5-SEP-2022 @NOW 2022

RECENT OSCILLATION RESULTS AND FUTURE PROSPECTS OF SUPER-KAMIOKANDE

Yasuo TAKEUCHI
(Kobe University)
for SK collaboration

Inside of SK detector during refurbishment work (July 15, 2018)

The Super-Kamiokande collaboration

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
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Fukuoka Institute of Technology, Japan
Gifu University, Japan
GIST, Korea
University of Hawaii, USA
IBS, Korea
IFIRSE, Vietnam
Imperial College London, UK
ILANCE, France

INFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
Keio University, Japan
KEK, Japan
King's College London, UK
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Okayama University, Japan
University of Oxford, UK

Rutherford Appleton Laboratory, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Stony Brook University, USA
Tohoku University, Japan
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
TRIUMF, Canada
Tsinghua University, China
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan

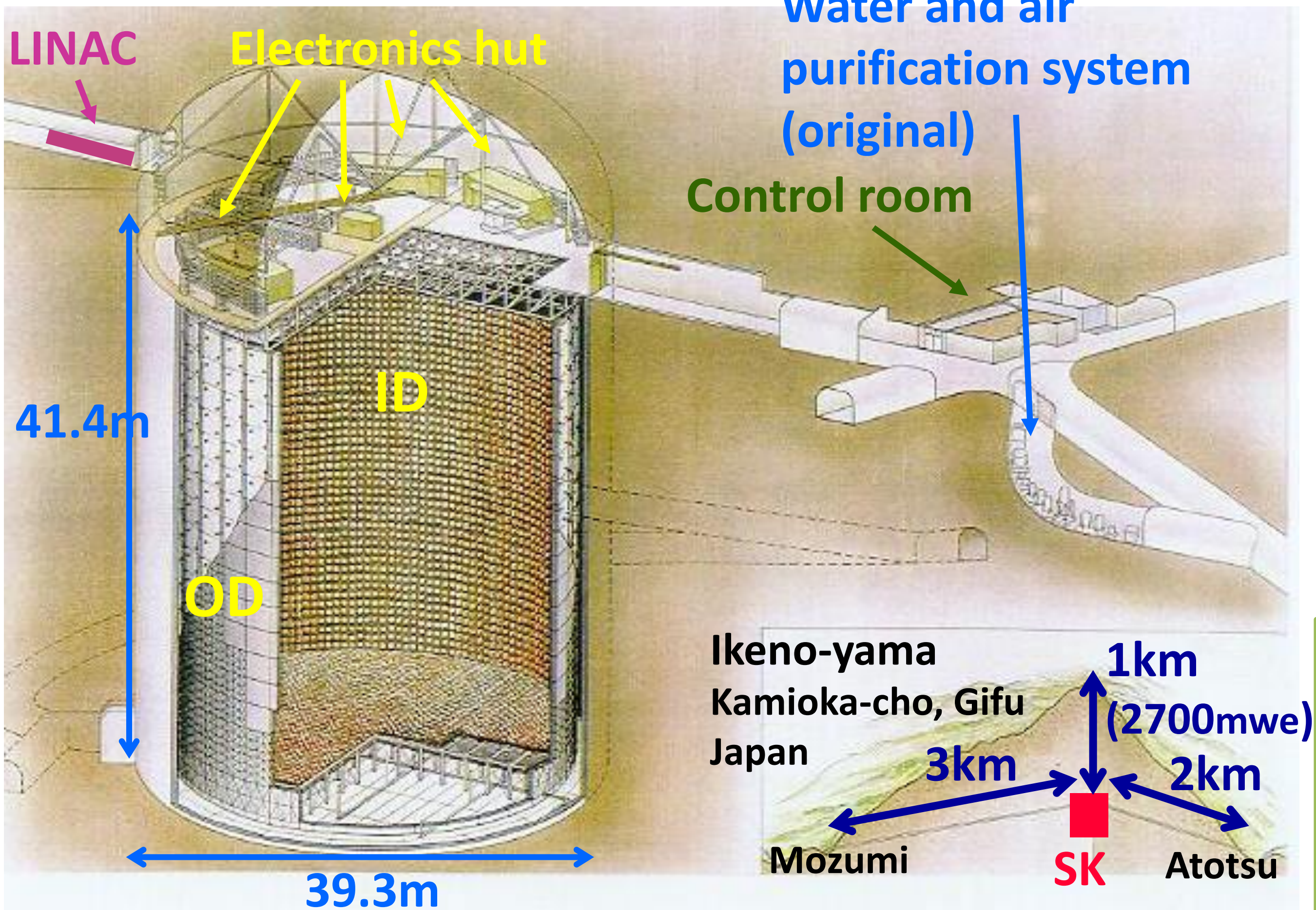
~230 collaborators from 51 institutes in 11 countries (as of May 2022)

Outline

- SK detector & summary of recent results
- Atmospheric neutrino oscillation results
- Solar neutrino oscillation results
- Status and prospects of SK-Gd
- Summary

Super-Kamiokande detector

https://www-sk.icrr.u-tokyo.ac.jp/sk/



- 50 kton water Cherenkov detector
- ~2 m OD viewed by 8-inch PMTs
- 32 kt ID viewed by 20-inch PMTs
- 22.5 kt fid. vol. (conventional)
- SK-I: April 1996~
- SK-VII is running

Physics targets:
- Nucleon decay search
- Neutrino oscillation study
- Astrophysical neutrino search

Inner Detector (ID) PMT: ~11100 (SK-I,III~VII), ~5200 (SK-II)
Outer Detector (OD) PMT: 1885

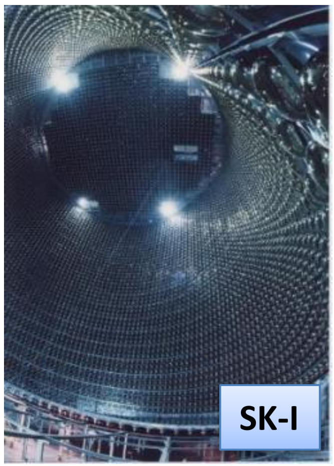
History of Super-Kamiokande

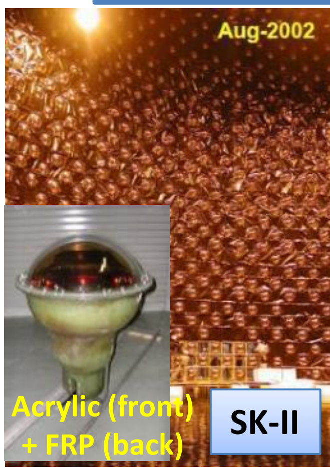
96 97 98 99 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28

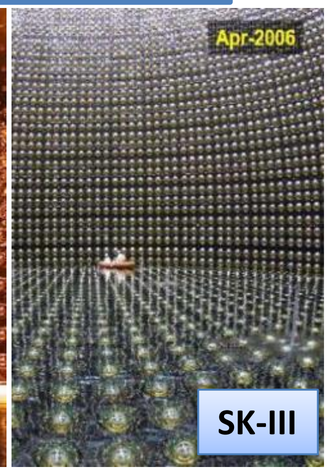
SK-I SK-II SK-III SK-IV SK-V SK-VI SK-VII

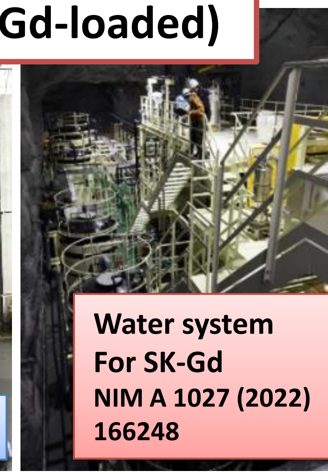
"SK" (pure water)

"SK-Gd" (Gd-loaded)









SK-I	SK-II	SK-III	SK-IV	SK-V	SK-Gd
11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade	Refurbishment for SK-Gd	Neutron tagging with Gd
4.49 MeV	6.49 MeV	4.49 MeV	3.49 MeV	(~3.49 MeV)	
1496 days	791 days	548 days	2970 days	(~380 days) *(preliminary)*	

Gd concentration
SK-VI: 0.011%
(18 Aug. 2020-)
SK-VII: 0.03%
(5 Jul. 2022-)

- Analysis energy threshold (recoil electron kinetic energy)
- Live time for solar neutrino analysis

Total live time for current oscillation analysis:
5805 days (SK-I~IV, for solar)
6511 days (SK-I~V, for atmospheric)

Summary of recent results

- **Nucleon decay search**
  - PRD 101, 052011 (2020), PRD 102, 112011 (2020), PRD 103, 012008 (2021)
  - Current result: SK 450 kt·yr (27.2 kt enlarged fid. vol., SK-I~IV)
    - $\tau/B(p \rightarrow e^{+} \pi^{0})$ > 2.4×10^{34} years (90%CL)
- **Atmospheric ν oscillation analysis**
  - PRD97, 072001 (2018): SK 5326 days, 328 kt·yr
  - Current preliminary analysis: SK-I~V 6511 days, 484.2 kt·yr — May 2022
- **Solar ν oscillation analysis**
  - PRD94, 052010 (2016): (SK-IV: until Feb. 2014, 1664 days)
  - Current data set: SK 5805 days (until end of SK-IV) — Updated in May 2022
- **Astrophysics**
  - Pre-supernova alert system: ApJ. 935, 40 (2022)
  - Solar anti ν search: Astropart. Phys. 139, 102702 (2022)
  - DSNB search: PRD 104, 122002 (2021)
  - GRB ν search: PTEP 2021, 103F01 (2021)
  - GW ν search: ApJ. 918, 78 (2021)

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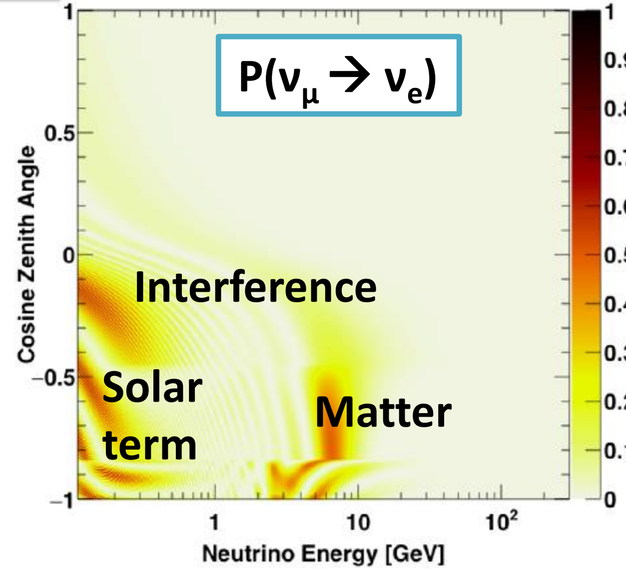
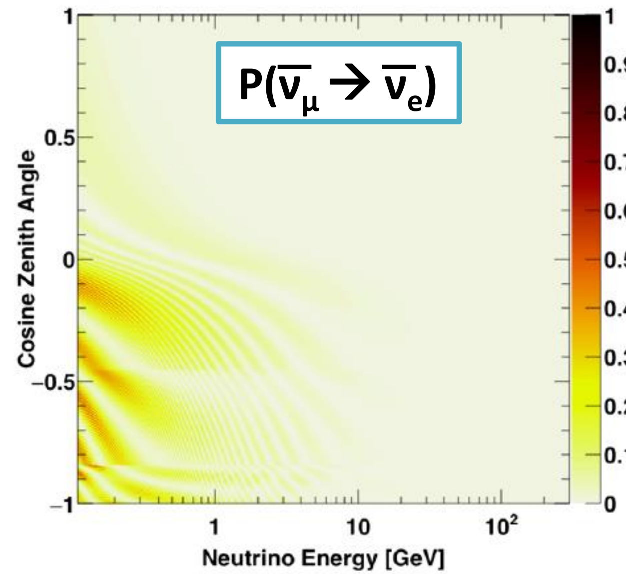
Atmospheric ν

PRD97, 072001 (2018)
(Normal mass hierarchy)

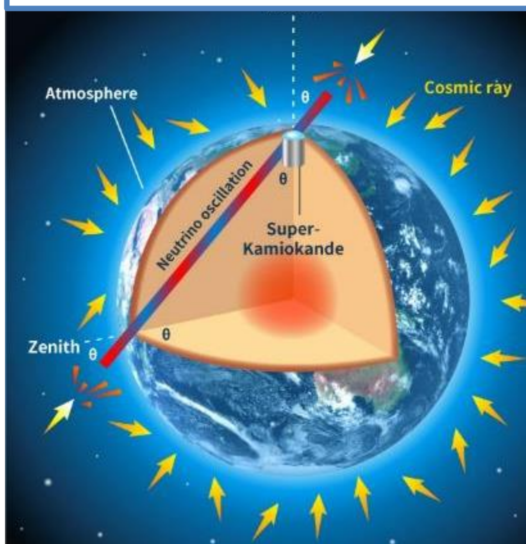
- Produced by cosmic-rays in Earth's atmosphere
- Measure ν flavor, energy, zenith angle, etc. in SK
  - Sensitive to θ_{23} and Δm^2_{32} parameters.
- Matter effect: enhancement of ν_e in several GeV energy region and in Earth core
  - θ_{13} and mass hierarchy could be studied.
- Solar term: enhancement of ν_e in sub-GeV region
  - θ_{23} octant degeneracy could be studied.
- Interference: CP phase could be studied.
- In SK-Gd: purity of ν_e-like will be improved.

