

Hyper-Kamiokande

gigantic detector to confront ementary particle unification theories and the mysteries of the Universe's evolution

The Hyper-Kamiokande

Experiment

EPS 2017



- On behalf of the Hyper-Kamiokande Collaboration



The Hyper-K Collaboration















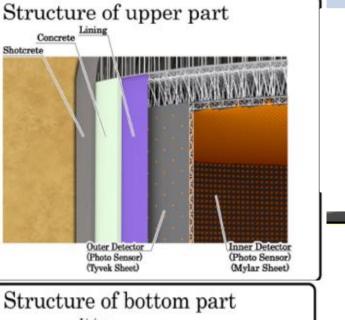


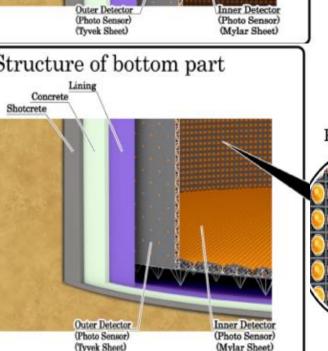


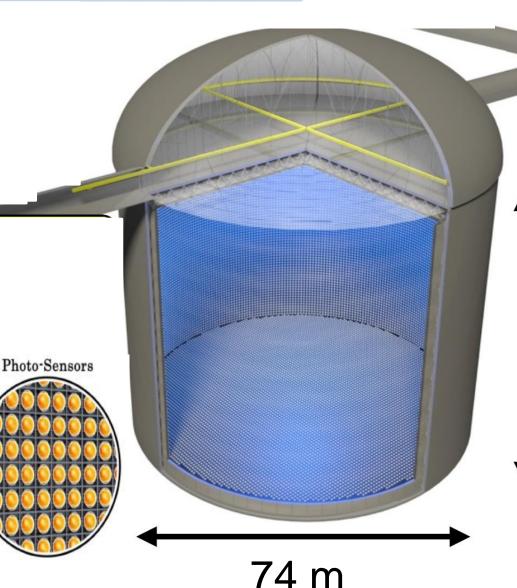
Collaboration formed in January 2015

~300 members and growing from 15 countries

Hyper-Kamiokande design







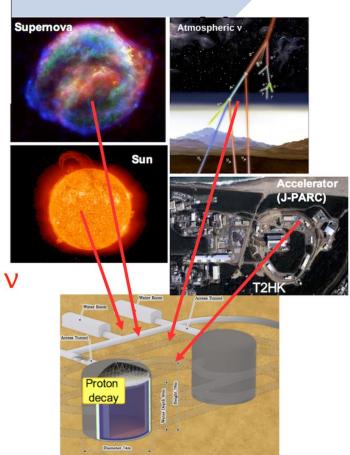
Optimized for cost and quick start

Total volume: 260kton × 2
Fiducial volume: 190kton × 2
(~×10 of Super-K per tank)
Start with one tank, staging
40% coverage with new sensor
×2 photon sensitivity
40,000 50cm ID PMTs
6,700 20cm OD PMTs

78 m

Broad Science Program with Hyper-K

- Neutrino oscillation physics
 - Comprehensive study with beam and atmospheric neutrinos
 CPV, hierarchy ,θ₂₃ octant
- Search for nucleon decay
 - Possible discovery with $\sim \times 10$ SK All visible modes $p \rightarrow e^+ \pi^0 p \rightarrow \bar{\nu}K^+$
- Neutrino astrophysics
 - Precision measurements of solar V
 - High statistics measurements of SN burst V
 - Detection and study of relic SN neutrinos
- Geophysics (neutrinography of interior of the Earth)
- Maybe more (unexpected)



Extend highly successful program of Super-K

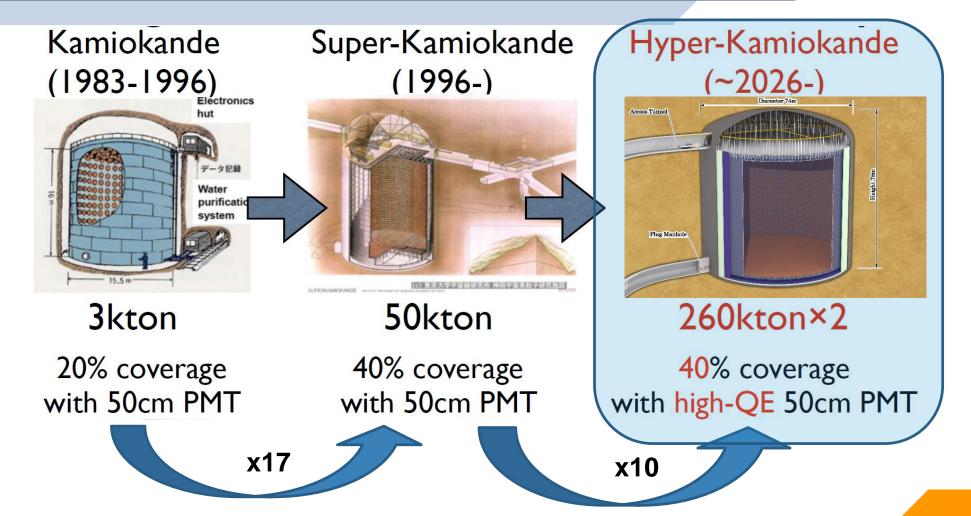
Please see:

Luis Labarga's talk: Neutrino oscillation physics at Hyper-Kamiokande 06/07/2017, 17:30

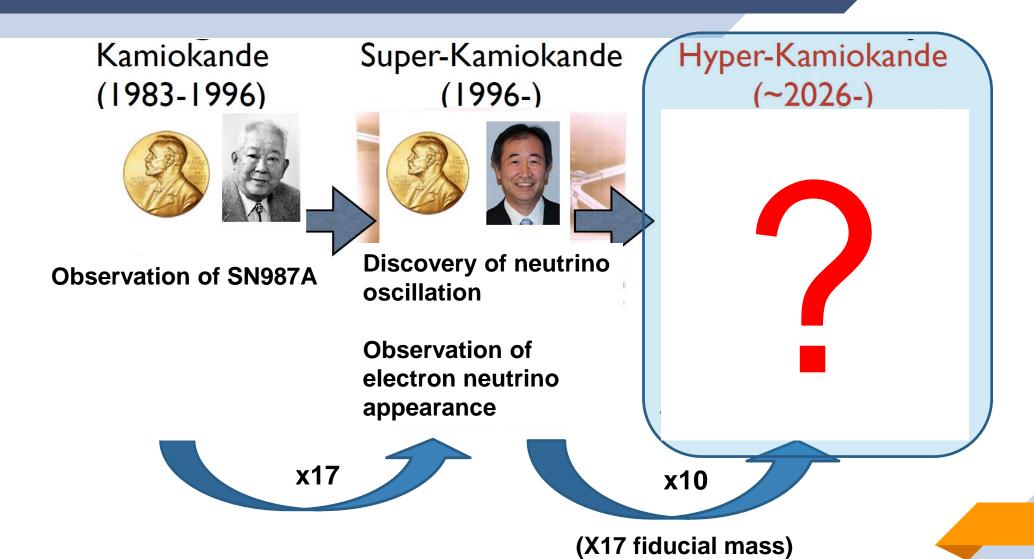
Jost Migenda talk:

Astroparticle Physics in Hyper-Kamiokande 08/07/2017, 10:45 (Astroparticle physics)

