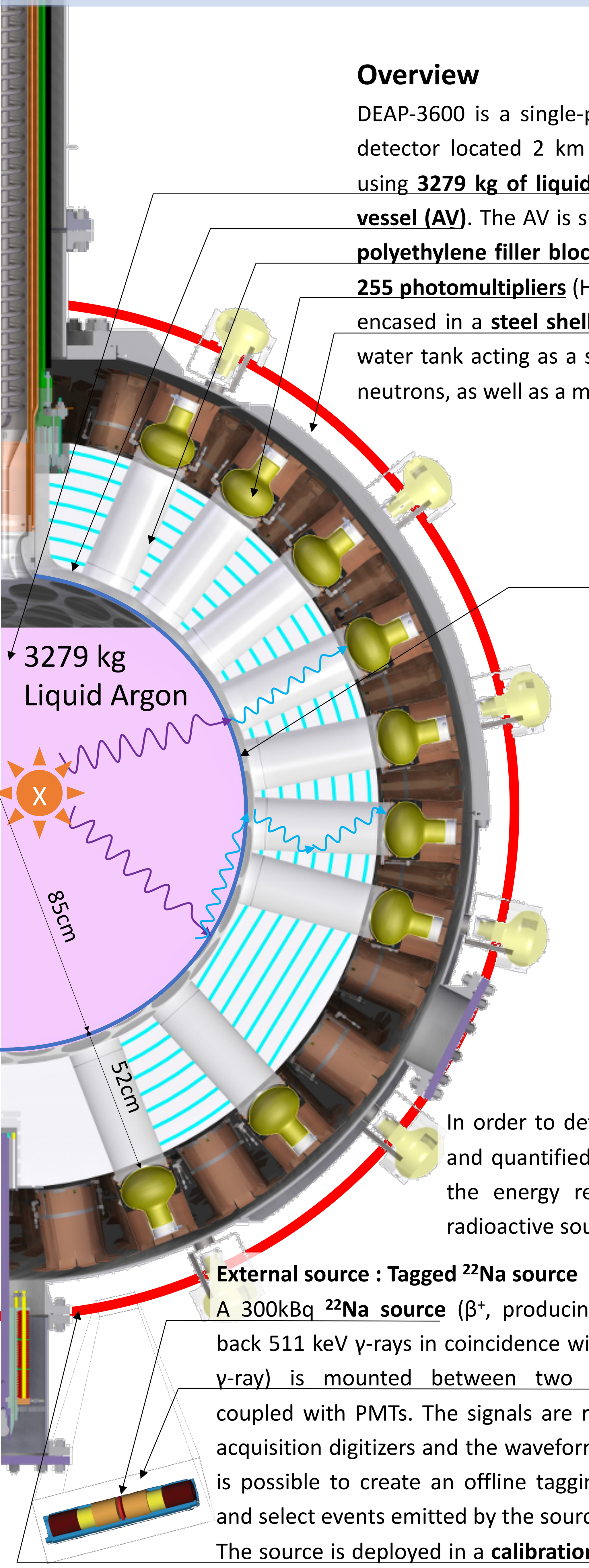
Calibrating an ultra-low background detector: DEAP rising to the challenges

The DEAP collaboration

DEAP-3600 is a single-phase liquid argon WIMP detector, operating at SNOLAB (Sudbury, Ontario) since 2016. With the 2km rock overburden, the facility boasts one of lowest muon flux in the world. DEAP-3600 was built with the goal of being background-free in the region of interest for three years of accumulated data. The design choices made to meet this requirement meant that no calibration source could be deployed inside the argon volume, leading to an interesting energy calibration challenge.

The use of two radioactive sources, ^{39}Ar (natural isotope) and ^{22}Na (external), provided sufficient information for the first WIMP search. However, improvements in sensitivity require a better understanding of the energy response, particularly at low energy. In order to solve this issue, the DEAP collaboration is now planning to use two short-lived internal radioactive sources: ^{37}Ar and ^{83m}Kr.



