Latest updates and results from the DEAP-3600 experiment

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(on behalf of the DEAP collaboration)

CAP Congress, 2023
University of New Brunswick, Canada

June 19, 2023

Carleton University

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

The DEAP Collaboration

- **D**ark matter **E**xperiment using **A**rgon **P**ulseshape discrimination
- The DEAP-3600 experiment searches for Weakly Interacting Massive Particle (WIMP) dark matter (DM) candidate.
- It is located approximately 2 km underground at SNOLAB in Sudbury, Canada.
- Collected data from 2016 – 2020, **now completing hardware upgrades.**
- Expected to fill the detector and start collecting data near early 2024.

~95 researchers from 9 countries:
Canada, Germany, Italy, Mexico,
Poland, Russia, Spain, UK, USA

Talks presented in this meeting:

DEAP-3600 experiment

- **Pushparaj Adhikari** [June 19, 2023 11:00 AM] Removal of dust particulates to reduce alpha backgrounds
- **Michael Perry** [June 19, 2023, 4:30 PM] Pulseshape discrimination using SiPM and Argon-1
- **Emma Ellingwood** [June 21, 2023 , 4:15 PM] Overview of ^{8}B-solar neutrino absorption search with DEAP-3600 detector.

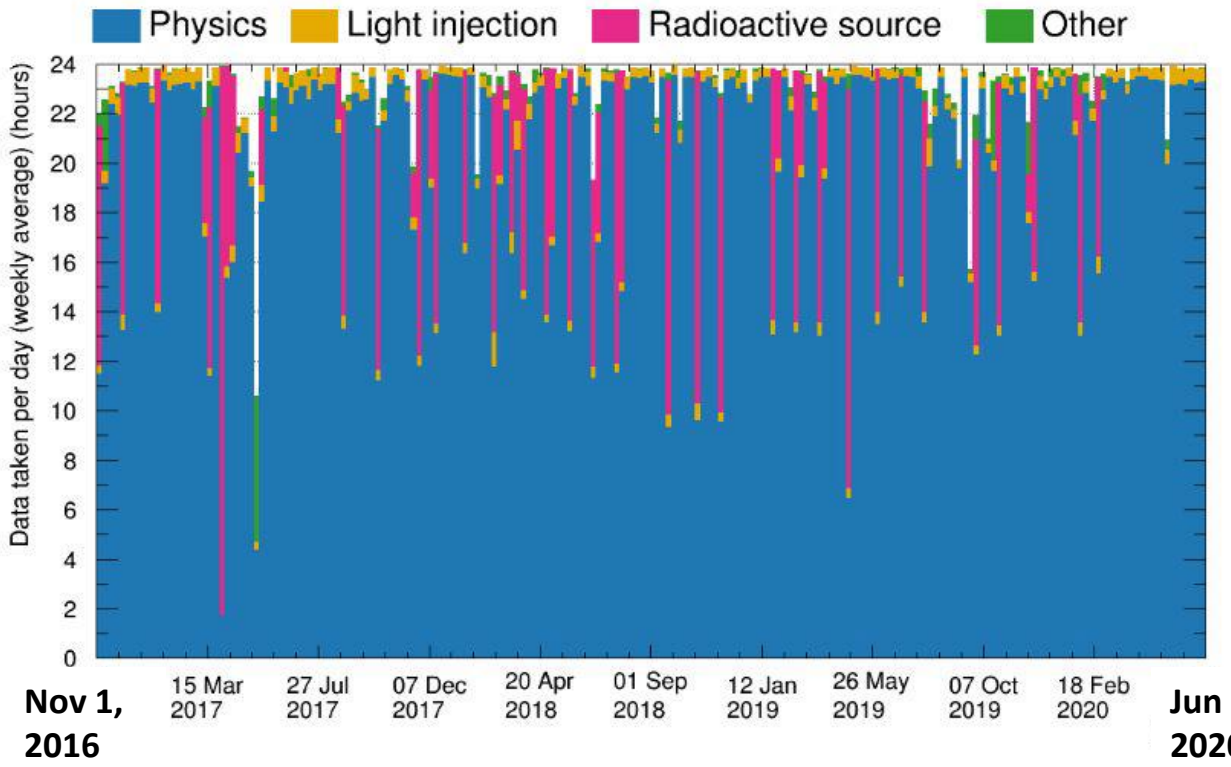
GADM Program

- **Chris Jillings** [June 20, 2023, 3:30 PM] Some aspects of future of **G**lobal **A**rgon **D**ark **M**atter program.
- **Bansari Vyas** [June 19, 2023, 4:00 PM] TPB coating for the DarkSide-20K detector.

The DEAP-3600 Experiment

Timeline

- Development and construction : 2006-2016
- Data collection (first DM run): 2016-2020
- Hardware upgrades: 2020 to end of 2023
- New running: 2024-on



Nov 1, 2016 — **Jun 30, 2020**

- Stable data collection for DM search.
- 80% blind since January, 2018.

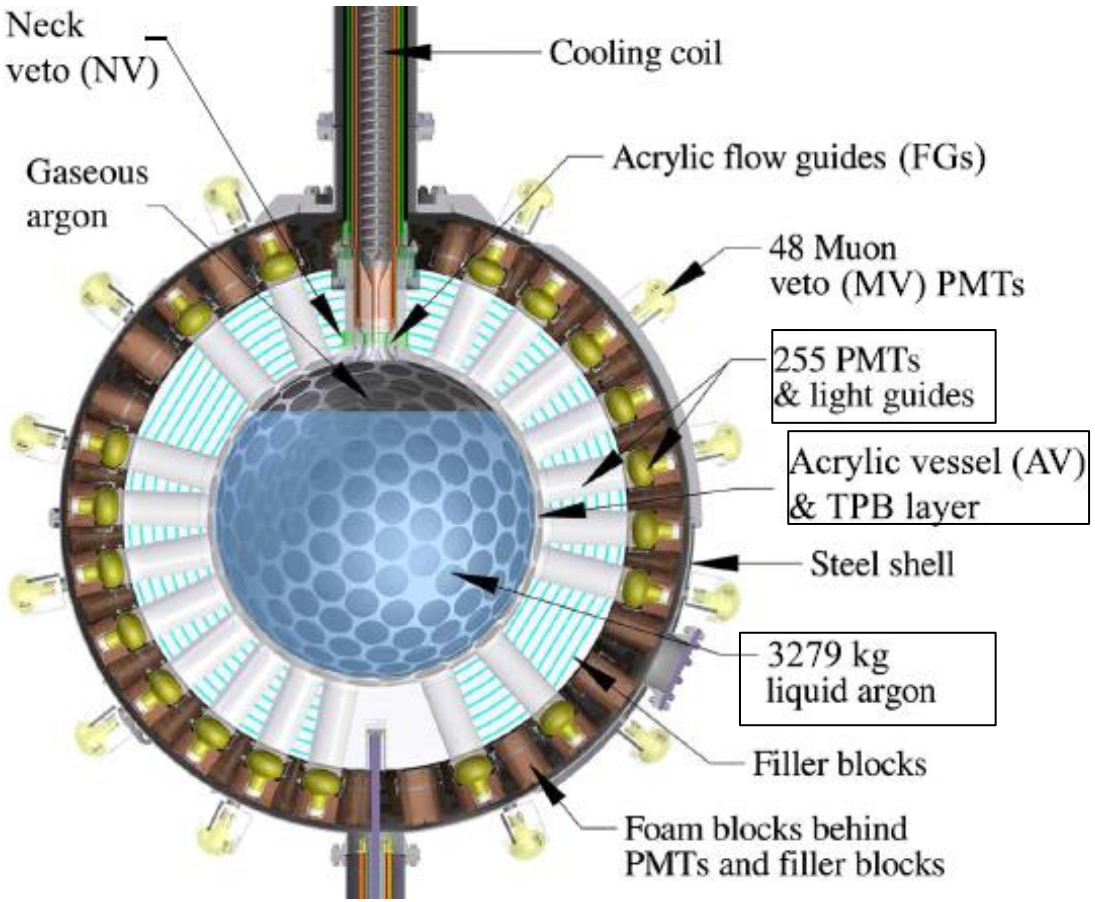
Analyses:

