Recent developments and analyses in the DEAP-3600 experiment

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14th February, 2025

Outline

- DEAP-3600 experiment
- Results
  - ^{39}Ar specific activity measurement
  - ^{39}Ar half-life measurement
  - Quenching measurement
  - WIMP and Planck-scale DM search
- On-going analysis
  - Muon flux measurement
- Future!

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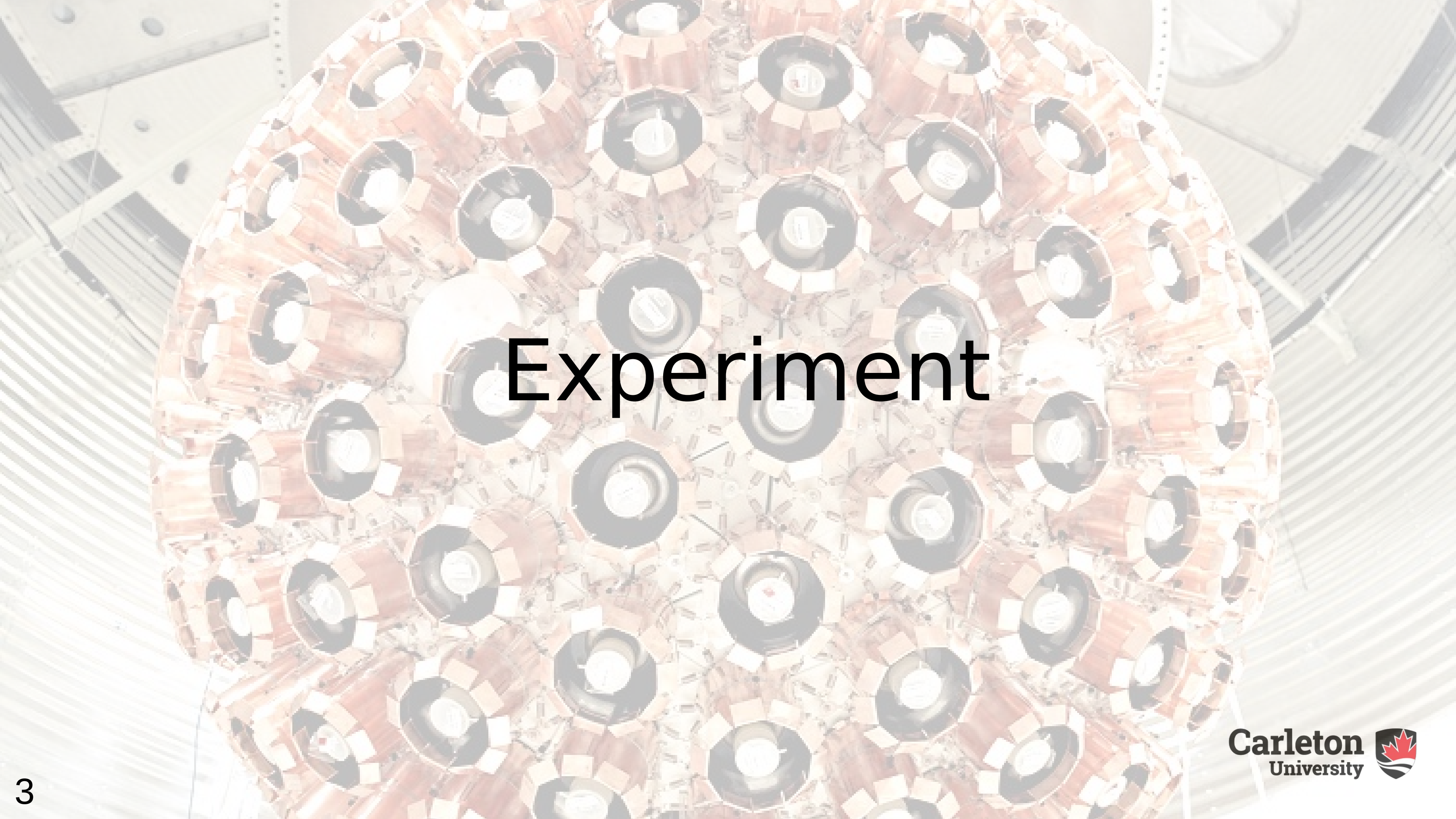
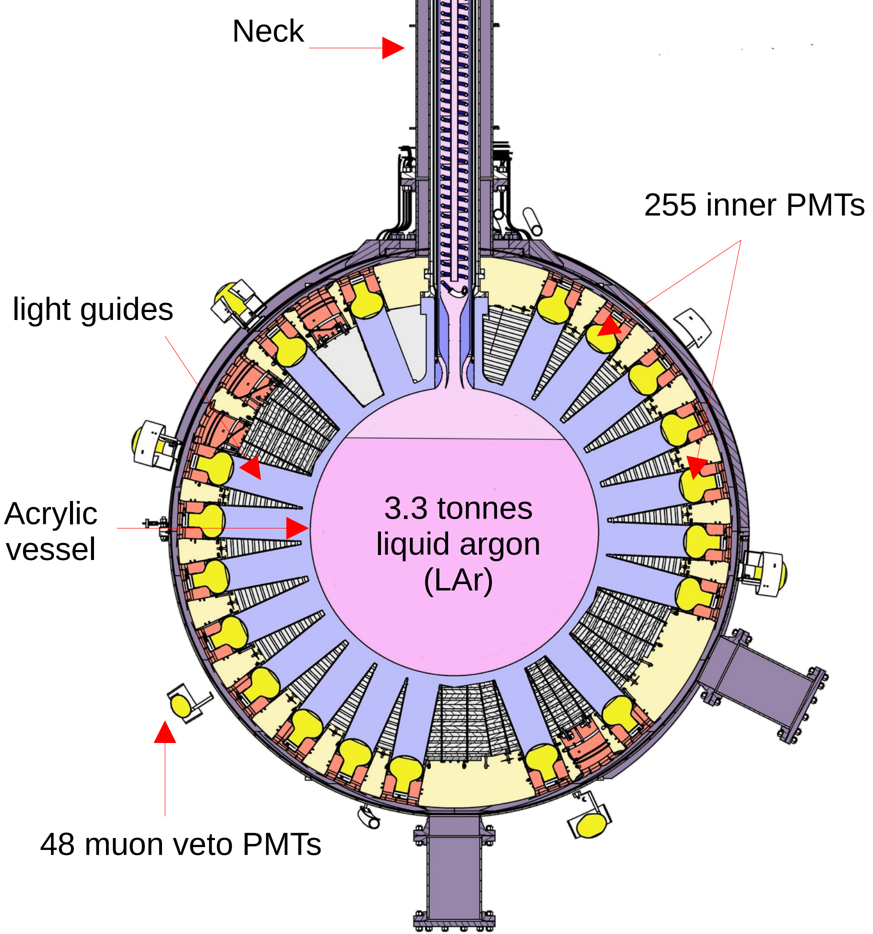


Experiment

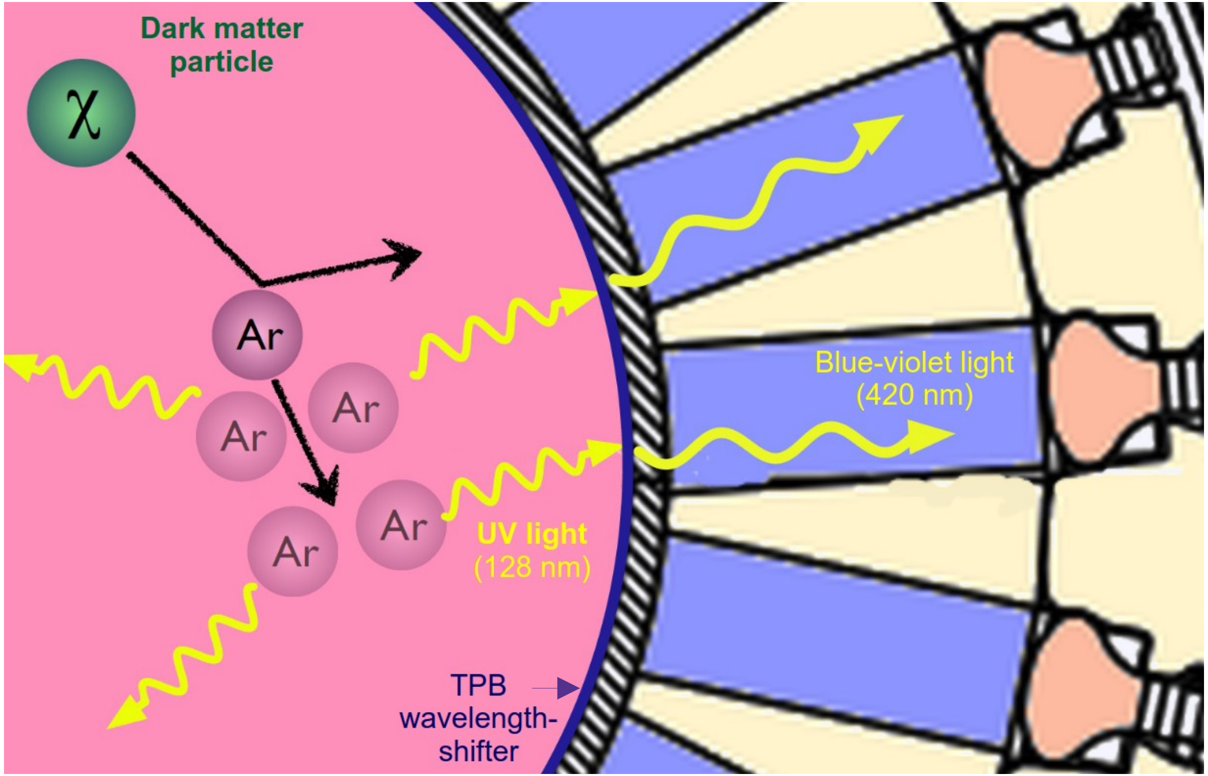
Detector

- Direct dark matter search experiment
  - **D**ark matter **E**xperiment using **A**rgon **P**ulse-shape discrimination (DEAP)
- (3269±24) kg liquid argon (LAr)
- Located at SNOLAB, Sudbury
- ~2km rock overburden (6000 m.w.e)



