The SK-Gd Experiment

A New Experimental Phase to Search for Supernova Relic Neutrinos

Okayama University Shintaro Ito

My Research History

- **Apr. 2011. The PIENU Experiment at TRIUMF in Canada.**
  - Precise measurement of the pion branching ratio <0.1%.

    Phys. Rev. Lett. 115 071801 (2015), final result is coming soon.

    Nucl. Instrum. Methods Phys. Res., Sect. A 609, 102 (2015).
  - Another new physics; heavy neutrinos, neutral bosons, etc.

    Phys. Rev. D 97, 072012 (2018), Phys. Lett. B 798 (2019)134980,

    Phys. Rev. D 101, 052014 (2020), Phys. Rev. D 102, 012001 (2020).

    KAKENHI Grant-in-Aid for Scientific Research (C)

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  - Preparations for the new experiment "SK-Gd".
  - Neutrino analyses.
    - ✓ Atmospheric neutrinos: Astrophysical neutrinos.
      - ➡ Solar Physics Journal (arXiv:1909.10715)
    - ✓ Solar neutrinos: Detector calibration, systematic studies.

- **Jul. 2020. New experimental phase "SK-Gd" !!!!!**

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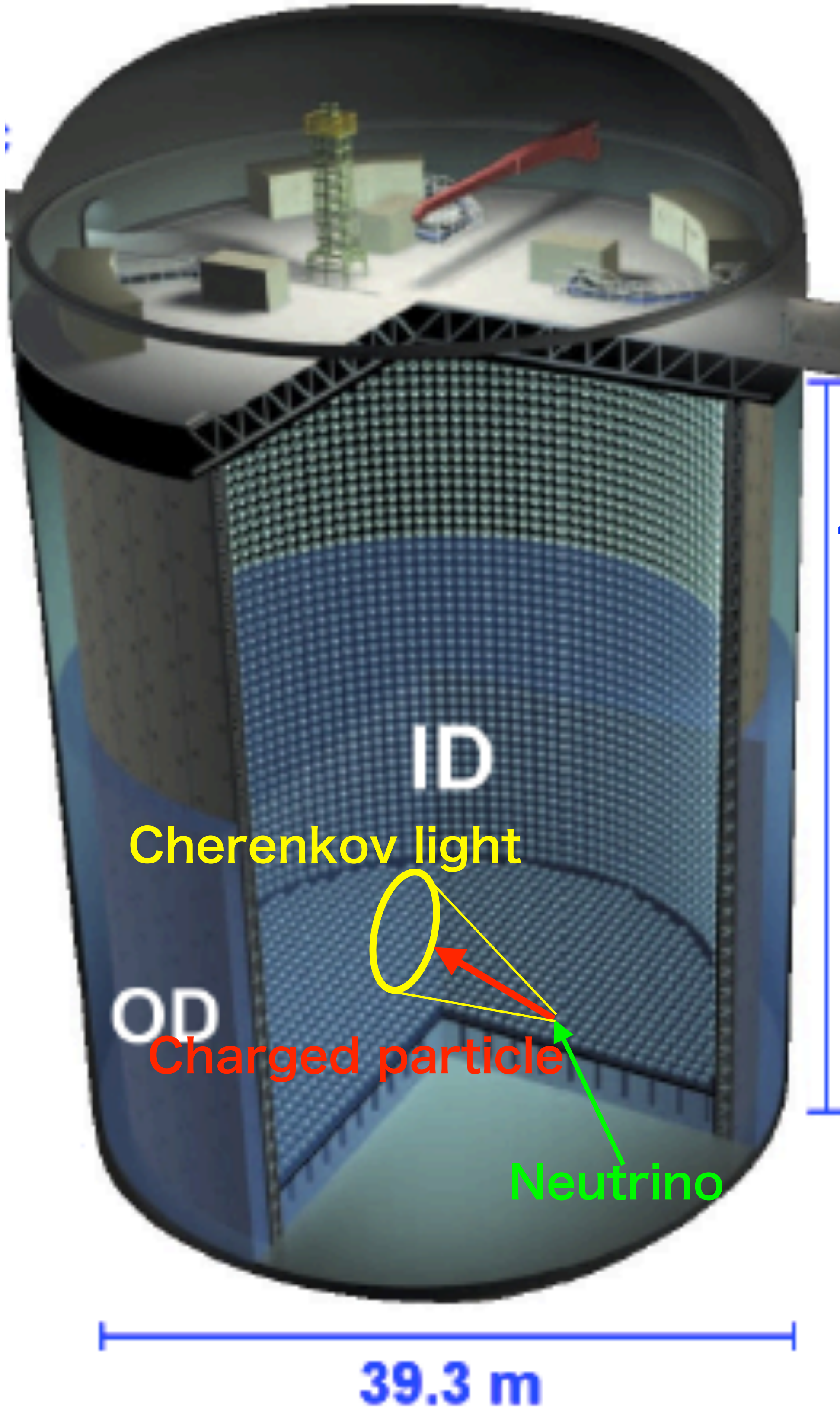
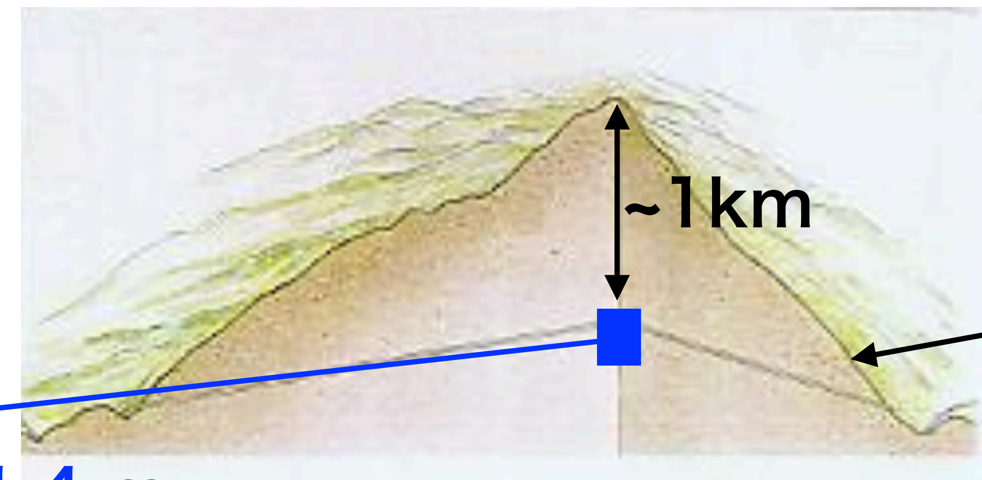
Super-Kamiokande (SK)



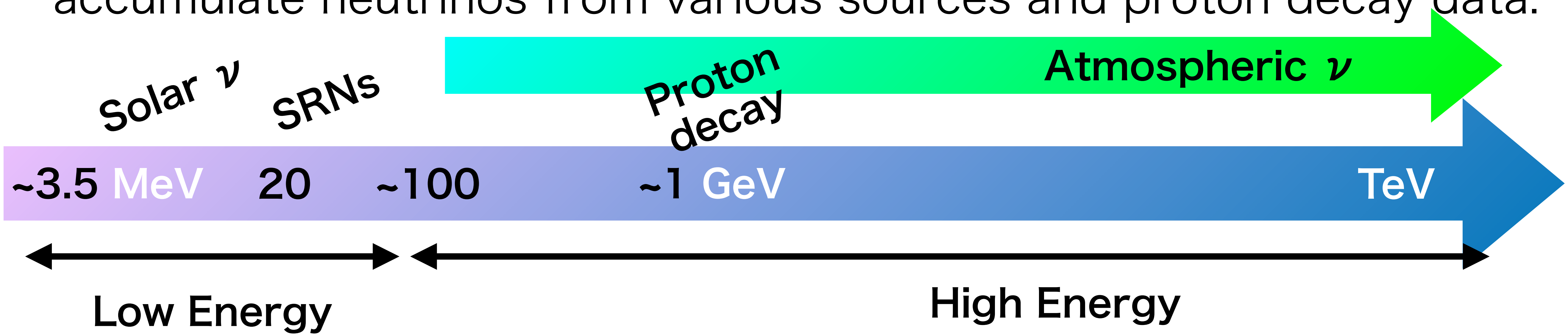


- ~1km underground the Mt.-Ikenoyama
  50kton of pure water Cherenkov detector.
- **Inner detector (ID)**: 11,126 20-inch PMTs
  ➡ 22.5 kton of fiducial volume.
- **Outer detector (OD)**: 1,885 8-inch PMTs
  ➡ For veto of incoming cosmic rays

Particle ID using Cherenkov ring's pattern, opening angle, and showering-type.

History of Super-Kamiokande Experiment

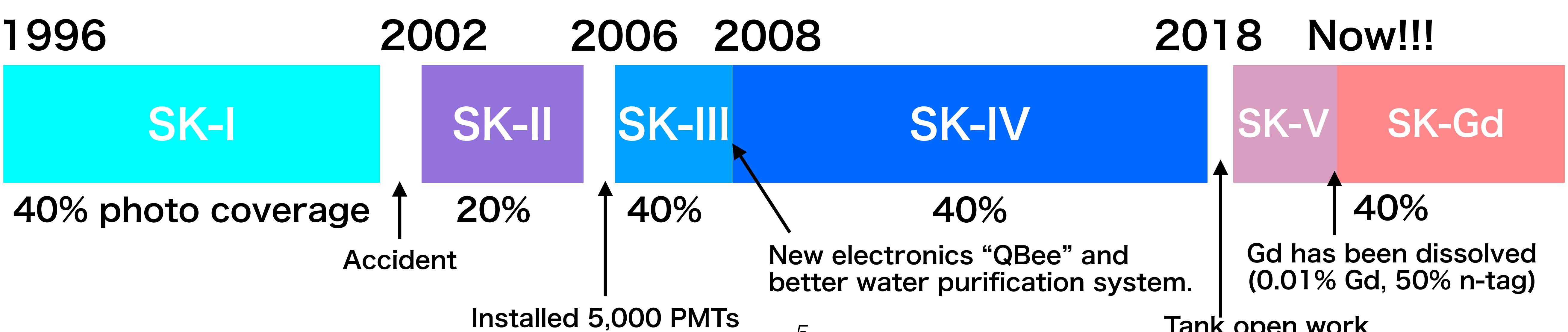
- Since April 1996, the SK experiment has been started to accumulate neutrinos from various sources and proton decay data.



- The SK experiment has several experimental phases.

  ➡SK-I~SK-V: pure water phase

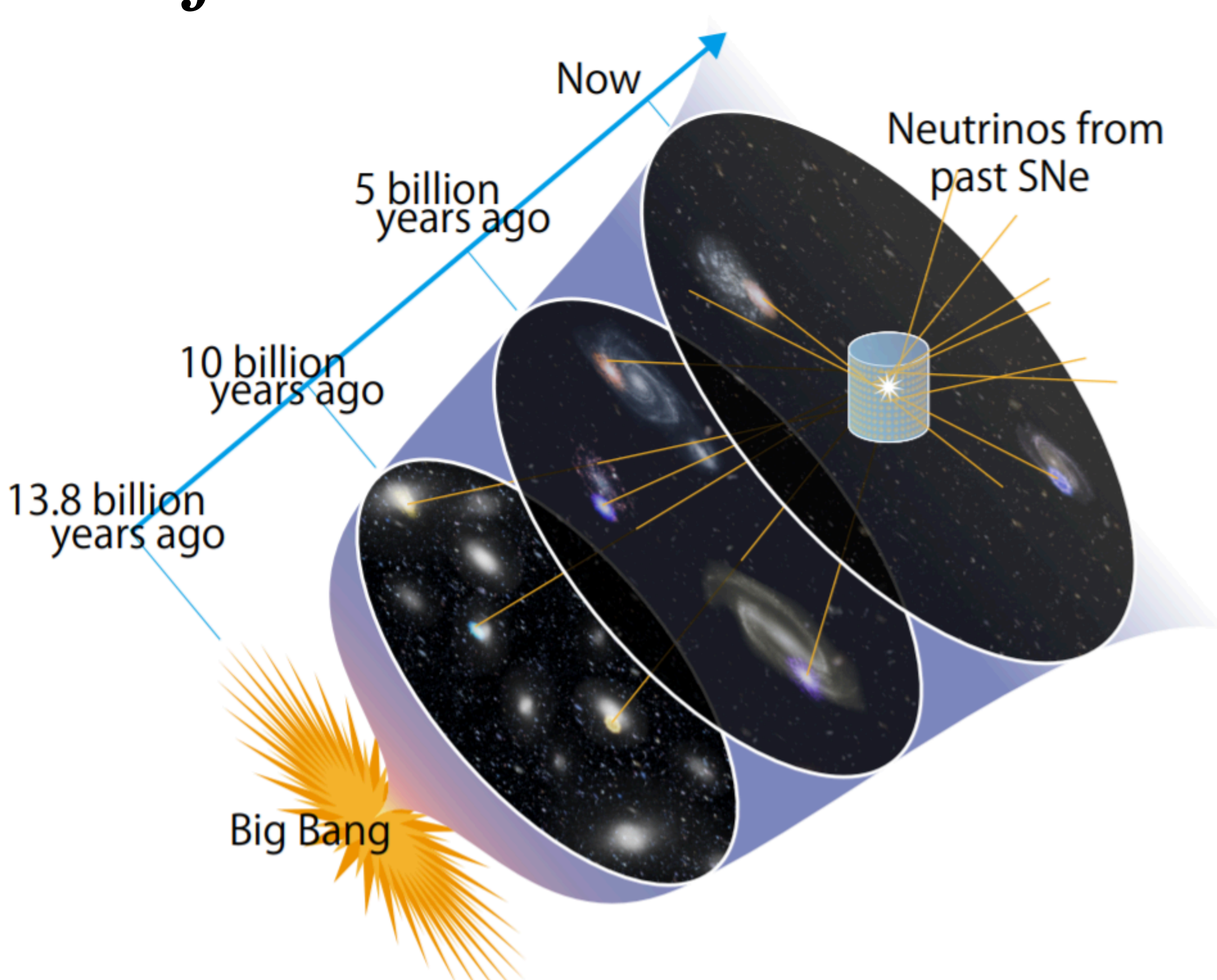
- **SK-Gd has started by loading 0.02% $Gd_2(SO_4)_3$ into SK to discover Supernova relic neutrinos (SRNs).**

