ハイパーカミオカンデ Hyper-Kamiokande

The Hyper-Kamiokande Experiment

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Queen Mary University of London

On behalf of the Hyper-K UK collaboration

PPAP Meeting
July 26, 2016

THE UNIVERSITY of EDINBURGH
Imperial College London
Lancaster University
UNIVERSITY OF LIVERPOOL
UNIVERSITY OF OXFORD
Queen Mary University of London
ROYAL HOLLOWAY UNIVERSITY OF LONDON
The University Of Sheffield.
Science & Technology Facilities Council Rutherford Appleton Laboratory
THE UNIVERSITY OF WARWICK

A Multi-purpose Experiment

Comprehensive study of ν oscillation

- CPV
- Mass hierarchy with beam+atmosph. ν
- θ_{23} octant
- Test of exotic scenarios

Nucleon decay discovery potential

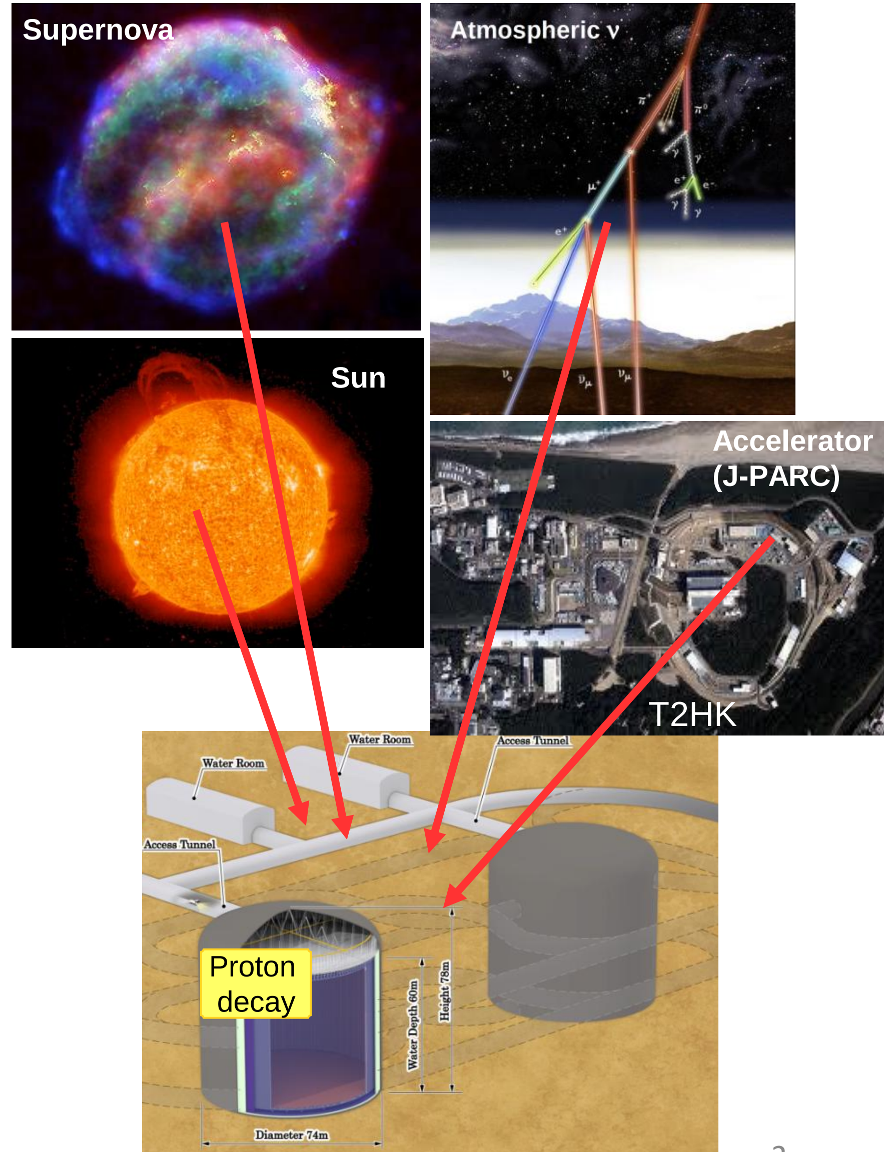
- All visible modes including p → $e^+ \pi^0$ and p→$\bar{\nu}K^+$ can be advanced beyond SK.
- Reaching 10^{35}yrs sensitivity

Unique Astrophysics

- Precision measurement of solar ν
- High statistics Supernova ν with pointing capability and energy info.
- Supernova relic ν (non-burst $\bar{\nu}$) observation is also possible

Earth core's chemical composition

Etc.



Inaugural Symposium of the HK proto-collaboration@Kashiwa, Jan-2015

12 countries, ~250 members and growing

- Proto-collaboration formed.
- International steering group
- International conveners
- International chair for international board of representative (IBR)

KEK-IPNS and UTokyo-ICRR signed a MoU for cooperation on the Hyper-Kamiokande project.

Proto-Collaboration

- Gifu University (Japan)
- High Energy Accelerator Research Organization (KEK) (Japan)
- Kobe University (Japan)
- Kyoto University (Japan)
- Miyagi University of Education (Japan)
- Nagoya University (Japan)
- Okayama University (Japan)
- Osaka City University (Japan)
- Tohoku University (Japan)
- Tokai University (Japan)
- University of Tokyo, Earthquake Research Institute (Japan)
- University of Tokyo, Institute for Cosmic Ray Research, Kamioka Observatory (Japan)
- University of Tokyo, Institute for Cosmic Ray Research, Research Center for Cosmic Neutrinos (Japan)
- University of Tokyo (Japan)
- University of Tokyo, Institute for the Physics and Mathematics of the Universe (Japan)
- Tokyo Institute of Technology (Japan)
- Boston University (USA)
- Chonnam National University (Korea)
- Dongshin University (Korea)
- Duke University (USA)
- Imperial College London (UK)
- Institute for Particle Physics Phenomenology, Durham University (UK)
- INFN and Dipartimento Interateneo di Fisica di Bari (Italy)
- INFN-LNF (Italy)
- INFN and Università di Napoli (Italy)
- INFN and Università di Padova (Italy)
- INFN Roma (Italy)
- Institute for Nuclear Research (Russia)
- Iowa State University (USA)
- IRFU, CEA Saclay (France)
- Laboratoire Leprince-Ringuet, Ecole Polytechnique (France)
- Lancaster University (UK)
- Los Alamos National Laboratory (USA)
- Louisiana State University (USA)
- National Centre for Nuclear Research (Poland)
- Pontificia Universidade Catolica do Rio de Janeiro (Brazil)
- Queen Mary, University of London (UK)
- Royal Holloway University of London (UK)
- Seoul National University (Korea)
- Seoyeong University (Korea)
- State University of New York at Stony Brook (USA)
- STFC Rutherford Appleton Laboratory (UK)
- Sungkyunkwan University (Korea)
- The California State University Dominguez Hills (USA)
- TRIUMF (Canada)
- University Autonoma Madrid (Spain)
- University of British Columbia (Canada)
- University of California, Davis (USA)
- University of California, Irvine (USA)
- University of Edinburgh (UK)
- University of Geneva (Switzerland)
- University of Hawaii (USA)
- University of Liverpool (UK)
- University of Oxford (UK)
- University of Pittsburgh (USA)
- University of Regina (Canada)
- University of Rochester (USA)
- Universidade de Sao Paulo (Brazil)
- University of Sheffield (UK)
- University of Toronto (Canada)
- University of Warsaw (Poland)
- University of Warwick (UK)
- University of Washington (USA)
- University of Winnipeg (Canada)
- Virginia Tech (USA)
- Wroclaw University (Poland)
- York University (Canada)

Organizational Structure

Collaboration General Assembly (CGA)
Hyper-K Proto-Collab.

International board of representative (IBR)
members from each Country
chair D.Wark

Speakers' Board (SB)
G. Catanesi, M. Yokoyama (chairs)

International Steering Committee (iSC)
Nakaya (chair)
D.Wark, Nakahata, Kobayashi, Shiozawa, F.Di Lodovico, Yokoyama, Aihara, A.Blondel, G.Catanesi, Y. Itow, E.Kearns, J.M.Poutissou

Project Leader
Shiozawa
co-leader
F.Di Lodovico

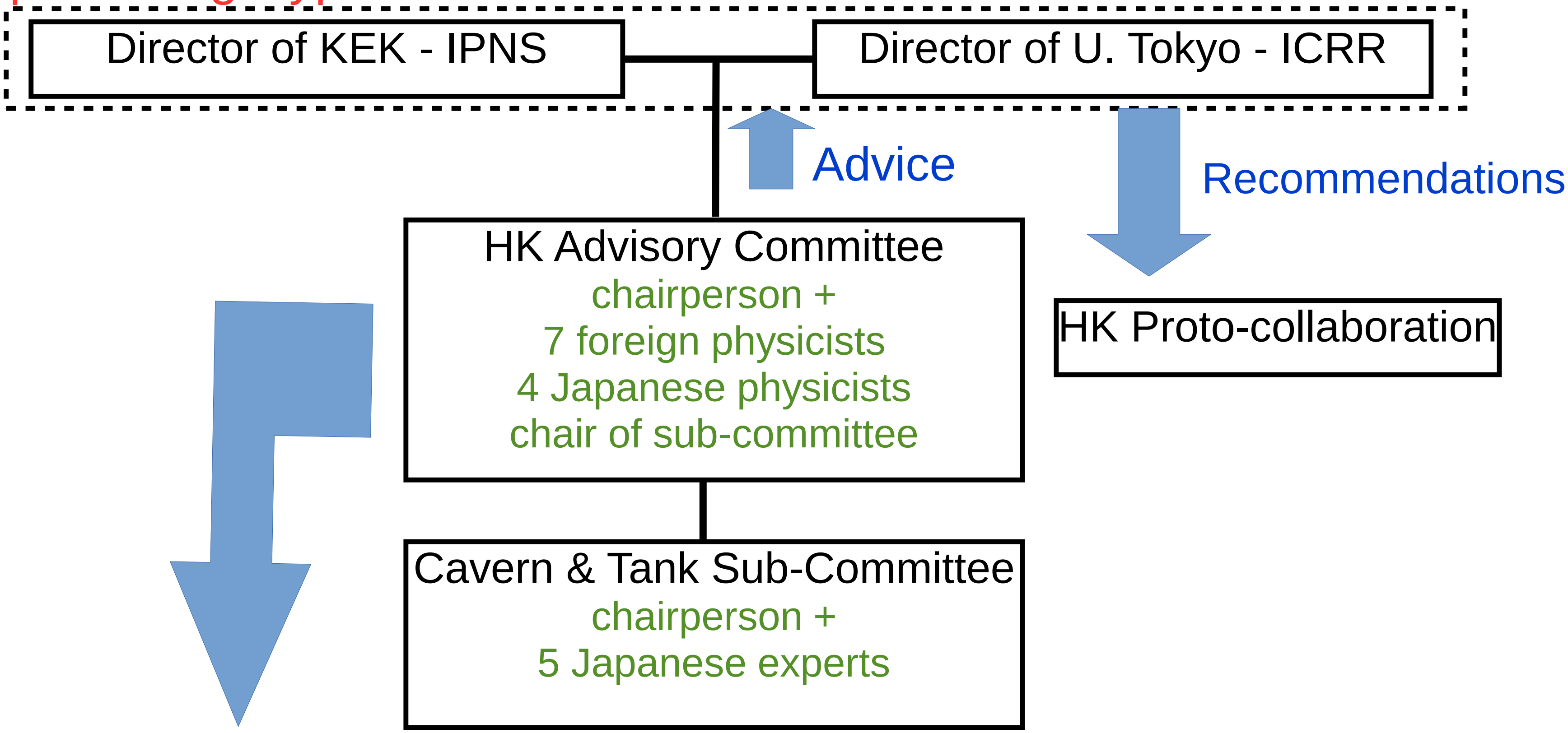
- **WG1** Shiozawa, Tanaka M.Smy
- **WG2** Sekiya, Vagins
- **WG3** Nakayama Nishimura
- **WG4** Hayato, T.Lindner
- **WG5** Miura Walter Di Lodovico
- **WG6** HideTanaka, Koshio,Mine, McCauley
- **WG7** Hartz, J.R.Wilson
- **WG8** Hartz, Fujii
- **Physics WGs** Yokoyama
  - **Phys-WG1** Yokoyama
  - **Phys-WG2** Wendell
  - **Phys-WG3** Takeuchi, Shimizu
- **WG10** S-H Seo

WG1: Cavity and Tank
WG2: Water
WG3: Photo-sensor
WG4: Electronics and DAQ
WG5: Software
WG6: Calibration
WG7: Near Detectors
WG8: Beam & Accelerator
WG10: 2^{nd} detector in Korea

Phys-WG1: Accelerator
Phys-WG2: Atmv+Nucleon decays
Phys-WG3: Astroparticle Physics (SN, solarv, etc)

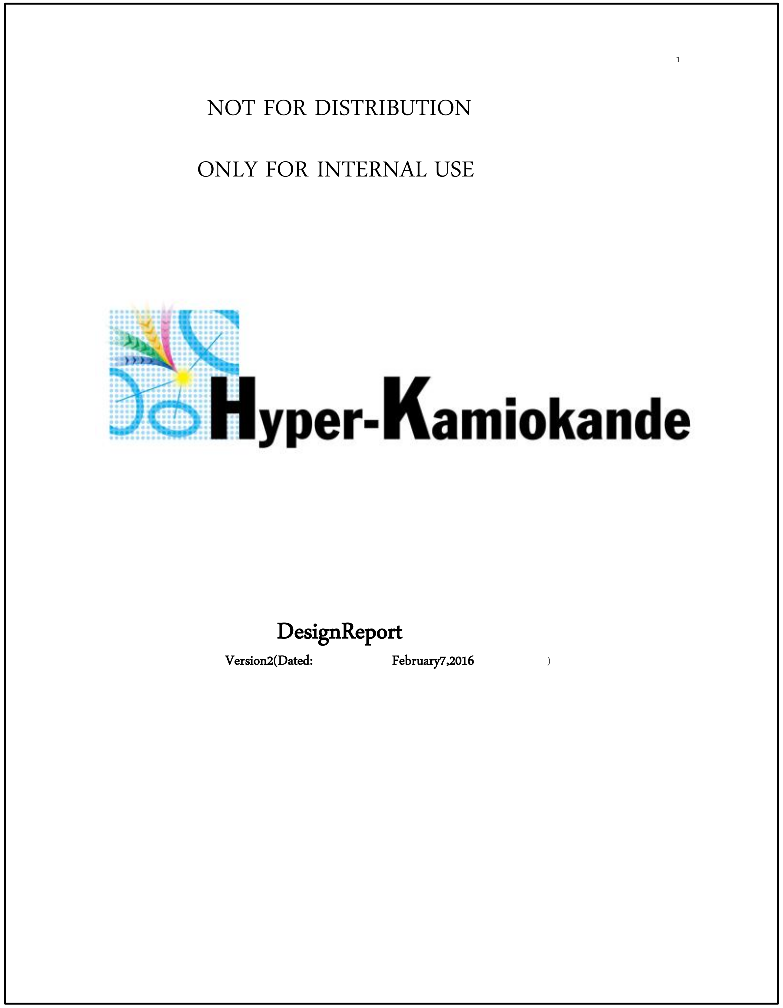
HK Advisory Committee (HKAC)

Established by the two supporting Labs in accordance with the MoU for promoting Hyper-K.



- Main committee members: Anne-Isabelle Etienvre, Klaus Kirch, Joshua R. Klein, Andrew, J. Lankford, Masaki Mori, Toshinori Mori (chair), David Sinclair, Jim Strait, Katsunobu Oide, Junji Hisano, Yifang Wang, Jiro, Yamatomi (chair of sub-committee)

Design Report



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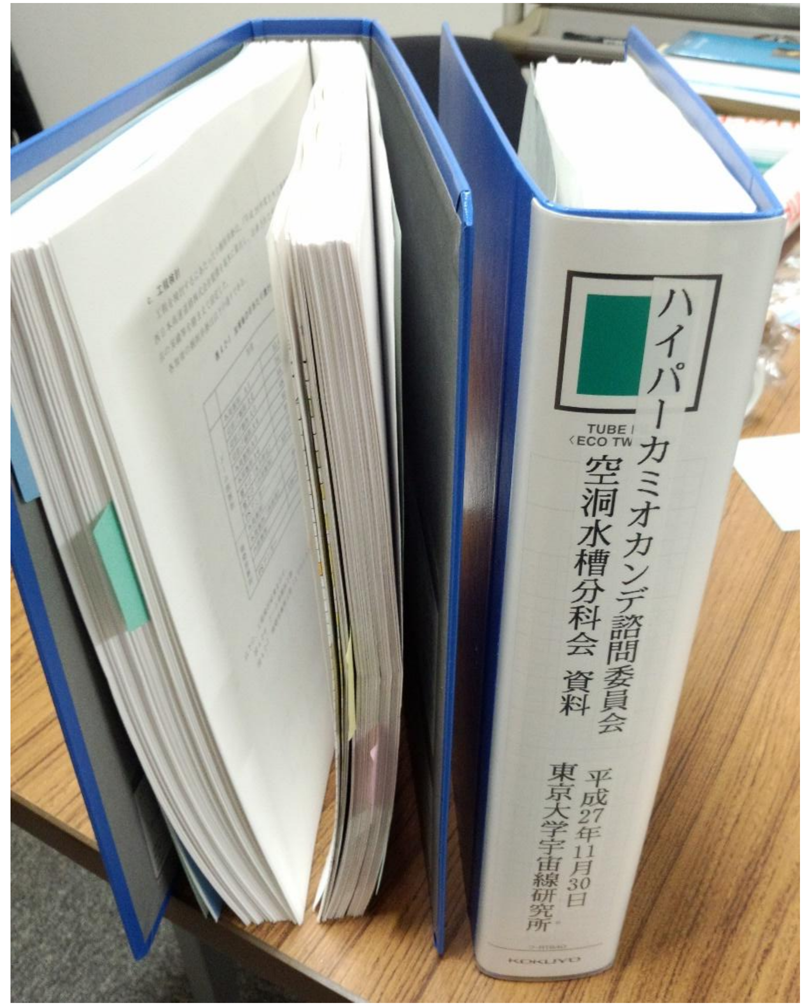
ONLY FOR INTERNAL USE

Hyper-Kamiokande

DesignReport

Version2(Dated: February7,2016)



Submitted to the Hyper-K Advisory Committee (January 2016).
It will be made public soon.

HKAC Review

Document available for ~1week and posted in: hyperk.org/?p=211

A very positive report.

Summary & Recommendations

Hyper-Kamiokande (Hyper-K) is an important new initiative which will enable important measurements that will greatly expand our understanding of some of the most fundamental questions in particle physics and in astroparticle physics. It is a straightforward extension of the highly successful program that started with the Kamiokande experiment and continues with Super-Kamiokande (Super-K), which has yielded two Nobel prizes. With an order of magnitude increase in detector mass and improvements in the photo-sensor system, it will provide major new capabilities to make new discoveries. In an international context, in which other experiments both operating and planned will address similar physics, Hyper-K stands out as the most capable experiment in a number of areas, and a highly competitive one in other areas. The complementarity of Hyper-K with other experiments using different techniques, most notably DUNE in the U.S., will provide important cross-checks that will add credibility to the results of what will be very challenging and important measurements.

2016 Experiment Updates

- **We have submitted the Hyper-K proposal to the Science Council of Japan in March** to be included in the shortlist of the future large projects. We were already in the shortlist in 2014 now updating with a new optimized tank.
  - Interview in the Summer. Schedule not announced yet.

- **Thereafter we will submit our request to MEXT** (Ministry of Education, Culture, Sport, Science & Technology). **Prof. T. Kajita (2015 Nobel Prize in Physics) as Director of ICRR (Tokyo university) will submit the request.**

- **ICRR is forming a future-project internal review committee** to internally review the Hyper-Kamiokande experiment and its costs before submission.

2016 Experiment Updates

- **Synergy with T2K phase 2:**
  - Beam upgrade up to 1.3 MW by 2025 was approved.
    - It's TWICE the beam power with which Hyper-K was supposed to start.
  - T2K is currently submitting a request for an extended run (2020-2025) to the J-PARC PAC (T2K phase 2)

- **The KEK Project Implementation Plan (PIP)** concluded that the **beam upgrade for Hyper-Kamiokande is the highest priority.**

- New **large Hamamatsu plant for Hyper-K PMT mass production** built.

"N. Saito, at the Third International Meeting for Large Neutrino Infrastructures (KEK, 30 May-1 June 2016).

KEK Project Implementation Plan Review

- Priority of new projects to be promoted with a major budget request was discussed.

