Simulation of the background from (α, n) reactions in the JUNO scintillator

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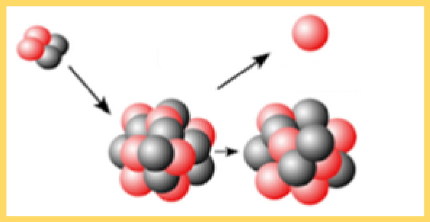
on behalf of the **JUNO** Collaboration



ICPPA-2024 conference

25.10.2024

JUNO experiment: detector

Jiangmen **U**nderground **N**eutrino **O**bservatory

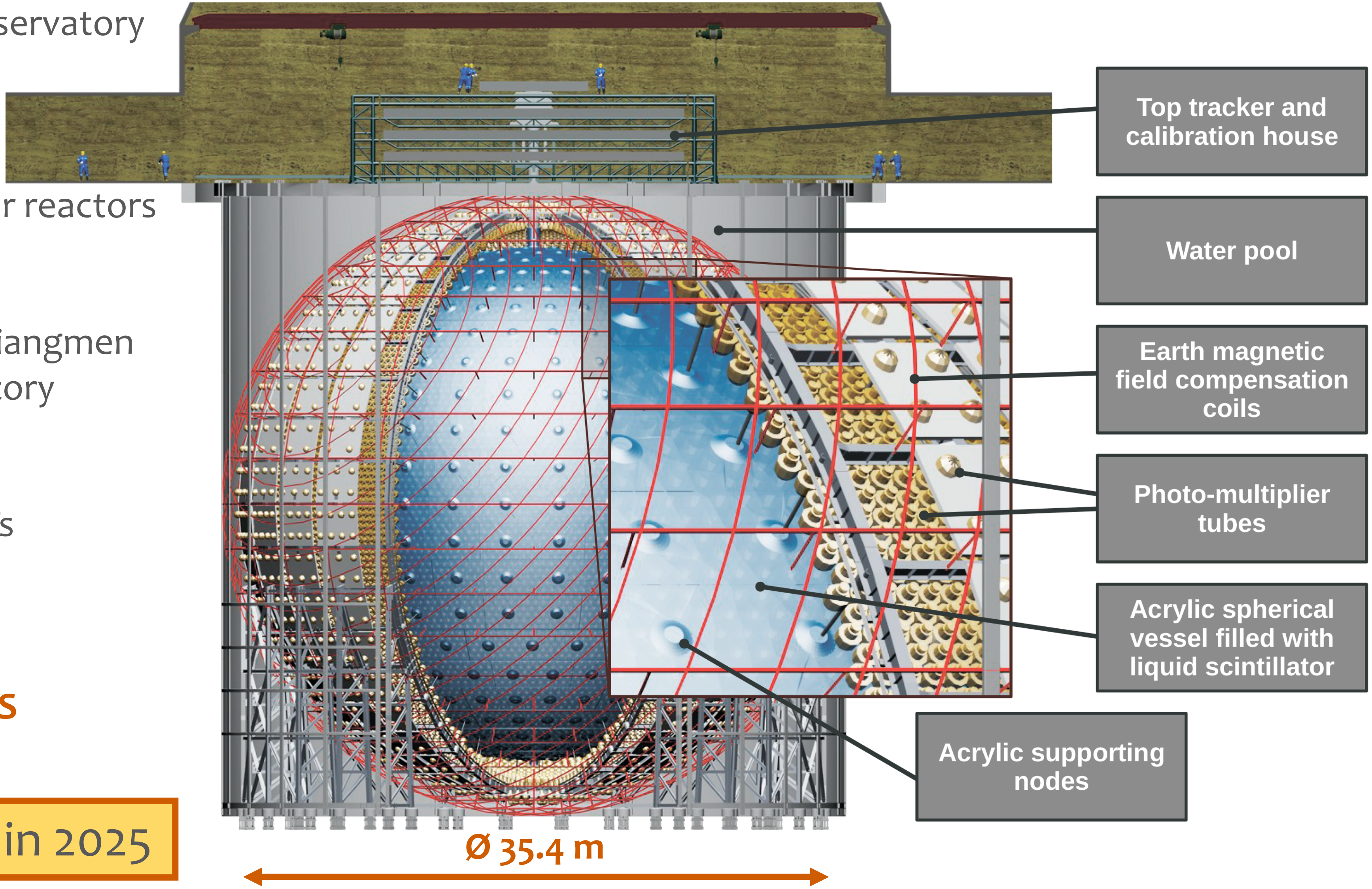
Type: Reactor antineutrino detector

Baseline: **52.5 km** away from **8** nuclear reactors ($26.6\ GW_{th}$ total)

