^{16}O beam experiment for precise modeling of neutrino-nucleus interactions

ニュートリノ原子核反応の精密理解のための酸素ビームを用いた原子核実験

Yasuhiro Nakajima (UTokyo)
中島　康博（東京大学）

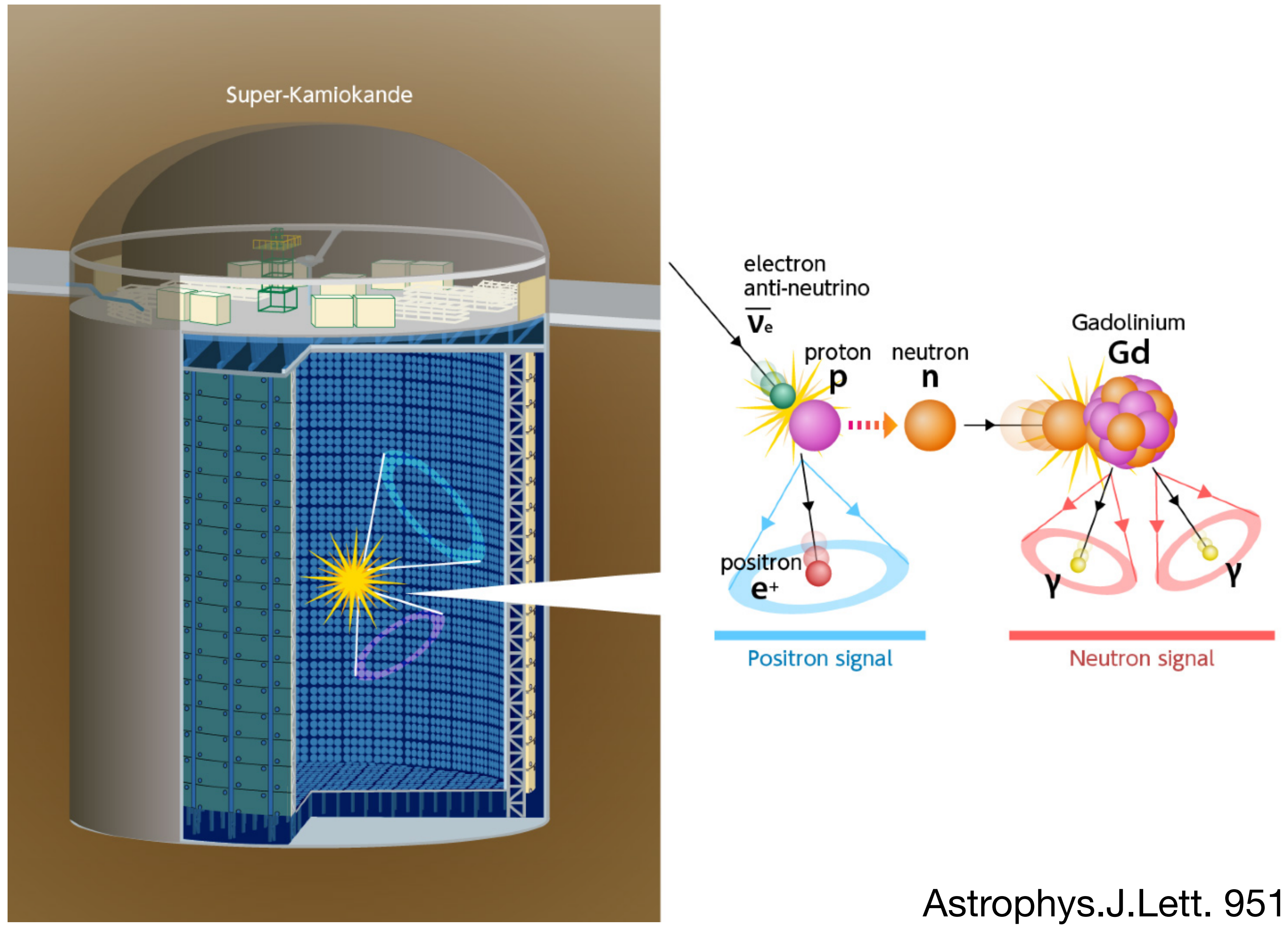
The 10th Supernova Neutrino Workhshop
Mar. 1st, 2024

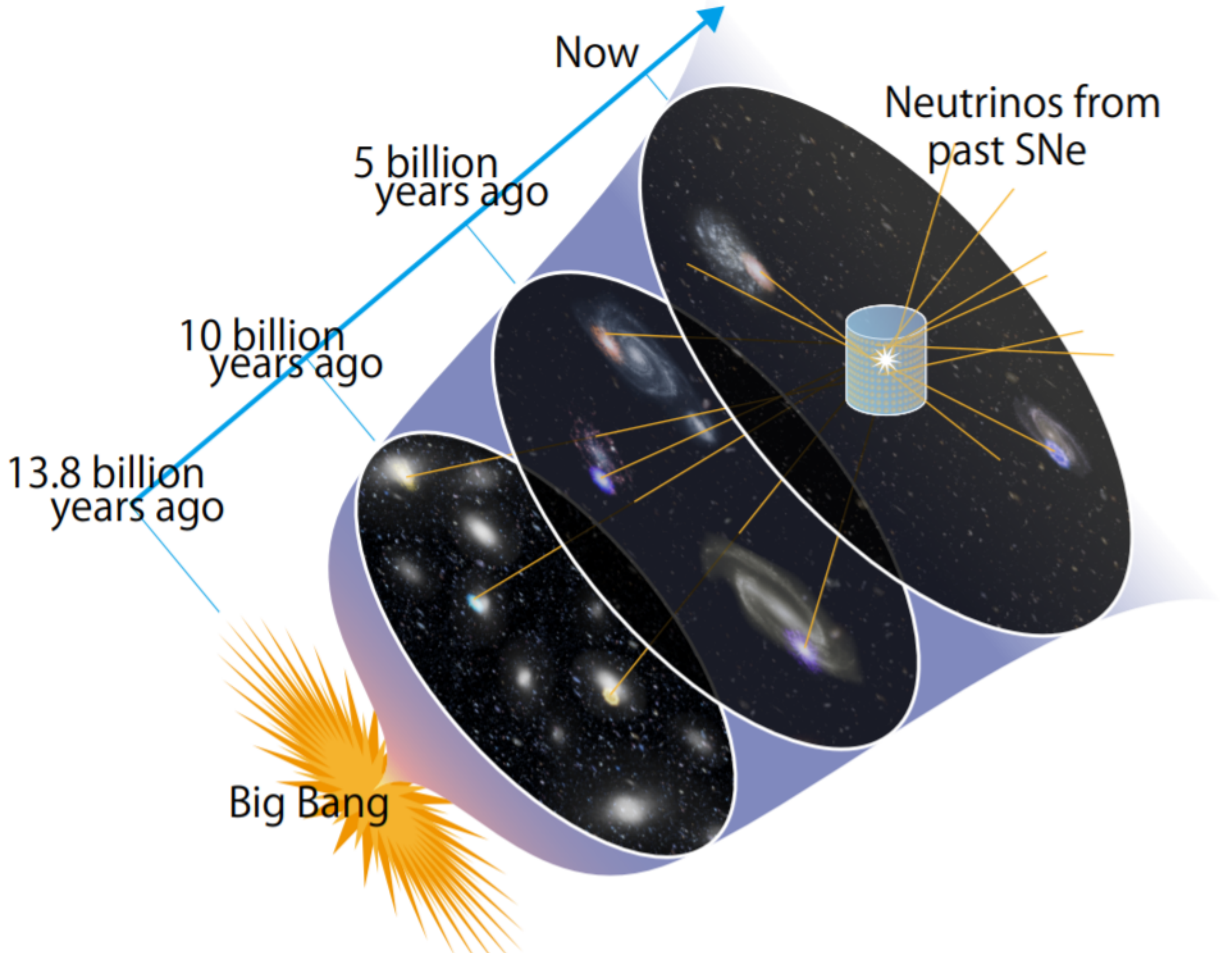
Contents

- Motivation: observation of DSNB at SK-Gd
- Nuclear physics involved in neutrino interactions
- Proposal of a ^{16}O experiment at RIKEN RIBF

Neutrino observation at Super-Kamiokande

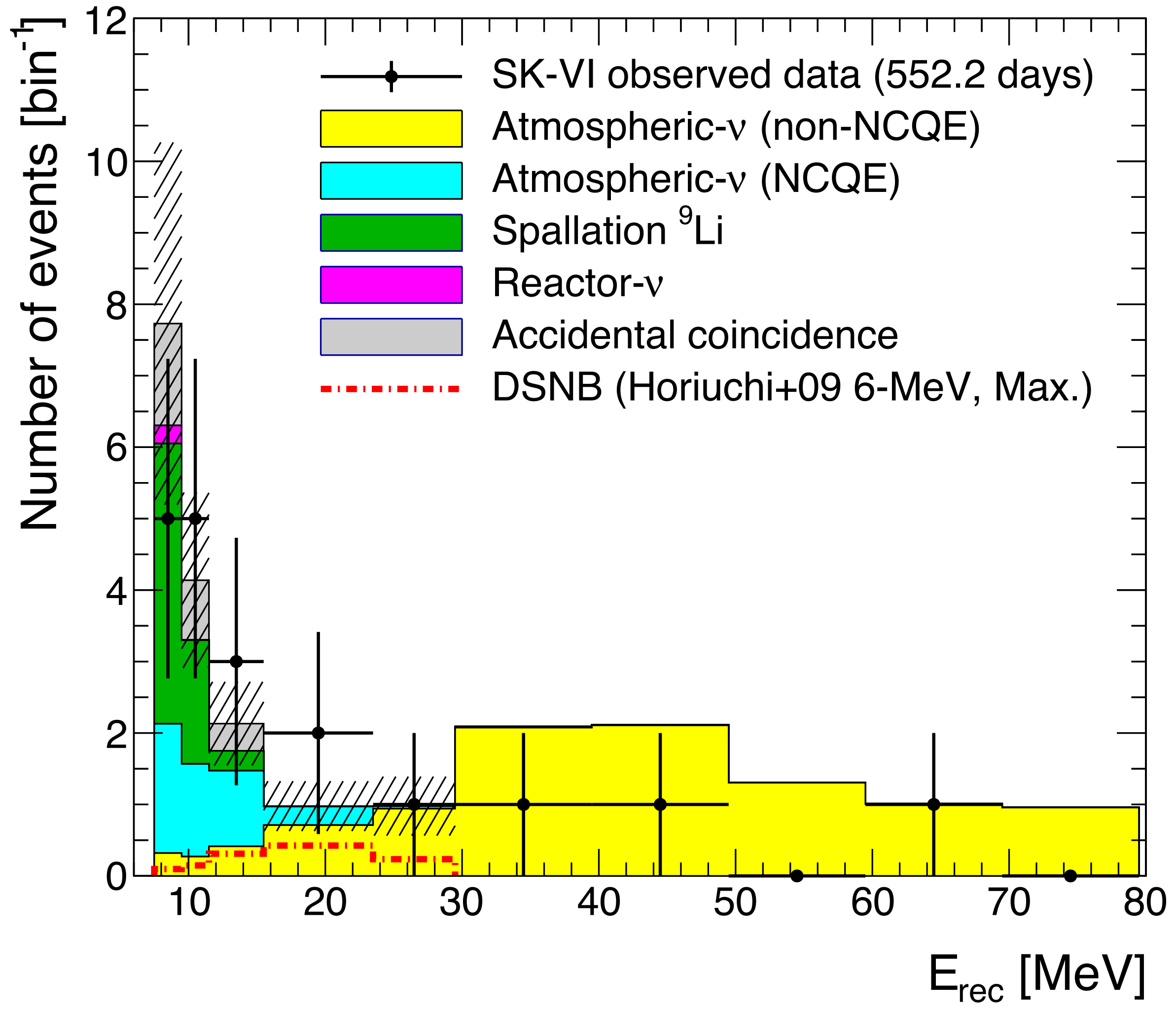
- Super-Kamiokade: the world-largest underground neutrino detector with 50 kton of water
- Dissolved Gadolinium to SK in 2020 (0.01%) and 2022 (0.03%)
    - Significantly enhanced neutron detection capability
- Major physics goals:
    - **First observation of Diffuse Supernova Neutrino Background (DSNB)**
    - Improved measurement of supernova burst neutrinos
    - Reactor neutrinos
    - Measurement of atmospheric and accelator neutrinos with improved reconstruction
    - And many more!





