Prospects for Neutrino Astrophysics with Hyper-Kamiokande

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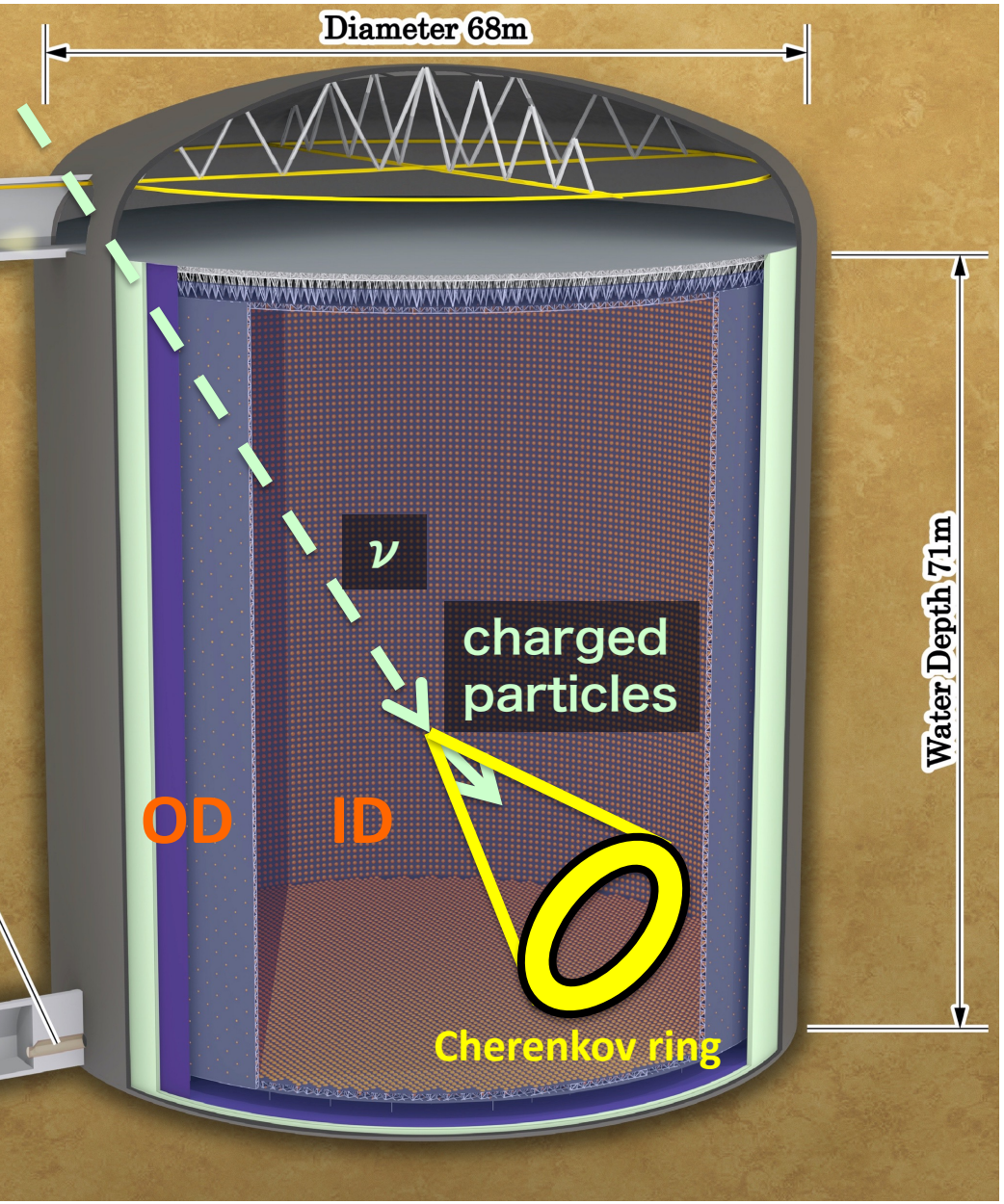
Hyper-Kamiokande Project

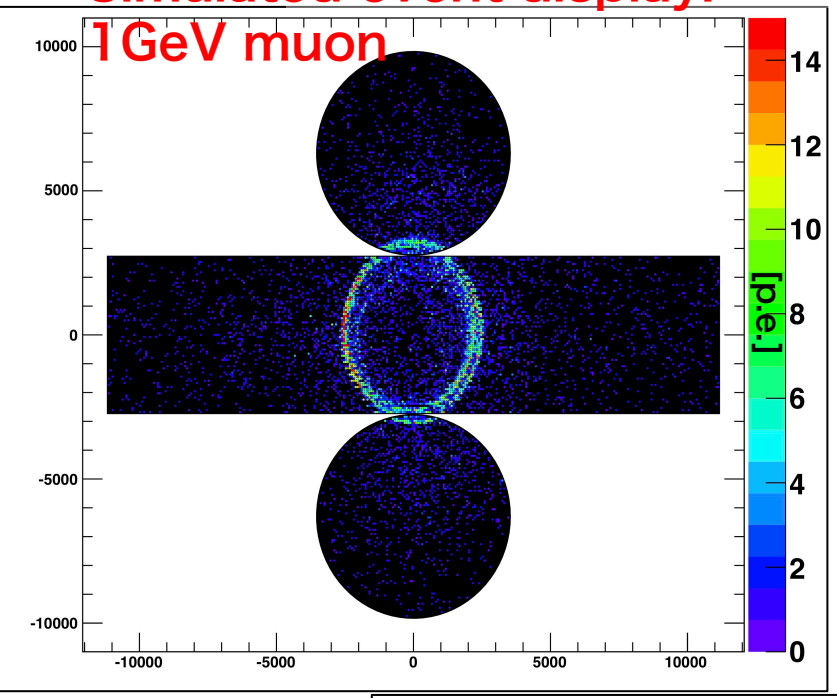


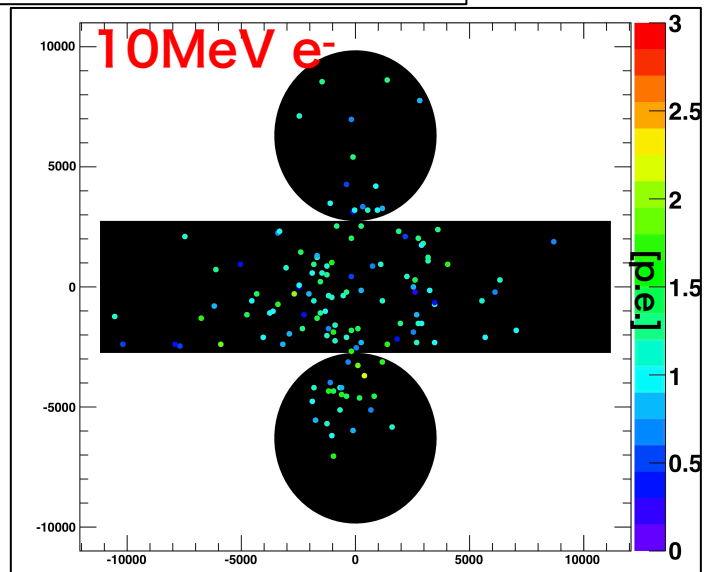
- **Next generation large water Cherenkov detector with 258 kt ultra pure water, providing 188 kt fiducial vol.**
  - Including J-PARC neutrino beamline at Ibaraki, Japan.
  - It will be constructed **600 m** under the Nijyugo-yama mountain at Kamioka, Gifu, Japan (**1600 m.w.e.**).
  - **Japanese construction budget** was **approved** in 2020.
  - **The operation will start in 2027**.
- The detailed detector design is now being settled.
  - **Inner detector (ID)**
    - **40,000 of 20" PMT**
      - 40% photocathode coverage (PC40%)

