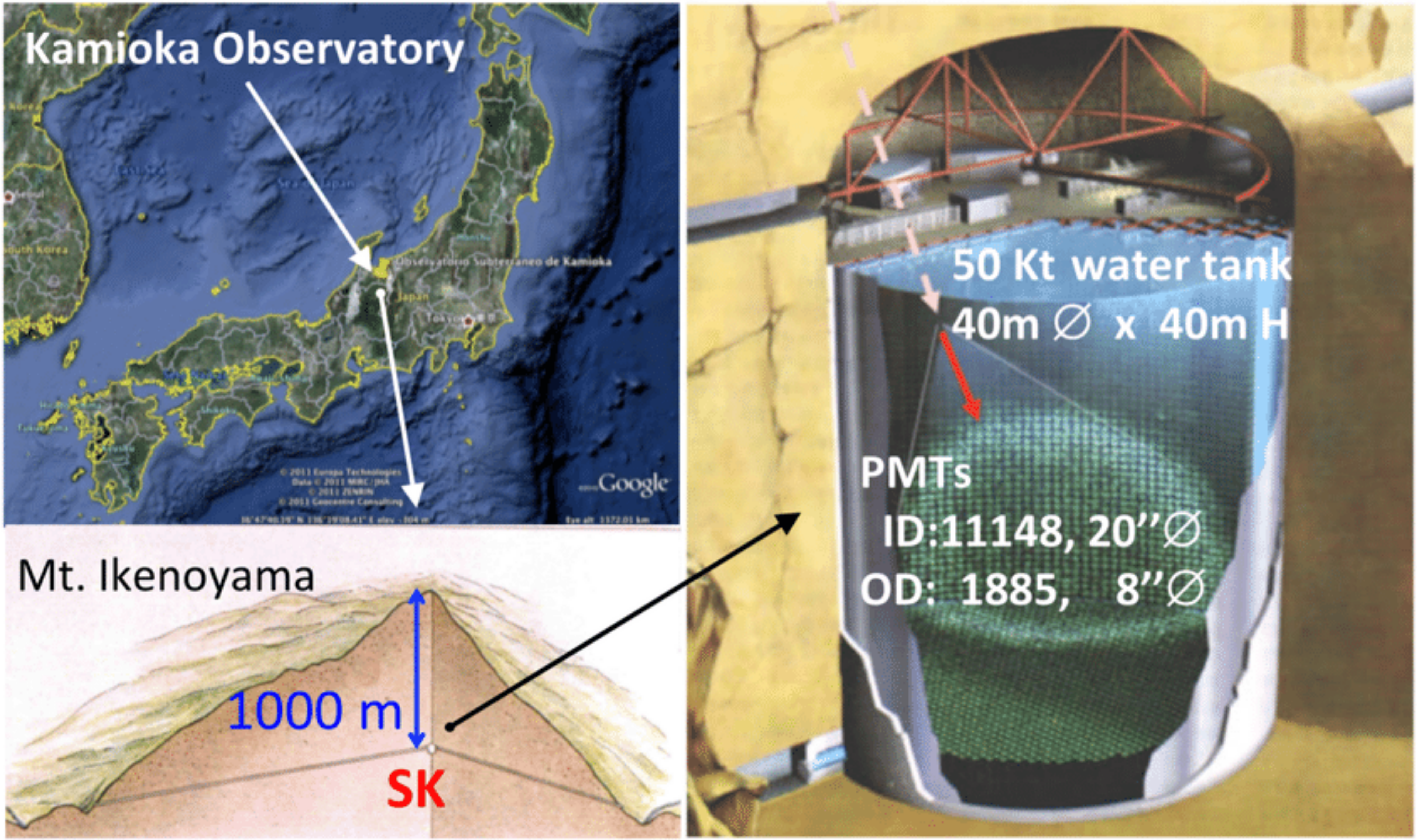
Dark matter searches using Low-E data of Super-Kamiokande

Koun Choi (IBS-CUP)

ibs CENTER FOR UNDERGROUND PHYSICS

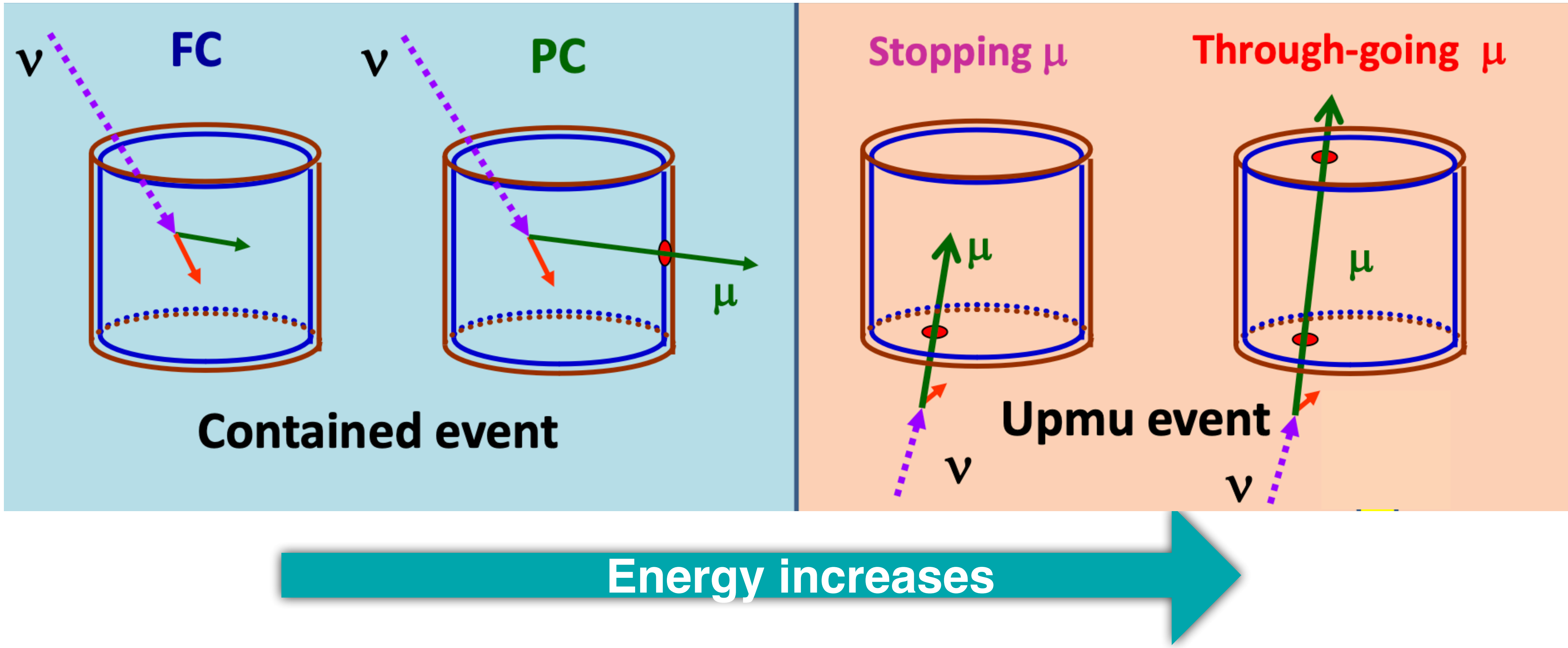
15th International Workshop on the Identification of Dark Matter July 8-12, 2024, L'Aquila

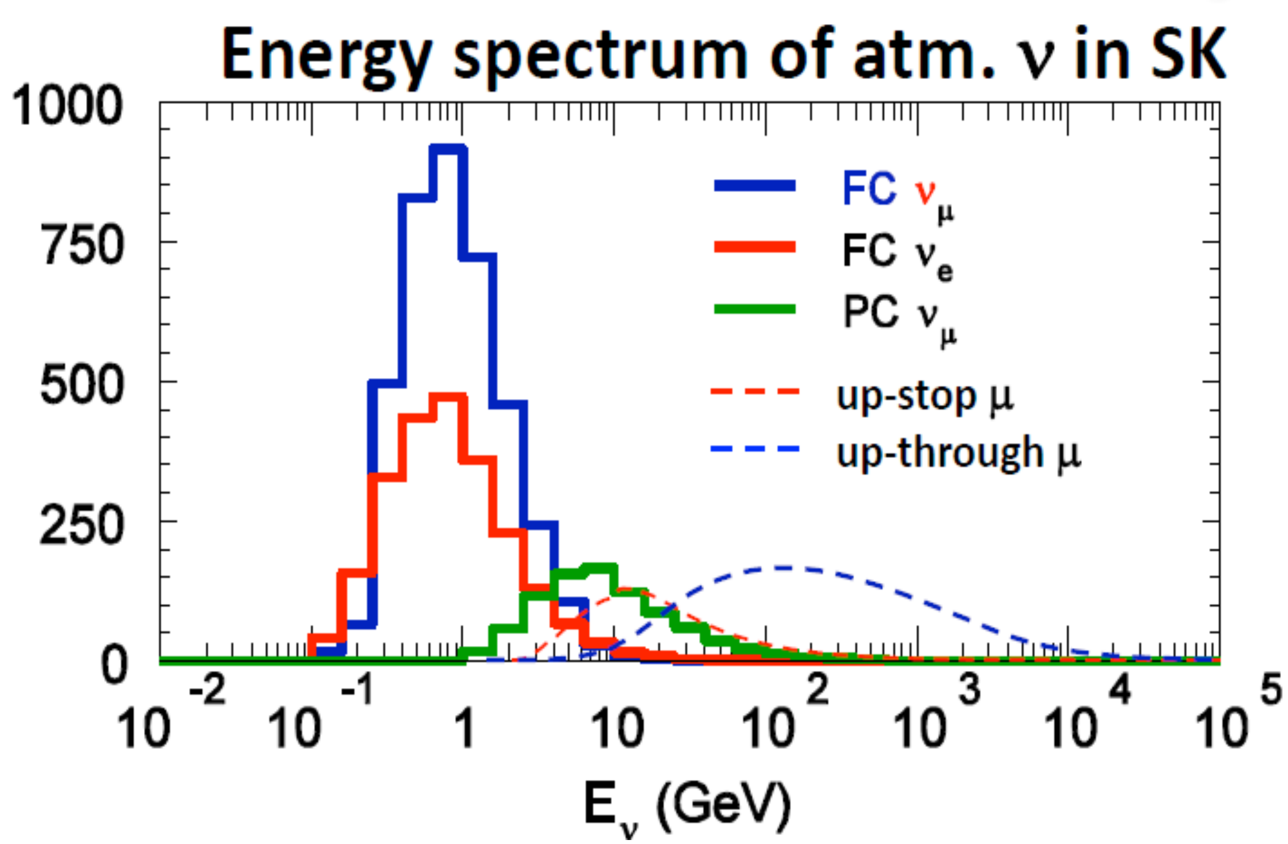
Super-Kamiokande Experiment (SK)



operating since 1996!

Events categories





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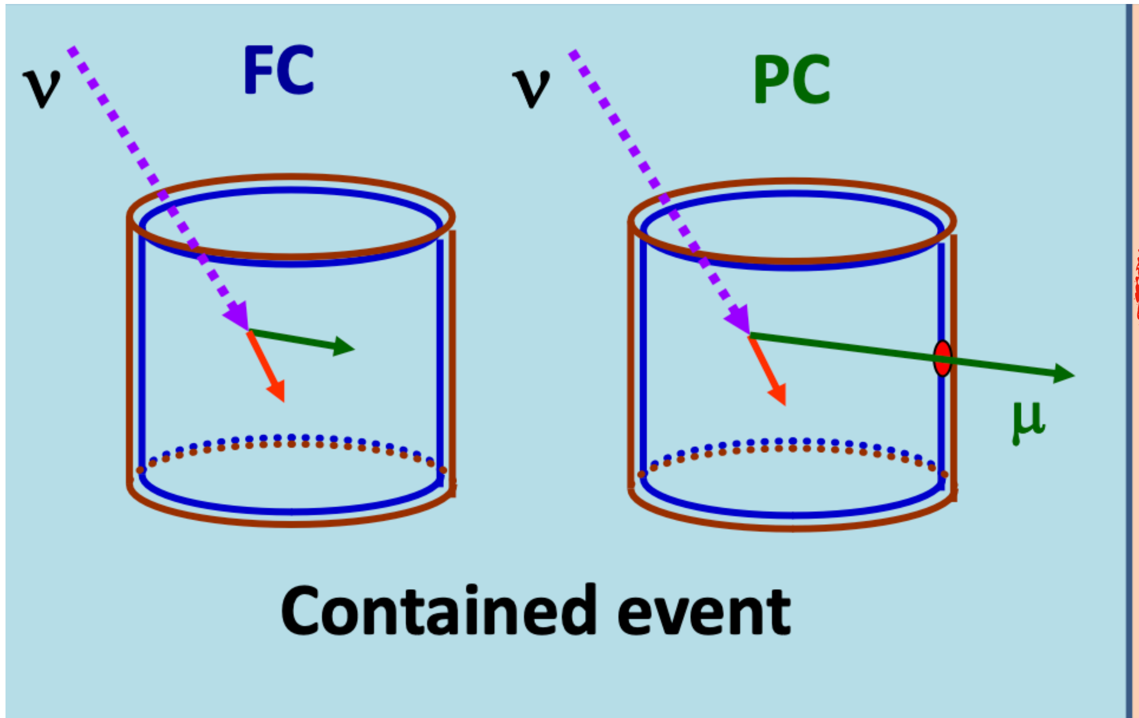
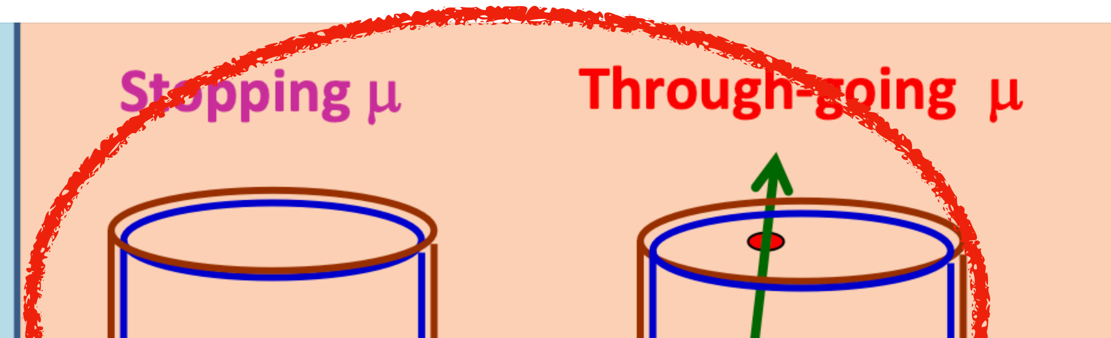
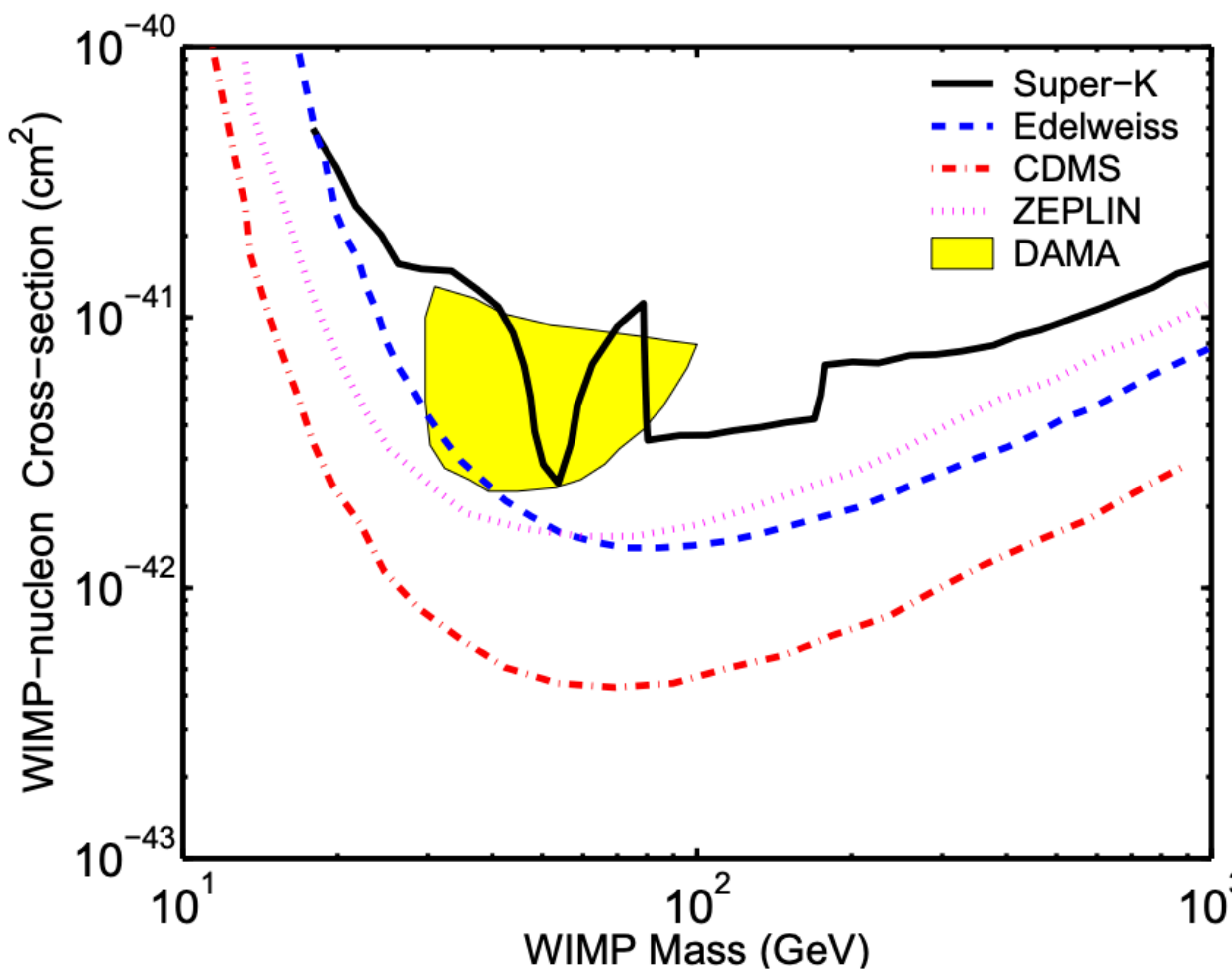
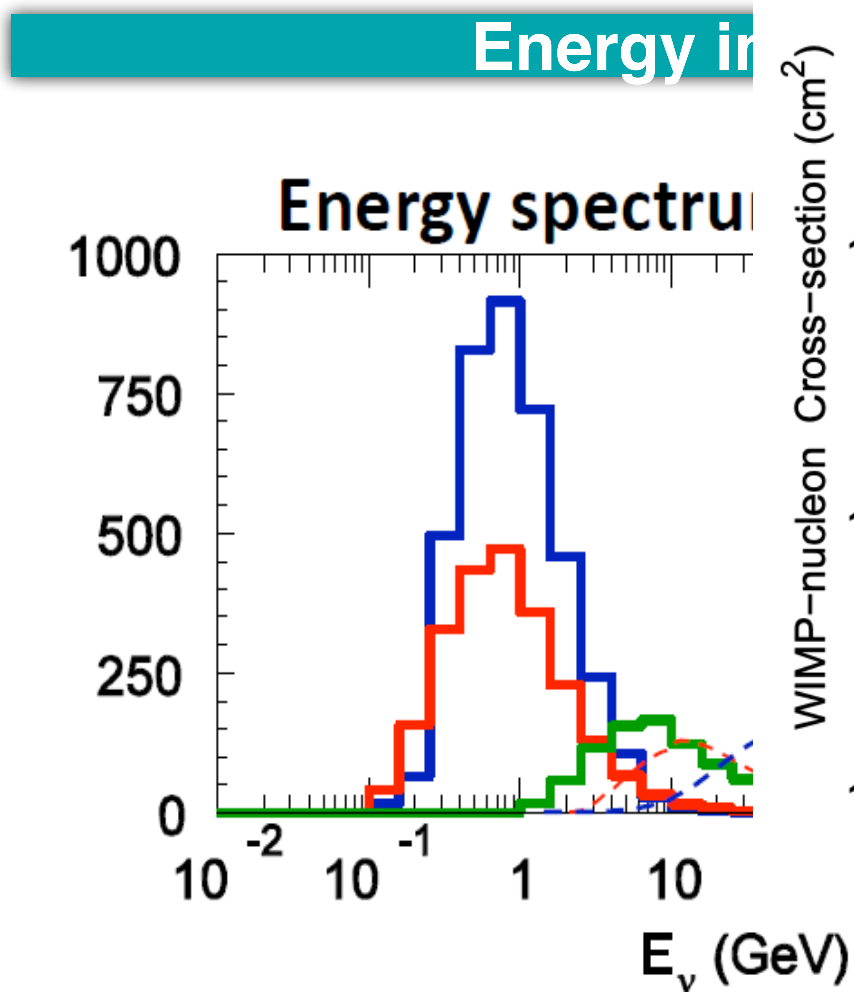




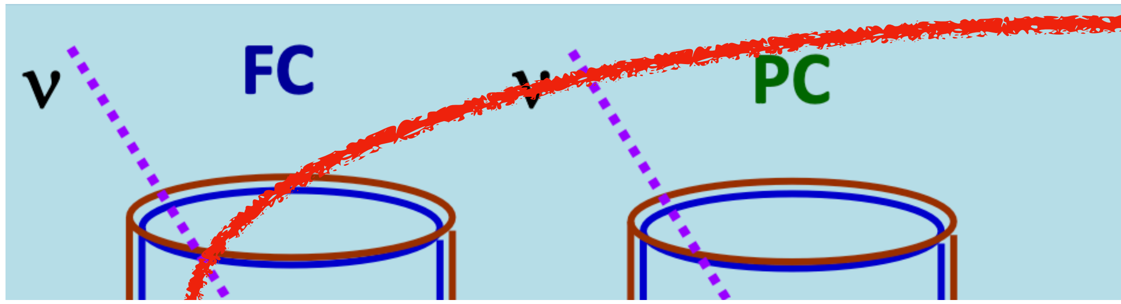
Search for Dark Matter WIMPs using Upward Through-going Muons in Super-Kamiokande

