Hyper-Kamiokande detector
and its capabilities in astrophysical neutrino search

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on behalf of the
Hyper-Kamiokande Collaboration

12th Cosmic Ray International Seminar - CRIS 2022, September 12-16th, 2022

Outline...

1. Overview of the Hyper-Kamiokande experiment

2. The mPMT inner detector and the INFN contribute for Hyper-K

3. The potentiality of Hyper-Kamiokande for the astrophycal neutrino search

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1. **Overview of the Hyper-Kamiokande experiment**
2. The mPMT inner detector and the INFN contribute for HK
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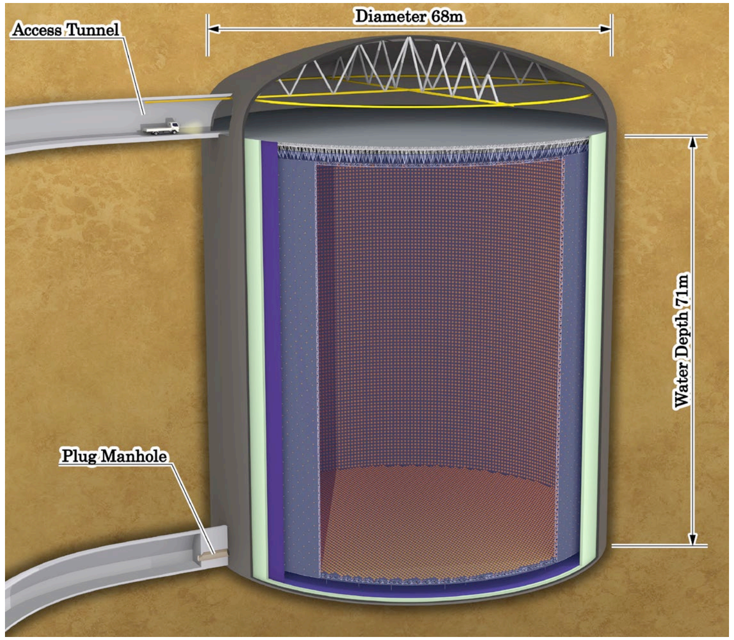
Hyper-K overview



Hyper-Kamiokande (Hyper-K, HK) is a multi-purpose **Water-Cherenkov detector** with a variety of scientific goals:

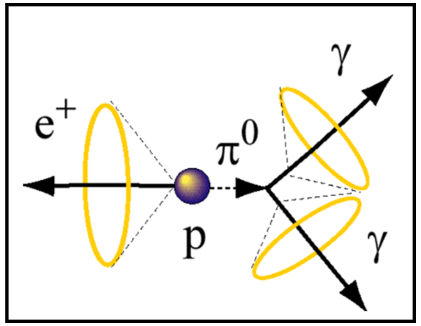
- ✧ Neutrino oscillations and CP violation (by atmospheric, accelerator and solar ν)
- ✧ Neutrino astrophysics
- ✧ Proton decay
- ✧ Non-standard physics

Hyper-K Far Detector (HK-FD)

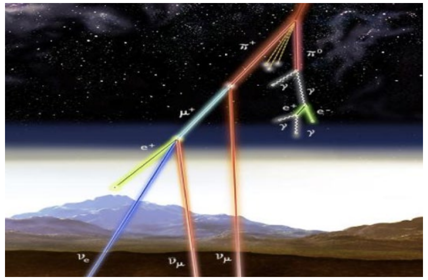
- ➢ Cylindrical tank: Φ 68 m and H 71 m
- ➢ Filled with 0.25 Mtons of ultra-pure water
- ➢ Fiducial volume: 0.19Mtons (~8 times SuperK)

Today, Hyper-K is under construction and its operation will begin in 2027!

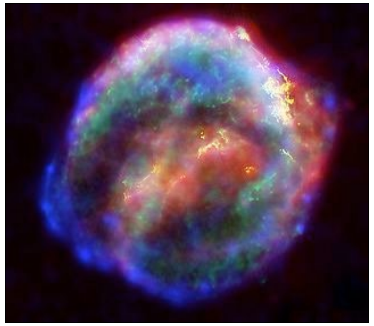
Proton decay



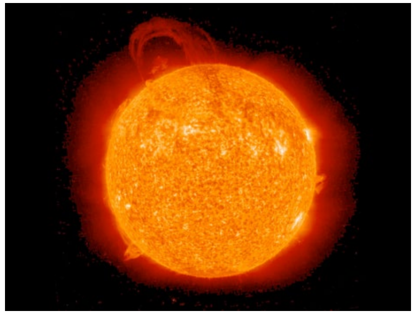
Atmospheric ν



Accelerator ν



Supernova ν



Solar ν

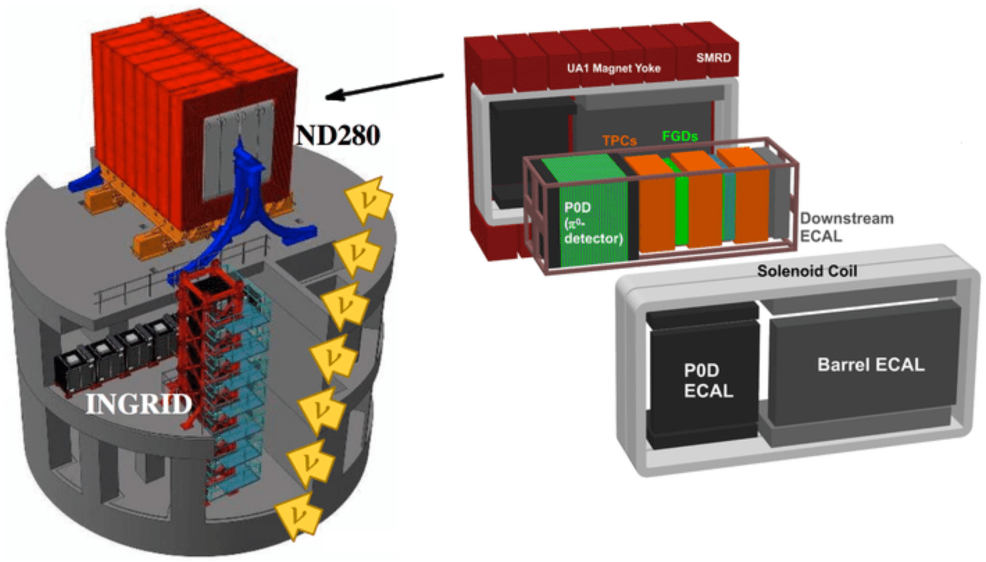
Hyper-K overview

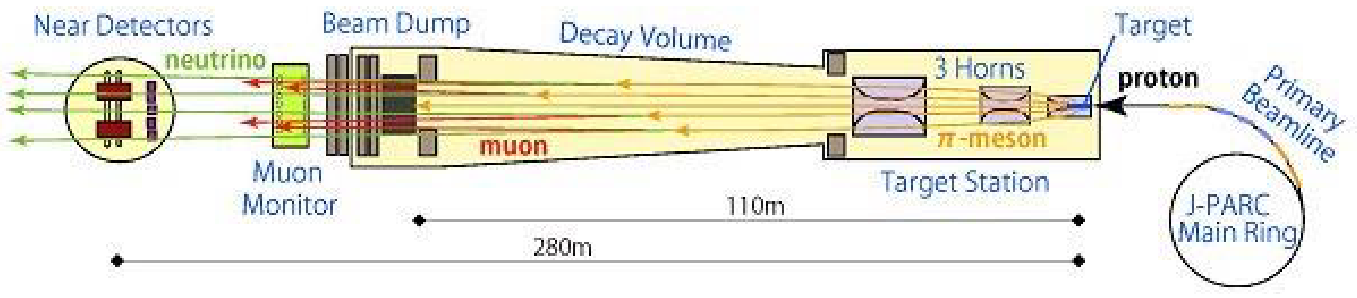
To give a complete scheme, the HK experiment consits of: the J-PARC accelerator; the INGRID and ND280 detectors; two off-axis detectors, i.e. HK-FD and the IWCD.

The **accelerator** at the **J-PARC** creates a 30 GeV proton beam, which hits a target to generate neutrinos through subsequent decays.

The **INGRID** (Interactive Neutrino GRID) detector measures the on-axis neutrino beam direction with a precision better than 1 mrad. It consists of 16 modules and placed around the beam center at 280 m downstream of the proton beam target.

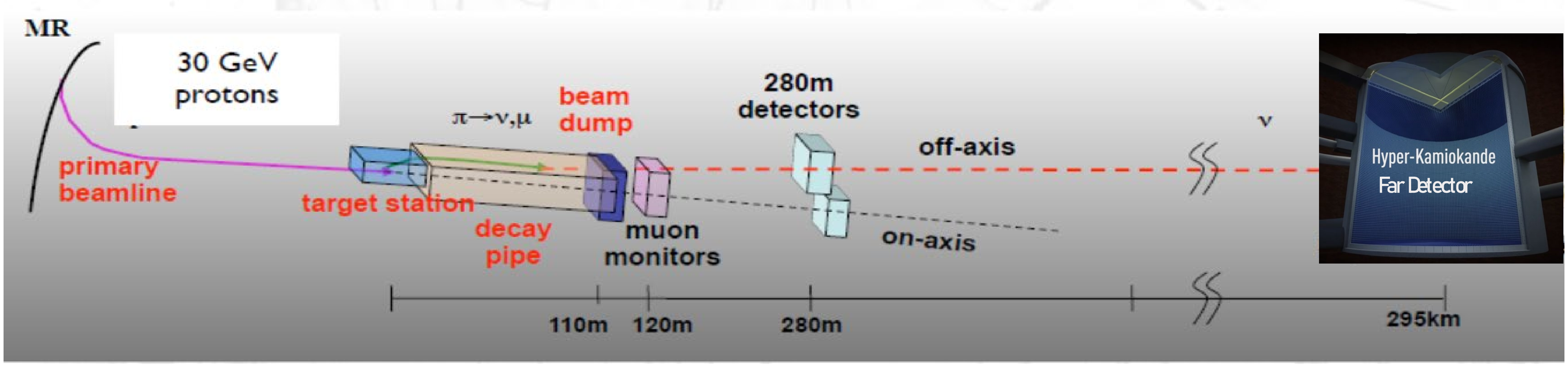
The **ND280** is the Near Detector placed at 280 m from the neutrino beam, 2.5° off-axis, and is dedicated to measure the initial condition of the beam.





Hyper-K overview

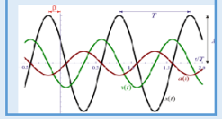
An overall schematic drawing from the accelerator to the FD in Kamioka



Neutrinos produced in a particle accelerators or nuclear reactors.

