

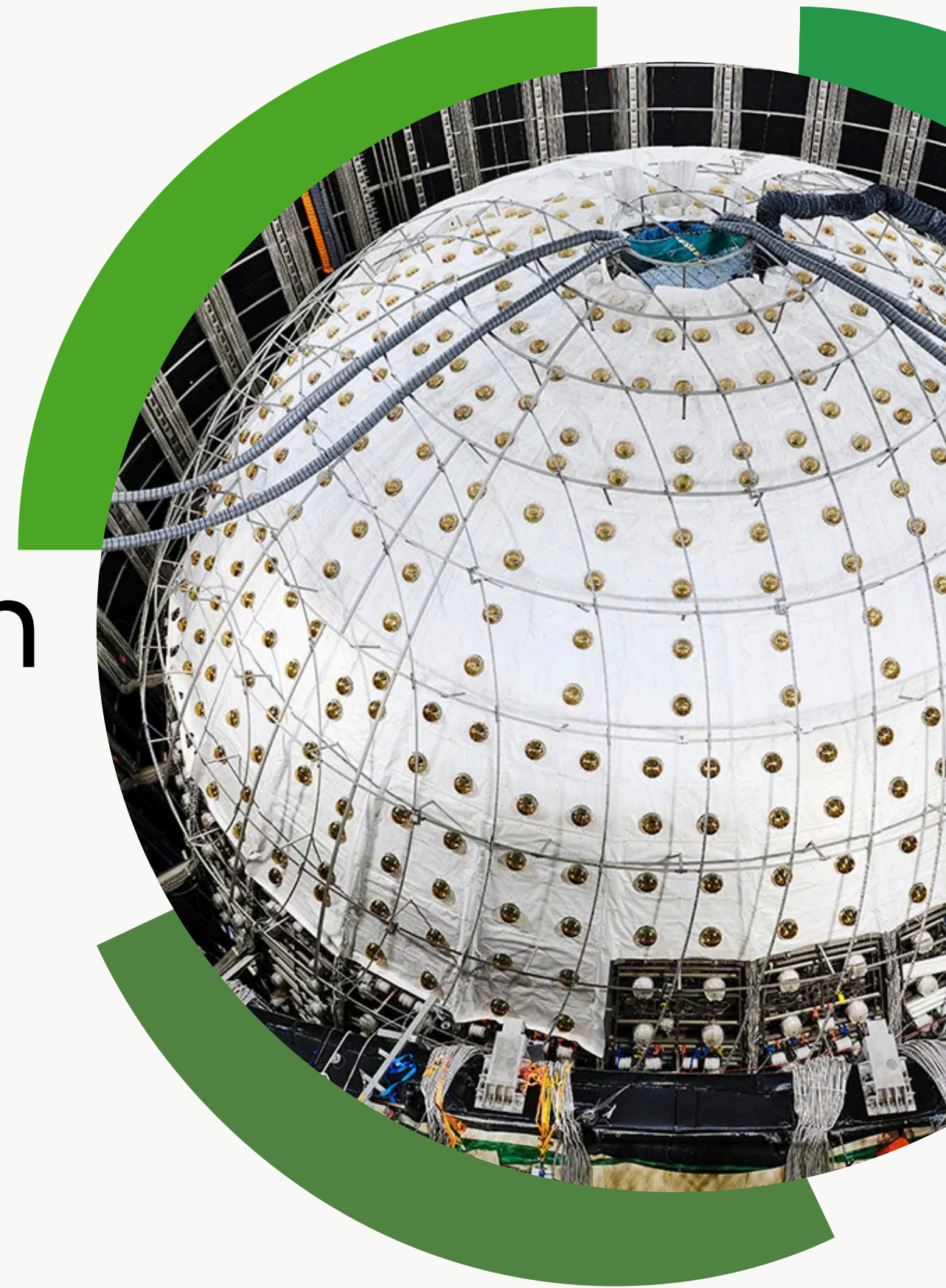


Jonas Buchholz

Heures thésards

Timing and Energy calibration of SPMT system in JUNO for CCSN detection

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"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do."

Wolfgang Pauli



Plan

1. Neutrino physics and open question

2. JUNO purposes and status

3. My Work :

- SPMT Performances and Calibration
- Supernova detection



Neutrino ID card

- **Second most abundant particle in the universe.**
- **3 neutrino flavors** that interact only through the weak and the gravitational forces.

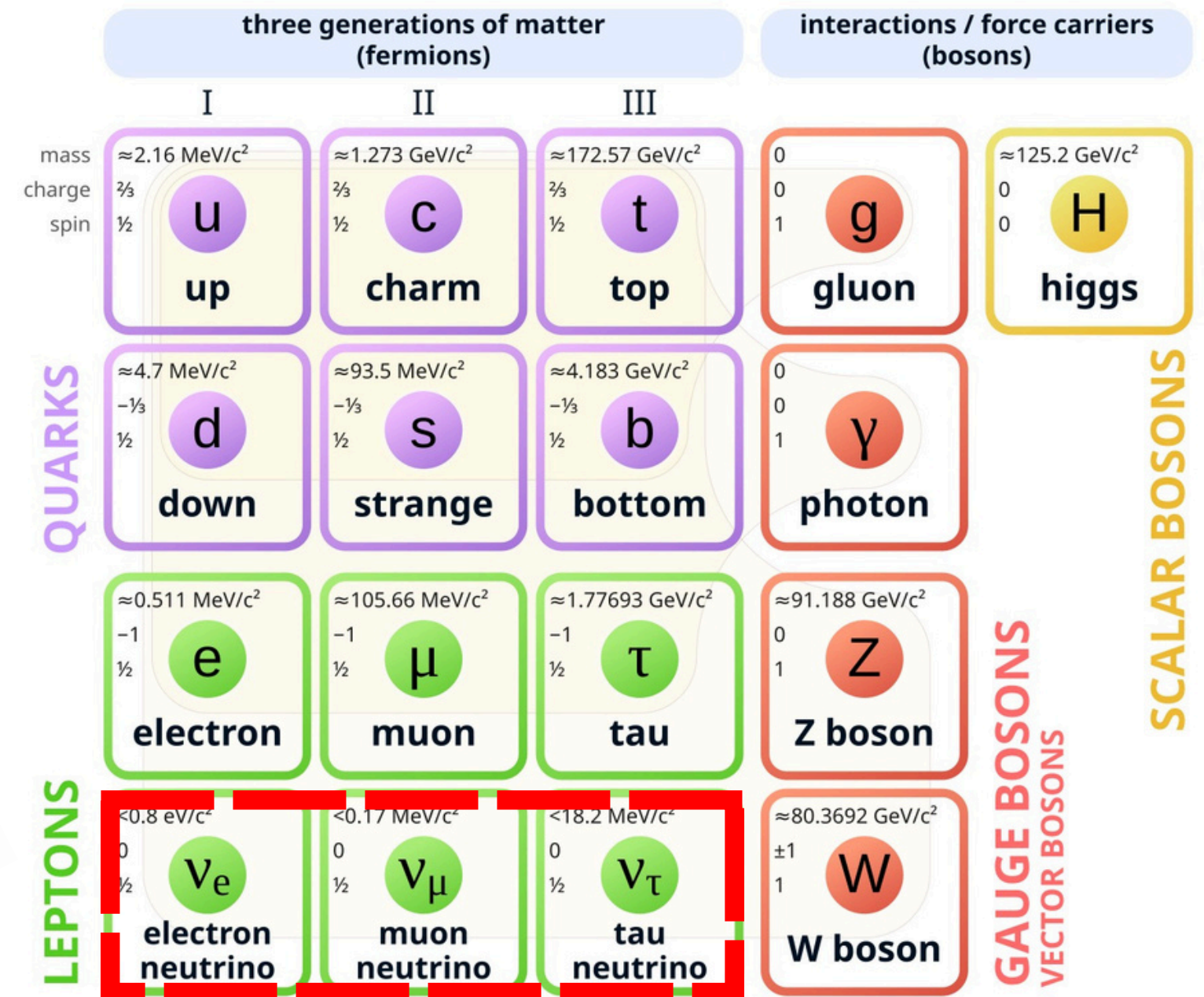
$$\frac{\sigma_\gamma}{\sigma_\nu} \sim 10^{20}$$

- **Extremely light** < 0.45 eV (KATRIN 2025).
- **Low interaction rate**
 → direct access to primary information of neutrino sources.
 → unique messenger for astrophysical sources

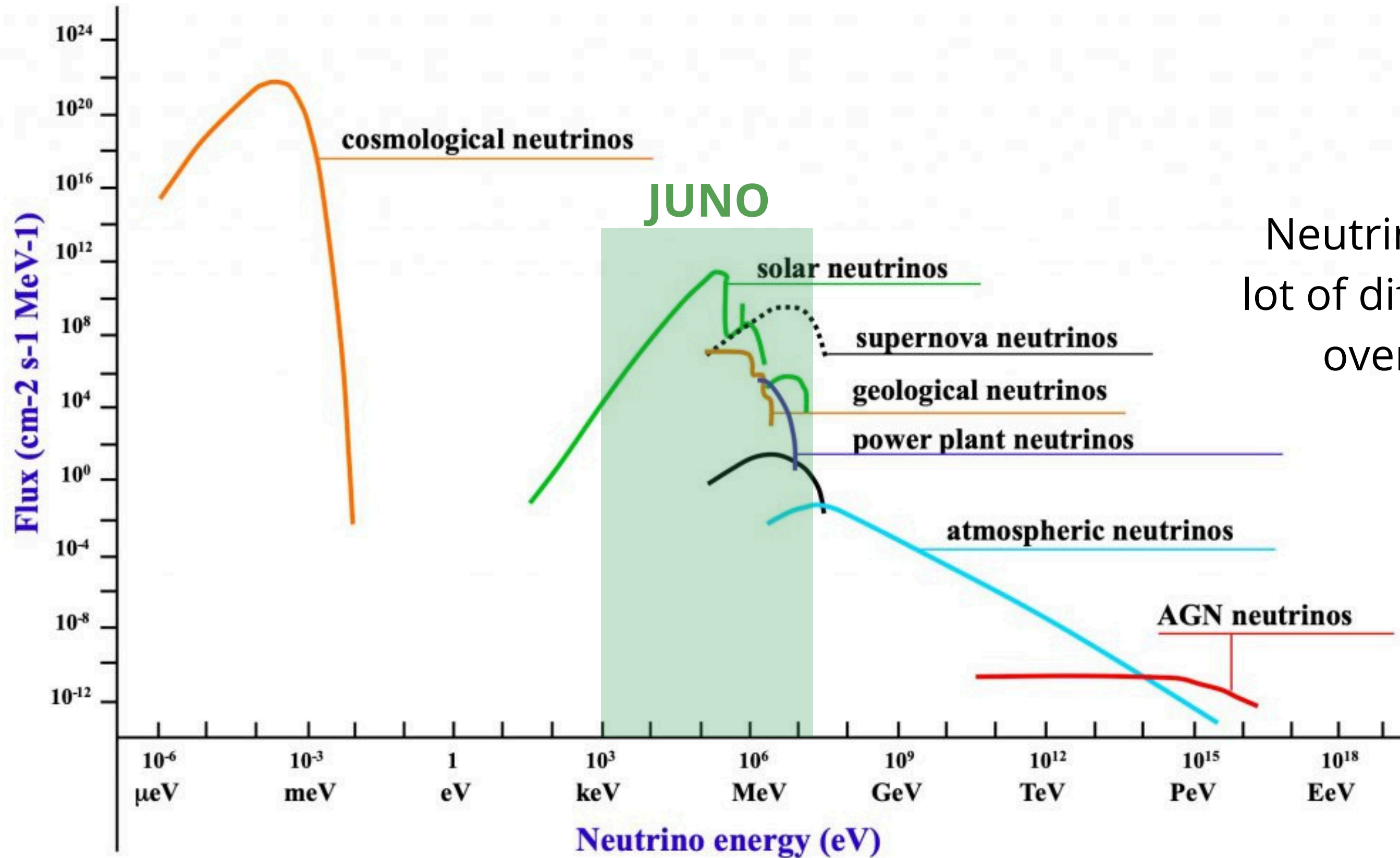
- **Neutrinos** can change flavor as they travel.



Standard Model of Elementary Particles

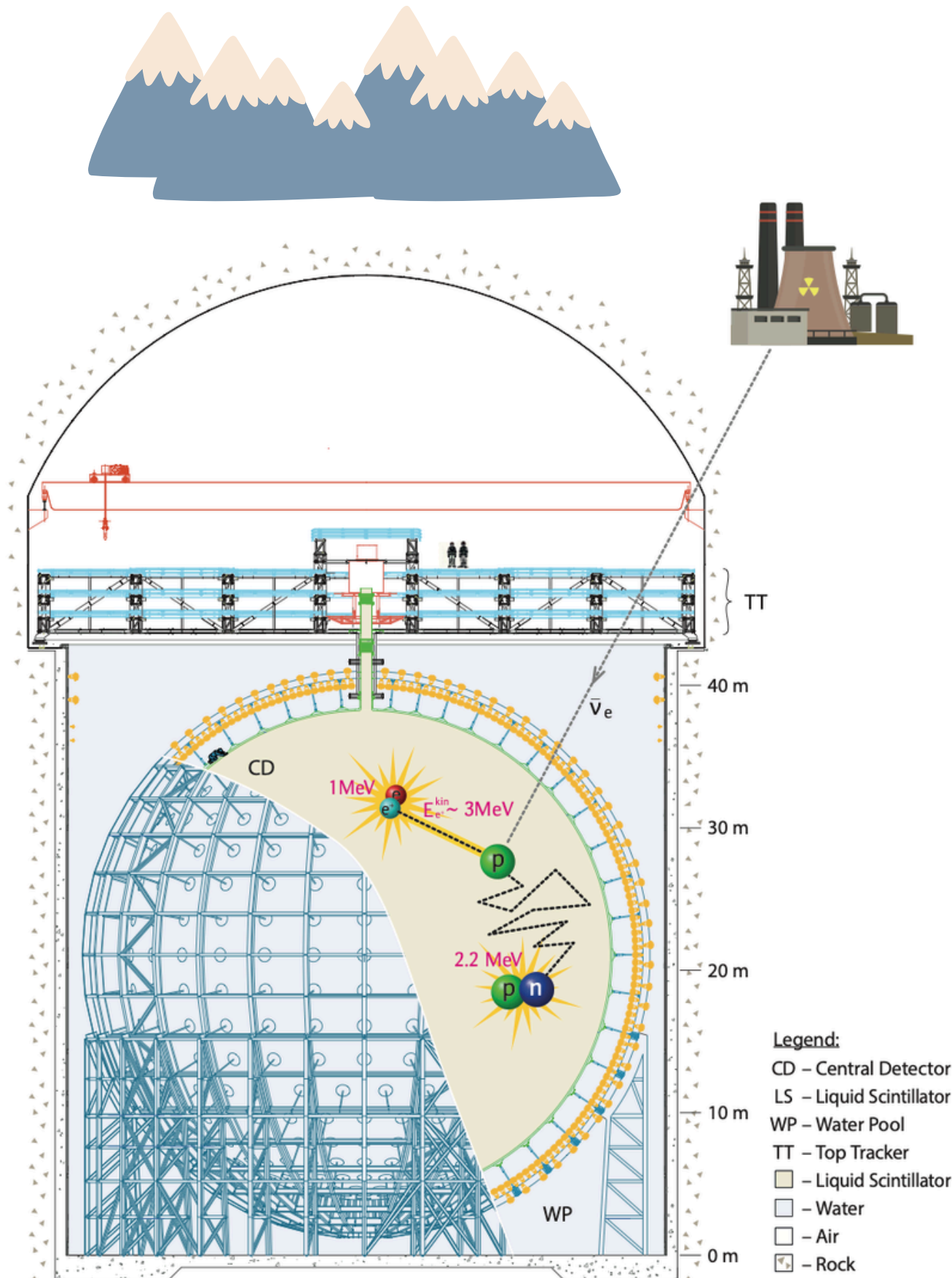


Neutrino sources

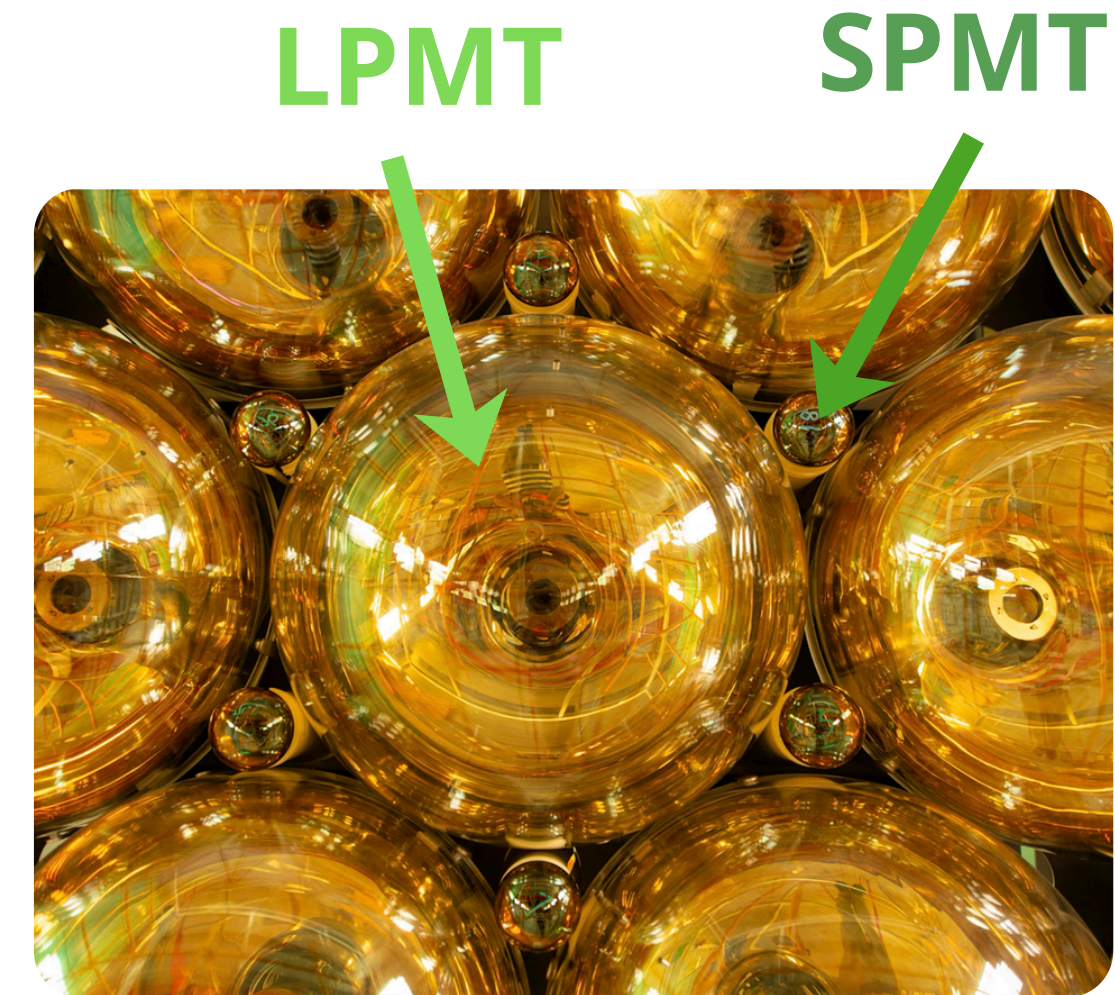
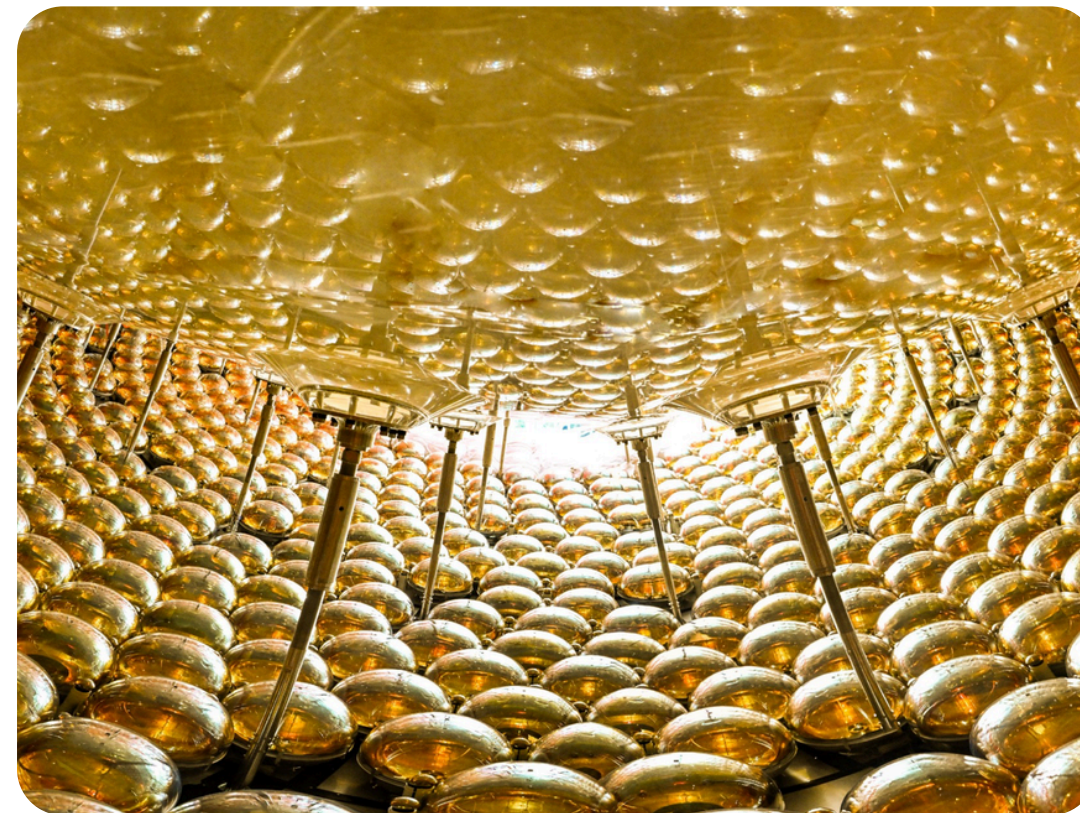


Neutrinos are created in lot of different sources and over a large energy spectrum !

JUNO detector

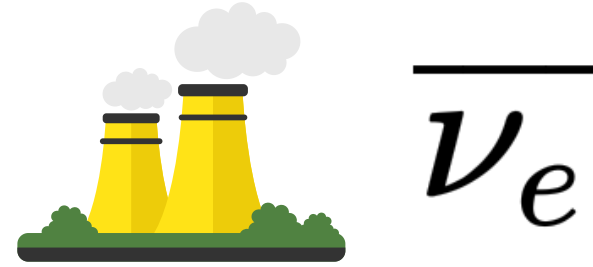


- 700 m underground to mitigate cosmic rays background.
- **20 kt**ons of **liquid scintillator** within a **17.7-m**-radius acrylic vessel
- Located **53 km** from two nuclear power plants in southern China.
- 2 photodetection systems: **25,600 Small Photomultipliers (SPMTs)** with a diameter of 3" and **17,200 Large Photomultipliers (LPMTs)** with a diameter of 20".
- Muon Veto: Water Pool and Top Tracker



JUNO scientific goals

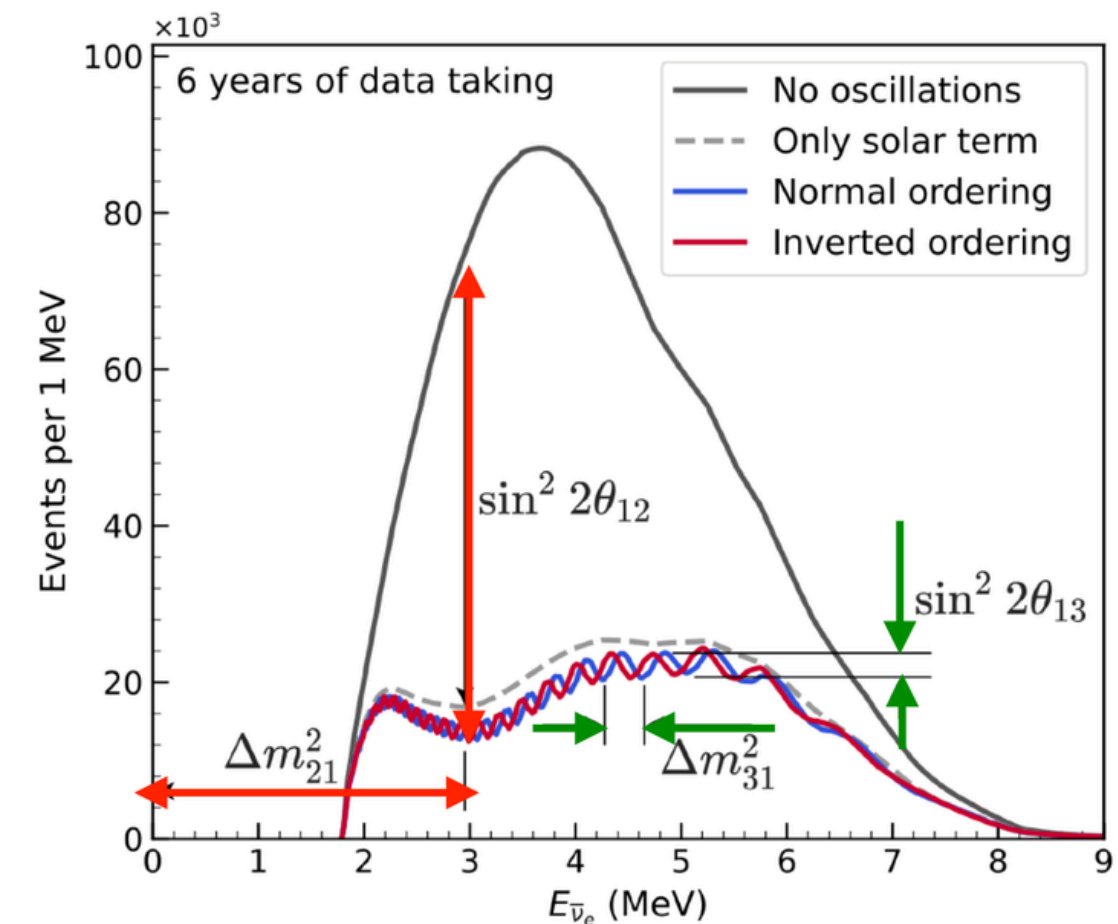
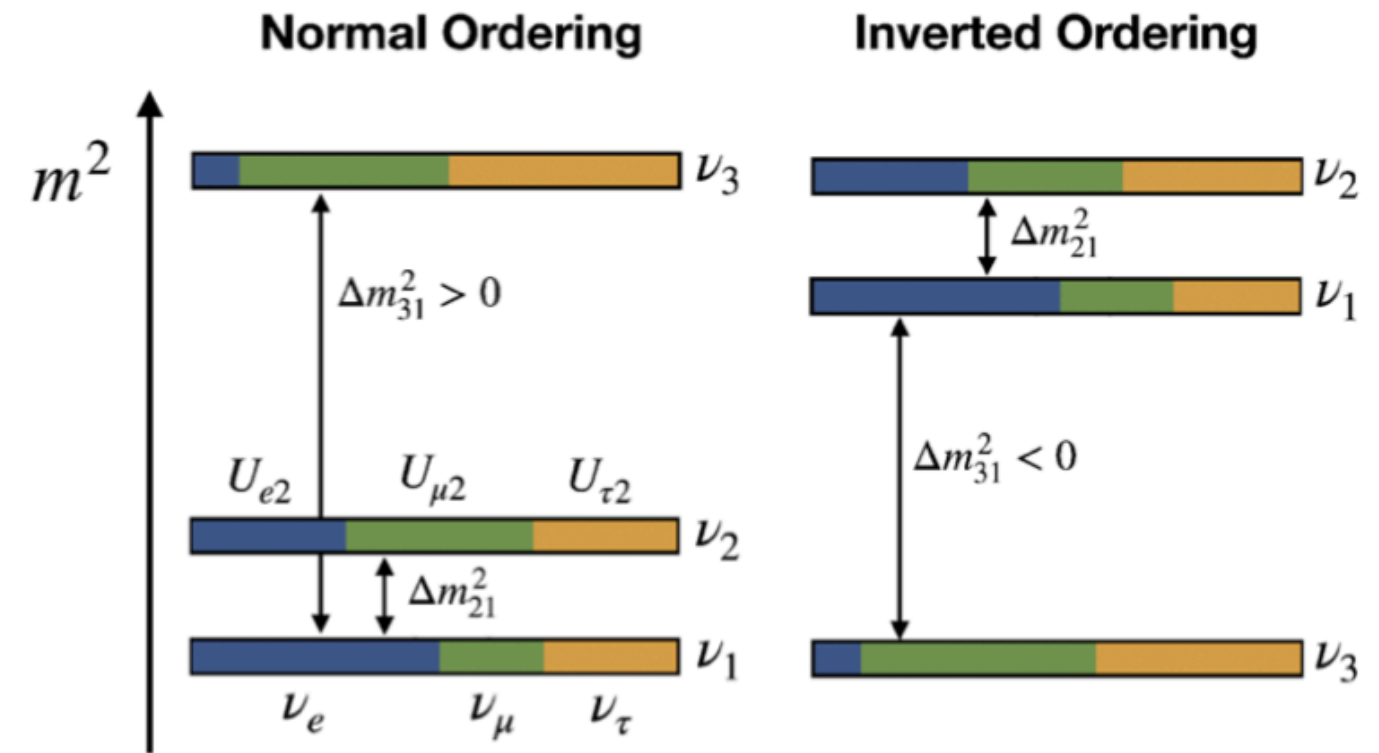
Reactor neutrinos