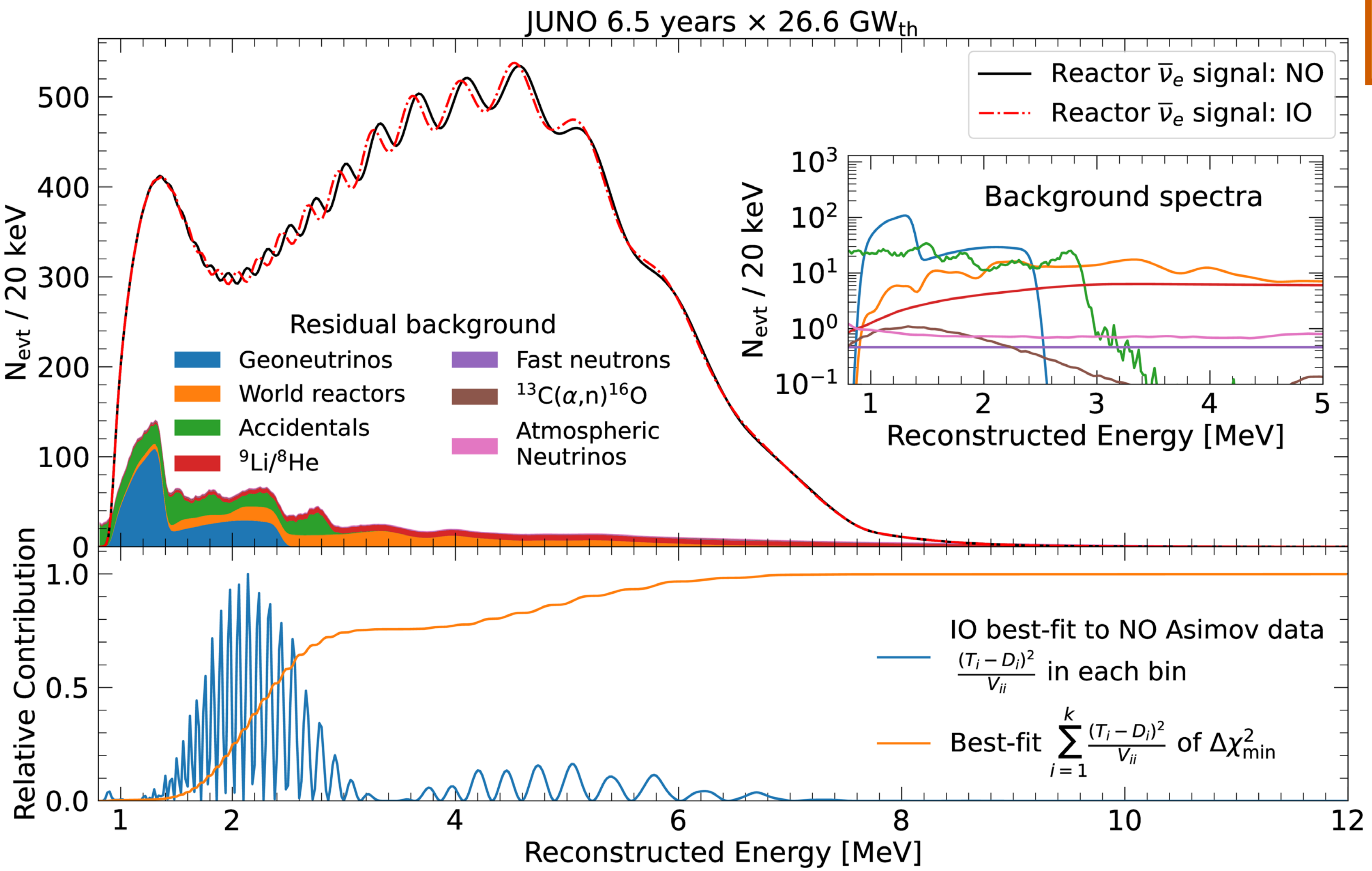
Location: South China, Guangdong, Jiangmen in a **700 m** deep underground laboratory

- **20 kt** of Liquid Scintillator (LS)
- 17612 20” PMTs and 25600 3” PMTs
- PMT optical coverage 78%
- Energy resolution: **σ < 3% at 1 MeV**
- Energy scale uncertainty: < 1%
- Two subdetectors: **TAO** and **OSIRIS**
- **Good radiopurity expected**

JUNO will start data taking in 2025



JUNO experiment: physics



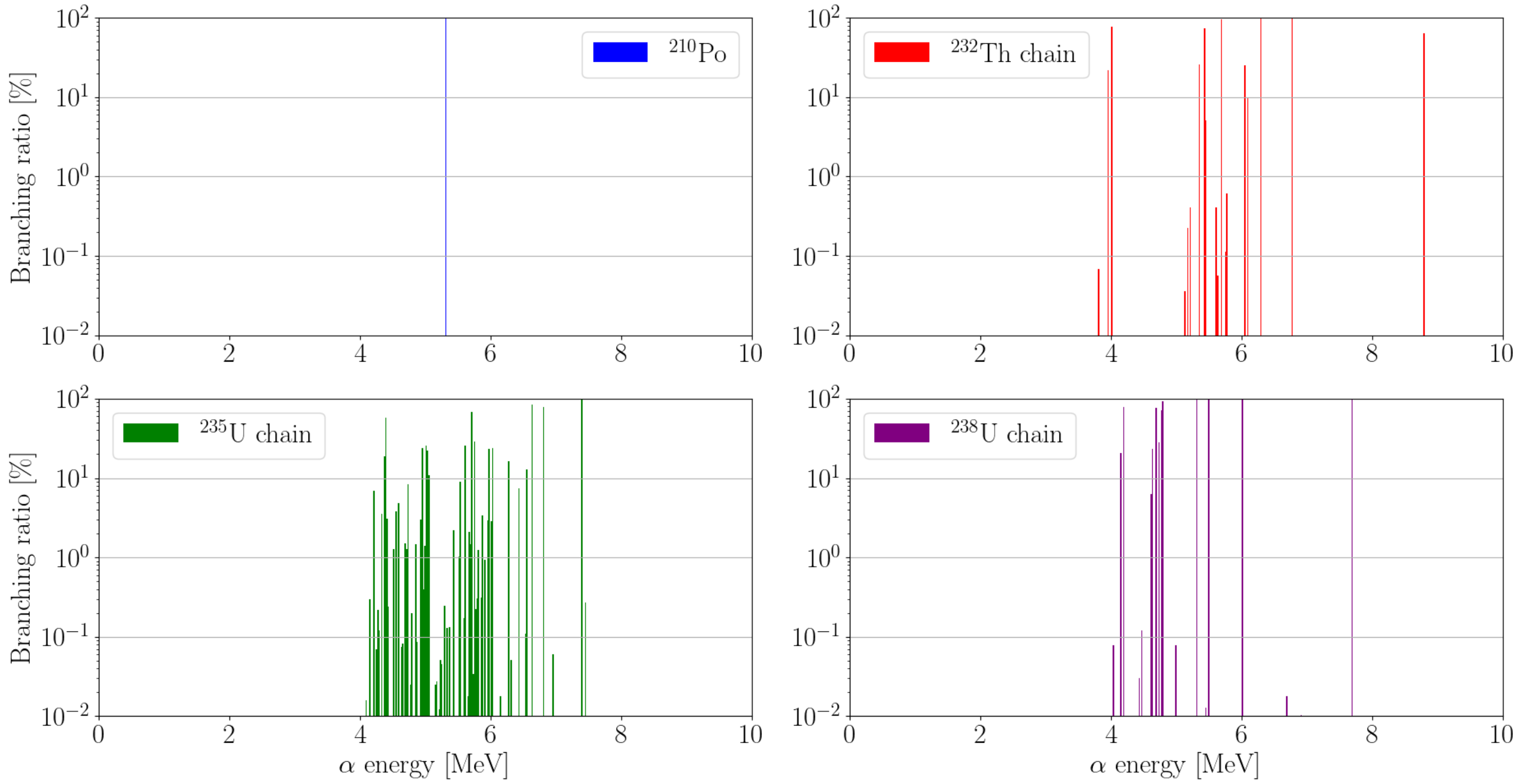
JUNO is
a **multi-purpose** neutrino experiment

Rich physical program including

- **Neutrino mass ordering** (NMO) with **3σ in ~6-7 years** of data-taking
- sub-percent measurements of the following oscillation parameters: $\sin^2\theta_{12}, \Delta m^2_{21}, \Delta m^2_{31}$
- Geoneutrino measurement to more accurately determine fluxes and probe Earth's properties and evolution
- Solar neutrino flux measurements and an attempt to investigate the metallicity problem

