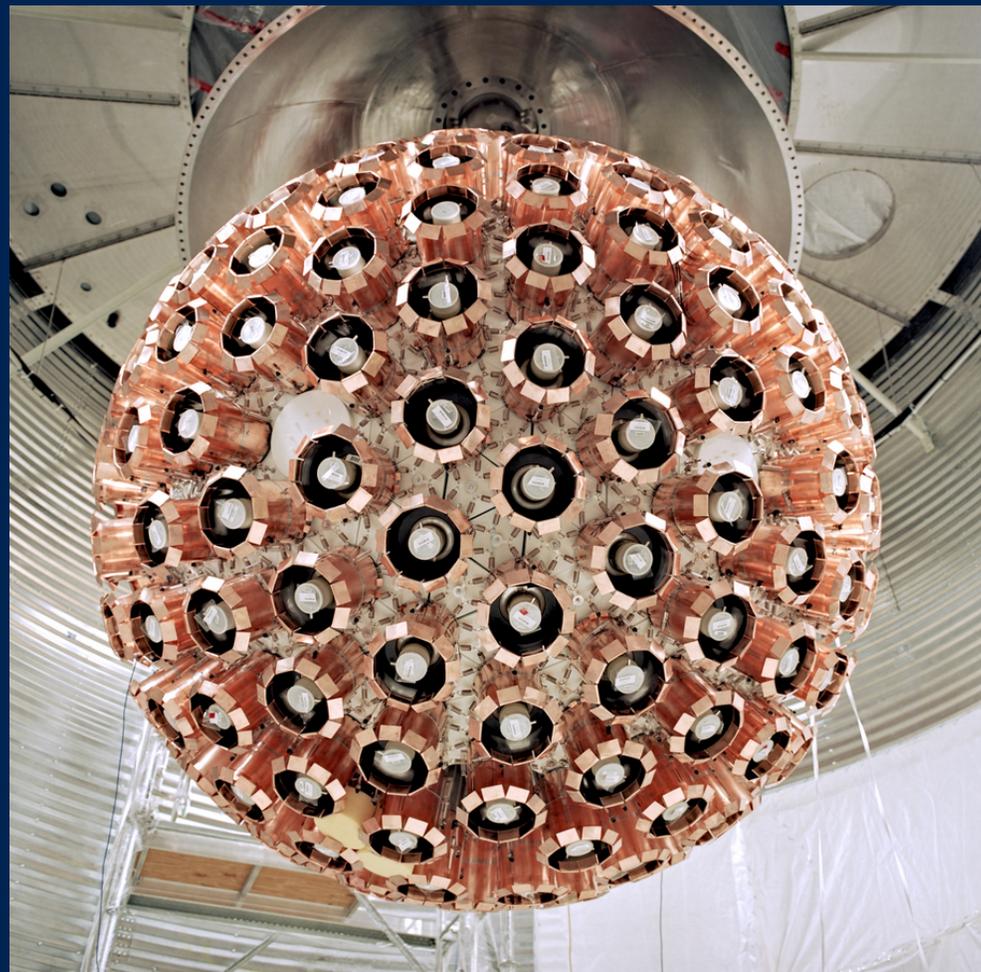# Nuclear Physics in Liquid Argon with DEAP-3600

WNPPC2026
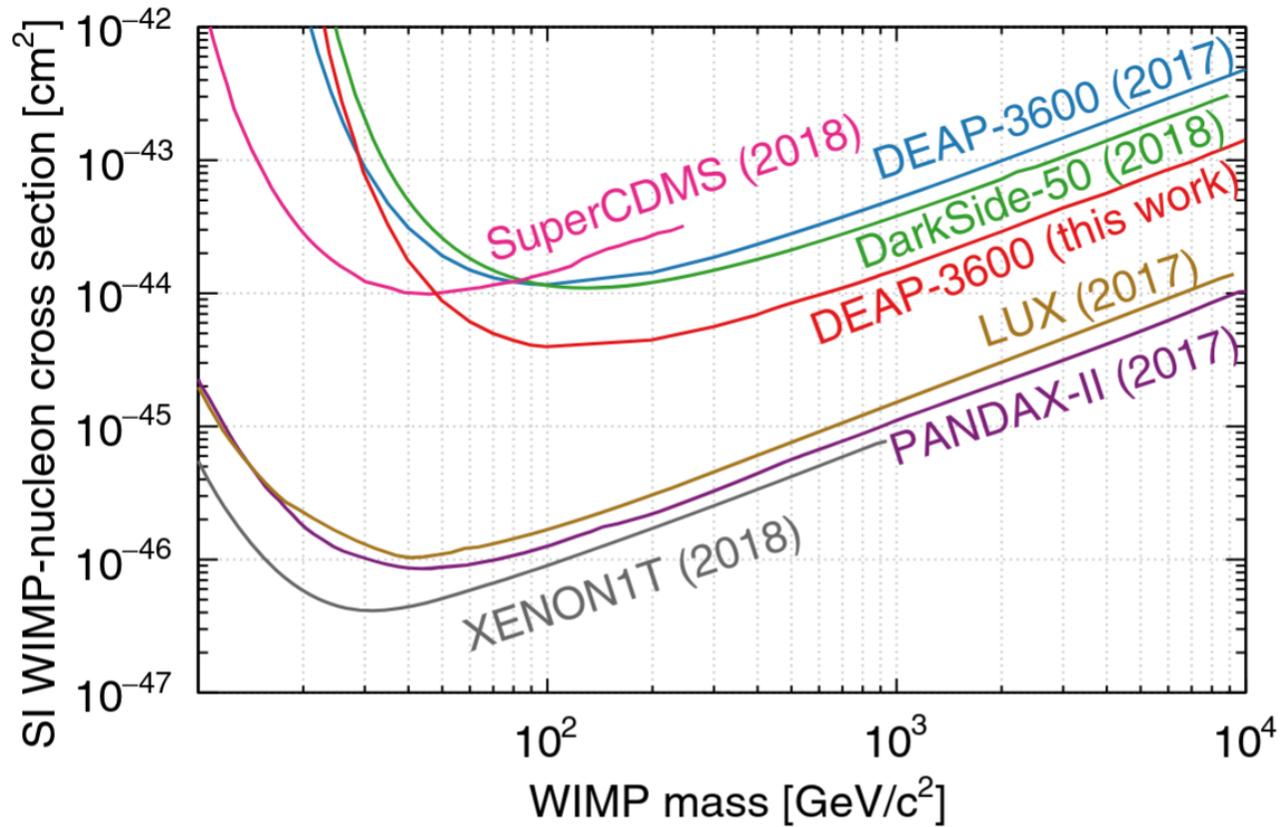
By: Peter Taylor

On behalf of the DEAP-3600 collaboration
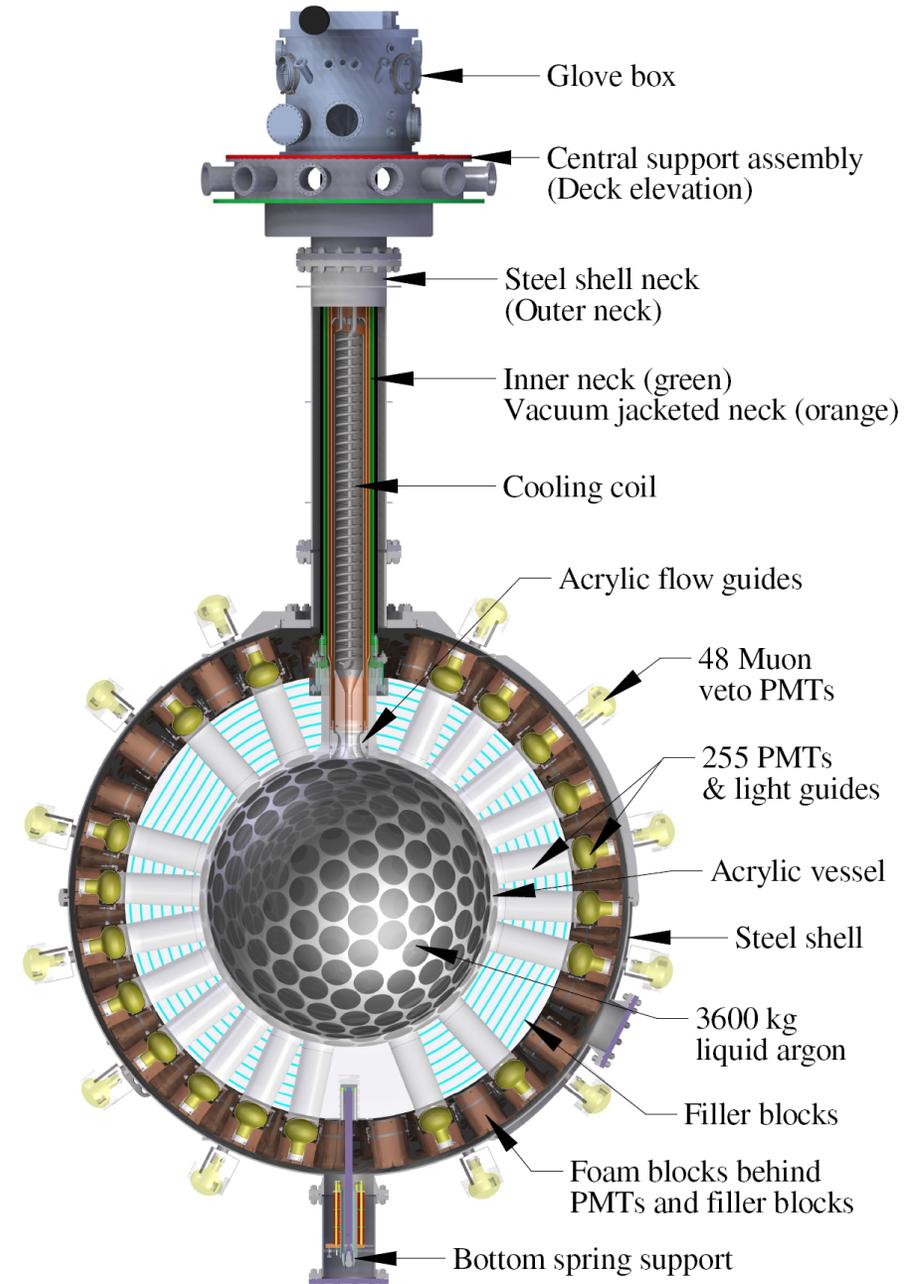
February 15, 2026

