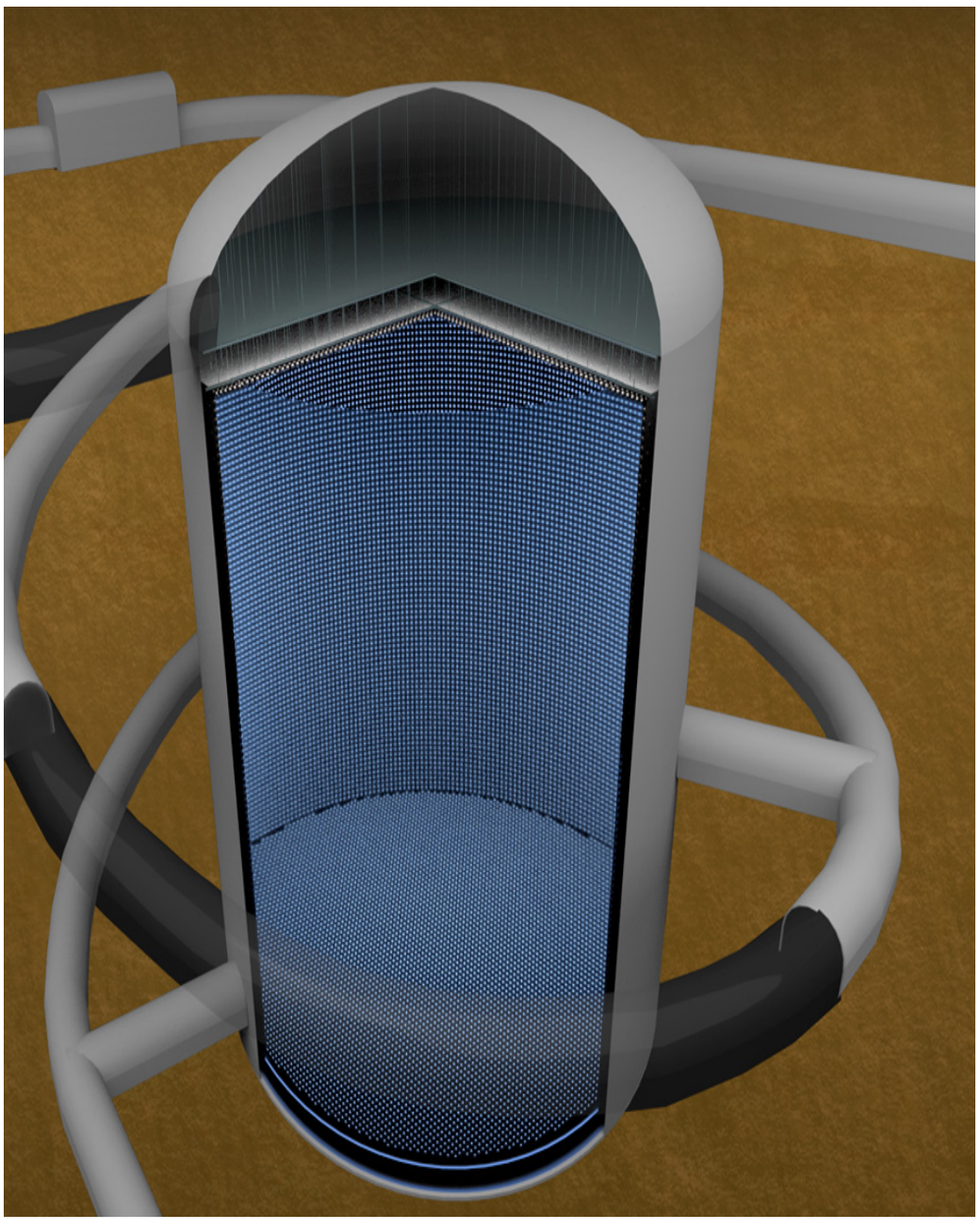
Hyper-Kamiokande experiment

Takuya Tashiro (ICRR, **University of Tokyo**)
on behalf of Hyper-Kamiokande collaboration

26th July 2021
EPS-HEP2021 conference

Conceptual design of the HK detector

Hyper-Kamiokande (HK) is the **new generation underground water Cherenkov detector** in Kamioka, Japan.



- A cylindrical tank with the diameter of 68 m and the depth of 71 m.
- Ultra-pure water of 258 kton is stored. The fiducial mass is 188 kton.
- Clean signal of neutrinos can be detected as it is built deep underground.
- PMTs are installed to detect the light caused by the Cherenkov radiation.
  - 20” PMTs for Inner-Detector
  - multi-PMTs for Inner-Detector
  - 3” PMTs for Outer-Detector
- **The construction started in 2020. The operation will start in 2027.**

Conceptual design of the HK detector

Construction and preparation is ongoing!

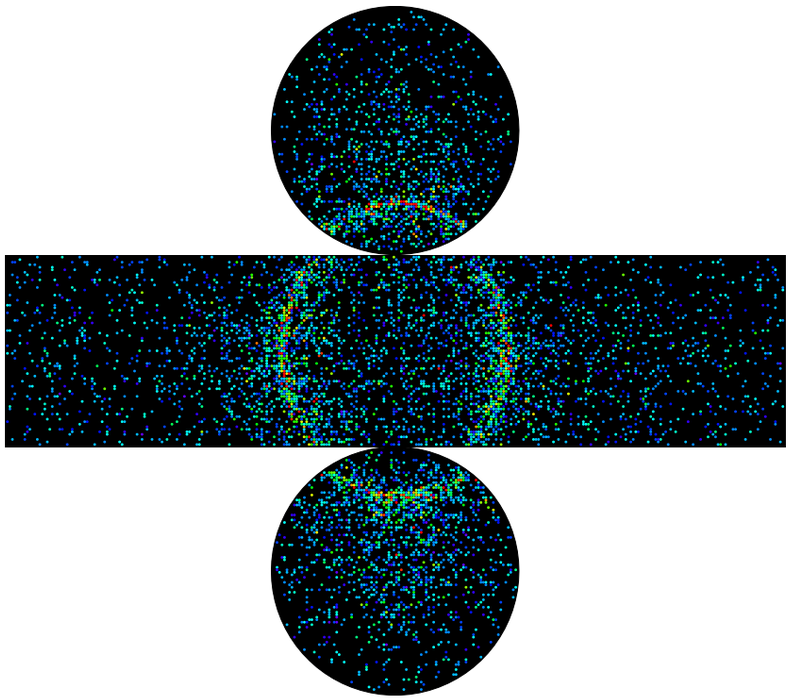
Event reconstruction in HK

- Charged particles passing through the water are identified using the Cherenkov radiation detected by the PMTs attached to the wall of the detector.

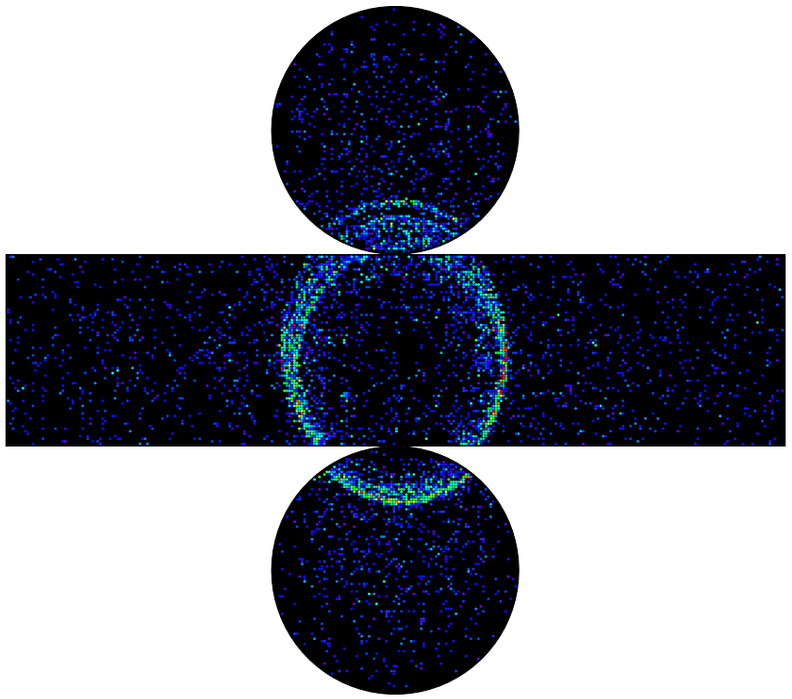
- Cherenkov radiation is reconstructed as a ring.
  The ring pattern reflects the **momentum, position, direction, and the type** of the particle.

HK simulation

electron



muon

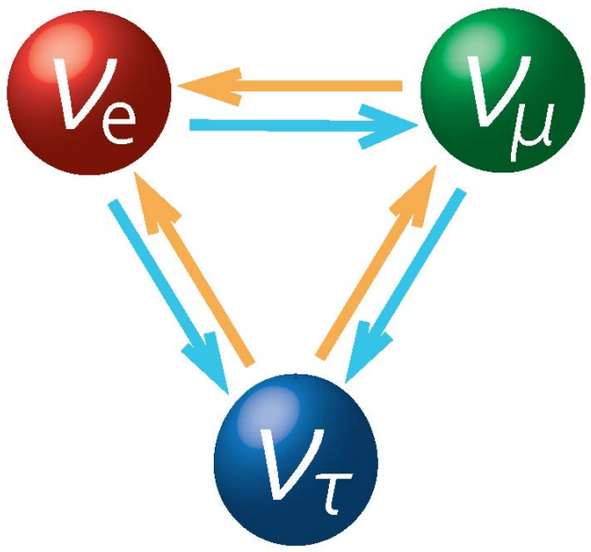


Physics goals of HK

HK aims at revealing important physics features.

Neutrino oscillation

Oscillation properties will be measured based on **accelerator** and **atmospheric** neutrinos.

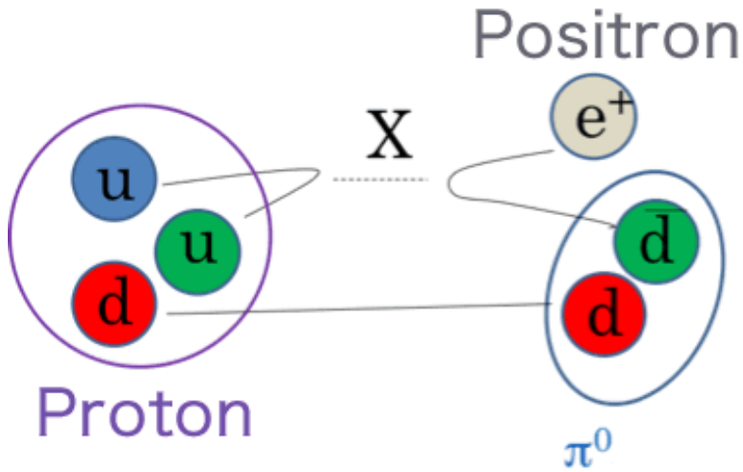


Neutrino astronomy

Solar, **supernova**, and **supernova relic** neutrinos will be explored for astronomical research.

Nucleon decay

Proton decay or **neutron decay** processes that violate baryon number will be searched to explore the GUT scale.



Neutrino oscillation

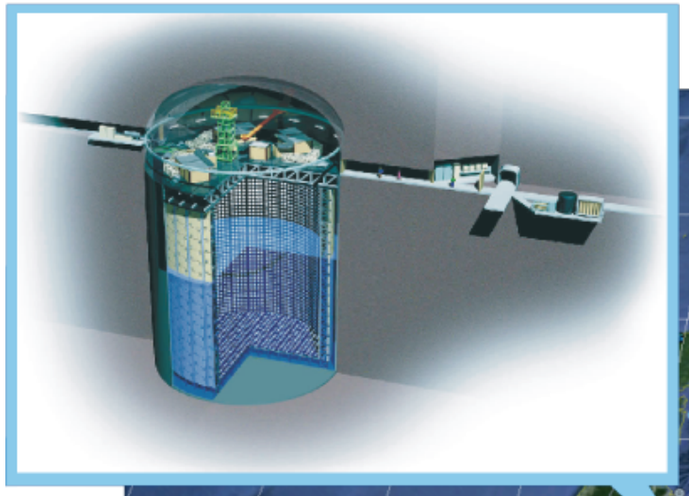
- The phenomenon of neutrino oscillation can be described by **<u>6 parameters</u>**.
  - 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
  - 1 CP phase: δ_{CP}
  - 2 mass squared differences:
    $\Delta m^2_{21} = m^2_2 - m^2_1$ and $\Delta m^2_{32} = m^2_3 - m^2_2$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13}\\ 0 & 1 & 0\\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- The value of δ_{CP} and sign of mass squared differences are not yet determined.

