7-Oct-2019 @PPNT19

DARK MATTER SEARCHES WITH SUPER-KAMIOKANDE

Yasuo Takeuchi
for SK collaboration
(Kobe University / Kavli IPMU)

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

Super-Kamiokande collaboration

- Host Institute
- Kamioka Observatory, Institute of Cosmic Ray Research (ICRR), University of Tokyo
- Research Center for Cosmic Neutrinos (RCCN), ICRR, University of Tokyo
- Collaboration Institutes in Japan
- Osaka University
- Okayama University
- GIfu University
- Keio University
- Kyoto University
- High Energy Accelerator Research Organization (KEK)
- Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU),The University of Tokyo
- Kobe University
- Junior College, Fukuoka Institute of Technology
- Shizuoka University of Welfare
- Tokai University
- University of Tokyo
- Department of Physics, Faculty of Science & Graduate School of Science, The University of Tokyo
- Tokyo Institute of Technology
- Nagoya University
- Miyagi University of Education
- Foreign Institutes
- Boston University
- British Columbia Institute of Technology
- University of British Columbia
- University of California, Irvine
- California State University
- Chonnam National University
- Duke University
- Gwangju Institute of Science and Technology
- University of Hawaii
- Stony Brook University
- Seoul National University
- Sungkyunkwan University
- University of Toronto
- TRIUMF
- Tsinghua University
- National Centre for Nuclear Research (NCBJ)
- University Autonoma Madrid
- Imperial College London
- Queen Mary University of London
- University of Liverpool
- University of Oxford
- University of Sheffield
- INFN, Sezione di Bari
- INFN, Sezione di Padova and Universita` di Padova
- INFN, Sezione di Napoli and Universita` di Napoli
- INFN, Sezione di Roma
- IN2P3- Laboratoire Leprince-Ringuet, Ecole Polytechnique
- University of Warsaw
- University of Winnipeg

10 countries, ~47 institutions, ~180 researchers (as of Oct. 2019)

Outline

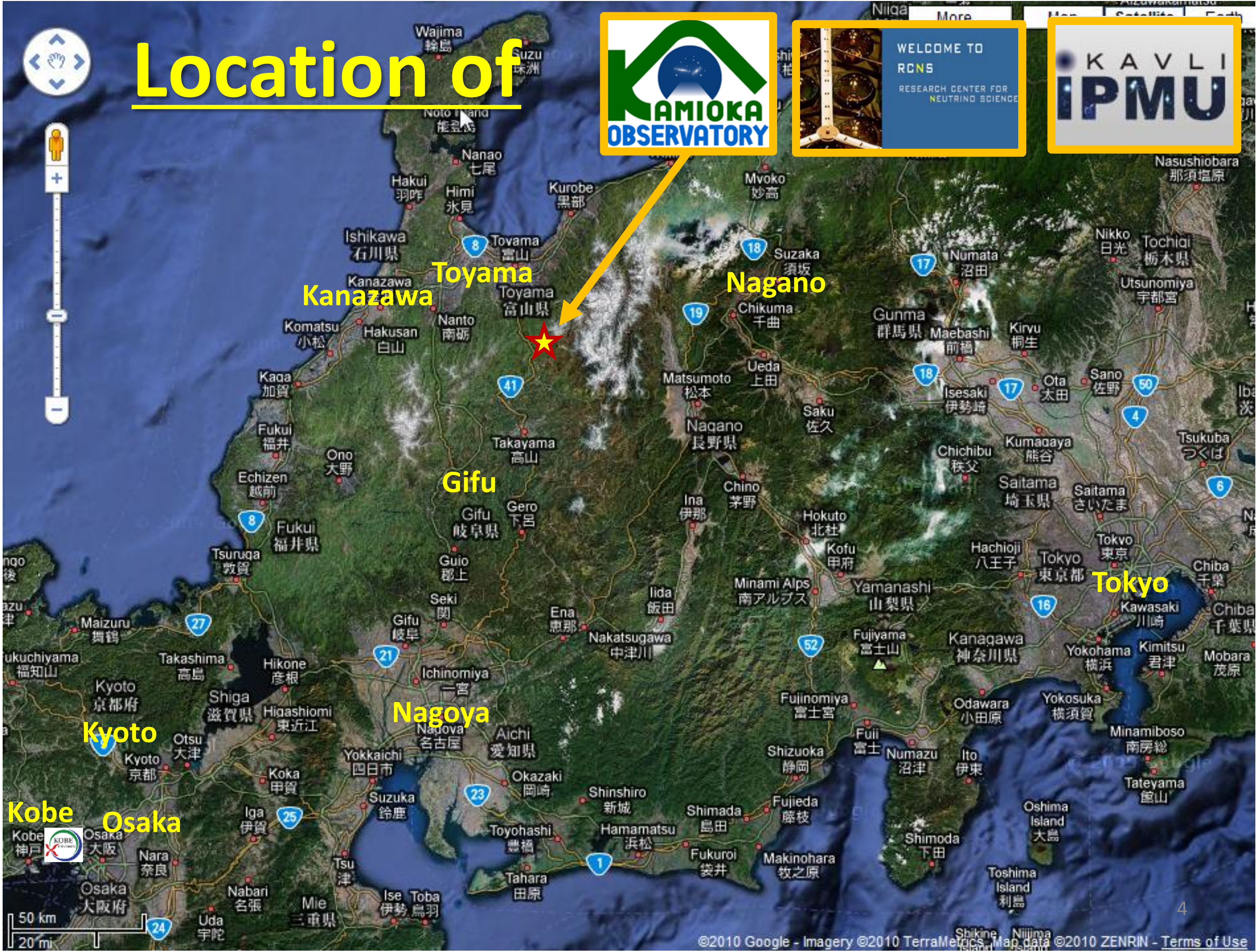
- SK detector & indirect WIMP search in SK
- DM search results
  - Galactic WIMP search
  - Boosted WIMP search
  - Solar WIMP search
  - Earth WIMP search
- Status of SK-Gd & prospects in HK
- Summary

Location of

KAMIOKA OBSERVATORY

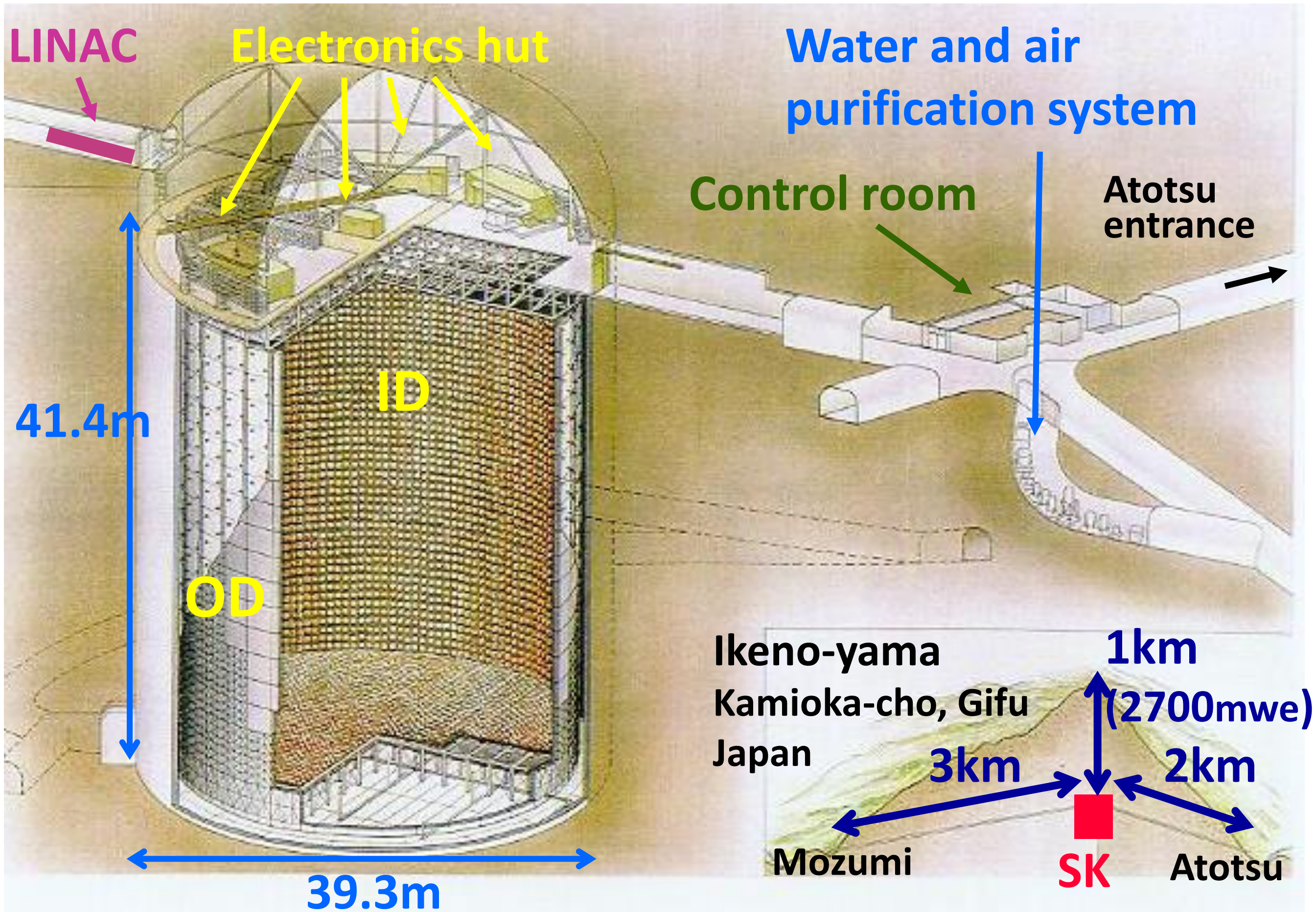
WELCOME TO RCNS
RESEARCH CENTER FOR NEUTRINO SCIENCE

KAVLI IPMU



Super-Kamiokande detector

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



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

Physics targets:

