28-OCT-2025 @DarkWorld 2025

RECENT RESULTS FROM SUPER-KAMIOKANDE

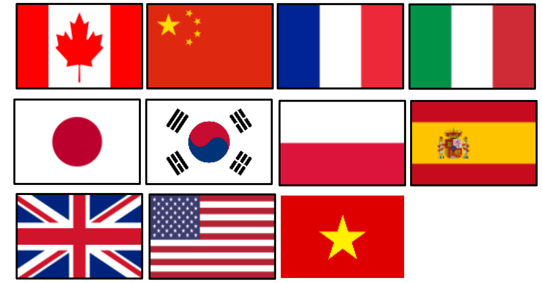
Yasuo TAKEUCHI
(Kobe University)
for SK collaboration

Partially supported by
JSPS KAKENHI Grant
Number 24H02243.

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

The Super-Kamiokande Collaboration

Collaboration meeting in Toyama (May 2025)



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
Chonnam National University, Korea
Duke University, USA
Gifu University, Japan
GIST, Korea
University of Glasgow, UK
University of Hawaii, USA
IBS, Korea
IFIRSE, Vietnam
Imperial College London, UK
ILANCE, France/Japan

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INFN Padova, Italy
INFN Roma, Italy
Institute of Science Tokyo, Japan
Kavli IPMU, The Univ. of Tokyo, Japan
Keio University, Japan
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University of Minnesota, USA
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
NIT, Numazu college, Japan

Okayama University, Japan
Osaka Electro-Communication Univ., Japan
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Rutherford Appleton Laboratory, UK
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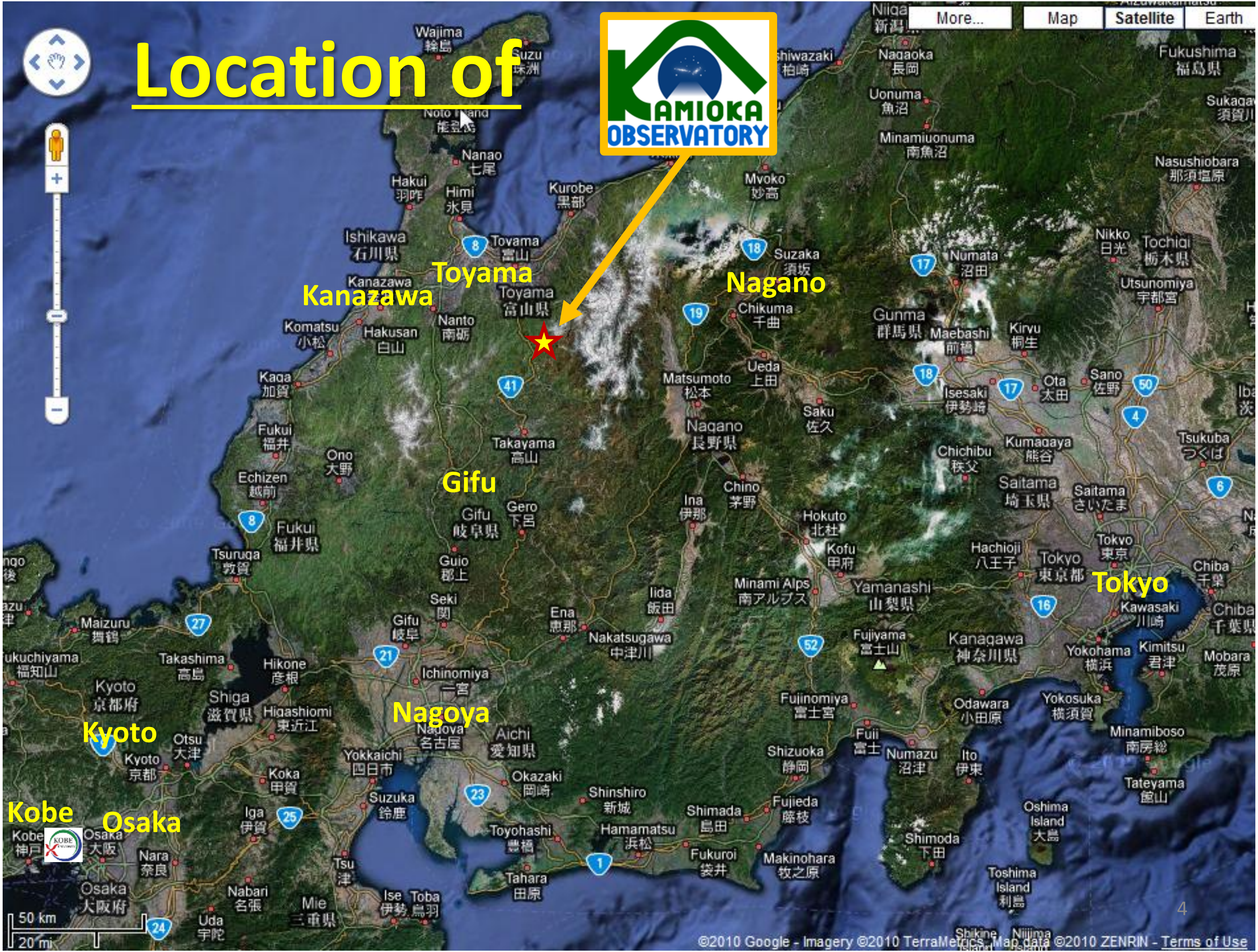
Sungkyunkwan University, Korea
Tohoku University, Japan
The University of Tokyo, Japan
Tokyo University of Science, Japan
University of Toyama, Japan
TRIUMF, Canada
Tsinghua University, China
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan

~240 collaborators from 55 institutes in 11 countries (as of May 2025)

Outline

- SK detector & summary of recent results
- Atmospheric neutrino oscillation results
- Solar neutrino oscillation results
- Dark matter searches at SK (and Hyper-K)
- Summary

Location of



Location of
KAMIOKA OBSERVATORY
Toyama
Kanazawa
Nagano
Gifu
Tokyo
Nagoya
Kyoto
Kobe
Osaka
50 km
20 mi
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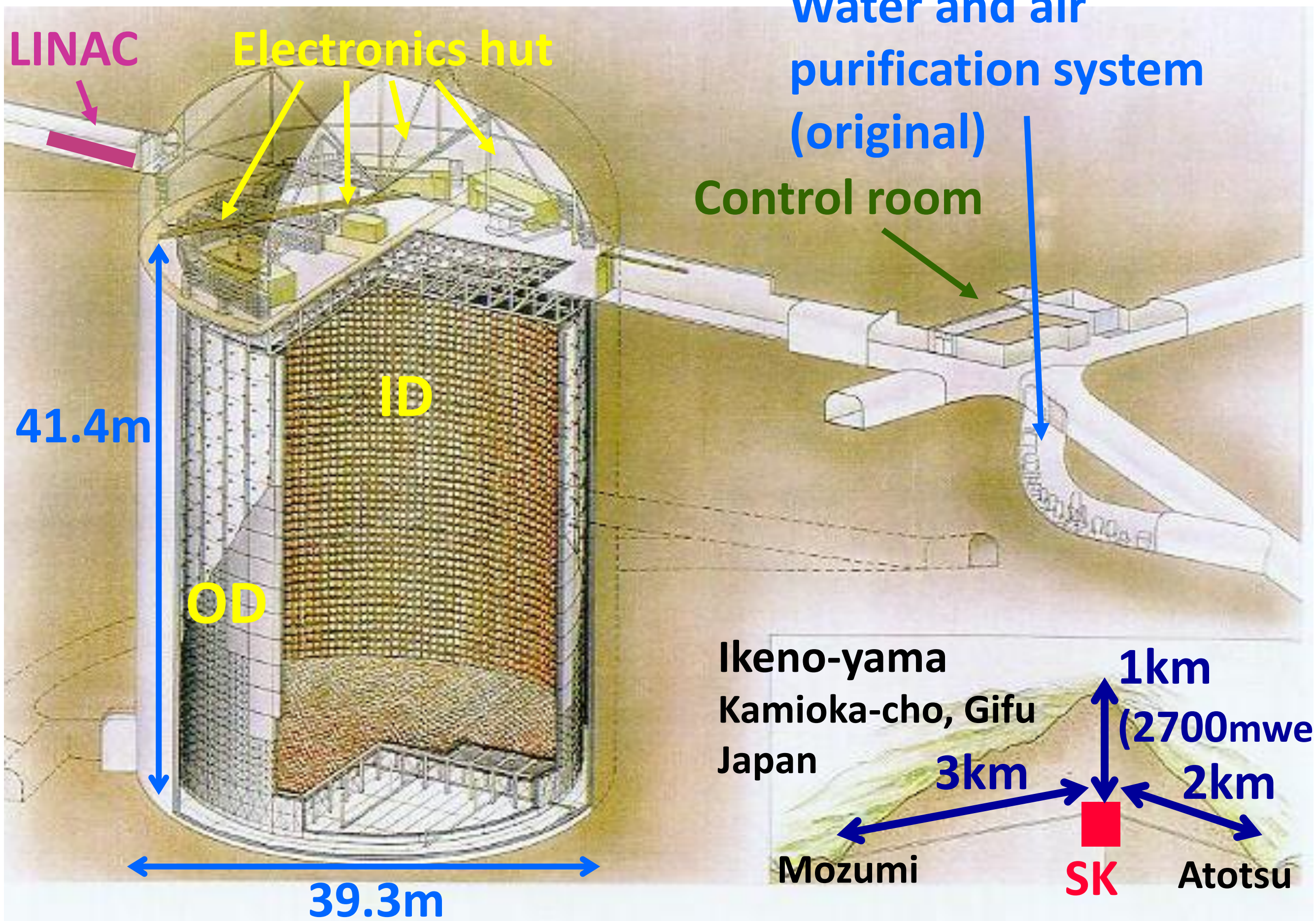
Super-Kamiokande detector

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-VIII is running

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

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

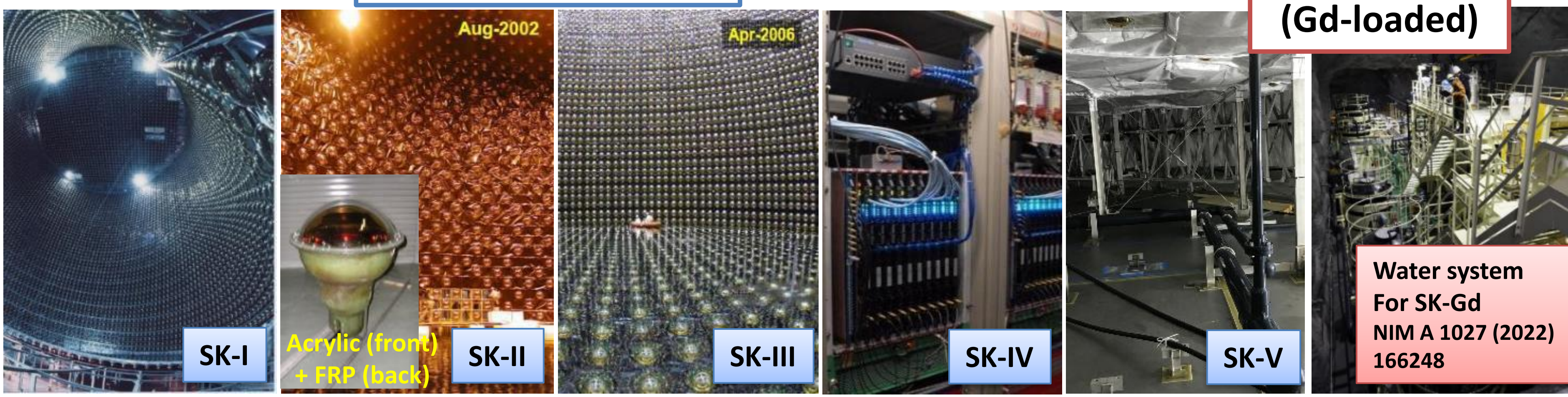
History of Super-Kamiokande

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 VII VIII

"SK" (pure water)

"SK-Gd" (Gd-loaded)



SK-I	SK-II	SK-III	SK-IV	SK-V	SK-VI, VII, VIII
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,VIII: 0.033%
(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)

SK-Gd Phase

SK-Gd Phase:

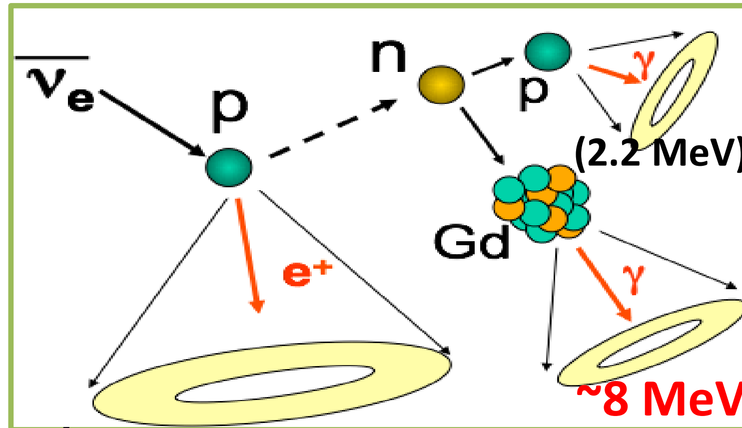
Add gadolinium (Gd) to enhance neutron tagging efficiency of the SK detector.

