Simulation of the background from $^{13}C(\alpha, n)^{16}O$ reaction in the JUNO scintillator

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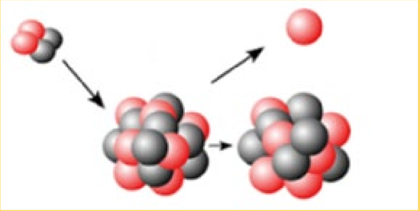
on behalf of the **JUNO** Collaboration



TAUP2025 conference

2025.08.26

JUNO experiment: detector

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

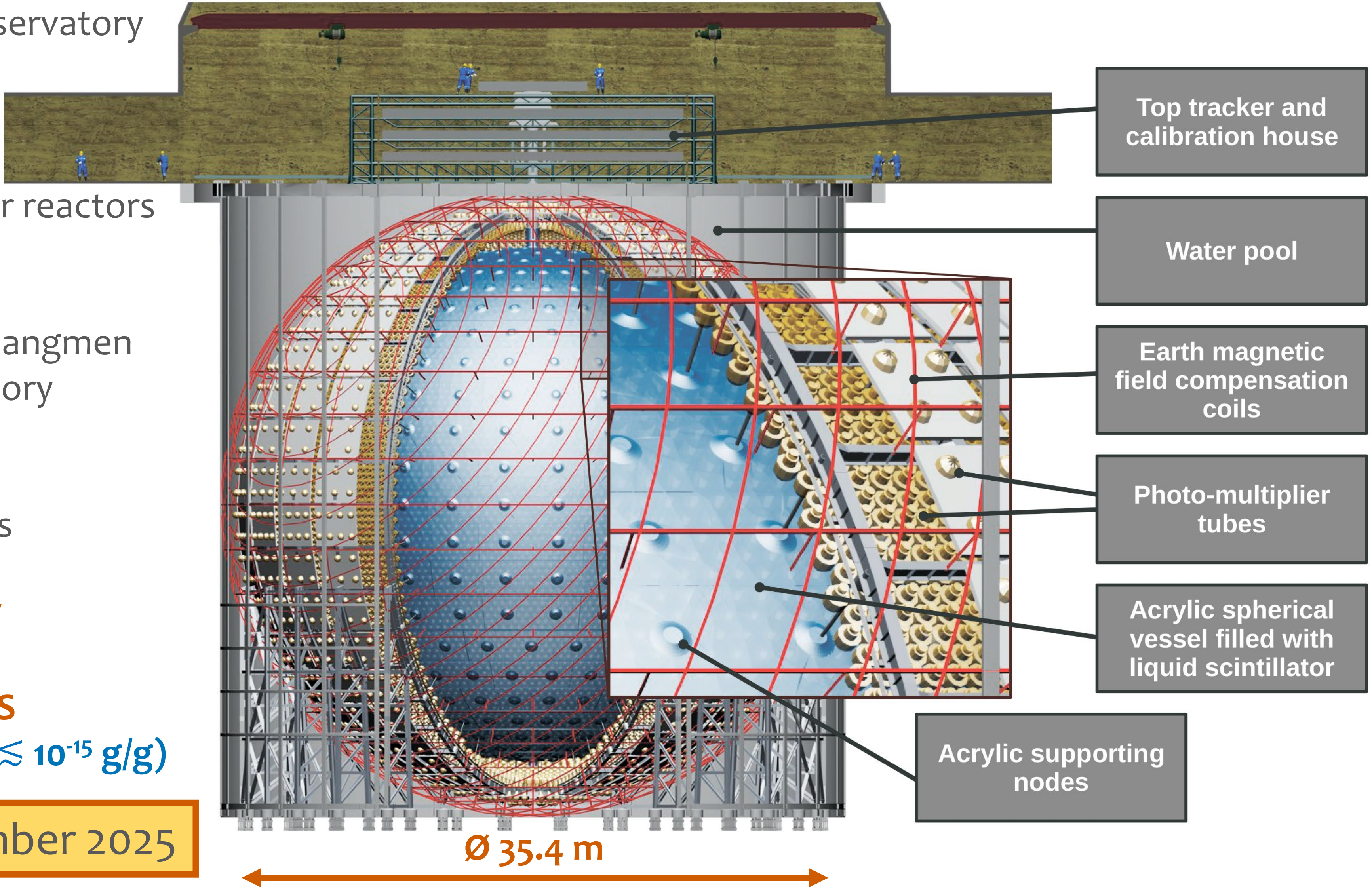
Type: Reactor antineutrino detector

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

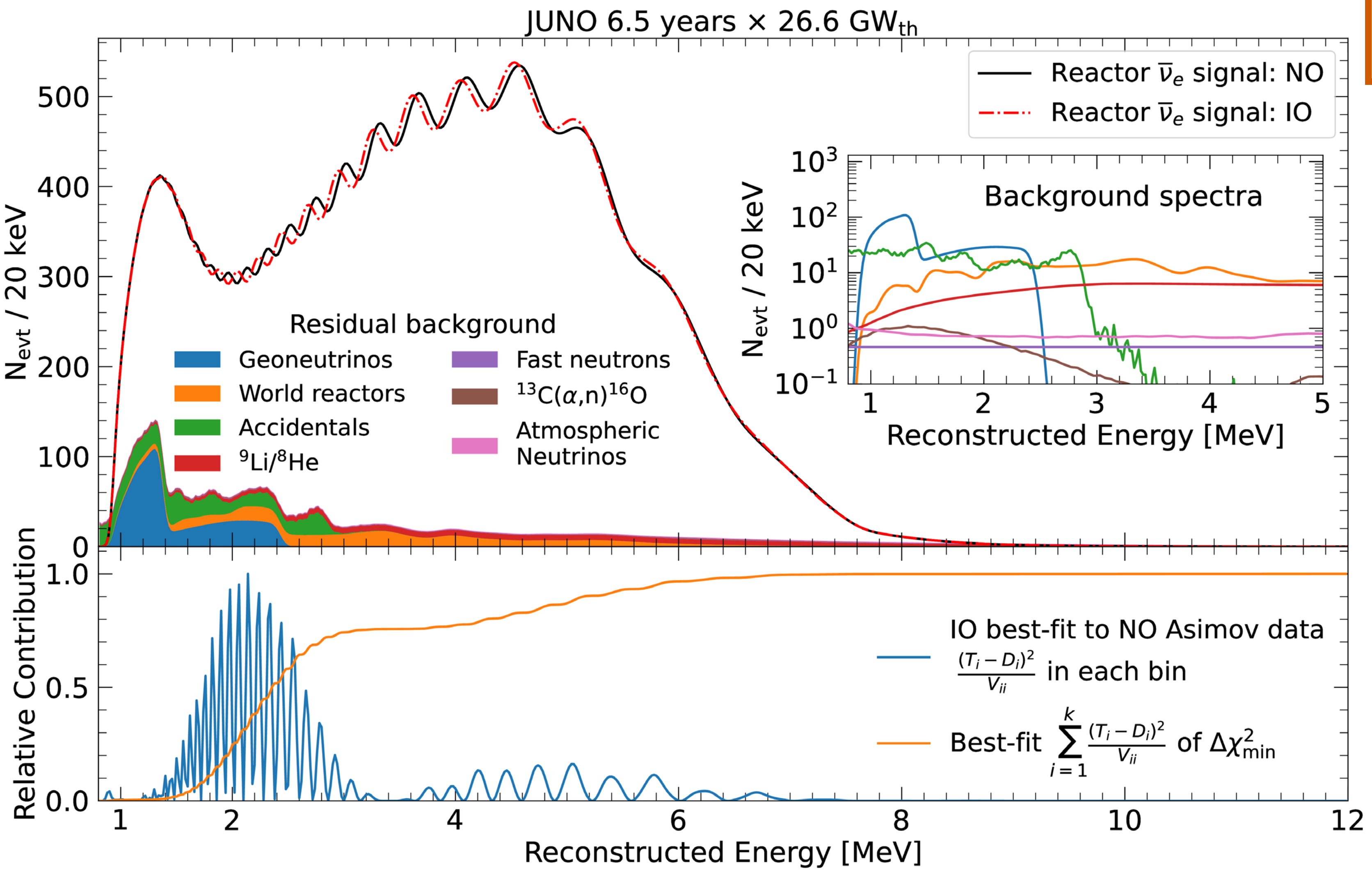
Location: South China, Guangdong, Jiangmen in a **700 m** deep underground laboratory

- **20 kt** of Liquid Scintillator (LS)
- 17612 20” PMTs and 25600 3” PMTs
- PMT optical coverage 78%
- Energy resolution: **$\sigma \lesssim 3\%$ at 1 MeV**
- Energy scale uncertainty: < 1%
- Two subdetectors: **TAO** and **OSIRIS**
- **Good radiopurity expected (Th/U $\lesssim 10^{-15}$ g/g)**