Water shielding

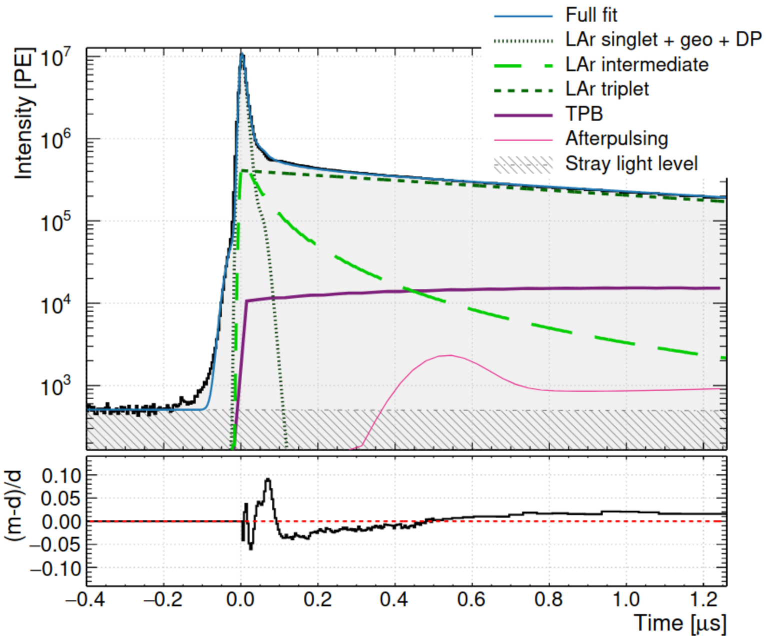
Detection

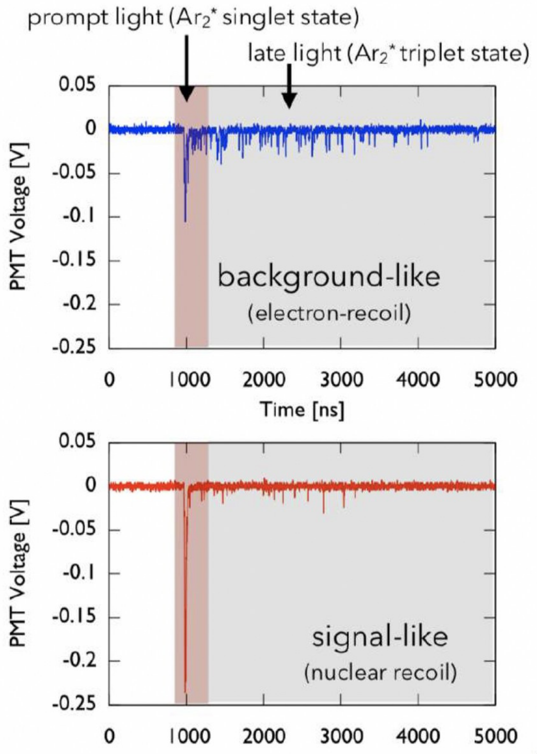

Dark matter particle
χ
Ar
Ar
Ar
Ar
Ar
Blue-violet light
(420 nm)
UV light
(128 nm)
TPB
wavelength-
shifter

Pulse-shape discrimination (PSD)

- Pulse shape model:

$$PSD = \frac{Prompt\ light}{Prompt\ light + Late\ light}$$





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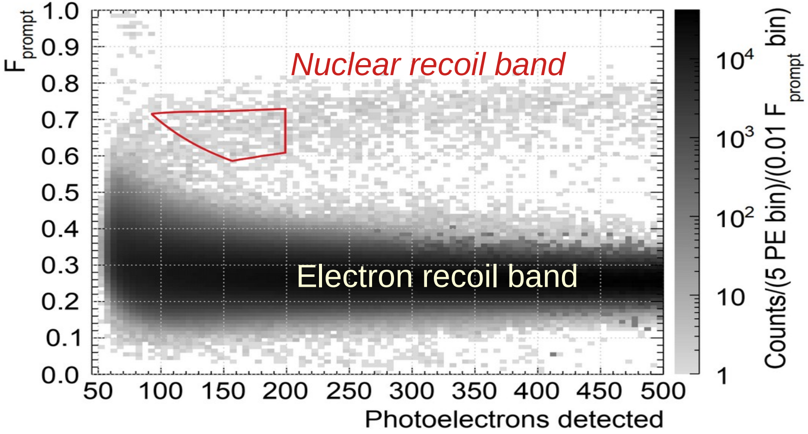
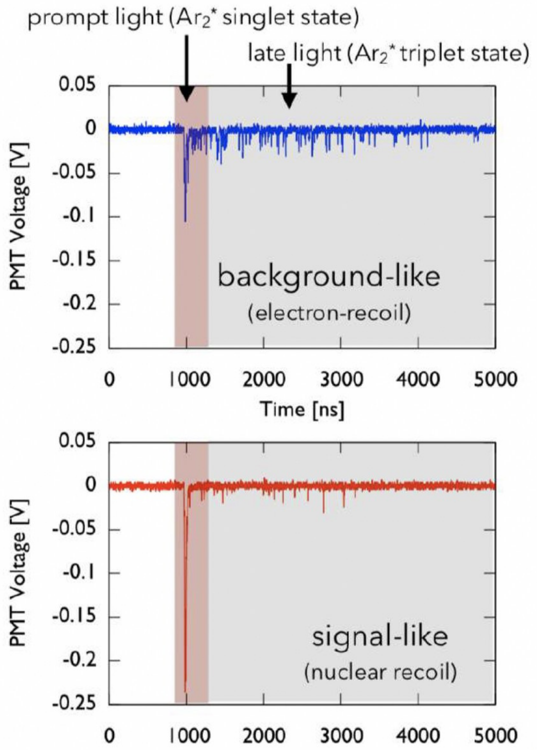
Pulse-shape discrimination (PSD)

- Pulse shape model: $$PSD = \frac{Prompt\ light}{Prompt\ light + Late\ light}$$
- Nuclear recoil band and electron recoil band can be easily distinguished using this method
- Need to study the backgrounds thoroughly

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





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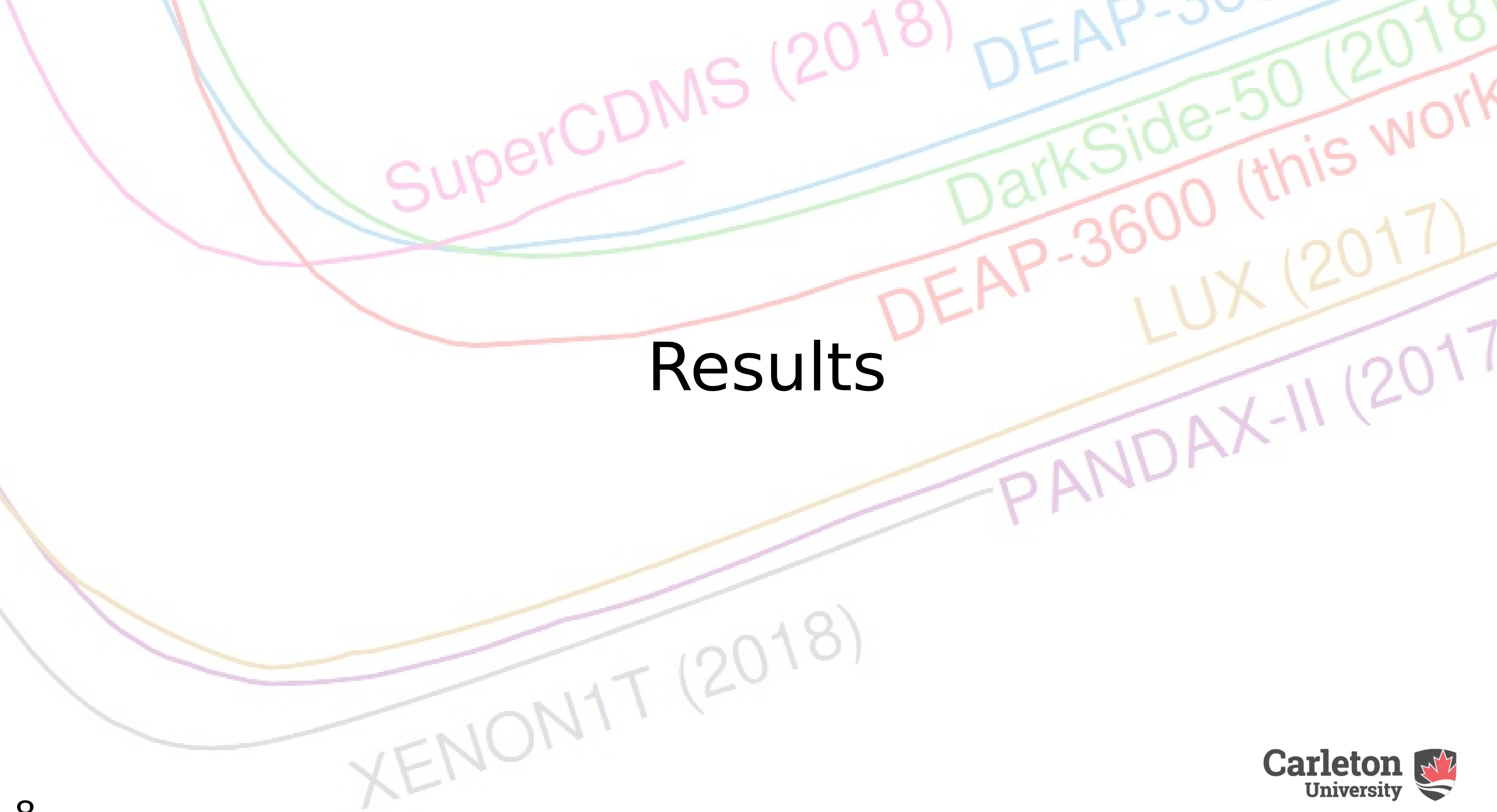
Results