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**

Neutron tagging efficiency

- **SK-IV (SK): ~19%** (ApJ 60, 41-46 (2015)) **~26%** (JINST17, P10029 (2022))
- **SK-VI (SK-Gd): ~35%** (ApJL 951, L27 (2023)) **~44%** (PRD112, 012004 (2025))
- **SK-VII (SK-Gd): ~55%** *(preliminary)*



- **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: 0.033% (5 Jul. 2022-)

Summary of recent results

- ## Nucleon decay search
  - PRD 110, 112011 (2024), PRD 106, 072003 (2022), …
  - 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) (PRD102, 112011 (2020))
- ## Atmospheric ν oscillation analysis
  - PRL134, 011801 (2025): SK 3244 days + T2K 19.7×10^{20} POT
  - PRD109, 072014 (2024): SK-I~V 6511 days, 484.2 kt·yr
- ## Solar ν oscillation analysis
  - PRD109, 092001 (2024): SK-I~IV 5805 days (until end of SK-IV)
- ## Astrophysics
  - Cosmic-ray muon charge ratio: PRD110, 082008 (2024)
  - Pre-supernova alert system (SK+KamLAND): ApJ 973, 140 (2024)
  - Supernova monitoring in SK-Gd: ApJ 970, 93 (2024)
  - Periodic time variation search of solar ^{8}B nu: PRL132,241803 (2024)
  - DSNB search in SK-Gd: ApJL 951,L27 (2023)
  - Boosted sub-GeV DM-proton search: PRL130, 031802 (2023)
  - DSNB search in SK-IV: PRD104,122002 (2021)

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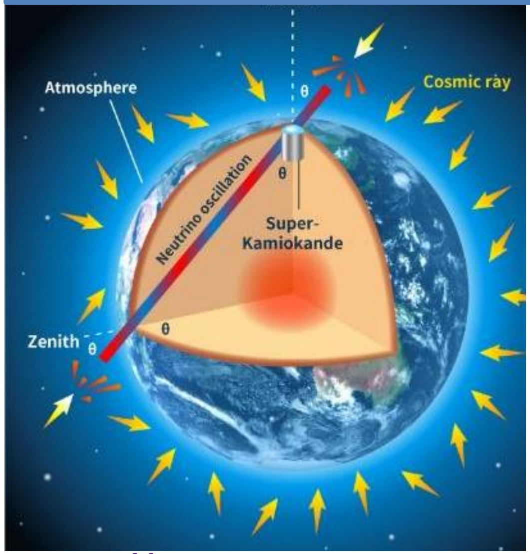
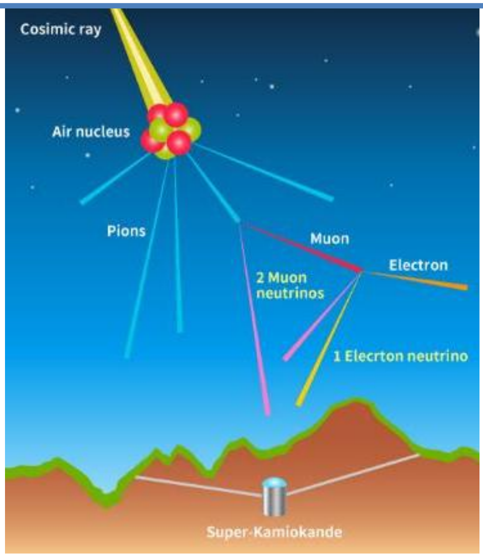
Atmospheric ν

PRD109, 072014 (2024)

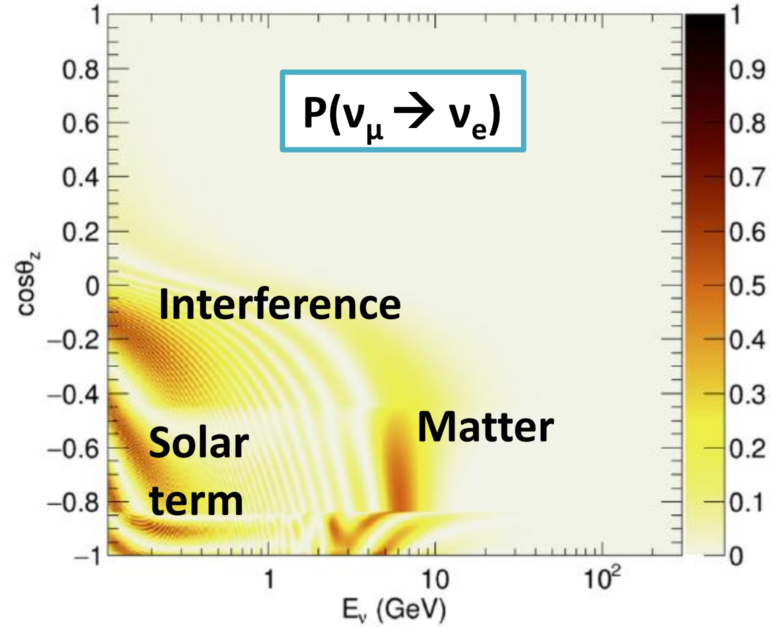
- Produced by cosmic-rays in Earth's atmosphere
- Measure ν flavor, energy, zenith angle, etc. in SK
  - Sensitive to θ_{23} and $\Delta m^2_{32,31}$ parameters.
- Matter effect: enhancement of ν_e in several GeV energy region and in Earth core
  - θ_{13} and mass ordering could be studied.
- Solar term: enhancement of ν_e in sub-GeV region
  - θ_{23} octant degeneracy could be studied.
- Interference: CP phase could be studied.
- In SK-Gd: separation between ν / $\bar{\nu}$ is improved.

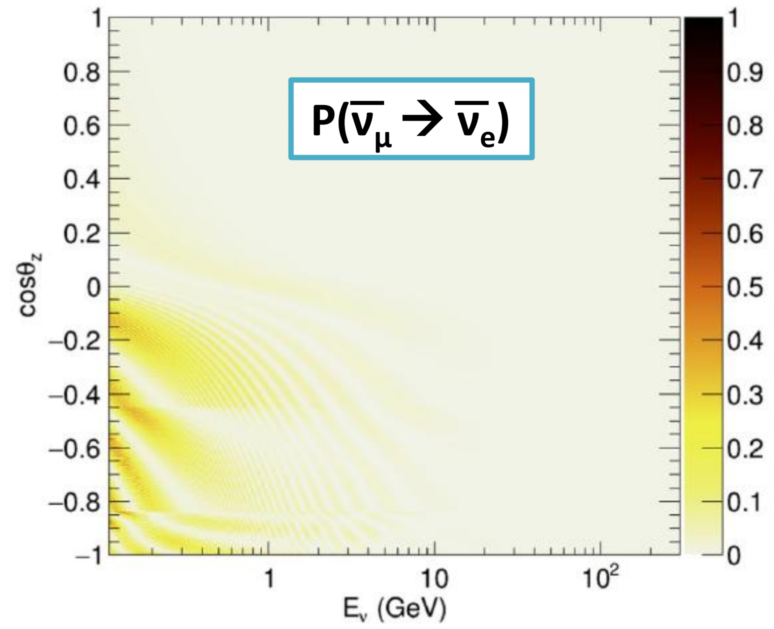




https://www-sk.icrr.u-tokyo.ac.jp/en/sk/about/research/

(Normal mass ordering)



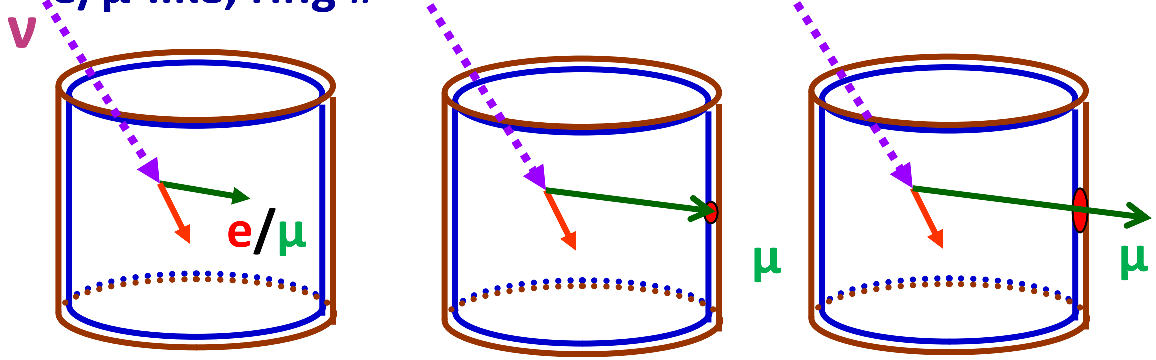


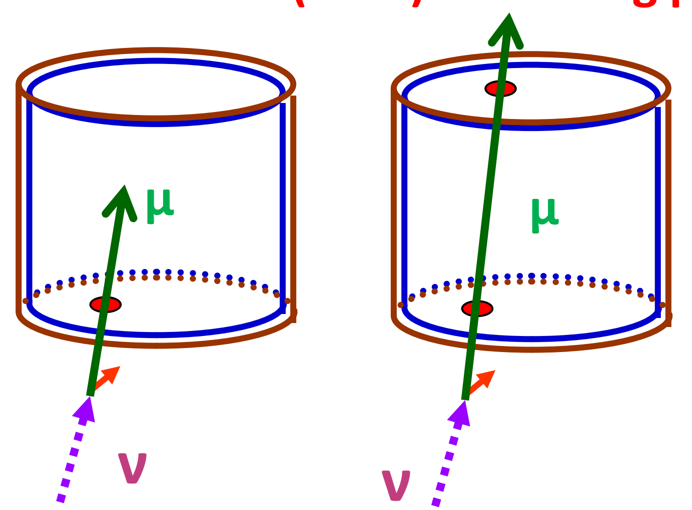
Atmospheric ν categories in SK

Fully contained (FC) — Sub/Multi-GeV, e/μ-like, ring #

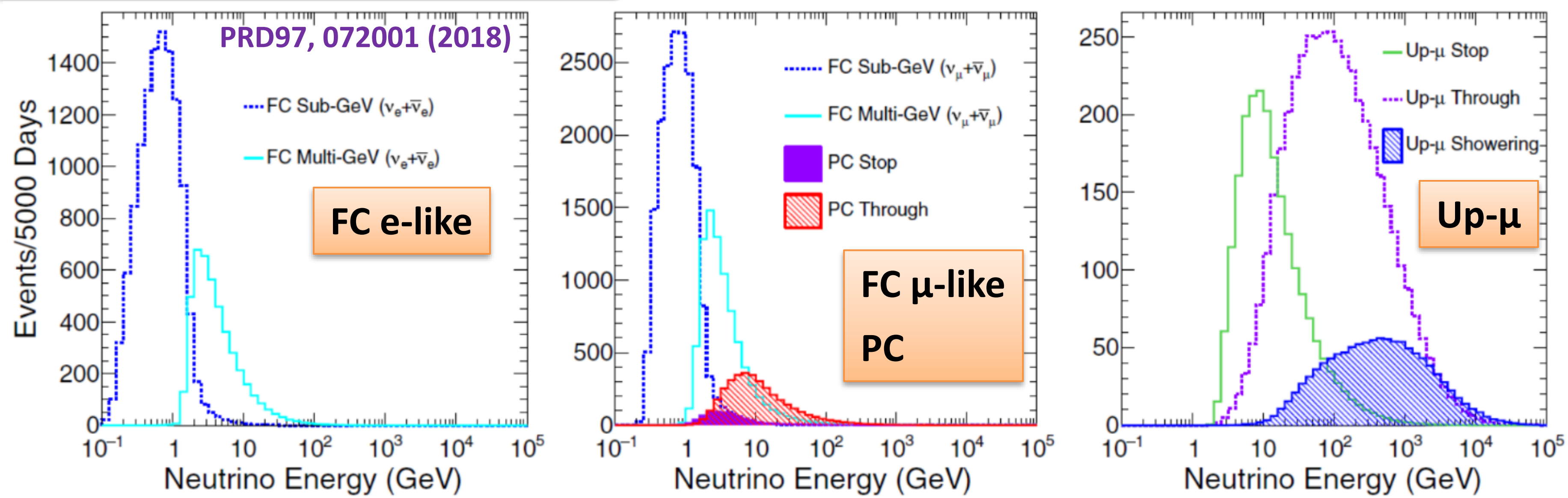
Partially contained (PC) — Stopping, through-going

