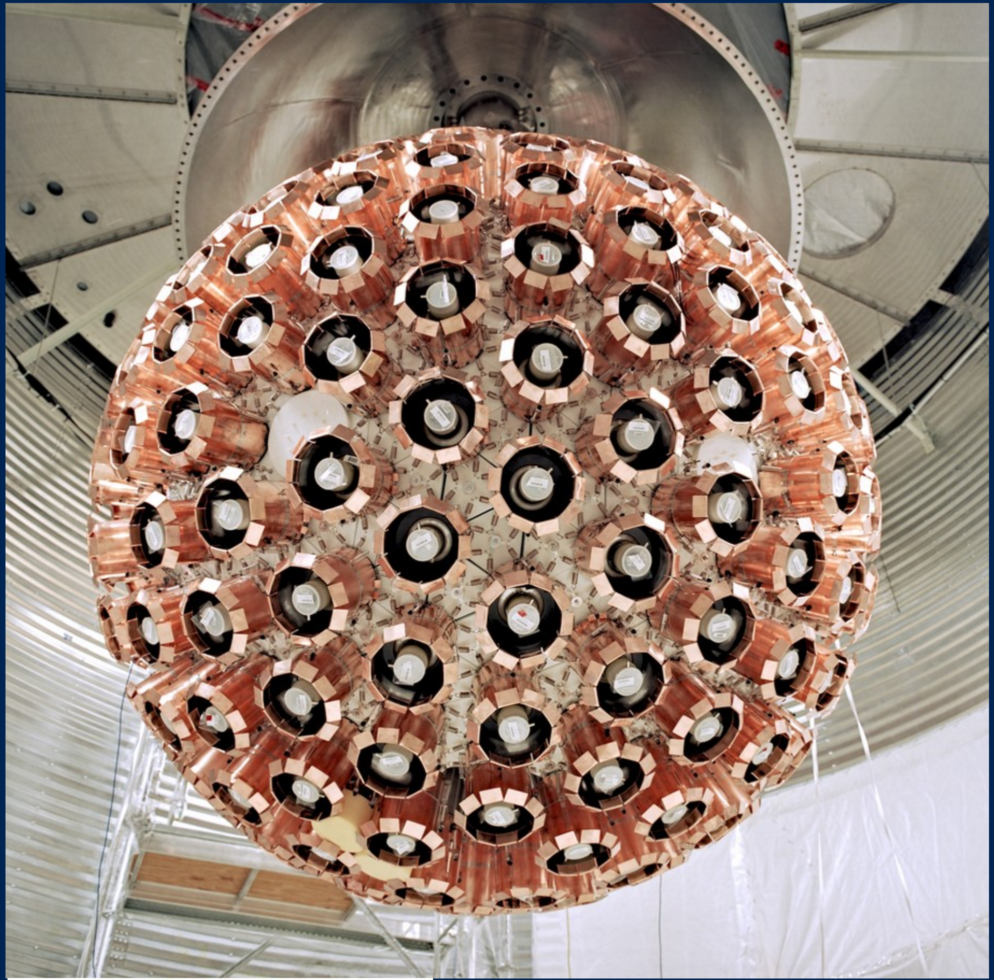
Nuclear Physics in Liquid Argon with DEAP-3600

CAP 2026

Peter Taylor

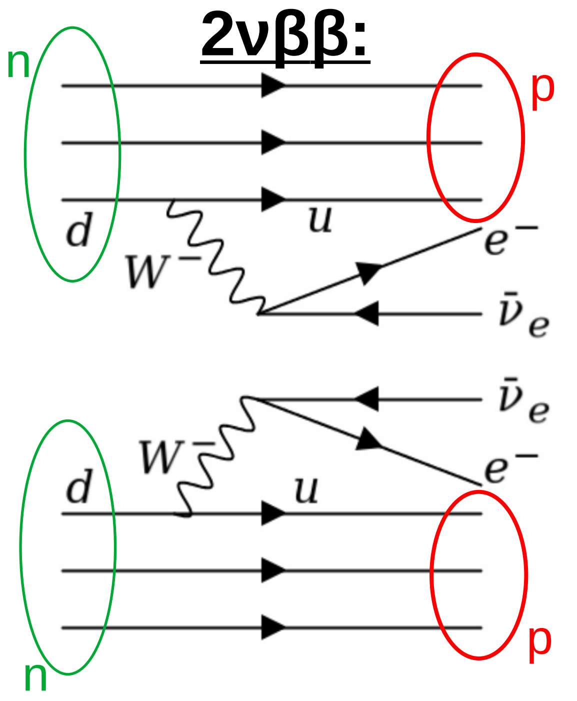
On behalf of the DEAP-3600 collaboration

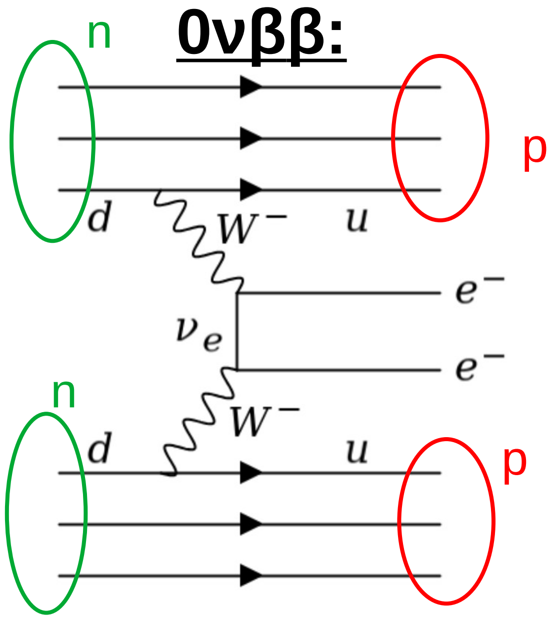
June 22, 2026

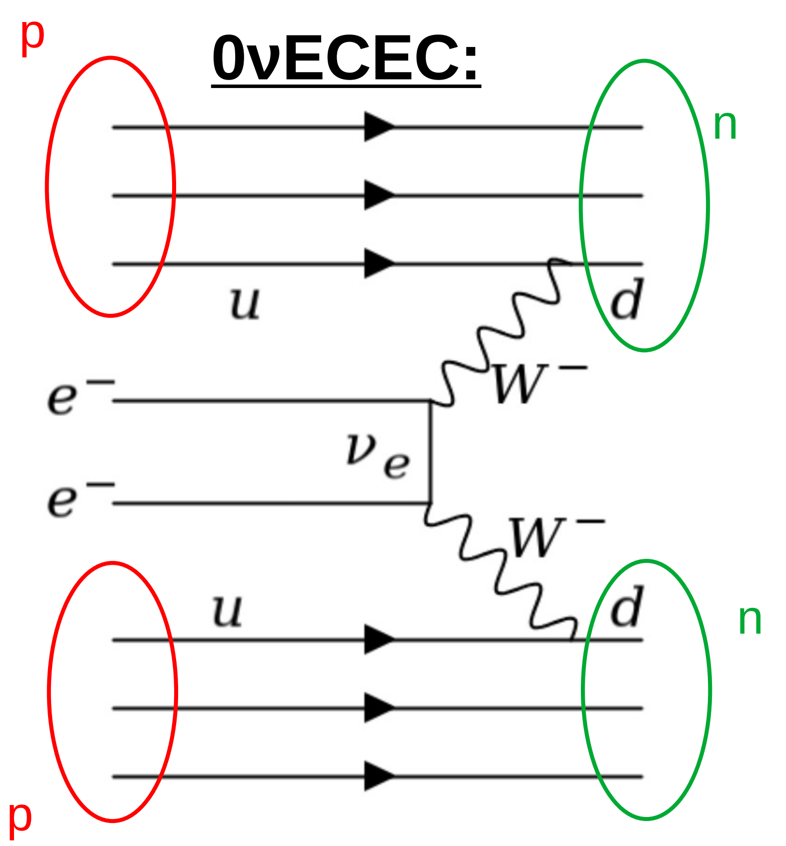


Searches for 0νECEC:

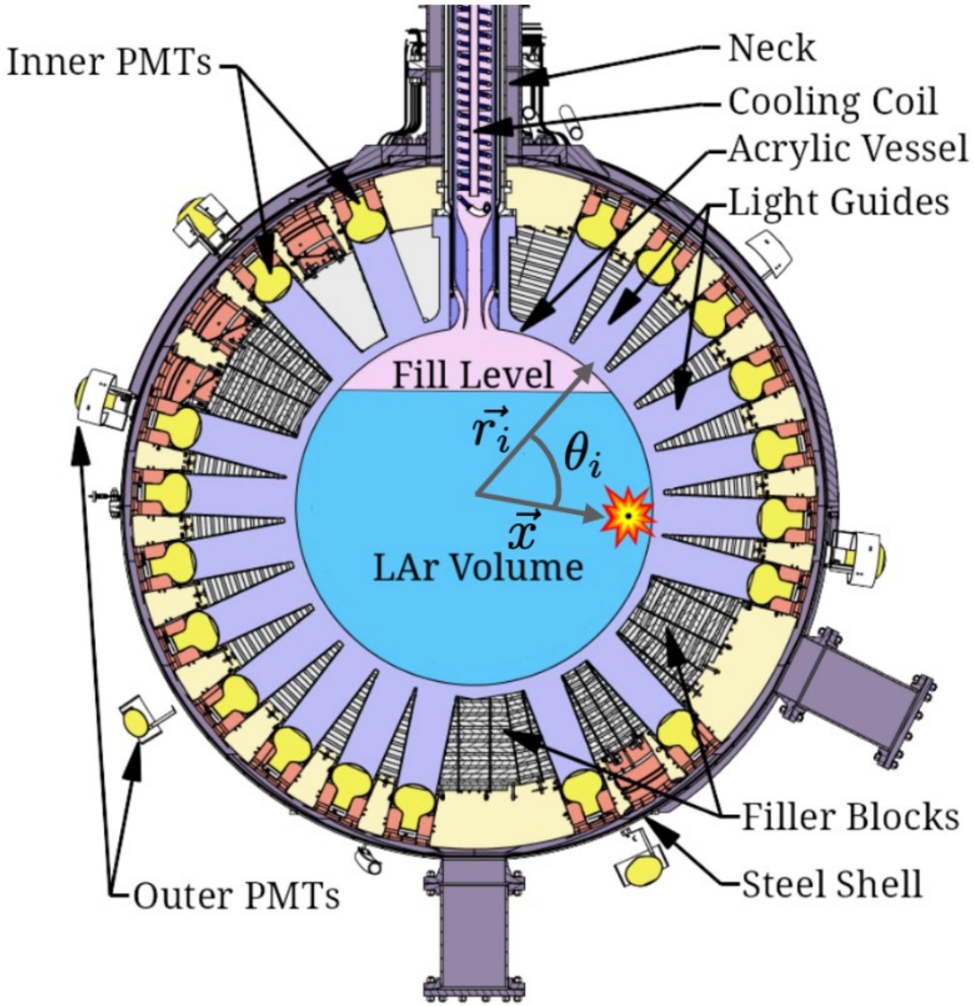
- Neutrinoless Double Beta decay (0νββ) isn't allowed by the Standard Model due to conservation of lepton number.
- Various observations of neutrinos imply that this decay can occur, such as neutrino-mixing and neutrino mass.
- The inverse process is known as Neutrinoless Double Electron Capture (0νECEC). Other noteworthy isotopes include ^{136}Xe, and ^{76}Ge.
- Other searches for this process include GERDA (DOI: 10.1140/epjc/s10052-023-12280-6) and LEGEND (DOI: 10.1103/25tk-nctn)