Astrophys.J.Lett. 951 (2023) 2, L27

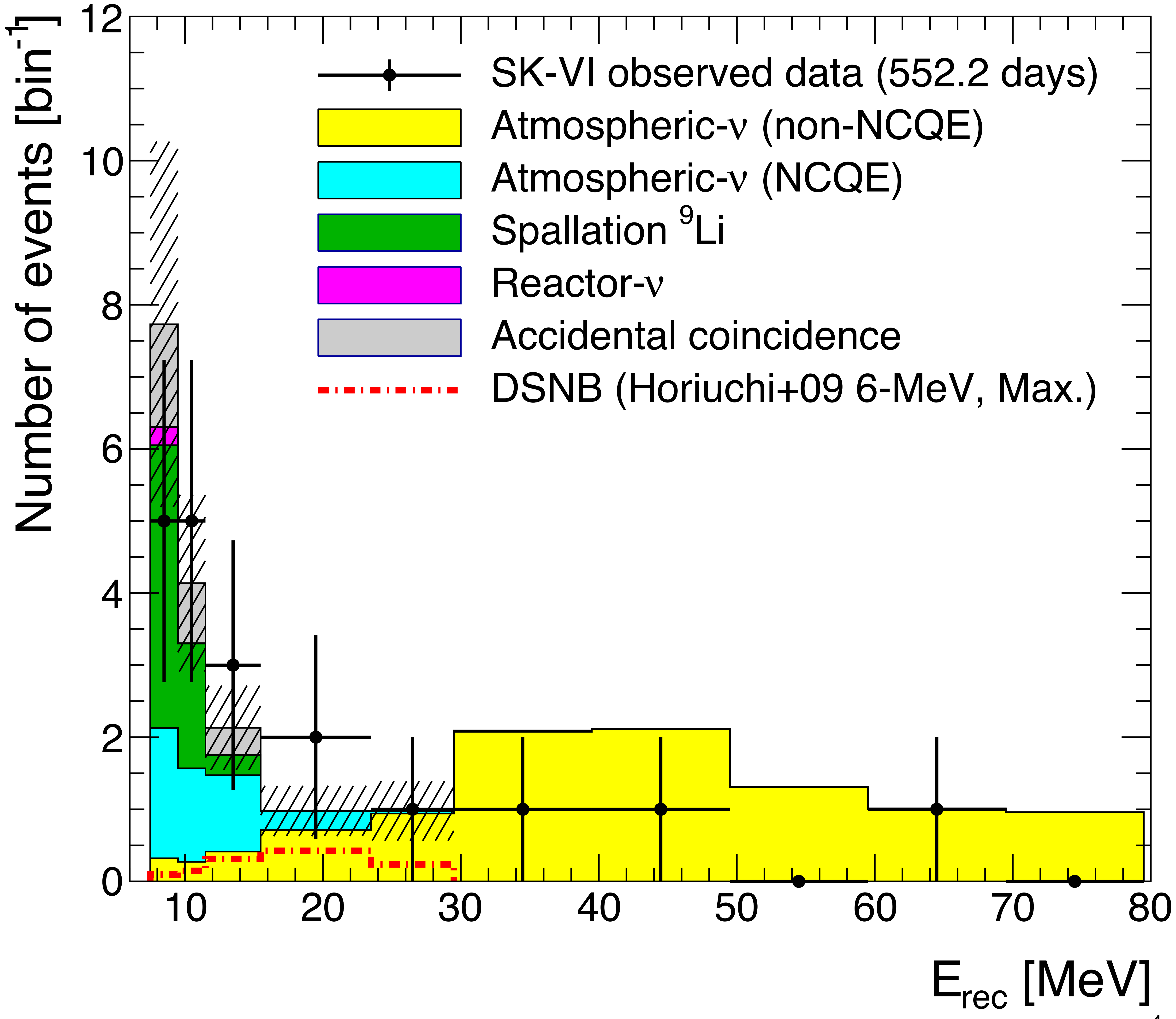
1.5 years of data with 0.01% Gd



Latest DSNB search results at SK-Gd

- First DSNB search result from SK-Gd with 1.5 year of the data with 0.01% Gd concentration
    - Already approacing the sensitivity with 10-years of pure-water SK data
- Experimental sensitivity approaching model prediction

Astrophys.J.Lett. 951 (2023) 2, L27



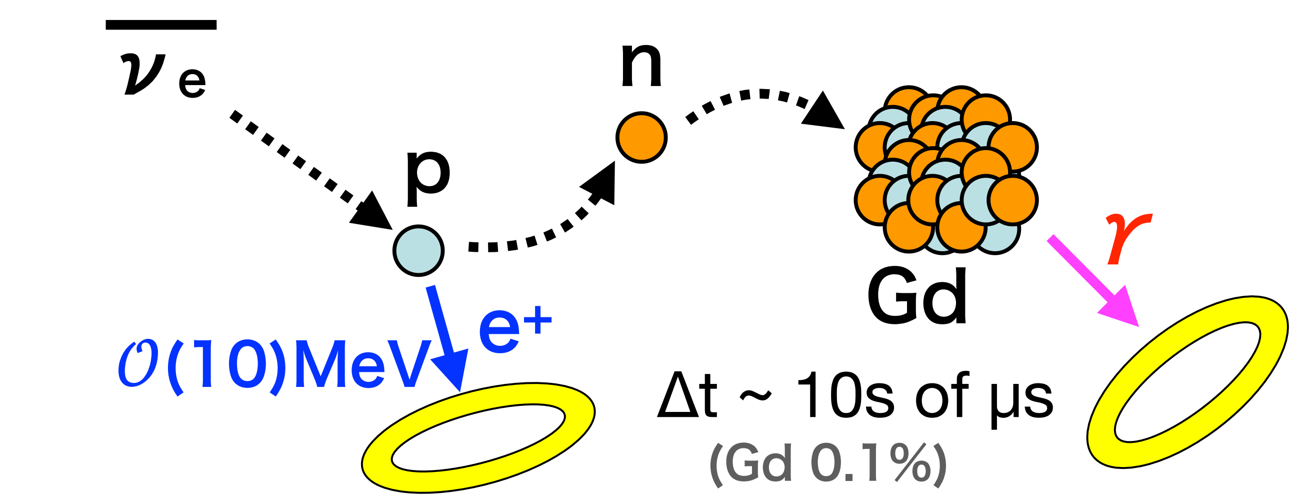
Diffuse Supernova Neutrino Background

- **Signal:** inverse beta decay of DSNB electron antineutrinos
  - Prompt positron and delayed neutron capture

- **Largest background:** atmospheric neutrino neutral-current quasi-elastic (NCQE) scattering
  - Prompt signal: **sum of all the de-excitation γs** from ν-^{16}O interaction (primary interaction) and secondary interactions of knocked-out nucleons and ^{16}O
  - Delayed signal: All the **neutrons produced by direct knock-out and evaporation**

Better understanding of these processes indispensable for the "discovery" of DSNB at Super-Kamiokande (and future Hyper-Kamiokande)

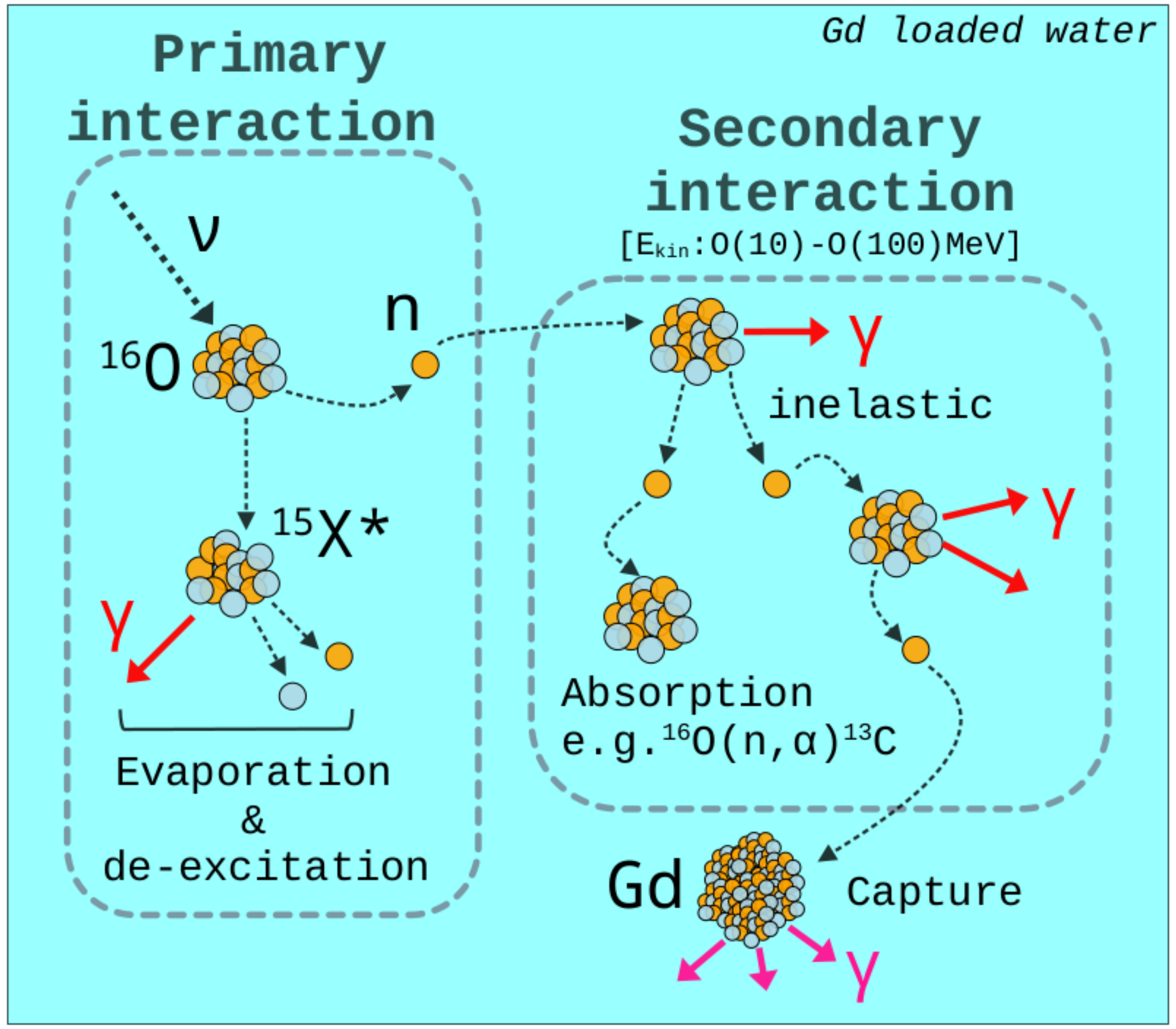
DSNB signal (inverse beta decay)



