Search for supernova relic neutrino search in SK-Gd experiment

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11th Supernova neutrino workshop
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Content

- **Supernova relic neutrino (SRN)**
- **SK-Gd experiment**
- **SRN search in SK-Gd**
  - Analysis
  - Search result in SK-Gd with 0.01w%
  - Current study for SRN search in SK-Gd
  - Prospects for upgraged SK-Gd
- **Summary**

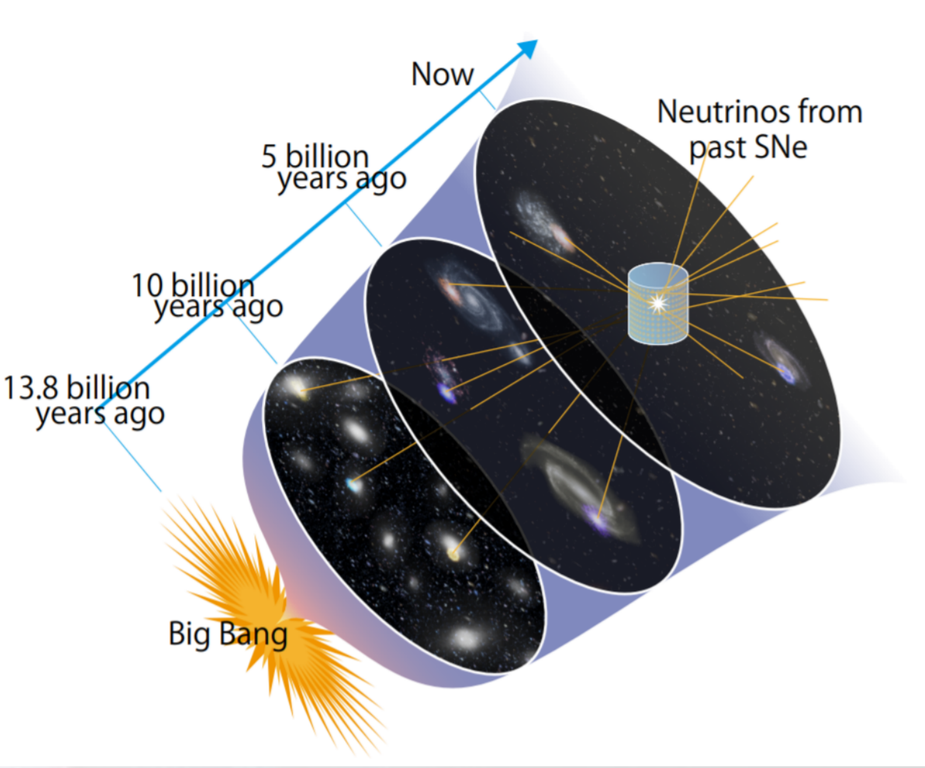
Supernova relic neutrinos

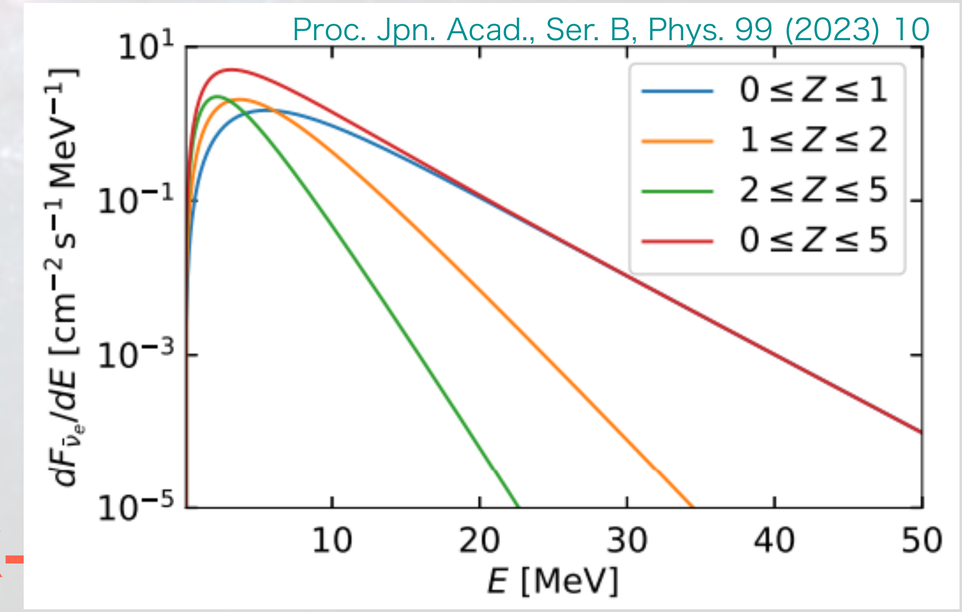
- **Supernova relic neutrinos (SRN)**
  An integrated flux of the neutrinos from all past CCSNe

- **SRN flux:**

$$\Phi_{\mathrm{SRN}} \propto \int [\ \text{SN rate}\ ] \otimes [\ \nu\ \text{emission from SN}\ ] \otimes [\ \text{Redshift}\ ]$$

  → **Information for star formation history**
  - Evolution of star formation rate
  - SN neutrino flux
  - Black hole formation rate
  - Neutrino physics…





Flux search from $\mathcal{O}$(1-10) MeV → SK-

Supernova relic neutrinos

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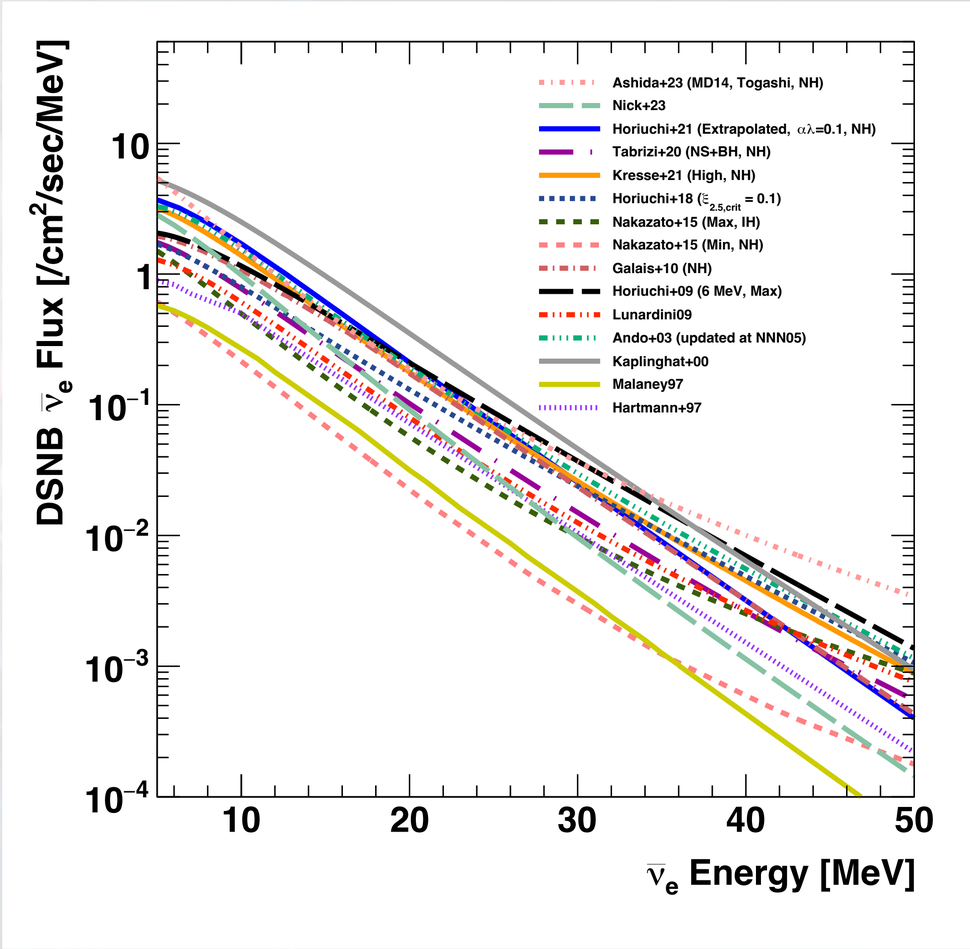
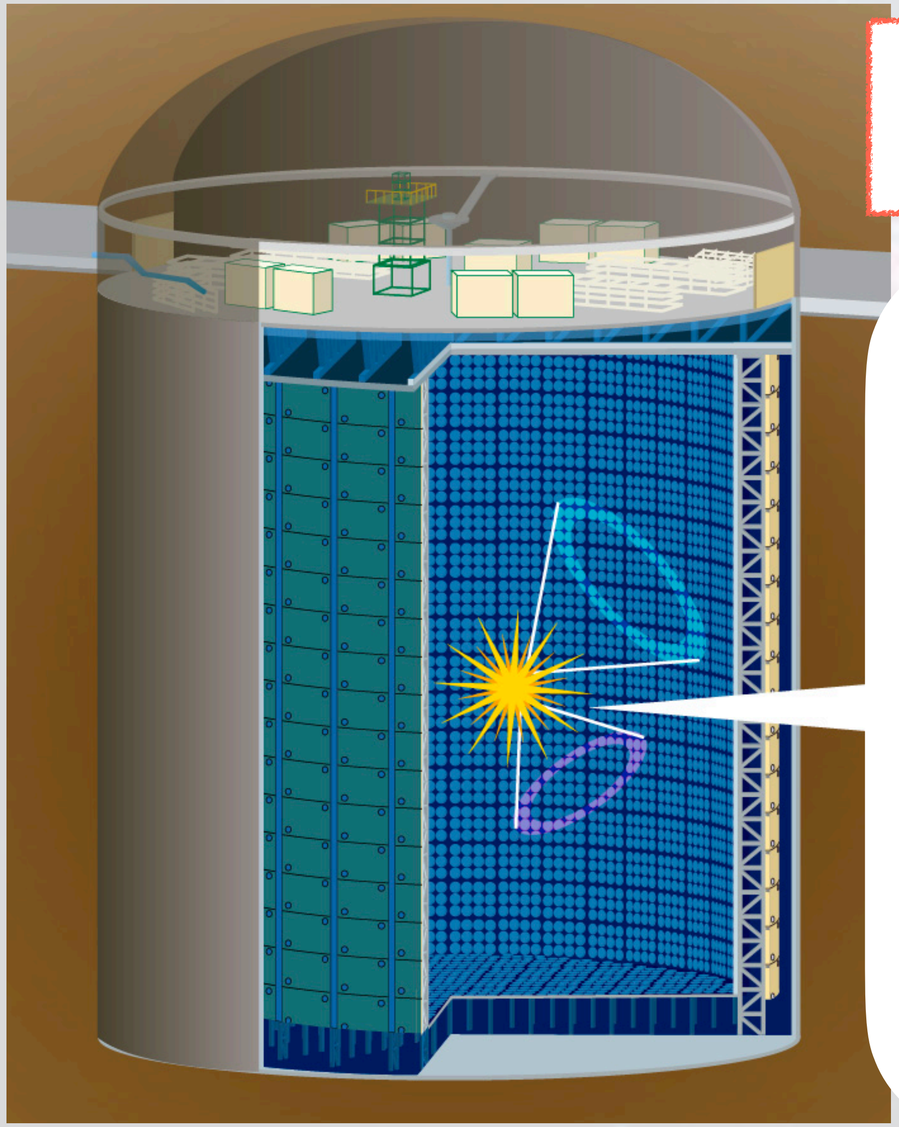


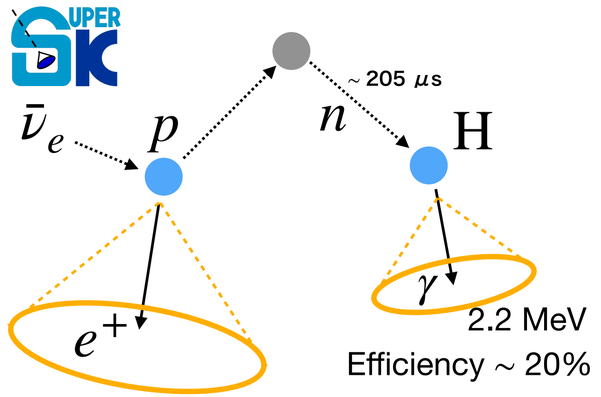
Flux search from $\mathcal{O}$(1-10) MeV ➡ **SK-Gd experiment**

SK-Gd experiment

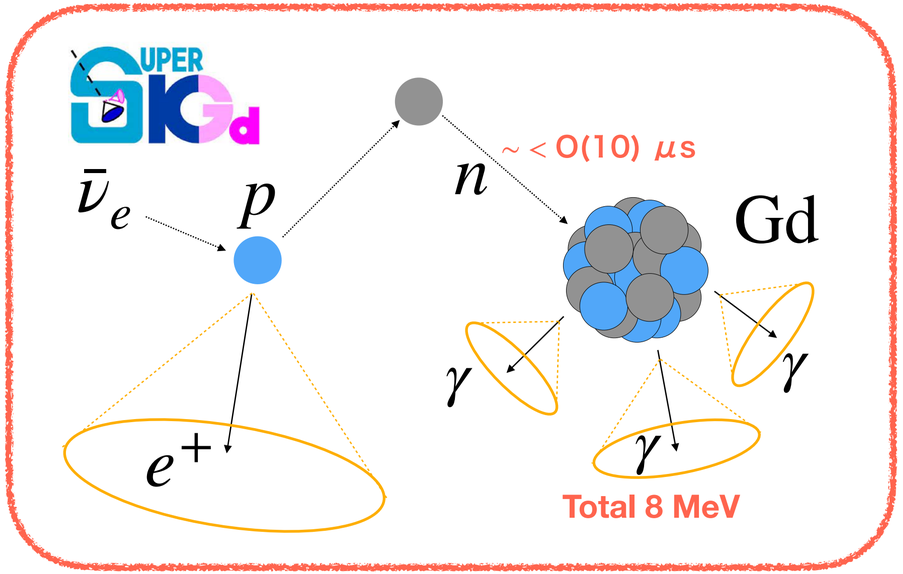


SK-Gd experiment

Improved neutron detection by loading Gd to the Super-K

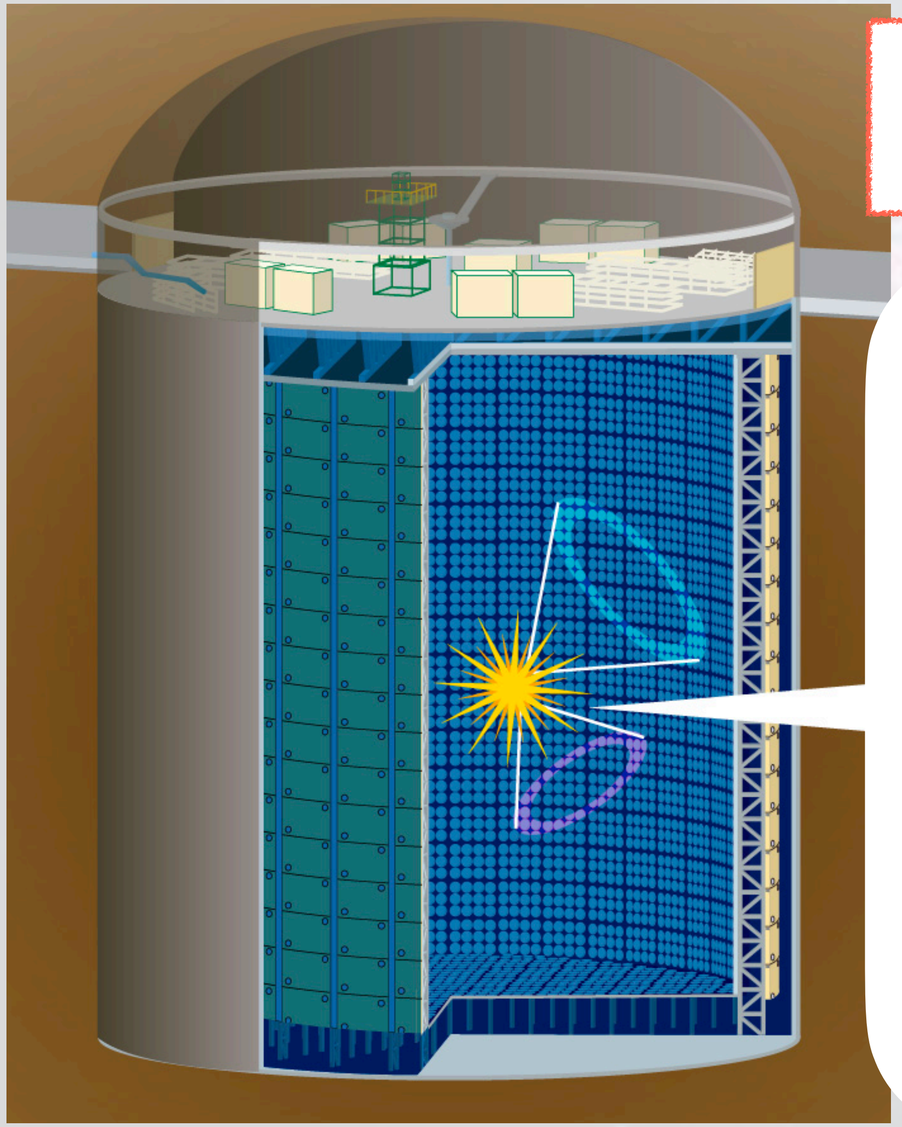


Loading Gd



Neutron signal is enhanced by Gd !

