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

SK-Gd実験における大気ニュートリノデータを用いたニュートリノ-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

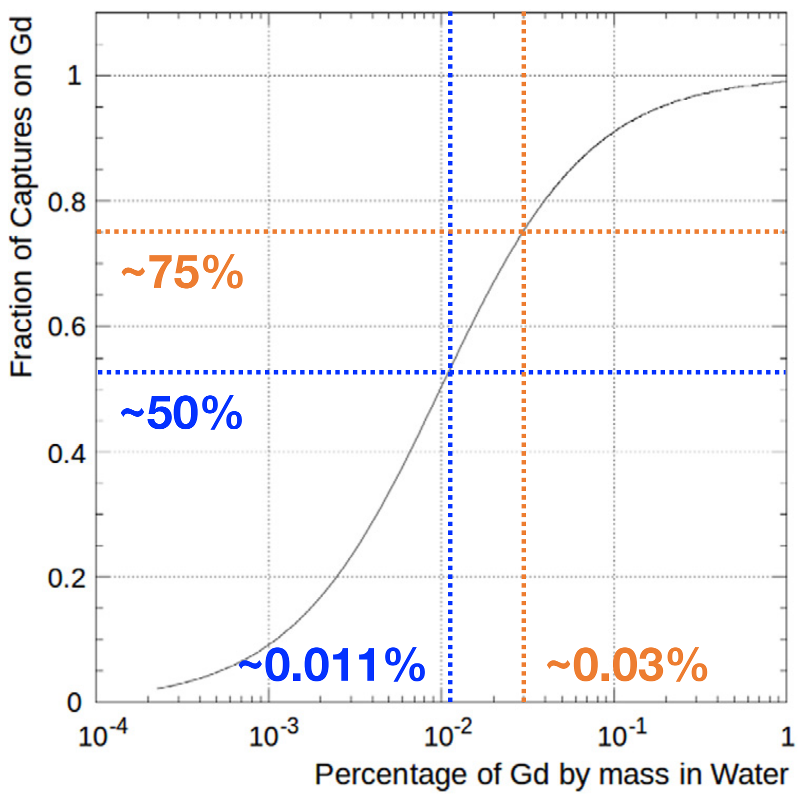
Seiya Sakai (RIKEN)

Mar. 11th, 2025

FY2024 1st CRC Town Meeting

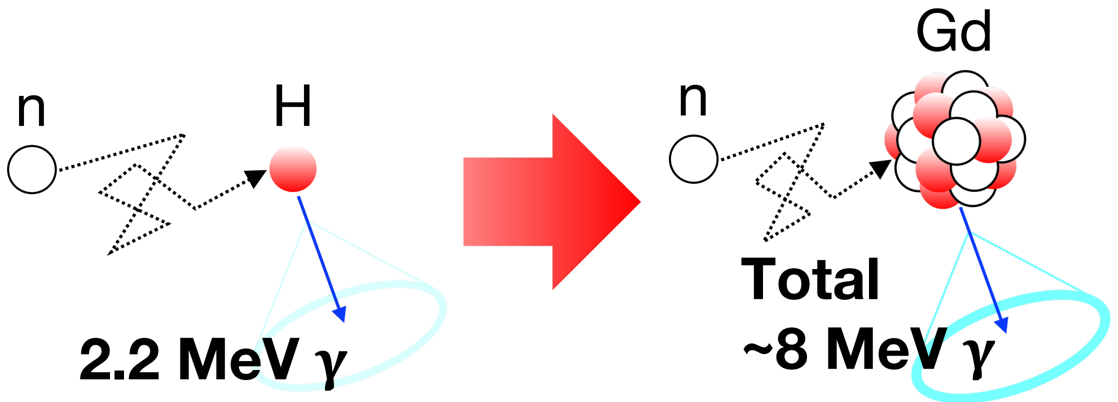
SK-Gd experiment

- In Jul. 2020, 0.011% by mass of Gd was loaded in SK
  → SK-Gd experiment started[1]
- Since Jul. 2022, 0.03% by mass of Gd has been loaded in SK



- Why Gd?
  - Largest thermal neutron capture cross section among natural elements
  - Emit a total of ~8 MeV of gamma rays
    → Neutron tagging efficiency is largely improved

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

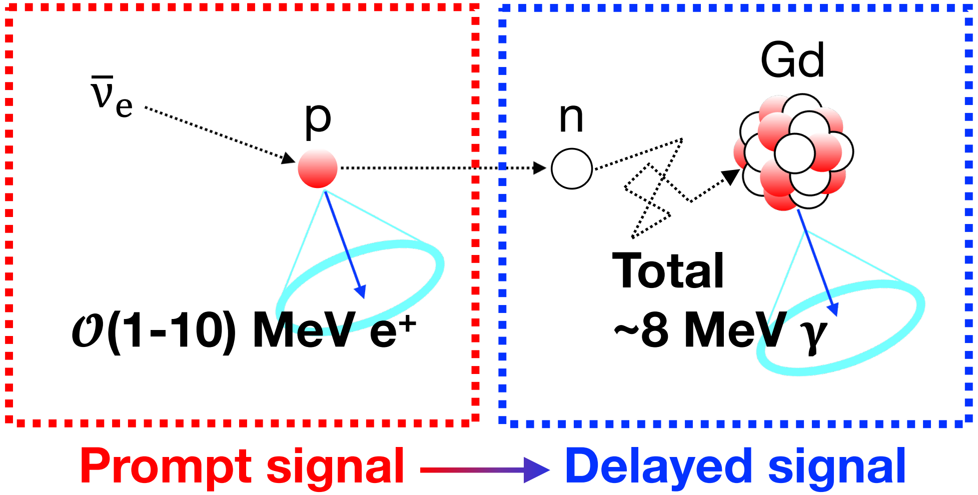


[1] J. F. Beacom and M. R. Vagins, Phys. Rev. Lett. **93**, 171101 (2004)
Ll. Marti *et al*., Nucl. Instrum. Methods Phys. Res., Sect. A **959**, 163549 (2020)

DSNB search in SK-Gd experiment

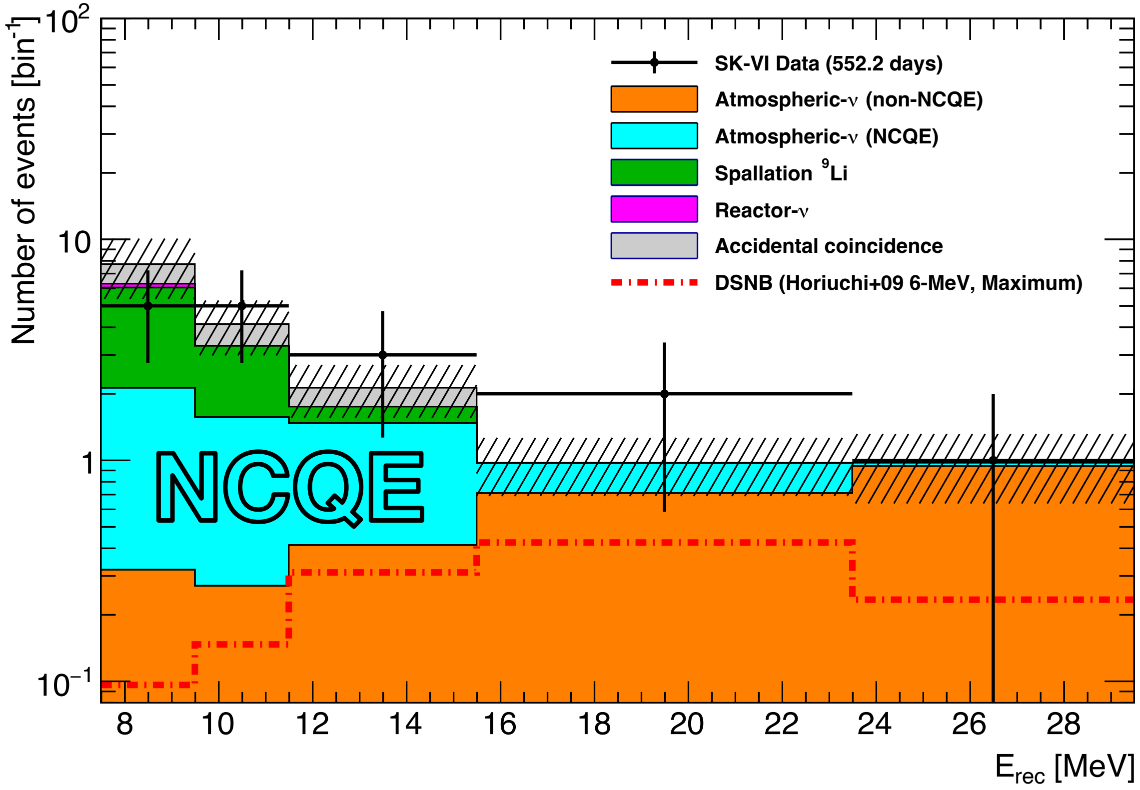
- Search for the inverse beta decay (IBD) by electron antineutrinos ($\bar{\nu}_e + p \rightarrow e^+ + n$)
- Detect positron (prompt signal) and neutron (delayed signal) pairs

  → Can remove backgrounds without neutrons



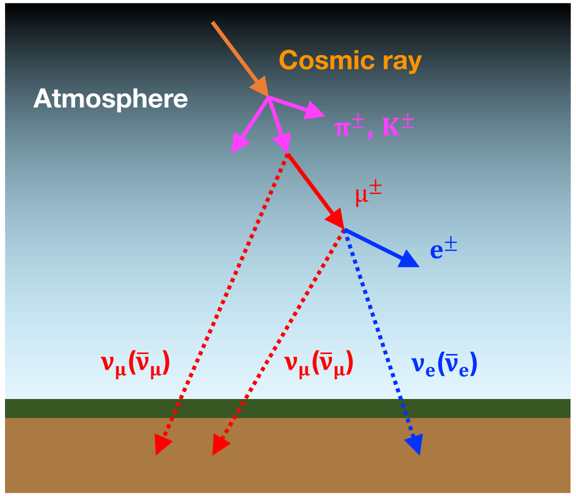
~115 μsec (0.011% by mass of Gd)
~62 μsec (0.03% by mass of Gd)

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



M. Harada *et al*., Astrophys. J. Lett. **951**, L27 (2023)
M. Harada, Ph.D. Thesis, Okayama University (2023)

NCQE events in DSNB search



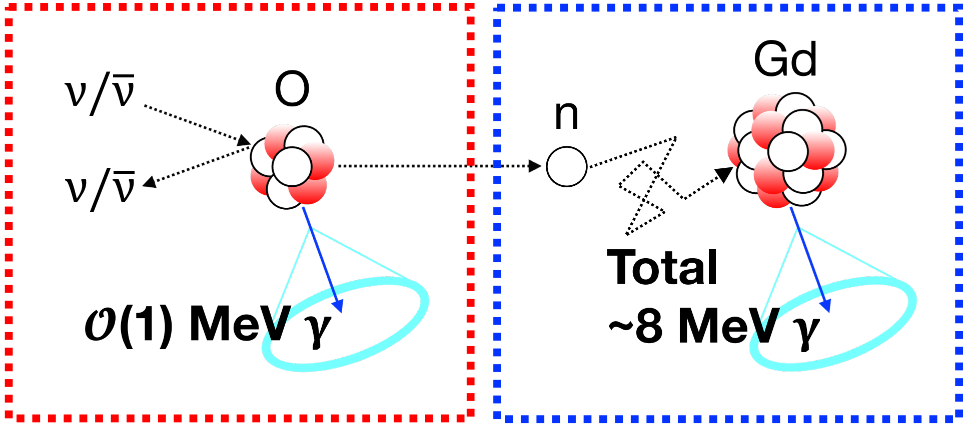
- Neutral-current quasielastic scattering (NCQE) reaction
- Atmospheric neutrino knocks out a nucleon of the oxygen nucleus

  → Deexcitation gamma ray and neutron pairs mimic DSNB events

  → Important to estimate NCQE events precisely

NCQE

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



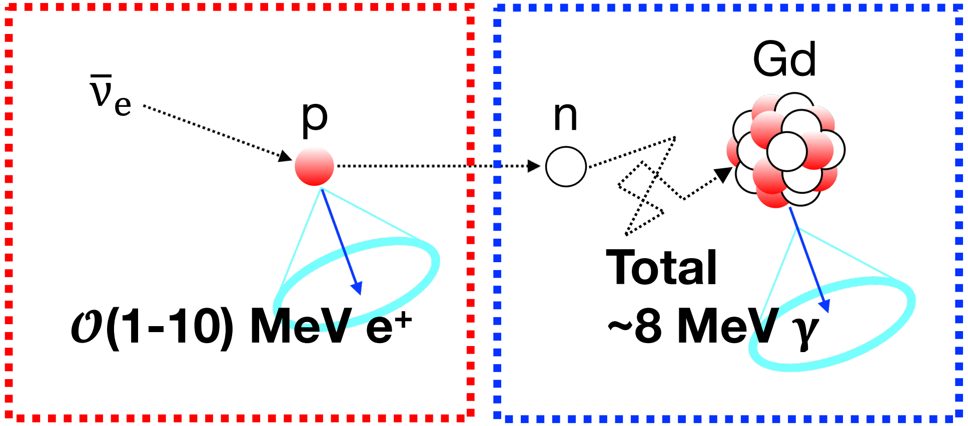
Prompt signal → Delayed signal

~115 μsec (0.011% by mass of Gd)

~62 μsec (0.03% by mass of Gd)

DSNB (IBD)

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



Prompt signal → Delayed signal

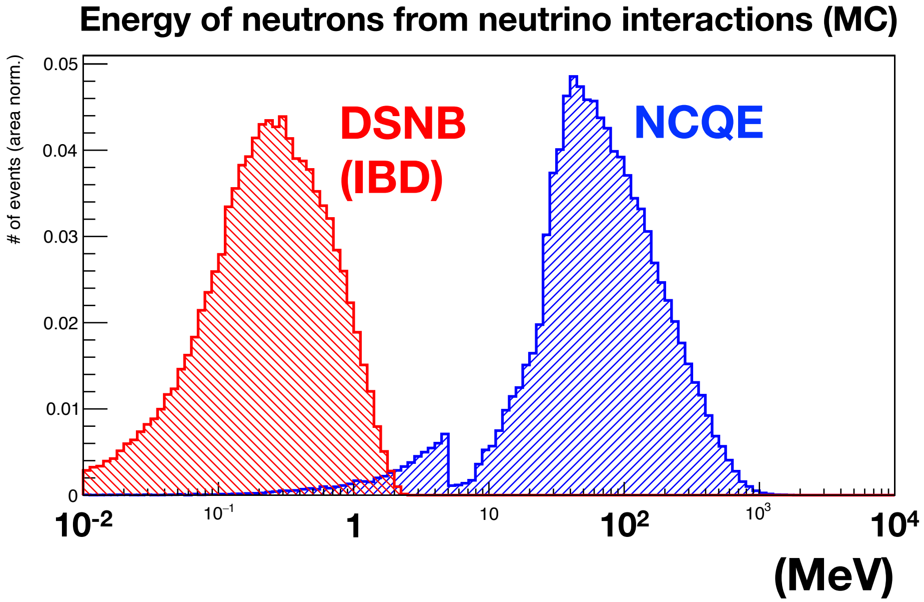
~115 μsec (0.011% by mass of Gd)

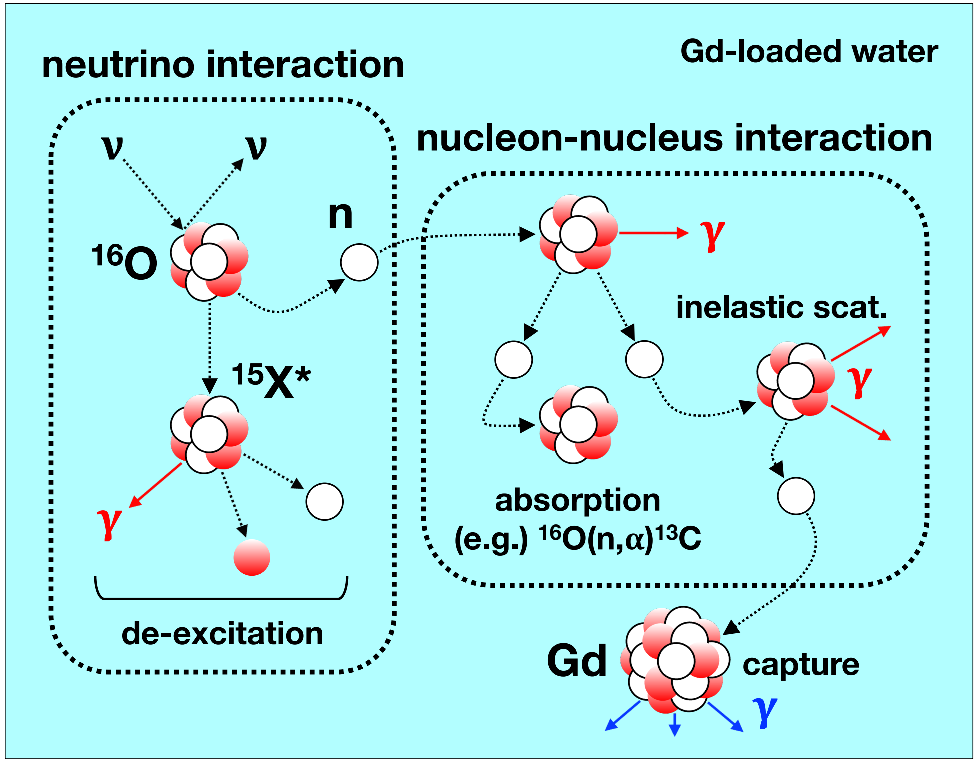
~62 μsec (0.03% by mass of Gd)

