Study of muon-induced background in MMC detector arrays for the ECHo experiment

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"Neutrino Mass Determination by Electron Capture in Holmium-163 (ECHo)"

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Introduction

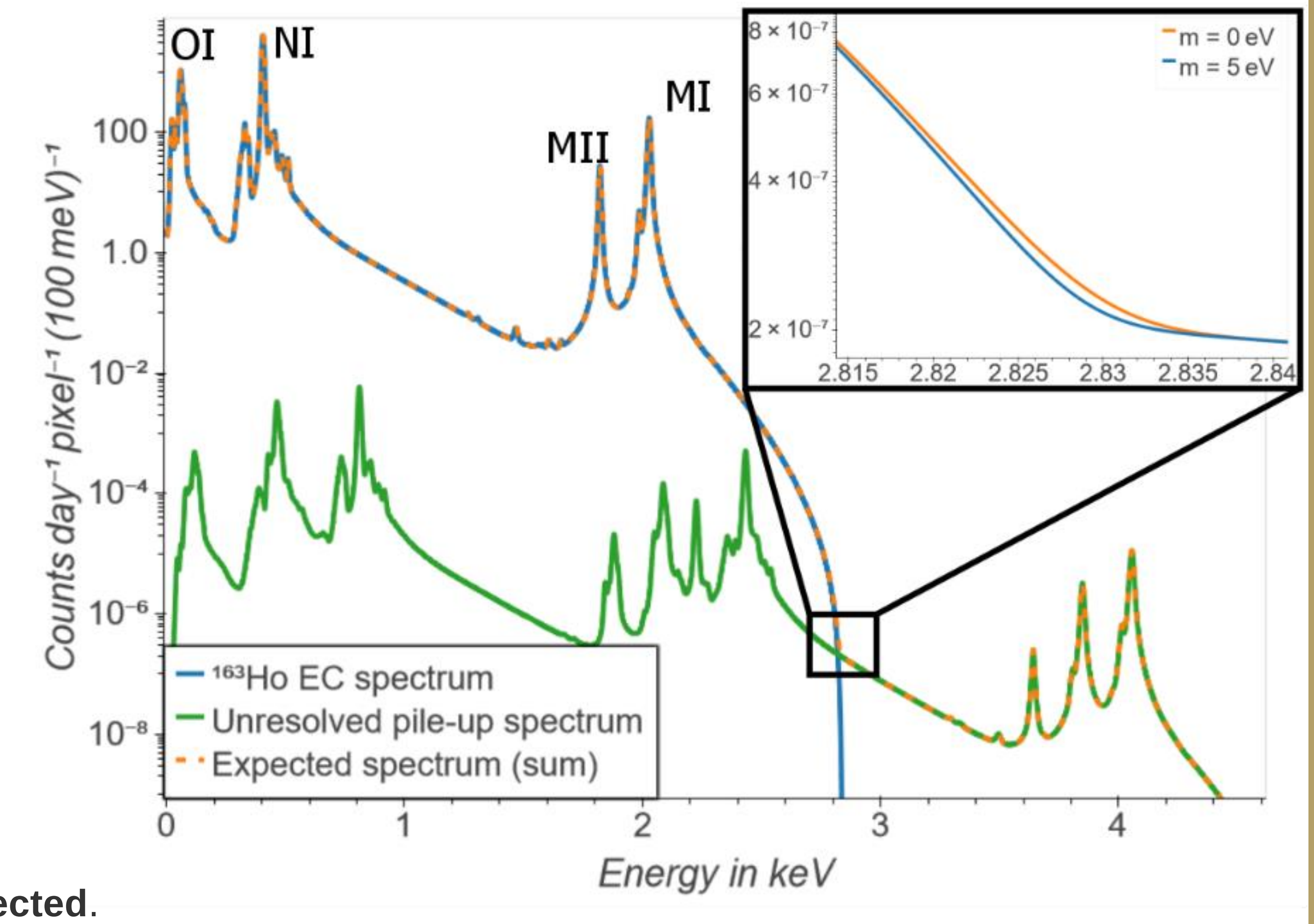
The ECHo experiment is designed to measure the effective ν_e mass by using arrays of cryogenic metallic magnetic calorimeters (MMCs).