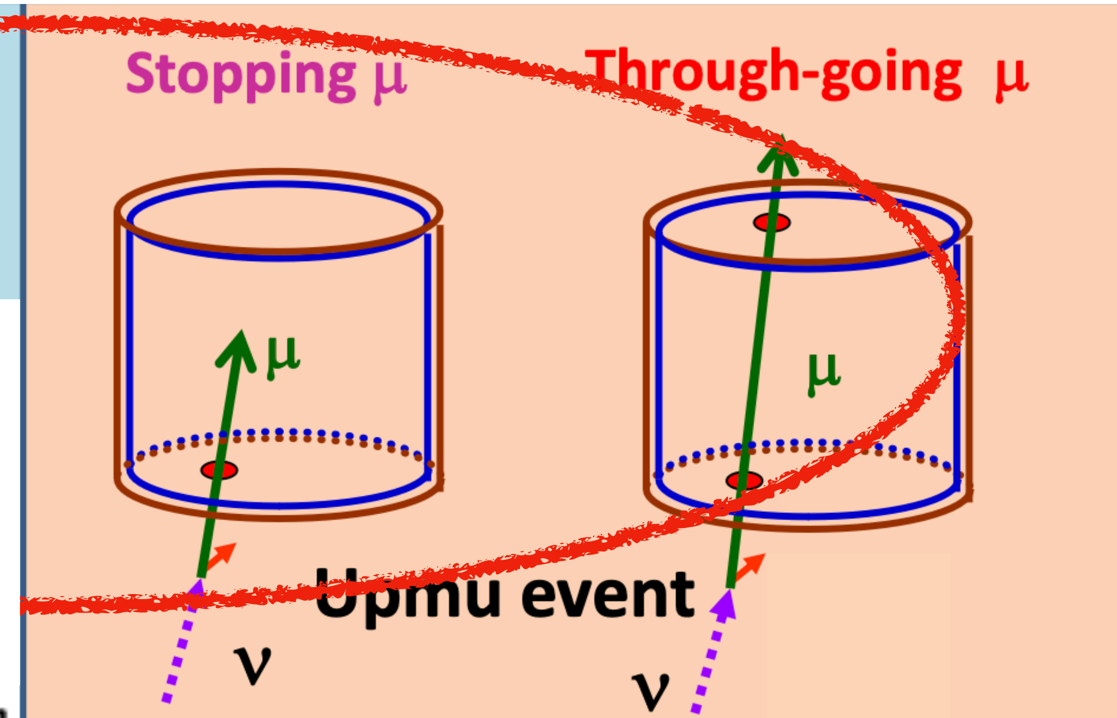
Phys.Rev.D 70 (2004) 083523, *Phys.Rev.D* 70 (2004) 109901 (erratum) • e-Print: hep-ex/0404025 [hep-ex]





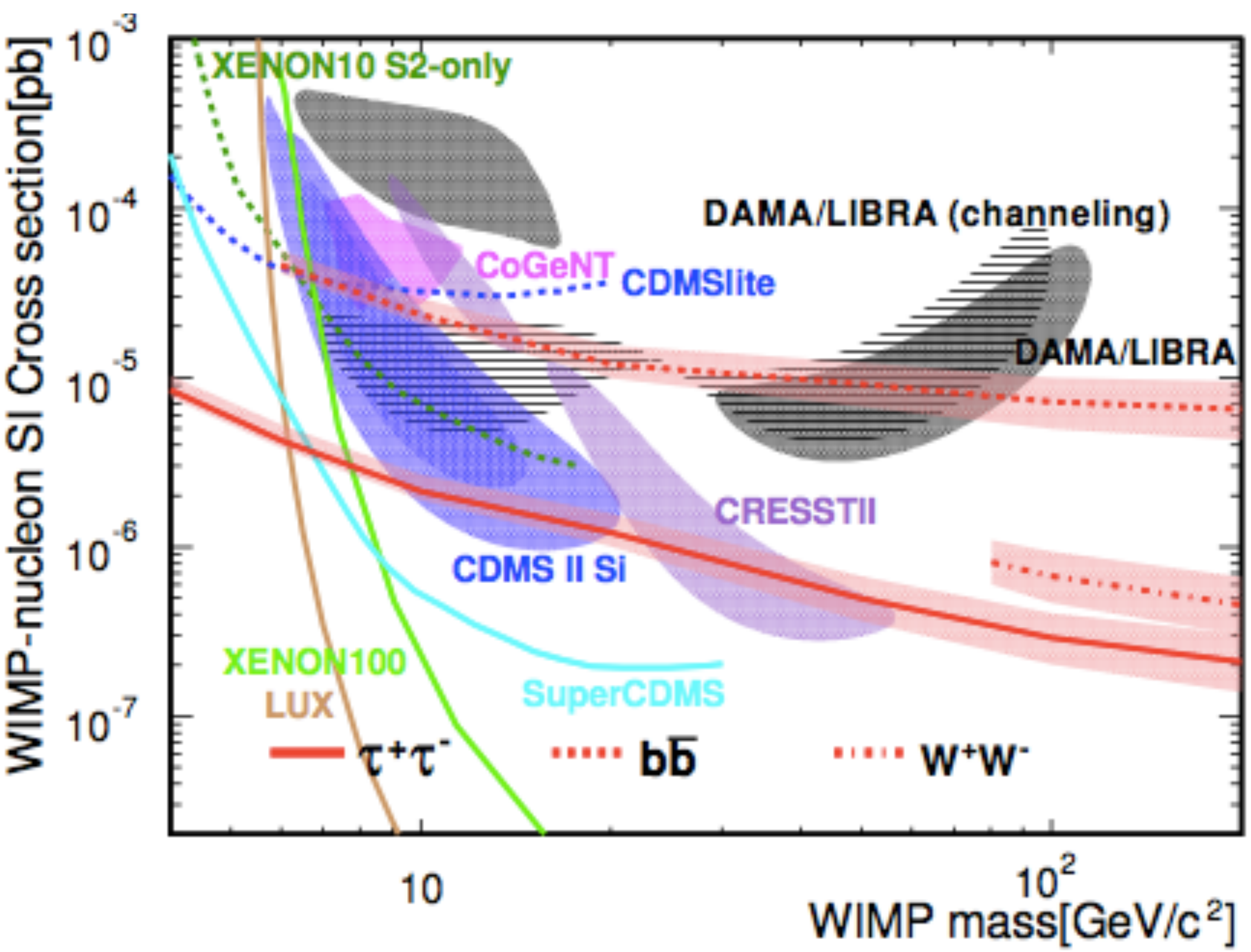
Events categories

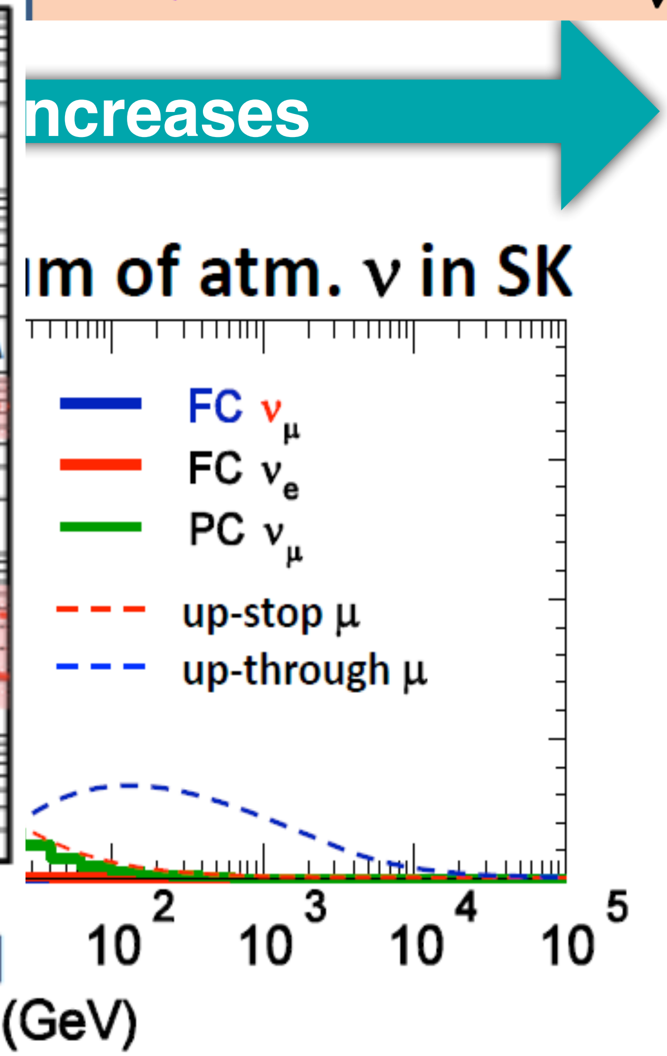




Search for neutrinos from annihilation of captured low-mass dark matter particles in the Sun by Super-Kamiokande

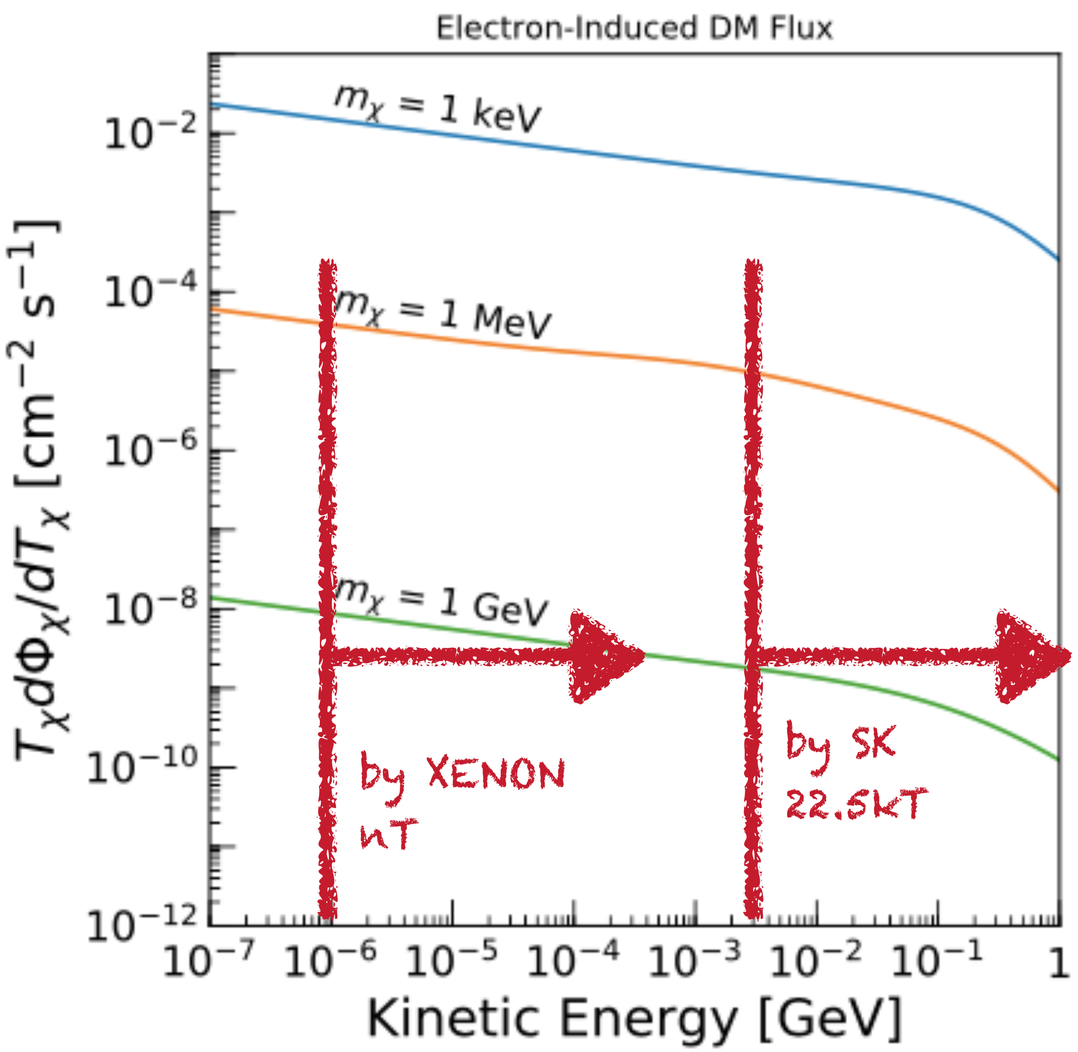
Phys.Rev.Lett. 114 (2015) 14, 141301 • e-Print: 1503.04858 [hep-ex]





New possibilities to directly search for DM in neutrino detectors

- momentum threshold O(1) MeV (SK) is too high to detect nuclear recoils from thermal relic DM (~keV)
- In case of boosted DM scenarios, neutrino experiments can see high tail of the signal spectrum



C.Cappiello et al., *Phys.Rev.D* 100 (2019) 10, 103011 • e-Print: 1906.11283 [hep-ph]

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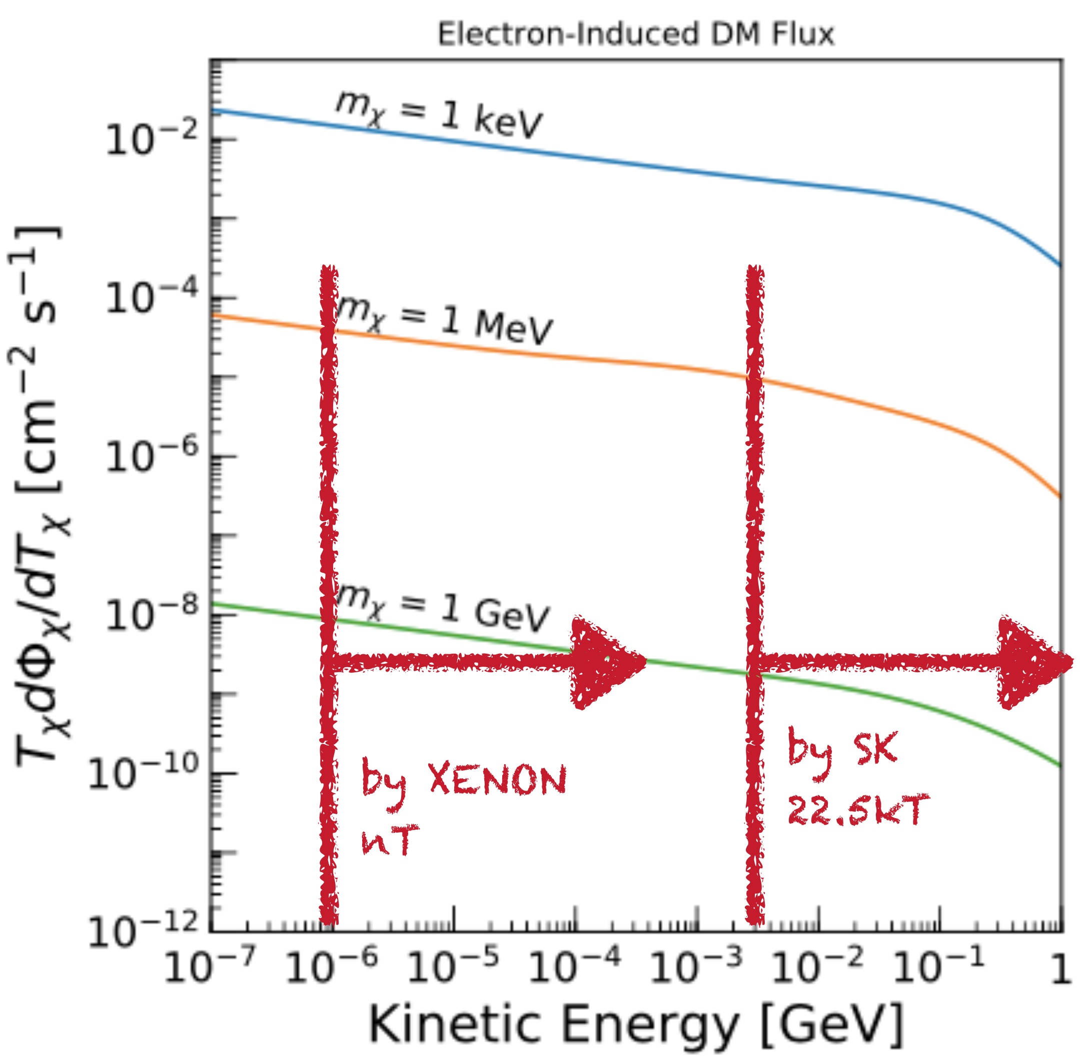

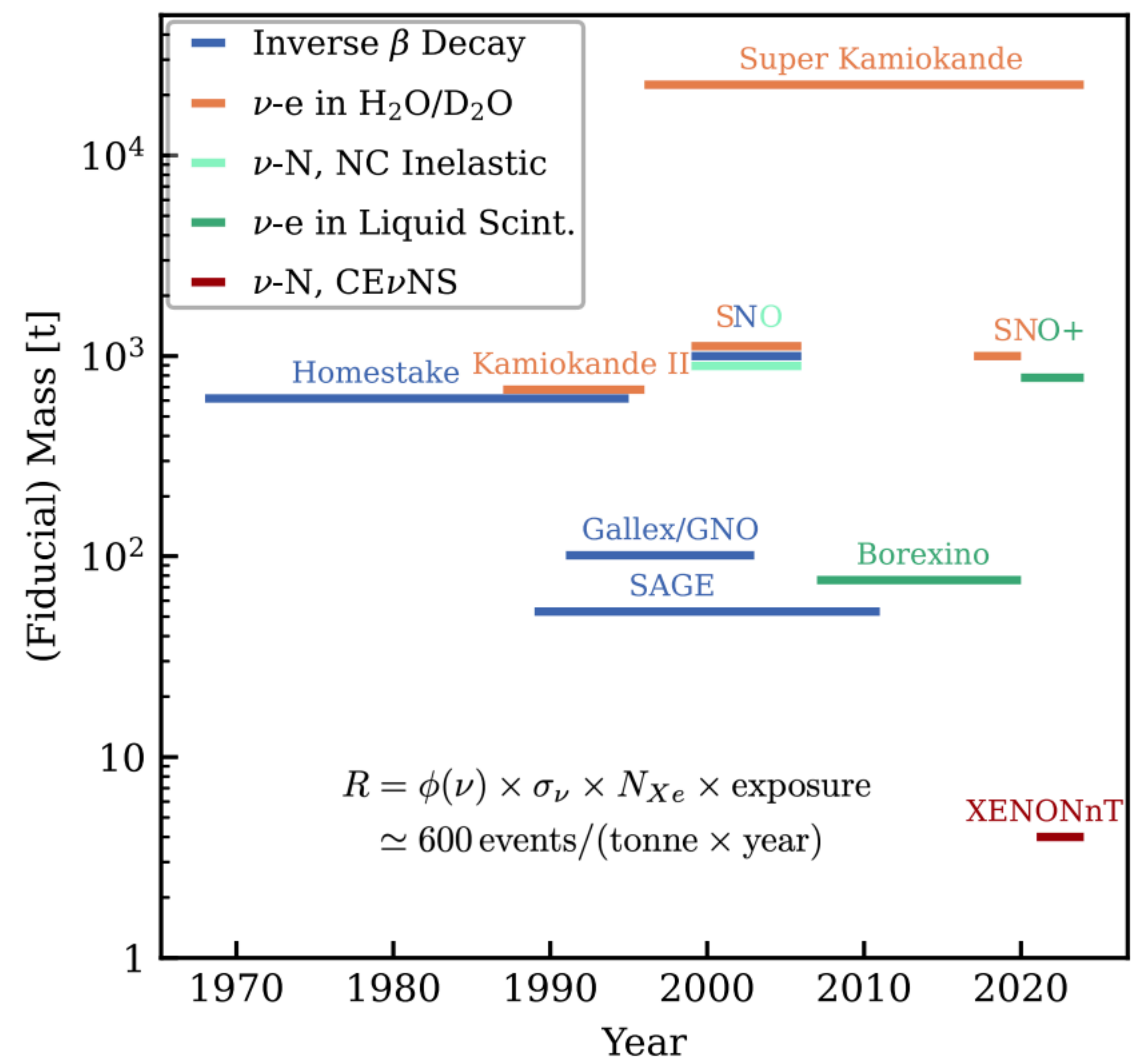

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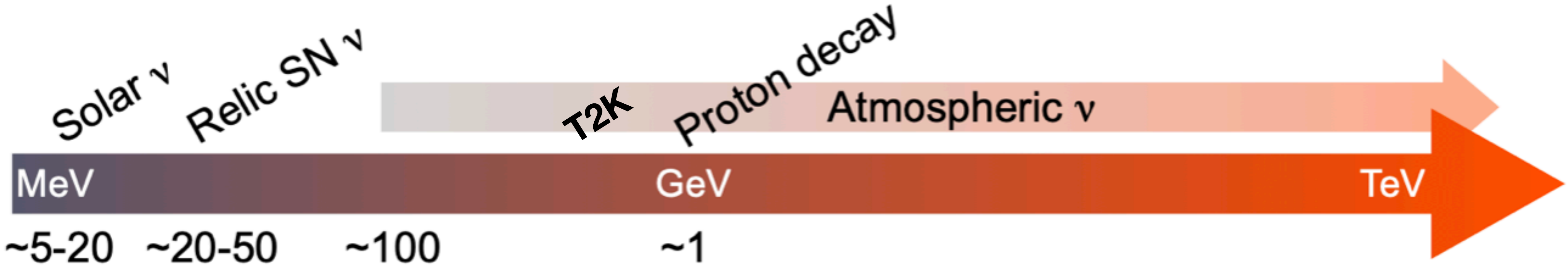
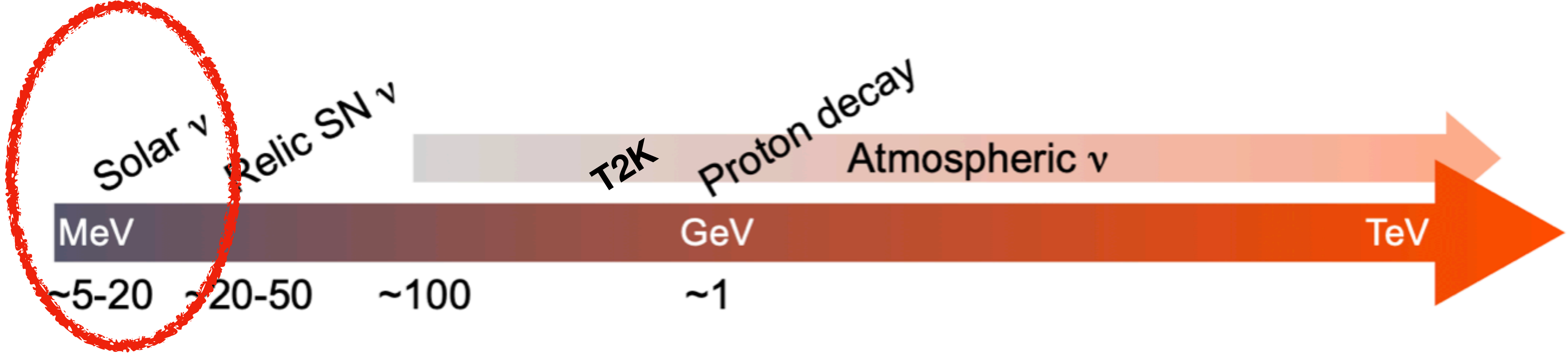