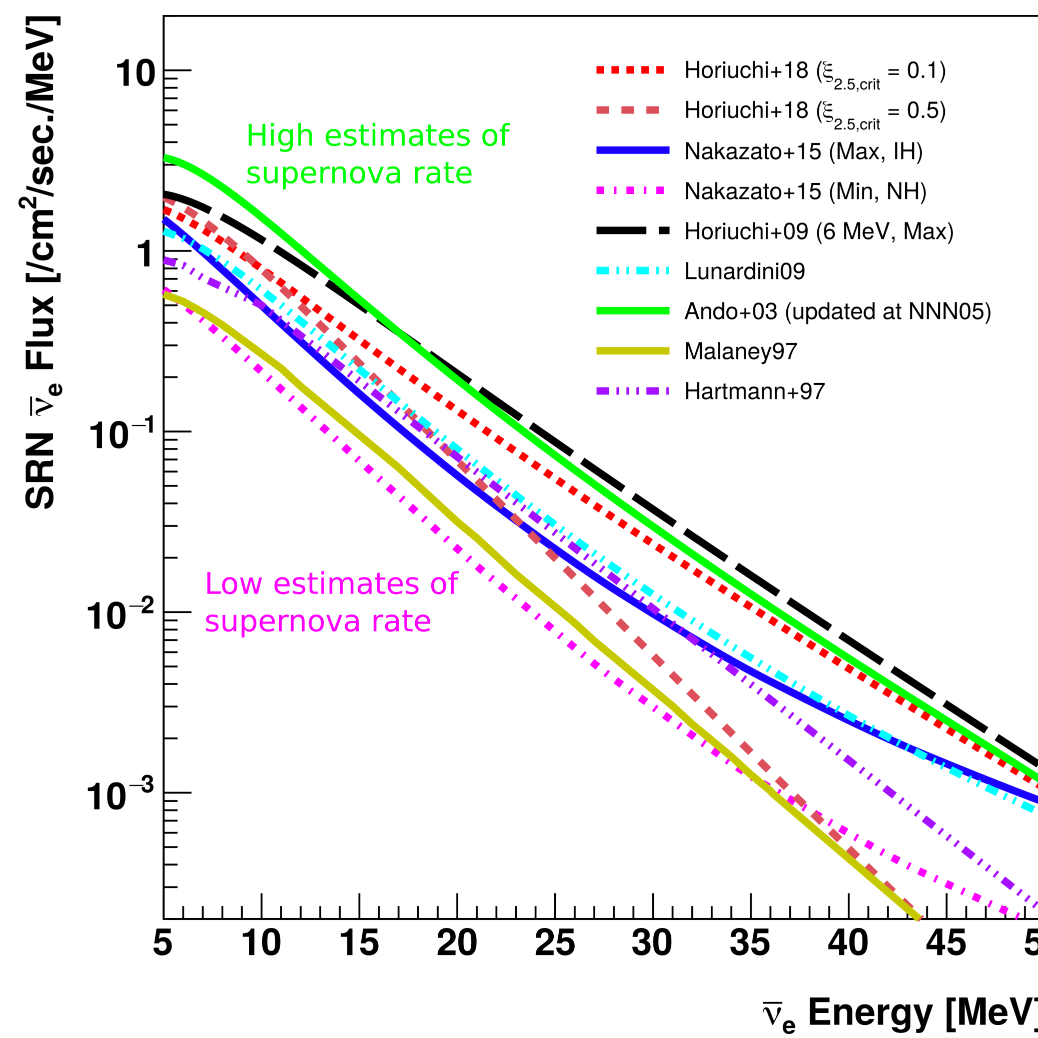


Supernova Relic Neutrinos (SRN)

- Neutrinos emitted from all past core-collapse supernovae.
- Many models have been constructed to predict the flux and shape of spectrum, but not observed yet.
- Many astro and particle physics implications.

$$\Phi = \int [\nu \text{ emission}] \otimes [\text{Star formation}] \otimes [\text{Universe expansion}]$$



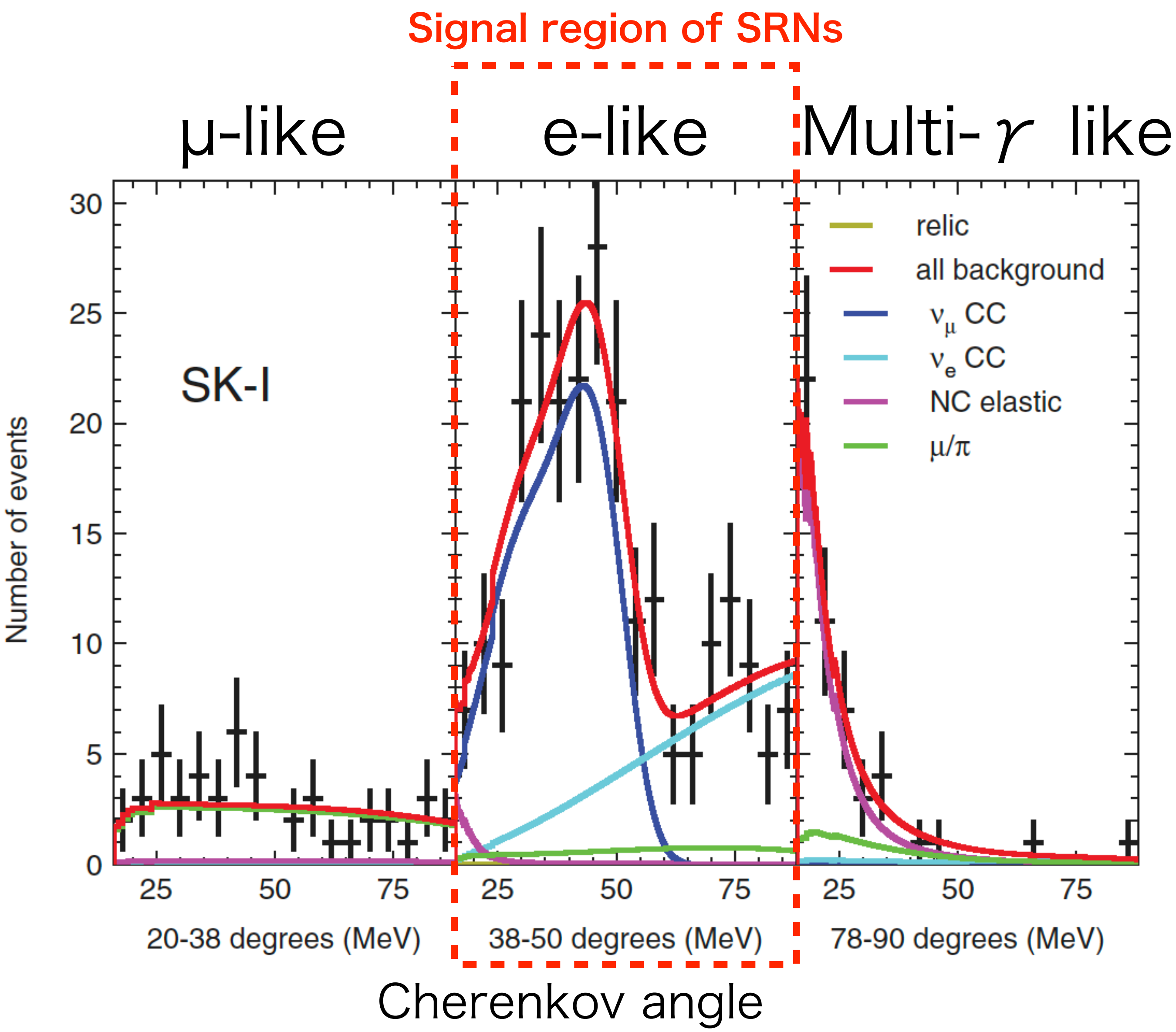


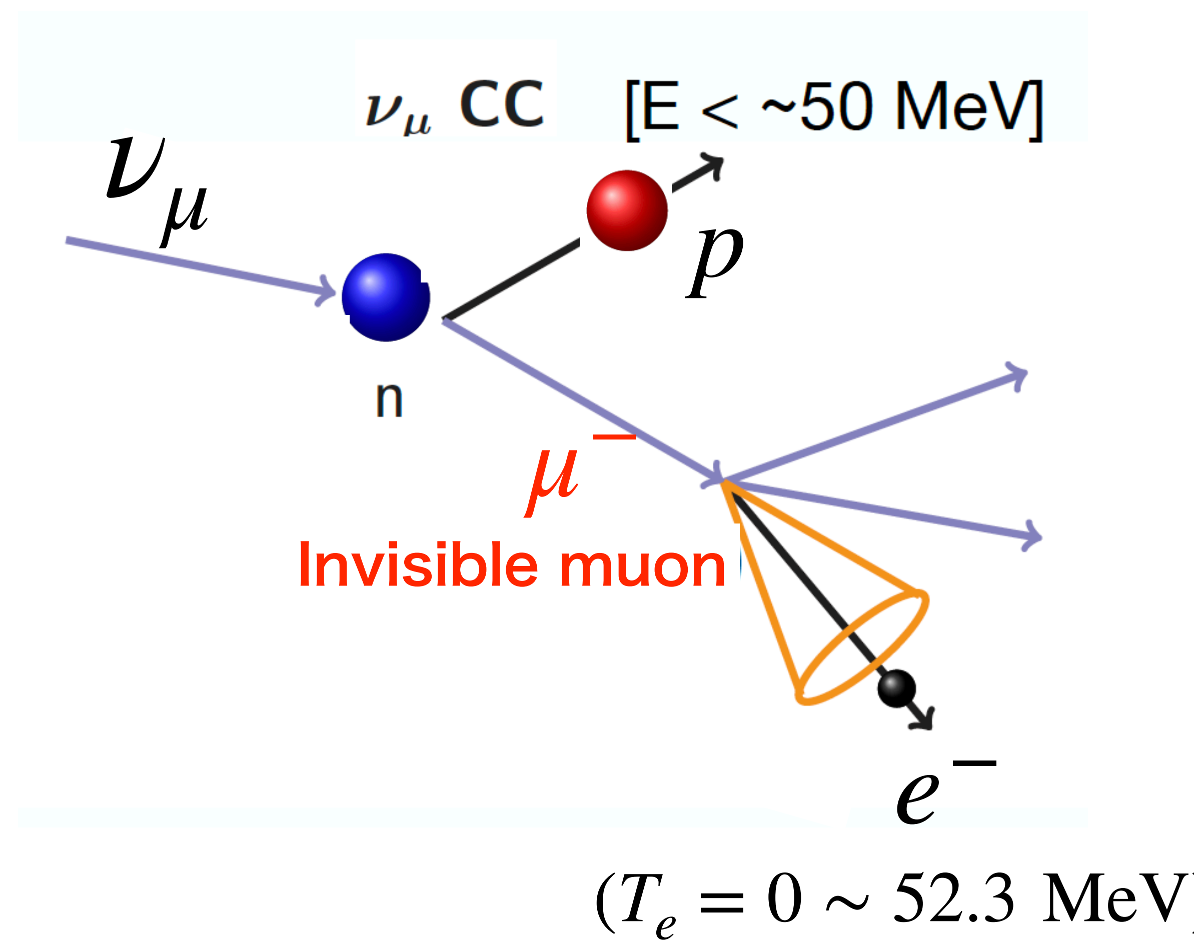
Search for SRNs in SK

- The sensitivity of SRNs is limited by the background; decay-e events due to the atmospheric muon neutrinos.
- Need to identify invisible muon events.

  <u>Phys. Rev. D 85, 052007 (2012).</u>

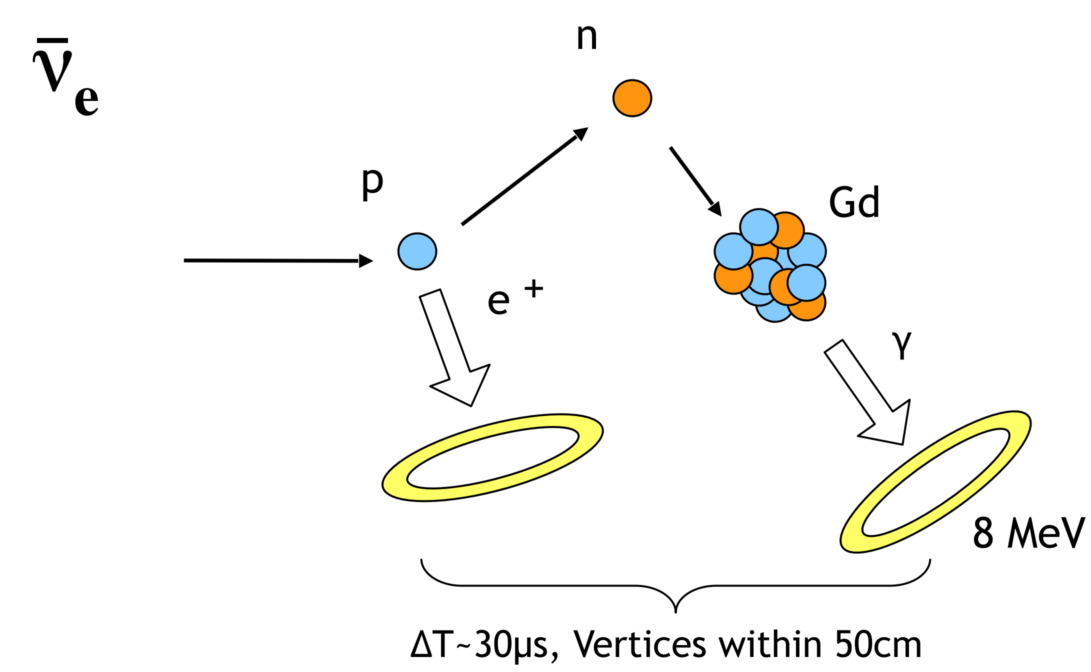
  ➡Neutron tagging to identify neutrinos and anti-neutrinos.





Neutron Tagging in SK

- Neutron tagging by Gadolinium (Gd).
  - Background rejection.
  - Observation of $\bar{\nu}_e$ SRNs.