^{163}Ho is implanted in the MMC's absorbers → 4π geometry → full energy absorption

The maximum energy Q_{EC} available for the ^{163}Ho electron capture (EC) is about 2833 eV.

In the first phase ("ECHo-1k"), an activity A = 10 Bq of ^{163}Ho in each pixel is assumed.
https://doi.org/10.1007/s10909-014-1187-4

Based on the theoretical spectrum described in https://arxiv.org/abs/2002.05989 by M. Brass and M. Haverkort,
from the signal in the ROI, the last 10 eV below Q_{EC}, a count rate of about 10^{-5} counts day^{-1} $pixel^{-1}$ is expected.



If two ^{163}Ho nuclei decay within the time resolution τ_r (= 300 ns), the two events can not be discriminated and superpose to one single event. This is called unresolved pile-up and happens with a rate of $r_{pu} = A^2 \cdot \tau_r$

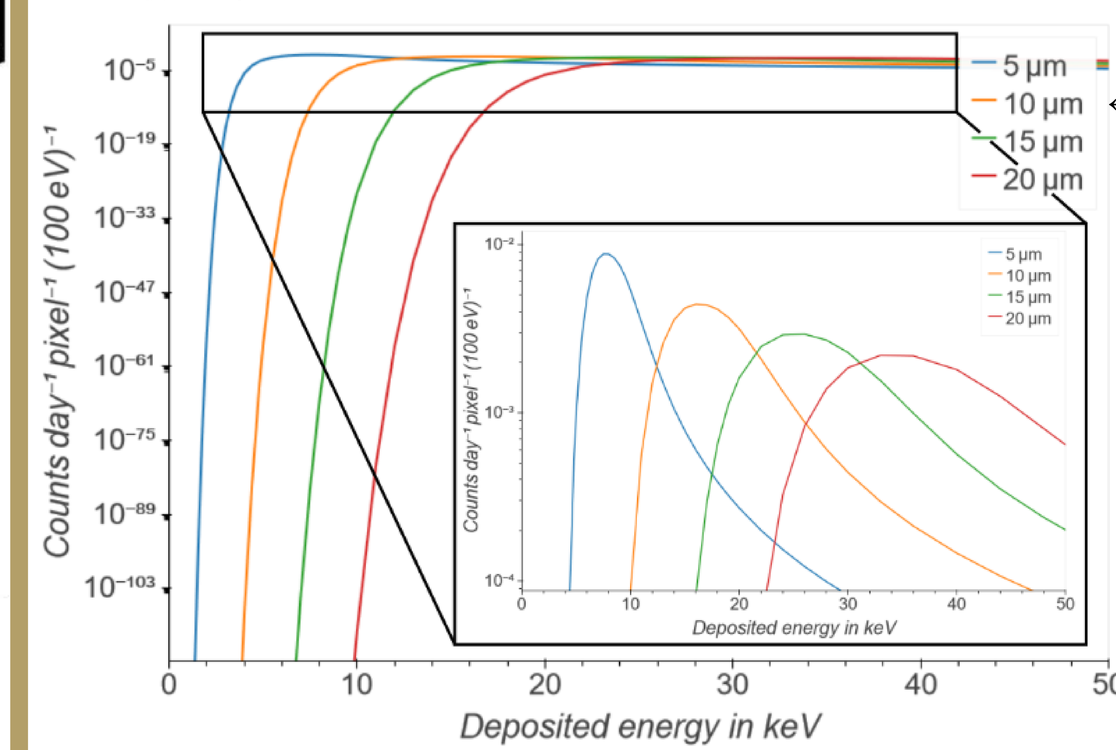
The ECHo collaboration aims to achieve the **unresolved pile-up** to be the **dominant background contribution** in the ROI, which is in the **same order as the signal**.
→ Other background contributions have to be reduced

Theory and Simulation Results

Expected: 180 muons s^{-1} m^{-2} at sea level
→ 0.5 direct muons hits day^{-1} $pixel^{-1}$

Deposited energy depends on path length, most dangerous are muons with small energies (muons from above).

Landau distribution:
Energy deposited in MMC's absorbers.

