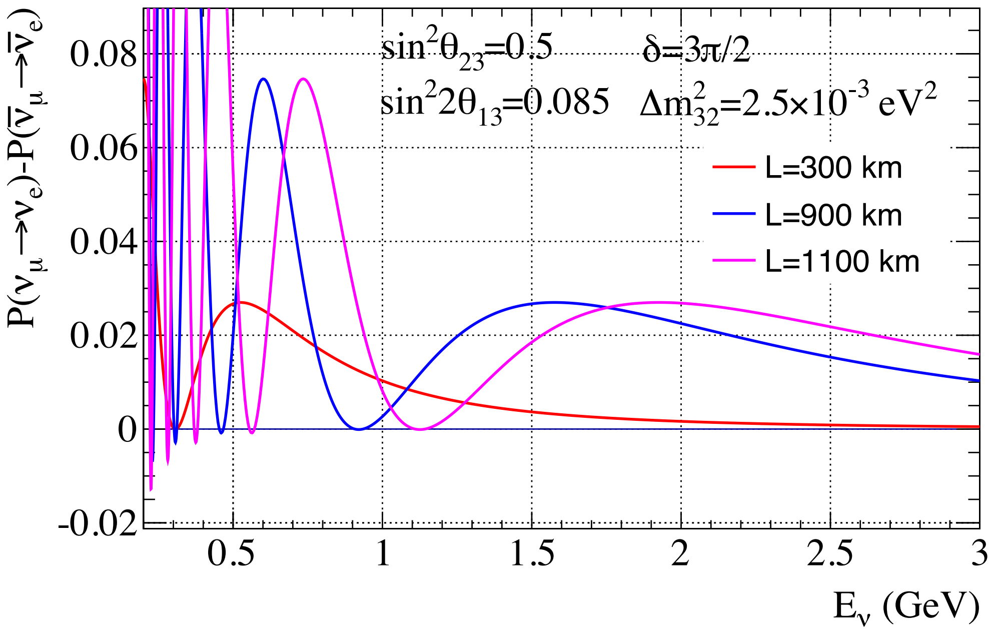
A number of sites are being considered with off-axis beam of 1 to 2 degrees.

Aim is to build this after Kamioka far detector is running.

