

Results, Status, and Prospects of SK-Gd

Andrew Santos ***(for the Super-K collaboration)***

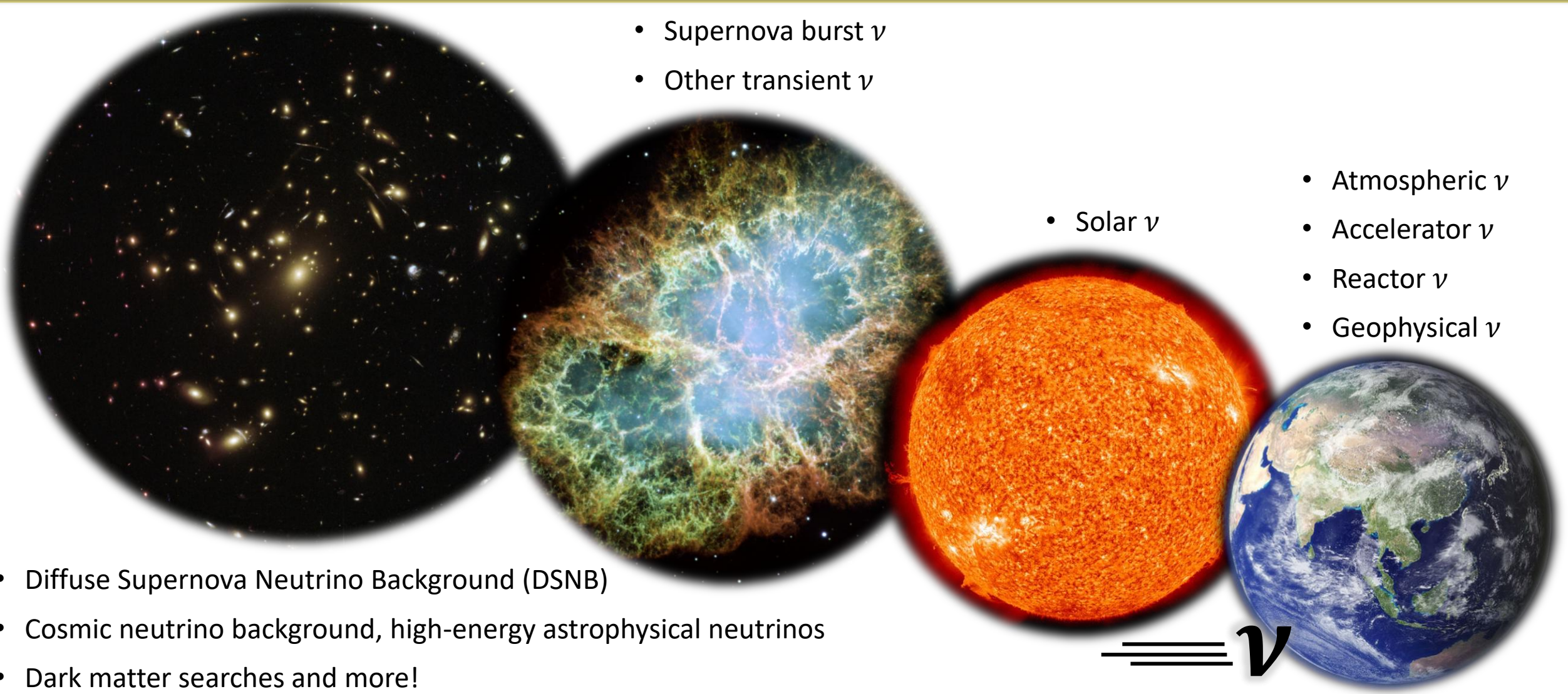
The University of Tokyo

Kavli IPMU

29 October 2026

NNN 2026 Seoul

A journey through the universe with neutrinos



- Supernova burst ν
- Other transient ν
- Solar ν
- Atmospheric ν
- Accelerator ν
- Reactor ν
- Geophysical ν

- Diffuse Supernova Neutrino Background (DSNB)
- Cosmic neutrino background, high-energy astrophysical neutrinos
- Dark matter searches and more!

Super-Kamiokande: Our international collaboration (1996-Now)

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
BC Institute of Technology, Canada
Boston University, USA
BMCC/CUNY, USA
University of California, Irvine, USA
California State University, USA
University of Chinese Academy of Sciences, China
Chonnam National University, Korea
Duke University, USA
Gifu University, Japan
GIST, Korea
University of Glasgow, UK
University of Hawaii, USA
Hiroshima University, Japan
IBS, Korea
IFIRSE, Vietnam
Imperial College London, UK
ILANCE, France/Japan
INFN Bari, Italyl
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Institute of Science Tokyo, Japan
Kavli IPMU, The Univ. of Tokyo, Japan
Keio University, Japan
KEK, Japan
King's College London, UK
Kobe University, Japan
Kyoto University, Japan
Kyungpook National University, Korea
University of Liverpool, UK
LLR, Ecole polytechnique, France
University of Minnesota, USA
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
NIT, Nihama college, Japan
NIT, Numazu college, Japan
Okayama University, Japan
Osaka Electro-Communication Univ.,Japan
University of Oxford, UK
Rutherford Appleton Laboratory, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
University of Silesia in Katowice, Poland
Sungkyunkwan University, Korea
Tohoku University, Japan
The University of Tokyo, Japan
Tokyo University of Science, Japan
University of Toyama, Japan
TRIUMF, Canada
Tsinghua University, China
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan



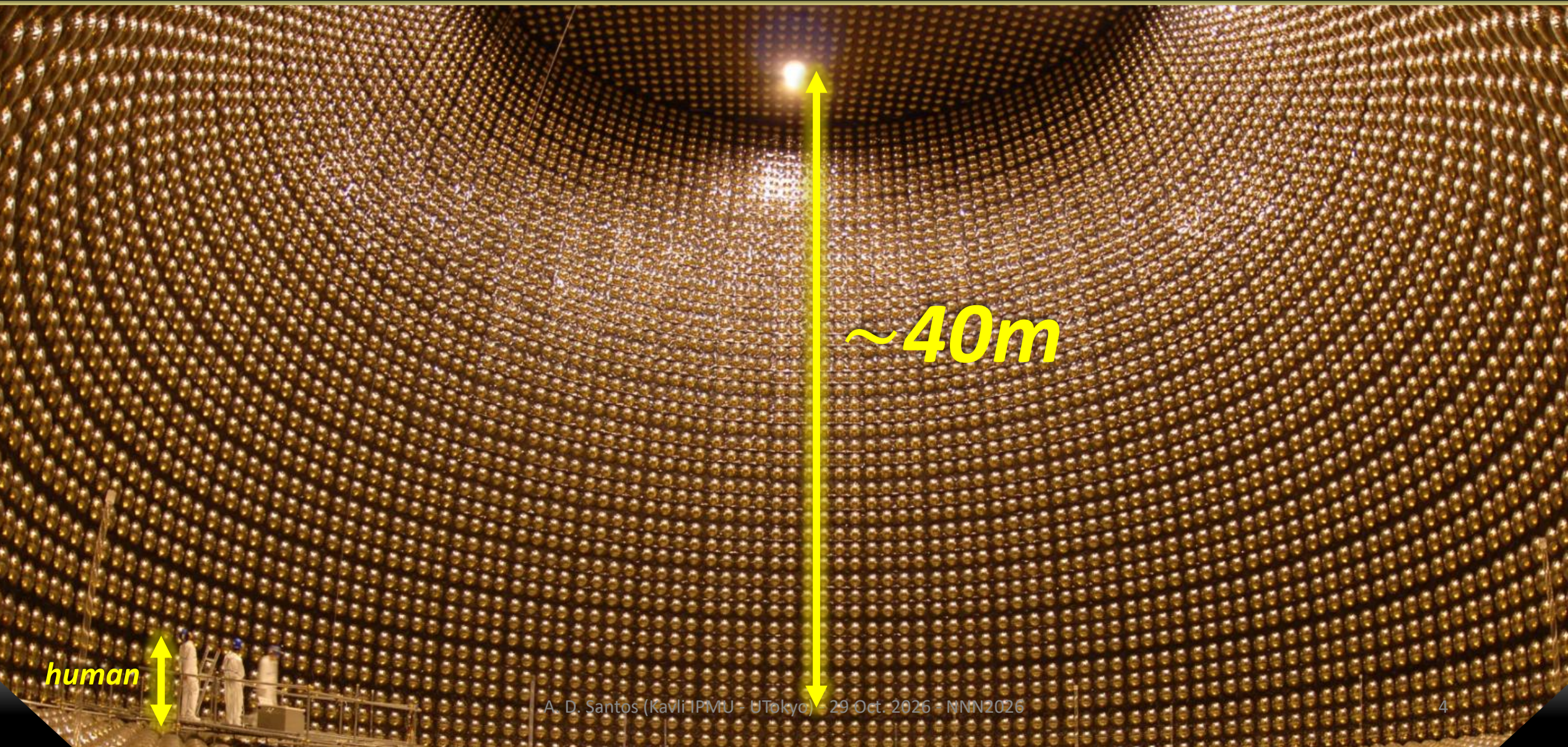




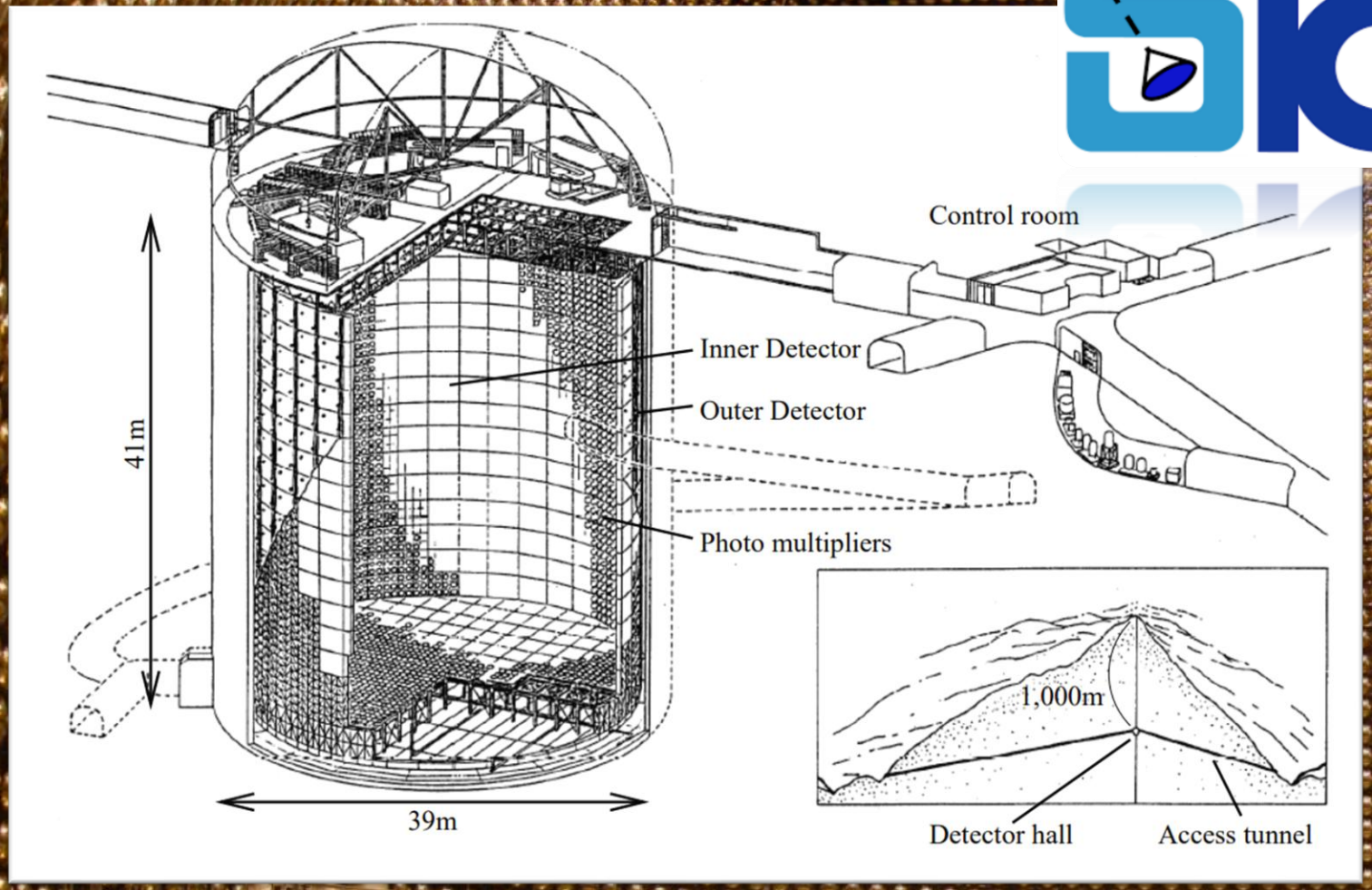
(Super-K collaboration in Toyama in 2026!)

30th Anniversary Year!!!

Super-Kamiokande: Our detector



Super-Kamiokande: Our detector



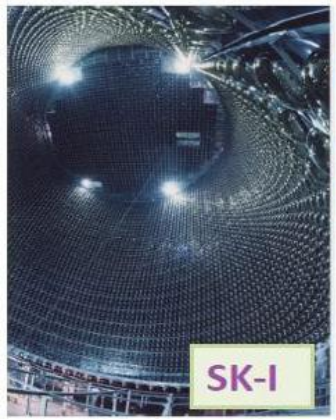
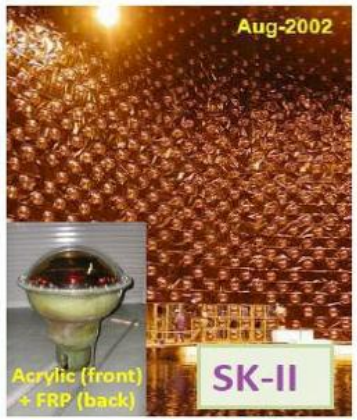
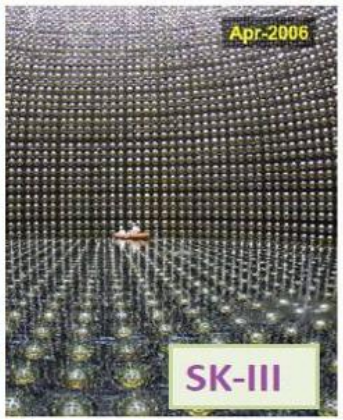
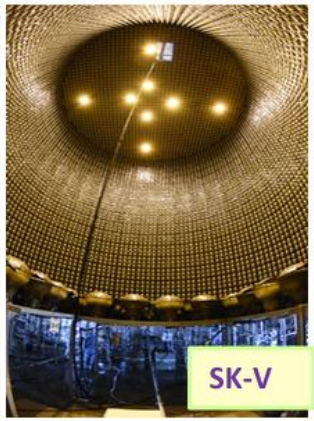
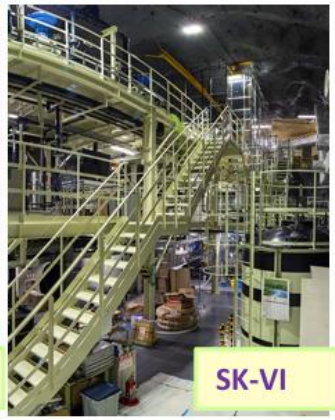


- Around **11,000 PMTs (photomultiplier tubes) in the inner detector** with an outer detector veto and **50 kton volume**.
- **Overburden of 1,000 m** (2,700 m.w.e.) to reduce cosmic ray muon flux by factor of $\sim 10^5$.

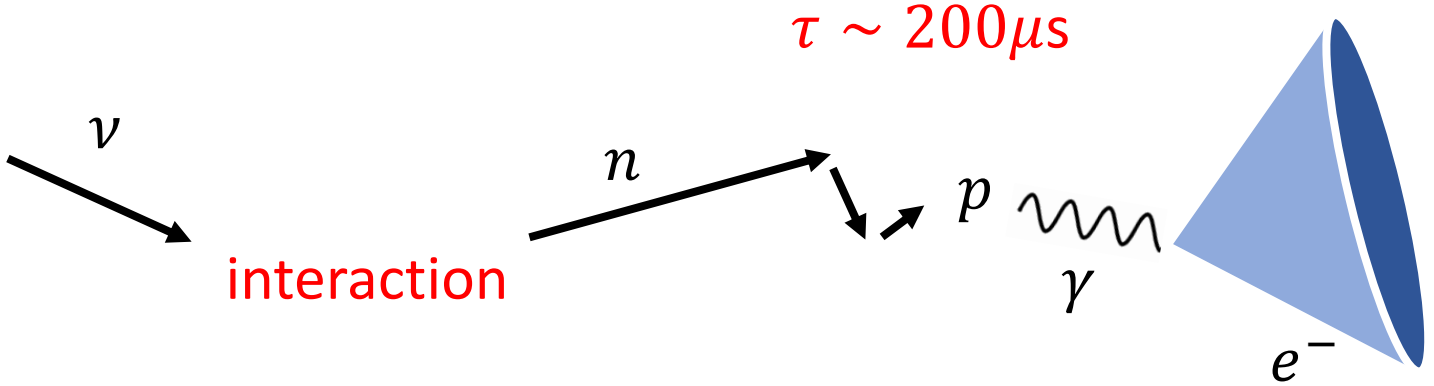
Super-K data-taking has now spanned more than 30 years!

SK-Gd era

Neutron capture "tagging"

1996	2002	2006	2008	2019	2020	2022	2024
							
SK-I	SK-II	SK-III	SK-IV	SK-V	SK-VI	SK-VII	SK-VIII
First data	Repair after PMT accident	Full recovery after PMT accident	**Electronics upgrade**	Tank refurbished	**0.01% Gd-loaded**	**0.03% Gd-loaded**	Coil repaired

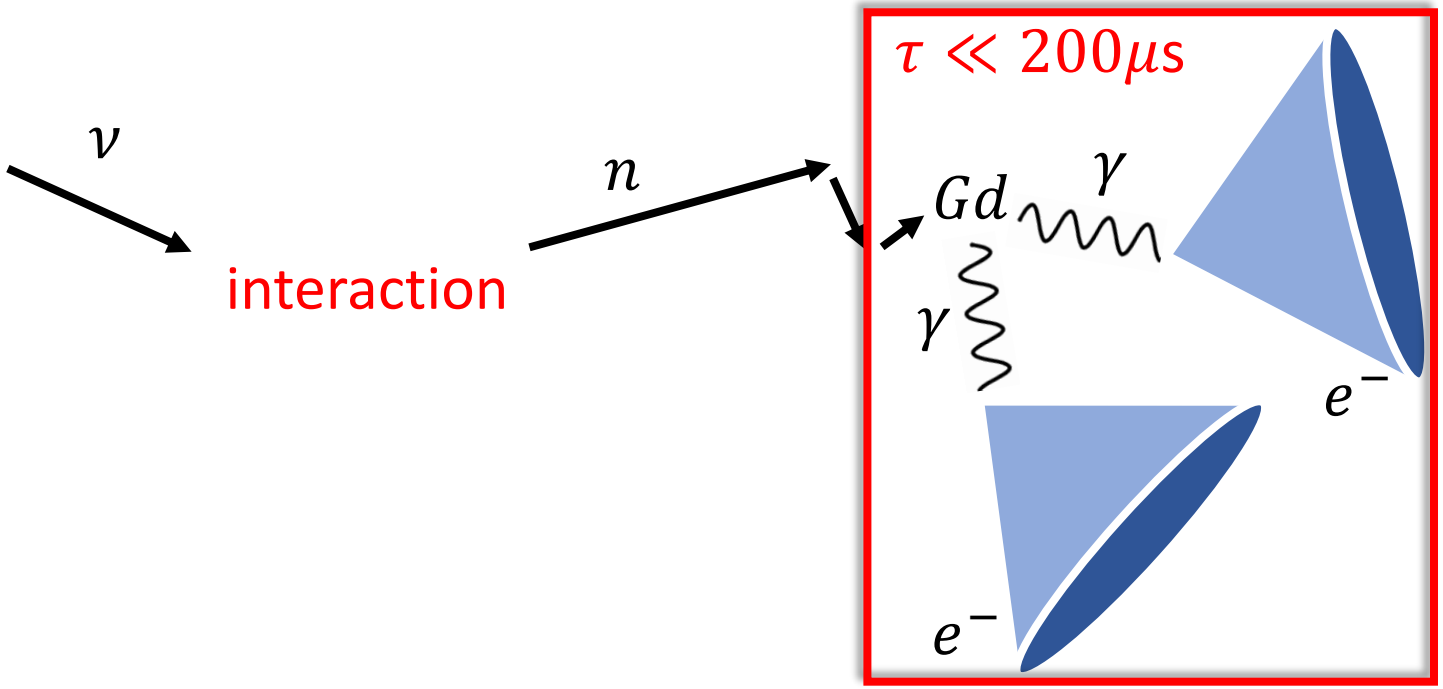
Upgrading Super-K with gadolinium (SK-Gd)



**neutrons can provide crucial information!*



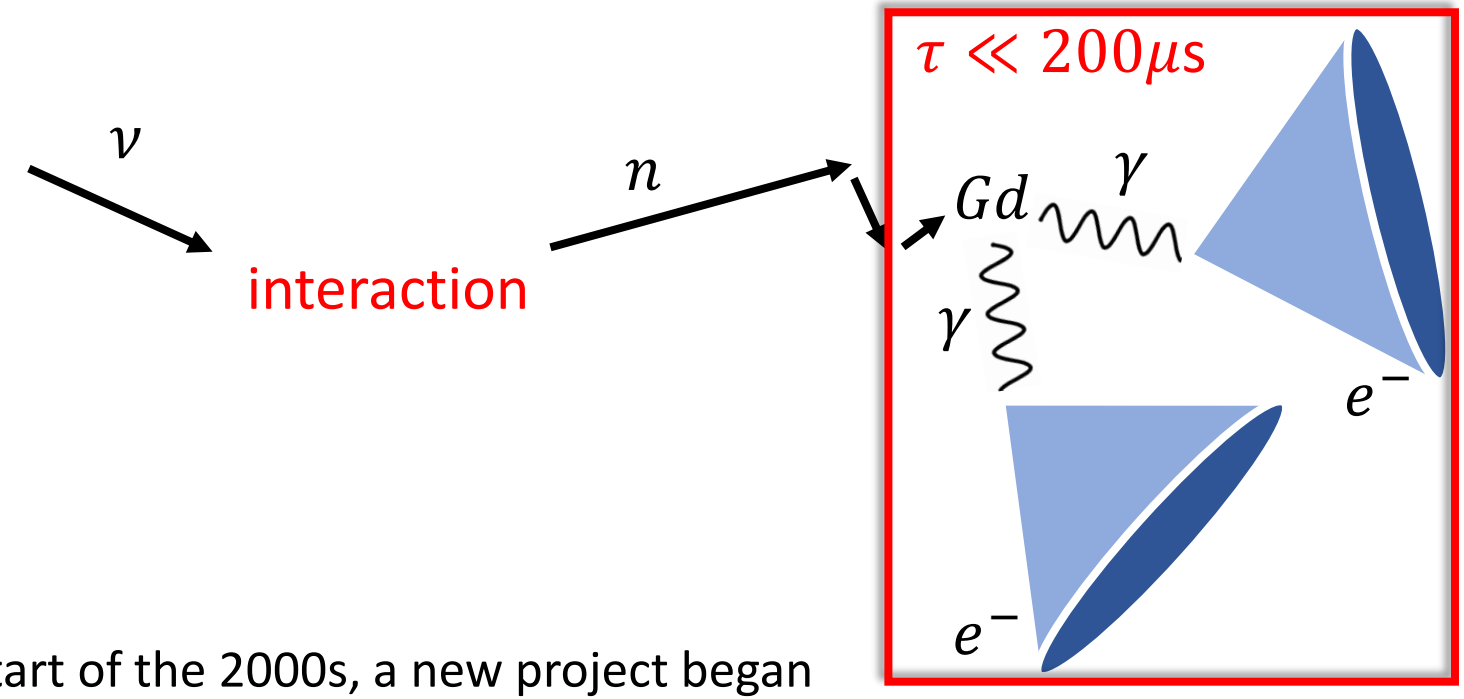
Upgrading Super-K with gadolinium (SK-Gd)



