Study of p-O interactions for improved neutrino observation at water Cherenvkov detectors:

- **Toward implementations of measurement results in event simulations** -

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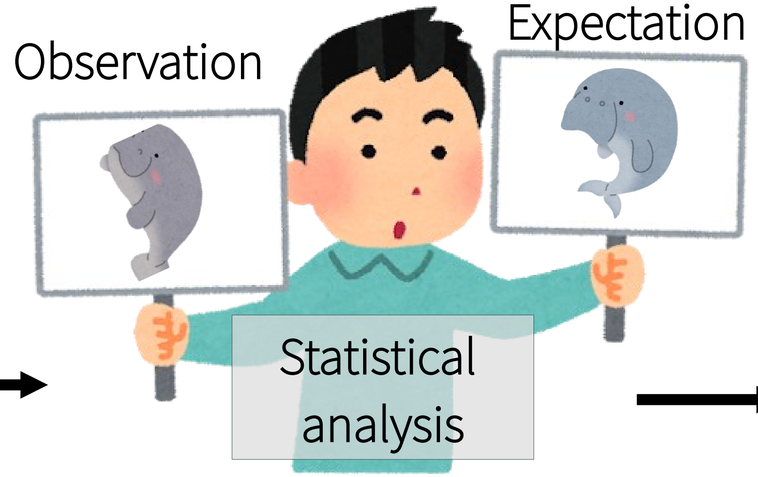
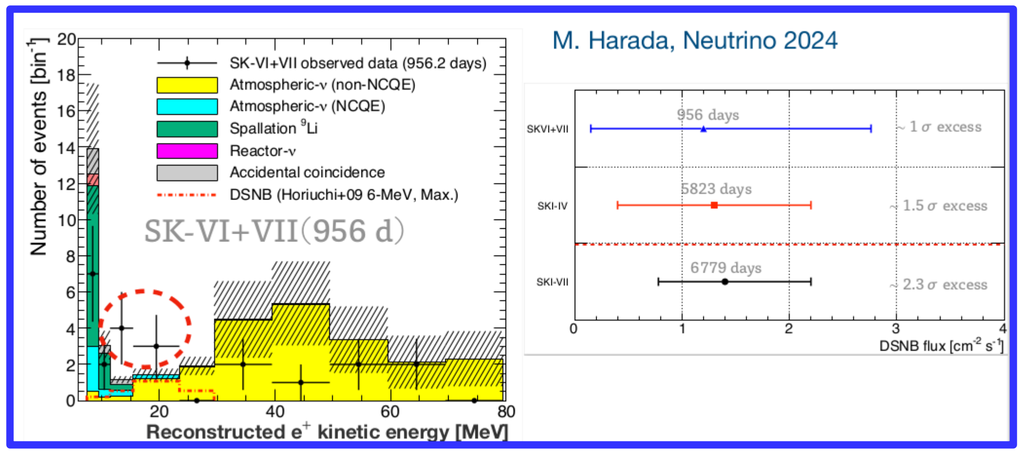
Typical analysis flow

Event simulation

Event generation → Detector simulation → Simulated data → Recon. & selection ← Real data → Statistical analysis → Results





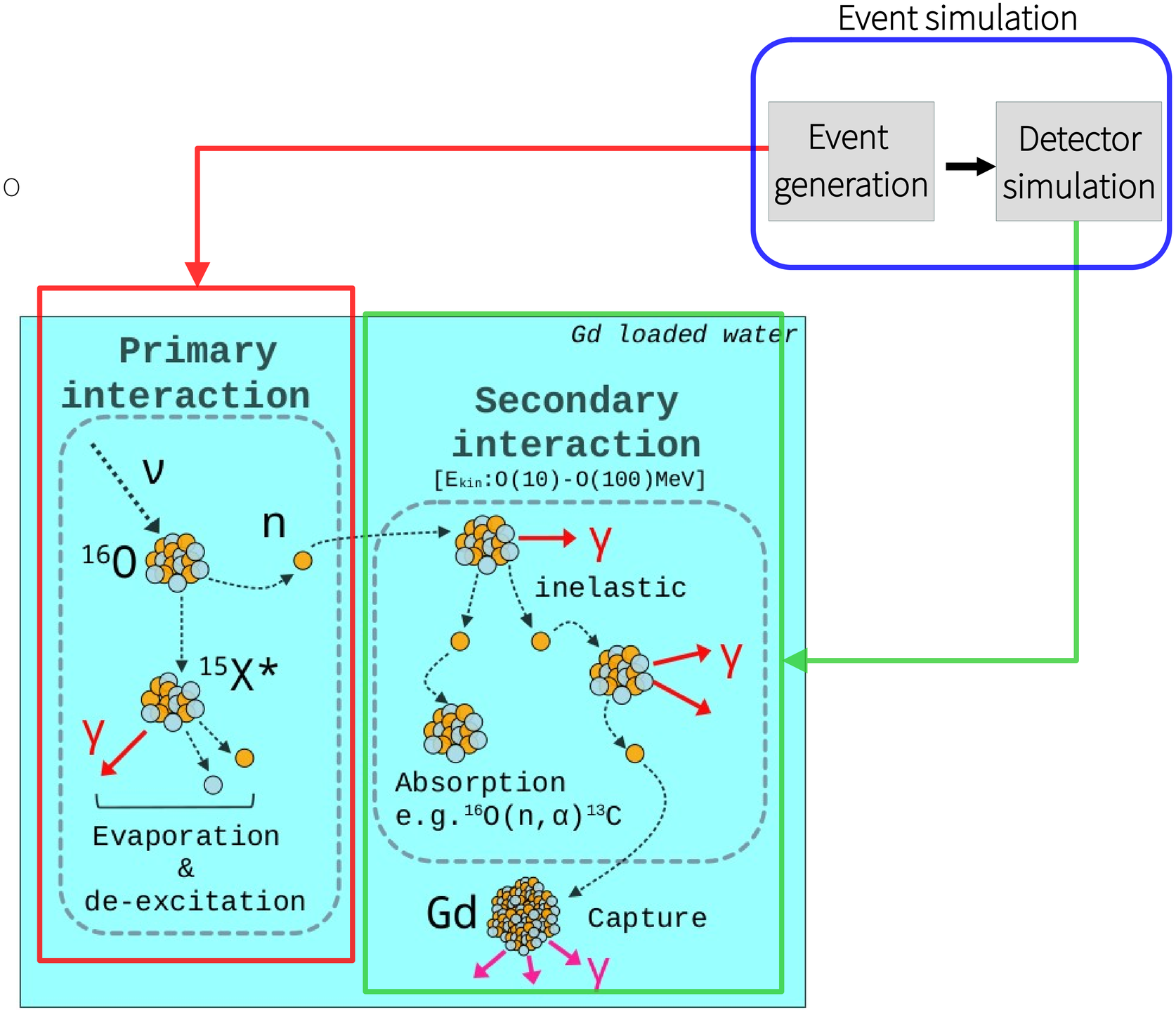
◆ Usually, results of physics analyses are obtained by comparing # events between observations and expectations