SK-Gd experiment



SK-Gd experiment

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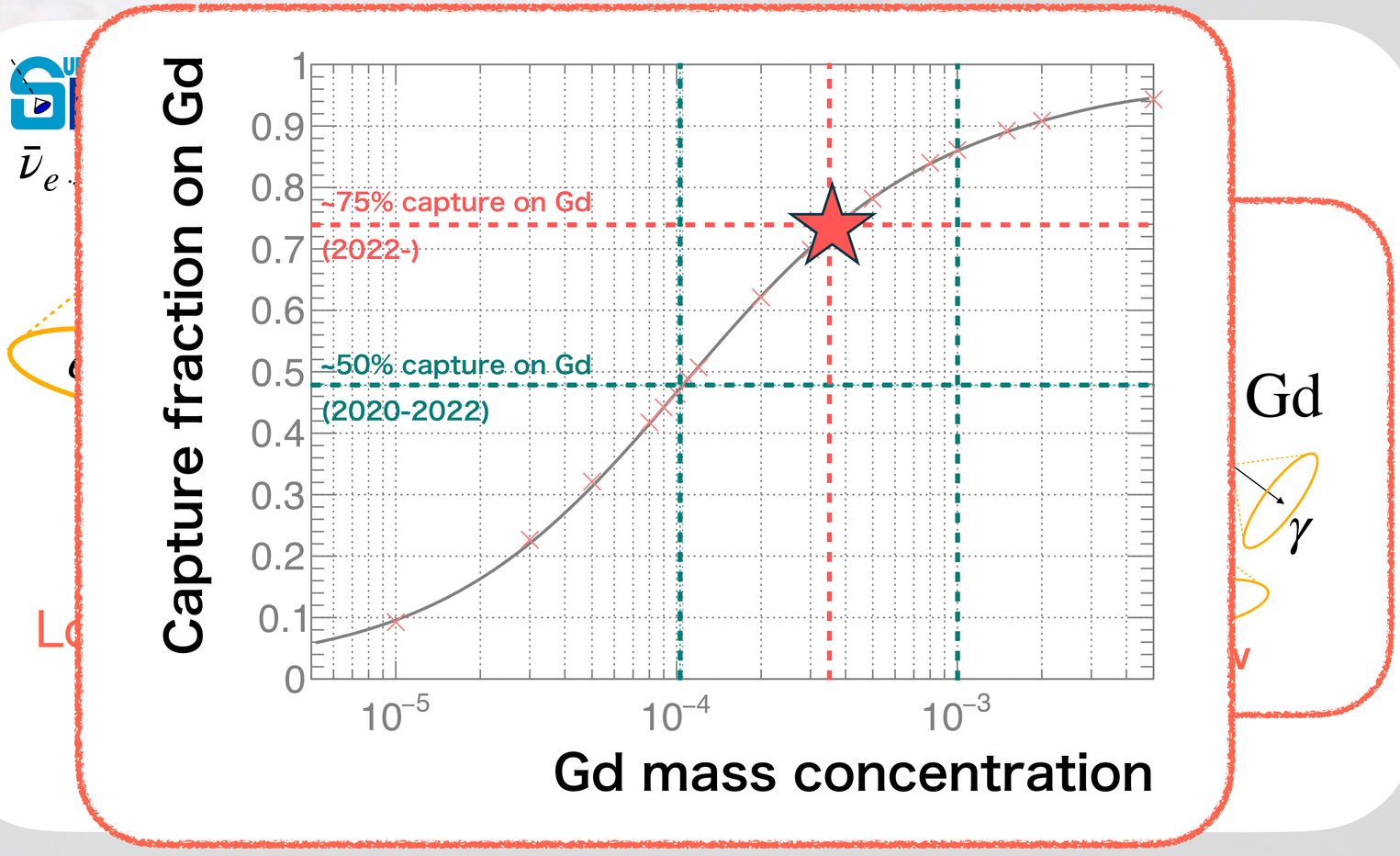


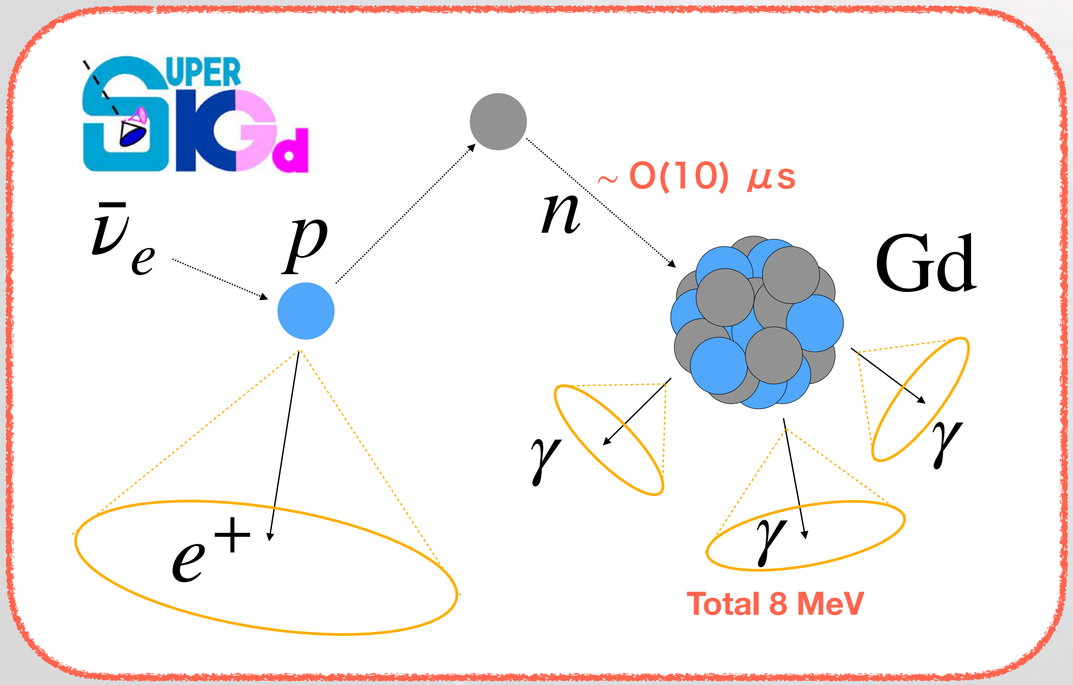
Analysis and results

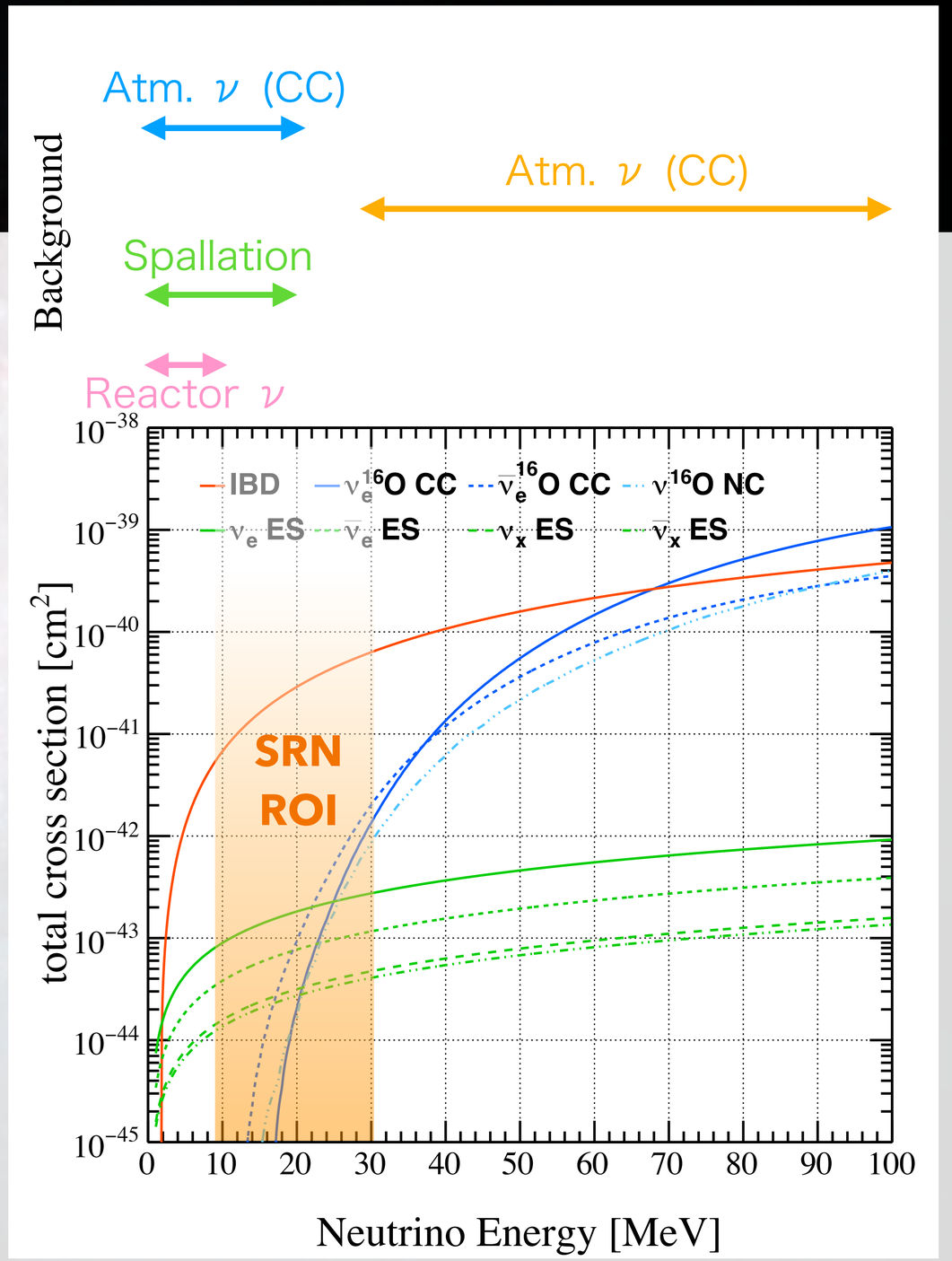
SRN signal in SK-Gd

- **Search for inverse-beta decay (IBD) of electron anti neutrinos**

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

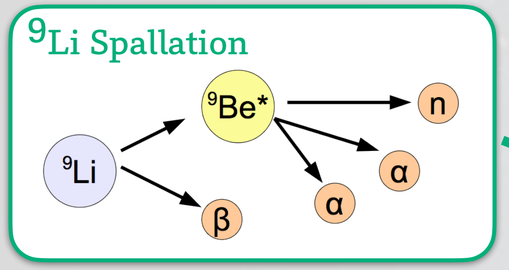
  - Largest cross-section @ SRN signal range
  - Simple event topology: 1 positron and 1 neutron
    → **Require only one delayed neutrons signal**