S. Sakai, Ph.D. Thesis, Okayama University (2024)

NCQE events in DSNB search

- Energy of atmospheric neutrinos: $\mathcal{O}(10^2)$-$\mathcal{O}(10^3)$ MeV
- Energy of neutrons from (atmospheric) neutrino interactions: $\mathcal{O}(1)$-$\mathcal{O}(10^3)$ MeV
  → More gamma rays and neutrons are generated by nucleon-nucleus interactions
- Cannot distinguish between neutrino and nucleon-nucleus interactions in SK
  → Must understand each process that generates gamma rays and neutrons



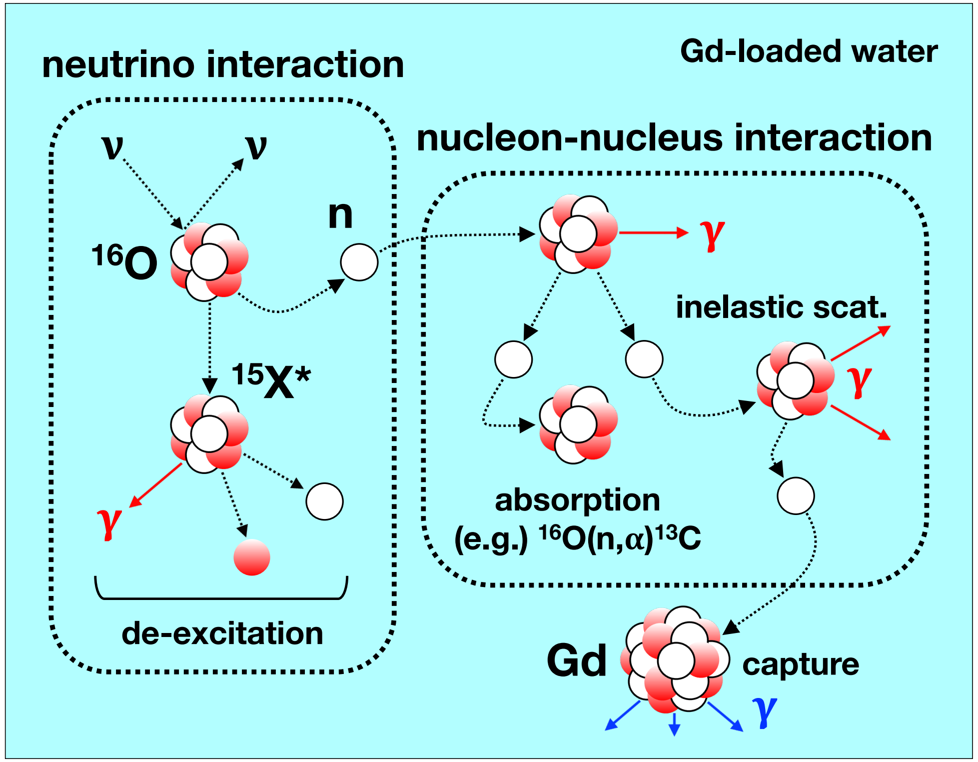


S. Sakai, Ph.D. Thesis, Okayama University (2024)

What I did

Measurement of the neutrino-oxygen NCQE cross section

- Previous studies
  - T2K (accelerator neutrinos)
    - K. Abe *et al*., Phys. Rev. D **90**, 072012 (2014)
    - K. Abe *et al*., Phys. Rev. D **100**, 112009 (2019)
  - SK (atmospheric neutrinos)
    - L. Wan *et al*., Phys. Rev. D **99**, 032005 (2019)
- For the first time in SK-Gd



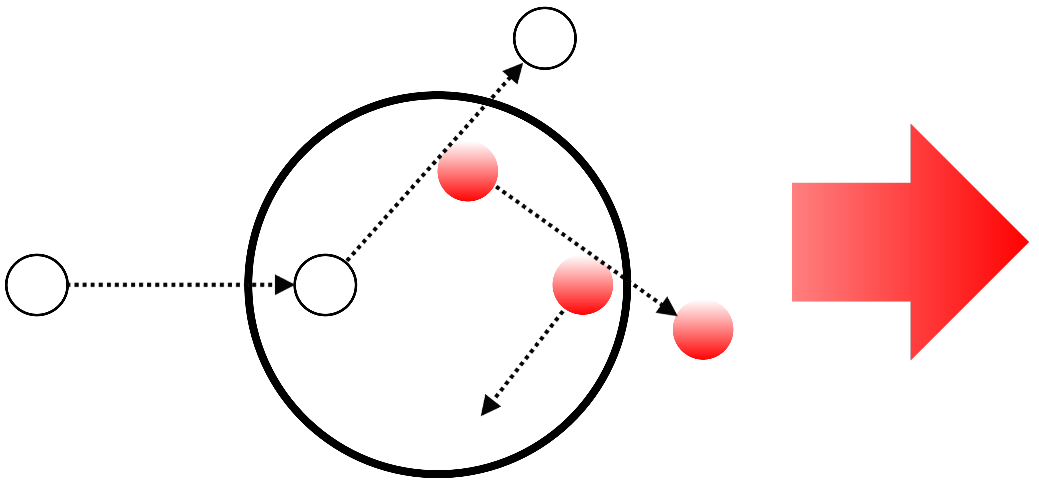
Study of nucleon-nucleus interaction model

- Evaluated nucleon-nucleus interaction models systematically for the first time

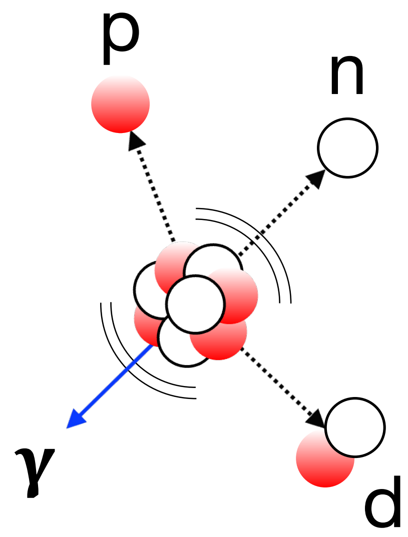
Nucleon-nucleus interaction model

- Consist of intranuclear cascade model and evaporation model
  - Intranuclear cascade model: Describe a chain of reactions triggered by a reaction between an incident particle and a nucleon in a nucleus
  - Evaporation model: Describe a process of emitting nucleons and gamma rays isotropically when an excited residual nucleus deexcites

Intranuclear cascade model



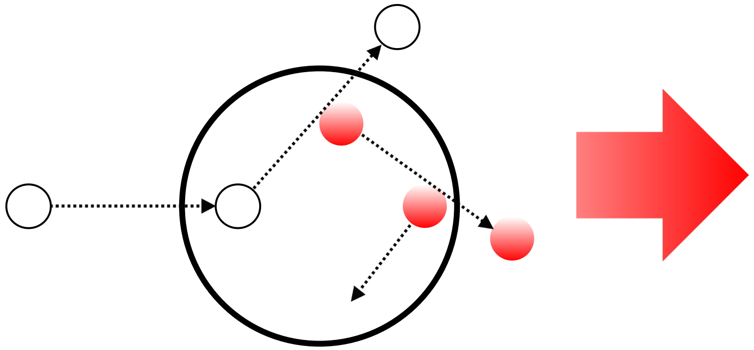
Evaporation model



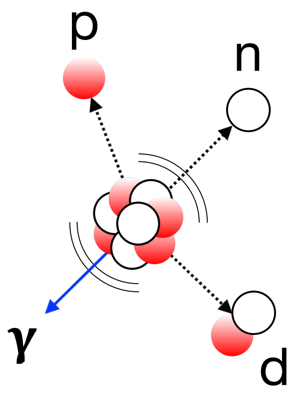
Nucleon-nucleus interaction model

- Evaporation model is so different
  - BERT unique (BERT): Continuous transitions till the end
  - G4PreCompound (BIC, INCL++): Continuous to discrete transitions (more realistic)

Intranuclear cascade model



Evaporation model



BERT unique
(BERT)

G4PreCompound
(BIC, INCL++)

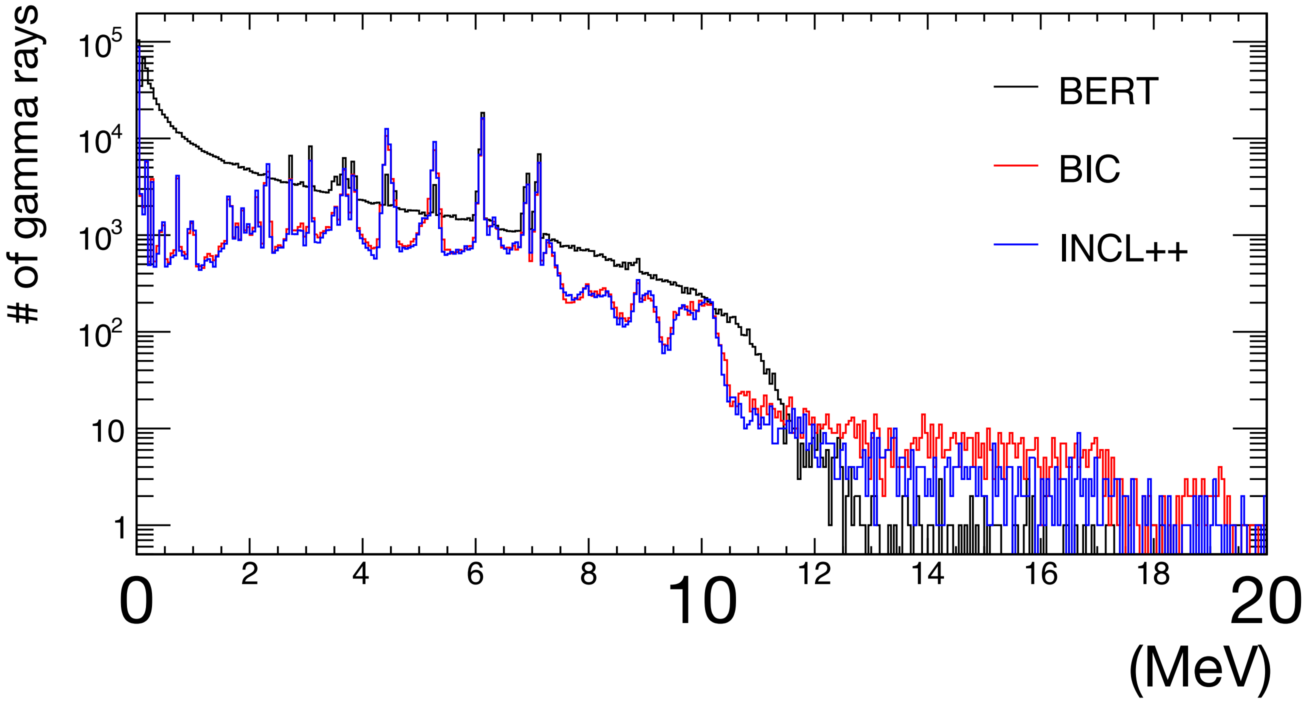
Can be used in Geant4-based SK detector simulation

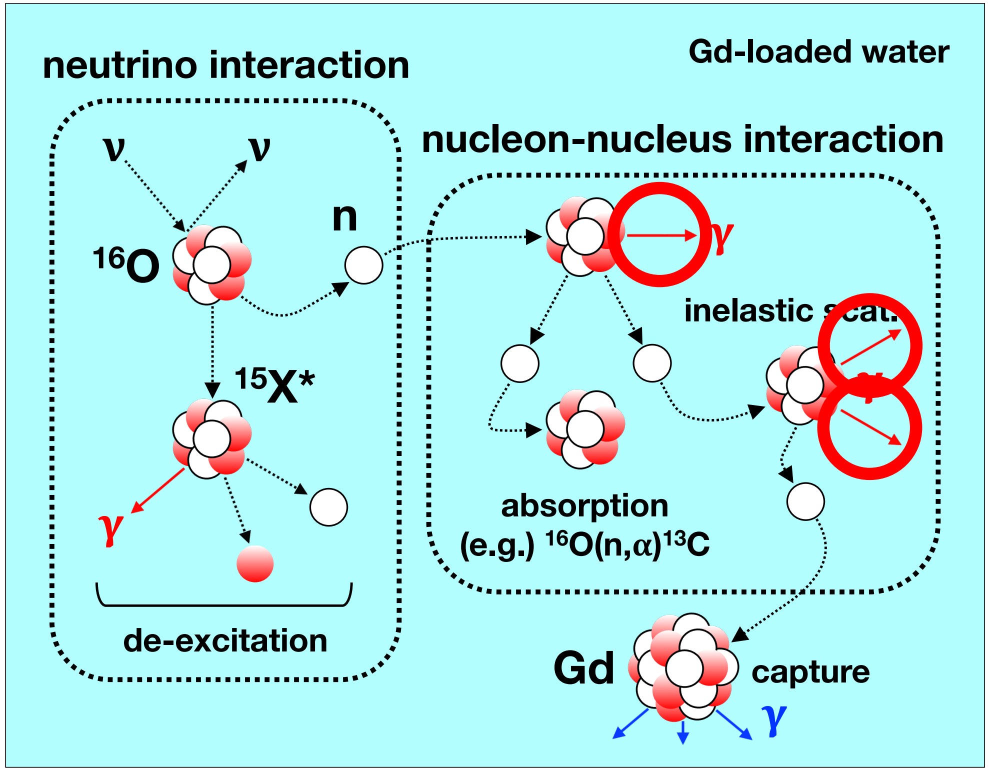
Bertini Cascade Model (BERT, SK official model)	→ BERT unique
Binary Cascade Model (BIC)	→ G4PreCompound
Liège Intranuclear Cascade Model (INCL++)	→ G4PreCompound

Energy of gamma rays

- BERT: Many continuous components in addition to peaks of deexcitation gamma rays
- BIC & INCL++: Similar tendencies

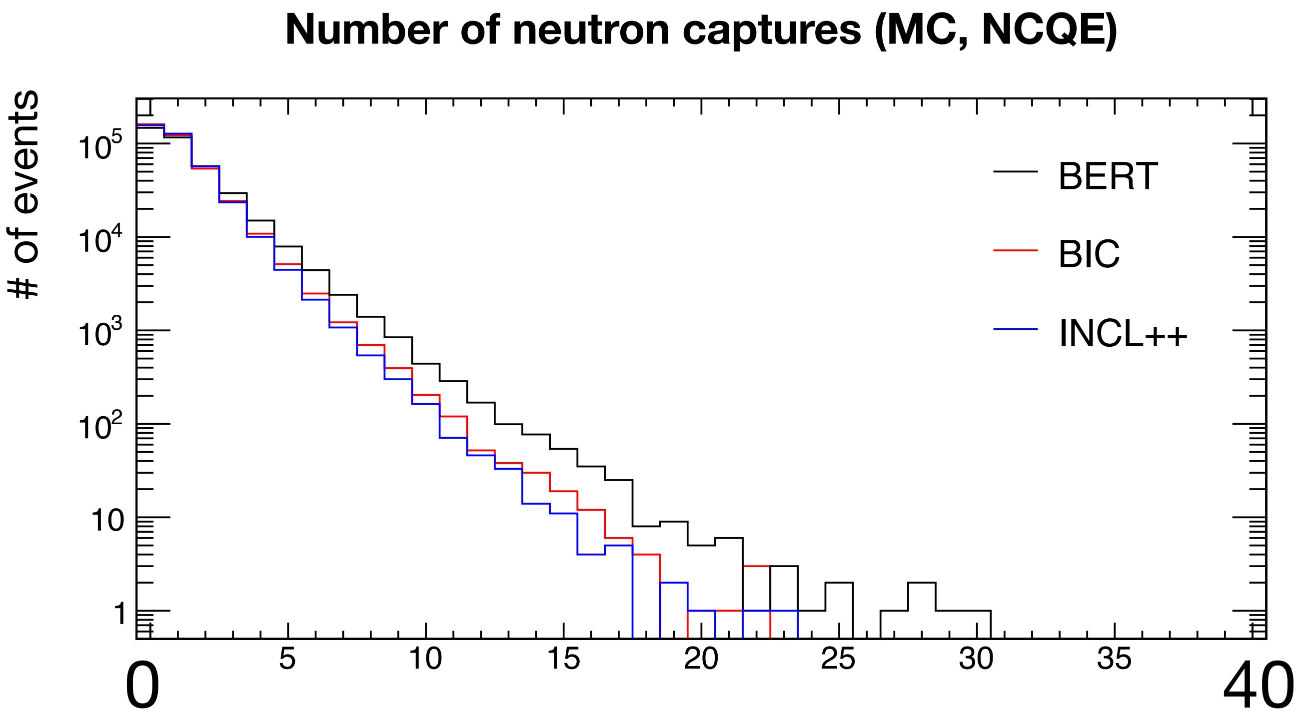
Energy of gamma rays by neutron inelastic scattering (MC, NCQE)