→ **Precise event simulations are essential**

- Typically required precision: several % for **gamma ray & neutron productions** (currently, several tens %)

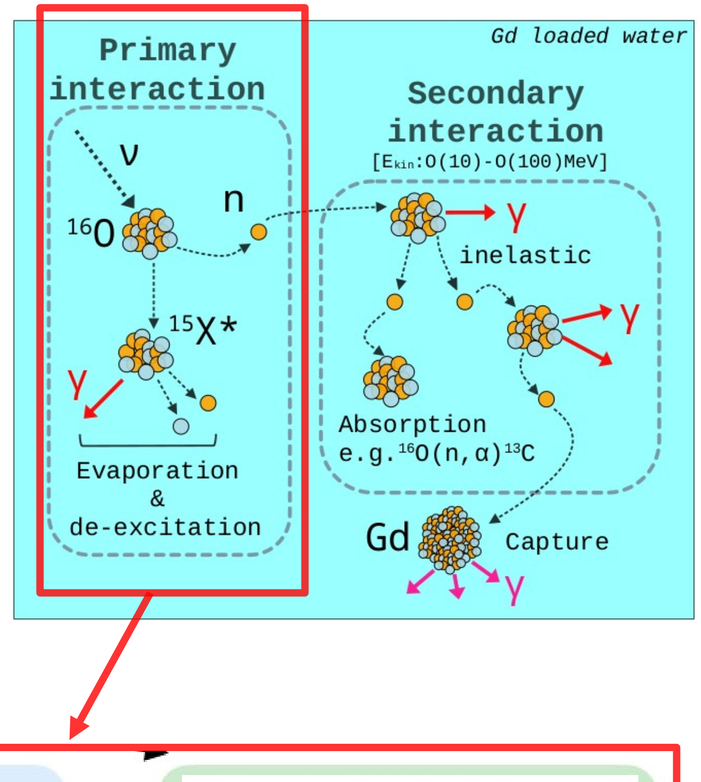
Event simulations

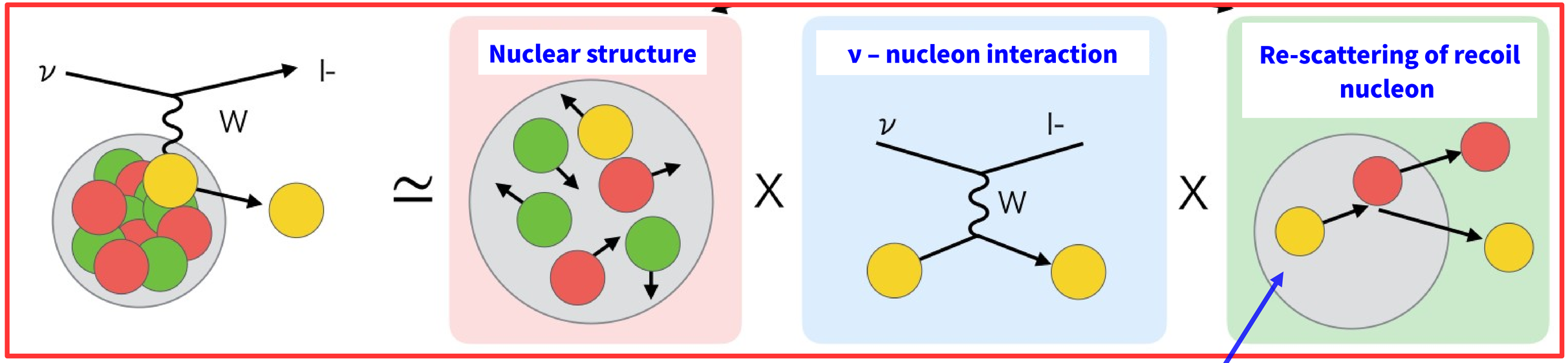
- Typically, event simulation of neutrino experiments consists of two steps:
  - ν-A interaction simulation
  - Detector simulation



Event generation

- In usual neutrino experiments, a “ν-A interaction” is treated as “an event”
- Factorized approach has been used for “event generation”
  - **Evaporation of the residual nucleus** is also simulated
- No unified framework (e.g. Geant4) exists, and several custom packages are being rampant



