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

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2023 Oct. 24

NeuTel2023,
Oct. 23– 27 @Venice, Italy

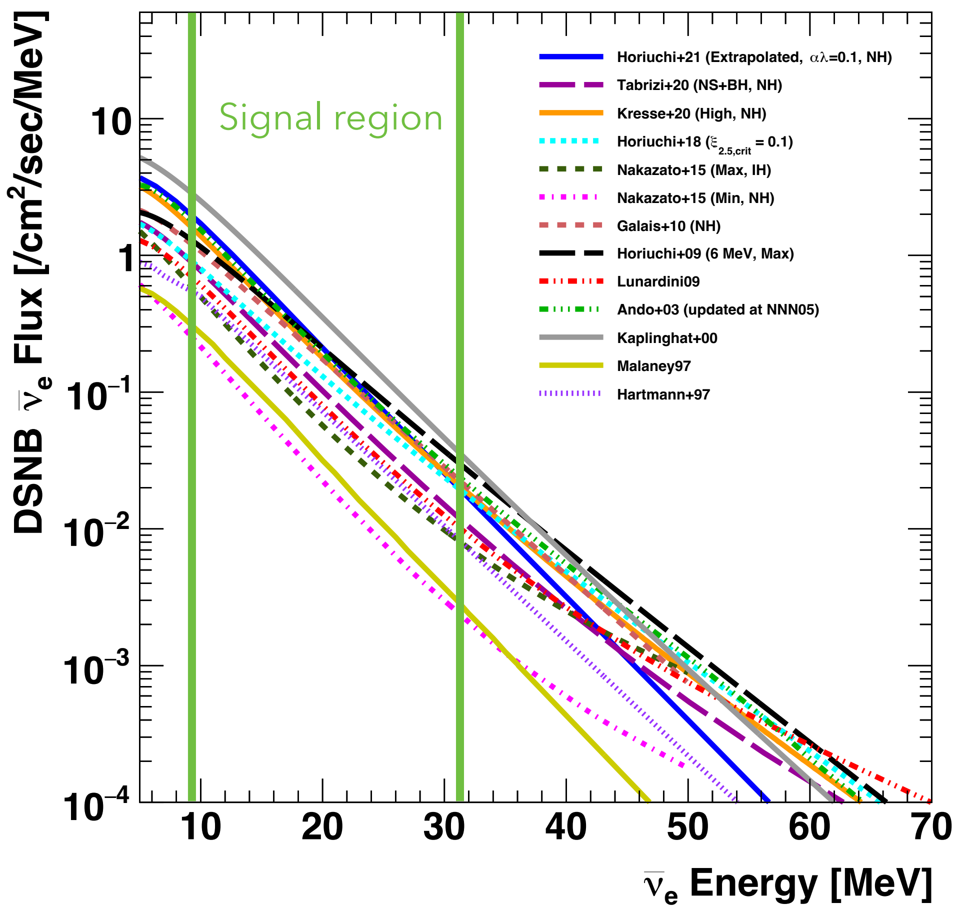
Diffuse Supernova Neutrino Background

- **Diffuse Supernova Neutrino Background (DSNB)：**
  Integrated flux of the neutrinos emitted from past all Supernovae

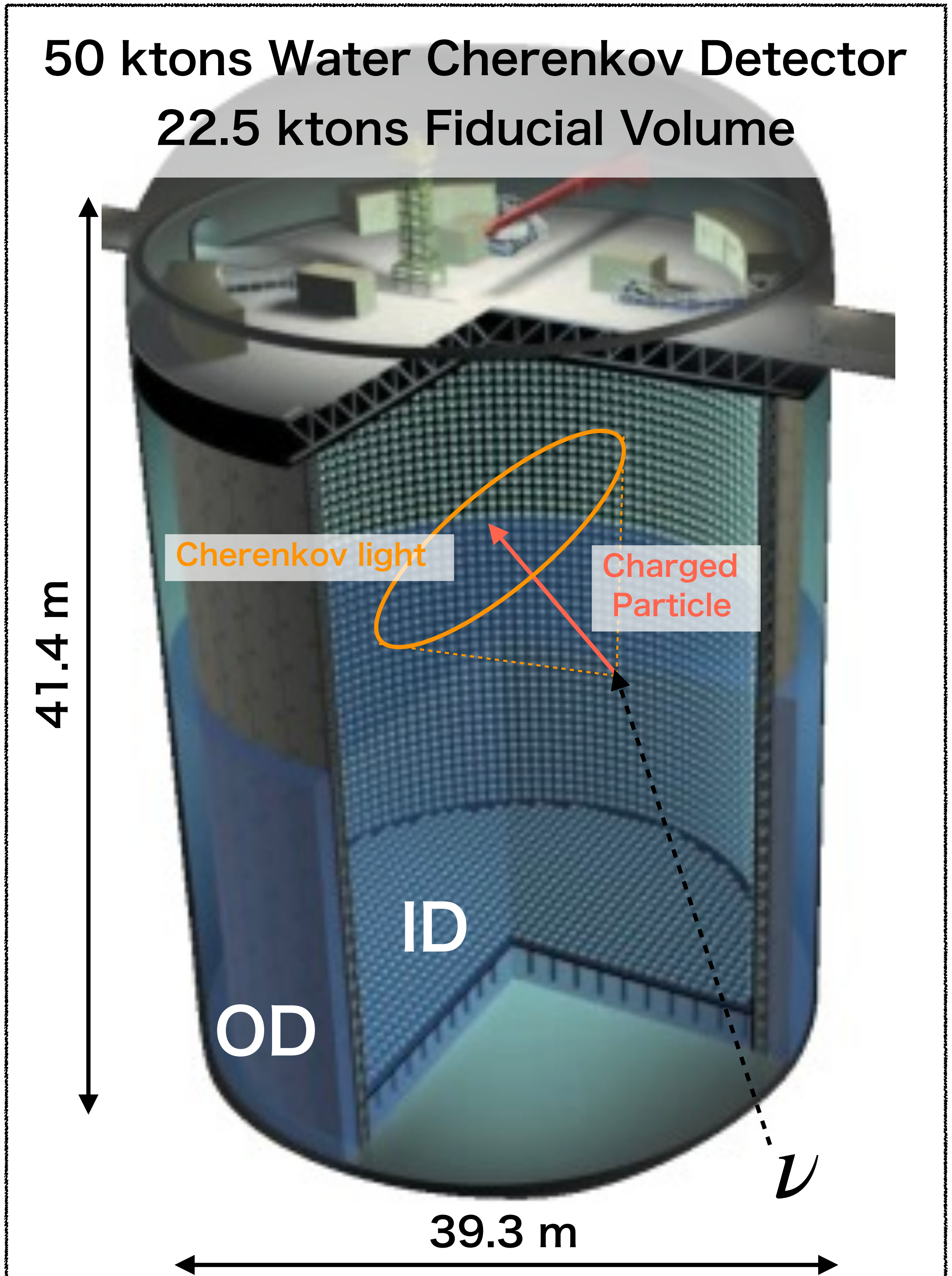
- DSNB flux is affected by various parameters including
  the star formation, metallicity (star evolution history)
  →Various theoretical models are proposed

- 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



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

- Located 1000 m underground in Kamiola, 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

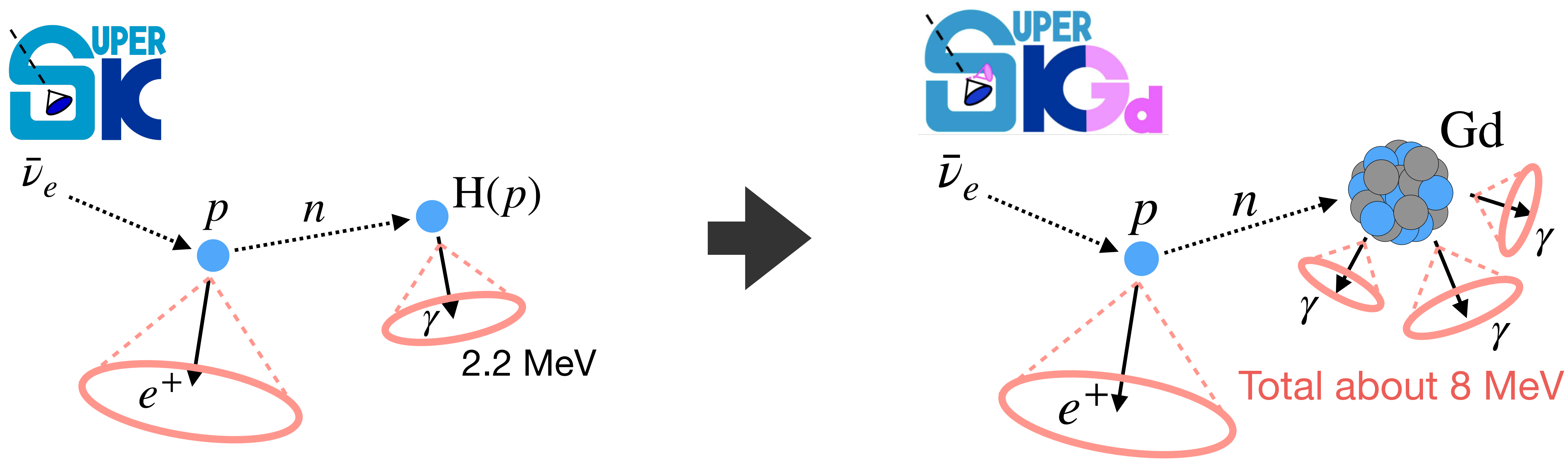
SK-Gd experiment

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

- DSNB signal : Inverse beta decay (IBD) $\bar{\nu}_{\rm e} + {\rm p} \rightarrow \mathbf{e}^{+} + n$

→ e^{+} (prompt) and n capture signal (delayed)

