# Latest results from the DEAP-3600 experiment at SNOLAB

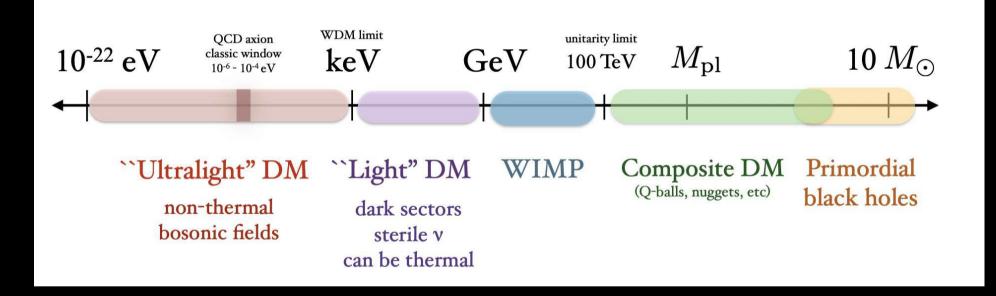
Simon Viel Carleton University **TAUP** *August 30<sup>th</sup>, 2023* 

# Outline

- 1. Status of the DEAP-3600 search for WIMP dark matter
- 2. First direct detection constraints on Planck-scale mass dark matter
- 3. Other searches and measurements
- 4. DEAP-3600 upgrade

Astrophysics gives us clear evidence that dark matter exists.

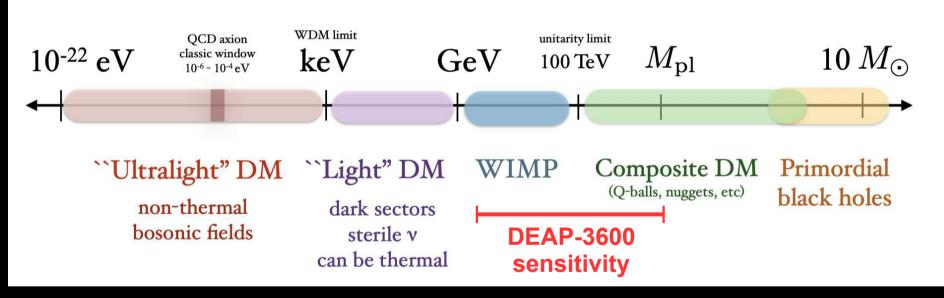
We know how much dark matter there is, but we don't know what it is!



**Direct detection experiments** in particle physics seek to observe interactions between dark matter particles and ordinary matter.

Astrophysics gives us clear evidence that dark matter exists.

We know how much dark matter there is, but we don't know what it is!



(18 orders of magnitude in mass)

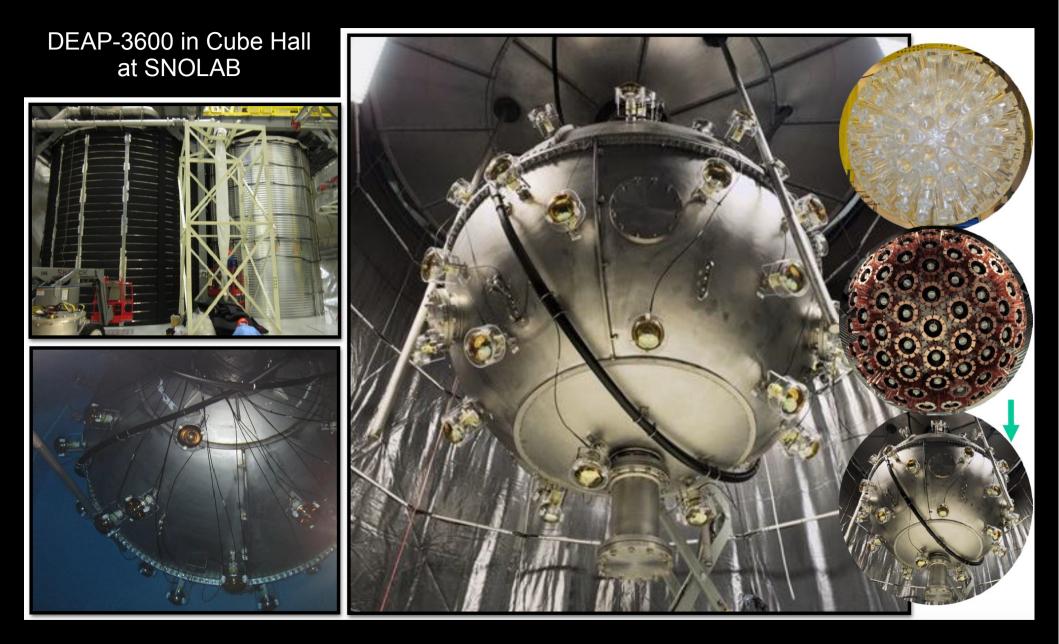
**Direct detection experiments** in particle physics seek to observe interactions between dark matter particles and ordinary matter.



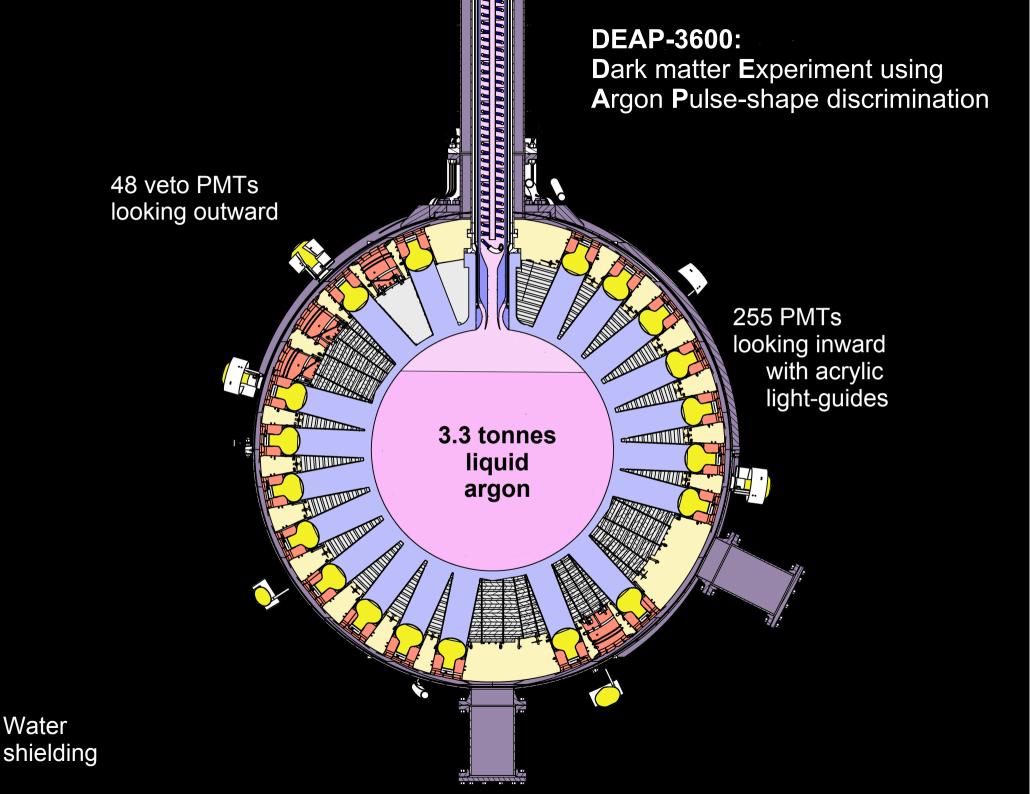
Video: A Day at SNOLAB https://www.snolab.ca/outreach

