Astrophysical vs
@ HyperK

David Bravo-Berguño, on behalf of the HyperK protoCollab.
Universidad Autonomy de Madrid (UAM)
Hyper-Kamiokande protoCollaboration

300+ member (proto)Collaboration, comprising 17 countries in Asia, Europe and the Americas, inscribed in 82 institutes (75% international)

March 2018 protoCollaboration meeting in UAM (Madrid, Spain)
Hyper-Kamiokande project

- UTokyo ratified funding to continue design and start construction next April, to **start DAQ in 2027**. One of MEXT’s higher priority large-scale projects in Japan.


- Several internal **Technical Reports** published.

- Intermediate Water Cherenkov Detector (IWCD) CDR released.

- Enlarged, improved version of SuperK (**10x statistics**) aiming for low background, and therefore low threshold.

- Second tank under detailed consideration (preferred location in Korea: HKK).

- Same **beam oscillation** possibilities as with SuperK through J-PARC’s T2HK(K) beam.
Hyper-Kamiokande’s physics

- Multipurpose detector with a wide breadth of physics reach; unparalleled projected sensitivity in many areas:

  √ **Neutrino oscillations** (MH, \( \delta_{CP} \), PMNS)
    - Long-baseline beam (T2HK)
    - Atmospheric
    - Solar

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    - Other sources (AGN, GRB, GW...)
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  √ Neutrino geophysics
  √ Nucleon decay

- For more on:
  - Nucleon decay searches and sensitivity with HK, see next talk!
  - Long-baseline beam neutrino physics, including sensitivity to neutrino CP violation ($\delta_{\text{CP}}$), see tomorrow’s talk and Near Detectors contribution at poster session!
Astrophysical neutrinos: HK aims

- **Supernova neutrinos**
  - √ Pinpoint directionality & reach (~80k events for a 10 kph SN; visible up to 4 Mpc)
  - √ Neutronization burst
  - √ Accretion phase
  - √ Black hole formation
  - √ Absolute neutrino mass
  - √ Nucleosynthesis, SASI...
  - √ High-energy νs (circumstellar material)
  - √ SN relic (DSNB): HK-Gd

- **Neutrinos from dark matter annihilation**
  - √ Mass (<100 GeV/c²)
  - √ Self-annihilation cross section
  - √ Scattering cross section, spin-independent interactions

- **Solar neutrinos**
  - √ Day-night asymmetry (∆m²12 tension)
  - √ Upturn in MSW transition region (NSI...?)
  - √ Determination of hep flux (metallicity)
  - √ Real-time solar variability analysis
  - √ Solar flare neutrinos

- **GRBs, newborn pulsar winds**

- **Neutron star GW events (ν annihilation?)**

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**Higher statistics** than any other next-generation experiment, while keeping **directionality** and sensitivity to **low energies** (beyond νe mode).
How will HK achieve this?

- A superior **energy resolution** in a wide dynamic range is the critical factor in achieving HyperK’s planned objectives.

- This will pair with the much enhanced **statistics** collection.

- Projected energy resolution relies on achieving high precision calibrations, as well as background suppression (esp. \(^{222}\)Rn), in line with SuperK’s SK-IV period (2009-18).

- **NEW** high-quantum-efficiency 50cm box-and-line (B&L) PMTs: R12860-HQE.
  - √ Commonality with SK’s shape and dimensions
  - √ ~40% faster time response
  - √ +8% Q.E. @ peak
  - √ Greater Sb-K-Cs collection area and efficiency
  - √ Improved SPE resolution
  - √ Linear response resilience to saturation
  - √ Twice the pressure bearing resistance (neck redesign)
  - √ Order-of-magnitude reduction (\(^{80}\)K) in background
  - √ Improved shockwave prevention PMT covers ->
    - -> **Spanish contribution**
  - √ Dark rate reduction effort ongoing
  - √ Possibility to include multi-PMT modules (19 3” PMTs) for increased granularity, or MCPs for detection efficiency…