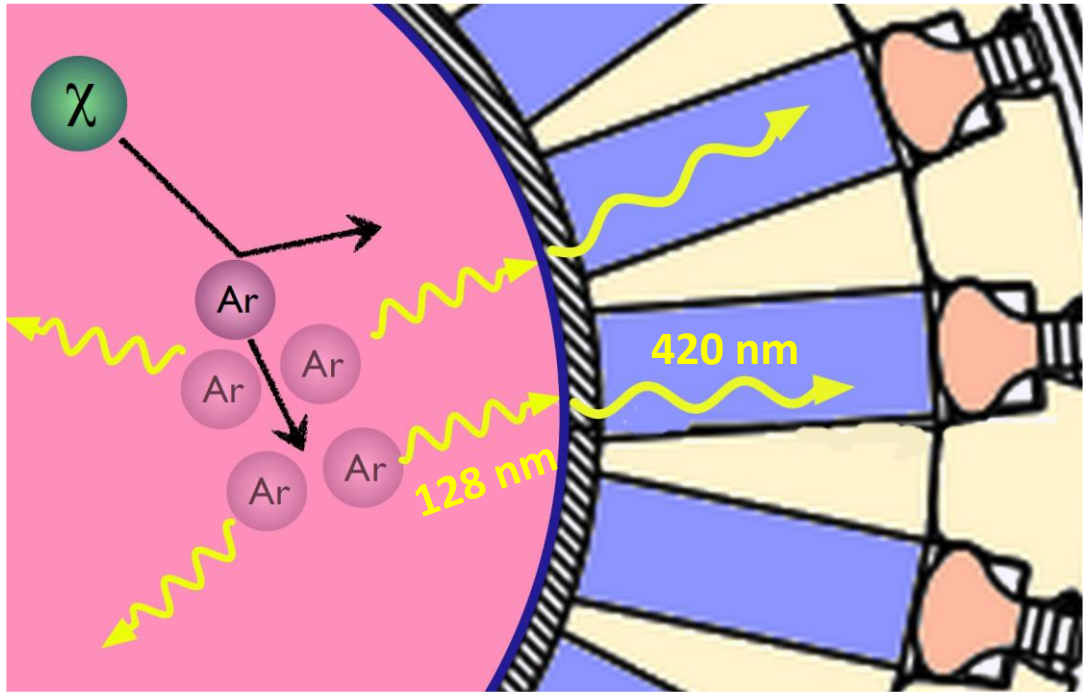
- Results with first-year (231 live days) dataset was published.

- **Development of Profile Likelihood Ratio (PLR) statistical analyses** for WIMP search using first-year dataset is underway.

- **The analysis of full (802 live days) dataset is ongoing.**
  - Improving background models
  - Improving position reconstruction
  - Including multivariate analysis (MVA) to improve WIMP signal acceptance.
    - Three MVA algorithms are trained against α – background events.
    - Developing new variables and validating background models.
    - Re-optimization of event selection will be performed to complete blind analysis.

The DEAP-3600 detector



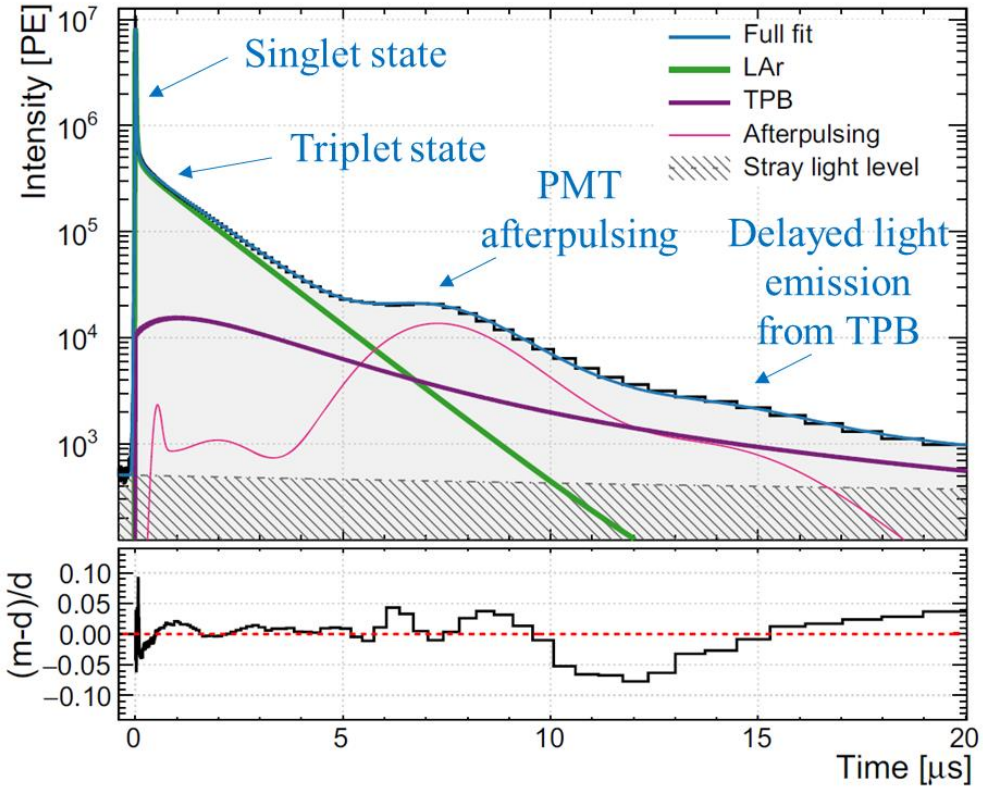


WIMP elastically scatters off argon nuclei .

Scintillation photons produced peaked at ultraviolet wavelength (128 nm) is shifted to visible wavelengths (~420 nm) via a layer of tetraphenyl butadiene (TPB) wavelength shifter coated on inner surface of acrylic vessel.

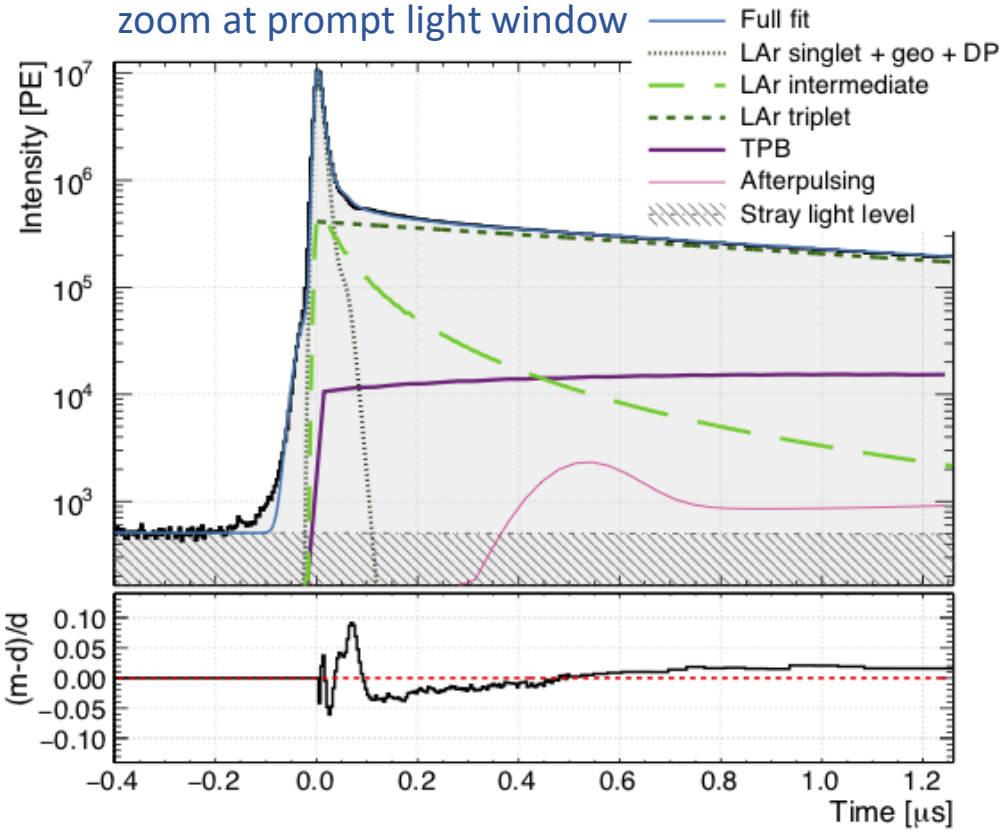
Photons are detected by 255 inward-facing PMTs