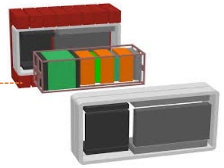
Neutrino flux properties

ν oscillations

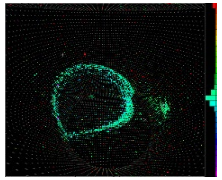


Neutrino flux & flavour

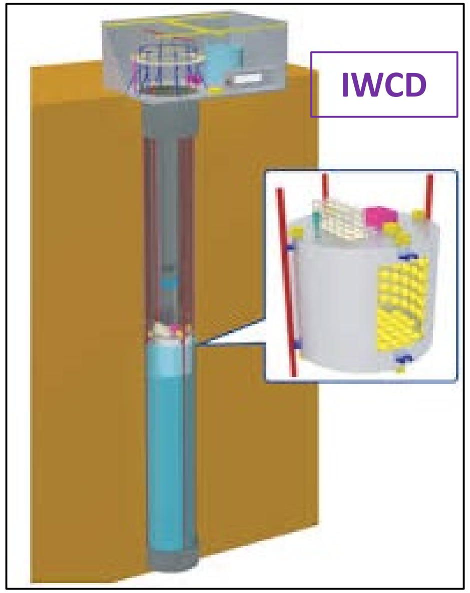
$\nu_\mu / \bar{\nu}_\mu$



$\nu_\mu / \bar{\nu}_\mu$ » $\nu_e / \bar{\nu}_e$

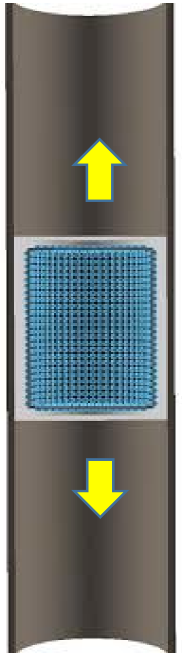


Hyper-K overview – The IWCD



Intermediate Water Cherenkov Detector (IWCD)

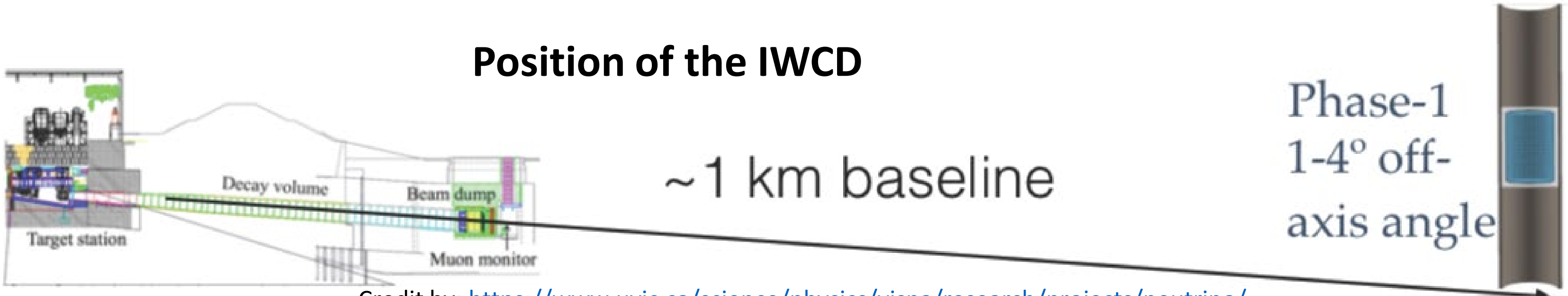
- 1 kilo-ton scale water Cherenkov detector
- It will be like an elevator, placed at ~ 1 km from the J-PARC accelerator
- mPMTs will be installed inside.



The Hyper-K IWCD
The instrumented portion will span a range of angles wrt the neutrino direction.

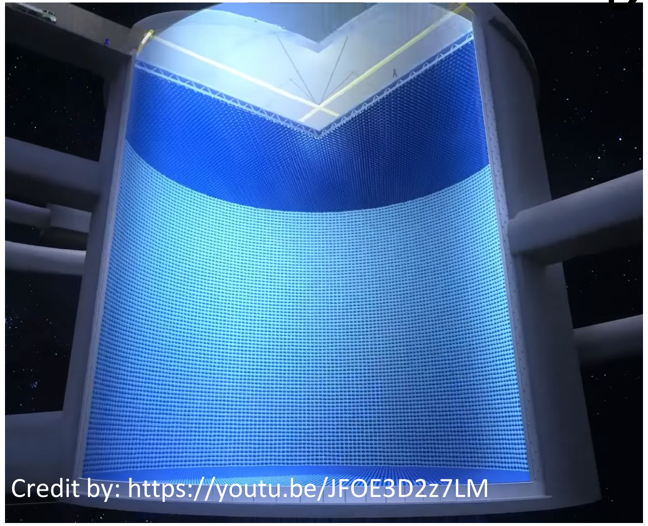
Inner detector:
- 8 m diameter and 6 m tall
- Planned to populate with ~**500 mPMT** modules.

Position of the IWCD



Credit by: https://www.uvic.ca/science/physics/vispa/research/projects/neutrino/

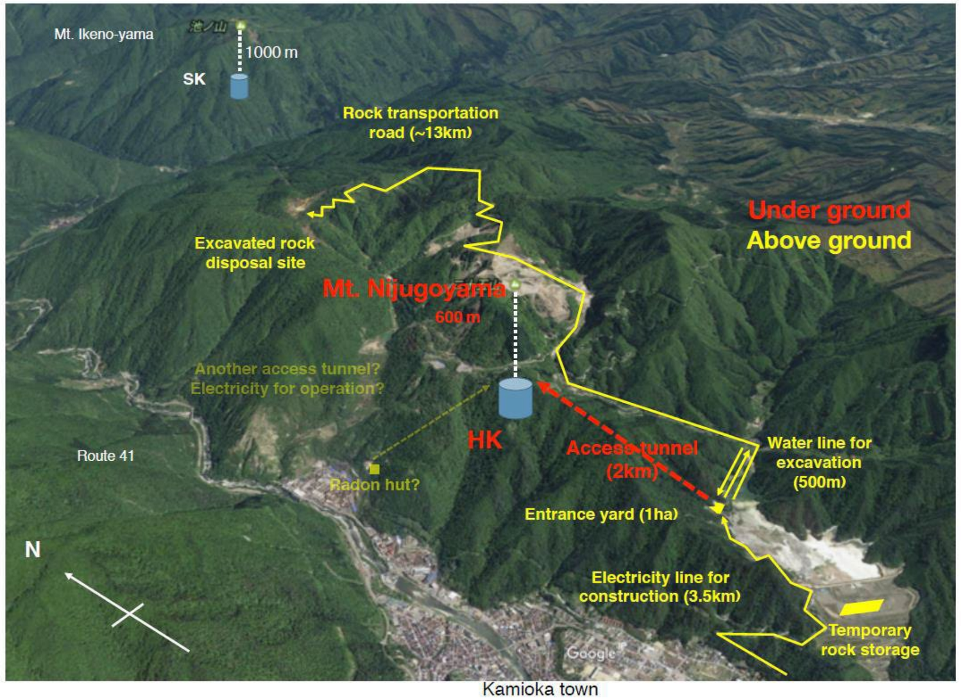
Hyper-K – Overview and its placement

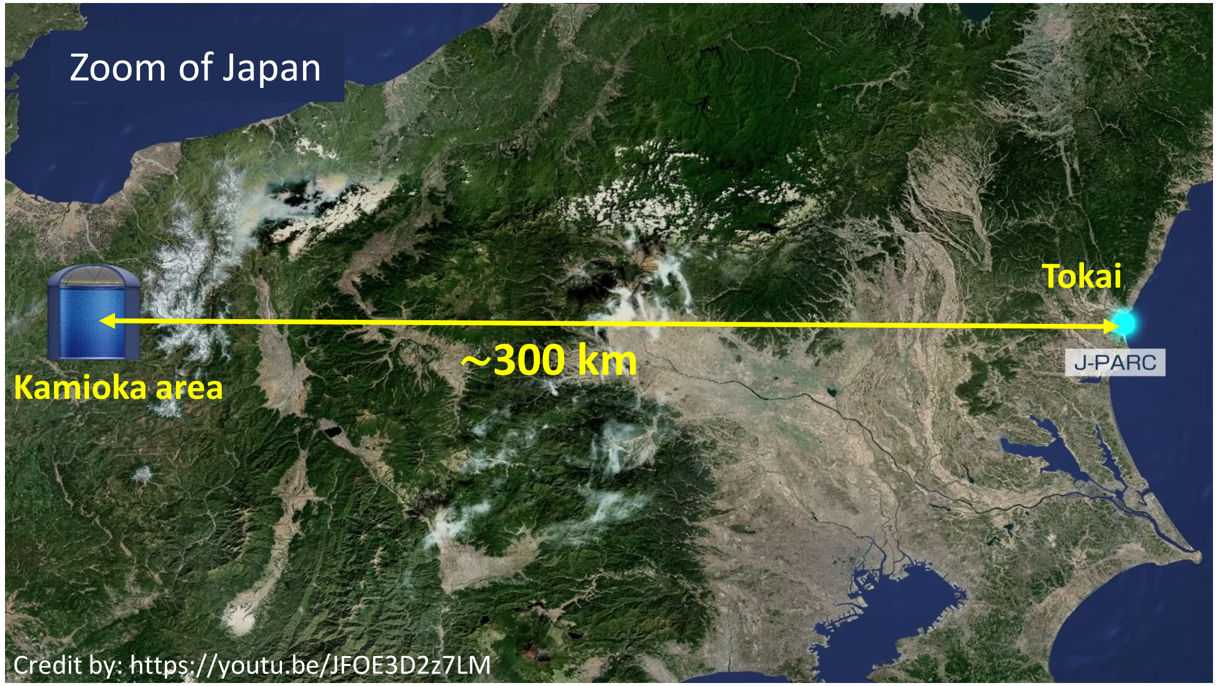


Hyper-K builds on the successful strategies used to study neutrino oscillations by Super-Kamiokande, K2K and T2K, but with some upgrades:

- ➢ Larger detector for increased statistics
- ➢ Improved photo-sensors for better efficiency
- ➢ Higher intensity beam and upgrated/new near detector for accelerator neutrino part

Detail of the Kamioka area (under constructions)

