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# Study of neutron multiplicity using atmospheric neutrino simulation in SK-Gd experiment

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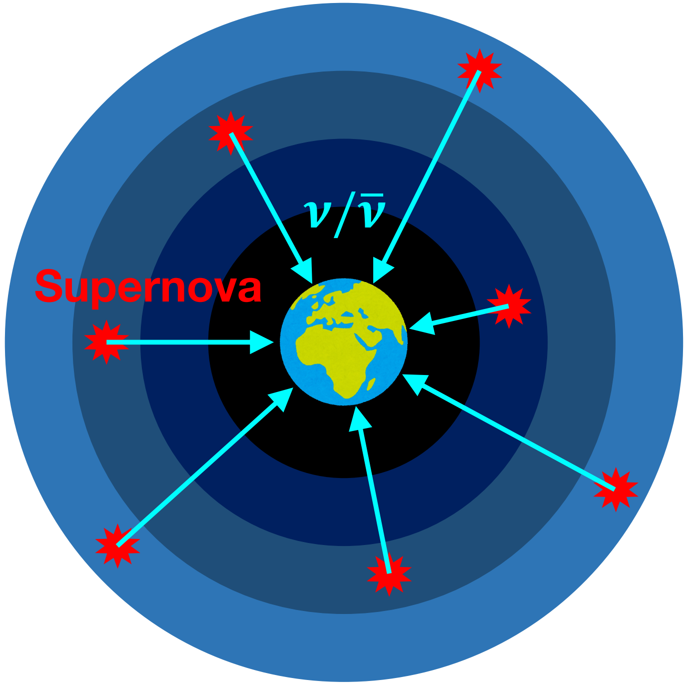
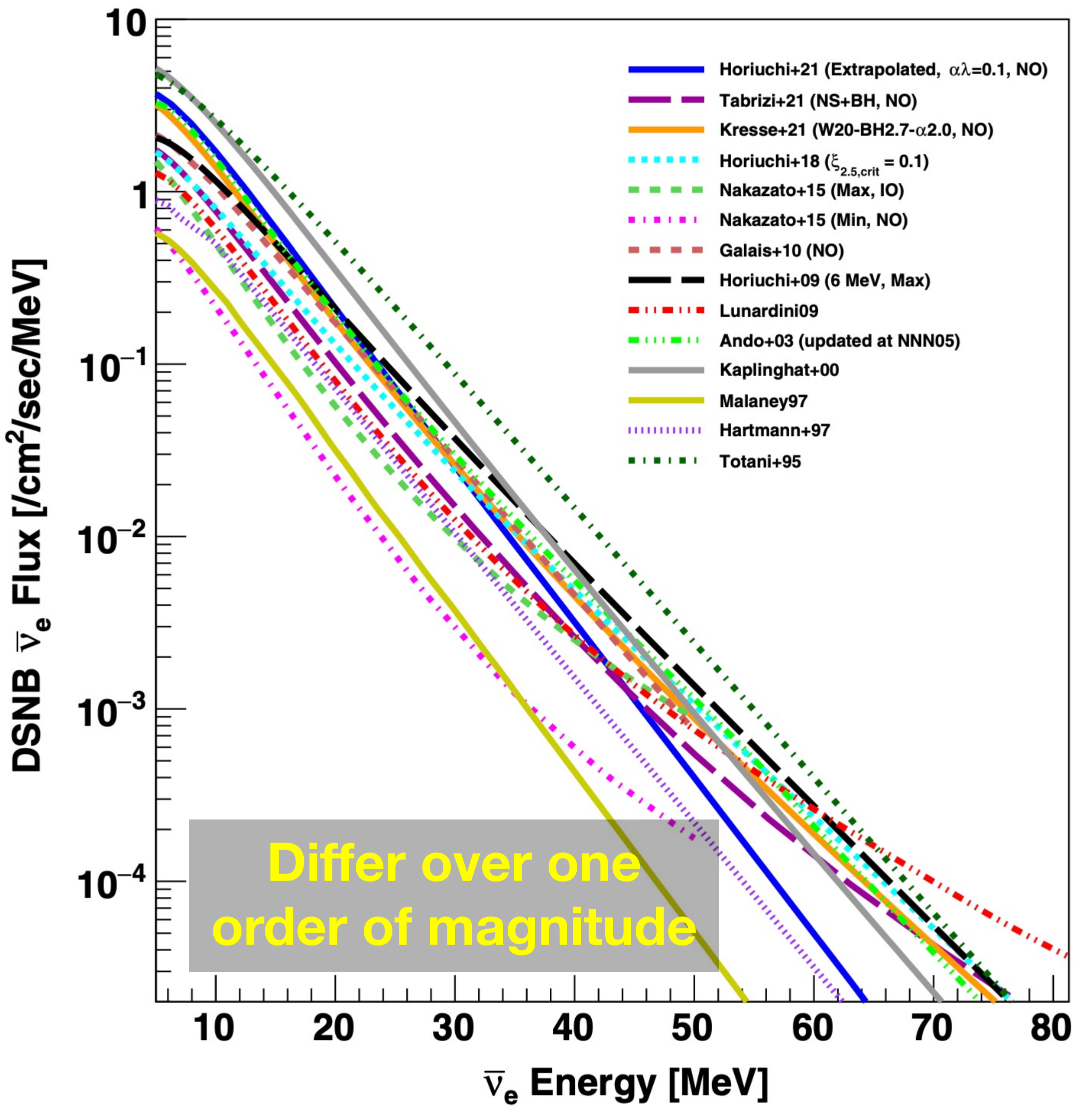
# Supernova Relic Neutrinos (SRN)

- Neutrinos from all past core-collapse supernovae are accumulated to form an integrated flux

  → **Supernova Relic Neutrinos (SRN**, DSNB**)**
- Detecting SRN would provide valuable information about **the supernova mechanism** and **the star formation history**



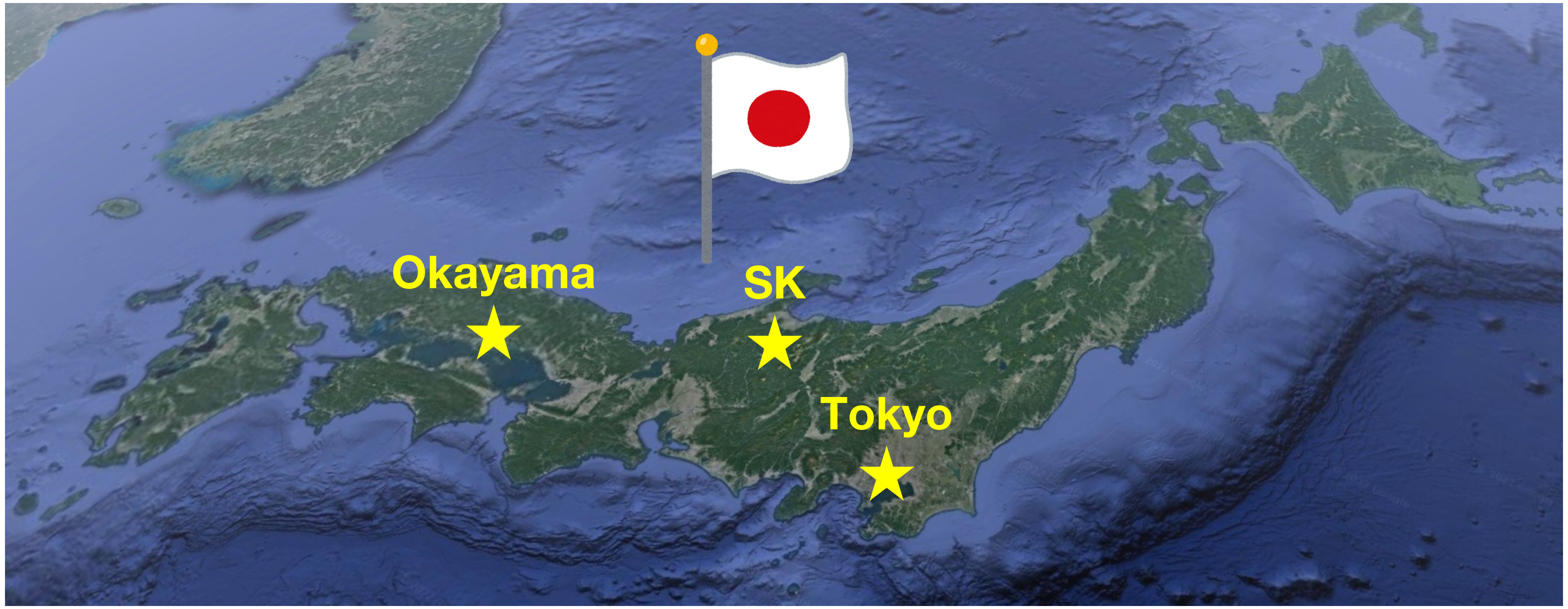


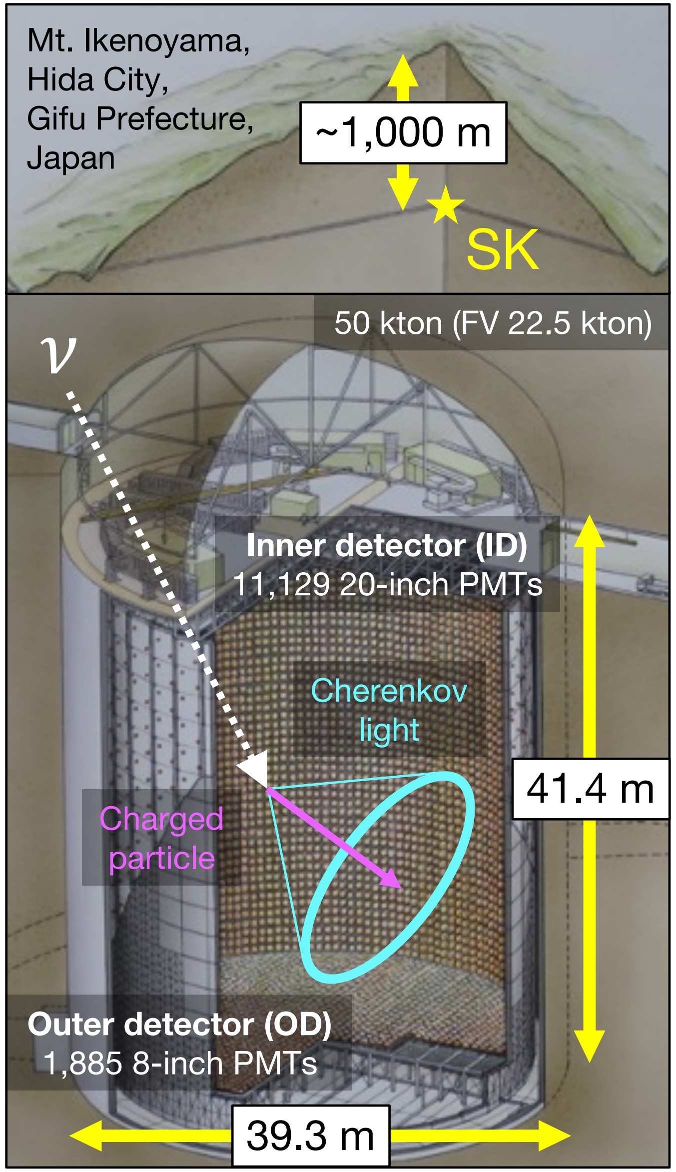
Differ over one order of magnitude

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

# Super-Kamiokande (SK)

- Large water Cherenkov detector
- Consist of tank filled with ultrapure water and photomultiplier tube (PMT)
- ID : Reconstruct the information of charged particle
- OD : Cosmic ray muons veto
- Now SK is aiming for **the world's first observation of SRN**





# SRN search in SK

- Target in SRN search

  → **Inverse beta decay by $\bar{\nu}_e$**

  $\bar{\nu}_e + p \rightarrow \boldsymbol{e^+}$ (Prompt signal) + $\boldsymbol{n}$ (Delayed signal)

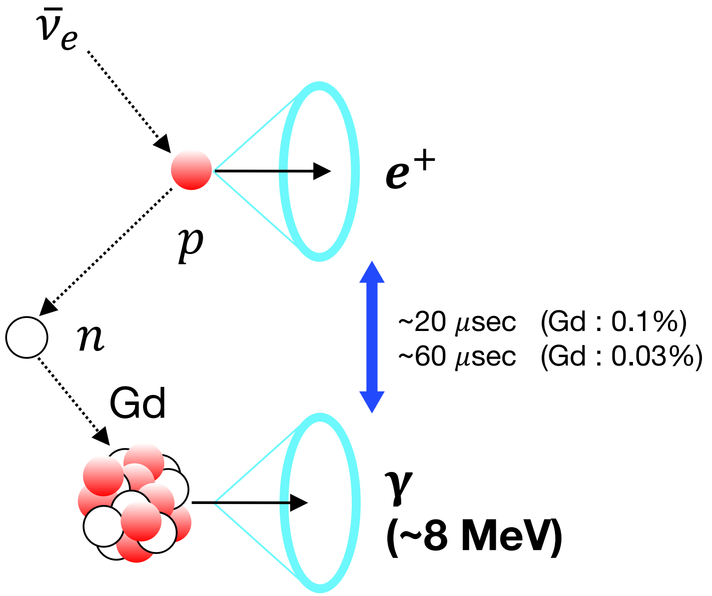
- **SK-Gd experiment** (Jul. 2020 - )