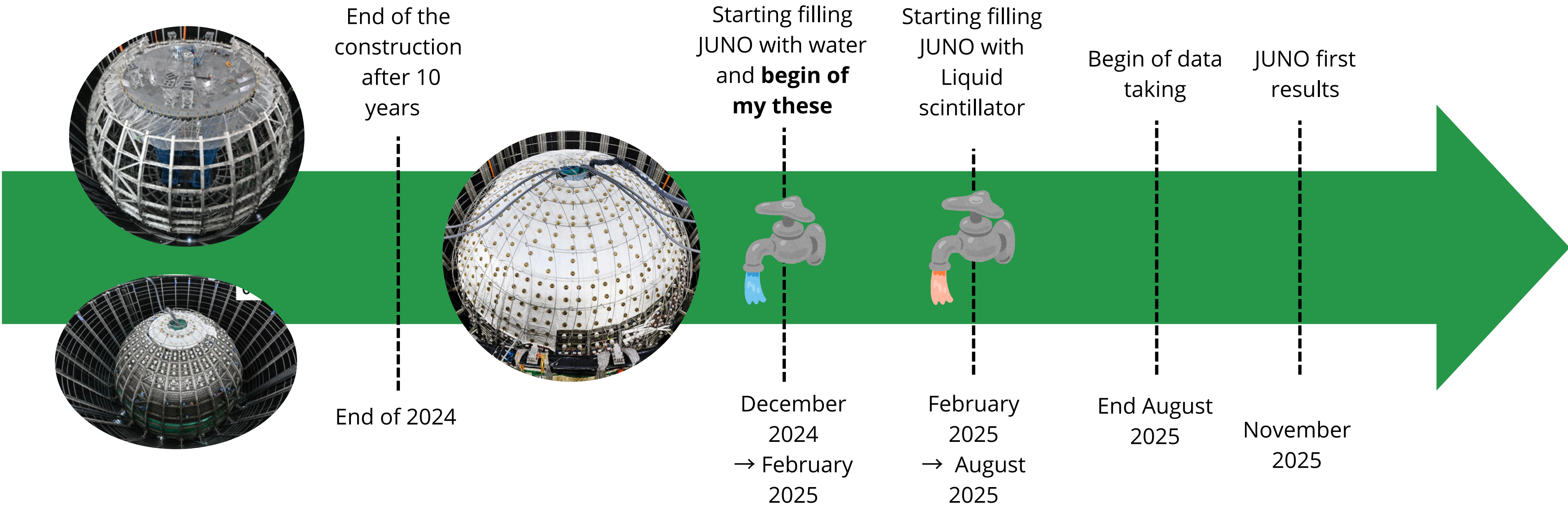
- Main goal: **Neutrino mass-ordering**
- $m_1 < m_2 < m_3$ or $m_3 < m_1 < m_2$?
- **Precision measurement of oscillation parameters** (x10 improvement).

→ Helps to measure δ_{CP} and Majorana neutrino experiment

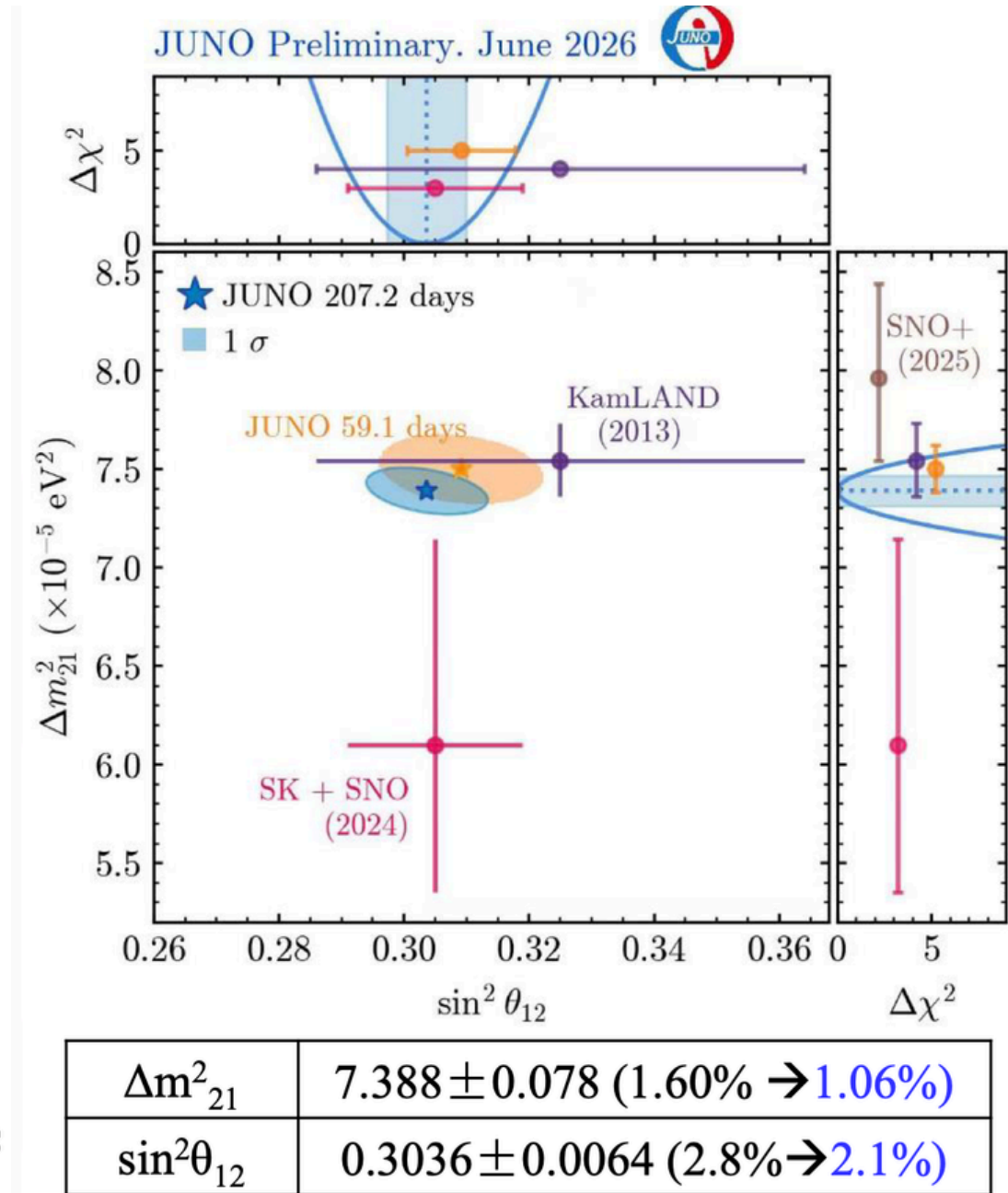
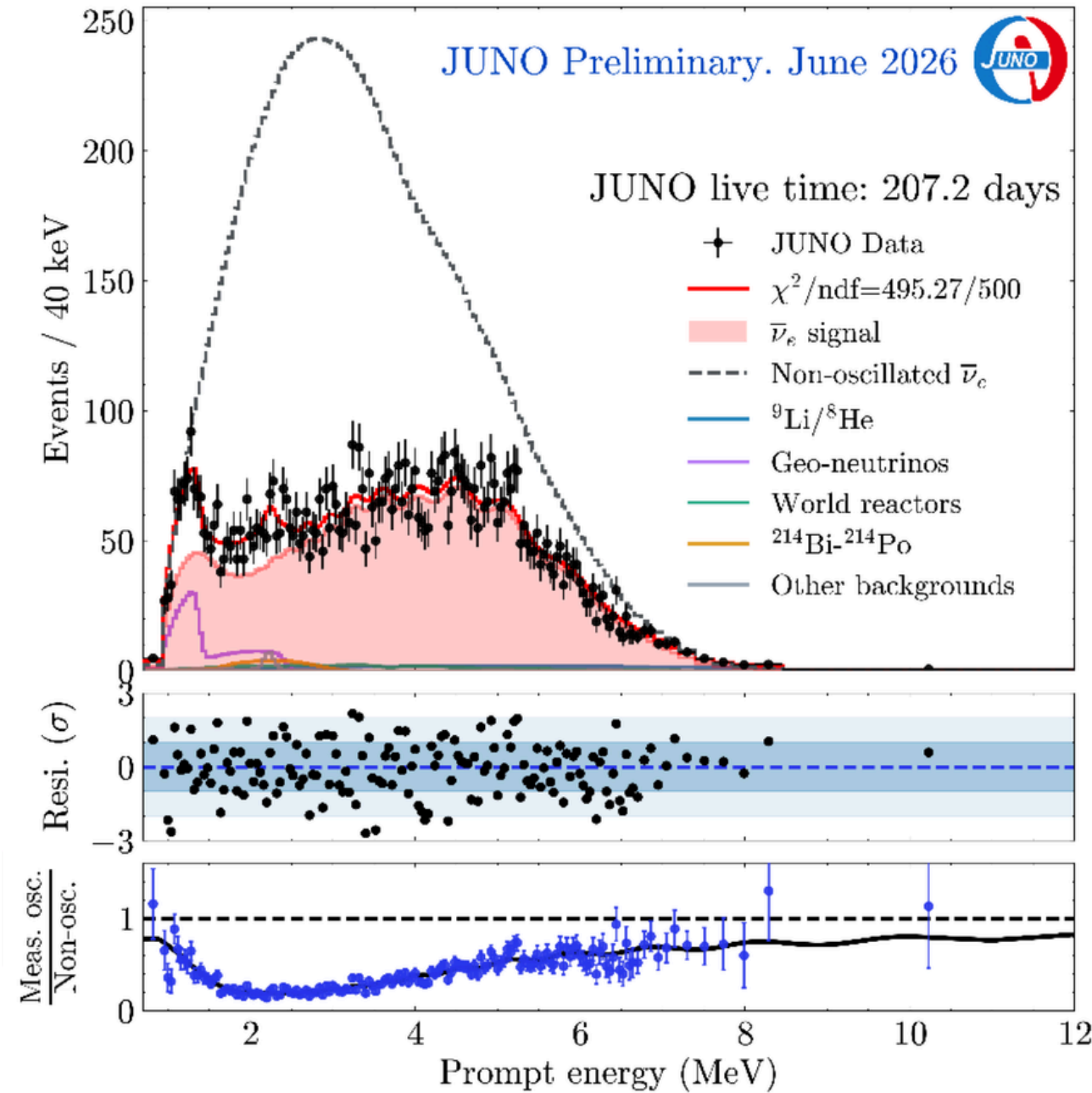
- Other topics :
 - **Supernova neutrinos.**
 - Solar and atmospheric neutrinos.
 - Diffuse Supernova Neutrino Background.
 - Geoneutrinos.
 - ...



Timeline in the past few years



JUNO first results (Nov 2025) and updates



World leading measurement of $\sin^2 \theta_{12} = 0.3036 \pm 0.0064$
and $\Delta m_{21}^2 = (7.388 \pm 0.078)$!

\rightarrow Same measurement using SPMT system in the future ?

My work

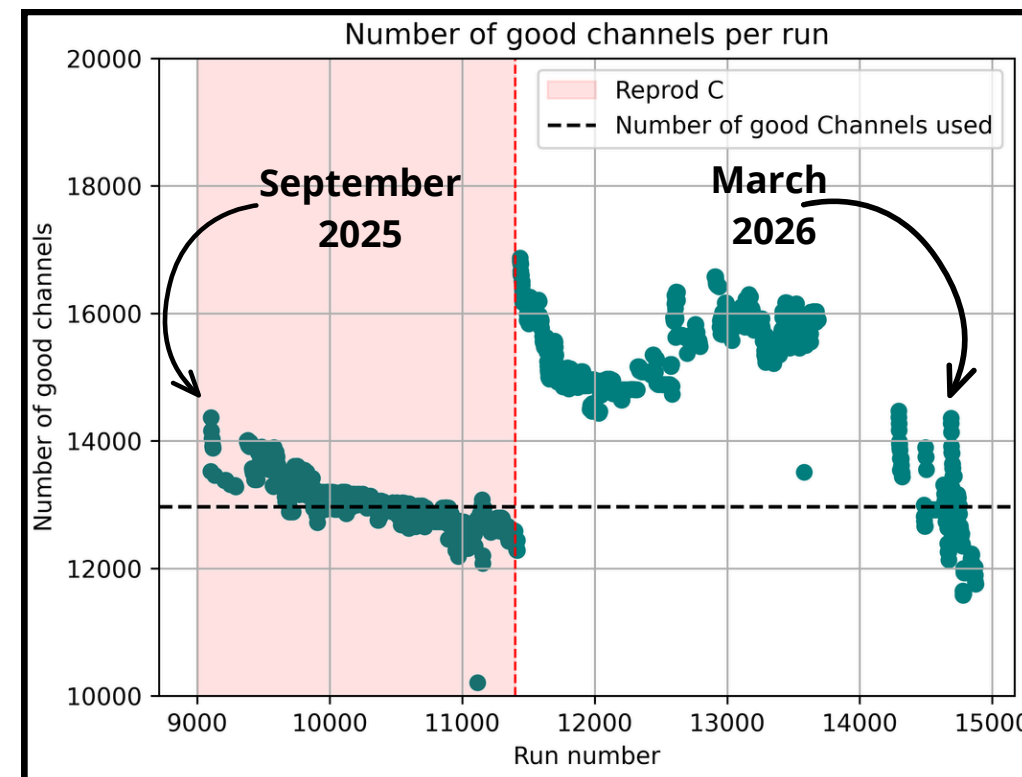
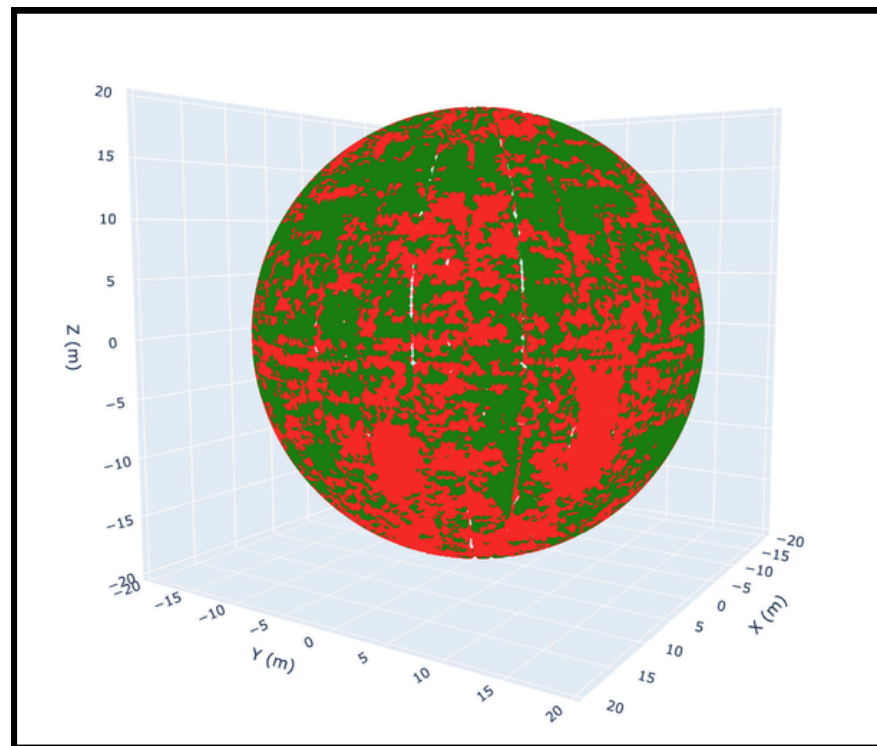
1. SPMT system
2. Timing synchronization :
3. Energy calibration :
 - a. Liquid scintillator non-linearity
 - b. Non-uniformity measurement
 - c. Calibration with cosmogenic secondaries
 - d. Supernova detection : first steps

SPMT system

System's characteristics :

- Operate in single photon-counting mode (**1 hit = 1 PE**)
→ help to calibrate LPMT instrumental non-linearity.
- Very good Time Transit Spread (TTS) of 1.6 ns.

System's status :



- During water filling, a degassing issue in the connector between SPMTs and electronics card implied instable High Voltage Power and dropped the number of “usable” SPMTs to ~13000.
- The loss of SPMTs was **not uniform** → mostly in the south hemisphere.
- Efforts from JUNO's SPMT team done to identify the problem and for the gradual SPMT recovery, has been introduced.

Time synchronization

- Laser calibration measurements were taken at the center of the detector.

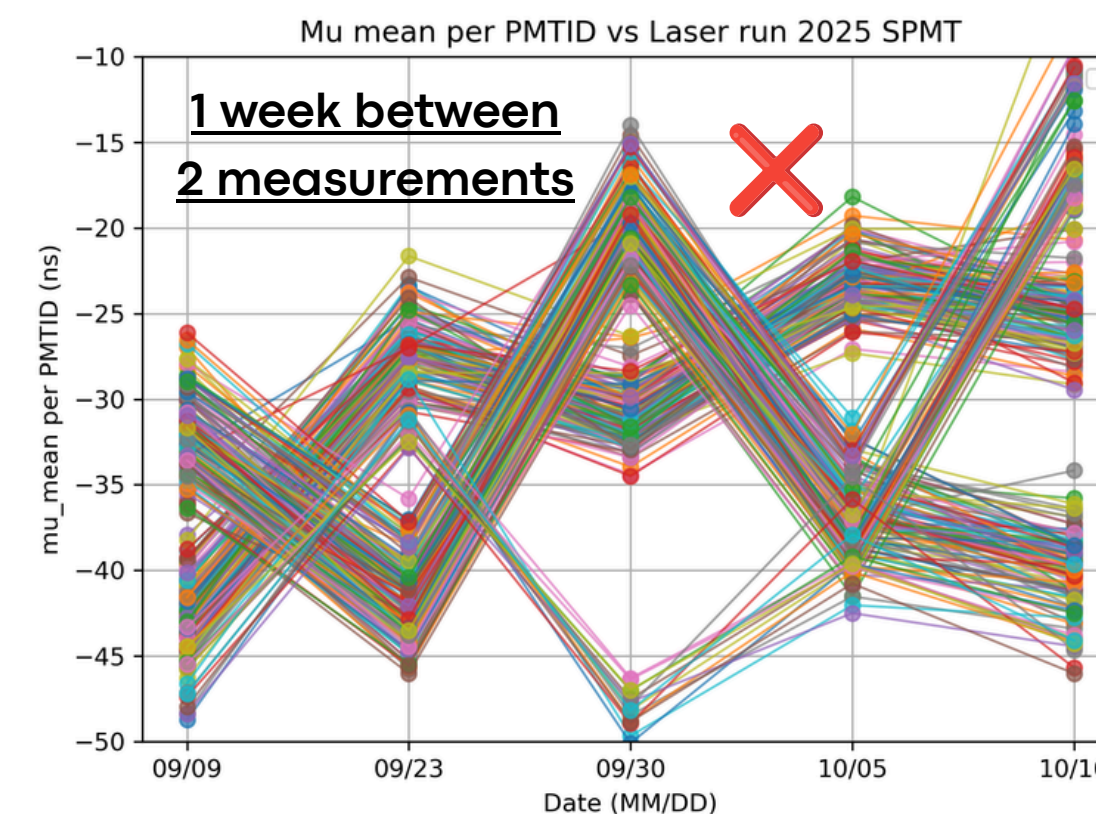
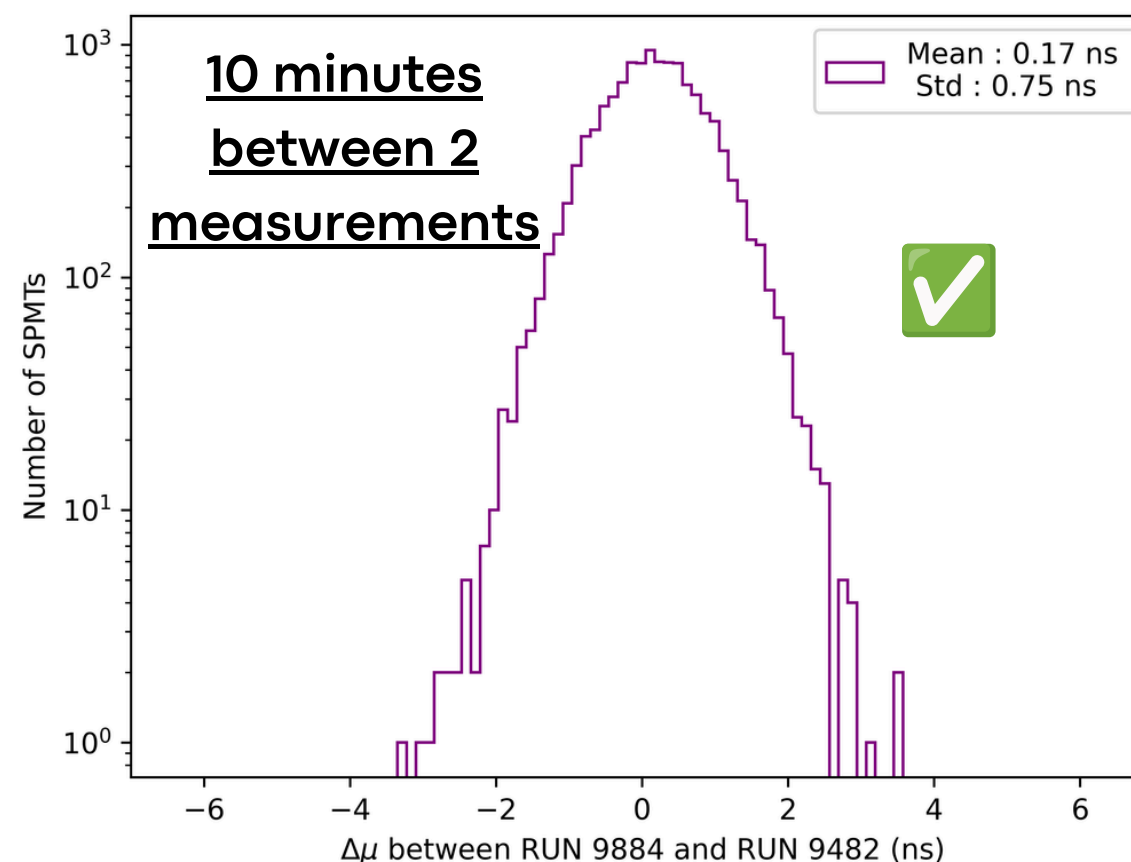
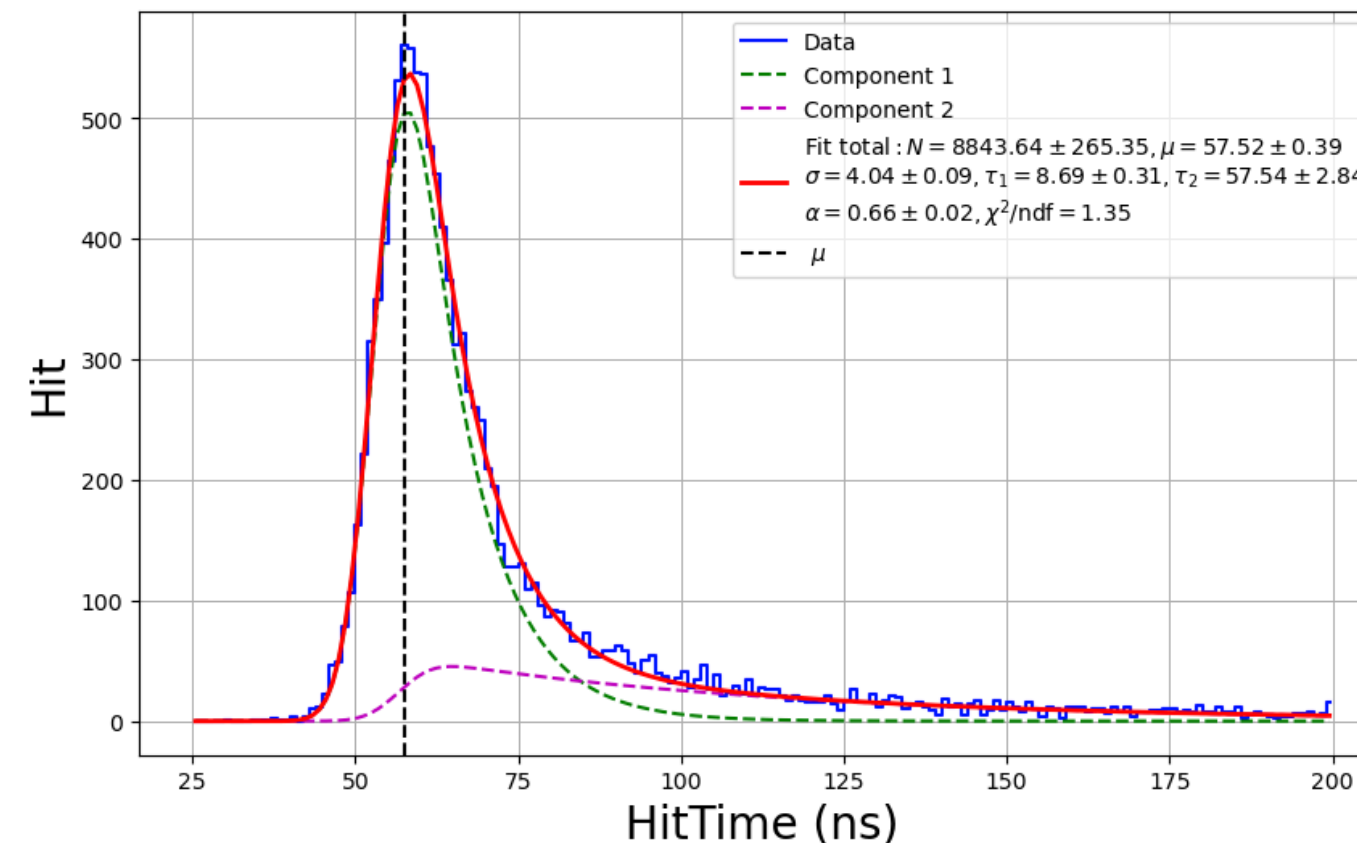
Response model:

$$f_S(t) = \left\{ \frac{\alpha}{2\tau_1} \exp\left(\frac{2\mu + \sigma^2/\tau_1 - 2t}{2\tau_1}\right) \operatorname{erfc}\left(\frac{\mu + \sigma^2/\tau_1 - t}{\sqrt{2}\sigma}\right) + \frac{(1-\alpha)}{2\tau_2} \exp\left(\frac{2\mu + \sigma^2/\tau_2 - 2t}{2\tau_2}\right) \operatorname{erfc}\left(\frac{\mu + \sigma^2/\tau_2 - t}{\sqrt{2}\sigma}\right) \right\}$$

- Good measurement accuracy between two laser data runs taken 10 minutes apart (< 1 ns).