      or
    - **20,000 of 20" PMT** & **thousands of multi-PMT** modules
      - 20% and more photocathode coverage
  - **Outer detector (OD)**
    - **3" PMT and wavelength shifting plates**
- See also: Y. Itow, NU 1118

Feature of the HK detector

Simulated event display:





- The property of neutrinos can be measured with the charged lepton generated by reactions in ultra pure water.
  - $\nu + e^- \rightarrow \nu + \mathbf{e^-}$ (electron scattering)
  - $\nu_\mu + n \rightarrow p + \boldsymbol{\mu^-}$ (charged-current interaction)

- The **energy**, **position**, **time**, **direction** and **type of the particle** can be identified at each event, with charge and time from PMT hits.
- "Real Time" and "Event-by-Event" measurement is possible.

- This will give capability for **wide variety of neutrino physics**.
  - Solar neutrino
  - Supernova neutrinos
  - Atmospheric neutrinos
  - Accelerator neutrinos

Solar neutrino, Supernova neutrinos: O(1) to O(10) MeV

Atmospheric neutrinos, Accelerator neutrinos: O(100) MeV to TeVs

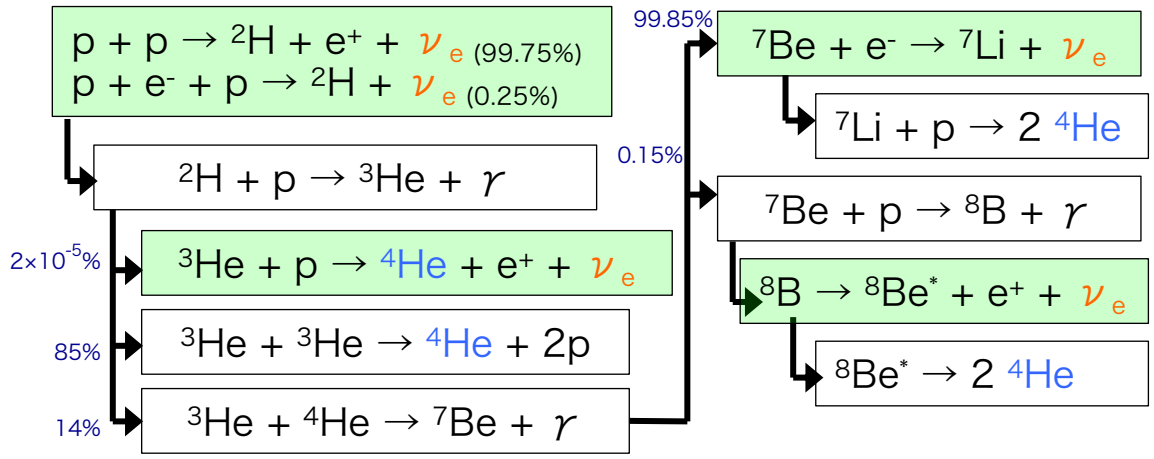
Solar neutrinos

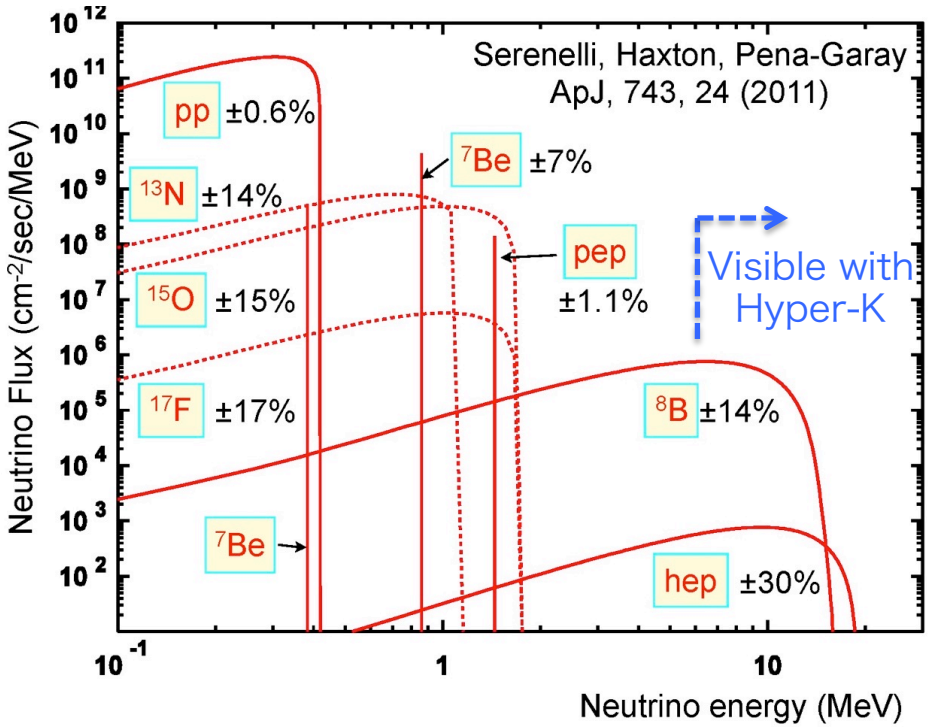
- The Sun burns through nuclear fusion reactions, i.e. pp-chain and CNO-cycle, emitting neutrinos.
- Only neutrinos can bring out information of “today’s” status of solar center.
- With Hyper-K, ^{8}B neutrino is the main observation target. A large statistics is expected :