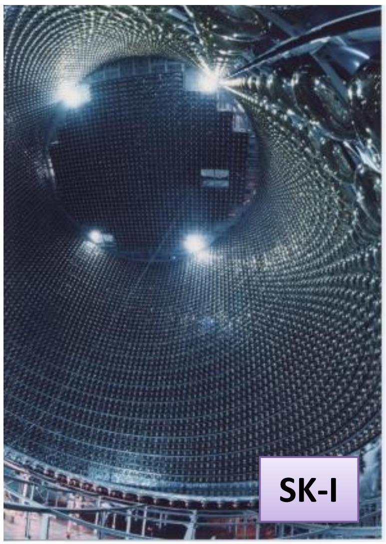
- Nucleon decay search
- Neutrino oscillation study
- Astrophysical neutrino search

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

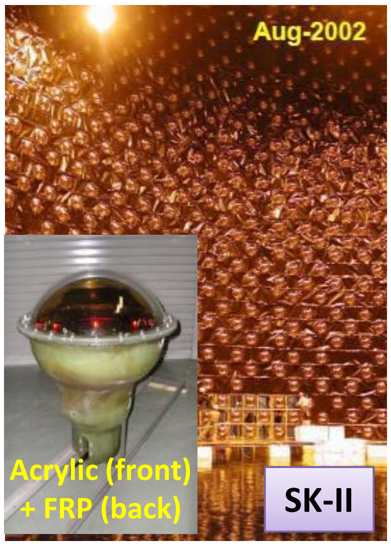
History & Plan of Super-Kamiokande

96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19

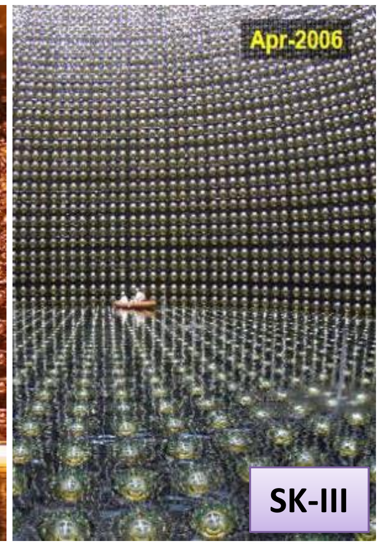
SK-I → SK-II → SK-III → SK-IV → SK-V → SK-Gd



11146 ID PMTs (40% coverage)
4.5 MeV
1496 days



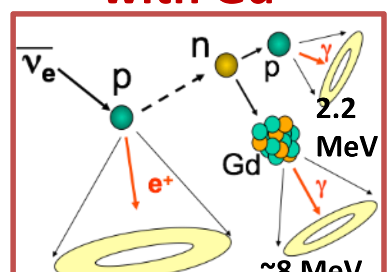
5182 ID PMTs (19% coverage)
6.5 MeV
791 days



11129 ID PMTs (40% coverage)
4.5 MeV
548 days

Electronics Upgrade
3.5 MeV
2970 days

Neutron tagging with Gd

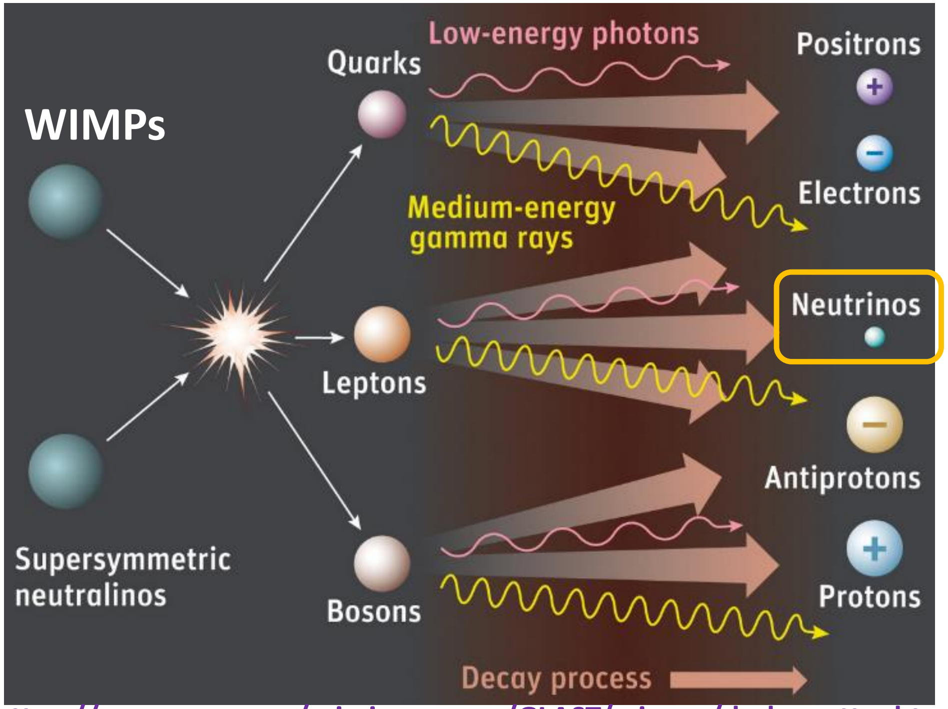


- Analysis energy threshold (recoil electron kinetic energy)
- Live time for solar neutrino analysis

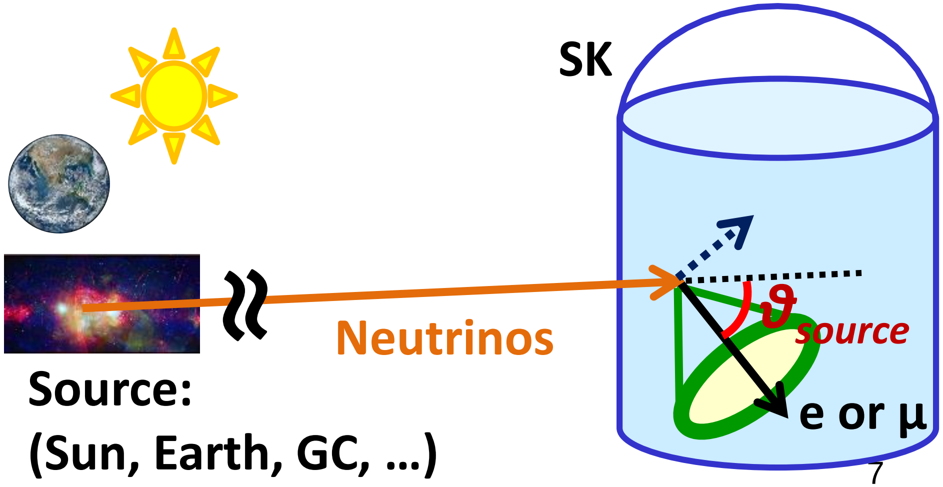
Current total: 5805 days

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 5326~5629 days (1996-2016), *preliminary*, paper in preparation
- **Galactic WIMP search: ϑ_{GC}**
  - SK-I~IV 5326~5629 days (1996-2016), *preliminary*, paper in preparation
    - 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)

