Super-Kamiokande at 30

Recent Results and the Era of Gadolinium

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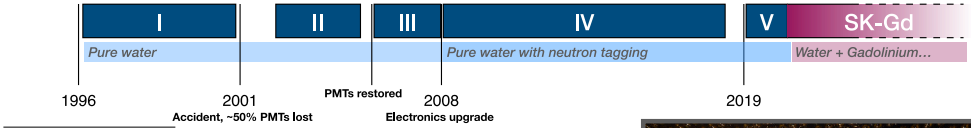
on behalf of the Super-Kamiokande Collaboration

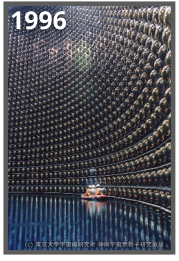
Tsinghua University

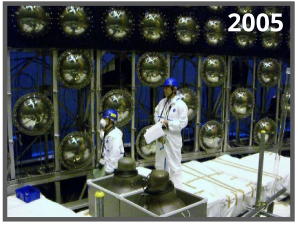
Moriond EW 2026

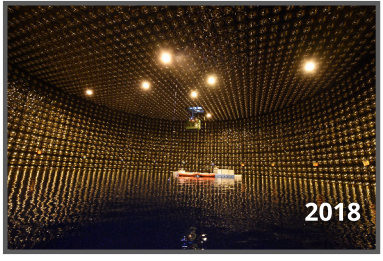
30 years of continuous operation & breakthroughs

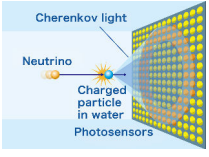
atmospheric anomalies, solar neutrino problem $\rightarrow$ precision oscillation, astrophysics









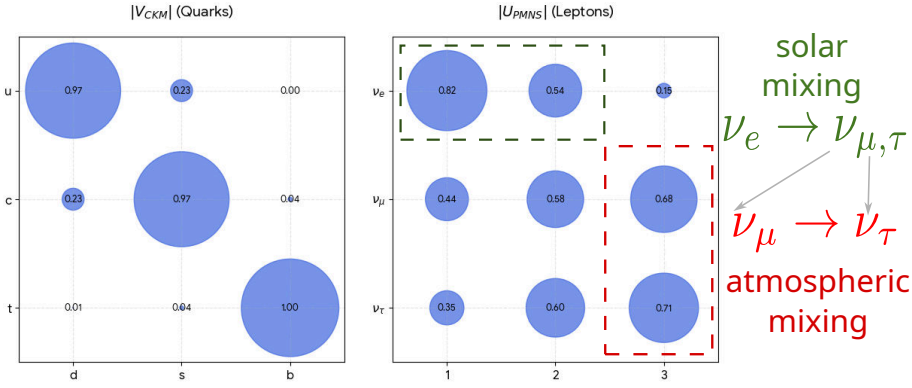


- At colliders (LHCb/Belle II), RICH is a thin PID layer.
- In Super-Kamiokande, the $50\,\mathrm{kt}$ water is simultaneously the Target, Calorimeter and 4π PID tracker.

Lepton Mixing with PMNS Matrix

Together we cross fire on the Flavor Puzzle

Mass Hierarchy and Mixing Patterns Problem

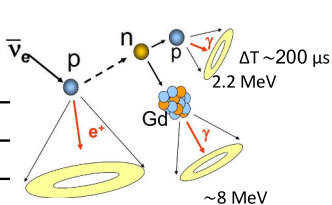


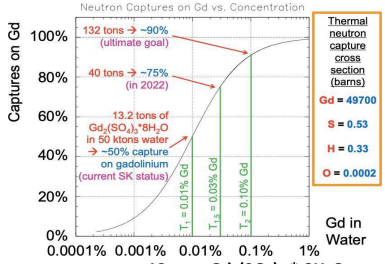
- Colliders aim for the CKM; we constrain (and first experimentally validated) the PMNS.