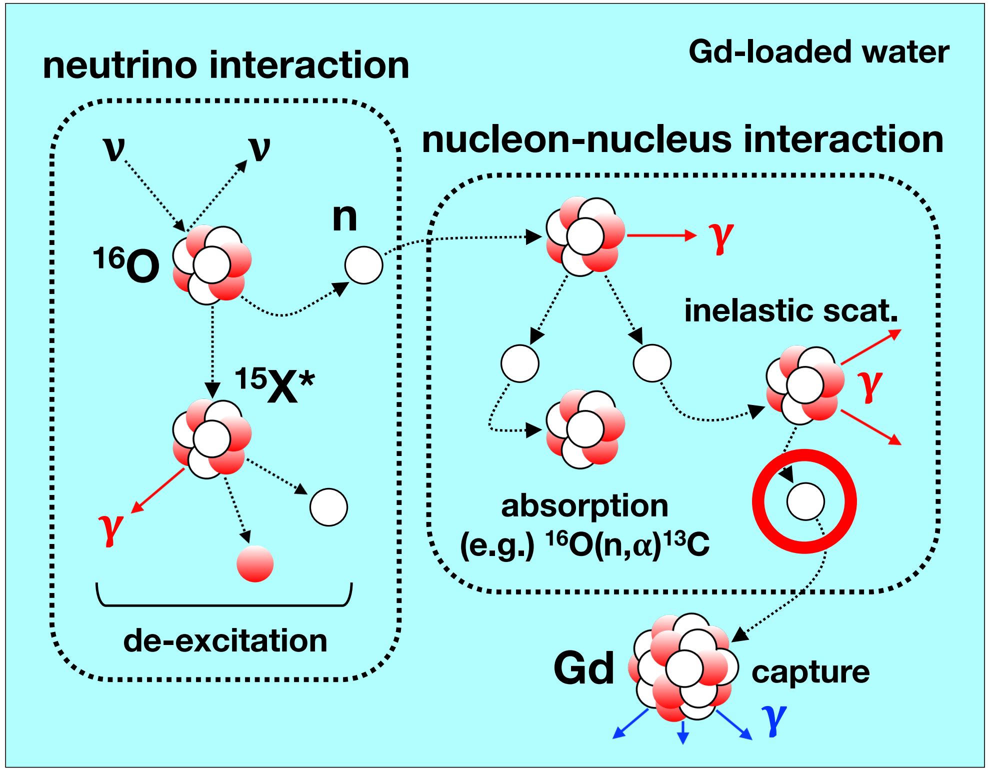




Number of neutron captures

- BERT: Number of neutron captures per NCQE event is large (1.29/NCQE event)
- BIC & INCL++: Similar tendencies (1.07(1.06)/NCQE event)



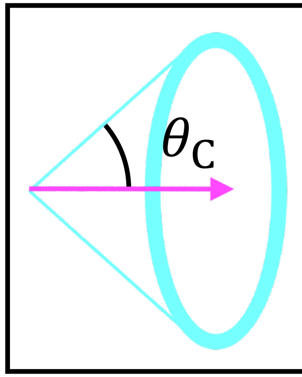


Comparison of nucleon-nucleus interaction model

- Select NCQE events from the 552.2 days of observed data with 0.011% by mass of Gd

  → Compare the following distributions in BERT, BIC, and INCL++

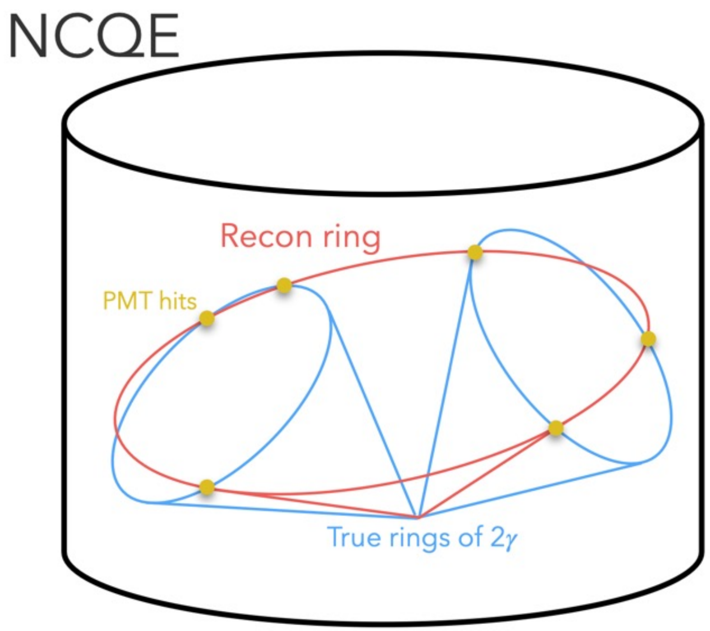
  - Cherenkov angle of prompt signal: Correspond to the number of gamma rays
  - Energy of prompt signal: Correspond to the energy of gamma rays
  - Number of delayed signals: Correspond to the number of neutron captures



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

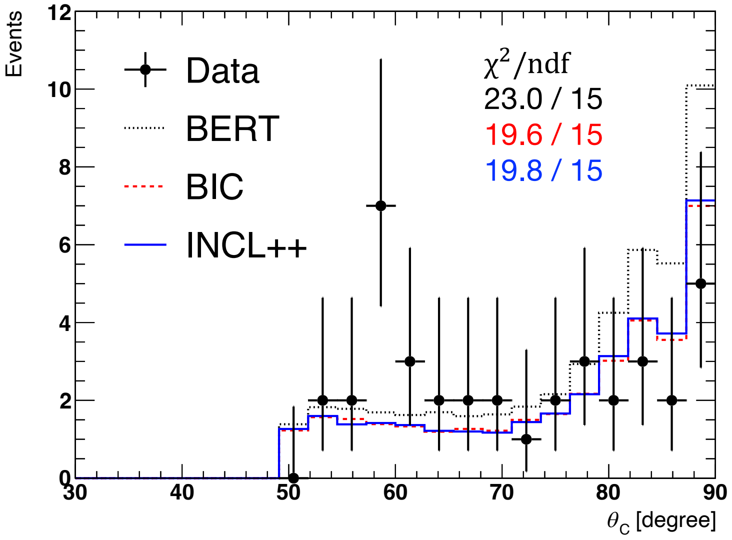
n: Refractive index
$\beta = v/c$

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



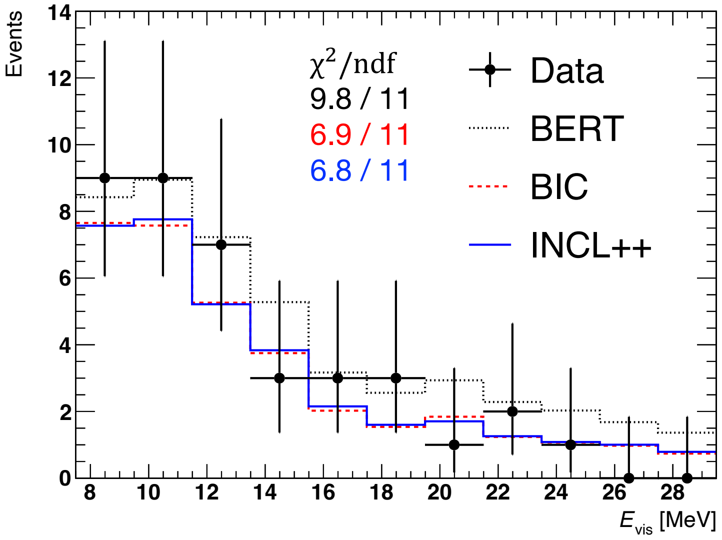
Comparison of nucleon-nucleus interaction model

Cherenkov angle of prompt signal



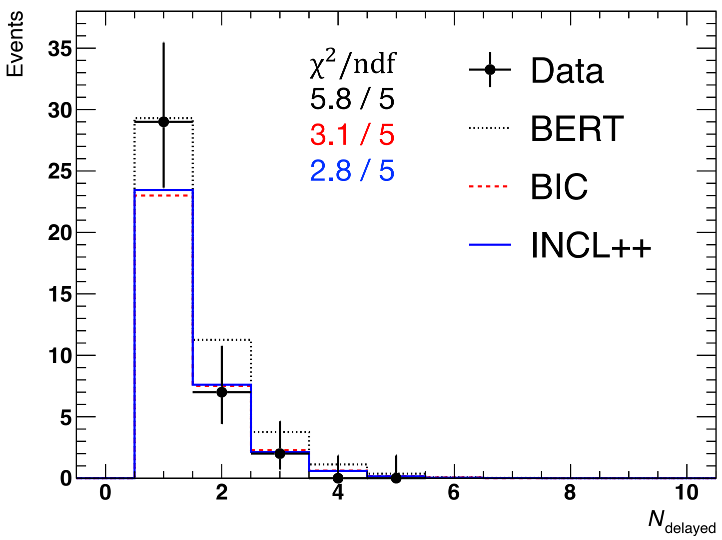
Correspond to the number of gamma rays

Energy of prompt signal



Correspond to the energy of gamma rays

Number of delayed signals



Correspond to the number of neutron captures

- Observed data: 38 events
- Evaluate each distribution using chi-square

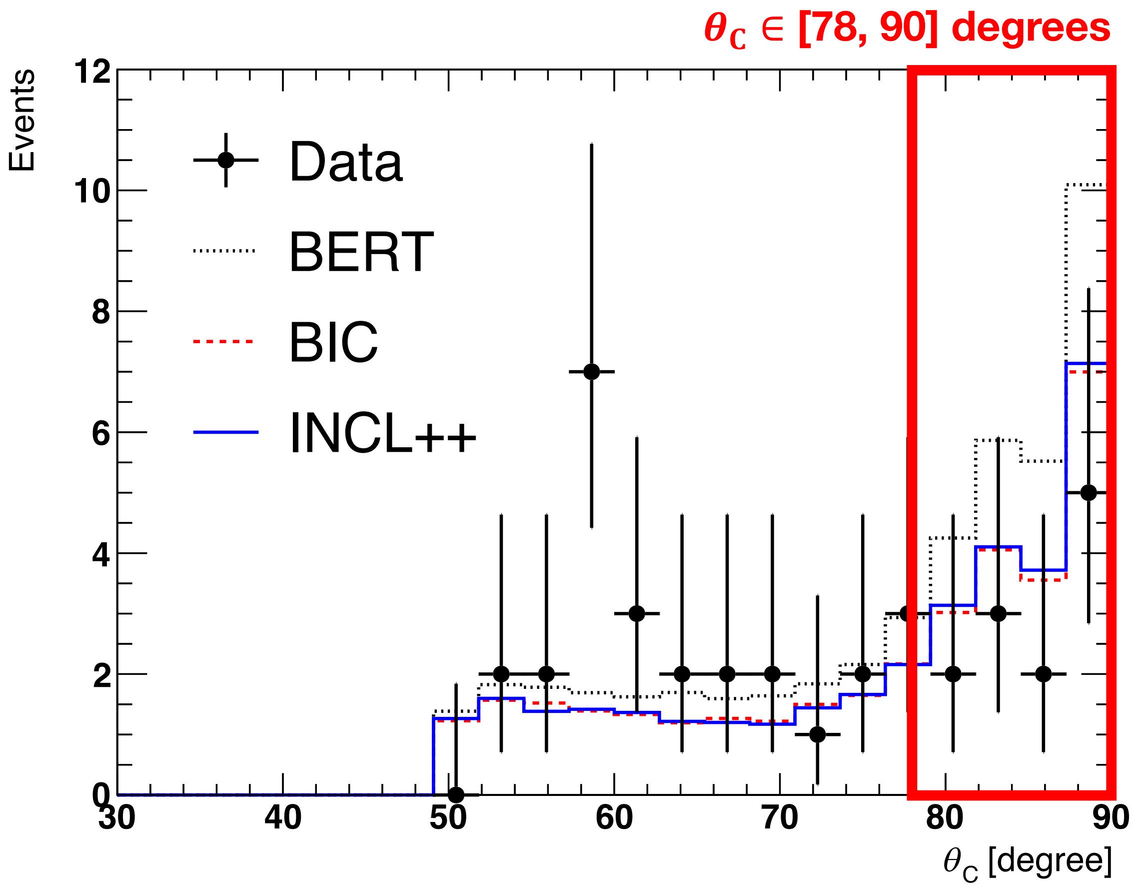
  → Not conclusive due to small statistics

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

Determination of nucleon-nucleus interaction model

- Focus on the number of events in Cherenkov angle of prompt signal (θ_C) ∈ [78, 90] degrees
- Consider statistical uncertainty of data and systematic uncertainty of MC

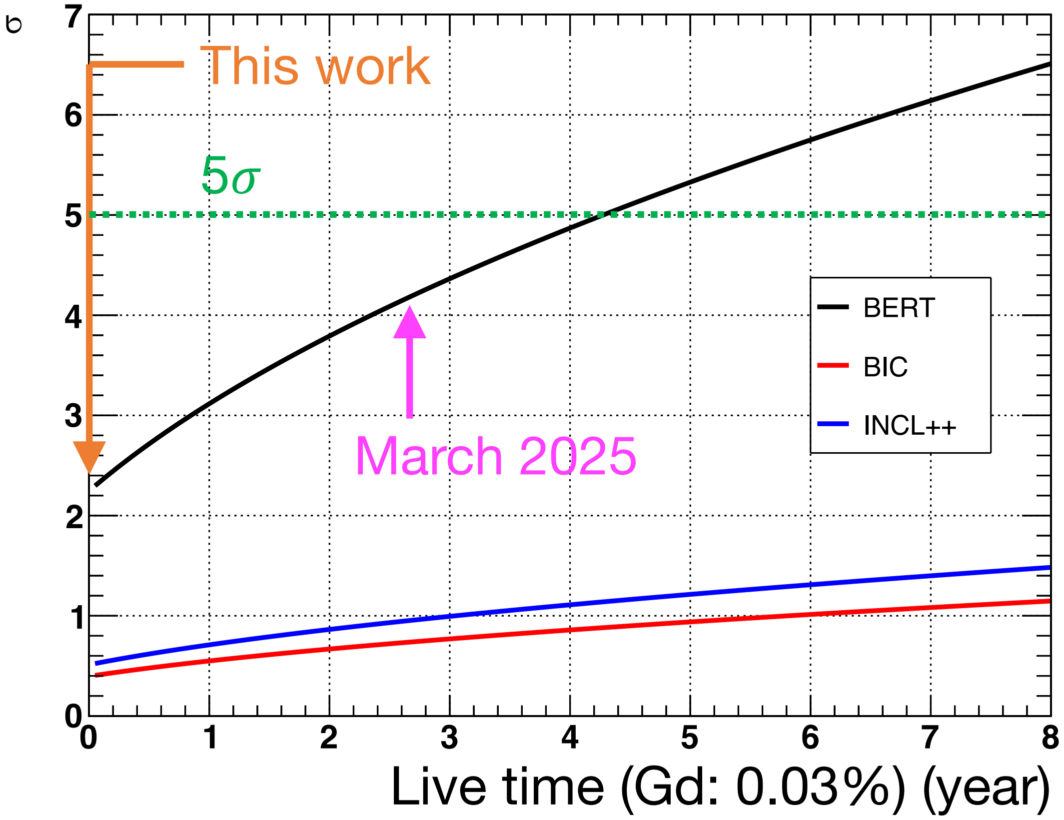
→ BERT is ~2.2σ far from data at this work



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

Determination of nucleon-nucleus interaction model

- SK continues to observe with 0.03% by mass of Gd
- Assume that neutron tagging efficiency improves from 35.6%[1] (Gd: 0.011%) to 63.0%[2] (Gd: 0.03%)
  → Statistics increases by about 1.4 times with the same live time
- Evaporation model can be determined at 5σ by using ~4 years of data (Gd: 0.03%)



[1] M. Harada *et al.*, Astrophys. J. Lett. **951**, L27 (2023)
[2] Y. Kanemura, “Improvement of neural network analysis in SK-VII”, SK internal slide (2023)

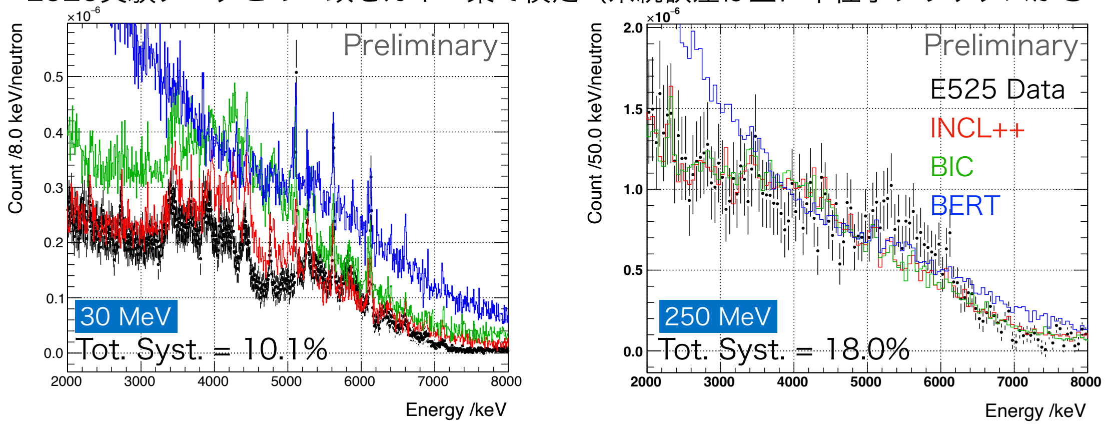
Results from other experiments

- RCNP[1] (quasi-mono energetic neutron beams + water target)
  - Evaluate energy spectrum of gamma rays using chi-square (See the right slide →)
    → Suggest that INCL++ reproduce data better than other models
- T2K[2] (accelerator neutrinos)
  - Compare the following distributions in BERT and INCL++
    - Cherenkov angle of prompt signal
    - Energy of prompt signal
    → Suggest that INCL++ reproduce data better than BERT

8

Cascade Models

- 核内カスケードモデル間の比較: それぞれデフォルトの脱励起モデルと結合させた
- E525実験データとの一致をカイ二乗で検定（系統誤差は主に中性子フラックスから



Model	χ^2/ndf @30 MeV	χ^2/ndf @250 MeV
INCL++	1933.4 / 750	303.1 / 120
BIC	2405.5 / 750	348.7 / 120
BERT	4632.9 / 750	592.7 / 120

preliminary

$$\chi^2 = \sum \left(\frac{N^{\mathrm{data}} - f \times N^{\mathrm{mc}}}{\sigma^{\mathrm{stat.}}} \right)^2 + \left(\frac{1-f}{\sigma^{\mathrm{syst.}}} \right)^2$$

- **Both dataset prefer INCL++** model.
  - BIC: similar due to the syst. error.
- Bertini shows a large inconsistency.