Overview

DEAP-3600 is a single-phase Weakly Interacting Massive Particle (WIMP) detector located 2 km underground at SNOLAB (Sudbury, Ontario). It is using **3279 kg of liquid argon**, contained in a ⌀1.7 m transparent **acrylic vessel (AV)**. The AV is surrounded by a 0.52 m thick plastic shield made of **polyethylene filler blocks and acrylic light guides**, on which are mounted **255 photomultipliers** (Hamamatsu HQE R5912, PMTs). The whole system is encased in a **steel shell**, immerged at the center of a 7.5 m-high, ⌀7.5 m water tank acting as a shield against the surrounding source of γ-rays and neutrons, as well as a muon detector.

When an ionizing particle looses energy in the argon, it creates excimers which return to the ground state with emission of VUV photons (~128nm). The VUV photons are absorbed by a thin layer of **wavelength shifter** (1,1,4,4-tetraphenyl-1,3-butadiene, TPB) evaporated on the surface of the AV. Visible photons (~400nm) are re-emitted and travel through the acrylic light guides before being detected by the PMTs. The signals are recorded as waveforms which contain the photo-electrons (PEs) pulses.

The waveforms are digitized and analyzed offline. For every waveform, a Bayesian technique determines for each pulse if it was generated by dark noise, afterpulsing or genuine photons. In the last case it determines how many.

In order to detect WIMPs, all backgrounds need to be identified and quantified. This is possible only after a careful calibration of the energy response of the detector. For this purpose, two radioactive sources were used : ^{39}Ar and ^{22}Na

External source : Tagged ^{22}Na source

A 300kBq **^{22}Na source** (β^+, producing two back-to back 511 keV γ-rays in coincidence with a 1.27 MeV γ-ray) is mounted between two **LYSO crystals** coupled with PMTs. The signals are readout by the acquisition digitizers and the waveforms recorded. It is possible to create an offline tagging information and select events emitted by the source.

The source is deployed in a **calibration tube** running around the steel shell. The activity of the source need to be sufficient so that enough γ-rays cross the shielding into the active volume.

Internal source : ^{39}Argon

^{39}Ar is a natural radioactive isotope present in atmospheric argon at about 1 Bq/kg. It decays as a β^- with an end-point of 565 ± 5 keV. The end product, ^{39}K, is stable.

Energy response parametrization

The energy response of the detector is the number of PE detected when a particle deposits an energy E in the liquid argon. It is assumed to be Gaussian with:

$$\text{Mean } \mu = <N_{DN}> + Y_{PE} * E$$
$$\text{Sigma } \sigma^2 = \sigma_{PE}^2 * \mu + \sigma_{rel,LY}^2 * \mu^2$$

- $<N_{DN}>$ is the amount of dark noise from the PMTs as the PEs non correlated with the event (long time constant of the TPB, for instance)
- Y_{PE} is the light yield of the detector convoluted with the detection efficiency.
- Y_{PE}, σ_{PE}^2 and $\sigma_{rel,LY}^2$ are free parameters, $<N_{DN}>$ is constrained by the number of PE detected before an event.

The data is fit with a ^{39}Ar spectra and additional contribution from ^{39}Ar-^{39}Ar pile-up and γ-rays backgrounds generated by Monte-Carlo simulations