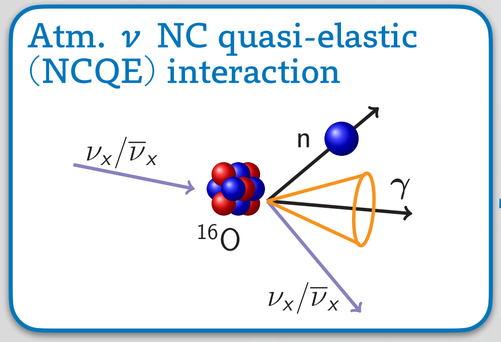


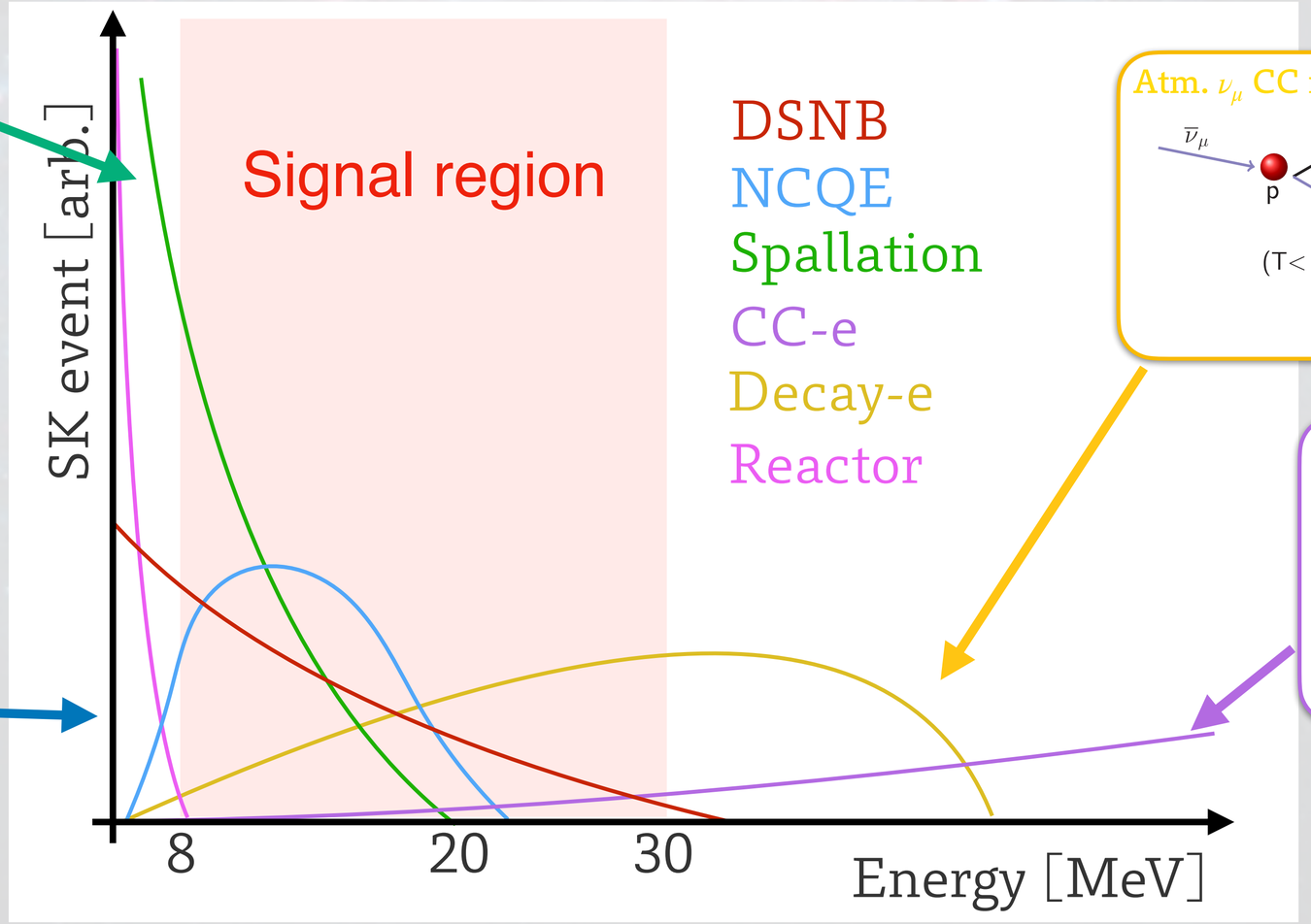


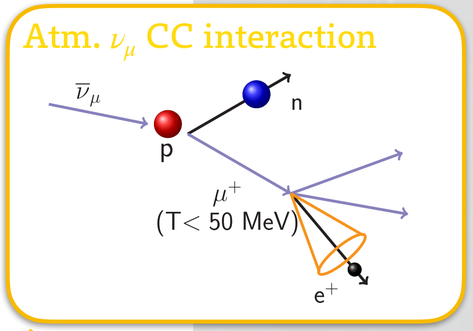
Background events in SK-Gd

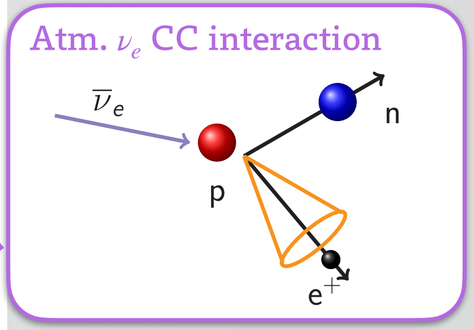
- **Neutron inducing background events remain after tagging neutrons**









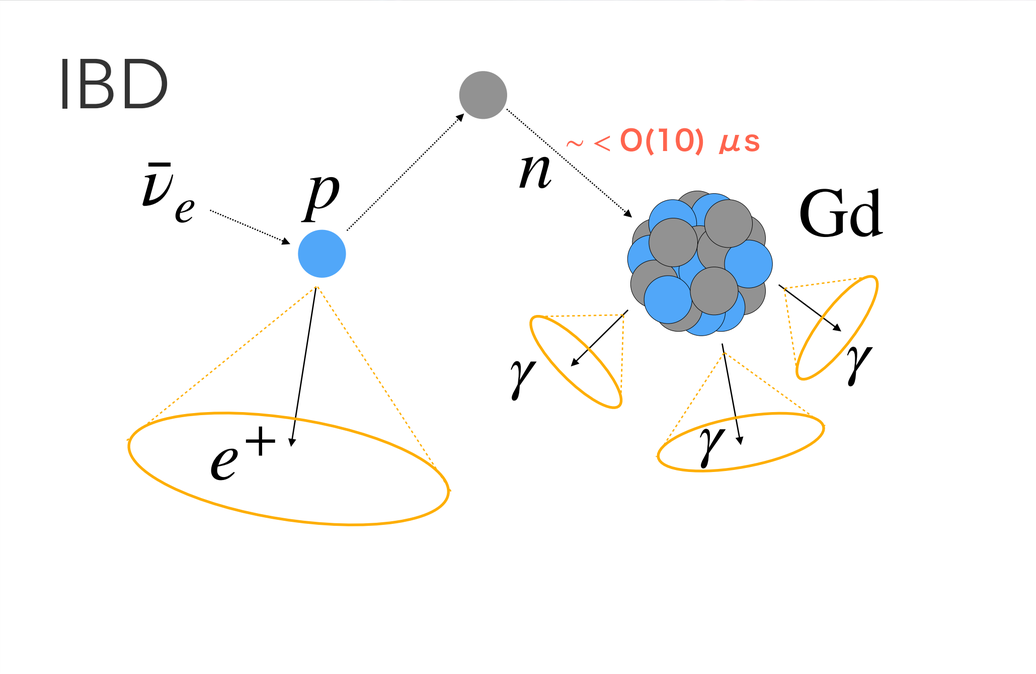


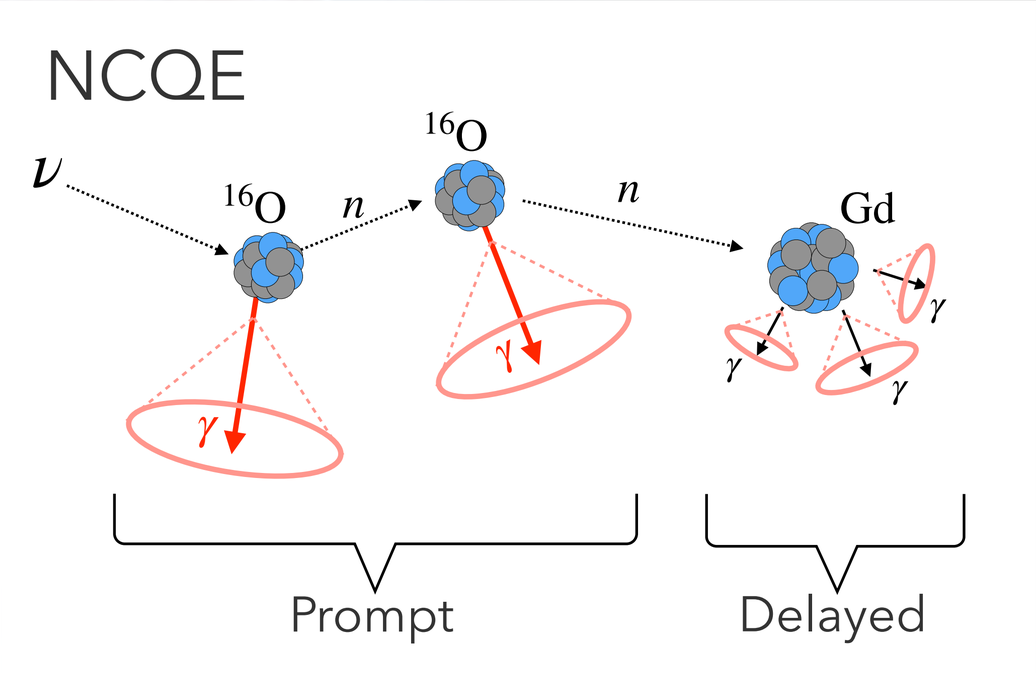
Analysis implovement

- **NCQE reduction**
- **Neutron detection using ML**
- **Spectrum fitting with various DSNB models**

Improvement of NCQE event reduction

- **Similar, but different event topology from DSNB signal**



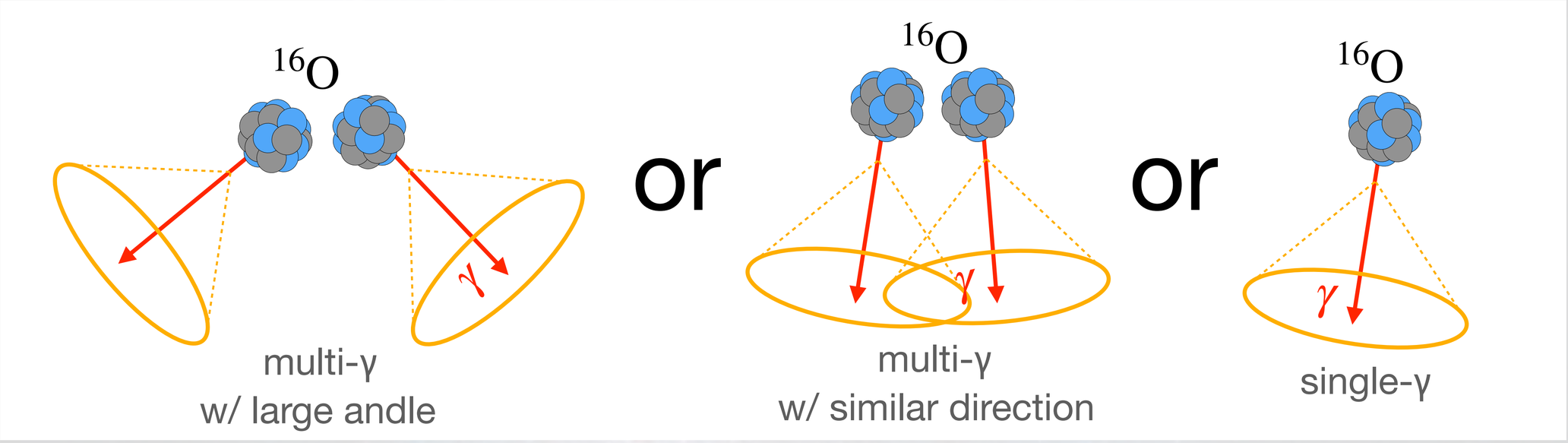


- **NCQE multiple gamma CANNOT distinguish by SK (= detected as same event)**

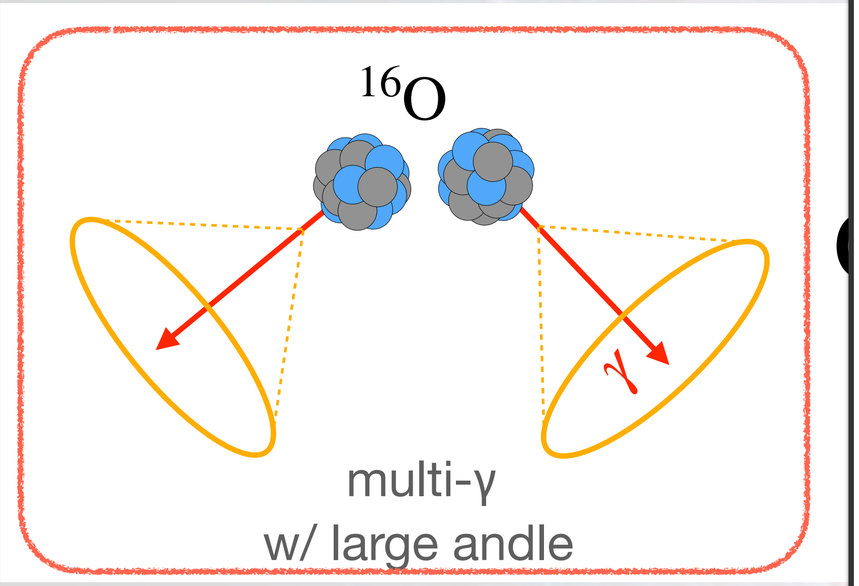
  → Hit pattern is crucial to reduce NCQE