Prompt signal at O(10) MeV and delayed neutron capture

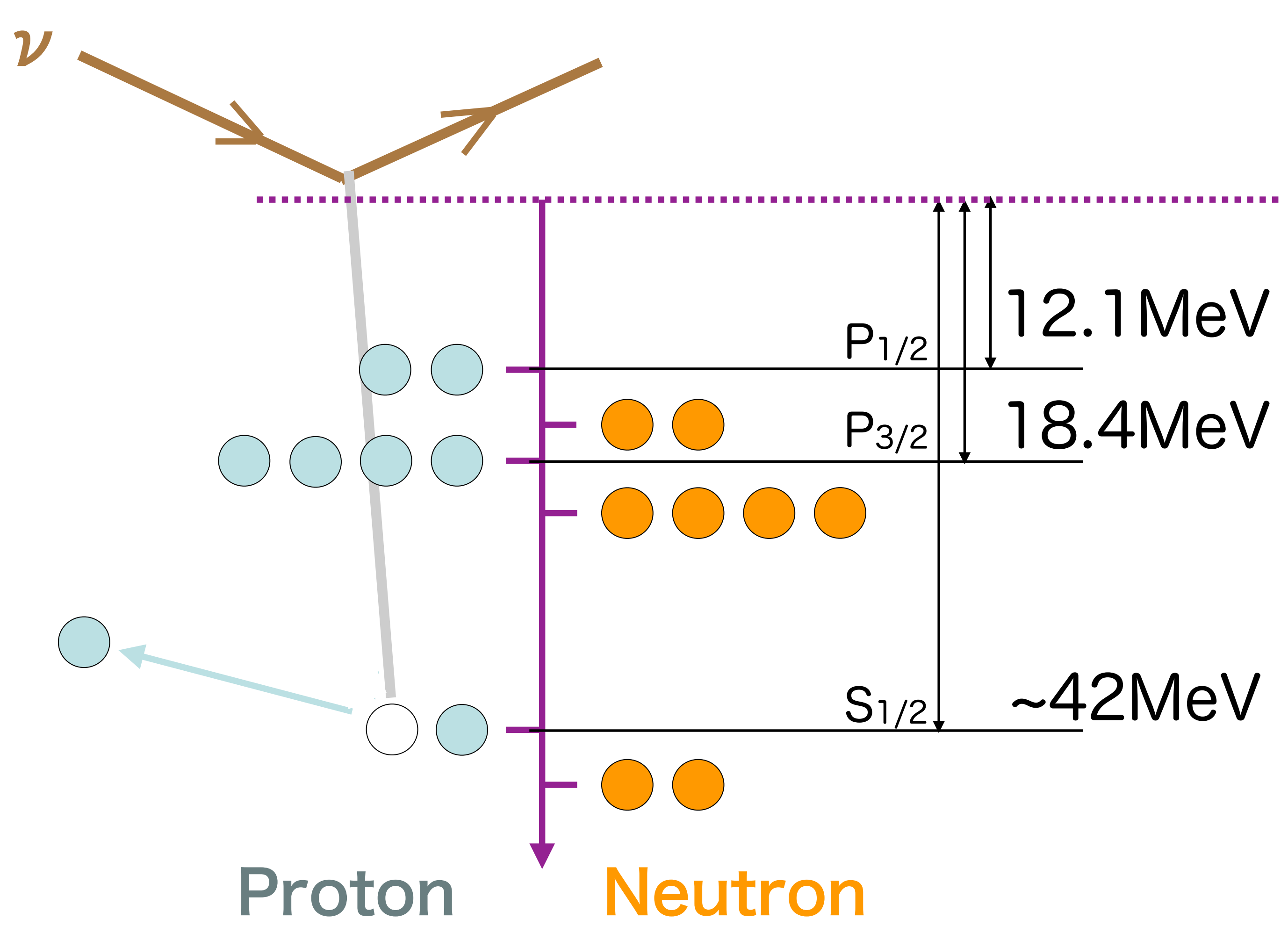
Backgrounds: Atmospheric ν NCQE

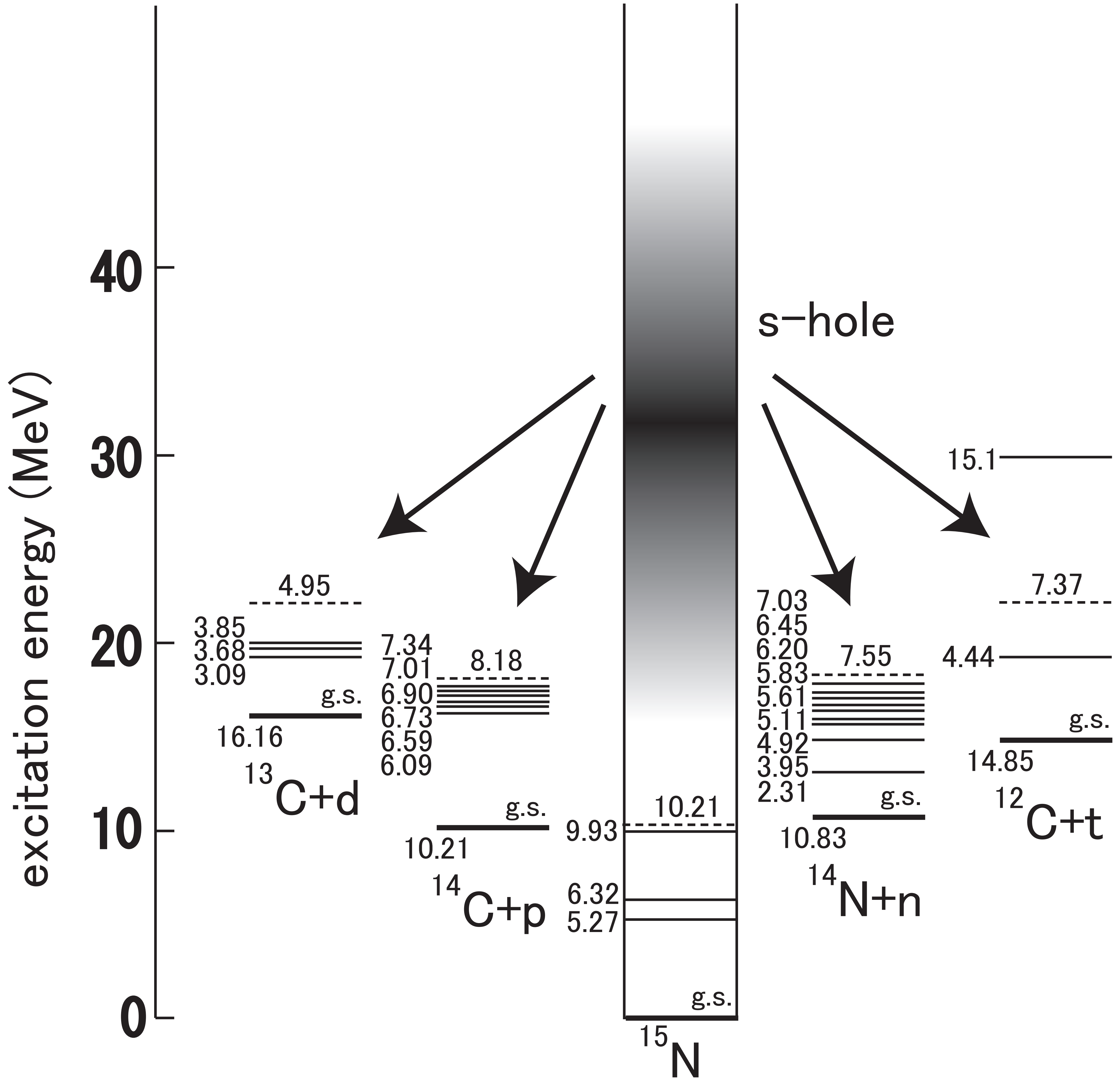
Neutrino energy: O(100) MeV - O(1) GeV



Key physical process

- De-excitation of highly excited states of $^{15}N^*$ and $^{15}O^*$, produced by nucleon knockout from ^{16}O
- Questions:
  - What is the distributions of the s-hole states?
  - What is the contribution of multi-nucleon knockout?
  - What is the multiplicity and energy distributions of de-excitation γ and nucleons?

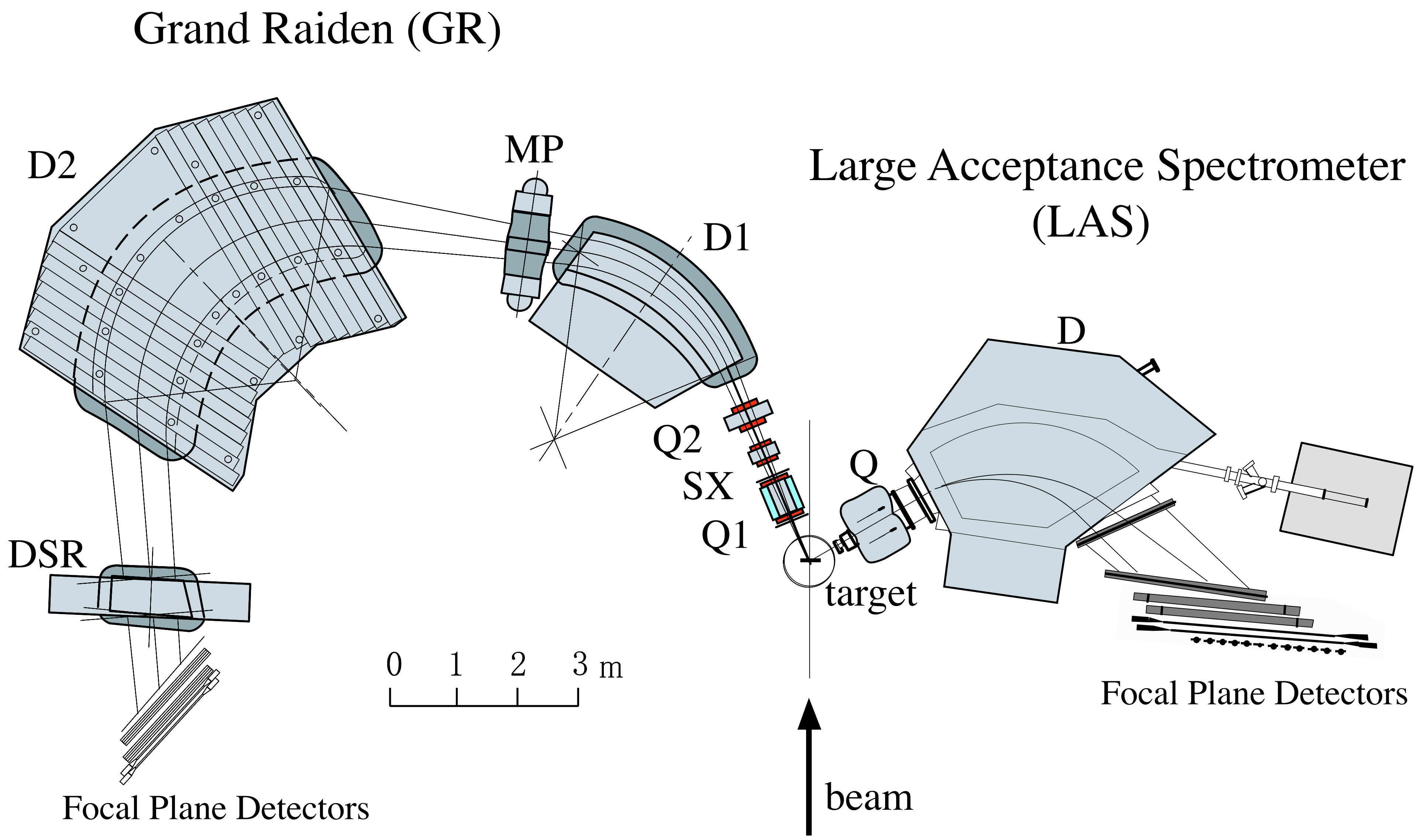


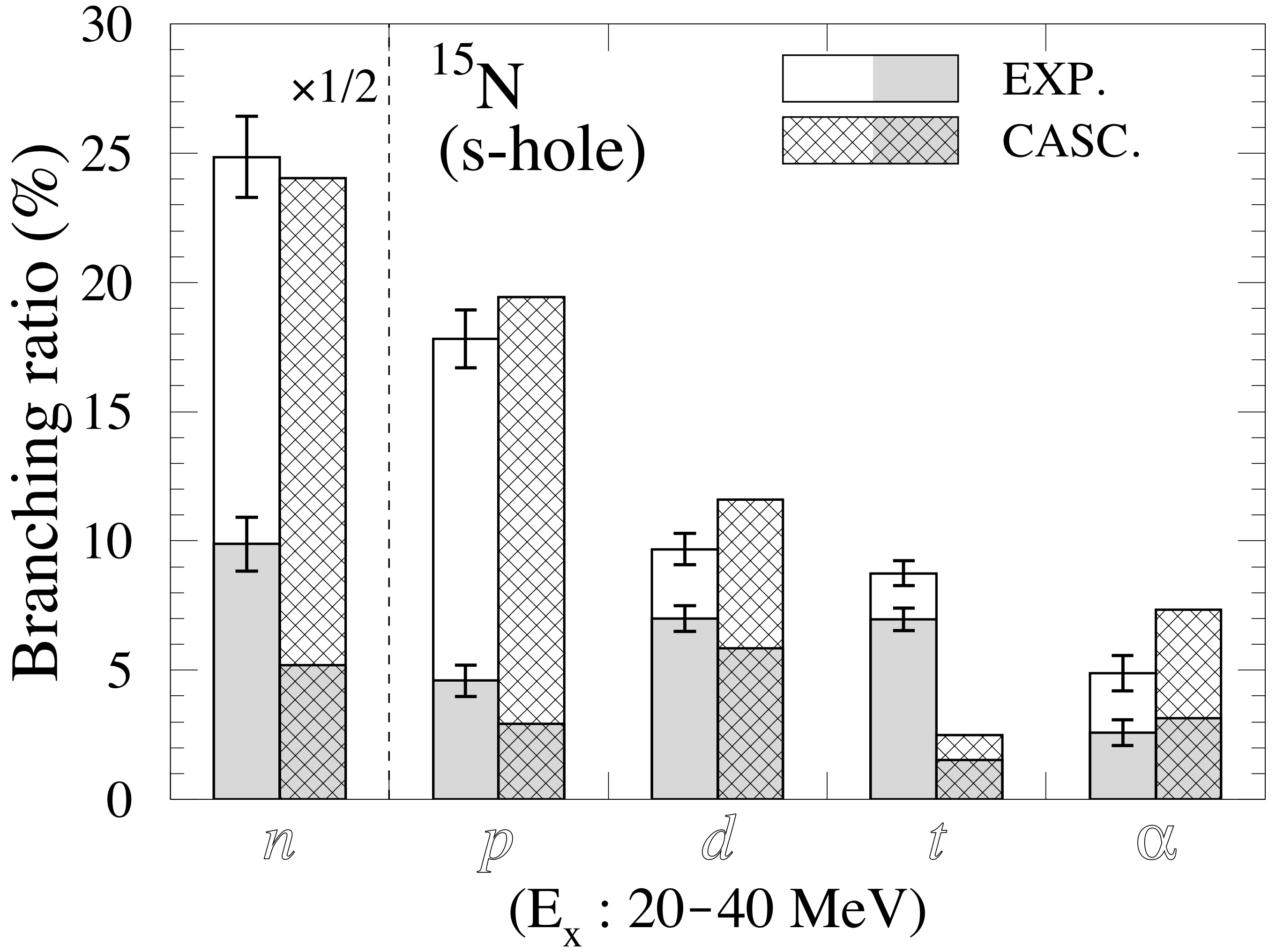


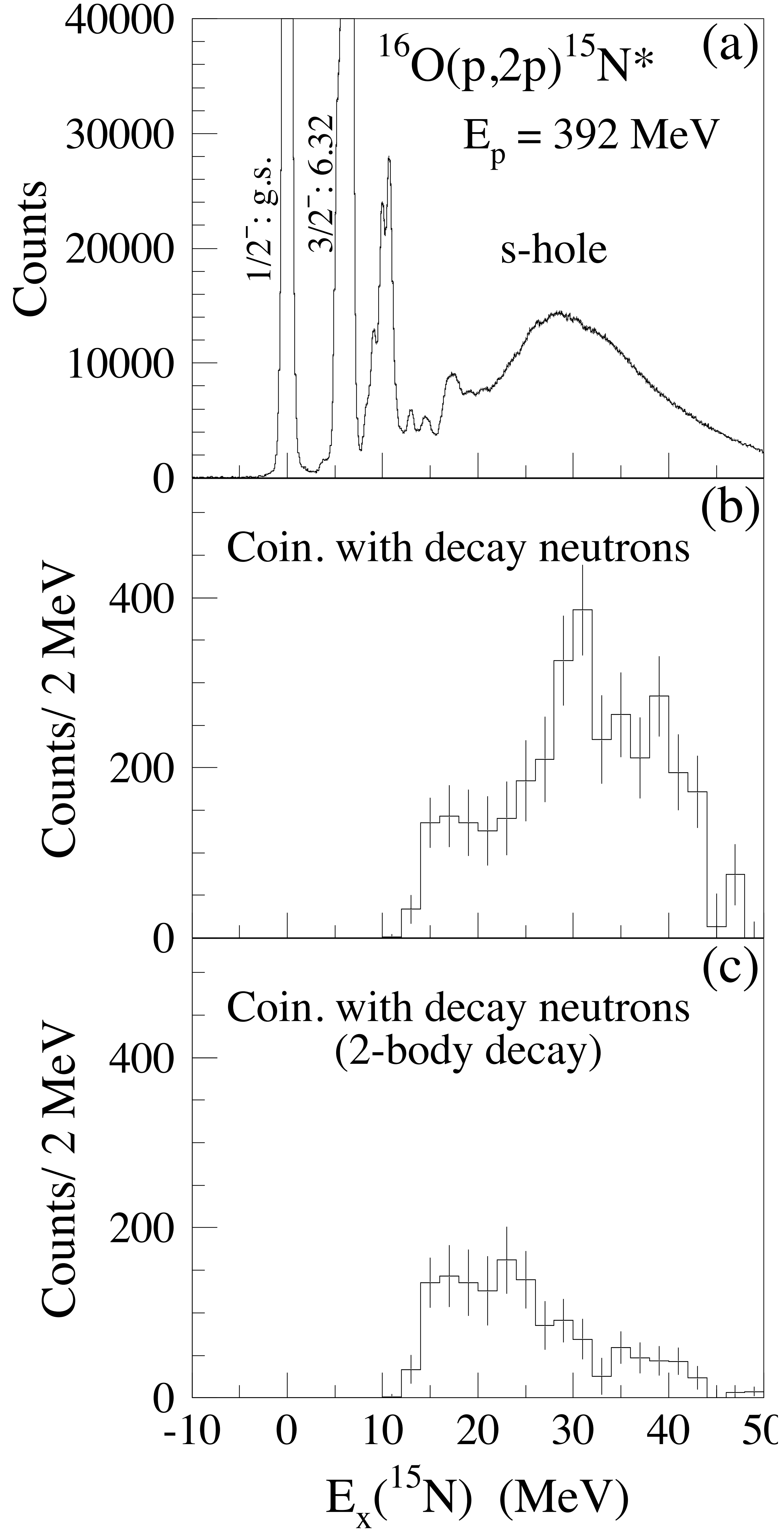
Previous experimental data

M. Yosoi, Ph.D. thesis (2003)

- Measurement of p-^{16}O interaction at RCNP (Yosoi, et al)
- Strike proton beam to an ice (^{16}O) target
  - Measure particle emission from $^{16}O(p,2p)^{15}N^*$ as a function of exciation energy of $^{15}N^*$
- Unique data for decay processes of highly-excited $^{15}N^*$ (and $^{11}B^*$)
- *But with some limitations*
  - Higher than ideal enery threshould for decay particle
  - Limited acceptance





