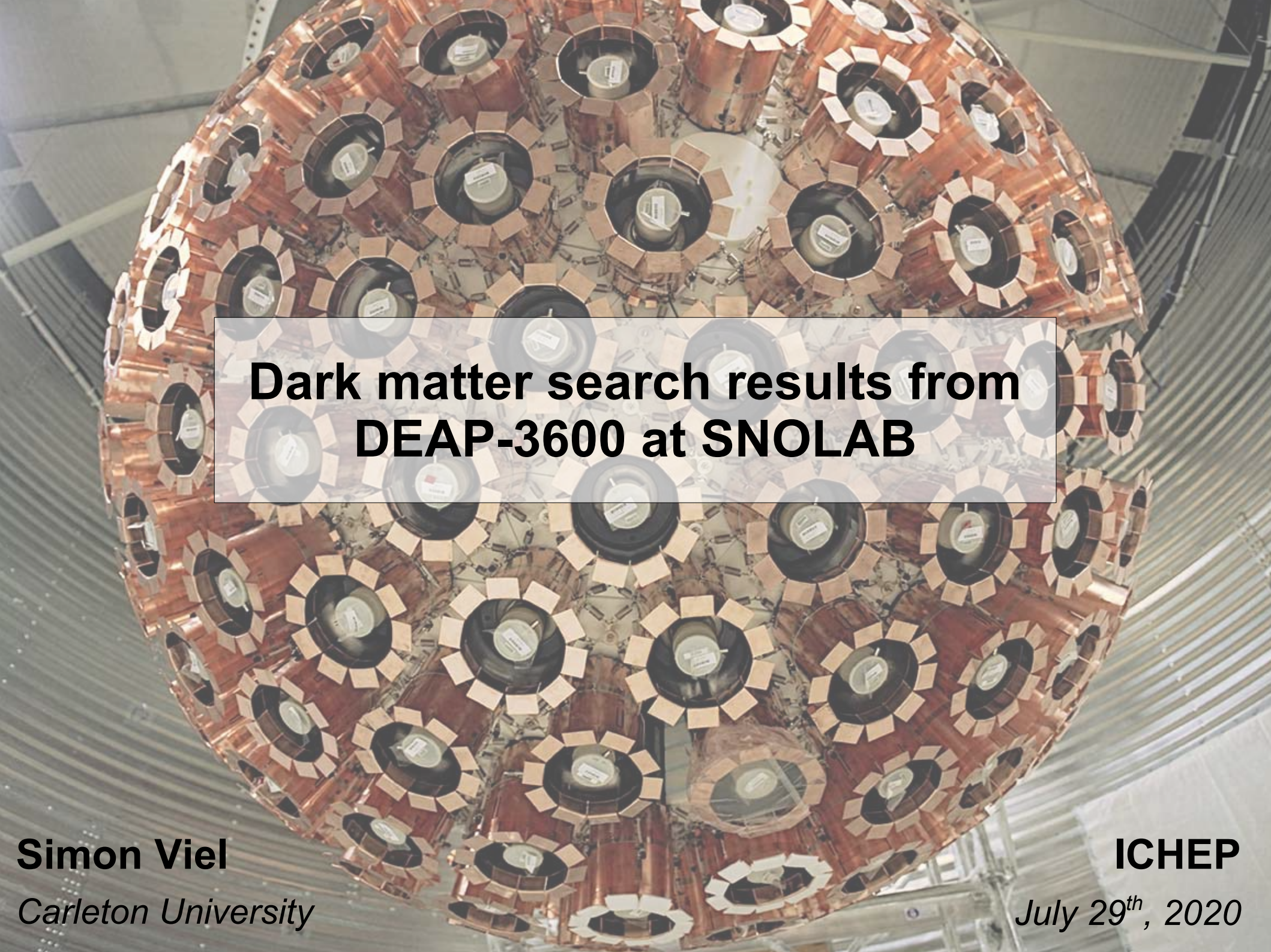


Dark matter search results from DEAP-3600 at SNOLAB

Simon Viel

Carleton University

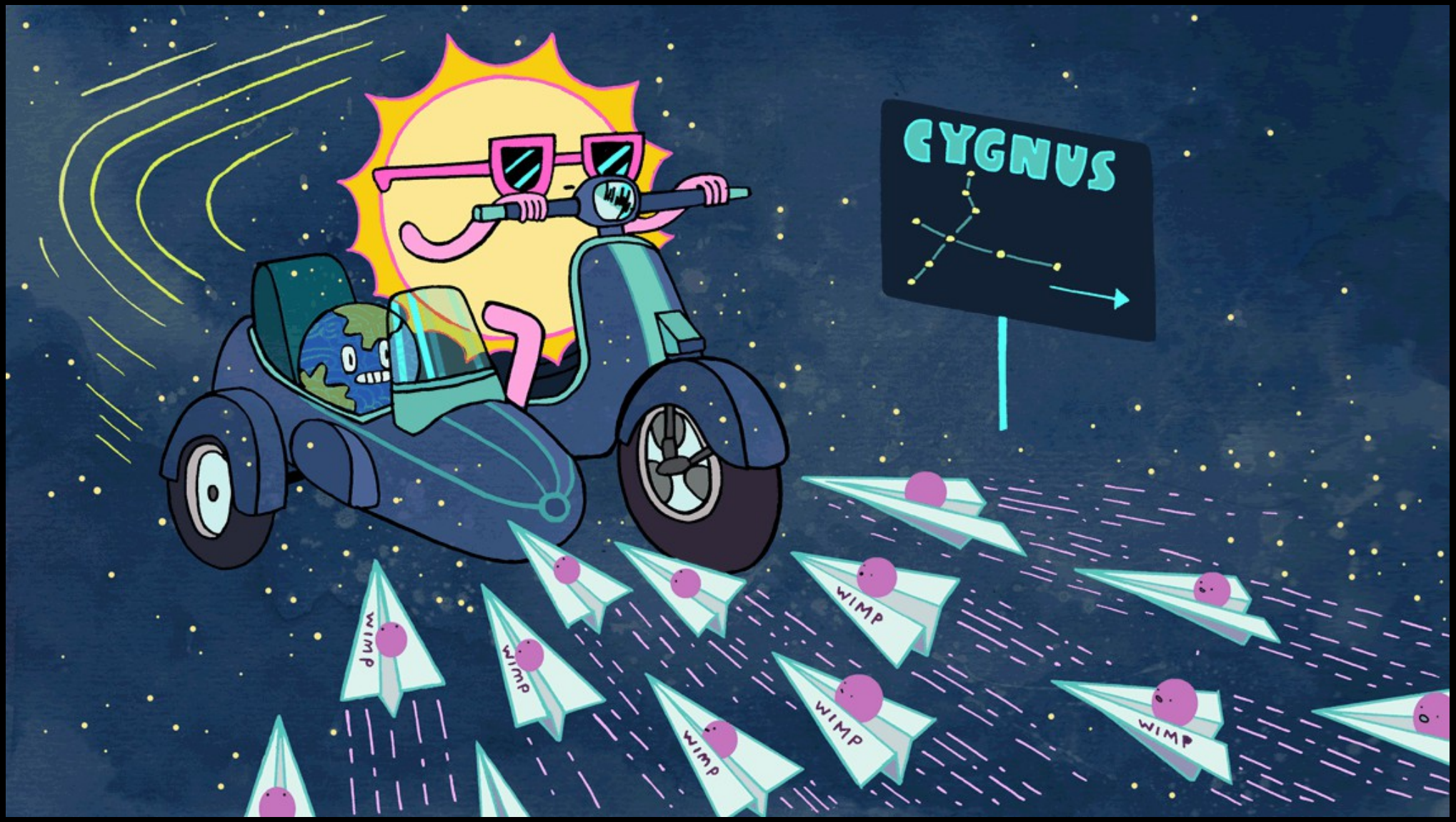
ICHEP

July 29th, 2020

DEAP Collaboration:

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

University of Alberta
AstroCeNT Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences
Canadian Nuclear Laboratories / Laboratoires Nucléaires Canadiens
Carleton University
Ciemat
Laurentian University / Université Laurentienne
Instituto de Física
INFN Istituto Nazionale di Fisica Nucleare
National Research Center "Kurchatov Institute"
Princeton University
Queen's University
Royal Holloway University of London
St. Petersburg Nuclear Physics Institute
SNOLAB
University of Sussex
Technical University of Munich
TRIUMF
Particle Physics Rutherford Appleton Laboratory



Riding in the Dark Matter Wind

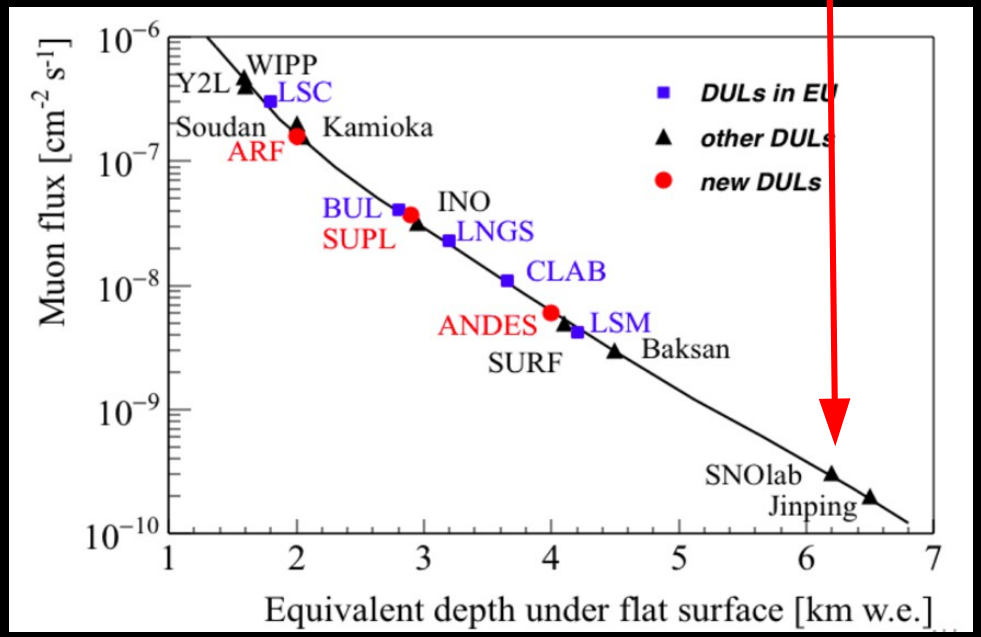
Source: Symmetry Magazine – Artwork by Sandbox Studio, Chicago with Corinne Mucha

