Measurement of the atmospheric neutrino-oxygen neutral-current quasielastic cross section and study of nucleon-nucleus interaction model in the SK-Gd experiment

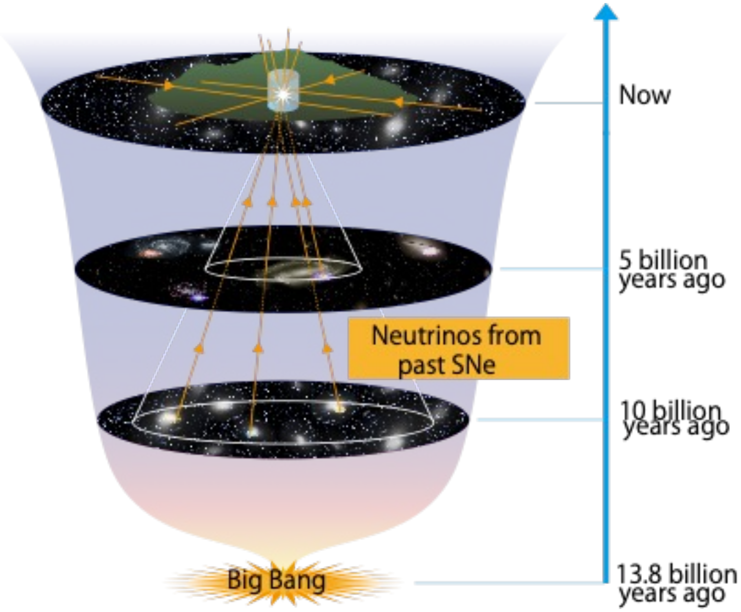
SK-Gd実験における大気ニュートリノ-酸素原子核中性カレント準弾性散乱反応断面積の測定および核子-原子核反応モデルの研究

The 10th Supernova Neutrino Workshop
February 29th - March 1st, 2024
Seiya Sakai (Okayama Univ.)

Super-Kamiokande Gadolinium (SK-Gd)

- Started from July 2020
- Load 0.011% mass concentration of Gd in SK

  → Aiming the first observation of the diffuse supernova neutrino background (DSNB)

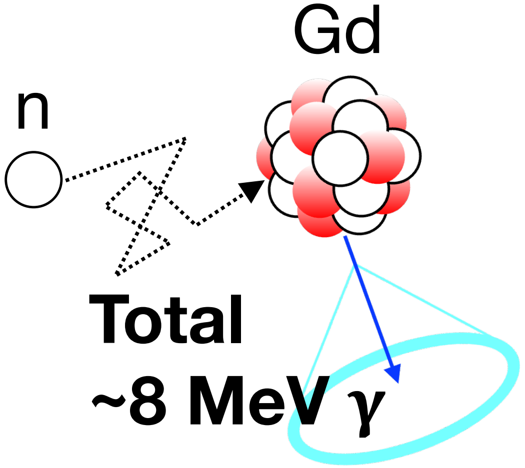


Why Gd?

- Largest thermal neutron capture cross section among natural elements

  → High capture rate at low concentrations
- Emit a total of ~8 MeV of gamma rays

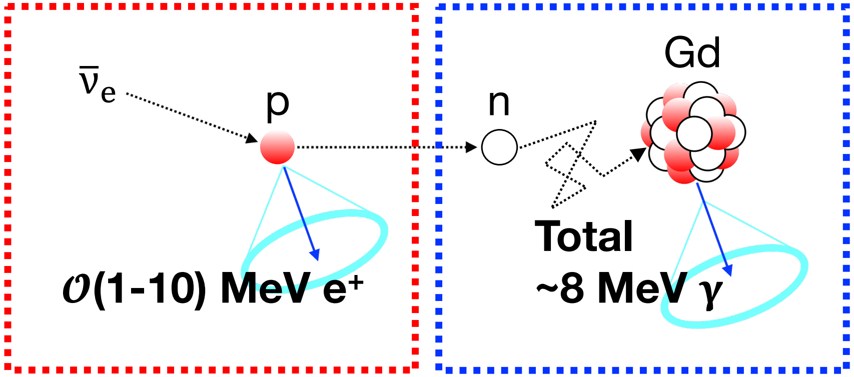
  → Neutron tagging efficiency is largely improved



DSNB search in SK-Gd experiment

- Search for the inverse beta decay by electron antineutrinos ($\bar{\nu}_e + p \rightarrow e^+ + n$)
- Detect positron (prompt signal) and neutron (delayed signal) pairs

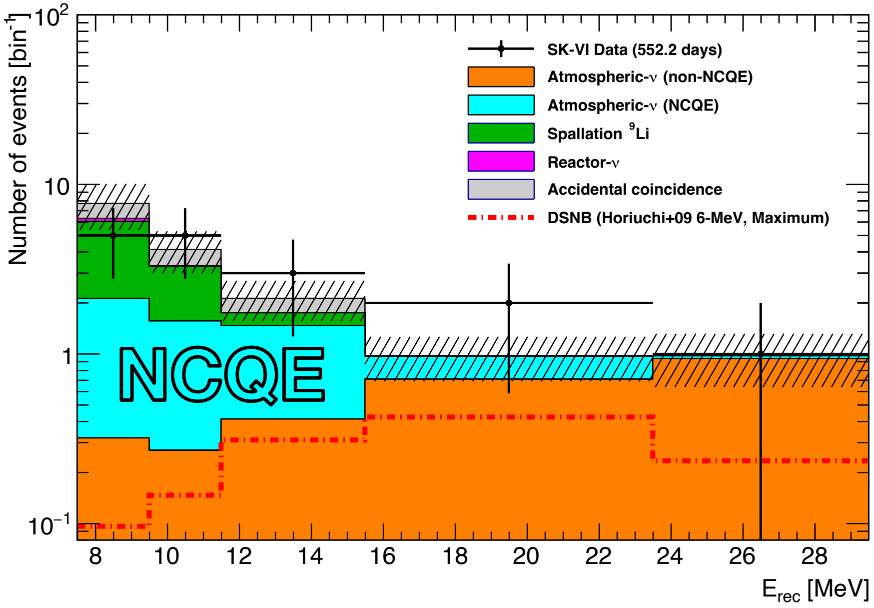
  → Can remove many backgrounds without neutrons



Prompt signal → **Delayed signal**

~115 μsec (0.011% by mass of Gd)

DSNB search result using the observed data of 0.011% mass concentration of Gd



NCQE events in DSNB search

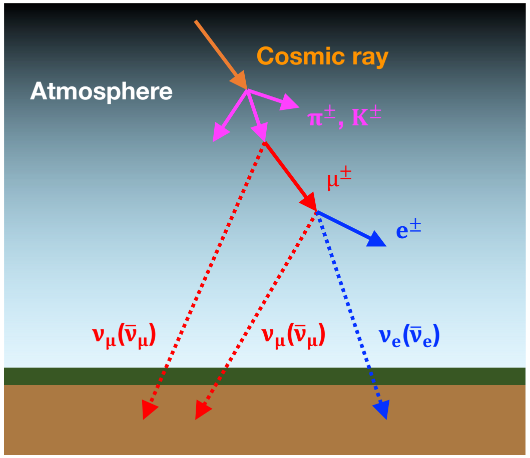
- Neutral-current quasielastic scattering (NCQE) reaction

  Atmospheric neutrino knocks out

  a nucleon (neutron) of the oxygen nucleus
- Gamma ray and neutron pairs mimic DSNB events

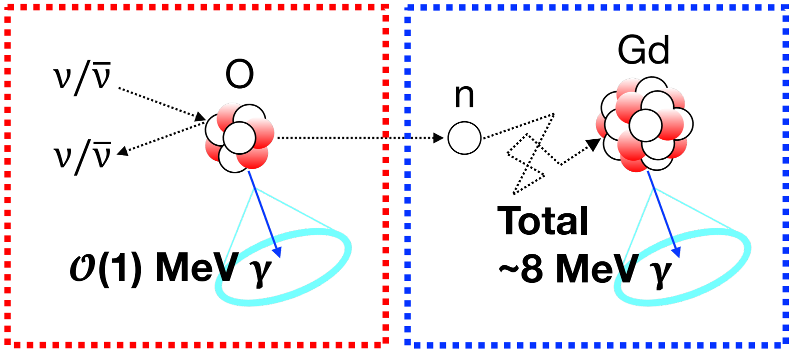
→ Difficult to distinguish from DSNB events

→ Important to estimate NCQE events precisely



NCQE

$$\nu(\bar{\nu}) + {}^{16}\mathrm{O} \rightarrow \nu(\bar{\nu}) + {}^{15}\mathrm{O} + \gamma + n$$

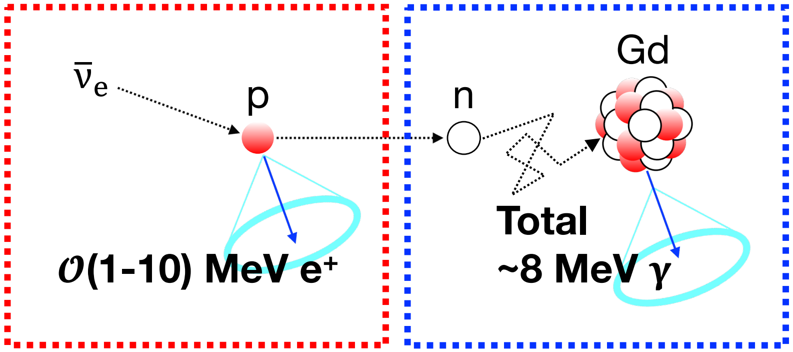


Prompt signal → Delayed signal

~115 μsec (0.011% by mass of Gd)

DSNB

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



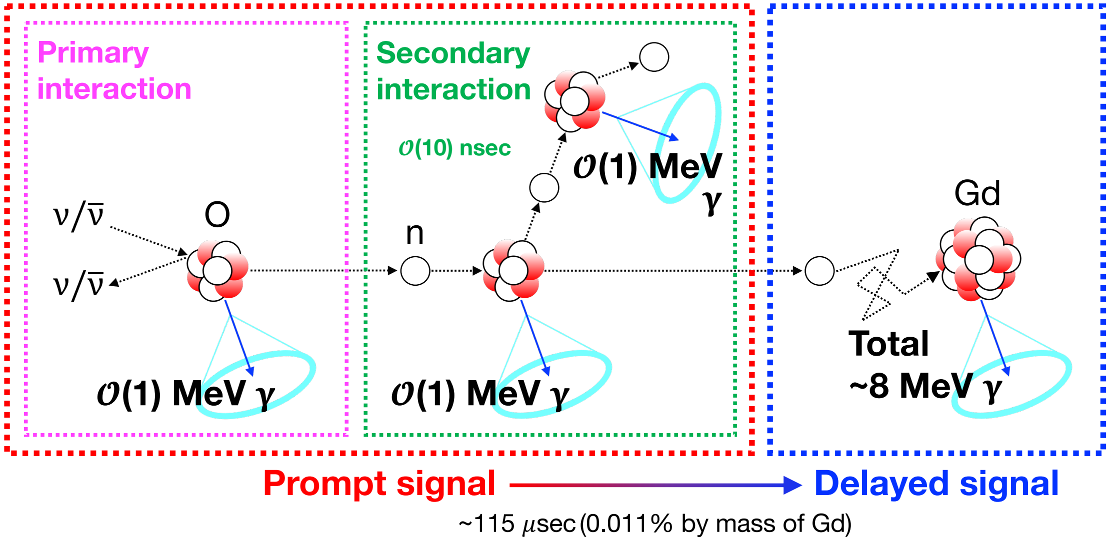
Prompt signal → Delayed signal

~115 μsec (0.011% by mass of Gd)

NCQE events in DSNB search

- Neutron energy by neutrino (primary) interaction: $\mathcal{O}(10)$ - $\mathcal{O}(10^3)$ MeV

  → Additional gamma rays and neutrons are generated by nucleon-nucleus (secondary) interaction
- Impossible to distinguish from primary interaction



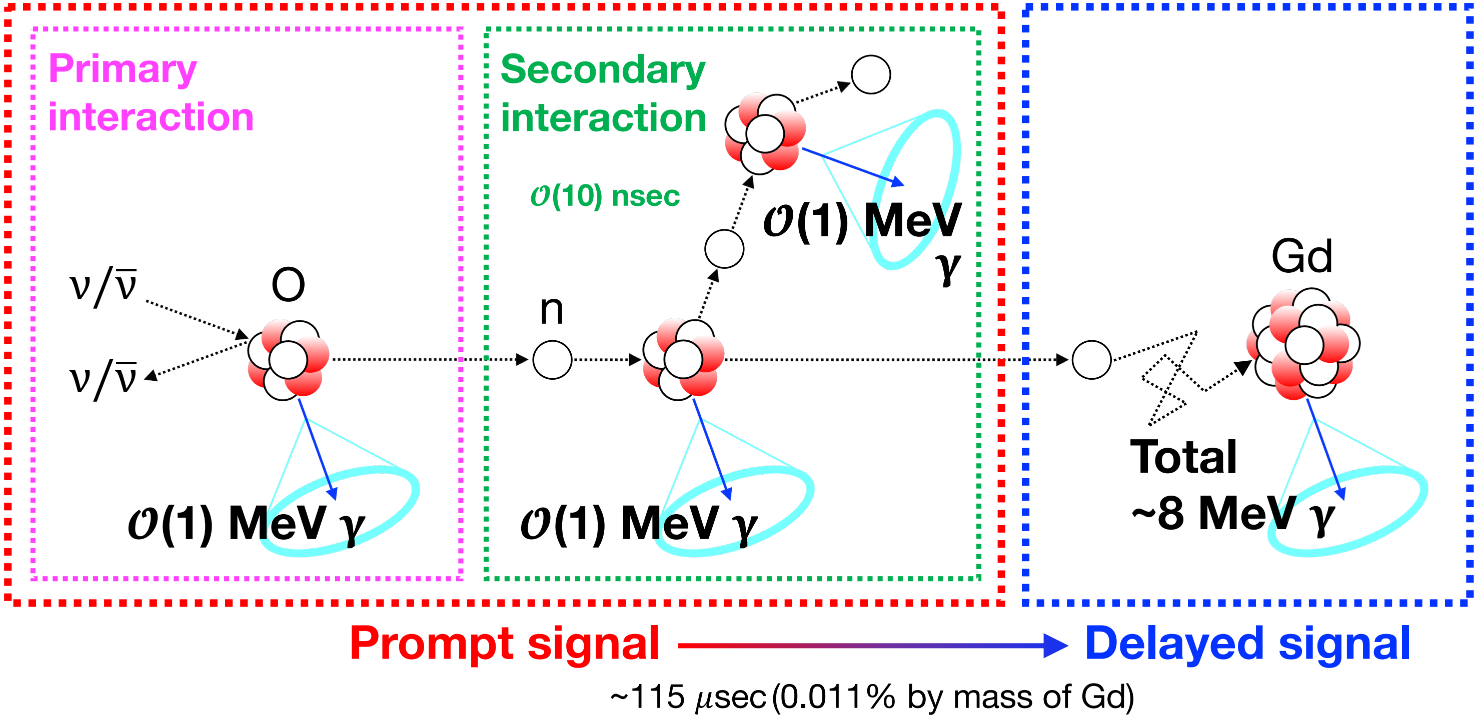
To estimate NCQE events precisely, we must understand NCQE cross section and secondary interaction

Measurement of the atmospheric neutrino-oxygen NCQE cross section

Data analysis

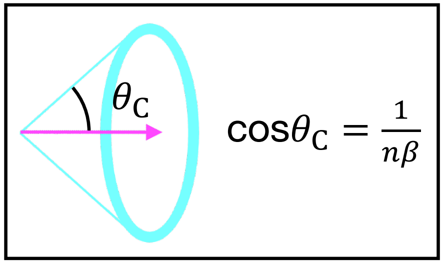
- Select NCQE events from a 552.2 day dataset

  (August 2020 - June 2022, Gd: 0.011%)
- Energy of prompt signal: 8 - 30 MeV
- Number of delayed signals ≥ 1



Data analysis

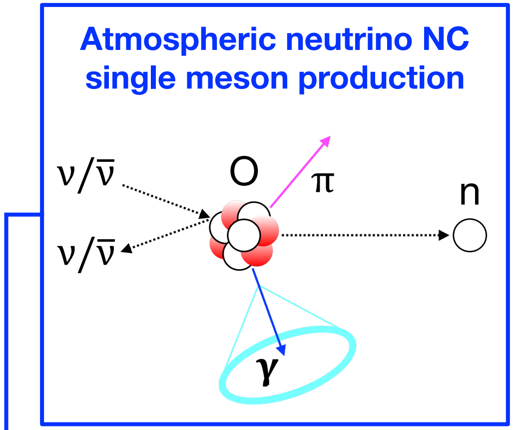
- Cherenkov angle of prompt signal > 50 degrees