DEAP 3600 χ χ

Queen's UNIVERSITY
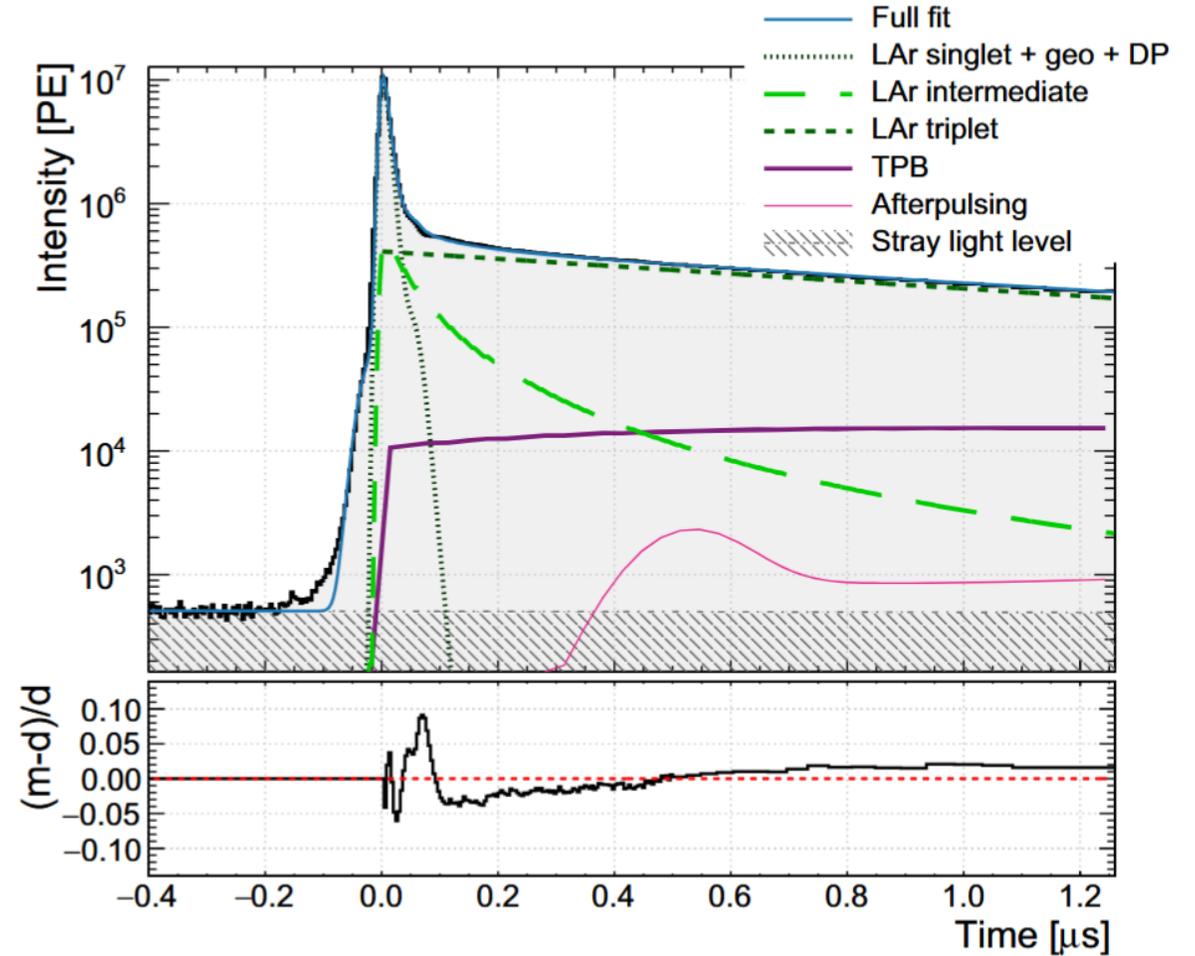
The Experiment

Phys. Rev. D. 100, 022004

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

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

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

3

How are we searching for Dark Matter?

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

$$^{39}Ar \rightarrow \beta^- + {}^{39}K$$
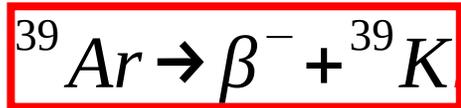
Q = 0.565 MeV

Degraded α-Quenching Factor:
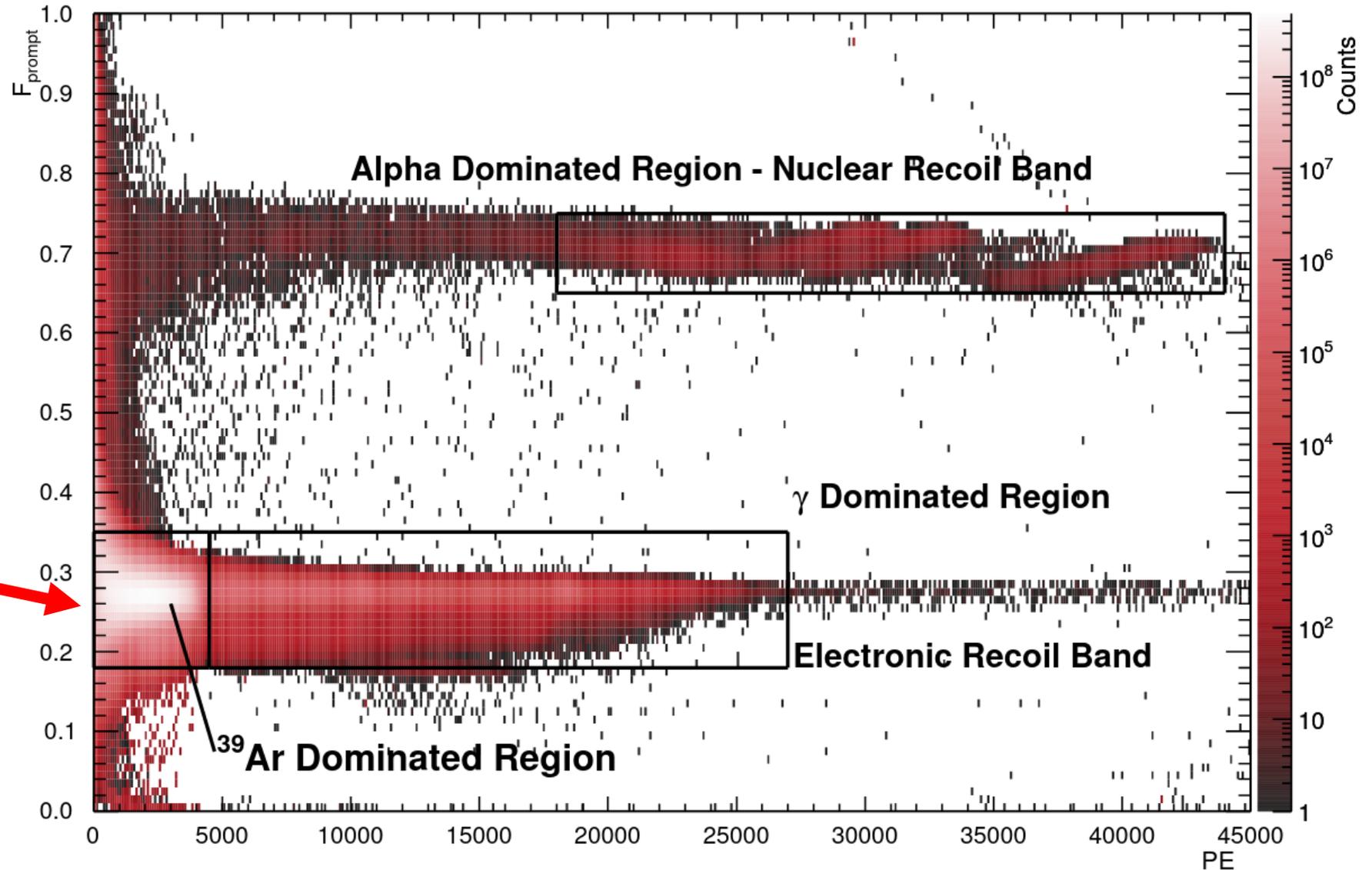
Atomic Electron Excimer QF:

Nuclear Recoil QF:

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

$$QF_\alpha^{nucl} = \frac{E_{dep,elec}}{E_{dep,elec} + E_{dep,nucl}}$$

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

$QF^{nucl}_\alpha * QF^M_\alpha$
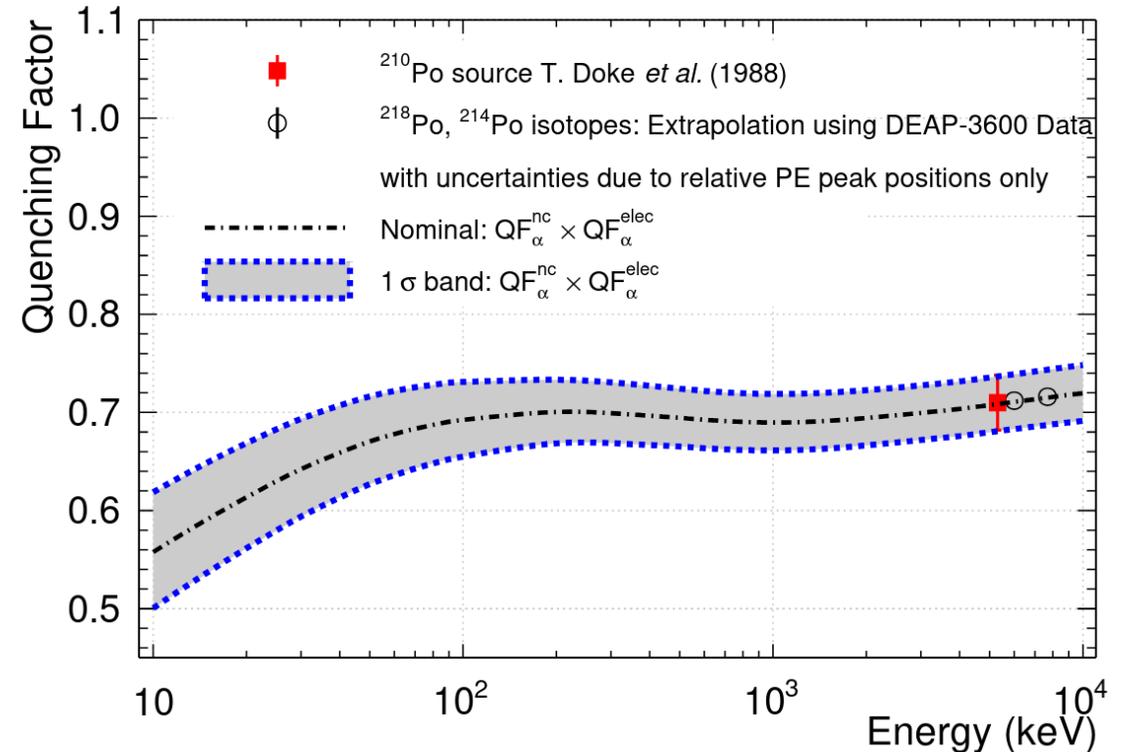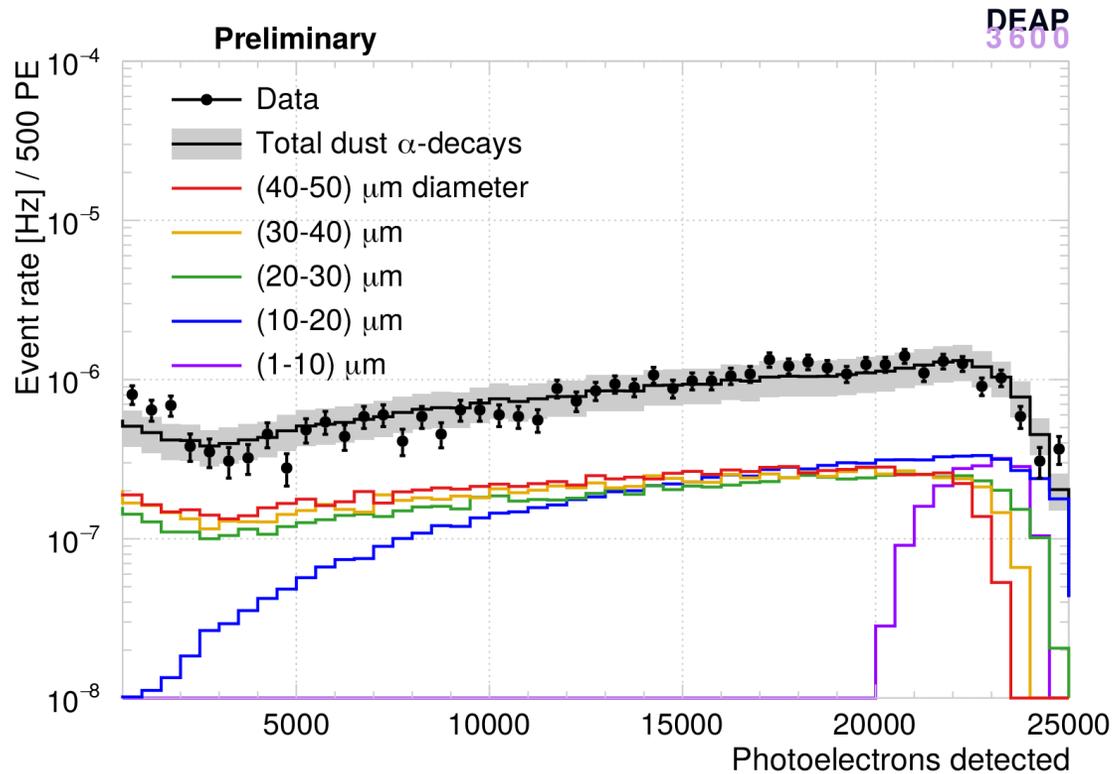
Specific Activity:
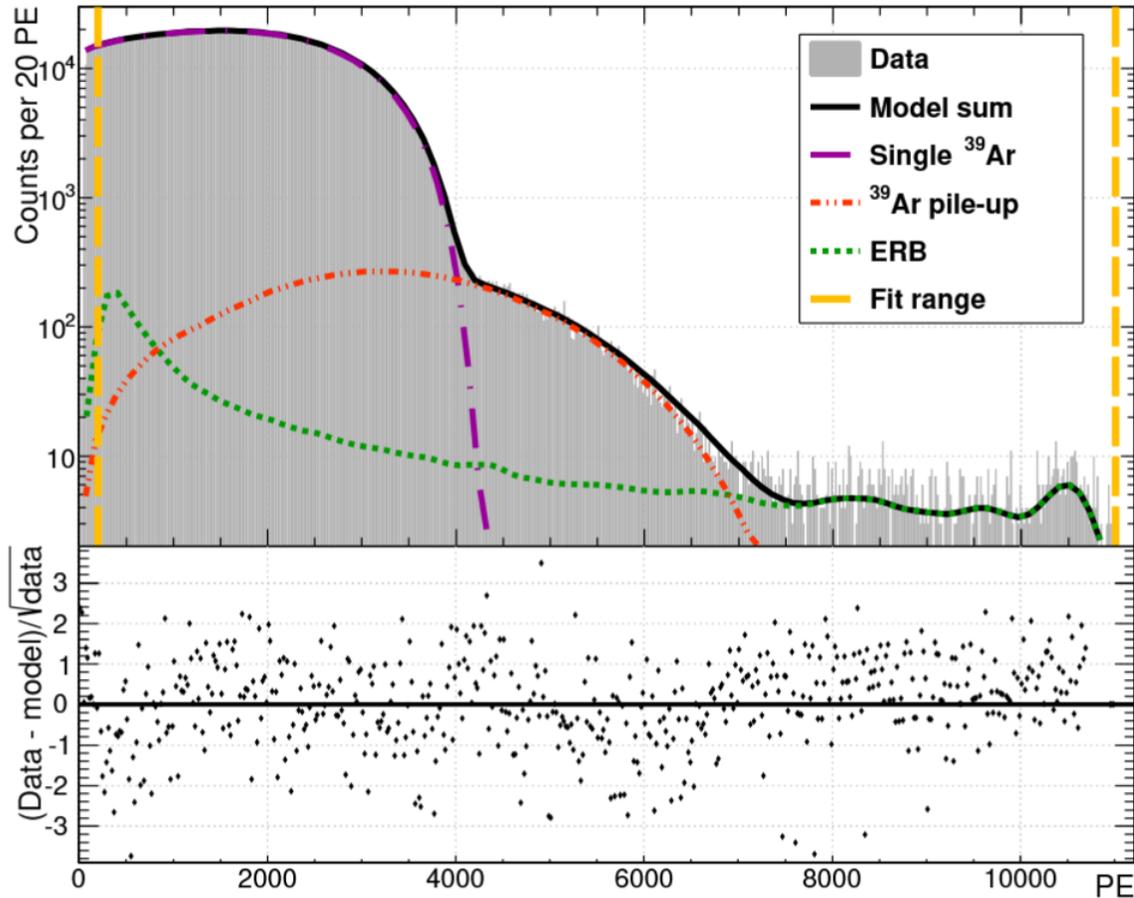
$$S_{^{39}Ar} = \frac{N_{single} + N_{pileup} + N_{ERB}}{m_{LAr} T_{livetime}} \; ; \; T_{livetime} = 167 \text{ days}$$
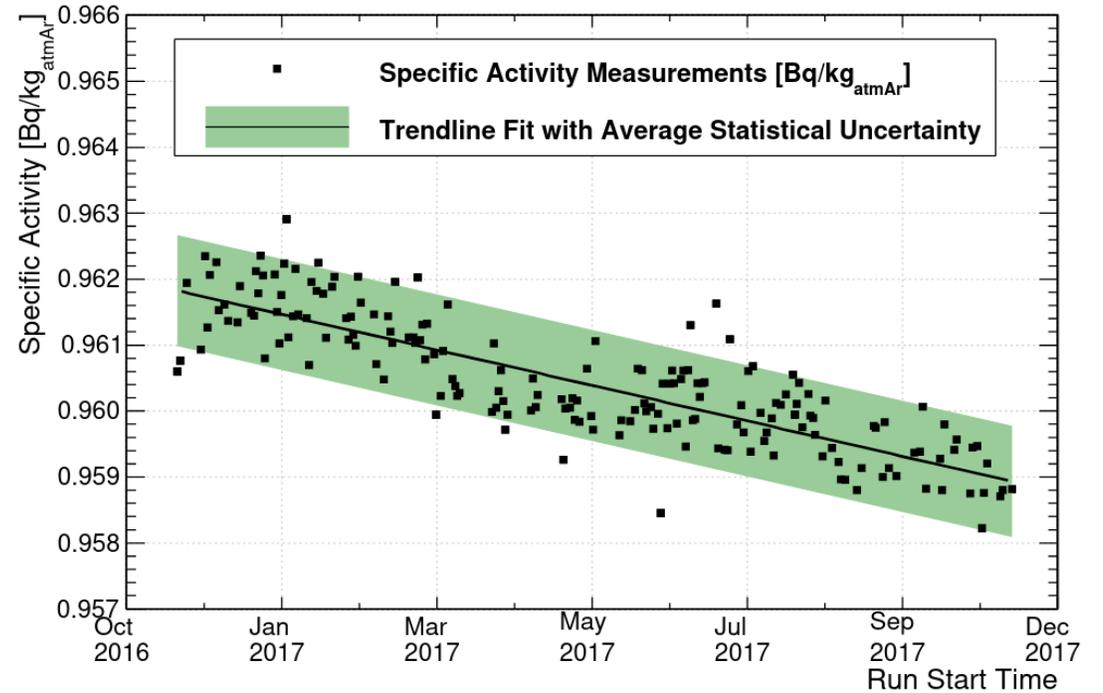
Measurement	Specific activity [Bq/kg$_{\text{atmAr}}$]
WARP [15]	$1.01 \pm 0.02_{\text{stat}} \pm 0.08_{\text{sys}}$
ArDM [16]	0.95 ± 0.05
DEAP-3600 (this work)	$0.964 \pm 0.001_{\text{stat}} \pm 0.024_{\text{sys}}$