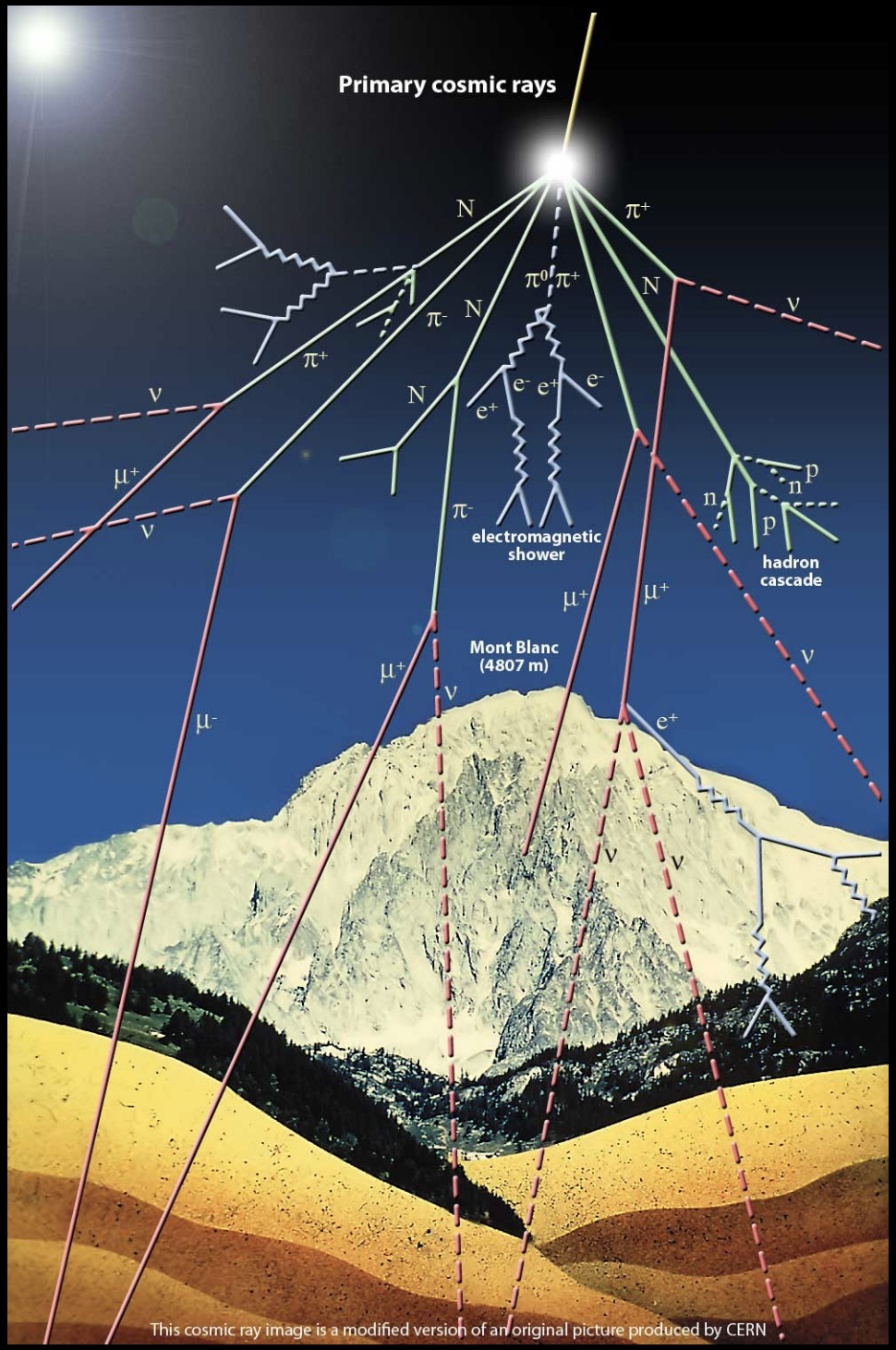
Why go underground?