KEK-PIP Advisory Committee Meeting

from Sunday, 22 May 2016 at **08:00** to Monday, 23 May 20
at **KEK Tsukuba (TBA)**

Description **Advisory Committee Members**

Tatsuya Nakada (Lausanne)
Nigel Smith (SNO lab)
Carlos Wagner (ANL)
Tadafumi Kishimoto (Osaka, RCNP)
Kenneth Hicks (Ohio)
Christine Davies (Glasgow)
Ki-bong Lee (Postech)
Yoshiyuki Amemiya (Tokyo)
Yasuhiro Iwasawa (Dentsudai, UEC)
Jun Akimitsu (Okayama/Hiroshima)
Michael Sullivan (SLAC)
Mei Bai (Juelich)

Go to day

Project to be prioritized:
- COMET II
- J-PARC upgrade for Hyper Kamiokande
- Hadron Hall Extension
- H-line and g-2/EDM
- LHC and ATLAS
- Super Computer
- RNB

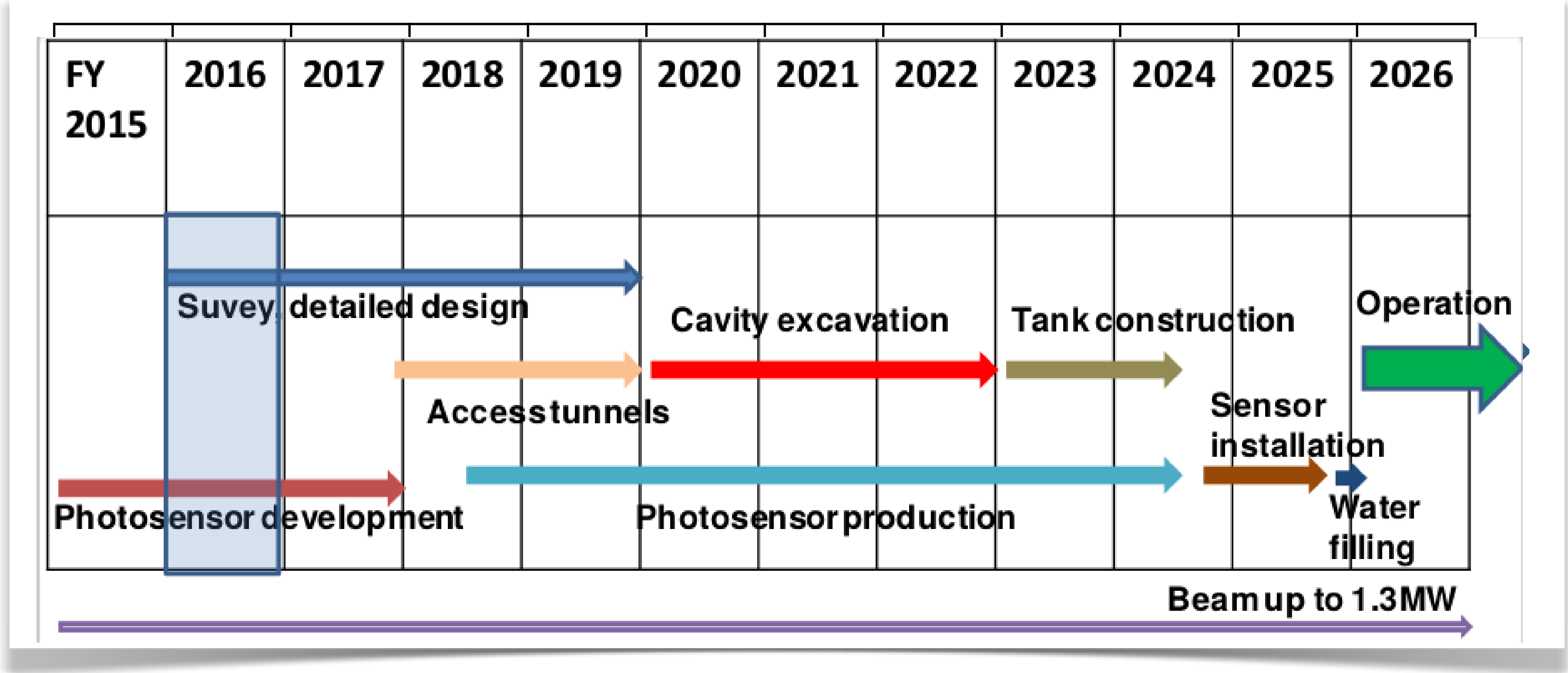
Separate prioritization
- Light Source

PIP review concluded that "J-PARC upgrade for HK is the highest priority".

Hamamatsu new plant for mass production

- **New large plant for mass production for HK built by Hamamatsu.**
- The PMT division is moving there.
- Around 6 years for mass production.

The Hyper-Kamiokande Timeline

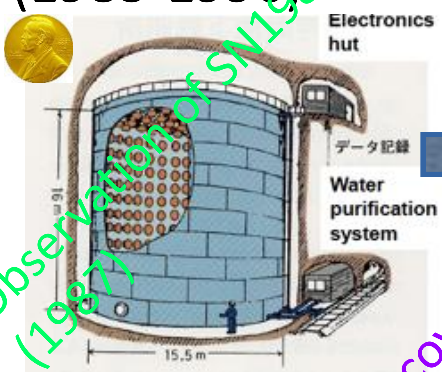


- 2018 - 2025 HK construction.
- 2026 onwards CPV study, Atmospherics ν, Solar ν, Supernova ν, Proton decay searches, …
- A 2nd identical tank starts operation 6yrs after the first one.

Kamiokande Evolution

- Three generations of large Water Cherenkov in Kamioka.
- **Tank design for Hyper-Kamiokande optimized .**

Kamiokande
(1983-1996)



Observation of SN1987A (1987)

3kton

Super-Kamiokande
(1996-)

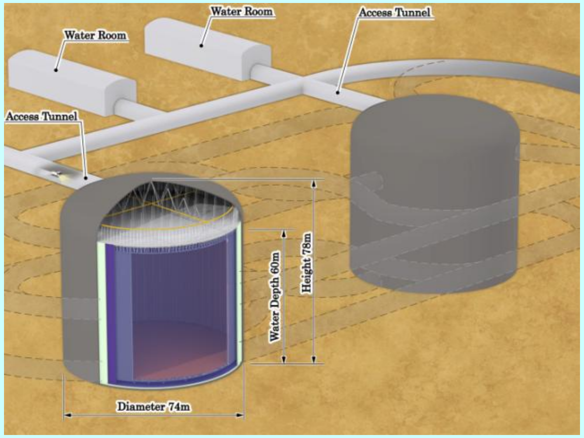
Discovery of neutrino oscillation (1998)

Observation of electron neutrino appearance (w/ beam, T2K, 2013)

50kton

x17

Hyper-Kamiokande
(2026-)



0.52Mton=520kton

(380kton fiducial)

x10
(x20 fiducial mass)

arXiv:1109.3262
arXiv:1309.0184
PTEP 2015, 053C02

Tank Optimization

	Super-K (SK)	Letter-of-Intent 2011 (LoI) configuration	2 Tanks w/ High Photocoverage
Total Volume (Fiducial Volume)	0.05Mton (0.022Mt)	1Mt (0.56Mt)	0.52Mt (0.38Mt)
Dimension	39mϕ × 42m (H)	48 (W) × 54 (H) × 250 (L) m^3 ×2	74mϕ × 60m(H) ×2
ID #of Photo-sensors (coverage)	11k (Super-K PMT) (40%)	99k (Super-K PMT) (20%)	80k (B&L) (40%)
Single-photon detection efficiency	12%	12%	24%
Photon-yield	1	0.5	2
Single-photon timing resolution	~2nsec	~2nsec	1nsec

- Optimized tank design based on physics, technology, costs.
- **2 High Photocoverage tanks 74mf × 60m(H)**
  - Better for lowE (~MeV) physics
  - No performance changes in highE (~GeV) physics.
- **A second identical tank 6y after the first. Being optimized.**

Hyper-K Sensitivity to δ_{CP}

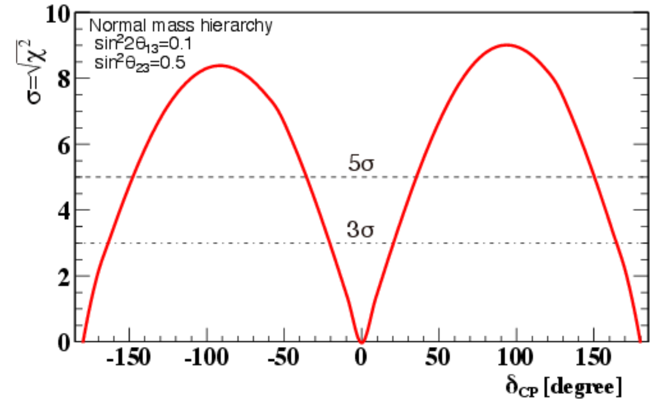
Exclusion of sinδ_{CP}=0
- >8σ(6σ) for δ_{CP}=-90°(-45°)
- ~80% coverage of δ_{CP} parameter space with >3σ

From discovery to δ_{CP} measurement:
- ~7° precision possible

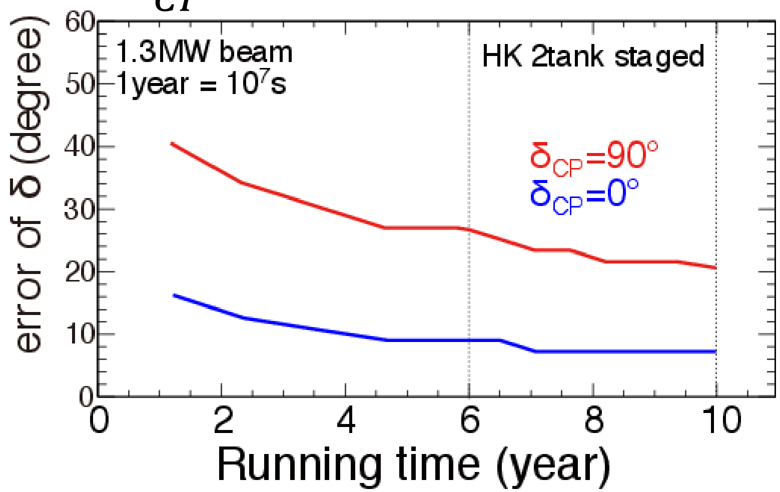
10 yrs	sinδ_{CP}=0 exclusion		1σ error	
	>3σ	>5σ	δ_{CP}=0°	δ_{CP}=90°
2 Tanks	78%	62%	7.2°	21°

Effect of tank configuration change is limited.

sinδ_{CP}=0 exclusion



δ_{CP} 1σ error



Mass Hierarchy and Octant Sensitivity: Atmospherics + Beam

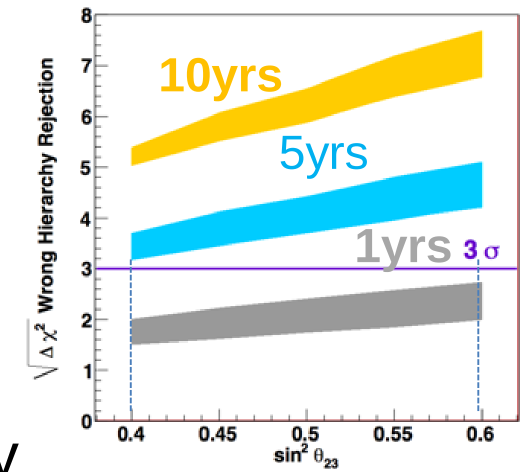
1,5,10 yrs exposure. NH

Variety of physics with atmospheric ν:

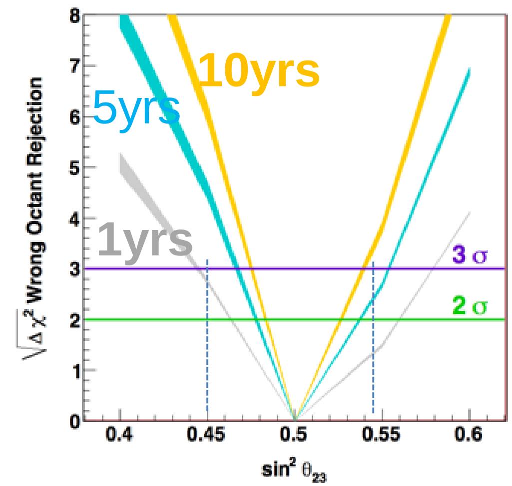
- MH, θ_{23} octant, CP
- Sterile neutrino , LV, etc

With atmospheric alone,

- mass hierarchy sensitivity
- >3σ octant determination for $|\theta_{23}$ -45°|>8°



Mass hierarchy determination



θ_{23} octant determination

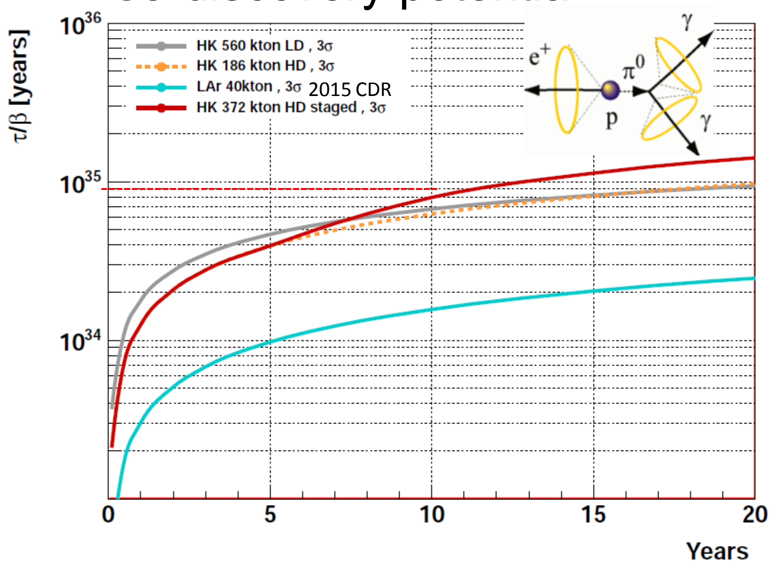
- Improved sensitivities combining atmospherics and beam.

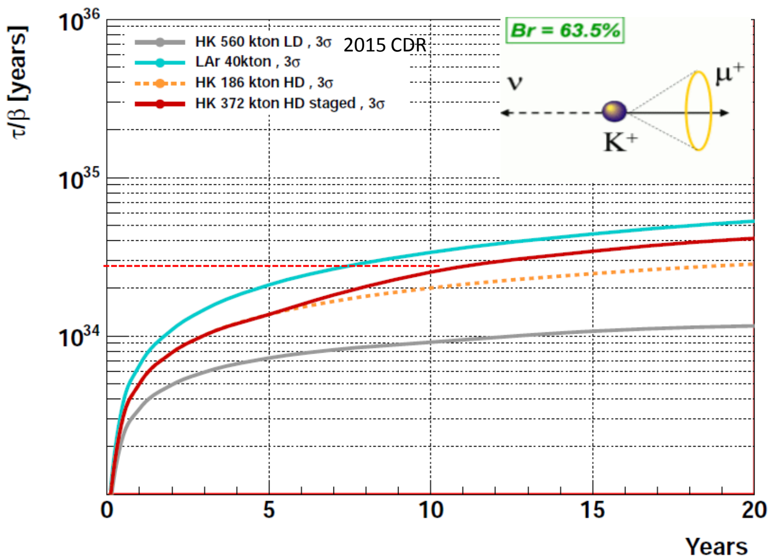
10 yrs NH		Mass Hierarchy (σ)	
		Atm	Atm+Beam
2Tanks	θ_{23}=0.4	2.2	5.3
	θ_{23}=0.6	5.2	6.9

10 yrs NH	Octant (σ)	
	Atm	Atm+Beam
θ_{23}=0.45	2.2	5.8
θ_{23}=0.55	1.7	3.7

Proton Decay Sensitivity

3σ discovery potential





Hyper-K has a sensitivity to a wide variety of modes. Current limits will be exceed by an order of magnitude or more.

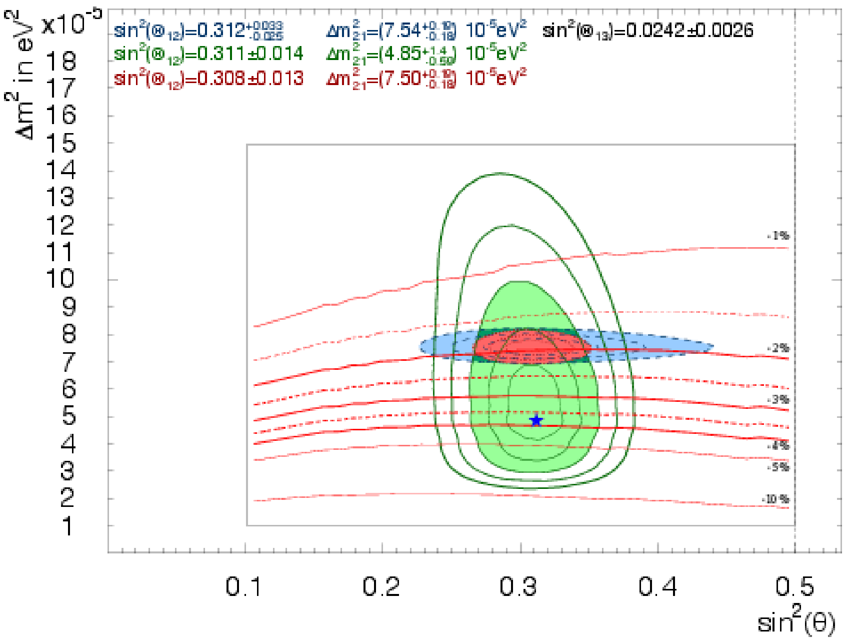
3σ discovery potential reaching $\tau \sim 10^{35}$ yrs.

Proton decay $p \rightarrow e^+ \pi^0$ is a favoured model of many GUTs.

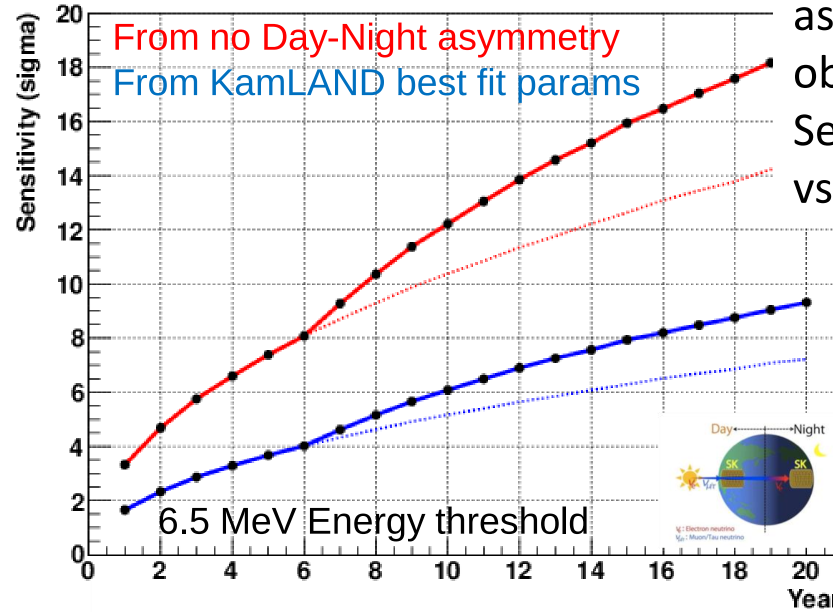
As SK analysis but with neutron tagging (remove events with a tagged neutron) thanks to improved PMTs.

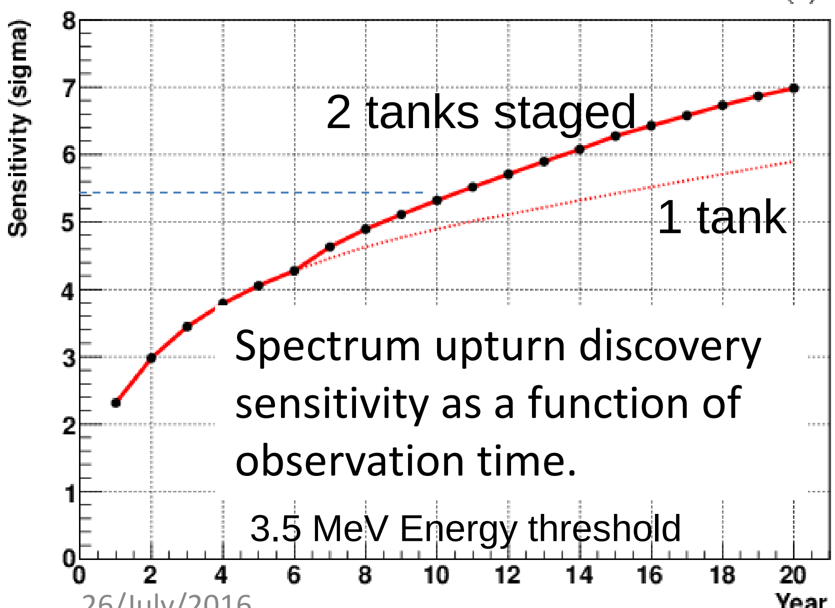
Proton decays into a lepton and a kaon, e.g. $p \rightarrow \bar{\nu}\, k^+$, are one of the most prominent features of Supersymmetric Grand Unified Theories.

