



First result of a search for Diffuse Supernova Neutrino Background in SK-Gd Experiment

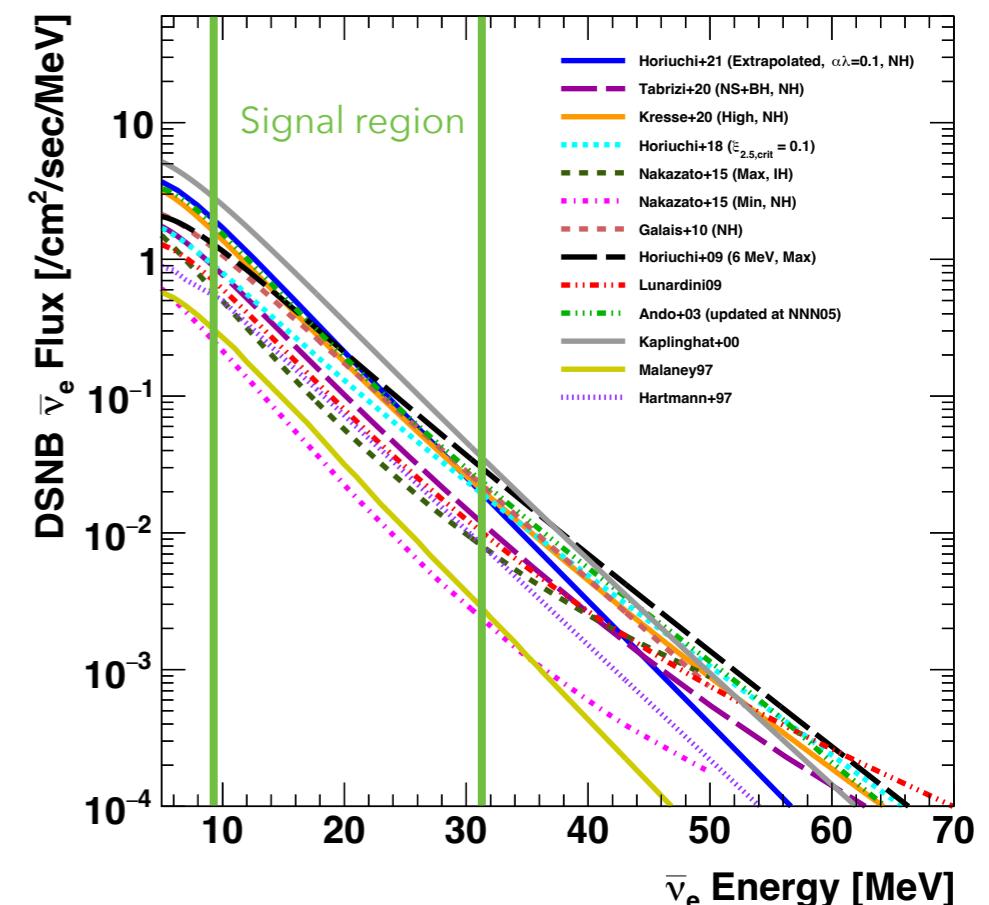
Masayuki Harada (Okayama Univ.)
On behalf of Super-Kamiokande Collaboration
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TAUP 2023,
Aug. 28 – Sep. 01 @Vienna, Austria



Diffuse Supernova Neutrino Background

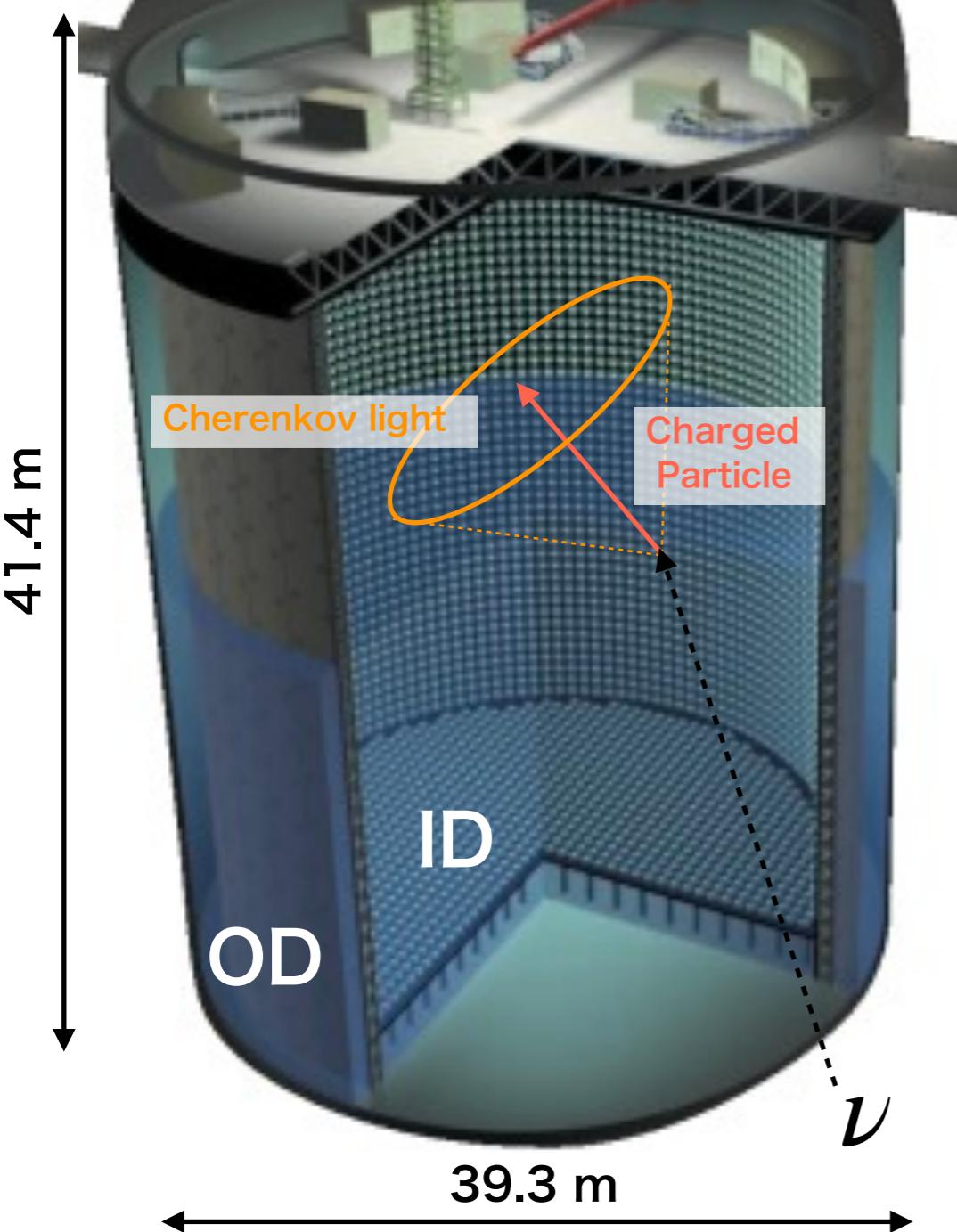
- **Diffuse Supernova Neutrino Background (DSNB) :**
 - Integrated flux of the neutrinos emitted from past all Supernovae
- DSNB flux is affected by various parameters including the star formation, metallicity (star evolution history)
 - Various theoretical models are proposed
- Previous search of Super-Kamiokande:
 - stringent flux upper limit above 15.3 MeV
 - limit for the some optimistic models.
- Aim for the first observation of DSNB
 - **SK-Gd Experiment**



Super-Kamiokande

50 ktons Water Cherenkov Detector

22.5 ktons Fiducial Volume

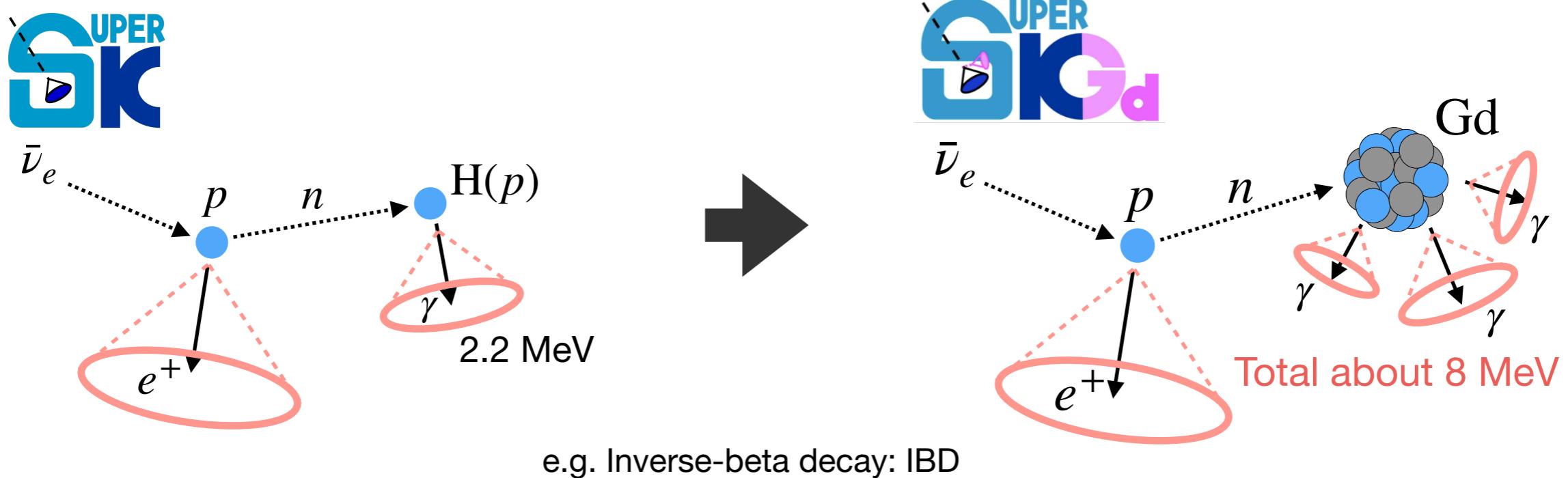


- Located 1000 m underground in Kamioka, Japan
- 11,129 50 cm PMTs is mounted in ID
- Energy threshold ~ 4 MeV
→ Sensitive to DSNB energy range
- **0.01w% of Gd** was loaded in 2020
→ **0.03w%** was loaded in 2022