- *More energy per neutron capture*
- *Large neutron capture cross-section*
- *Faster neutron capture timescale*



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GADZOOKS! Antineutrino Spectroscopy with Large Water Čerenkov Detectors

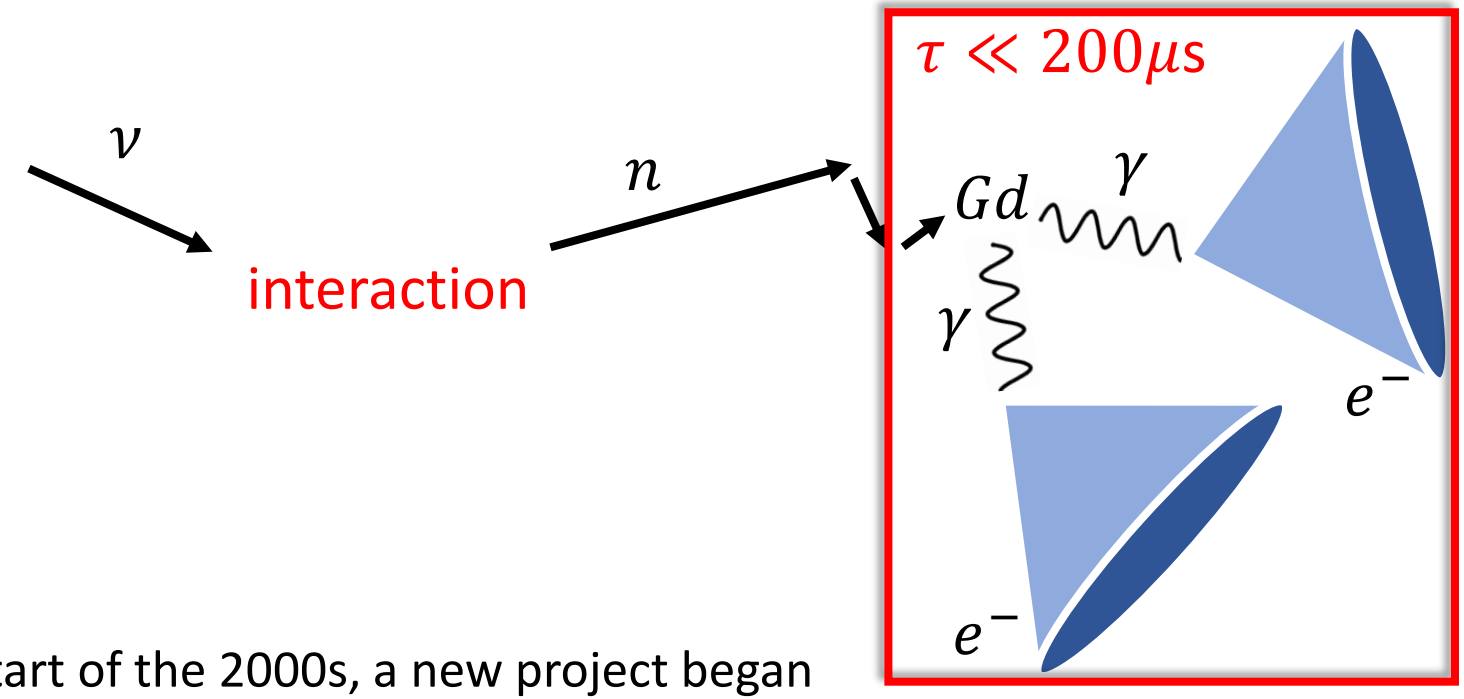
John F. Beacom[1] and Mark R. Vagins[2]

[1] *NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500*
[2] *Department of Physics and Astronomy, 4129 Reines Hall, University of California, Irvine, CA 92697*

(Dated: 25 September 2003)

PRL 93 (2004) 171101

Upgrading Super-K with gadolinium (SK-Gd)



- At the start of the 2000s, a new project began in **doping the water with gadolinium (Gd)**.
- In the 2020s, we have **doped the water with gadolinium (Gd)** at 0.01% and 0.03% by mass.

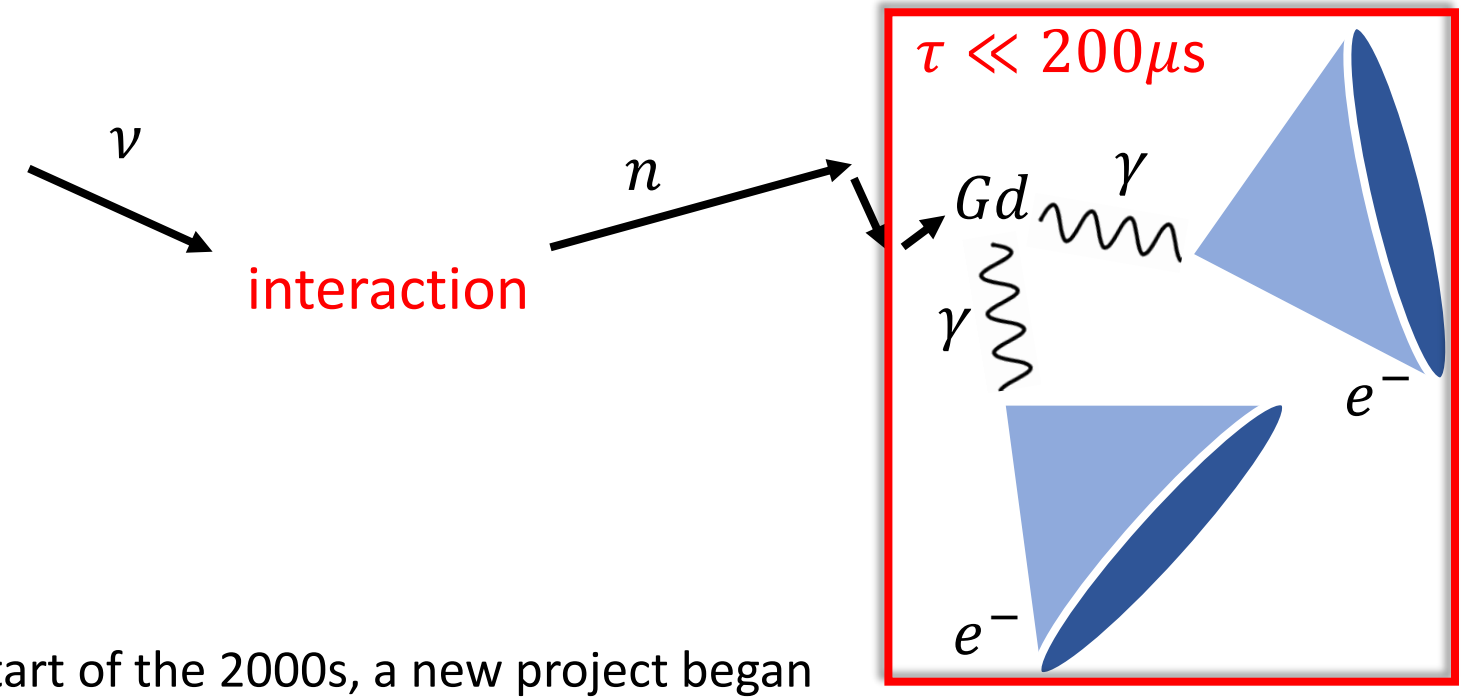
SK gadolinium-loading 2020s!



NIMA 1027 (2022) 166248

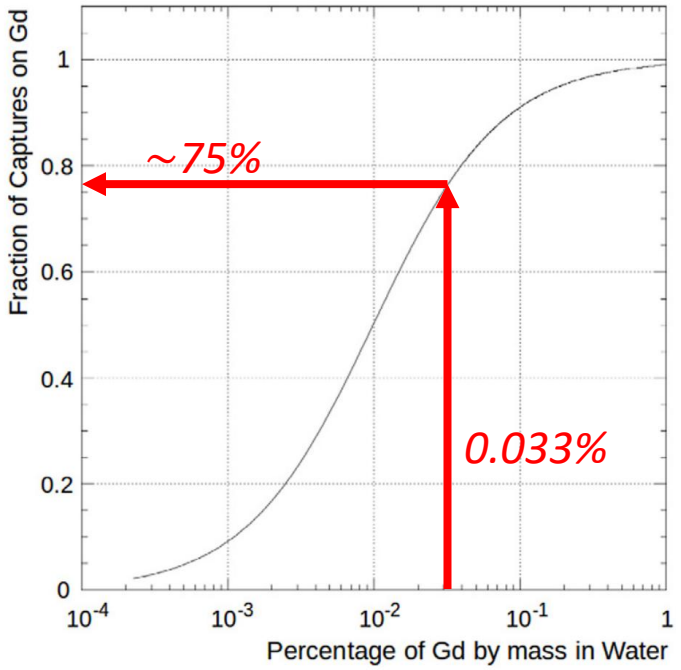
NIMA 1065 (2024) 169480

Upgrading Super-K with gadolinium (SK-Gd)

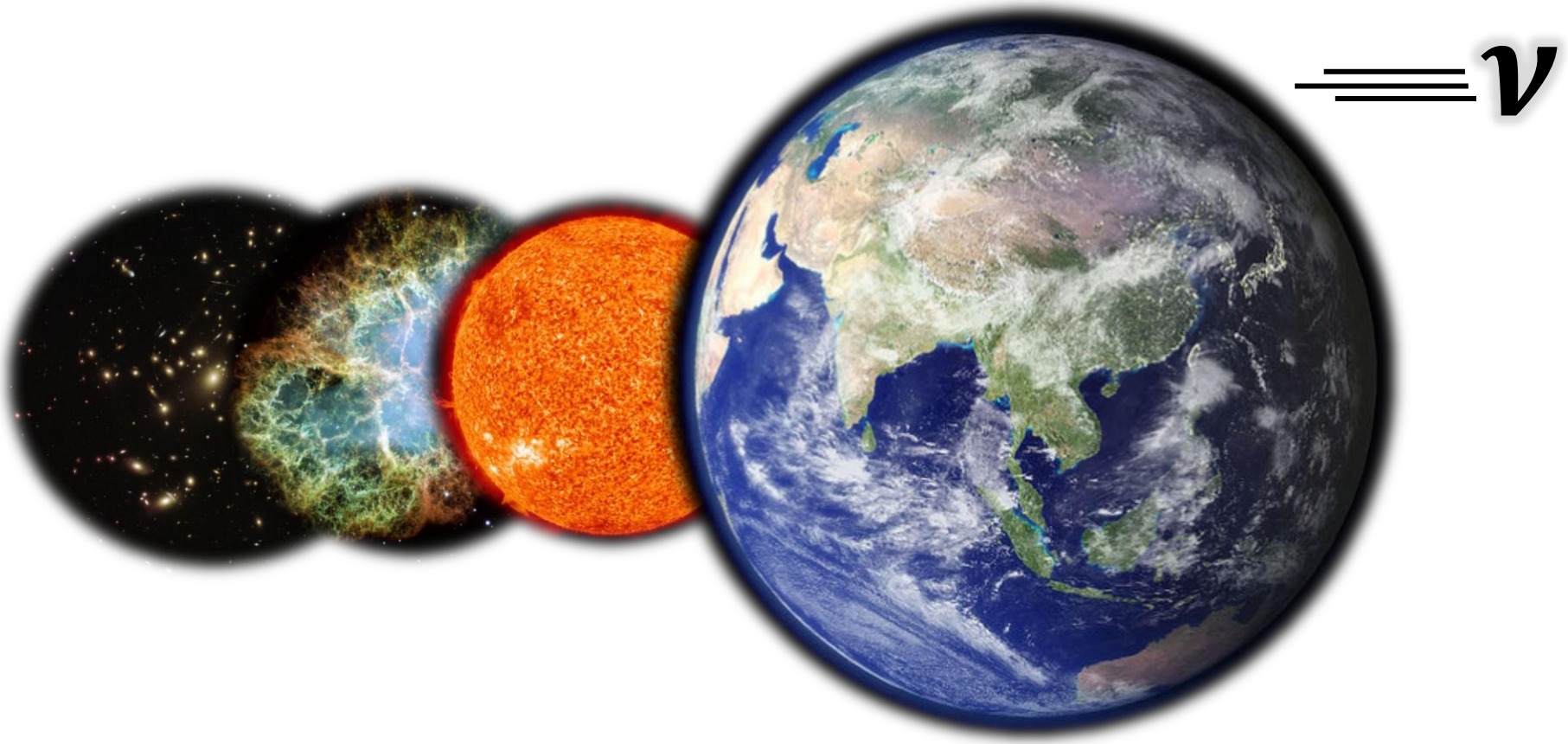


- At the start of the 2000s, a new project began in **doping the water with gadolinium (Gd)**.
- In the 2020s, we have **doped the water with gadolinium (Gd)** at 0.01% and 0.03% by mass.
- At 0.03% Gd-loading, **~75% of neutron captures happen on Gd nuclei**.

NIMA, 959 (2020) 163549

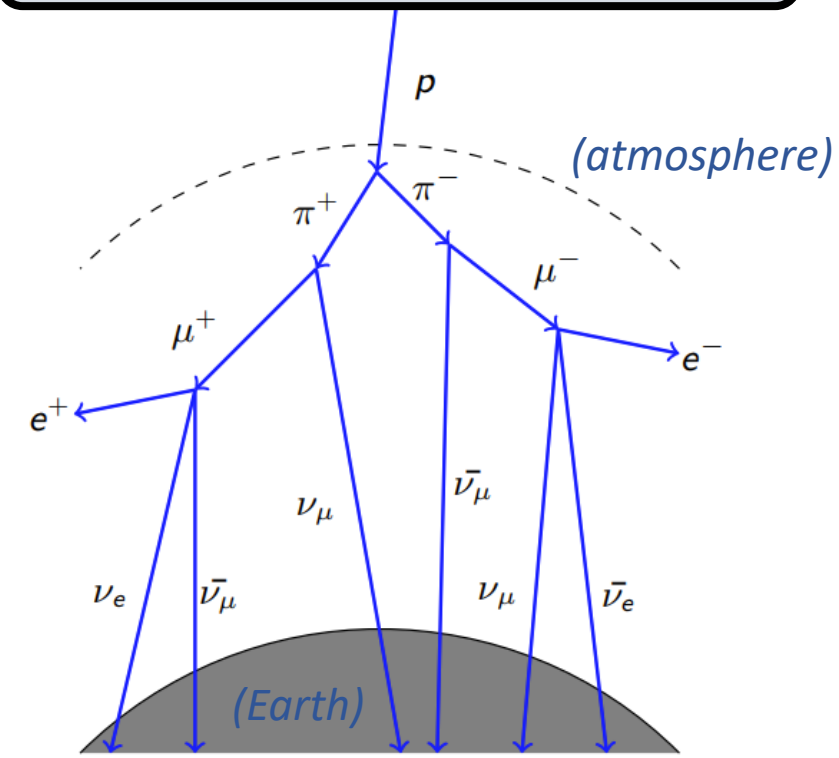


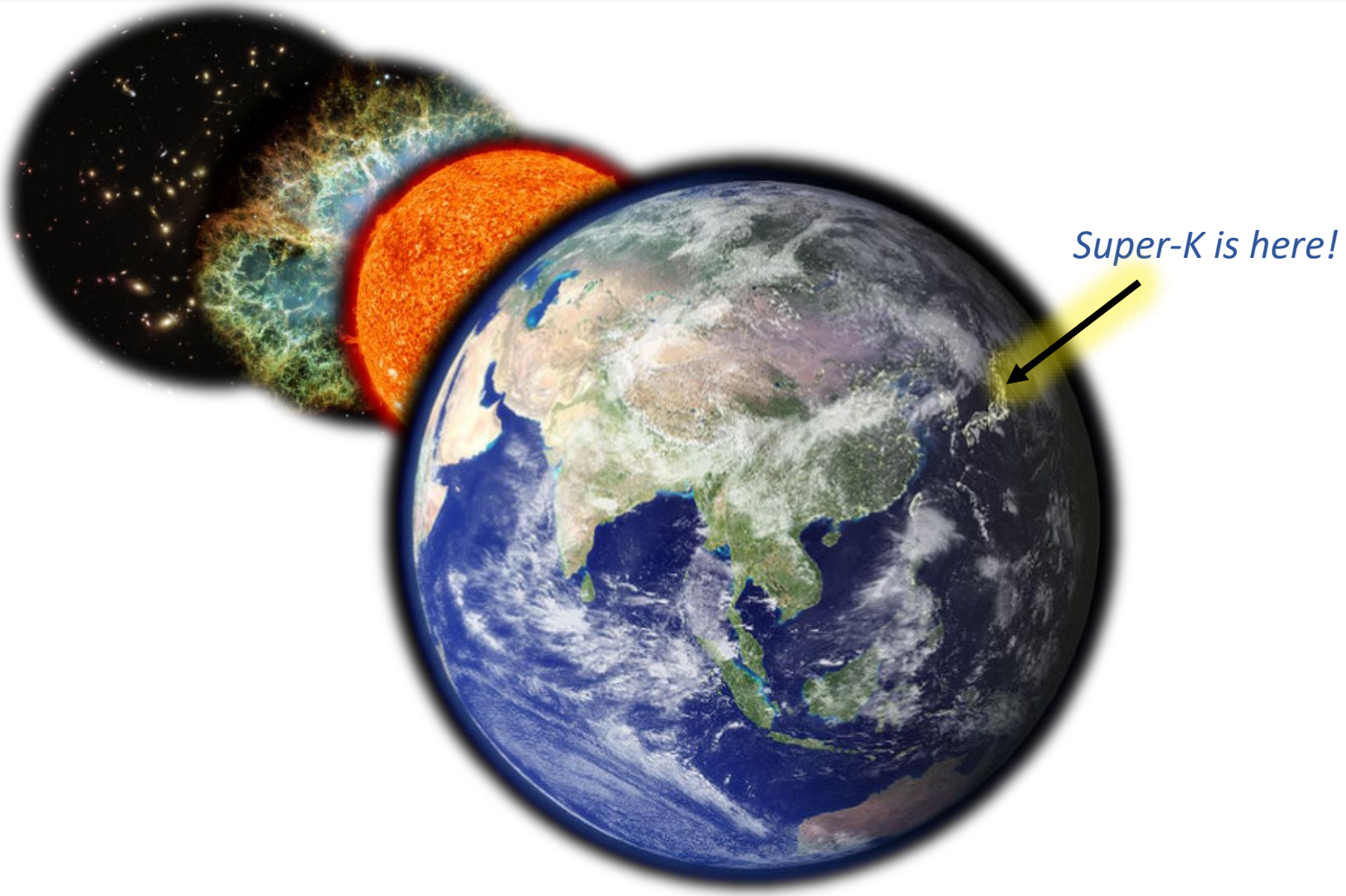
Atmospheric neutrinos!



Extracting physics from atmospheric neutrino oscillations

Neutrinos produced by cosmic rays!

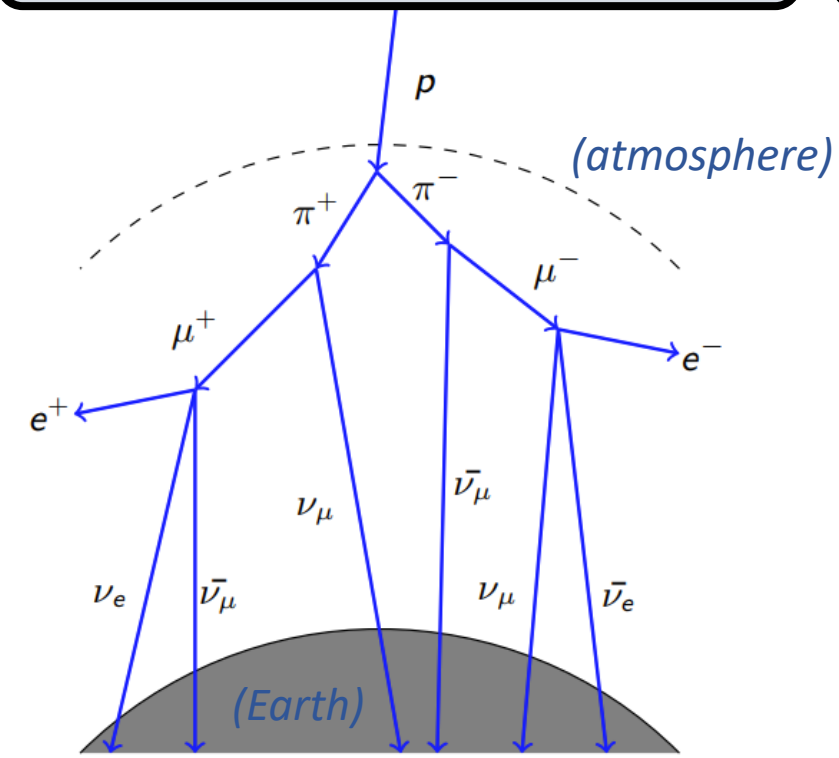




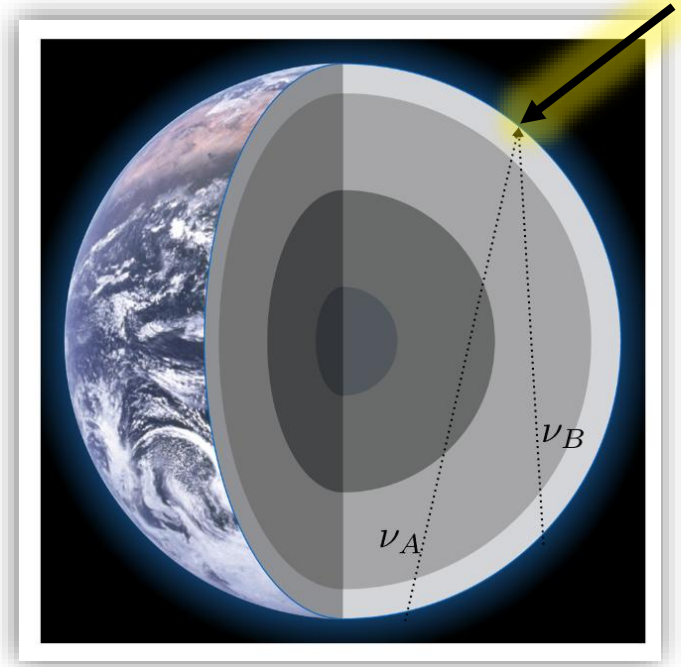
Extracting physics from atmospheric neutrino oscillations

Neutrinos produced by cosmic rays!

Large range in energy and distances!

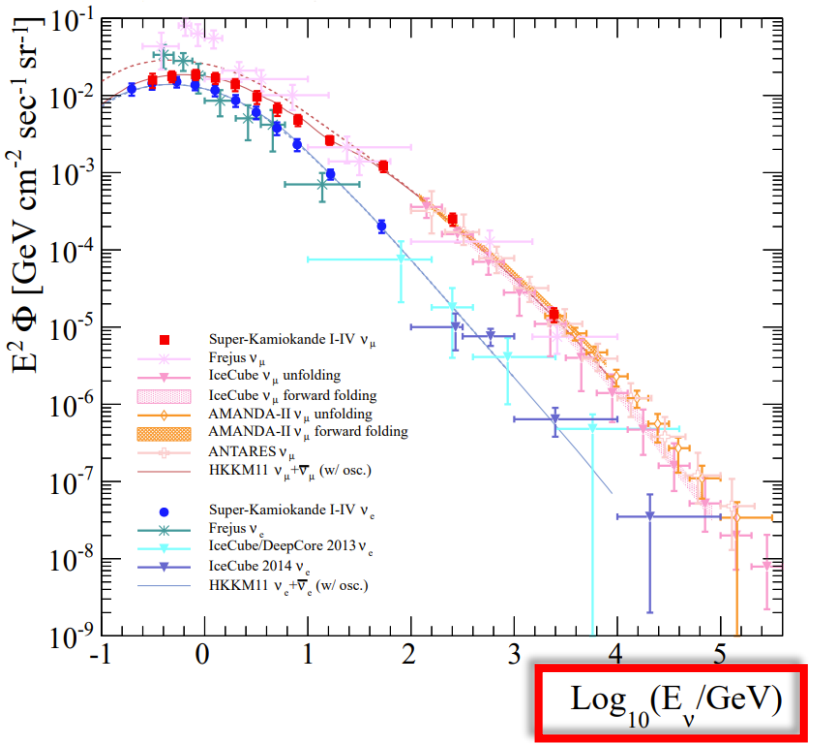


Super-K is here!