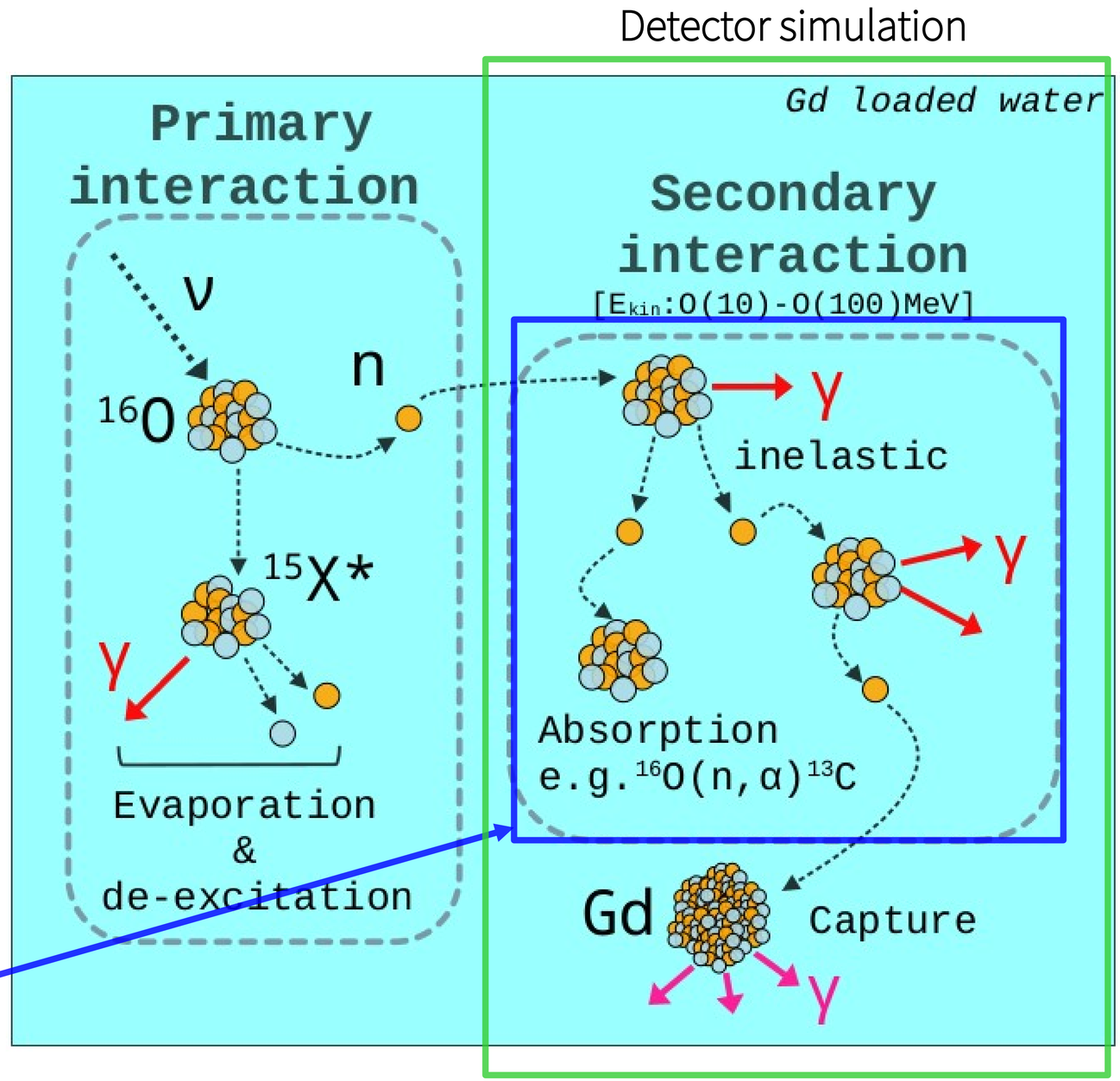


Detector simulation

- The particles produced by “event generation” are propagated through the detector of a experiment to simulate what the ν-A interaction would look like

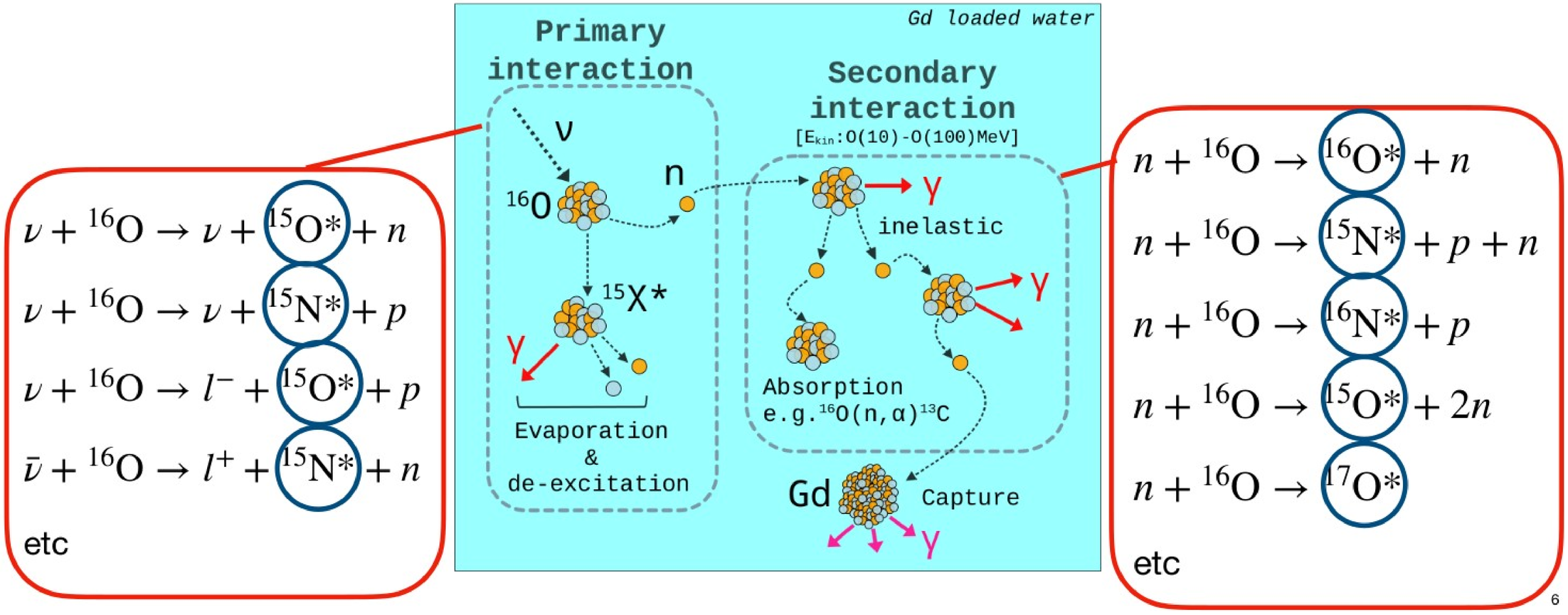
  - Geant4-based program used

- During the propagation, additional gamma rays and neutrons can be produced by **the secondary interactions** of the primary particles



Currently “INCL++ & G4PreCompound” used (one of Geant4 models)

What is the dominant systematics?



◆ Several **evaporation** simulations available, but they

- produce largely different predictions

- are not tested with proper data (oxygen for Super-Kamiokande)

→ Very likely be **the dominant uncertainty** on event predictions that use gamma ray & neutron multiplicity information

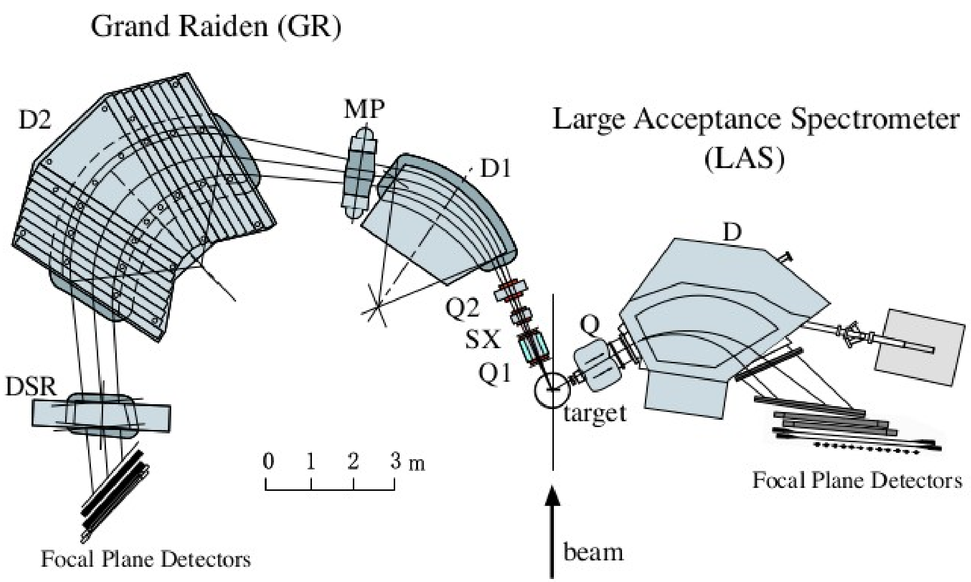
Difficulty in existing data (example)