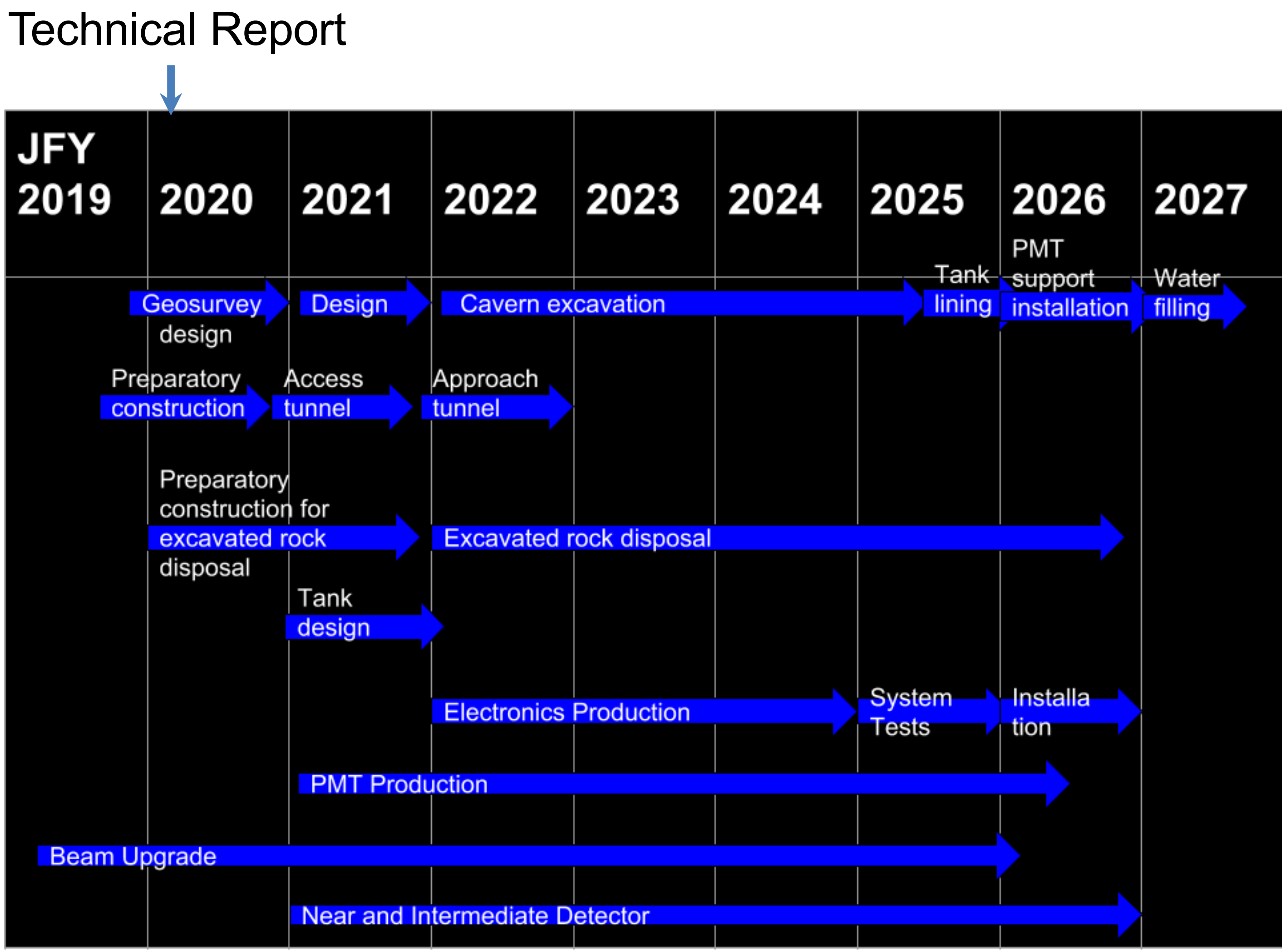
First far detector (Kamioka)

Second far detector (Korea)

CP violation at 2nd max is x3
Compensates for $1/R^2$
Same δ_{CP} statistical accuracy
Systematics smaller
More sensitivity to matter effects and non-SM physics



Construction Timeline



2018 - Japanese seed-funding and U.Tokyo commitment to 2020 start
June 2019 - Full Japanese funding application submitted
2020 onwards - Funding applications in other participating countries