Liquid argon scintillation pulseshape



Ref : [European Physical Journal C, 80 (2020) 303]

zoom at prompt light window

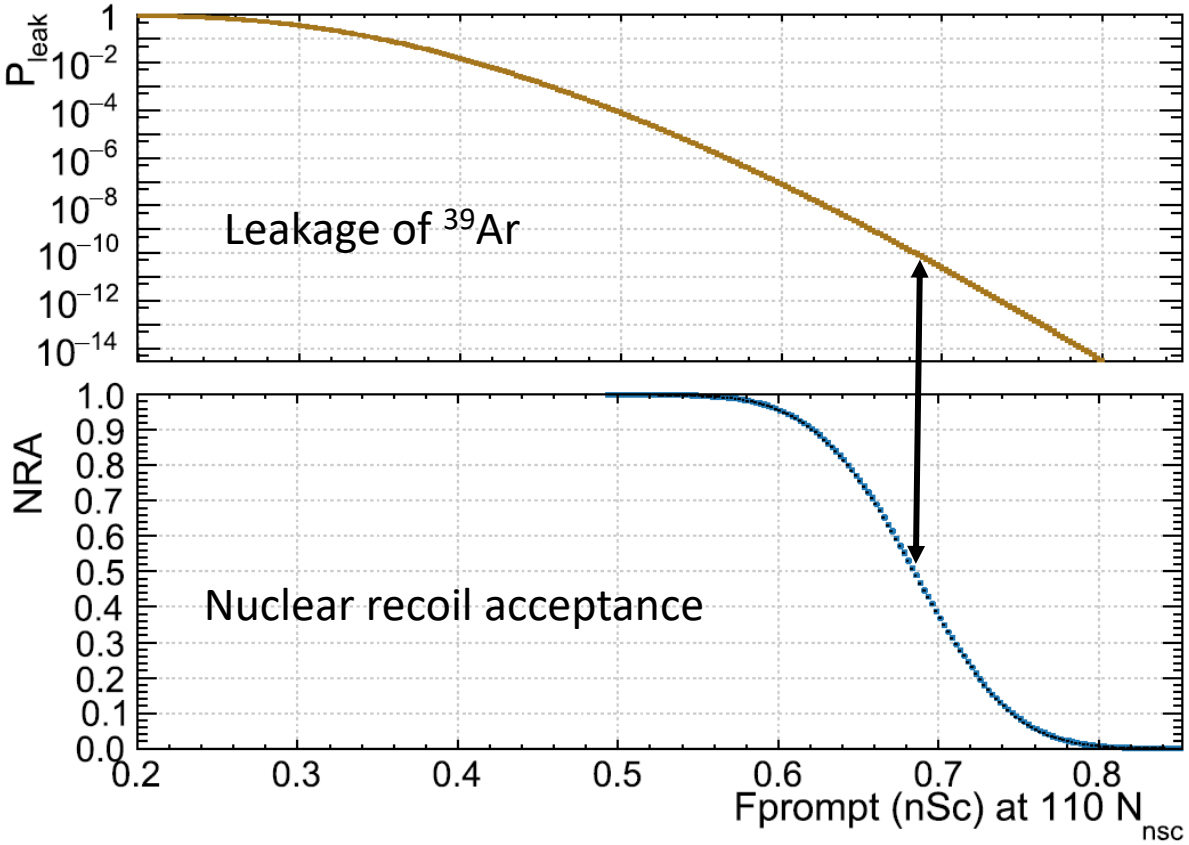


- A pulseshape model is developed for electromagnetic background events in the energy region of interest for WIMP search.
- Pulseshape from ^{39}Ar beta decay has been used.
- Model contains: (a) liquid argon scintillation including intermediate scintillation, (b) time response of TPB wavelength shifter, (c) PMT response.

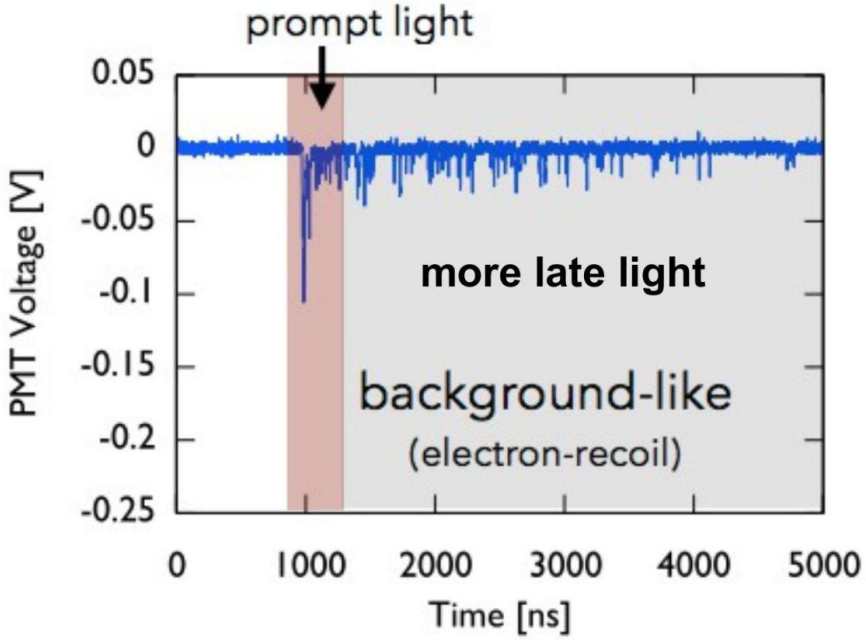
Pulseshape discrimination (PSD)

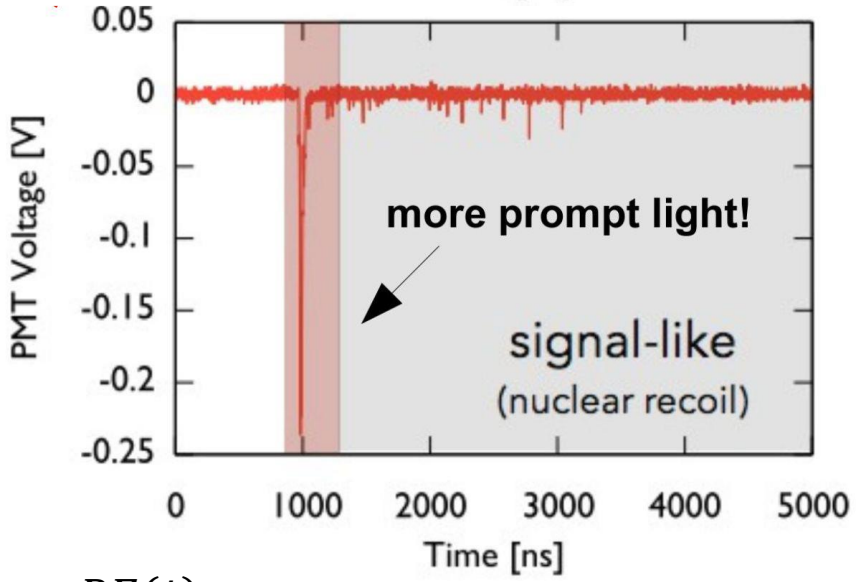
- **Scintillation time profile provides discrimination** between nuclear recoil and electron-recoil events ---nuclear recoil event produces more light in prompt time window.

- **World leading performance for rejection of electron recoils (ERs)** : At 110 photoelectron (PE) (~18 keV_{ee}), leakage probability of about 10^{-10} is achieved at nuclear recoil acceptance 50%.



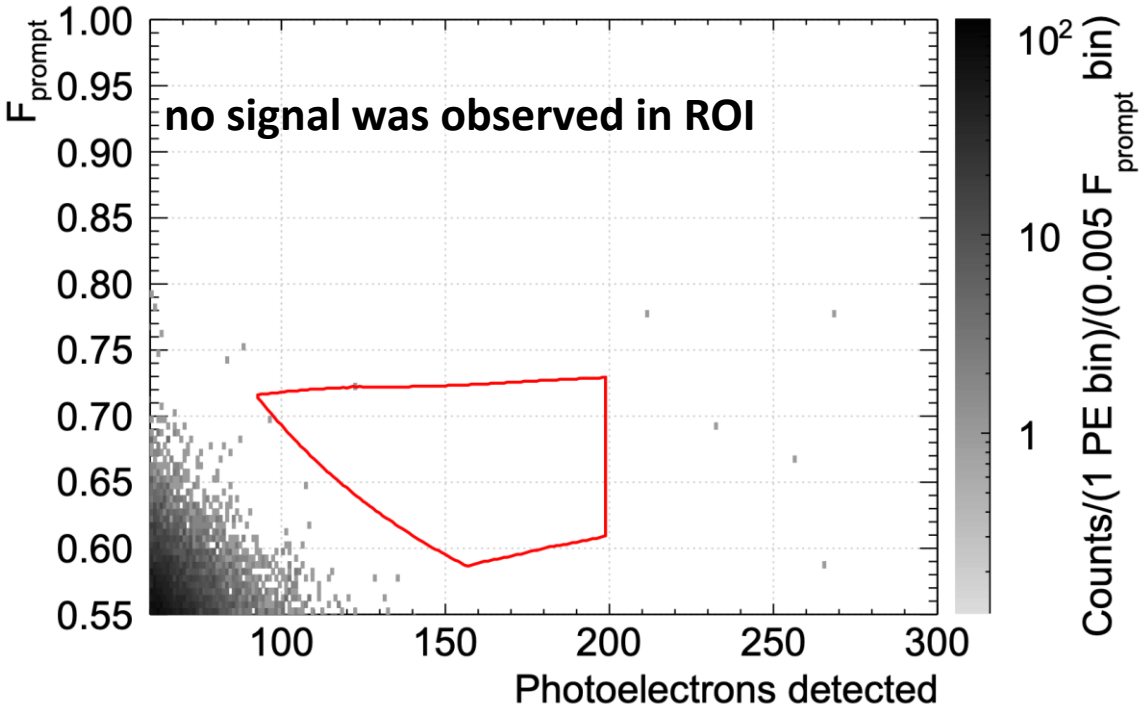
Ref : [European Physical Journal C 81 (2021) 823]