Solar ν
Relic SN ν
T2K
Proton decay
Atmospheric ν
MeV
GeV
TeV
~5-20
~20-50
~100
~1

Contents

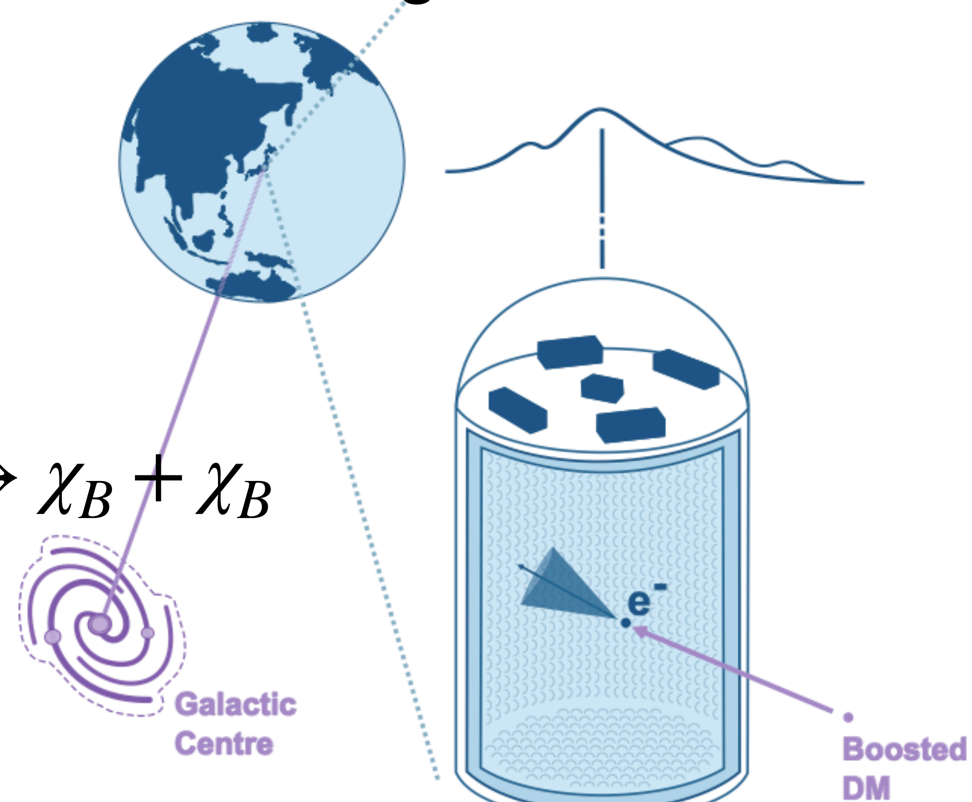
- intro (done)
- boosted DM - electron scattering
- boosted DM - proton scattering
- boosted DM - neutron scattering
- thermal relic sub-GeV DM annihilation
- conclusion



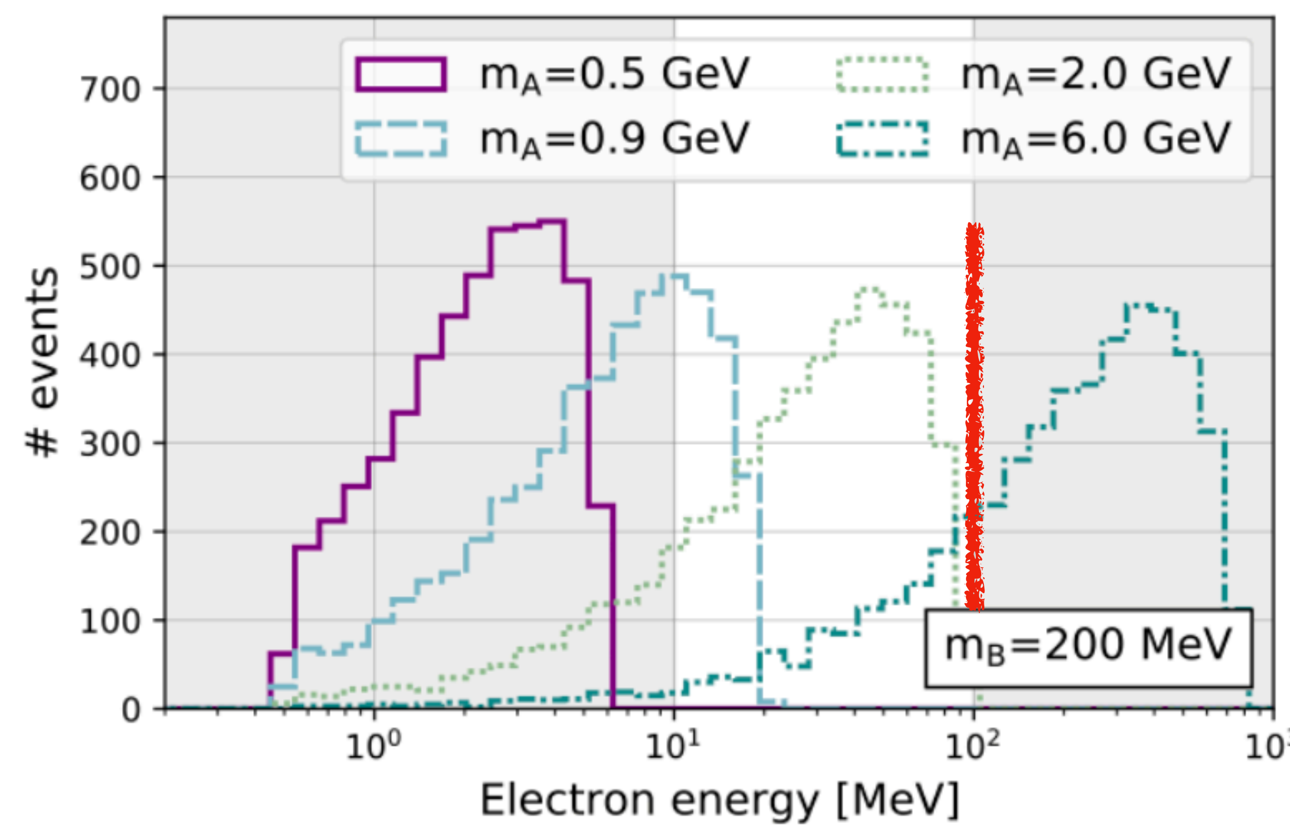
Boosted dark matter searches with electrons

- search for dark matter A annihilating from the GC (NFW profile) to dark particle B
- dark matter scattering off electrons in the SK mediated by dark photon

$$\chi_A + \chi_A \rightarrow \chi_B + \chi_B$$

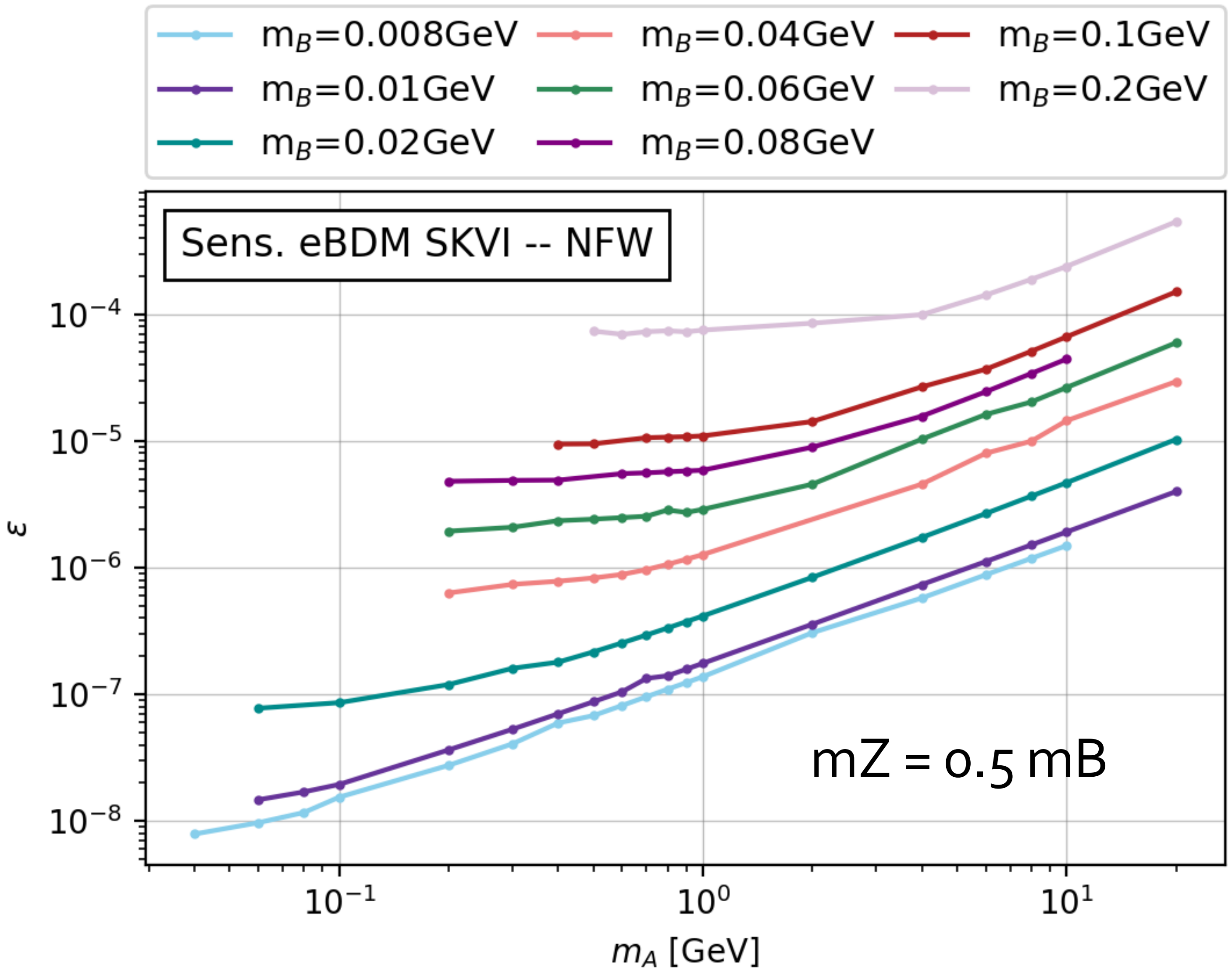


$$\chi_B + e^- \rightarrow \chi_B + e^-$$



GENIE-BDM e-Print: 1812.05616 [hep-ph]

SK-VI sensitivity on DM-electron scattering cross section



- binned spectral likelihood fit for reconstructed Energy & Right ascension (RA) & Declination (δ)
- 10-100 MeV MC set (actually DSNB flow without neutron tagging)

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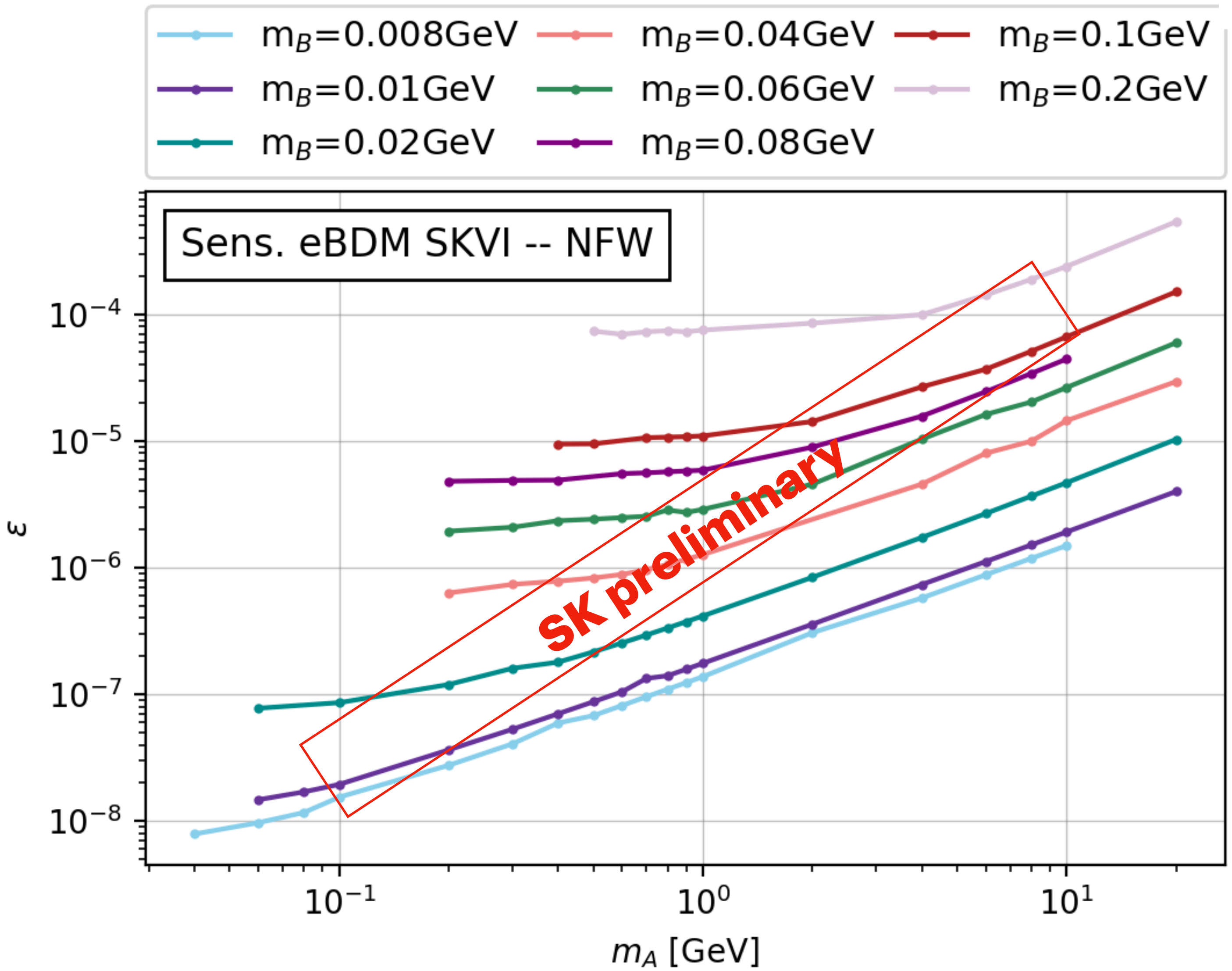

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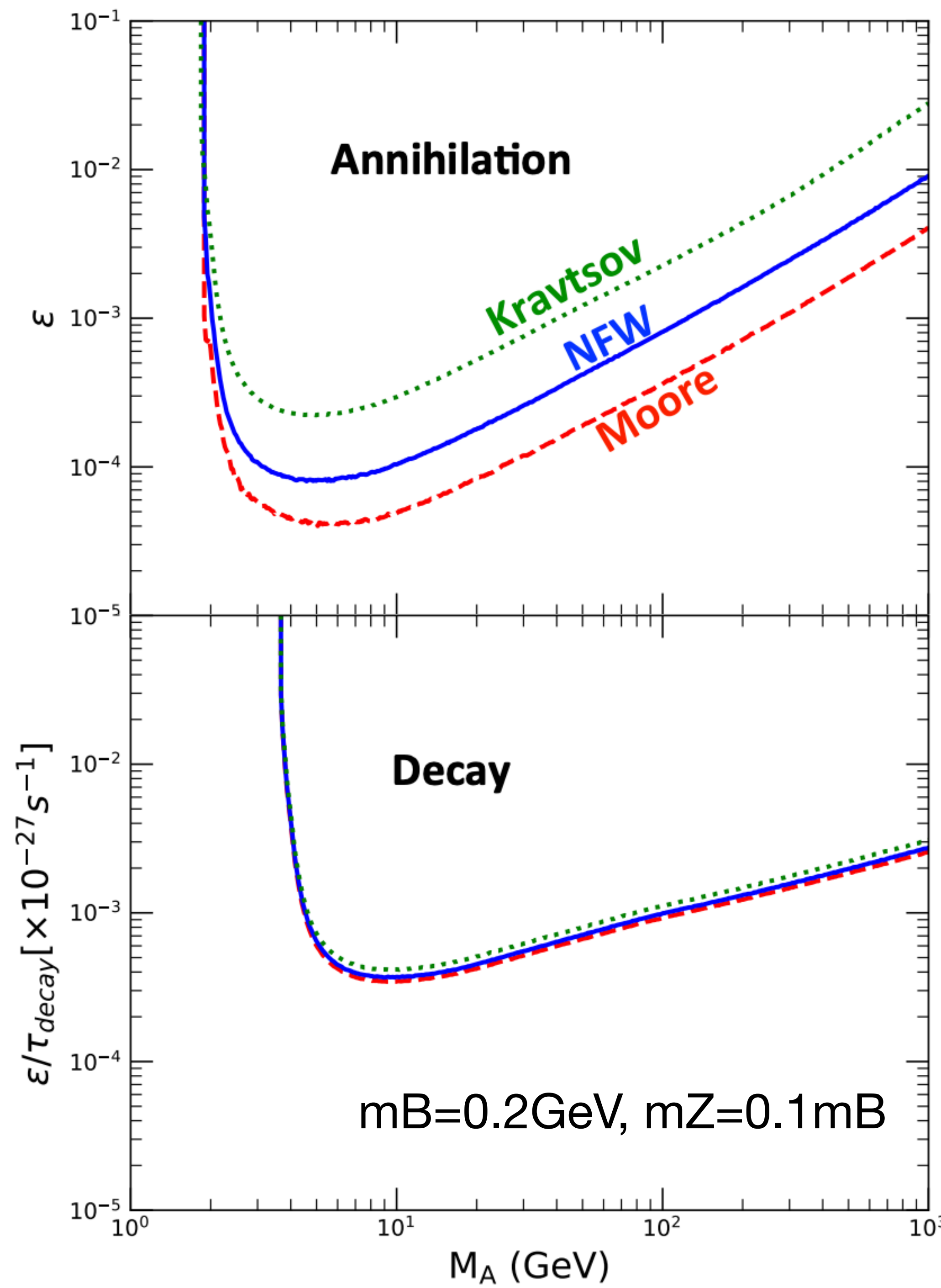
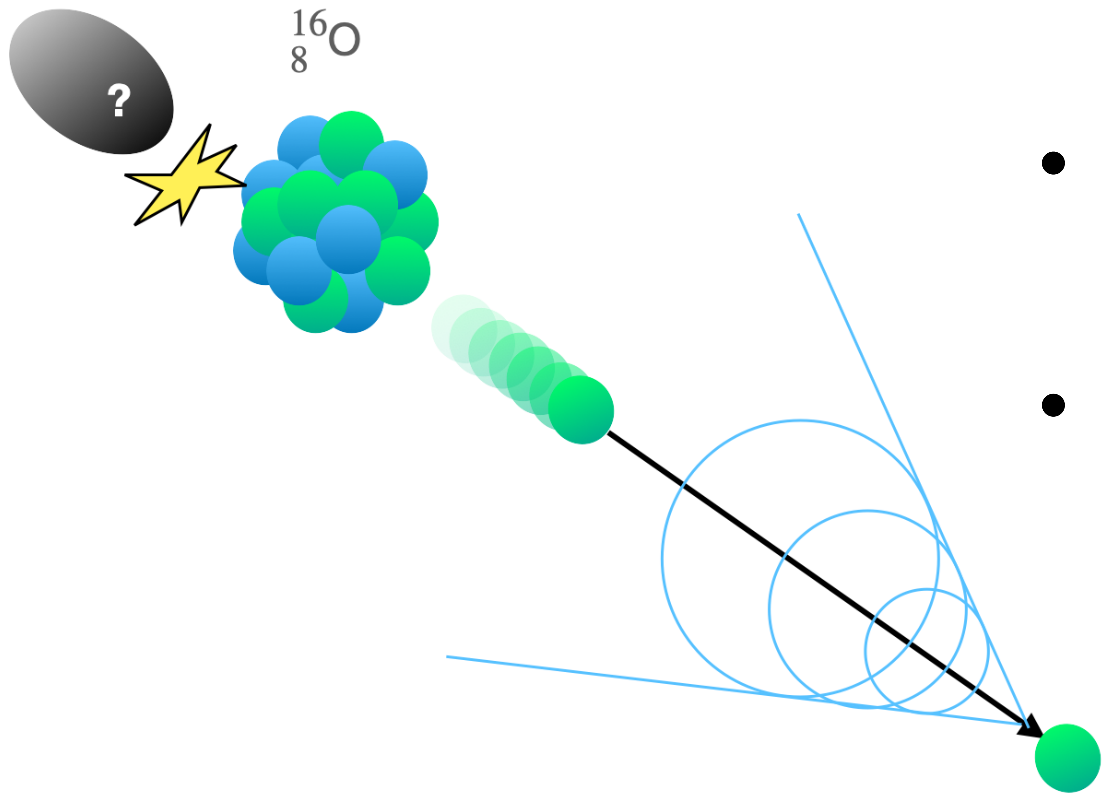
Search for Boosted Dark Matter Interacting With Electrons in Super-Kamiokande