  → Load 0.1% (now 0.03%) of gadolinium (Gd) in ultra-pure water

- Gd has the largest thermal neutron capture cross section among natural elements
- Emit $\gamma$-rays of total ~8 MeV when Gd captured thermal neutron

  → Neutron tagging efficiency : ~90% (now ~70%)

  → Can reduce the backgrounds of SRN search

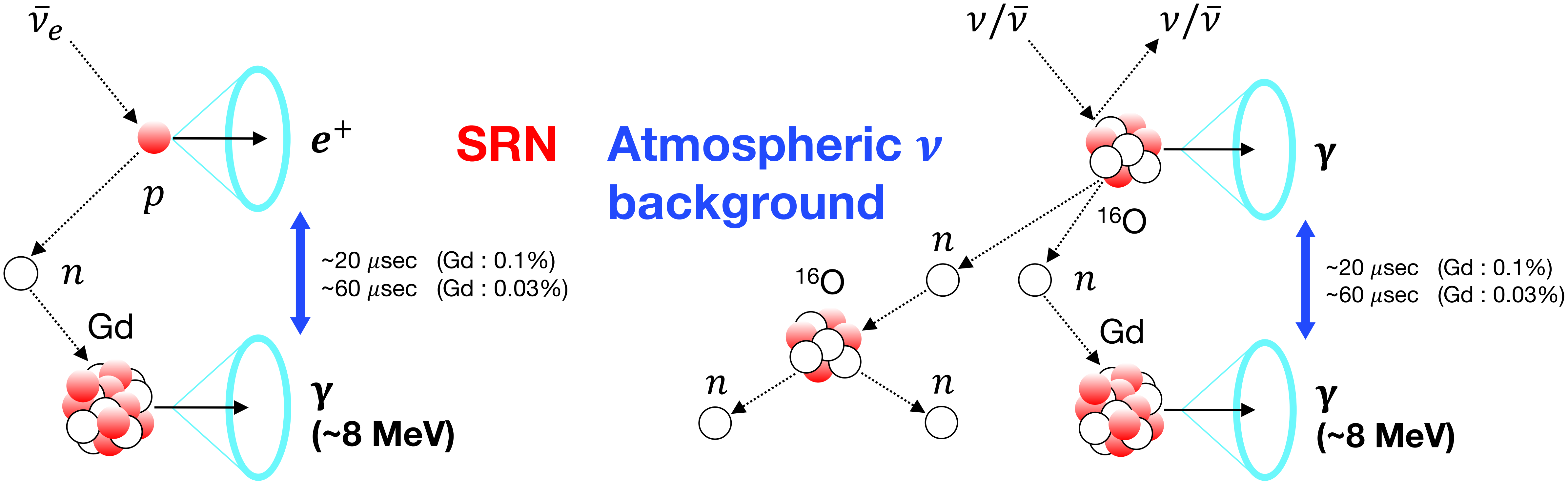


- But...

  **There are some backgrounds that we cannot distinguish even in SK-Gd experiment**

# Atmospheric neutrino background

- Mimic the signal of SRN event → Need to estimate # of events precisely
- **Neutron multiplicity** (# of emitted neutrons per event) is different
- Understand the neutron multiplicity → Can reduce the background and estimate it more precisely



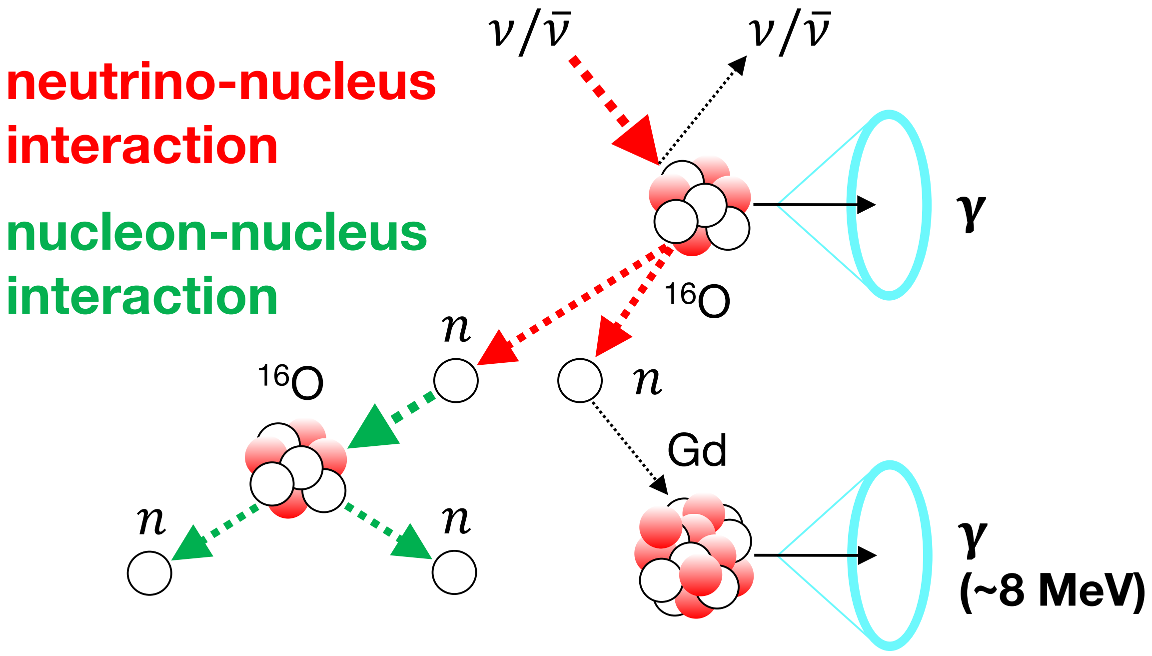
**SRN**

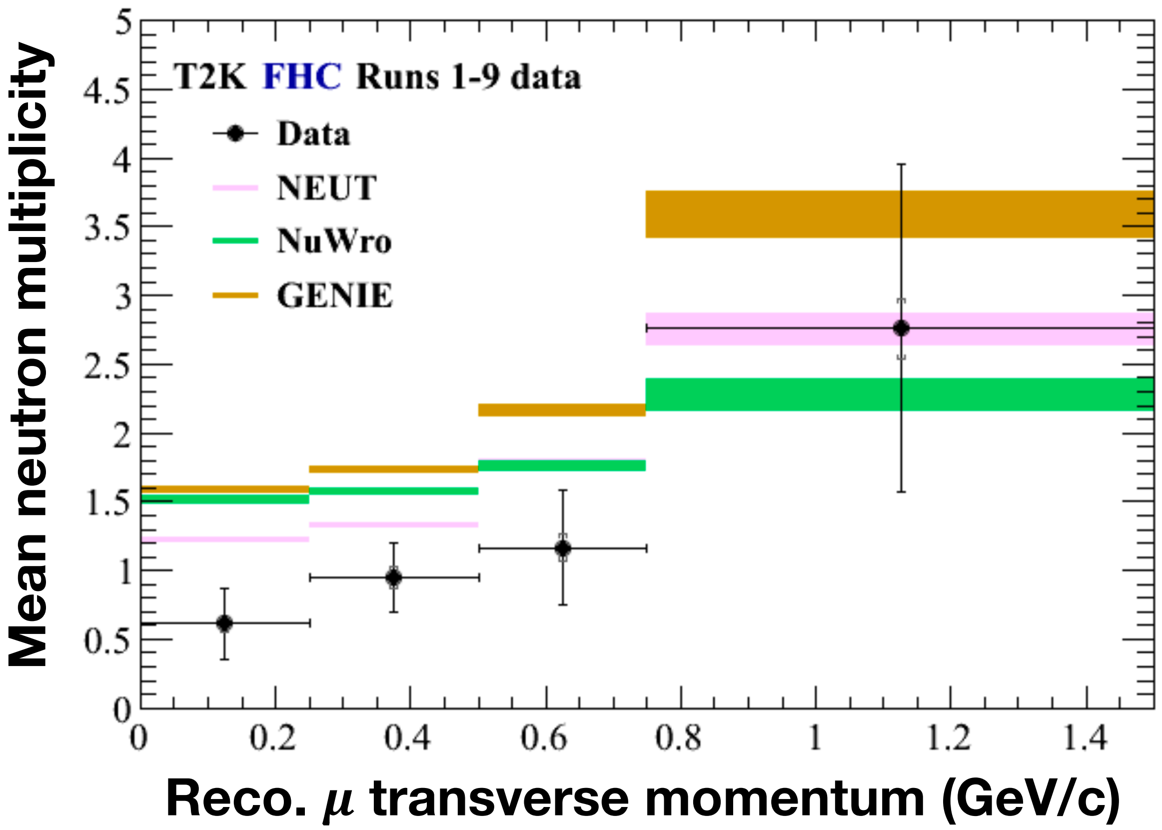
**Atmospheric $\nu$ background**

# Neutron multiplicity

- Neutron multiplicity expected from simulation is larger than observed data

  → Caused by **neutrino-nucleus interaction**? or **nucleon-nucleus interaction**?





R. Akutsu, Ph.D. Thesis, The University of Tokyo (2019)

# Purpose

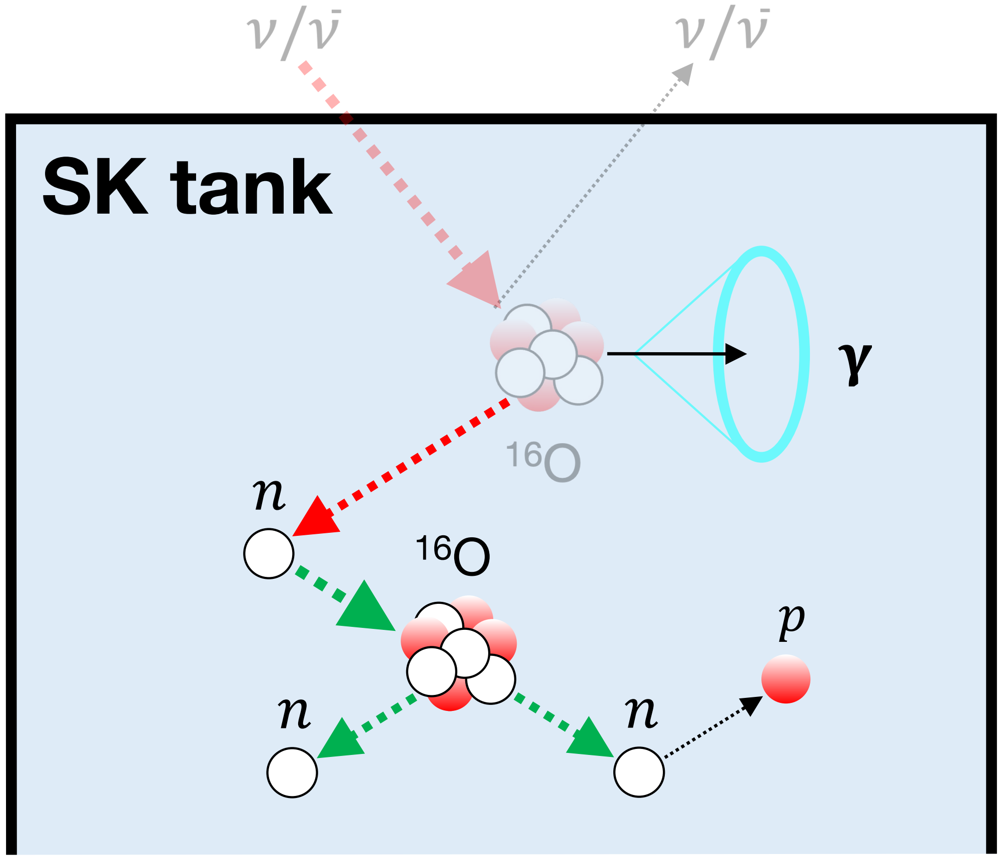
- **Check the change of neutron multiplicity by the difference of nucleon-nucleus interaction model**

- Make 500 years worth of atmospheric neutrino events (0 - 2 GeV) using neutrino reaction simulation (NEUT)

  → Check neutron multiplicity by nucleon-nucleus interactions using Geant4-based detector Monte Carlo simulation

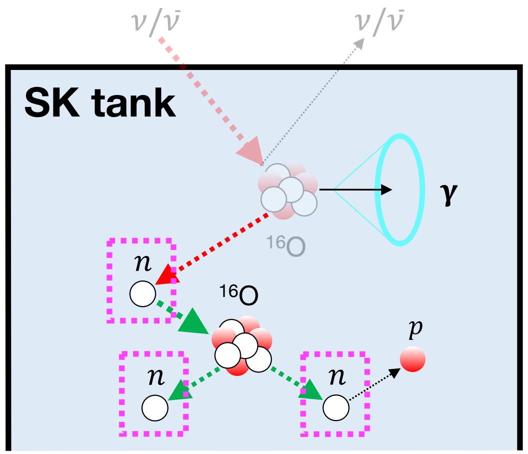
- Nucleon-nucleus interaction model we compared