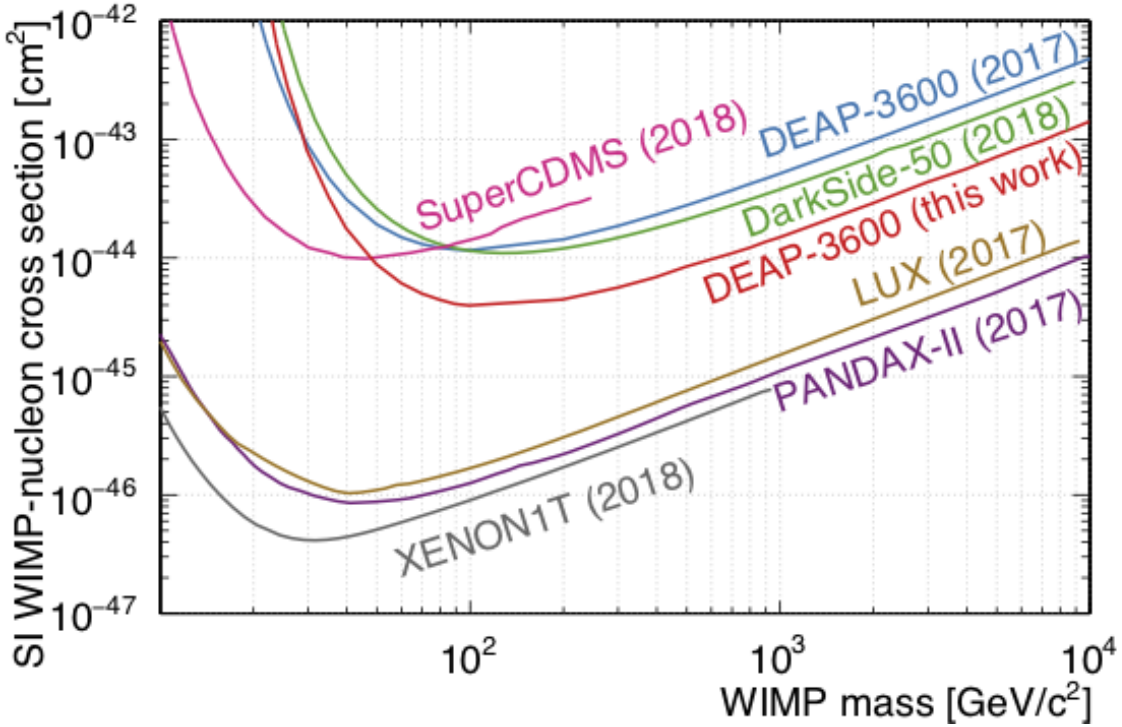




$$F_{prompt} = \frac{\sum_{t=-28\,ns}^{60\,ns} PE(t)}{\sum_{t=-28\,ns}^{10\mu s} PE(t)}$$

Results of WIMP search from first-year dataset





Region of Interest (ROI) is defined in F_{prompt} and PE parameter space such that expected background is less than 1 events.

- Most stringent limit on spin-independent WIMP-nucleon cross-section **among argon-based experiments.**
- Further improvement is limited by alpha-backgrouds -- -- requires improvements in background model along with hardware upgrades.

Ref: Phys. Rev. D 100, 022004 (2019)

Development of additional α-background model

- **A background component model is developed:**

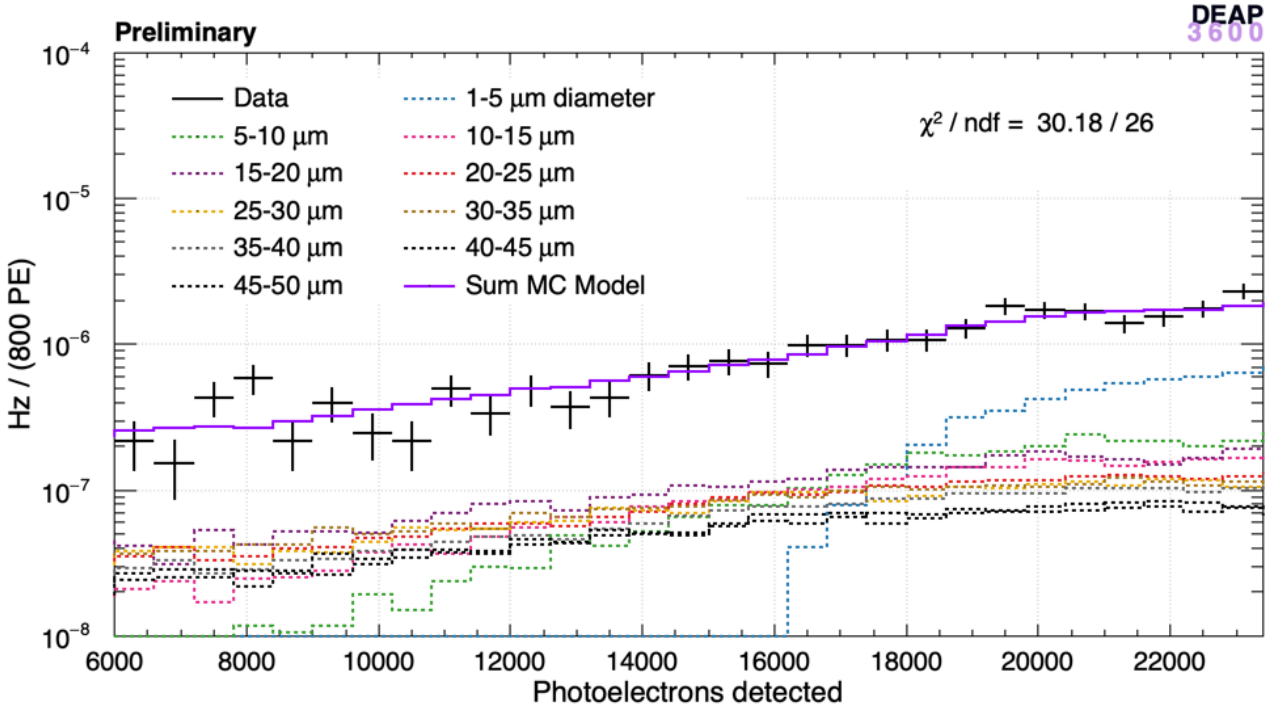
α-decays from trace amount of dust particulate contamination within liquid argon.

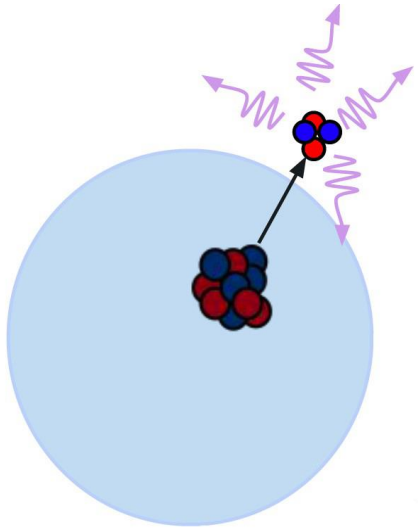
  - Attenuation of energy before entering in liquid argon and scintillation light is shadowed by dust particulates itself.
  - Causes fewer scintillation photons.

- During installation, dust particulates could enter DEAP-3600 detector.
  - Ex-situ measurements of metallic dust using nitrogen gas supports this hypothesis.

- Different dust sizes are simulated and the size distribution is modelled by a power law.

- Fit performed in photoelectron spectrum and extrapolated to lower energy region.

