Oxygen ion beam experiment for precise prediction of neutrino-oxygen quasielastic interactions

Yusuke Mizuno (UTokyo)
for the SAMURAI-79 Collaboration

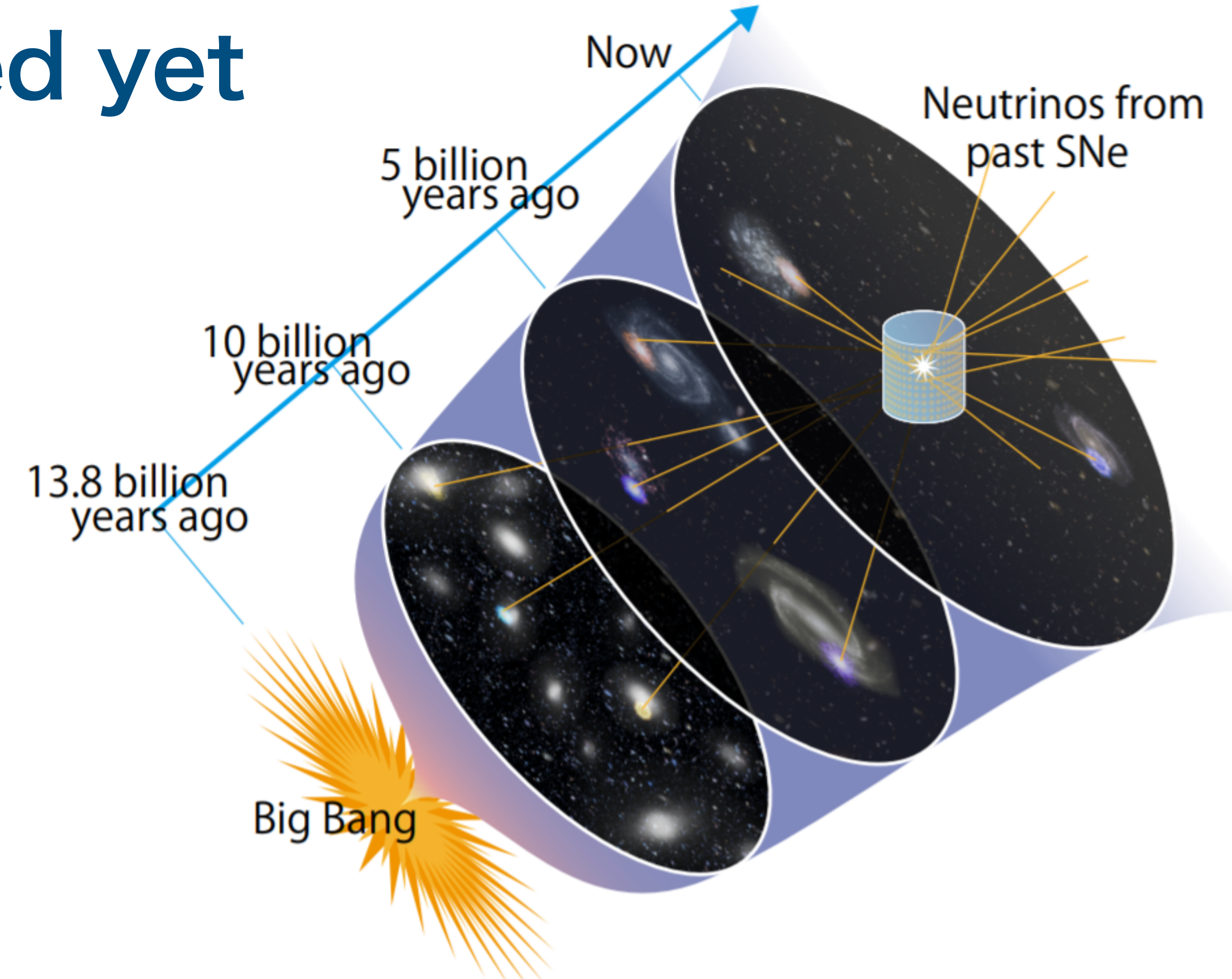
2026/5/27
NPN2026 @ Mito

Neutrino-Nucleus Interactions

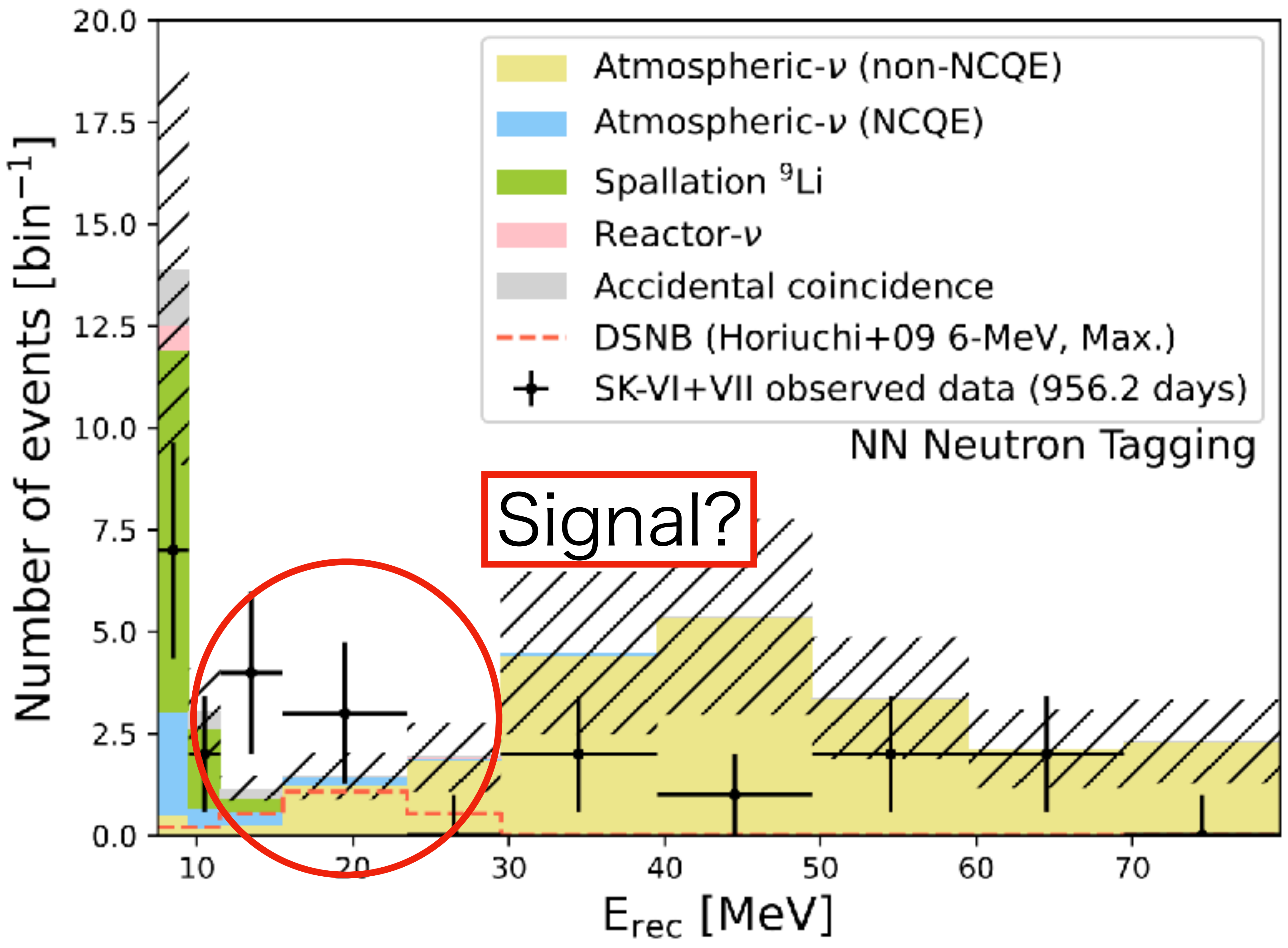
- Our primary goal:
  First observation of Diffuse Supernova Neutrino Background (DSNB) at Super-Kamiokande (SK)

Accumulated flux of all the past supernovae

Not discovered yet

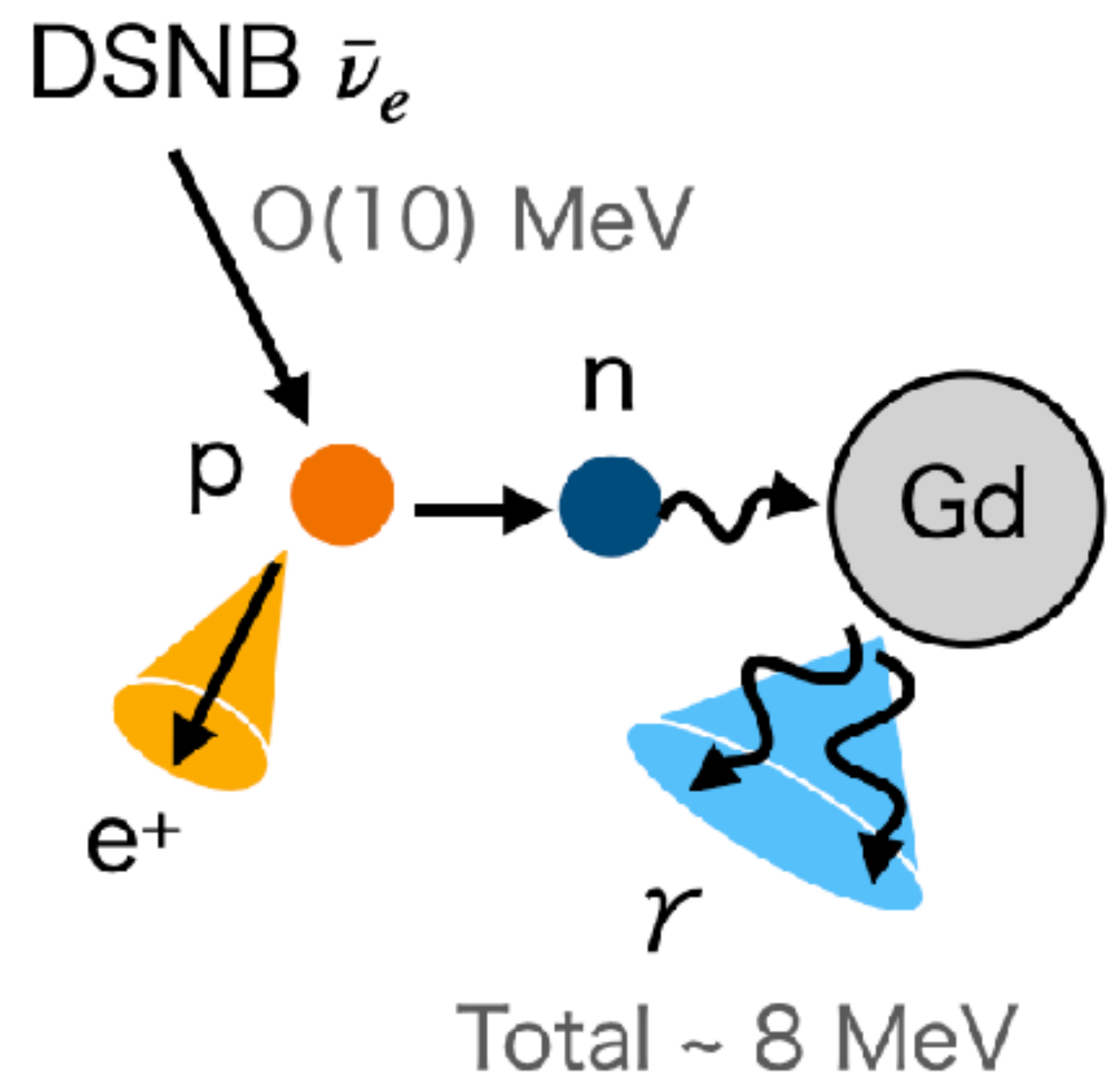


Latest result of DSNB search at SK



K. Abe, et al. arXiv:2511.02222 [astro-ph.HE]

DSNB signal (Inverse β)



