3 generations of Kamiokande family


- Larger mass for more statistics
- Better sensitivity by more photons with improved sensors

3kton  50kton  260kton×2

20% coverage with 50cm PMT  40% coverage with 50cm PMT  40% coverage with high-QE 50cm PMT
Why water Cherenkov detector?

Well proven, scalable technology

- Feasibility of ~Mton size detector confirmed by various studies over past decade
- 20 years experience with Super-Kamiokande
- “Ready-for-construction” design developed
- Still improving with new technology and new ideas
Hyper-K: a multi purpose Experiment

- **Neutrino oscillation physics**
  - CP violation
  - $\Theta_{23}$ octant determination
  - Mass hierarchy with beam and atmospheric $\nu$’s

- **Nucleon decay discovery potential**
  - Possible discovery with $\sim \times 10$ better sensitivity than Super-K

- **Neutrino astrophysics**
  - Precision measurements of solar $\nu$
  - High statistics measurements of SN burst $\nu$
  - Detection and study of relic SN neutrinos

- **Unexpected…**

This talk extend highly successful program of Super-K
Hyper-Kamiokande: new design

2 TANKS:
- Fiducial Volume: 2/3 of original design
- Vertical tanks
- Possibility of staging
- Significant reduction for the cost of the project

EACH TANK:
- 260 Kton total
- 10 x SK fiducial volume
- Very good PMT coverage (40%)
- 60 m height x 74 m diameter
  - 40,000 50cm ID PMTs
  - 6,700 20cm OD PMTs

Sensitivity goals are maintained for HK oscillations physics
The candidate site locates under Mt. Nijugo-yama
- ~8km south from Super-K
- Identical baseline (295km) and off-axis angle (2.5deg) to T2K
- Overburden ~650m (~1755 m.w.e.)
Making huge (74mD×60mH) caverns is not trivial
Detailed geological surveys at the candidate site
Rock core sampling, initial stress of bedrock, etc.
Bedrock condition confirmed for HK cavern construction
Tank design: ready

Water containment system and PMT support structure have been designed.

Support structure design

- Truss structure made of shaped stainless steel (SUS304)
  - Top/Barrel → Hung from the ceiling
  - Bottom → Set on the ground
 Newly developed 50cm PMT

Super-K PMT

New PMT

- ×2 better photon efficiency and timing resolution
  - Enhance physics potential (neutron tagging, low energy events)
- Higher pressure tolerance (> 80m)
Photo-sensor R&D

- International efforts for further improvement:
  - 50cm Hybrid Photo-detector (HPD)
  - 20-30cm photo-sensors for OD / ID
- “Multi-PMT” module
  - Being developed based on KM3NeT optical module
  - MoU with KM3NeT to exchange knowledge
- PMT housing to prevent chain implosion
  - Confirmed functionality at 80m under water

KM3NeT

Multi-PMT

8cm (3”) PMT

28cm (11”) PMT
### Hyper-K construction timeline

- **Assuming funding from 2018**
- **The 1st detector construction in 2018~2025**
  - Cavern excavation: ~5 years
  - Tank (liner, photosensors) construction: ~3 years
  - Water filling: 0.5 years
Hyper-K proto-collaboration

- International proto-collaboration formed on January 2015
- Reviewed by an International HK Advisory Committee
- New proposal submitted in March 2016 selected as one of important large scale projects by Science Council of Japan.
- J-PARC upgrade for Hyper-K is top priority in KEK Project Implementation Plan (KEK-PIP)
- Budget request for detector construction in preparation
- 15 countries, ~300 members and growing
Tokai to Hyper-K (T2HK)

- Long baseline oscillation using the J-PARC neutrino beam-line (as T2K)
- Same off-axis angle (2.5°) as Super-K
- Improved Neutrino Beam (1.3 MW)
J-PARC neutrino beam upgrade

- Continuous upgrade of neutrino beam up to 2030
- Present beam power ~470 kW
- New MR power supply for 750 kW by 2019
- Repetition rate increase to 0.86 Hz for 1.3 MW by 2026

J-PARC upgrade for Hyper-K is top priority in KEK Project Implementation Plan (KEK-PIP)

Strong commitment for future neutrino program
Near Detector upgrade

- Under consideration by T2K
  - Goal: systematics reduction in T2K-II era
  - Expand angular acceptance with new TPCs and new target detectors
  - Lol “Neutrino Near Detectors based on gas TPCs” @CERN (Neutrino Plat.)
  - Technical design in ~2017, aim for installation around 2020/21
  - Operation foreseen to continue in HK (possibly further improvement)

※ Large angular acceptance detector with plastic scintillator grid (WAGASCI)
Intermediate Detectors

- Water Cherenkov detectors at ~1-2 km distance being investigated for HK (or possibly before).
- The same technology as the far detector
  - Further reduction of systematic uncertainties
- Two proposals:
  - Off-axis angle spanning orientation.
  - Gd loading, magnetized $\mu$ range detector.
  - Will merge in unique detector/collaboration.