Solar neutrino physics



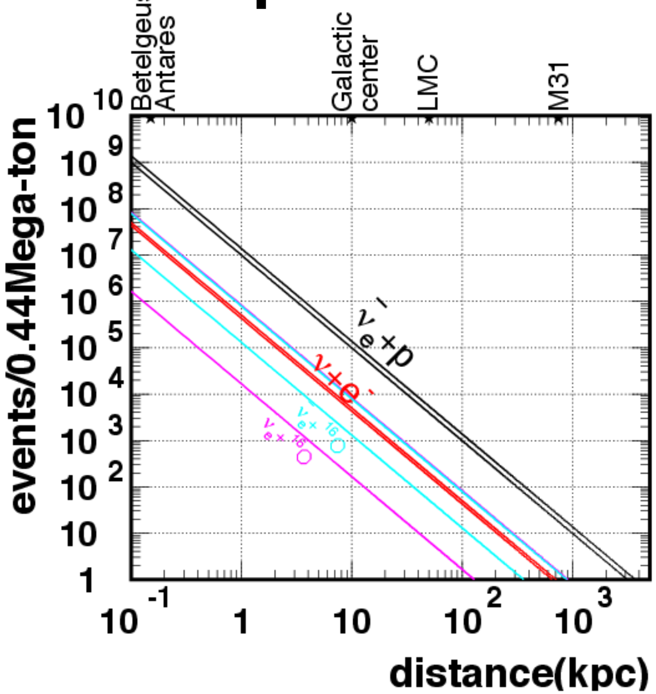
Day-night asymmetry observation Sensitivity vs time

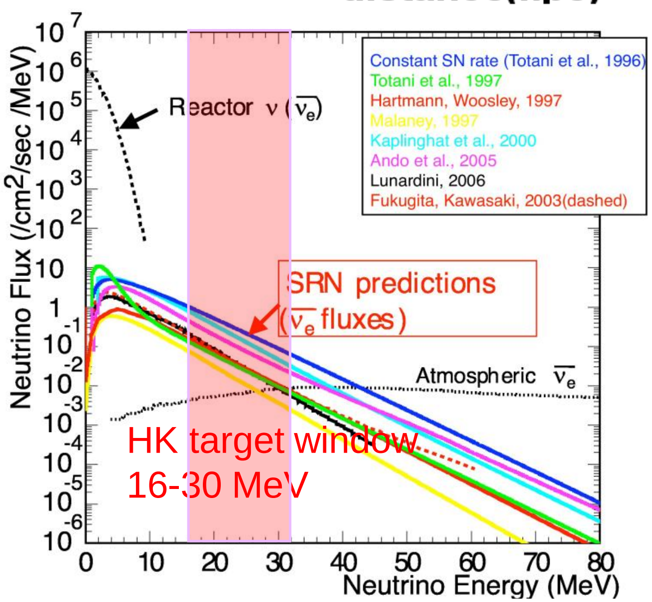




- Spallation background = 2.7 x SK
- Sensitivity to address solar and reactor neutrinos discrepancy.
- Sensitivity between solar and reactor neutrino parameters by day-night asymmetry is ~6σ
- Spectrum upturn observation at ~5σ level.

Supernova Burst & Relic Neutrinos





Galactic SN (<1 Mpc)

- Large statistics: 104,000~158,000 events (10kpc)
- Time spectrum of SNν: SN model separation, SN burst time
- Energy spectrum measurement: $\Delta E/E$~20% at 10-20 MeV
- Direction, time, fluctuations of ν flux

Nearby Galactic SN (>1 Mpc): ~2-20 SNν for 20y

Supernova Relic Neutrinos:

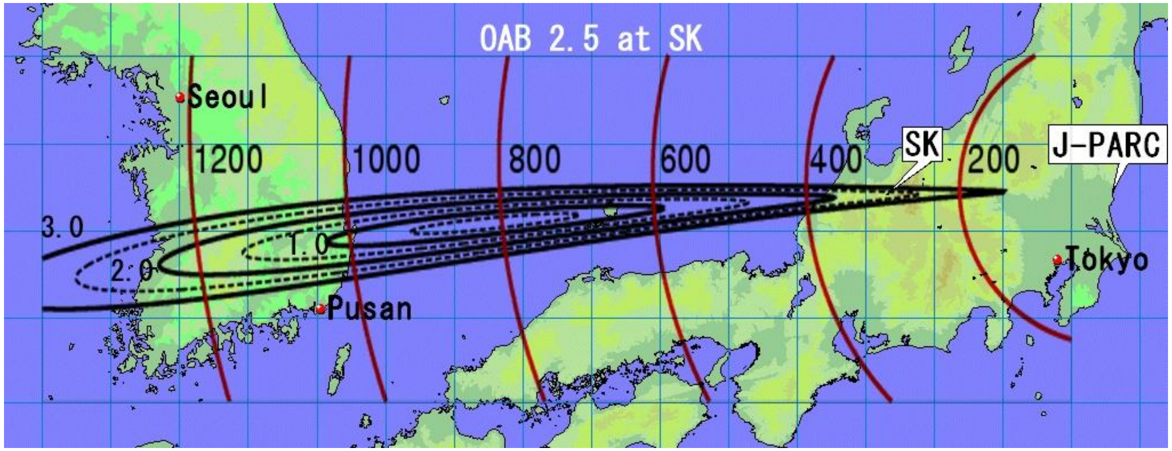
- Diffused or integrated ν from past SN
- Measurement will probe:
  - Star formation rate
  - Energy spectrum SN ν
  - …

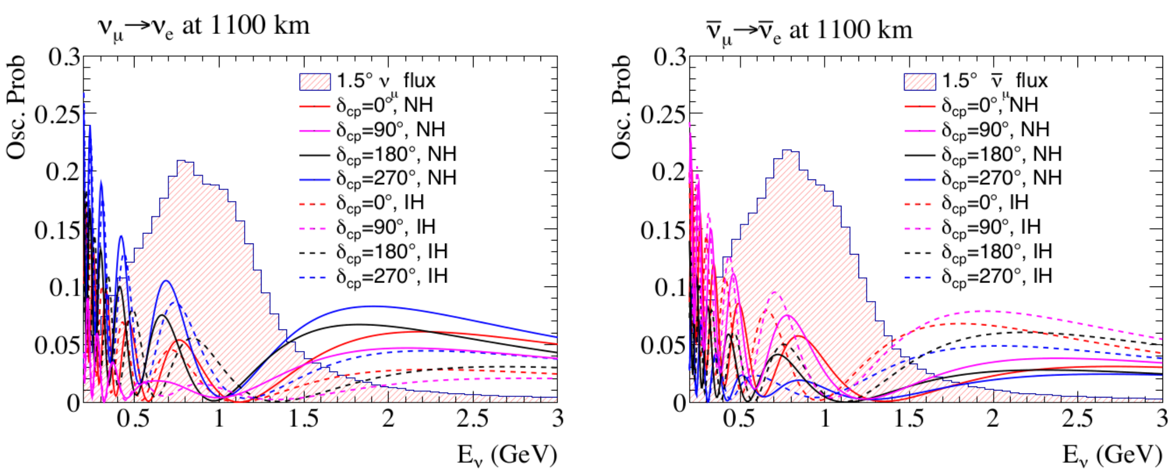
Expected events in 10y: ~98 ± 20 (4.8σ

Summary of Physics Potential

		2Tanks (10 yrs)
Beam (1.3 MW)	δ_{CP} precision (0°,90°)	7°-21°
	CPV coverage (3/5σ)	78%/62%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.015
Atmospherics+Beam	MH determination ($\sin^2\theta_{23}$=0.40)	>5.3σ
	Octant ($\sin^2\theta_{23}$=0.45)	5.8σ
Proton Decay	$p \to e^+ \pi^0$ 90%CL	1.2×10^{35} yrs
	$p \to \bar{\nu}K^+$ 90%CL	2.8×10^{34} yrs
Solar	Day/Night (from 0/from KamLAND)	12σ/6σ
	Upturn	~5σ
Supernova	Burst	104k-158k
	Nearby galaxies	2~20 events
	Relic	98evt/4.8σ

2nd Hyper-K Detector in Korea





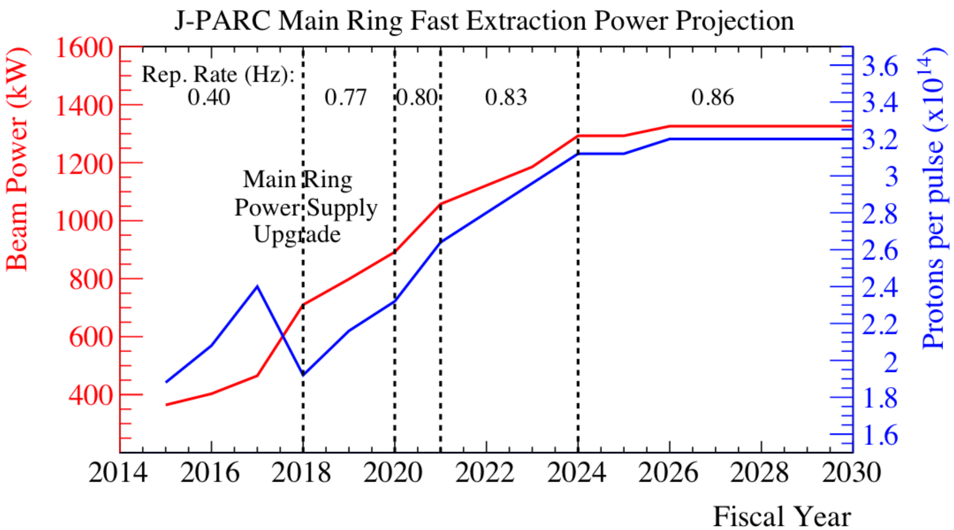
The idea for a second detector in Korea has been studied for more than 10 years.

A detector in Korea can probe the first, second and even third oscillation maximum, breaking oscillation parameter degeneracy and giving sensitivity to the mass hierarchy.

Future Planning for T2HKK

- First official meeting on July 10, 2016.
- Studies on a 2nd detector is now a new working group in Hyper-Kamiokande.
- Large support in Korea.
- White paper planned.
- A workshop on T2HKK in Seoul in Nov 20-21 2016.

Beam



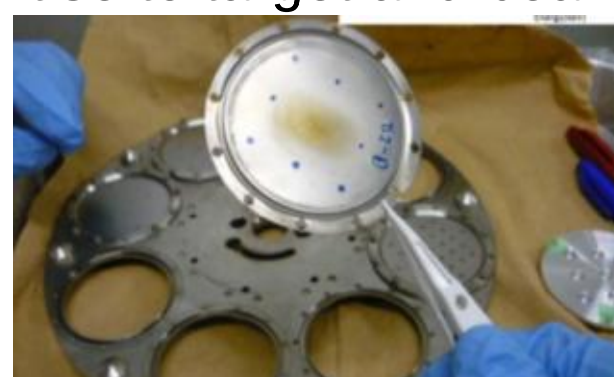
Continuous upgrade of neutrino beam up to 2030.

- 0.75 MW by MR upgrade starting in 2018
- 1.326 MW by 2026 by increasing rep. rate to 0.86 Hz
- 3.2e14 protons per spill

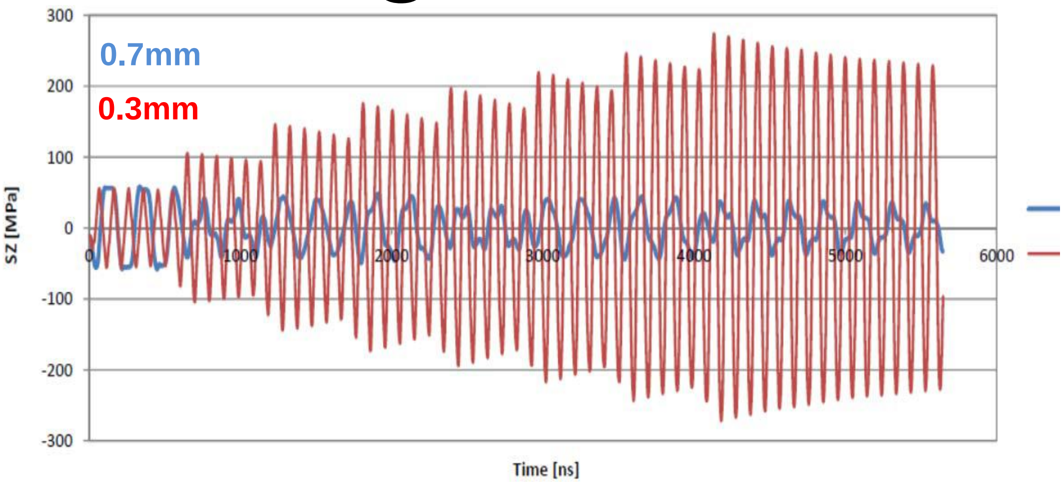
RaDIATE Collaboration on accelerator target materials:

http://www-radiate.fnal.gov/index.html

- Introduce materials scientists with expertise in radiation damage to accelerator targets community. Apply expertise to target and beam window issues.
- Co-ordinate in-beam experiments and post-irradiation examination.
- Analysis T2K allow foils OTR.

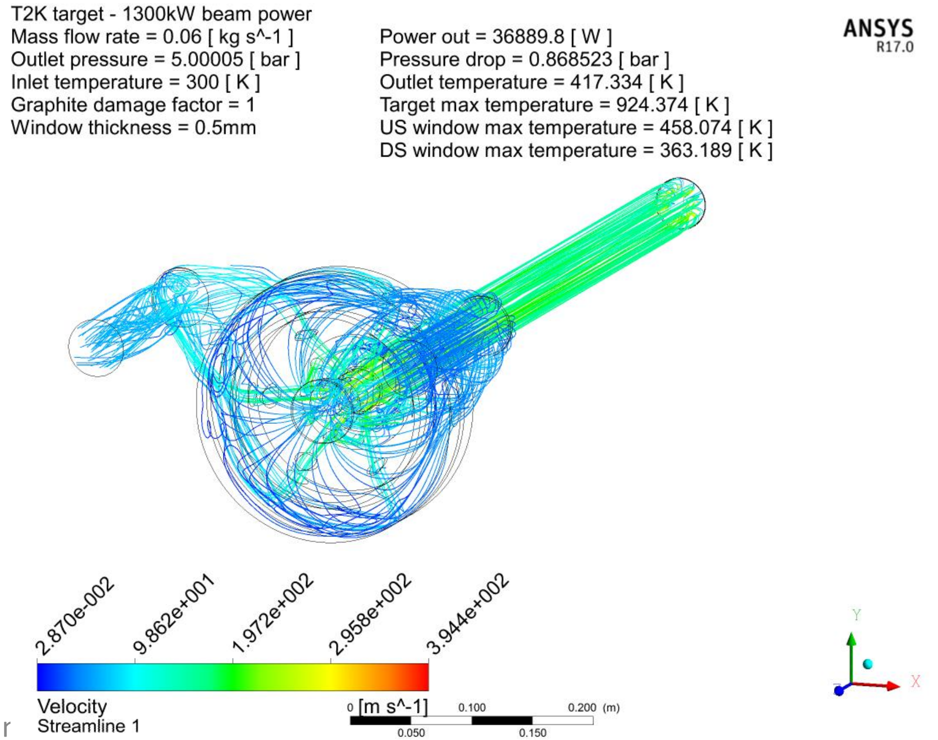


Target and Beam Window



New beam window studies for 1.3MW are underway. Early indications that 0.3mm is not the optimal thickness.

Z(beam direction) stress as function of time at window centre (max stress point) @ 1.3MW



Studies of the current target design operating at increased flow rate and pressure are in progress.

Tokai to Hyper-Kamiokande

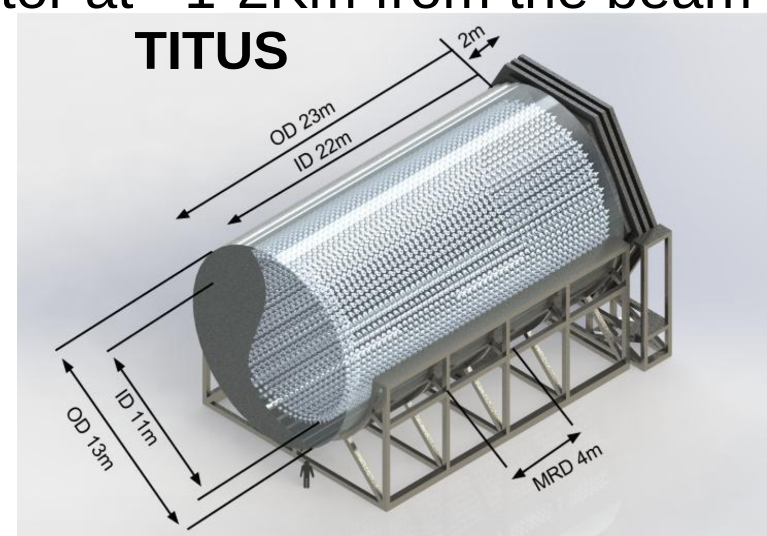
Upgraded near ND280 detector to continue for HK.

Intermediate (at ~1,2 km) WC detector being investigated.

TITUS is a ~2kton Gd-doped WC detector at ~1-2Km from the beam target.

Advantages:

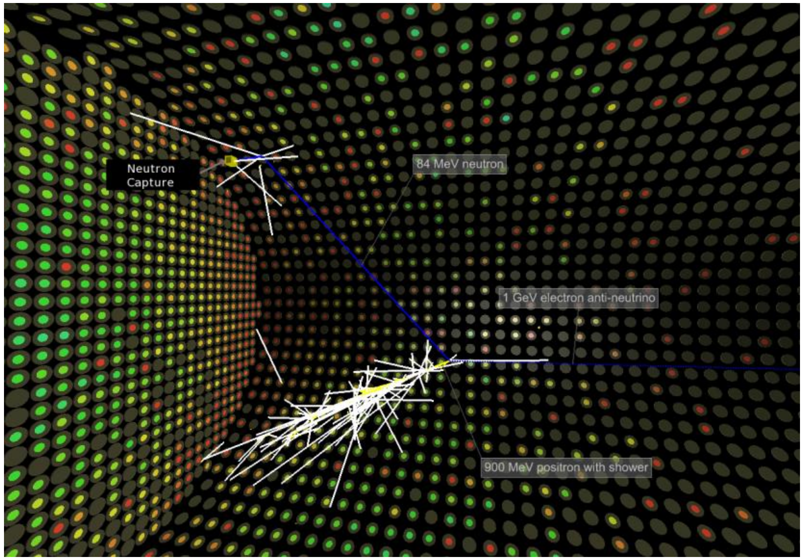
- Same target as Hyper-K.
- Gd-doping: separate ν and $\bar{\nu}$
- Minimize flux errors
- Current detector optimized for Hyper-Kamiokande but optimal for T2K phase 2 too.

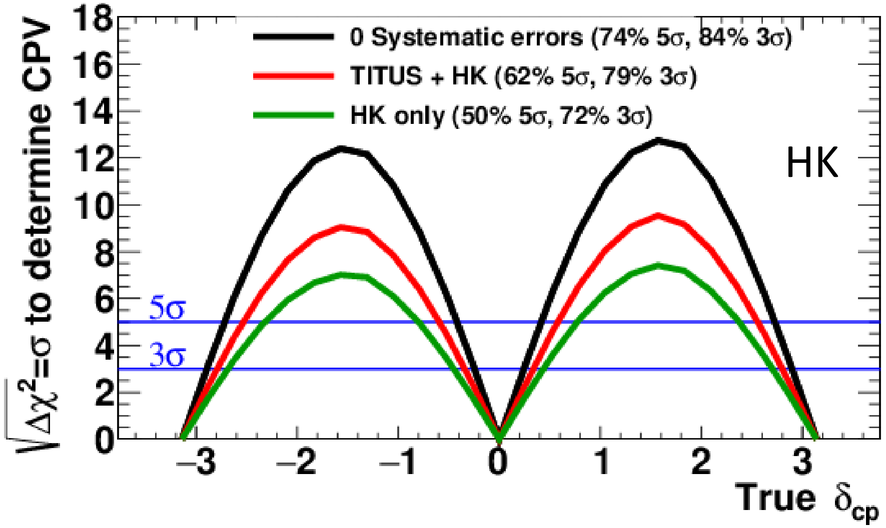


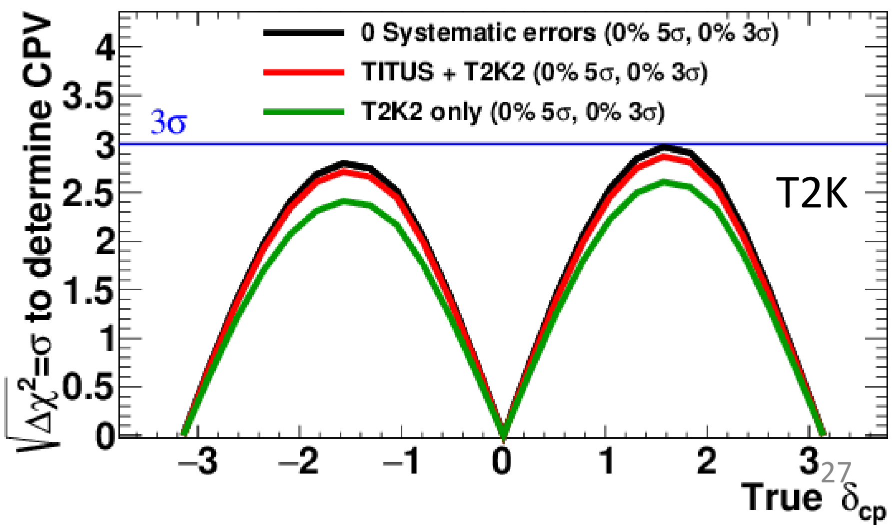
arXiv:1606.08114 [physics.ins-det]

TITUS Physics Potential

- **Neutrons tagged to distinguish ν and $\overline{\nu}$ and CCQE and other events.**
- Shown improvement in CP violation both for Hyper-K and T2K (SK).
- All results obtained w/o the MRD.