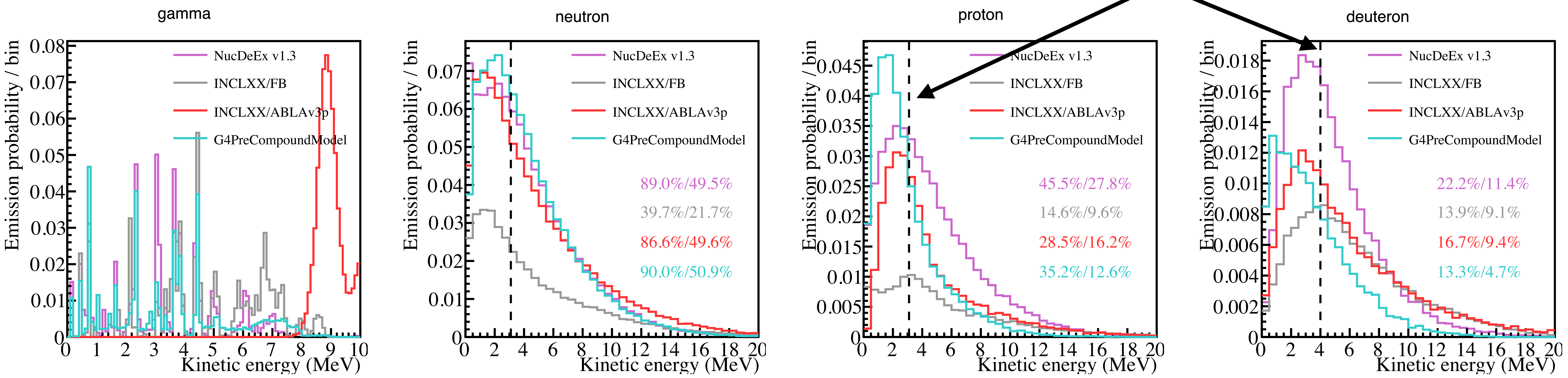


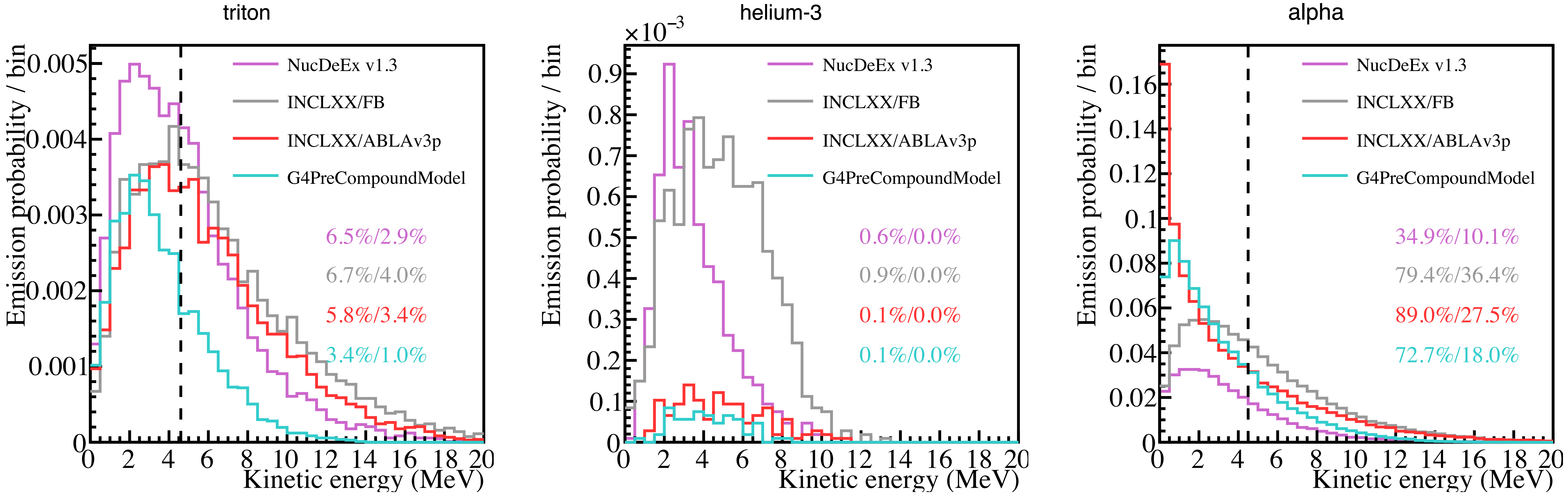
Predicted eneryg distributions from various model

$^{15}N^*$ 20 < Ex < 40 MeV

Detection threshould at the RCNP experiment by Yosoi et al.

S. Abe





~50% inefficiency due to the energy threshould

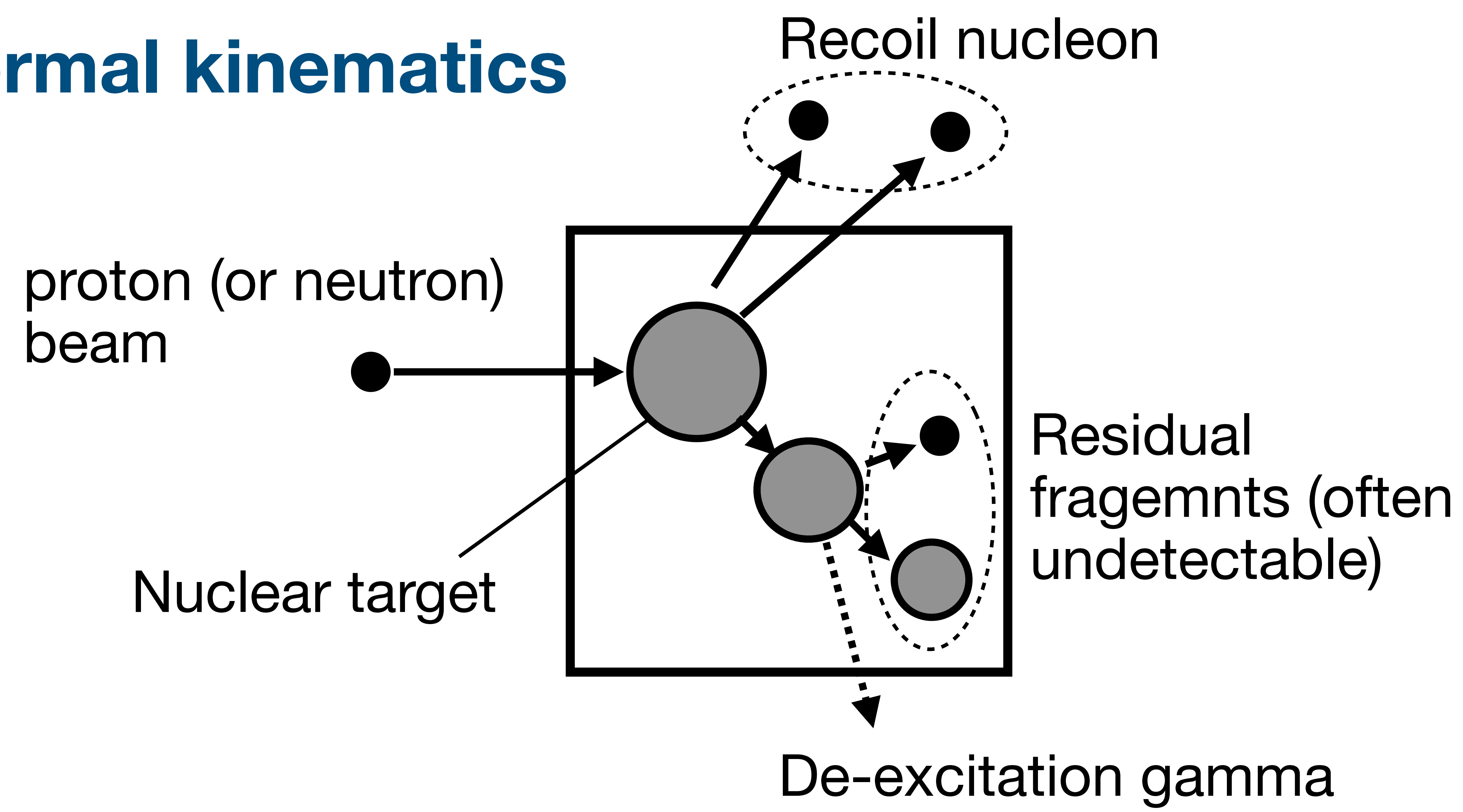
NucDeEx (de-excitation simulator):

- S. Abe, poster (P16) at UGAP2024 (Mar. 4-6, Sendai)
- S. Abe, talk at UGAP 若手研究会 (Mar. 7, Sendai)
- S. Abe, Phys. Rev. D 109, 036009 (2024)

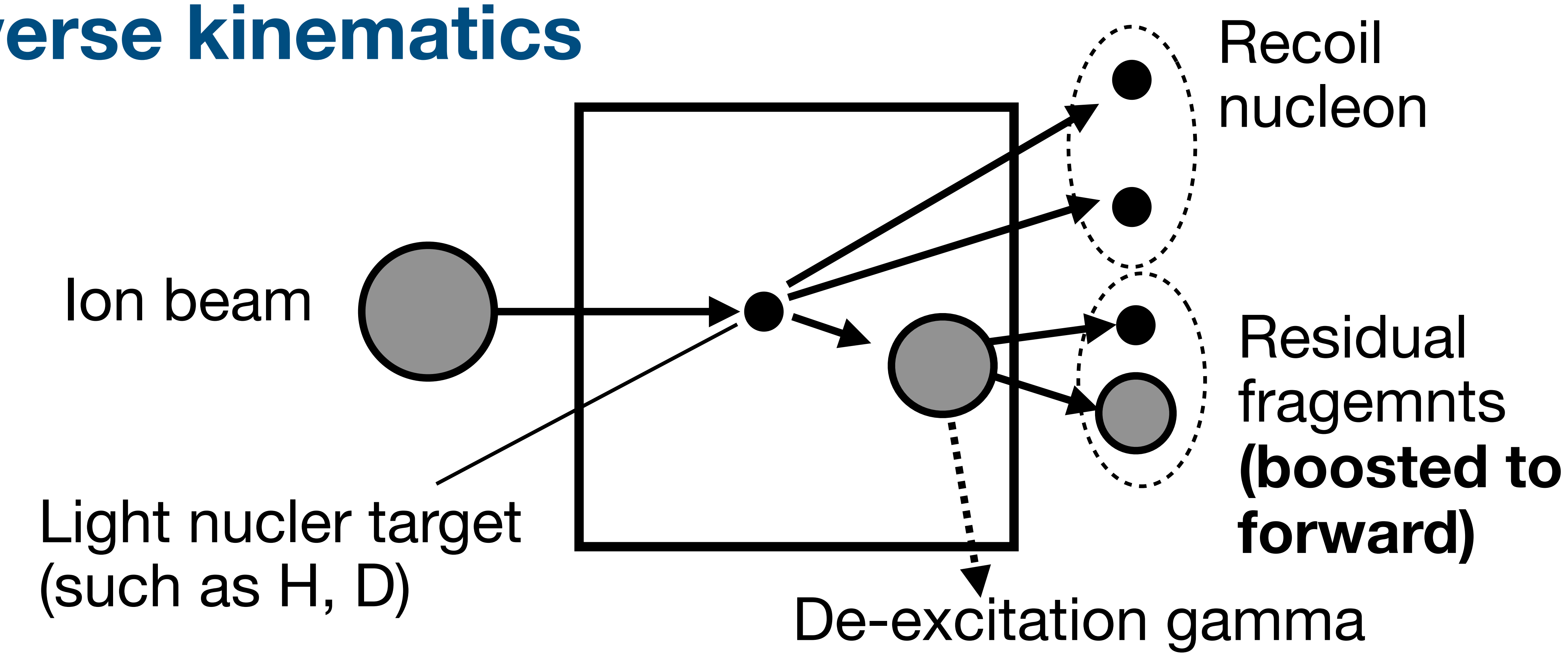
How to improve the situation: An experiment with *inverse kinematics*

- Strike (heavy) ion beam into a target with light molecule (such as liquid hydrogen)
- The system is boosted to the forward regions
  - Makes detection of low-energy fragments (typically < 10 MeV in the CM frame) thanks to their higher energy in the lab frame
  - Contained in a smaller solid angle region in the lab frame