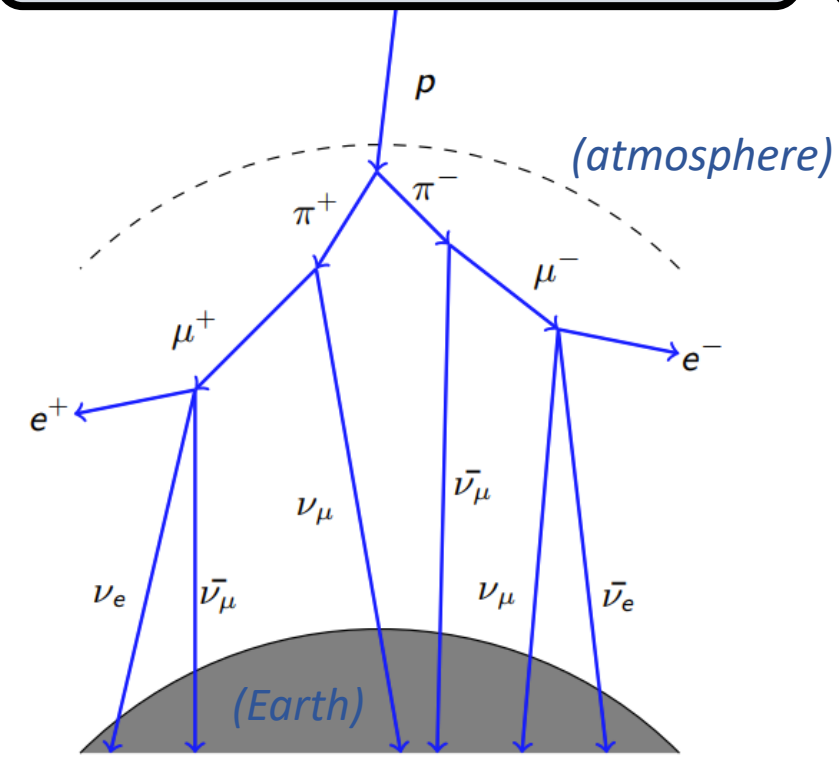
Neutrinos traverse the Earth (matter effects)!

*E. Richard et al., PRD **94,** 052001 (2016)*

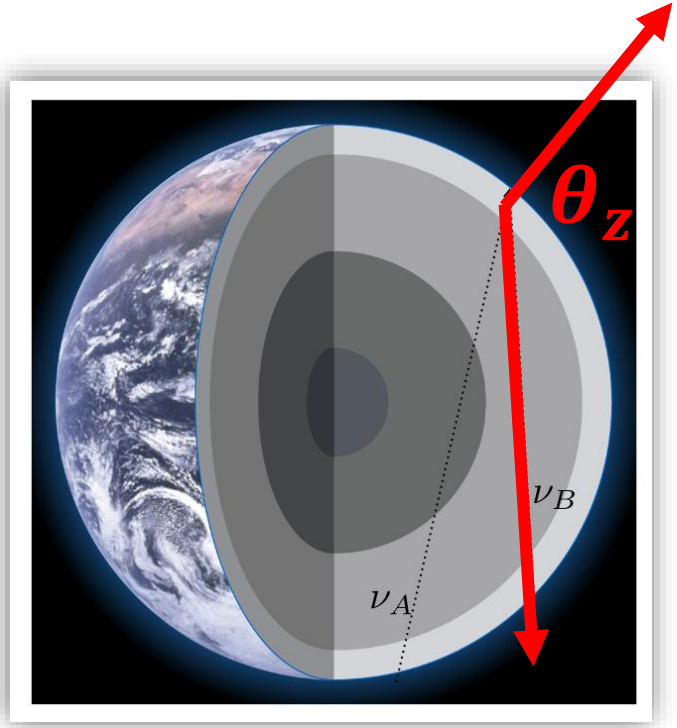


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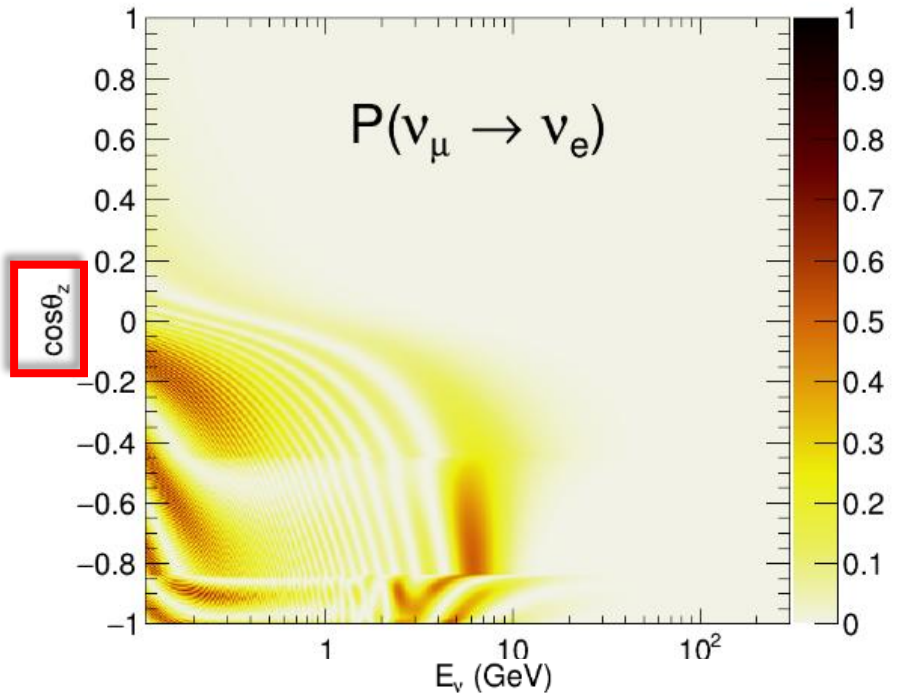


Large range in energy and distances!



Rich landscape of flavor oscillations!

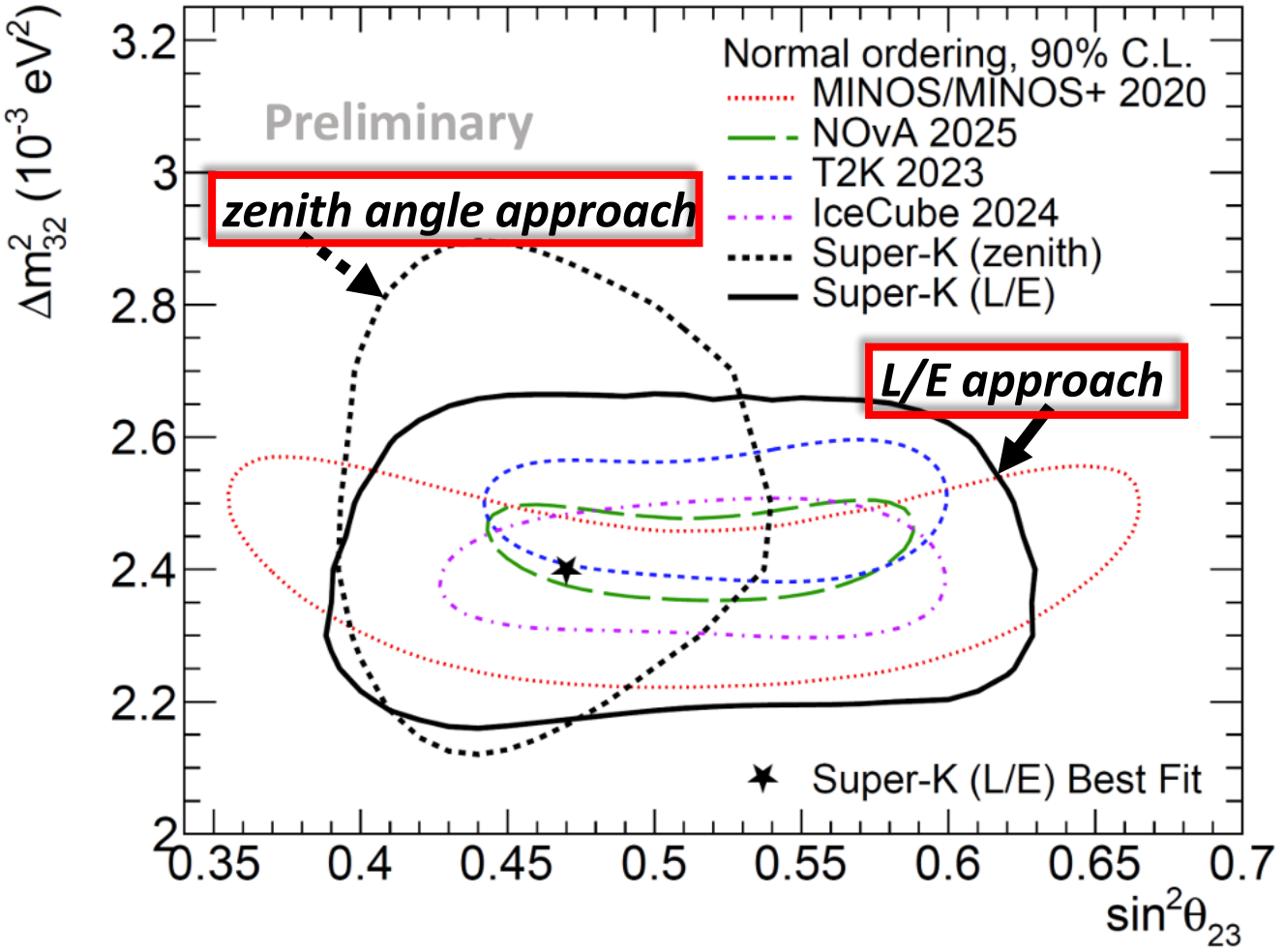
PRD 109 (7), 072014 (2024)



- We have **two different approaches** to extract neutrino physics from these data!

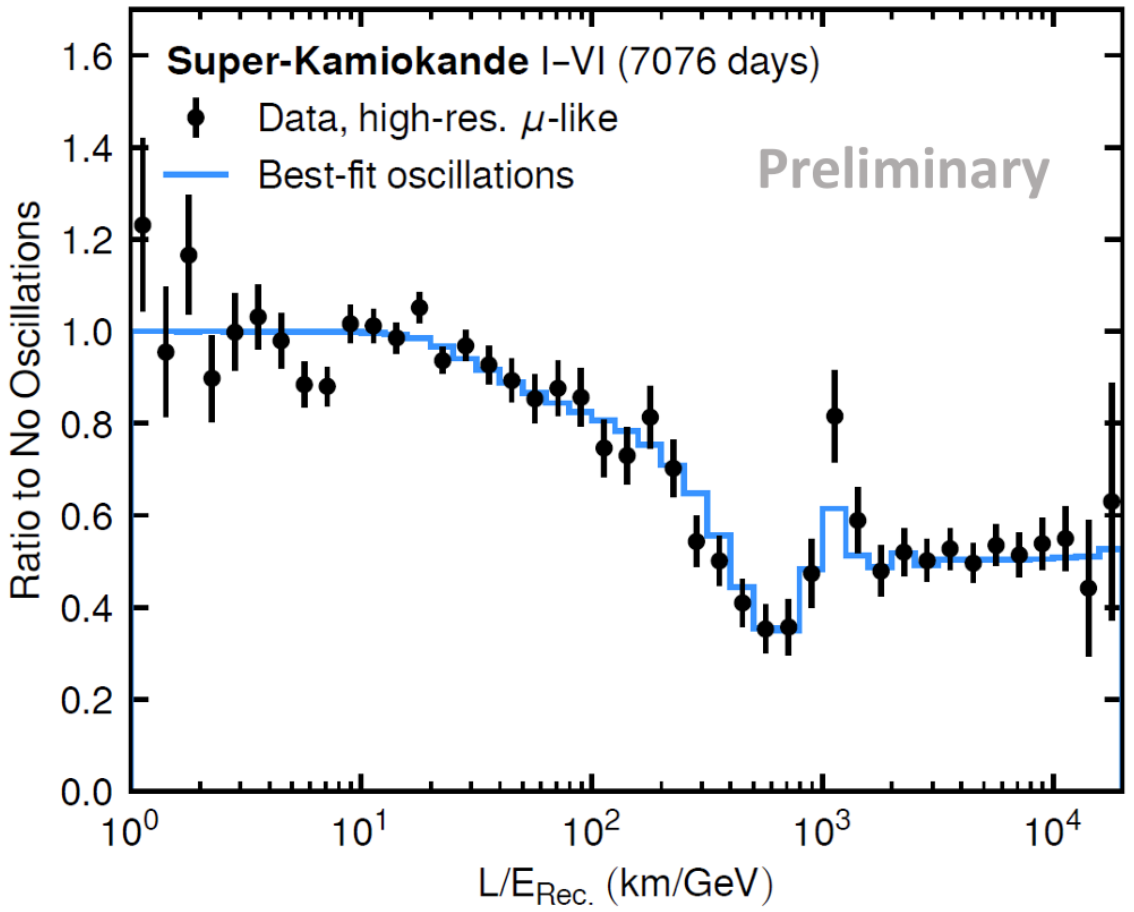
Probing θ_{23} and Δm^2_{32} with atmospheric neutrinos

- At Neutrino 2026 in Irvine, CA, we presented **new results** for a **zenith angle** analysis as well as an **"L/E" analysis**.
- Results on **oscillation parameters** can be **compared** across zenith-vs-L/E and other experiments.
- The **L/E analysis is stronger in Δm^2_{32}** because of high-resolution oscillatory pattern in L/E.
- The **zenith analysis is stronger in $\sin^2\theta_{23}$** because it contains ν_e-enhanced samples as well when binning samples in $\cos\theta_z$.
- **Prospects**: Integrate L/E analysis into standard zenith one!
- Let's cover some key details of the two studies!

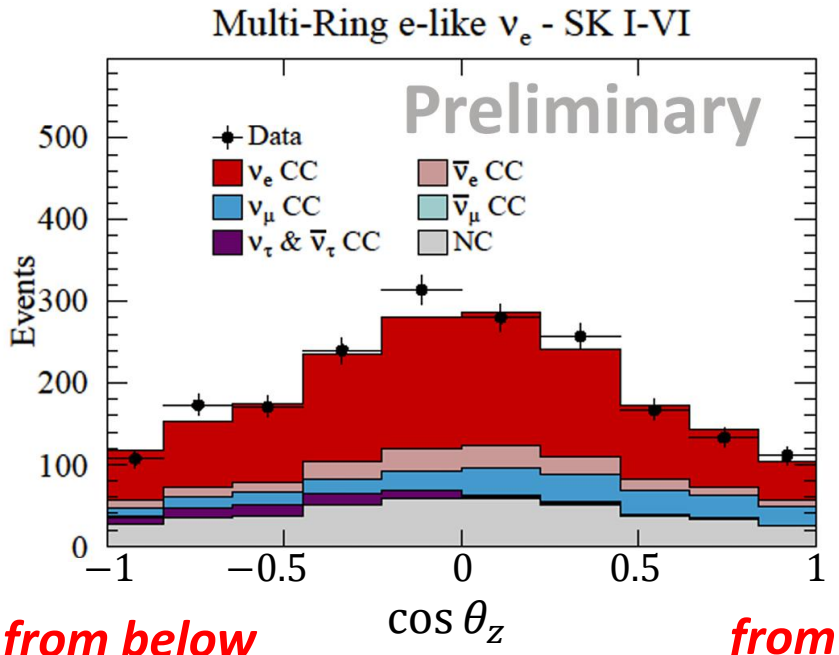


L/E analysis for atmospheric neutrinos

- Neutrino oscillations are naturally modeled from an “L/E” ratio, which motivates **binning data in L/E ratio** to see the effect clearly.
- Each L/E bin, then, contains interesting combinations of data from various zenith angles and energies.
- These data are **SK I-VI** (7076 livedays), and we focus solely on $\nu_\mu \rightarrow \nu_\mu$ oscillations, the **survival probability** over L/E.
- We can easily visualize the **characteristic wiggle** in the ratio of data-to-non-oscillations on the vertical axis.
- Again, this gives us more sensitivity in Δm^2_{32} than in θ_{23} compared to the zenith angle approach.

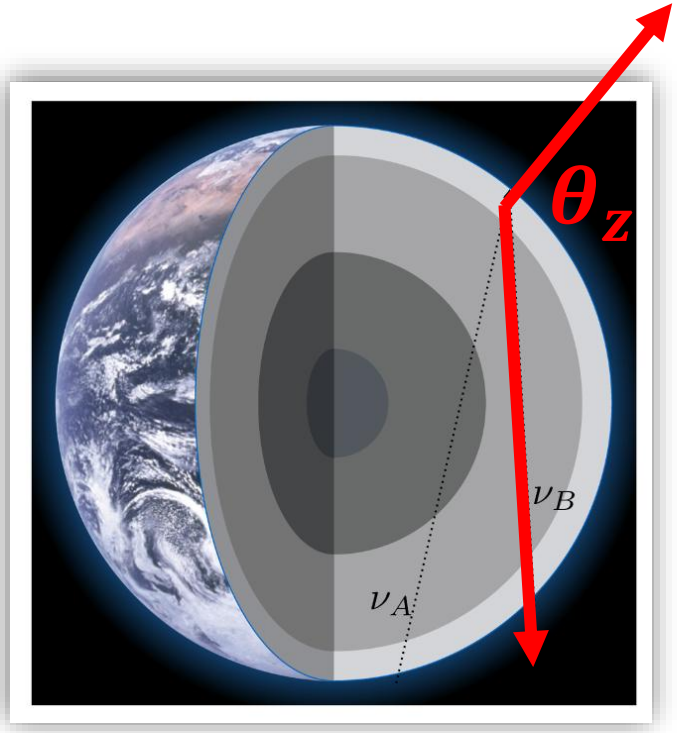


Zenith angle analysis for atmospheric neutrinos

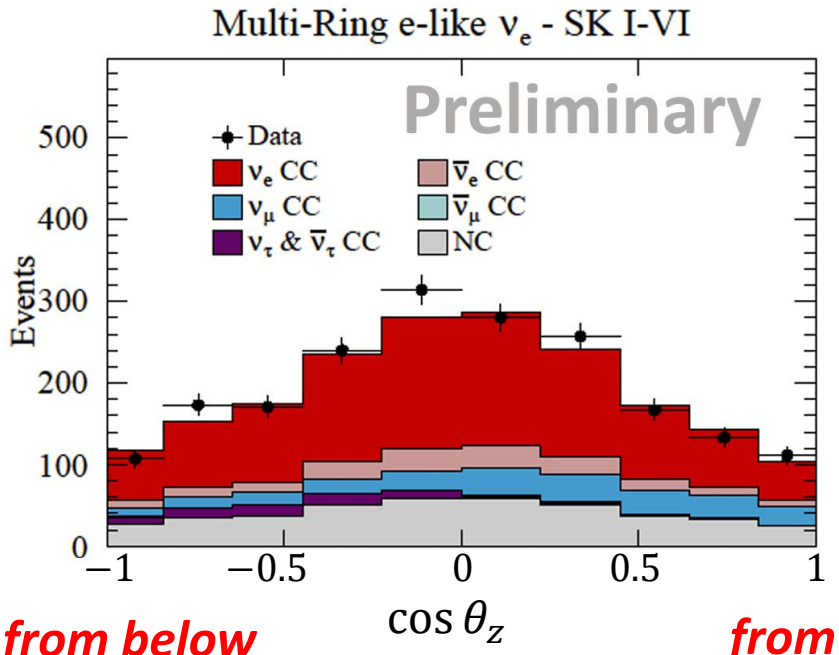


from below ***from above***

- The data also come from **SK I-VI** (7075.7 livedays).
- Data are **binned by zenith angle**, plotted by the cosine of the angle…



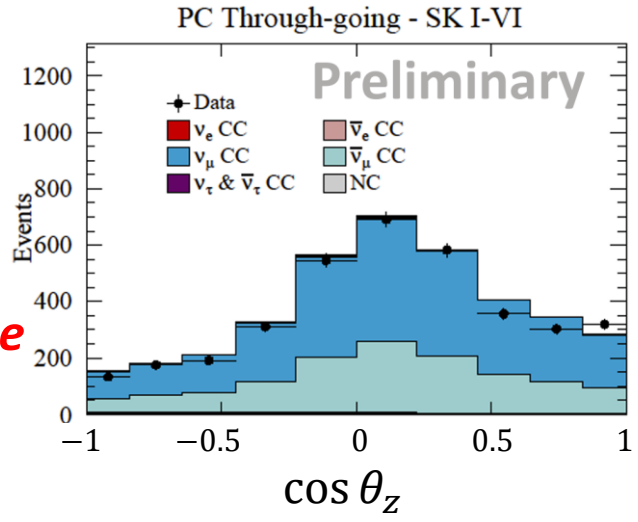
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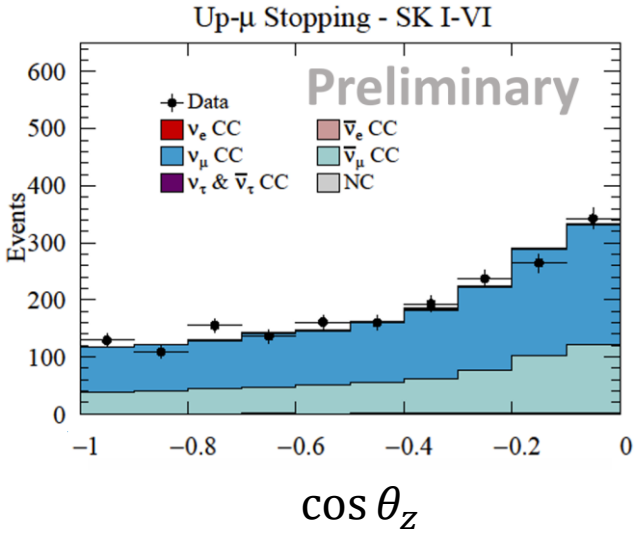


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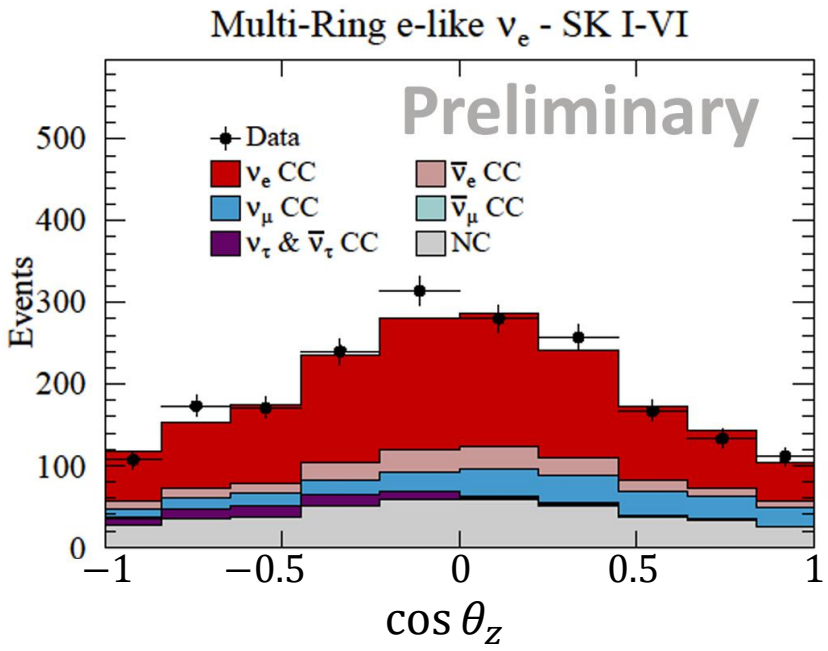
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Zenith angle analysis for atmospheric neutrinos



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- Data are **binned by zenith angle**, plotted by the cosine of the angle, and separated into samples that enhance certain interaction channels.
- New **highlights** in this measurement compared to last published result:
  - **Addition of SK-VI** data from SK-Gd.
  - Updated neutrino **event generator**.
  - New **neutron-based reconstruction** for SK-VI thanks to Gd.
  - Improved **BDT classifier** for multi-ring events.
  - Better **constraints on ν_τ** with a neural network in crucial ν_e samples.
- We have **8.8% increase in sample size** and a **~10% improvement** to mass ordering sensitivity!