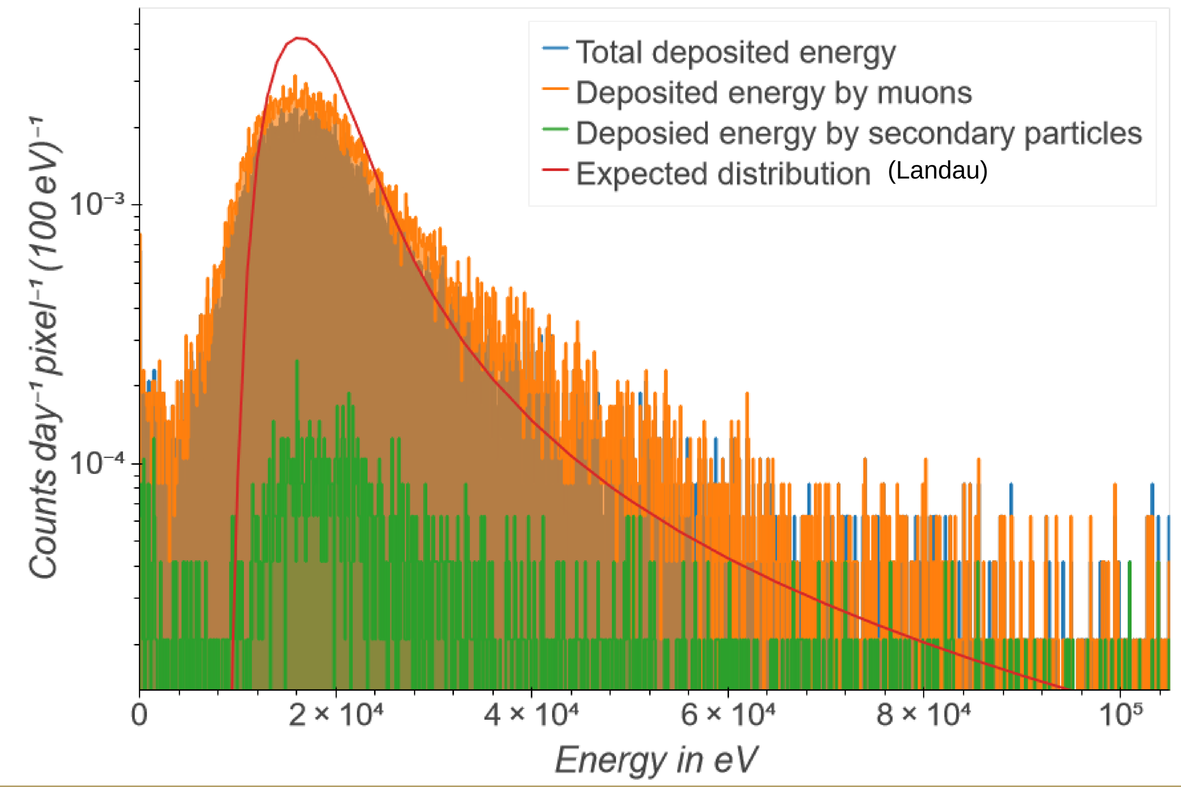


Events with energy larger than 10 keV are typically not acquired during measurement
→ **direct muon hits might not be seen.**

https://doi.org/10.1142/S0217751X18501750 https://doi.org/10.1016/S0168-9002(96)00774-7

Simulation shows that **mostly muons and,** in the substrate and Al shield, muon induced **δ-rays deposit energies directly** in the MMC's absorbers.

About 10^{-5} counts day^{-1} $pixel^{-1}$ are expected in the ROI due to muon induced events (direct hits).



Setup

Simulation

Muons can generate **secondary radiation** (X-rays, δ-rays, etc.). These particles and the muons can be studied in **Monte Carlo** (MC) simulations (GEANT 4). Only **direct energy deposition** (= energy loss) are included and the production energy – the minimum kinetic energy of produced particles – needs to be defined. Only affects particles generated by processes with infrared divergence (bremsstrahlung, δ-ray production,…). This energy is equal to a minimum distance the particles have to travel before getting absorbed. Particles with lower energies are not produced, and the energies are deposited locally.