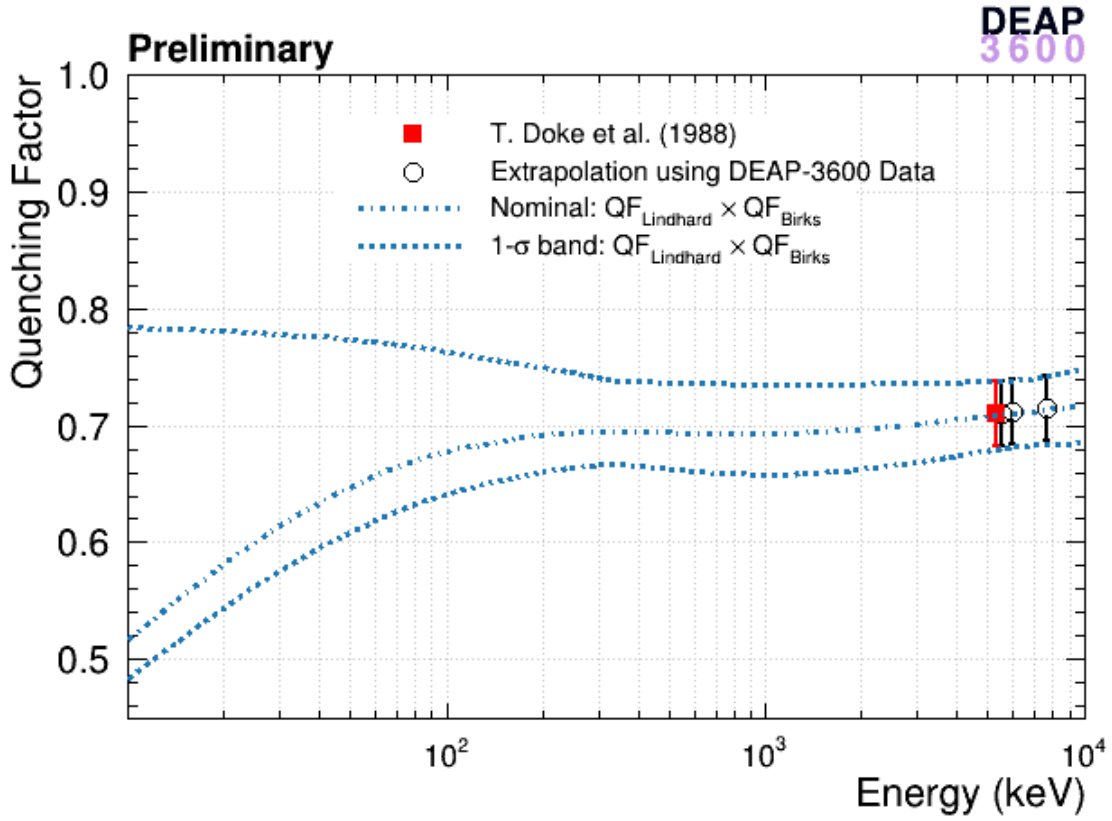




[*see talk presented by Pushparaj Adhikari on June 19, 2023 11:00 am*]

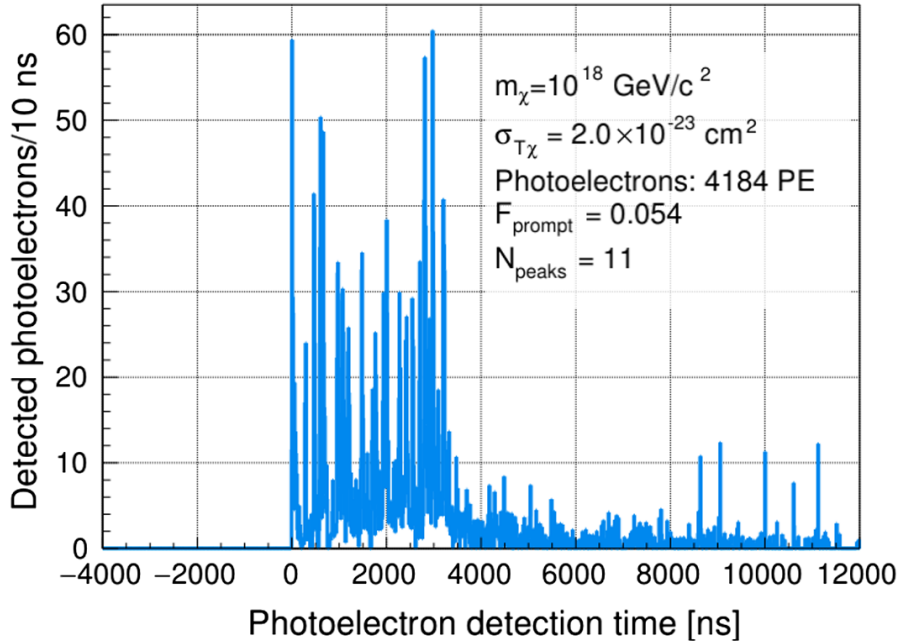
Improvement in alpha quenching model

- A relative measurement is performed in the high energy region (~ 5-8 MeV) with alpha-decays from ^{222}Rn, ^{218}Po and ^{214}Po.
- Quenching data from T. Doke et.al's measurement [Ref: NIM A 292(1988) 269] for ^{210}Po source is taken as calibration data.
- Probed the uncertainty of extrapolating the quenching factor to the low-energy region (up to 10 keV).
- Direct measurement of alpha quenching (few hundreds of keV – few MeV) at Carleton University in a small argon detector is underway.
- Preparing paper for publication.

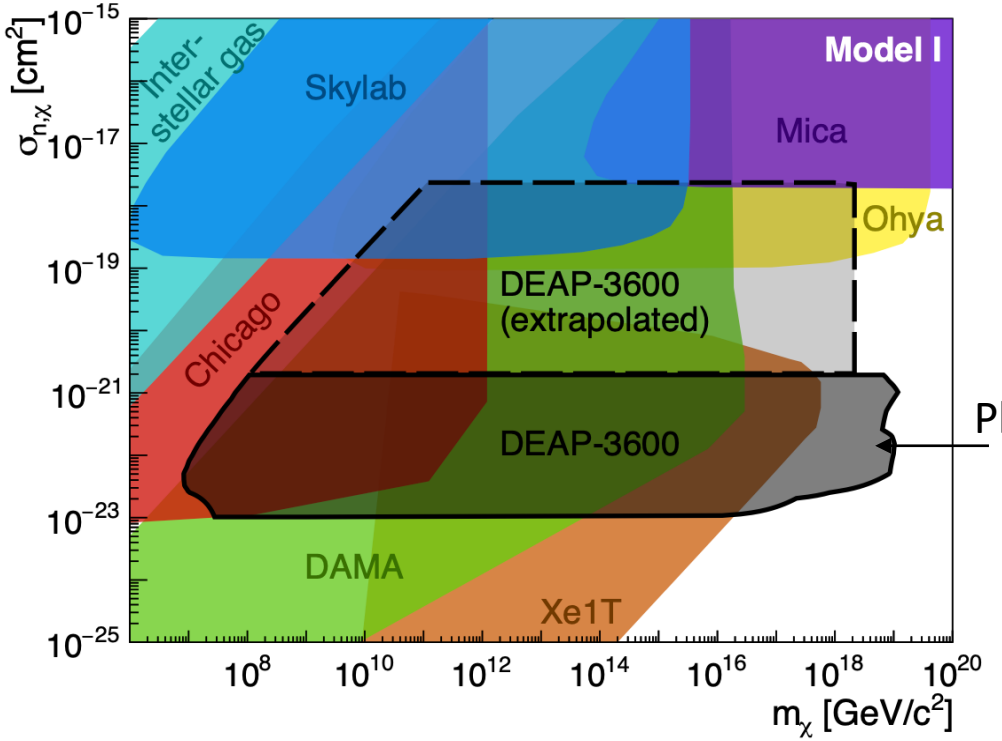


Planck-scale mass DM particles

- Well motivated dark matter candidate with Planck-scale mass; could have higher cross-section than WIMPs.
- Event signature:
  - Contains multiple nuclear recoil scatters : produces multiple peaks in the signal
  - Low F_{prompt}
- Distinguishable from pile-up signals.



Ref :Phys. Rev. Lett. **128**, 011801 (2022)



Planck- scale mass DM

In 813 live days data, no event was found in the ROI for this search.

Constrain the DM masses between $(8.3 \times 10^6$ - $1.2 \times 10^{19})$ GeV/c^2 and ^{40}Ar-scattering cross-sections between 1×10^{-23} and 2.4×10^{-18} cm^2

First experiment to reach Planck-scale sensitivity due to large detector size.