Accelerator neutrinos

Ongoing experiment: T2K



Super-Kamiokande
(ICRR, Univ. Tokyo)

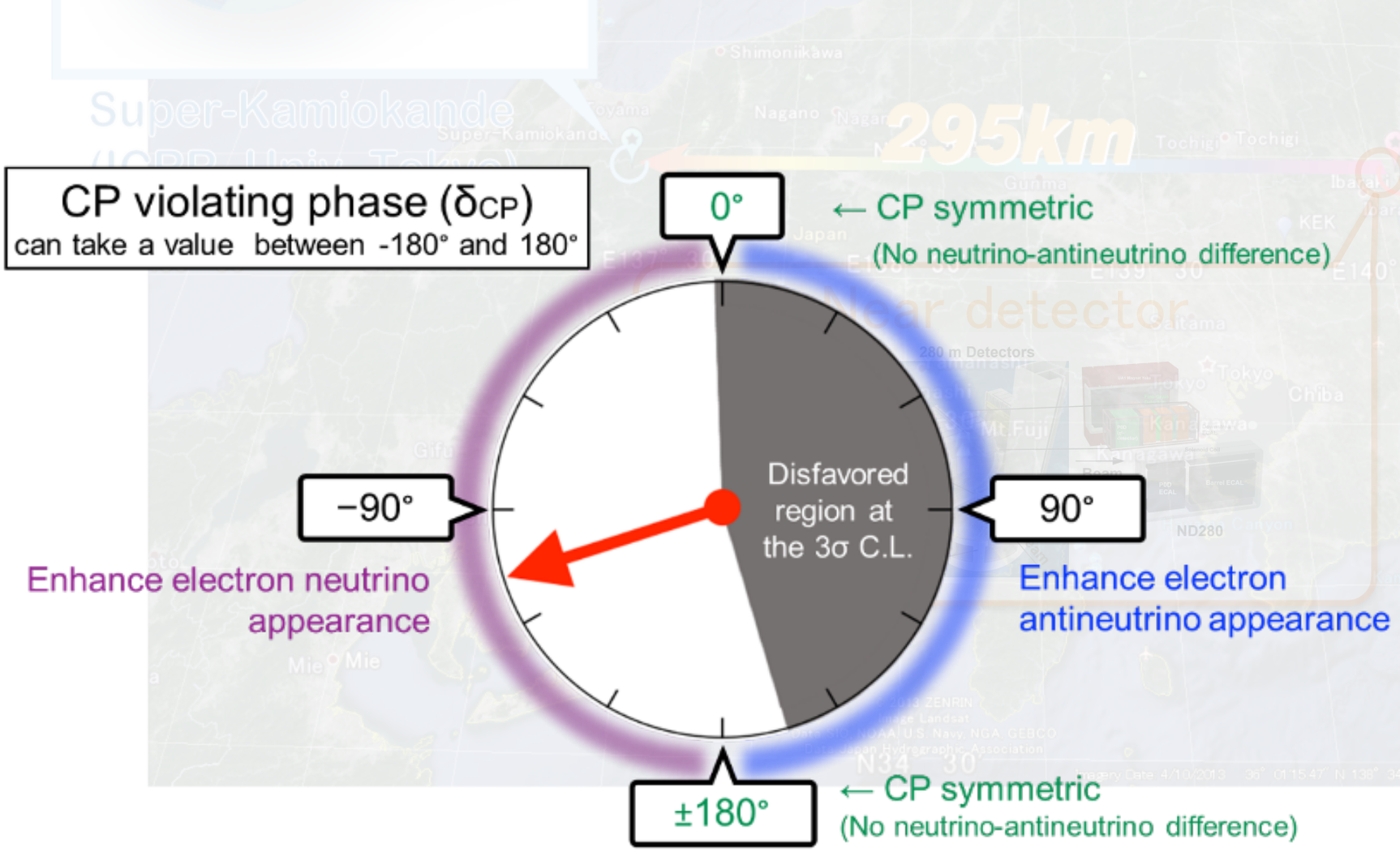
295km

Neutrino Facility
at J-PARC
(KEK-JAEA, Tokai)

Near detector

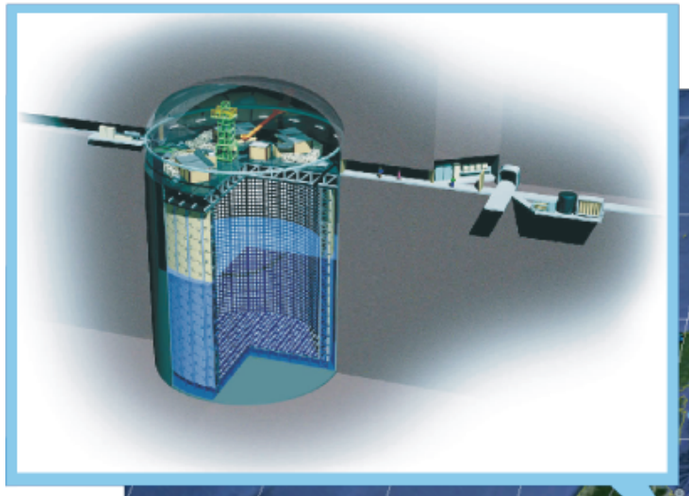
Accelerator neutrinos

- The most strong constraint on the lepton CP violation was achieved by T2K.
- Almost half of the possible δ_{CP} values is disfavored at the 3σ confidence level.



Upgrade plan for HK long-baseline

Ongoing experiment: T2K



Super-Kamiokande
(ICRR, Univ. Tokyo)

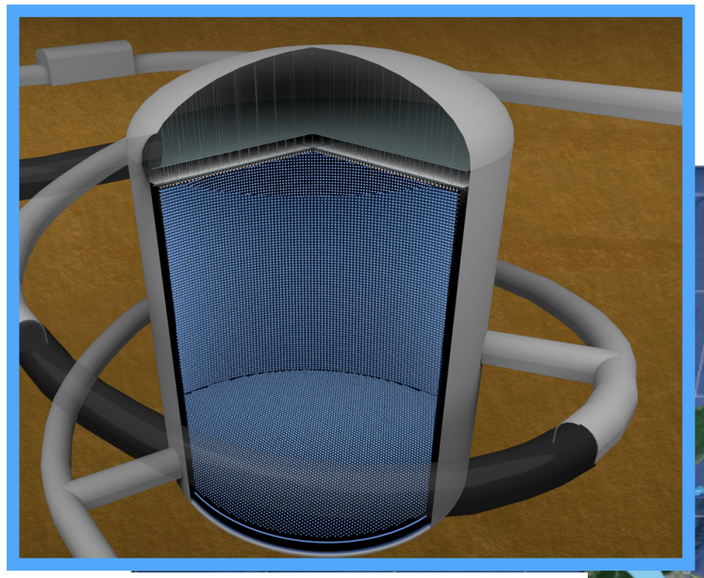
295km

Neutrino Facility
at J-PARC
(KEK-JAEA, Tokai)

Near detector

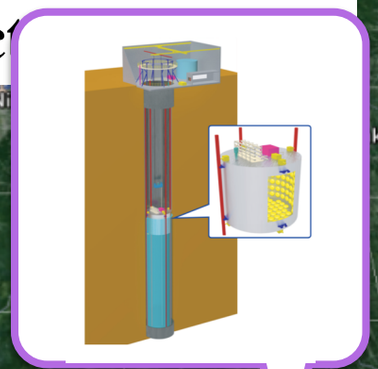
Upgrade plan for HK long-baseline

HK long-baseline

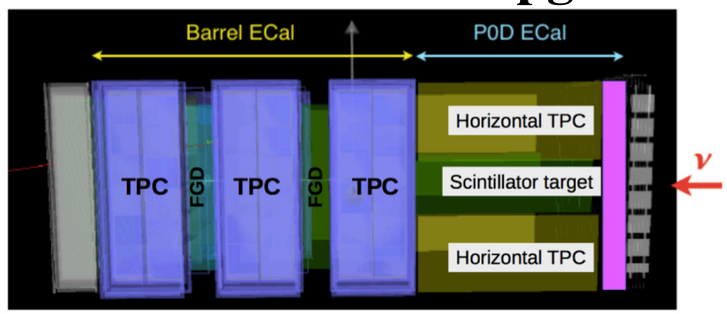


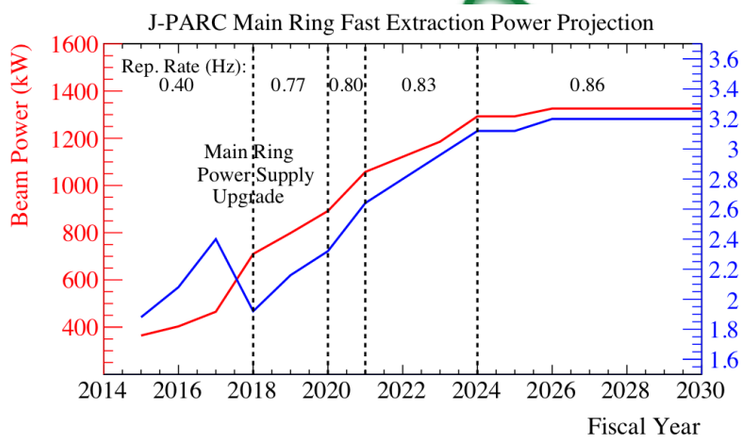
HK will be used as the far detector

New intermediate water-Cherenkov detect



Near detector will be upgraded.