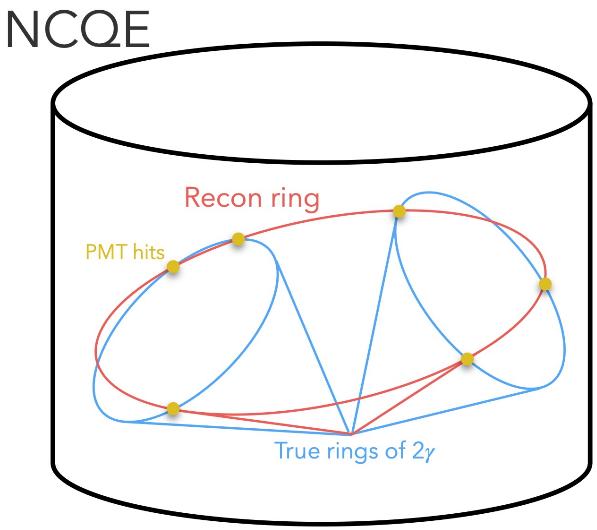


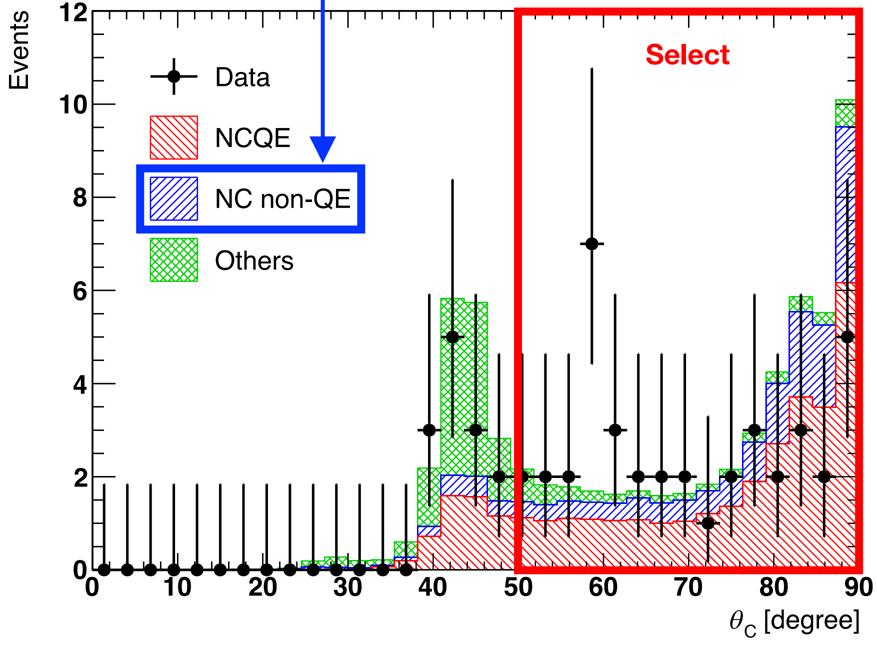
$$\cos\theta_C = \frac{1}{n\beta}$$

n: Refractive index
$\beta = v/c$

$n \sim 1.34$
$\beta \sim 1$
$\rightarrow \theta_C \sim 42$ degrees


Atmospheric neutrino NC single meson production





Results

NCQE cross section

- Flux-averaged theoretical cross section

$$\left\langle \sigma_{\mathrm{NCQE}}^{\mathrm{theory}} \right\rangle = \frac{\int_{160\ \mathrm{MeV}}^{10\ \mathrm{GeV}} \sum_{i=\nu,\bar{\nu}} \phi_i(E) \times \sigma_i(E)_{\mathrm{NCQE}}^{\mathrm{theory}} dE}{\int_{160\ \mathrm{MeV}}^{10\ \mathrm{GeV}} \sum_{i=\nu,\bar{\nu}} \phi_i(E) dE} = 1.02 \times 10^{-38}\ \ \mathrm{cm}^2/\mathrm{oxygen}$$

- Ratio of observed NCQE events to expected NCQE events (f_{NCQE})

$$f_{\mathrm{NCQE}} = \frac{N^{\mathrm{obs}} - N_{\mathrm{NC\,non-QE}}^{\mathrm{exp}} - N_{\mathrm{Others}}^{\mathrm{exp}}}{N_{\mathrm{NCQE}}^{\mathrm{exp}}} = 0.725$$

N^{obs}	38
$N_{\mathrm{NCQE}}^{\mathrm{exp}}$	28.7
$N_{\mathrm{NC\,non-QE}}^{\mathrm{exp}}$	13.3
$N_{\mathrm{Others}}^{\mathrm{exp}}$	4.0

- Measured cross section

$$\left\langle \sigma_{\mathrm{NCQE}}^{\mathrm{measured}} \right\rangle = f_{\mathrm{NCQE}} \times \left\langle \sigma_{\mathrm{NCQE}}^{\mathrm{theory}} \right\rangle$$
$$= 0.74 \pm 0.22(\mathrm{stat.}) \times 10^{-38}\ \ \mathrm{cm}^2/\mathrm{oxygen}$$

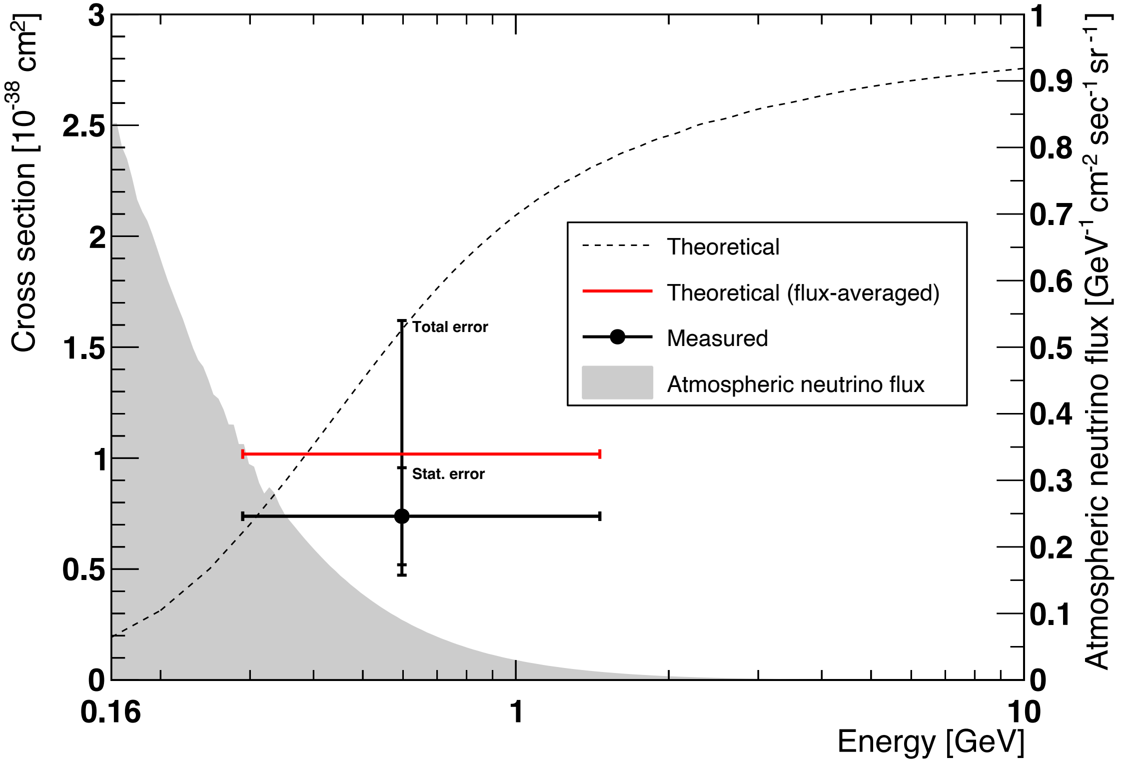
Systematic uncertainties

	$N_{\mathrm{NCQE}}^{\mathrm{exp}}$	$N_{\mathrm{NC\ non-QE}}^{\mathrm{exp}}$
Atmospheric neutrino flux	±18.0%	
Atmospheric neutrino/antineutrino ratio	±5.0%	
Cross section	-	±18.0%
Primary interaction	+1.5%/−9.4%	+0.0%/−2.4%
Secondary interaction	−30.9%	−24.3%
Energy cutoff	−2.1%	−1.5%
Data reduction	±1.4%	
Neutron tagging	±6.4%	

Results

- $\langle \sigma_{\mathrm{NCQE}}^{\mathrm{measured}} \rangle = 0.74 \pm 0.22(\mathrm{stat.})^{+0.85}_{-0.15}(\mathrm{syst.}) \times 10^{-38}\ \mathrm{cm}^2/\mathrm{oxygen}$

→ Consistent with $\langle \sigma_{\mathrm{NCQE}}^{\mathrm{theory}} \rangle = 1.02 \times 10^{-38}\ \mathrm{cm}^2/\mathrm{oxygen}$ within the uncertainties



Systematic uncertainty is so large, why?

Comparison of secondary interaction models using atmospheric neutrinos

Systematic uncertainties

- Systematic uncertainty of secondary interaction is largest

	$N_{\mathrm{NCQE}}^{\mathrm{exp}}$	$N_{\mathrm{NC\,non-QE}}^{\mathrm{exp}}$
Atmospheric neutrino flux	±18.0%	
Atmospheric neutrino/antineutrino ratio	±5.0%	
Cross section	-	±18.0%
Primary interaction	+1.5%/−9.4%	+0.0%/−2.4%
Secondary interaction	−30.9%	−24.3%
Energy cutoff	−2.1%	−1.5%
Data reduction	±1.4%	
Neutron tagging	±6.4%	

Why so large?

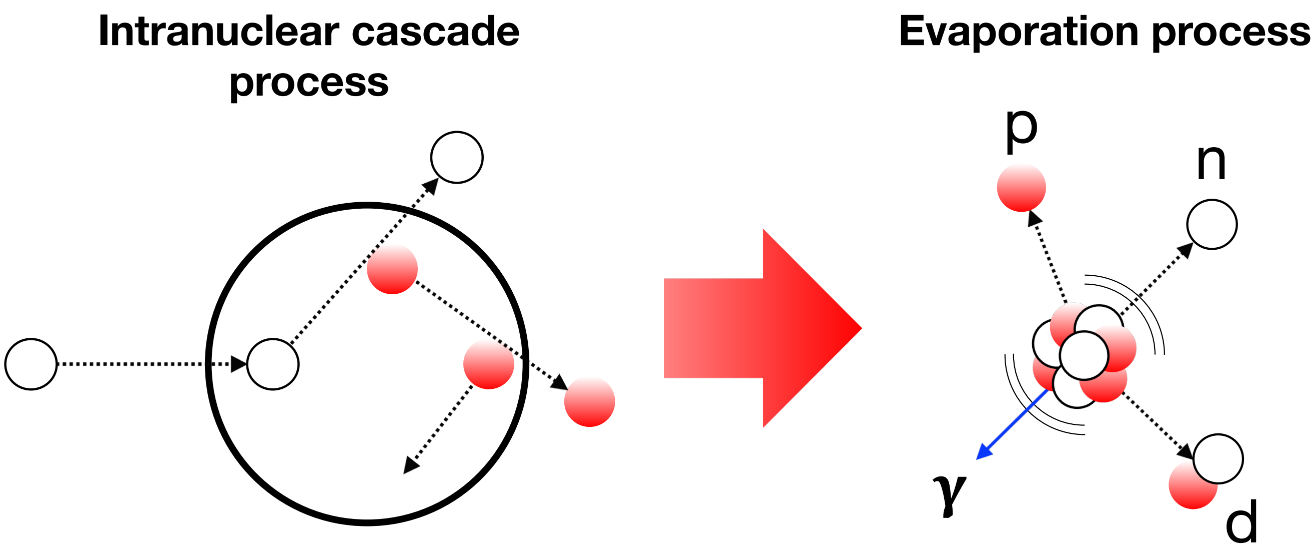
Secondary interaction models

- Intranuclear cascade process

  Process of a chain of reactions triggered by a reaction between an incident particle and a nucleon in a nucleus

- Evaporation process

  Process of emitting nucleons and gamma rays isotropically when an excited residual nucleus deexcites



Secondary interaction models

- Available secondary interaction models

    Bertini Cascade Model (BERT, SK official model)

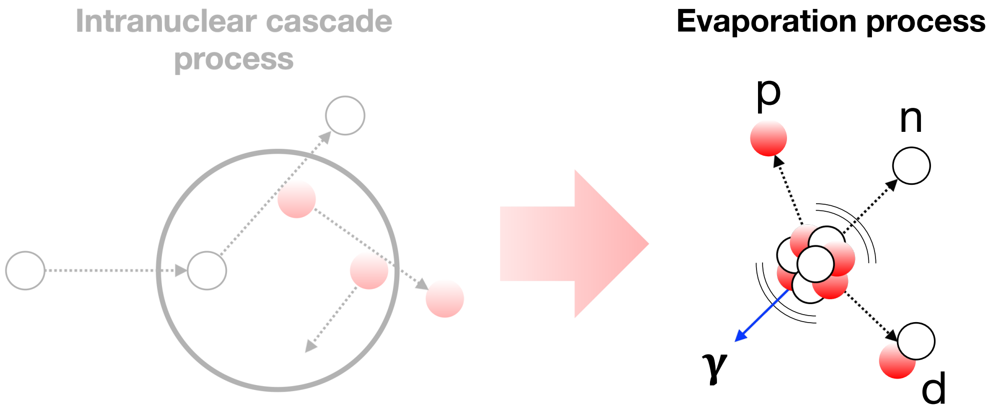
    Binary Cascade Model (BIC)

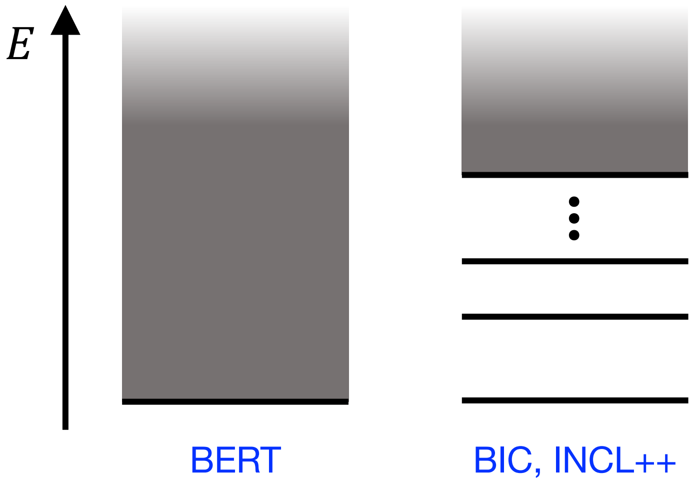
    Liège Intranuclear Cascade Model (INCL++)

    → Evaporation process is so different

    BERT → Continuous transitions till the end

    BIC, INCL++ → Continuous to discrete transitions (more realistic)

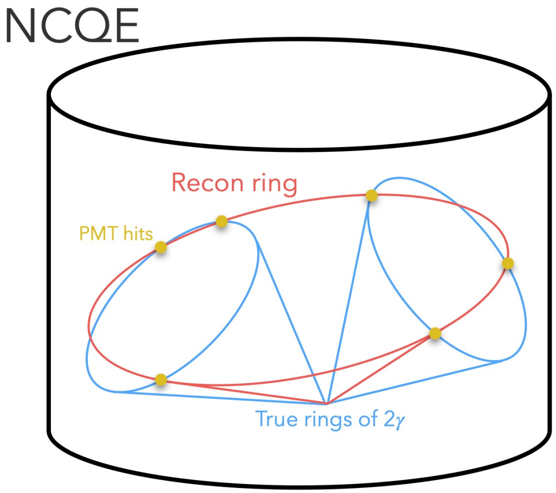


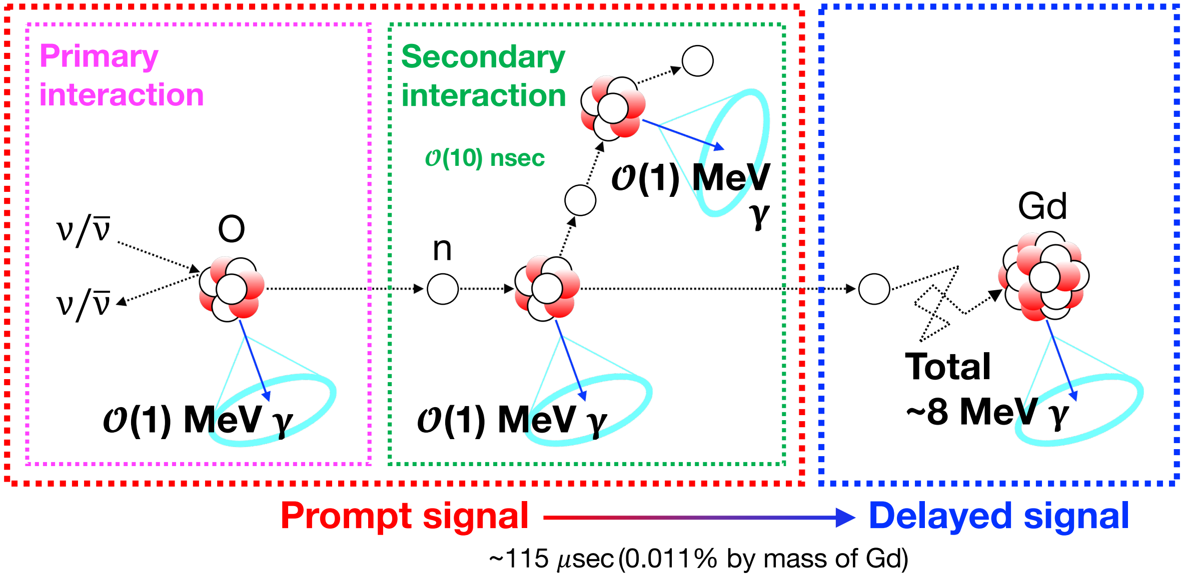


Comparison of secondary interaction models

- Compared the following distributions in BERT, BIC, and INCL++

Cherenkov angle of prompt signal	←	Number of gamma rays
Energy of prompt signal	←	Energy of gamma rays
Number of delayed signals	←	Number of neutrons

