XXI Workshop on Neutrino Telescopes

Results from the Super-Kamiokande Experiment

September 30th, 2025

L. N. Machado [a,+], on behalf of the Super-Kamiokande Collaboration

[a] School of Physics & Astronomy, University of Glasgow

[+] Correspondence: lucas.nascimentomachado@glasgow.ac.uk

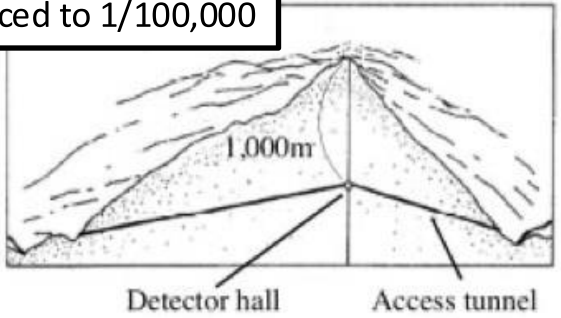
University of Glasgow

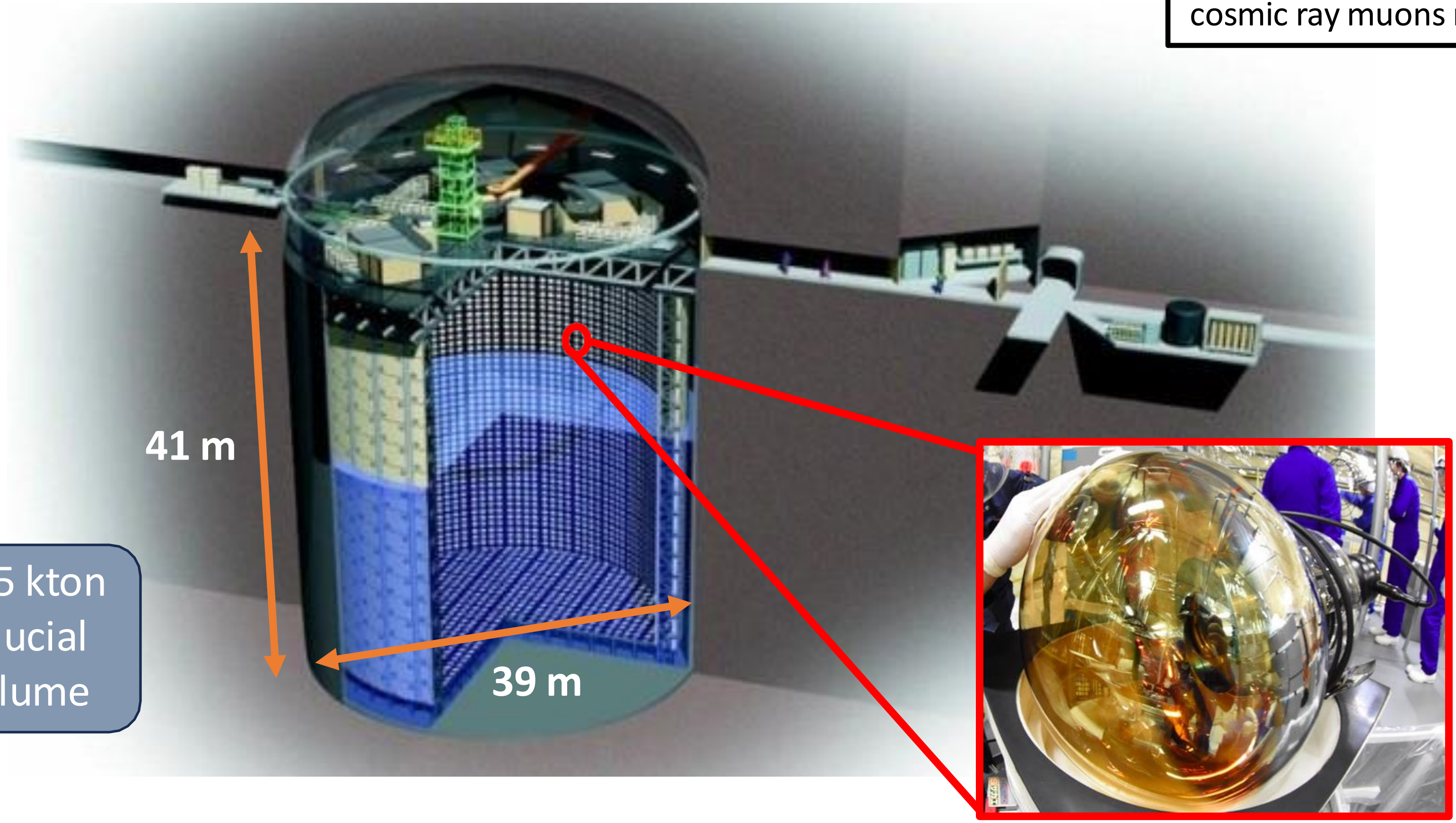
SUPER K

The Super-Kamiokande Experiment

The Super-Kamiokande (SK) Neutrino Detector is a **50 kton water Cherenkov** located in the Kamioka mine in Japan, overburden with 1000 m of rock. In operation since April 1996.

Overburden ~1 km rock:
cosmic ray muons reduced to 1/100,000





22.5 kton fiducial volume

Inner detector: currently has around 11,000 20-inch PhotoMultipliers Tubes (PMTs).

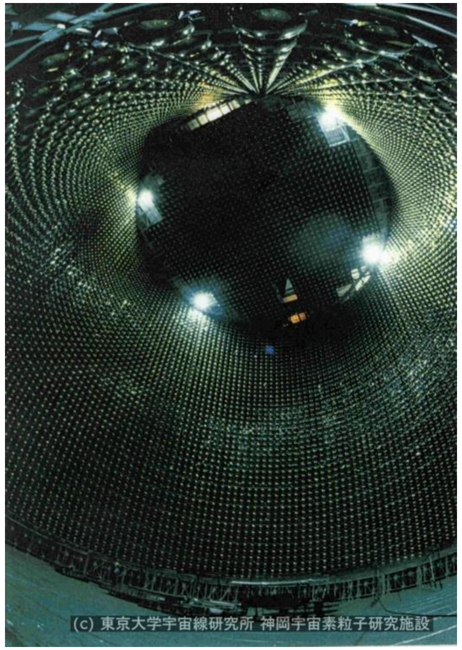
Outer detector: water layer ~2m thick, with ~1,885 8-inch PMTs, facing the outside of the detector.

The Super-Kamiokande Collaboration

The Super-Kamiokande Collaboration consists of approximately 240 members from 54 institutions.

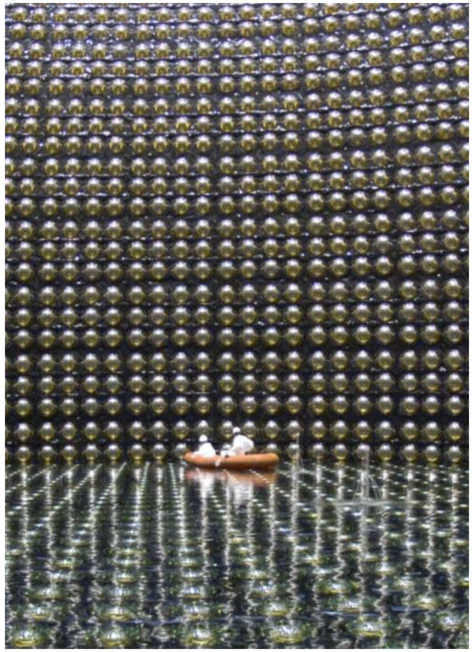
History of Super-Kamiokande

1996 — 2002 — 2006 — 2008 — 2019



SK-I, 1996-2001
11,146 ID PMTs
(with 40% coverage)

SK-II, 2002-2005
5,182 ID PMTs
(with 19% coverage + FPR)



SK-III, 2006-2008
11,129 ID PMTs
(again, 40% coverage)

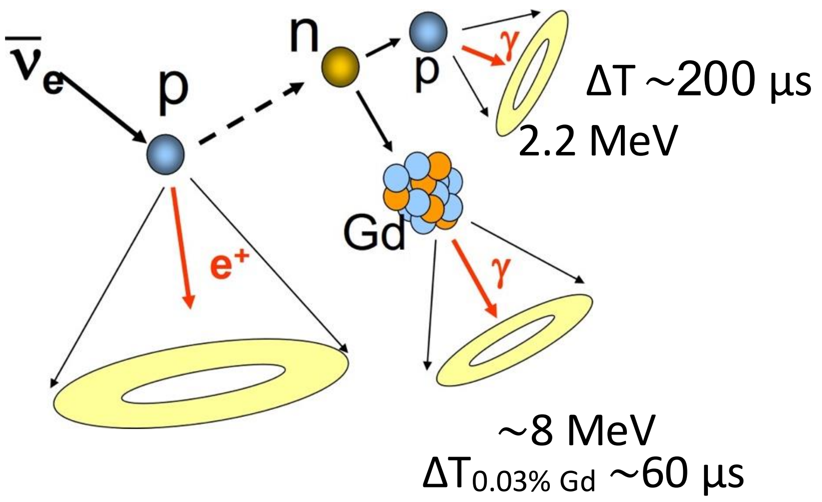
SK-IV, 2008-2018
11,129 ID PMTs
(upgraded electronics)

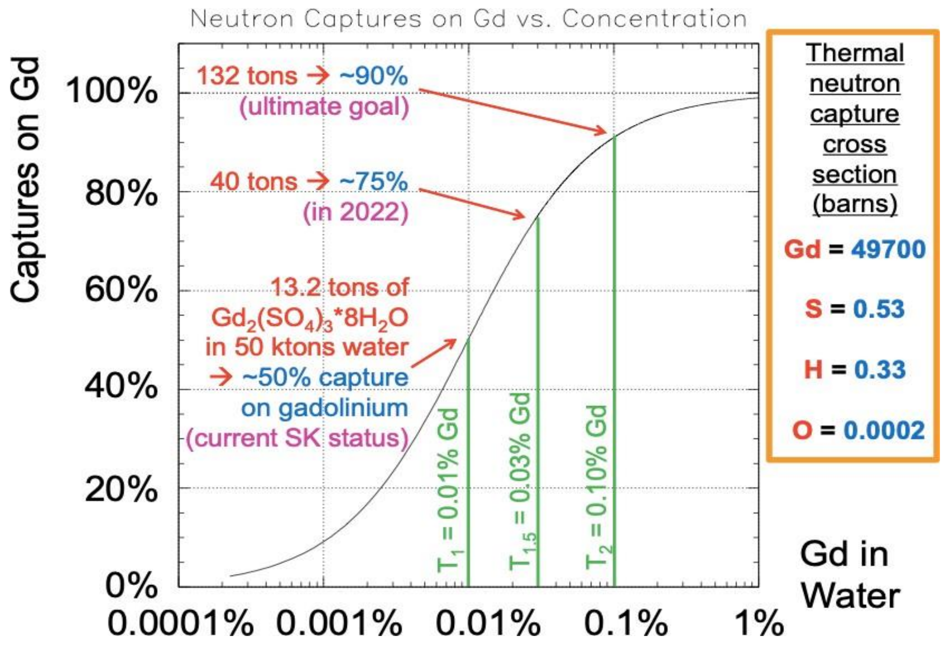
SK-V, 2019-2020
11,129 ID PMTs
(refurbished for Gd and with Hyper-K PMTs)

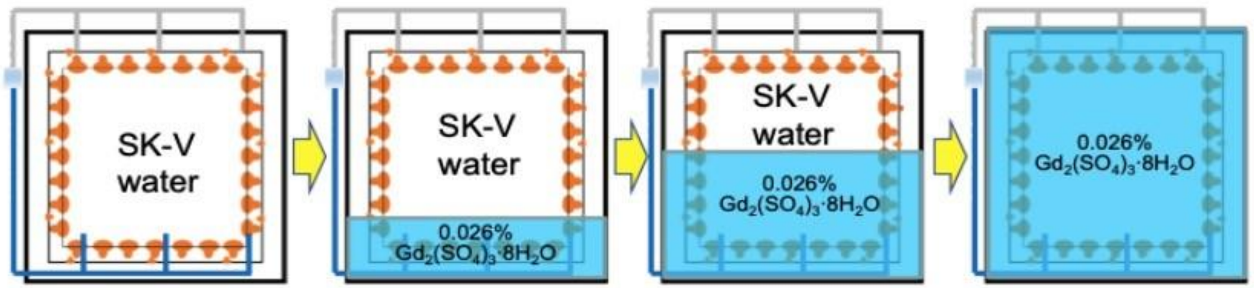
Super-Kamiokande with Gadolinium (SK-Gd)

Improve Super-Kamiokande's sensitivity electron anti-neutrinos by adding water-soluble gadolinium (Gd) salt to the water in the detector.