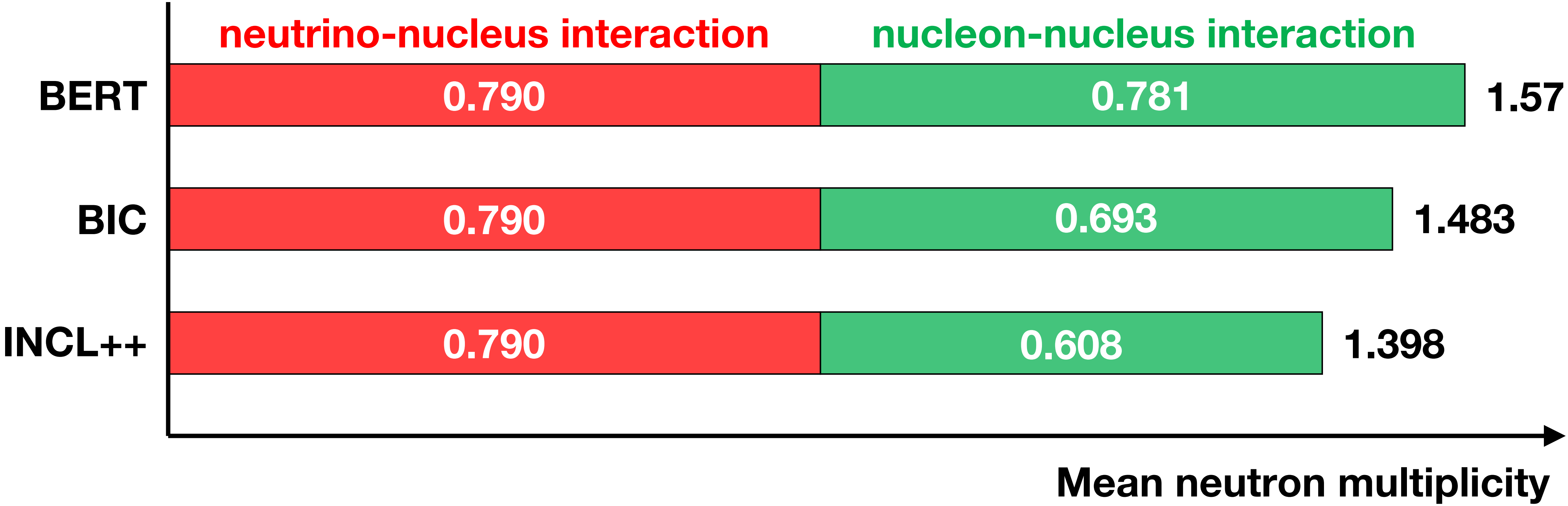
| | |
|---|---|
| **BERT** | (Binary cascade model) |
| **BIC** | (Binary cascade model) |
| **INCL++** | (Liege cascade model) |



# Mean neutron multiplicity

- Convert # of neutrons generated by 500 years worth of atmospheric neutrino events (0 - 2 GeV, total 3,857,094 events) into per event

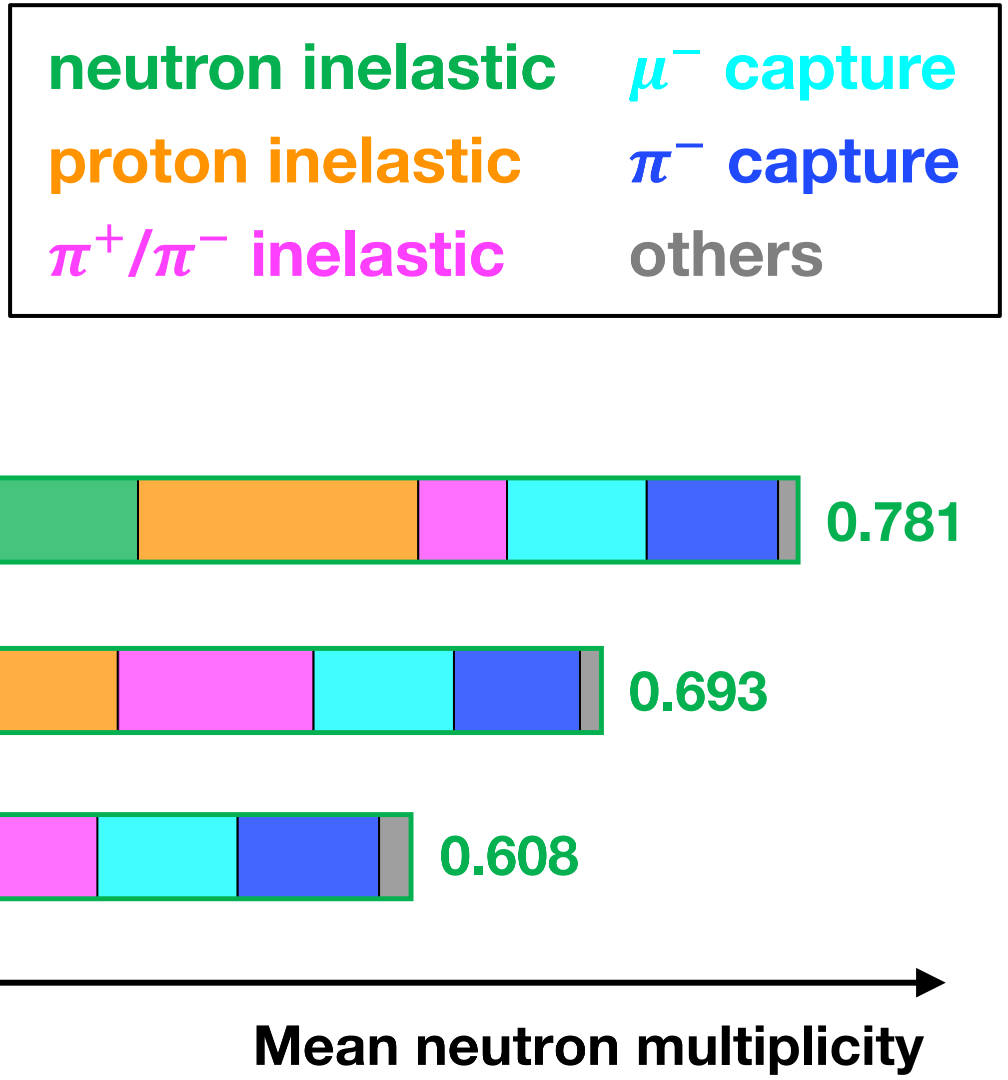




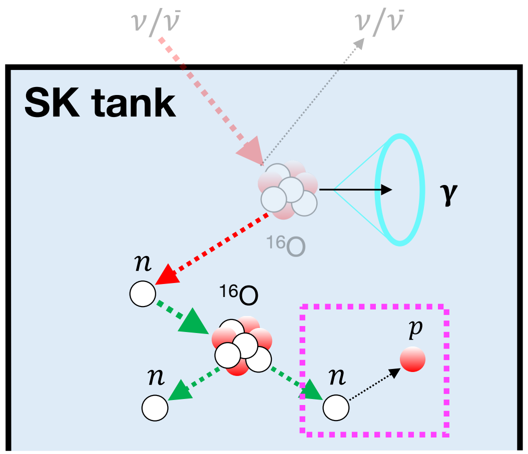
# Difference among nucleon-nucleus interaction models

- Large difference in neutron inelastic scattering
- Cross section of neutron inelastic scattering is the same among the models

  → **Neutrons are easy to be generated by neutron inelastic scattering in BERT**



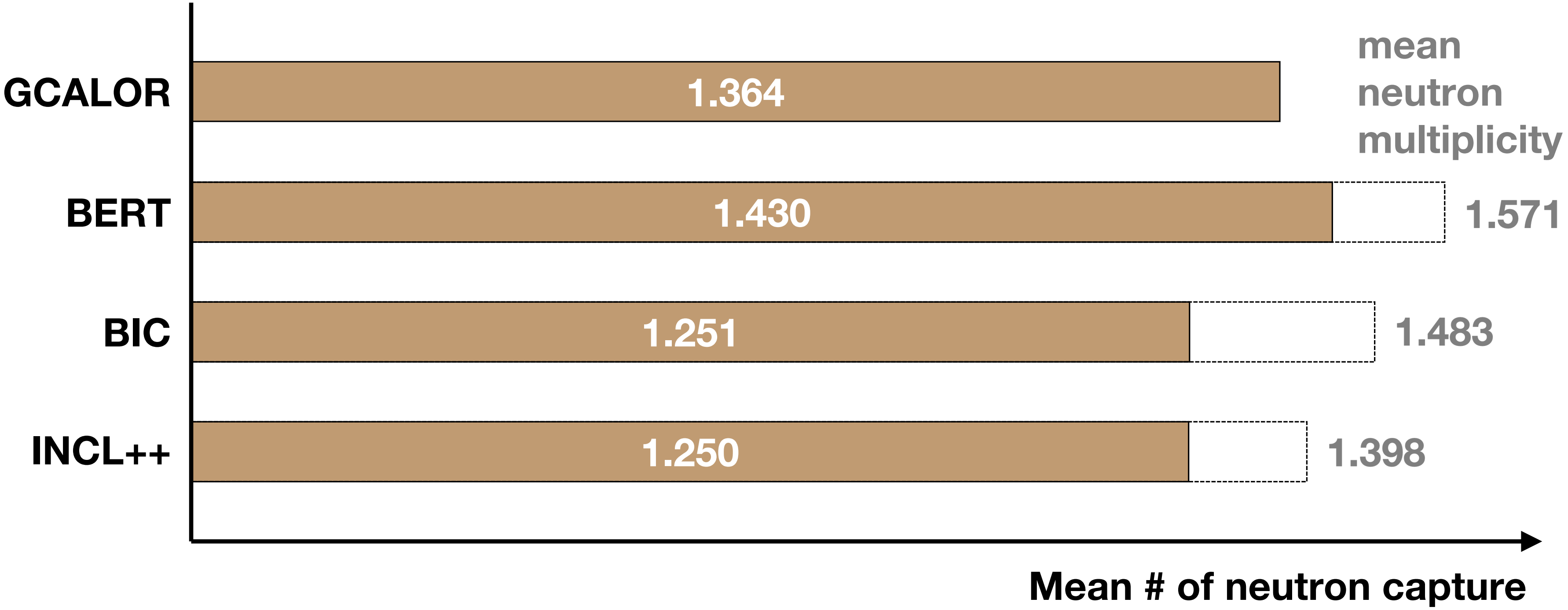
# Mean # of neutron capture



- **GCALOR** : Physics model used in GEANT3-based detector Monte Carlo simulation (Close to BERT)
- Mean # of neutron capture is smaller than mean neutron multiplicity

→ Annihilate neutrons that have escaped from the detector

→ Neutron is annihilated by neutron inelastic scattering (e.g.) $n + {}^{16}\mathrm{O} \rightarrow {}^{13}\mathrm{C} + \alpha$