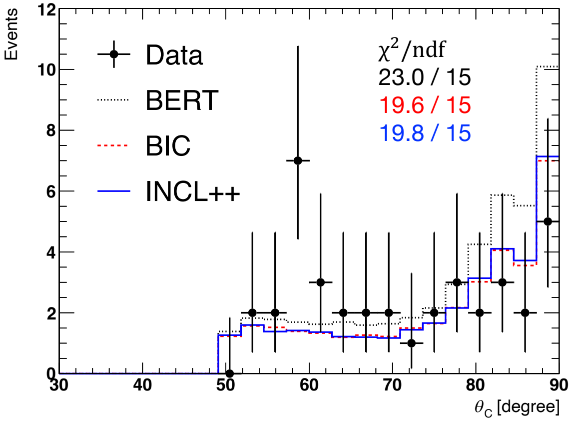




Results

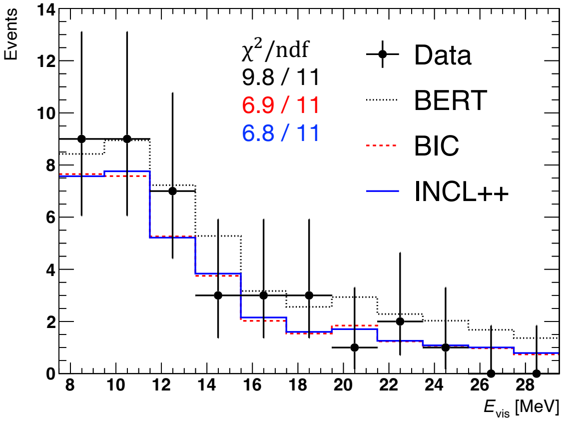
- Evaluated each distribution using chi-square
  - → Not conclusive due to small statistics
  - → χ^2 in BIC and INCL++ is smaller than that in BERT in all distributions
  - → Suggested that BIC and INCL++ reproduce data better than BERT

Cherenkov angle of prompt signal



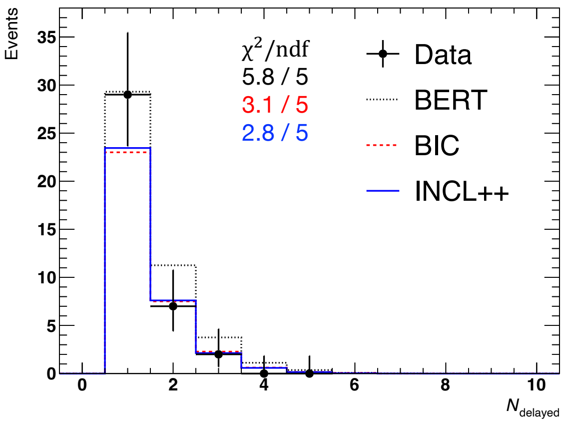
Correspond to the number of gamma rays

Energy of prompt signal



Correspond to energy of gamma rays

Number of delayed signals



Correspond to the number of neutrons

Systematic uncertainty

Why systematic uncertainty of secondary interaction is large?

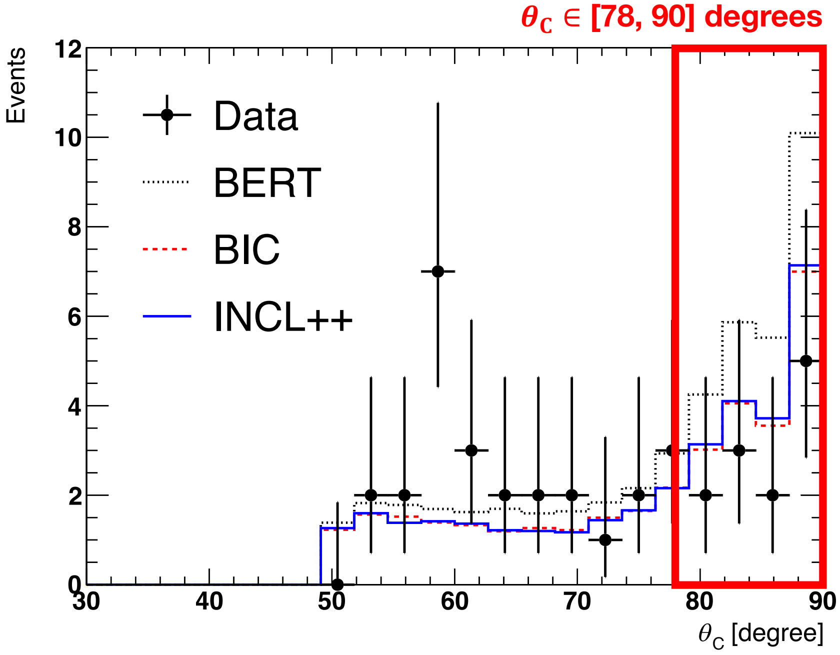
- Compared various secondary interaction models for the first time
  → Suggested that BIC and INCL++ reproduce data better than BERT

- Cannot determine which model is correct at this work
  → The difference in the number of events is taken as the systematic uncertainty

	BERT	BIC	INCL++
$N_{\mathrm{NCQE}}^{\mathrm{exp}}$	28.7	19.8 (−30.9%)	20.2 (−29.6%)
$N_{\mathrm{NC\,non-QE}}^{\mathrm{exp}}$	13.3	10.2 (−23.2%)	10.1 (−24.3%)

Systematic uncertainty

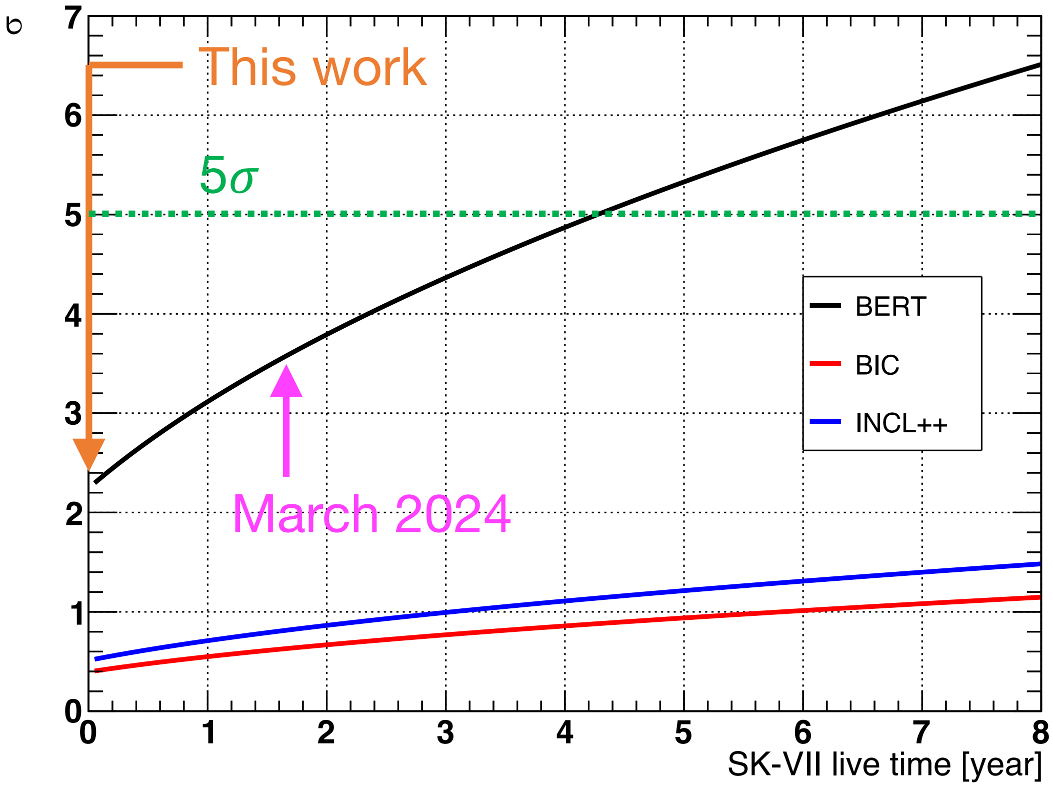
- Number of events in Cherenkov angle of prompt signal (θ_C) ∈ [78, 90] degrees
  → BERT is ~2.2σ far from data at this work



	Number of events (θ_C ∈ [78, 90] degrees)
Data	14
BERT	26.8
BIC	18.4
INCL++	18.9

Systematic uncertainty

- SK continues to observe at 0.03% Gd mass concentration (SK-VII)
- Evaporation model can be determined at 5σ by using ~4 years of data in SK-VII
  → Systematic uncertainty of NCQE cross section can be reduced



Summary

- Performed NCQE cross section measurement using a 552.2 day dataset in SK-Gd experiment (Gd: 0.011%)

  → $\left\langle \sigma_{\mathrm{NCQE}}^{\mathrm{measured}} \right\rangle = 0.74 \pm 0.22(\mathrm{stat.})^{+0.85}_{-0.15}(\mathrm{syst.}) \times 10^{-38}\ \mathrm{cm}^2/\mathrm{oxygen}$

  → Consistent with $\left\langle \sigma_{\mathrm{NCQE}}^{\mathrm{theory}} \right\rangle = 1.02 \times 10^{-38}\ \mathrm{cm}^2/\mathrm{oxygen}$

- Compared several secondary interaction models for the first time

  → Suggested that BIC and INCL++ reproduce data better than BERT

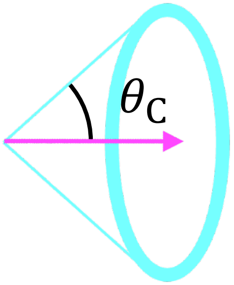
- Evaporation model can be determined at 5σ by using ~4 years of data in SK-VII

  → Systematic uncertainty of NCQE cross section can be reduced

Backup

Super-Kamiokande (SK)

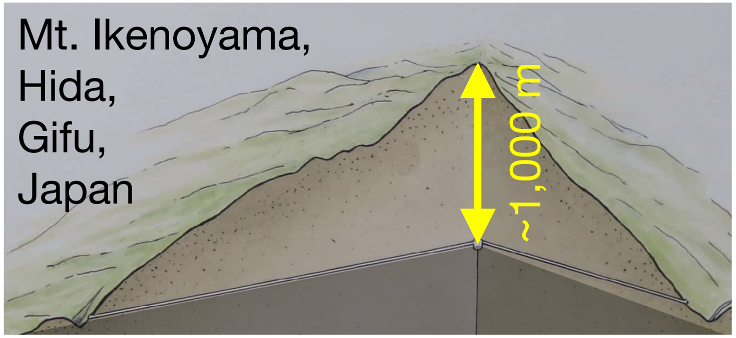
- Large water Cherenkov detector
- Started in 1996
- Consist of 50 kilotons ultrapure water and photomultiplier tubes (PMTs)

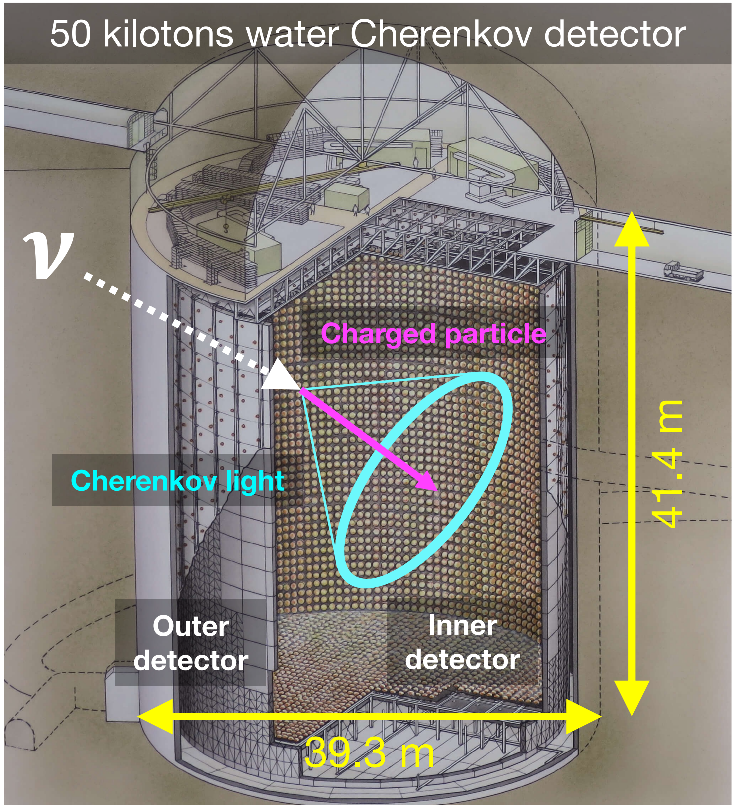


$$\cos\theta_C = \frac{1}{n\beta}$$

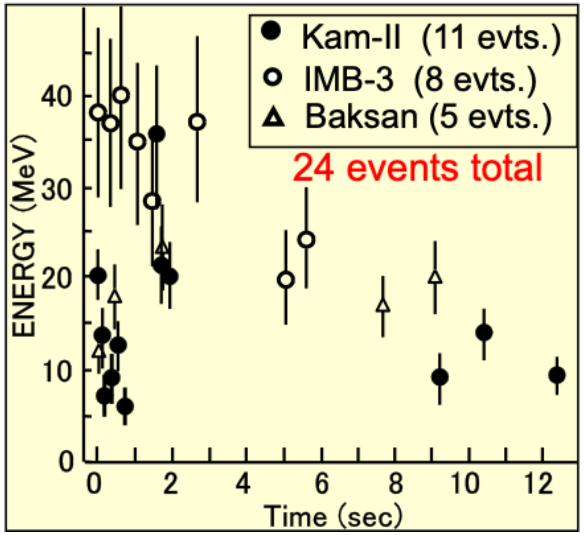
n: Refractive index
$\beta = v/c$

$n \sim$ 1.34
$\beta \sim$ 1
$\rightarrow \theta_C \sim$ 42 degrees





Supernova neutrino observation



- Supernova (SN)

  Explosion caused by a star with more than

  8 times the solar mass at the end of its life

- More than 99% of released energy is carried away by neutrinos

- Kamiokande, IMB, and Baksan observed neutrinos from SN1987A

  → Next neutrino observation is expected

- Rare in the vicinity where SN neutrinos are observable

  → SN neutrino observation is only SN1987A

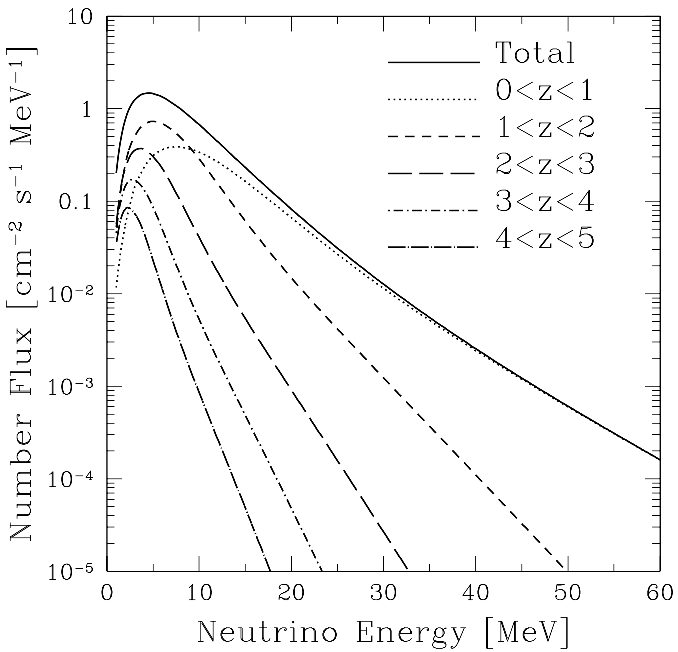
Diffuse Supernova Neutrino Background

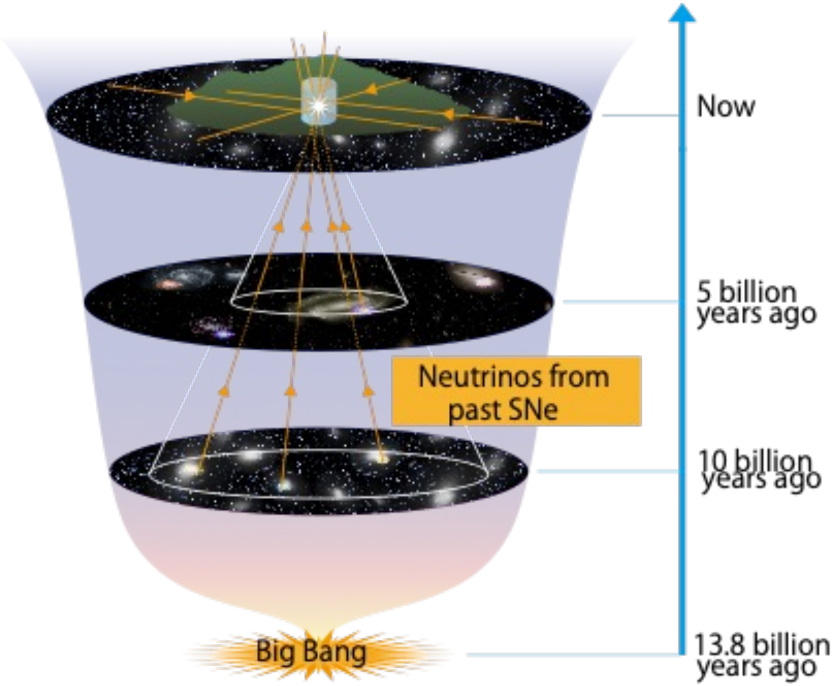
- Diffuse Supernova Neutrino Background (DSNB)

  Superposition of neutrinos emitted from all past SNe

  → Floating in space like background radiation

  → Small in number, but always potentially observable





Energy spectrum with time information

Diffuse Supernova Neutrino Background

- Diffuse Supernova Neutrino Background (DSNB)

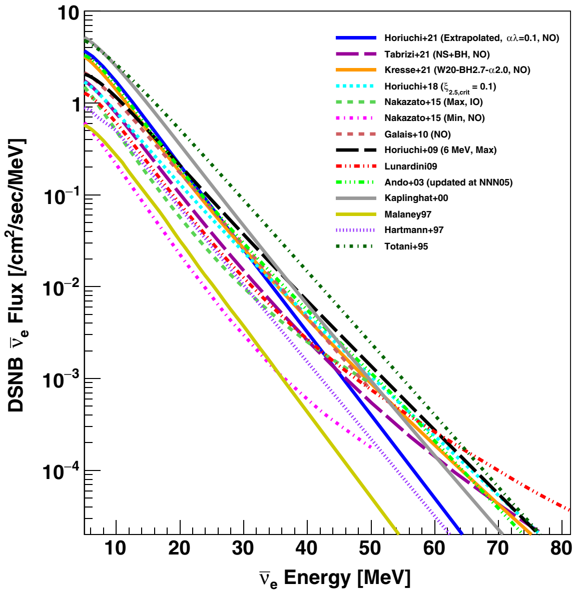
  Superposition of neutrinos emitted from all past SNe

- DSNB flux

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

→ Depend on SN rate, metallicity, initial mass function,

Number of neutrinos generated by SN, etc.