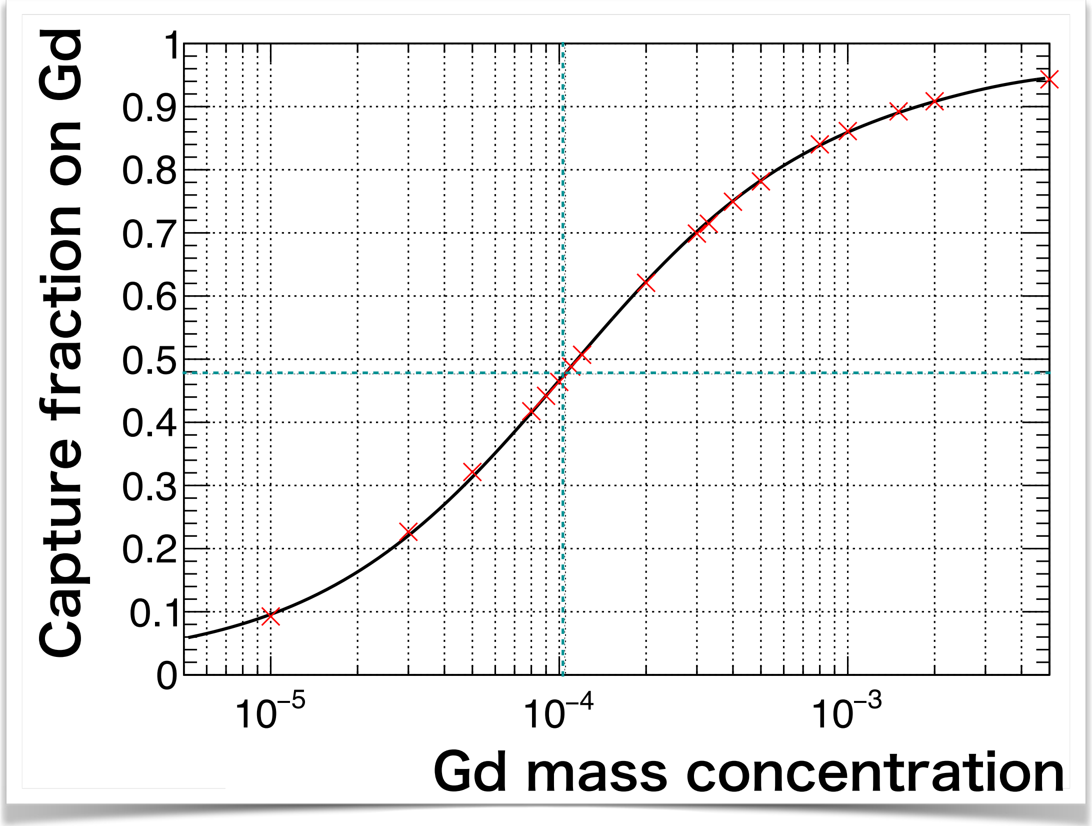
- Pure-water: 2.2 MeV gamma-ray from capture on p
- **SK-Gd** : Neutron signal is capture on Gd (~8MeV)



e.g. Inverse-beta decay: IBD

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

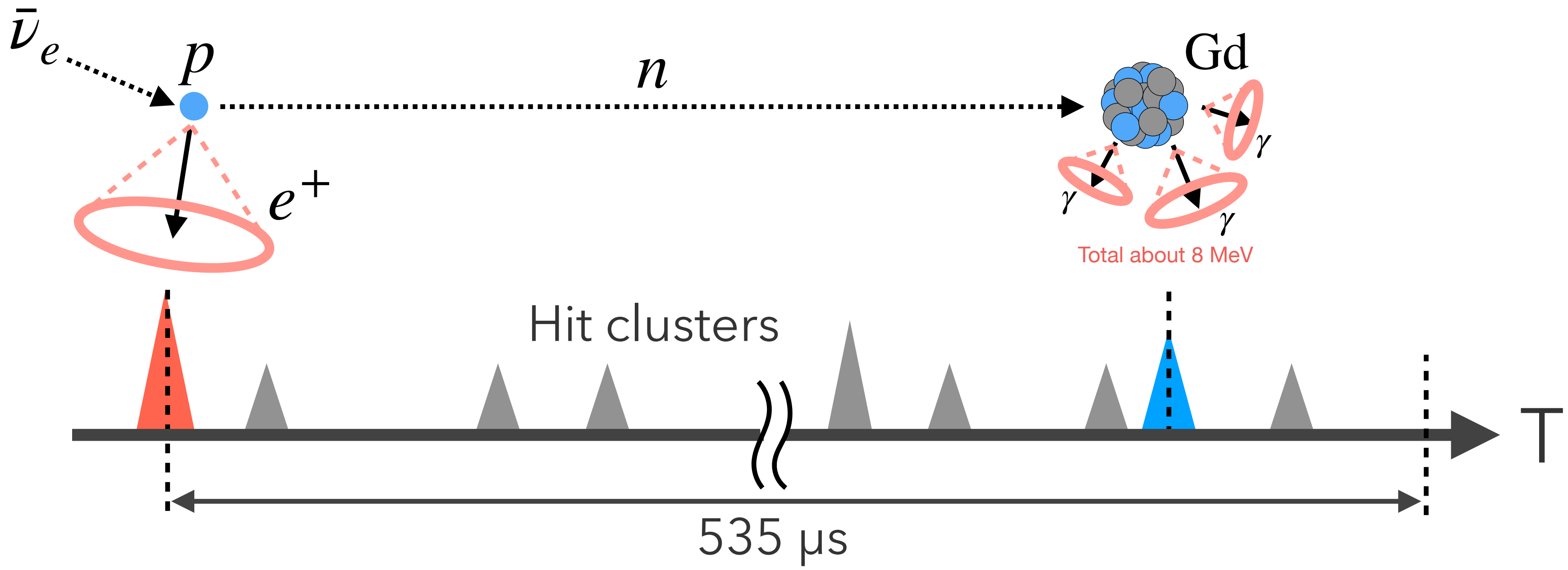


	pure-water SK	**SK-Gd(0.01%)**
Time constant	~205 μs	**~115 μs**
n detection eff.	~20%	**~40%**
mis-ID rate	O(10^{-2}~10^{-1}) %	**2.8×10^{-2} %**

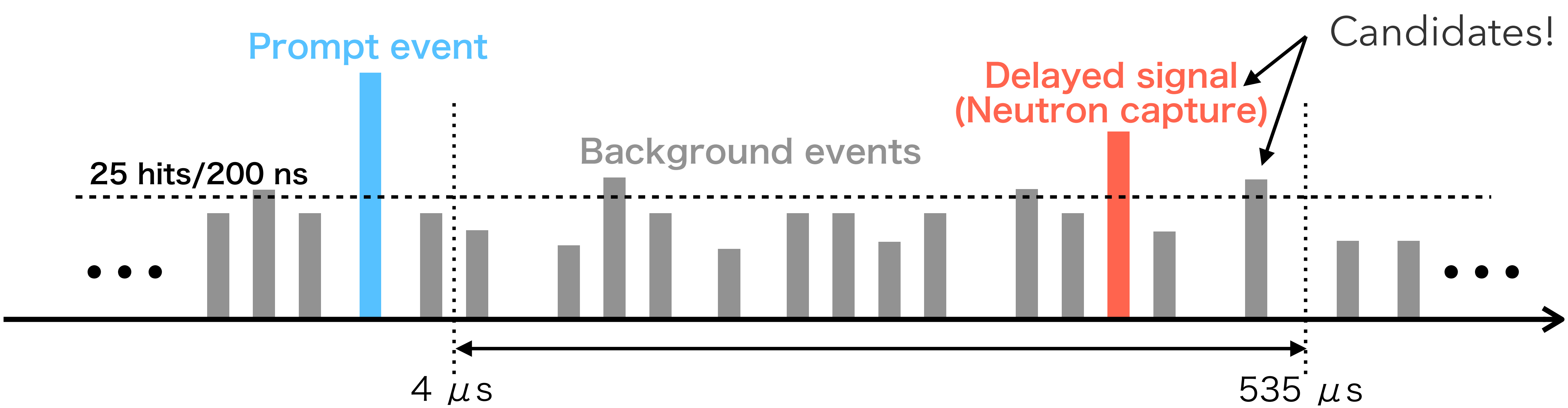
Neutron tagging in SK-Gd

Neutron search in SK-Gd

- Save all hits within 535 μs after high energy (> ~6 MeV) event



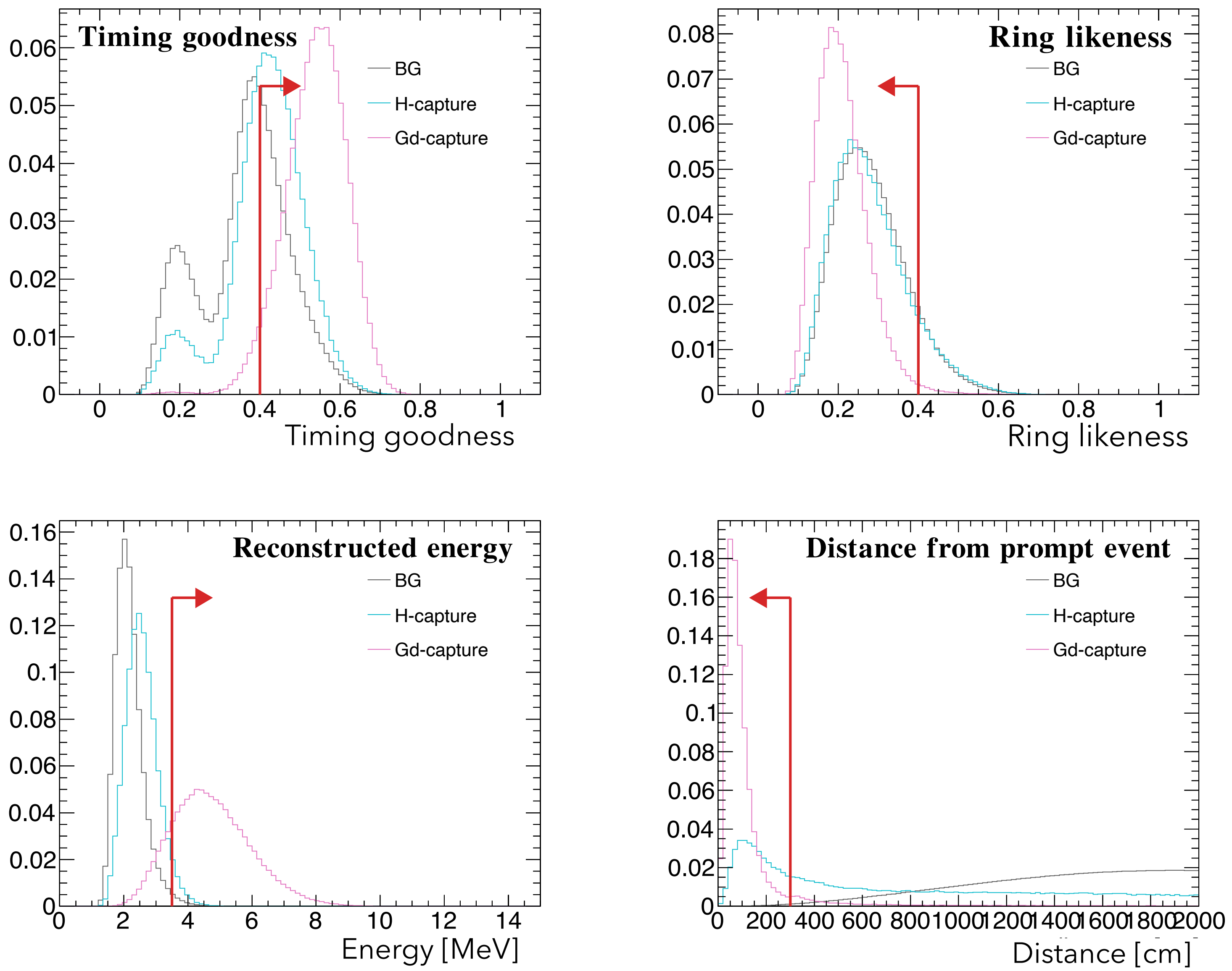
- Candidate search by 25 hits/200 ns threshold
  → Event reconstruction for each candidate