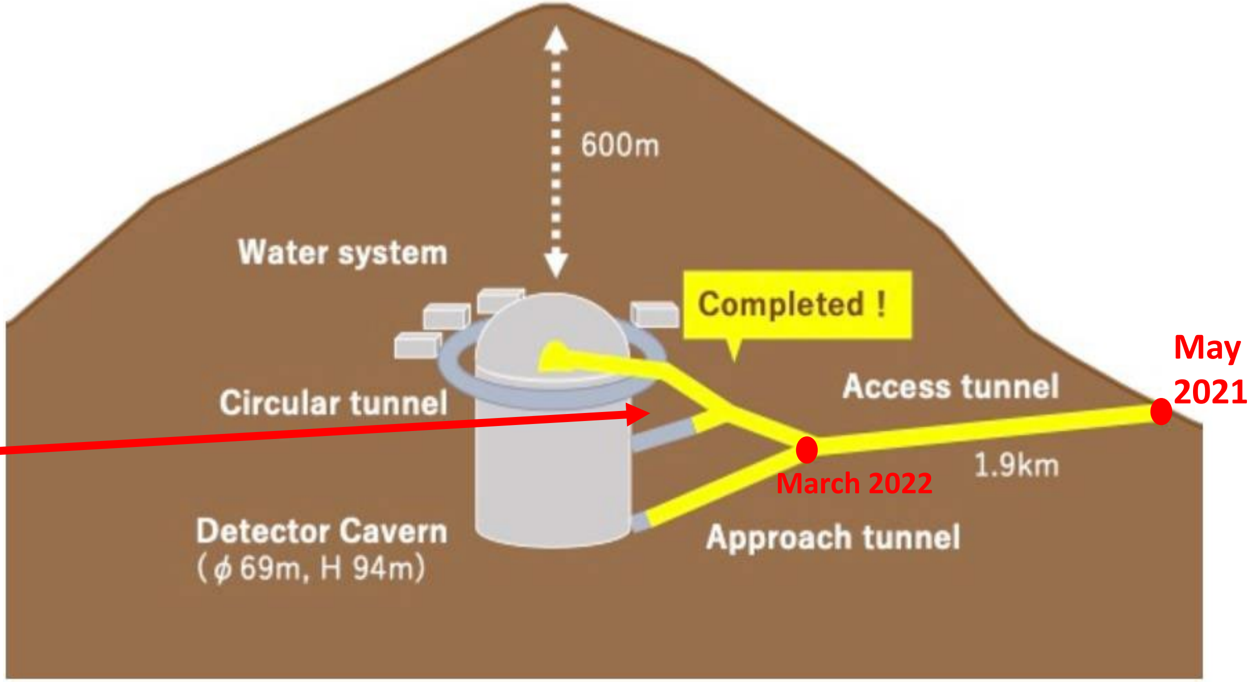




Hyper-K – Overview and its placement

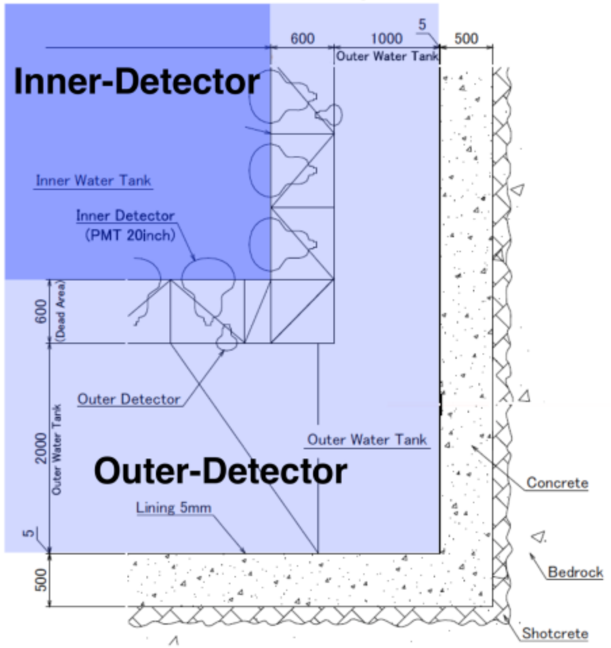
The HK location is in the Kamioka area, 600 metres underground.
The access tunnel works started the 6 May '21 and the center of the cavern dome was reached in the last June.

News and detail can be read here: https://www-sk.icrr.u-tokyo.ac.jp/en/hk/report/



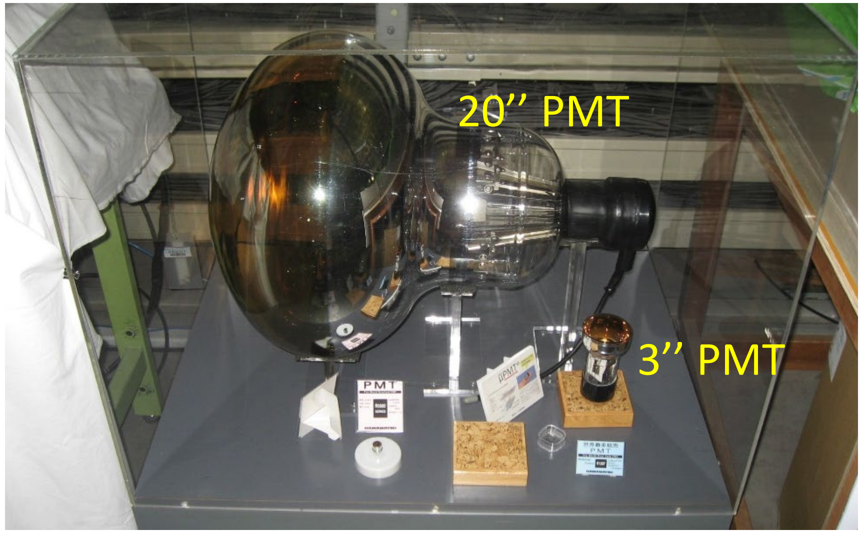
Hyper-K Far Detector inside

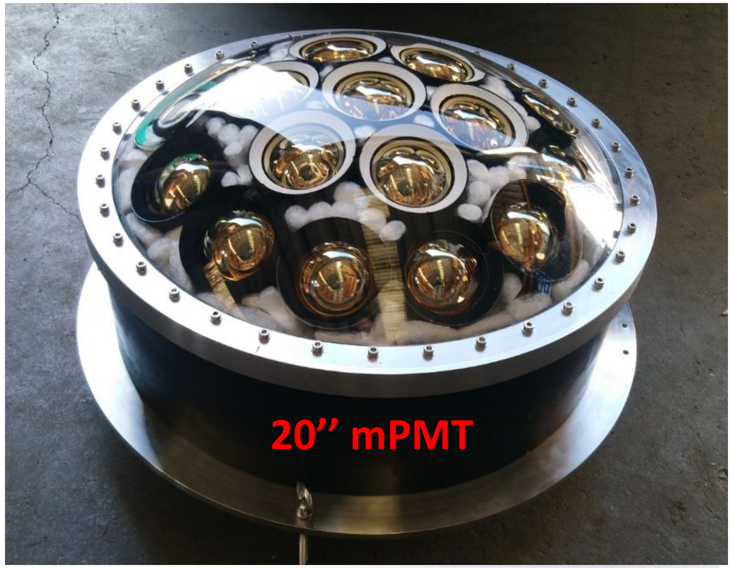
The **FD** will consist of a hybrid configuration of detectors to watch the inner and outer part of the tank: a structure frame supports all detectors and divides the water volume into two regions.

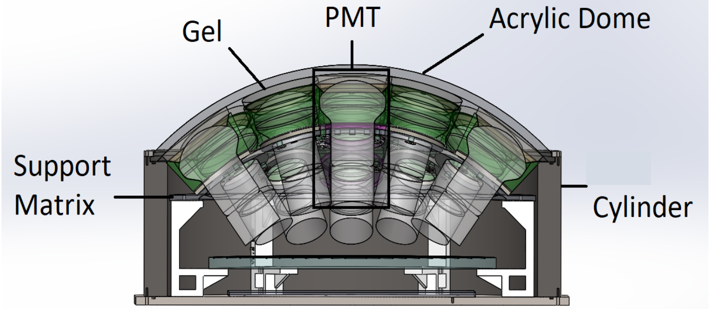


Inner detectors (IDs):

- ❖ 20'' PMTs (#20'000)
- ❖ 20'' mPMTs (->19 3'' PMTs inside) (#thousands)
  - ❖ [Photo-coverage (PC) 20%)]







New high-QE 50-cm Box&Line PMT

If compared to the Super-K PMT:
× 2 higher pressure bearing for 60-m depth
× 2 higher detection efficiency
and half time&charge resolutions

Outer detectors (ODs):

- ❖ 3'' PMTs + Wave Length Shifter (WLS) plates

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The multi-PMT designs

The mPMT is a vessel which houses and protects an array of 19 3” PMTs, and the original concept was realized for the **KM3NeT** experiment.
WRT single 20’’ PMTs the mPMT configuration:

- ✓ improves the granularity and timing response over larger number of photo-sensors
- ✓ has got an additional intrinsic directional information
  - ✓ Important point for astrophysical neutrino

This detector is a common effort from Italy, Canada and Poland.
Two mPMT designs are planned, but very similar each other ⟹ Same assembly, similar components where possible.

Different constrains for the IWCD and FD mPMTs:
- in the FD a higher resistance to pressure is required (in comparison with IWCD)
- in the IWCD mPMT electronics needs to be able to distinguish between different hits in different bunches

➢ Currently, the number of the mPMT for the HK FD is under discussion.

Principal mPMT componets	Characteristic for the FD	Caracteristic for the IWCD
Dome	UV-transmitting acrylic	UV-transmitting acrylic
3’’ PMT	19 items	19 items
Vessel cylinder	POM-C material (TBC)	PVC material (TBD)
Back plate	AISI-304 stainless steel	AISI-304 SS (TBD)
Optical gel	For an optical connection between the acrylic dome and the PMT photo-cathode	For an optical connection between the acrylic dome and the PMT photo-cathode
Clamping ring	AISI-304 stainless steel	AISI-304 SS (TBD)
Electronic board	Q/T digitization based on discrete components	FADC digitization, with on-board signal processing

The multi-PMT – About its tests

Many tests on the mPMT prototype and its material/components:

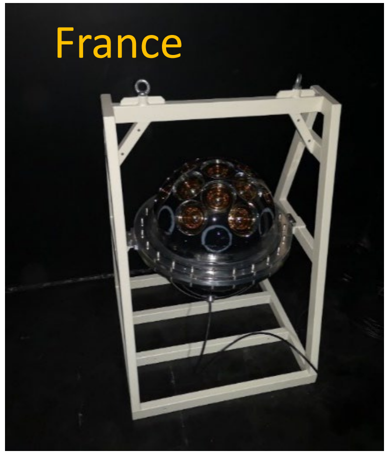
- Optical, mechanical and nuclear contamination tests on the UV-transmittance acrylic material
- Water absorption into acrylic sample
- Pressure tests of the external-component vessel
- Functional test of the first prototype in MEMPHYNO lab (a second test is scheduled soon with the last design)
- A preliminary installation into a mock-up frame in Hokkaido
- An anti-implosion test where the detector survived with no external damages and connections resisted
- Assembly tests
- ...