Prompt signal   Delayed signal

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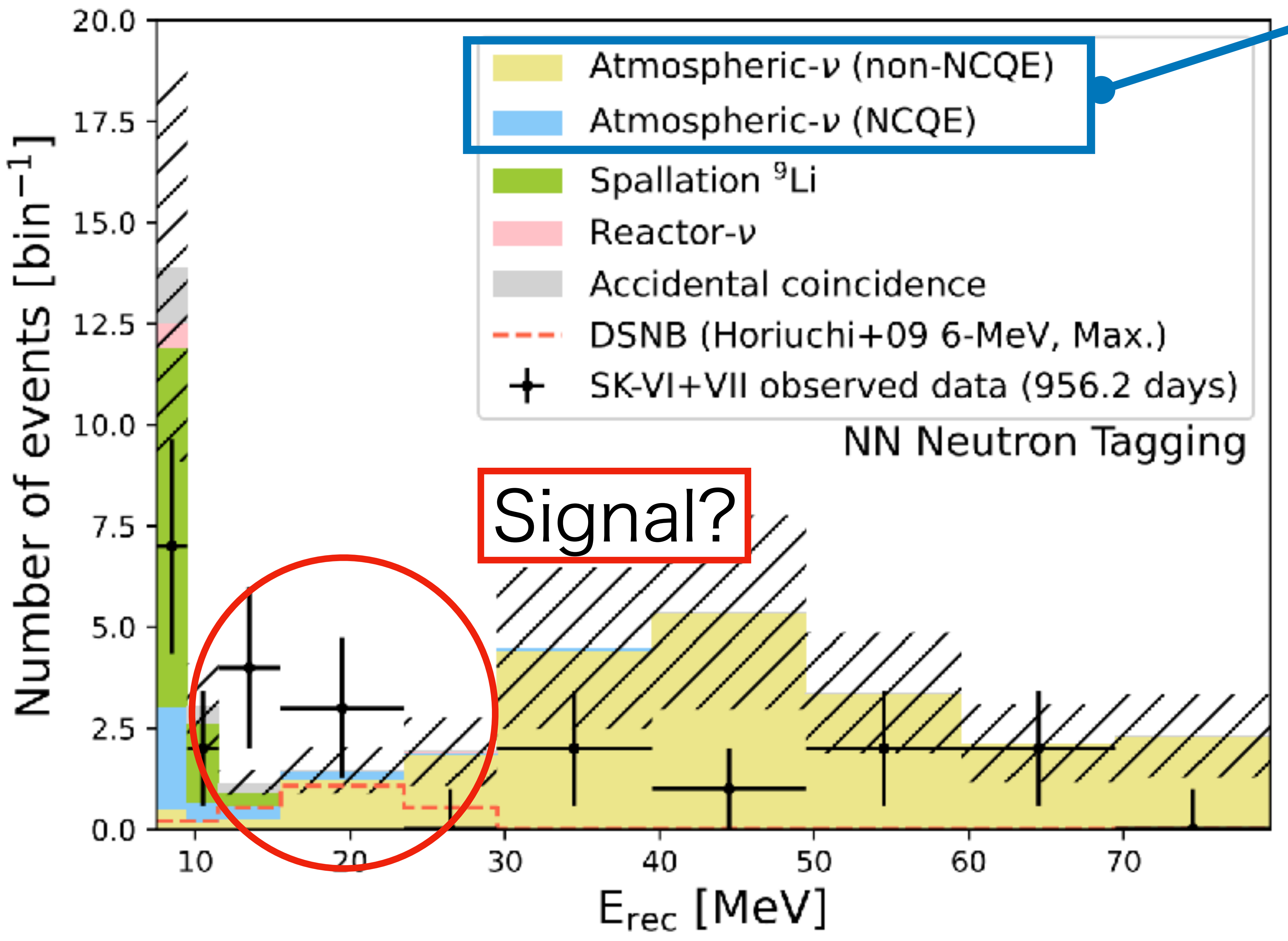
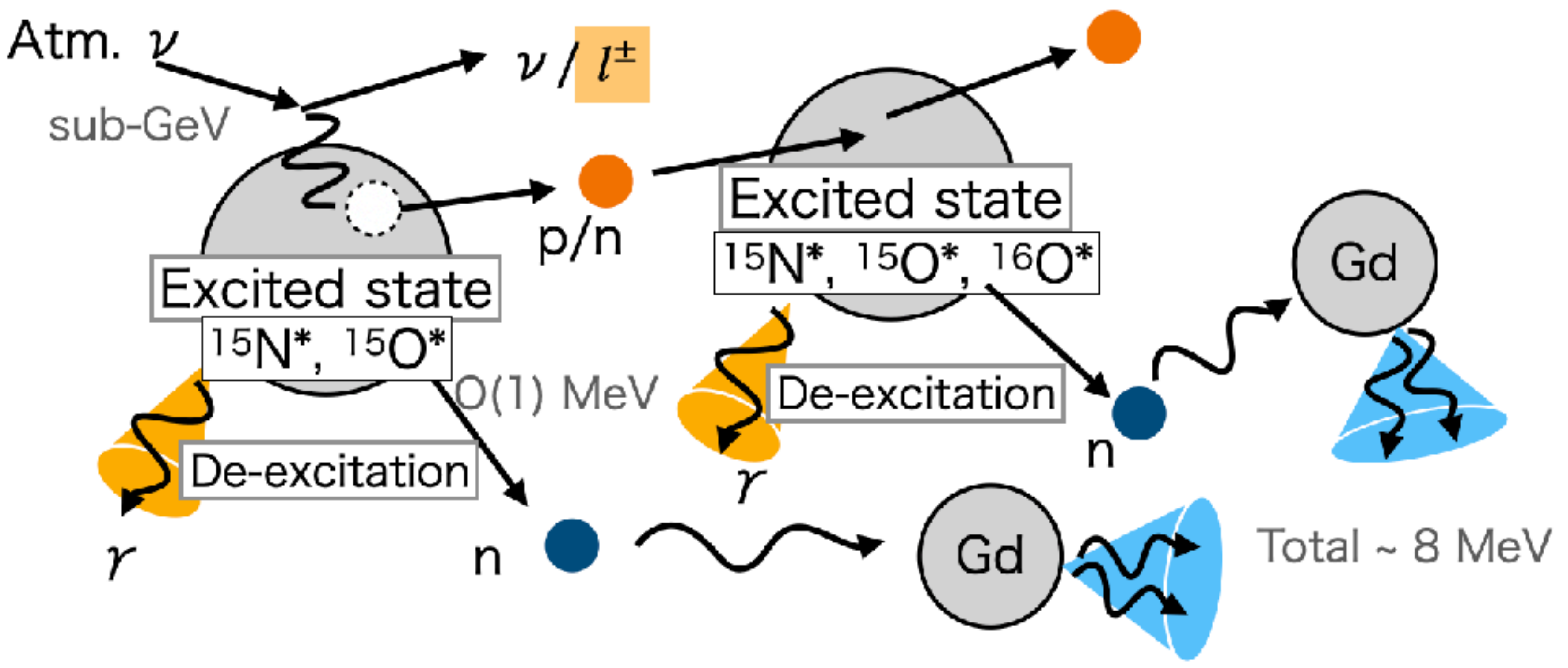


K. Abe, et al. arXiv:2511.02222 [astro-ph.HE]

Uncertainties of atmospheric neutrino-oxygen quasi-elastic interaction limit the sensitivity

Background (Atm. ν-oxygen interaction & secondary interaction)



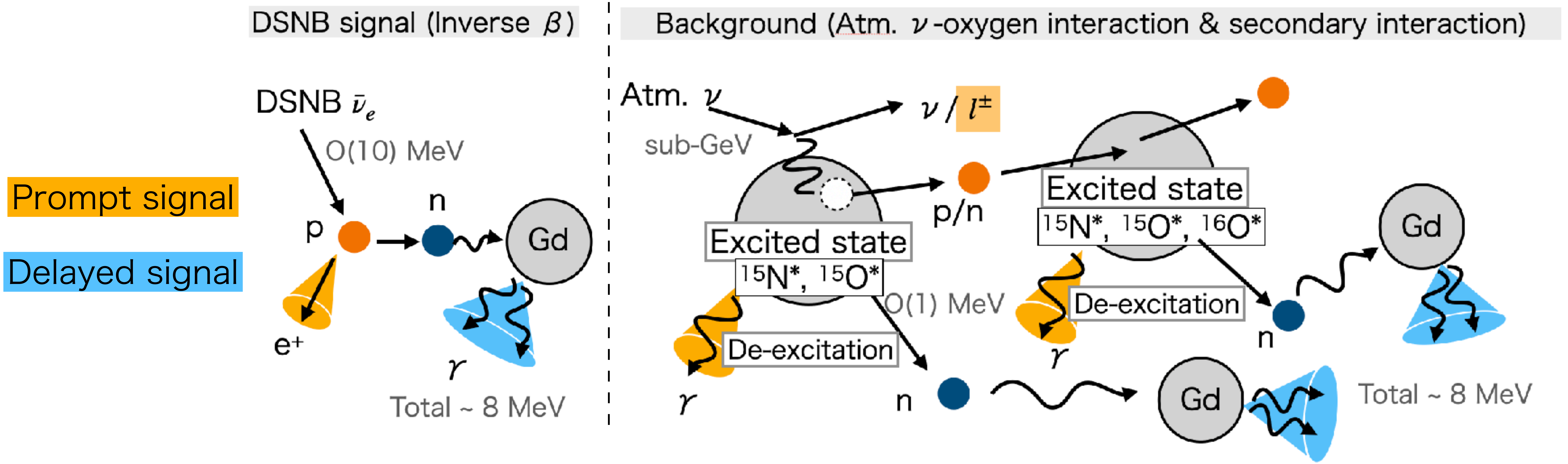
Prompt signal

Delayed signal

De-excitation

- Key process: De-excitation of $^{15}N^*$, $^{15}O^*$, $^{16}O^*$
  - Produced by atmospheric ν-oxygen interactions and secondary interactions
  - Emit neutron & γ
    - Neutron: Detected by Gad capture γ → No energy threshold

Key: Precise prediction of **Multiplicity** (regardless of energy)



Measurement of De-excitation

- Experimental data of de-excitation of ^{15}N*, ^{15}O*, ^{16}O* ?

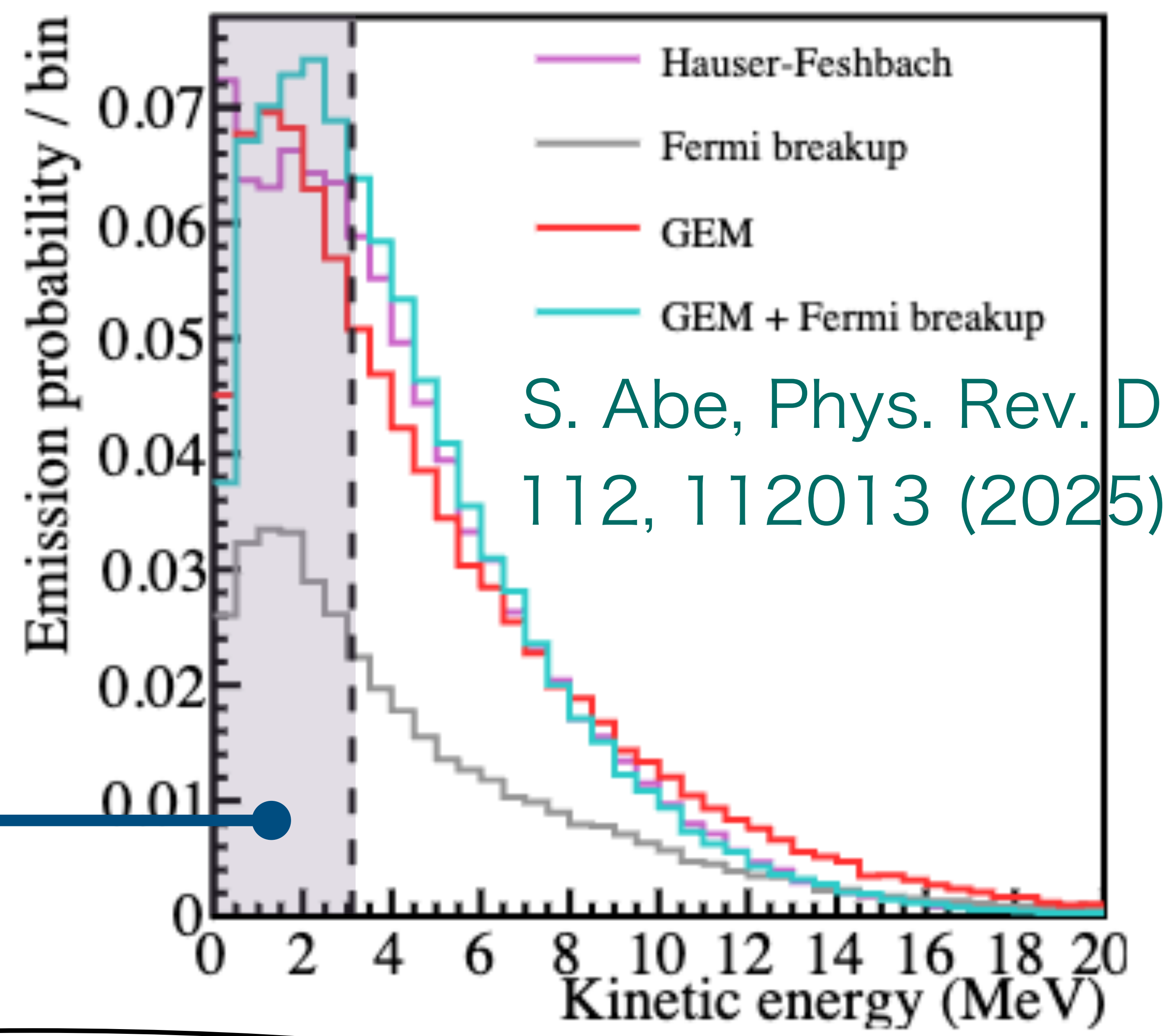
  How many neutrons & γs are emitted from highly excited state?

- ^{16}O(p, 2p)^{15}N* (Proton beam & oxygen target)
- Measured branching ratio of ^{15}N*

  M. Yosoi, et al., Phys. of Atomic Nuclei, 67, 10, (2004)

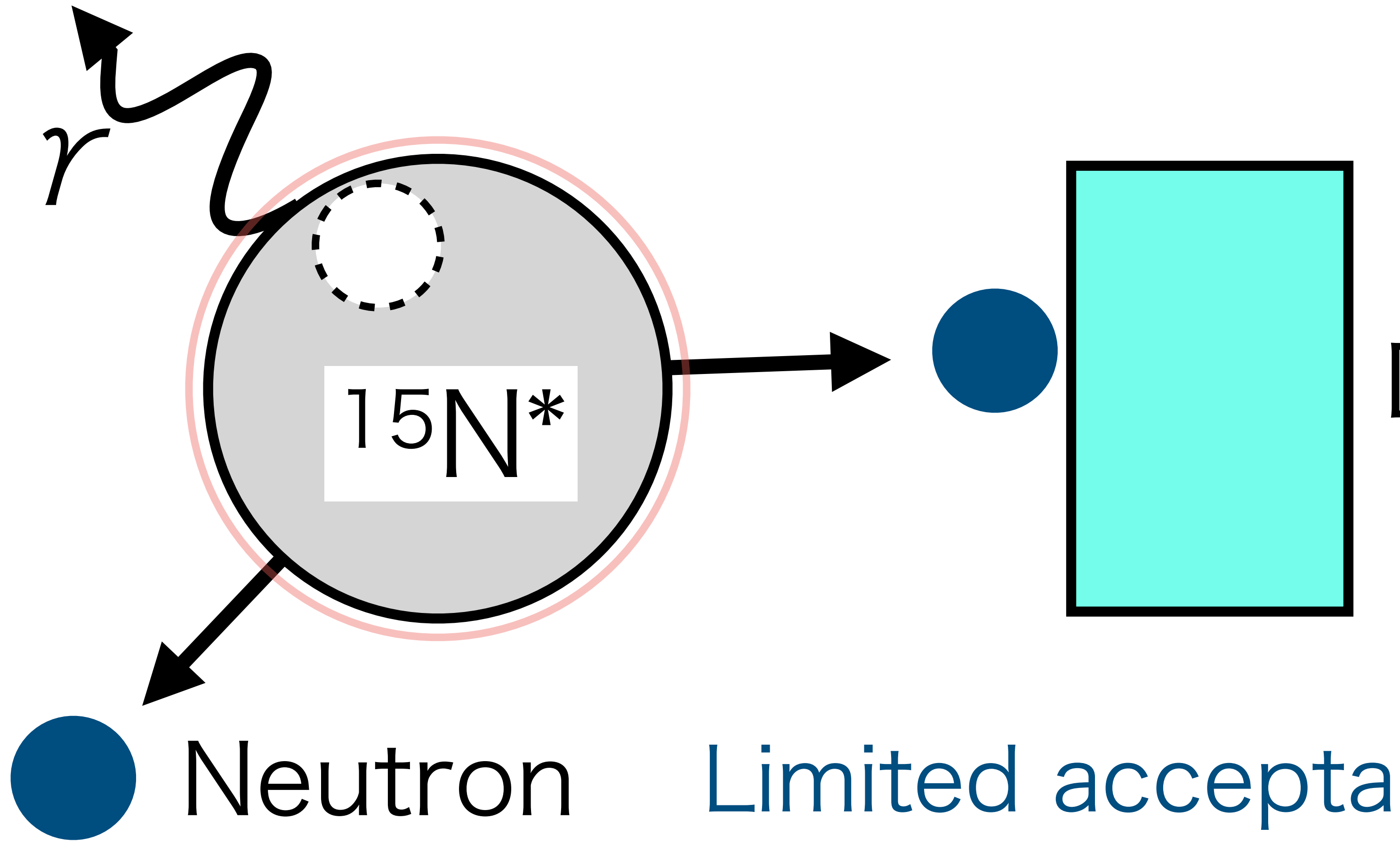
  - ~3 MeV detection threshold for neutron
  - Single particle detection
- ^{15}O*, ^{16}O*: No experimental data

Neutron energy from ^{15}N* with 20 < Ex < 40 MeV (Prediction)