Upward-going muons (Up-μ) — Stopping μ, Through-going (non-)showering μ



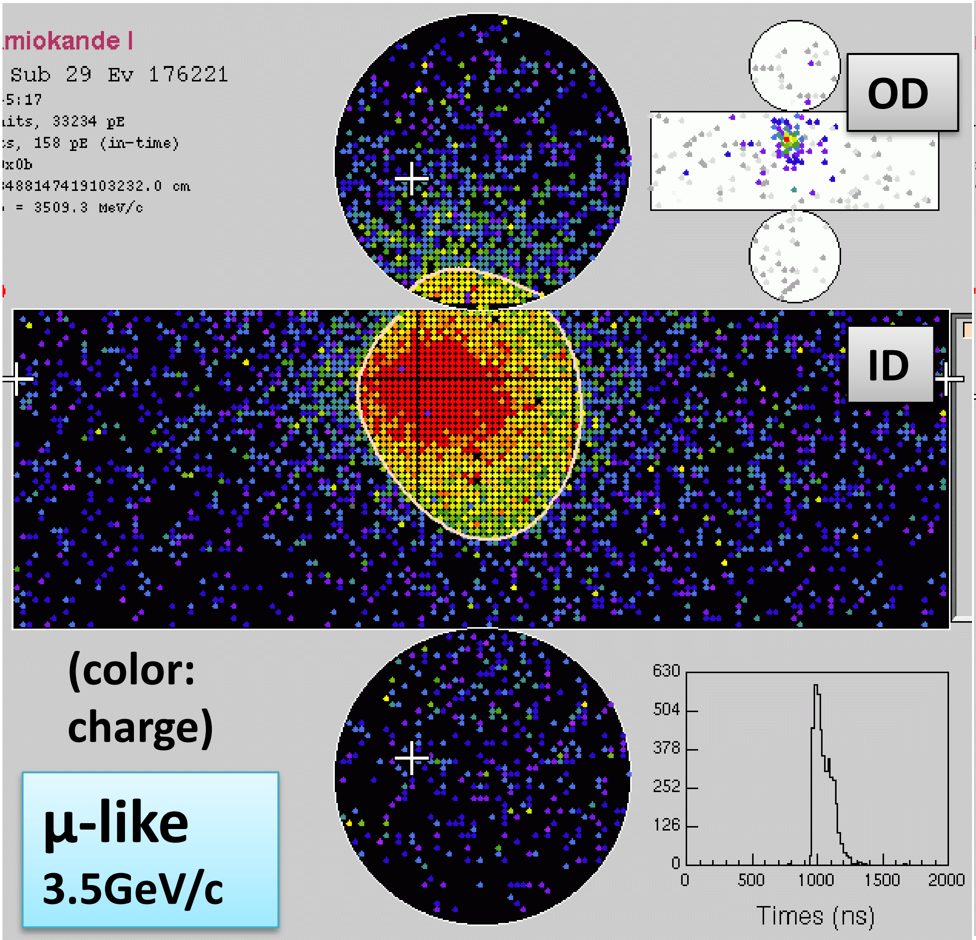


Expected energy spectrum of ν

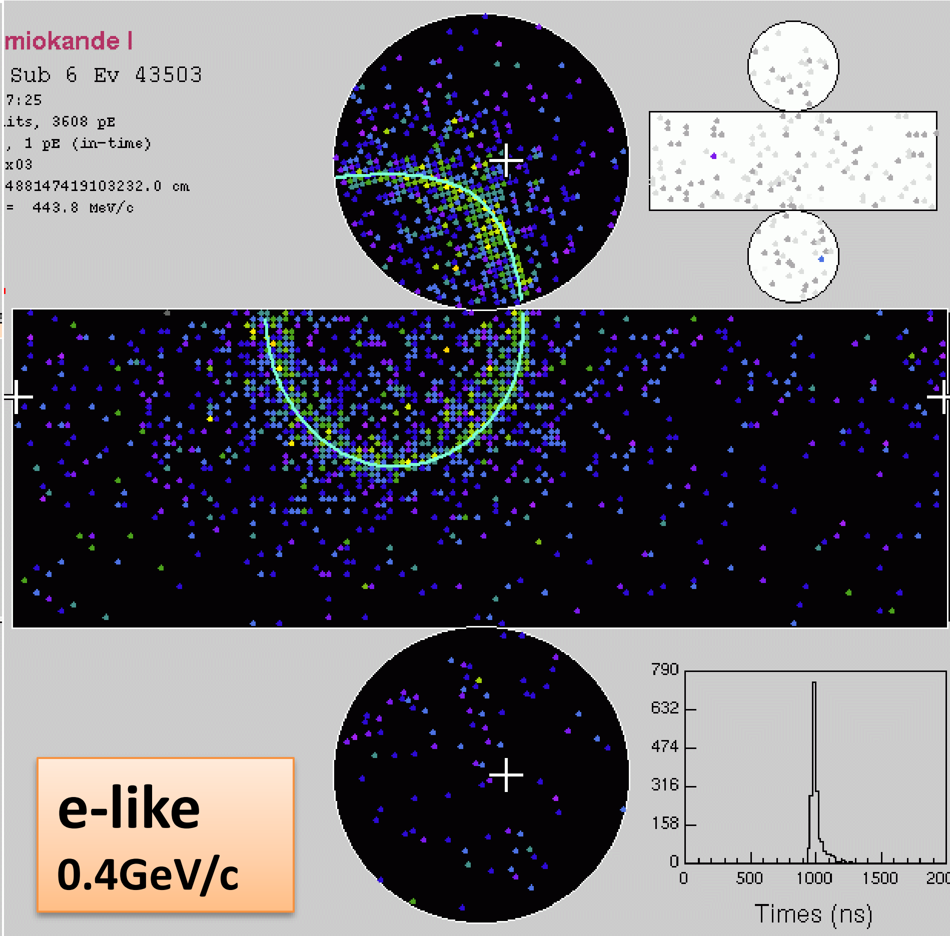


Typical high-energy events

Atmospheric ν:
Partially contained (PC)



Atmospheric ν:
Fully contained (FC)



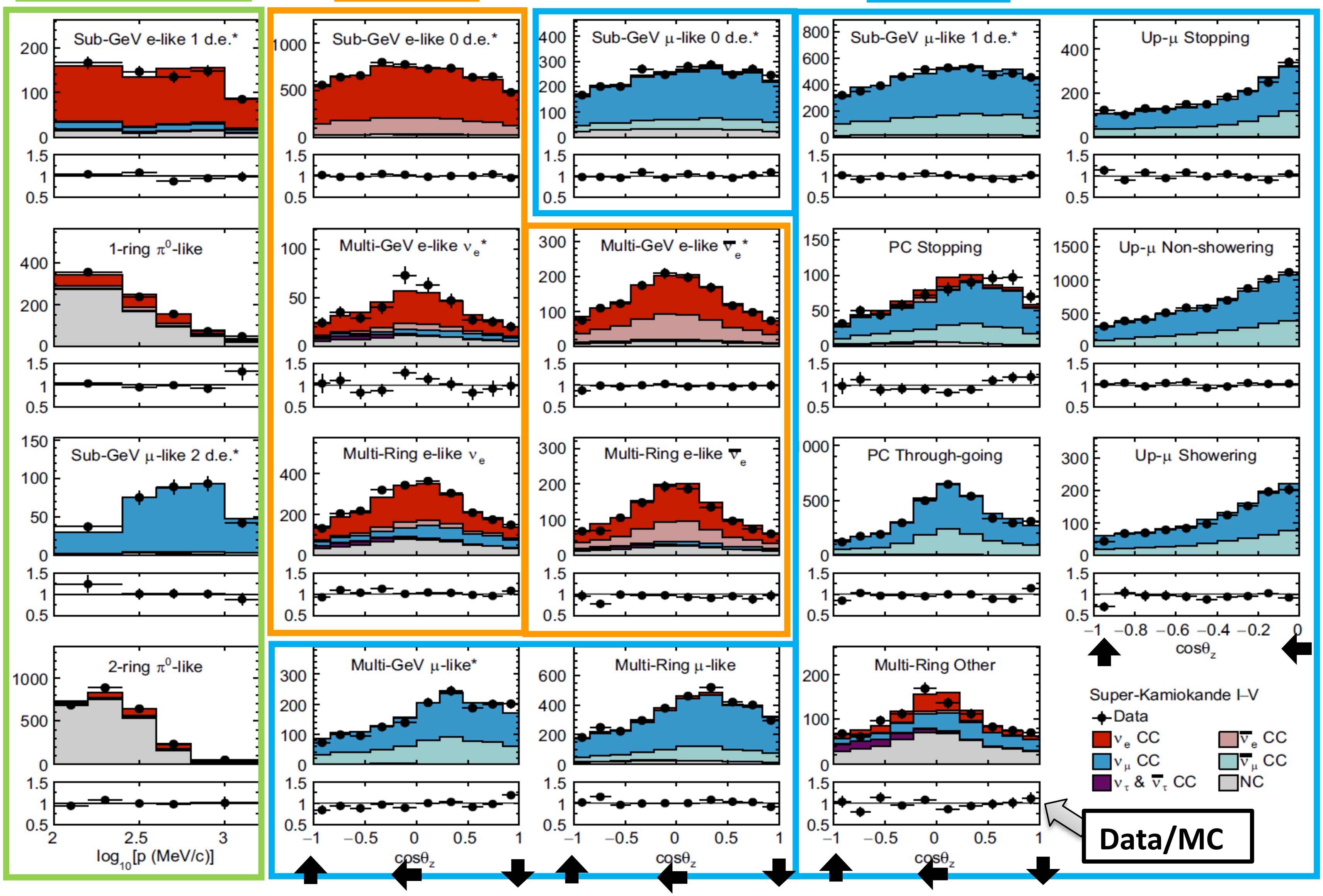
Zenith angle & lepton momentum distributions