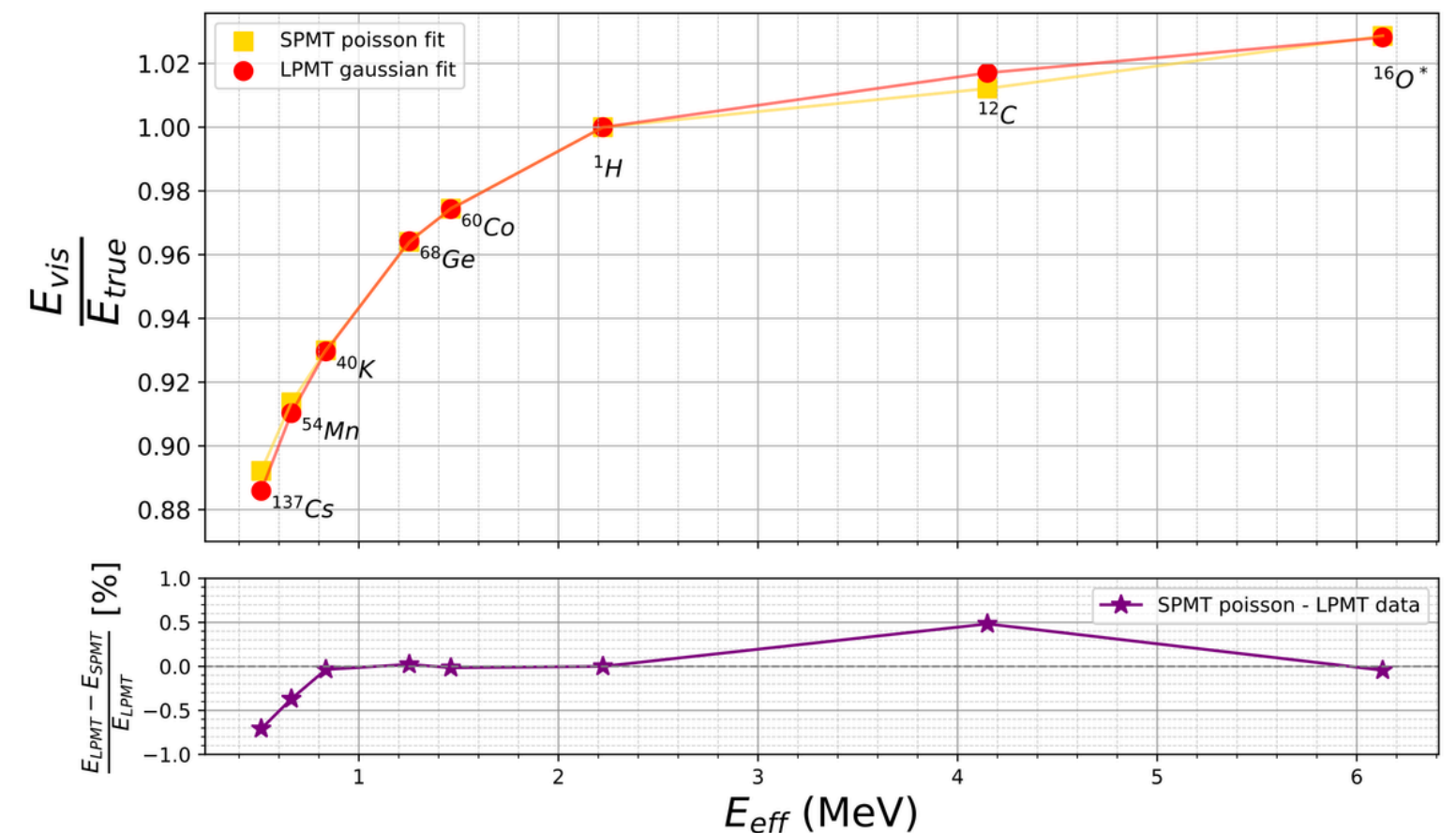
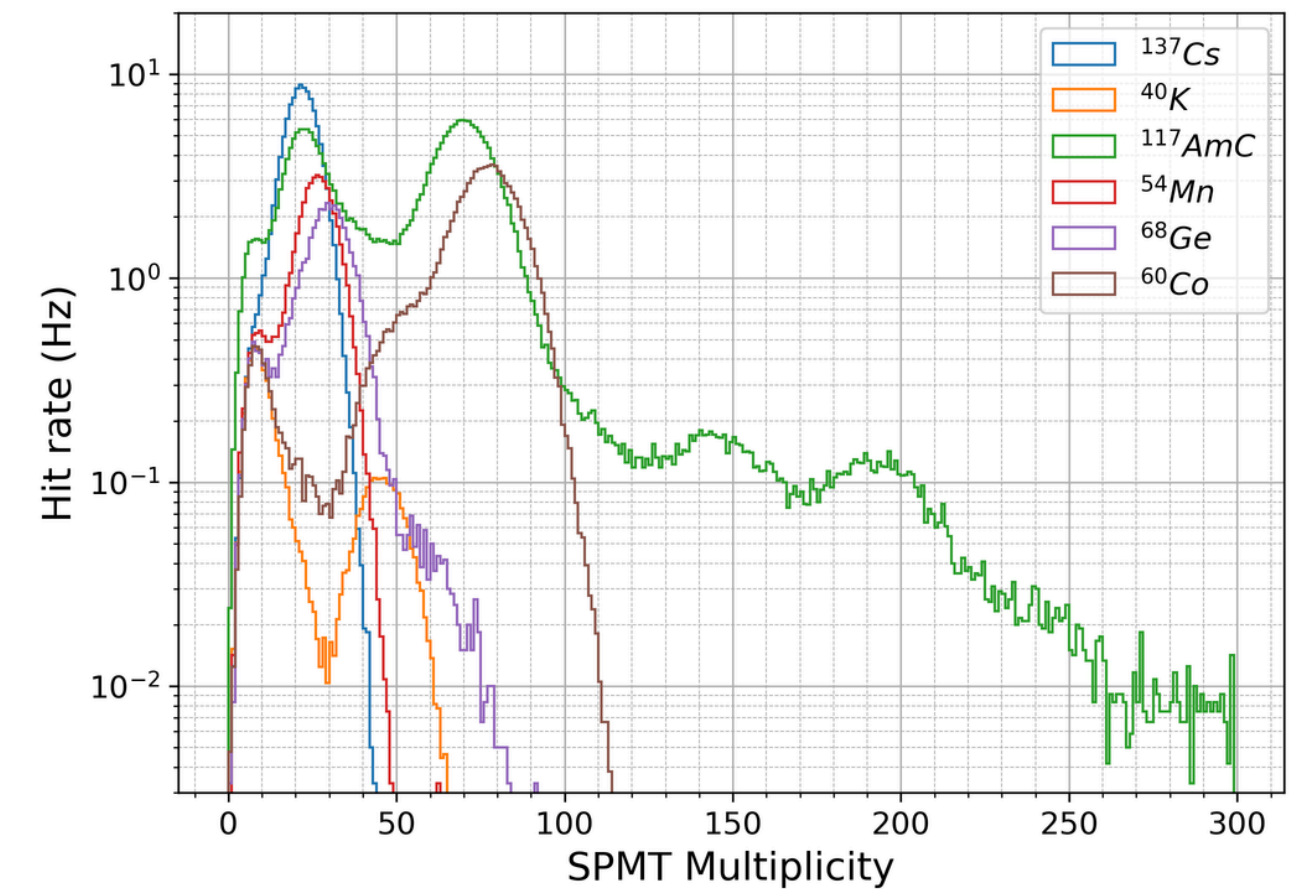
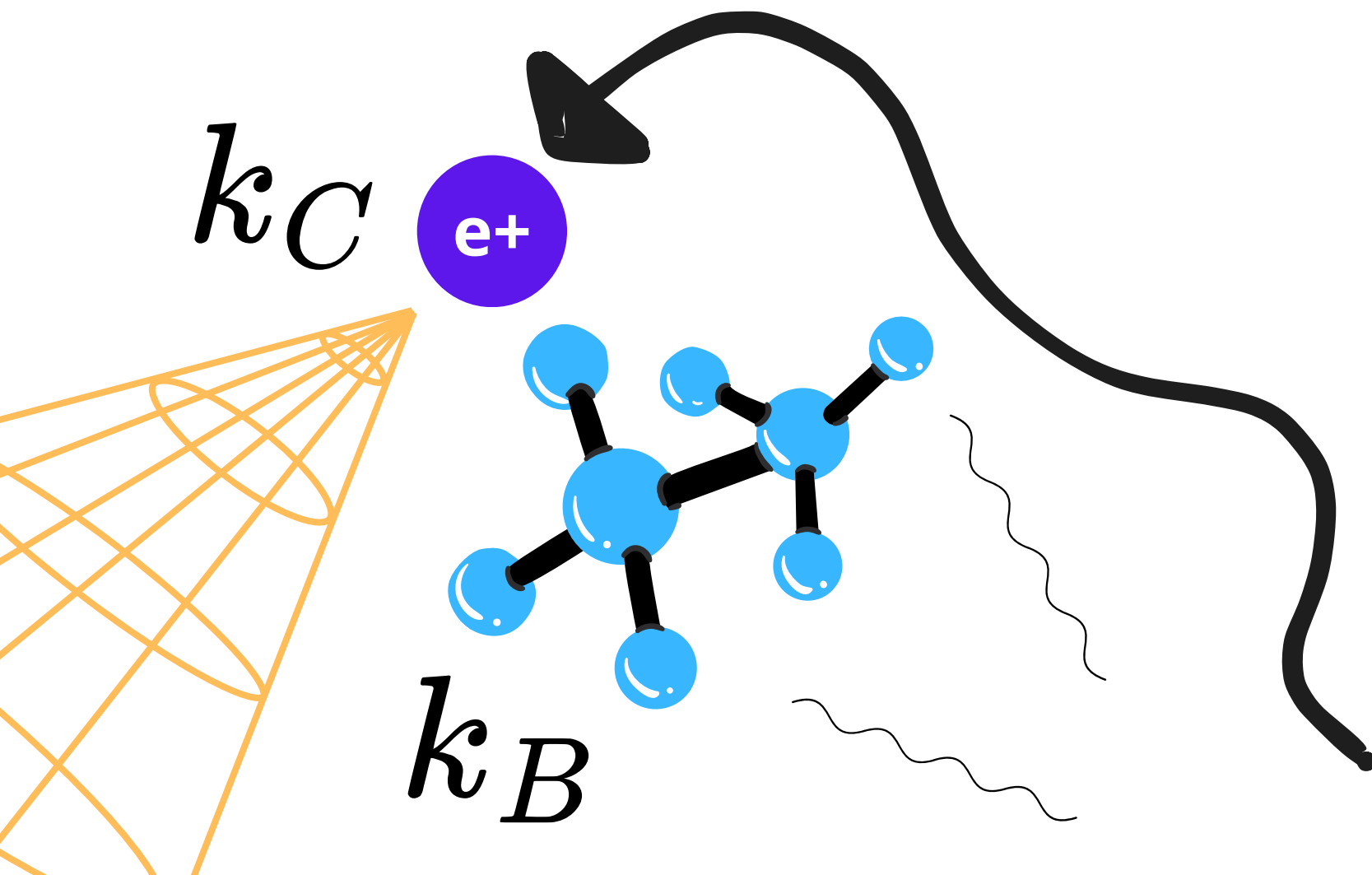
- Time calibration is not stable on longer scale.
- Possible origin of the problem in the firmware time reset.
- Under investigations :
→ new results expected in the coming weeks

Fit for SPMT : 20000



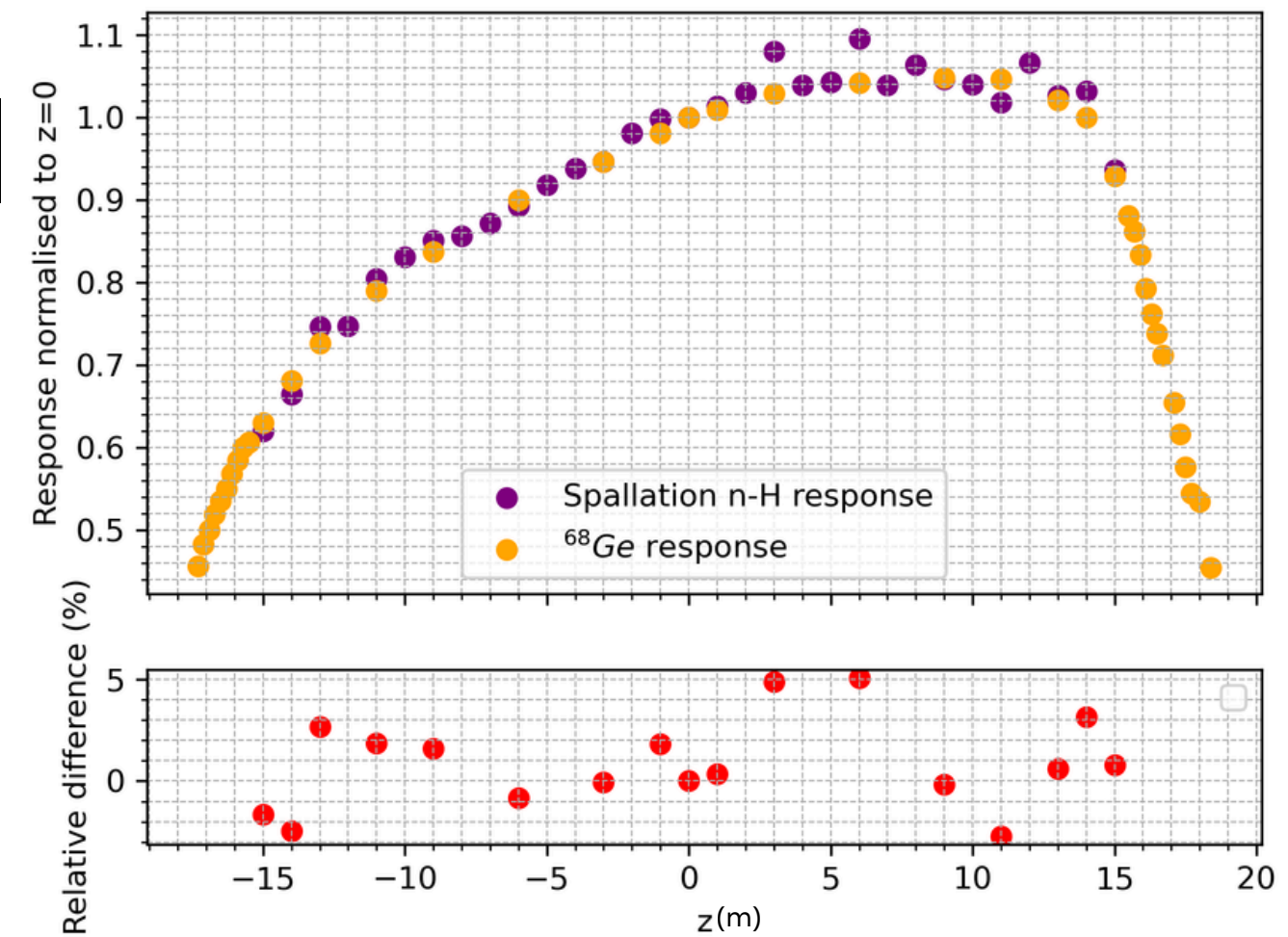
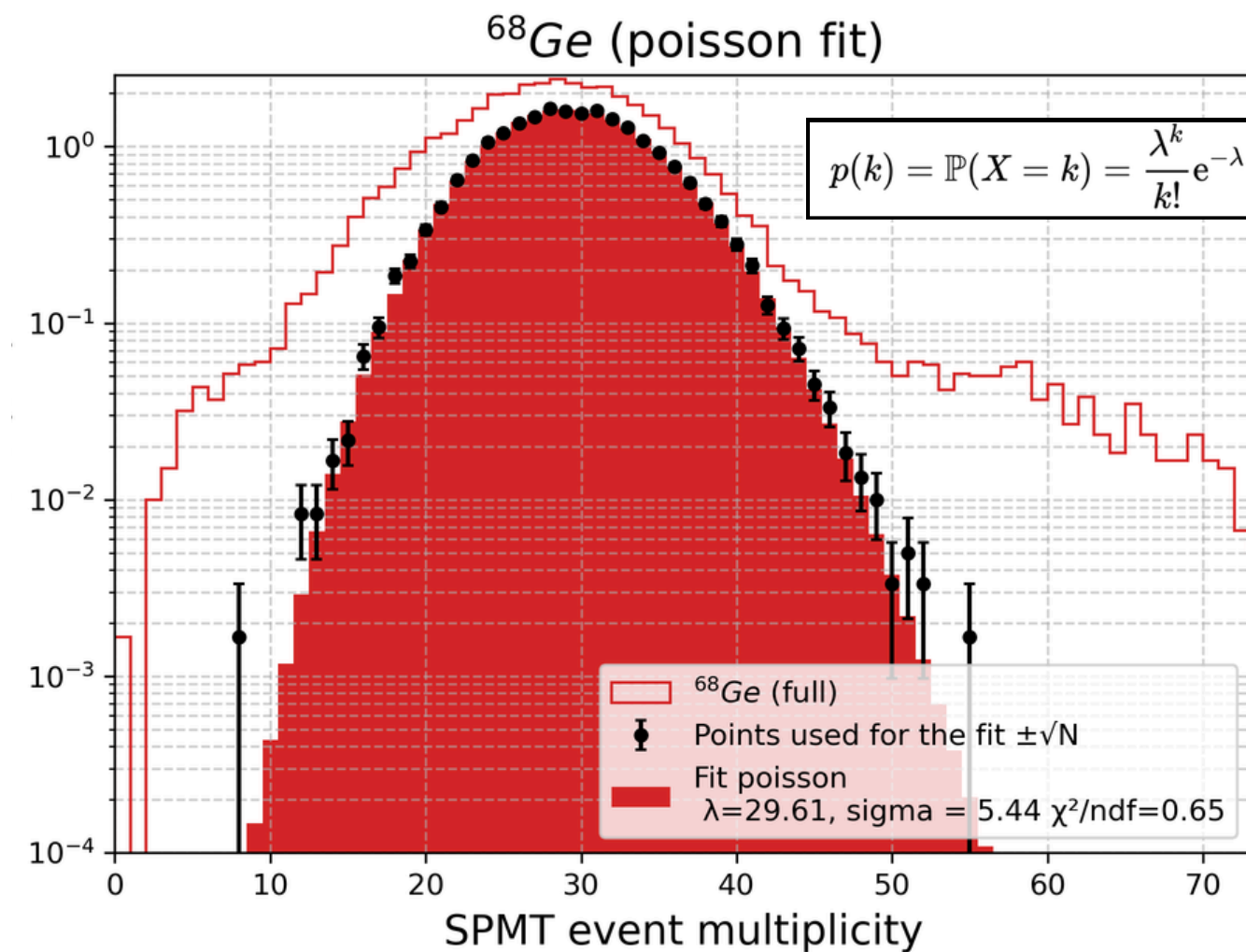
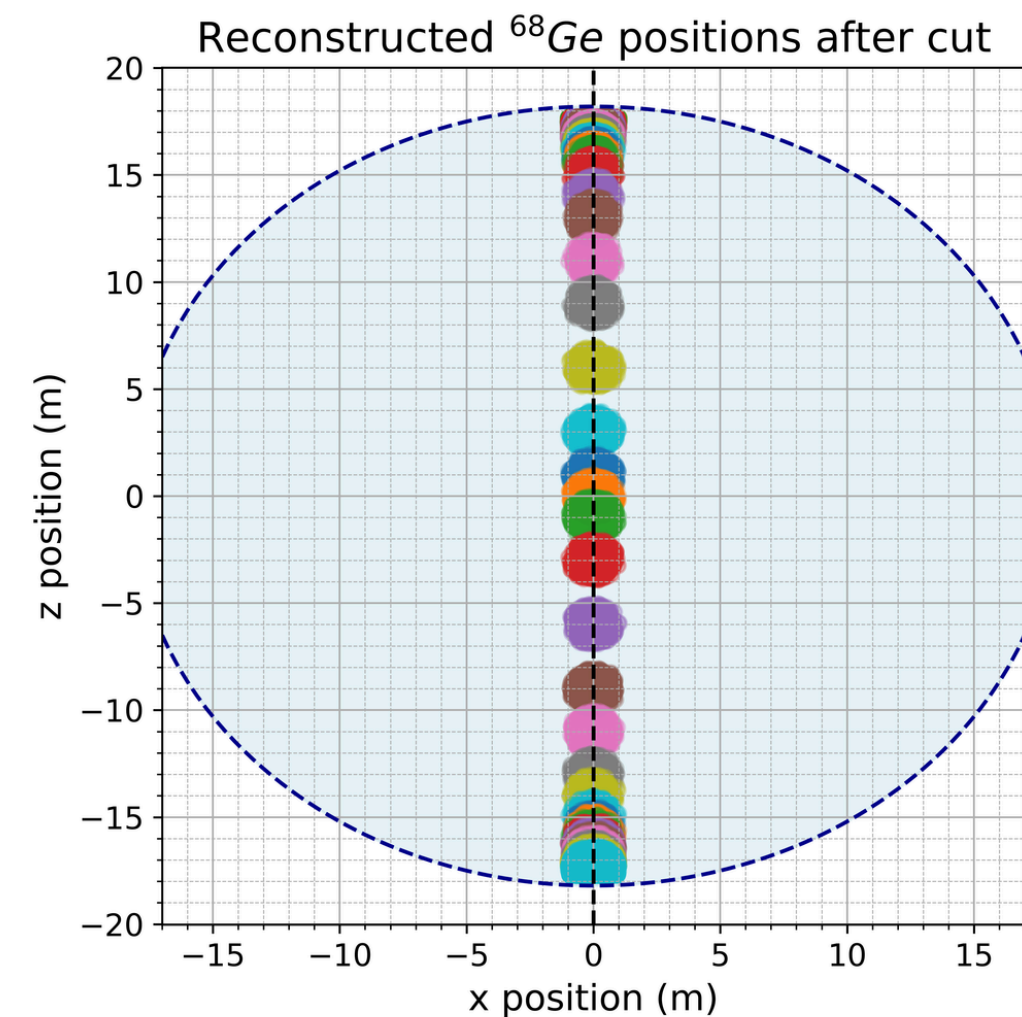
Liquid scintillator non-linearity measurement

- 2 sources of nonlinearity in the liquid scintillator:
 - Quenching effects → Low energies.
 - Cherenkov emissions → High energies.
- Compare the measurement of scintillator nonlinearity using the SPMT system with the results from the LPMTs.
 - Through a semi-independent study, SPMTs are capable of measuring scintillator nonlinearity with an accuracy comparable to that of LPMTs, within 0.5%.