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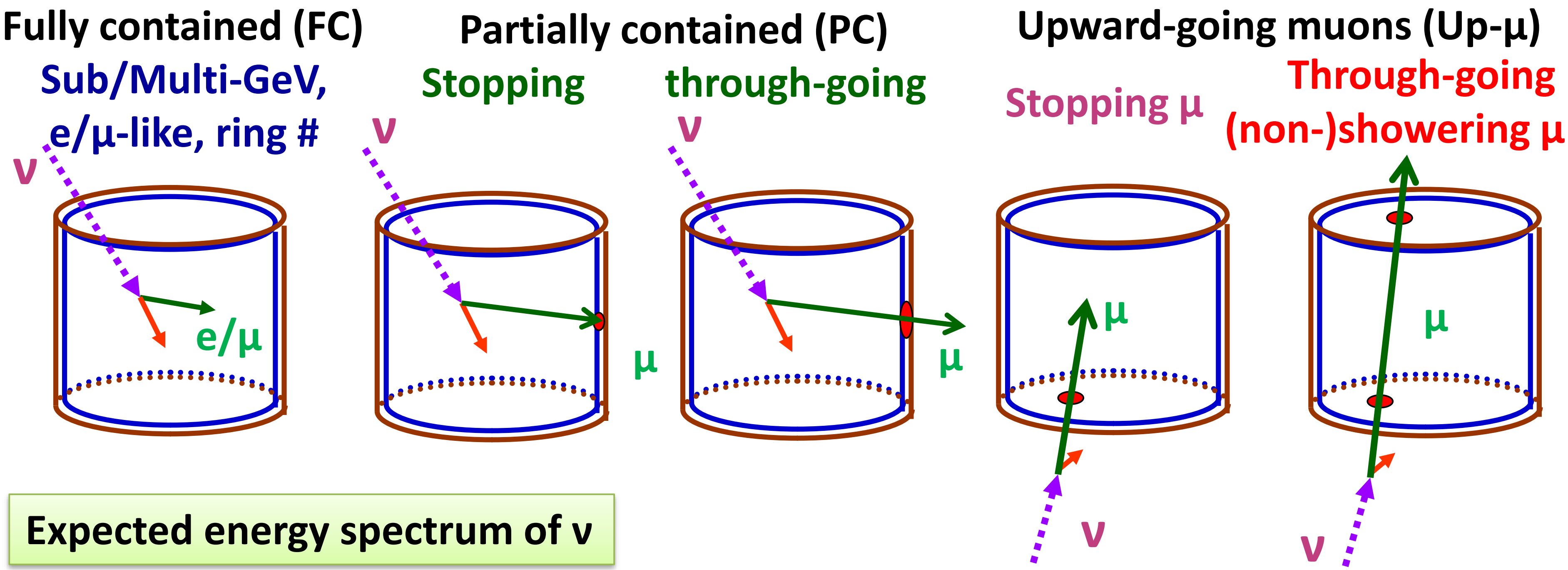
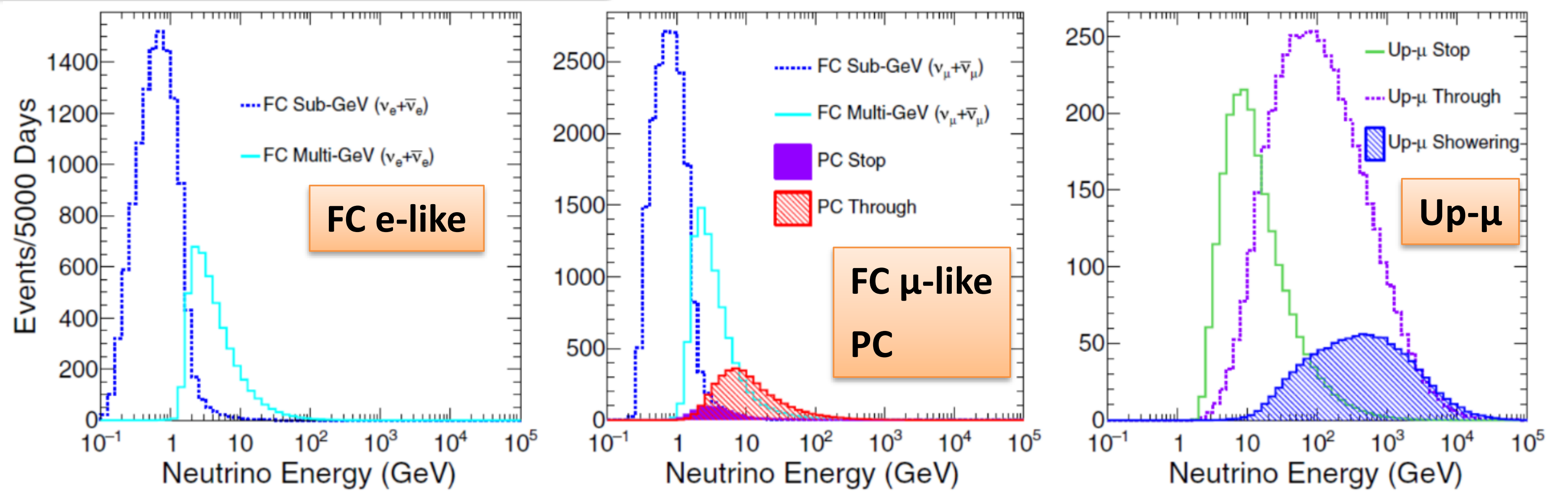
Atmospheric ν categories in SK

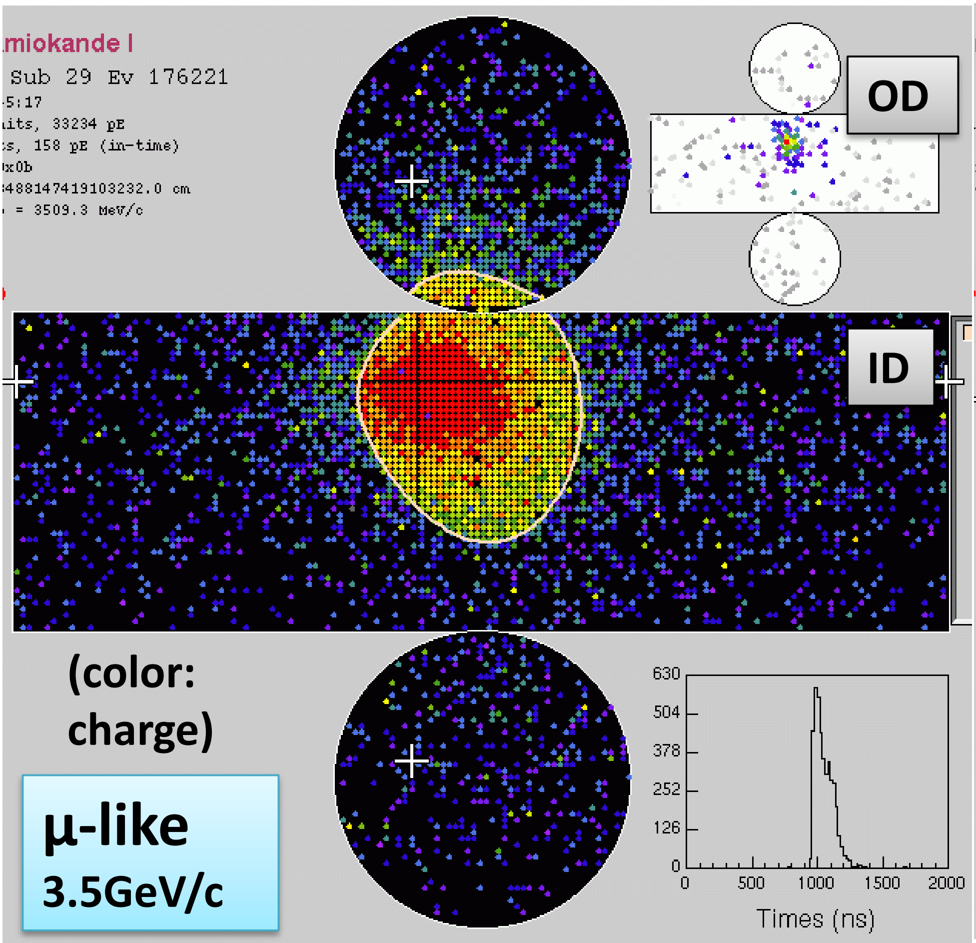


Expected energy spectrum of ν

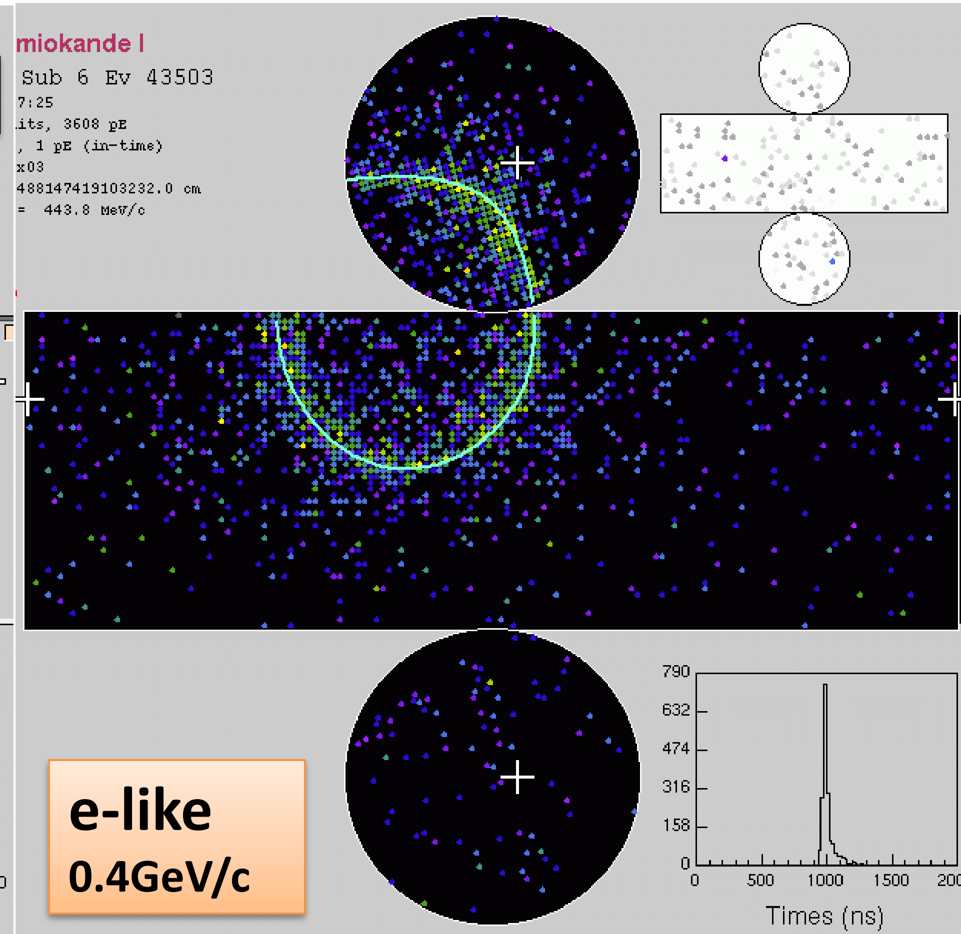


Typical high-energy events: 1

Atmospheric ν: Partially contained (PC)