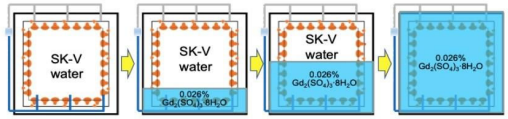
The SK-Gd Era: Neutron Tagging Phase

- Enormous cross-section for thermal neutron capture ($\sim 49,700$ barns).

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







Beacom, Vagins PRL.93, (2004) 171101

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

NIM **A 1027 (2022) 166248**

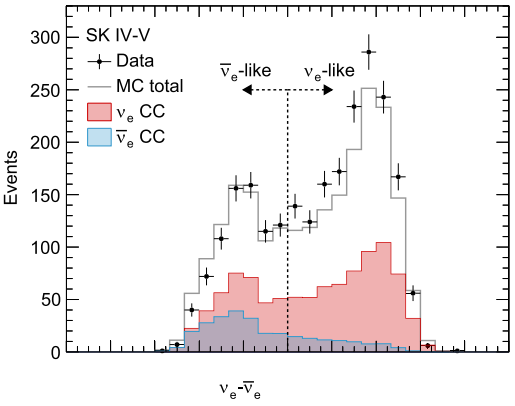
SK-VII/ SK-VIII: June/July 2022 → **40 tons $Gd_2(SO_4)_3$ * $8H_2O$**, **0.03% Gd**

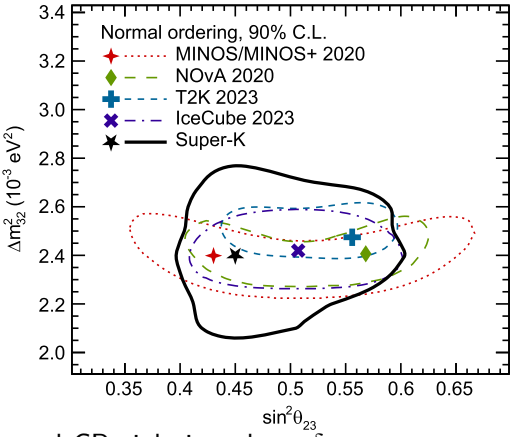
NIM **A 1065 (2024) 169480**

- Breaks the degeneracy between ν and $\bar{\nu}$ $\rightarrow$ precision PNMS elements.
- Drastically reduces backgrounds for inverse β decay
  $\rightarrow$ probing into Diffused Supernova Neutrino Background.

Atmospheric Neutrinos with Neutron Tagging

- Utilizing neutron multiplicity to separate neutrino and antineutrino interactions (ν_e vs $\bar{\nu}_e$, ν_μ vs $\bar{\nu}_\mu$). nGd utilization under integration.



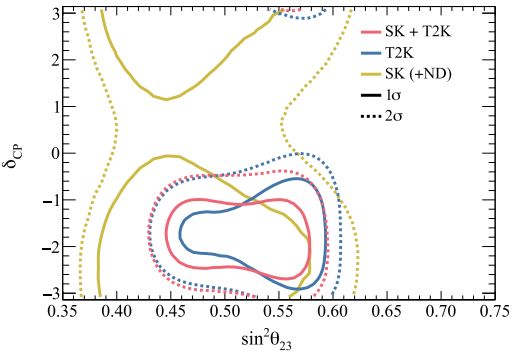


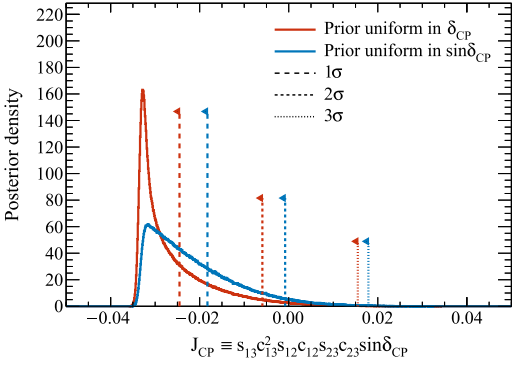
- Enhanced sensitivity to mass hierarchy and CP violation phase δ_{CP}.