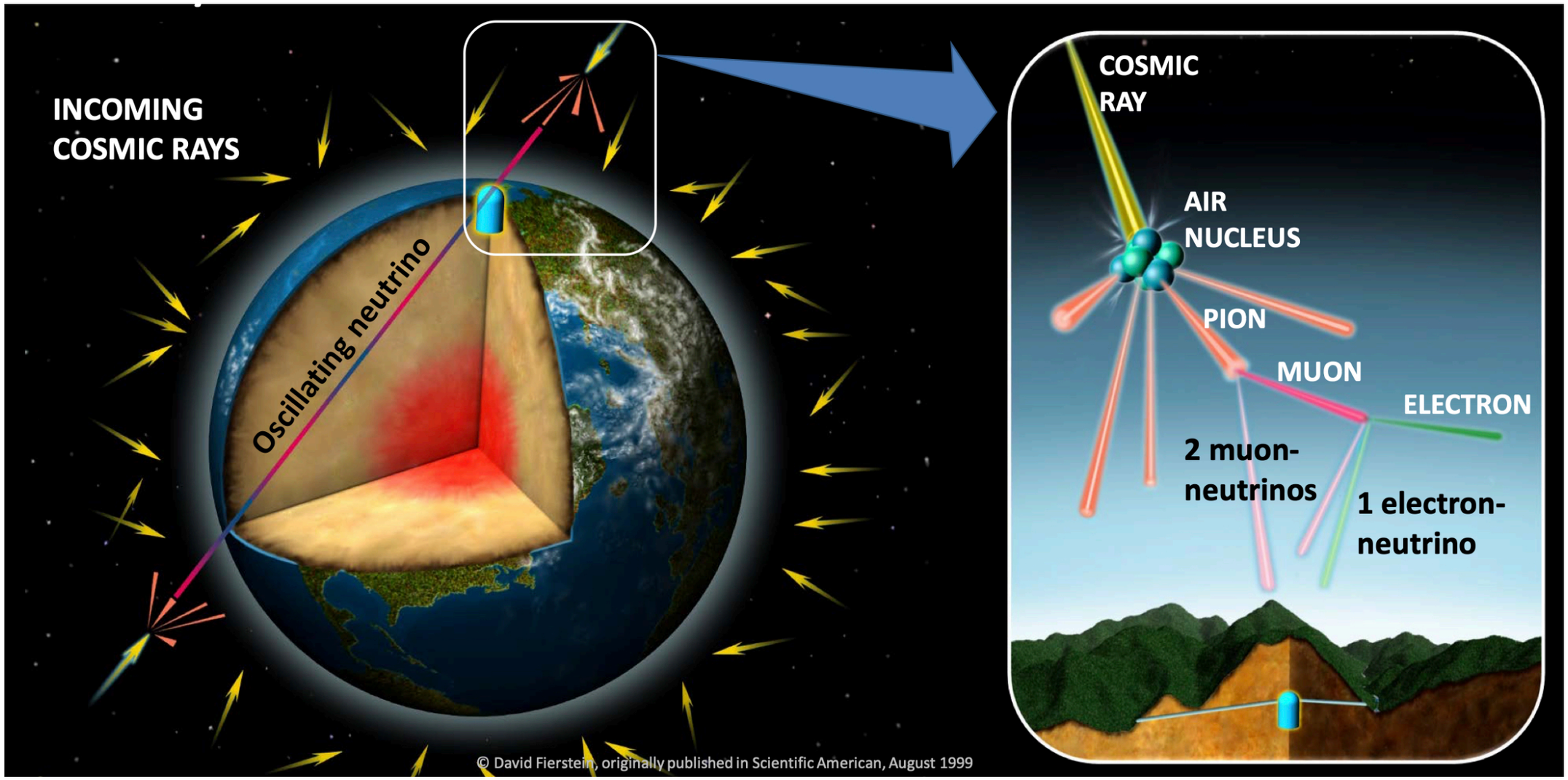


Beam power will be upgraded to 1.3 MW

Atmospheric neutrinos

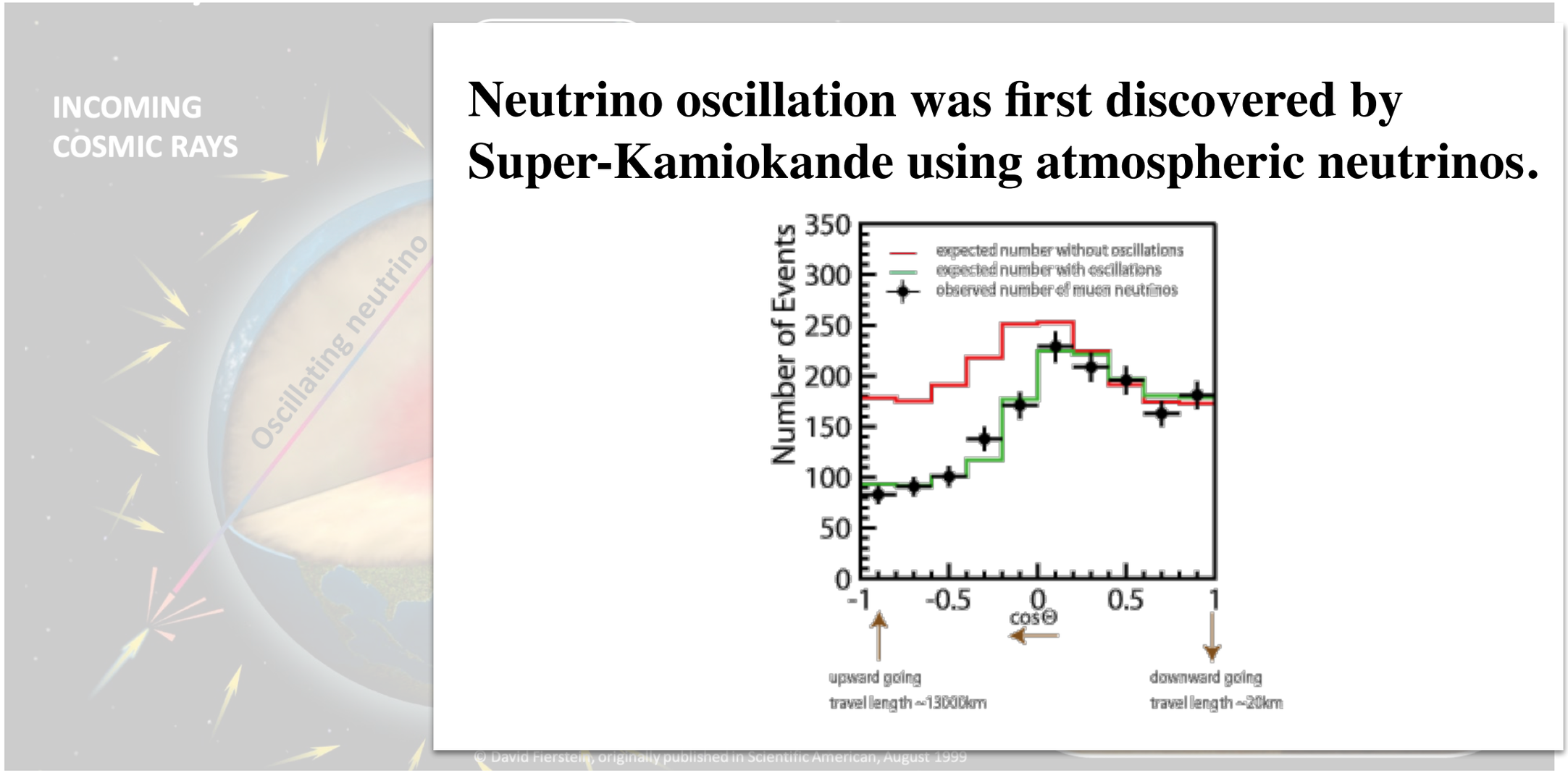
- **Atmospheric neutrinos** are generated by interactions between primary cosmic ray and atmospheric nucleus.

- Wide range of energies and pathlength can be used to measure oscillation parameters.



Atmospheric neutrinos

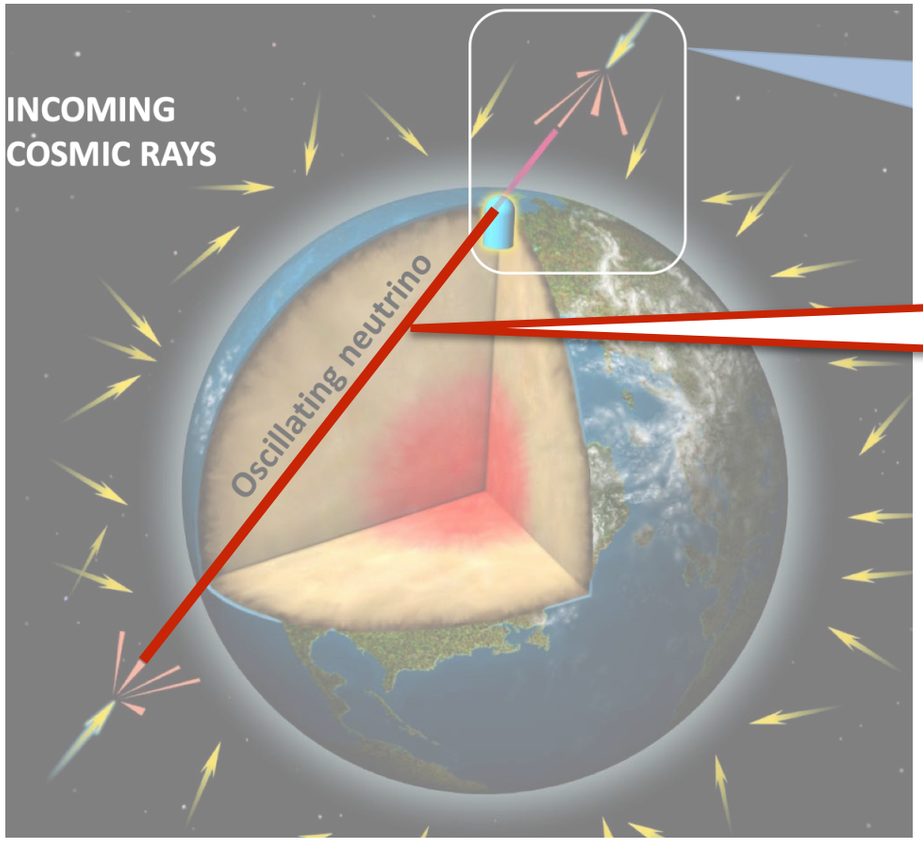
- **Atmospheric neutrinos** are generated by interactions between primary cosmic ray and atmospheric nucleus.
- Wide range of energies and pathlength can be used to measure oscillation parameters.



Neutrino oscillation was first discovered by Super-Kamiokande using atmospheric neutrinos.

Atmospheric neutrinos

- One of the most important topics in the atmospheric neutrinos study is the mass hierarchy.
  - Neutrinos mass ordering is still unknown.
  - Normal hierarchy: $m_2 < m_3$.
  - Inverted hierarchy: $m_2 > m_3$.



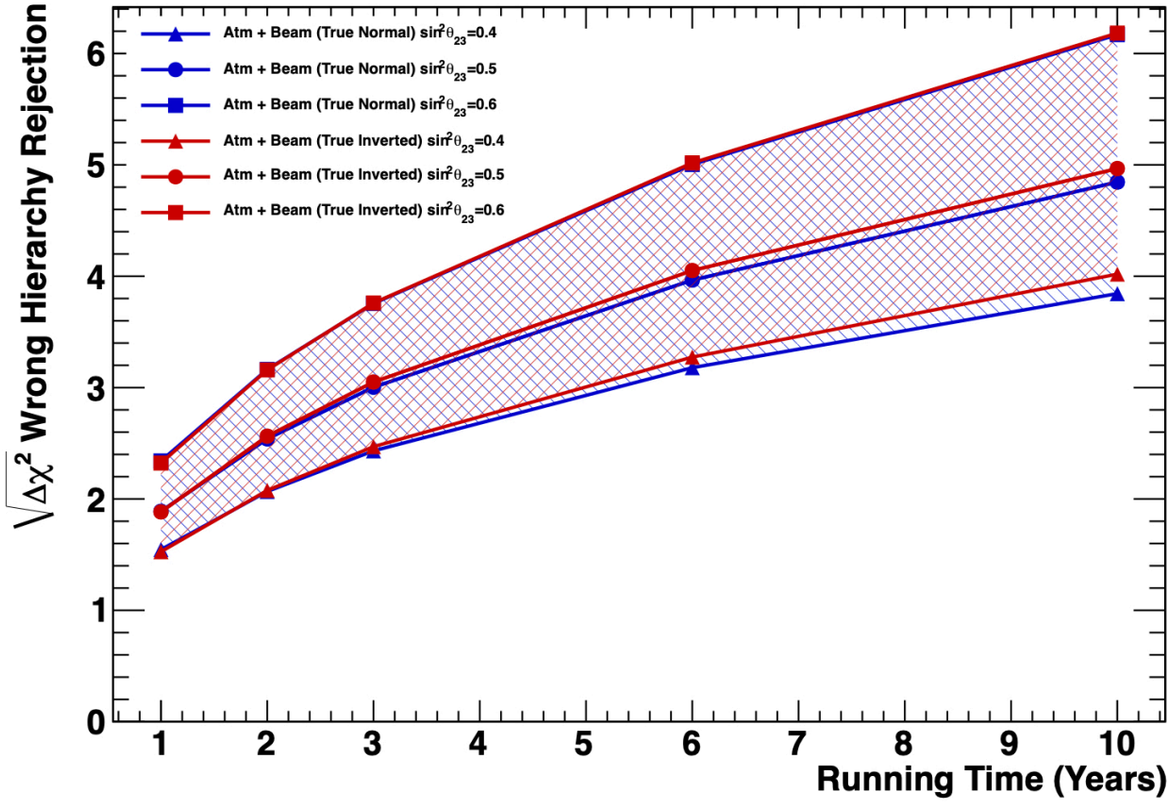
- Neutrinos penetrating the earth are affected by the matter effect.
  - Normal hierarchy:
    $\nu_\mu \rightarrow \nu_e$ is enhanced.
  - Inverted hierarchy:
    $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ is enhanced.

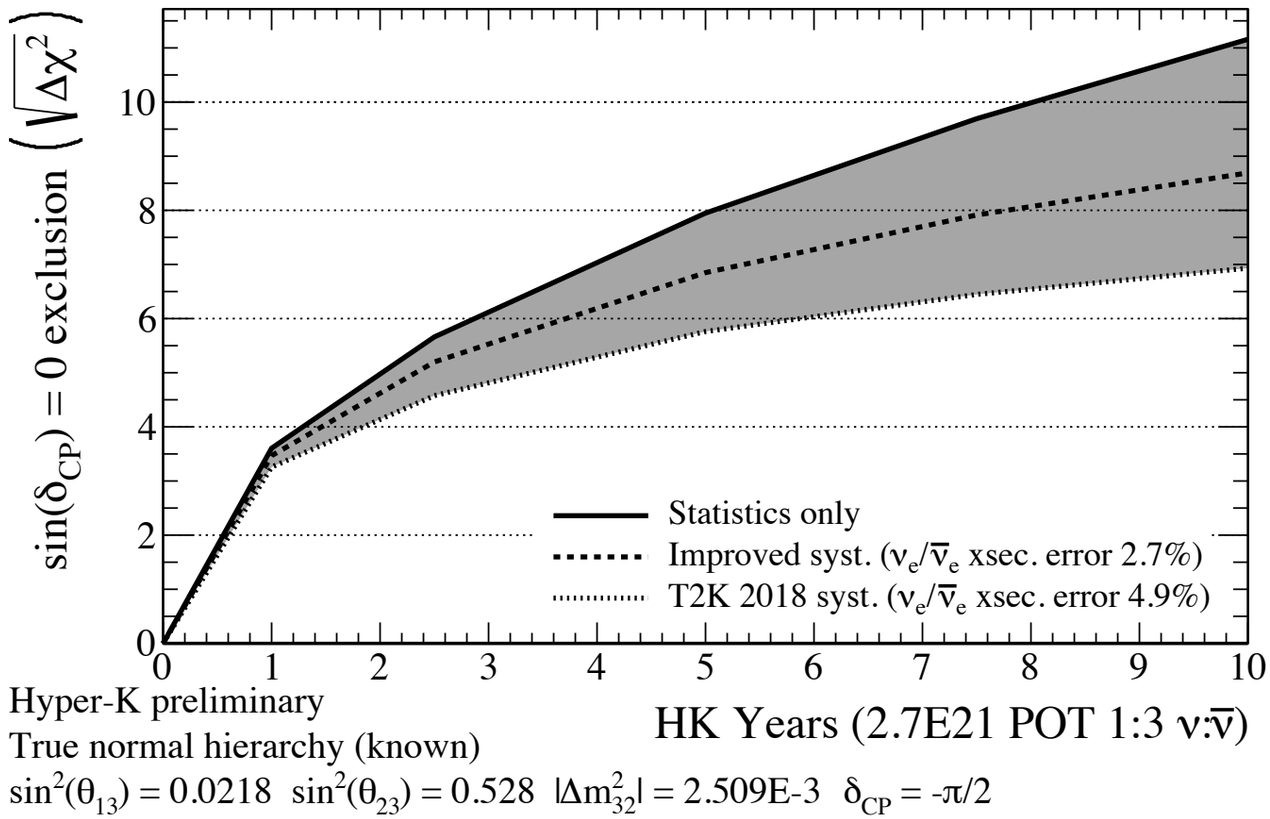
- Comparison between neutrino and anti-neutrino oscillation can be used to determine the hierarchy.

Expected sensitivity on neutrino oscillation

- The atmospheric and accelerator measurements will be combined to determine the oscillation parameters.

- Both the mass hierarchy and CP violation are expected to be determined within < 10 years of operation.