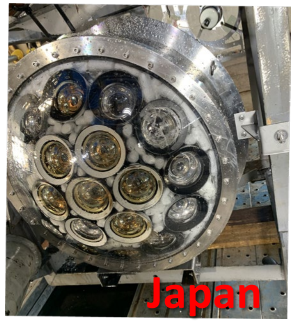
The mPMT is ready for some last verifications and final assemblies checks with the updated components.

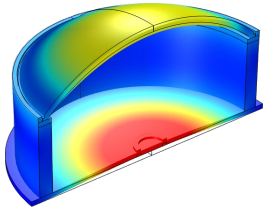
Nuclear contamination analysis at the National Gran Sasso Laboratories of INFN

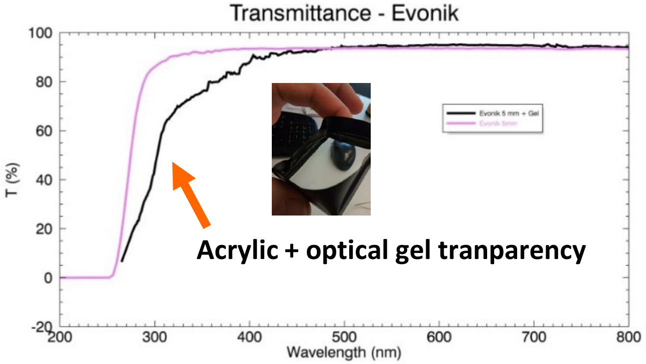
Isotope	Activity	Contamination
^{232}Th: Thorium series		
Ra-228	< 0.11 mBq/kg	< 0.027 ppb
Th-228	< 93 μBq/kg	< 0.023 ppb
^{238}U: Uranium series		
Ra-226	< 65 μBq/kg	< 0.0052 ppb
Th-234	< 4.6 mBq/kg	< 0.38 ppb
Pa-234m	< 2.5 mBq/kg	< 0.20 ppb
U-235	(0.15 ± 0.07) mBq/kg	$(3 \pm 1) \cdot 10^{-1}$ ppb
K-40	< 0.69 mBq/kg	< 0.022 ppm
Cs-137	< 25 μBq/kg	-

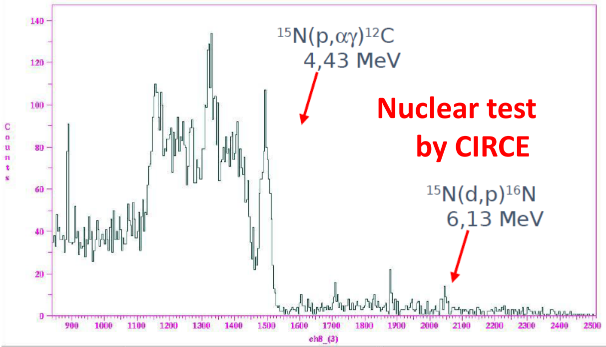
Table 5: Results of nuclear contamination of Evonik samples.

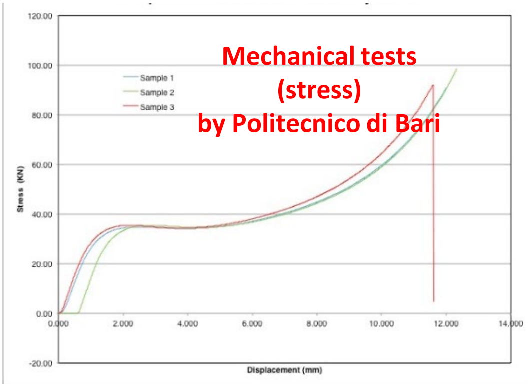


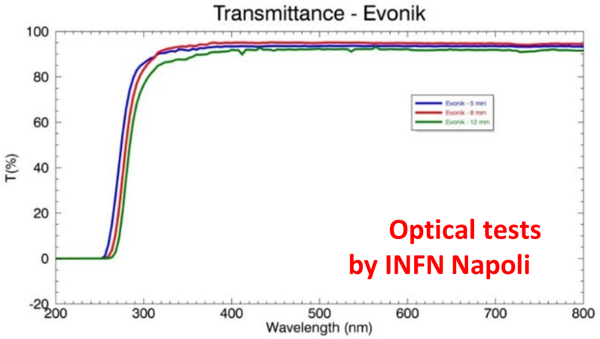




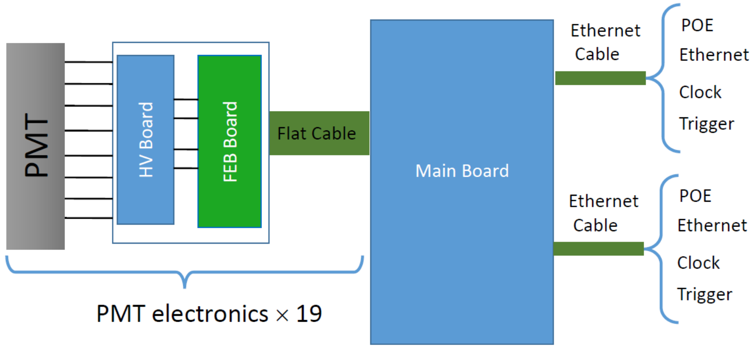








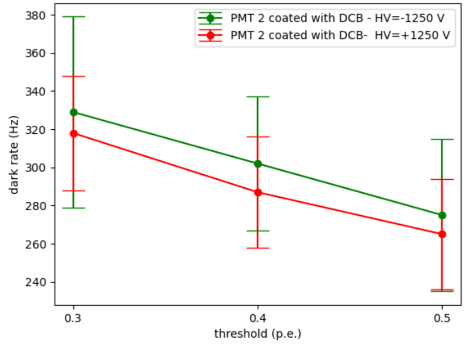
The multi-PMT – PMTs and electronics

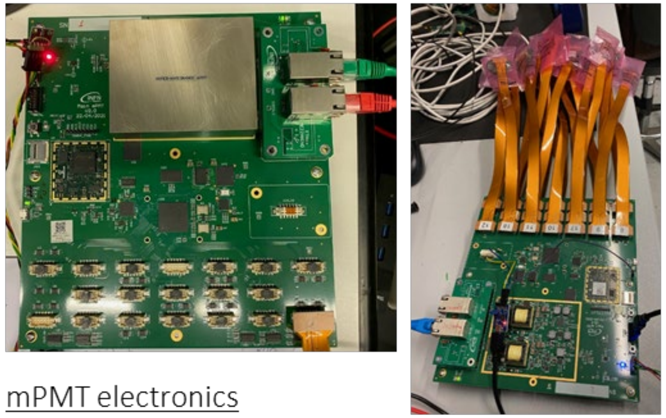


Requirement : Total Power consumption <4 W

HV board

Basic Cockcroft-Walton voltage multiplier circuit designed for HV up to 1.5 kV





mPMT electronics

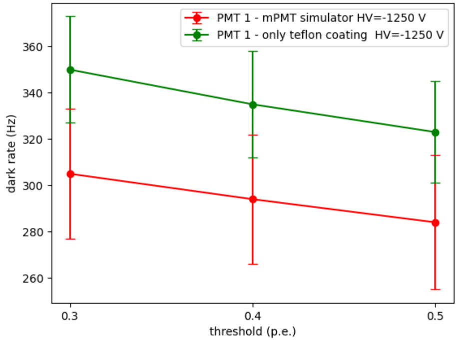
Ready to start reliability validation:

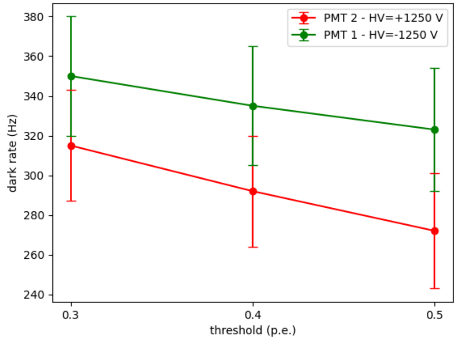
Contract started with company

Automatic testing procedure defined

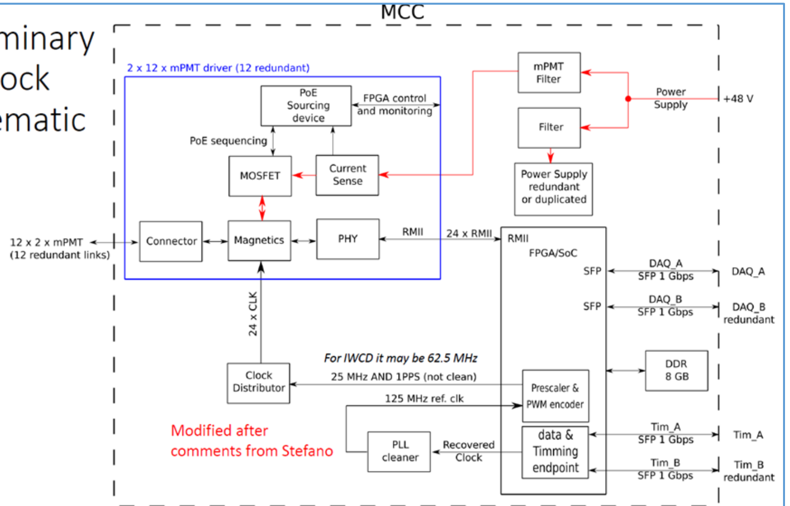
Installed in INFN mPMT prototype

LED calibrator card integration started





Preliminary block schematic



MCC Electronics

Started writing the MCC specification document

Estimating board size for MCC vessel design

Checking critical components aviability for prototypes

Some information:

- mPMT electronics is ready for realibility validation;
- Cables and feedthrough: prototypes ready for testing
- MCC: started writing specification document for electronics; studies for vessel started
- PMT tests and their charaterization are ongoing

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Solar neutrinos

Credits by: https://www.positivelynaperville.com/2018/08/20/science-corner-why-is-the-sun-so-hot/92664

Solar neutrinos

As mentioned, HK is a multipurpose experiment, where the study of CP Violation is the main goal, anyway relevant impacts can be given in astrophysics.