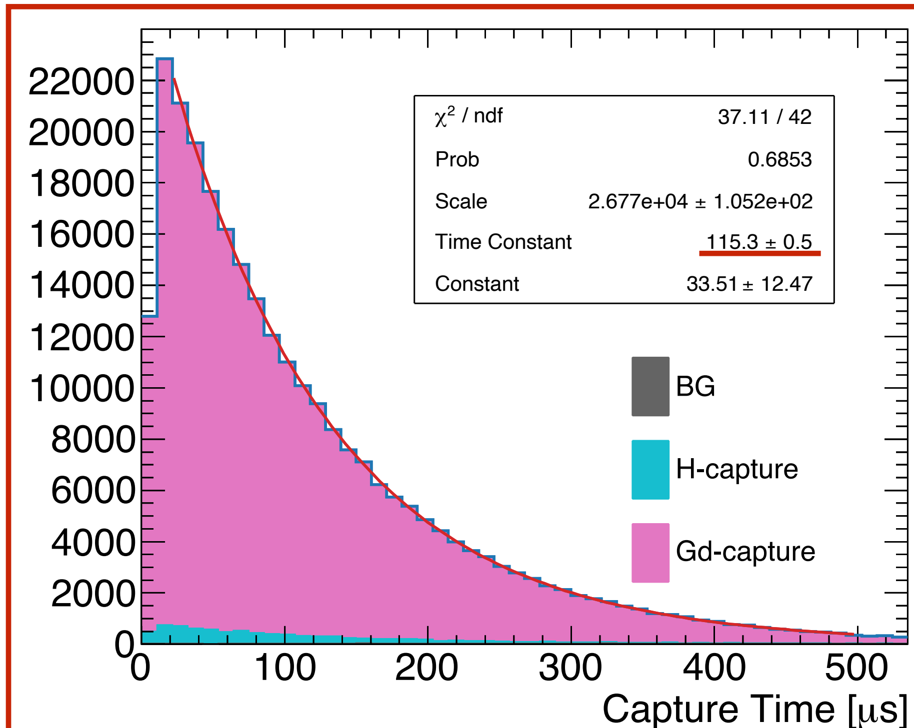


Neutron search in SK-Gd

- 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





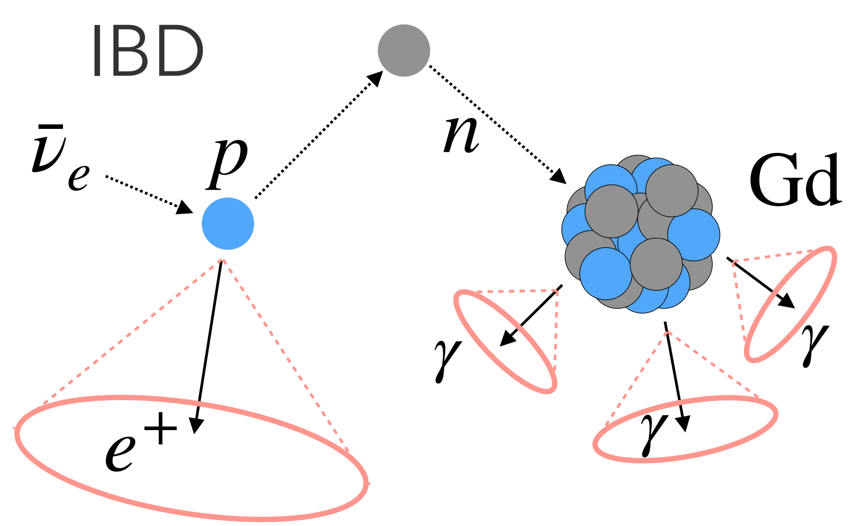
- ~70% of Gd is identified
  →Totally **~35% of n**
- Mis-ID rate: 2.8×10^{-2}%

Background reduction using neutron

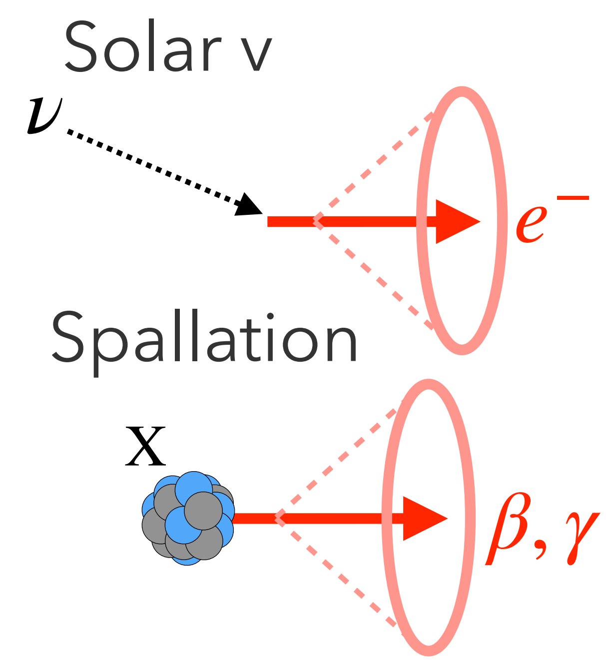
Selection using neutron:

Require **only one neutron**
after prompt positron event

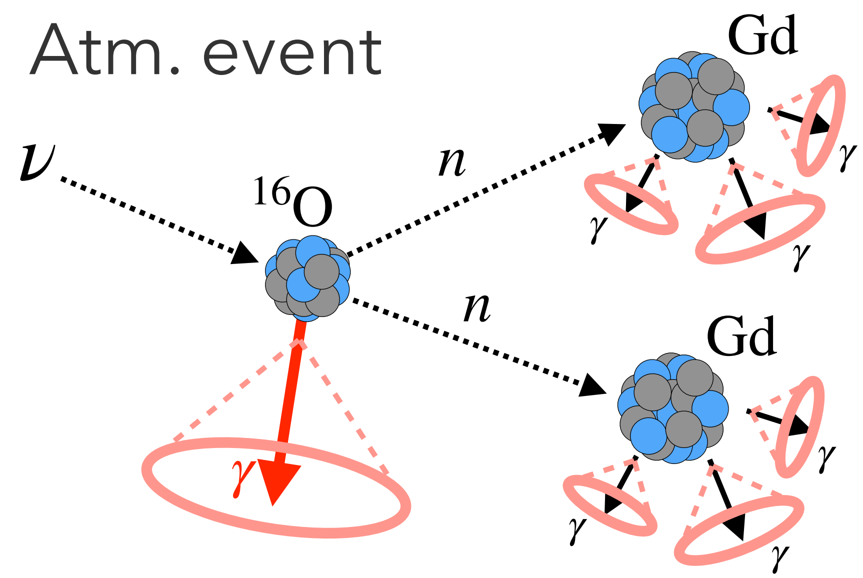
Only one neutron



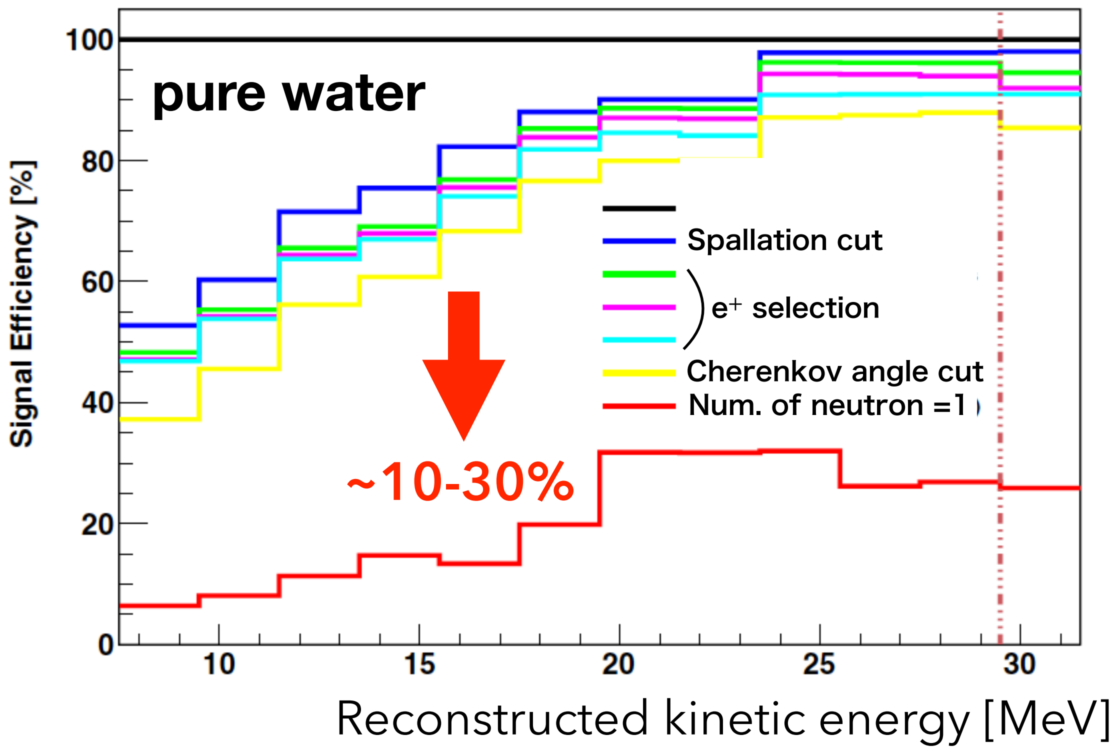
Without neutron



Multiple neutron

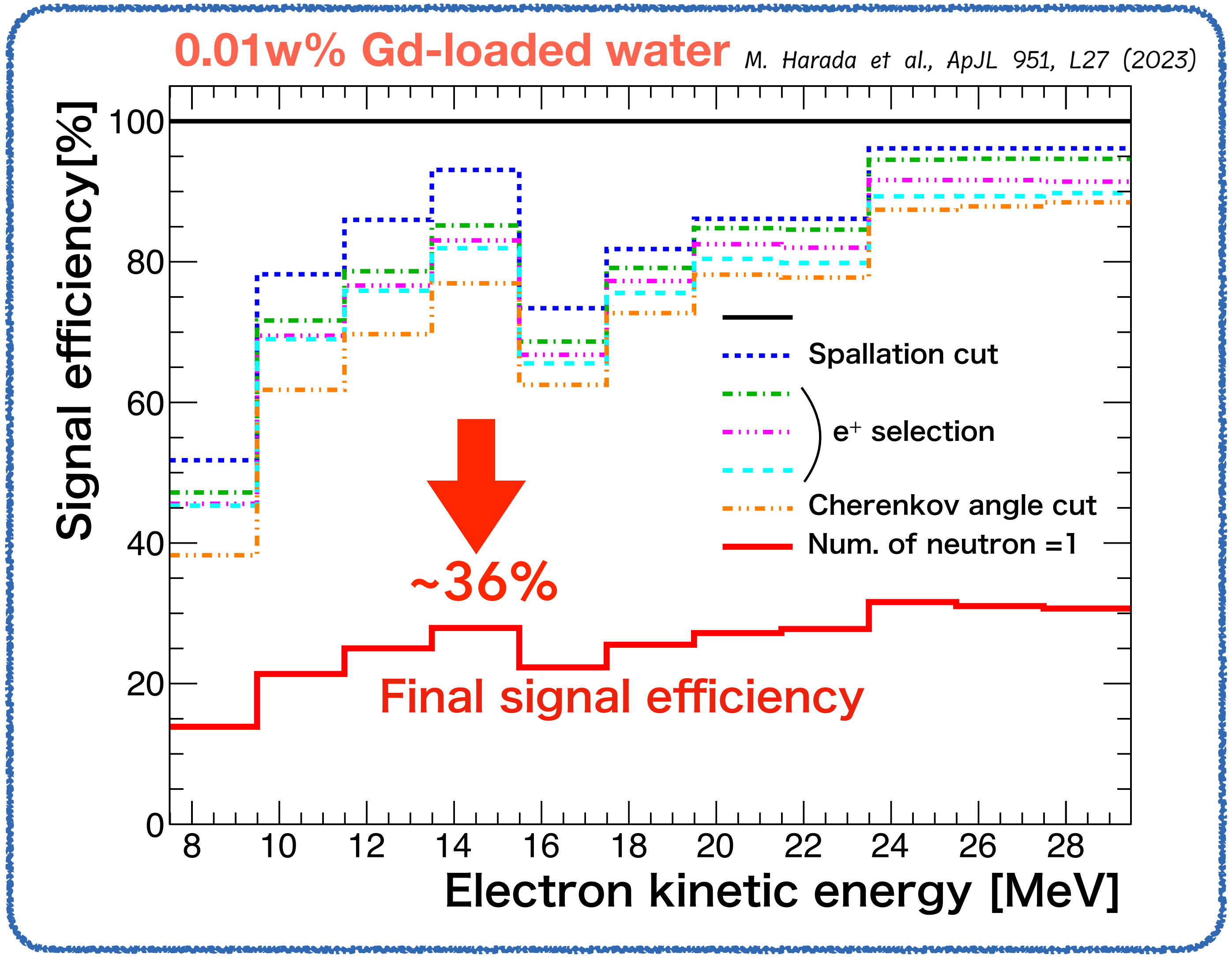


Signal efficiency



- Spallation cut reduces signal efficiency at low-energy side
- Atm. Neutrino reduction well conserve signal efficiency

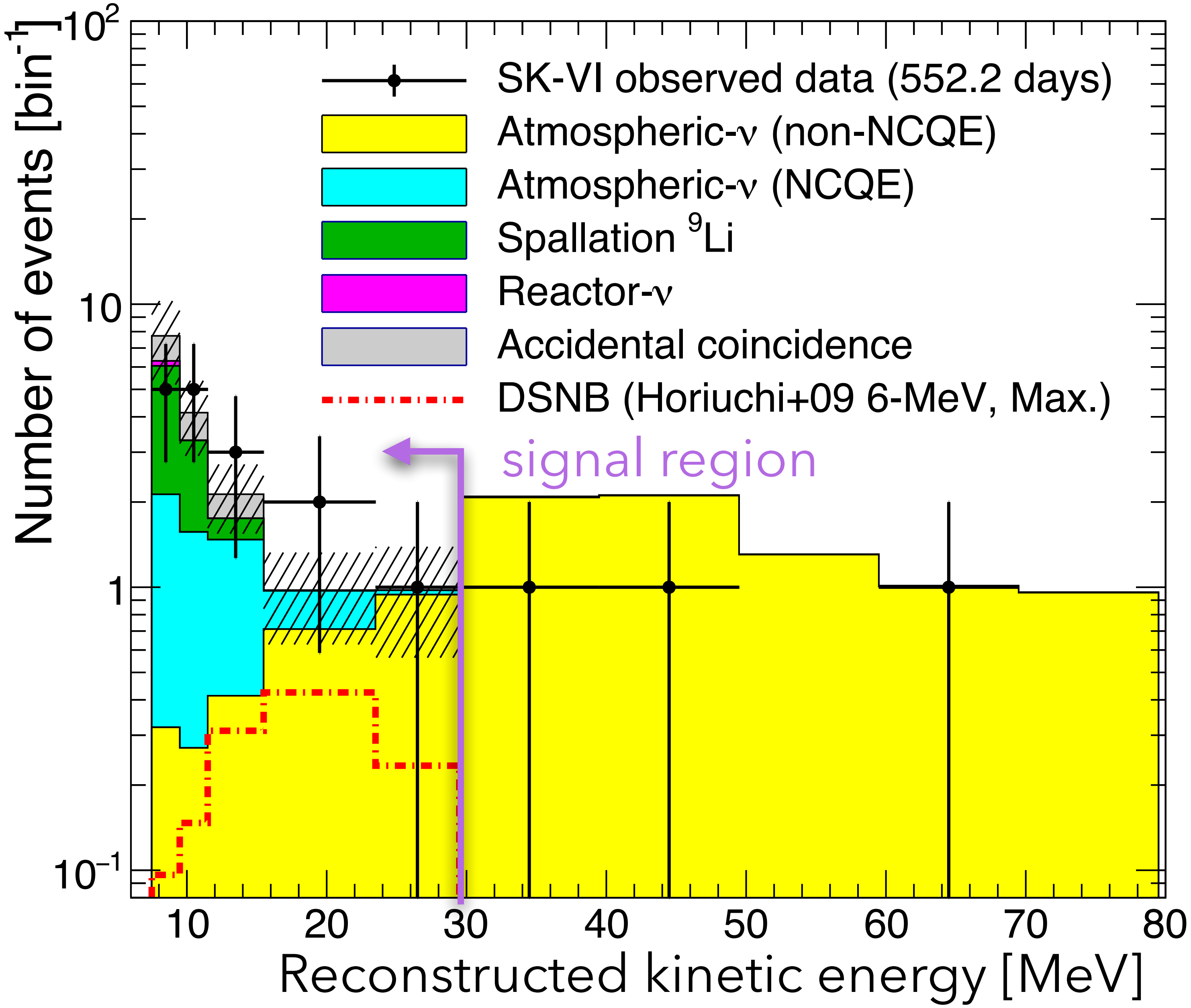
2-3 times higher efficiency due to neutron tagging!!