Isotope	neutron capture cross section
^{157}Gd	255,000 barns
^{155}Gd	61,000 barns
H	0.3 barn







SK-VI: July/August 2020 → **13 tons $Gd_2(SO_4)_3$ * $8H_2O$**
0.01% Gd

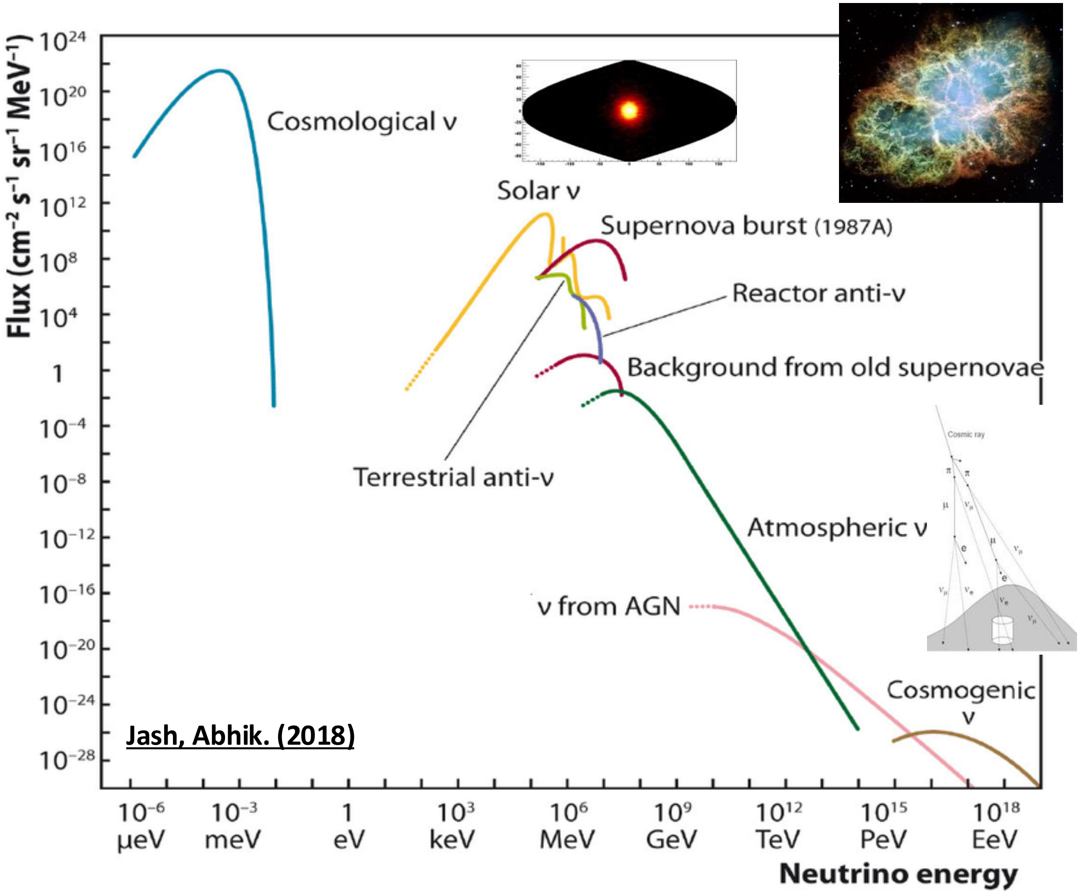
Nuclear Inst. and Methods in Physics Research, A 1027 (2022) 166248

SK-VII/ SK-VIII: June/July 2022 → **40 tons $Gd_2(SO_4)_3$ * $8H_2O$**
0.03% Gd

Nuclear Inst. and Methods in Physics Research, A 1065 (2024) 169480

Beacom, Vagins PRL.93, (2004) 171101

Super-Kamiokande – Physics Goals

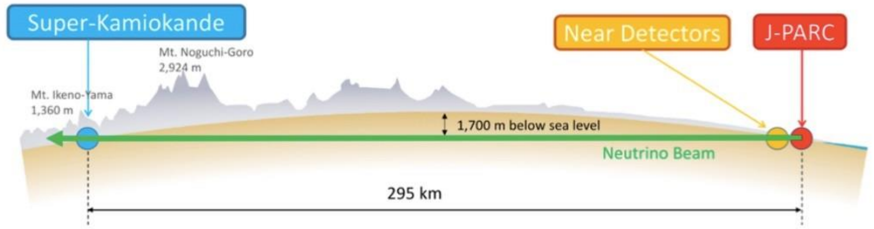


Super-Kamiokande is unique in covering neutrinos from MeV solar energies to TeV cosmic rays, while probing rare processes like nucleon decay.

- **Astrophysics**
  - Solar neutrinos (~15 events/day)
  - Supernova burst neutrinos (~10,000 events galactic SN)
  - Diffuse Supernova Neutrino Background (few events/year, relic of all past stars)
  - Pre-supernova neutrinos (hours early warning signal)

- **Neutrino Oscillations**
  - Atmospheric neutrinos (flux from ~100 MeV to >10 TeV)
  - Accelerator, T2K (controlled beam, precision θ_{13}, δ_{CP} studies)

- **Rare Searches**
  - Nucleon Decay (lifetime sensitivity $>10^{34}$ years)
  - Exotic/astrophysical neutrinos (test for dark matter, GW/GRB/AGN coincidence, new physics)



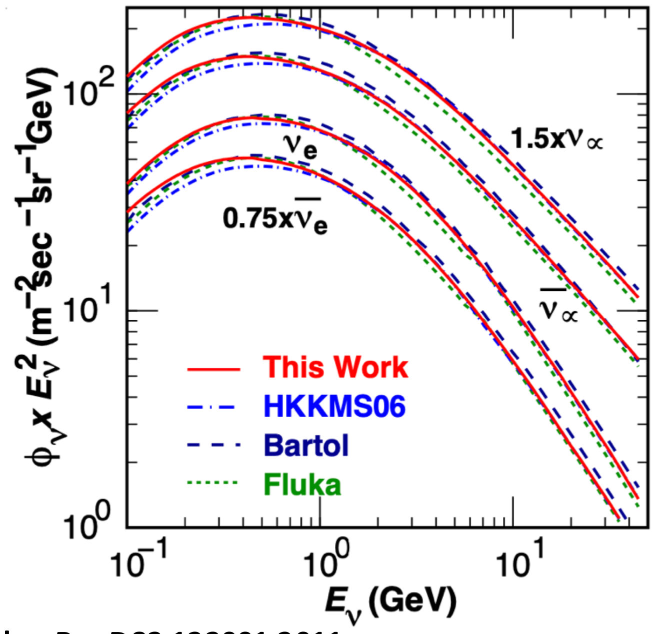
T2K long-baseline program

Atmospheric Neutrinos

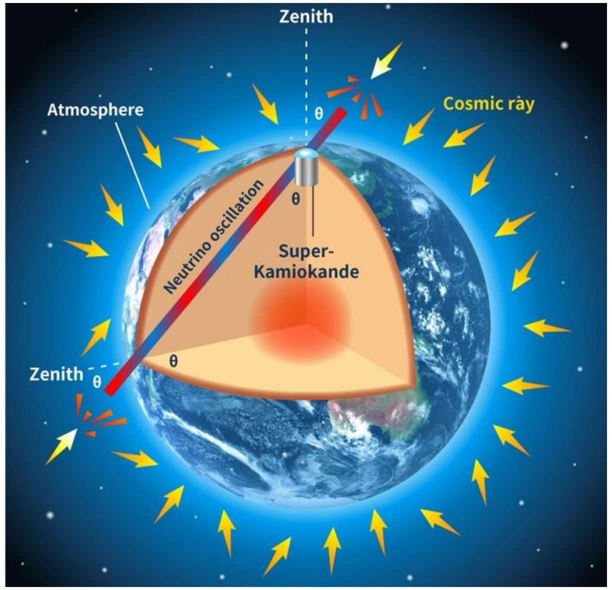
Cosmic rays (mainly protons) interact with nuclei in the atmosphere, producing particle hadronic showers (e.g., pions, kaons). These decay into neutrinos, called atmospheric neutrinos.

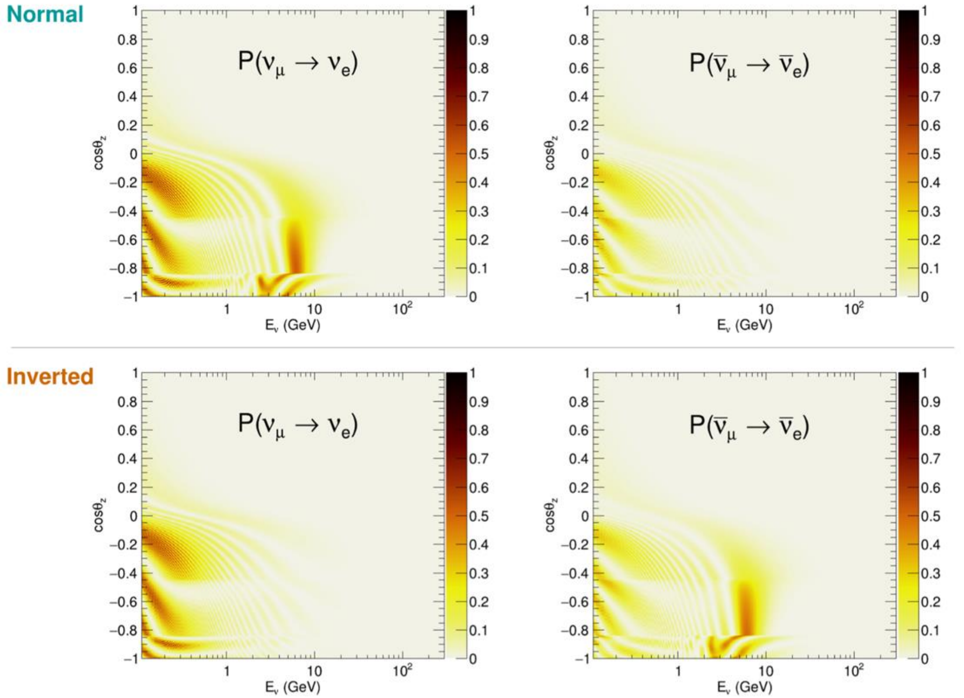
- Energy range few MeV to several TeV.
- Super-K observes ~8 events/day

Travel length of atmospheric neutrinos varies 15 km to ~13000 km.
Zenith angle describes different atmospheric neutrino baselines
-> matter effects induced by passage through Earth.



Phys.Rev.D83:123001,2011





Oscillation probabilities for atmospheric neutrinos as a function of the cosine of the zenith angle and the neutrino energy E_ν.