Physical data taking in September 2025



JUNO experiment: physics



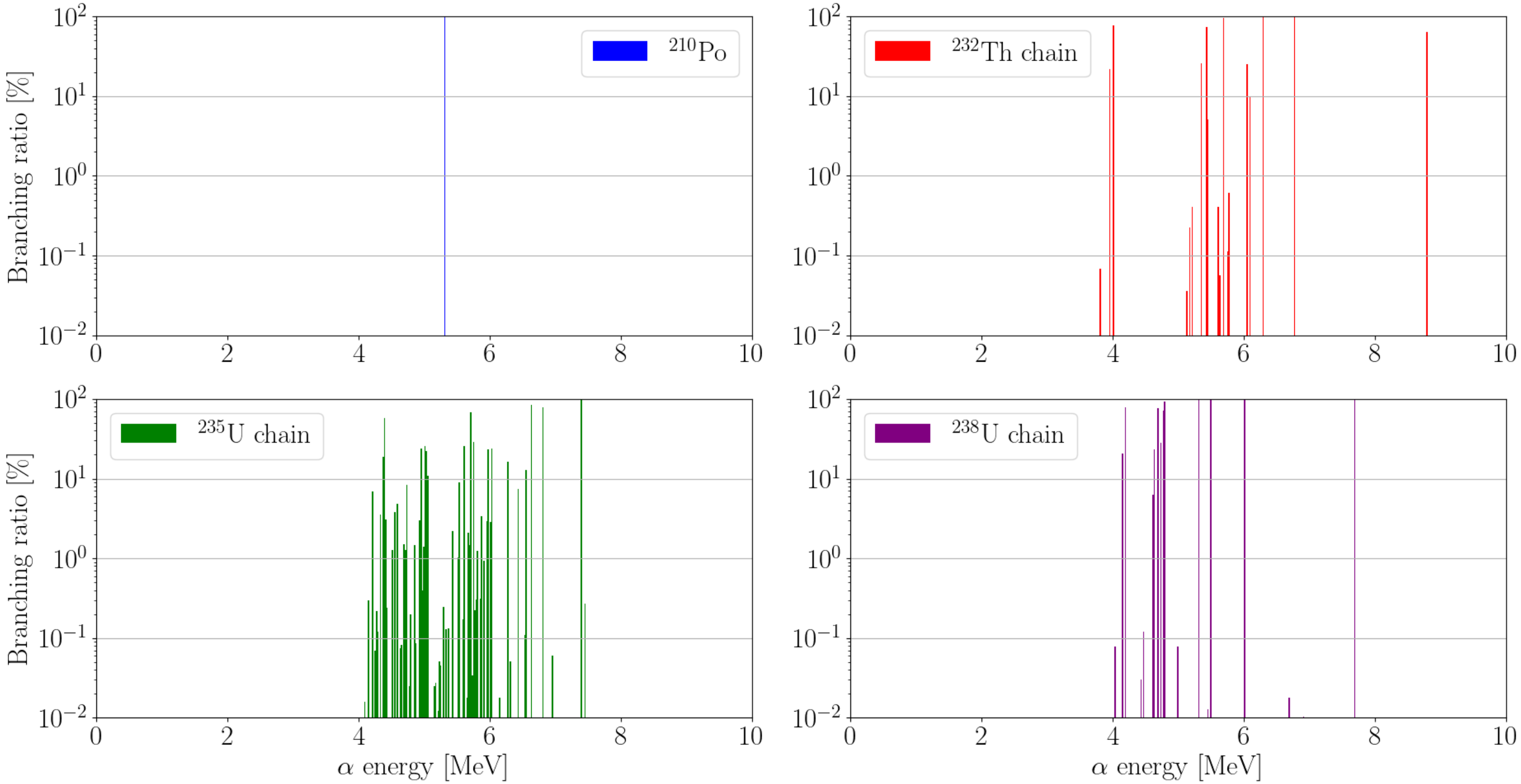
JUNO is
a **multi-purpose** experiment

Rich physics program including

- **Neutrino mass ordering** (NMO) with **3σ in ~7 years** of data-taking
- sub-percent measurements of oscillation parameters: $\sin^2\theta_{12}, \Delta m^2_{21}, \Delta m^2_{31}$
- Accurate determination of geoneutrino fluxes and their use to probe the Earth's properties and evolution
- Solar neutrino flux measurements and (probable) investigation of the metallicity problem

Sources of α particles in JUNO