Final goal:
Reduce systematic uncertainties from 5-6% (T2K) to 3-4%
Physics performance for oscillation studies: $\nu_e$ appearance

- 10 years of running
- 1.3 MW for JPARC proton beam
- 1 tank then 2 tanks
- ~ 40% PMT coverage in HK
- 3-4% systematic uncertainties
Physics performance for oscillation studies: $\nu_e$ appearance

- Possibility of using shape information in energy to distinguish different values for $\delta$ (CP)
- 10 years of running
- 1.3 MW for JPARC proton beam
- 1 tank then 2 tanks
- ~40% PMT coverage in HK
- 3-4% systematic uncertainties
With 10 years exposure, can exclude $\sin \delta_{CP}=0$ and demonstrate CP violation:

- $>8 \sigma$ if $\delta_{CP} = \pm 90^\circ$
- $>5 \sigma$ for 62% of $\delta_{CP}$ values
- $>3 \sigma$ for 78% of $\delta_{CP}$ values

$\delta_{CP}$ resolution:

- $21^\circ$ precision at $\delta_{CP}=90^\circ$
- $7^\circ$ precision at $\delta_{CP}=0^\circ$
Towards leptonic CP asymmetry

Note: “exact” comparison sometimes difficult due to different assumptions

~3 $\sigma$ indication with T2K→T2K-II,
>5 $\sigma$ discovery and measurement with HK
Precision measurements of $\Theta_{23}$

- Large improvements in $\sin^2\Theta_{23}$ measurements
  - $\sim 0.015$ precision at $\sin^2\Theta_{23} = 0.5$
  - $\sim 0.006$ precision at $\sin^2\Theta_{23} = 0.45$

- For non-maximal $\Theta_{23}$, reactor constraint breaks octant degeneracy
Atmospheric neutrinos data has sensitivity to mass hierarchy and $\Theta_{23}$ octant. Sensitivity is enhanced by combining atmospheric and beam neutrinos.

- $>5\sigma$ determination of the mass hierarchy (10 years)
- Improved performance for octant determination
Build second tank in Korea to enhance mass hierarchy and $\delta_{CP}$ sensitivities

- 1000 – 1200 km baseline
- $1.3^0$ – $3.0^0$ off axis beam direction
$\nu_e$ appearance at the Korean site

- Covers the 2nd oscillation maximum where the CP asymmetry between $\nu$ and anti-$\nu$ is 3 times larger than the 1st oscillation maximum
- Less sensitive to systematics errors due to larger CP effect
  - Lower statistics due to flux reduction
- Longer baseline (1100km) leads to larger matter effects
  - MH better determination
Additional benefits of the Korean site

- >1000 m high mountains with hard granite rocks
- Smaller background due to its larger overburden (> 800m)
- Improved sensitivity in solar neutrino physics
  - Day/night asymmetry due to MSW matter effect in Earth
  - HEP solar neutrinos
  - Energy spectrum upturn
- Supernova relic neutrino detection capability below 20 MeV improves
  - Detection efficiency is more than twice HK site in 16-18 MeV range

K. Abe et al., “Physics Potentials with the Second Hyper-Kamiokande Detector in Korea”, November 2016, arXiv:1611.06118
Mass Ordering Sensitivities

True Normal Hierarchy

Significance ($\sigma_{L_{\text{MH}}}$) vs $\delta_{\text{CP}}$ (rad.)

- HK x2
- HK+KD at 2.5°
- HK+KD at 2.0°
- HK+KD at 1.5°

True Inverted Hierarchy

Significance ($\sigma$) vs $\delta_{\text{CP}}$ (rad.)