Why to study Solar neutrino?
- Confirmation of the solar model predictions (direct information from the core);
- Study of the neutrino itself (i.e., oscillations by $\sin\theta_{12}$, Δm^2_{21}, $\tan^2\theta_{12}$)

In the 2015 the SK and SNO experiments received the Nobel Prize in physics by discovering the neutrino oscillations (with an evidence of their mass).
Indirectly, this discovery found the solution to the solar missing neutrino problem too, because the detected ν_e flow was inexplicably too much low.

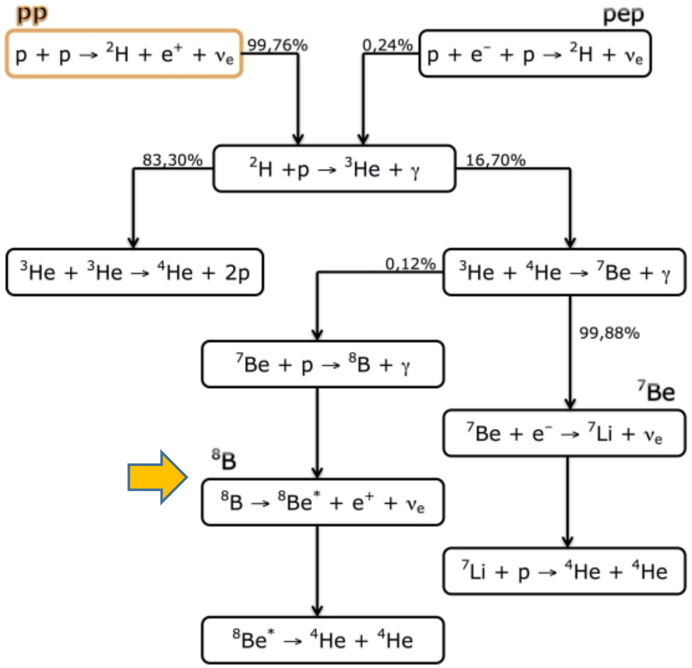
- ➢ Roughly two-thirds of ν_e change their flavor as they traveled, arriving as μ or τ neutrinos.

Sun produces electron neutrinos in its core by fusion nuclear reactions, principally by converting H into He through the **p-p** (>99%) and **CNO** (<1%) cycles...

Credits by: https://www.positivelynaperville.com/2018/08/20/science-corner-why-is-the-sun-so-hot/92664

Solar neutrinos

p-p chain



https://www.scientificast.it/neutrini-ci-parlano-del-sole/

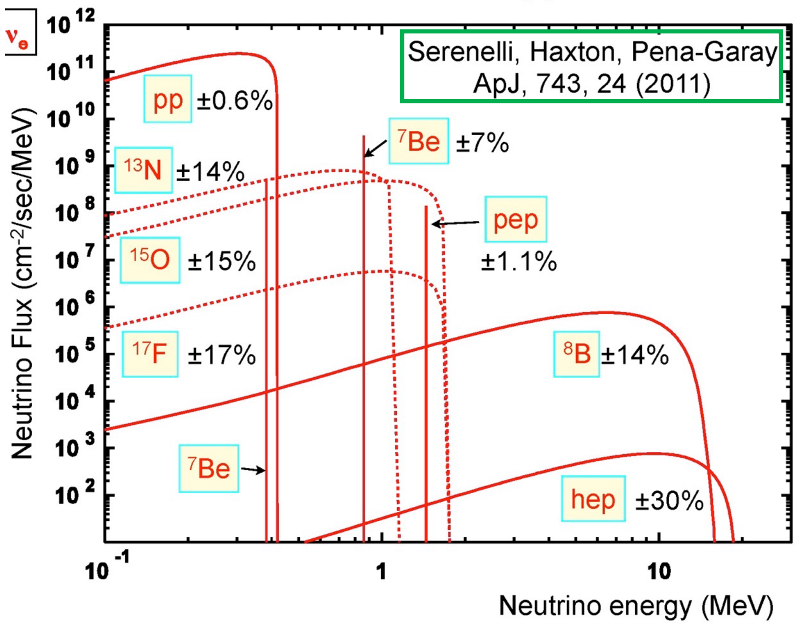
CNO cycle

$$^{12}_{6}C + ^{1}_{1}H \rightarrow ^{13}_{7}N + \gamma \quad +1{,}95\ MeV$$
$$^{13}_{7}N \rightarrow ^{13}_{6}C + e^{+} + \nu_e \quad +1{,}37\ MeV$$
$$^{13}_{6}C + ^{1}_{1}H \rightarrow ^{14}_{7}N + \gamma \quad +7{,}54\ MeV$$
$$^{14}_{7}N + ^{1}_{1}H \rightarrow ^{15}_{8}O + \gamma \quad +7{,}35\ MeV$$
$$^{15}_{8}O \rightarrow ^{15}_{7}N + e^{+} + \nu_e \quad +1{,}86\ MeV$$

$$^{15}_{7}N + ^{1}_{1}H \rightarrow ^{12}_{6}C + ^{4}_{2}He \quad +4{,}96\ MeV$$

http://ramanujan25449.blogspot.com/2014/06/las-estrellas-con-mayor-masa-de-la.html

Solar neutrino energy spectrum



- ➢ <u>HK detects</u> solar neutrino with **E_ν> 4.5 MeV**, corresponding to the reaction of the <u>boron-8 neutrinos</u> (^{8}B) of the III p-p branch.
- ➢ In HK we expect about 130 events/day, with $E_{e,kin}$ > 4.5 MeV (15 events/day in SK-I ~ IV), through neutrino-electron elastic scattering, ν + e → ν + e.
- ➢ The energy, direction and time of the original neutrinos can be measured through the recoil electron.

Solar neutrinos

Solar ν measurements can give information for ...

...Particle physics...:

- ✓ Precision measurement, Δm^2_{21}
- ✓ Day/Night asymmetry of solar ν flux caused by terrestrial matter effect is indicated by SK. [PRL 1212, 091805(2014)]
- ✓ The «upturn» of the Solar ν spectrum

...And astrophysics:

- ✓ Variation of solar ν flux
- ✓ Discovery of hep neutrino

Solar neutrinos

Solar ν measurements can give information for ...

...Particle physics...:

- ✓ Precision measurement, Δm^2_{21}
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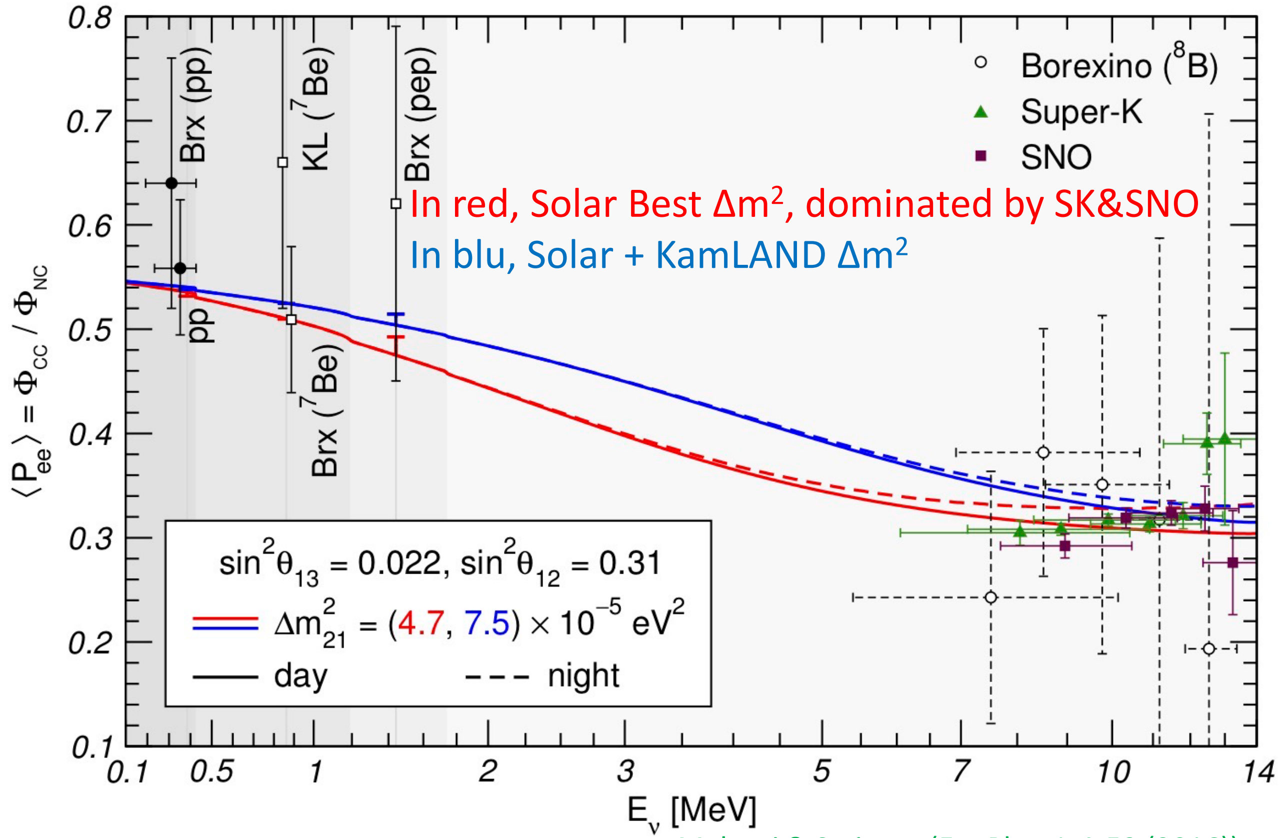
Currently, there is a tension between solar best Δm^2_{21} and reactor best value.