SK-Gd experiment

SK-Gd : improved neutron detection efficiency by loading Gd in SK detector

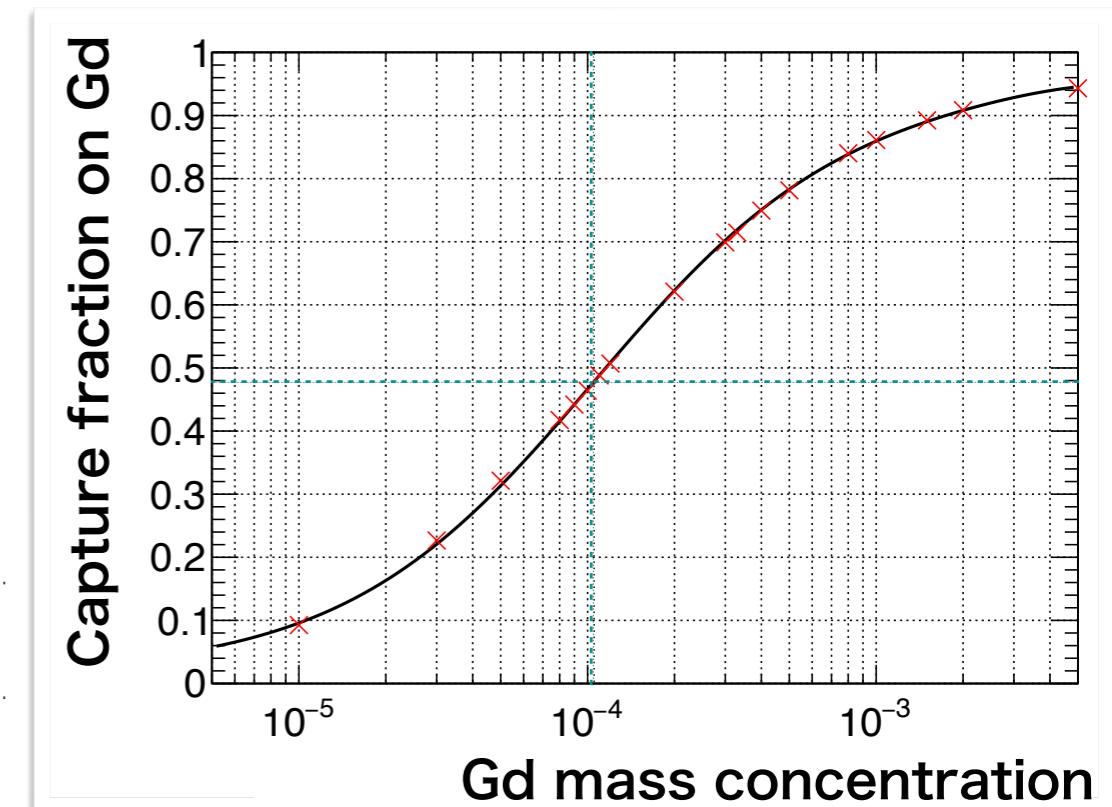
- DSNB signal : Inverse beta decay (IBD) $\bar{\nu}_e + p \rightarrow e^+ + n$
 $\rightarrow e^+$ (prompt) and n capture signal (delayed)
 - Pure-water: 2.2 MeV gamma-ray from capture on p
 - SK-Gd : Neutron signal is capture on Gd (~ 8 MeV)



First search for DSNB in SK-Gd

- Initial phase of SK-Gd was completed
→ **DSNB search is performed**
- Data set:
 - Aug. 2020 – Jun. 2022 → **552.2 days × 22.5 kton FV**
 - Neutrino energy : 9.3 - 31.3 MeV
(positron energy : 8-30 MeV)
- Gd mass concentration : **0.011%**
→ ~50% of neutrons are captured on Gd

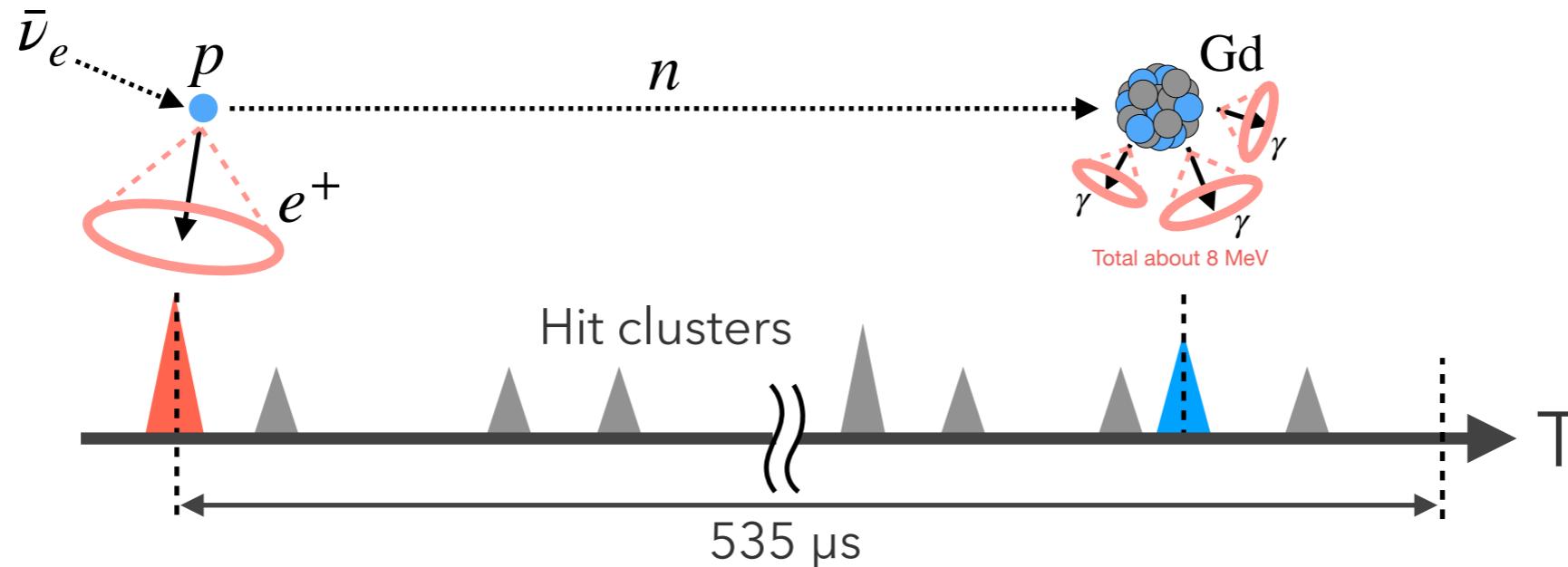
	pure-water SK	SK-Gd(0.01%)
Time constant	~205 μs	~115 μs
n detection eff.	~20%	~40%
mis-ID rate	$O(10^{-2} \sim 10^{-1})$ %	2.8×10^{-2} %