- HK x2
- HK+KD at 2.5°
- HK+KD at 2.0°
- HK+KD at 1.5°

HK+KD 1.5°: 6 ~ 8 $\sigma$ for all $\delta_{\text{CP}}$
HK x2: 1 ~ 4.5 $\sigma$ for all $\delta_{\text{CP}}$
($< 3 \sigma$ for most cases)

HK+KD 1.5°: 5.5 ~ 7 $\sigma$ for all $\delta_{\text{CP}}$
HK x2: 1 ~ 5 $\sigma$ for all $\delta_{\text{CP}}$
($< 3 \sigma$ for most cases)
$\delta_{\text{CP}}$ Sensitivities

- **Known MO**
- **Unknown MO**
an Hyper-Kamiokande primary goal: nucleon decay

status & next generation expectations (10 y exposure), most important modes:

design emphasizes $p \rightarrow e^+\pi^0$, $p \rightarrow \nu K^+$ while keeping sensitivity to many other
\[ p \rightarrow e^+ \pi^0 \]

favored by non super-symmetric GUTs

a nearly model independent reaction

back-to-back $e^+$, $\pi^0$ (459 MeV)

$e^+, \pi^0 \rightarrow \gamma \gamma$ are detected

fully final state reconstructed in Water Cherenkov detectors

90% C.L. limits achievable if no event is observed

$\tau_p = 1.7 \times 10^{34}$ (SK limit), 10 years exposure

Some of the benefits from increased photon yield:

- Neutron tagging (veto)

* LAr discovery potential computed using numbers from DUNE CDR 2015: signal efficiency: 97%, background: 1 event

Mton/year, no systematic errors
$p \rightarrow \bar{\nu} K^+$

feature of super-symmetric GUTs

decay mode rather interesting but difficult to reconstruct

at decay $p(K^+)= 340 \text{ MeV}$, $K^+$ light threshold: $749 \text{ MeV}$

$\rightarrow$ reconstruct $K^+$ from its decay products

$K^+ \rightarrow \nu \mu^+ (64\%), \ K^+ \rightarrow \pi^+\pi^0 (21\%)$

discovery potential (3 $\sigma$)

90% C.L. limits achievable if no event is observed

Benefits from increased photon yield and better timing resolution
## Summary of physics potential

<table>
<thead>
<tr>
<th></th>
<th>HK (2TankHD w/ staging)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LBL (13.5MWyr)</strong></td>
<td></td>
</tr>
<tr>
<td>δ precision</td>
<td>7°-21°</td>
</tr>
<tr>
<td>CPV coverage (3/5 σ)</td>
<td>78%/62%</td>
</tr>
<tr>
<td>sin² θ₂₃ error (for 0.5)</td>
<td>±0.017</td>
</tr>
<tr>
<td><strong>ATM+LBL (10 years)</strong></td>
<td></td>
</tr>
<tr>
<td>MH determination</td>
<td>&gt;5.3 σ</td>
</tr>
<tr>
<td>Octant (sin² θ₂₃=0.45)</td>
<td>5.8 σ</td>
</tr>
<tr>
<td><strong>Proton Decay (10 years)</strong></td>
<td></td>
</tr>
<tr>
<td>e⁺π⁰ 90%CL</td>
<td>1.2×10³⁵</td>
</tr>
<tr>
<td>ν K 90%CL</td>
<td>2.8×10³⁴</td>
</tr>
<tr>
<td><strong>Solar (10 years)</strong></td>
<td></td>
</tr>
<tr>
<td>Day/Night (from 0/from KL)</td>
<td>6 σ /12 σ</td>
</tr>
<tr>
<td>Upturn</td>
<td>4.9 σ</td>
</tr>
<tr>
<td><strong>Supernova</strong></td>
<td></td>
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<tr>
<td>Burst (10kpc)</td>
<td>104k-158k</td>
</tr>
<tr>
<td>Nearby</td>
<td>2-20 events</td>
</tr>
<tr>
<td>Relic (10 yrs)</td>
<td>98evt/4.8 σ</td>
</tr>
</tbody>
</table>

**for DM search see backup slides**
Hyper-Kamiokande will have a rich program with world-leading science output

- Technology established with past/ongoing experiments
- Fast and robust approach to lepton CPV
  + long term program with a wide range of science
- Multi-purpose approach crucial (huge investment)
  new design optimized with better sensors

Project being accelerated towards an early approval

- International collaboration open for new groups

Conclusion

MeV to TeV with a single detector

Atmospheric
Backup
Cavern stability analysis

- Cavern stability analyses based on geol. survey results
  - 3D finite element analysis
  - Excavation steps taken into account in stability analysis
  - Evaluate plastic region depth and design cavern support
- Confirmed the Hyper-K cavern can be constructed with the existing technologies
  - Detailed construction timeline established
DM WIMP-induced neutrino searches at the Galactic Center

DM induced event excess for $\chi\chi \rightarrow bb$

SENSITIVITY 99% CL (DM annihilation, NFW profile)

WIMP velocity averaged annihilation cross-section
DM WIMP-induced neutrino searches the Sun

90% CL limits on WIMP nucleon scattering cross-section

- Spin dependent
- Spin independent

in black is SK for the same modes as HK