3 Generations of Kamioka Detector



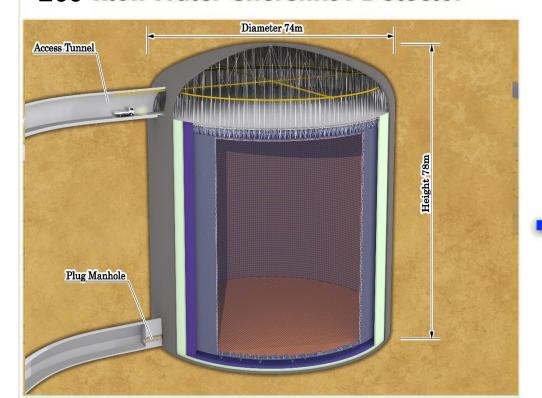
3 Generations of Kamioka Detector





Nominal Design: 1st tank in Tochibora with the second tank following after 6 years

260 kton Water Cherenkov Detector

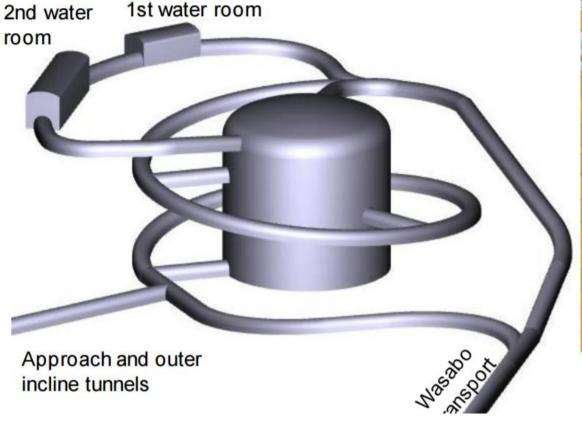


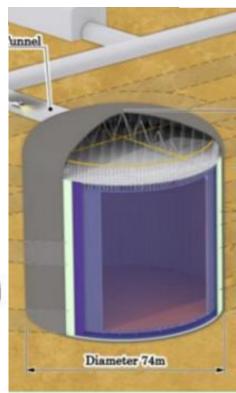
Upgraded J-PARC neutrino beam. New/upgraded near detectors

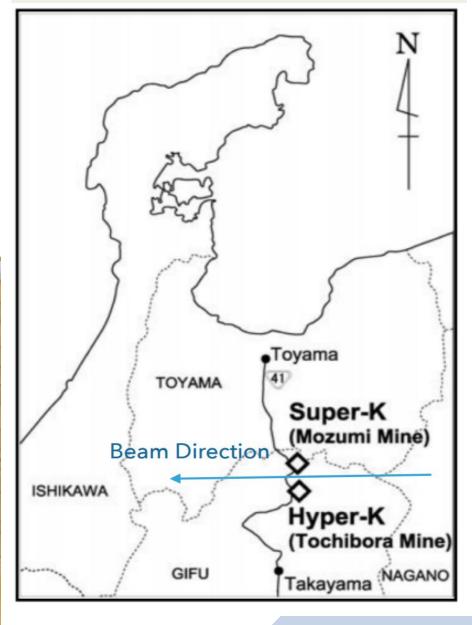


- The candidate site located in Tochibora, under Mt. Nijugoyama:
 - ~8km south from Super-K, 295km from J-PARC, 2.5°
 off-axis

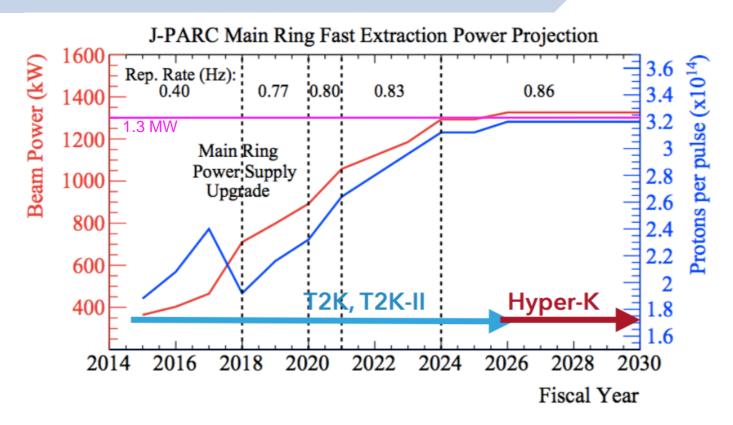
Overburden ~650m (~1755 m.w.e.)





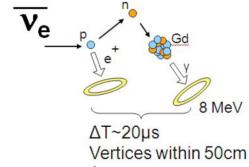


J-PARC Neutrino Beam Upgrade

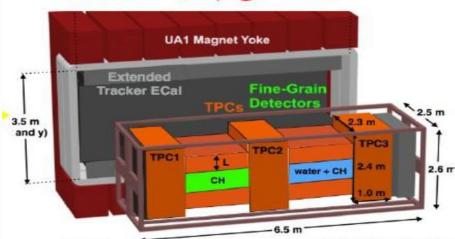


- Increase of protons per pulse from current 2.1x10¹⁴ to 3.2x10¹⁴
- Power improvement largely achieved through rep rate increase from 0.4 to 0.8 Hz
- 750 kW will be achieved after 2018 Main Ring power supply magnet upgrade
- Increase of the J-PARC beam power to >1.3 MW by 2026 (Hyper-K start)

Tokai to Hyper-Kamiokande



ND280 (Upgrade)

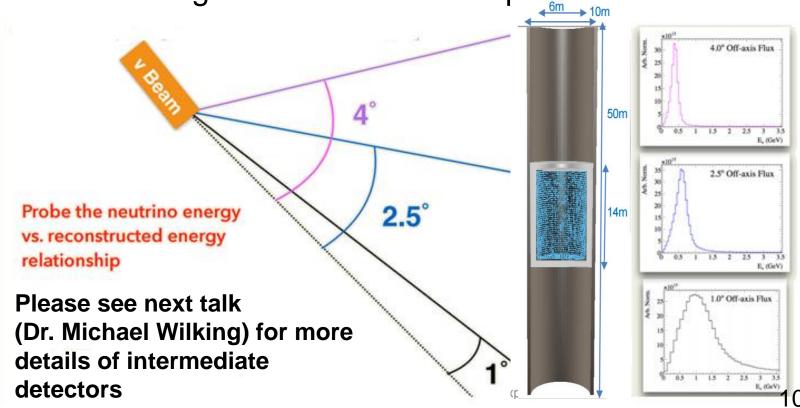


Near detector ND280 to continue for Hyper-K

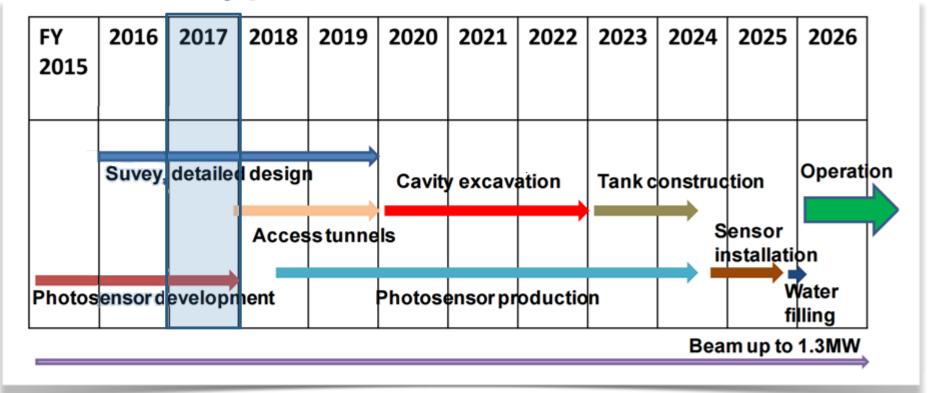
Use upgraded J-PARC neutrino beam line (same as T2K) with expected beam power > 1.3MW, 2.5° off-axis angle, narrow-band beam at ~600MeV

New Intermediate WC detector (at ~1.2 km) being investigated (E61, merger of TITUS and NuPrism)

- Off-axis angle spanning orientation
- Gd loading to measure neutron production



The Hyper-Kamiokande Timeline



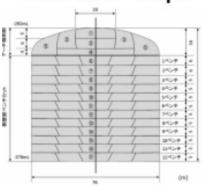
- 2018 2025 HK construction.
- 2026 onwards CPV study, Atmospherics v, Solar v, Supernova v, Proton decay searches, ...
- The 2nd identical tank starts operation 6yrs after the first one.