Zenith angle analysis for atmospheric neutrinos

Result	SK I-V (previous)	SK I-VI (now)
$\sin^2\theta_{23}$	0.45	0.44
$\Delta m^2_{32}[10^{-3}\ \mathrm{eV}]$	2.40	2.40
δ_{CP}	$-\pi/2$	$-3\pi/4$
$\Delta\chi^2_{\mathrm{IO-NO}}$	5.69	3.69

(with $\sin^2\theta_{13}$ *prior* 0.0220 ± 0.0007)

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- We have **8.8% increase in sample size** and a **~10% improvement** to mass ordering sensitivity!
- Our best-fit δ_{CP} and $\Delta\chi^2_{\mathrm{IO-NO}}$ changed more than oscillation parameters, but they are still largely consistent with our previous results.

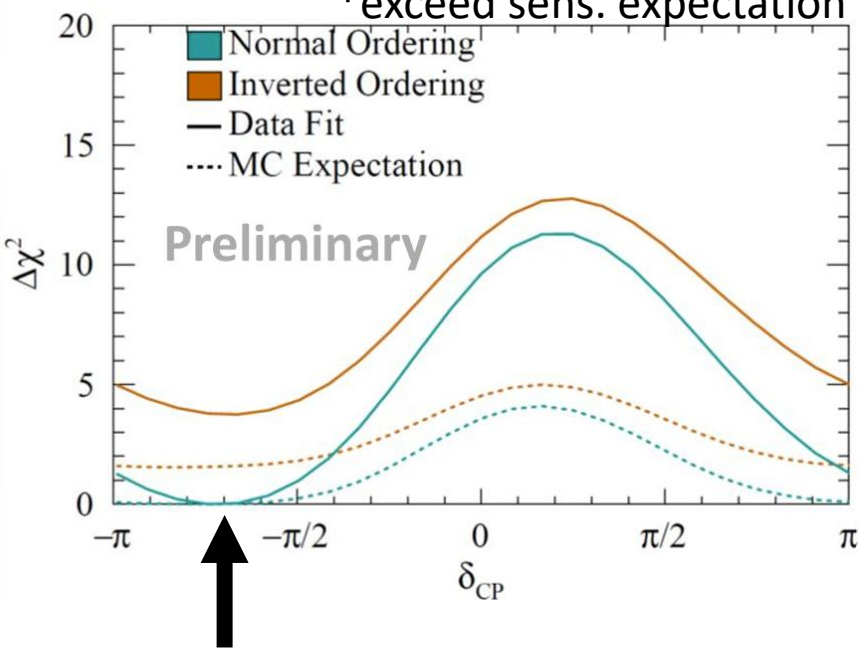
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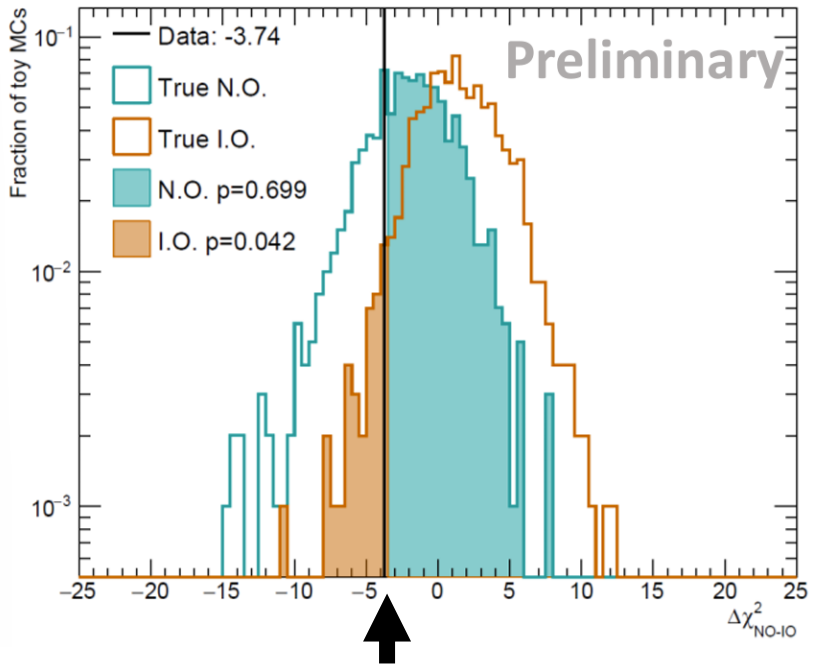
(with $\sin^2\theta_{13}$ *prior* 0.0220 ± 0.0007)

CP Phase

*exceed sens. expectation

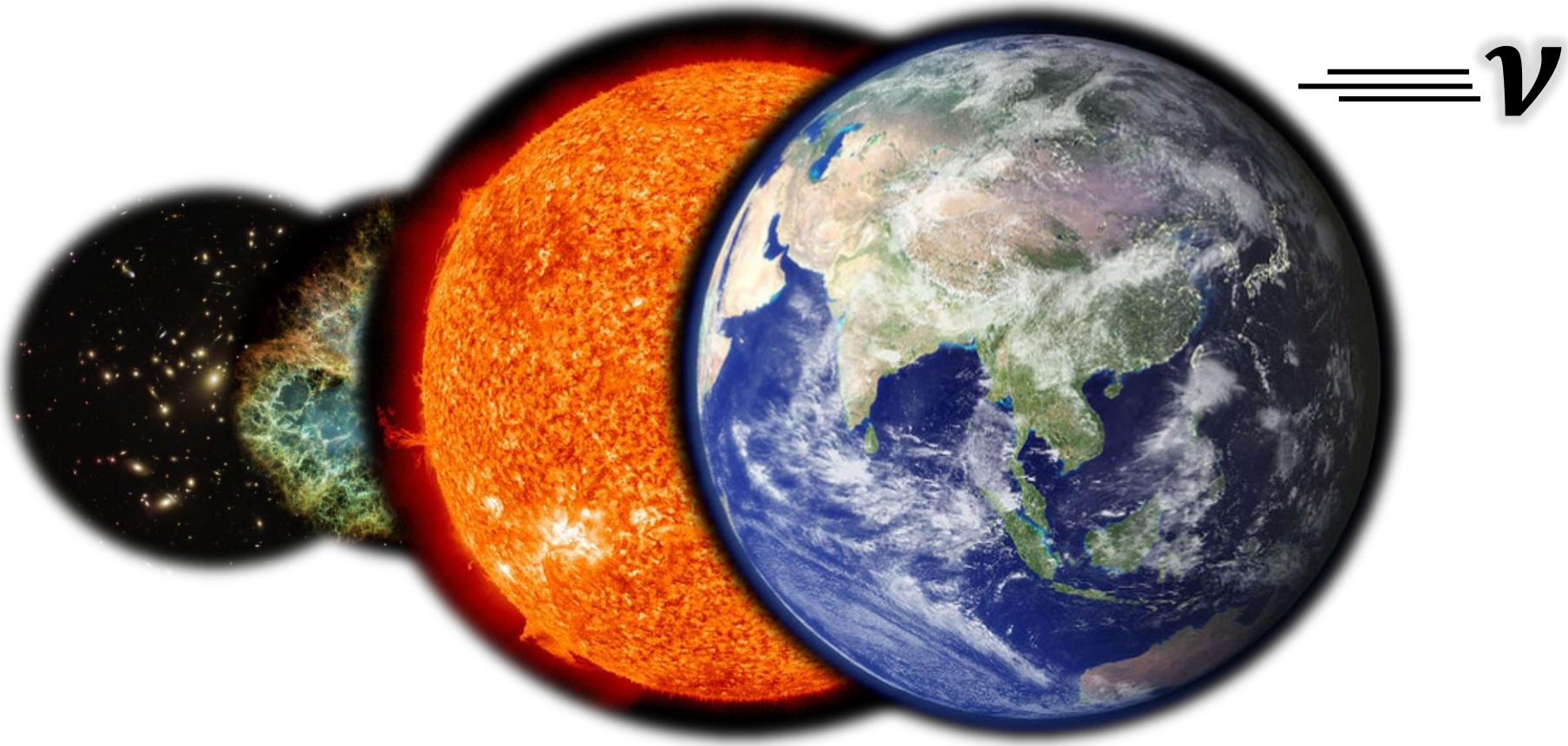


Mass Ordering

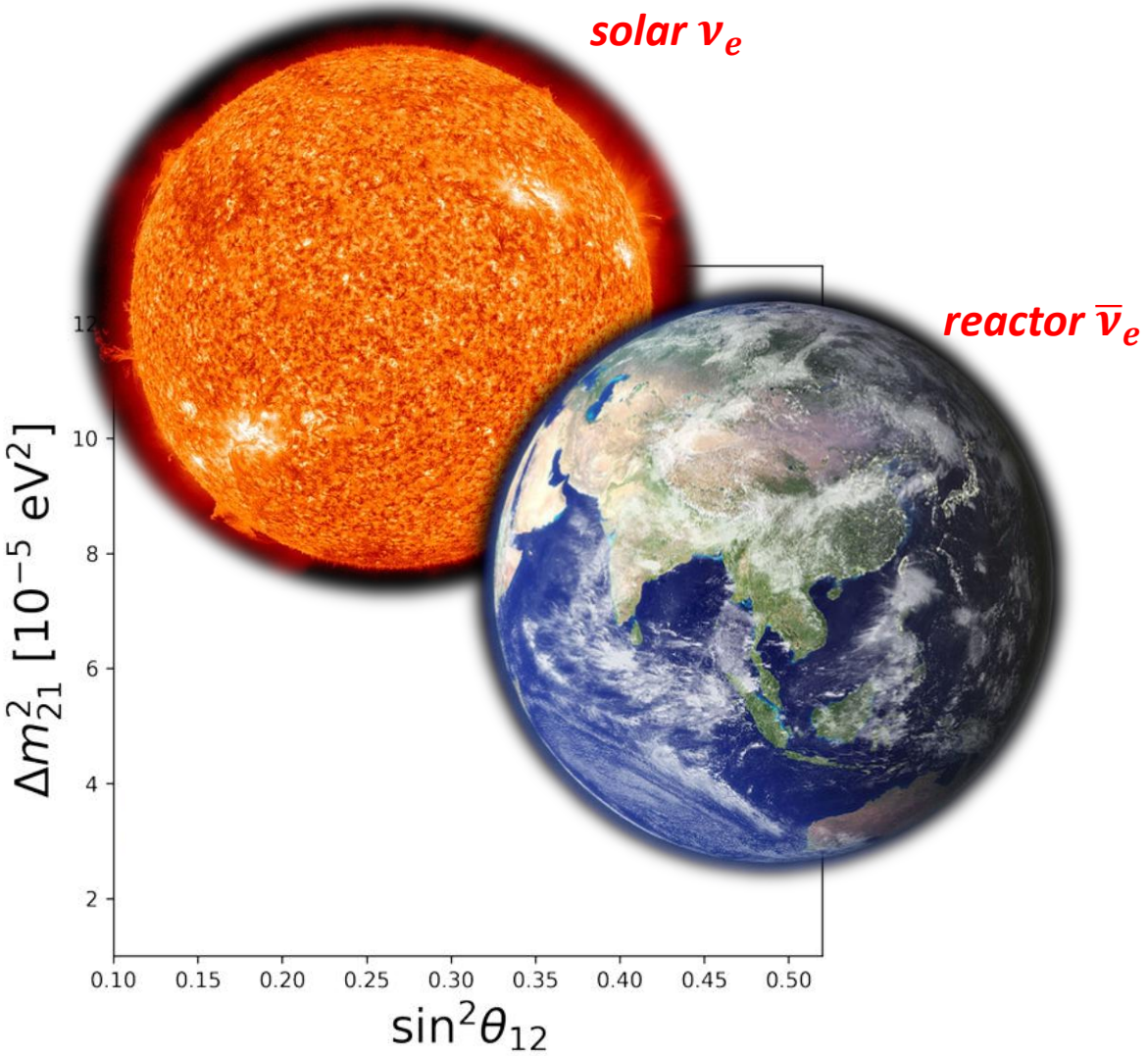


- Our best-fit δ_{CP} and $\Delta\chi^2_{\mathrm{IO-NO}}$ changed more than oscillation parameters, but they are still **largely consistent with our last-published results**.
- We still **favor** the **lower θ_{23} octant**, **normal ordering** ($\sim 1.1\sigma$), and **CPV**.

Nuclear reactor $\bar{\nu}_e$ and solar ν_e!



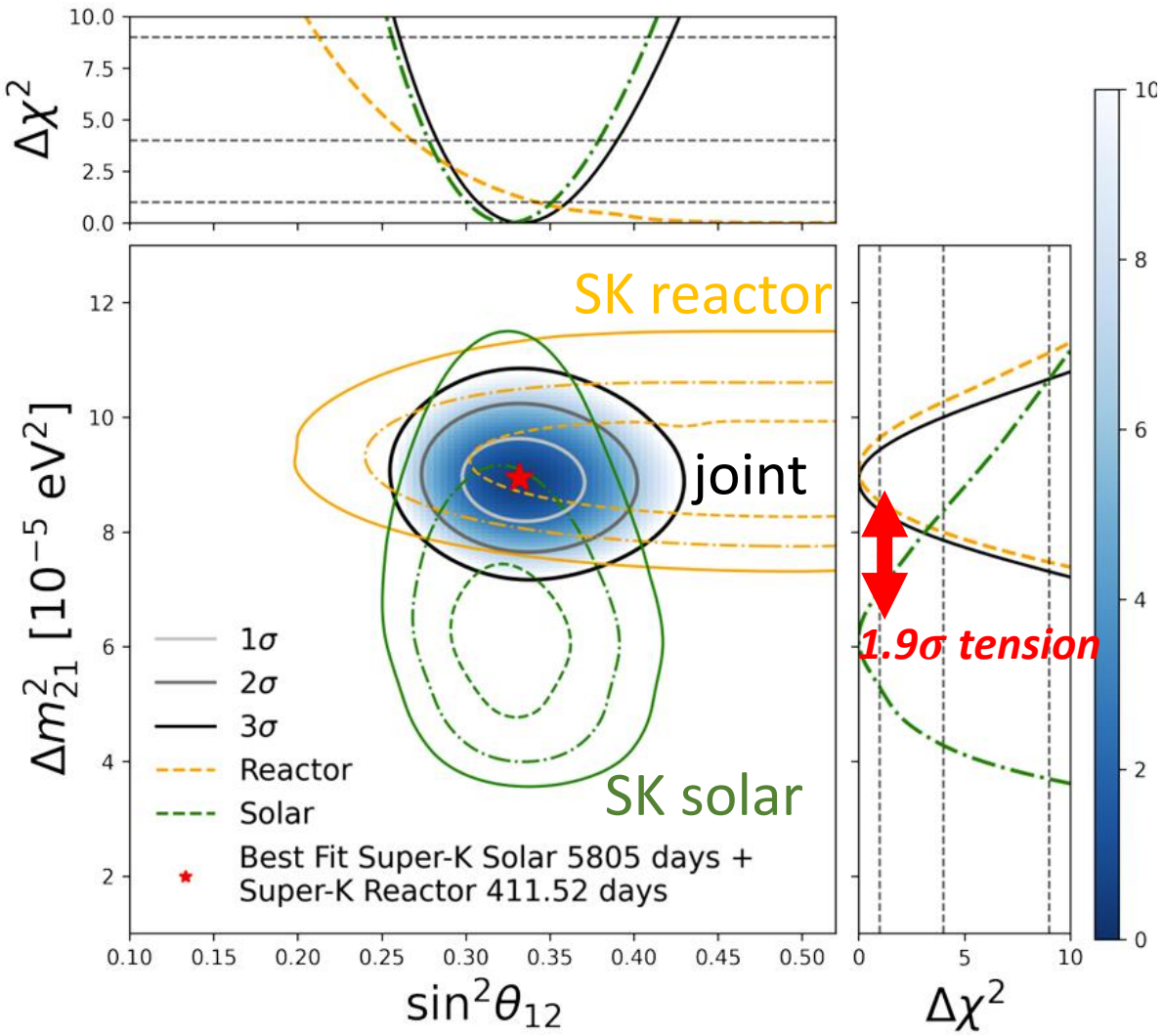
First observation of reactor anti-neutrinos with SK-Gd



arXiv:2610.03143

- We can use Super-K to measure the **solar mixing parameters** θ_{12} and Δm^2_{21} from both **solar** ν_e and **nuclear reactor** $\overline{\nu}_e$.
- Not only does **combining** these two sources **increase precision**, but it reveals whether there is any tension (e.g., **possible CPT-violation**).

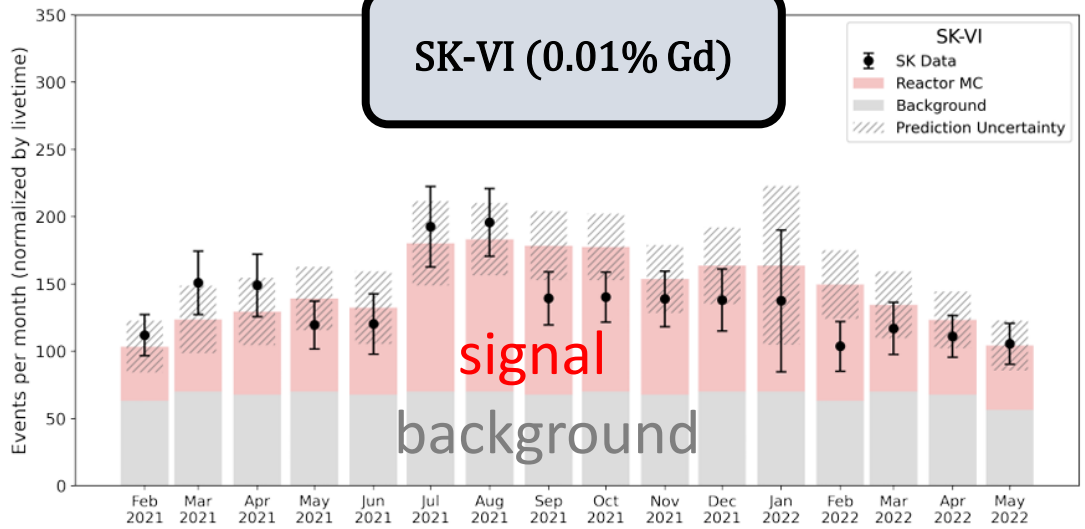
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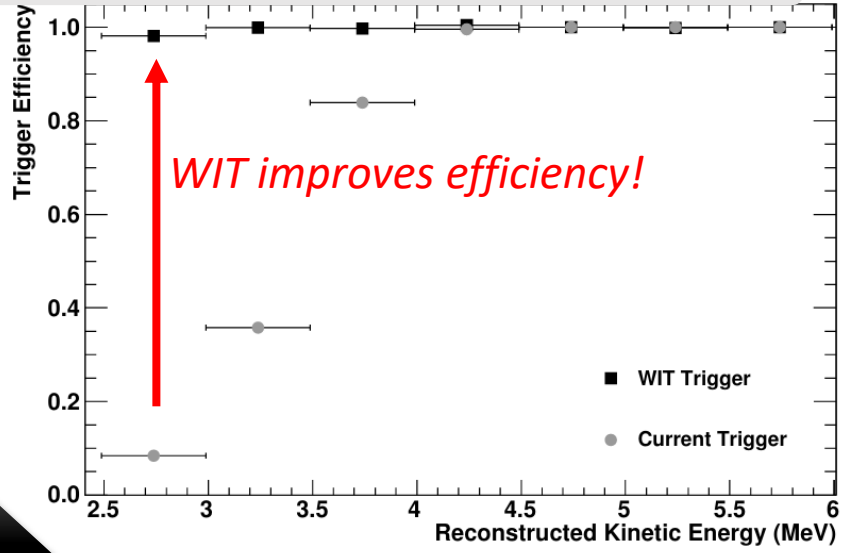
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- This is the first time SK has **observed reactor** $\overline{\nu}_e$ (reject the null hypothesis at 6σ)!
- Currently, a **1.9σ discrepancy** exists between the SK solar ν_e and SK reactor $\overline{\nu}_e$ best-fit Δm^2_{21} values.