PRD109, 072014 (2024)

momentum

e-like

μ-like



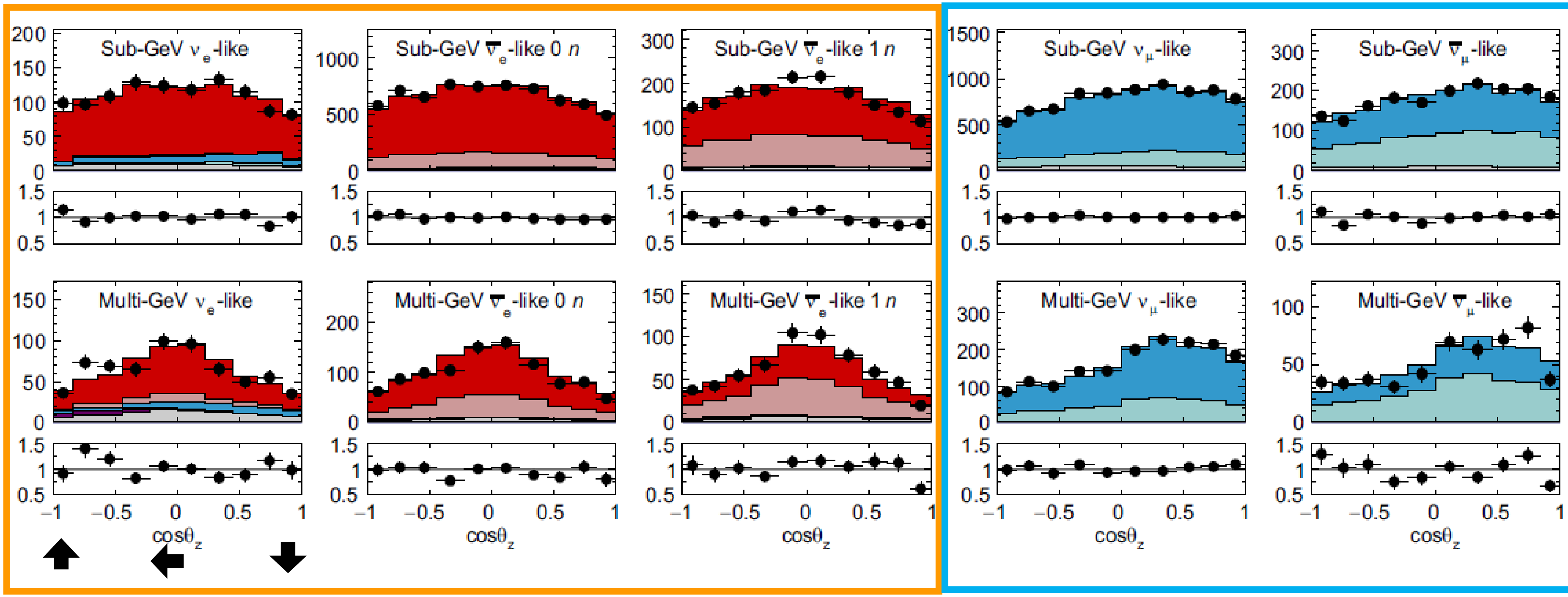
No neutron tagging

Zenith angle distributions using neutrons (SK-IV, V)

PRD109, 072014 (2024)

e-like

μ-like



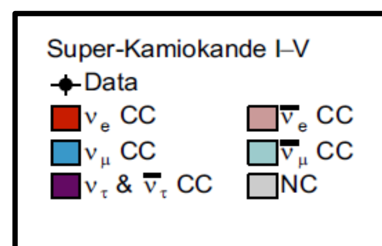
ν_e-like:
Decay-e >= 1
Neutron: any

$\bar{\nu}_e$-like 0 n:
Decay-e = 0
Neutron = 0

$\bar{\nu}_e$-like 1 n:
Decay-e = 0
Neutron >=1

ν_μ-like:
others

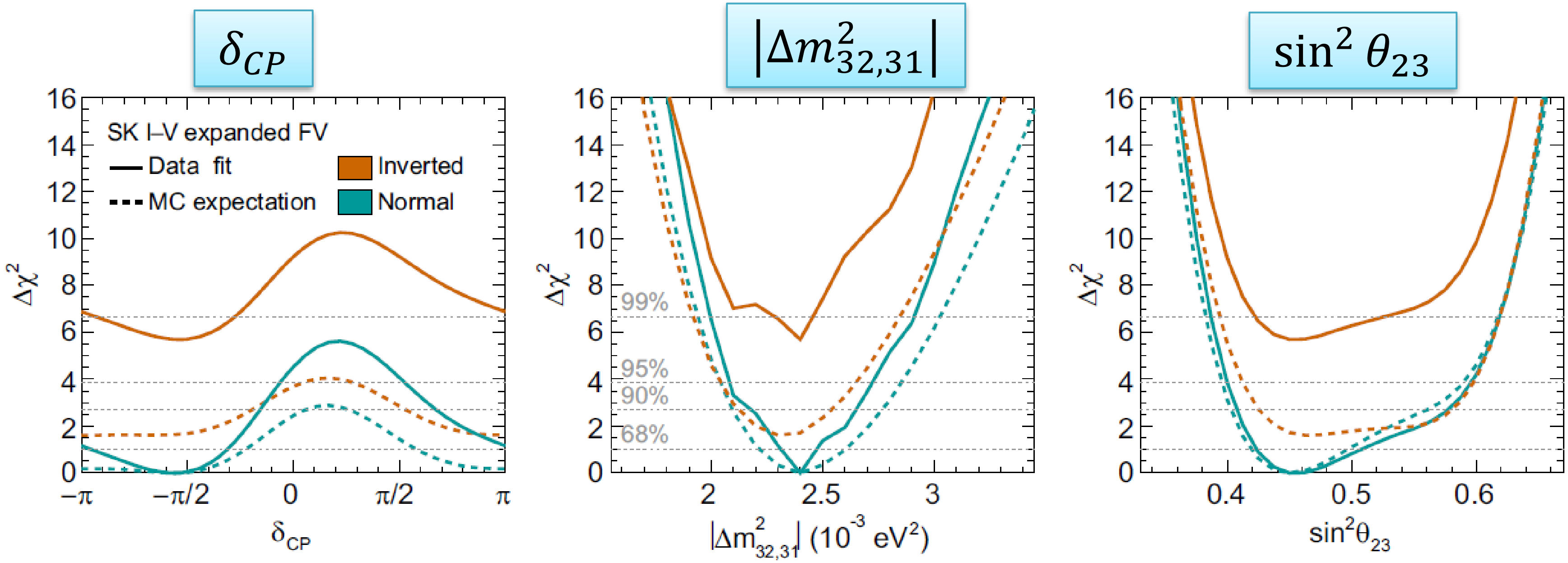
$\bar{\nu}_\mu$-like:
Decay-e = 1
Neutron >=1



Number of observed decay-electrons and neutrons are considered.

SK Atm. ν oscillation analysis results

PRD109, 072014 (2024)



$\sin\theta_{13} = 0.0220 \pm 0.0007$

FIG. 16. 1D $\Delta\chi^2$ profiles of oscillation parameters in the analysis with $\sin^2\theta_{13}$ constrained. Solid lines correspond to the data fit result, while dashed lines correspond to the MC expectation at the data best-fit oscillation parameters, cf. Table IV. Dotted lines show critical values of the χ^2 distribution for 1 degree of freedom corresponding to 68%, 90%, 95%, and 99% probabilities.

Best-fit: (for Normal mass ordering)

- $\sin^2\theta_{23} = 0.45^{+0.06}_{-0.03}$
- $|\Delta m^2_{32,31}| = (2.40^{+0.07}_{-0.09}) \times 10^{-3}\mathrm{eV}^2$
- $\delta_{CP} = -1.75^{+0.76}_{-1.25}$ (−π, +π)

SK atmospheric ν data favors:

- $\delta_{CP} \approx -\frac{\pi}{2}$
- Normal mass ordering ($\Delta\chi^2 = 5.69$)
  - 92.3%

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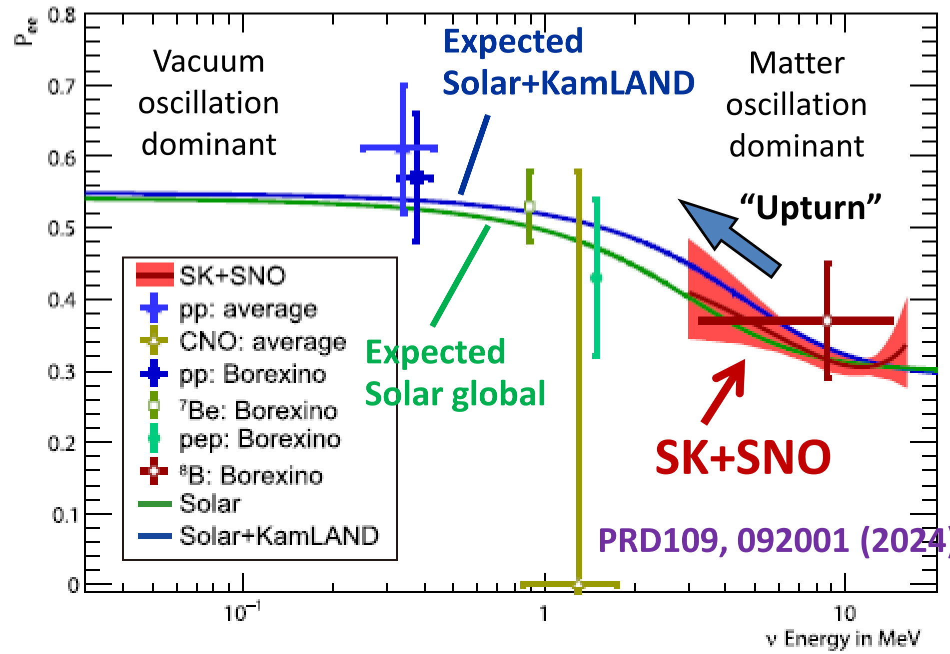
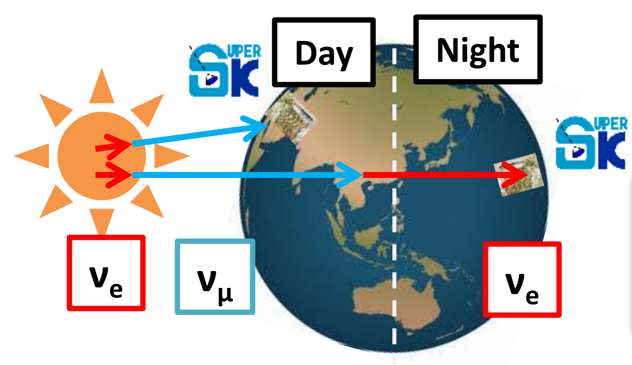
Solar neutrinos

- Produced by nuclear fusion in the sun (initial = ν_e)
- High statistics measurement of flux, energy spectrum, and time variations of ^{8}B solar neutrinos in SK.
- Energy spectrum: sensitive to θ_{12} and Δm^2_{21} parameters. Global solar 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

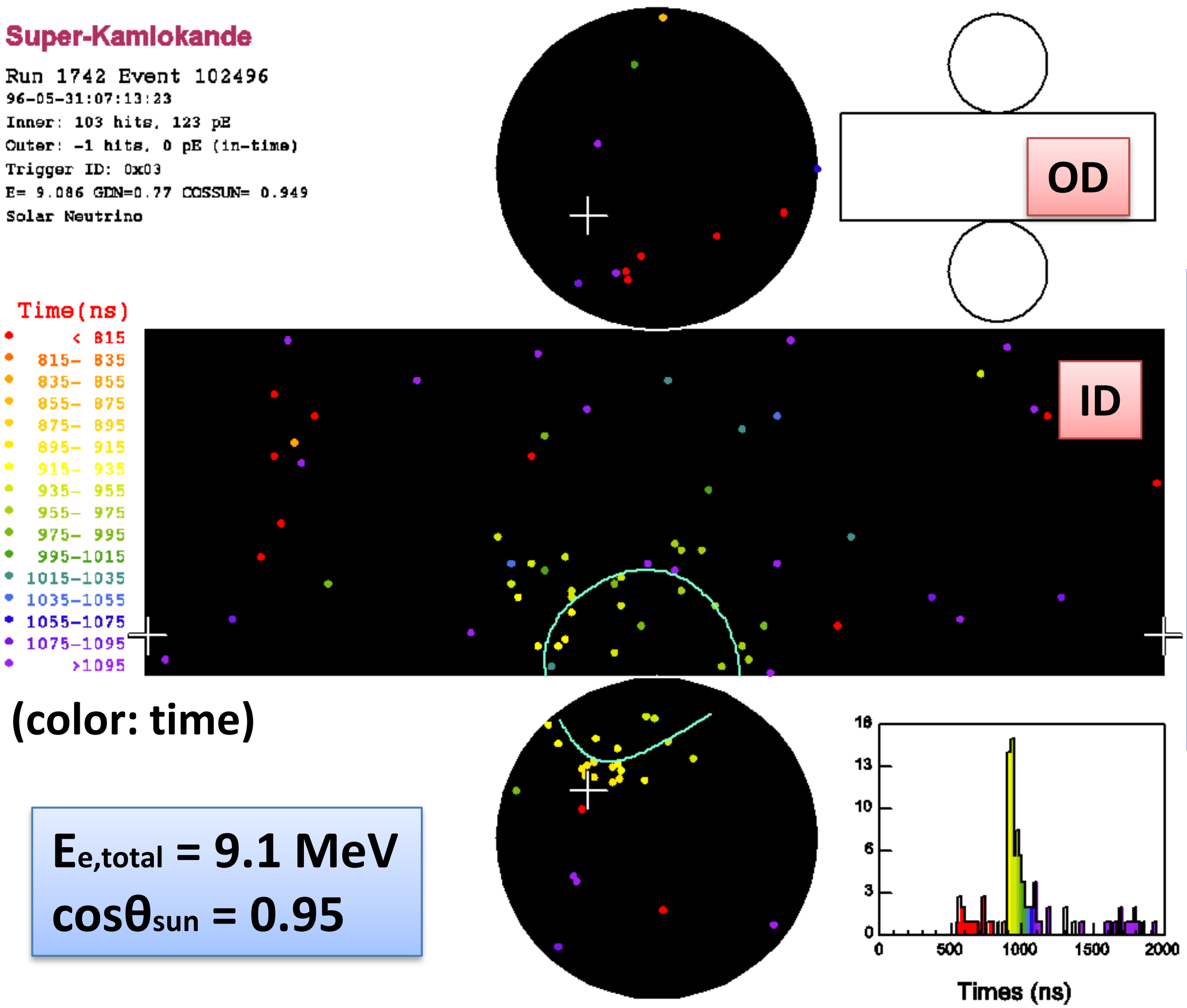


Regenerate ν_e by Earth's matter effect

Typical low-energy event

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

(for solar neutrinos)