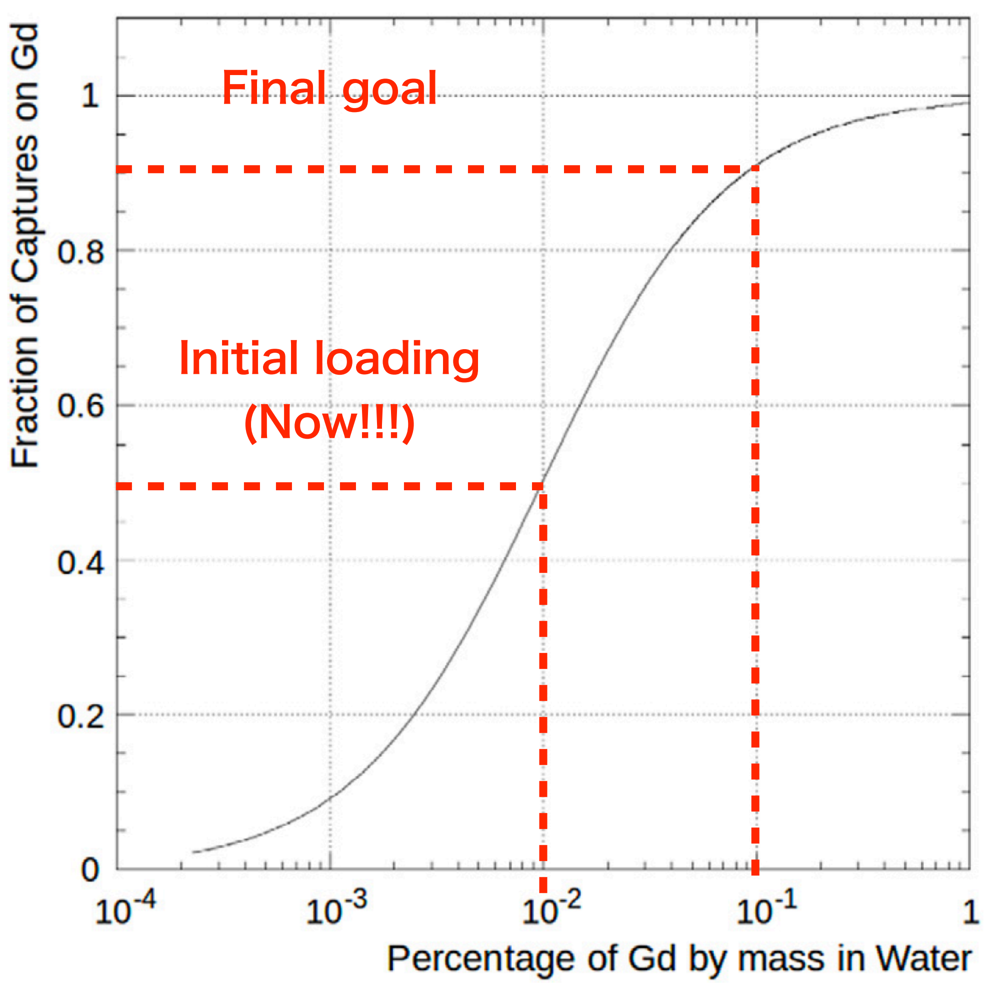


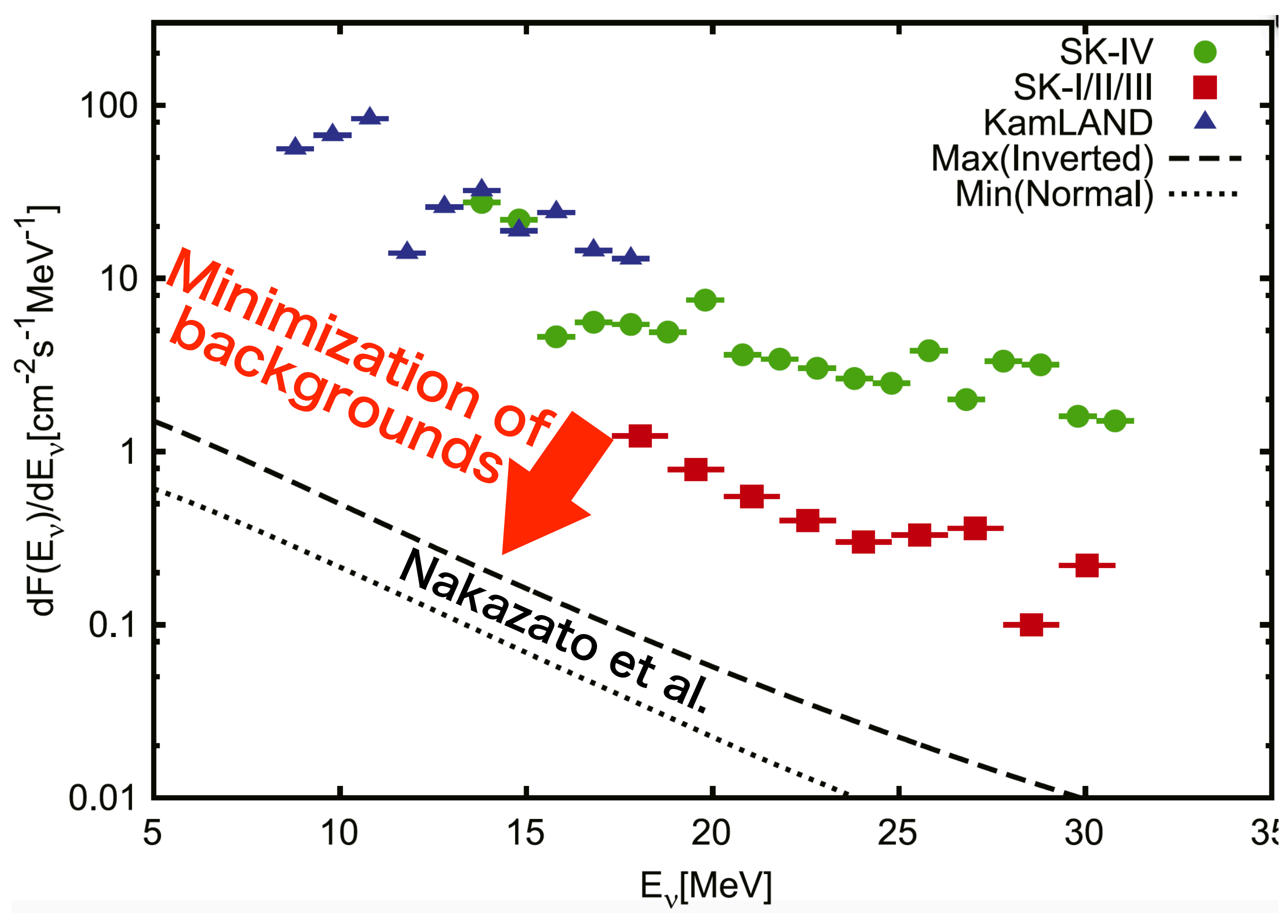
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$| + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma(s)$$ (8 MeV)

$$| + H \rightarrow D + \gamma$$ (2.2 MeV)

~18% of n-tag





The SK-Gd Experiment

- The Super-Kamiokande Gadolinium (SK-Gd) experiment aims to detect SRNs by dissolving Gd into the SK tank.
  ➡For solubility, $Gd_2(SO_4)_3 \cdot 8H_2O$ is used for.
- **14 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$ were initially dissolved into SK**
  ➡50% n-tag efficiency (0.01% Gd)
- Final goal: 140 tons, 90% n-tag efficiency (0.1% Gd)
- To dissolve $Gd_2(SO_4)_3 \cdot 8H_2O$, there were many R&D.
  1.Low radio-impurity $Gd_2(SO_4)_3 \cdot 8H_2O$.
  2.Water leakage fixing from the SK tank.

Why We Need Low Radio-Impurity $Gd_2(SO_4)_3 \cdot 8H_2O$???

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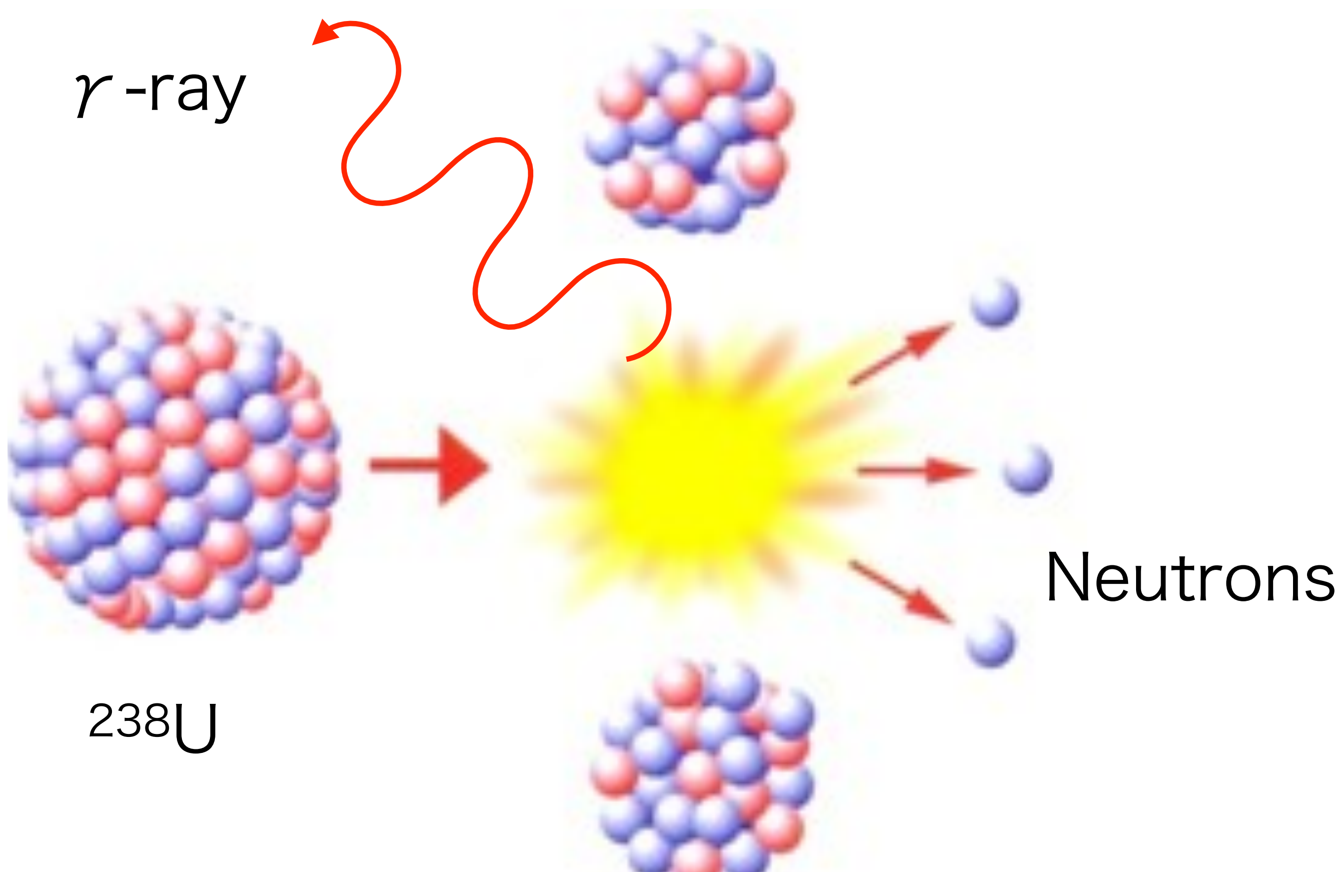
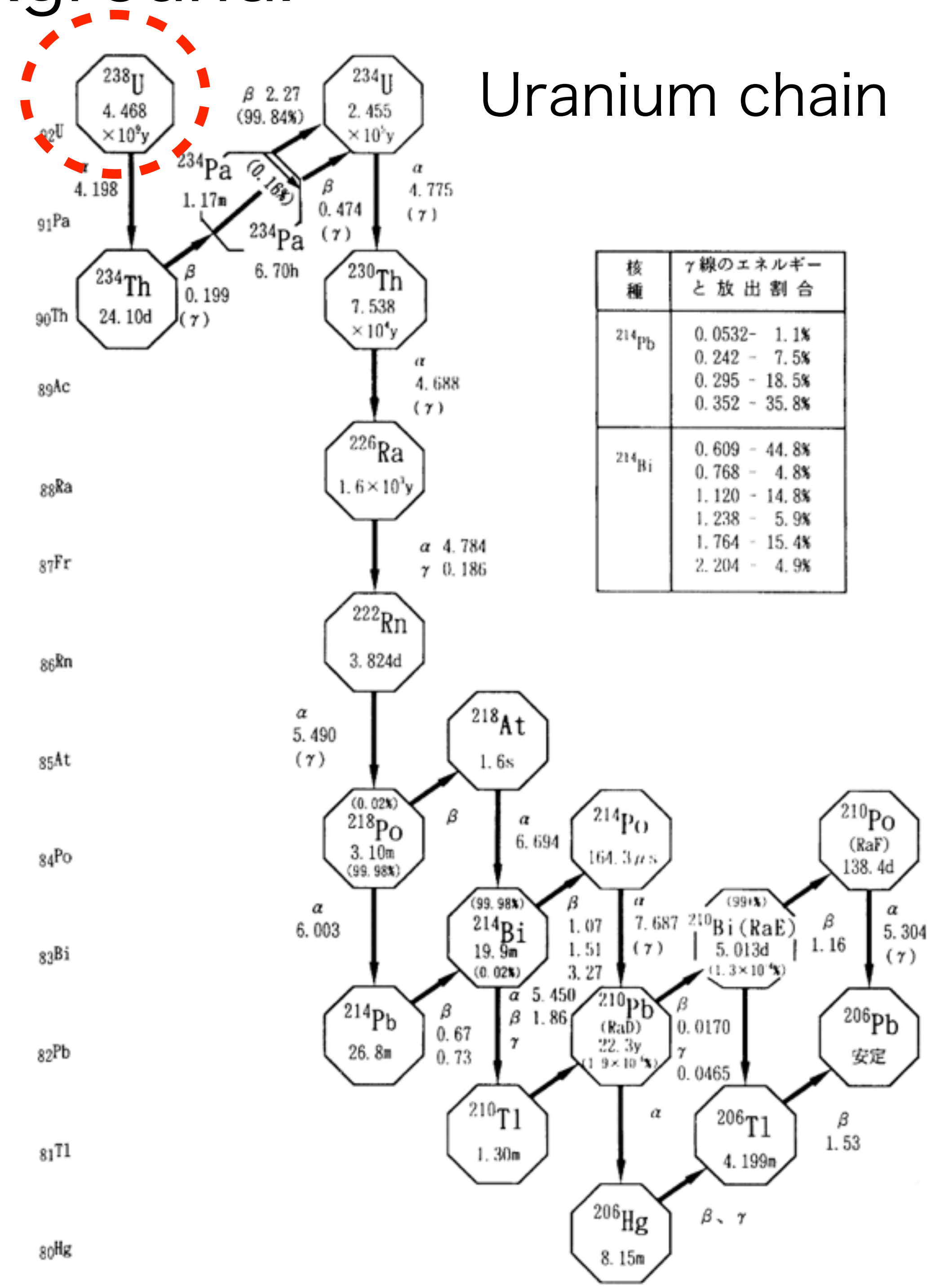
- For SRNs searches, no neutron background.
- ^{238}U: spontaneous fission

➡~10 MeV γ-ray + neutron

➡Mimics n-tag signal.