Cavern & Tank

Cavern geological surveys and fine element analysis

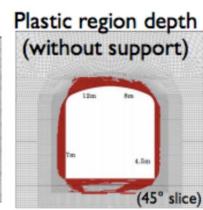
undertaken

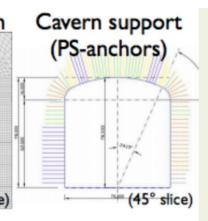
Excavation steps



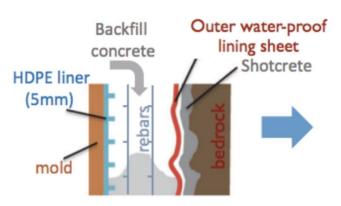
3D model for stability analysis

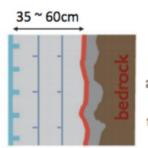
(ex. at an excavation step)





Water containment: 3 layers of lining





HDPE liner automatically fastened on the concrete

Studded HPDE lining sheet



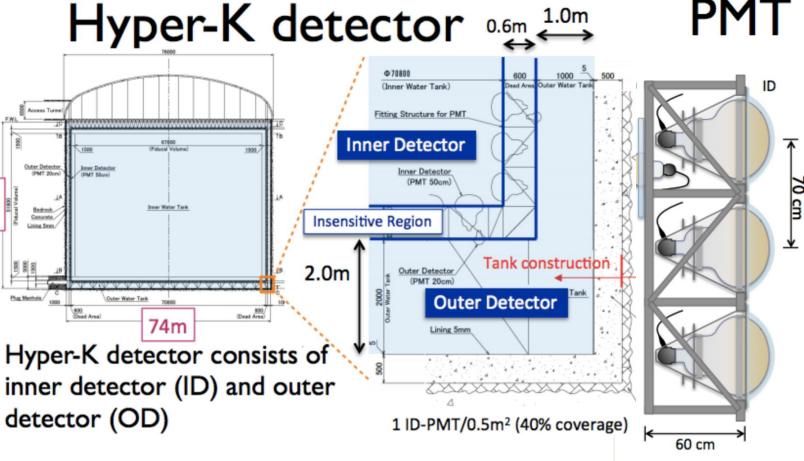


Three layers of liners are constructed simultaneously

→ Minimize the const. time

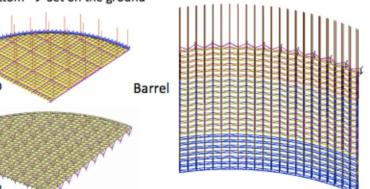
- 1. Outer water-proof sheet
- 2. Concrete linning
- 3. High Density Polyethylene (HDPE) lining

Tank & PMT Support



PMT support structure

- PMT support structure adopts a truss structure made of SUS members (angles)
- Seismic response analysis confirmed earth quake do not make damage to the detector
 - even if no water in the tank
 - Top/Barrel → Hung from the ceiling
 - Bottom → Set on the ground

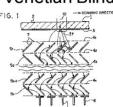


Upgraded Photo sensors

Photo Multipliers (PMTs)

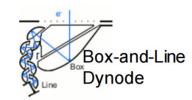


Venetian Blind





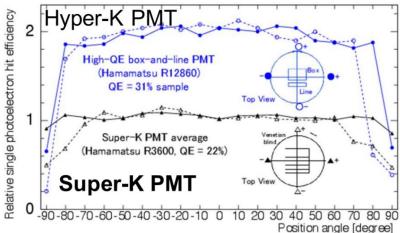
50cm HQE Box&Line PMT



The H

Efficiency x 2, Timing resolution x 2
 Pressure tolerance x 2 (>100m)
 Enhance n→vK⁺ signal, solar y, neutro

Enhance $p \rightarrow \overline{\nu} K^+$ signal, solar ν , neutron signature of $np \rightarrow d+\gamma(2.2 \text{MeV}),...$



Other Developments:

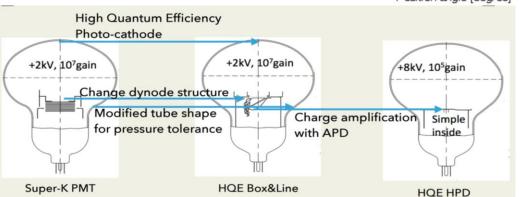
Hybrid Photo Detectors (HPDs)



w/ 20mm o AD



Under viability study

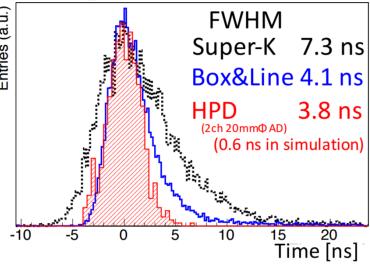


Single Photoelectron (PE) Charge [σ / peak] Supre-K 53% Box&Line 35% HPD 10% (Limited by preamp noise) y 2 PE

Single Photoelectron Time

Photoelectron)

Loss in backscattering of e



OD, Pressure Vessels and MPMTs

PMT Covers

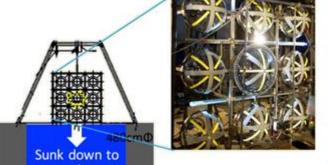
Prototype acrylic + stainless steel cover has been developed

Limit the flow of water into evacuated area if PMT implodes → avoid shockwave

Optimization and reduction of cost are under

consideration

60m/80m



Test in Furano, Hokkaido



Implosion test carried out at 60 m and 80 m water depths

No chain implosion observed

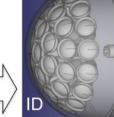
- **OD:** Working on designs for the OD including:
 - 3" and 5" PMTs from various manufacturers (good tts)
 - PMT housing and distributions
 - Use of wavelength shifting plates and housings

Multi-PMTs (MPMTs)

- 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

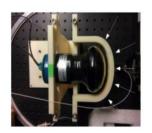




20cm PMT for OD

1 of concepts

33 8cm(3-inch) PMTs



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

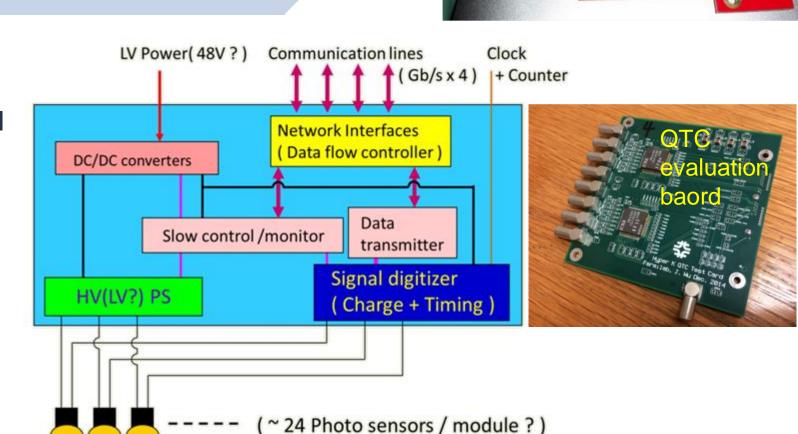
Electronics

Candidates for signal digitisation:

- 1. Charge to time converter with FPGA-based TDC (similar to sk)
- FADCC (~100MHz) +digital signal processing
- Digitisation based on switch capacitor array

Front-end electronics requirements:

- Wide Charge dynamic range
 - 0.1 ~ 1250 p.e.
- Good timing resolution
 - ~ Sub ns
- Self triggering
 - ~ Channel by channel
- Low power consumption
 - < 1W/ch</p>
- Place modules in the water



DAQ

DAQ Requirements

- DAQ system will readout all the digitised hits
- Hits will be buffered in case of supernova
- Simple nhits trigger and more advanced triggering
- System needs to be fault tolerant

ToolDAQ

ToolDAQ is an open source modular scalable DAQ Framework that is being used to develop the DAQ software for Hyper-K.