- There is a range of one order of magnitude on theoretical predictions of DSNB flux

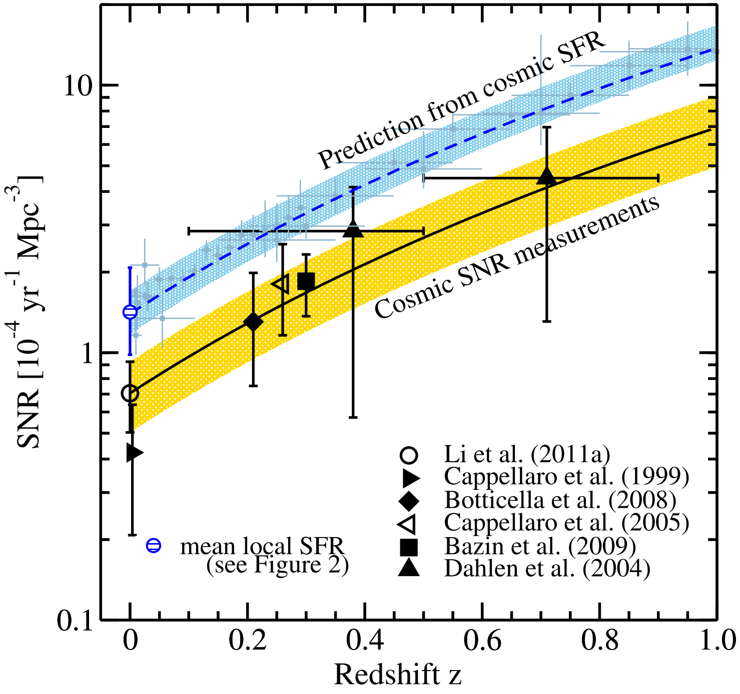
→ DSNB observation would contribute to our understanding of SN mechanism and star formation

Supernova rate

- Lifetime of a massive star occurring supernova is short enough compared to the time scale of the evolution of the universe
  → Star formation and supernova can be approximated as the same time
  → Should be possible to predict the supernova rate from the star formation rate

- Rate obtained from optical observations is about half of that predicted from the star formation rate
  → Dark supernovae?
  Is there light-blocking material?

- Can understand the star formation rate, supernova rate, and supernova mechanism from DSNB energy spectra



Thermal neutron capture cross sections

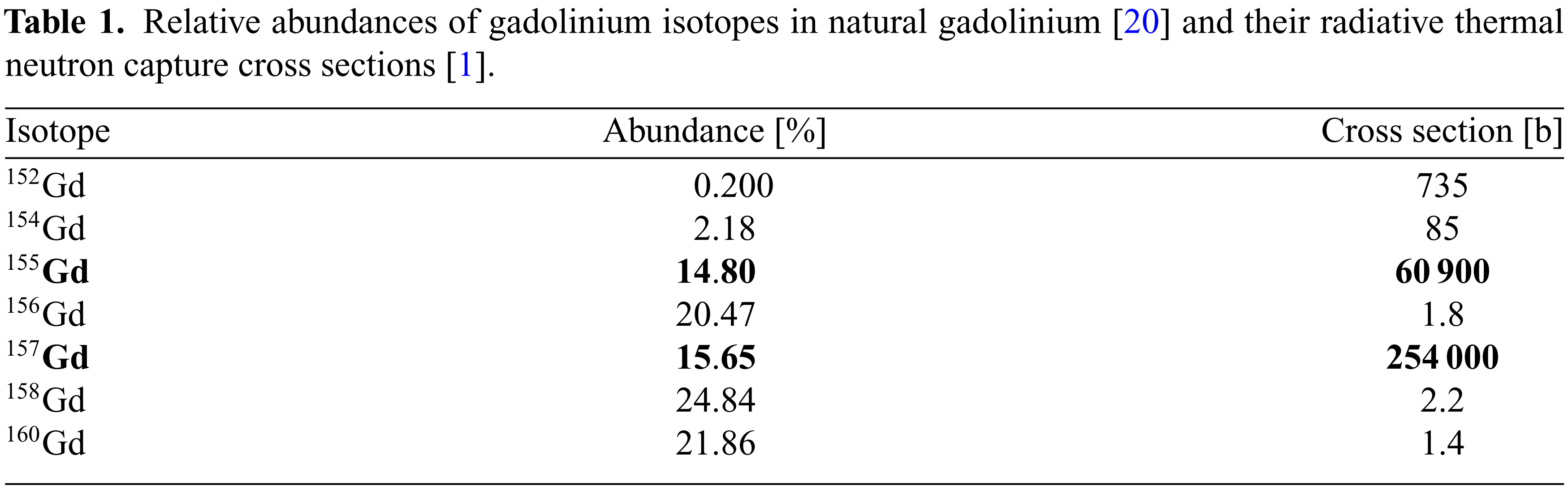
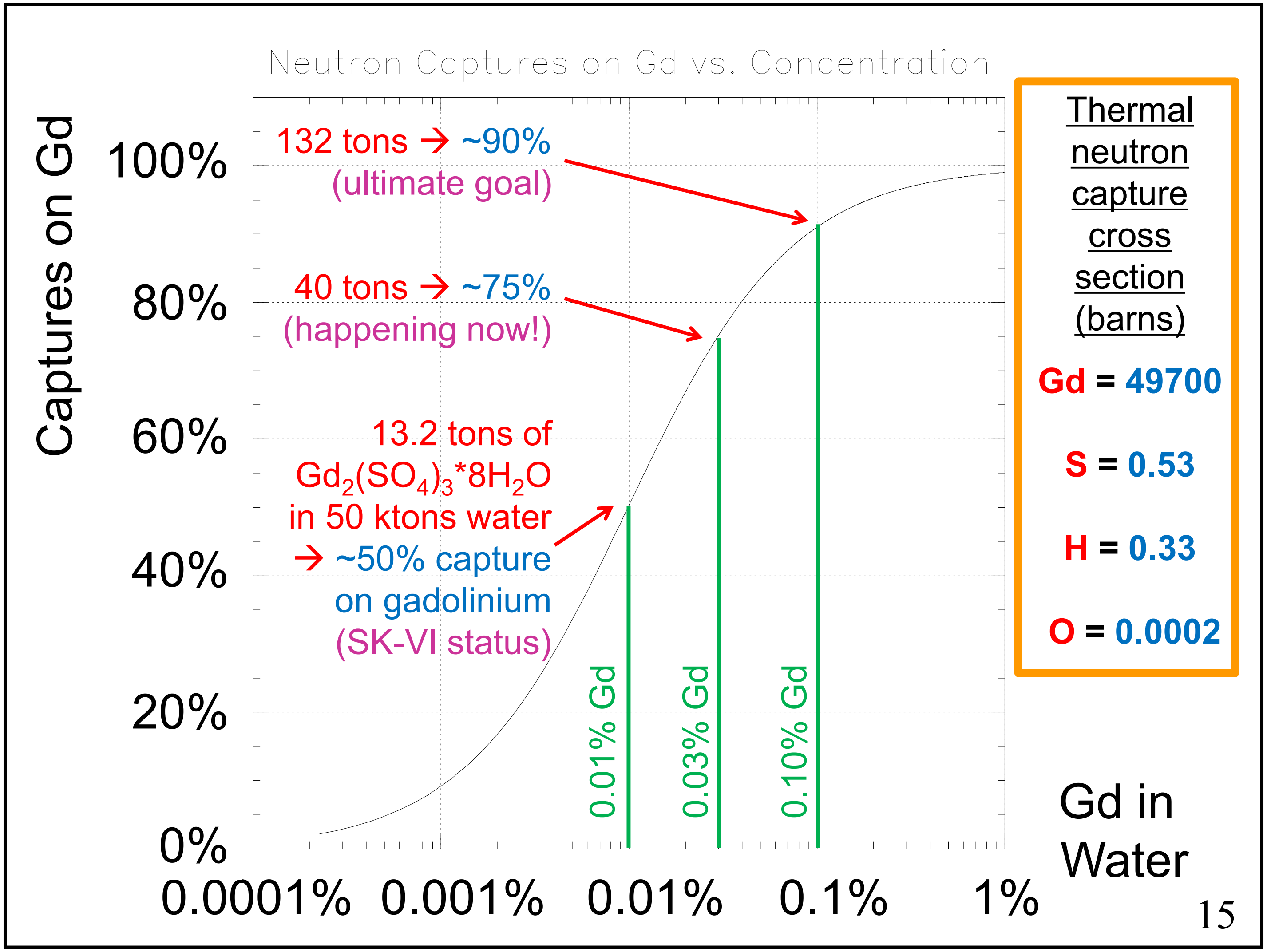


Table 1. Relative abundances of gadolinium isotopes in natural gadolinium [20] and their radiative thermal neutron capture cross sections [1].

Isotope	Abundance [%]	Cross section [b]
^{152}Gd	0.200	735
^{154}Gd	2.18	85
^{155}**Gd**	**14.80**	**60 900**
^{156}Gd	20.47	1.8
^{157}**Gd**	**15.65**	**254 000**
^{158}Gd	24.84	2.2
^{160}Gd	21.86	1.4

Neutron capture rate



132 tons → ~90% (ultimate goal)

40 tons → ~75% (happening now!)

13.2 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$ in 50 ktons water → ~50% capture on gadolinium (SK-VI status)

Thermal neutron capture cross section (barns)