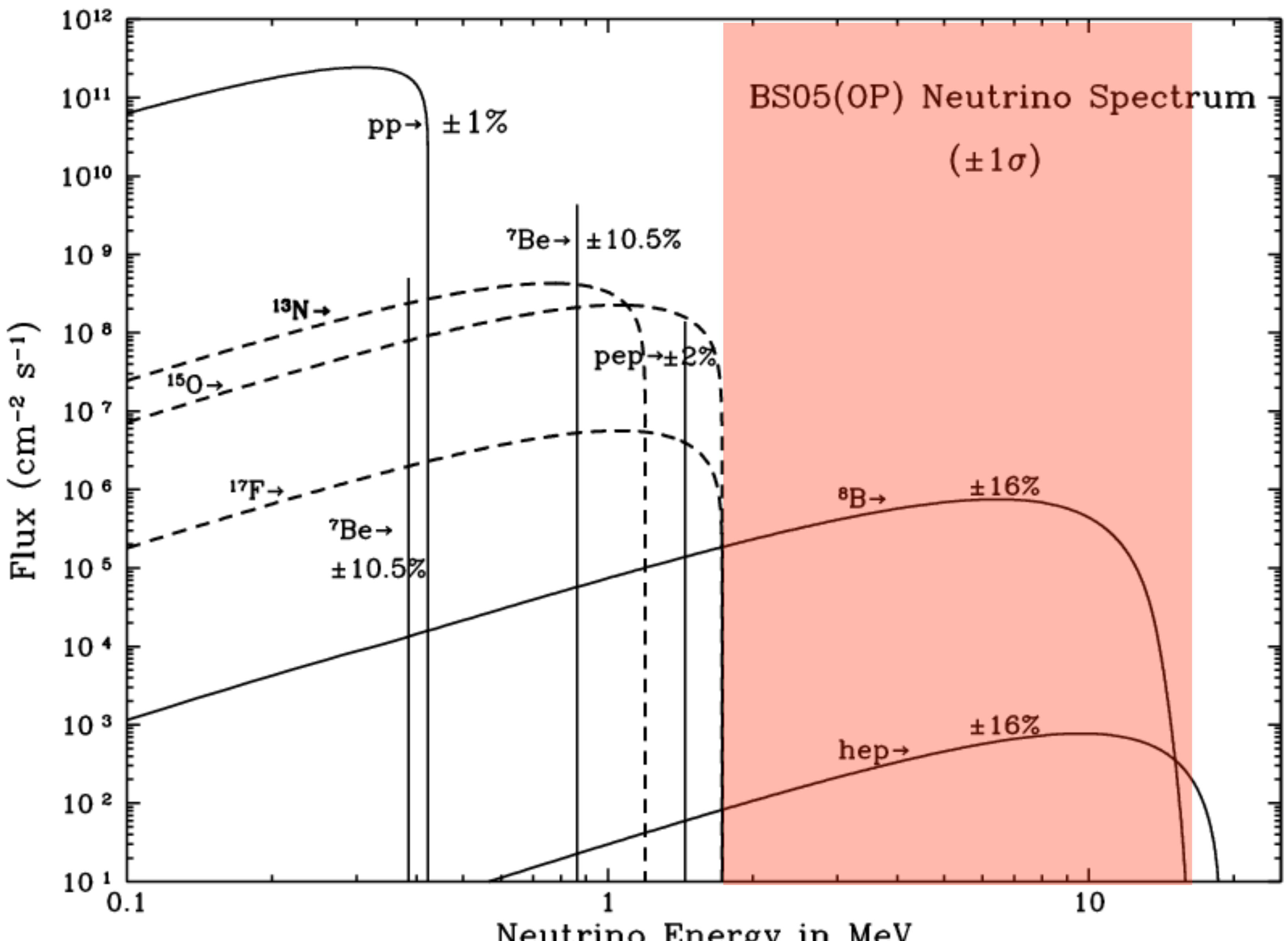
Spontaneous fission



Uranium chain

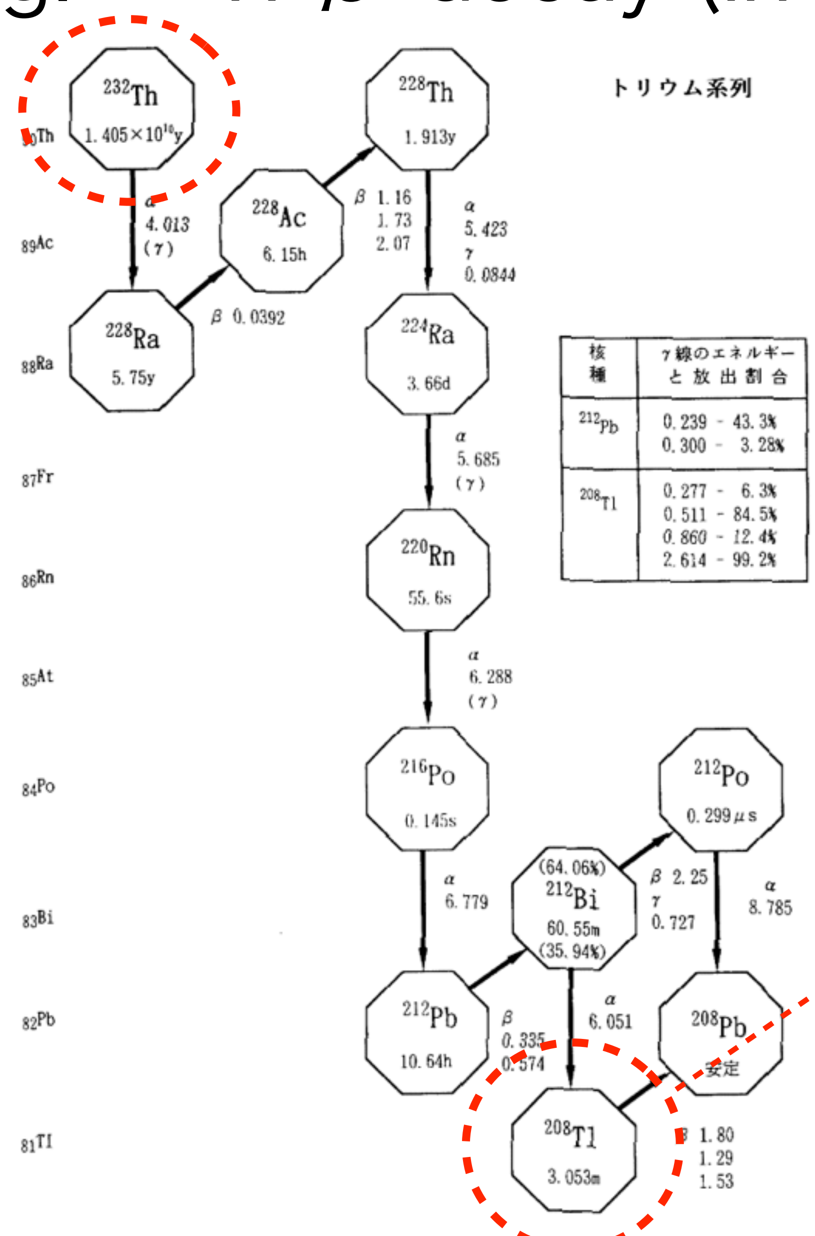
Why We Need Low Radio-Impurity $Gd_2(SO_4)_3 \cdot 8H_2O$???

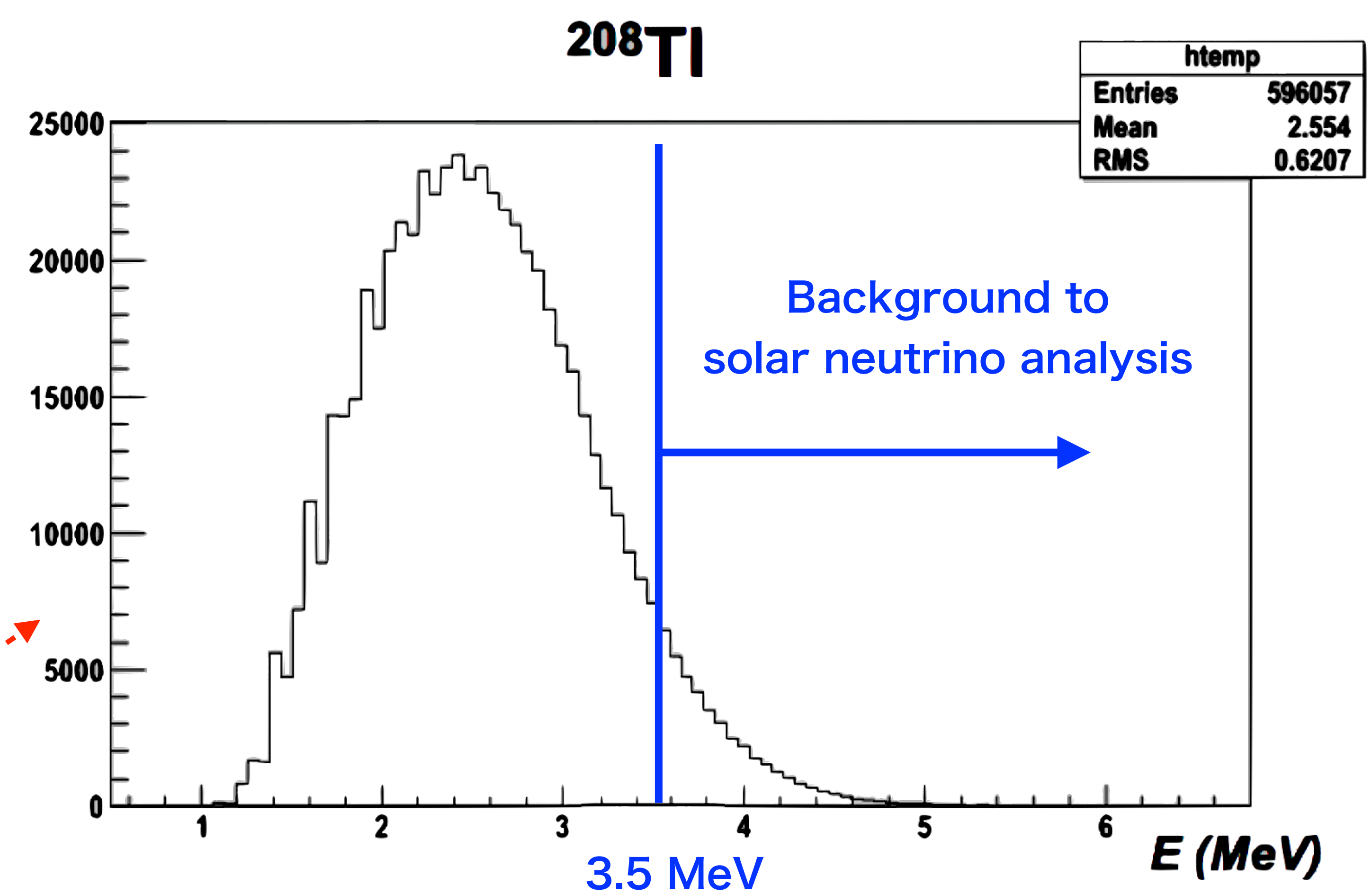
- In SK-Gd, solar neutrino measurement will also be continued.
- ^8B solar neutrinos, energy region 3.5~17 MeV.



Why We Need Low Radio-Impurity $Gd_2(SO_4)_3 \cdot 8H_2O$???

- In SK-Gd, solar neutrino measurement will also be continued.
- ^{8}B solar neutrinos, energy region 3.5~17 MeV.
- e.g. ^{208}Tl β-decay (in ^{232}Th chain)





Reconstructed energy spectrum of ^{208}Tl β-decay.

How We Developed Low Radio-Impurity $Gd_2(SO_4)_3 \cdot 8H_2O$???

- Table shows the requirements for SK-Gd.
  ➡We contacted several companies to produce very clean Gd.
  ➡Measurement of radio-impurity and feedback to companies
- **I have developed very sensitive methods to measure low radio-impurities in $Gd_2(SO_4)_3 \cdot 8H_2O$.**
  - Long lifetime (^{238}U (4.5e9 y), ^{232}Th (1.4e10 y)): **ICP-MS**
    S. Ito et al. Prog. Theor. Exp. Phys. 2017, 11 113H01
  - Short lifetime (^{226}Ra (1.6e3 y)): **Ge detector**
    Accepted in PTEP (S. Ito et al., arXiv: 2006.09664)

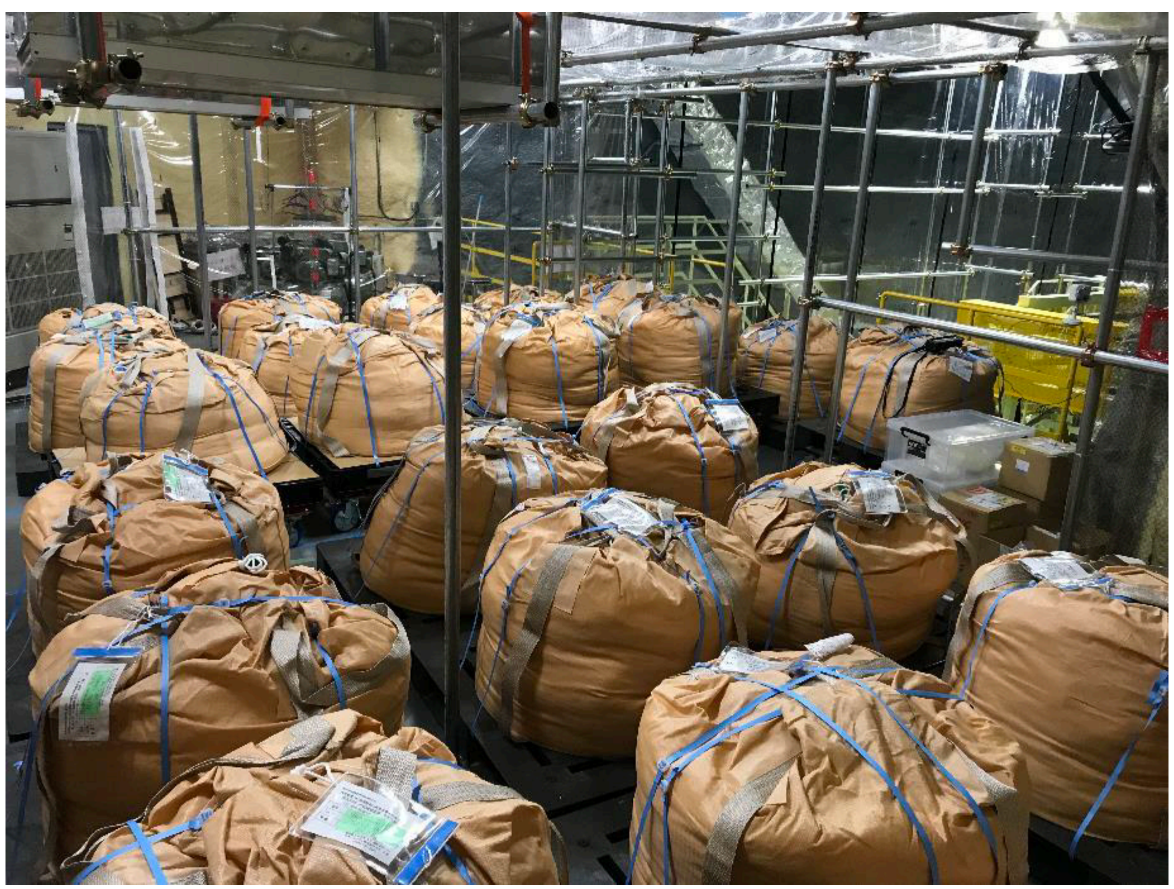
Radio Impurity	^{238}U	^{232}Th	^{226}Ra
Commercial	50 (4ppb)	100 (25ppb)	5 (0.14ppt)
SK-Gd requirement	<5 (0.4ppb)	<0.05 (13ppt)	<0.5 (0.014ppt)