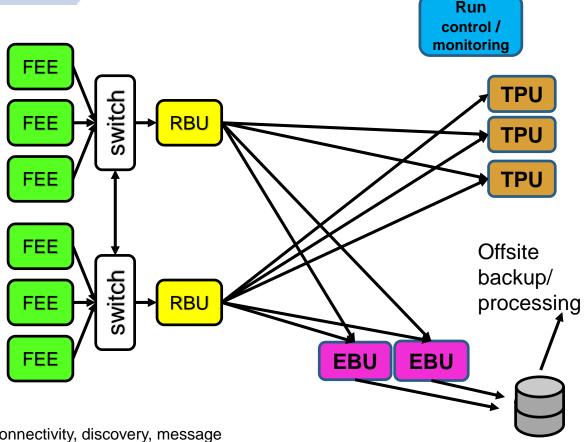
GPUs have been used to develop some of the advanced trigger algorithms and integrated into the DAQ using ToolDAQ.

Preliminary results show a 5 order of magnitude performance increase

ToolDAQ Features

- Pure C++
- Fast Development
- Very Lightweight
- Modular
- Highly Customisable / Hot swappable modules
- Scalable (built in service discovery and control)

- Fault tolerant (dynamic connectivity, discovery, message caching)
- Underlying transport mechanisms ZMQ (Multilanguage Bindings)
- JSON formatted message passing
- Few external dependencies (Boost, ZMQ)



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Hyper-K Calibration

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

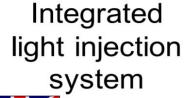
Feasible techniques/methods in Hyper-K

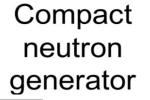
Several R&D projects are in progress to develop more sophisticated calibration systems and sources for Hyper-K

Photosensor Test Facility



Automated calibration system





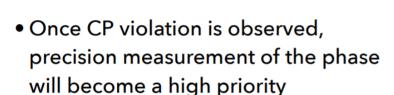




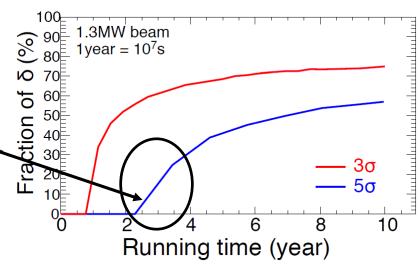


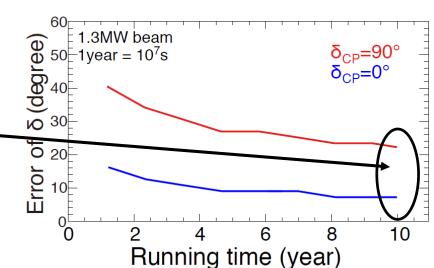
Hyper-K Sensitivity to δ_{cp}

• If CP violation is near maximal, HK can make a 5σ discovery in 2-4 years



- Near maximal CP violation, the HK precision is ~20° compared to ~8° near CP conserving values
- HK precision appears to hit a systematics limit around ~18° (see 3 tank case)



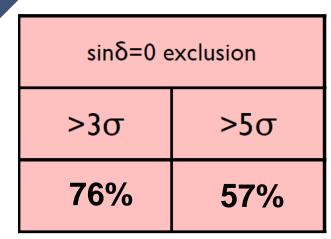


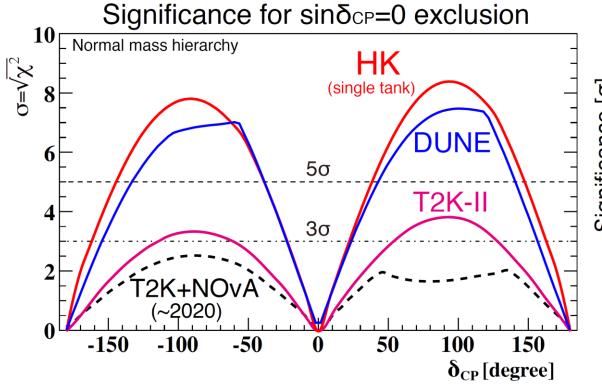
error		
δ=0°	δ=90°	
7.2°	23°	

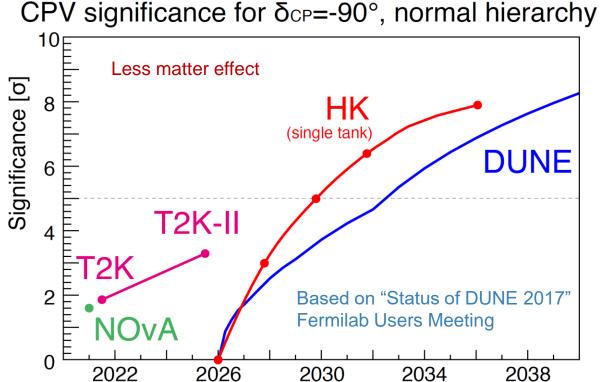
δ_{cp} Comparison with DUNE

Exclusion of $\sin \delta_{cp} = 0$

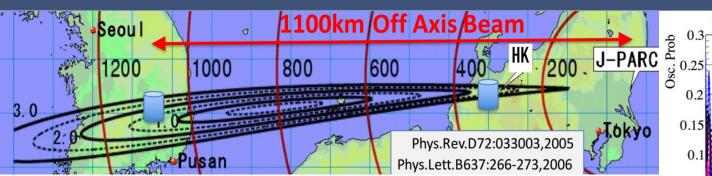
- $> 8\sigma(6\sigma)$ for $\delta_{cp} = -90^{\circ}(-45^{\circ})$
- = ~80% coverage of δ_{cp} parameter space with >3 σ







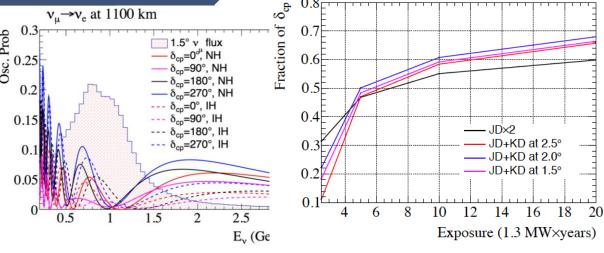
CP with Korean detector (T2HKK)



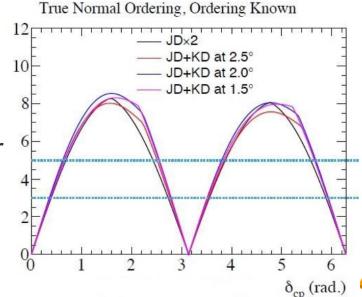
As the second tank will be staged, the concept of putting the second tank in Korea with a different baseline has been studied.