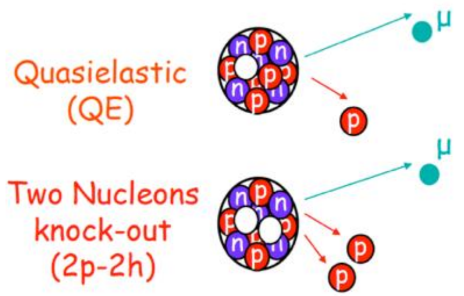


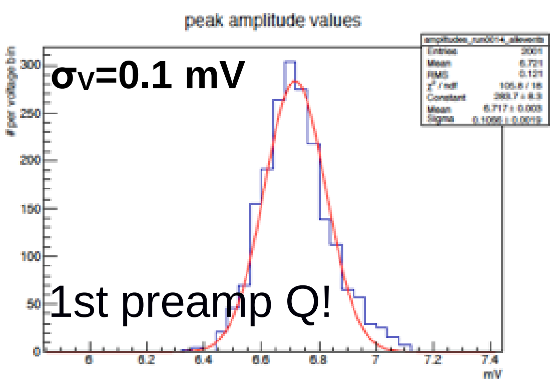


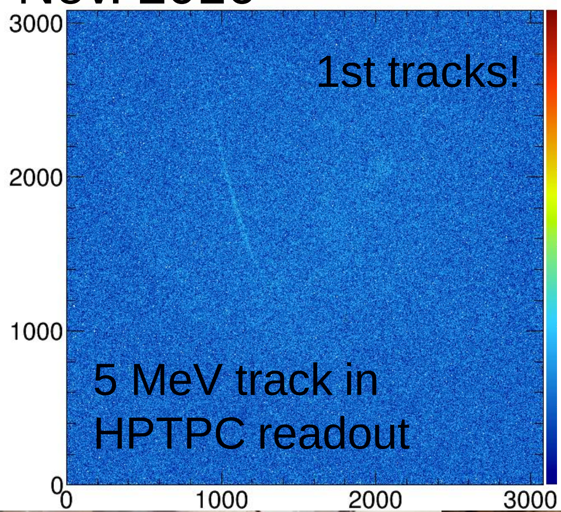
High Pressure (HP)TPC Progress

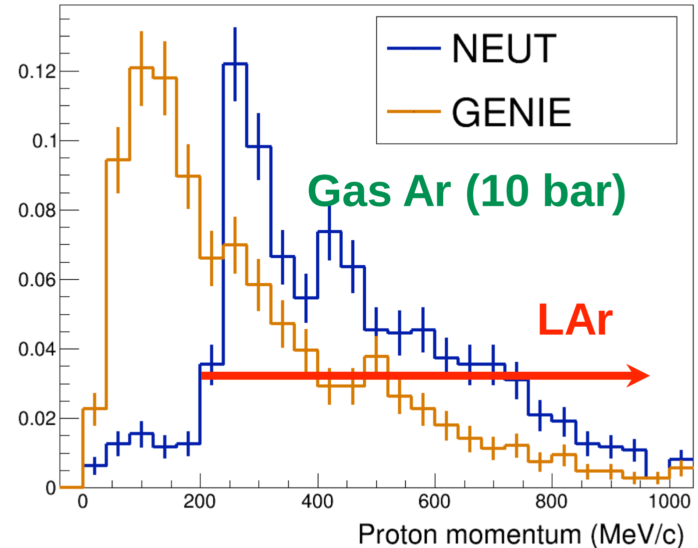
UK-led R&D towards high resolution detector with low momentum threshold for final state particles, to reduce dominant neutrino cross section errors from final states

- design and start of construction on HPTPC prototype
- commissioning of readout for HPTPC beam test
- workshop at CERN Nov. 2016

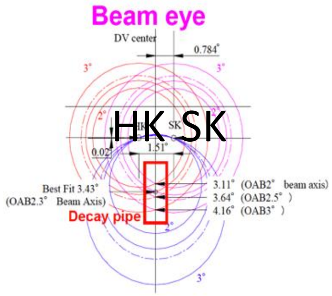




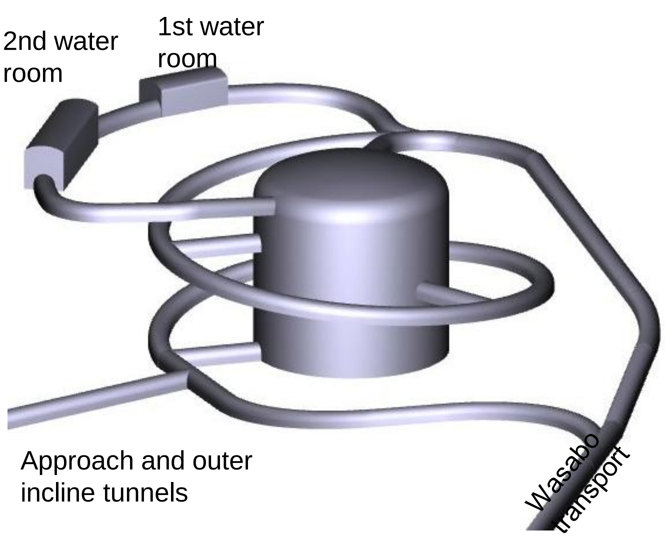


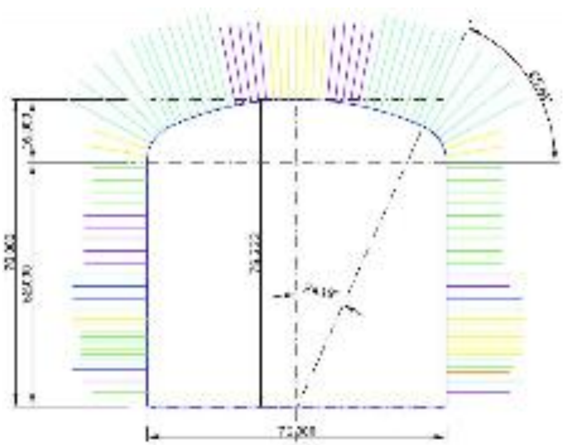


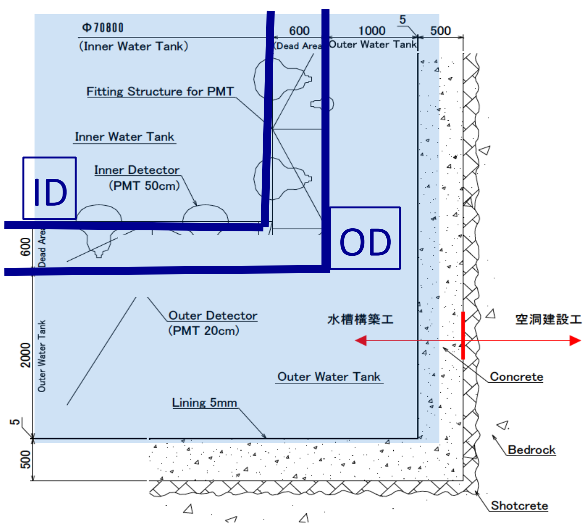
Cavern & Tank



- The candidate site located in Tochibora, under Mt. Nijugo-yama:
  - ~8km south from Super-K, 295km from J-PARC, 2.5° off-axis
  - Overburden ~650m (~1755 m.w.e.)
- Details of cavern construction addressed:
- Cavern can be built with existing technologies.
- Tank lining, PMT support, construction timeline ready.
- In the following close-up on DAQ, calibration, Gd screening





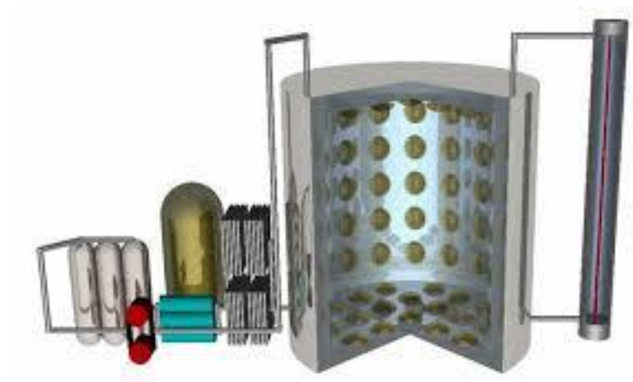


Water Cherenkov “Prototypes”

- Several Water Cherenkov detectors in the world.
- We are working together with those collaborations on several items for Hyper-K.

ANNIE (~113t), Fermilab
- ToolDAQ

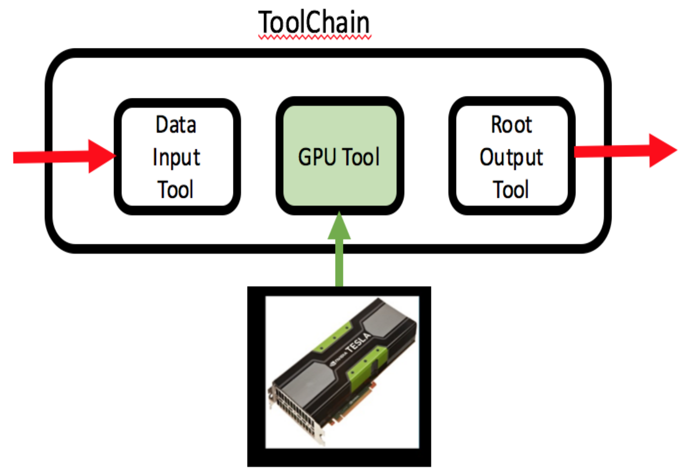
Super-Kamioka (~50kton), Kamioka
- Calibration
- Gadolinium
- Software trigger

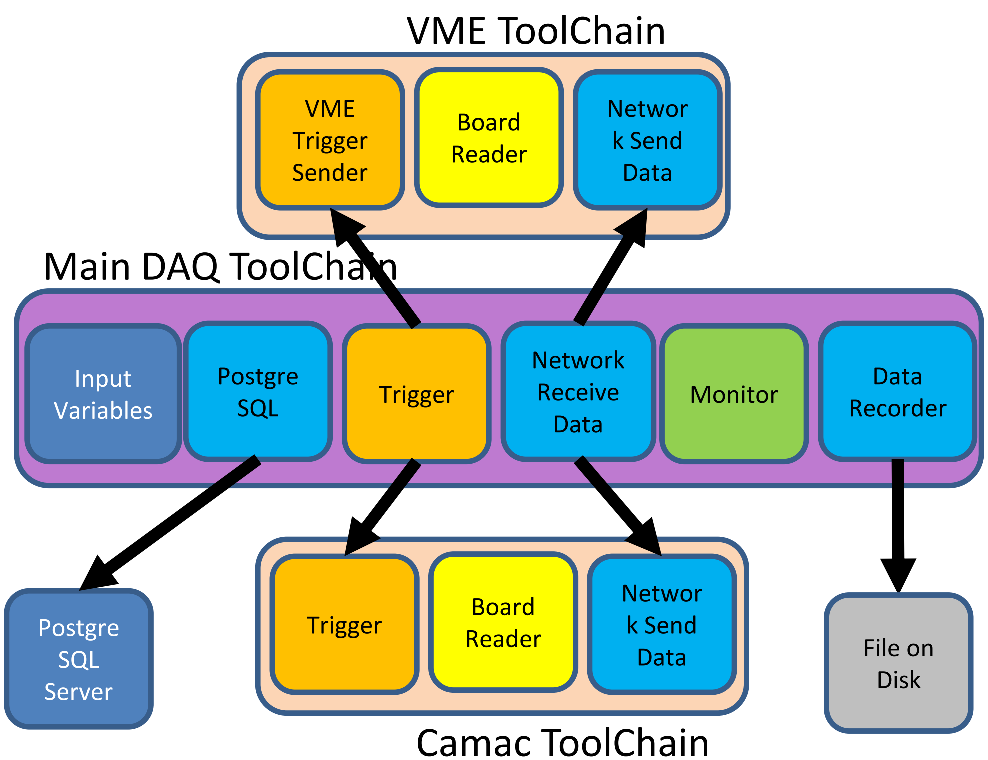


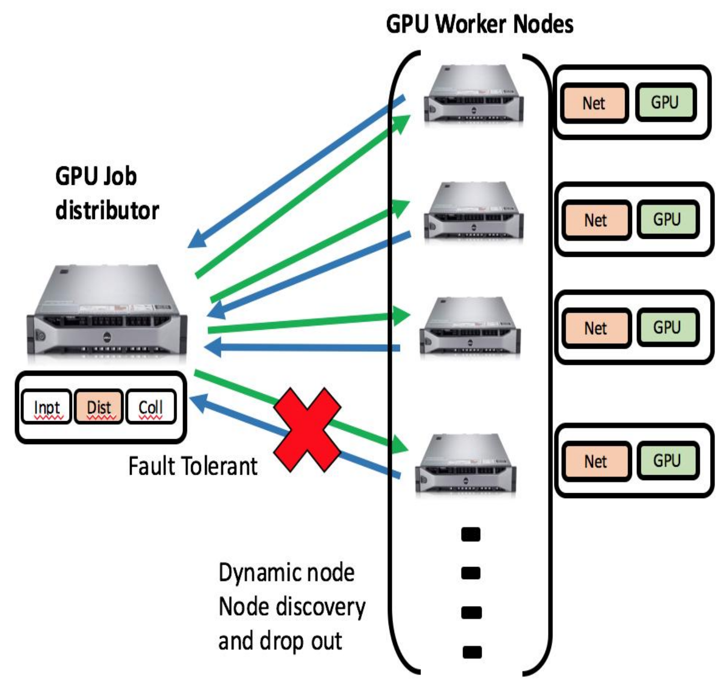
EGADS (~200t), Kamioka
- Calibration
- Gadolinium

DAQ

ToolDAQ: DAQ Framework developed by the UK DAQ group for Hyper-K and hardware testing. Currently being used by ANNIE experiment.



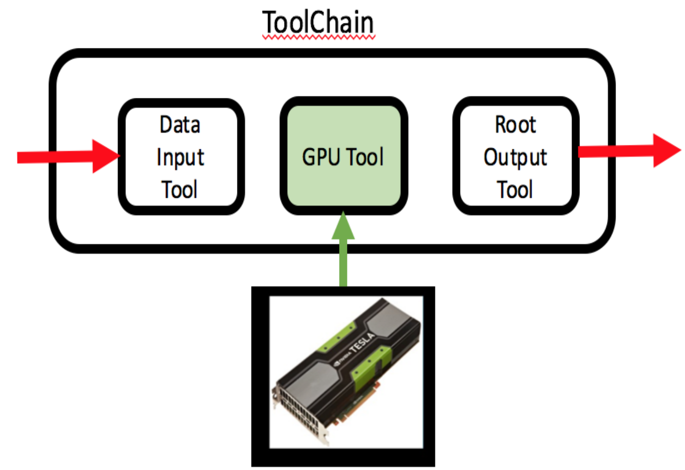


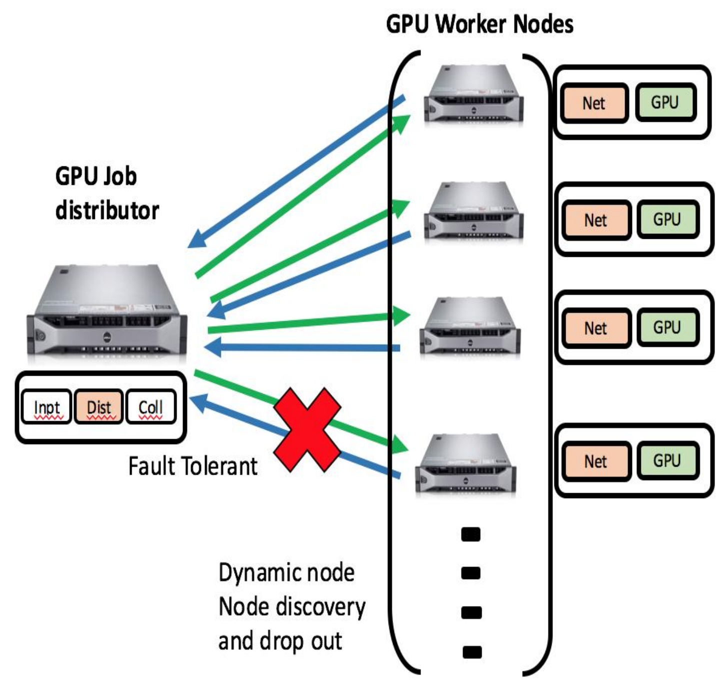


DAQ

ToolDAQ: DAQ Framework developed by the UK DAQ group for Hyper-K and hardware testing. Currently being used by ANNIE experiment. Main features:

- Pure C++
- Fast Development
- Very Lightweight
- Modular
- Highly Customisable / Hot swappable modules
- Scalable (built in service discovery and control)
- <u>Fault tolerant (dynamic connectivity, discovery, message caching) distributed computation</u>
- Underlying transport mechanisms ZMQ (Multilanguage Bindings)
- JSON formatted message passing
- Few external dependencies (Boost, ZMQ)



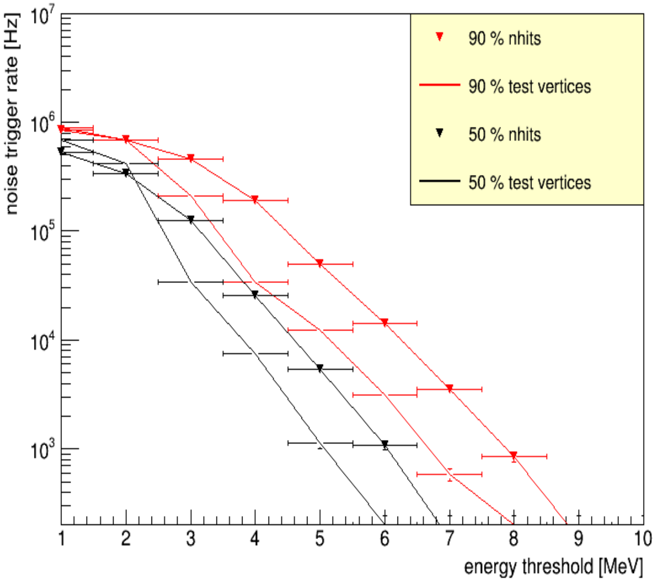


Triggers

Intelligent triggers for HK. low-energy events (solar neutrinos, SN, n capture) hard to identify without reaching high trigger rates

<u>Test-vertices trigger</u>:

- Test-vertices algorithm for HK low energy DAQ on GPU
- Good identification of vertex position (< 2.5 m) and time (< 10 ns)
- Lower the energy threshold by 1-2 MeV



<u>In-Time-Channel trigger</u>:

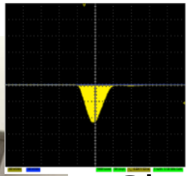
- It can improve noise rejection but not trigger efficiency

<u>TMVA trigger</u>:

- It can combine variables for fast identification of solar neutrinos
- 93% trigger efficiency and 90% noise rejection @ 3 MeV

Calibration

- Main efforts in LED Optical calibration
  – Ongoing tests with water tank.
  – Optical diffuser studies
- Linearity calibration with SK data.
- Started effort on neutron calibration sources.

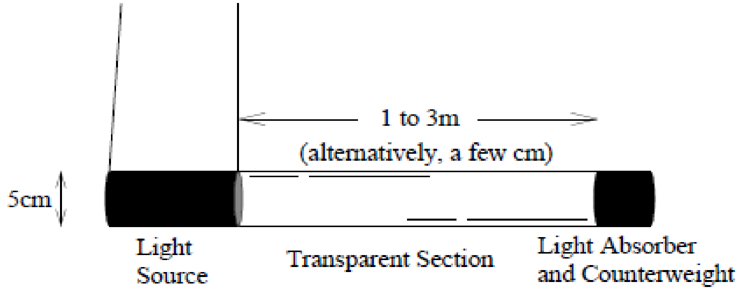


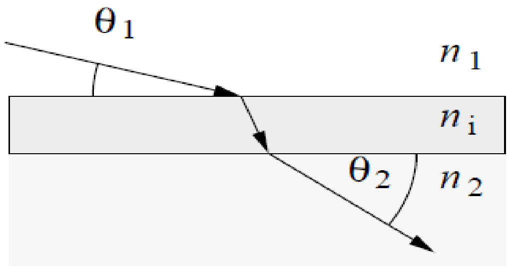
Size is 2m*1.8m*0.6m, material is stainless steel. University of Liverpool.

Quad Mosfet layout

Optical diffuser studies

- Muon fake calibration: a source to simulate muons Cherenkov ring and test calibration.

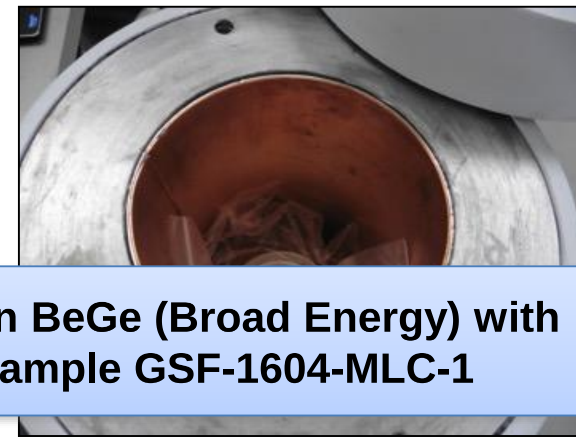




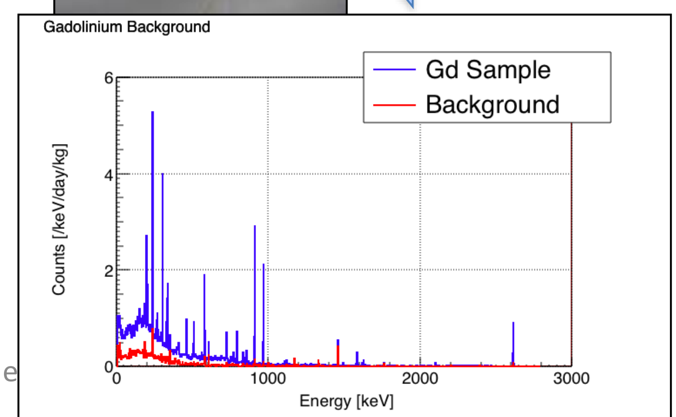
SK screening of Gd at Boulby lab

- Super-K intends to load the main Water tank with Gd in the form of Gd salts. Test samples from different manufacturer and before doping SK.
- 3 labs performing the checks: Kamioka, Canfranc, Boulby

Preparation and storage in class 1000 cleanroom



Wilton BeGe (Broad Energy) with sample GSF-1604-MLC-1



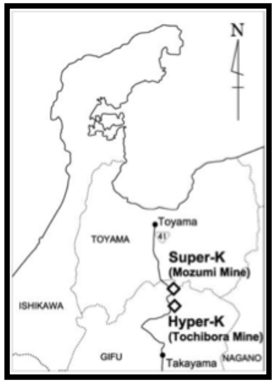
First results at Boulby

Conclusions

- Great progress in Japan.
  - Strong support from KEK/J-PARC and ICRR/Tokyo
  - Design report written and reviewed by the HK Advisory Committee.
  - Proposal submitted to the Science Committee and being ready for submitting it to MEXT.
  - Hamamatsu has already built a factory for HK.
- New Optimized detector tank configuration:
  - Higher photodensity, improved PMTs.
  - Cavern can be built with existing technology
  - Improved low energy physics performance
  - Two tanks, staged approach.
  - Possibly second tank in Korea: MH from beam, degeneracies,..
- A wealth of physics (CP, proton decay, atmospherics, SN…)
- Intensive UK and world-wide R&D. UK leading several parts of the experiment.