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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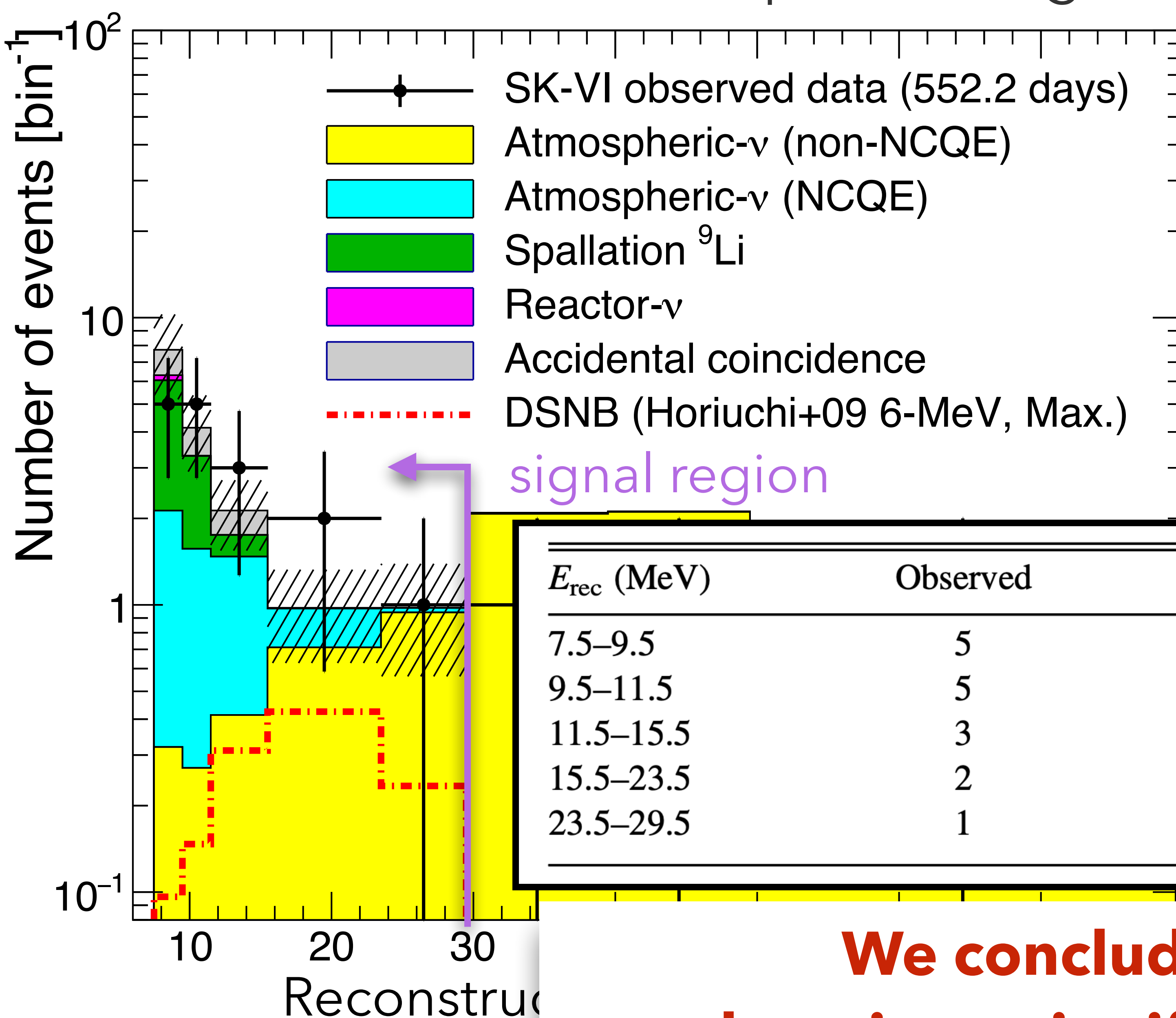
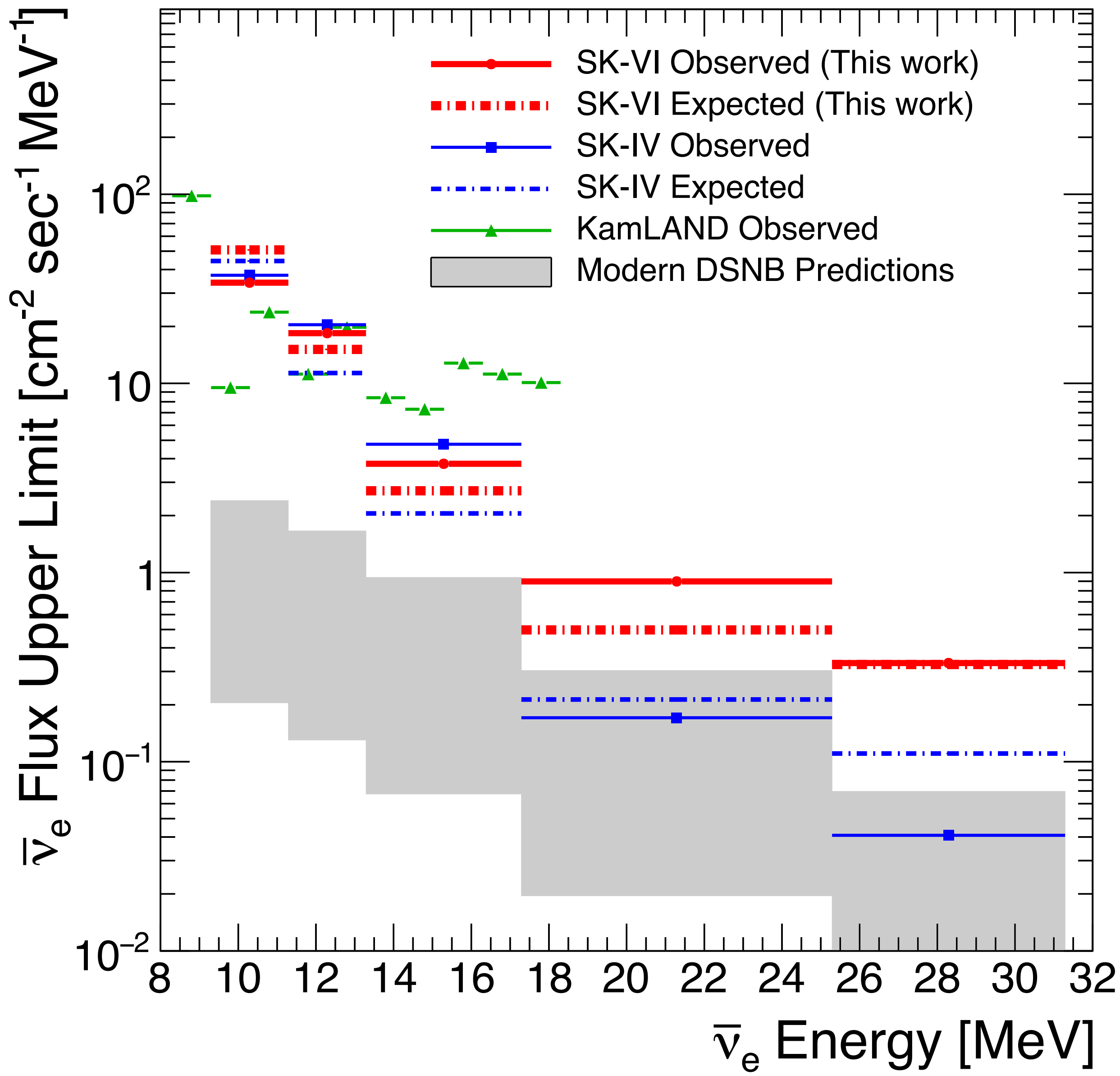


E_{rec} (MeV)	Observed	Expected	p-value
7.5–9.5	5	7.73 ± 2.54	0.798
9.5–11.5	5	4.14 ± 1.23	0.398
11.5–15.5	3	2.13 ± 0.59	0.359
15.5–23.5	2	0.98 ± 0.35	0.258
23.5–29.5	1	0.98 ± 0.41	0.597

We concluded that there is no significant excess

Flux upper limit

Calculated model-independent flux upper limit



Flux upper limit

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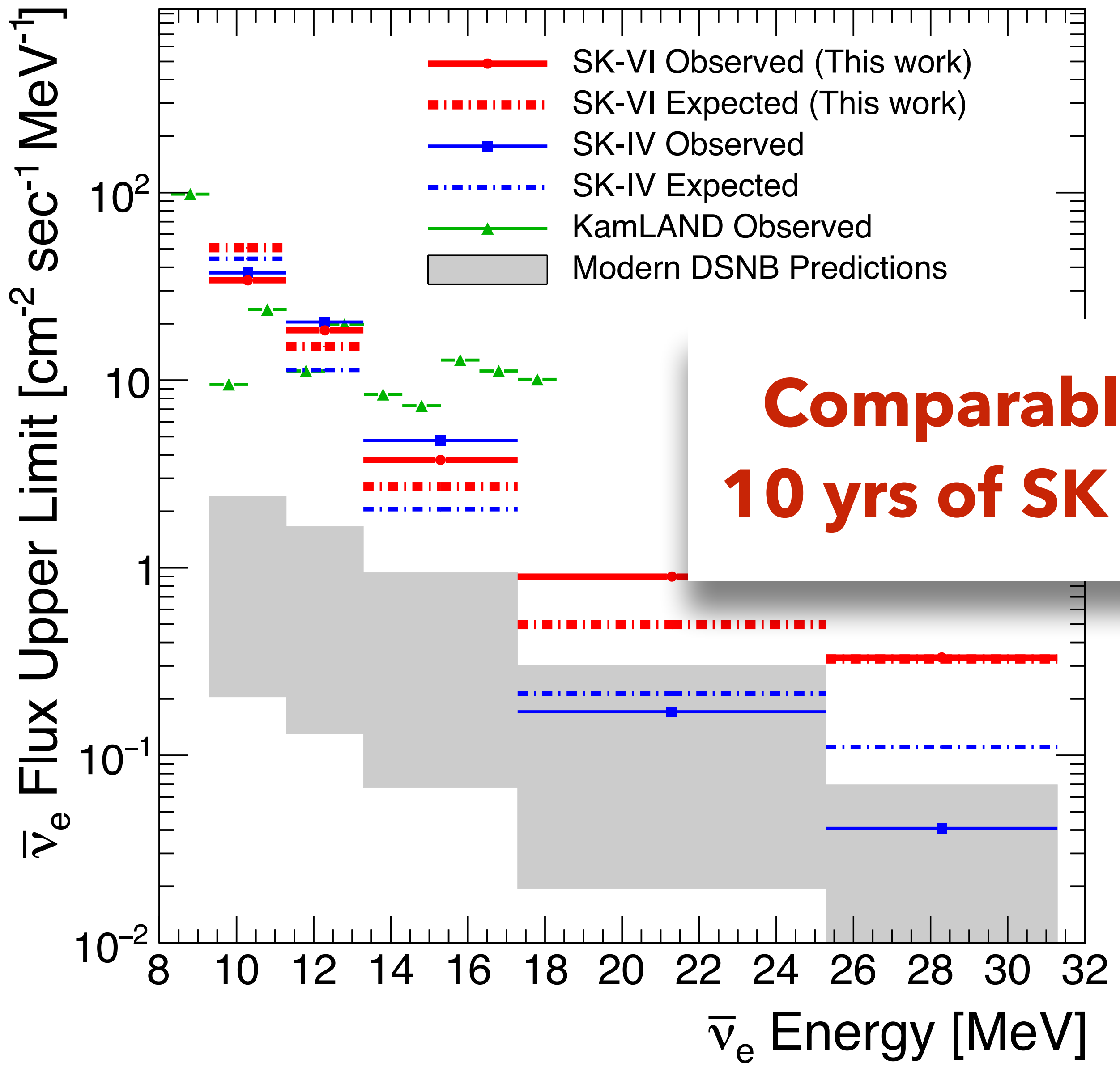


Comparable result with the 10 yrs of SK pure-water limit !

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.

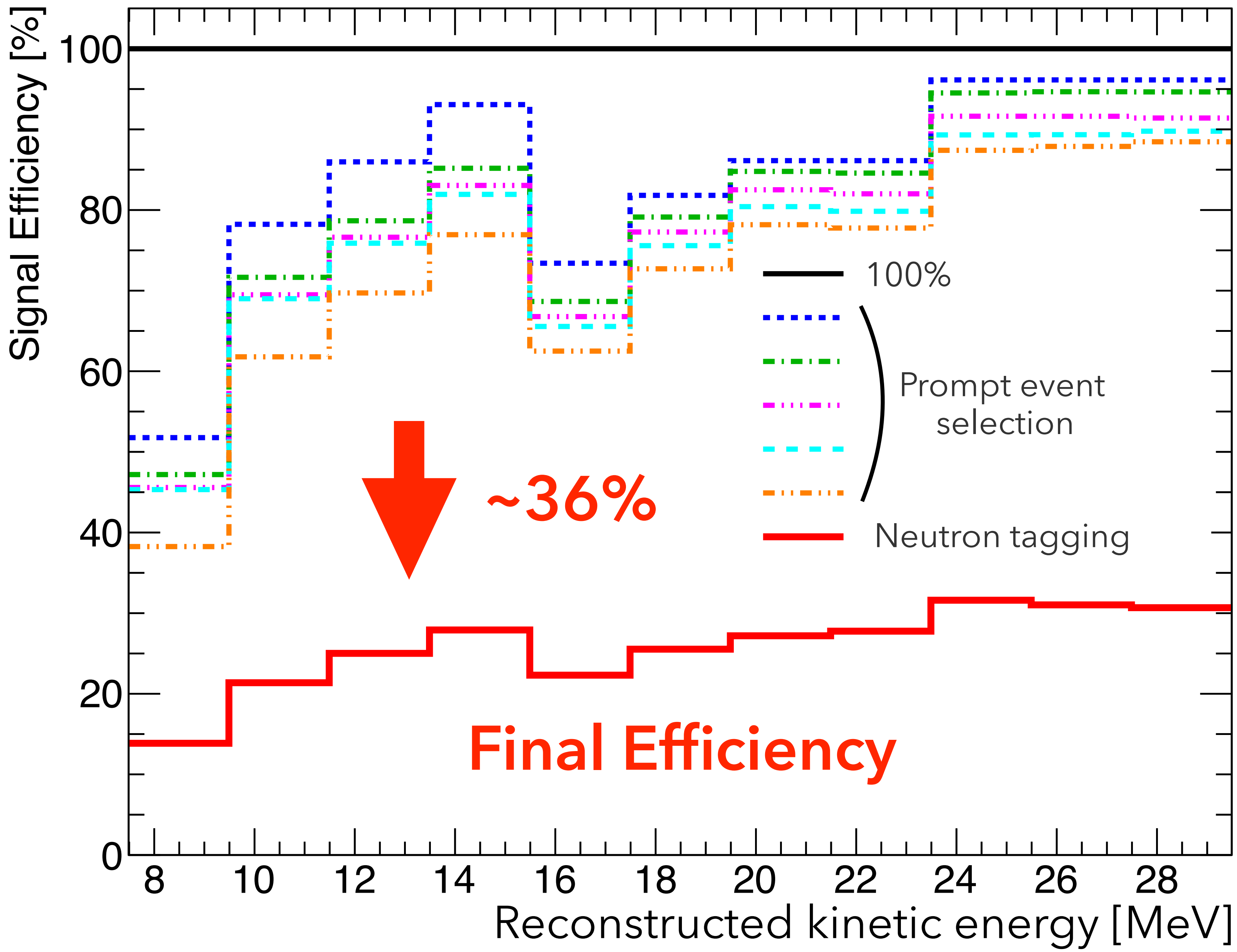
- First DSNB search in SK-Gd was performed using the data from Aug. 2020 to Jun. 2022.
  →No significant excess over expected background