SuperCDMS (2018)
DarkSide-50 (2018)
DEAP-3600 (this work)
LUX (2017)
PANDAX-II (2017)
XENON1T (2018)

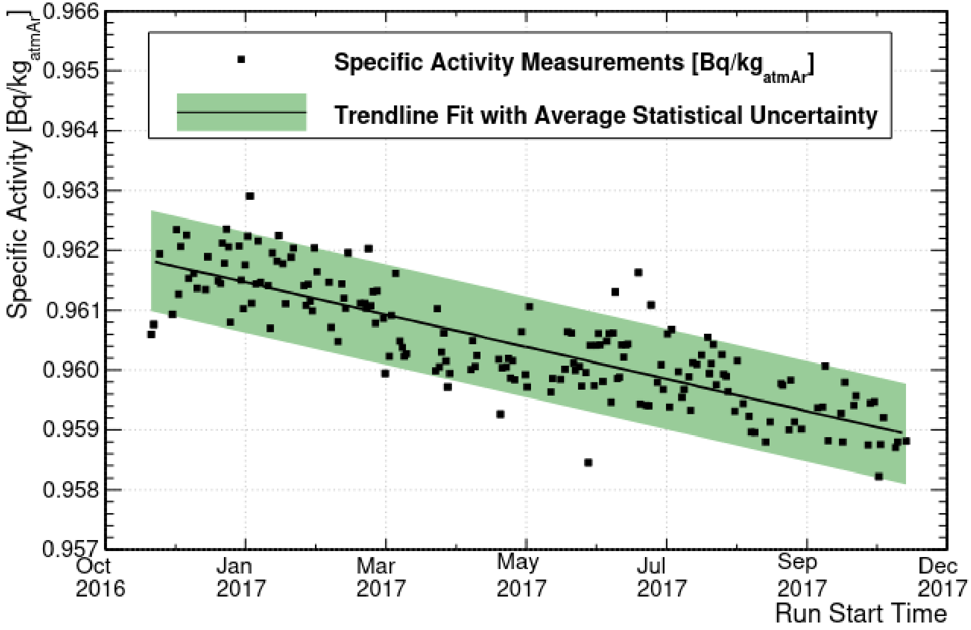
Results – ^{39}Ar specific activity measurement

- 167 live-days of data
- Specific activity

$$S_{\mathrm{Ar39}} = \frac{N}{T_{\mathrm{live}} \cdot m_{LAr}},$$

- Results:

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



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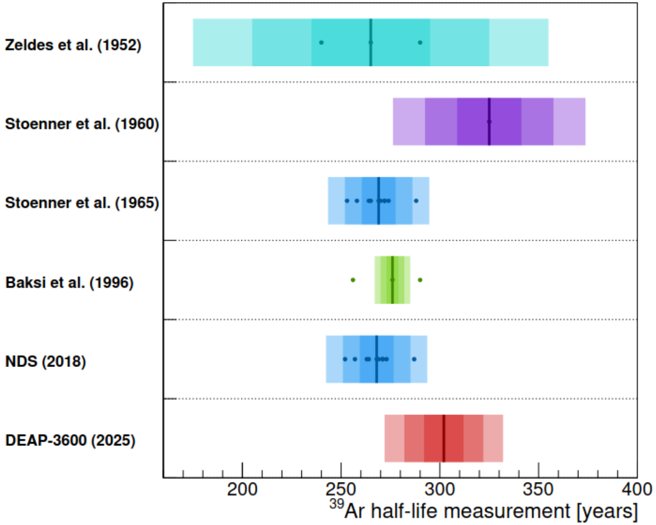
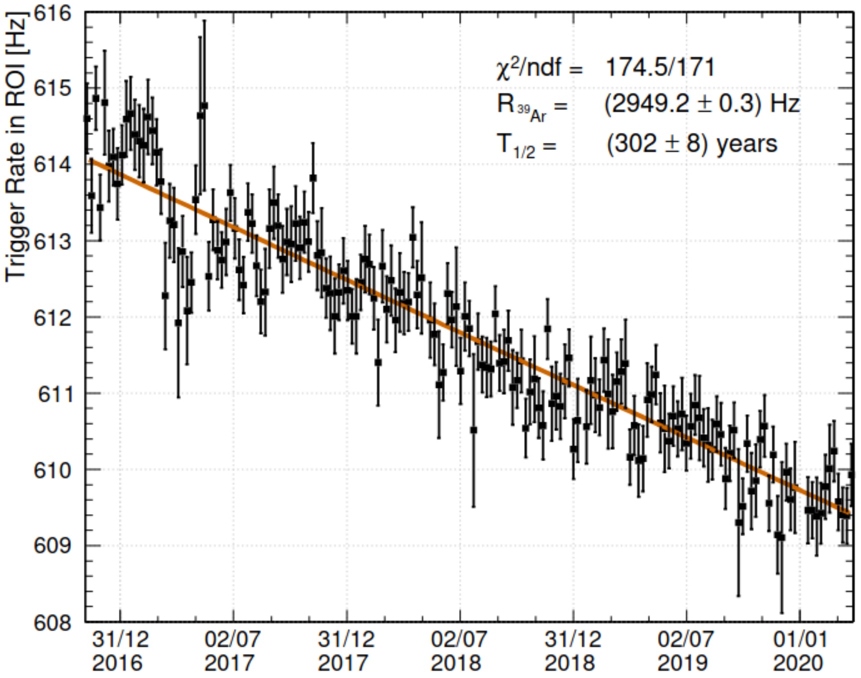
EPJ C, 83, 642 (2023), arxiv:2302.14639

Results – ^{39}Ar half-life measurement

- First continuous direct measurement of ^{39}Ar decay
- 3.4 years of data





Submitted to EPJ C, (2025), arXiv:2501.13196

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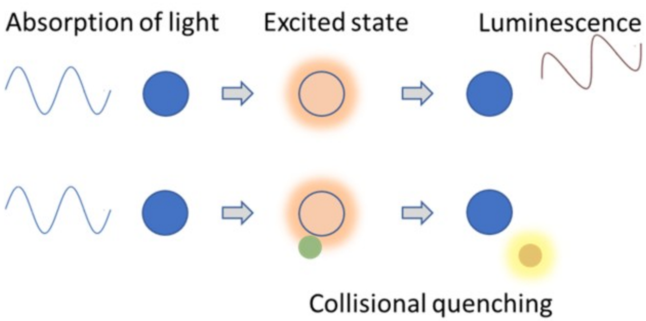
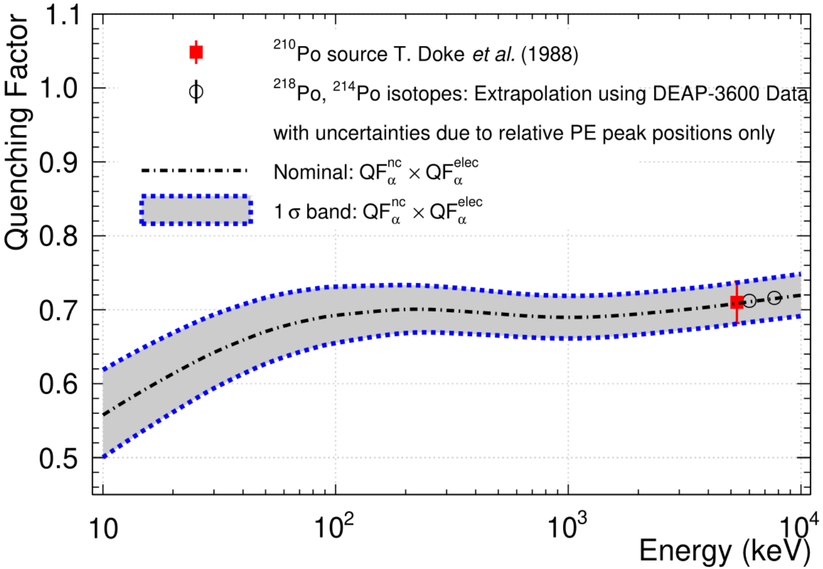
Results – Relative measurement and extrapolation of the quenching factor of α-particles in LAr

$$QF_\alpha = \frac{PE_\alpha}{Y \times E_{\alpha,\mathrm{dep}}}$$

- Measure at full α-energy peaks
- Theoretical extrapolation to low energy





More about this in the next talk by Michael Perry

EPJ C, 85, 87 (2025), arXiv:2406.18597

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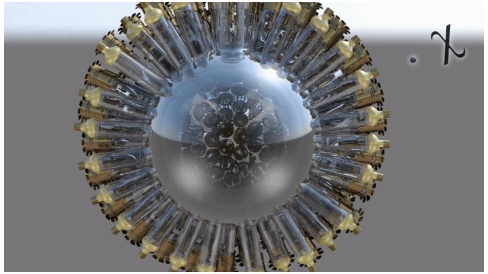
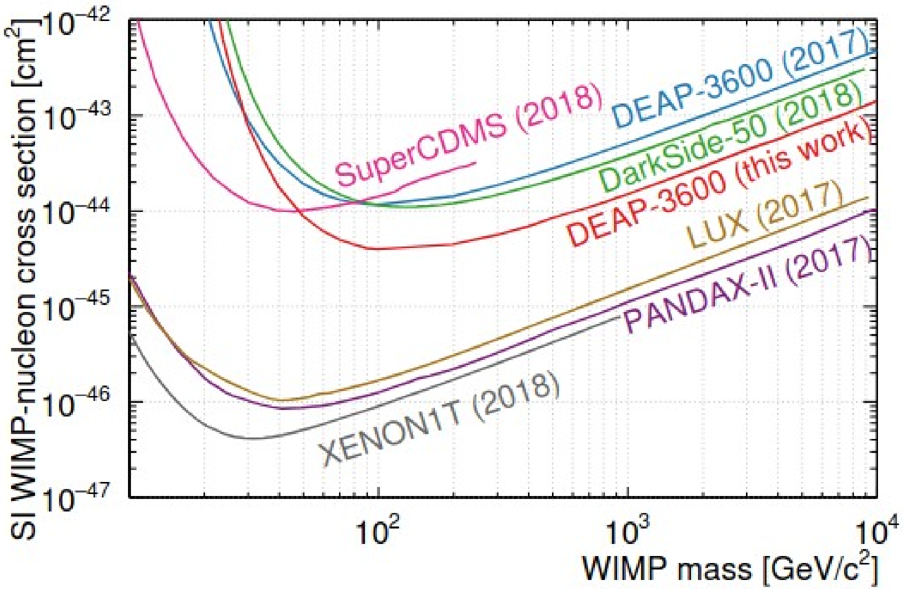
Results – WIMP dark matter search