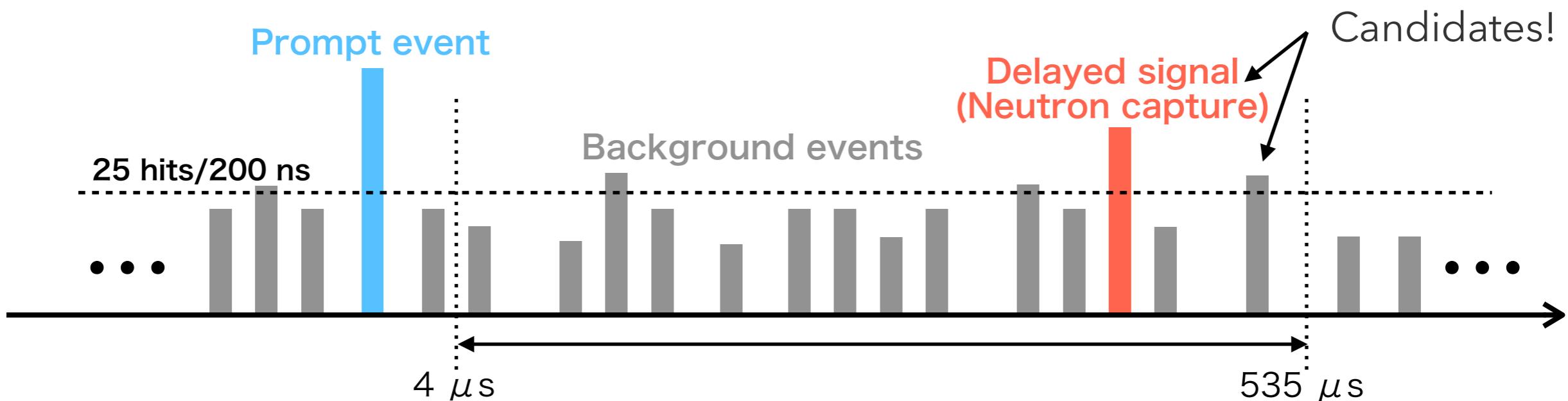
Neutron tagging in SK-Gd

Neutron search in SK-Gd

- Save all hits within 535 μs after high energy ($> \sim 6 \text{ MeV}$) event



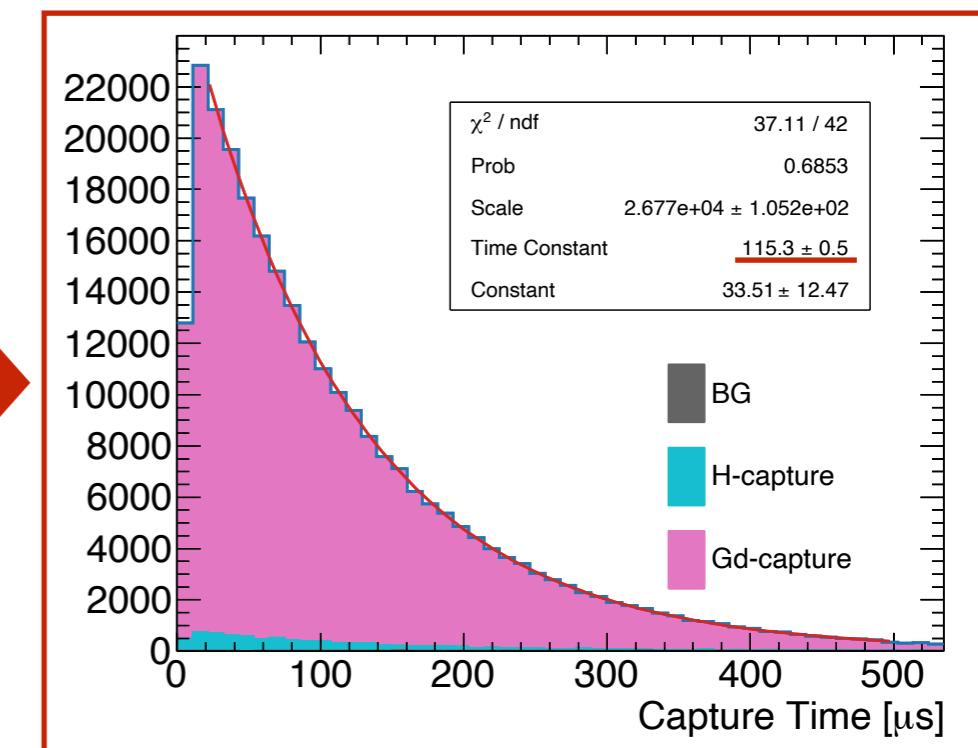
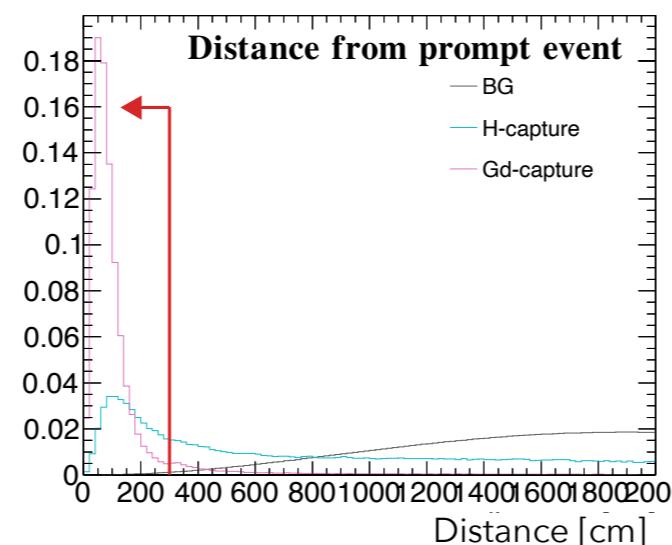
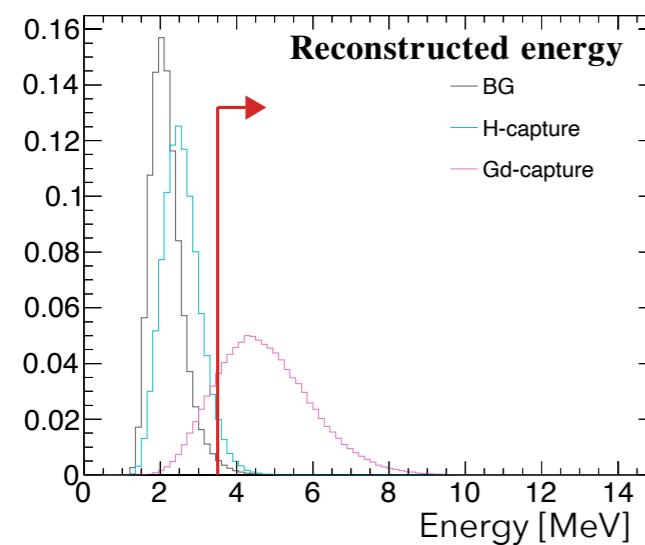
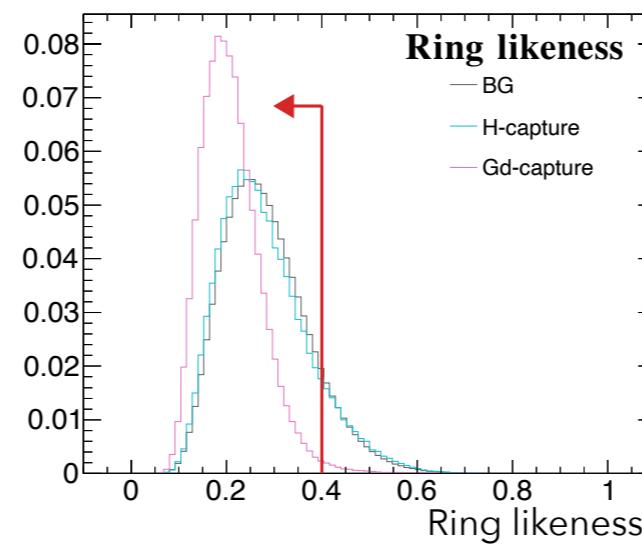
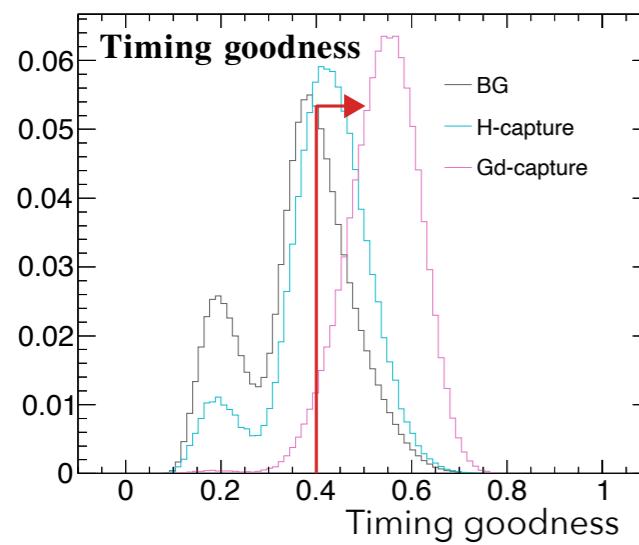
- Candidate search by 25 hits/200 ns threshold
→ Event reconstruction for each candidate



Neutron search in SK-Gd

- pure-water: ML method to select 2.2 MeV gamma-ray (~ 20%)
- **This analysis: Simple rectangular cut to select Gd gamma-rays**