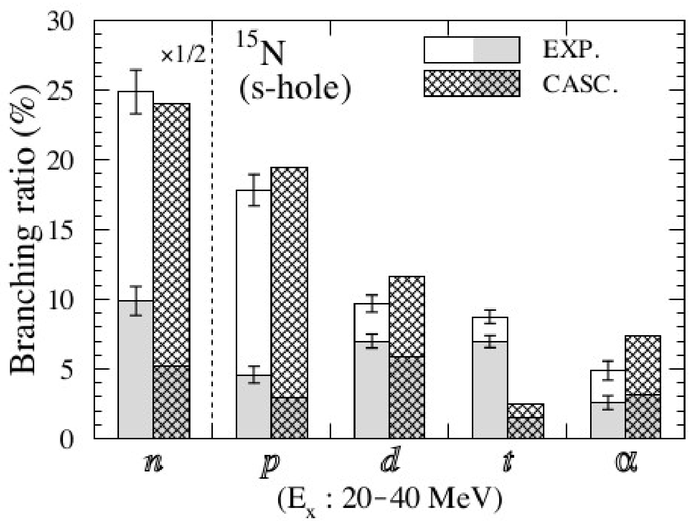
◆ p – ^{16}O interaction measurements with normal kinematics at RCNP (M.Yosoi et al)

- Laser-focusing on ^{16}O(p, 2p)^{15}N* reaction
  → Cannot address evaporation from other important excited nuclei (^{17}O*, ^{16}O*, ^{16}N*, ^{15}O*, etc)

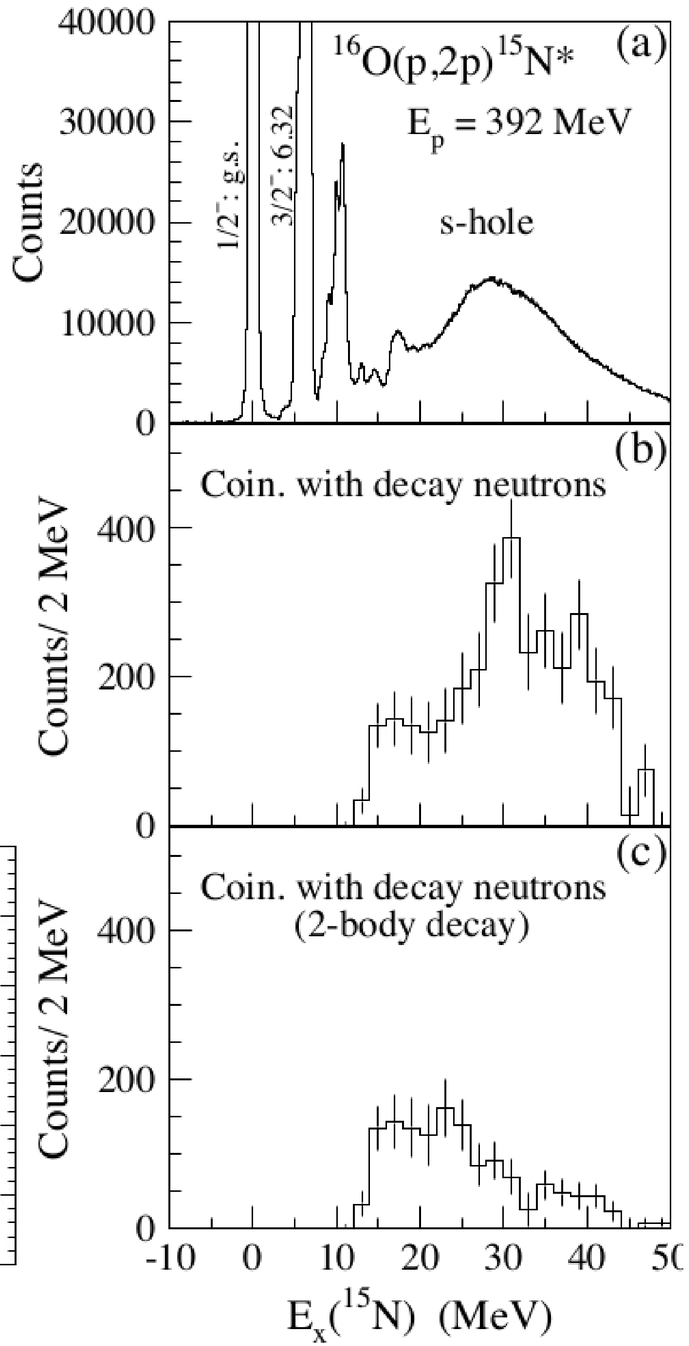
- Neither correlation measurements (e.g. γ & n) nor 4π measurements
  → Difficult to use simulation improvement even for ^{16}O(p, 2p)^{15}N* reaction

- **Relatively high energy threshold** for decay particles
  → **Cannot address "low-energy" component of evaporation**



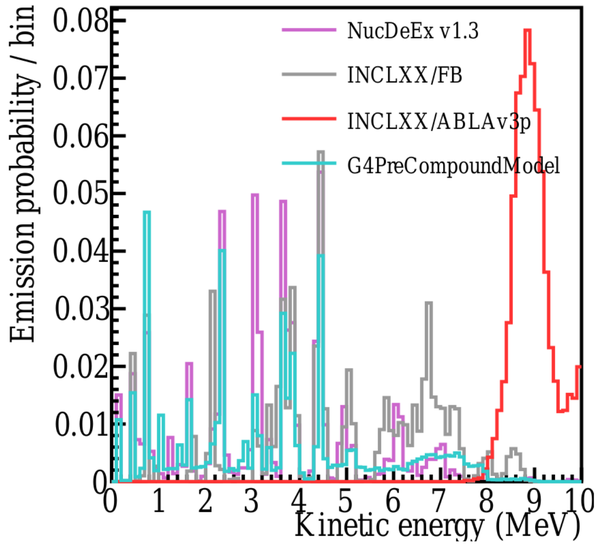


M. Yosoi, Ph.D. thesis (2003)

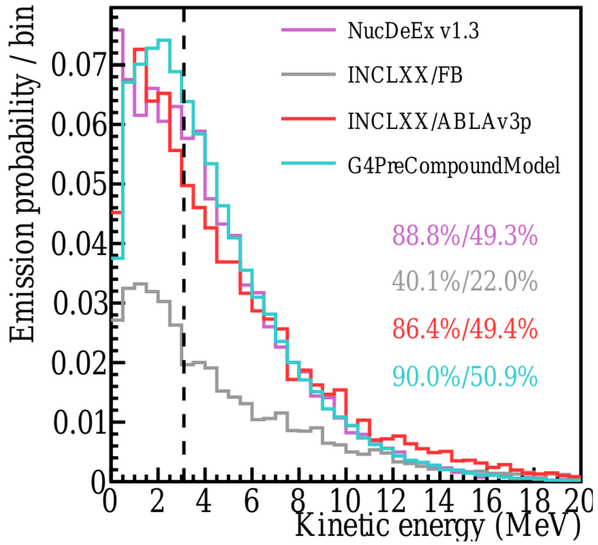


Evaporated particles from $^{15}N^*$ (simulation)