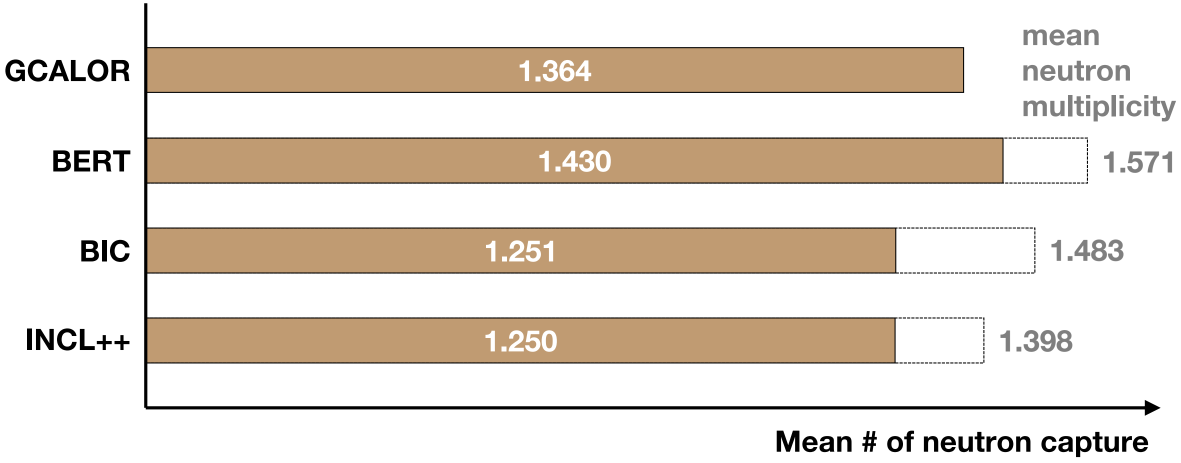


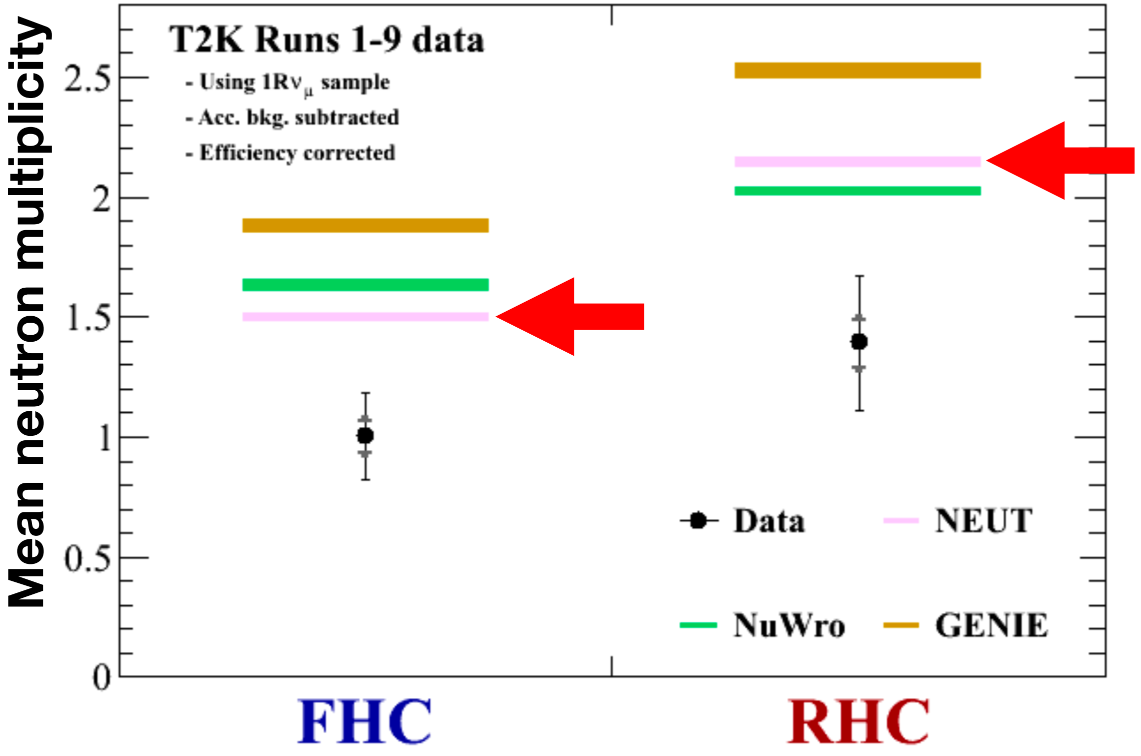
※ In GCALOR, only neutron capture by Hydrogen is considered

# Mean # of neutron capture

- From T2K experiment, neutron multiplicity of simulation (**NEUT & GCALOR**) is ~51% larger than that of observed data
  → Estimated to be ~39% larger than that of observed data even at NEUT & BIC or NEUT & INCL++
  → **Need to reconsider neutrino-nucleus interaction**

| **FHC** | **RHC** |
|---|---|
| **$1.50 \pm 0.02(\text{Stat.})$** | **$2.14 \pm 0.02(\text{Stat.})$** |
| **$1.00 \pm 0.17(\text{Stat.})^{+0.07}_{-0.08}(\text{Sys.})$** | **$1.40 \pm 0.26(\text{Stat.})^{+0.10}_{-0.11}(\text{Sys.})$** |





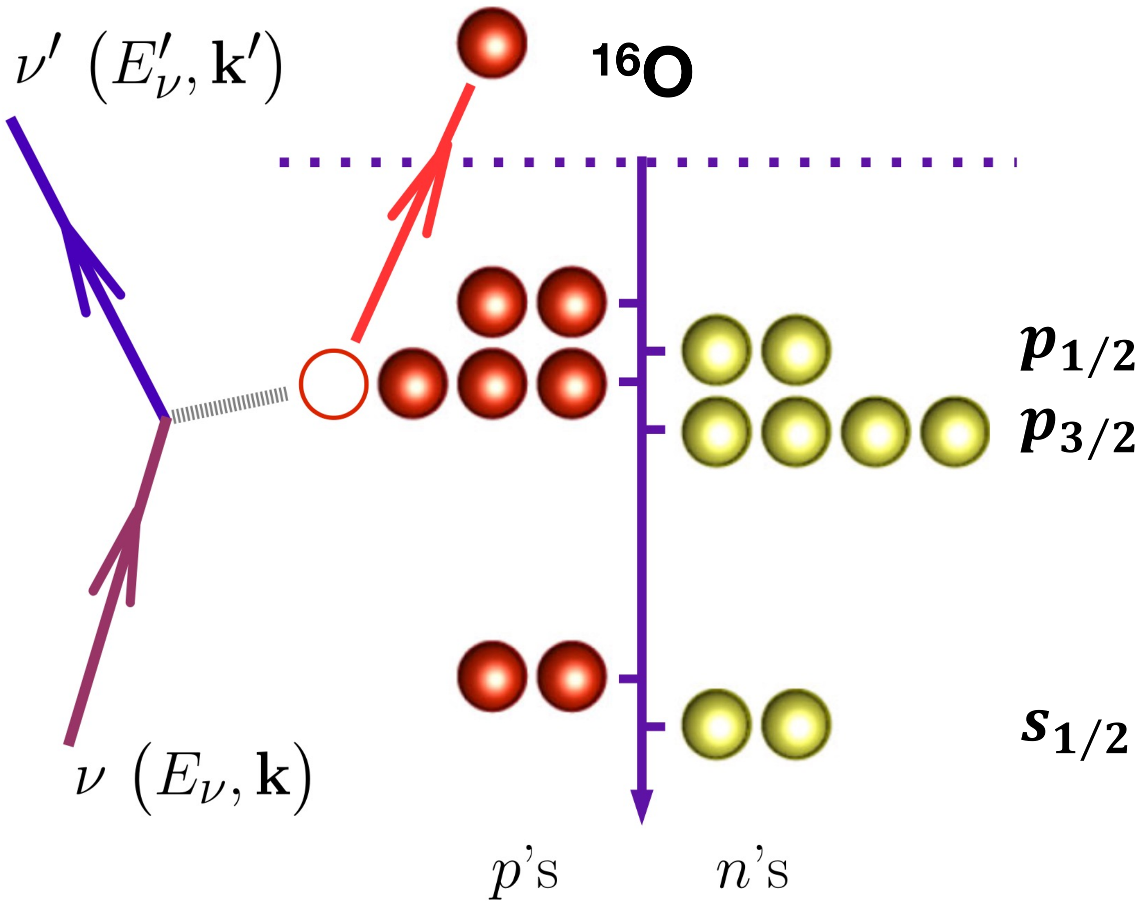
R. Akutsu, Ph.D. Thesis, The University of Tokyo (2019)

# Problems of neutrino-nucleus interaction model

- The probability of knocking out a nucleon of the $p_{1/2}$, $p_{3/2}$, $s_{1/2}$ or "others" state

※ "others" state is not understood well

| State | Probability |
|---|---|
| $p_{1/2}$ | 15.80% |
| $p_{3/2}$ | 35.15% |
| $s_{1/2}$ | 10.55% |
| others | 38.50% |



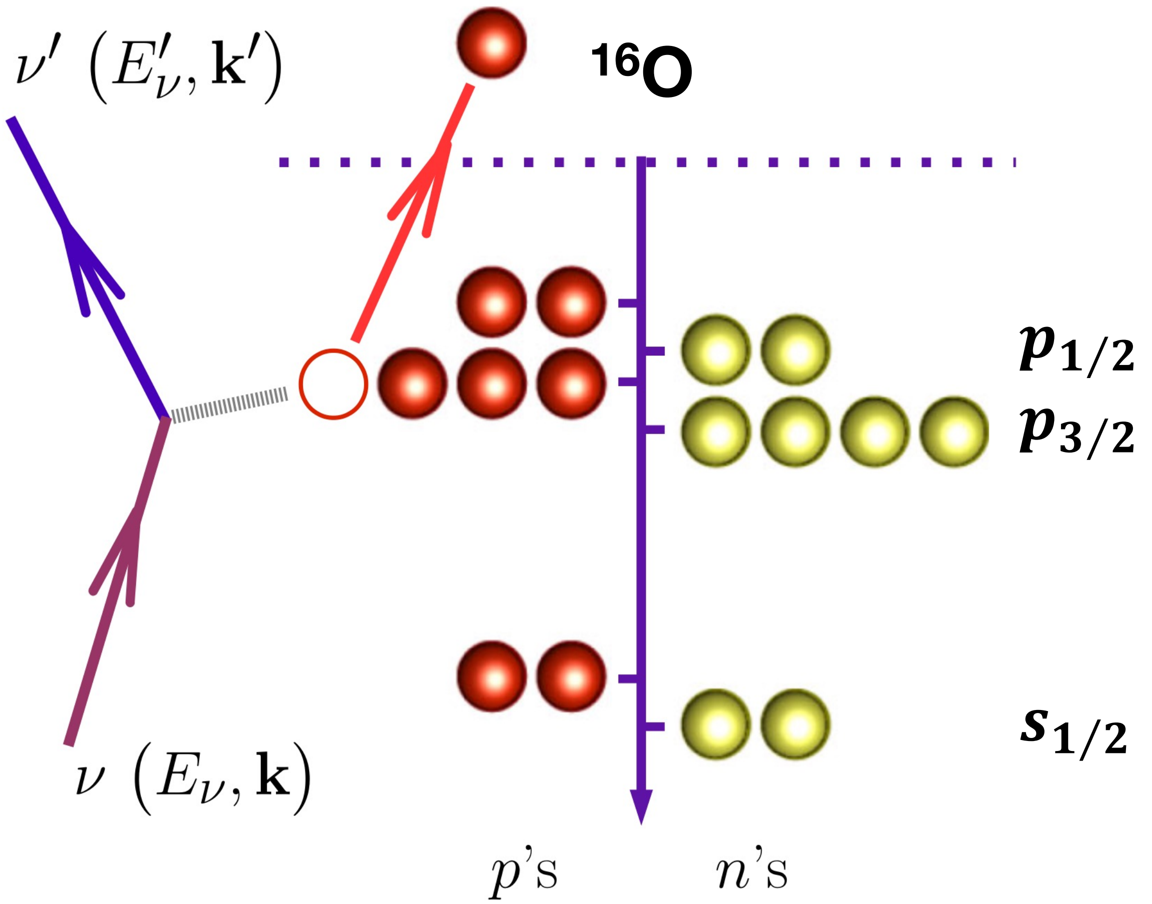
A. M. Ankowski *et al*., Phys. Rev. Lett. **108**, 052505 (2012)

# Problems of neutrino-nucleus interaction model

- The probability of knocking out a nucleon of the $p_{1/2}$, $p_{3/2}$, $s_{1/2}$ or “others” state

**In NEUT...**

| State | Probability |
|---|---|
| $p_{1/2}$ | 15.80% |
| $p_{3/2}$ | 35.15% |
| $s_{1/2}$ | **49.05%** (= 10.55% + 38.50%) |



- The energy level of nucleons of the $s_{1/2}$ state is deep

→ When a nucleon of the $s_{1/2}$ state is knocked out, nucleons are easy to be emitted during the de-excitation

→ **Important to understand “others” state**

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

# Summary

- Neutron multiplicity expected from atmospheric neutrino event simulation is larger than observed data

  → We do not understand that the cause is neutrino-nucleus interaction or nucleon-nucleus interaction

  → Check the change of neutron multiplicity by the difference of nucleon-nucleus interaction model
- Neutron multiplicity changes largely by neutron inelastic scattering
- As for neutrino-nucleus interaction, it is important to understand “others” state

## Plan

- Check neutron multiplicity in higher energy atmospheric neutrino events
- Compare basic distributions of SRN events with those of atmospheric neutrino background events using simulation
- Estimate atmospheric neutrino background of SRN search