Negligible contribution of ^{235}U



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

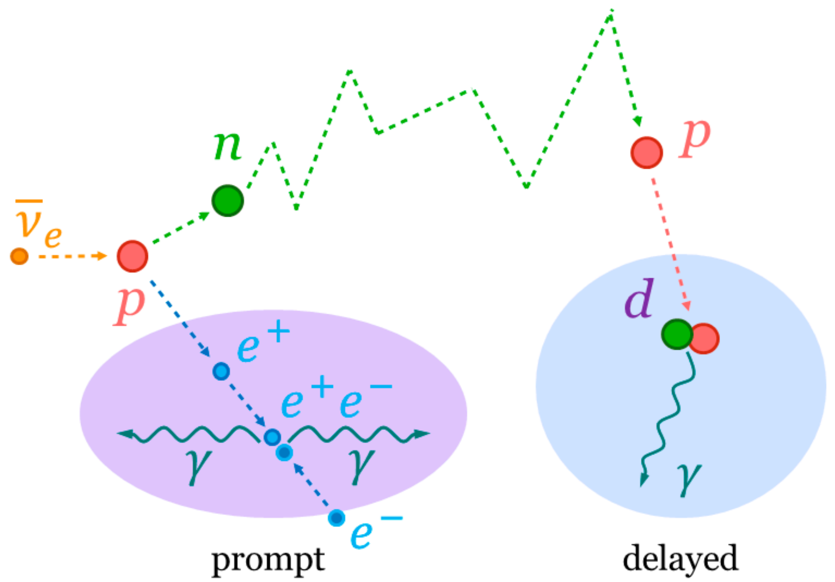
Source	^{238}U	^{232}Th	^{210}Pb	^{210}Po (unsupported)
c [g/g]	10^{-15}	10^{-15}	5×10^{-23}	3×10^{-22}

Note: the **minimal radiopurity** levels requested for the NMO measurement are considered, see *JHEP* **11** (2021) 102

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

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

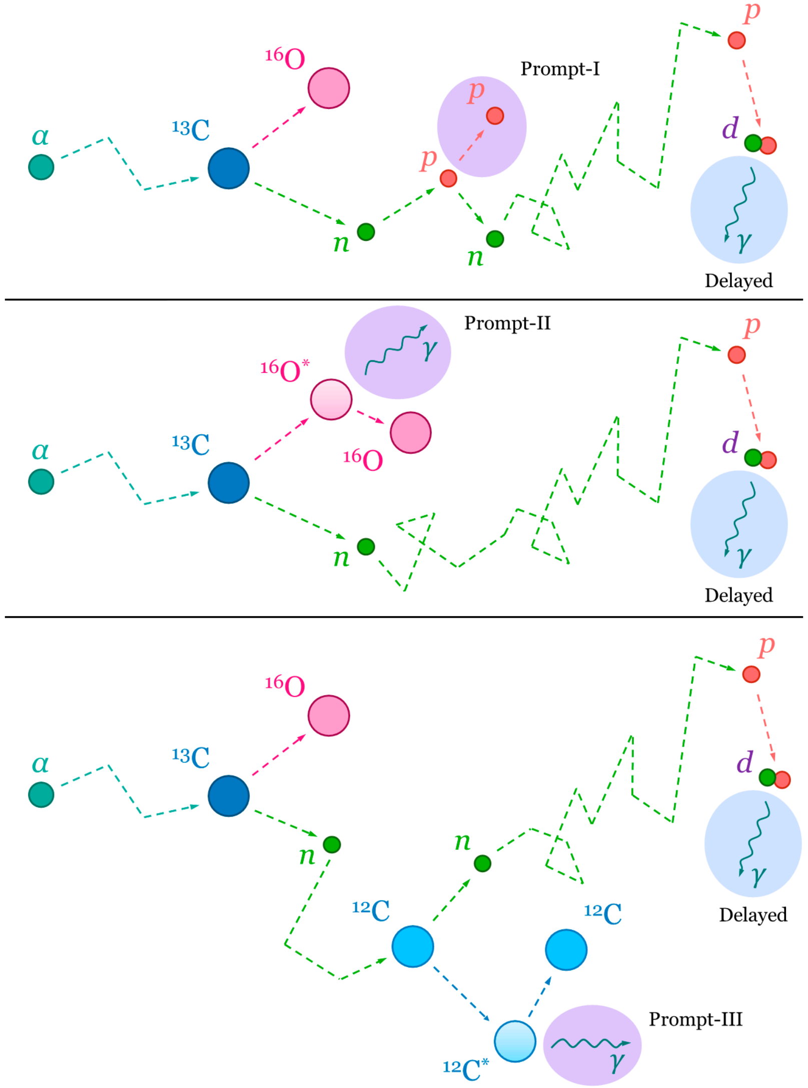
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