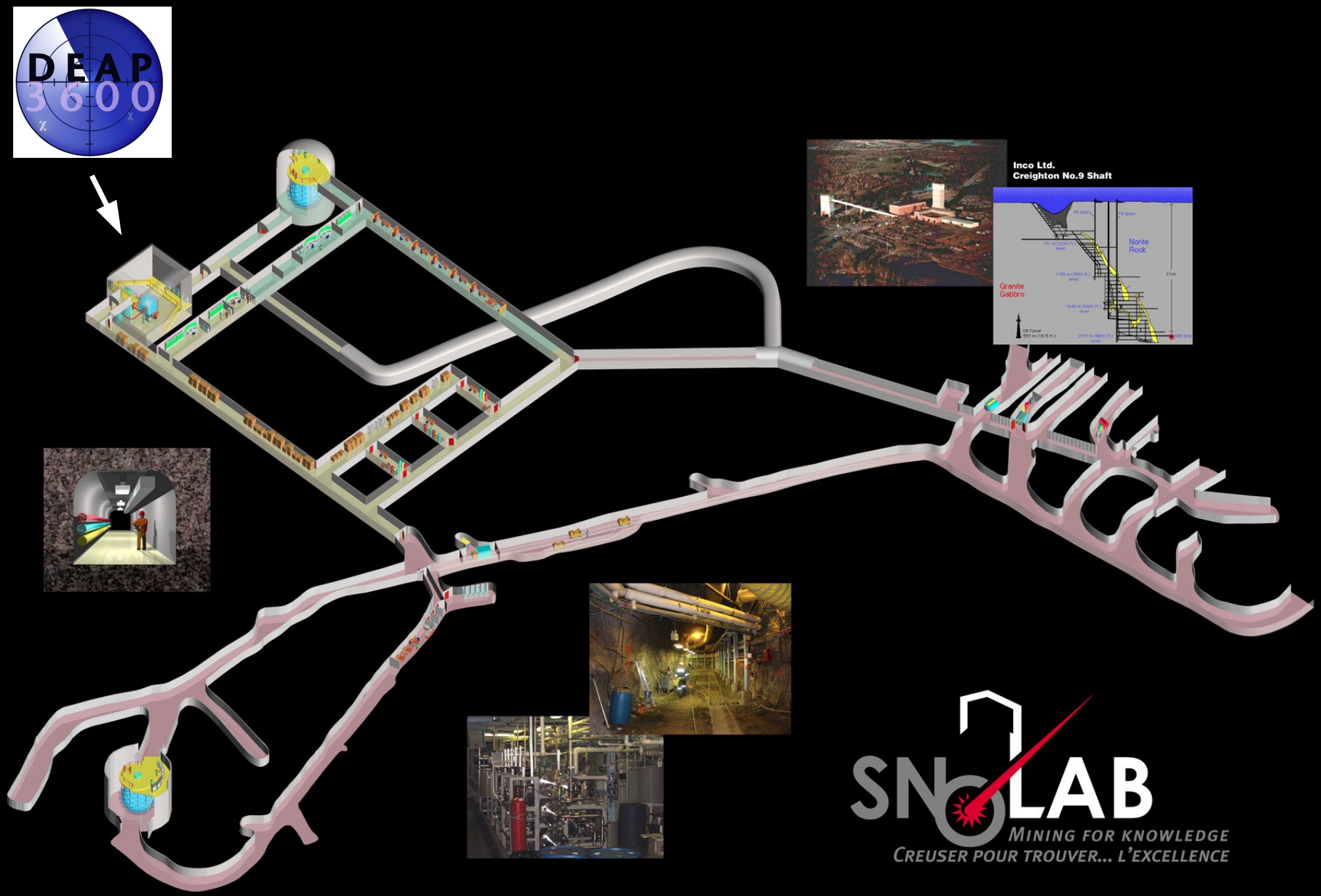
To shield detectors against cosmic rays

- Surface:
  ~ 1 muon / cm^2 / minute
  ~ 14.4 million muons / m^2 / day

SNOLAB:
0.27 muons / m^2 / day





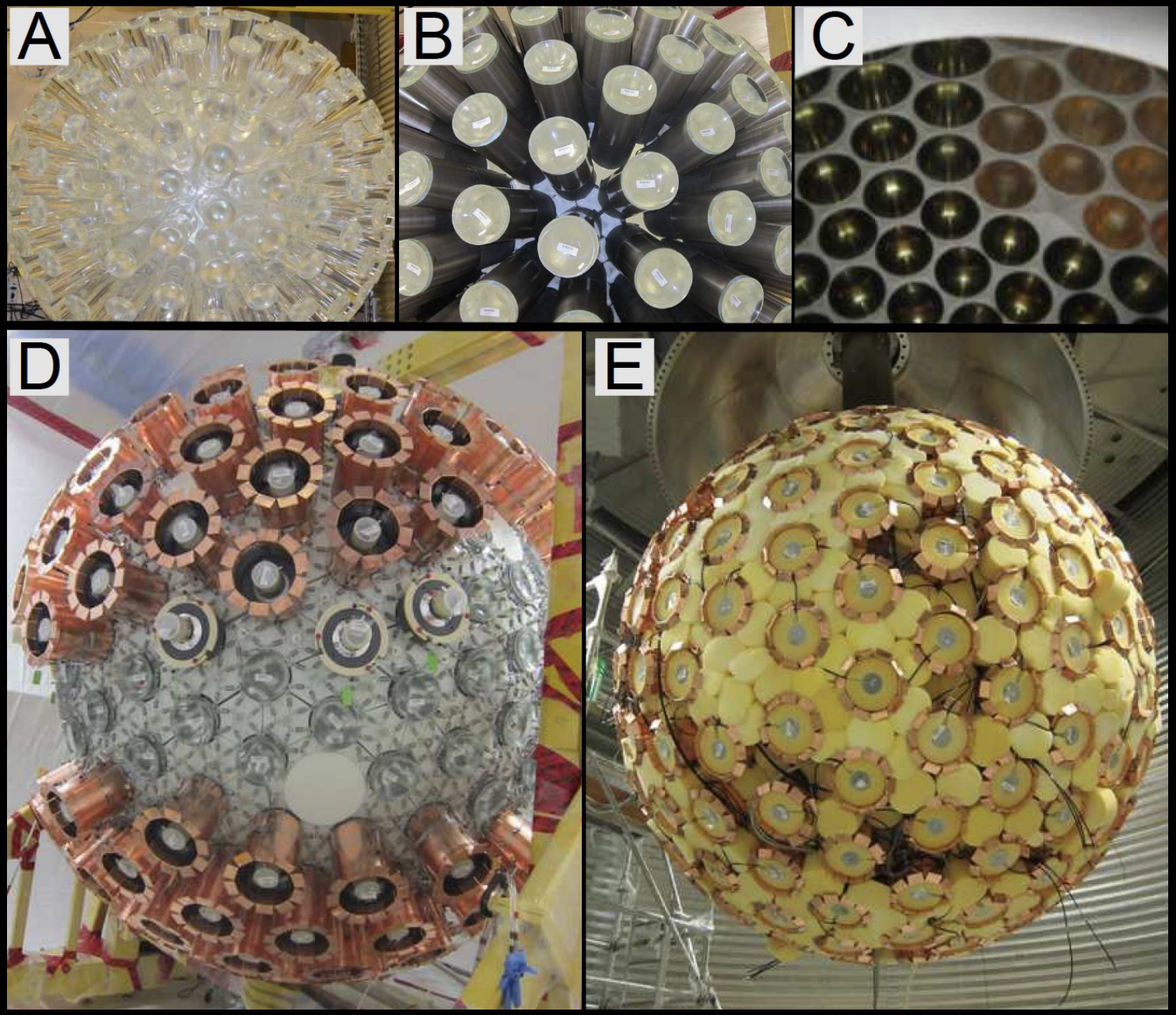


Video: A Day at SNOLAB
https://www.snolab.ca/outreach

2070 m underground

Acrylic vessel underground at SNOLAB

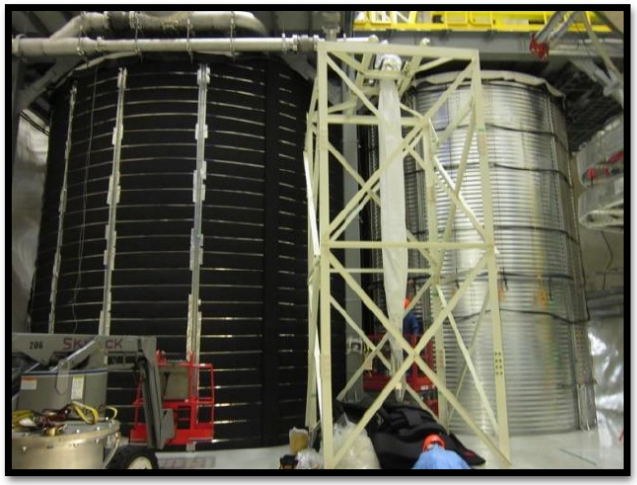
Light guides Reflectors Inside view

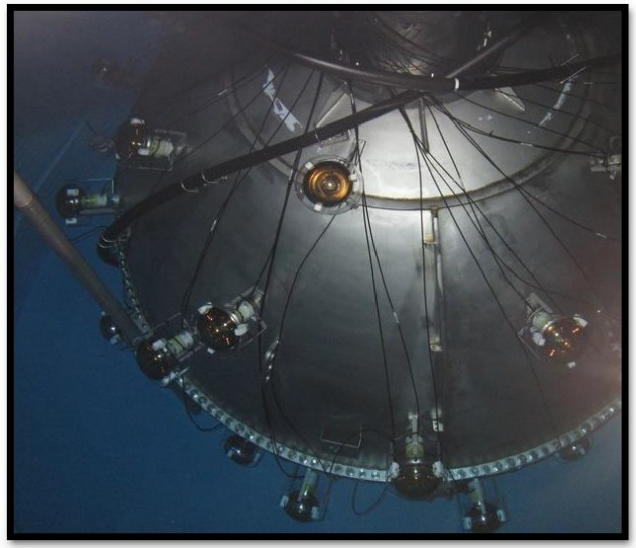


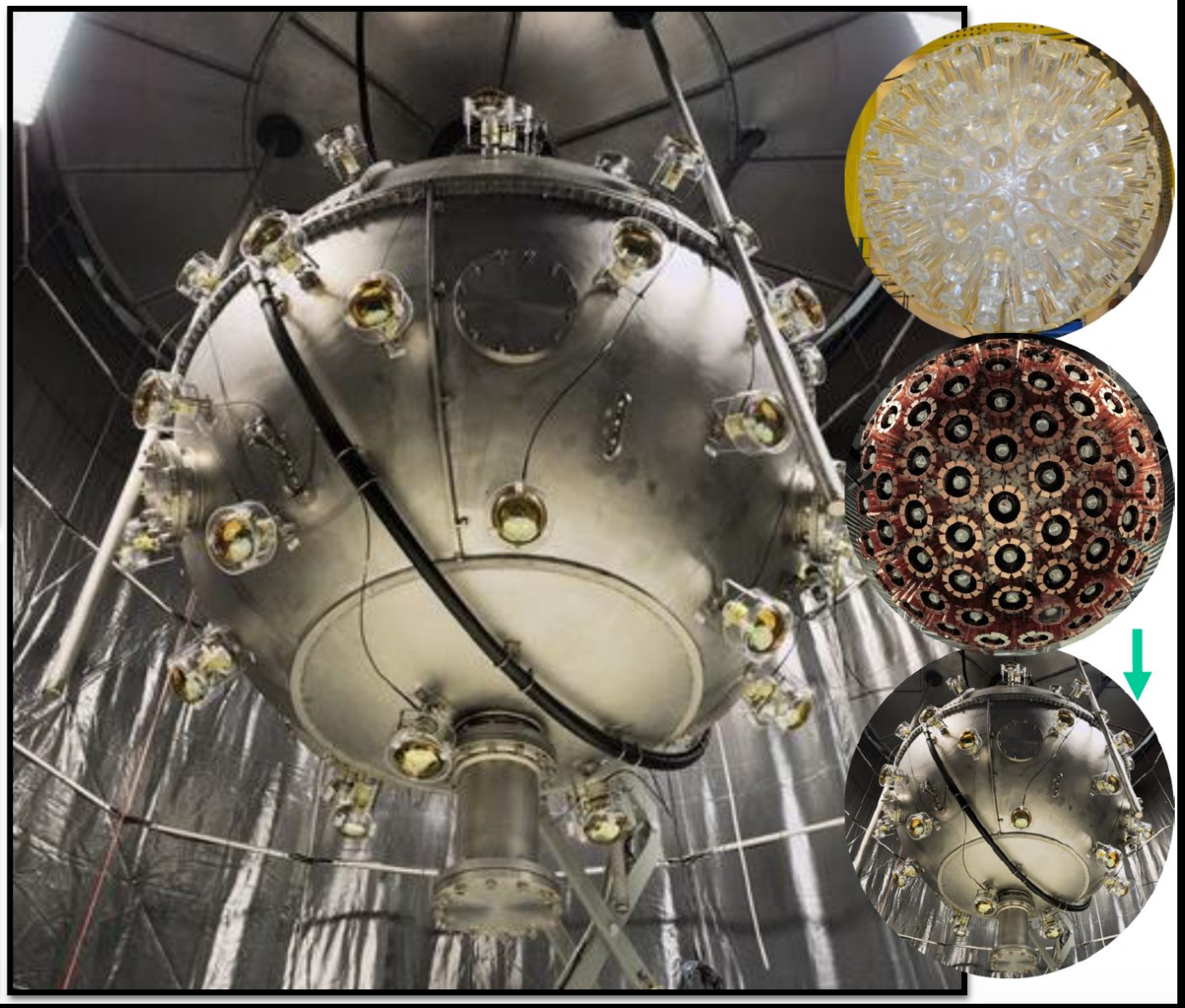
PMT installation Backing foam installation

Steel shell, Veto PMTs

Water tanks in Cube Hall



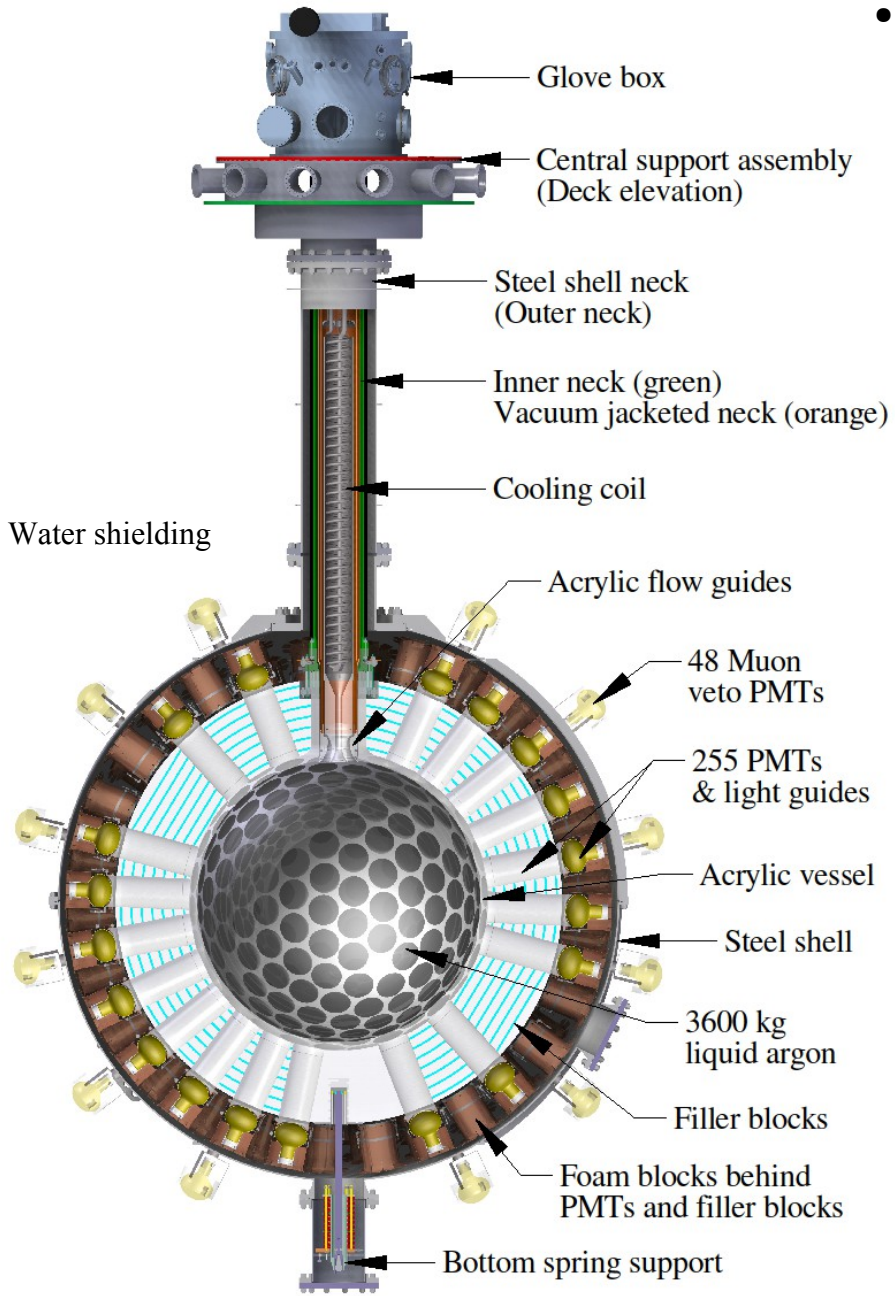




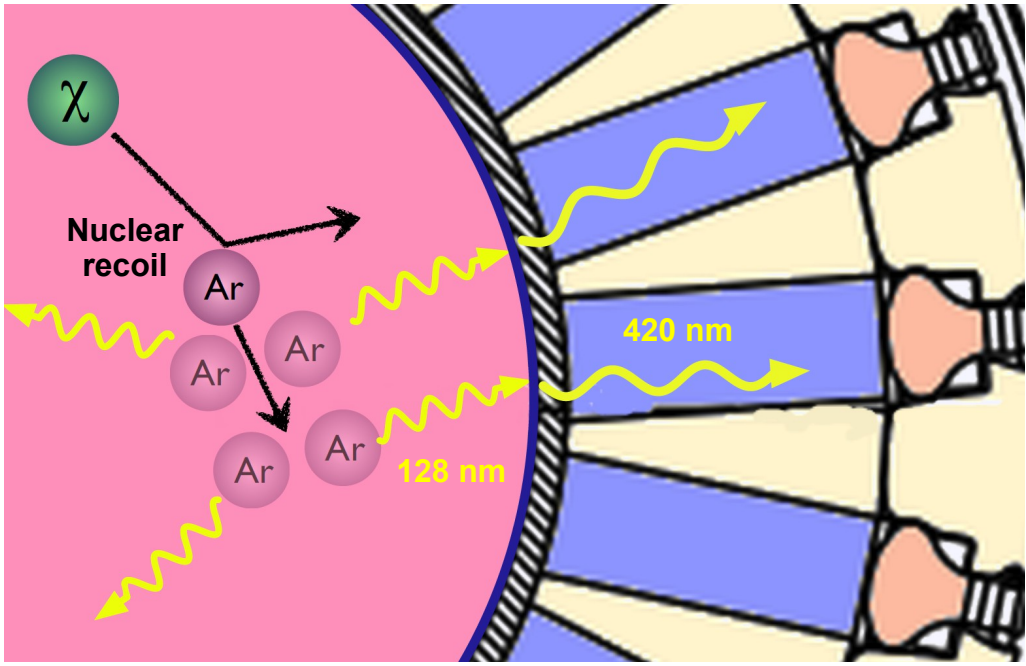
All details available in the DEAP-3600 detector publication!