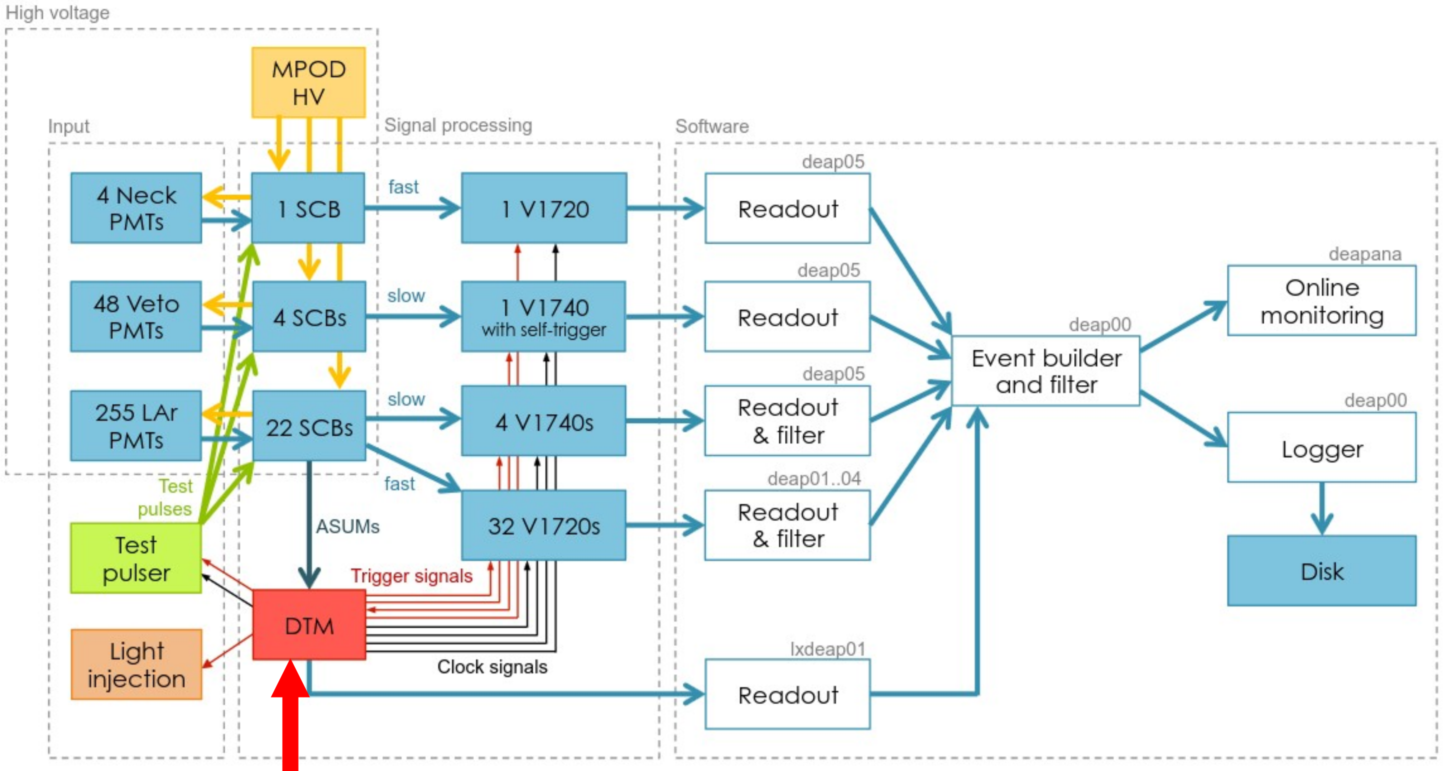






The Experiment





Digitizer and Trigger Module (DTM)

10.1016/j.astropartphys.2018.09.006 + https://arxiv.org/pdf/1712.01982

How are we searching for Dark Matter?

- The scintillation of LAr produces two excimers, a short-lived ($\tau_s < 6.2$ ns) singlet state and a long-lived ($\tau_t = 1300 \pm 60$ ns) triplet state.

$$I_{LAr}(t) = \frac{R_s}{\tau_s} e^{-t/\tau_s} + \frac{1-R_s-R_t}{(1+t/\tau_{rec})^2} \frac{1}{\tau_{rec}} + \frac{R_t}{\tau_t} e^{-t/\tau_t}$$

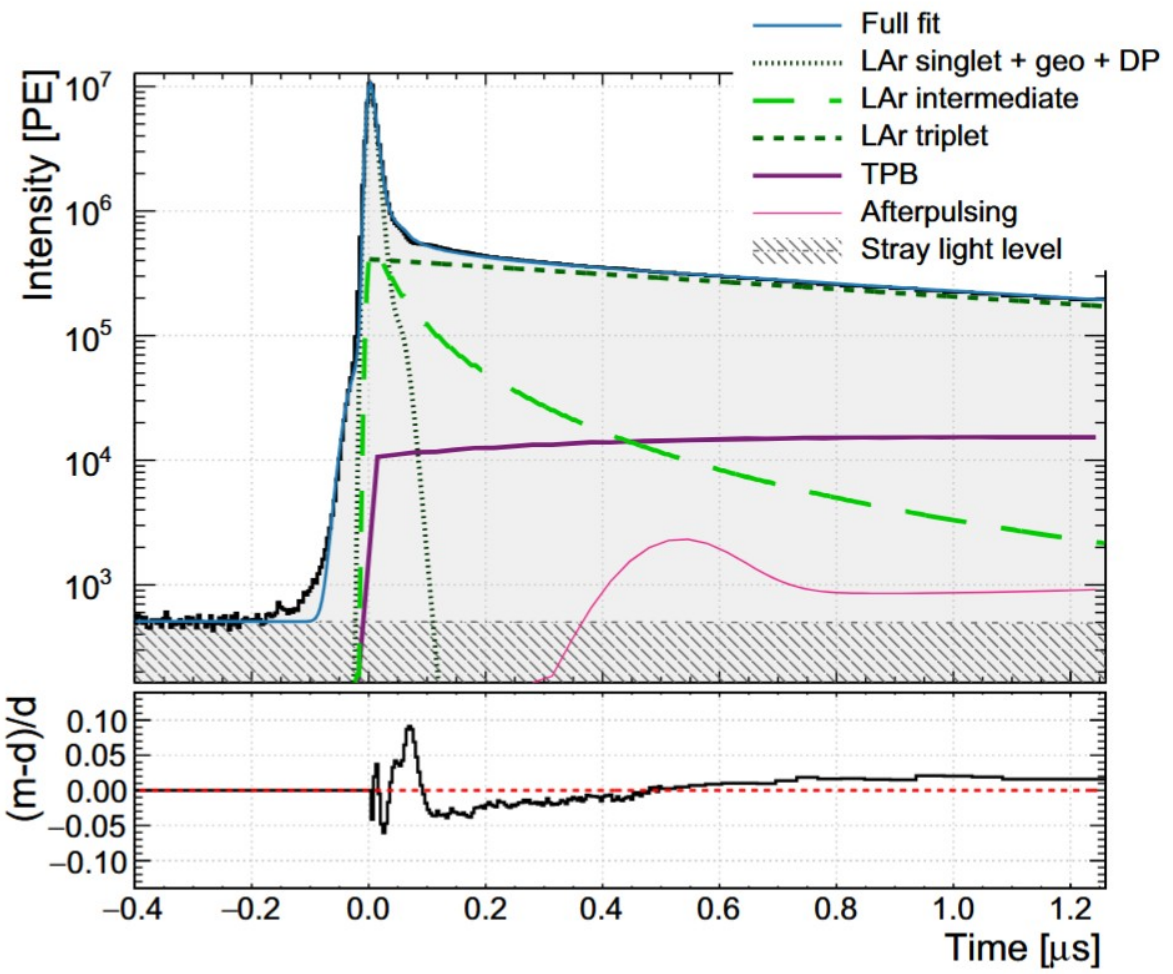
Singlet

Random Walk Recombination

Triplet

$$F_{prompt} = \frac{\sum_{-28ns}^{150ns} PE(t)}{\sum_{-28ns}^{10\mu s} PE(t)}$$

LAr		
Par	Start	Fit
R_p	0.3	0.23
τ_p	3 ns	8.2 ns
τ_{rec}	–	75.5 ns
R_t	0.7	0.71
τ_t	1564 ns	1445 ns



https://link.springer.com/article/10.1140/epjc/s10052-020-7789-x

How are we searching for Dark Matter?