Advantages of second tank in Korea:

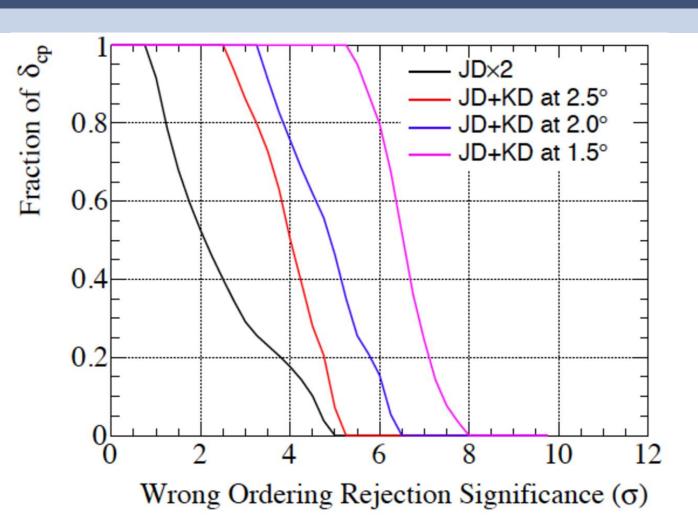
- Measure CP effect at second oscillation maximum: 3 times larger
- Mass hierarchy sensitivity to compliment the measurement with atmospheric neutrinos
- Reduced backgrounds due to deeper site (>800m)



5σ Significance, Ordering Known



Hierarchy in Korea



0.10 0.08 JP inverted 0.06 0.04 0.02 0.10 KD 0.08 norm al inverted 0.06 0.04 0.02 2.0 3.0 5.0 0.0 Neutrino Energy (GeV)





- Collaboration growing ~300 members from 15 countries
- Optimized detector tank configuration:
- Built on technology established with past/ongoing experiments
- Higher photodensity, improved PMTs.
- International R&D efforts in photo-sensors, calibration, geological surveys and electronics well underway
- CP violation:
- \sim δ_{CP} precision 7°(23°) for δ_{CP} =0°(90°)
- − 76% coverage $δ_{CP}$ at 3σ
- A rich physics program (atmospherics, SN, solar,...)
- Construction to begin in 2018 with turn on in 2026

Many talks about Hyper-K physics:

Next: An Intermediate Water Cherenkov Detector for the T2K and Hyper-K

Experiments

Later: Neutrino oscillation physics at Hyper-Kamiokande and p decay

Astro: Astroparticle Physics in Hyper-Kamiokande

Summary of Hyper-K physics potential

· ·		
		HK (1 tank)
	δ precision	7°-23°
LBL (1.3MW×10years)	CPV coverage (3/5σ)	76%/57%
	$\sin^2\!\theta_{23} ext{error} ext{(for 0.5)}$	±0.017
ATM+LBL	MH determination	3-7σ
(10 years)	Octant determination (30)	θ ₂₃ -45° >2°
Proton Decay (20 years)	e ⁺ π ⁰ (3σ)	I×10 ³⁵
	⊽K (3σ)	3×10 ³⁴
Solar	Day/Night (from 0/from KL)	8σ/4σ
(10 years)	Upturn	>3σ
Supernova	Burst (10kpc)	52k-79k
Supernova	Relic	3σ(5σ) in 5(15) years

Extra

	$\sin \delta_{CP}$ =	= 0) exclusion	68% uncert	ainty of δ_{CP}
Configuration	$> 3\sigma$	$> 5\sigma$	$\delta_{CP} = 0^{\circ}$	$\delta_{CP} = 90^{\circ}$
1 tank	76%	57%	7.2°	23°
Staging	78%	62%	7.2°	21°
PTEP [168]	76%	58%	7°	19°

Uncertanties

Systematic uncertainties

Systematic uncertainty on number of Ve events at T2K

$$18\%(2011) \rightarrow 9.9\%(2012) \rightarrow 8.8\%(2013) \rightarrow 6.8\%(2014) \rightarrow 5.5\%(2016)$$

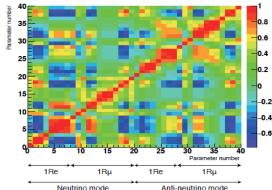
Target systematic uncertainty in T2K-II: ~4%

With further improvements foreseen in

- Cross section with near and intermediate detector
- Detector uncertainties with better calibration

Size of systematic uncertainties assumed in HK study:

	v m	ode	anti-∨	mode
	Ve	νμ	Ve	νμ
Total	3.2	3.6	3.9	3.6



With correlation between energy/flavor bins taken into account based on the T2K error matrix

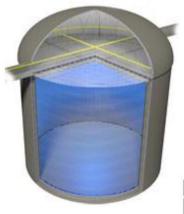
Extrapolation from T2K experience

- 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 V control sample and fundamental detector response understanding with improved calibration

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

	v mode		anti-∨	mode
	Ve	νμ	Ve	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)



Hyper-Kamiokande systematic errors

Estimations and simulations will be based on T2K and SK studies with real data

v-mode v_e candidates .

T	2	R
_		

\overline{v} -mode \overline{v}_e candidates \square
--

Source of uncertainty	$\delta N_{SK}/N_{SK}$
SKDet+FSI+SI	3.48%
SKDet only	2.28%
FSI+SI only	2.63%
Flux	3.67%
2p-2h (corr)	3.90%
2p-2h bar (corr)	0.05%
NC other (uncorr)	0.15%
NC 1gamma (uncorr)	1.47%
XSec nue/numu (uncorr)	2.61%
XSec Tot (corr)	4.26%
XSec Tot	5.21%
Flux+XSec (ND280 constrained)	2.90%
Flux+XSec (All)	4.17%
Flux+XSec+SKDet+FSI+SI	(5.45%)
Flux+XSec+SKDet+FSI+SI (pre-fit)	12.1%
Oscillations	(4.20%)
All	6.91%
All (pre-fit)	12.6%

Source of uncertainty	$\delta N_{SK}/N_{SK}$
SKDet+FSI+SI	3.95%
SKDet only	3.11%
FSI+SI only	2.43%
Flux	3.84%
2p-2h (corr)	3.04%
2p-2h bar (corr)	2.36%
NC other (uncorr)	0.33%
NC 1gamma (uncorr)	2.95%
XSec nue/numu (uncorr)	1.46%
XSec Tot (corr)	4.46%
XSec Tot	5.55%
Flux+XSec (ND280 constrained)	3.20%
Flux+XSec	4.60%
Flux+XSec+SKDet+FSI+SI	(6.28%)
Flux+XSec+SKDet+FSI+SI (pre-fit)	13.5%
Oscillations	4.00%
All	(7.38%)
All (pre-fit)	14.1%

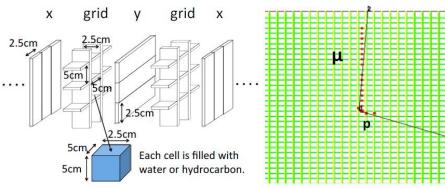
Goal

Reduction from ~ 6-7% in T2K to ~3-4% in T2HK for the expected number of events in HK. Beam Flux, XSections, HKDet + New near detectors constraint.

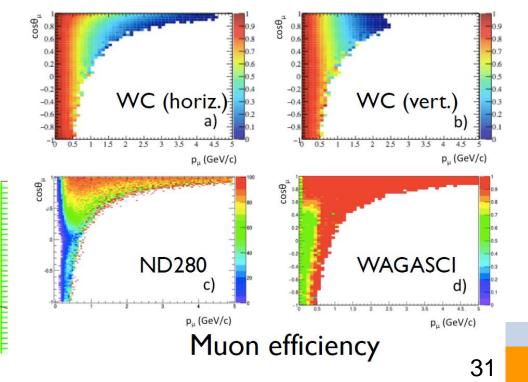
Near detectors

Near detector measurements

- Cross section measurements with large statistics and high quality data
 - Larger phase space to reduce model dependence
 - Expected number of events after selection per 10²¹ POT:
 - ~40k V_{μ} CC events /Iton @ 280m
 - \bullet ~IM ν_{μ} and ~20k ν events for 2kton intermediate detector
- Exotic physics searches
 - Sterile neutrino
 - Lorentz/CPT violation
 - Heavy neutral lepton
 - ...