Delayed Event Selections

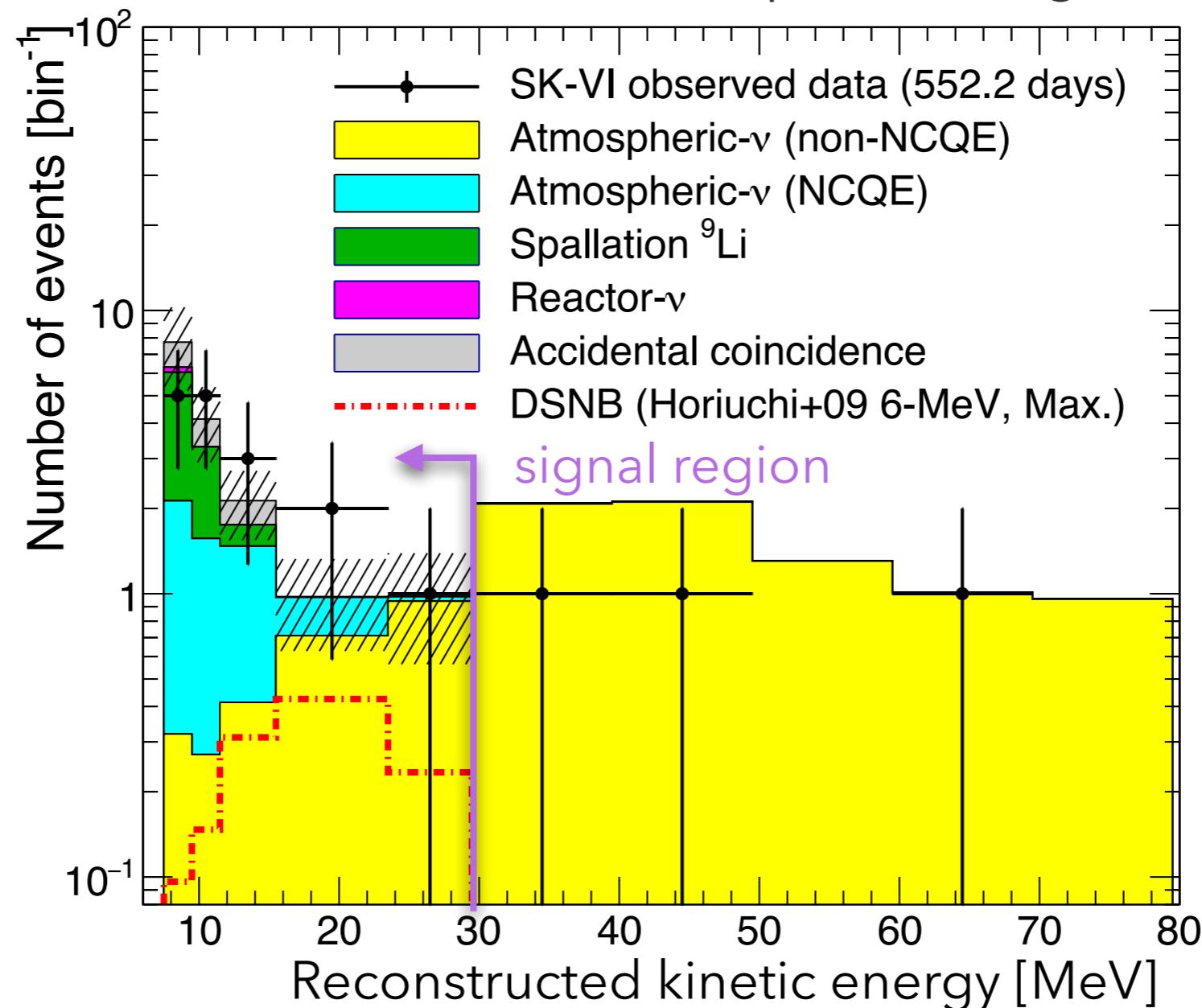


- ~70% of Gd is identified
- → Totally **~35% of n**
- Mis-ID rate: $2.8 \times 10^{-2}\%$

Search result

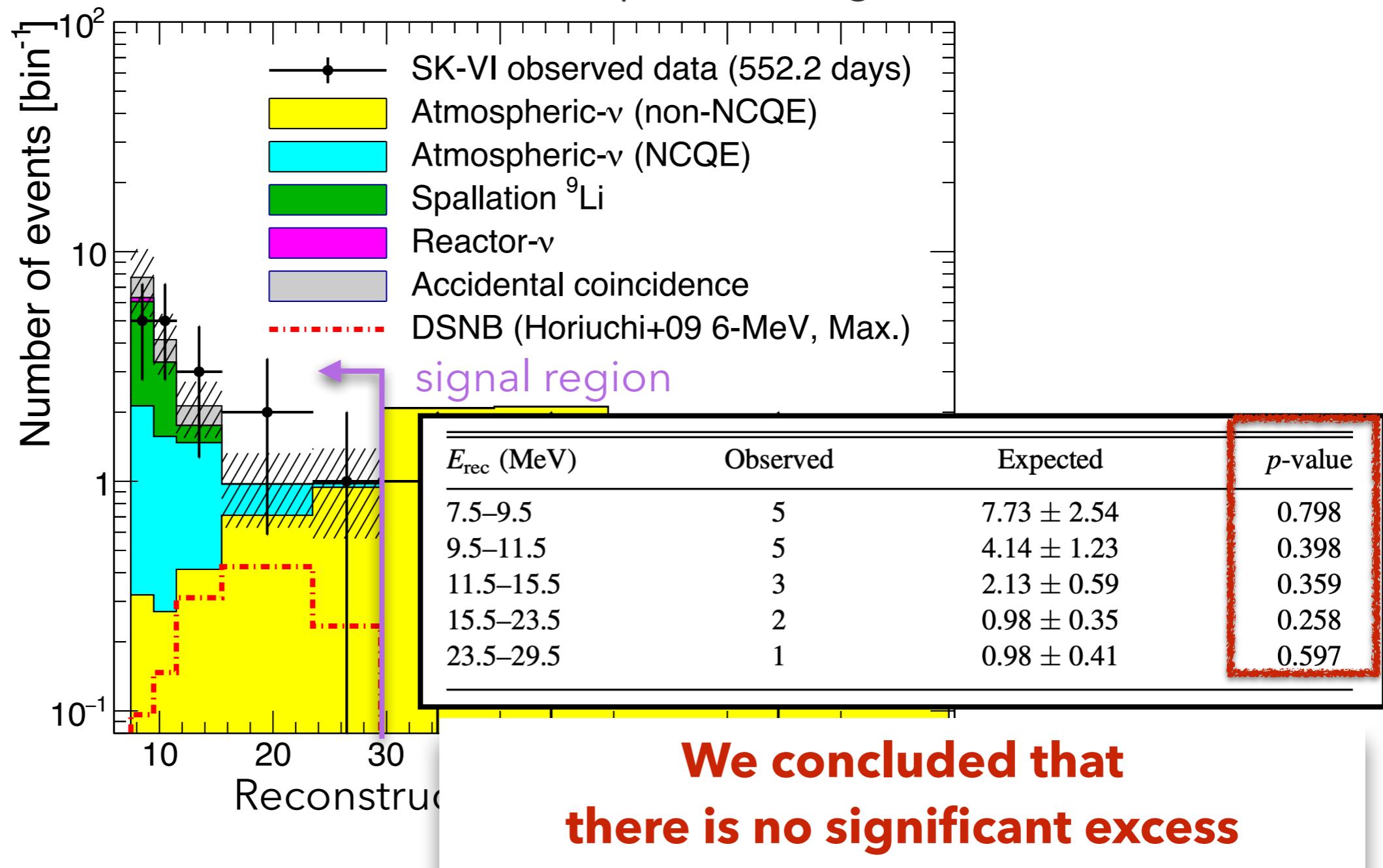
Search Result (Energy Spectrum)

- Search by dividing the search energy region into 5 bins.
→ Compare the observed data with expected bkg. for each bin