$$F_{prompt} = \frac{\sum_{-28ns}^{150ns} PE(t)}{\sum_{-28ns}^{10\mu s} PE(t)}$$

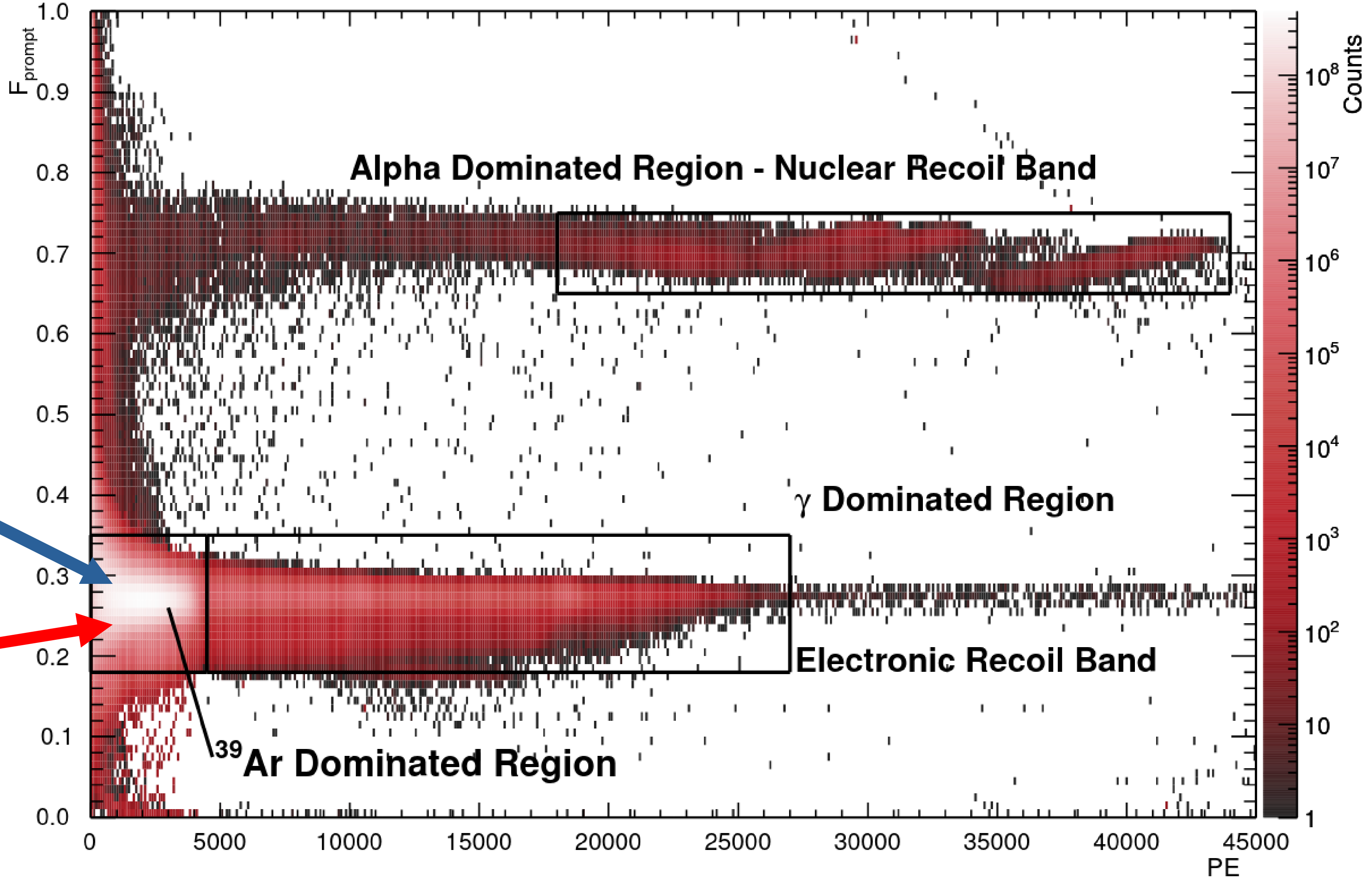
$$D_{prompt} = \frac{\sum_{-28ns}^{177ns} dtm(t)}{\sum_{-28ns}^{3.1\mu s} dtm(t)} = \frac{dtm_{Narrow}}{dtm_{Wide}}$$

$$^{36}Ar \rightarrow \gamma + \gamma + {}^{36}S$$

Q_{36Ar} = 0.432 MeV

$$^{39}Ar \rightarrow \beta^- + {}^{39}K$$

Q_{39Ar} = 0.565 MeV



Degraded α-Quenching Factor:

- Degraded α are present in the detector due to α needing to "break-out" of variable sized dust

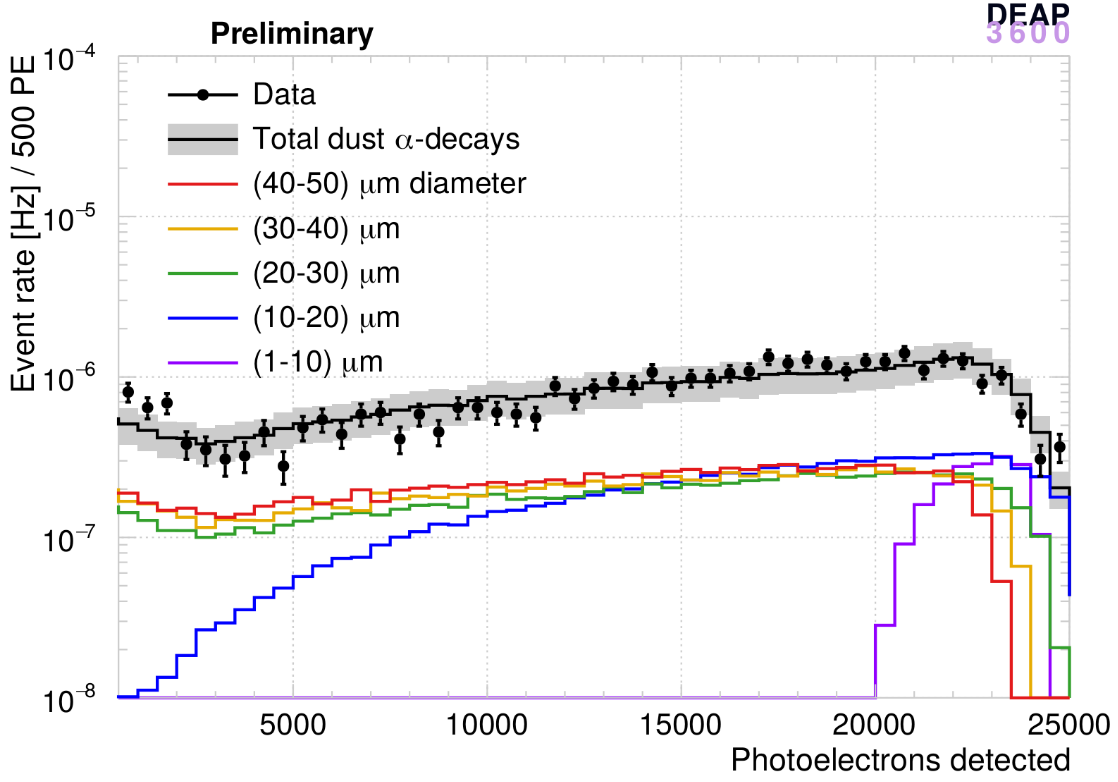
Nuclear Recoil QF:

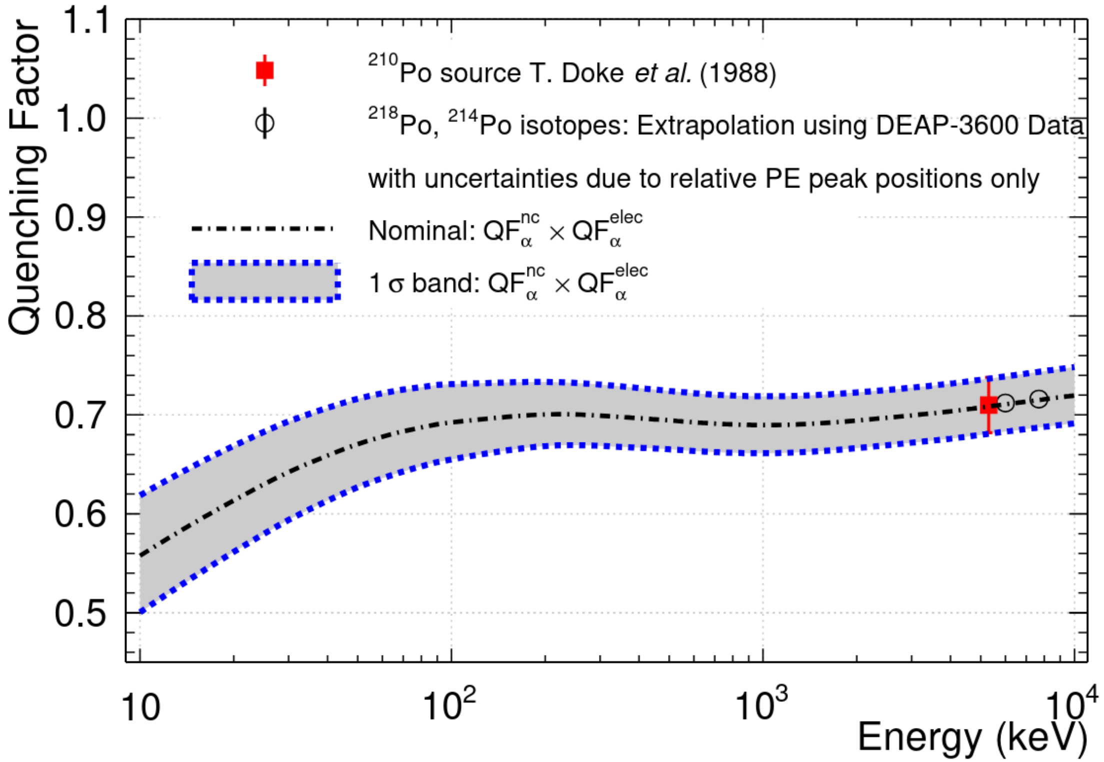
$$\mathrm{QF}_{\alpha}^{\mathrm{nucl}} = \frac{E_{\mathrm{dep,elec}}}{E_{\mathrm{dep,elec}} + E_{\mathrm{dep,nucl}}}$$

Atomic Electron Excimer QF:

$$\mathrm{QF}_{\alpha}^{M} = \frac{y(E_\alpha)}{E_\alpha} = \frac{A}{E_\alpha}\int_0^{E_\alpha}\frac{dE}{1+B\frac{dE}{dx}}$$

$\mathrm{QF}^{\mathrm{nucl}}_{\alpha} * \mathrm{QF}^{M}_{\alpha}$





10.1140/epjc/s10052-024-13518-7

Status on search for 0νECEC:

$$D_{prompt} = \frac{\sum_{-28\,ns}^{177\,ns} dtm(t)}{\sum_{-28\,ns}^{3.1\,\mu s} dtm(t)} = \frac{dtmNarrowQ}{dtmWideQ}$$