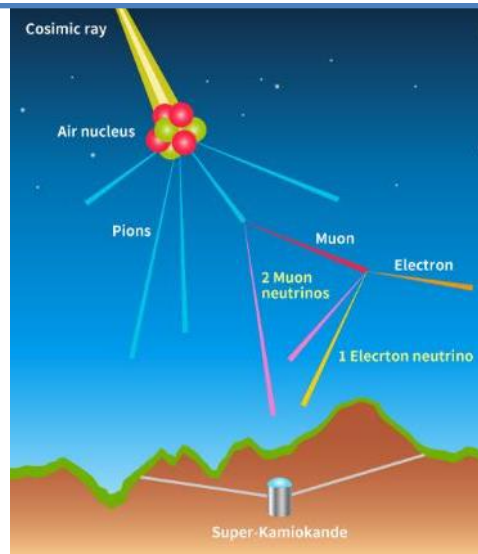


(b) $P(\nu_\mu \to \nu_e)$



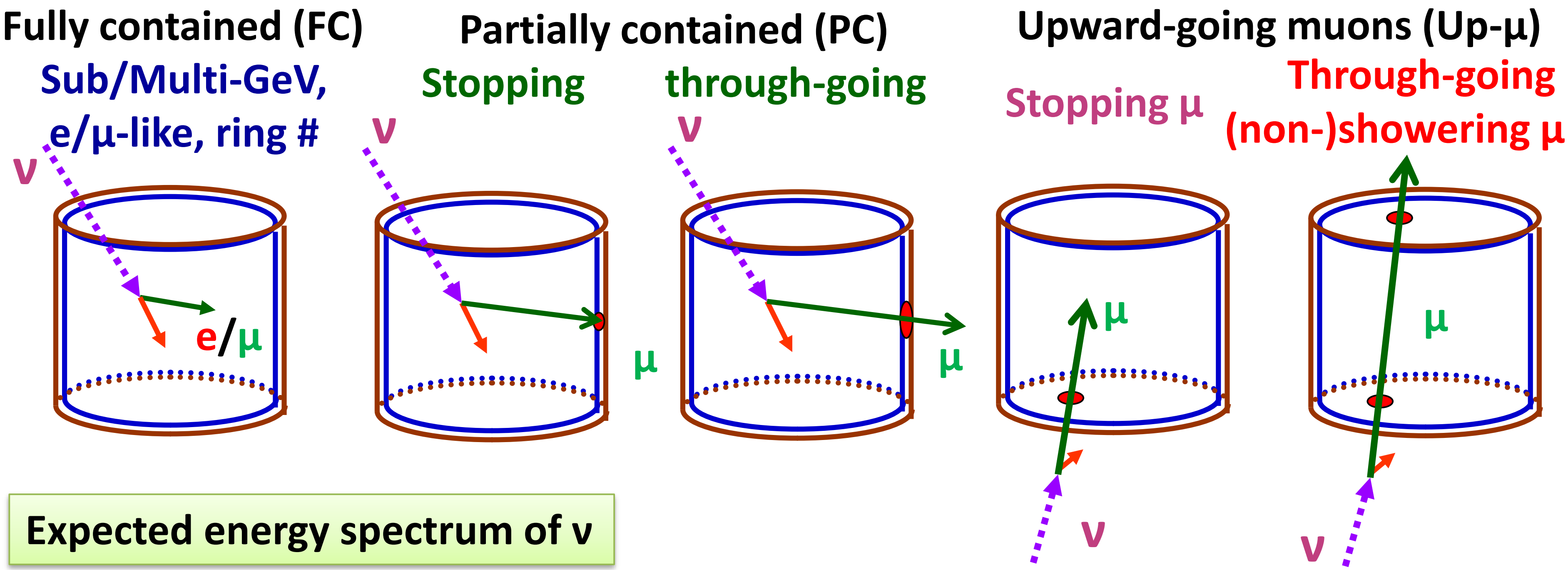
(d) $P(\bar{\nu}_\mu \to \bar{\nu}_e)$



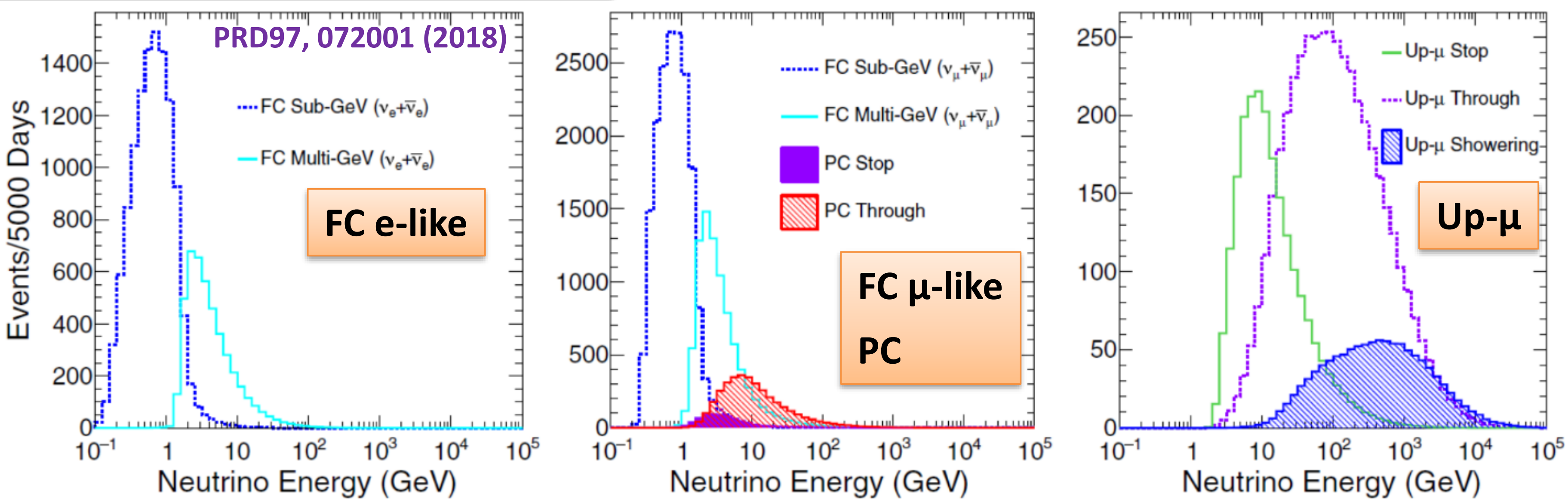


https://www-sk.icrr.u-tokyo.ac.jp/en/sk/about/research/

Atmospheric ν categories in SK



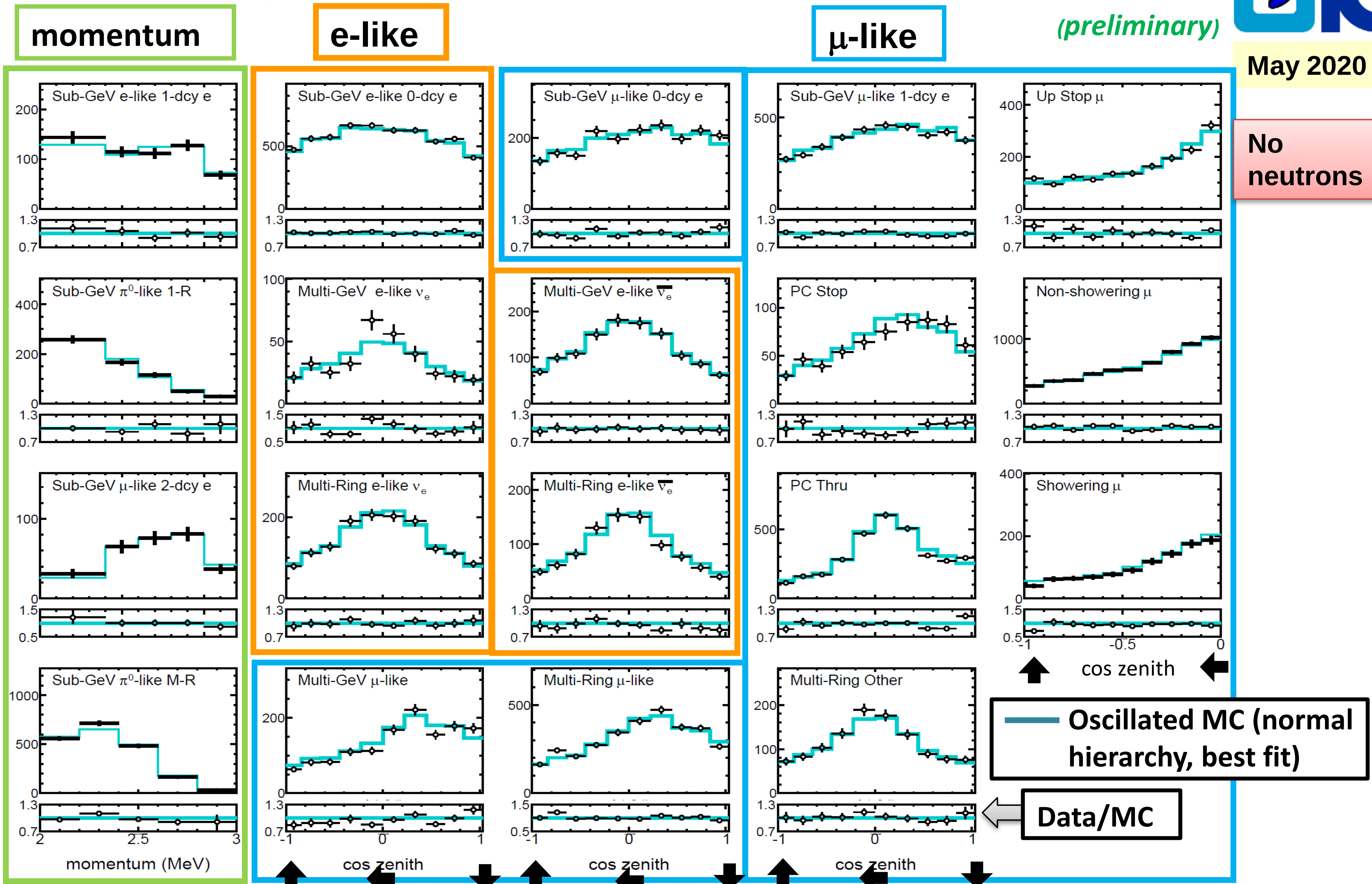
Expected energy spectrum of ν



Zenith angle & lepton momentum distributions

(preliminary)

May 2020



Data files (PRD97, 072001 (2018) version): https://www-sk.icrr.u-tokyo.ac.jp/sk/publications/result-e.html#atmosci2018

Recent progresses in atm. ν analysis

- PRD97, 072001 (2018): SK 5326 days, 328 kt·yr
- Updates in May 2020
  - 364.8 kt·yr
  - Incorporated neutron tagging for ν / $\bar{\nu}$ separation
  - New multi-ring event selection (likelihood → BDT)
  - Updated MC simulation (NEUT 5.4.0), improved systematic errors
  - Changed zenith binning
  - Applied constrain with $\sin^2\theta_{13}$
- Updates in May 2022
  - Added SK-V: SK-I ~ V, 6511 live days, 484.2 kt·yr
  - Enlarged fid. vol.: 27.2 kt (conventional: 22.5 kt)
  - Applied improved T2K model constrain
    - Run 1-9, including recent $\bar{\nu}$ data
    - with $\sin^2\theta_{13}$=0.0220+/-0.0007
    - Cf. joint fit: SK-IV only + T2K Run 1-10

In this afternoon:
Junjie Xia (ICRR), "T2K-SK joint nu oscillation sensitivity"

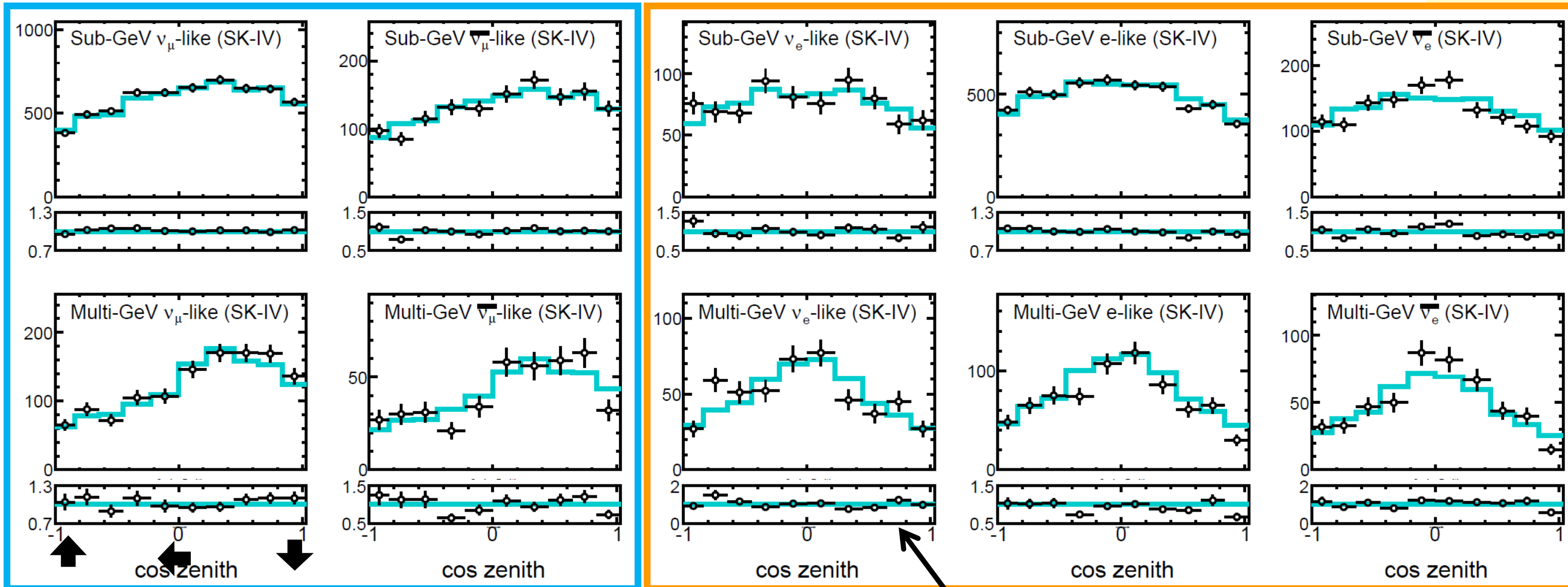
Zenith angle distributions using neutrons (SK-IV)

May 2020

(preliminary)

μ-like

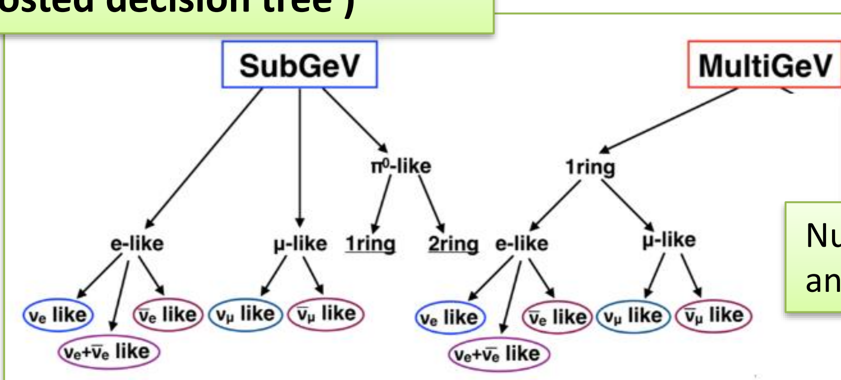
e-like



Data/MC

Oscillated MC (normal hierarchy, best fit)

Multi-ring category with BDT (boosted decision tree)



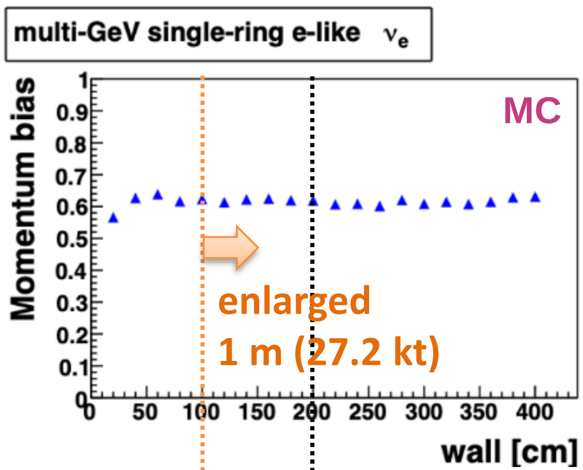
Number of observed decay-electrons and neutrons are considered.