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

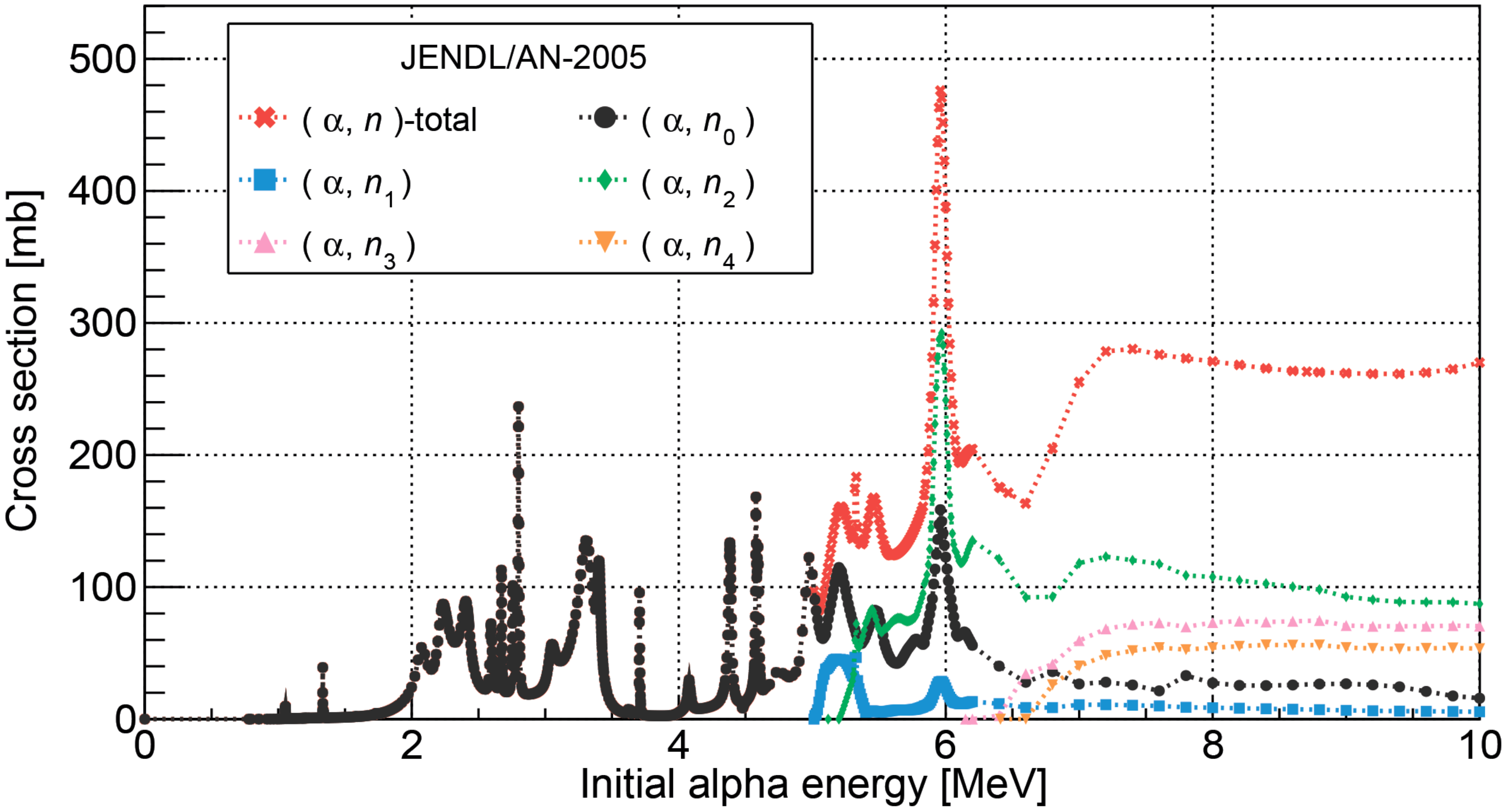
- **Prompt** γs from e^+ ionization and annihilation (1-8 MeV)
- **Delayed** γ from n capture on H (2.2 MeV)

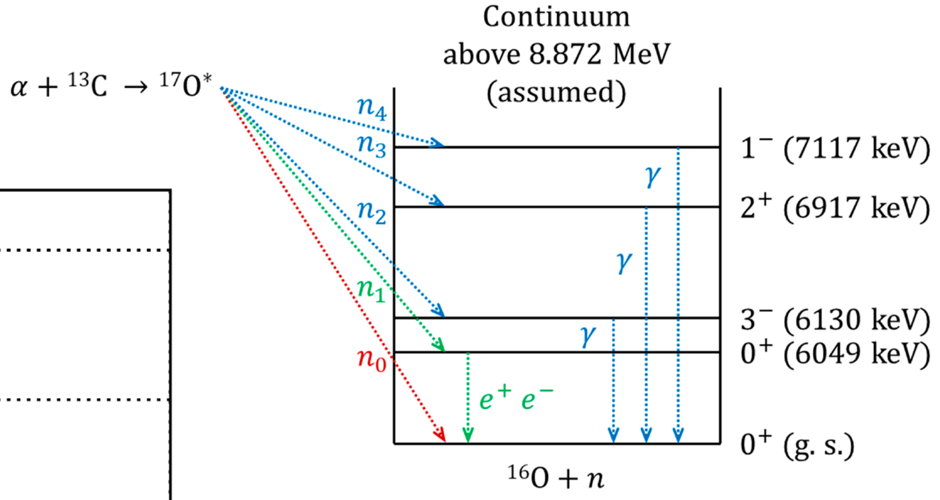
$^{13}C(\alpha, n)^{16}O$ interaction can mimic IBD coincident signals