[1] 日野陽太 他, “ニュートリノ反応理解に向けた中性子酸素原子核非弾性散乱事象の実験データとシミュレーションモデルの比較”, JPS 第79回年次大会 (2024)
[2] 竹谷浩鷹 他, “T2K実験によるニュートリノ中性カレント反応測定のためのGeant4ベースの検出器シミュレーションの研究”, JPS 第79回年次大会 (2024)

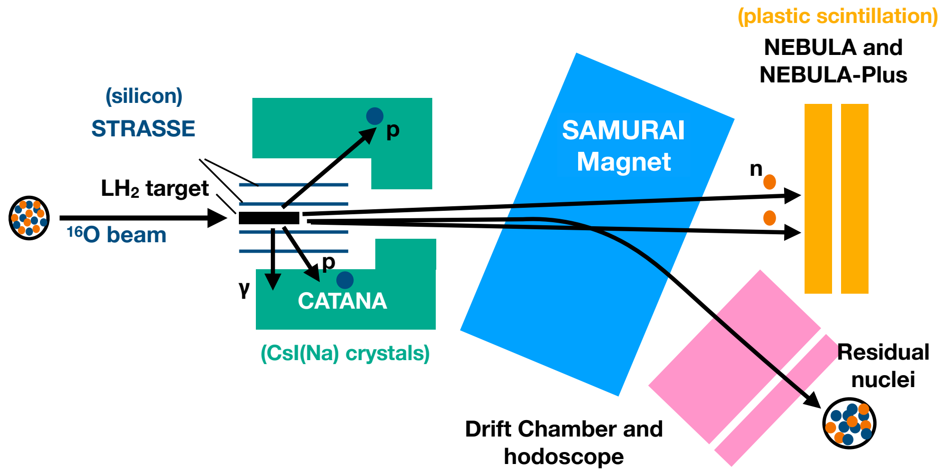
Prospects (SAMURAI-79 experiment)

- RIKEN RIBF (^{16}O and ^{17}O (200 MeV/u) beams + liquid hydrogen target + SAMURAI spectrometer)
  - Measure the particle decay branching ratio from ^{15}N*, ^{15}O* and ^{16}O* as a function of excitation energy
  - Measure the energy spectrum of deexcitation gamma rays and neutrons <u>without energy threshold</u>

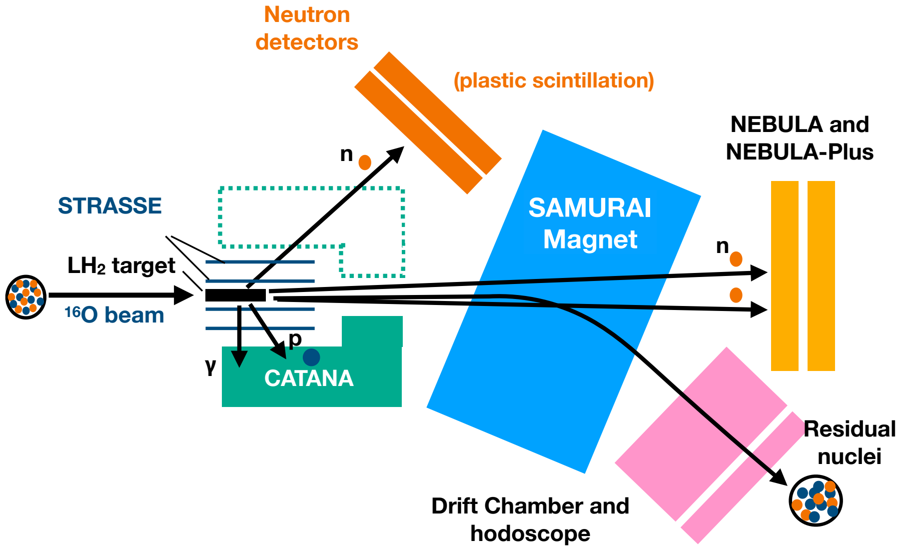
    → Tune the deexcitation model

    → Reduce uncertainties of atmospheric neutrino backgrounds ($\gtrsim$ 40% → ~10%)

Setup for ^{16}O(p, 2p)^{15}N*



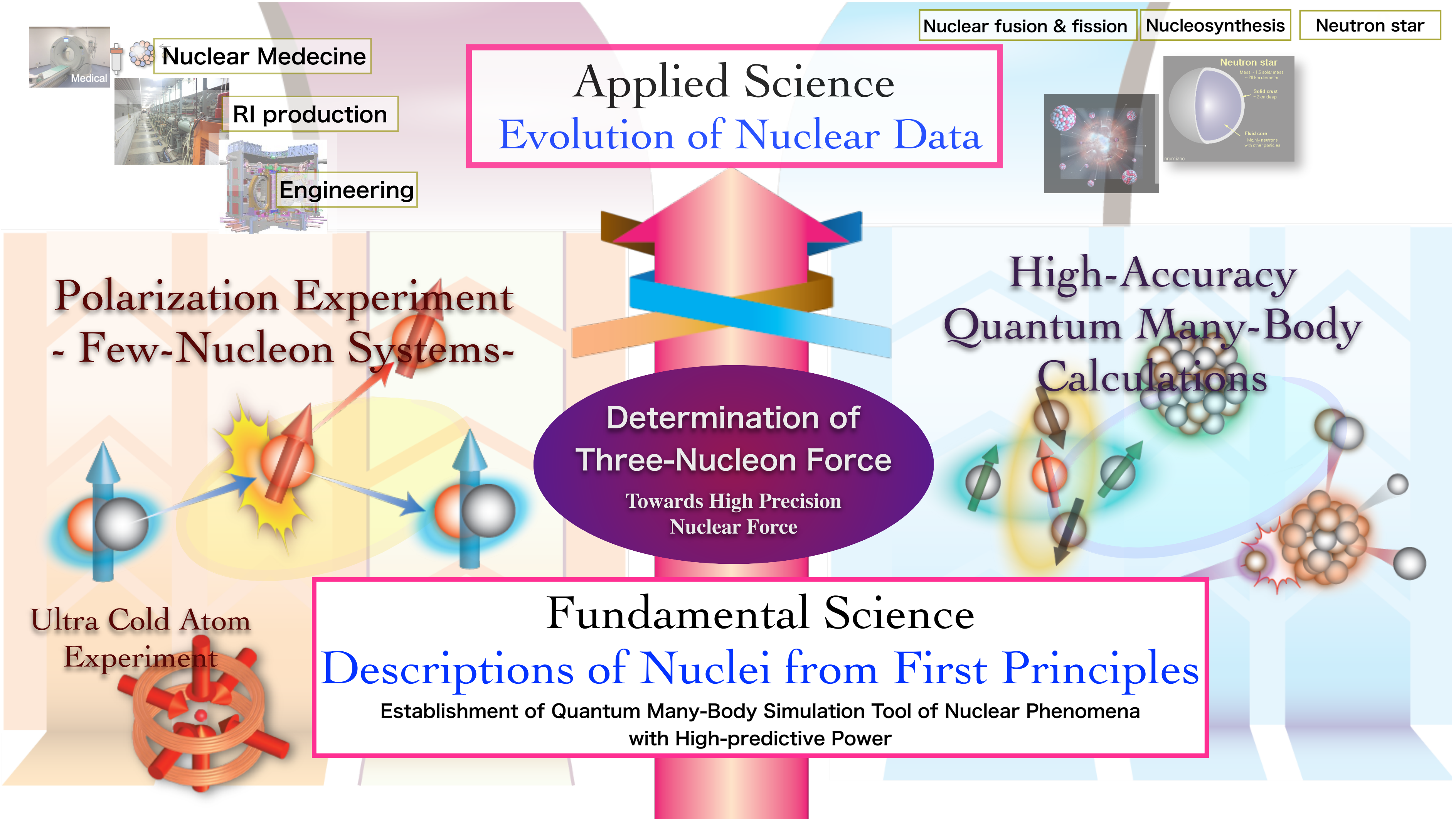
Setup for ^{16}O(p, pn)^{15}O* and ^{17}O(p, pn)^{16}O*



S. Sakai, "Inverse-kinematics experiment using oxygen beams at the RIBF: Toward the observation of diffuse supernova neutrino background at the SK-Gd project", ADRIB25 (2025)

Prospects (TOMOE project)

- JST ERATO SEKIGUCHI Three-Nucleon Force (TOMOE) Project (Oct. 2023 - Mar. 2029)



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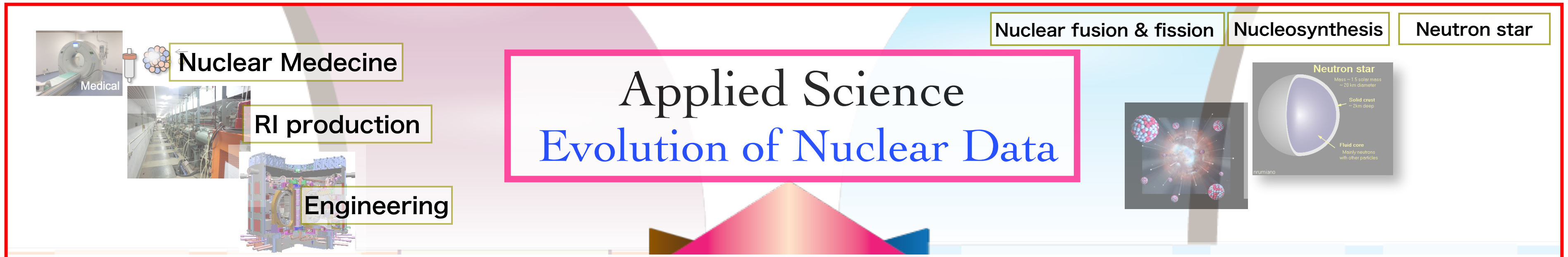


- Developing a system to calculate and illustrate nuclide production cross sections from light particle (n, p, d, t, ^{3}He, α, γ) injection reactions
  → Understanding the status of nuclear reaction model calculations and evaluated nuclear data libraries
  → Considering the optimal production methods for nuclides useful in the field of applied science

Summary

- Aiming the first observation of the DSNB in SK-Gd

  → Important to estimate NCQE events precisely

- Performed the measurement of the neutrino-oxygen NCQE cross section and the study of nucleon-nucleus interaction model

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

  → Similar results are obtained from other experiments (RCNP, T2K)

- Will reduce uncertainties of atmospheric neutrino backgrounds by the SAMURAI-79 experiment
- Will promote ‘evolution of nuclear data’ by the TOMOE project

Backup

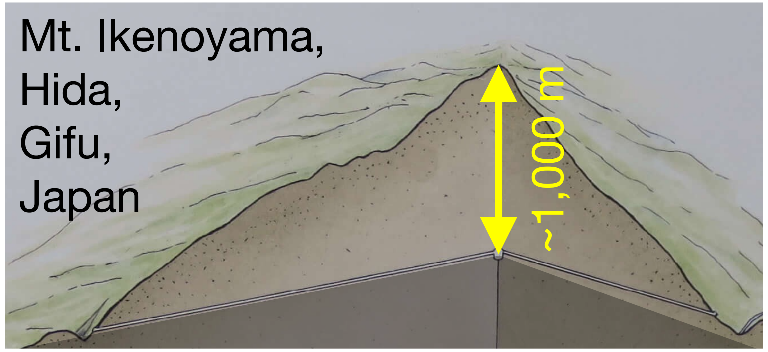
Super-Kamiokande (SK)

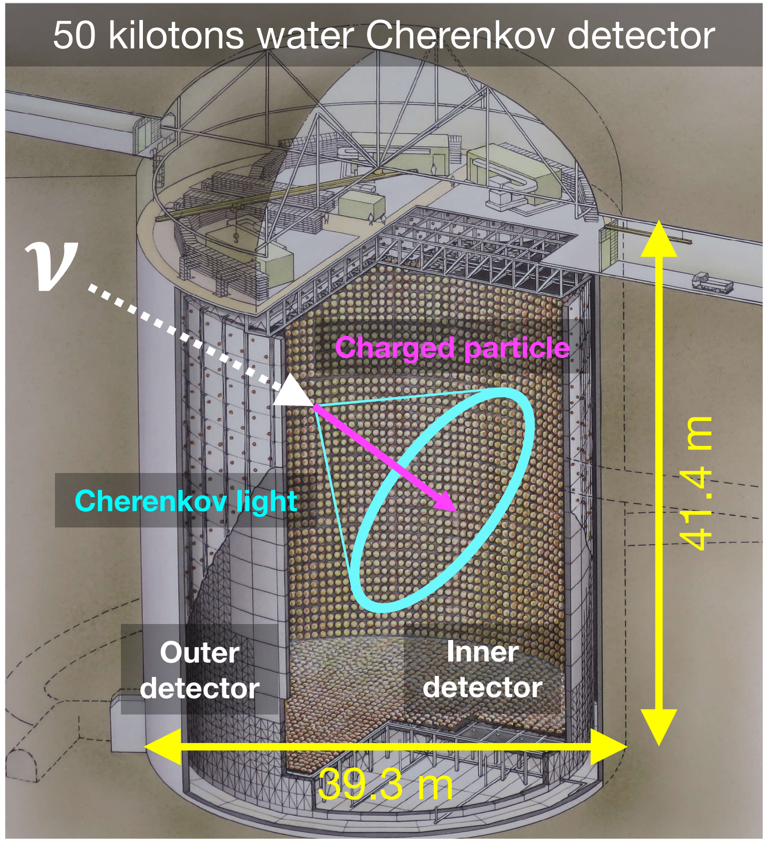
- Large water Cherenkov detector (1996-)
- Consist of 50 kilotons ultrapure water and photomultiplier tubes (PMTs)
- Inner detector (11,129 20-inch PMTs)

  → Reconstruct vertex, direction, and energy of charged particles
- Outer detector (1,885 8-inch PMTs)

  → Distinguish between neutrinos and cosmic ray muons

I was a member of the SK Collaboration (Apr. 1st, 2019-Mar. 31st, 2024)





https://www-sk.icrr.u-tokyo.ac.jp/en/sk/experience/gallery/

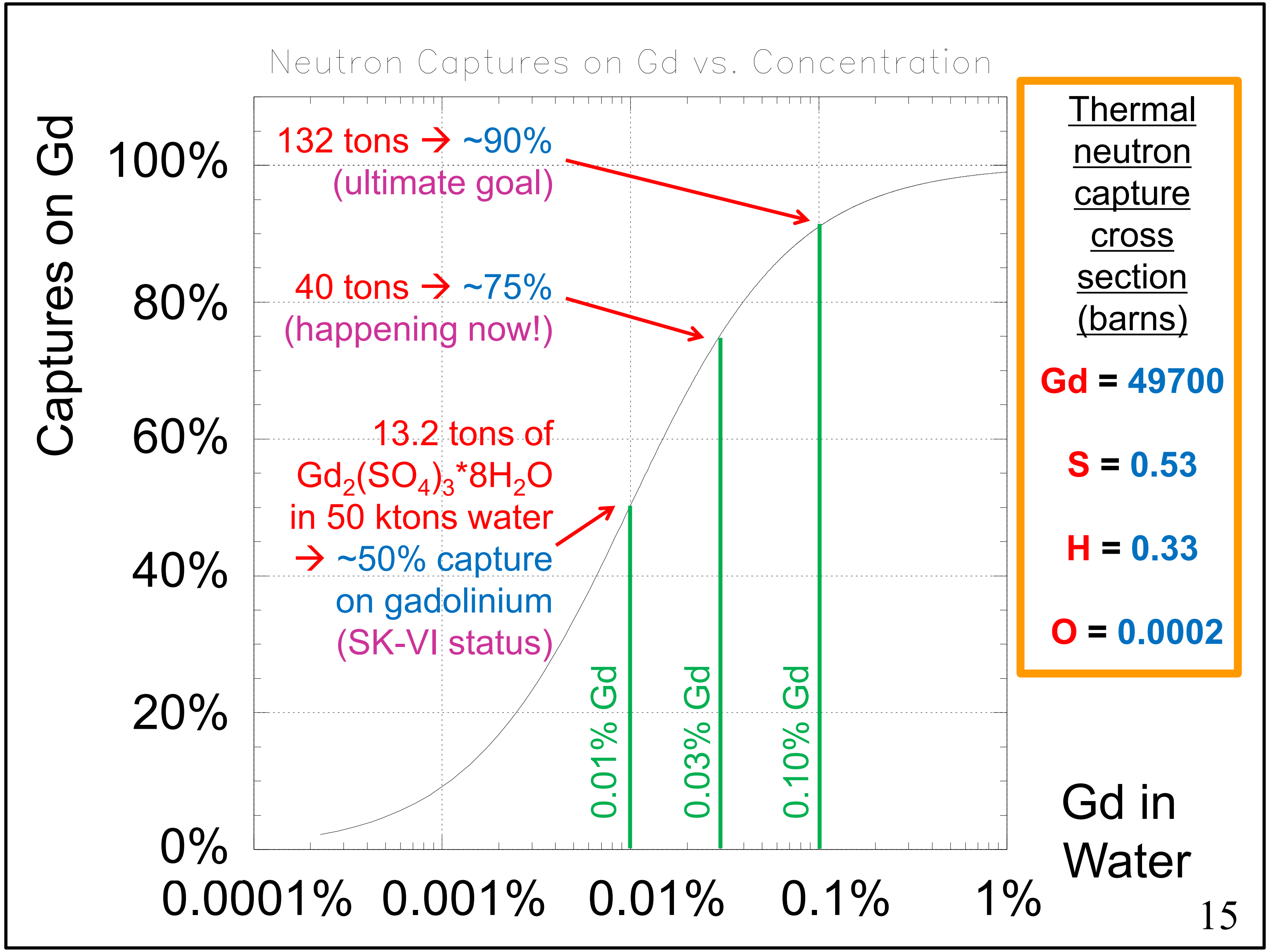
Thermal neutron capture cross sections on Gd