Atmospheric ν: Fully contained (FC)

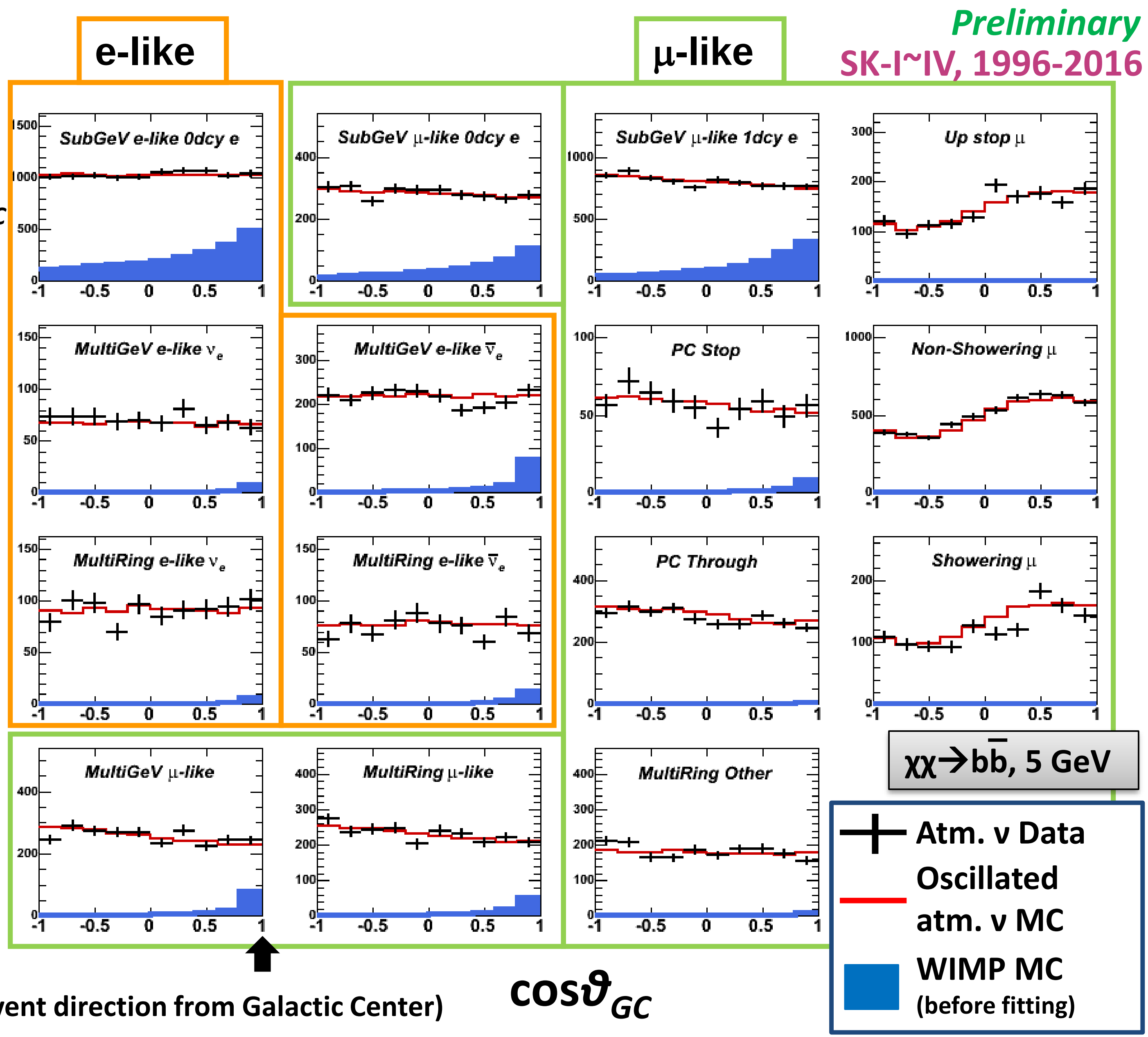


Galactic WIMP search: fitting

- 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



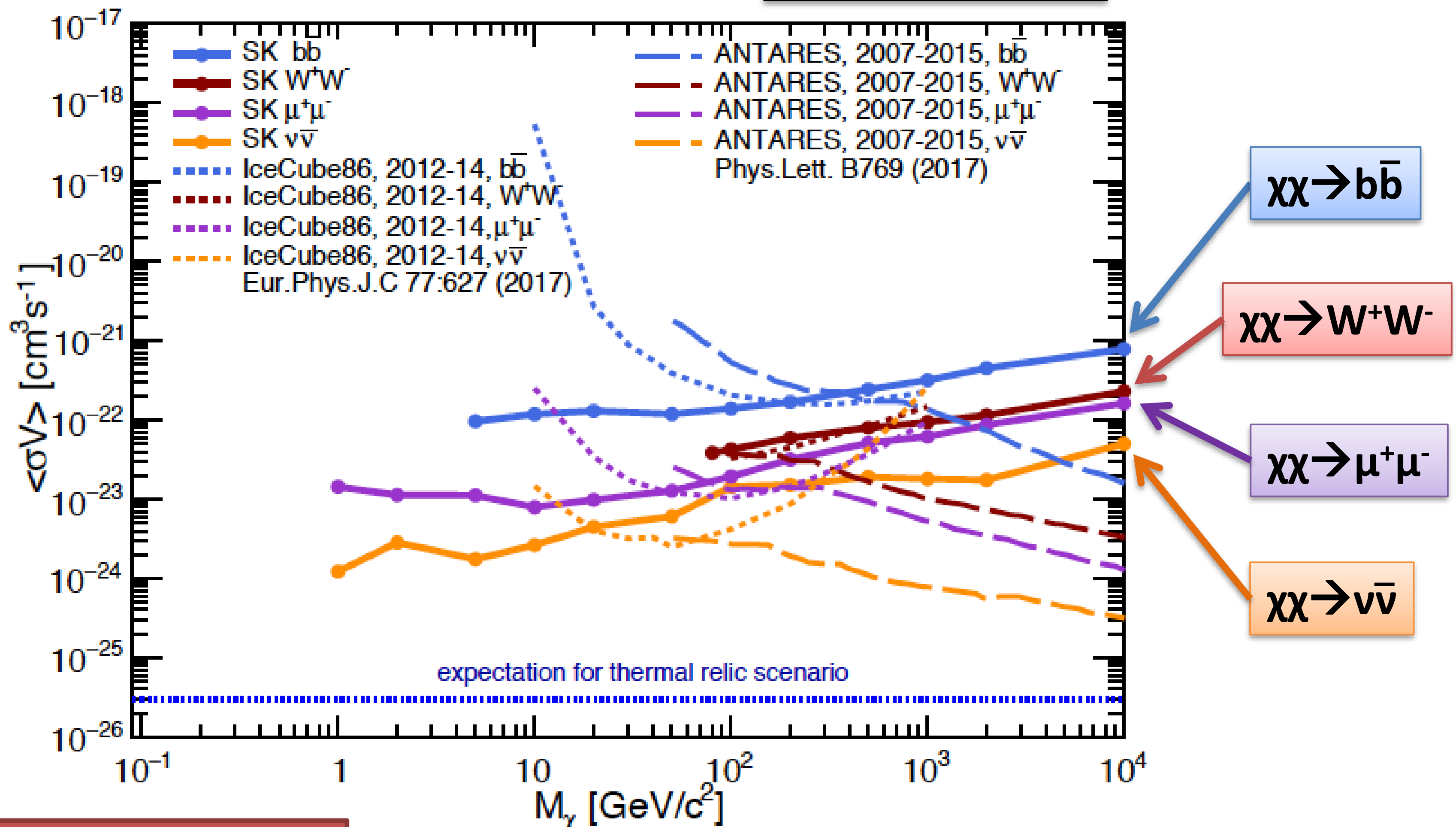
Galactic WIMP search: fitting

Preliminary

SK-I~IV, 1996-2016

WIMP self-annihilation cross section <σV>

90% C.L. upper limit

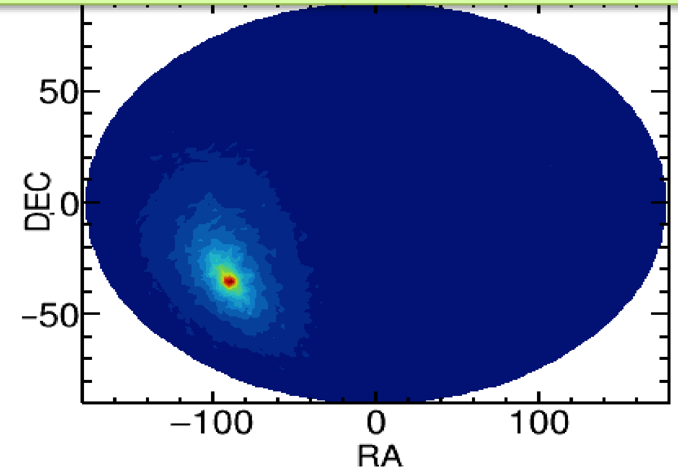


Paper is in preparation

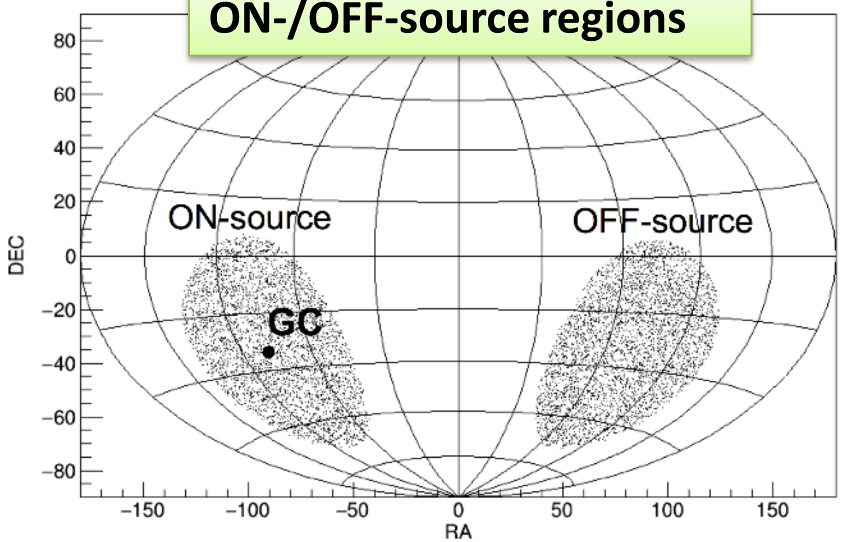
Galactic WIMP search: ON/OFF

- 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



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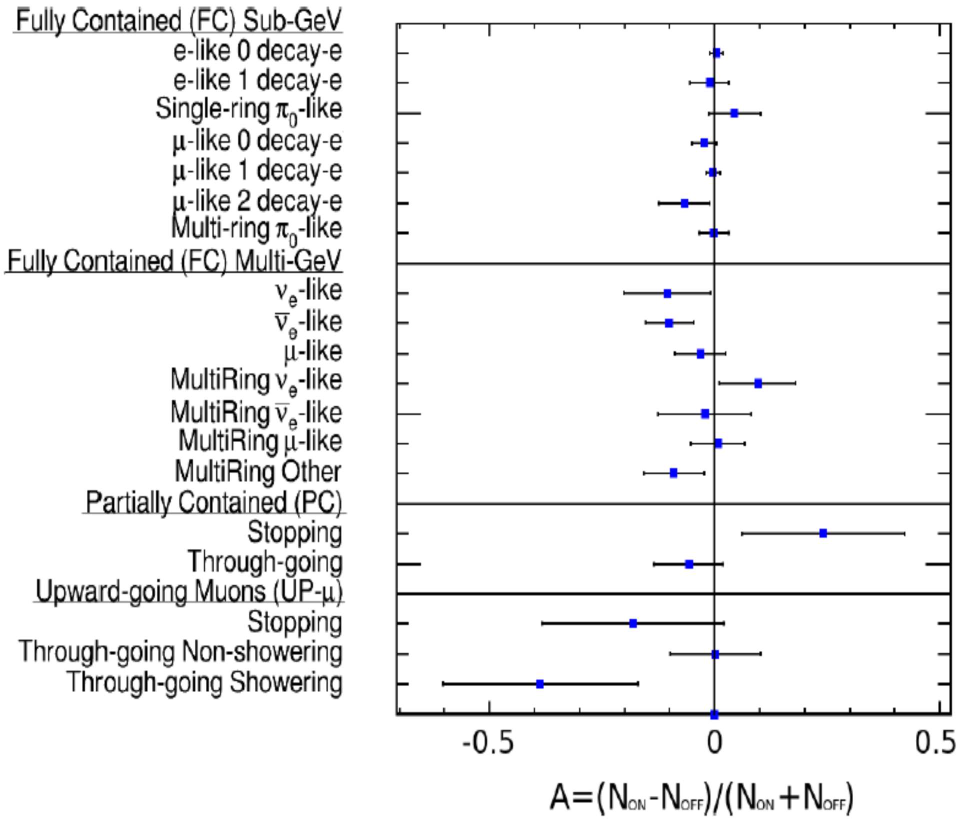