Additional slides to peruse

Cavern/Tank



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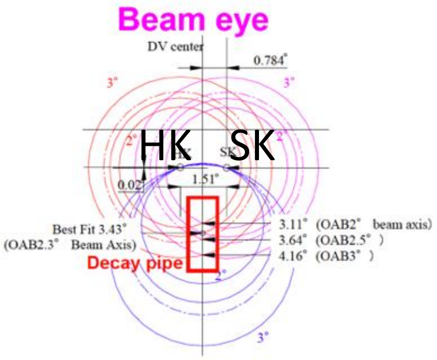
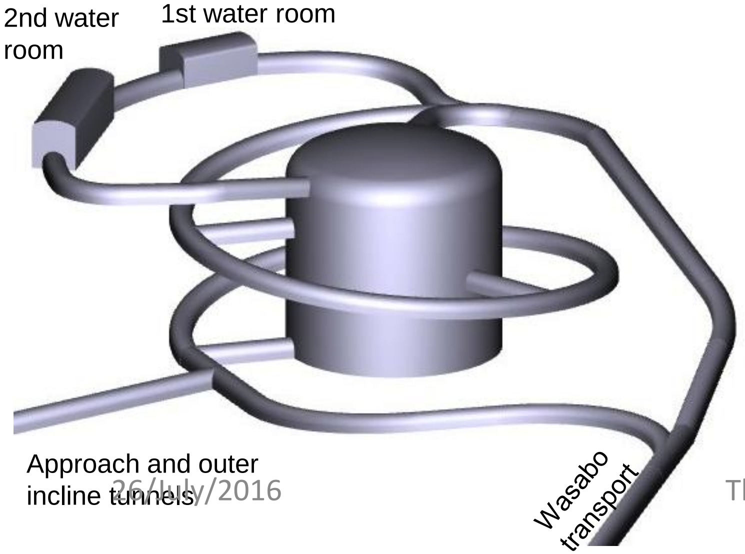
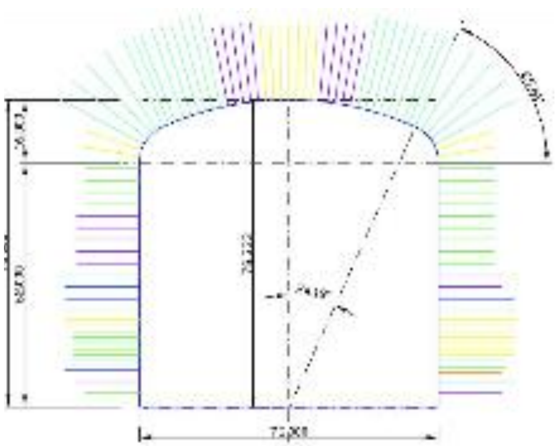
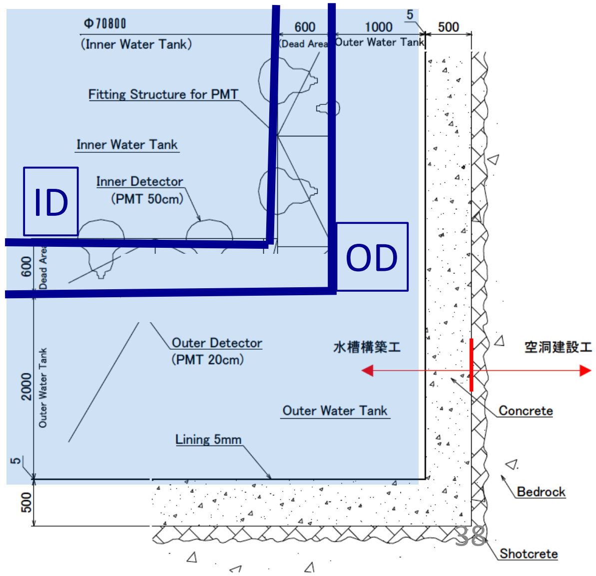








PhotoDetector Candidates

Photo Multipliers (PMTs)

Super-K PMT

Used in SK for 20 years

High QE Photocathode

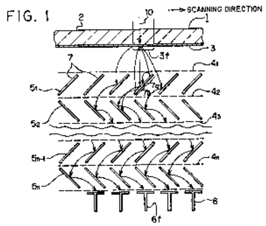
HQE SK PMT

Under Viability Test

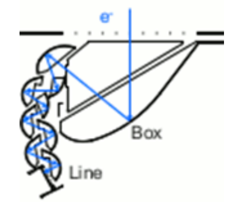
Dynode Improvement

50cm HQE Box&Line PMT

Under Viability test



Venetian Blind



Box-and-Line Dynode

Hybrid Photo Detectors (HPDs)

20 cm HPD

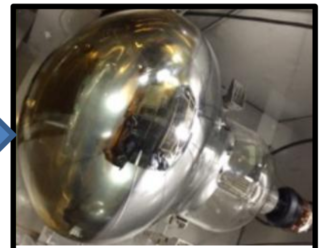
Under Viability Test

Larger Aperture

50cm HQE HPD w/ 5mm ϕ AD

Already Developed.
Low Collection Efficiency

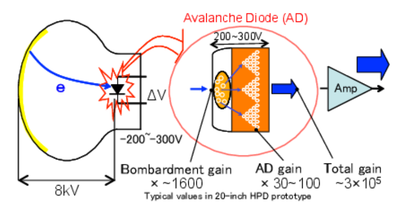
Larger Avalance Diode



50cm HQE HPD w/ 20mm ϕ AD

Under Development

Avalance Photo diode

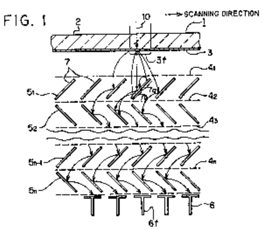


Photosensor Improvements

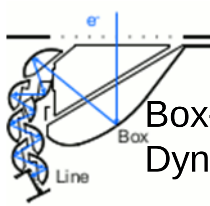
Photo Multipliers (PMTs)

Super-K PMT

Venetian Blind



50cm HQE Box&Line PMT

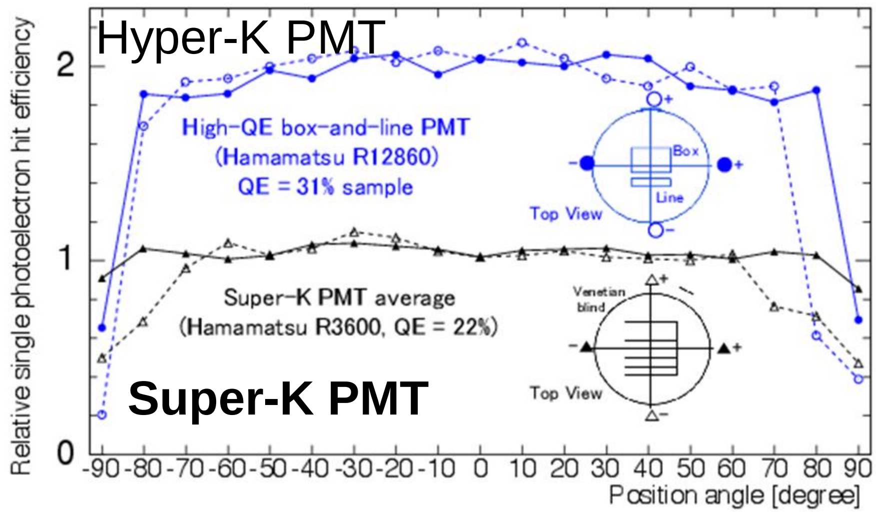


Box-and-Line Dynode

- Efficiency x 2, Timing resolution x 1/2

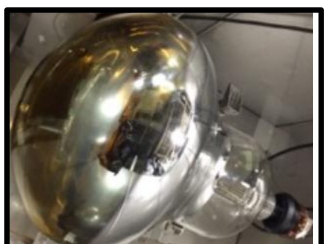
  Pressure tolerance x 2 (>100m)

  Enhance p→$\bar{\nu}K^+$ signal, solar ν, neutron signature of np→d+γ(2.2MeV),..

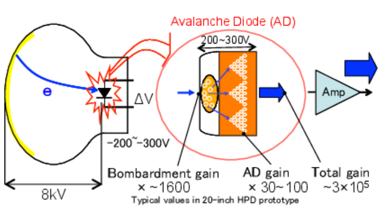


Other Developments:

Hybrid Photo Detectors (HPDs)

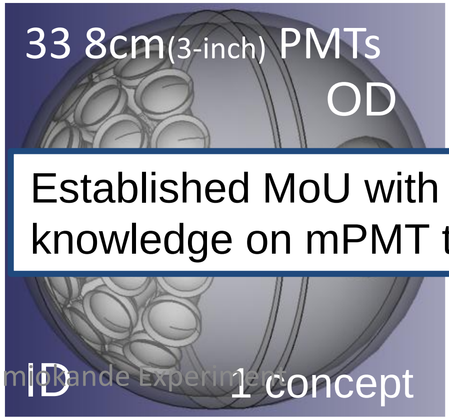


50cm HQE HPD w/ 20mm φ AD



Under viability study

Multi-PMTs



Working concept from KM3NeT but:

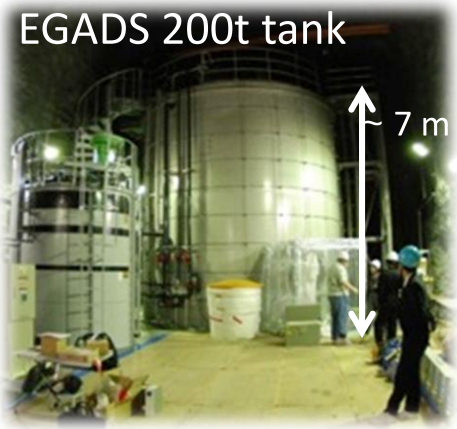
- Usage for ID/OD
- ultrapure water.

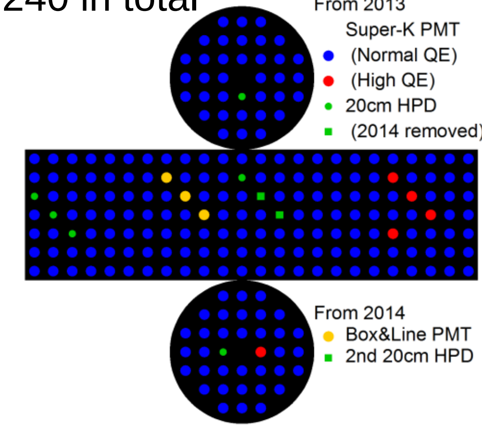
International contribut.

Established MoU with KM3NeT to exchange knowledge on mPMT technology.

Tests in water

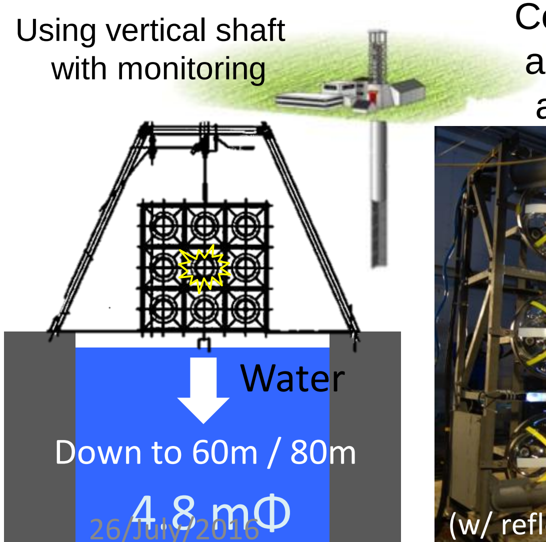
Tests in the EGADs tank



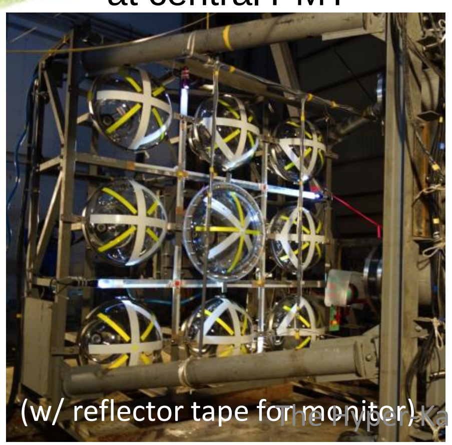


- The aim of 200t EGADS (Kamioka) is to test Gd for addition in SK, but agreed to use it to test new PMTs for Hyper-K.
- Tests ongoing since 2013.

Validation test of cover at Kamisunagawa in 60 m / 80 m water



Confirmed with artificial implosion at central PMT



Prototype of cover to stop chain implosion

15 mm acrylic

Stainless steel (3 mm)

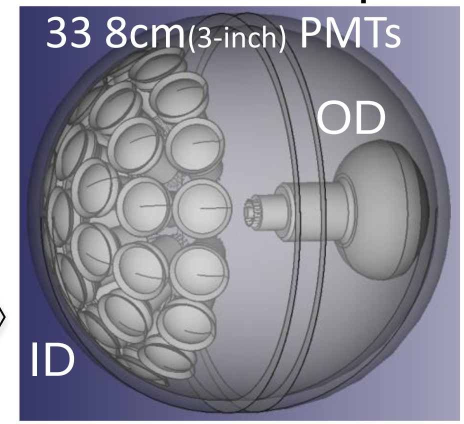
- No damage for all tests:
  - 3 times w/cover (2 with surrounding PMTs)
  - OK for 60m (HK), and for 80m also
- Cover established for HK.

Multi-Channel Optical Module

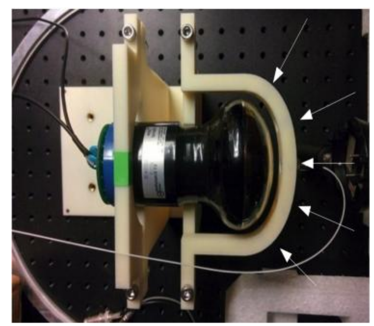
- Working concept from KM3NeT but:
  - peripheral Inner Detector/Outer Detector.
  - lower pressure tolerance required.
  - ultrapure water.
- Large fiducial volume by directional sensitivity cut and less dead area.
- No geomagnetism compensation.
- Many PMTs and readout channels.
- Acrylic pressure vessel:
  - low radioactive background
  - high optical transmittance
  - contain radon from PMT glass
  - pressure vessel for protection of PMTs and electronics.
  - same vessel and electronics for Inner and Outer (veto)Detector

Based on KM3NET optical module

1 of concepts



20cm PMT for OD



3’’ PMT
Dark box setup to measure dark and position dependent resolution

Electronics and DAQ Systems

Candidates for signal digitization:

- Charge to Time converter with FPGA-based TDC (similar to SK)
- ~100MHz FADC + digital signal processing
- Digitizers based on capacitor array

Required specifications: 0.1 p.e. to 1250 p.e., ΔT=sub-nsec, Ch-by-Ch self triggered digitization, and < 1W/ch

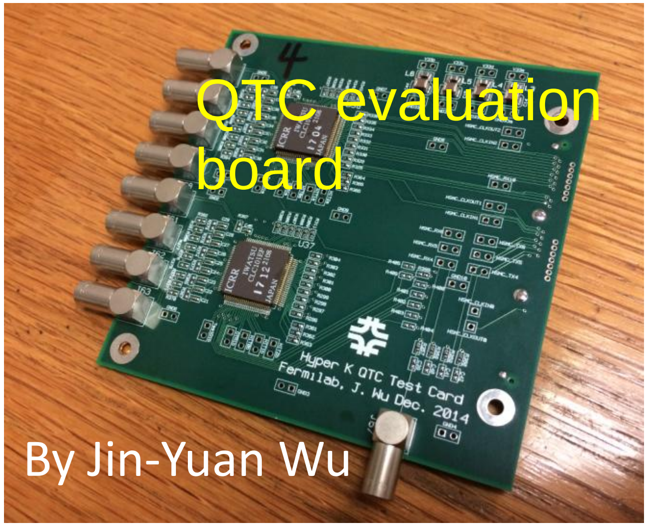
Front-end electronics and network connections under water

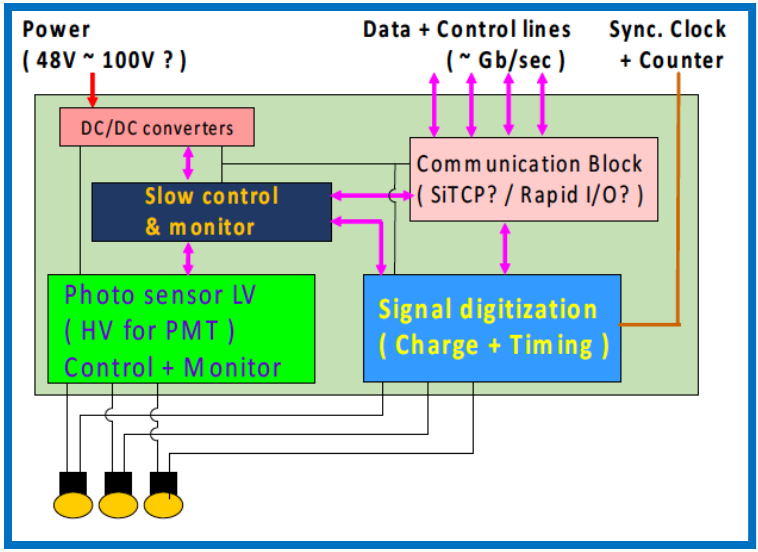
- Need redundant, fail-safe system

DAQ system above water reads out all the digitized hit signals

Simple majority trigger and intelligent trigger will follow

Use of GPUs, new algorithms to reduce noise.





Front-end module schematic diagram

Hyper-K Calibration

Hyper-Kamiokande detector calibrations has been designed based on Super-K calibrations

Feasible techniques/methods in Hyper-K

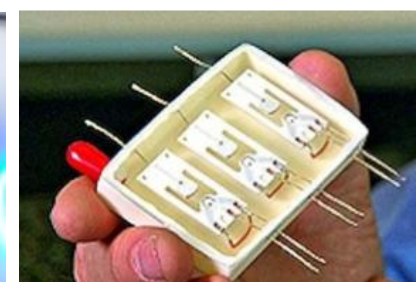
Several R&D projects are in progress to develop more sophisticated calibration systems and sources for Hyper-K

Photosensor Test Facility

Automated calibration system

Integrated light injection system

Compact neutron generator



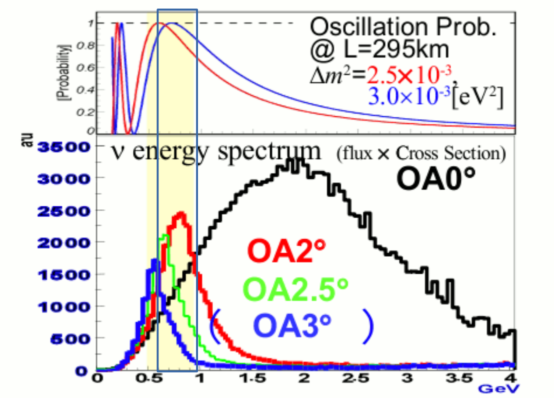
IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 40, NO. 9, SEPTEMBER 2012

Upgrade of J-PARC Neutrino Beam

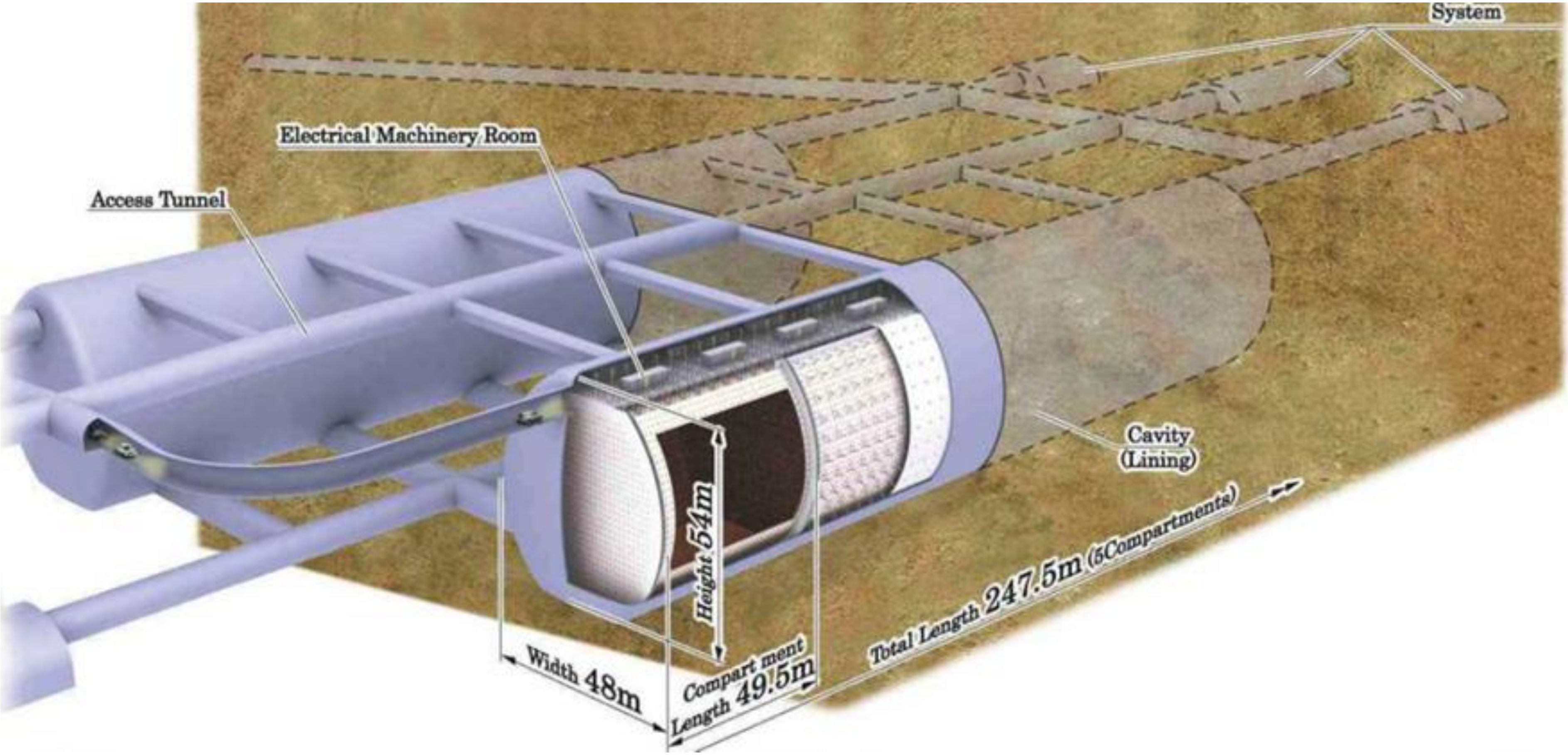
- All components will be able to receive the 1.3 MW beam when it is ready
- Current limitations and achievable limitations for the neutrino beam line:

TABLE II. Acceptable beam power and achievable parameters for each beamline component after proposed upgrades. Limitations as of May 2015 are also given in parentheses.