Normal kinematics

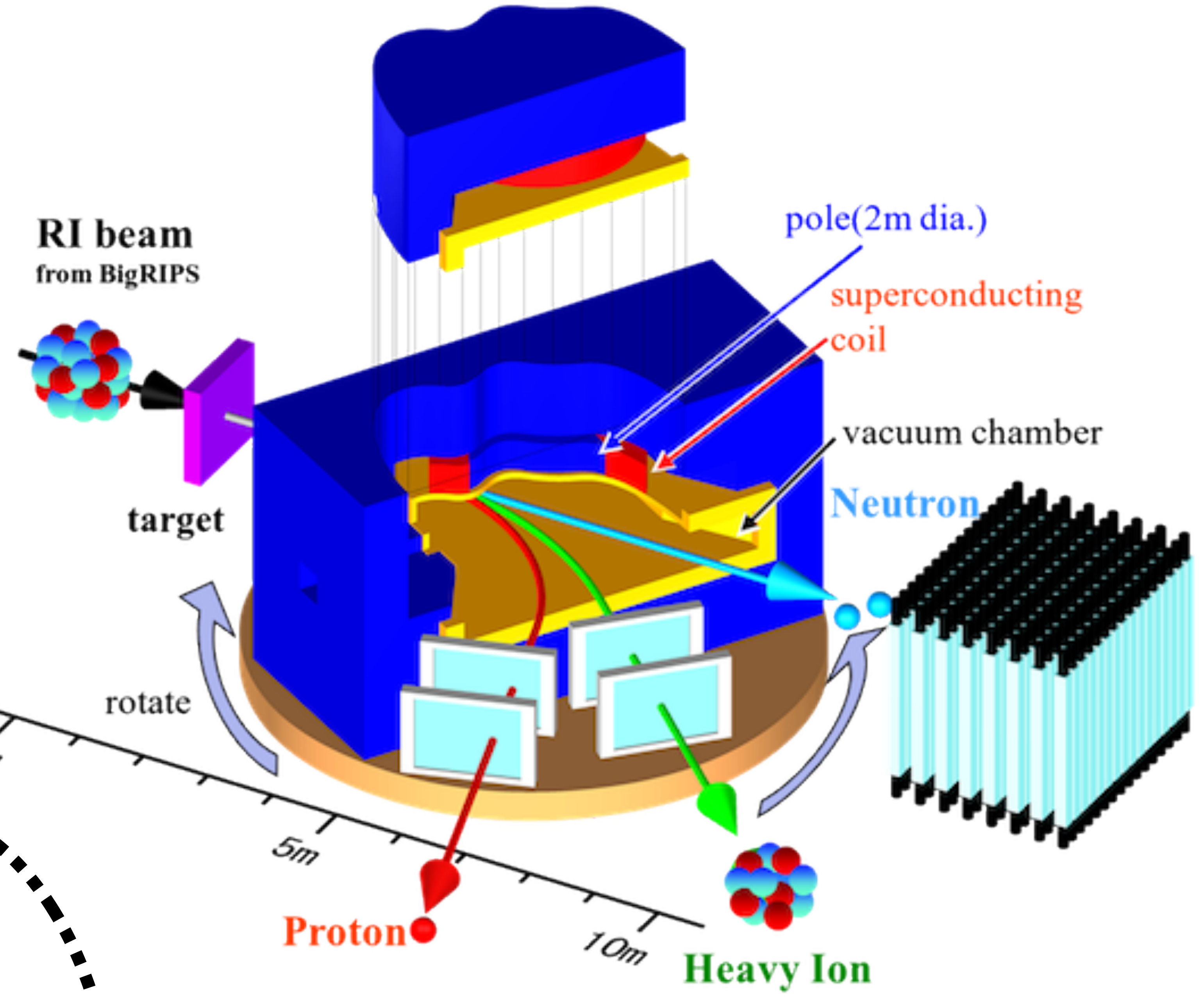


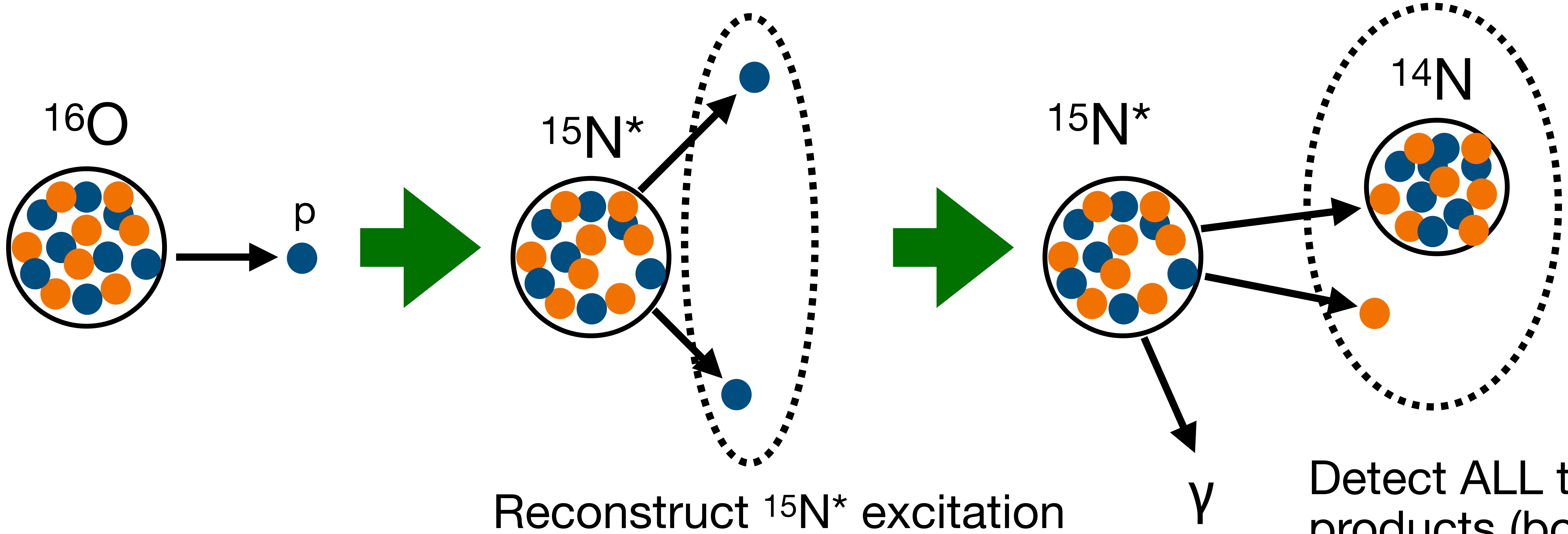
Inverse kinematics



Proposal of an experiment at RIKEN RIBF

- Proposing an inverse-kinematics experiment with ^{16}O beam available at RIKEN Rare Isotope Beam Facility (RIBF)





Reconstruct ^{15}N* excitation energy from kinematics for recoil nucleons

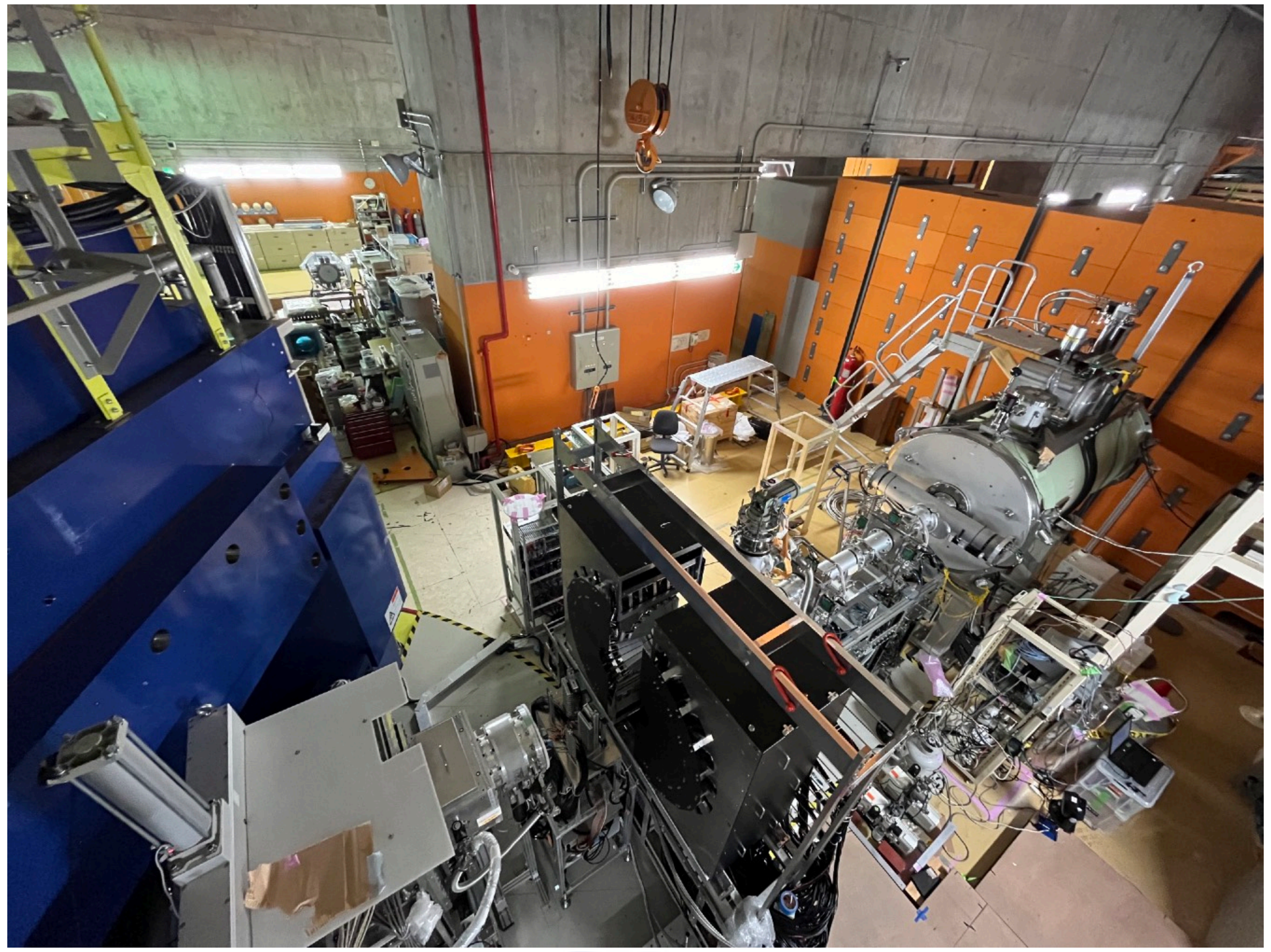
Detect ALL the decay products (boosted to forward region)

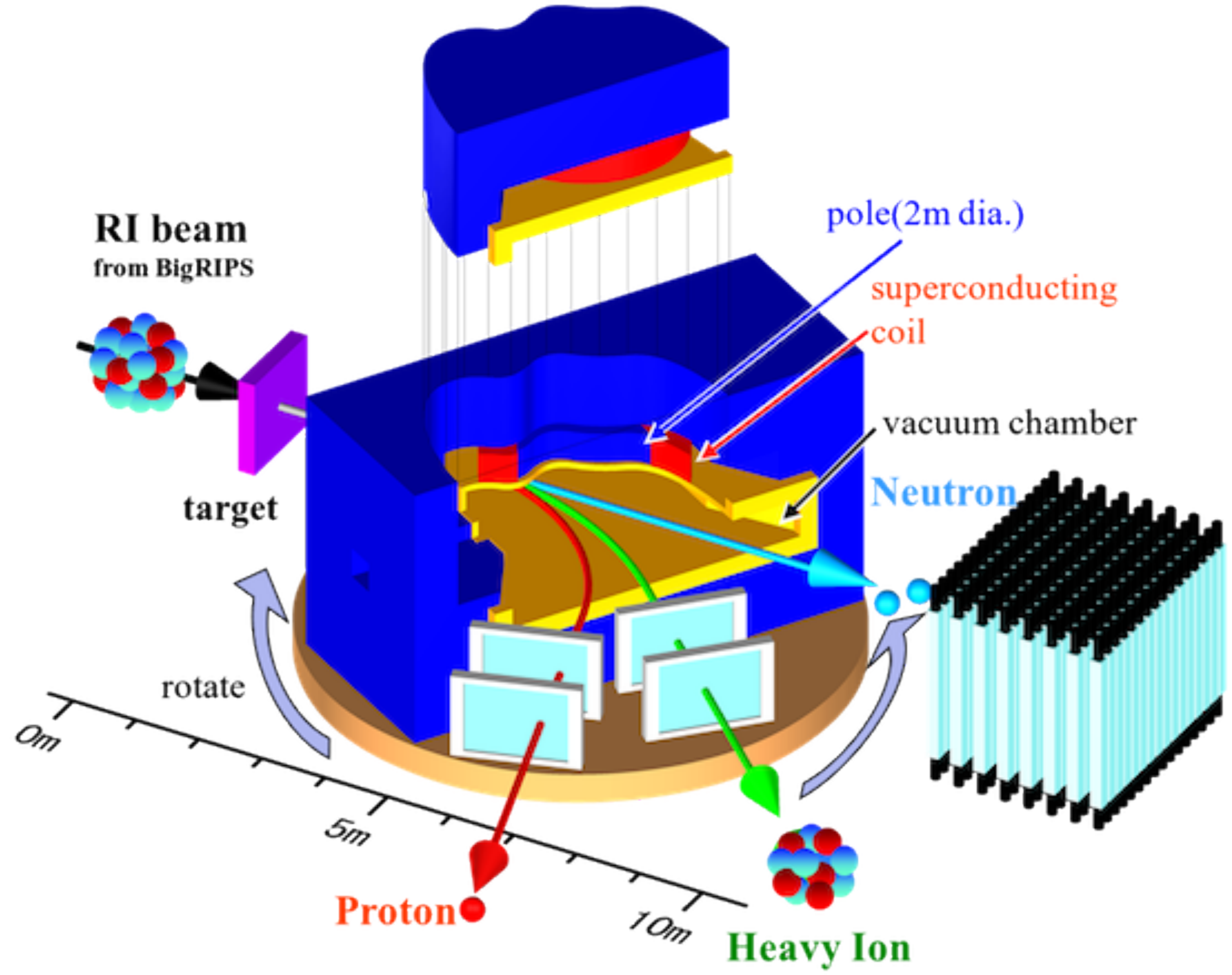
Proposal of an experiment at RIKEN RIBF

- Many necessary experimental apparatus already available or under development:
  - Liquid H_2 target system
  - Proton and gamma detectors around the target
  - The SAMURAI spectrometer

Aiming to collect a complete new set of experiemtal data for ^{16}O-nucleon interaction

→Improve neutrino interaction model for current and future water-Cherenkov experiments





Collaboration

- **~40 participants including experts on key detector components**
- **Active members (experimentalists):**
  - S. Abe, R. Akutsu, Y. Koshio, L. Feng, Y. Mizuno, Y. Nakajima, T. Tada