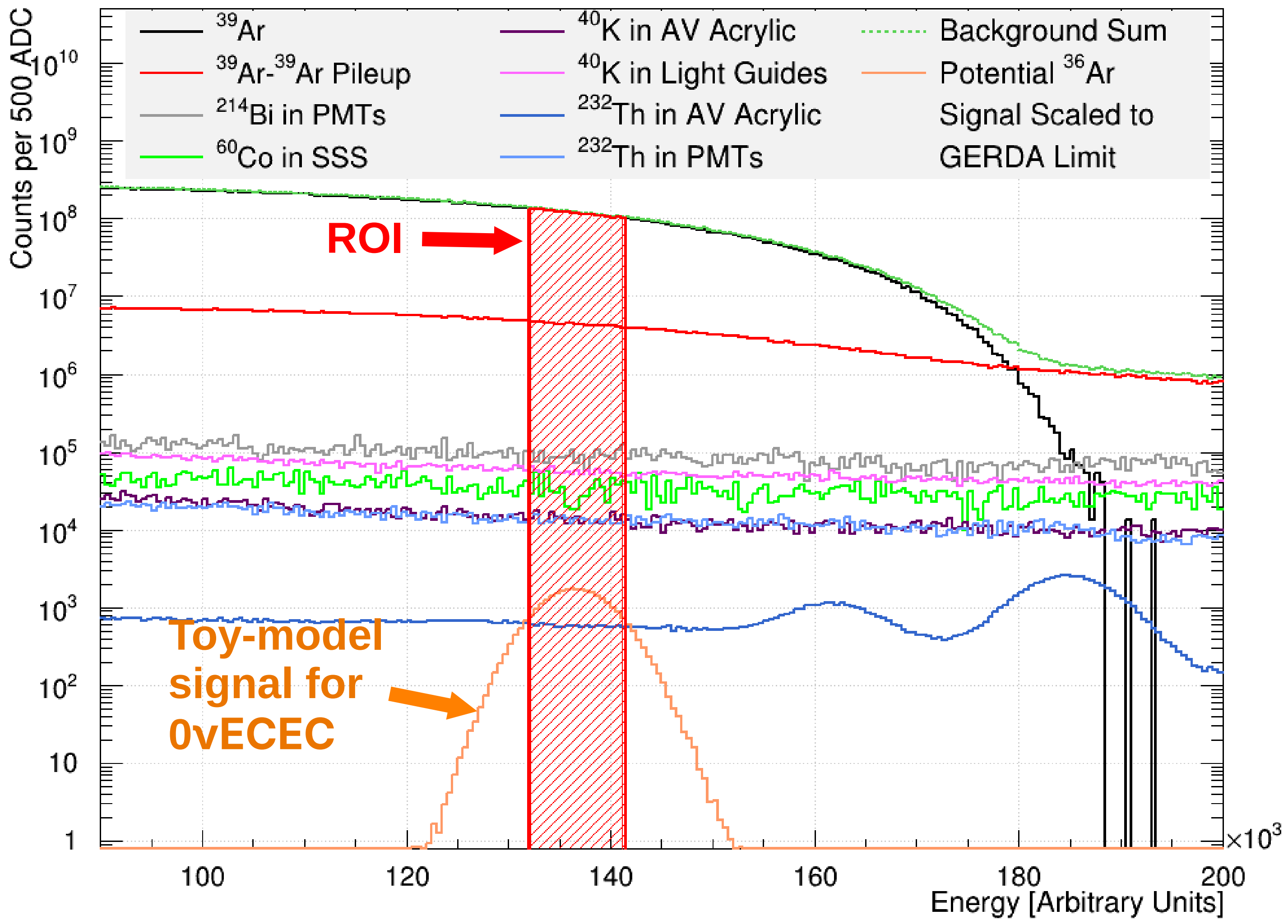
$$^{36}Ar \rightarrow \gamma + \gamma + {}^{36}S$$

$$^{36}Ar \rightarrow \gamma + {}^{36}S$$

$$^{36}Ar \rightarrow \beta^{-} + {}^{36}S$$

- 0νECEC events should be contained in the Region of Interest.

Preliminary



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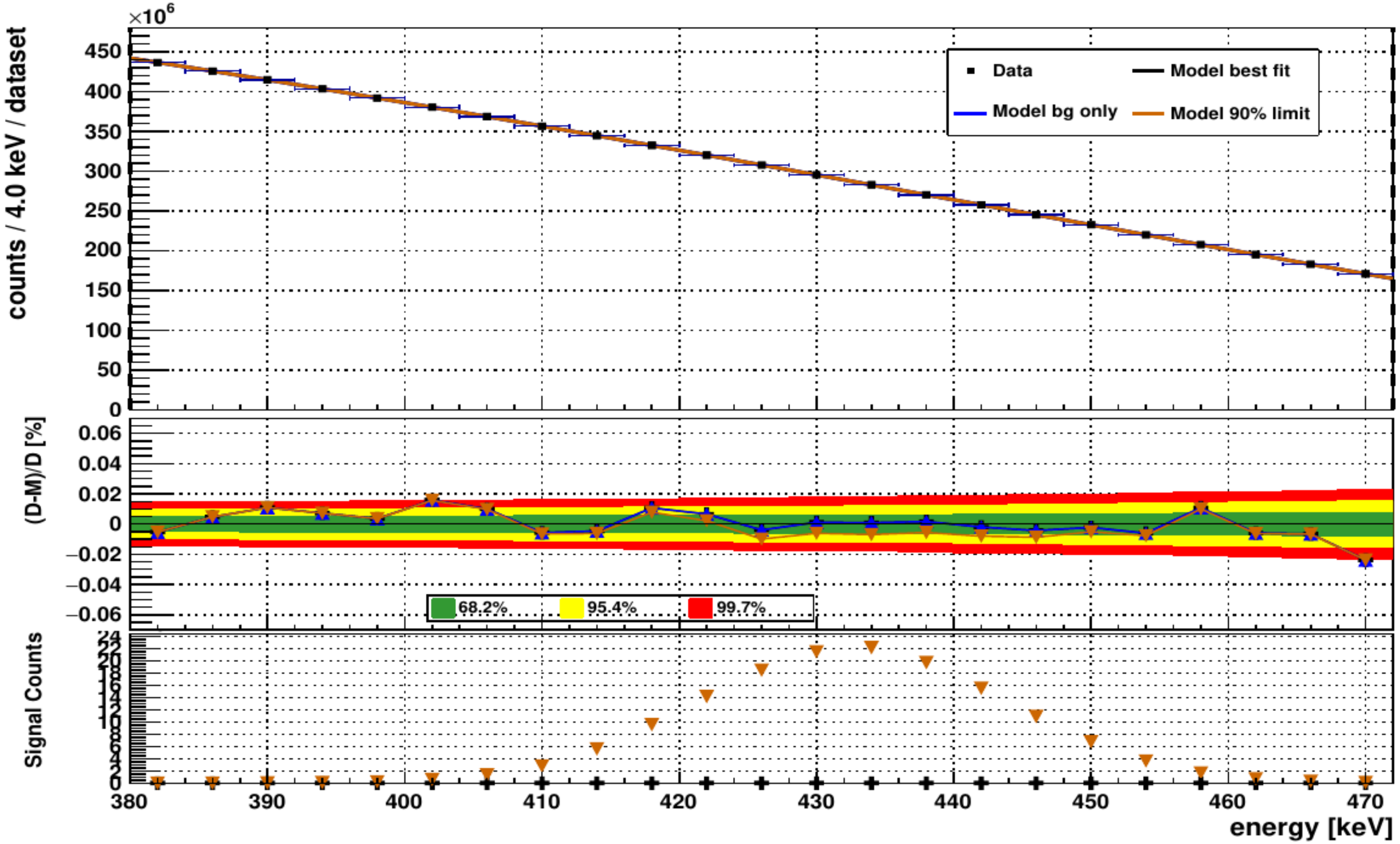
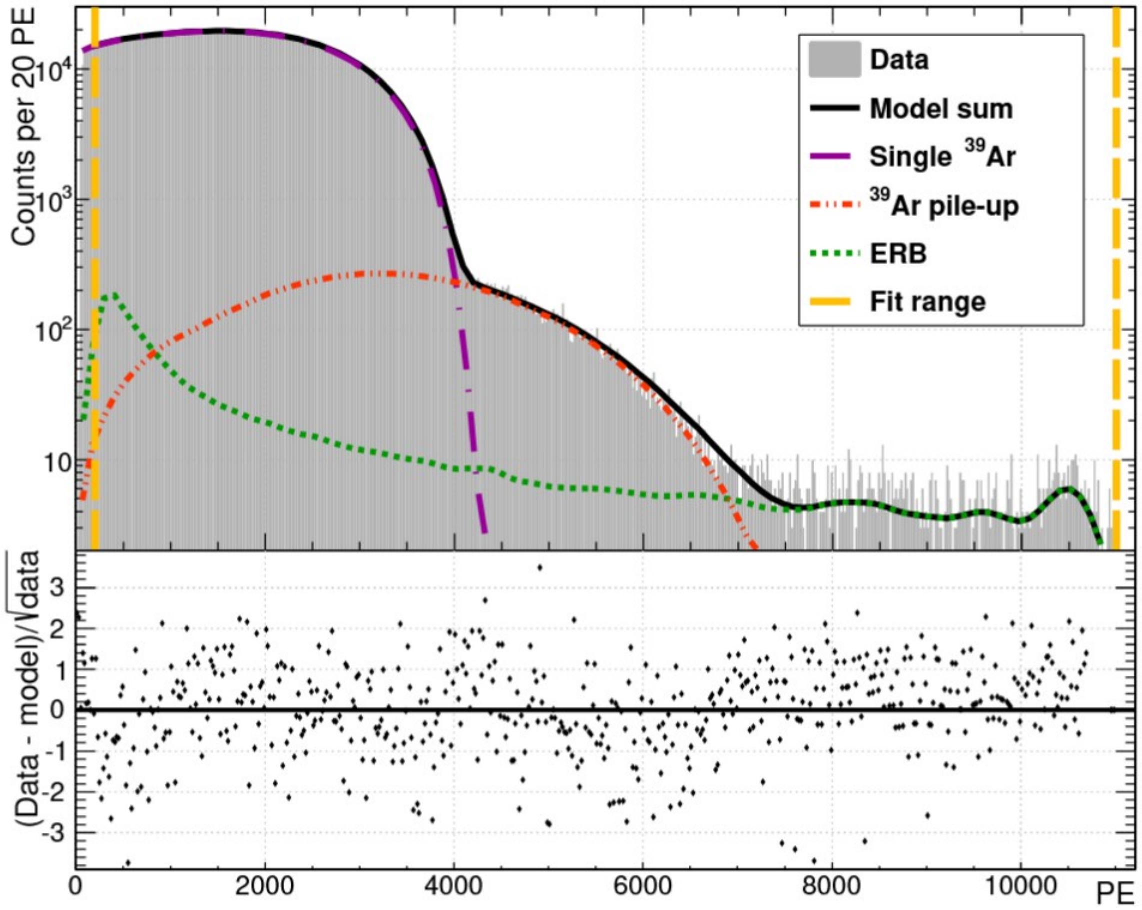
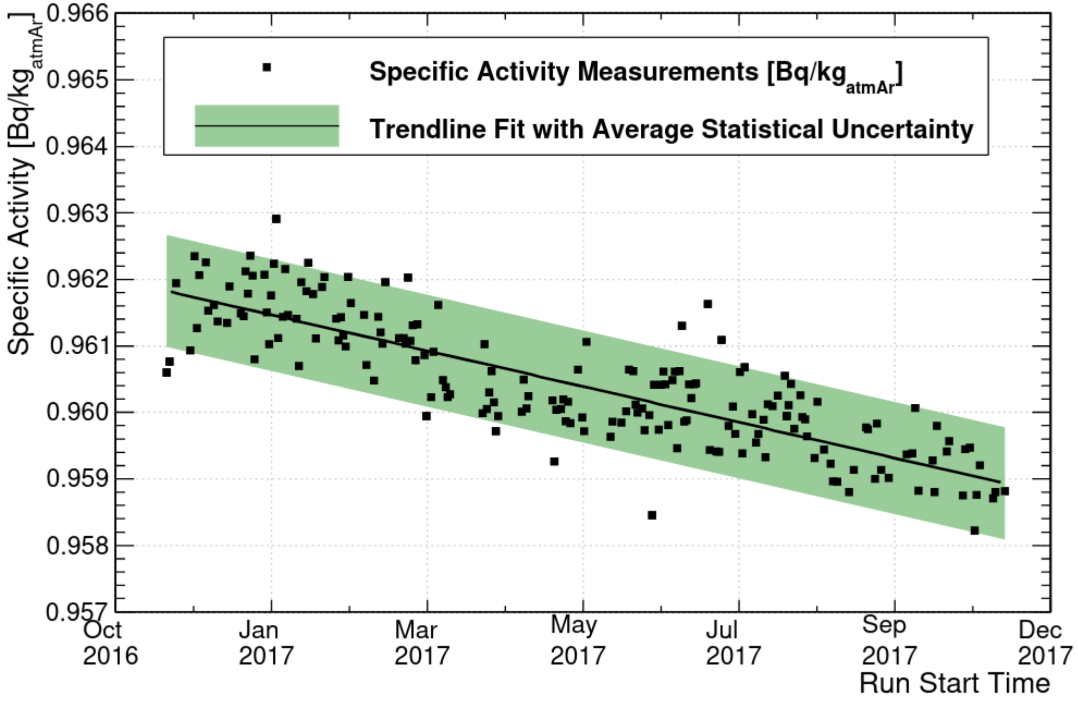


- Previous efforts within DEAP-3600 by Matt Dunford show ^{36}Ar to be observationally stable (>10^{21} years).