Phys. Rev. D 109, 072014 (2024)

Joint Analysis: T2K + SK Atmospheric

- Breaking degeneracies by combining accelerator and atmospheric data.

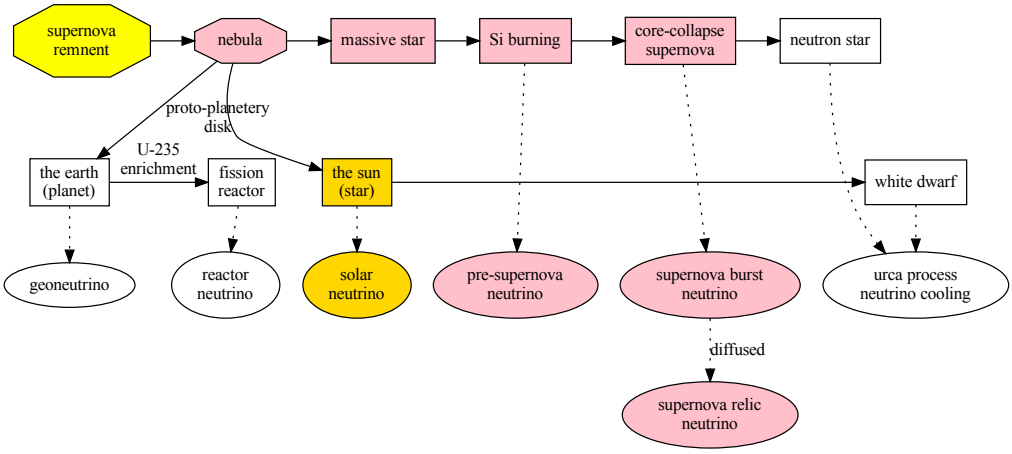




- World-leading precision on Δm^2_{32} and $\sin^2\theta_{23}$.
- $1.9\,\sigma$ exclusion of lepton CP-conservation.

Phys. Rev. Lett. 134, 011801 (2025). See also Artur Sztuc's NOvA-T2K talk.

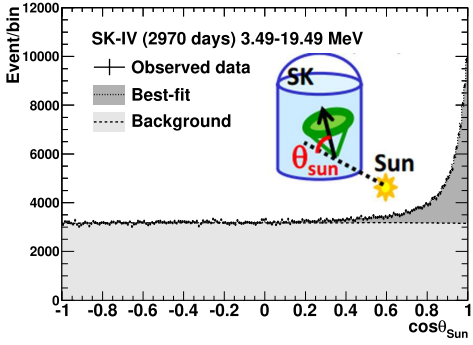
ν Telescope for Stellar Evolution

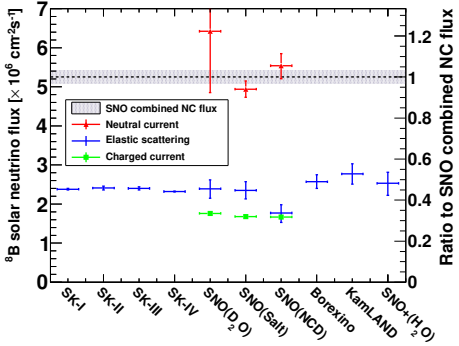


SK is sensitive to ν from all the phases of stellar evolution ... if they are close!

Active Star Solar ν from Main Sequence

- Measurement of ^{8}B solar neutrinos over the full SK-IV (2008–2018) period.
- High-precision constraint on the solar mixing parameters ($\Delta m^2_{21}, \sin^2\theta_{12}$).