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

arxiv.org/pdf/2302.14639

6

Half-life of ^{39}Ar

$$\chi^2/\text{ndf} = 174.5/171$$
$$R_{^{39}\text{Ar}} = (2949.2 \pm 0.3) \text{ Hz}$$
$$T_{1/2} = (302 \pm 8) \text{ years}$$

Zeldes et al. (1952) — 265 ± 30

Stoenner et al. (1960) — $325 \pm 16_{stat}$

Stoenner et al. (1965) — $269 \pm 3_{stat} \pm 8_{sys}$

Baksi et al. (1996) — $276 \pm 3_{sys}$

NDS (2018) — $268 \pm 8_{sys}$

DEAP-3600 (2025)
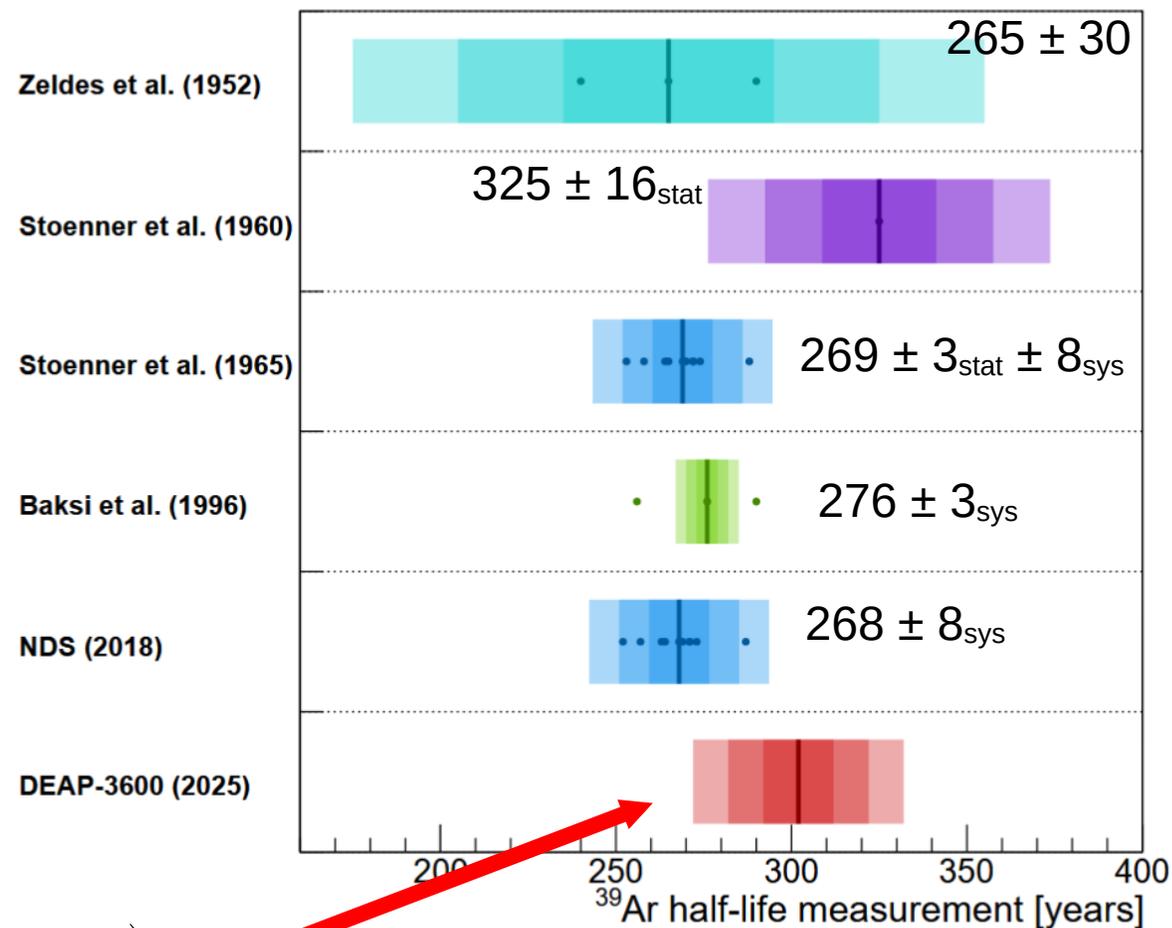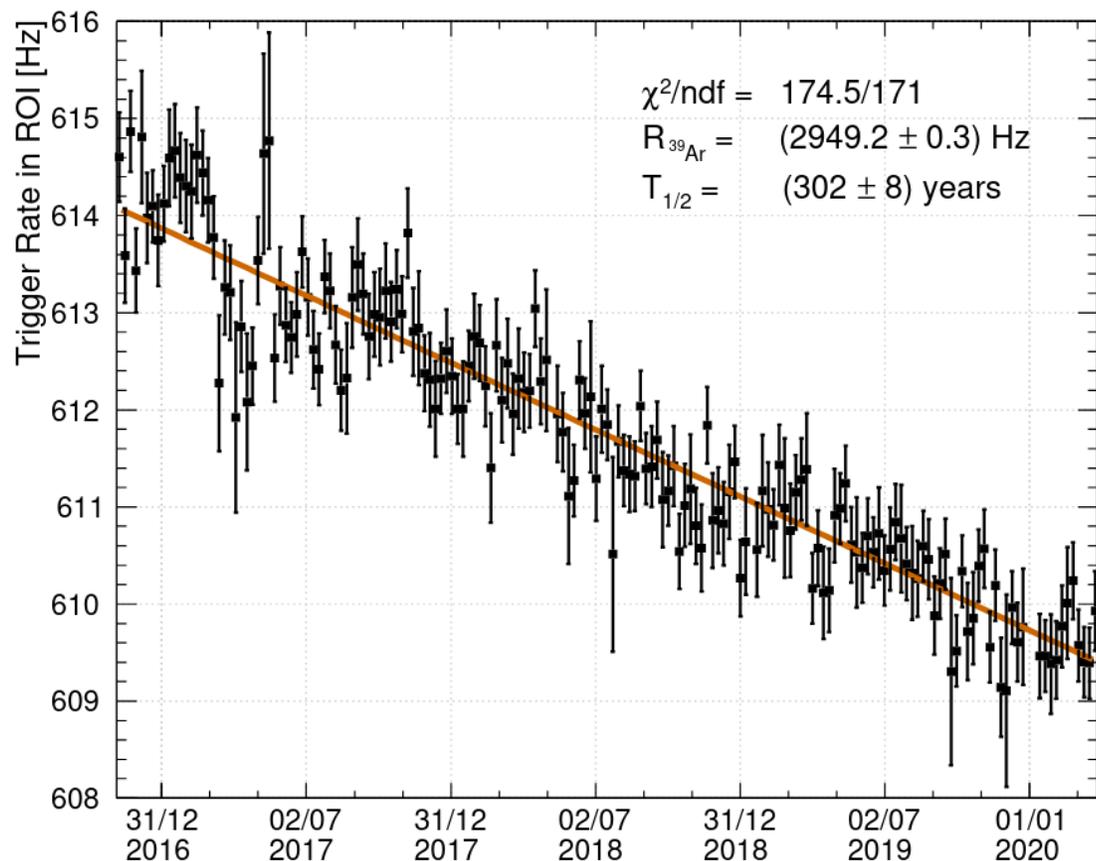
$$T_{1/2} = \left(302 \pm 8_{stat} \pm 6_{syst}\right) years$$

Search for 0νECEC:

- Neutrinoless Double Beta decay (0νββ) isn't allowed by the Standard Model by conservation of lepton number.