Sources of α particles in JUNO

Negligible contribution of ^{235}U



Expected concentration level c of natural radioactive impurities in the JUNO LS:

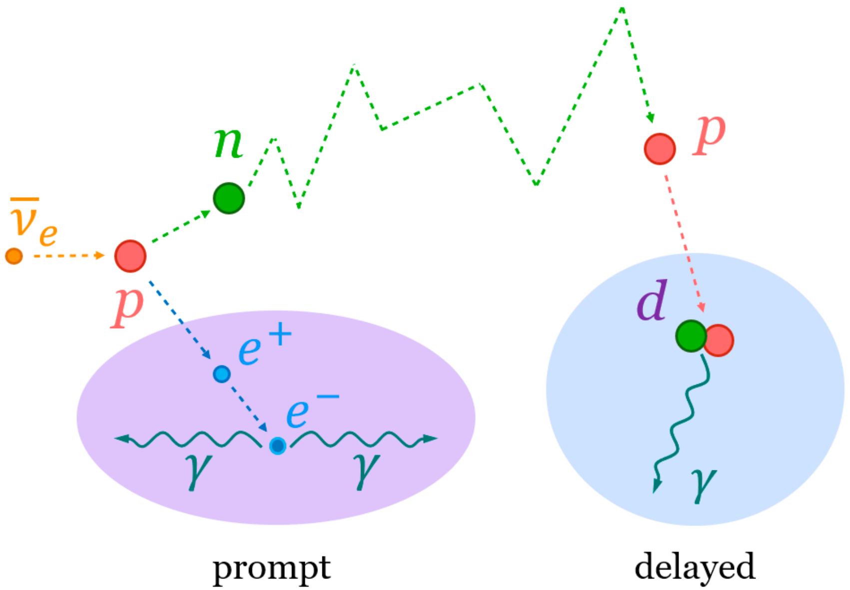
Source	^{238}U	^{232}Th	^{210}Pb	^{210}Po (unsupported)
c [g/g]	10^{-15}	10^{-15}	5×10^{-23}	3×10^{-24}

Note: the **minimum radiopurity** levels requested for the NMO measurement are considered

$^{13}C(\alpha, n)^{16}O$ reaction in liquid scintillator

Reactor antineutrinos are detected via **Inverse Beta Decay (IBD)**

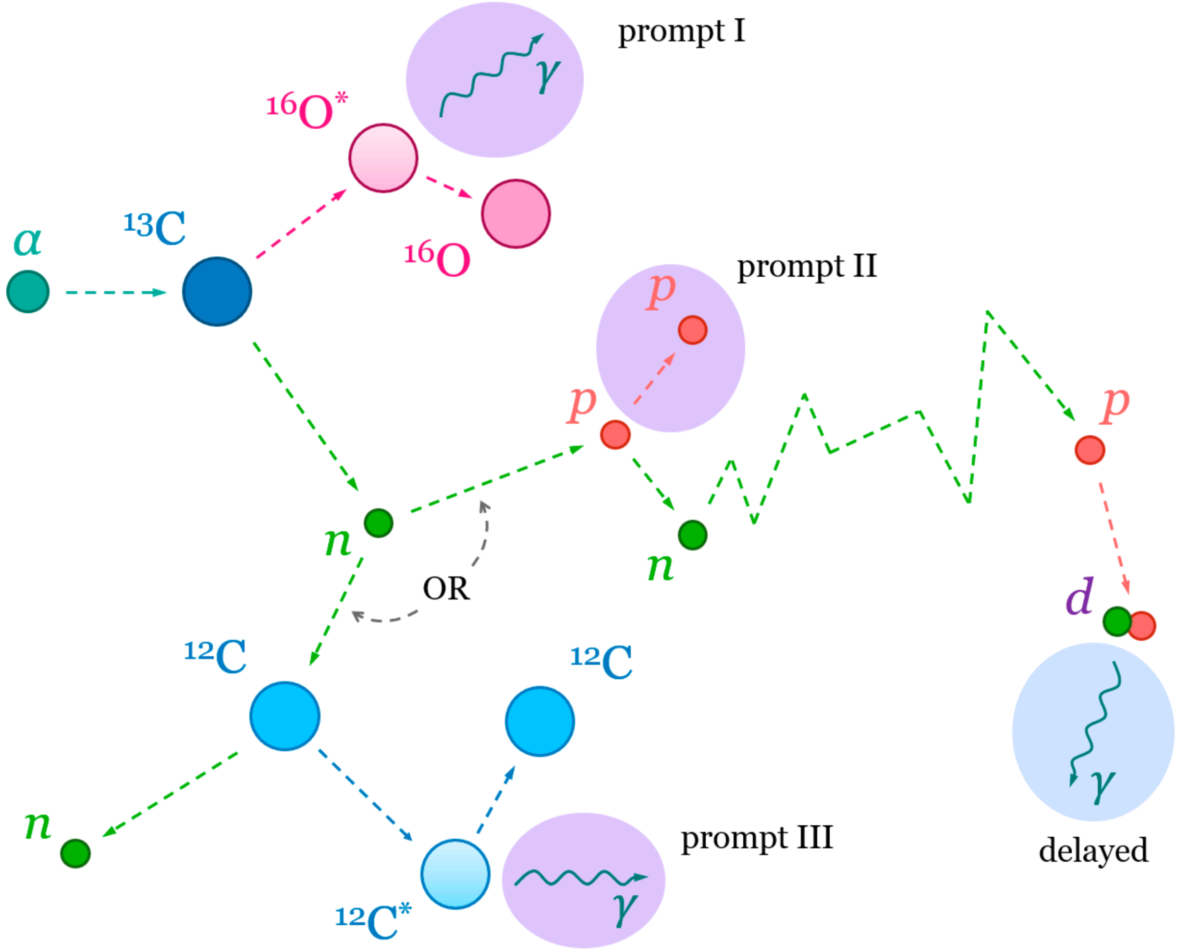
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