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

$$\Phi_{\text{B}} = (2.314 \pm 0.014 \pm 0.040) \times 10^6 \text{cm/s}$$

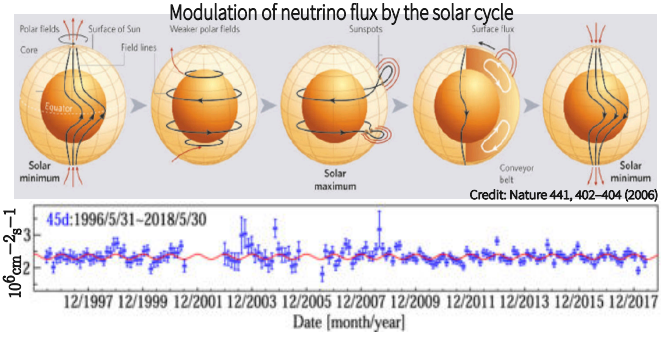
Phys. Rev. D 109, 092001 (2024)

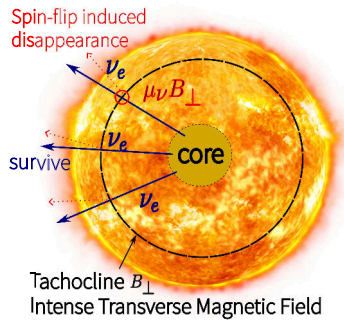
- Best ^{8}B-ν flux precision

$$^8\text{B} \rightarrow {}^8\text{Be} + e^+ + \nu_e$$

Active Star Resonant Spin-Flavor Precession

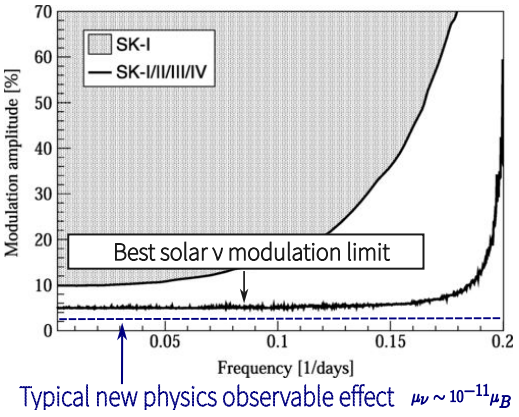
- νMSM predicts $\mu_\nu \sim 10^{-19}\mu_B$.
- If an existing experiment discover $\mu_\nu \gg 10^{-19}\mu_B \rightarrow$ new physics.
- Resonant Spin-Flavor Precession (RSFP) in dynamic solar magnetic fields is a sensitive probe at SK.

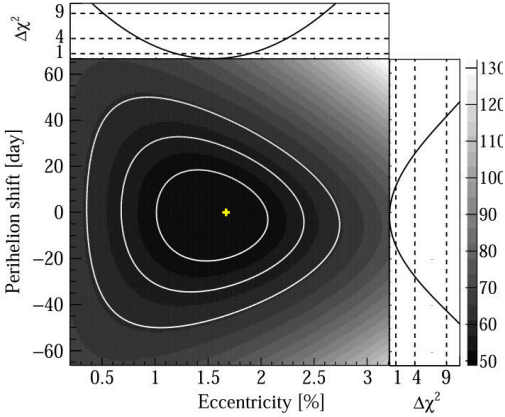




Active Star Astrophysical Dynamics in Modulation Limits

- Lomb-Scargle periodogram analysis of 22 years of SK data (1996-2018).





- Directly targets the $10^{-11}\mu_B$ parameter space dynamically.

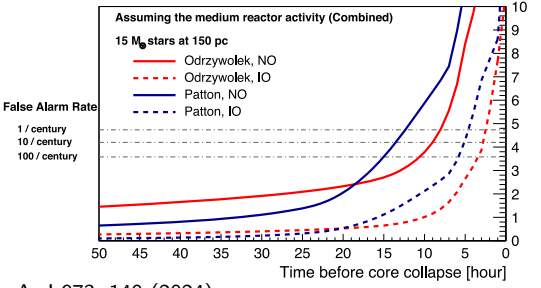
Phys. Rev. Lett. 132, 241803 (2024)