  130 events/day, $E_{e,kin} > 4.5$MeV

  (15 events/day in SK-I ~ IV)

pp-chain & ν Energy specturm

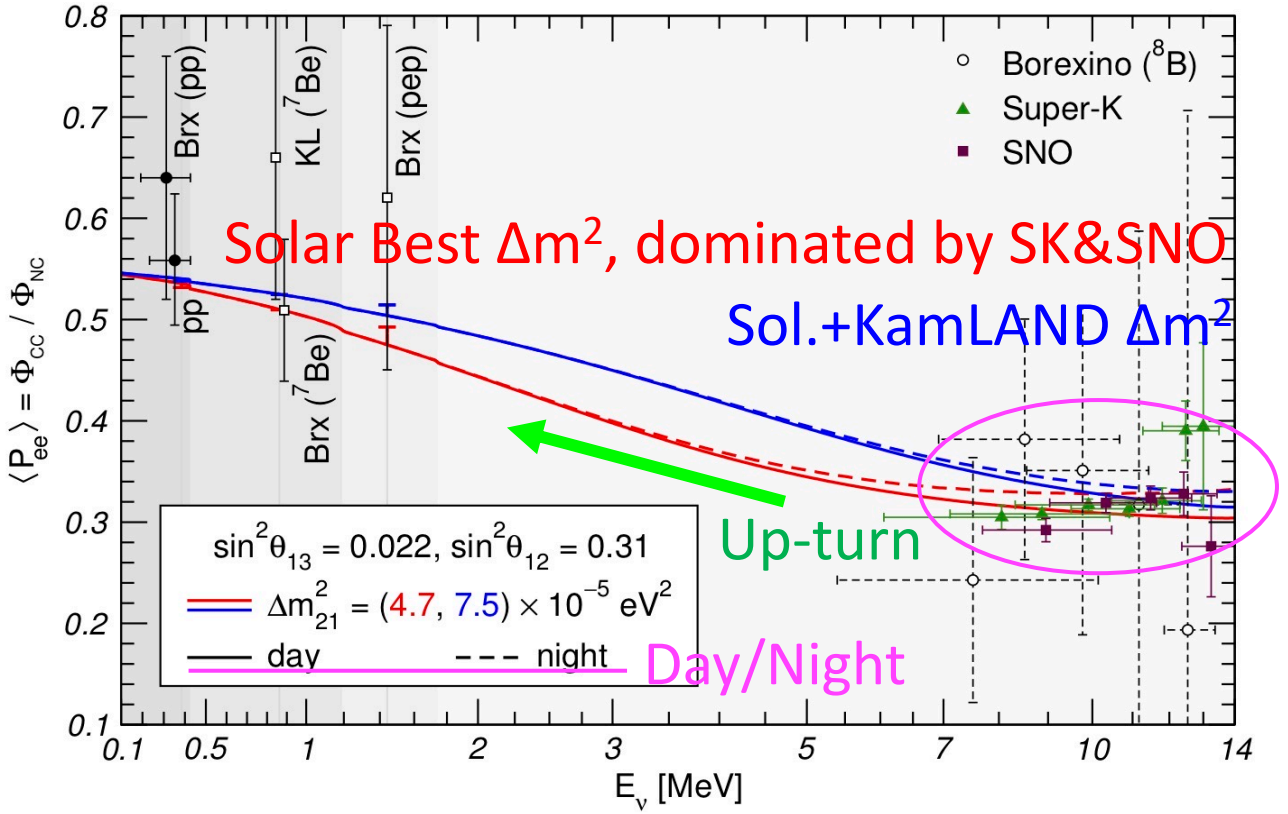




Solar neutrino observation

- Importance of solar ν measurements in particle physics and astrophysics:
  - Precision measurement, Δm^2_{21}
    - Day/Night asymmetry
    - Tension between solar best Δm^2_{21} and reactor best value.
  - Solar nu spectrum up-turn
  - Variation of solar ν flux
  - Discovery of hep neutrino

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

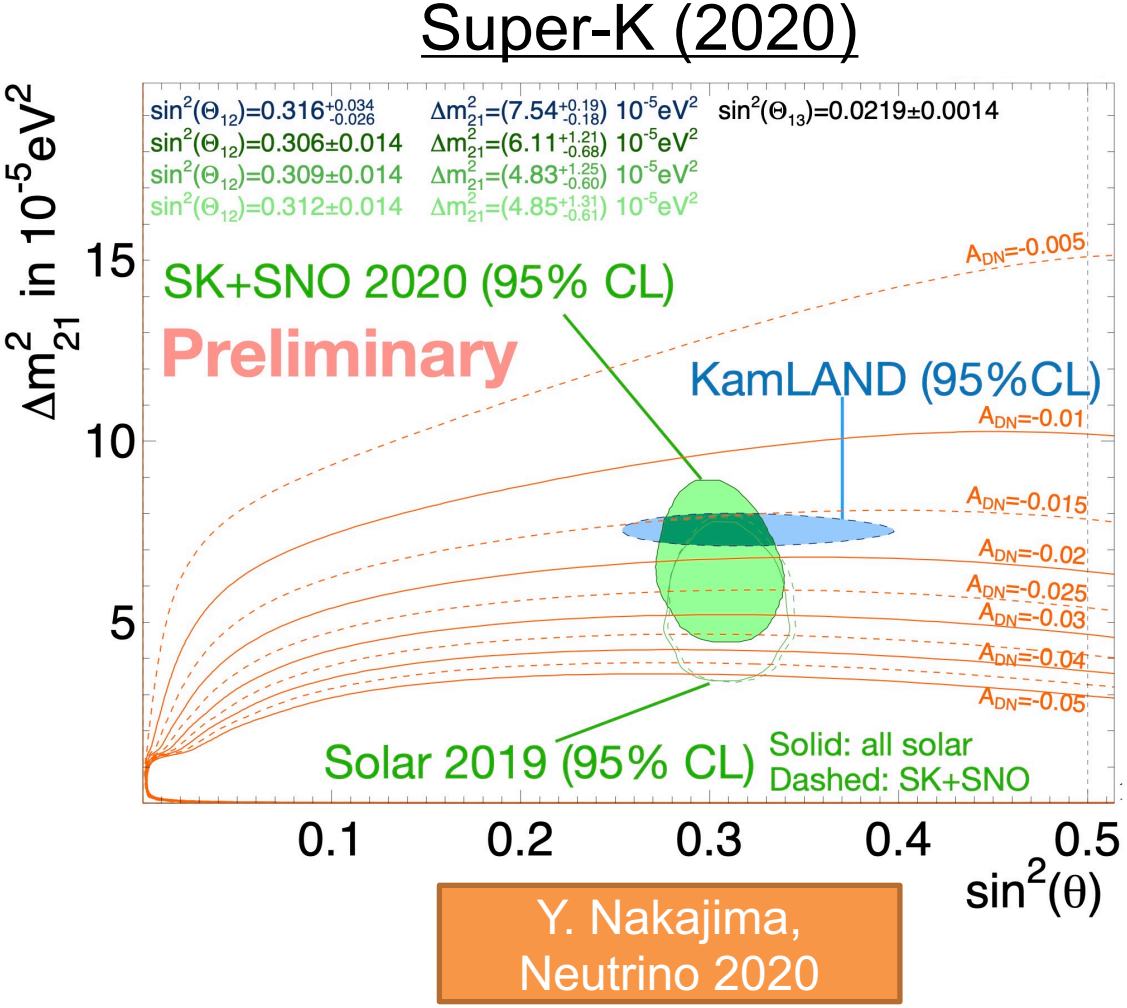


Solar Neutrino Day/Night Asymmetry

- Non-zero D/N asymmetry of solar ν flux caused by terrestrial matter effect is indicated by SK.
  [PRL 1212, 091805(2014)]