- More info:
  - Role of multi-PMTs in HK’s superior sensitivity through energy resolution, **in this afternoon’s talk and poster!**
  - DAQ/trigger strategies for statistics collection, especially for SN, **in tomorrow morning’s talk!**

<table>
<thead>
<tr>
<th></th>
<th>HK</th>
<th>SK CM</th>
</tr>
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<tbody>
<tr>
<td>Rise time</td>
<td>6.7 ns (SPE)</td>
<td>10.6 ns (SPE)</td>
</tr>
<tr>
<td>FWHM (w/o ringing)</td>
<td>13.0 ns</td>
<td>18.5 ns</td>
</tr>
<tr>
<td>Timing res.</td>
<td>2.6±0.1 ns</td>
<td>~5 ns</td>
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<tr>
<td>QE (peak)</td>
<td>30%</td>
<td>22%</td>
</tr>
<tr>
<td>Ph.cath. area</td>
<td>49.2 cm</td>
<td>46 cm</td>
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<tr>
<td>CE within ph.c.</td>
<td>87%</td>
<td>73%</td>
</tr>
<tr>
<td>Sigma res.</td>
<td>35%</td>
<td>50%</td>
</tr>
<tr>
<td>Output linearity</td>
<td>470 p.e.</td>
<td>250 p.e.(specs)</td>
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<tr>
<td></td>
<td></td>
<td>700 p.e.(measured)</td>
</tr>
<tr>
<td>Dark rate</td>
<td>~6 kHz (reducing)</td>
<td>4.2 Khz</td>
</tr>
<tr>
<td>Pressure rating</td>
<td>80 m</td>
<td>50 m</td>
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SuperNovae with HK

- 99% of released energy ($\sim 3 \cdot 10^{53}$ erg) in core collapse SN expected to be carried out by neutrinos.

\[ \sqrt{10^{51}} \text{ erg in short } e^- \text{ capture burst: } \nu_e (\text{neutronization burst, } \sim 10 \text{ ms}) \]
\[ \sqrt{\text{Majority of energy in accretion+cooling phase (} \leq 1 \text{ s). All flavors & antinus.}} \]

- 25 SN neutrinos observed (ever!): SN1987A, mainly IBD, in KamiokaNDE II (12) + IMB (8) + Baksan (5).

**Want more!**

- HK will have a low threshold (3 MeV)
- Can reconstruct with 1°-1.3° accuracy (pinpoint)
- DAQ stable at >50 kHz.

- Backgrounds negligible: full IV (instead of FV) of 220 kt (1 Tank)

**Superior sensitivity:**
- $\sqrt{\text{FV 8-16x SK’s -> Statistics!}}$
- $\sqrt{\text{IBD possible (as opposed to just like } \nu_e \text{ LArTPCs}}$
- $\sqrt{\text{Event-by-event “low-E” recognition (as opposed to statistical,}}$
- $\sqrt{\text{like ice arrays) -> Time-dependent } E_{SN} \text{ spectrum.}}$
- $\sqrt{\text{3-6% detection probability of 4Mpc SN; 27-48% at 2 MPc ->}}$
- $\sqrt{\text{with these sensitivities, SN signal every 3 y.}}$
SuperNovae with HK: physics

✓ Collective inter-neutrino effects: swap e-flavor spectra to $\mu, \tau$ in energy intervals bound by sharp splits.
✓ Shape of neutrino flux/energy within 1 ms: model downselect.
✓ Sharp flux drop: direct observation of BH formation.
✓ Sharp burst rise: absolute $\nu$ mass $\rightarrow \Delta t = 5.15 ms (D/10kpc) (m/1 ev)^2 (E/10 MeV)^{-2}$
  Sensitivity to [0.5,1.3] eV, regardless of mass mechanism (Dirac/Maj.)
✓ Electron neutrino temperature lower than $\mu, \tau$: nucleosynthesis.
✓ Characteristic flux modulations within 15 kpc: are neutrinos driver of SN burst?
  (Standing Accretion Shock Instability (SASI): controversial!)
✓ Neutrino oscillation due to SN rotation.
✓ Merged energy spectrum from extragalactic SN: reference spectrum
  (“DSNB w/o redshift”).
✓ Dim supernovae (threshold >10 MeV).
✓ Shock breakout in interaction-powered SN:
  Galactic CR acceleration by SN remnants.
Diffuse Supernova Neutrino Background (SN relic)

- DSNB/SNR neutrinos are the neutrino background left over by all past supernovae. Theorized to constitute $\Phi \sim \mathcal{O}(10) \text{cm}^{-2} \text{s}^{-1}$.