Atmospheric neutrinos as probe of neutrino oscillations:

- ν_μ disappearance: Δm^2_{32}, $\sin^2\theta_{23}$
- ν_e appearance: δ_{CP}, θ_{23} octant, mass ordering

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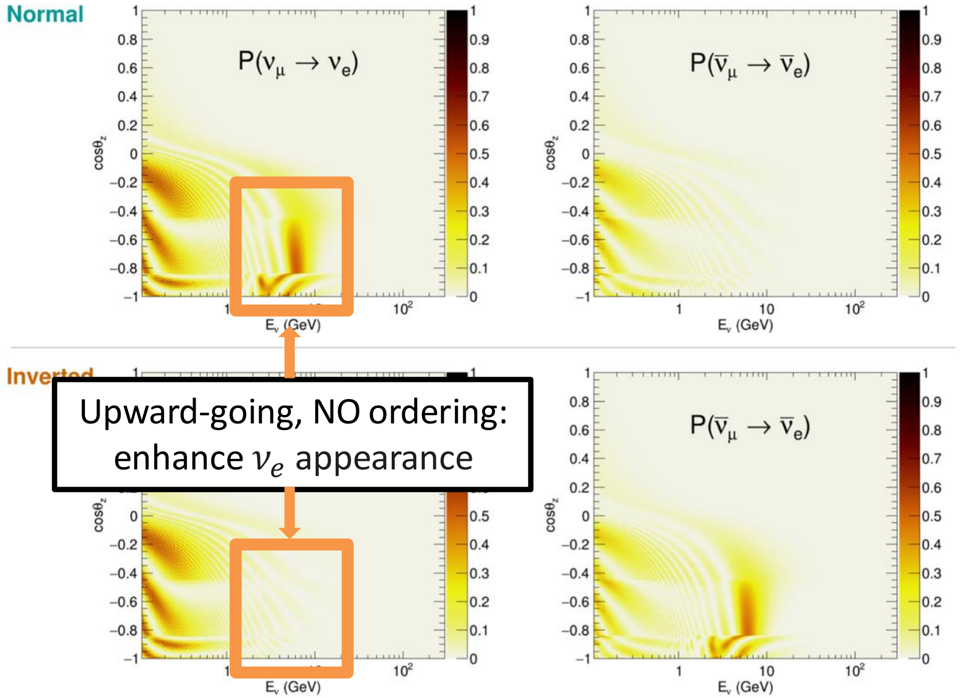

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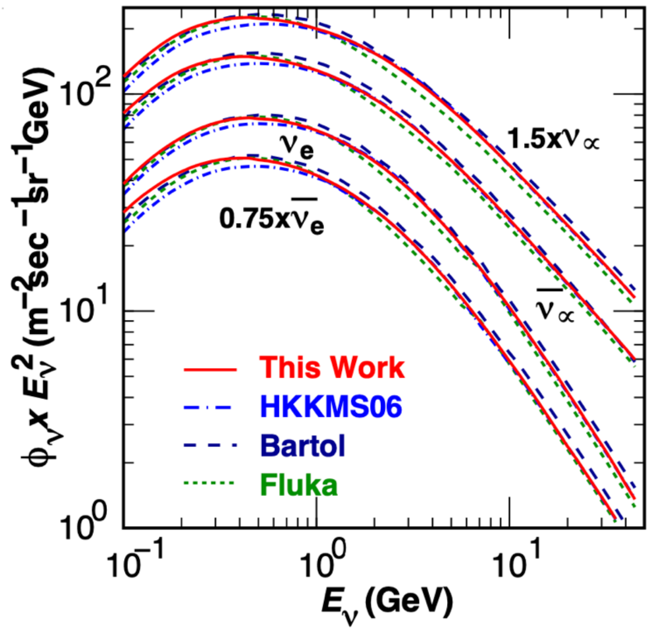

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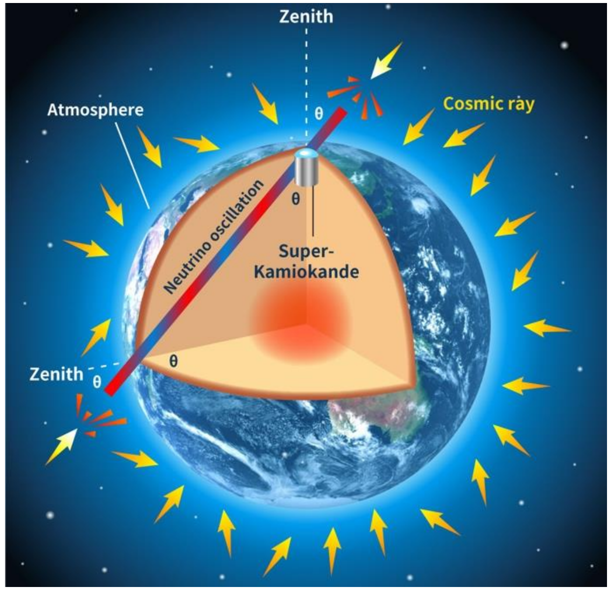

Atmospheric neutrinos as probe of neutrino oscillations:

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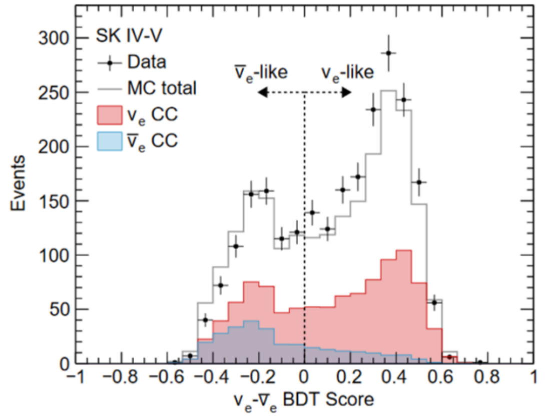
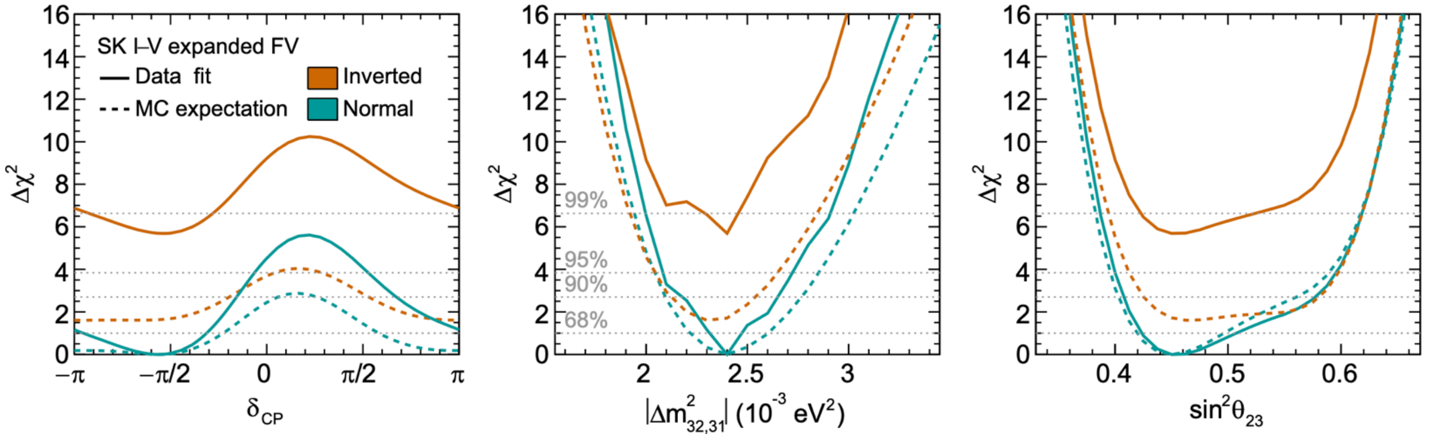
Atmospheric Neutrinos in Super-Kamiokande (1)

<u>Most recent analysis: **Phys. Rev. D 109, 072014 (2024):**</u>



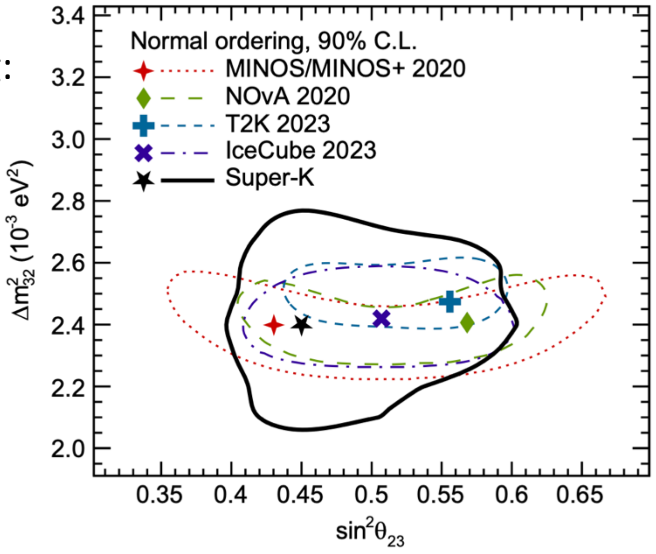
- **6,511 days** of atmospheric neutrino data (SK-I to SK-V, start until July 2020)
- Expanded fiducial volume: cut 100 cm from detector walls (before 200 cm) -> 20% increase in statistics.
- Search for neutron captures to improve $\nu/\bar{\nu}$ separation using Boosted Decision Tree, improved charged current/neutral current separation.

29 analysis samples: Sub-divided by event topology: (FC/PC,UP-μ), energy range, e/μ–like, and number of rings, number of neutron candidates. Multi-GeV e-like samples are divided into ν-like and ν-like samples to improve sensitivity for mass hierarchy.



Best-fit, normal ordering:
$\delta_{CP} \sim -\pi/2$
$\sin^2\theta_{23} \sim 0.45$
$\Delta m^2_{32} \sim 2.4 \times 10^{-3}$ eV^2

Mass ordering:
$\Delta\chi^2$ (NO - IO) ~ -5.7



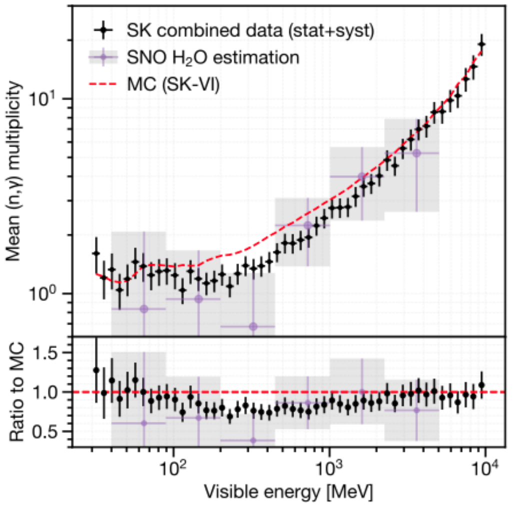
Reject inverted ordering at the 92.3% CL

Atmospheric Neutrinos in Super-Kamiokande (2)

Phys.Rev.D 112 (2025) 1, 012004: Measurement of total neutron production following atmospheric neutrino interactions in SK (including SK-VI).

Compare neutrino **generator/interaction models** to data (from **atmospheric neutrino**).

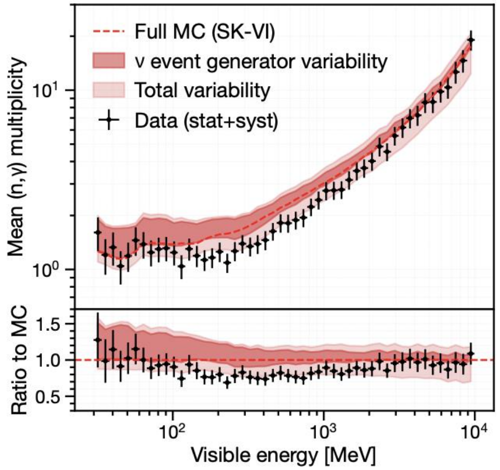
- ➢ Better-tuned neutron modeling → stronger **ν/ν̄ separation** → improved **mass ordering** & **δ_{CP}** sensitivity
- 4,270 days total; includes **564 days at 0.01% Gd.**
- New **neural network-based selection**, validated with **Am/Be** source.
- Compute average neutron-capture multiplicity per event vs visible energy (30 MeV–10 GeV).