Phys.Rev.Lett. 120 (2018) 22, 221301 • e-Print: 1711.05278 [hep-ex]

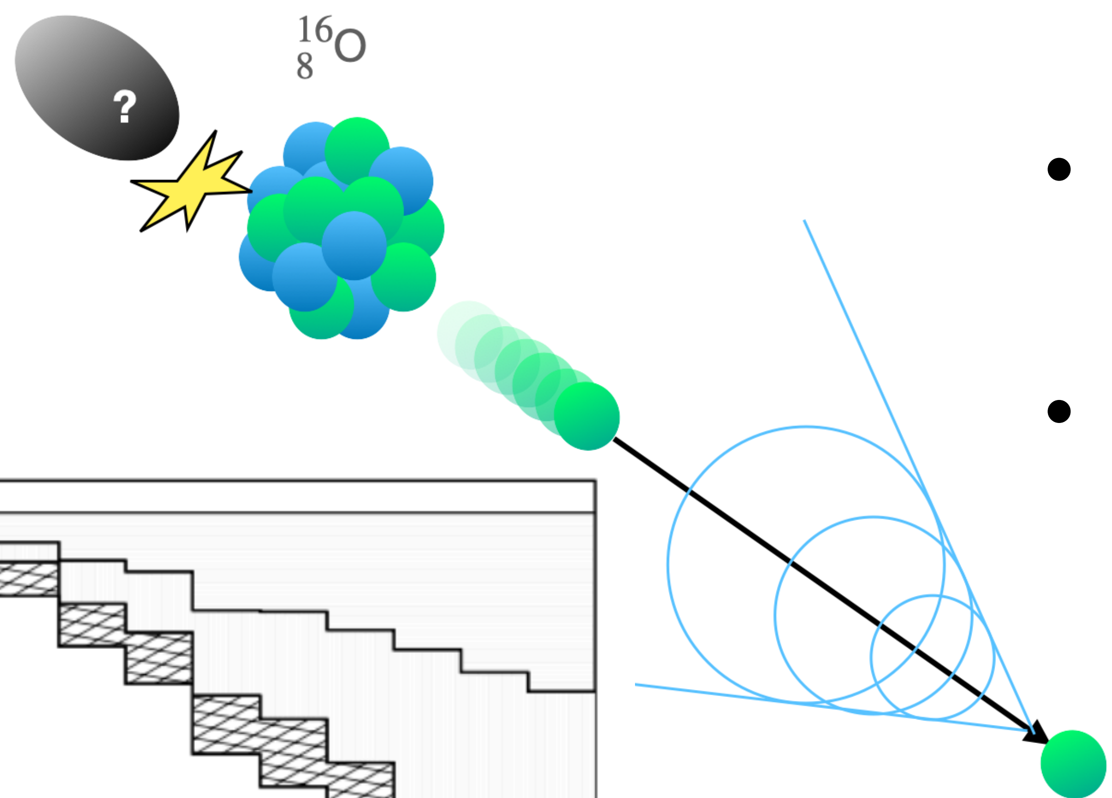


Boosted dark matter searches with nucleons



- DM particle can be energetic enough to knock out a nucleon
- Cherenkov radiation from proton is detectable in WCD

Boosted dark matter searches with nucleons



- DM particle can be energetic enough to knock out a nucleon
- Cherenkov radiation from proton is detectable in WCD

$$v > \frac{c}{n}$$

  - Cherenkov momentum threshold of proton ~ 1.1 GeV
  - difficult to reconstruct high-energy protons due to hadronic interactions

→ limited signal window: 1.2 GeV < p < 2.3 GeV

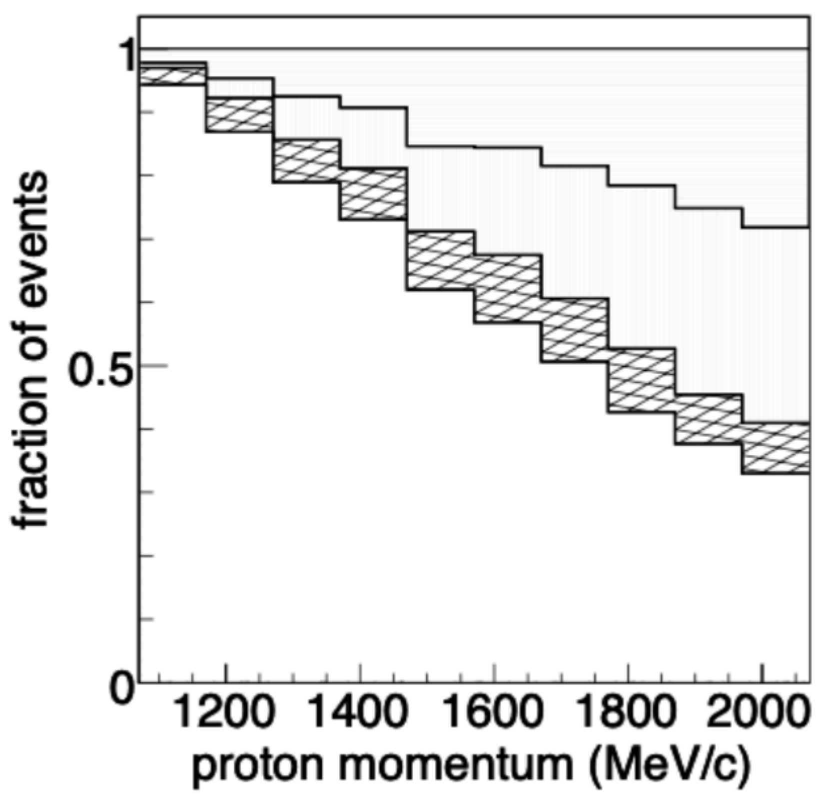
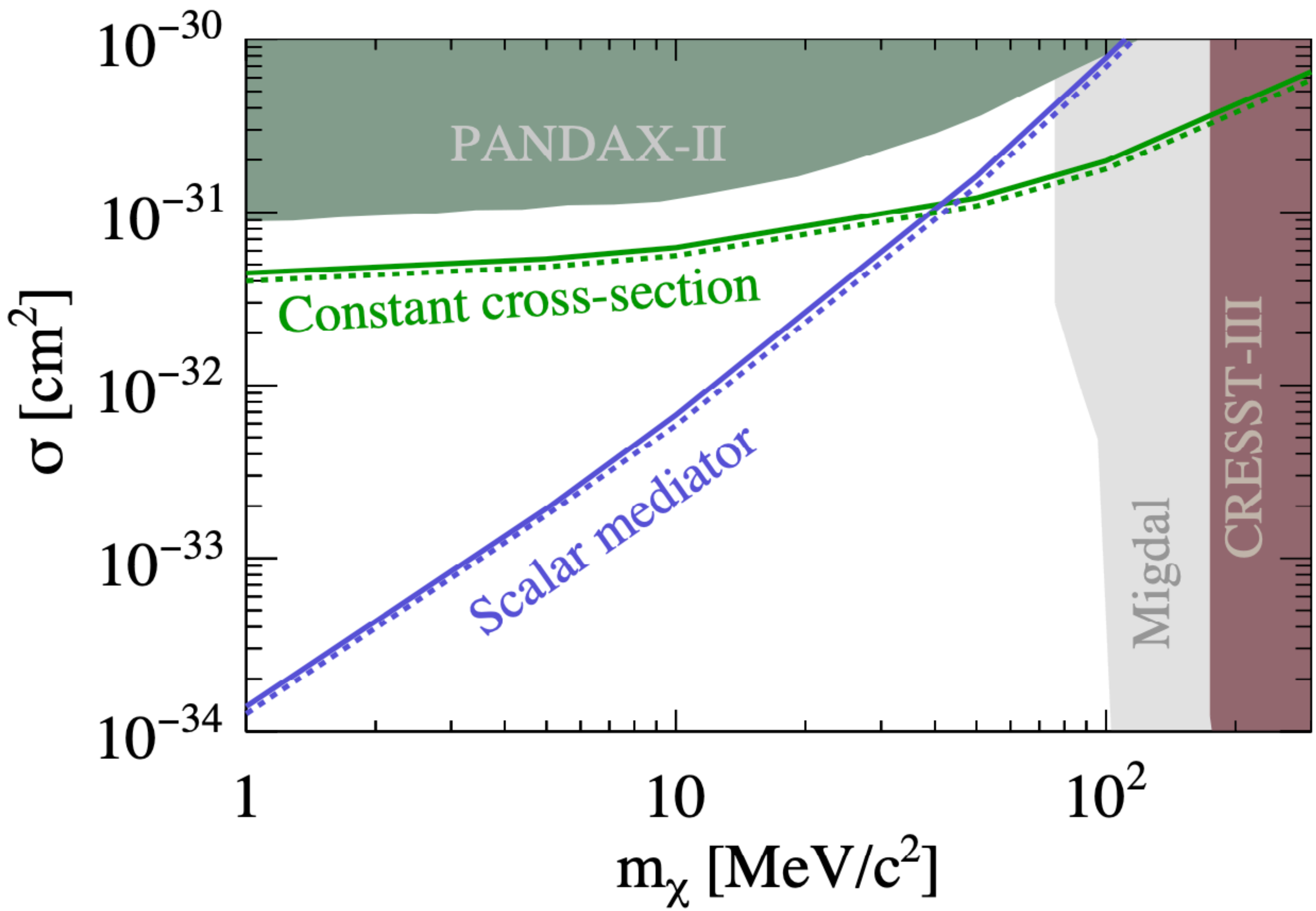


FIG. 2: Probability of hadronic interactions in the water as a function of proton momentum. The clear region shows the fraction of protons that do not interact hadronically in the water. The cross-hatched region shows events whose interactions produce only sub-threshold secondaries. The region with a vertical hatch pattern corresponds to production of above-threshold charged secondaries, with no π^0. The horizontally hatched region shows the amount of π^0 production.

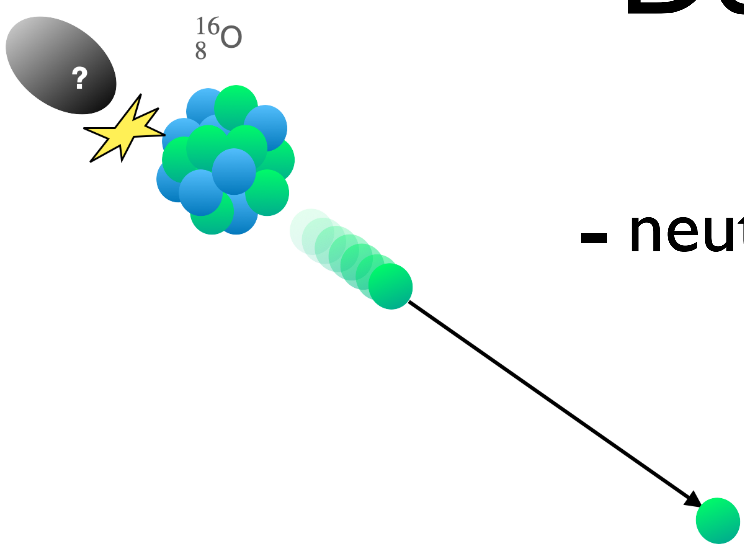
Phys.Rev.D 79 (2009) 112010

Search for Cosmic-Ray Boosted Sub-GeV Dark Matter Using Recoil Protons at Super-Kamiokande

Phys.Rev.Lett. 130 (2023) 3, 031802, *Phys.Rev.Lett.* 131 (2023) 15, 159903 (erratum) • e-Print: 2209.14968 [hep-ex]



Boosted dark matter searches in Water Cherenkov Detector with neutrons



- neutrons don't emit Cherenkov radiation

Boosted dark matter searches in Water Cherenkov Detector with neutrons

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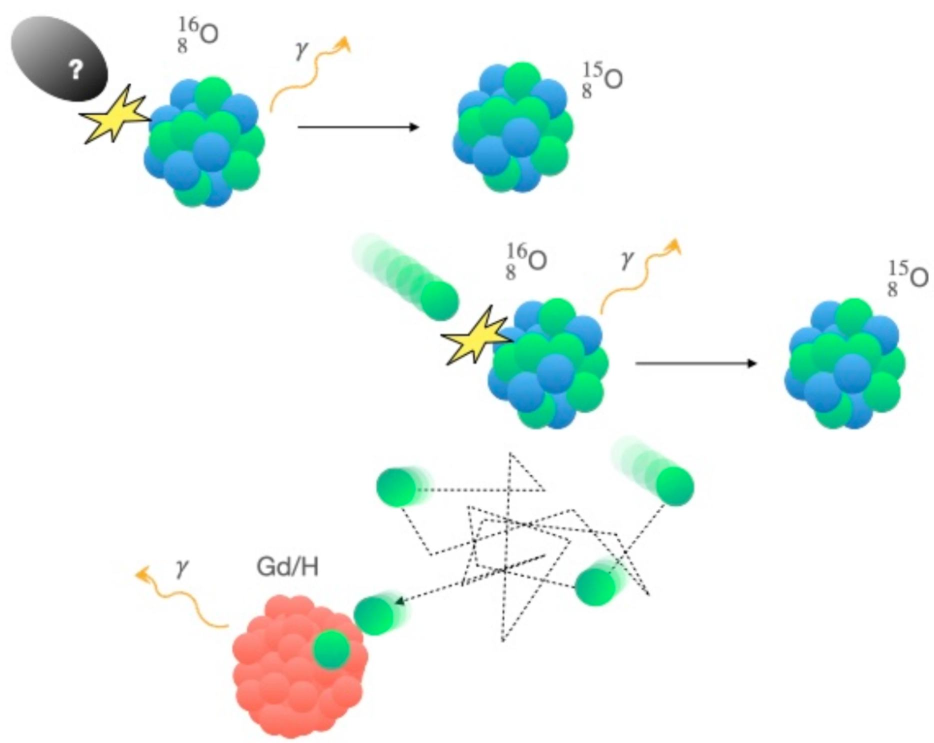

- instead, O(MeV) gammas are emitted when neutrons are captured by a nucleus

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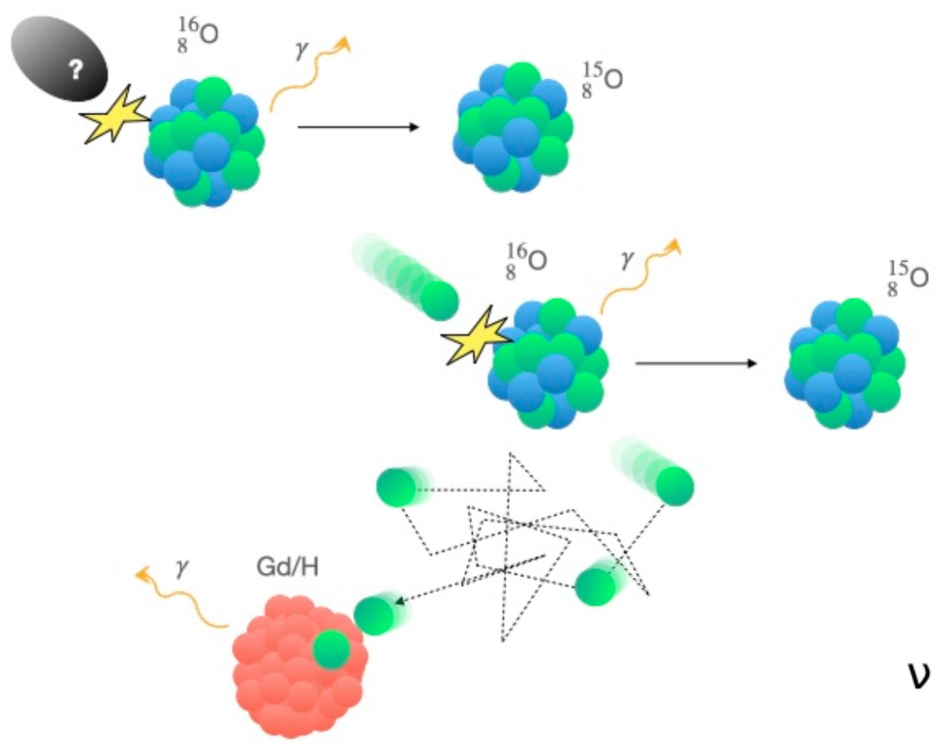

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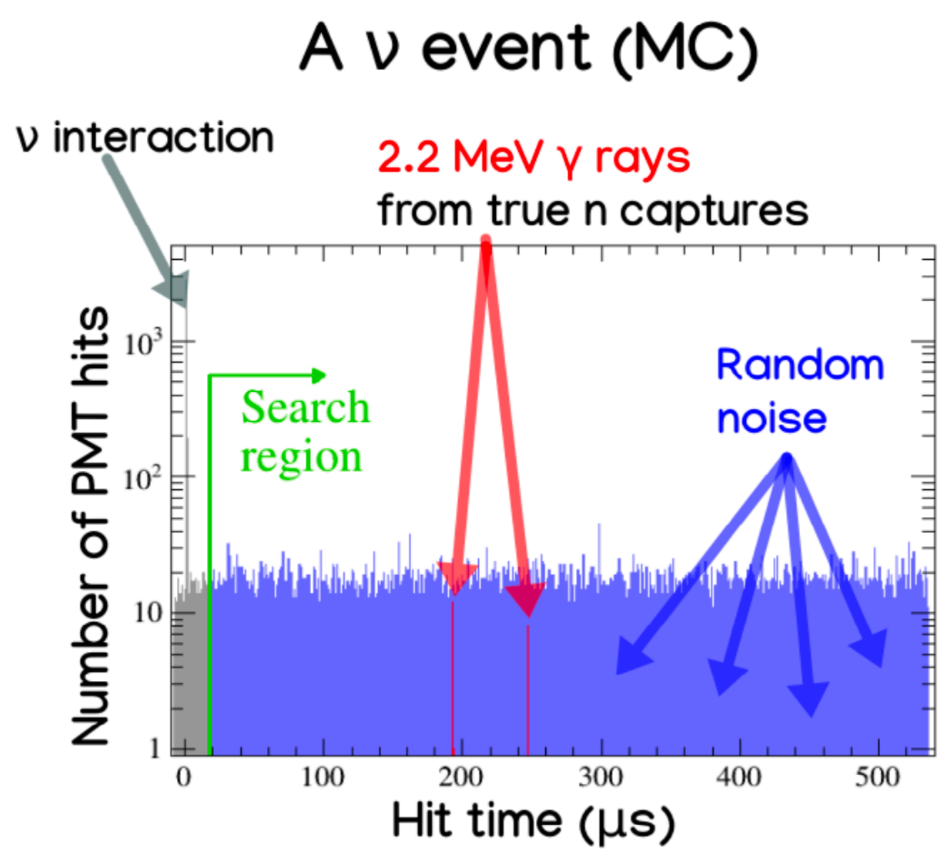

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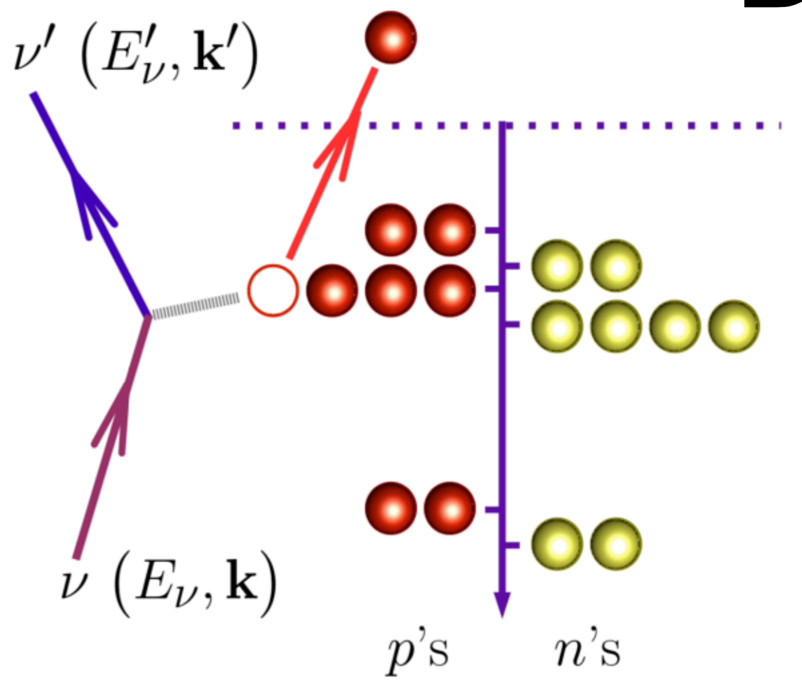