- Independent from atmospheric ν simulation and related systematic uncertainties

- No asymmetry in neutrino flux is observed

Observed asymmetry between number of ν events in ON- and OFF-source region in various event subcategories for the NFW halo model



Galactic WIMP search: ON/OFF

Preliminary

SK-I~IV, 1996-2016

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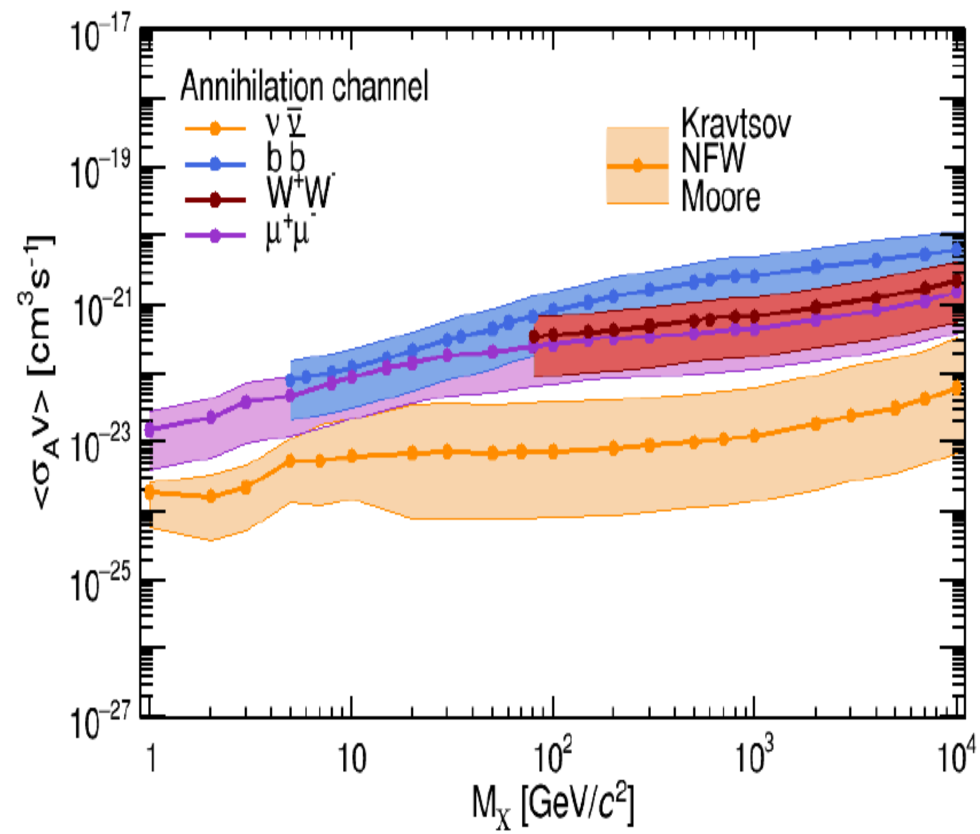
- Independent from atmospheric ν simulation and related systematic uncertainties

- 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

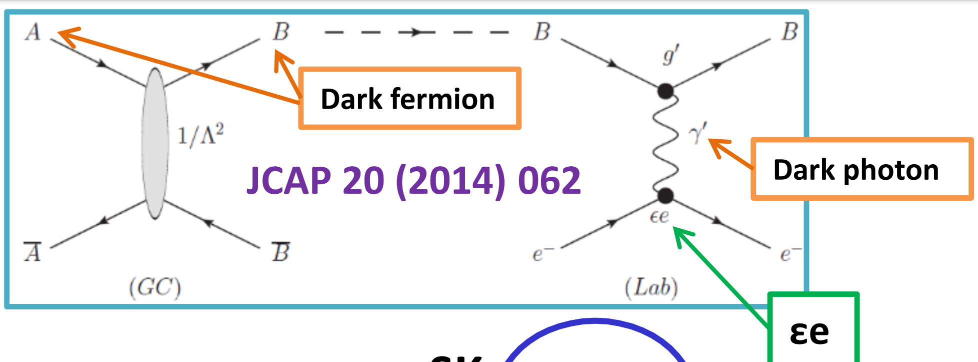
90% C.L. upper limits on WIMP self-annihilation cross-section & influence of the halo model