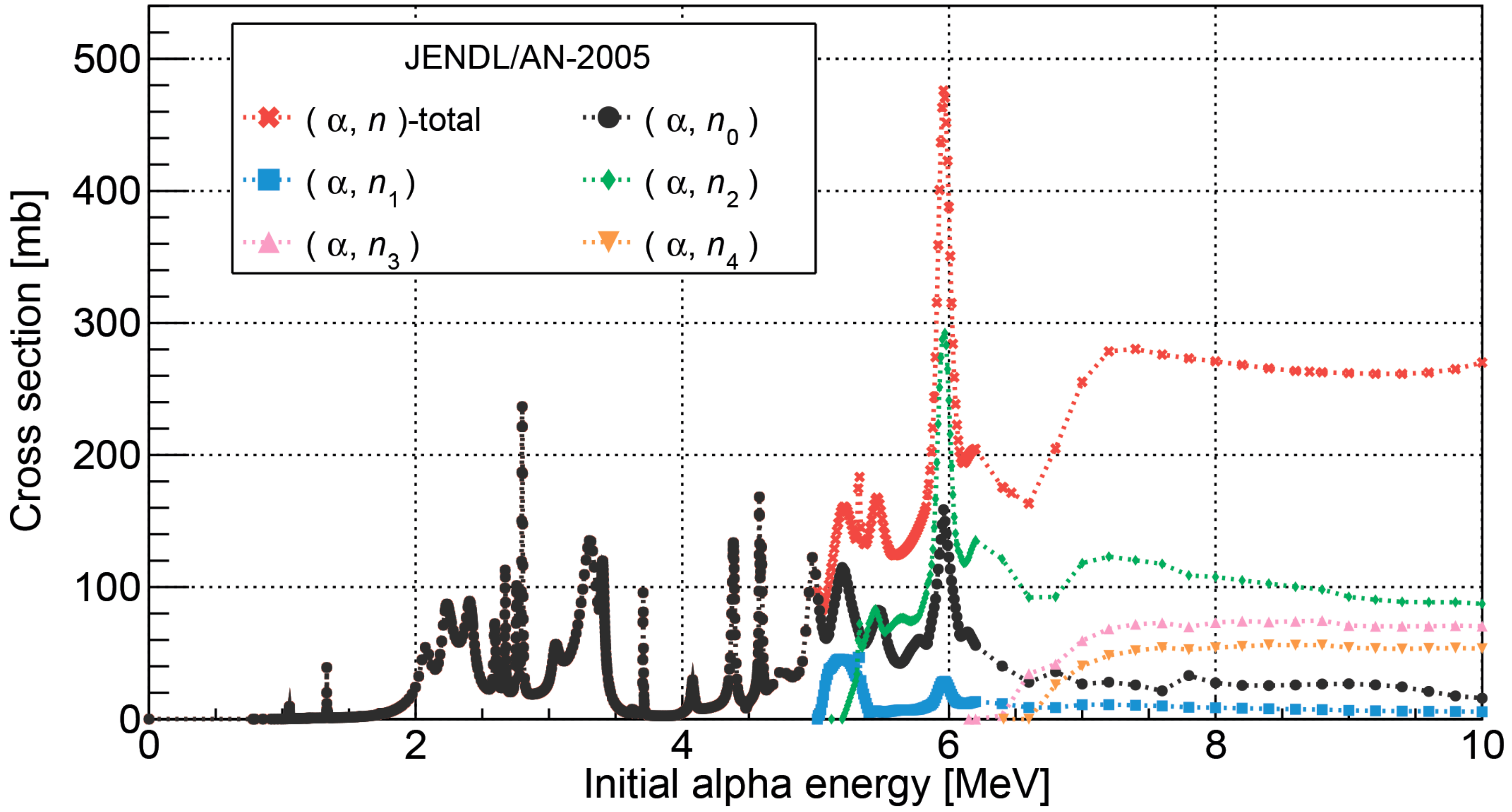
The reaction provides a **clear signal signature**, namely a **delayed coincidence**

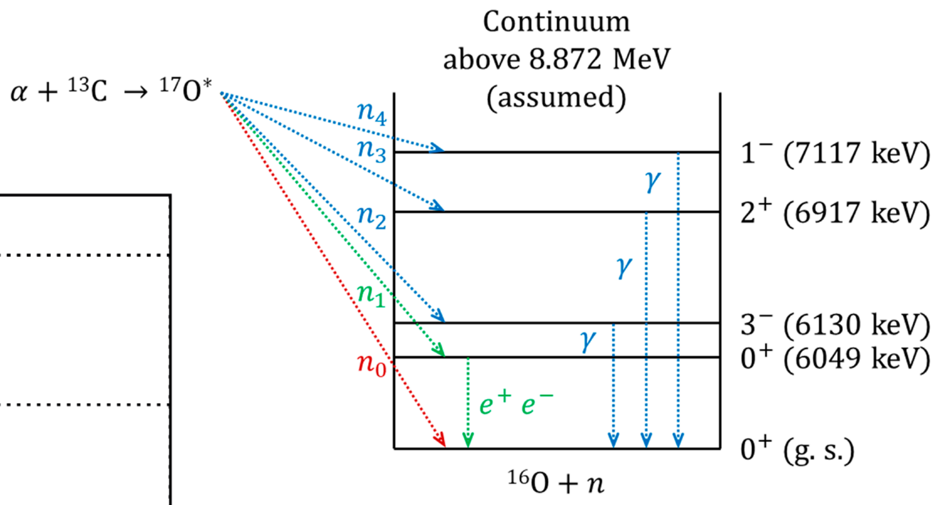
- **Prompt** photons from e^+ ionization and annihilation (1-8 MeV)
- **Delayed** photon from *n* capture on H (2.2 MeV)