- 231 live-days of data
- Leading limit on SI WIMP-nucleon cross section on LAr target
- No candidate signal events found
- Working on PLR analysis with the full dataset





Phys. Rev. D 100, 022004 (2019), arXiv:1902.04048

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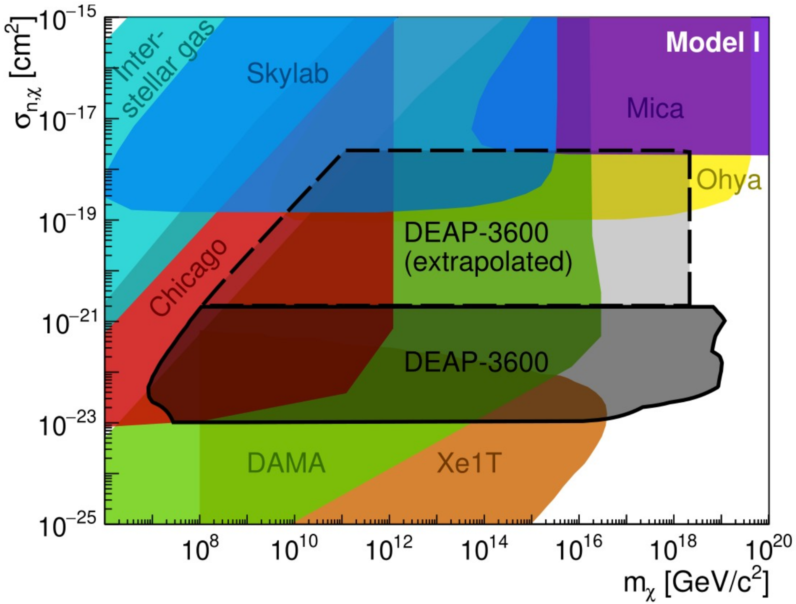
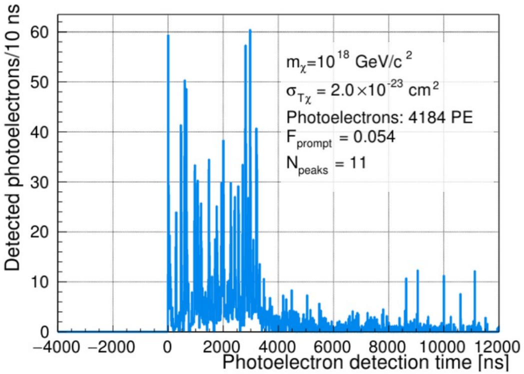
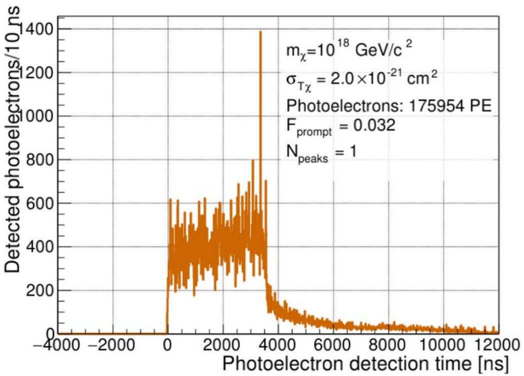
Results – Planck scale mass dark matter search

- First of its kind probe at Planck-scale mass ($m_\chi \simeq 10^{19}$ GeV/c^2) DM
- 813 live-days of data
- Look for very high energy events
- Multiple interaction in LAr







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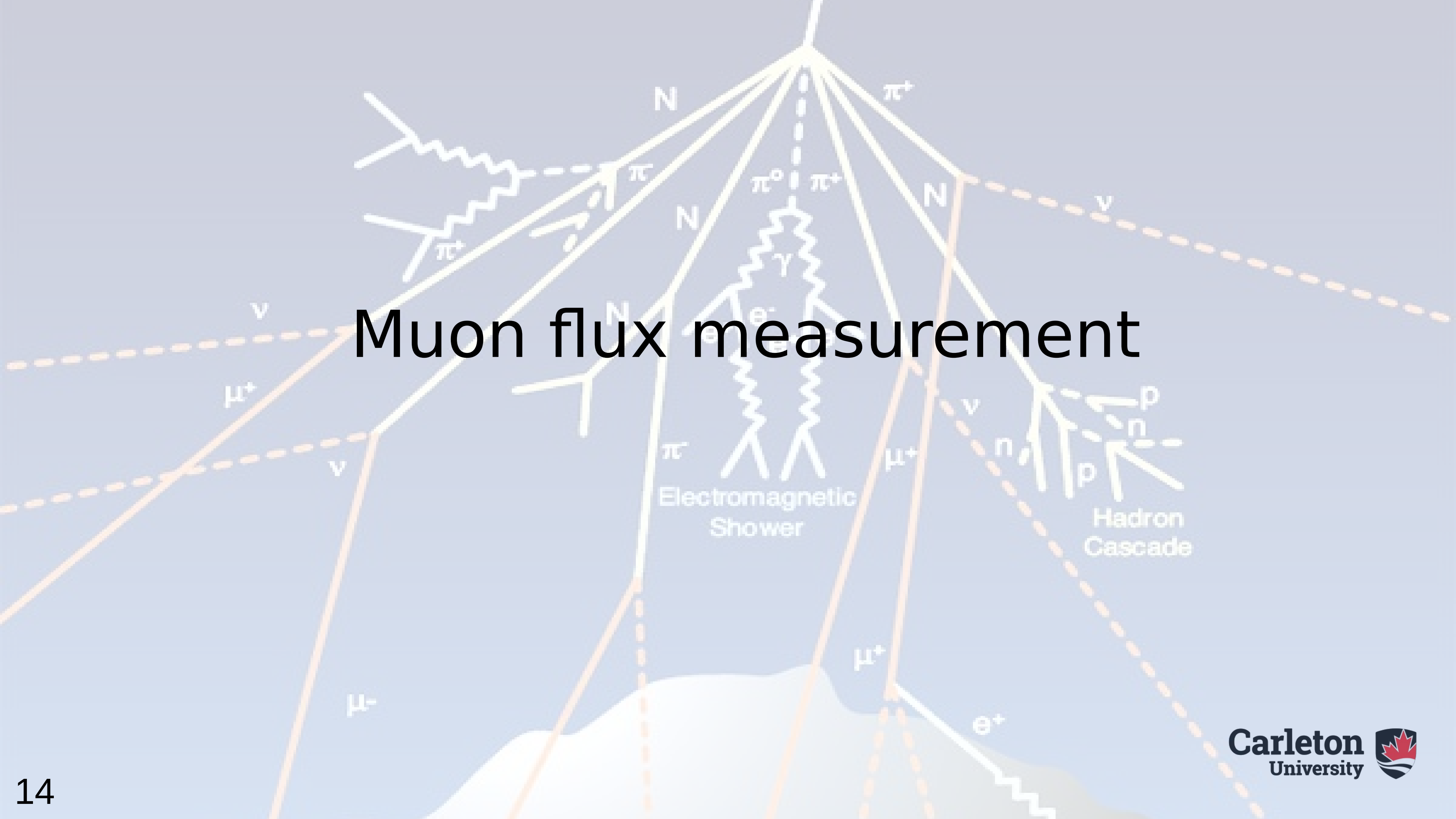
Phys. Rev. Lett. 128, 011801 (2022), arXiv:2108.09405v2

Muon flux measurement



Muon flux measurements!

- What do we need?

$$Muon\,Flux = \frac{No.\,of\;Muons}{Acceptance \cdot Livetime \cdot Effective\;Area}$$

- Why do we need it?

Muons → cosmogenic neutrons → DM-like events → Bad!

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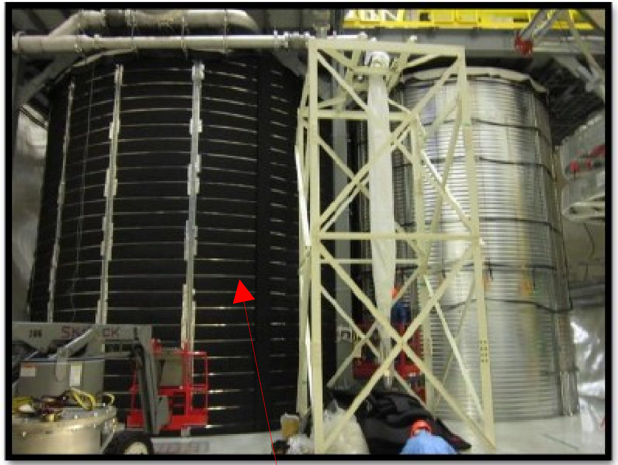
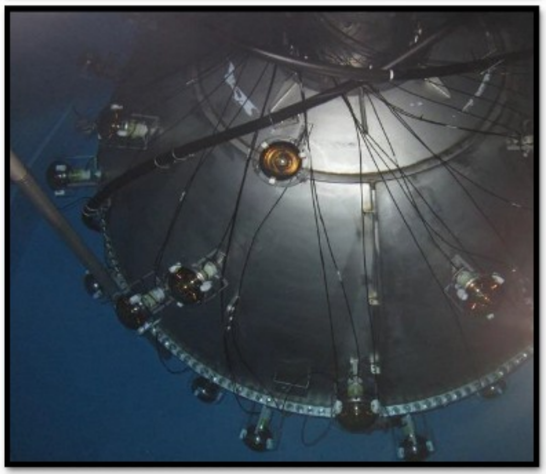
$$Muon\ Flux = \frac{No.\ of\ Muons}{Acceptance * Livetime * Effective\ Area}$$

Flux measurements!

