Outline

- Water Cherenkov detectors in Japan
- Hyper-Kamiokande technical design
- physics program
  - beam neutrinos
  - atmospheric neutrinos
  - solar neutrinos
  - supernova neutrinos
  - nucleon decay searches
- summary
Water Cherenkov detectors in Japan

- **Kamiokande** 4.5 (0.68) kton
  (1983-1996) PMT coverage 20%
  - neutrinos from SN1987a, deficit of atmospheric neutrinos
- **Super-Kamiokande** 50 (22.5) kton
  (1996- ) PMT coverage 40%
  - oscillations of solar and atmospheric neutrinos
  - world leading limit on proton lifetime
  - $\nu_e$ appearance
- mature, known, scalable technology
- **Hyper-Kamiokande** 258 (187) kton
  (~2027- ) PMT coverage 40%
  - proto-collaboration formed January 2015
  - ~300 people, ~80 institutes
The photodetectors

- new Hamamatsu 50 cm B&L PMT with improved dynode and higher pressure tolerance
  - 2x better photon efficiency
  - improved charge and timing resolution (1 ns)
  - 40 000 in the inner detector
  - 40% photocoverage
  → almost 2x better overall photon efficiency than Super-K
- other considered solutions
  - multiPMT – arrays of 19 smaller (8 cm) PMTs
  - possible light collection devices (reflectors, photon traps etc.)
- outer detector: 10-20k PMT of 8 cm diameter
- covers to protect PMT from sudden pressure changes
Physics program

• neutrino oscillations
  - with beam and atmospheric neutrinos
  - CP violation
  - precise measurement of $\theta_{23}$
  - mass hierarchy determination
• neutrino astrophysics
  - precise measurement of solar neutrinos,
    sensitivity to address solar and reactor
    neutrinos discrepancy.
  - supernova burst and relic supernova neutrinos
• searching for nucleon decay
  - sensitivity 10x better than Super-K
    ($10^{35}$ years)
  - all visible modes can be advanced
• and other
Location and beam neutrinos

- candidate site 8 km south of Super-K
  - the same baseline (295 km) and off-axis angle as Super-K
- the J-PARC beamline
  - 2.5 degree off-axis
  - narrow band beam at ~600MeV
- upgrade of beam power
  - 0.75 MW upgrade starting in 2021 (currently ~485 kW)
  - increasing repetition rate to 0.86 Hz → 1.326 MW by 2026
  - 3.2e14 protons per pulse
- upgrade power supplies for horns
  - design current of 320 kA (wrt 250 kA)
  - 10% higher neutrino flux.
  - reduction of wrong-sign neutrino contamination by 5-10%.
Near and Intermediate Detectors

- upgrade of ND280 near detector to reduce systematic uncertainties
  - expanded angular acceptance
  - lower energy threshold
  - systematic uncertainties
    \[ \sim 18\% \text{ (2011)} \rightarrow \sim 9\% \text{ (2014)} \rightarrow \sim 6\% \text{ (2016)} \rightarrow 4\% \text{ (2020...)}? \]

- N61 intermediate water Cherenkov detector
  - distance 1-2 km
  - Gd loading
  - off-axis angle spanning coverage (1-4°)
  - energy dependence of neutrino interactions
  - further reduction of systematic uncertainties

CERN-SPSC-2018-001, talk by Y. Kudenko tomorrow

[Diagram of detector setup with new and existing trackers, surrounded by TOF]

arXiv:1412.3086
Expected systematics

- based on T2K experience with some assumptions on better knowledge of the neutrino beam, interactions and detector
### Expected numbers of events

- **10 years exposure**
  - $2.7 \cdot 10^{22}$ POT
  - $\nu:\bar{\nu}$ data taking 1:3
- **$\nu_e$ appearance**
  - Shape information can be used to distinguish different values of $\delta_{CP}$
- **$\nu_\mu$ disappearance**

<table>
<thead>
<tr>
<th>$\delta_{CP} = 0$</th>
<th>right-sign $\nu_\mu \rightarrow \nu_e$ CC</th>
<th>wrong sign $\nu_\mu \rightarrow \nu_e$ CC</th>
<th>$\nu_\mu, \bar{\nu}_\mu$ CC</th>
<th>intrinsic beam $\nu_e$</th>
<th>NC</th>
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</thead>
<tbody>
<tr>
<td>$\nu$ beam</td>
<td>1643</td>
<td>15</td>
<td>7</td>
<td>259</td>
<td>134</td>
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<tr>
<td>$\bar{\nu}$ beam</td>
<td>1183</td>
<td>206</td>
<td>4</td>
<td>317</td>
<td>196</td>
</tr>
</tbody>
</table>

#### Neutrino mode: appearance

- $\nu_\mu \rightarrow \nu_e$ CC

#### Antineutrino mode: appearance

- $\bar{\nu}_\mu \rightarrow \nu_e$ CC

### Disappearance $\nu$ mode

- $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e + \bar{\nu}_e$

### Disappearance $\bar{\nu}$ mode

- $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e + \bar{\nu}_e$
Precise measurements of $\theta_{23}$