- 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



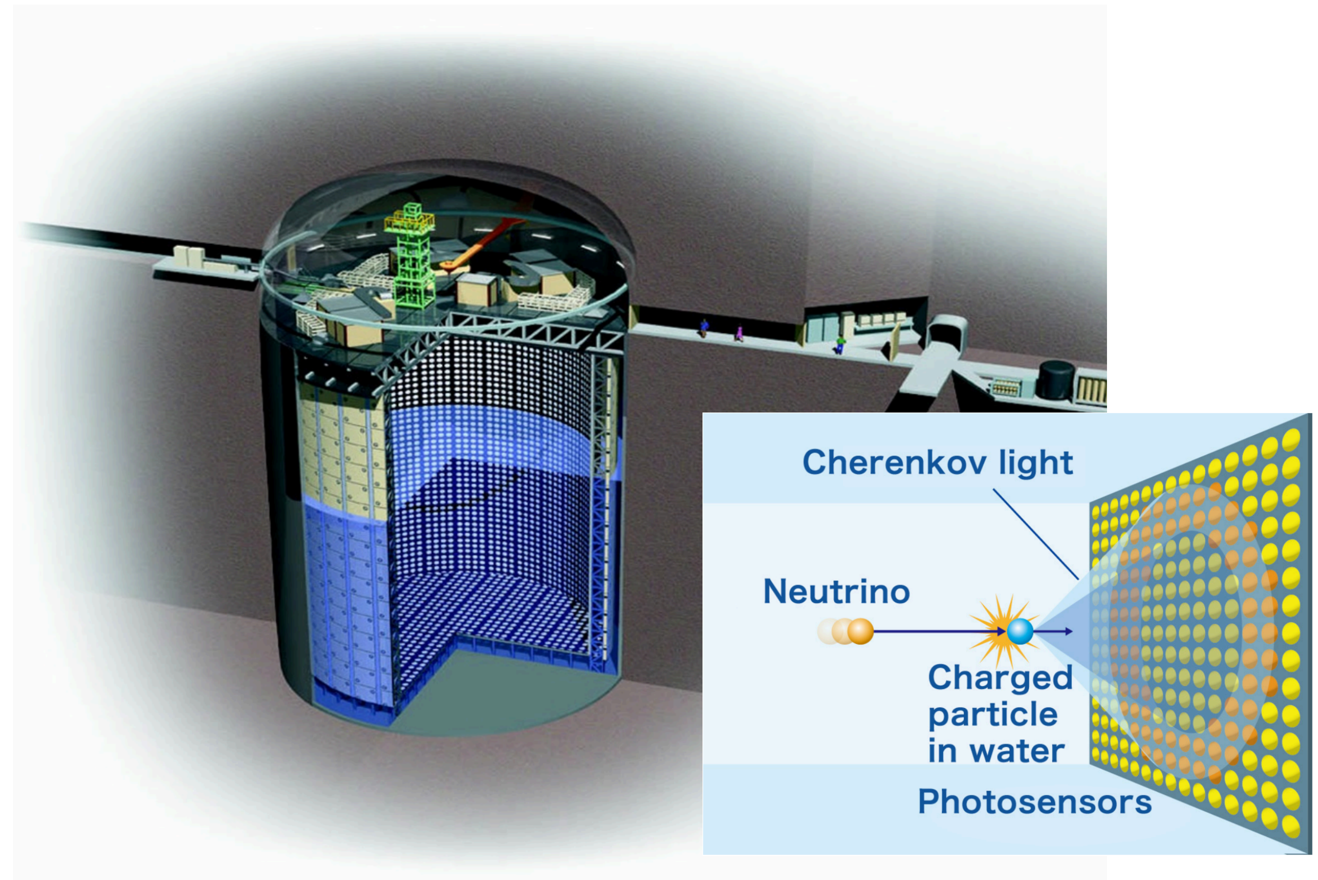
Achieved ~36% signal efficiency in the signal energy region with O(10^{-2})% of neutron mis-ID rate !

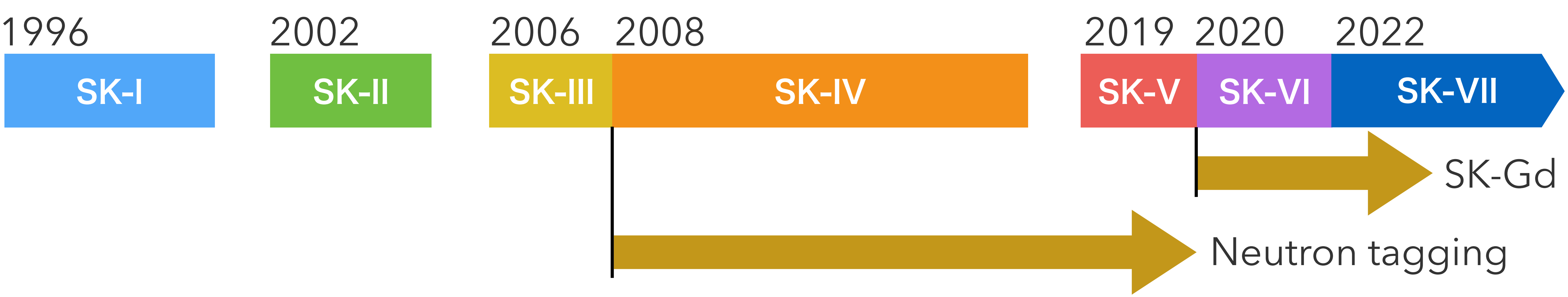
Theoretical formation of DSNB flux

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

Super-Kamiokande

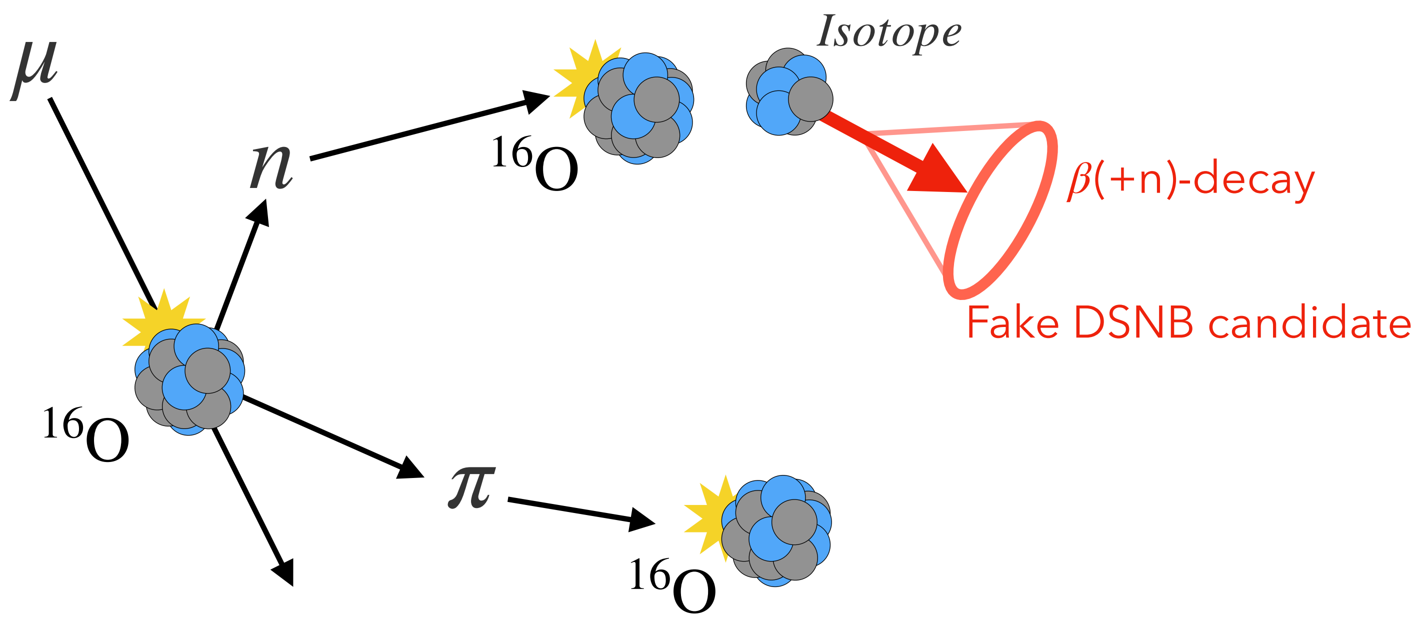
- Water Cherenkov Detector @1000 m underground
  - Fiducial volume (FV): 22.5 kton
- Sensitive to MeV ~ 10 TeV
- Directional observation
- ~20 years data taking from 1996
- SK-Gd: August 2020~