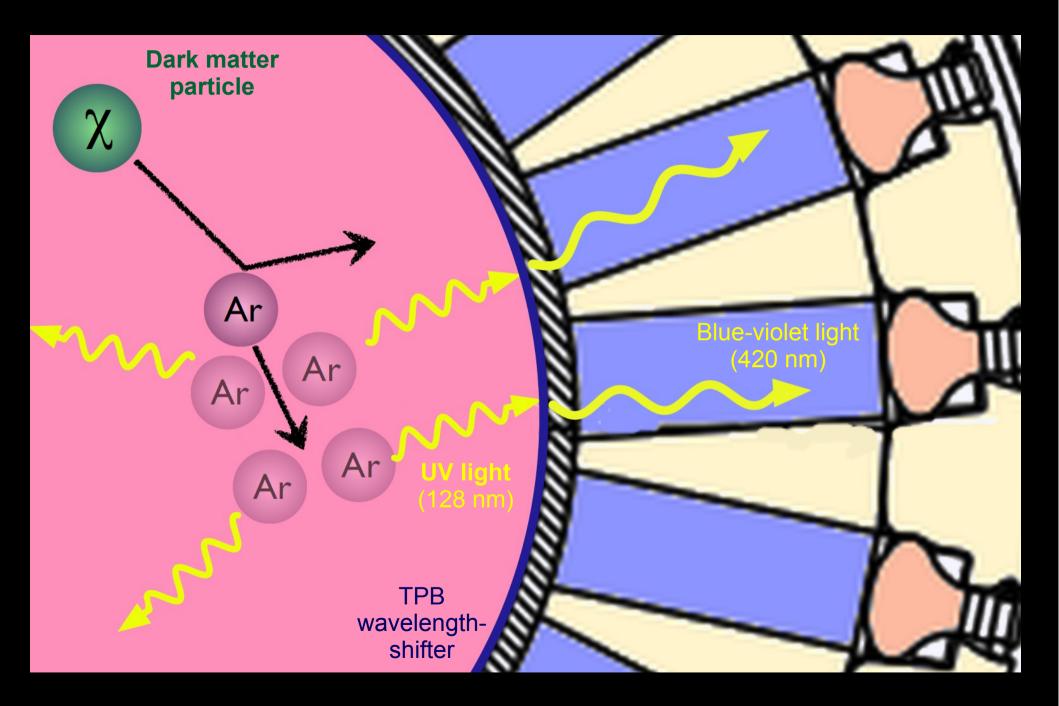
2070 m underground

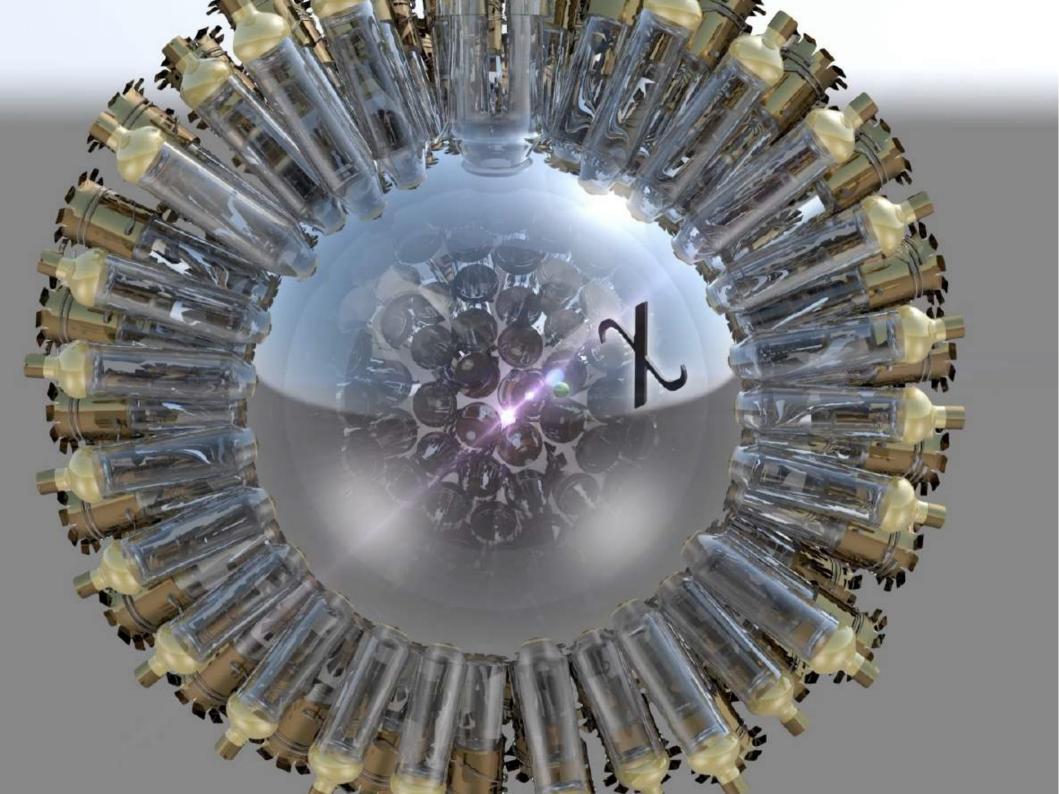




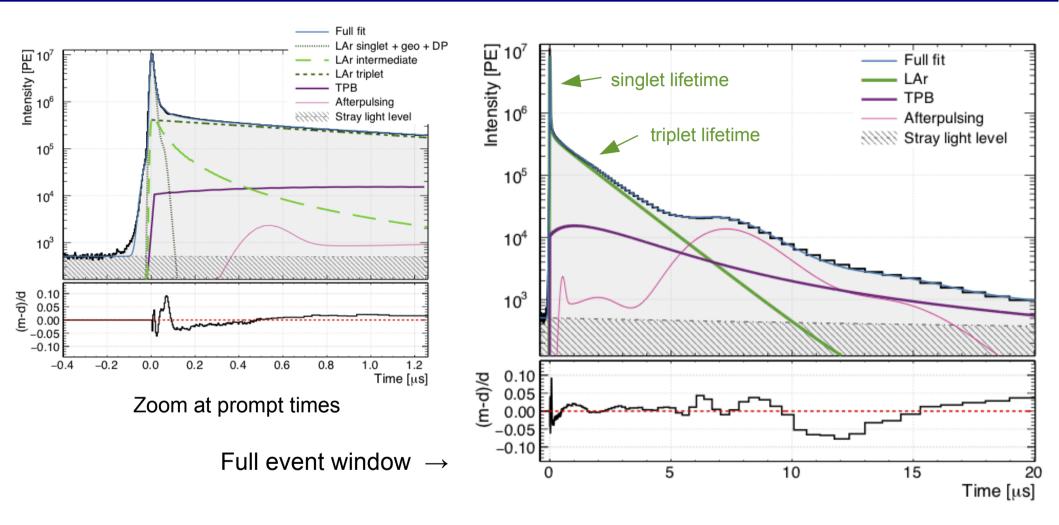
DEAP-3600 detector publication: Astroparticle Physics 108, 1-23 (2019) arXiv:1712.01982







## Liquid argon scintillation pulse-shape in DEAP-3600

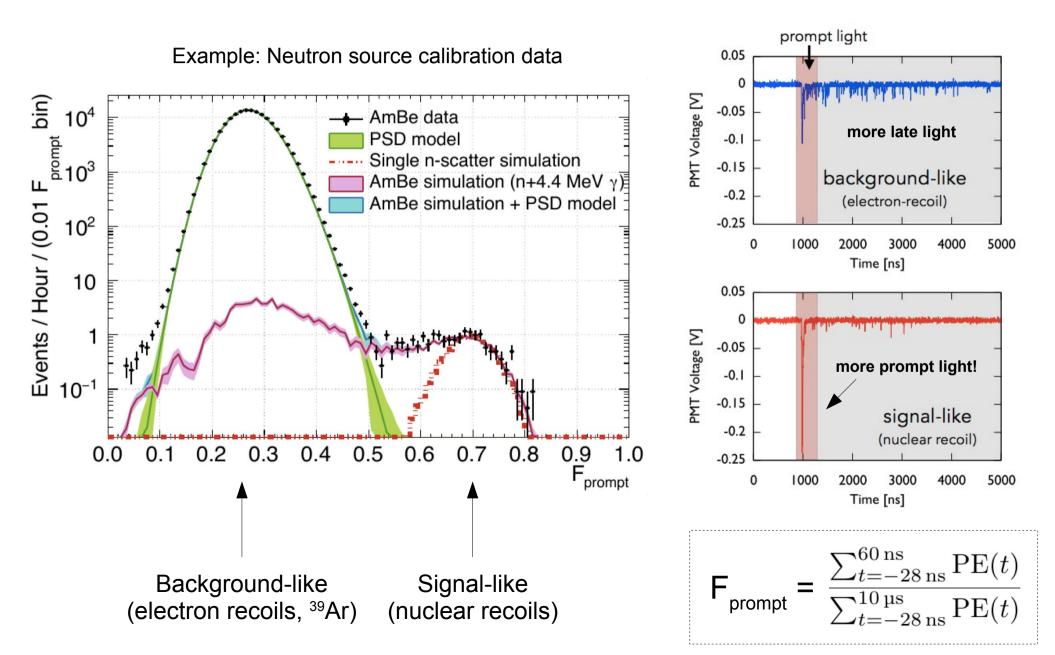


Visible photons  $\rightarrow$  Photoelectrons at PMT cathode  $\rightarrow$  PMT pulses