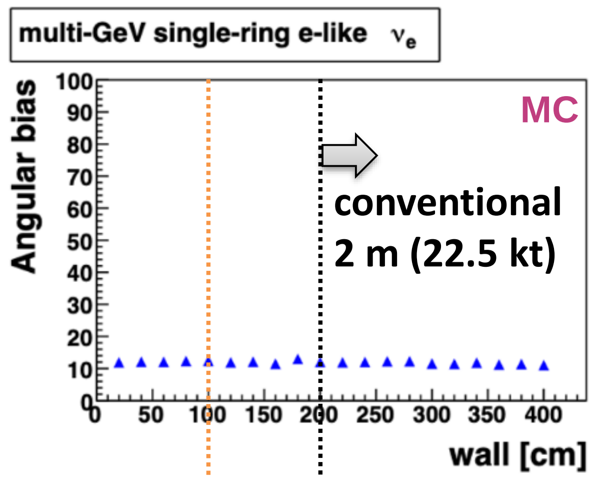
Enlarged fiducial volume

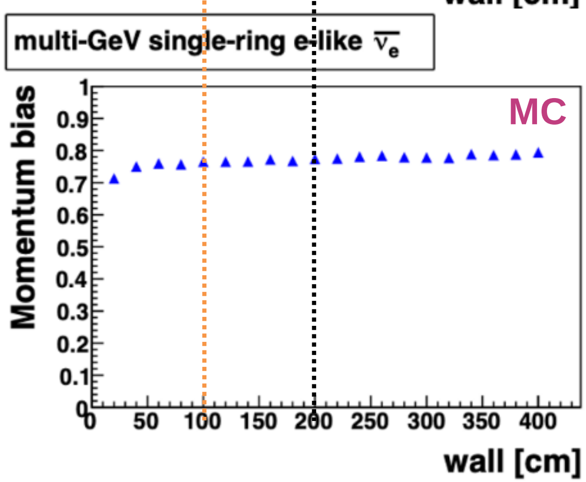
May 2022

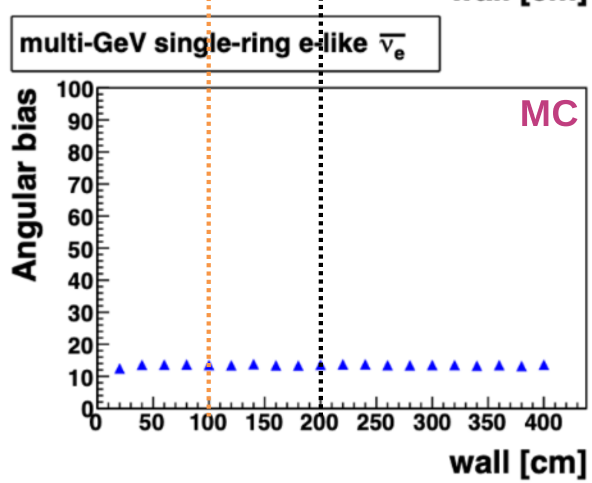
(preliminary)

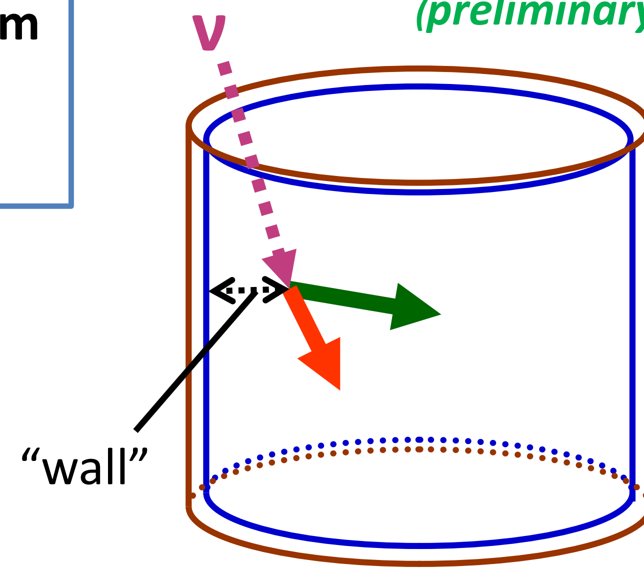
- Vertex distance from nearest ID surface = "wall"
- "wall > 2 m" is conventional in SK → enlarged to 1 m
- No significant bias in reconstruction
- No significant increase of external background

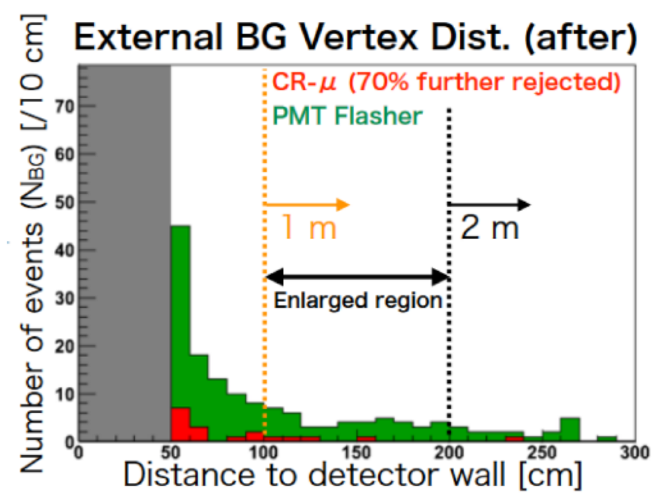










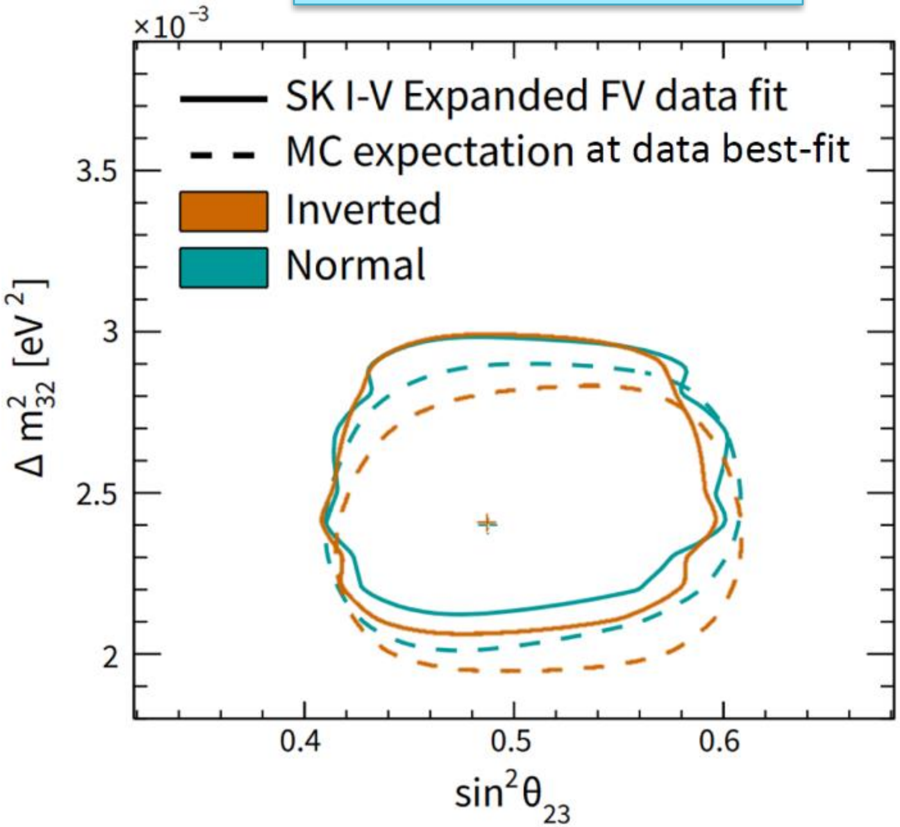


Atm. ν oscillation analysis (SK only)

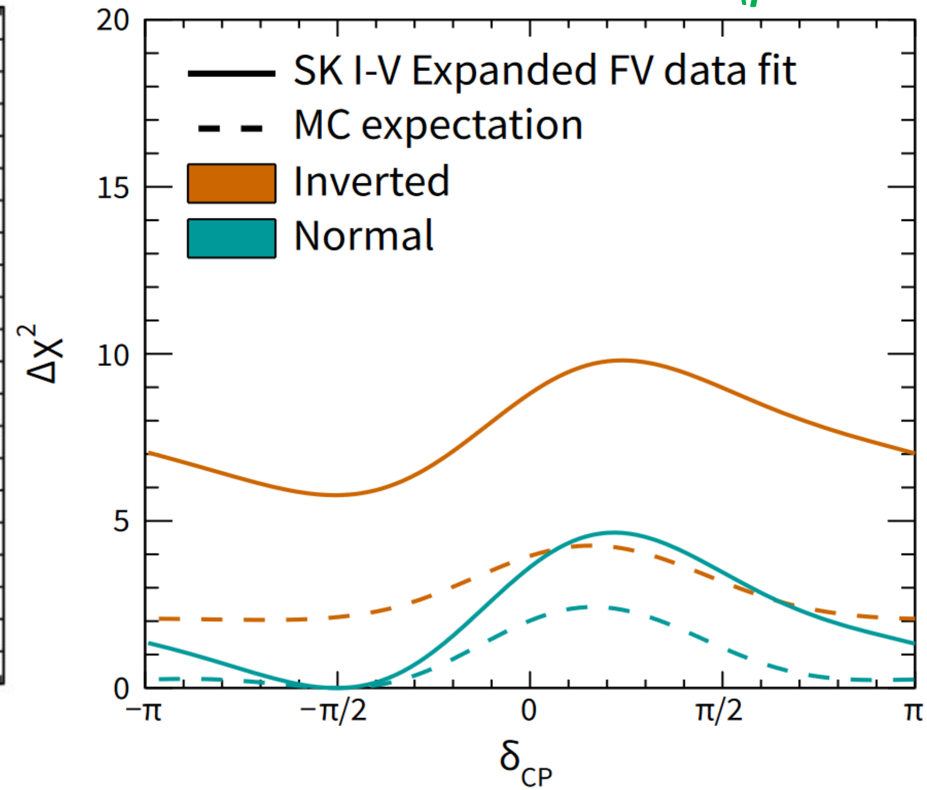
May 2022

SK 484.2 kt·yr *(preliminary)*

$sin^2\,\theta_{23}$ vs. Δm^2_{32}



δ_{CP}



Best-fit: (for both NH and IH)

- $sin^2\,\theta_{23} = 0.49$
- $\delta_{CP} = 4.71$ (in 0-2π)
- $\Delta m^2_{32} = 2.4 \times 10^{-3}\text{eV}^2$

SK atmospheric ν data favors:

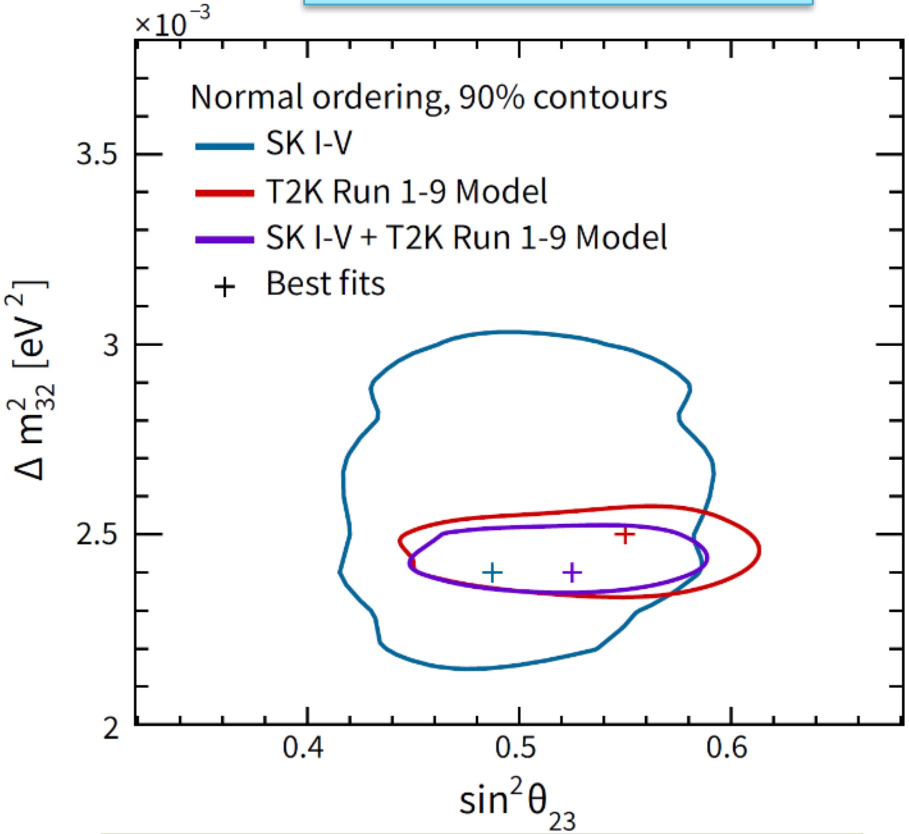
- **Maximal mixing**
- $\delta_{CP} \approx -\frac{\pi}{2}$
- **Normal mass hierarchy** ($\Delta\chi^2 = 5.8$)

Atm. ν oscillation analysis with T2K model

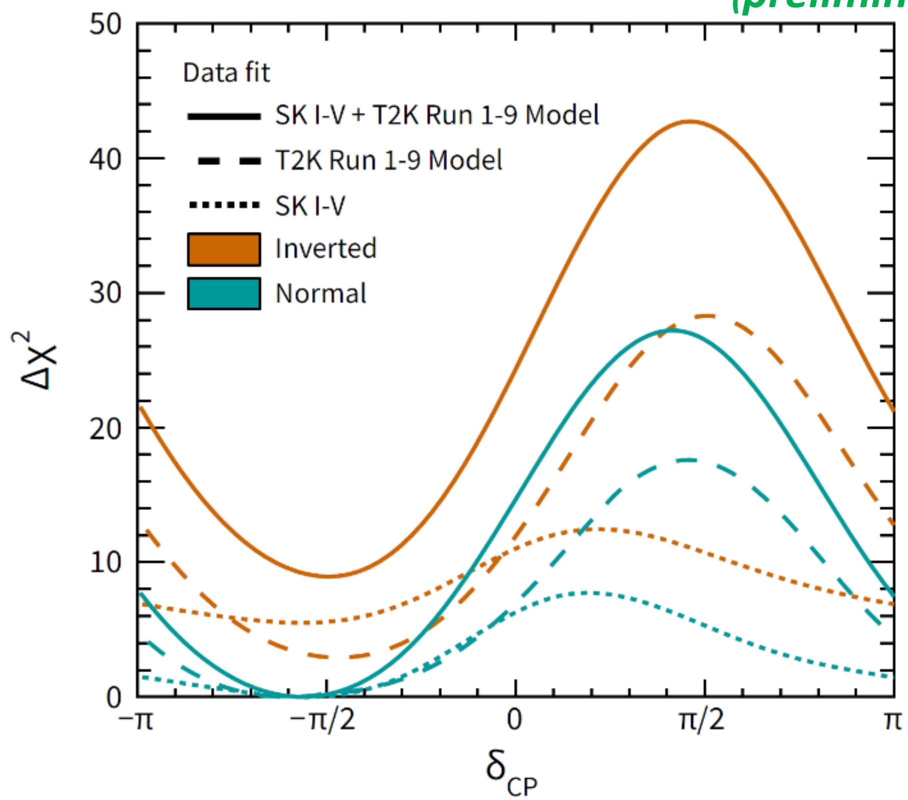
May 2022

SK 484.2 kt·yr *(preliminary)*

$sin^2\,\theta_{23}$ vs. Δm^2_{32}



δ_{CP}



Best-fit: (for NH)