(color: time)

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

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

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

Resolutions (for 10 MeV electrons) (software improvement)

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

SK-IV solar neutrino signal

PRD109, 092001 (2024)

- **Signal (in SK-IV): 65,443 +390 -388(stat.) +/-925 (syst.) events.**
  - **Total: > 10^5 solar ν events (during SK-I~IV, 5805 days)**

Solar angle dist. (3.49-19.49 MeV)

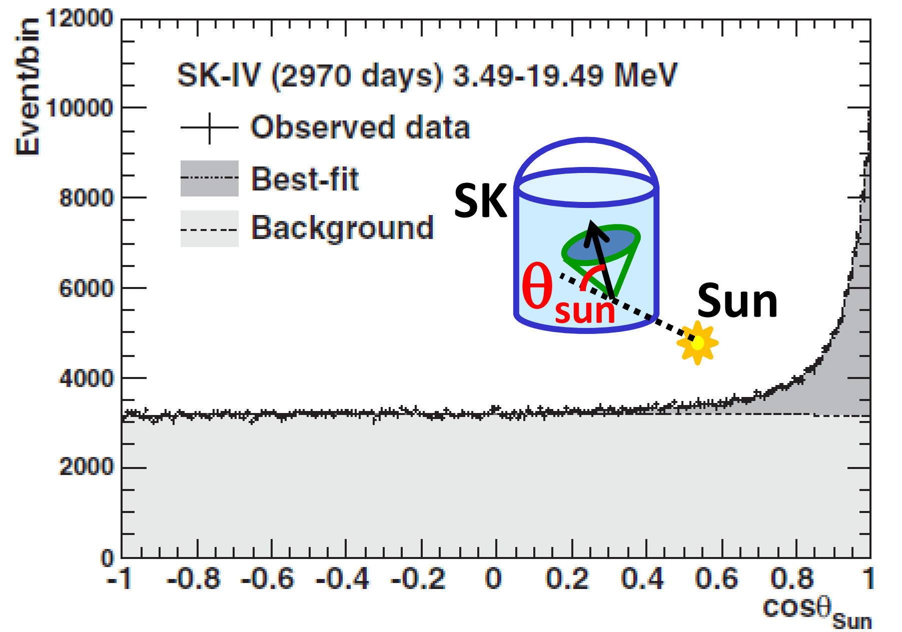


FIG. 30. Solar angle distribution for the energy range of 3.49–19.49 MeV using SK-IV 2970-day dataset. The black points show the observed data, the dark and light gray shades show the background and the best-fit signal, respectively.

Energy spectrum

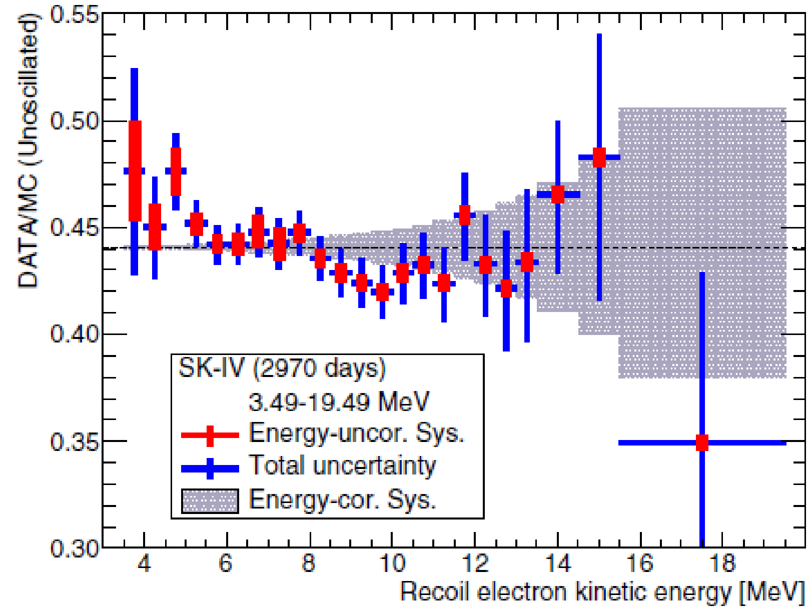


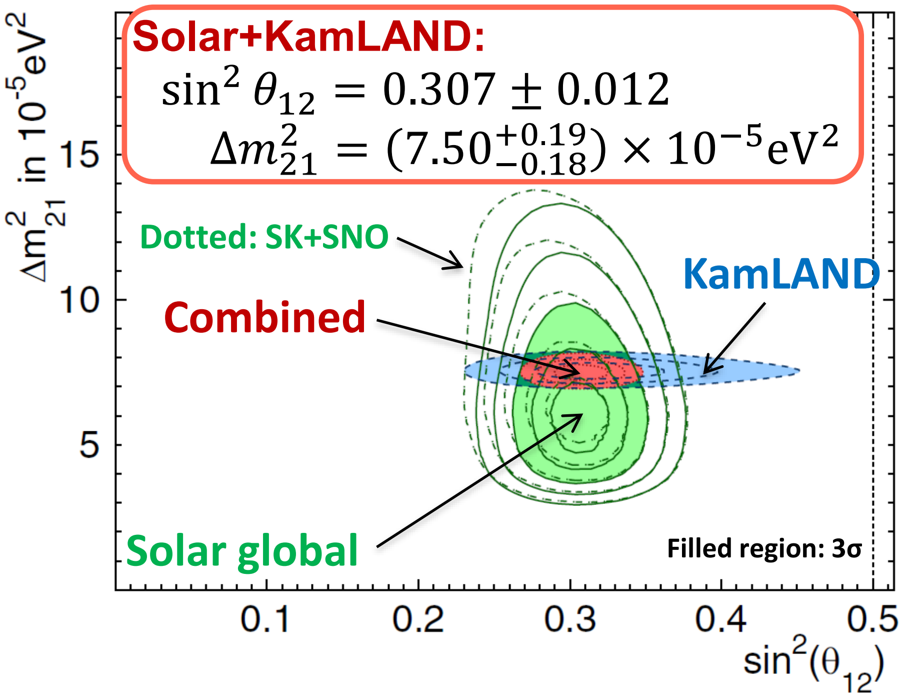
FIG. 37. The measured energy spectrum in SK-IV. The blue points and bars show the observed rate divided by the expected event rate assuming no neutrino oscillation, with statistical and energy-uncorrelated uncertainties. The red bars and gray bands show the energy-uncorrelated and energy-correlated systematic uncertainties.

SK solar ν (oscillation) results

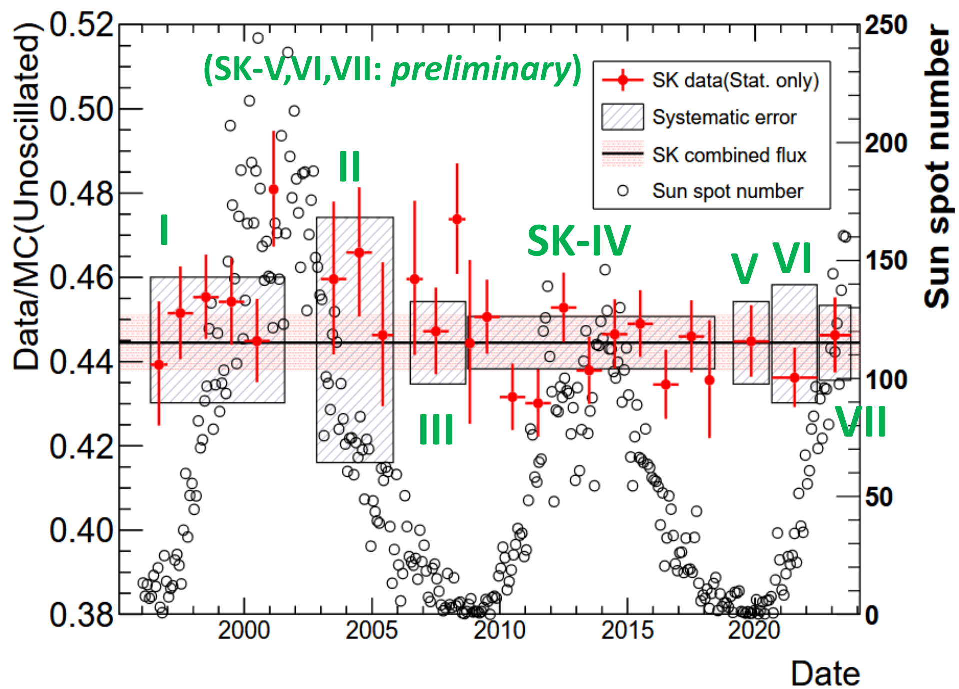
PRD109, 092001 (2024)

- ~1.5 σ level tension in Δm^2_{21} between SK+SNO analysis and KamLAND is remaining.
- No significant variation has been observed in the solar neutrino flux measured annually.

Solar ν oscillation parameters



Annual solar ν flux



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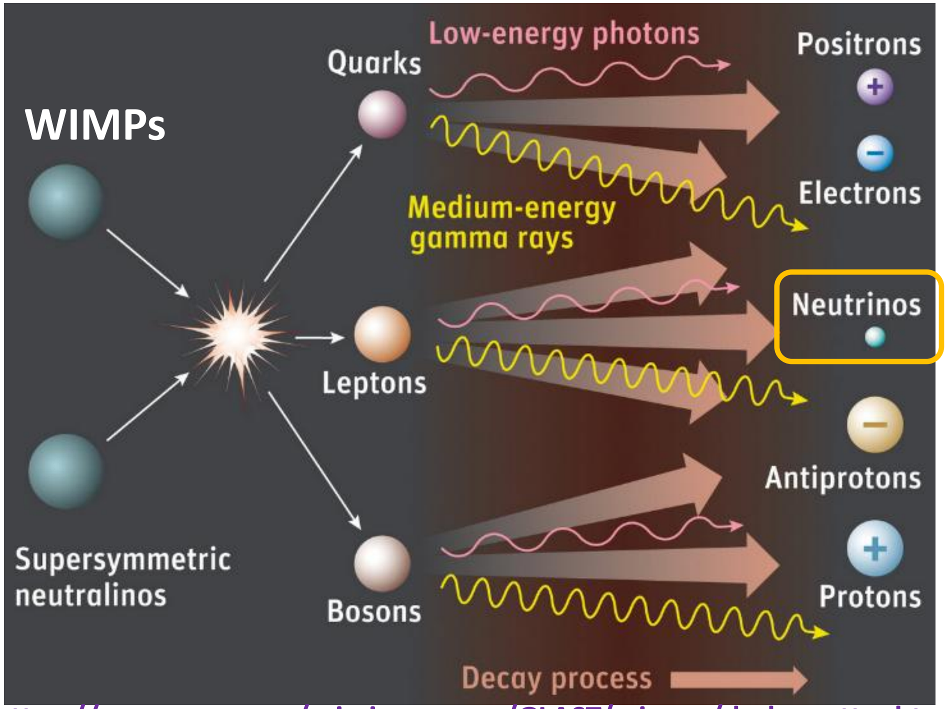
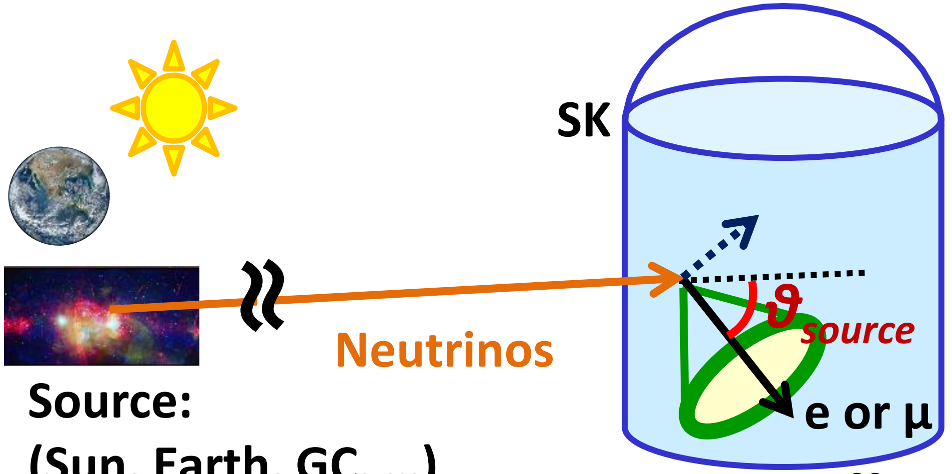
Indirect WIMP search in SK