Volume	Min range
MMC	100 nm
Thermal baths	100 nm
(*)Substrate	1.0 µm
SQUID chips	1.0 µm
PCB	10 mm
Plugs	1.0 mm
(*)Copper holder	1.0 mm
(*)Shielding	1.0 mm

For each volume, the minimum distance (range) is defined. Some components (marked with '*') consist of sub volumes with different (smaller) minimum distances.

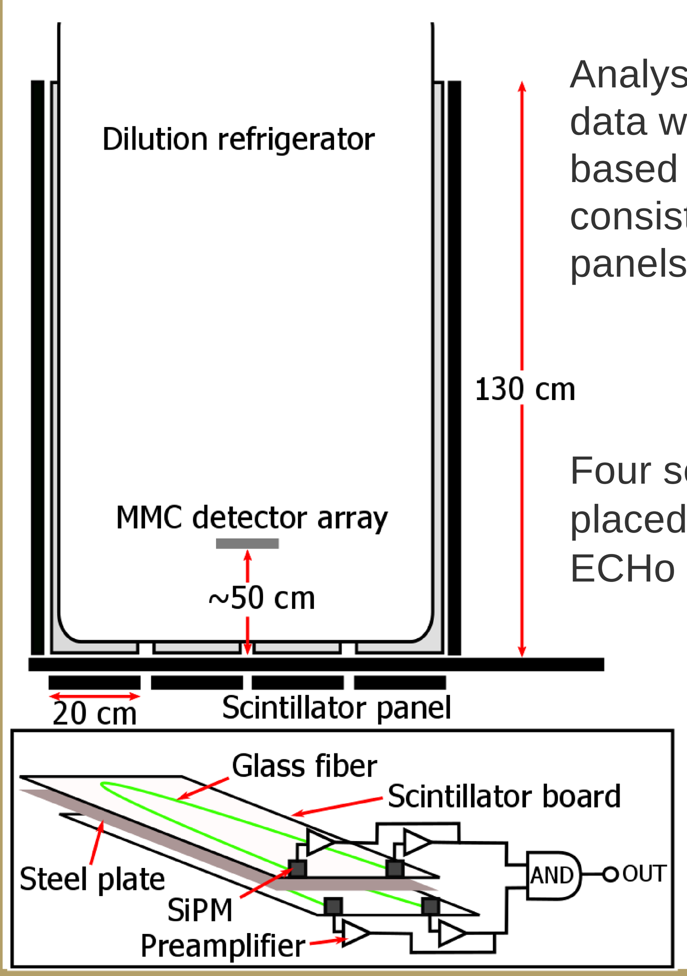
Measurement

Muons are used as a **sample of ‚substrate' events**, signals caused by energy deposition in the substrate next to the MMCs.

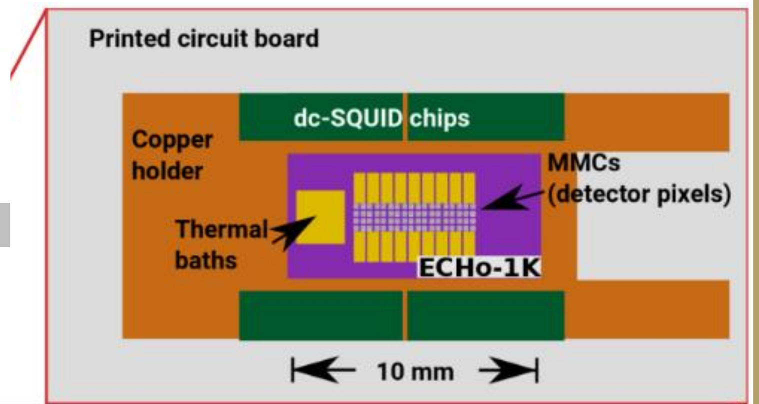
Analysis of **36 pixel-days** of data with a plastic scintillator based active **muon veto**, consisting 24 scintillator panels.