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

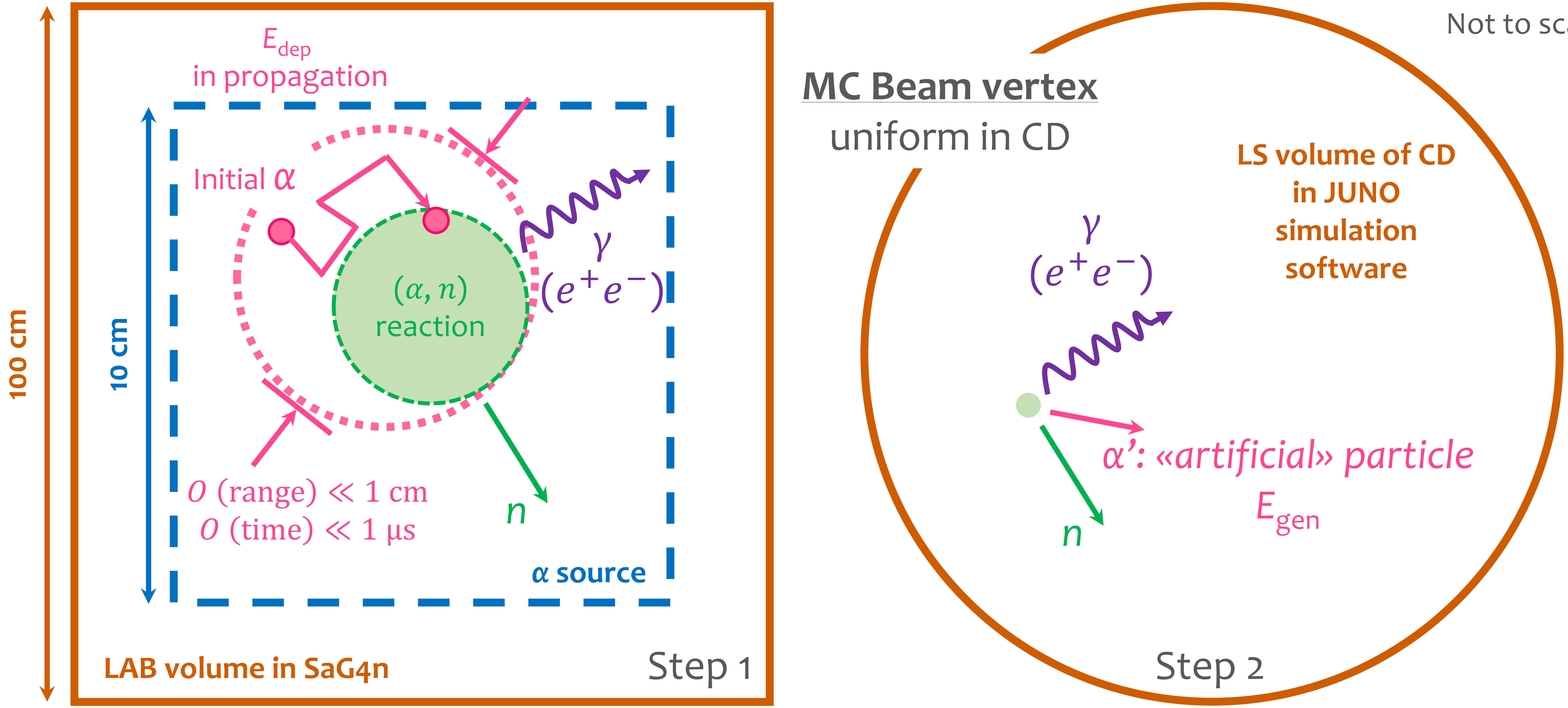
T. Murata, H. Matsunobu, K. Shibata,
Tech. Rep. JAEA-Research 2006-052, JAEA, Japan (2006)





JUNO LAB:
(LAB is the base of the LS)
$C_6H_5C_{14}H_{29}$
~1.1% of ^{13}C in natural carbon

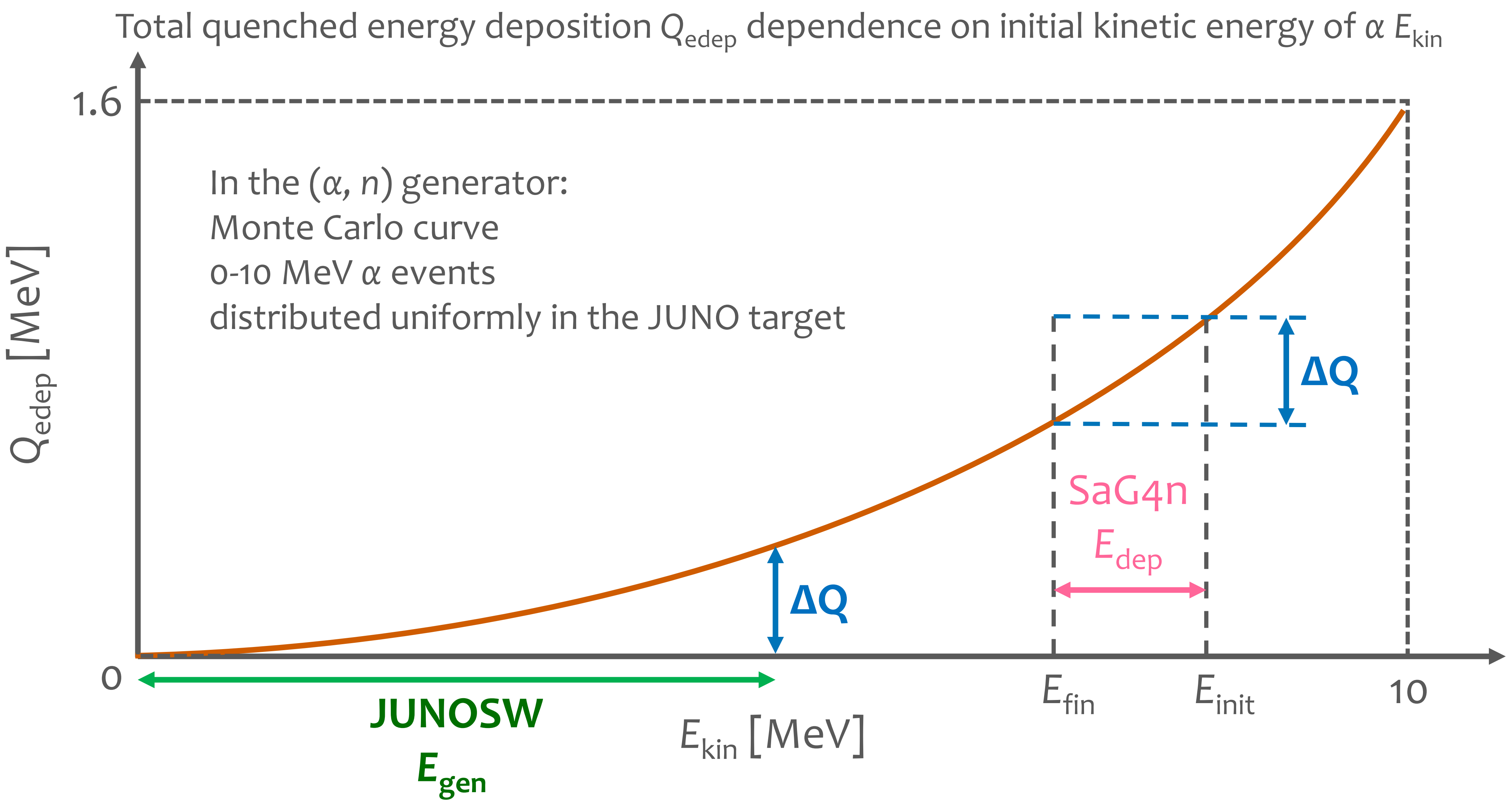
Simulation $^{13}C(\alpha, n)^{16}O$ with SaG4n and JUNOSW