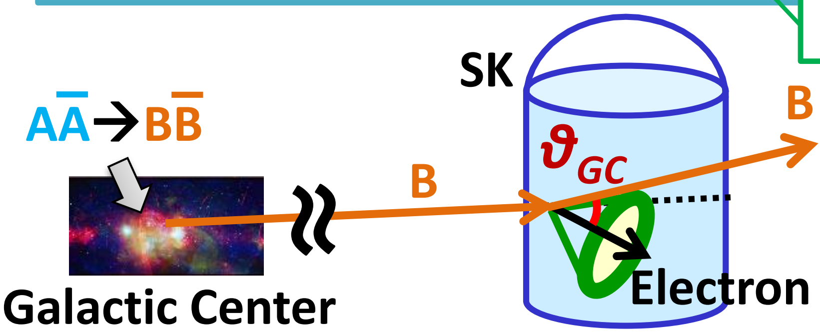


Paper is in preparation

Boosted DM search in SK

- "A" is heavy DM particle, which constitutes dominant CDM component, but does not couple to SM particle
- "B" is lighter DM particle, boosted from annihilation or decay of A and couples to SM electron through a massive dark photon
- Searched for (elastically scattered) electrons from GC direction, in 100 MeV - 1TeV, in cone regions ($\vartheta_{GC} < 5^o \sim 40^o$), above the atmospheric neutrino background, in SK-IV 2628-day data.
- No excess → Upper limit on production of B





PRL 120, 221301 (2018)

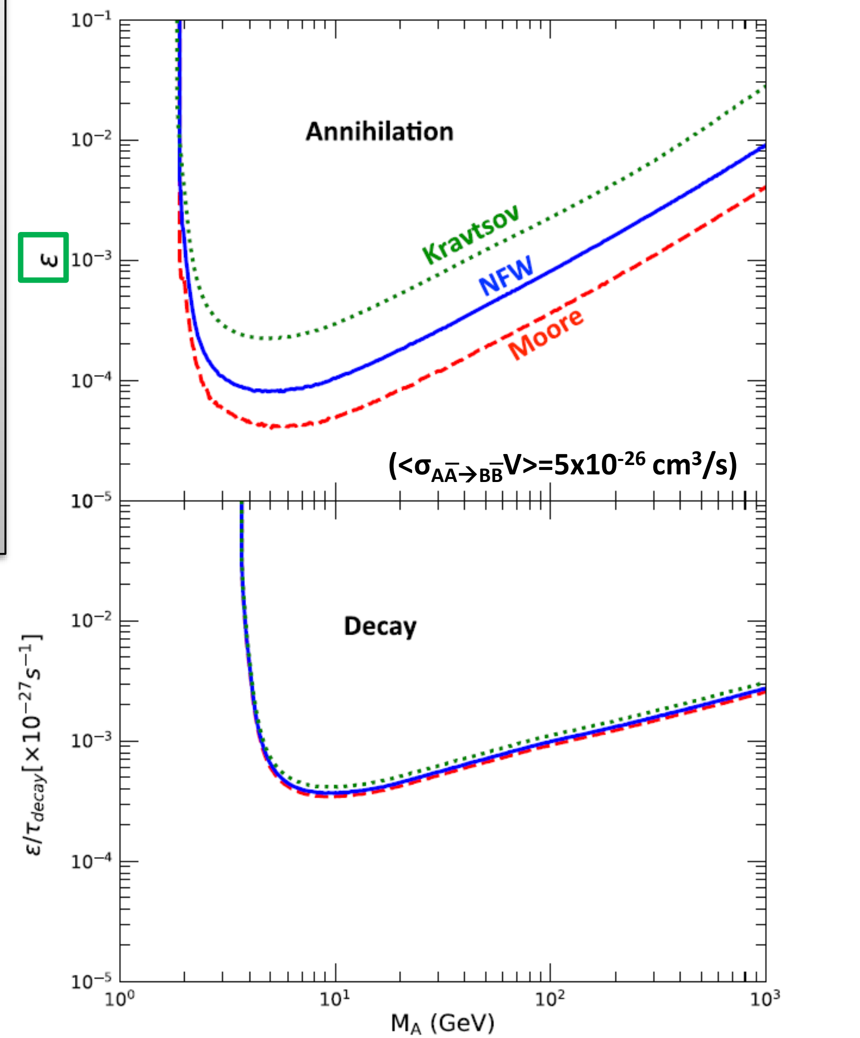


FIG. 3. 90% confidence interval upper limits for $m_B = 200$ MeV, $m'_\gamma = 20$ MeV, and $g' = 0.5$, for boosted dark matter produced by annihilation (top) and decay (bottom).

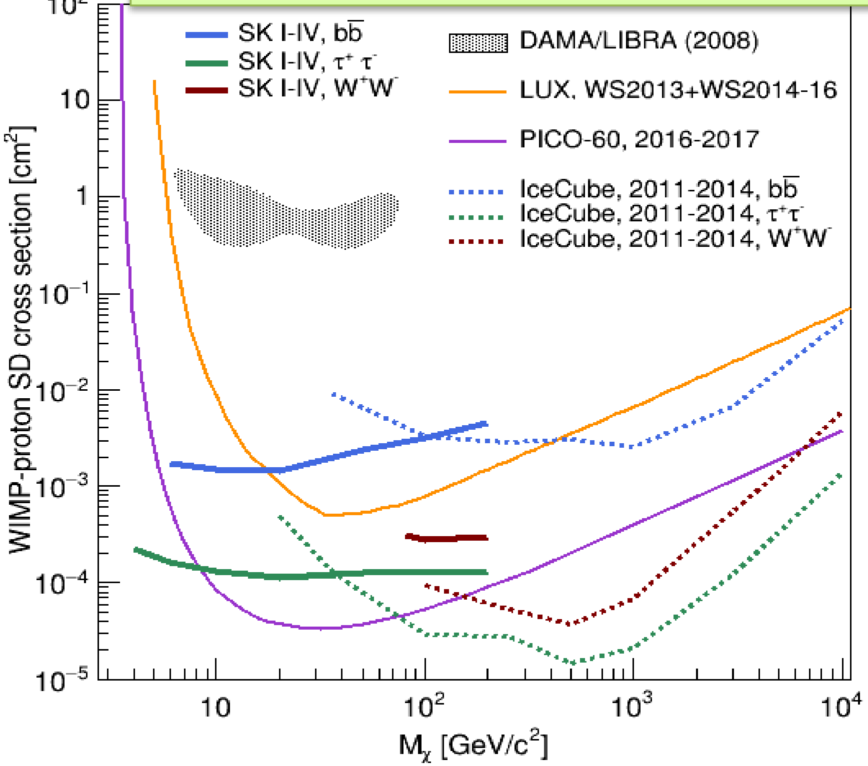
Solar WIMP search

- WIMPs could be occasionally trapped after losing energy by scattering off nuclei in the Sun. (H, He, C, N, O, …)
- Spin-Dependent (SD) & Spin-Independent (SI) interactions of WIMP-proton/nucleon scattering cross section can be constrained and compared with results from direct DM experiments
- No excess → 90% C.L. upper limits

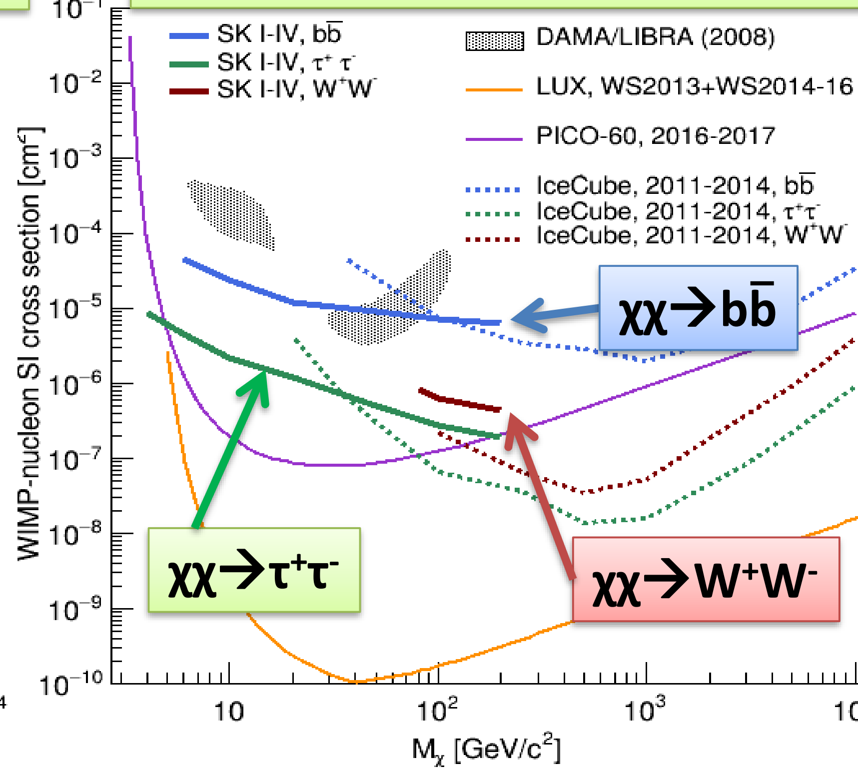
PRL 114, 141301 (2015)