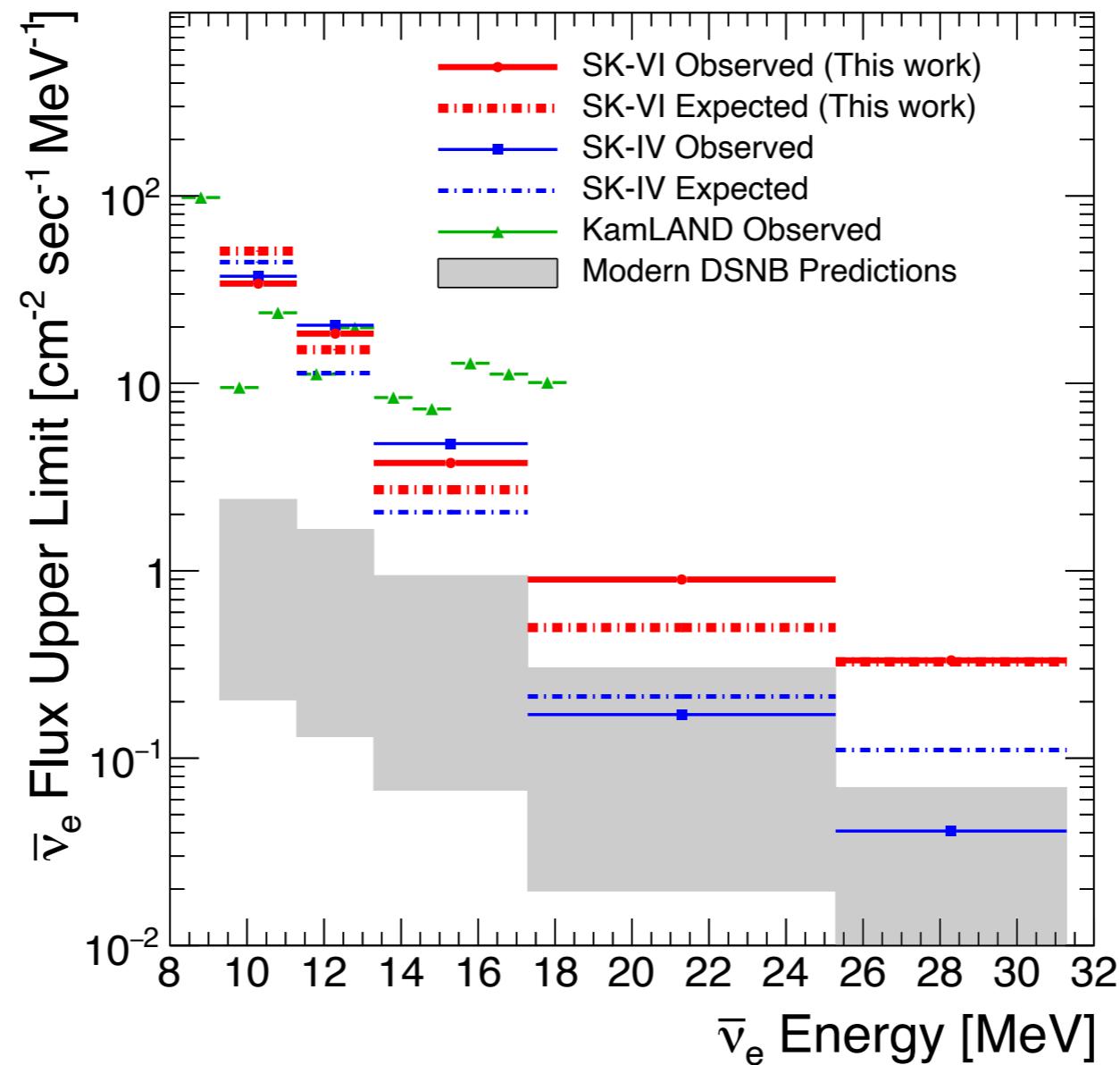
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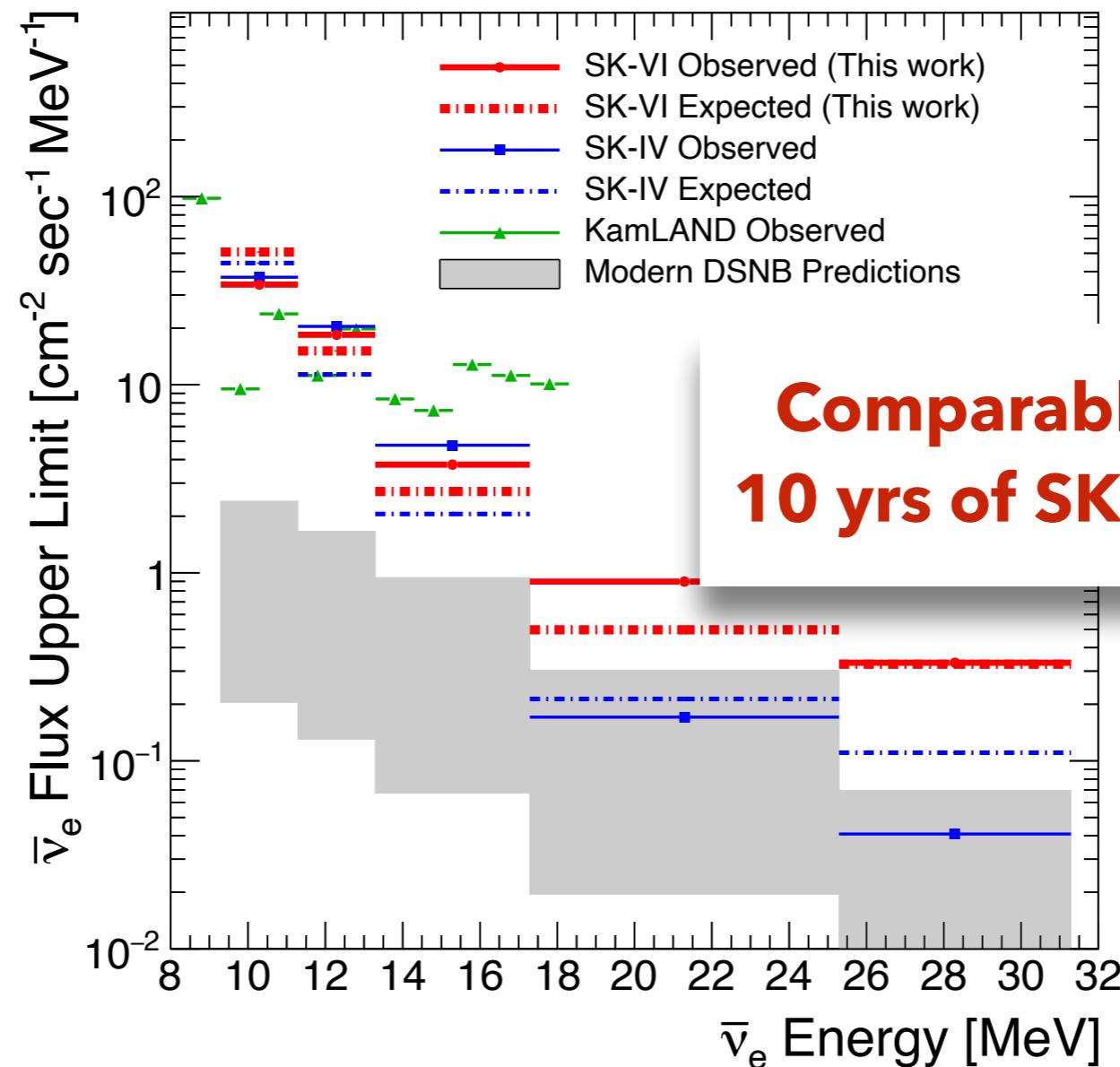
Flux upper limit

Calculated model-independent flux upper limit



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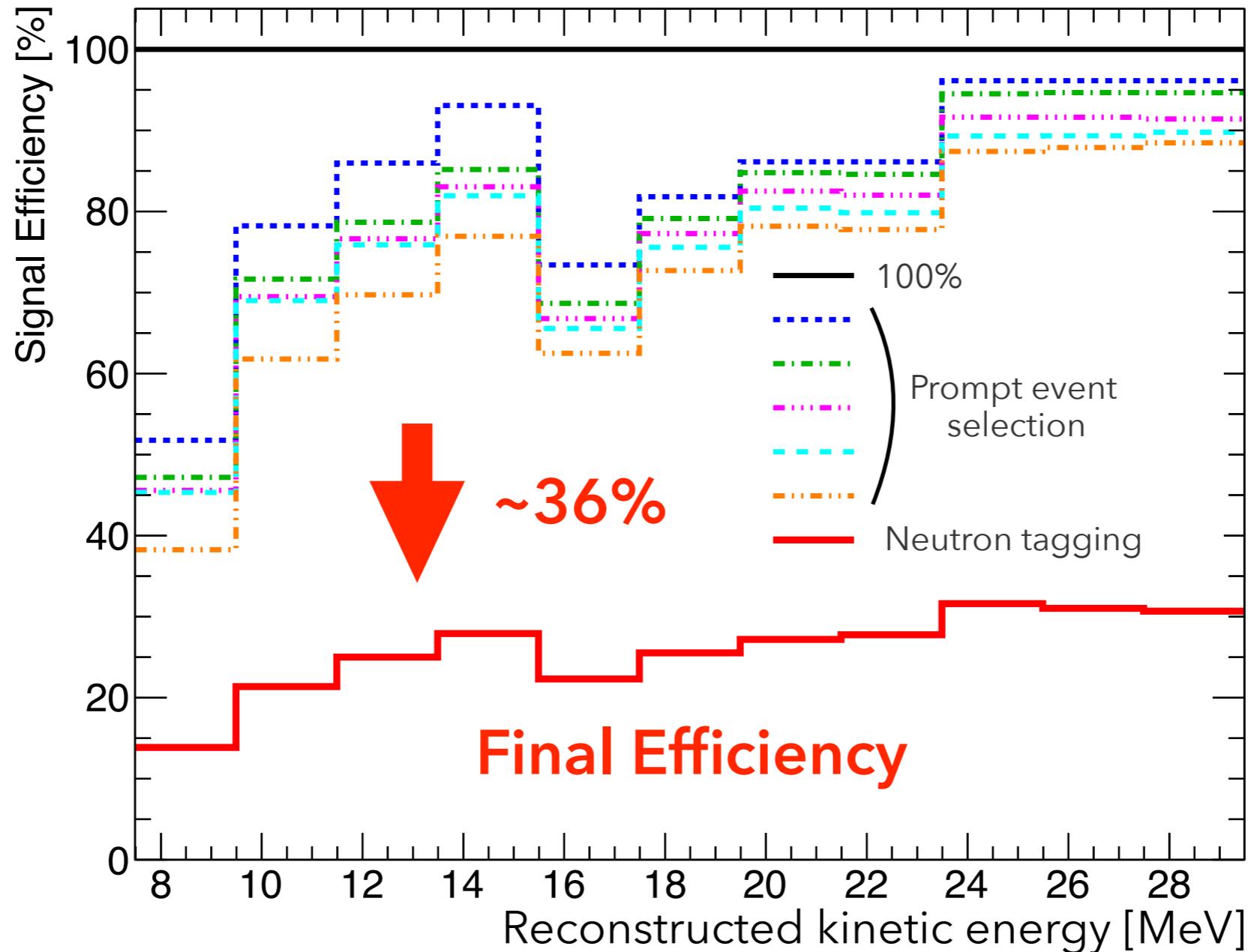
Considering about 20% of live time than previous search,
this result proves SK-Gd is most sensitive to DSNB

Summary and Future prospect

- Started SK-Gd experiment from Jul. 2020.
 - Initial phase with 0.01% Gd mass concentration was completed.
- First DSNB search in SK-Gd was performed using the data from Aug. 2020 to Jun. 2022.
 - No significant excess over expected background
- Flux upper limit is placed
 - Comparable level with 10 years of pure-water SK result due to the improvement of neutron detection efficiency.
 - Proves the SK-Gd is the most sensitive to the DSNB search.
- Currently, SK-Gd with 0.03% Gd, is in operation
 - Aiming for world's first discovery