"WAGASCI" 3D-grid scintillator concept

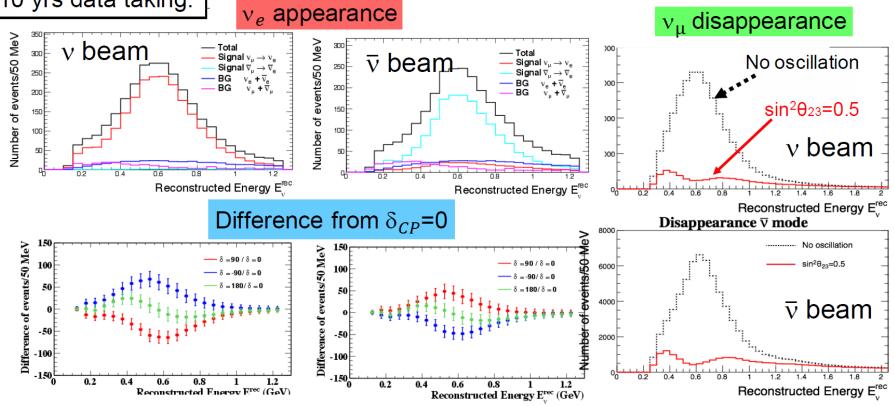


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Oscillation

Expected Events

10 yrs data taking.



 $\delta_{CP} = 0^{\circ}$, 180° can be distinguished using shape information.

δ=0	Signal $(v_{\mu} \rightarrow v_e \text{ CC})$	Wrong sign appearance	$ u_{\mu}$, \overline{v}_{μ} CC	Beam v_e, \bar{v}_e contamination	NC
V beam	2300	21	10	362	188
$\overline{\mathcal{V}}$ beam	1656	289	6	444	274

	$ u_{\mu}$, \overline{v}_{μ} CCQE	ν _μ CC nonQE	Others
V beam	8947	4444	721
	12317	6040	859
$ar{oldsymbol{ abla}}$ beam	12017	0040	659

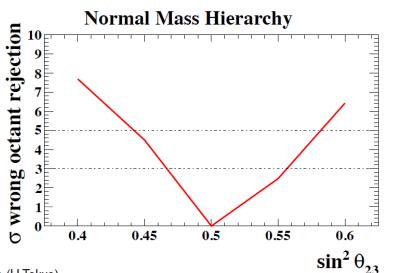
θ_{23} and Δm^2_{32}

 $\delta(\Delta m^2_{32}) \sim 1.4 \times 10^{-5} \text{eV}^2$

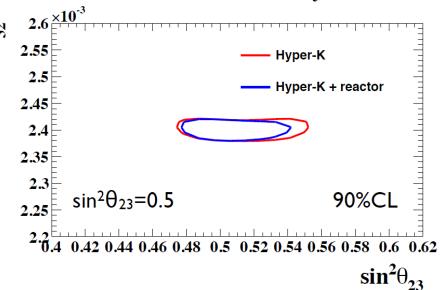
→ Mass hierarchy sensitivity in combination with reactor

$$\delta(\sin^2\theta_{23})\sim 0.015$$
 (for $\sin^2\theta_{23}=0.5$)
 ~ 0.006 (for $\sin^2\theta_{23}=0.45$)

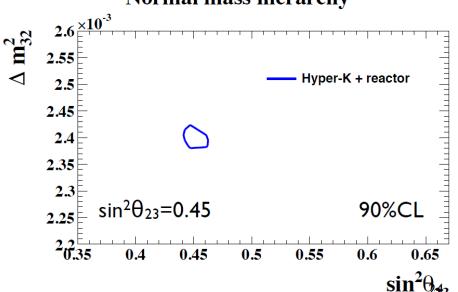
→Octant determination, input to models



Normal mass hierarchy



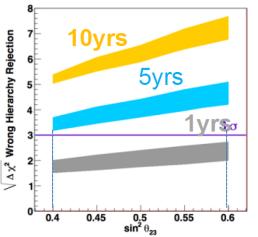
Normal mass hierarchy



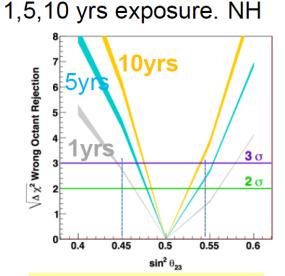
Mass Hierarchy and Octant Sensitivity: Atmospherics + Beam 1,5,10 yr

Variety of physics with atmospheric v:

- MH, θ_{23} octant, CP
- Sterile neutrino , LV, etc With atmospheric alone,
- mass hierarchy sensitivity
- >3 σ octant determination for $|\theta_{23}|$ -45°|>8°



Mass hierarchy determination



θ₂₃ octant determination

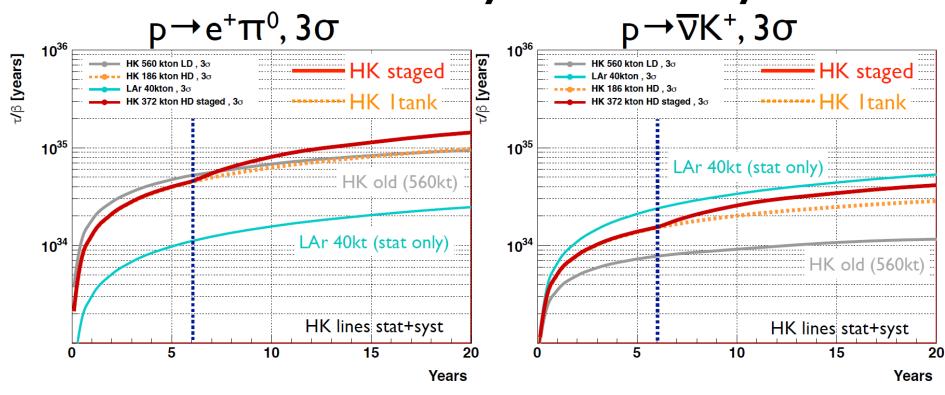
10 yrs		Mass Hierarchy (σ)		
NH		Atm	Atm+Beam	
PTEP	θ ₂₃ =0.4	3.8	6.9	
	θ ₂₃ =0.6	8.4	9.9	
2Tanks	θ ₂₃ =0.4	2.2	5.3	
	θ ₂₃ =0.6	5.2	6.9	

10 yrs	Octant (σ)	
NH	Atm	Atm+Beam
θ ₂₃ =0.45	3.6	7.2
θ ₂₃ =0.55	2.7	4.0
θ ₂₃ =0.45	2.2	5.8
θ ₂₃ =0.55	1.7	3.7

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Proton decay

Proton decay sensitivity



- Improved sensitivity with BG free search!
 - ~> 10^{35} years for $p \rightarrow e^+ \pi^0$
 - >3×10³⁴ years for p $\rightarrow \nu K^+$

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

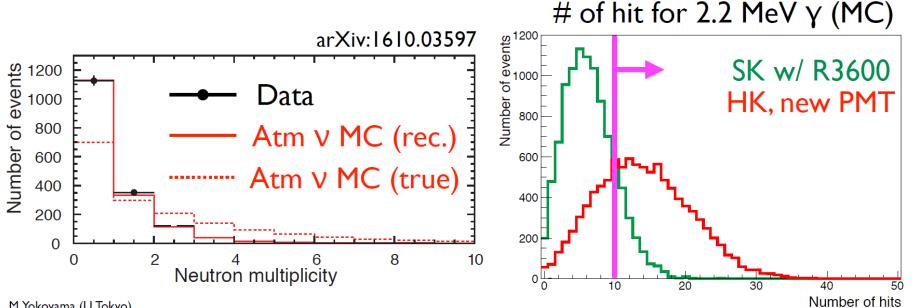


Similar analysis as in SK but with neutron tagging (remove events with a tagged neutron) thanks to improved PMTs.

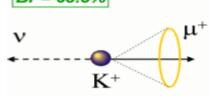
Best discovery potential for GUT signal!