^{39}Ar specific activity measurement

- Specific activity :

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

where m_{LAr} is mass of LAr and total number of ^{39}Ar decays N = N_{single} + $N_{pile\text{-}up}$

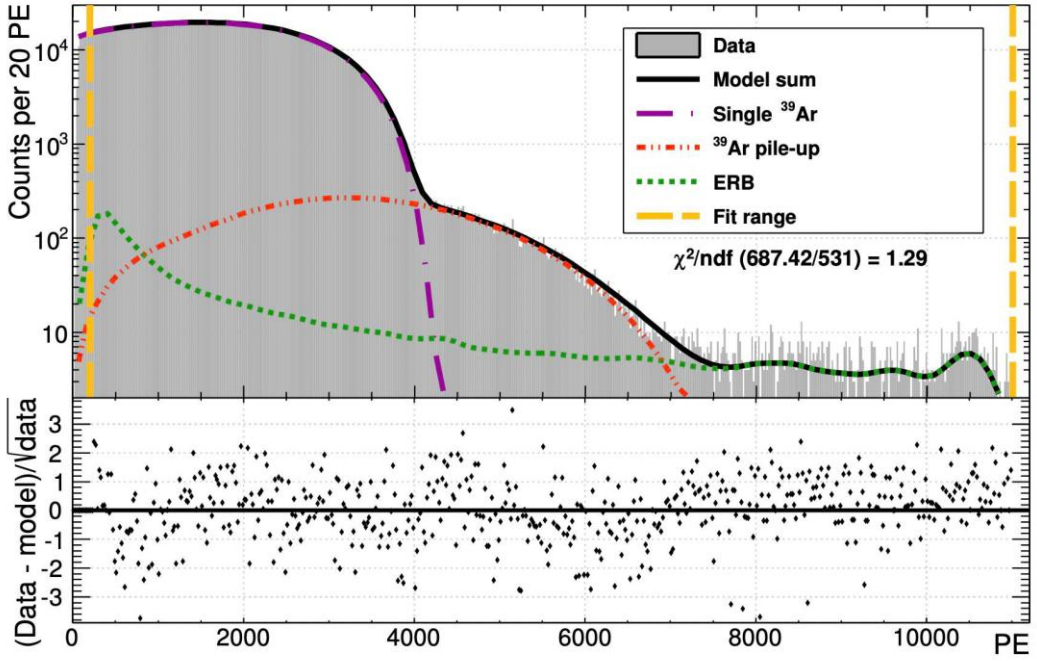
- Measured individually for each run in the dataset based on a fit to low F_{promt} energy spectrum.

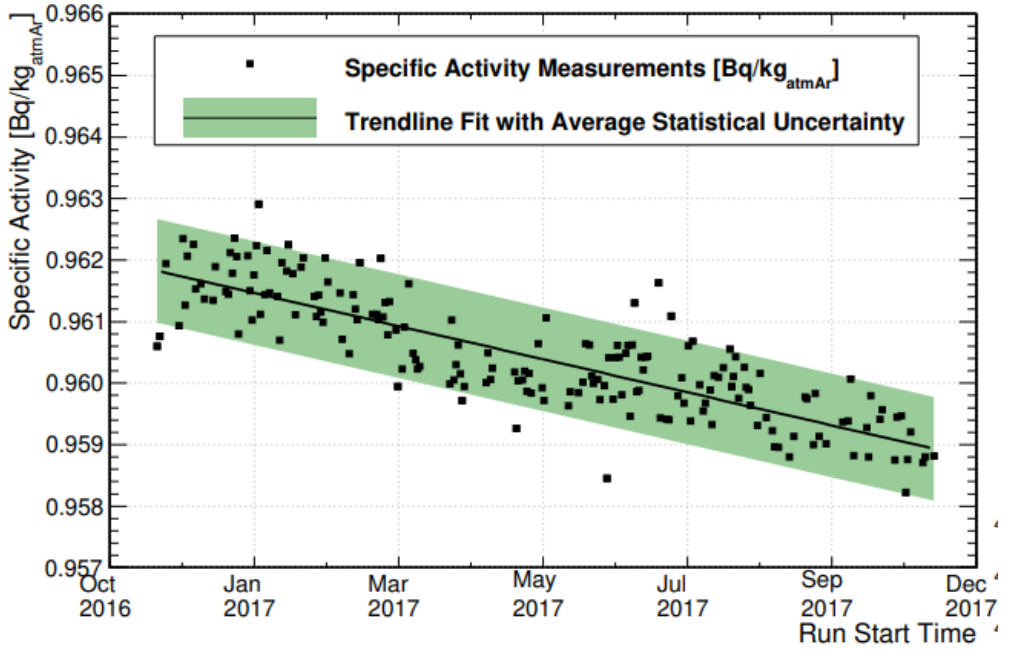
- $m_{LAr} = (3279 \pm 96)$ kg (Previous)

$m_{LAr} = (3269 \pm 24)$ kg (This work)

Measurement	Specific activity [Bq/kg_{atmAr}]
WARP [13]	$1.01 \pm 0.02_{stat} \pm 0.08_{sys}$
ArDM [14]	0.95 ± 0.05
DEAP-3600 (this work)	$0.964 \pm 0.001_{stat} \pm 0.024_{sys}$

The most precise measurement of the specific activity of atmospheric ^{39}Ar to date.





Ref: arXiv:2302.14639, accepted in EPJ C

Physics Searches and Measurements

Published/coming up

- WIMP dark matter search
  - Sensitivity using 231 live-days data [PRD 100, 0022004 (2019)]
  - Re-interpretation of result using Non-Relativistic Effective Field Theory (NREFT) and considering effect of DM halo substructures [PRD 102, 082001 (2020)]
  - PLR analysis with first-year dataset
  - Analyses is in progress with three-year dataset
- Planck-scale dark matter search [PRL 128, 011801 (2022)]
- Measurements and Event Reconstruction
  - Electromagnetic backgrounds and potassium-42 activity [PRD 100, 072009 (2019)]
  - Pulseshape model [EPJ C, 80, 303 (2020)], Pulseshape discrimination [EPJ C 81, 823 (2021)]
  - ^{39}Ar specific activity [arXiv:2302.14639, accepted EPJ C] , ^{39}Ar lifetime measurement
  - Alpha quenching model, Position reconstruction in DEAP-3600 detector
- Other searches
  - ^{8}B solar neutrino absorption in argon *[see talk by Emma Ellingwood on June 21, 2023 , W3-1 4:15 PM]*
    - Search for inverse $\beta -$ decay of ^{40}Ar induced by ^{8}B solar neutrino.
  - Solar axion search
    - 5.5 MeV axion could be produced in the Sun's core: p + $^{2}H \rightarrow {}^{3}H + a$ (instead of γ)
    - This search requires detailed knowledge of gamma backgrounds at high energy (MeV region)

Summary

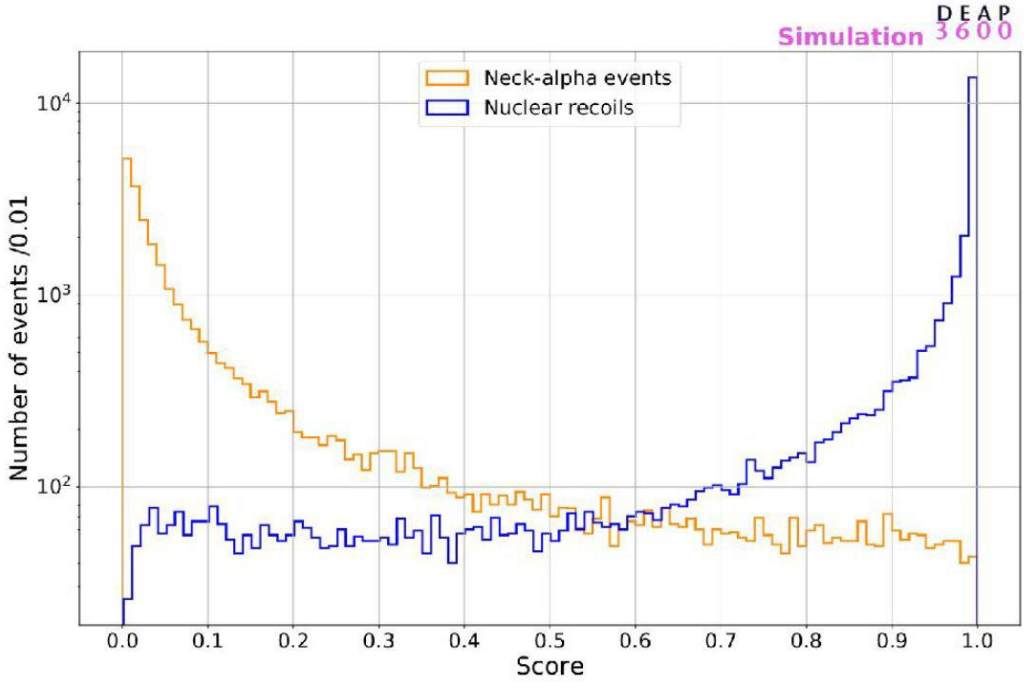
- The DEAP-3600 experiment is primarily looking for dark matter particles and is sensitive to various physics searches and measurements as well.
  - **Excellent performance :**
    - pulseshape discrimination (nuclear and electron recoil events)
    - Background rejection
    - Event reconstruction
  - **Analyses in progress:**
    - Analyses with full dataset for WIMP search
    - New searches/measurements
  - **New data taking starting soon after completing hardware upgrades .**

- **Project is part of Global Argon Dark Matter (GADM) program:**
  - Completion of the DEAP experiment (~2 years of new data)
  - The DarkSide-20K experiment is starting in 2026
  - Developing ARGO experiment for 2030

