Recent Results from Super-K Ed Kearns – Boston University CIPANP 2025 Madison WI



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## Super-Kamiokande Experimental Phases



SK-Gd (gadolinium enhanced neutron capture)			$\boldsymbol{\varepsilon}_{capture}$
2019	SK-V	still pure water	25%
2020	SK-VI	0.011% Gd	50%
2022	SK-VII	0.033% Gd	75%
2024	SK-VIII	0.033% Gd after recovery of magnetic coil issue	75%

#### **Challenges:**

- Purify water without removing Gd
- Maintain high light transparency
- Maintain low radioactivity
- No degradation or corrosion of materials
- Prevent any Gd-water from leaking
- into the environment

#### **Neutron Capture in SK-IV and SK-Gd SK-VI MC:** $\bar{\nu}_{\mu}$ CCQE, $E_{\nu} = 0.63$ GeV SK-IV Electronics and DAQ upgrade: "record every hit" architecture allows us to detect neutron capture



### **Neutron Capture Performance**



visible energy higher for capture on Gd

## Science Goals as we complete Super-K

- Continue to extract information from solar neutrinos
- Be ready for supernova neutrinos and find diffuse ones
- Study 3-flavor oscillation of atmospheric neutrinos
- Search for nucleon decay
- Astrophysical searches of all kinds

increasing neutrino energy



+

Be the far detector for **T2K** 

# Solar Neutrinos







# Supernova

## Galactic Supernova at 10 kpc







Angular resolution ~ 2x improved by SK-Gd

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



	Livermore	Nakazato
$\overline{\nu}_{e}p \not\rightarrow e^{\scriptscriptstyle +}n$	7300	3100
$v+e^{-} \rightarrow v+e^{-}$	320	170
<sup>16</sup> O CC	110	57

## Diffuse Relic Supernova Neutrinos



#### DSNB rate depends on:

- supernova rate
- star formation
- black hole formation
- supernova neutrino production
- cosmic expansion
  Wide range of predictions:











#### Recent improvements to "ATMPD" analyses



Enlarge fiducial volume (adds 4.7 kton)

![](_page_13_Figure_3.jpeg)

future: count and detect neutrons to estimate hadronic energy and direction

#### Matter Effects

![](_page_14_Figure_1.jpeg)

![](_page_15_Figure_0.jpeg)

# $v_e/\bar{v}_e$ separation by boosted decision tree

![](_page_16_Figure_1.jpeg)

17

![](_page_17_Figure_0.jpeg)

Super-K atmospheric oscillation\* result with reactor constraint

- Favors lower octant (upper octant in 2018 paper)
- Favors normal ordering  $\Delta \chi^2_{NO-IO} = -5.7$
- Preference for normal ordering using CLS = 0.077 (reject inverted ordering at 92.3%)

#### Particle physics Fundamental physics is frustrating physicists

The Economist

No GUTs, no glory

Jan 13th 2018

![](_page_18_Picture_4.jpeg)

https://www.economist.com/news/science-and-technology/21734379-no-guts-no-glory-fundamental-physics-frustrating-physicists

![](_page_19_Figure_0.jpeg)

![](_page_19_Figure_1.jpeg)

background reduction in <sup>16</sup>O region improved by roughly x2 using n-capture

 $au/B(e^+\pi^0) > 2.4 \times 10^{34}$  years  $au/B(\mu^+\pi^0) > 1.6 \times 10^{34}$  years

preliminary, 450 kt y expanded fiducial volume neutron capture

![](_page_20_Figure_0.jpeg)

![](_page_20_Figure_1.jpeg)

Unfortunately – no nucleon decay signal, all limits, so far.

![](_page_21_Figure_0.jpeg)

something new... (most of our astrophysical searches have emphasized muon neutrinos, especially upward-going)

#### Search for Astrophysical Electron Neutrinos in Multi-GeV Sample

motivated by IceCube evidence for cascade events from galactic plane

![](_page_22_Figure_3.jpeg)

61% efficiency70% pure CC electron neutrino

0

![](_page_23_Figure_0.jpeg)

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Conclusion

- Continue to extract information from solar neutrinos important constraints on  $\theta_{12}$ , 1.5 $\sigma$  tension with KamLand in  $\Delta m^2$ , try to find upturn
- Be ready for supernova neutrinos and find diffuse ones we are ready for galactic supernova burst ~ 99% live use SK-Gd to discover DSNB
- Study 3-flavor oscillation of atmospheric neutrinos neutrino ordering, octant, CP violation more data and improvements for Neutrino 2026
- Search for nucleon decay By 2029, 9 years SK-Gd of data yet to be analyzed (50% increase)
- Astrophysical searches of all kinds look back in past data, valuable to check new or bursting sources

![](_page_24_Picture_6.jpeg)