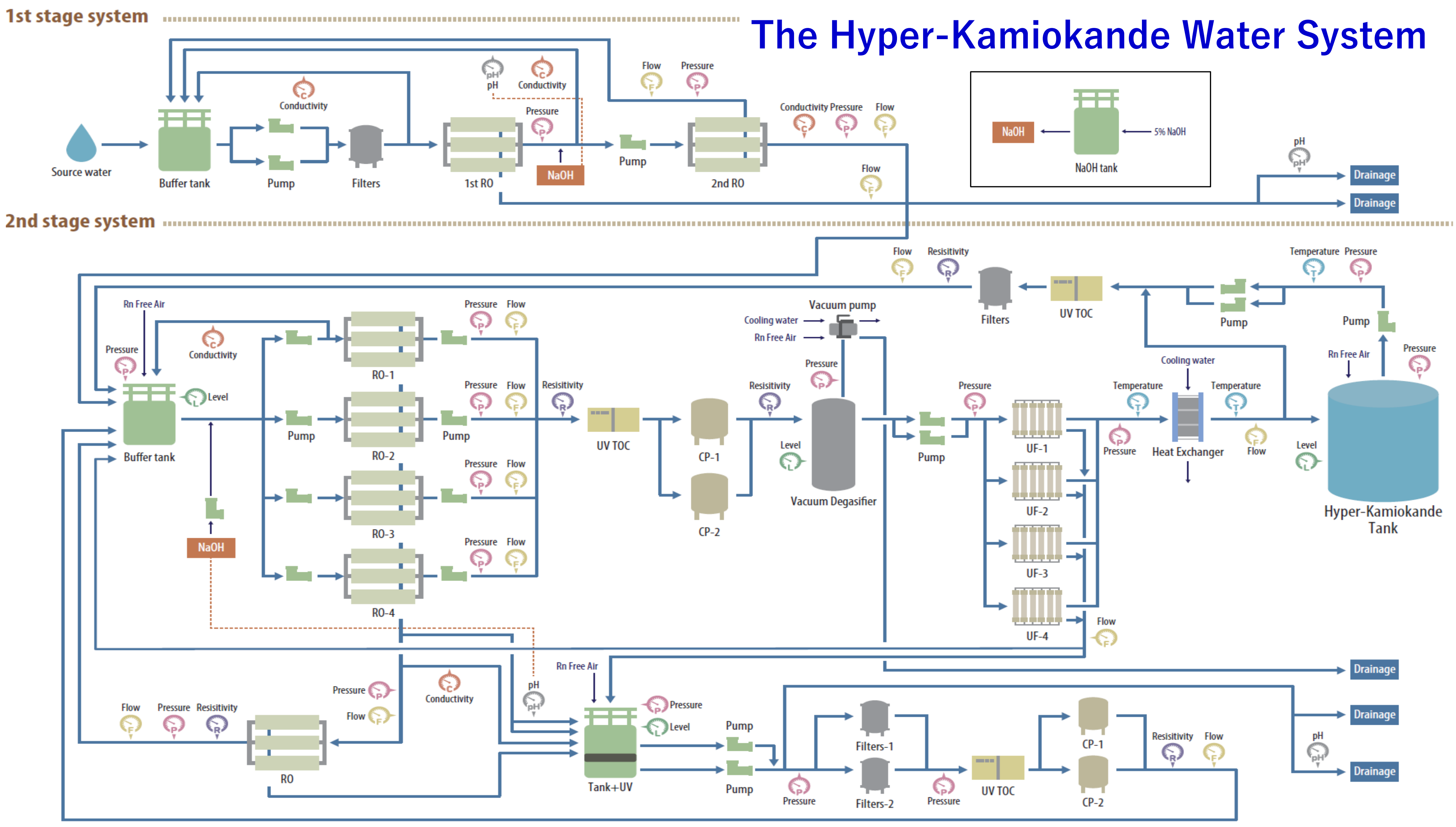
メリークリスマス　そして　年賀状

December 13th 2019
Japanese cabinet approves
35 Oku Yen ($35M) for first year
of Hyper–K construction in 2020.

Nature – December 16th 2019
Japan will build the world's largest neutrino detector
Cabinet greenlights US$600-million Hyper-Kamiokande experiment, which scientists hope will bring revolutionary discoveries.

BACKUP SLIDES

Source water fills tank in 240 days at 45 tons/hour.

