Light Dark Matter Search in the Super-Kamiokande

Light Dark World International Forum
14 December 2022

Koun Choi
IBS-CUP

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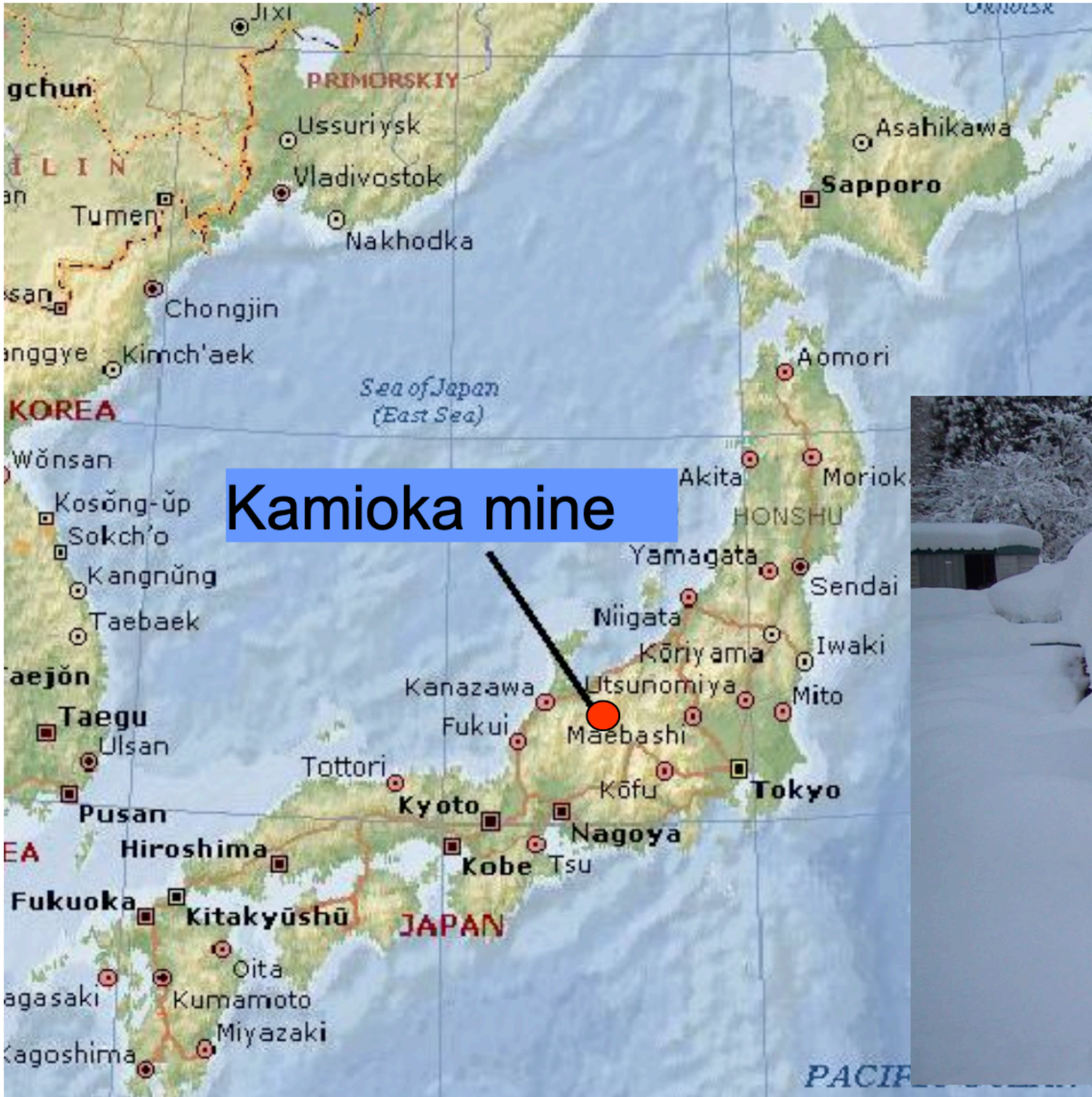
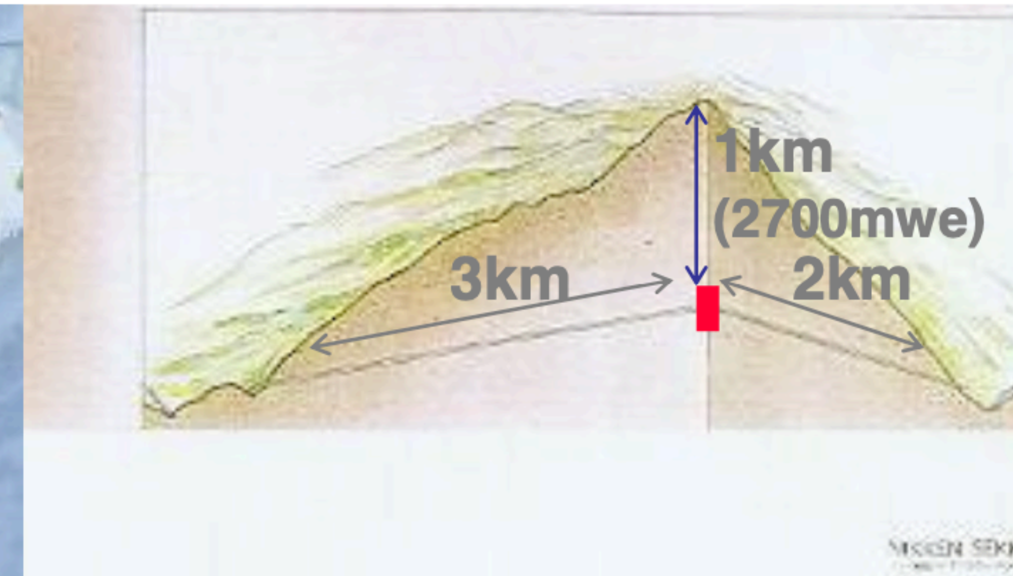
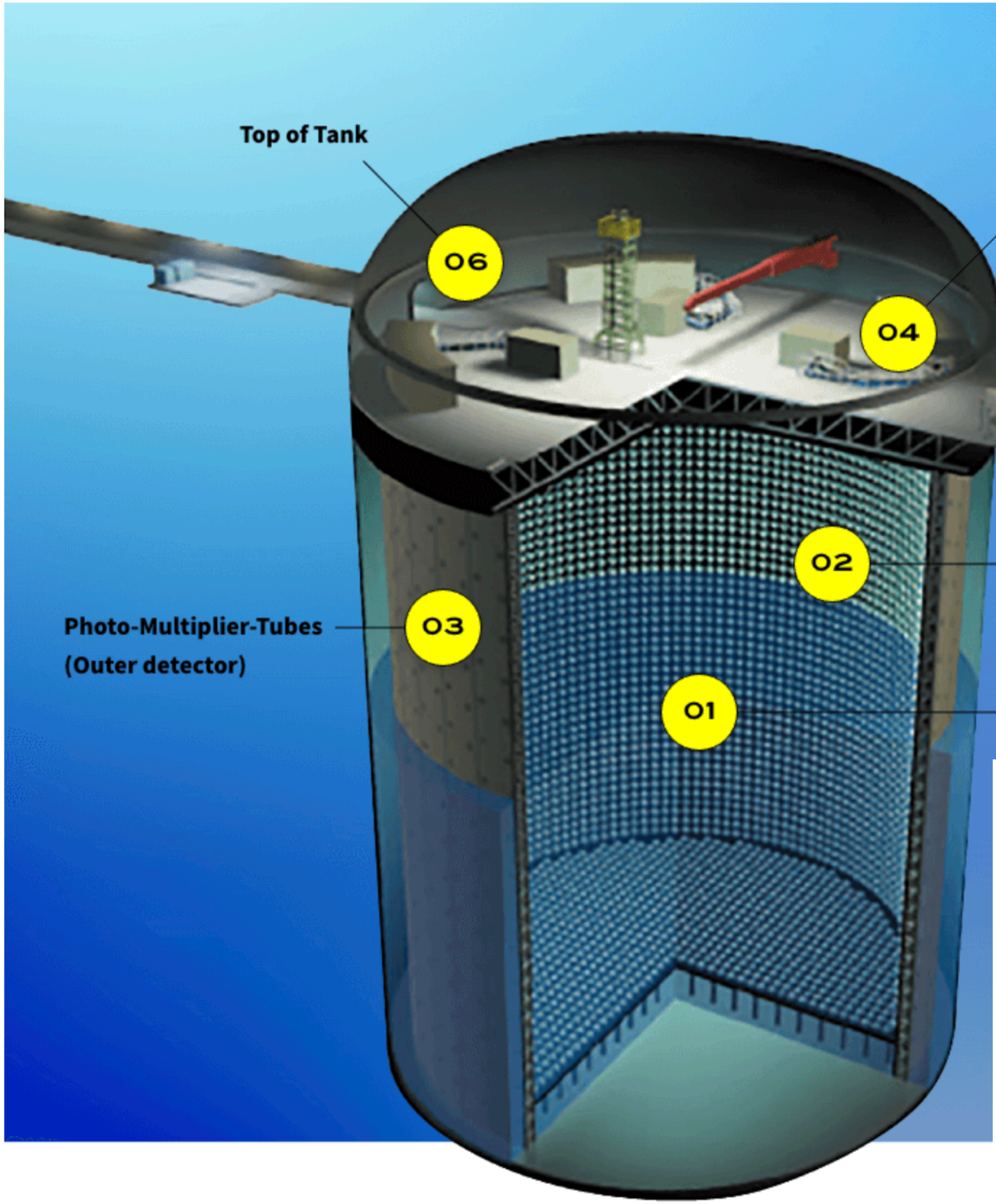
Kamioka underground observatory







https://www-sk.icrr.u-tokyo.ac.jp/en/sk/about/detector/
visit there and click the buttons to find more information!

- Water Cherenkov detector
- 50 ktons water (22.5 ktons fiducial volume)
- ID viewed by 11,000 20" photo-multiplier tubes (PMTs)
- ~2 m OD viewed by 8" PMTs (muon veto)
- Operating since 1996, with 10 countries, 40 institutions, ~180 members

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)

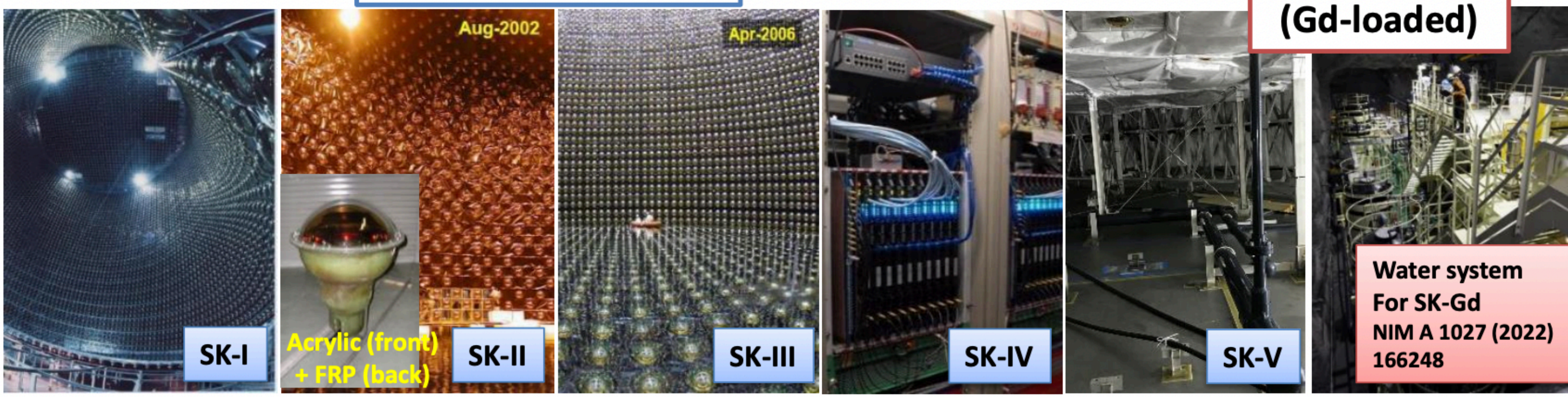
History of Super-Kamiokande

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-VI / SK-VII
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)*	

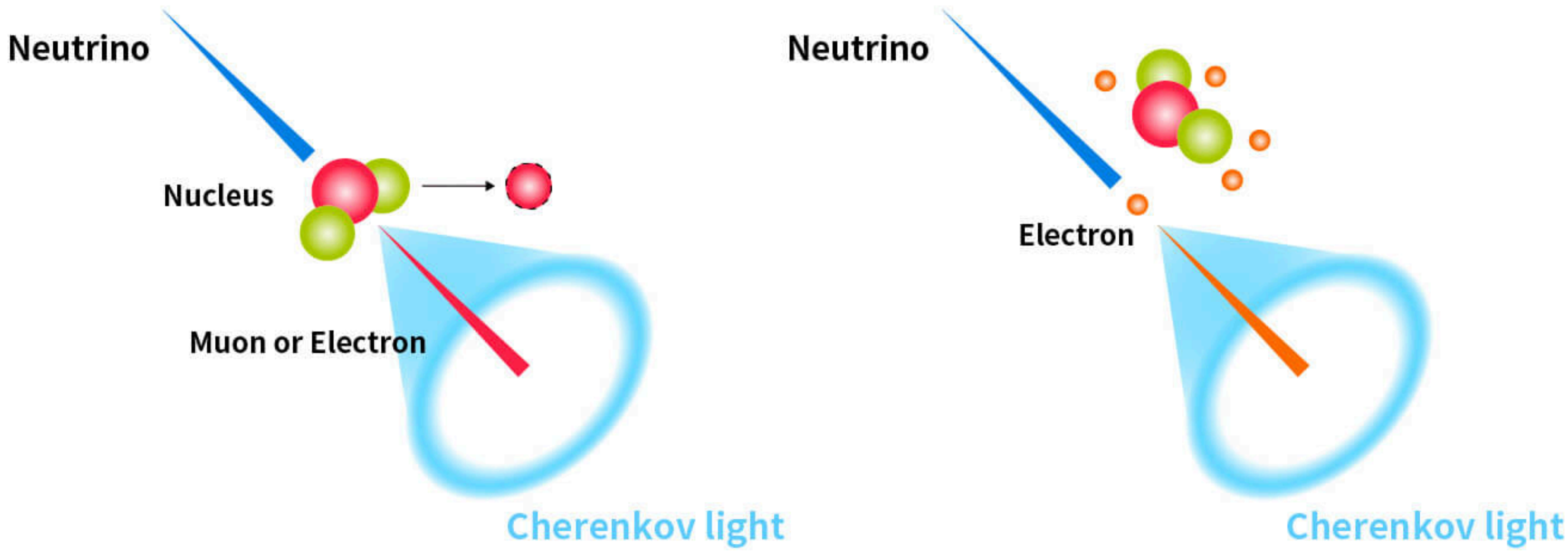
Gd concentration
SK-VI: 0.011% (18 Aug. 2020-)
SK-VII: 0.03% (5 Jul. 2022-)

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

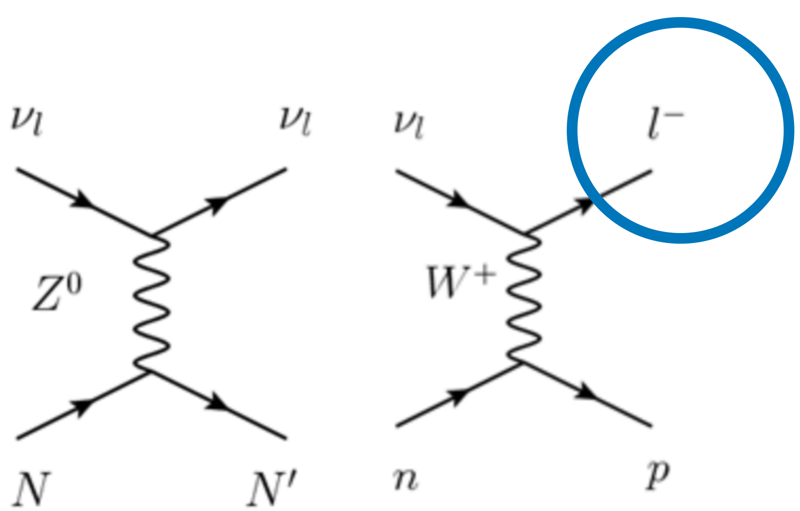
Total live time for current oscillation analysis:
5805 days (SK-I~IV, for solar)
6511 days (SK-I~V, for atmospheric)

Y.Takeuchi's slides

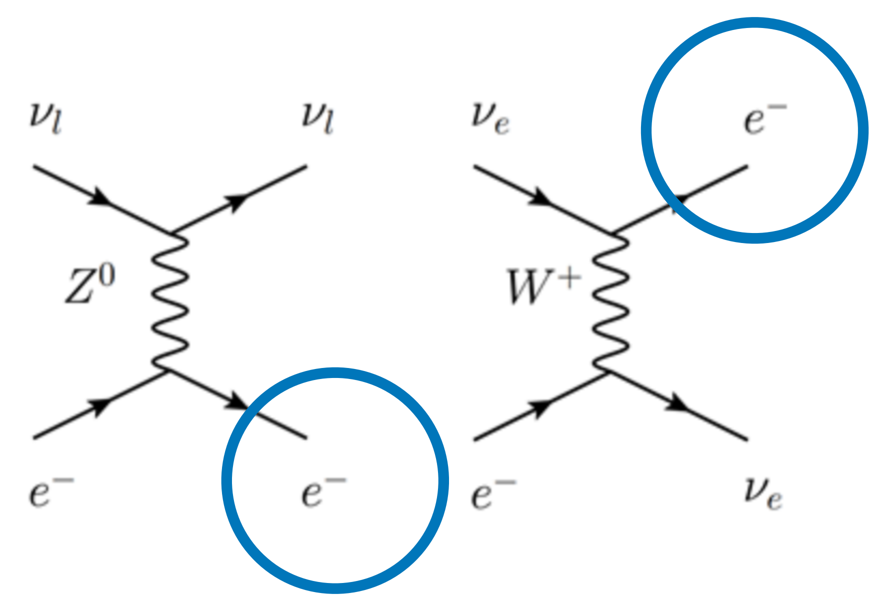
Detecting neutrinos in the SK



The generated charged particles emit Cherenkov light.



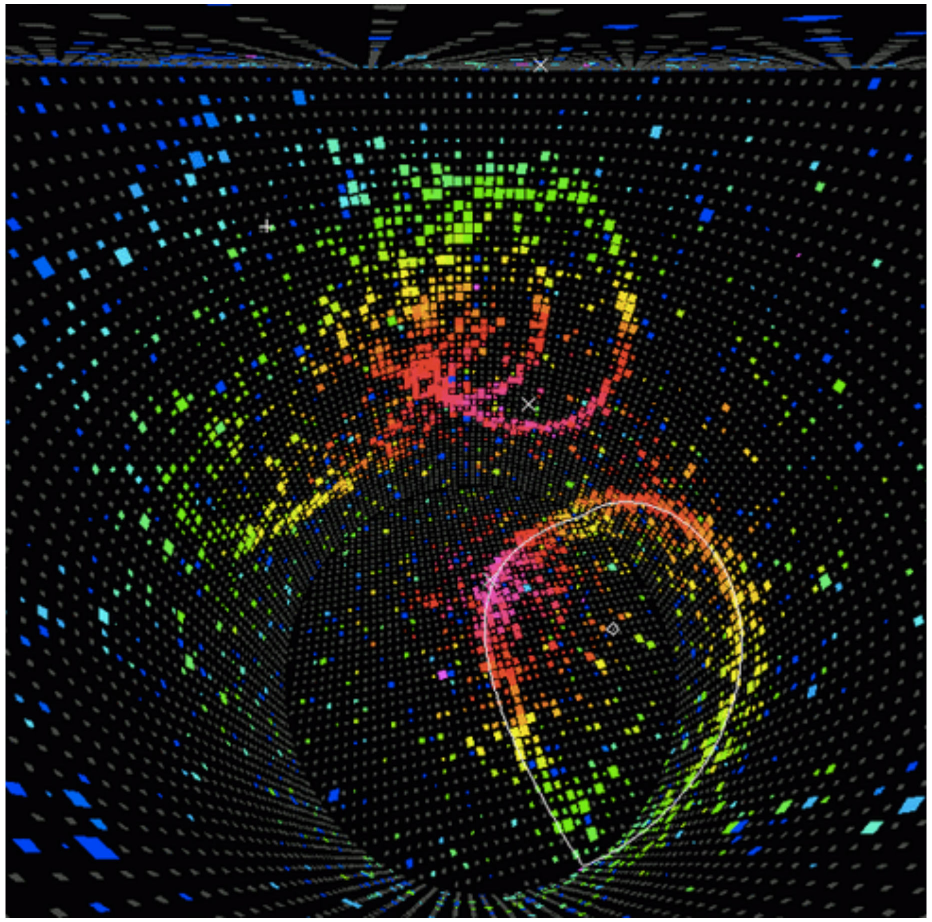
Charged current quasi-elastic scattering (CCQE)

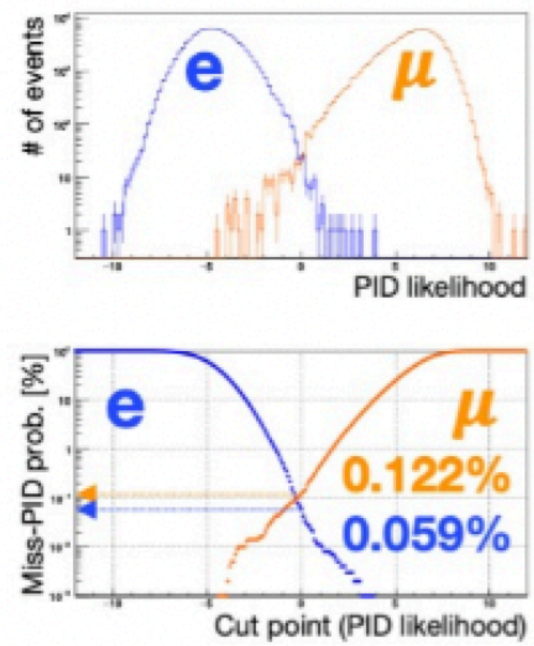


ν-electron scattering

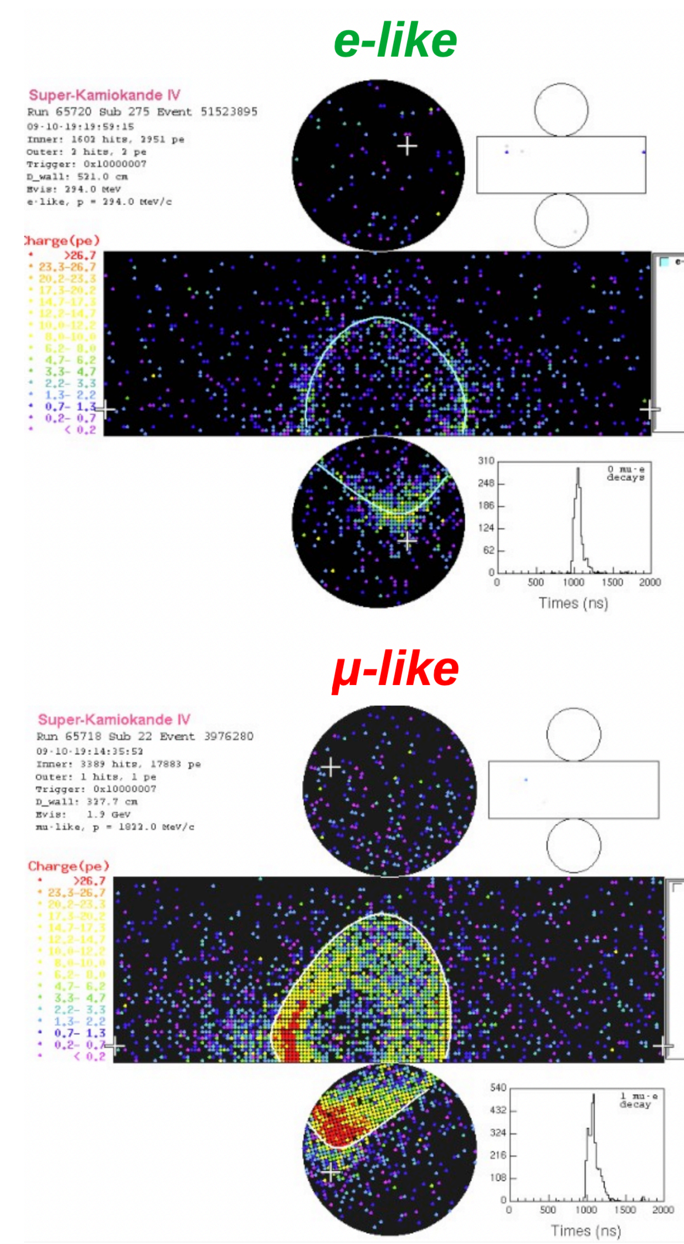
Insensitive to charge sign and (most of the) nucleons

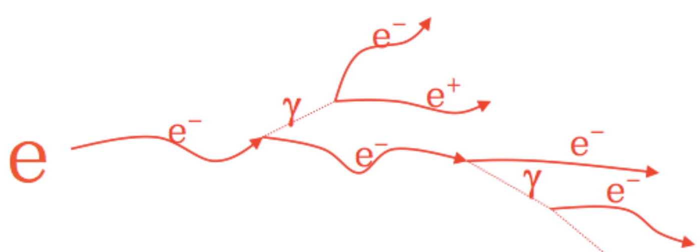
e/mu separation via Cherenkov ring "fuzziness"





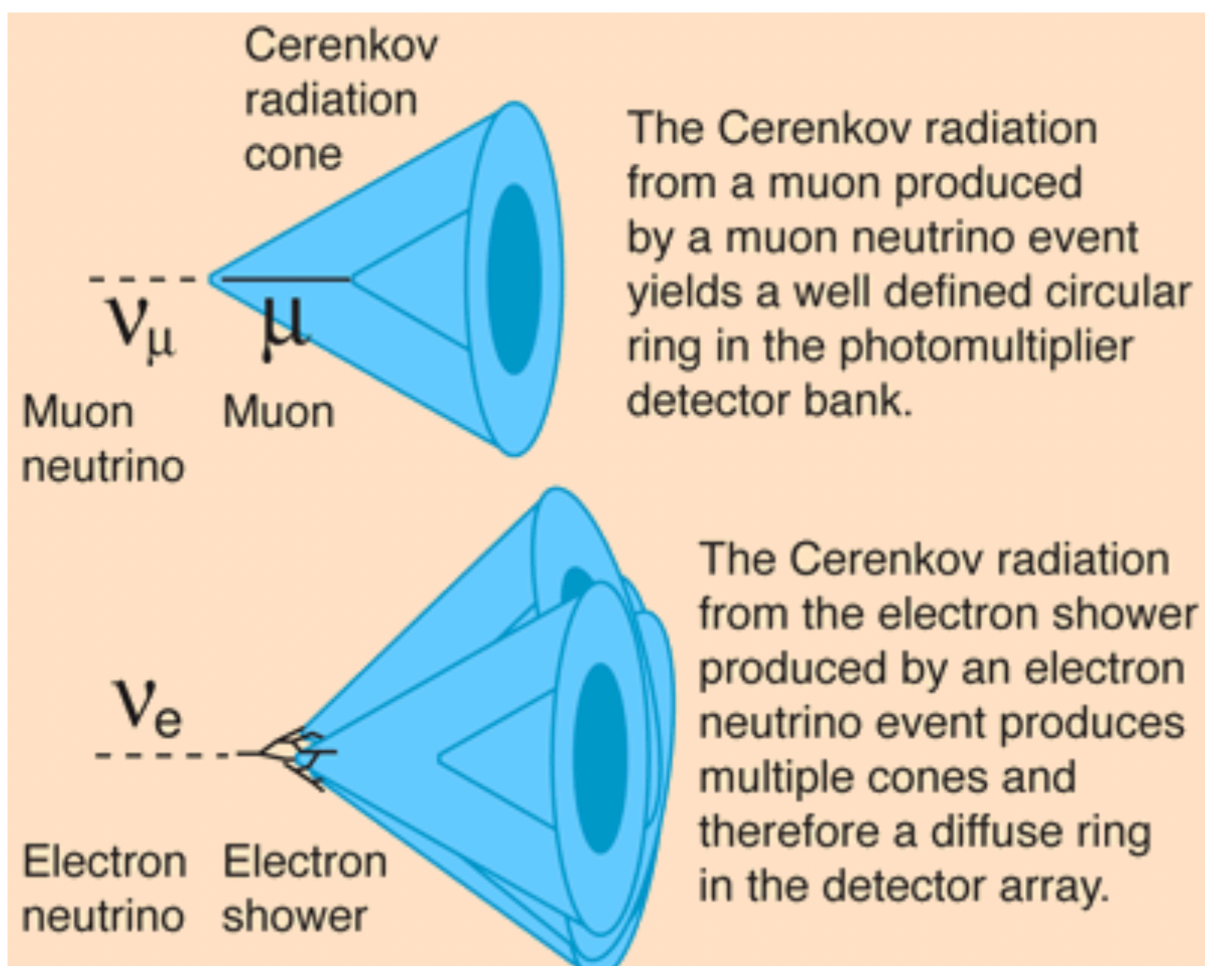
Seiya Sakai @neutrino2022

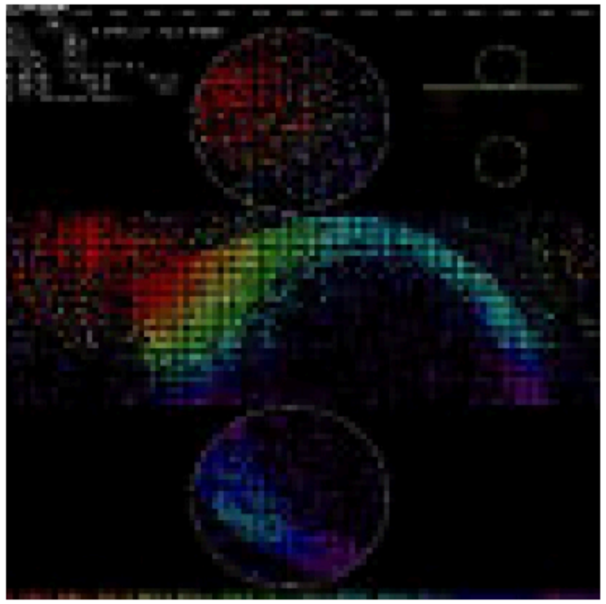




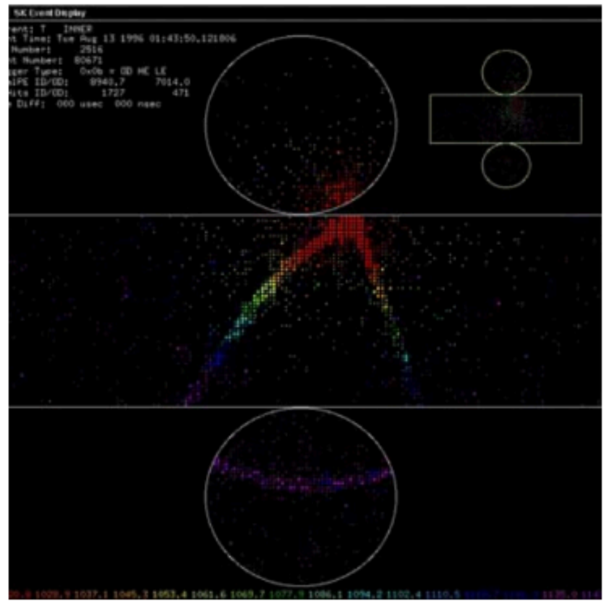
Not clear ring because of 'electric-magnetic shower'