Component		Acceptable beam power or achievable parameter
Target		3.3×10^{14} ppp
Beam window		3.3×10^{14} ppp
Horn		
cooling for conductors		2 MW
stripline cooling	(400 kW $\rightarrow$)	1$\sim$2 MW
hydrogen production	(300 kW $\rightarrow$)	1$\sim$2 MW
power supply	(250 kA $\rightarrow$)	320 kA
	(0.4 Hz $\rightarrow$)	1 Hz
Decay volume		4 MW
Hadron absorber (beam dump)		3 MW
water-cooling facilities	(750 kW $\rightarrow$)	$\sim$2 MW
Radiation shielding	(750 kW $\rightarrow$)	4 MW
Radioactive air leakage to the TS ground floor	(500 kW $\rightarrow$)	$\sim$2 MW
Radioactive cooling water treatment	(600 kW $\rightarrow$)	$\sim$2 MW



Past Hyper-K Configuration



- Water Cherenkov, proven technology & scalability:
- Excellent PID at sub-GeV region >99%
- Large mass → statistics always critical for any measurements.

Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton ´ 10 compartments)
Outer Volume	0.2 Megaton
Photo-sensors	• 99,000 20”Φ PMTs for Inner Detector (ID)(20% photo-coverage) • 25,000 8”Φ PMTs for Outer Detector (OD)
Tanks	• 2 tanks, with egg-shape cross section » 48m (w) ´ 50m (t) ´ 250 m (l) • 5 optically separated compartments per tank

Extrapolation from T2K experience

- Beam flux + near detector constraint
  - Conservatively assumed to be the same
- Cross section uncertainties not constrained by ND
  - Nuclear difference removed assuming water measurements
- Far detector
  - Reduced by increased statistics of atmospheric ν control sample and fundamental detector response understanding with improved calibration

Uncertainty on the expected number of events at Hyper-K (%)

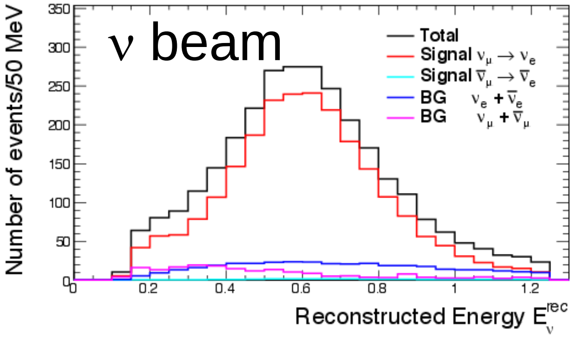
	ν mode		anti-ν mode	
	νe	νμ	νe	νμ
Flux&ND	3.0	3.3	3.2	3.3
XSEC model	0.5	0.9	1.5	0.9
Far Det. +FSI	0.7	1.0	1.5	1.1
Total	3.2	3.6	3.9	3.6

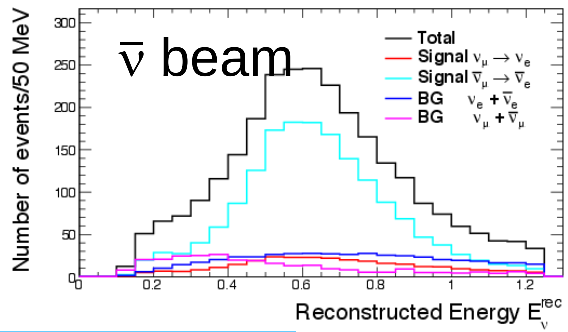
- Further reduction by new near detectors under study
- Benefit from experience with T2K(-II)

Expected Events

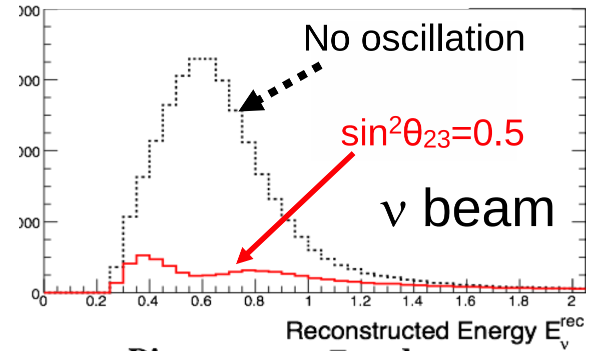
10 yrs data taking.

ν_e appearance

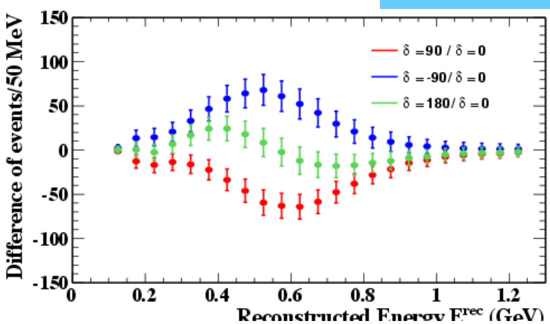


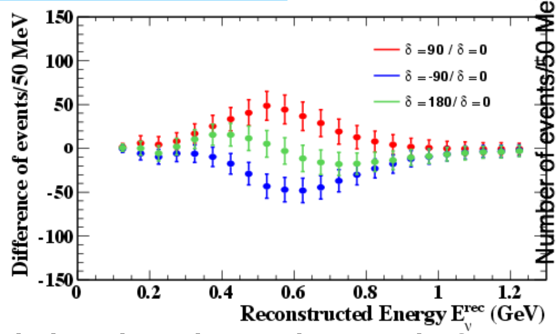


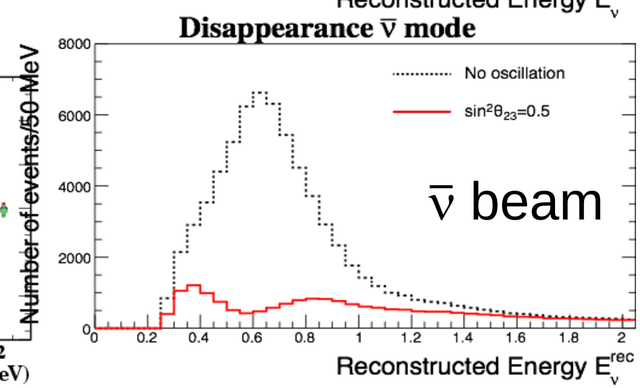
ν_μ disappearance



Difference from $\delta_{CP}=0$







δ_{CP} = 0°, 180° can be distinguished using shape information.

δ=0	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	2300	21	10	362	188
$\bar{\nu}$ beam	1656	289	6	444	274

	ν_μ , $\bar{\nu}_\mu$ CCQE	ν_μ CC nonQE	Others
ν beam	8947	4444	721
$\bar{\nu}$ beam	12317	6040	859

Precision measurements

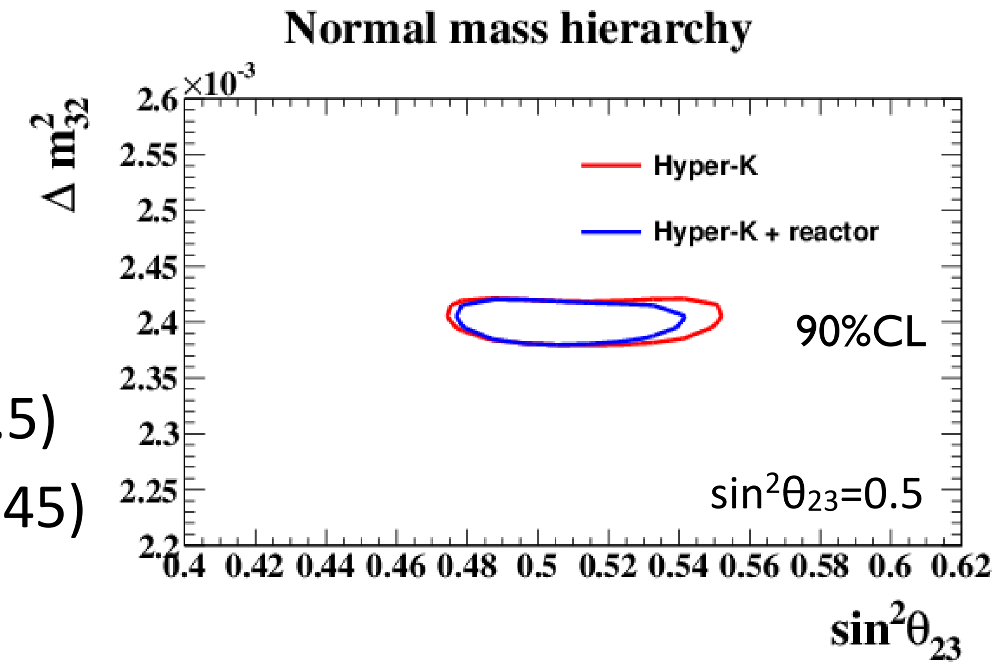
$\delta(\Delta m^2_{32})$~$1.4\times10^{-5}eV^2$

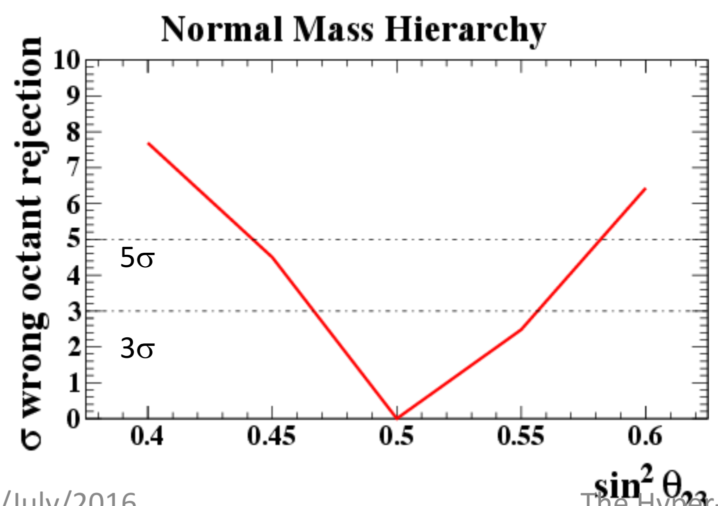
→Mass hierarchy sensitivity in combination with reactor.

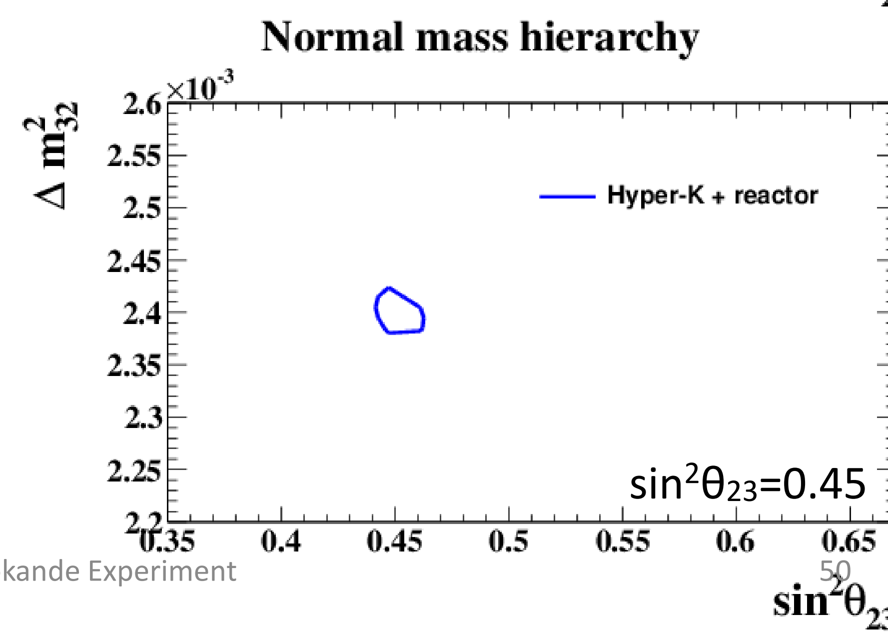
$\delta(\sin^2\theta_{23})$~0.015 (for $\sin^2\theta_{23}$=0.5)

~0.006 (for $\sin^2\theta_{23}$=0.45)

→Octant determination input to models.







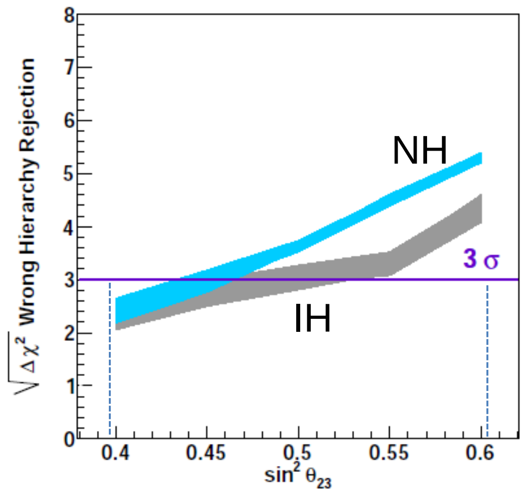
Mass Hierarchy and Octant Sensitivity: Atmospherics

Variety of physics with atmospheric ν:

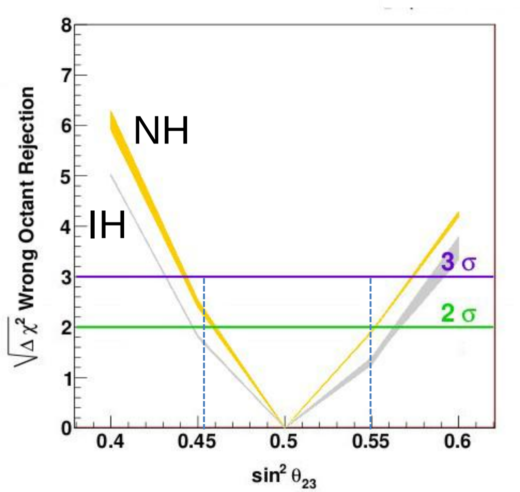
- MH, θ_{23} octant, CP
- Sterile neutrino , LV, etc

With atmospheric alone,

- mass hierarchy sensitivity
- >3σ octant determination for | θ_{23} -45°|>8°



Mass hierarchy determination



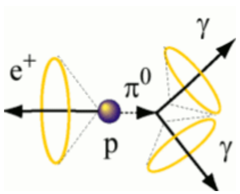
θ_{23} octant determination

10 yrs NH		Mass Hierarchy (σ)	
		Atm	Atm+Beam
PTEP	θ_{23}4.0=	3.8	6.9
	θ_{23}6.0=	8.4	9.9
2Tanks	θ_{23}=0.4	2.2	5.3
	θ_{23}=0.6	5.2	6.9

10 yrs NH	Octant (σ)	
	Atm	Atm+Beam
θ_{23}45.0=	3.6	7.2
θ_{23}55.0=	2.7	4.0
θ_{23}=0.45	2.2	5.8
θ_{23}=0.55	1.7	3.7

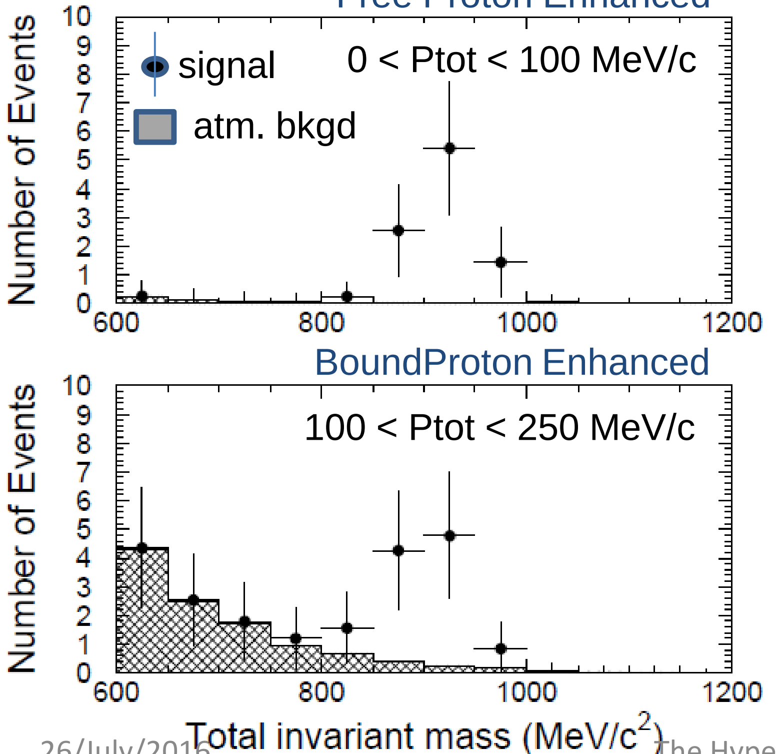
Proton Decay Sensitivity, p → $e^+ \pi^0$

Proton decay p → $e^+ \pi^0$ is a favoured model of many GUTs.

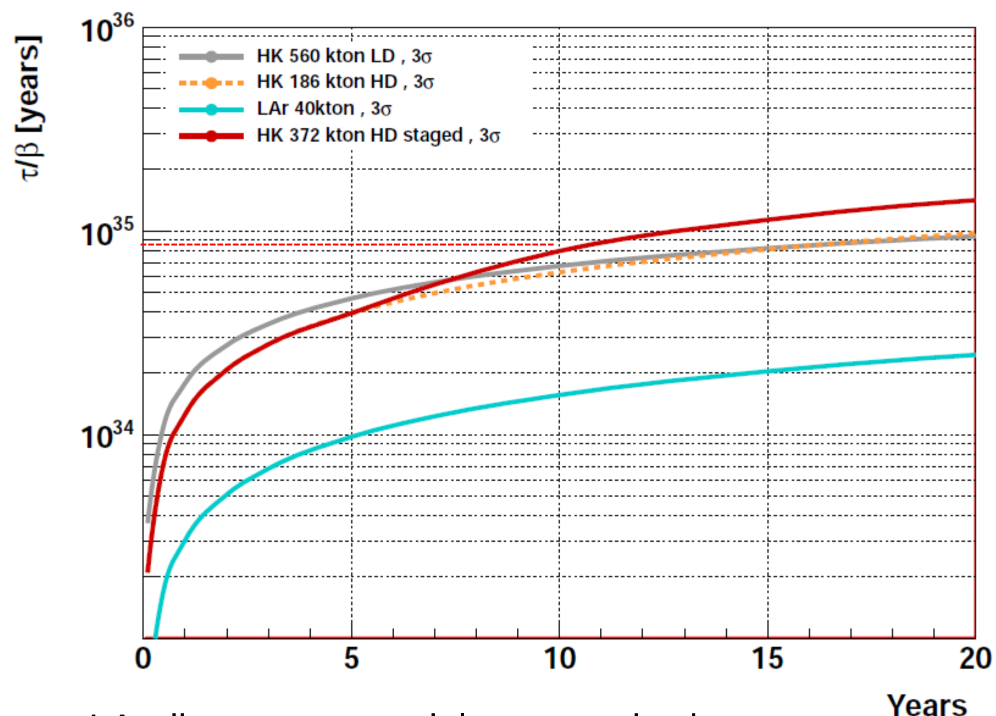


Similar analysis as in SK but with neutron tagging (remove events with a tagged neutron) thanks to improved PMTs.