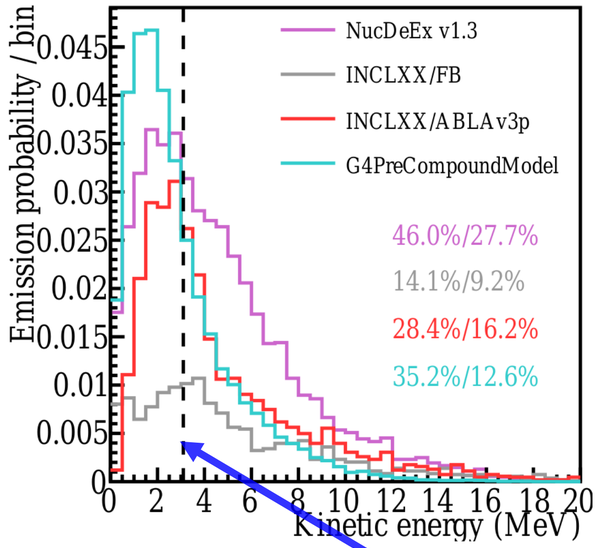
Gamma



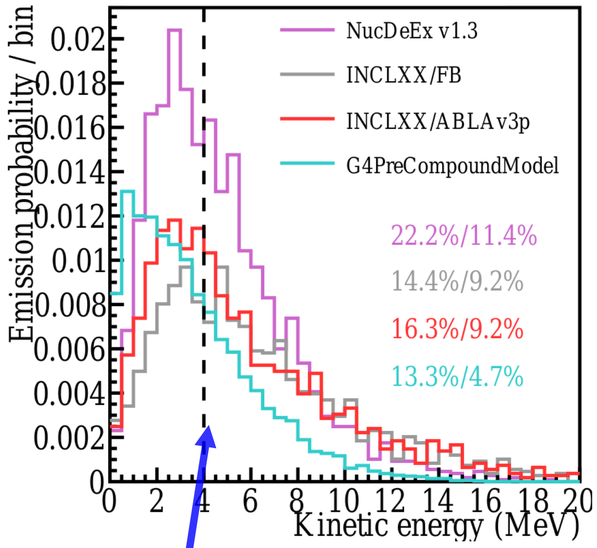
Neutron



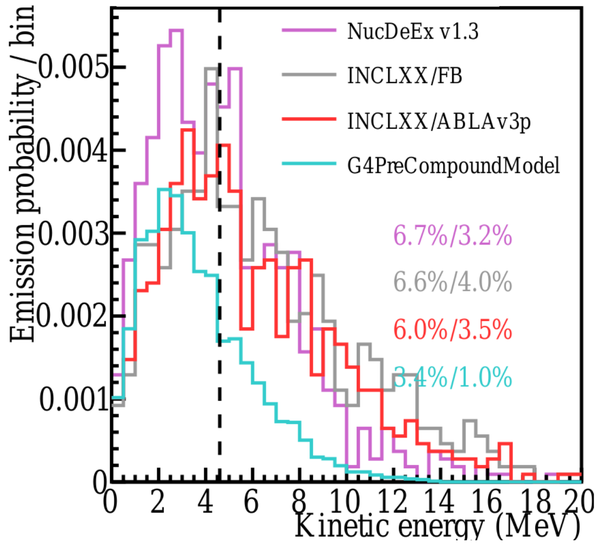
Proton



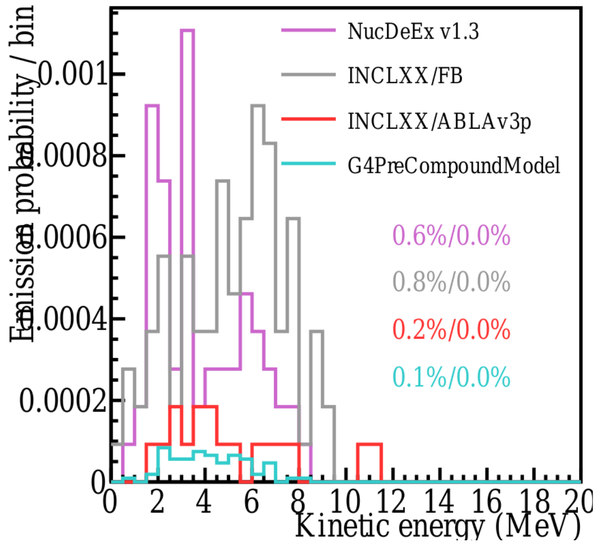
Deuteron



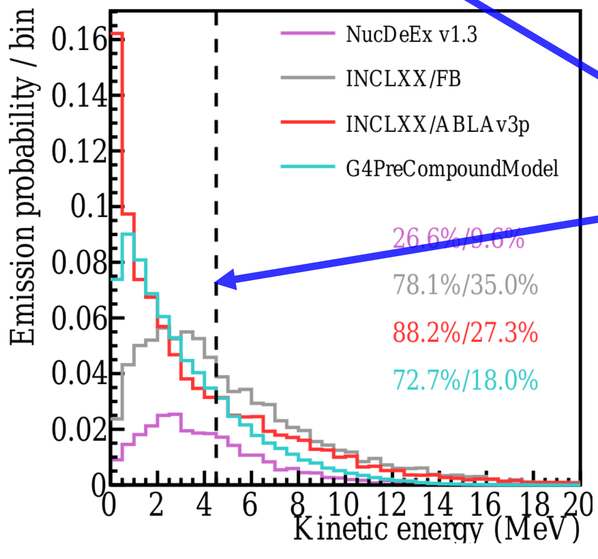
Triton



^{3}He



Alpha



Detection threshold adopted in the experiment by M.Yosoi et al

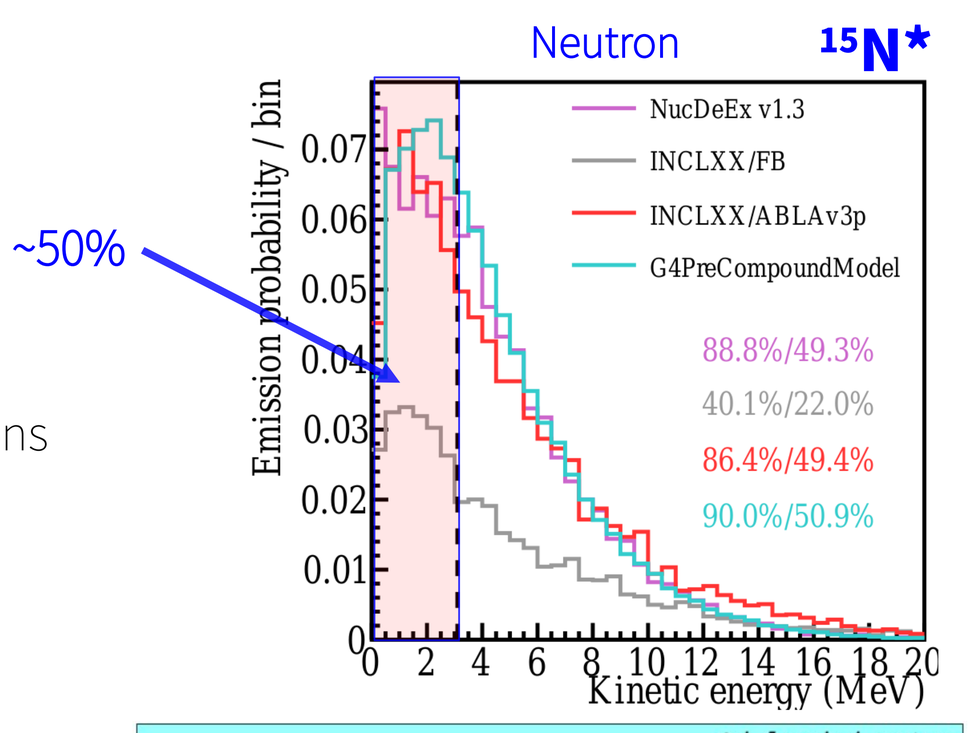