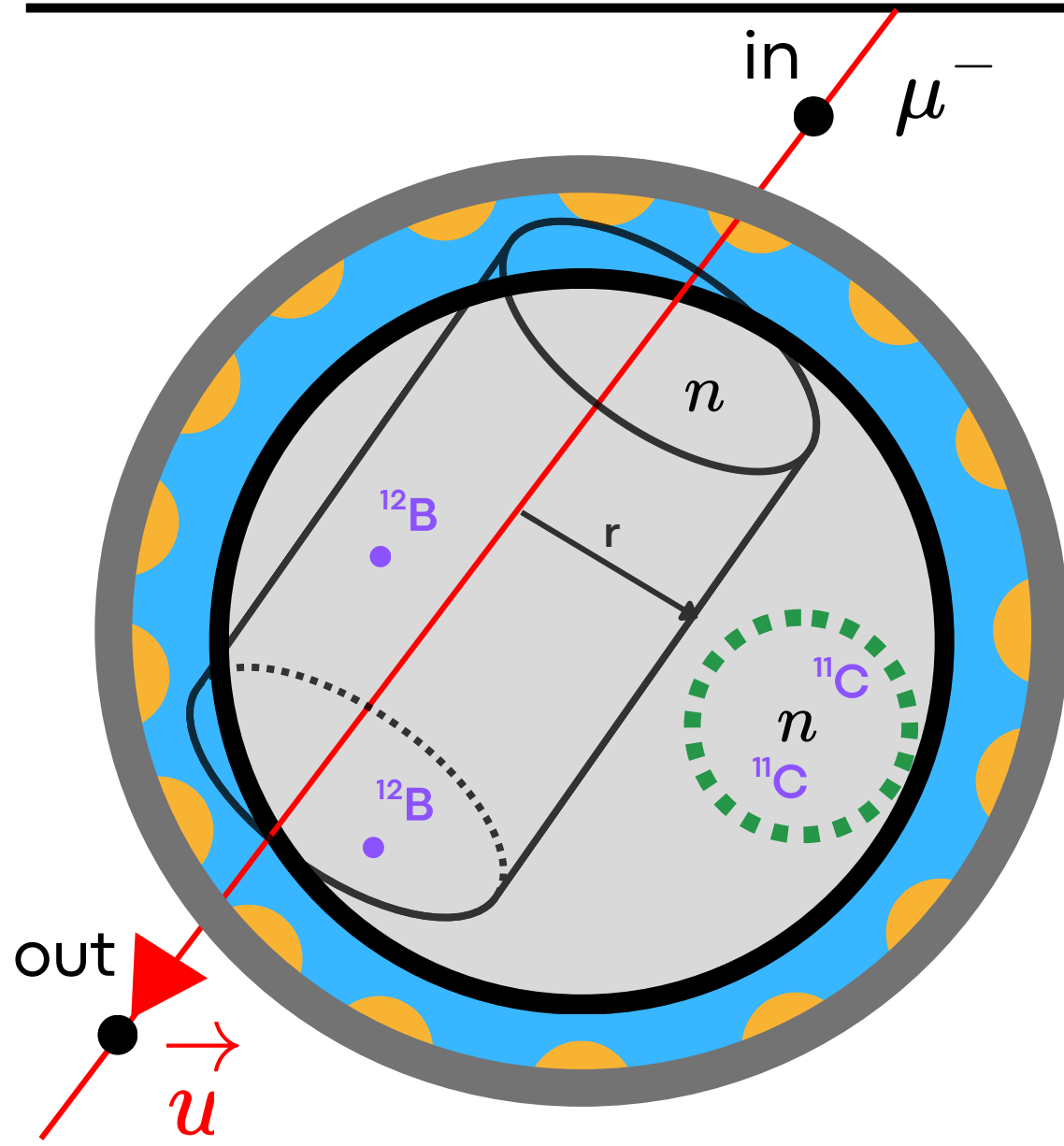


SPMT non-uniformity response

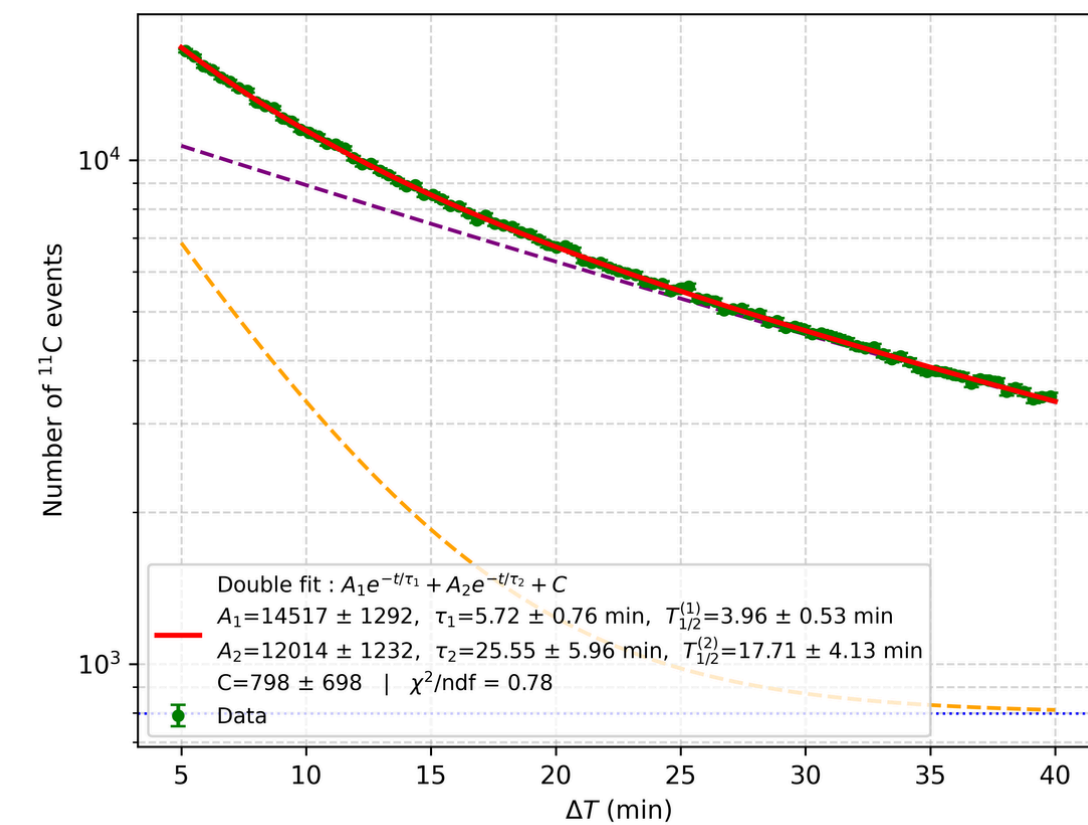
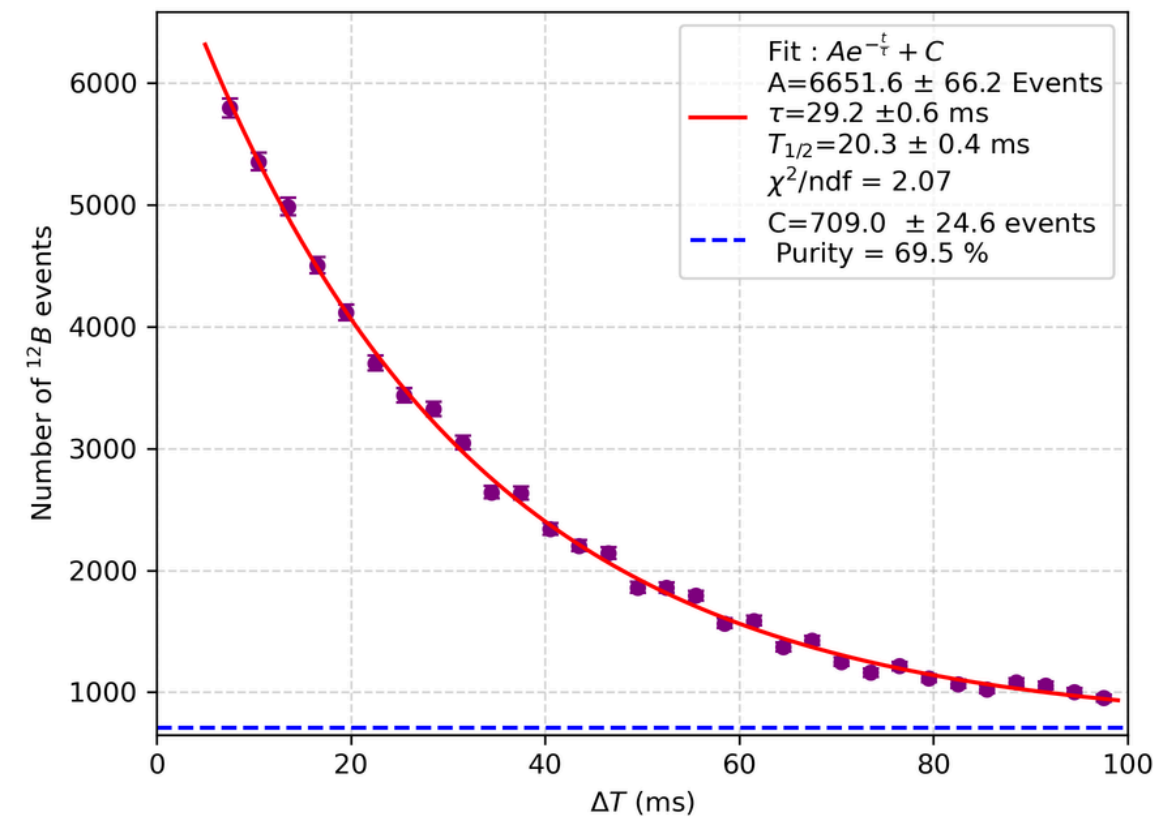
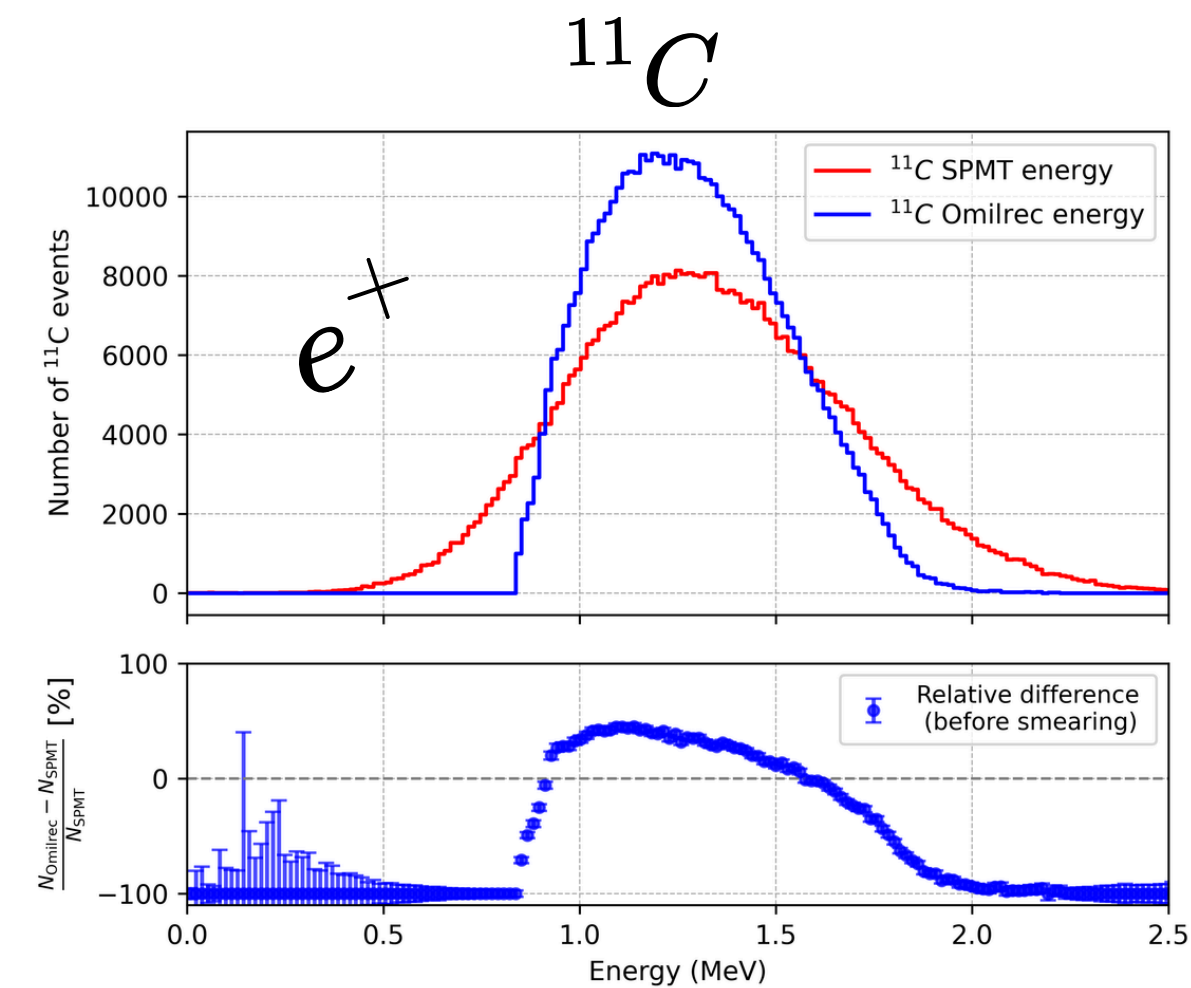
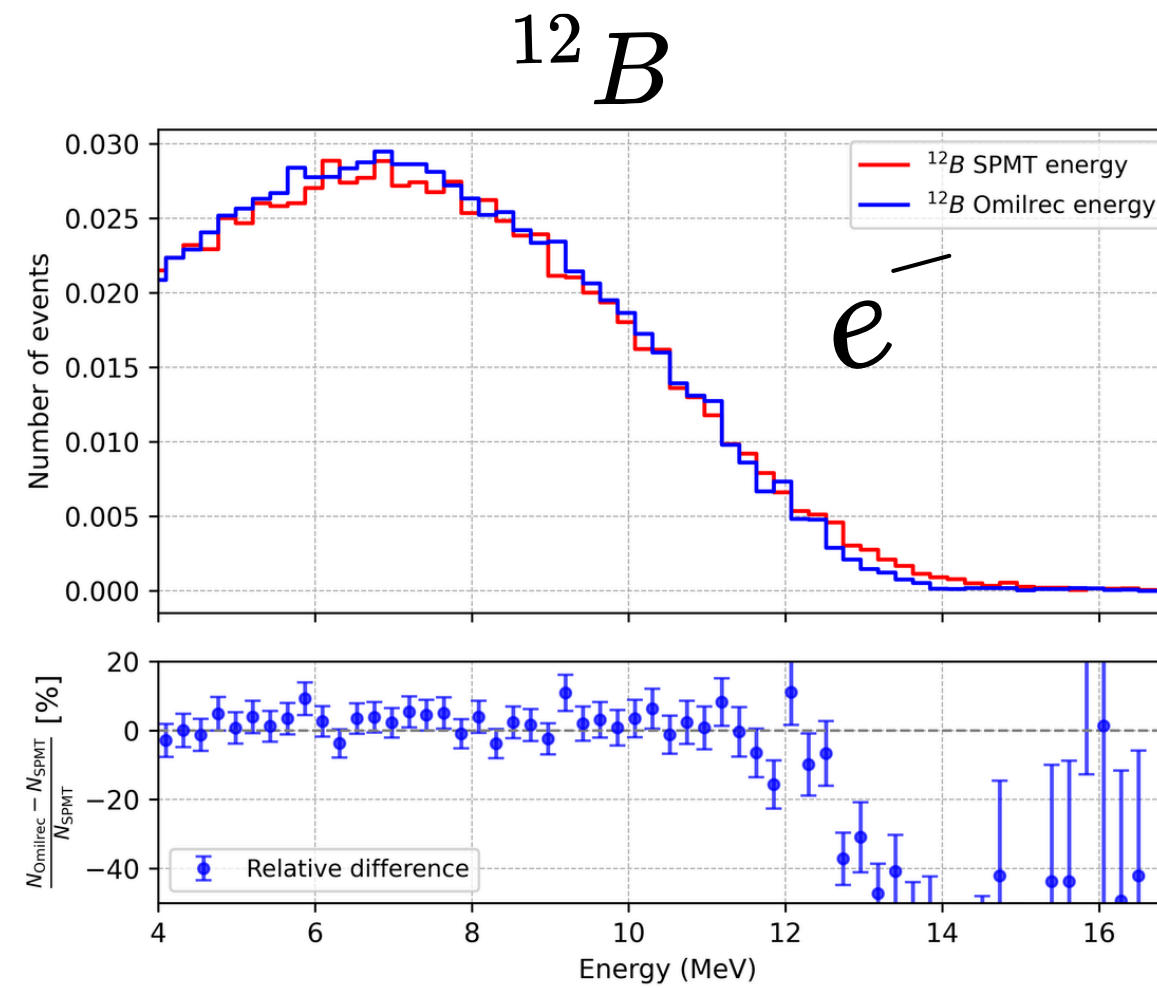
- The loss of a large number of SPMTs disrupted the expected spatial response symmetry in the SPMT system.
- We conducted to measure the system's spatial response using a Ge68 source positioned along the vertical z-axis.
- Cross-check using spallation neutrons from cosmogenic muons (Raphael Gazzini, post-doc @LP2IB)



Calibration with cosmogenic secondaries



- A selection of cosmogenic events (^{12}B and ^{11}C) was made to measure the LS's overall nonlinearity.
- Allows us to evaluate the performance of our energy reconstruction,
- Provides a high-energy anchor point for supernovae studies.

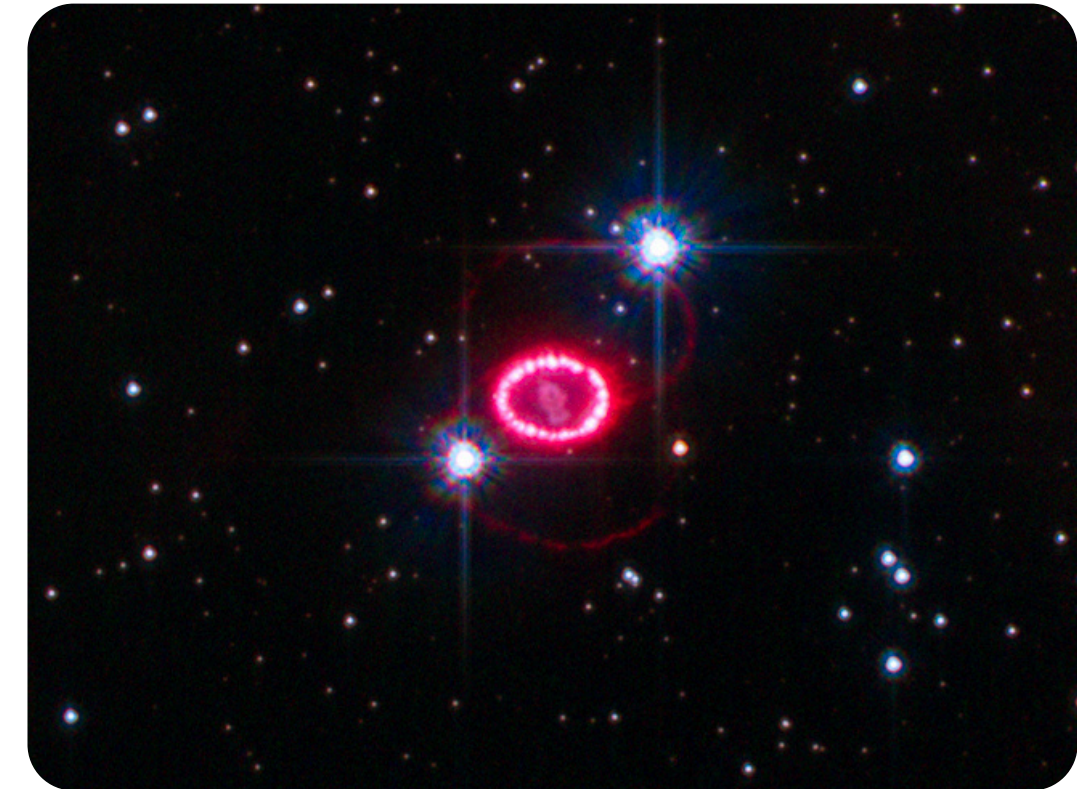


Core Collapse Supernova with JUNO

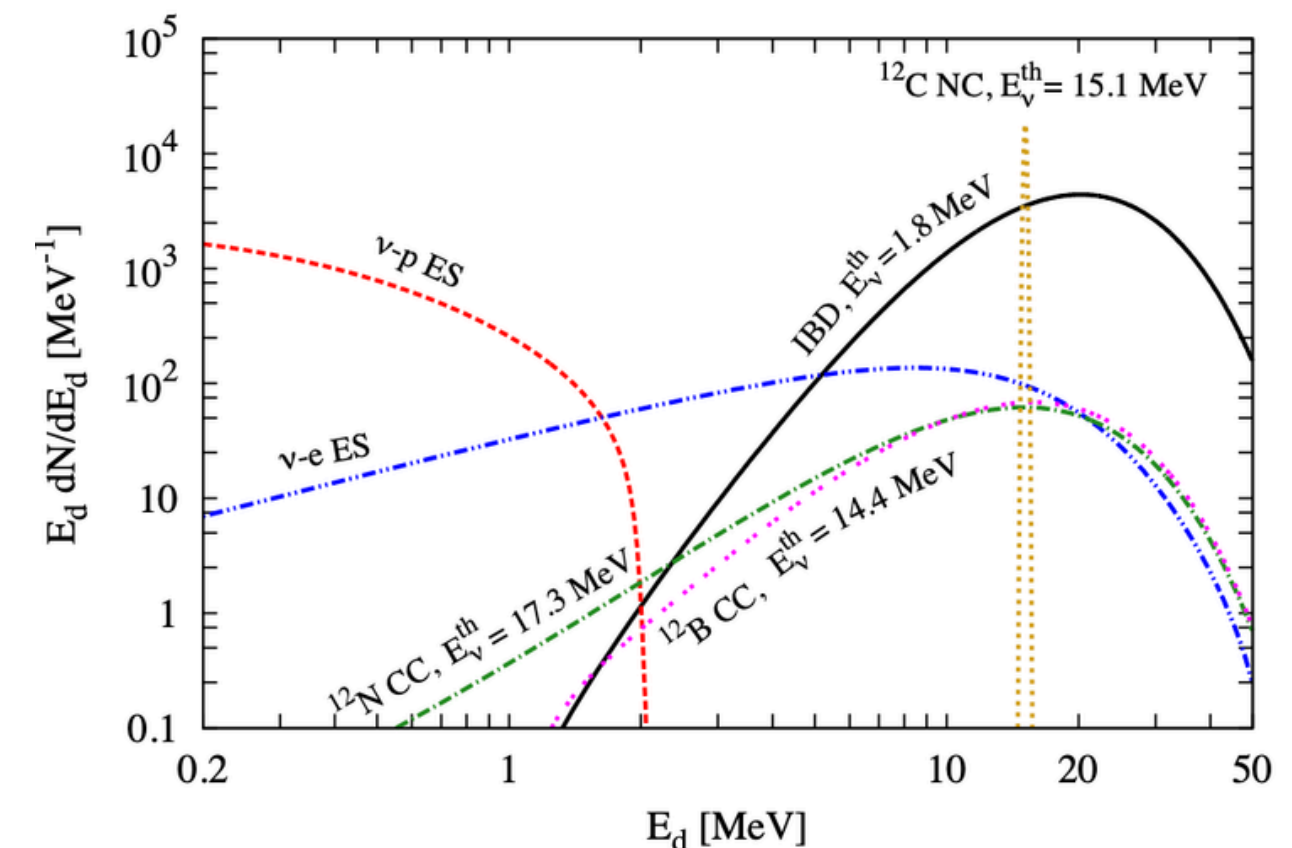
Explosion of massive stars ($M > 8 M_{\text{sol}}$), one of the most violent phenomena in the universe

- **99%** of the energy is released to neutrinos ! ($E < 100 \text{ MeV}$, $\langle E \rangle \sim 15 \text{ MeV}$).
 - Explosion mechanisms unknown.
 - Neutrinos unique messengers of the core of the star
-
- Expected number of events in JUNO : 5000 IBDs at 10 kpc in 10s, up to millions of events for close by CCSN.
 - Only 1-5 galactic CCSN per century expected.
 - Last time append : **SN1987A** in Magellanic Cloud (24 events collected).
 - Multi-channel detection in JUNO

→ Distinguish which CCSN model in the comprehension of explosion mechanisms.