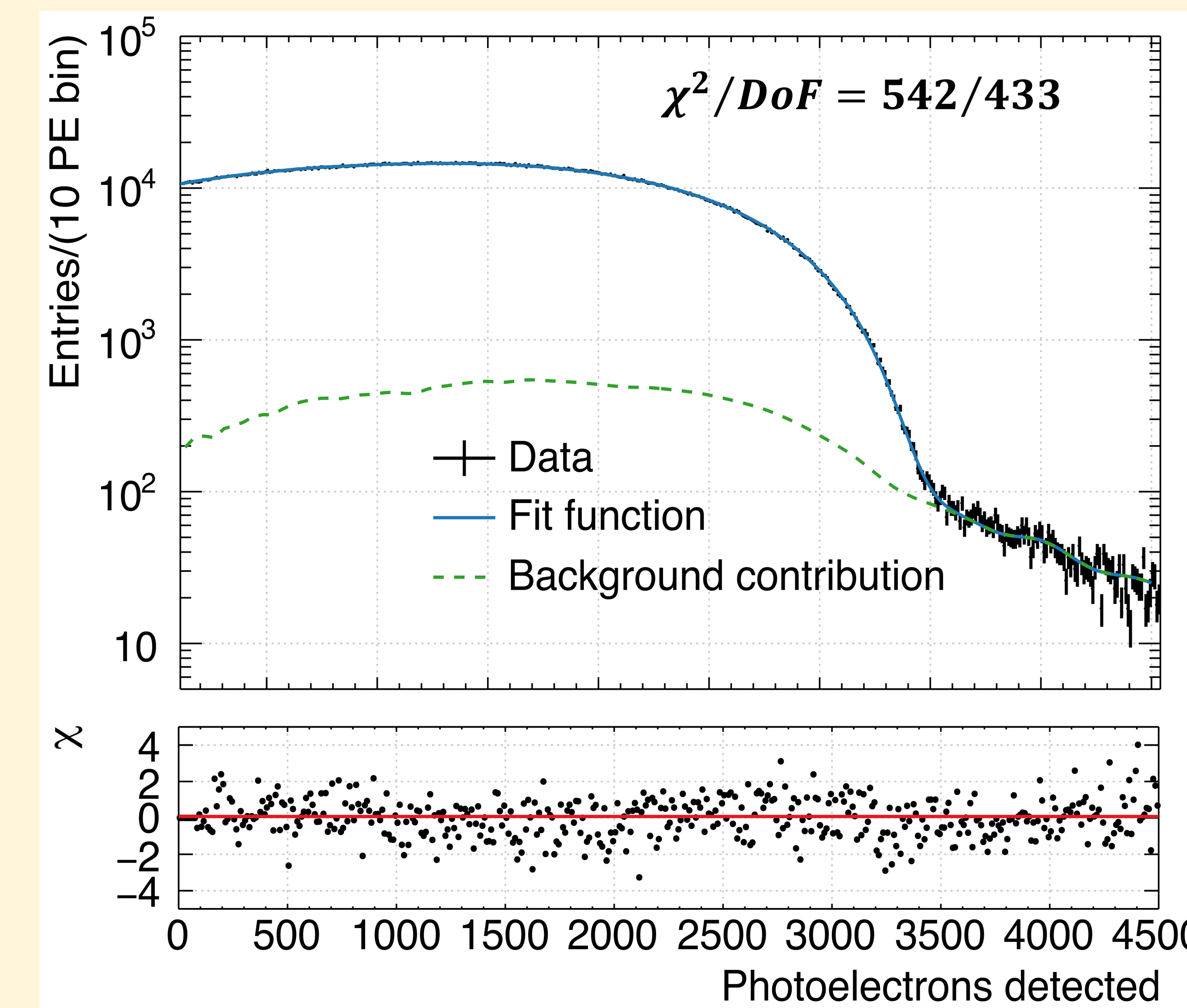
Due to uncertainties in the spectral shape, several theoretical spectra were tested:

- J. Kostensalo, et al., J. Phys. G 45, 025202 (2018).
- J. P. Davidson, Phys. Rev. 82, 48 (1951).
- M. Morita, Progr. Theor. Exp. Phys. 26, 1 (1963).
- L. Hayen et al., Rev. Mod. Phys. 90, 015008 (2018).

➢ The best fit is obtained with Kostensalo et al, with $\chi^2/DNF = 1252/534$

To account for mis-modeling uncertainties, a first-order correction to the spectra was implemented:

$$S'_{Ar}(E) = (1 - a_0(1 - 2E/500))S_{Ar}(E) \text{ with } a_0 \text{ constrained near zero.}$$