Backup

Signal Efficiency



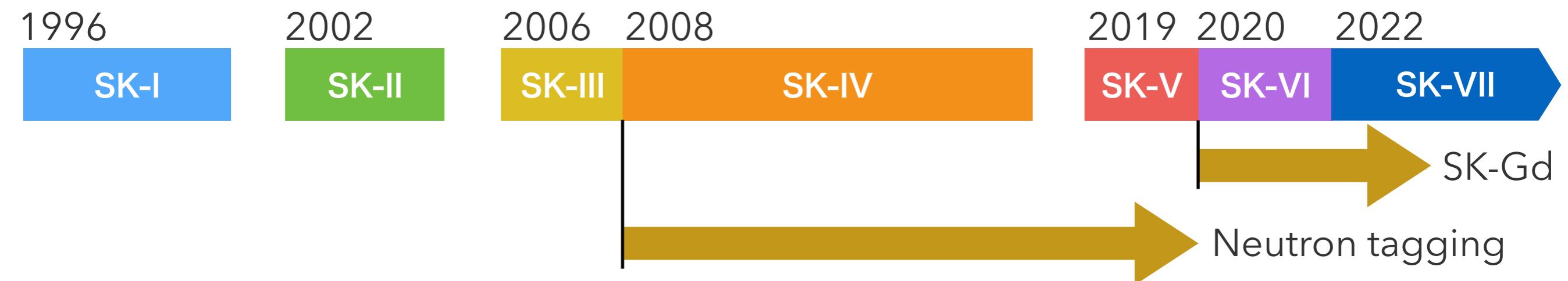
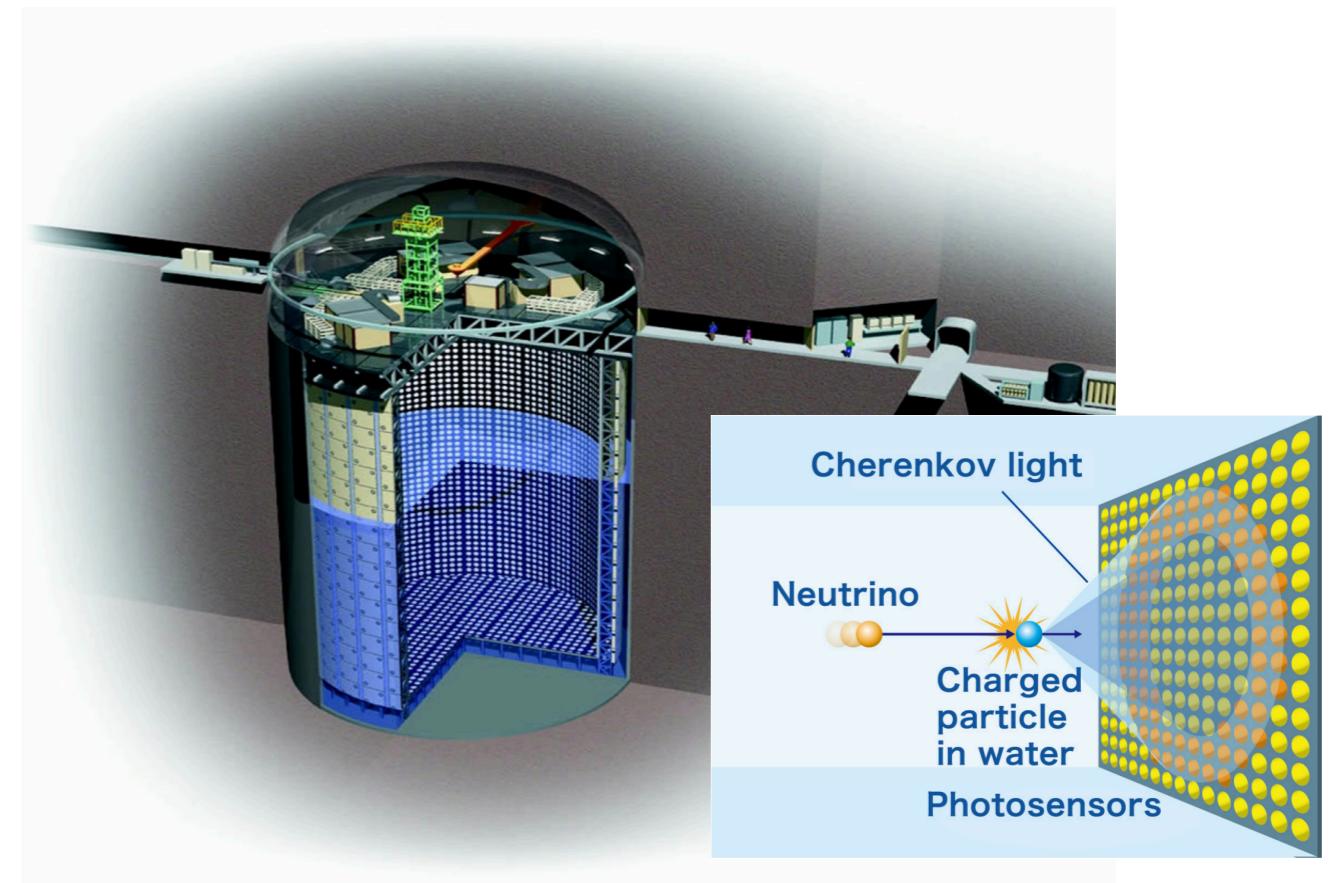
Achieved ~36% signal efficiency in the signal energy region
with $O(10^{-2})\%$ of neutron mis-ID rate !

Theoretical formation of DSNB flux

$$\frac{dF_\nu(E_\nu)}{dE_\nu} = c \int_0^{z_{\max}} \frac{dz}{H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}$$
$$\times \left[R_{\text{CC}}(z) \int_0^{Z_{\max}} \psi_{\text{ZF}}(z, Z) \left\{ \int_{M_{\min}}^{M_{\max}} \psi_{\text{IMF}}(M) \frac{dN(M, Z, E'_\nu)}{dE'_\nu} dM \right\} dZ \right]$$

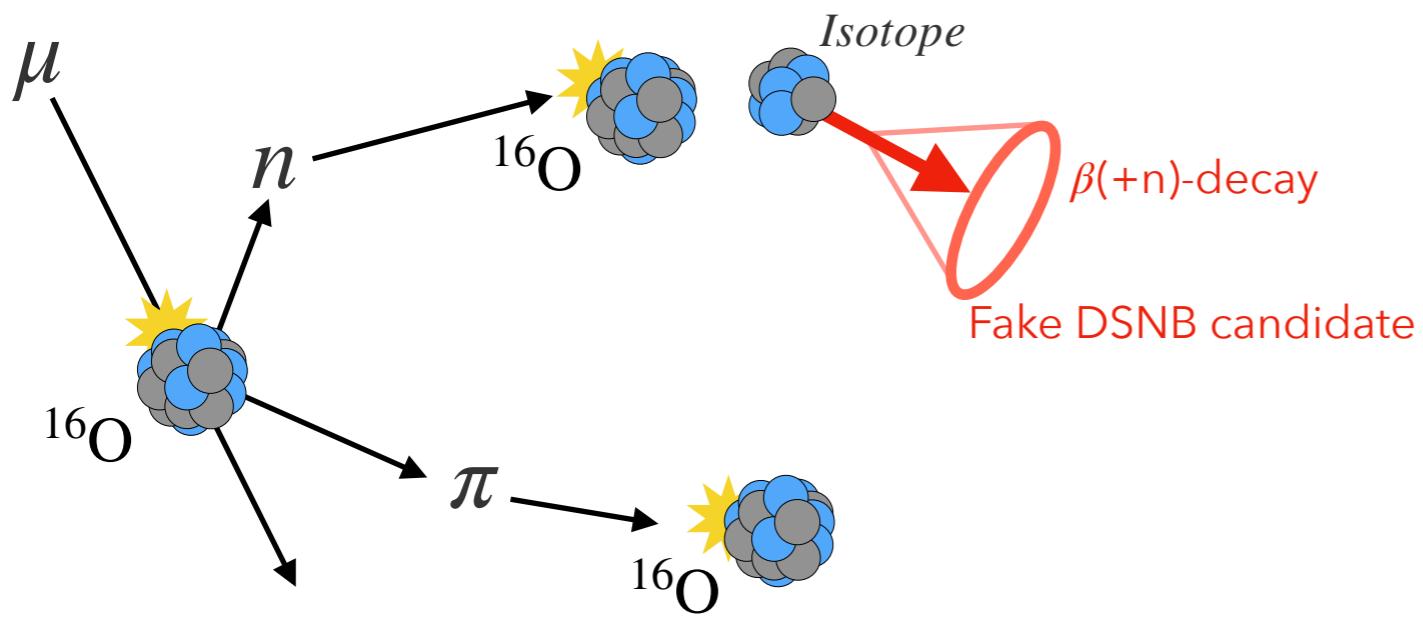
Super-Kamiokande

- Water Cherenkov Detector @1000 m underground
 - Fiducial volume (FV): 22.5 kton
- Sensitive to MeV ~ 10 TeV
- Directional observation
- ~20 years data taking from 1996
- SK-Gd: August 2020~