Specific Activity:





Measurement	Specific activity [Bq/kg$_{atmAr}$]
WARP [15]	$1.01 \pm 0.02_{stat} \pm 0.08_{sys}$
ArDM [16]	0.95 ± 0.05
DEAP-3600 (this work)	$0.964 \pm 0.001_{stat} \pm 0.024_{sys}$

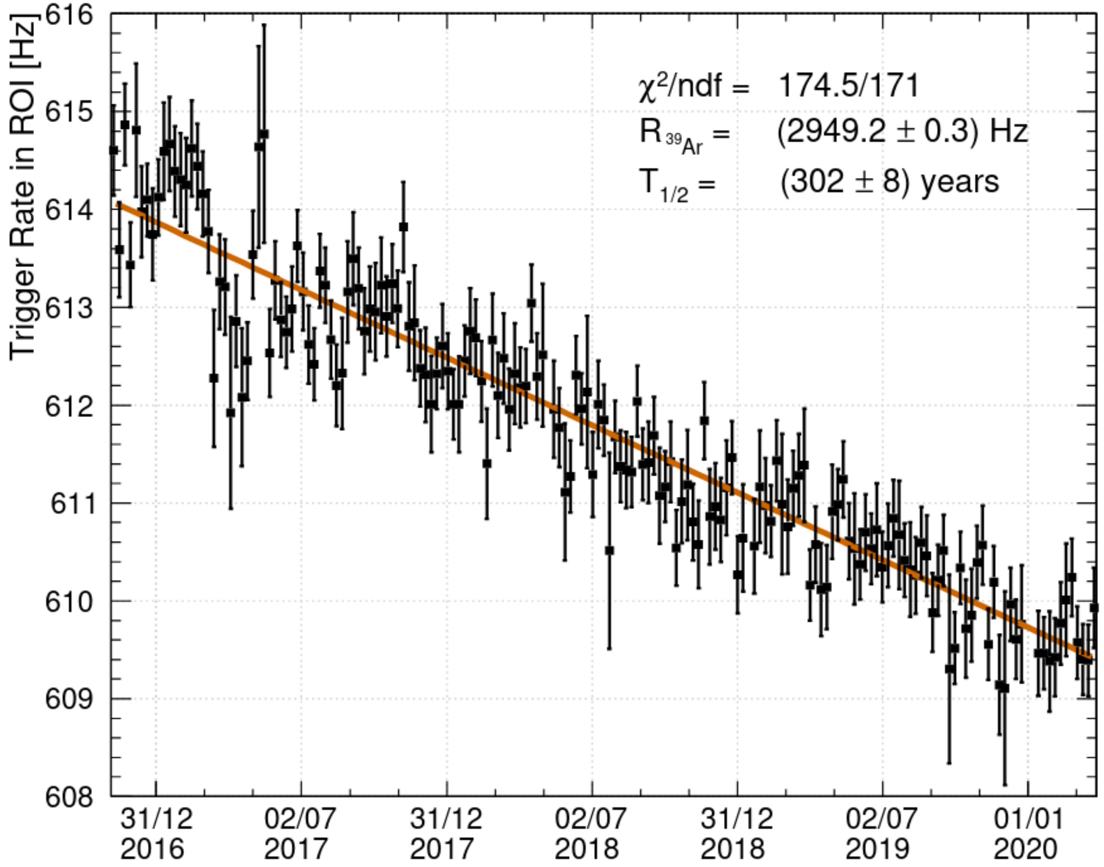
$$S_{^{39}Ar} = (0.964 \pm 0.001_{stat} \pm 0.024_{syst})\, Bq/kg_{Ar}$$

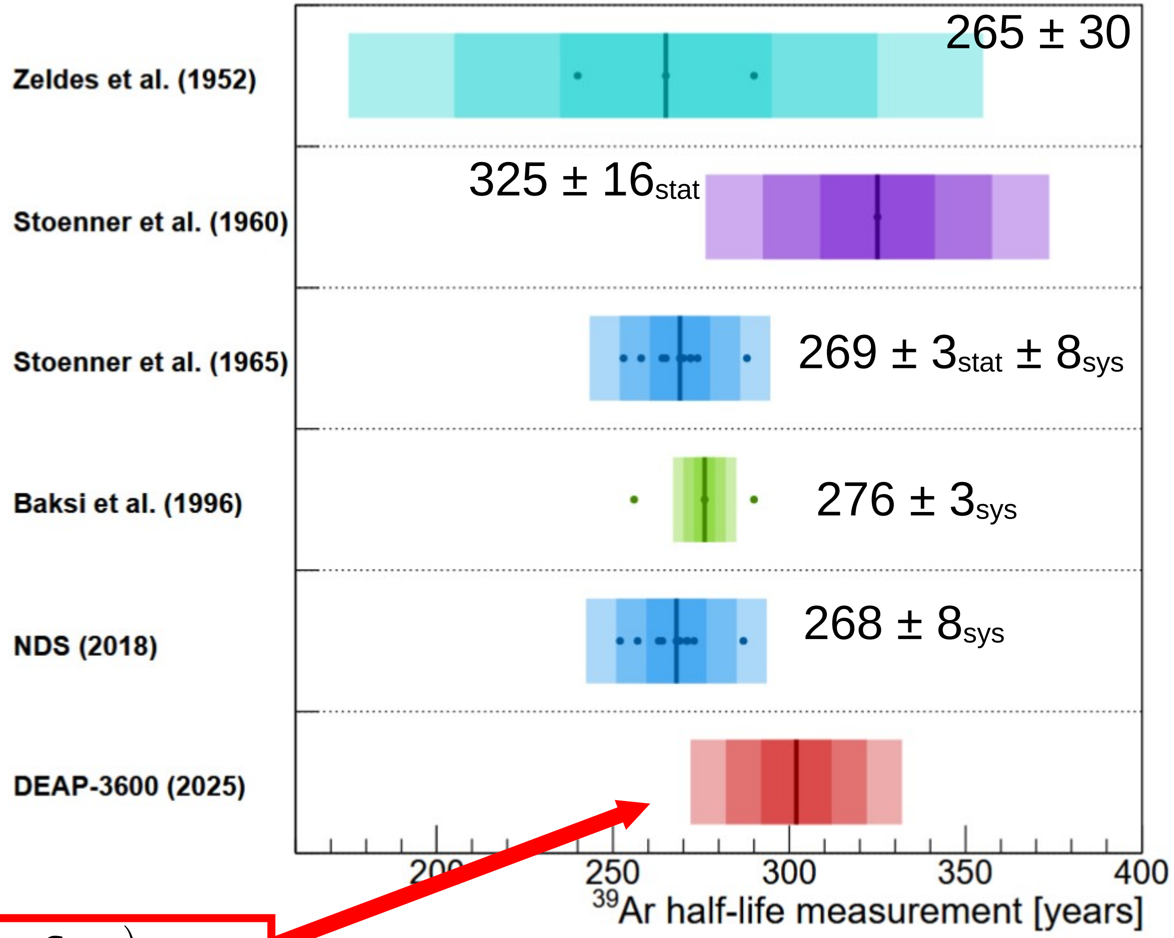
$$S_{^{39}Ar} = \frac{N_{single} + N_{pileup} + N_{ERB}}{m_{LAr} T_{livetime}}$$; $T_{livetime}$ = 167 days