How important?

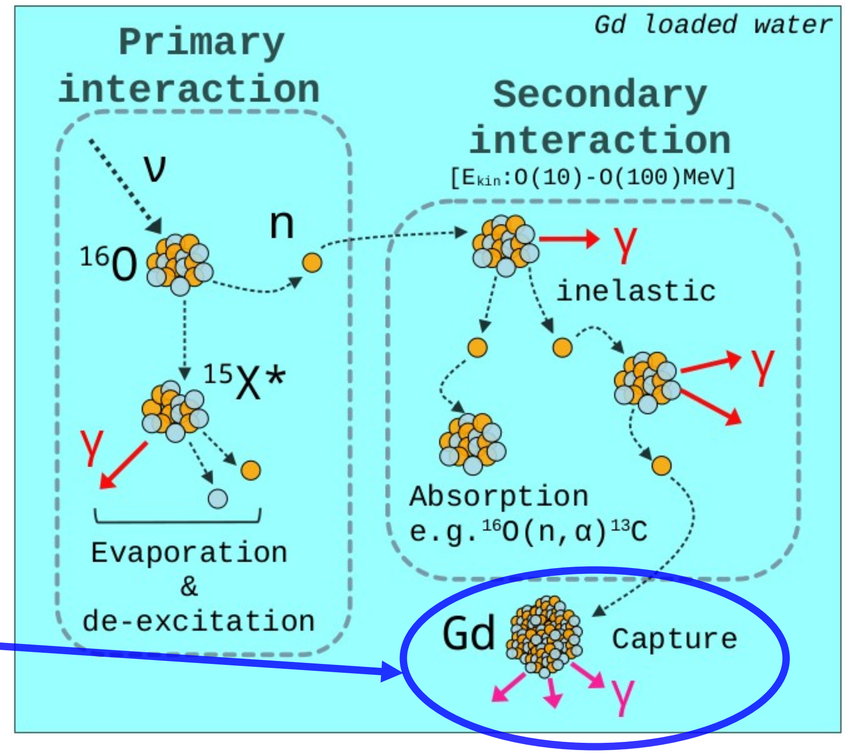
◆ **~50%** of evaporation neutrons are not detected due to detection threshold in normal kinematics experiments

- This generally holds for other nuclei relevant for our event simulations

◆ According to the NCQE event simulation, these undetectable neutrons correspond to **~25% of the total neutron captures**