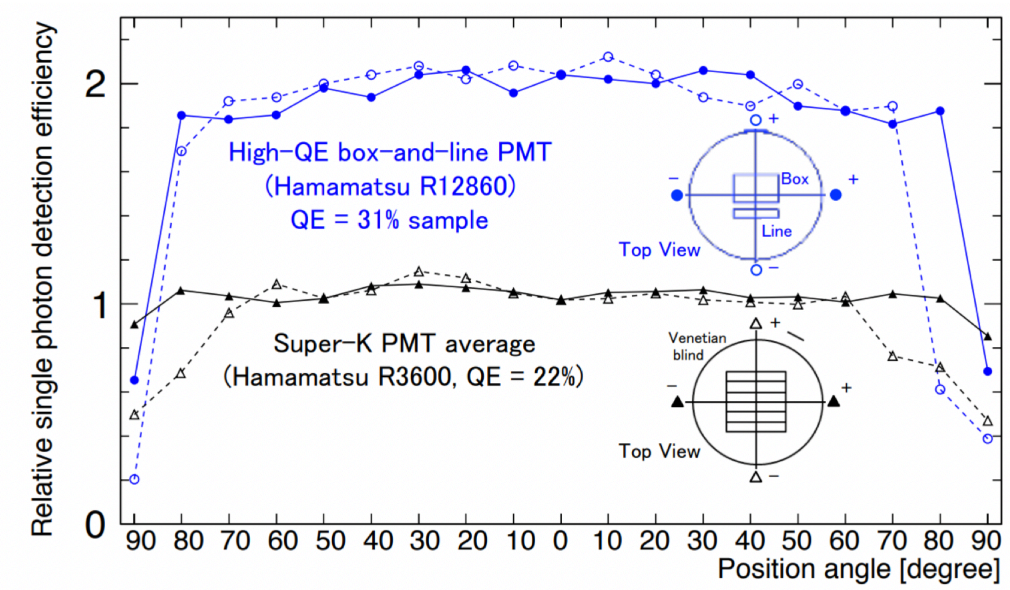


Purification, cooling and recirculation of water at 155 tons/hour.

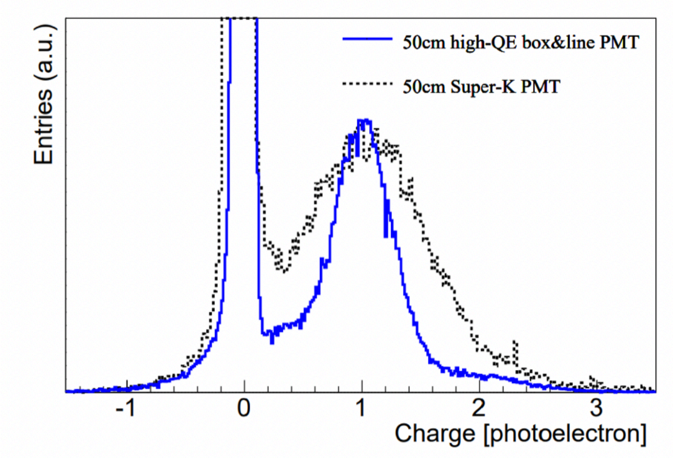
May double this after start of experiment and add Gd.

Comparison of SK and HK PMTS

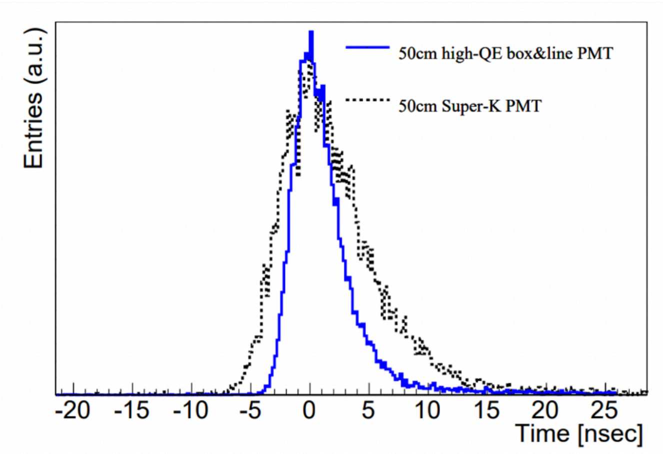
Detection efficiency x 1.9



Based on 136 HK PMTs installed in Super-K in 2018



Charge and time resolutions almost x2 better



Readout Electronics

Three signal digitizers are being considered:

1) QTC chip developed for Super-K in 2008
2) FADC waveform sampling 100-250MHz
3) Switched capacitor arrays