Astroparticle Physics 108, 1-23 (2019) arXiv:1712.01982

DEAP-3600

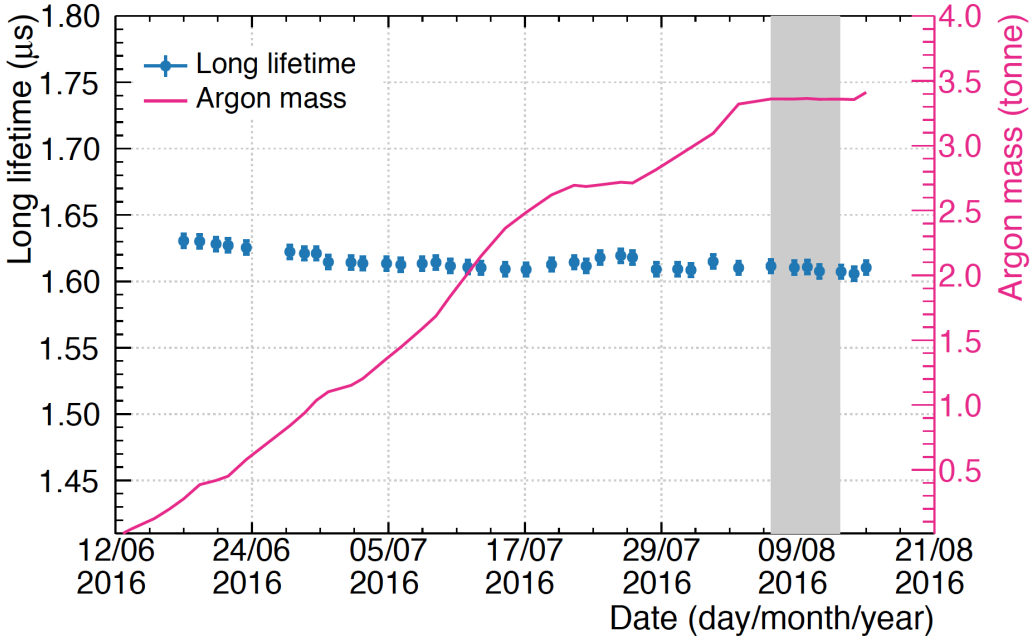


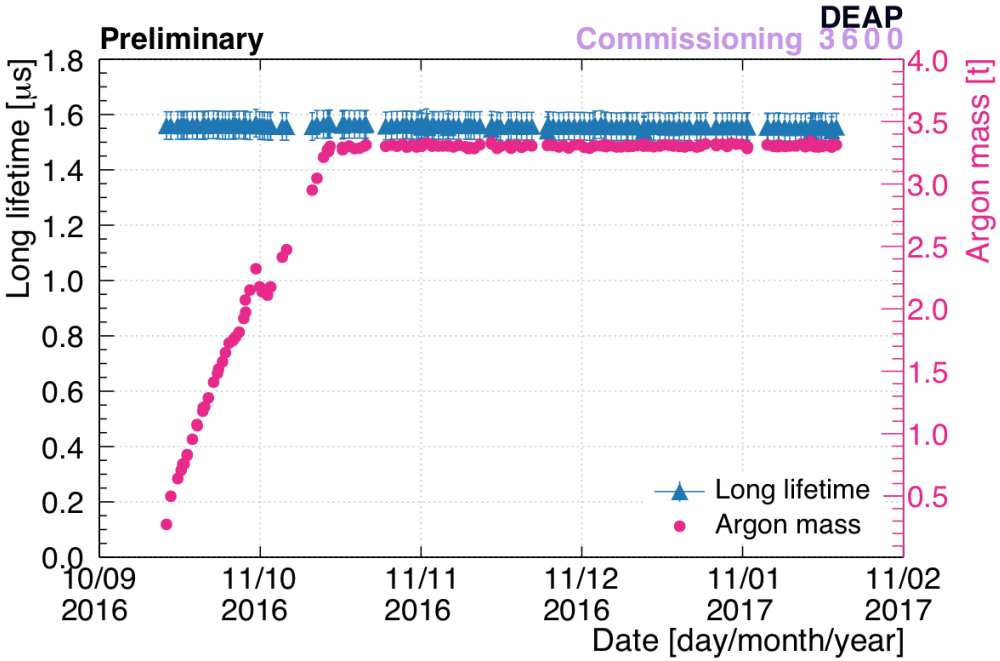
- **D**ark matter **E**xperiment using **A**rgon **P**ulse-shape discrimination
  - Design mass: 3600 kg of liquid argon (LAr)
    - Largest acrylic cryostat ever built
  - Goal: Detect dark matter particles colliding with argon nuclei



- **UV scintillation light** from LAr nuclear recoils is wavelength-shifted to visible at TPB layer, then collected by photomultiplier tubes (PMT)

DEAP-3600: Datasets





First fill dataset
August 2016

3322 kg LAr
4.4 live-days passing data quality

Phys. Rev. Lett. 121, 071801 (2018)
arXiv:1707.08042

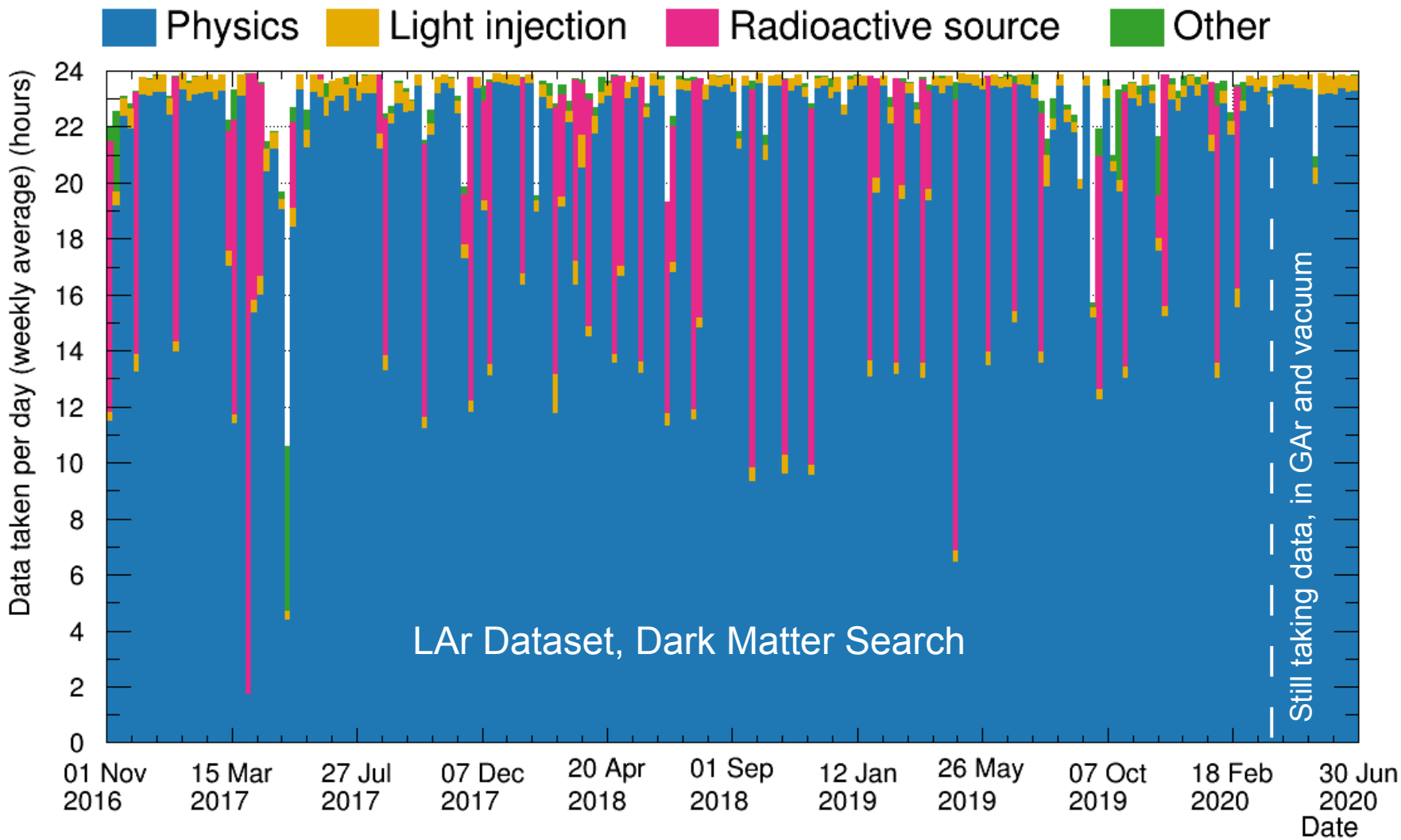
Second fill: **First year dataset**
November 2016 – October 2017