S. Abe, Phys. Rev. D 112, 112013 (2025)

Cannot detect low-energy neutrons



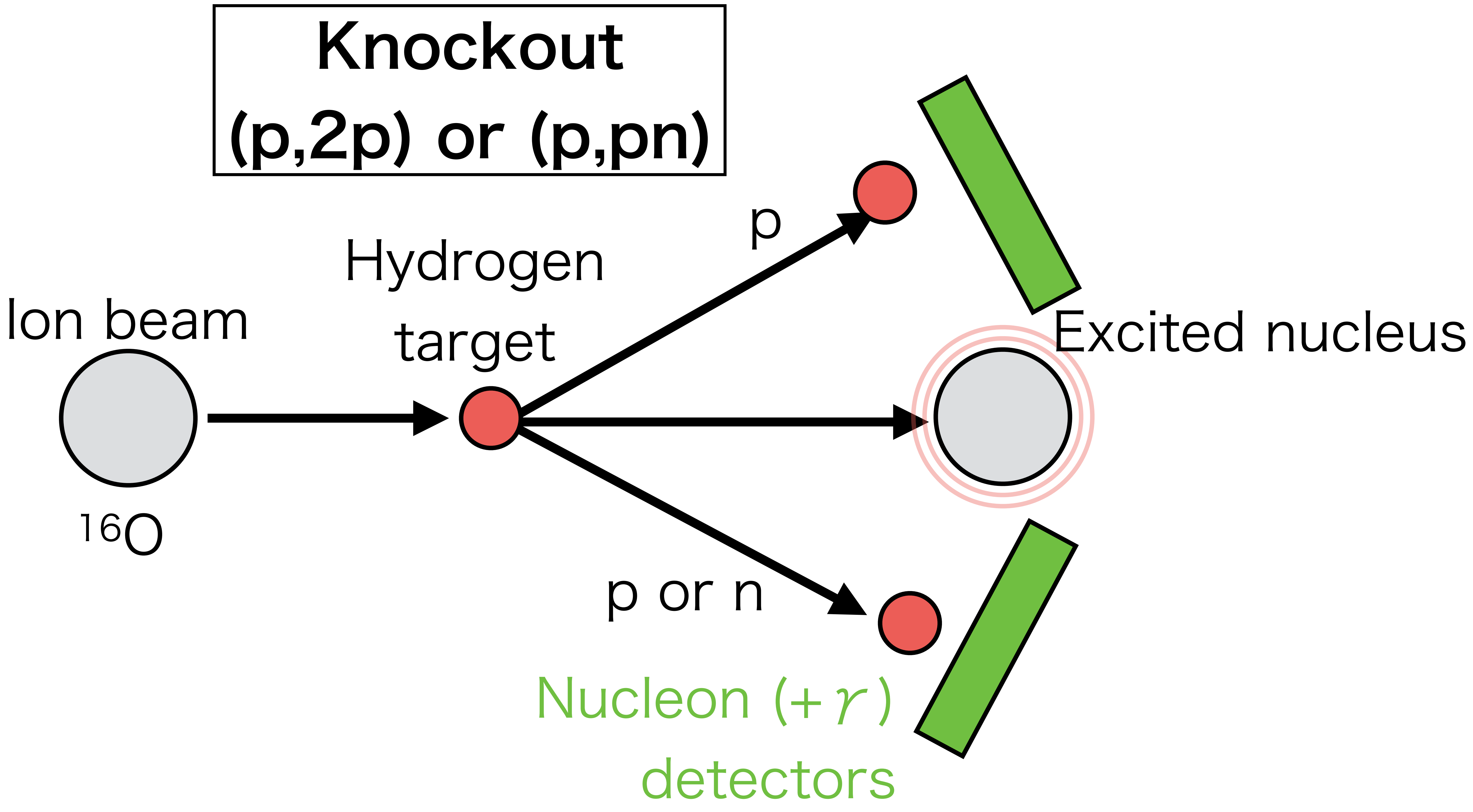
Limited acceptance

Identifying the final state by detecting residual nuclei, neutrons, γs

More experimental data is needed for deeper understanding

Inverse Kinematics

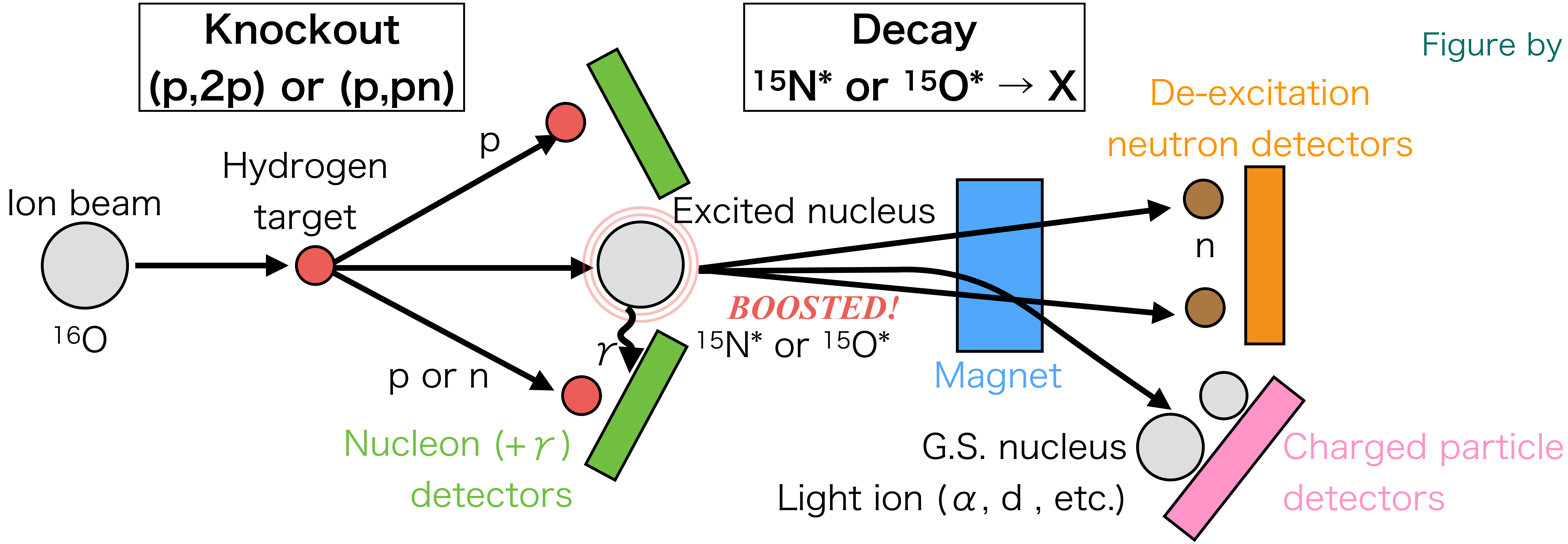
Figure by S. Abe



1. Bombard a 200 MeV/u ^{16,17}O beam at a liquid hydrogen target, producing ^{15}N*, ^{15}O*, ^{16}O*

2. Reconstruct the excitation energy of ^{15}N*, ^{15}O*, ^{16}O* by detecting knocked-out nucleons

Inverse Kinematics



1. Bombard a 200 MeV/u $^{16,17}O$ beam at a liquid hydrogen target, producing $^{15}N^*$, $^{15}O^*$, $^{16}O^*$

2. Reconstruct the excitation energy of $^{15}N^*$, $^{15}O^*$, $^{16}O^*$ by detecting knocked-out nucleons

3. Detect de-excitation products (residual nuclei, neutron, light ions)

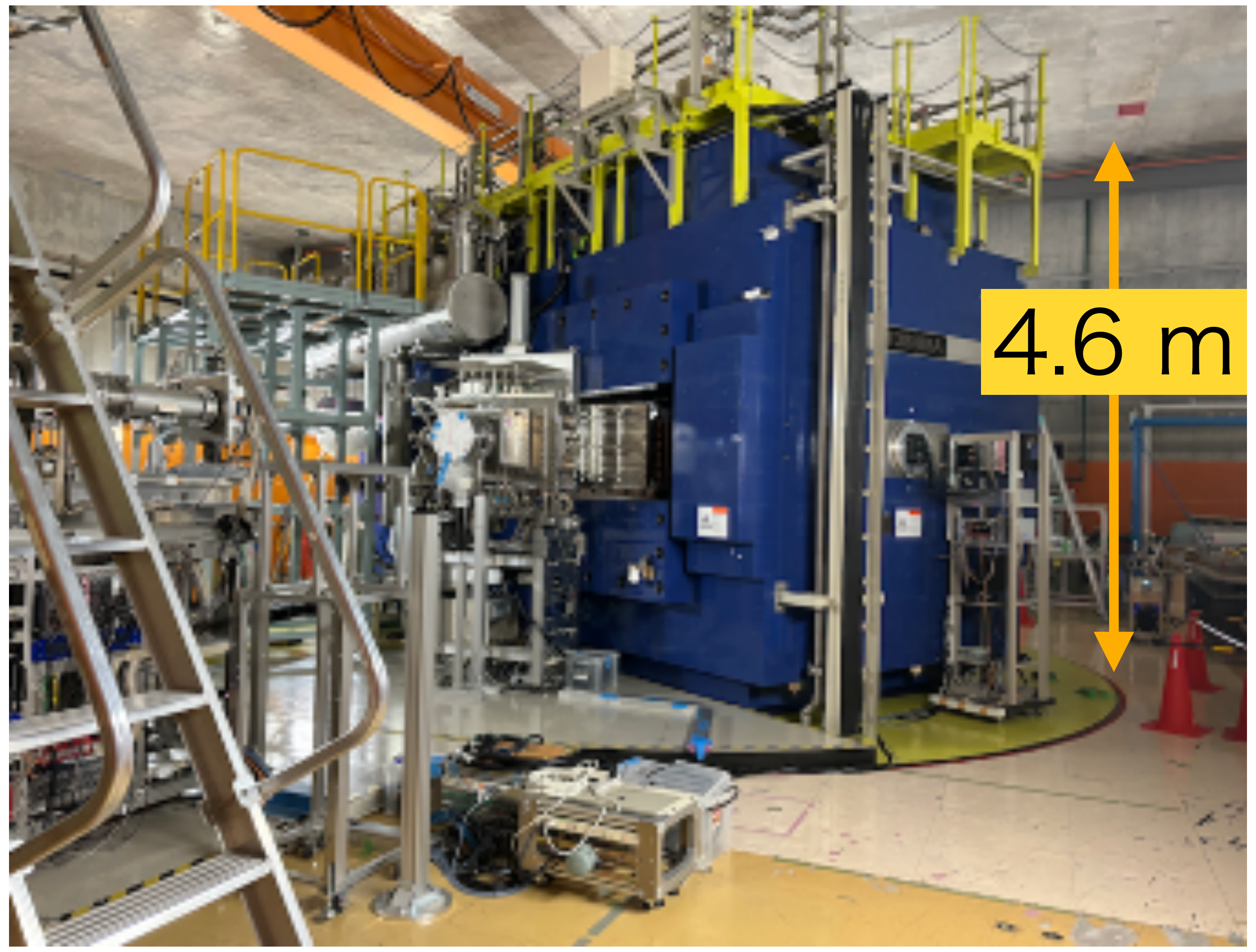
high energy & narrow angle @ lab frame

Can be detected with high efficiency

Branching ratio of $^{15}N^*$, $^{15}O^*$, $^{16}O^*$ as a function of excitation energy

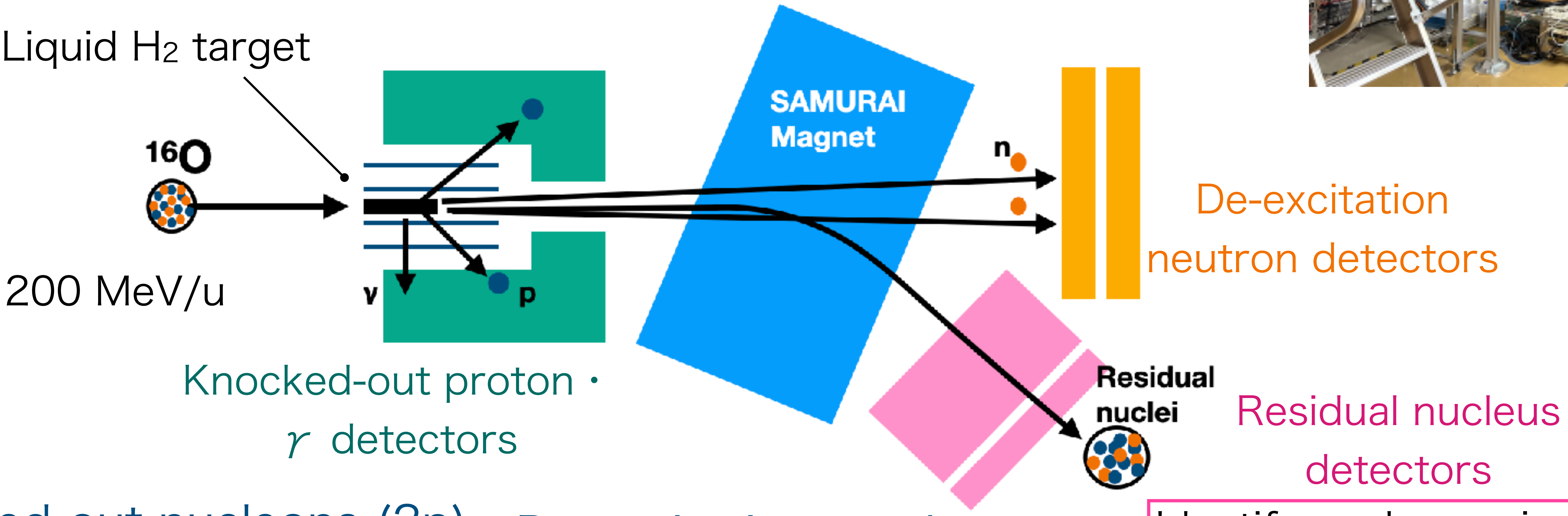
SAMURAI-79 Experiment

- Oxygen ion beam experiment @ RIKEN RIBF
- Measure (p, 2p), (p, pn) reactions and following de-excitation products using SAMURAI spectrometer



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

T. Kobayashi, et al., NIMB 317, 294 (2013)



Identify nucleus using TOF, light yield, track

Knocked-out nucleons (2p)