# Backup

# SRN flux

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

Hubble constant

Density parameter

Cosmological constant

Total core-collapse rate

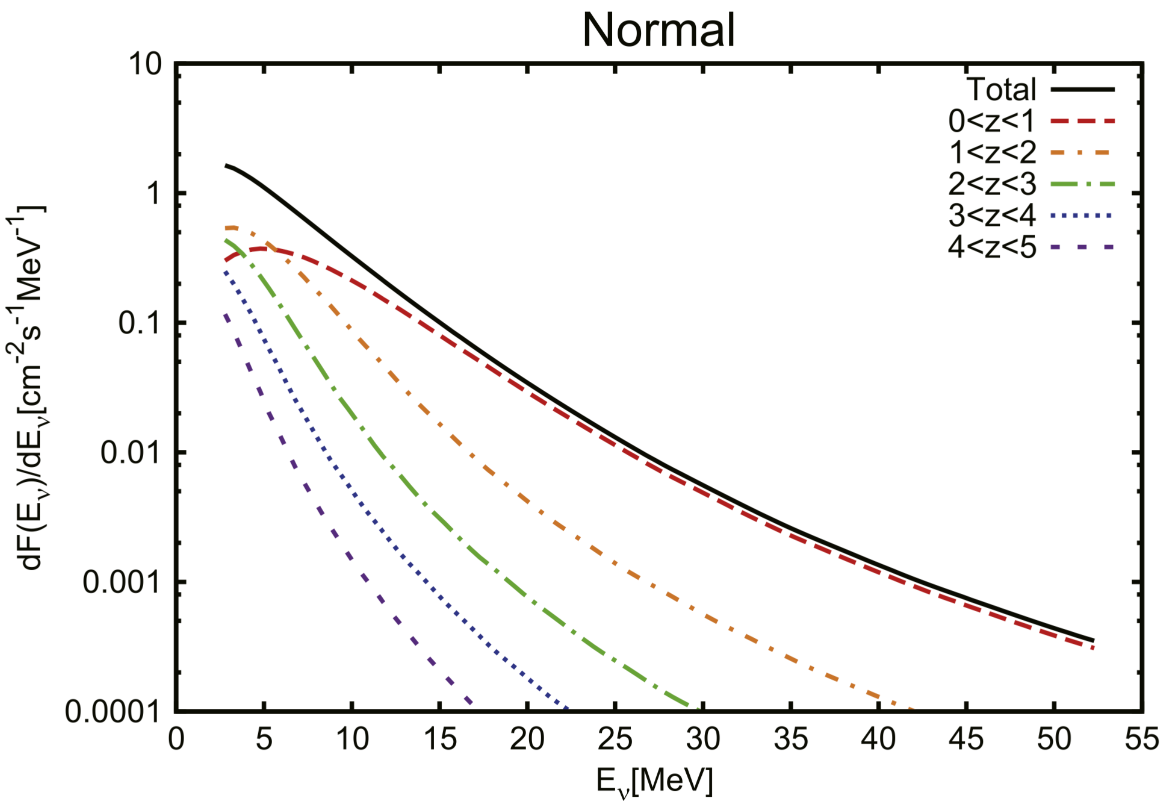
Metallicity distribution function of progenitors

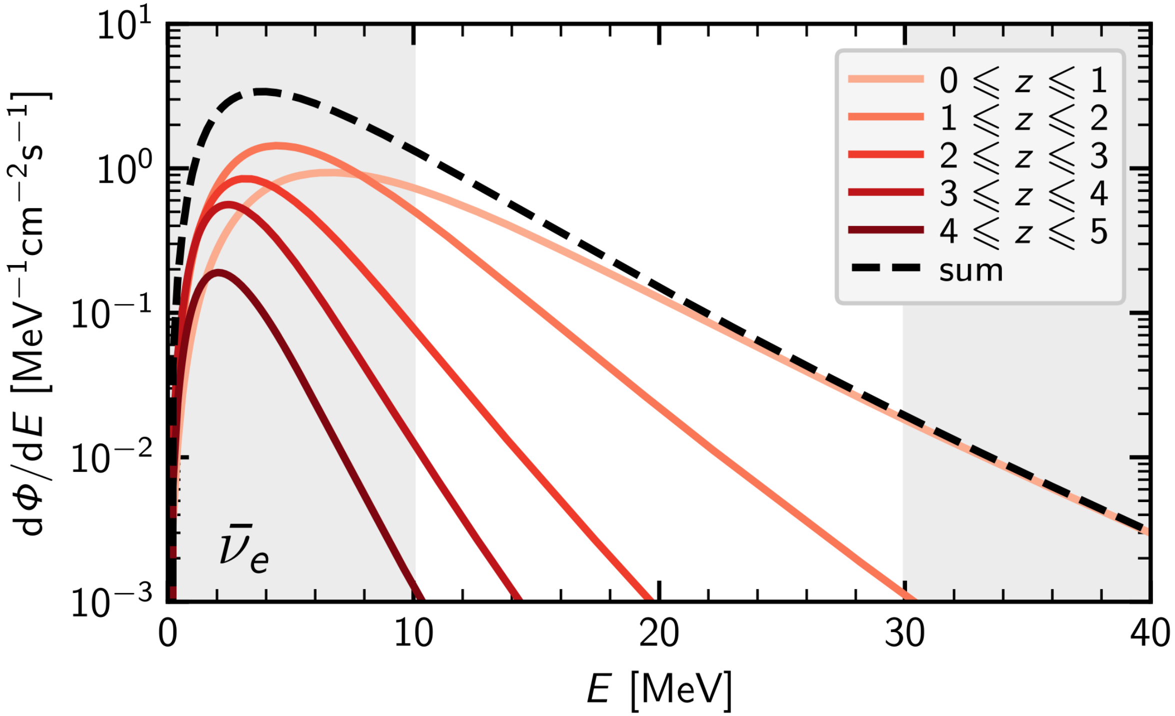
Initial mass function of progenitors

Neutrino number spectrum from the core-collapse of a progenitor ($E_\nu' = (1+z)E_\nu$)

K. Nakazato *et al*., Astrophys. J. **804**, 75 (2015)

# SRN flux





K. Nakazato *et al*., Astrophys. J. **804**, 75 (2015)
D. Kresse *et al*., Astrophys. J. **909**, 169 (2021)

# SK-Gd experiment

| | Atomic weight |
|---|---|
| Gd | 157.25 u |
| S | 32.065 u |
| O | 15.999 u |
| H | 1.00784 u |

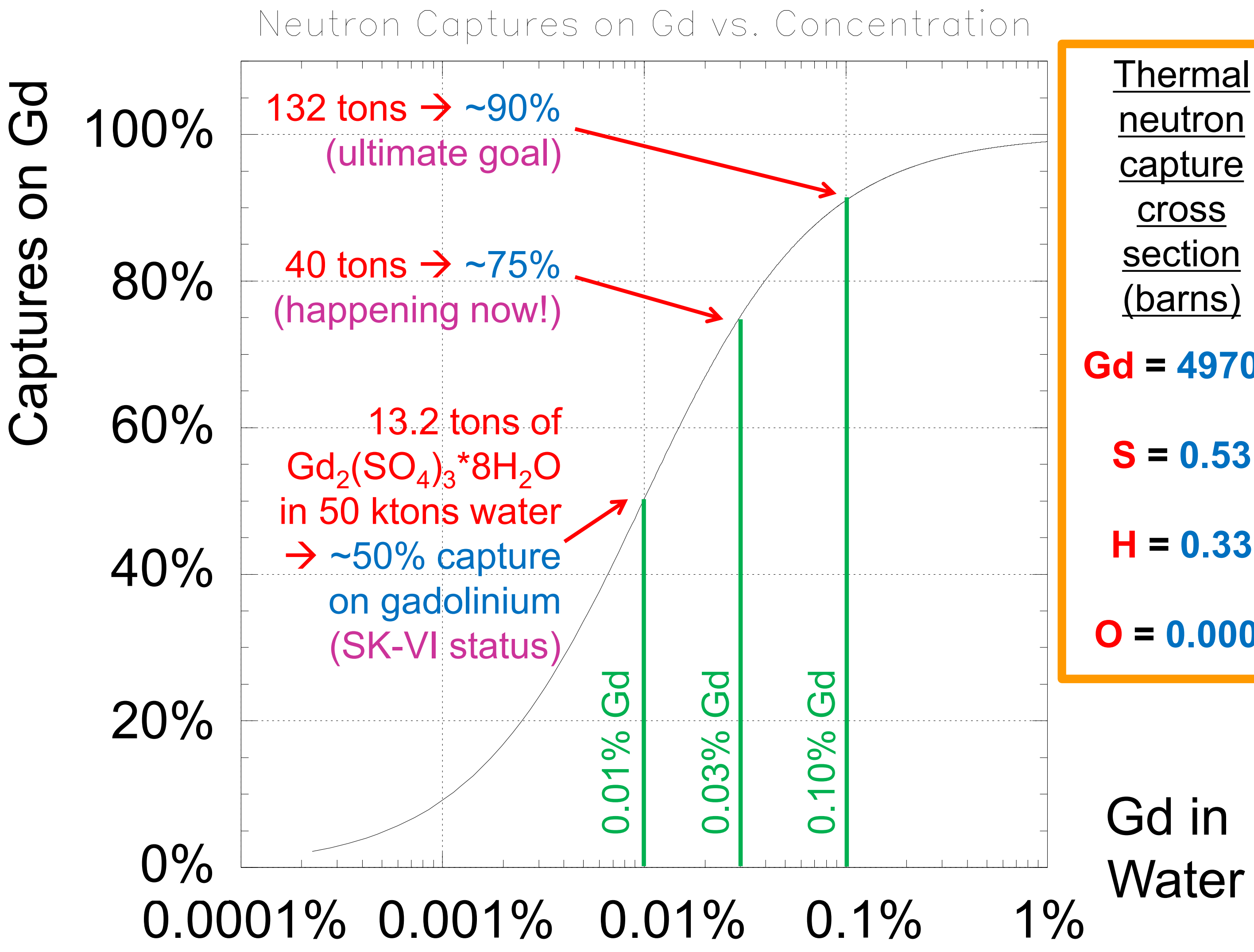
u : atomic mass unit

1 u = $1.66054 \times 10^{-27}$ kg = 931.478 MeV/$c^2$

$Gd_2$ : 314.5 u

$(SO_4)_3$ : 288.18 u

$8H_2O$ : 144.12 u


Neutron Captures on Gd vs. Concentration

132 tons → ~90% (ultimate goal)

40 tons → ~75% (happening now!)

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

Thermal neutron capture cross section (barns)