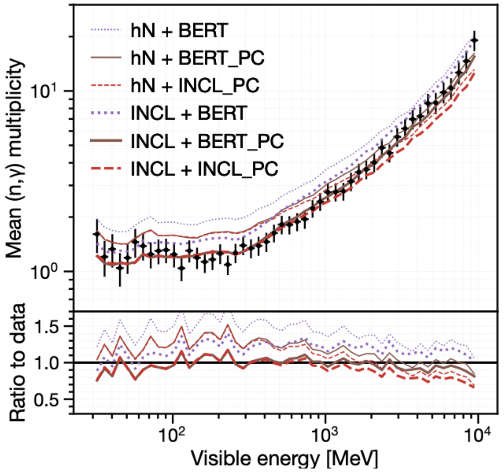


Mean (n,γ) multiplicity vs visible energy

Models used: NEUT 5.4/5.6; GENIE (hA, hN, BERT, INCL) × hadron transport (GCALOR/Geant4 Bertini/INCL)

Model discrimination: Predictions vary by up to ~50%;





Best agreement:

GENIE-INCL + **G4 BERT-PC** are preferred -> baseline for future modelling of neutron production.

Reduces uncertainty in total neutron production from atmospheric neutrinos in approximately 10%.

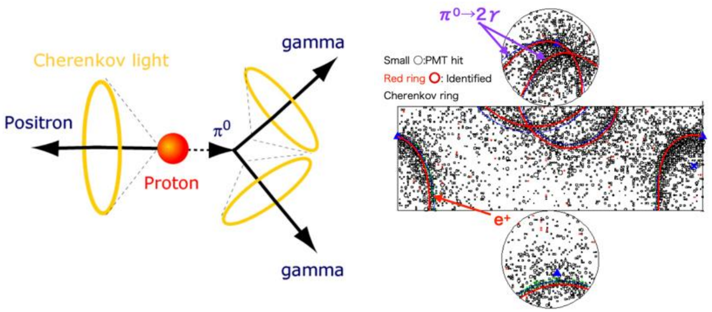
Early SK-Gd validates n-tagging; **full atmospheric-ν fits with Gd are in preparation.**

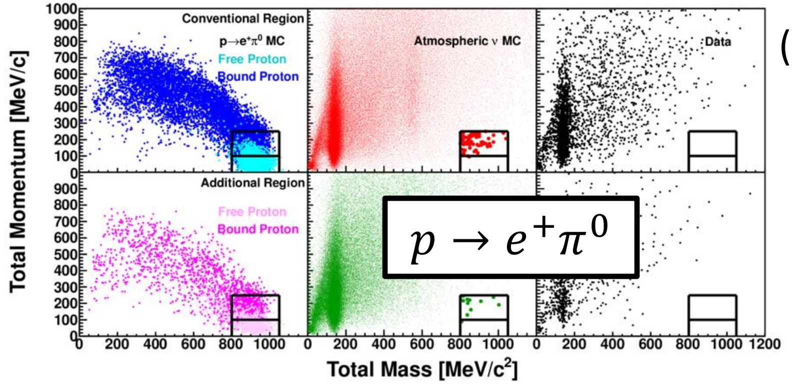
SK + T2K joint fit -> **Results from the T2K Experiment** talk (S. King)

Nucleon Decay Searches (1)

Grand Unified Theories (GUTs): most predict protons to decay into lighter particles (baryon-number-violating proton decay). Nucleon decay is direct probe for GUTs.

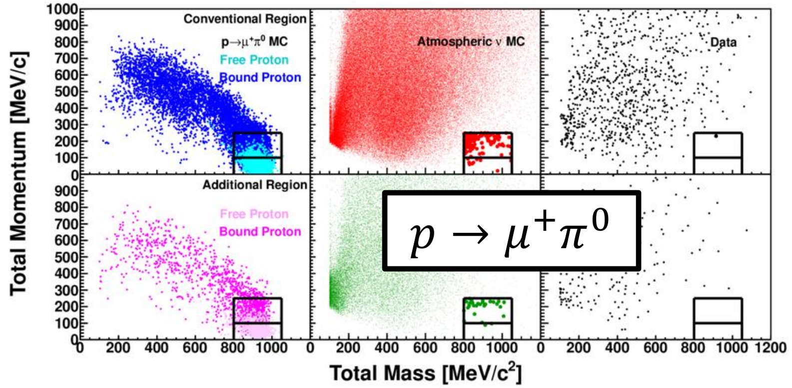
Phys.Rev.D 102 (2020) 11, 112011: Improvement in analysis: enlarge fiducial volume 22.5 kton to 27.2 kton -> exposure 450 kton·years. Reanalyzed past data (SK-I to SK-IV)





Lifetime limit
(90% CL,450 kton·years)

$p \to e^+\pi^0$
2.4 × 10^{34} yr



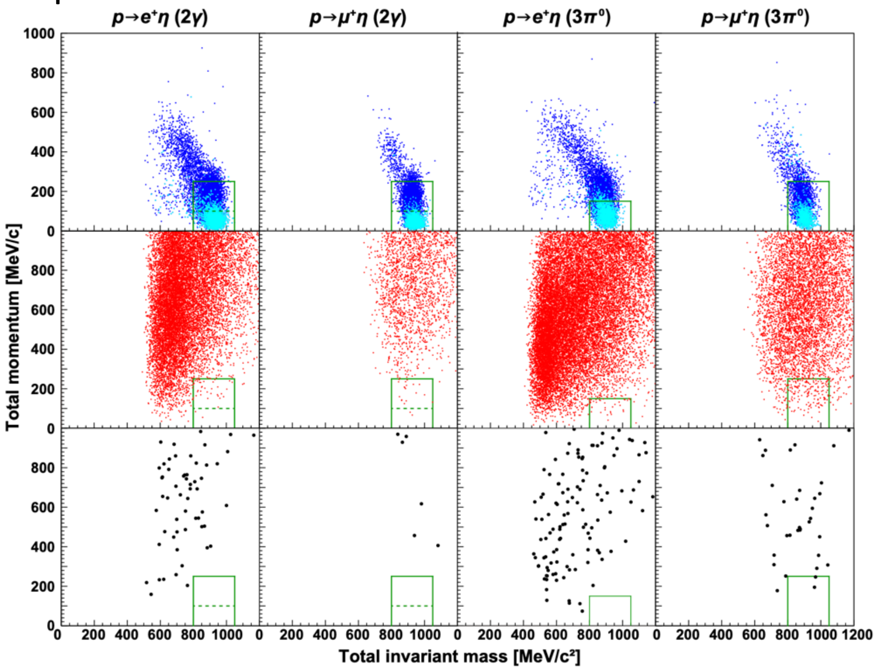
$p \to \mu^+\pi^0$
1.6 × 10^{34} yr

Phys. Rev. D 110 (2024), 112011: Search for proton decay into e⁺=μ⁺ and a η meson, 373 kton·years exposure.

Lifetime limit
(90% CL,450 kton·years)

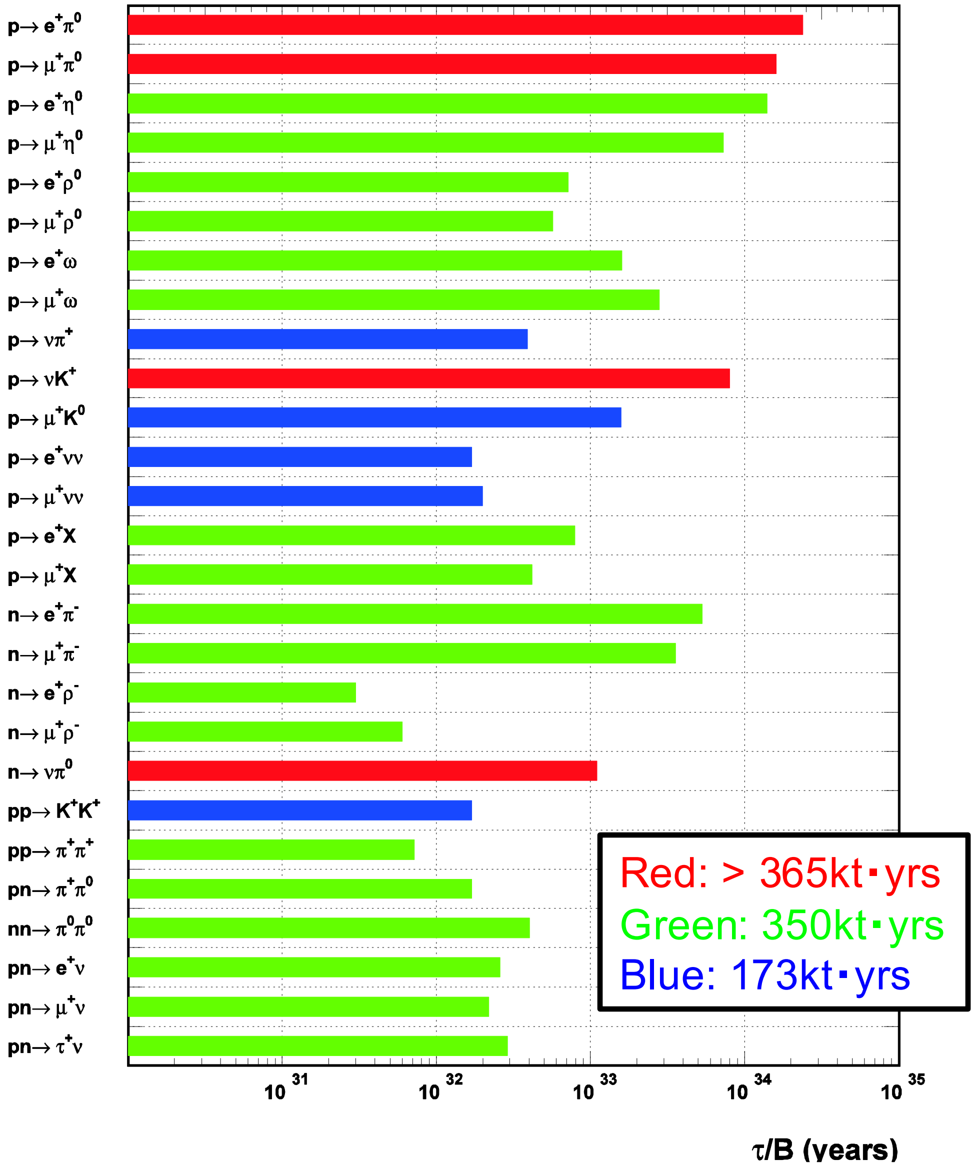
$p \to e^+ \eta$
1.4 × 10^{34} yr

$p \to \mu^+ \eta$
7.3 × 10^{33} yr



No significant event excess above the atmospheric neutrino backgrounds.

Nucleon Decay Searches (2)



Many searches for other decay modes.

Analysis advances:

- Enlarged fiducial volume → more exposure
- Refined analysis techniques (spectrum fit, multivariate techniques, etc).
- Improved atmospheric ν background modeling.

$p \rightarrow \mu^+ K^0$, 370 kton·years, **Phys.Rev.D 106 (2022) 7, 072003.**
Lifetime limit: 3.6×10^{33} year sat 90% C.L.

$n \rightarrow \bar{\nu} K^0$ (new SK result), 401 kton·years, **e-Print: 2506.14406.**
Strongest limits to date: 7.8×10^{32} years at 90% C.L.

Systematic searches yield limits in the 10^{32}–10^{34} year range.

Super-Kamiokande sets the world's strongest constraints on nucleon decay.