- $sin^2\,\theta_{23} = 0.53$
- $\delta_{CP} = 4.54$ (in 0-2π)
- $\Delta m^2_{32} = 2.4 \times 10^{-3}\mathrm{eV}^2$

SK atm. ν + T2K model favors:

- **Maximal mixing**
- $\delta_{CP} \approx -\frac{\pi}{2}$
- **Normal mass hierarchy** ($\Delta\chi^2 = 8.9$)

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- Solar neutrino oscillation results
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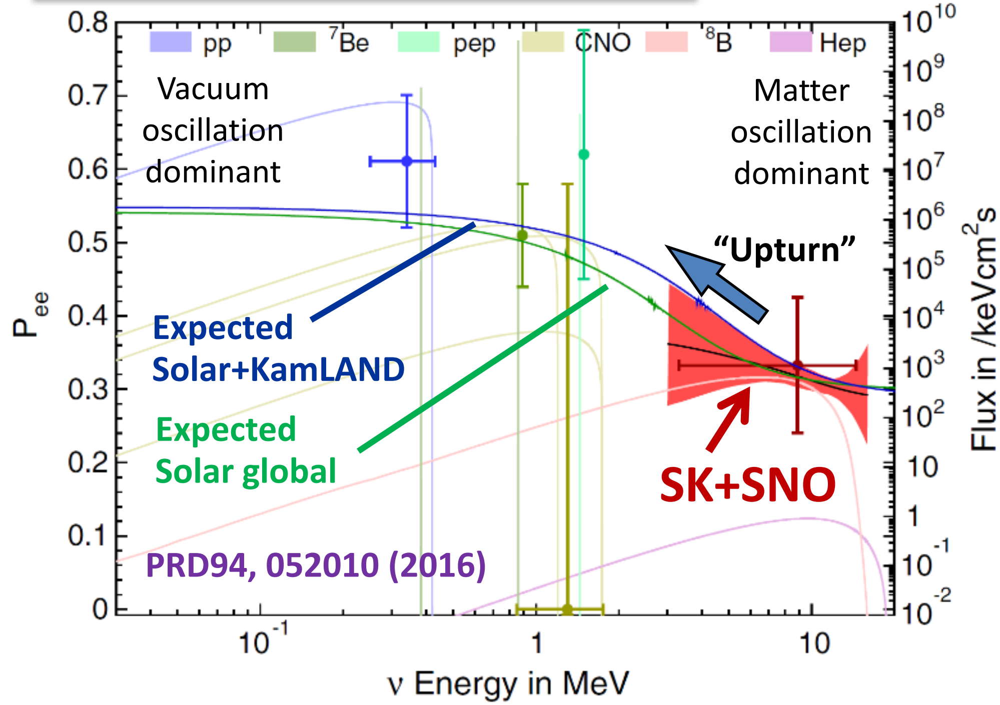
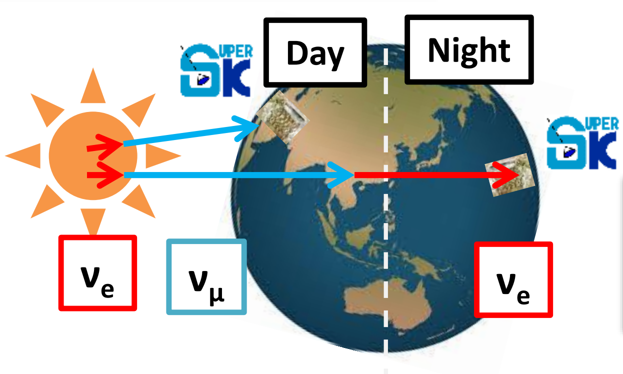
Solar neutrinos

- Produced by nuclear fusion in the sun (initial = ν_e)
- High statistics measurement of flux, energy spectrum, and time variations of ^8B solar neutrinos in SK.
- Energy spectrum: sensitive to θ_{12} and Δm^2_{21} parameters. Global analysis is more powerful.
- Matter effect in the sun: energy dependence of ν_e survival probability is observed.
  - SK is trying to measure "Upturn"
- Time variation: matter effect in the earth could be studied from day-night flux asymmetry.
  - Sensitive to Δm^2_{21} parameter.

ν energy vs. ν_e survival probability



Day−Night flux asymmetry



Regenerate ν_e by Earth's matter effect

Recent progresses in solar ν analysis

May 2022

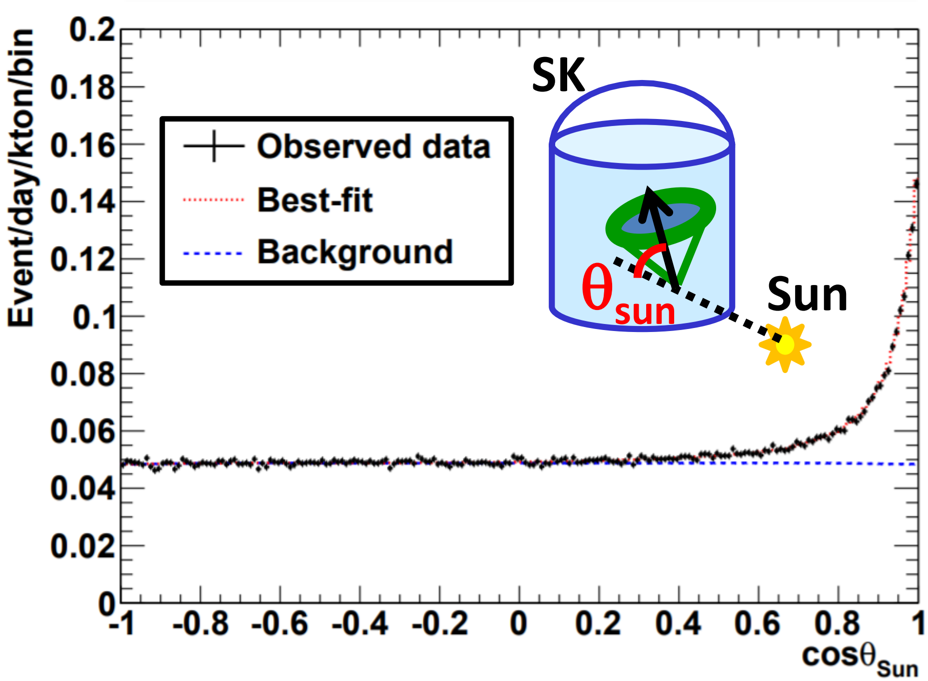
- PRD94, 052010 (2016): (SK-IV: until Feb. 2014, 1664 days)
- Updates in May 2020
  - Improved analysis tools: energy reconstruction, spallation cut
    - Spallation cut: consider cosmogenic neutrons (arXiv:2112.00092)
  - Did oscillation analysis (spectrum and day-night) with full SK-IV (2970 days)
    - Δm^2 difference between Solar and KamLAND reduced.
  - Confirmed low-energy data quality in SK-V
- Updates in May 2022
  - Re-estimated systematic errors, then re-do oscillation analysis (spectrum and day-night) up to SK+SNO (using SK-I~IV data).
  - Global analysis with other solar experiments is ongoing.
  - First solar signal in 2.49-3.49 MeV (kinetic) in SK was obtained.
  - Confirmed energy scale in low-energy region in SK-V and SK-VI

SK-IV solar neutrino signal

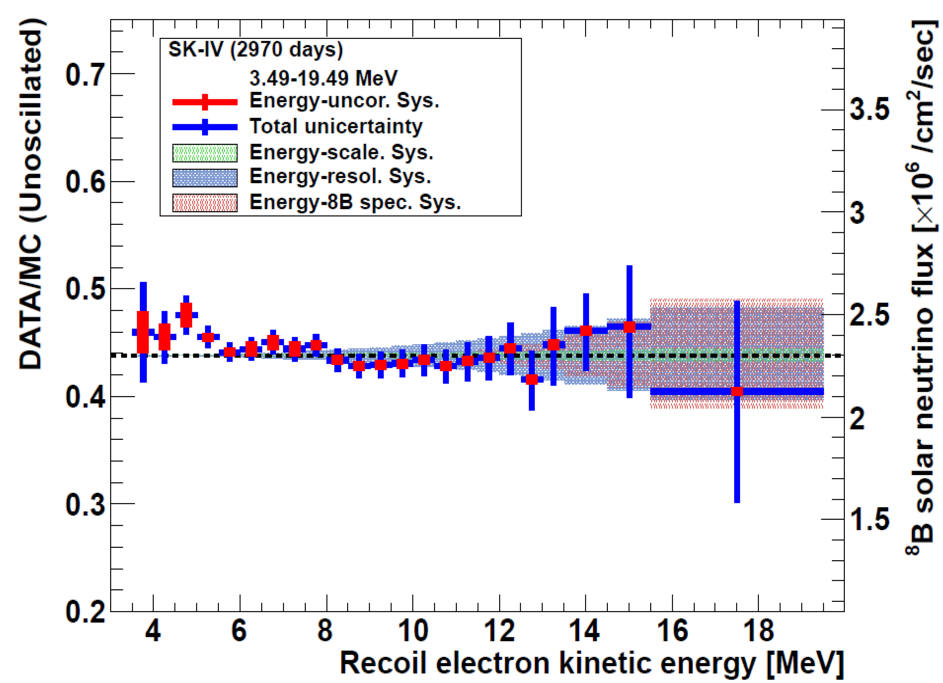
(preliminary) May 2020

- According to improved spallation cut, signal efficiency in solar analysis was increased by 12.6% in 3.49-19.49 MeV (kinetic).
- Signal (in SK-IV): 63890 +381 -379(stat.) +/-907 (syst.) events.
  - Total: > 10^5 solar ν events (during SK-I~IV, 5805 days)

Solar angle dist. (3.49-19.49 MeV)



Energy spectrum



Solar ν oscillation results

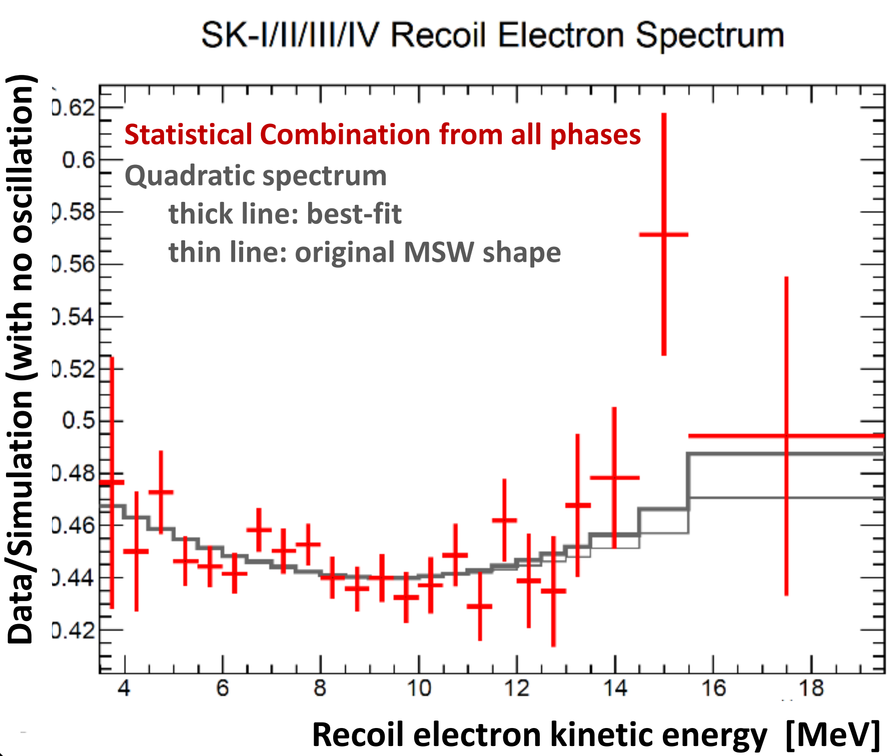
May 2022

Preliminary

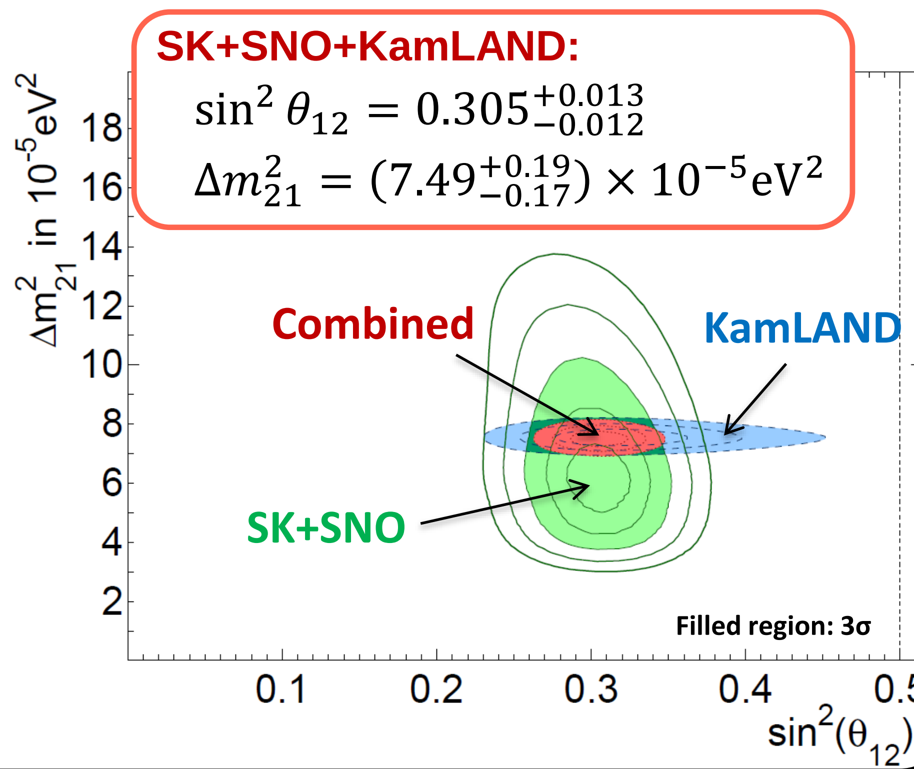
SK 5805 days

- Re-estimated systematic errors, then re-do oscillation analysis
- No big change from the preliminary results in 2020
- ~1.5 σ level tension in Δm^2_{21} between SK+SNO analysis and KamLAND is still remaining.

Solar ν energy spectrum



Solar ν oscillation parameters



Spectral fitting (quadratic)

May 2022

- The same parametrization with SNO (PRC 88, 025501 (2013))
- A combined fitting can be done.