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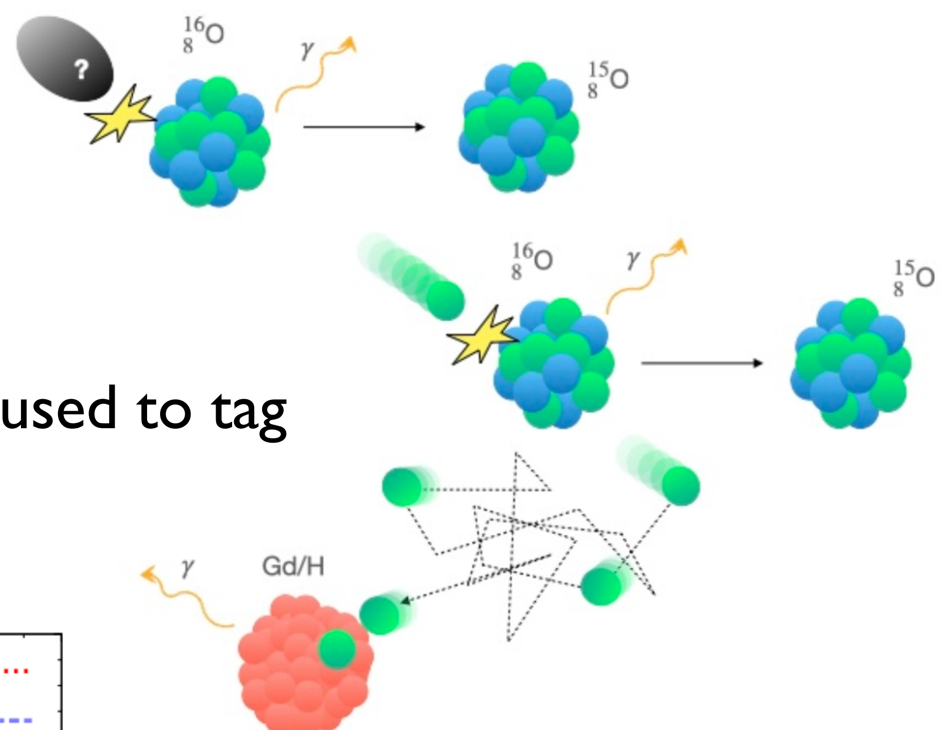
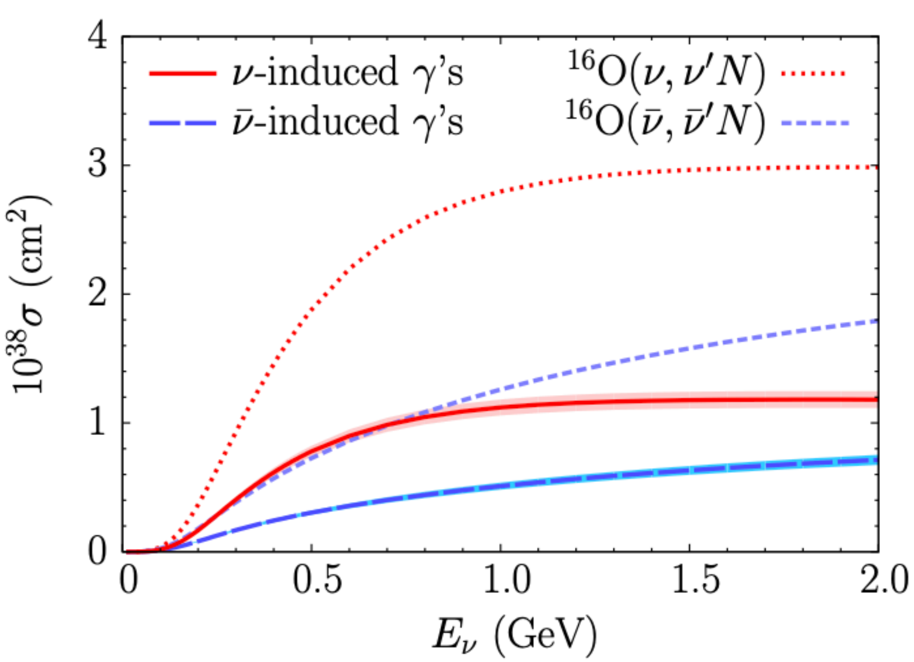


- de-excitation gammas can be used to tag these neutrons



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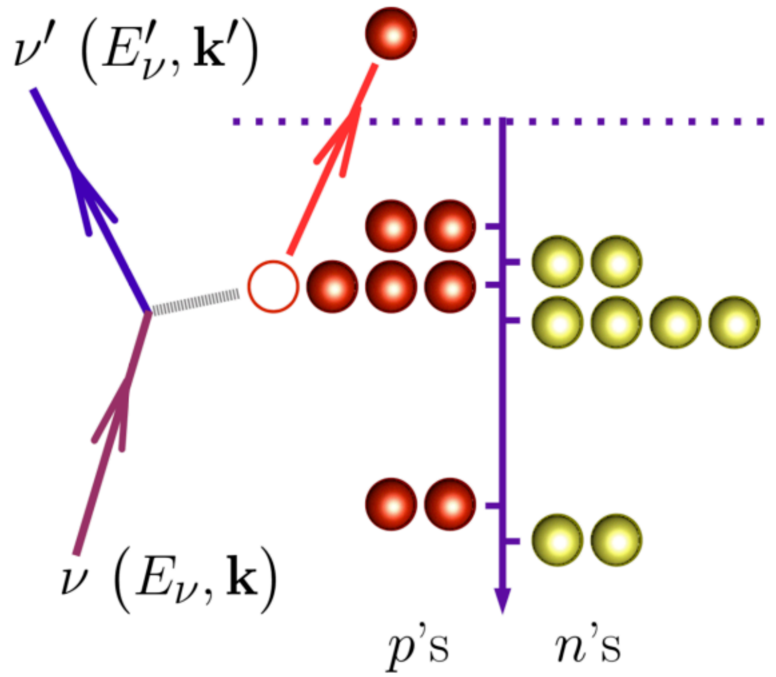
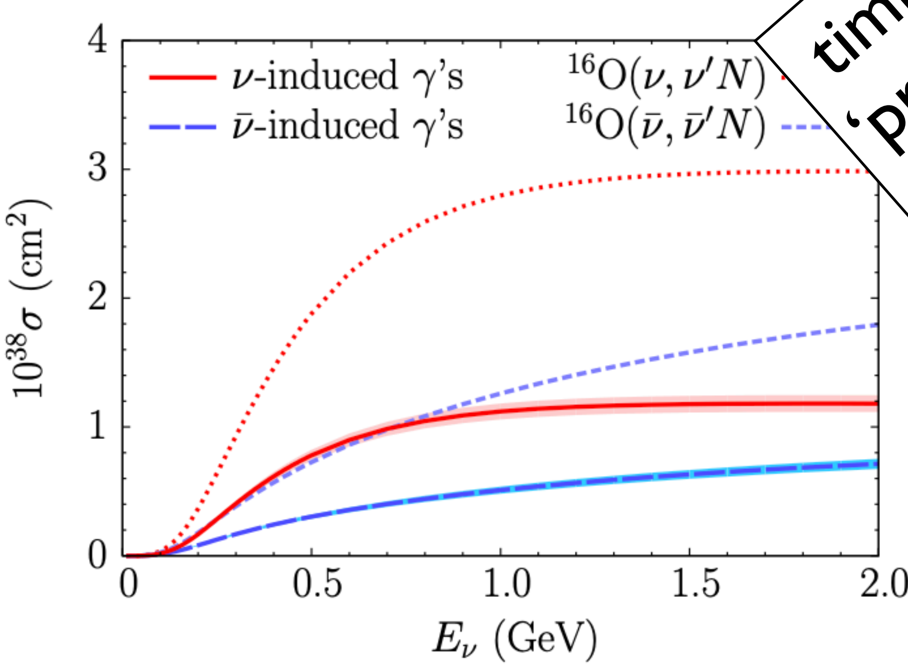


utrons don’t emit Cherenk tion

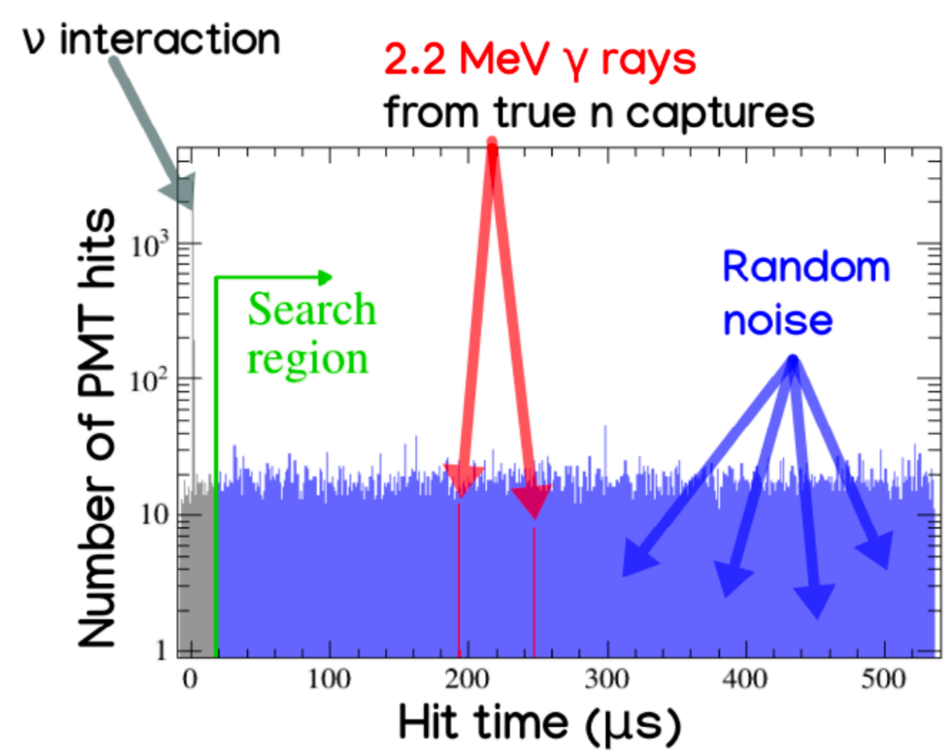
timing and spatial coincidence between ‘prompt gamma’ and ‘delayed neutron’ → can search for rare signals!

- de-excitation gammas can be used to these neutrons



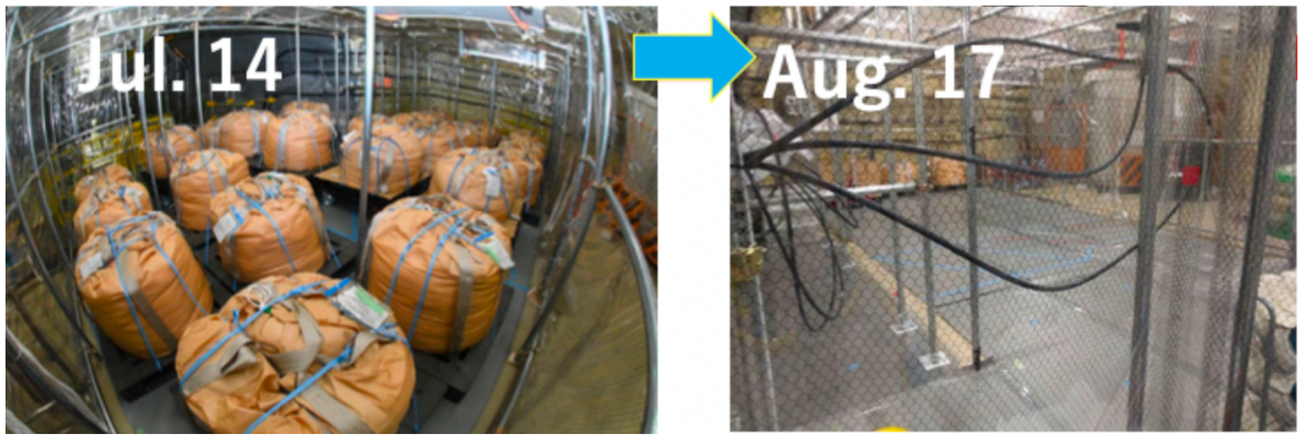
- instead, O(MeV) gammas are emitted when neutrons are captured by a nucleus

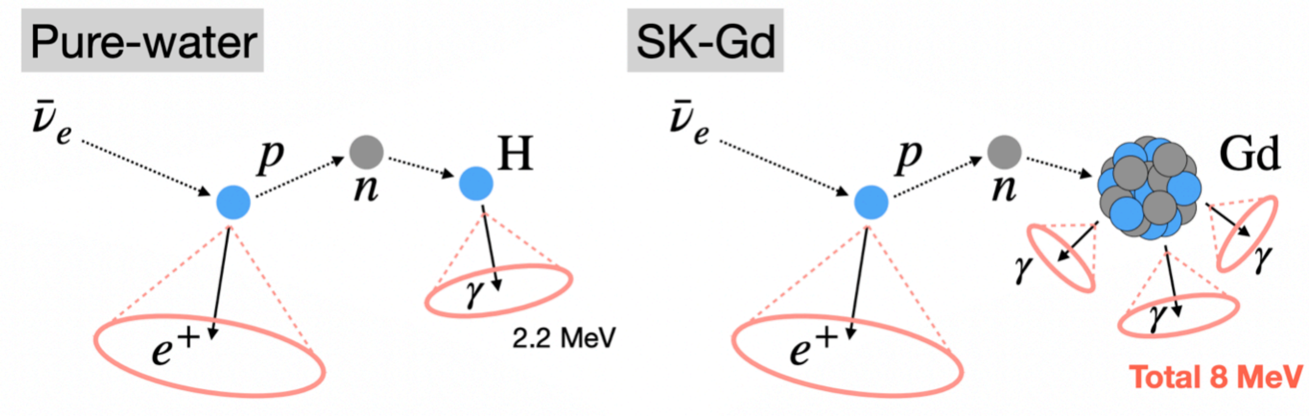
A ν event (MC)



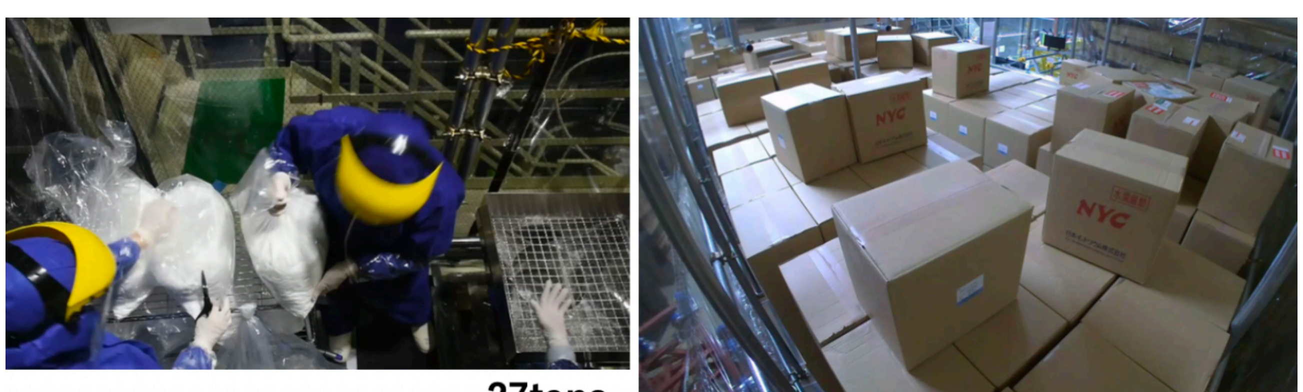
Super-Kamiokande Gadolinium Project (SK-Gd)

The 1st Gd-loading Jul. 14 - Aug. 18, 2020 (35 days to replace 50,000 tons of water at 60 m3/h) → start of SK-VI !

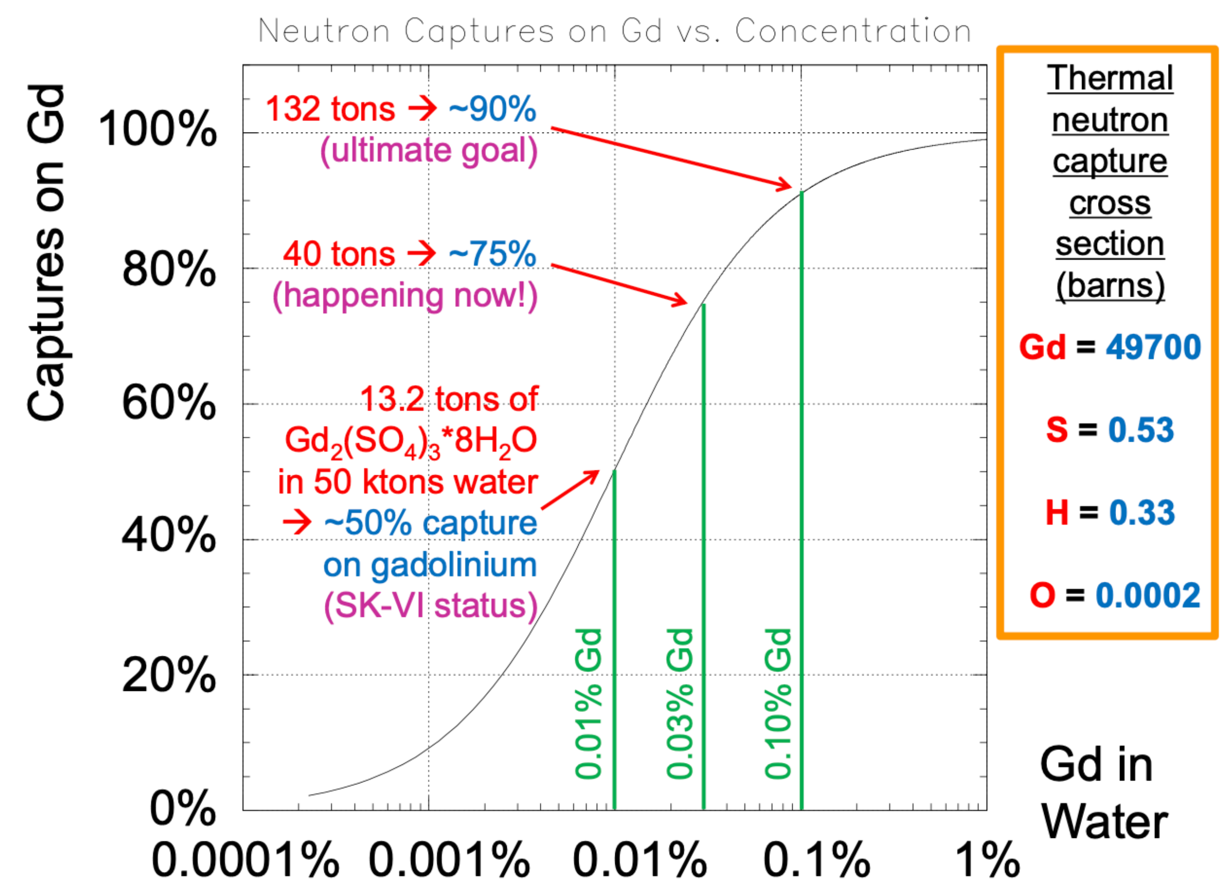




The 2nd Gd-loading Jun. 1 - Jul. 5, 2022 (35 days to replace 50,000 tons of 0.01 Gd water with 0.06% Gd water at 60 m3/h) → start of SK-VII !

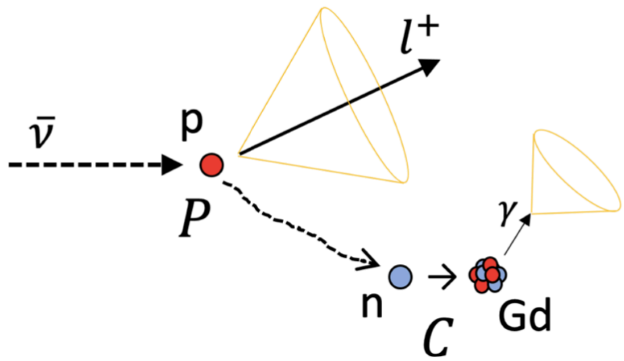


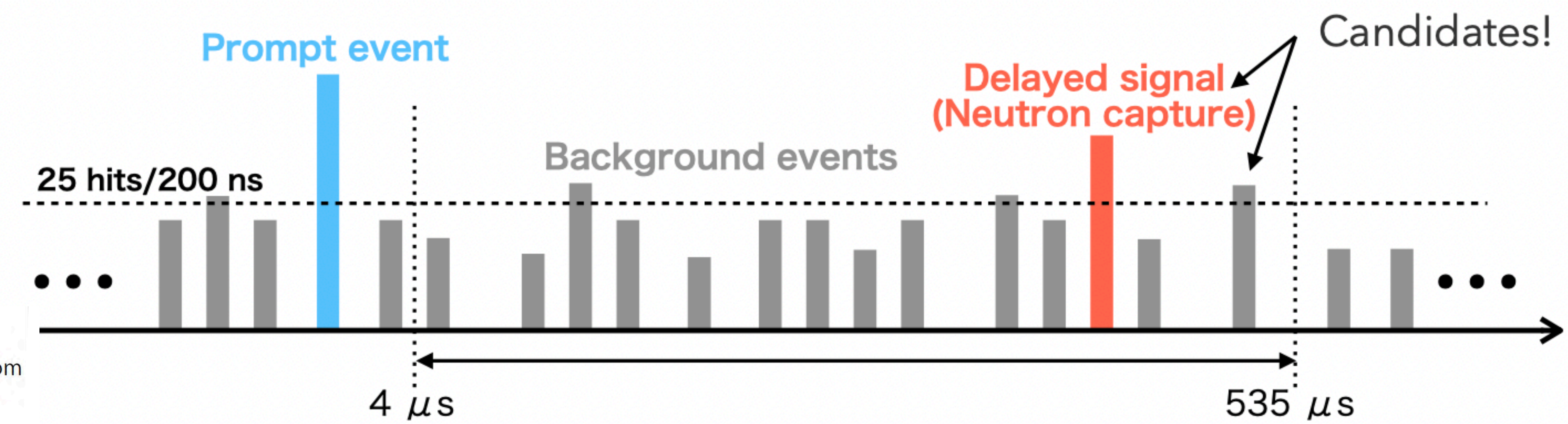
27tons
=1350 x 20kg cardboard boxes!