**Gd = 49700**

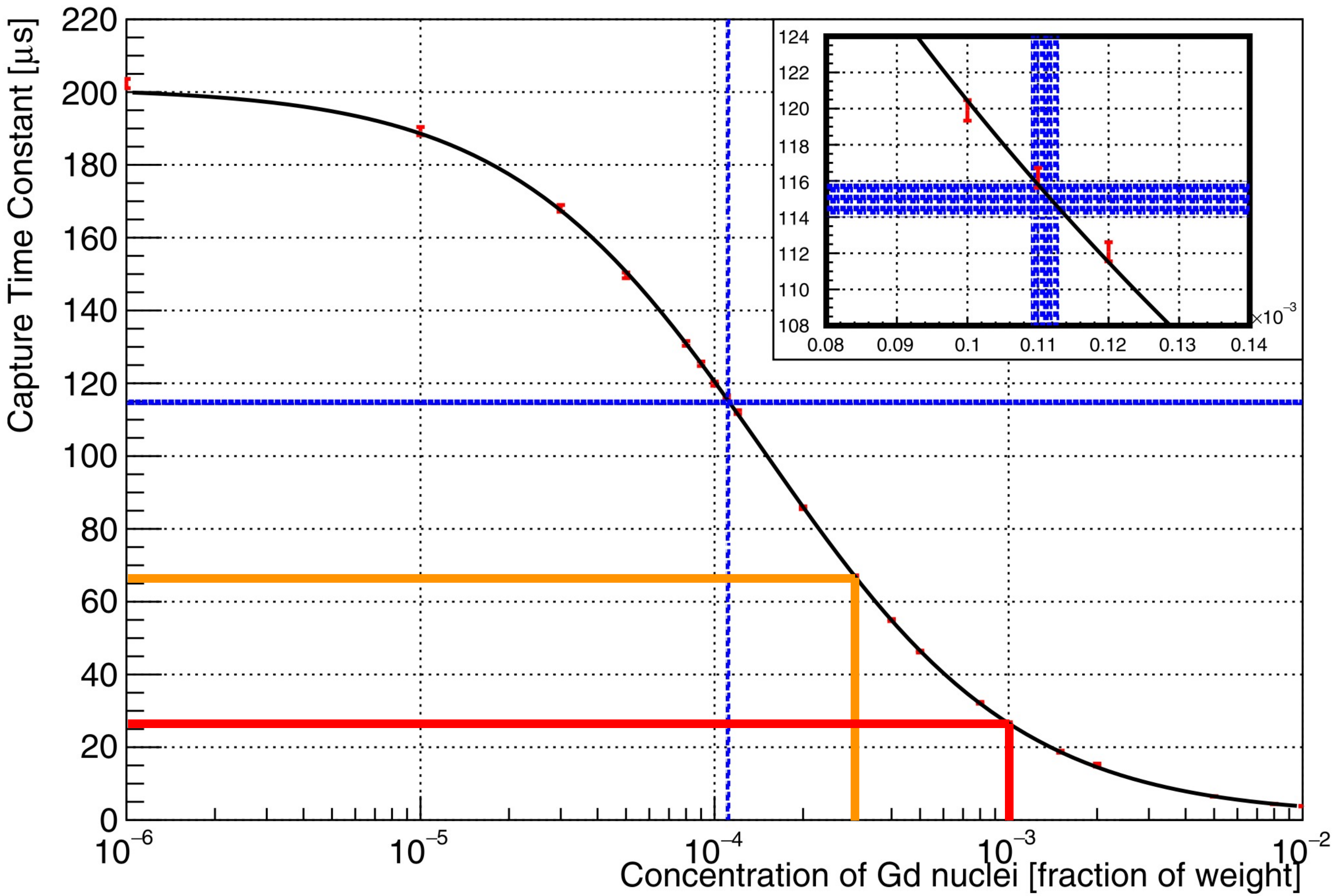
**S = 0.53**

**H = 0.33**

**O = 0.0002**

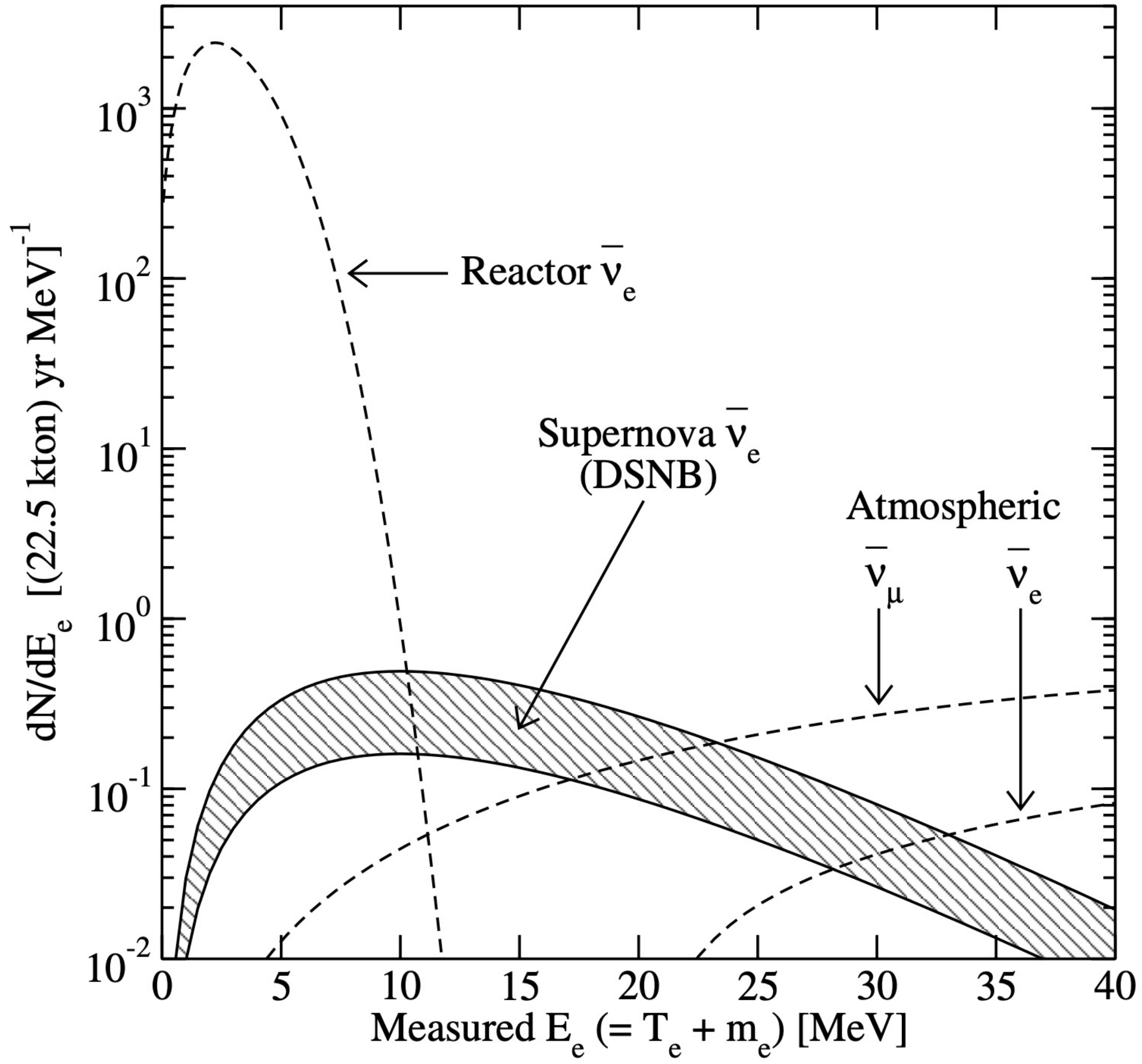
M. Vagins, “A Gadolinium-loaded Super-Kamiokande”, Neutrino 2022 (Jun. 2, 2022)

# Neutron capture time constant



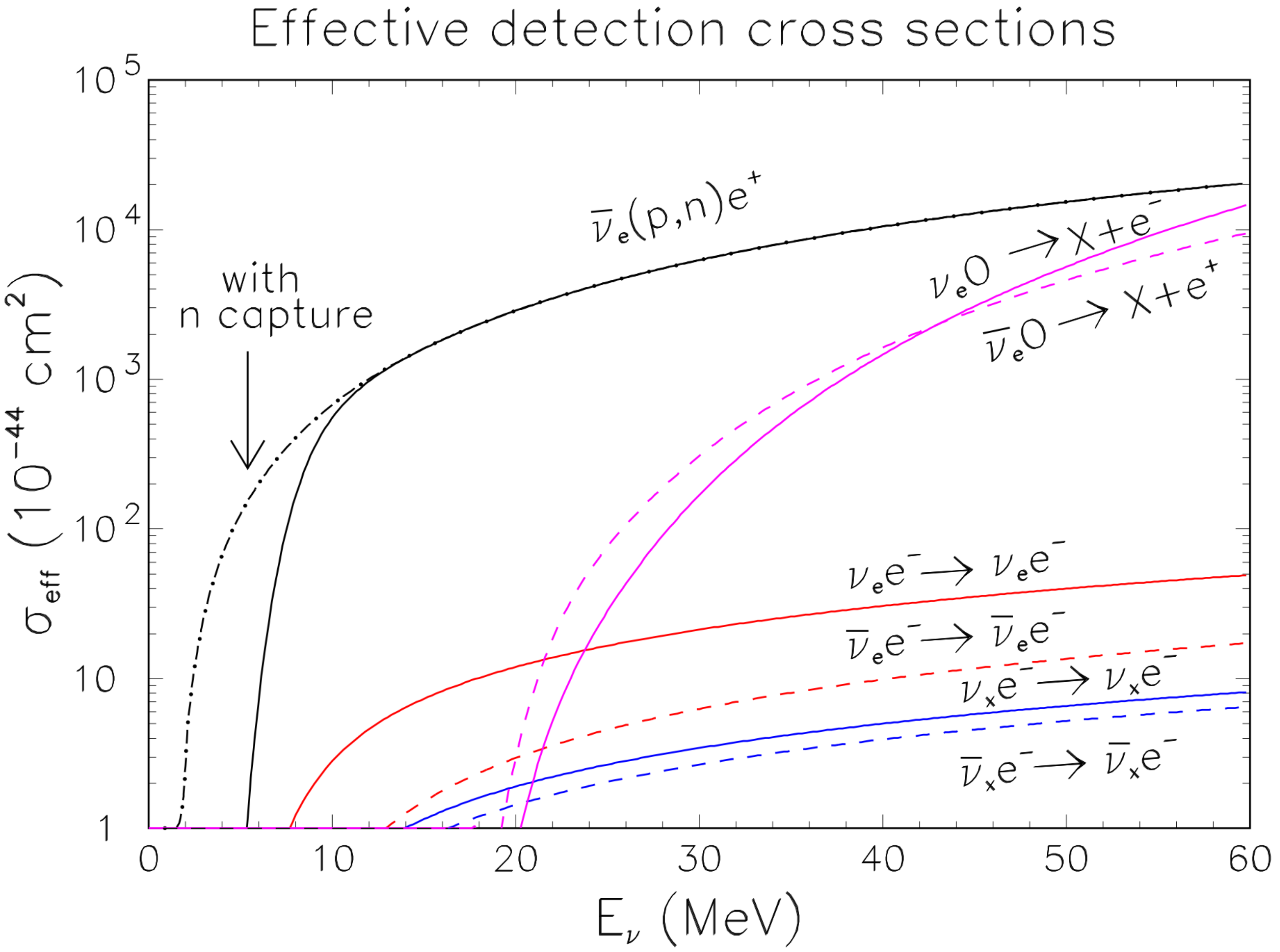
K. Abe *et al.*, Nucl. Instrum. Methods A 1027 (2022)

# SRN and backgrounds



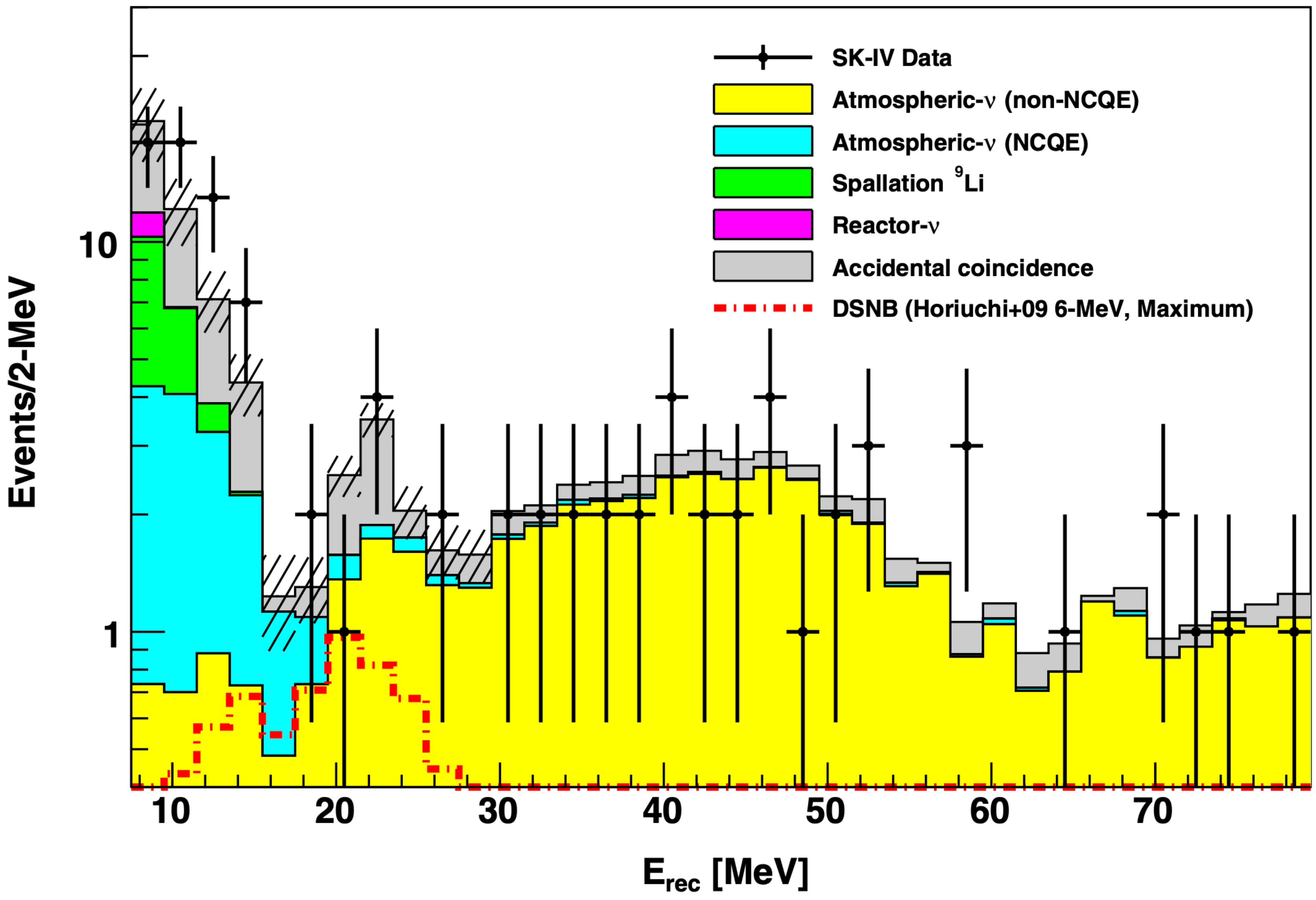
J. F. Beacom and M. R.Vagins, Phys. Rev. Lett. **93**, 171101 (2004)