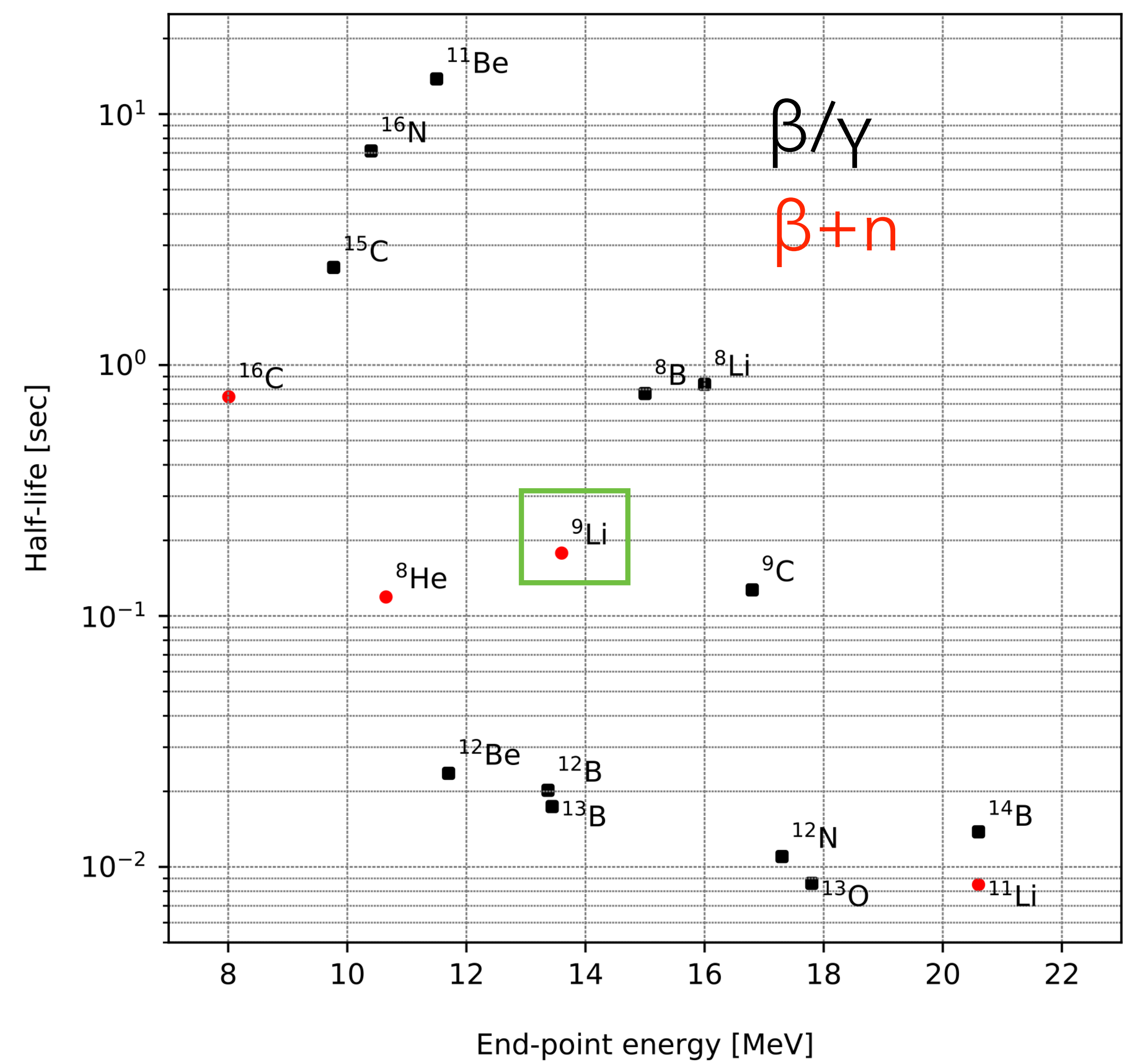




Background: Muon Spallation Products (Li9)

- Cosmic Muon comes ~2 Hz at SK site
  →Isotope decays are fake low-energy event (~x10^6 as DSNB rate)



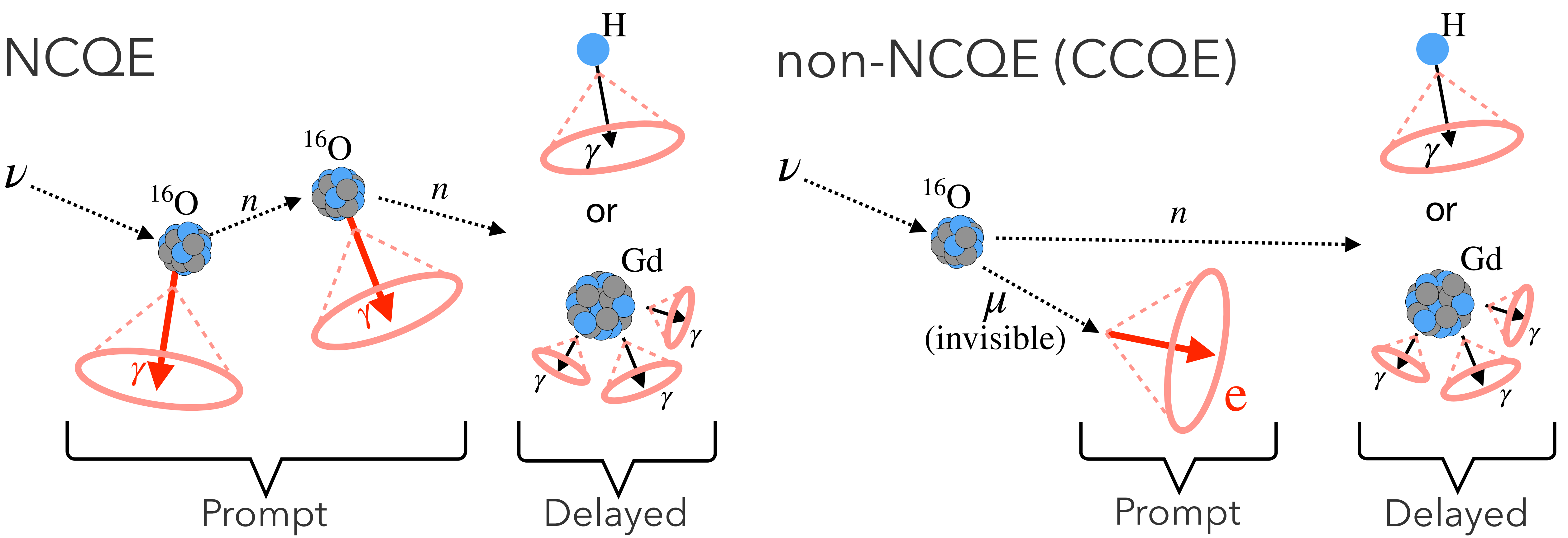


- Lithium-9 (^{9}Li)
  - Relatively high yield, long lifetime
  - Has β + n decay branch
    →**Remaining background**

Background: Atmospheric Neutrinos

- Neutral-Current Quasi-Elastic (NCQE) interactions
  - De-excitation gamma-ray (dominant < ~20 MeV)

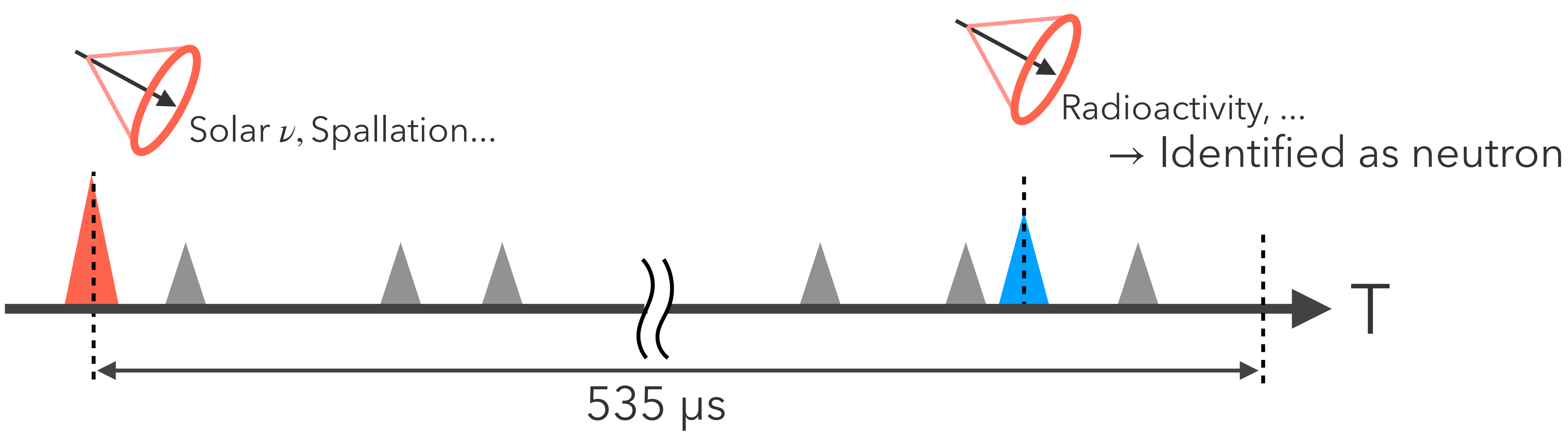
- non-NCQE interactions
  - Decay electron (from invisible muon) + n



Background: Other sources

- Reactor Neutrinos
  - Truly same signal topology (IBD) for E_{rec} < 10 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