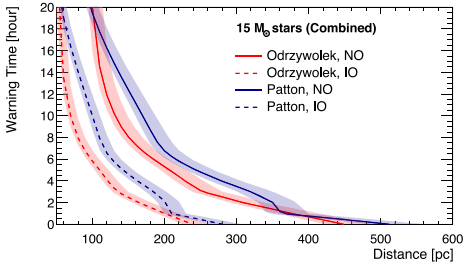
Dying Star Multi-Messenger Watchtower of Pre-SN Alert

- End of Life Silicon Burning: hours/days before core collapse.
- SK-Gd is now an active early warning system for thermal pair-annihilation $\bar{\nu}$.

$$\gamma\gamma \to e^+e^- \to \nu\bar{\nu} \text{ via } \bar{\nu}_e + p \to e^+ + n$$

- *Signal*: prompt e^+ and delayed neutron capture on Gd.

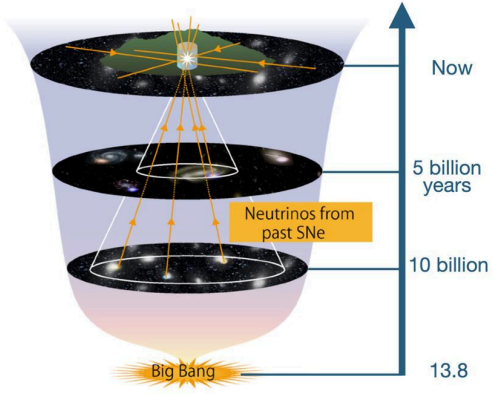


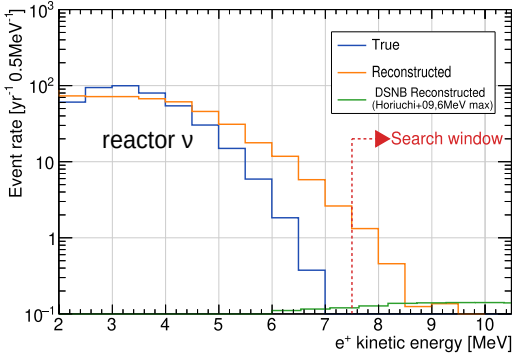


ApJ 973, 140 (2024)

Stellar Graveyard Diffuse Supernova Neutrino Background

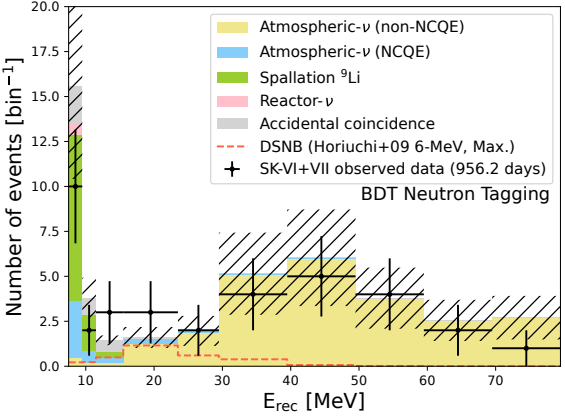
- Relic neutrinos from all core-collapse supernovae in the universe.
  - A holy grail of neutrino astrophysics.
- SK-Gd is uniquely positioned to discover this flux.

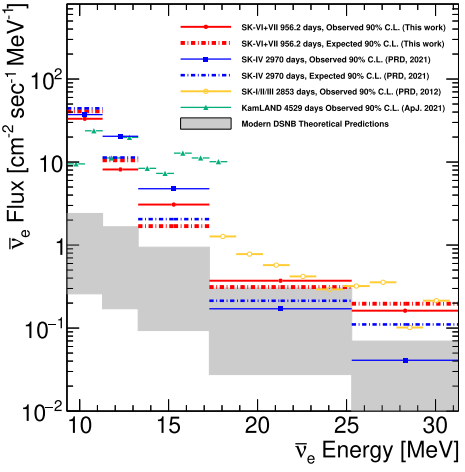




Stellar Graveyard Latest Limits from SK-Gd

- Analyzed 956.2 days of SK-Gd dataset.
- *Result:* pushing the boundaries into the theoretical prediction models.