First observation of reactor anti-neutrinos with SK-Gd



Carminati et al., Phys. Proc. 61 (2015) 672

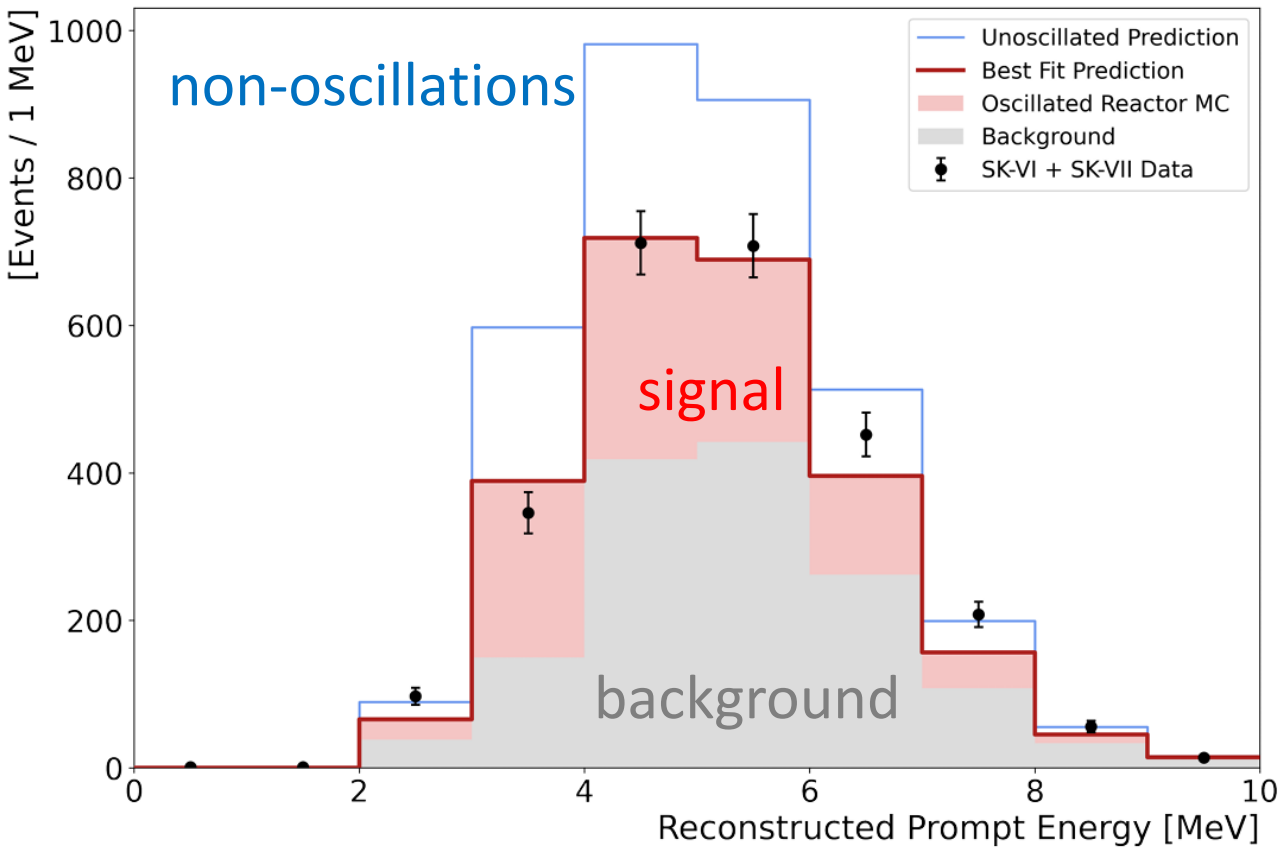


arXiv:2610.03143

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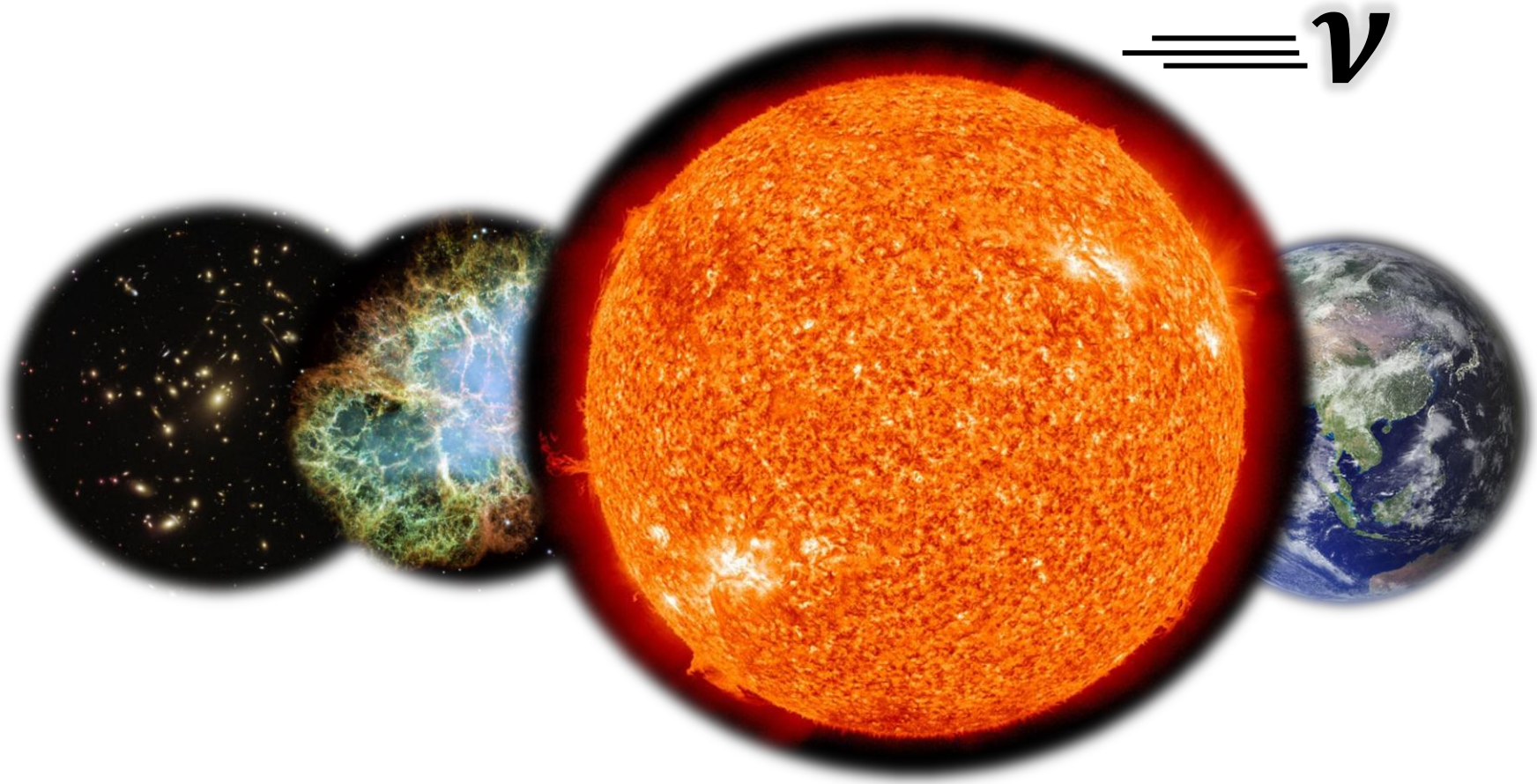
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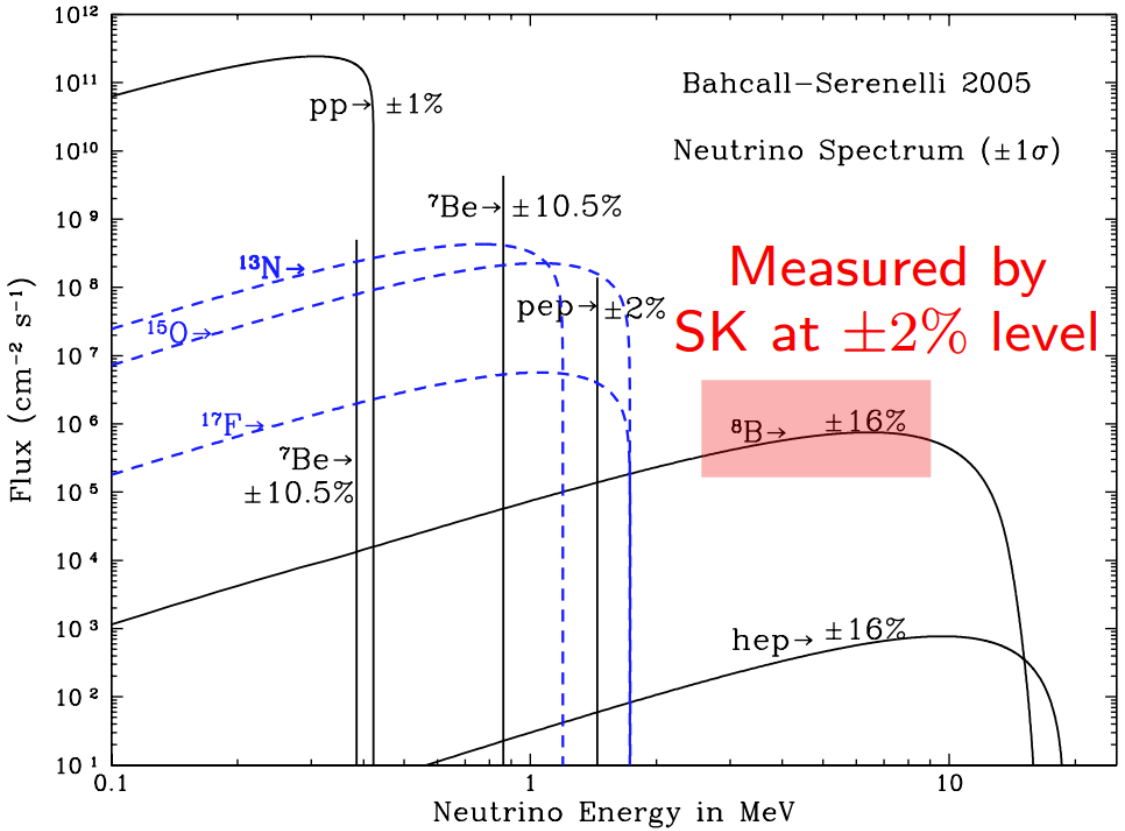


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- For reactor $\bar{\nu}_e$, background and signal predictions were compared to data from the **SK Wideband Intelligent Trigger** or (WIT) system.
- We extract parameters from the energy spectrum!

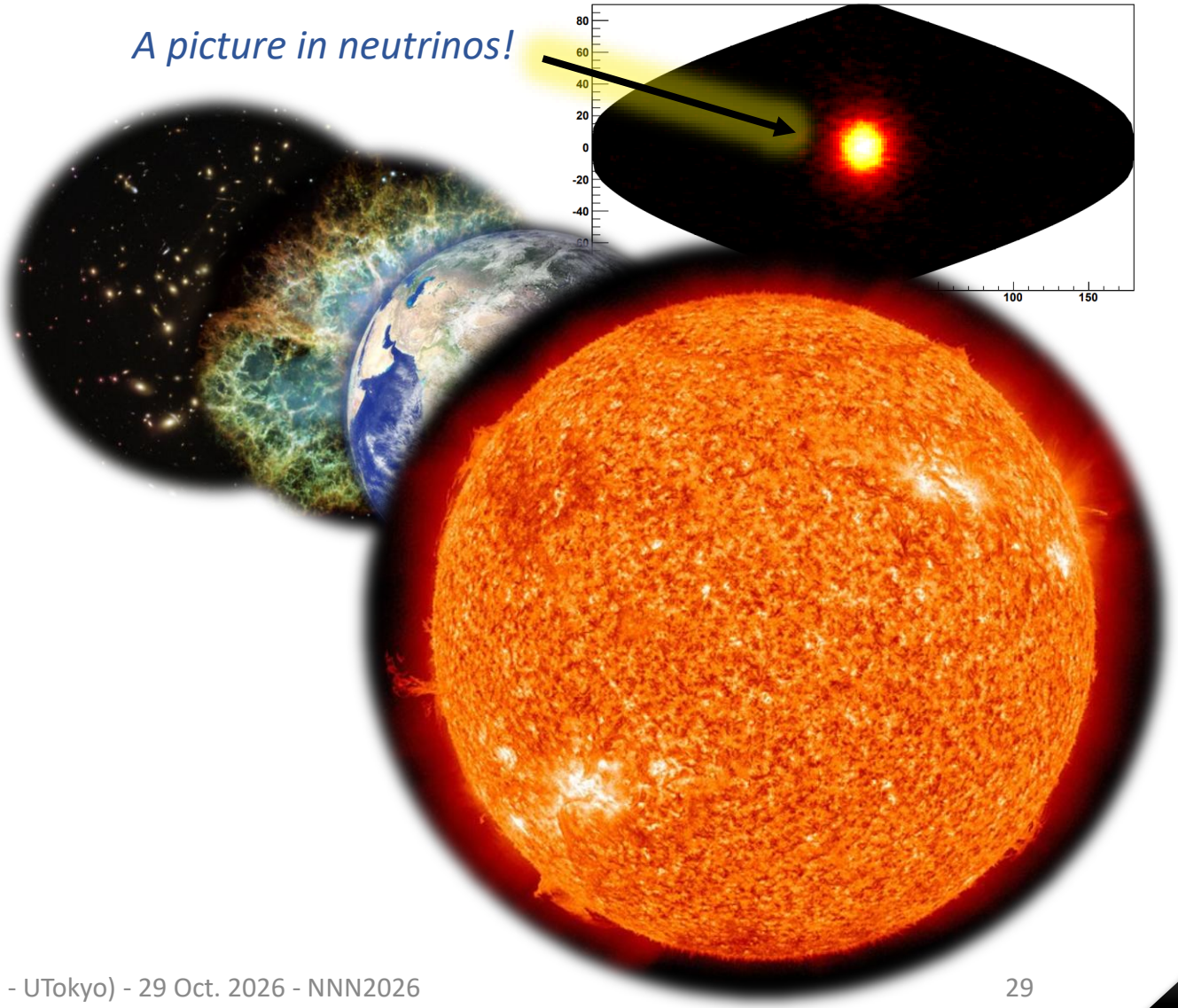
More solar neutrinos!



The Sun as seen by neutrinos

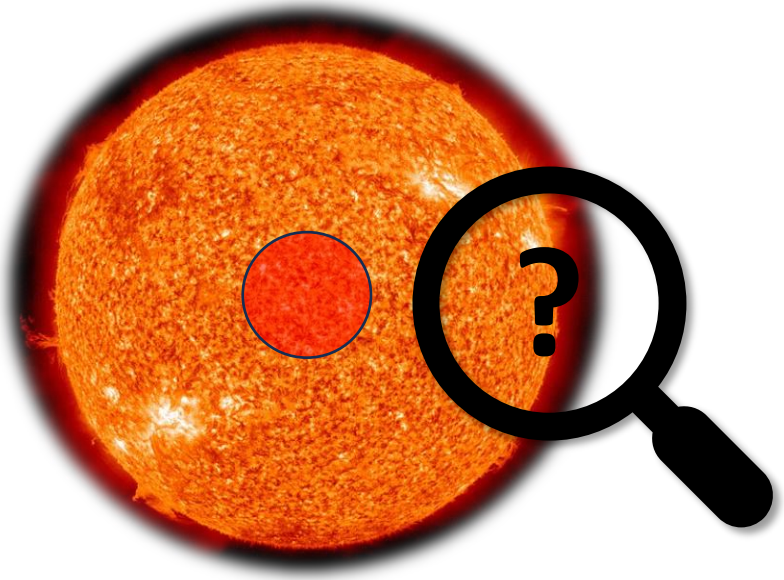


A picture in neutrinos!



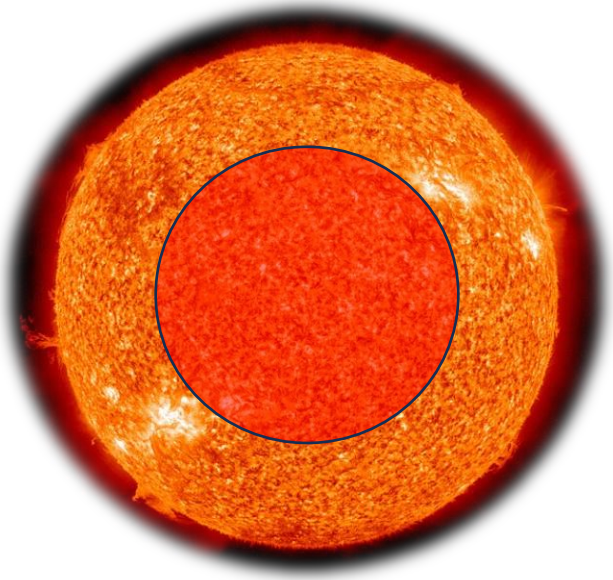
Probing the solar core in neutrinos

Smaller core size



More MSW transition away from ν_e

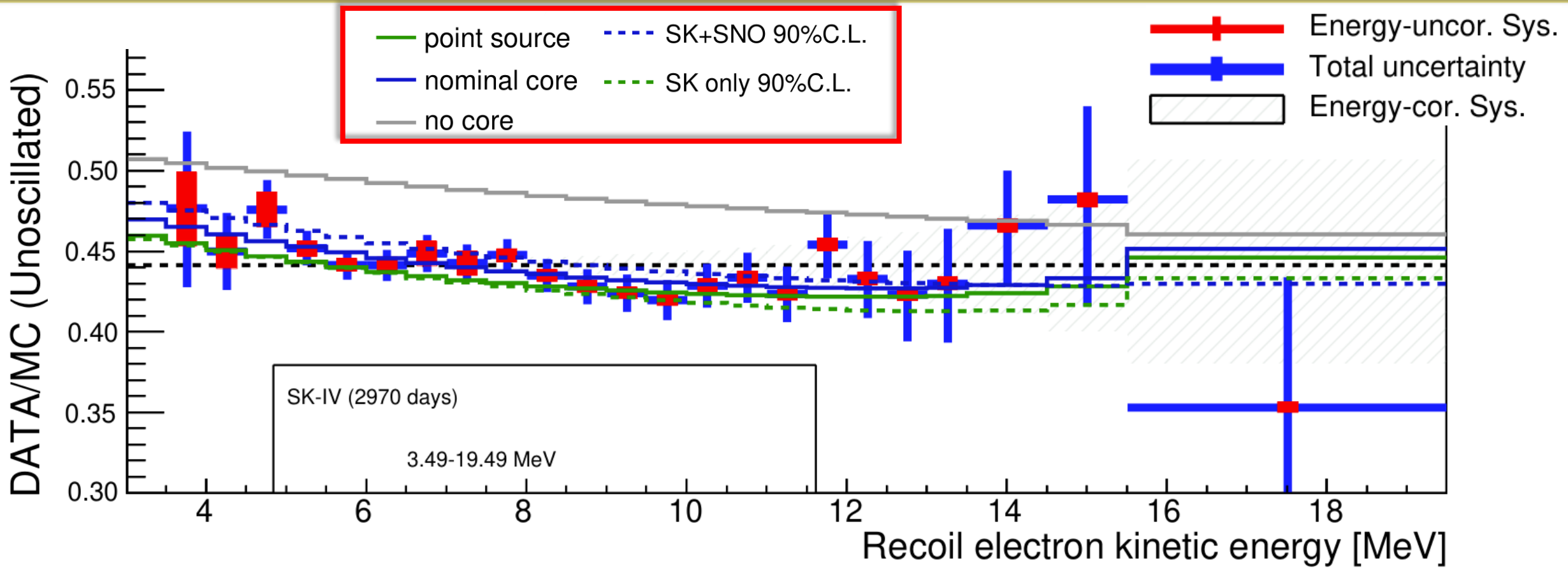
Larger core size



Less MSW transition away from ν_e

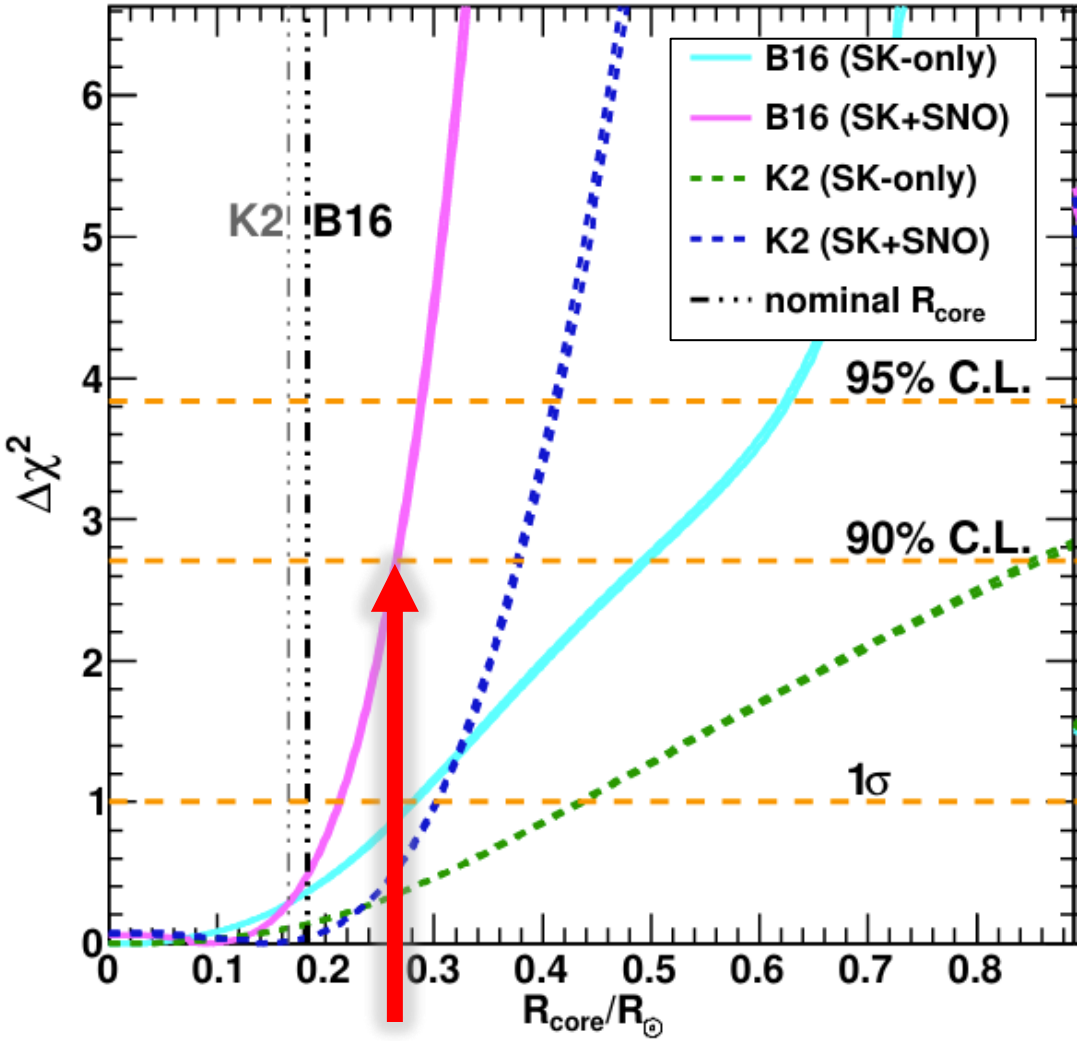
- We can also **probe the solar core**, since the size of the core influences the energy-dependent flavor profile of solar neutrinos.

Probing the solar core in neutrinos



- We can also **probe the solar core**, since the size of the core influences the energy-dependent flavor profile of solar neutrinos.
- The broader the neutrino production zone is, the higher the ratio of data-to-unoscillated-MC becomes.

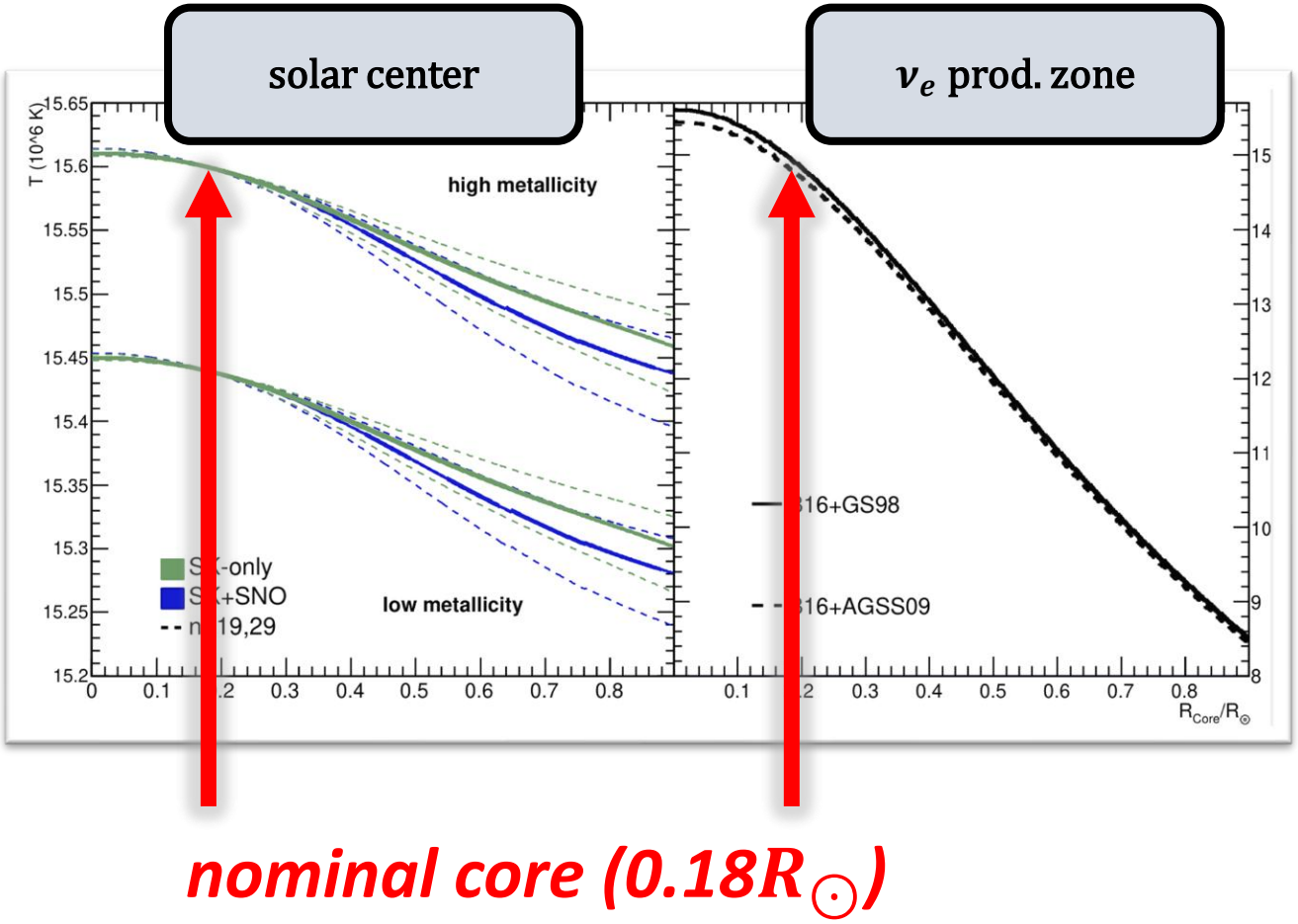
Probing the solar core in neutrinos



- The analysis is **solar model-dependent**, and we consider both the standard solar model (SSM) B16+GS98 and variation K2-A09-Mzvar-12.
- At zero solar core density scaling, the **solar core is constrained** to be $0.268R_\odot$ ($0.381R_\odot$) with SK+SNO data for B16 (K2) model at 90% C.L.