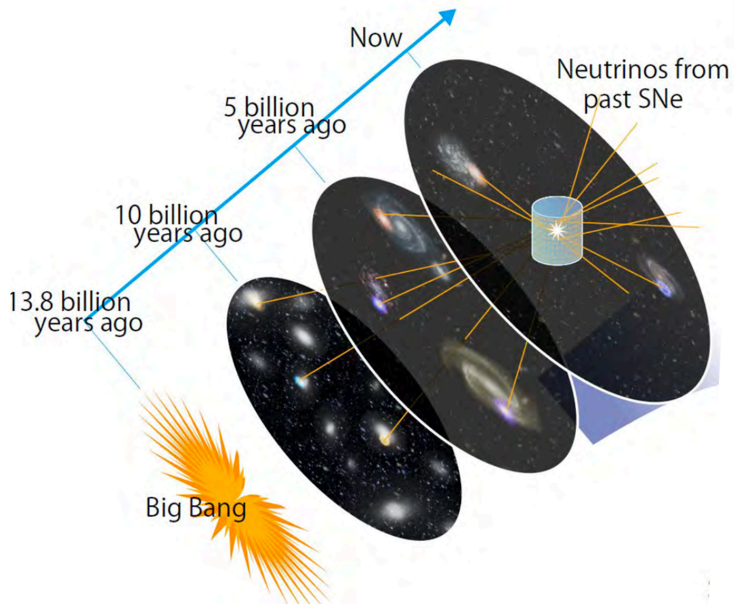
photos taken by H.Sekiya (Yemilab workshop 2022)

Neutron tagging with Gadolinium



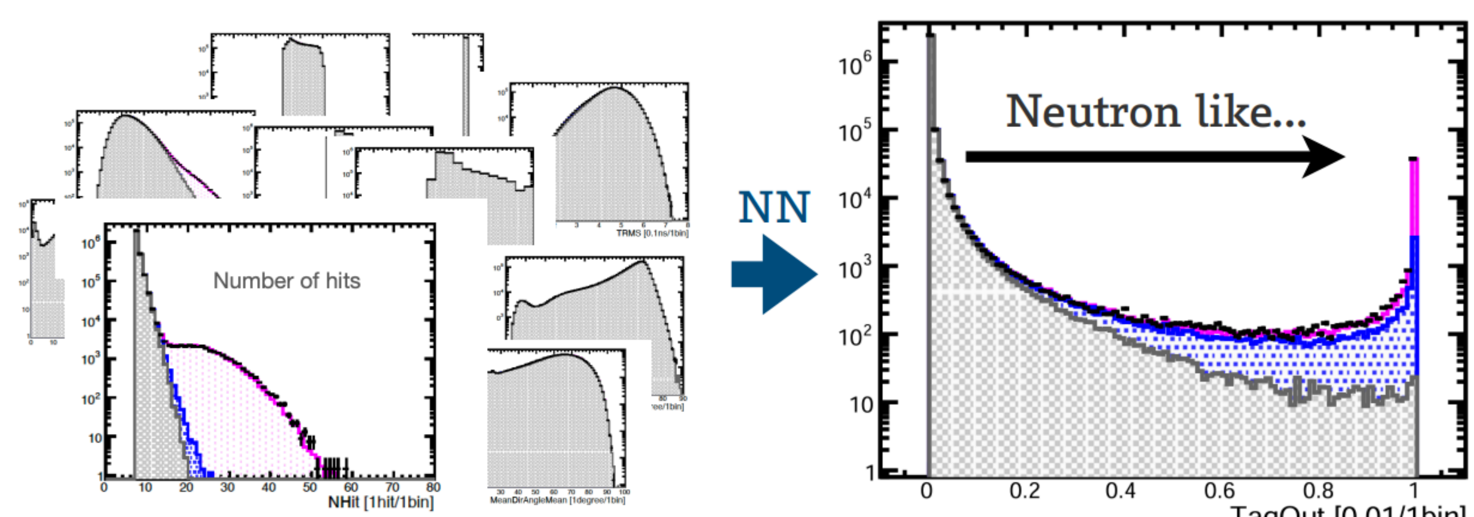


When SHE trigger is issued without an OD trigger, AFT trigger is issued → all hits in the 535 μsec recorded for neutron tagging (reduce BG)



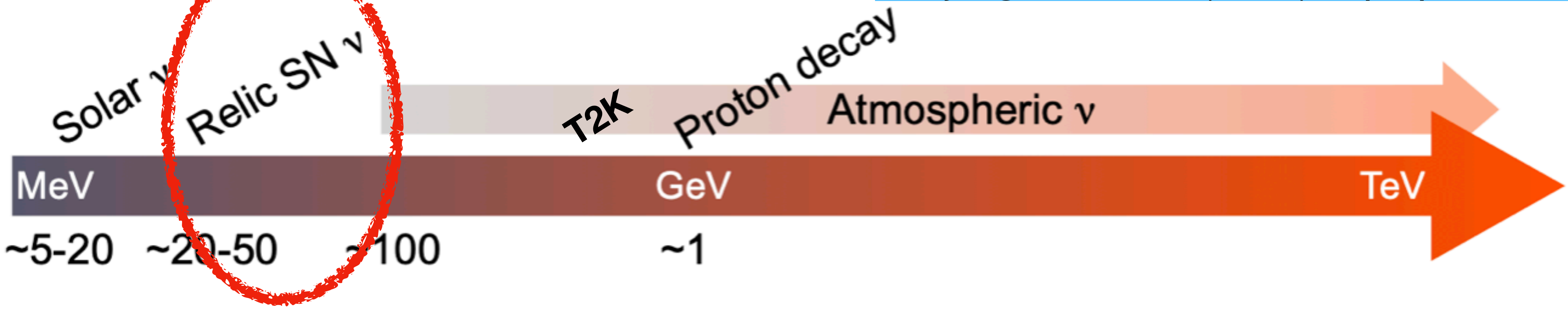
Primary goal for SK-Gd: first observation of DSNB!

new neutron tagging methods based on multi-variate analysis ➡ achieving >60% efficiency in SK-VII



M.Harada, @Neutrino2024

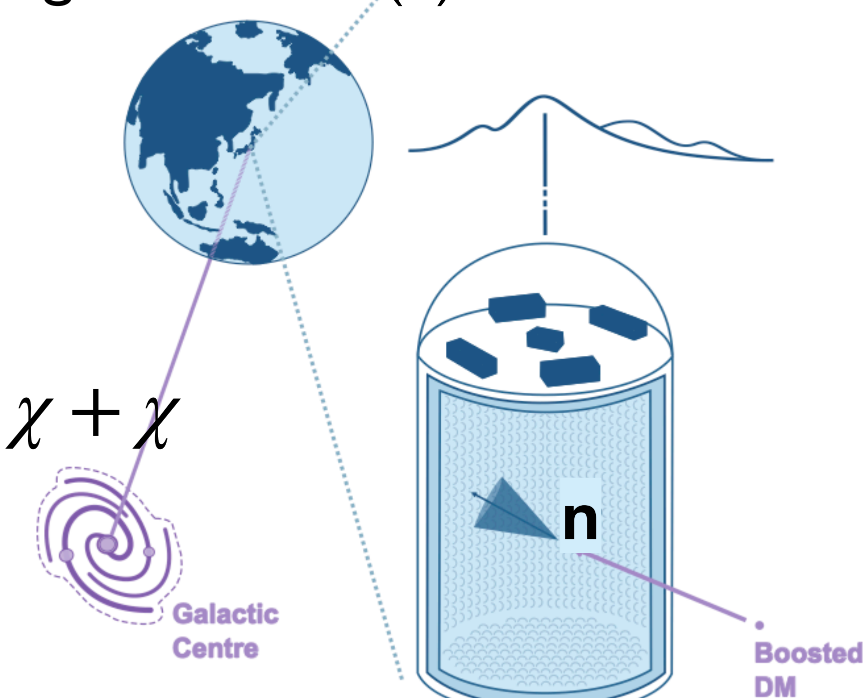
KC, Jong-Chul Park (CNU) in preparation

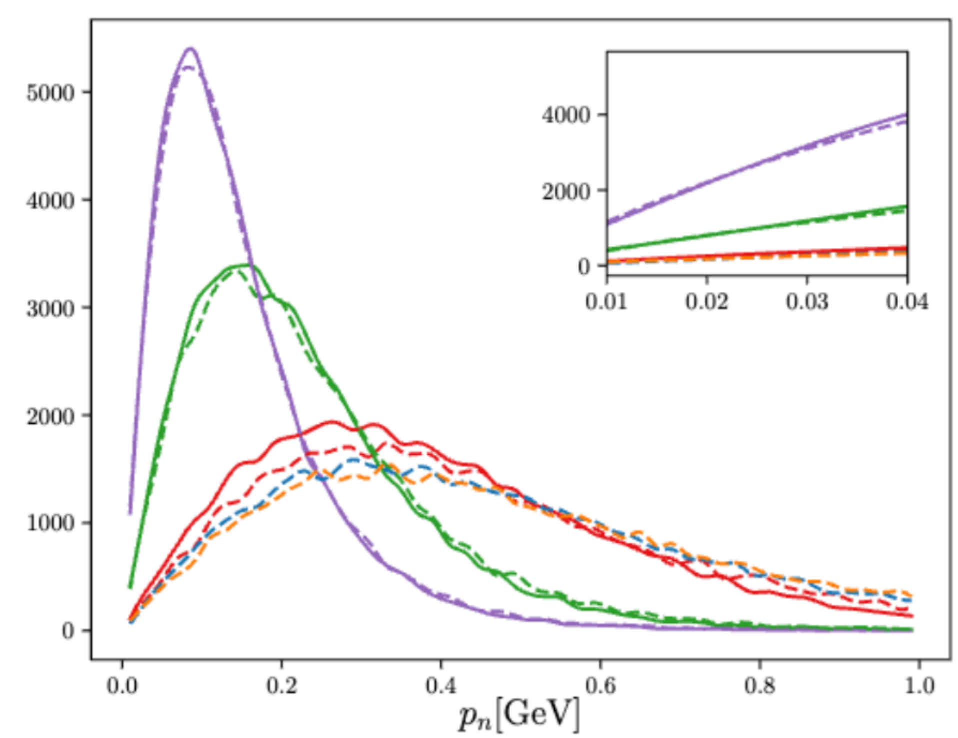


Search for de-excitation γ + neutron pair

- Promote SM baryon number symmetry to gauge symmetry; SU(3)C ⊗ SU(2)L ⊗ U(1)Y ⊗ U(1)B
- A,B are charged under U(1)’
- dark matter B is charged under U(1)B, can talk to SM

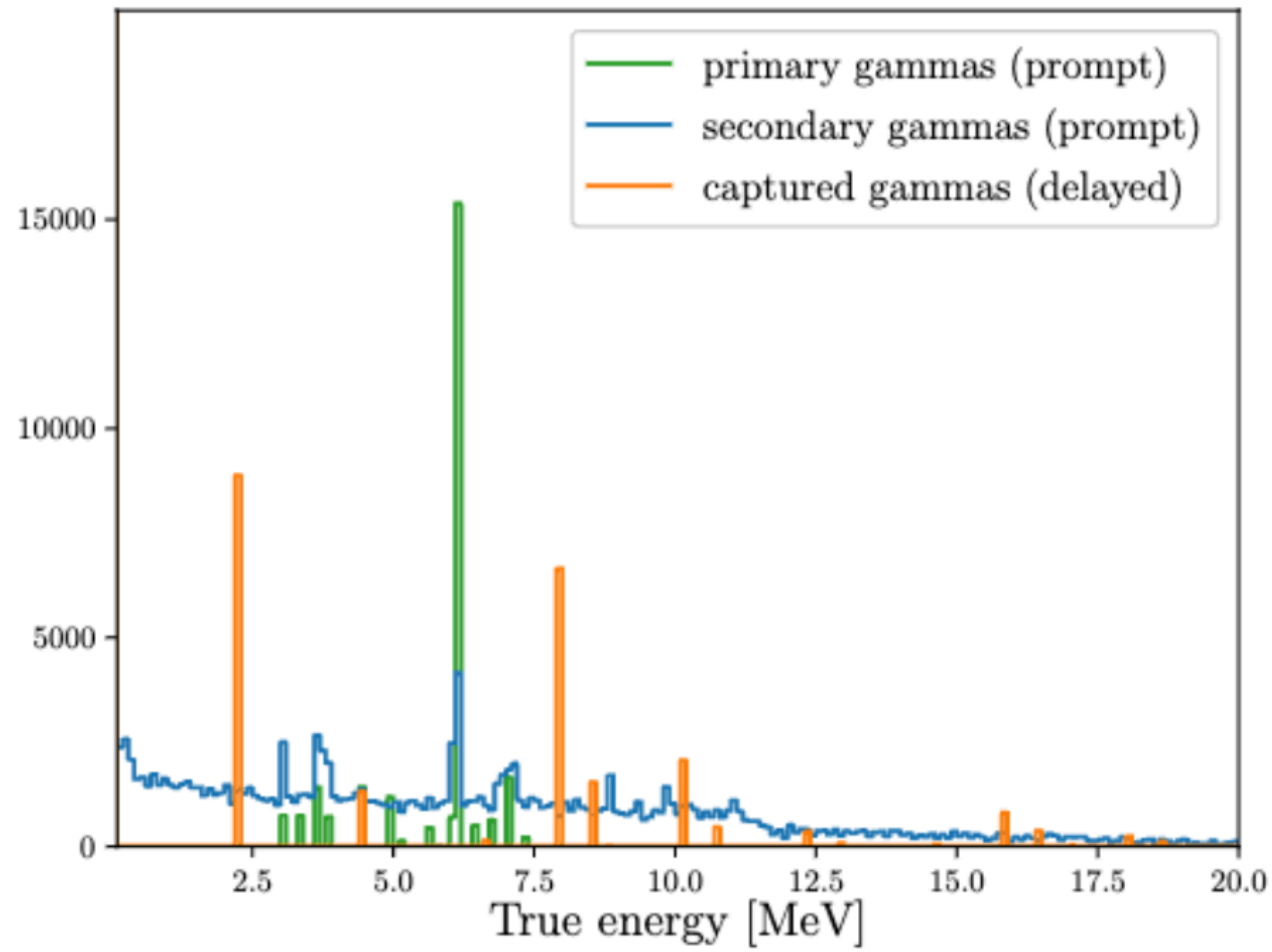
$$\chi_0 + \chi_0 \rightarrow \chi + \chi$$



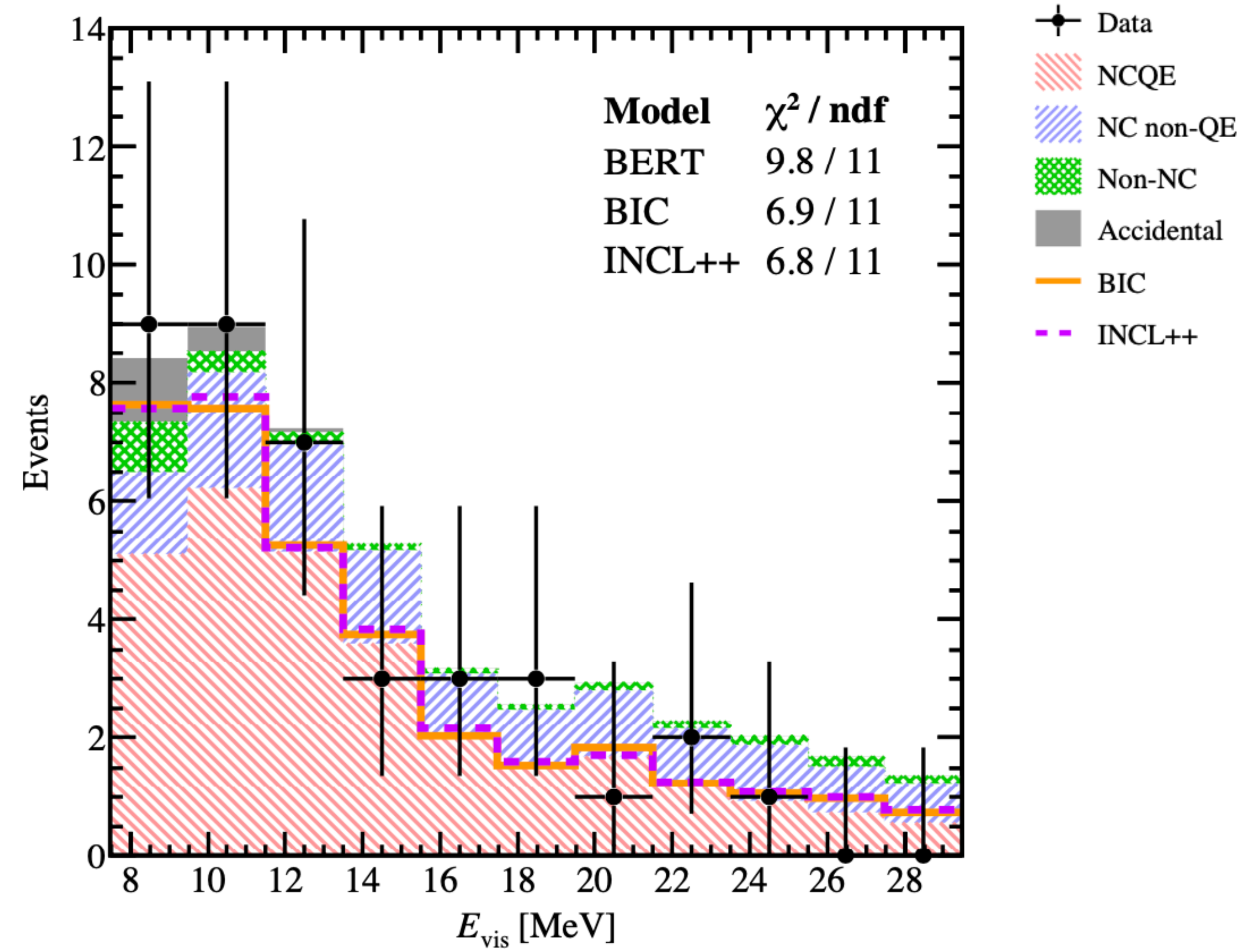


$$\chi +^{16}_{8} O \rightarrow \chi + n +^{15}_{8} O*$$

Signal simulation: BdNMC (https://github.com/pgdeniverville/BdNMC) +NEUT + WCSim (https://github.com/WCSim)



Background (mostly atm ν) simulation: *Phys.Rev.D* 109 (2024) 1, L011101

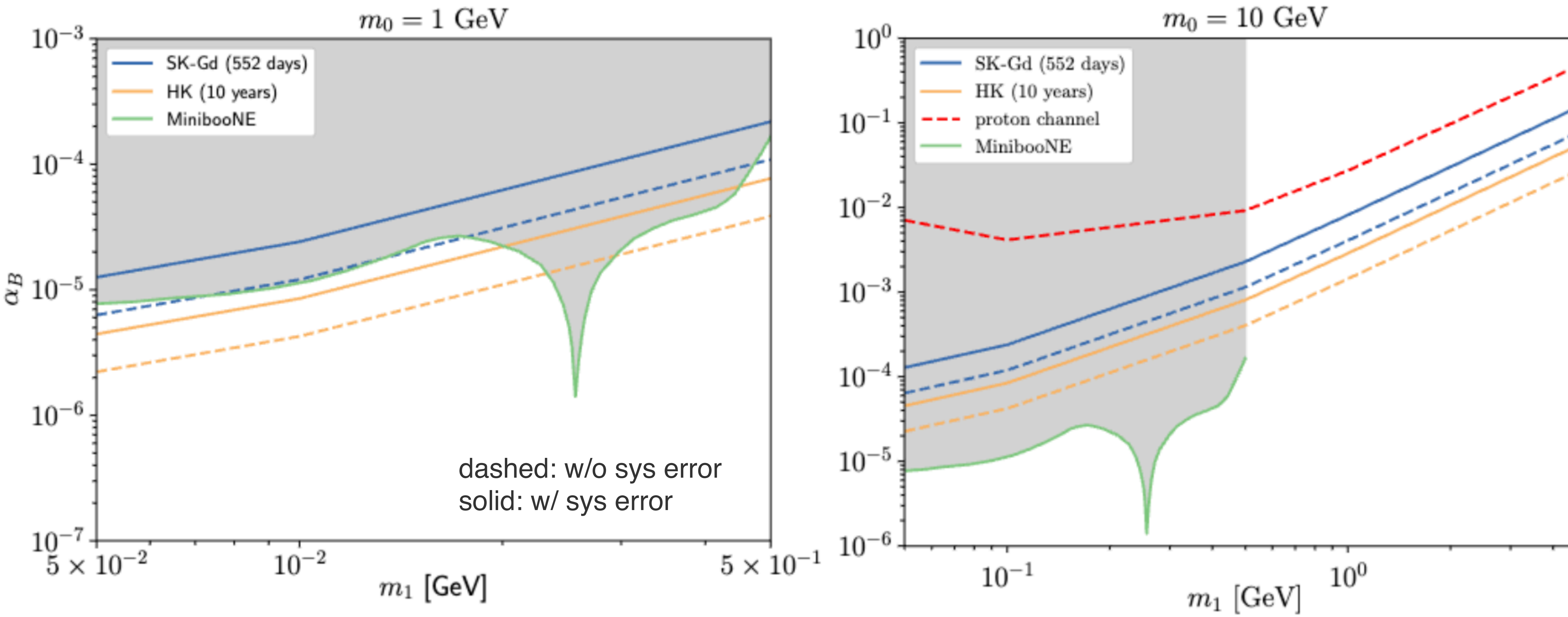


- pros: observable energy is not function of DM physics *
- cons: observable energy is not function of DM physics