BG suppression in proton decay

- Neutron tagging with hydrogen capture (2.2MeV Y)
 - Tag and suppress atmospheric V background
 - Already in use for p-decay search in SK-4 (~20% eff.)
- Extrapolated to Hyper-K with 40% high-QE PMT
 - 70% tagging eff. possible → assumed in study
- Gd option also under consideration

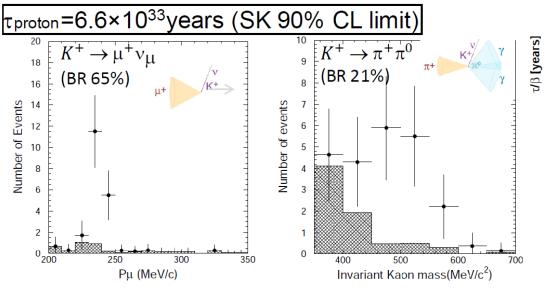


Other Proton Decay Sensitivities

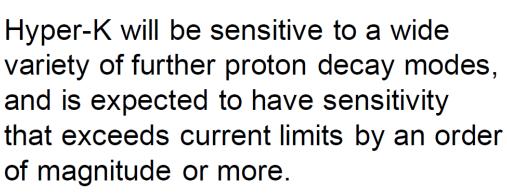


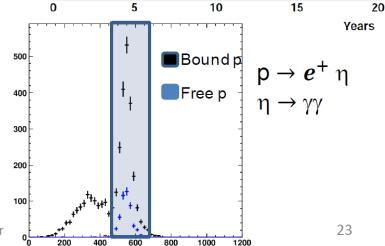
Proton decays into a lepton and a kaon are one of the most prominent features of Supersymmetric Grand Unified Theories.

 10^{34}



3σ discovery potential

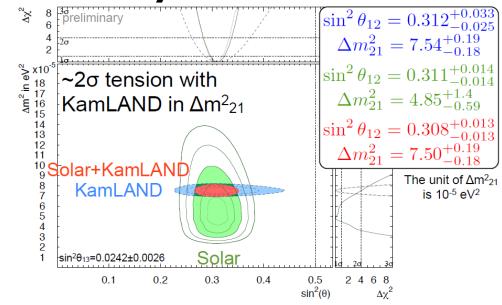


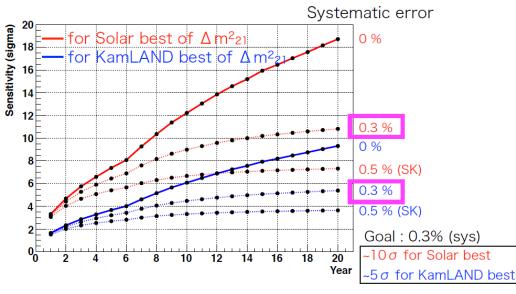


Solar & SN

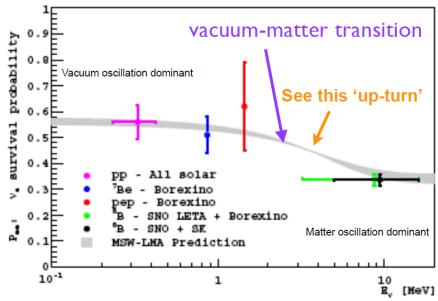
Day/Night asymmetry of solar V

- ~2 σ tension of Δ m²₂₁ by solar and KamLAND
 - Measurement with V_e
 only possible w/ solar V
- Day-Night asymmetry due to Earth matter effect sensitive to Δm^2_{21}
 - ~4% for solar best
 - ~2% for KL best
- ~5σ resolution expected with 0.3% syst error (0.5% achieved by SK)

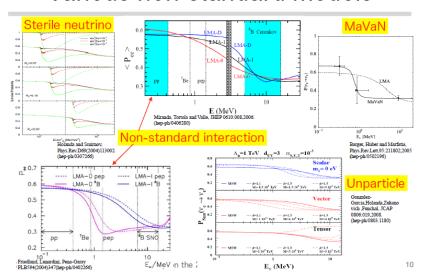




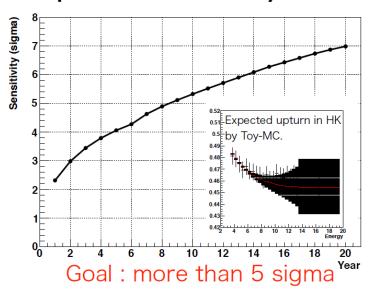
Spectrum upturn of solar V



Various non-standard models



- Spectrum upturn in low energy not yet seen
 - Various non-standard scenario possible
- >5σ possible with BG/ calibration similar to SK
 - Low E threshold w/ high photon efficiency essential



Supernova burst neutrinos

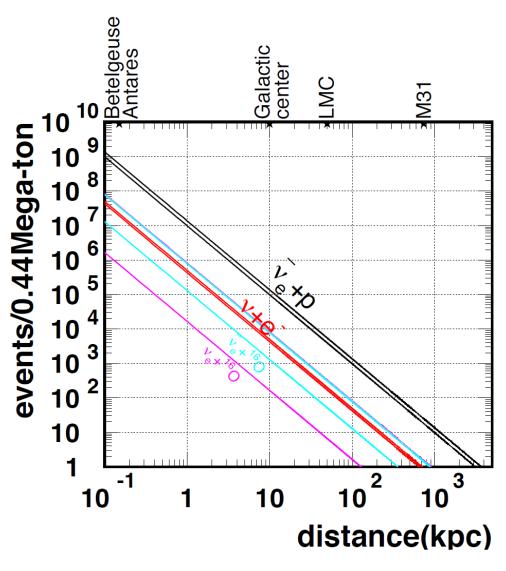
 Measurements of neutrino flavor, energy, time profile will provide detailed information of corecollapse supernova

Expected number of event

98k~136k ev (IBD) 4.2k~5k ev (ve ES) (12~80 for neutronization) 160~8200 ev (ve CC) 1300~7800 ev (ve CC)

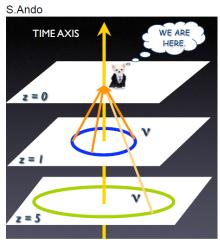
Livermore simulation

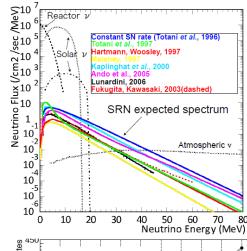
Totani, Sato, Dalhed, Wilson, ApJ. 496 (1998) 216

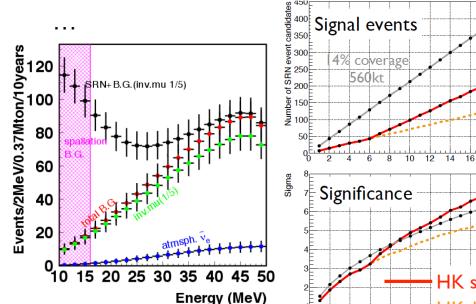


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SN relic neutrinos





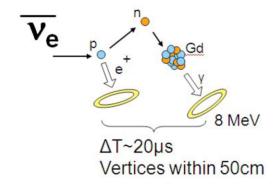


- Neutrinos from past
 SN fill our universe
 - History of star formation and black hole generation process encoded
- BG suppression with more light
 - → Measurement with
 - >5σ signal

Investigate dim-SN's and BH formation

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

Install Gadolinium

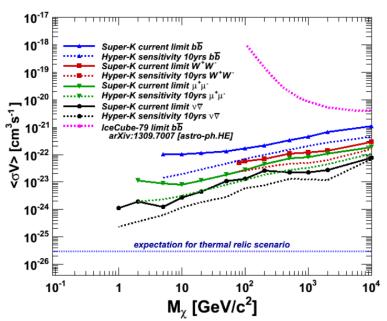


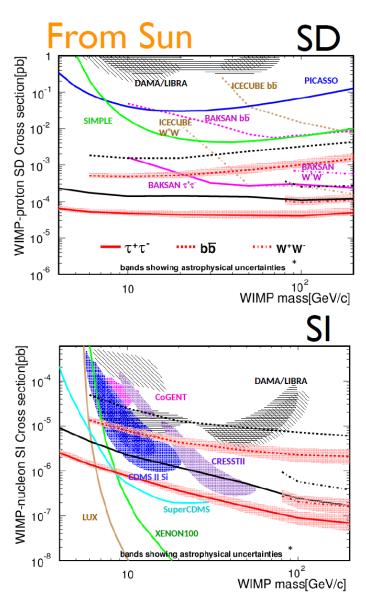
Other physics

Indirect DM searches

- Unique sensitivities, especially for low mass region
- Improve ×3-10 over SK limit