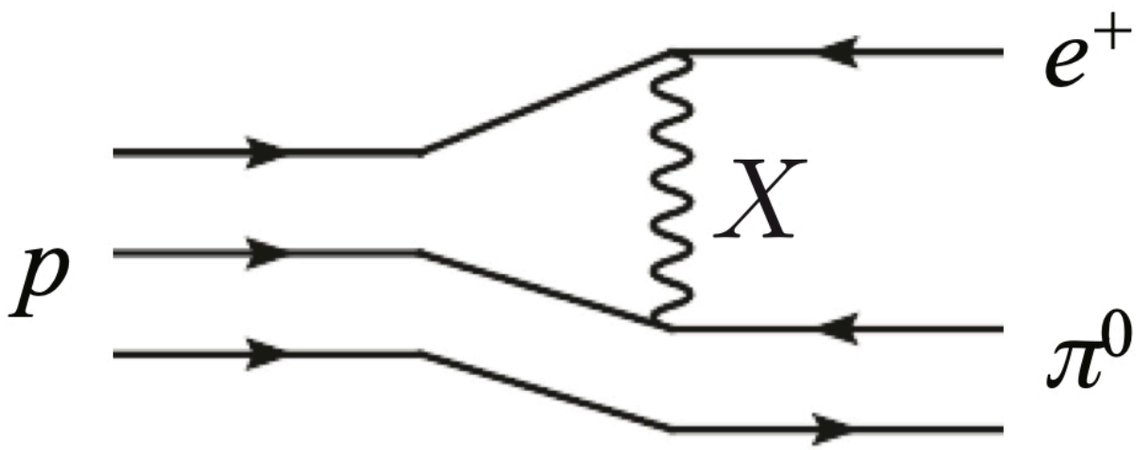




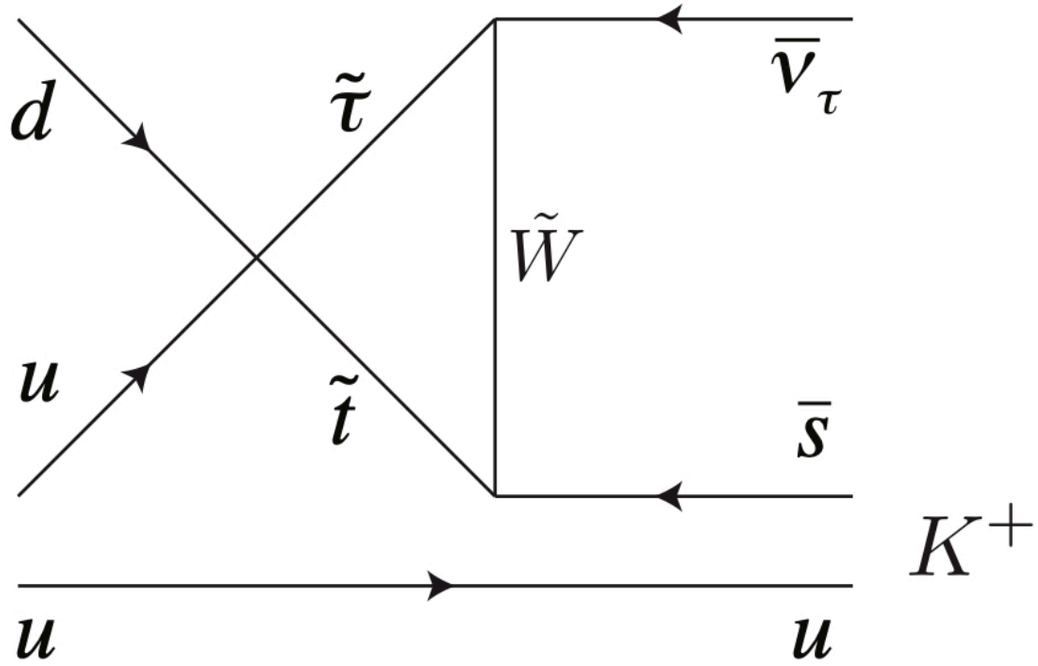
Nucleon decay searches

- The nucleon decay phenomena, which violates the baryon number conservation, is one of the main physics goals in HK.
- The search by HK is expected to reach the proton lifetime predicted by various theories.
- HK has sensitivity to various decay modes.

$p \to e^+\pi^0$ diagram

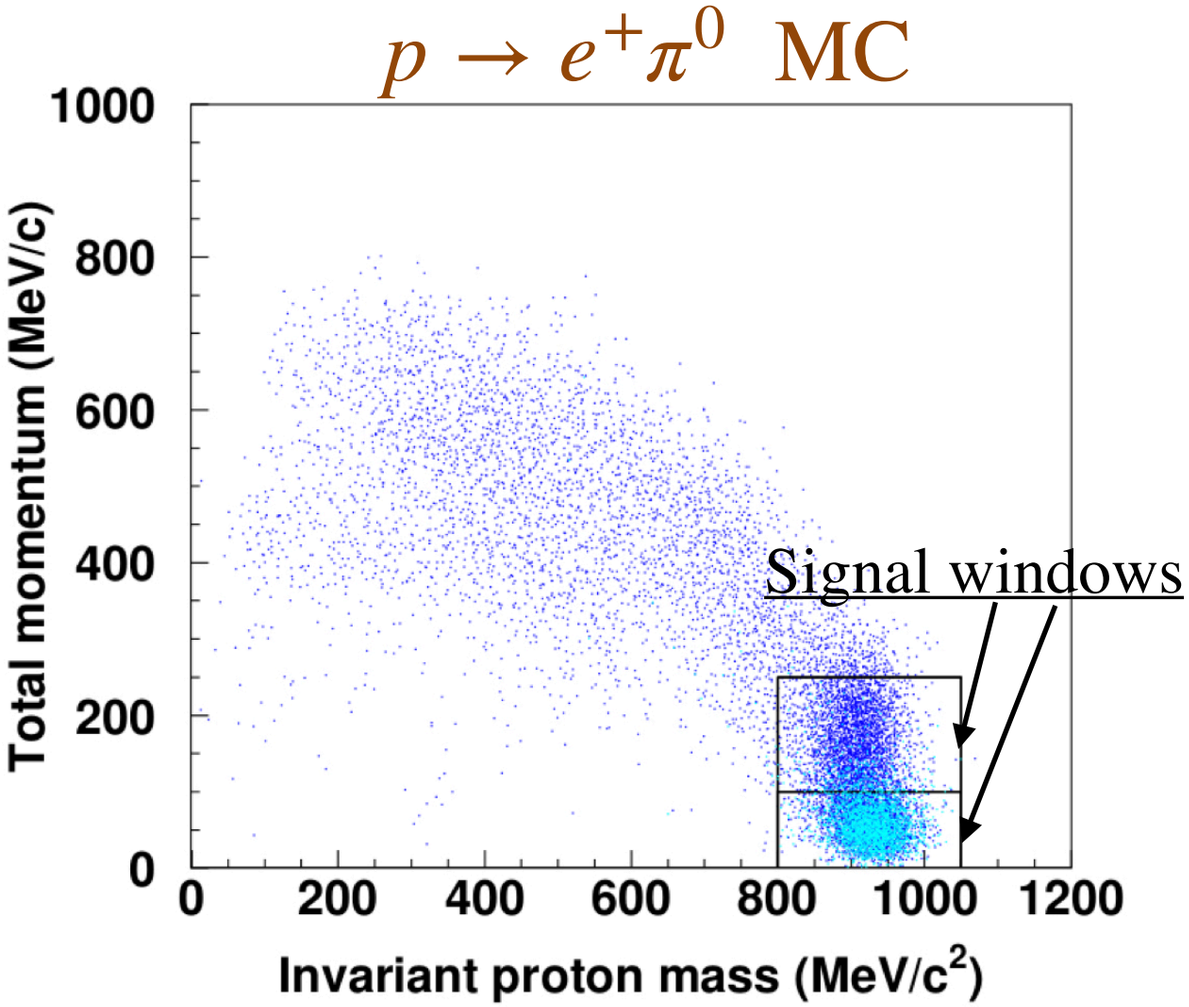


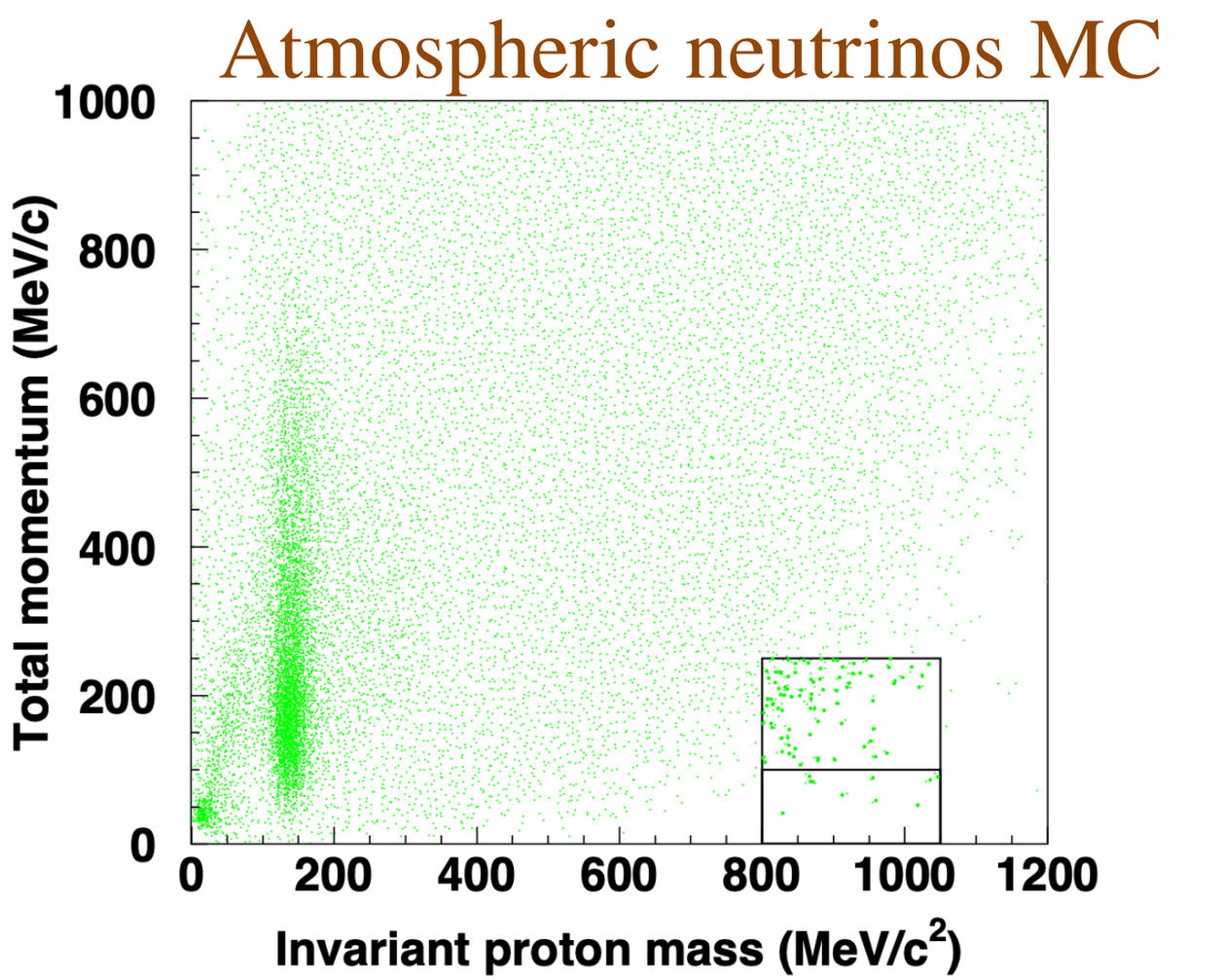
$p \to K^+\bar{\nu}$ diagram



Nucleon decay searches

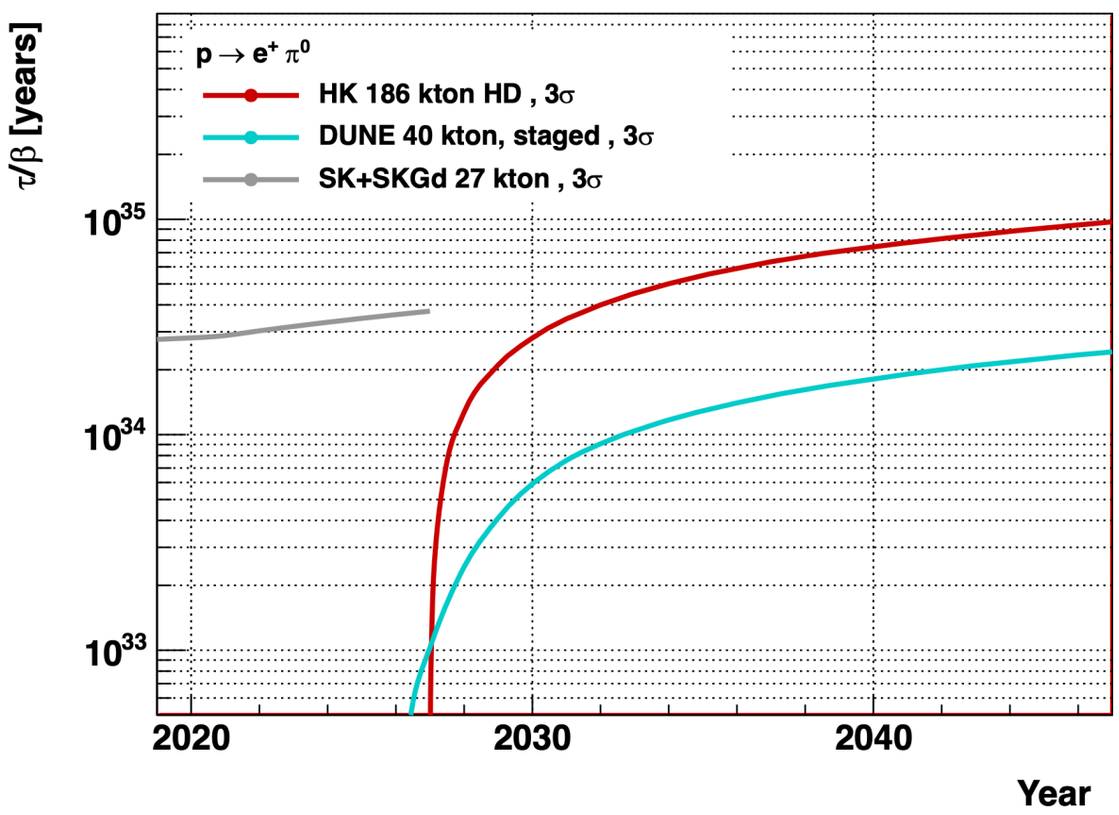
- In the nucleon decay searches in HK, event selection based on the rings kinematics is applied.
- After the selection, **the invariant mass** and **total momentum** are calculated using all the reconstructed rings and then the number of events in signal windows is calculated.