Hit rate is driven by Supernova burst

Dynamic range is x10 less for mPMTs

Front-end electronics is inside tank
Power limit driven by water cooling

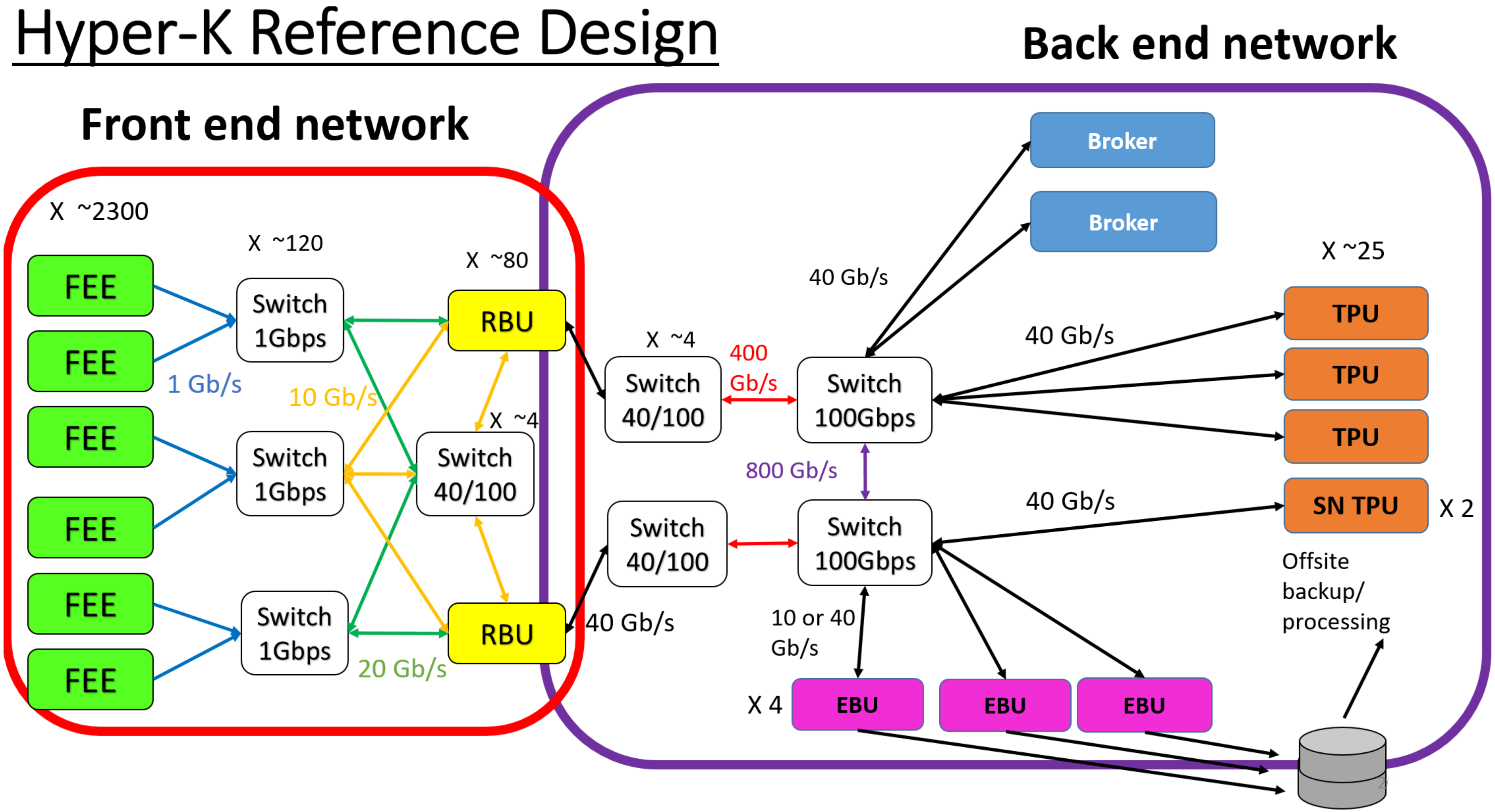
Item	Requirements
Trigger	self triggering for each channel
PMT impedance	50Ω
Signal reflection	$<0.1\%$
Discriminator threshold	<0.25 p.e. (well below 1 p.e.)
Processing speed/hit (channel dead time)	$<1\ \mu s$
Maximum hit rate	>1 MHz for each channel
Charge dynamic range	0.1 to 1250 p.e. (0.2 to 2500 pC)
Charge resolution	RMS$\sim$ 0.05 p.e. (below 25 p.e.)
Timing LSB	<0.5ns
Timing resolution	RMS <0.3ns at 1 p.e. RMS <0.2ns above 5 p.e.
Power consumption	<1W per channel