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

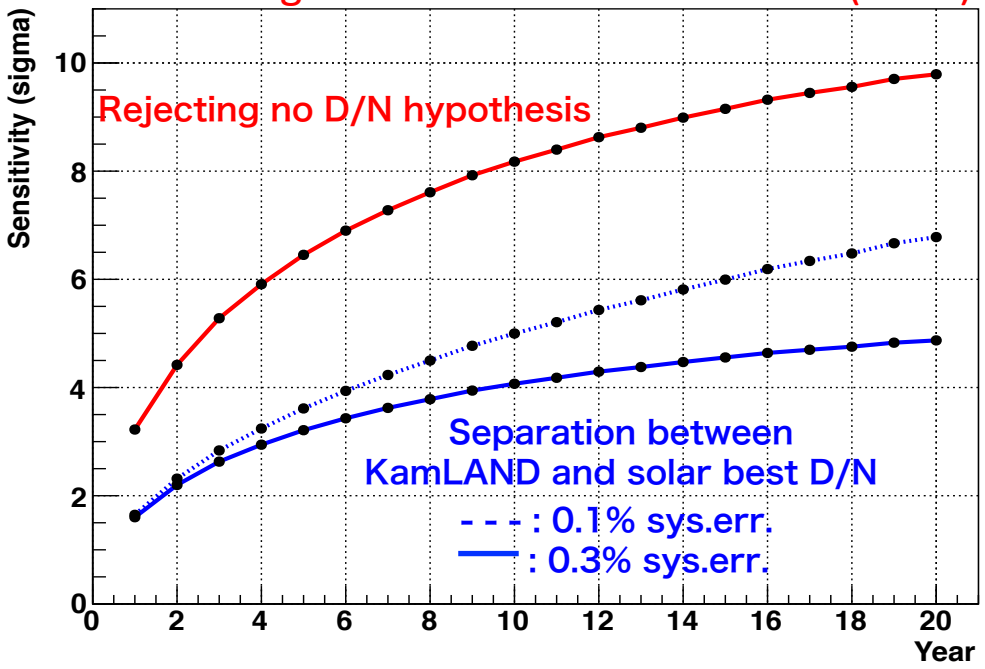
- With Hyper-K statistics, we can investigate the terrestrial matter effect, and the tension between solar best Δm^2_{21} and KamLAND best Δm^2_{21}.
- We can test if CPT is violated,
  i.e. $P_{\nu e \to \nu x}$ and $P_{\bar{\nu} e \to \bar{\nu} e}$.



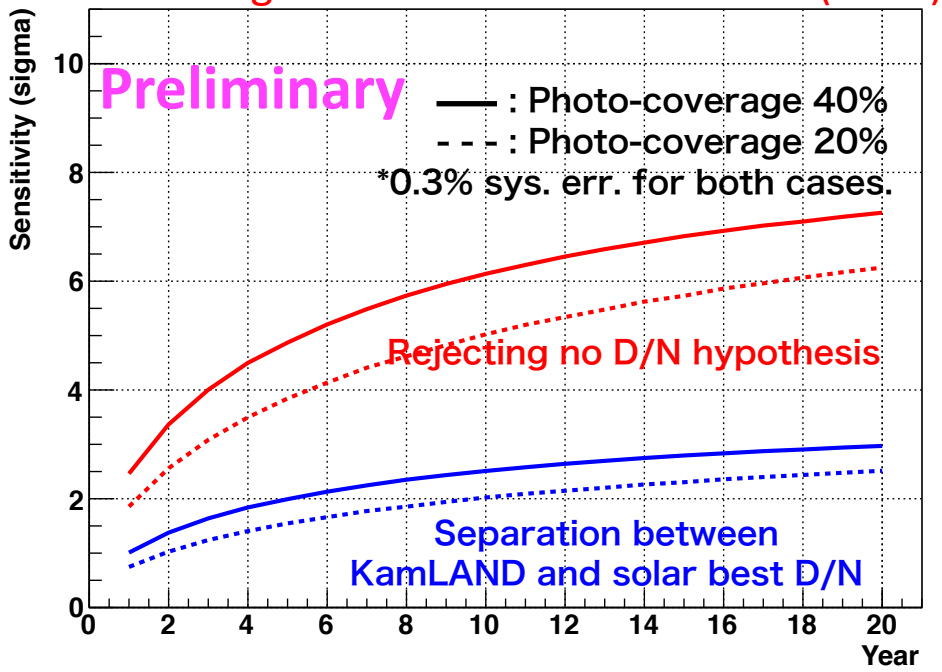
Solar Neutrino Day/Night Asymmetry

Δm^2 separation, only w/ HK

Assuming SK best $\Delta m^2 = 4.8 \times 10^{-5}$ eV^2 (2019)



Assuming SK best $\Delta m^2 = 6.1 \times 10^{-5}$ eV^2 (2020)



- **New solar Δm^2_{21}, 6.1×10^{-5} eV^2** (Super-K, 2020) makes the separation between solar and reactor best value Δm^2_{21} difficult for Hyper-K.
  - It is still possible to prove if the Day/Night asymmetry = earth matter effect with **$>5\sigma$** sensitivity after **10 years** measurement.
- In case of Δm^2_{21} of 4.8×10^{-5} eV^2 (Super-K, 2019), it is still possible to separate solar and reactor best above 4σ. (10 yrs, 0.3% sys. err.)

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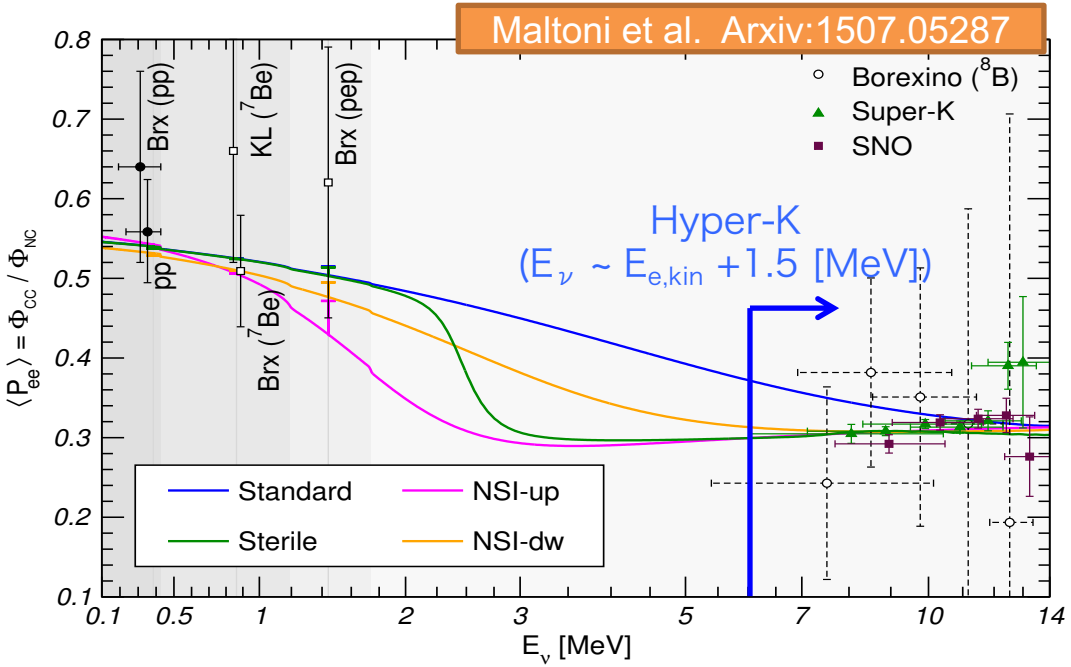
Solar Spectrum Up-turn