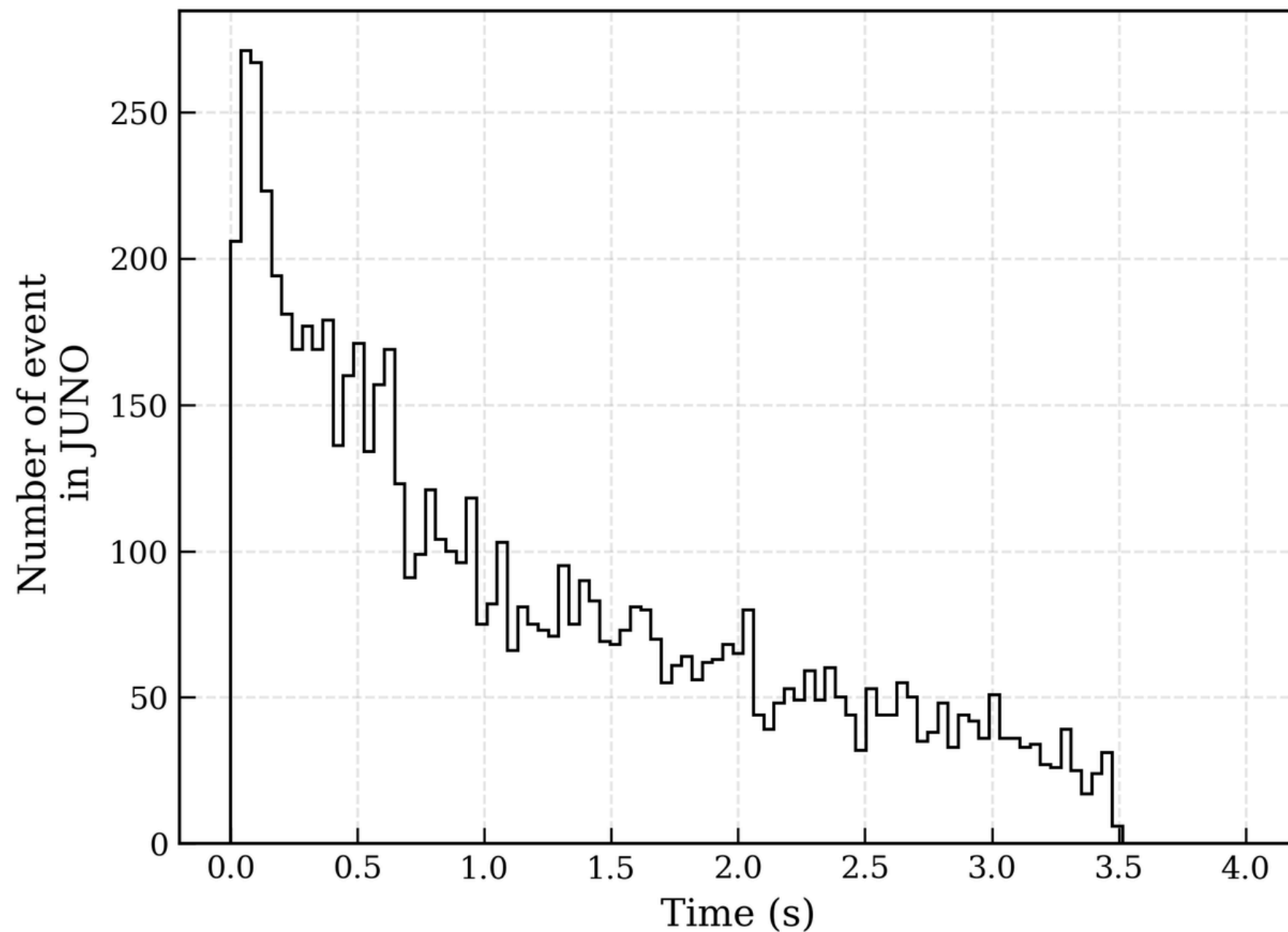
Expected JUNO response to a Supernova signal



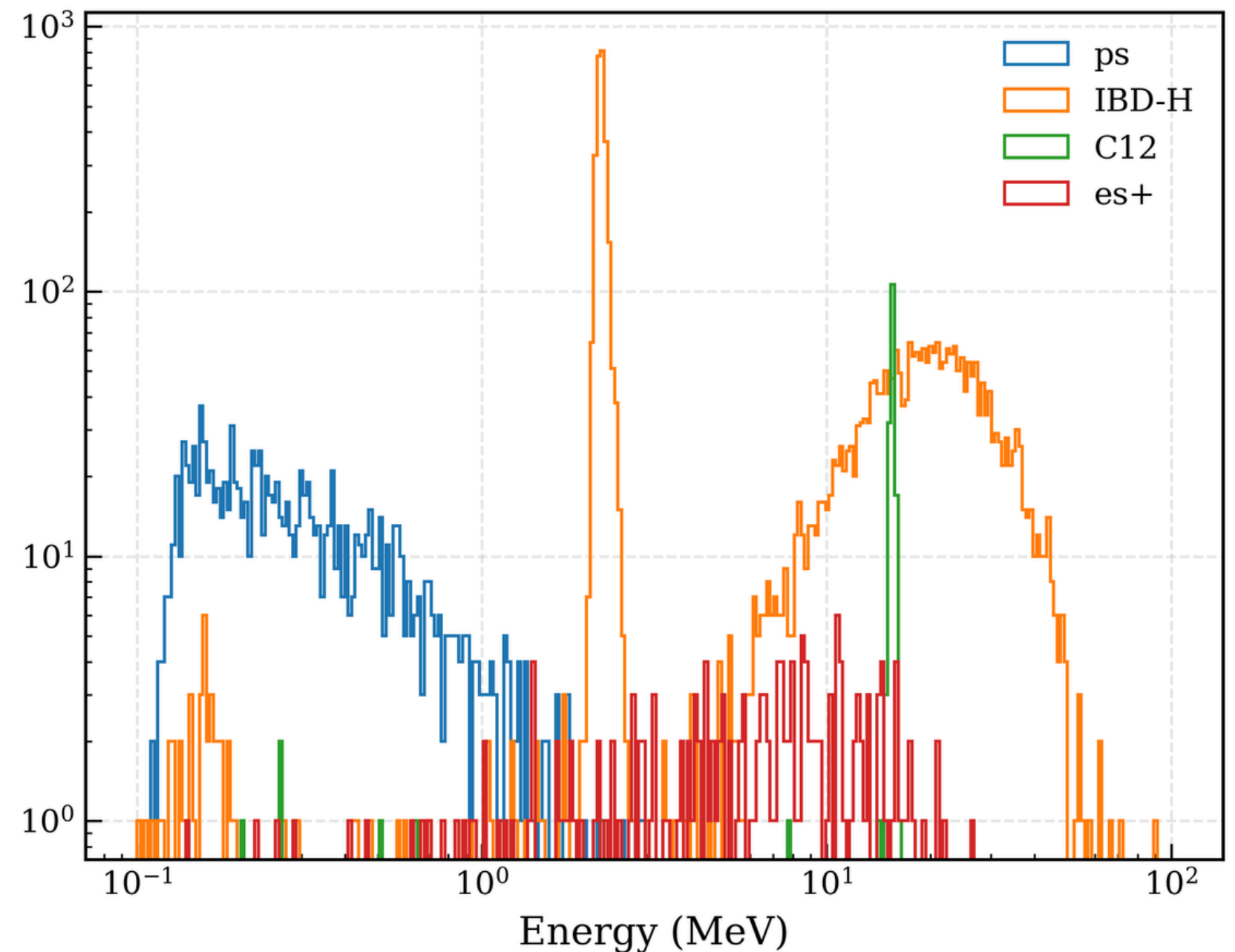
Simulation of CCSN in JUNO

Work in progress

Number of event vs time in JUNO :



Reconstructed energy spectrum in JUNO :

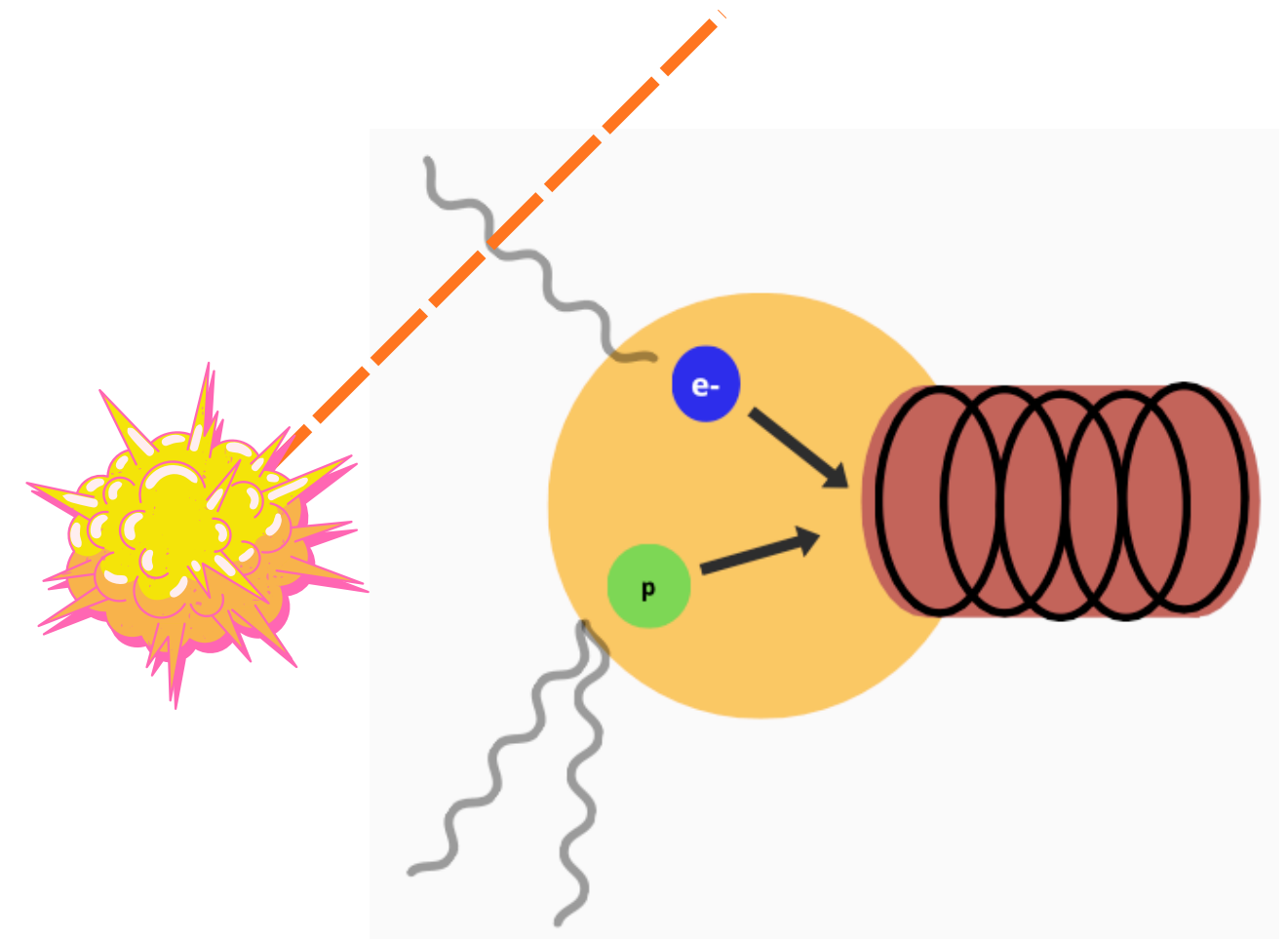


Simulation of a Garching CCSN model at 90 kpc in a normal mass ordering hypothesis

Difficulty : Manage the reconstruction while the rate of events is higher than reactor's IBDs ($\sim 50/\text{day}$), the high energy of SN's neutrinos and the multiples interactions channels.

What's next

- Framework for the CCSN neutrino event selection for multiple channels which adapts to close-by sources (and based on the realistic JUNO response, calibration and background)
- Main challenges : for close-by CCSN (<10 kpc) mixing and pile-up between consecutive events as well as the effect of PMTs after-pulses are not negligible anymore (we expect about 10^6 to 10^7 interactions in JUNO in a few seconds) → Biased energy and neutrino flavor determination
- Develop Machine Learning techniques to improve signal treatment for close-by CCSN events.



Conclusion

- JUNO is the largest liquid scintillator detector in operation
- Data taking started in Aug 2025, after 10 years of construction
- (Luckily) these initial and exciting phases of the detector coincided with the beginning of my thesis

During this first 1.5 years of thesis :

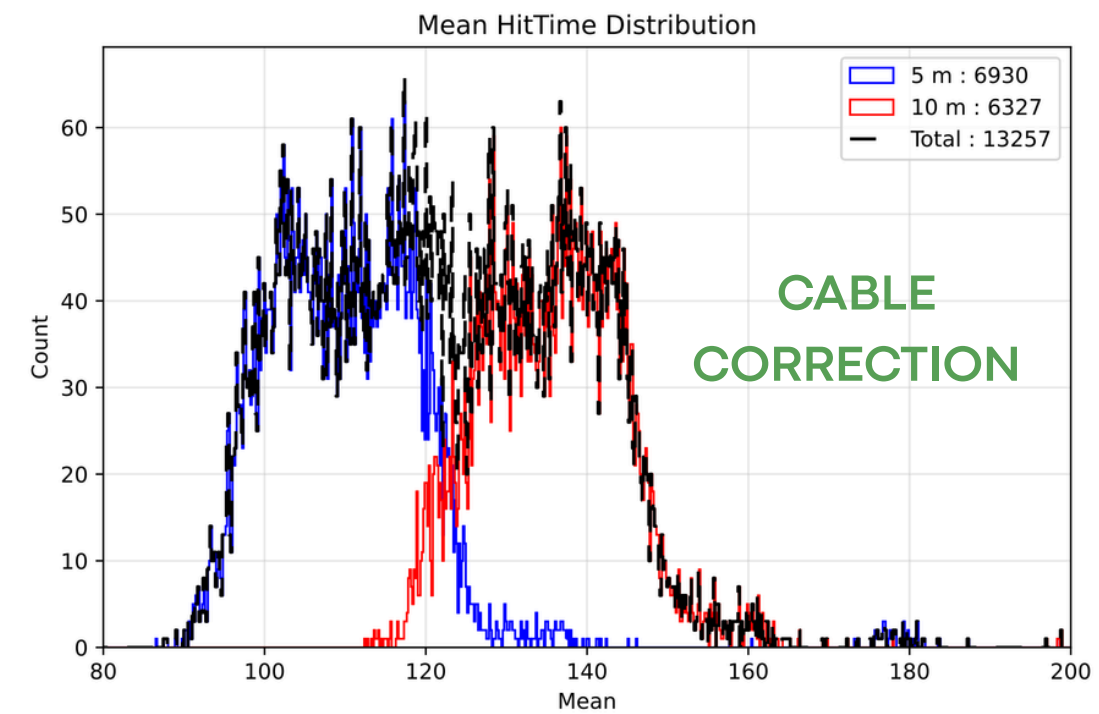
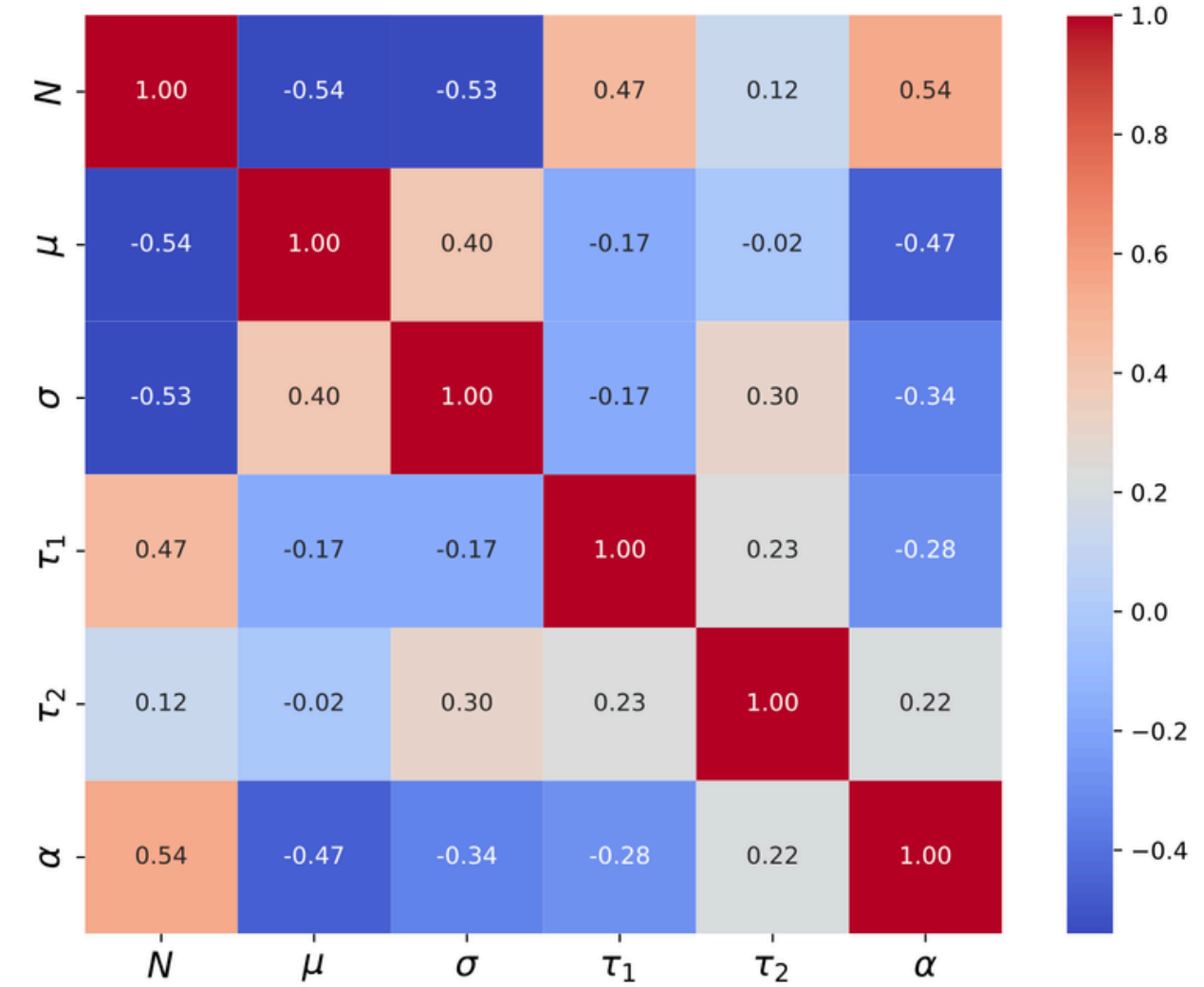
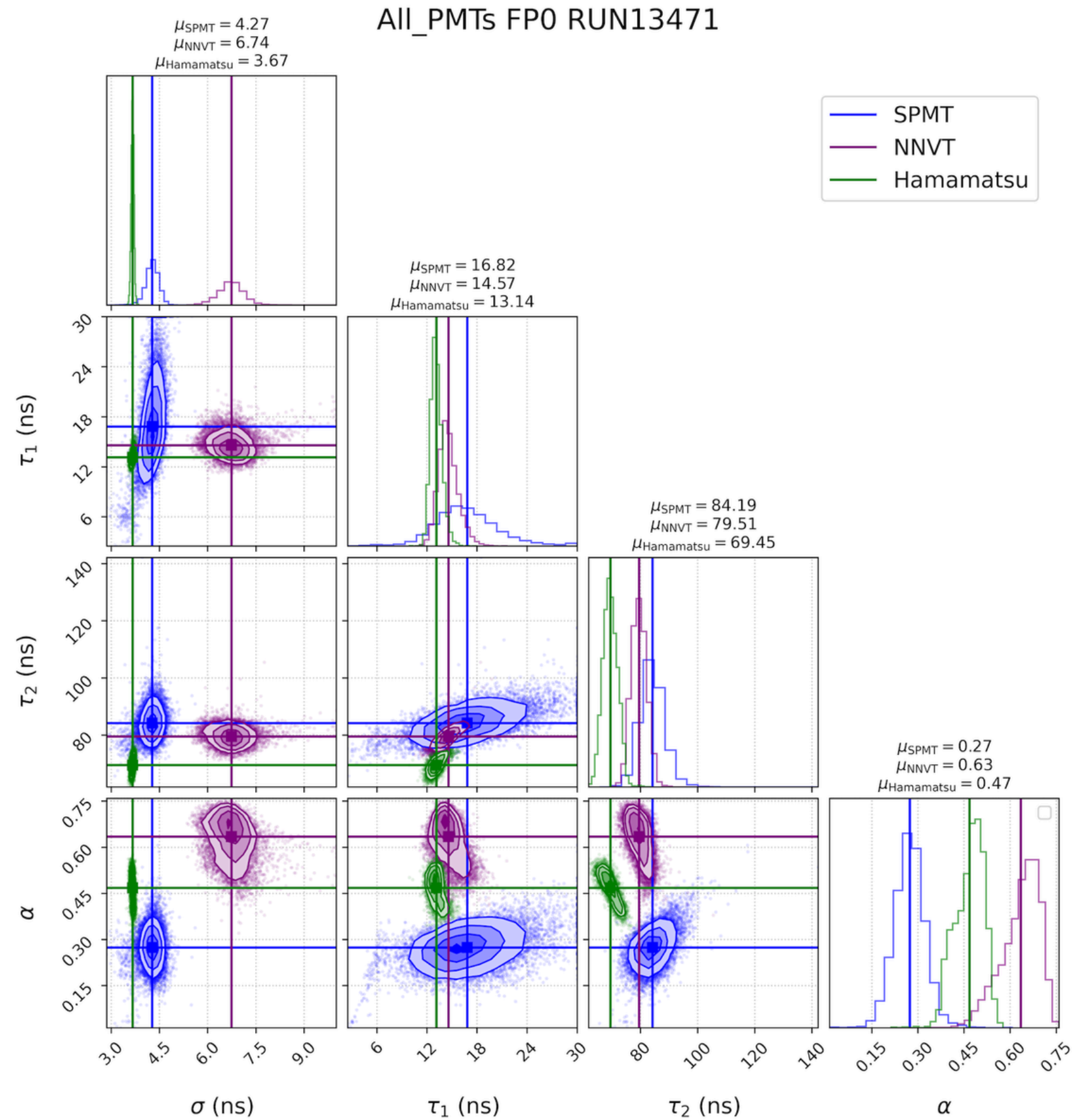
- Several issues encountered with the SPMT operation : real world is not always as expected
 - Contributions to the commissioning of the SPMT system (and monitoring of good / bad channels)
 - Understanding of the detector response with the time and energy calibration: key elements for the reactor energy spectrum reconstruction (and in general for any real data analysis)
- LS non-linearity measurement with the SPMT showed a good performance
- Non-uniformity of the SPMT determined and impact on the energy spectrum reconstruction ongoing

Starting the work for SN detection : be ready for the next CCSN, even the closest one!

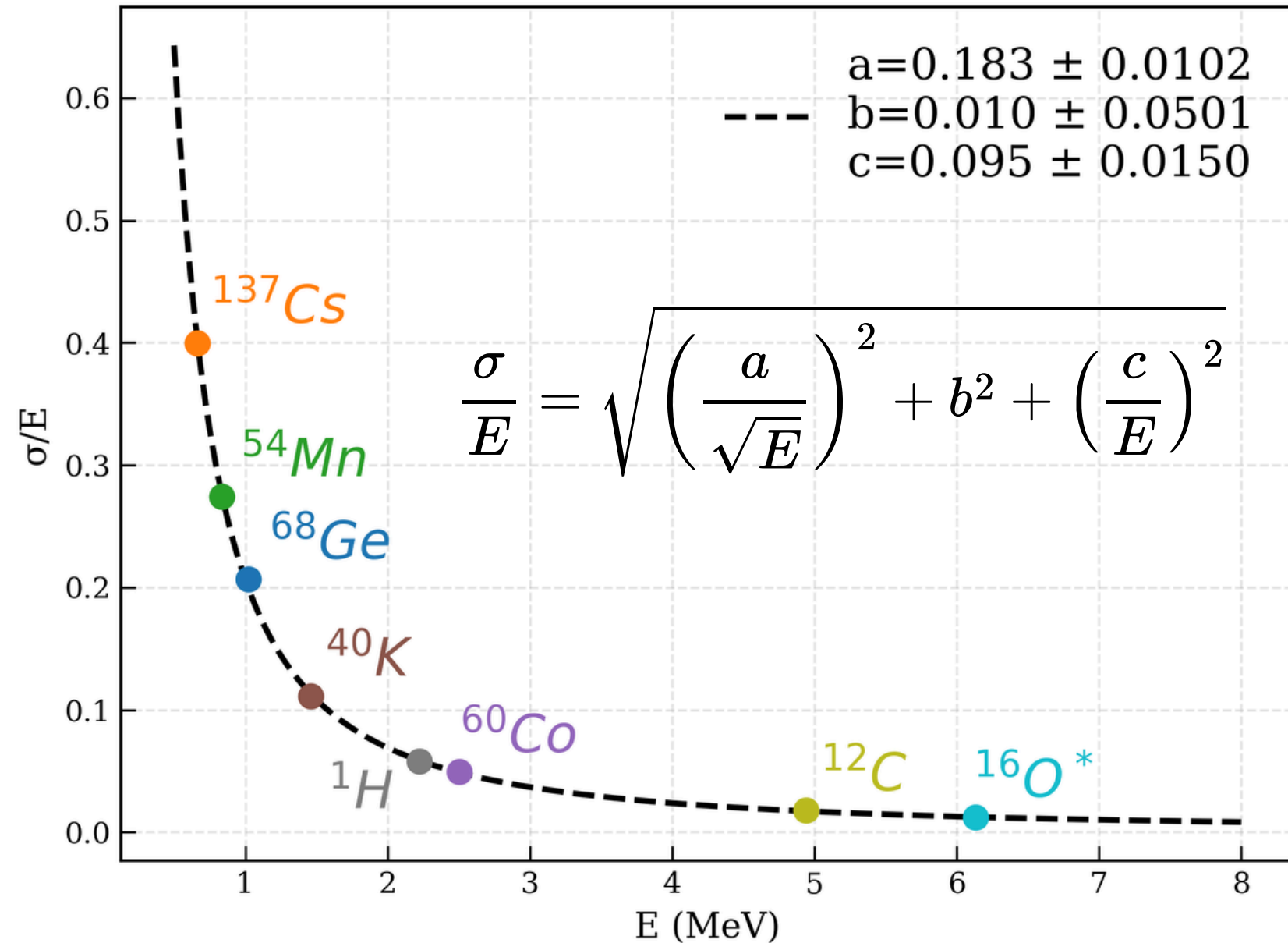
Questions?