- Hypothesized to exist due to observations of neutrino-mixing implying both mass and differences in mass.

- The inverse process is known as Neutrinoless Double Electron Capture (0νECEC). Other noteworthy isotopes include ^{136}Xe, and ^{76}Ge.

8
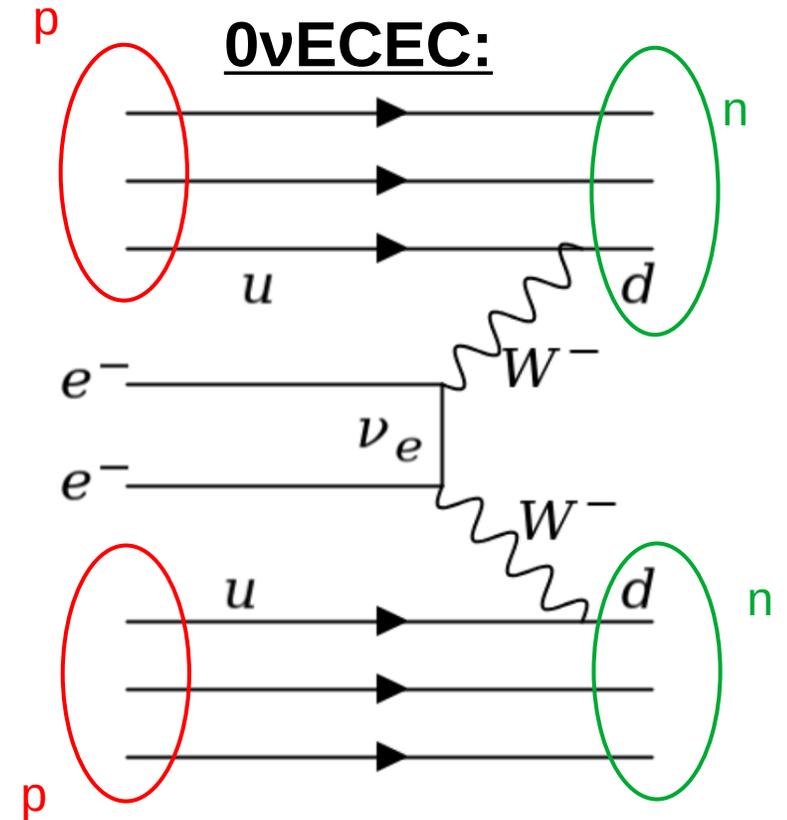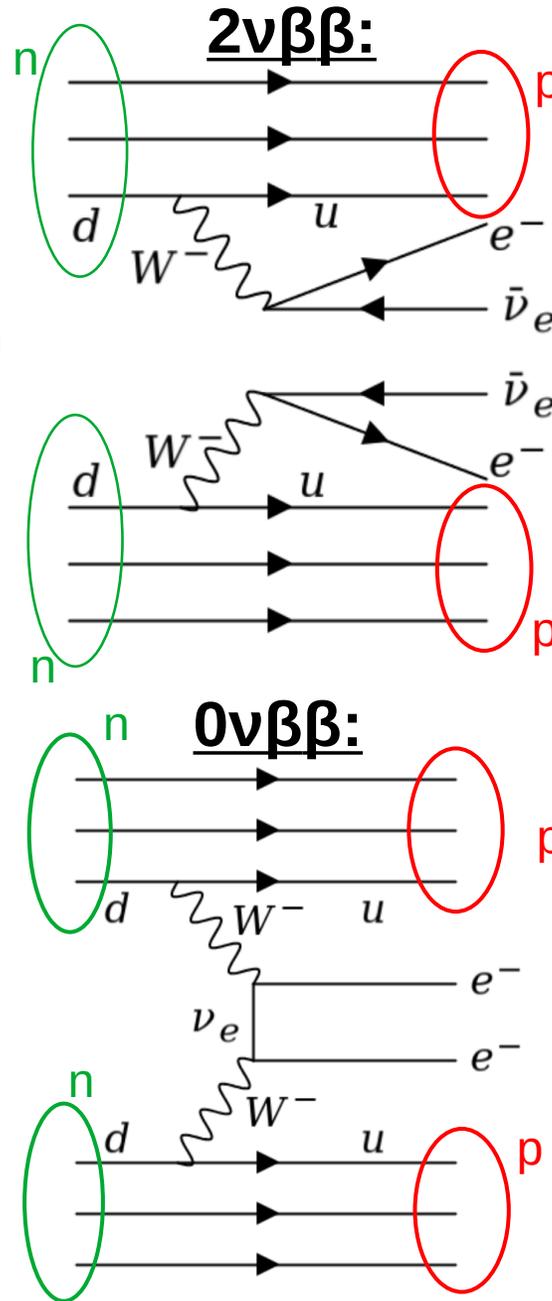
Status on future search for 0νECEC:

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

- Observationally stable (>10^{21} years)

- Next steps:
  - Improve calibration
  - Update selection cuts
  - Extend to the full dataset

9
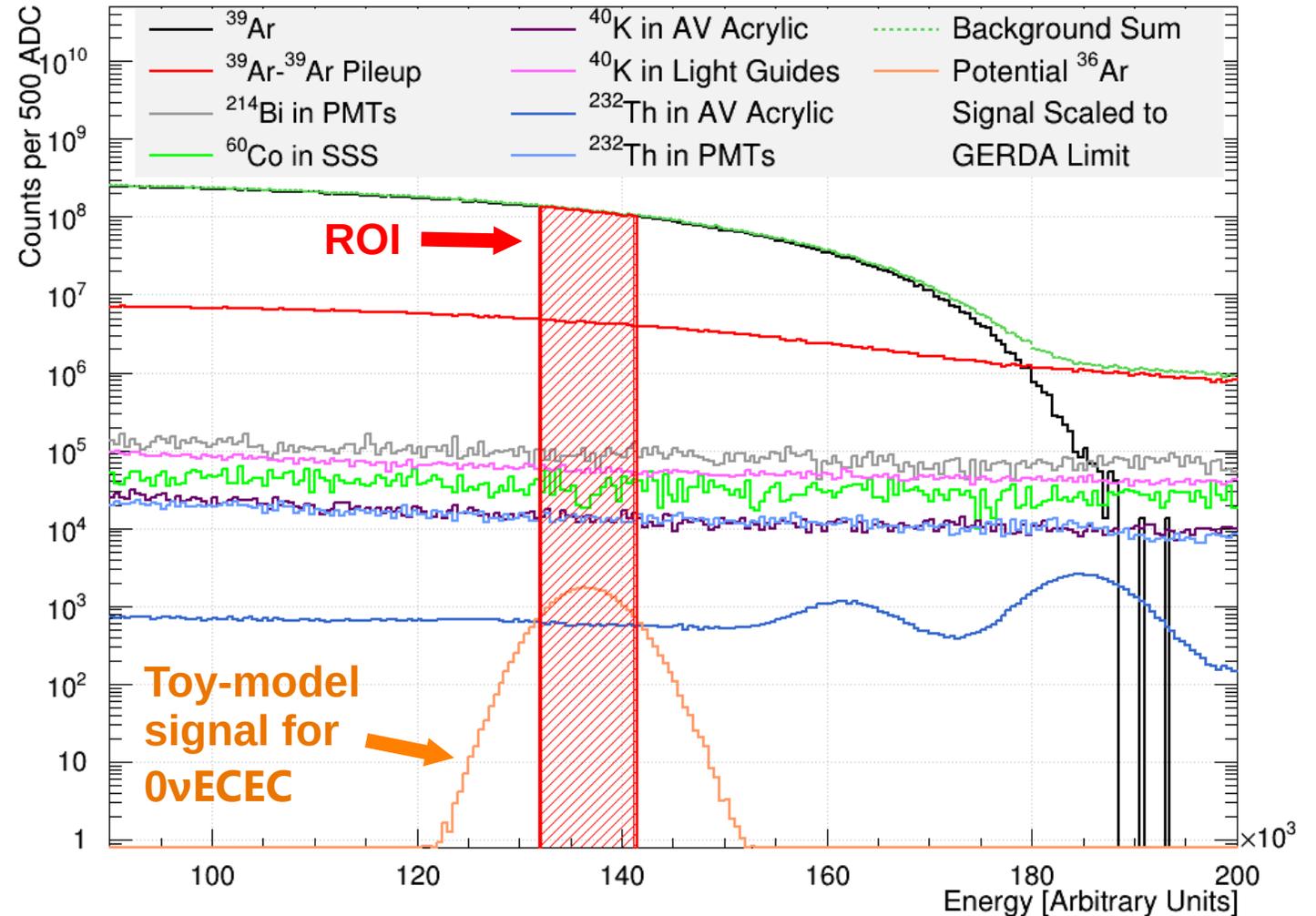
Supplementary Material

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.

11

Comparison of PMTs and SiPMs

- Once the scintillation light is produced, shifted, and then makes its way along the light guides, it is detected by a Photomultiplier (PMT).

- These may have issues operating at the cryogenic temperatures of the LAr, depending on model.

- Light guides are needed to reduce ^{40}K present in the glass.