Thank you for your kind attention

Extra Slides

WIMP Search: Coming Up

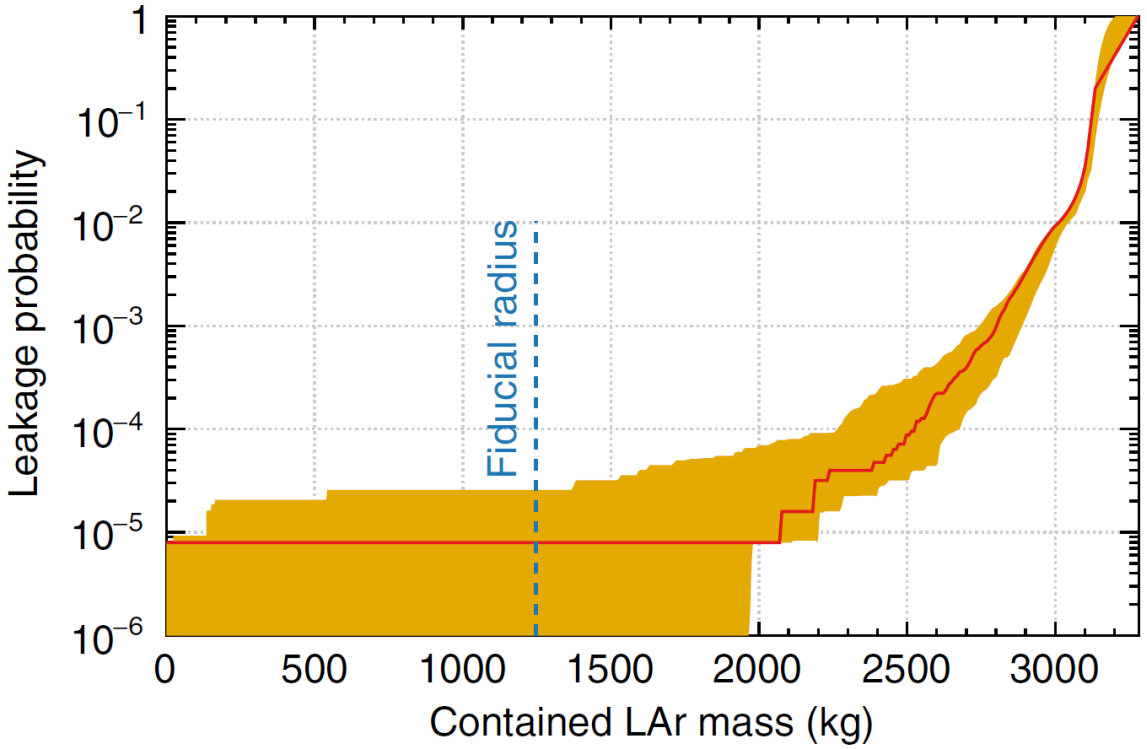


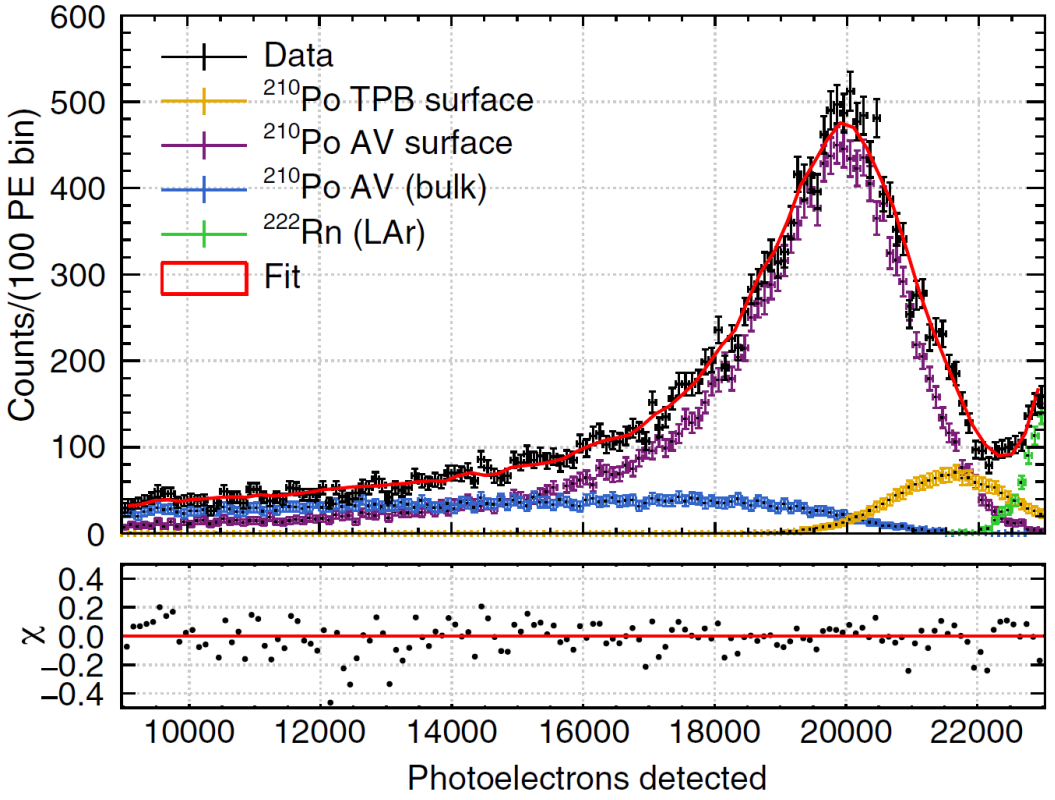
Multivariate analysis (MVA) [Random forest (RF), Boosted decision trees (BDT), Neural networks (NN)] **for background rejection** (neck alpha, dust alpha for example).

Developing new variables and validating backgrounds models.

Surface Alpha Backgrounds

- Originated from ^{210}Po α-decays on inner surface of the acrylic vessel.
  - Results in peak in 18000- 22000 PE range
- Surface alpha background is constrained by fiducial cuts.

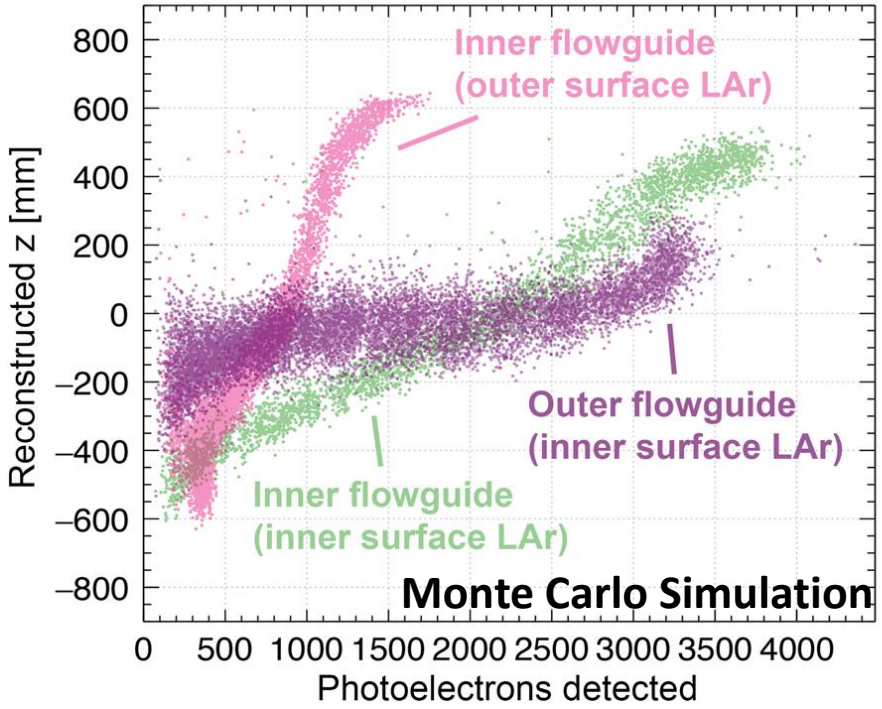




Phys. Rev. D 100, 022004 (2019)