Improvement of NCQE event reduction

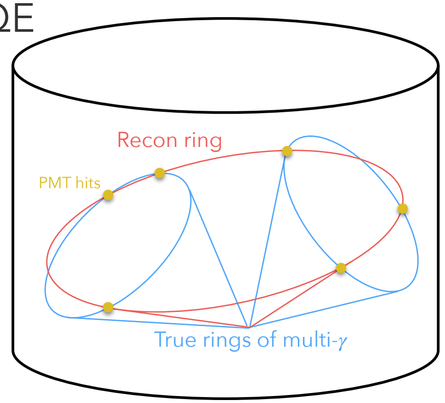
- **NCQE events**

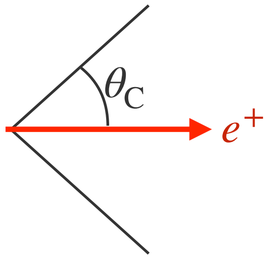


Improvement of NCQE event reduction

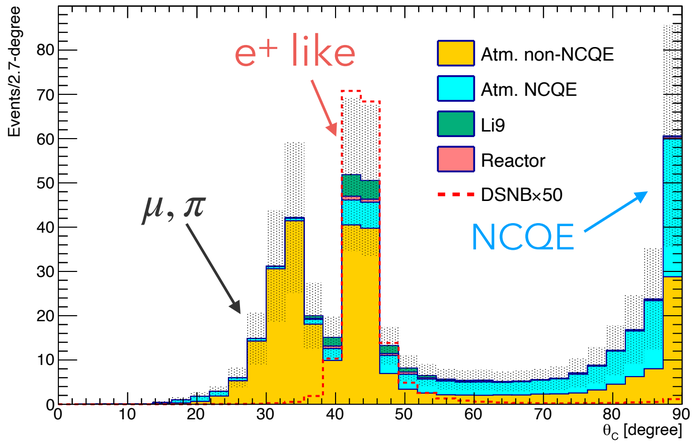


NCQE





Appeared in
reconstructed Cherenkov angle

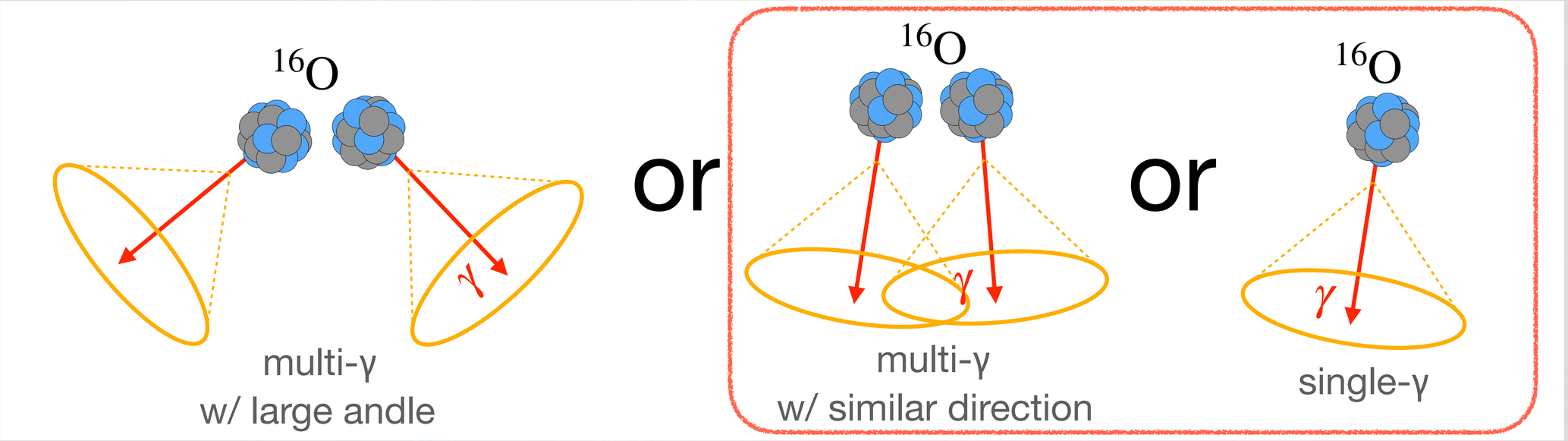


Clear difference of angle

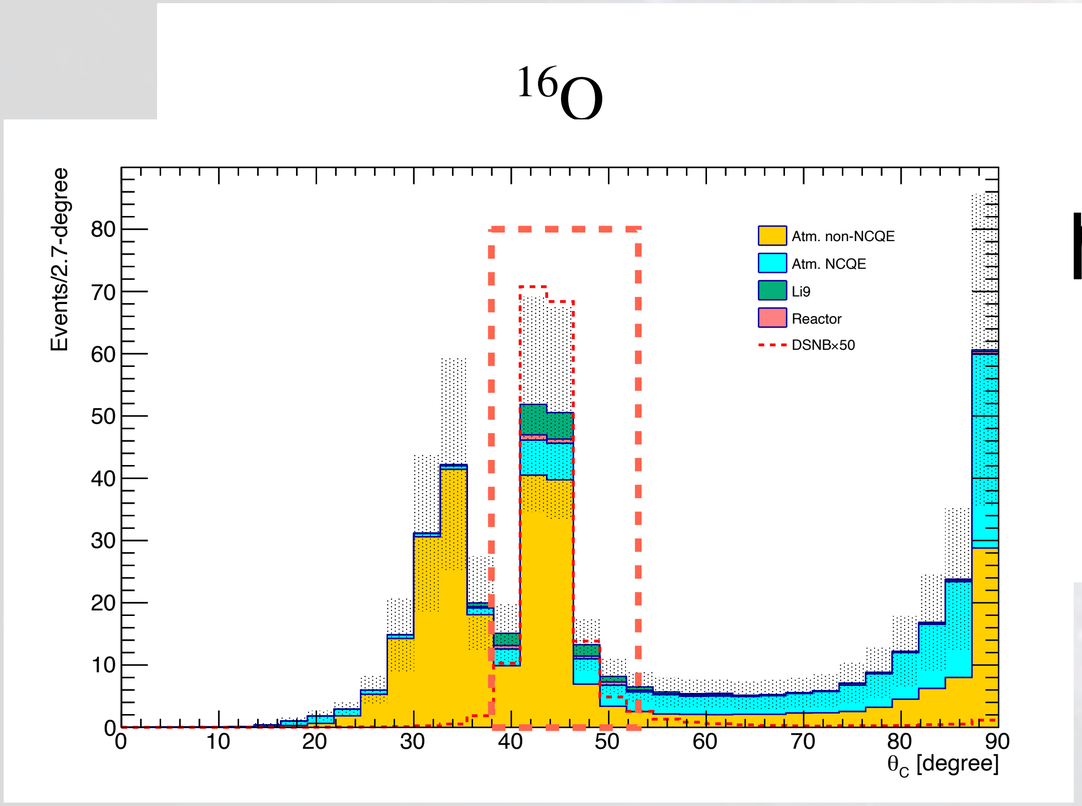
Cherenkov angle cut is powerful variable to reduce obvious multi-ring NCQE

Improvement of NCQE event reduction

- **Single/hard to classify multi-γ event**



Improvement of NCQE event reduction



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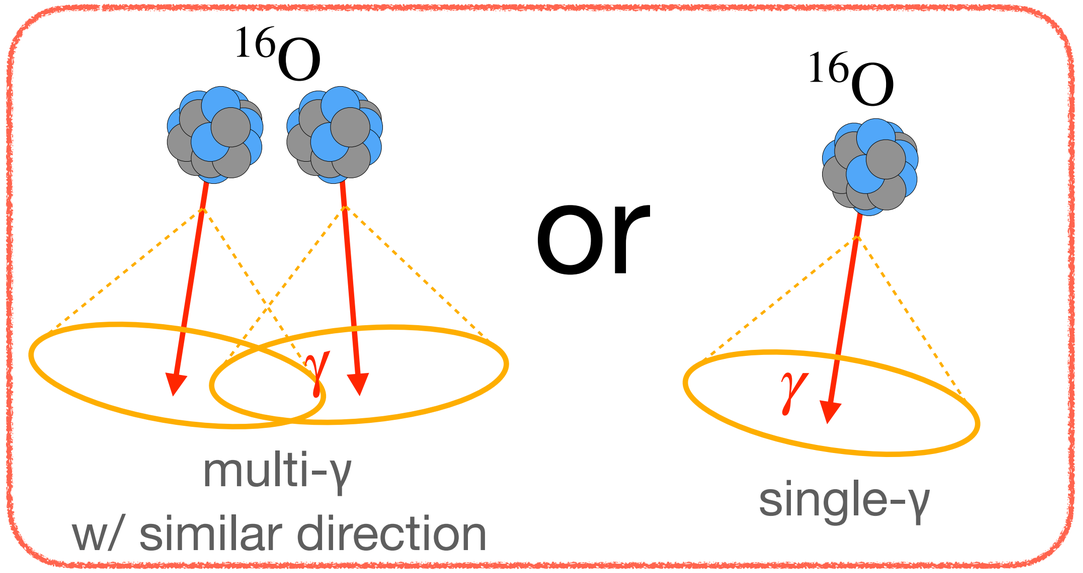
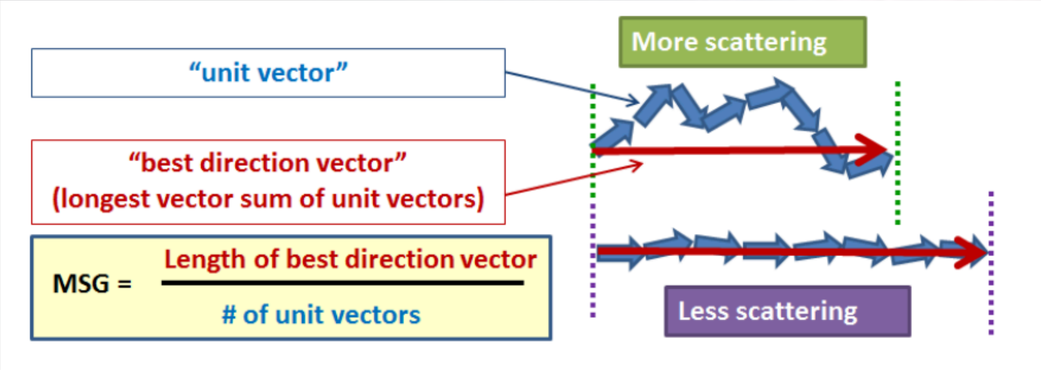


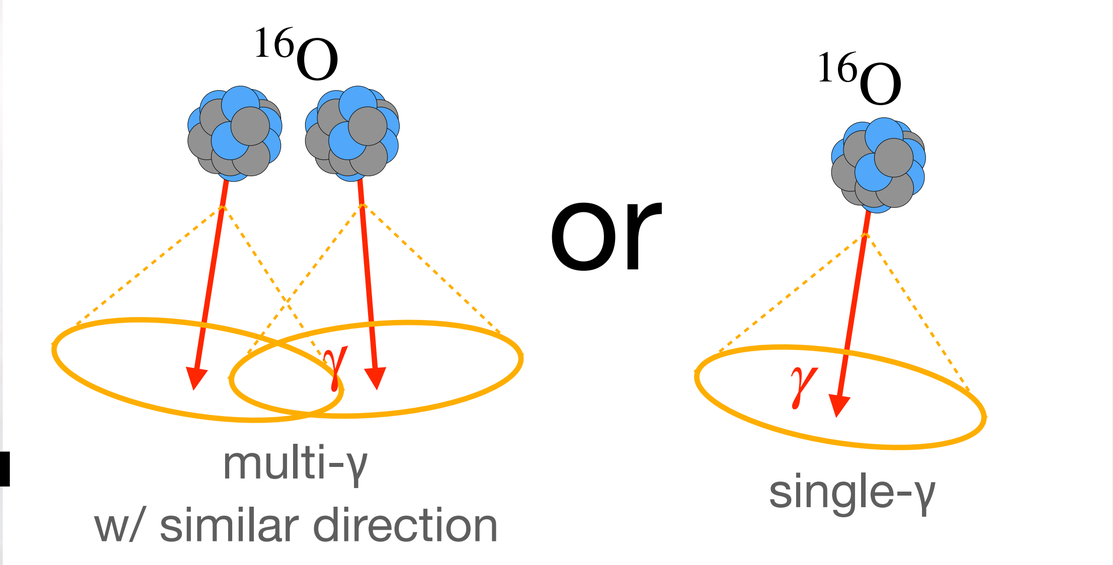
Difficult to see the clear difference from reconstructed θ_C

New variable: Multiple scattering goodness

Multiple scattering goodness

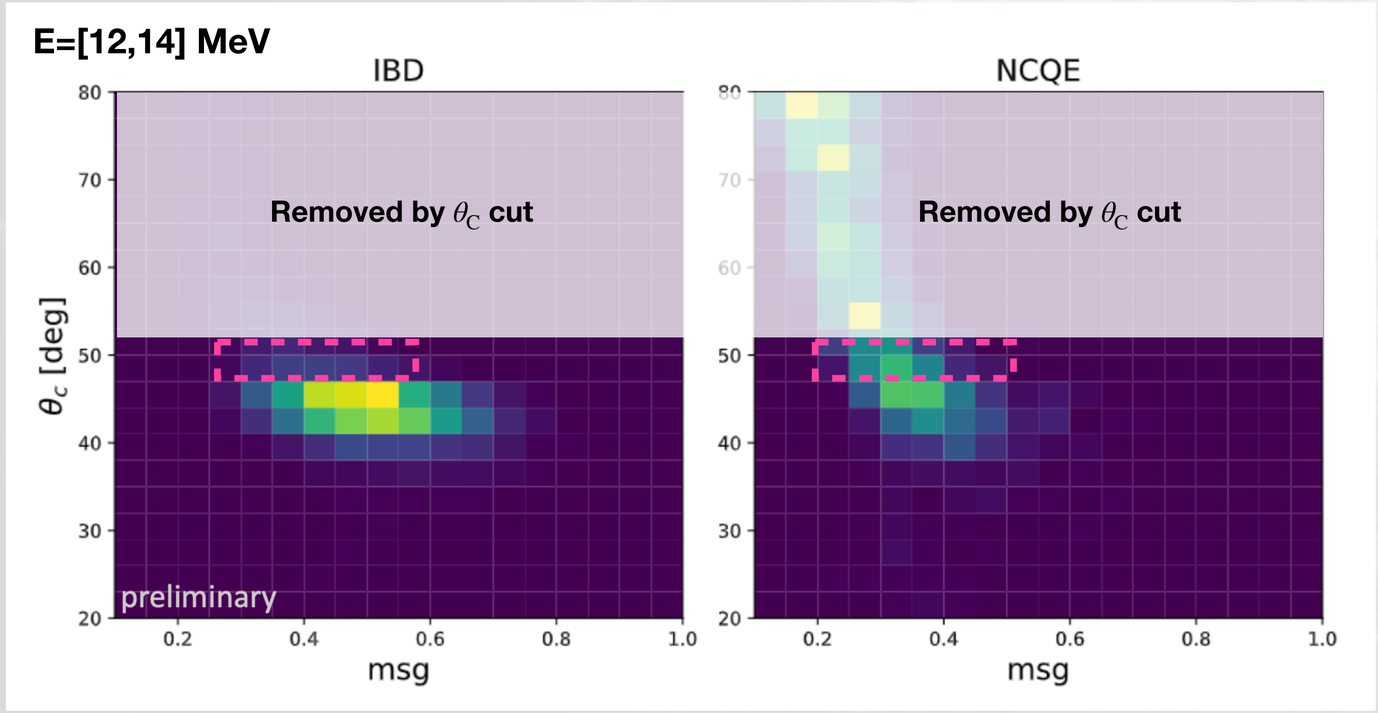
- **Multiple scattering goodness (MSG)**
  - Originally prepared for solar neutrino analysis to identify low-energy background event
    → **Found to be employed to remove gamma-ray events**