Make a clear ring

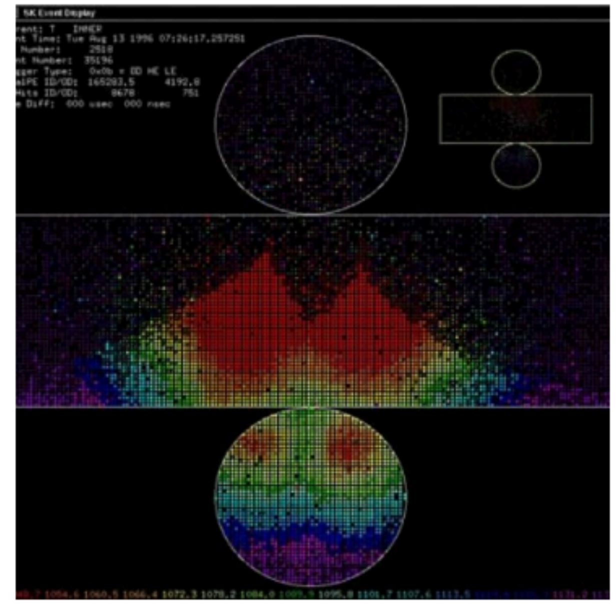




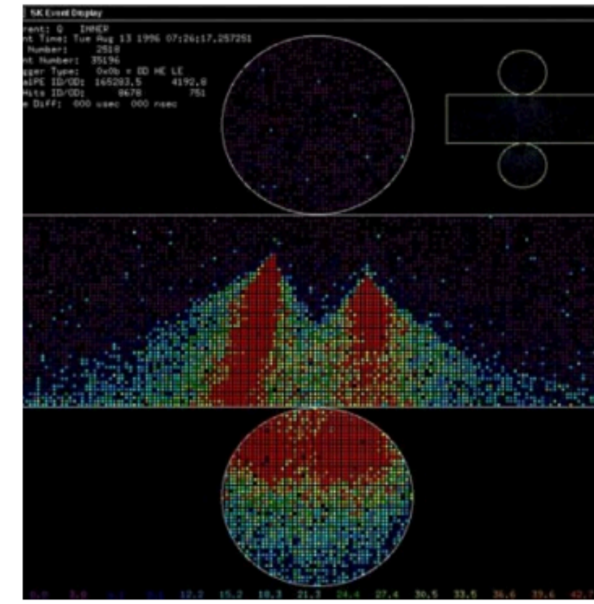
Stopping muon



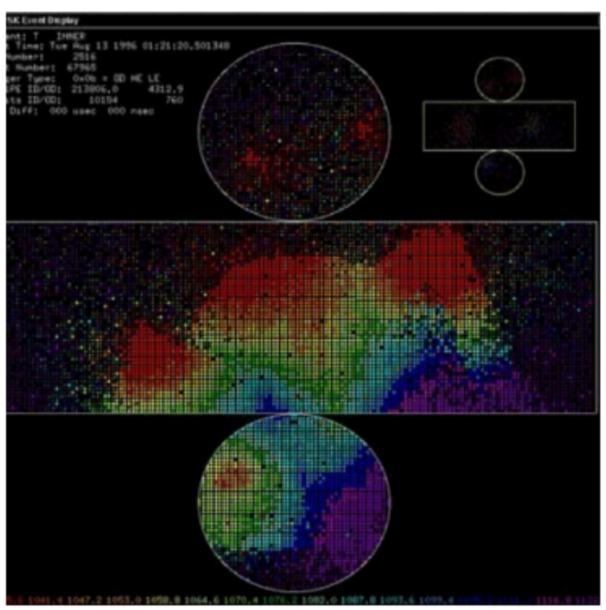
Corner edge clipping muon



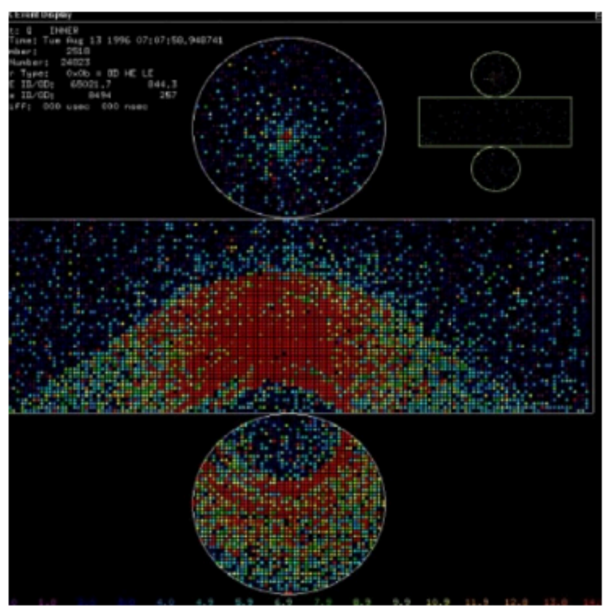
Double muon (Timing distribution)



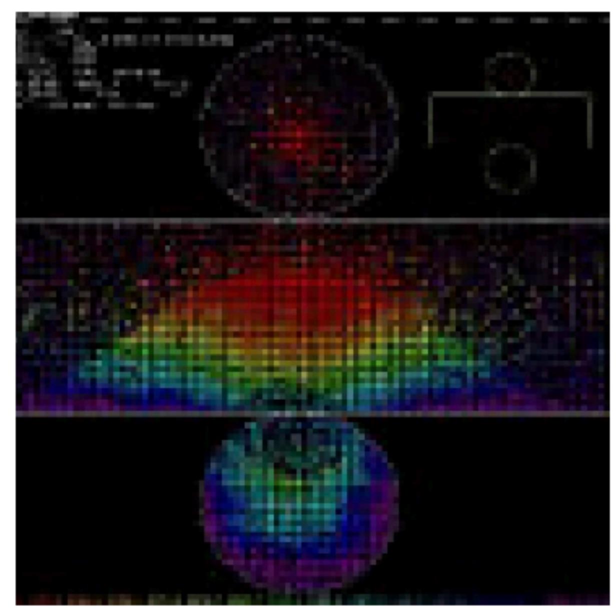
Double muon (Charge distribution)



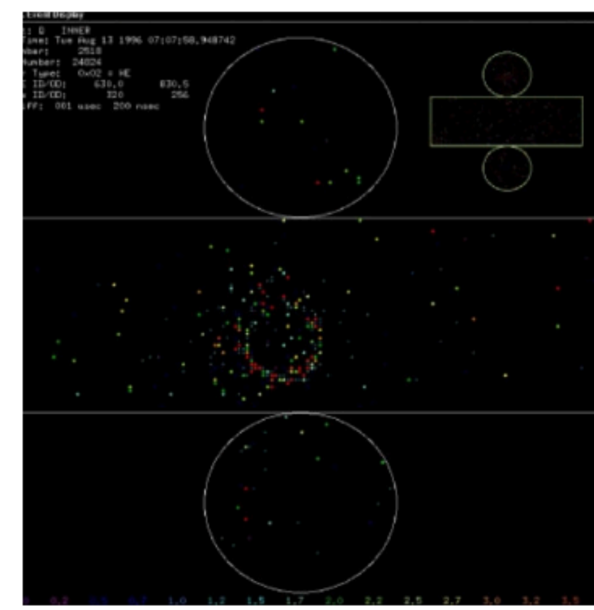
Triple muons



Stopping muon entering from the top (Charge distribution)

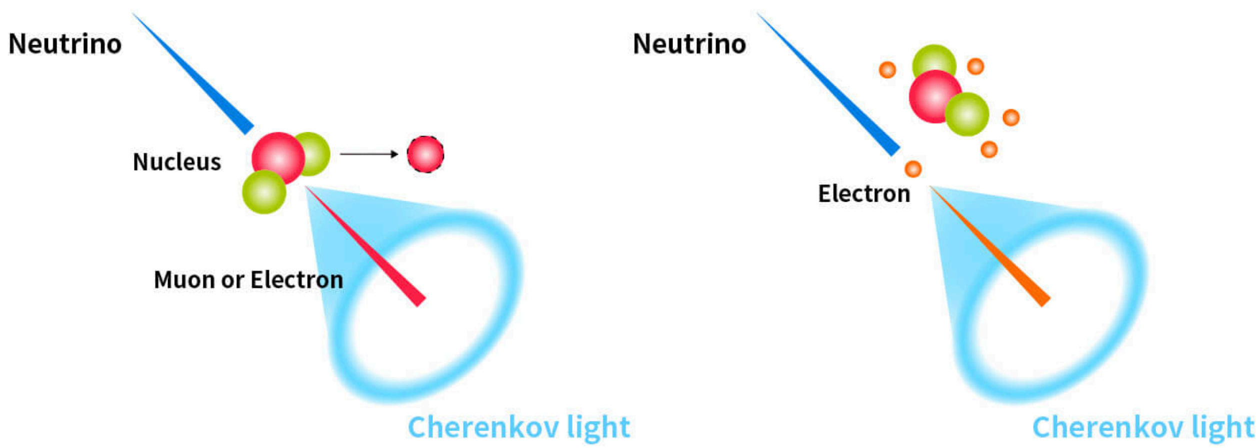


Stopping muon entering from the top (Timing distribution)



An electron emitted from muon decay

Detecting dark matter in the SK

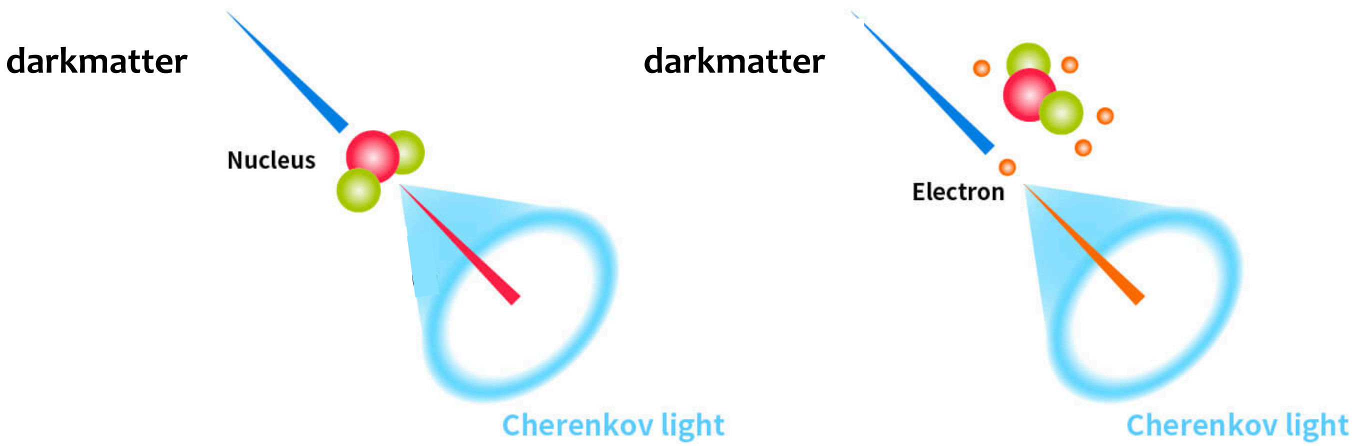


The generated charged particles emit Cherenkov light.

Indirect search for dark matter from the Galactic Center and halo with the Super-Kamiokande detector (2020)

Search for Neutrinos from Annihilation of Captured Low-Mass Dark Matter Particles in the Sun by Super-Kamiokande (2015)

Search for Neutrinos from Dark Matter Annihilation in the Earth's Core with the 2 Super-Kamiokande Detector (coming soon)



The generated charged particles emit Cherenkov light.

Search for Boosted Dark Matter Interacting With Electrons in Super-Kamiokande (2018)

Search for Cosmic-ray Boosted Sub-GeV Dark Matter using Recoil Protons at Super-Kamiokande (2022)

Outline

- Indirect Searches for dark matter

  - Sun (2015)
  - Galactic Center & Halo (2020)
  - Earth (to be soon)

  < reminder that SK-Gd makes the searches more promising!

  - low energy (future)

- Direct searches for dark matter

  - motivation
  - DM-electron elastic scattering (2018)
  - DM-proton elastic scattering (2022)

  < reminder that SK-Gd makes the searches more promising!

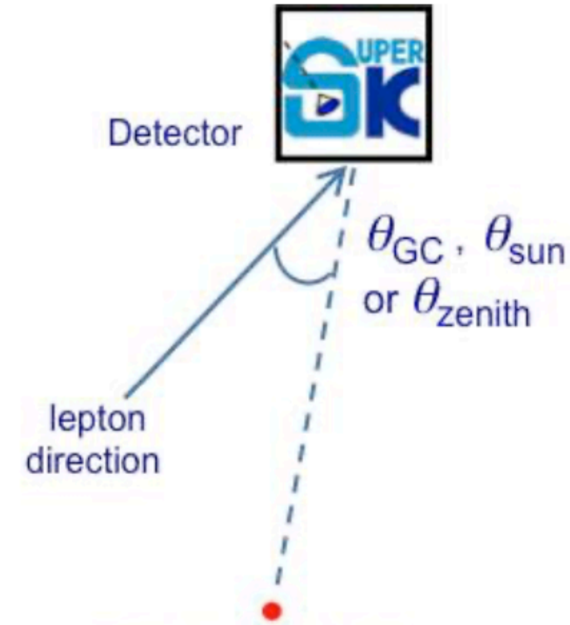
  - low energy DM-Oxygen scattering (future)

SK astrophysical neutrino search (>100MeV)

Q: How to find astrophysical neutrinos where atm v dominates your signal?
A: We rely on our understanding of atm v, and adopt the atm v oscillation analysis framework.

Global Fit method: DM searches at Super-K

- Search for excess of neutrinos form **Earth/Sun/Milky Way**
- **FIT:** for each tested WIMP mass & ann. mode, find configuration of ATM ν + DM signal that would match DATA the best using reconstructed angular & momentum distributions

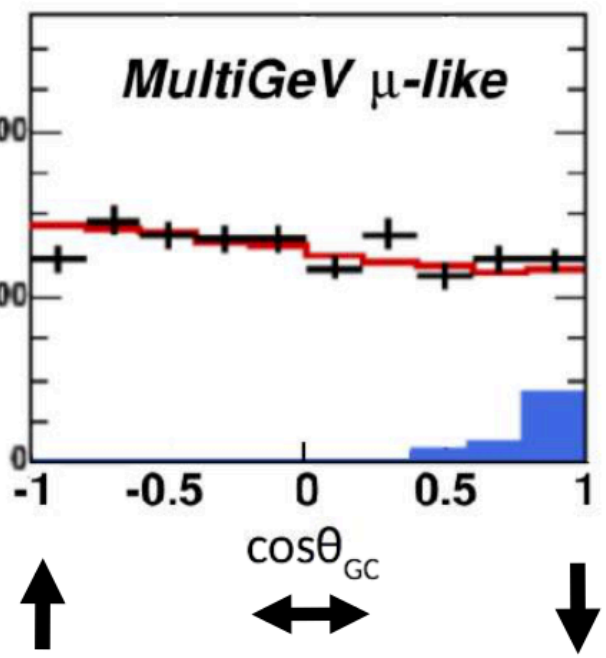


Earth

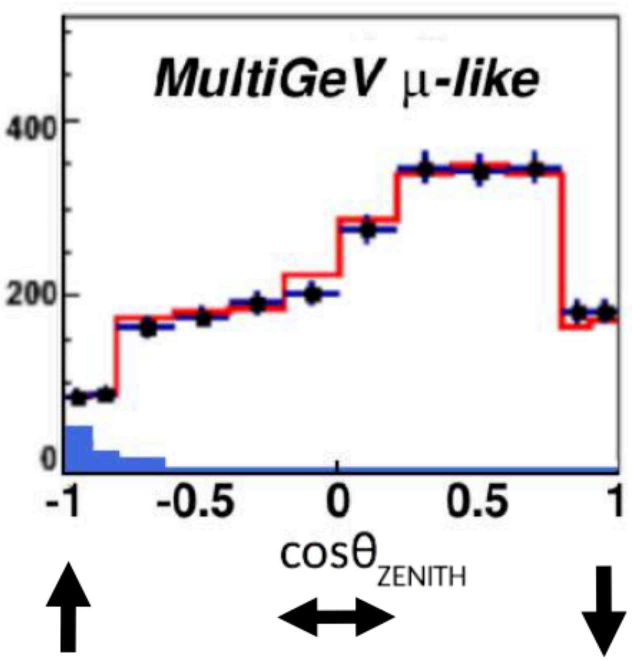
$$\chi\chi \rightarrow \nu\bar{\nu}, W^+W^-, b\bar{b}, \mu^+\mu^- \rightarrow \ldots \nu_{e/\mu/\tau}$$

DM-induced ν simulated using DarkSUSY

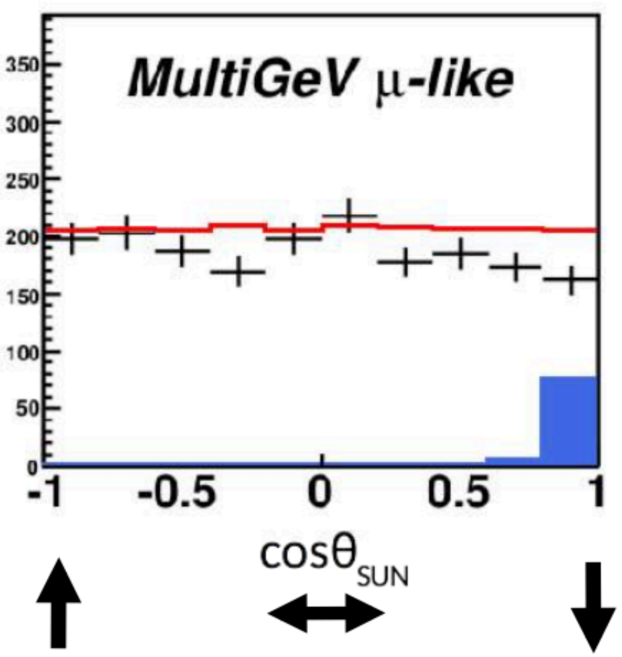
Galactic WIMP search



Earth WIMP search



Solar WIMP search
point-like source



SK DATA

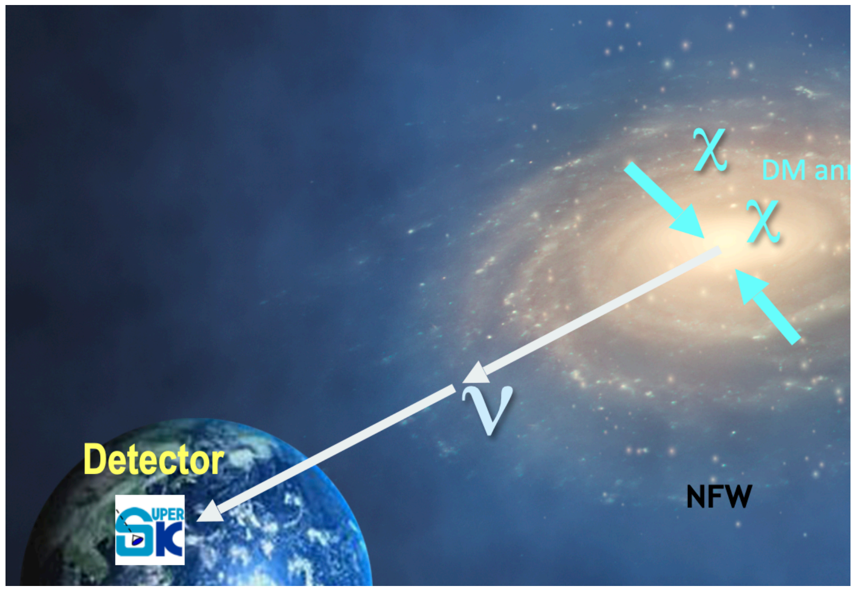
ATM MC (BKG) with oscillations

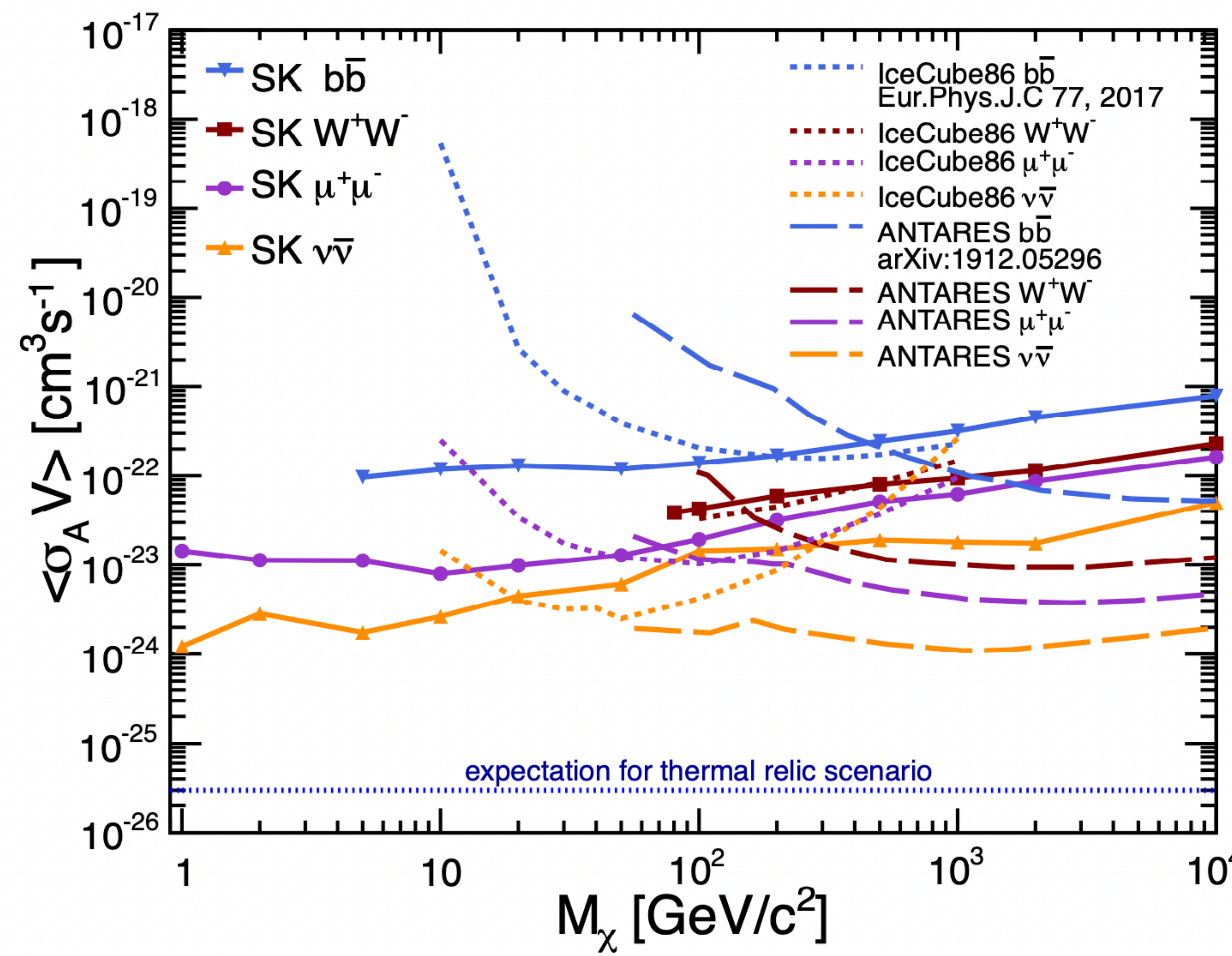
WIMP signal enhanced for illustration

- In these coordinate systems signal is easy to distinguish from atmospheric neutrino background

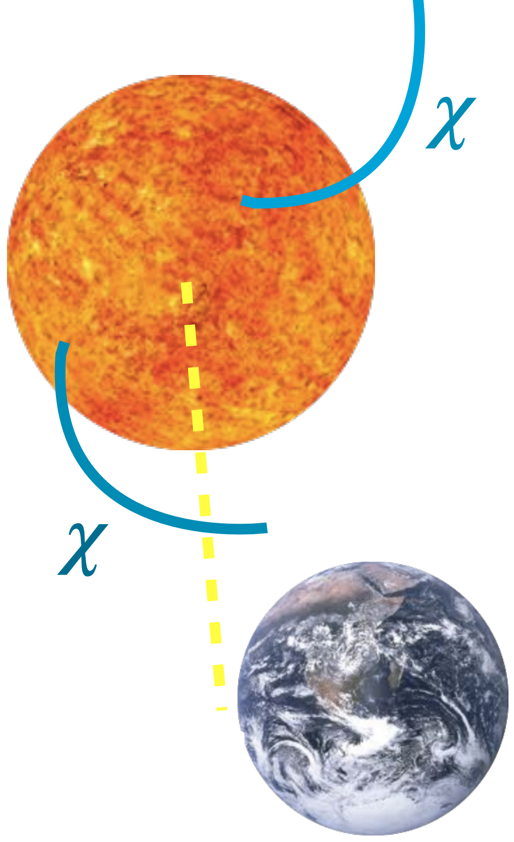
90% upper limits on annihilation cross section

SK-I - IV data taken from 1996 to 2016
(5325.8 live-days)





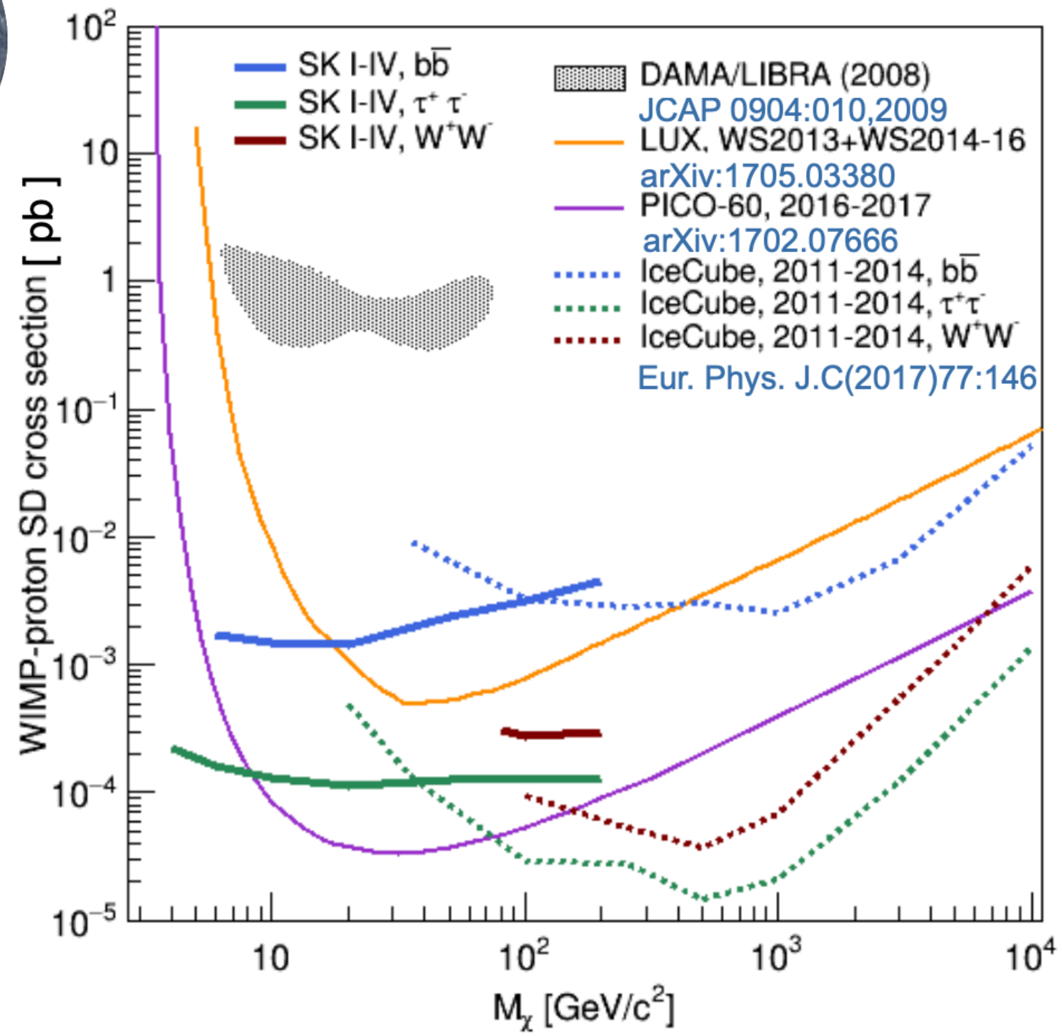
Super-Kamiokande collaboration, Phys.Rev.D 102 (2020) no.7, 072002