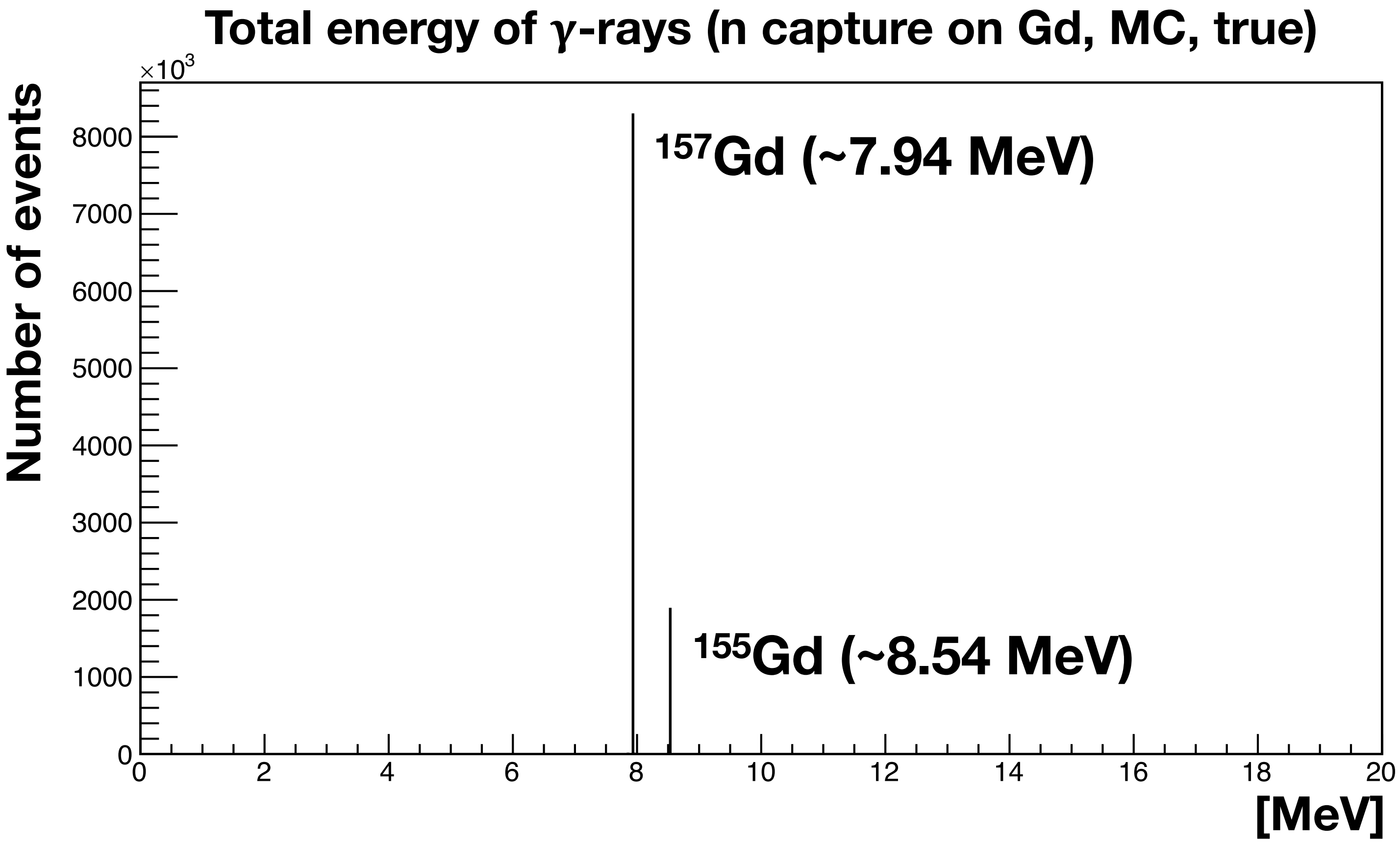
Gd = 49700

S = 0.53

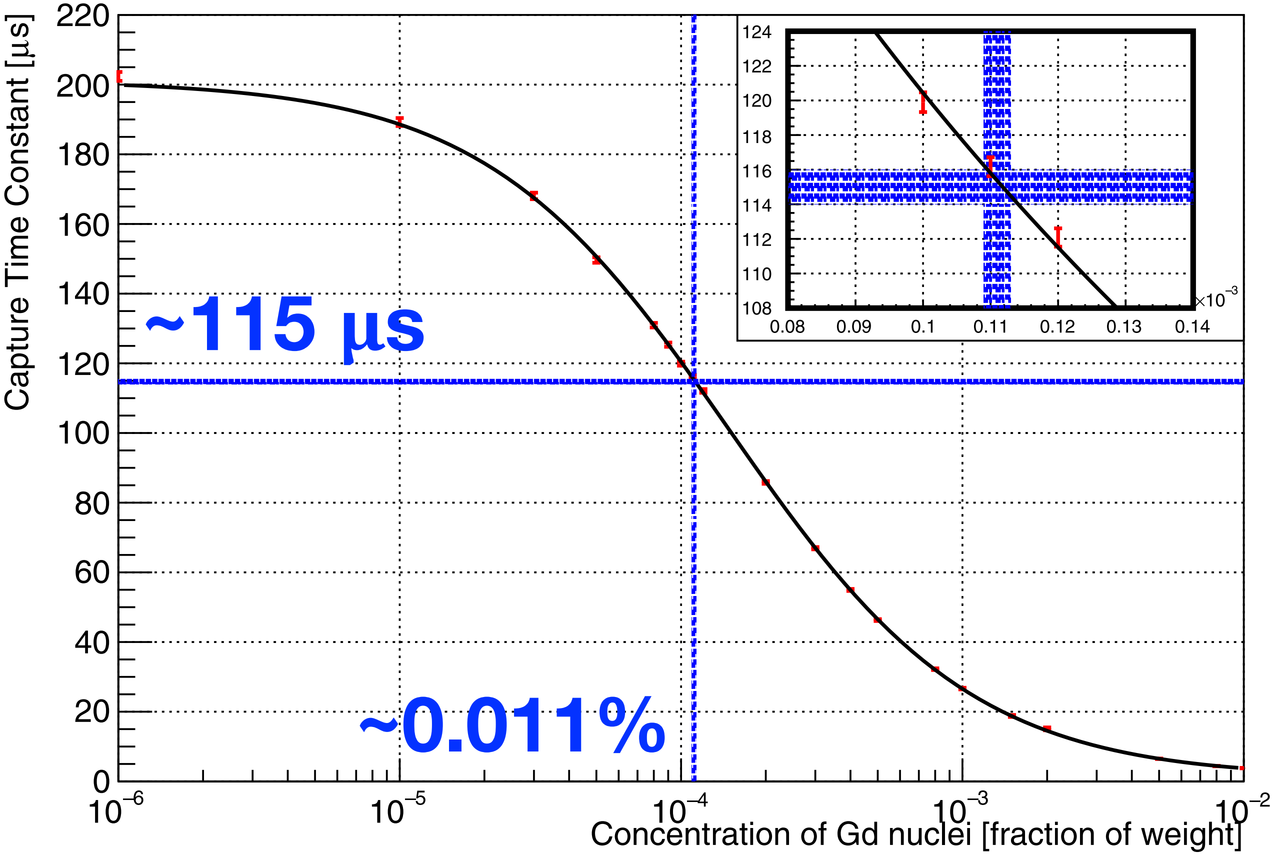
H = 0.33

O = 0.0002

Total energy of gamma rays



Neutron capture time constant

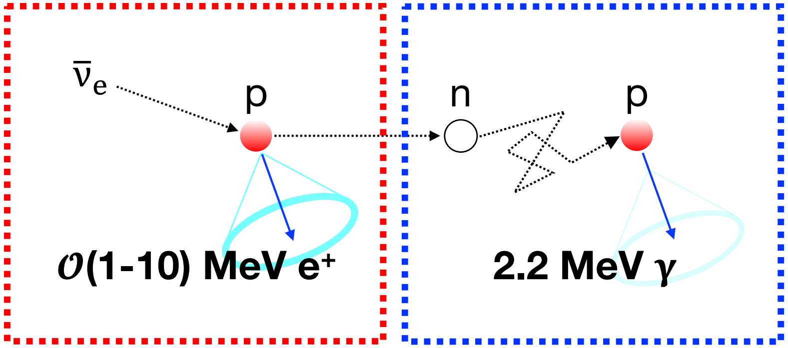


~115 µs

~0.011%

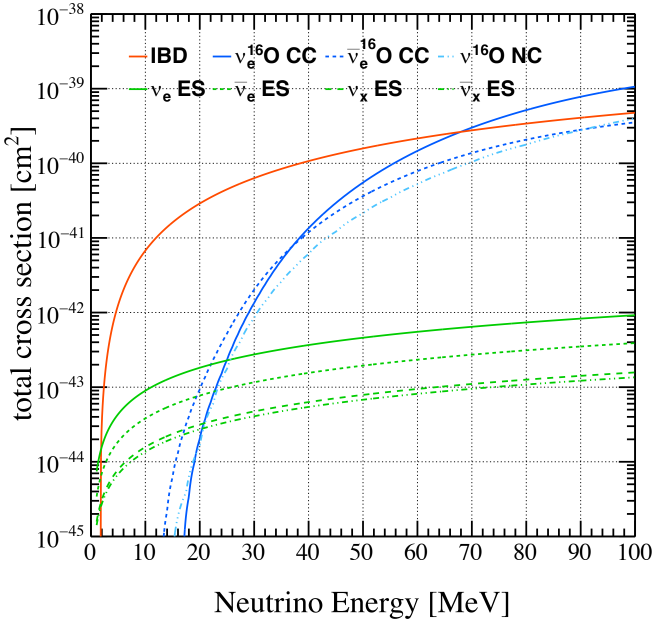
DSNB search in SK experiment

- Search for the inverse beta decay by electron antineutrinos ($\bar{\nu}_e + p \rightarrow e^+ + n$)
  - → Cross section is 1-2 orders of magnitude larger than others at < 30 MeV
- Detect positron (prompt signal) and neutron (delayed signal) pairs
  - → Can remove backgrounds without neutrons
- So far, delayed signal was 2.2 MeV gamma ray by neutron capture on proton
  - → Neutron detection efficiency was low (~20%)

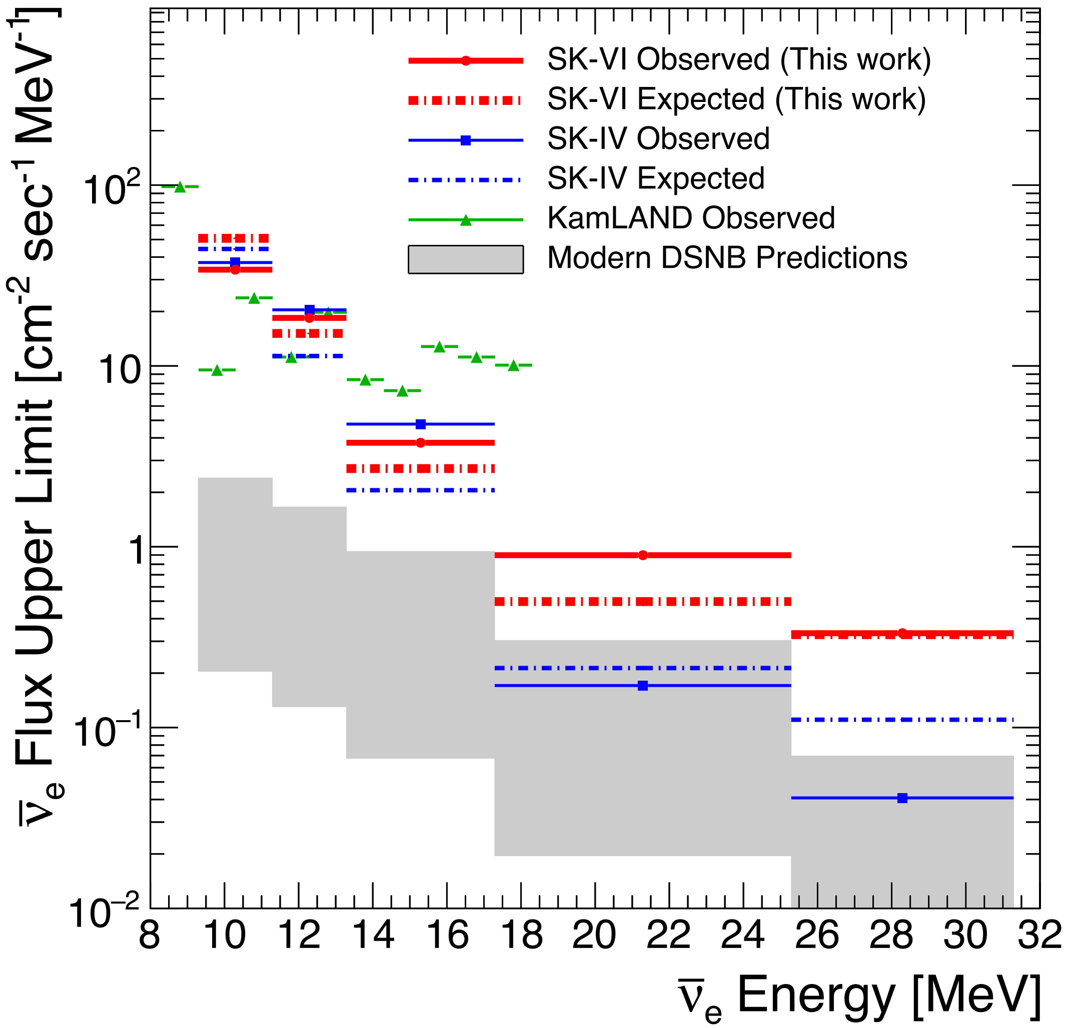


Prompt signal → **Delayed signal**

~200 μsec



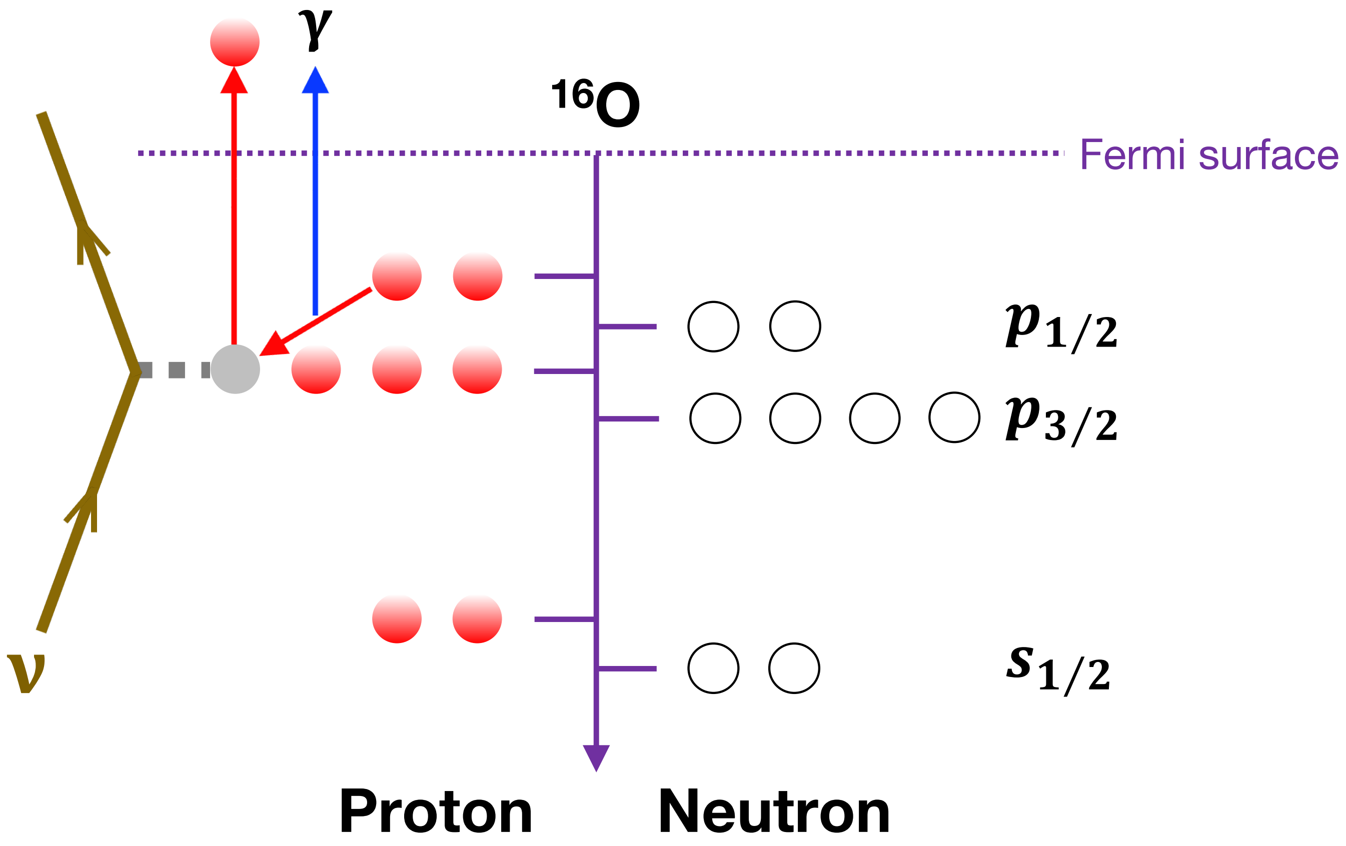
DSNB flux upper limits



NCQE reaction

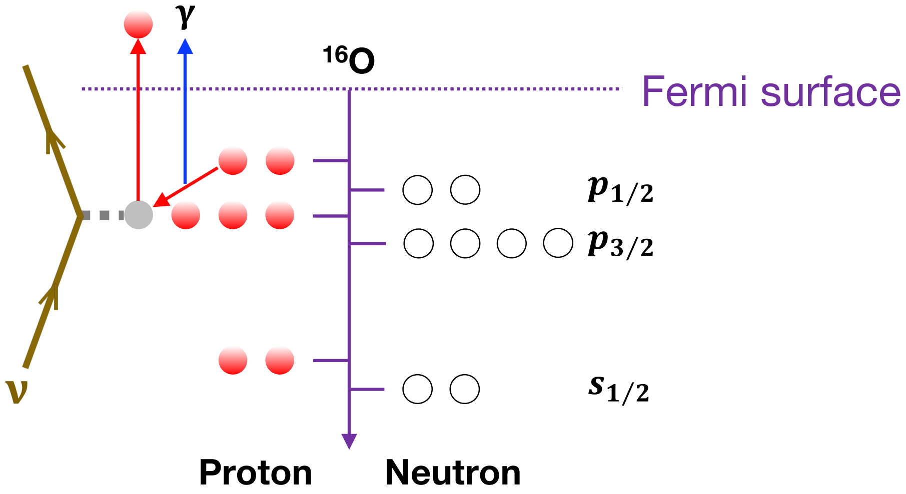
- Neutral-current quasielastic scattering (NCQE) reaction

  → Neutrino ($\mathcal{O}(10^2)$ - $\mathcal{O}(10^4)$ MeV) knocks out a nucleon in a nucleus



NCQE reaction on oxygen

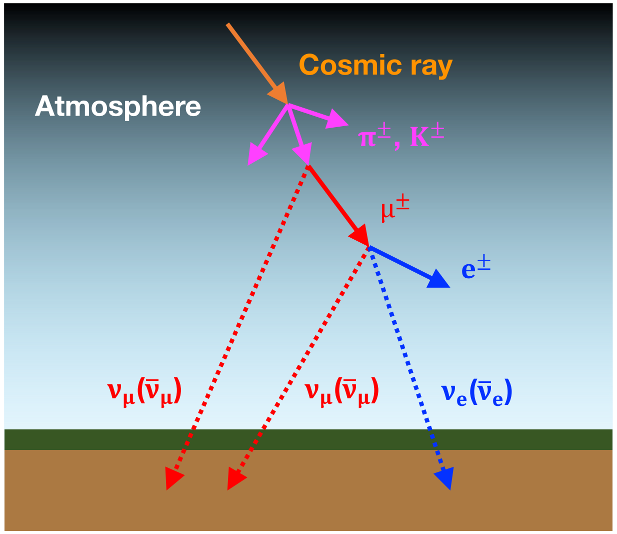
- ^{16}O has three states ($p_{1/2}$, $p_{3/2}$, and $s_{1/2}$)
- $p_{1/2}$ state is knocked out
  - → Residual nucleus: ^{15}N or ^{15}O (ground state)
  - → No particle is generated
- $p_{3/2}$ or $s_{1/2}$ state is knocked out
  - → Residual nucleus: ^{15}N or ^{15}O (excited state)
  - → Gamma rays and nucleons are generated

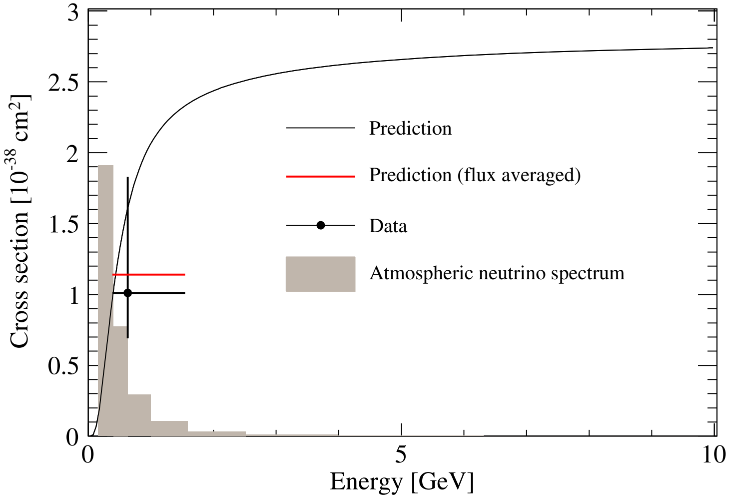


NCQE cross section measurement in SK

- Measured NCQE cross section using atmospheric neutrinos

→ $\langle\sigma^{\text{measured}}_{\text{NCQE}}\rangle = 1.01 \pm 0.17(\text{stat.})^{+0.78}_{-0.30}(\text{syst.}) \times 10^{-38}\ \text{cm}^2/\text{oxygen}^*$





- Only one secondary interaction model was available
- Delayed signal: 2.2 MeV gamma ray by neutron capture on proton

→ Neutron detection efficiency was low (~20%)

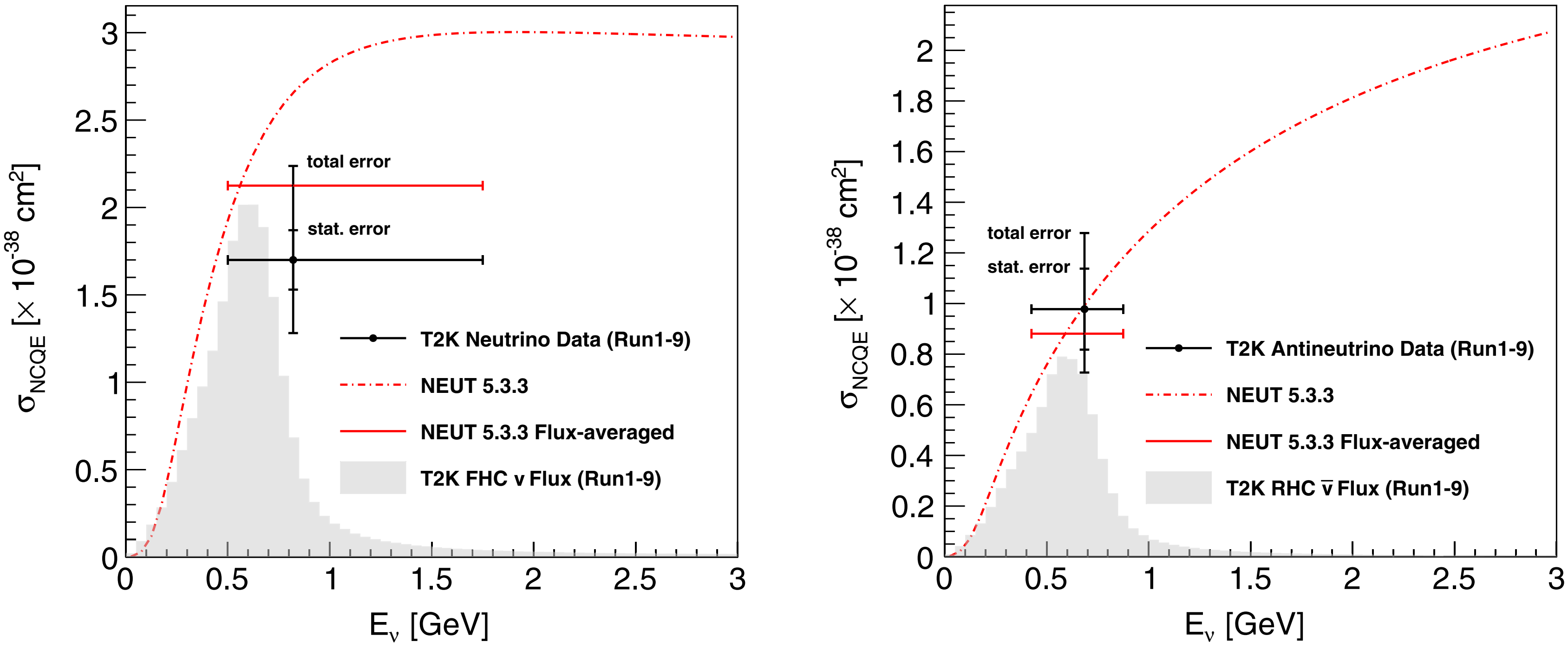
* L. Wan *et al*. (SK Collaboration), Phys. Rev. D **99**, 032005 (2019)