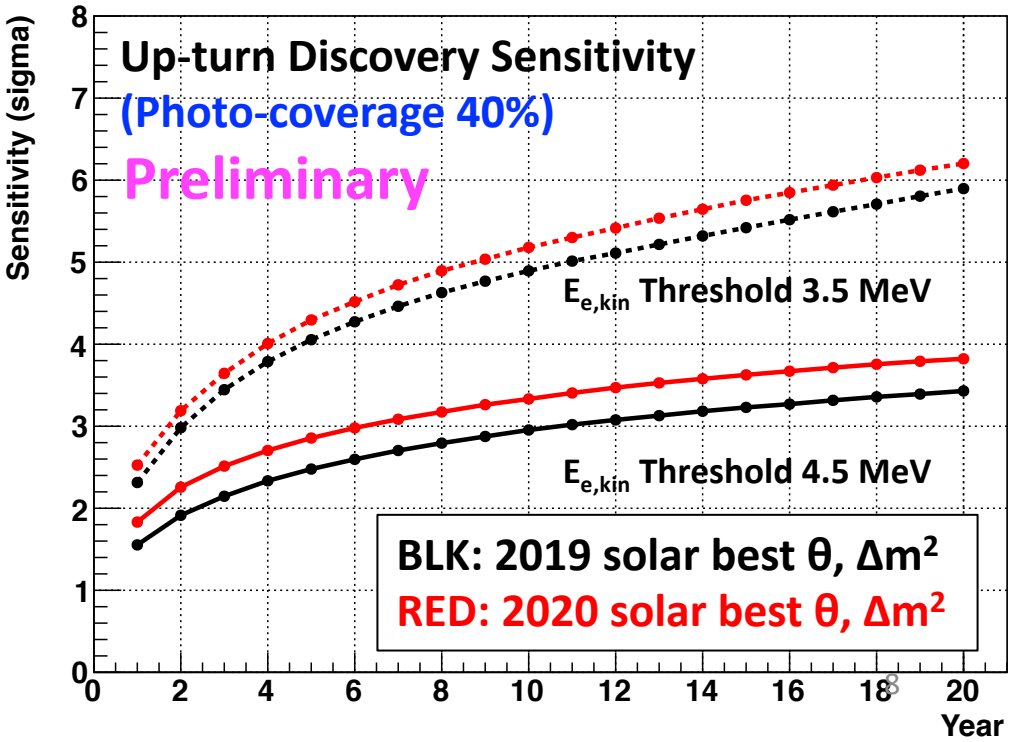
What is solar up-turn?

- A continuous variation of the solar neutrino survival probability, at the middle energy of MSW-dominated and vacuum-oscillation-dominated energies.
  - It is expected but not directly observed yet.
  - There is room for new BSM physics.

What is HK capability?

- Hyper-K will separate the cases with up-turn and w/o up-turn by **~ 3 or 5** sigma.
  - **4.5 or 3.5** MeV analysis threshold is assumed in electron kinetic energy equivalent.
  - Effect of photo-coverage is limited, here.