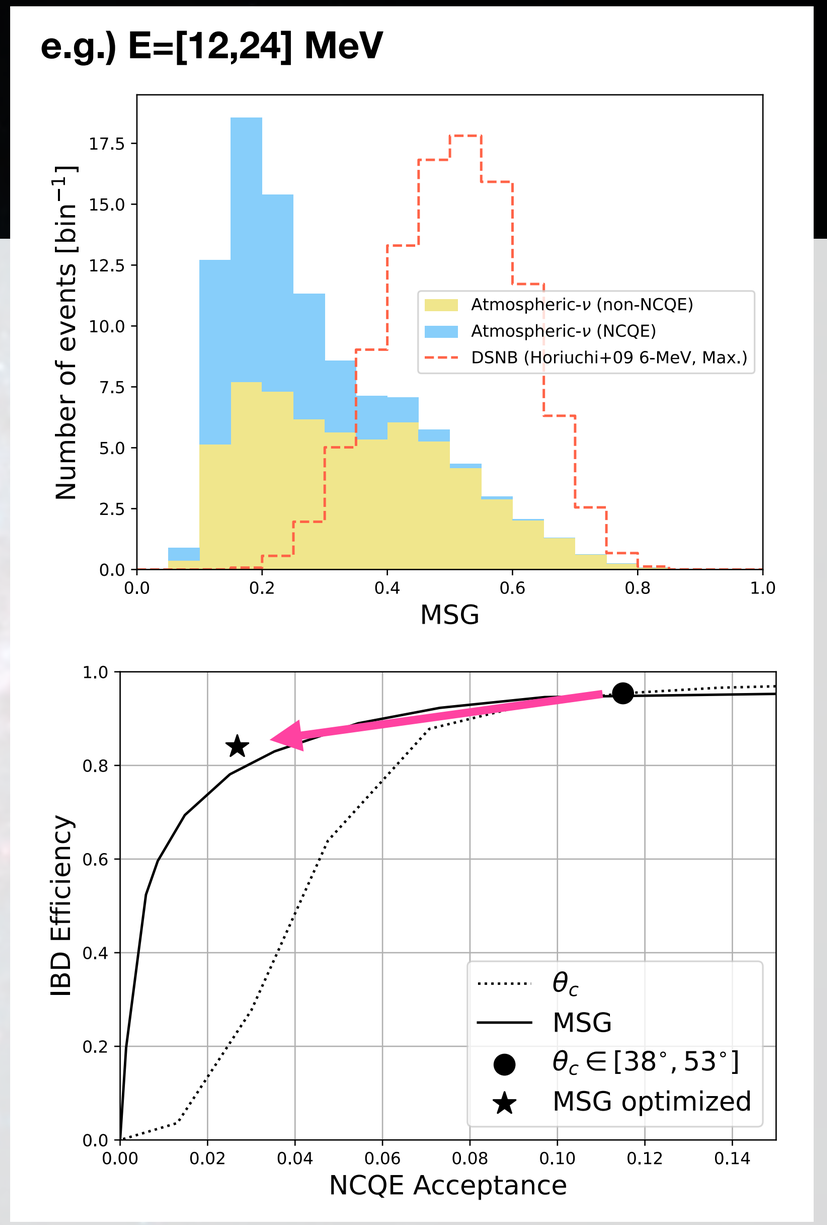




Looks to be more multiple scattering than single electron with similar energy

Multiple scattering goodness



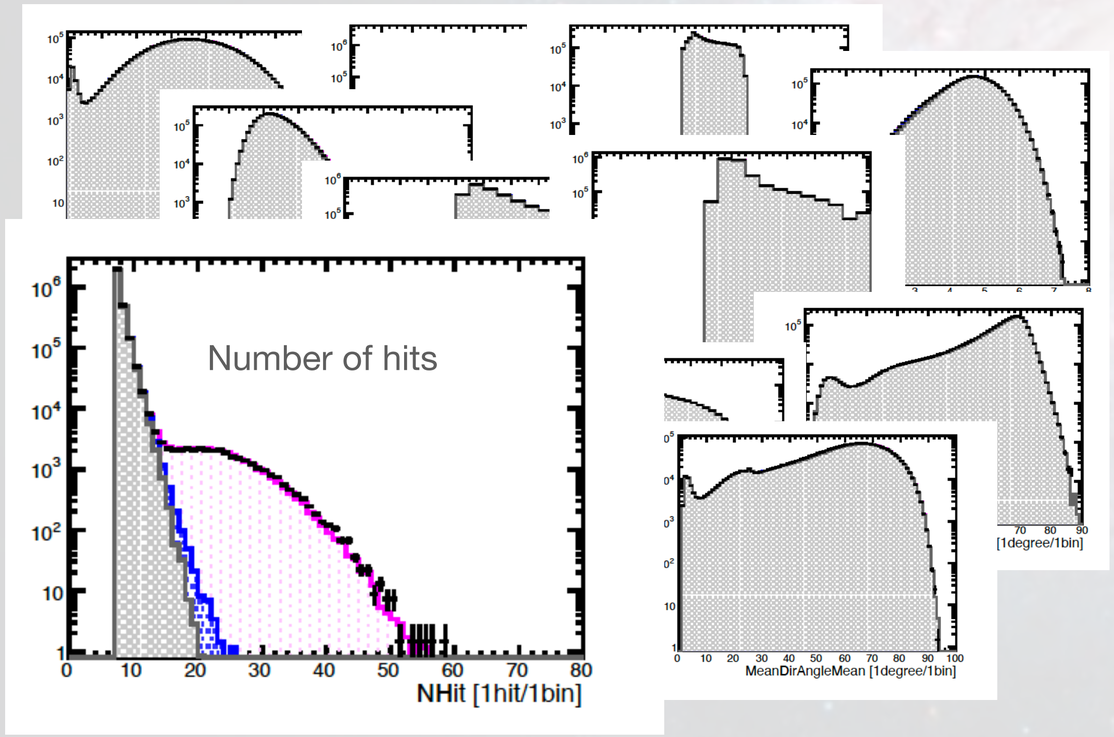


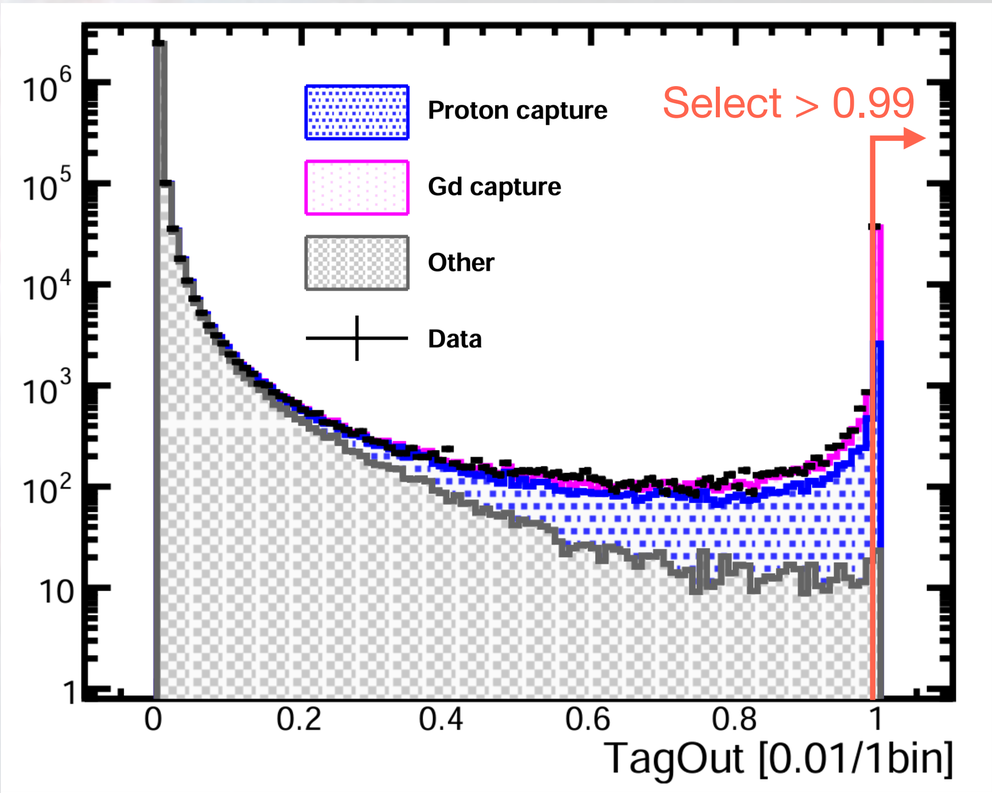
Reduce background by 20% while keeping IBD efficiency!!!

Improvement of neutron tagging

- **Neutron tagging using Neural Network**
  - Well understanding for Gd-capture gamma-rays

12 Feature variables





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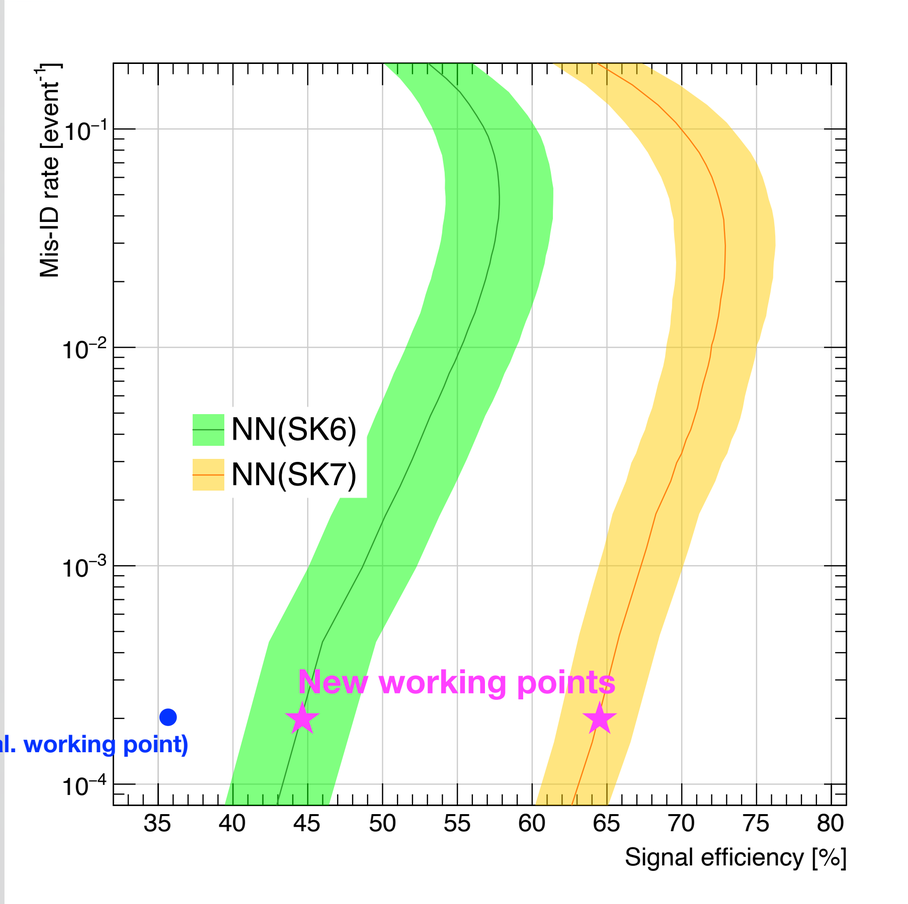
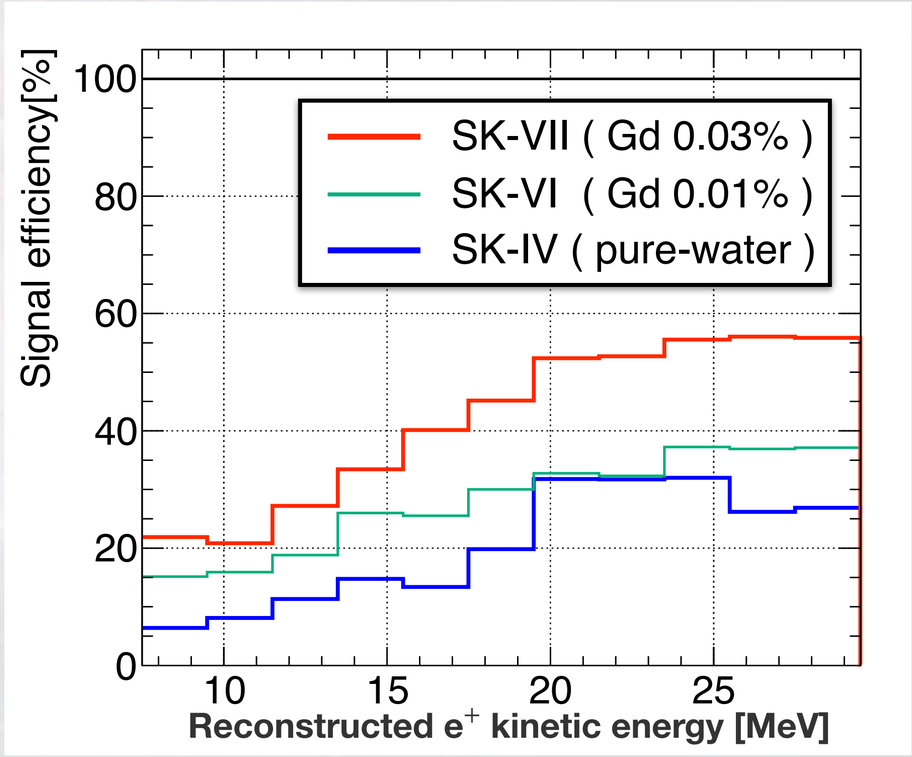
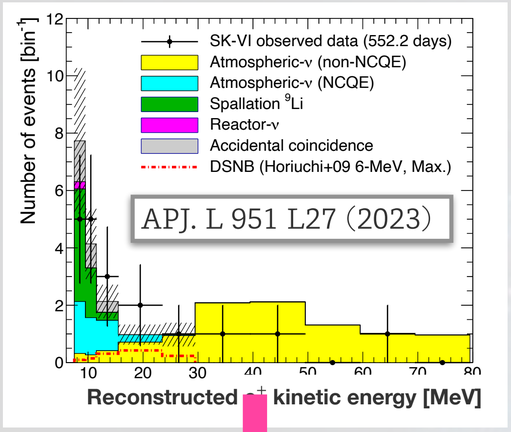




✓ **Achieve 10% (SK6) / 30%(SK7) higher efficiency than previous result**

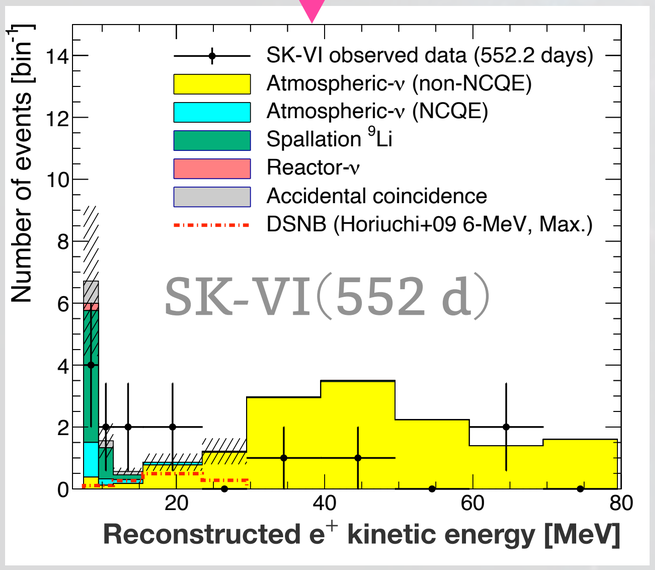
Results

SRN search result 956.2 days SK-Gd



- **552.2 d @0.01w% and 404.0 d @0.03w% SK-Gd data**
  - With MSG cut and ML neutron tagging
  - No apparent signal excess, but indicates (min. p-value = 0.04)

New n-tag, NCQE reduction



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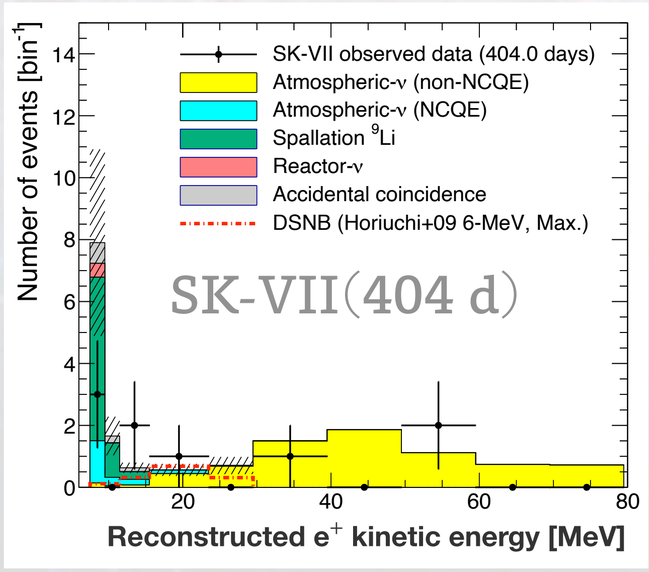