3279 kg LAr
231 live-days passing data quality

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

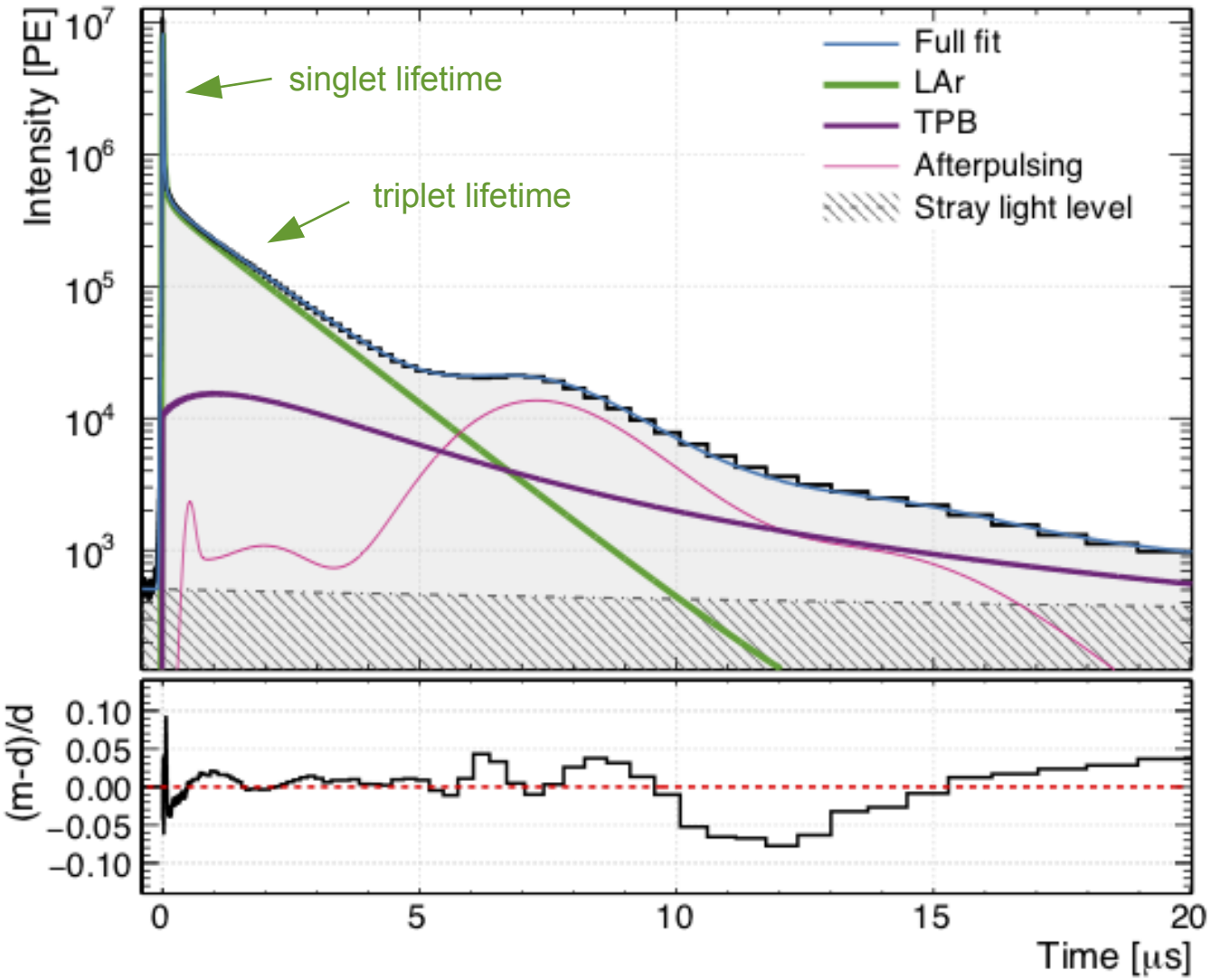
- Stable data collection for DM search: November 1st, 2016 – March 28th, 2020
  - 80% blind since January 1st, 2018

DEAP-3600: Datasets



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

Liquid Argon Scintillation Pulse-Shape in DEAP-3600



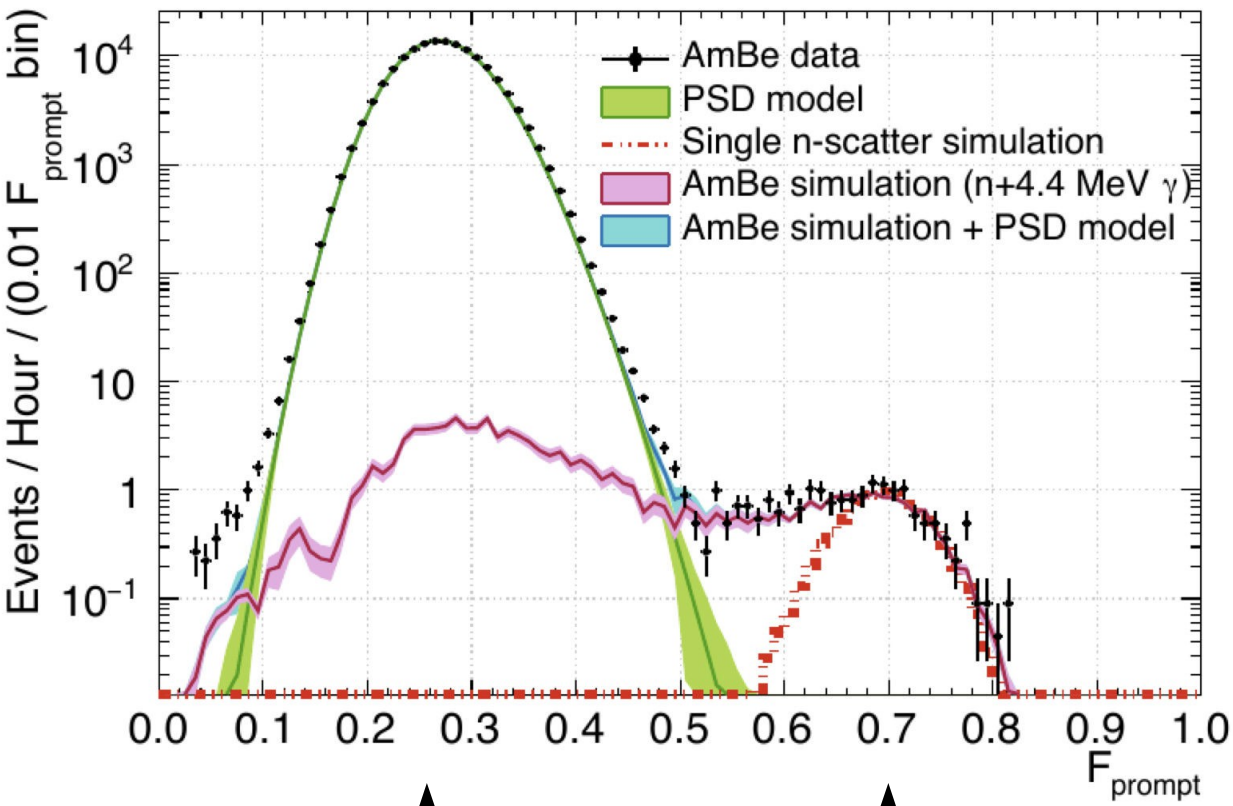
Visible photons → Photoelectrons at PMT cathode → PMT pulses

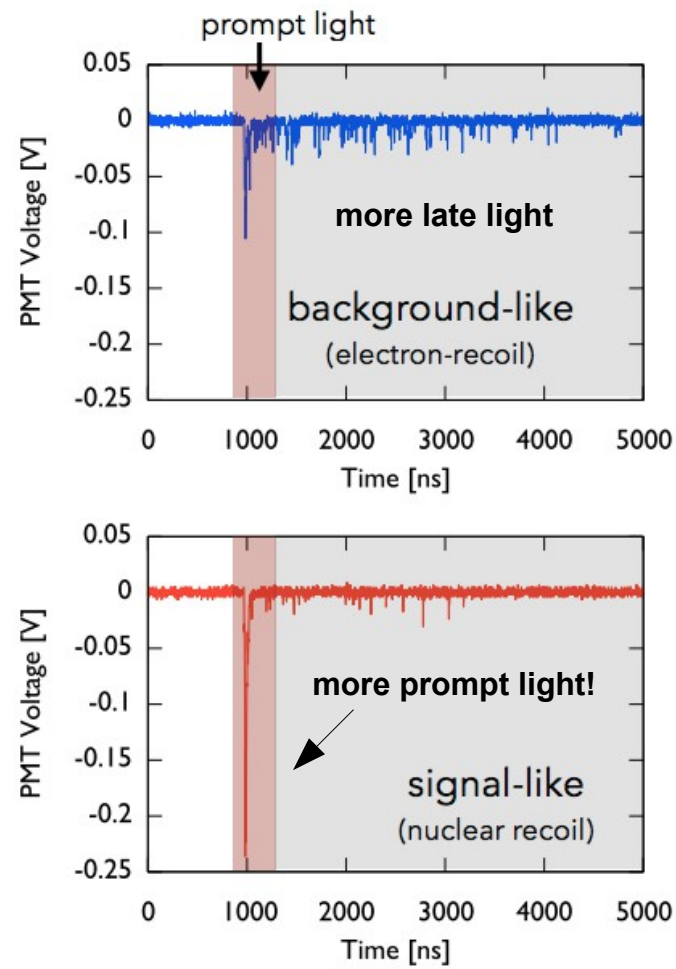
Full pulse-shape model: European Physics Journal C, 80, 303 (2020) arXiv:2001.09855

Pulse-Shape Discrimination (PSD)

The goal is to **select dark matter signal events**, and <u>reject background events</u>

Example: Neutron source calibration data





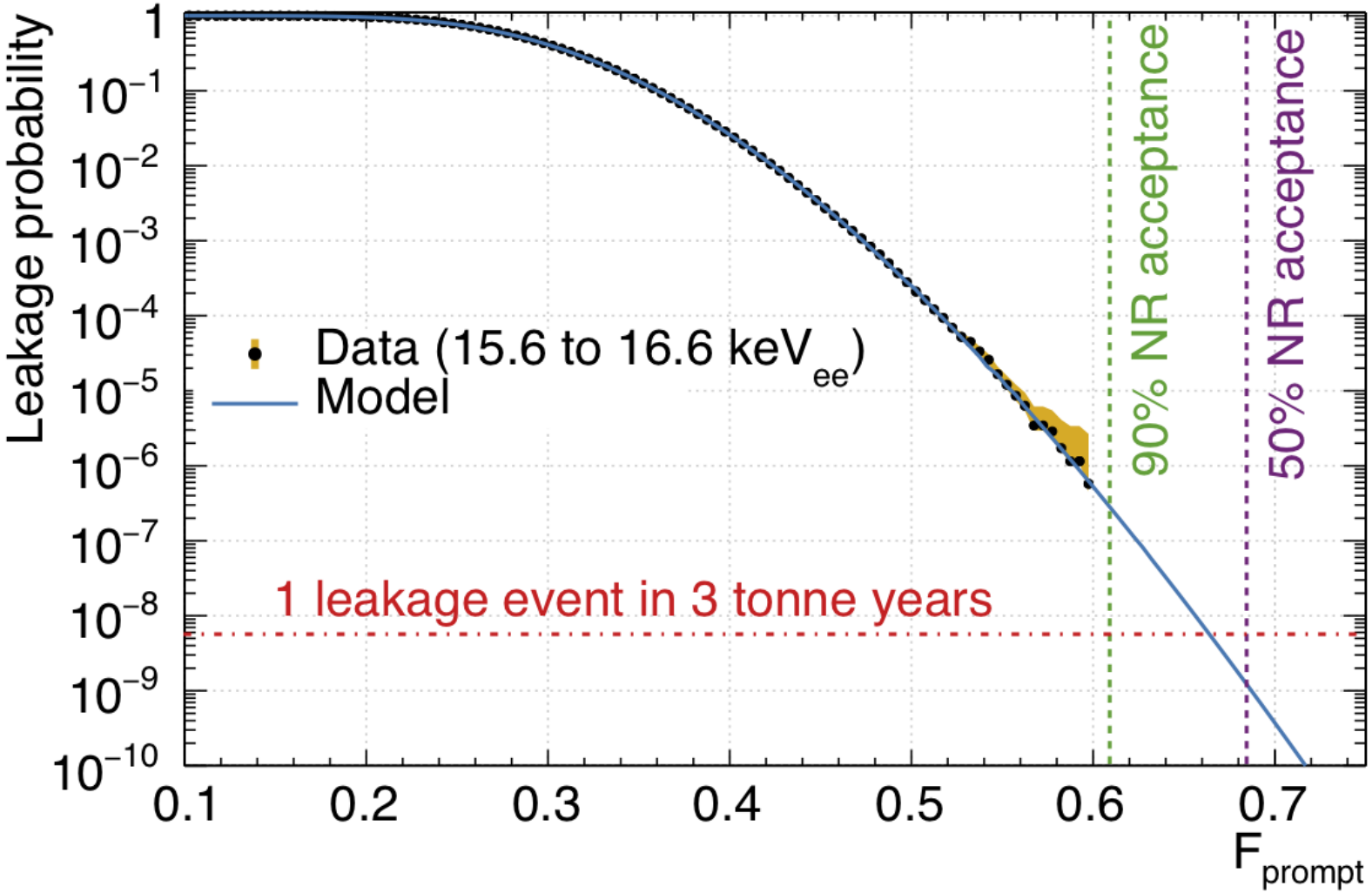
Background-like
(electron recoils, ^{39}Ar)