$^{15}N^*$ excitation energy

De-excitation products

$^{15}N^*$ branching ratio

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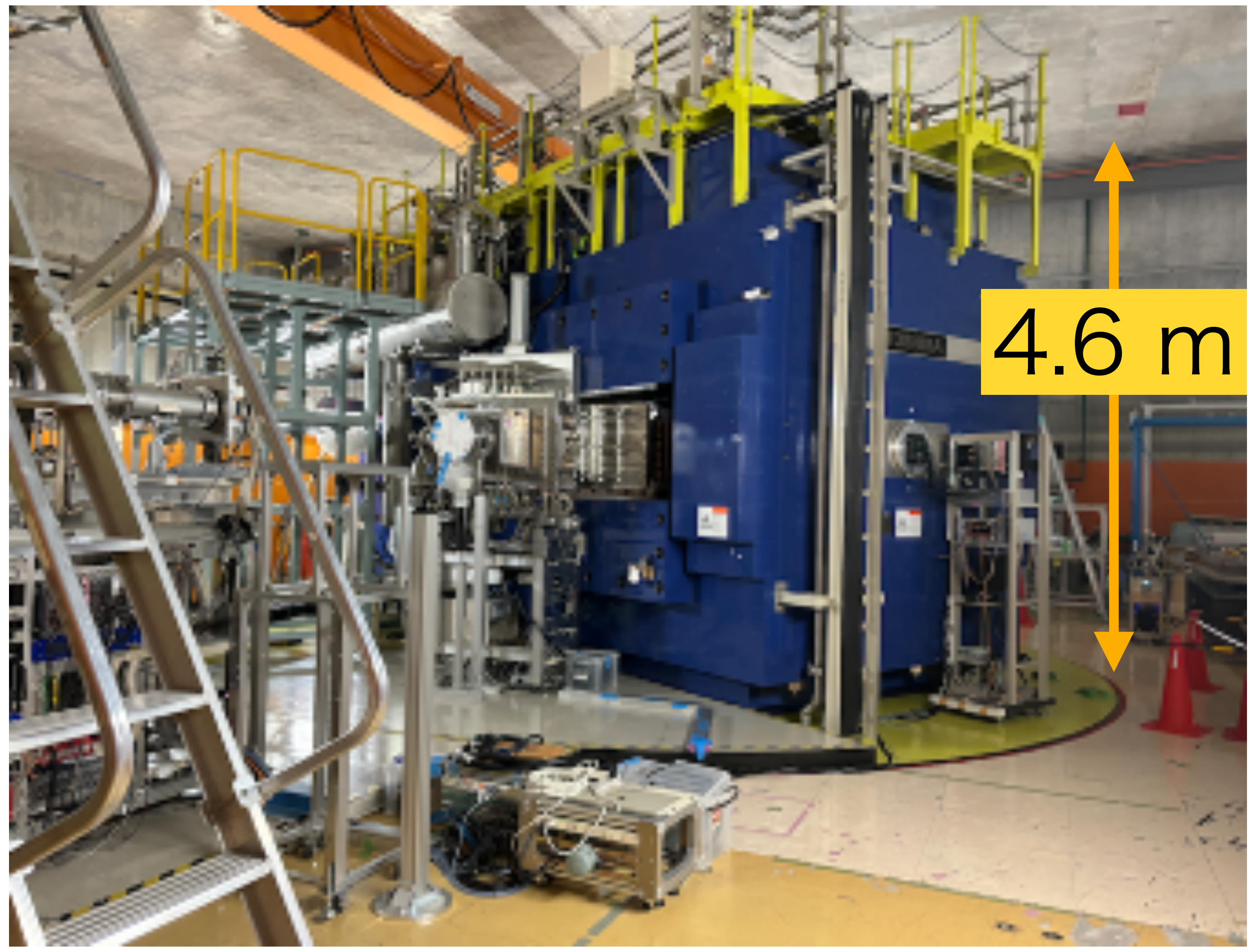

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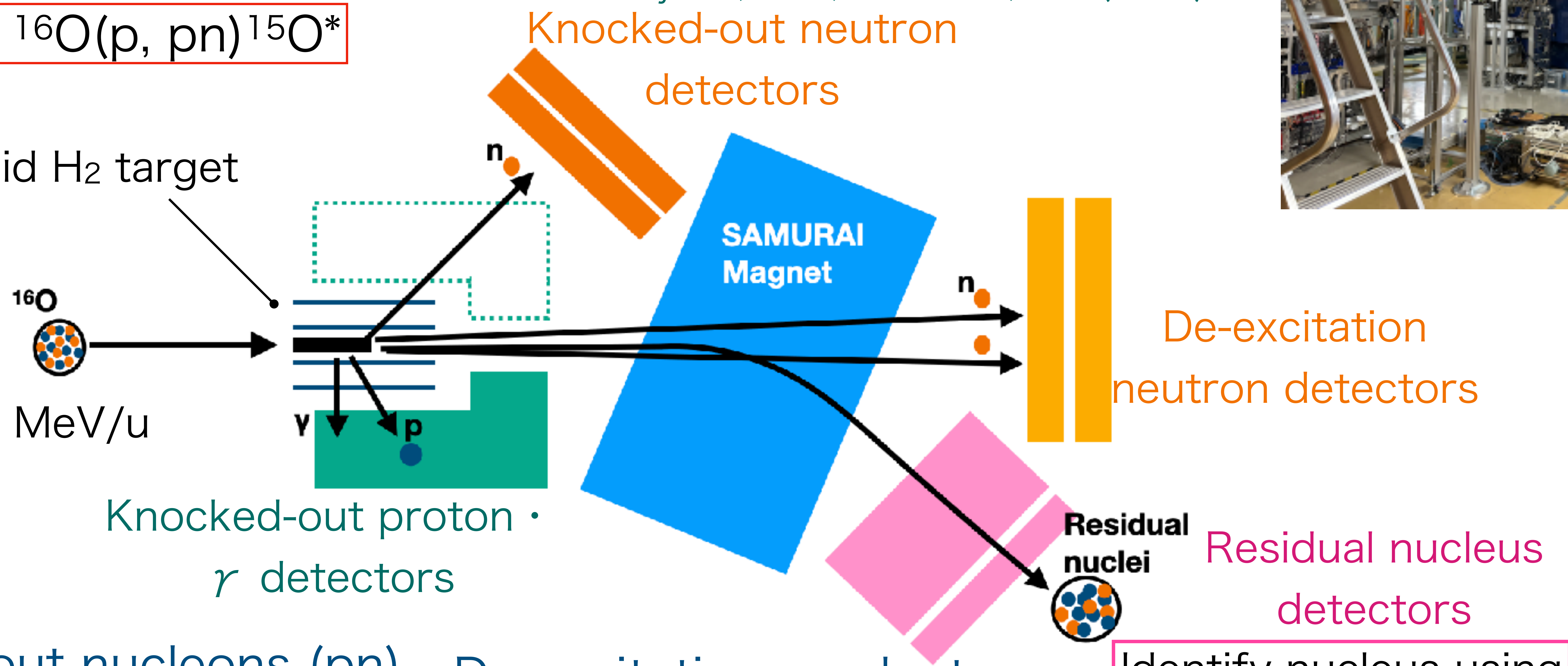


Identify nucleus using TOF, light yield, track

Knocked-out nucleons (pn) → **$^{15}O^*$ excitation energy**

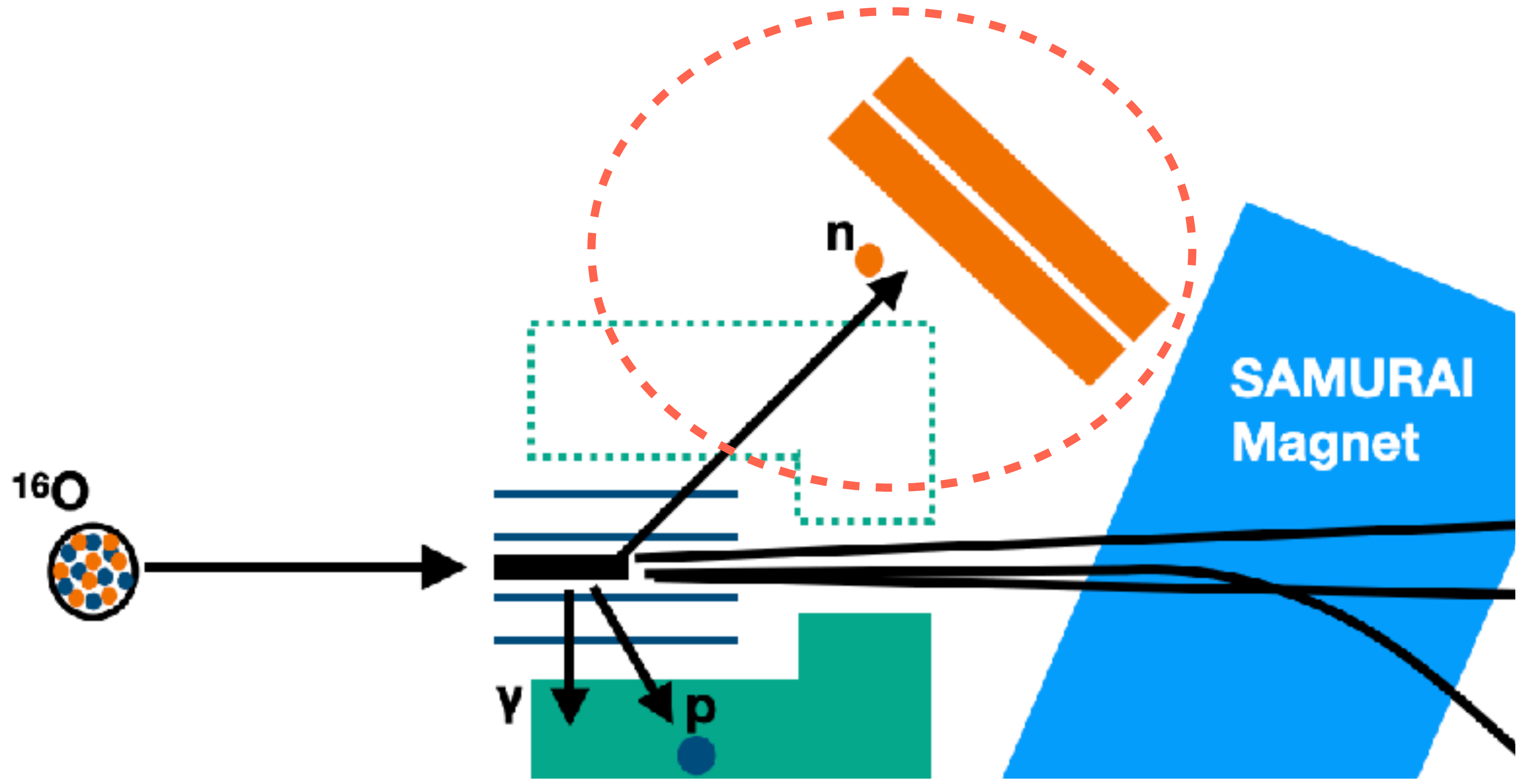
De-excitation products → **$^{15}O^*$ branching ratio**

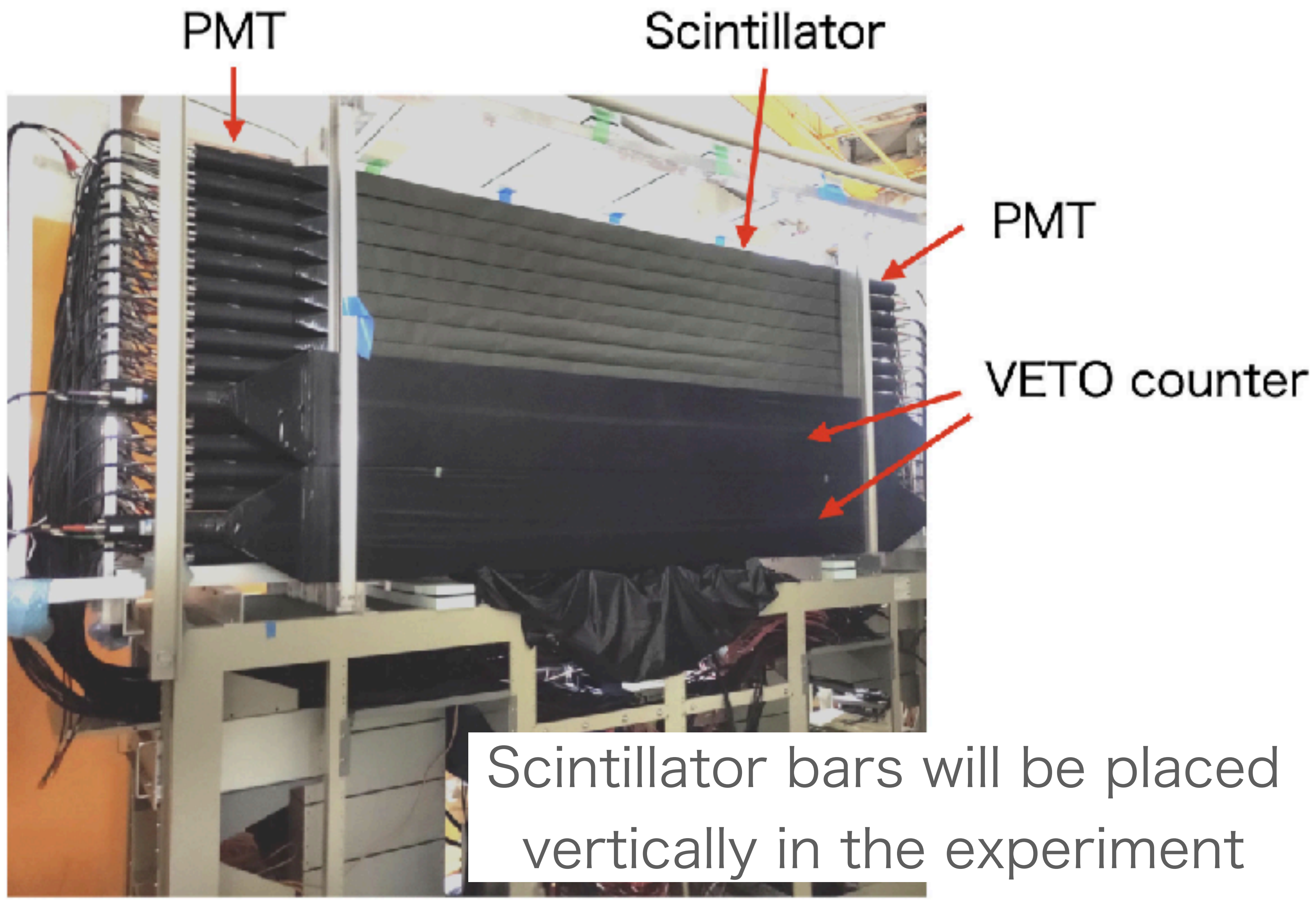
Preparation Status of SAMURAI-79

- Preparing for beam time (date to be determined)
- Development of (p, pn) knocked-out neutron detector MNEUT
  ① Parasitic measurement
  ② Performance evaluation of new digitizer: MDPP-32
- Development of optimization method of de-excitation model

Reaction	Beam time (Our hope)
$^{16}O(p, 2p)^{15}N^*$	2027 Spring
$^{16}O(p, pn)^{15}O^*$	2027 Autumn
$^{17}O(p, pn)^{16}O^*$	