**Pulse-shape model:** European Physical Journal C, 80, 303 (2020) arXiv:2001.09855 Including intermediate time component of LAr scintillation, PMT response, and long TPB time constant

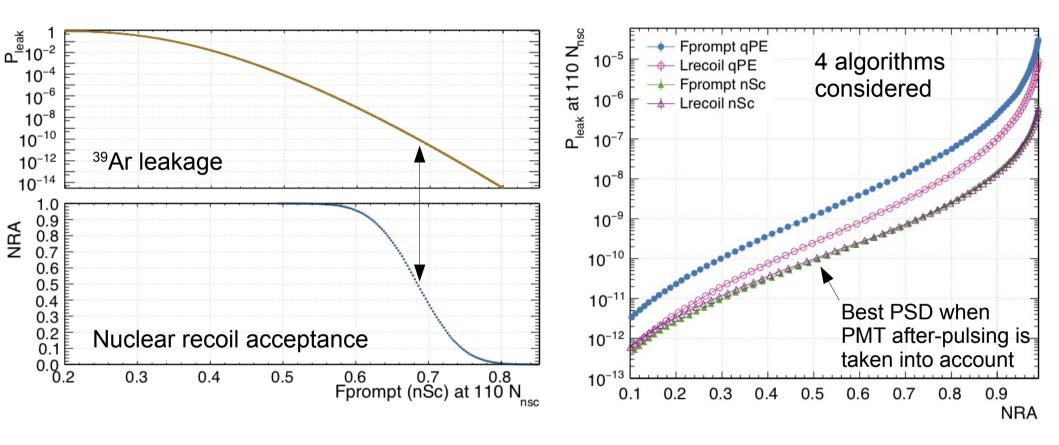
#### Pulse-shape discrimination (PSD)

The goal is to select dark matter signal events, and reject background events



## Pulse-shape discrimination (PSD)

#### **World-leading PSD performance!**

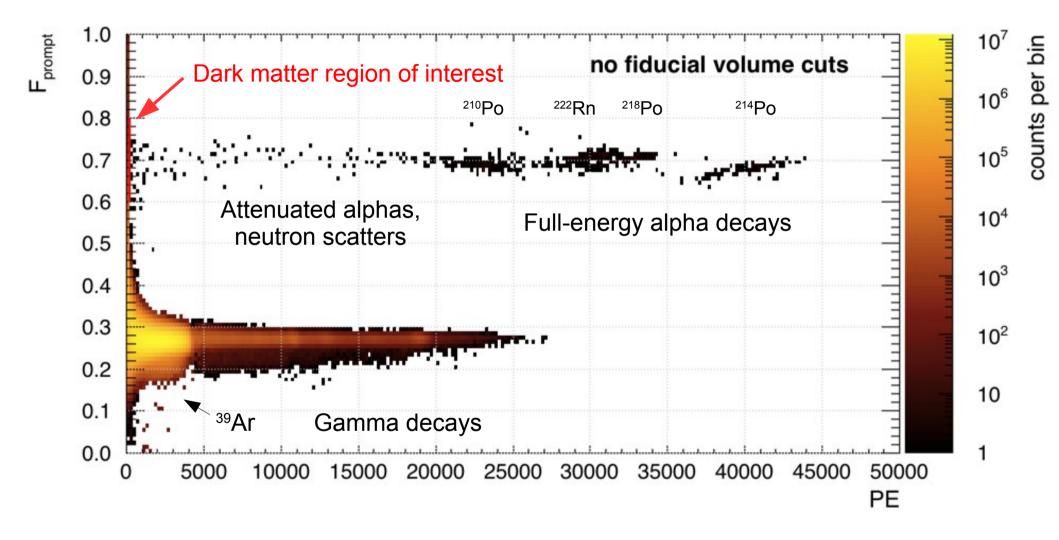


Using our best PSD algorithm:

Leakage probability at 110 PE (~ 17.5 keVee) is 10<sup>-10</sup> at 50% nuclear recoil acceptance

Detailed PSD paper: European Physical Journal C, 81, 823 (2021) arXiv:2103.12202

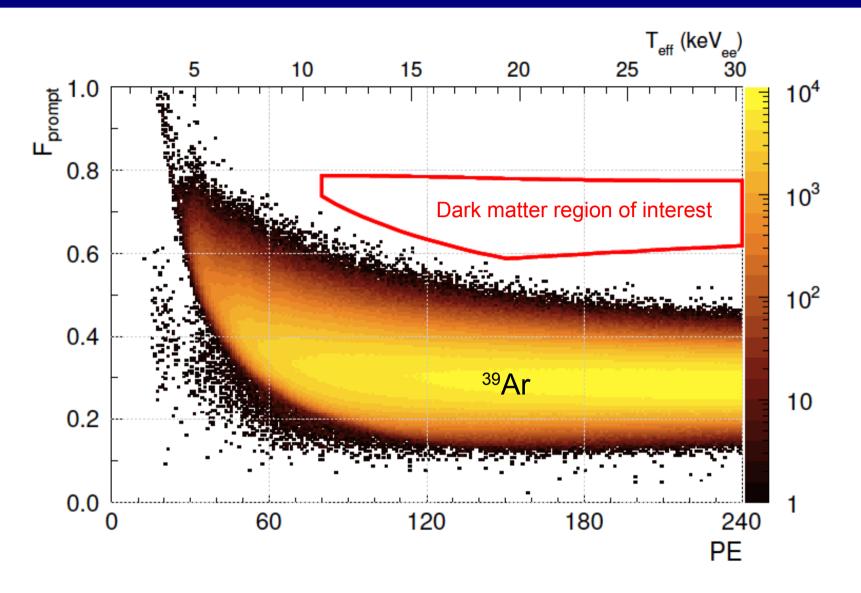
## Early physics data



First DEAP-3600 dark matter search, with 4.4 live days

Physical Review Letters, 121, 071801 (2018) arXiv:1707.08042

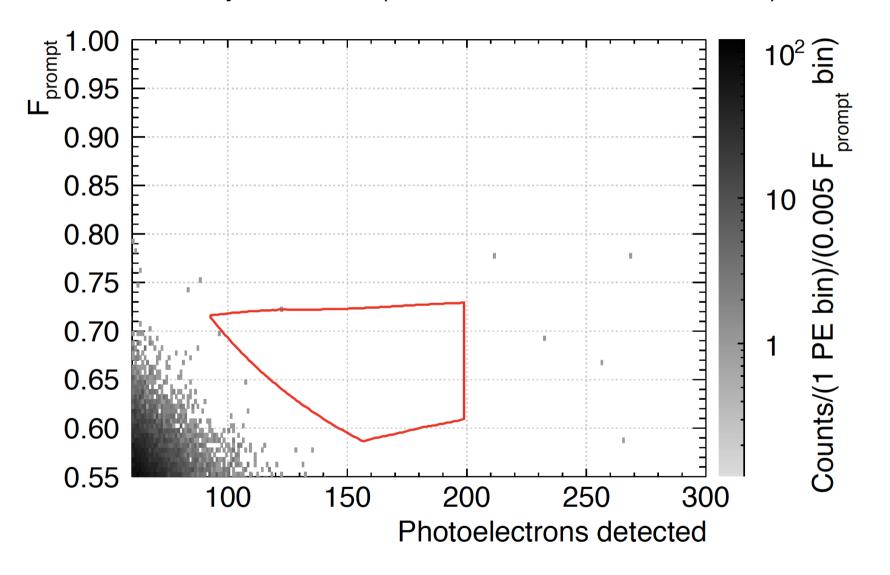
#### First dark matter search results



First DEAP-3600 dark matter search, with 4.4 live days Physical Review Letters, 121, 071801 (2018) arXiv:1707.08042