Designing watertight front-end boxes (24 channels)
and watertight fibre-optic/LV and signal/HV connectors

Need up to 2200
of these boxes

Another area where international contributions are expected

Data Acquisition System



Designed to handle nearby Supernova (Betelgeuse) :

75M ν events in 1s, 180M events in 10s, 327GB of data, 1MHz hits/PMT

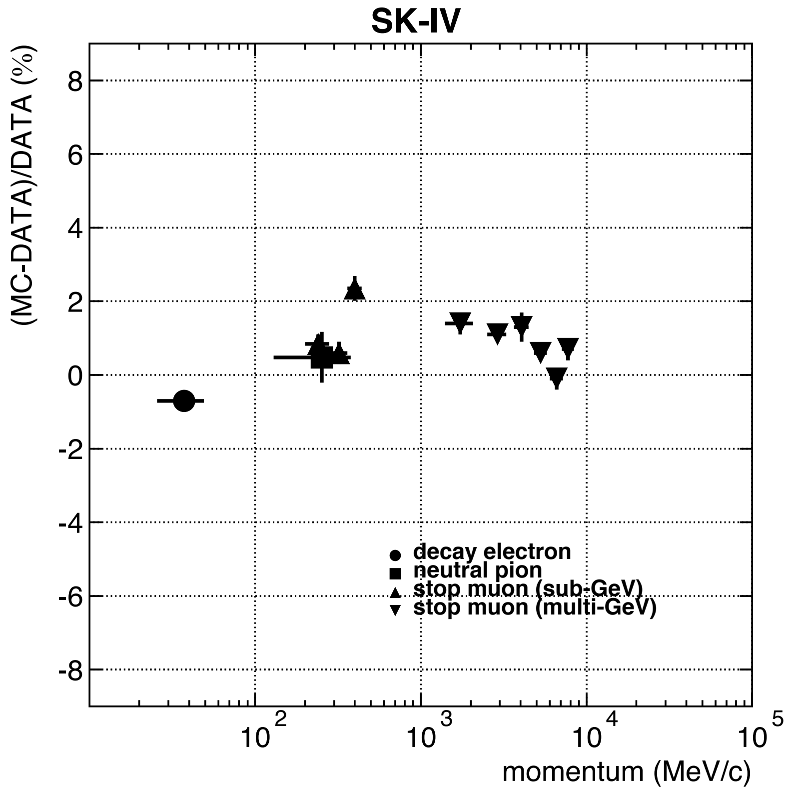
Calibration systems

These are based on 20 year of experience at Super-K,
but need to improve accuracy at Hyper-K.