# Neutrino reaction cross section



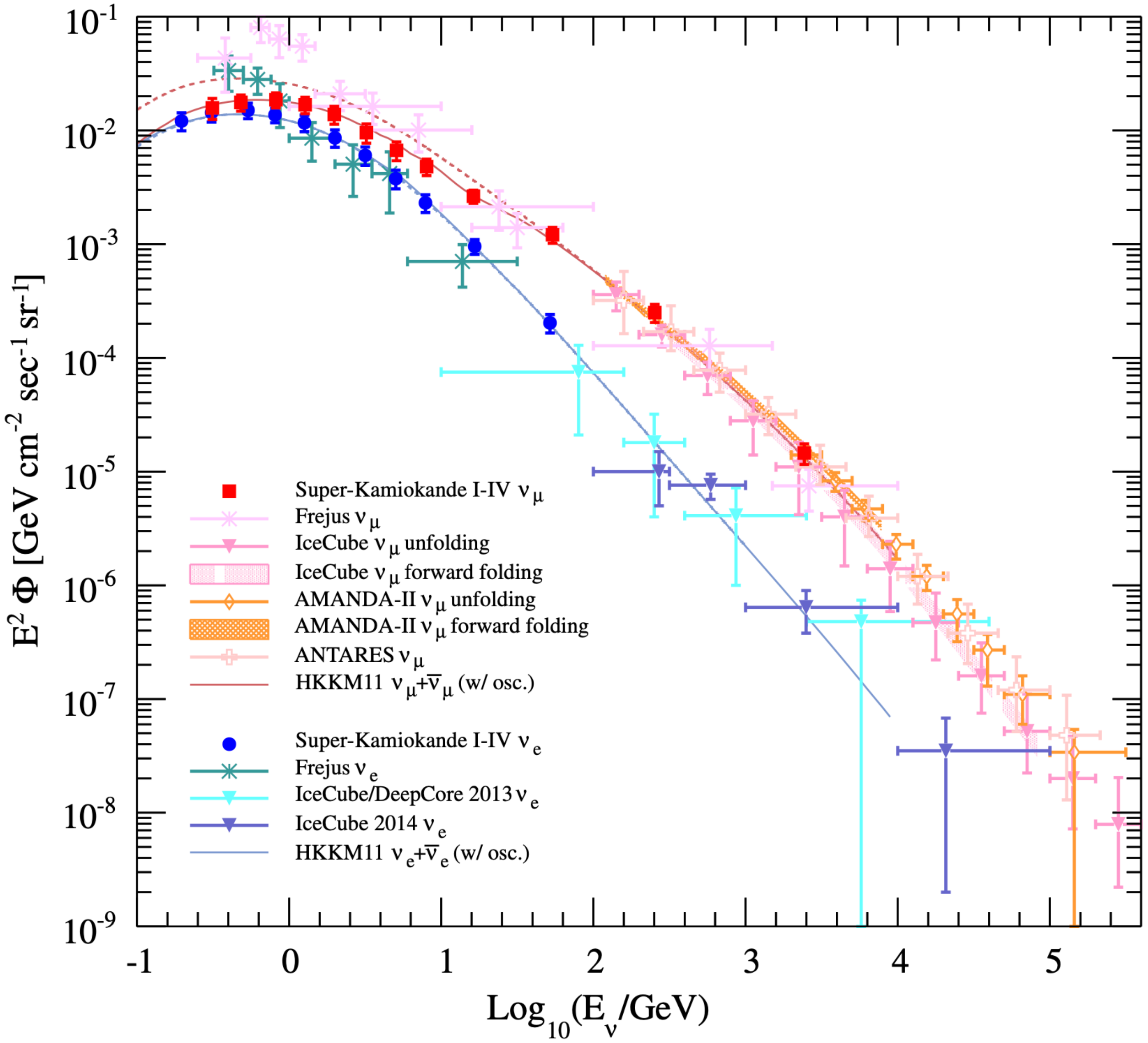
G. L. Fogli *et al*., JCAP, April 2005 (2005)

# SRN search in SK-IV



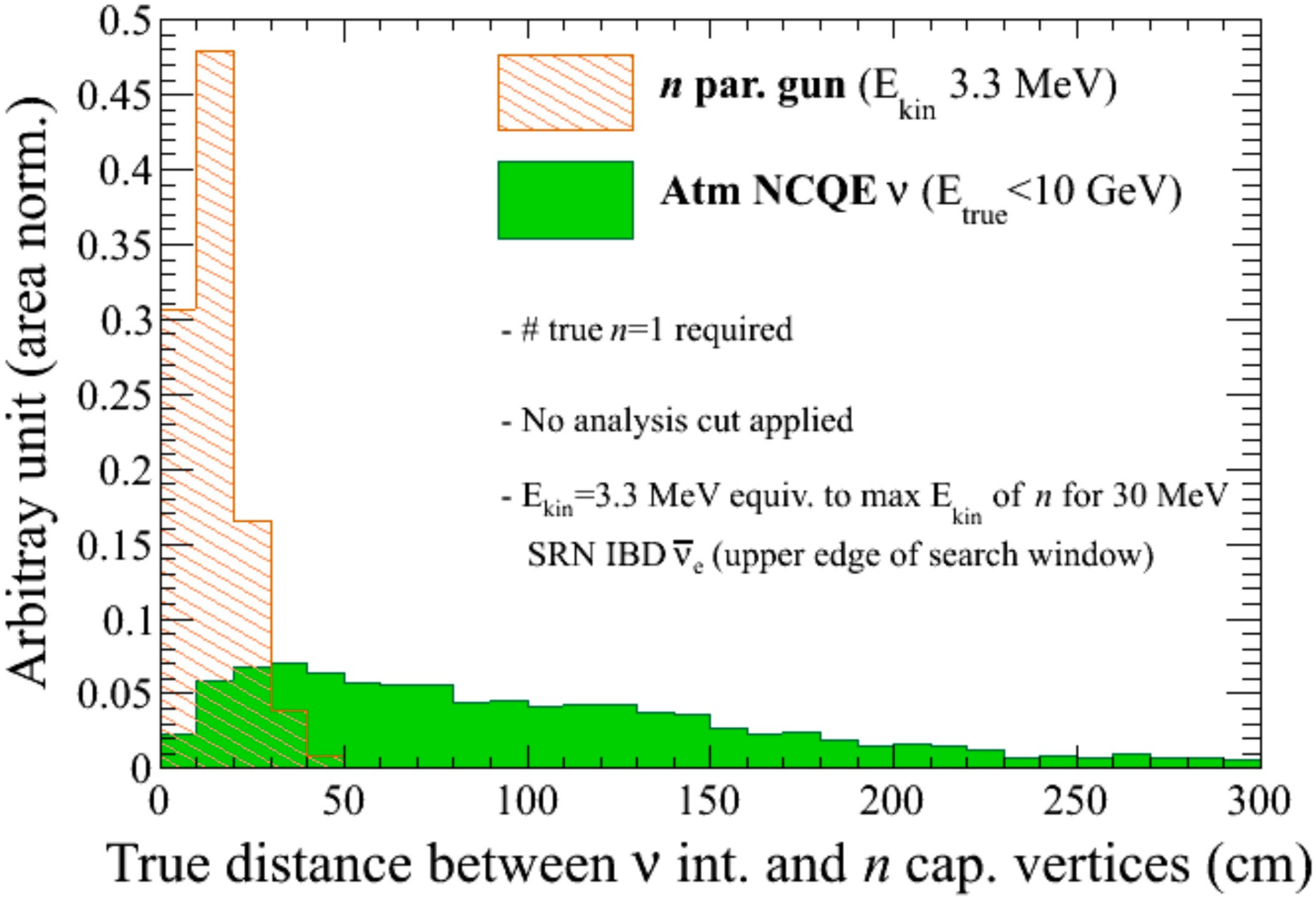
K. Abe *et al.*, Phys. Rev. D **104**, 122002 (2021)

# Atmospheric neutrino flux



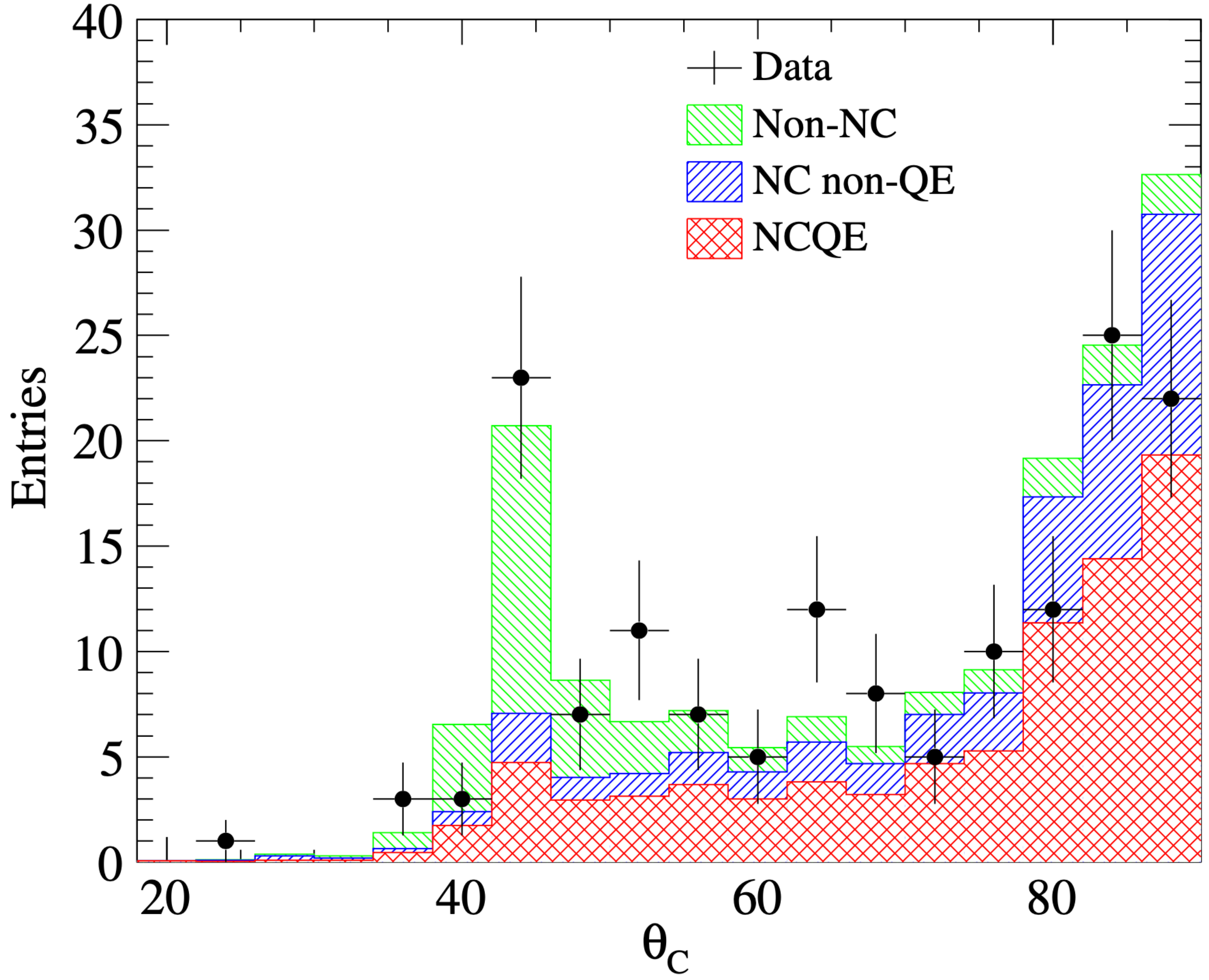
E. Richard *et al.*, Phys. Rev. D **94**, 052001 (2016)

# Distance between reaction point and capture point



R. Akutsu, Ph.D. Thesis, The University of Tokyo (2019)

# Cherenkov angle distribution



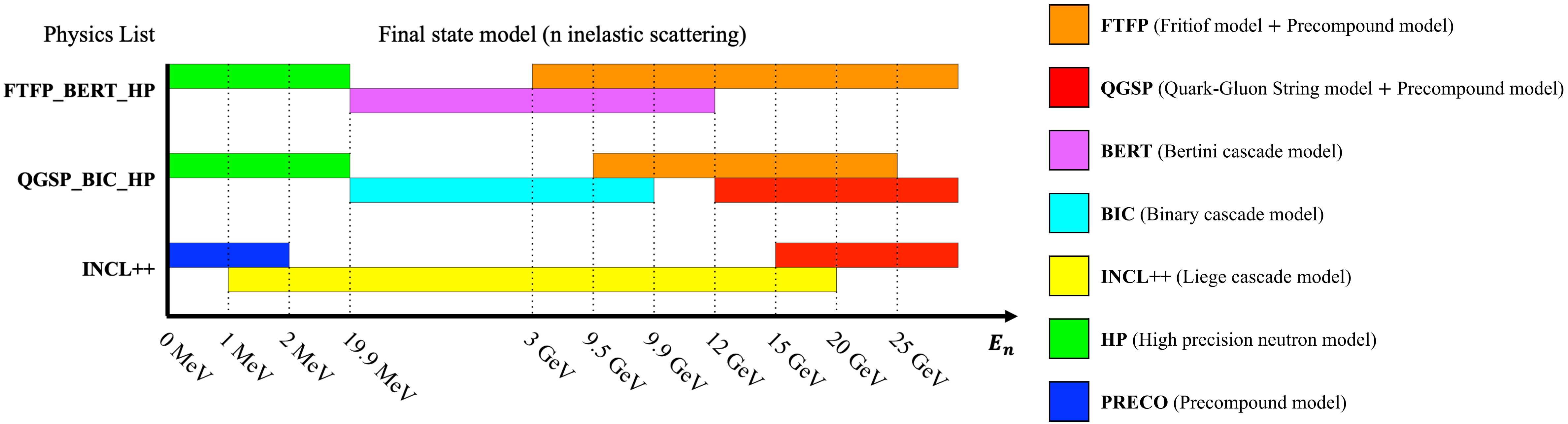
L. Wan *et al.*, Phys. Rev. D **99**, 032005 (2019)