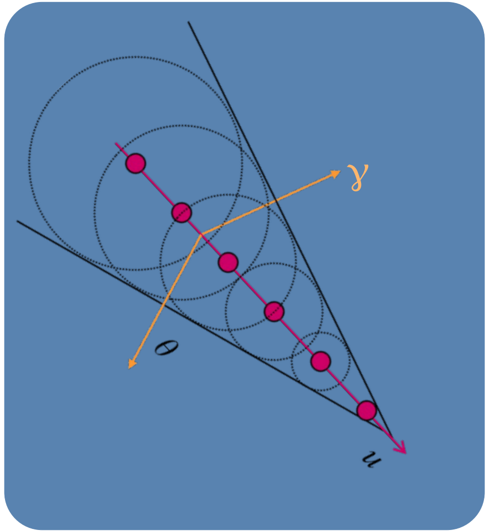
- Watertank data (MV)
  - #(muons) = 3395



DEAP-3600



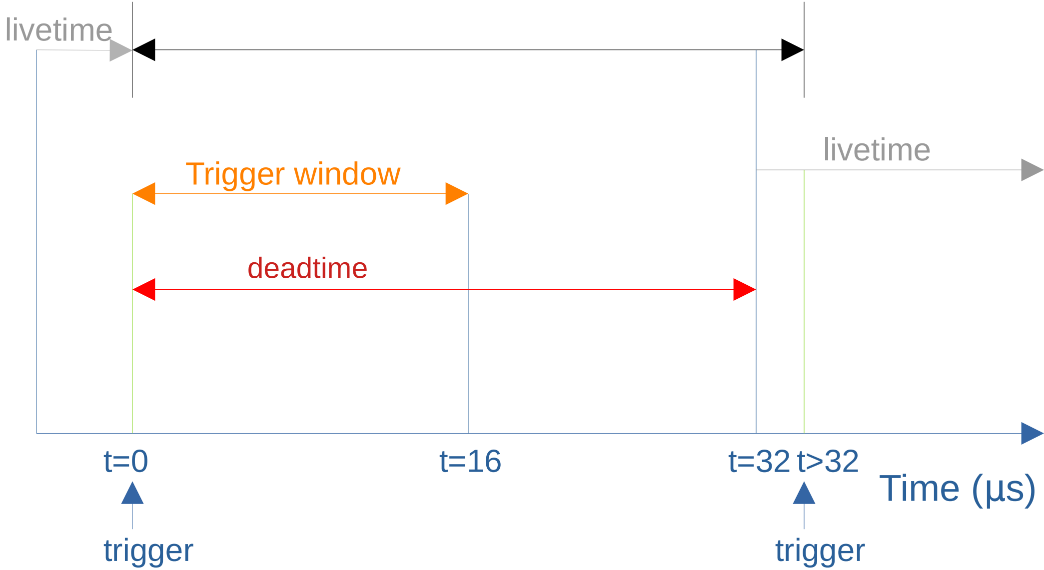
Cherenkov radiation in water



$$Muon\,Flux = \frac{No.\,of\;Muons}{Acceptance * Livetime * Effective\;Area}$$

Flux measurements!

- Livetime
  - Trigger counting
  - Runtime ~ 20-22 hr
  - Need to subtract deadtime between two events
  - Livetime = runtime – deadtime
  - $2.77 * 10^7$ s

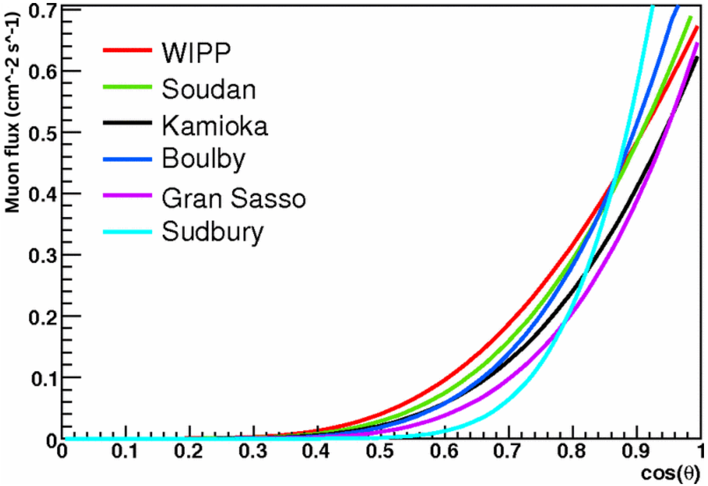


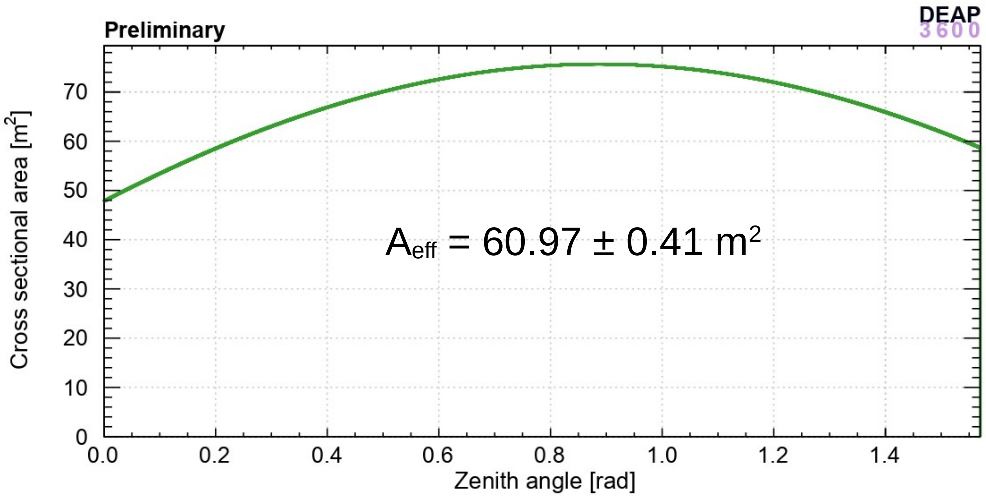
$$Muon\ Flux = \frac{No.\ of\ Muons}{Acceptance * Livetime * Effective\ Area}$$

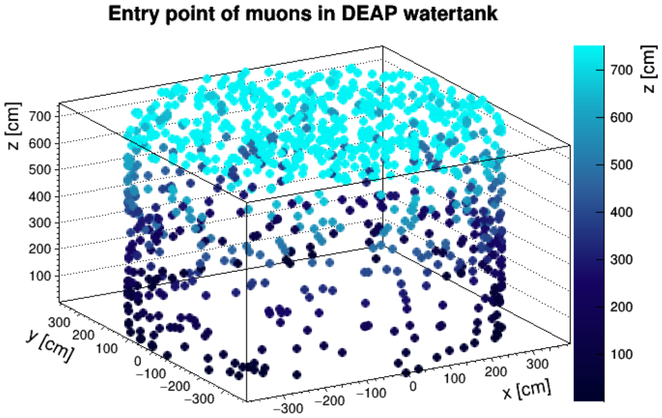
Flux measurements!

- Effective area
  - $A_{eff} = 2\pi rh \sin\Theta + \pi r^2 \cos\Theta$

Mei-Hime angular distribution of muons







Toy MC

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$$Muon\ Flux = \frac{No.\ of\ Muons}{Acceptance * Livetime * Effective\ Area}$$

Flux measurements!

- Acceptances *(on-going)*
  - Matching simulation models to the data
  - External muGenCNL generator to simulate muons in RAT software
  - Tuning optical parameters of the detector in the simulation

$$Acceptance = \frac{Number\ of\ events\ passing\ cuts}{Total\ number\ of\ events}$$

- Optical Parameters:
  - QE: Quantum Efficiency of the photocathode in the PMTs
  - TLR: Tank Liner Reflectivity of the watertank
  - ABSL: Absorption Length of the photons

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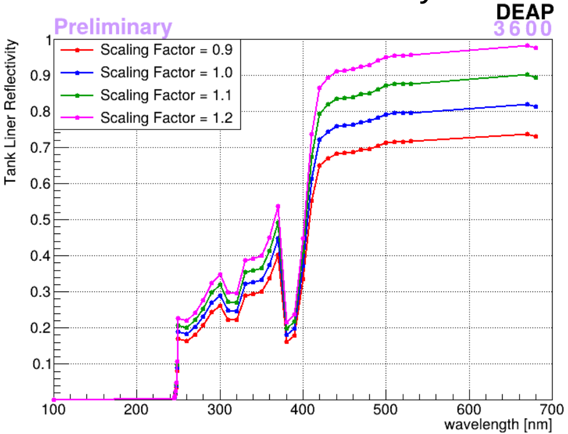
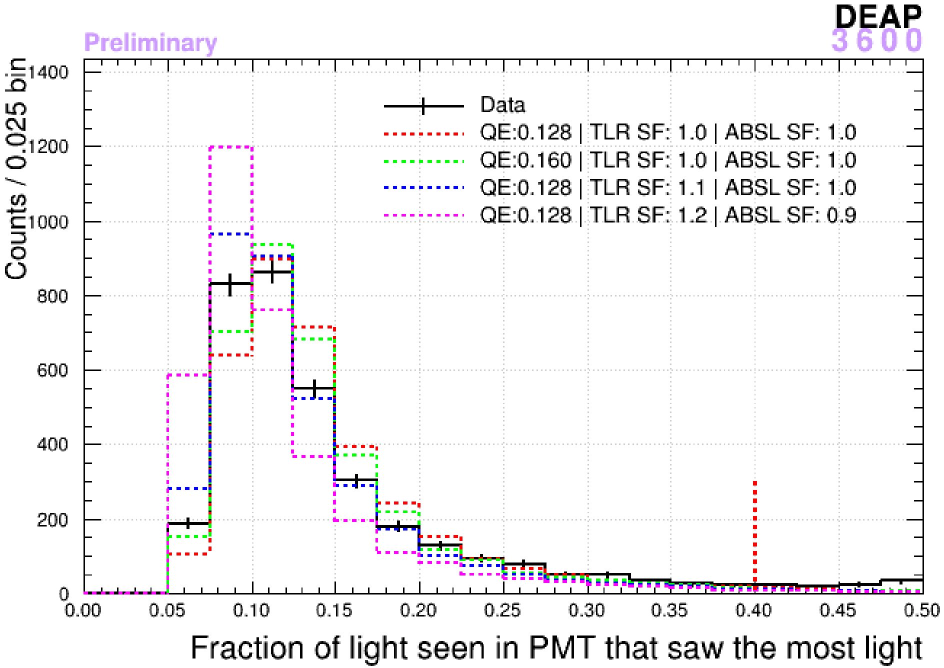
$$Muon\,Flux = \frac{No.\,of\ Muons}{Acceptance * Livetime * Effective\ Area}$$

Flux measurements!