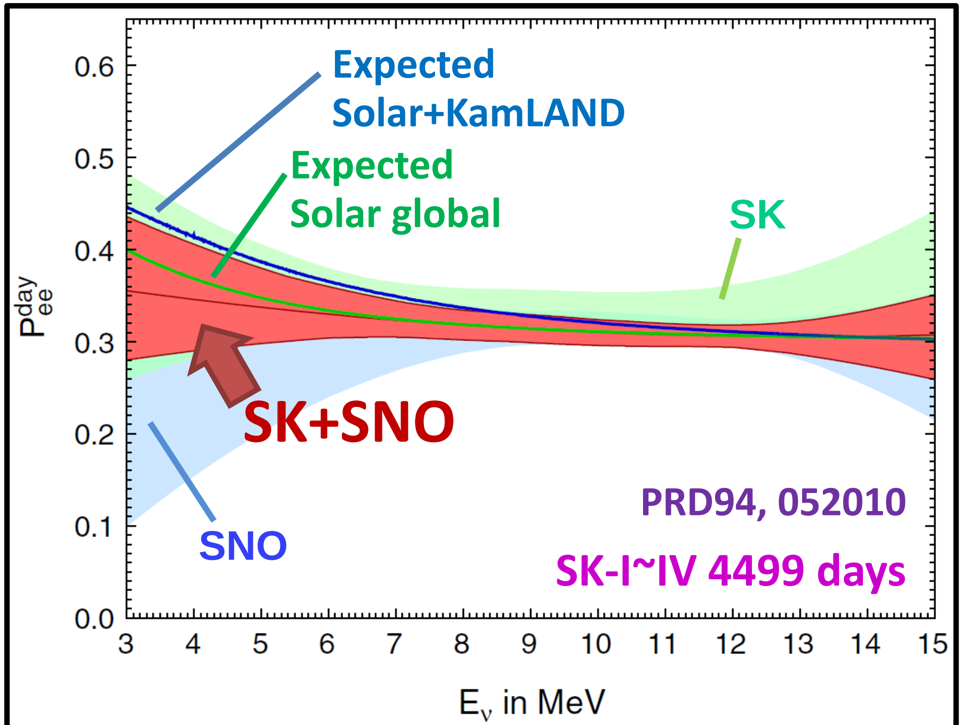
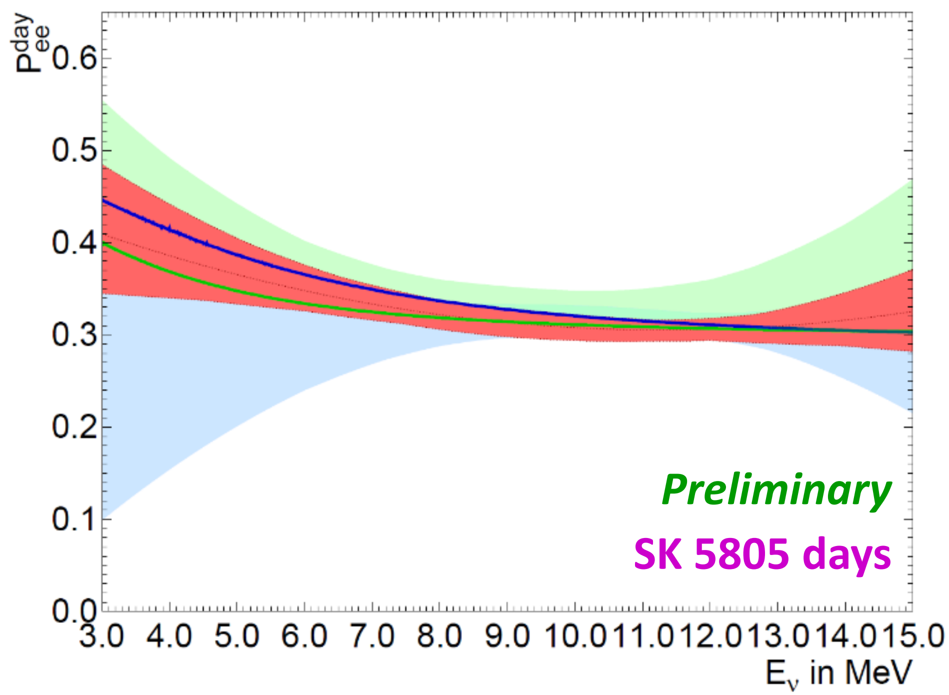


FIG. 29. Allowed survival probability 1σ band from the combined data of SK and SNO (red). Also shown are predictions based on the oscillation parameters of a fit to all solar data (green) and a fit to all solar + KamLAND data (blue). The pastel colored bands are the separate SK (green) and SNO (blue) fits.



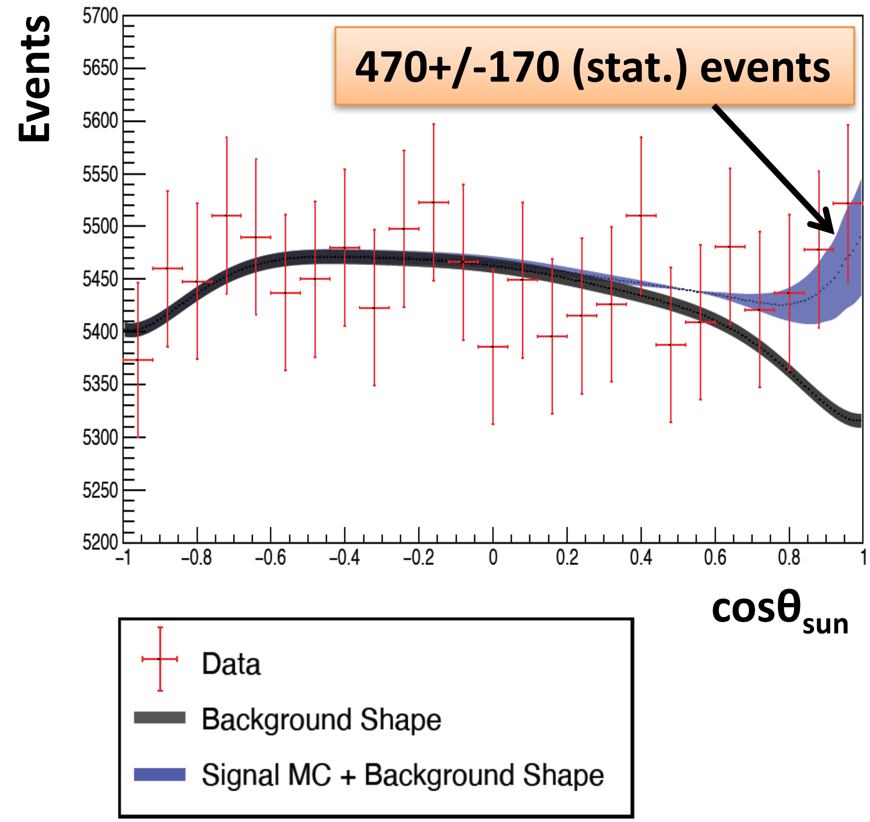
Solar ν signal with lowest energy in SK

May 2022

Preliminary

- Use Wideband Intelligent Trigger (WIT) data in SK-IV
  - SK-IV WIT data, 2.49 MeV - 3.49 MeV electron kinetic energy, 858 live days good data during Oct. 2015 - May 2018
- Applied a boosted decision tree (BDT) selection and the standard spallation cut for the 858 days WIT sample.
  - Inputs: standard reconstructed variables in the traditional solar analysis
  - ~6 times better background rejection comparing to the traditional solar analysis
- A clear peak is observed.
  - First time in SK
- References:
  - 10.5281/zenodo.6759244
  - J. Phys. Conf. Ser. 888, 012189 (2017)

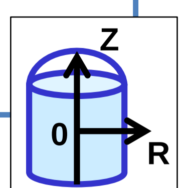
Solar angle distribution
(SK-IV WIT 858 days, 2.49-3.49 MeV)



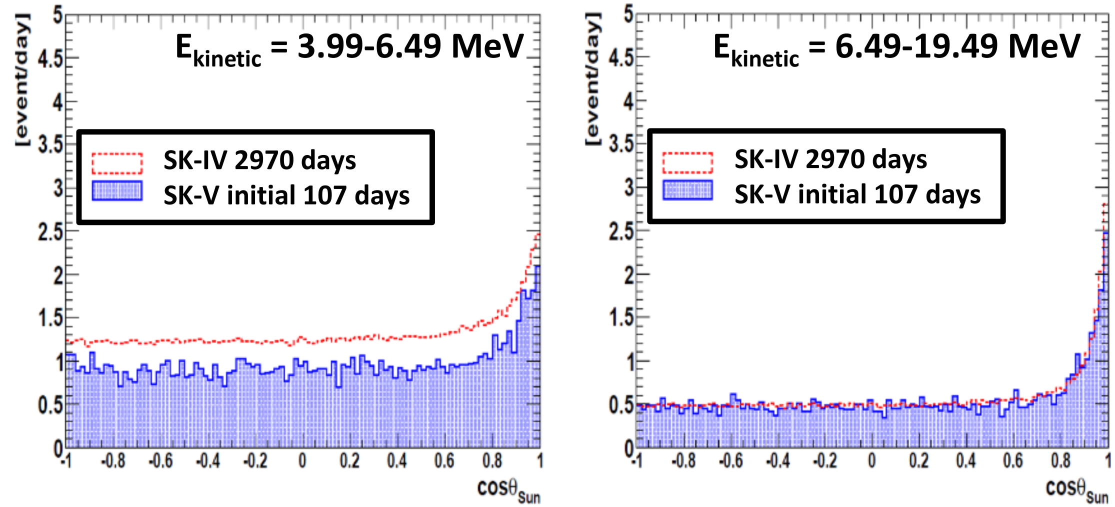
SK-V solar ν data

(preliminary) May 2020

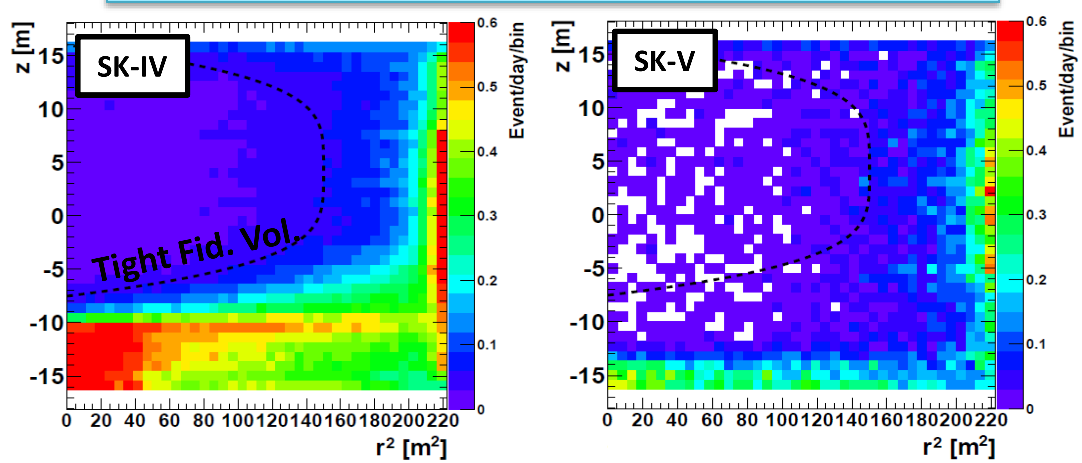
- **Cleaning of inside detector was done during the refurbishment work before SK-V.**
- **Better water flow control was achieved in SK-V using additional water piping.**
- **Low-energy background level in SK-V is lower than SK-IV.**
  - Probably lower radon-222 contamination



Solar angle distribution



Vertex distribution ($E_{kinetic}$ = 3.99-4.49 MeV)



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SK-Gd Phase

SK-Gd Phase:

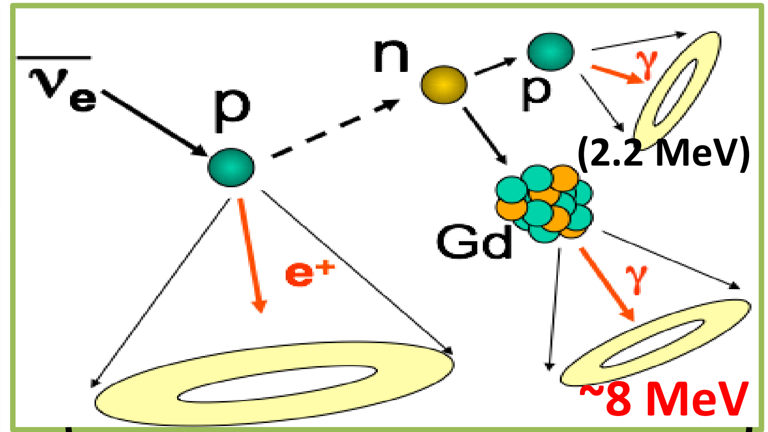
Add gadolinium (Gd) to enhance neutron tagging efficiency of the SK detector.

Physics targets:

- **Detect the world's first Supernova Relic Neutrinos (SRN) (or Diffuse Supernova Neutrino Background, DSNB)**
- **Improve pointing accuracy for supernova**
- **Early warning of nearby supernova from pre-burst signal (silicon burning)**
- **Enhance ν or $\bar{\nu}$ discrimination in atmospheric ν & T2K analysis**
- **Reduce backgrounds in proton decay search**

SK refurbishment was done before SK-V

- **Fix water leakage, clean inside the detector**
- **Replace dead PMTs**
- **Improve water piping in the SK detector**



- **Reduce BG of $\bar{\nu}_e$ signal**
  - **Delayed coincidence**
  - **ΔT ~ 30 μs (@0.1% Gd)**
  - **Vertices within ~ 50 cm**

Capture efficiencies in water

- **0.01% Gd [$Gd_2(SO_4)_3$ 10t] : ~50%**
- **0.03% Gd [$Gd_2(SO_4)_3$ 30t] : ~75%**
- **0.1% Gd [$Gd_2(SO_4)_3$ 100t] : ~90%**

Gd concentration

SK-VI: 0.011% (18 Aug. 2020-)

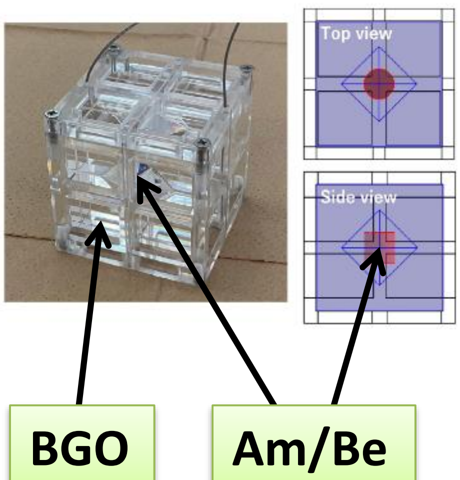
SK-VII: 0.03% (5 Jul. 2022-)