SK-I~IV, 1996-2012
3903 days

WIMP-proton SD cross-section limit



WIMP-nucleon SI cross-section limit

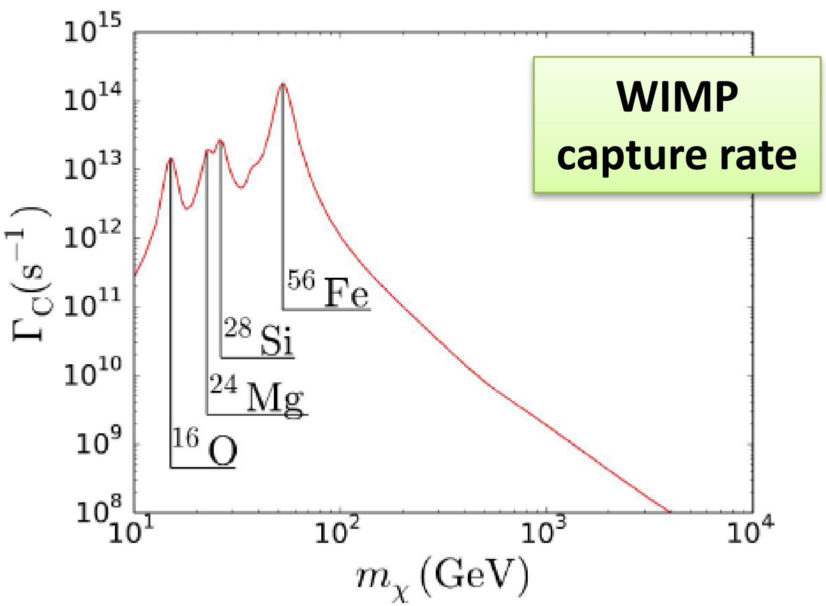


Earth WIMP search

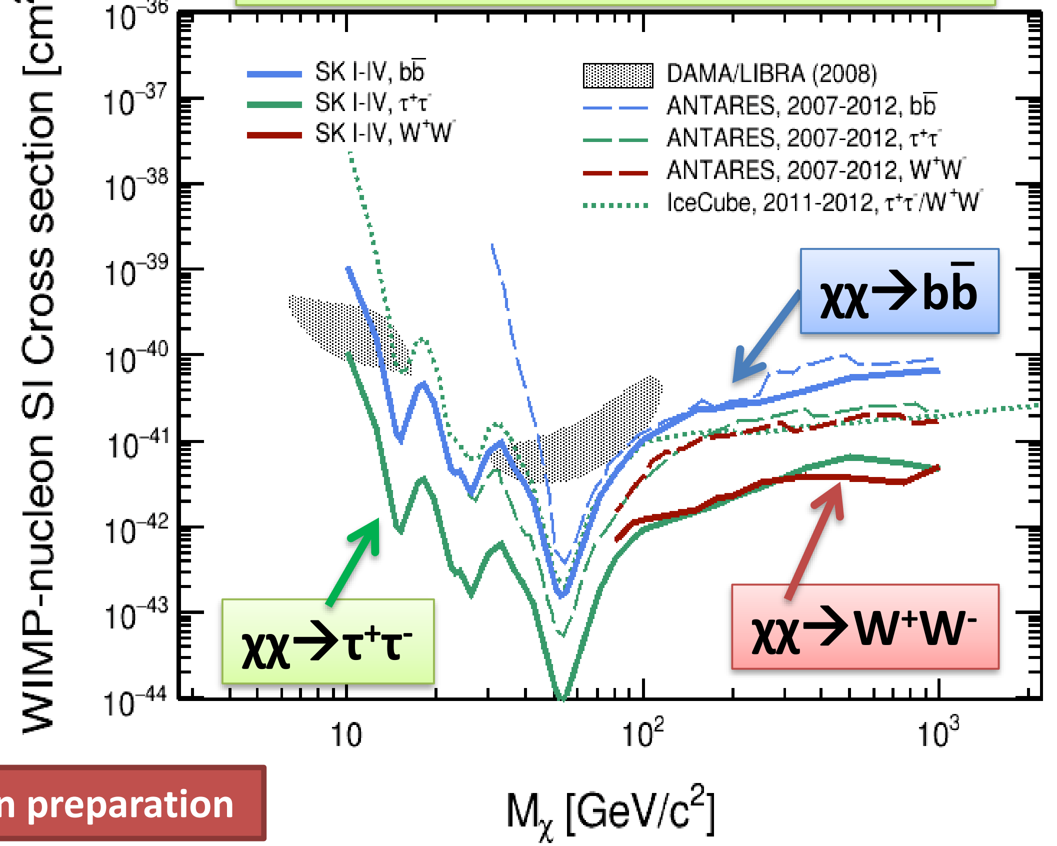
Preliminary
SK-I~IV, 1996-2016

- Spin-Independent (SI) interactions dominate in the capturing process of WIMPs by Earth
- WIMP-nucleon SI scattering cross section can be constrained and compared with results from direct DM experiments
- If the mass of WIMP matches abundant elements in the Earth, the capture rate increases considerably.

- No excess → 90% C.L. upper limits



WIMP-nucleon SI cross-section limit



Paper is in preparation

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Next step: SK-Gd Phase

SK-Gd Phase:

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

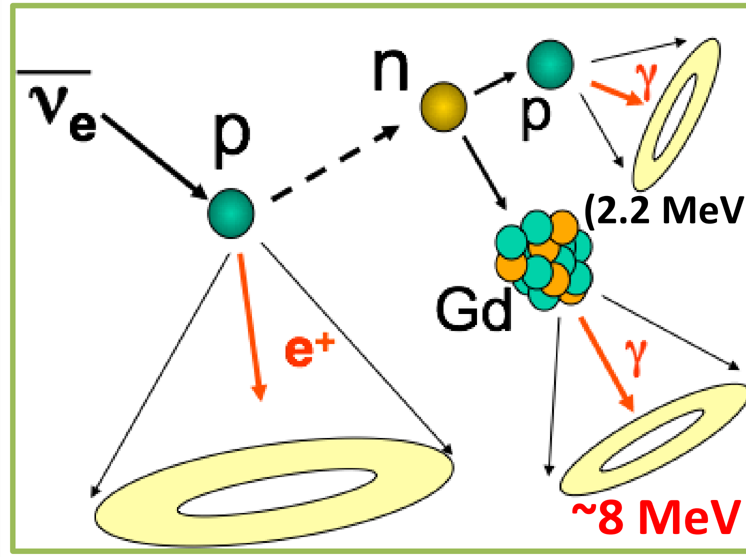
Physics targets:

- 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

Refurbishment of the SK detector was done in June 2018 – January 2019

- Fix water leakage, Replace dead PMTs, Improve water piping…

Planning to start 0.01% Gd run in early 2020 (adjusting schedule with T2K)



- Reduce BG of $\bar{\nu}_e$ signal
  - Delayed coincidence
  - ΔT ~ 30 μs
  - Vertices within ~ 50 cm

Capture efficiencies in water

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

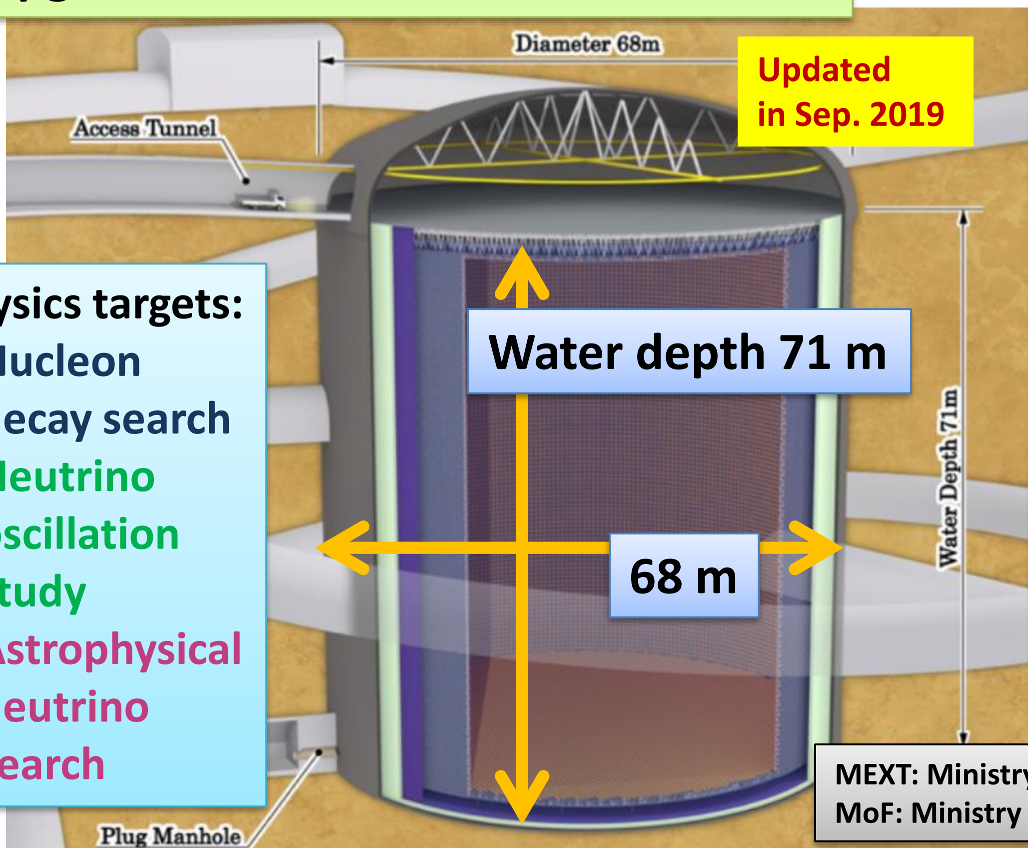
Hyper-Kamiokande (HK)