$^{13}C(\alpha, n)^{16}O$ interaction can mimic IBD coincident signals



$^{13}C(\alpha, n)^{16}O$ reaction in liquid scintillator



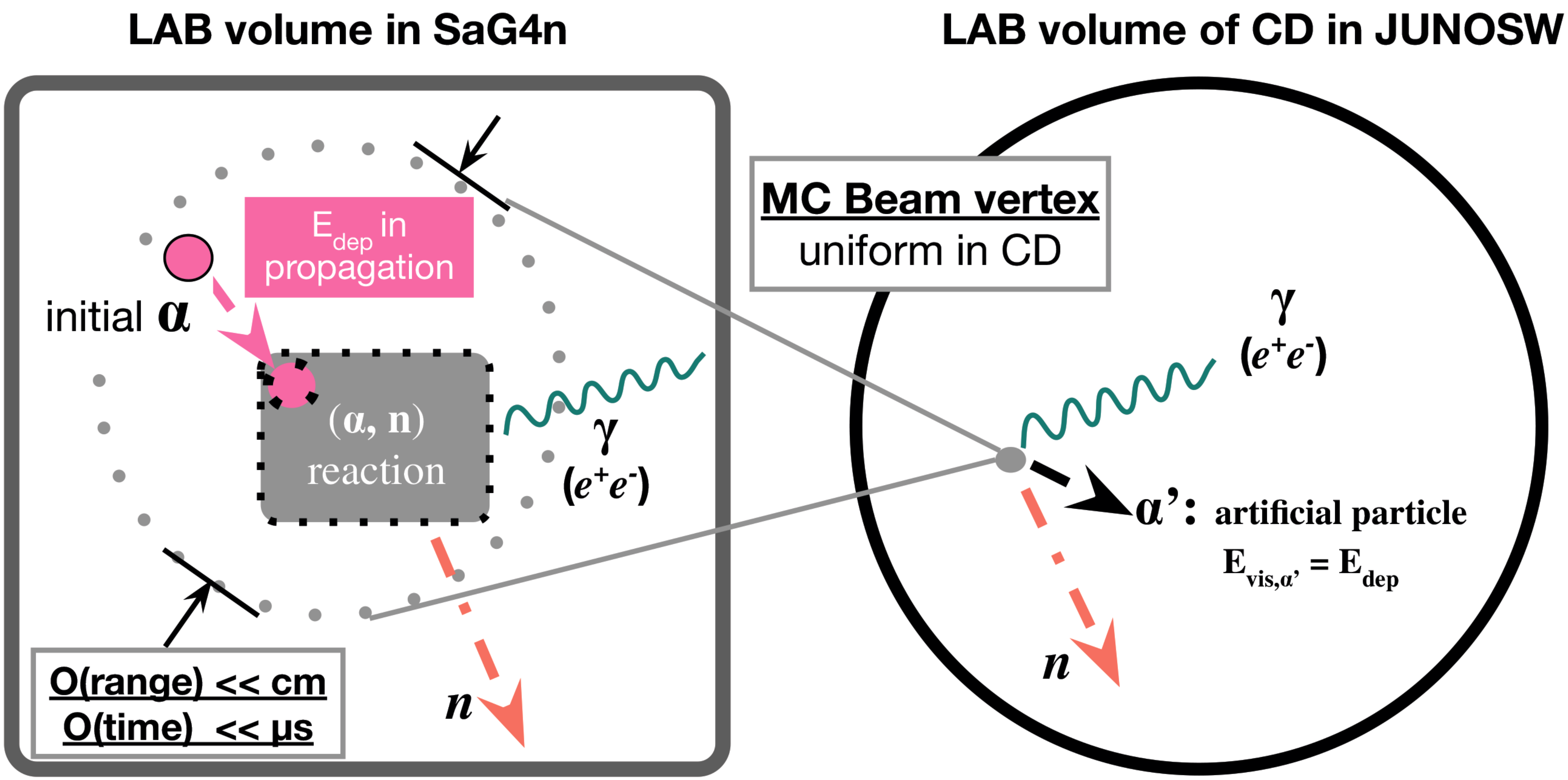


JUNO LAB:

$C_6H_5C_{14}H_{29}$

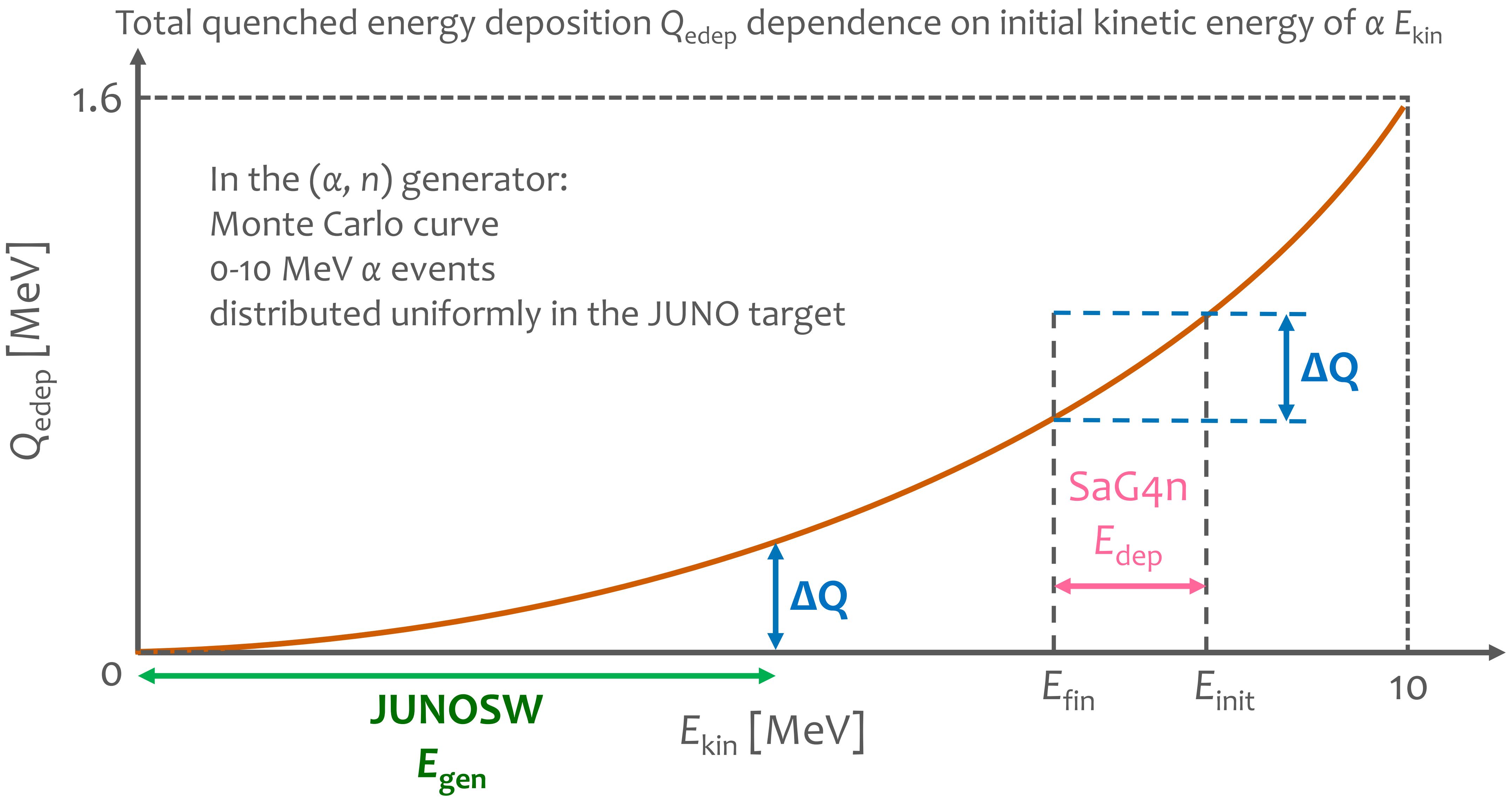
~1.1% ^{13}C in natural carbon

Simulation $^{13}C(\alpha, n)^{16}O$ with SaG4n and JUNOSW

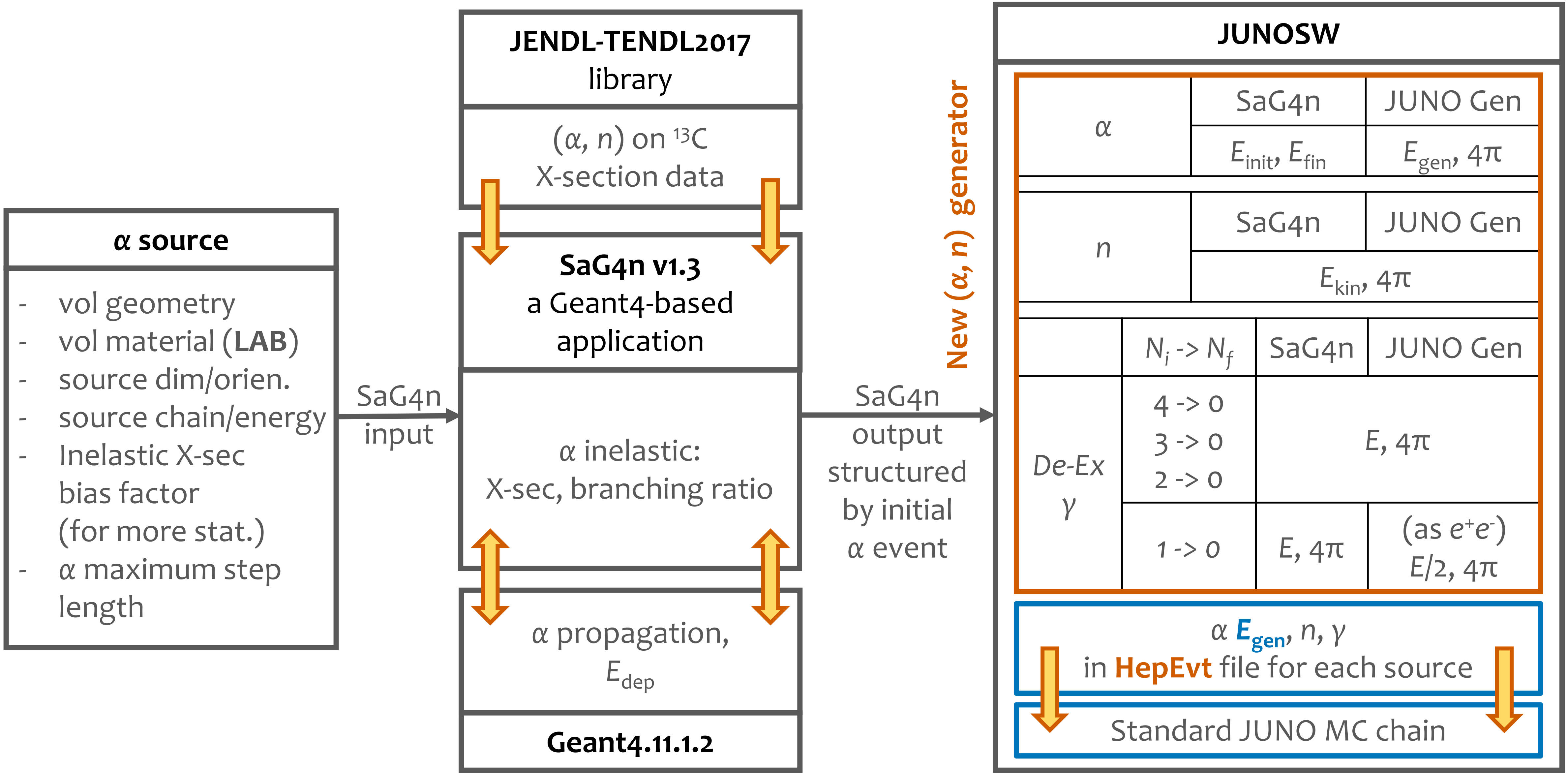


For further details about SaG4n see *Nucl. Instrum. Methods Phys. Res. A* **960** (2020) 163659 [arXiv:1906.03903]