m_{LAr} = 3269 ± 24 kg

10.1140/epjc/s10052-023-11678-6

Half-life of ^{39}Ar

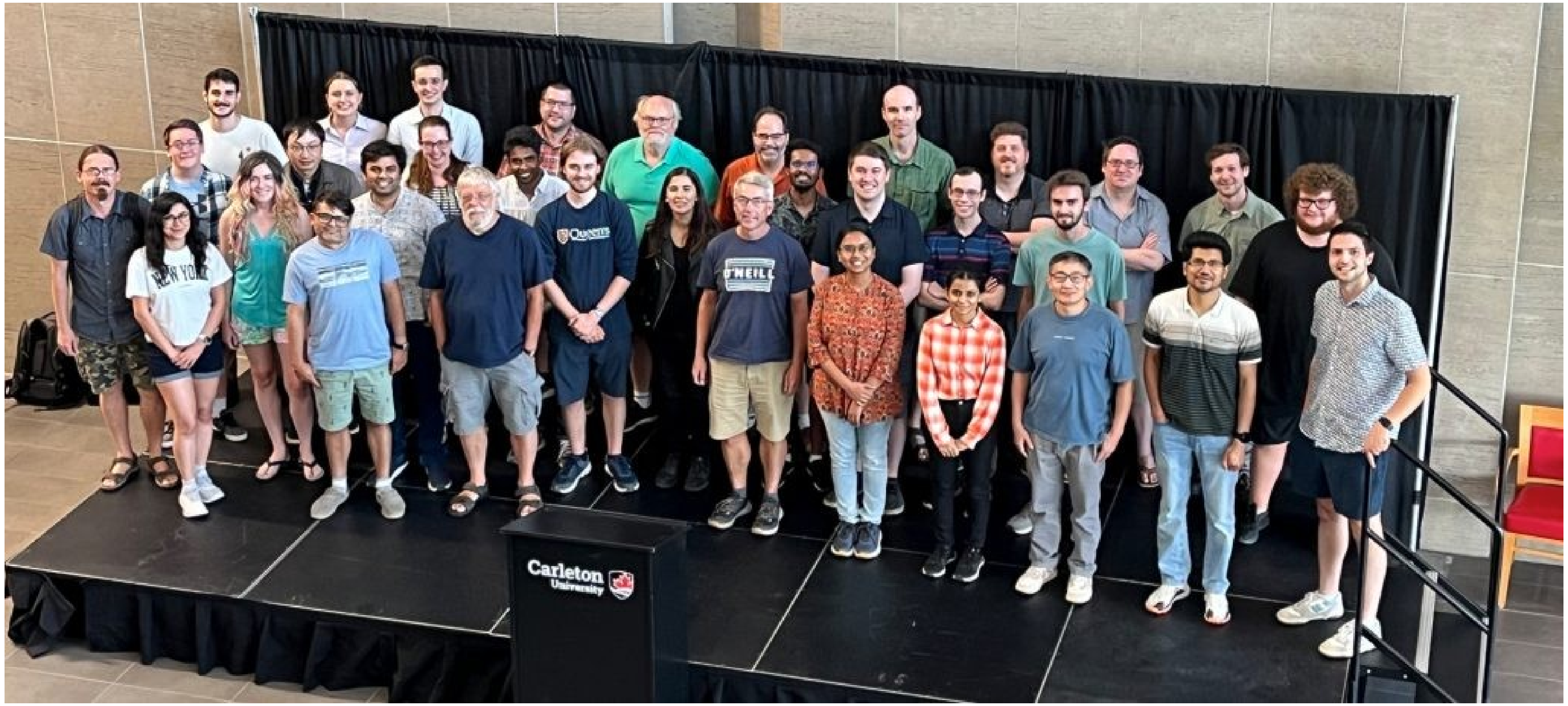


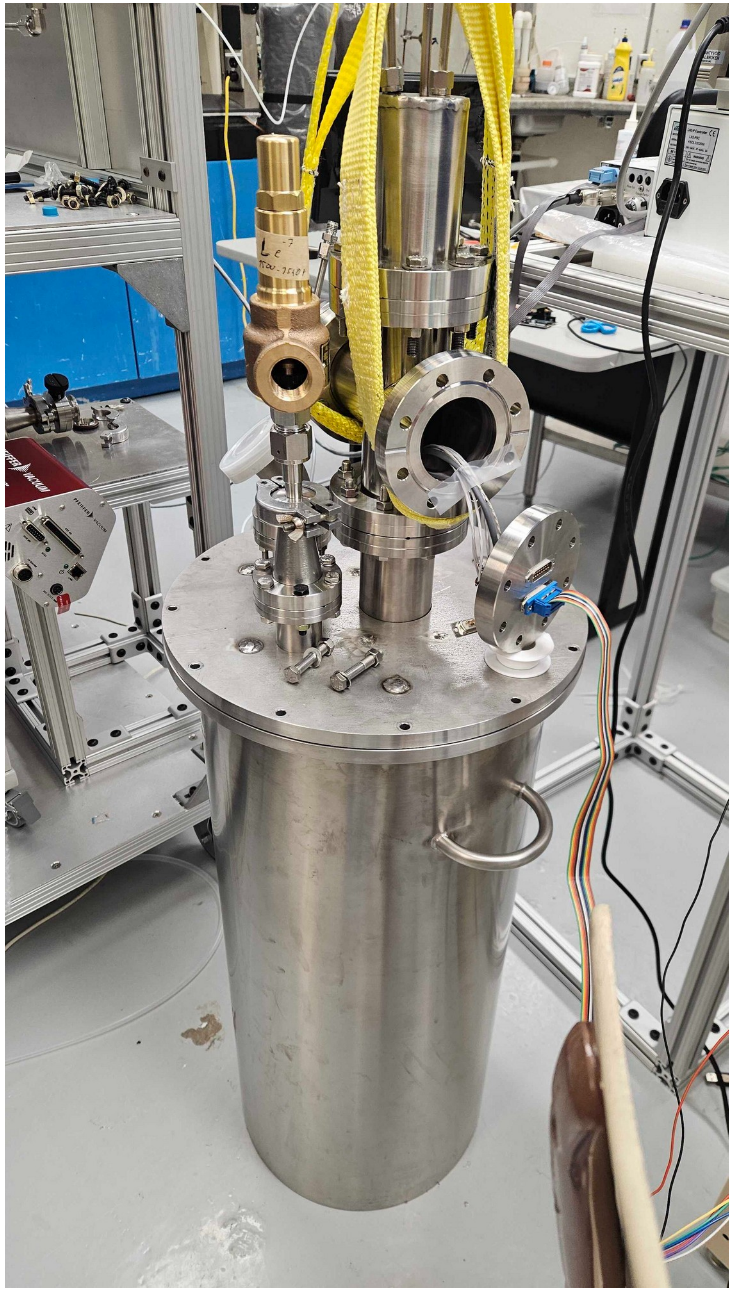


$$T_{1/2} = (302 \pm 8_{stat} \pm 6_{syst})\ years$$

10.1140/epjc/s10052-025-14289-5

THANK YOU!





Supplementary Material

The Physics

- Generally there are two methods for detection in Dark Matter searches:
  - Indirect detection: looking for the byproducts of an interaction, or involves collider physics.
  - Direct detection: looking for the interaction of Dark Matter with atoms (method that DEAP uses).
- For both DM and 0νECEC, you need to collect such a large amount data and in such a clean environment that you may observe such processes. This requires that you understand what is happening in and around your detector to be able to distinguish your signals from background processes and noise.

- LAr requires cryogenic temperatures, and thus requires active cooling to condense gaseous argon.
- LAr is contained within a spherical Acrylic vessel (AV), necessary to insulate the cryogenic LAr from the currently used PMTs (may not be necessary if moving on to SiPMs).
- LAr scintillation produces photons in the ultra-violet range (127nm) and requires a wavelength shifter (TetraPhenyl-Butadiene) to convert to a wavelength that is detectable by the PMTs (~420nm). Layered on inside of the AV.
- In order to guarantee that light is collected by detectors, light guides are used to ensure scintillation light arrives at PMT.
- Lower assembly surrounded by μ-veto water tank to detect spallation neutrons and flag ionizations.

The Experiment

- Modern experiments have been tending towards noble gas scintillators; Liquid Argon (LAr) in DEAP's case.
- LAr possesses many benefits over other scintillator types:
  - Very commonly available gas in Earth's atmosphere.
  - Easily purified and isn't prone to mechanical imperfections/degradation.
  - An effective recoil target candidate for DM interactions while also having desirable differences in scintillation signal discrimination caused by various processes (ie. Nuclear Recoil and Electron Recoil).
  - Requires cryogenics to exist within detector, is benefits certain scintillation detectors.

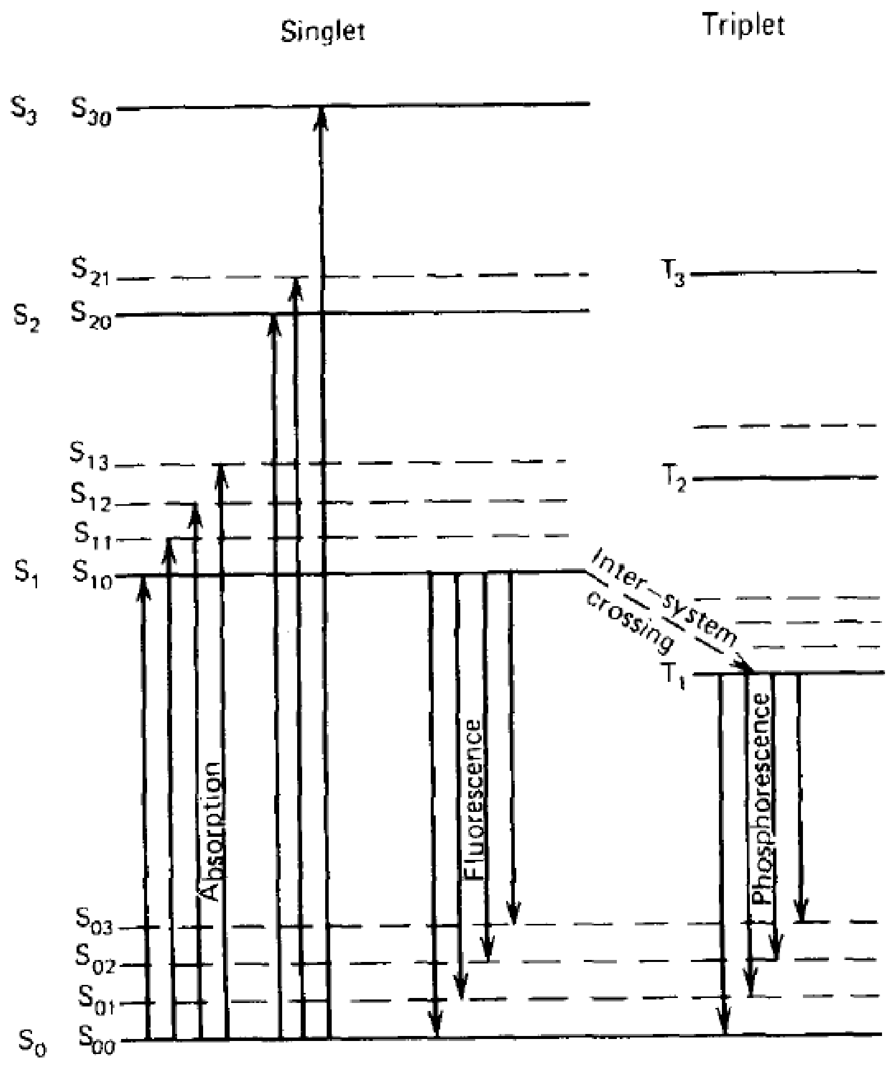
1) $\chi + Ar + Ar \rightarrow Ar^{*} + Ar \rightarrow Ar_2^{*} \rightarrow 2\,Ar + \gamma$