Unit: [mBq/kg] (ppt=10^{-12} g/g)

14 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$

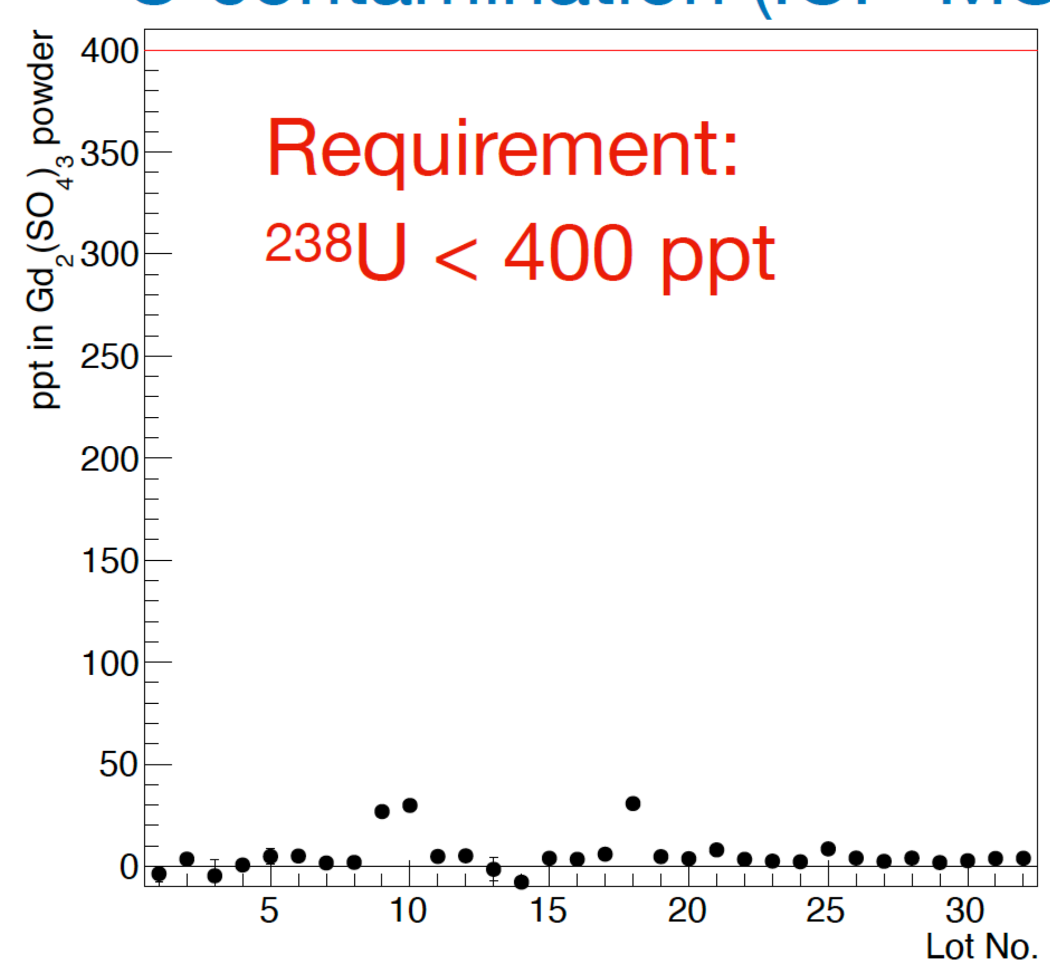
- I've measured radio-impurities in many $Gd_2(SO_4)_3 \cdot 8H_2O$ samples from several companies, and **achieved the requirements.**
- We ordered mass production (14 tons for "real" $Gd_2(SO_4)_3 \cdot 8H_2O$ loaded to the SK tank) to the company.
- I've measured all real Gd products to check radio-impurities.

➡ ^{238}U, ^{232}Th, and ^{226}Ra are less than our requirements



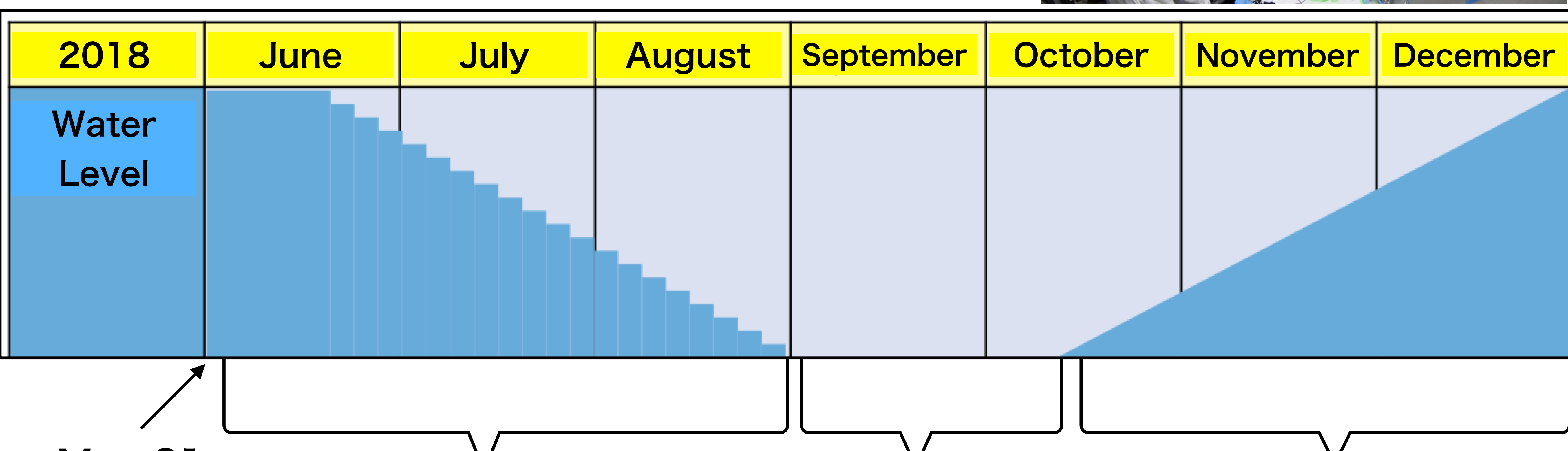
14 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$
(500 kg/bag)

U contamination (ICP-MS)



Water Leakage Fixing

- The SK tank had to be refurbished to fix water leakage before loading $Gd_2(SO_3)_4 \cdot 8H_2O$.
- The SK experiment was stoped on 2018/May/31 and the tank was opened.
  - Fixing water leakage: ~1 ton/day
    ➡goal **<0.03 ton/day**
  - Replacement of broken PMTs.
  - Cleaning works.



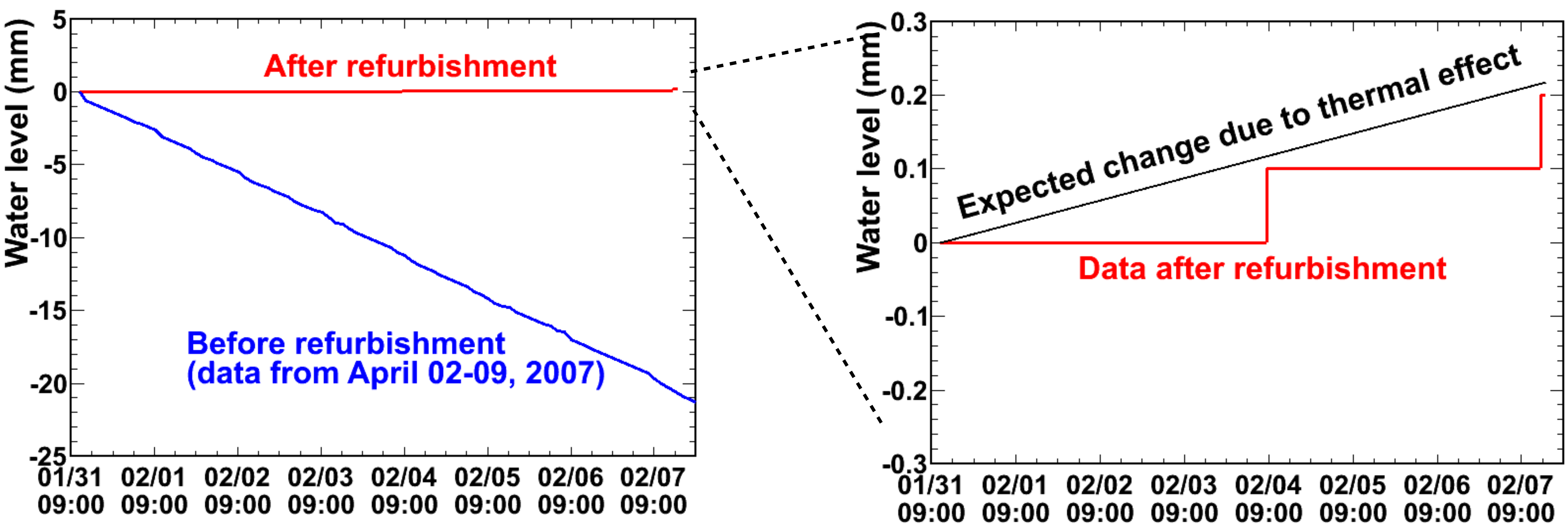
Leakage Monitor —Water Level—

- Water circulation system was stopped from 2019. Jan. 31 to Feb. 7 to monitor the water level.

  ➡ No any significant water leakage.

  ➡ <0.017 ton/day (Goal: 0.03 ton/day)

- Water level is still being monitored, and $Gd_2(SO_4)_3 \cdot 8H_2O$ was introduced into SK in 2020 Jul., but no any leakage is observed.



Leakage Monitor —ICP-MS—

- It's important to monitor concentration of Gd around SK.
- I have
  - introduced another ICP-MS to monitor Gd.
  - setup clean room.
  - developed another chemical extraction procedure.

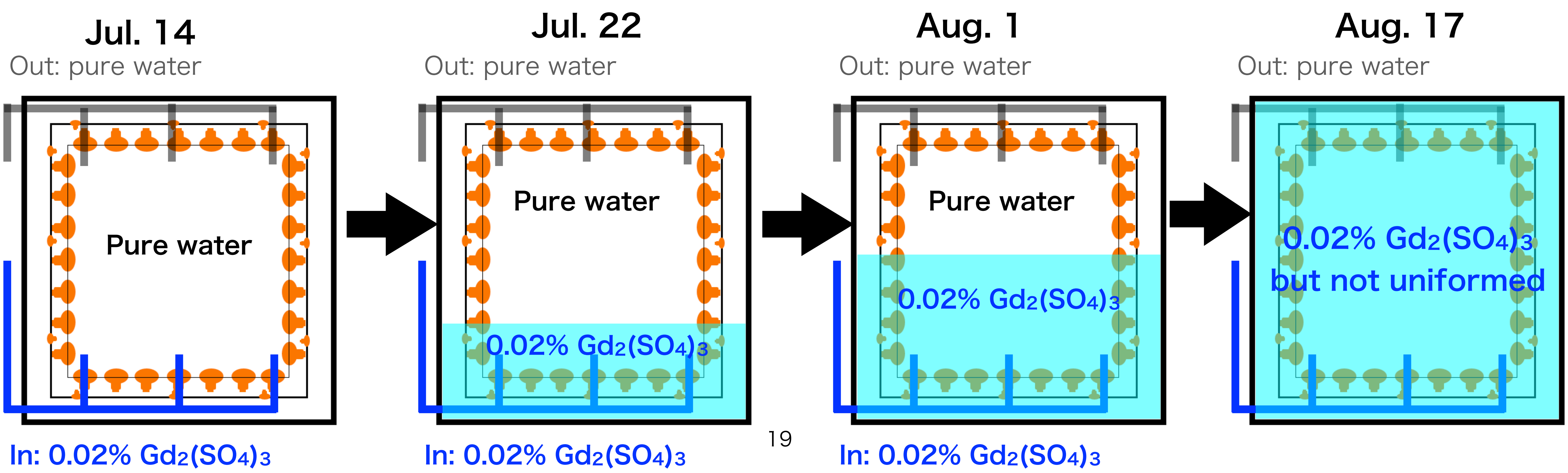
  ➡ S. Ito et al., PTEP 2019 6 063H03

  ➡ Monitor of Gd is being continued since 2020 June, **currently no any Gd excess is observed.**

ICP-MS and clean room

Current Status of SK-Gd

- Dissolving Gd2(SO4)3·8H2O was started from July 14th.
- SK water circulation system
  ➡Supply to the bottom and return from the top.
- 0.02% $Gd_2(SO_4)_3$ is supplied to the bottom.
- ~33 days to achieve “full" 0.02% $Gd_2(SO_4)_3$.
- For uniformed concentration of Gd in the tank, recirculation with higher flow rate (~120 t/h) than usual data taking is being performed.