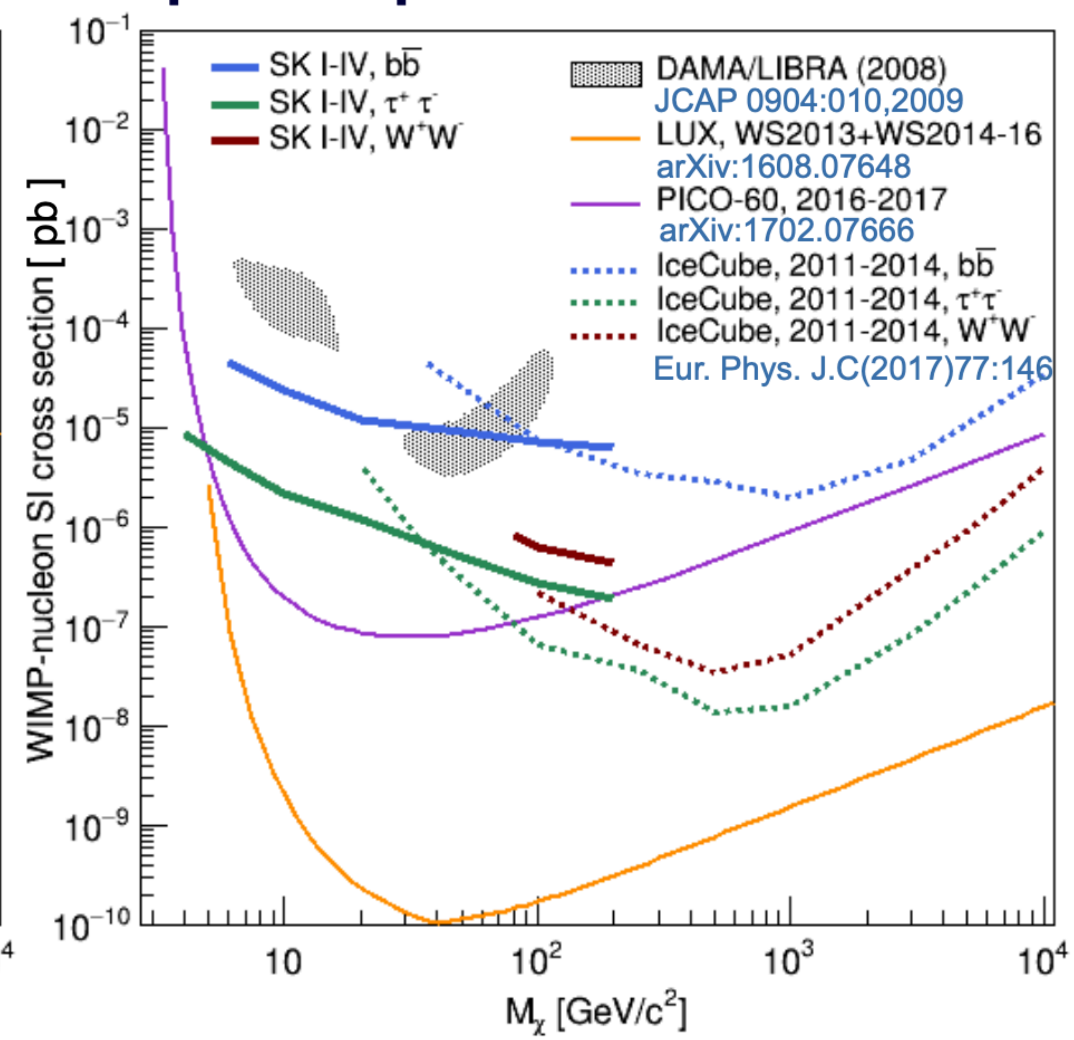
Solar WIMP search: WIMP-nucleon SI & SD cross section limit

90% CL upper limit

spin dependent interactions

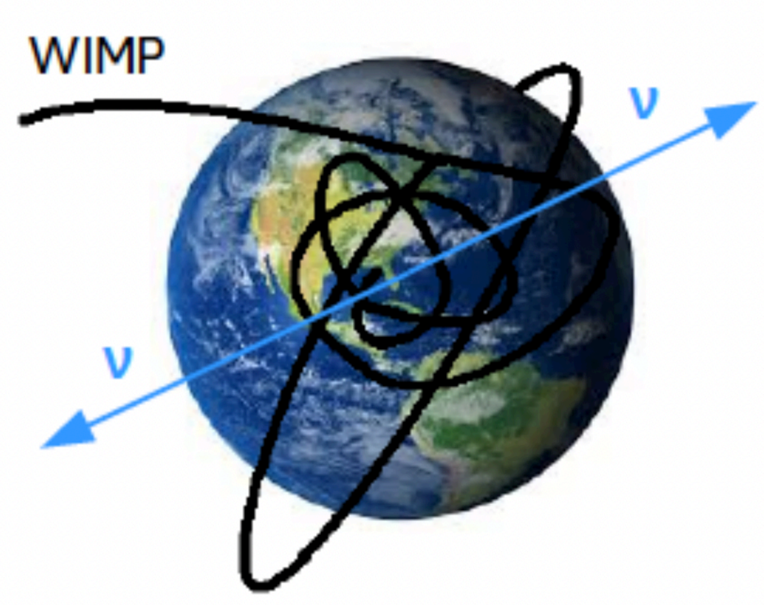


spin independent interactions

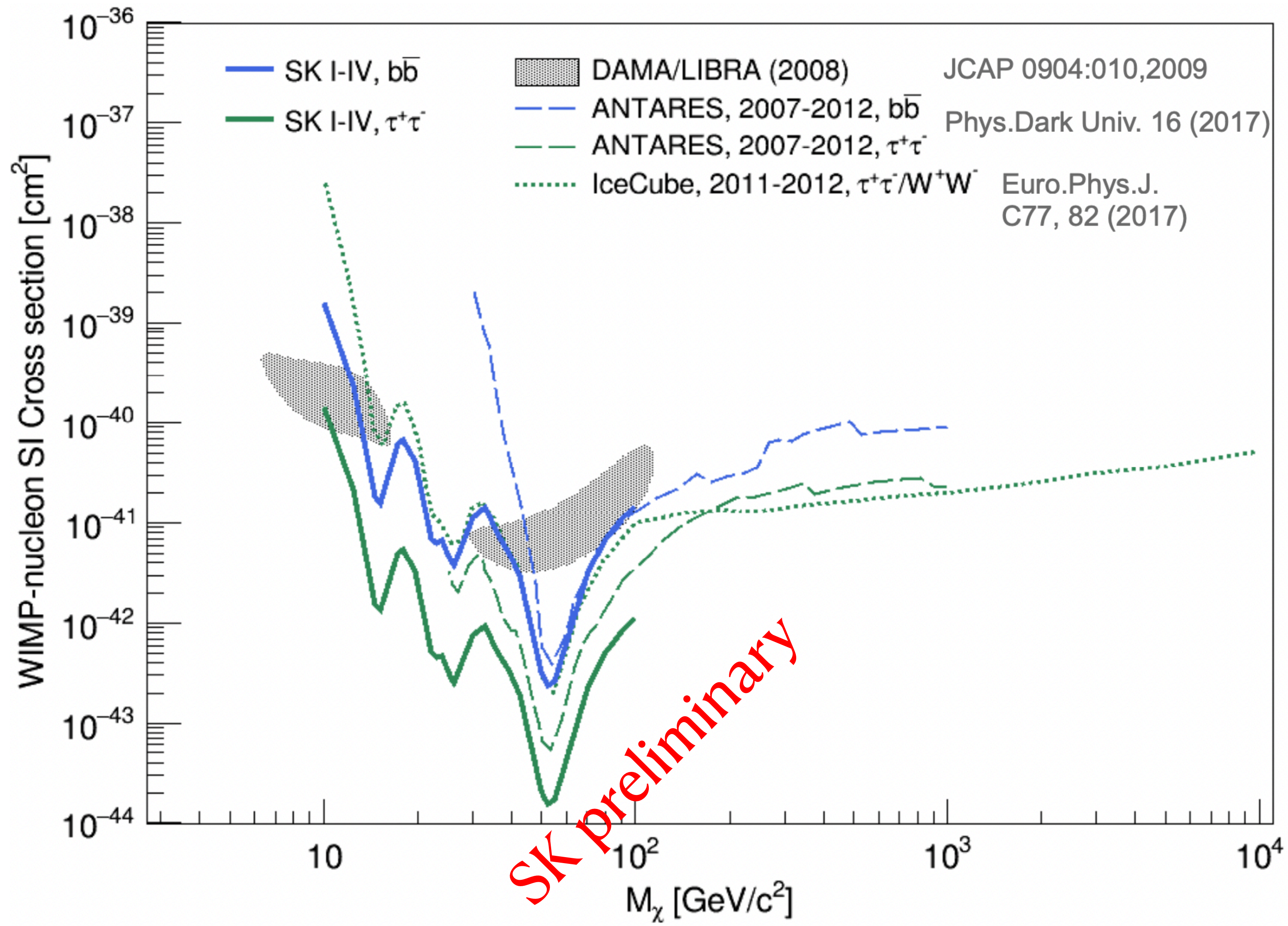


Super-Kamiokande collaboration, Phys. Rev. Lett. 114, 141301 (2015)

90% upper limits on SI scattering cross section



SK-I - IV data taken from 1996 to 2016



K.Frankiewicz thesis (paper under preparation)

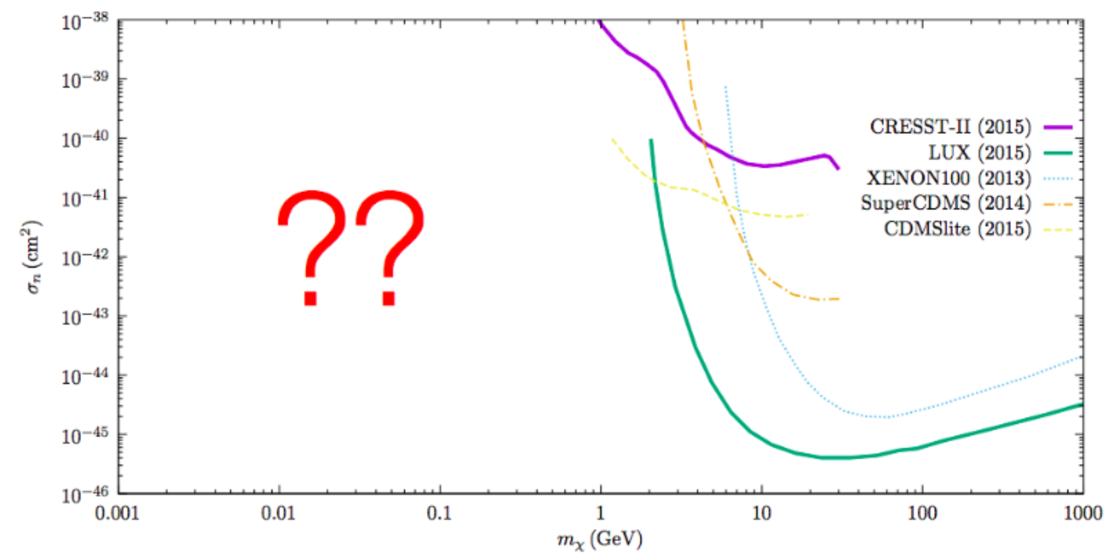
https://www-sk.icrr.u-tokyo.ac.jp/sk/_pdf/articles/2018/Frankiewicz_PhD_final.pdf

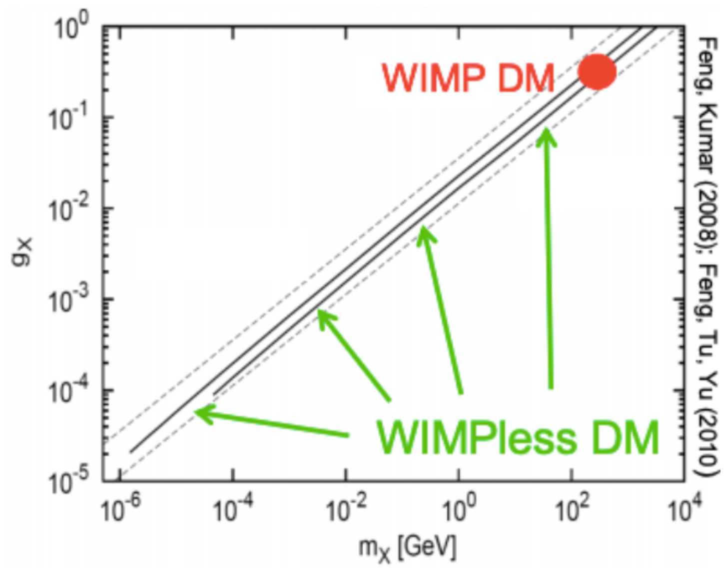
dark matter not found so far…

- A few anomalies (i.e. DAMA modulation) but no consistent signal
- Dark matter may not be WIMP? Then what do we do?
  - persistently prove the WIMP parameter spaces (not yet closed)
  - look in every corner that’s not been searches for
  - do a better thing if you have an idea

Go to Sub-GeV

- Sub-GeV DM is less searched as
  - "WIMP miracle" >2 GeV
  - direct detection experiments lose sensitivity



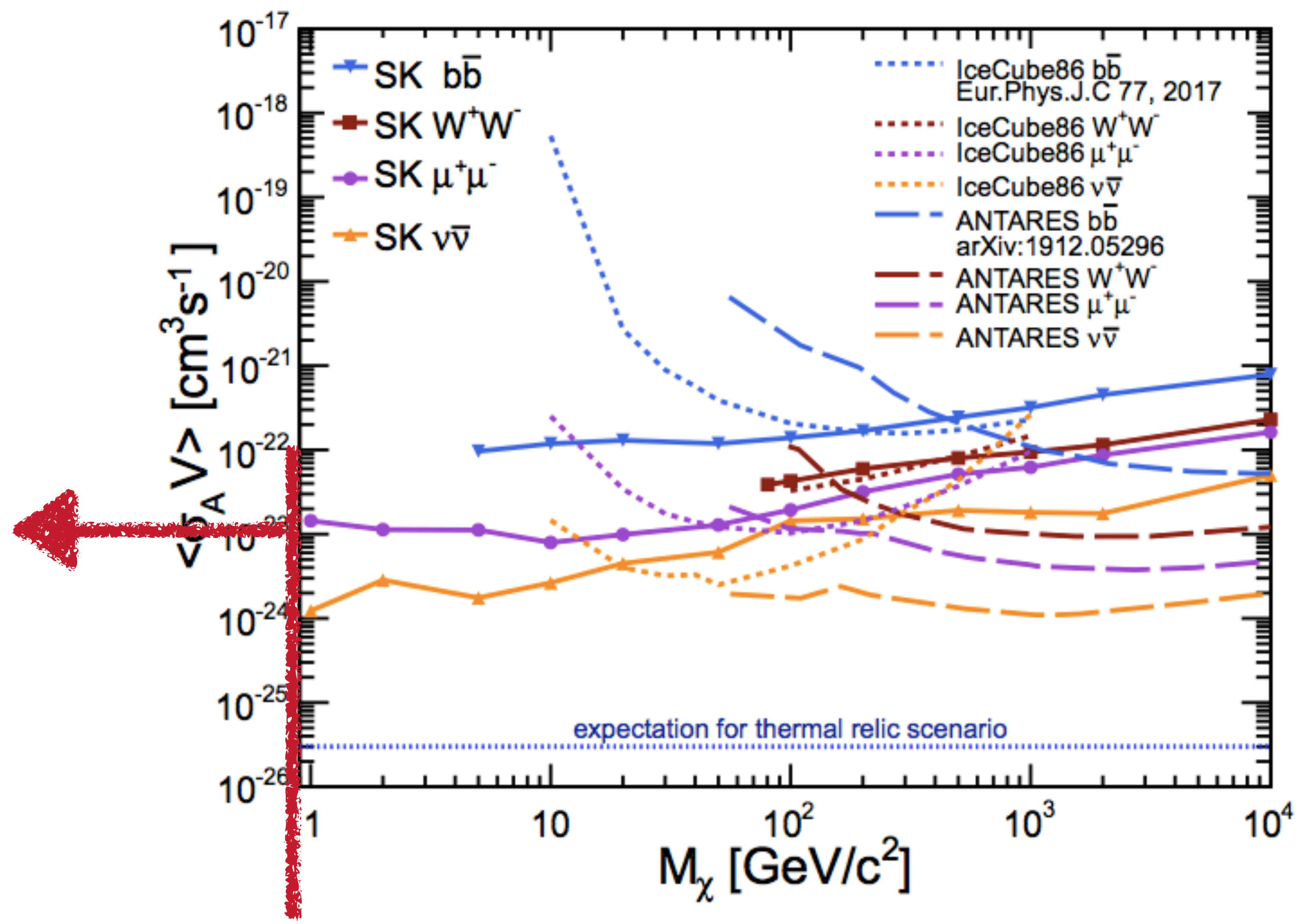


- However,
  Sub-GeV DM can also be a minimal thermal relic candidate &
  comes from wider modelings

- Current efforts in direct detection to detect sub-GeV signal (CRESST, DAMIC, SENSEI, CDMS, …)

- How can SK contribute?
  - Indirect detection of sub-GeV DM - very doable
  - Direct detection of sub-GeV DM - also doable!

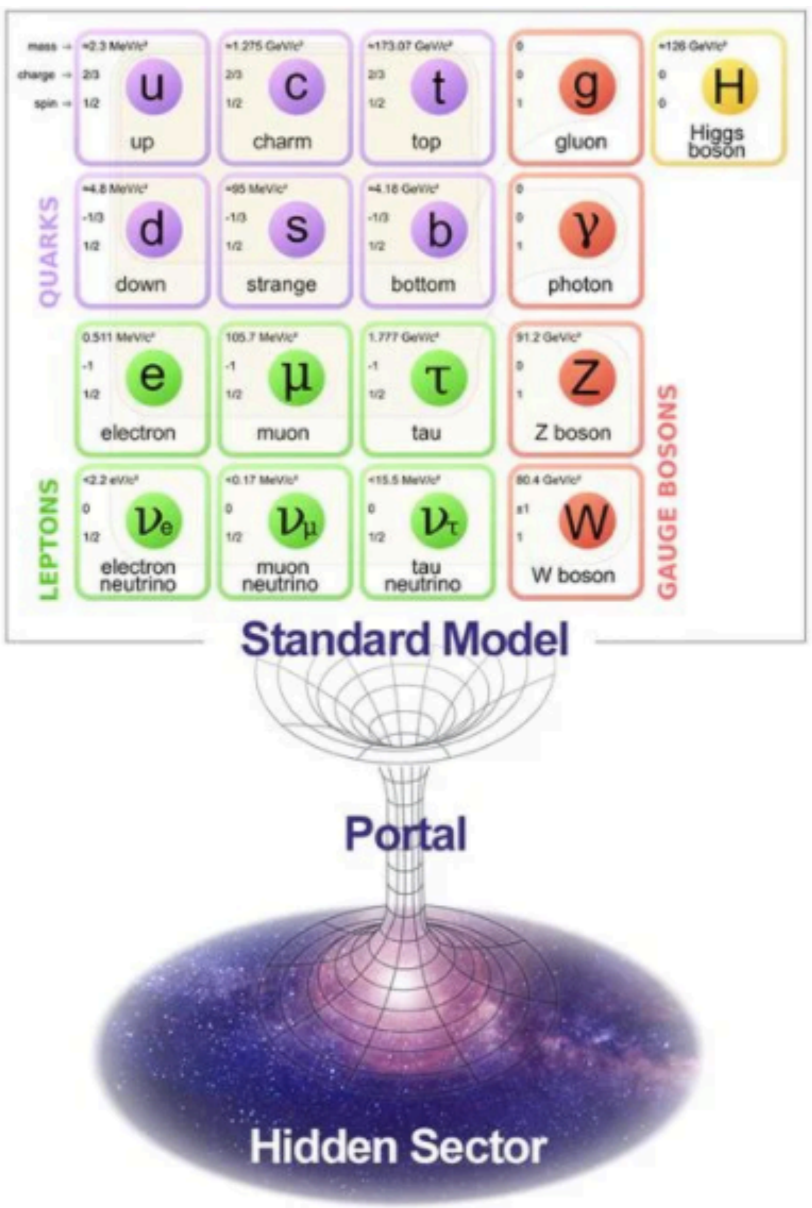
Super-Kamiokande Galactic Dark Matter Search



Super-Kamiokande collaboration, Phys.Rev.D 102 (2020) 7, 072002

why below 1 GeV not explored?
1) no interest in sub-GeV dark matter so far
2) not using <100MeV ν data so far → signal acceptance for sub-GeV dark matter was bad

Search for Dark matter in Dark Sector via ν



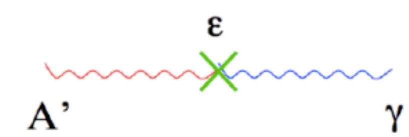
"A tantalizing possibility of a strong connection between these two sectors"

"N_R (right-handed neutrino) connects to the evidence of neutrino masses"

rather natural to expect that the connection to DM will be via singlets of the SM gauge group

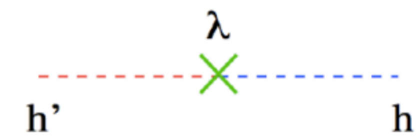
- Vector Portal:
  (A' = "hidden photon")

$$\epsilon F'_{\mu\nu} F^{\mu\nu}$$

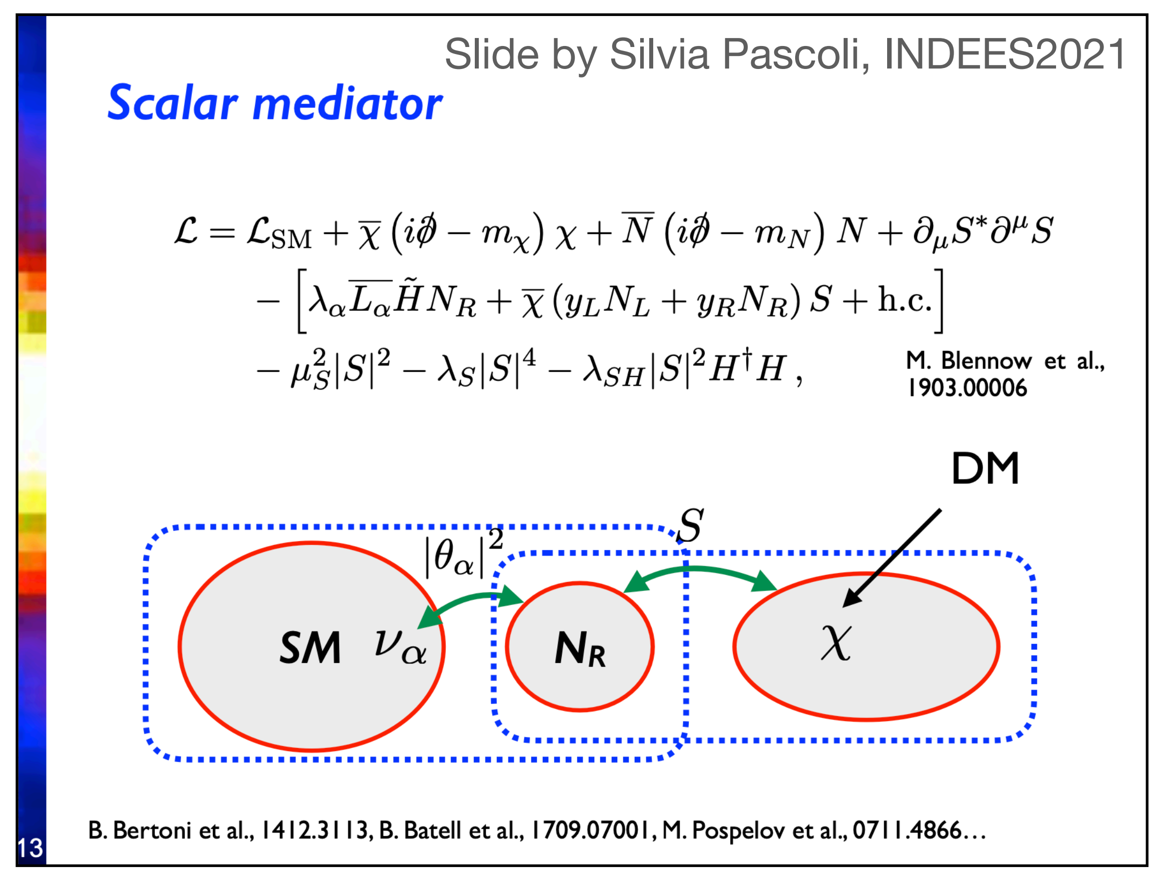


- Higgs Portal:
  (H' = "hidden Higgs")

$$\lambda |H'|^2 |H|^2$$

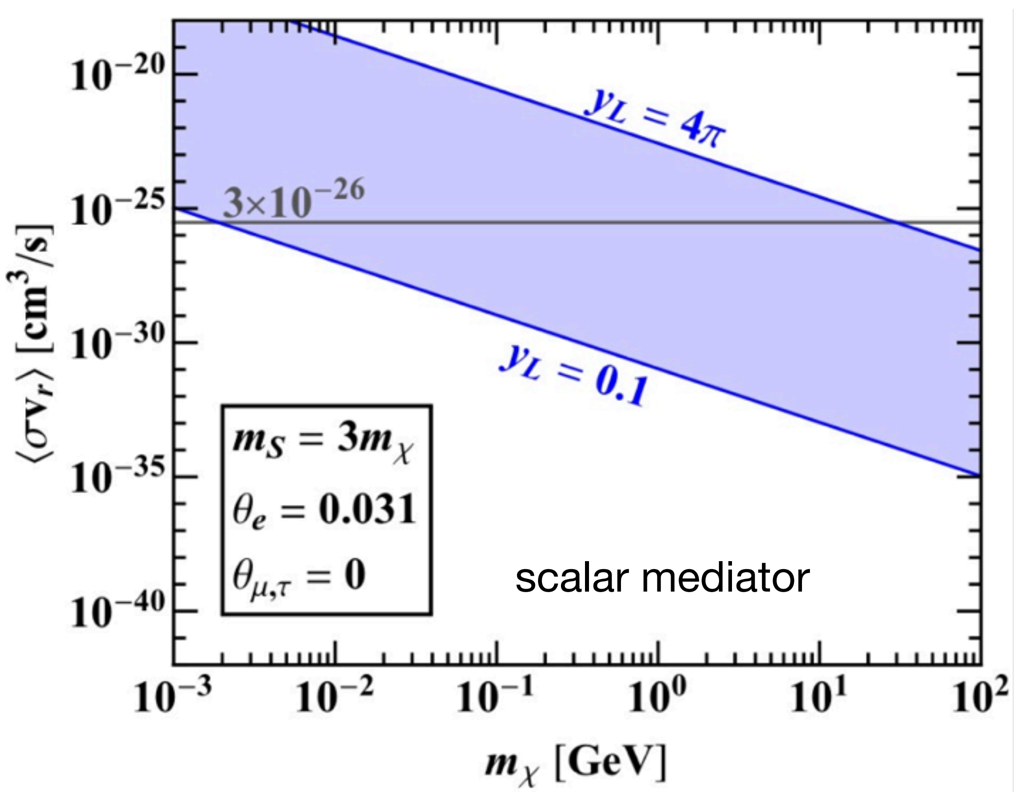


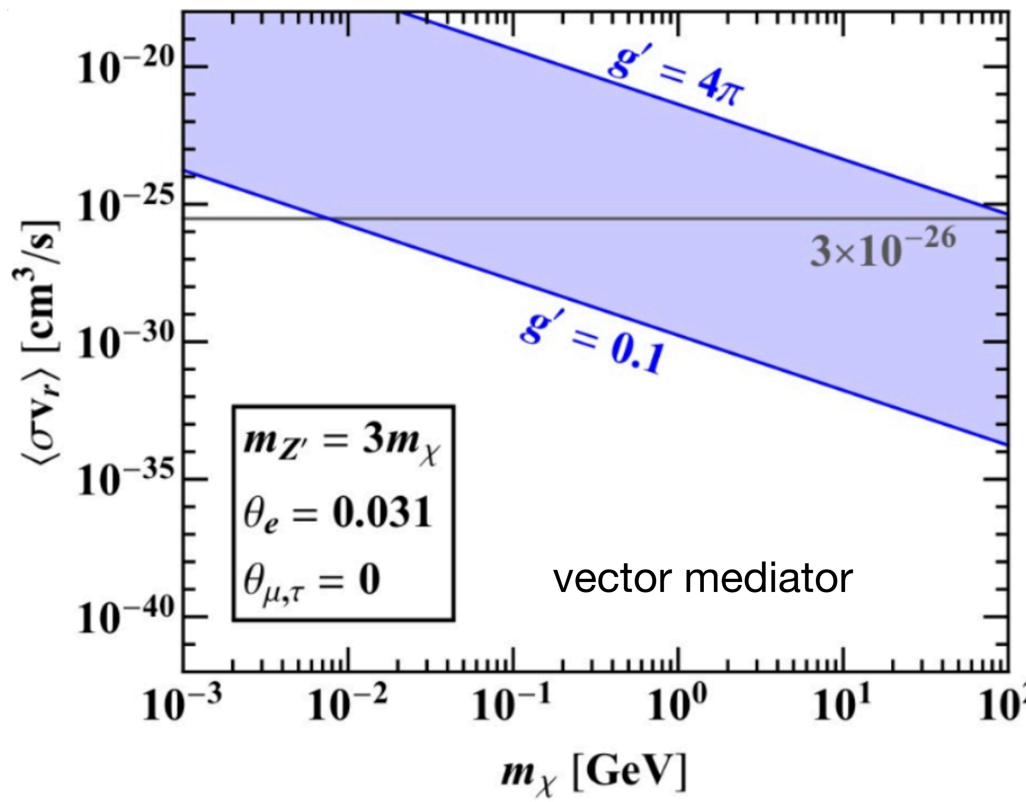
- Neutrino portal:



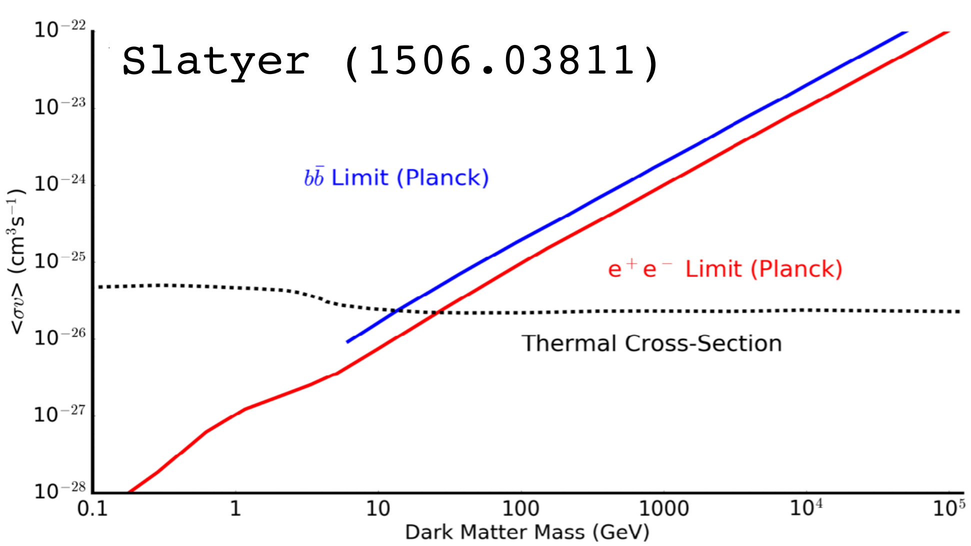
Dark Matter Search through Neutrino Portal