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

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

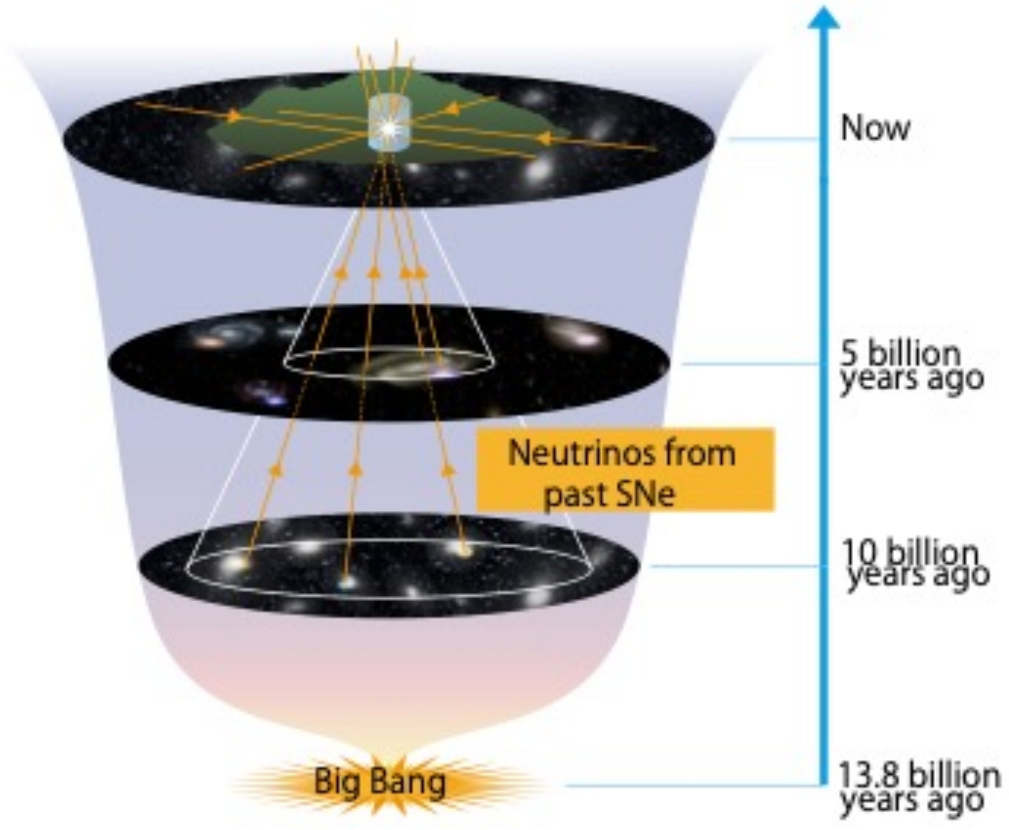
Fraction of neutron captures on Gd

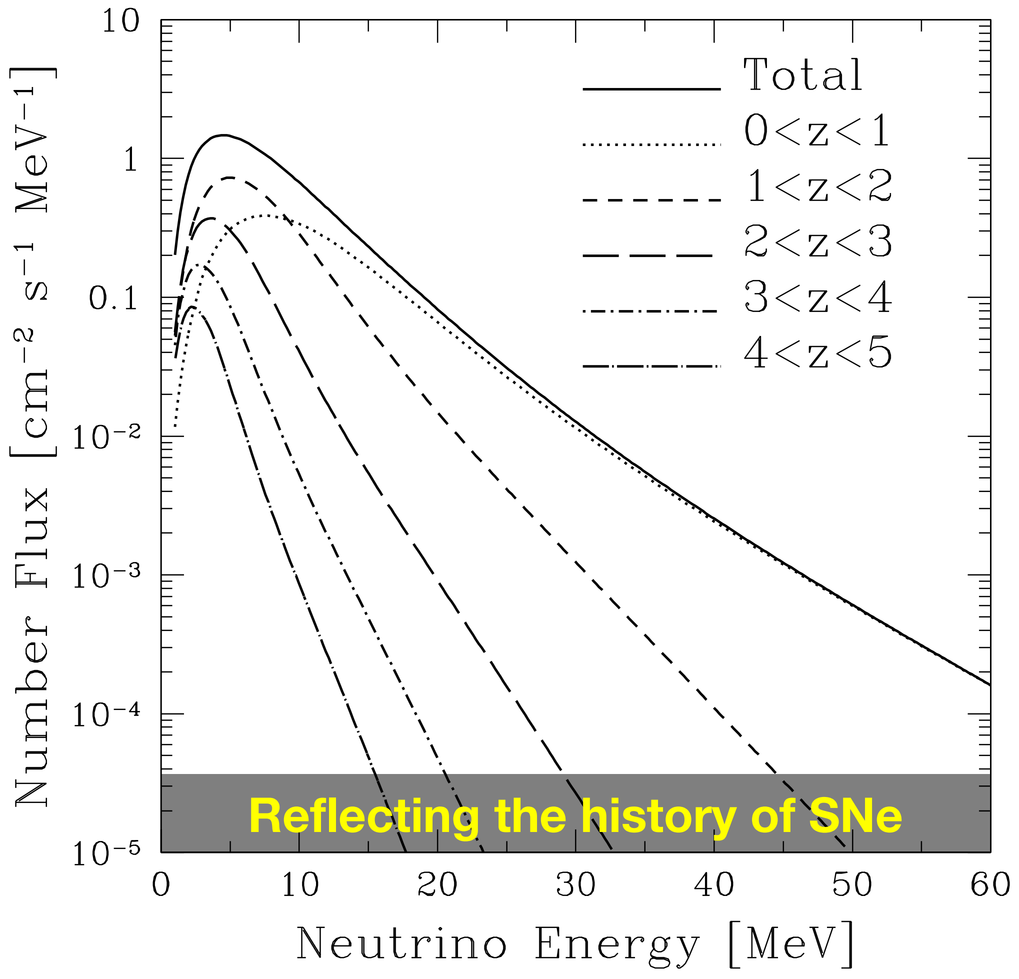


M. Vagins, “A Gadolinium-loaded Super-Kamiokande”, NEUTRINO 2022, online (2022)

Diffuse Supernova Neutrino Background (DSNB)

- **DSNB**: Superposition of neutrinos emitted from all past SNe
- Floating in the universe like background radiation
- Flux is small, but always potentially observable





Y. Koshio, "The supernovae neutrino detection in Super- and Hyper-Kamiokande", LPNHE, Paris, France (2023)
S. Ando, Astrophys. J. **607**, 20 (2004)

Diffuse Supernova Neutrino Background (DSNB)

- DSNB flux:

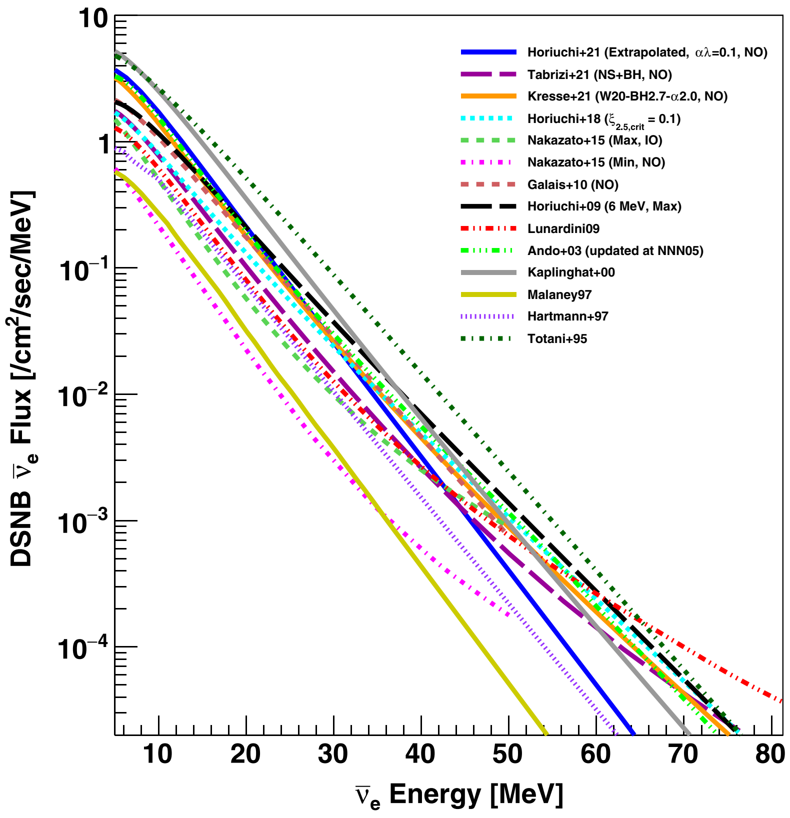
$$\frac{dF(E_\nu)}{dE_\nu} = c \int_0^{z_{\max}} \frac{dz}{H_0\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}} \left[R_{\mathrm{CC}}(z) \int_0^{Z_{\max}} \psi_{\mathrm{ZF}}(z,Z) \left\{ \int_{M_{\min}}^{M_{\max}} \psi_{\mathrm{IMF}}(M) \frac{dN(M,Z,E'_\nu)}{dE'_\nu} dM \right\} dZ \right]$$

→ Depend on SNR, metallicity, initial mass function, number of neutrinos per SN, etc.

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

→ DSNB observation would contribute to our understanding of the mechanism of SNe, SFR, and SNR

- Aiming the first observation of the DSNB in the Super-Kamiokande



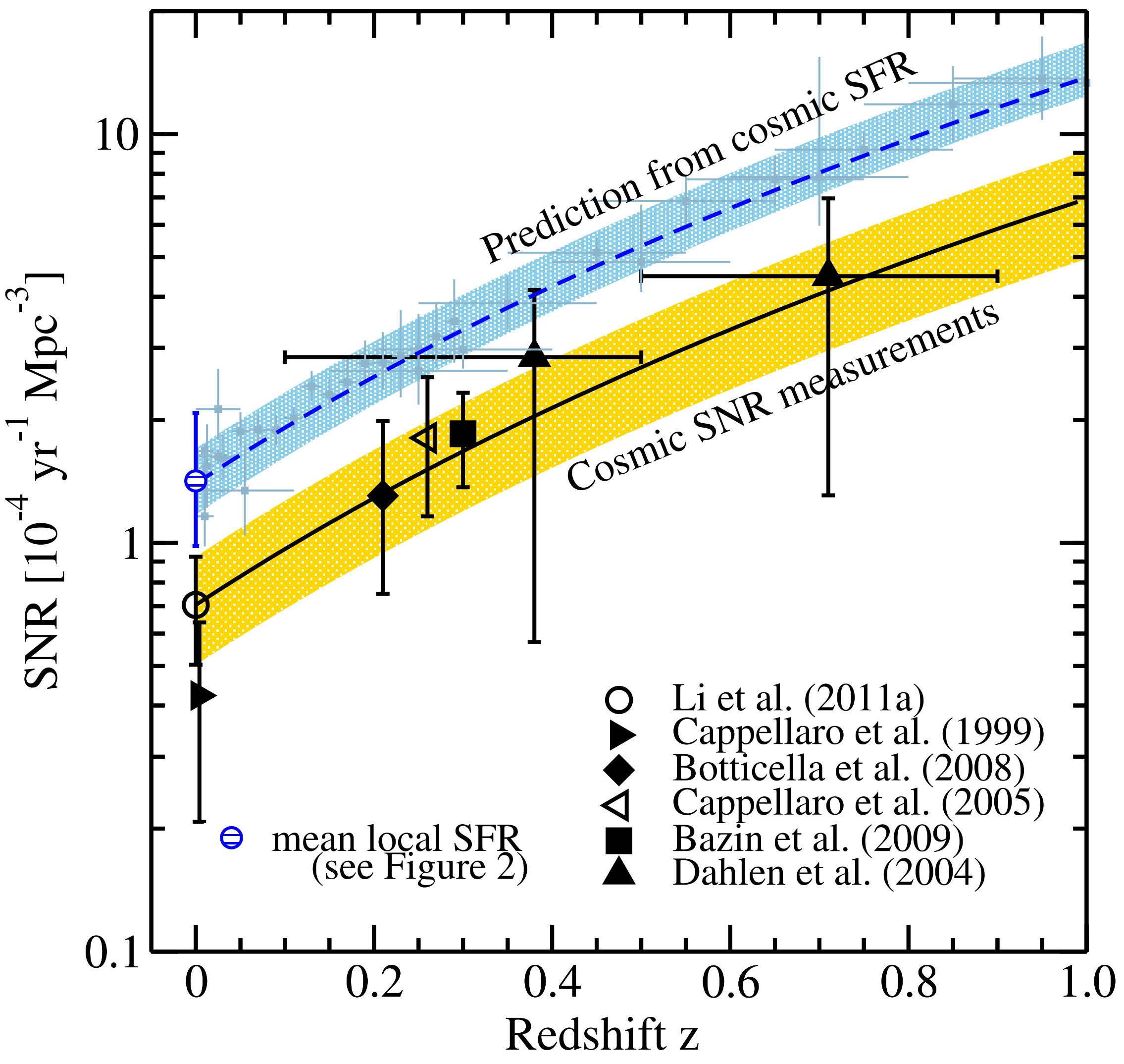
K. Abe *et al.*, Phys. Rev. D **104**, 122002 (2021)

What we do not understand

(e.g.) SN rate problem

- Lifetime of a massive star going SN is short enough compared to the time scale of the evolution of the universe
  - → Star formation and SN can be approximated to occur at the same time
  - → Should be possible to predict the SN rate (SNR) from the star formation rate (SFR)

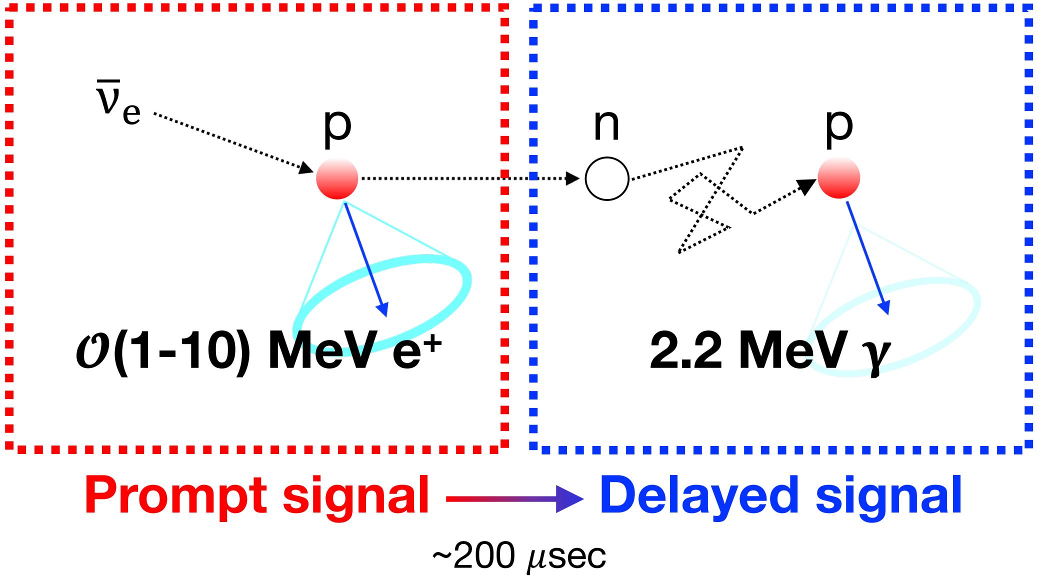
- SNR obtained from optical observations is about half of prediction from the SFR
  - Some SNe are too dark to be observed?
  - There is something preventing observation?
  - → Would like to observe SN neutrinos more!