- Weakly interacting massive particle (WIMP) is a Dark Matter (DM) candidate
- Annihilation (or decay) of WIMPs could produce neutrinos.
  - Directory, or via SM particles
- WIMPs could accumulate in massive object.
  - Trapped by gravity
- SK searches for WIMP-induced neutrinos from possible sources
  - Targets: Solar core, Earth core, Galactic Center (GC)
  - Use ϑ_{source}, above atmospheric neutrino (atm. ν) background.



https://www.nasa.gov/mission_pages/GLAST/science/dark_matter.html



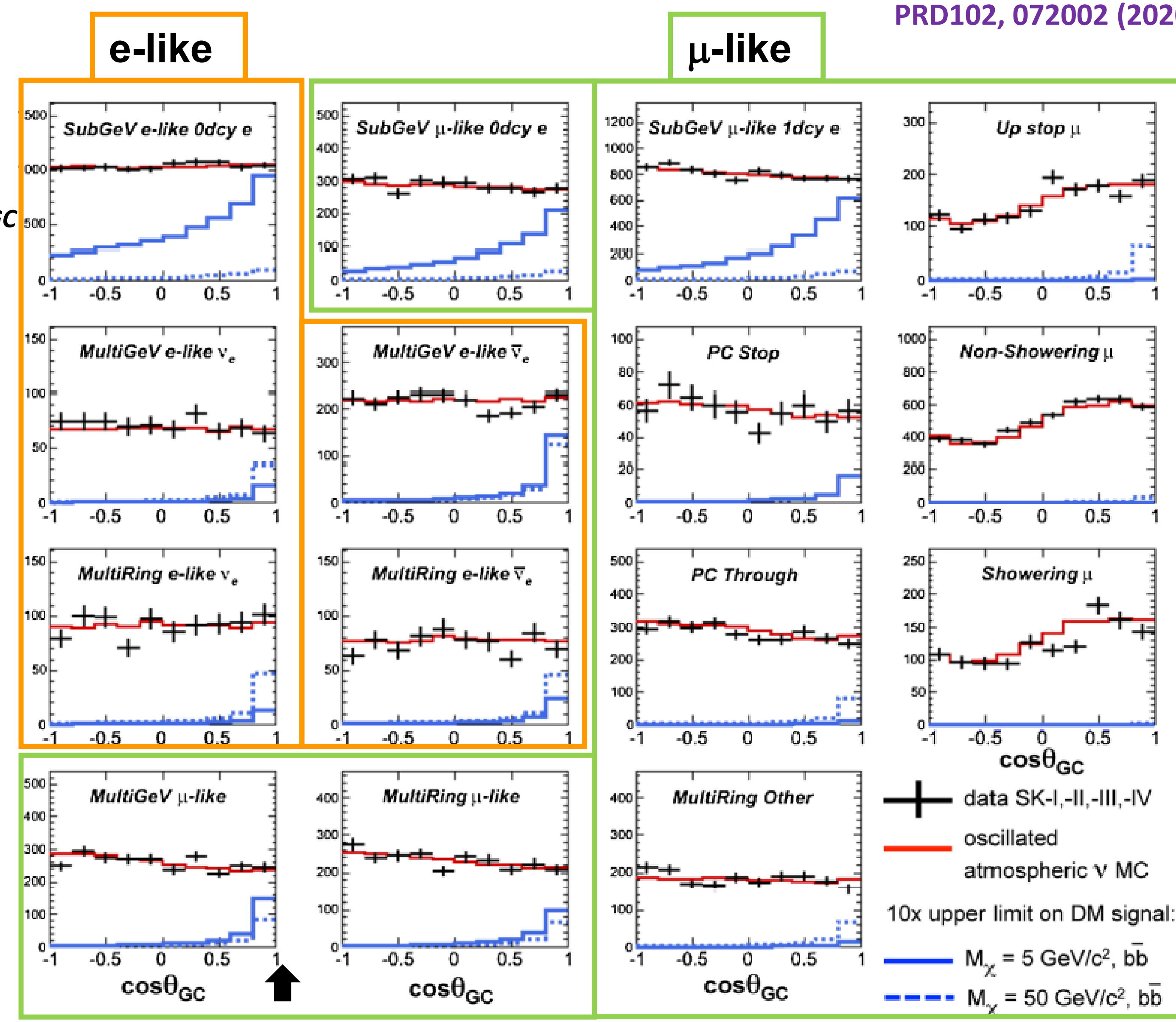
Summary of DM searches in SK

- Solar WIMP search: ϑ_{sun}
  - PRL 114, 141301 (2015): SK-I~IV 3903 days (1996-2012)
- Earth WIMP search: ϑ_{zenith}
  - SK-I~IV 5326 or 5629 days (1996-2016), *preliminary*
- Galactic WIMP search: ϑ_{GC}
  - PRD 102, 072002 (2020): SK-I~IV 5326 or 5629 days
    - Fit analysis & ON-/OFF-source analysis
- Boosted DM search: ϑ_{GC}
  - PRL 120, 221301 (2018): SK-IV 2628 days
    - Search for an excess of elastically scattered electrons above the atm. ν background (ON-/Off-source analysis)
  - PRL 130, 031802 (2023): SK-I~IV 6050 days (1996-2018)
    - Search for cosmic-ray boosted DM (CRDM) with recoil protons (sensitive to light DM: 1~300 MeV)
- DM searches with low-energy electrons (on going)
  - Another probe for light DM, led by a Korean team (IBS people).

Galactic WIMP search: fitting

PRD102, 072002 (2020)

- Use Atm. ν Data & oscillated MC
- Horizontal axis: $\cos\vartheta_{GC}$
- WIMP MC
  - DarkSUSY simulation is used
  - NFW halo model is assumed
- Fitted results are consistent with null WIMP
- 90% C.L. upper limit on WIMP self-annihilation cross section <σV> is obtained



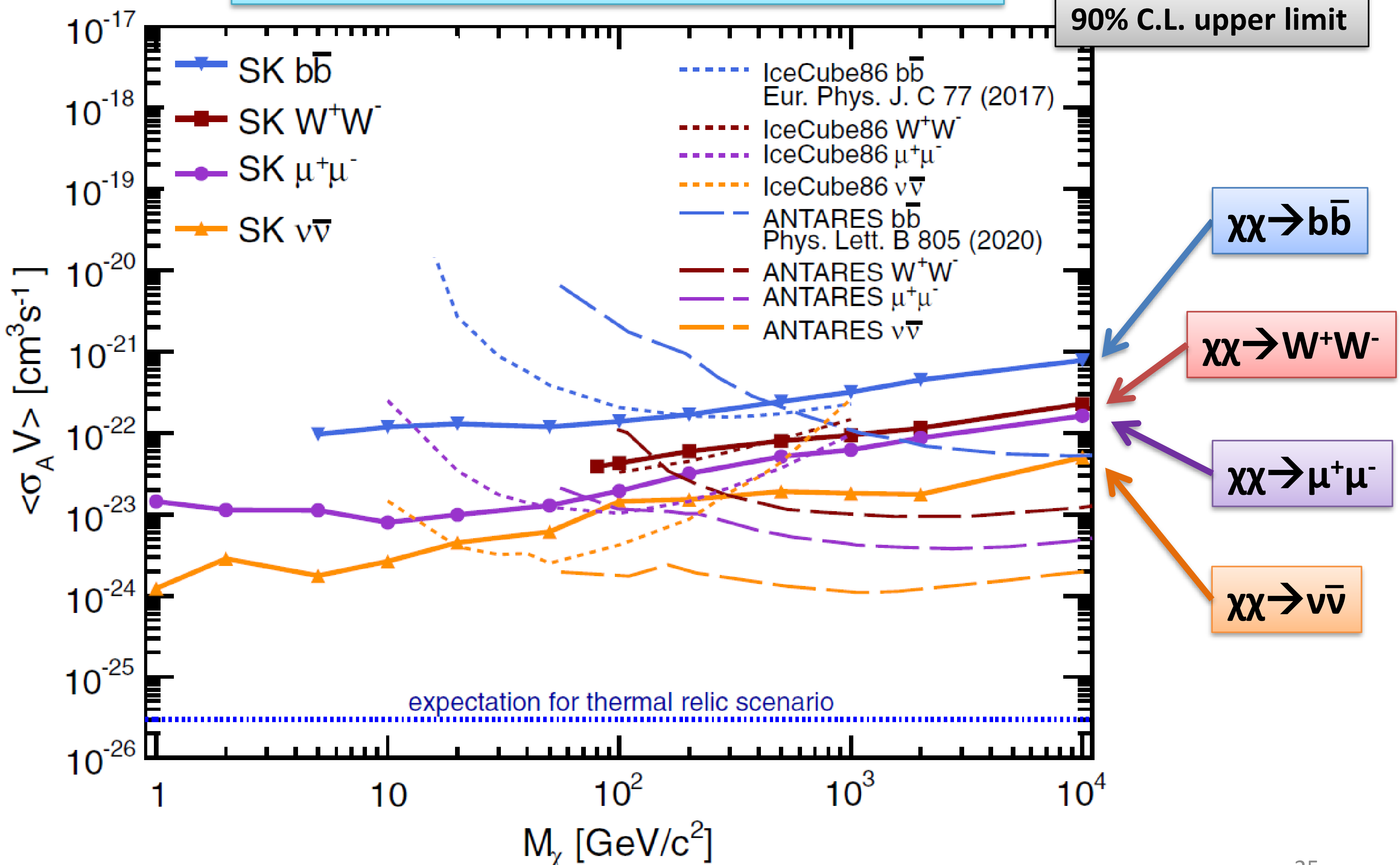
(Event direction from Galactic Center)

Galactic WIMP search: fitting

PRD102, 072002 (2020)

WIMP self-annihilation cross section <σV>

90% C.L. upper limit

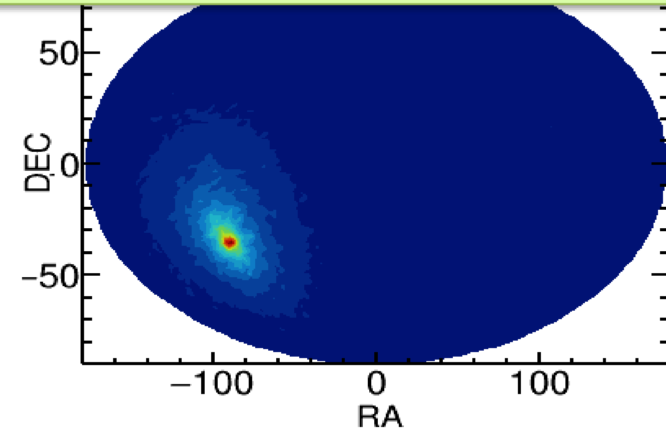


Galactic WIMP search: ON/OFF

PRD102, 072002 (2020)

- Search for large-scale anisotropy due to DM-induced ν's from our Galaxy
- **Compare the number of ν events in a certain angular region**
  - ON-source: around Galactic Center (GC)
  - OFF-source: shifted by 180° in right ascension (RA)
- Any excess of events in the ON-source part should indicate a possible unknown source, since atm. ν background equally affects those two regions.
- Independent from atmospheric ν simulation and related systematic uncertainties

Expected DM-induced neutrinos from Galaxy (diffused, peaked from GC)



ON-/OFF-source regions

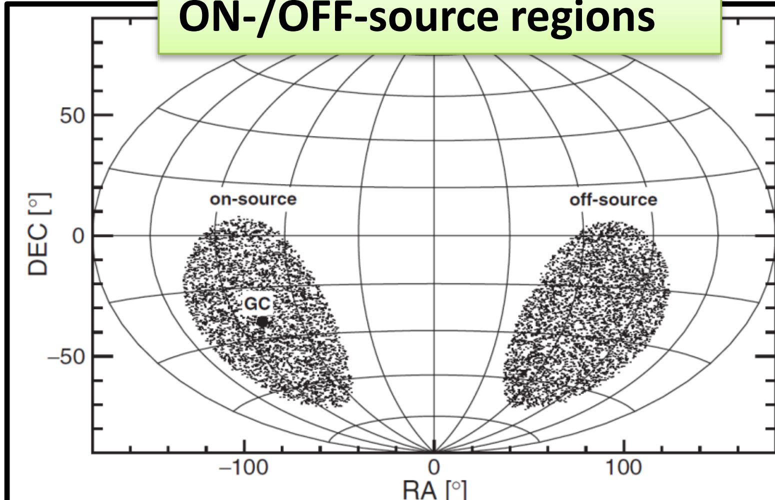


FIG. 9. The on-source/off-source regions defined in equatorial coordinates.