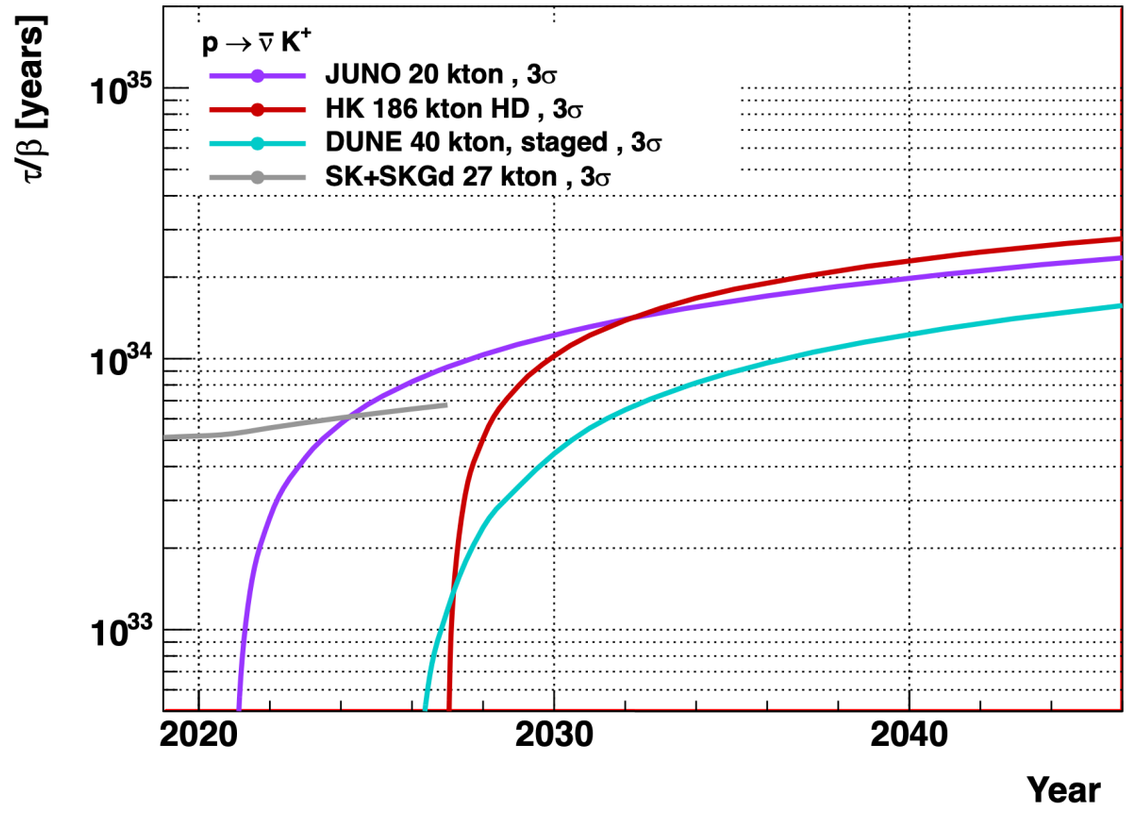




Expected sensitivity on nucleon decay searches

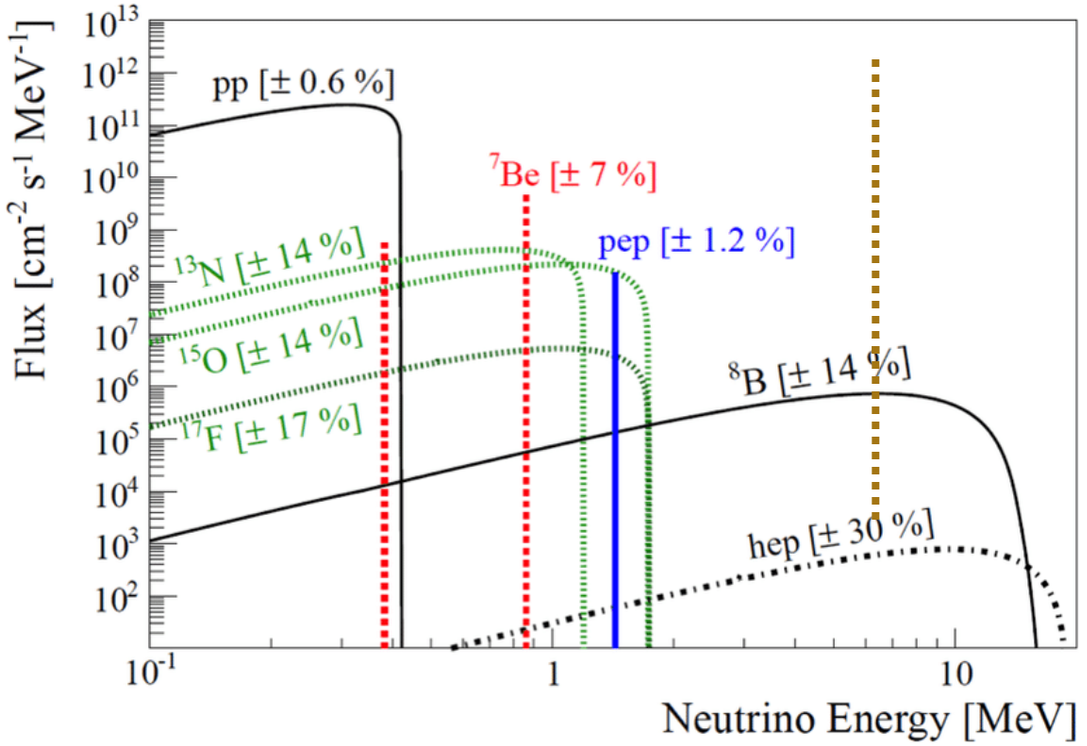
- In the nucleon decay searches in HK, event selection based on the rings kinematics are applied.
- After the selection, **the invariant mass** and **total momentum** are calculated using all the reconstructed rings and then the number of events in signal boxes is calculated.
- **The sensitivity can reach up to 5x10^{34}(1x10^{34}) years of lifetime in $e^+\pi^0(\bar{\nu}K^+)$ mode within 5 years of operation.**





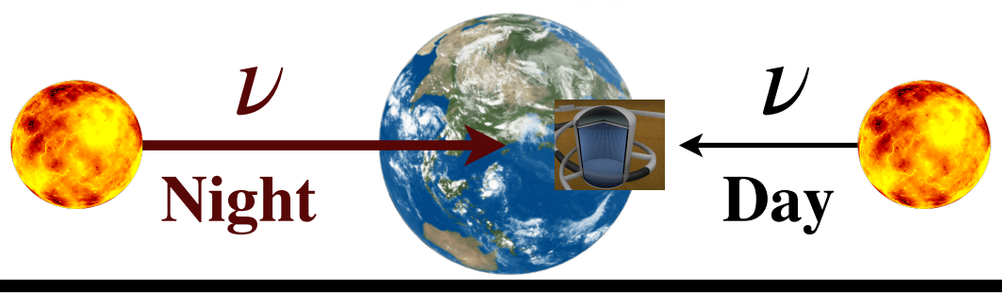
Solar neutrinos

- Solar neutrinos are the neutrinos originated from nuclear reactions in the Sun.
- The measurement of solar neutrinos include several important topics.



Day/Night (D/N) asymmetry

- The terrestrial matter effect can result in **D/N asymmetry**.
- This can affect Δm^2_{21} measurement.

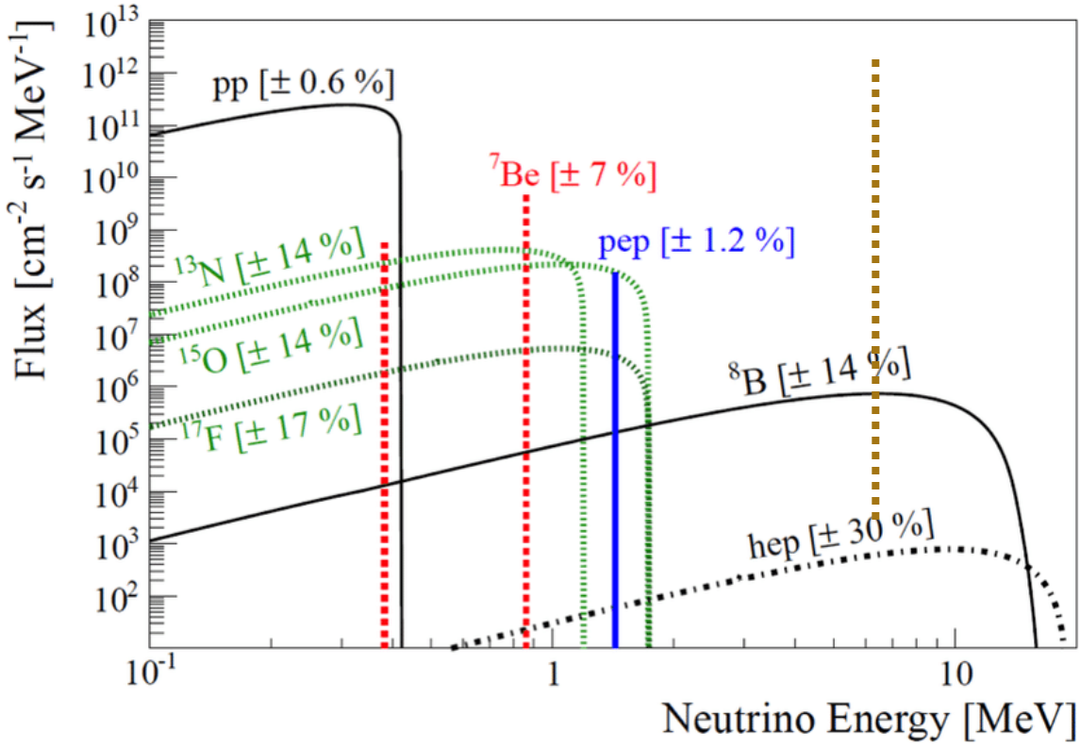


Upturn of the spectrum

- Upturn is the variation of the ν_e survival probability between the vacuum and MSW dominated energy region.
- This is not observed yet and can be a hint for BSM physics.

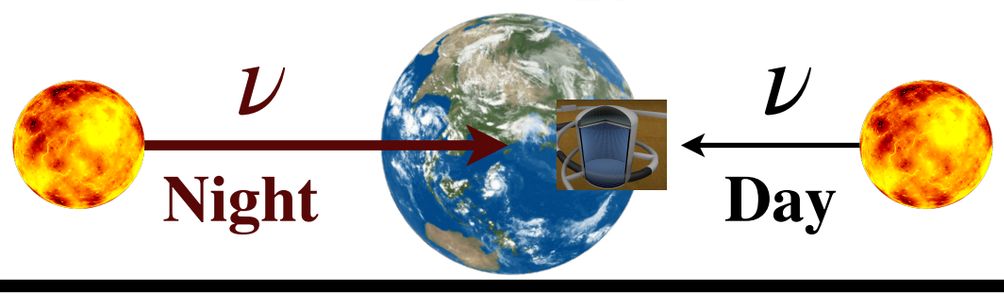
Solar neutrinos

- Solar neutrinos are the neutrinos originated from nuclear reactions in the Sun.
- The measurement of solar neutrinos include several important topics.



Day/Night (D/N) asymmetry

- The terrestrial matter effect can result in **D/N asymmetry**.
- This can affect Δm^2_{21} measurement.