90% C.L. upper limit

Probing the solar core in neutrinos



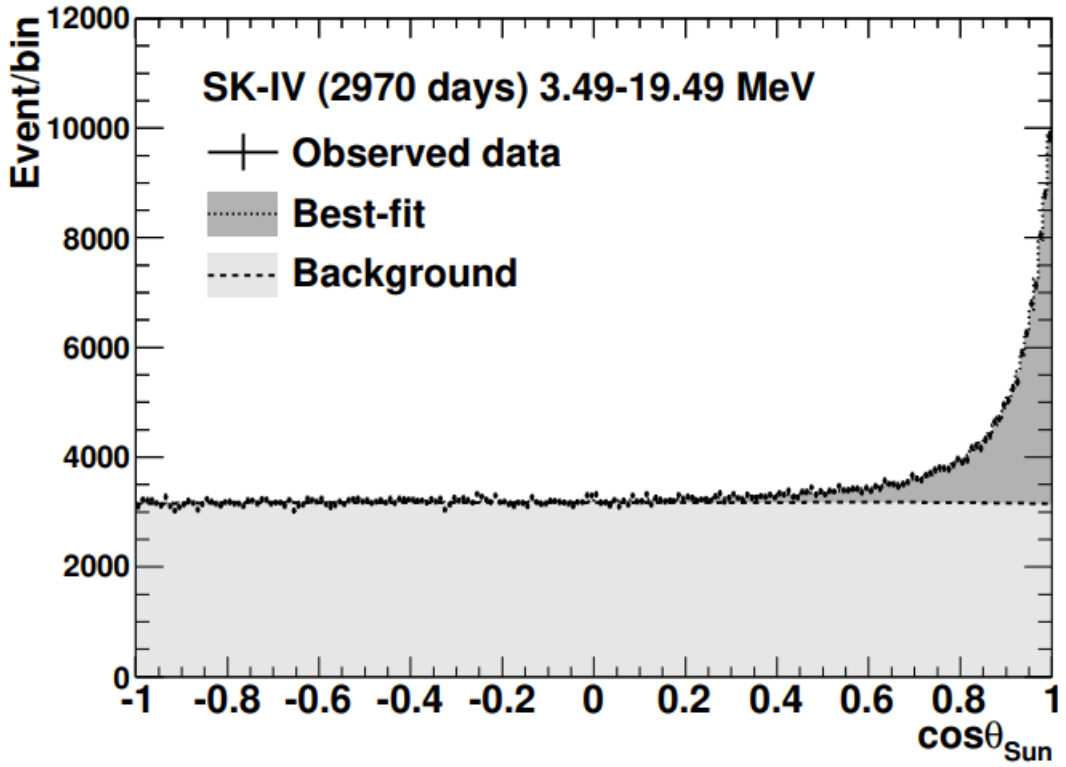
nominal core ($0.18R_\odot$)

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- At zero solar core density scaling, the **solar core is constrained** to be $0.268R_\odot$ ($0.381R_\odot$) with SK+SNO data for B16 (K2) model at 90% C.L.
- At the nominal core size and high metallicity, the **temperature at the solar center** is $(15.599 \pm 0.0016) \times 10^6$ K, and the **temperature of the neutrino production zone** is $(14.492 \pm 0.0017) \times 10^6$ K.

$T \propto \Phi_{8B}^{24\pm5}$ (temp. scaling)

The Sun as seen by neutrinos

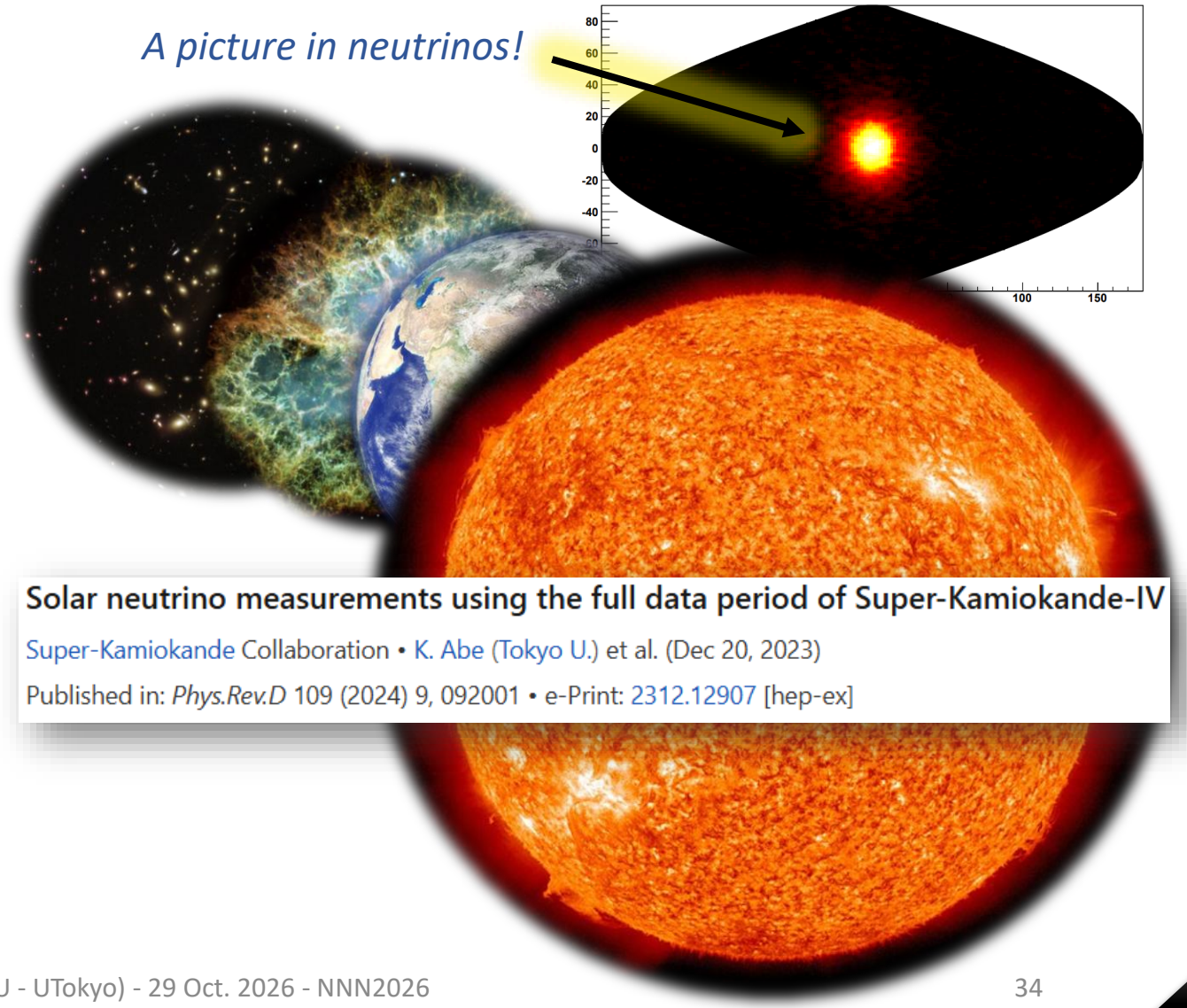
$$\nu + e^- \rightarrow \nu + e^-$$



Solar ν: $65{,}443^{+390}_{-388}(\text{stat.}) \pm 925(\text{sys.})$

PRD 109 (9), 092001 (2024)

A picture in neutrinos!

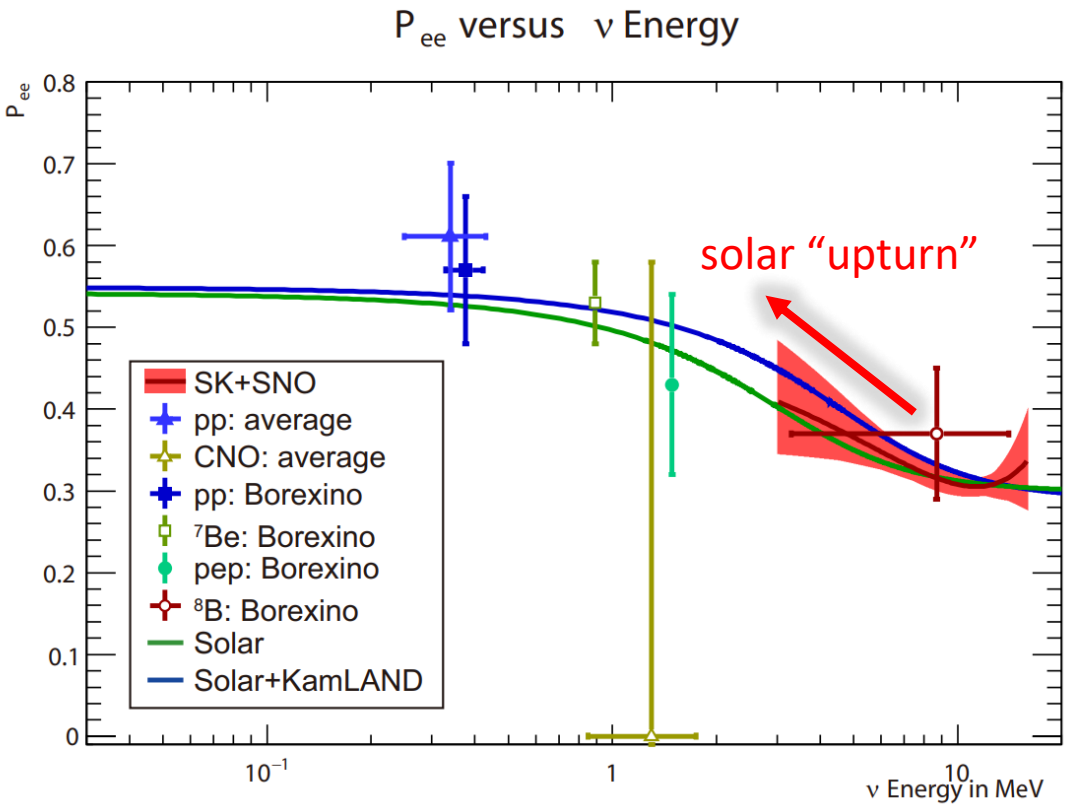


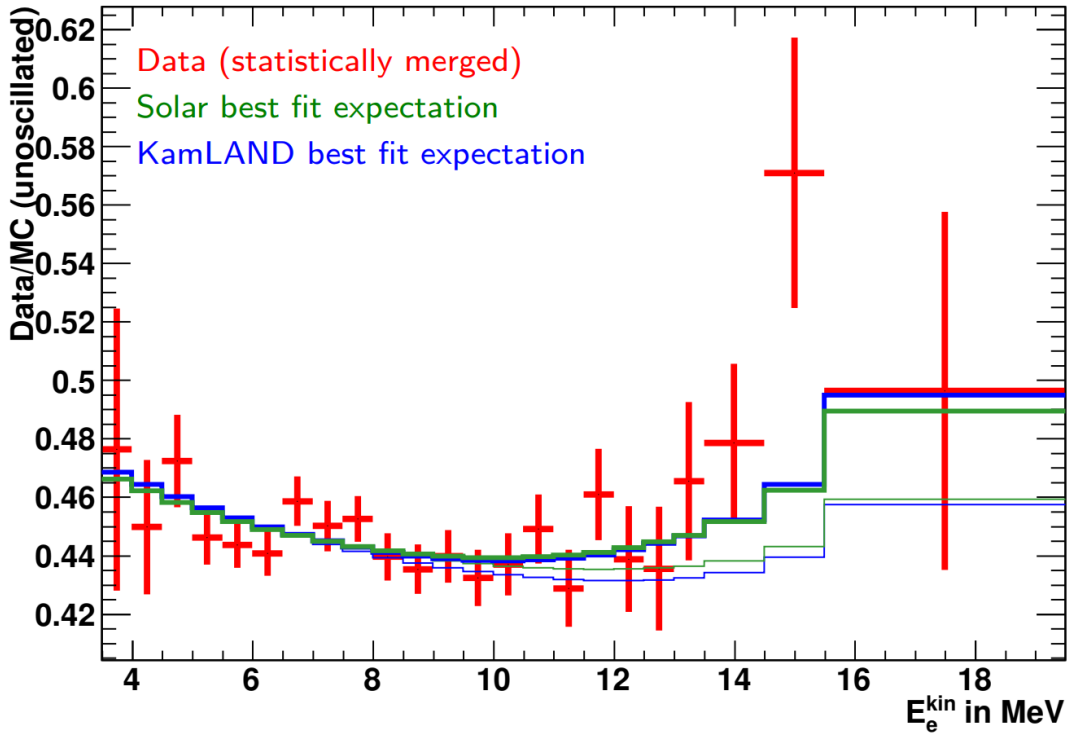
Solar neutrino measurements using the full data period of Super-Kamiokande-IV

Super-Kamiokande Collaboration • K. Abe (Tokyo U.) et al. (Dec 20, 2023)

Published in: *Phys.Rev.D* 109 (2024) 9, 092001 • e-Print: 2312.12907 [hep-ex]

Solar "upturn" in P_{ee} as function of ν energy

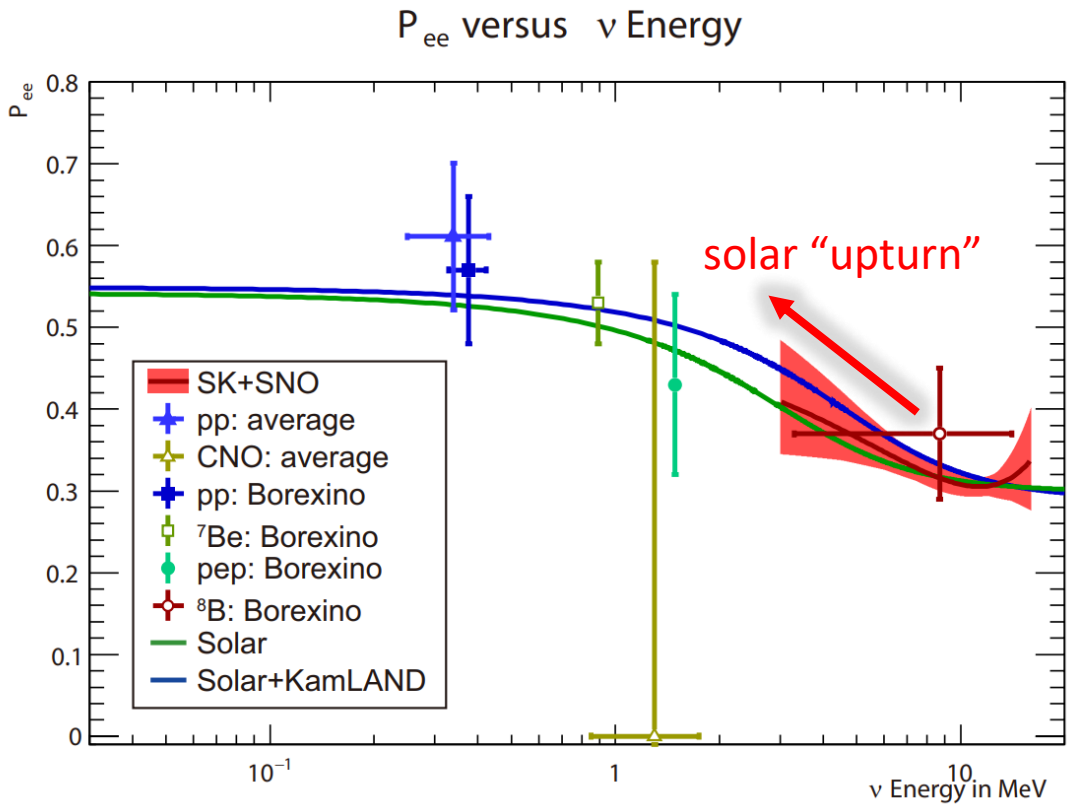




PRD 109 (9), 092001 (2024)

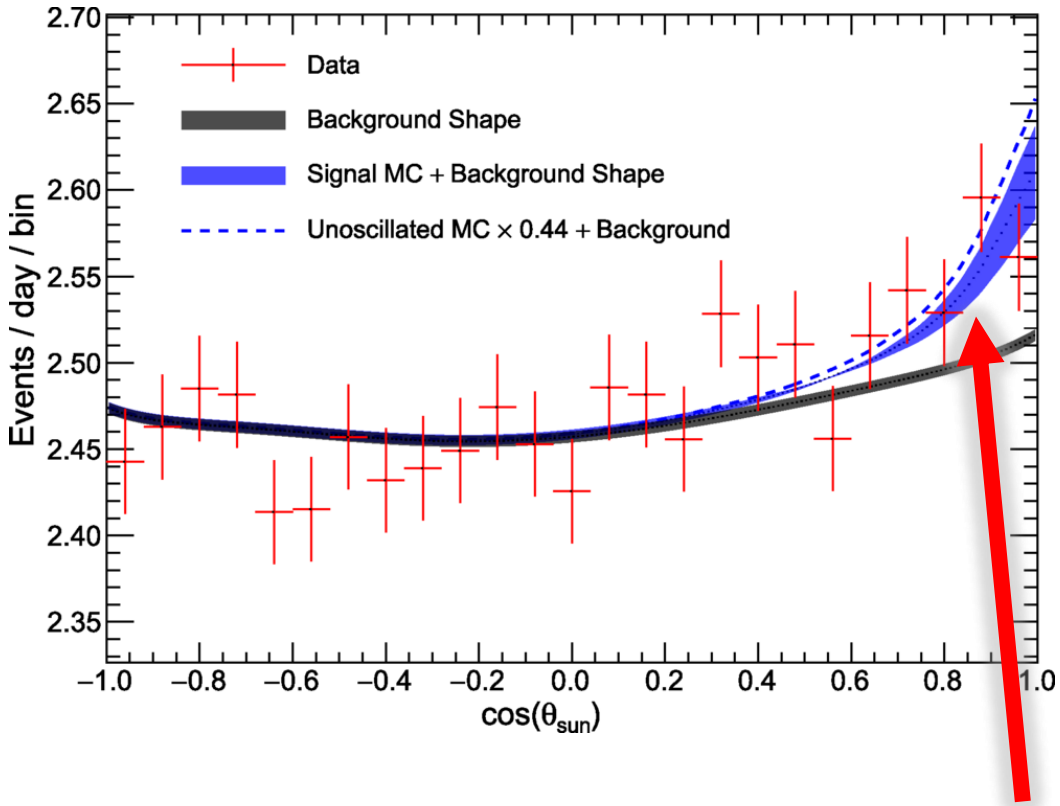
- Going **from high to low energies**, the solar ν_e have a higher survival probability, the so-called "**upturn**."
- Our **current fit disfavors flat distribution** at 1.2σ (2.1σ) with SK (SK+SNO).

Lowered threshold for solar neutrino energy



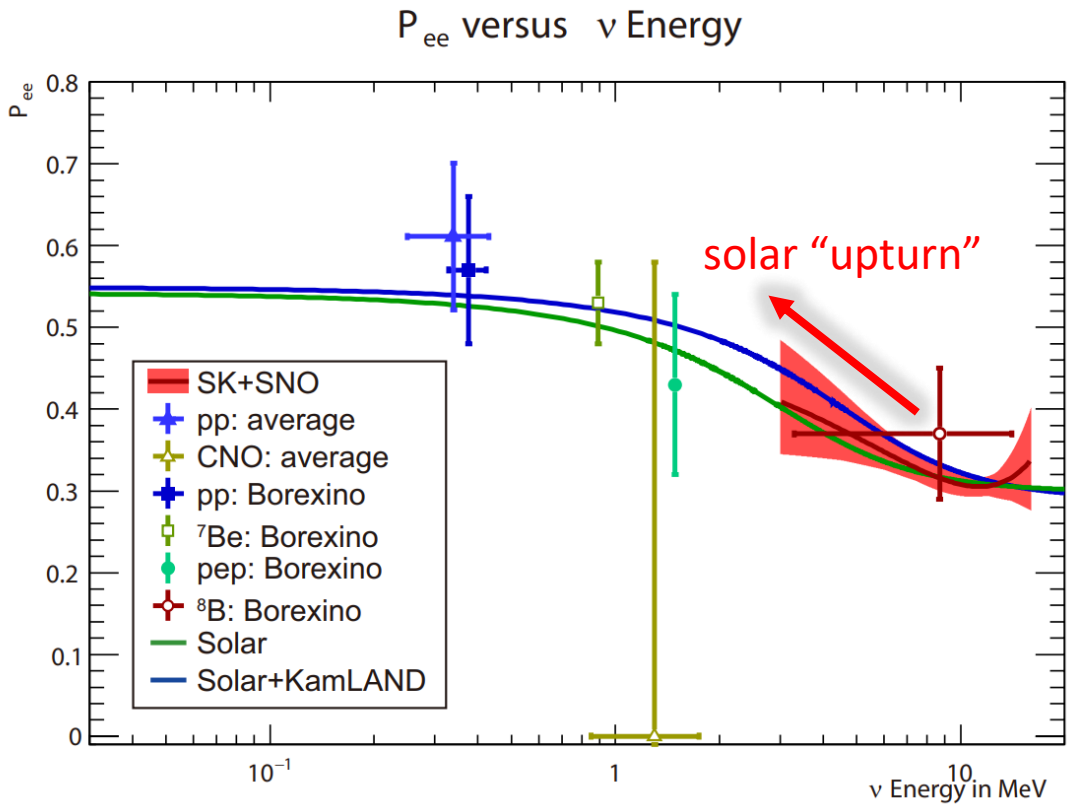
PRD 109 (9), 092001 (2024)

Yankelevich et al., PRD 113, 112001 (2026)



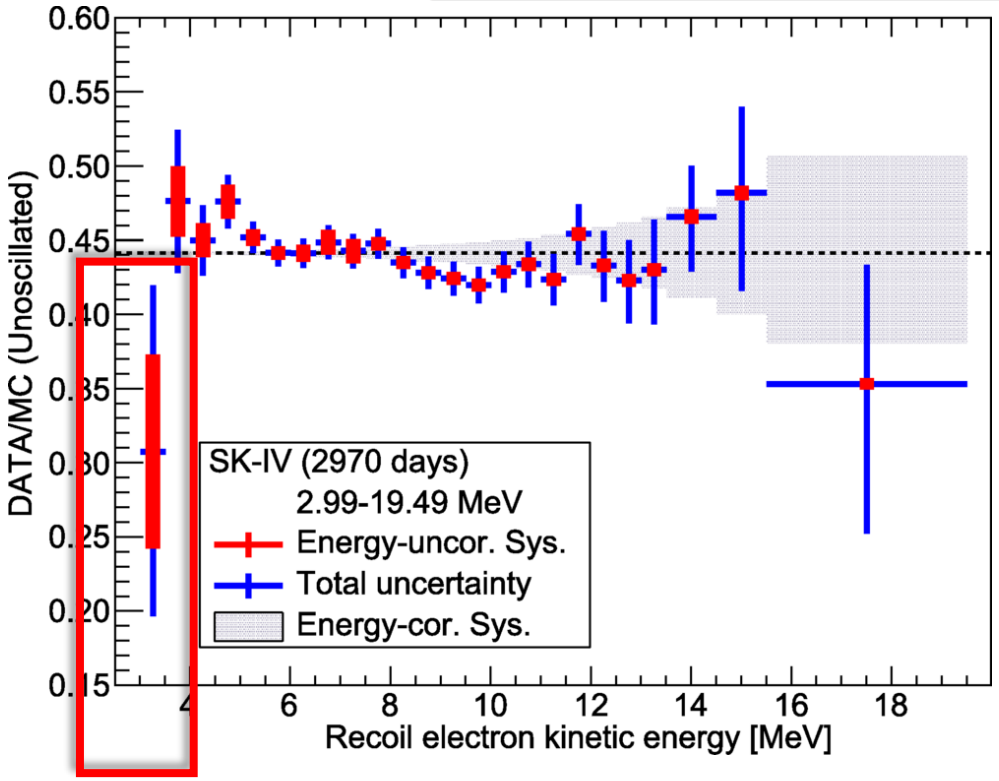
- Using a BDT and lower-energy WIT data (**2.99 to 3.49 MeV**), we observed a **solar neutrino signal** at 2.8σ.