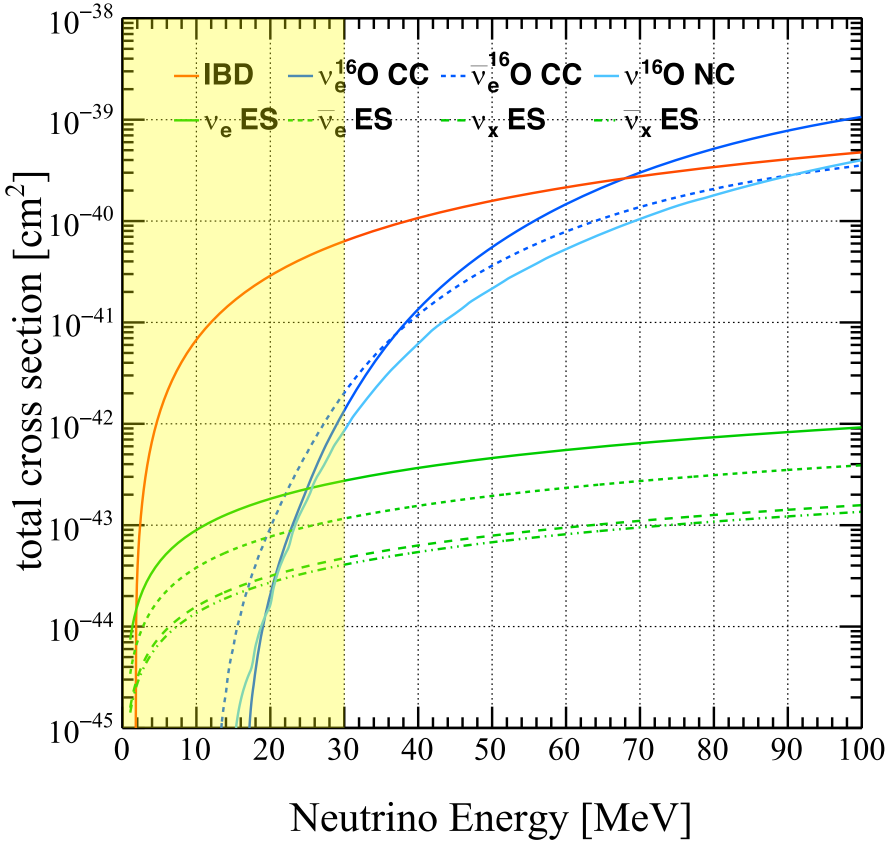


S. Horiuchi *et al.*, Astrophys. J. **738**, 154 (2011)

DSNB search in SK

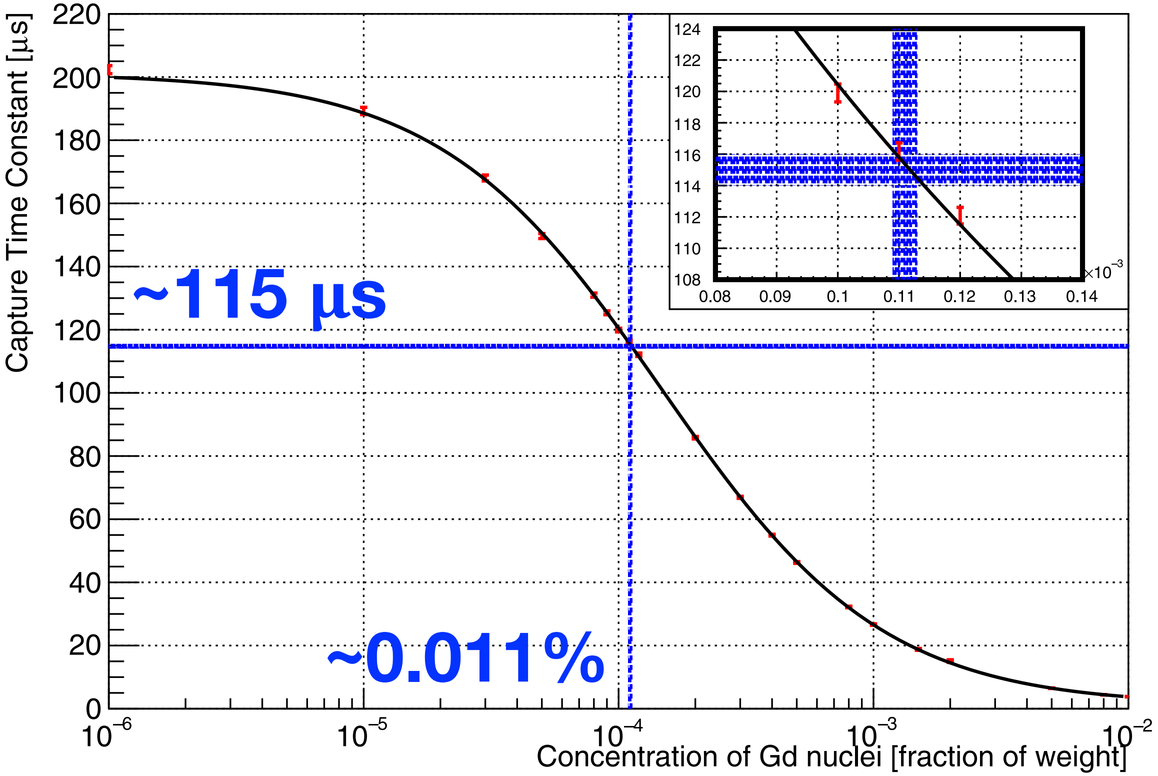
- Search for the inverse beta decay (IBD) by electron antineutrinos ($\bar{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$)
  → Cross section is 1-2 orders of magnitude larger than others at < 30 MeV
- Detect positron (prompt signal) and neutron (delayed signal) pairs
  → Can remove backgrounds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

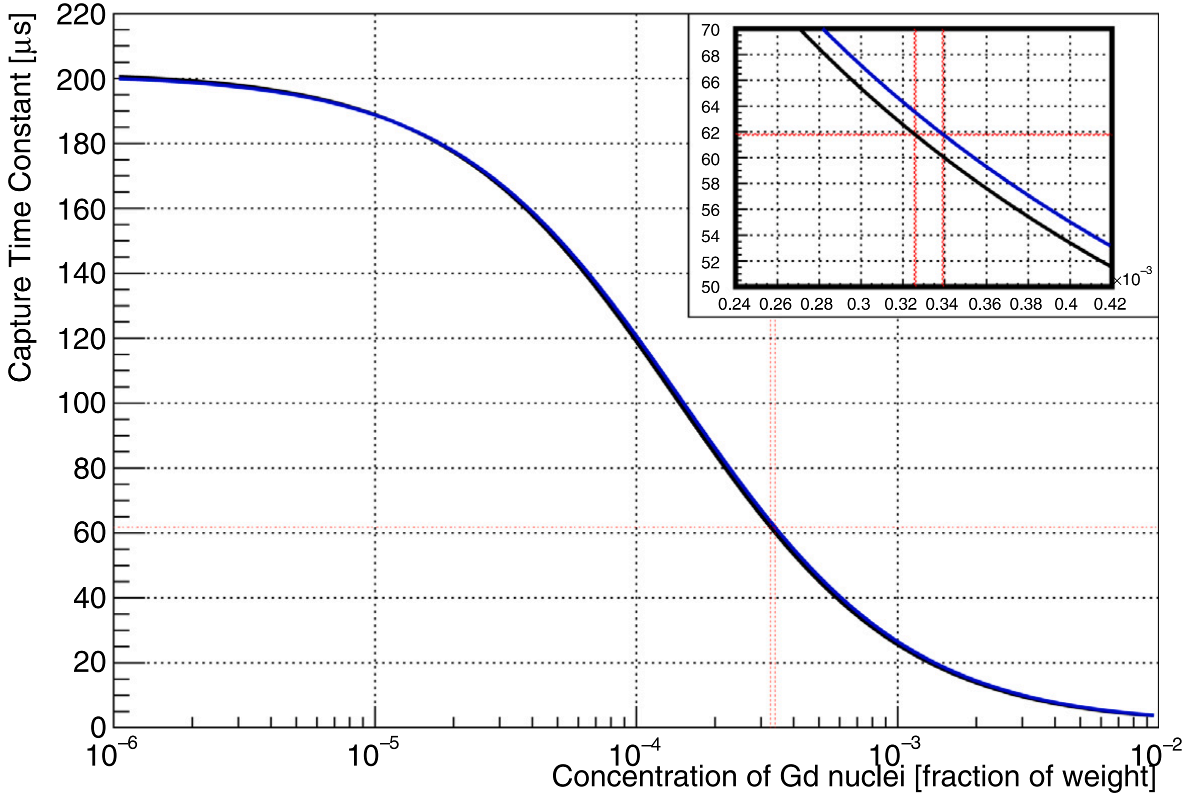




Y. Kashiwagi *et al.*, Astrophys. J. **970**, 93 (2024)

Neutron capture time constant





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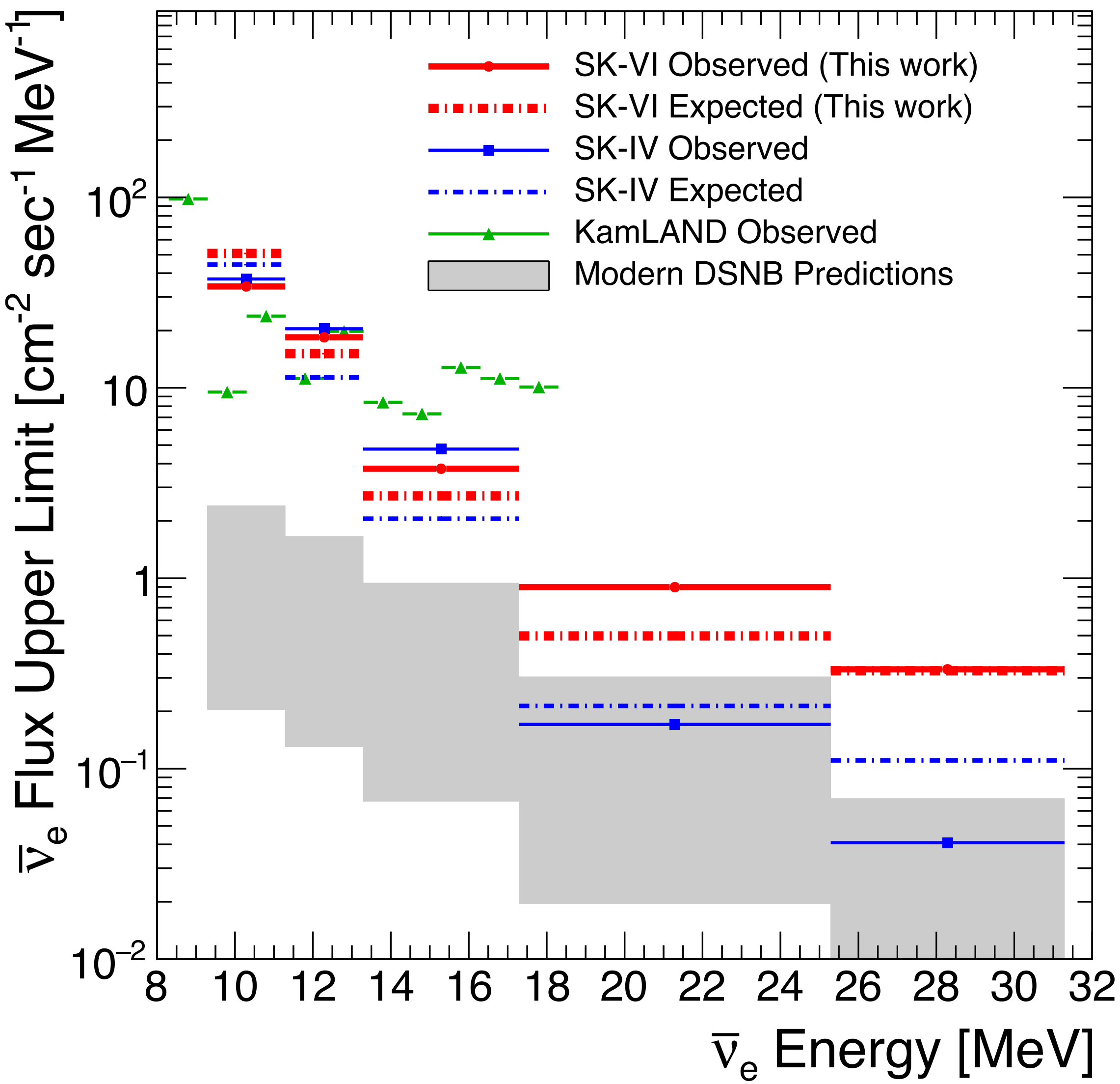
DSNB flux upper limits



M. Harada *et al*., Astrophys. J. Lett. **951**, L27 (2023)
M. Harada, Ph.D. Thesis, Okayama University (2023)

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}):

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

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

- Measured cross section:

$$\left\langle \sigma_{\mathrm{NCQE}}^{\mathrm{measured}} \right\rangle = f_{\mathrm{NCQE}} \times \left\langle \sigma_{\mathrm{NCQE}}^{\mathrm{theory}} \right\rangle$$

$$= 0.74 \pm 0.22(\mathrm{stat.}) \times 10^{-38}\ \mathrm{cm}^2/\mathrm{oxygen}$$

NCQE cross section

- Number of events

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

NCQE cross section

- Systematic uncertainties

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

NCQE cross section

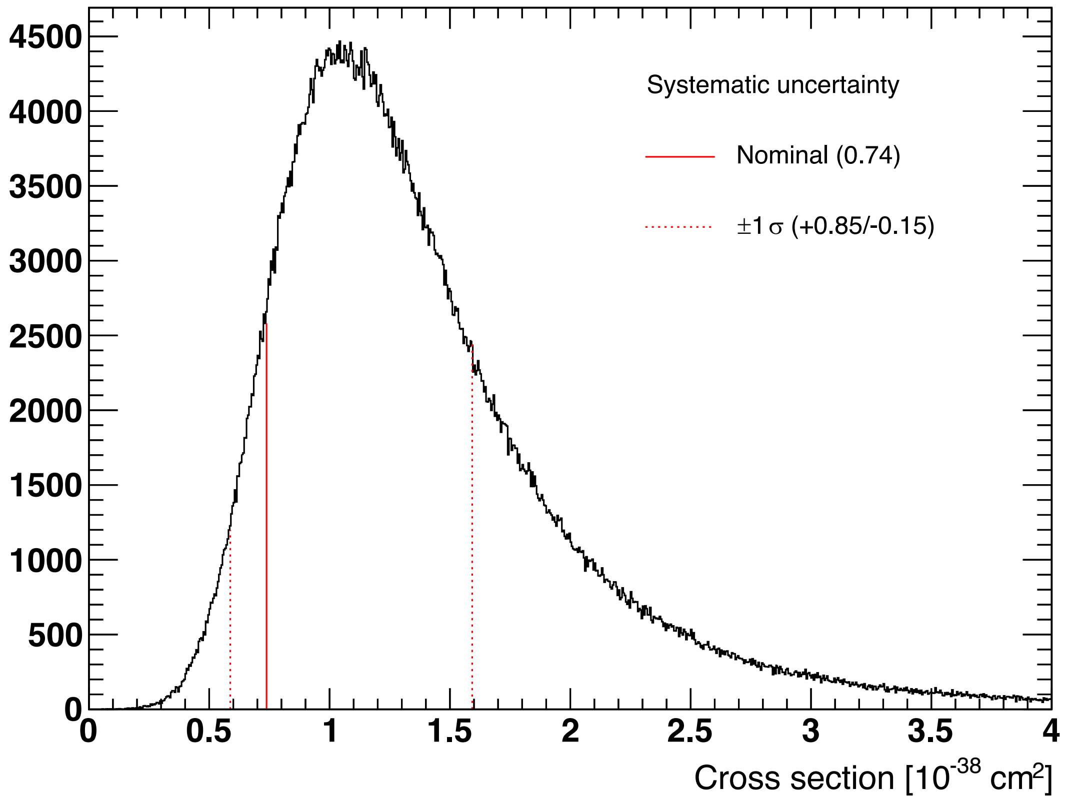
- Systematic uncertainties
  - $N^{\mathrm{exp}}_{\mathrm{spallation}}$: 60.0%
    - From DSNB analysis
  - $N^{\mathrm{exp}}_{\mathrm{Reactor}}$: 100.0%
    - From DSNB analysis
  - $N^{\mathrm{exp}}_{\mathrm{Accidental}} = \epsilon_{\mathrm{mis}} \times N^{\mathrm{obs}}_{\mathrm{pre-ntag}}$: 4.6%
    - 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	$\pm 18.0\%$
Atmospheric neutrino/antineutrino ratio	$\pm 5.0\%$
Cross section	$\pm 24.0\%$
Primary interaction	$+1.2\%/-8.0\%$
Secondary interaction	-20.7%
Energy cutoff	-19.9%
Data reduction	$\pm 1.4\%$
Neutron tagging	$\pm 6.4\%$

NCQE cross section

- Determine systematic uncertainty of $\langle \sigma_{\mathrm{NCQE}}^{\mathrm{measured}} \rangle = \frac{N^{\mathrm{obs}} - N_{\mathrm{NC\,non-QE}}^{\mathrm{exp}} - N_{\mathrm{Others}}^{\mathrm{exp}}}{N_{\mathrm{NCQE}}^{\mathrm{exp}}} \times \langle \sigma_{\mathrm{NCQE}}^{\mathrm{theory}} \rangle$ 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 $\langle \sigma_{\mathrm{NCQE}}^{\mathrm{measured}} \rangle$ to plot
3. Repeat procedures above 1 million times
4. Range of 1σ from $\langle \sigma_{\mathrm{NCQE}}^{\mathrm{measured}} \rangle = 0.74 \times 10^{-38}\ \mathrm{cm}^2/\mathrm{oxygen}$ is the systematic uncertainty