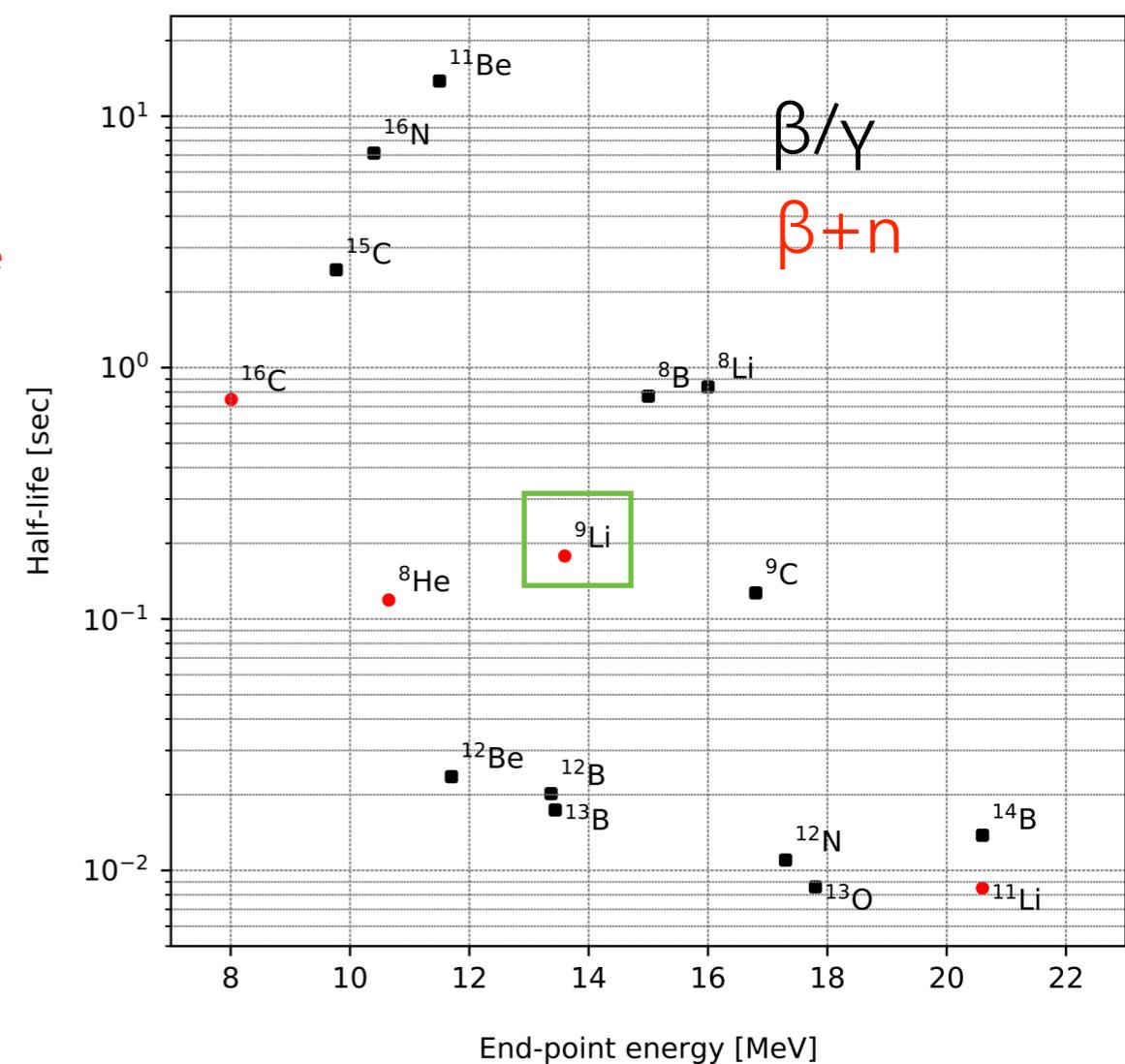


Background: Muon Spallation Products (Li9)

- Cosmic Muon comes ~ 2 Hz at SK site
 - Isotope decays are fake low-energy event ($\sim \times 10^6$ as DSNB rate)

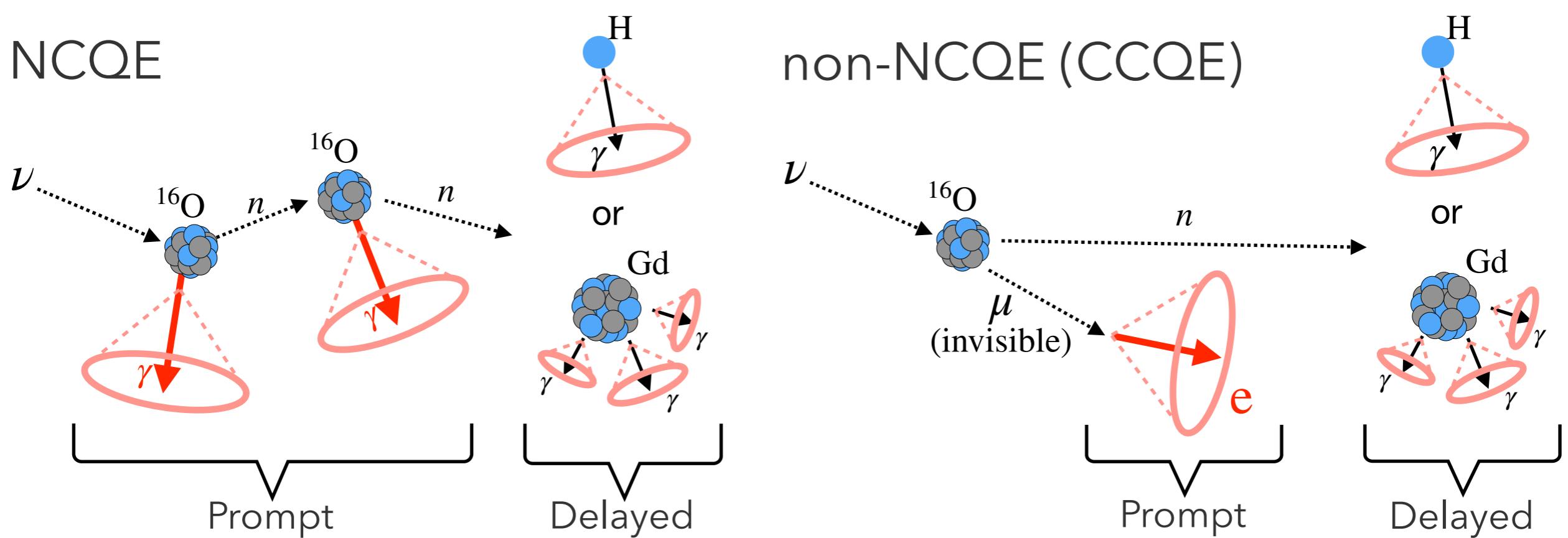


- Lithium-9 (^9Li)
 - Relatively high yield, long lifetime
 - Has $\beta + n$ decay branch
- Remaining background



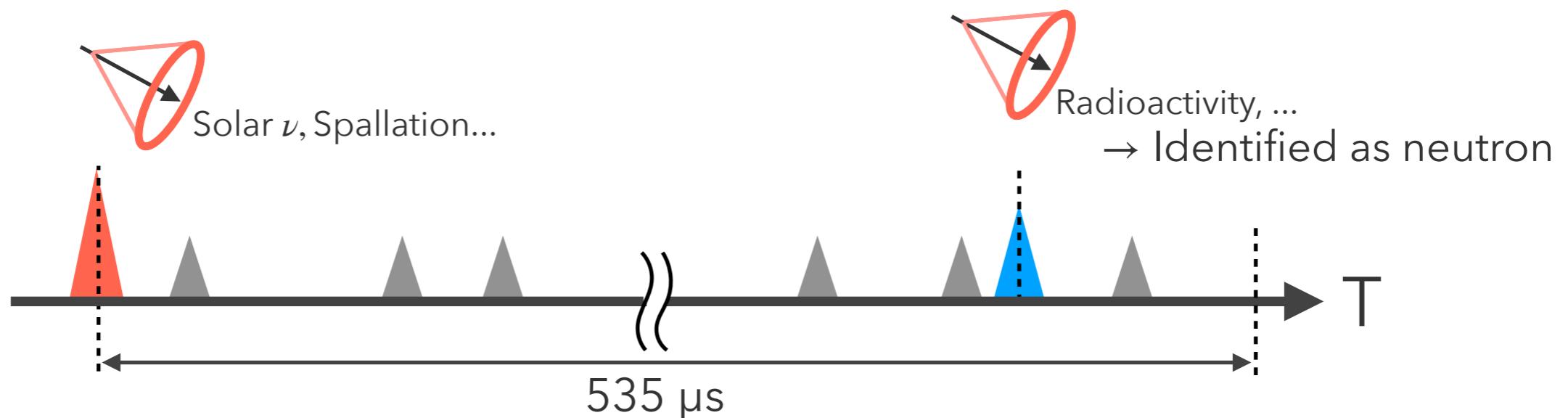
Background: Atmospheric Neutrinos

- Neutral-Current Quasi-Elastic (NCQE) interactions
 - De-excitation gamma-ray (dominant $< \sim 20$ MeV)
- non-NCQE interactions
 - Decay electron (from invisible muon) + n



Background: Other sources

- Reactor Neutrinos
 - Truly same signal topology (IBD) for $E_{\text{rec}} < 10 \text{ MeV}$
 - Estimated from the Japanese reactor activity and IAEA database
- Accidental Coincidence
 - e^+ like (e^+ , gamma,...) + n-like (radioactivity, noise hit, ...)
 - Estimated from the randomly triggered data