- Watertank data (MV)
  - #(muons) = 3395
  - Livetime = $2.77 * 10^7$ s
  - Effective area = $60.97 \pm 0.41\ m^2$
- Acceptances *(on-going)*
  - Tank Liner Reflectivity





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Future!

Future work

- Detector upgrades done!
- Third fill starts soon
- Multiple analyses close to done:
  - Muon flux measurement
  - WIMP search analysis
  - Neutrino absorption in LAr
- New results coming out soon! Stay tuned!

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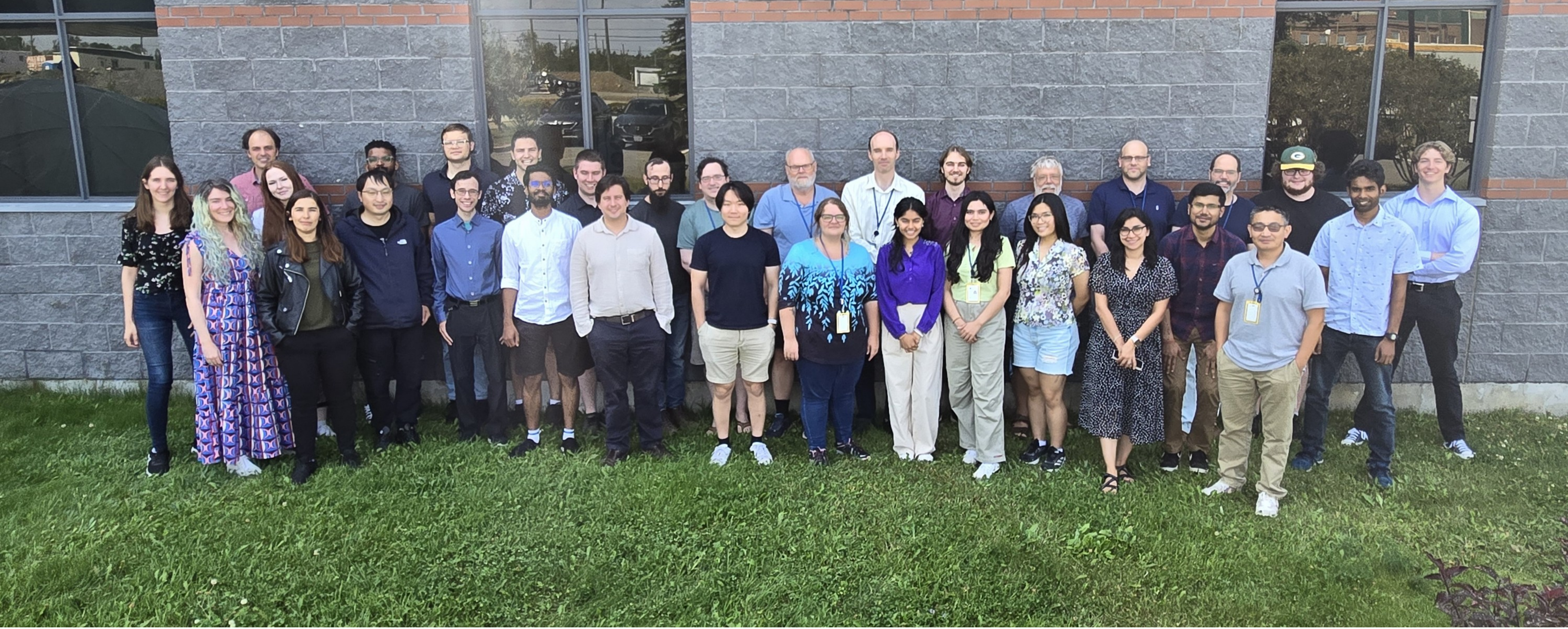

SNOLAB

DEAP 3600

University of Alberta

INFN Istituto Nazionale di Fisica Nucleare

Instituto de Física

Royal Holloway University of London

Technical University of Munich

TUM

Princeton University

US University of Sussex

National Research Center "Kurchatov Institute"

UC Riverside

AstroCeNT Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences

Queen's University

Canadian Nuclear Laboratories / Laboratoires Nucléaires Canadiens

Laurentian University / Université Laurentienne

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Ministerio de Ciencia, Innovación y Universidades

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Particle Physics Rutherford Appleton Laboratory

Thank You

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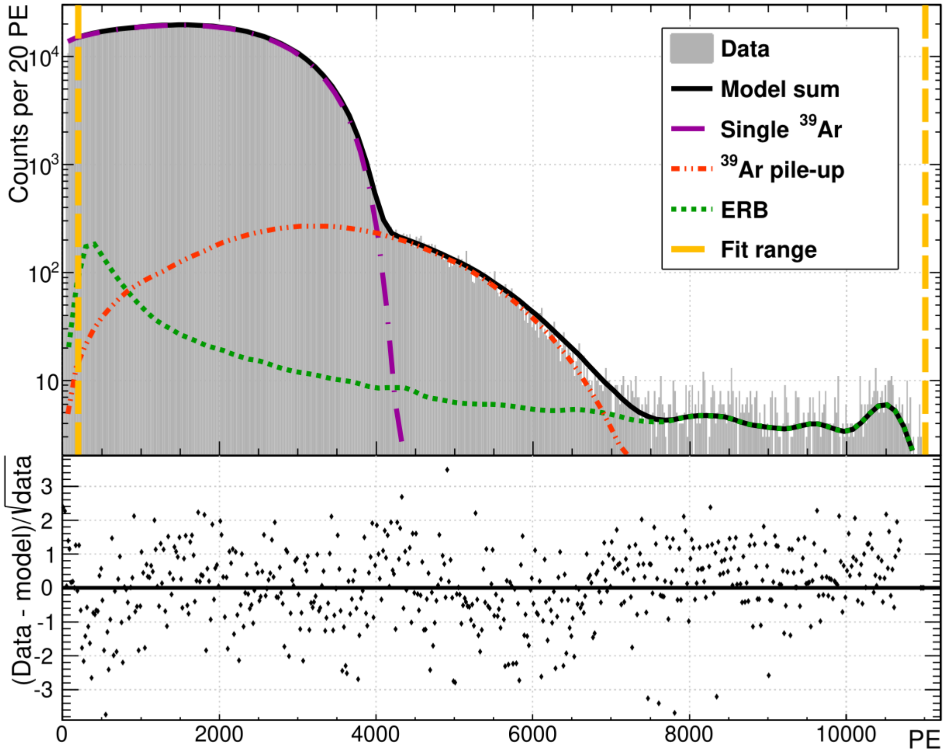
Backup

Specific activity measurement of ^{39}Ar



$$N = N_{\text{single}} + N_{\text{pile-up}},$$

$$N_{\text{single}} = \frac{n \cdot a_{\text{presc}}}{\varepsilon \cdot b},$$

$$N_{\text{pile-up}} = N_{\text{double}} + N_{\text{triple}} + N_{\text{ERB,Ar39}} + N_{\text{hFp,Ar39}}.$$

$$R_{\text{Ar39}} = \sqrt{\frac{N_{\text{double}}}{2 \cdot T_{\text{live}} \cdot \delta t_{\text{int}}}}.$$

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Specific activity measurement of ^{39}Ar

Table 1 Parameters, their values and constraints, and the resulting contributions to the uncertainty for the specific activity measurement. Negligibly small systematic uncertainties are indicated with '–'. The dominant uncertainty on S_{Ar39} arises from the uncertainties on event selection cut efficiency values as determined with the data-driven method (d-d) and the Monte Carlo method (MC).