Maltoni & Smirnov (Eur.Phys.J. A 52 (2016))

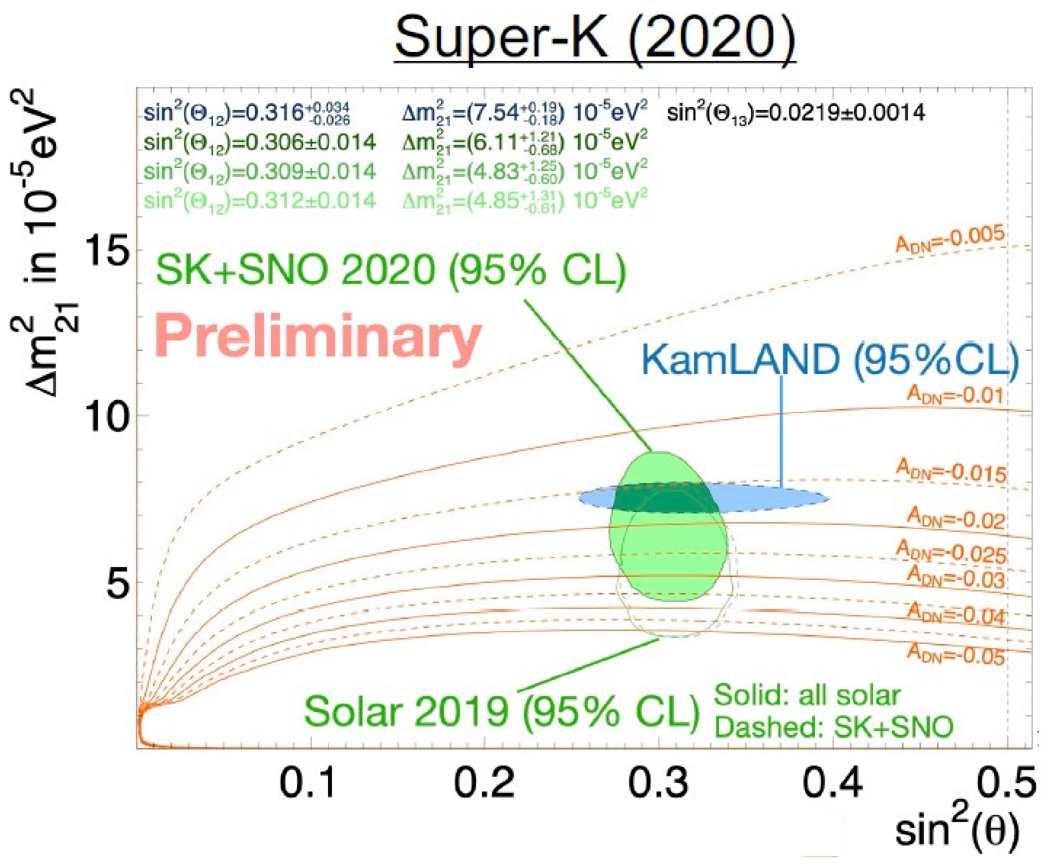
Solar neutrinos

Solar ν measurements can give information for ...
...Particle physics...:

Currently, there is a tension between solar best Δm^2_{21} and reactor best value.

By HK statistics, we can investigate:

- ✓ the terrestrial matter effect and the tension between solar best Δm^2_{21} and KamLAND best Δm^2_{21}.



The D/N asymmetry causes smaller Δm^2_{21} value in solar neutrino analysis, when compared to reactor neutrino analysis: ~1.4σ tension (It was 2σ at 2019.)
[Y. Nakajima (SK collaboration), Neutrino 2020]

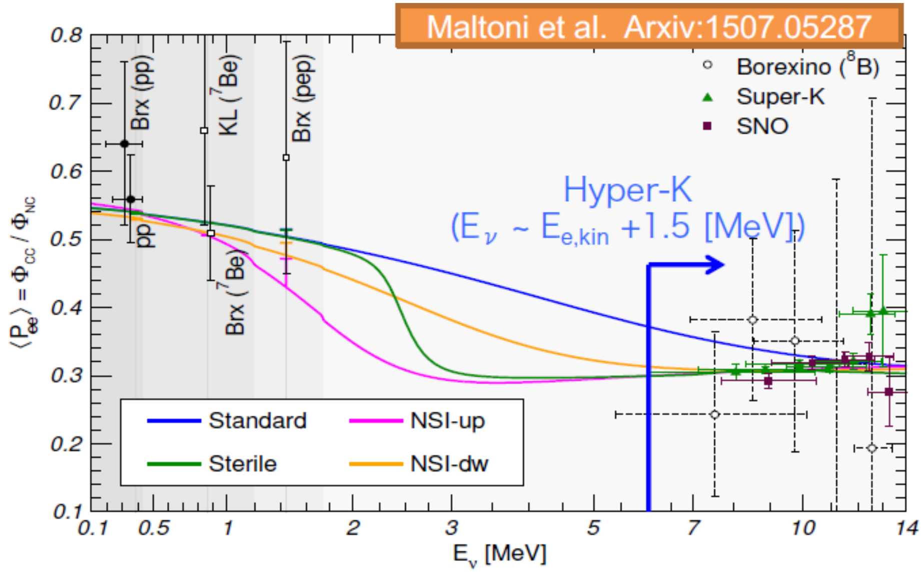
Solar neutrinos

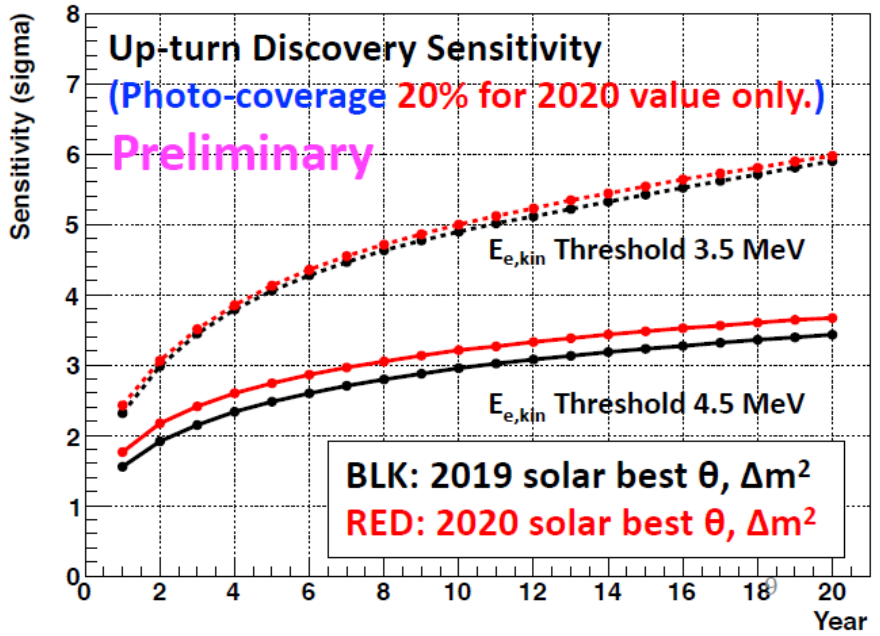
Solar ν measurements can give information for ...
...Particle physics...:

✓ The «upturn» of the Solar ν spectrum

Upturn is a fluctuation of the solar neutrino survival probability, at the middle energy of MSW-dominated and vacuum oscillation-dominated energies not observed yet, but expected (new BSM considerations).

The HK contribute:
To separate the cases with upturn and w/o upturn by **~ 3 or 5** sigma.
In the simulation, **4.5 and 3.5** MeV analysis threshold are assumed in electron kinetic energy equivalent.





Solar neutrinos

... and Astrophysics advantage:

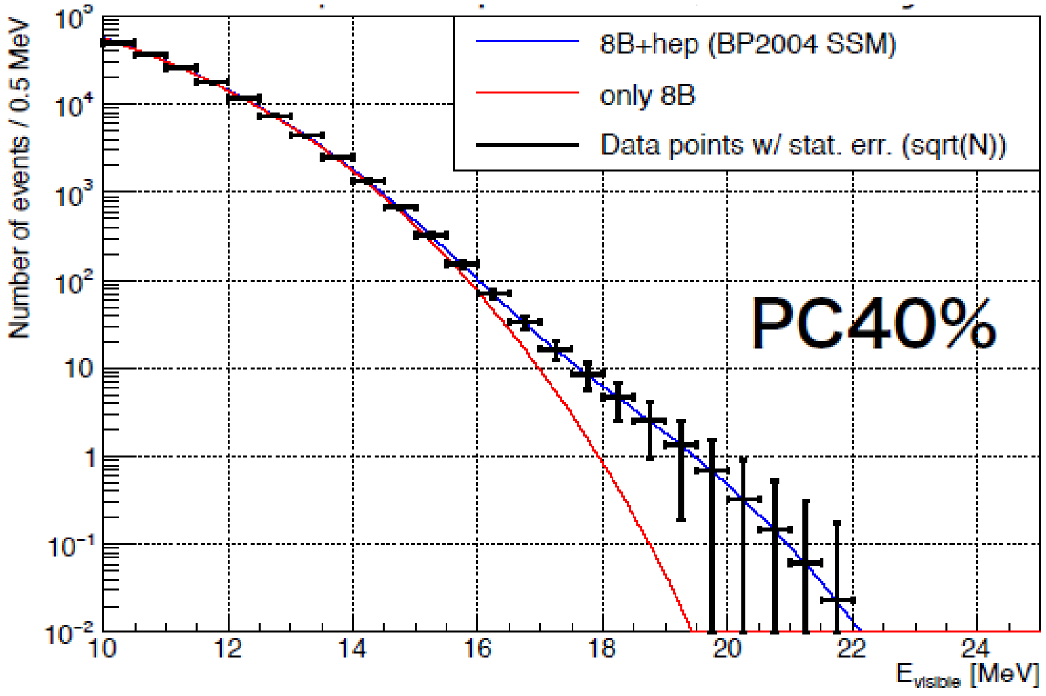
✓ **Discovery of Hep process neutrino** ($^3He+p \to {}^4He+e^++\nu_e$)

Undiscovered neutrinos, with small branching ratio. 10y-long HK observations can help to discover this process.