NCQE cross section measurement in T2K

- Measured NCQE cross section using accelerator neutrinos

$$\rightarrow \langle \sigma_{\nu-\mathrm{NCQE}}^{\mathrm{measured}} \rangle = 1.70 \pm 0.17(\mathrm{stat.})^{+0.51}_{-0.38}(\mathrm{syst.}) \times 10^{-38}\ \mathrm{cm}^2/\mathrm{oxygen}^*$$

$$\rightarrow \langle \sigma_{\bar{\nu}-\mathrm{NCQE}}^{\mathrm{measured}} \rangle = 0.98 \pm 0.16(\mathrm{stat.})^{+0.26}_{-0.19}(\mathrm{syst.}) \times 10^{-38}\ \mathrm{cm}^2/\mathrm{oxygen}^*$$



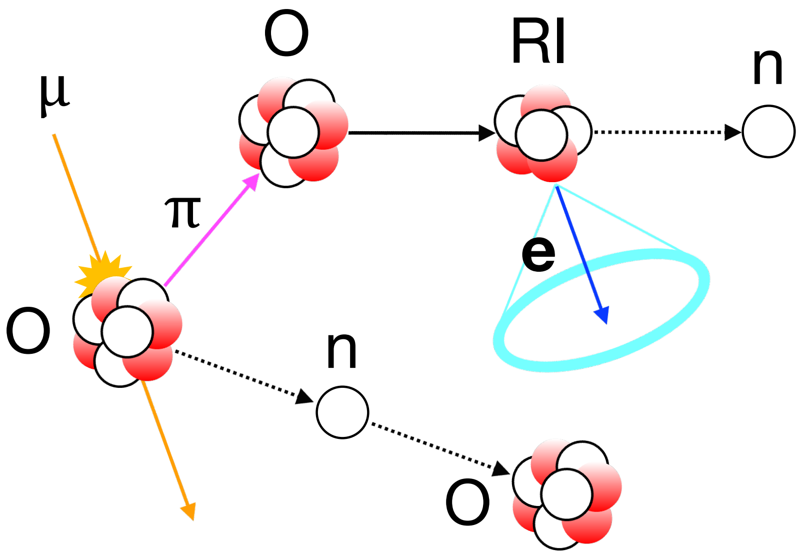
* K. Abe *et al*. (T2K Collaboration), Phys. Rev. D **100**, 112009 (2019)

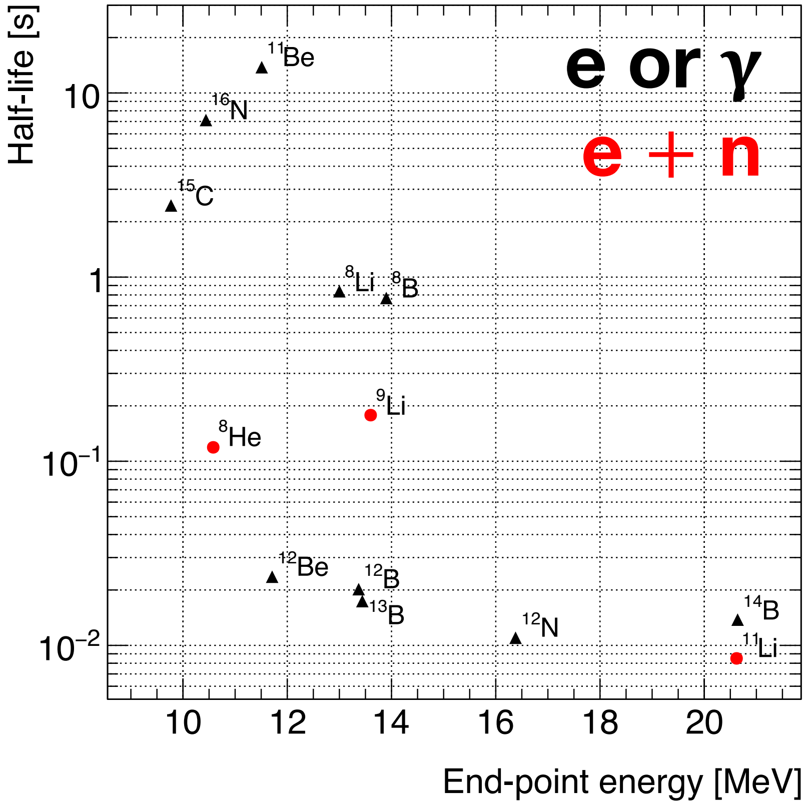
Backgrounds

Decays of radioactive isotopes by muon nuclear spallation (Spallation events)

- Lithium-9 (^{9}Li)

  → High rate and long half-life





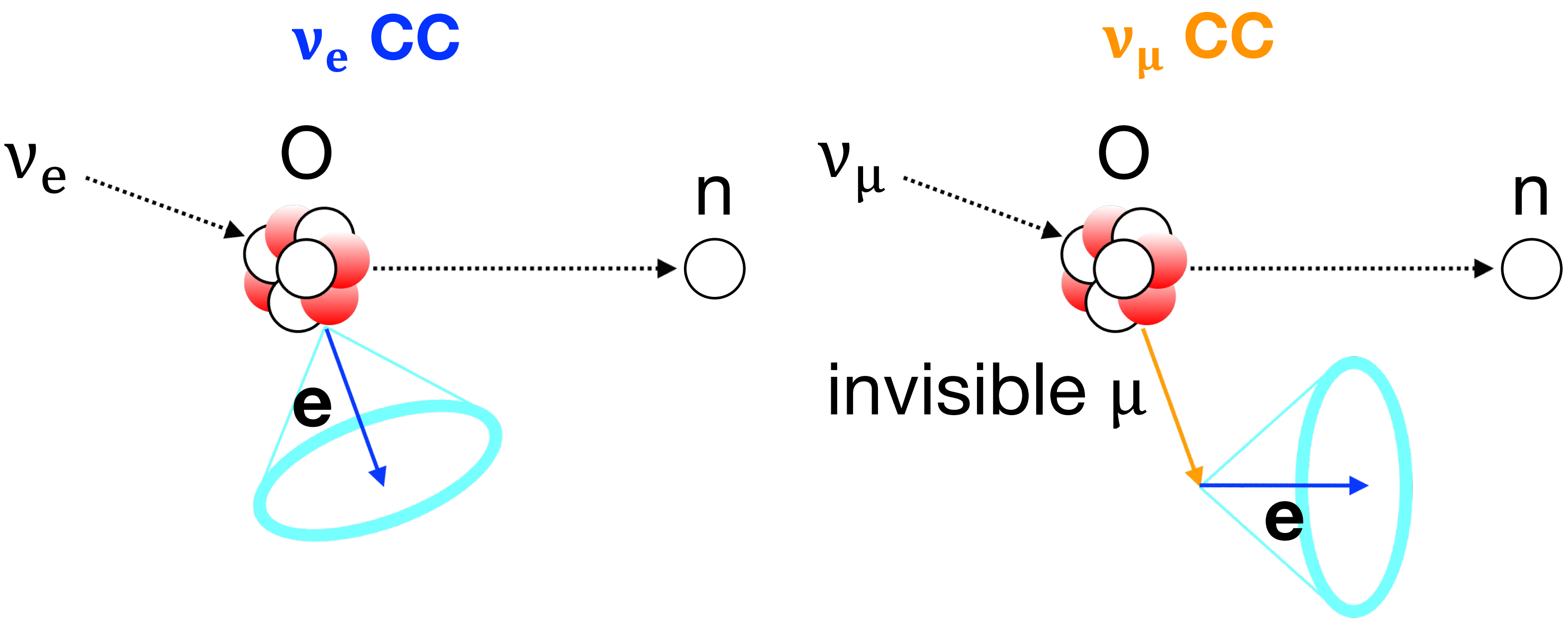
Backgrounds

Atmospheric neutrino charged-current (CC) reactions (CC events)

- Electron or muon (prompt signal) and neutron (delayed signal) are generated
- Muon energy is below Cherenkov threshold

  → Decay electron is generated

  → Electron-neutron pair

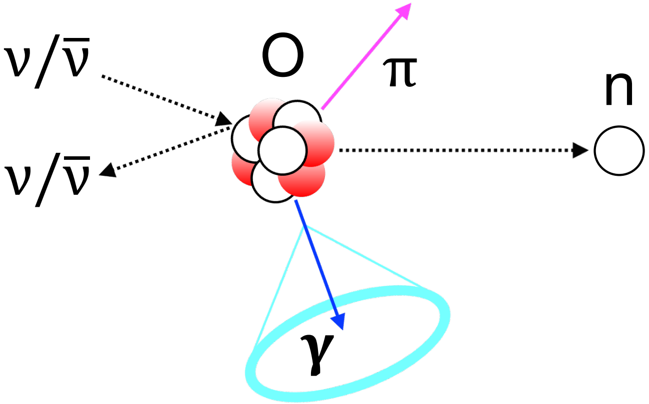


Backgrounds

Atmospheric neutrino NC single meson production

- Similar to NCQE events

→ Remains a lot even after event selection

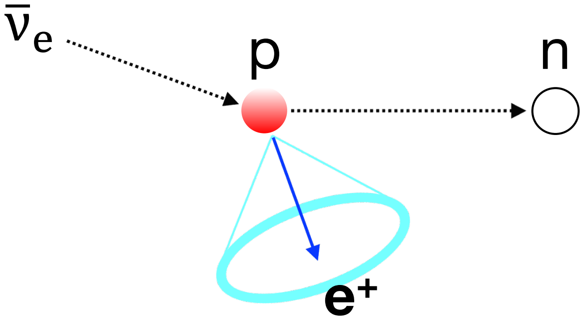


Reactor neutrinos (Reactor events)

- IBD same as DSNB
- Low energy and little effect on this analysis

Accidental events

- Accidentally electron-neutron pair is formed
- Mostly nuclear spallation events without neutrons and neutron misidentification events



Number of events

- 38 events remained after event selection
- $N_{\mathrm{NCQE}}^{\mathrm{exp}}$ is different largely among secondary interaction models

	BERT	BIC	INCL++
N^{obs}	38		
$N_{\mathrm{NCQE}}^{\mathrm{exp}}$	28.7	19.8	20.2
$N_{\mathrm{NC\ non-QE}}^{\mathrm{exp}}$	13.3	10.2	10.1
$N_{\mathrm{CC}}^{\mathrm{exp}}$	1.4	1.1	1.2
$N_{\mathrm{Spallation}}^{\mathrm{exp}}$	0.9	0.9	0.9
$N_{\mathrm{Reactor}}^{\mathrm{exp}}$	0.1	0.1	0.1
$N_{\mathrm{Accidental}}^{\mathrm{exp}}$	1.6	1.6	1.6

Systematic uncertainties

- $N^{\mathrm{exp}}_{\mathrm{spallation}}$: 60.0% ← From DSNB analysis
- $N^{\mathrm{exp}}_{\mathrm{Reactor}}$: 100.0% ← From DSNB analysis
- $N^{\mathrm{exp}}_{\mathrm{Accidental}} = \epsilon_{\mathrm{mis}} \times N^{\mathrm{obs}}_{\mathrm{pre-ntag}}$: 4.6% ← From systematic uncertainty of ϵ_{mis} and statistical uncertainty of $N^{\mathrm{obs}}_{\mathrm{pre-ntag}}$(= 5,447)

	$N^{\mathrm{exp}}_{\mathrm{CC}}$
Atmospheric neutrino flux	±18.0%
Atmospheric neutrino/antineutrino ratio	±5.0%
Cross section	±24.0%
Primary interaction	+1.2%/−8.0%
Secondary interaction	−20.7%
Energy cutoff	−19.9%
Data reduction	±1.4%
Neutron tagging	±6.4%

Systematic error of NCQE cross section

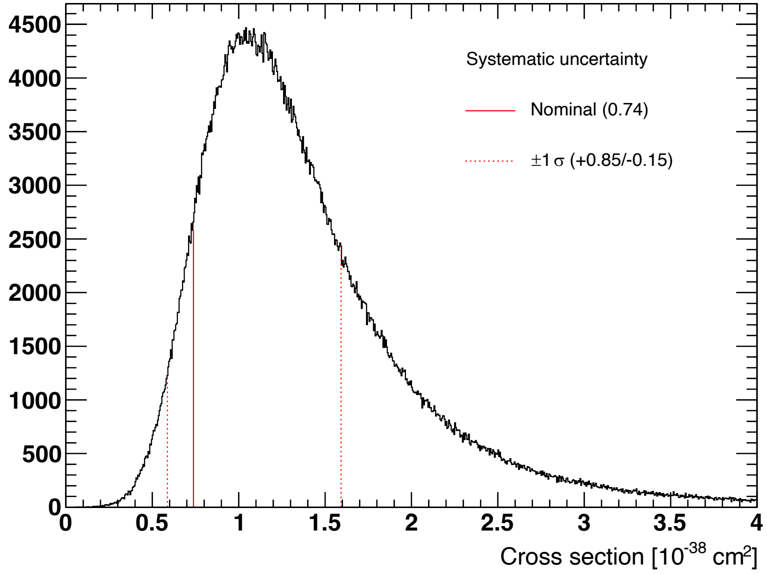
- Determine systematic uncertainty of

$$\left\langle\sigma_{\mathrm{NCQE}}^{\mathrm{measured}}\right\rangle = \frac{N^{\mathrm{obs}} - N_{\mathrm{NC\,non-QE}}^{\mathrm{exp}} - N_{\mathrm{Others}}^{\mathrm{exp}}}{N_{\mathrm{NCQE}}^{\mathrm{exp}}} \times \left\langle\sigma_{\mathrm{NCQE}}^{\mathrm{theory}}\right\rangle$$ using toy MC

1. Determine $N_{\mathrm{NCQE}}^{\mathrm{exp}}$, $N_{\mathrm{NC\,non-QE}}^{\mathrm{exp}}$, and $N_{\mathrm{Others}}^{\mathrm{exp}}$ according to each uncertainty
2. Calculate $\left\langle\sigma_{\mathrm{NCQE}}^{\mathrm{measured}}\right\rangle$ to plot
3. Repeat procedures above 1 million times
4. Range of 1σ from

   $$\left\langle\sigma_{\mathrm{NCQE}}^{\mathrm{measured}}\right\rangle = 0.74 \times 10^{-38}\ \mathrm{cm}^2/\mathrm{oxygen}$$

   is the systematic uncertainty



- $$\left\langle\sigma_{\mathrm{NCQE}}^{\mathrm{measured}}\right\rangle = 0.74 \pm 0.22(\mathrm{stat.})^{+0.85}_{-0.15}(\mathrm{syst.}) \times 10^{-38}\ \mathrm{cm}^2/\mathrm{oxygen}$$

Secondary interaction models

- GEANT3-based SK detector simulation was used in previous study*
- Geant4-based SK detector simulation was developed

→ Can compare various secondary interaction models

Bertini Cascade Model (BERT, SK official model)

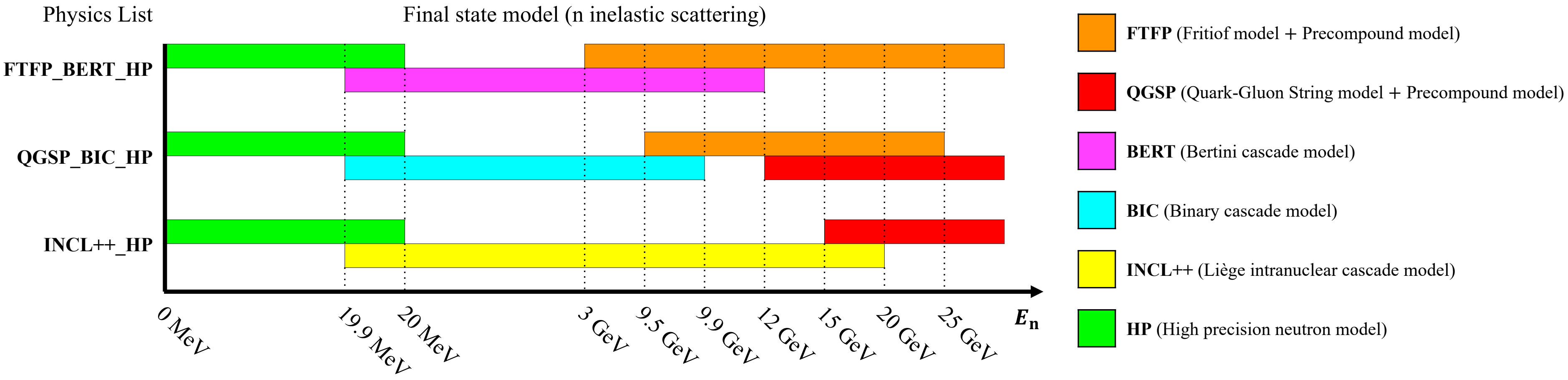
Binary Cascade Model (BIC)