Parameter	Symbol	Value	Constraints	Absolute uncertainty on S_{Ar39} [Bq/kg_{atmAr}]
Fit range		[200, 11000] PE	Fixed	0.001
Histogram bin width	b	20 PE	Fixed	0.001
Constant energy scale parameter	p_0	(1.3 ± 0.4) PE	Fixed	–
Linear energy scale term	p_1	[7.1, 7.3] PE/keV	Free-floating, run-dependent	0.009
Quadratic energy scale term	p_2	–	Not considered in this method	–
Linear resolution parameter	p_3	[1.67, 1.73] PE	Free-floating, run-dependent	0.009
Quadratic resolution parameter	p_4	$[2.1, 3.8] \times 10^{-4}$	Free-floating, run-dependent	0.001
^{39}Ar β-shape nuisance parameter	a_0		Free-floating, constrained by a penalty term	0.001
^{39}Ar normalization	n		Free floating, run-dependent	–
Double ^{39}Ar pile-up normalization	n_{double}		Free floating, run-dependent	–
ERB normalization	n_{ERB}		Free-floating, run-dependent	–
^{85}Kr normalization	n_{Kr85}		Upper limit, see Section 5.2	0.010
Liquid argon mass	m_{LAr}	(3269 ± 24) kg	Measured, see Section 3	0.007
Live-time	T_{live}	167 d [sum of all runs]	Measured, see Section 4	–
Cut efficiency on single ^{39}Ar	ε	0.983 [d-d], 0.999 [MC]	Measured, see Section 5.2	0.016
Cut efficiency on double ^{39}Ar pile-up	ε_{double}	Run- & energy-dependent		

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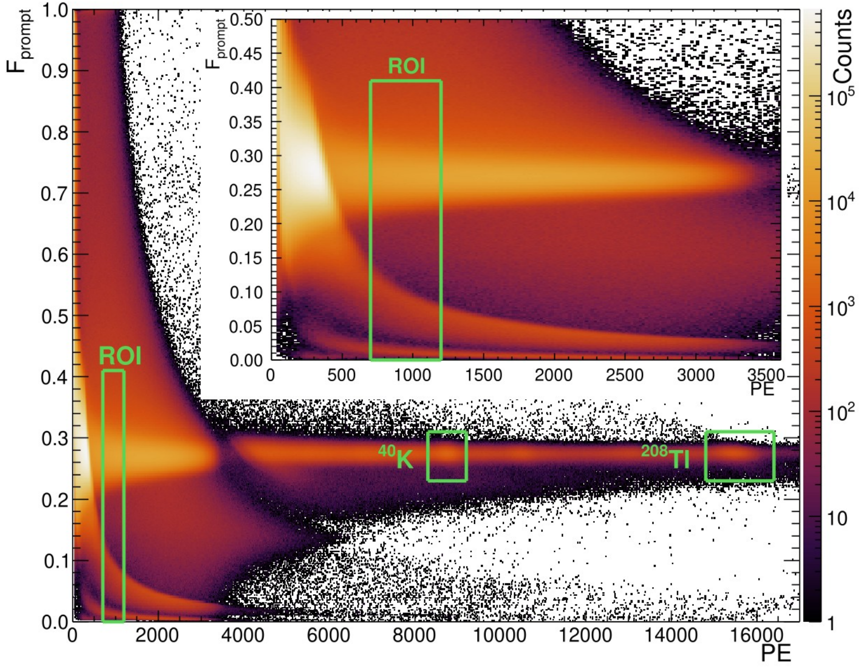
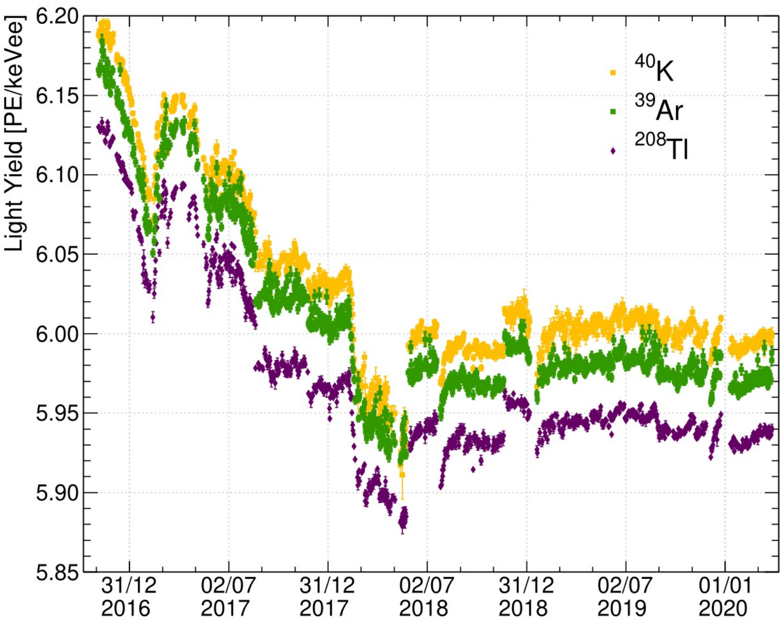
Half-life measurement of ^{39}Ar





$$R(t) = e^{-R_{39\mathrm{Ar}}(t)\delta t}\Big[R_{39\mathrm{Ar}}(t) f_1 \varepsilon_1 + \frac{1}{2} R^2_{39\mathrm{Ar}}(t)\delta t f_2 \varepsilon_2 + \frac{1}{6} R^3_{39\mathrm{Ar}}(t)\delta t^2 f_3 \varepsilon_3 + \frac{1}{2} R_{39\mathrm{Ar}}(t) R_{\mathrm{Chv}} e^{-R_{\mathrm{Chv}}\delta t}\delta t f_4 \varepsilon_4\Big] + R_{\mathrm{bg}}.$$

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Half-life measurement of ^{39}Ar

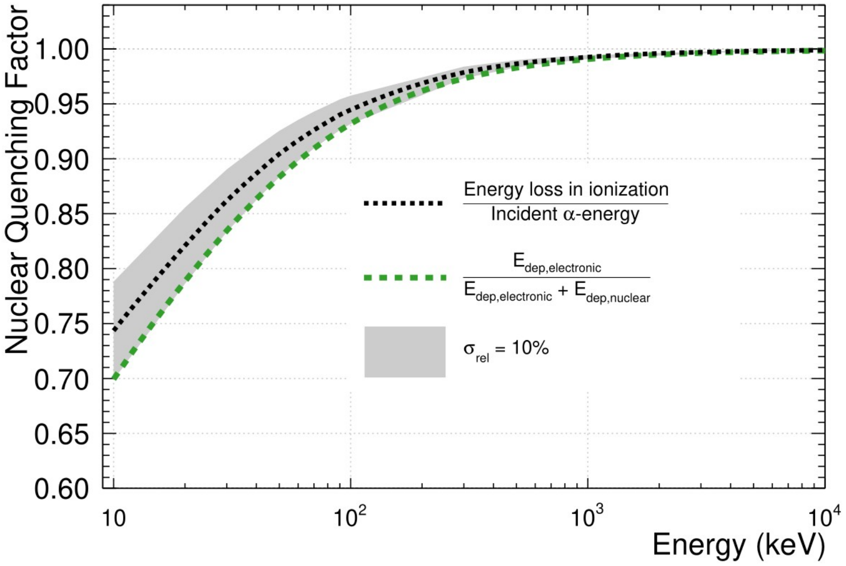
Table 2 List of parameters used in the model of ^{39}Ar trigger rates (Sections 4, 5) along with their uncertainties. The uncertainties due to the event selection efficiencies for each event type are given as a combined value. The uncertainties are estimated with respect to the measured mean lifetime and converted to half-life values. The character '–' indicates a negligibly small uncertainty.

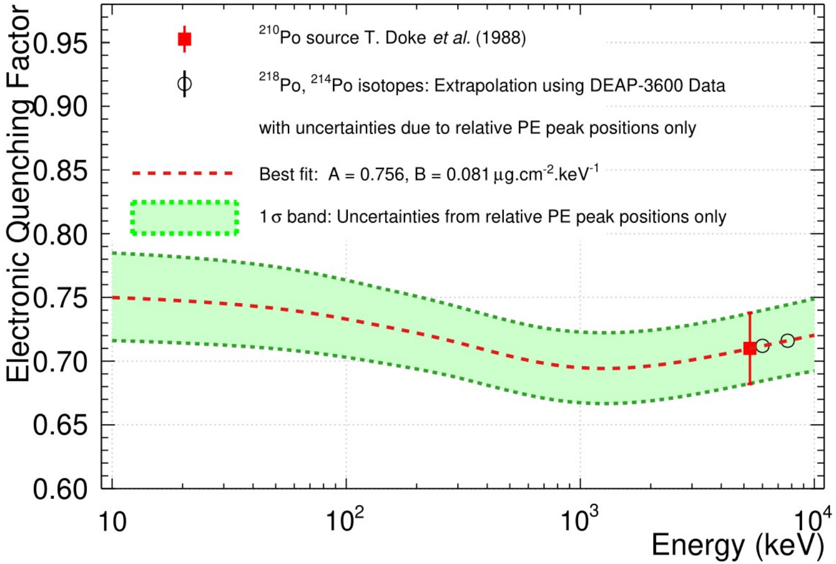
Parameter	Symbol	Value	Constraints	Absolute uncertainty on $T_{1/2}$ [years]
^{39}Ar trigger rate at dataset start	$R_{^{39}\mathrm{Ar}}$		Free-floating	
^{39}Ar lifetime	$\tau_{^{39}\mathrm{Ar}}$		Free-floating	
Cherenkov trigger rate	R_{Chv}	(538 ± 4) Hz	Fixed	–
ERB background rate	R_{bg}	(1.65 ± 0.31) Hz	Fixed	0.15
Livetime	T_{live}	1.80 years	Fixed	–
Bin width for trigger rate averages		7 days	Fixed	1.3
Fraction of single ^{39}Ar spectrum in the ROI	f_1	0.21 ± 0.05	Fixed	0.21
Cut efficiency for single ^{39}Ar	ε_1	1	Fixed	–
Fraction of double ^{39}Ar spectrum in the ROI	f_2	0.20 ± 0.05	Fixed	1.1
Cut efficiency for double ^{39}Ar	ε_2	0.9099 ± 0.0033	Fixed	1.8
Fraction of triple ^{39}Ar spectrum in the ROI	f_3	0.19 ± 0.05	Fixed	0.01
Cut efficiency for triple ^{39}Ar	ε_3	0.860 ± 0.039	Fixed	0.19
Fraction of ^{39}Ar-Cherenkov pile-up spectrum in the ROI	f_4	0.21 ± 0.05	Fixed	0.04
Cut efficiency for ^{39}Ar-Cherenkov pile-up	ε_4	1	Fixed	–
Light yield corrections (constant)		Run-dependent	N/A	2.3
Light yield corrections (differential)		Run-dependent	N/A	5.1
Correlated triggers		Run-dependent	N/A	2.1