# Difference among nucleon-nucleus interaction models

| **Model** | **BERT** | | **BIC** | | **INCL++** | |
|---|---|---|---|---|---|---|
| Mean neutron multiplicity | **0.781** | | **0.693** | | **0.608** | |
| neutron inelastic scattering | 1,874,645 | 62.26% | 1,307,306 | 48.94% | 1,106,647 | 47.20% |
| proton inelastic scattering | 482,229 | 16.02% | 533,767 | 19.98% | 455,211 | 19.42% |
| $\pi^+/\pi^-$ inelastic scattering | 151,877 | 5.05% | 336,647 | 12.60% | 243,446 | 10.38% |
| $\mu^-$ capture | 240,354 | 7.98% | 241,151 | 9.03% | 241,329 | 10.29% |
| $\pi^-$ capture | 226,287 | 7.51% | 218,310 | 8.17% | 242,773 | 10.35% |
| others | 35,481 | 1.18% | 34,288 | 1.28% | 55,173 | 2.36% |

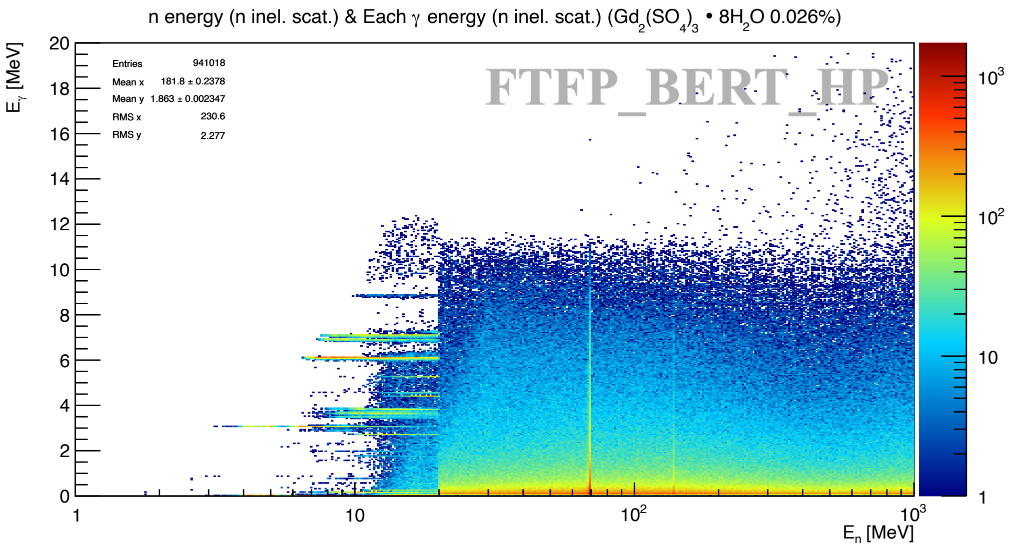
# Neutron inelastic scattering

- Cross section : G4NeutronInelasticXS (& NeutronHP)

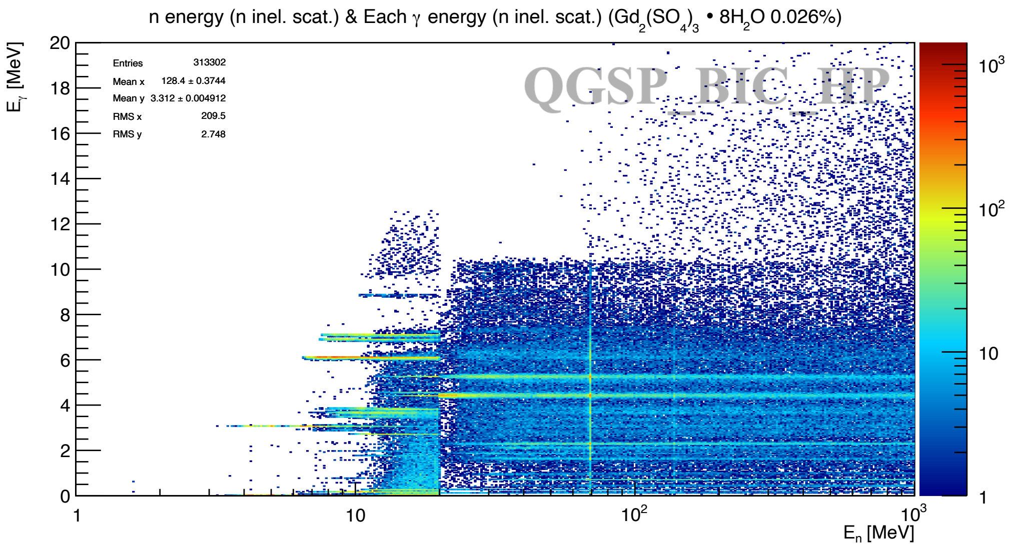


# $\gamma$-ray energy generated by neutron inelastic scattering

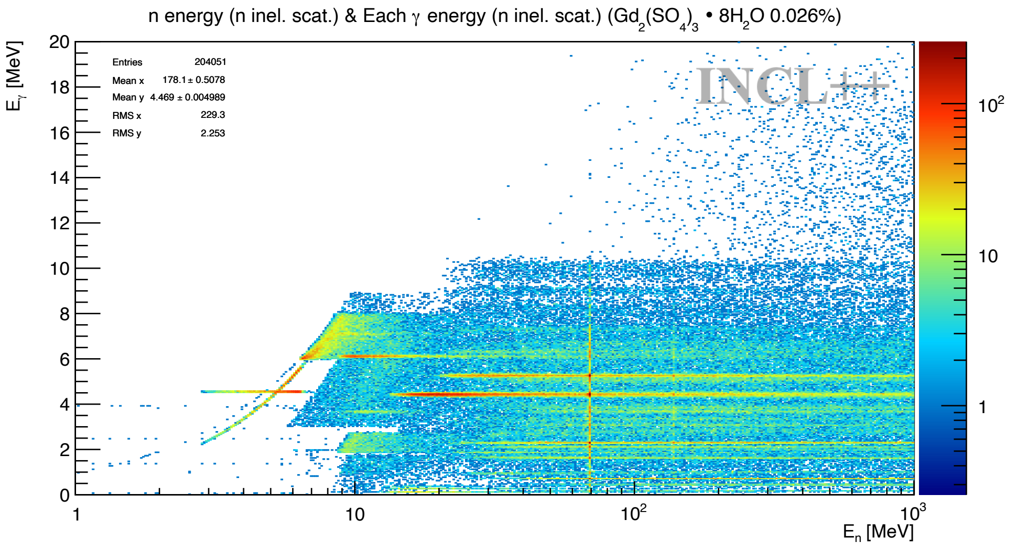
| Particle | neutron |
|---|---|
| Kinetic energy | 1 MeV - 1 GeV |
| Position | Center of SK tank ((0, 0, 0) m) |
| Direction | random |
| # of events | 100,000 |



n energy (n inel. scat.) & Each $\gamma$ energy (n inel. scat.) ($Gd_2(SO_4)_3 \cdot 8H_2O$ 0.026%)

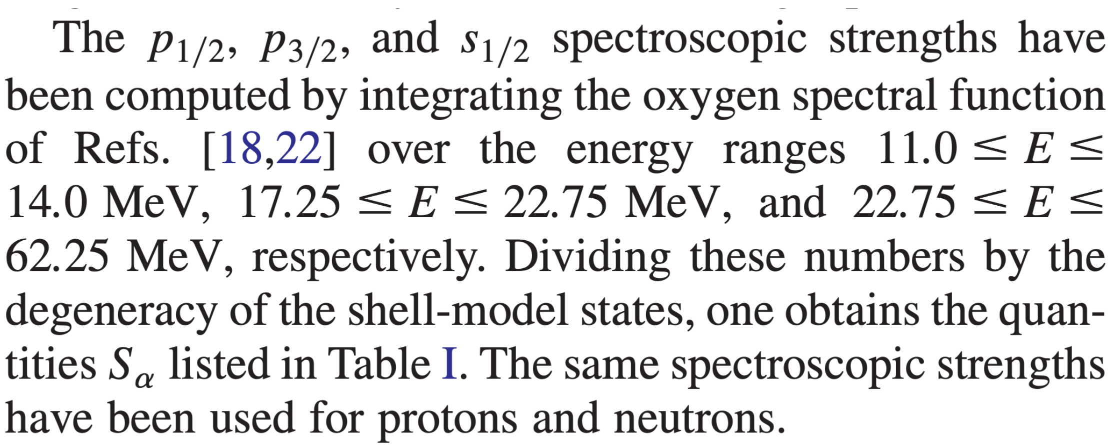


n energy (n inel. scat.) & Each $\gamma$ energy (n inel. scat.) ($Gd_2(SO_4)_3 \cdot 8H_2O$ 0.026%)



n energy (n inel. scat.) & Each $\gamma$ energy (n inel. scat.) ($Gd_2(SO_4)_3 \cdot 8H_2O$ 0.026%)

# Spectroscopic strength



The $p_{1/2}$, $p_{3/2}$, and $s_{1/2}$ spectroscopic strengths have been computed by integrating the oxygen spectral function of Refs. [18,22] over the energy ranges $11.0 \leq E \leq 14.0$ MeV, $17.25 \leq E \leq 22.75$ MeV, and $22.75 \leq E \leq 62.25$ MeV, respectively. Dividing these numbers by the degeneracy of the shell-model states, one obtains the quantities $S_\alpha$ listed in Table I. The same spectroscopic strengths have been used for protons and neutrons.

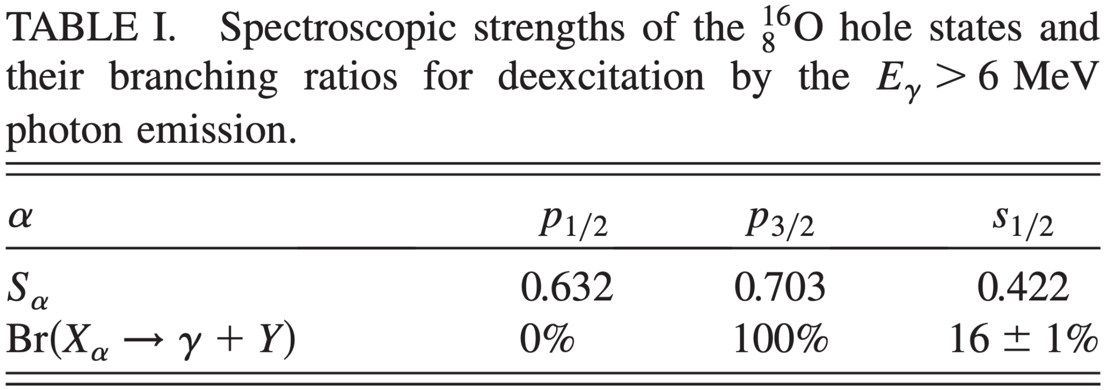


TABLE I. Spectroscopic strengths of the ${}^{16}_{8}$O hole states and their branching ratios for deexcitation by the $E_\gamma > 6$ MeV photon emission.

| $\alpha$ | $p_{1/2}$ | $p_{3/2}$ | $s_{1/2}$ |
|---|---|---|---|
| $S_\alpha$ | 0.632 | 0.703 | 0.422 |
| $\mathrm{Br}(X_\alpha \to \gamma + Y)$ | 0% | 100% | $16 \pm 1\%$ |

$p_{1/2}$ : $0.632 \times (2/8) = \mathbf{0.1580}$

$\left(\because\ S_{p_{1/2}} \times \left(\text{protons}_{p_{1/2}}/\text{protons}_{\text{total}}\right)\right)$

$p_{3/2}$ : $0.703 \times (4/8) = \mathbf{0.3515}$

$s_{1/2}$ : $0.422 \times (2/8) = \mathbf{0.1055}$

others : $1 - (0.1580 + 0.3515 + 0.1055) = \mathbf{0.3850}$

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

# Reference

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

2 R. Akutsu, Ph.D. Thesis, The University of Tokyo (2019)

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

4 K. Nakazato *et al*., Astrophys. J. **804**, 75 (2015)

5 D. Kresse *et al*., Astrophys. J. **909**, 169 (2021)

6 M. Vagins, “A Gadolinium-loaded Super-Kamiokande”, Neutrino 2022 (Jun. 2, 2022)

7 K. Abe *et al*., Nucl. Instrum. Methods A 1027 (2022)

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

9 G. L. Fogli *et al*., JCAP, April 2005 (2005)

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

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