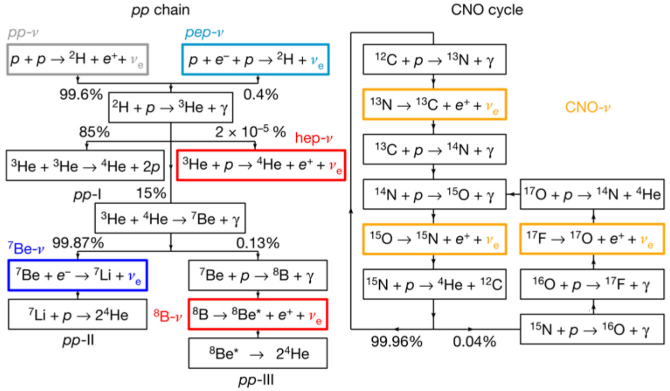
Solar Neutrinos (1)

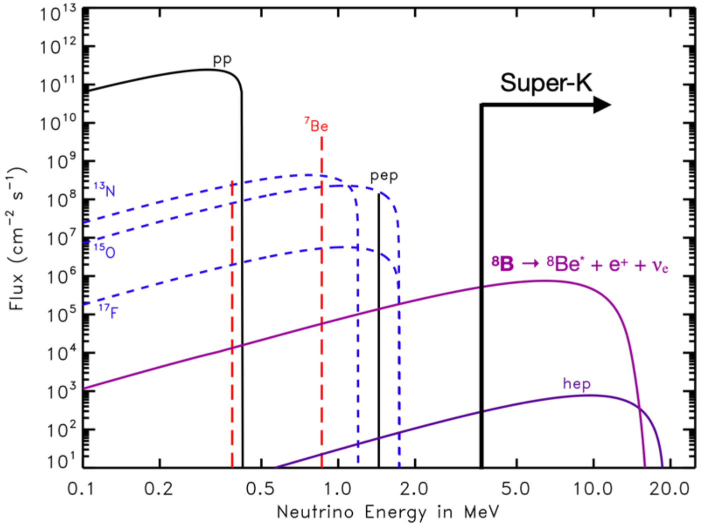
Neutrinos produced in the sun through fusion processes. SK: ^{8}B and hep neutrinos.
Measurements of ^{8}B neutrinos with high statistics recorded by SK with direction and energy information.

Study of neutrino oscillations

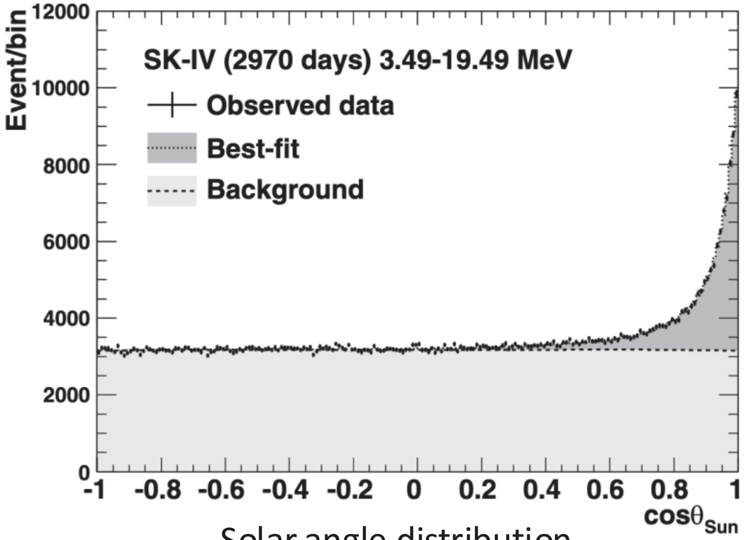
- θ_{12}, Δm^2_{21}
- Day/night asymmetry
- Solar upturn: MSW oscillations between 1-5 MeV

Other topics such as flux modulation and anti-neutrino search.





Phys. Rev. D 109 (2024), 092001: full SK-IV (October 2008 to May 2018) data.



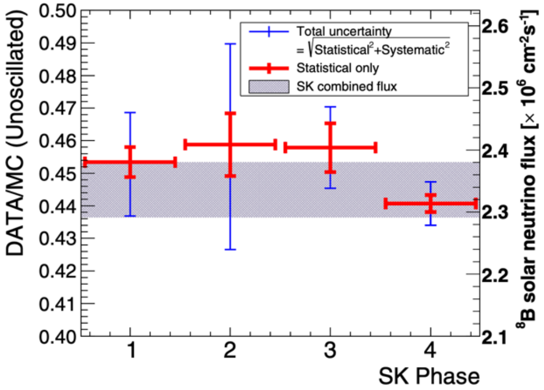
Solar angle distribution

Analysis improvements (lower threshold, reduction in spallation background using neutron clustering events, improved energy reconstruction).

[3.49-19.49] MeV electron kinetic energy region (SK-IV):

$$65443^{+390}_{-388}\,(\text{stat.}) \pm 925(\text{syst.})\text{ events}$$

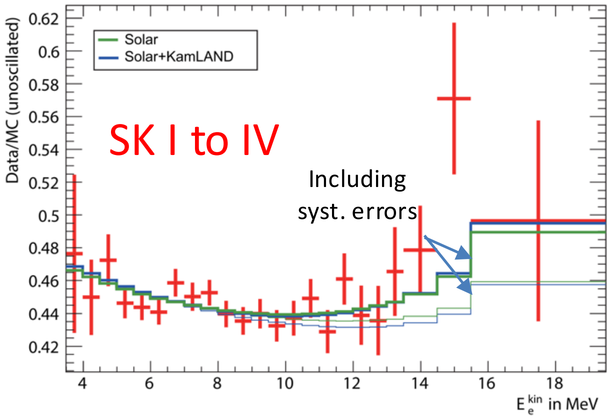
$$\Phi_B = (2.314 \pm 0.014 \pm 0.040) \times 10^{6}\,\text{cm}^{-2}\text{s}^{-1}$$



Comparison of ^{8}B solar neutrino flux among different SK phases.

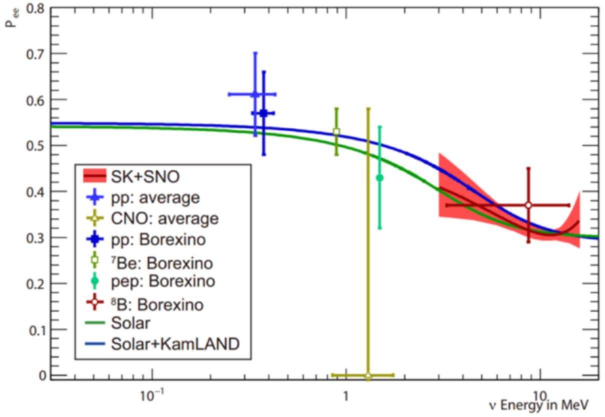
Solar Neutrinos (2)

Recoil electron spectrum



Recoil electron spectra and combination of the MSW predictions.

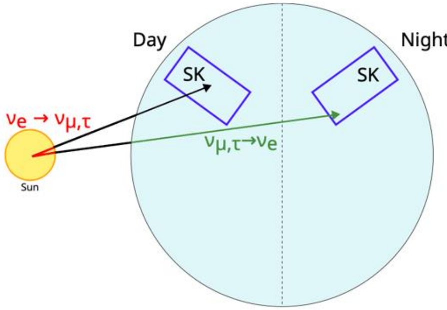
ν_e survival probability

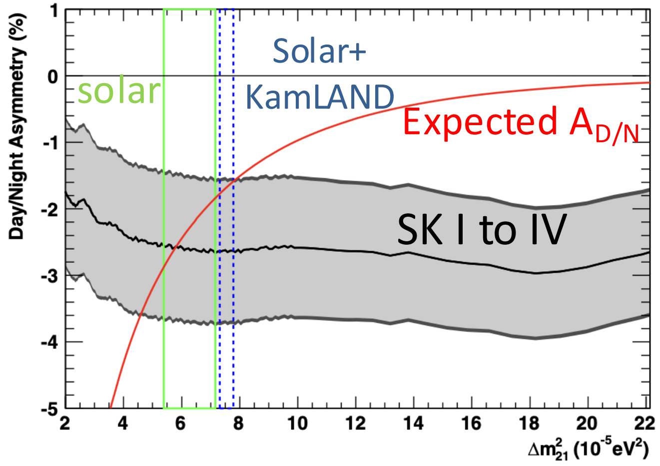


SK+SNO fitted solar ν_e survival probability

Day/night asymmetry:

$$A_{D/N} = \frac{\Phi_{^8B}^{day} - \Phi_{^8B}^{night}}{\frac{1}{2}\left(\Phi_{^8B}^{day} + \Phi_{^8B}^{night}\right)},$$





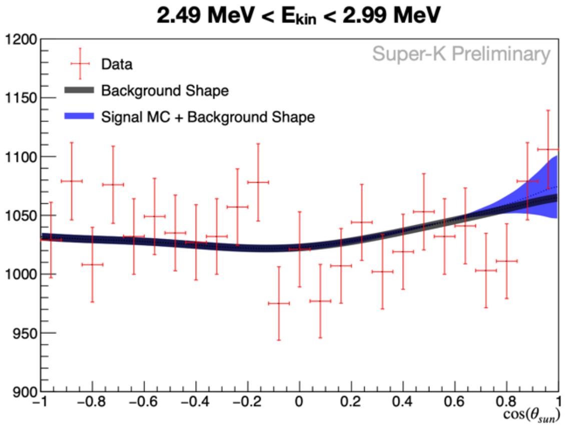
$A_{D/N}$ (all SK, fit) = −0.0286 ± 0.0085 (stat.) ± 0.0032 (syst.)
3.2σ direct evidence of earth matter effects!

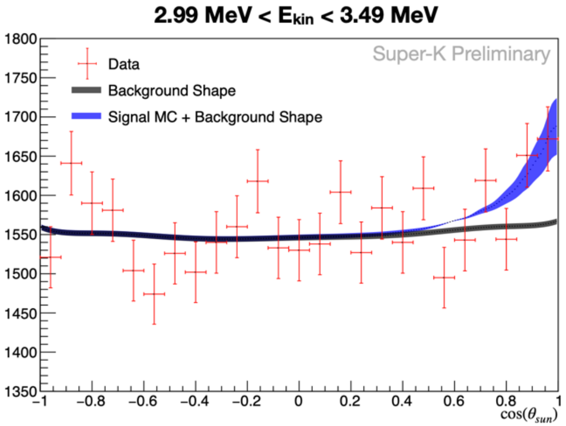
Solar upturn favoured by 2.1σ for SK+SNO.

Checking solar angle distributions < 4 MeV using the Wideband Intelligent Trigger (WIT) data.

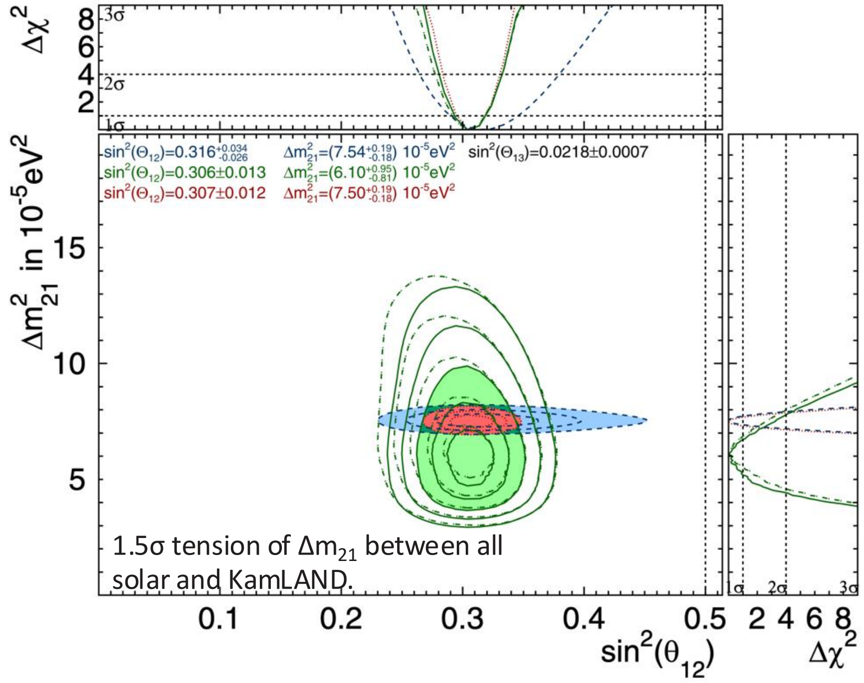
- Signal not observable in E_{kin} < 2.99 MeV.
- Hint of solar peak in 2.99 MeV < E_{kin} < 3.49 MeV. -> 2.66σ.