New neutron detector **MNEUT**





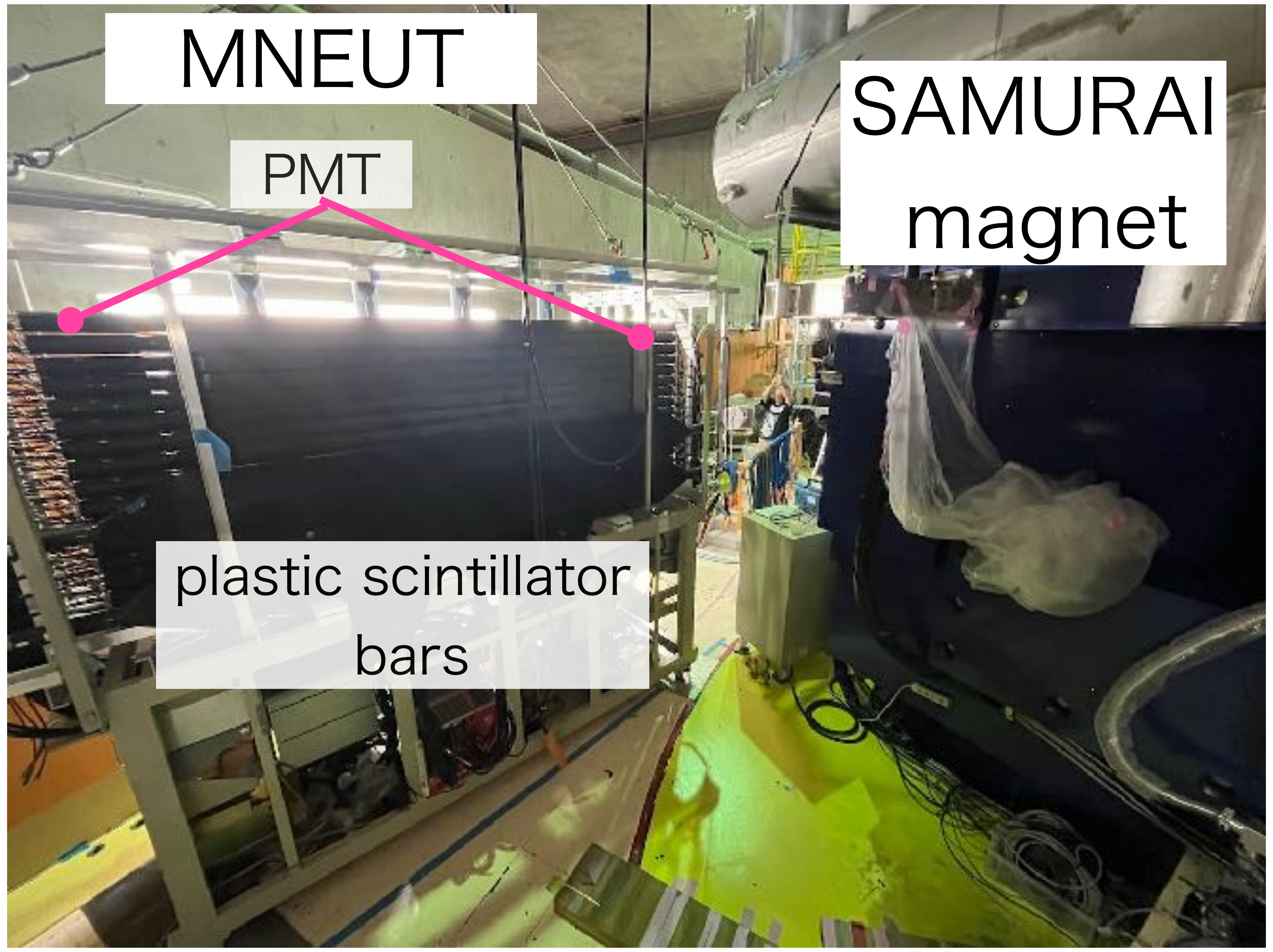
Scintillator bars will be placed vertically in the experiment

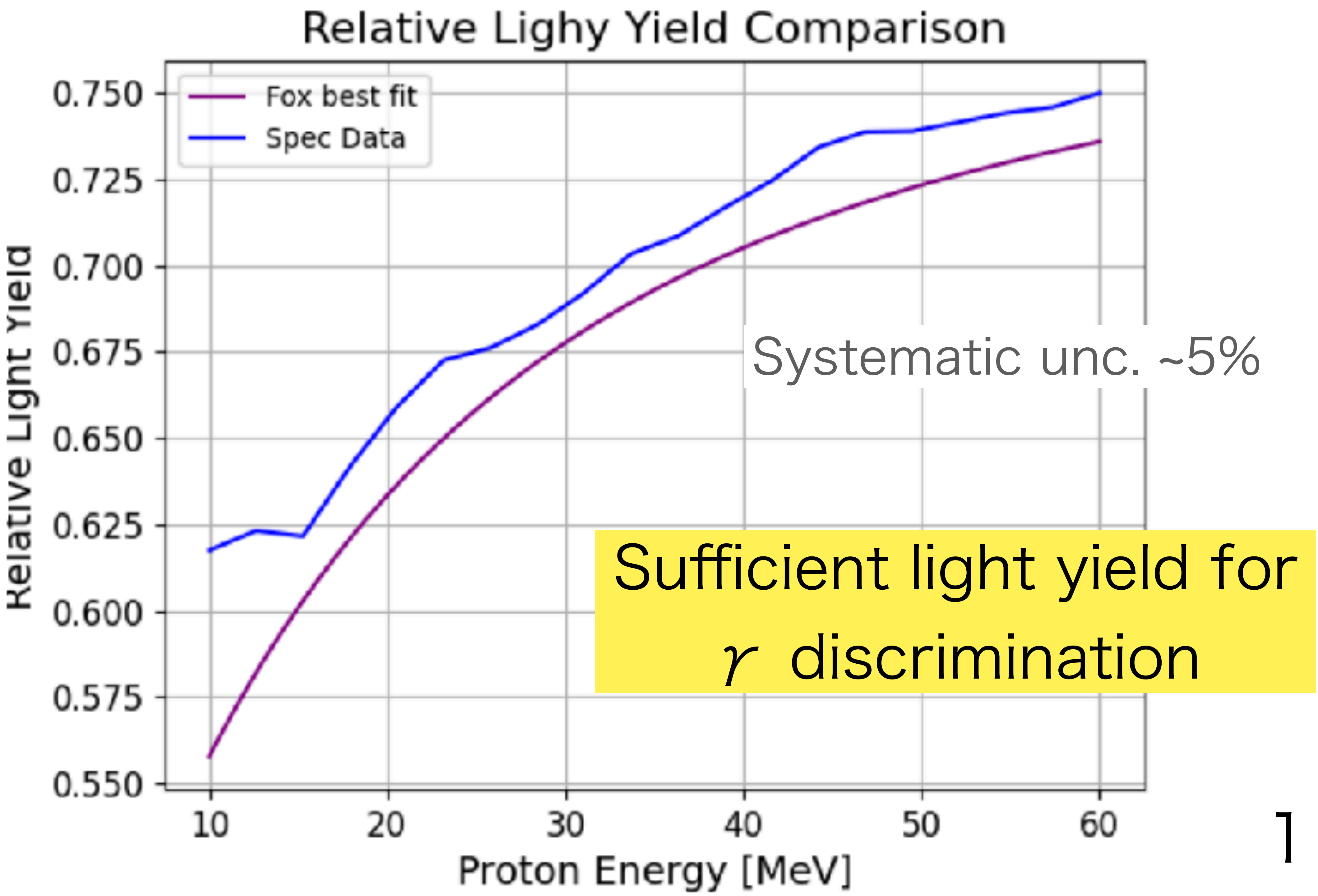
Parasitic Measurement of MNEUT

①Parasitic measurement in June 2025

- Placed the prototype of MNEUT during the beam time
- Calibration (Energy, time-walk correction, …)
- Energy reconstruction of neutron
- Light yield

H. Hayasaki





DAQ Upgrade of MNEUT

②Performance evaluation of new digitizer: MDPP-32

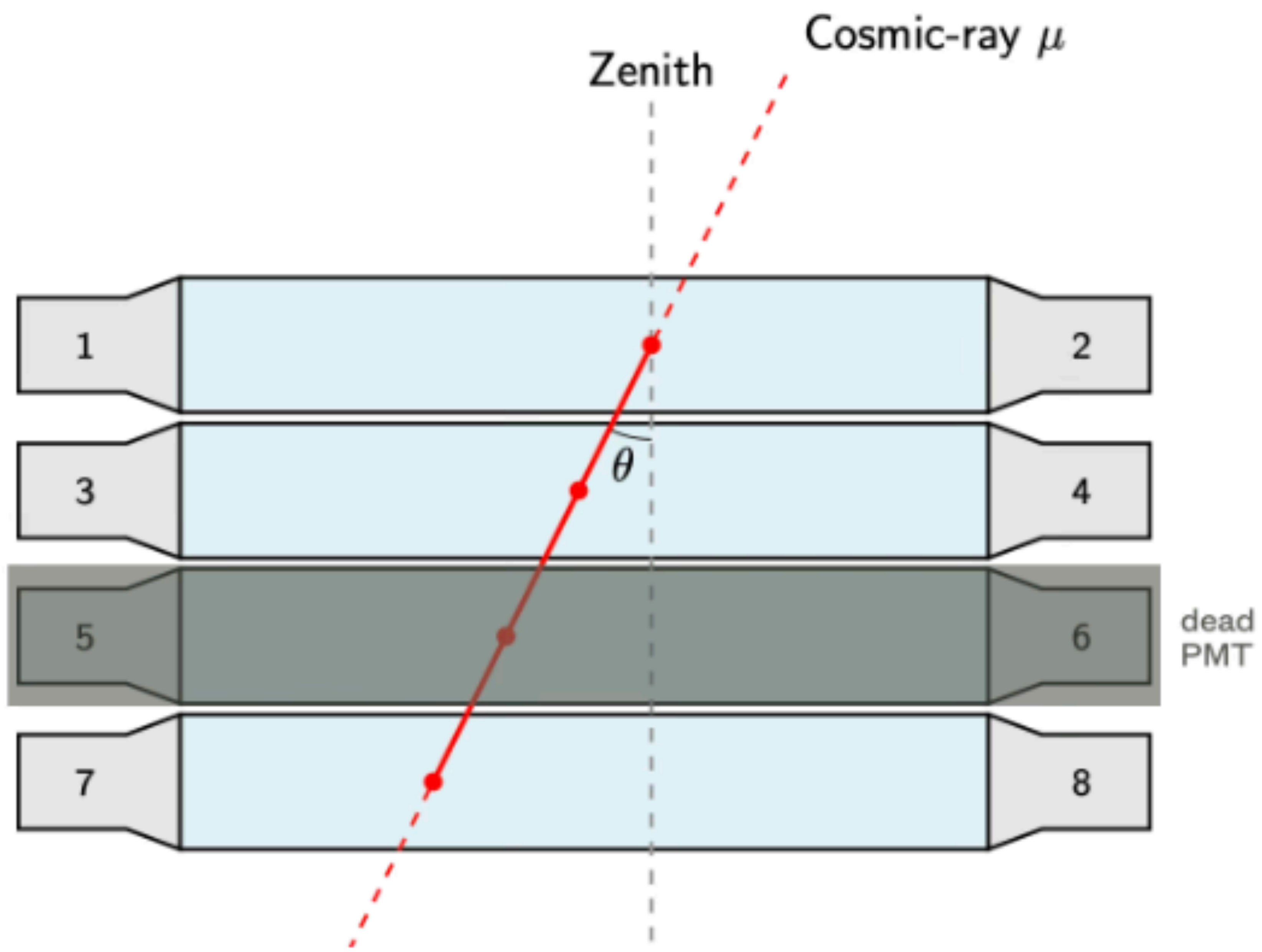
- Verifying that MDPP-32 meets the requirements for use in the experiment
- Basic performance check has been finished

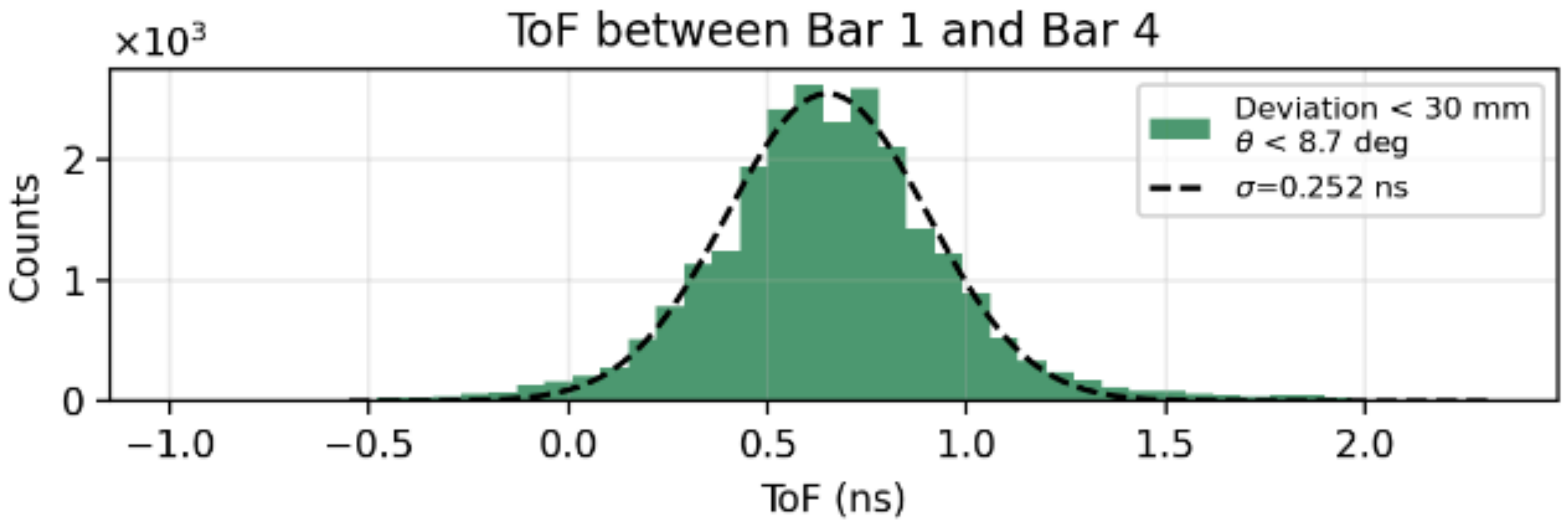
Example of requirements

Requirments	Status
Pre-trigger window > ~ 1 μs	Up to 25.56 μs ✅
DAQ rate tolerance >~ kHz	A few 10 kHz ✅
MNEUT timing performance > ~ 1 ns	σ_{vertex} = 0.2 ns ✅

W. Cai

Timing performance measurement w/ cosmic





Achieved sufficient timing resolution (0.18 ns)