#### First-year WIMP dark matter search results

The detector is sensitive to dark matter, but no signal event was observed in our first-year dataset (November 2016 – October 2017)



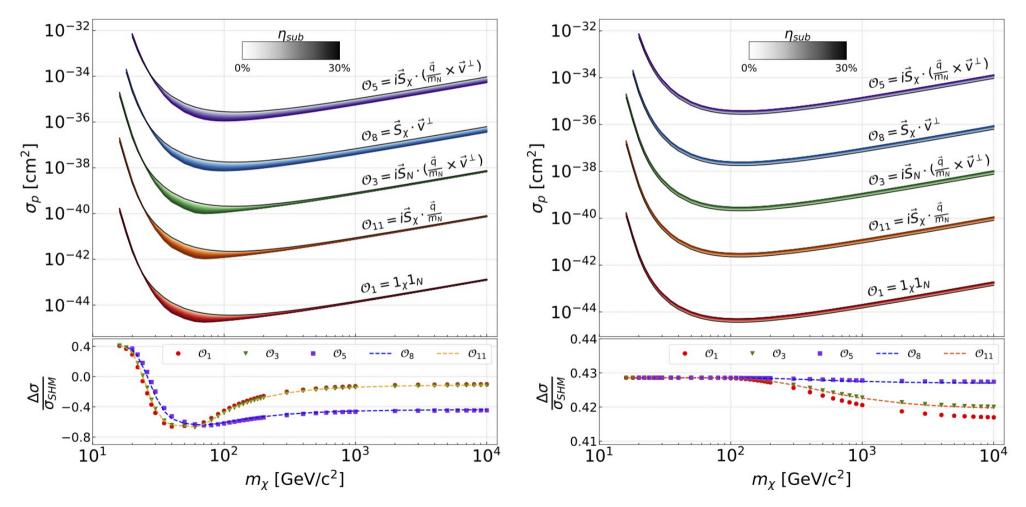
Physical Review D, 100, 022004 (2019) arXiv:1902.04048

#### Further constraints on WIMP dark matter

 Results are reinterpreted in a more general non-relativistic EFT framework, and exploring how possible substructures in DM halo affect these constraints

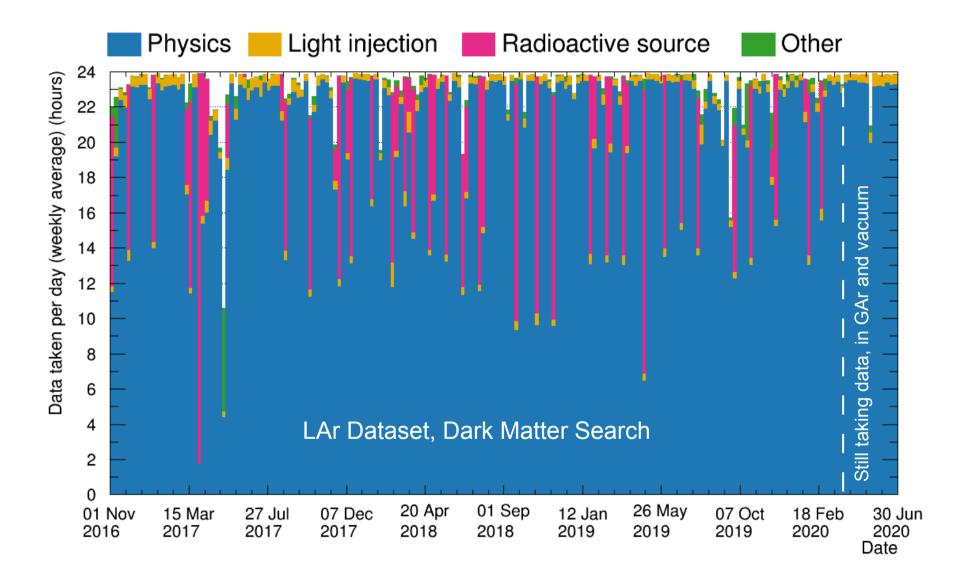
Example retrograde stellar stream, e.g. S1

Example prograde stellar stream, e.g. Nyx



Physical Review D, 102, 082001 (2021) arXiv:2005.14667

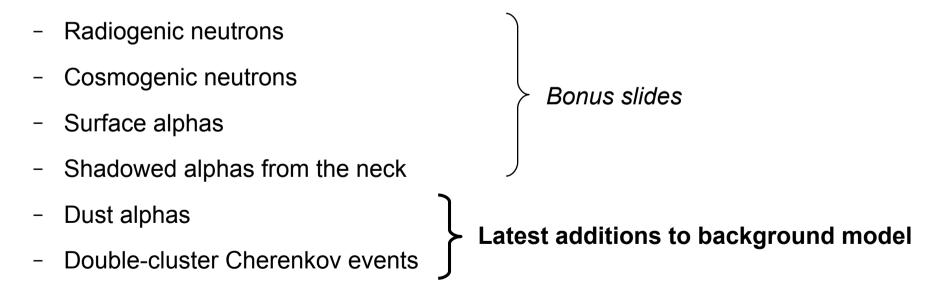
#### **DEAP-3600** dataset



- Stable data collection for DM search: November 1<sup>st</sup>, 2016 March 28<sup>th</sup>, 2020
  - 80% blind since January 1<sup>st</sup>, 2018

# Next steps in the search for WIMP dark matter

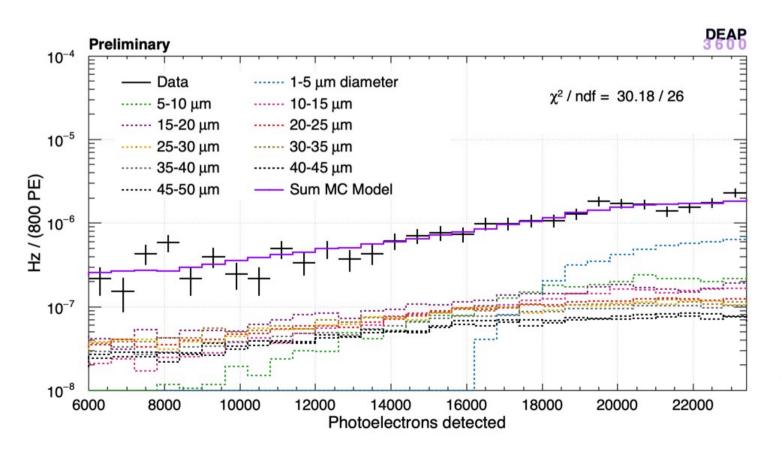
- Profile-likelihood ratio (PLR) Bayesian analysis framework developed
  - Drastically increase WIMP acceptance by relaxing event selection cuts
  - Consider background probability distribution functions explicitly in the PLR fit
- Detailed background model:
  - <sup>39</sup>Ar beta decays
  - Cherenkov radiation from gamma rays



- Analysis on open dataset (388 live-days) is *almost* ready to publish!
- Open+Blind analysis results based on 813 live-days of data will follow

## Dust alpha background

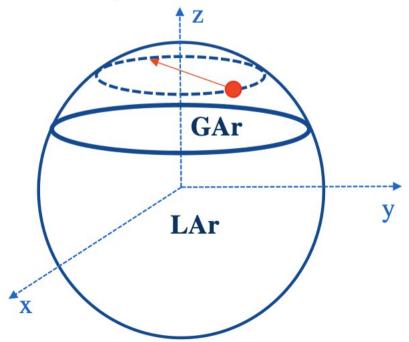
- Alpha decays from trace amounts of dust particulates in liquid argon create low-PE events originating from the LAr bulk volume
  - Attenuation before entering liquid argon, and scintillation light shadowed
  - Now included in background model
    - Pure control region defined at intermediate PE