Calibration with neutrons in SK-VI

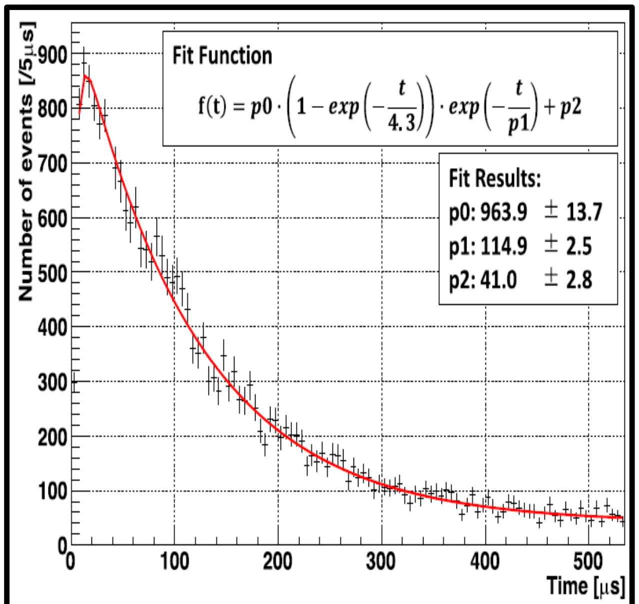
NIM A 1027 (2022) 166248

- Using Am/Be + BGO source, response of SK-Gd detector to neutrons was studied.
  - Trigger: scintillation light of BGO by 4.4 MeV gamma-ray from Am/Be
  - Neutron capture time was measured
- Geant4.9.6p04 and G4NDL4.2 are used to obtain the relation between Gd concentration and capture time constant.
- Observed neutron capture time = 115+/-1 μs ←→ 111+/2 ppm Gd concentration.
  - Consistent with other estimations

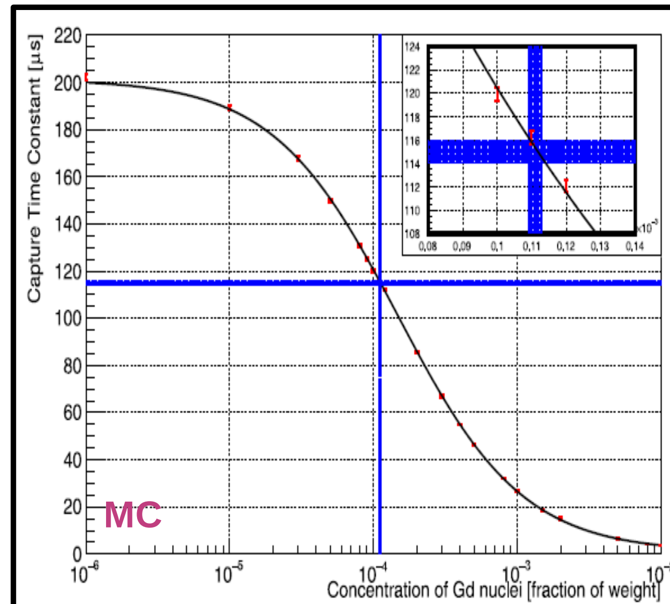
Am/Be + BGO



Time dist. of neutron capture



Concentration vs. capture time



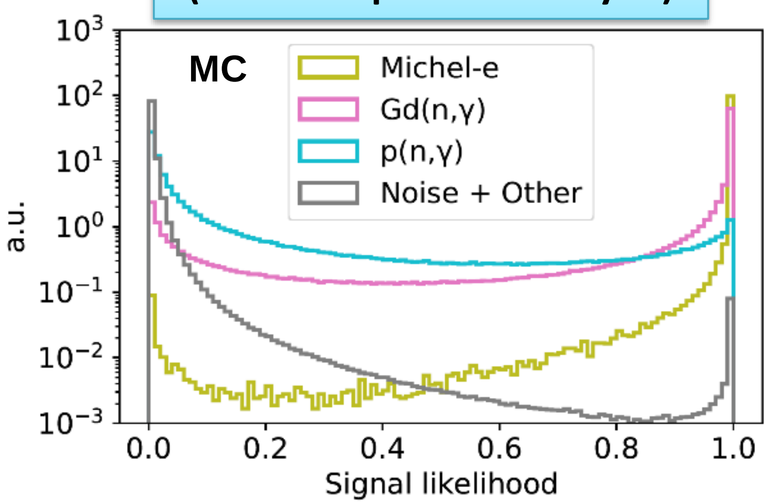
Neutron tagging tools in SK-Gd

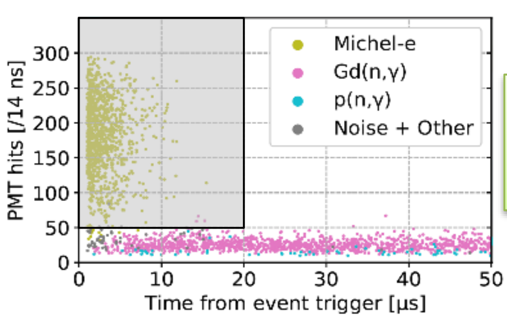
May 2022

Preliminary

- Several tools are under development to detect neutron events in SK-Gd
  - Neural network, cut-based method, …
- They are almost ready, but need more fine tunings
  - Neutron multiplicity, neutron tag efficiency, …

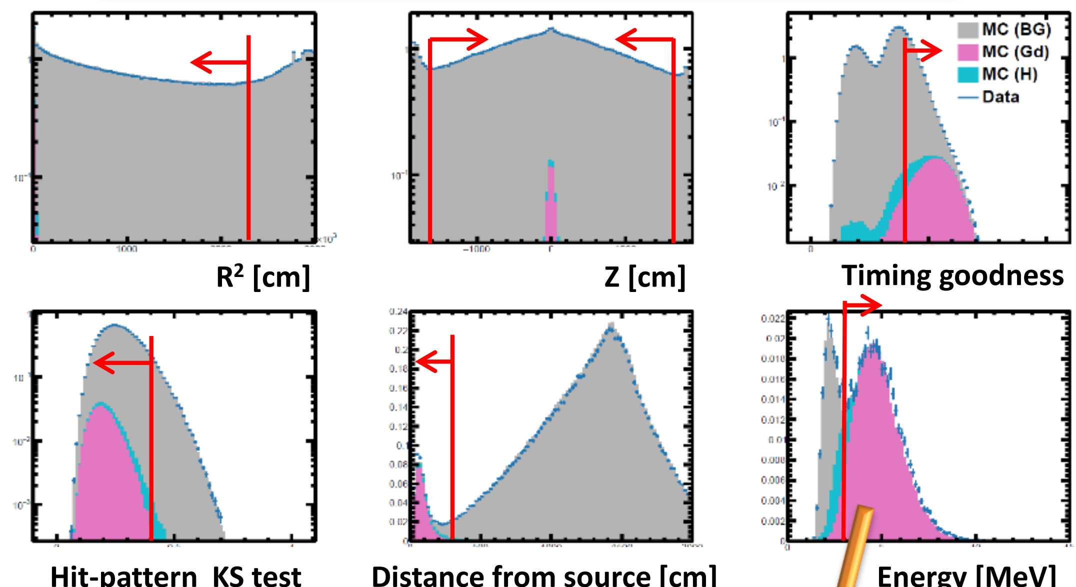
Neural network output (for atmospheric ν analysis)





Michel-e can be removed

Delayed event selection of cut-based method (for Am/Be + BGO calibration)



- Tag efficiency in SK-VI without BGO (MC): 40.5 +/- 0.1 (stat.) +1.0/-2.1(syst.)%
- about x2 efficient than pure water

Tag efficiencies (data, MC) are obtained. Small diff. → syst. err.

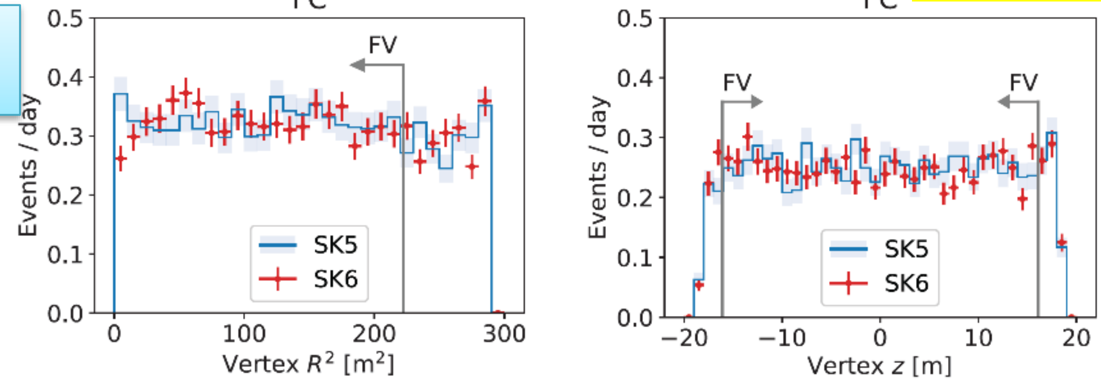
Atmospheric ν in SK-V & SK-VI

Preliminary

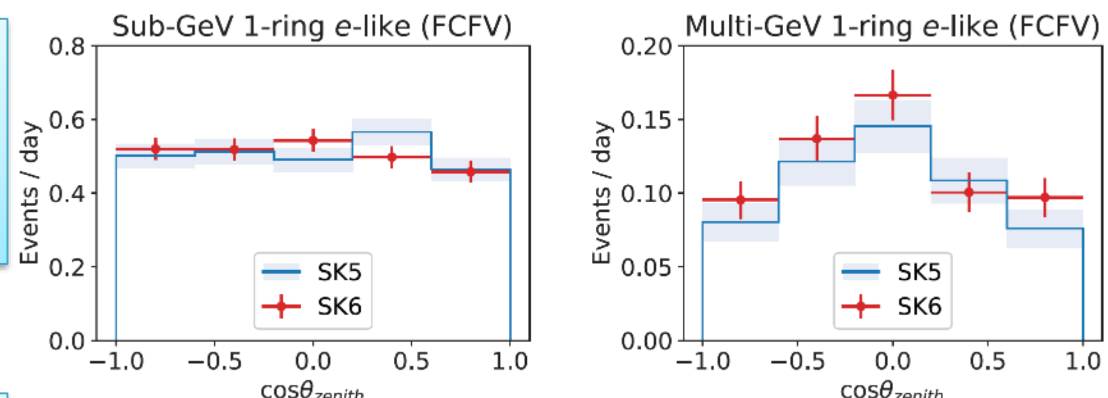
May 2022

- **Compare basic distributions and event rates in SK-V and SK-VI data.**
- **Data set:**
  - **SK-V 461 days**
    Feb. 2019 – Jul. 2020
  - **SK-VI 577 days**
    Jul. 2020 – Apr. 2022
- **They are consistent.**

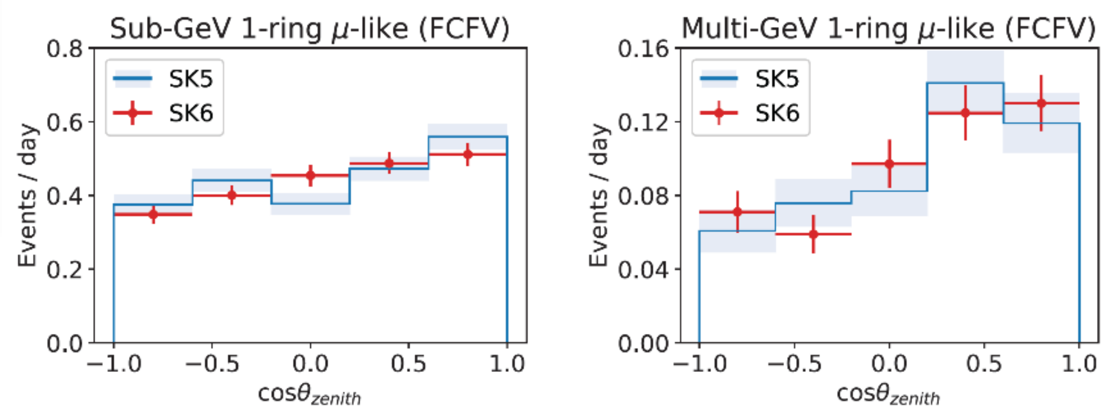
Vertex (FC events)



Zenith angle (e-like FC events in fid. vol.)



Zenith angle (μ-like FC events in fid. vol.)



Neutron signals in SK-VI atmospheric ν

May 2022

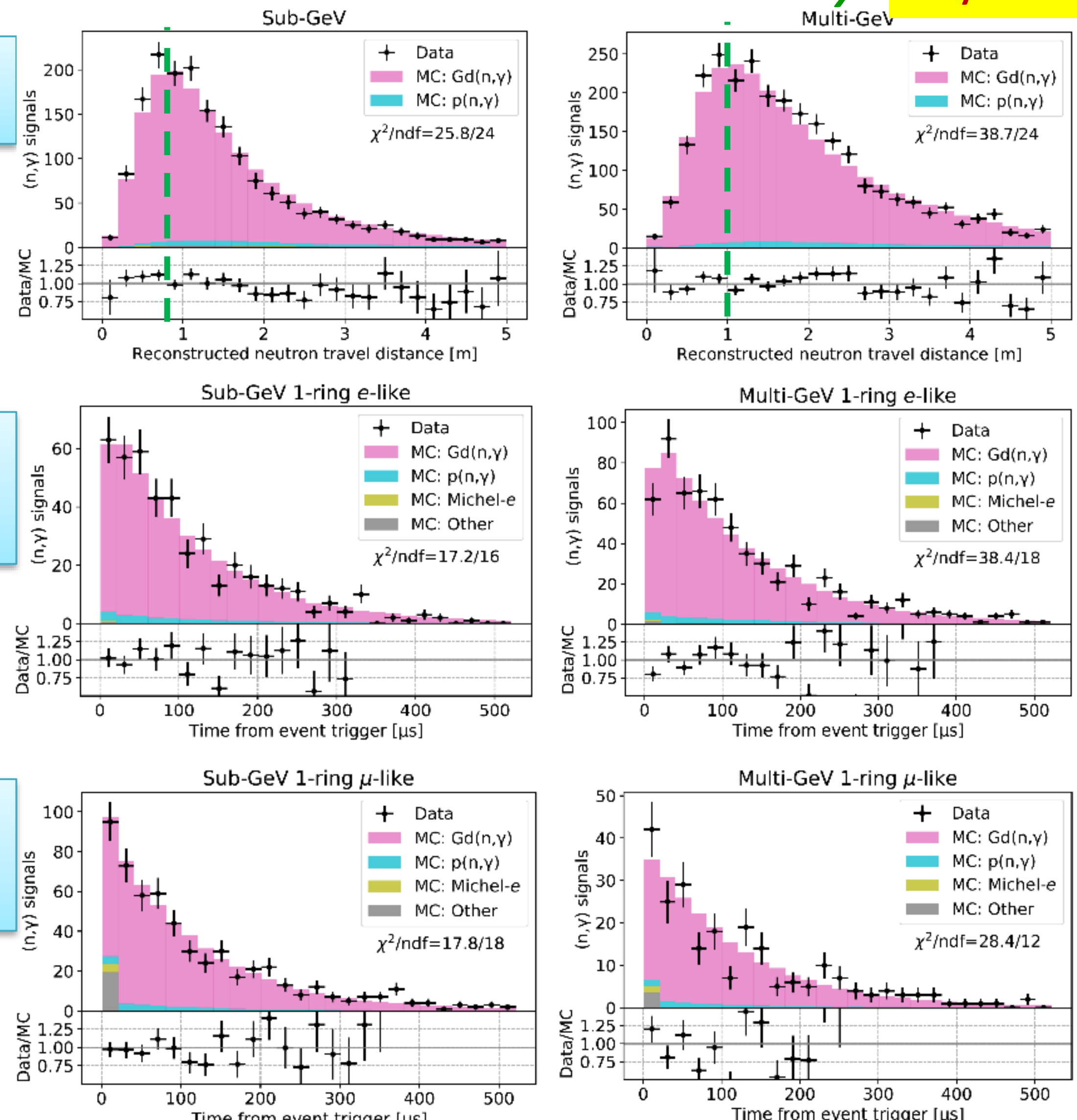
- Applied the neural network neutrino tagging to the SK-VI 577 days atmospheric ν sample.
- The peak position of the neutron travel distance looks to be energy dependent.
- The capture time of neutron looks similar.
- Expected improvement in atmospheric ν analysis in SK-Gd:
  - Purity of ν_e-like will be improved. It improves δ_{CP} and MH sensitivities.
  - Reference: [10.5281/zenodo.6781493](https://doi.org/10.5281/zenodo.6781493)