Current Status of SK-Gd
—Neutron Tagging Events—

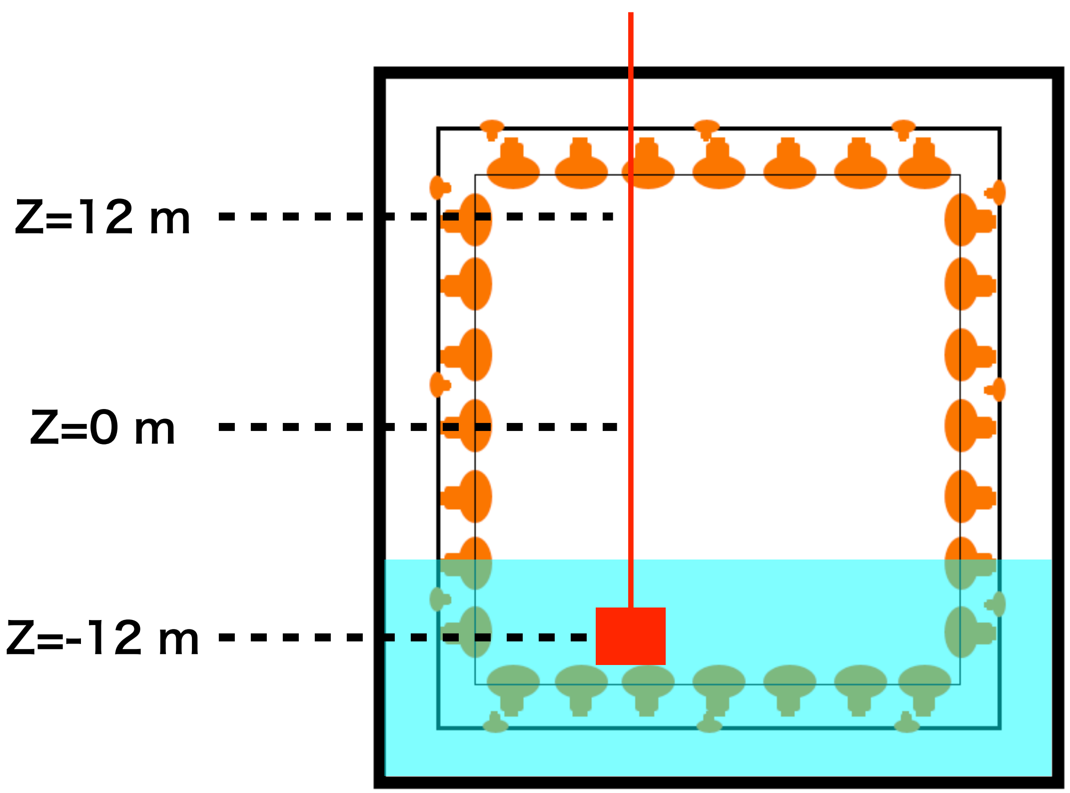
- To check the neutron tagging events, the calibration data were taken on 22 July 2020: Gd at Z=-10m.
- Am/Be source + BGO crystal.

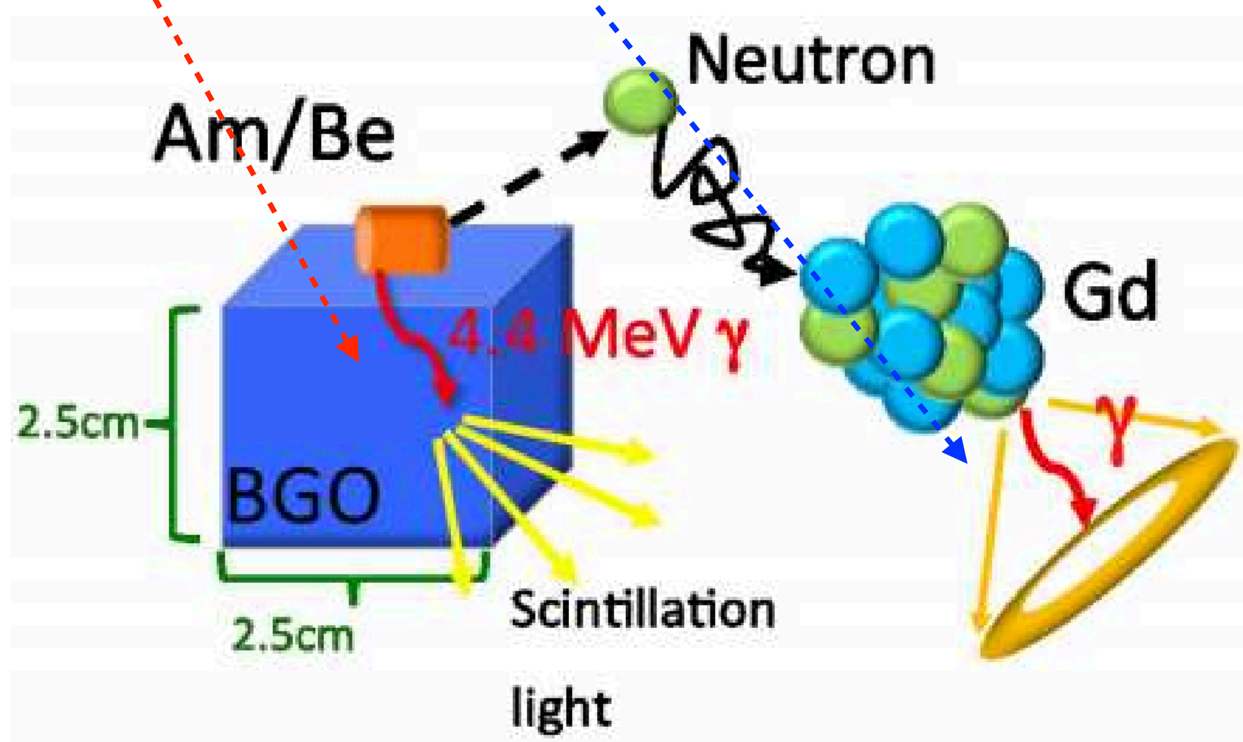
$$^{241}\mathrm{Am} \rightarrow ^{237}\mathrm{Np} + \alpha$$

Prompt signal | Delayed signal captured by Gd

$$^{9}\mathrm{Be} + \alpha \rightarrow ^{12}\mathrm{C} + \gamma(4.4\ \mathrm{MeV}) + n$$

- 4.4 γ-ray produces scintillation light: prompt trigger signal.
- The calibration data were taken at Z=-12, 0, and +12 m.





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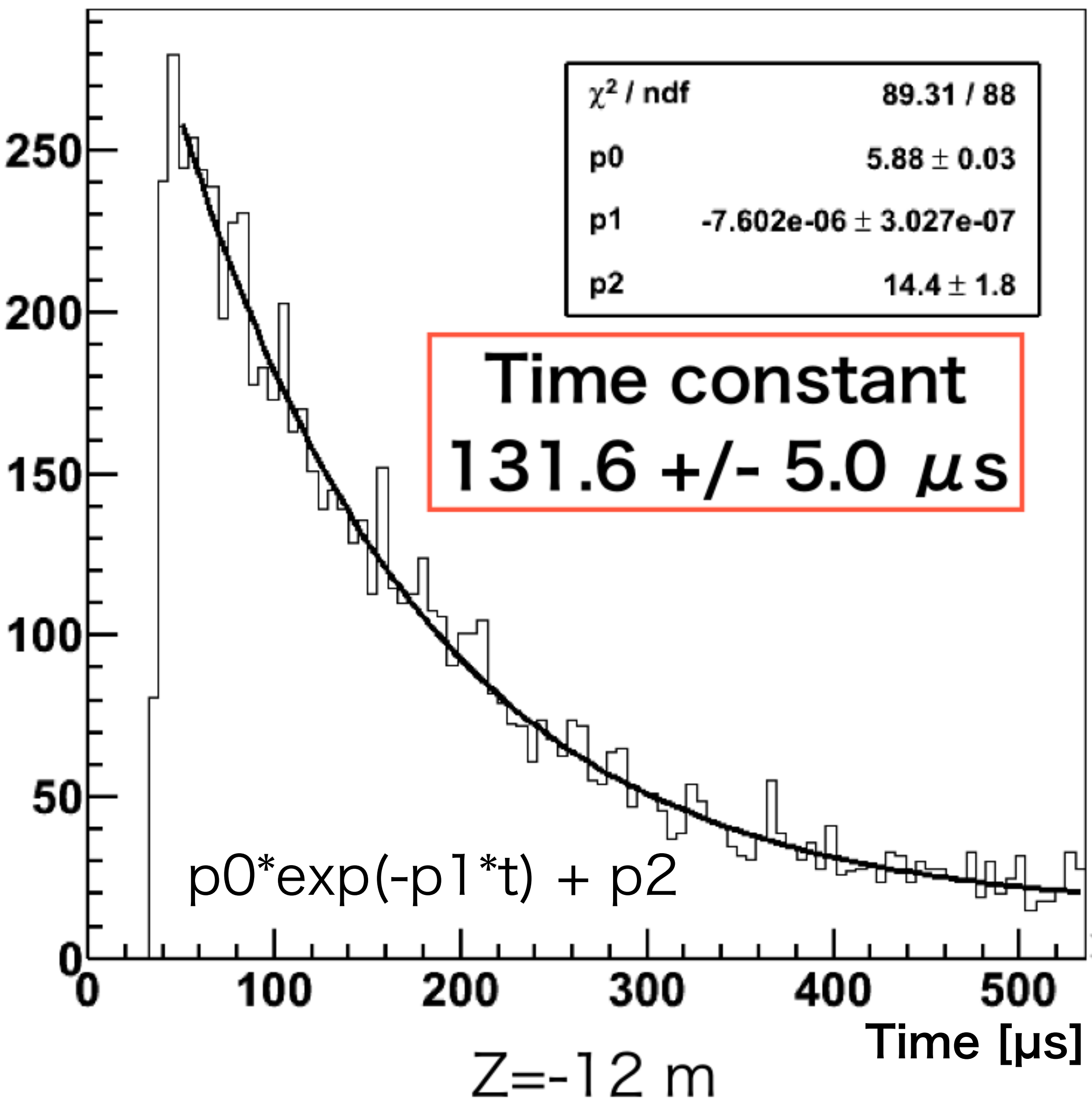
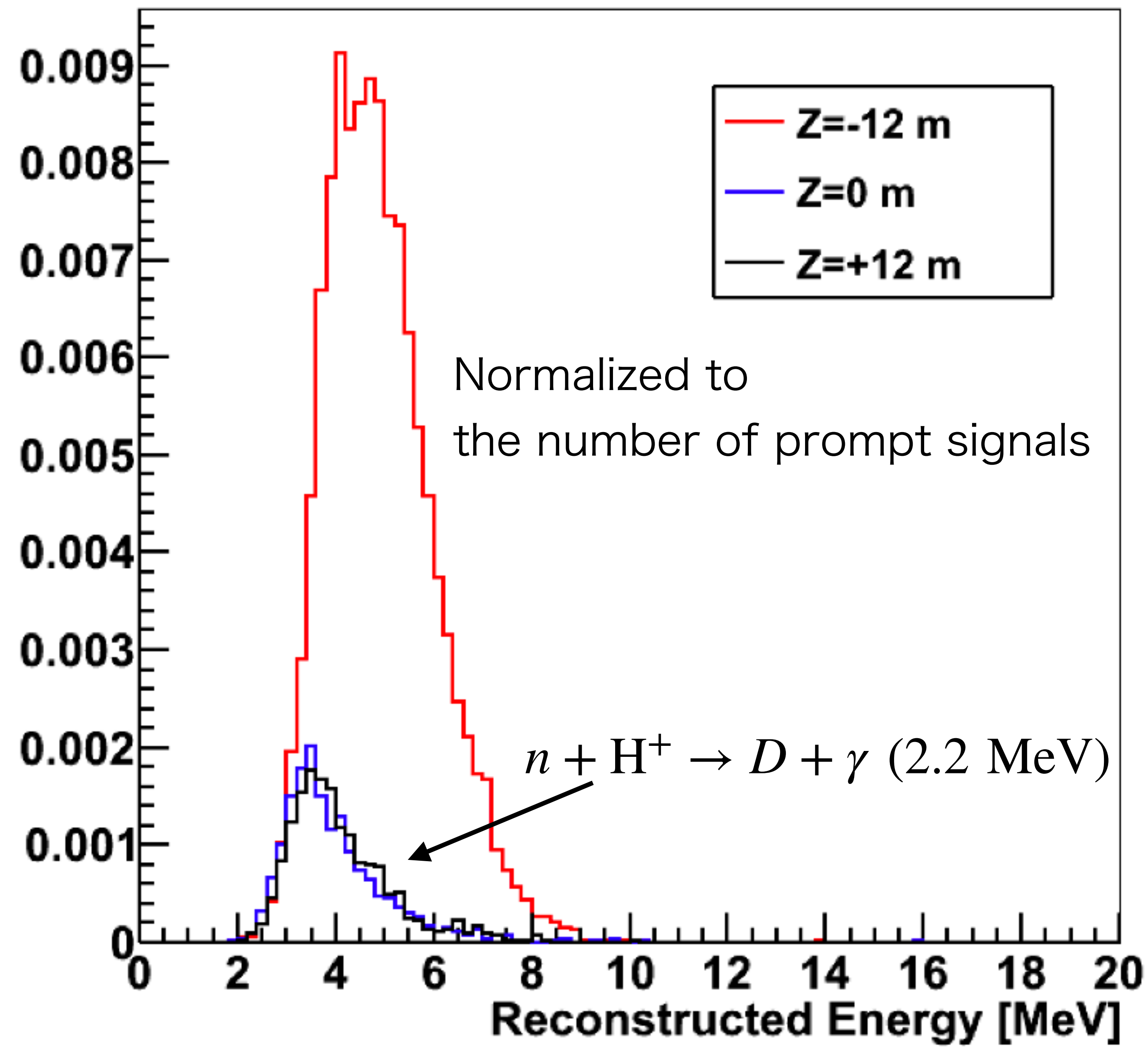




Expected time constant: ~130 us for 0.01% Gd (~50 us for 0.1% Gd)

Neutron tagging events by Gd can be seen!!!
New physics with neutron tagging in SK-Gd is coming soon!!!