Transition from SaG4n α E_{dep} to JUNOSW α E_{gen}

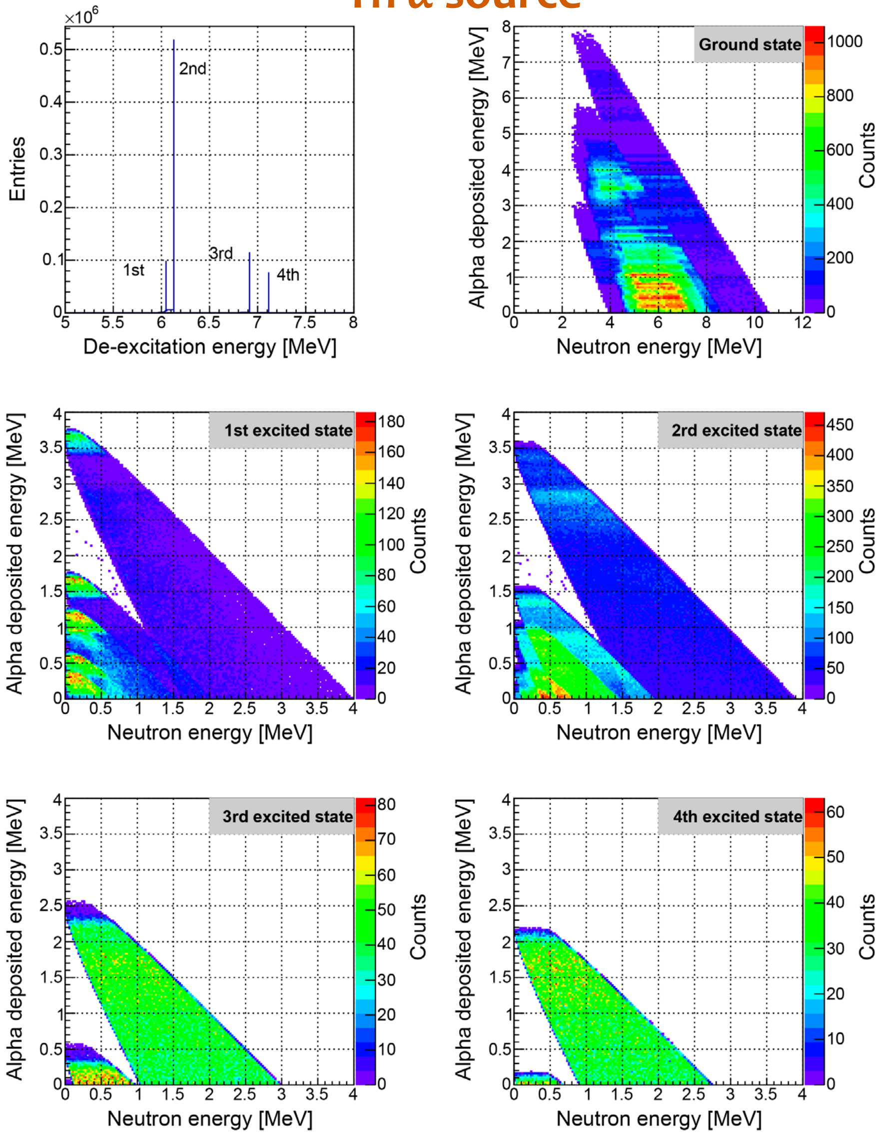


Simulation pipeline



SaG4n output

^{232}Th α source



Number of simulated full chain decays for each chain: 2×10^9

Chain or α source	Branching ratio [%]				
	n_0	n_1	n_2	n_3	n_4
^{238}U	51.5	7.9	29.3	7.0	4.3
^{232}Th	43.9	8.5	34.2	8.1	5.3
^{210}Pb	89.3	9.3	1.4	0.0	0.0

Chain or α source	Y [n/α]	α/chain	Y [n/chain]
^{238}U	7.95×10^{-8}	8	6.36×10^{-7}
^{232}Th	1.43×10^{-7}	6	8.58×10^{-7}
^{210}Pb	5.11×10^{-8}	1	5.11×10^{-8}

IBD coincident event selection

10^5 (α, n) **events** were generated uniformly inside the Central Detector volume using JUNOSW, for each of the α sources ^{210}Pb, ^{232}Th, and ^{238}U

A standard set of cuts was applied:

- prompt-delayed time difference: dT **< 1 ms**;
- prompt-delayed vertex distance: dL **< 1.5 m**;
- fiducial volume of prompt vertex: R **< 17.2 m**;
- prompt reconstructed energy: **(0.7, 12) MeV**;
- delayed reconstructed energy: **(1.9, 2.5) MeV or (4.4, 5.5) MeV**

Estimated $^{13}C(\alpha, n)^{16}O$ event rates

For each individual source the rate of the α decay R_{decay}, assuming secular equilibrium in the decay chain, can be given by

$$R_{\text{decay}} \left[\frac{\text{cpd}}{\text{kt}}\right] = c \left[\frac{\text{g}}{\text{g}}\right] \times \frac{N_{\text{A}}}{\tau\ [\text{day}] \times M} \times 10^9 \left[\frac{\text{g}}{\text{kt}}\right],$$

where c is the concentration of the mother of the decay chain, N_A is the Avogadro constant, M is the molar mass of the parent isotope of the chain, τ is its lifetime, and **cpd** stands for counts per day

The expected rate of (α, n) background events in 20 kt LS R_{AC} or R_n (w/ and w/o efficiency) can be calculated as follows

$$R_{\text{AC}}\ [\text{cpd}] = \varepsilon \times R_n\ [\text{cpd}] = R_{\text{decay}} \left[\frac{\text{cpd}}{\text{kt}}\right] \times Y_n \left[\frac{n}{\text{chain}}\right] \times M_{\text{LS}}[\text{kt}],$$

where ε is the IBD selection efficiency, Y_n is the neutron yield, and M_{LS} is the 20 kt mass of the LS

But for **unsupported ^{210}Po** in JUNO the respective rate in Borexino is **scaled**, assuming upon LS filling, that the ^{210}Po will be stripped from the surface into the LS volume

Note:

A rate of **8×10^4 cpd/kt was reported in Borexino** as the average value in the whole LS volume, at the beginning of data taking after filling (see *Phys. Rev. D* **101** (2020) 012009 [arXiv:1909.02257])

Estimated $^{13}C(\alpha, n)^{16}O$ event rates

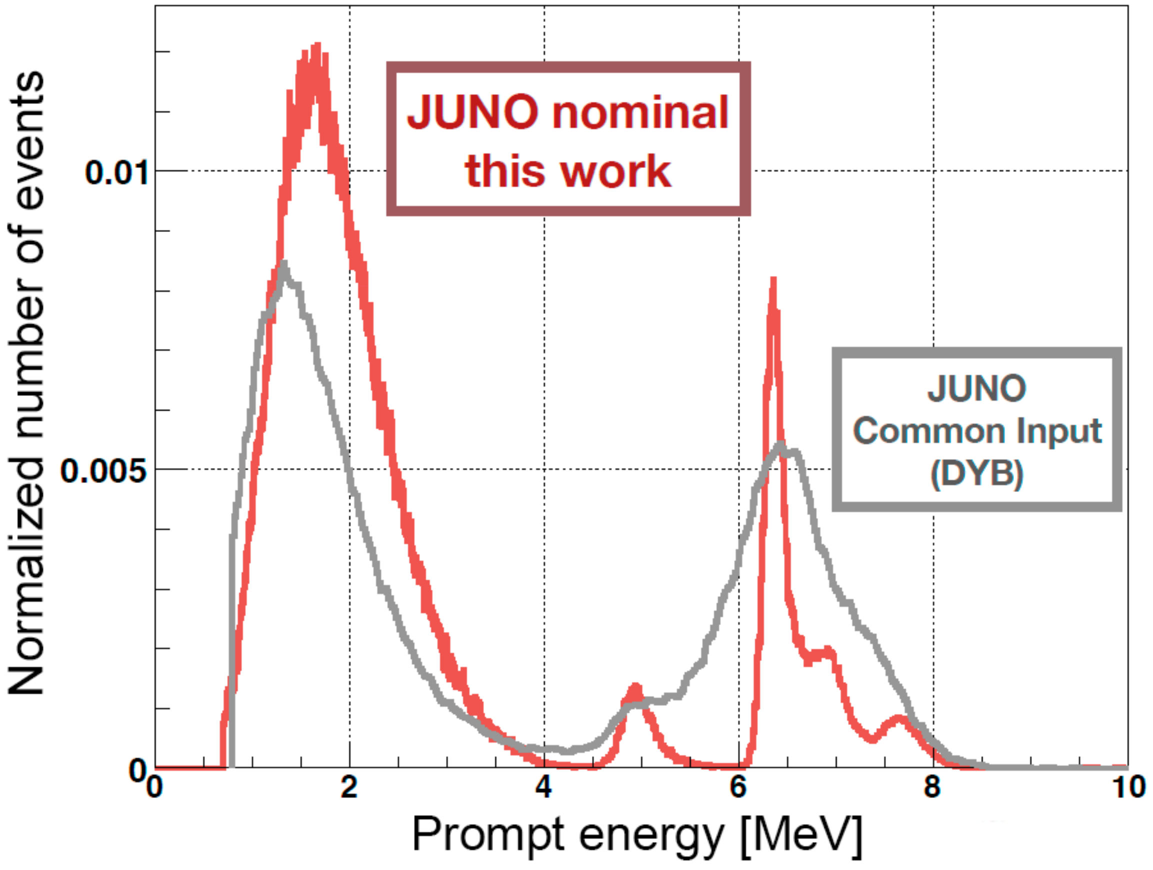
Source	Y_n [n/chain] neutron yield	c [g/g] expected concentration	R_{decay} [cpd/kt]	R_n [cpd] rate 20 kt LS	IBD selection efficiency	R_{AC} [cpd] IBD-like rate after cuts
^{238}U	6.36×10^{-7}	10^{-15}	1068	0.014	0.845	0.012
^{232}Th	8.58×10^{-7}	10^{-15}	352	0.006	0.84	0.005
^{210}Pb	5.11×10^{-8}	5×10^{-23}	12265	0.0125	0.88	0.011
^{210}Po unsupported	5.11×10^{-8}	3×10^{-24}	70400	0.072	0.88	0.063