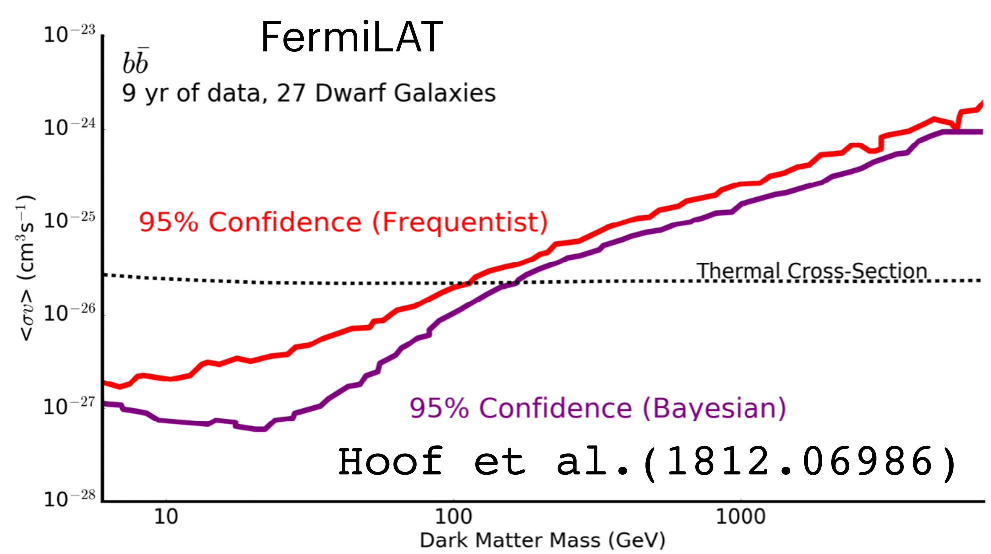
Blennow et al. (1903.00006) “Can successfully produce thermal relic”





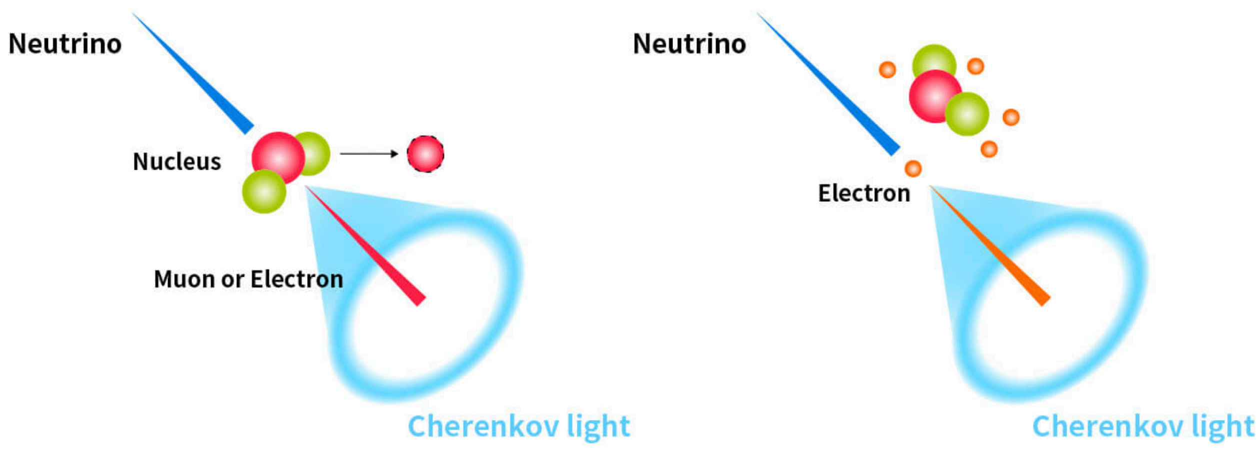
light DM already ruled out by EM particle annihilation channels but neutrinos





in case of neutrino portal, neutrino probes could dominate sensitivity to the dark sector

Detecting dark matter in the SK



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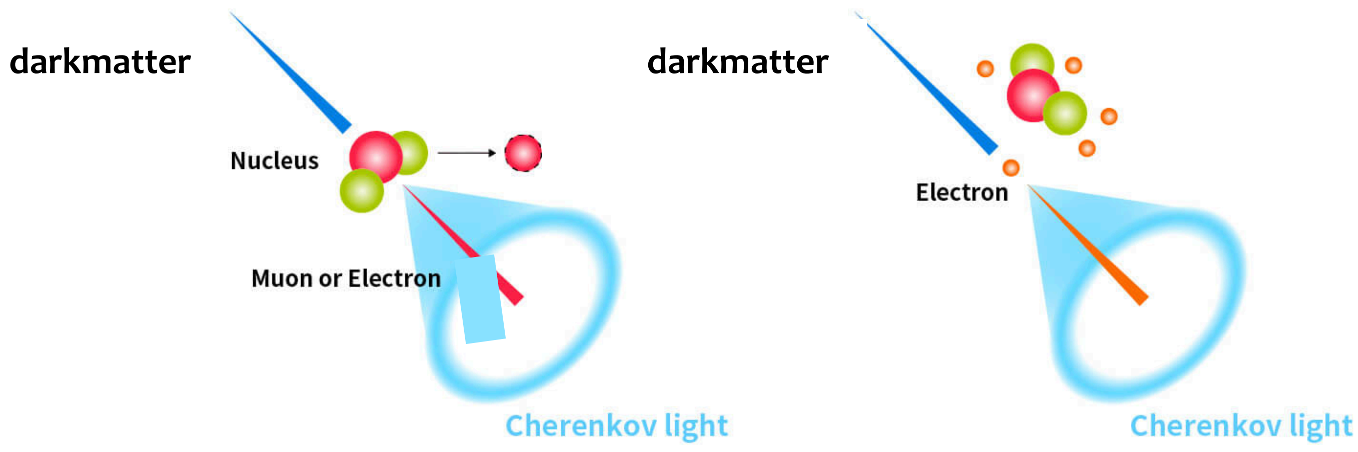

The generated charged particles emit Cherenkov light.

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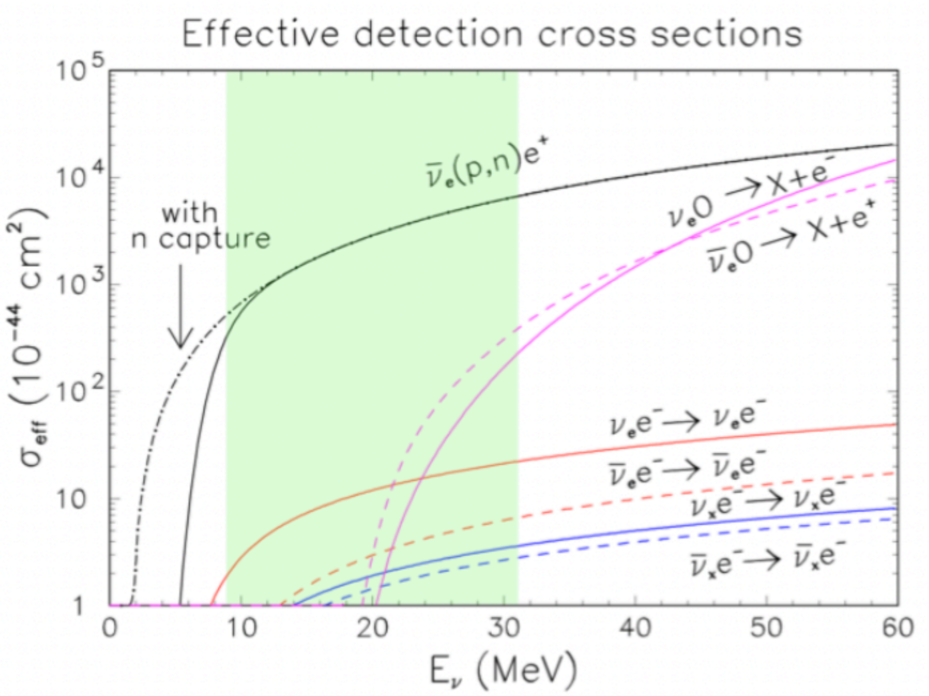
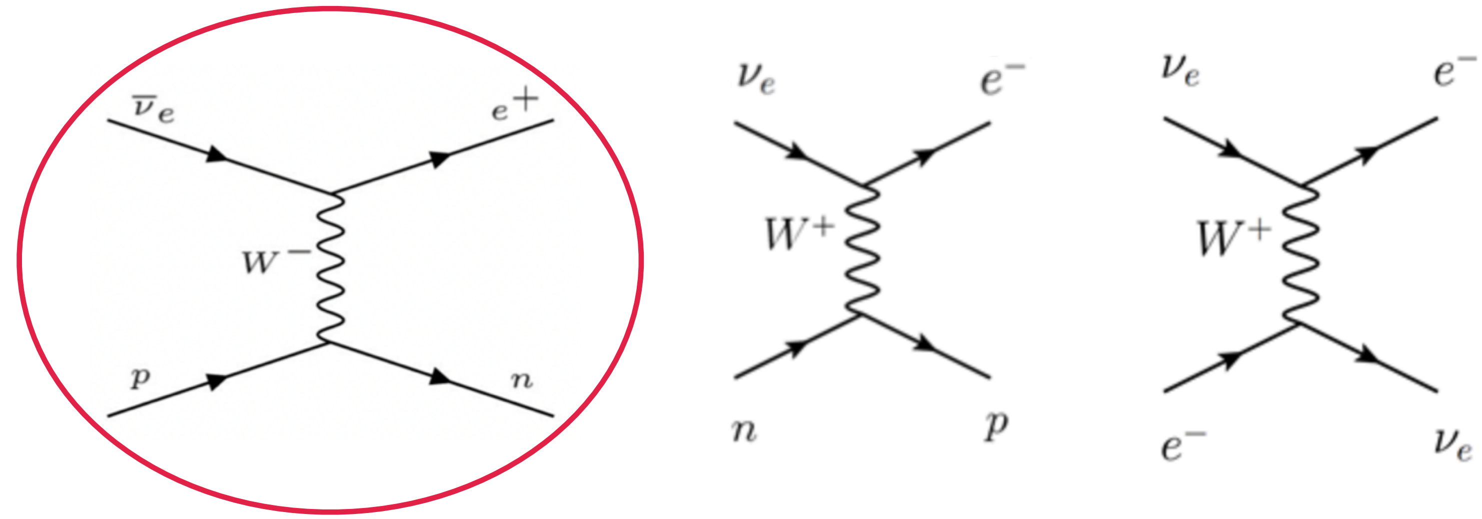
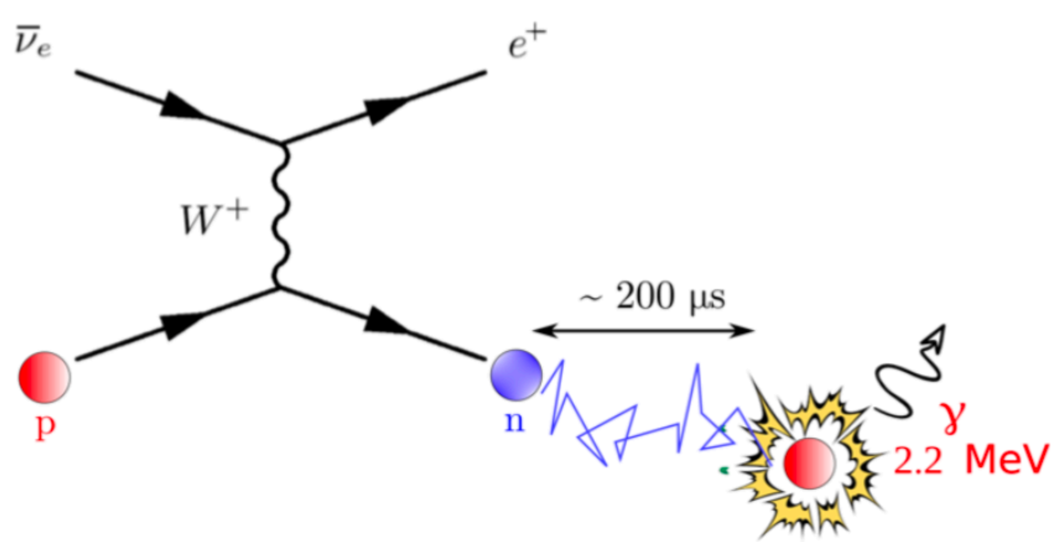
- Search for Neutrinos from Annihilation of Captured Low-Mass Dark Matter Particles in the Sun by Super-Kamiokande (2015)
- Search for Neutrinos from Dark Matter Annihilation in the Earth's Core with the 2 Super-Kamiokande Detector (coming soon)
- Search for low-energy neutrinos from Dark Matter Annihilation in the Galactic Center and halo (on-going analysis)
- Search for Boosted Dark Matter Interacting With Electrons in Super-Kamiokande (2018)
- Search for Cosmic-ray Boosted Sub-GeV Dark Matter using Recoil Protons at Super-Kamiokande (2022)

Sub-GeV signal in SK-Gd

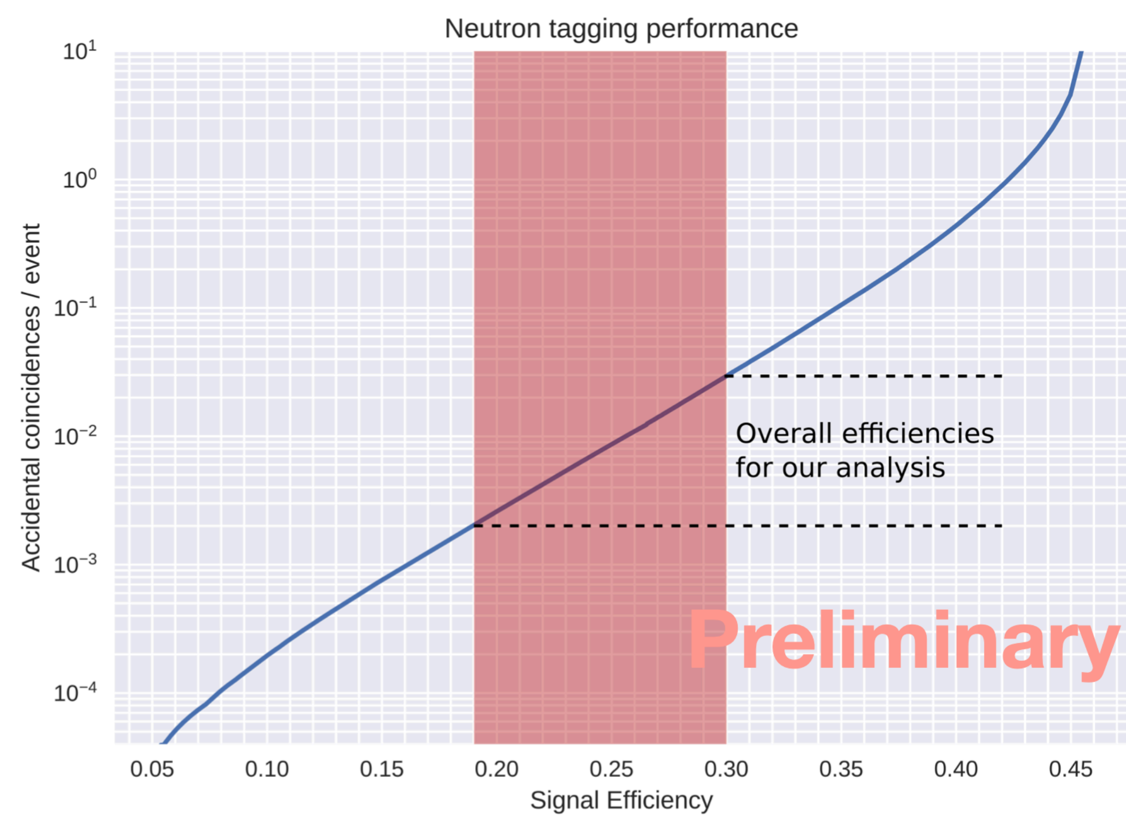




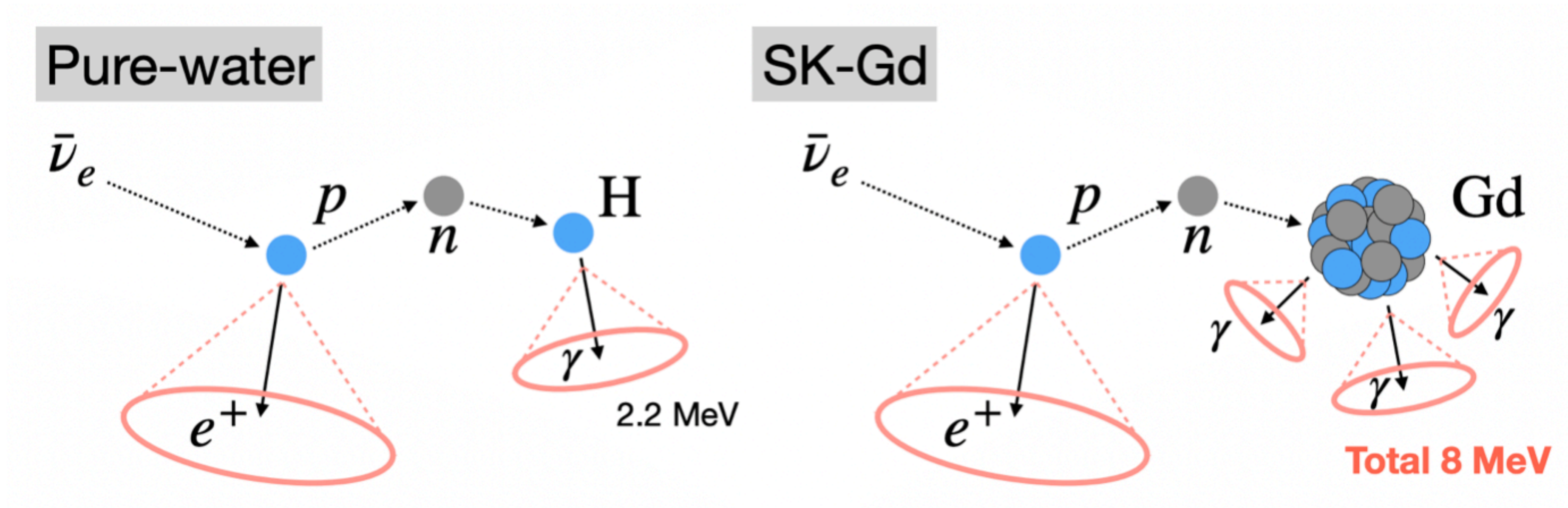
Inverse Beta Decay (IBD) :1.8 MeV energy threshold
Coincidence search: spatial & timing correlation between prompt & delayed events



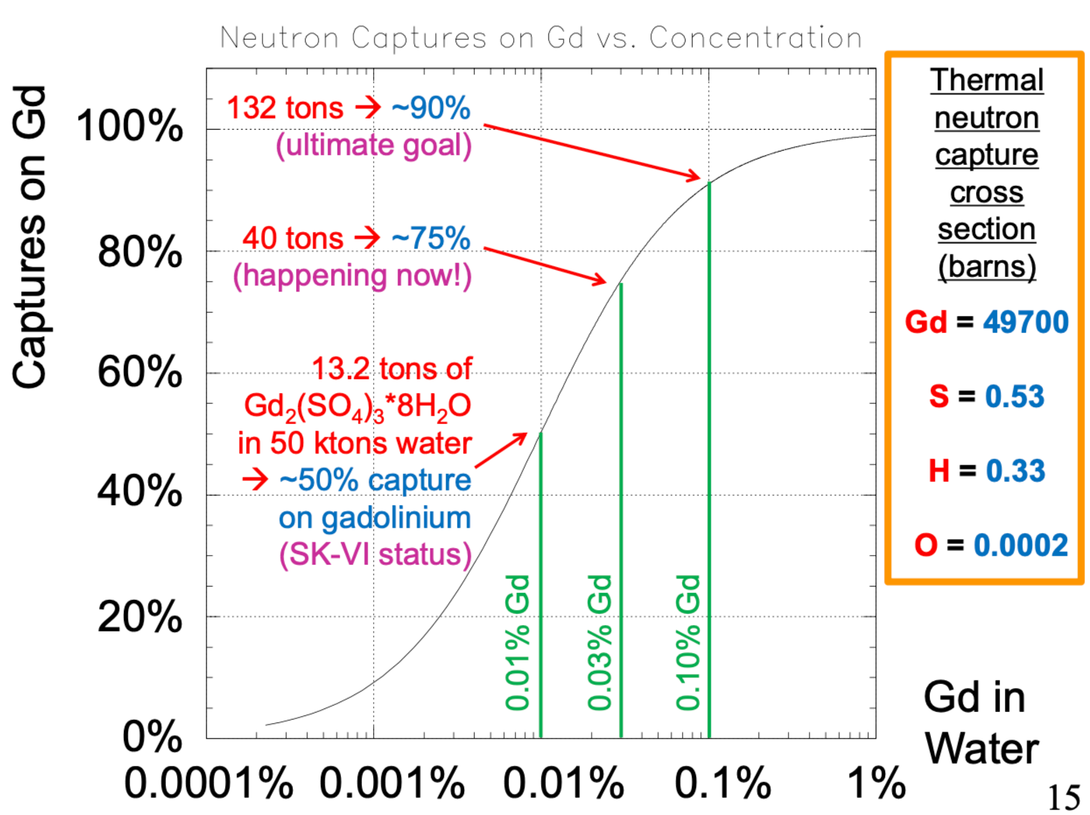
2.2 MeV is very low for SK
(typically ~7 hits in the entire tank)
but not impossible to catch as coincident signal



SK Gd doping



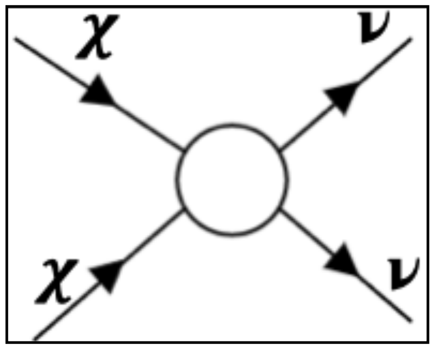
Gd loading of SK can tag neutrons more effectively due to higher energy deposited (8.5 MeV gamma cascade instead of 2.2 MeV from H)

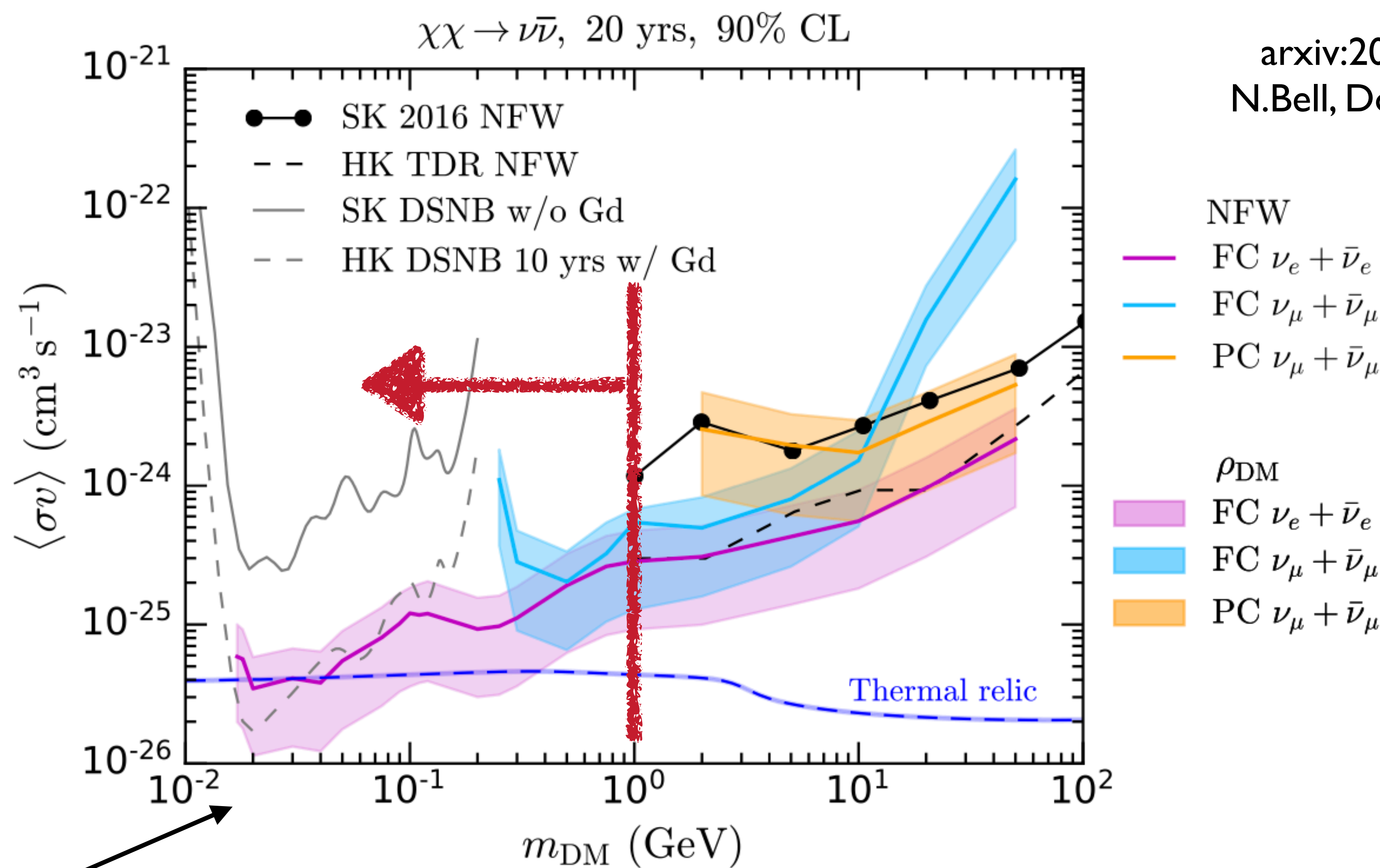


Seungho Han @neutrino2022

improve DSNB (Diffuse Supernova Neutrino Background) search with IBD channel selection (+ atmospheric ν oscillation study)

Sub-GeV Galactic Dark Matter Search





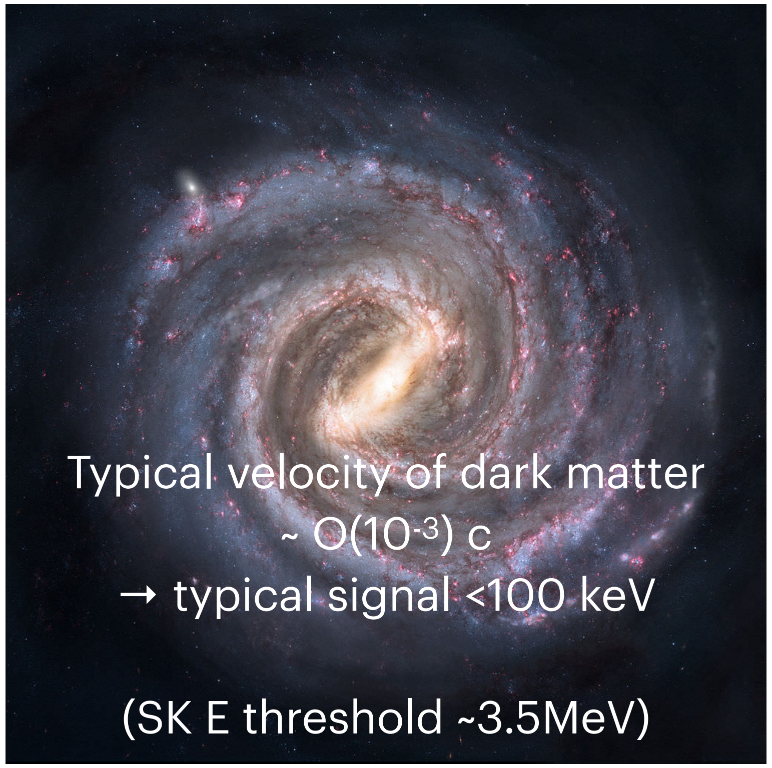
arxiv:2005.01950
N.Bell, Dolan, Robles

also Palomares-Ruiz et al. (0710.5420), Del Campo et al. (1711.05283), Klop et al. (1809.00671), Blennow et al. (1903.00006), Arguelles et al. (1912.09486)

where SK can do the best

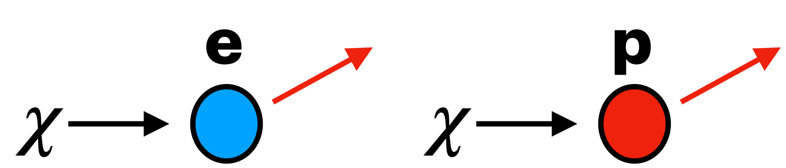
- using 20-yr SK low-energy data (<100MeV),
  SK sensitivity is expected to be fairly close to the thermal relic cross-section
  & can demonstrate HK sensitivity

Boosted Dark Matter



Boost mechanism:
beam/reactor-produced dark photon decaying to dark matter
dark matter annihilation to dark particle
cosmic-ray boosted dark matter
astrophysical source-boosted dark matter
atmospheric-shower produced dark matter
...