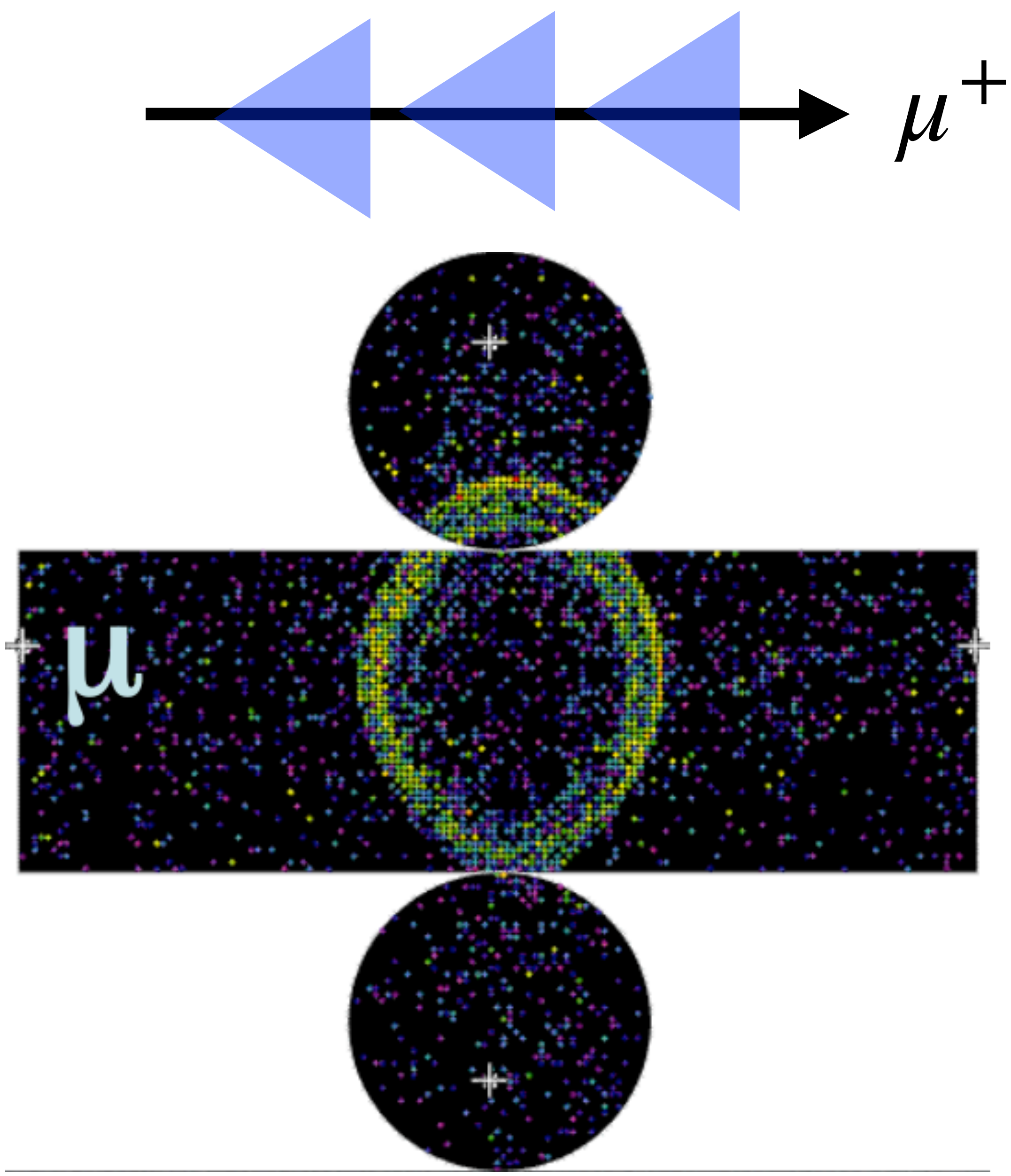
Summary of SK-Gd

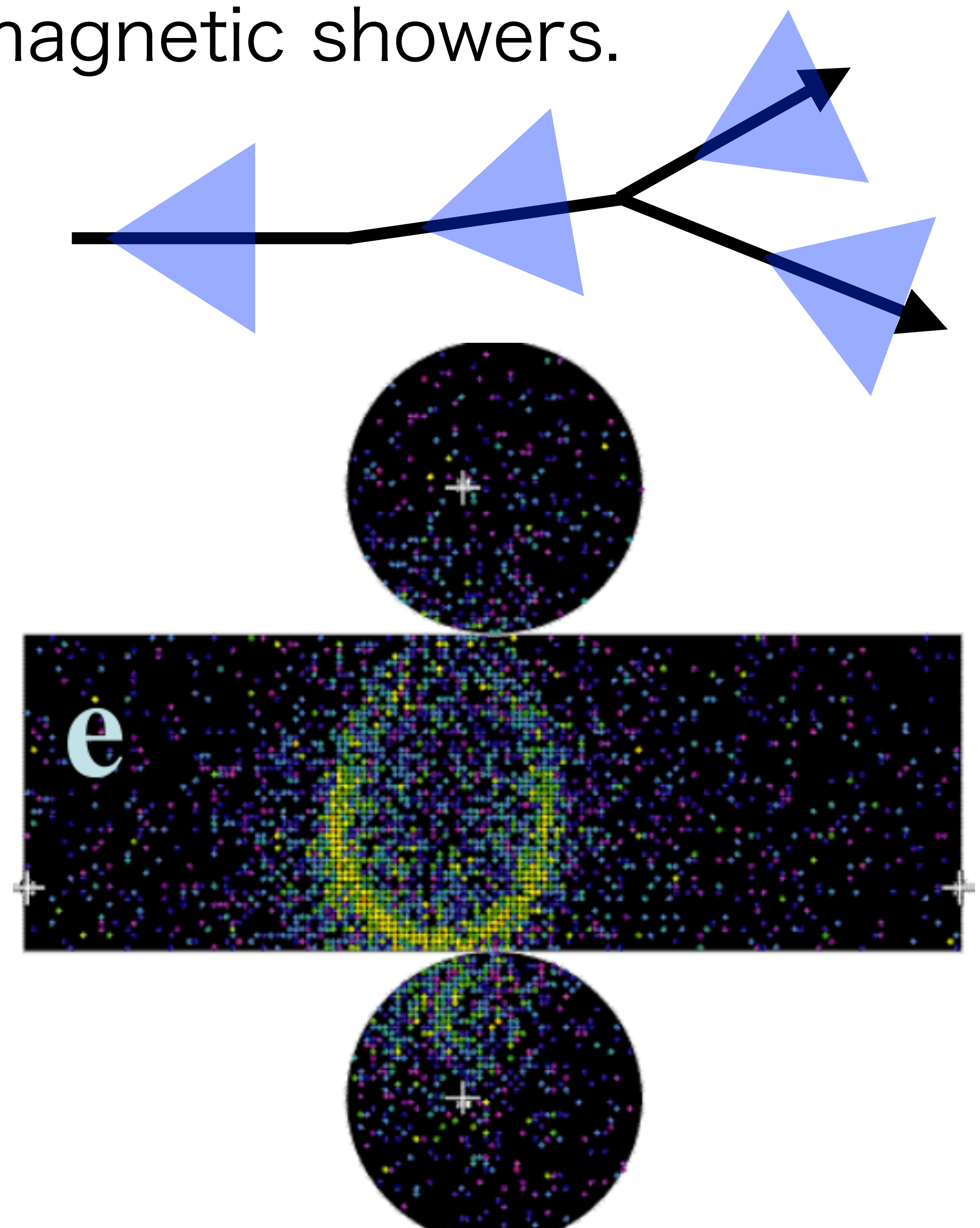
- The SK-Gd experiment has been started since this July!!!
  ➡ Loading $Gd_2(SO_4)_3 \cdot 8H_2O$ for neutron tagging.
- Many R&D before loading.
  - Low radio-impurity $Gd_2(SO_4)_3 \cdot 8H_2O$
    - ✓ICP-MS (PTEP 2017 11 113H01)
    - ✓Ge detector (PTEP 2018 9 091H01, arXiv: 2006.09664)
  - Water leakage fixing
    - ✓Tank open work.
    - ✓Gd monitoring (PTEP 2019 6 063H03)
- 0.02% $Gd_2(SO_4)_3$ is currently dissolved in SK and the signals by Gd capture can clearly be seen.
- More calibration data will be taken and measurement will be continued 1 year, then the concentration of Gd will be increased.
  ➡Grant-in-Aid for Scientific Research on Innovation Area.

Analysis of SK Neutrino Data

Particle ID in SK

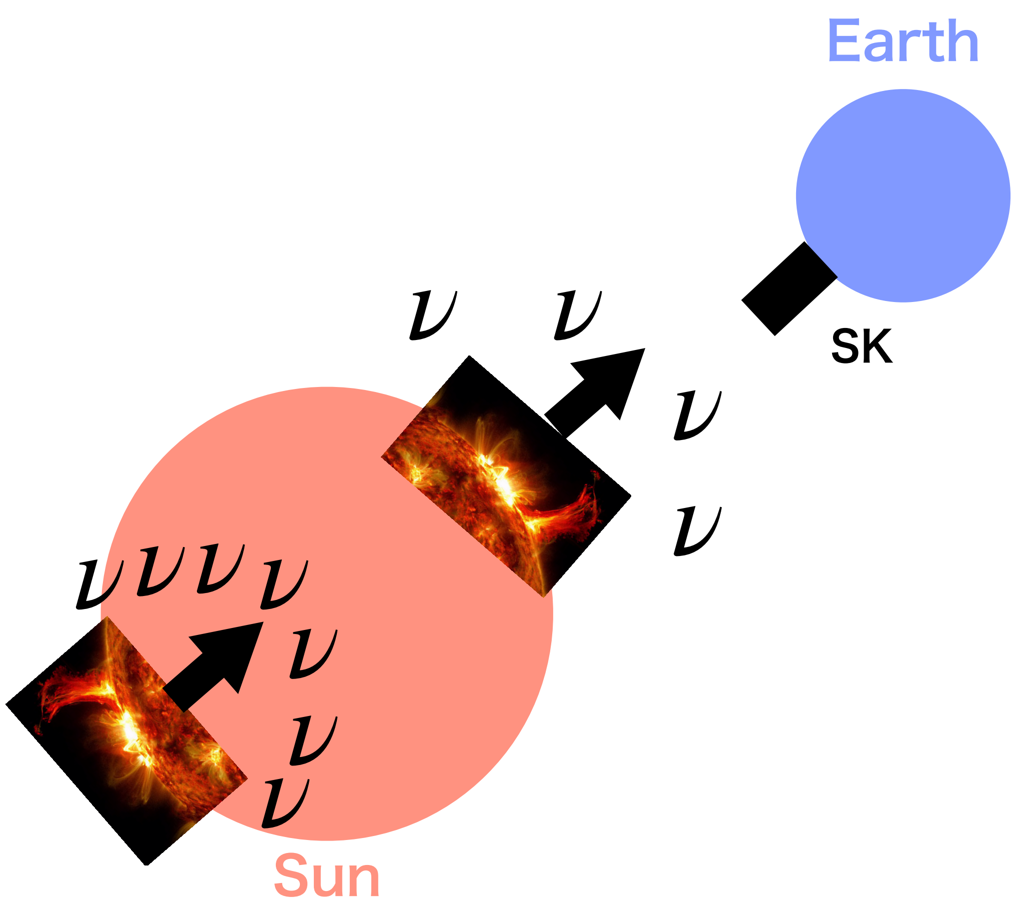
- The particle flavor can be identified using the ring patterns.
  - Muon: Minimal scattering so clear rings with sharp edges.
  - Electron: The shapes of the rings are “fuzzy” due to multiple scatterings and electro magnetic showers.

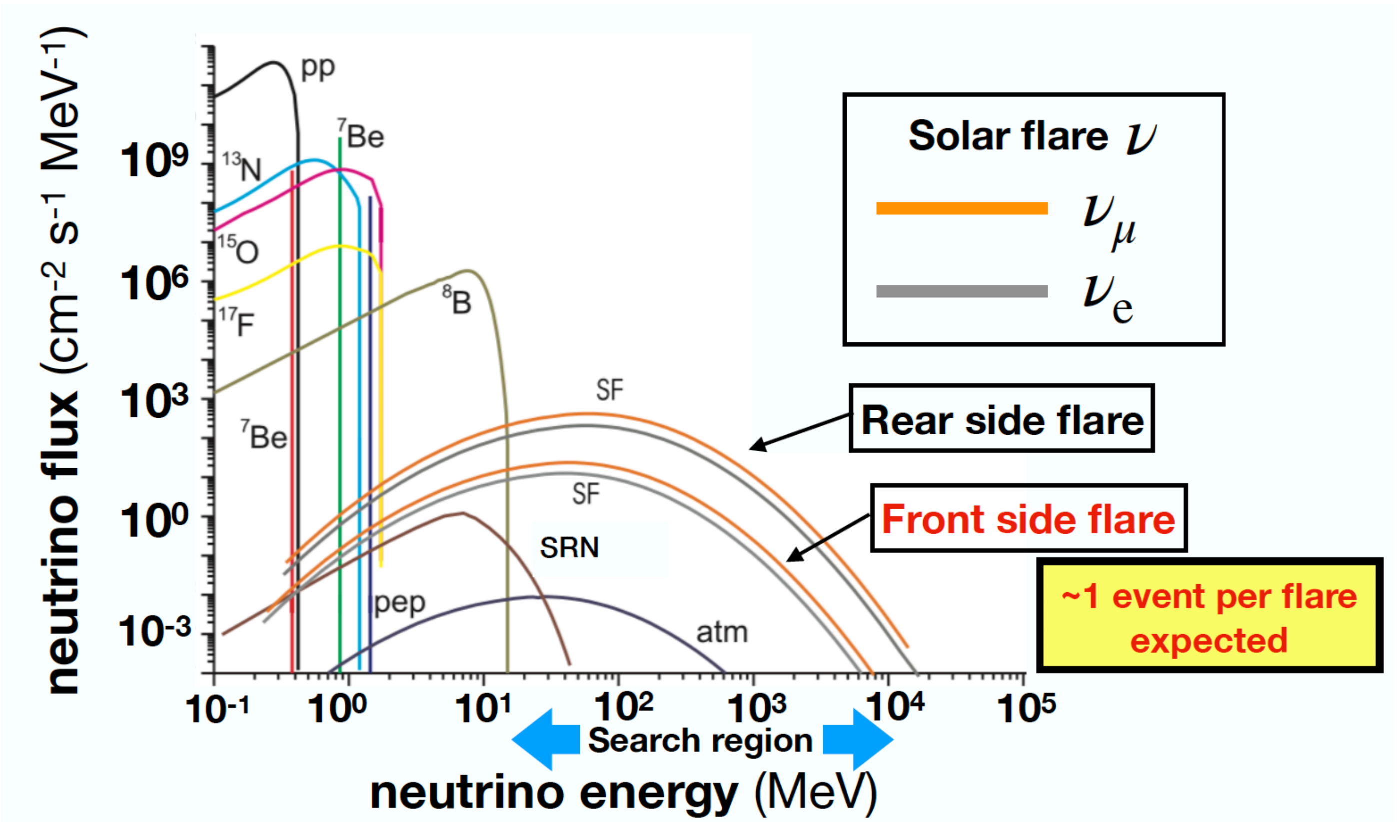




Solar Flare Neutrinos

- A solar flare is an explosive event at the surface of the sun.
  ➡Through a process of magnetic reconnection, a solar flare releases energy 10^{26}~10^{32} erg.
- To study the proton acceleration process in the solar flare, the neutrino events were searched for in SK.
- Flux highly depends on the model, but Fargion predicted **"solar flare neutrino" can be observed ~1 events/flare.**