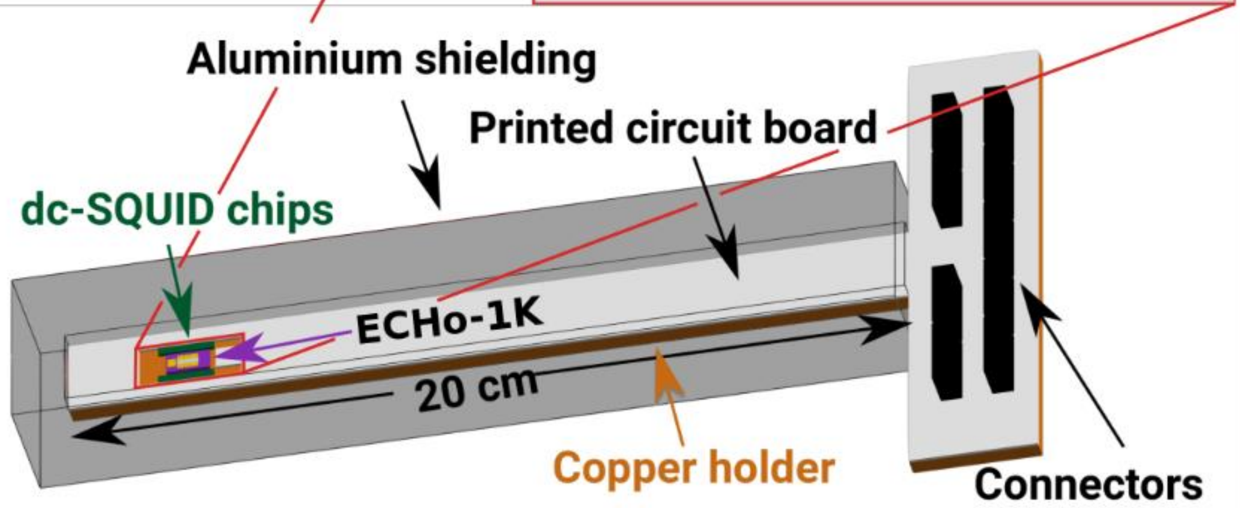
Four scintillator panels are placed at each side of the ECHo dilution refrigerator.

A veto signal raises, if at least two panels from two different sides raise a signal. In this setup the veto efficiency is larger than $(80\,\%)^2 = 64\,\%$.



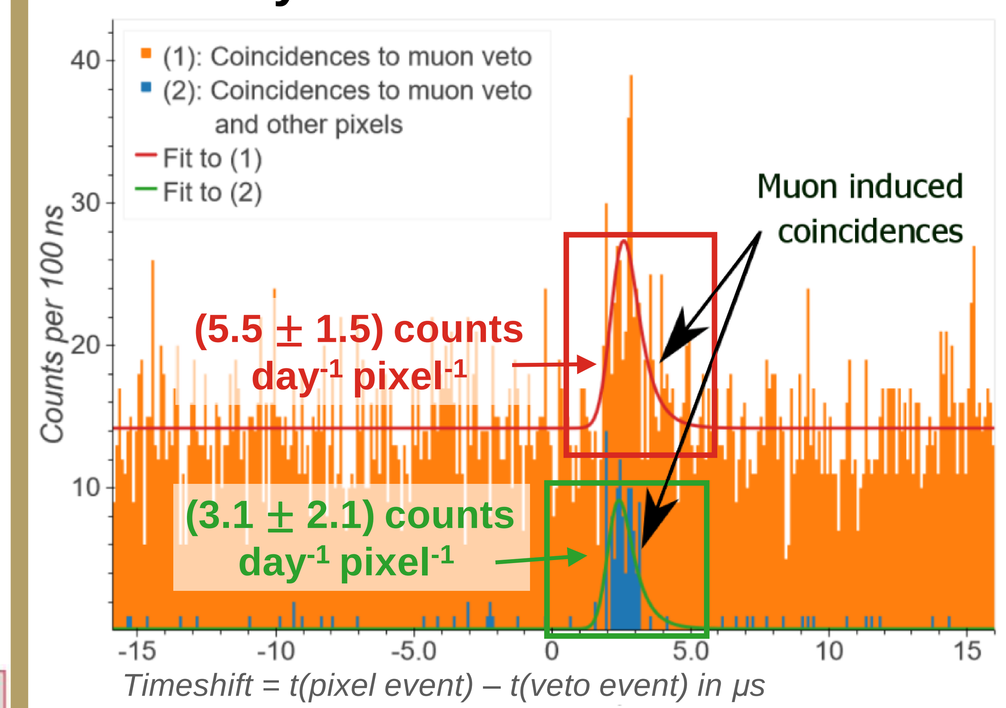
Dimension of MMCs:
180 µm x 180 µm x 10 µm gold absorber
on top of an Ag:Er sensor with a thickness of 1.35 µm