Blue: graduate students

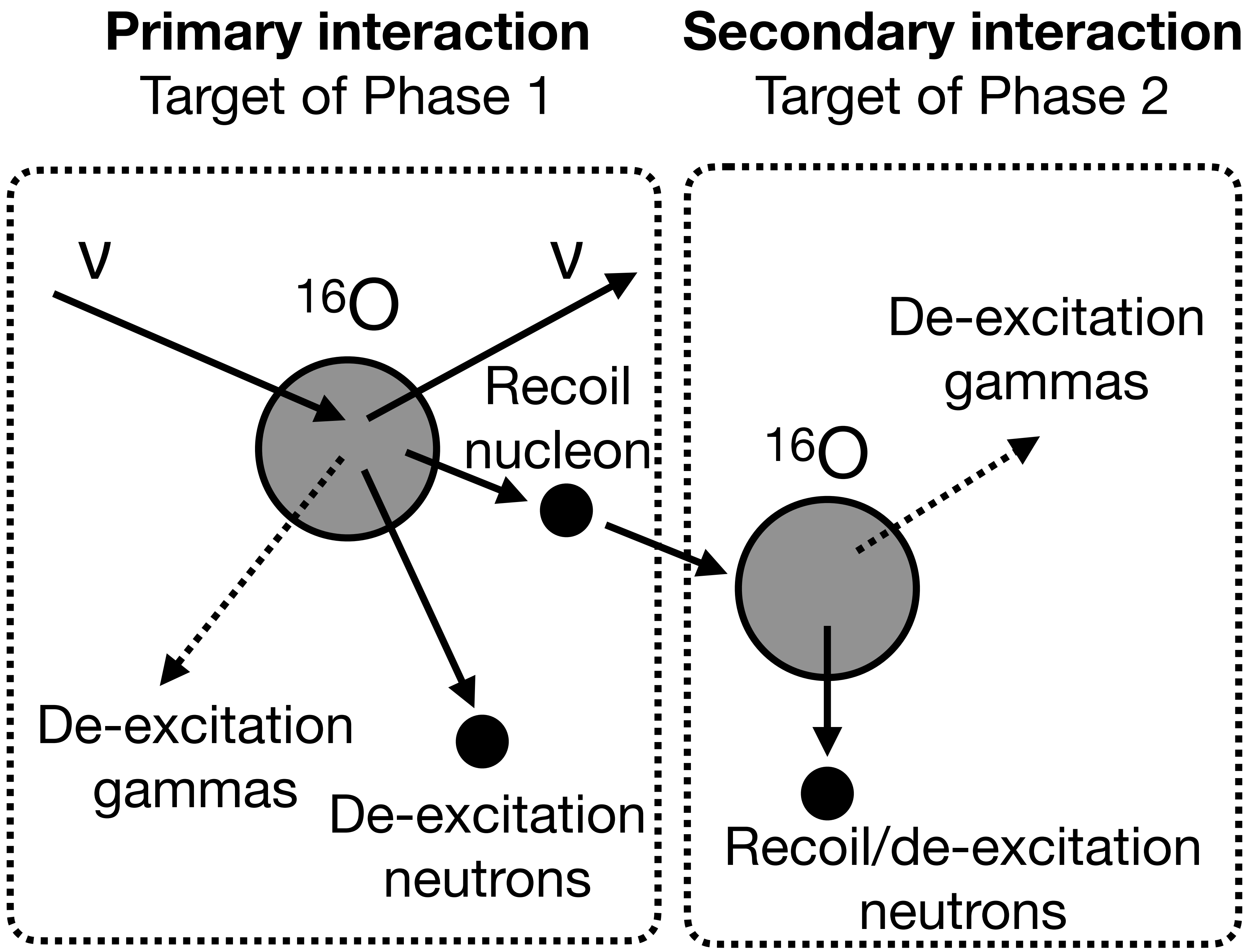
- **Collaboration with nuclear theorists**
  - K. Ogata, S. Nakayama, F. Minato, Y. Watanabe
- S. Abe, N. L. Achouri, R. Akutsu**, T. Aumann, F. Delaunay, M. Duer, M. Enciu, L. C. Feng, F. Flavigny, J. Gibelin, T. Isobe, T. Kobayashi, Y. Kondo, Y. Koshio, Y. Kubota, F. M. Marqués, A. Matta, Y. Matsuda, R. Matsumura, Y. Mizuno, Y. Nakajima*, T. Nakamura, S. Nakayama, M. Niikura, M. Nishimura, A. Obertelli, K, Ogata, N. A. Orr, H. Otsu, H. Sakurai, M. Sasano, H. Sato, A. Stefanescu, T. Tada, Y. Togano, T. Uesaka, Y. Watanabe, C. Xanthopoulou

*spokesperson **co-spokesperson

Goals of the experiment(s)

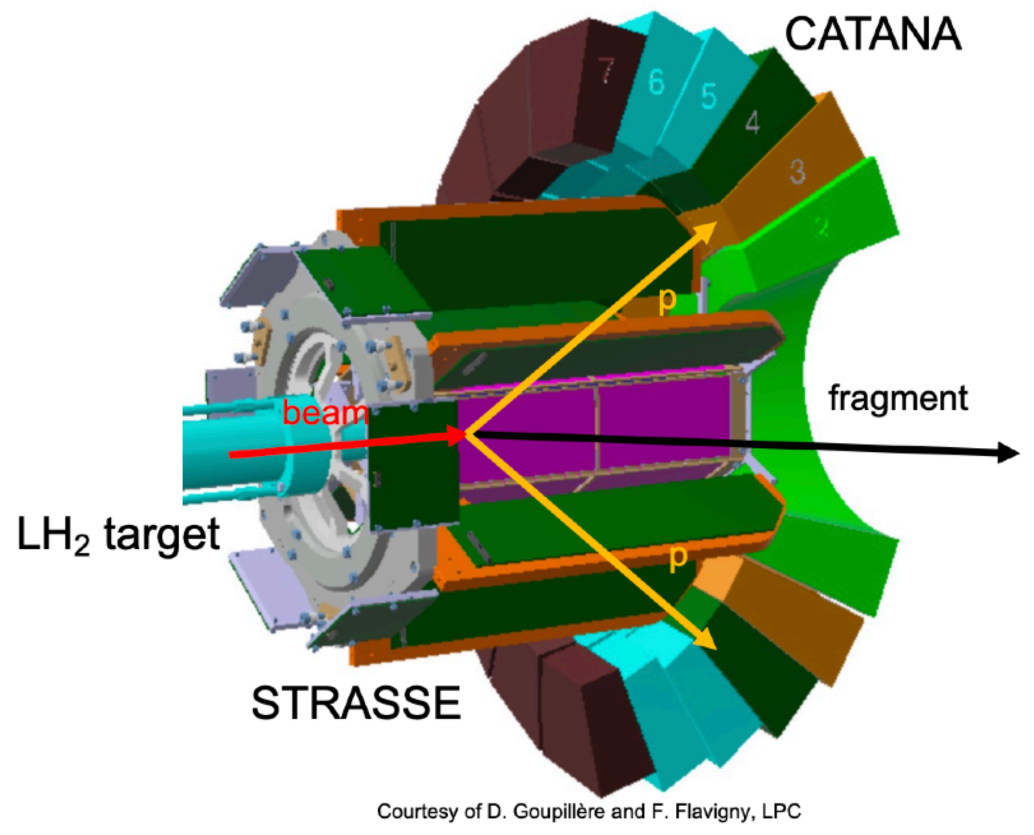
Comprehensive measurement of nucleon-^{16}O interactions including their decay products at O(10) to O(100) MeV

- Phase 1 (targeting primary interaction):
  - $^{16}O(p,2p)^{15}N^*$ and $^{15}N^*$ decay at 100 MeV/u and 200 MeV/u
  - $^{16}O(p,pn)^{15}O^*$ and $^{15}O^*$ decay at 100 MeV/u and 200 MeV/u
- Phase 2 (targeting secondary interaction):
  - Inclusive $^{16}O(p,X)$ and $^{16}O(n,X)$ at 50 MeV/u to 300 MeV/u

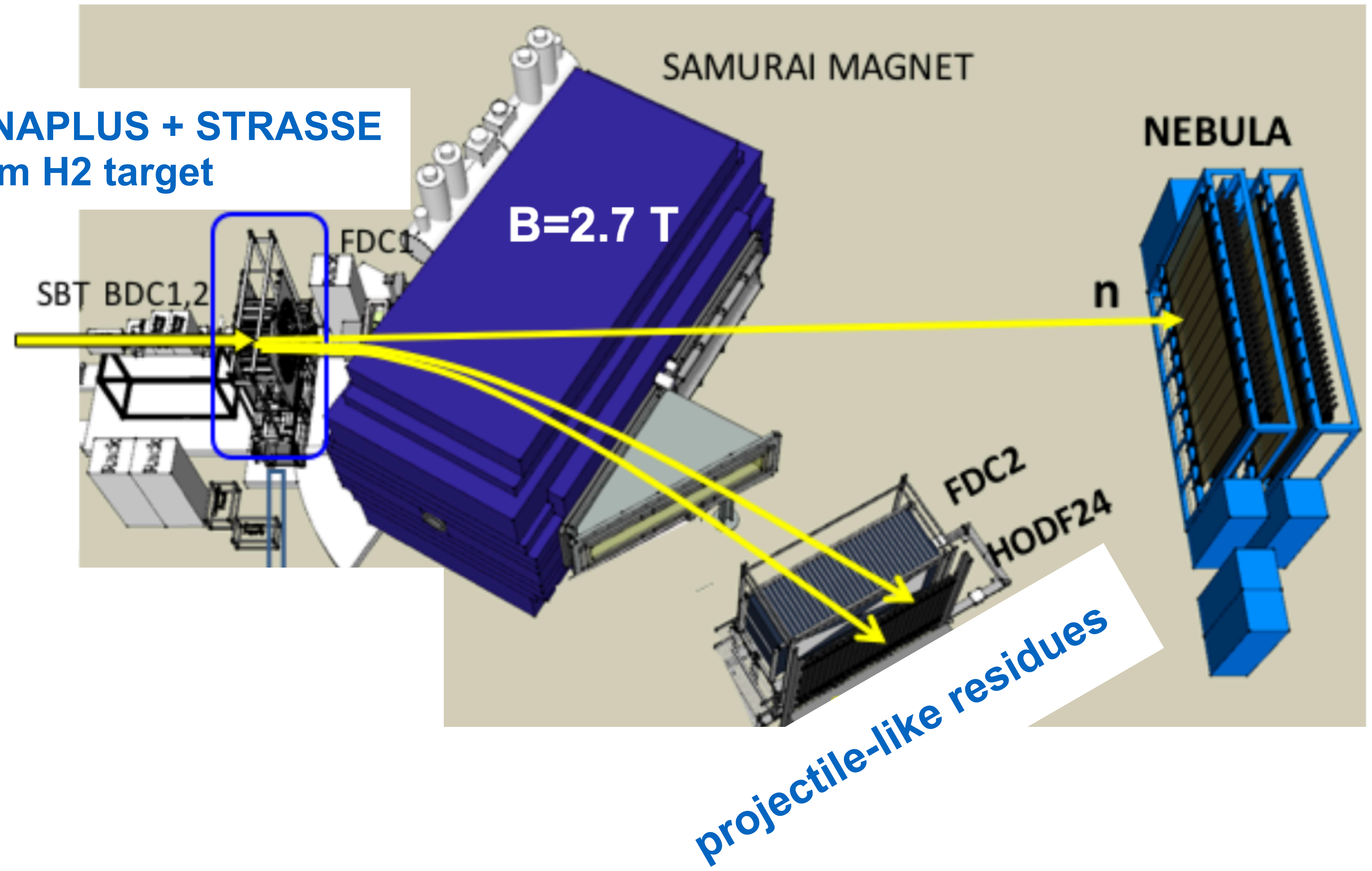


Experimental setup for $^{16}O(p,2p)$ measurement

- Parasite with the already-approved SAMURAI-69 experiment (SP: A. Obertelli)
- Detect knock-out proton with Si tracker (STRASSE) + CsI calorimeter (CATANA) surrounding the LH_2 target
    - Used to identify $^{16}O(p,2p)$ reaction and reconstruct excitation eneryg for the residual $^{15}N^*$
- Detect residual nuclei and decay products with SAMURAI superconducting magnet and downstream detectors.



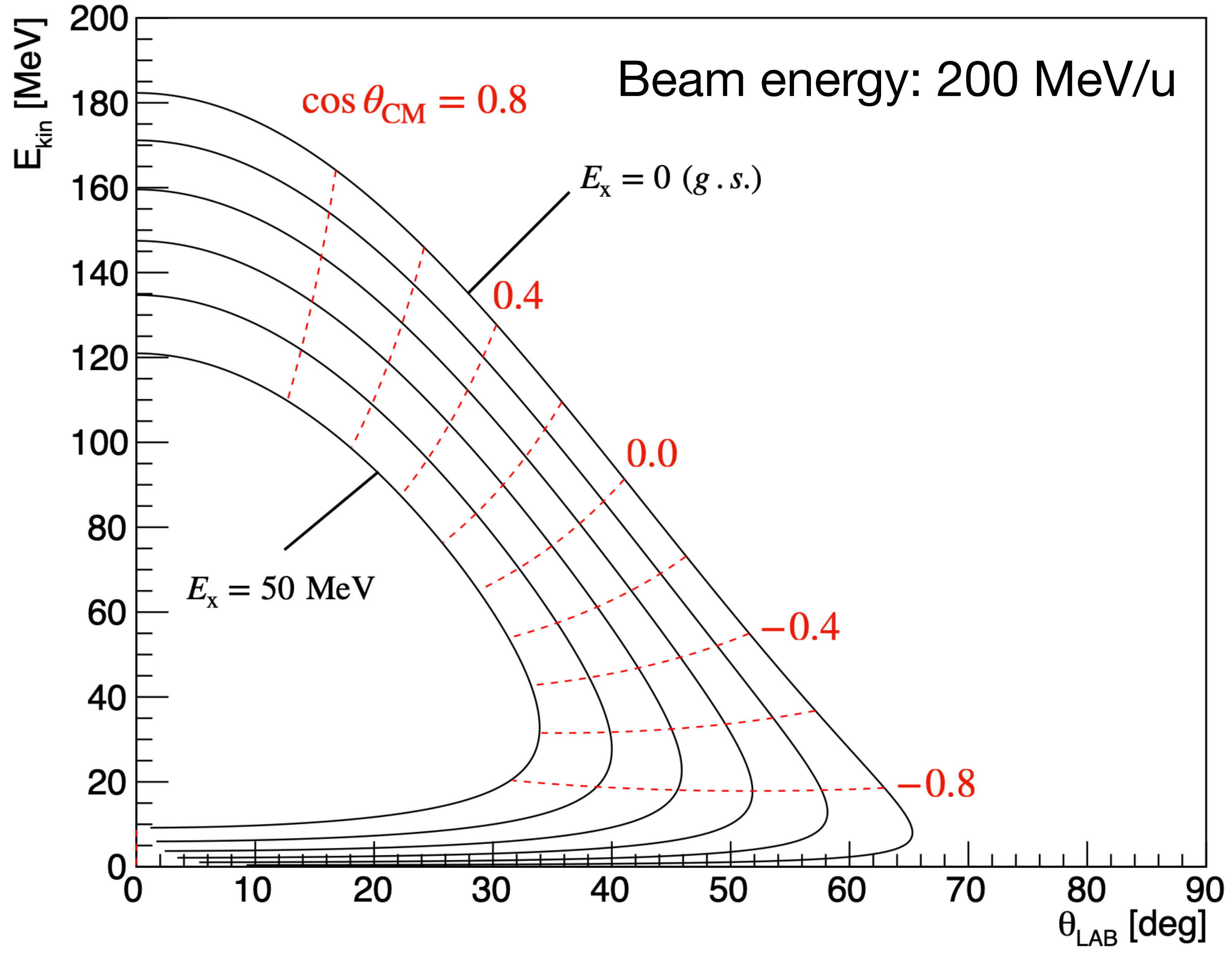
(p,2p) detection efficiency: 30-45%
Missing momentum resolution: 2 MeV/c
Missing mass resolution: 2 MeV