Back-up

Timing Calibration



Energy resolution



Energy resolution with SPMTs :

- Energy resolution was measured using same calibration sources than for LS non-linearity
- **~20%** energy resolution at 1 MeV
- 3 parameters impact the resolution :
 - a : Statistical term driven by **photostatistics**
 - b : **Non-uniformity**
 - c : **Dark Count Rate**

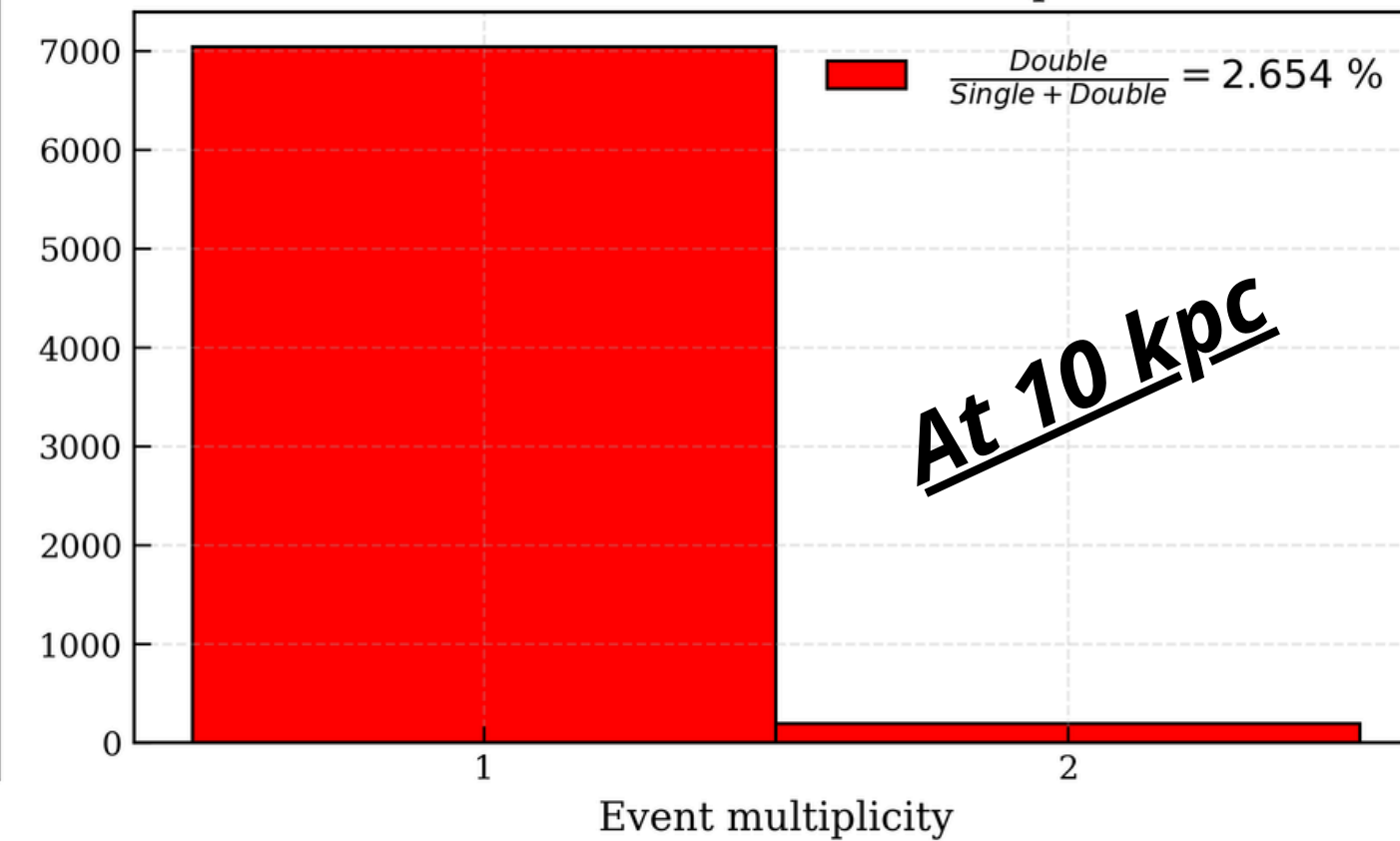
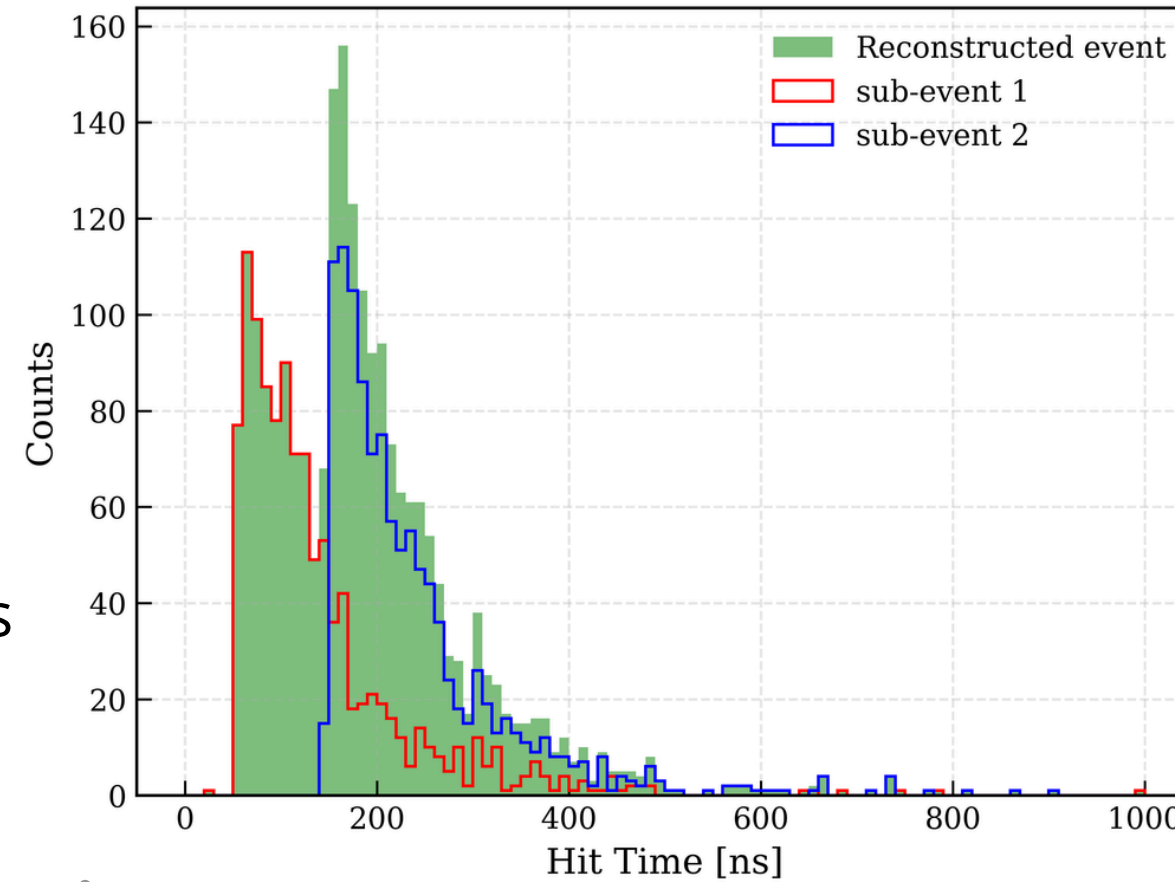
For the coming year

Work in progress

Mixing of event

If a CCSN happened close enough, pairs of events could be reconstructed as one single event or IBDs signals could be mixed.

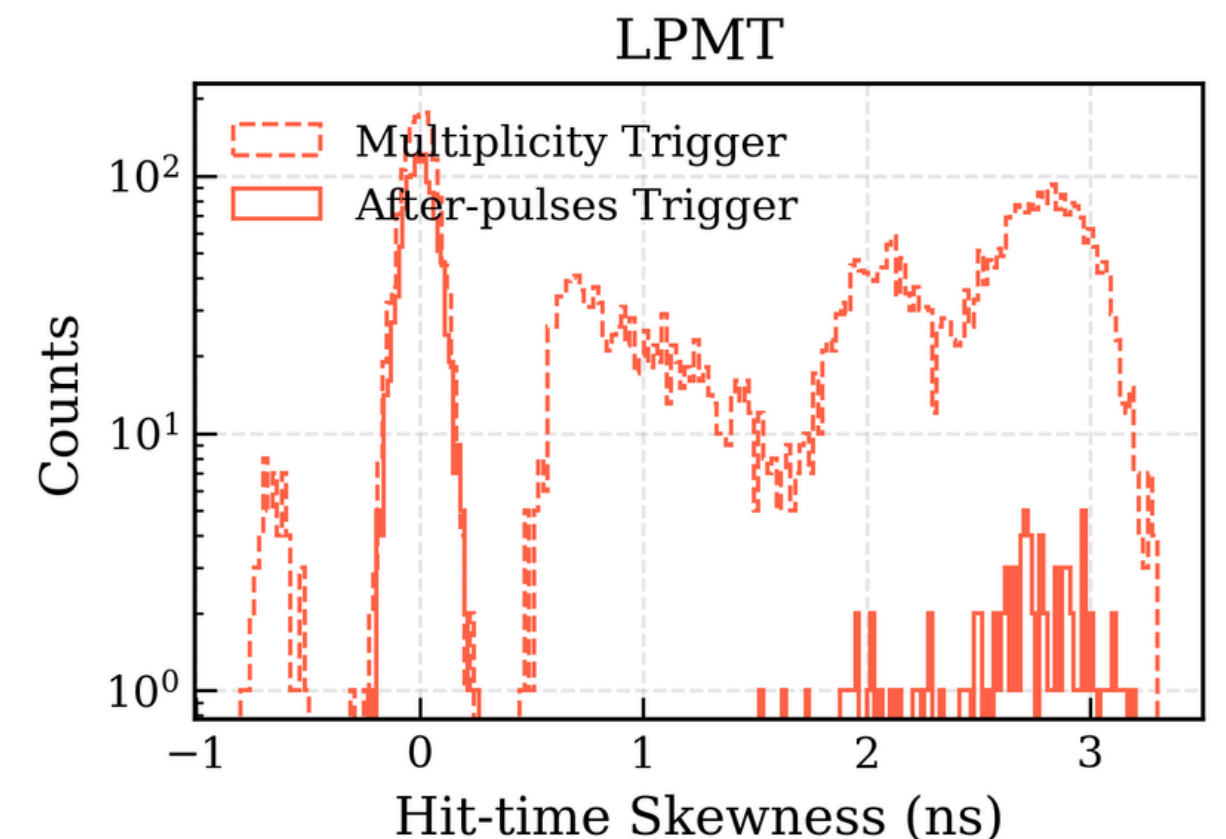
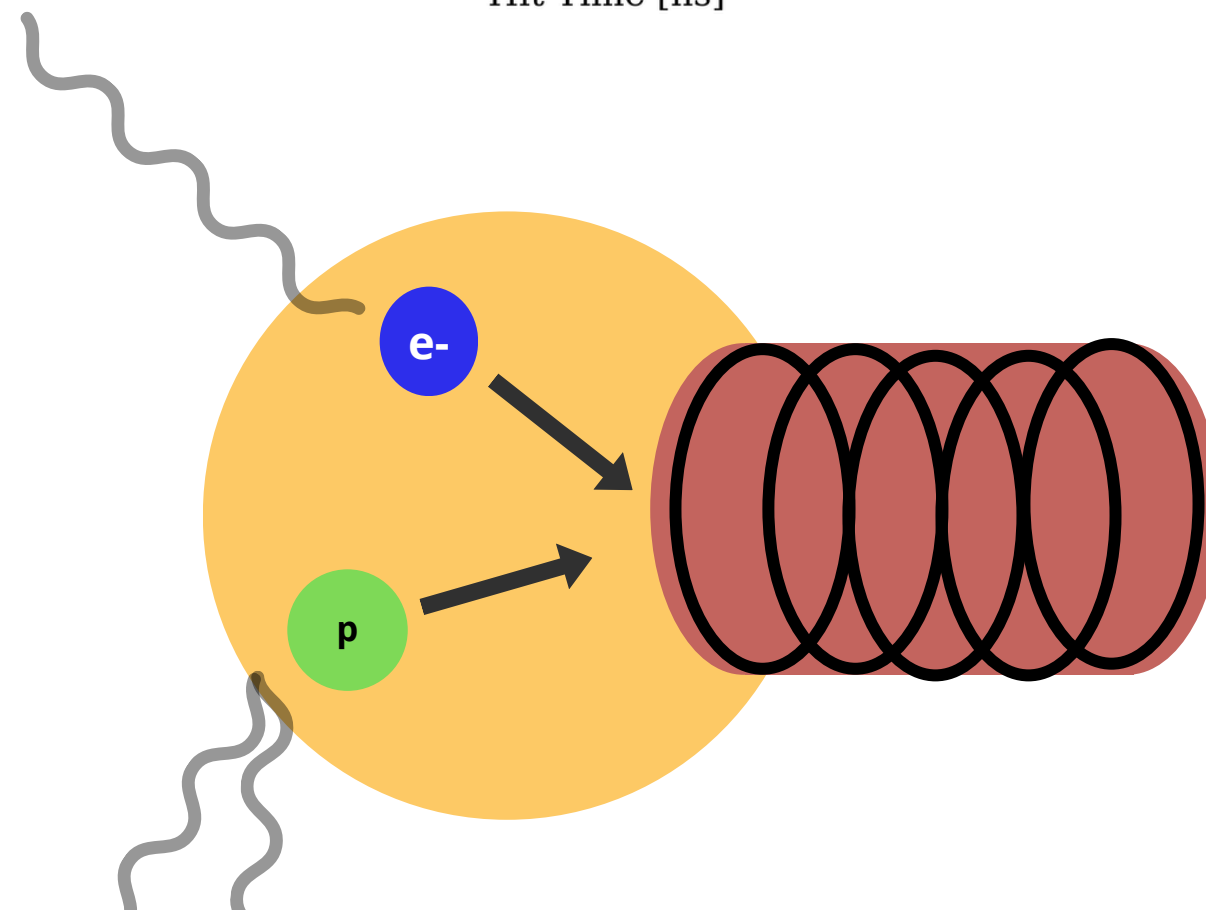
→ uses of machine learning techniques to make a better reconstruction.



After-pulses

After a powerful event LPMTs could be blind during tens of microseconds due to after-pulses.

→ Study how SPMT could help to reconstructed events when LPMTs are blinds



Build an energy reconstruction model

- The model used to measure energy using SPMTs is a model normalized to the energy of n-H: 2.223 MeV at the center of the CD.

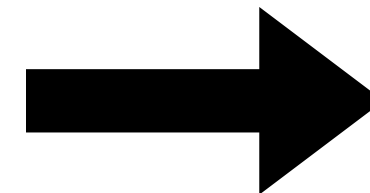
$$E_{SPMT} = \left(\frac{N_{hits} - DC_{hits}}{M_n(x, y, z)} \right) \times \frac{E_{n-H}}{N_{hits}^{n-H}(0, 0, 0)}$$

N_{hits} : The number of hits during one event, with the assumption that 1 hit = 1 PE.

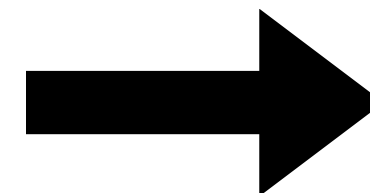
DC_{hits} : Estimating the contribution of the Dark Count during an event.

$M_n(x, y, z)$: The non-uniformity correction factor, normalized with respect to the number of PE reconstructed at $x, y, z = 0$.

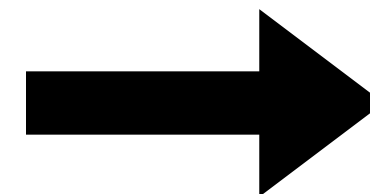
$N_{hits}^{n-H}(0, 0, 0)$: The number of hits during a neutron capture event at the center of the CD.



Calculated based on the average number of hits during a periodic trigger.

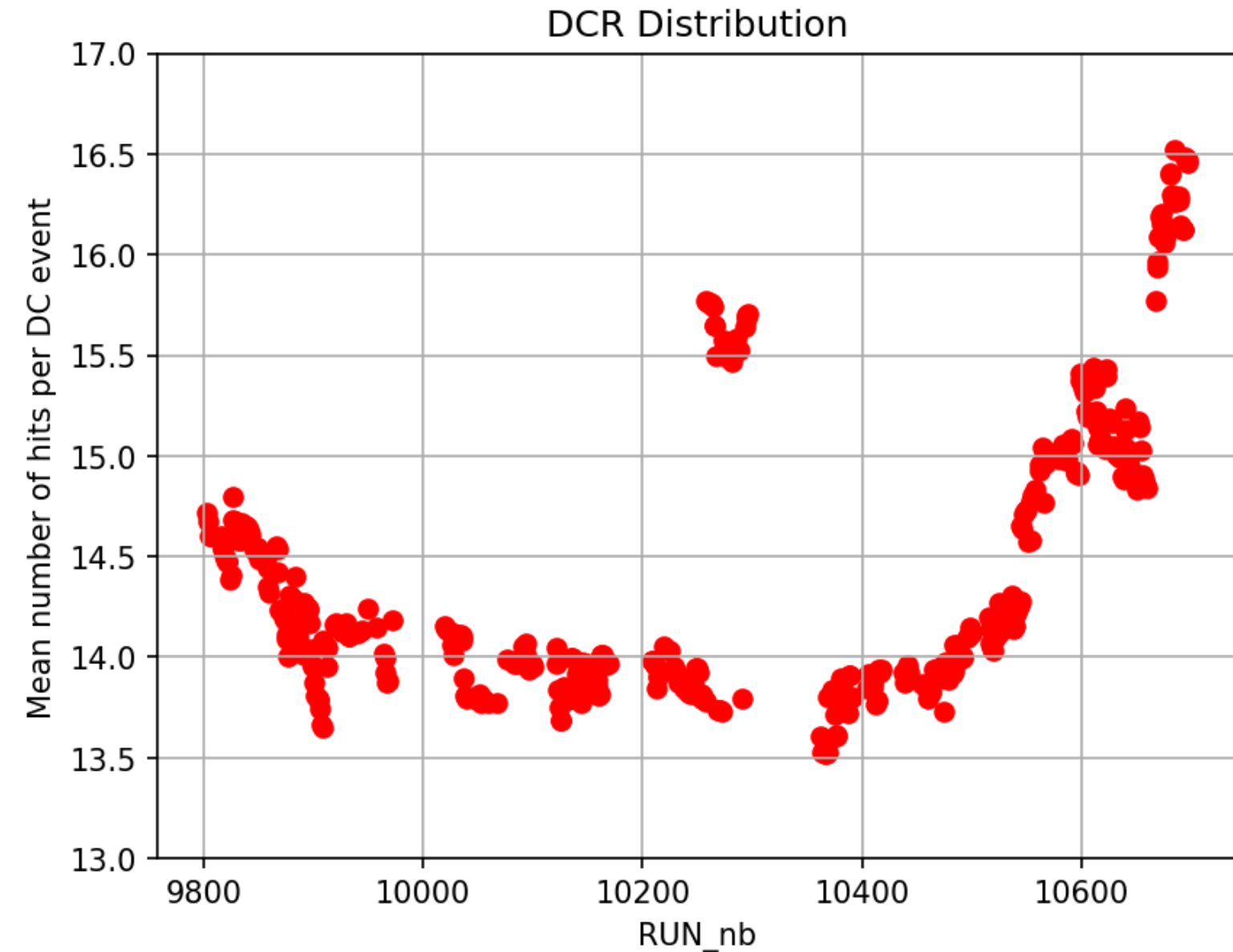
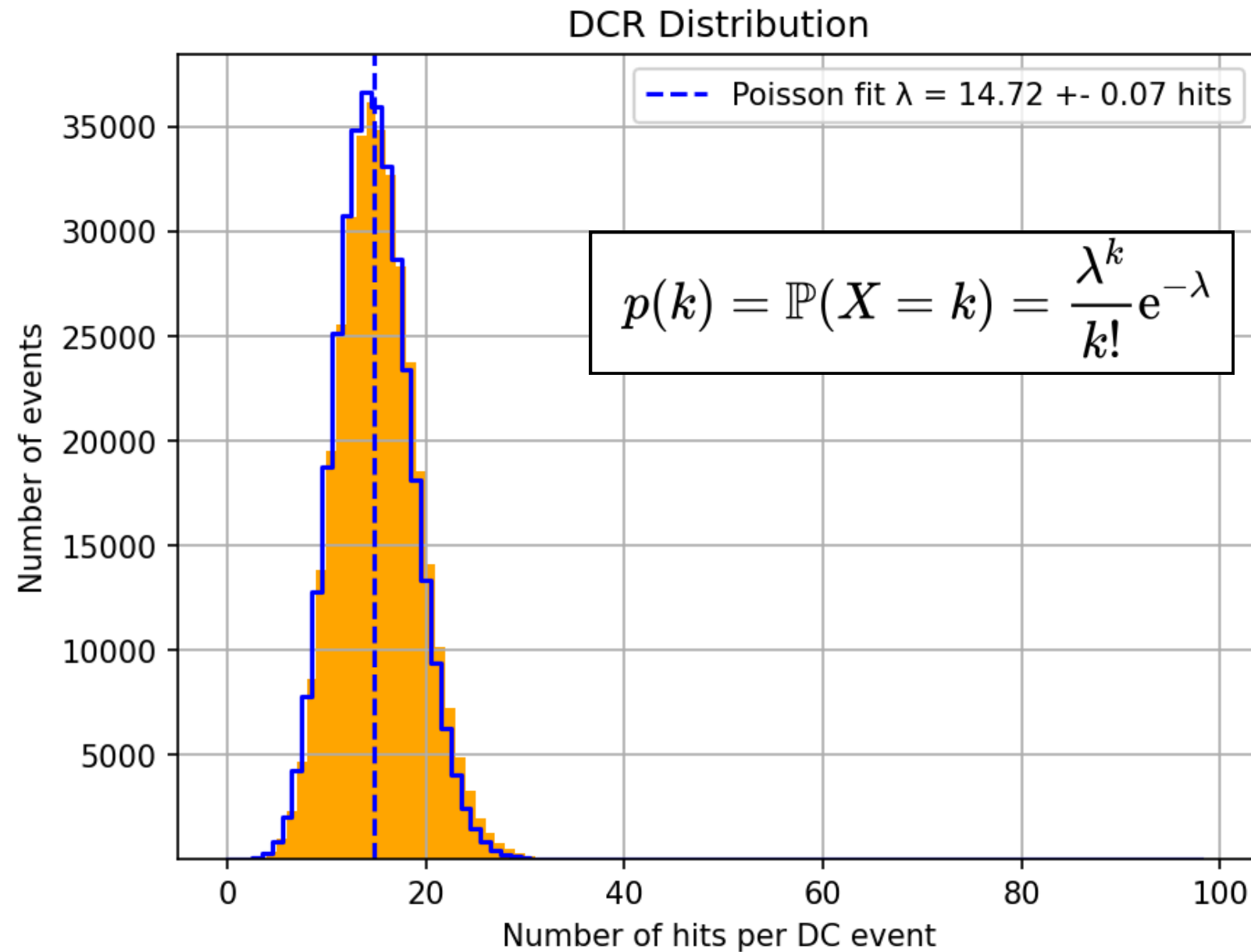


Measured using spallation neutrons and cross-checked with ^{68}Ge and AmC.



Measured using the number of hits at the center of CD of n-H using AmC runs.

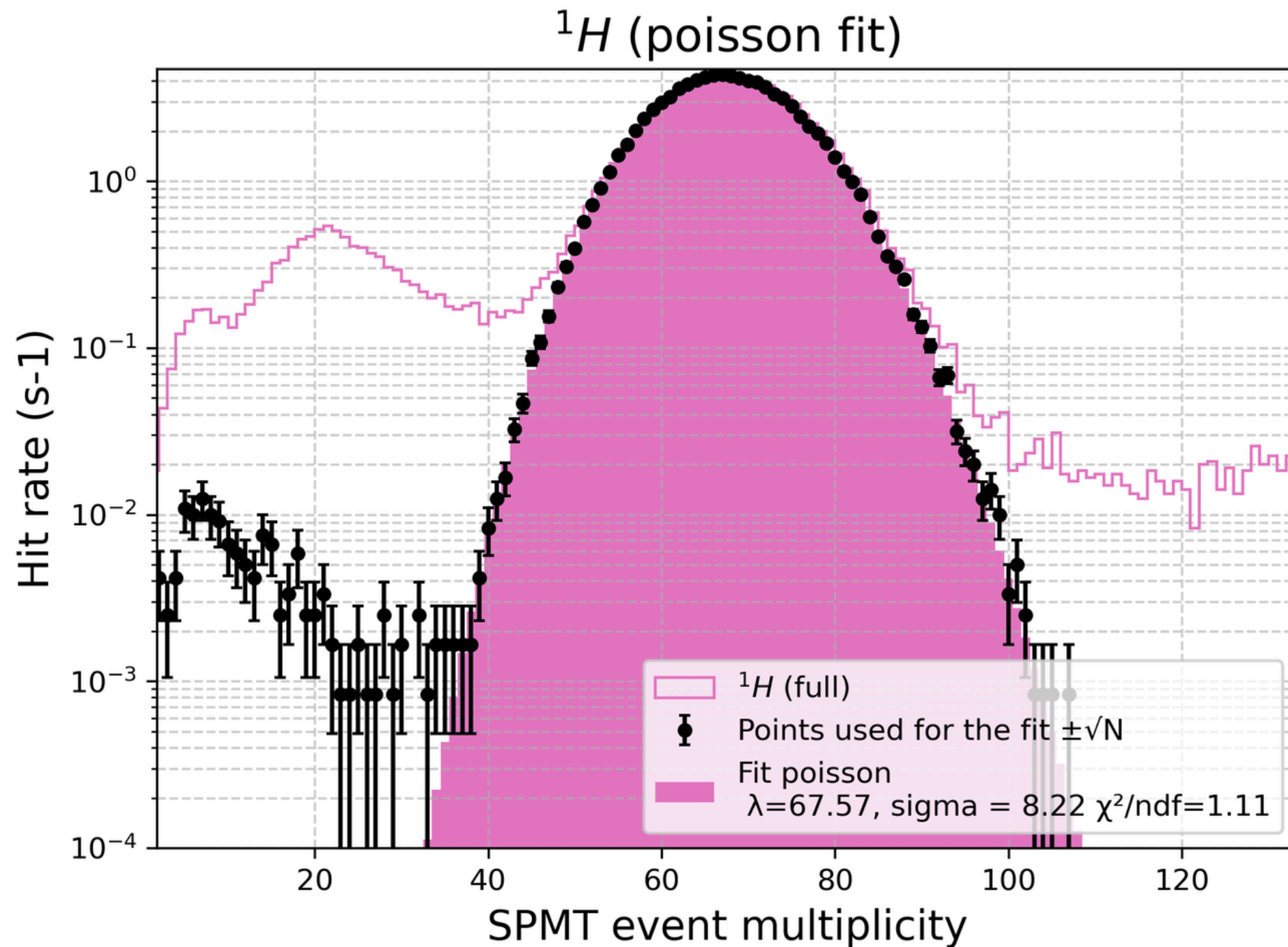
Dark Count rate contribution DC_{hits}



- The DC contribution is calculated for each run as the number of hits per Periodic Trigger event in the SPMT system.
- A 5ms muon veto is applied using the Amber muon reconstruction method, which helps to eliminate after-pulses that could affect the DC spectrum.
- The mean of the histogram is taken as the DC contribution after applying a Poisson fit and extract λ .
- Bad channels are removed from the DC calculation.