Pulse Shape Analysis

1. Identify muon induced events



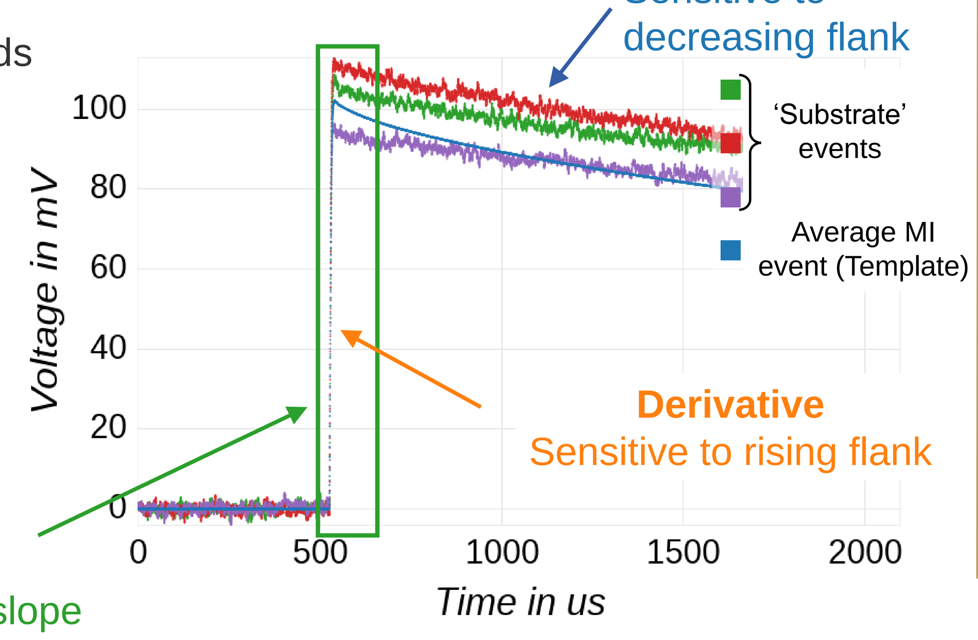
About 10 – 20 times the exception from the simulation is observed.

(Muon induced) substrate events are seen by Neighboring channels.