- While Silicon Photomultipliers (SiPMs) can operate better at those temperatures, current SiPMs are only sensitive down to ~175nm in cryogenics environments.
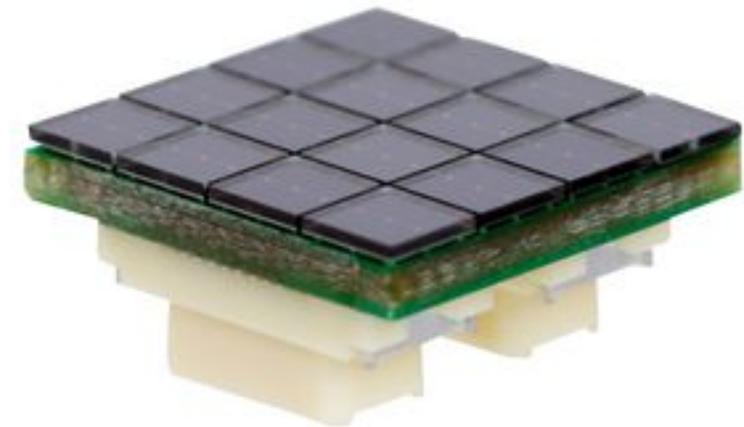
The Experiment

- 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) $Ar^+ + Ar \rightarrow Ar_2^+$

 $Ar_2^+ + e^- \rightarrow Ar_2^* \rightarrow 2\,AR + \gamma$
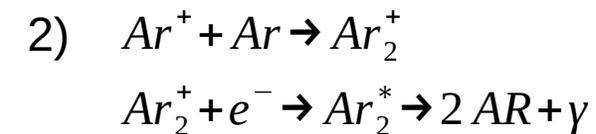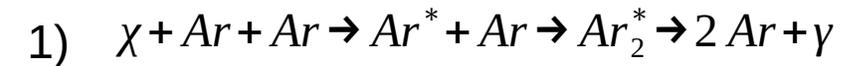
The Physics

- What do we use to detect such interactions?

- 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.
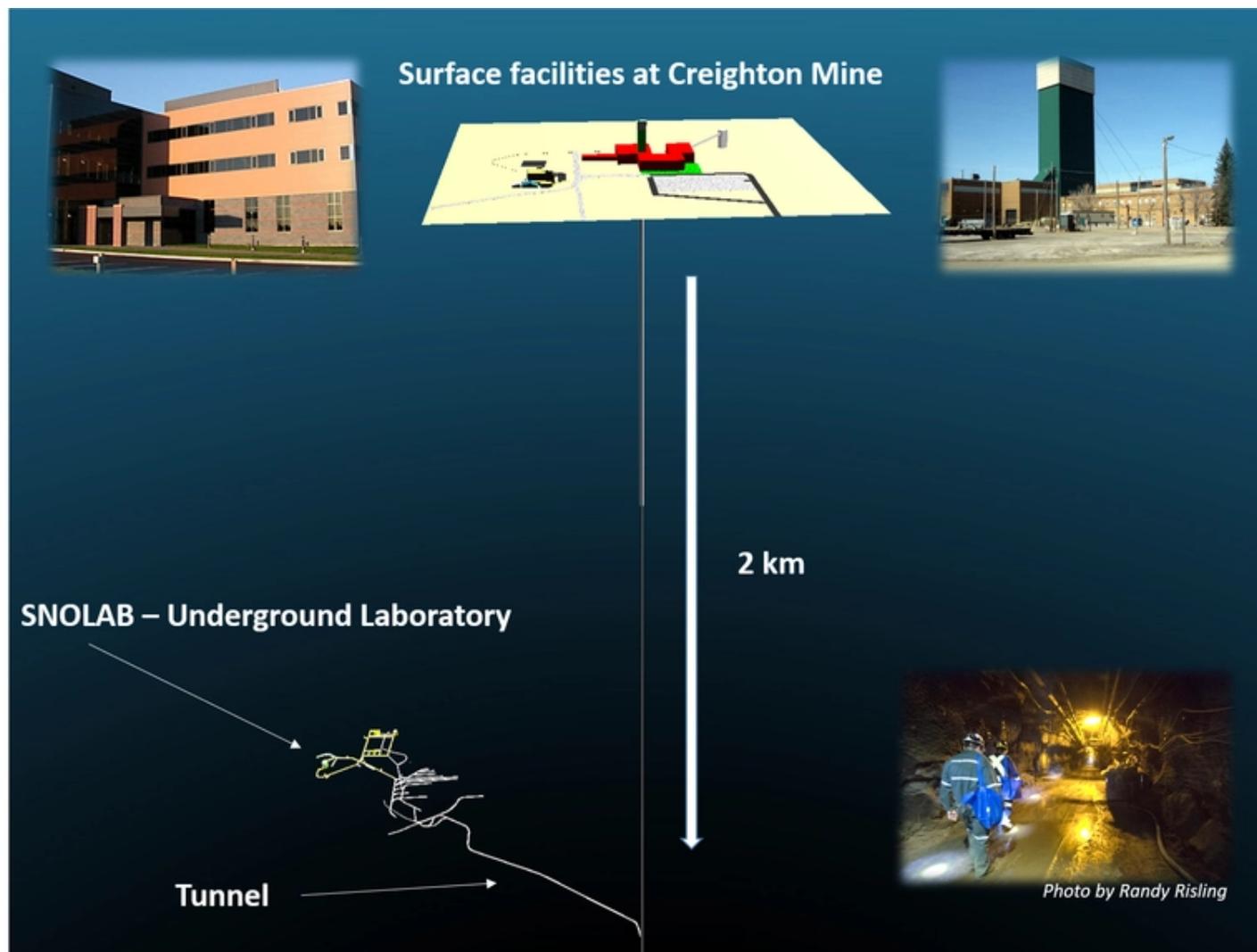

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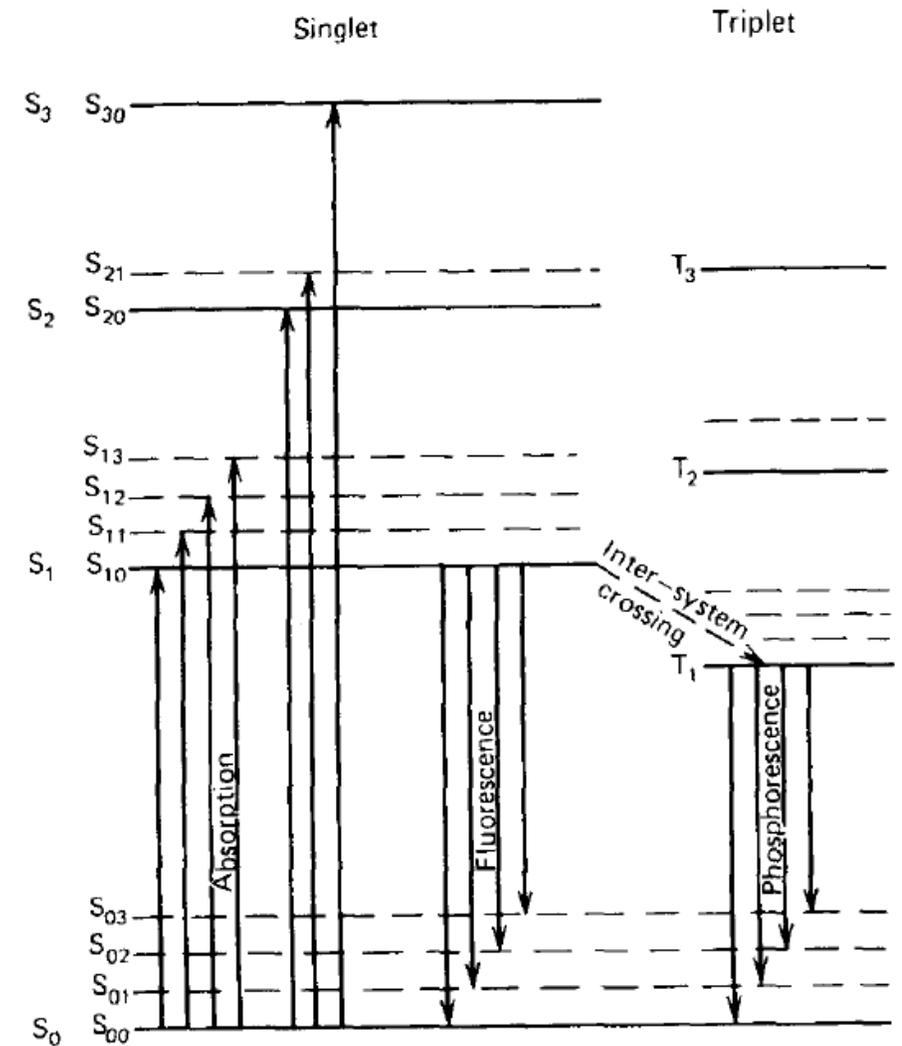
The Physics

- Radiation types: α, β, γ, and neutrons. These can cause any number of interactions that can resemble what you're looking for.

- The background of your environment and detector needs to be known in extreme detail. This lets you simulate what your signals/spectrum ***should*** look like and compare that to what you're actually measuring.