Preliminary

Travel distance

Capture time (e-like)

Capture time (μ-like)



Sub-GeV (<1.33 GeV)

Multi-GeV (> 1.33 GeV)

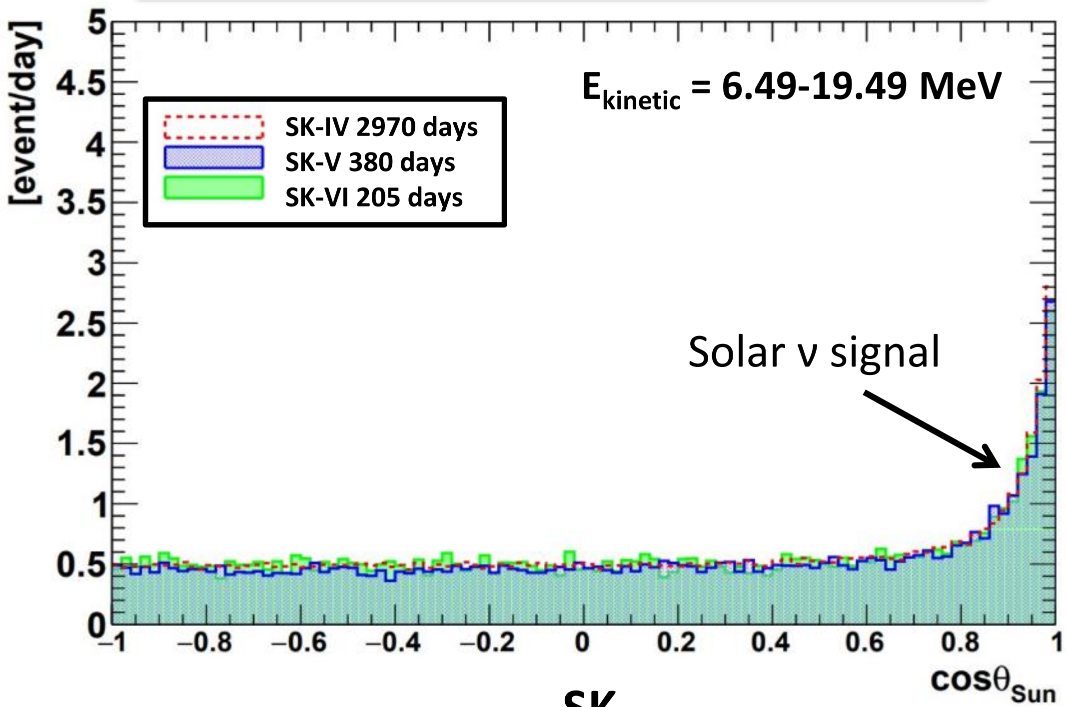
Solar neutrino signal in SK-VI

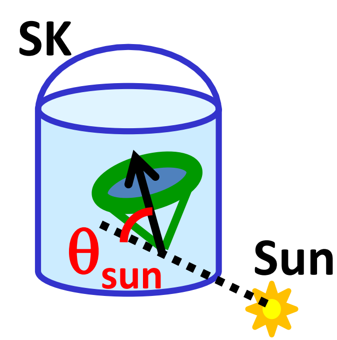
May 2022

Preliminary

- Applied conventional solar selections to SK-V and SK-VI data above 6.49 MeV.
- No significant difference among SK-IV, SK-V, and SK-VI.
- Spallation cut in solar neutrino analysis would be more efficient in SK-VI & VII, thanks to improved cosmogenic neutron tagging (under study)
- Below 6.49 MeV: under study (need careful treatment of trigger efficiency, water convection, PMT dark rate, etc.)

Solar angular distributions in SK-IV, V, and VI



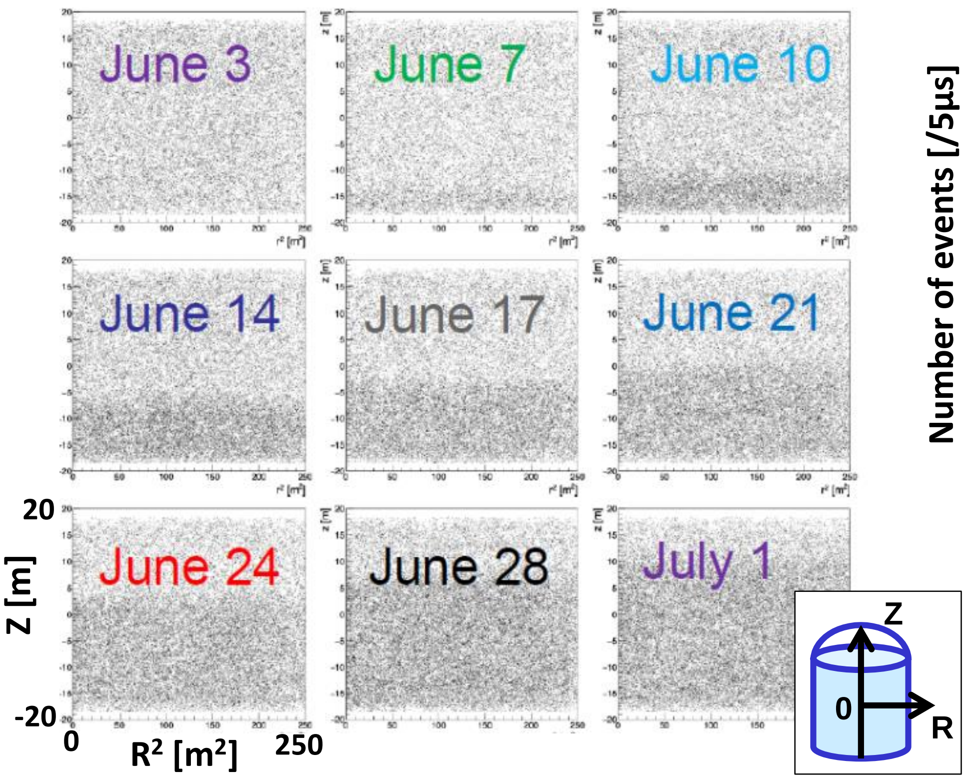


Neutron events in SK-VII

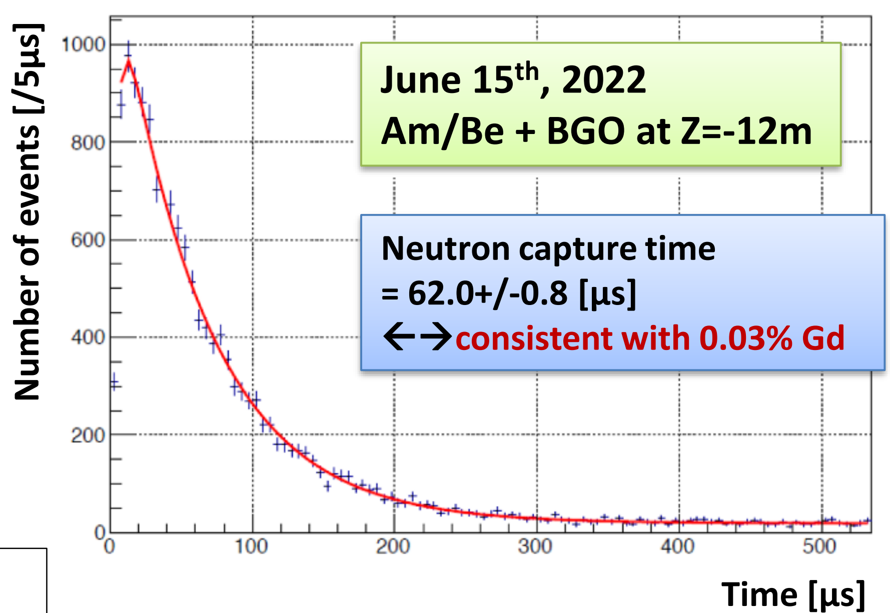
Preliminary

- Cosmic-ray muons produce neutrons by spallation.
- Theses cosmogenic neutrons are observed in SK-IV and in SK-VI
  - Reference: arXiv:2112.00092 (SK-IV) and M. Shinoki@UGAP2022 (SK-VI)
- At the beginning of SK-VII, the cosmogenic neutron candidates are monitored when the additional Gd is being loaded from the bottom of the SK detector.
- Am/Be + BGO calibrations are also carried out.
- **Clear increase of the neutron candidates and shorter capture time is observed.**

Vertex dist. of cosmogenic neutron candidates



Neutron capture time of an Am/Be + BGO calibration in SK-VII

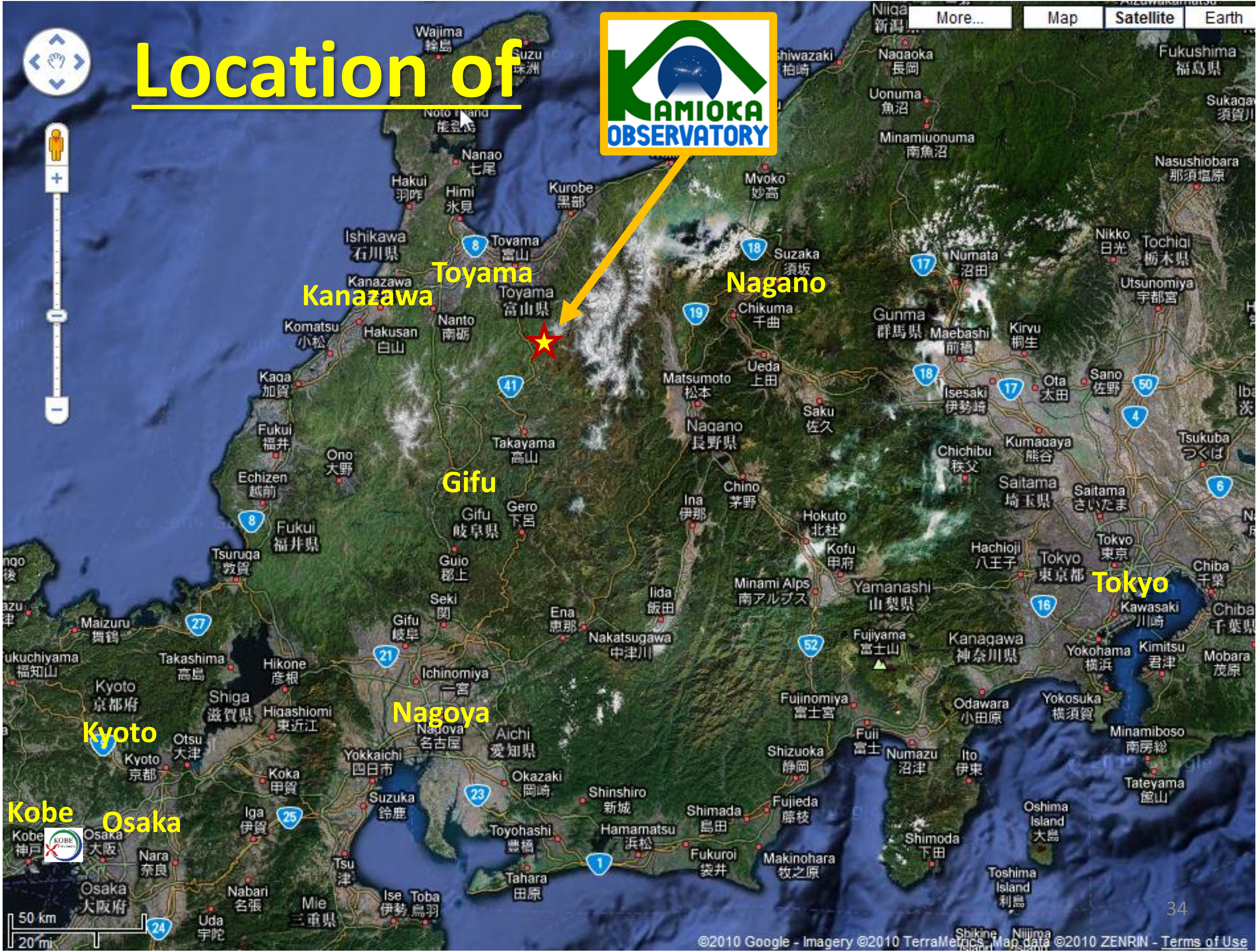


Summary

- **We are improving atmospheric and solar neutrino oscillation analyses at SK, continuously.**
  - **Current preliminary results use:**
    - **6511 live days (SK-I~V, for atmospheric)**
    - **5805 live days (SK-I~IV, for solar)**
- **The new phase (SK-Gd) is started in 2020.**
  - **SK-VI: 0.011% Gd concentration (18 Aug. 2020-)**
  - **SK-VII: 0.03% (5 Jul. 2022-)**
- **Clear neutron signals are observed in SK-VI and SK-VII.**
- **Improvements in the oscillation analyses are expected.**
  - **Atmospheric ν: better ν / $\bar{\nu}$ separation → better ν_e-like purity → improve δ_{CP} and mass hierarchy sensitivities**
  - **Solar ν: better efficiency of cosmogenic neutron tagging → better spallation cut → less statistical uncertainties of solar ν measurements**