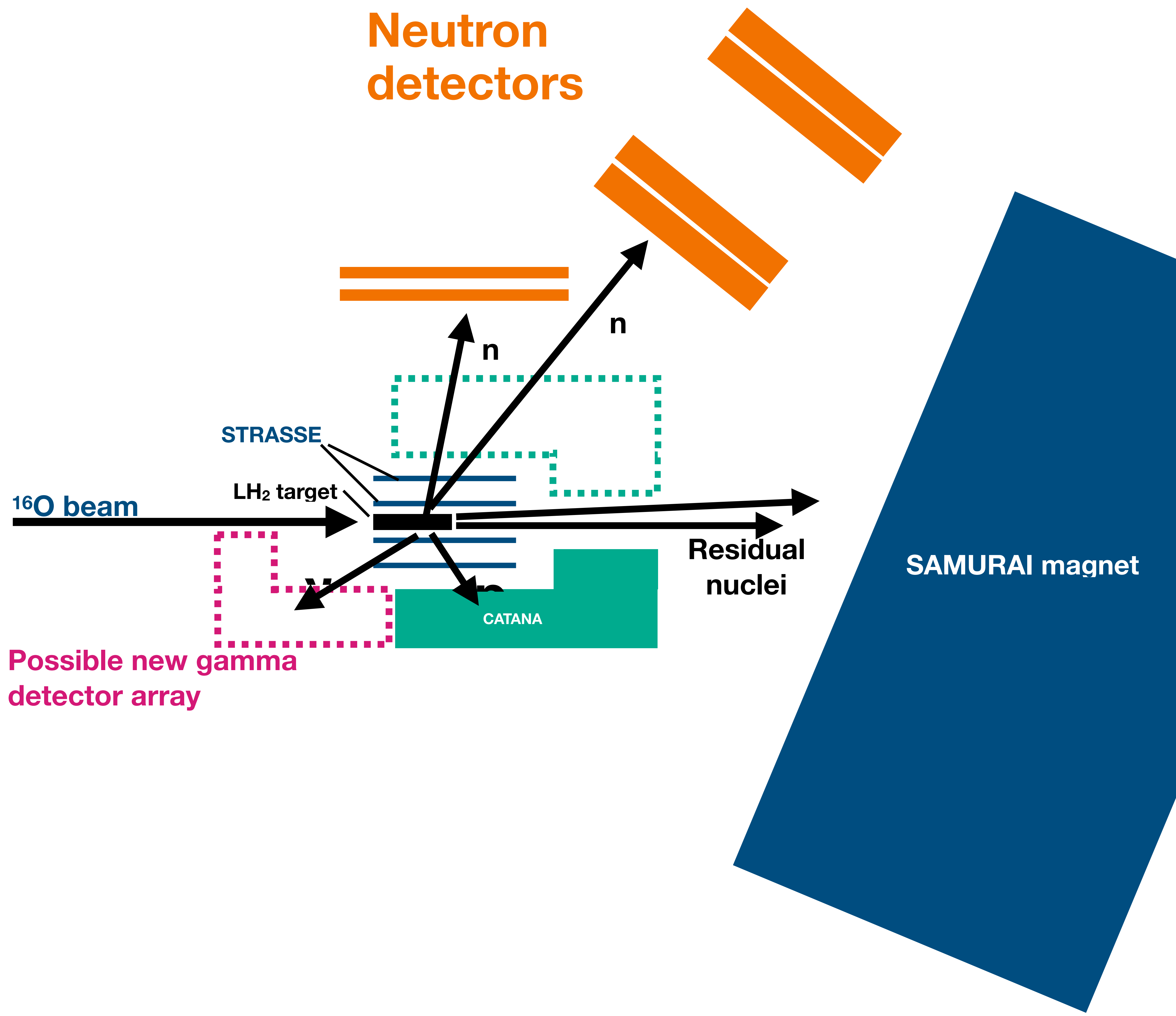


Experimental setup for ^{16}O(p,pn) measurement

- Additional neutron detectors
  - Measure angle and kinetic energy (with ToF) of recoil neutrons
  - A half of the CsI calorimeter will be removed
- Downstream detector will be same as the O(p,2p) experiment

Neutron kinematics for various excitation energies





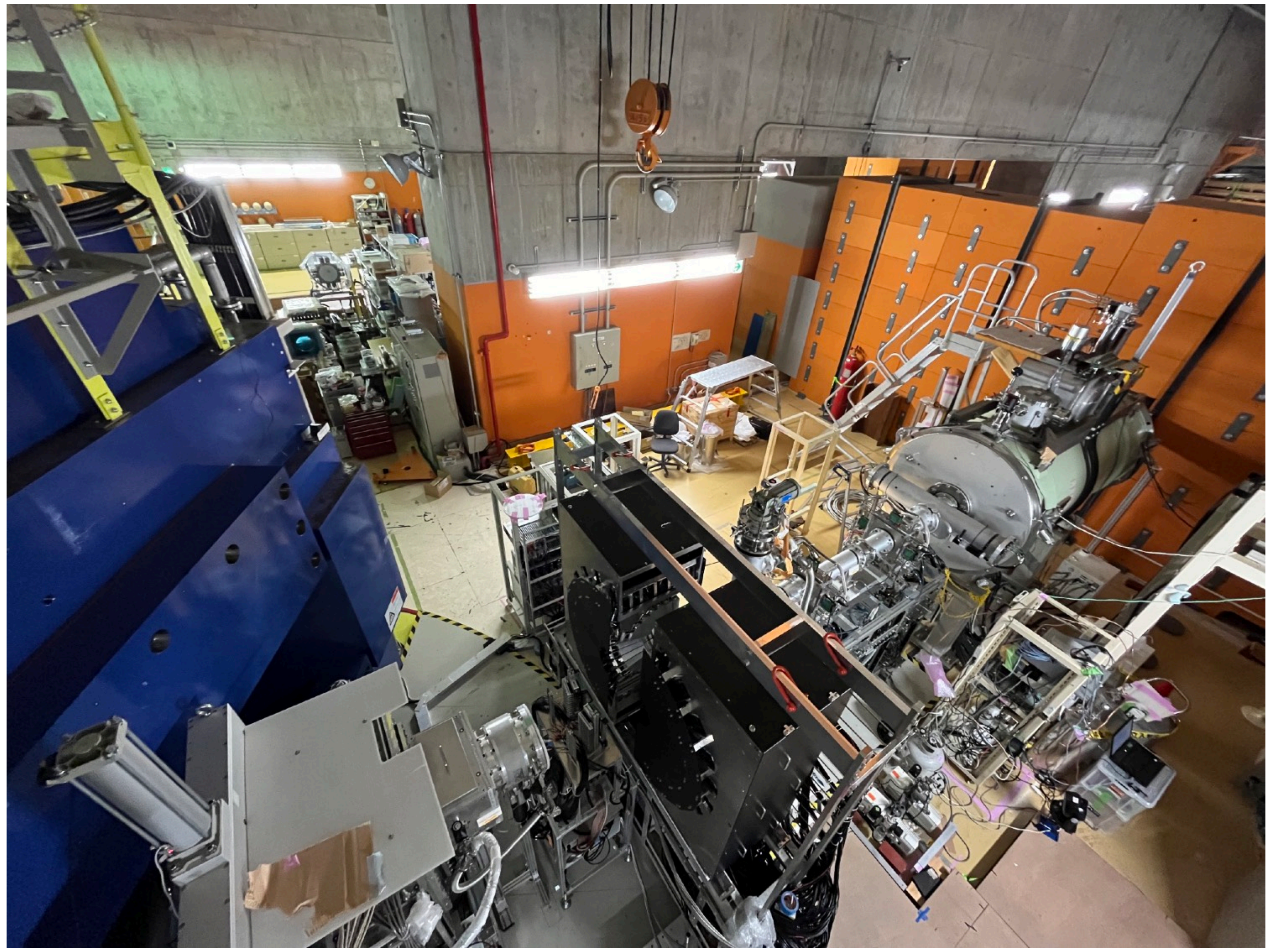
Current status and plan

- Simulation studies to optimize the detector configuration and running plan
    - Many things to be optimized: target thickness, arrangement of neutron detectors, strength of magentic field etc..
- Integrating nuclear model(s) to the simulation
- Preparing an experimental proposal for RIKEN RIBF

Aiming to conduct the measurements in the next few years!

Summary

- SK-Gd is exploring new frontier of neutrino observations using neutrons
  - The first observation of DSNB
  - Improved reconstruction for atmospheric and acceletor neutrinos with neutrons
- Precise knowledge of nucleon-^{16}O interaction essential for fully exploit neutron information
  - Large uncertainty in nucleon-^{16}O scattering and subsequent nuclear de-excitation
  - More complehensive data needed to improve the nuclear models
- Working to realize an ^{16}O beam inverse-kinematics experiment at RIKEN RIBF

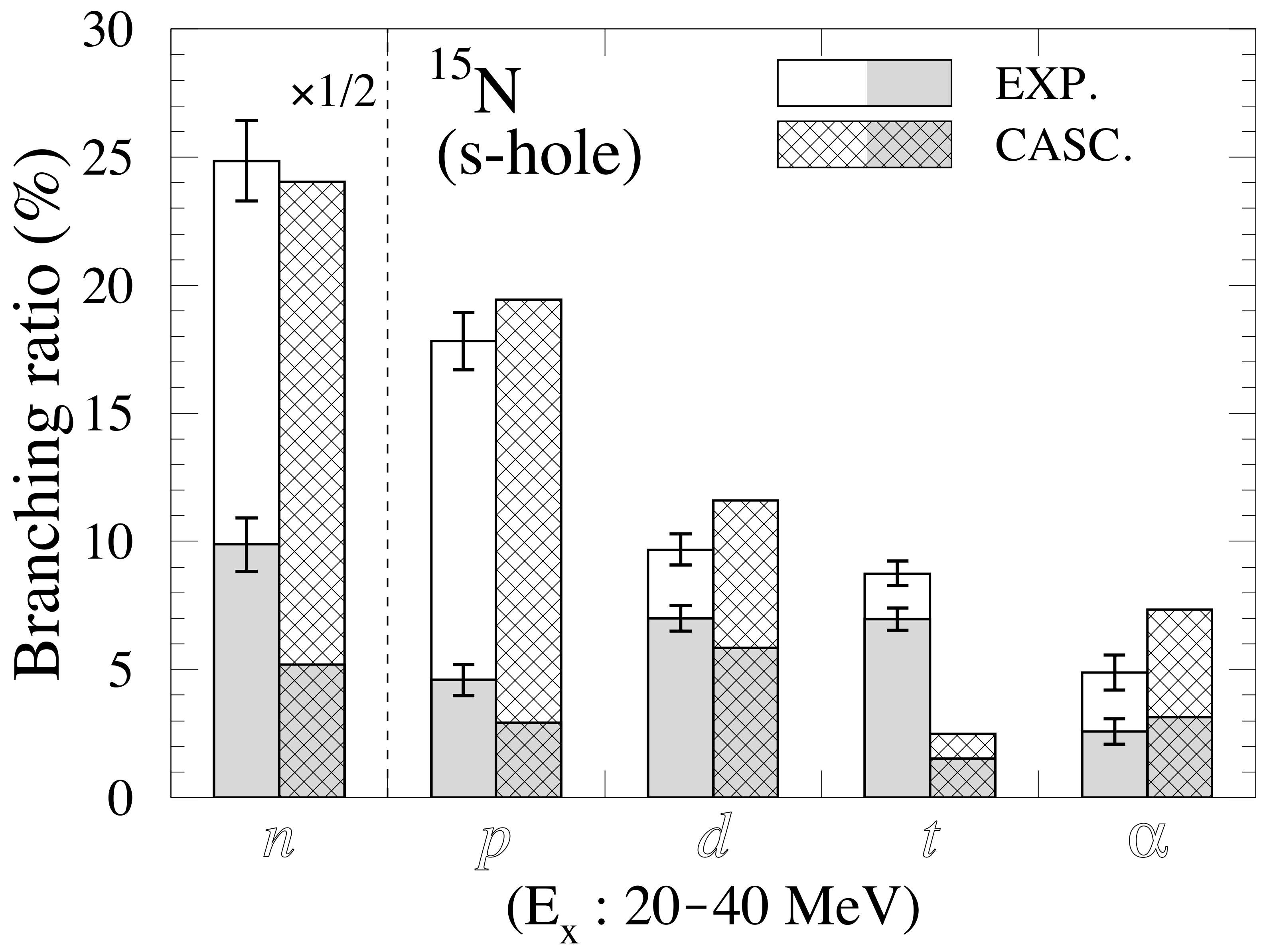


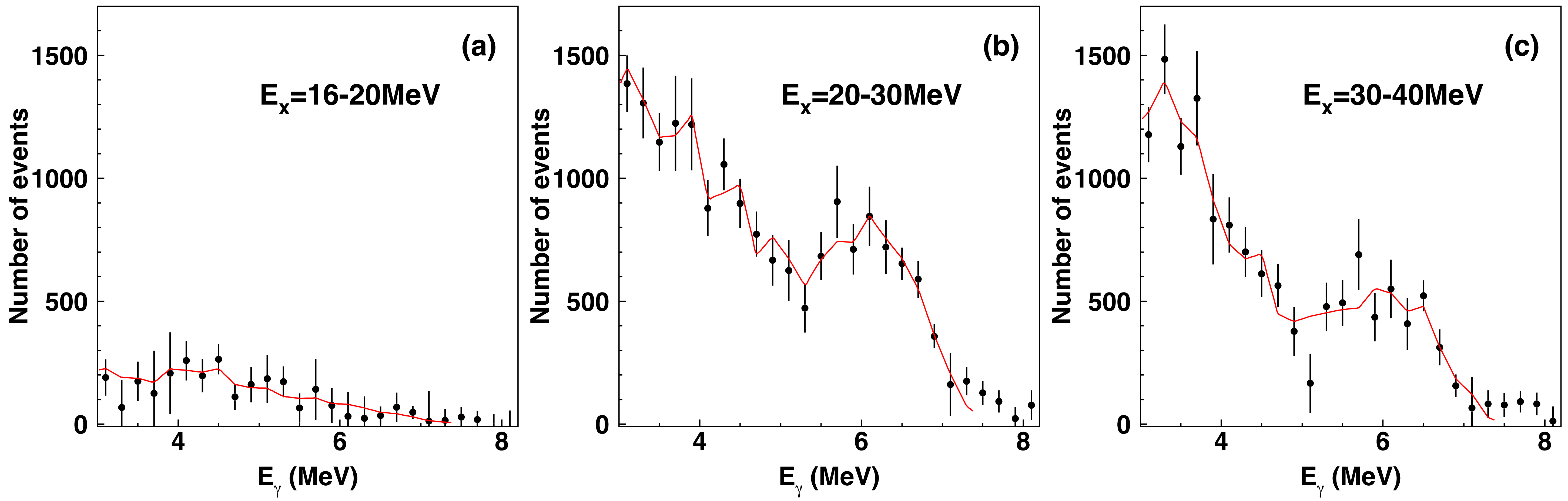
Welcoming new collaborators!