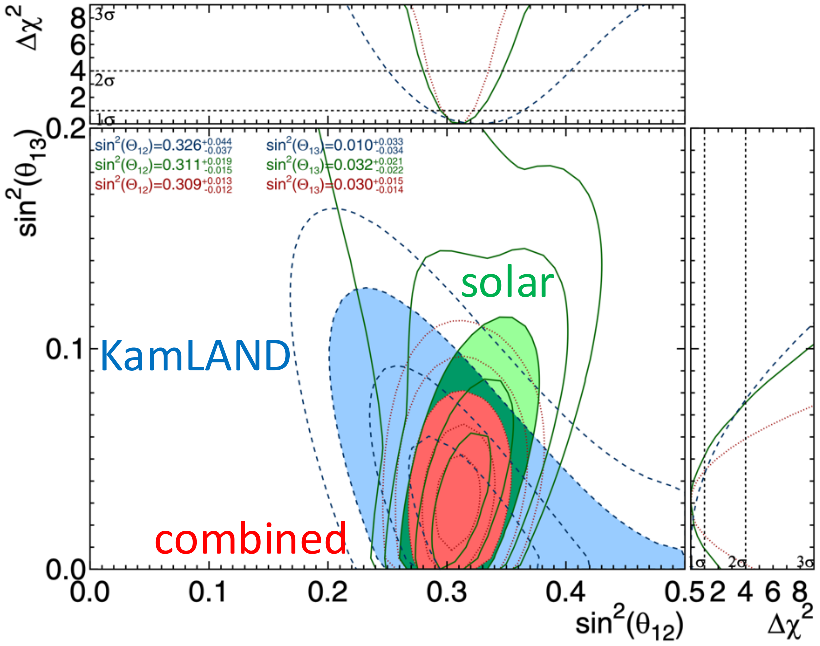
More details in the contributed talk "Enhancing Low-Energy Neutrino Sensitivity in Super-Kamiokande with the Wide-band Intelligent Trigger".





Solar Neutrinos (3)





Solar oscillation parameters, for combined 5805 days of SK data:

$$sin^2\theta_{12} = 0.324^{+0.027}_{-0.023}$$
$$\Delta m^2_{21} = (6.10^{+1.26}_{-0.86}) \times 10^{-5}\ \text{eV}^2$$

All solar experiments:

$$sin^2\theta_{12} = 0.306^{+0.013}_{-0.013}$$
$$\Delta m^2_{21} = (6.10^{+0.95}_{-0.81}) \times 10^{-5}\ \text{eV}^2$$

Solar + KamLAND:

$$sin^2\theta_{12} = 0.307^{+0.012}_{-0.012}$$
$$\Delta m^2_{21} = (7.50^{+0.19}_{-0.18}) \times 10^{-5}\ \text{eV}^2$$

Best-fit from all solar data:

$$sin^2\theta_{13} = 0.032^{+0.021}_{-0.022}$$

Solar + KamLAND:

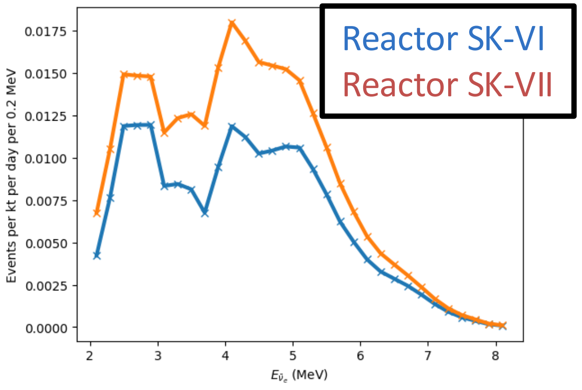
$$sin^2\theta_{13} = 0.030^{+0.015}_{-0.014}$$

Analysis of additional SK data in on-going.

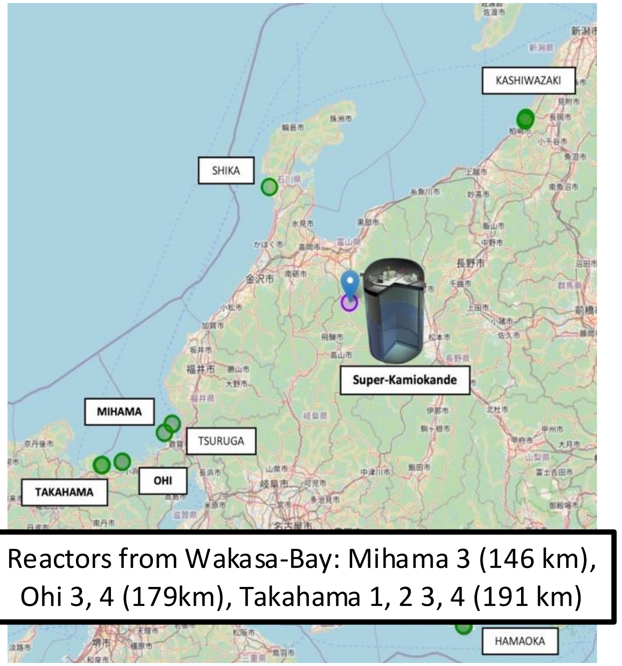
Reactor Neutrinos

The efficient neutron identification provided by gadolinium allows the search for signals from nuclear power reactors (electron anti-neutrinos from fission products).

- Primarily a result of the activity of Japanese nuclear power reactors (small contribution from Korean reactors);
- Constrain neutrino oscillation parameters, complementary to solar sector.
- Expected ~ 5 events/day in SK.



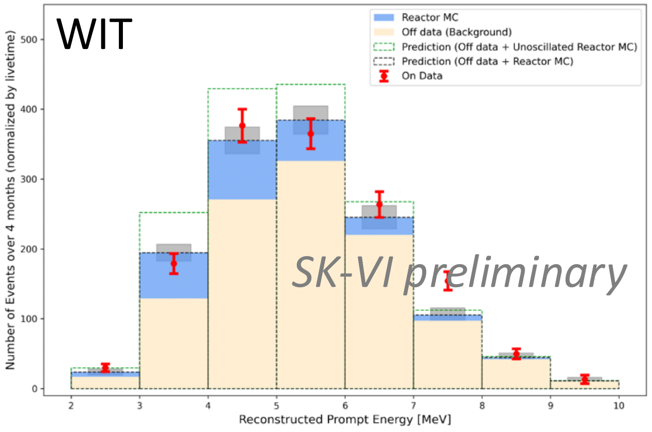
Expected reactor events in SK (model Huber/Muller)



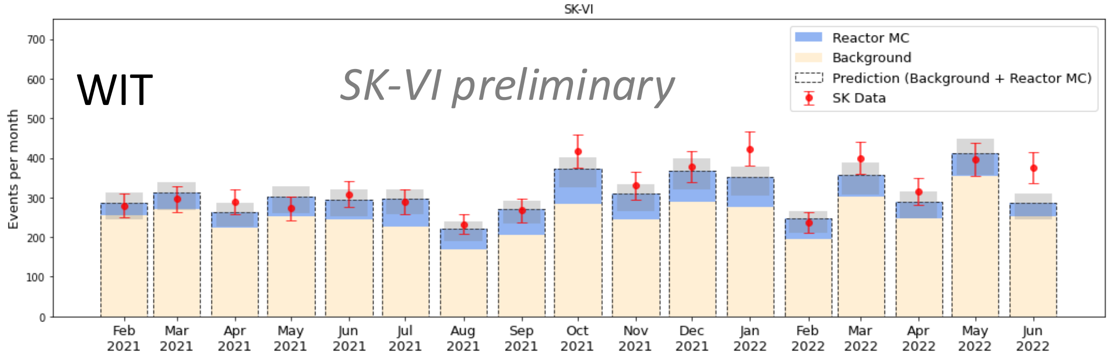
Reactors from Wakasa-Bay: Mihama 3 (146 km), Ohi 3, 4 (179km), Takahama 1, 2 3, 4 (191 km)

Two analyses are currently being carried out using two different low energy triggers (SLE and WIT).

ON/OFF analysis



Energy spectrum



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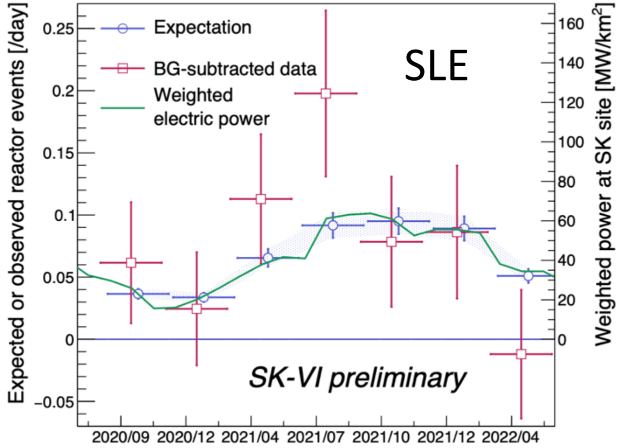
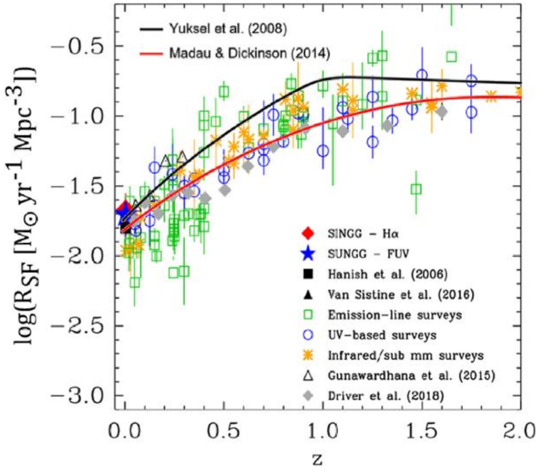


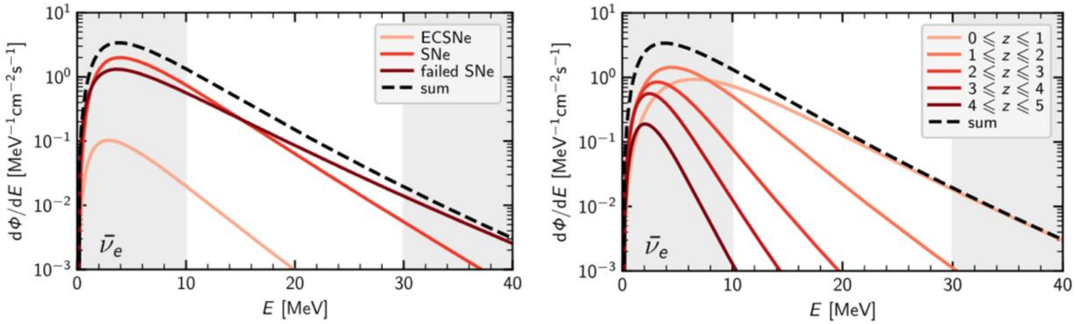
Diffuse Supernova Neutrino Background (1)

The Diffuse Supernova Neutrino Background (DSNB) is a steady redshifted flux of neutrinos from all past core-collapse supernovae in the history of the Universe.