Lowered threshold for solar neutrino energy



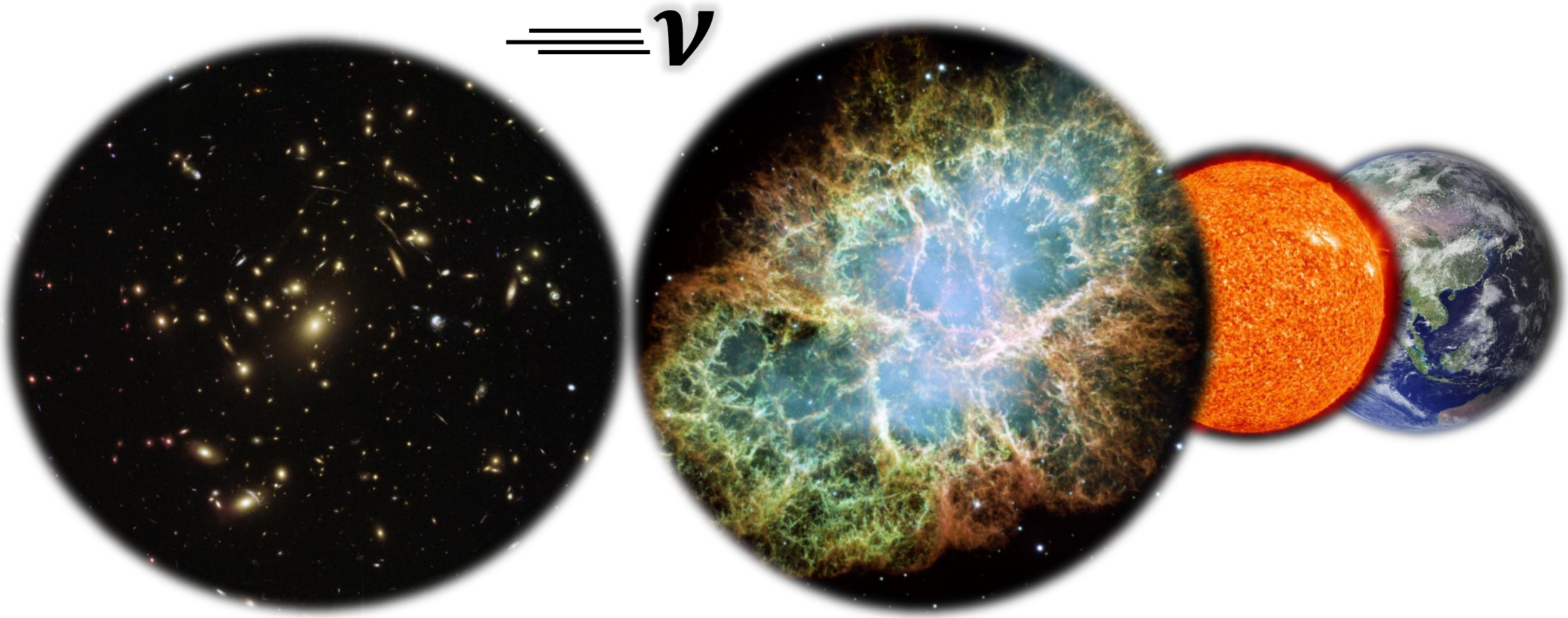
PRD 109 (9), 092001 (2024)

Yankelevich et al., PRD 113, 112001 (2026)



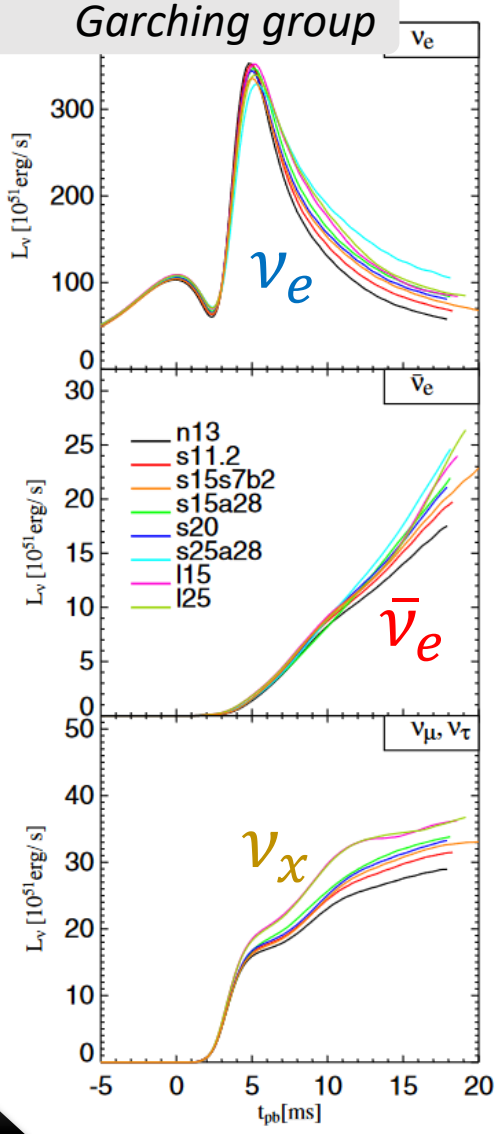
- Using a BDT and lower-energy WIT data (**2.99 to 3.49 MeV**), we observed a **solar neutrino signal** at 2.8σ.
- We can then add a **new lowest-energy bin** in our solar neutrino spectrum.

Core-collapse supernova neutrinos!



Probing core-collapse supernovae using neutrinos in Super-K

Garching group



Combined Pre-supernova Alert System with KamLAND and Super-Kamiokande

KamLAND and Super-Kamiokande Collaborations • Seisho Abe (RCNS, Sendai) et al. (Apr 15, 2024)

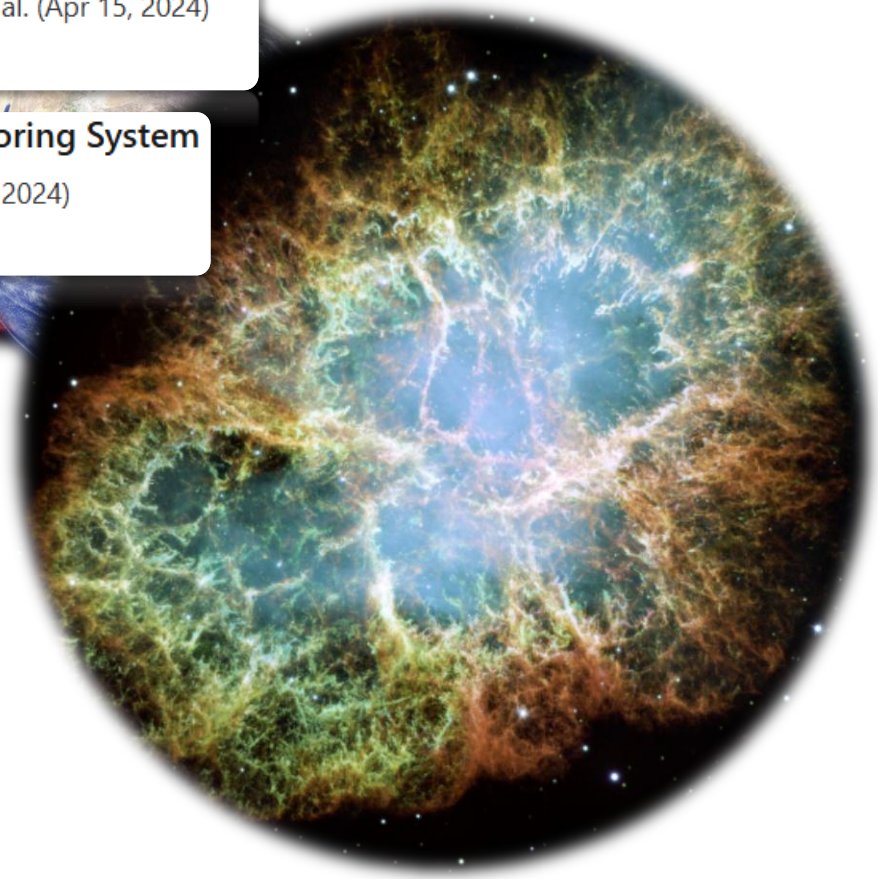
Published in: *Astrophys.J.* 973 (2024) 2, 140 • e-Print: 2404.09920 [hep-ex]

Performance of SK-Gd's Upgraded Real-time Supernova Monitoring System

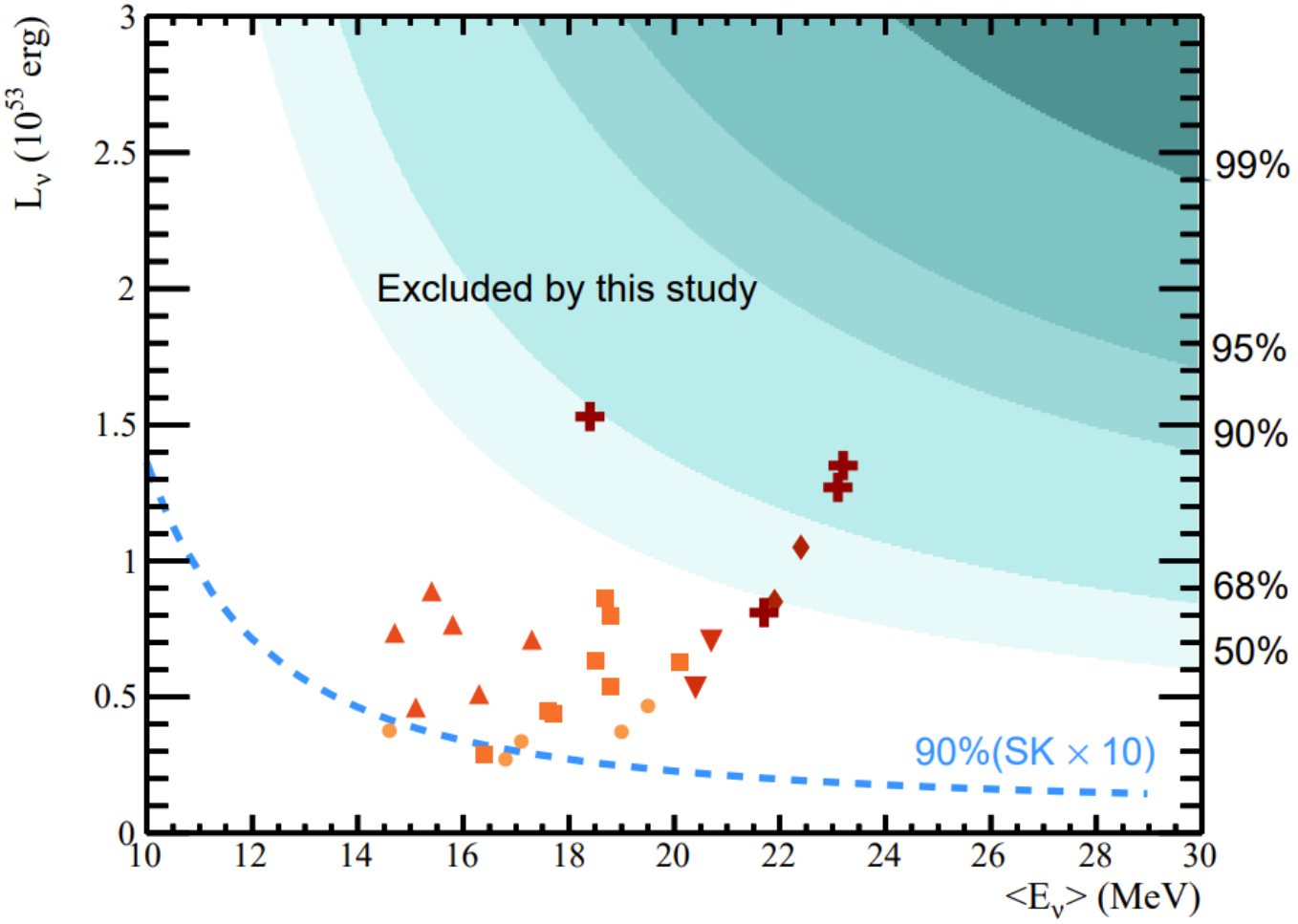
Super-Kamiokande Collaboration • Y. Kashiwagi (Kamioka Observ.) et al. (Mar 11, 2024)

Published in: *Astrophys.J.* 970 (2024) 1, 93 • e-Print: 2403.06760 [astro-ph.HE]

- More than **99% of all energy** released in core-collapse supernovae is in **neutrinos**.
- We are minimizing detector downtime to **detect one nearby**… (last close one in 1987).
- **Recent papers** share our real-time SN monitoring system and combined pre-SN alarm with KamLAND.
- We are even developing a **new lower-energy WIT-driven SN alarm** to complement these!



First Super-K search for failed supernovae neutrinos

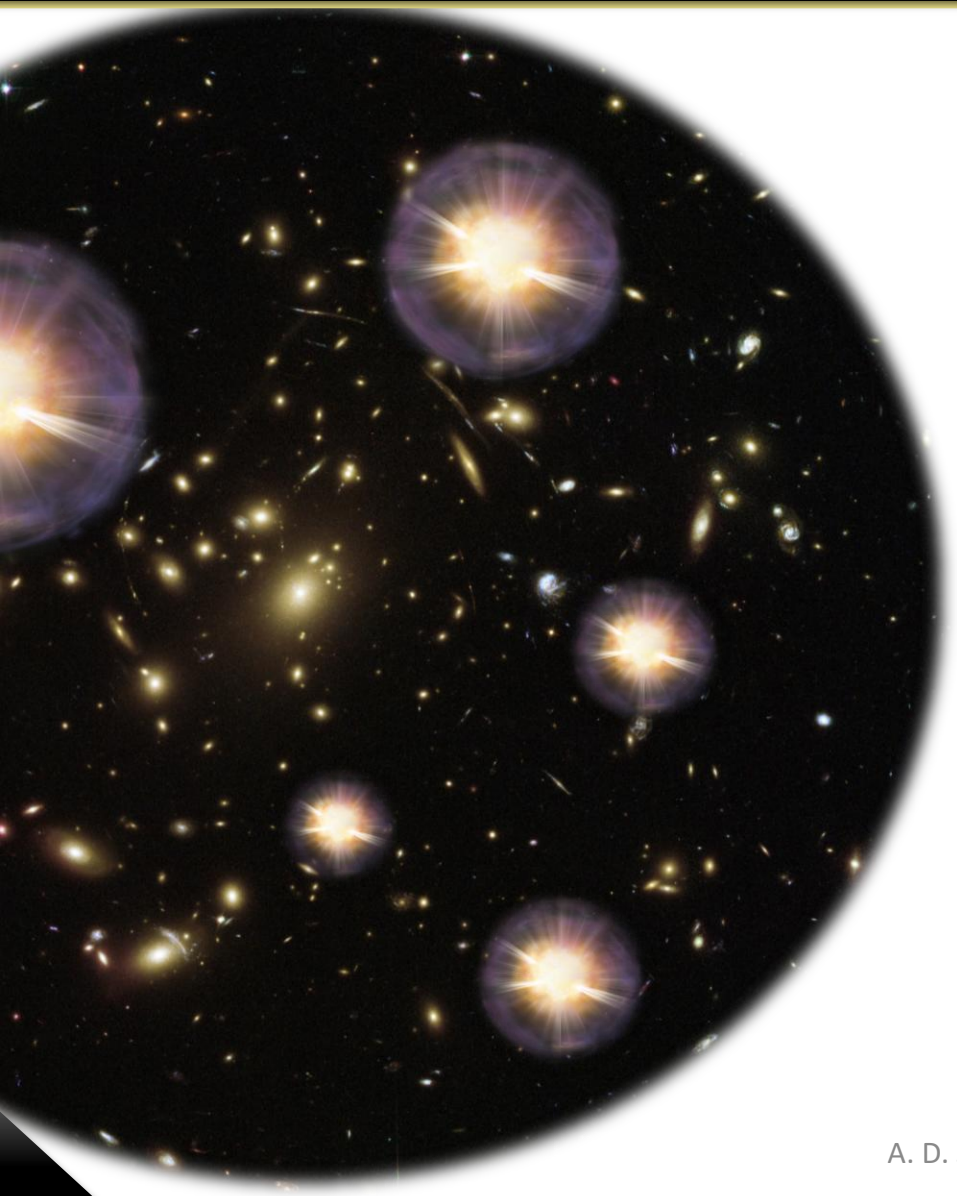


- LS180 ($M^{max}_{s=4} = 2.0\ M_\odot$)
- Shen-TM1 ($M^{max}_{s=4} = 2.6\ M_\odot$)
- LS220 ($M^{max}_{s=4} = 2.1\ M_\odot$)
- Shen-TM1e ($M^{max}_{s=4} = 2.5\ M_\odot$)
- Togashi ($M^{max}_{s=4} = 2.4\ M_\odot$)
- SFHo ($M^{max}_{s=4} = 2.3\ M_\odot$)

- Used Super-K to **follow up on failed supernova for first time** (candidate M31-2014-DS1).
- Scanned in time from 2013-June-1 to 2017-December-31.
- Searched for clusters of neutrino events within 10 seconds above 18 MeV in positron energy (specifically, inverse beta decay or IBD).
- No cluster found and **upper limits** were set.

Nakanishi et al. 2026 ApJL ***997*** *L9*

The Diffuse Supernova Neutrino Background (DSNB)



- Local CCSNe are rare, but **one CCSN happens** somewhere in the universe **$\sim$1/sec**.
- About **99% of all energy** released per CCSN is in the form of **$\sim 10^{58}$ neutrinos**.
- Neutrinos from all such CCSNe should form an ambient sea of particles, the **Diffuse Supernova Neutrino Background** (DSNB).
- Super-K is on the hunt!

What is the Diffuse Supernova Neutrino Background?

$$\frac{d\Phi_{\nu_\alpha}}{dE_{\nu_\alpha}} = \iint R_{CCSN}(z, \vec{Q}) \times \cdots \, dz d\vec{Q}$$

(flux) (energy) (redshift) (progenitor characteristics, e.g., mass)

DSNB = **Supernova** rate $\times \cdots$



- In a **general modeling approach** for the DSNB, we need the **CCSN rate**,…

What is the Diffuse Supernova Neutrino Background?

$$\frac{d\Phi_{\nu_\alpha}}{dE_{\nu_\alpha}} = \iint R_{CCSN}(z, \vec{Q}) \times \left[\frac{dF_{\nu_\alpha}(E'_{\nu_\alpha}, \vec{Q})}{E'_{\nu_\alpha}} \frac{dE'_{\nu_\alpha}}{dE_{\nu_\alpha}} \right] \cdots dz d\vec{Q}$$

(flux) (energy) (redshifted energy) (redshift) (progenitor characteristics, e.g., mass)

DSNB = **Supernova** rate × **Neutrinos** emitted per supernova × ...





- In a **general modeling approach** for the DSNB, we need the **CCSN rate**, the **ν emission flux**,...

What is the Diffuse Supernova Neutrino Background?

$$\frac{d\Phi_{\nu_\alpha}}{dE_{\nu_\alpha}} = \iint R_{CCSN}(z,\vec{Q}) \times \left[\frac{dF_{\nu_\alpha}(E'_{\nu_\alpha},\vec{Q})}{E'_{\nu_\alpha}}\frac{dE'_{\nu_\alpha}}{dE_{\nu_\alpha}}\right] \times \left|c\frac{\mathrm{dt}}{dz}\right| dz d\vec{Q}$$

(flux) (energy) (redshift) (progenitor characteristics, e.g., mass)

DSNB = **Supernova** rate × **Neutrinos** emitted per supernova × Universe **expansion**







- In a **general modeling approach** for the DSNB, we need the **CCSN rate**, the **ν emission flux**, and **expansion**.

What is the Diffuse Supernova Neutrino Background?

$$\frac{d\Phi_{\nu_\alpha}}{dE_{\nu_\alpha}} = \iint R_{CCSN}(z, \vec{Q}) \times \left[\frac{dF_{\nu_\alpha}(E'_{\nu_\alpha}, \vec{Q})}{E'_{\nu_\alpha}} \frac{dE'_{\nu_\alpha}}{dE_{\nu_\alpha}} \right] \times \left| c \frac{\mathrm{dt}}{dz} \right| dz d\vec{Q}$$

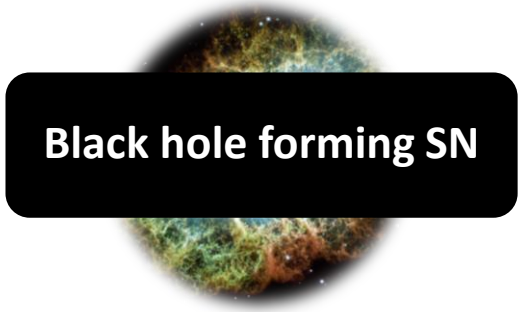
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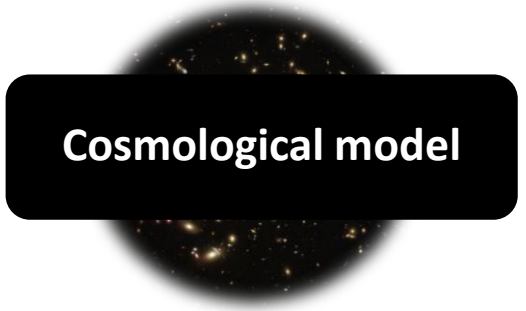
Probe these!