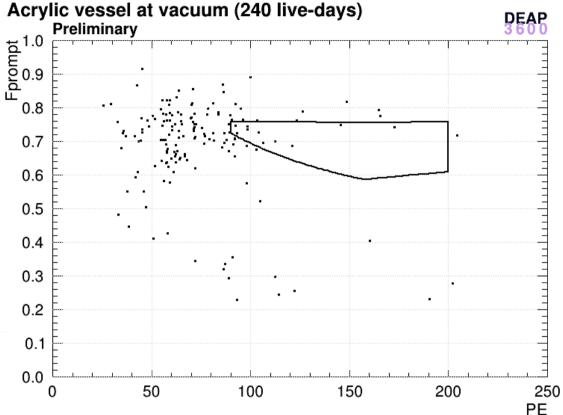


Ex-situ measurements of metallic dust in liquid nitrogen support this hypothesis

## Double-cluster Cherenkov background

- Data taken with DEAP-3600 at vacuum in 2021-2022 revealed a surprise: events passing all WIMP selection cuts into the search region of interest
- Working hypothesis:
  Cherenkov radiation at two sites in the acrylic vessel from gamma traveling across the detector





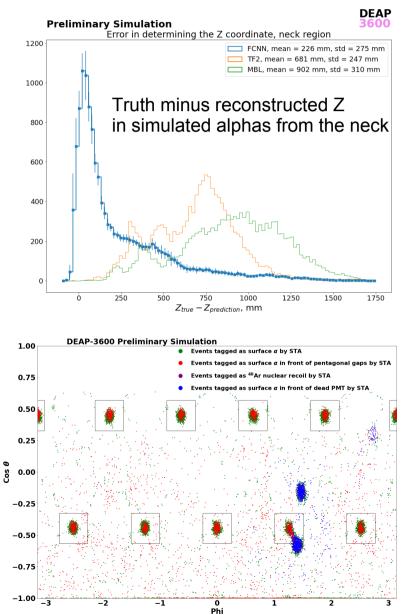
- Developed a **dedicated algorithm** against this background based on double-cluster identification
- Remove events where a single PMT sees a high fraction of the prompt light

# New algorithms against alpha backgrounds

- WIMP search on the full DEAP-3600 dataset will benefit from new algorithms
- Machine-learning against shadowed alphas
  - Random forest
  - Boosted decision trees
  - Neural network for classification
  - Neural network for position reconstruction
    - Including simulated shadowed alphas in the training sample improves accuracy of position reconstruction for these events

#### Surface alpha tagging

- Position reconstruction algorithms are used to define fiducial region
- Dedicated algorithm against surface alpha leakage
- Could allow expanding the fiducial region in an upcoming WIMP search



Simulated surface alphas within reconstructed R < 800 mm

# Search for Planck-scale mass DM particles

Preliminary

80 60 40

20

-4000

-2000

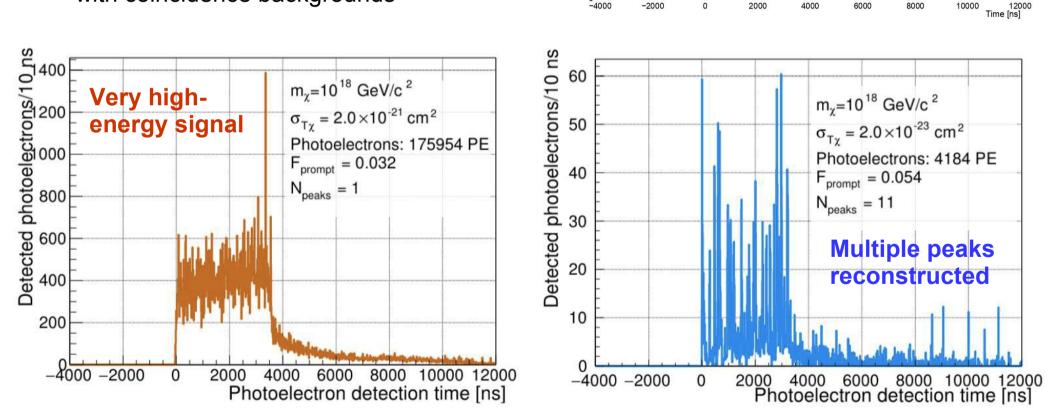
0

2000

4000

#### **Multiply-interacting massive particles**

- Distinct signature consistent with • multiple recoils in succession
  - Or a very high-energy, low F<sub>prompt</sub> event
- Expected signal pulse-shape is inconsistent with coincidence backgrounds



DEAR

Simulation

Coincidence

background

8000

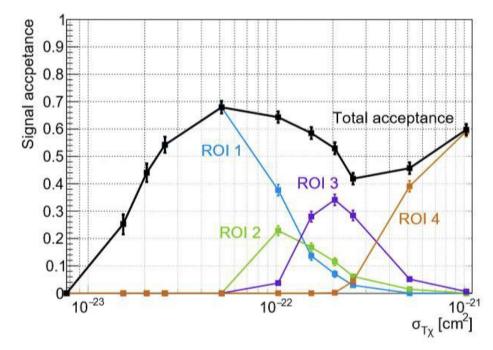
6000

## Search for Planck-scale mass DM particles

#### **Multiply-interacting massive particles**

- Distinct signature consistent with multiple recoils in succession
  - Or a very high-energy, low F<sub>prompt</sub> event
- Expected signal pulse-shape is inconsistent with coincidence backgrounds
- DEAP-3600 is especially sensitive due to its large detector size
- Four regions of interest are defined with high signal acceptance, and very low expected background << 1 event</li>
- Unblinded 813 live-days of data...

#### Signal acceptance vs. cross-section

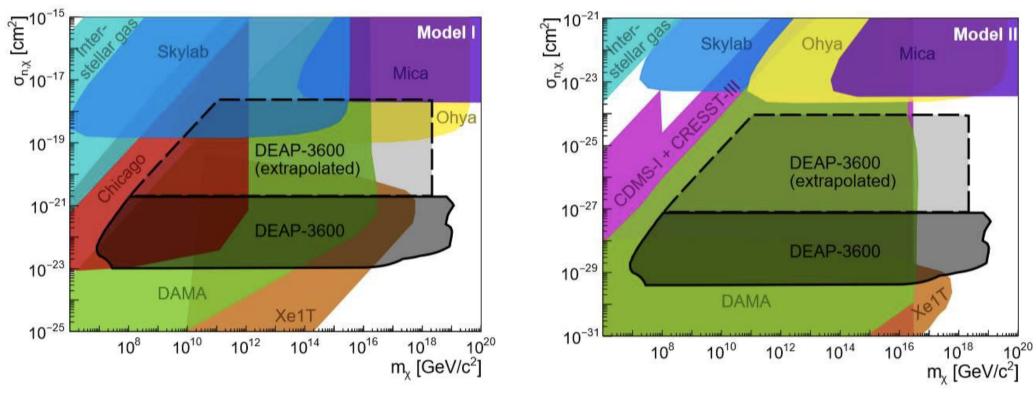


ROI	PE range	Energy [MeV]	$\rm N_{peaks}^{min}$	$\mathrm{F}_{\mathrm{prompt}}^{\mathrm{max}}$	$\mu_b$
1	4000 - 20000	0.5 - 2.9	7	0.10	$(4 \pm 3) \times 10^{-2}$
2	20000 - 30000	2.9 - 4.4	5	0.10	$(6 \pm 1) \times 10^{-4}$
3	30000 - 70000	4.4 - 10.4	4	0.10	$(6 \pm 2) \times 10^{-4}$
4	$70000-4 \times 10^8$	10.4 – 60000	0	0.05	$(10 \pm 3) \times 10^{-3}$