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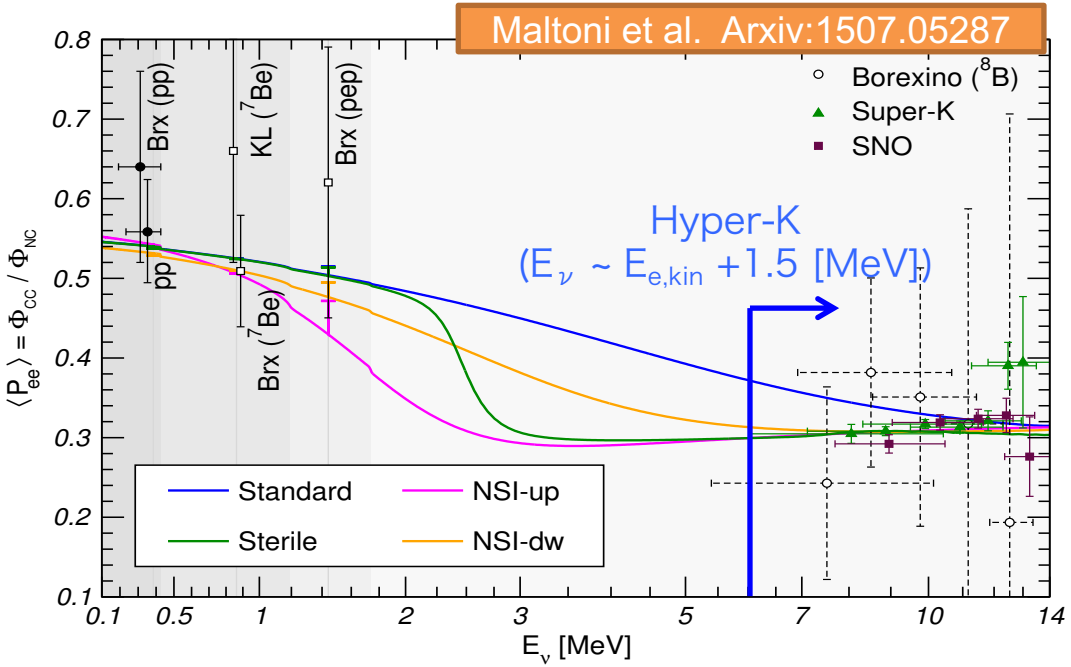
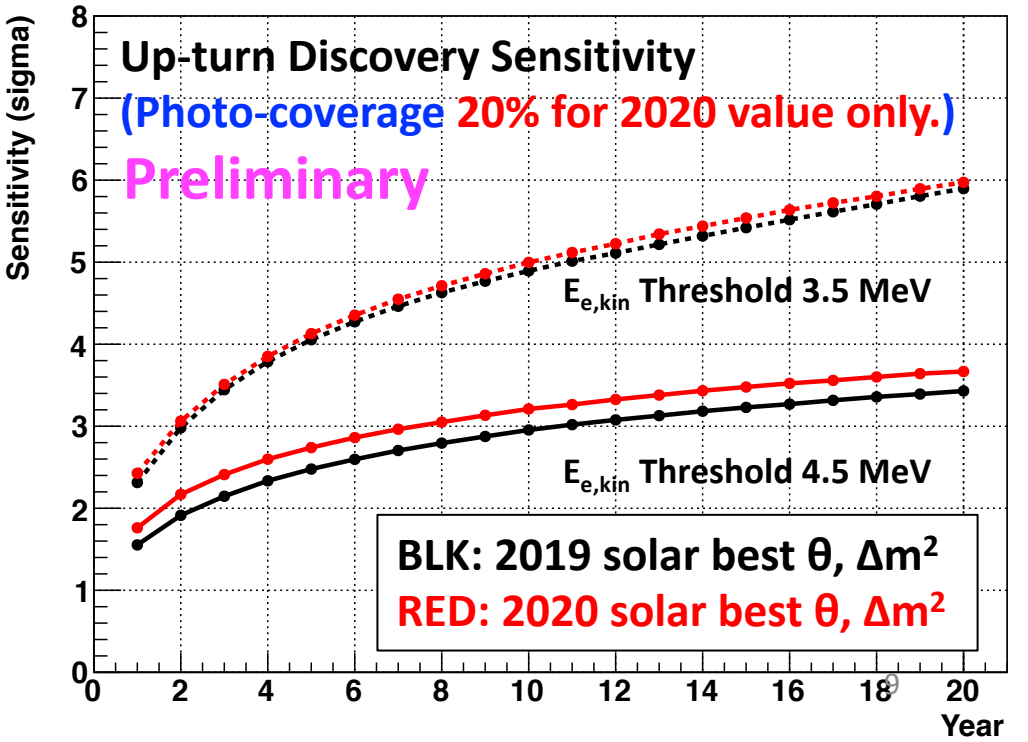
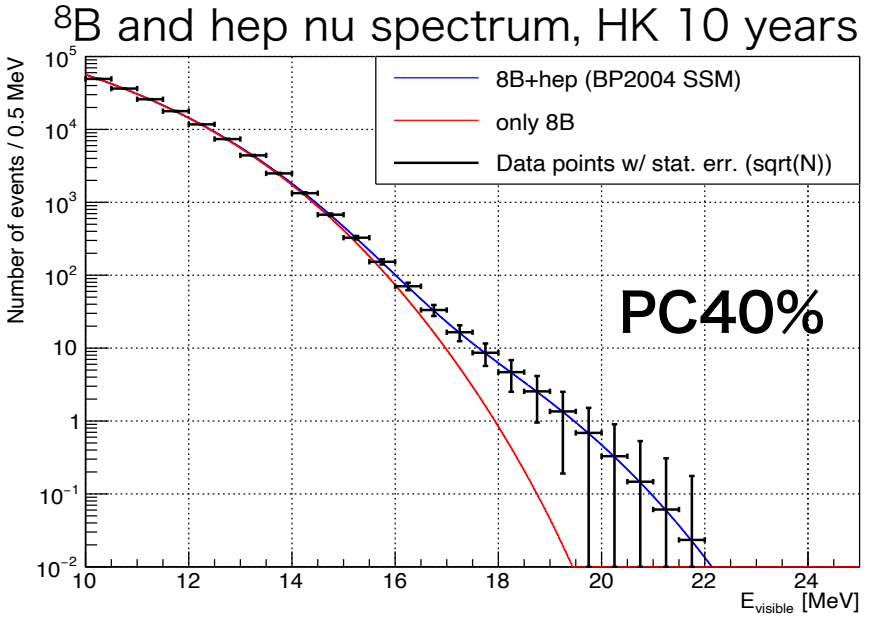




Other solar ν topics

hep process neutrino

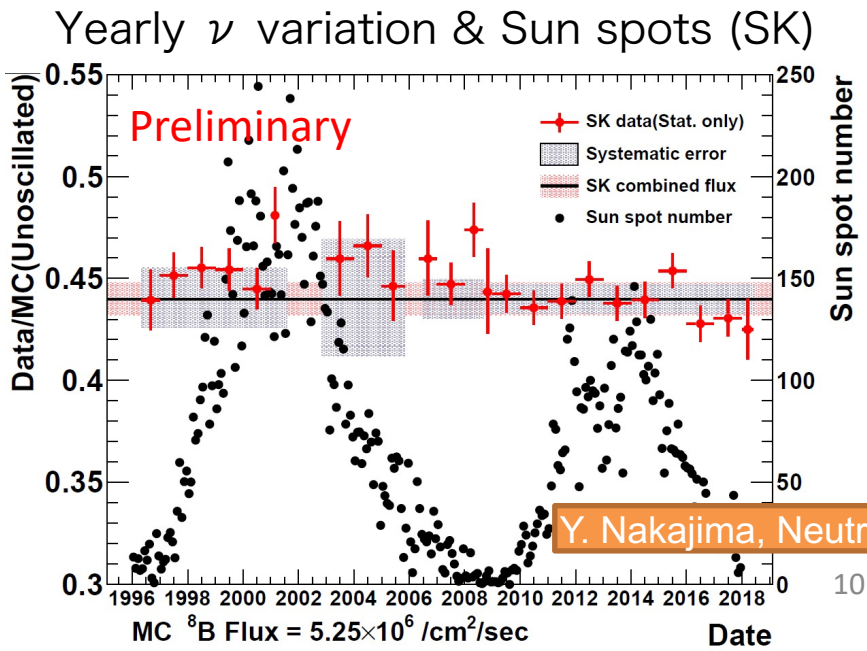
- Undiscovered solar neutrinos, with small branching ratio.
- With Hyper-K 10 years data, there is chance to discover.
- → To test the solar models.
  - 1.8 ~ 3 σ, 10y (PC40%)



Variation of solar neutrino flux

- High statistics observation with Hyper-K will help to observe the variation of solar neutrino flux.

- Hyper-K: 130 [events/day], $E_{e,kin} > 4.5$MeV
  - Super-K: 15 [events/day]