Star formation history



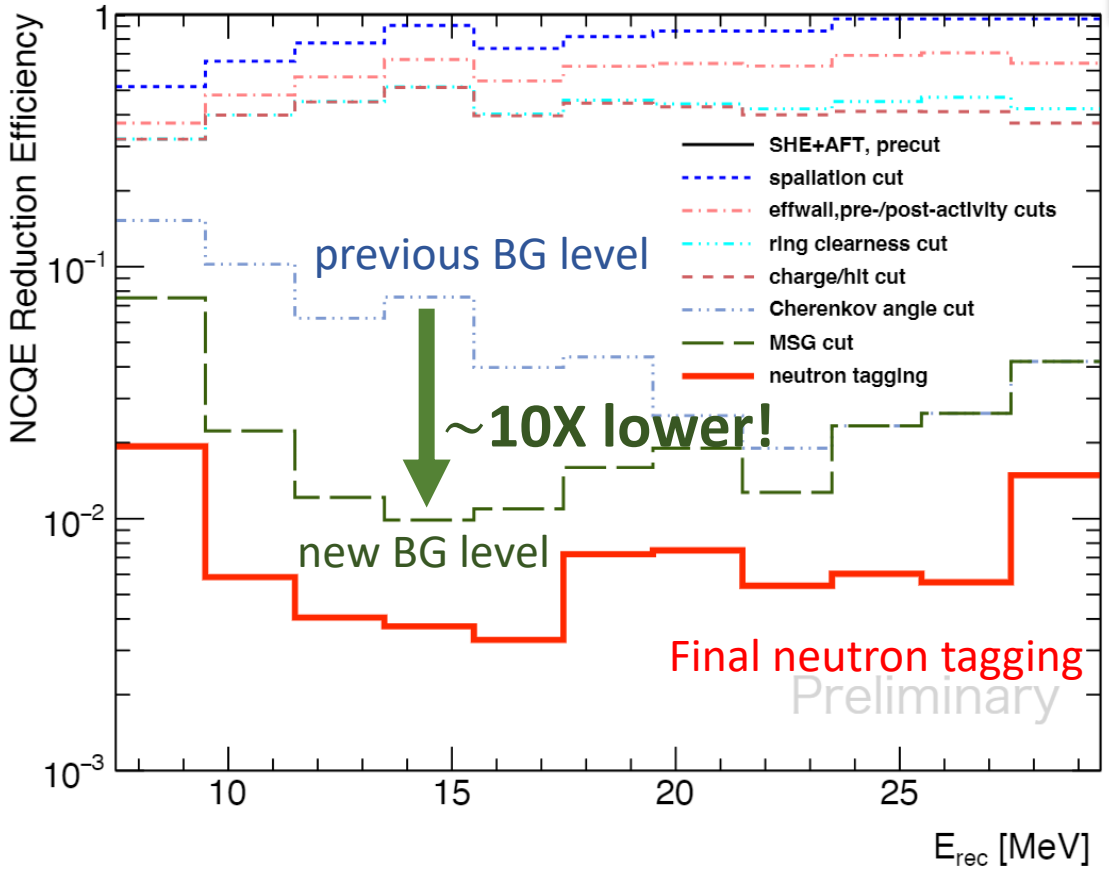
Black hole forming SN



Cosmological model

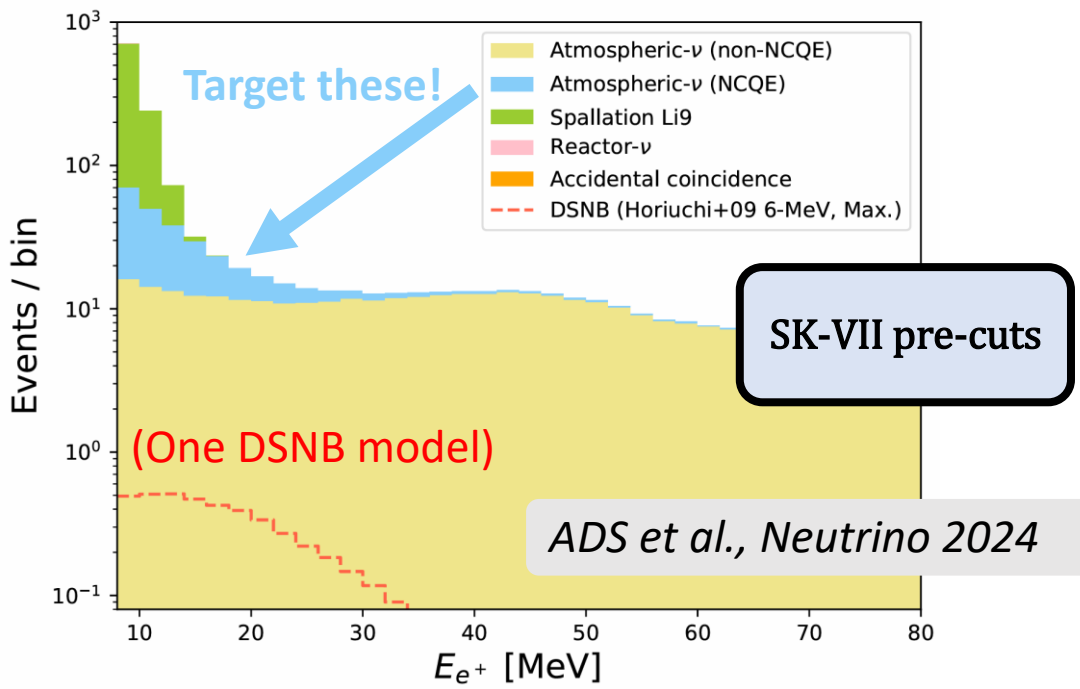
- In a **general modeling approach** for the DSNB, we need the **CCSN rate**, the **ν emission flux**, and **expansion**.
- DSNB predictions are dependent on a variety of **parameters** (e.g., the **star formation rate** in the universe, the fraction of supernovae that form **black holes**, and **simulation approaches**).
- We are then capable of probing aspects across **astrophysics**, **particle physics**, and **cosmology**.

Improved atmospheric background reduction for DSNB



Search for Diffuse Supernova Neutrino Background with 956.2 Days of Super-Kamiokande Gadolinium Dataset

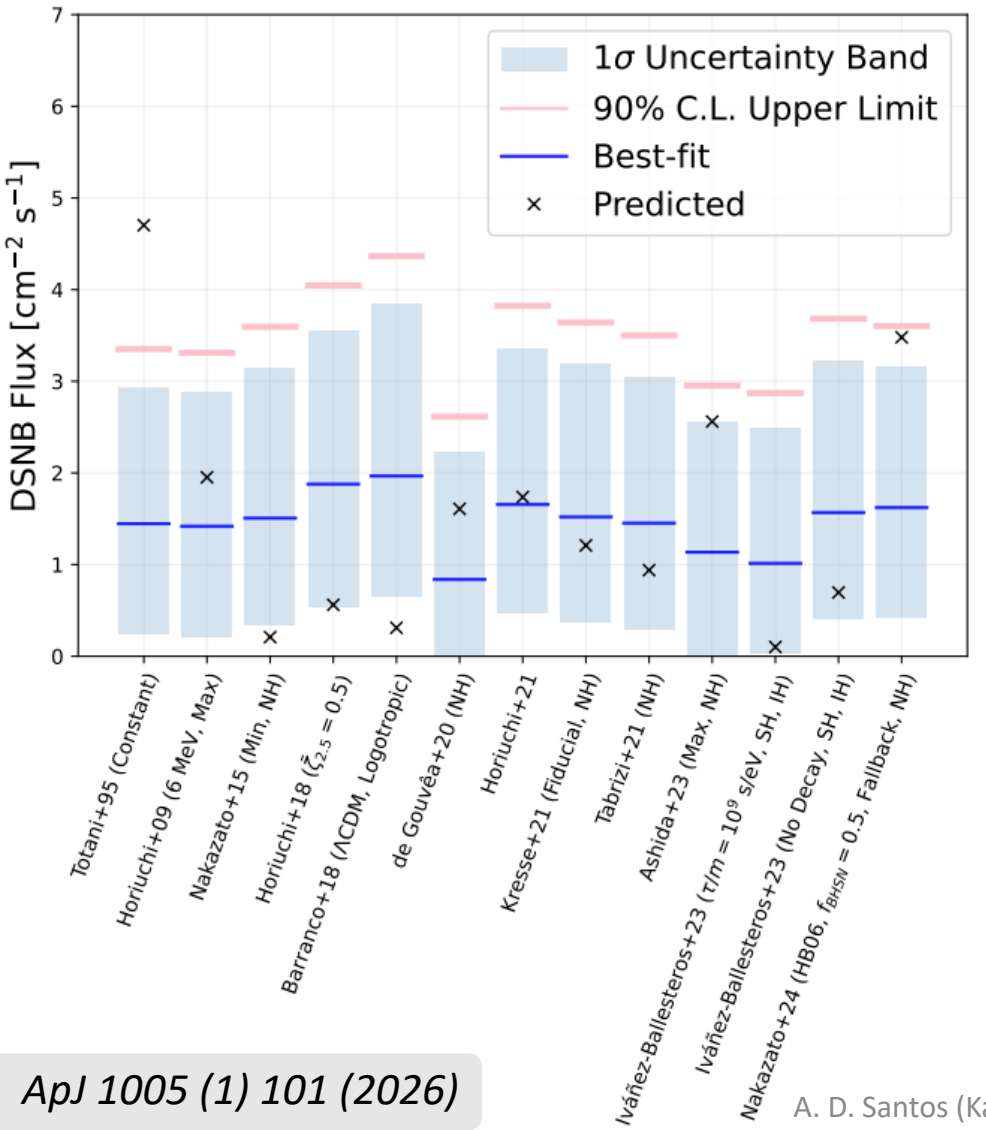
- We improved **atmospheric ν rejection** with a variable targeting Cherenkov cone substructure.



ADS et al., Neutrino 2024

ApJ 1005 (1) 101 (2026)

First SK-Gd spectrum fitting results (SK-VI/VII)



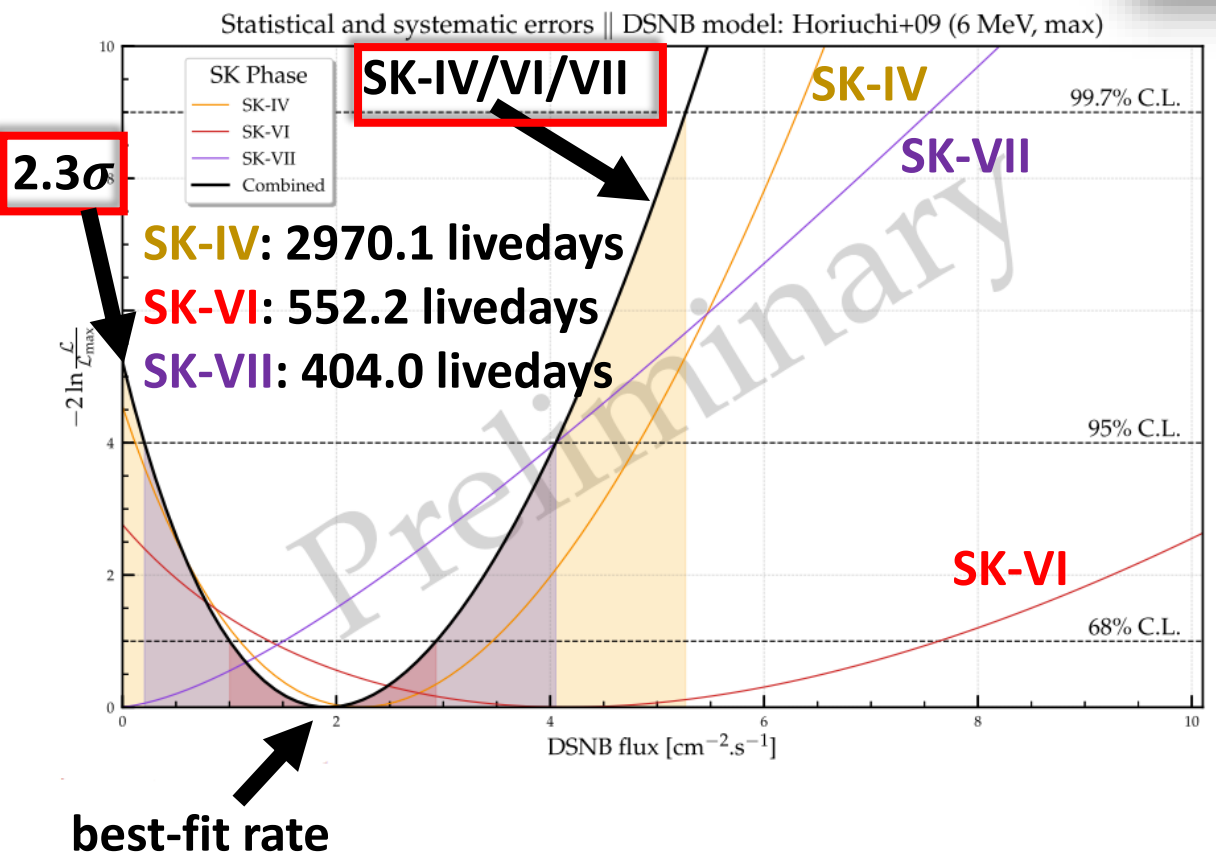
ApJ 1005 (1) 101 (2026)

Search for Diffuse Supernova Neutrino Background with 956.2 Days of Super-Kamiokande Gadolinium Dataset

- We improved **atmospheric ν rejection** with a variable targeting Cherenkov cone substructure.
- We observed **$\sim 1.2\sigma$ rejection** of BG-only hypothesis in an energy spectrum fitting approach for SK VI/VII.

First SK neutron tagging era spectrum fitting results

XXXI International Conference on Neutrino Physics and Astrophysics
June 16-22, 2024 Milan, Italy

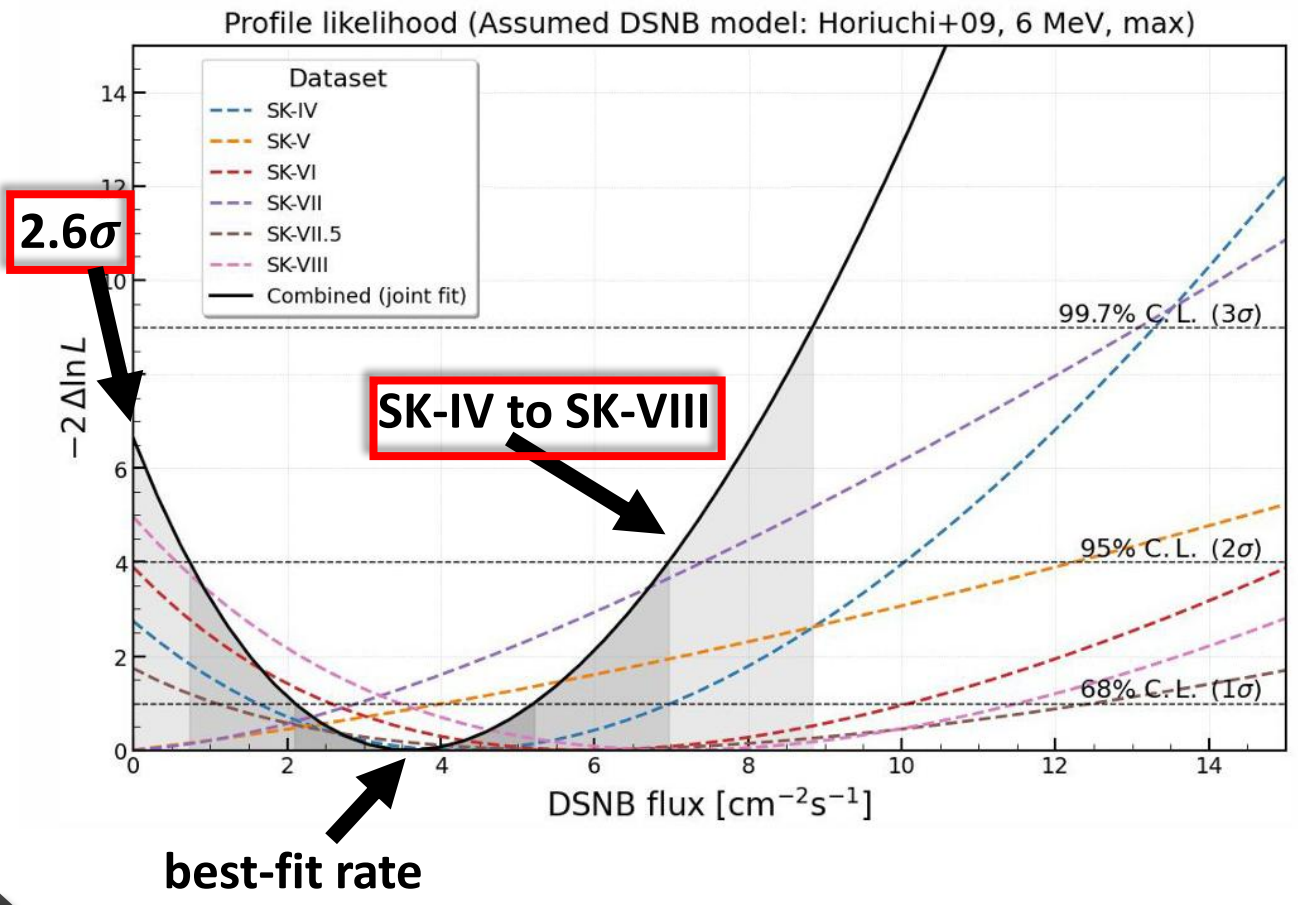


- We improved **atmospheric ν rejection** with a variable targeting Cherenkov cone substructure.
- We observed ~**1.2σ rejection** of BG-only hypothesis in an energy spectrum fitting approach for SK VI/VII.
- Likelihood combination of **SK IV/VI/VII** in spectral approach **preliminarily demonstrated ~2.3σ** level.

Newest Result: First indication of the DSNB at $\sim 2.6\sigma$

arXiv:2610:35619

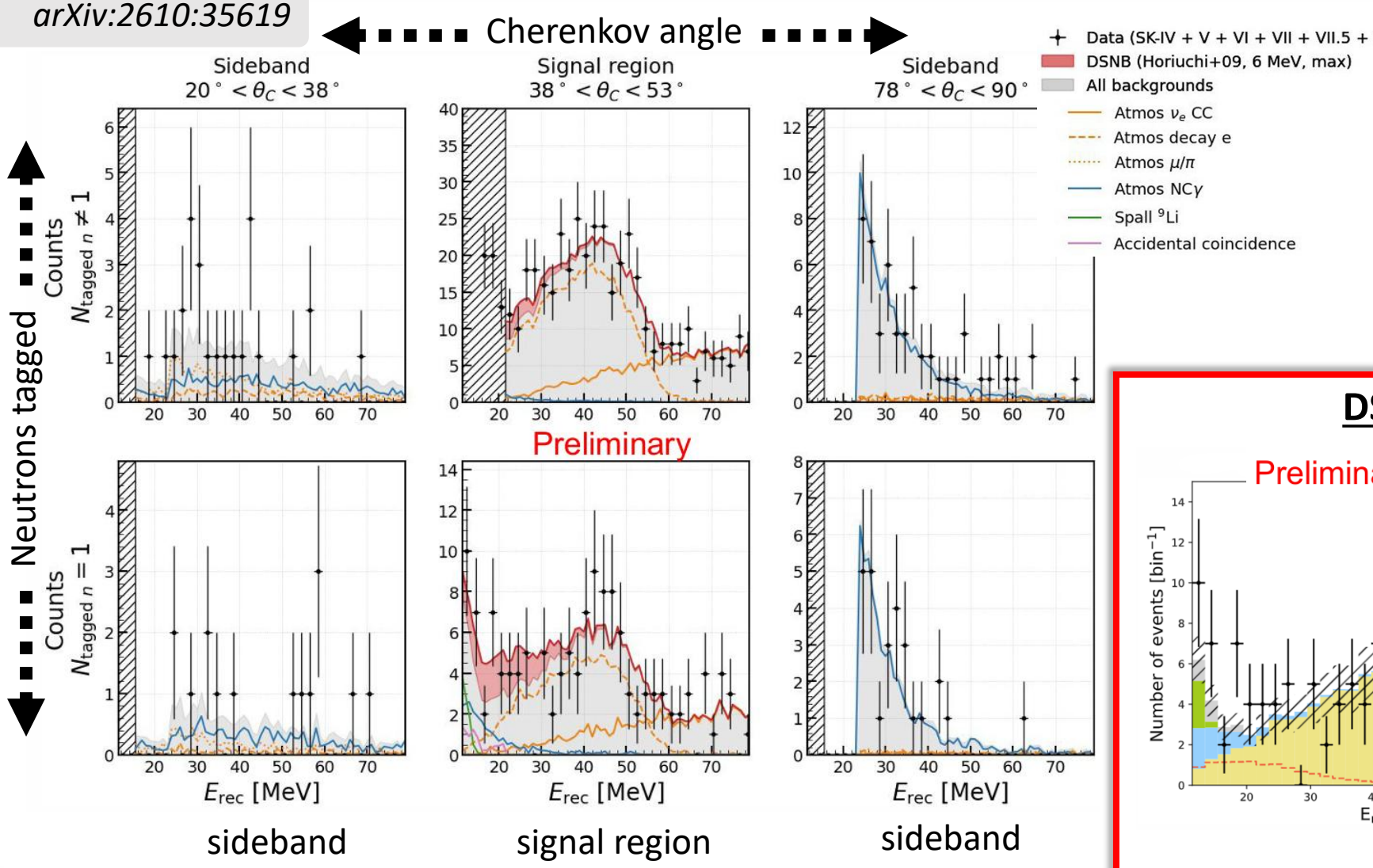
International Conference on Neutrino Physics and Astrophysics
June 22nd - 26th, 2026



- We improved **atmospheric ν rejection** with a variable targeting Cherenkov cone substructure.
- We observed $\sim$**1.2σ rejection** of BG-only hypothesis in an energy spectrum fitting approach for SK VI/VII.
- Likelihood combination of **SK IV/VI/VII** in spectral approach **preliminarily demonstrated** $\sim$**2.3σ** level.
- Full combination until SK-VIII leads to **$\sim$2.6σ** level!
- The other key analysis updates are:
  - **Refining** spallation reduction, neutron identification, and NC background removal.
  - **Lowering** the energy threshold for the sample with one tagged neutron and $\theta_c \in [38°, 53°]$.
  - **Improving** modeling and systematics for Li-9, neutron multiplicity, and NCQE backgrounds.

Newest Result: First indication of the DSNB at ~2.6σ

arXiv:2610:35619



Spectral fitting approach

DSNB Flux ($E_{rec} > 11.5$ MeV)

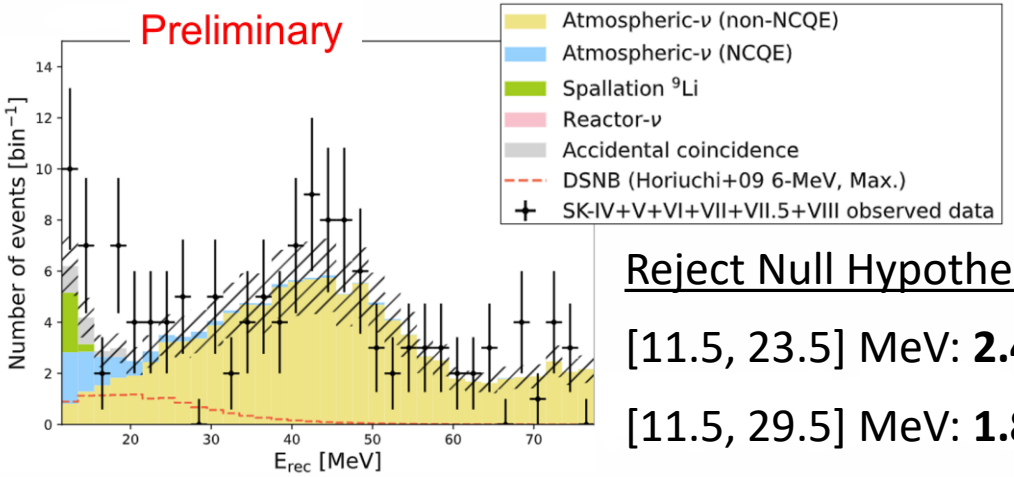
Reject Null Hypothesis: **2.6σ**

Best-fit: $3.6^{+1.6}_{-1.5}$ cm^{-2} s^{-1}

Predicted: $(2.1 - 3.9)$ cm^{-2} s^{-1}

(Horiuchi+09, 6MeV, min-max)

DSNB model-independent approach



Reject Null Hypothesis:

[11.5, 23.5] MeV: **2.4σ**

[11.5, 29.5] MeV: **1.8σ**

SK-Gd: Summary and conclusions

Highlights of results, status, and future

- **Atmospheric oscillation** measurements of $|\Delta m^2_{31,32}|, \theta_{23}$ preferring the lower octant.
- Normal **hierarchy** favored at 1σ and best-fit $\delta_{CP} = -3\pi/4$ favoring large **CP violation**.
- First **observation of reactor $\overline{\nu}_e$** at 6σ thanks to Gd-loading.
- First measurements of the **solar core** (size, temperature).
- Seeing even **lower-energy solar neutrinos** thanks to WIT.
- First SK neutrino follow-up search for **failed supernova** and limits set on neutrino emission.
- **First indication** ($\sim 2.6\sigma$) of the **Diffuse Supernova Neutrino Background** using SK all neutron tagging phases.
- **Next**: Continue data-taking at **0.033% Gd-loading through the 2020s** until stable Hyper-Kamiokande operation.