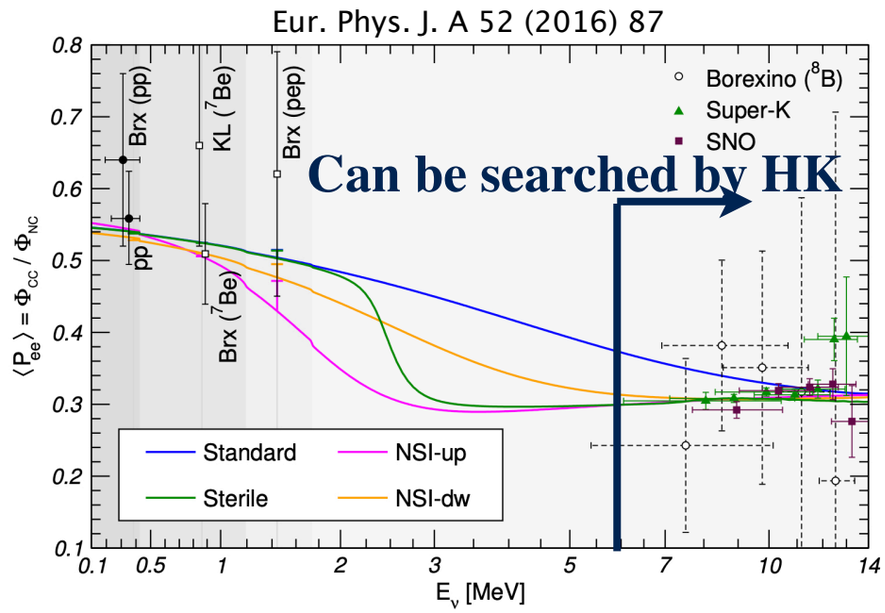


Upturn of the spectrum

- Up
- ve s
- vac
- en
- Thi
- a h

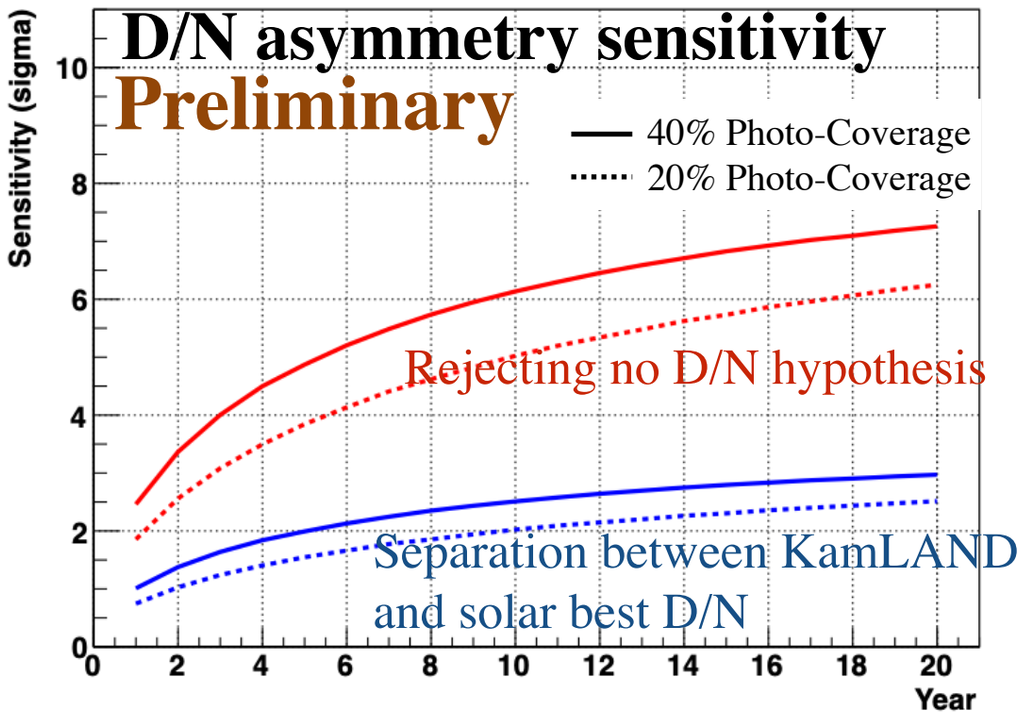
the

n be

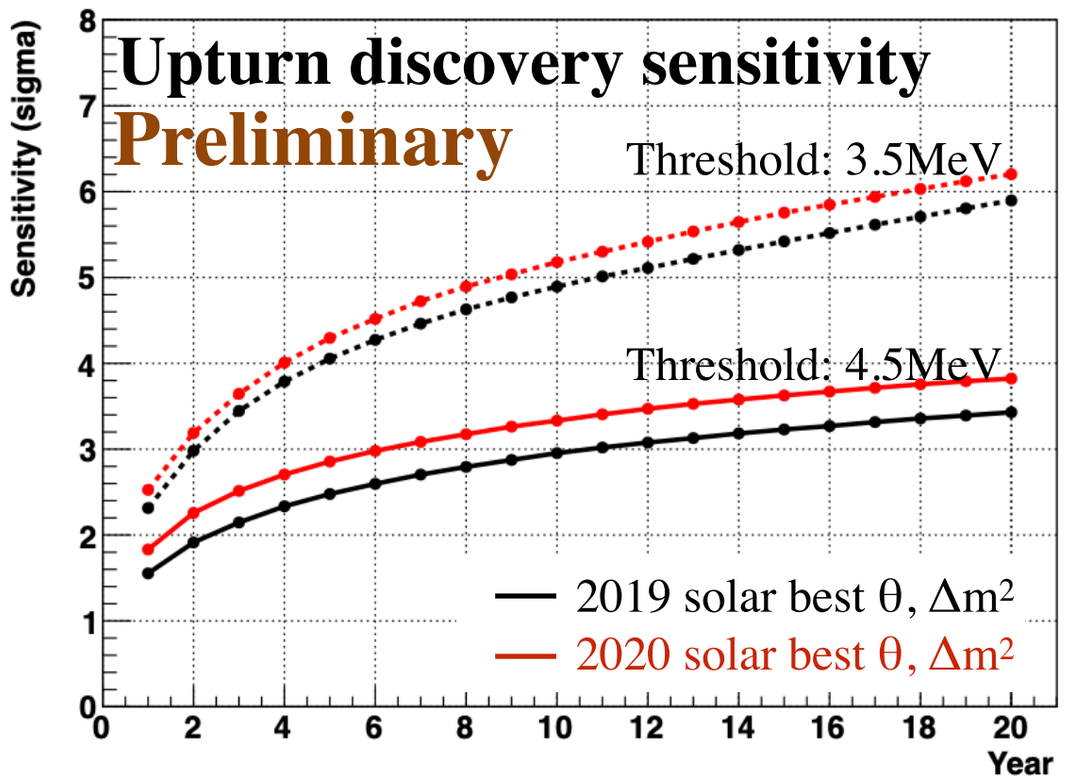


Expected sensitivity on solar neutrinos

- The sensitivity on the search for D/N asymmetry is computed based on the detector configuration of 20% and 40% photo-coverage.
- In both cases, the asymmetry is expected to be observed with > 5σ after 10 years of operation.



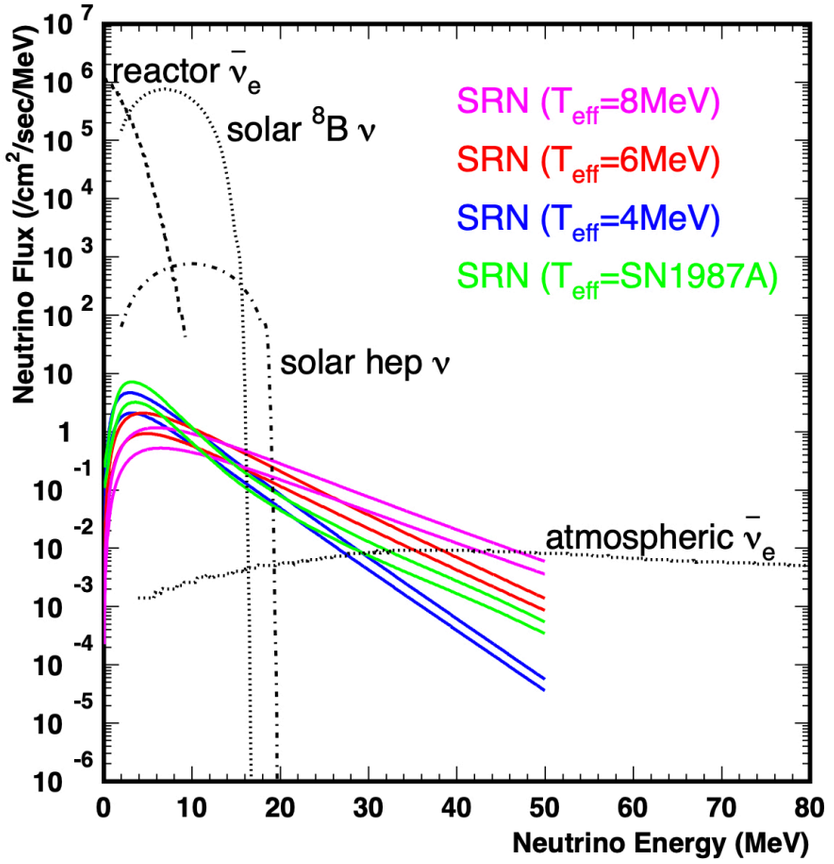
- In the upturn analysis, it is expected that **the sensitivity exceeds 5(3)σ** after 10 operation years with the threshold of 3.5(4.5) MeV.



Supernova and Supernova relic neutrinos

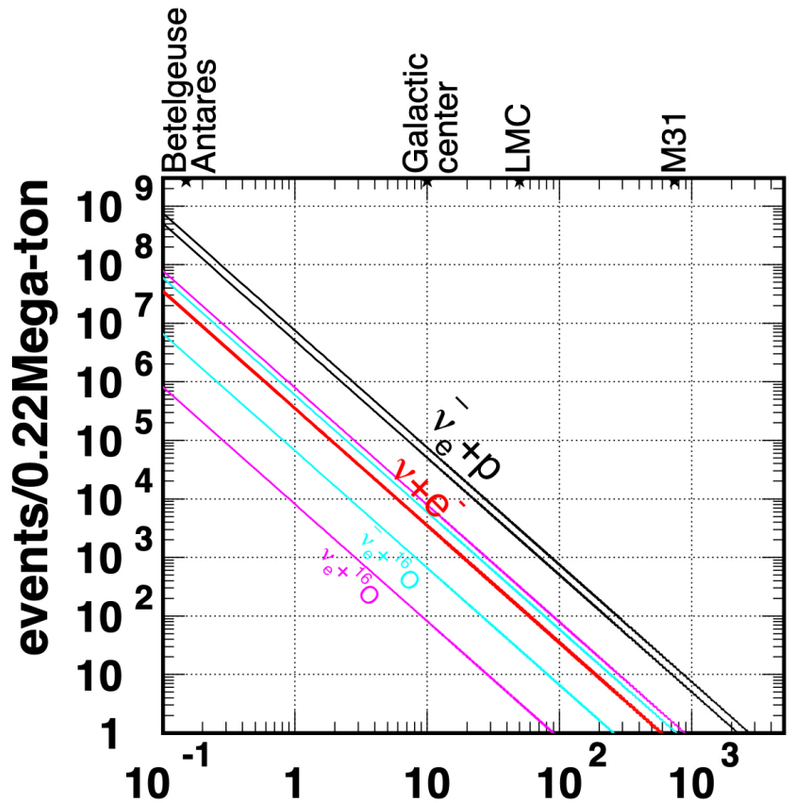
- **Supernova (SN) neutrinos** are emitted by core-collapse SN.
  - Large amounts of neutrinos is expected to be detected by HK if a SN happens in our galaxy(distance of 10 kpc).
    - 11 events were observed by Kamiokande(2.14 kton) in SN1987a (distance of 50 kpc)

- **Supernova relic neutrinos (SRN)** are the diffused neutrinos emitted from past SNe.
  - The existence of SRN is widely accepted, but it has not been observed yet.
  - The spectra of SRN is predicted by various models.
  - The measurement of SRN can be new tool to explore the history of the universe.

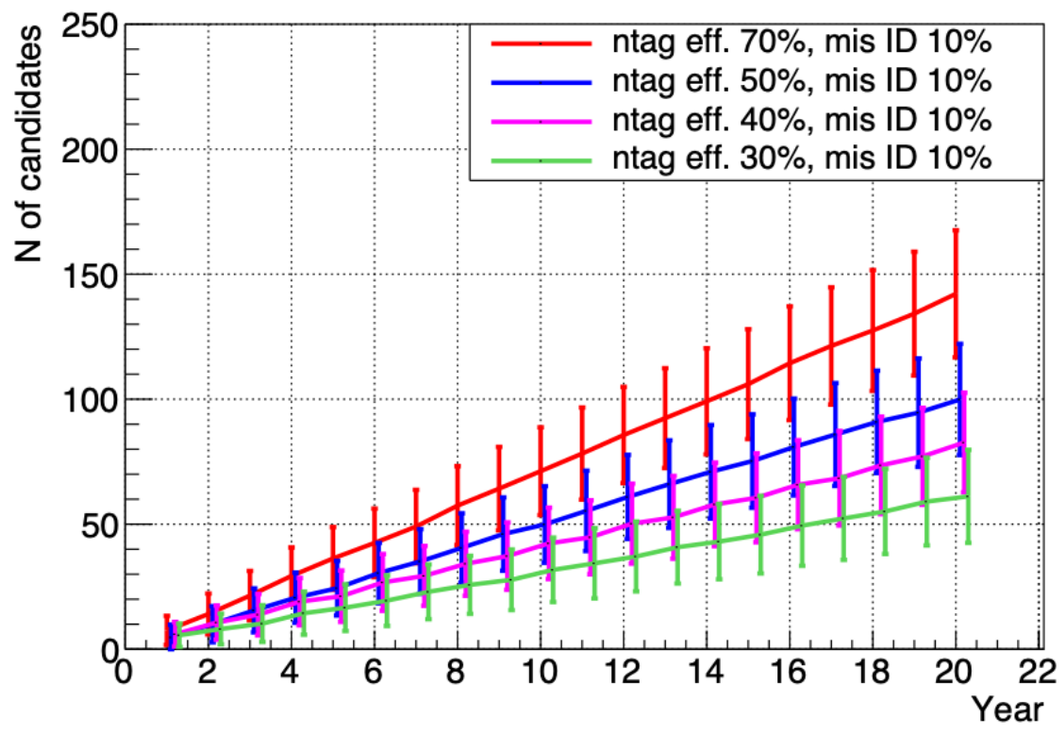


Sensitivity on SN and SNR neutrinos

- The event rate of SR neutrinos is computed as a function of the distance between the earth and SN.
  - O(10k) events if a SN happens in the galactic center.
  - O(10) events if a SN happens in M31 (Andromeda galaxy, ~750 kpc away).