From Galactic center

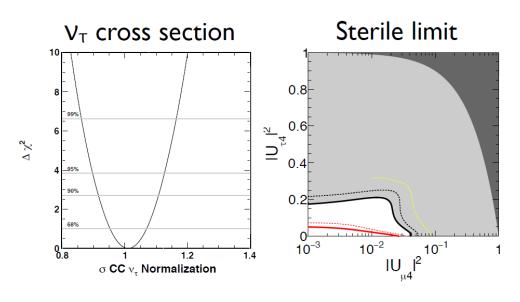




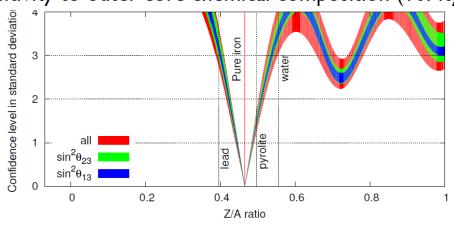
Other science with atmospheric V

Provides neutrinos with various energy, flight length, and flavor

- V_T cross section measurement
- Sterile neutrino
- Lorentz violation
- Geophysics
 - Information on the chemical composition of Earth's outer core using matter effect



Sensitivity to outer core chemical composition (10Mtyr)



DAQ

ToolDAQ Framework

ToolDAQ is an open source DAQ Framework developed here in the UK.

It was deigned to incorporate the best features of other frameworks whilst:

- Being very easy and fast to develop DAQ implementations in a very modular way.
- Including dynamic service discovery and scalable network infrastructure to allow its use on large scale experiments.

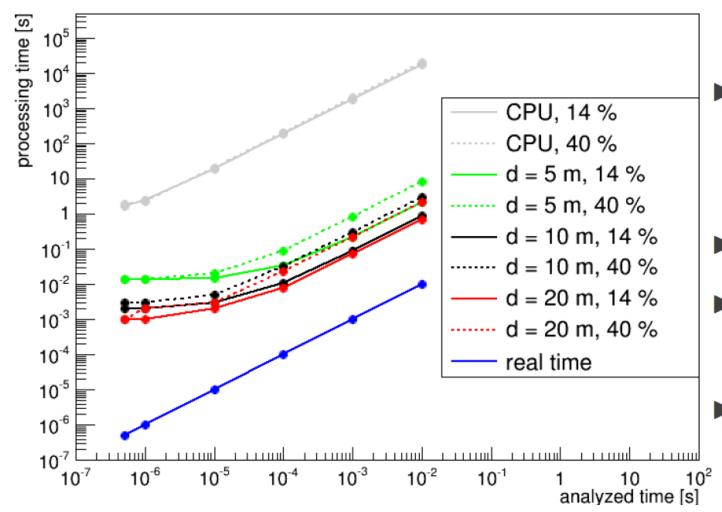
Features

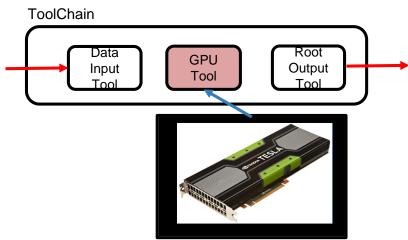
- Pure C++
- Fast Development
- Very Lightweight
- Modular
- Highly Customisable / Hot swappable modules
- Scalable (built in service discovery and control)
 Few external dependencies (Boost, ZMQ)

- Fault tolerant (dynamic connectivity, discovery, message caching)
- Underlying transport mechanisms ZMQ (Multilanguage Bindings)
- JSON formatted message passing

GPU TPU Development

Test Vertices Algorithm Processing time

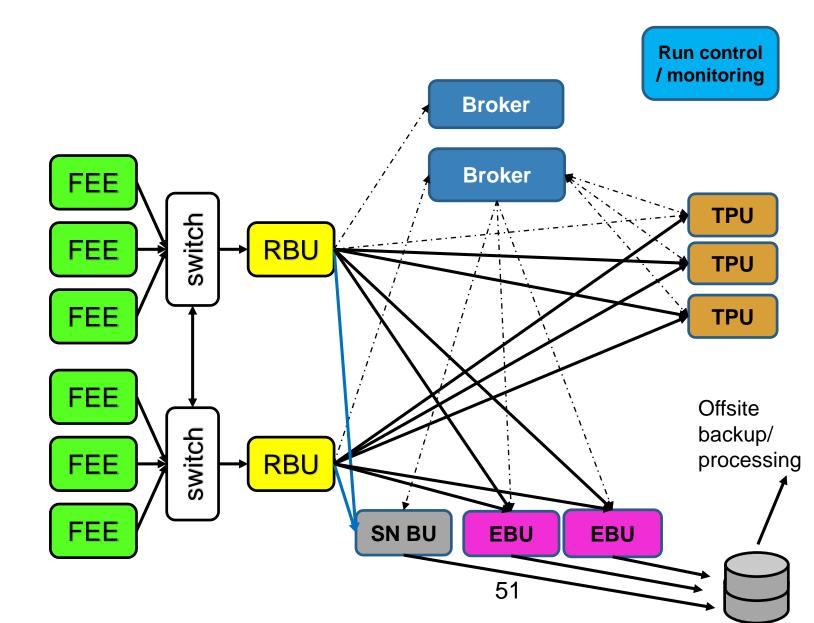




- GPU reduces the time with respect to CPU by 4 orders of magnitude
- ▶ ideal data chunk = 1 ms
- need 400 GPUs for real-time processing
- projected cost $\approx 400k\$$

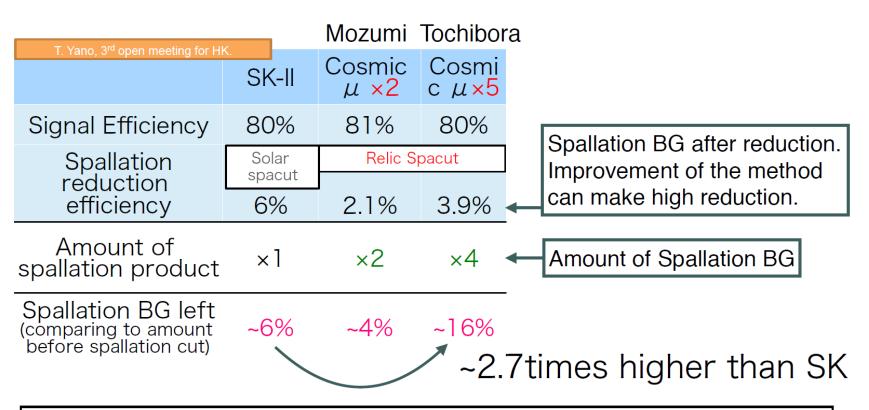
Features:

- FEEs can be rerouted to be read out by any RBU
- Broker assisted communication between RBU TPU and EBU
- Master slave Broker redundancy
- Dynamic routing and fault tolerance (hot swapable)
- Ability to switch on and off parts of the detector from the data stream
- TPU farm (GPU based)
- Supernova buffer
- Centralised run control and monitoring/logging



Other

Spallation BG in Hyper-K



High density (~40% P.C.) with HQE PMT can reduce ~1/3, the effect of Spallation BG becomes similar as SK.