- joint fit of $\nu_\mu$ and $\nu_e$ samples allows to precisely measure $\sin^2\theta_{23}$ and $\Delta m^2_{32}$
- expected precision
  - $\sim 0.017$ at $\sin^2\theta_{23} = 0.5$
  - $\sim 0.006$ at $\sin^2\theta_{23} = 0.45$

- for non-maximal $\theta_{23}$ the reactor constraint breaks octant degeneracy

True $\sin^2\theta_{23} = 0.5$

True $\sin^2\theta_{23} = 0.45$
CPV sensitivity

- exclusion of $\sin \delta_{\text{CP}} = 0$ with
  - $\sim 8\sigma$ if true $\delta_{\text{CP}} = \pm 90^\circ$
  - $> 5\sigma$ for 57% of $\delta_{\text{CP}}$ values
  - $> 3\sigma$ for 76% of $\delta_{\text{CP}}$ values
- $\delta_{\text{CP}}$ resolution
  - $23^\circ$ precision at $\delta_{\text{CP}} = \pm 90^\circ$
  - $7.2^\circ$ precision at $\delta_{\text{CP}} = 0^\circ$ or $180^\circ$
- combination with atmospheric data enhances the sensitivity
Atmospheric neutrinos

- flux of electron neutrinos – affected by matter effects
  - presence of a resonance in multi-GeV region → mass hierarchy
  - magnitude of the resonance → $\theta_{23}$ octant
  - scale and direction of the effect at 1 GeV → $\delta_{\text{CP}}$

$v_e$ flux relative to no oscillations
Atmospheric+beam neutrinos

- improved performance for octant determination
- $3\sigma$ ability to reject the incorrect mass hierarchy after 5 years

\[ \sin^2 \theta_{23} = 0.45 \]
\[ \sin^2 \theta_{23} = 0.55 \]
\[ \sin^2 \theta_{23} = 0.6 \]
\[ \sin^2 \theta_{23} = 0.5 \]
\[ \sin^2 \theta_{23} = 0.4 \]

Wrong octant rejection

$3\sigma$ for $|\theta_{23} - 45^\circ| \geq 2.3^\circ$

Wrong hierarchy rejection
Solar neutrinos

- tension $\sim 2\sigma$ between Kamland and global solar analysis in $\Delta m^2_{21}$
  - from the recent Super-K result of the solar neutrino day-night asymmetry and energy spectrum shape
  - day-night asymmetry caused by electron component regeneration in Earth (3$\sigma$ indication in Super-K)
  - few percent higher event rate at night
- Hyper-K goal:
  - precise measurement of $\Delta m^2_{21}$ and day-night asymmetry
    - expected $>5\sigma$ sensitivity
- new physics needed if the tension is a real effect
Solar neutrino spectrum upturn

- transition region between the vacuum oscillations and matter-dominated energy regions
- precise measurement of the spectrum shape allow to distinguish the usual neutrino oscillation scenario from exotic models
- $5\sigma$ discovery sensitivity to spectrum upturn in 10 years thanks to lower energy threshold (3.5 MeV)
  - $3\sigma$ for 4.5 MeV
- other possible measurements
  - first measurement of $hep$ component (2-3$\sigma$) providing more information on the Sun core
  - time variation measurement (with rate of 200$\nu$/day) → monitoring of the Sun core temperature
**Supernova burst neutrinos**

- $\nu_e$ from neutronization peak – elastic scattering on electrons (directional information, accuracy 1-1.3° expected for supernova at 10kpc)
- $\bar{\nu}_e$ from cooling phase – inverse beta decay
  
  expectations:  
  50-80k events (10kpc)  
  2-3k (SN1987a)

- Information on  
  - neutrino oscillations and properties (mass, mass hierarchy)  
  - core-collapse supernova models

Early warning for telescopes
Supernova relic neutrinos

or diffuse supernova neutrino background
- expected flux few tens/cm$^2$/sec
- search limited by background:
  - spallation for low energies
  - atmospheric neutrinos for high energies
- first measurement may be done by SK-Gd
- Hyper-K may measure the spectrum
- different search window (~16-30 MeV),
  - complementary to SK-Gd searches (10-20 MeV)
  - contribution of extraordinary supernova bursts (like black hole formation, BH): provides information on the star formation history and metallicity
Search for $p \rightarrow e^+\pi^0$ decay

- decay mode $p \rightarrow e^+\pi^0$ is favoured by many GUTs
  - $e^+$ and photons are detected as e-like rings → final state is fully reconstructed (practically background free)

- analysis similar as in SK but with neutron tagging (veto) thanks to improved PMTs
  - neutron capture in water $n(p,d)\gamma$ (2.2 MeV)
  - efficient tagging of prompt $\gamma$ from residual nuclei deexcitation
  - ~50% reduction of atmospheric background
Search for $p \rightarrow \bar{\nu} K^+$ decay

- favored by SUSY GUTs
- kaon not visible in Water Cherenkov detector: reconstructed from decay products
  - monochromatic muon (236 MeV) + prompt deex. photon (6.3 MeV)
  - excess in muon spectrum
  - or search for $K^+ \rightarrow \pi^0 \pi^+$ decay (BR 21%)