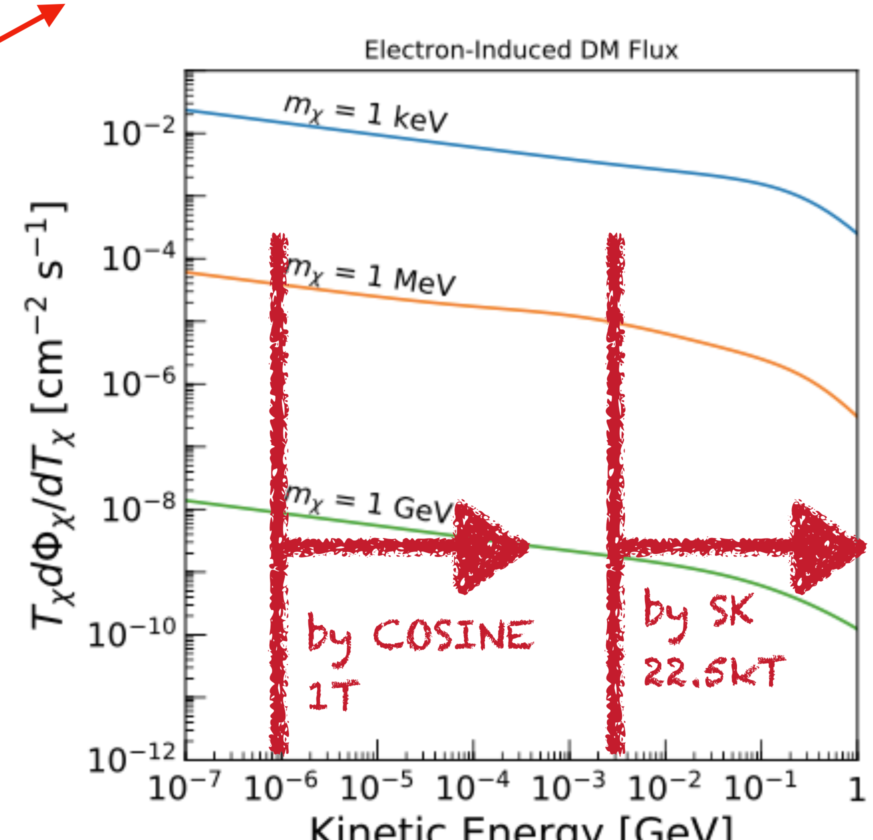
Leave Neutral-current ν like signal in the SK



If dark matter signal is expected above O(1)MeV
→ direct detection of "boosted dark matter" in the Super-Kamiokande

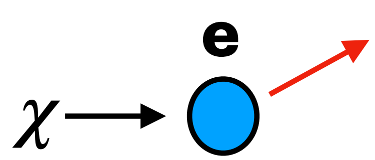
- sees high tail of the boosted dark matter spectrum,
  smaller signal acceptance of neutrino detector can be overcome by size -
  complementary observations

boosted spectrum by DM-electron scattering

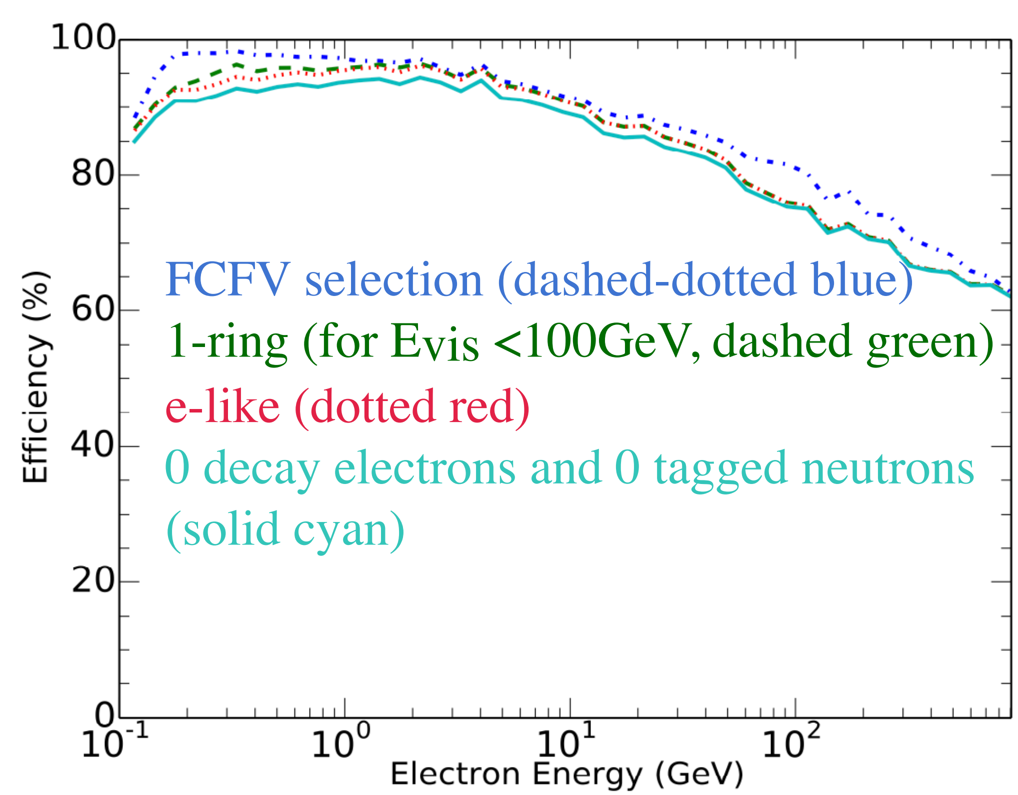


Cappiello et al., arxiv:1906.11283

DM-e scattering in the SK



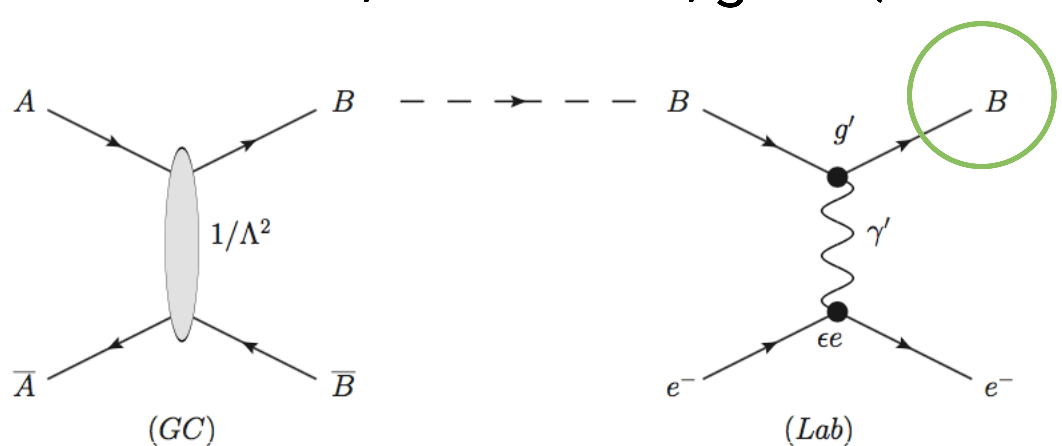
- Very forward elastic scattering - good angular pointing even at low energy
- e-like single ring, no hadrons -> no decay e, no neutron tagging
- background = atm ν elastic scattering, atm ν CCQE, IBD, …
- cut & count analysis for various cone-half angle to cover wide range of potential signal
- background modeled by off-source data (except high-energy where not enough statistics)
- Only SK-IV data used (previous data has no neutron trigger)



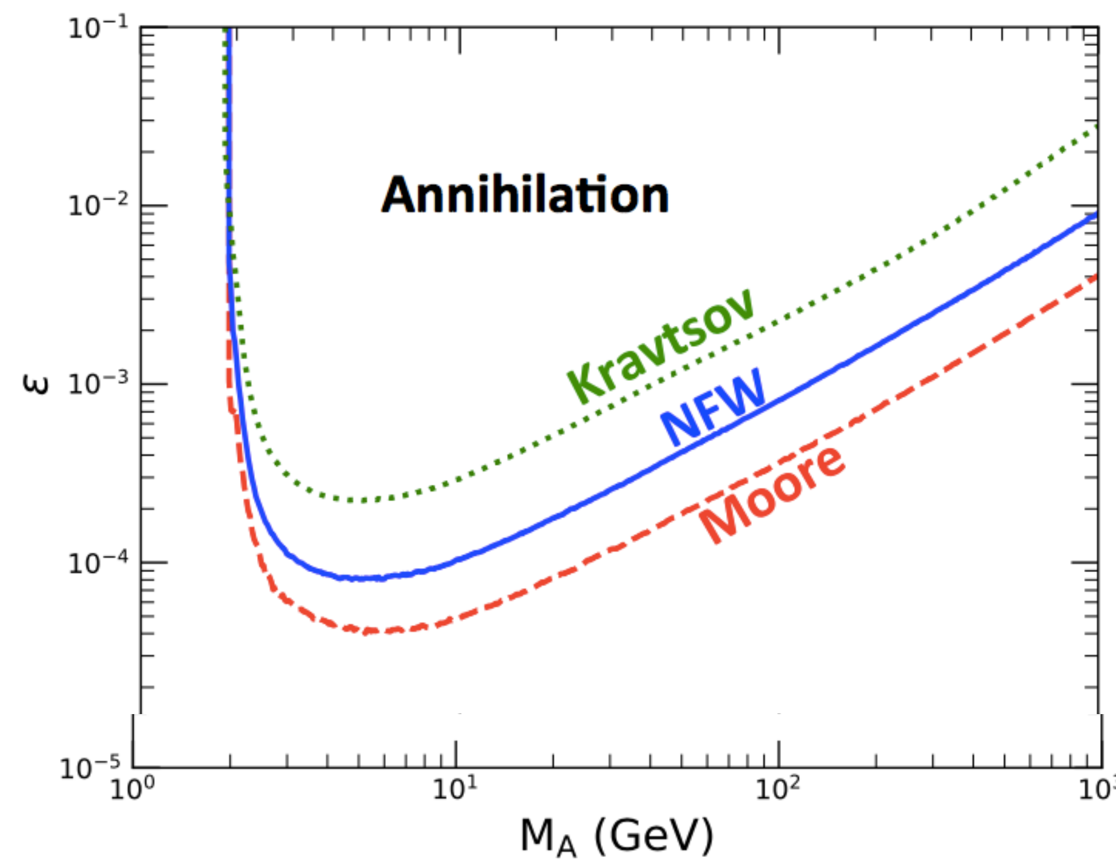
Search Cone	100 MeV< E_{vis} < 1.33 GeV Expected Bckg	Data	Sig Rate Limit $(\text{kT-y})^{-1}$	1.33 GeV < E_{vis} < 20 GeV Expected Bckg	Data	Sig Rate Limit $(\text{kT-y})^{-1}$	E_{vis} > 20 GeV Expected Bckg	Data	Sig Rate Limit $(\text{kT-y})^{-1}$
GC 5°	8.4 ± 0.7	5	0.017	1.6 ± 0.3	1	0.018	0.016 ± 0.005	0	0.015
GC 10°	32.0 ± 1.9	24	0.023	6.3 ± 0.84	5	0.026	0.060 ± 0.018	0	0.015
GC 15°	72.5 ± 3.5	69	0.078	13.6 ± 1.6	11	0.032	0.14 ± 0.04	0	0.014
GC 20°	126.5 ± 5.4	125	0.123	23.3 ± 2.3	18	0.028	0.25 ± 0.07	0	0.014
GC 25°	196.8 ± 7.6	202	0.201	35.4 ± 3.3	31	0.049	0.37 ± 0.11	0	0.013
GC 30°	283.7 ± 10.1	285	0.214	49.3 ± 4.3	48	0.081	0.53 ± 0.16	0	0.012
GC 35°	384.8 ± 12.8	375	0.187	68.1 ± 5.4	67	0.101	0.70 ± 0.21	0	0.011
GC 40°	499.6 ± 15.9	494	0.249	90.2 ± 6.9	90	0.124	0.90 ± 0.27	0	0.011
Sun 5°	7.59 ± 0.18	5	0.017	1.25 ± 0.07	1	0.020	0.015 ± 0.004	0	0.015

- The analysis was done in a model-independent way for any electron-scattering signal coming from the GC & the Sun

- One example constraint for dark photon interaction given for boosted dark matter B produced by annihilation in the GC (for m_B=200 MeV, $m_{\gamma'}$=20 MeV, g'=0.5)

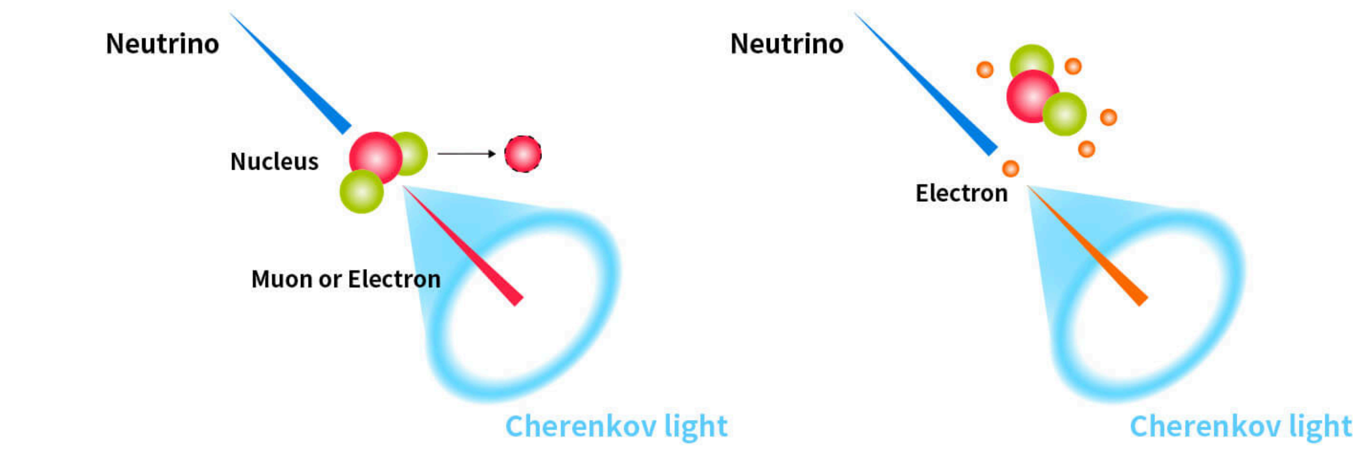


2628.1 days of SK-IV data



C. Kachulis for the Super-Kamiokande, Phys.Rev.Lett. 120 (2018) no.22, 221301

Detecting dark matter in the SK



The generated charged particles emit Cherenkov light.

Indirect search for dark matter from the Galactic Center and halo with the Super-Kamiokande detector (2020)

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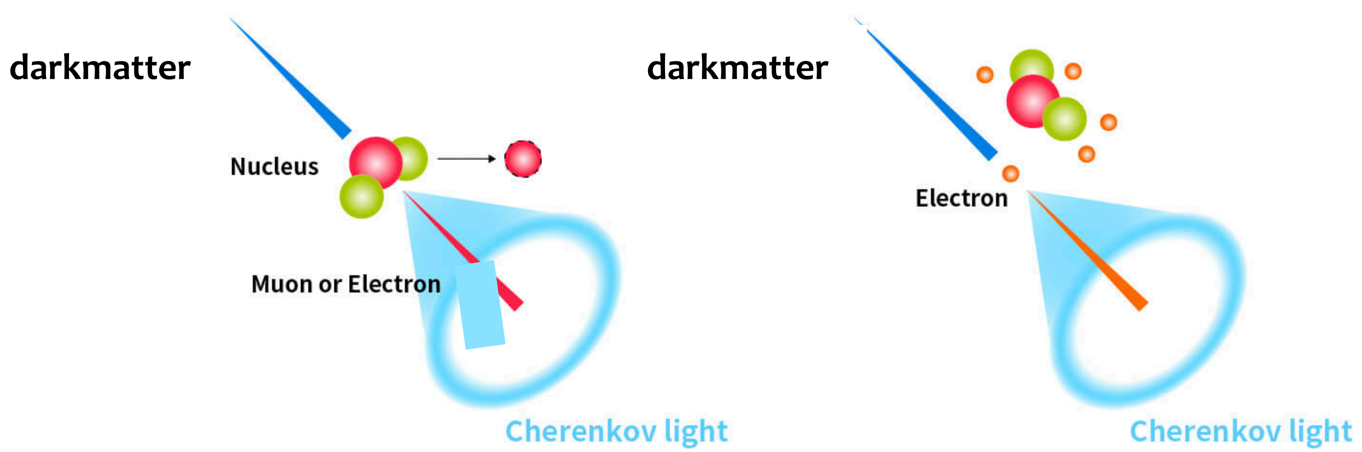

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Search for Boosted Dark Matter Interacting With Electrons in Super-Kamiokande (2018)

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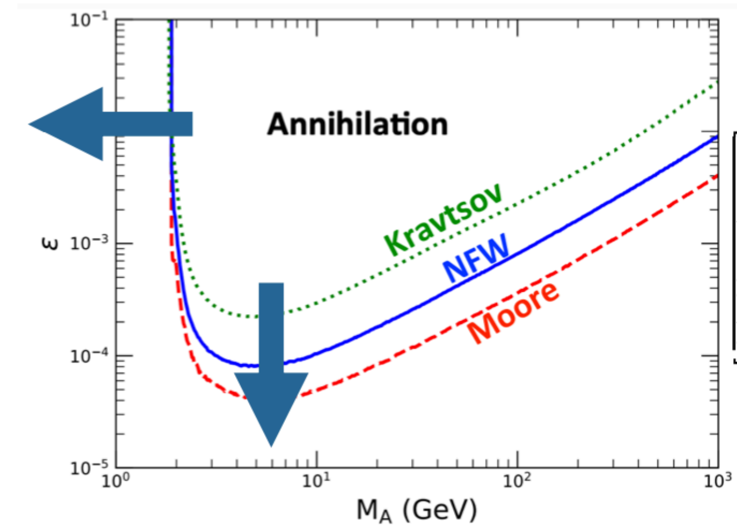
Two-Component Boosted DM Search Strategy

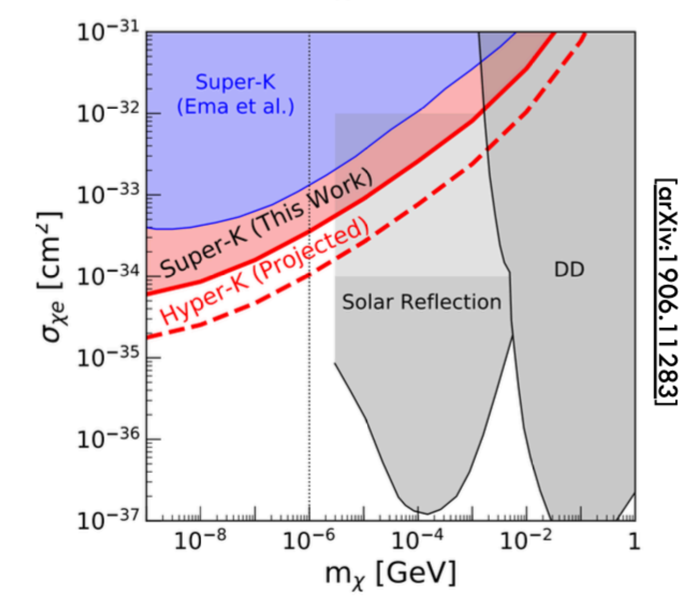
Goals

- **Improve sensitivity** of previous work with increased signal acceptance
- **Explore new parameter space** with respect to previous work
- **LE + HE unified analysis**
  - → Intermediate DM masses will deposit signal in LE and HE samples
  - → No good motivation to cut at a specific energy

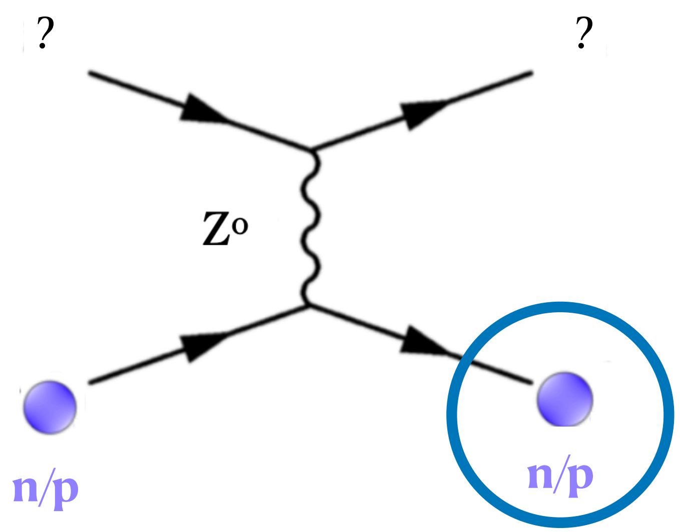


Benefits

- Provide **consistent treatment of LE and HE data**
- Production of **atmospheric MC consistent through LE and HE**
  → See Alberto's work
- Consistent use of the fitters: **Apfit** and **Lowfit** (Bonsai)

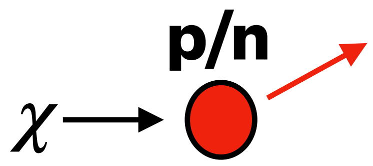


Proton identification



Not a primary interest in the neutrino analyses

but in case of unknown neutral particle…



Proton identification

FIG. 1: Event displays of a Monte-Carlo NC elastic event, with proton momentum of 1490 MeV/c (left), and a Monte-Carlo 300 MeV/c muon. The proton stopped early, causing a thin ring pattern on the wall. The muon ring is thicker than most proton rings with similar opening angles.

Super-Kamiokande-I	Data	Total MC NEUT	Signal MC NEUT
FC, FV, single-ring, spallation removed	8946 (100%)	8138.1(100%)	45.1 (100%)
Sparse ring removal cut	8509 (95.1%)	7729.7 (95.0%)	31.7 (70.4%)
$E_{vis} < 200$ MeV	2101 (23.5%)	1894.2 (23.3%)	29.7 (65.9%)
Cone opening angle $< 37°$	1161 (13.0%)	1020.0 (12.5%)	28.9 (64.2%)
Pattern ID estimator cut	74 (0.83%)	68.8 (0.85%)	25.6 (56.8%)

Phys.Rev.D 79 (2009) 112010, axriv:0901.1645

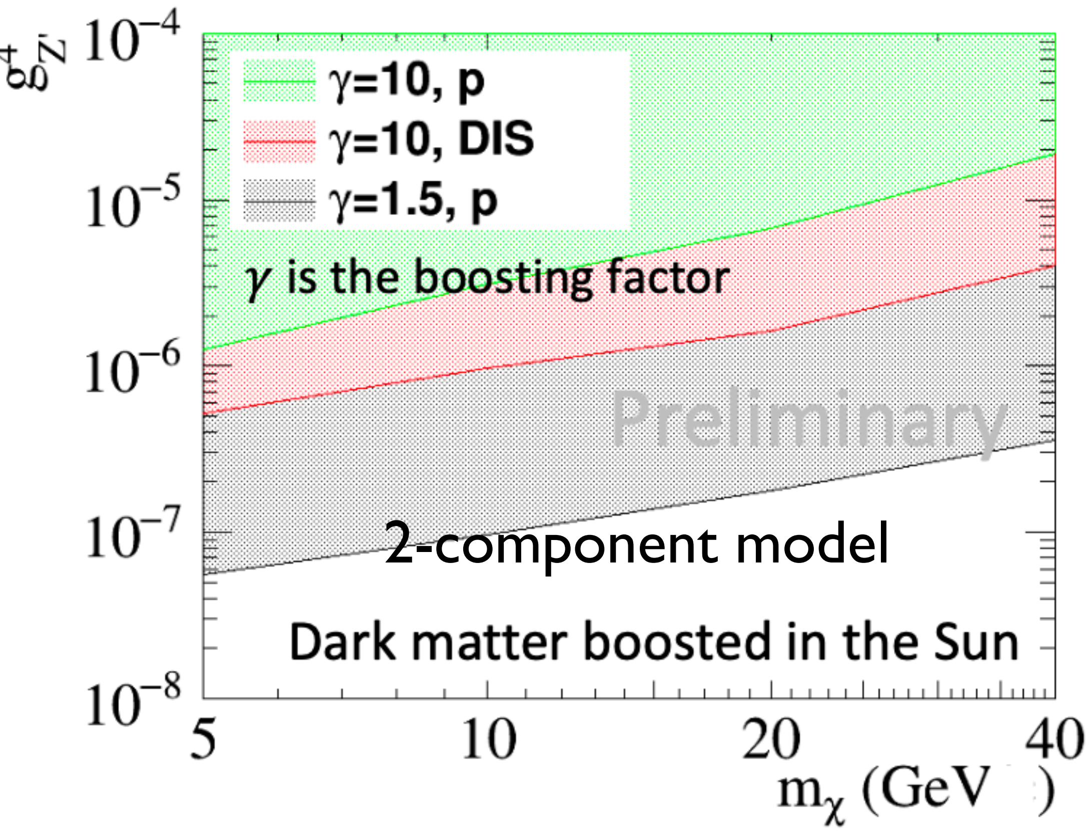
DM-p (free proton) Elastic scattering

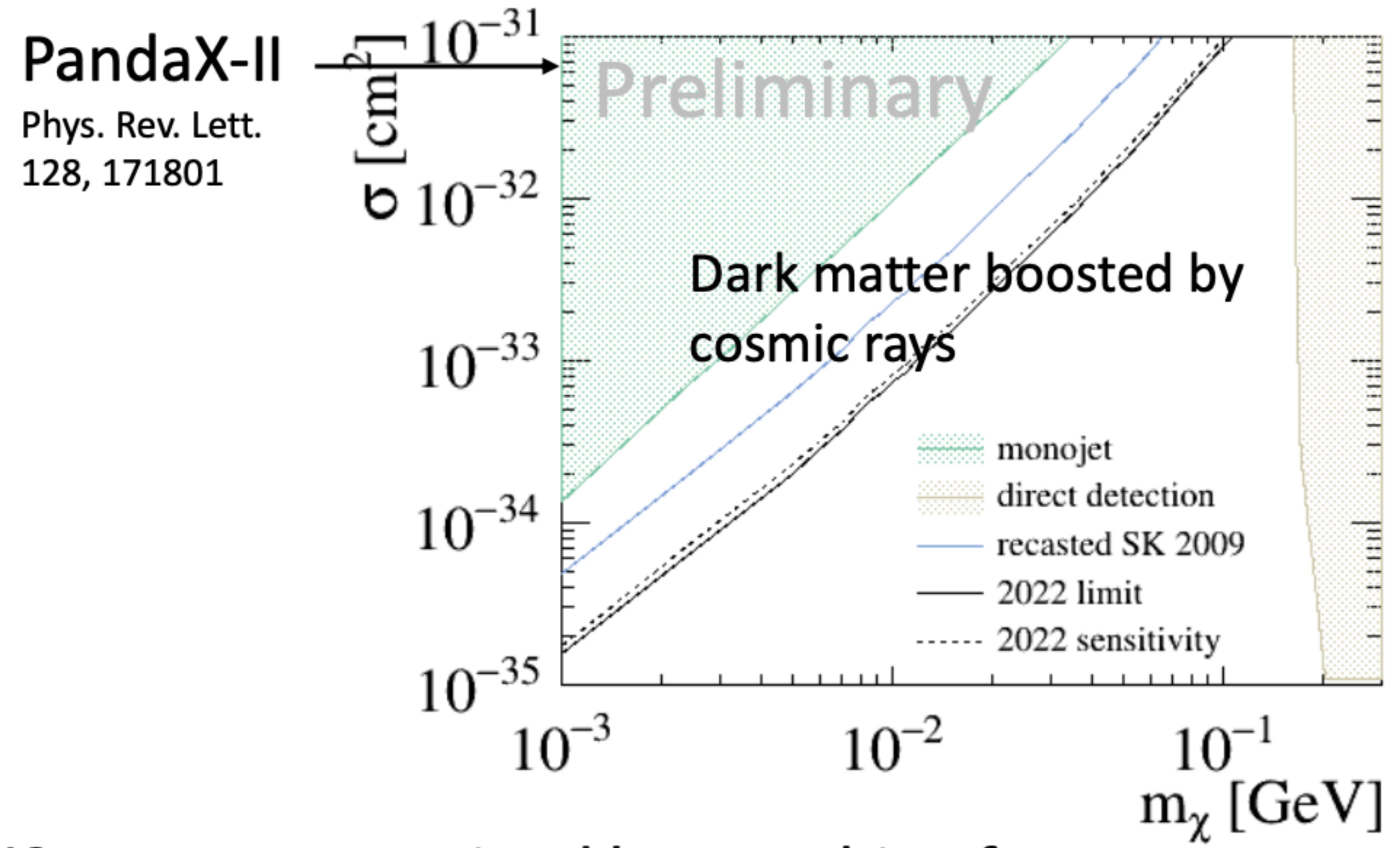
- Proton recoil Cherenkov threshold ~ 1.07 GeV narrows down the signal region & reconstruction of proton track is challenging
- Pattern fitting based reconstruction,
- a multi-variate analysis (MVA) to select protons over low energy muons
- Feasible for proton momentum 1.2 GeV < p < 2.3 GeV. Above, protons tent to make extra rings

DM-p (free proton) DIS

- Sensitive to higher dark matter mass / boosting parameters
- E > 1.33 GeV, n_ring > 1
- Better angular resolution
- BG: CC DIS from atm ν

Constraints on Boosted Dark Matter Models





Constrained by searching for proton and DIS sample excess in the direction of the Sun.

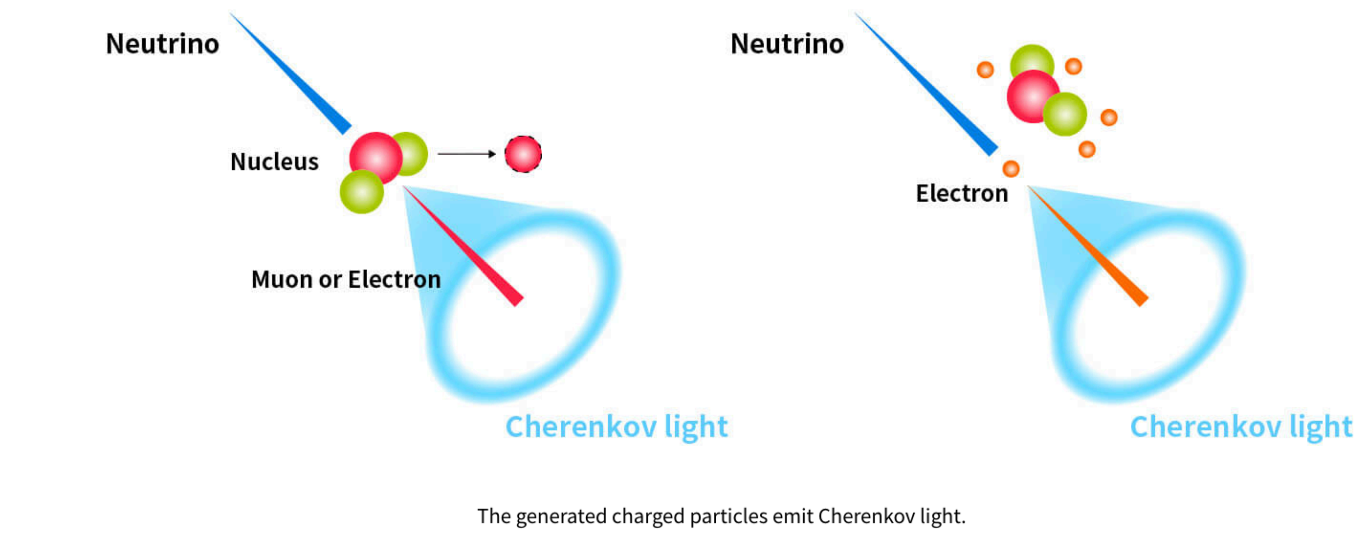
Scalar DM, mediator $m_{Z'} = 1$ GeV
Flux from Phys. Rev. D 103, 095012 (2021)
Cross-section by GENIE r3.00.06, Berger et al.

Constrained by searching for proton excess in the direction of the galactic center.