$\tau_{proton}=1.4\times10^{34}$years (SK 90% CL limit)

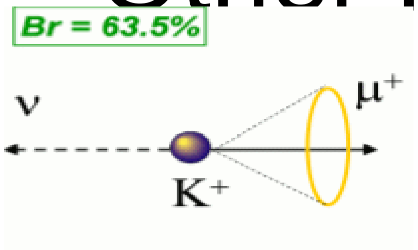


3σ discovery potential reaching τ ~ 10^{35} yrs. Similar sensitivity to PTEP, thanks to the neutron tagging.



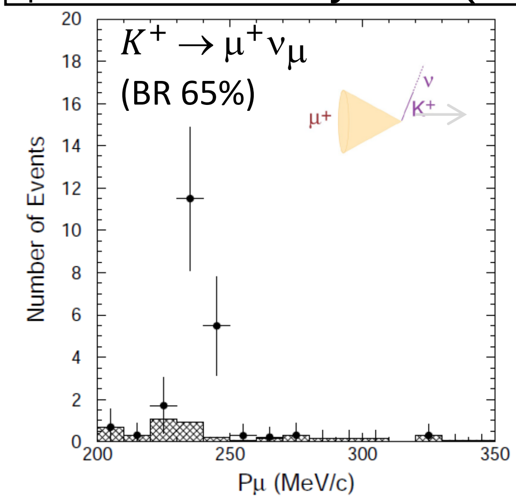
LAr discovery potential computed using numbers from DUNE CDR 2015.

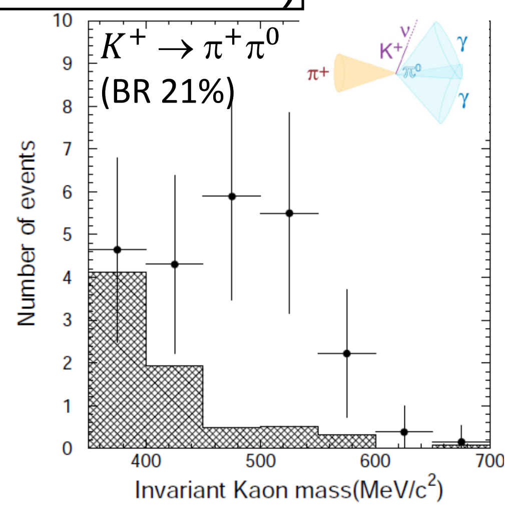
Other Proton Decay Sensitivities



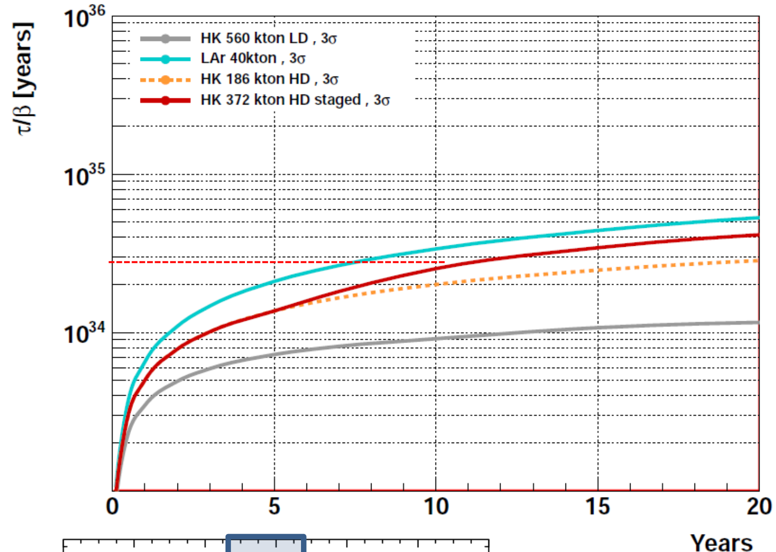
Proton decays into a lepton and a kaon are one of the most prominent features of Supersymmetric Grand Unified Theories.

τ_{proton}=6.6×10^{33}years (SK 90% CL limit)

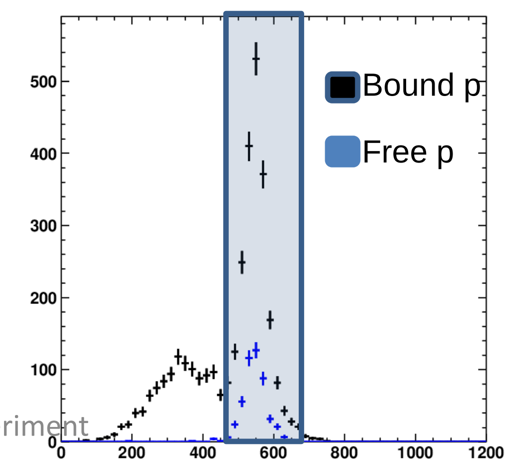




3σ discovery potential



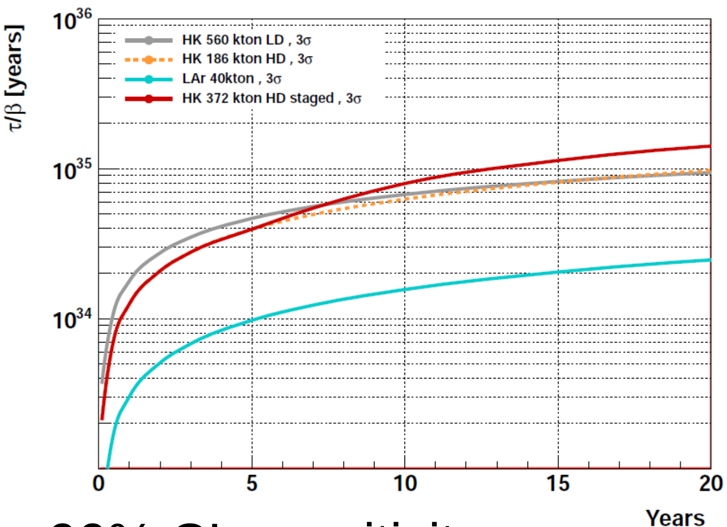
Hyper-K will be sensitive to a wide variety of further proton decay modes, and is expected to have sensitivity that exceeds current limits by an order of magnitude or more.



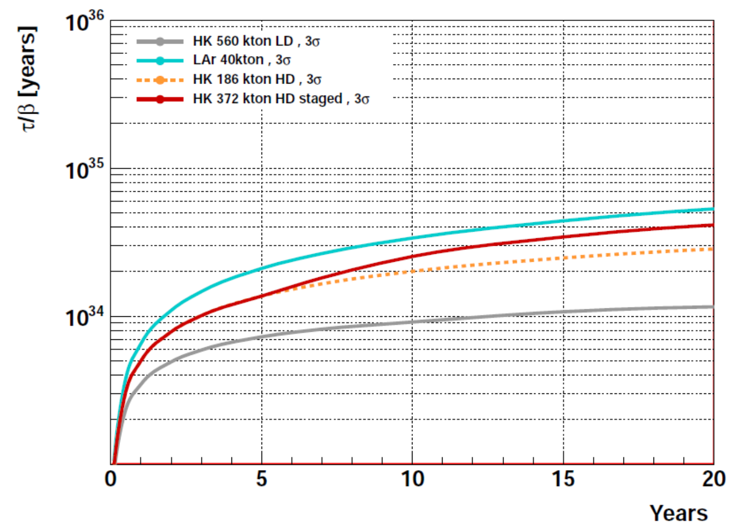
$p \to e^+ \eta$

$\eta \to \gamma\gamma$

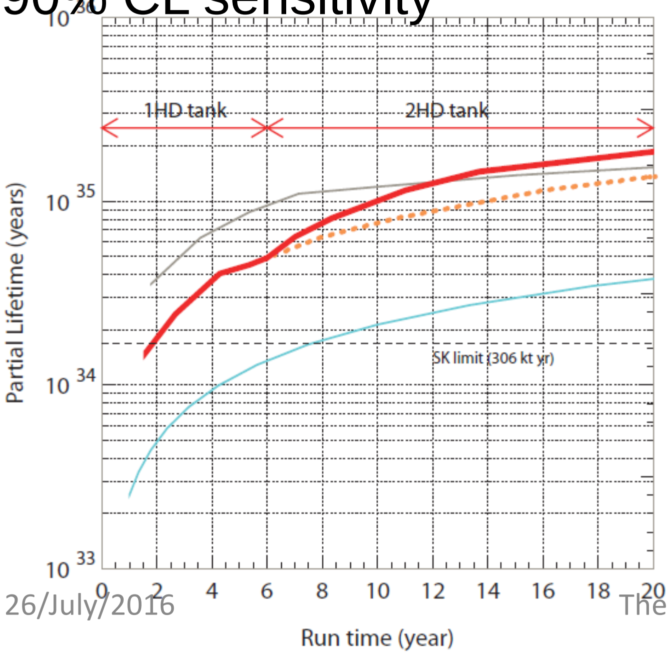
p → $e^{+}\ \pi^{0}$
3σ discovery potential



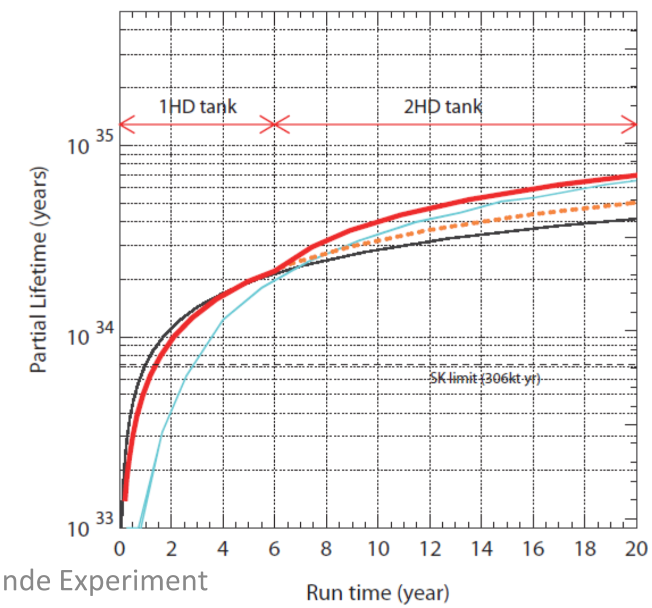
p→$\bar{\nu}K^{+}$
3σ discovery potential



90% CL sensitivity



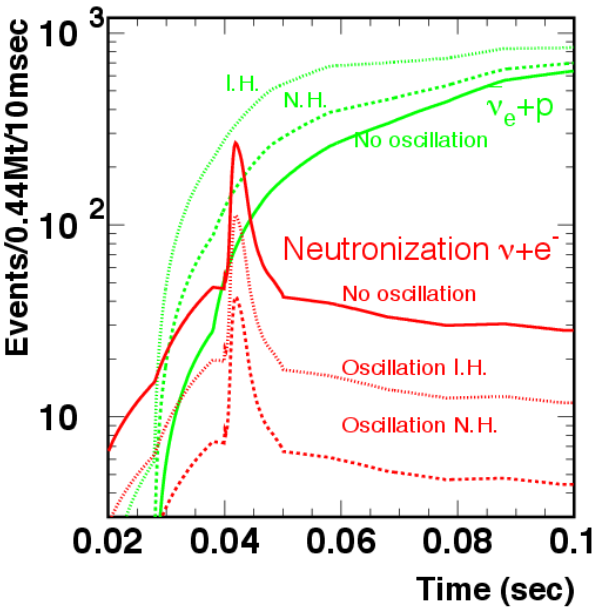
90% CL sensitivity

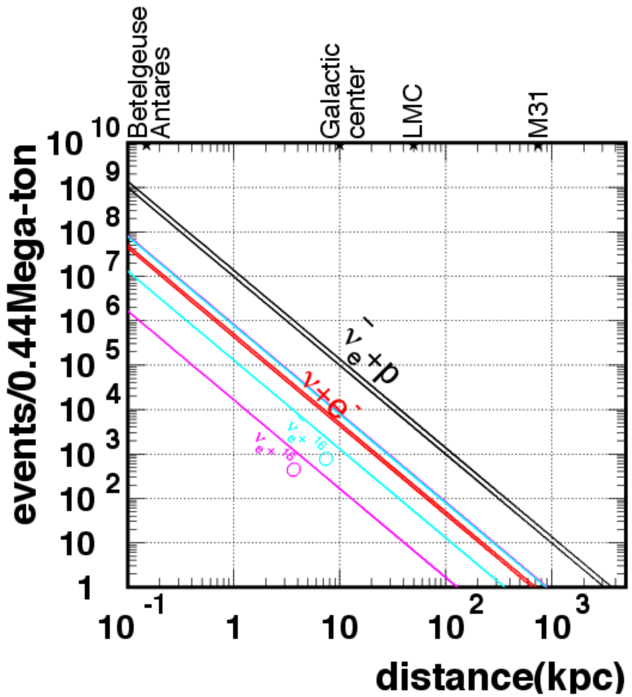


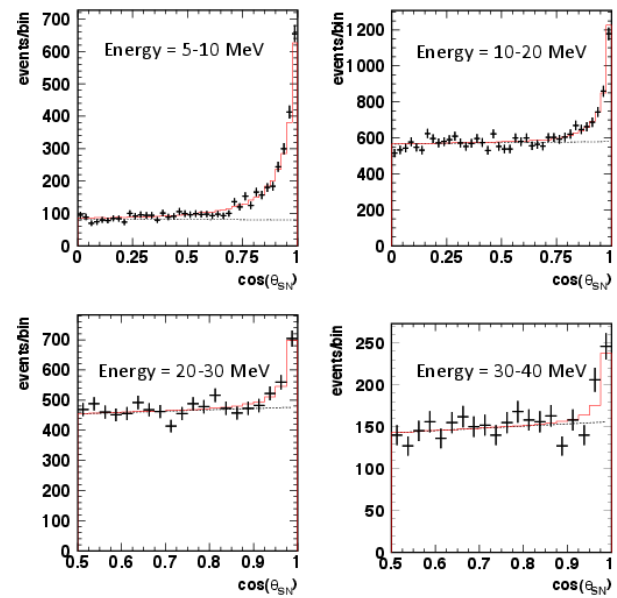
Supernova Burst Neutrinos

ν_e from neutronization:12~80 ev
SN explosion mechanism

SN directional info
by ν + e scattering







Galactic SN (<1 Mpc)

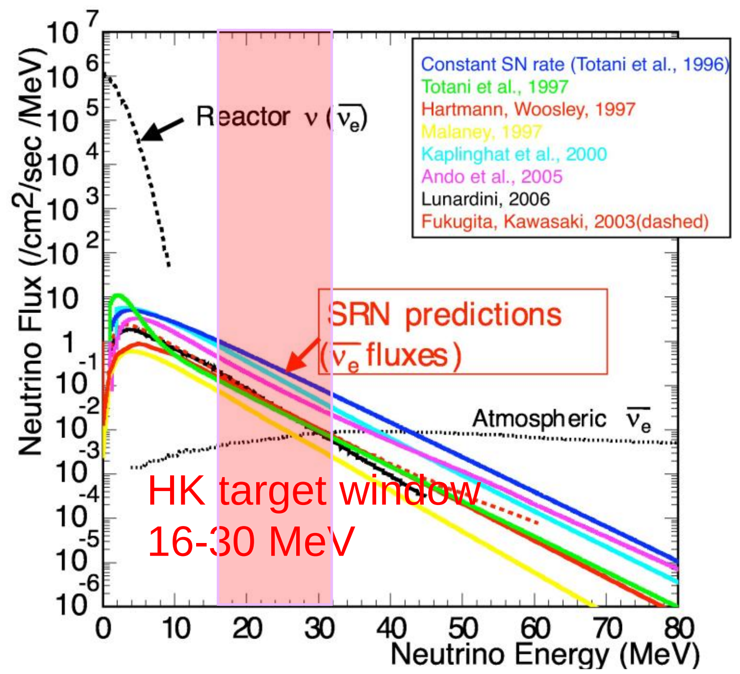
- Large statistics: 104,000~158,000 events (10kpc)
- Time spectrum of SNν: SN model separation, SN burst time
- Energy spectrum measurement: ΔE/E~20% at 10-20 MeV
- Direction, time, fluctuations of ν flux

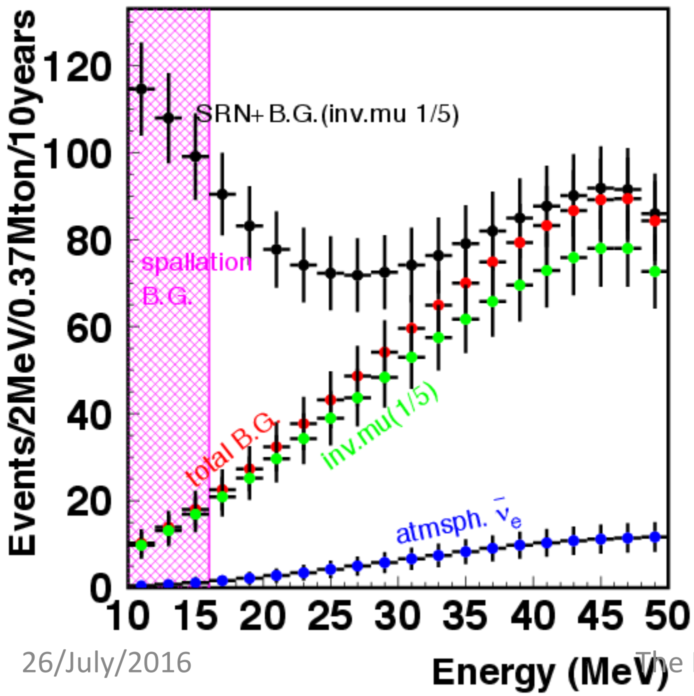
Nearby Galactic SN (>1 Mpc): ~2-20 SNν for 20y

SuperNova Relic Neutrinos

Supernova Relic Neutrinos:

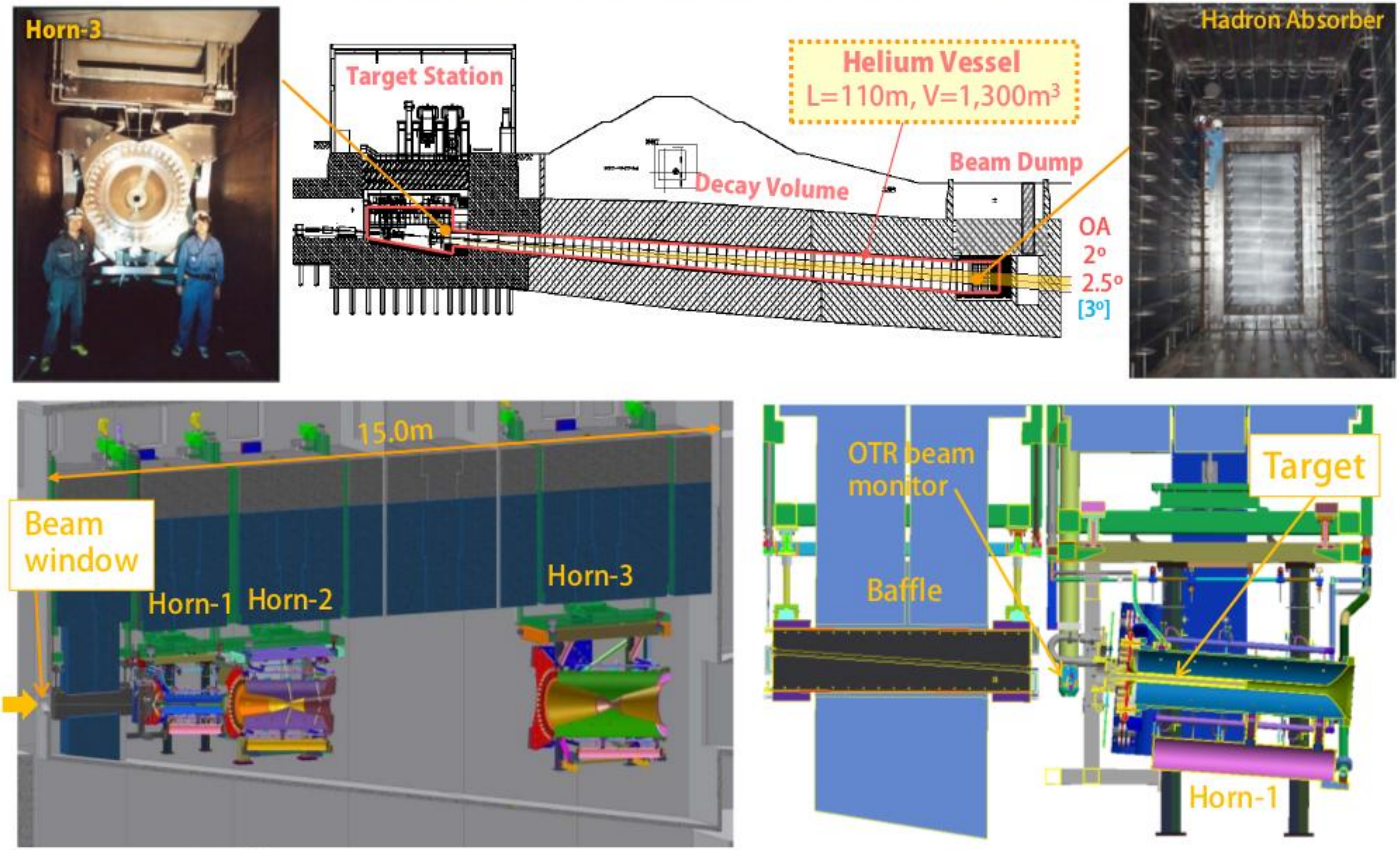
- Diffused or integrated ν from past SN
- Detectable with enough sensitivity
- Measurement will probe:
  - Star formation rate
  - Energy spectrum SN ν
  - …



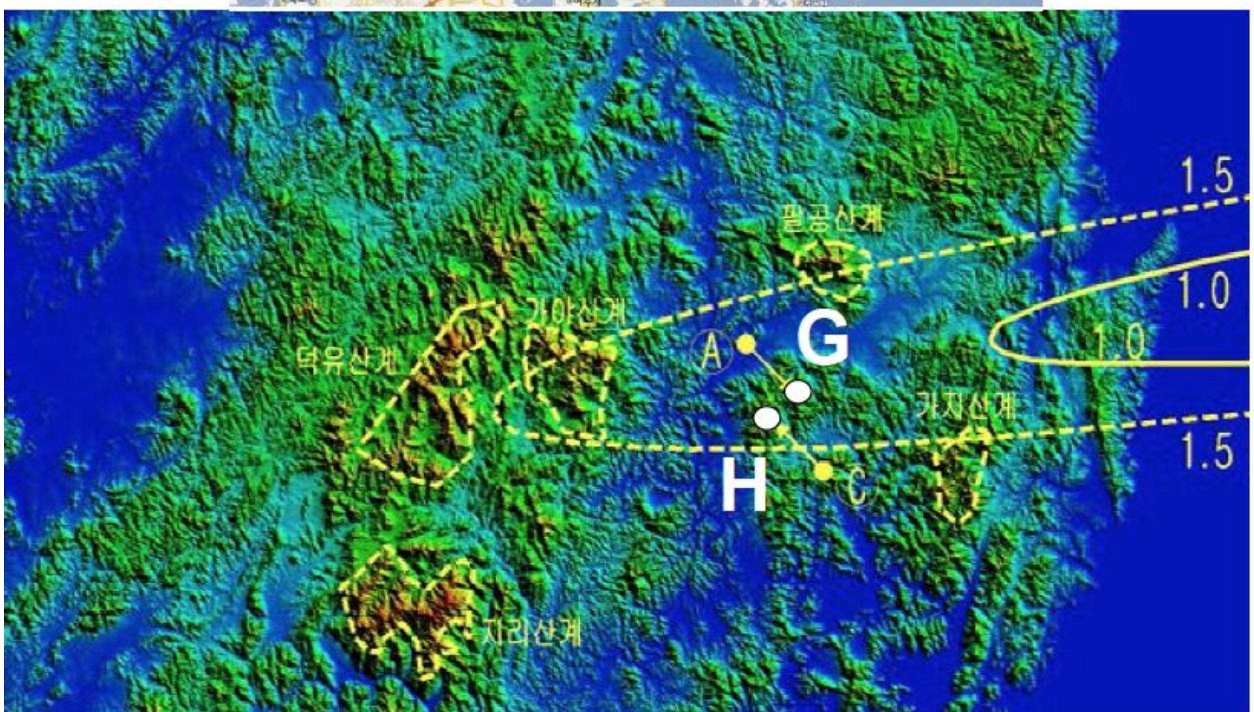


- Use neutron tagging.
- Expected events in HK in 10y: ~98 ± 20 (4.8σ).