Optimization of De-excitation Model

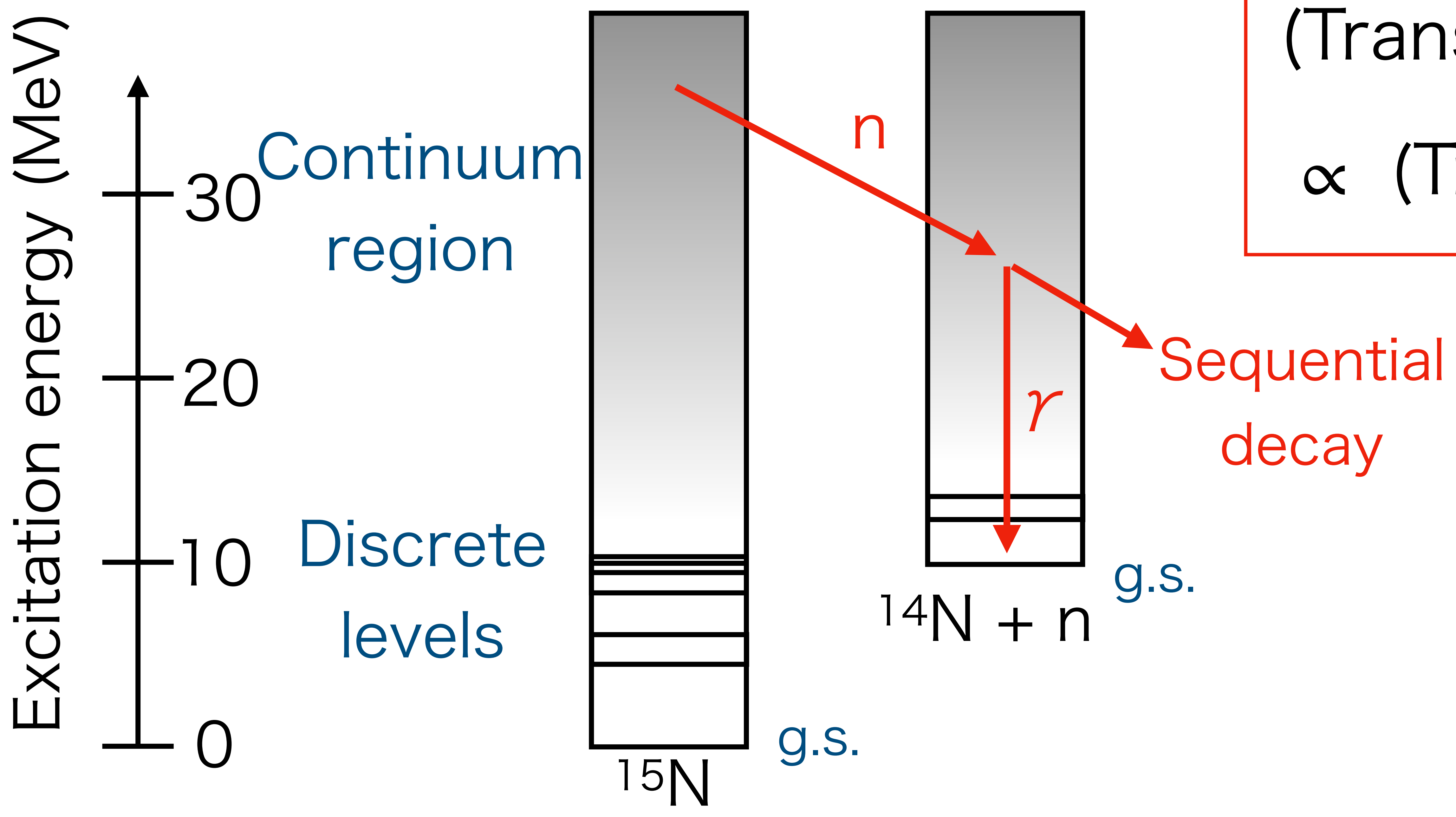
- Will optimize the parameters in the de-excitation model to fit the data obtained by SAMURAI-79 using nuclear reaction code **CCONE**
  - Developing model optimization method

O. Iwamoto, J. Nucl. Sci. Technol. Vol. 44, No. 5, 687-697 (2007).
O. Iwamoto et. al., Nuclear Data Sheets, 131, 259-288 (2016).

- **Hauser-Feshbach model**

W. Hauser, H. Feshbach, Phys. Rev., 87(2):366-373 (1952)

  - Sequential decays until nucleus reaches to its ground state



(Transition probability)

∝ (Transmission coefficient (TC)) × (Level density (LD))

How easily particle can pass through potential (**Optical model potential**)

How dense the state after transition is

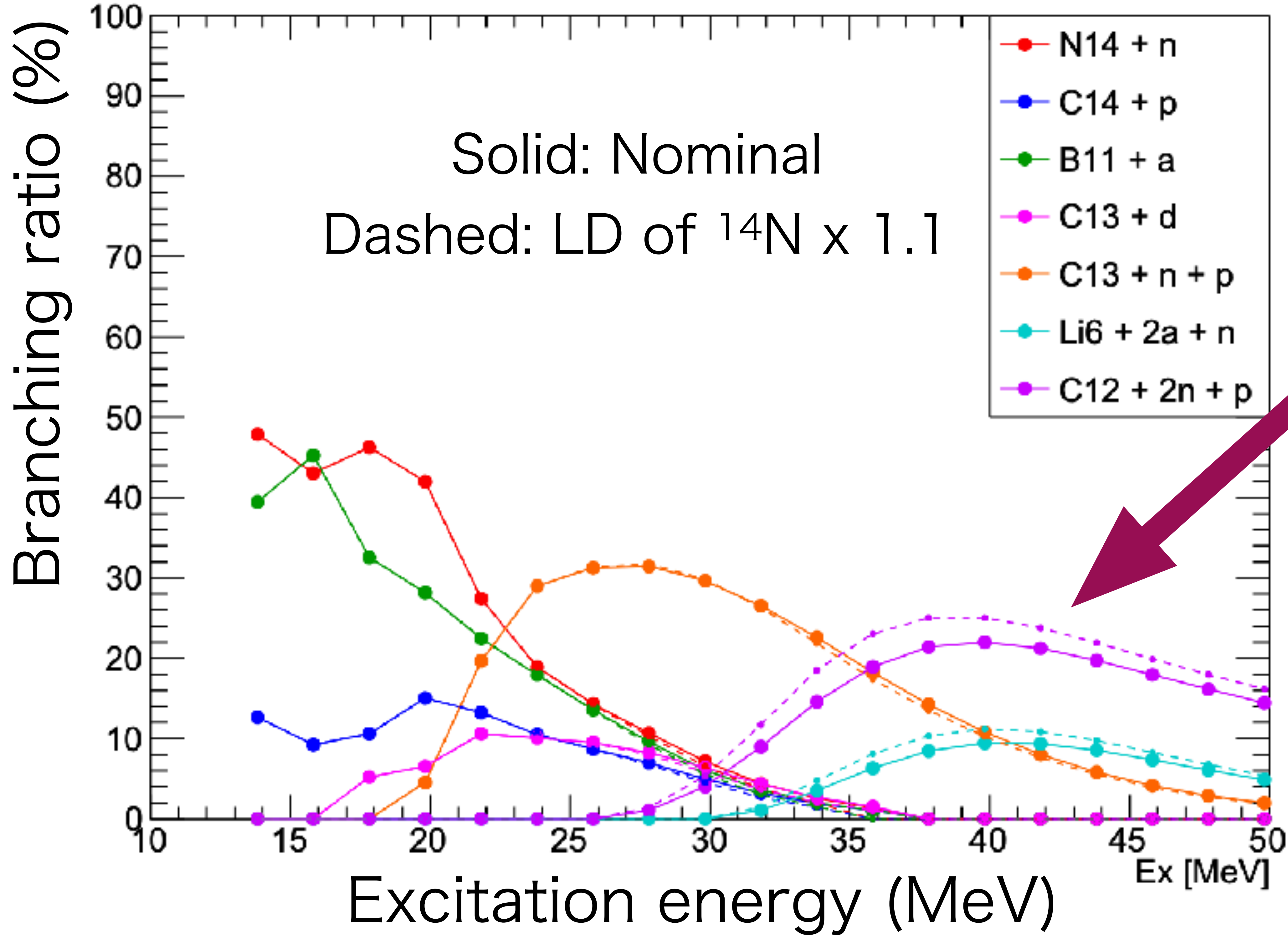
Level Density

(Transition probability) $\propto$ (Transmission coefficient (TC)) $\times$ (Level density (LD))

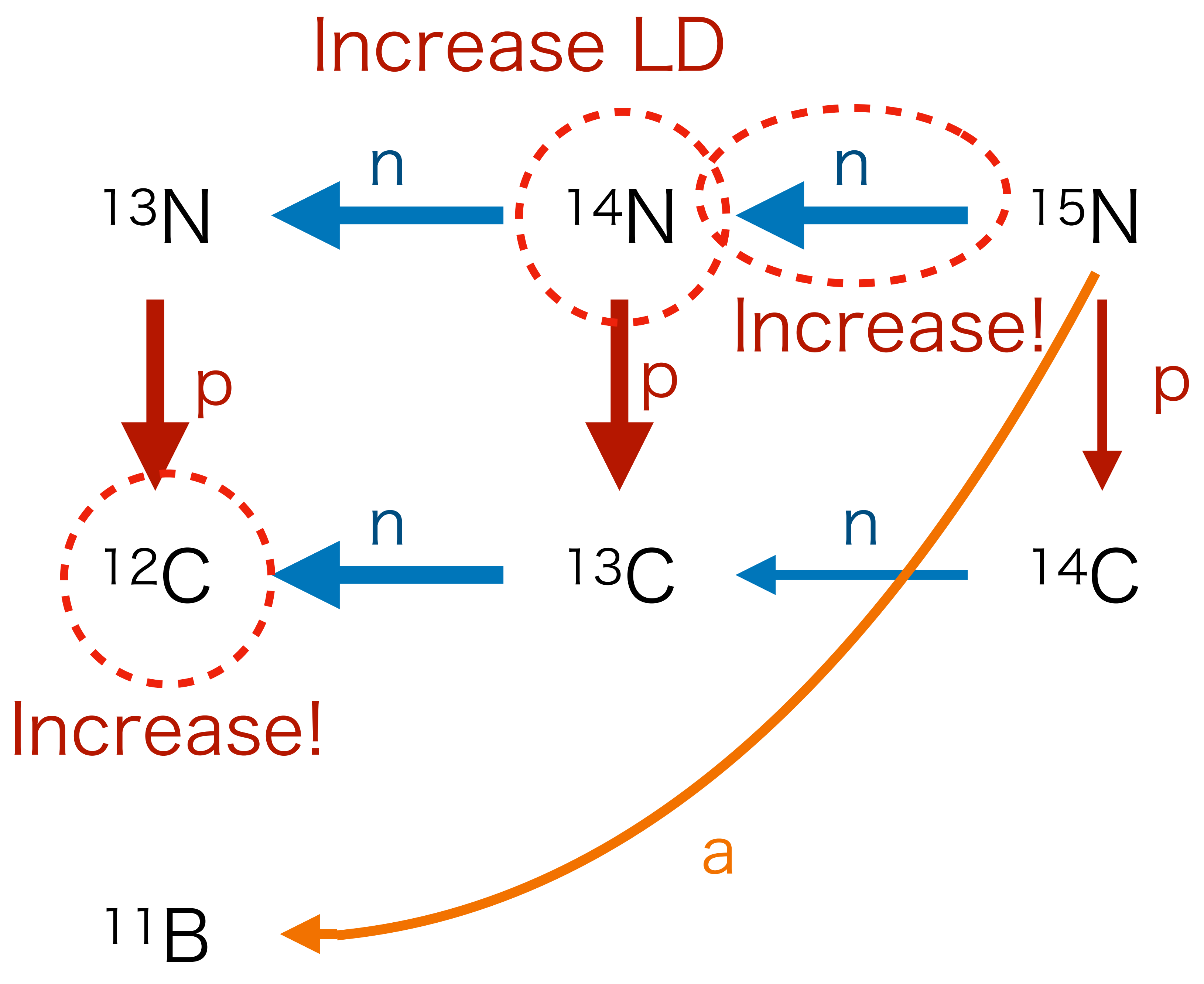
- Increase LD of ^{14}N by +10%
- Change in decay which pass through ^{14}N
- ~10% change in higher excitation energy