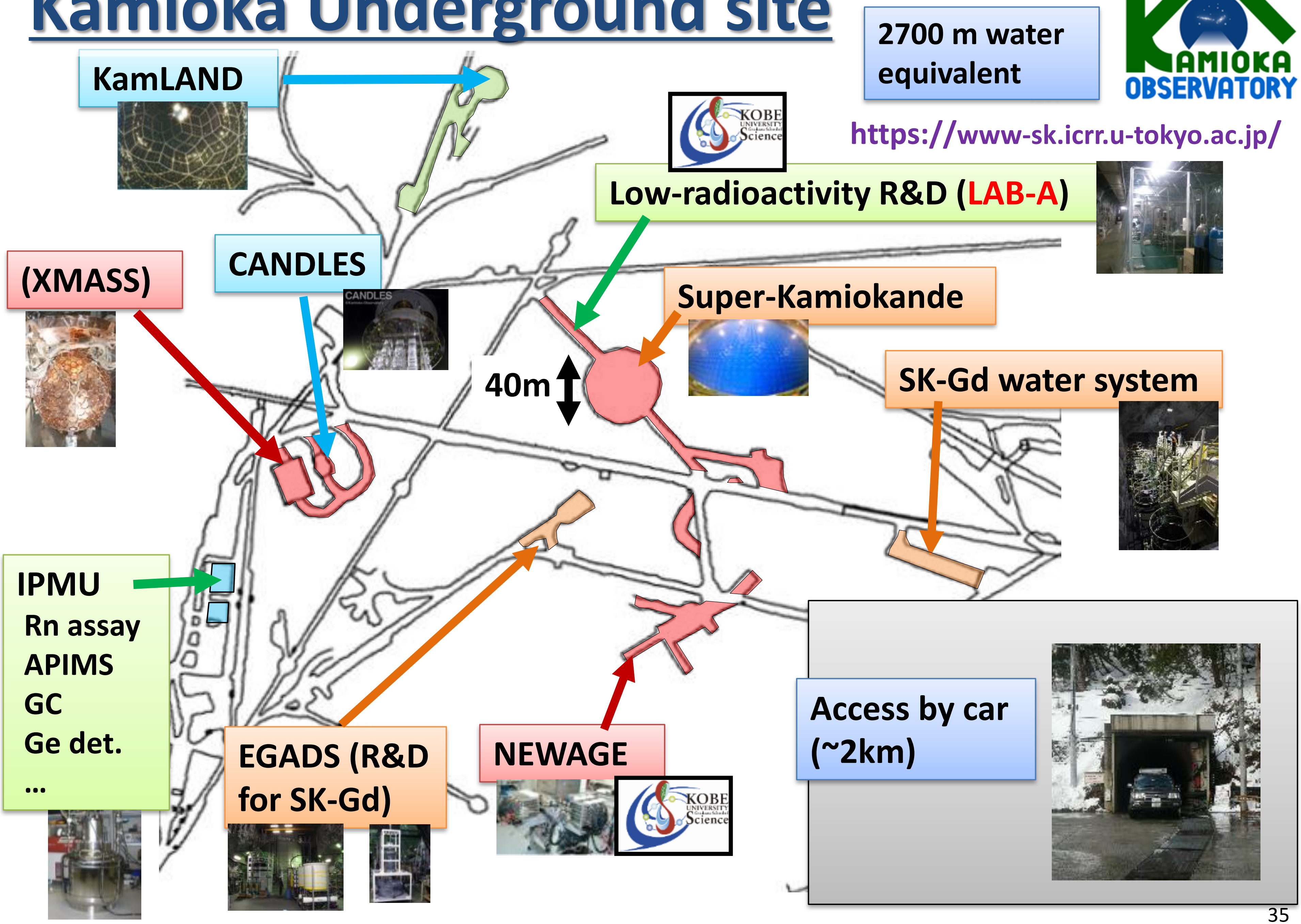
Supplements

Location of



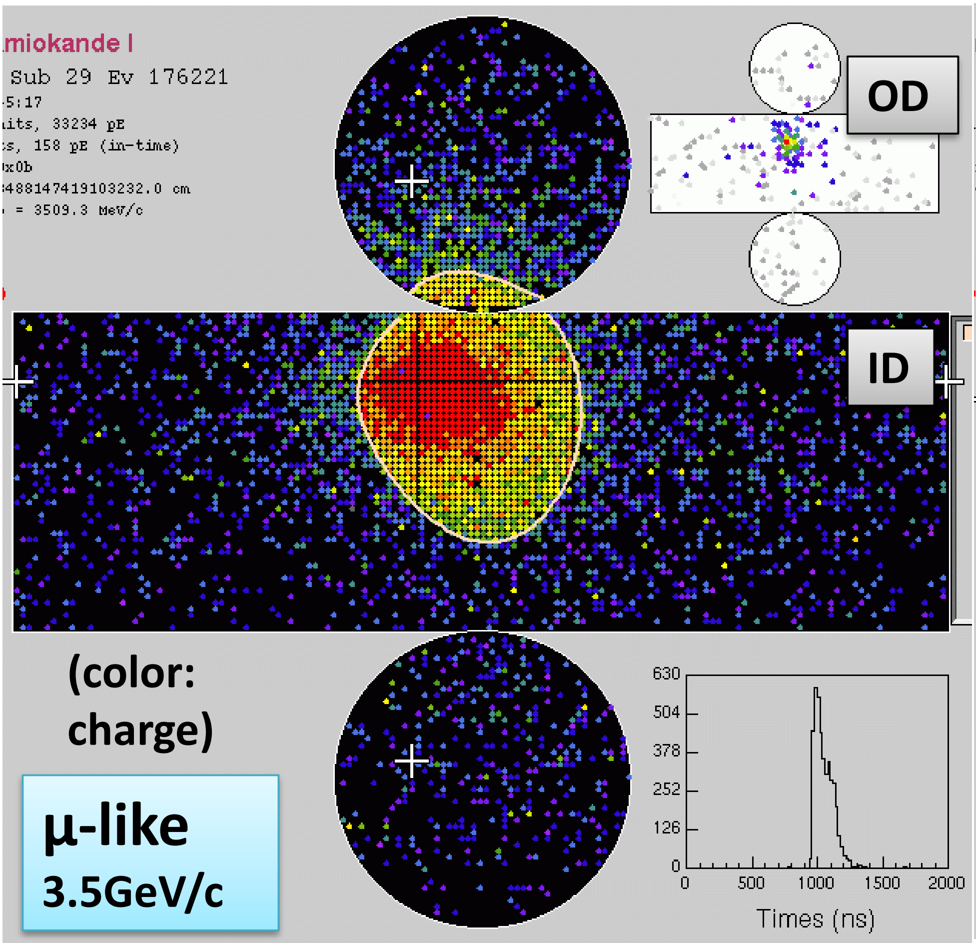
KAMIOKA
OBSERVATORY
Toyama
Kanazawa
Nagano
Gifu
Tokyo
Nagoya
Kyoto
Kobe
Osaka
50 km
20 mi
©2010 Google - Imagery ©2010 TerraMetrics, Map data ©2010 ZENRIN - Terms of Use

Kamioka Underground site

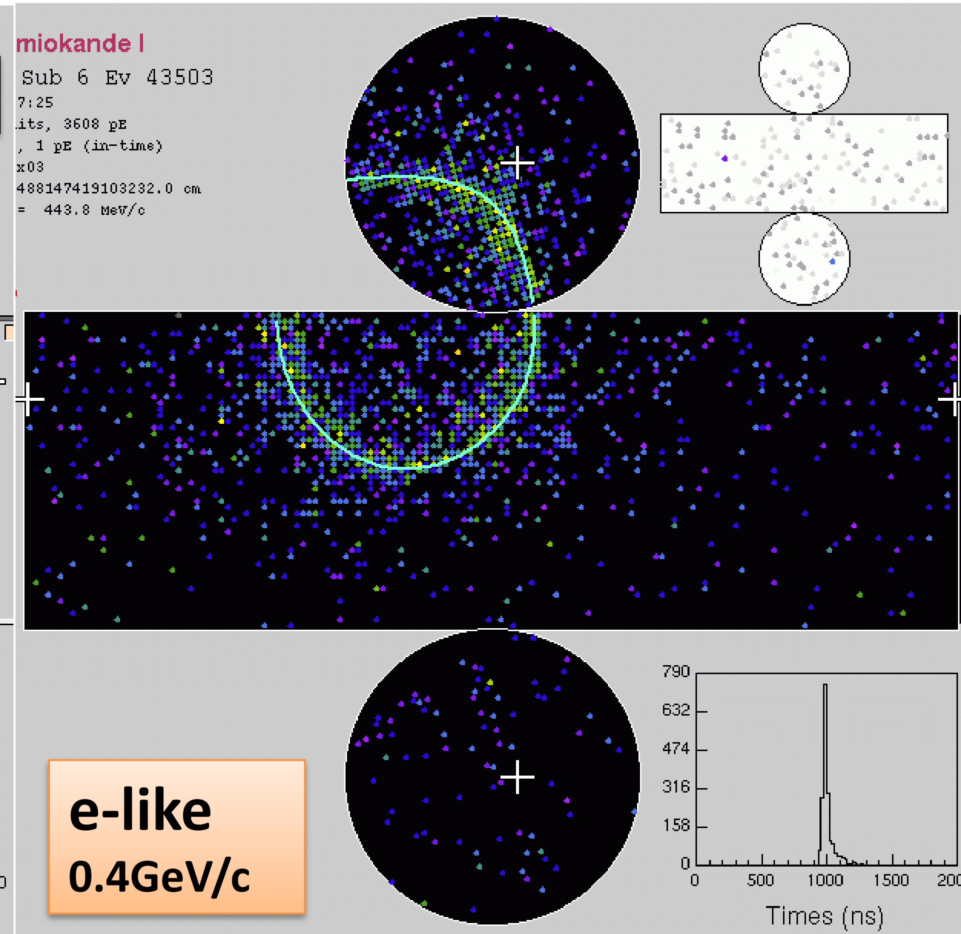


Typical high-energy events

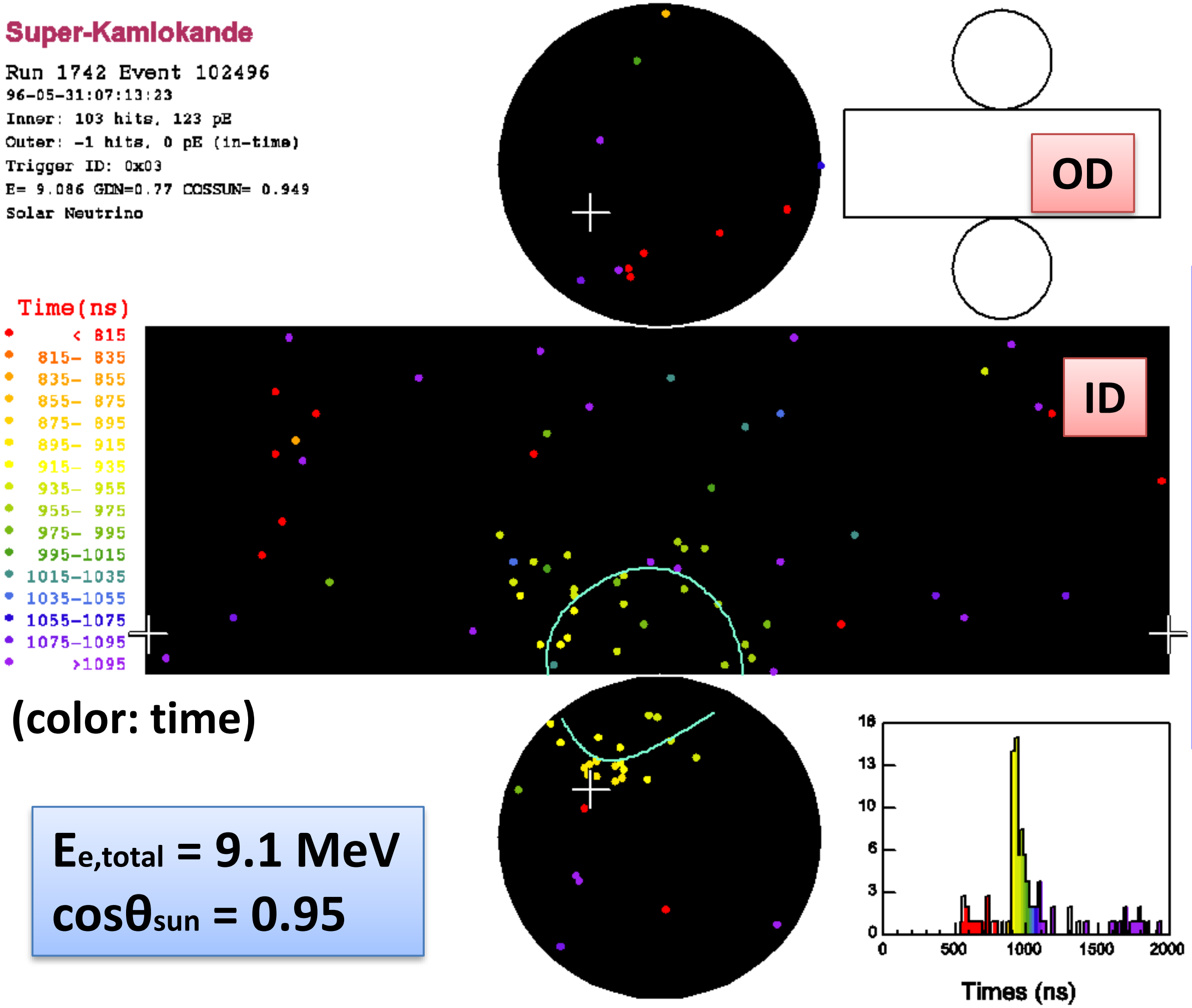
Atmospheric ν:
Partially contained (PC)



Atmospheric ν:
Fully contained (FC)



Typical low-energy event



(color: time)

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

(for solar neutrinos)

- Timing information ➡ vertex position
- Ring pattern ➡ direction
- Number of hit PMTs ➡ energy

$E_{e,total}$ = 9.1 MeV
$\cos\theta_{sun}$ = 0.95

~6 hit / MeV
(SK-I, III ~ VII)

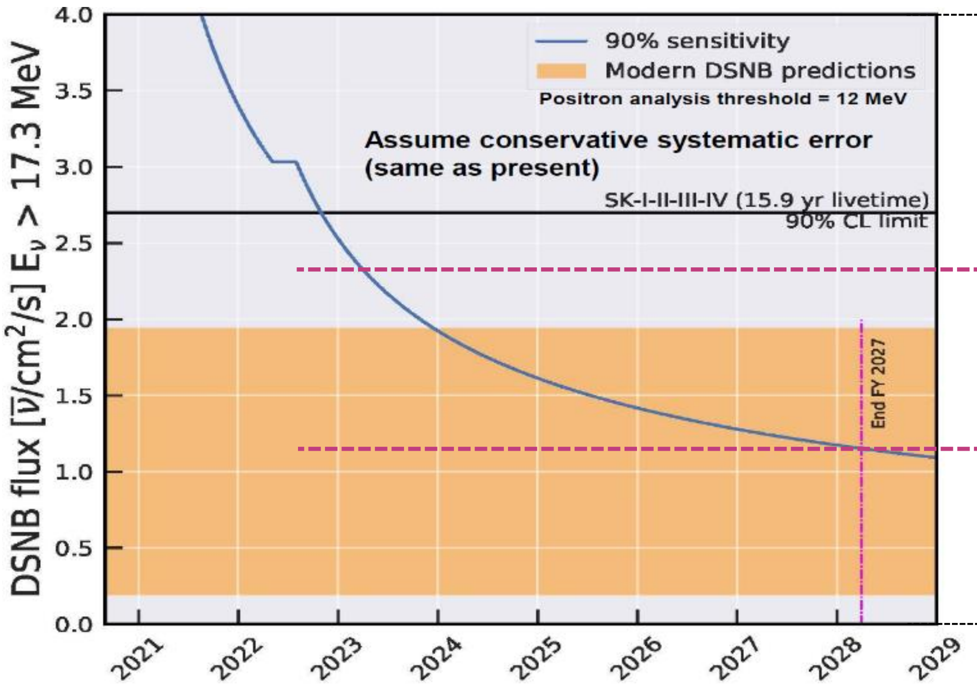
Resolutions (for 10 MeV electrons) (software improvement)

Energy: 14%	Vertex: 87cm	Direction: 26°	SK-I
Energy: 14%	Vertex: 55cm	Direction: 23°	SK-III, IV

SK-Gd sensitivity on DSNB search

Preliminary May 2022

Expected SK-Gd sensitivity of DSNB spectral fitting



Comparison among predictions