It is expected:

- Hyper-K: 130 [events/day], $E_{e,kin}$ > 4.5MeV –> over 10y = 1.8 ~ 3 σ (PC40%) (Super-K: 15 [events/day])

Expected ^8B and hep ν spectrum, over 10y by HK



Solar neutrinos

... and Astrophysics advantage:

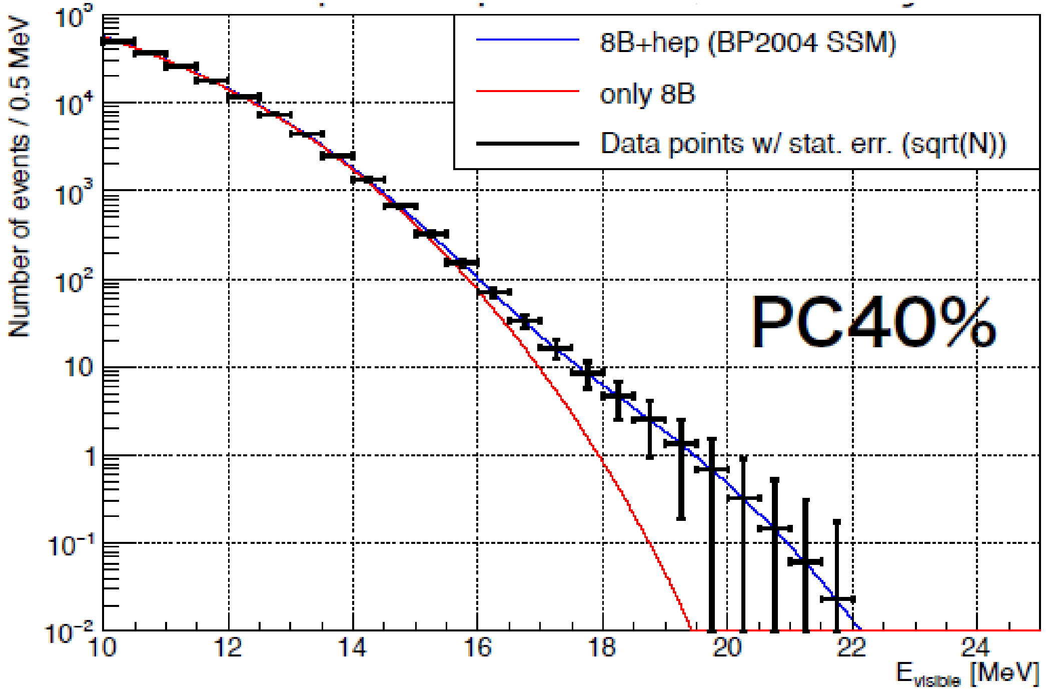
✓ **Discovery of Hep process neutrino** ($^3He+p \rightarrow {}^4He+e^+ + \nu_e$)

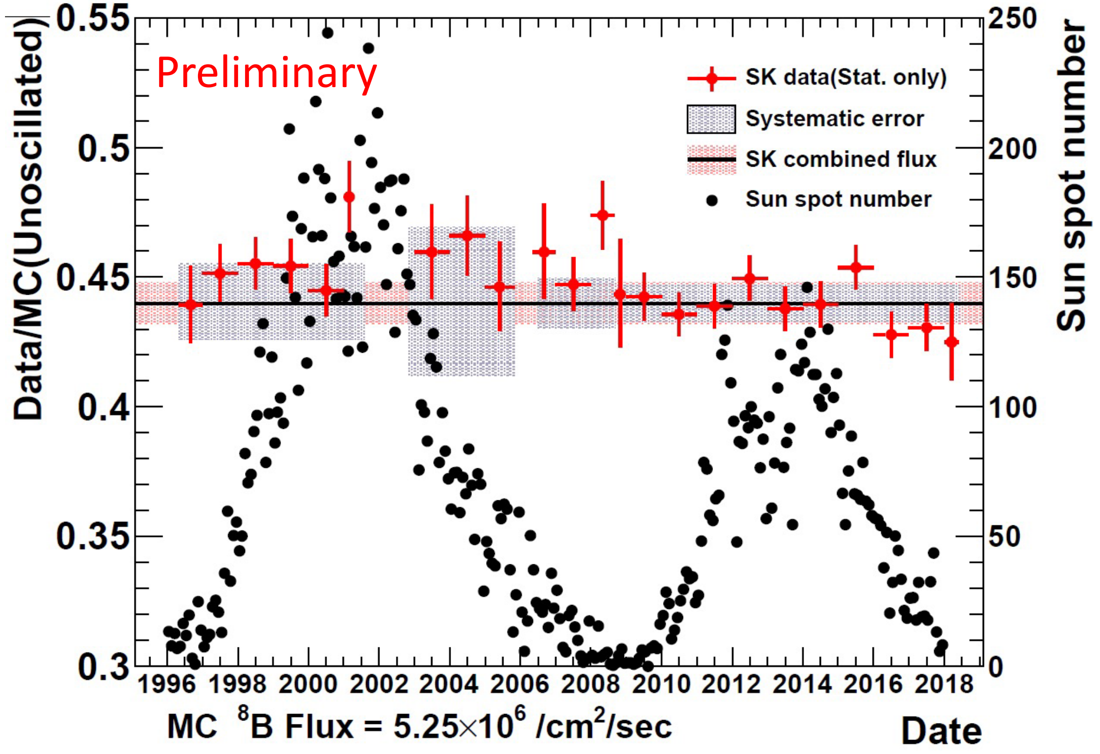
Undiscovered neutrinos, with small branching ratio. 10y-long HK observations can help to discover this process.
It is expected:

- Hyper-K: 130 [events/day], $E_{e,kin}$ > 4.5MeV –> over 10y = 1.8 ~ 3 σ (PC40%) (Super-K: 15 [events/day])

✓ **Variation of the solar neutrino flux**

Expected ^8B and hep ν spectrum, over 10y by HK





Y. Nakajima, Neutrino 2020

Supernova neutrinos

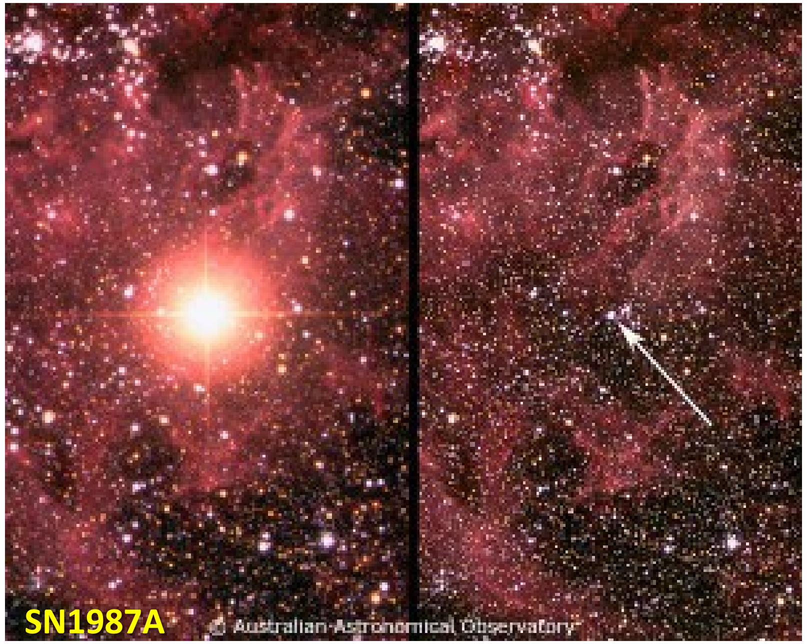
At the depletion of their nuclear fuel, stars with mass >8 $M_\odot$ go toward a core collapse which can origin SN explosions (w/ or w/o BH-NS).
The energy released by a SN event is estimated to be ~ 3 ×10^{53} ergs and about the 99% of the energy is carried out by all three flavours of neutrinos and anti-neutrinos, since they interact weakly with matter.

In the 2002, the Kamioka experiment shared the Nobel Prize in Physics for the neutrino detection related to the SN1987A.
This discovery opens the neutrino astronomy era!
Detection of these neutrinos can give direct information of energy flow during SN explosions.

The dominant signal at Hyper-K is the inverse beta reaction ($\bar{\nu}_e + p \rightarrow e^+ + n$).

Aspected events in HK with:
threshold = 3 MeV, E_ν emitted < 100 MeV. SN distance ~ 10 kpc

Neutrino source	Single Tank (220 kt Full Volume)
$\bar{\nu}_e + p$	50,000 - 75,000 events
$\nu + e^-$	3,400 - 3,600 events
$\nu_e +^{16} O$ CC	80 - 7,900 events
$\bar{\nu}_e +^{16} O$ CC	660 - 5,900 events
$\nu + e^-$ (Neutronization)	9 - 55 events
Total	54,000 - 90,000 events

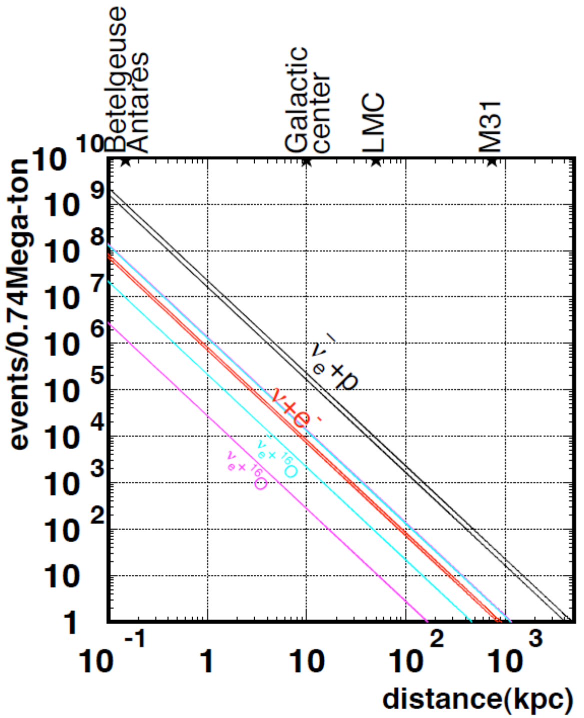


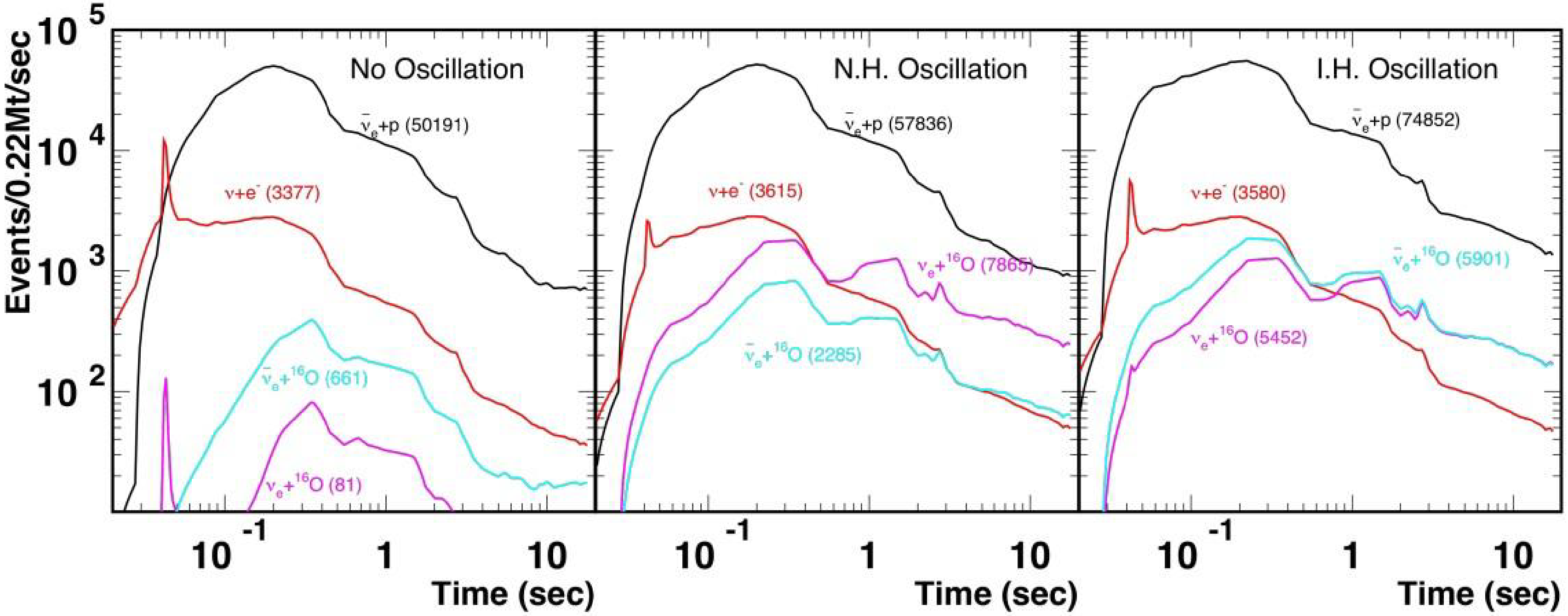
Copyright Australian Astronomical Observatory, photo by David Malin, https://www.maas.museum/observations/2012/02/24/25-years-since-sn1987a-was-discovered/