Fermionic DM, scalar mediator $m = 1$ GeV
Flux & cross-section from Ema et al., SciPost Phys. 10, 072 (2021)

- Best upper limit on boosted dark matter coupling with hadron
- Probing relic mass above direct detection experiment mass region

Detecting dark matter in the SK



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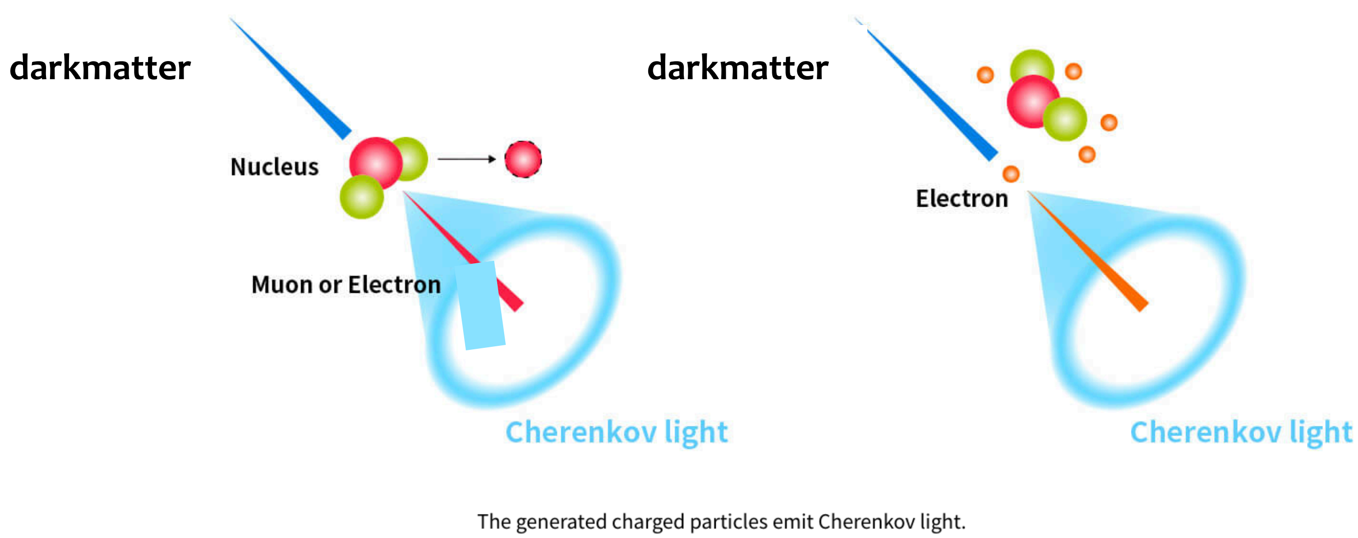

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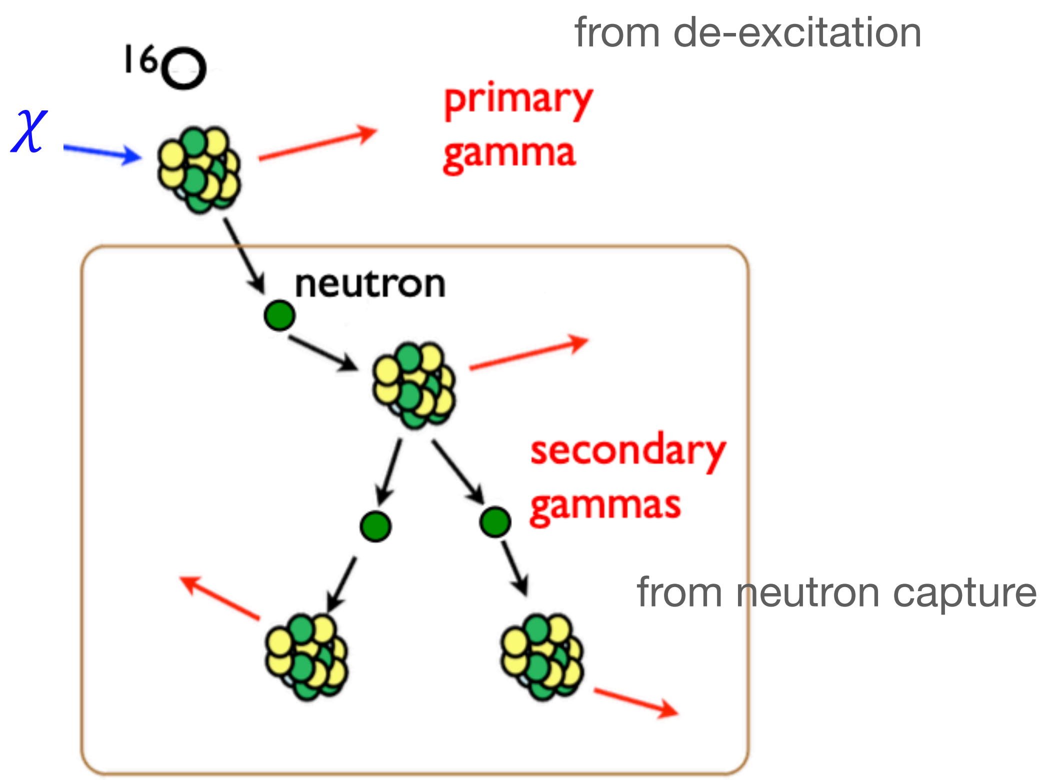
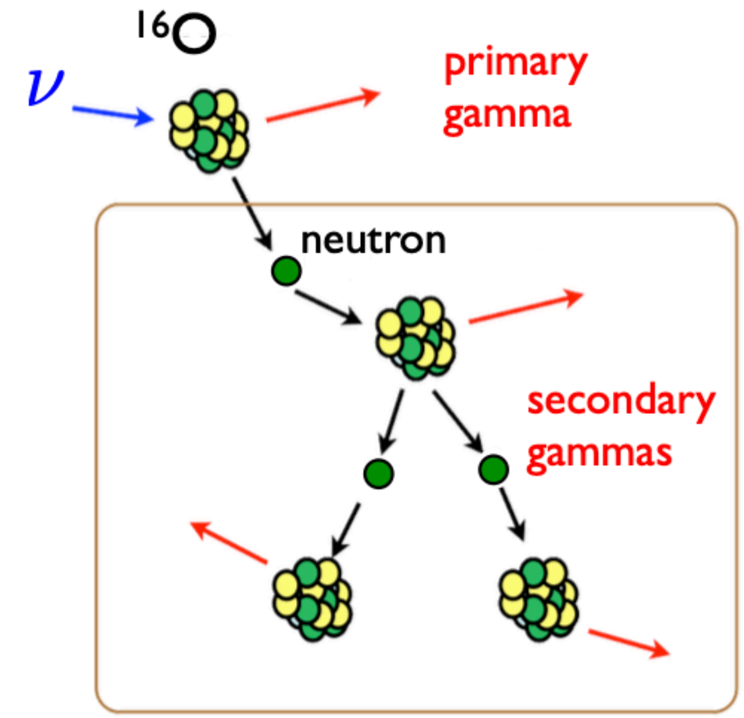
Search for de-excitation gammas and neutrons produced in DM-O interactions (on-going analysis)

DM-O scattering in SK - neutron + de-excitation gamma



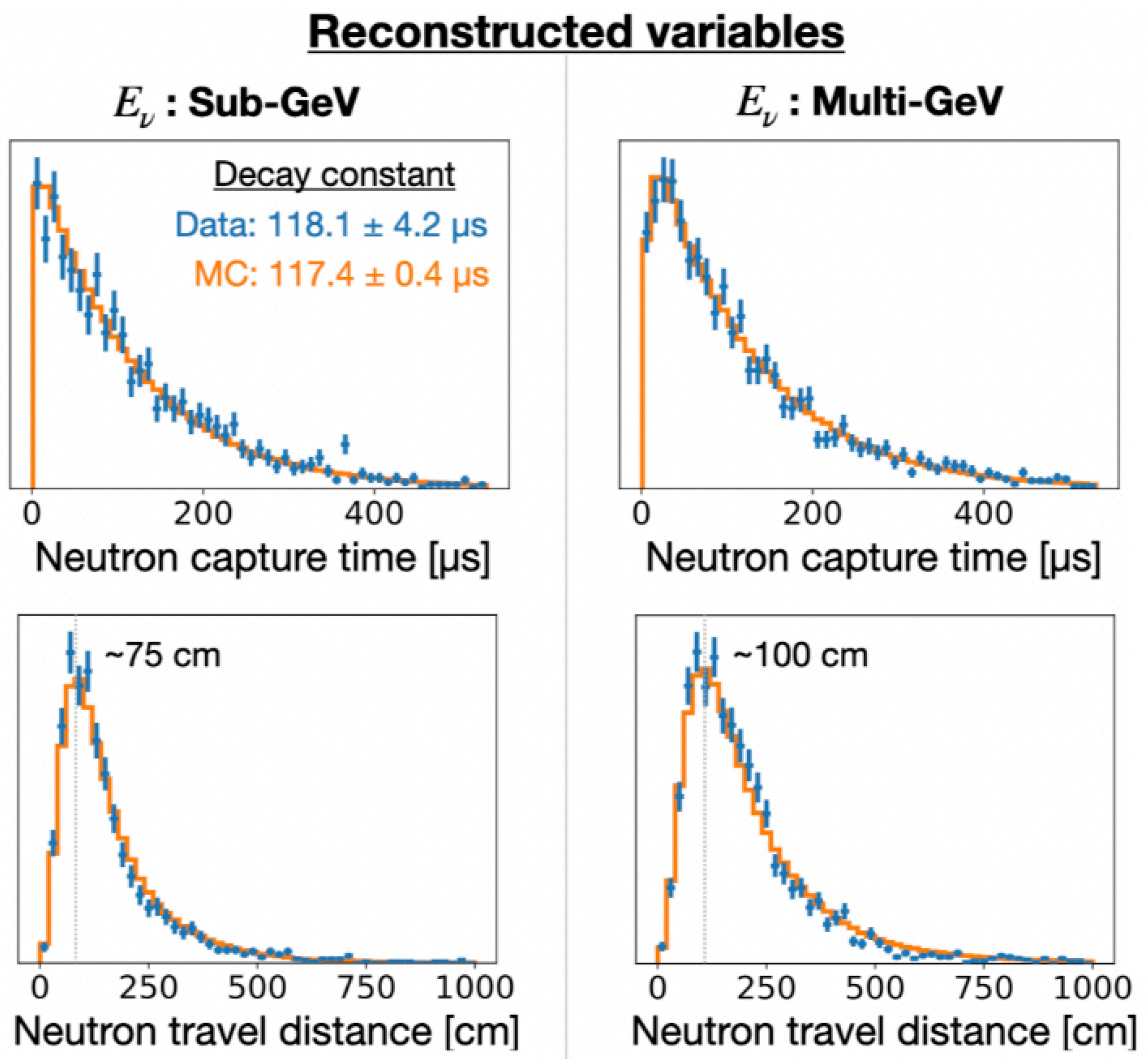


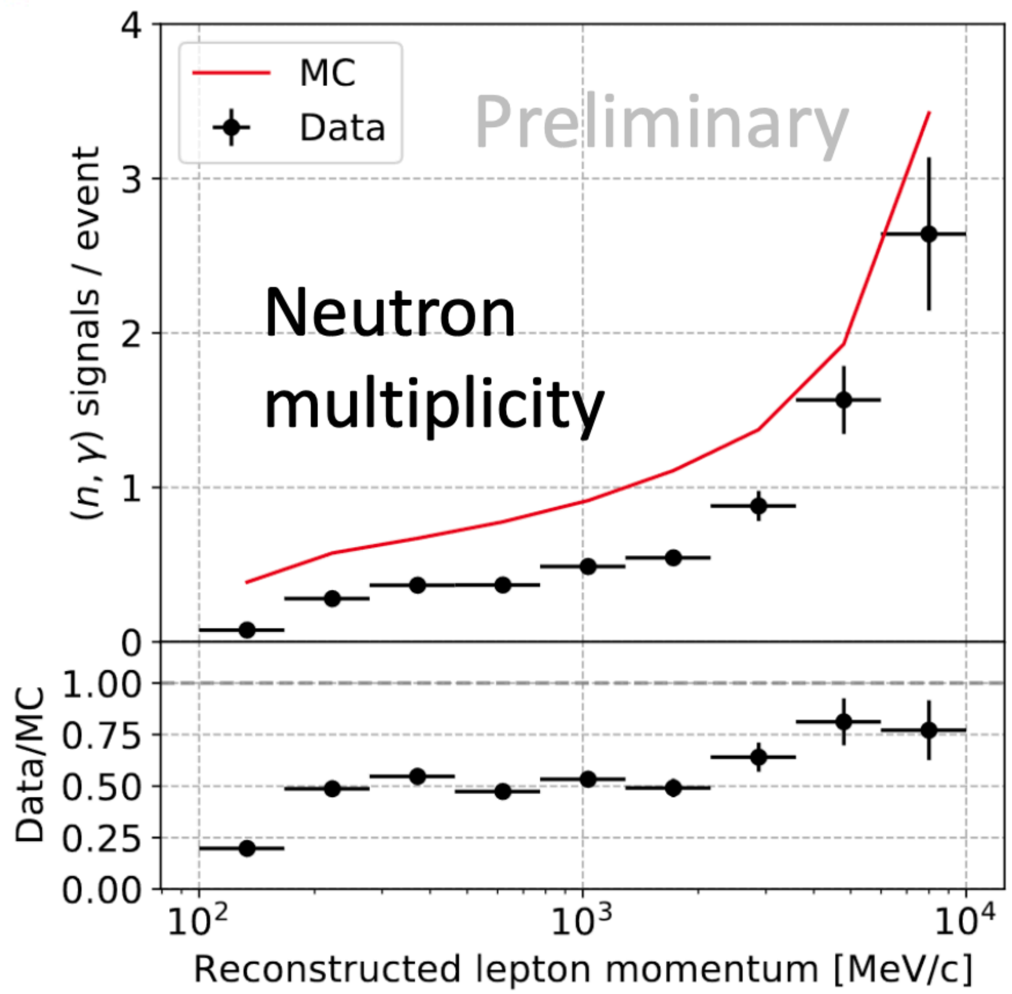
ν-O collision emitting n or p

Neutral Current Quasi-Elastic (NCQE) interaction by atmospheric neutrinos can mimic IBD signal: dominant background for DSNB search

ν energy: ~GeV

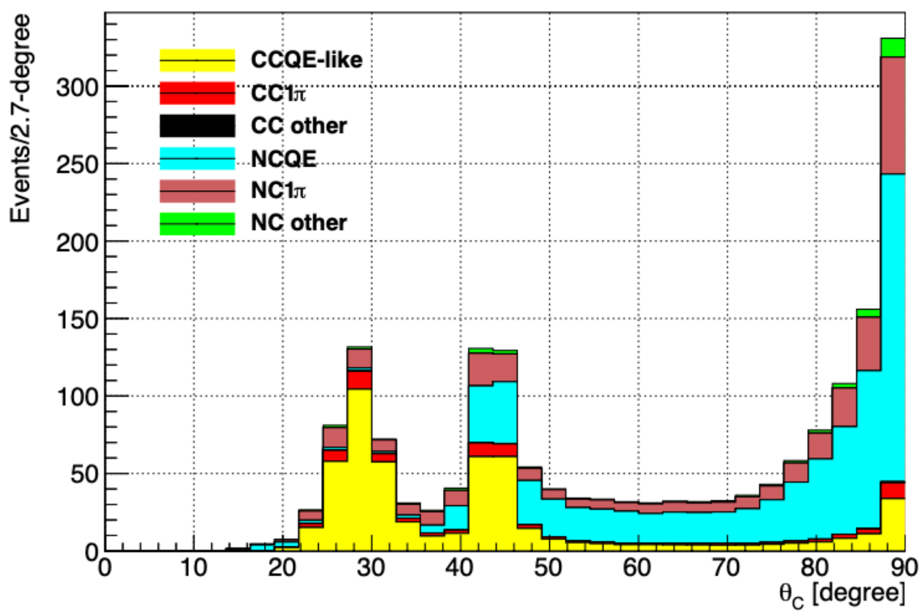
γ energy: ~O(10) MeV

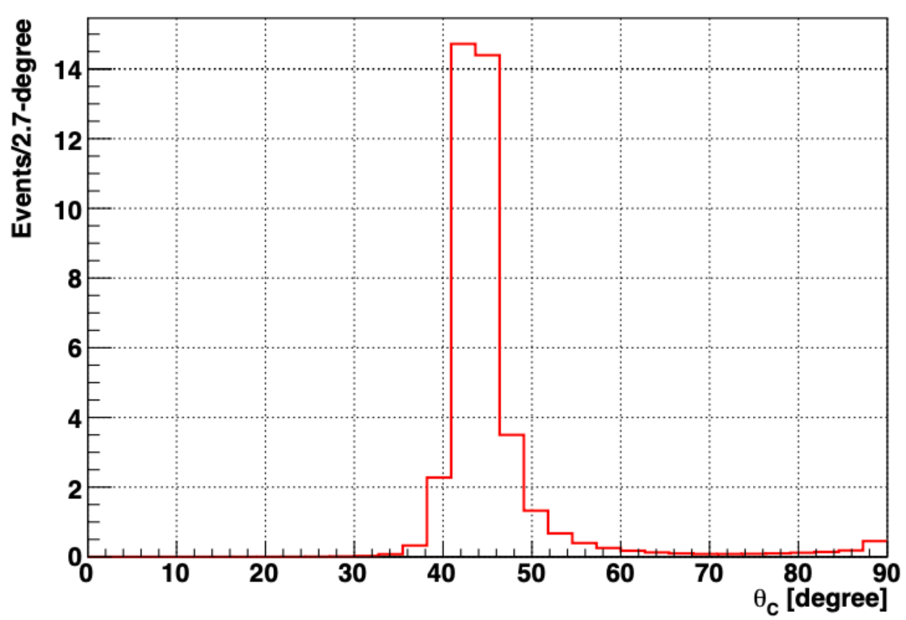

Reconstructed variables
E_ν : Sub-GeV
E_ν : Multi-GeV
Decay constant
Data: 118.1 ± 4.2 μs
MC: 117.4 ± 0.4 μs
0
200
400
Neutron capture time [μs]
~75 cm
~100 cm
0
250
500
750
1000
Neutron travel distance [cm]


MC
Data
Preliminary
Neutron
multiplicity
(n,γ) signals / event
Data/MC
Reconstructed lepton momentum [MeV/c]

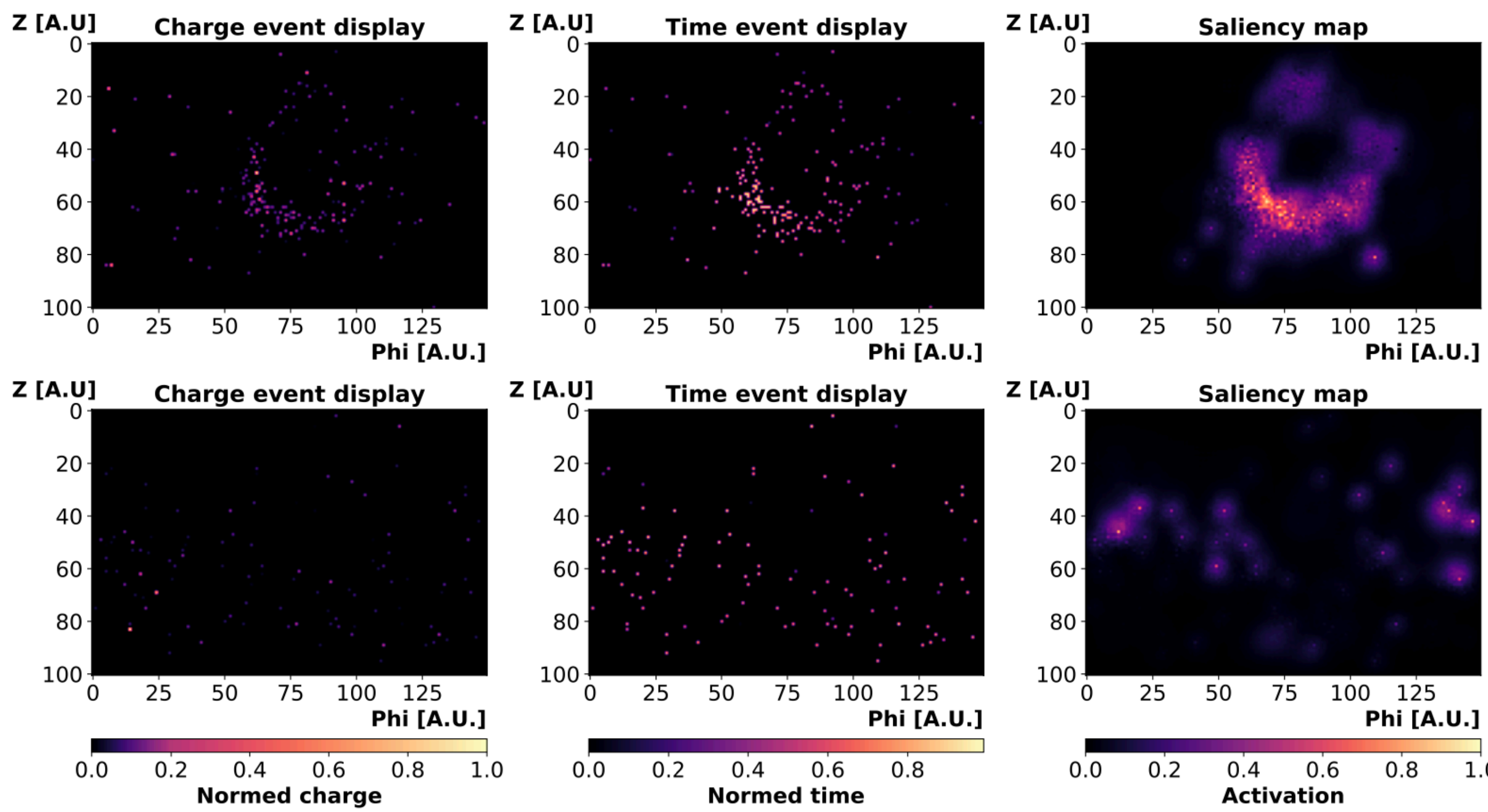
Cherenkov angular cut works well to distinguish atm NCQE vs DSNB IBD events

Excellent performance of CNN using directly the topology of the hit patterns recorded by the PMTs





atm ν (top) and IBD ν (bottom) MC in [7.5, 29.5] MeV

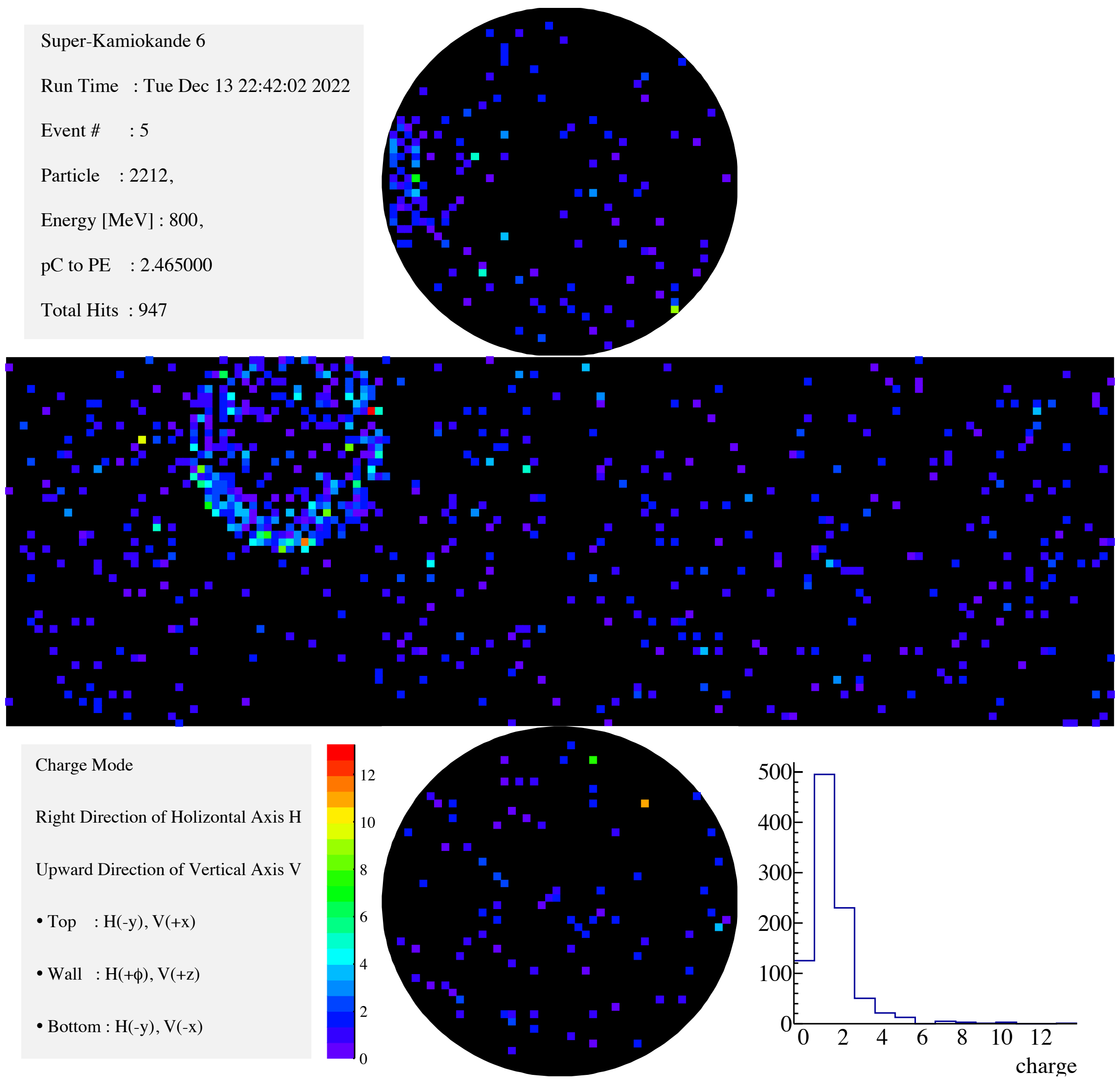


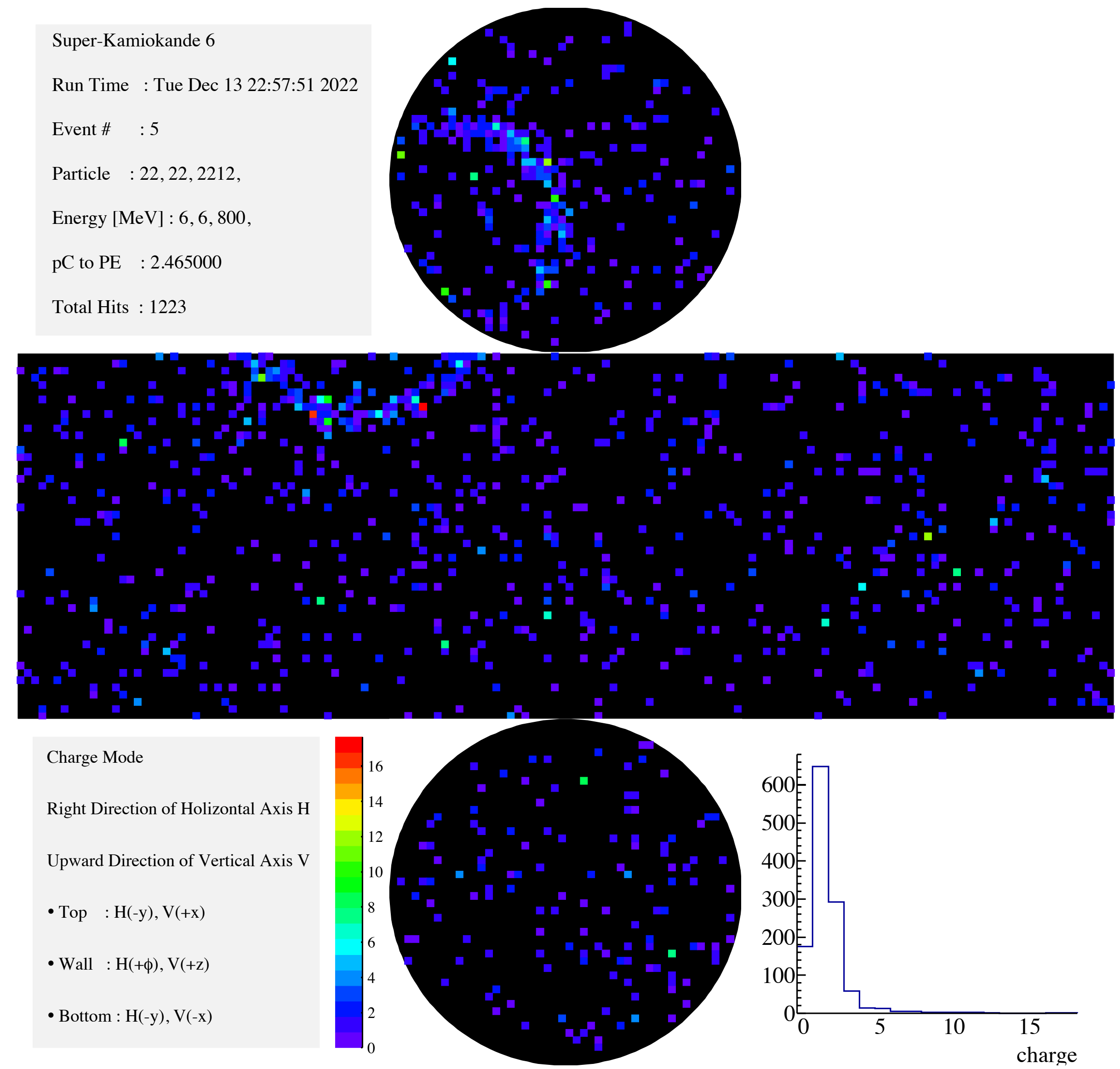
event hit maps prepared for classification by the CNN.
Upper panel: a DSNB event (22 MeV) with a single ring
Lower panel: a NCQE event (total energy of 19 MeV) with several weak rings

Super-Kamiokande collaboration, *Phys.Rev.D* 104 (2021) 12, 122002

D. Maksimović et al., 2104.13426

X-O scattering in SK - proton + de-excitation gamma





Gamma Tagging

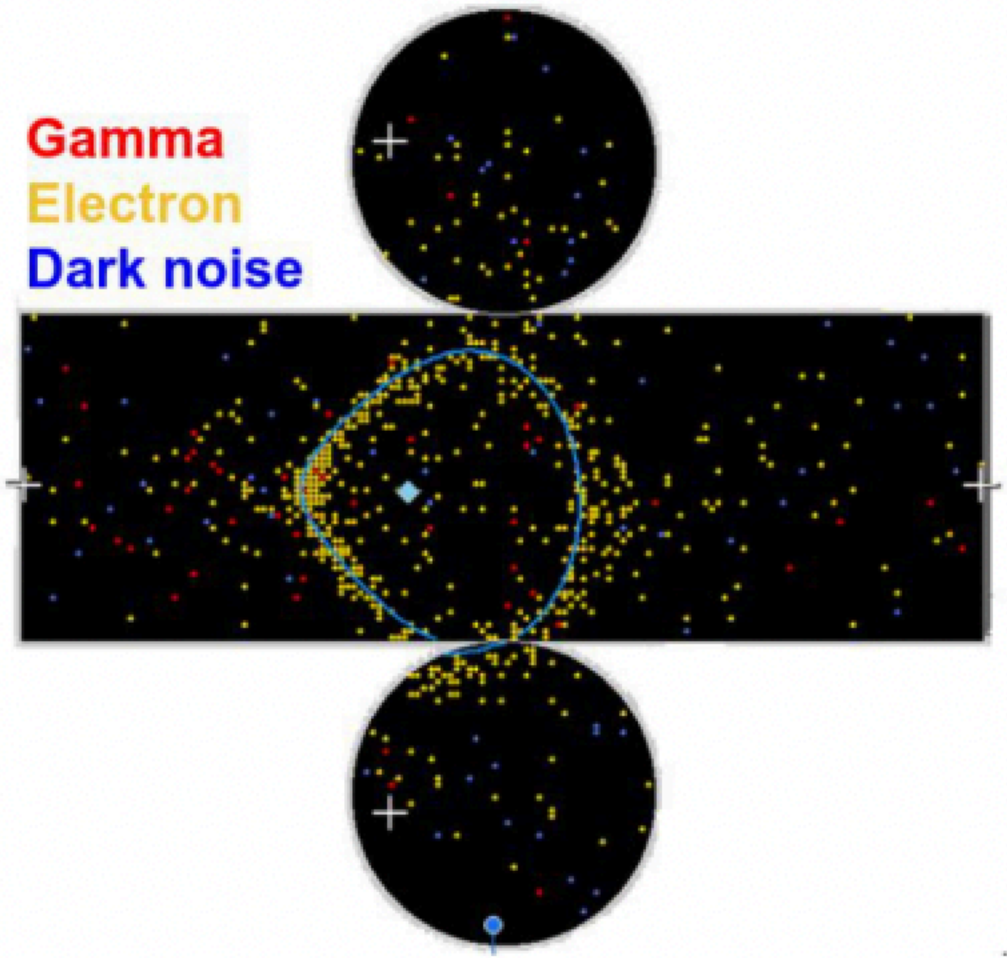
Can we identify hits due to gamma rays (red) alongside the hits due to main electron signal (orange)?