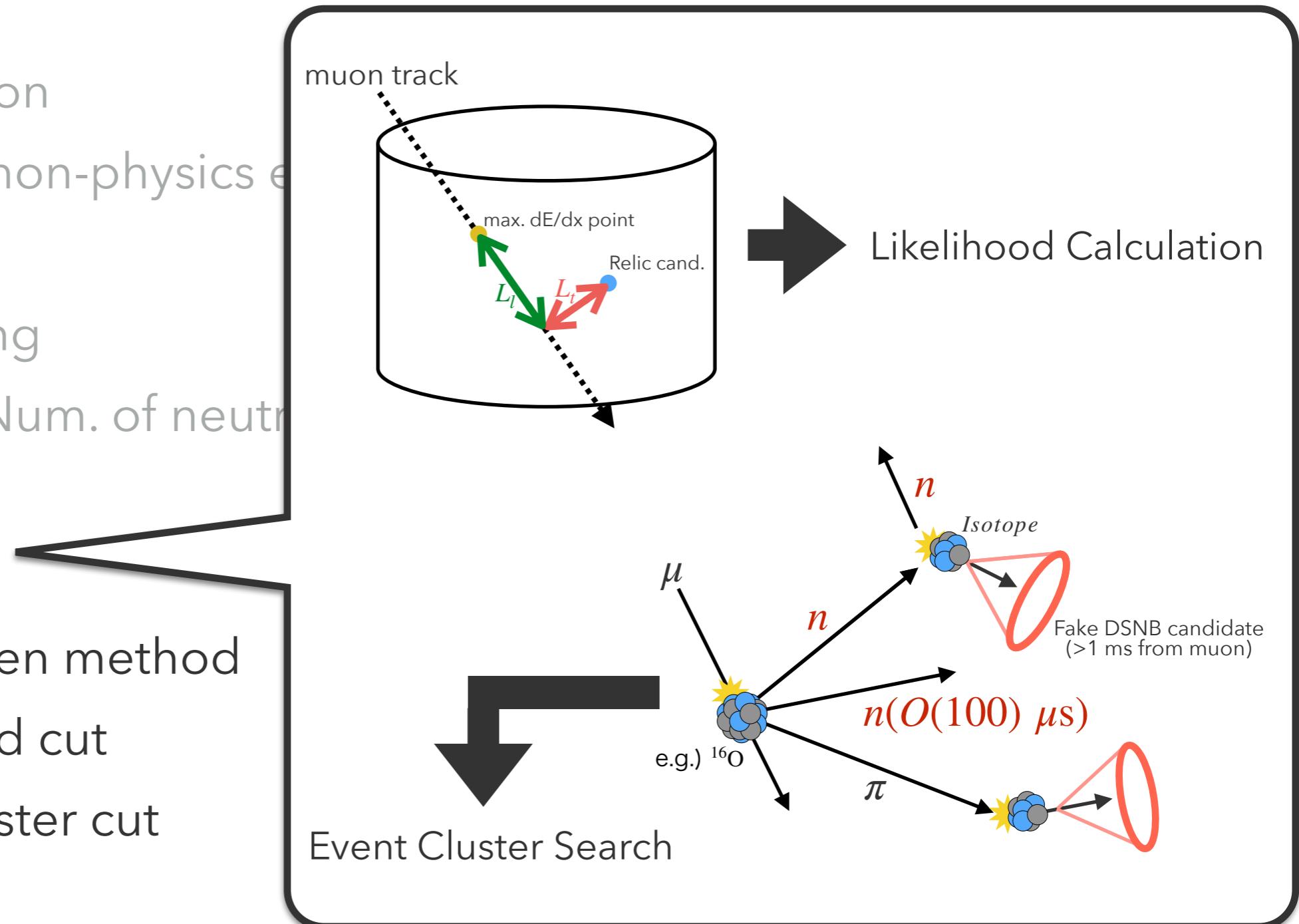


Event Reduction

- Noise Reduction (pre-cut)
 - Remove non-physics event, bad event, etc...
- Neutron tagging
 - Require Num. of neutron = 1
- Spallation Cut
- Positron identification

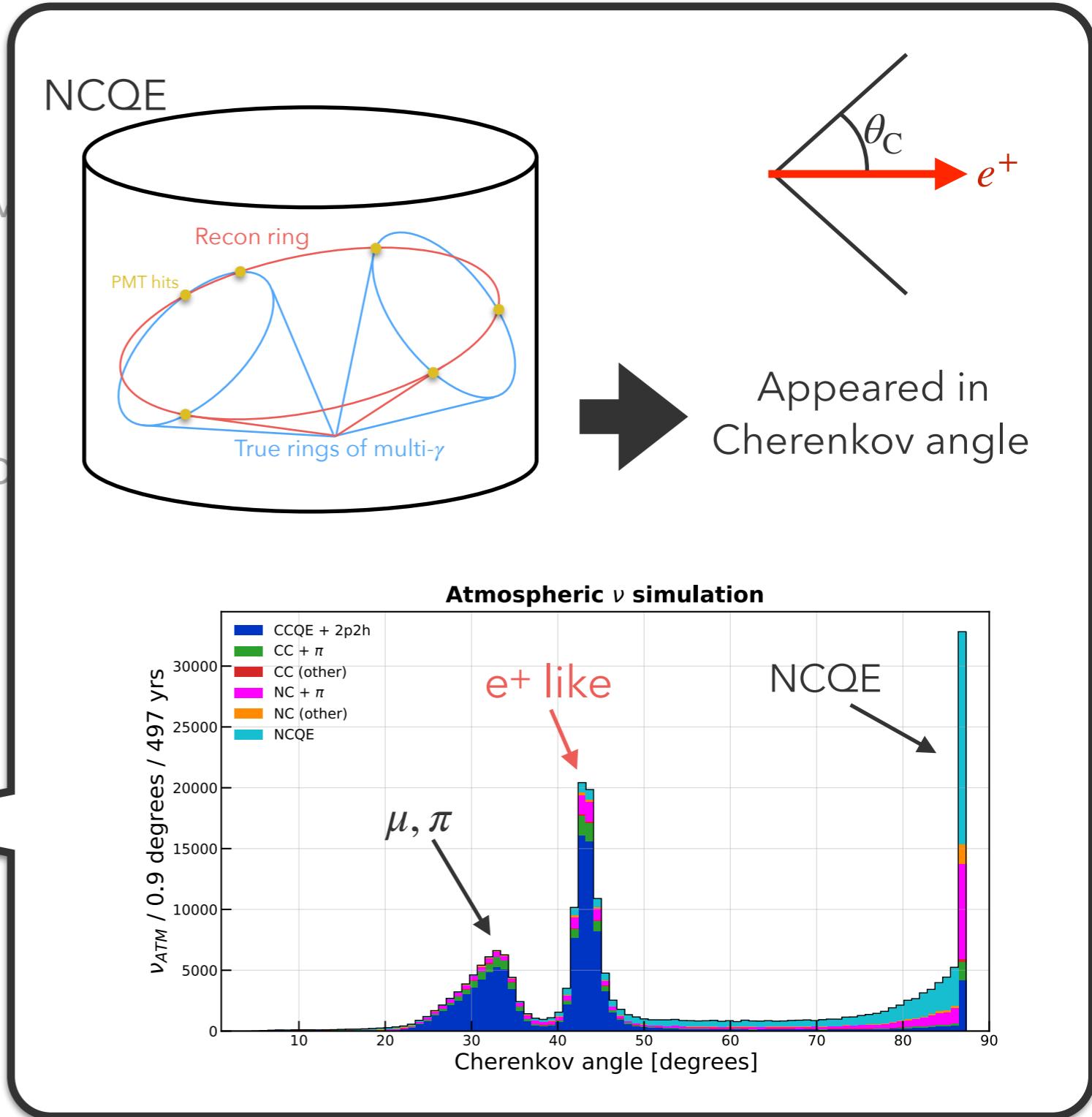
Event Reduction: Spallation cut

- Noise Reduction
 - Remove non-physics events
- Neutron tagging
 - Require Num. of neutrons
- Spallation Cut
 - Data driven method
 - Likelihood cut
 - Event cluster cut
- Positron identification



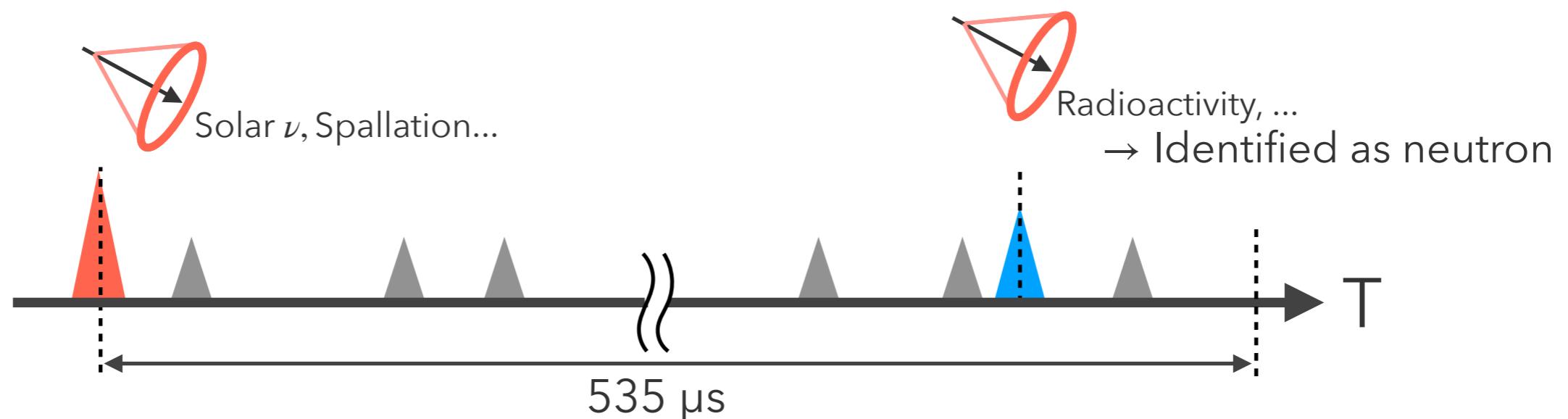
Event Reduction: Positron identification

- Noise Reduction
 - Remove non-physics events
- Neutron tagging
 - Require Num. of neutrons
- Spallation Cut
- Positron identification
 - Cherenkov angle
 - Ring clearness
 - Charge/Hit



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Future Prospect