How dense the state after transition is

Branching ratio of ^{15}N* for each excitation energy



BR of ^{12}C + 2n + p: ~ +10%



Y. Mizuno

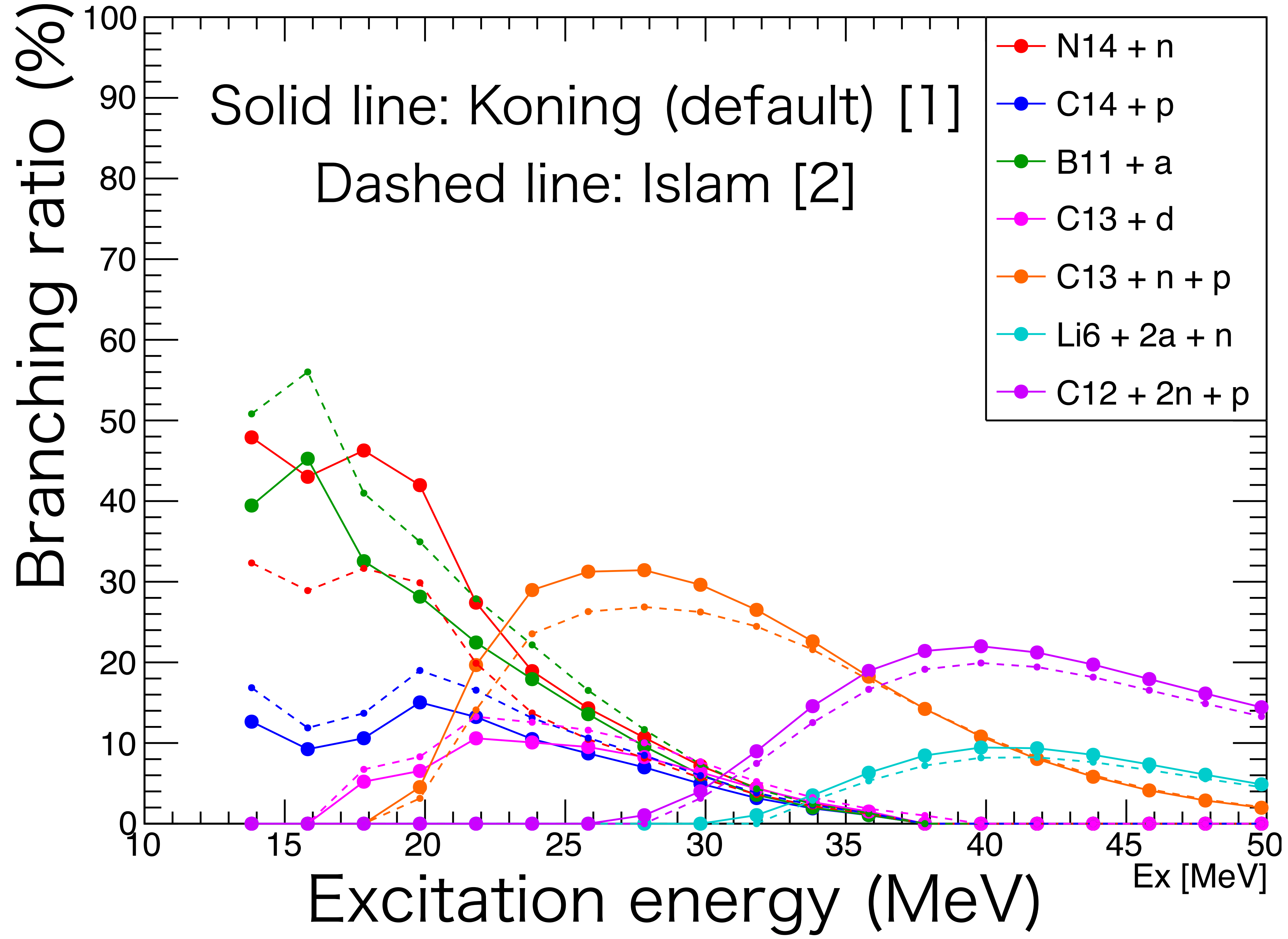
Optical Model Potential

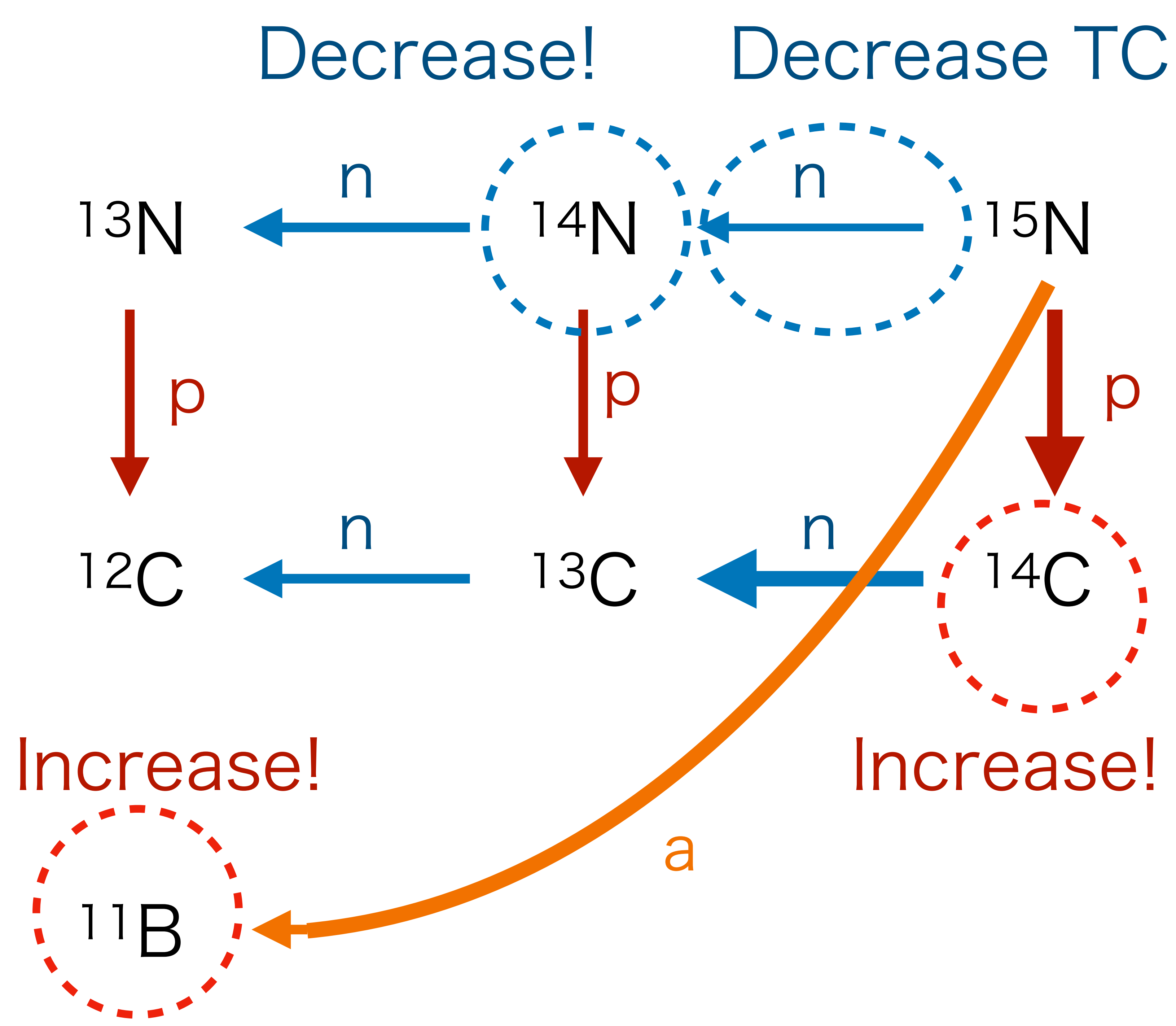
(Transition probability) ∝ (Transmission coefficient (TC)) × (Level density (LD))

How easily particle can pass through potential

- Change the potential of neutron emission from ^{15}N (**Optical model potential**)
  - Neutron emission is suppressed
- Change in lower excitation energy

Branching ratio of $^{15}N^*$ for each excitation energy





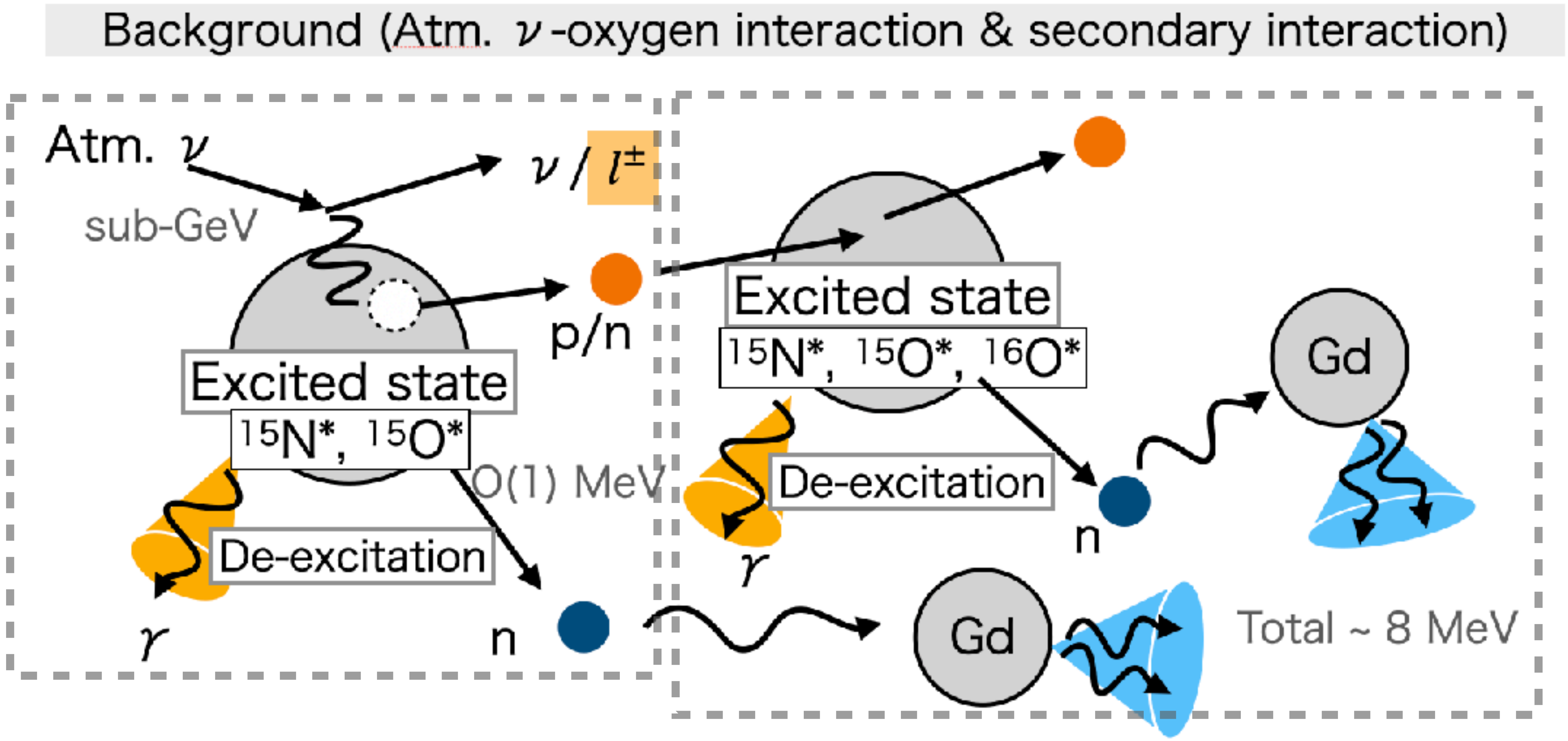
[1] A.J.Koning, J.P.Delaroche, Nucl. Phys. A713, 231 (2003)
[2] M. S. Islam, R. W. Finlay, J. S. Petler, J. Rapaport, R. Alarcon, Phys. in Med. and Biol. 33, 315 (1988).

Application to Neutrino Physics Analysis

- Developing the optimization method
  - Level density: High-Ex, Optical model potential: Low-Ex
  - Simultaneously fit to the data
- Implement the optimized model into neutrino simulation (NEUT, Geant4)

Construction of nuclear data
→ Contribution to nuclear physics

NEUT
(ν reaction MC)



Geant4
(Detector MC)

→ **Precise prediction of neutrino-oxygen quasielastic interactions**

Summary

- Toward precise prediction of the neutrino-oxygen quasielastic interactions
  - Primary goal: First observation of diffuse supernova neutrino background at Super-Kamiokande
- SAMURAI-79 experiment will measure de-excitation of $^{15}N^*$, $^{15}O^*$, $^{16}O^*$ using inverse kinematics
  - Developing new neutron detector MNEUT
- Will construct nuclear data using CCONE
  → Implement it into NEUT・Geant4
  → Apply to neutrino physics
  - Developing optimization method of nuclear de-excitation model (Hauser-Feshbach model)

Back up

Neutrino-Nucleus Interactions

- In physics analysis of neutrino experiments, **neutrino-nucleus interactions**, following **nucleon-nucleus interactions**, and detector response are dominant systematics
  - Oxygen ion beam experiment to measure nuclear de-excitation process (**SAMURAI-79 experiment**)
  - Aiming to improve the prediction of neutrino-oxygen quasielastic interactions

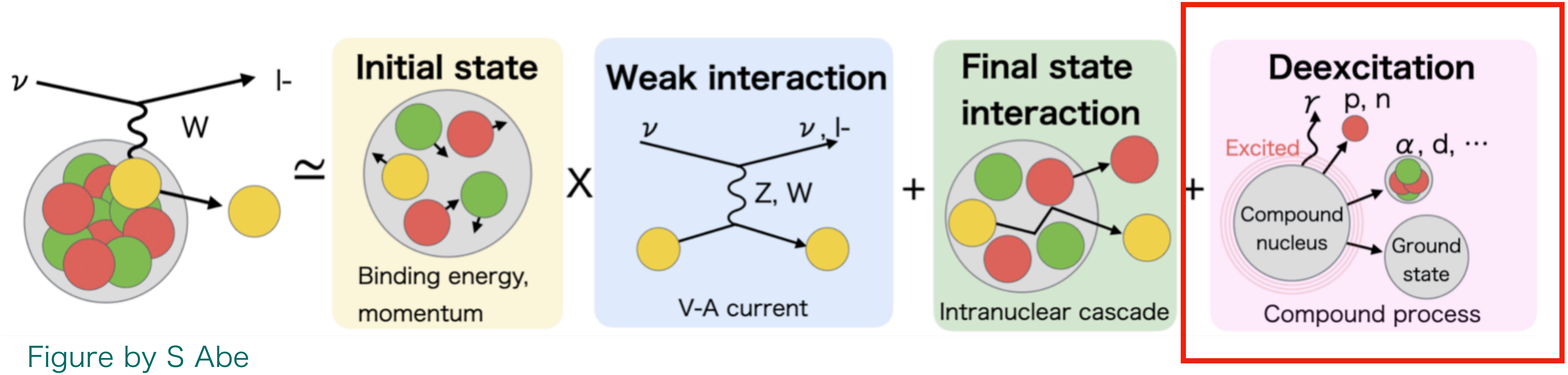
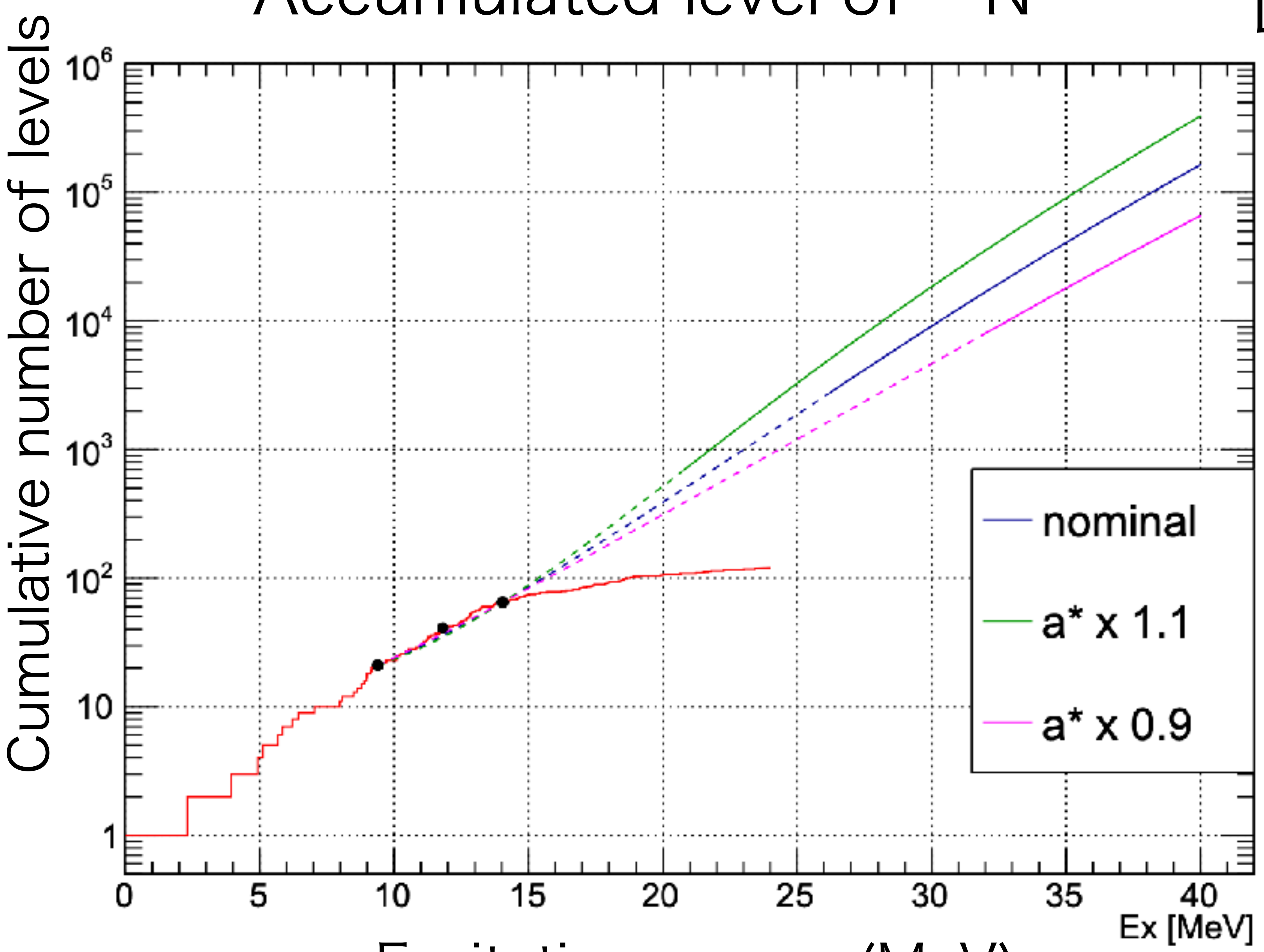


Figure by S Abe

Level Density Parameter

- a* determines the scale of the level density

Accumulated level of ^{14}N



Excitation energy (MeV)

$$U = E_x - \Delta$$

Level density

$$\rho(U) = \begin{cases} K_r \dfrac{e^{2\sqrt{aU}}}{12\sqrt{2}\sigma U (aU)^{1/4}}, & (U > U_m) \quad \text{Fermi gas} \\ \dfrac{1}{T} \exp \dfrac{U + \Delta - E_0}{T}, & (U \le U_m) \quad \text{Constant temperature} \end{cases}$$

Δ: Pairing energy
K_r: Collective enhancement factor for rotational excitation
σ: Spin-cutoff parameter
E_{th}: Shell correction energy
γ: Shell correction dumping factor