Liège Intranuclear Cascade Model (INCL++)

	Previous study*	This study
SK detector simulation	GEANT3-based	Geant4-based
BERT (SK official model)	○	○
BIC	×	○
INCL++	×	○

* L. Wan *et al*. (SK Collaboration), Phys. Rev. D **99**, 032005 (2019)

Secondary interaction models



Differences

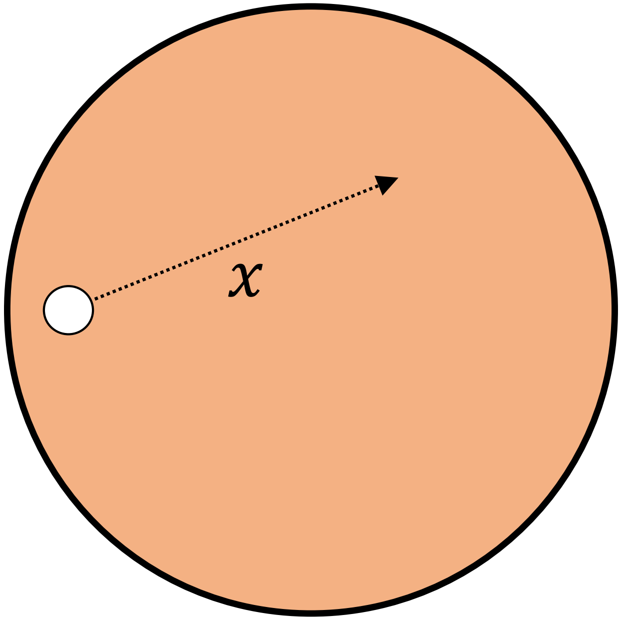
- Reaction point with nucleons in the nucleus

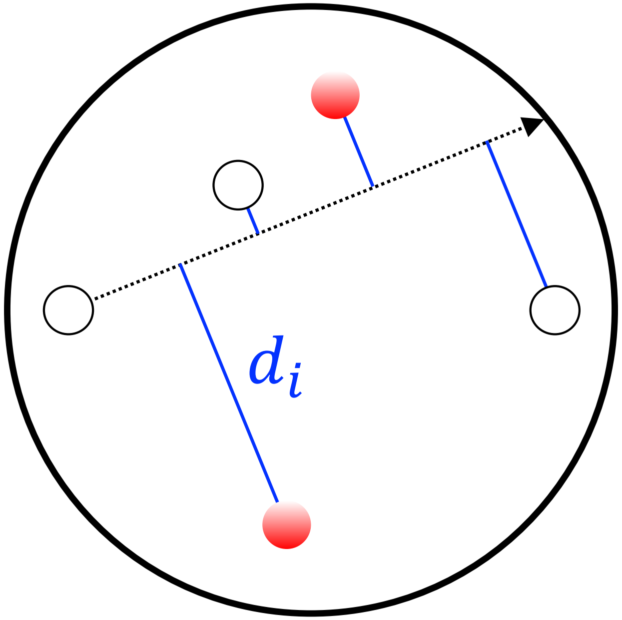
  BERT → Determined using mean free path

  BIC, INCL++ → Determined using closest approach distance

$$x = -\frac{1}{\rho\sigma}\ln\xi$$

$$d_i < \sqrt{\frac{\sigma_i}{\pi}}$$





Differences

- Stopping time of intranuclear cascade process

  BERT, BIC → Stop when all (escapable) particles escape the nucleus

  INCL++ → Forced to stop at the following time (t_{stop})

$$t_{\mathrm{stop}} = 70\ \mathrm{fm}/c \times \left(\frac{A}{208}\right)^{0.16}$$

- Nuclear model (nucleon density)

  BERT → Change discretely with distance from center of the nucleus

  BIC, INCL++ → Change smoothly with distance from center of the nucleus

- Condition for termination of the evaporation process

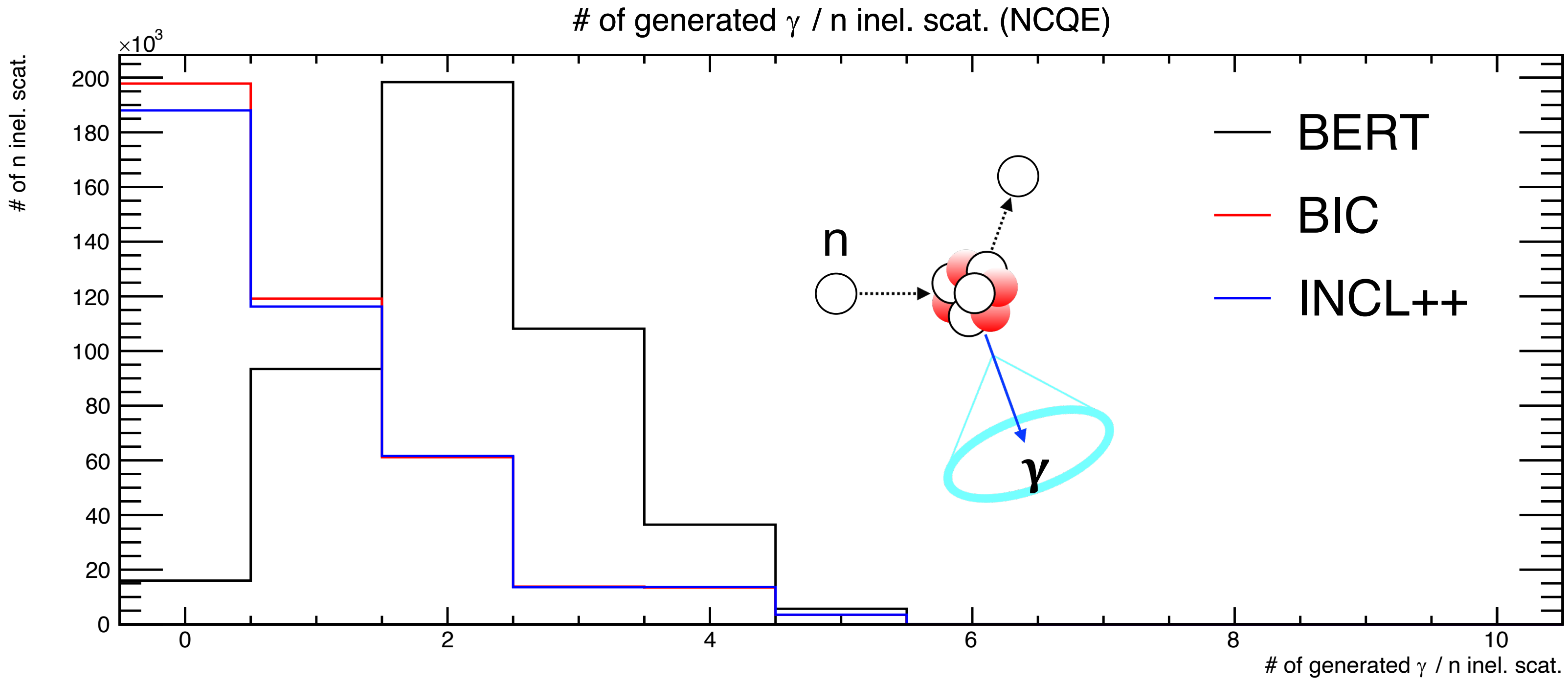
  BERT → End when excitation energy falls below 10^{-15} MeV

  BIC, INCL++ → End after continuous and discrete transitions

Number of gamma rays

- In BERT, the number of gamma rays per neutron inelastic scattering is large
- BIC and INCL++ show similar tendency

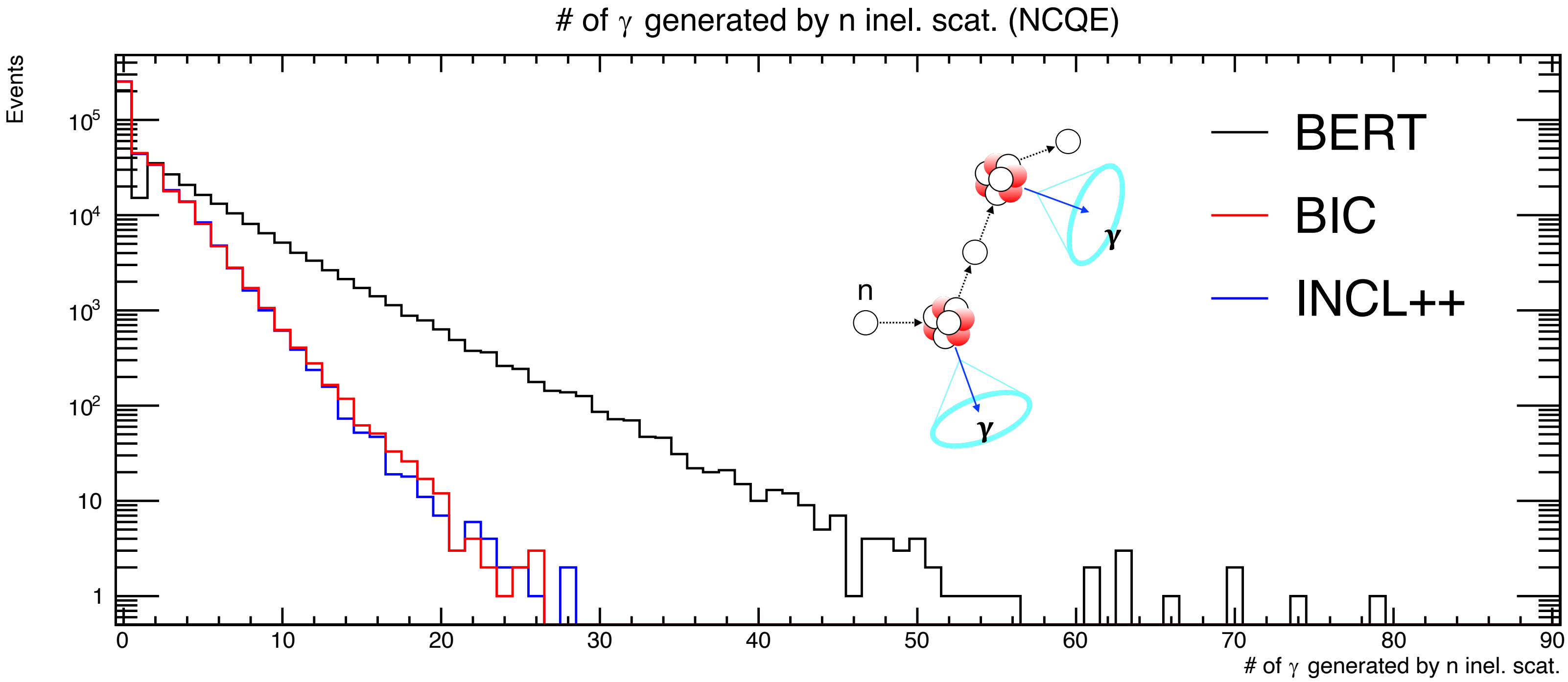
	Per neutron inelastic scattering
BERT	2.16
BIC	0.87
INCL++	0.89



Number of gamma rays

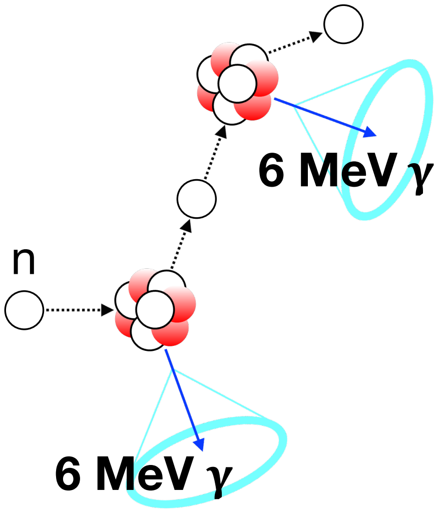
- In BERT, the number of gamma rays by neutron inelastic scattering per event is large
- BIC and INCL++ show similar tendency

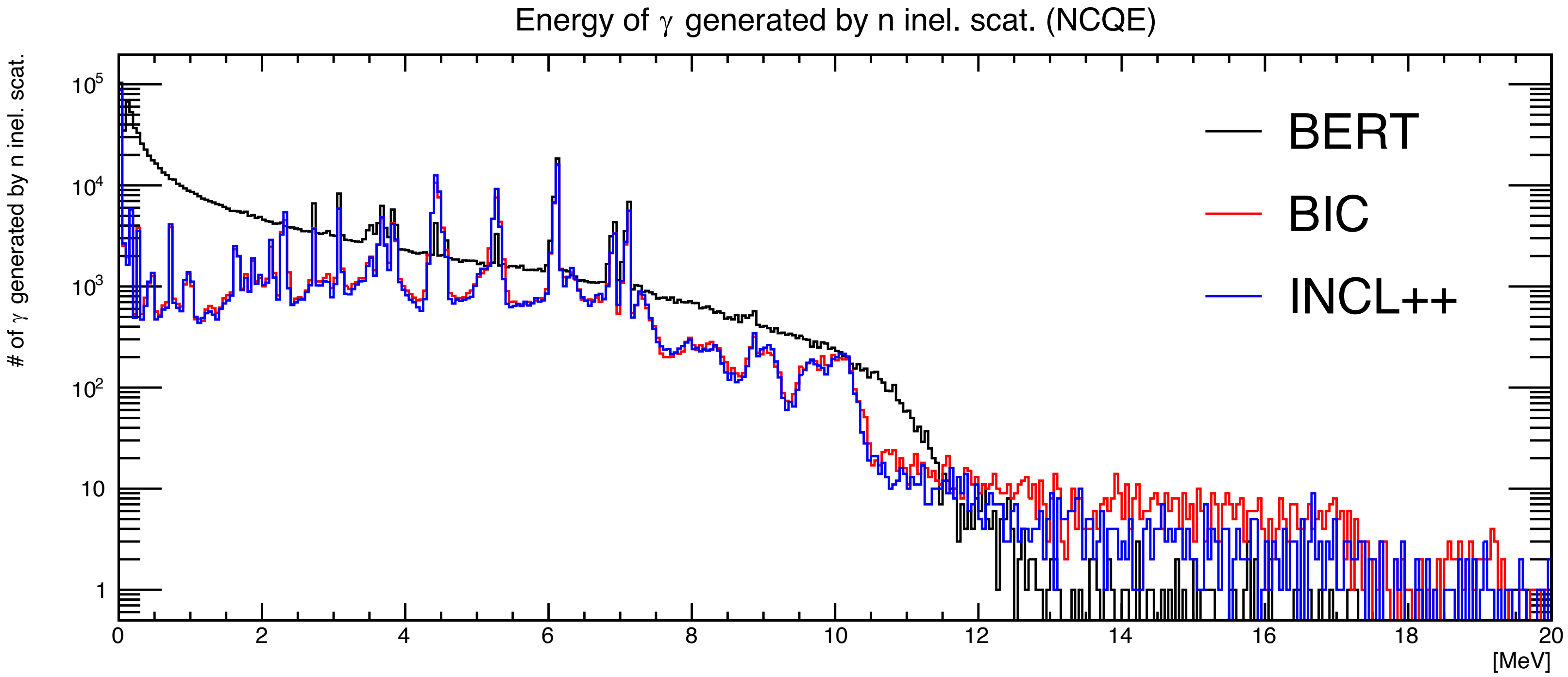
	Per event
BERT	2.58
BIC	0.93
INCL++	0.92



Energy of gamma rays

- In BERT, there are many continuous components in addition to peaks of deexcitation gamma rays
- BIC and INCL++ show similar tendency

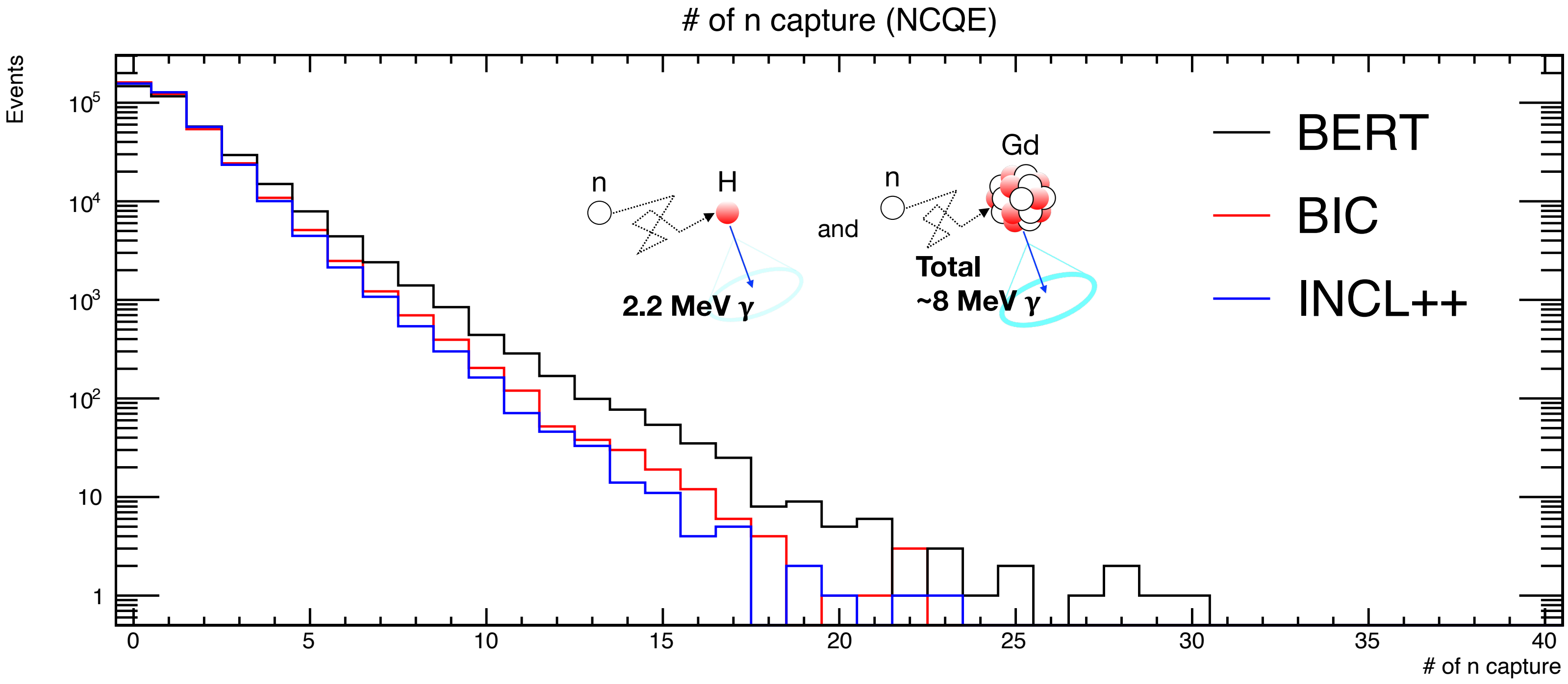




Number of neutron captures

- In BERT, the number of neutron captures per event is large
- BIC and INCL++ show similar tendency