- Low energy calibration uses Linac and radioactive sources:
  D-T generator, Cf(Ni), Am(Be)
  Aiming at 0.5% calibration of energy scale for solar ν

- High energy calibration uses cosmic ray data:
  Stopping muons, Michel electrons, π^0 mass
  Statistics will increase at Hyper-K

- Light injection system monitors water transparency and PMT response



Motivation for Near Detectors

- To measure the product of the unoscillated neutrino flux (N_ν) times cross-section (σ_ν) as a function of E_ν, off-axis angle, horn current (F/B) and ν flavour ($\nu_e/\overline{\nu}_e/\nu_\mu/\overline{\nu}_\mu$)

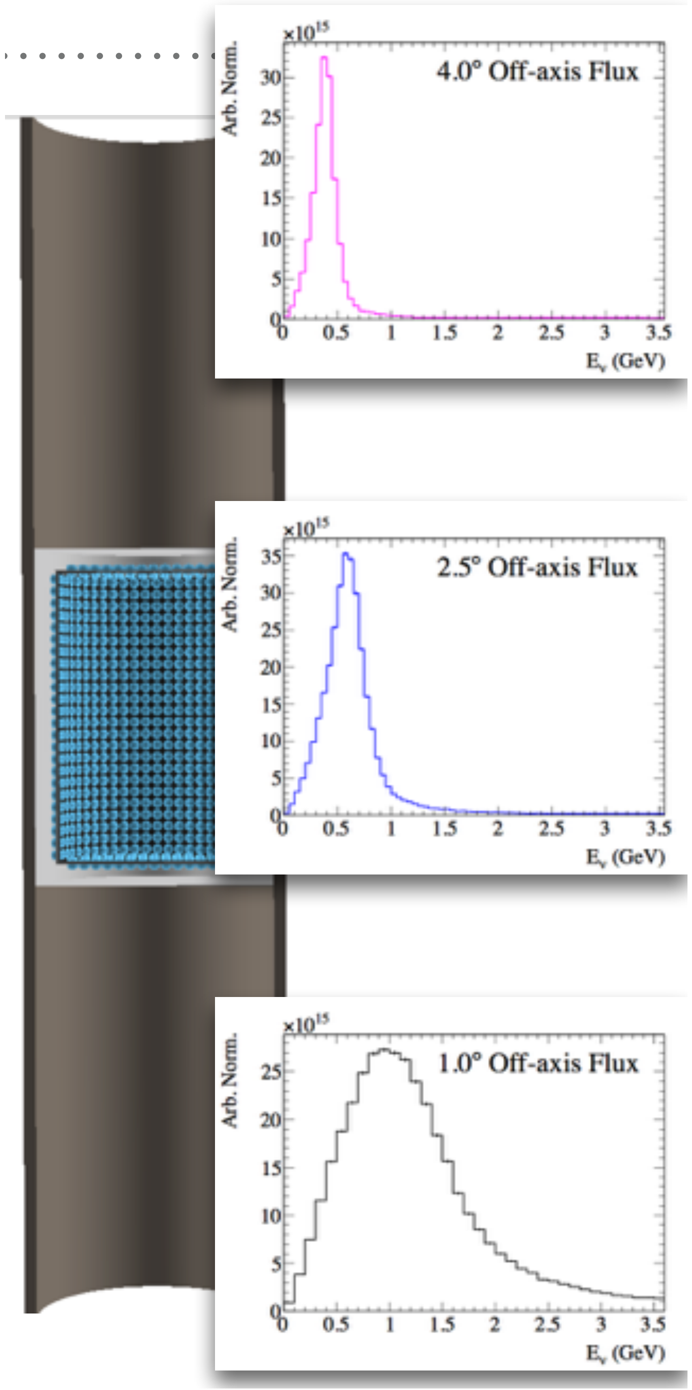
- To predict the expected event rates in the far detector as a function of the oscillation parameters.
  Uncertainties in these predictions enter as systematic errors on Hyper-K CP violation measurements.

- To measure the properties of ν interactions, their detector signatures and final state particles.