- The number of detected SRN events is predicted for various neutron-tagging configuration.
  - In the case of 70% efficiency, ~70 events will be observed within 10 years of operation. This corresponds to **4σ sensitivity.**



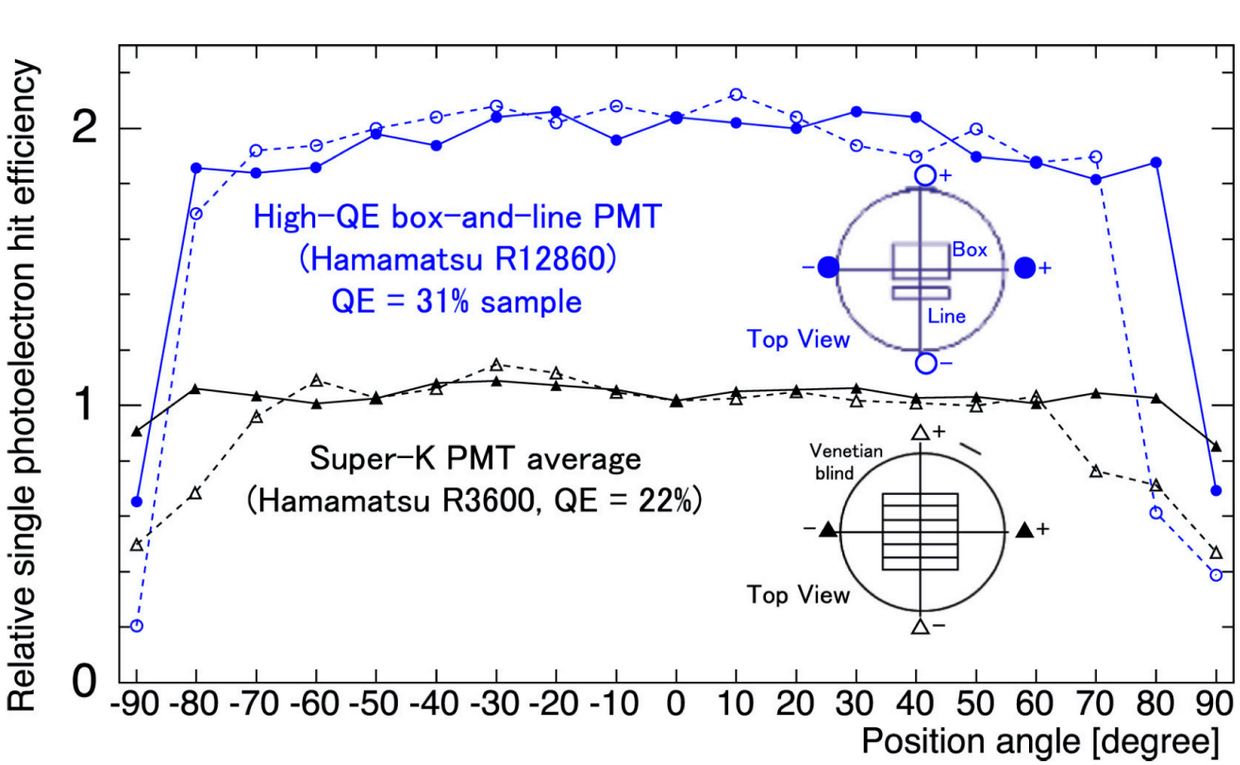
Summary

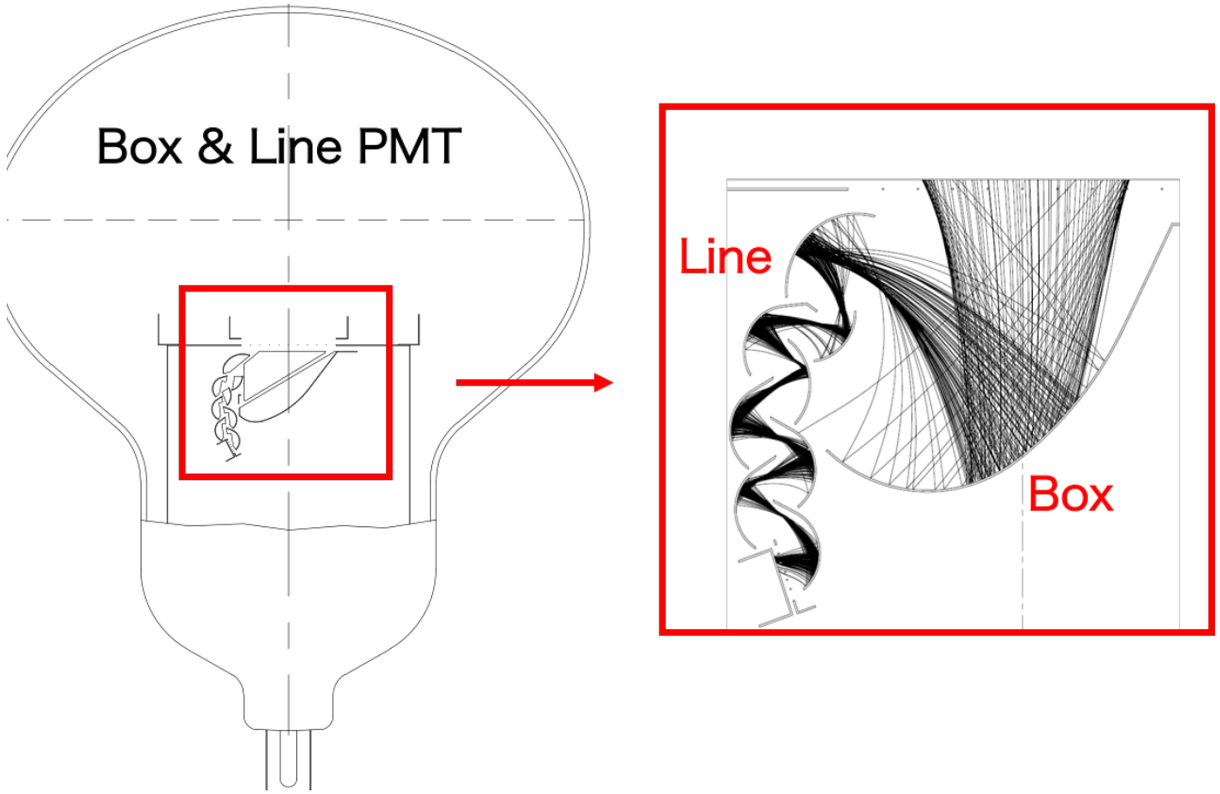
- HK, new water-Cherenkov detector with 188 kton fiducial mass, is being constructed and the operation will start in 2027.
- Various important physics features including neutrino oscillation, nucleon decay, and neutrino astronomy will be explored.
- HK is expected to have sensitivity to conclude various physics questions within ~10 years of operation.
  - δ_{CP} and mass hierarchy in neutrino oscillation.
  - $O(10^{34})$ years of proton lifetime
  - D/N asymmetry and upturn in solar neutrinos.
  - Existence of SRN neutrinos.
- HK has an ability to observe the SN neutrinos if the SN burst occurs in our galaxy.

Back up

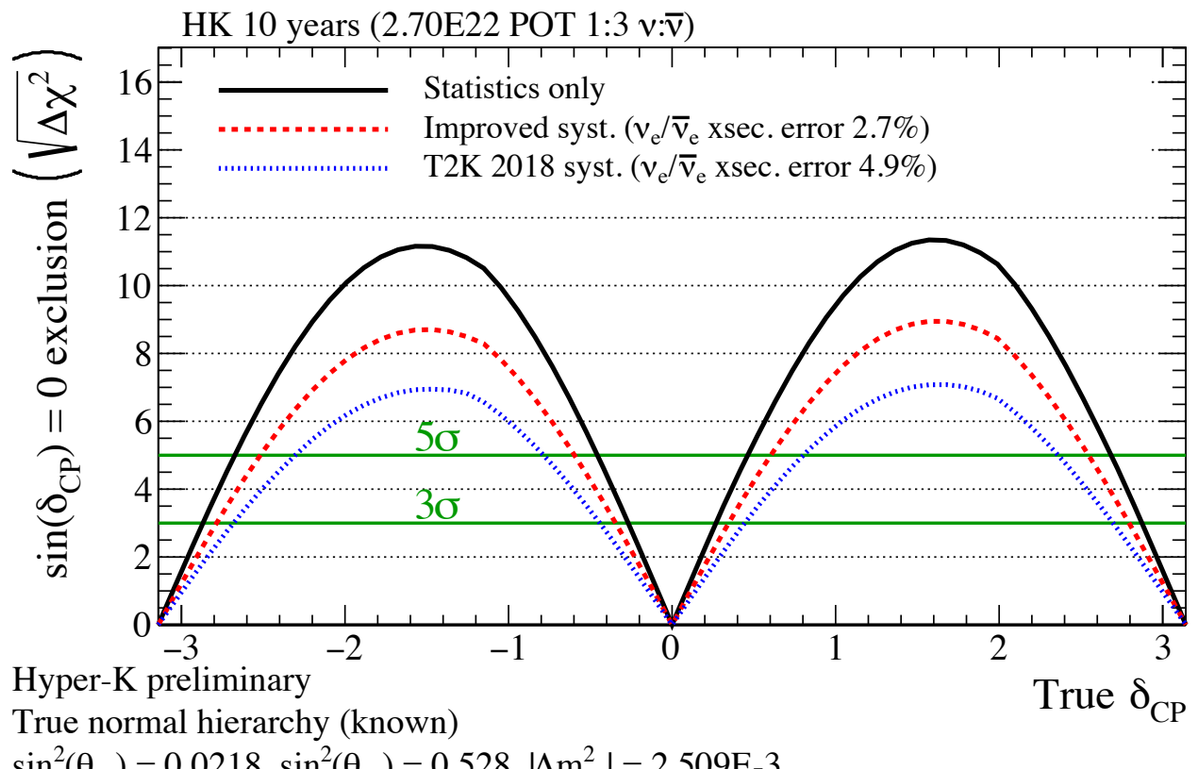
New 50cm PMT

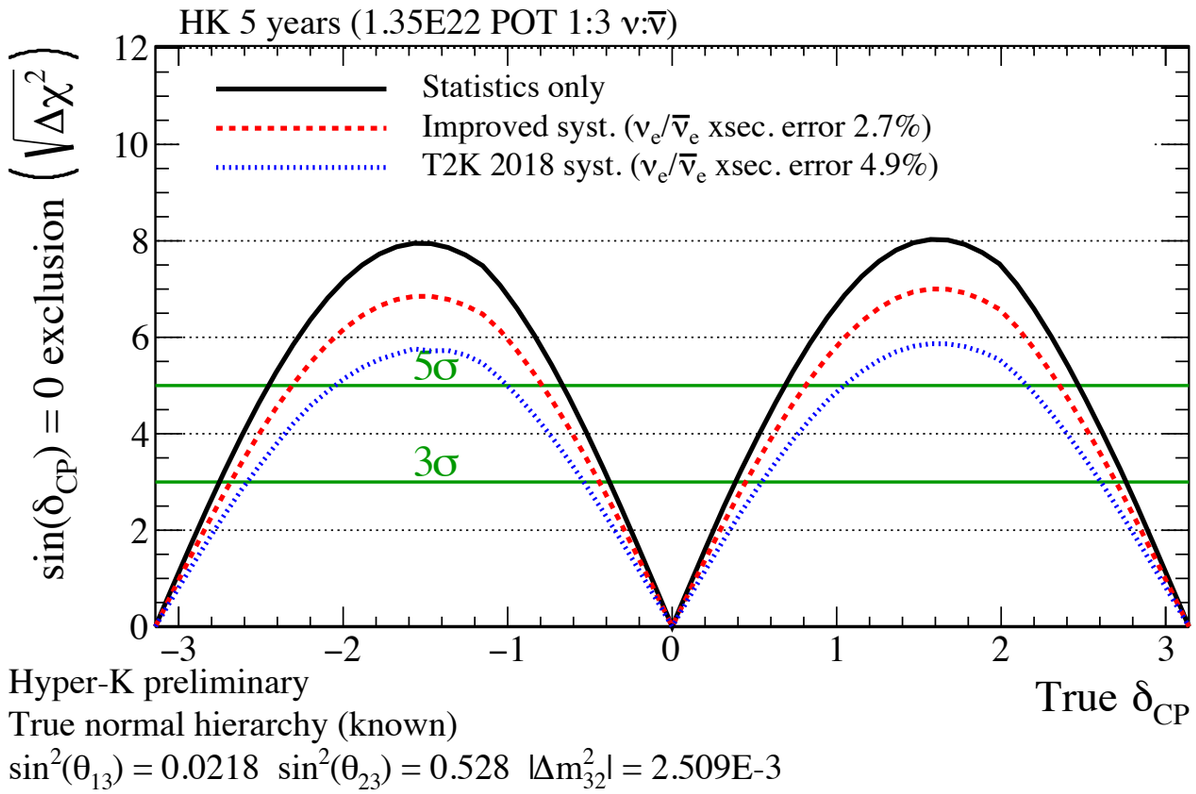
- In HK, Box&Line PMTs will be employed as the 50cm ID PMTs.
- The dynode structure is modified and larger quantum and correction efficiency is realized.
  The detection efficiency is ~twice as large as the SK PMTs.
- The timing and energy resolution are also improved and they are about 2 times better than SK PMTs.