Target Facility (Secondary Beam-line)



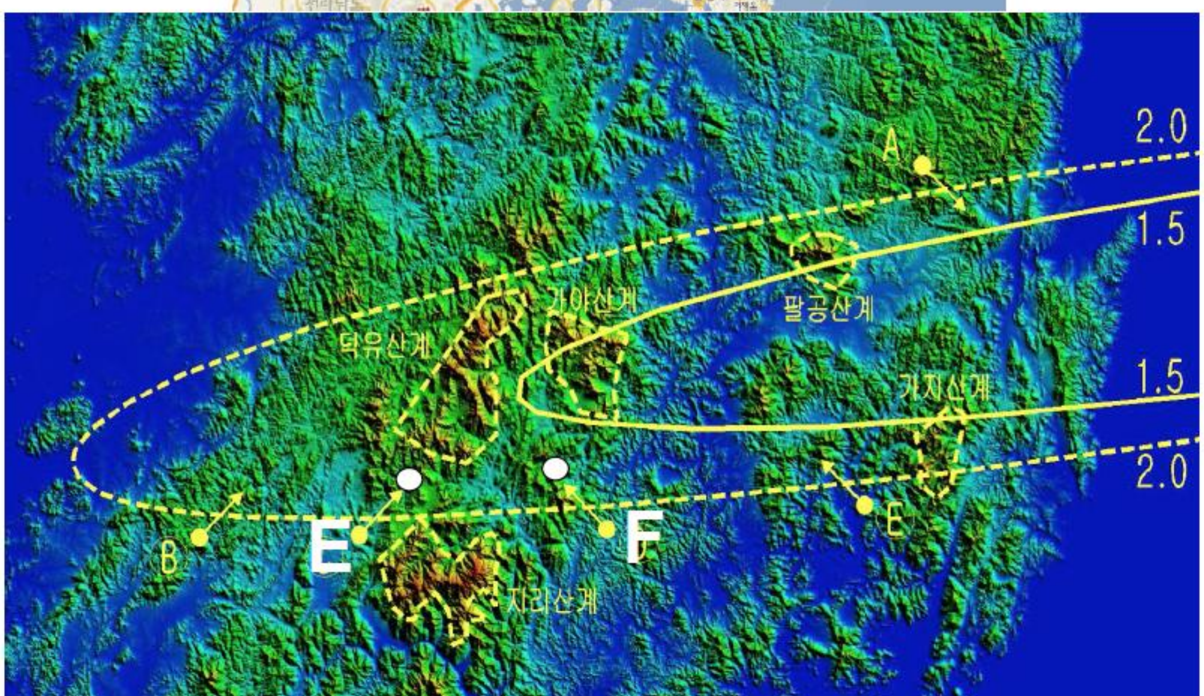
Candidate sites in Korea (OA 1~1.5º)



G : Mt. **Choejung**
(906 m high)
[granite porphyry, andesitic breccia]

H : Mt. **Bisul**
(1,084 m high)
[granite porphyry, andesitic breccia]

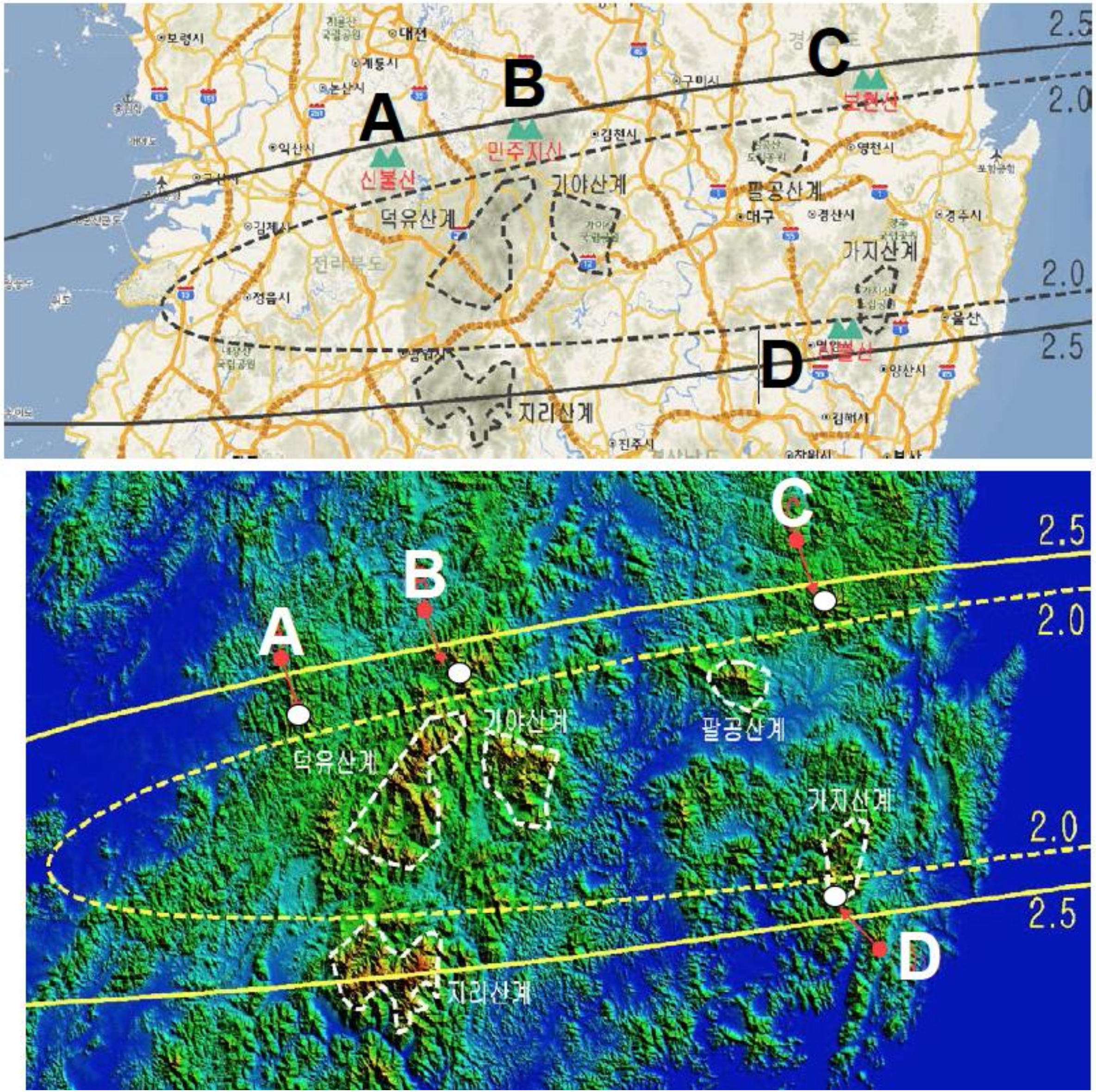
Candidate sites in Korea (OA 1.5~2.0º)



E : Mt. Sambong
(1,186 m high)
[porphyritic granite, biotite gneiss]

F : Mt. Hwangmae
(1,113 m high)
[Flake granite, porphyritic gneiss]

Candidate sites in Korea (OA 2~2.5º)



- **Rock condition :**

Most rocks are solid granite.
(Felsic igneous rocks: 규장질 화성암)

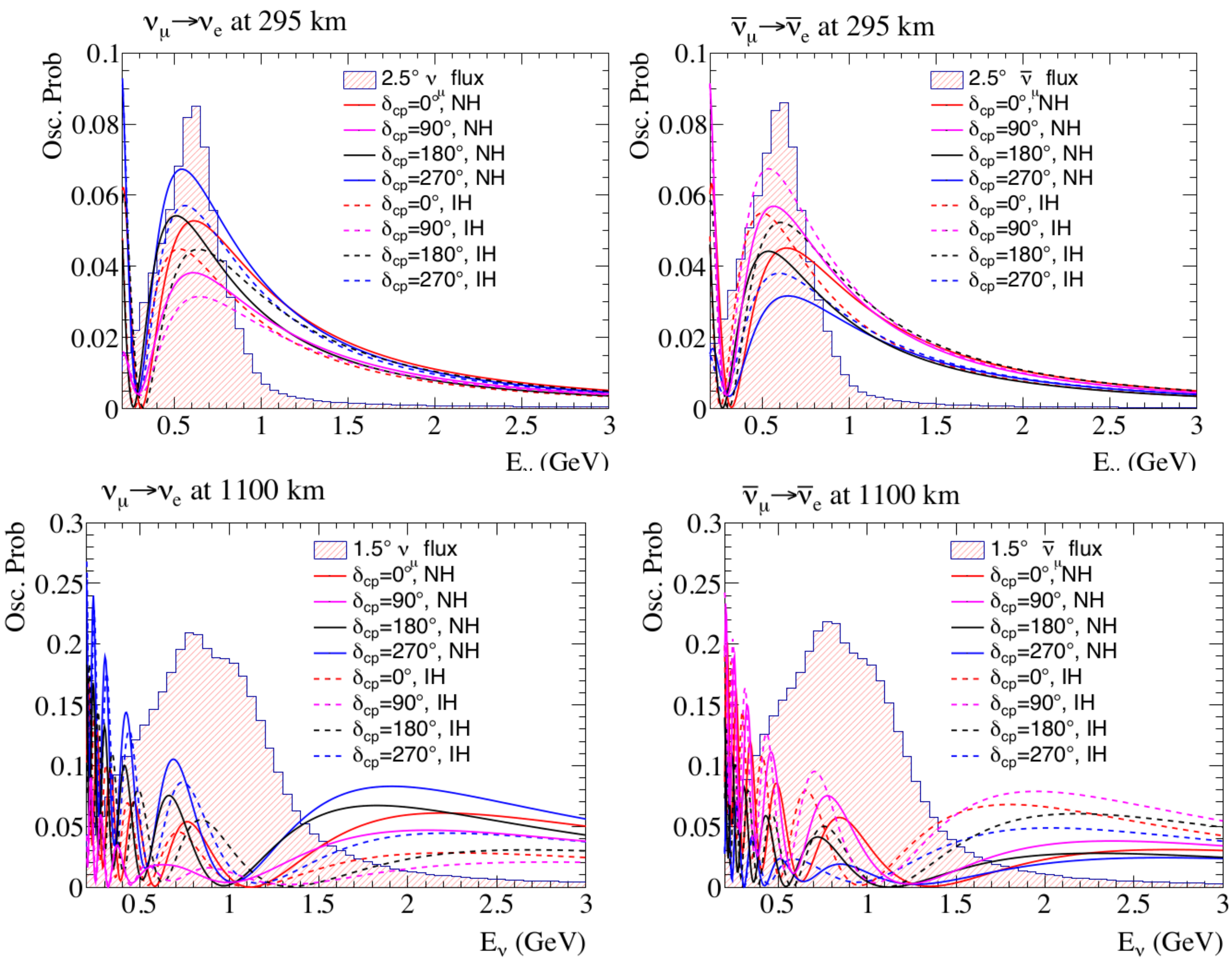
A : Mt. **Unjang**
(1,125 m high)
[rhyolite, granite porphyry, quartz porphyry]

B : Mt. **Minjuji**
(1,242 m high)
[granite, biotite gneiss]

C : Mt. **Bohyun**
(1,126 m high)
[granite, volcanic rocks, volcanic breccia]

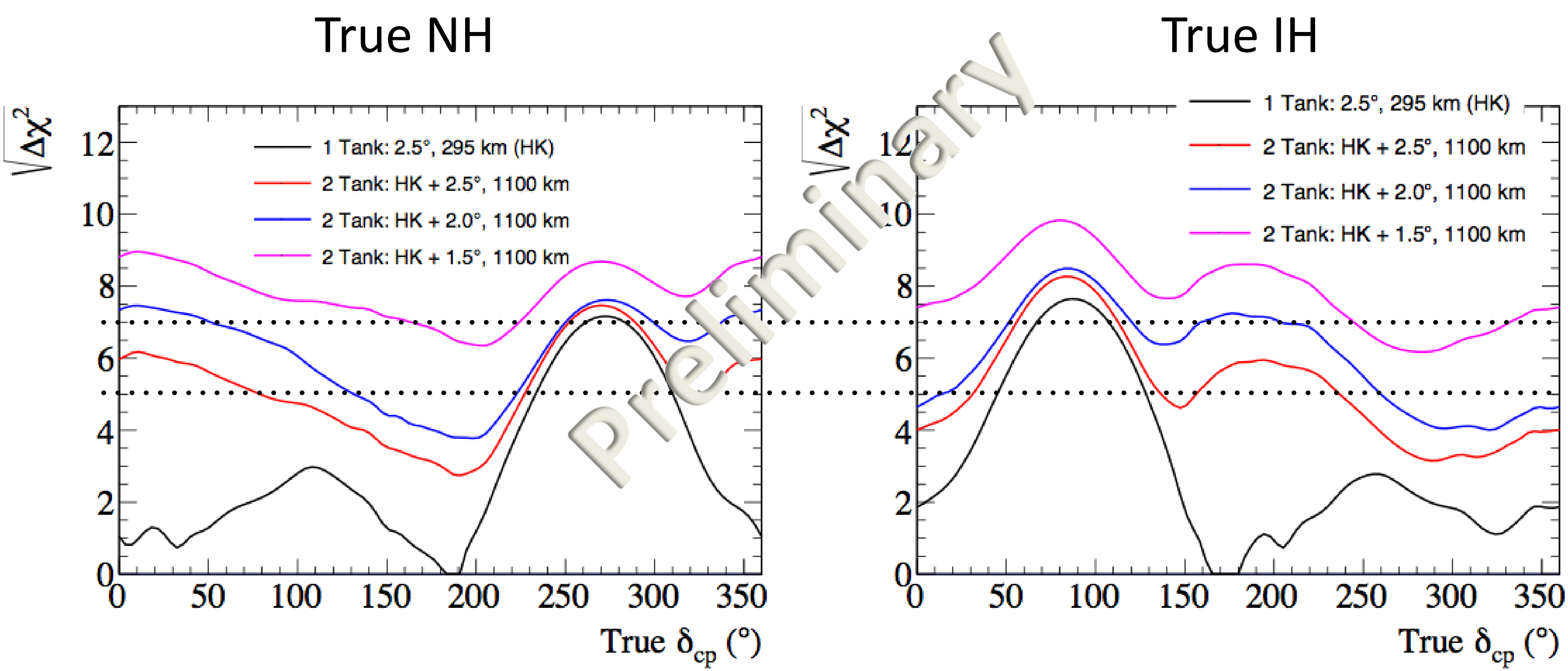
D : Mt. **Shinbul**
(1,159 m high)
[andesite, andesite porphyry, tuff]

Beam Fluxes



$\nu_\mu \to \nu_e$ at 295 km
$\bar{\nu}_\mu \to \bar{\nu}_e$ at 295 km
$\nu_\mu \to \nu_e$ at 1100 km
$\bar{\nu}_\mu \to \bar{\nu}_e$ at 1100 km
Osc. Prob
E_ν (GeV)
2.5° ν flux
2.5° $\bar{\nu}$ flux
1.5° ν flux
1.5° $\bar{\nu}$ flux
δ_{cp}=0°, NH
δ_{cp}=90°, NH
δ_{cp}=180°, NH
δ_{cp}=270°, NH
δ_{cp}=0°, IH
δ_{cp}=90°, IH
δ_{cp}=180°, IH
δ_{cp}=270°, IH

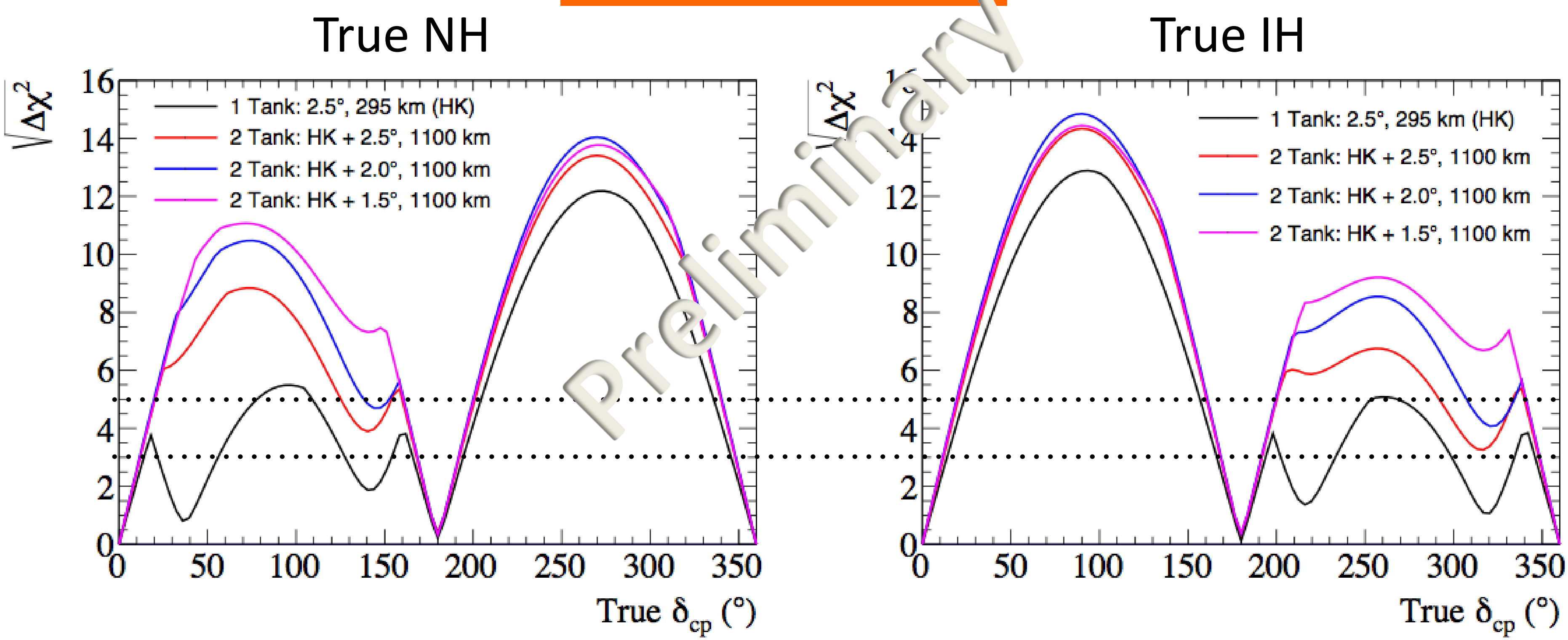
Mass Hierarchy Sensitivity, 2Detector



- With two detectors, the 1.5 degree KD+HK is the only option giving over 5 "sigma" for all true values of δ and the hierarchy

δ_{cp} Sensitivity, 2 Detectors

Unknown hierarchy



- In combination with the HK detector, it looks like the KD at 1.5 degrees is best for ensuring 5 sigma significance over the widest range of δ values