2) $Ar^{+} + Ar \rightarrow Ar_2^{+}$

$Ar_2^{+} + e^{-} \rightarrow Ar_2^{*} \rightarrow 2\,Ar + \gamma$

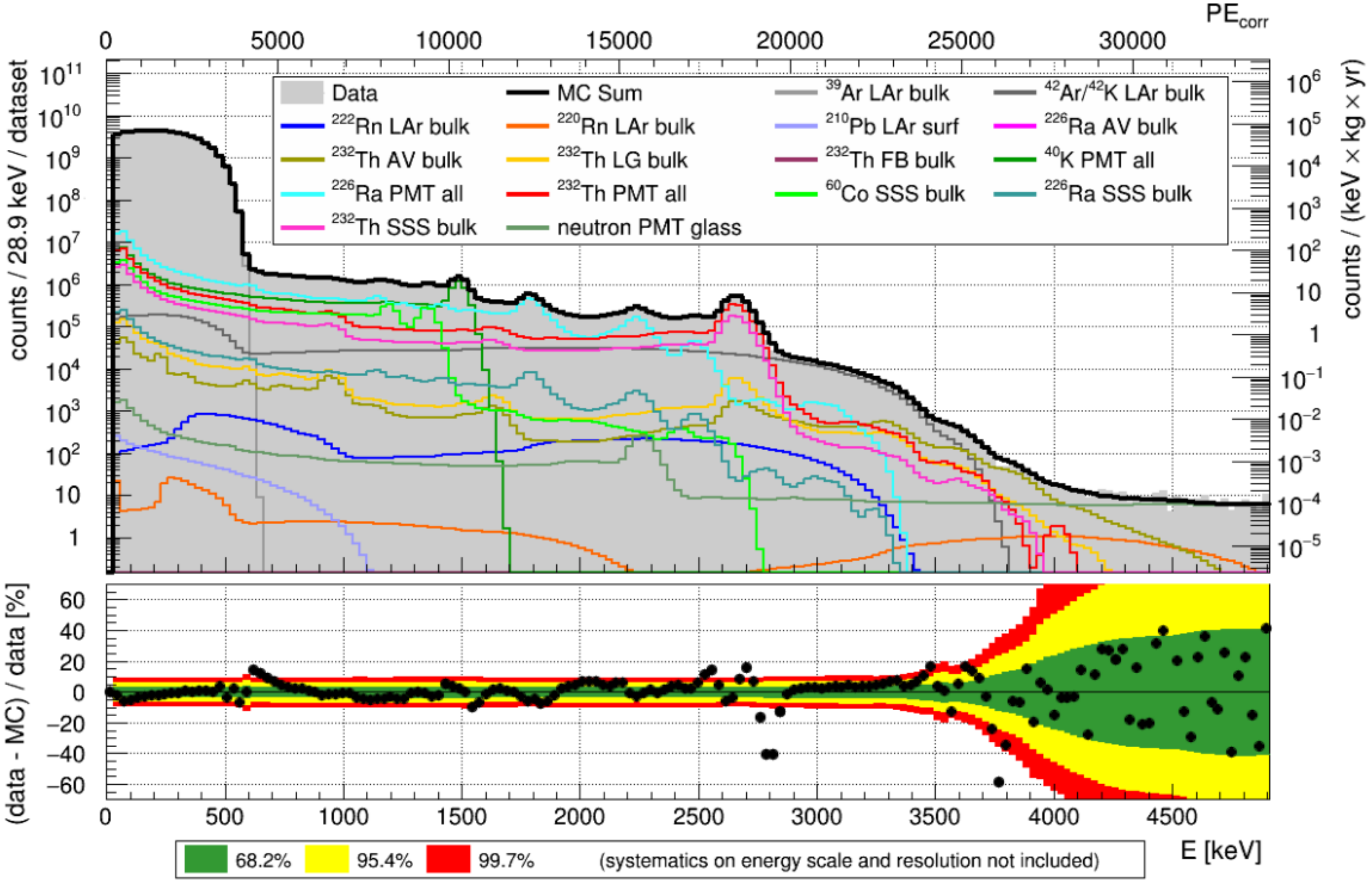
The Physics

- For most direct detection experiments, we rely on the principal of ionization and scintillation.
- Scintillation can be done in three major ways:
  - Electronic excitation: Compton scattering, charges moving through a medium, photo-electric effects, pair-production, electron-hole production, ionization, etc.
  - Nuclear recoil: Incident Particle physically “hits” atoms and the recoil causes either ionization or an excited state which then decays via the emission of a photon.
  - Electron recoil: Rather than hitting the atom as a whole, it is possible for a particle to recoil off of an electron, which similarly will result either in ionization or excitation.



The Physics

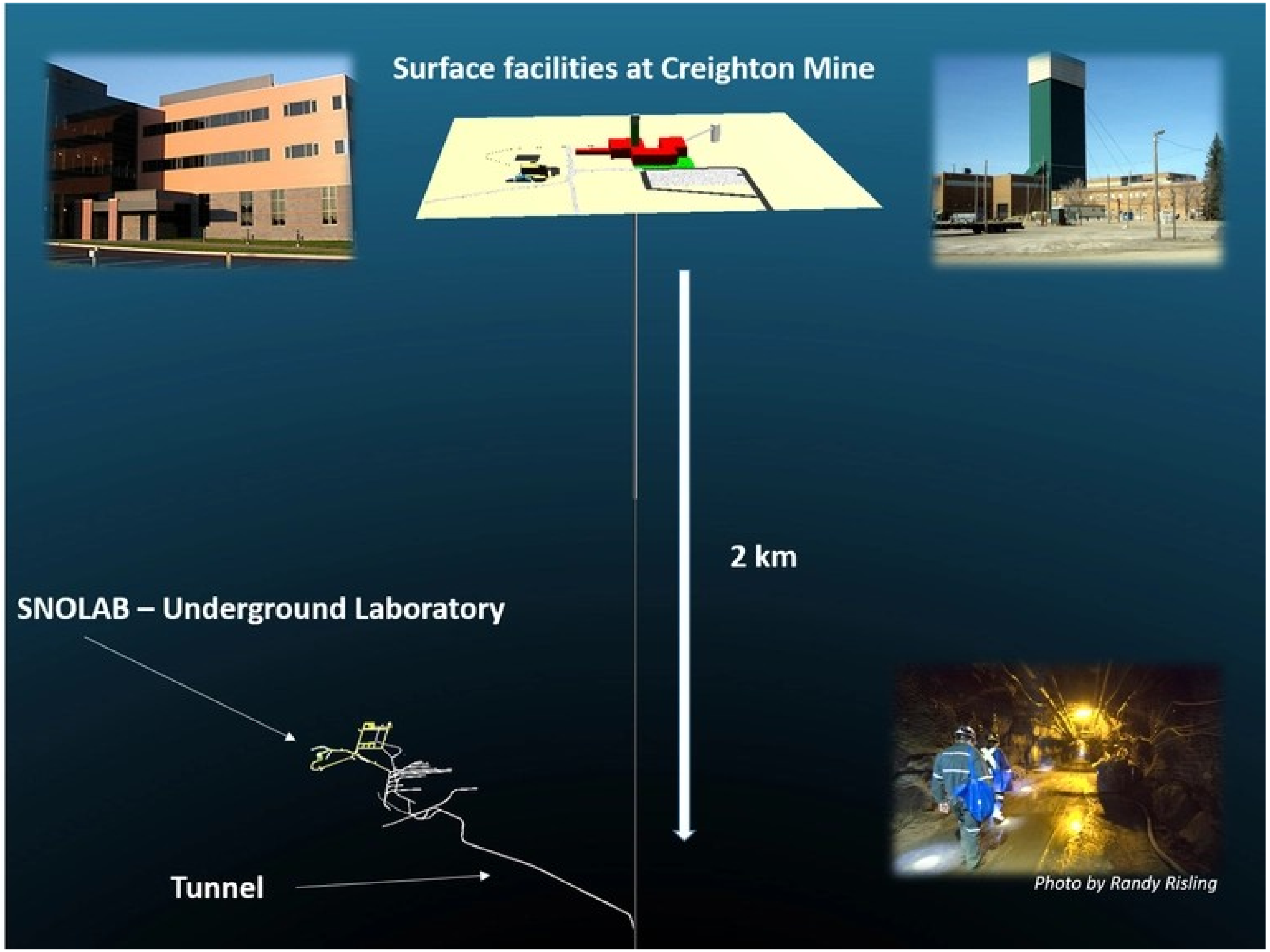
- Radiation types: α, β, γ, and neutrons. These can cause any number of interactions that can resemble physics signal.
- For DEAP, the rough conversion factor between PE and energy is 6 PE/keV.



arxiv.org/pdf/1905.05811

The Experiment

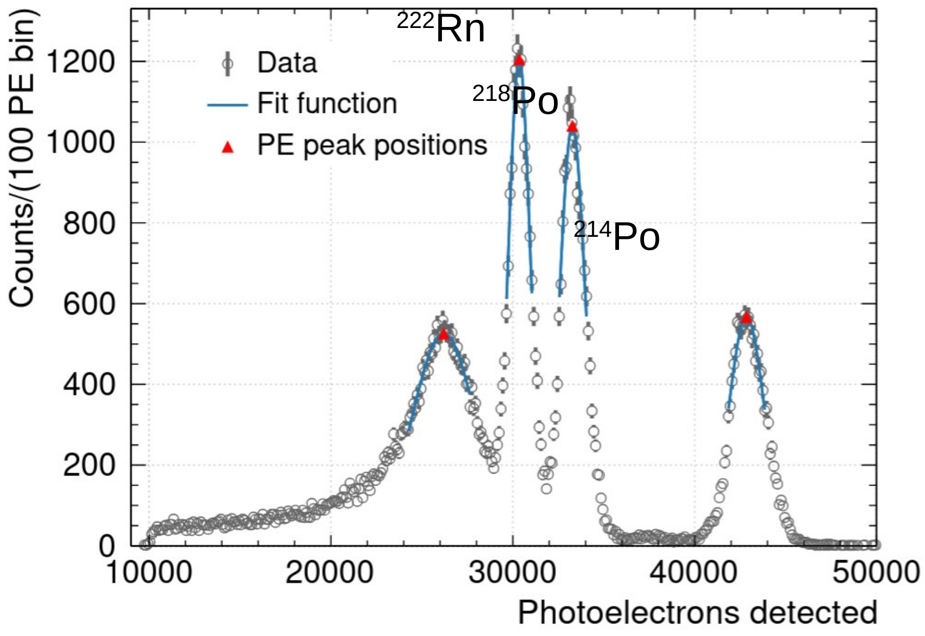
- Both as a general practice for nuclear physics experiments, and in order to look for such rare processes as DM and 0νECEC, it is necessary to minimize undesirable backgrounds as much as possible.
- DEAP does this is by being 2km underground to minimize background sources (such as from cosmic rays). This also lets them understand their environmental backgrounds more consistently.



What have we found so far?

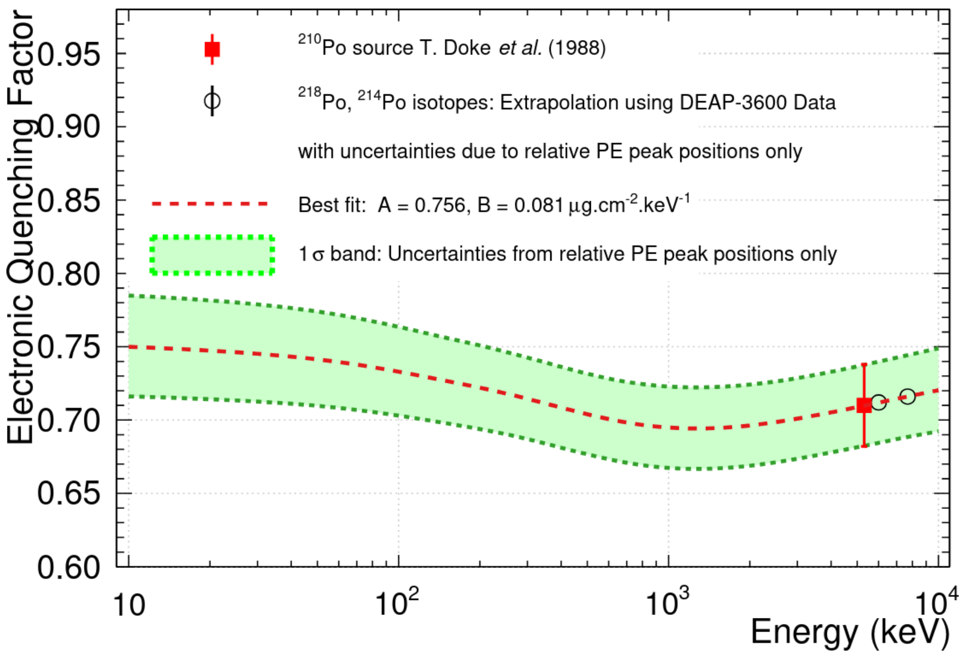
$$\mathrm{QF}_{\alpha}^{\mathrm{nucl}} = \frac{E_{\mathrm{dep,elec}}}{E_{\mathrm{dep,elec}} + E_{\mathrm{dep,nucl}}}$$

$$\mathrm{QF}_{\alpha}^{M} = \frac{y(E_\alpha)}{E_\alpha} = \frac{A}{E_\alpha}\int_0^{E_\alpha}\frac{dE}{1+B\frac{dE}{dx}}$$