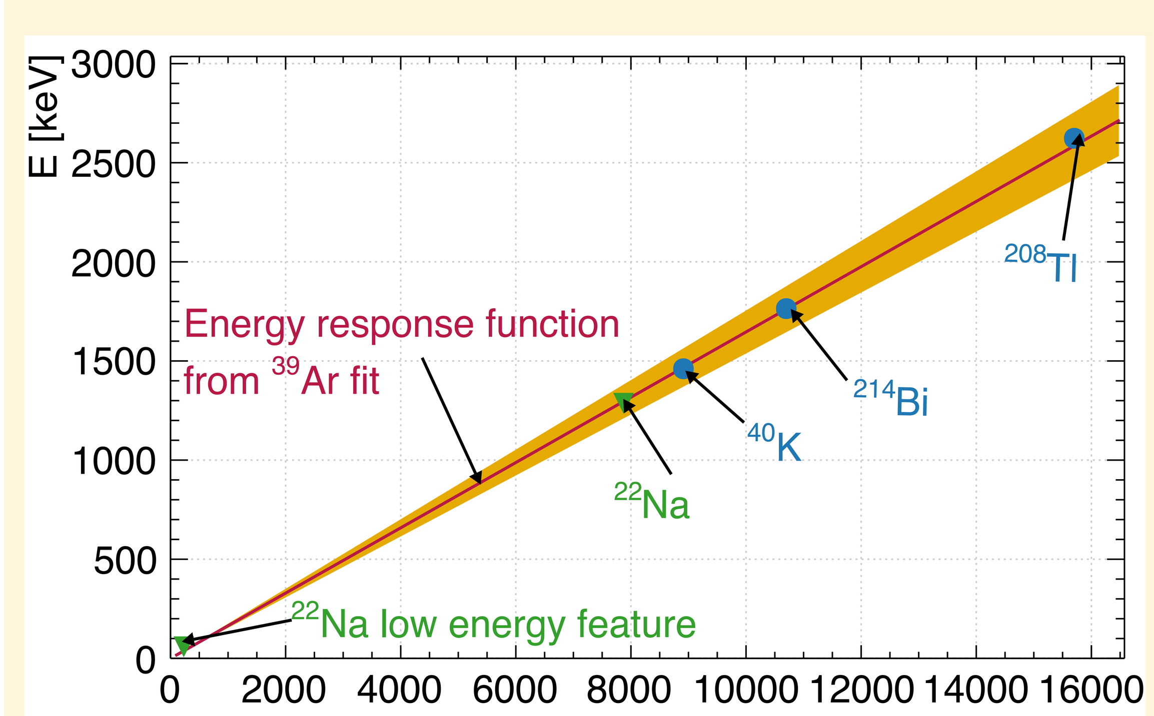


➔ **Best fit (Kostensalo), $\chi^2/DoF = 542/433$ (deviation from model <9%)**

	$<N_{DN}>$	Y_{PE}
PE Mean	$(\mathbf{1.1 \pm 0.2})$ **PE**	$(\mathbf{6.1 \pm 0.4})$ **PE/keV$_{ee}$**
	σ_{PE}^2	$\sigma_{rel,LY}^2$
Resolution	$(\mathbf{1.4 \pm 0.1})$ **PE**	$\mathbf{0.004^{+0.0010}_{-0.0004}}$

Consistency at higher energies

The data with ^{22}Na present a predominant peak at 1.27 MeV as well as a low energy feature due to the attenuation of γ-rays in acrylic. The peak position is consistent with the result of the fit. Cross checked with higher energy γ-rays peaks present in the detector shows a good linearity up to 1.46 MeV, where saturation effects start to be observed.



New low-energy calibration sources: ^{83m}Kr and ^{37}Ar

Although the uncertainties due to the linear correction were not the driving effect in the results recently released, they will become critical with more advance analysis technics in preparation. To mitigate this effect, two short-lived calibration sources are being prepared to improve the energy calibration around the region of interest.

- **^{83m}Kr** decays by internal conversion ($\tau_{1/2}$=1.8 h) and emits two successive γ-rays for a total energy of **41.5 keV**. With the separation of the two γ, two additional calibration points will be available: **32.1 keV** and **9.4 keV.** A small ^{83}Rb source will be prepared, continuously emanating ^{83m}Kr.

- **^{37}Ar** decays by electron capture ($\tau_{1/2}$=35 d) with emission of **2.8 keV** X-rays. The isotope is created by irradiation of Ca by fast neutrons at a reactor. The argon outgases and drifts in evacuated canisters used for transportation.

Both gaseous sources will be mixed with natural argon gas and injected in the detector through the purification system preventing a potential contamination of the detector. Thanks to its short life time, ^{83m}Kr can be used anytime and repetitively. The first deployment is expected in **fall 2019**. ^{37}Ar will have relatively long term effects (pile-up) and is not expected to be used before the **end of the blind data taking, in 2020**.

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