Signal-like
(nuclear recoils)

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

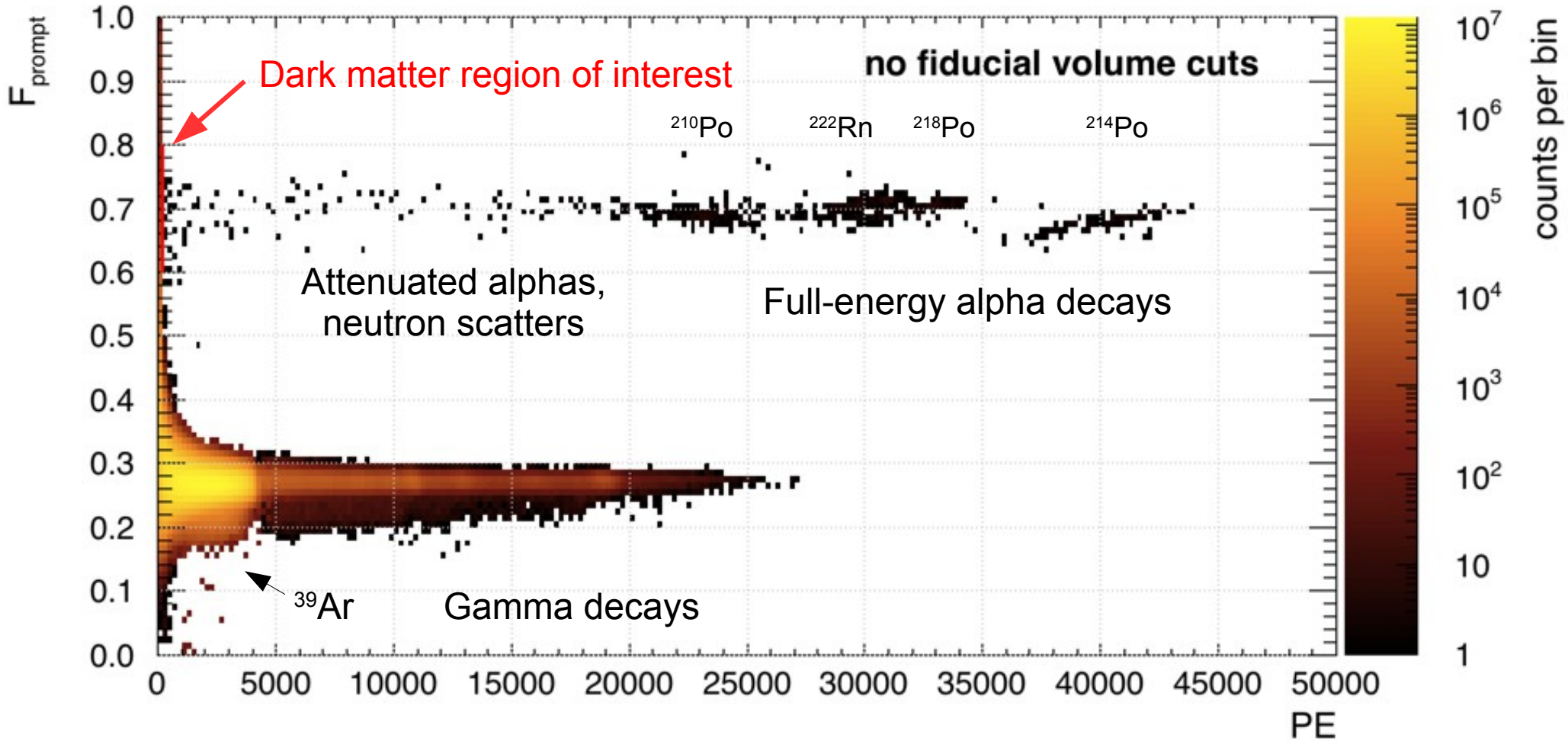
Pulse-Shape Discrimination (PSD)

World-leading PSD performance!



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

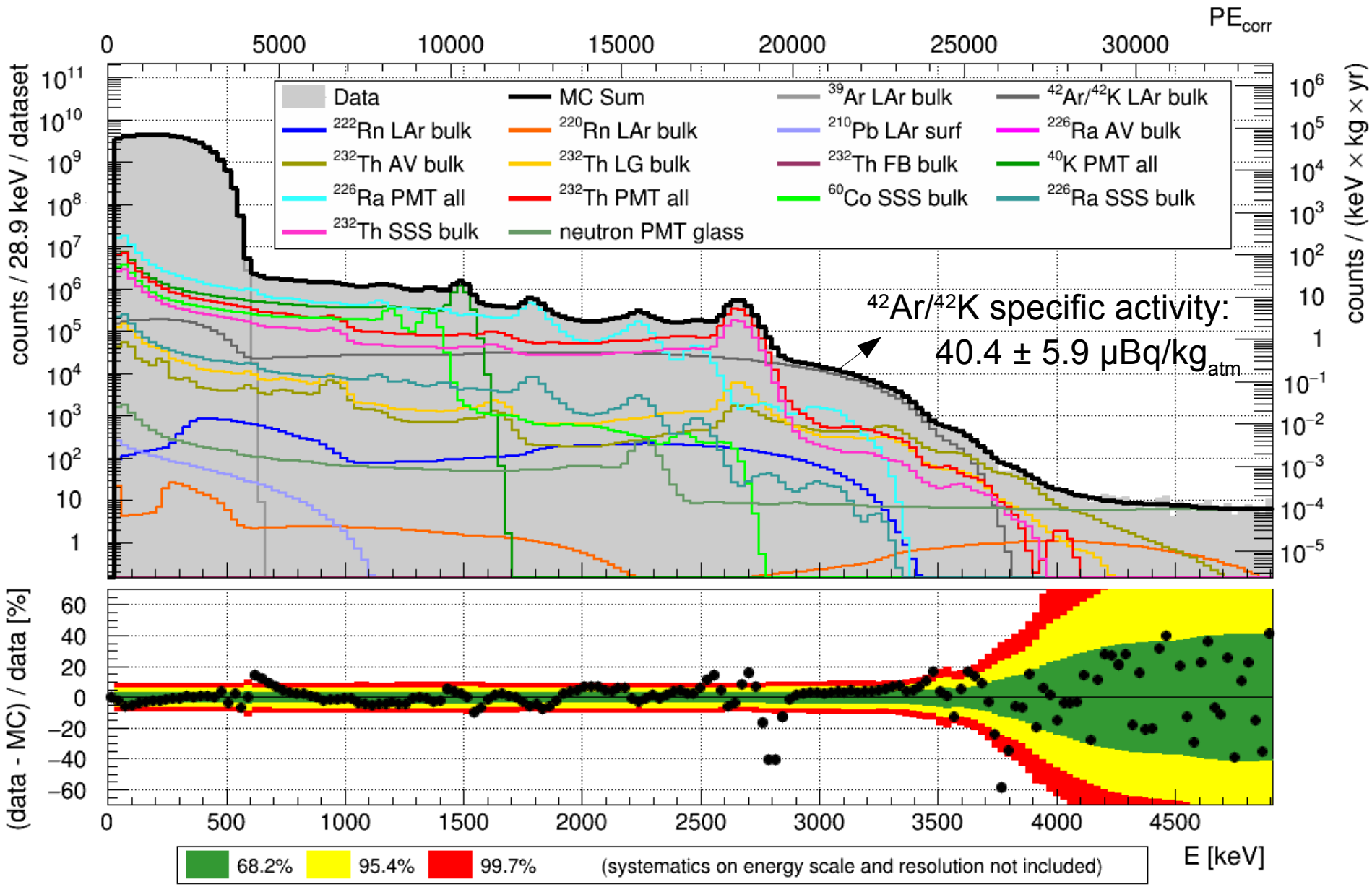
DEAP-3600: Early Physics Data



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

Phys. Rev. Lett. 121, 071801 (2018) arXiv:1707.08042

Electromagnetic Backgrounds in First-Year Dataset



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

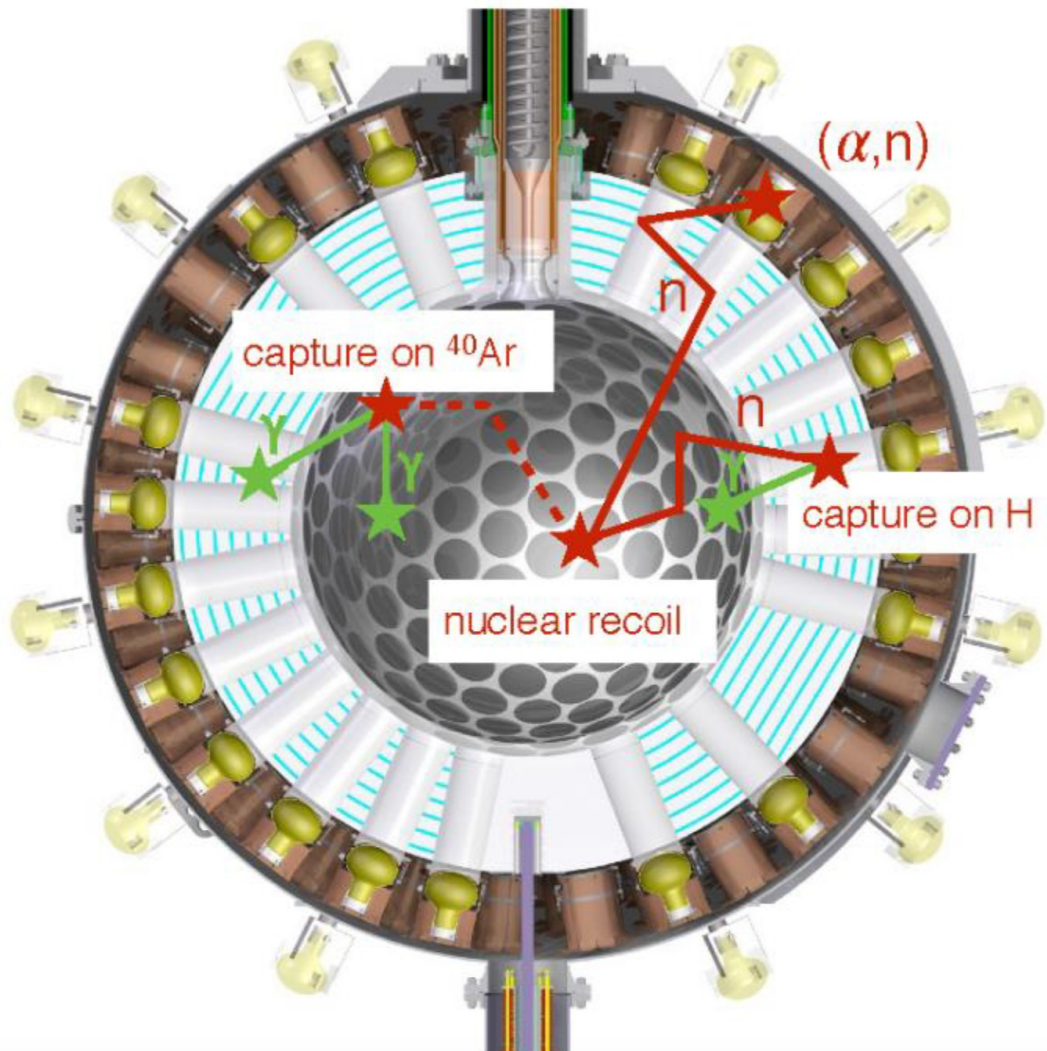
Neutron Backgrounds

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

→ 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



Bulk and Surface Alpha Backgrounds

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

Alphas in **LAr bulk**: Much more energy deposited than in dark matter interactions (50-100 keV)