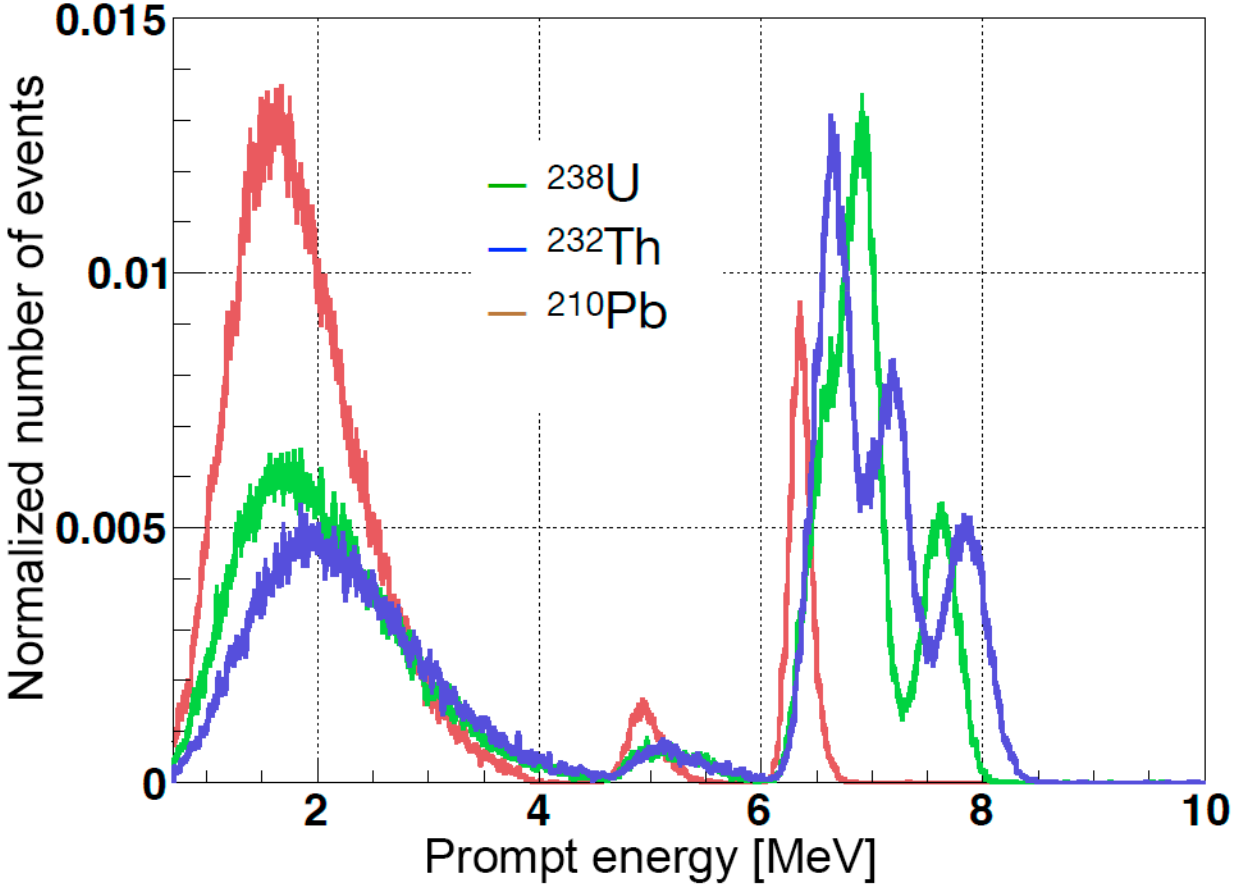
"cpd" stands for counts per day

0.091 total

$^{13}C(\alpha, n)^{16}O$ background reconstructed spectra

SaG4n v1.3 + Geant4.11.1.2, JUNOSW, 10^5 events per source





Neutron yield uncertainty

Uncertainty source	Relative uncertainty
SaG4n reference value discrepancy	18%
$^{13}C(\alpha, n)^{16}O$ cross section	15%
α maximum step length dependence (SaG4n's input parameter)	5%
Detector response	5%
Radioactivity concentration	5%
Total (quadratic sum)	**25%**

Conclusions

- Estimated the $^{13}C(\alpha, n)^{16}O$ event rates and the respective spectra in JUNO liquid scintillator

- Developed and set up a two-stage pipeline for evaluating the (α, n) background that includes among other things
  - a modern simulation tool SaG4n as a basis of the first stage;
  - a new Monte Carlo generator which uses the output of SaG4n and creates HepEvt files for the detector simulation;
  - a new approach to accounting for the α energy deposition before the (α, n) interaction
  - flexibility in case of re-evaluation of the background

- Considered additional contamination from non-equilibrium ^{210}Po

- Analyzed different sources of uncertainties and demonstrated the level of expected accuracy at 25%

The results can be applied in further antineutrino studies in the JUNO experiment and they are useful for any general antineutrino detector with a liquid scintillator target


Thank you for your attention!