Use a multi-variable approach:

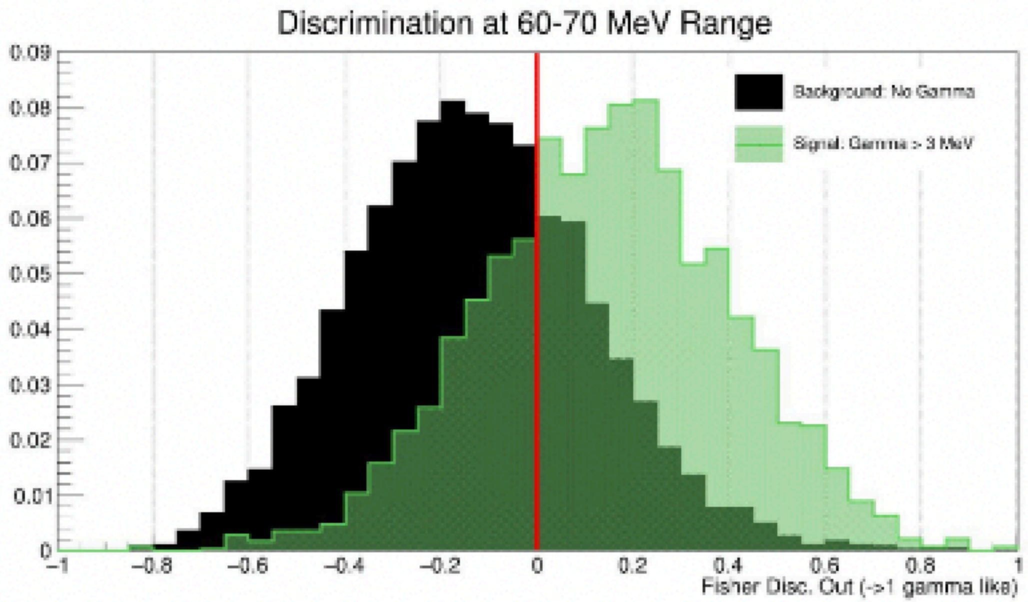
- # of hits outside the Cherenkov ring
- Isotropy of hits
- Timing and position distribution of hits

Combine variables with a Fisher Discriminant trained separately for each SK phase for 1 ring e-like events.

On the right: Discrimination for events with no gamma rays (black) and with gamma rays (green)



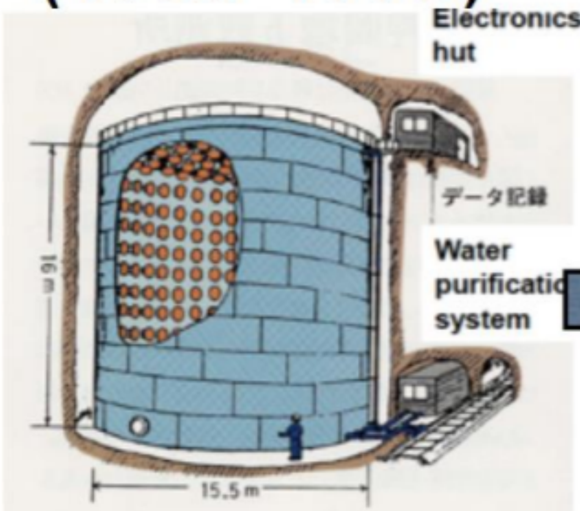
MC ν_e-^{16}O event: A 90 MeV electron accompanied by 3 gamma rays (total of 10 MeV) in SK



Barn Bodur @neutrino2022

3 Generations of Kamioka Detector

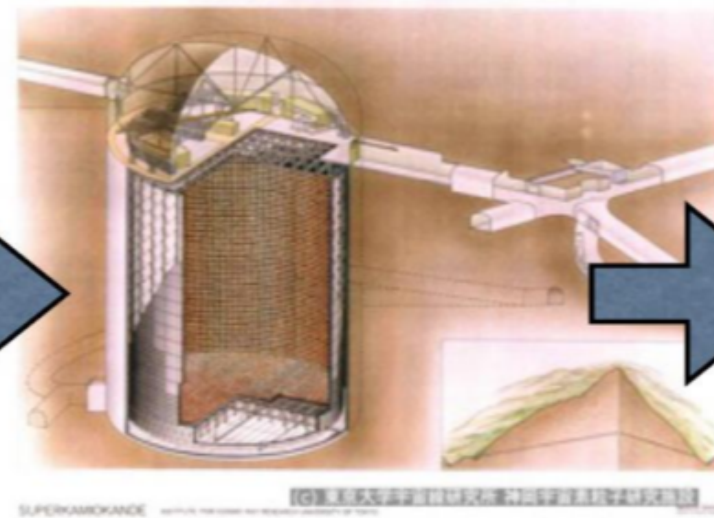
Kamiokande (1983-1996)



3kton

20% coverage with 50cm PMT

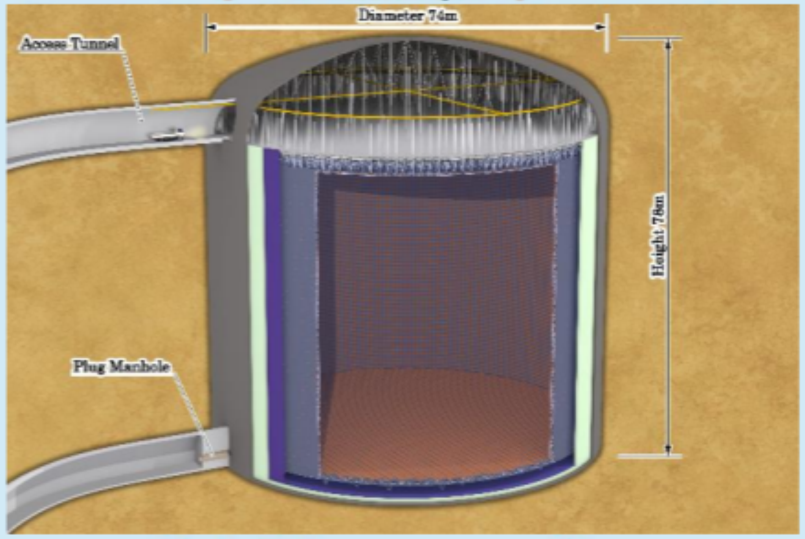
Super-Kamiokande (1996-)



50kton

40% coverage with 50cm PMT

Hyper-Kamiokande (~2026-)



260kton×2

40% coverage with high-QE 50cm PMT

x17

x10

(X17 fiducial mass)

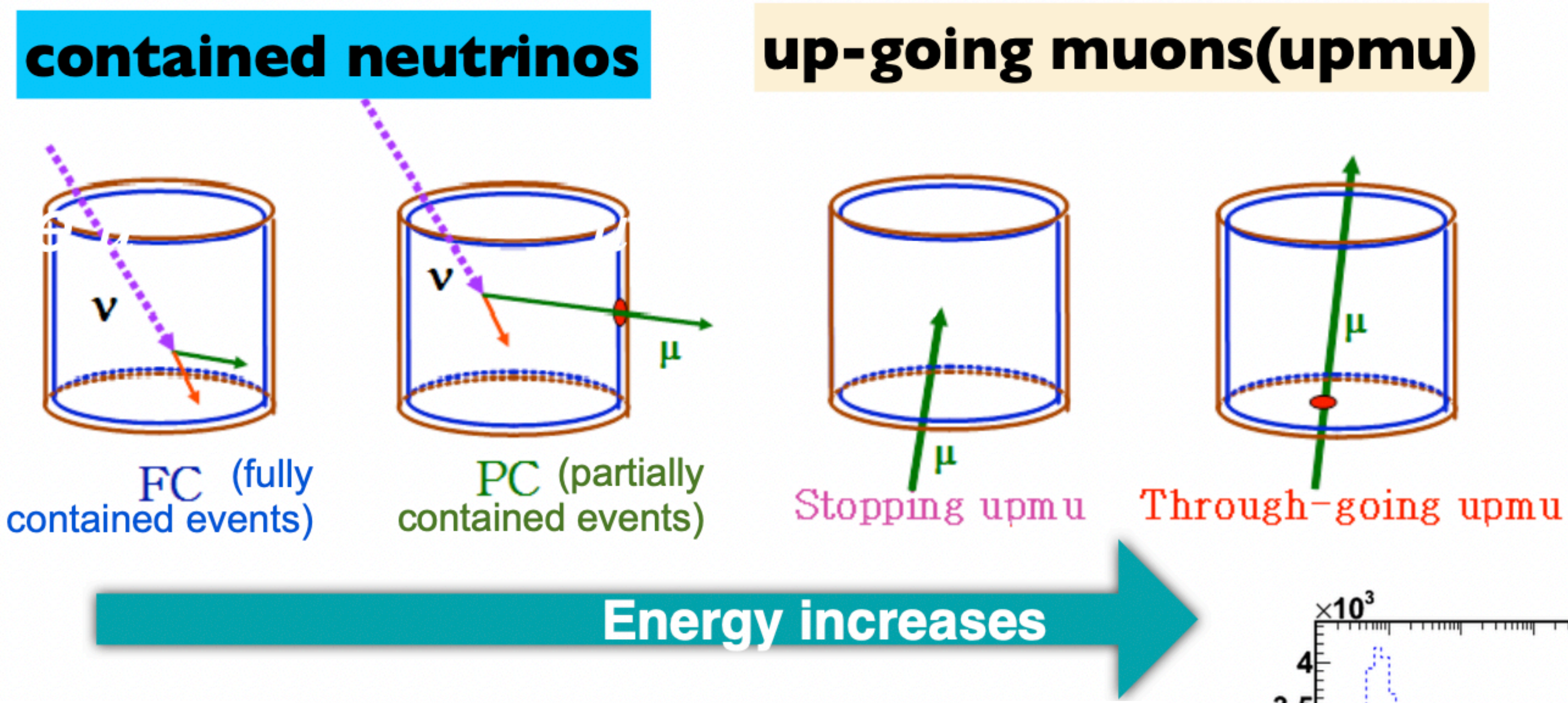
Conclusion

- SK has shown competitive sensitivity to WIMP-like dark matter, setting limits on DM annihilation cross-section to neutrinos, SD/SI scattering cross section with nucleon, especially well at O(GeV) energy
- SK also has great potential for sub-GeV dark matter searches in both direct & indirect ways - complementarity between neutrino and dark matter experiments keeps go on
- First search for boosted dark matter from the Galactic Center and the Sun scattering off electron & free proton are done using the SK high energy sample, and more to come in the low-energy data
- After 25 years since the beginning, SK has renovated once again to stay at the forefront of ν physics: SK-Gd - which is also exciting news for new-physics searches
- 27-years of high-quality data waiting for your new ideas!

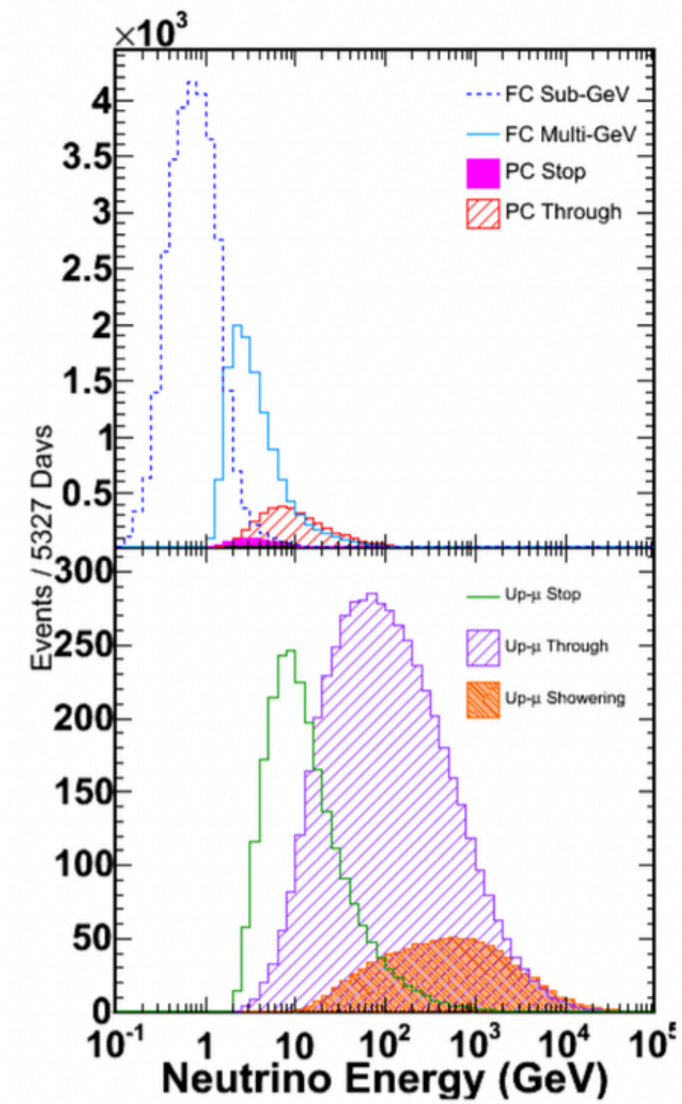
Thank you for listening!

Back Up

Events categories



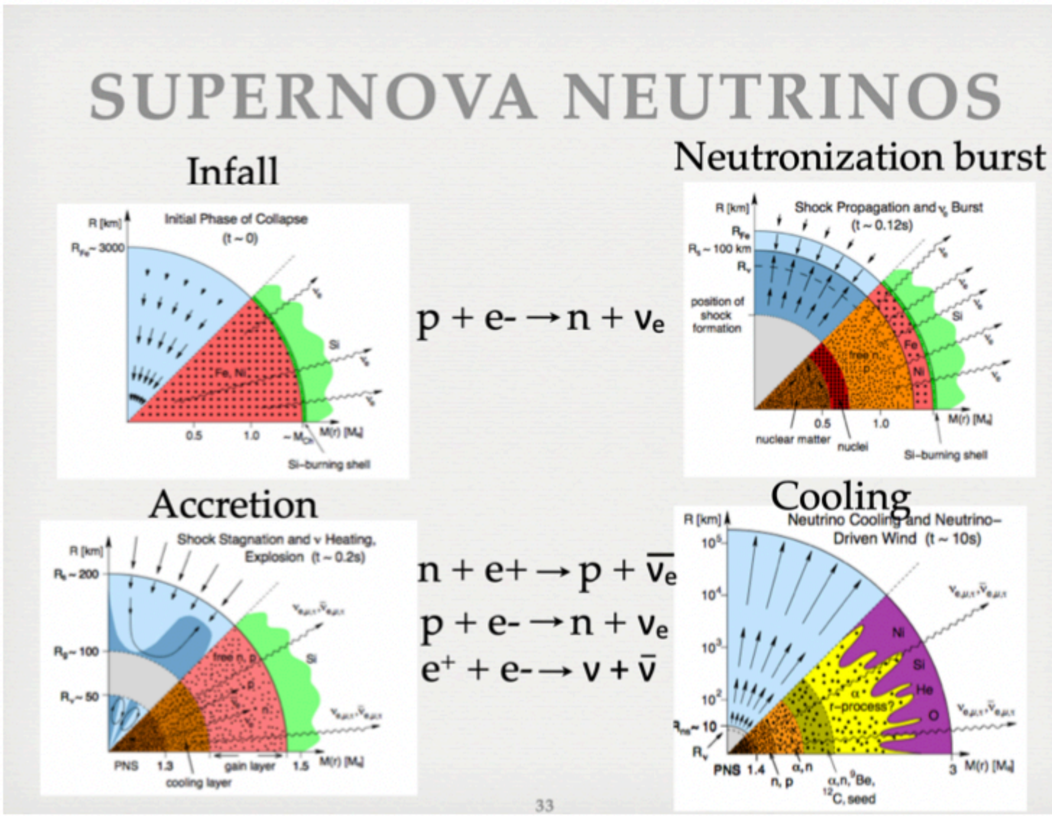
FC events: Tracks of entire particles are contained inside the Inner detector(ID).
PC events: One of the particles exits the ID and deposits energy to the outer detector(OD)
Upmu Stopping : Enters from outside the detector and stops inside the ID
Upmu Through going : Enters the detector and exits the ID



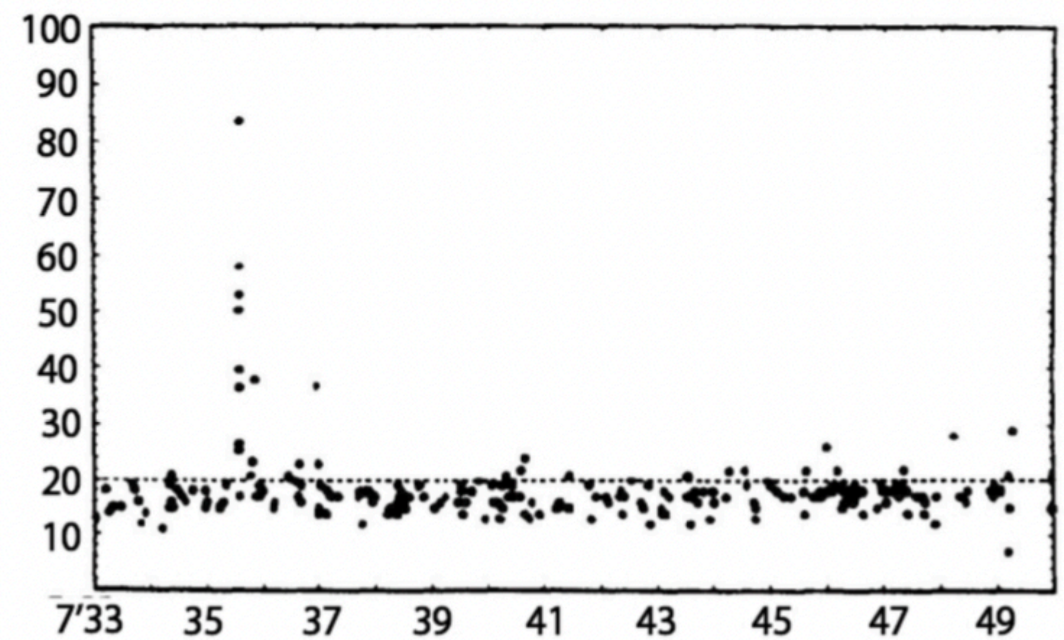
・LE (low energy) data: >3.5 MeV (used for solar & supernova neutrino analyses)

・HE data: >100 MeV (used for atmospheric & beam neutrino analysis, proton decay, DM & other BSM searches)

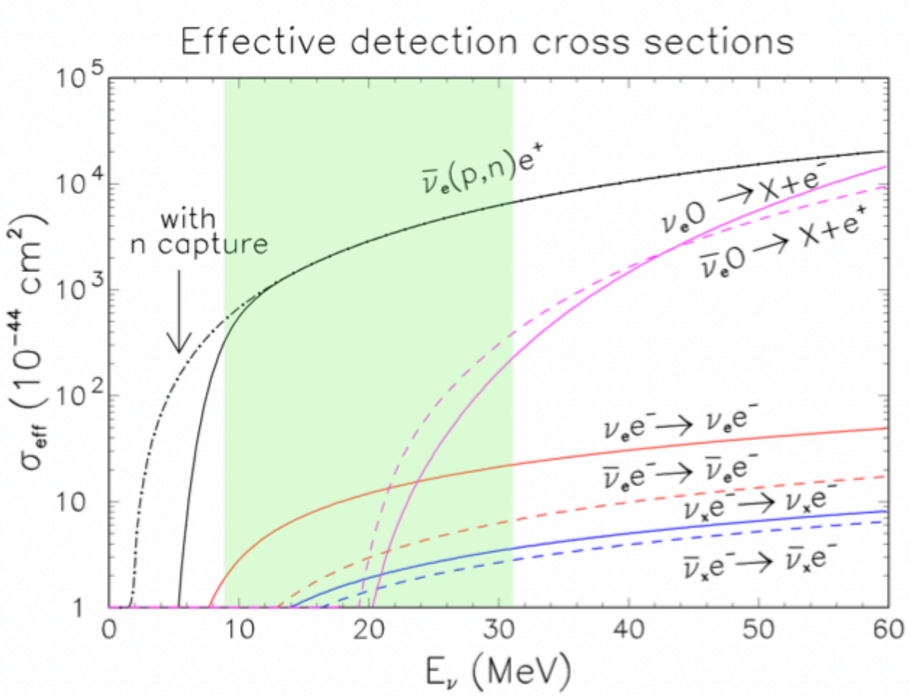
SK astrophysical neutrino search (<100MeV)



slide by E. O'SULLIVAN



Neutrino events observed in Kamiokande from supernova SN 1987A.
The horizontal and the vertical axes show the time (minutes) and the number of PMTs which detected photons, respectively.



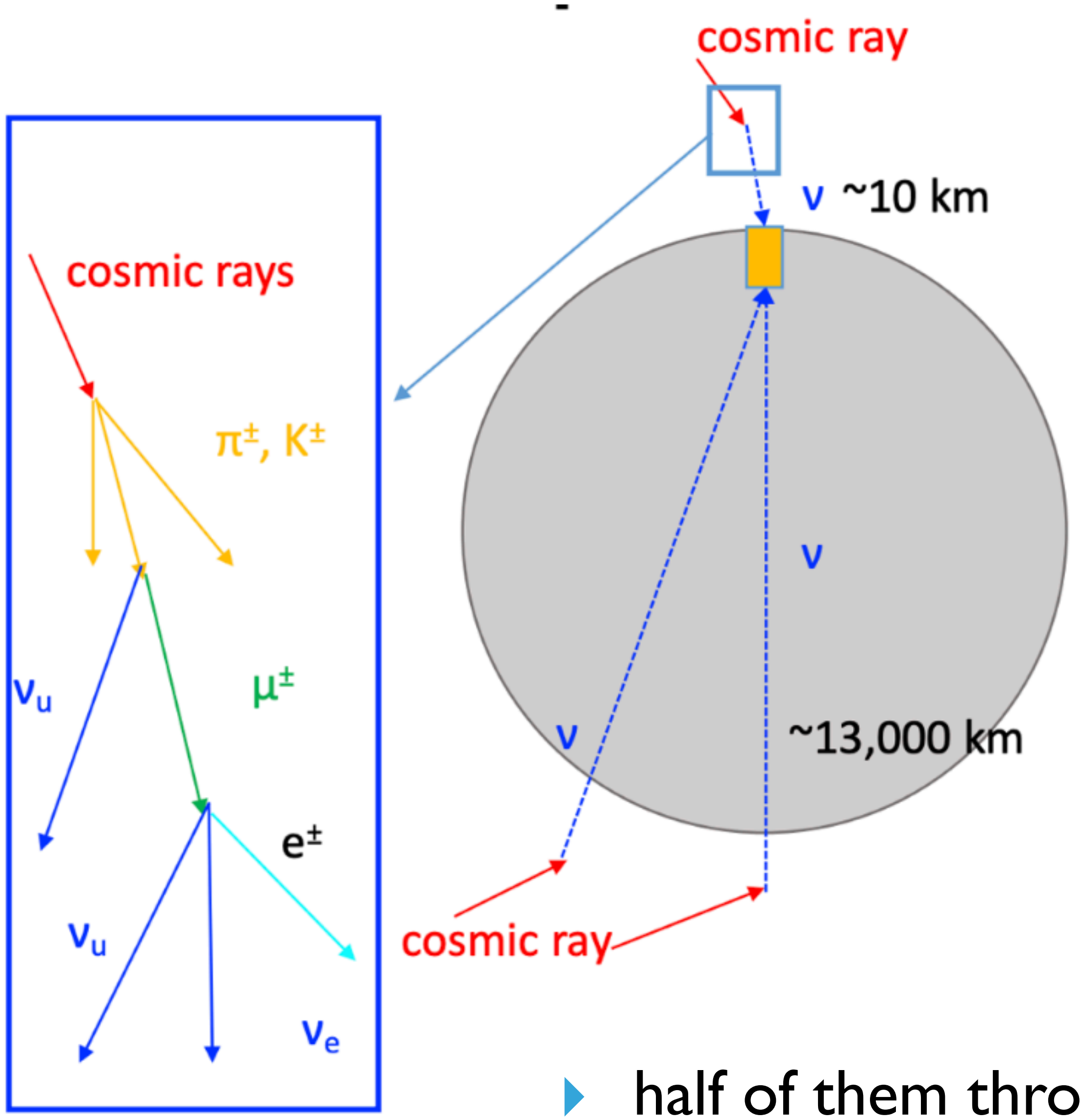
electron ✓

- if comparable anti-neutrino flux is predicted, IBD channel dominates the signal acceptance → most of the astrophysical searches are proceeded with IBD signal
  * caveat : no directional information

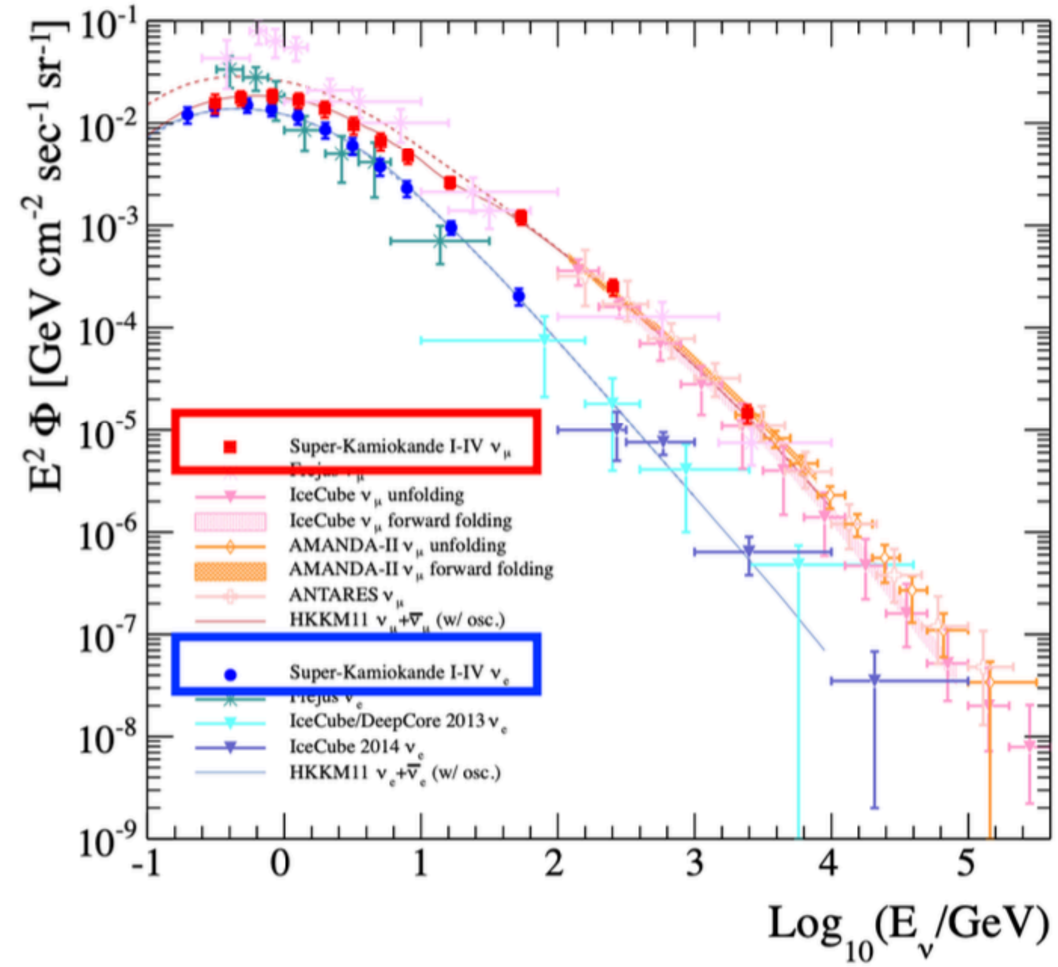
High energy ν (>100MeV) = atmospheric ν

Atmospheric (atm) neutrinos produced by cosmic rays come from all direction

-



arxiv:1510.08127



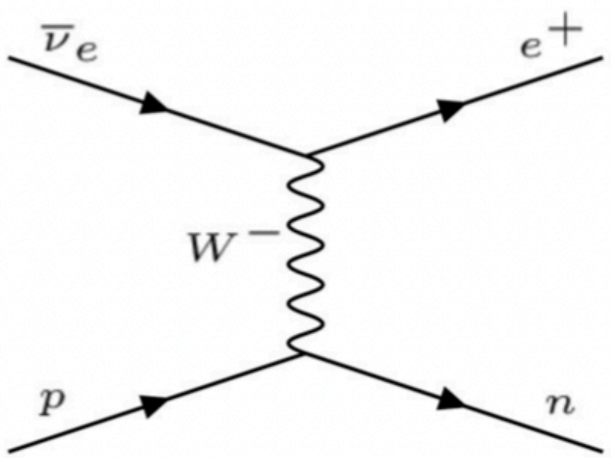
2:1 flavor ratio

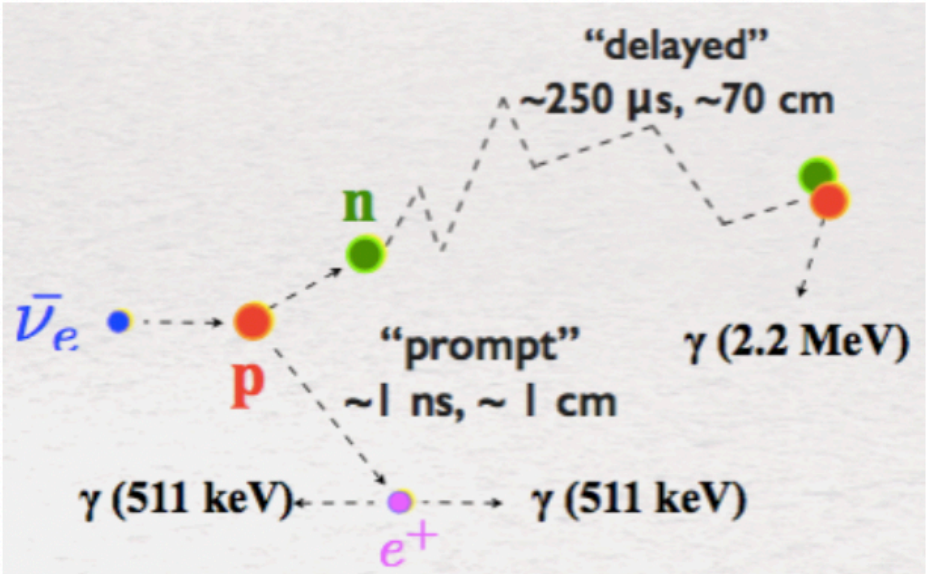
- half of them through the Earth

- ~10 events/day

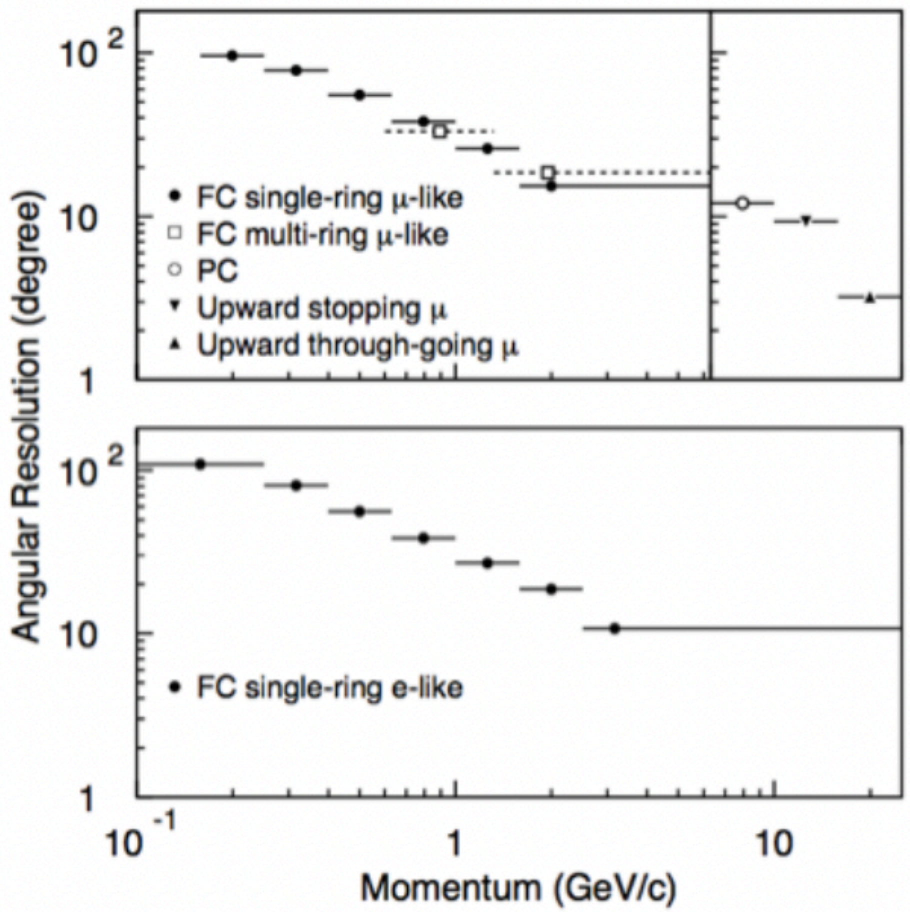
image by Z. Li

Inverse Beta Decay





- 1.8MeV energy threshold
- Coincidence search: spatial & timing correlation between prompt & delayed events
- electron anti-neutrino energy reconstruction:
  $E_{\bar{\nu}_e} = E_{\mathrm{prompt}} + 0.784\,\mathrm{MeV}$
- energy resolution = ~14% in SK at 10 MeV
  (c.f. ~1-2% in scintillator detectors)
- Angular correlation between neutrino and lepton:
  >60° at 100 MeV