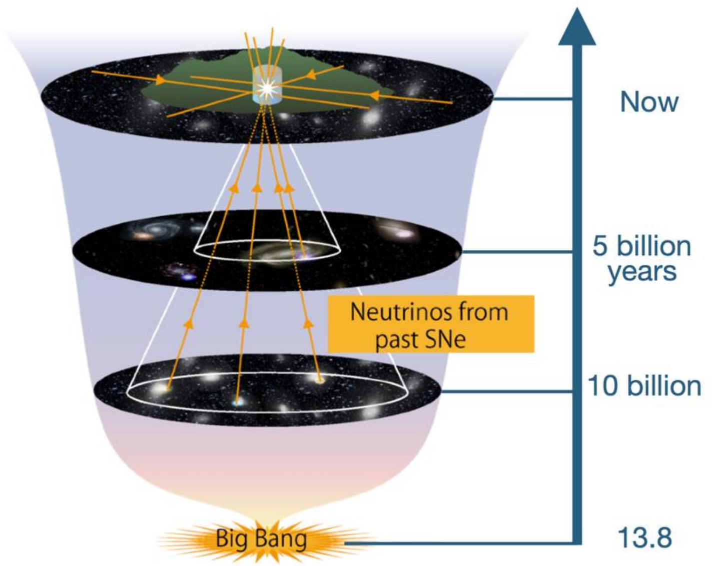
$$\Phi_{DSNB}(E) \propto \int R_{SN}(z) \frac{dF_{\bar{\nu}}(E,z)}{dE} \left|\frac{dt}{dz}\right| dz$$



Redshift-dependent star formation rate



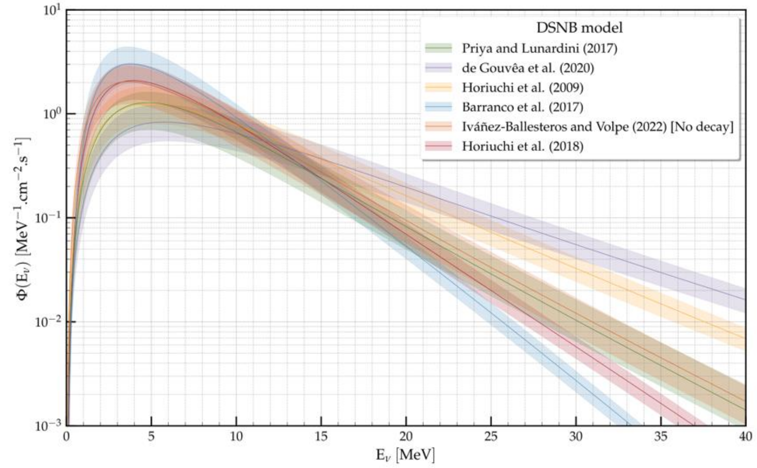
Supernova neutrino emission spectrum



Detecting it would provide unique insight into stellar evolution and the cosmic supernova rate, but the signal is extremely faint.

Super-K has the world's leading sensitivity. Detection through IBD, main backgrounds:

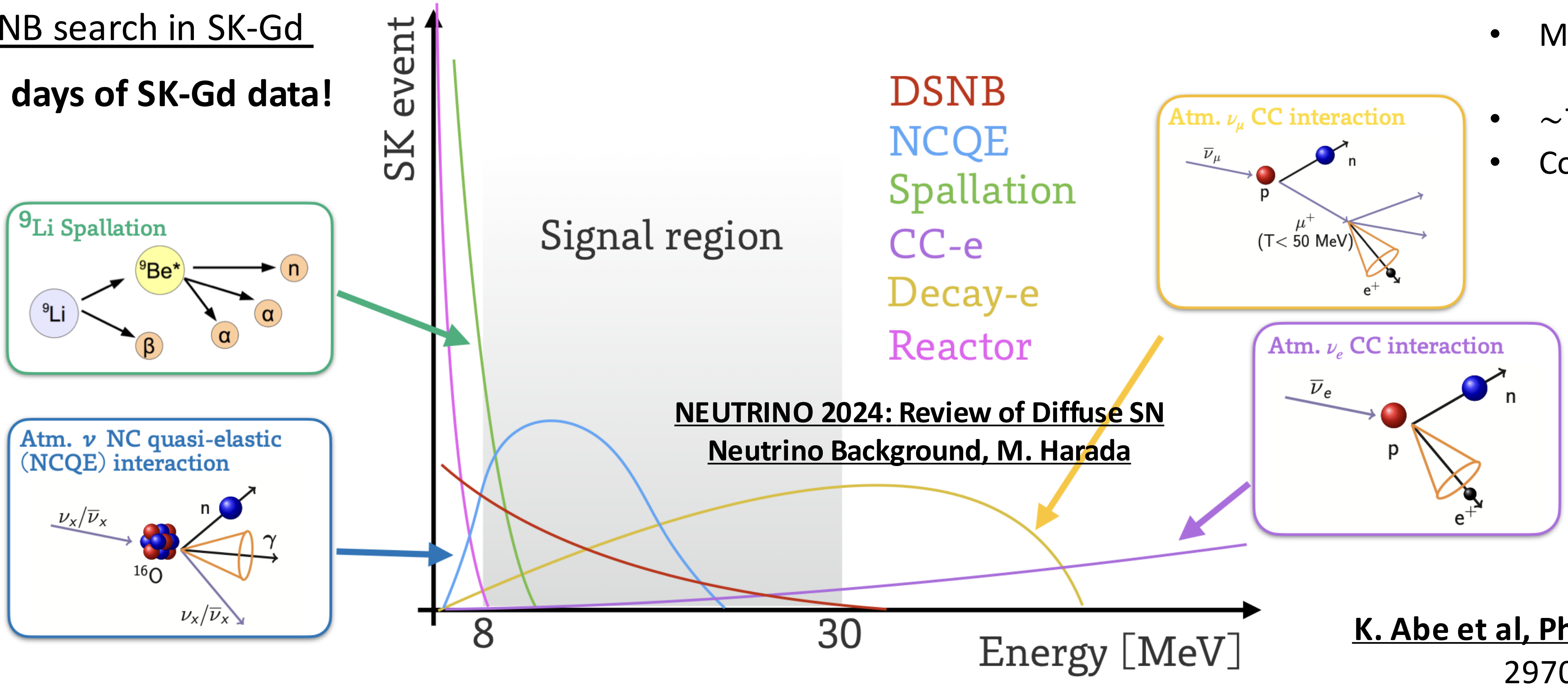
- Reactor neutrinos
- Spallation-induced (mainly ^{9}Li)
- Atmospheric neutrinos (both CC, NC)



Diffuse Supernova Neutrino Background (2)

DSNB search in SK-Gd

956 days of SK-Gd data!



- Main channel IBD:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- ~7.5–30 MeV signal window
- Constraints to > 30 MeV side-band

K. Abe et al, Phys. Rev. D 104, 122002 (2021):
2970.1 days of SK-IV data
+
M. Harada et al, Phys. Rev. Lett. 951, L27 (2023):
552 days (SK-VI, 0.01% Gd)
+
Recent studies:
404 days (SK-VII, 0.03% Gd)

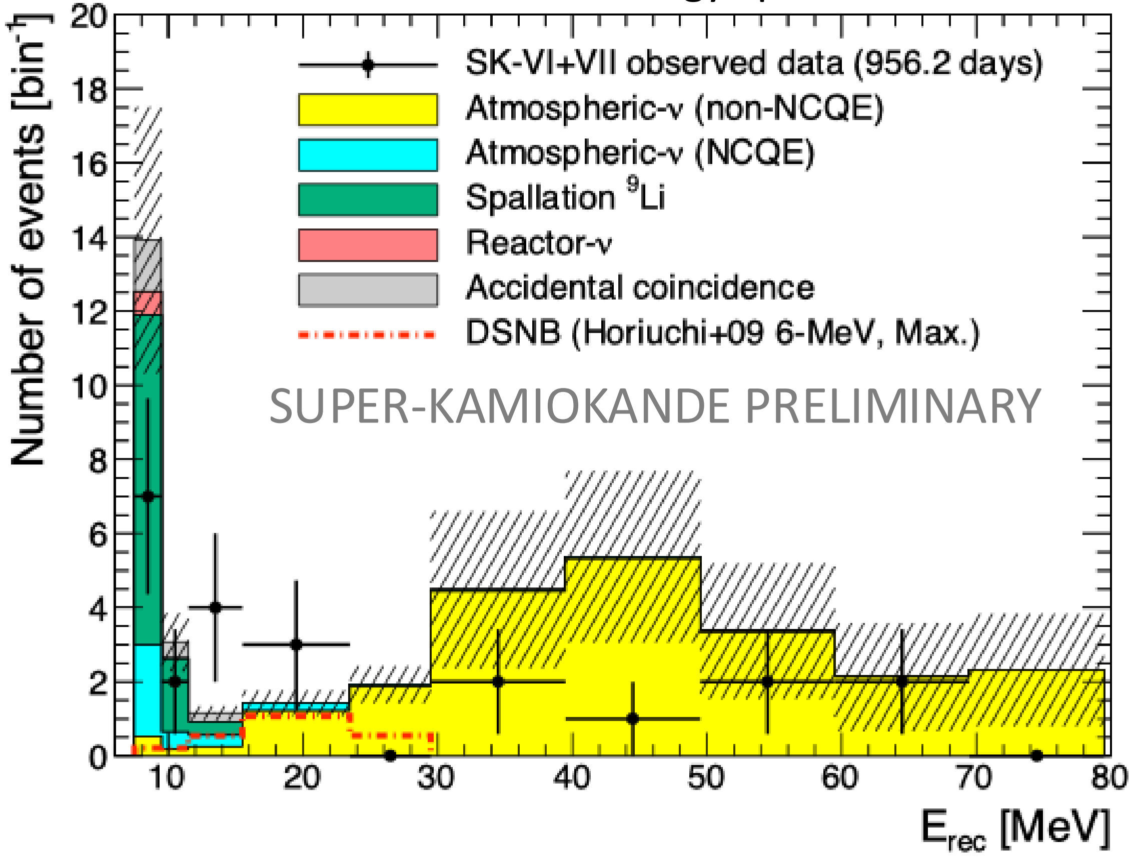
Many analysis improvements:

- New reduction for atmospheric NCQE interactions event using gamma-ray cut variable (further 90% reduction)
- Dedicated machine learning techniques implemented for neutron tagging.

Performed both energy-binned analysis and unbinned energy spectrum fitting.

Diffuse Supernova Neutrino Background (3)

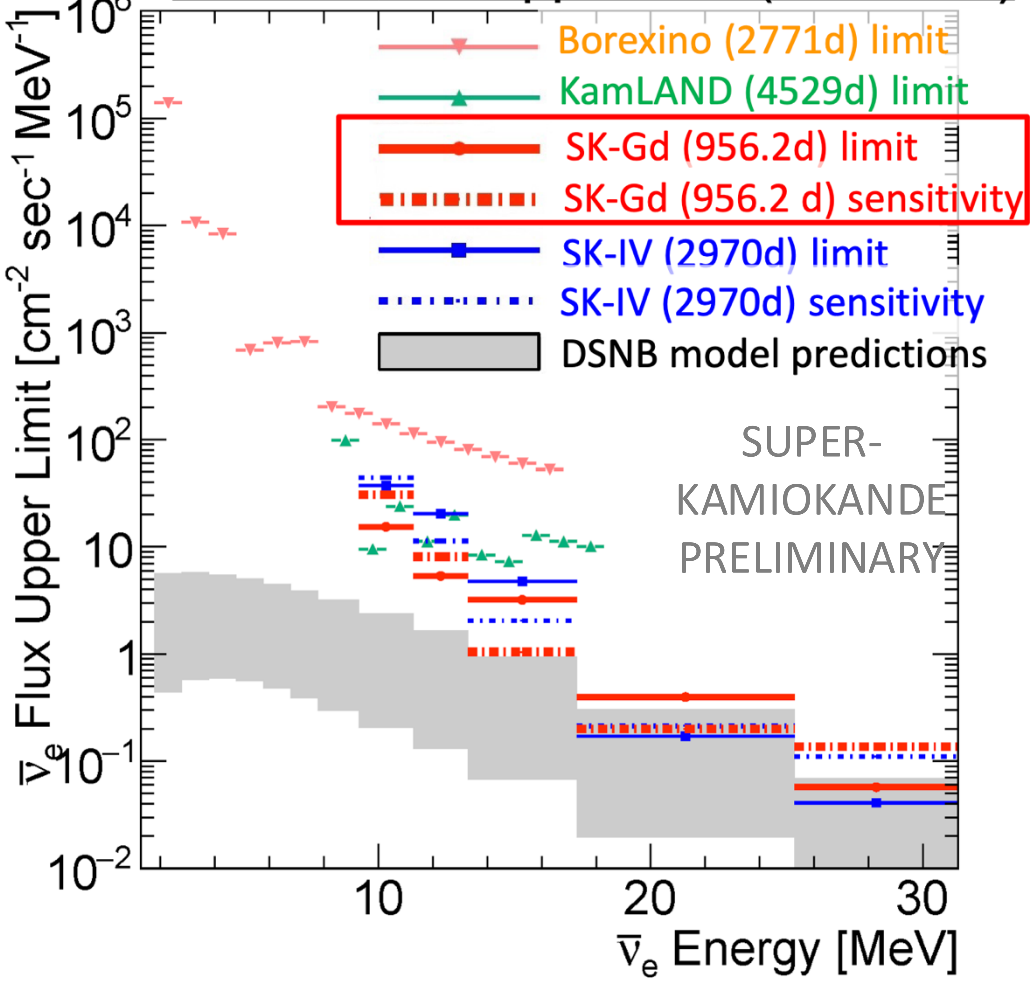
SK-VI + SK-VII energy spectrum



No significant excess observed (min. p-value=0.04).
Sensitivity reaches model prediction region for $E_\nu > 14$ MeV.