#### Search for Planck-scale mass DM particles

No event was found in any of the regions of interest for this search

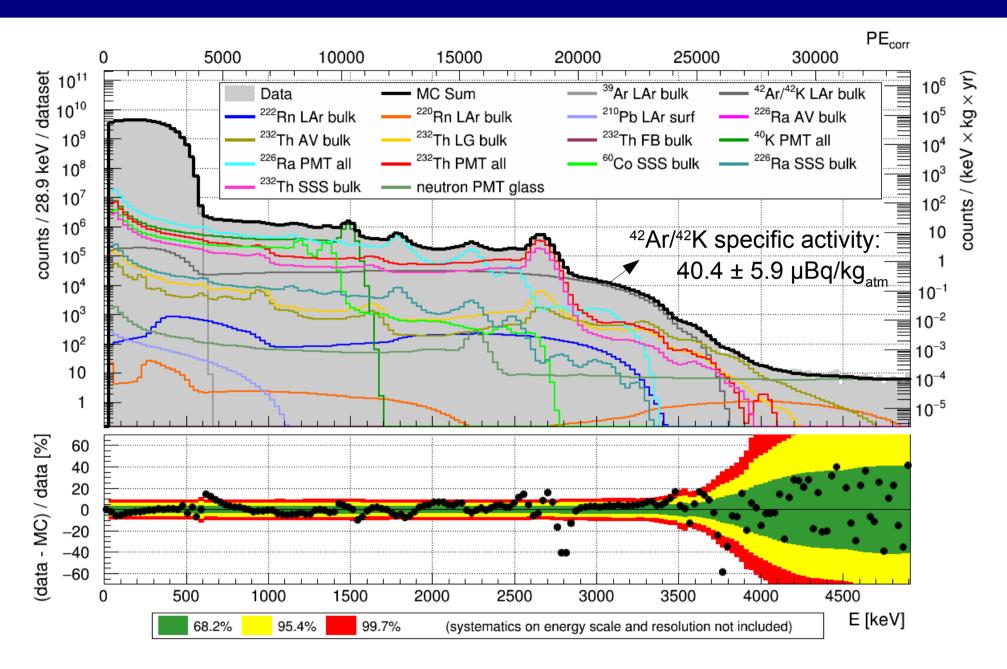
#### World-leading sensitivity to Planck-scale mass dark matter!



N.B. We do exclude the "extrapolated" regions

Physical Review Letters, 128, 011801 (2022) arXiv:2108.09405

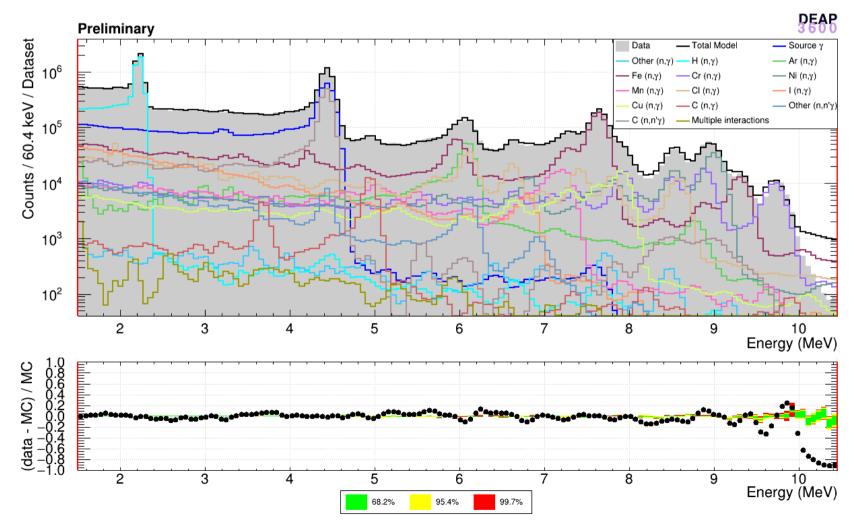
## Electromagnetic backgrounds in first-year dataset



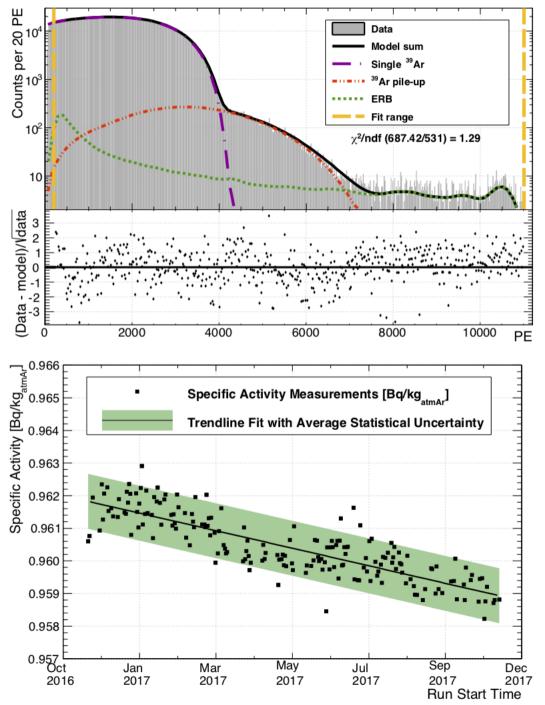
Physical Review D, 100, 072009 (2019) arXiv:1905.05811

## Search for 5.5 MeV solar axion-like particles (ALPs)

- 5.5 MeV ALPs could be produced in the Sun's core:  $p + d \rightarrow {}^{3}He + a$  (instead of  $\gamma$ )
- Search requires excellent understanding of gamma backgrounds at high energy
  - Blind analysis in internal collaboration review
  - Shown here: preliminary fit to AmBe neutron source calibration data



# Measurement of the specific activity of <sup>39</sup>Ar in air



#### <sup>39</sup>Ar specific activity

- Requires precise determination of data acquisition live time vs. dead time
- Reduced uncertainty on liquid argon mass in DEAP-3600 by a factor 4: m<sub>LAr</sub> = 3269 ± 24 kg
- Data-driven efficiency determination for single decays vs. pile-up events
- Constraints on other sources of electronic recoil backgrounds such as <sup>85</sup>Kr
- Result: S<sub>39Ar</sub> = 0.964 ± 0.024 Bq/kg<sub>atmAr</sub>

European Physical Journal C, 83, 642 (2023) arXiv:2302.14639

#### <sup>39</sup>Ar half-life (measurement in progress)

- Requires very good understanding of detector conditions, detector stability
- Impact on radiometric dating

## DEAP-3600 hardware upgrades

#### Hardware upgrades

- Main objective: Mitigate limiting background sources
  - Neck seal replacement, allowing a complete fill with LAr
  - Pyrene: slow wavelength shifter on neck flowguides, to remove shadowed alpha background with PSD
  - Alternate cooling system, to filter out dust
  - Also perform maintenance on cryogenic systems
- Current status
  - Detector now empty of liquid argon
    - Still taking data in vacuum
  - COVID delays: Plan to complete upgrades later this year
- New DM search data in upgraded detector expected in 2024
  - Expecting much improved sensitivity
  - Inform design of next-generation liquid argon dark matter experiments



## Summary: DEAP-3600 physics programme

#### • Measurements

- Pulse-shape [2001.09855], Pulse-shape discrimination [2103.12202]
- Electromagnetic backgrounds and <sup>42</sup>K activity [1905.05811]
- <sup>39</sup>Ar specific activity [2302.14639], <sup>39</sup>Ar half-life
- Muon flux at SNOLAB
- Alpha quenching factor in liquid argon

#### • WIMP dark matter search

- Published search with 231 live-days [1902.04048]
- Constraints on DM halo substructures and non-relativistic EFT [2005.14667]
- Profile likelihood ratio analysis on 388 live-days open dataset
- Analysis in progress towards unblinding the full 813 live-days of data
- Background mitigation in hardware, data-taking to resume in 2024
- Planck-scale mass dark matter search [2108.09405]
- Other searches
  - Neutrino absorption (inverse beta decay) [Talk by V. Shalamova, Thursday 17:15]
  - 5.5 MeV solar axions



**DEAP** Collaboration:

95 researchers in Canada, Germany, Italy, Mexico, Poland, Russia, Spain, UK, USA



# Thank you!



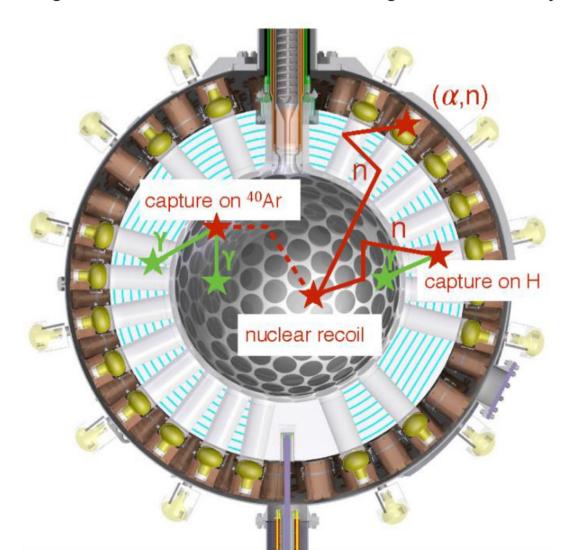
# **Bonus slides**

Background model for the first-year WIMP search

## Neutron backgrounds

**Neutrons** can cause multiple **nuclear recoils** in close succession, or result in γ-ray emission

- $\rightarrow$  Reject events consistent with multiple interactions
- → Estimate remaining neutron backgrounds using dedicated **data control region** results in agreement with simulations taking material assays as input