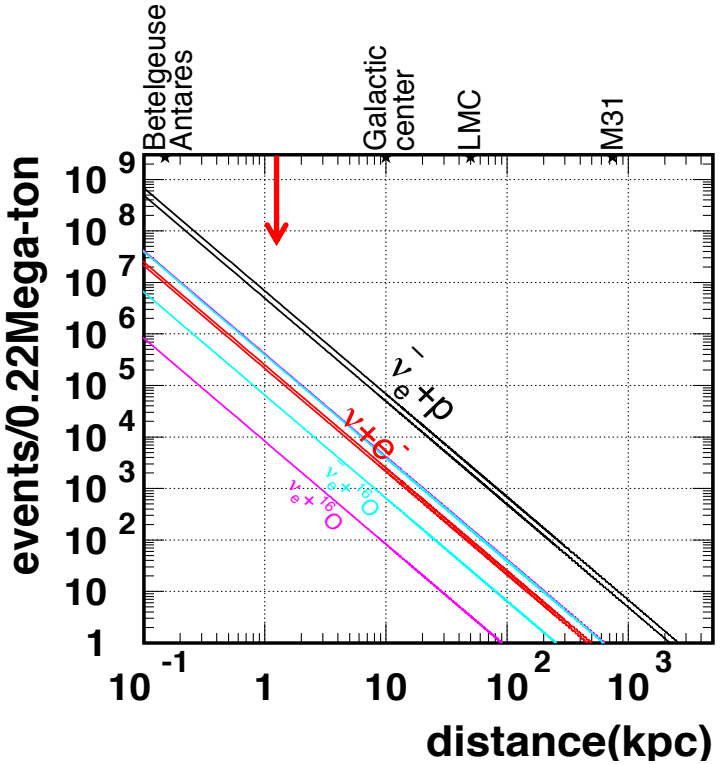
Supernova Neutrinos

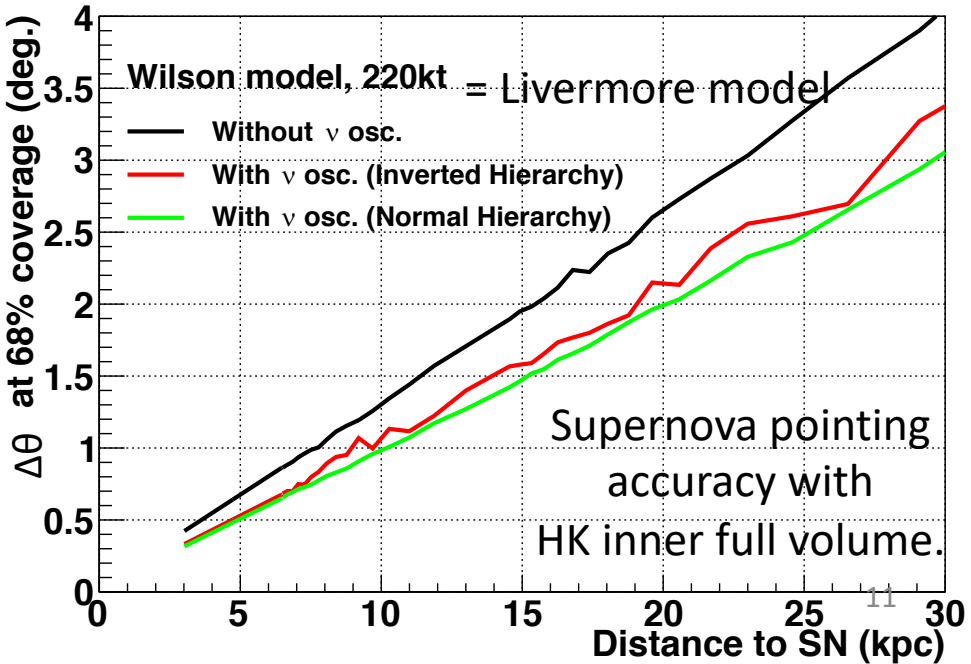
Core-collapse supernova emits all kinds of neutrinos.

- 11 neutrino events by Kamiokande from SN1987A at 50 kpc (LMC).
- **50k ~ 80k events** are expected in HK from a SN at 10 kpc (galactic center).

Physics Motivation

- **Core-collapse SN physics**
  - Explosion mechanism
  - Proto-neutron star formation
  - Black hole formation
- **Neutrino physics**
- **Multi-messenger analysis**
  - SN alert with directional information
  - With gravitational wave, gamma-ray, X-ray, telescope…





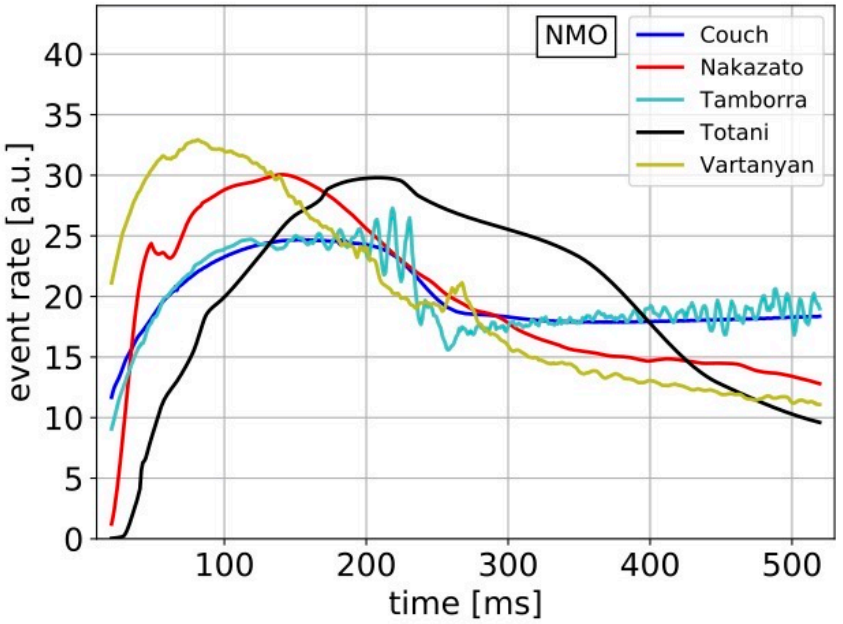
SN Features

- Supernova neutrino observation
  - Precise SN neutrino time profile
  - Energy spectrum measurement
    - Investigation of the SN mechanism (SASI/Rotation/Convection)

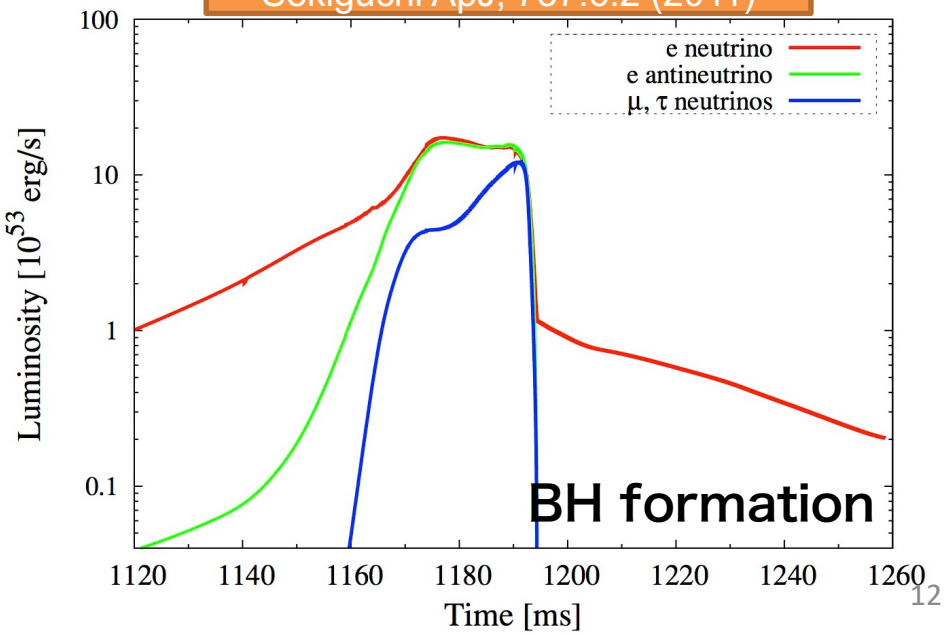
- Supernova model discrimination
  - Model discrimination between five supernova models are recently studied.
    - https://arxiv.org/abs/2101.05269
  - With 300 events, corresponds to supernova at 60-100 kpc, >97% SN model identification.