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

S. Sakai *et al.*, Phys. Rev. D **109**, L011101 (2024)
S. Sakai, Ph.D. Thesis, Okayama University (2024)

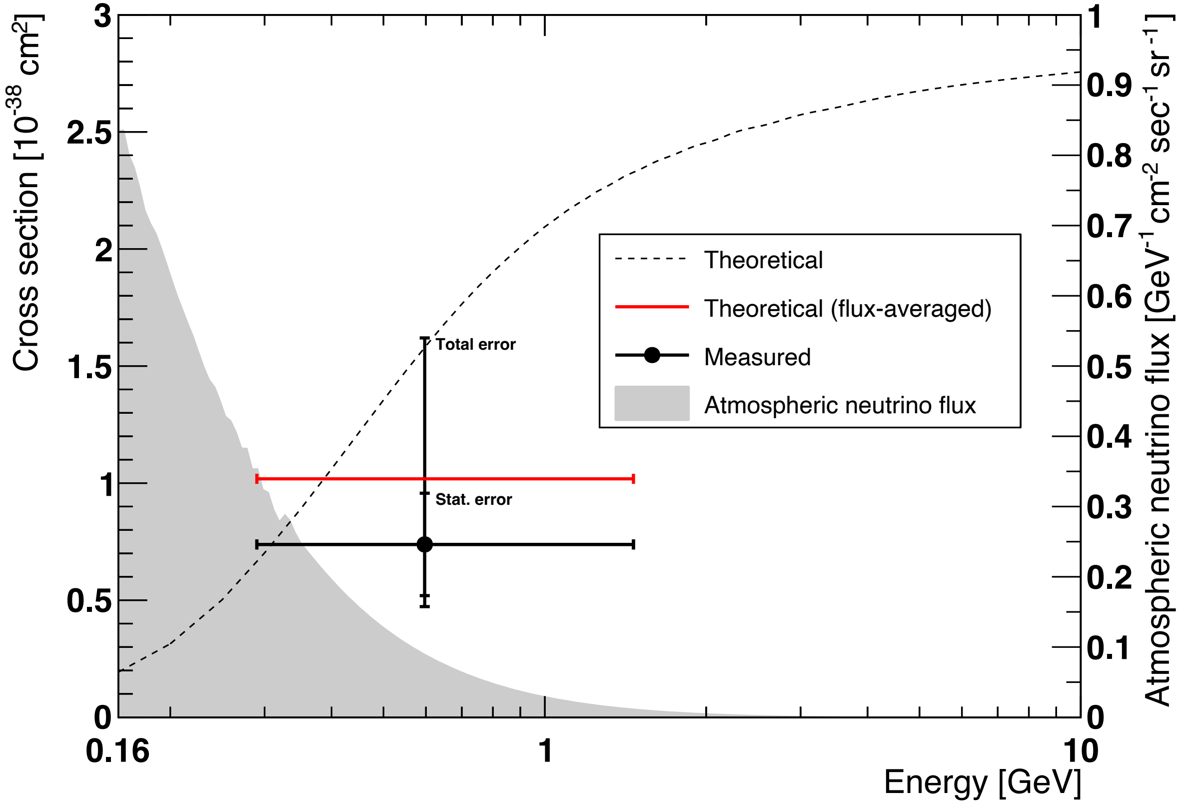
NCQE cross section

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

  → Consistent with

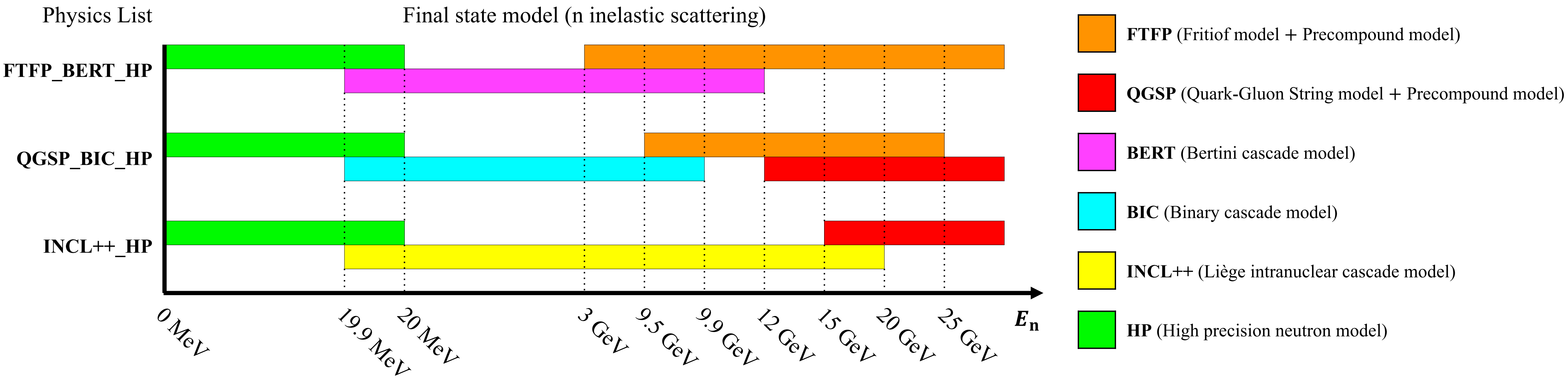
  $\left\langle \sigma_{\mathrm{NCQE}}^{\mathrm{theory}} \right\rangle = 1.02 \times 10^{-38}\ \mathrm{cm}^2/\mathrm{oxygen}$

  within the uncertainties



S. Sakai *et al*., Phys. Rev. D **109**, L011101 (2024)
S. Sakai, Ph.D. Thesis, Okayama University (2024)

Nucleon-nucleus interaction model



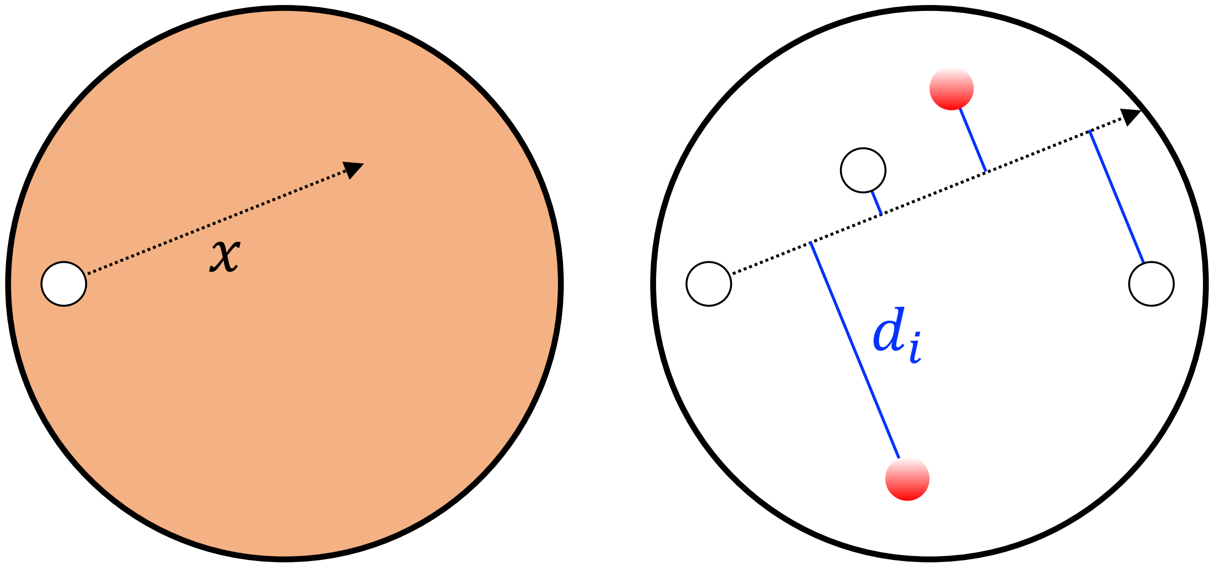
S. Sakai, Ph.D. Thesis, Okayama University (2024)

Differences of nucleon-nucleus interaction model

- Reaction point with nucleons in the nucleus
  - BERT: Determine using mean free path
  - BIC, INCL++: Determine using closest approach distance

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

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



Differences of nucleon-nucleus interaction model

- Stopping time of intranuclear cascade process
  - BERT, BIC: Stop when all (escapable) particles escape the nucleus
  - INCL++: Force 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

Comparison of nucleon-nucleus interaction model

- Calculate χ^2 using Poisson likelihood

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

- 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

	$\chi^2/\mathrm{ndf}\ (\theta_C)$	$\chi^2/\mathrm{ndf}\ (E_{\mathrm{vis}})$	$\chi^2/\mathrm{ndf}\ (N_{\mathrm{delayed}})$
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

Comparison of nucleon-nucleus interaction model

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

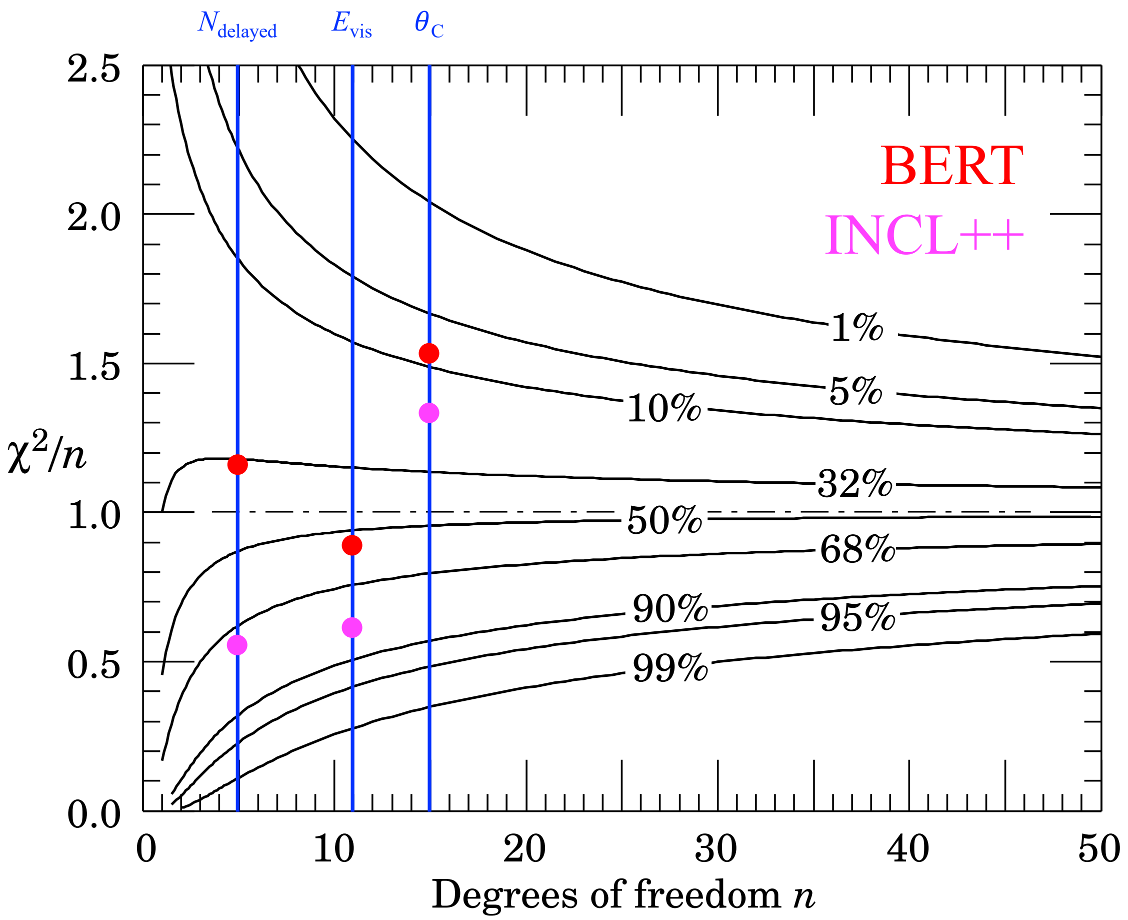
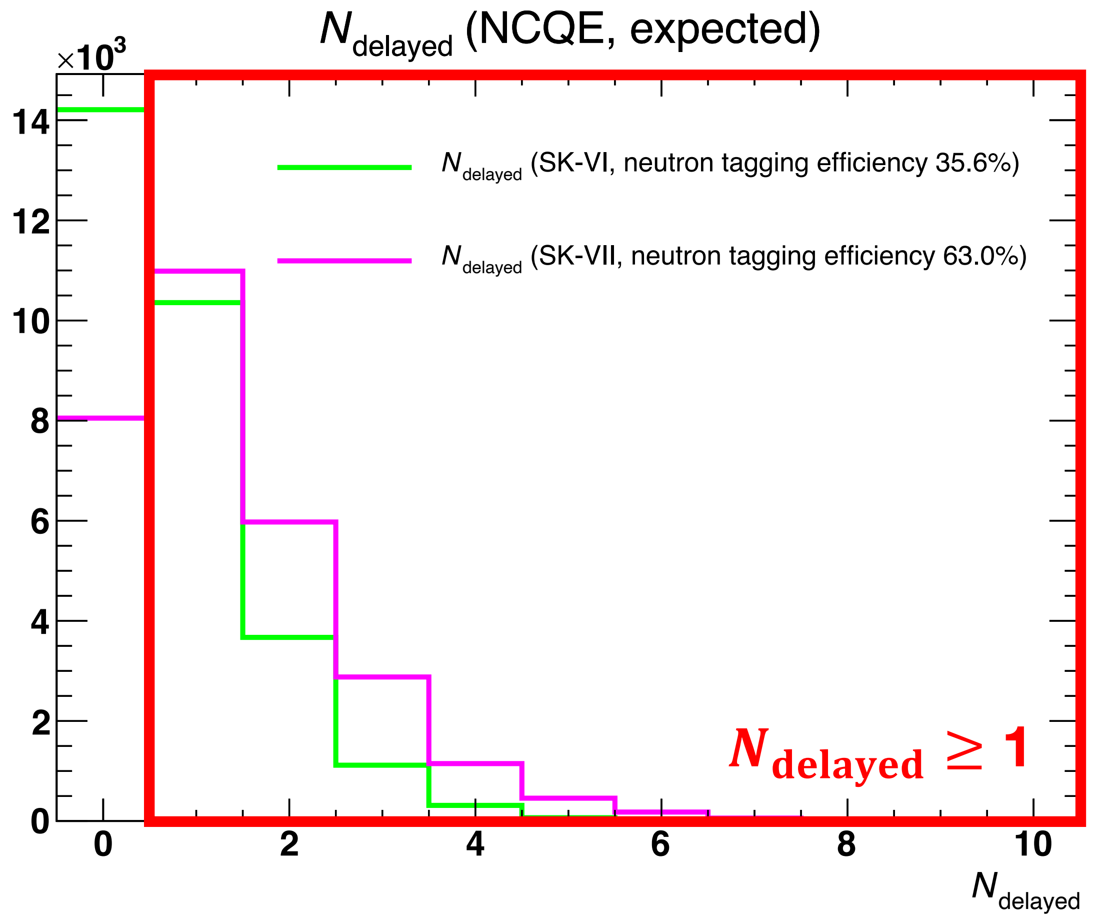


Figure 40.2: The 'reduced' χ^2, equal to χ^2/n, for n degrees of freedom. The curves show as a function of n the χ^2/n that corresponds to a given p-value.

Determination of nucleon-nucleus interaction model

- SK continues to observe with 0.03% by mass of Gd (SK-VII)

- Assume that neutron tagging efficiency improves from 35.6%[1] (Gd: 0.011%, SK-VI) to 63.0%[2] (Gd: 0.03%, SK-VII)
  → Statistics increases by about 1.4 times with the same live time



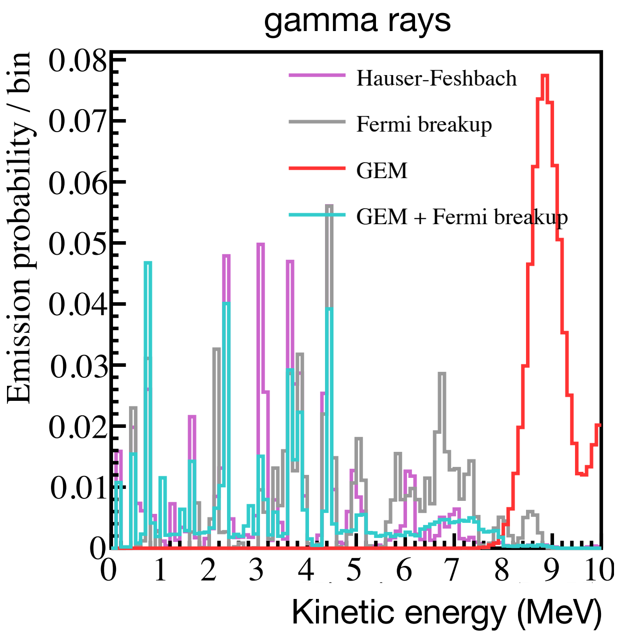
[1] M. Harada *et al.*, Astrophys. J. Lett. **951**, L27 (2023)
[2] Y. Kanemura, "Improvement of neural network analysis in SK-VII", SK internal slide (2023)

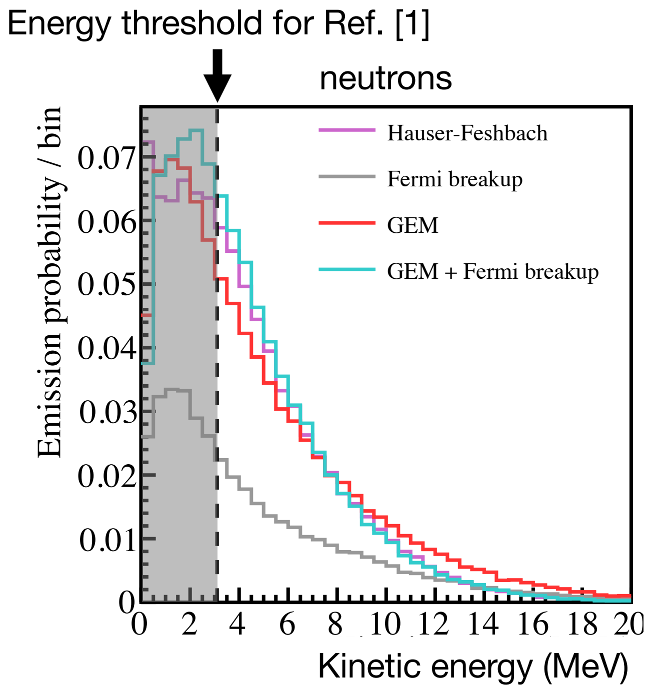
Current situation

- No published data for particle decay branching ratio from highly excited states of $^{15}O^*$ and $^{16}O^*$
- Normal-kinematics experiment with $^{16}O(p, 2p)^{15}N^*$ reaction[1]
  - Only particles with energy above ~3 MeV are detected
  - SK is sensitive to all thermalized neutrons regardless of their initial energy