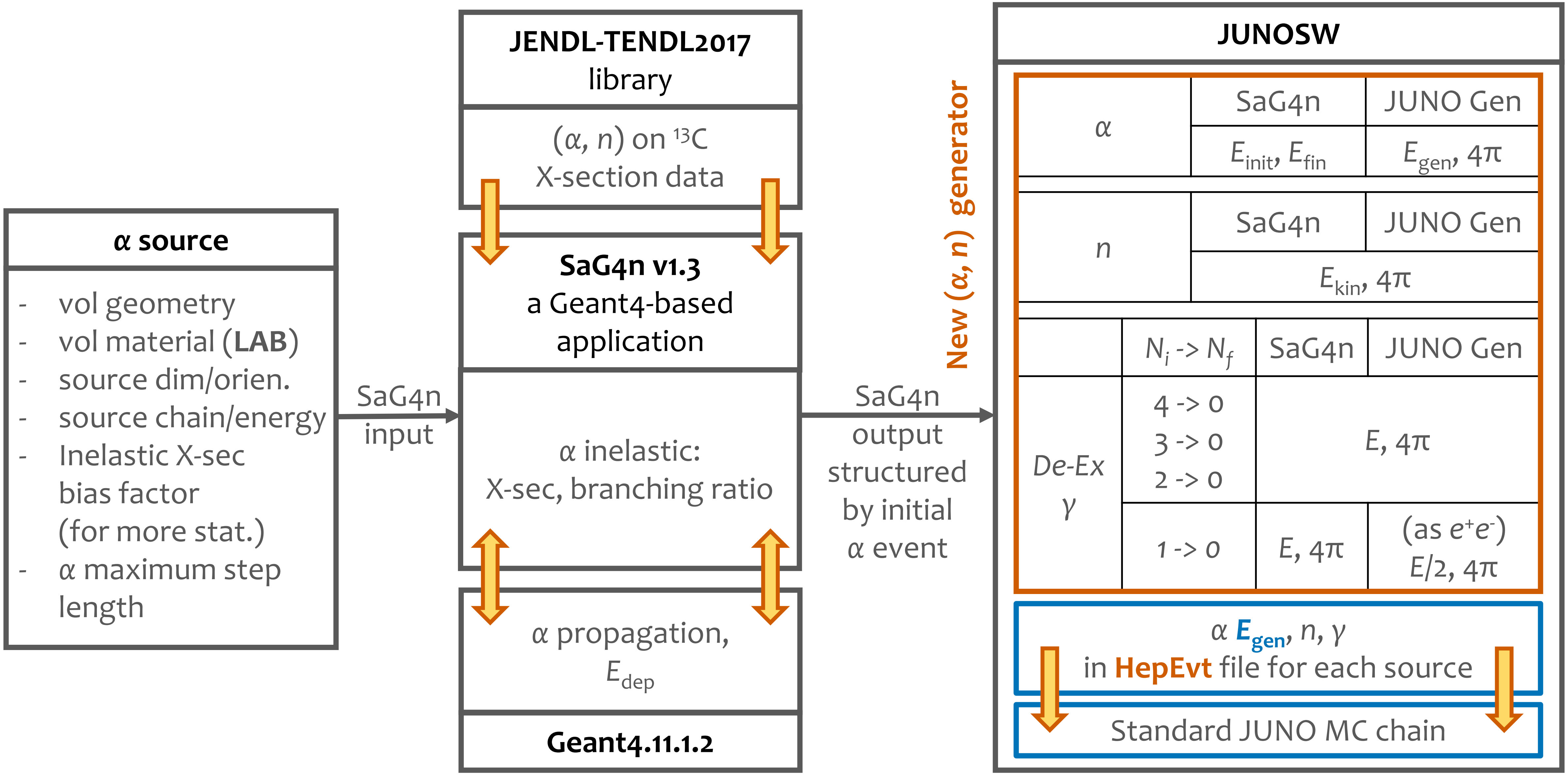
Eur. Phys. J. C **83** (2023) 5, 382, *Eur. Phys. J. C* **83** (2023) 7, 660 (erratum)

For further details about SaG4n see *Nucl. Instrum. Methods Phys. Res. A* **960** (2020) 163659