Main level density parameter

$$a(U) = a^* \left(1 + E_{sh} \frac{1 - e^{-\gamma U}}{U}\right)$$

Global fit depending on mass number

$$a^*(A) = 0.058025A(1 + 5.9059A^{-1/3})$$

Mengoni-Nakajima, JNST 31, 151(1994)

Deviation of the local values from the global fit: ~ 10%

A.J. Koning et al., Nucl. Phys. A 810(1), 13-76 (2008)

OMP

- Optical potential depends on radius
- Sum of Woods-Saxon and Coulomb potential

$$V(r) = V_1 f_1(r) + iW_2 f_2(r) + V_3 g_3(r) + iW_4 g_4(r) + \left(V_5 h_5(r) + iW_5 h_5(r)\right) \sigma \cdot \mathbf{l} + V_C(r)$$

Volume   Surface derivative   Spin-orbit   Coulomb

$$f_i(r) = \frac{1}{1 + \exp\left(\frac{r - R_i}{a_i}\right)}$$

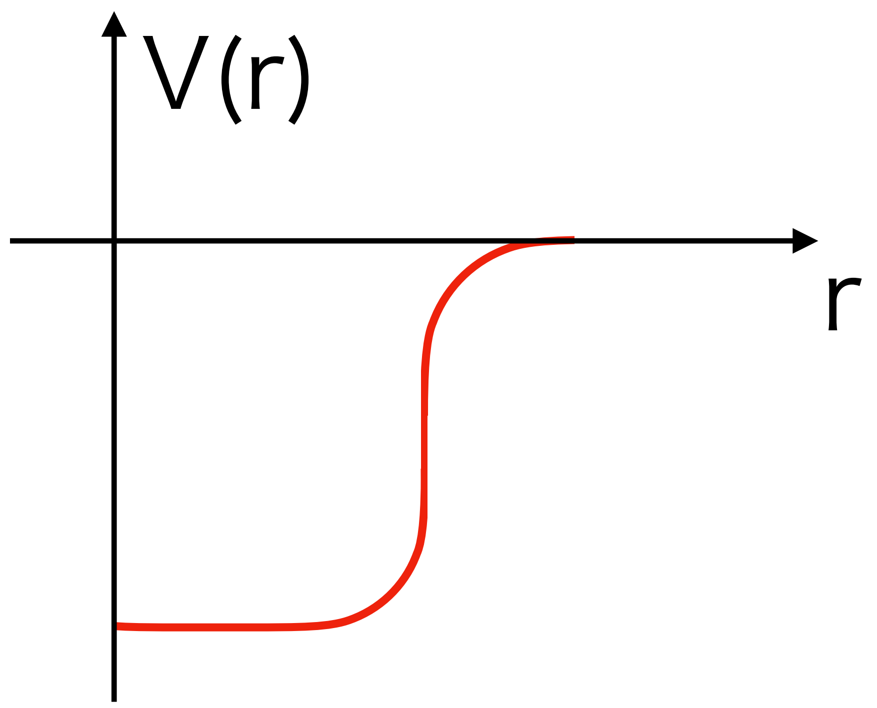
$$g_i(r) = -4a_i \frac{d}{dr} f_i(r)$$

$$h_i(r) = -\left(\frac{\hbar}{m_\pi c}\right)^2 \frac{1}{r}\frac{d}{dr} f_i(r)$$

V, W : Depth of potential

R : Radius of nucleus

a : Diffuseness of nucleus



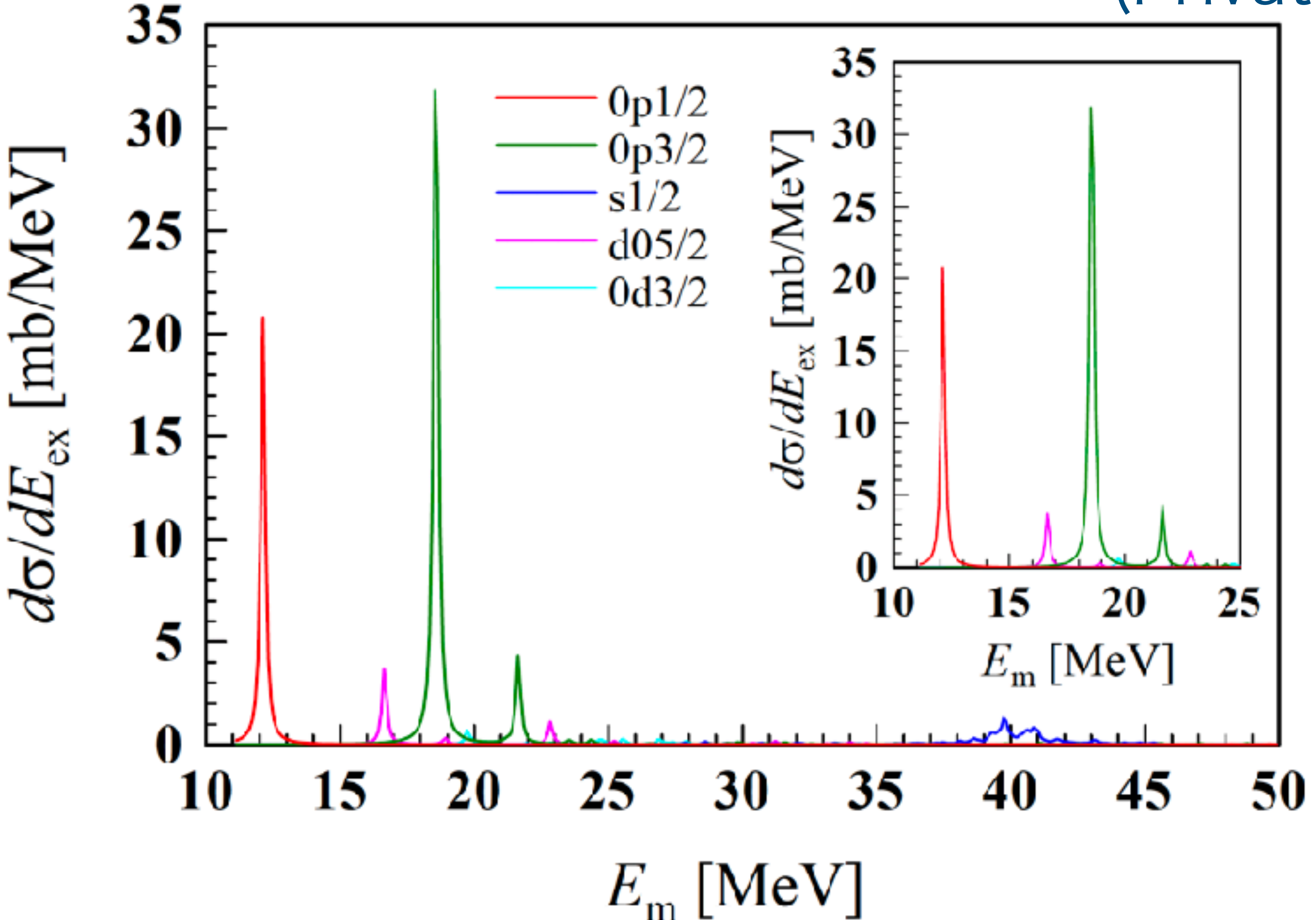
- Parameters in Woods-Saxon potential depend on mass number and incident energy

Proton & Neutrino Injection

- Generally matching, although there are some parts of phase space that are not covered
  - Reasonable to apply the result of p to ν reactions
- The exciton model does not explicitly take spin into account

^{16}O(p, 2p) @ 200 MeV
(Theory)

K. Ogata and Y. Utsuno
(Private communication)



^{16}O(e, e'p)
(Experiment)

M. Leuschner+, PRC**49**, 955 (1994).

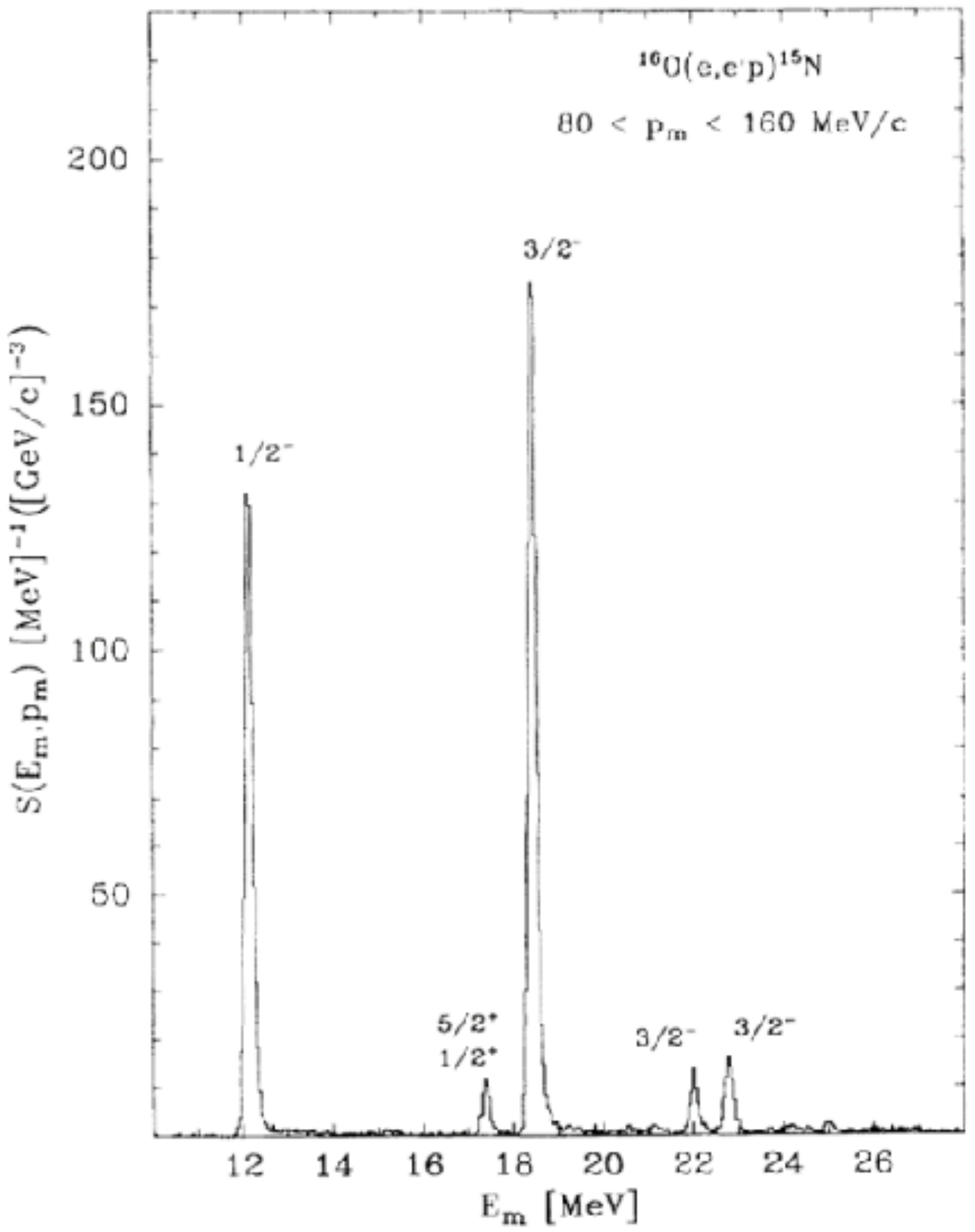


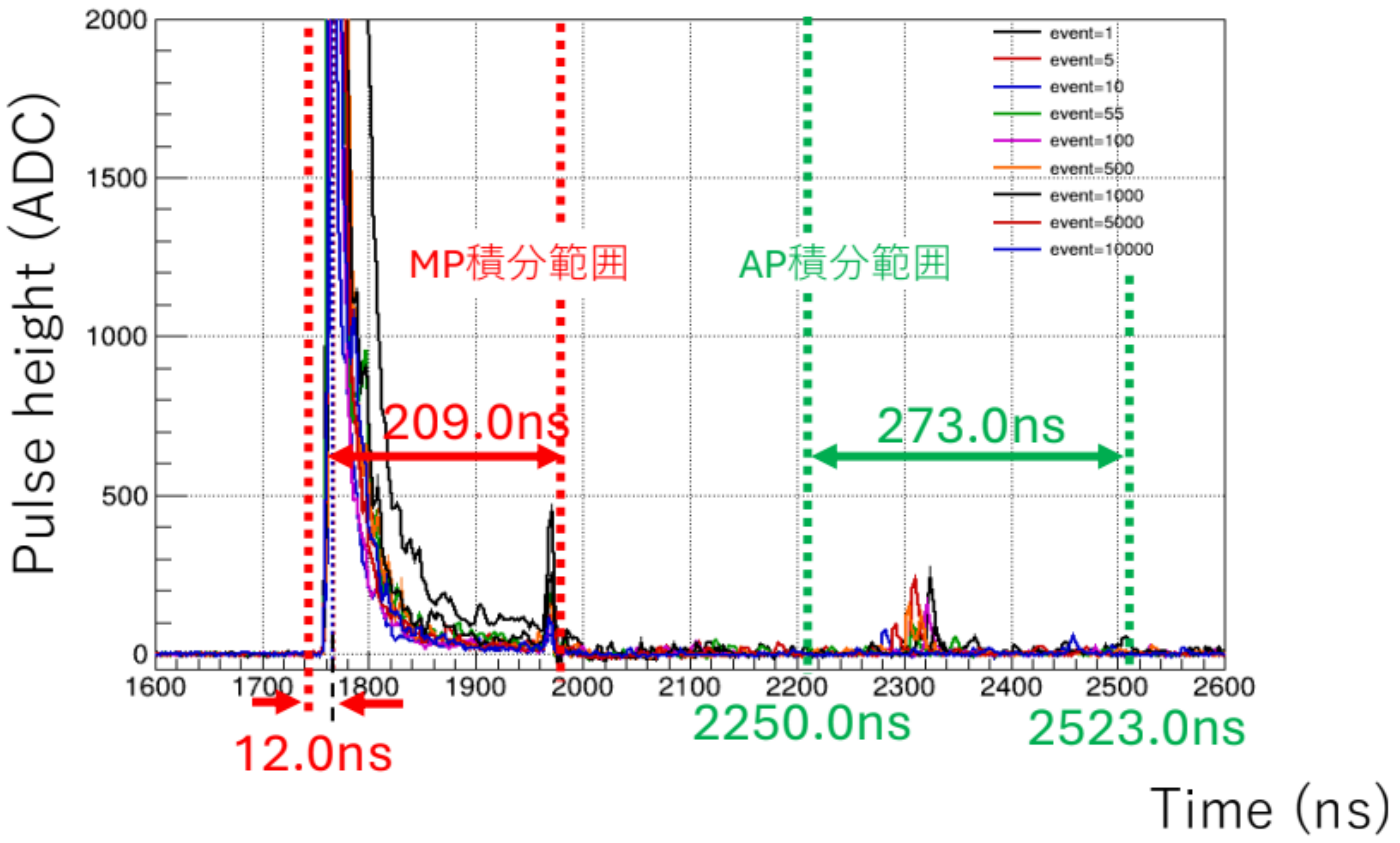
FIG. 1. ^{16}O$(e,e'p)^{15}$N missing energy spectrum for the kinematics centered about $\mathbf{p}_m = 120$ MeV/c.

Neutron Detector MNEUT

- Measurement of PMT after-pulse

Quantitative study is ongoing

Y. Hanakawa



Strategy towards application to neutrino physics