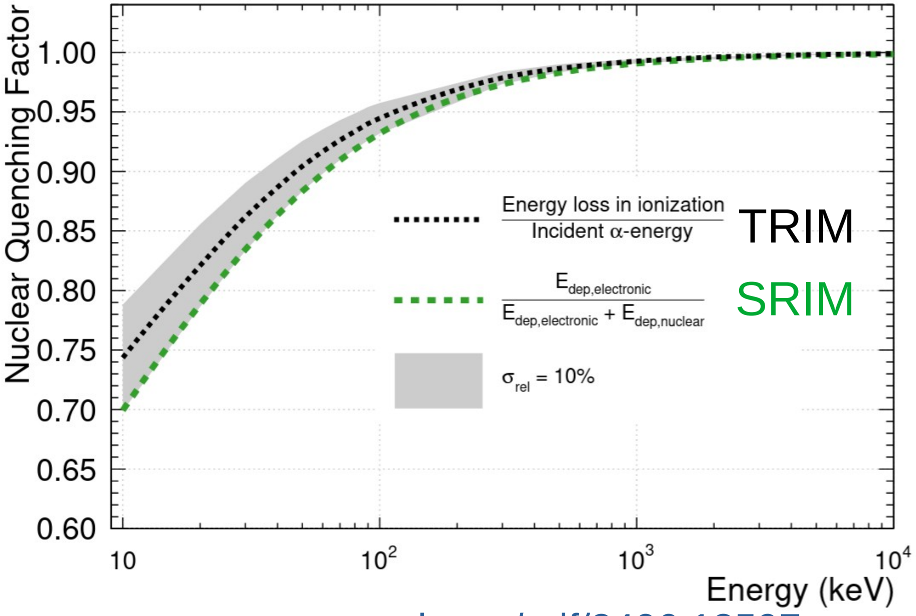
Electronic QF:

Non-radiative de-excitation of eximers



Nuclear QF:

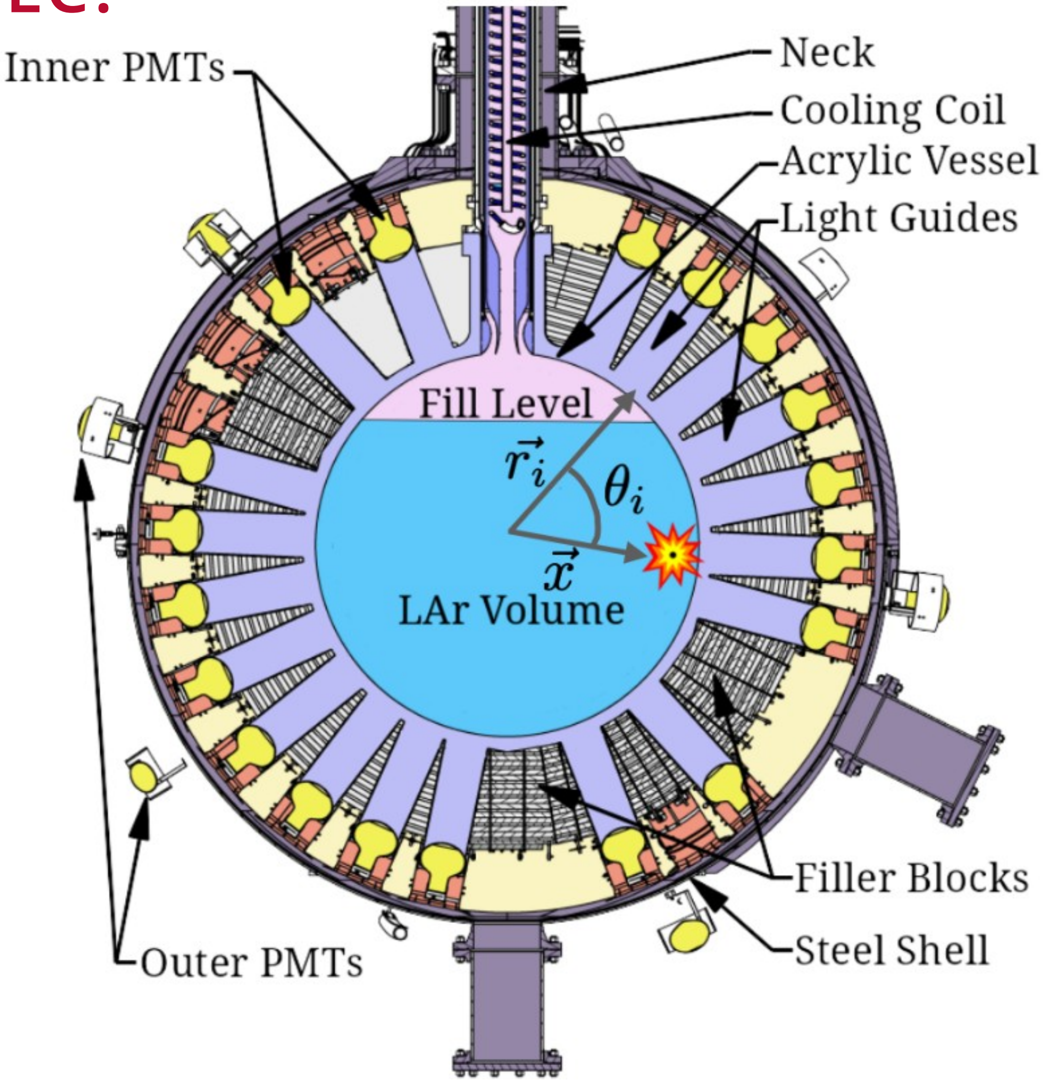
Energy lost via translation due to nuclear collisions along α's path



arxiv.org/pdf/2406.18597

How are we searching for DM/0νEC?

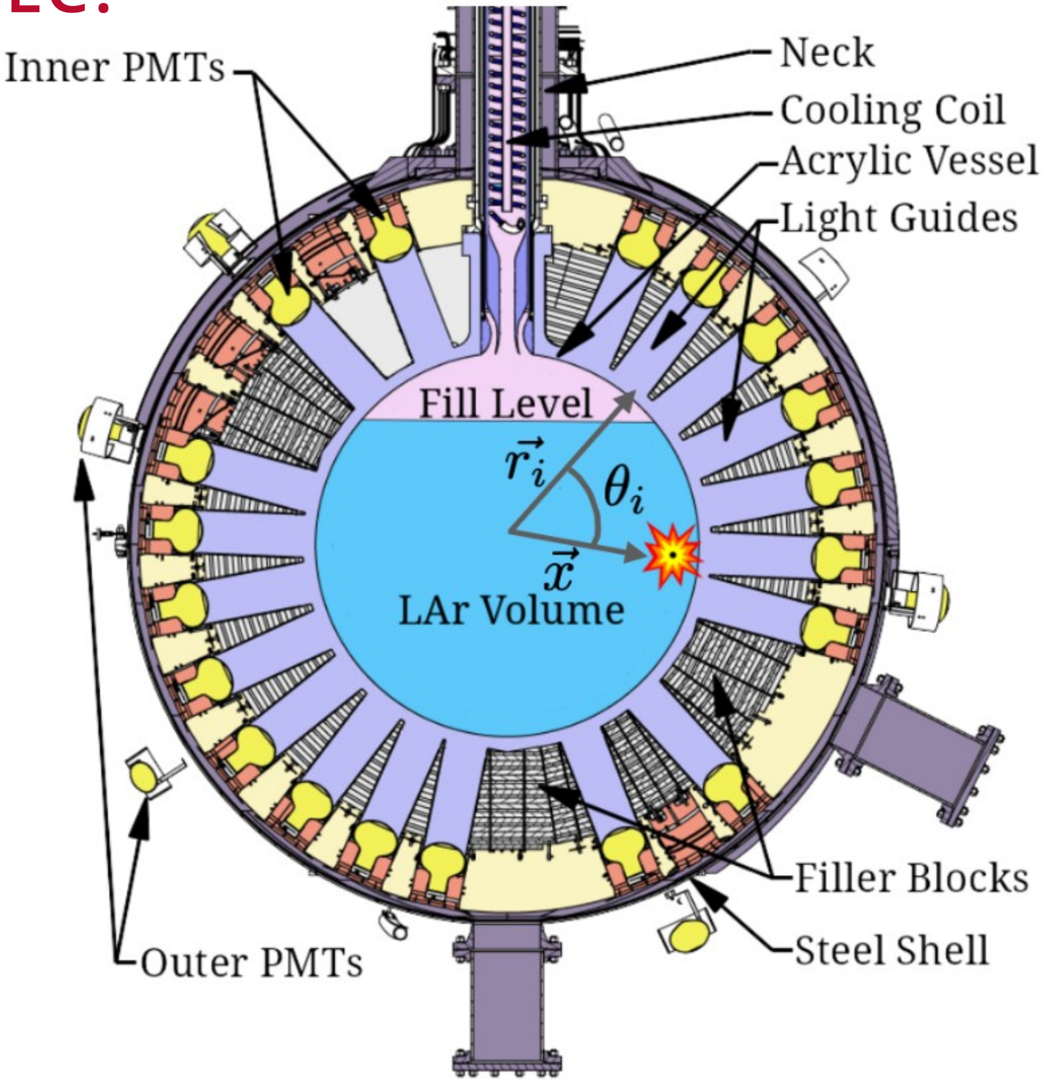
- Due to the Data Acquisition System (DAQ) recording all 255 inward facing PMTs independently, the individual signals for each PMT can be isolated.
- This allows for position reconstruction based on the amount of PE collected by each PMT.
- Based on where we see an increased collection of PE, we are similarly able to reject events that, for various reasons, are considered non-physics events.
- Alternatively, time-of-flight reconstruction can be done based on the arrival time of signals for each PMT.



arxiv.org/abs/2503.10383

How are we searching for DM/0νEC?

- In addition to position reconstruction, we also employ several veto systems, including the previously mentioned μ-veto.
- The μ-veto, triggered by the outer PMTs detecting Cherenkov light produced within the surrounding water bath, allow for the exclusion of spallation events.
- Neck and near-neck area of the AV are coated in Pyrene to delay scintillation light wavelength shift to avoid collecting non-LAr scintillation/ionization events.
- Fill mass is estimated by calculating the density of LAr at a given temperature, measuring the fill level, and calculating the AV radius after cooling.



arxiv.org/abs/2503.10383

Bibliography

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