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

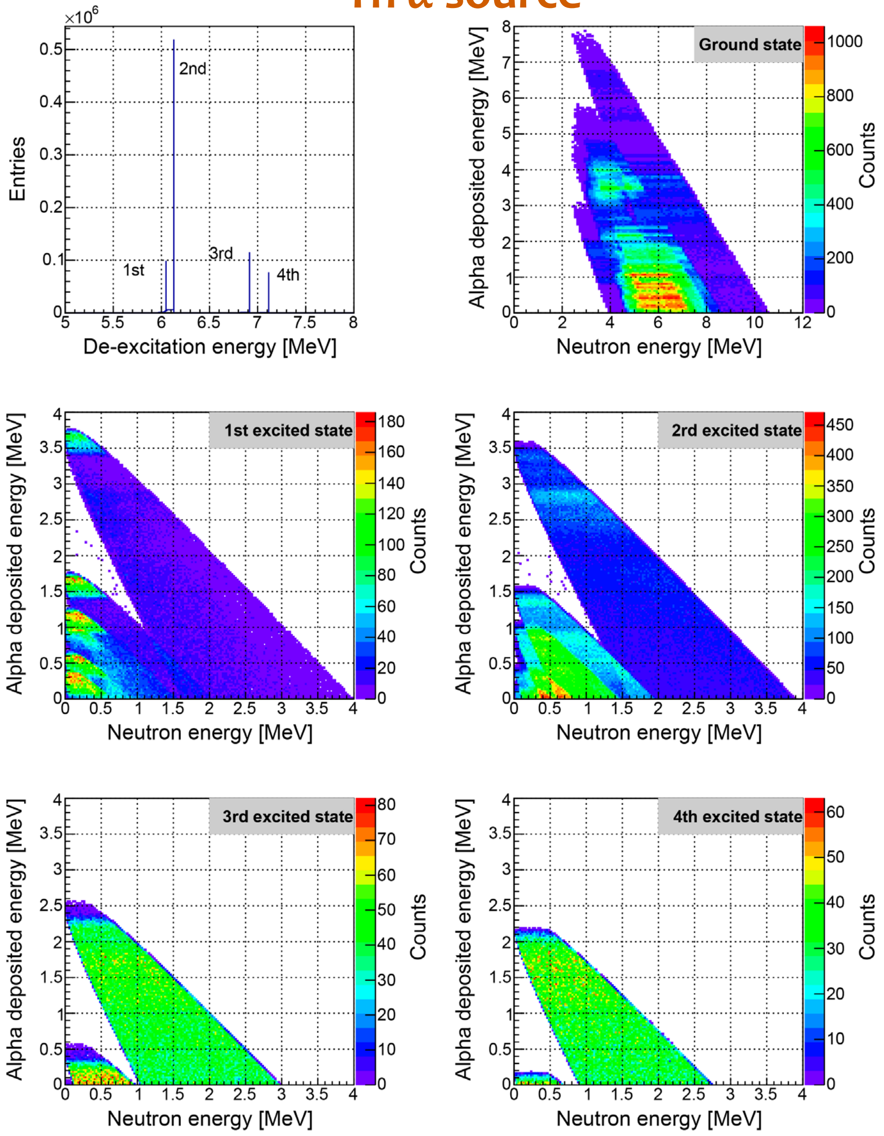


Simulation pipeline



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 coincident cuts for signal IBDs 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_α, assuming secular equilibrium in the decay chain, can be given by

$$R_\alpha \left[\frac{\text{cpd}}{\text{kt}}\right] = c \left[\frac{\text{g}}{\text{g}}\right] \times \frac{N_A \left[\frac{1}{\text{mol}}\right]}{\tau\,[\text{day}] \times M \left[\frac{\text{g}}{\text{mol}}\right]} \times 10^9 \left[\frac{\text{g}}{\text{kt}}\right],$$

where **c** is the assumed 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 **$R^{IBD}_{(\alpha, n)}$** or **$R_{(\alpha, n)}$** (w/ & w/o efficiency) can be calculated as follows

$$R^{\text{IBD}}_{(\alpha,n)}\,[\text{cpd}] = \varepsilon \times R_{(\alpha,n)}\,[\text{cpd}] = \varepsilon \times R_\alpha \left[\frac{\text{cpd}}{\text{kt}}\right] \times Y_n \left[\frac{n}{\text{chain}}\right] \times M_{\text{LS}}[\text{kt}],$$

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

In particular, for **unsupported ^{210}Po**, the rate in JUNO is **scaled** from Borexino under the assumption ^{210}Po will be stripped from the acrylic surface during LS filling

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) 1, 012009)

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

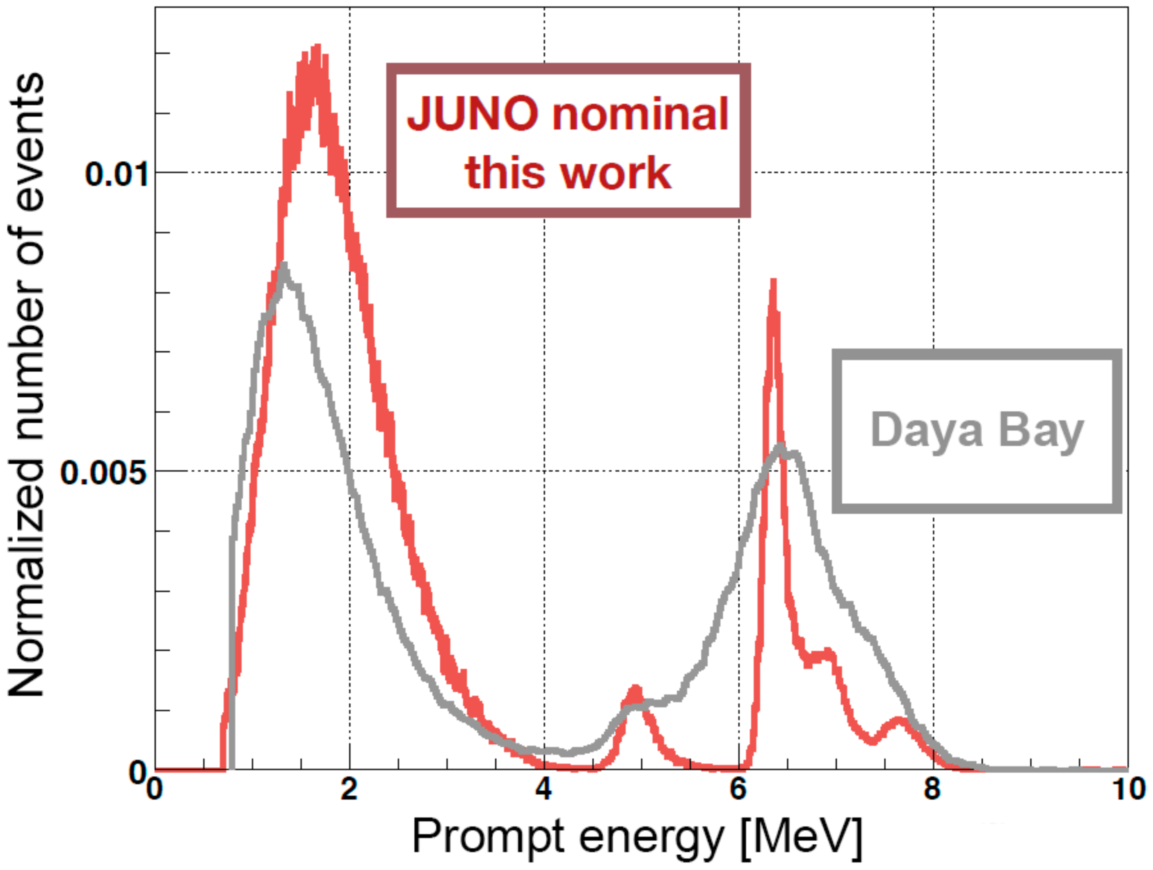
Source	Y_n [n/chain] neutron yield	c [g/g] assumed concentration	R_α [cpd/kt]	$R_{(\alpha, n)}$ [cpd] rate 20 kt LS	IBD selection efficiency	$R^{IBD}_{(\alpha, n)}$ [cpd] IBD-like rate after cuts
^{238}U	6.36×10^{-7}	10^{-15}	1068	0.013	0.84	0.011
^{232}Th	8.58×10^{-7}	10^{-15}	352	0.006	0.84	0.005
$^{210}Pb/^{210}Po$	5.11×10^{-8}	5×10^{-23}	12265	0.012	0.87	0.011
^{210}Po unsupported	5.11×10^{-8}	3×10^{-22}	70400	0.071	0.87	0.063