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PRD102, 072002 (2020)

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- **Compare the number of ν events in a certain angular region**
  - ON-source: around Galactic Center (GC)
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- Any excess of events in the ON-source part should indicate a possible unknown source, since atm. ν background equally affects those two regions.
- Independent from atmospheric ν simulation and related systematic uncertainties

- No asymmetry in neutrino flux is observed

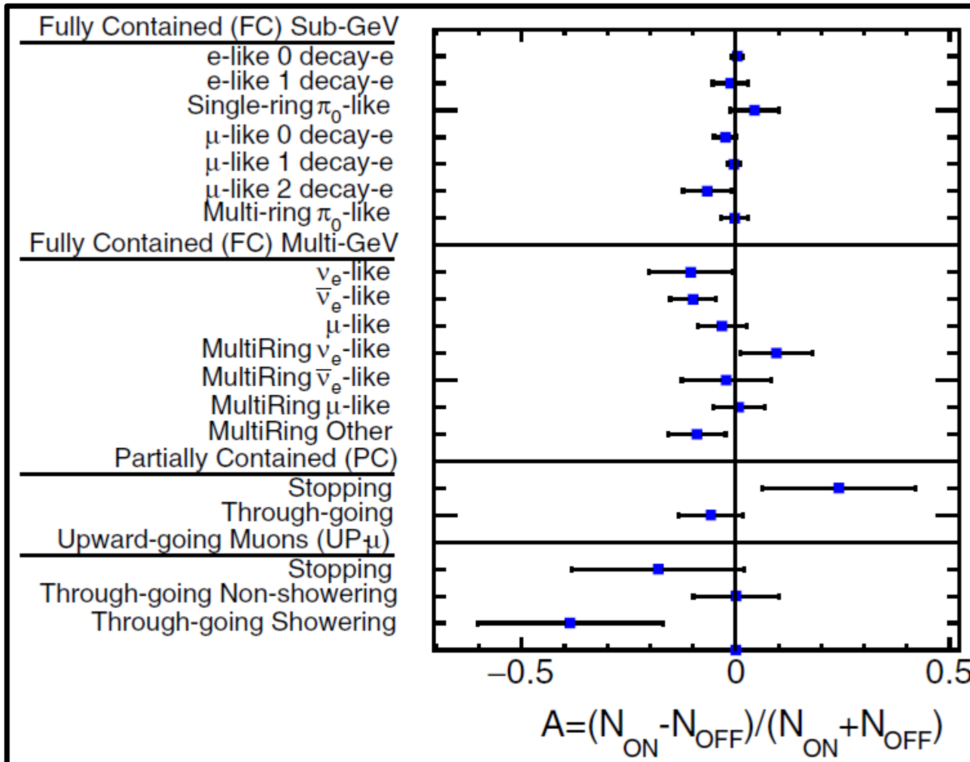


FIG. 10. Observed asymmetry between the number of neutrino events in the on- and off-source regions across the event subcategories for the NFW halo model. Errors on the points are statistical.

Galactic WIMP search: ON/OFF

PRD102, 072002 (2020)

- Search for large-scale anisotropy due to DM-induced ν's from our Galaxy
- Compare the number of ν events in a certain angular region
  - ON-source: around Galactic Center (GC)
  - OFF-source: shifted by 180° in right ascension (RA)
- Any excess of events in the ON-source part should indicate a possible unknown source, since atm. ν background equally affects those two regions.
- Independent from atmospheric ν simulation and related systematic uncertainties

- No asymmetry in neutrino flux is observed

- 90% C.L. upper limit on WINP self-annihilation cross section $<\sigma_A V>$ and influence of the halo model choice are obtained

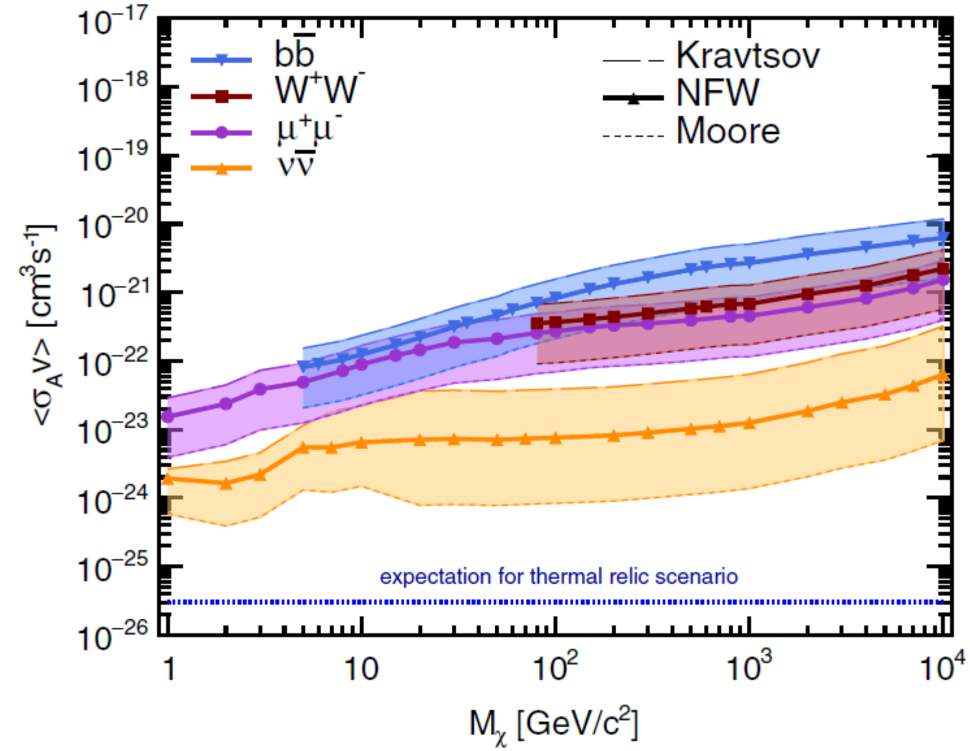
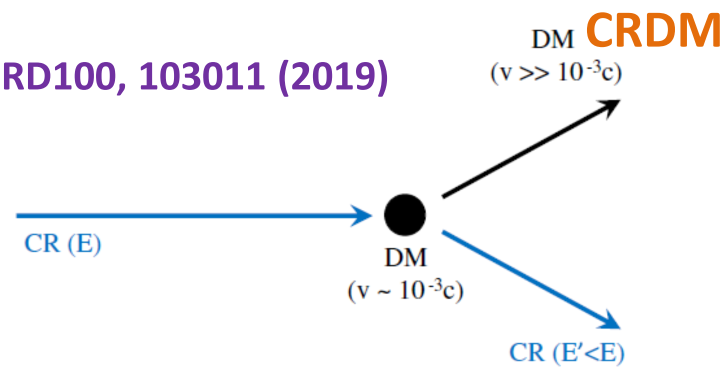


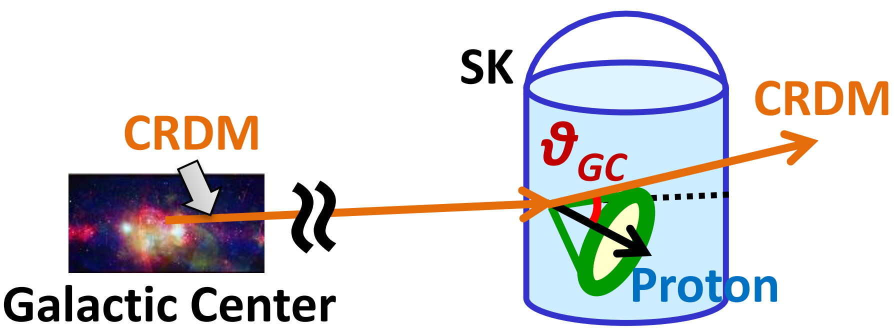
FIG. 11. Upper limits at 90% C.L. on the DM self-annihilation cross section $\langle\sigma_A V\rangle$ as a function of M_χ for the $b\bar{b}$ (blue), W^+W^- (maroon), $\mu^+\mu^-$ (purple), and $\nu\bar{\nu}$ (orange) annihilation channels as obtained in the on-source/off-source analysis. The influence of the halo model choice is shown as bands around the results for the benchmark NFW profile.

Boosted DM-proton search

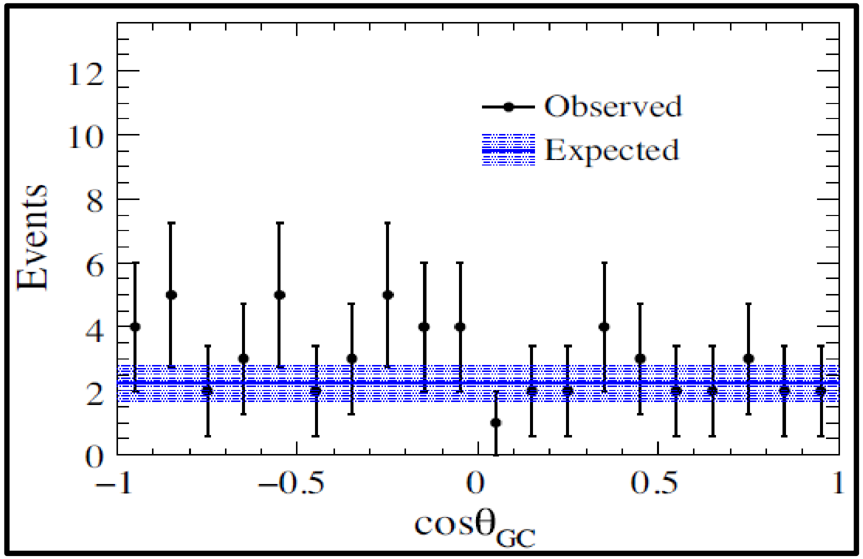
- High-energy cosmic-ray scatters with DM, then DM is boosted (CRDM)
- Since DM is abundant near the GC, CRDM should come from the direction of the GC.
- Search for CRDM from MeV to GeV with recoil protons.
- No excess → upper limit of DM-nucleon cross section in 1 ~ 300 MeV.