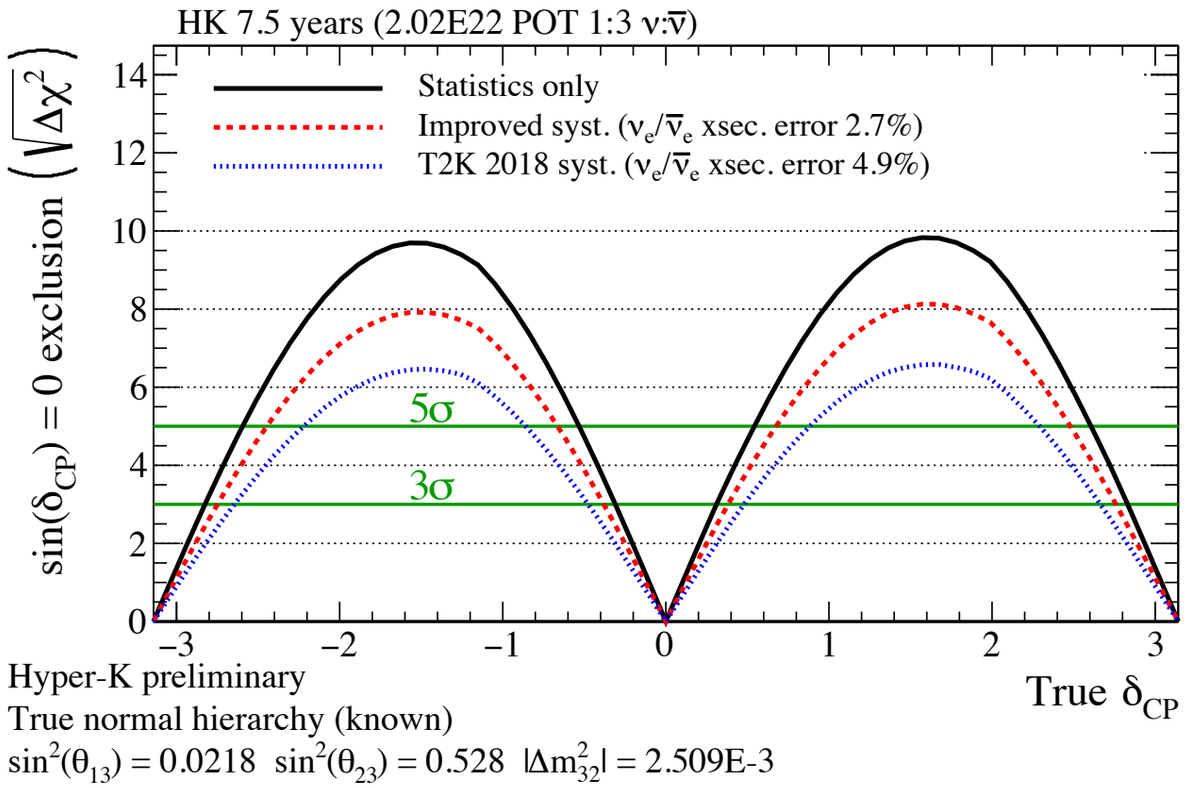




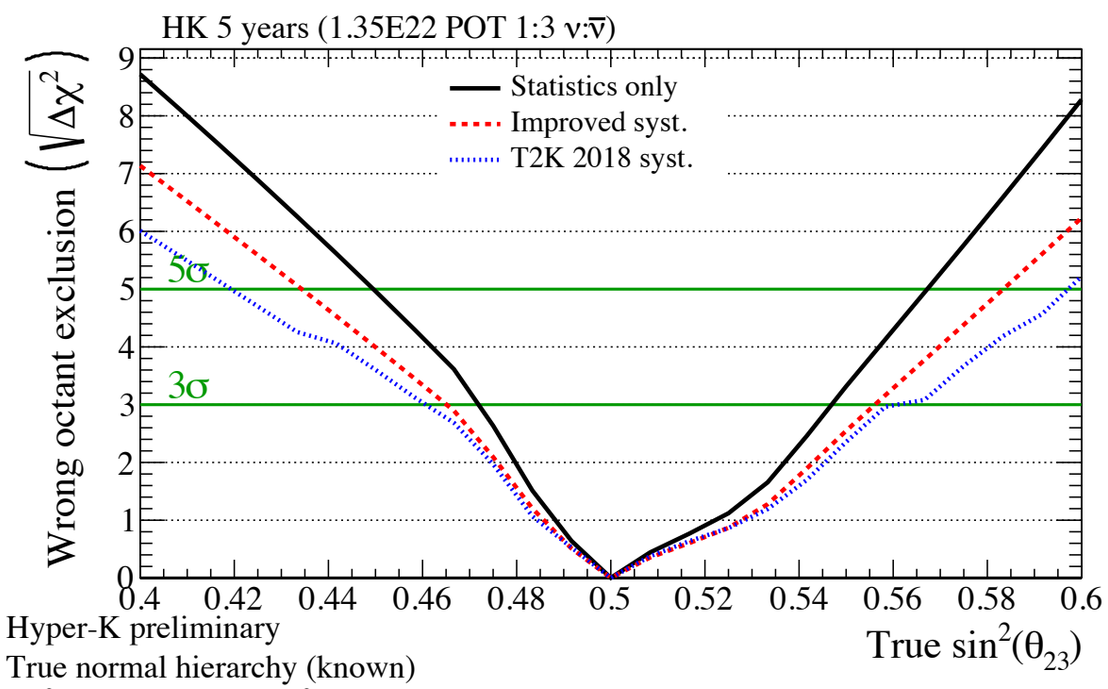
Sensitivity to CP violation



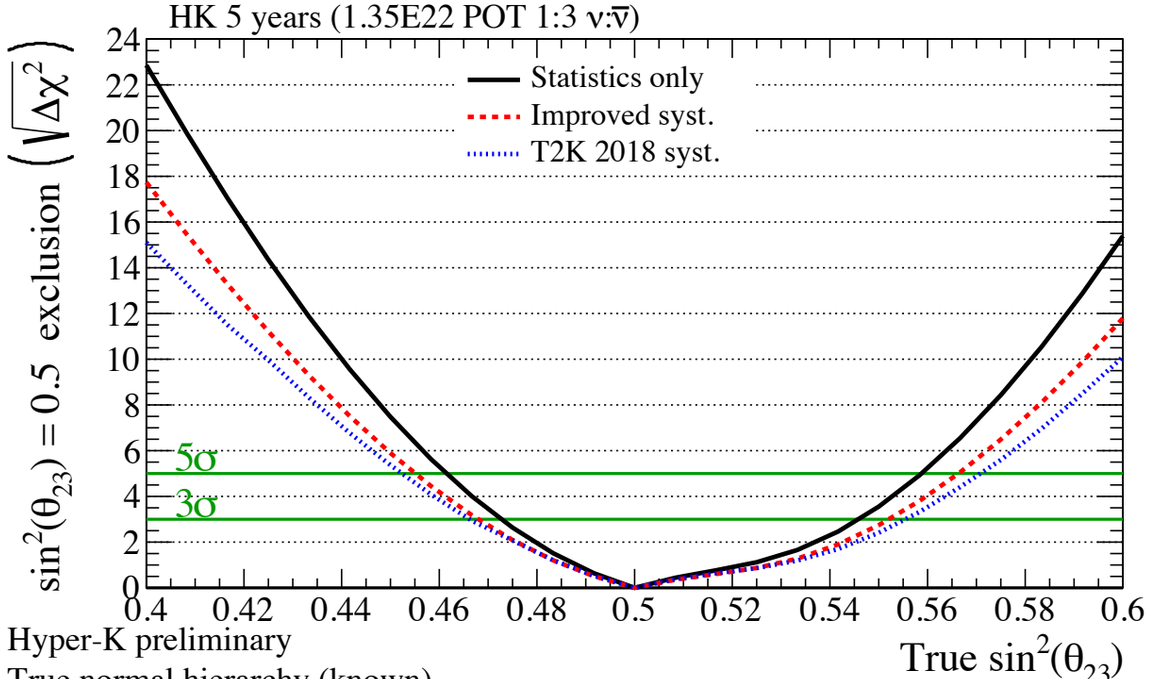




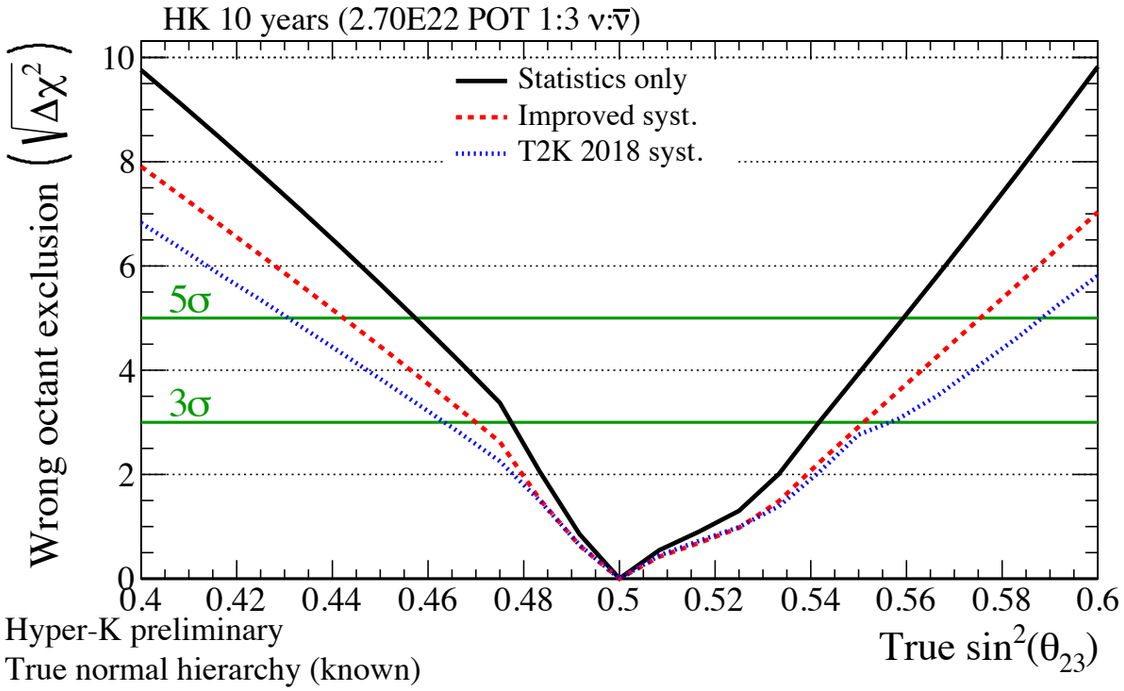
Sensitivity to $\sin^2\theta_{23}$



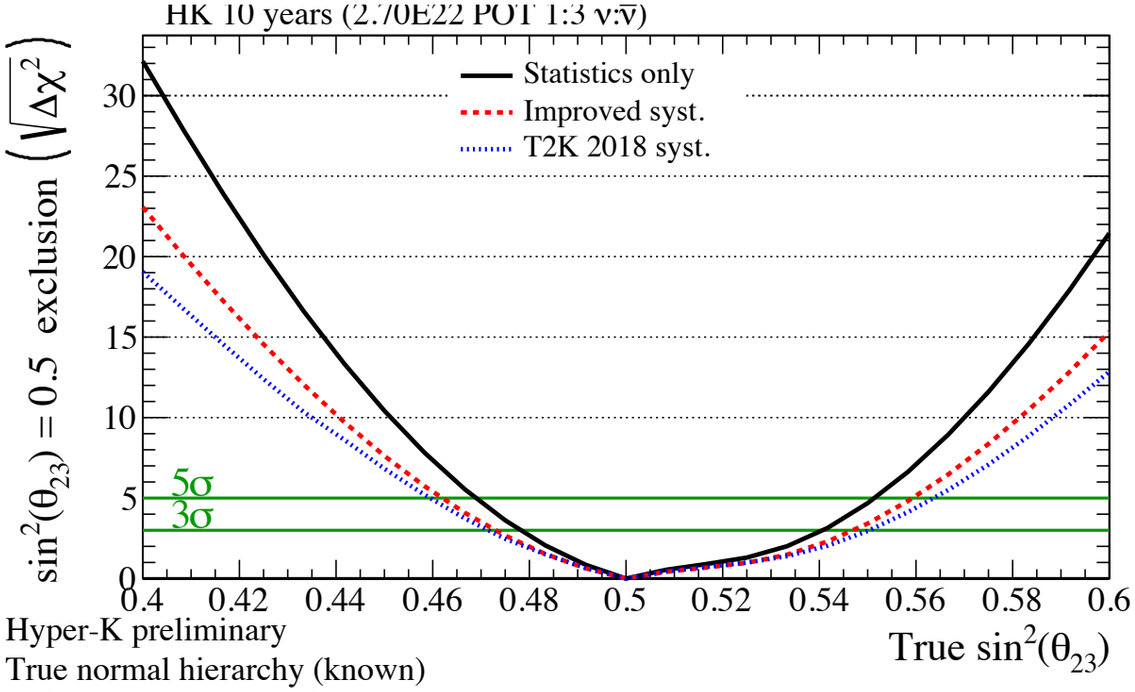
Hyper-K preliminary
True normal hierarchy (known)
$\sin^2(\theta_{13}) = 0.0218$ $|\Delta m^2_{32}| = 2.509\text{E-}3$ $\delta_{CP} = -1.601$



Hyper-K preliminary
True normal hierarchy (known)
$\sin^2(\theta_{13}) = 0.0218$ $|\Delta m^2_{32}| = 2.509\text{E-}3$ $\delta_{CP} = -1.601$



Hyper-K preliminary
True normal hierarchy (known)
$\sin^2(\theta_{13}) = 0.0218$ $|\Delta m^2_{32}| = 2.509\text{E-}3$ $\delta_{CP} = -1.601$



Hyper-K preliminary
True normal hierarchy (known)
$\sin^2(\theta_{13}) = 0.0218$ $|\Delta m^2_{32}| = 2.509\text{E-}3$ $\delta_{CP} = -1.601$