→ Insufficient to reduce uncertainties of atmospheric neutrino backgrounds to ~10% level

Emission probability from de-excitation process of $^{15}N^*$ (Excitation energy: 20-40 MeV)





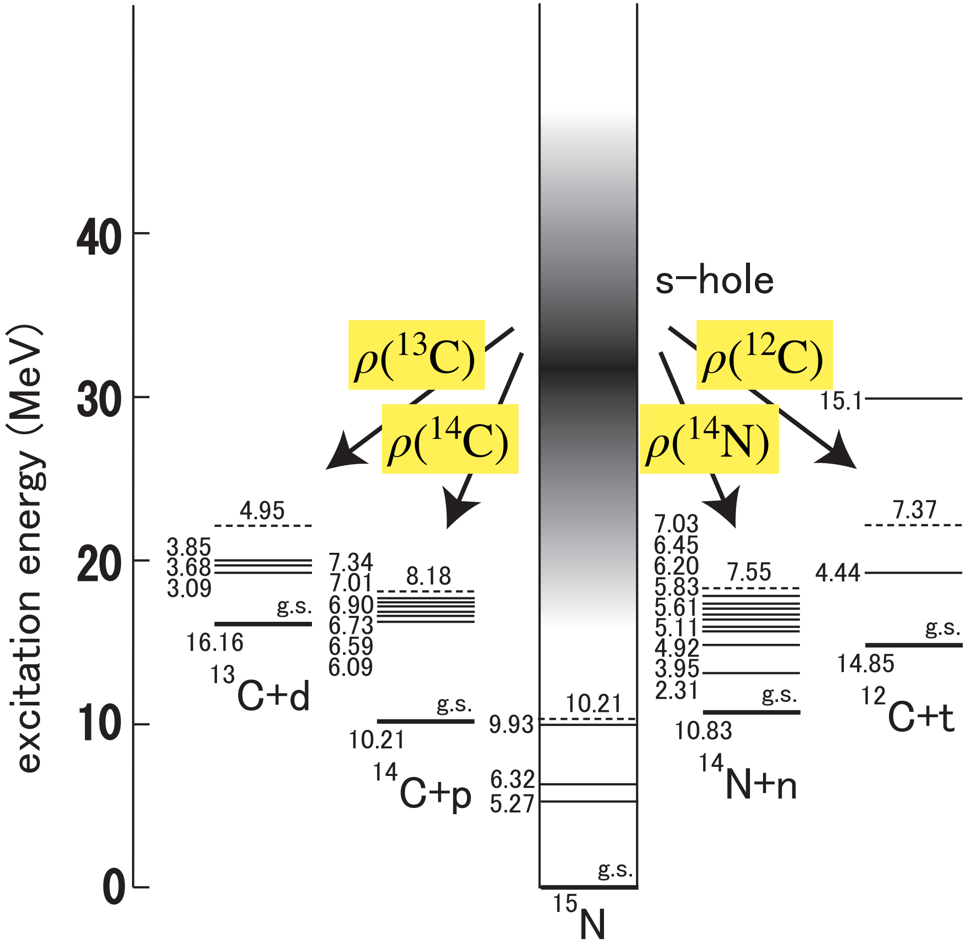
[1] M. Yosoi, Ph.D. Thesis, Kyoto University (2003)

Oxygen beam experiment at the RIBF

- Plan to perform the inverse-kinematics experiment with ^{16}O(p, 2p)^{15}N*, ^{16}O(p, pn)^{15}O*, and ^{17}O(p, pn)^{16}O* reactions using the SAMURAI spectrometer
  - Beam: ^{16}O and ^{17}O (200 MeV/u)
  - Target: Liquid hydrogen

- Would like to measure
  - Particle decay branching ratio from ^{15}N*, ^{15}O* and ^{16}O* as a function of excitation energy
  - Energy spectrum of de-excitation gamma rays and neutrons <u>without energy threshold</u>

  → Tune the level densities in the Hauser-Feshbach (statistical) model

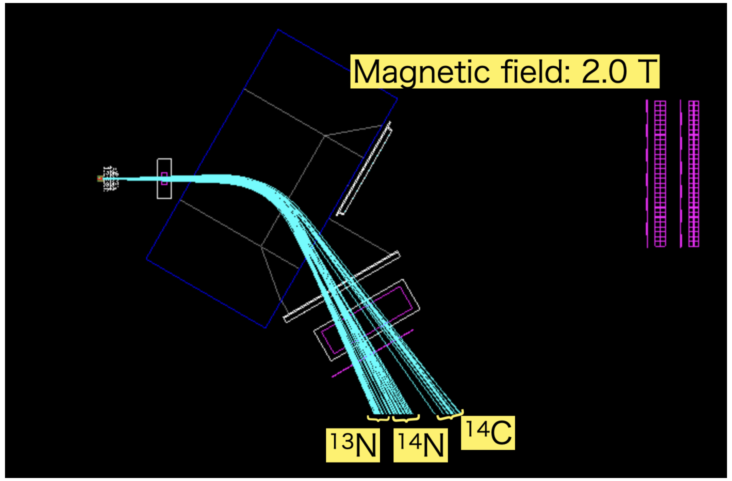


K. Kobayashi *et al.*, arXiv:nucl-ex/0604006v1 (2006)

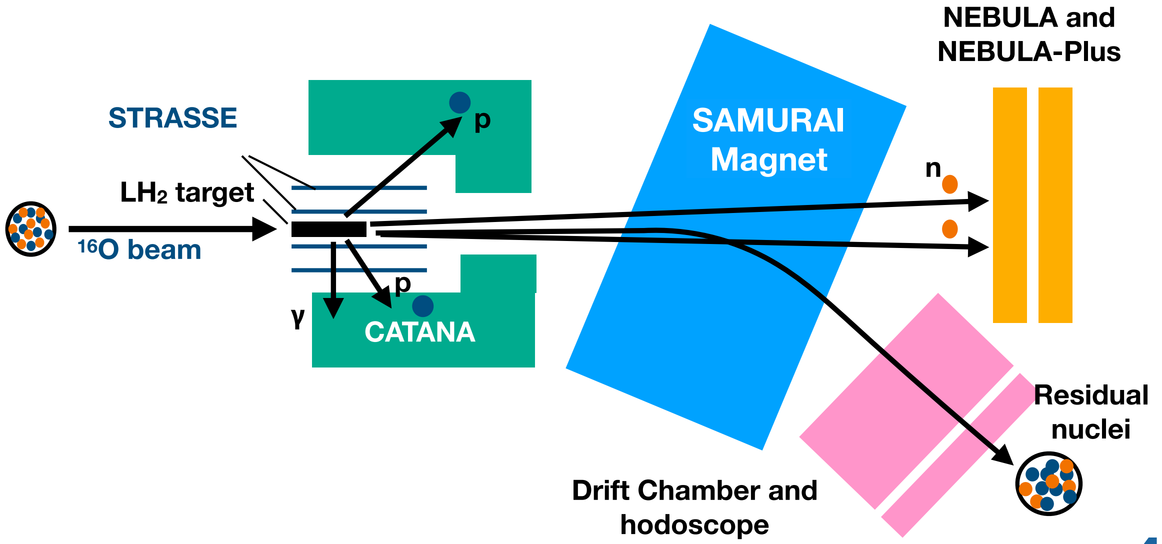
Oxygen beam experiment at the RIBF

Experimental setup for $^{16}O(p, 2p)^{15}N^*$

- Detect <u>knock-out protons</u> with STRASSE (silicon) and CATANA (CsI(Na) crystals) detectors
  - → Identify $^{16}O(p, 2p)^{15}N^*$ reaction
  - → Reconstruct excitation energy of $^{15}N^*$



- Detect <u>de-excitation gamma rays</u> with CATANA detector
- Detect <u>de-excitation neutrons</u> with NEBULA and NEBULA-Plus (plastic scintillation) detectors
- Detect <u>residual nuclei and all other decay products</u> with the downstream detectors



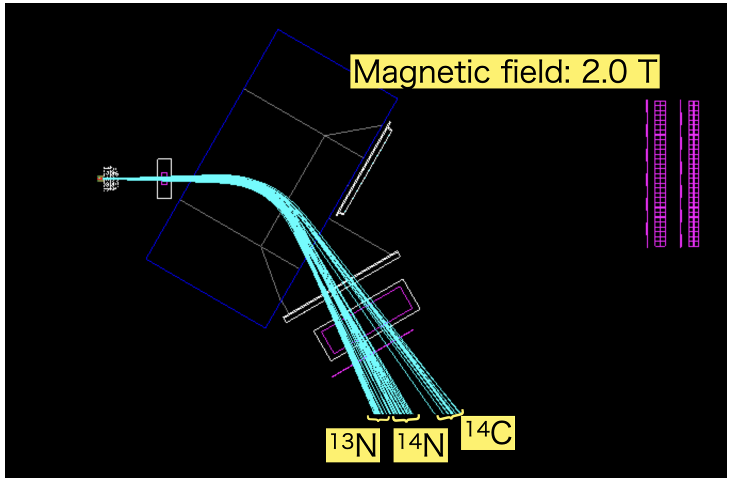
Oxygen beam experiment at the RIBF

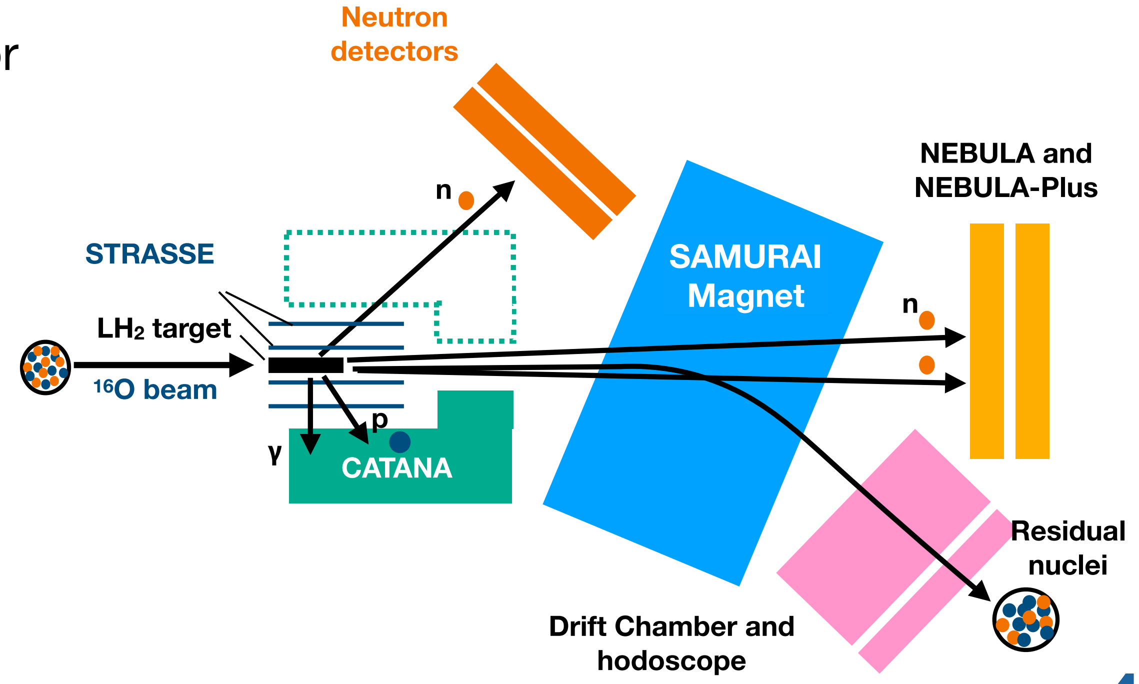
Experimental setup for ^{16}O(p, pn)^{15}O* and ^{17}O(p, pn)^{16}O*

- Detect <u>knock-out protons</u> with STRASSE and (half of) CATANA detectors
- Detect <u>knock-out neutrons</u> with HIME and MNEUT (plastic scintillation) detectors

  → Identify ^{16}O(p, pn)^{15}O* and ^{17}O(p, pn)^{16}O* reactions

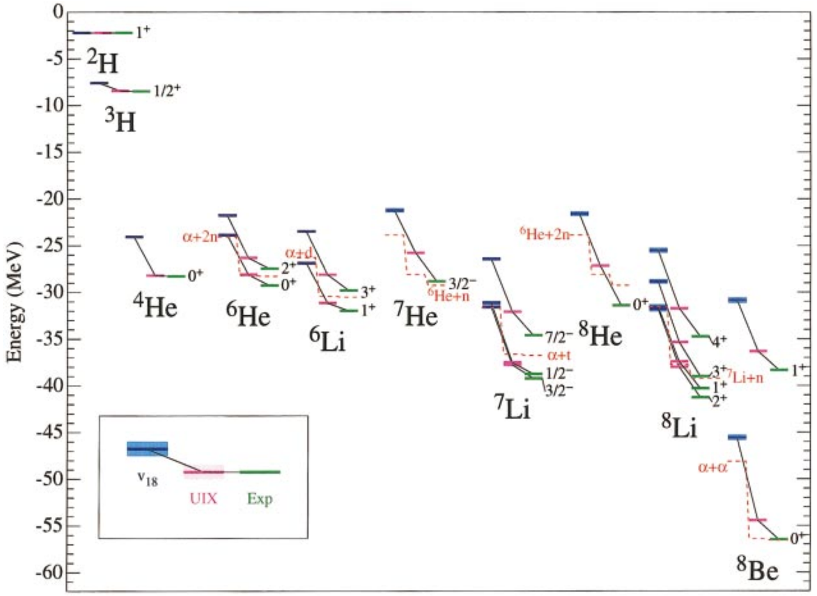
  → Reconstruct excitation energy of ^{15}O* and ^{16}O*
- Detect <u>de-excitation gamma rays</u> with CATANA detector
- Detect <u>de-excitation neutrons</u> with NEBULA and NEBULA-Plus (plastic scintillation) detectors
- Detect <u>residual nuclei and all other decay products</u> with the downstream detectors



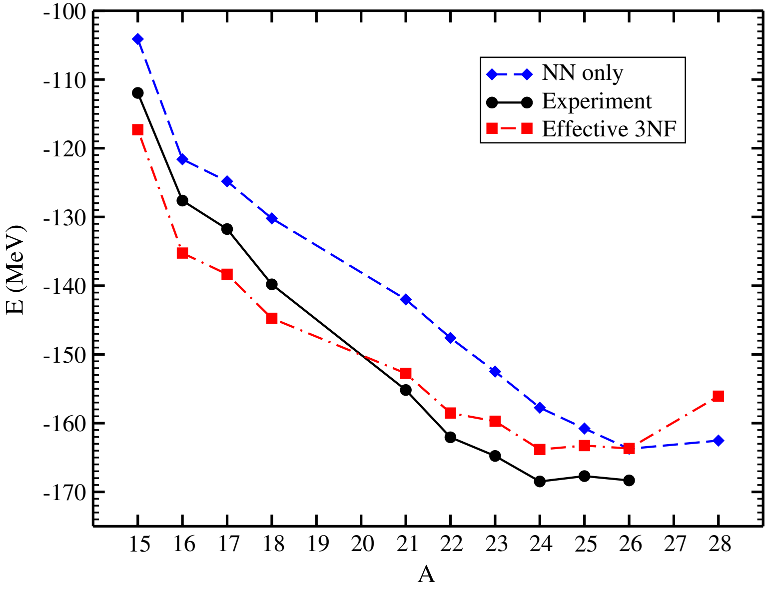


Three-nucleon force

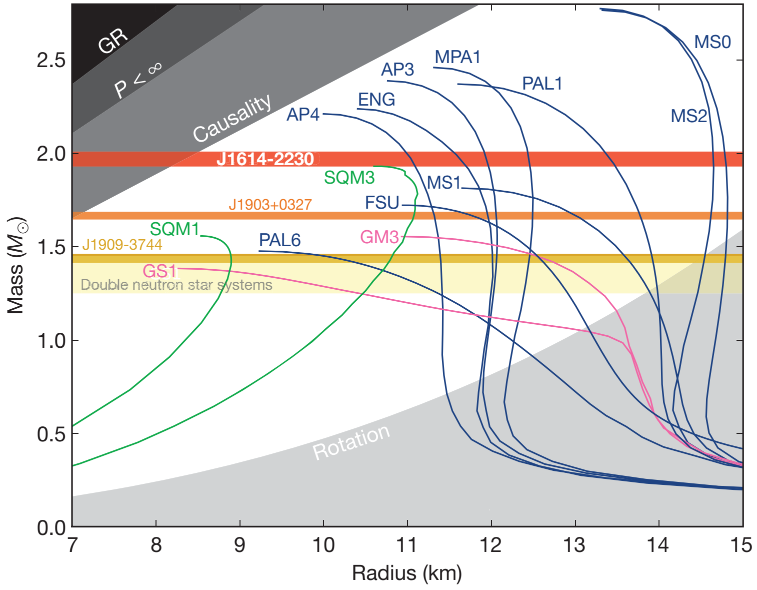
Binding energies of light nuclei



Binding energies of oxygen nuclei



Mass of neutron stars



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