→ These neutrons can get constrained only by inverse kinematics experiment



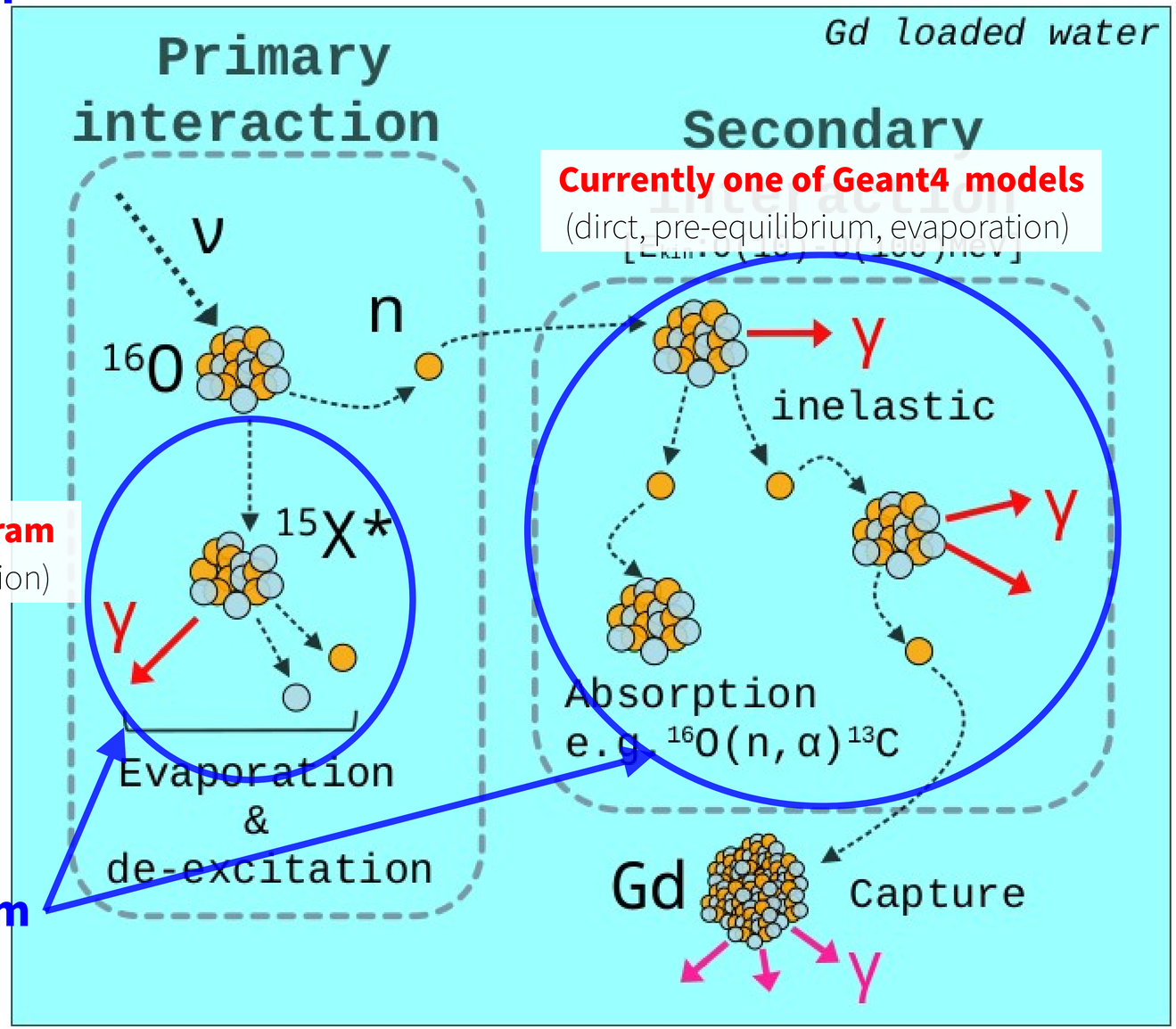


~50% of evaporation neutrons correspond to ~25% neutron captures

How to technically improve?

◆ Plan to replace **the existing simulations for the common nuclear processes with a single simulation program** that will be developed

- Core program being developed by S. Nakayama (JAEA) with CCONE
- Geant4 interface being developed by R. Akutsu
- Event generation interface to be developed



Currently custom program
(pre-equilibrium,evaporation)

To be replaced with single simulation program
(direct, pre-equilibrium, evaporation processes)

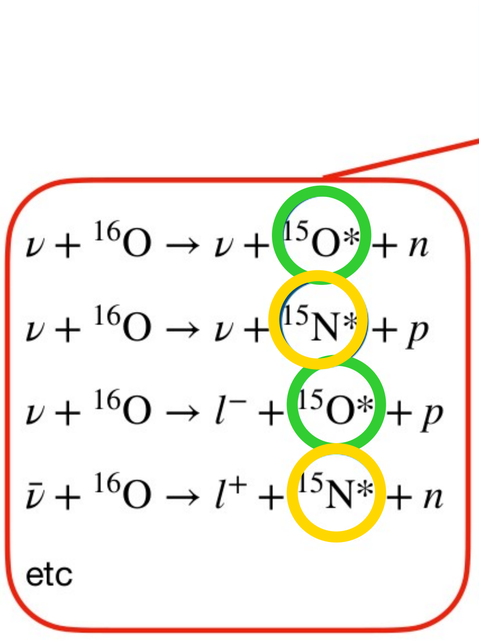
Ideas for model tuning

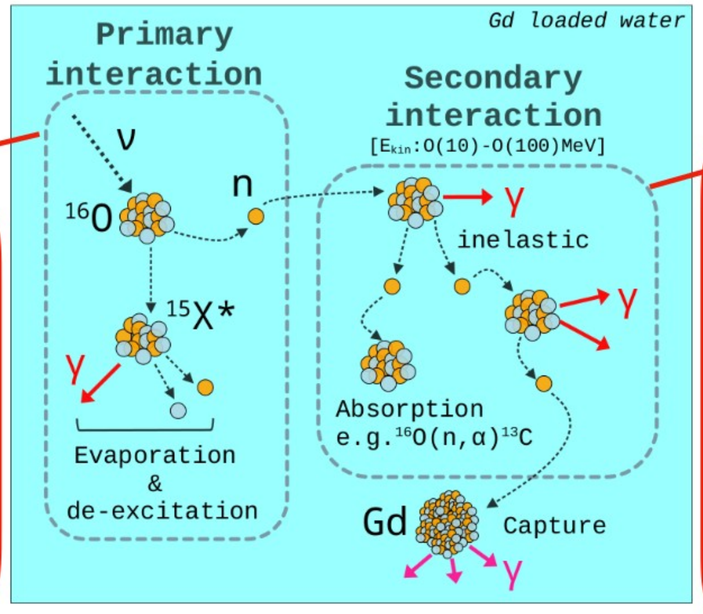
◆ Will tune the model parameters relevant for evaporation process to ^{18}O, ^{17}O, ^{16}O beam data to be taken at 200MeV/u

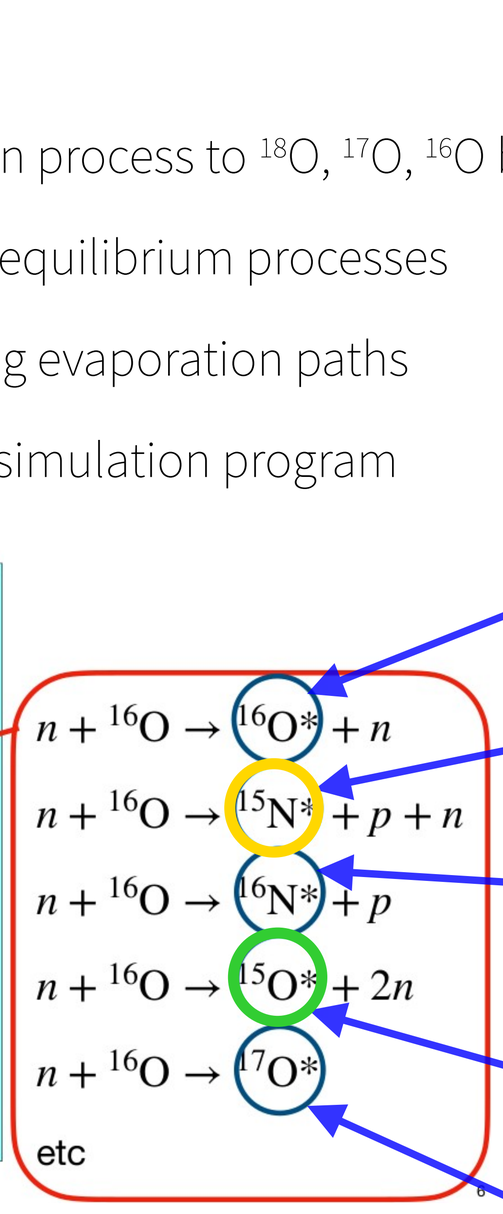
- Will also tune parameters describing direct and pre-equilibrium processes