Partial lifetimes limits (90% C.L., 10 y exposure)
- $7.8 \cdot 10^{34}$ years for $p \rightarrow e^+ \pi^0$
- $3.24 \cdot 10^{34}$ years for $p \rightarrow \bar{\nu} K^+$

basically one order of magnitude improvement for many other nodes
Conclusions

- Hyper-Kamiokande is a multi-purpose project with long-term, wide physics program
  - high sensitivity to CP violation and other oscillation measurements
  - neutrino astrophysics
  - sensitivity to nucleon decay over 5 times higher than current limits
- Construction to start in April 2020 (data taking in ~2027)
- Plan to build a second tank in the future (in Korea?)
- An updated TDR in preparation

![Diagram showing the evolution of neutrino detectors from Kamiokande to Hyper-Kamiokande](image-url)
Backup slides
What so special about $\nu_\mu \rightarrow \nu_e$ channel?

- allows for CP violation studies

$$P(\nu_\mu \rightarrow \nu_e) = 4 c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31}$$

$$+ 8 c_{13}^2 s_{13} s_{12} s_{23} (c_{12} c_{23} \cos \delta_{CP} - s_{12} s_{13} s_{23}) \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$$

$$- 8 c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin \delta_{CP} \sin \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$$

$$+ 4 s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 - 2 c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta_{CP}) \sin^2 \Delta_{21}$$

$$- 8 c_{13}^2 s_{13}^2 s_{23}^2 \frac{a L}{4 E_\nu} (1 - 2 s_{13}^2) \cos \Delta_{32} \sin \Delta_{31} + 8 c_{13}^2 s_{13}^2 s_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2 s_{13}^2) \sin^2 \Delta_{31}$$

for $\bar{\nu}$

$$\delta_{CP} \rightarrow - \delta_{CP}$$

$$a \rightarrow - a \quad a = 2 \sqrt{2} G_F n_e E_\nu$$

$n_e$ related to matter density

subleading effect, can be as large as 30% of dominant
How to look for CP violation?

- **method 1**: use $\theta_{13}$ from reactor experiments for predictions and compare to neutrino data

- **method 2**: compare measured $P(\nu_\mu \rightarrow \nu_e)$ with $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

- **method 3** (for wide band beams): compare $1^{st}$ and $2^{nd}$ maximum
Neutrino interactions in WC

- low energies: scattering on electrons, inverse \( \beta \) decay
  - CC interactions observed only for \( \nu_e \)
- high energies: scattering on nuclei
- \( \Delta E/E \sim 10\% \) for 2-body kinematics
- very good \( \mu/e \) separation
  - muons misidentified as electrons: <1\%
- \( \pi^0 \) detection (2 e-like rings)
- delayed signal detection (Michel electrons, deexcitation)

(MC simulation)
under investigation: put 2\textsuperscript{nd} tank in Korea
- 1000-1200km baseline
- 1.3-3.0\degree off-axis beam
- enhances sensitivity to mass hierarchy and CP violation
Situation with one tank in Korea

- 2\textsuperscript{nd} oscillation maximum covered
  - CP asymmetry for $\nu_e\bar{\nu}_e$ appearance is 3x larger than at 1\textsuperscript{st} maximum
  - larger CP effect $\rightarrow$ less sensitive to systematic errors
- larger matter effect for longer baseline
  - better sensitivity for mass hierarchy
- smaller number of events because of flux reduction
Sensitivities

mass hierarchy
- for 1.5° off-axis
  6-8σ (true NH)
  5.5-7σ (true IH)
  for all $\delta_{\text{CP}}$

CP violation
- known hierarchy
- unknown hierarchy
Nucleon decays in GUTs
Hints on CP violation from T2K

expected numbers of events

\( \nu: 1.49 \times 10^{21} \text{ POT} \)
\( \bar{\nu}: 1.63 \times 10^{21} \text{ POT} \)

<table>
<thead>
<tr>
<th>( \delta_{\text{CP}} )</th>
<th>(-0.5\pi)</th>
<th>0</th>
<th>0.5\pi</th>
<th>\pi</th>
<th>observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_e \text{ CCQE} )</td>
<td>74.4</td>
<td>62.2</td>
<td>50.6</td>
<td>62.7</td>
<td>75</td>
</tr>
<tr>
<td>( \nu_e \text{ CC1}\pi )</td>
<td>7.0</td>
<td>6.1</td>
<td>4.9</td>
<td>5.9</td>
<td>15</td>
</tr>
<tr>
<td>( \bar{\nu}_e \text{ CCQE} )</td>
<td>17.1</td>
<td>19.4</td>
<td>21.7</td>
<td>19.3</td>
<td>15</td>
</tr>
</tbody>
</table>

\( \delta_{\text{CP}} = [-2.966, -0.628] \) (NH)
\( [-1.799, -0.979] \) (IH)

@ 90% CL

- CP conserving values \( (\delta_{\text{CP}} = 0 \text{ or } \pi) \)
  disfavored at 2\( \sigma \) level