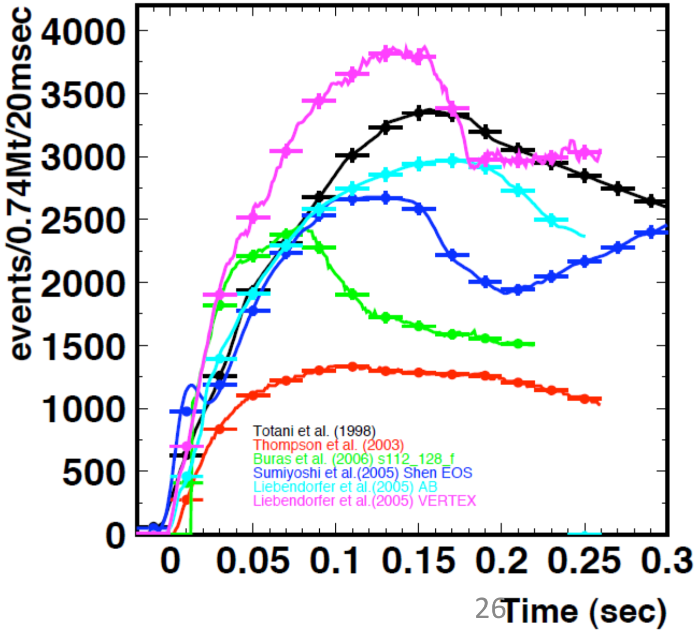
Supernova neutrinos

The figures show simulated values:

- (below) The numbers in brackets report the total interactions integrated over a 10s burst
- (Right-up) Events vs Source distance
- (right-down) Inverse beta event rate predicted by SN simulations within the first 300 ms after the onset of a 10kpc-distant neutrino burst







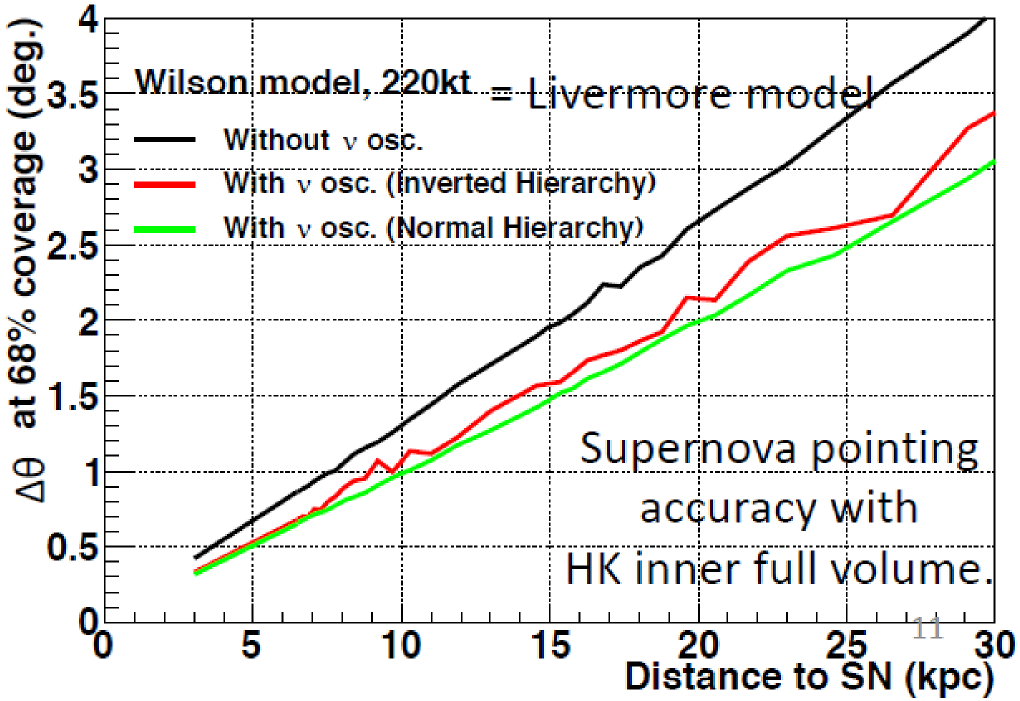
T. Totani, K. Sato, H. E. Dalhed, and J. R. Wilson, Astrophys. J. 496, 216 (1998)
Abe K et al 2011 Preprint arXiv:1109.3262 [hep-ex]
SN Model discrimination with HK, K. Abe et al 2021 ApJ 916 15

Supernova neutrinos

Why should SN neutrinos be investigated?

To study and to better understand:

- **Core-collapse SN physics**
  – Explosion mechanism
  – Proto neutron star formation
  – Black hole formation
- **Neutrino physics**
- **Multi-messenger analyses**
  – SN alert with directional information
  – Combined observations with gravitational wave, gamma-ray, X-ray emissions



In HK and SK, many efforts are focused on a SN alert and create an observational network, to give an important contribute to point satellites and telescopes in a specific part of the sky and catch a SN event with some instants in advance

Supernova Relic Neutrino (SRN)

Relic neutrinos come from the all SNe exploded in the Universe since its origin. They transport traces of their original sources and can add information about:

- star formation rate;
- energy spectrum of supernova burst neutrinos;
- black hole formations.

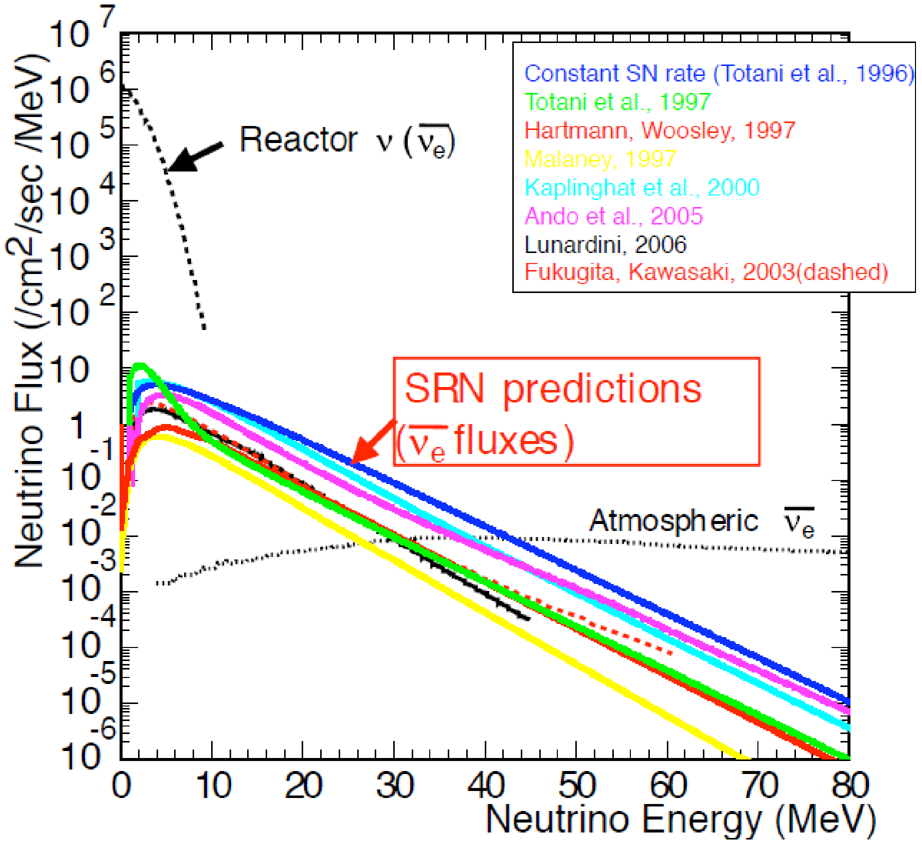
They are not discovered yet but extra-galactic ν are expected.

By HK detector:

• SRN can be observed in 10y with ~70±17 events and > 4σ non-zero significance (photo-coverage 40%).

• ~40±13 events and 3σ with a 20% photo-coverage

Anyway, HK will go beyond the discovery and aim to measurement of SRN.



Abe K et al 2011 Preprint arXiv:1109.3262 [hep-ex]
Takatomi Y., Journal of Physics: Conference Series **718** (2016) 062071 doi:10.1088/1742-6596/718/6/062071

Conclusions

Further technical details:

- Design Report is available (https://arxiv.org/abs/1805.04163).
- Technical Report will be published soon.

Project status:

- Japanese construction budget was approved by MEXT in Japan, in 2020.
- We are in construction phase:
  - Cavern excavation is ongoing
  - Mass production of new 20-inch PMTs started
- Basic design of tank, mPMT, electronics, etc., will be finalized soon.
  - Their mass production is scheduled at the end 2023
- PMT installation is foreseen in 2025-2026
- Hyper-K observation will start in 2027.

Astrophysical scientific aspects:

Astrophysical neutrino measurements are one of the features of HK:

- Solar neutrinos
  - Hep neutrino, seasonal variation, upturn, etc…
- Supernova neutrino
  - Energy and time spectrum measurement, SN alarming, etc..
- Supernova Relic Neutrino
  - Supernova and star formation rate models, extraordinary SN
- Neutrino observation for other astrophysical events
  - E.g. multi-messenger observation with gravitational-wave and electromagnetic events.

Thank you!!!