Supplemental slides

Previous experimental data (1)

- Normal kinematics measurements on O(p,2p) at RCNP
  - M. Yosoi, Ph.D thesis (1999)
  - K. Kobayashi et al, arXiv:0604006 [nucl-ex]
- Particle decay and de-excitation gamma was measured, but with
  - Relatively high threshold for charged particle (3.1 - 4.6 MeV)
  - No correlation data among decay particles

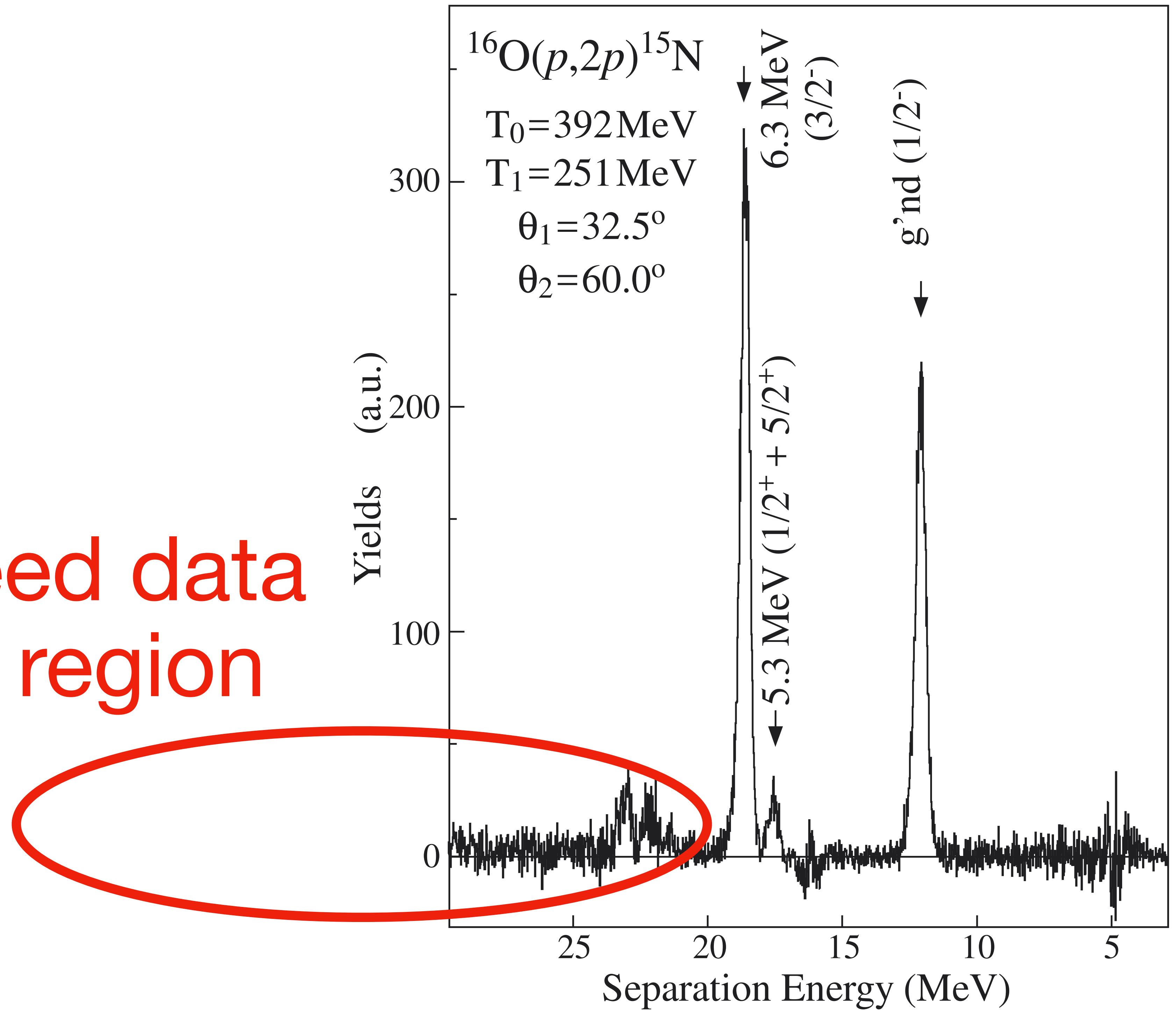


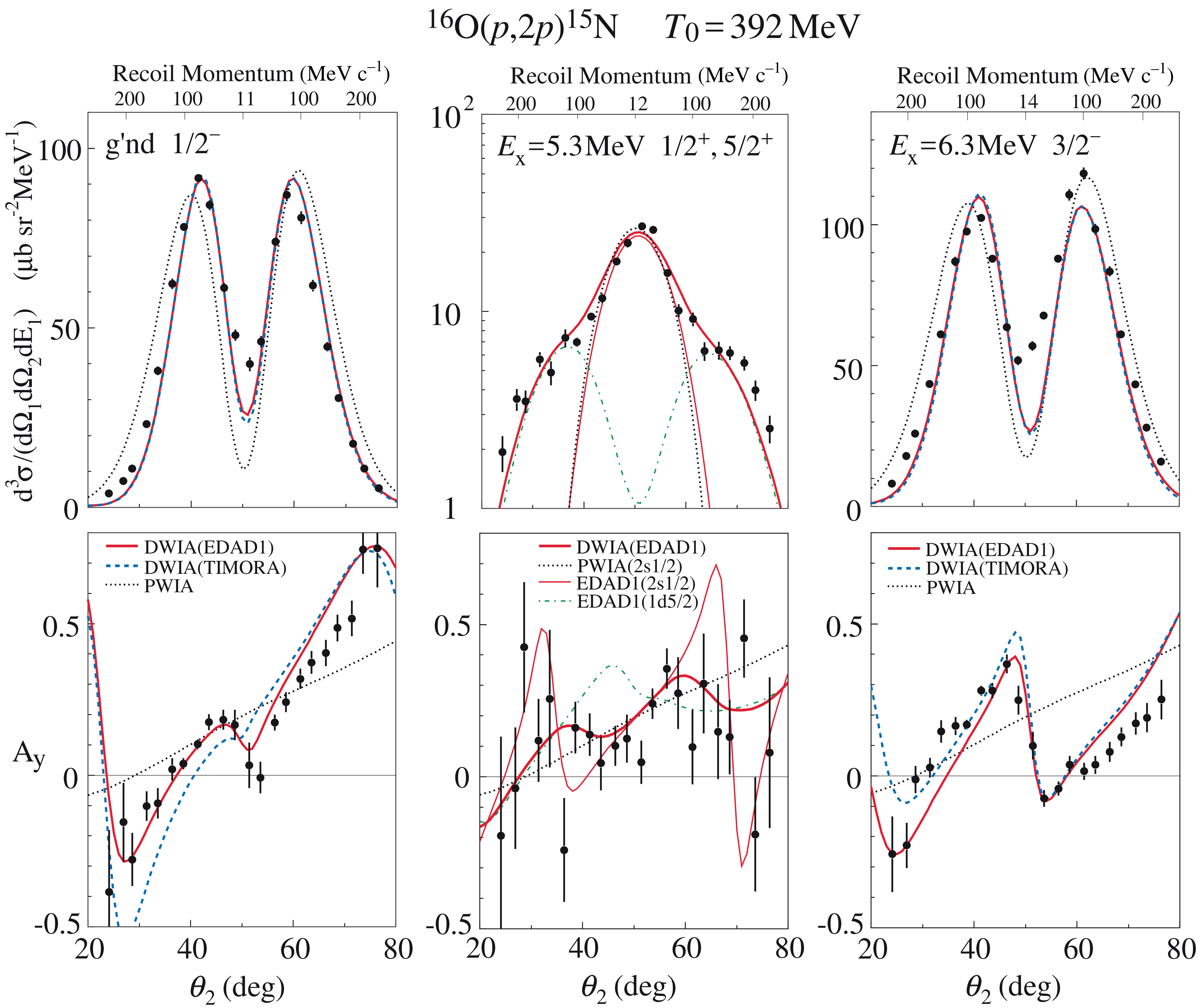


Previous experimental data (2)

- T. Noro et al PTEP 2020, 093D02 discusses measurements of $^{16}O(p,2p)$
- Focuses on knock-out of nucleons near Fermi-surface

We need data in this region





Previous experimental data (3)

- PRL 120, 052501 (2018)
- Inverse kinematics measurement of O(p,2p)
- Focuses on p-state hole
- No data for $^{15}N^{*}$ particle decay provided

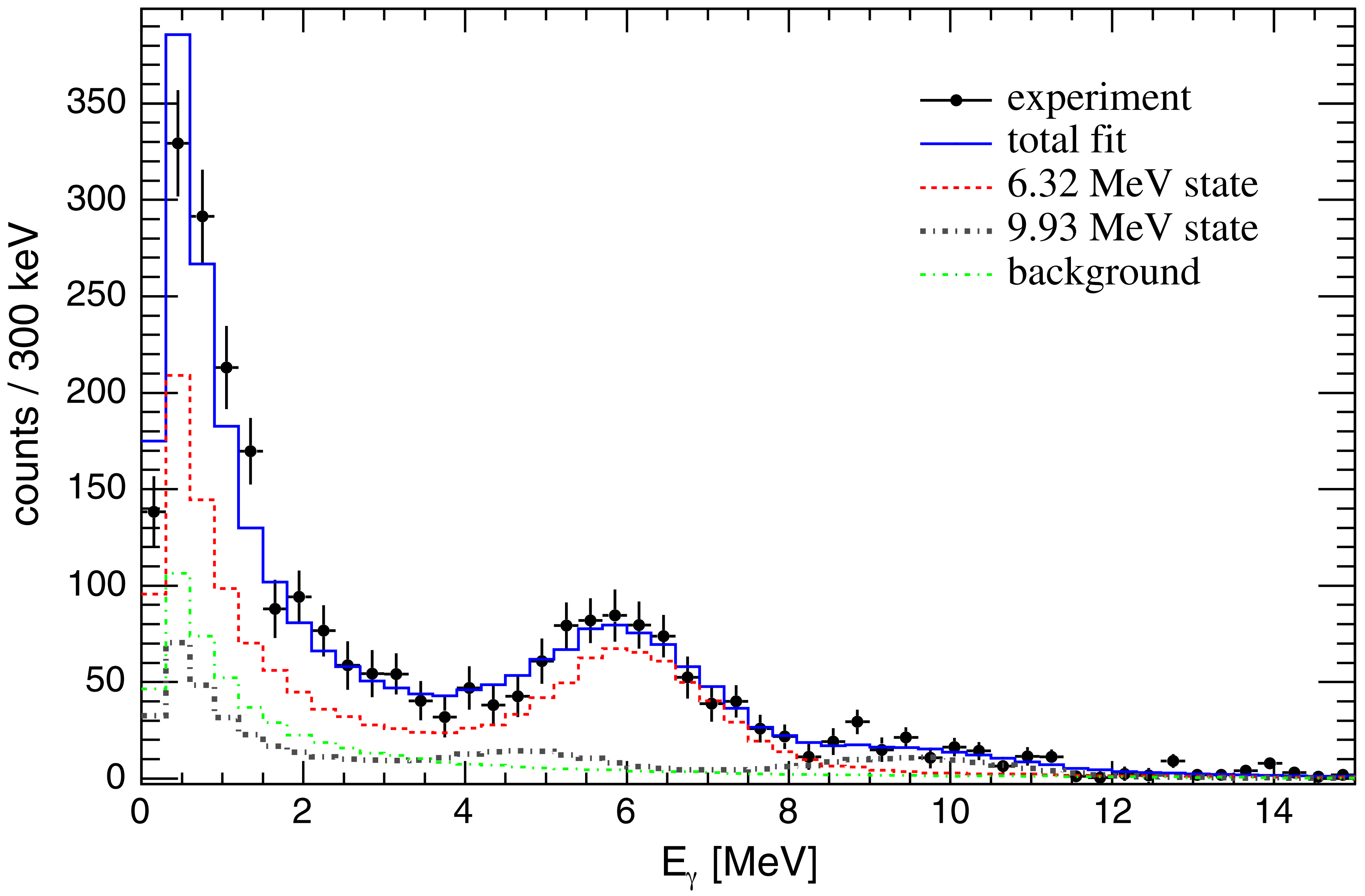


FIG. 3. Doppler-corrected single-γ spectrum measured in coincidence with ^{15}N and two protons in CB. The simulated decays of the $3/2^{-}$ states at 6.32 and 9.93 MeV were fitted to the experimental data together with the background contribution. The total fit is displayed by the solid curve.

Expected neutron and photon distributions

Final state topology	Br(%)
$^{15}O + n + p + \gamma$	12.5
$^{14}N + n + 2p + \gamma$	10.8
$^{15}N + 2p + \gamma$	8.9
$^{12}C + 3p + 2n + \gamma$	1.9
$^{16}O + p + \gamma$	1.7
$^{13}C + n + 3p + \gamma$	1.6
$^{14}N + D + p + \gamma$	1.4
$^{13}N + 2n + 2p + \gamma$	1.4
$^{15}O + D + \gamma$	1.0
Other with γs	13.1
Other with no γs	45.7

Neutron kinematics