- Can tell history of heavy element synthesis since stellar formation commenced.

- Can in principle be discovered by current-generation experiments. Hopefully SK-Gd, currently obscured in pure-$\text{H}_2\text{O}$ SK by spallation and low-E atmospherics.

- Megaton-scale needed to measure spectrum and characteristics: HyperK ($\sim 20 \text{ ev/y}$)

- Comparison with (optical) SN rate will give rate of failed explosions (optically-dark).
Supernovae with HK: neutron tag (+ digression on SK-Gd)

• Pre-SN (O-Si burning), SN burst pinpointing, DSNB + $\delta_{CP}$, pdk... benefit from increased $\nu$ tagging efficiency. Antineutrinos generate more final-state neutrons in their interactions by charge exchange.

• Hydrogen tagging possible, but low efficiency (~50% w new HK PMTs)

• 0.1% Gd$_2$(SO$_4$)$_3$ (~500tonne, 90% neutron tag) for SRN $\nu$:
  - HyperK -> $E\sim[16,30]$MeV
  - SuperK -> $E\sim[10-20]$MeV

Limits dictated by spallation products (increased in HK wrt SK, but can be coincidence-rejected away) and atmospheric $\nu$.

• Lower threshold (~10 MeV) to study SN bursts down to the epoch of $z\sim1$:
  - Time correlation (30 $\mu$s)
  - Vertex correlation (50 cm)
  - Prompt=Cherenkov-like ; Delayed=isotropic

- Reduction of spallation backgrounds by orders of magnitude.
- Invisible $\mu$ backgrounds (decay-e from muons below Cherenkov thresholds produced by atmospheric $\nu$) by factor of 5x.

SuperK is gearing up to start (early) SK-Gd phase by the end of this year / early next.
  - Leak fixing ($<17$ L/day) and refurbishment+upgrade work performed last summer.
  - Calibrations, new water system exercising and stabilization ongoing now (SK-V). Already close to SK-IV levels.
Solar neutrinos in HK

D/N asymmetry

- MSW matter effect -> enhanced solar $\nu$ flux at night (@ main $^{8}$B energies).
- Aim to reduce 0.5->0.3% syst. thanks to energy thr., calibration & background shape.
- Paired with much higher statistics, can get $4\sigma$ evidence in 2 years (no asymmetry) or 6 years (asymmetry from KL).
- Assumes SK's $^{222}$Rn content in full FV (challenging but deemed workable).
- Spallation background larger *per se*, but can be reduced by 3x (vs SK-IV) because of photodetection efficiency.

Upturn (Pee transition region)

- Unprobed shape of survival probability between low-E ($pp$, $pep$, $^{7}Be \leftrightarrow vacuum-dominated)$ and high-E solar $\nu$ ($^{8}B \leftrightarrow matter enhanced$).
- Shape can reveal NSI, MaVaN, sterile neutrinos...
- Possible to measure thanks to better energy resolution and reduction of (higher than threshold, but possibly misreconstructed) backgrounds.

Together imply $\Delta m_{12}^{2}$ tension (with KamLAND’s antineutrino data, i.e. between $\nu$ and $\bar{\nu}$) that may be indicative of new physics, NSI...
**Solar neutrinos in HK**

**hep neutrinos**

- Smaller solar neutrino flux component. Comes from main *pp* chain; most externally-produced neutrino in chain.
- Hints that may be higher than expected by SSM (Winchester, PhD).
- Holds 2nd-most important key to solar metallicity problem (after CNO).
- Probe for NSI at ~18 MeV (possible enhancement).