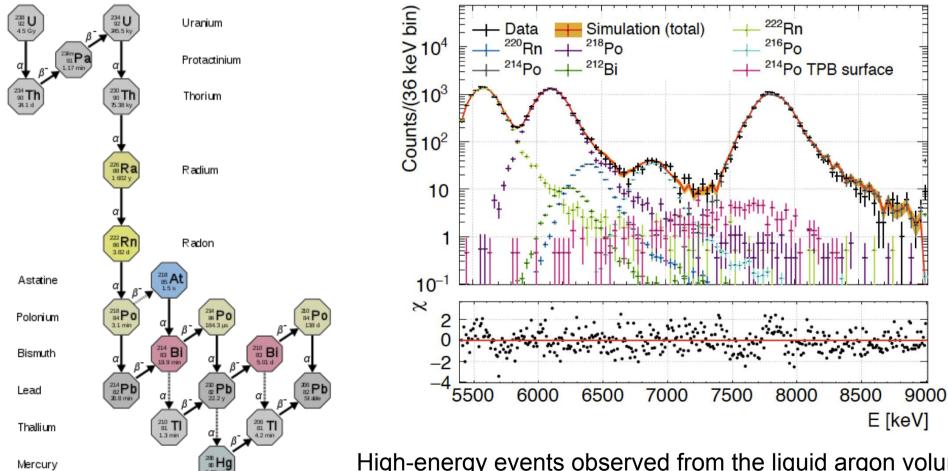


#### Alphas decays in liquid argon bulk

Signal-like events can be produced by radioactive decays in the liquid argon

These events deposit **much more energy** than dark matter interactions (50-100 keV)

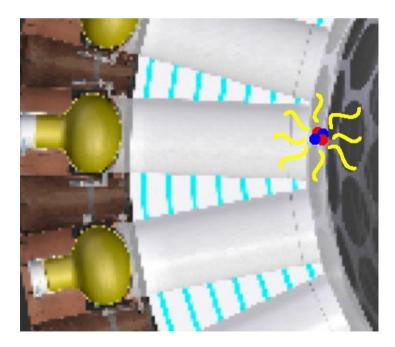
 $\rightarrow\,$  Much more light detected  $\,\rightarrow\,$  No impact on the dark matter search



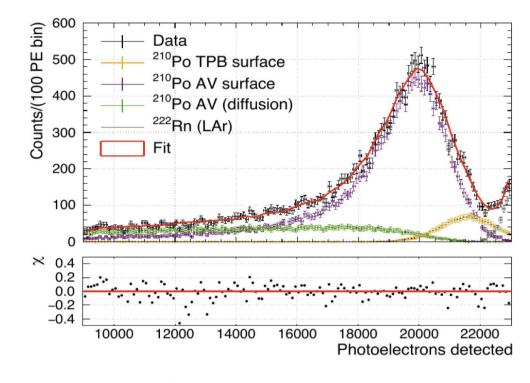
High-energy events observed from the liquid argon volume are well-explained by our background model

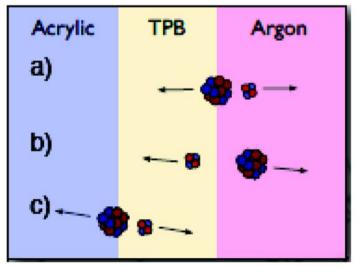
## Surface alpha backgrounds

- Alpha particles emitted from surface impurities cause nuclear recoils
  - Mitigation:
    - Strict radon control
    - Resurfacing
    - Position reconstruction



Surface events send a high fraction of the light towards a single PMT



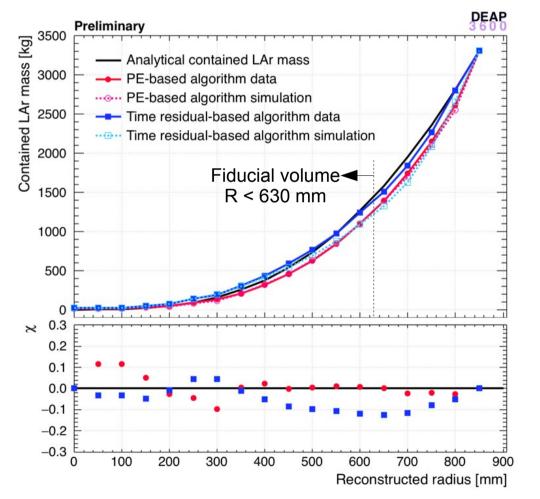


Possible surface event topologies

## Position reconstruction: Against surface alphas

Two main algorithms for position reconstruction

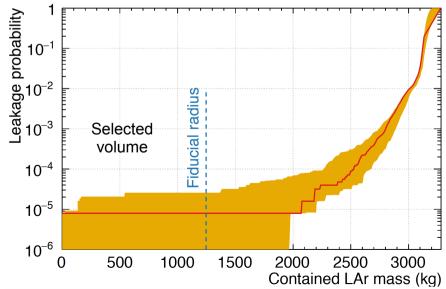
- "PE-based": more PE are detected closer to the event (use full 10 µs event window)
- "Time-based": **PE are detected earlier** closer to the event (use first 40 ns of event)



Data-driven measure of resolution:

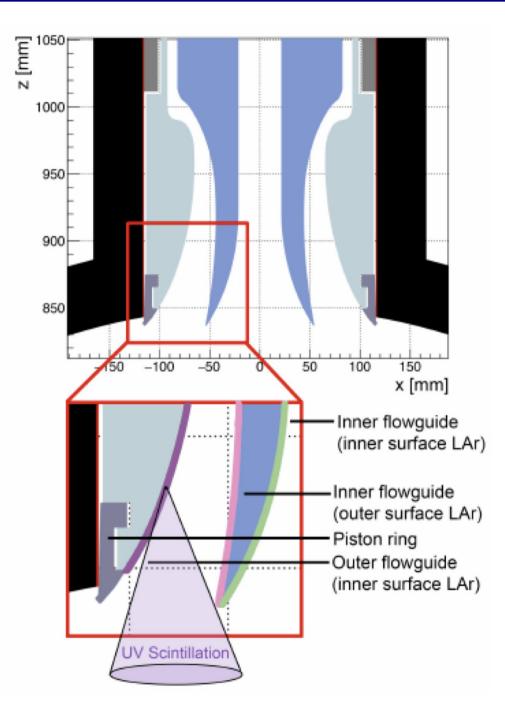
**30-45 mm** at fiducial volume boundary for low-energy events (better at high-energy)

#### Very low surface alpha leakage



JINST 15, 05, C05061 (2020) arXiv:2004.02058

## Shadowed alpha backgrounds from the neck



Alpha decays in the detector bulk typically release many more photons than dark matter nuclear recoils.

Alpha decays in the detector neck can result in shadowing of scintillation light, such that only a small fraction of photons are detected by the PMTs.