SK starting to probe into the predicted DSNB signal region!

Neutrino flux upper limit (90% C.L.)



Competitive SK-Gd with < 1000 days exposure with 3000 days of pure-water period.

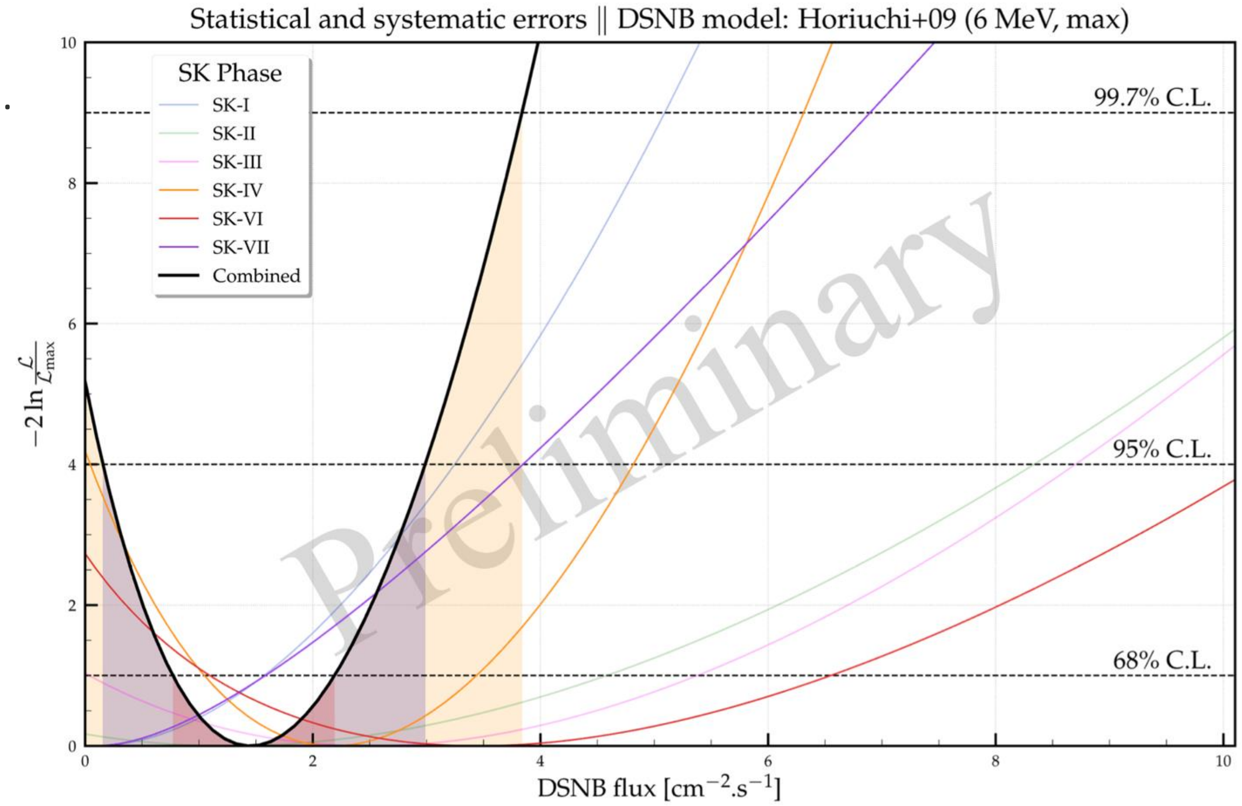
Diffuse Supernova Neutrino Background (4)

<u>Spectrum fitting analysis to extract detection significance:</u>

- Total of 6779 days of SK (5823 days pure-water + 956 days with Gd).
- Analysis threshold: E_ν> 17.3 MeV (to avoid spallation background).
- Define main/side-band regions based on Cherenkov angle
- Suppress uncertainty of background prediction by fitting IBD-like and non IBD-like events.
- Profile likelihood ratio.

Best-fit rate:
2.9 events · year^{-1}

Best-fit flux:
1.4 cm^{-2} s^{-1}



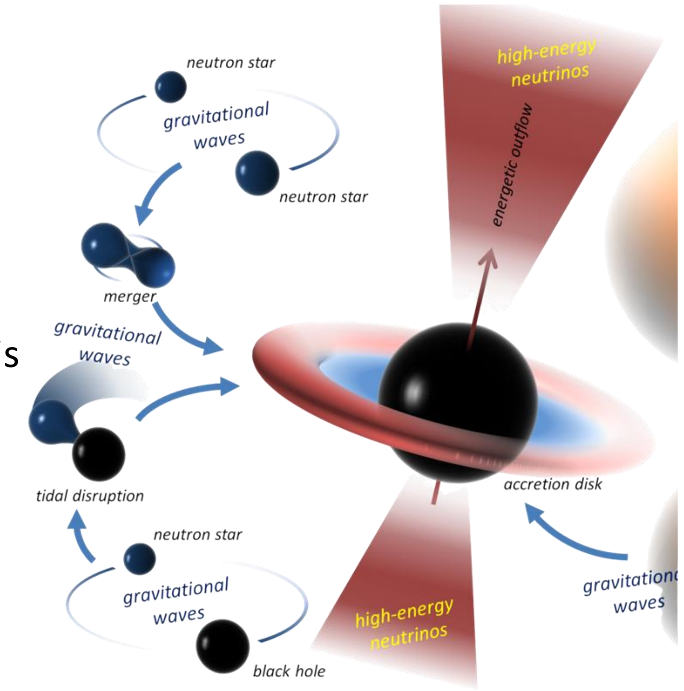
Spectral fitting for a DSNB theoretical model (Horiuchi+09), showing all individual SK phases considered and their combination

2.3σ rejection of a background-only hypothesis (very preliminary).

Gravitational Wave Coincidence Searches

Compact binary mergers are prime candidates for neutrino–gravitational wave coincidence searches:

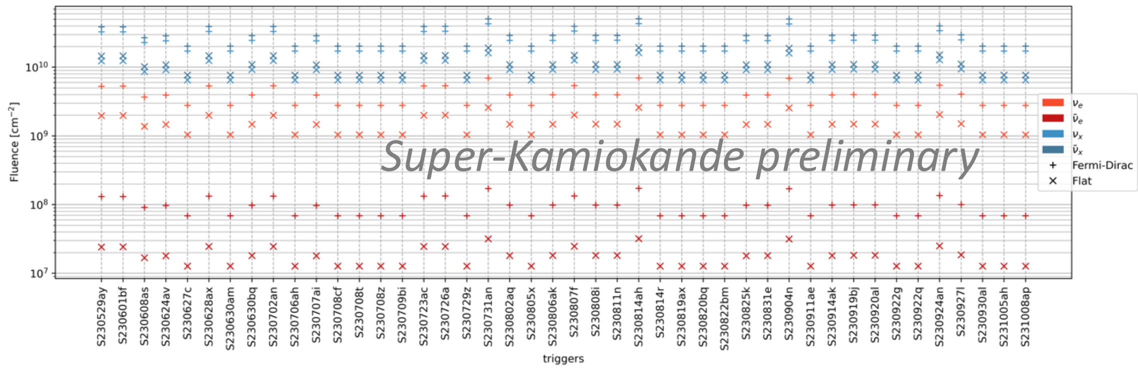
- **Neutron Star–Black Hole (NSBH) mergers:**
  may produce both high-energy and thermal neutrinos, depending on remnant and ejecta.
- **Binary Neutron Star (BNS) mergers:**
  emit low-energy neutrinos (MeV) within milliseconds of the GW signal.
- **Black Hole–Black Hole (BBH) mergers:**
  no neutrino emission expected, but some models allow for high-energy neutrino production if matter is present (e.g. accretion disk).

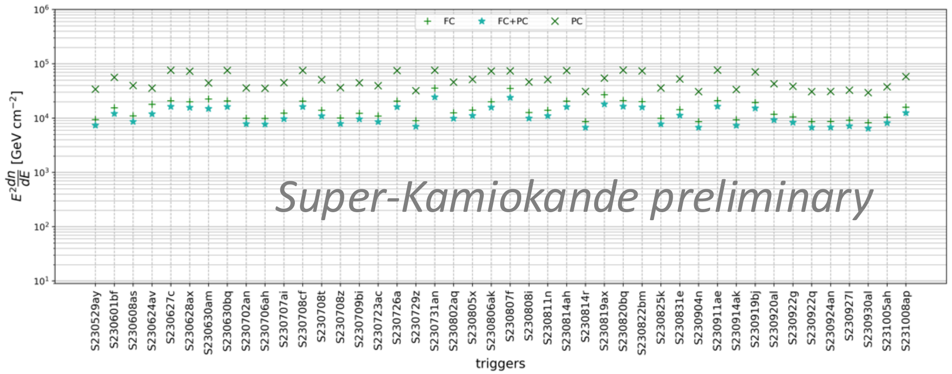


Models expect that BNS and NSBH mergers emit thermal MeV neutrinos within < 1 s of merger, with peak luminosity > 10^{53} erg/s, in the 5 to 30 MeV range.

Searches in SK for coincidences with the first period of GW-O4 run (O4a) from May to October 2023.
No significant excess is observed.

Upper limits (90% confidence level) were obtained for both low and high energy samples:





Flux limits:
~10^3–10^4 GeV cm^{-2}

Summary

Super-Kamiokande is a neutrino observatory running since 1996, with a broad physics program in **neutrino astrophysics**, **neutrino oscillations** and **rare searches**. In 2020, the experiment started the **SK-Gd** phase, in which gadolinium was added to the water in the detector to increase its sensitivity to electron antineutrinos.

Atmospheric neutrinos:
- Combined SK-I to V data with expanded fiducial volume (27.2 kton) and improved selections
- Preference for normal mass ordering, rejecting inverted ordering at the 92.3% CL;
- Analysis in agreement with T2K on mass ordering & δ_{CP} (previous talk).
- Neutron production modeling validated with early SK-Gd data.

Search for Nucleon Decay:
- Systematically searches for many different decay modes to probe Grand Unified Theories;
- Imposing very strict lifetime limits.

Solar Neutrinos:
- Full SK-IV (October 2008 to May 2018) data analyzed;
- Solar upturn favoured by 2.1σ for SK+SNO;
- 3.2σ direct evidence of earth matter effects.

Reactor Neutrinos:
- First searches of reactor neutrino signal in SK, using two low energy triggers;
- Expected event rates consistent with data
- On/off reactor analysis shows excellent agreement.

Diffuse Supernova Neutrino Background:
- There is no significant DSNB signal, but SK starting to probe into the predicted DSNB signal region.
- 2.3σ tension from non-DSNB hypothesis

Coincidence with gravitational waves:
- GW-O4as search of neutrino counterparts. No significant excess observed.
- Flux limits set $\sim 10^3 - 10^4$ GeV cm^{-2}.