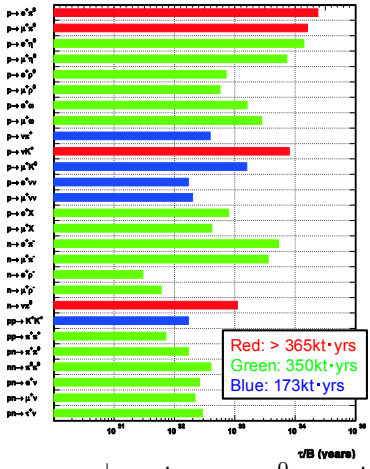


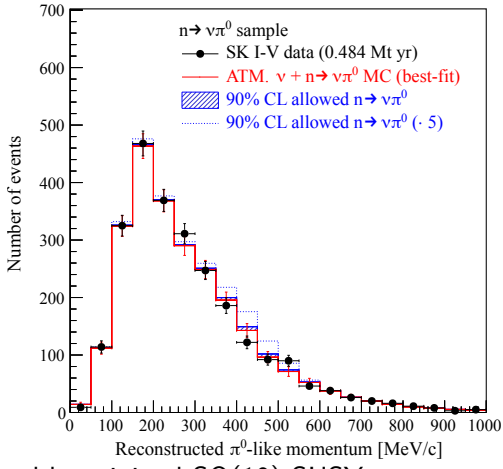


arXiv:2511.02222

Nucleon Decay: the GUT Benchmark

- Continuous search and most stringent (pushing beyond 10^{34} yr.) constraints.





- $p \to \nu\pi^+$ and $n \to \nu\pi^0$ search motivated by minimal SO(10) SUSY.
  - $> 3.5 \times 10^{32}$ yr. and $> 1.4 \times 10^{33}$ yr. at 90% CL with 484kt.yr exposure.

Phys. Rev. D 113, 012015 (2026)

Summary & The Road to Hyper-K

Neutron Tagging (SK-Gd) Revolutionized our physics reach.

The Stellar Pipeline Unprecedented sensitivity spanning from active Solar dynamics, to Pre-SN early warnings, to the DSNB relic graveyard.

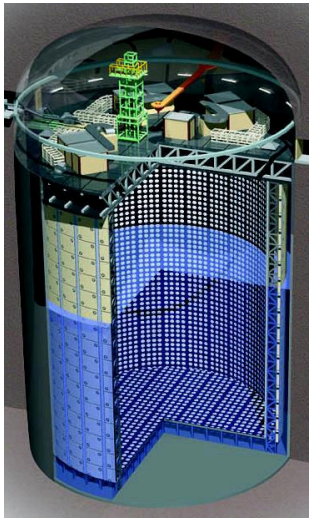
Precision PMNS T2K+SK joint analysis leading the charge on δ_{CP}.

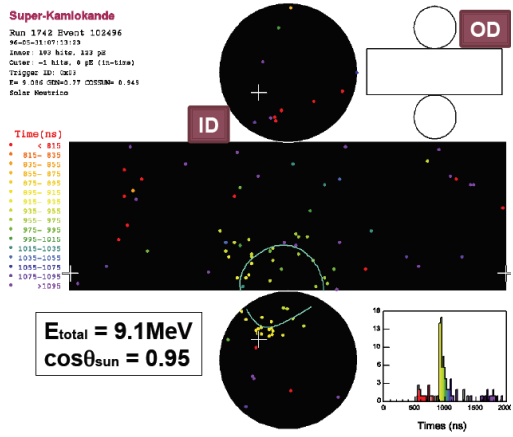
Beyond Standard Model Pushing bounds on Solar RSFP and Nucleon Decay.

The Near Future

Hyper-Kamiokande is under construction. The legacy continues. See also HK talks by Ben Carew and Ryotaro Shinoda.

Detector and event display





Detection Principle