- Proving dim supernova/BH formation at nearby galaxy.
  - By detecting the neutrinos from nearby-galactic supernovae.

Hyper-K, https://arxiv.org/abs/2101.05269



Sekiguchi ApJ, 737.6.2 (2011)



SRN with HK

Supernova Relic Neutrino (SRN)

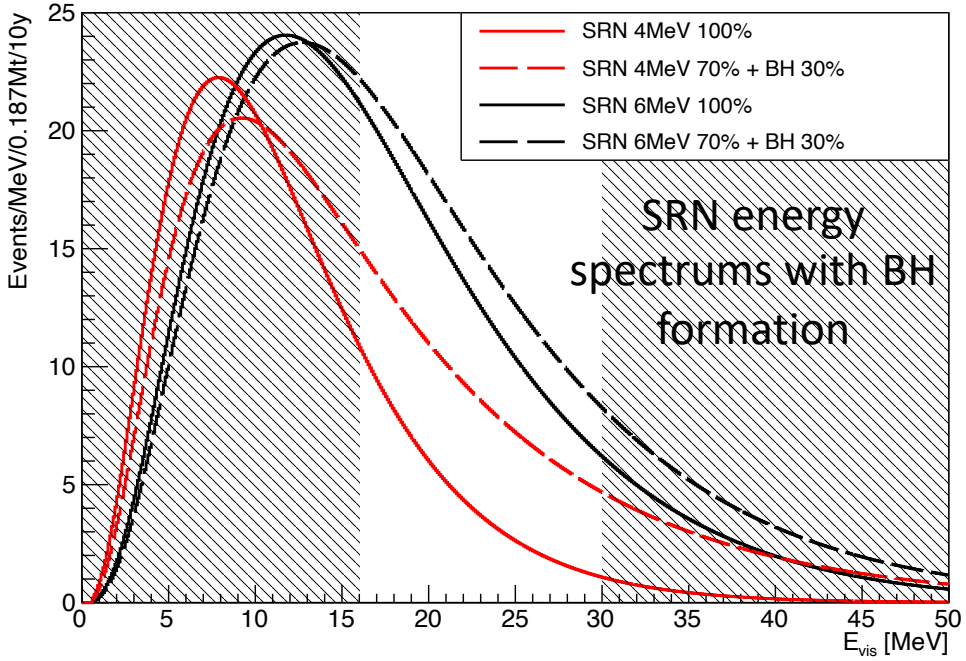
- Diffused neutrinos coming from all past supernovae.
- Not discovered but **promising** extra-galactic ν.

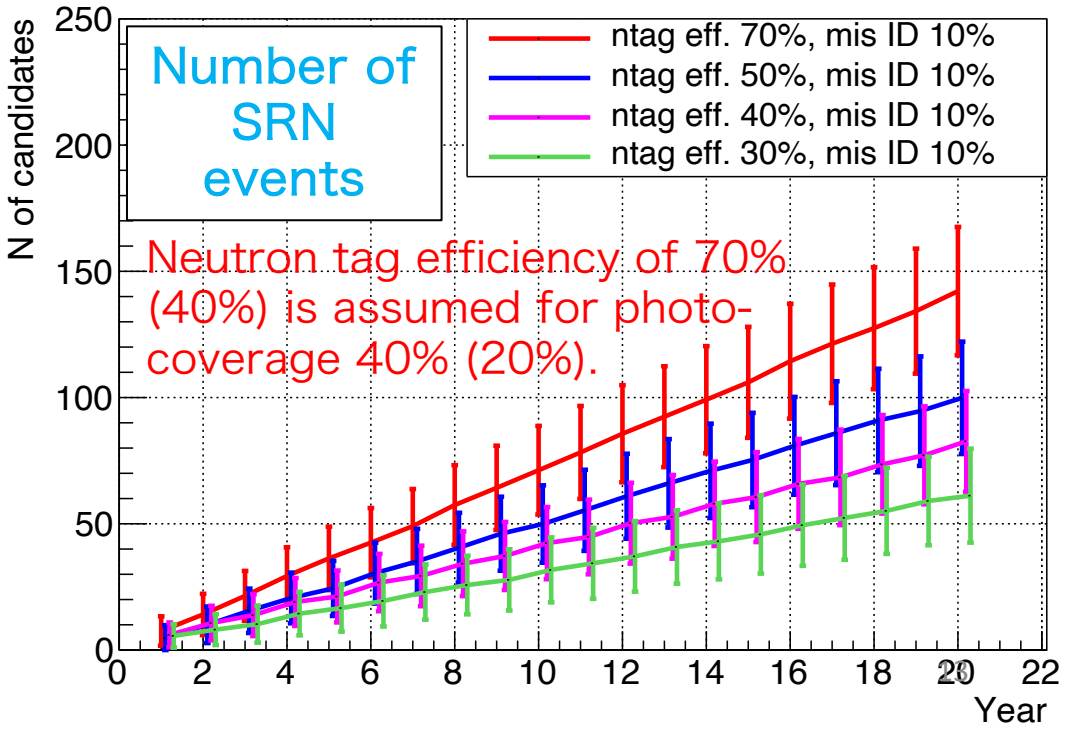
Physics of SRN

- Test of star formation rate
  - Factor ~2 discrepancy between rates of formations and SNe.
- Energy spectrum of supernova burst neutrinos
  - Temperature inside the SN
- Extraordinary SN
  - BH formation, dim supernova

SRN with Hyper-K

- SRN can be observed by HK in 10y with **~70±17** events with $> 4\sigma$ non-zero significance (photo-coverage 40%).
  - **~40±13** events and 3σ for PC20%.
- We will go beyond the discovery and aim to measurement of SRN.





Summary

- **Hyper-K project is a next generation large water Cherenkov detector.**
  - Design Report is available. Technical Report will be published soon.
    - https://arxiv.org/abs/1805.04163
  - Hyper-K observation will start in 2027.
  - Japanese construction budget was approved by MEXT in Japan, in 2020.
    - We are in construction phase!

- **Astrophysical neutrino measurements is one of the features of Hyper-Kamiokande.**
  - Solar neutrinos
    - Hep neutrino, seasonal variation, up-turn 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. follow-up observation with gravitational-wave events.