Anchor energy point

$$\frac{E_{n-H}}{N_{hits}^{n-H}(0,0,0)}$$

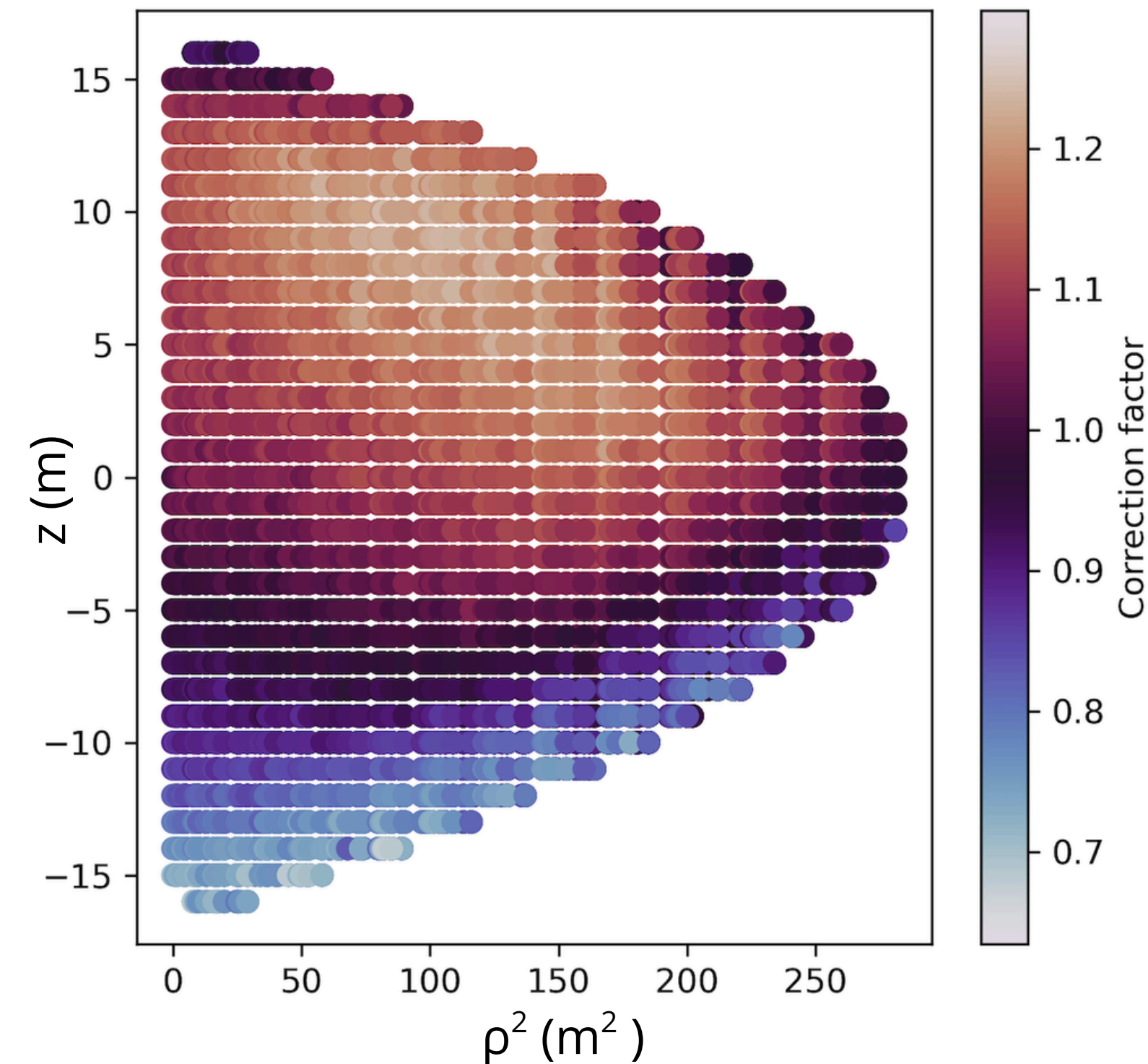


- The anchor energy is measured using delayed neutrons from an AmC source located at the center of the CD.
- The anchoring coefficient is measured at 61.14 hits for 2.223 MeV at the center of the CD after subtracting dark count.

$$\frac{E_{n-H}}{N_{hits}^{n-H}(0,0,0)} = \frac{2.223}{61.14} \text{MeV} \cdot \text{Hits}^{-1}$$

2.223 MeV n-H cosmogenic map

- From Raphael Gazzini selection

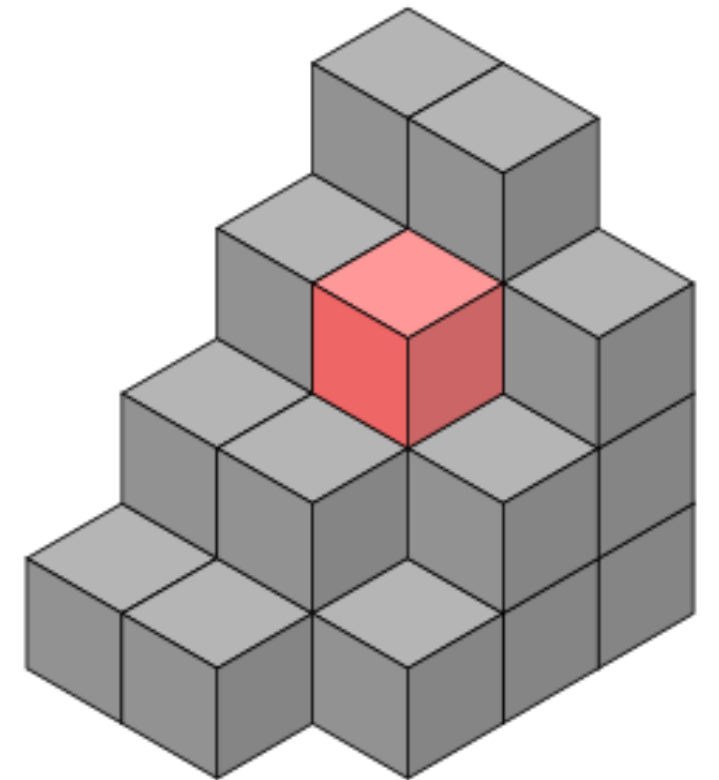


Event vertex affects detector response:

- Collected light depends on **event vertex**
- In the first data taking phase, part of the SPMTs were turned off, mostly in the south hemisphere, leading to **z-axis asymmetry**

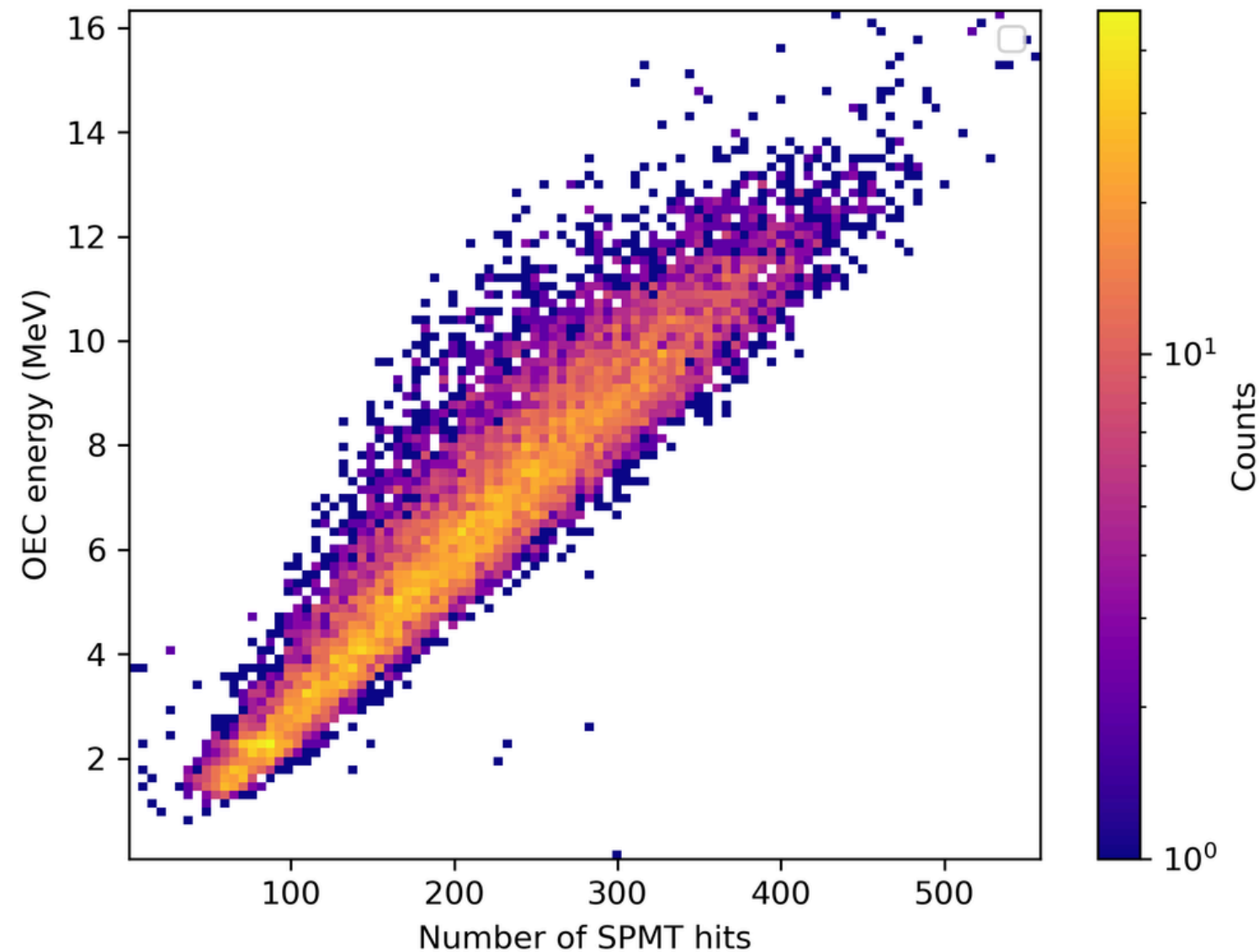
Correction using a non-uniformity map:

- Detector cut in **1m³ voxels**, 1 correction factor per voxel
- **Spallation neutrons**: 2.2 MeV gamma uniformly distributed
- Compared z axis correction with calibration ⁶⁸Ge runs

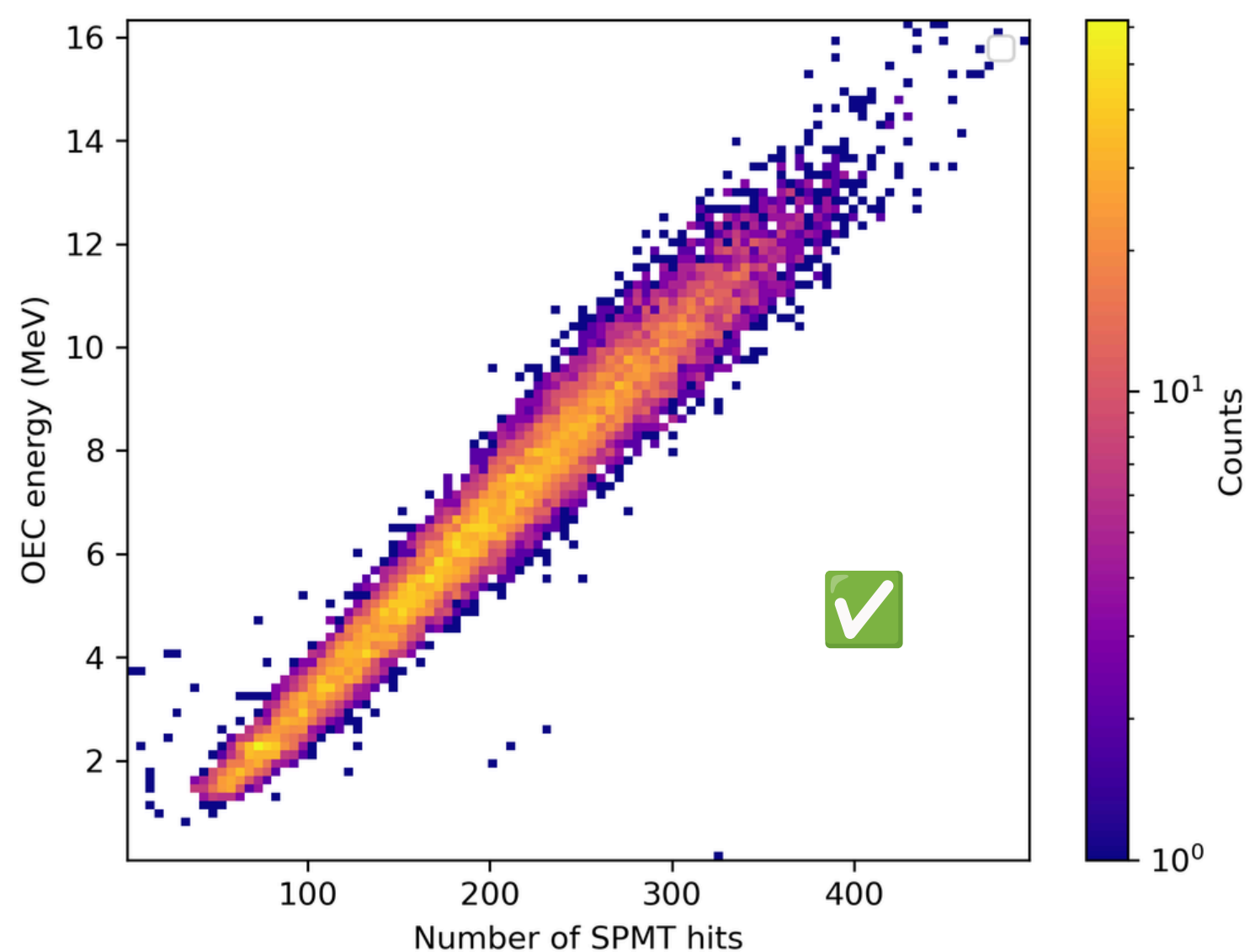


Non-uniformity correction $M_n(x, y, z)$

^{12}B before correction



^{12}B after correction

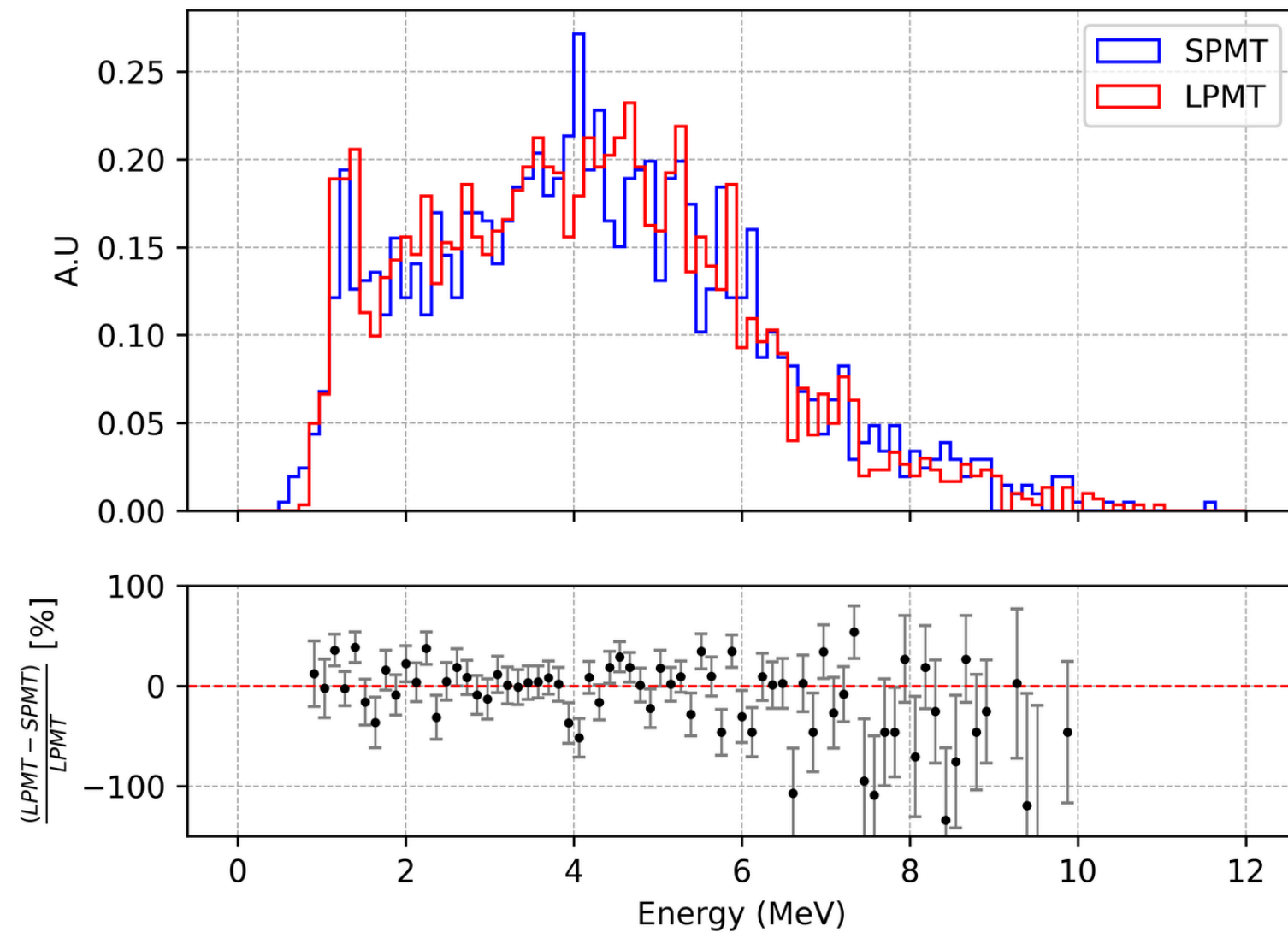


- A good way to verify that the map is working is to apply the corrections factors to a SPMT spectrum such as ^{12}B and compare it to the Omilrec reconstruction, which accounts for the non-uniformity of the LPMT system.
- Once the correction is made, the trend becomes linear.

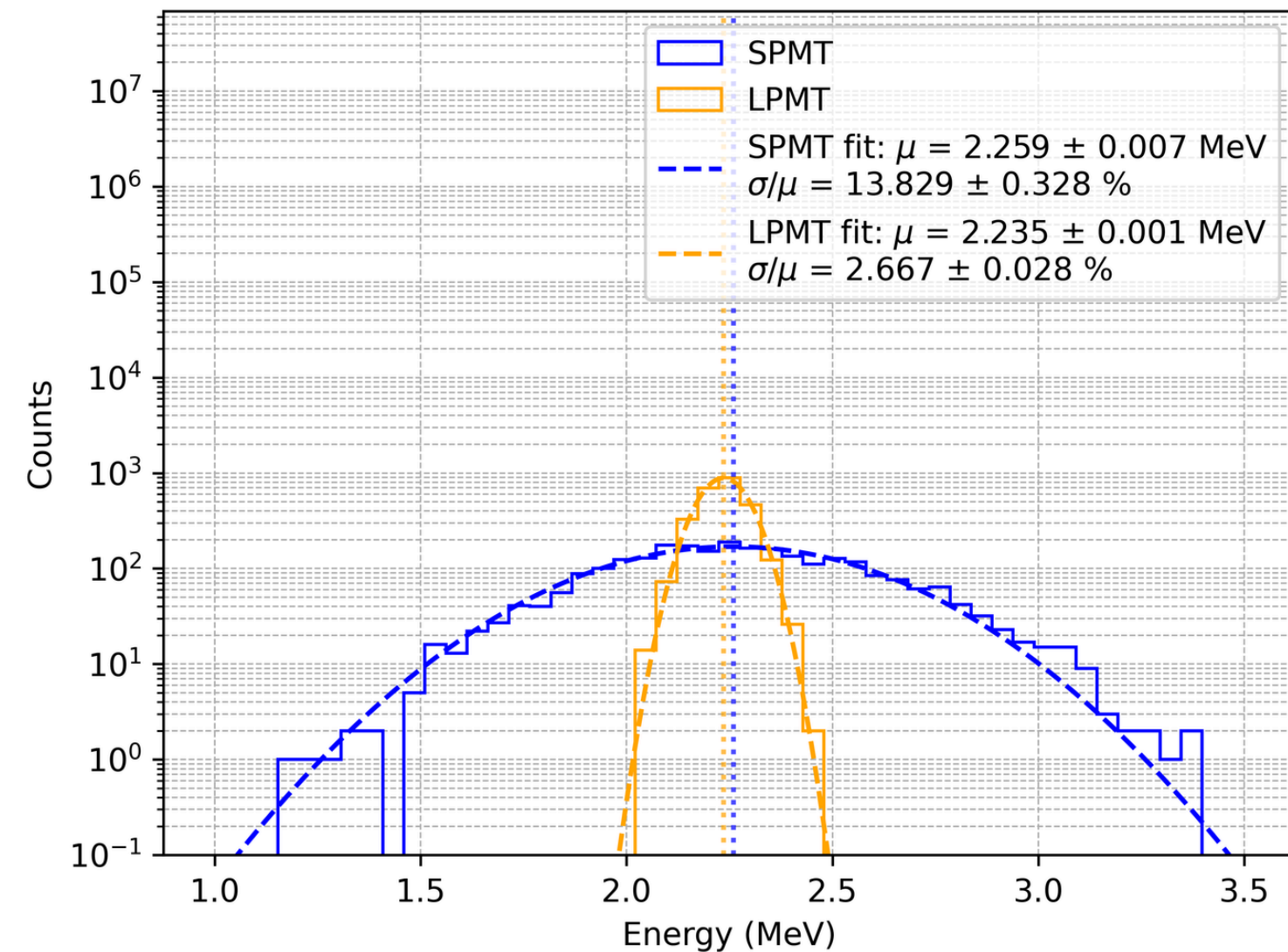
Effect on IBD spectrum

- From Matthieu Lecocq selection cross-checked

Prompt IBD spectrum Reprod C

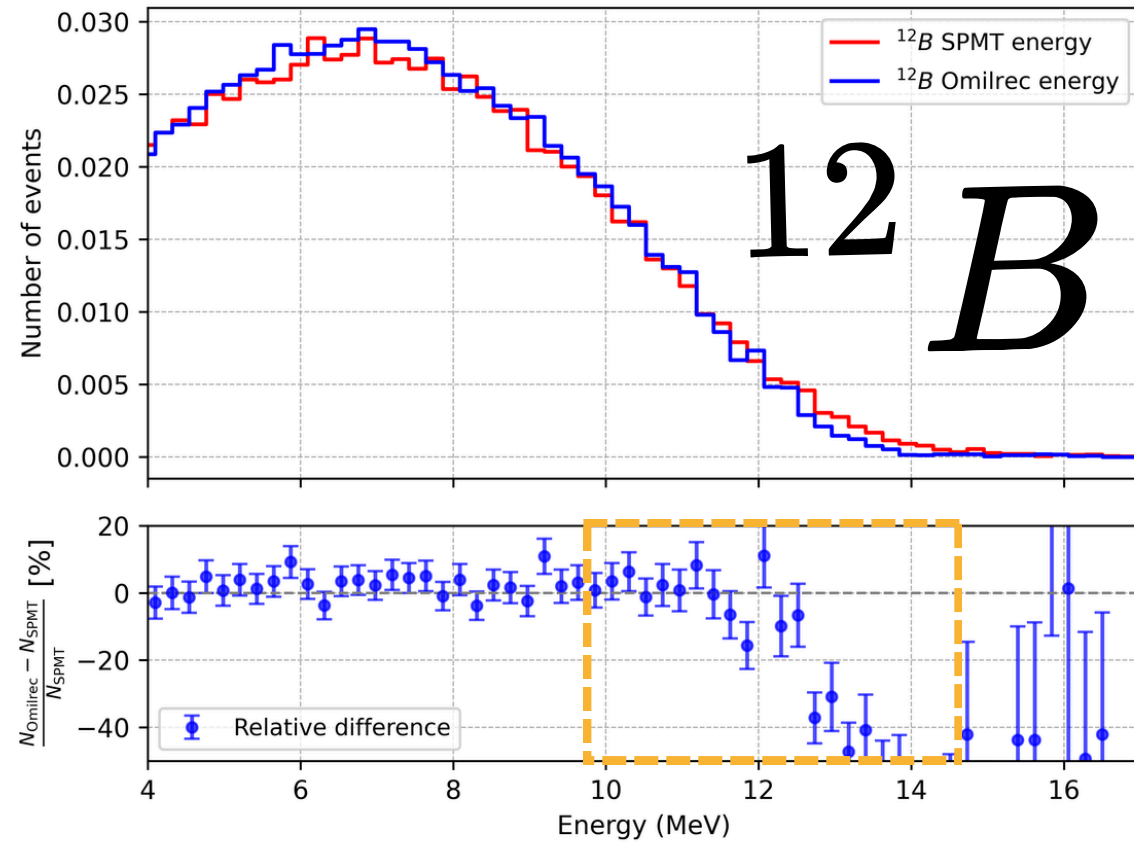


Delayed IBD spectrum Reprod C

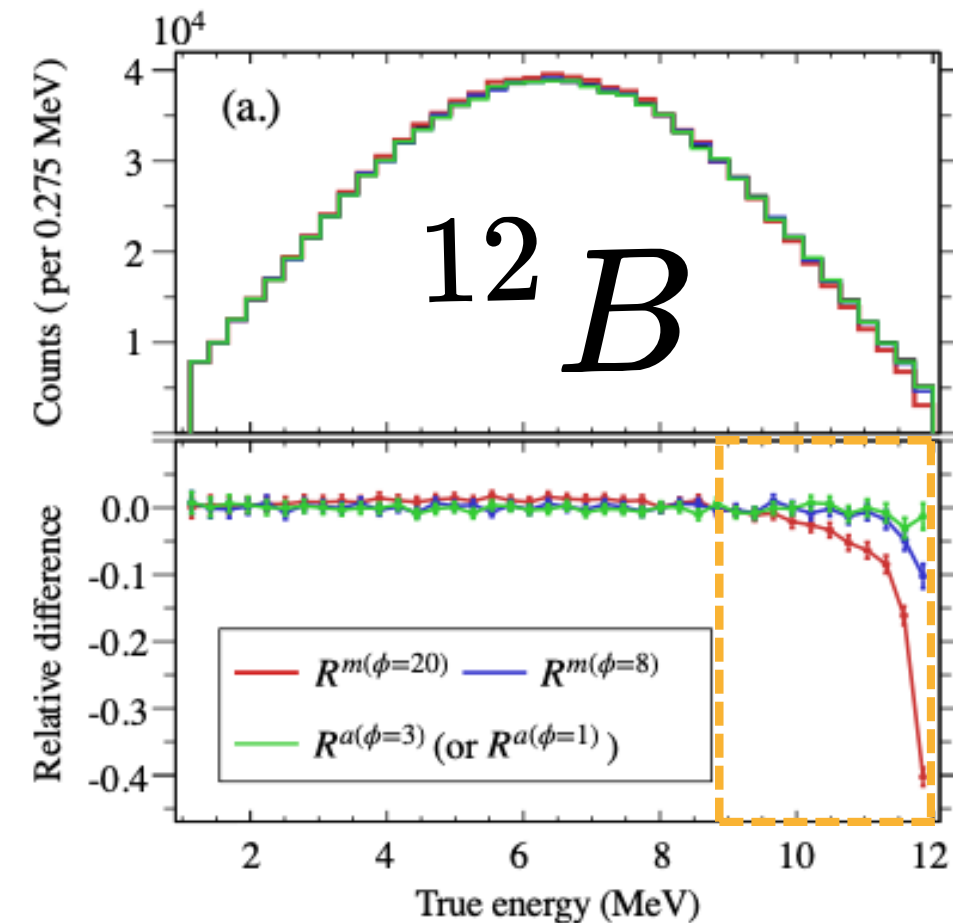


- The SPMT's IBD response spectrum matches that of the Omilrec. At low energies, the effect of poor resolution is evident in the SPMT system.
- For the delayed spectrum, the effect of resolution is clear, the SPMT energy (2.259 MeV) is not consistent with the Omilrec one (2.23 MeV) even with error bars.