15
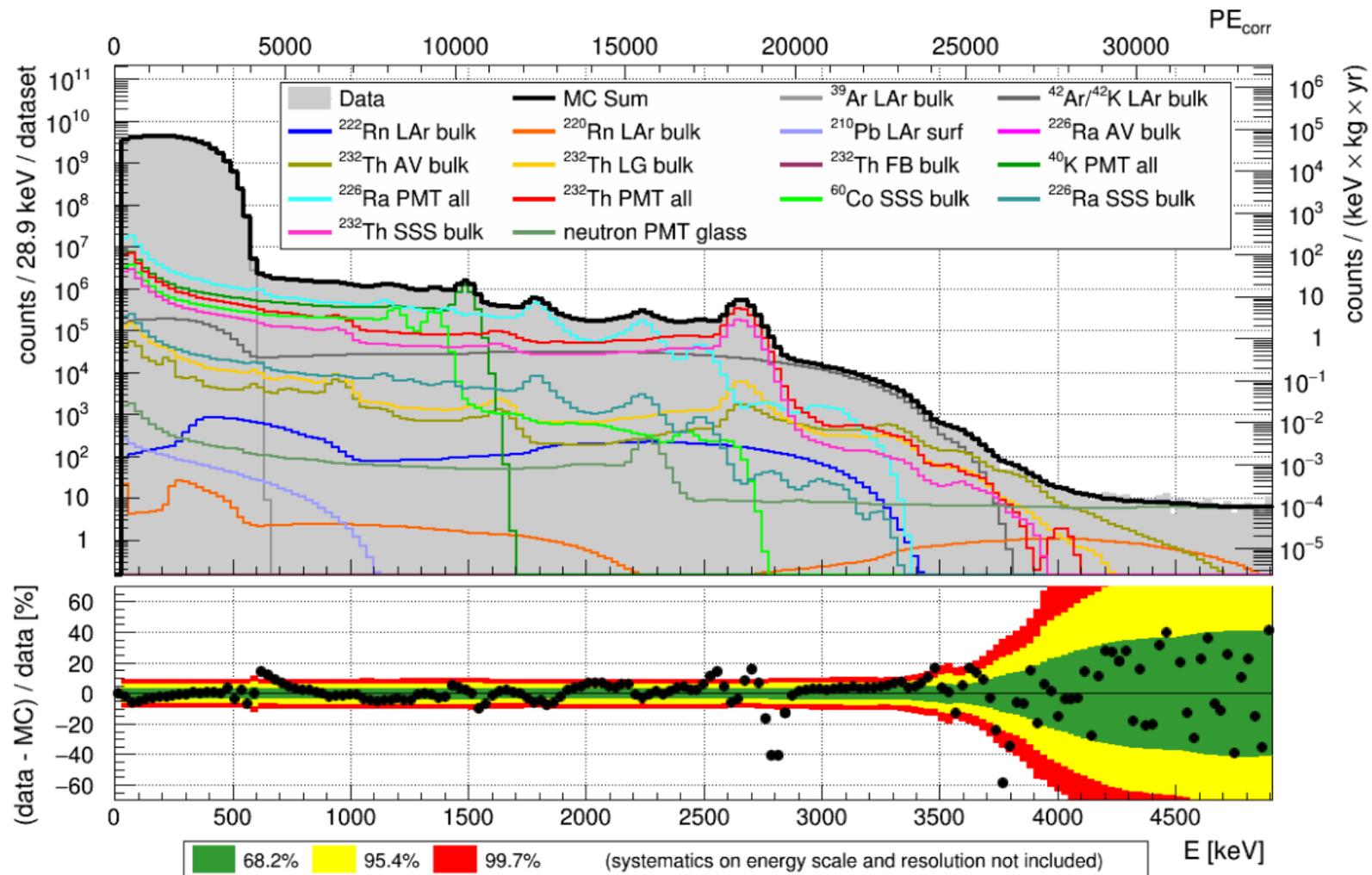
The Experiment

- Both as a general practice for nuclear physics experiments, and in order to look for such rare processes as DM and 0vECEC, 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.
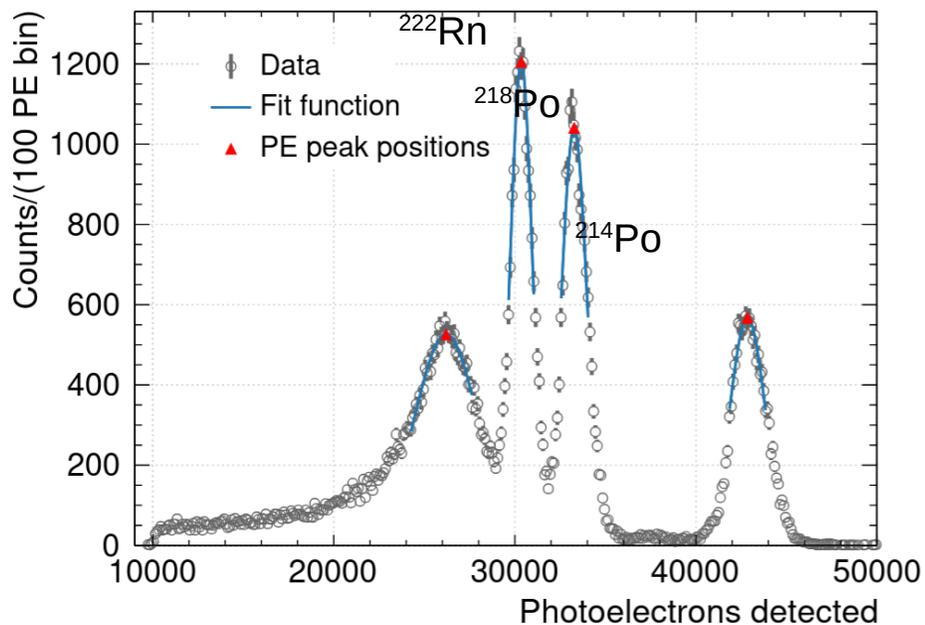

Surface facilities at Creighton Mine
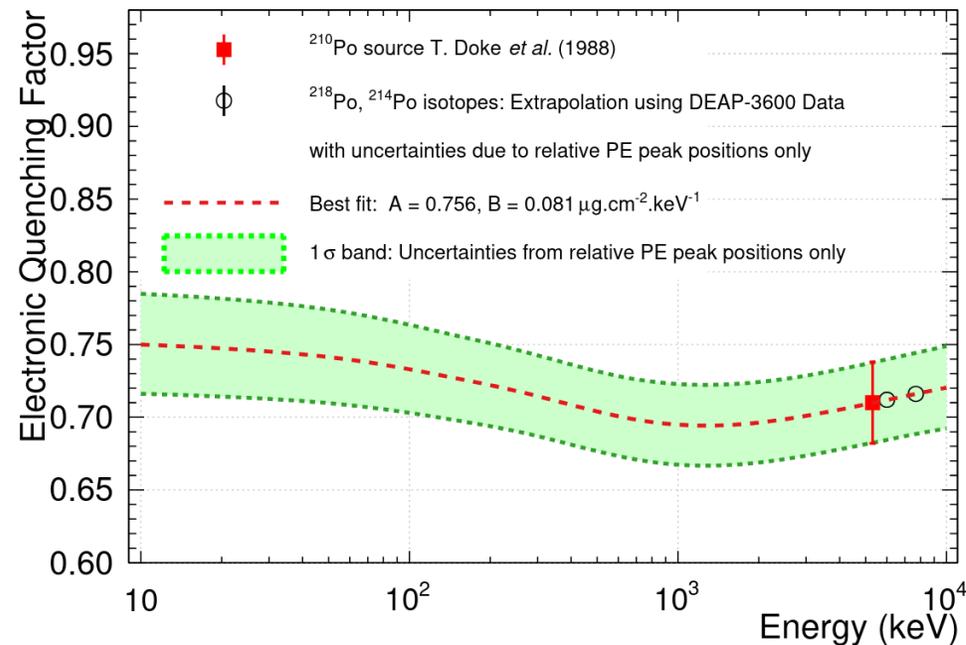
2 km

SNOLAB – Underground Laboratory

Tunnel

Photo by Randy Risling

What have we found so far?
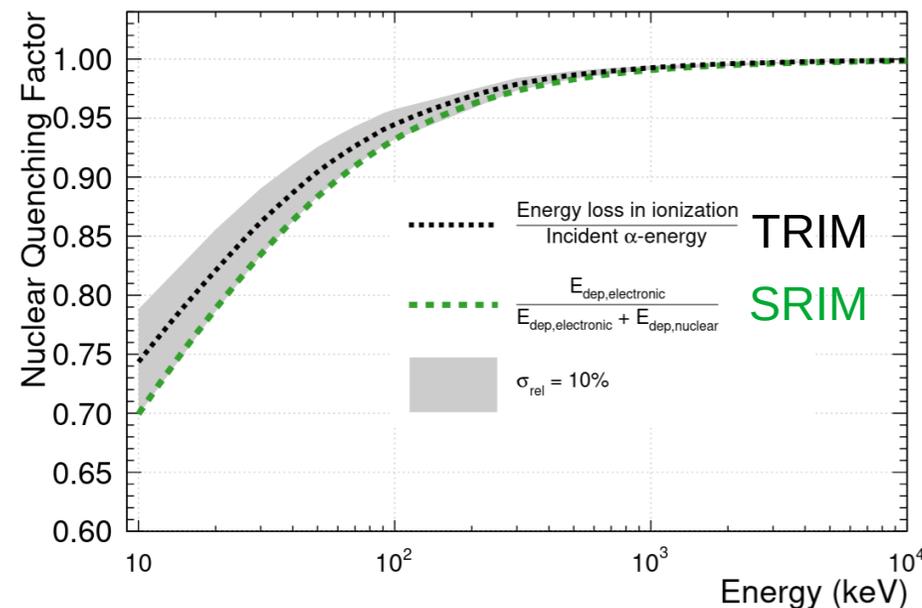
$$QF_\alpha^{nucl} = \frac{E_{dep,elec}}{E_{dep,elec} + E_{dep,nucl}}$$

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

Electronic QF:

Nuclear QF:

17

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.
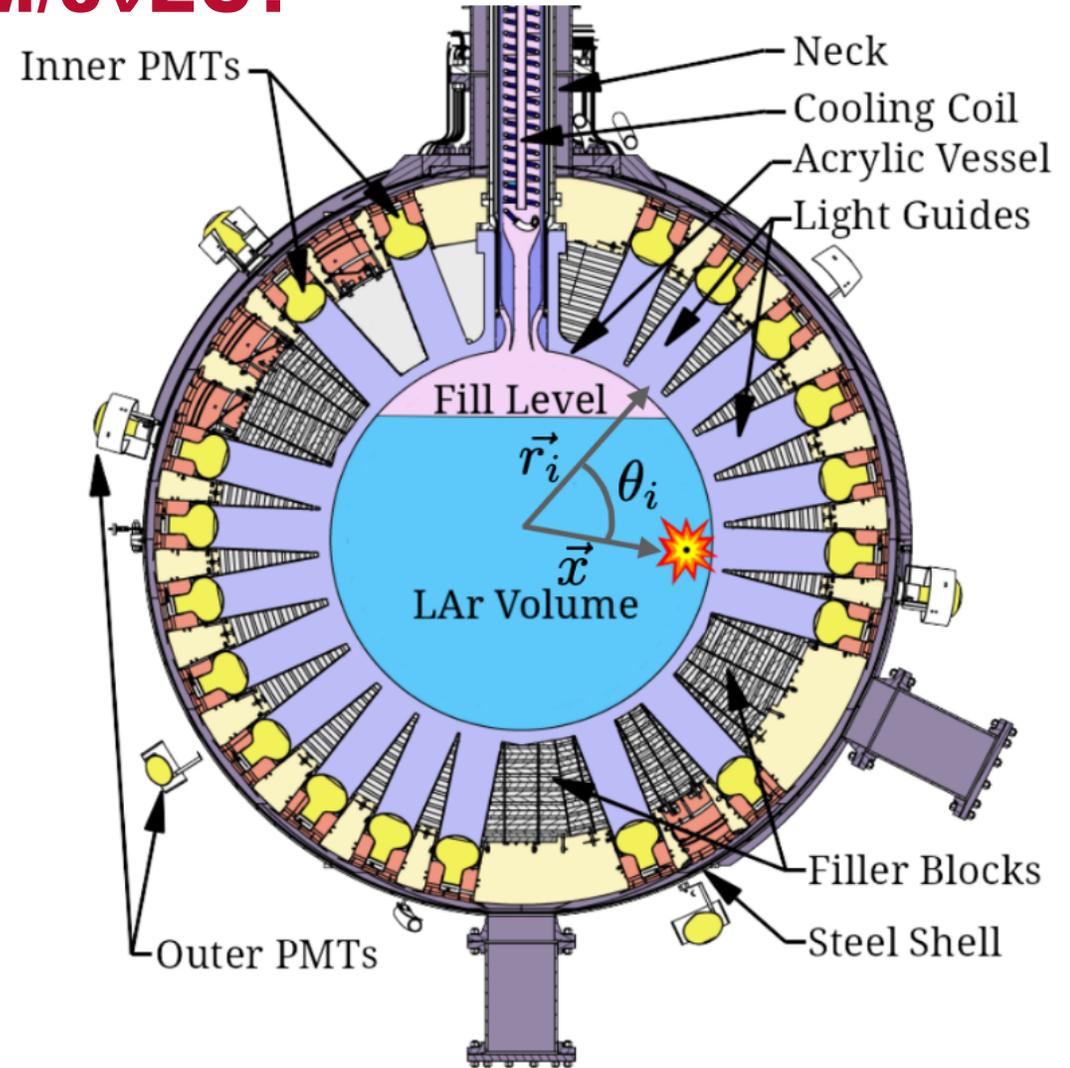
How are we searching for DM/0νEC?

- 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.

19
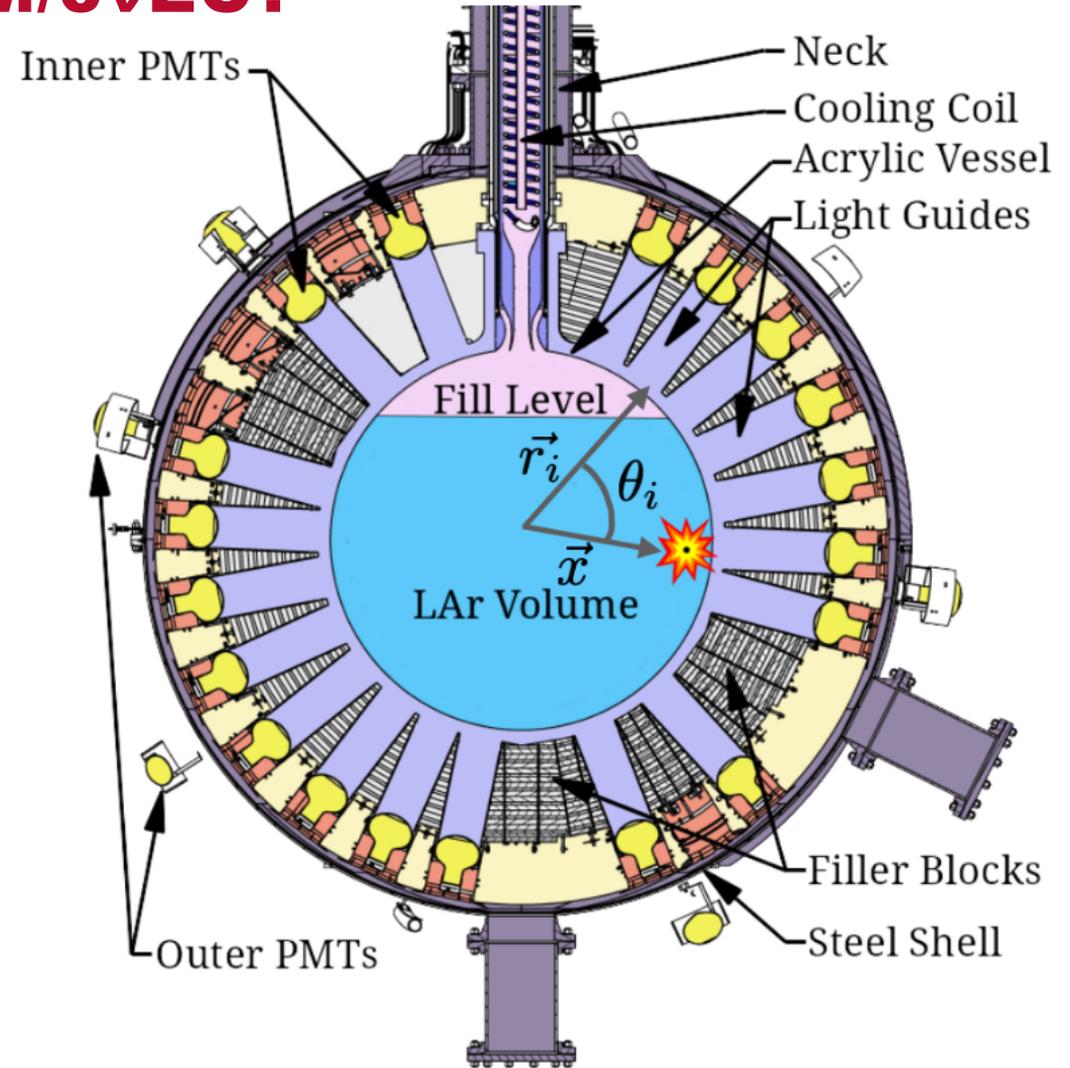
Bibliography for images

- [pg 1] https://deap3600.ca/

- [pg 2] https://doi.org/10.1103/PhysRevD.100.022004

- [pg 8] https://www.aidansean.com/feynman/

- [pg 16] https://www.queensu.ca/physics/news-g/projects/news-g-snolab

- [pg 2] https://theconversation.com/a-clock-in-the-rocks-what-cosmic-rays-tell-us-about-earths-changing-surface-and-climate-228094

- [pg 12] https://lampes-et-tubes.info/pm/pm045.php

- [pg 12] https://www.newark.com/onsemi/arrayj-30035-16p-pcb/silicon-photomultiplier-4x4-array/dp/82AC2416

- [pg 14] Knoll, "Radiation Detection and Measurement"; Third Edition. Pg 221

- [pg 4] Dunford, M. "A Search for the Neutrinoless Double Electron Capture of 36Ar and a Measurement of the Specific Activity of 39Ar in Atmospheric Argon with the DEAP-3600 Detector "; Carleton University, July 2018.

- [pg. 18, 19] The DEAP Collaboration. "Position Reconstruction in the DEAP-3600 Dark Matter Search Experiment", 2025 https://arxiv.org/abs/2503.10383

  [pg 5] https://www.snolab.ca/deap/private/TWiki/bin/view/Main/PlotApprovalRequestx302

- [pg 5, 17] The DEAP Collaboration. "Relative Measurement and Extrapolation of the Scintillation Quenching Factor of α-Particles in Liquid Argon using DEAP-3600 Data", https://arxiv.org/pdf/2406.18597

- [pg 6] The DEAP Collaboration. "Precision Measurement of the Specific Activity of ^{39}Ar in Atmospheric Argon with the DEAP-3600 Detector", https://arxiv.org/pdf/2302.14639

- [pg 7] The DEAP Collaboration. "Direct Measurement of the ^{39}Ar Half-life from 3.4 Years of Data with the DEAP-3600 Detector", https://arxiv.org/pdf/2501.13196

- [pg 6, 9] https://www.snolab.ca/deap/private/TWiki/bin/view/Main/PlotApprovalRequestx190

- [pg 15] The DEAP Collaboration. "Electromagnetic Backgrounds and Potassium-42 Activity in the DEAP-3600 Dark Matter Detector", https://arxiv.org/abs/1905.05811