→ Much more light detected

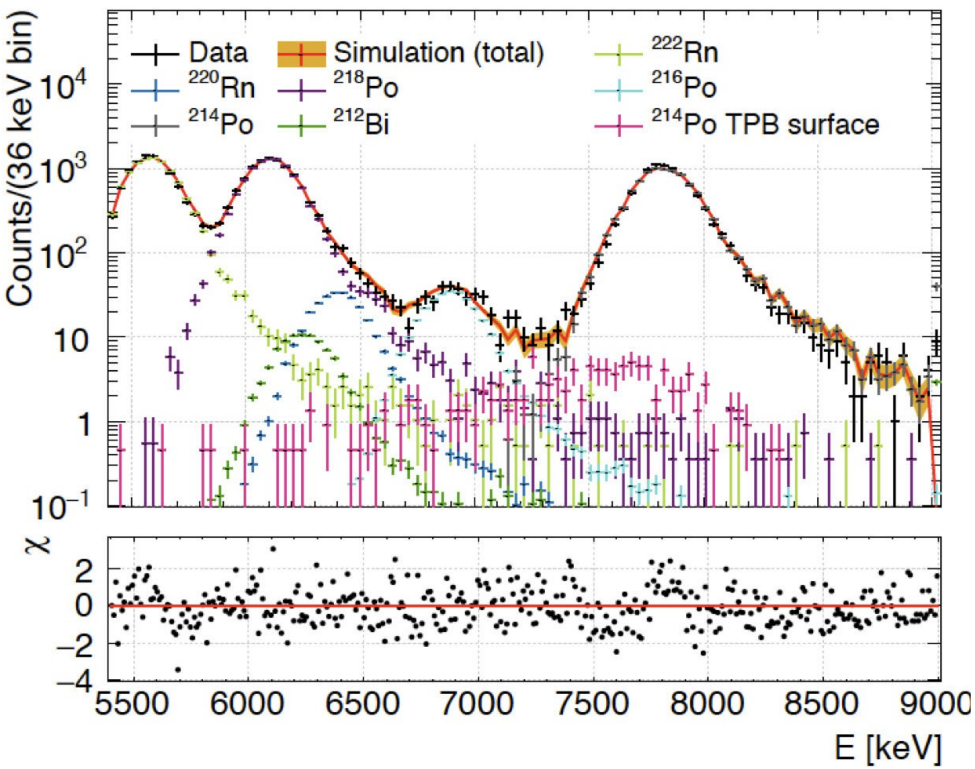
→ **No impact** on the dark matter search

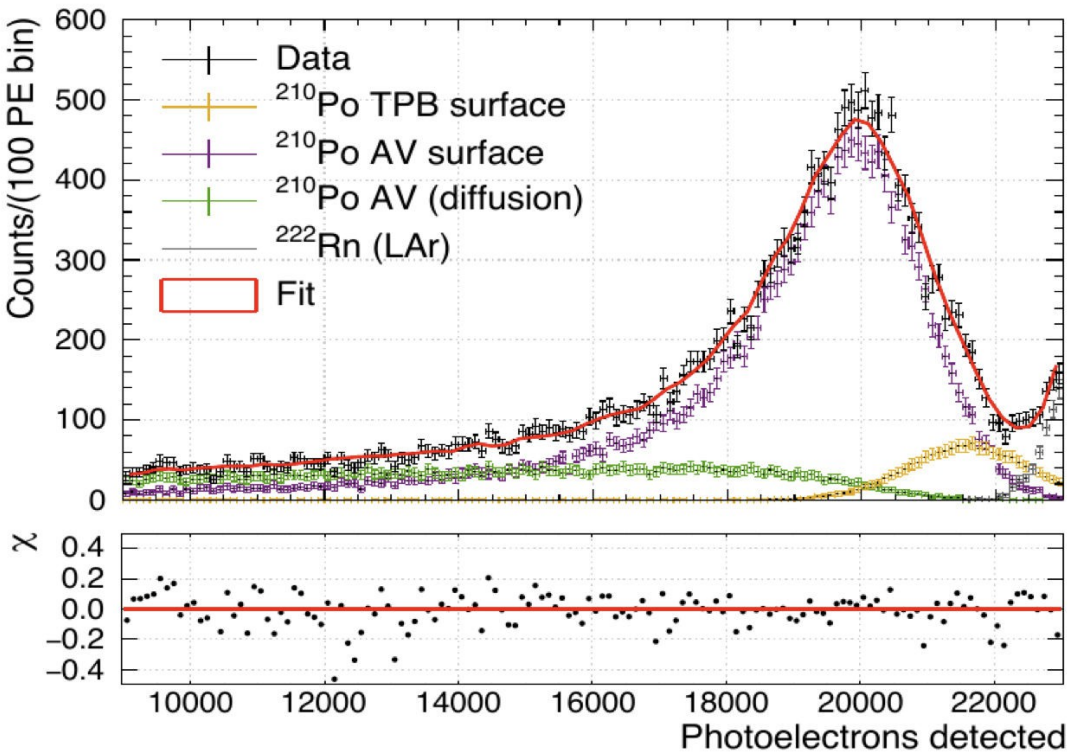
Alphas from **acrylic vessel surface** may be attenuated

→ Some reconstruct at intermediate energy

→ Rejected with position reconstruction

→ Select **fiducial volume** for dark matter search



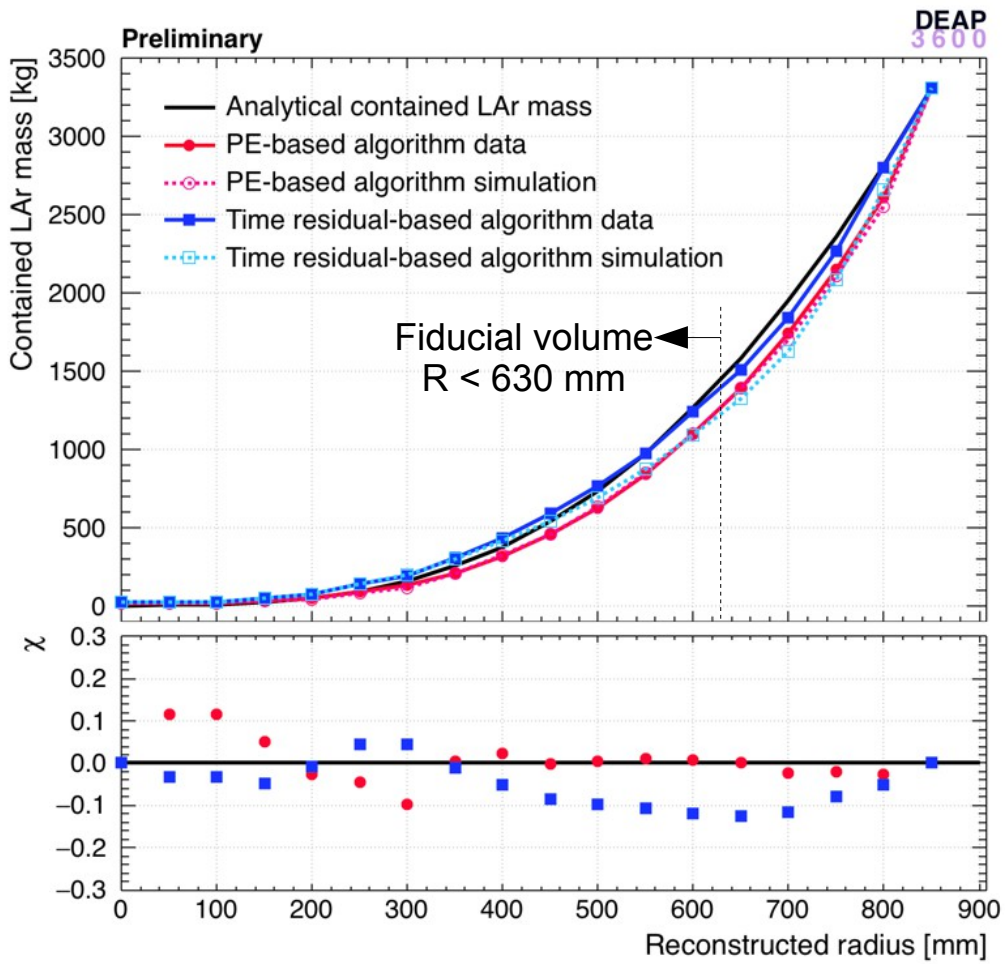


High-energy alpha decays observed from the liquid argon volume are **well-described** by our background model, demonstrating extremely low levels of radon backgrounds

Position Reconstruction: Against Surface Alphas

Two main algorithms for position reconstruction

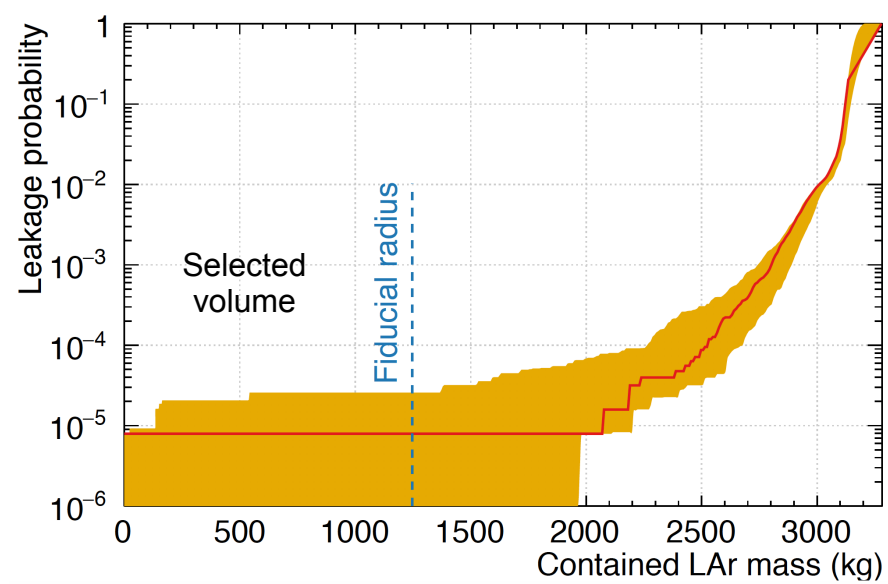
- "PE-based": **more PE are detected** closer to the event (use full 10 μs event window)
- "Time-based": **PE are detected earlier** closer to the event (use first 40 ns of event)