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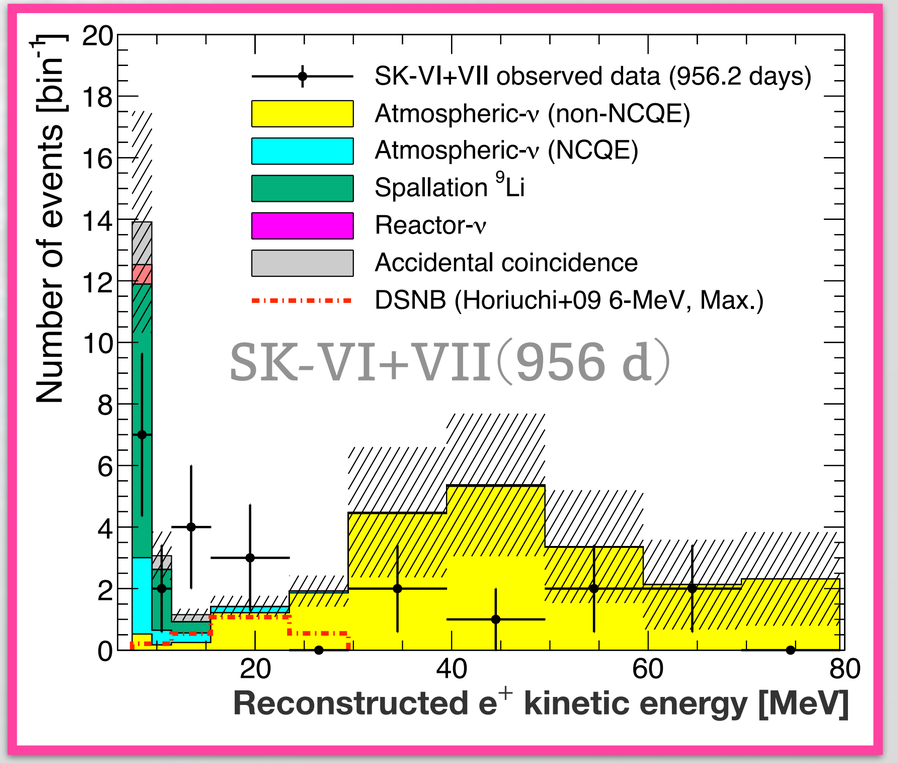
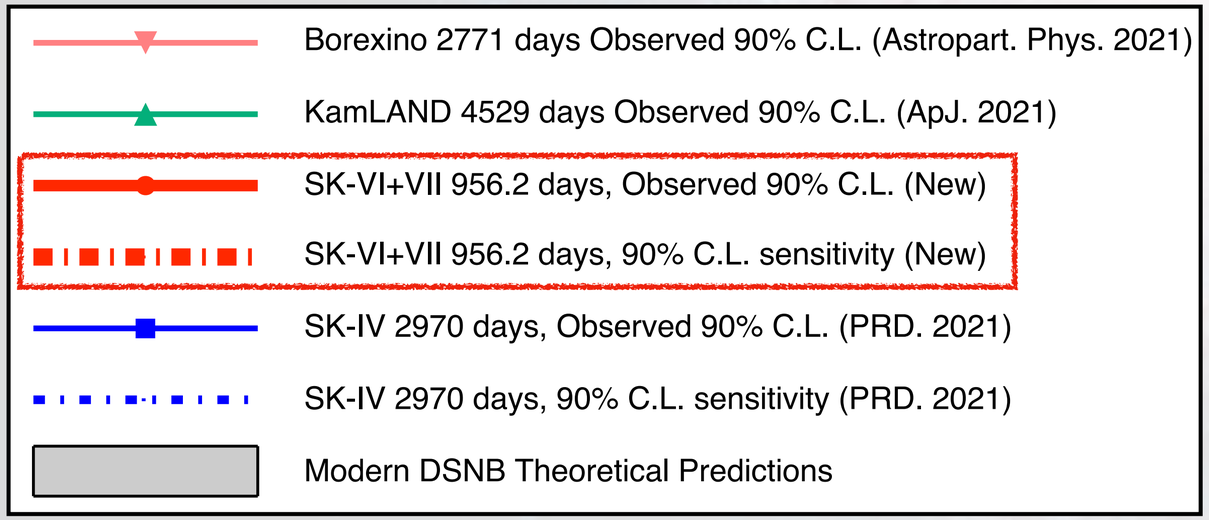
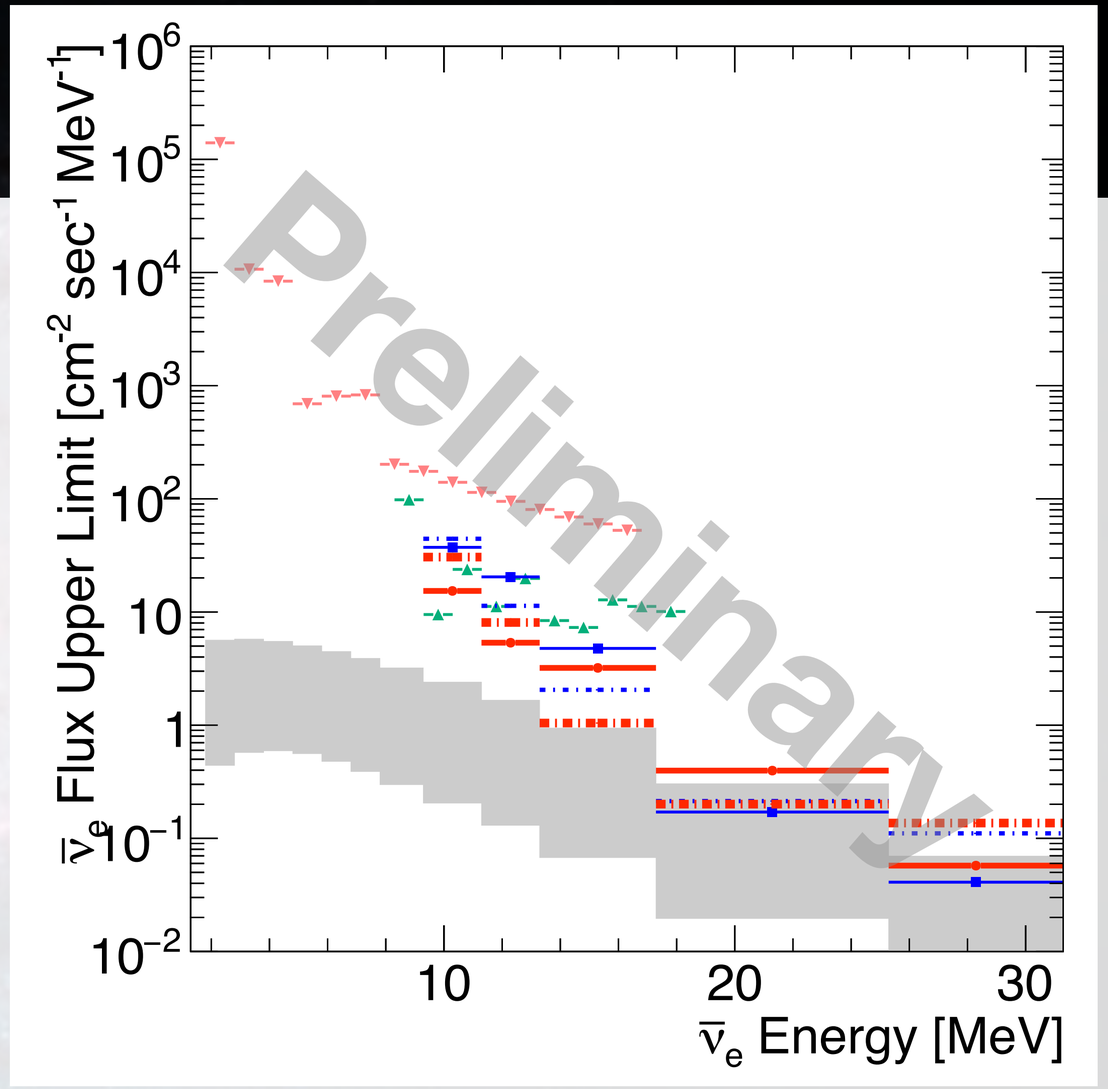


Flux upper limit

- **Spectrum-independent astrophysical $\bar{\nu}_e$ flux limit with 956.2 d SK-Gd data**

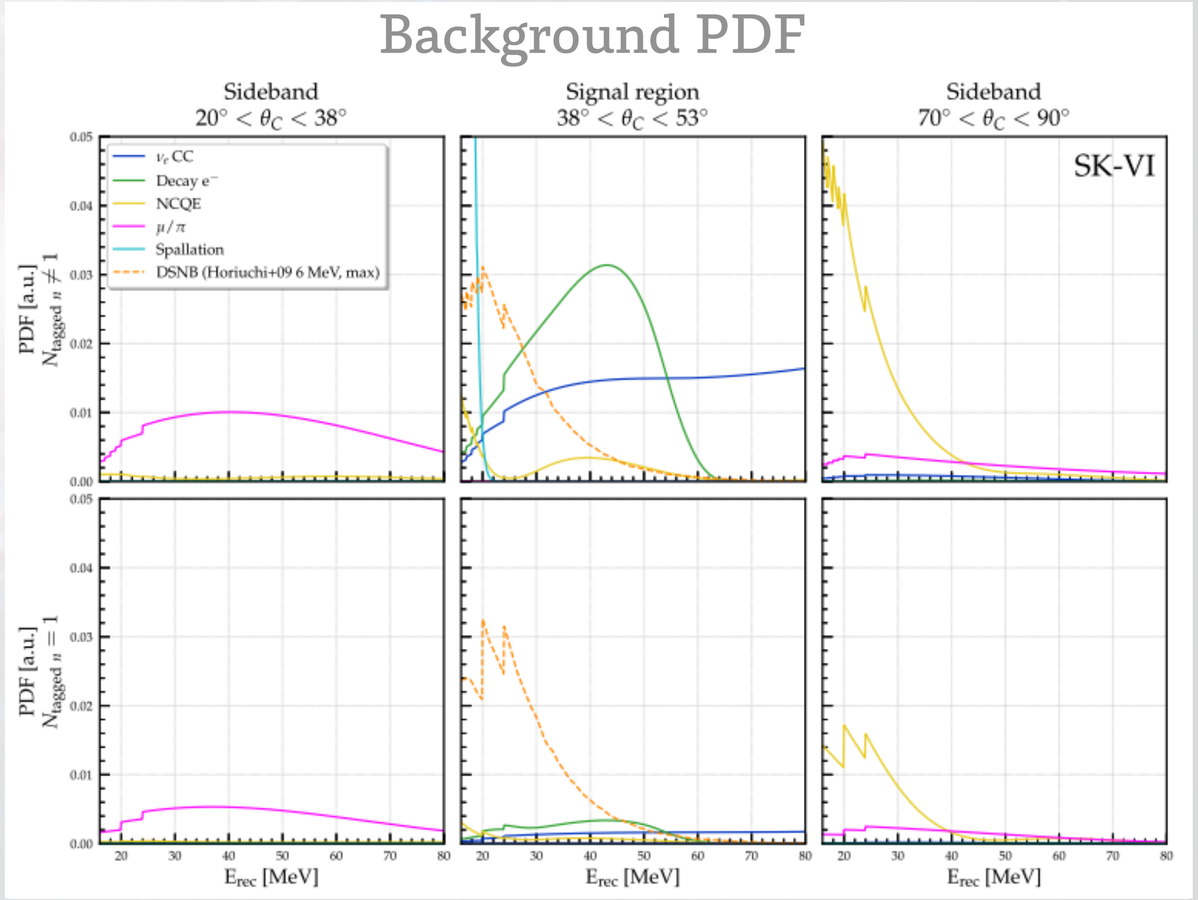




Update the world stringent sensitivity for some bins

Spectral fitting

- **Make PDFs for**
  - ν_e CC, Decay-e, NCQE, μ/π, spallation
  - E > 16 MeV to avoid uncertainty
- **To constraint background, 6 panels for**
  - Number of neutrons (n=1, n≠1)
  - Cherenkov angle
    - small(20-38˚): μ/π
    - mid(38-53˚): signal, spallation, decay-e
    - Large(70-90˚): NCQE, μ/π



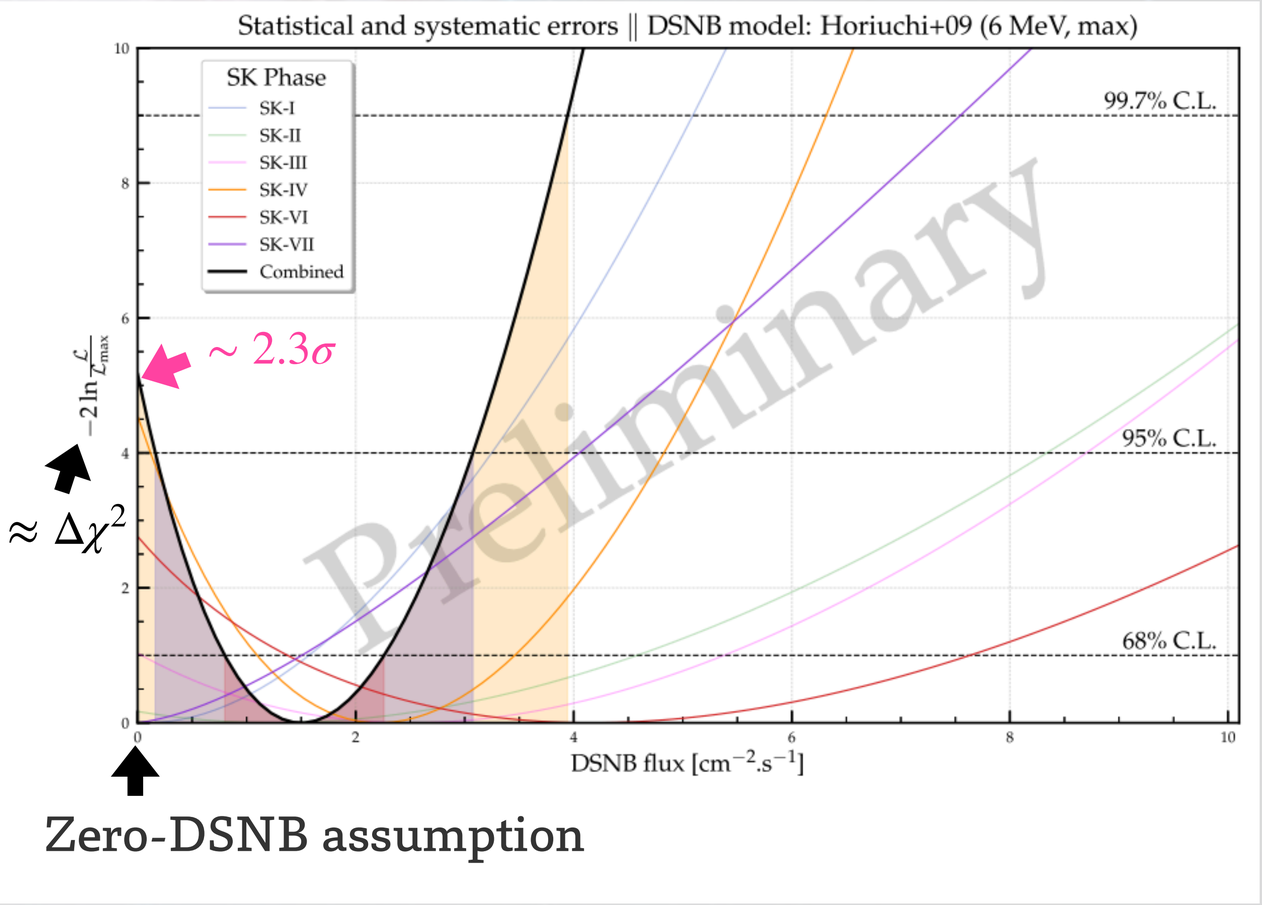
Spectral fitting

- **Calculate combined likelihood**

$$\mathscr{L}\left(\text{Data}\,|\,N_s, \vec{N}_b, \vec{\varepsilon}\right) = e^{-\sum_{j\in s+b} N_j} \prod_{i=1}^{N_{\text{data}}} \sum_{j\in s+b} N_j \,\text{PDF}_j\left(E^i, \theta_C^i, N^i_{\text{tagged } n}\,|\,\vec{\varepsilon}\right)$$

$$\mathscr{L}_{combined}\left(N_{DSNB}\right) = \prod_{SK-phase=1}^{7} \mathscr{L}_{SK-phase}\left(N_{DSNB}, \hat{\vec{N}}_b\right)$$

- **Best fit DSNB flux:**
  - 1.9 [(>16 MeV) /s/cm^2]
    ➡ Within the range of flux predictions
  - Reject zero hypothesis of DSNB with ~2.3σ level
  - Reported at NEUTRINO 2024