Hyper-Kamiokande

http://www.hyper-k.org/en/

Design Report 2018: arXiv:1805.04163

- Gigantic neutrino and nucleon decay detector in Kamioka, Japan
- 188 kton fiducial mass: ~8.4 x SK
- x 2 higher photon sensitivity than SK
- MW-class world-leading ν-beam by upgraded J-PARC



Updated in Sep. 2019

Physics targets:

- Nucleon decay search
- Neutrino oscillation study
- Astrophysical neutrino search

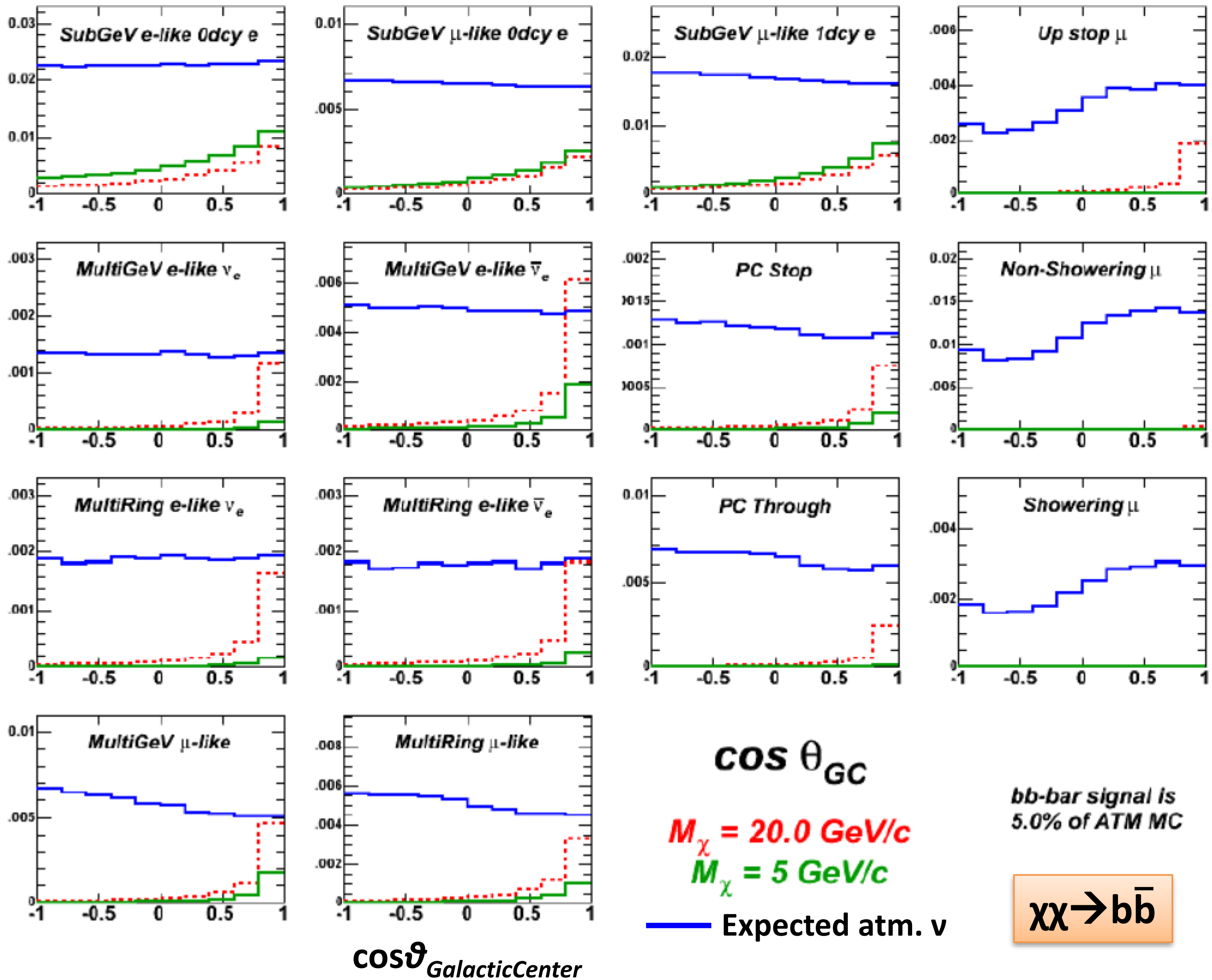
Current status:

- HK is a priority project by MEXT's Roadmap 2017
- MEXT included HK in their FY2020 budget request to MoF.
- The constriction of HK will be started in April 2020.
- Start observation in ~2027
- To enhance neutrino oscillation physics, a 2nd detector in Korea is under study

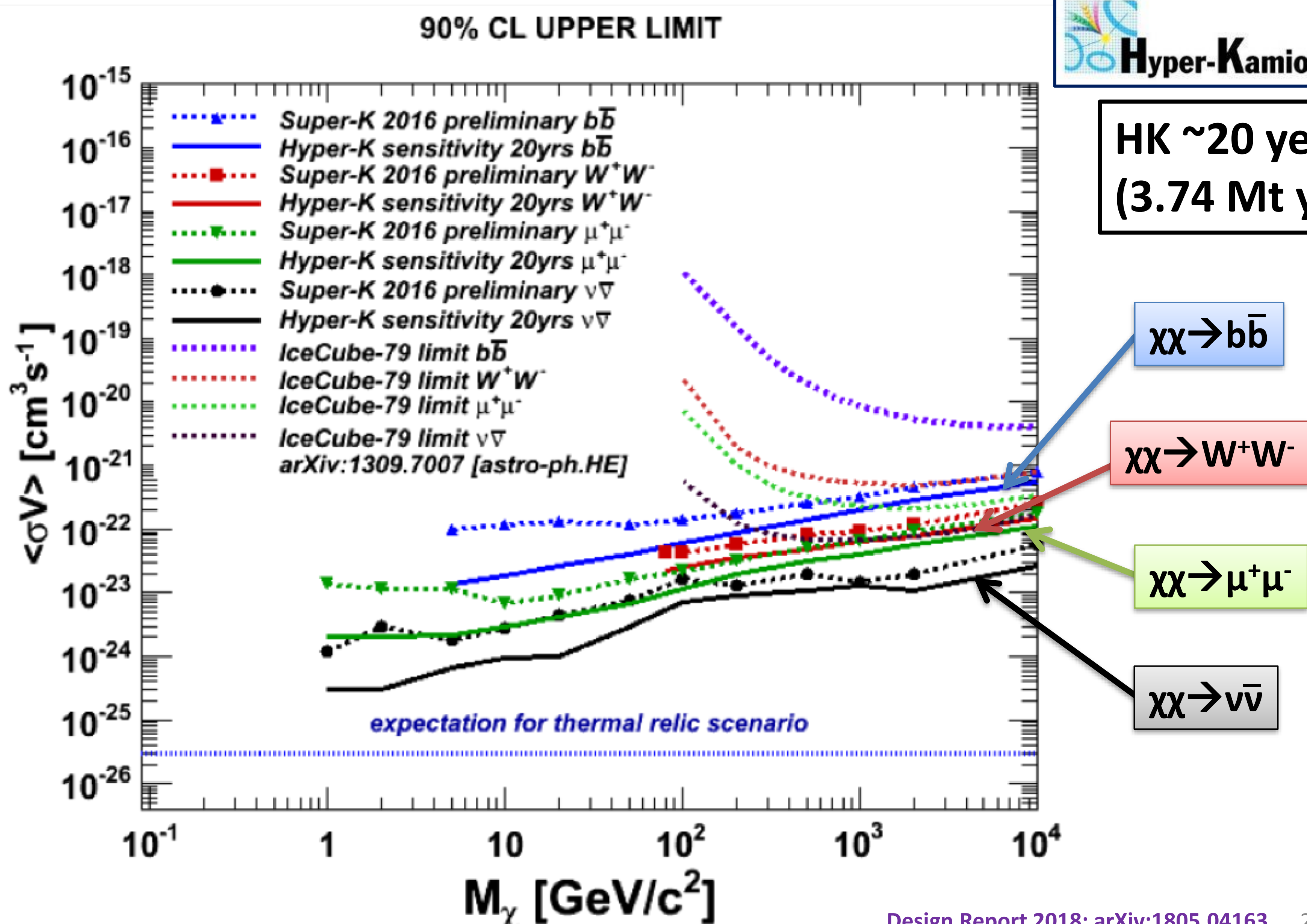
MEXT: Ministry of Education, Culture, Sports, Science and Technology
MoF: Ministry of Finance, Japan

Galactic WIMP search in atm. ν

Hyper-Kamiokande



Expected sensitivity of Galactic WIMP search



Hyper-Kamiokande

HK ~20 years
(3.74 Mt yr)

Design Report 2018: arXiv:1805.04163

Summary

- **Super-Kamiokande is a 50-kton water Cherenkov detector located 1,000 m underground in Japan.**
- **Indirect DM searches are carried out with SK.**
  - **Sun, Earth, & Galactic Center**
- **Planning to start SK-Gd in early 2020.**
  - **Adjusting schedule with T2K**
- **MEXT submitted FY2020 budget request including Hyper-Kamiokande to MoF.**
  - **188 kton fiducial mass: ~8.4 x SK**
  - **Construction of HK: April 2020~, Observation: 2027~**