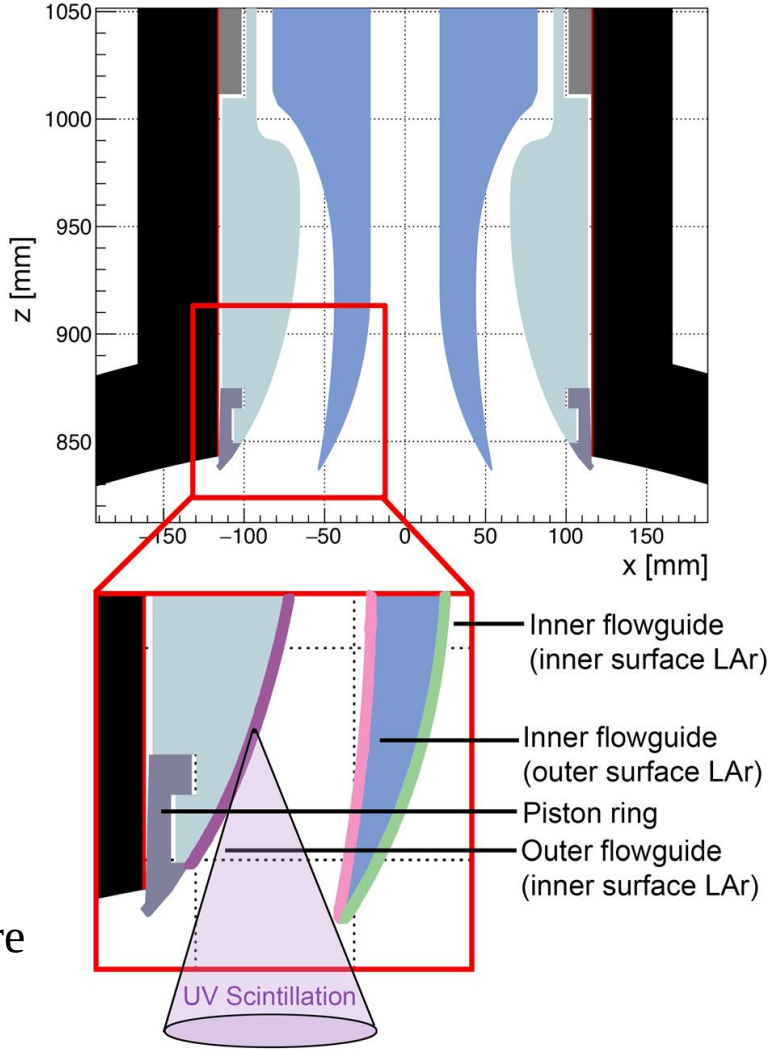
WIMP Search: Neck Alpha Backgrounds

- Originated from ^{210}Po α-decays on the acrylic surfaces of flowguides located at the neck of the detector.
- Produces significant backgrounds at low energy due to **shadowed/degraded** alpha decays.
- Position of shadowed alpha-decay events tends to reconstruct within fiducial volume.



Optical model :

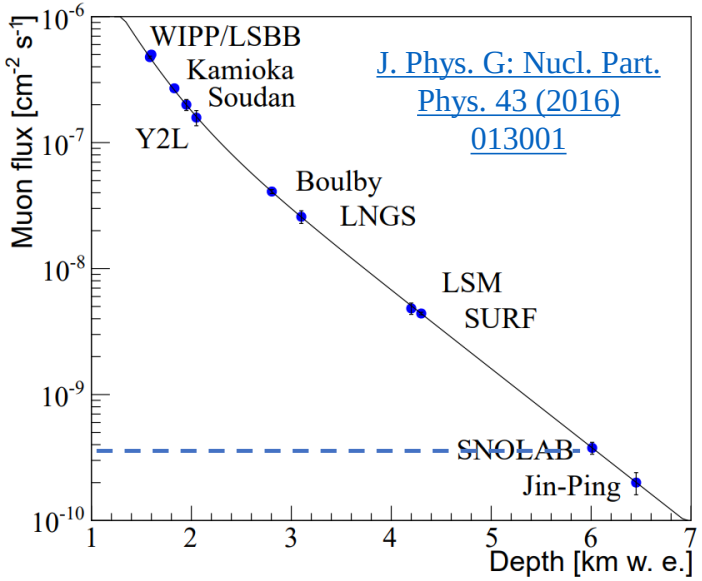
- Assumes the surfaces of flowguides are coated with a thin liquid argon layer.
- Results in an F_{prompt} distribution consistent with data.

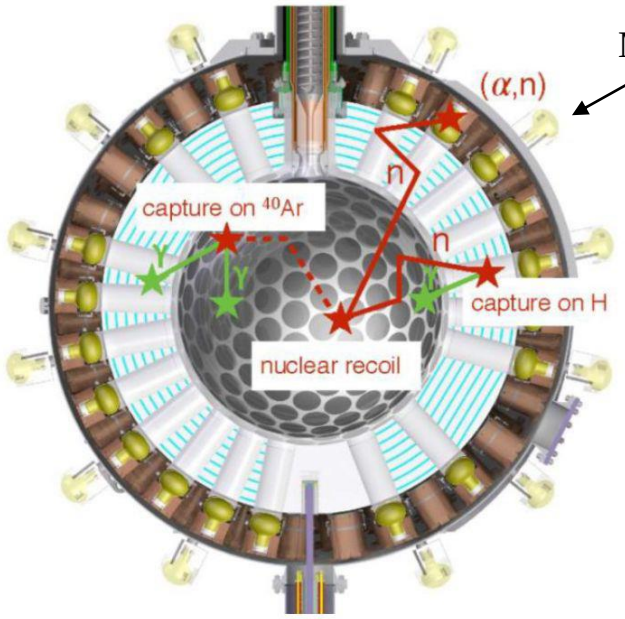


Phys. Rev. D 100, 022004 (2019)

WIMP Search: Neutron Backgrounds

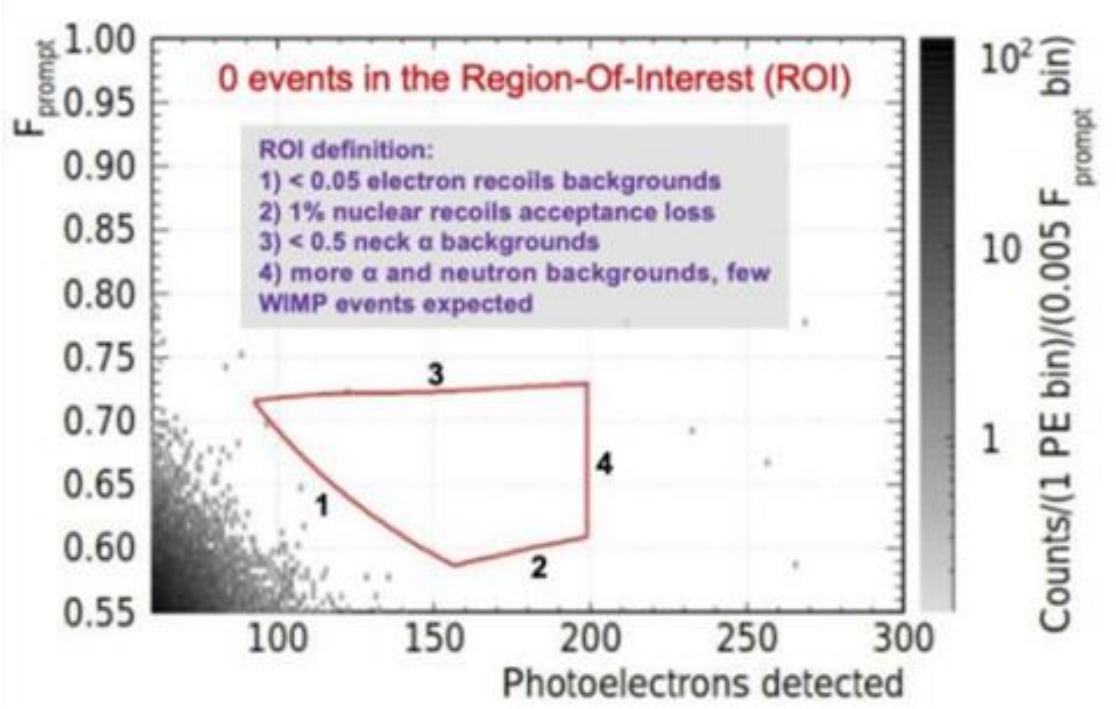
- **Cosmogenic neutron backgrounds :** Produced by high energy atmospheric muon interactions with the detector and its surroundings.
  - *Reduction process:*
    - tagging muon induced Cherenkov signal in the water tank.
- **Radiogenic neutron backgrounds:** Produced by (α, n) reactions induced by α-particles emitted from Uranium/Thorium decay chains or by spontaneous fission of ^{238}U isotope present in different detector components.
  - *Mitigation process:*
    - Estimation of neutron flux and energy spectra from each detector components.
    - Neutron capture analysis : tagging NR event closely followed (1ms) by high energy ER event.





Neutrons thermalize within acrylic and liquid Argon by producing high energy γ-rays (2.2 MeV, 6.1 MeV).

WIMP Search



- Selection of nuclear recoil using PSD technique.
- Rejection of α-decays from ^{210}Po on acrylic vessel inner surface using fiducial cuts.
- Rejection of shadowed of α-decays from ^{210}Po on the acrylic flowguides in the neck of the detector with dedicated cuts.