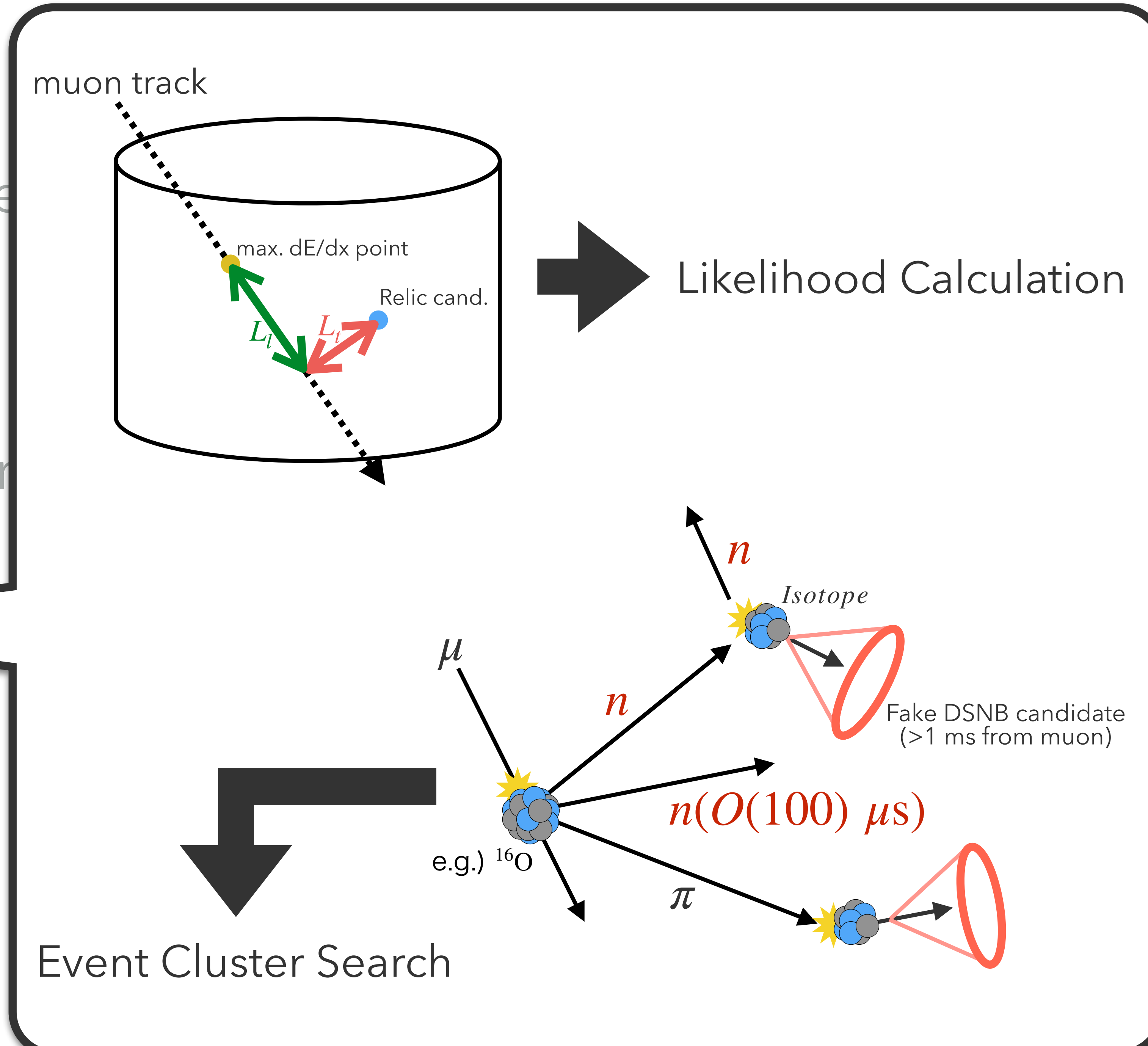


Event Reduction

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

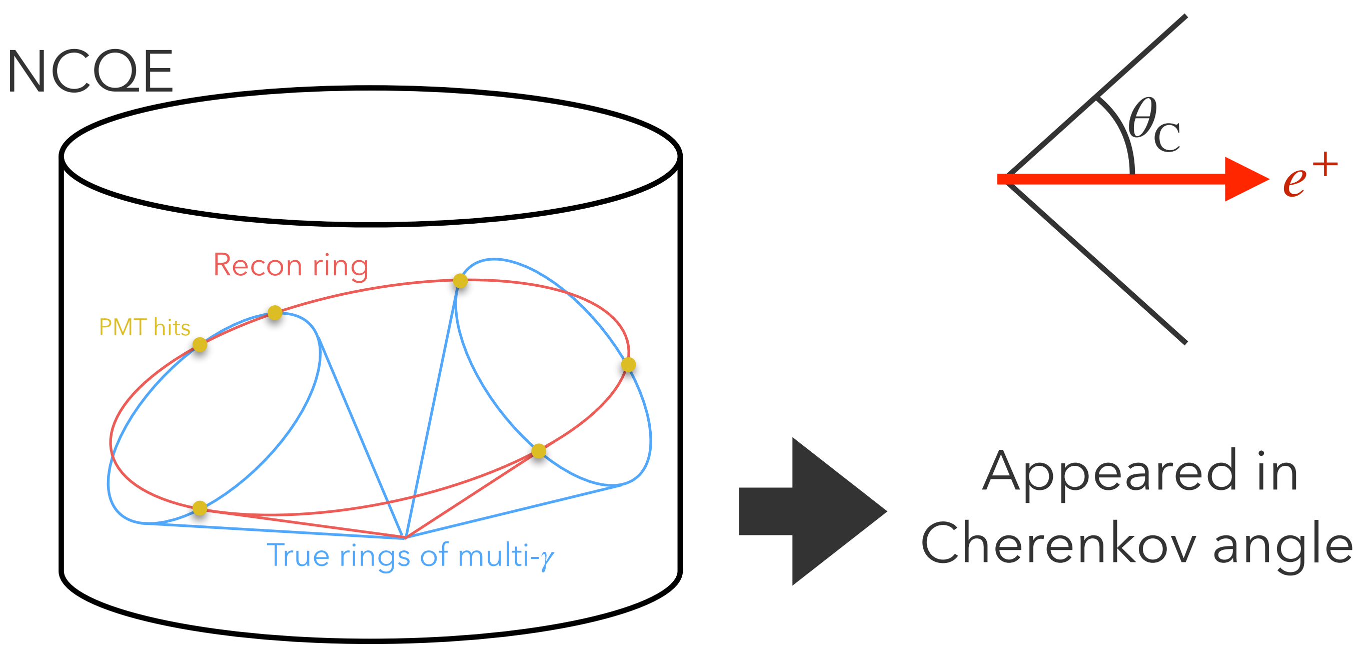
Event Reduction: Spallation cut

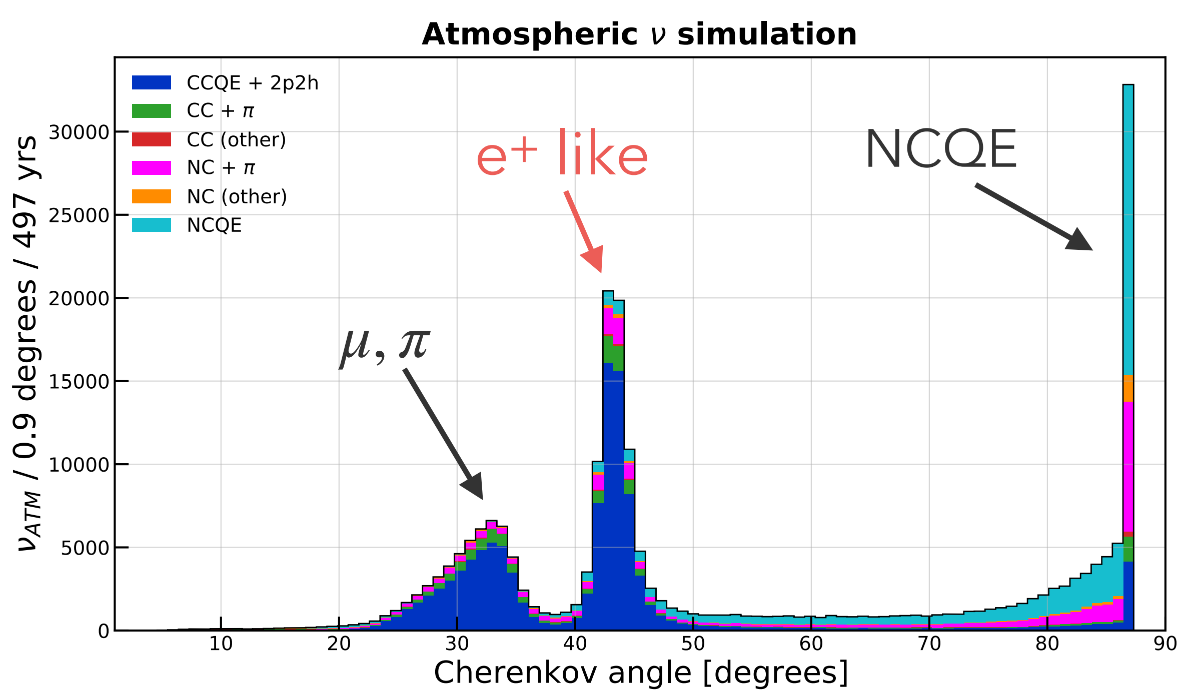
- Noise Reduction
    - Remove non-physics e
- Neutron tagging
    - Require Num. of neutr
- Spallation Cut
    - Data driven method
    - Likelihood cut
    - Event cluster cut
- Positron identification



Event Reduction: Positron identification

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





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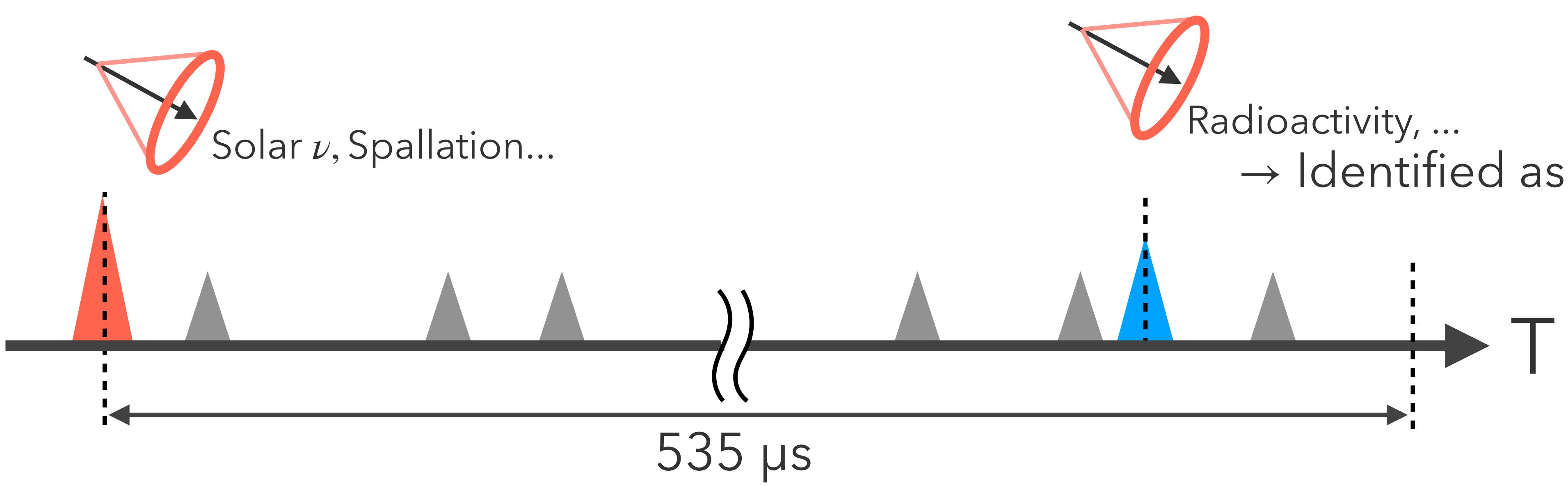

Future Prospect