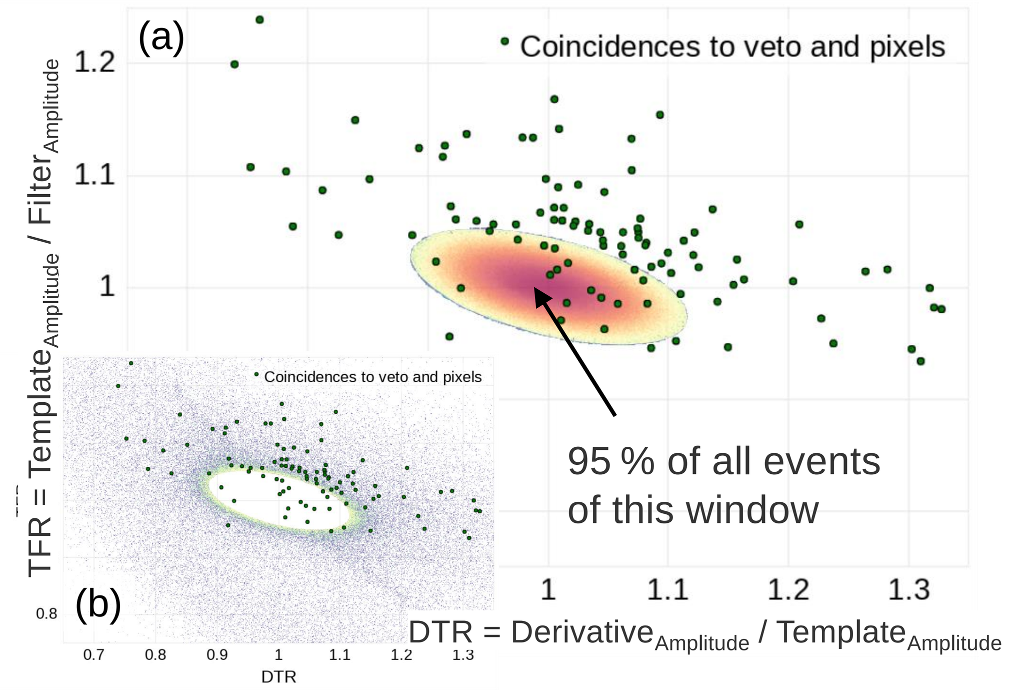
2. Define pulse shape parameters

Different methods To reconstruct deposited energy:

Template fit
Matched Filter
Derivative



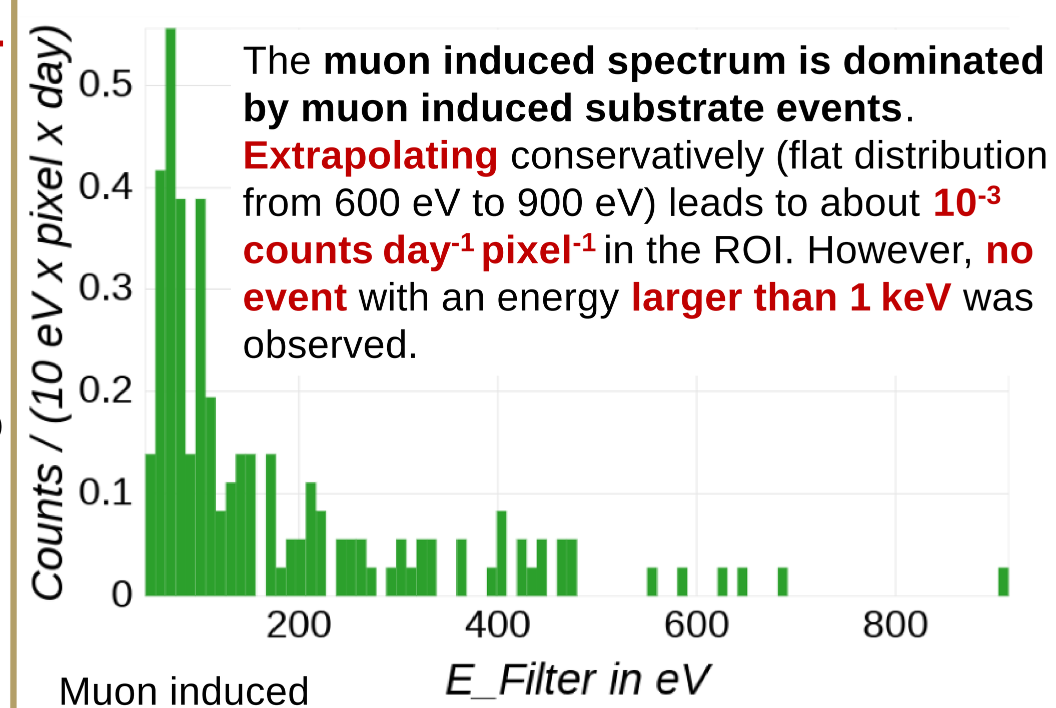
Ratio of reconstructed energies is the same for all energies, but different for different kind of pulses.



(a) ‚good' pulses
(b) ‚bad' pulses

Calibrate ratio, so that ratio = 1 for Ho-MI pulses.

By counting the events (only) **coincidental to the muon veto** (the orange events of histogram) within the ellipse, about **(6.5 ± 1.2) counts day^{-1} $pixel^{-1}$** are measured.



Muon induced (substrate) events

The **muon induced spectrum is dominated by muon induced substrate events**. **Extrapolating** conservatively (flat distribution from 600 eV to 900 eV) leads to about **10^{-3} counts day^{-1} $pixel^{-1}$** in the ROI. However, **no event** with an energy **larger than 1 keV** was observed.

Conclusion

Muon induced events are recognized by a muon veto, but PSA and pixel coincidences can also be used to identify muon induced events.

In 36 pixel-days, no muon induced events with energies larger than 1 keV were observed.