Instrumental non-linearity



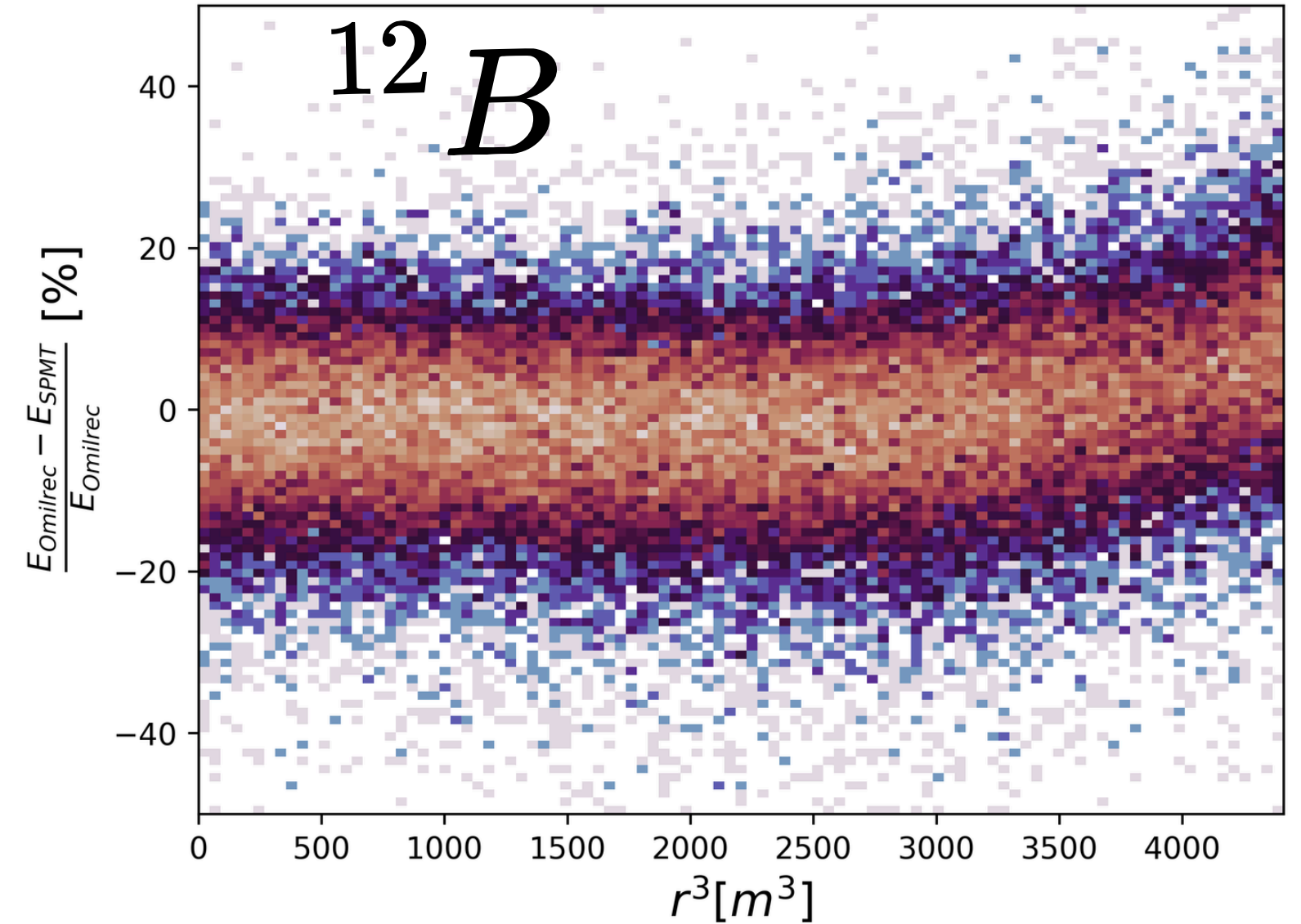
Data



Simulation

Multi-Calorimetry in Light-based Neutrino Detectors

Anatael Cabrera^{1,2,3}, Yang Han^{1,2,4}, Steven Calvez⁵, Emmanuel Chauveau⁶, Hanyi Chen¹, Hervé de Kerret¹²,



Issues with the energy reconstruction.
→ Single photo-counting assumption not available at the edges of the Central Detector.

Poisson-likelihood techniques will be used

Comparison SPMT/LPMT

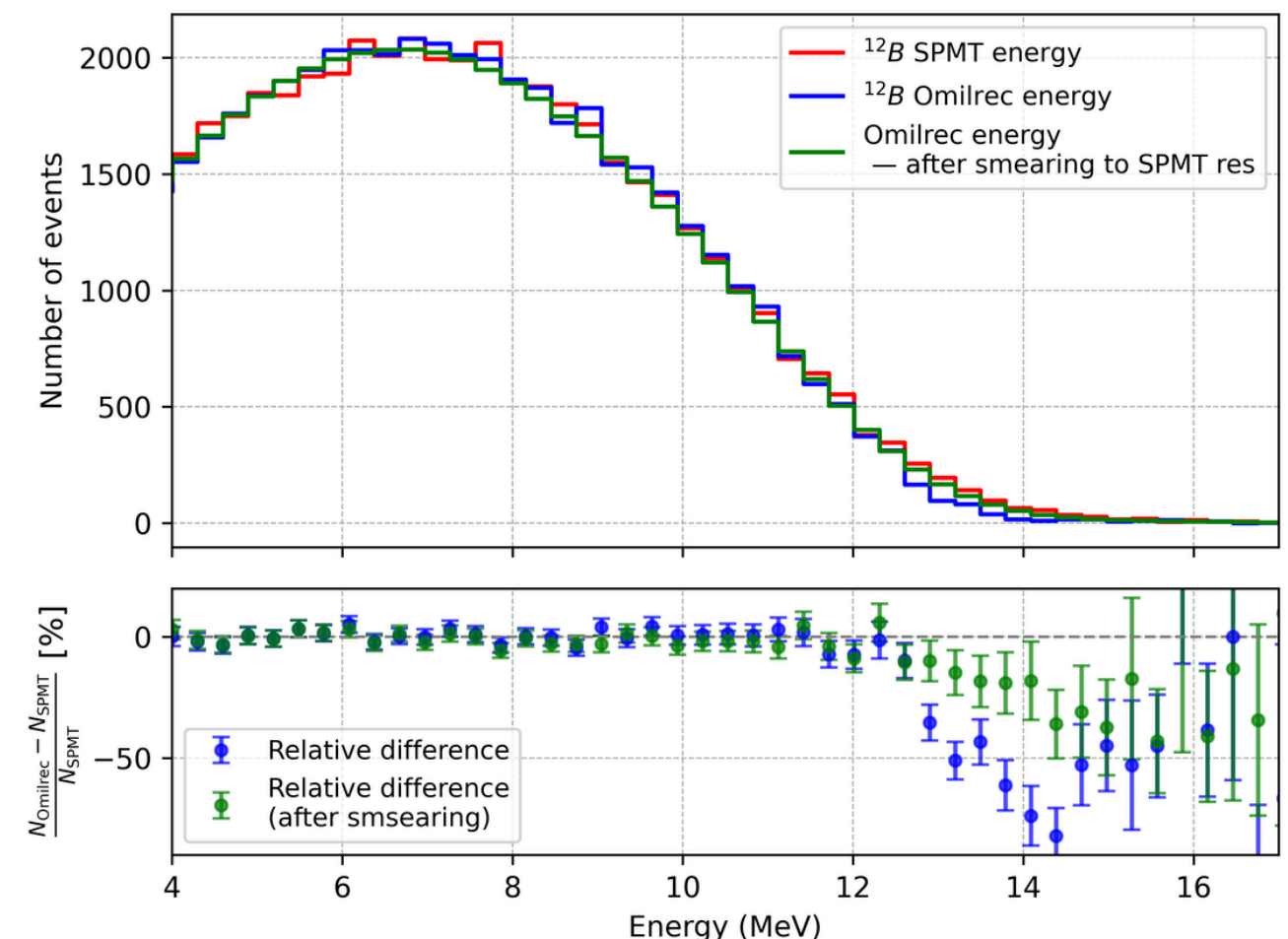
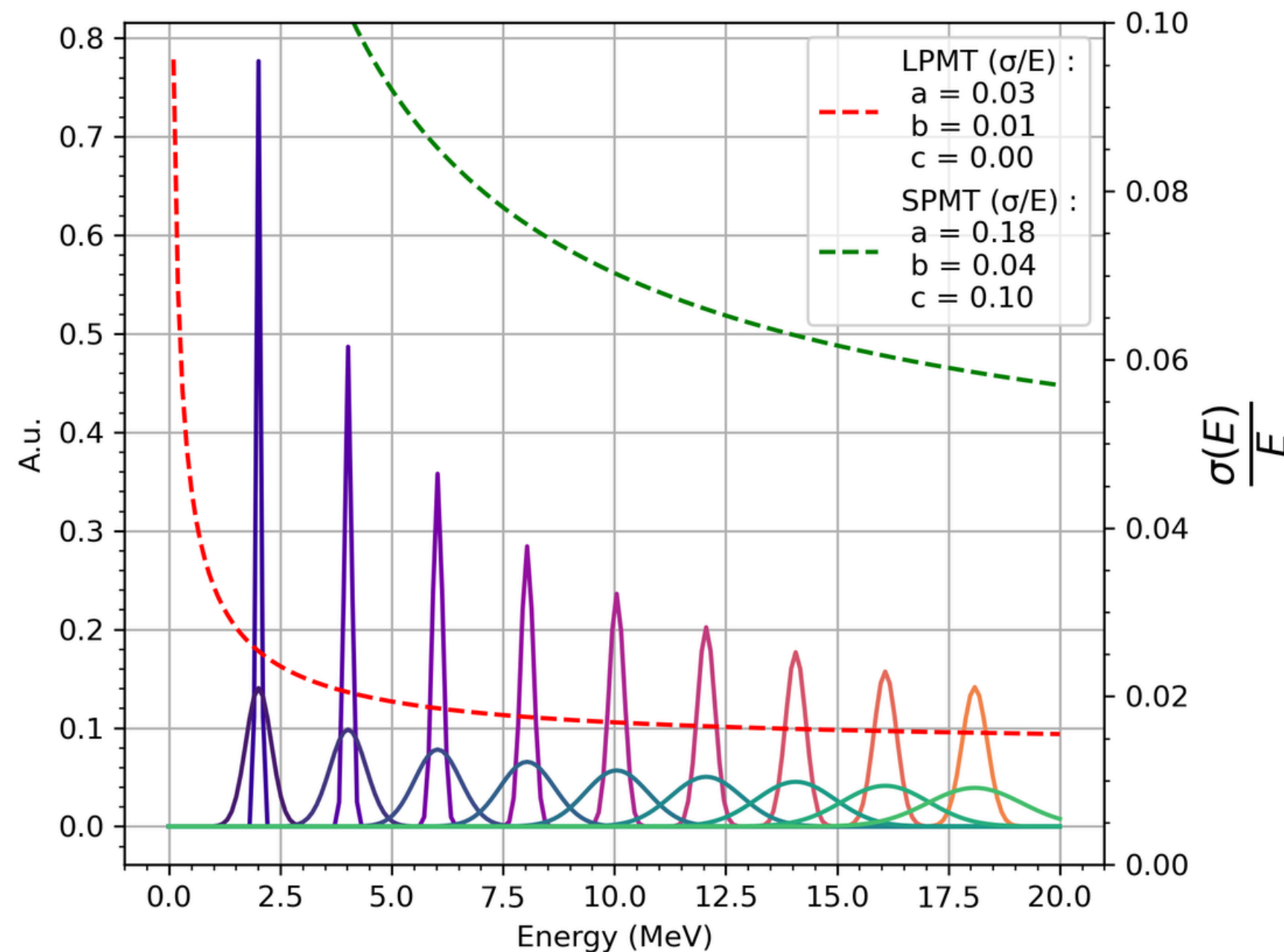
In order to compare the energy reconstruction obtained with LPMT to that obtained with SPMTs, the LPMT spectrum is smoothed by reducing its resolution to that of the SPMT system.

$$\sigma(E) = E \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

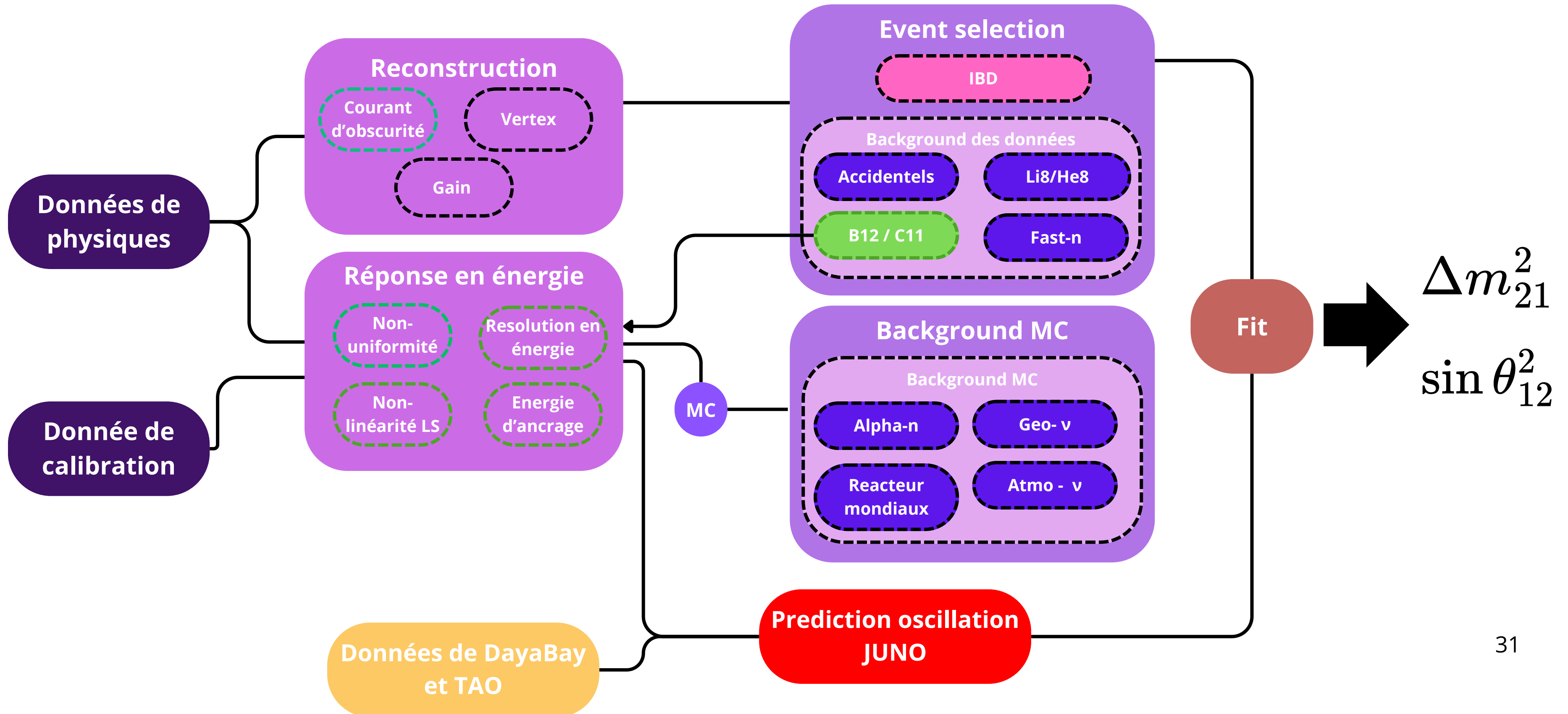
$$S(E) \star G(E) = \sum_{m=0}^{E_{max}} S(m)G(n-m)$$

$$\text{With : } G(E) = \frac{1}{\sqrt{2\pi}\sigma(E)} e^{-\frac{E^2}{2\sigma_{degrad}^2(E)}}$$

$$\text{Assumption: } \sigma_{degrad}^2 = \sigma_{SPMT}^2 - \sigma_{LPMT}^2$$

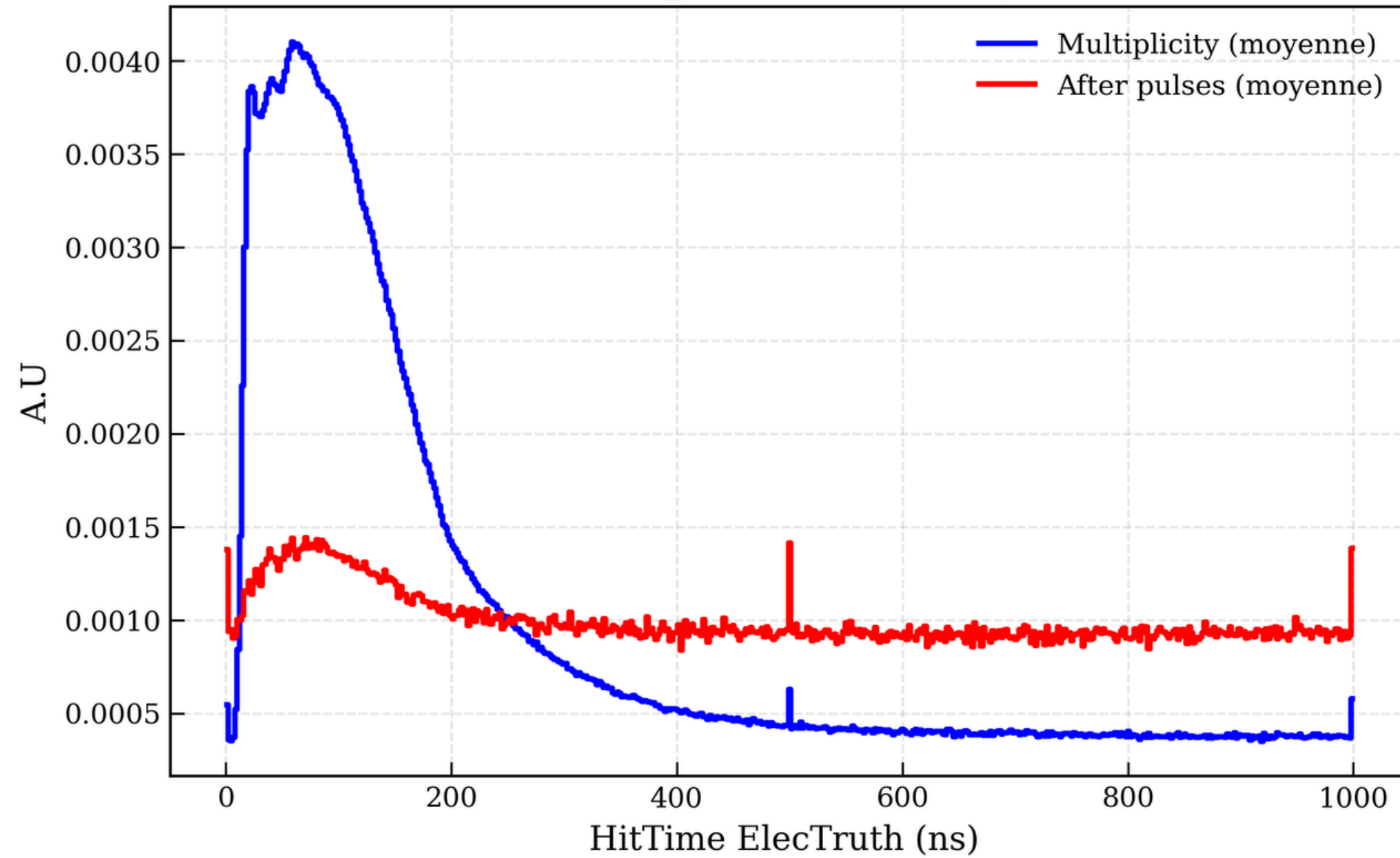


Mesure d'oscillation pipeline

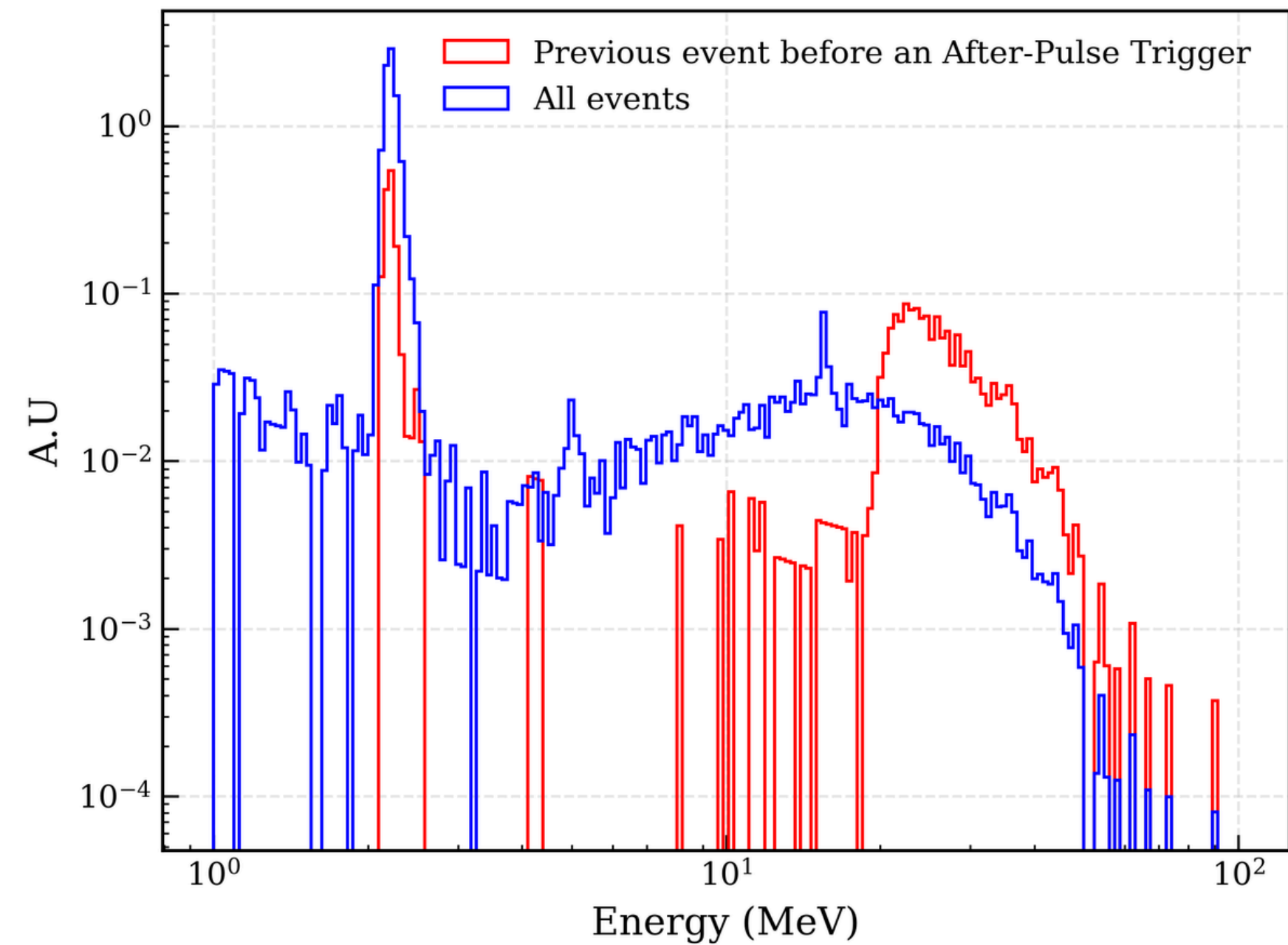


After-pulses

After-pulse Time profile

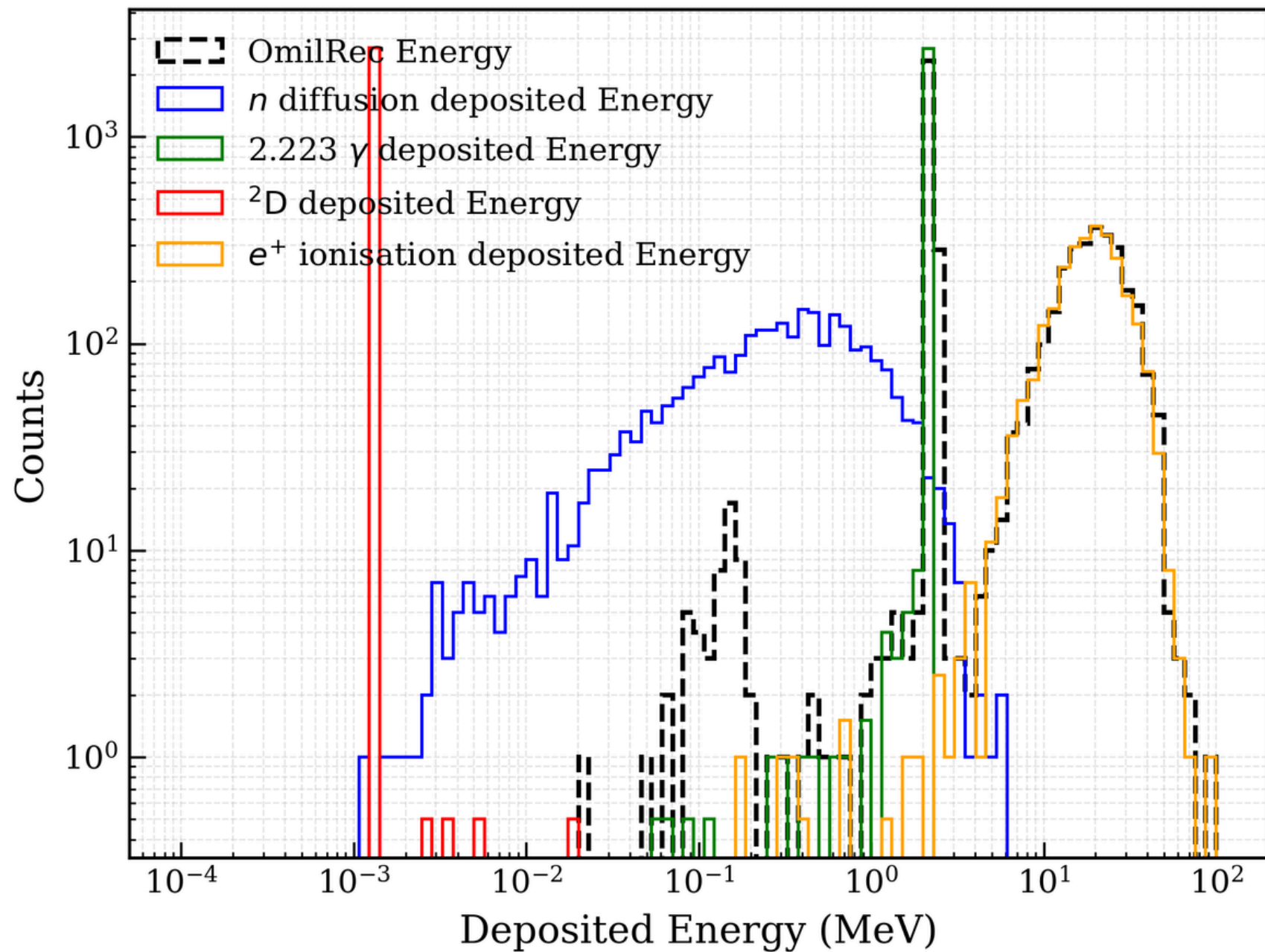


Previous event after an after-pulses



IBDs

IBDs deposited energy
vs reconstructed energy



First IBD selection