**Solar variability**

- Core temperatures influence directly $^8$B production. Neutrinos give us a real-time probe of that process.
- Statistical power in HK means short-time variability analysis of Sun’s core temperature.

**Flares**

- $10^{33}$ erg emitted over $\sim O(10)$ min scale when magnetic reconnections occur.
- Protons can be accelerated $\sim 10$ GeV. Interactions in solar atmosphere can produce mesons that decay into neutrinos.
- 6-7 events can be expected in HK, but large uncertainties still exist for these estimates -> Discovery?
**Multimessenger astronomy with HK**

### GRB jets & pulsar winds

- GRBs are most luminous \(10^{52}\) erg/s astrophysical phenomena: prompt ~MeV gamma rays.
- Relativistic jet, caused by a black hole’s accretion disk (or magnetized neutron star), variable in the ~ms scale —→ unsteady outflows \(\Longleftrightarrow\) shock dissipation.
- UHE CRs come from them as recently proven (Fermi / IceCube, EHT…). TeV/PeV neutrinos emitted too.
- Mechanism still debatable (low-E photon spectrum, inelastic nucleon-neutron collision…)
- GRB neutrino detection if <100 Mpc (can be, but unlikely).
- Trans-relativistic supernovae or low-luminosity GRBs (“choked jets”) more plentiful.

- How jets are accelerated, jet composition, connection between GRBs and energetic SN.

- Outflows do not have to be jets: can be proto-neutron star winds (newborn pulsar) —→ neutrino heating.
- 0.1-1 GeV neutrinos (20-30 events in HK @10kpc).
- Spatio-temporal coincidence to reduce atmospheric backgrounds crucial —→ multimessenger at its best (information from other wavelengths).

### Gravitational wave correlations

- As discovered by IceCube/LIGO, GW events can emit neutrinos (presumably only when at least a NS is involved)
- Models predict up to \(10^{53}\) erg in neutrinos.
- HyperK will be able to detect thermal neutrinos from <10 kpc merger events.
Self-annihilation of DM particles in gravitational wells can theoretically lead to SM pairs.

\[ \chi \chi \rightarrow W^+ W^-; \tau^+ \tau^-; b \bar{b}; \mu^+ \mu^-; \nu \bar{\nu} \]

Atmospheric neutrinos = background (signal = \( \nu_e \), \( \nu_\mu \) components)

Angular distribution -> discern peak towards center of gravitational wells (Sun, Earth, galactic center...). Similar to discerning Sun in solar \( \nu \).

Momentum distribution -> \( \chi \) candidate mass (HK sensitive \( \leq 100 \text{ GeV/c}^2 \) )

Self-annihilation cross section sensitivity 3x-10x SK’s.

WIMP-nucleon scattering cross section (+ spin independent interactions) sensitivity through neutrinos coming from Earth’s core (scattered & decayed \( \chi \))
MOAR HK: HK-Korea and sensitivity reports

Sensitivity reports

Letter of Intent - arXiv:1109.3262
Option for 2nd tank in Korea (HKK) - arXiv:1611.06118
Hyper-Kamiokande Timeline and outlook

• Digging set to start in a few months (early JFY2020). It’s happening! Water filling in late ’26 / early ’27. DAQ start in late 2027.

• Hyper-Kamiokande will be in the forefront of the neutrino oscillations, astroparticle physics and nucleon decay research, thanks to its unprecedented size, resolution and sensitivity.

• HyperK will expand frontiers of knowledge in particle astrophysics on:
  √ Supernovae (core collapse, rotation, modulations, DSNB, pre-SN, trans-relativistic, dim, failed, interaction-powered, absolute neutrino mass, pinpoint location…)
  √ Solar neutrinos (\(^{8}\)B spectrum, hep, flares, variability, temperature…)
  √ Dark matter (self-annihilation, scattering, distribution, mass…)
  √ GRBs, pulsars, GWs…

• Second tank (in Korea? <= HKK) would extend the project’s sensitivity much further — under consideration.
HK proto-Collaboration (and myself) thank you for your attention. Let’s enjoy EPS’20!

Questions, comments? New collaborators?