* γ energy is always ~O(10) MeV irrelevant to the momentum transfer, no Cherenkov threshold concerned here

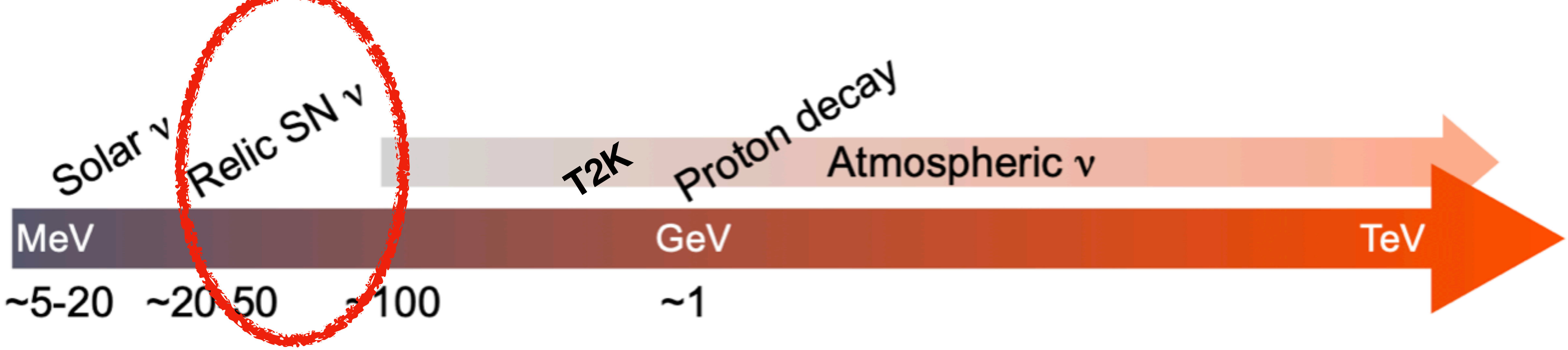
KC, Jong-Chul Park (CNU) in preparation

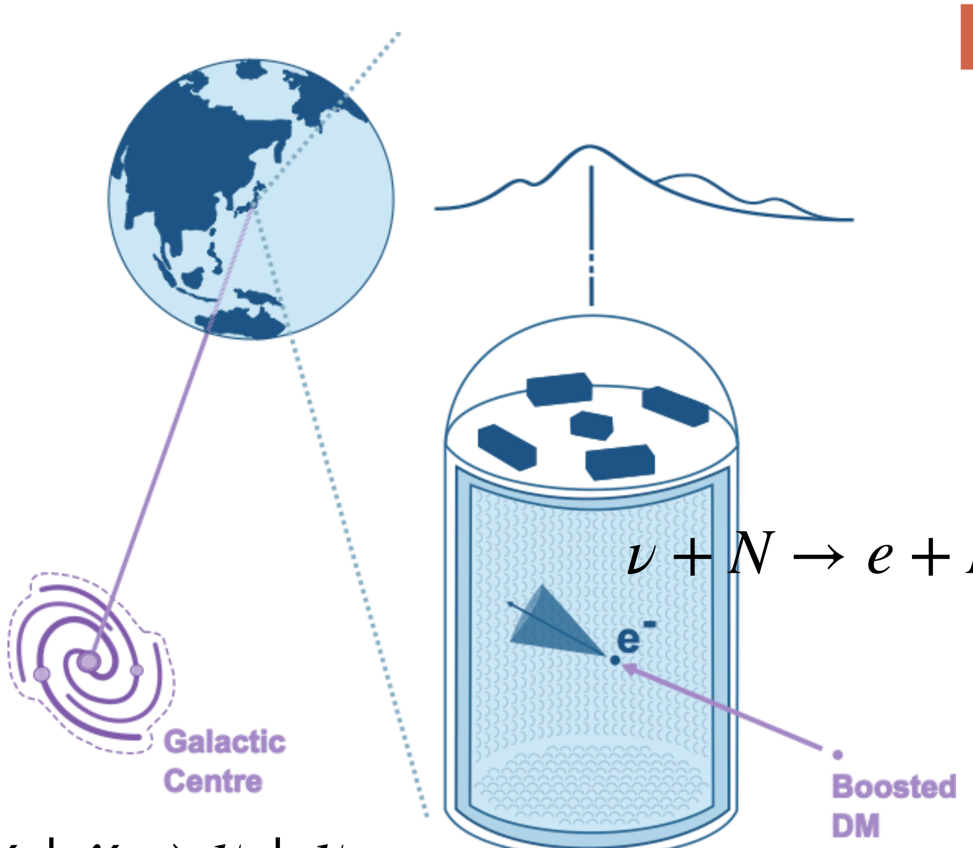
Sensitivity for SK-VI (552 days)



- neutrons enhance sensitivity by an order of magnitude compared to recoiled protons
- neutrons allow to explore a wider range of (in particular low-mass) DM models that could not be accessed using protons

MinibooNE: *Phys.Rev.D* 98 (2018) 11



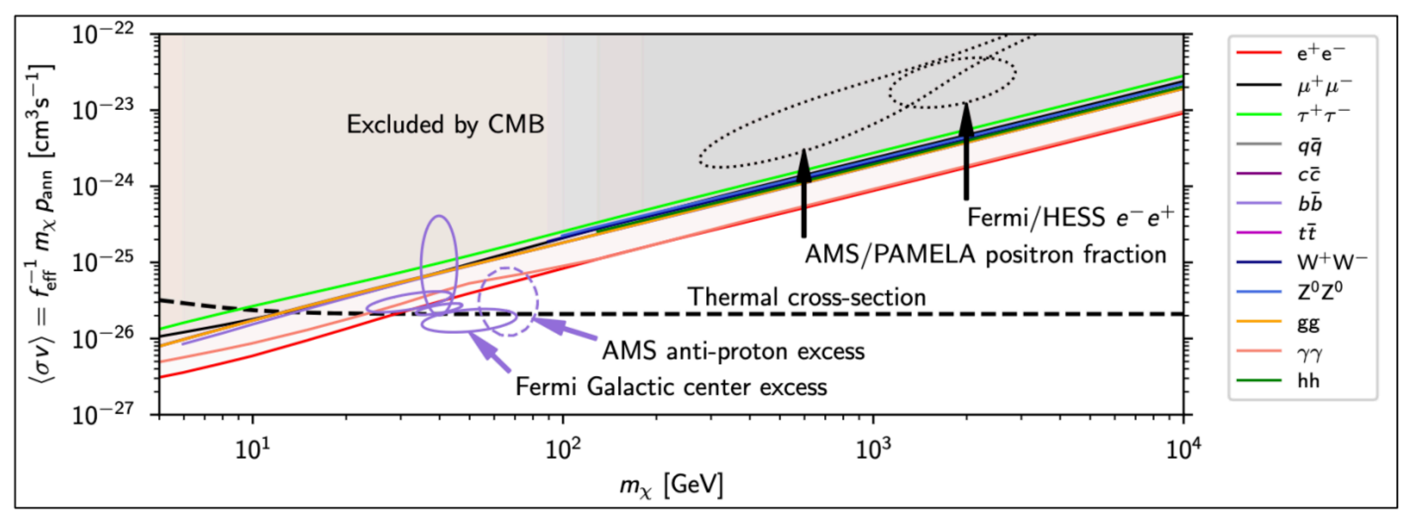


$$\nu + N \rightarrow e + N'$$

$$\chi + \chi \rightarrow \nu + \nu$$

Dark Matter Annihilation in the Era of Recombination

- The angular power spectrum of the CMB is highly sensitive to any energy that may have been injected into the universe during the era of recombination
- Planck data has been used to exclude dark matter candidates with velocity-independent (s-wave) annihilation cross sections lighter than ~10-30 GeV (unless they annihilate mostly to neutrinos)



Planck, arXiv:1807.06209

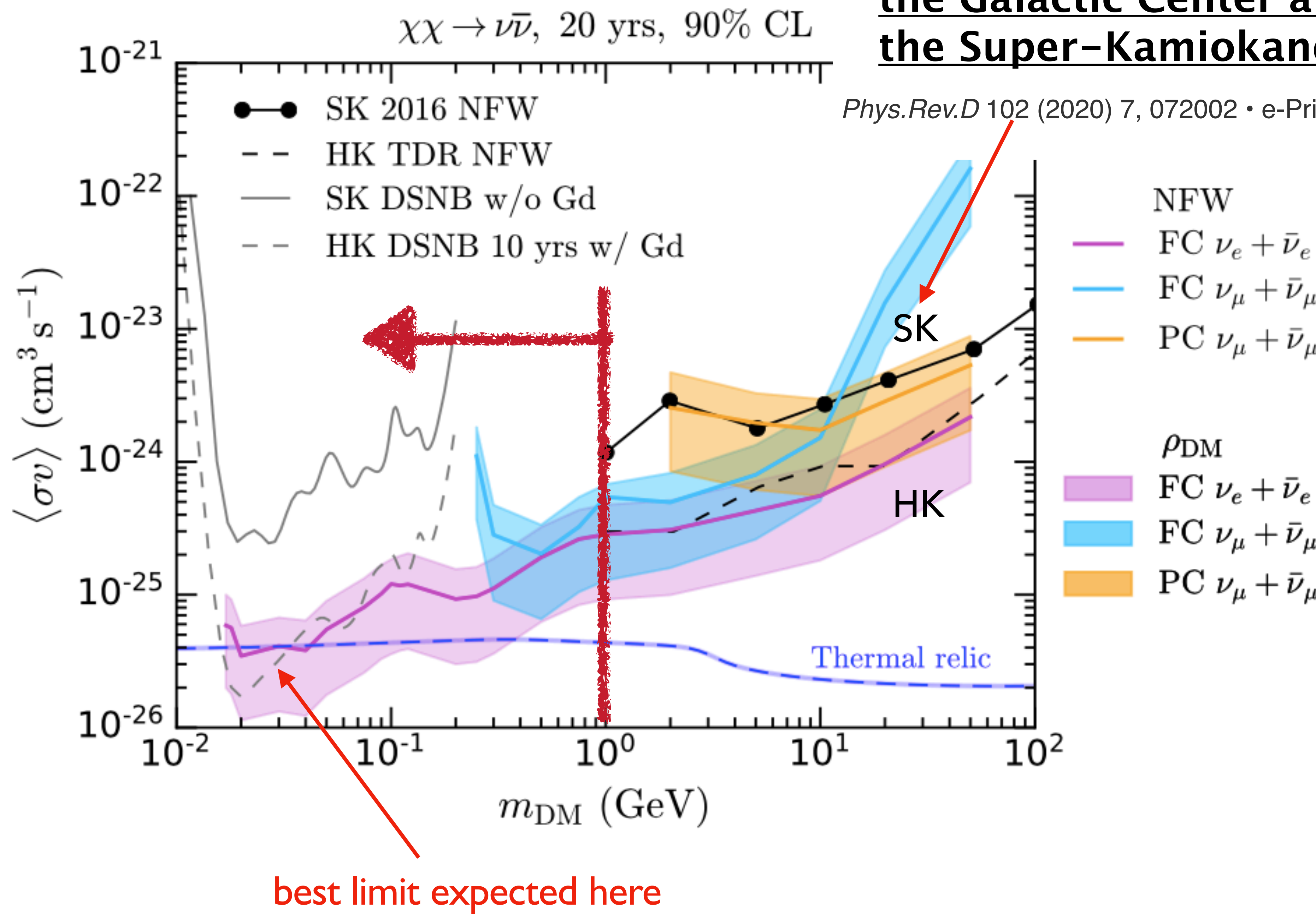
Dan Hooper, @IDM2024

Sub-GeV DM annihilation to neutrinos

N.Bell et al., JCAP 09 (2020) 019 • e-Print: 2005.01950 [hep-ph]

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

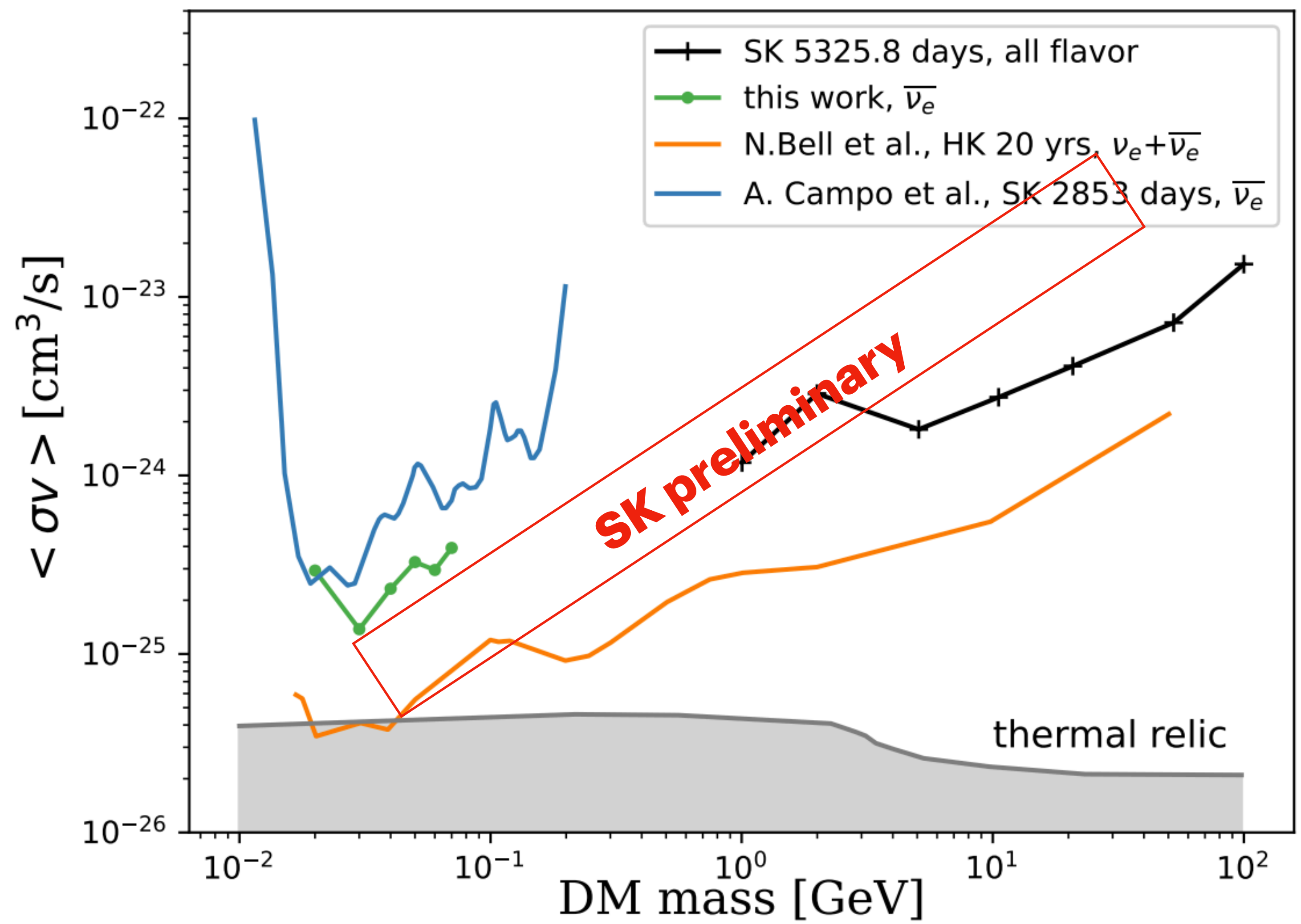
Phys.Rev.D 102 (2020) 7, 072002 • e-Print: 2005.05109 [hep-ex]



Goal: examine simple thermal freeze out scenario for s-wave annihilation with neutrinos
Hope: reach the thermal relic cross-section using SK & SK-Gd data,
or demonstrate HK can do it!

Sub-GeV DM annihilation to neutrinos

5325.8 days SK sensitivity



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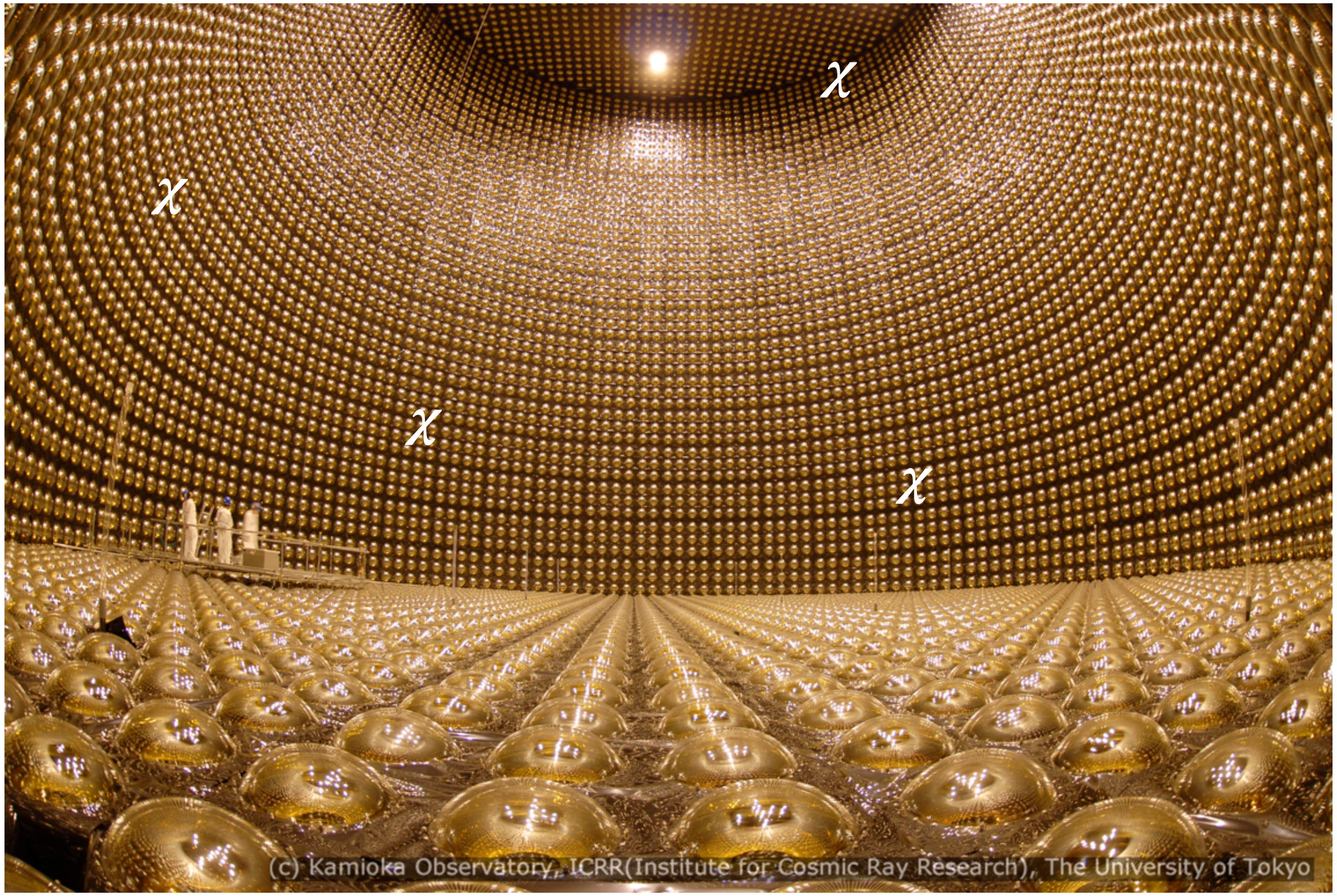
Conclusion



- SK already has a data ready for leading dark matter searches
- SK-Gd offers new opportunity for DM search
- Results & techniques developed for SK DM searches highlight the HK as multipurpose detector