Current status and prospects

Analysis update

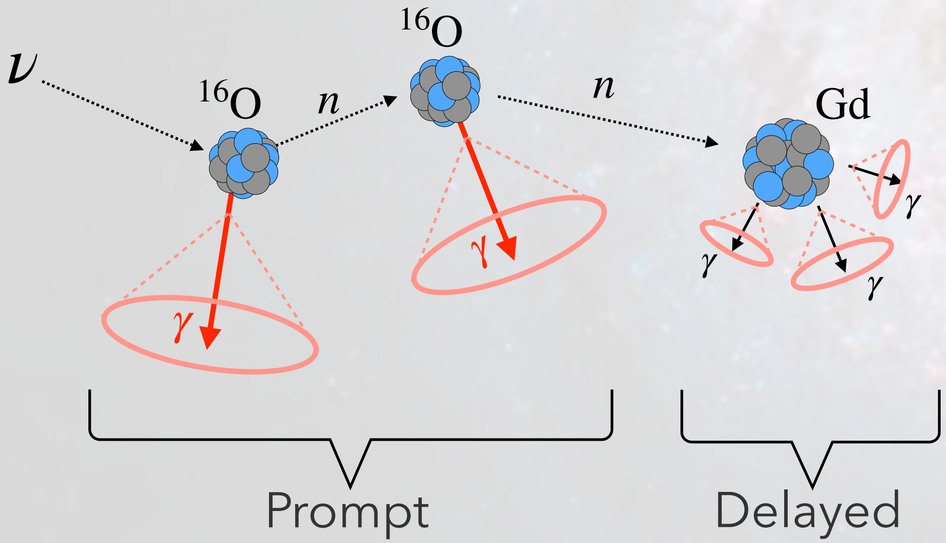
- Developing multiple scattering reduction variable
- Neutron tagging using neutral network
- Better understanding of the NCQE interaction (→later talks)
- Investigation for new neutrino interaction model

Backups

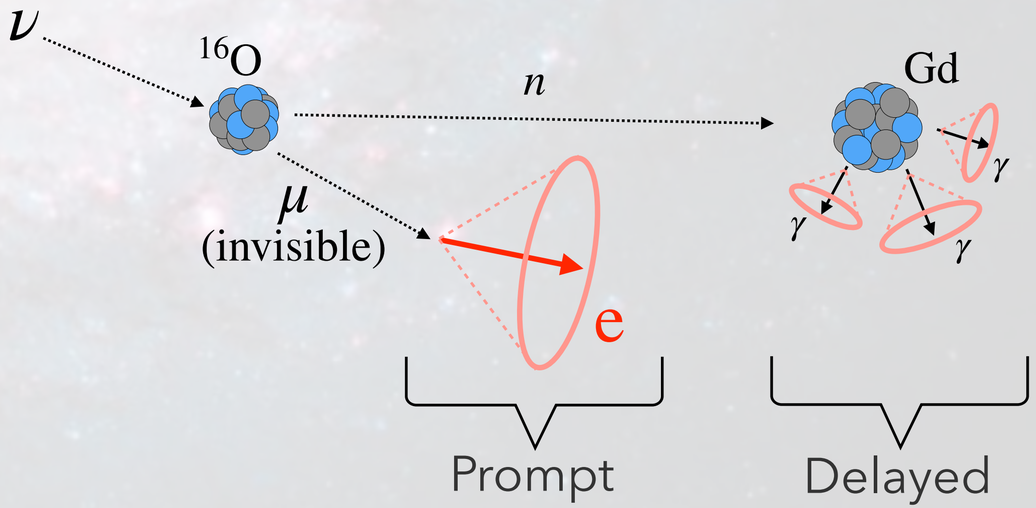
Background: Atmospheric neutrinos

- **Hadronic interaction with oxygen nucleus leads to neutron emission**

NCQE



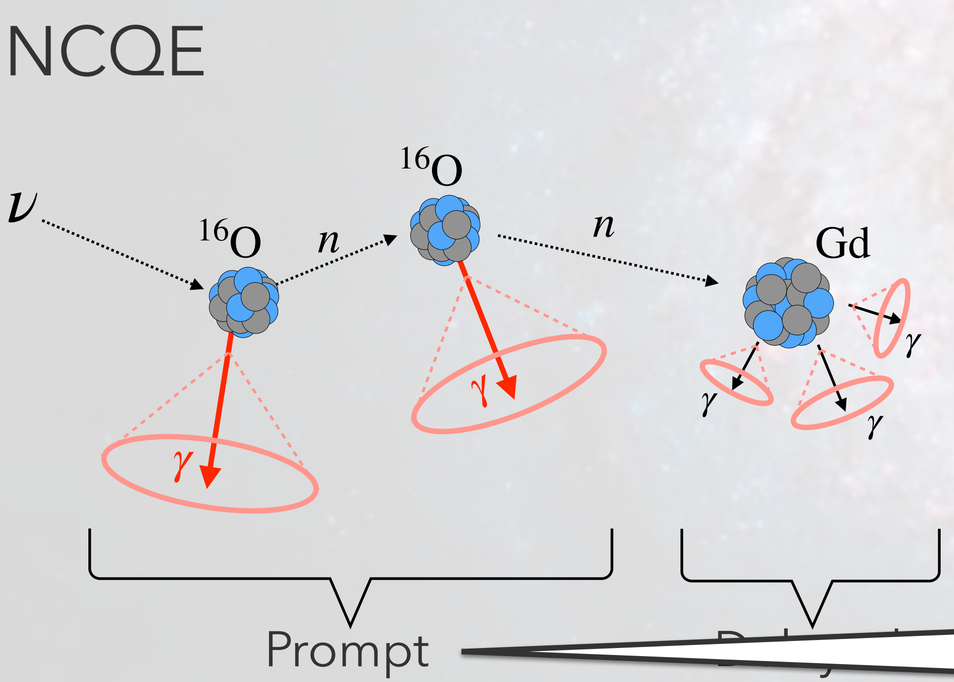
non-NCQE (CCQE)

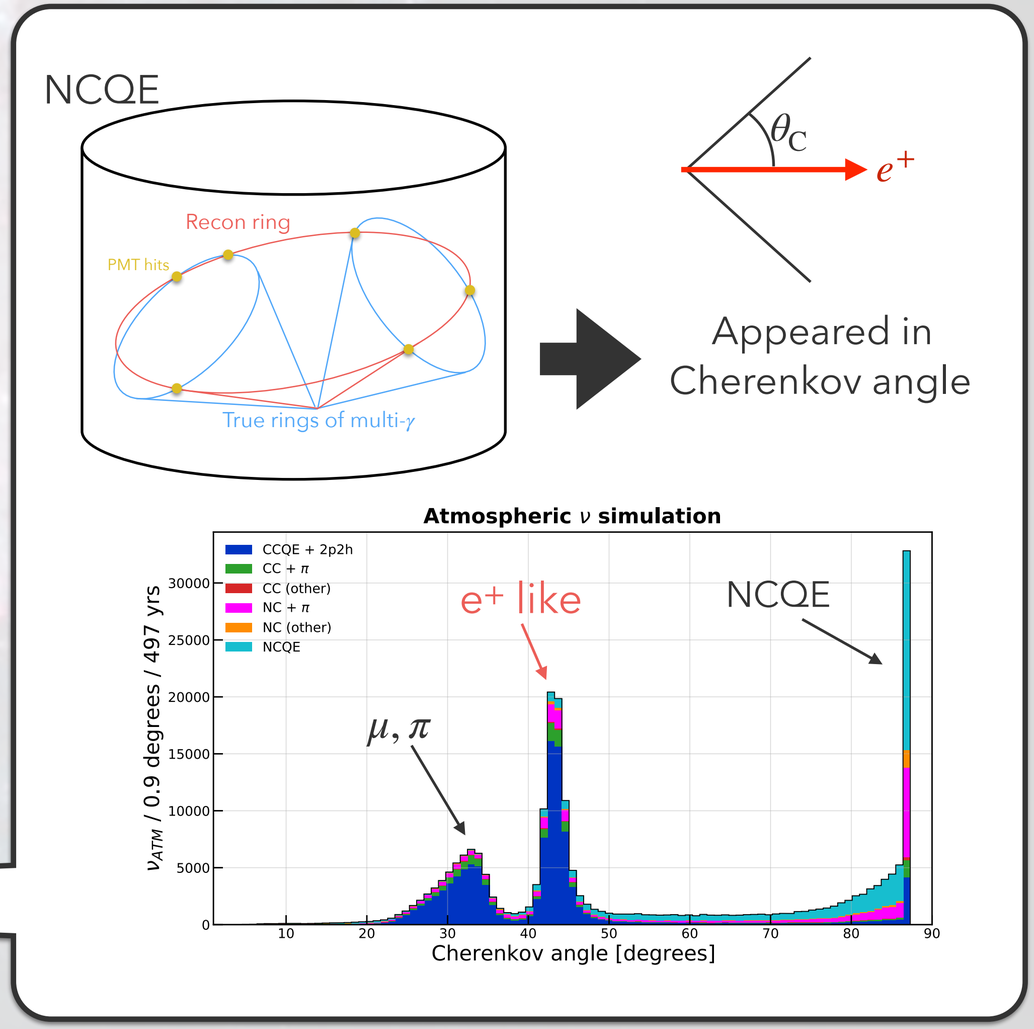


Remove using PMT hit pattern, charge, existence of other hit cluster

Background: NCQE event reduction

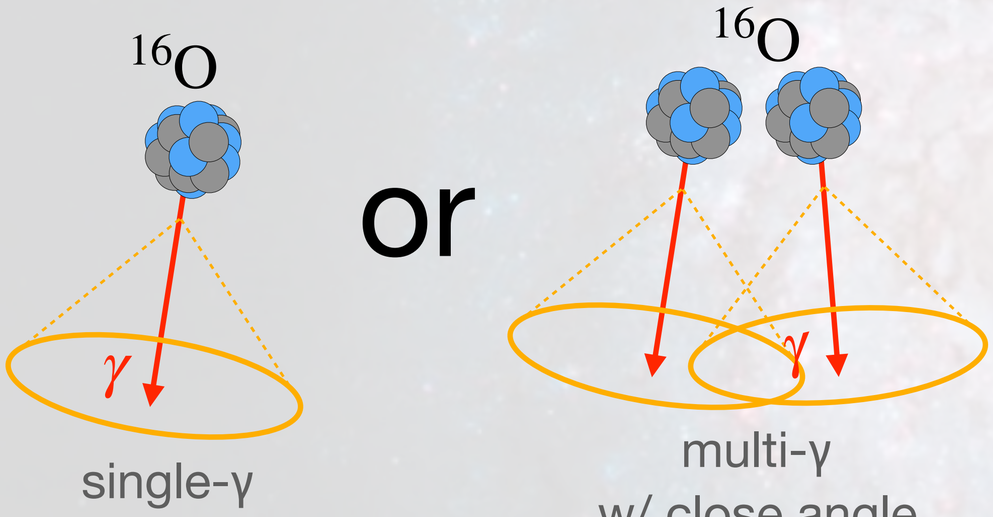
- **Reduce by Cherenkov angle**
  - NCQE events tend to have larger angle





Improvement of NCQE reduction

- **Remaining NCQE events: Cherenkov angle is reconstructed to ~42 deg**



CANNOT distinguish from SRN

Improvement of NCQE reduction

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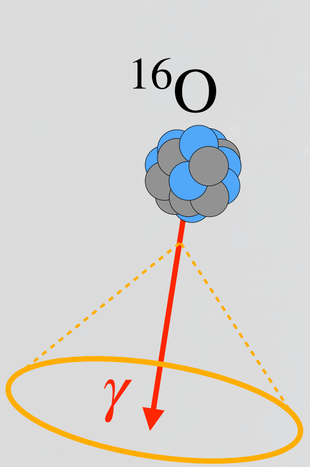
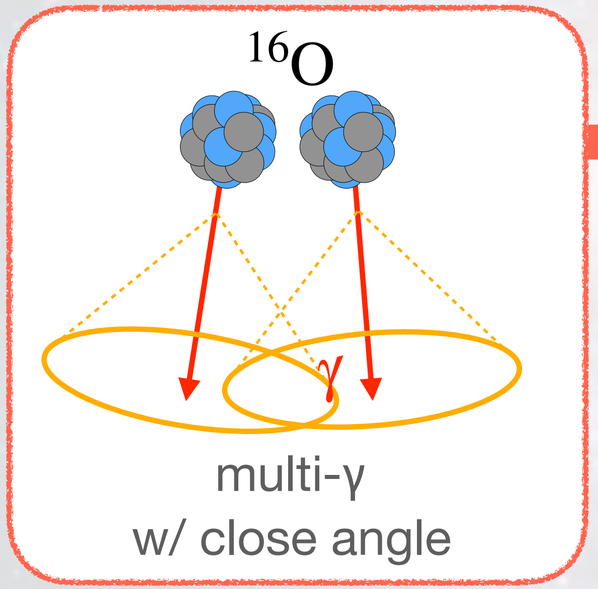


single-γ

or

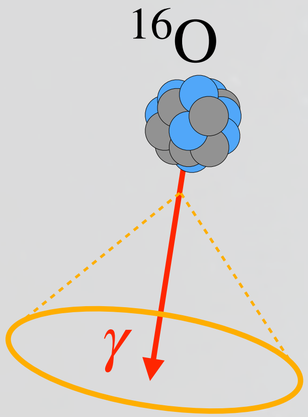


multi-γ
w/ close angle

Looks like an event with
more multiple scattering than electrons

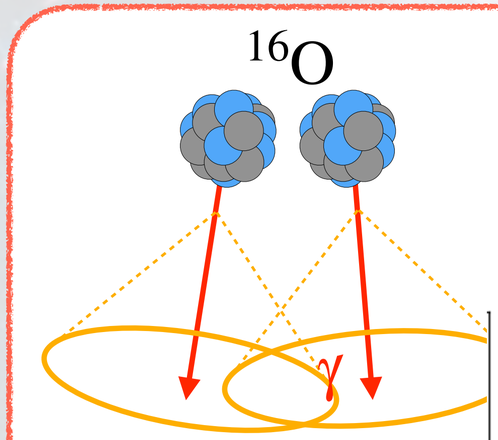
Improvement of NCQE reduction

- **Remaining NCQE events: Cherenkov angle is reconstructed to ~42 deg**



single-γ

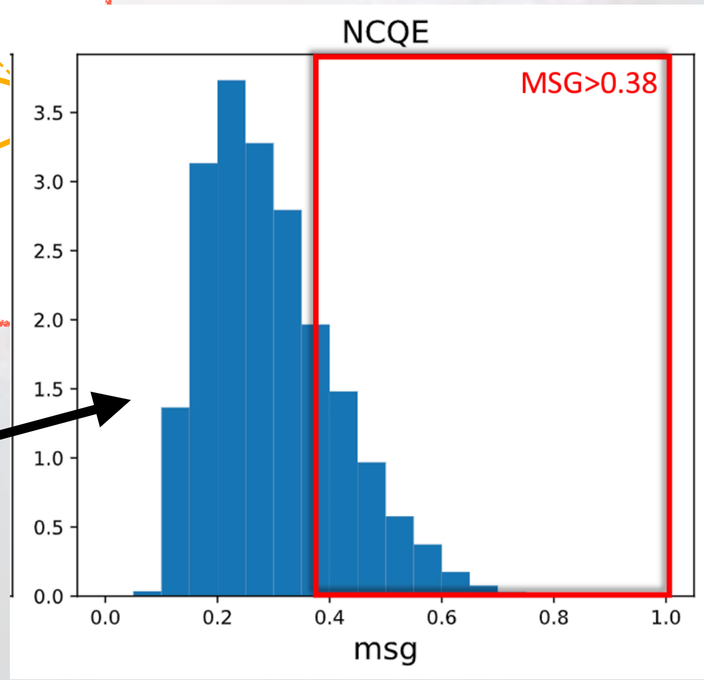
or

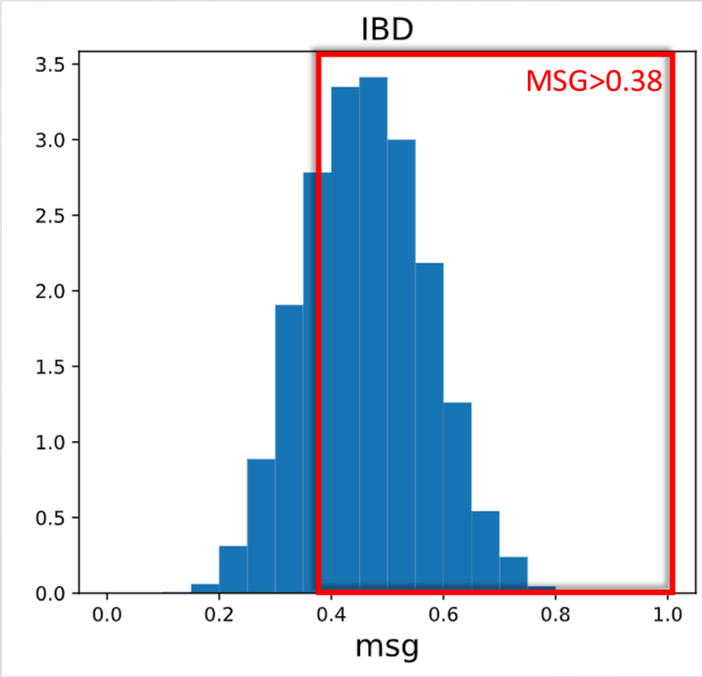


multi-γ
w/ close angle

Looks like an event with
more multiple scattering than electrons

New variable
Multiple-scattering goodness (MSG)