	Per event
BERT	1.29
BIC	1.07
INCL++	1.06

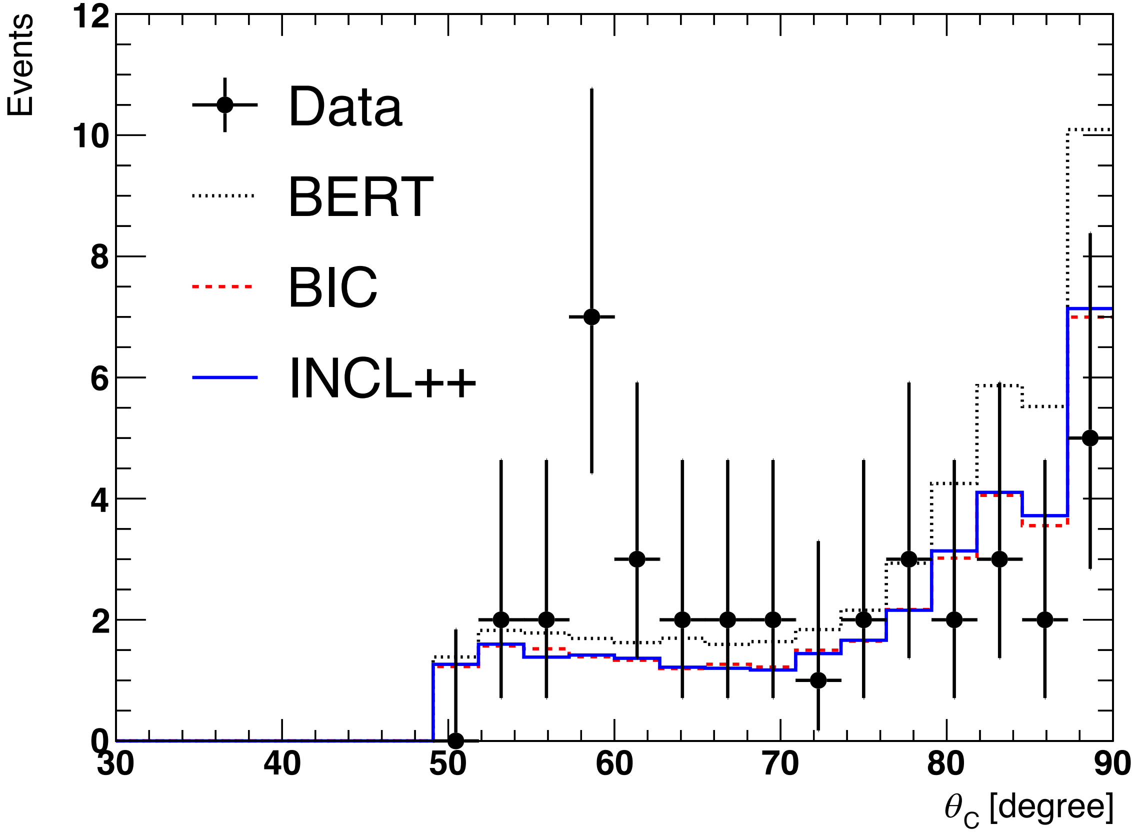


Cherenkov angle of prompt signal

- What is the peak around 60 degrees?

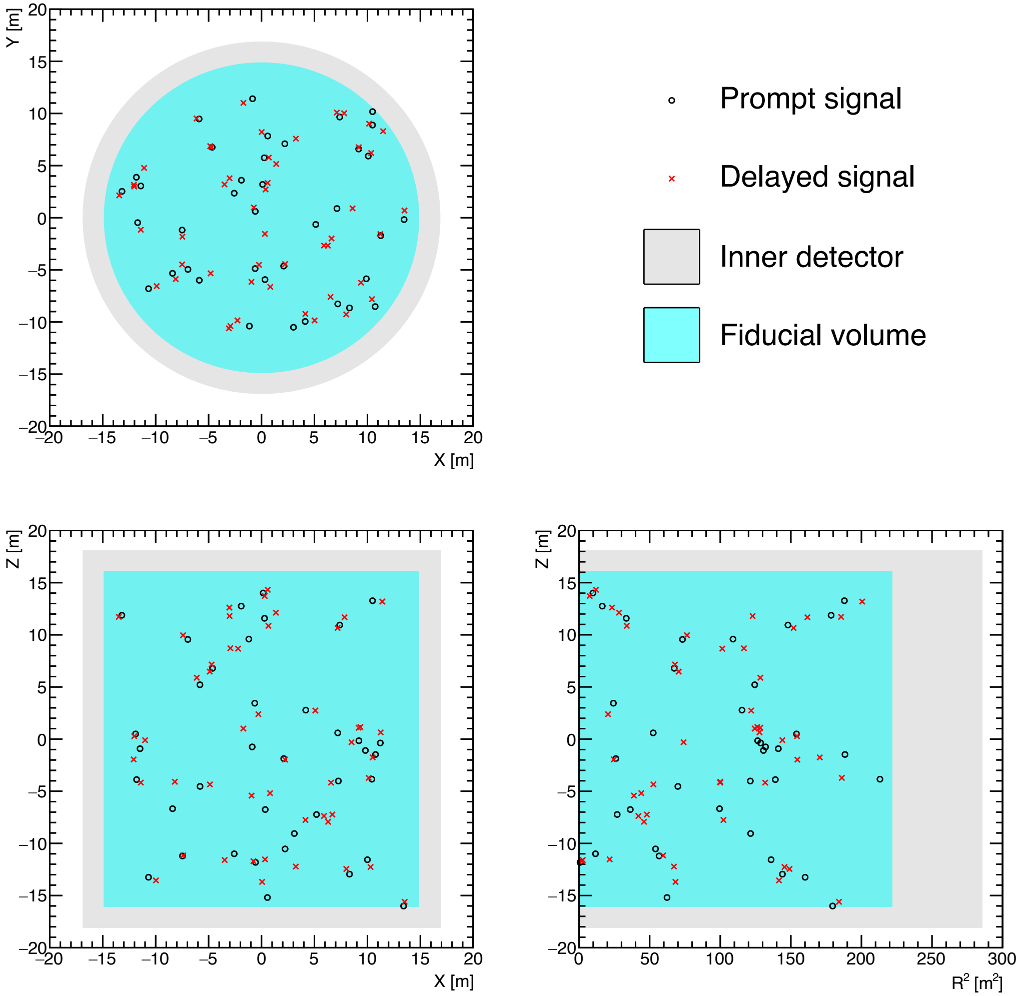
  → No problem in reconstructed vertex and other variables

  → Concluded that it was a statistical fluctuation



Reconstructed vertex

- Events are uniformly distributed



χ^2

- Calculate χ^2 using Poisson likelihood

$$\chi^2 = 2\sum_{i=1}^{\text{bin}}\left(N^{\text{exp},\,i} - N^{\text{obs},\,i} + N^{\text{obs},\,i}\ln\frac{N^{\text{obs},\,i}}{N^{\text{exp},\,i}}\right)$$

N^{obs} : The observed number of events

N^{exp} : The expected number of events

→ Not conclusive due to small statistics

→ χ^2 in BIC and INCL++ is smaller than that in BERT in all distributions

	$\chi^2/\text{ndf}\ (\theta_{\text{C}})$	$\chi^2/\text{ndf}\ (E_{\text{vis}})$	$\chi^2/\text{ndf}\ (N_{\text{delayed}})$
BERT	23.0 / 15	9.8 / 11	5.8 / 5
BIC	19.6 / 15	6.9 / 11	3.1 / 5
INCL++	19.8 / 15	6.8 / 11	2.8 / 5

χ^2/ndf

- p-value is larger (model is closer to data) as χ^2/ndf is smaller

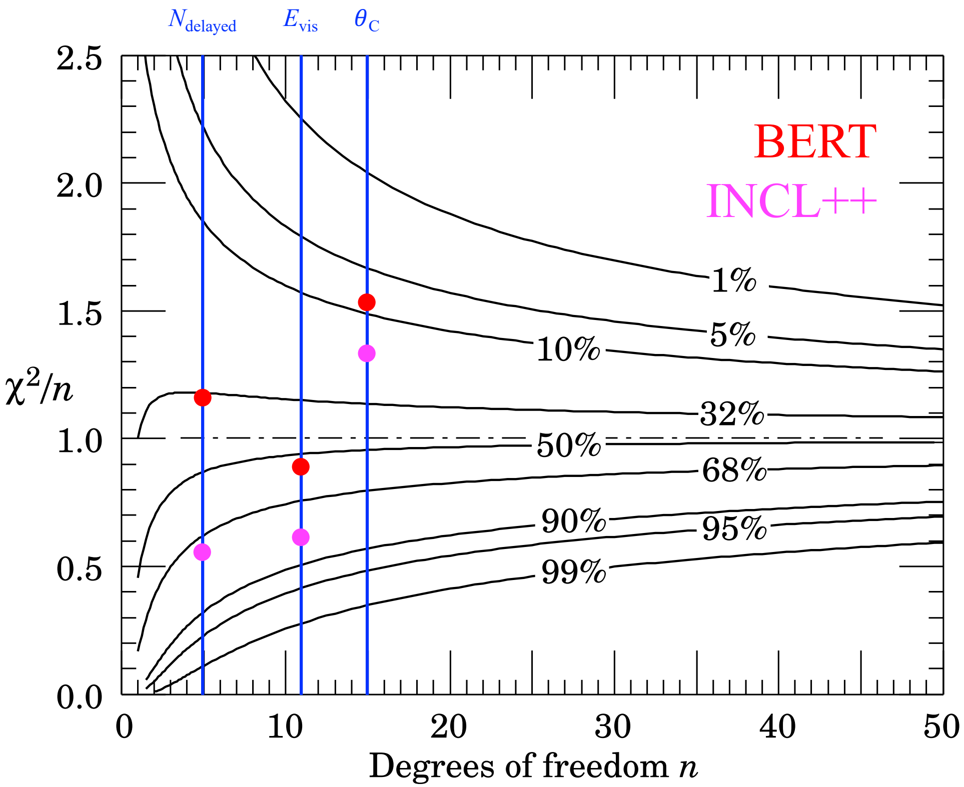
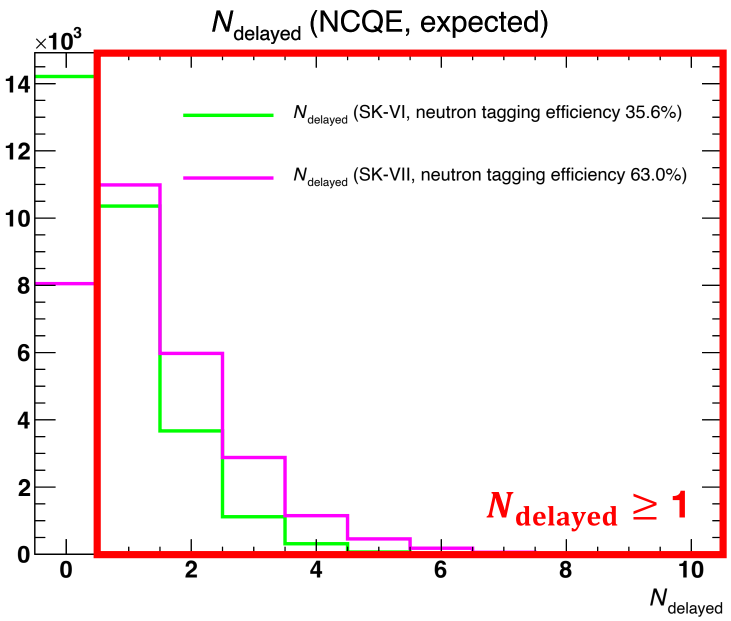


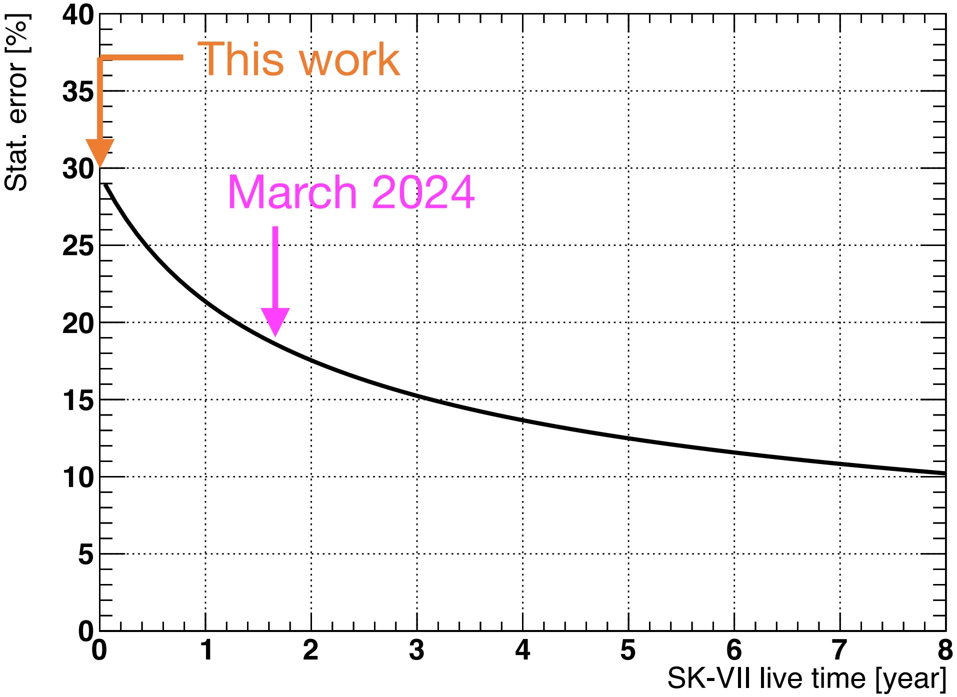
Figure 40.2: The 'reduced' χ^2, equal to χ^2/n, for n degrees of freedom. The curves show as a function of n the χ^2/n that corresponds to a given p-value.

Statistics

- SK continues to observe at 0.03% Gd mass concentration (SK-VII)
- Neutron tagging efficiency improved from 35.6% (Gd: 0.011%, SK-VI) to 63.0% (Gd: 0.03%, SK-VII)

  → Statistics increases by about 1.4 times with the same live time





References

1 S. Sakai *et al*., Phys. Rev. D **109**, L011101 (2024)

2 J. F. Beacom and M. R. Vagins, Phys. Rev. Lett. **93**, 171101 (2004)

3 Y. Koshio, “The supernovae neutrino detection in Super- and Hyper-Kamiokande”, LPNHE, Paris, France (2023)

4 M. Harada *et al*., Astrophys. J. Lett. **951**, L27 (2023)

5 M. Harada, “Development of Neutron Tagging Algorithm and Search for Supernova Relic Neutrino in SK-Gd Experiment”, Ph.D. Thesis, Okayama University (2023)

6 A. M. Ankowski *et al*., Phys. Rev. Lett. **108**, 052505 (2012)

7 E. Richard *et al.*, Phys. Rev. D **94**, 052001 (2016)

8 Super-Kamiokande, “Gallery”

9 S. Ando, Astrophys. J. **607**, 20 (2004)

10 K. Abe *et al*., Phys. Rev. D **104**, 122002 (2021)

References

11 S. Horiuchi *et al*., Astrophys. J. **738**, 154 (2011)

12 T. Tanaka *et al*., Prog. Theor. Exp. Phys. **2020**, 043D02 (2020)

13 M. Vagins, “A Gadolinium-loaded Super-Kamiokande”, Neutrino 2022 (2022)

14 K. Abe *et al*., Nucl. Instrum. Methods Phys. Res., Sect. A **1027**, 166248 (2022)

15 F. Nakanishi, “Developing a novel analysis method for supernova neutrino observations in Super-Kamiokande”, Master’s Thesis, Okayama University (2023)

16 L. Wan *et al*., Phys. Rev. D **99**, 032005 (2019)

17 K. Abe *et al*., Phys. Rev. D **100**, 112009 (2019)

18 R. L. Workman *et al*., Prog. Theor. Exp. Phys. **2022**, 083C01 (2022)