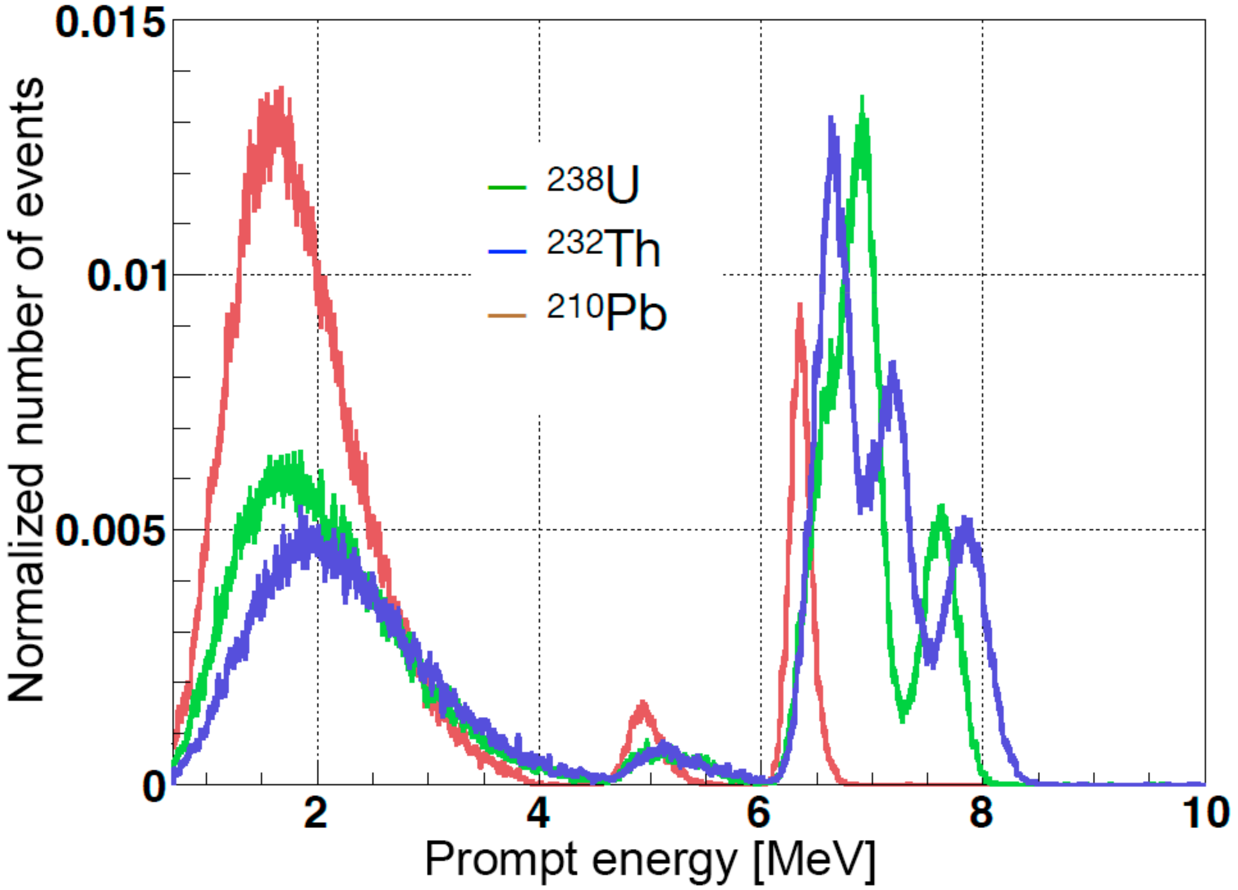
"cpd" stands for counts per day

0.090 total

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

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





Event rate systematic uncertainties

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%**

Conservatively neglect possible correlations among different sources

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 for the calculation;
  - a new Monte Carlo generator which uses the output of SaG4n and creates HepEvt files for the detector simulation;
  - a new approach to account for α energy deposition before the (α, n) reaction
  - 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%
- **Negligible impact on the JUNO's sensitivity to neutrino mass ordering (Th/U $\lesssim 10^{-15}$ g/g, ^{210}Po $\sim 10^{-22}$ g/g)**

The results can be applied in further antineutrino studies in the JUNO experiment and are useful for any general liquid scintillator antineutrino detector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See the article at
arXiv:2503.00968
Thank you
for your attention!