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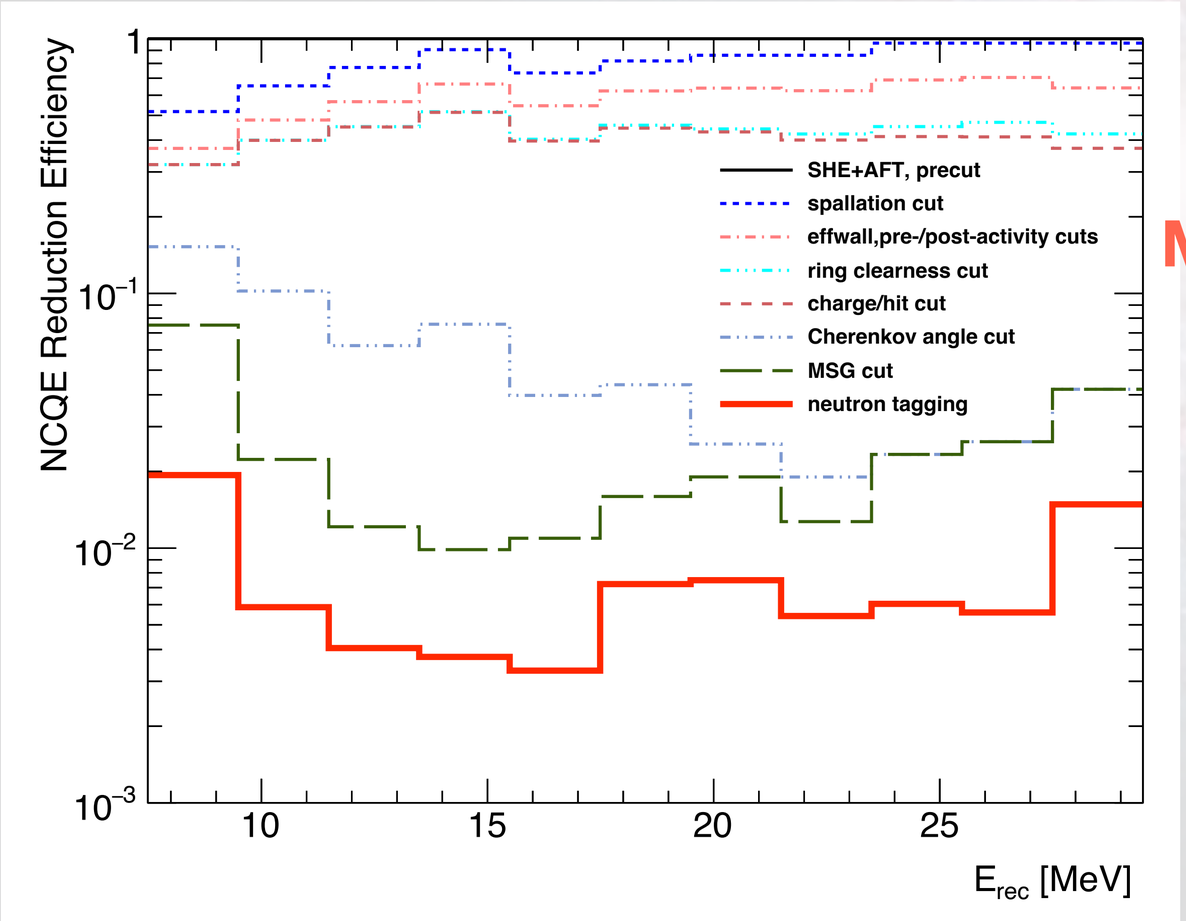


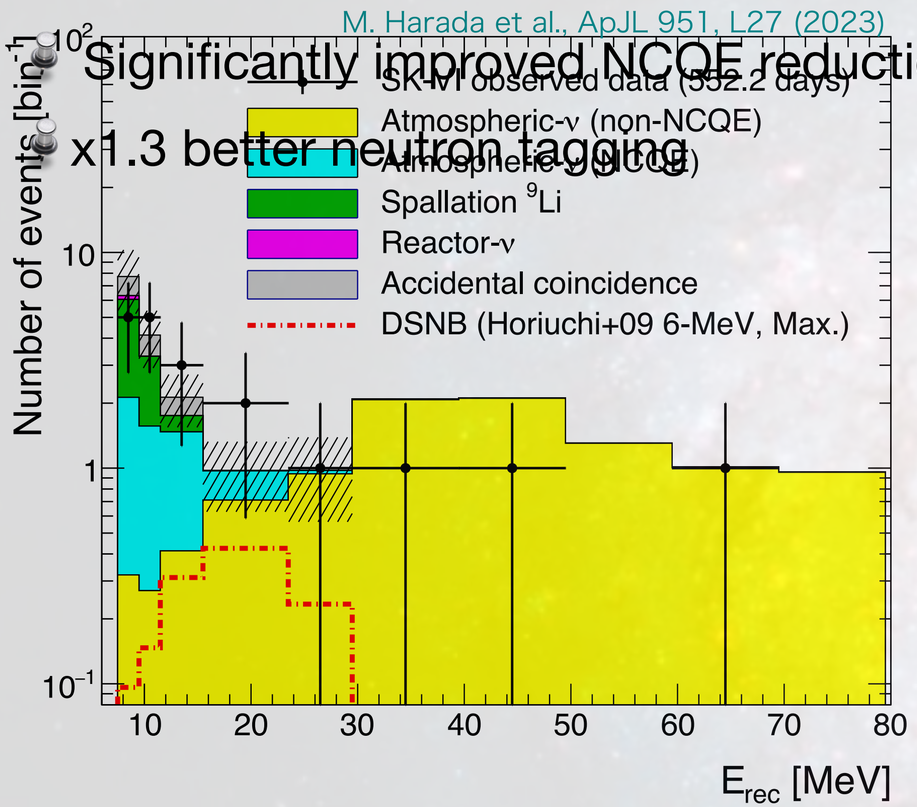
MSG cut significantly reduces NCQE events at low-energy region

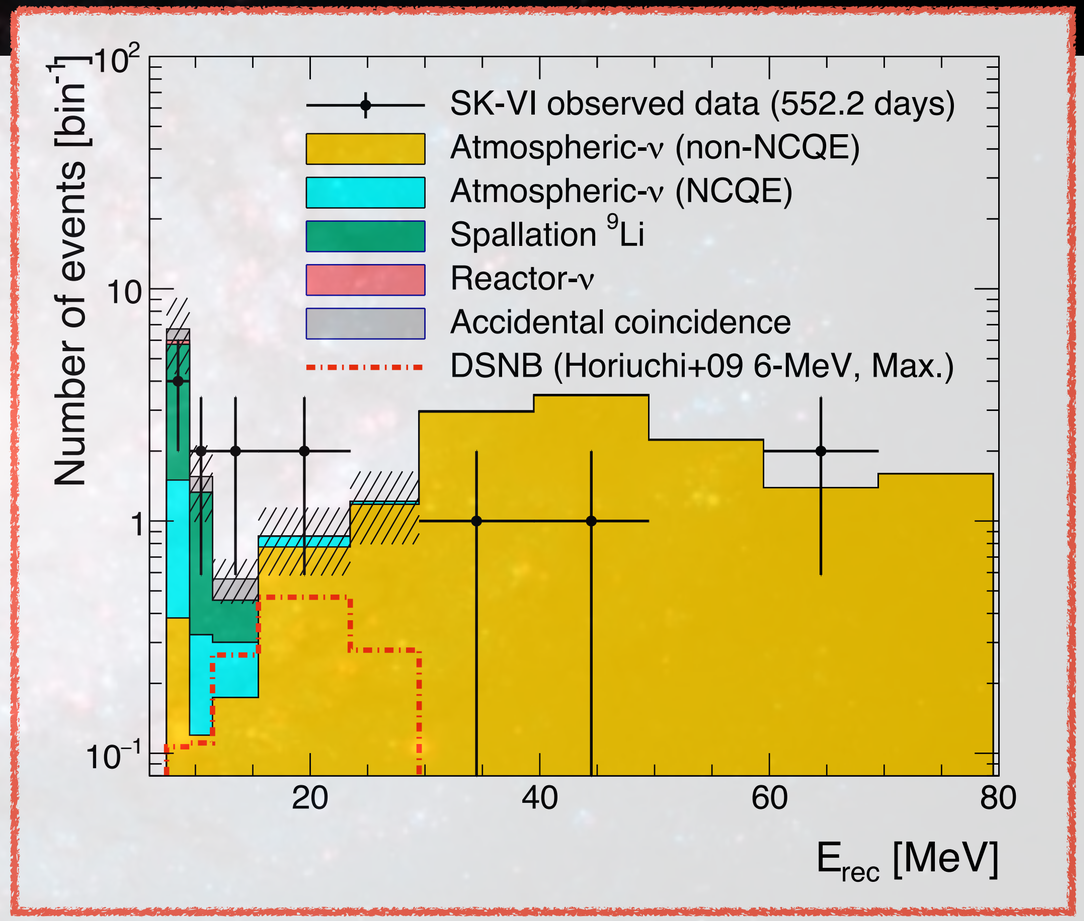
In future:
Develop ML-based NCQE reduction including MSG cut

Result of improvement

M. Harada et al., ApJL 951, L27 (2023)

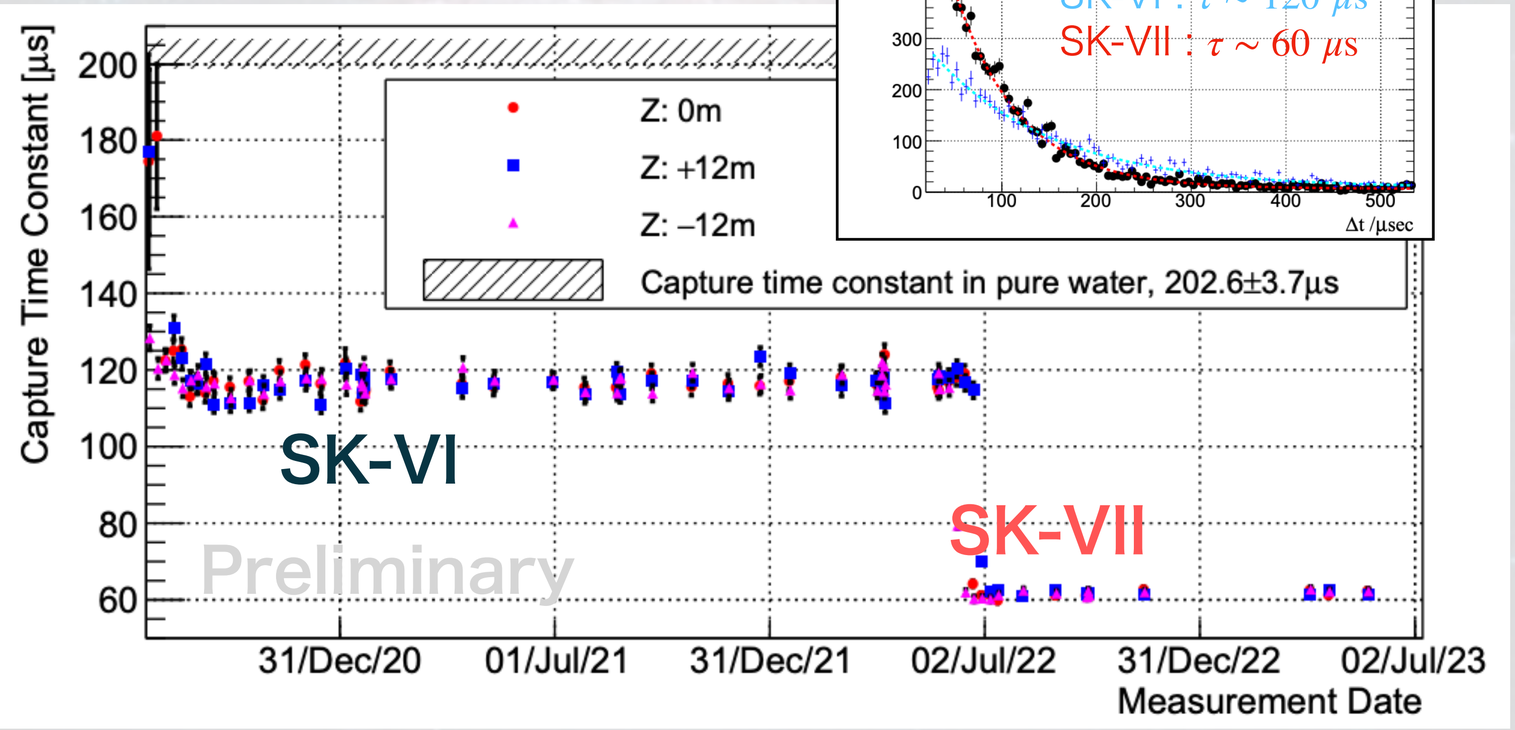
- Significantly improved NCQE reduction
- x1.3 better neutron tagging





Neutron tagging in 0.03% Gd conc.

- **Neutron tagging in 0.03% Gd conc.**



Apply same NN method to SK-VII data

✓ **63.1±1.1% with 0.02% mis-ID**
→1.4 times improvement

Summary

- **First result of SRN search in SK-Gd was published**
- **In 2022, the Gd concentration was increased to 0.03%**
  → neutron tagging efficiency x1.4!
- **Multitude of efforts towards understanding and reducing NCQE events**
  - Multiple scattering reduction
  - Neutron tagging using neutral network
  - Better understanding of the NCQE interaction (later talk)
- **Analysis of data up to 2023 is also on-going.**