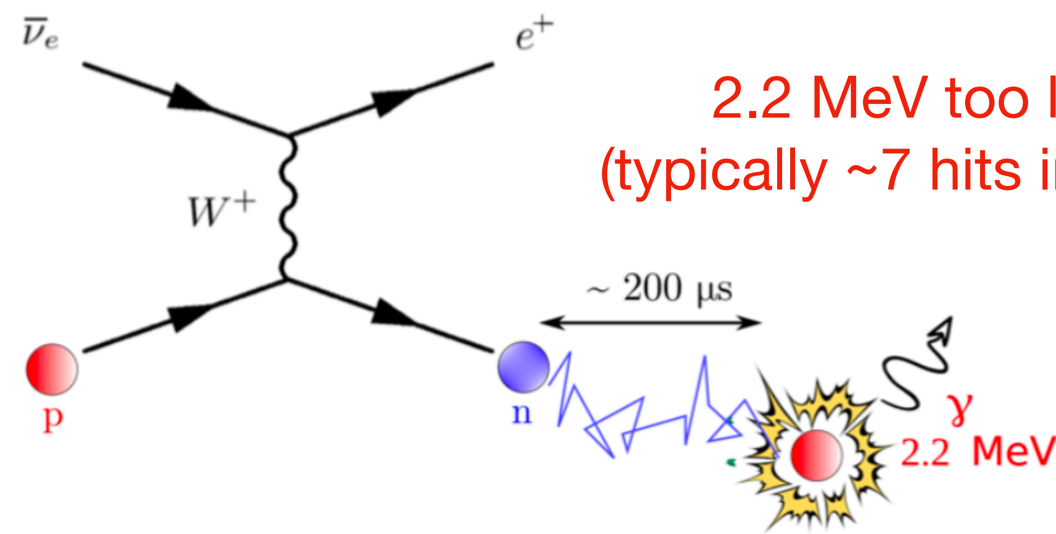


* note: ring direction resolution is < 3° for FC single ring events

* multi-ring events: vector sum of the reconstructed momentum of each Cherenkov ring

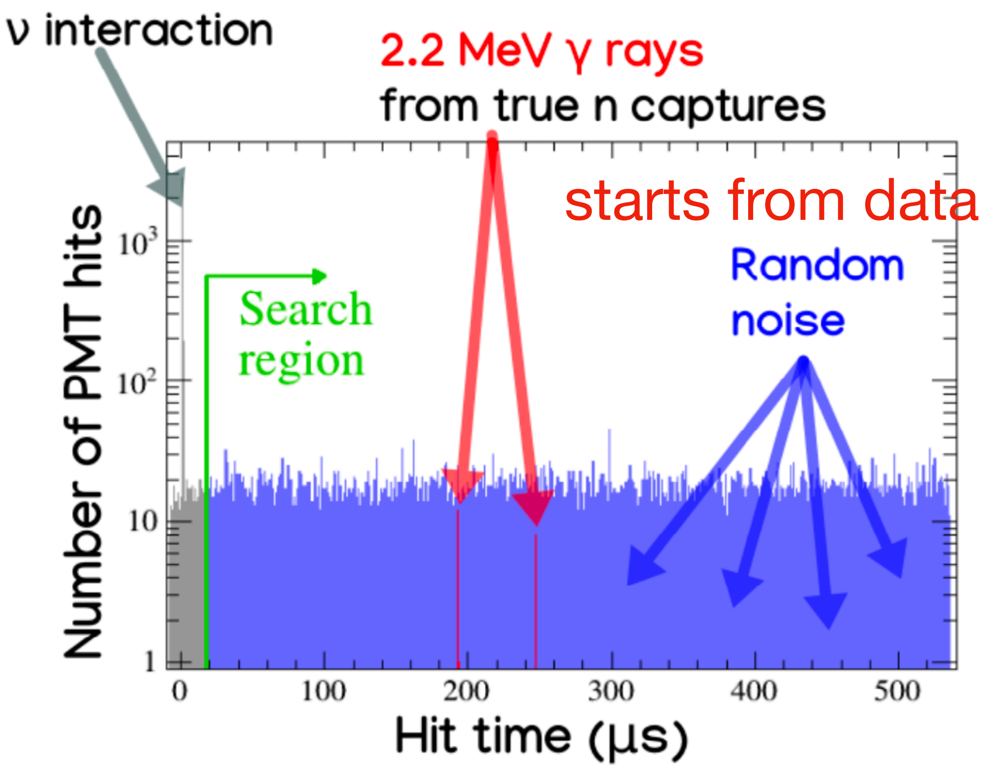
* Upmu scatters before entering the detector

Finding neutron in pure-water data…



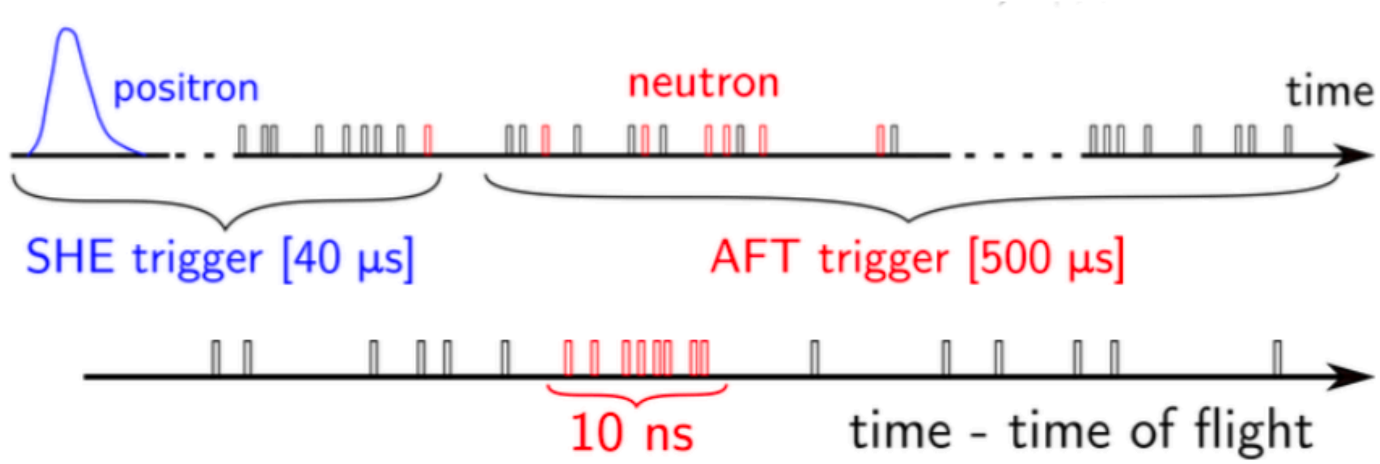
2.2 MeV too low for SK…
(typically ~7 hits in the entire tank)

A ν event (MC)



starts from data looking like this…

Noise hit reduction → Hit cluster search → Vertex reconstruction → Feature variable calculation → Signal-background classification by MVA or BDT



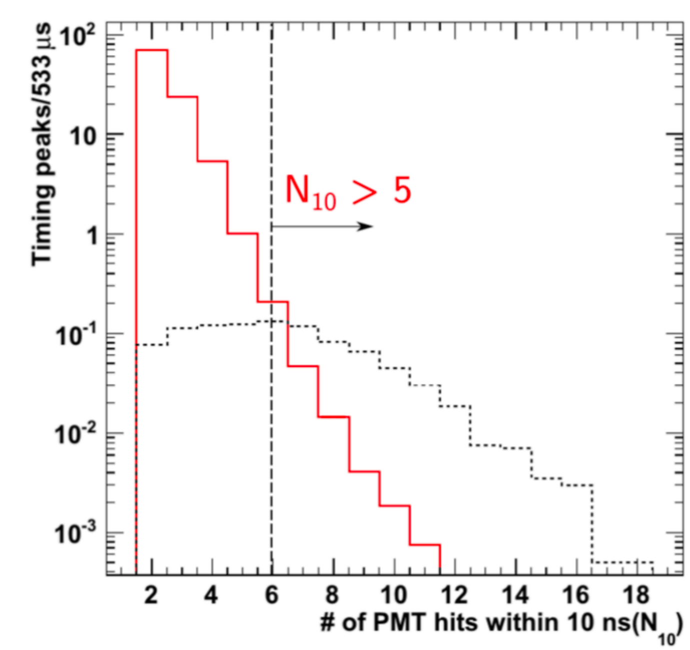
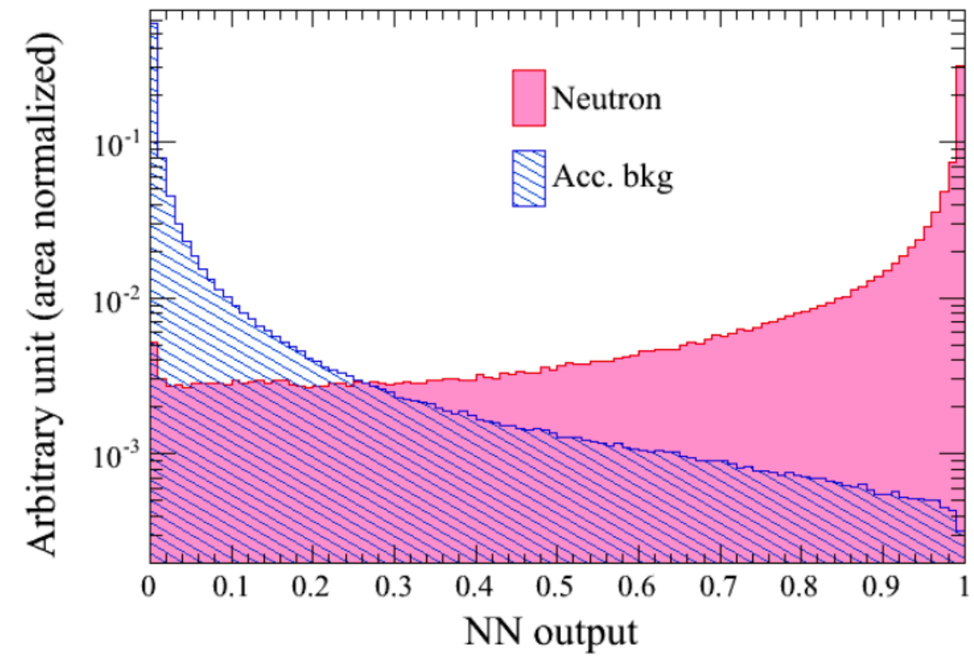


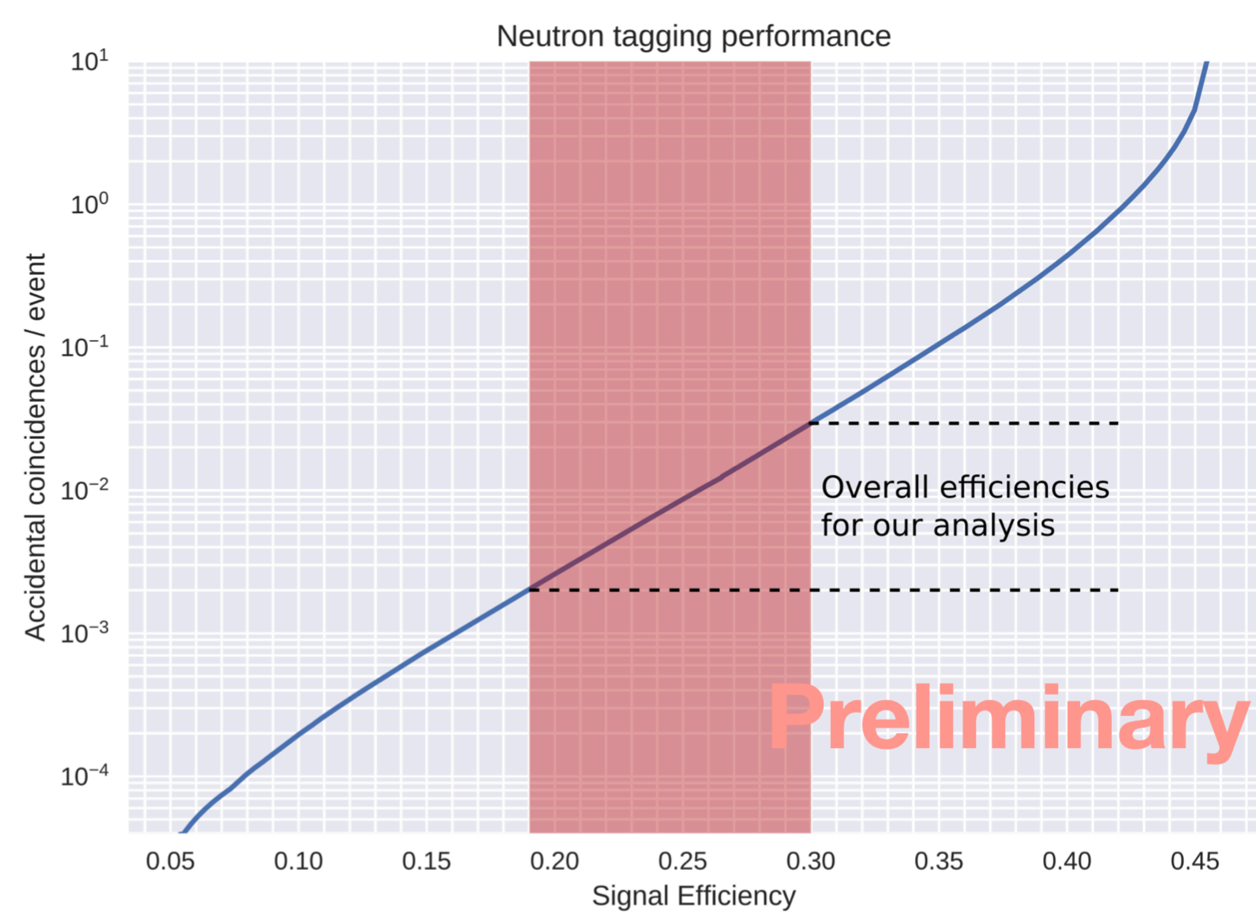
Image by R.Akutsu

Neutron tagging in the pure water

Noise hit reduction → Hit cluster search → Vertex reconstruction → Feature variable calculation → Signal-background classification by MVA or BDT



Final performance: 0.2% - 3% background acceptance & 18% - 30% signal efficiency



Further improvement on neutron tagging on going - CNN, even lower trigger (WIT), …
to overcome E threshold & vertex separation

Neutron signals in SK-VI atmospheric ν

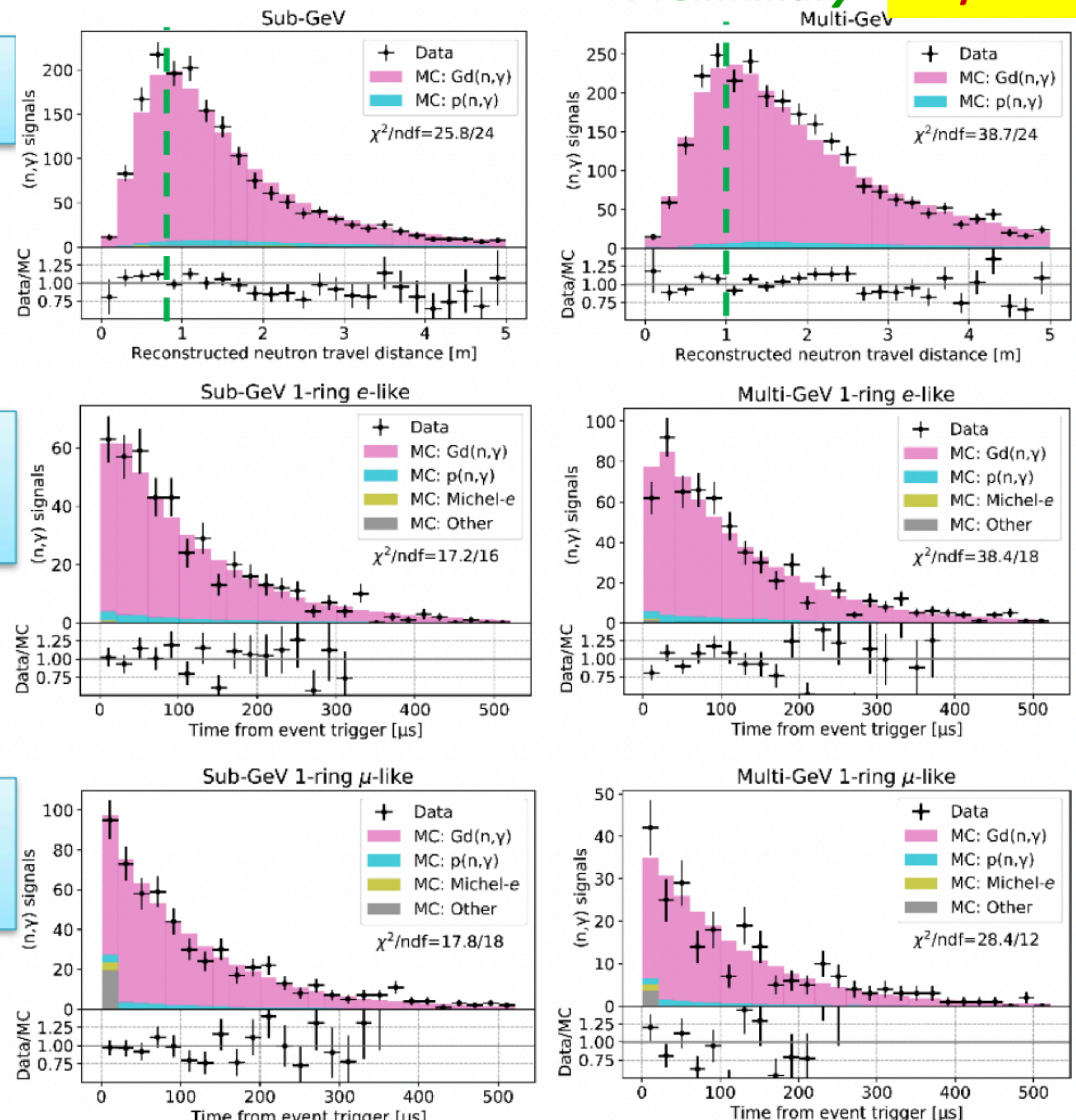
- **Applied the neural network neutrino tagging to the SK-VI 577 days atmospheric ν sample.**
- **The peak position of the neutron travel distance looks to be energy dependent.**
- **The capture time of neutron looks similar.**
- **Expected improvement in atmospheric ν analysis in SK-Gd:**
  - **Purity 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 — May 2022

Travel distance

Capture time (e-like)

Capture time (μ-like)

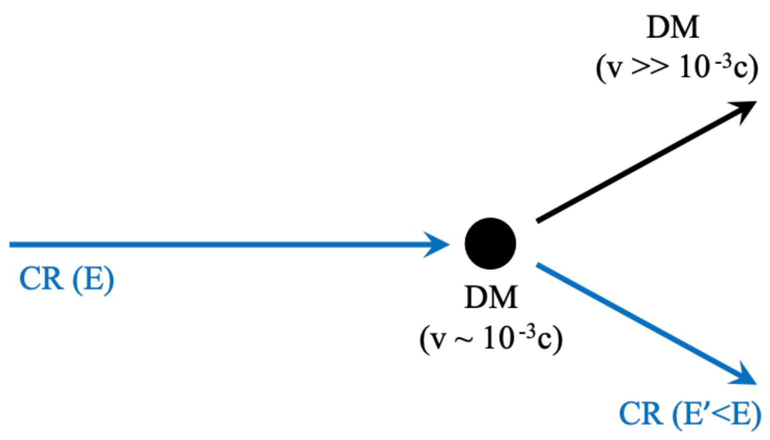


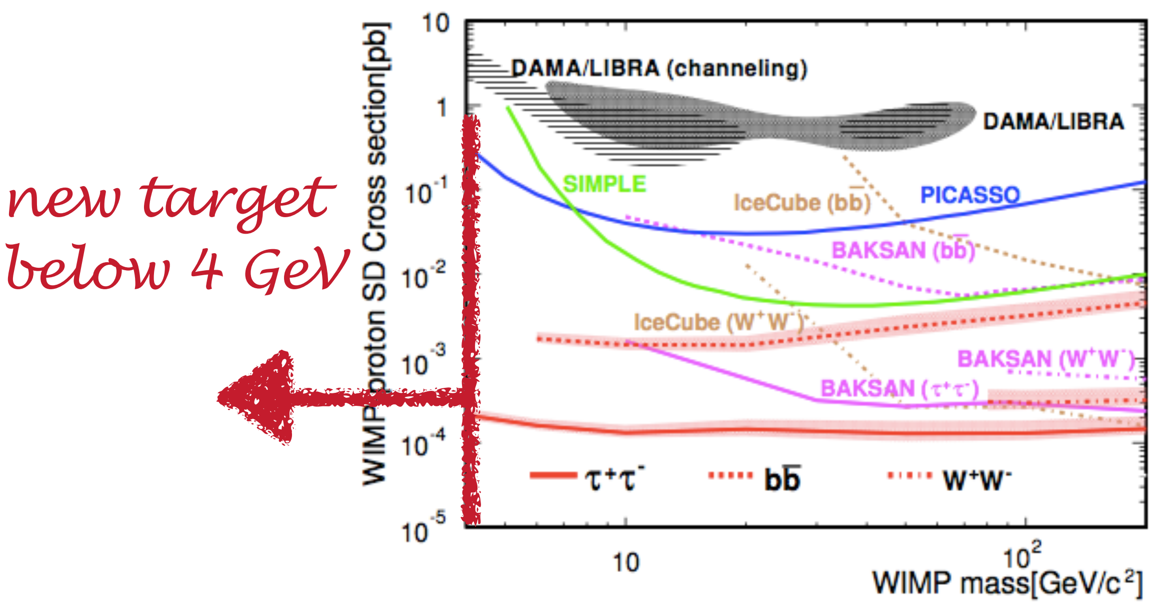
Sub-GeV (<1.33 GeV)

Multi-GeV (> 1.33 GeV)

Cosmic-ray boosted dark matter search

- Cosmic rays can hit abundant dark matter and accelerate towards the Earth
- For X-p scattering, Minimal thermal relic scenario can be tested for new mass region (below 4 GeV)

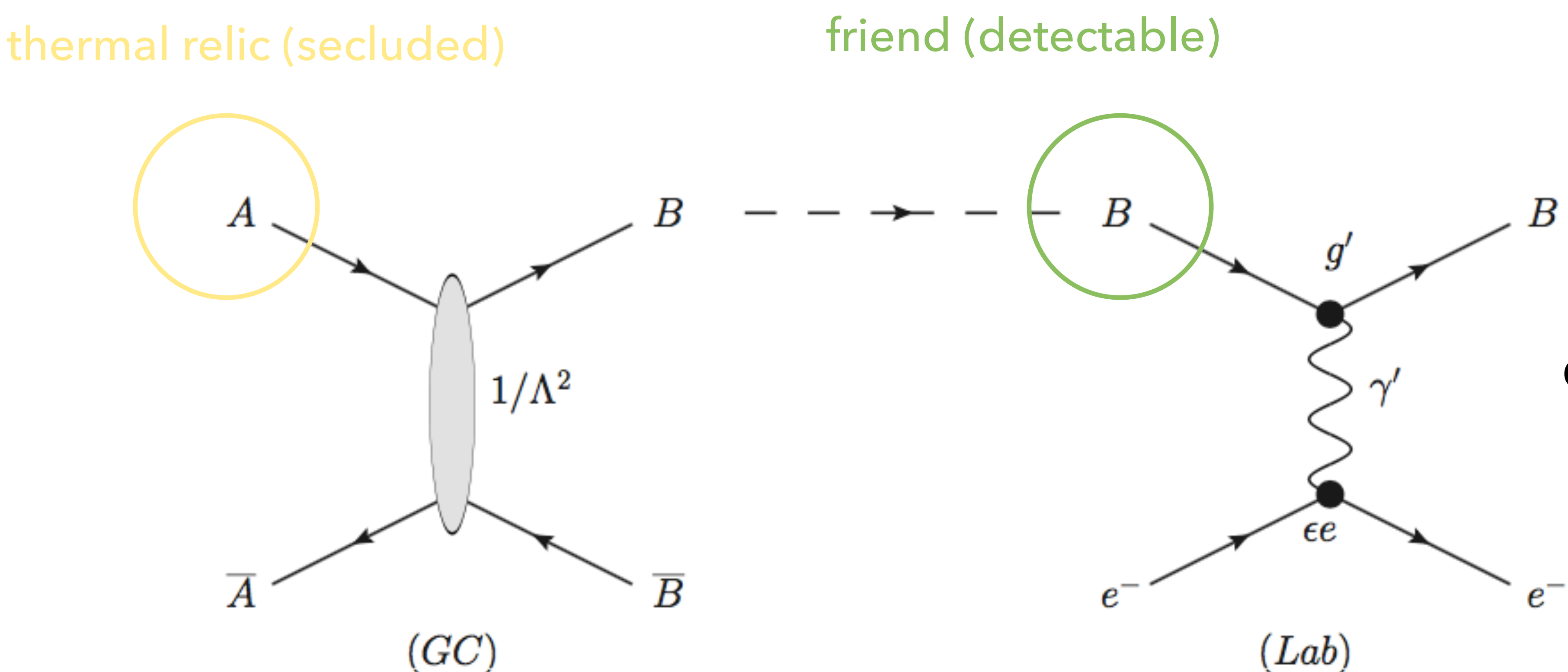




Cappiello et al., arxiv:1906.11283,
also Cappiello et al. 1810.07705, Bringmann et al. 1810.10543, Ema et al. 1811.00520, Dent et al. 1907.03782, Guo et al. 2004.03161, 2008.12137, Ge et al. 2005.09480, Cao et al. 2006.12767, Xia et al. 2009.00353, Jho et al. 2006.13910, 2101.11262, …

Boosted DM Search in SK

- insight: sometimes it's easier to find "friend" of dark matter than dark matter itself (Agashe et al., arxiv:1405.7370)



one example interaction - via dark photon

If scattering signal of B is expected above SK E threshold
→ direct detection of "boosted dark matter"

electron + gamma in atm ν CCQE interaction

what was the energy of ν...?

Gamma & Neutron Emissions

Difference in gamma and neutron emissions of ν_e-^{16}O from backgrounds such as IBD, $\overline{\nu}_e$-^{16}O and Michel electrons is critical for this measurement.

50% of ν_e-^{16}O events (blue) have gamma rays above 3 MeV emitted from nuclear de-excitations.

^{16}F* is proton rich so almost no neutron emissions from its decays are expected (supported by TALYS)