Quenching factor extrapolation

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

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





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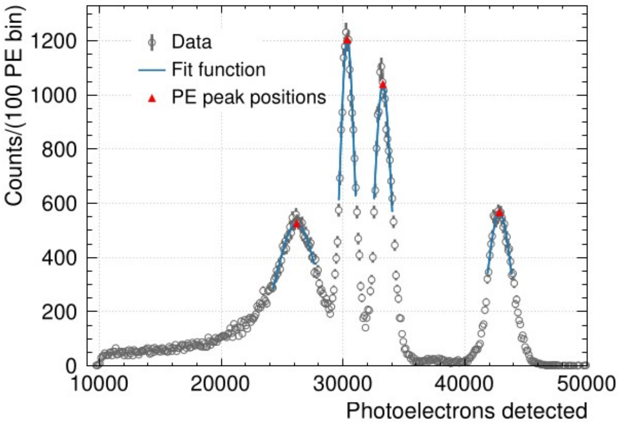
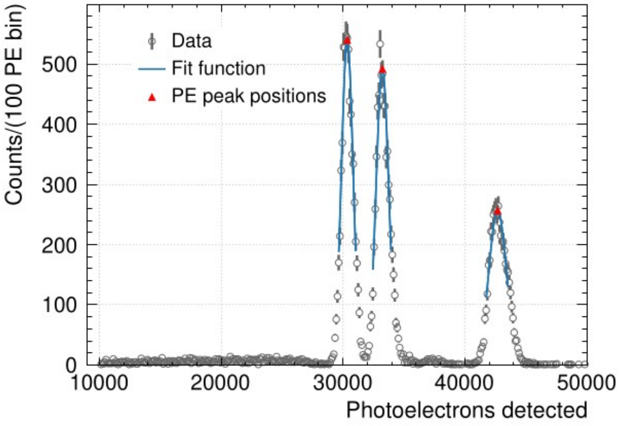
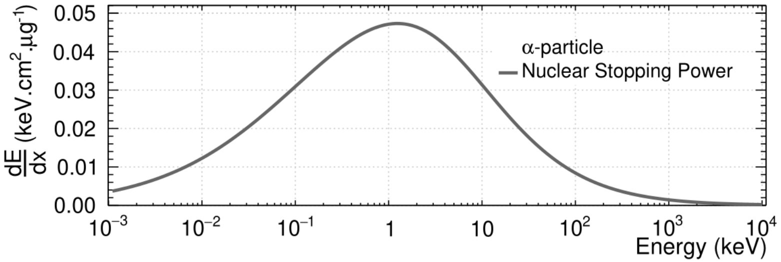
Quenching factor extrapolation







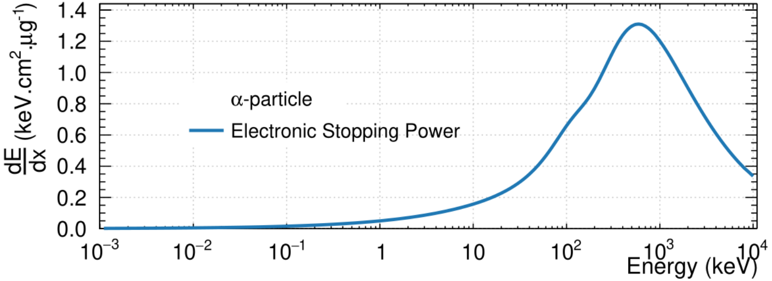
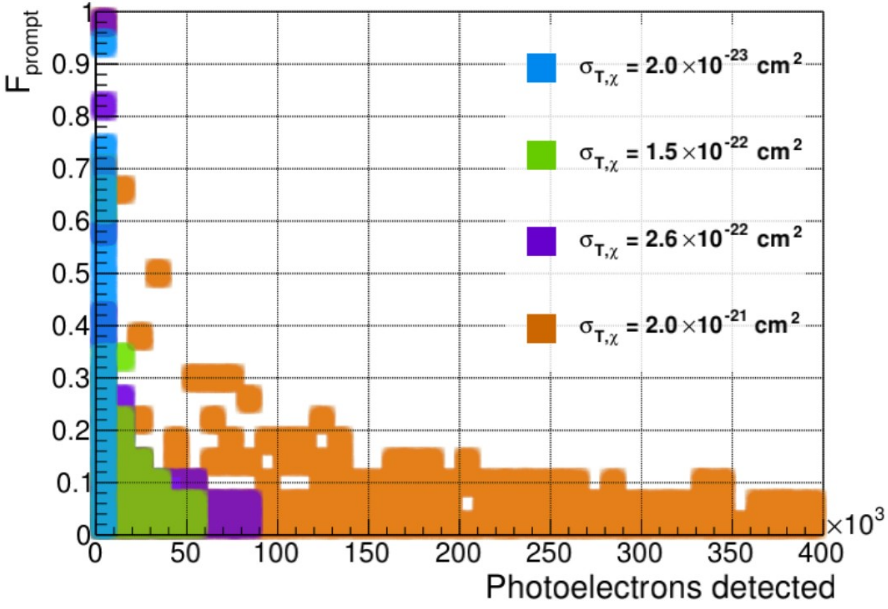
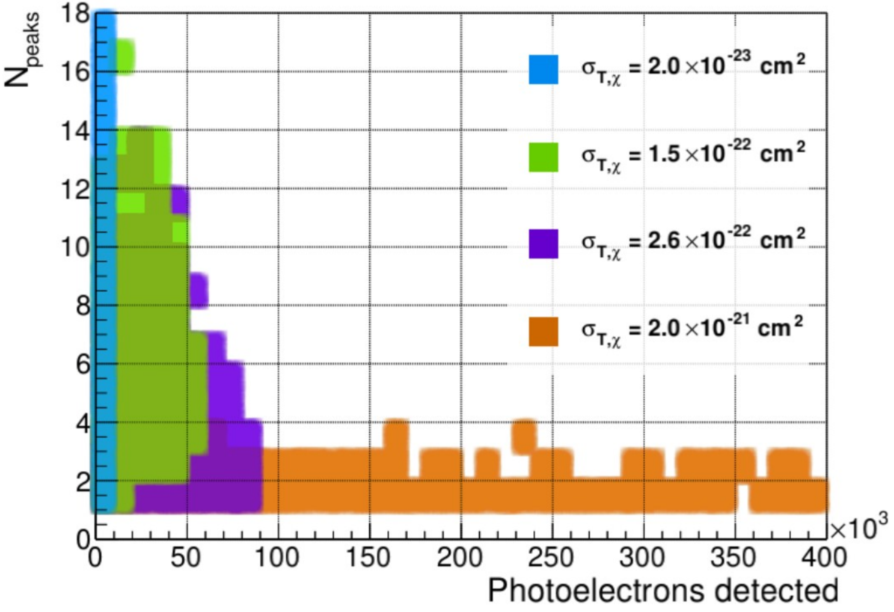


Table 2 Quenching factor of α-particles obtained from the relative measurement using ^{222}Rn, ^{218}Po and ^{214}Po decays within the DEAP-3600 detector. The measured value by Ref. [16] of the QF for α-particles from ^{210}Po decays is also shown.

Radioactive isotope	Energy of α-particle (MeV)	Ratio of PE peak to ^{222}Rn PE peak (R_i)	Uncertainty on the peak PE ratio (σ_i)	Quenching factor (QF_α)	Uncertainty on QF_α due to PE peak ratios	Absolute uncertainty on QF_α
^{210}Po	5.305	-	-	0.710 [16]	-	0.028 [16]
^{218}Po	6.002	1.096	0.002	0.712	0.001	-
^{214}Po	7.686	1.411	0.006	0.716	0.003	-

Planck scale mass DM search





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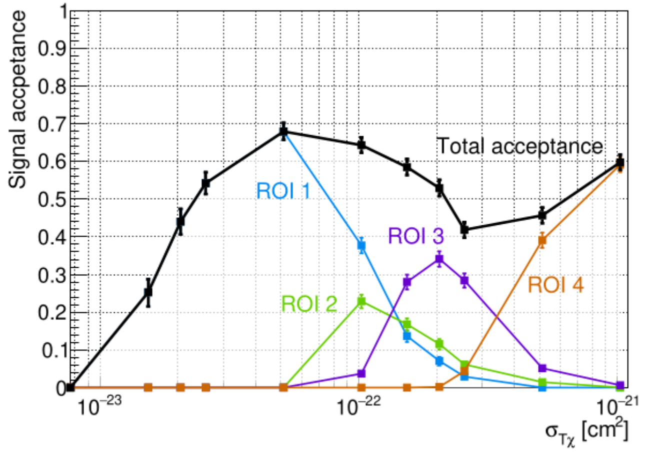
Planck scale mass DM search



ROI	PE range	Energy [$\mathrm{MeV_{ee}}$]	$N_{\mathrm{peaks}}^{\mathrm{min}}$	$F_{\mathrm{prompt}}^{\mathrm{max}}$	μ_b	$N_{\mathrm{obs.}}$
1	4000–20 000	0.5–2.9	7	0.10	$(4 \pm 3) \times 10^{-2}$	0
2	20 000–30 000	2.9–4.4	5	0.10	$(6 \pm 1) \times 10^{-4}$	0
3	30 000–70 000	4.4–10.4	4	0.10	$(6 \pm 2) \times 10^{-4}$	0
4	70 000–4×10^8	10.4–60 000	0	0.05	$(10 \pm 3) \times 10^{-3}$	0

TABLE I. ROI definitions, background expectations μ_b, and observed event counts $N_{\mathrm{obs.}}$ in the 813 d exposure. A cut rejecting events in a [−10, 90] µs window surrounding each MV trigger is applied to all ROIs; low-level cuts requiring that signals be consistent with bulk LAr scintillation are applied to ROIs 1–3. The upper energy bound on ROI 4 is estimated assuming a constant light yield above 10 $\mathrm{MeV_{ee}}$, the highest energy at which the detector is calibrated.