Fargion and Moscato, 2003 Chin. J. Astron. Astrophys. 3, 75

Solar Flare Neutrinos

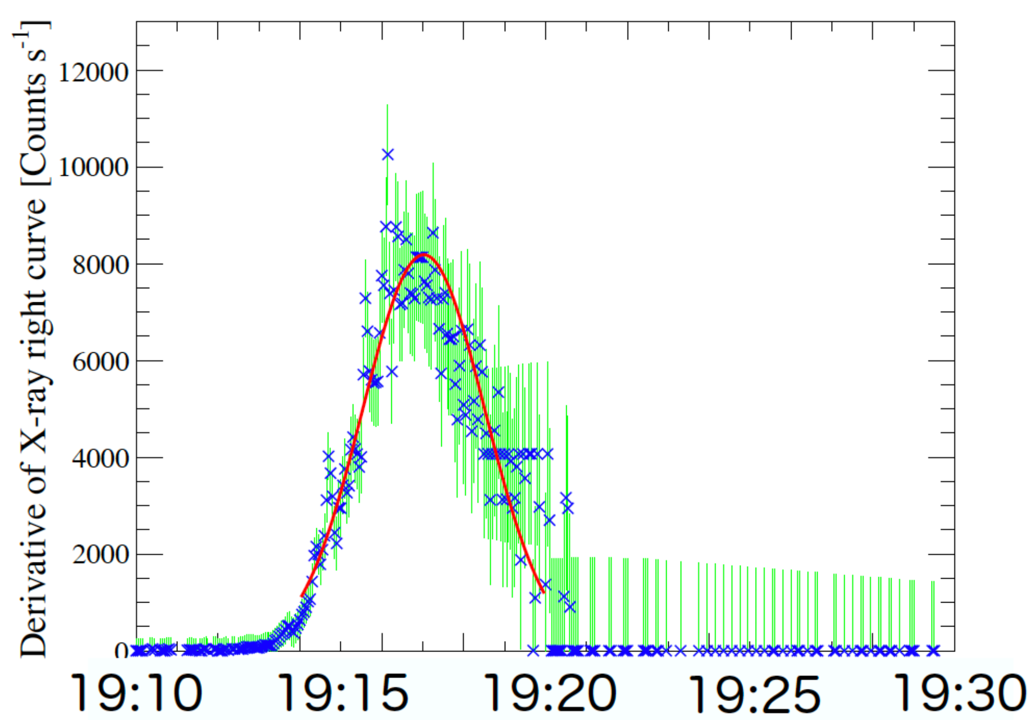
- Production process is the same with the atmospheric neutrinos.

  ➡**~10 events/day,** major background.

  ➡Determination of the search time window using the information of satellites **to minimize backgrounds**
- Solar satellites such as GOES, RHESSI, and GEOTAIL.

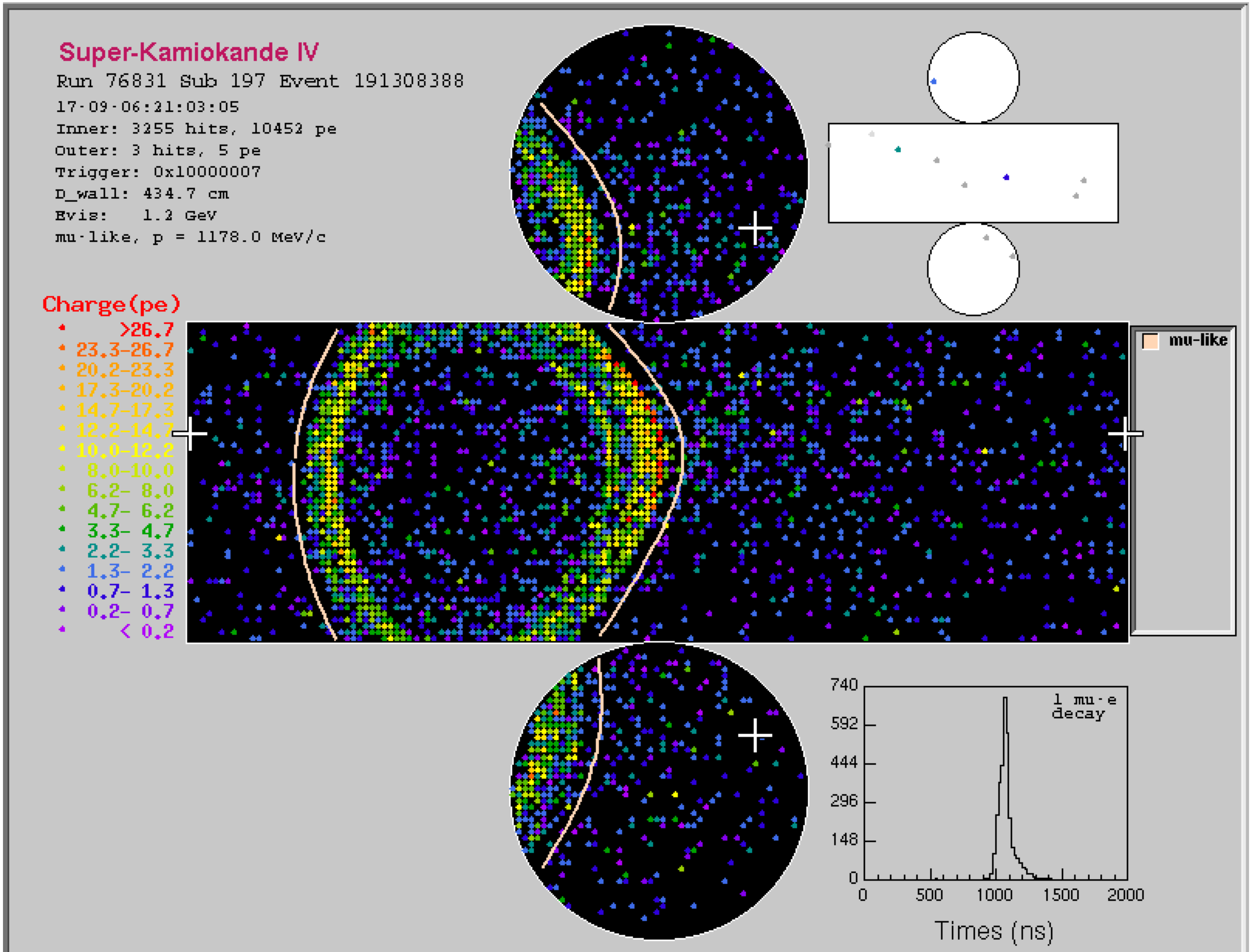
  ➡**Accepted in Solar Physics Journal, arXiv: 1909.10715**
- All solar flares in SK-I to SK-IV were studied (23 flares)

  ➡Two candidate events, but consistent with background.



GOES soft X-ray.
±3σ for the time window.

Solar Flare Neutrinos Candidate

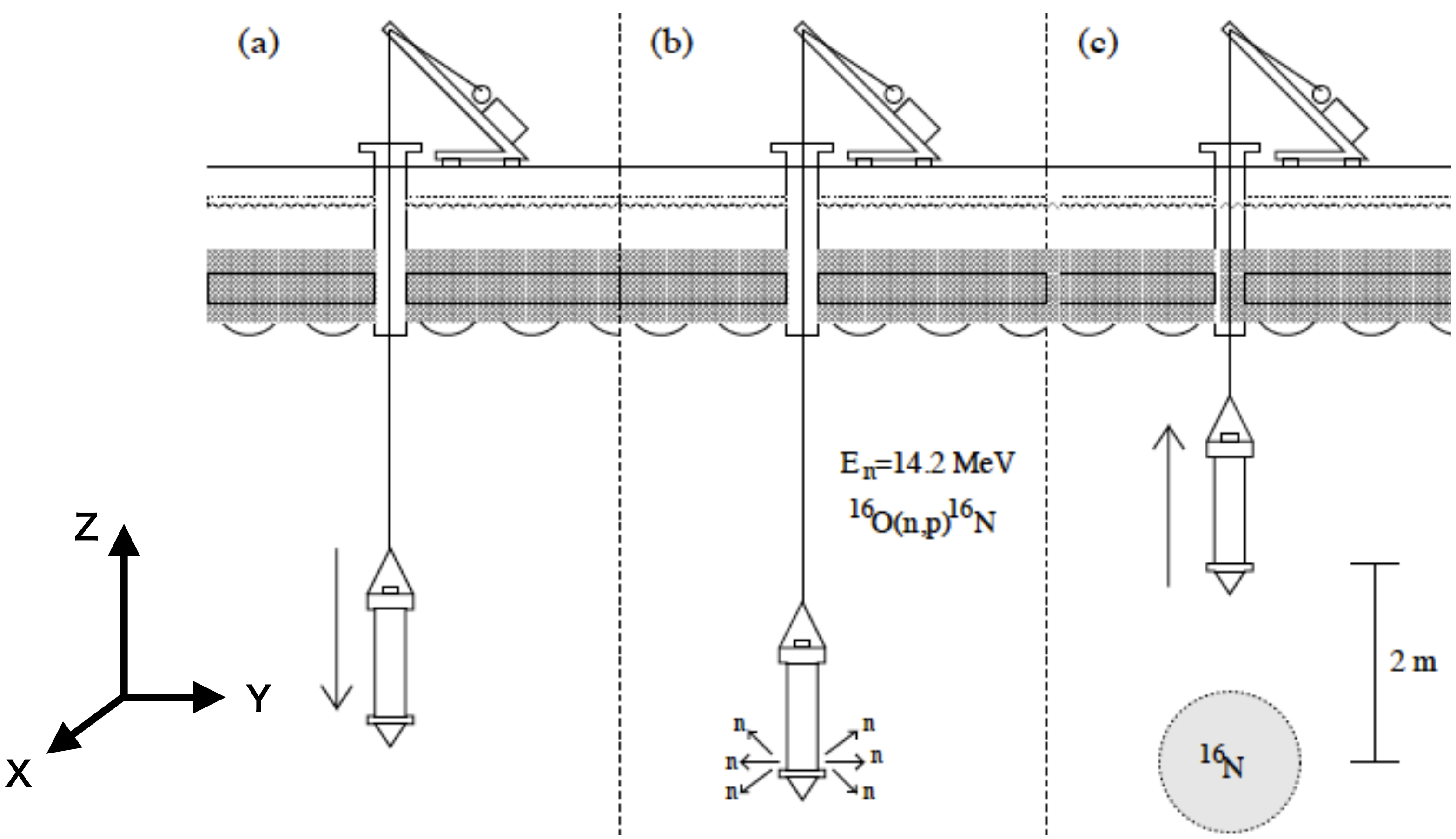


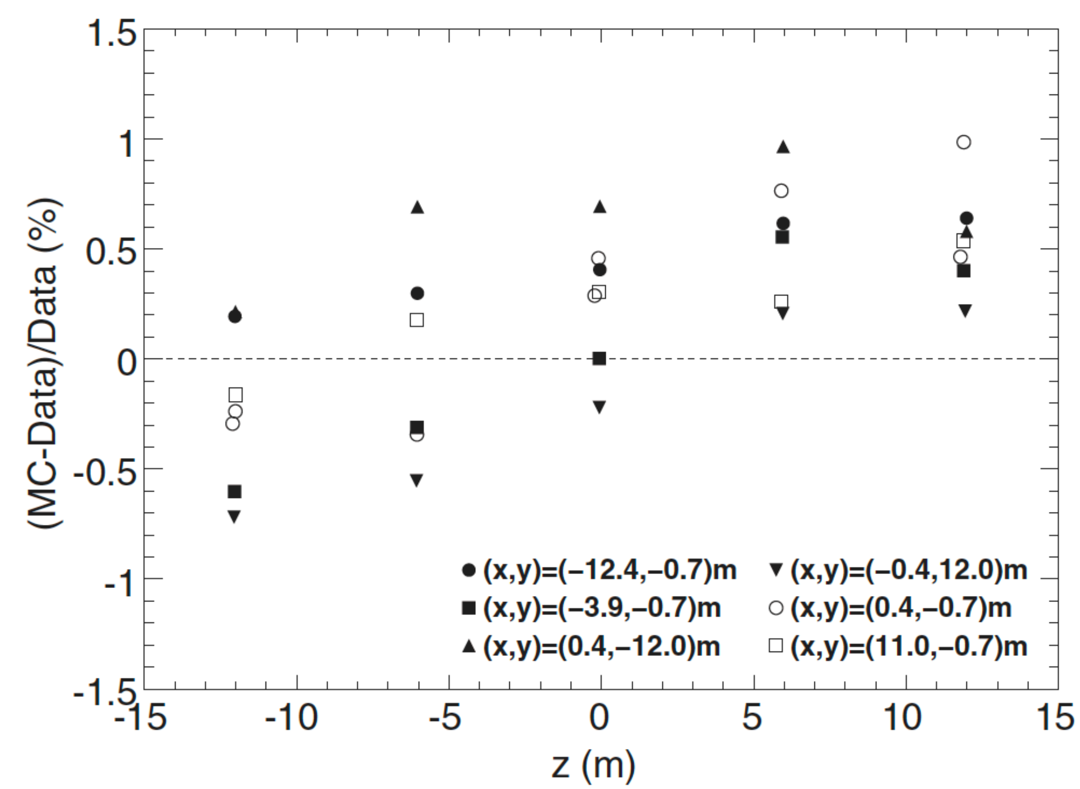
SK Calibration —DT—

- DT(deuteron-tritium) generator

$^{2}H + ^{3}H \rightarrow n + He \Rightarrow {}^{16}O(n,p) \rightarrow {}^{16}N \Rightarrow \gamma$-rays are isotropically emitted

  - Energy scale
  - Position dependence.
  - Zenith angle dependence.





SK Calibration —LINAC—

- To determine the energy scale, electron LINAC is directory inserted into the SK tank.
- Single monoenergetic electrons with 5~16 MeV are ejected.

LINAC