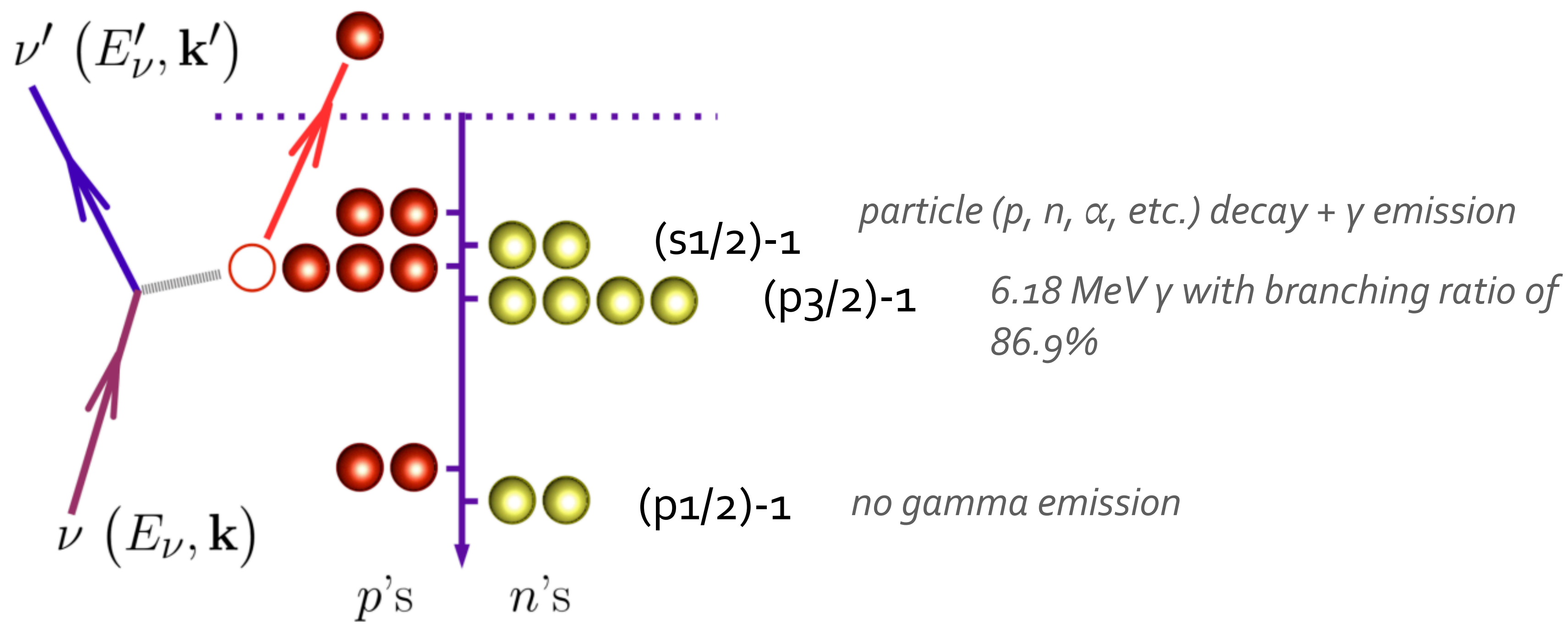
Back Up

A. M. Ankowski, Phys. Rev. Lett. 108, 052505 (2012)

KC, Jong-Chul Park (CNU) in preparation

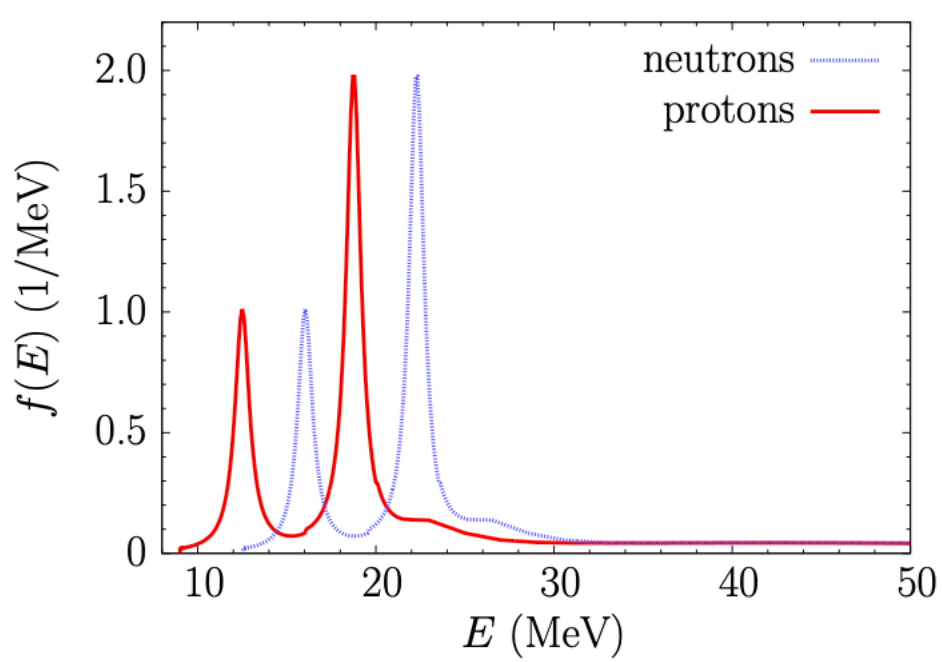
Nuclear de-excitation Gamma-rays

simple shell model:
$(p1/2)^{-1}$: removal E = 17.6MeV
$(p3/2)^{-1}$: removal E = 21.9MeV
$(s1/2)^{-1}$: removal E ~ 45MeV



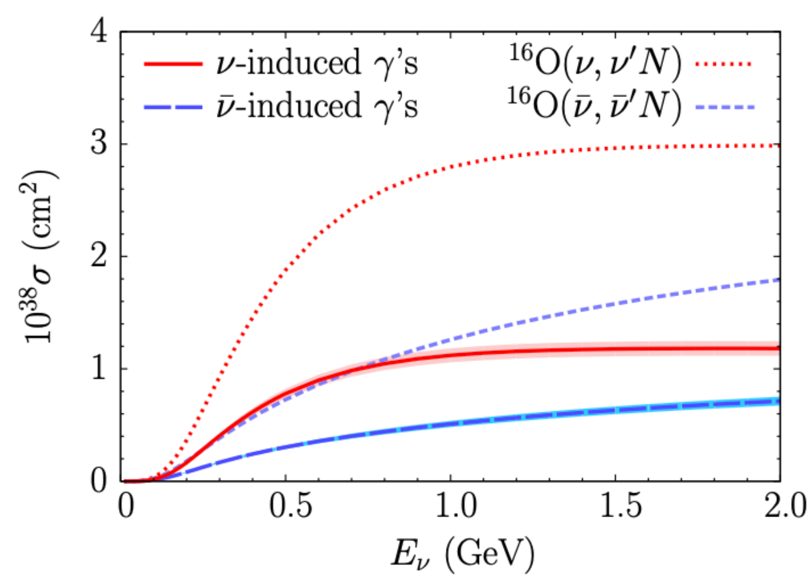
$$\sigma_\gamma \equiv \sigma(\nu + {}^{16}_{8}\mathrm{O} \to \nu + \gamma + Y + N)$$
$$= \sum_\alpha \sigma(\nu + {}^{16}_{8}\mathrm{O} \to \nu + X_\alpha + N)\,\mathrm{Br}(X_\alpha \to \gamma + Y)$$

Spectroscopic function: removal probability for each shell state ~ integrated area



	Simple shell model	Ankowski et.al.
$P_{1/2}$	0.25	0.158
$P_{3/2}$	0.50	0.3515
$S_{1/2}$	0.25	0.1055
Others	0	0.385

Theoretical calculation (LDA approximation) based on the O(e, e'p) experiment in JLab



emission of γ rays of energy larger than 6 MeV is ~41% (contribution of the (p3/2) state is overwhelming)

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Signal simulation

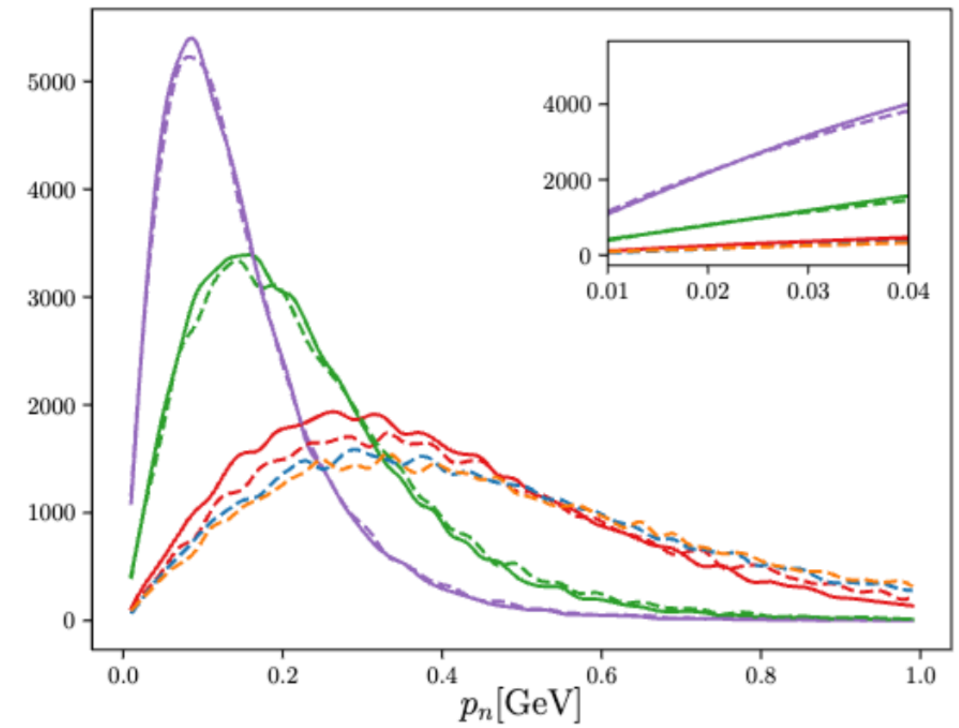
DM signal simulation:

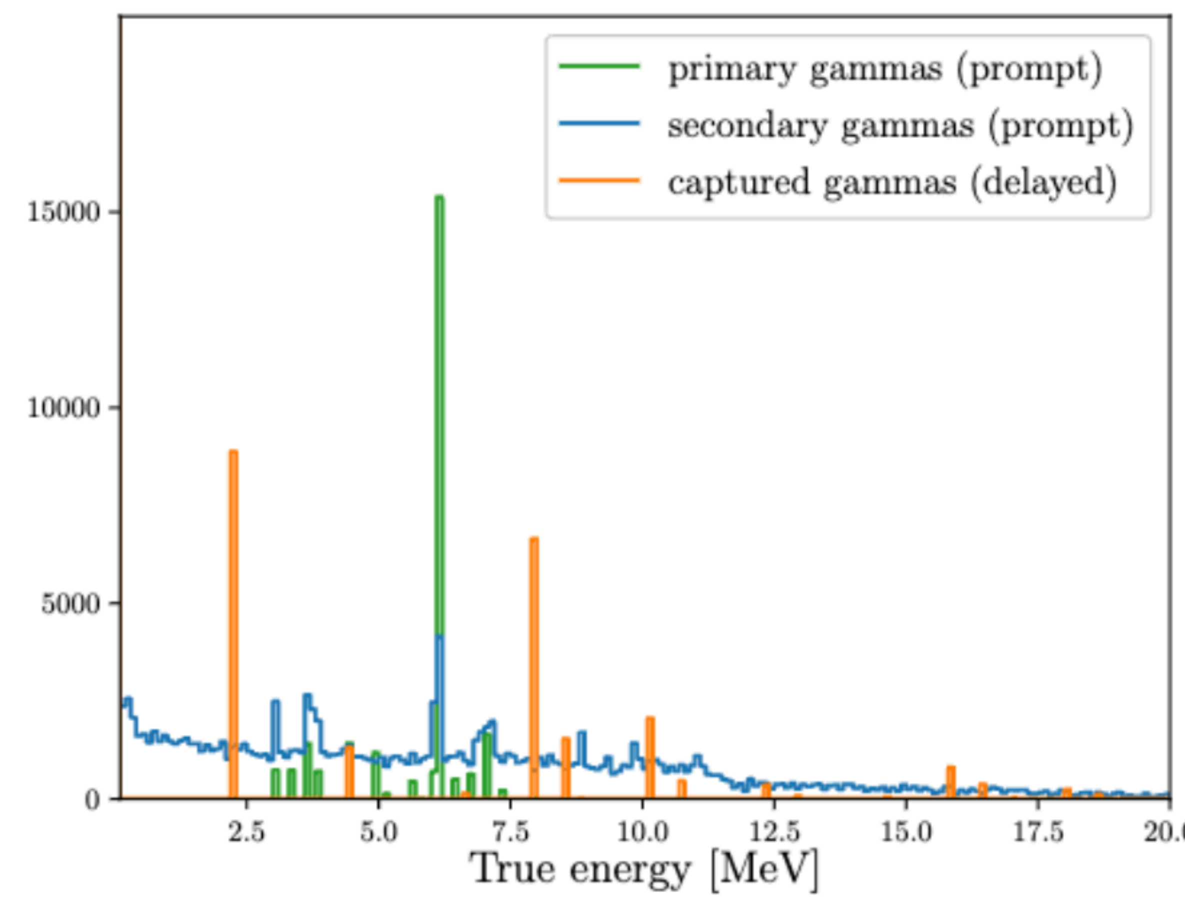
BdNMC (https://github.com/pgdeniverville/BdNMC): calculates dark matter-nulceon scattering events for a two-component DM charged under the gauged baryon number symmetry $U(1)_B$

+ NEUT (partially public): a neutrino-nucleus interaction simulation, including nuclear effects such as nuclear binding energy and final state interactions (FSI)

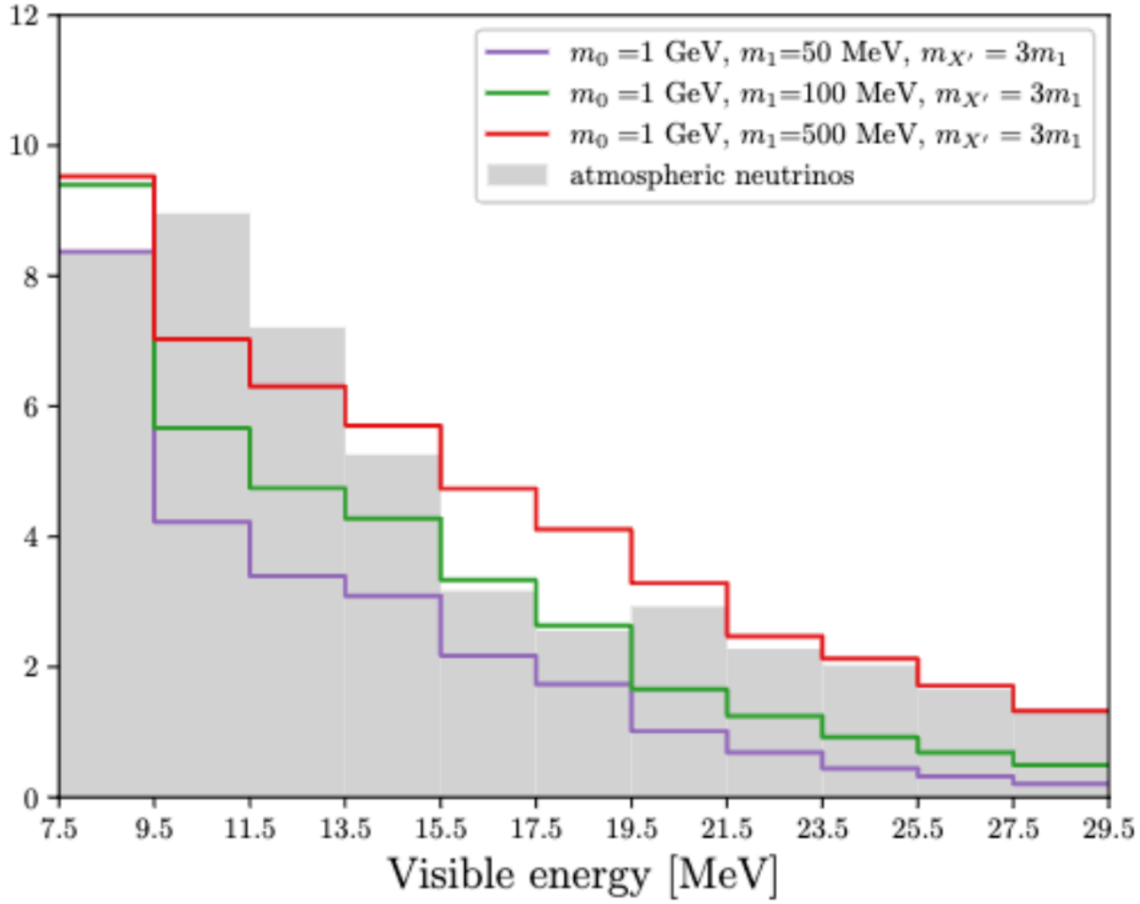
+ WCSim (https://github.com/WCSim): a GEANT4-based program for simulating particle propagation in 0.1% gadolinium-doped water, including secondary interactions + capture processes of neutrons (FTFP BERT HP model)

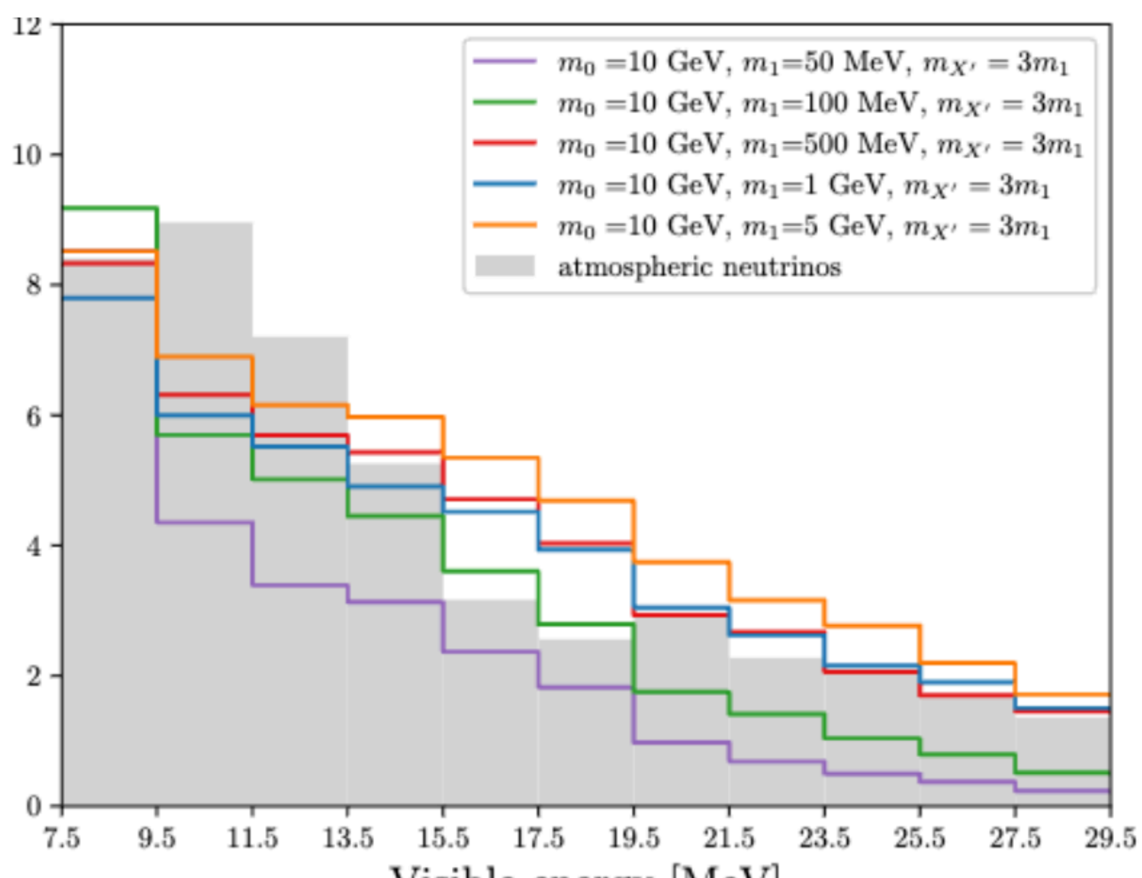
m_A [GeV]	m_B [GeV]
10	0.05
10	0.1
10	0.5
10	1
10	5
1	0.05
1	0.1
1	0.5





Signal





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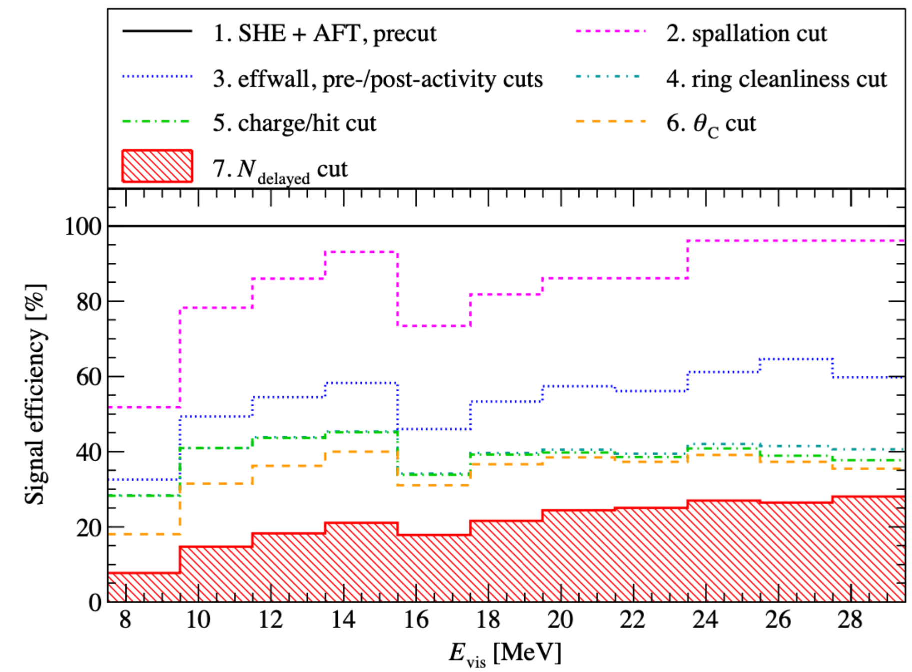

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m_A [GeV]	m_B [GeV]	signal fraction in [7.49-29.49] MeV [%]	signal collection efficiency [%]
10	0.05	64	12
10	0.1	72	14
10	0.5	79	16
10	1	79	17
10	5	80	17
1	0.05	65	12
1	0.1	72	14
1	0.5	78	16