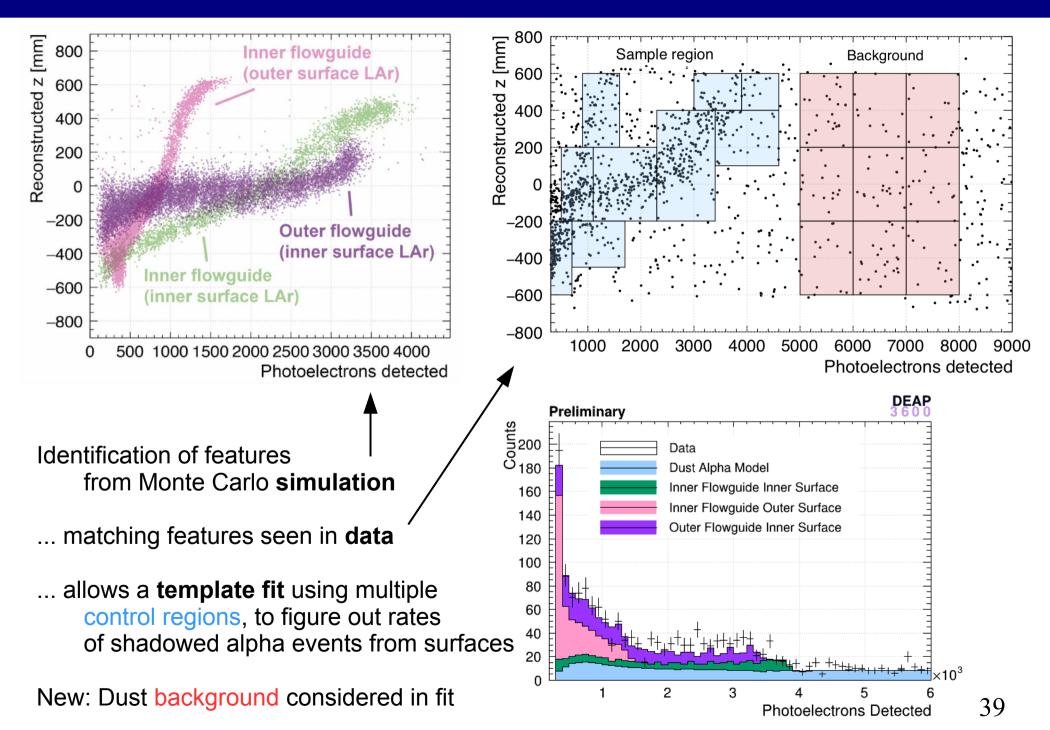
Low number of photons  $\rightarrow$  Signal-like!

This results in a particularly **challenging** source of background events

Colour code (this slide and next):

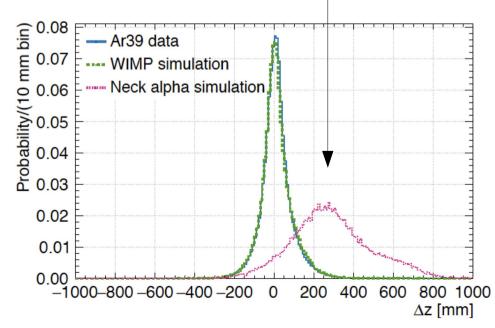
Outer flowguide, inner surface LAr Inner flowguide, outer surface LAr Inner flowguide, inner surface LAr

# Shadowed alpha backgrounds: Event rate determination

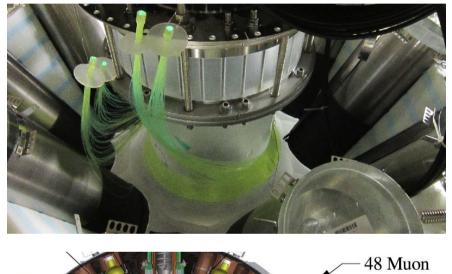


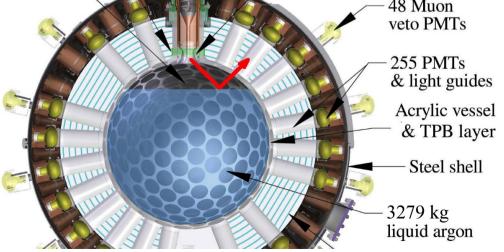
# Known handles against shadowed alpha backgrounds

- Developed a dedicated event selection, to reject background events
- In contrast to signal, shadowed alphas from the neck more frequently have:
  - light in the neck veto fibres -
  - excess light in the top rows of PMTs
  - *early* light in the top rows of PMTs
  - PE-based position reconstruction disagrees with time-based method



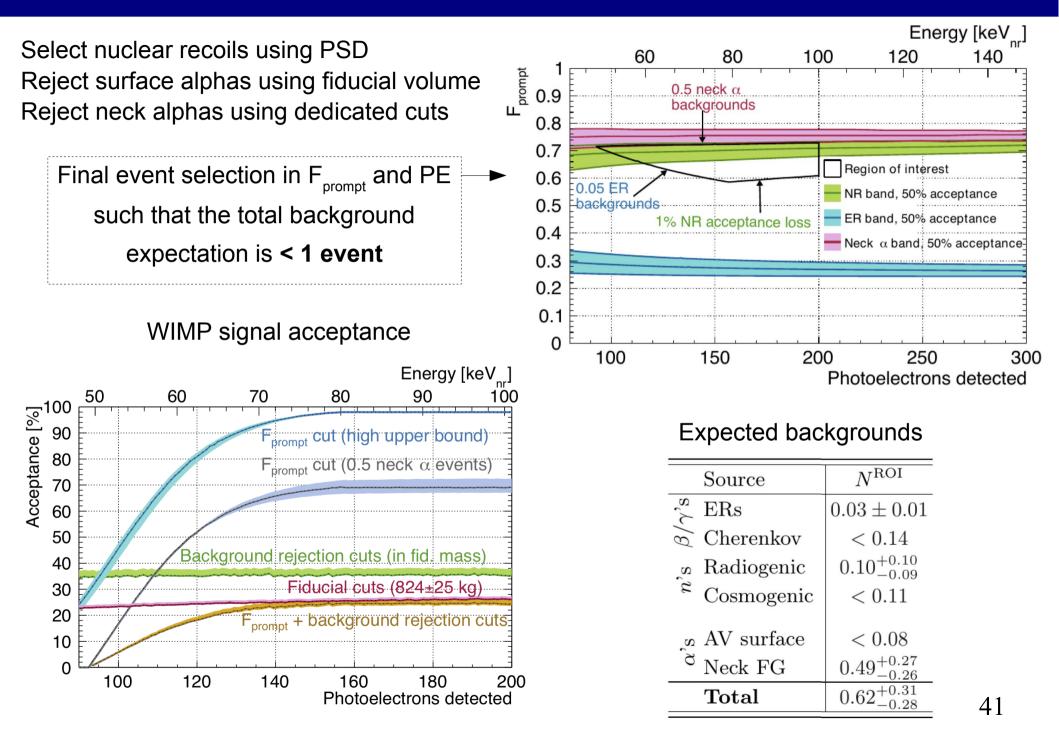
Time-based vs. PE-based reconstructed vertical position





UV photon reflection at the liquid argon surface 40

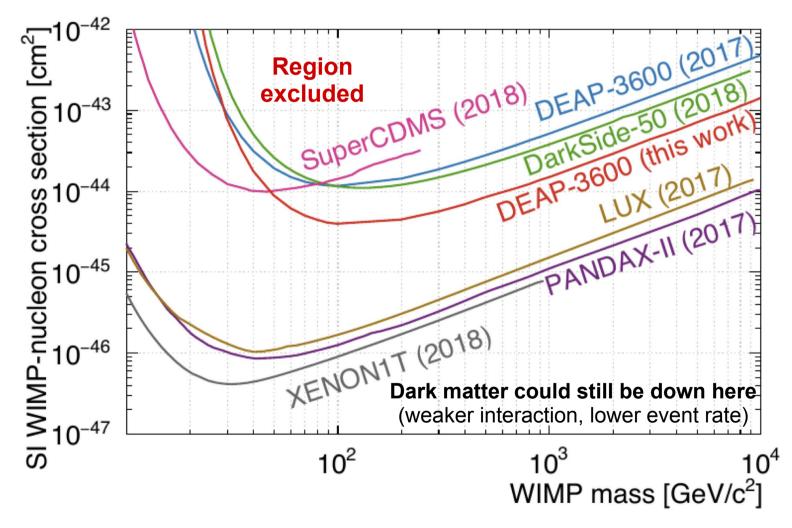
# Signal region definition in the first-year WIMP search



#### First-year WIMP dark matter search results

The detector is sensitive to dark matter, but no signal event was observed in our first-year dataset (November 2016 – October 2017)

Therefore we **exclude** certain dark matter hypotheses



Physical Review D, 100, 022004 (2019) arXiv:1902.04048