- Fragment information by HODF to be used for tracing evaporation paths

→ Exact tuning method to be developed with the new simulation program







Measurements to be at SAMURAI

{$\mathcal{F}$}: fragments detected by HODF

^{17}O(p,np)^{16}O*
^{16}O* → {$\mathcal{F}$} + particles

^{16}O(p,2p)^{15}N*
^{15}N* → {$\mathcal{F}$} + particles

^{17}O(p,2p)^{16}N*
^{16}N* → {$\mathcal{F}$} + particles

^{16}O(p,np)^{15}O*
^{15}O* → {$\mathcal{F}$} + particles

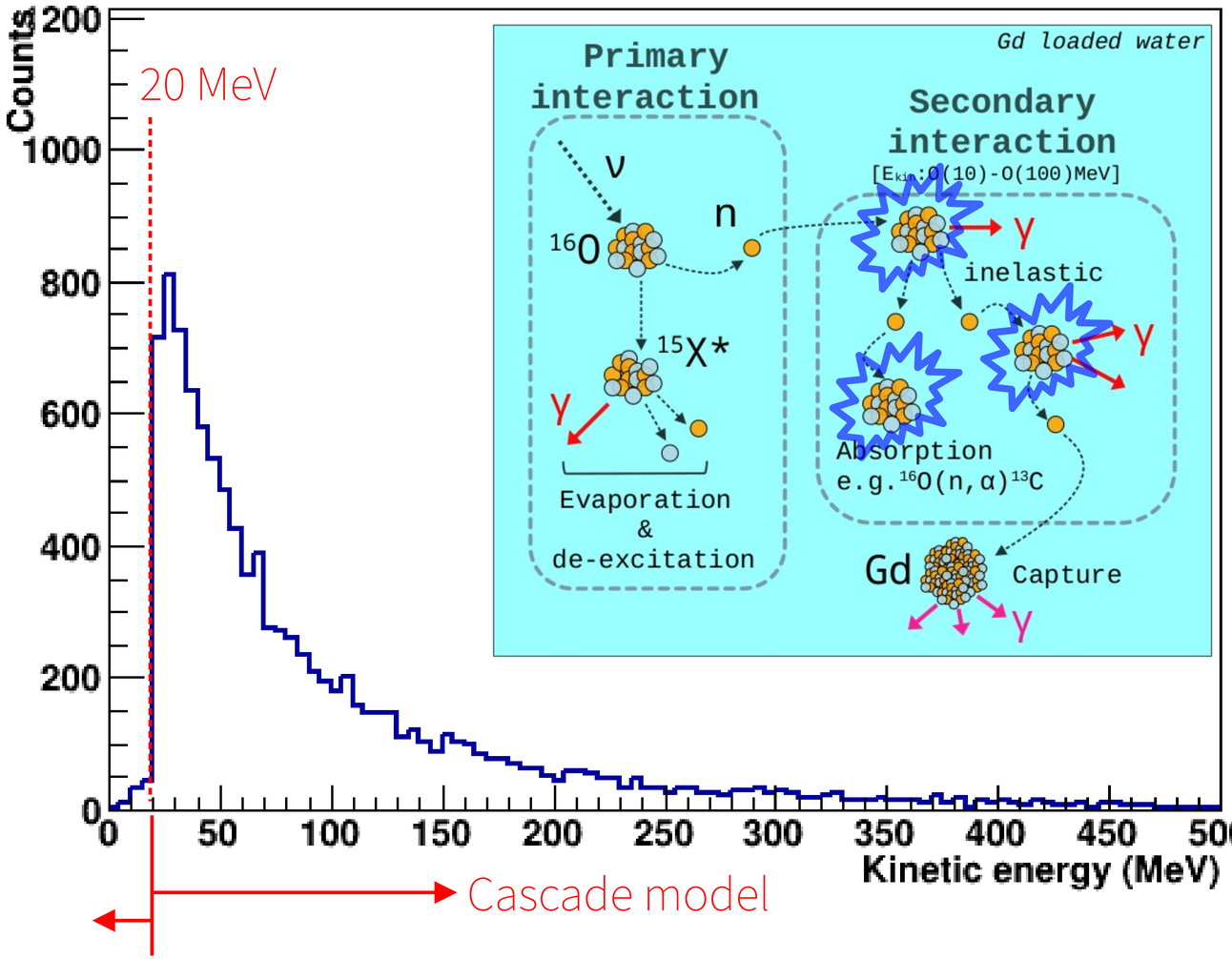
^{18}O(p,np)^{17}O*
^{17}O* → {$\mathcal{F}$} + particles

Beyond evaporation measurement @ 200 MeV/u

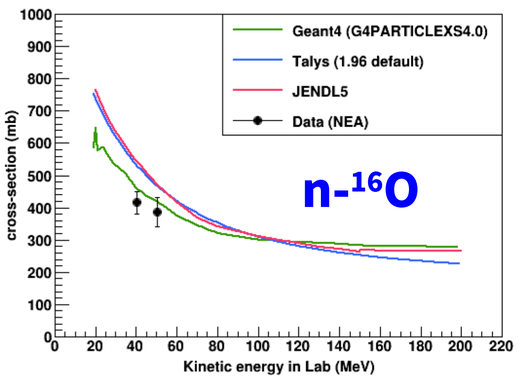
- Median energy of neutron secondary interactions for the NCQE background is ~70 MeV
- In the current event simulation, cascade model is used even for such low energy region, where the cascade picture is believed to be broken
- Eventually we may want to study the validity of cascade model in these low incident energies

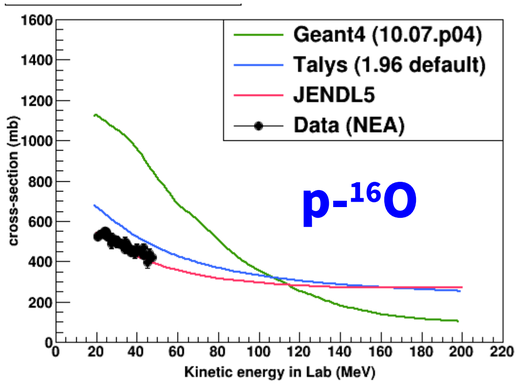
→ Need varying beam energy of ~50 - ~200 MeV/u, since there have never been measurements in this region

Neutron kinetic energy at n – ^{16}O interactions for the NCQE background events



Total reaction cross-section





Summary

- Precise event simulations are essential for analyses in neutrino experiments including Super-Kamikande

- There are large variations in predictions between nuclear interaction simulations

  - The largest uncertainty is very likely evaporation simulation

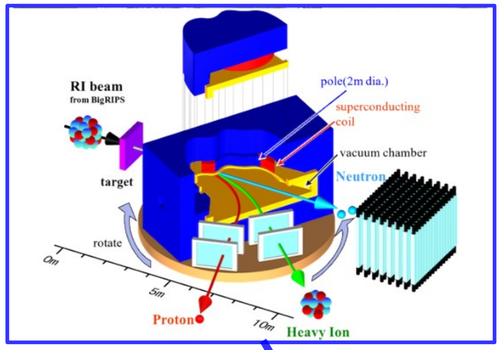
  → Needs to be improved, based on proper measurements that can only be made in inverse kinematics experiment

- Where and how to technically improve the evaporation simulation have been identified, starting the development of a novel integrated framework

  - Details of model tuning method to be developed

- Eventually we want to develop nuclear interaction simulation relevant for ~100 MeV energy region, where cascade model is believed to be irrelevant to use

Inverse kinematics experiment



Nuclear interaction theory

Event simulation

Robust physics results!