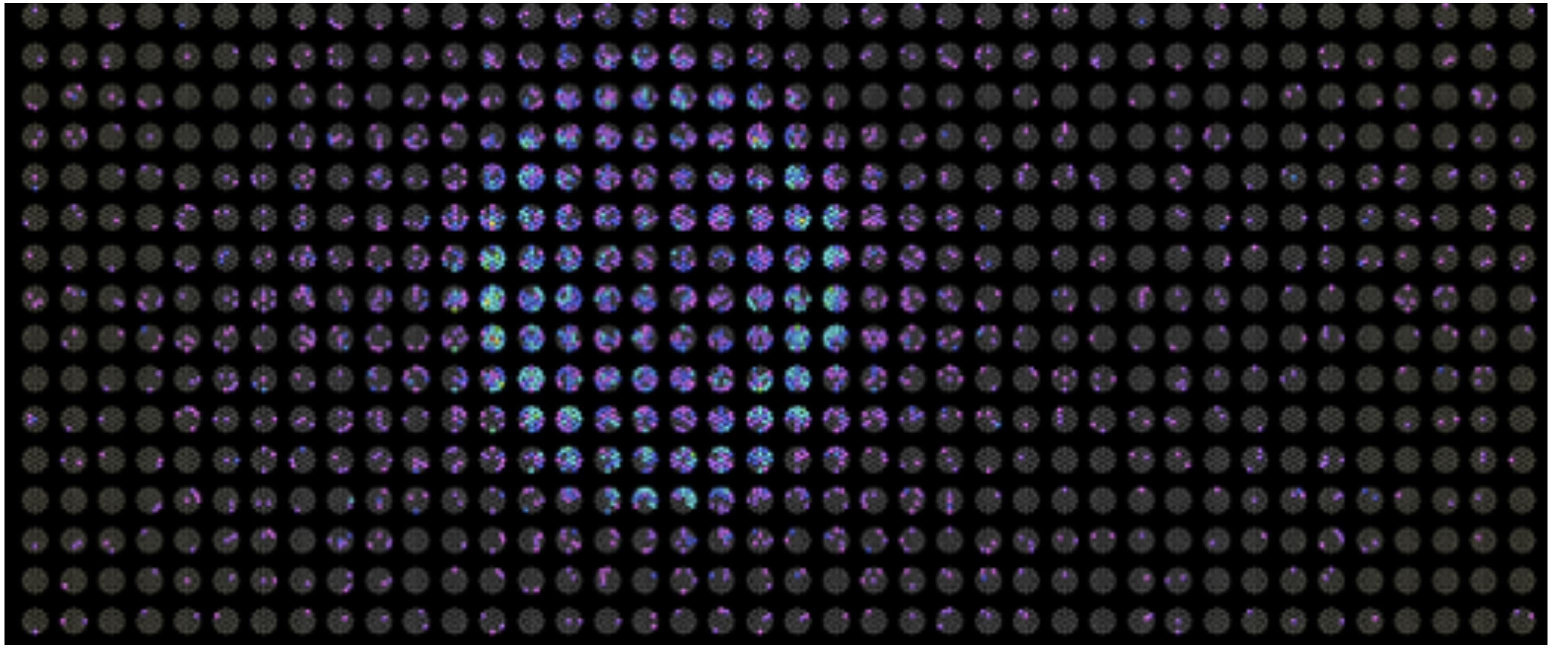
The differences between the near and far detectors should be minimized.

Off Axis Measurements

- Probe cross-sections and final states as a function of E_ν
- Mean energy varies from 0.4GeV (4°) to 1.0GeV (1°)
- Fraction of ν_e varies from 0.5% (1°) to 1.5% (4°), with a high energy tail from Kaon decays
- Can use linear combinations of different angles to define "quasi-monochromatic" beams
- Aim for direct measurement of $\sigma(\bar{\nu}_e)/\ \sigma(\nu_e)$ to few % accuracy



IWCD Reconstruction



mPMTs improve vertex resolution compared to 8” PMTs

Tuning of event reconstruction ongoing

Also expect better angular resolution and $e/\mu/\pi^0$ separation