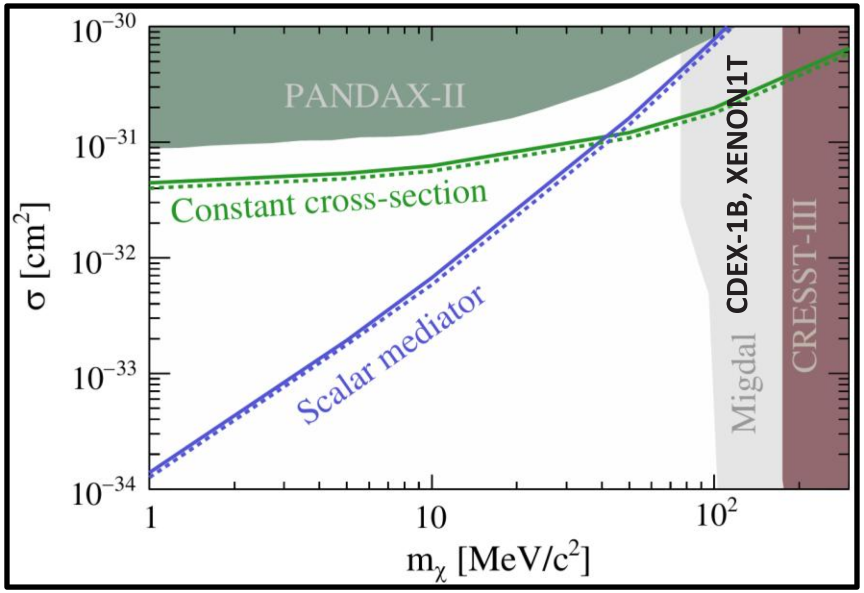
PRD100, 103011 (2019)





PRL 130, 031802 (2023); 131, 159903(E) (2023)



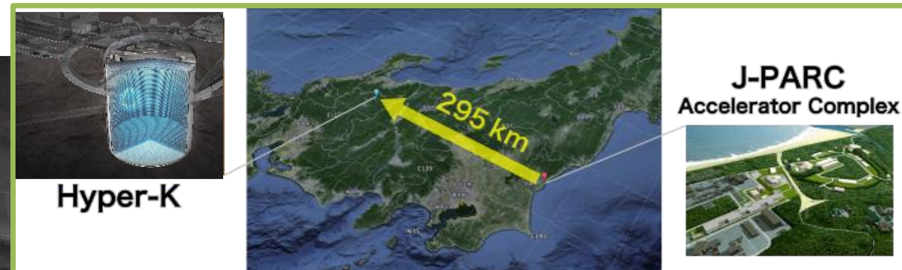


Hyper-Kamiokande (HK)

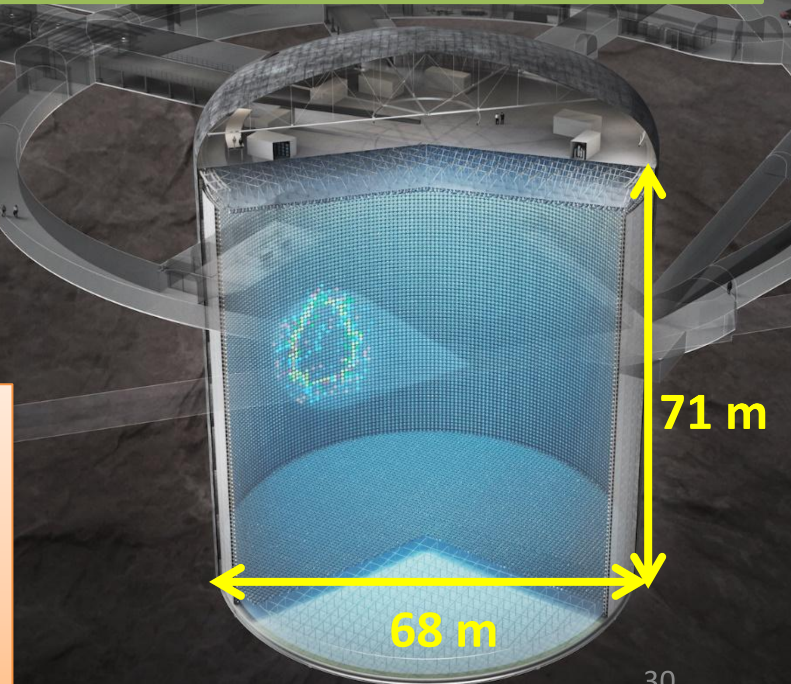
https://www-sk.icrr.u-tokyo.ac.jp/en/hk/

Exploring grand unification and the origin of matter dominance with next-generation detector.

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



- ID: ~20,000 new 20-inch PMTs + ~800 mPMTs (19 3-inch PMTs in a vessel)
- OD: ~3,600 3-inch PMTs +WLS plates
- 258 kton (total water)
- 188 kton (fiducial volume) ~8 x SK's FV

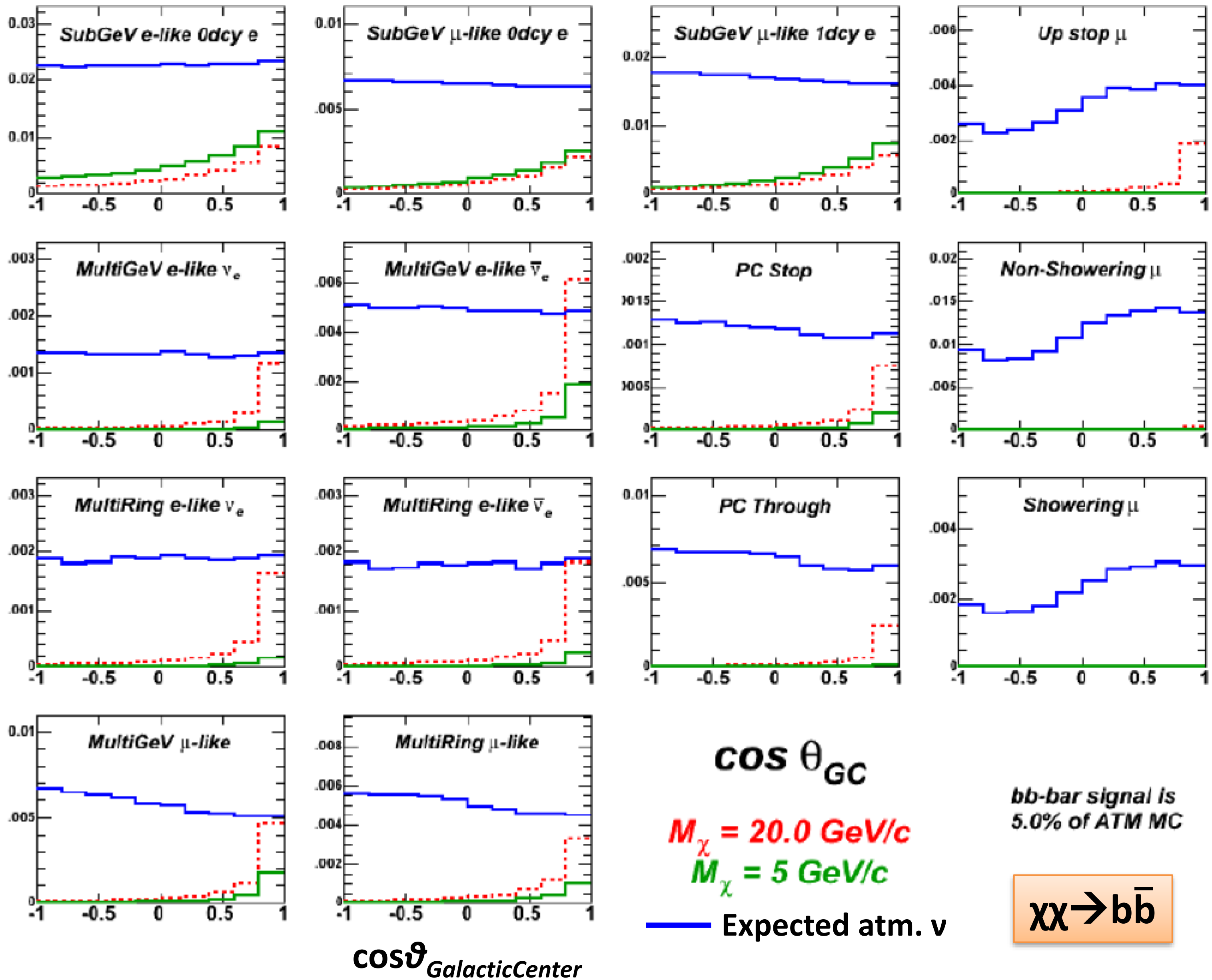


- Collaboration: 22 countries, ~650 researchers
- Construction: since April 2020
- Current status : Final design & construction
  - Cavern excavation: Completed in Aug. 2025
- Observation: 2028~

http://www-sk.icrr.u-tokyo.ac.jp/hk/

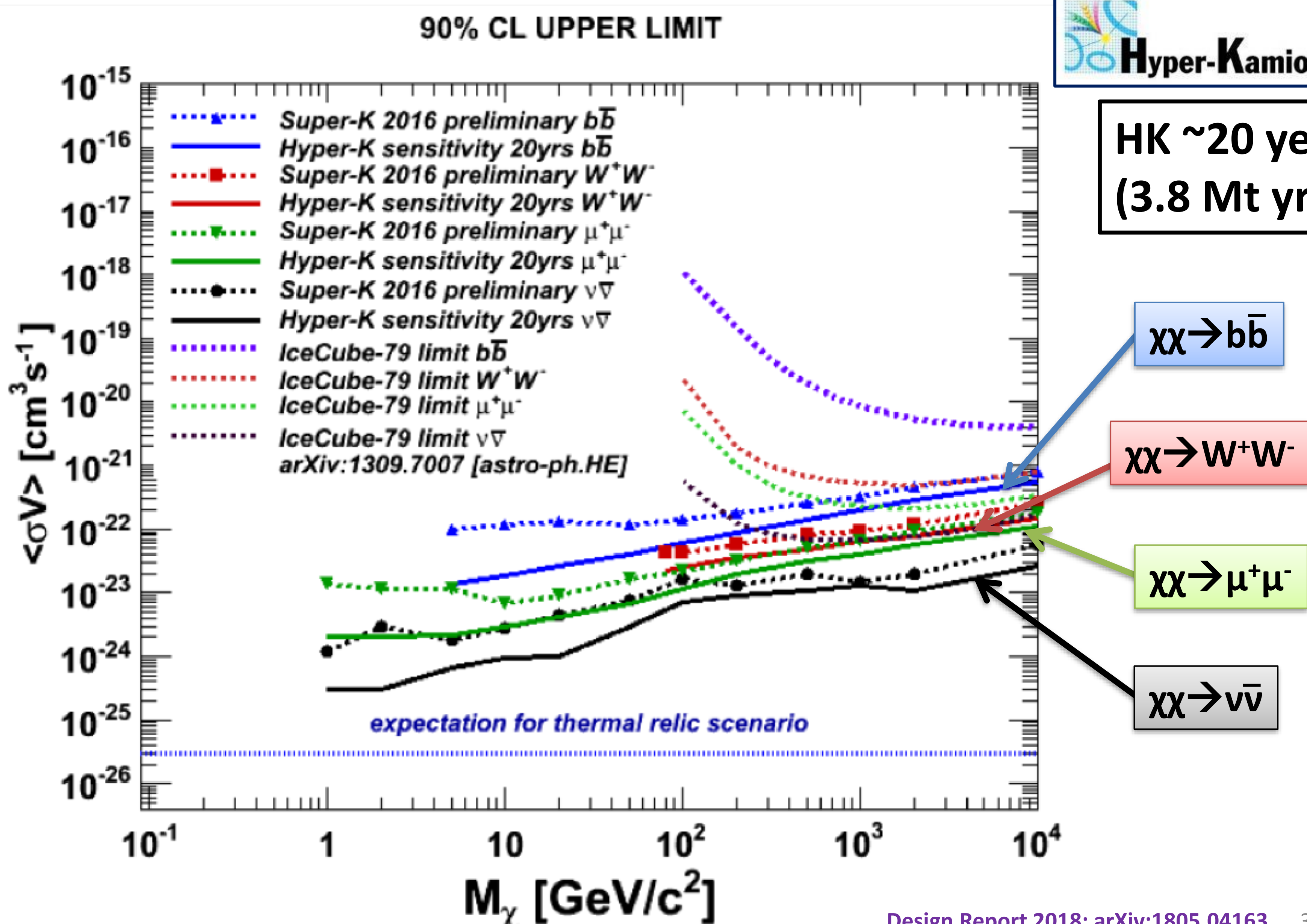
Galactic WIMP search in atm. ν

Hyper-Kamiokande



Expected sensitivity of Galactic WIMP search

HK ~20 years
(3.8 Mt yr)



Design Report 2018: arXiv:1805.04163

Summary

- SK has continuously advanced searches for nucleon decay, neutrino oscillation measurements, and astrophysical observations.
  - Current oscillation 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~: 0.033% (5 Jul. 2022-)
- (Indirect) DM searches are carried out with SK.
  - Neutrinos from Sun, Earth, & Galactic Center
  - Boosted DM
- Hyper-Kamiokande: Observations start in 2028