Data-driven measure of resolution:

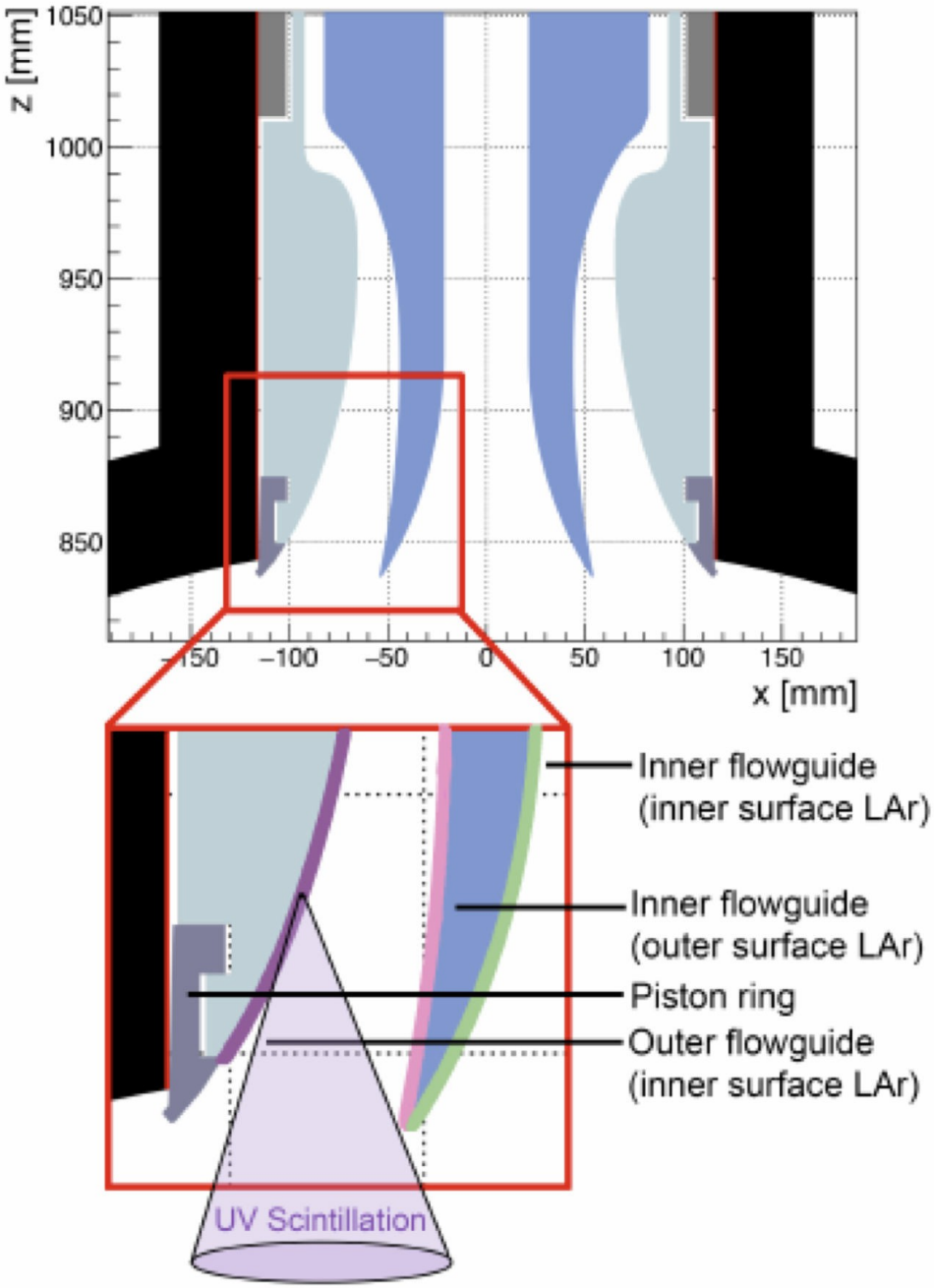
30-45 mm at fiducial volume boundary for low-energy events (better at high-energy)

Very low surface alpha leakage



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

Neck Alpha Backgrounds



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 → Signal-like!

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

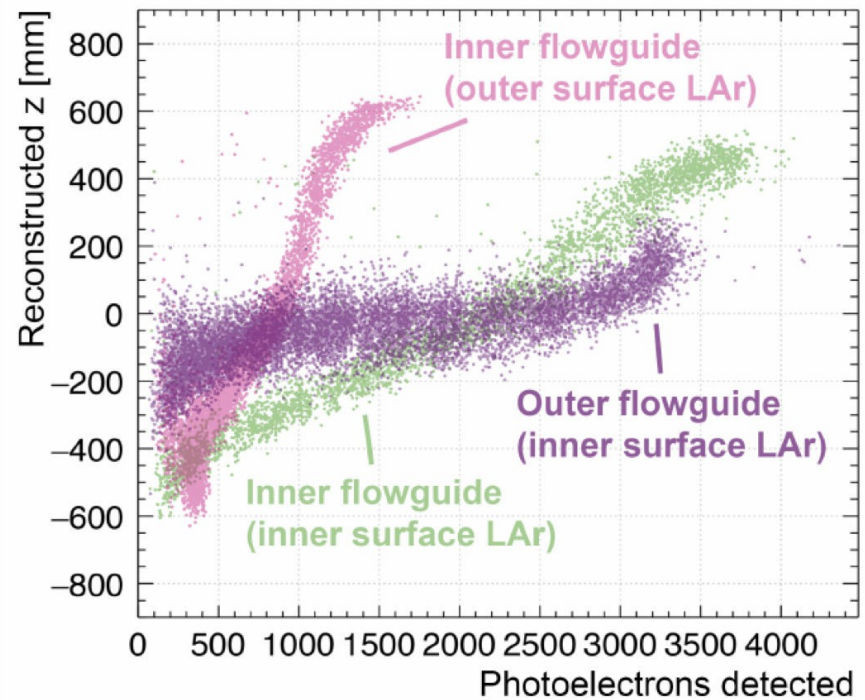
Colour code (this slide and next):

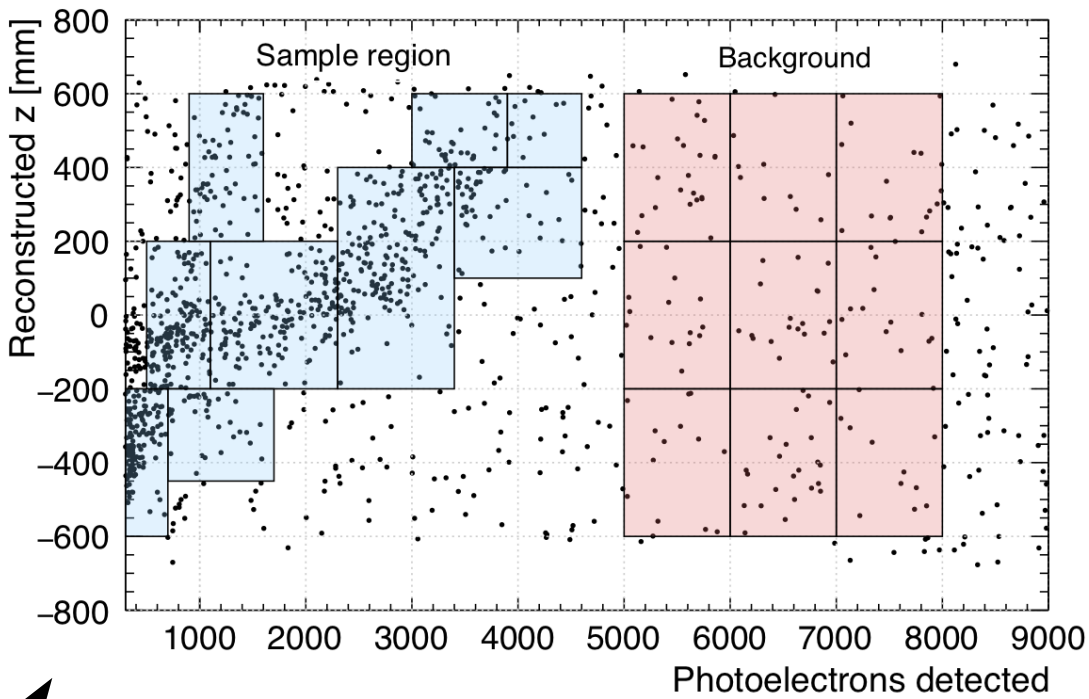
Outer flowguide, inner surface LAr

Inner flowguide, outer surface LAr

Inner flowguide, inner surface LAr

Neck Alpha Backgrounds: Event Rate Determination



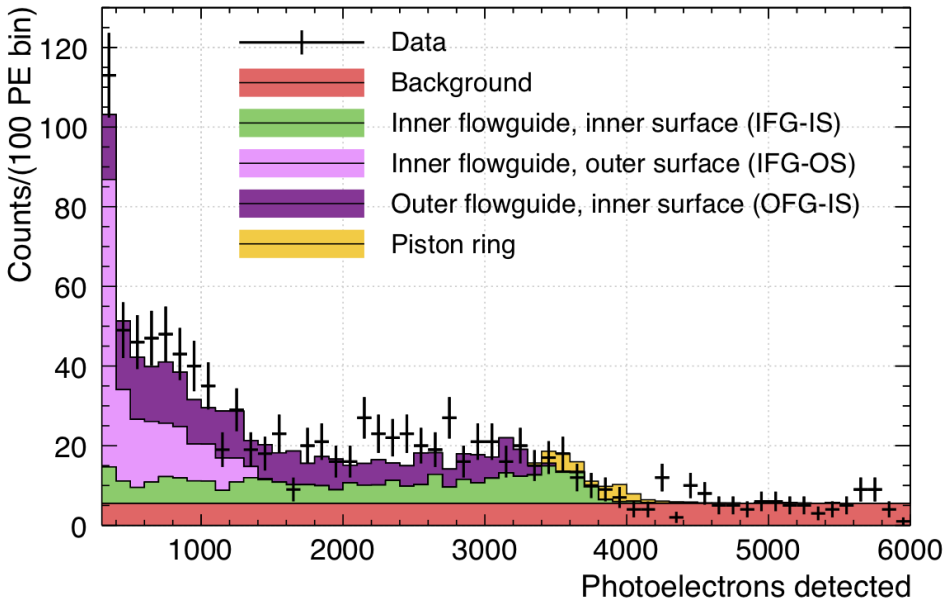


Identification of features
from Monte Carlo **simulation**

... matching features seen in **data**

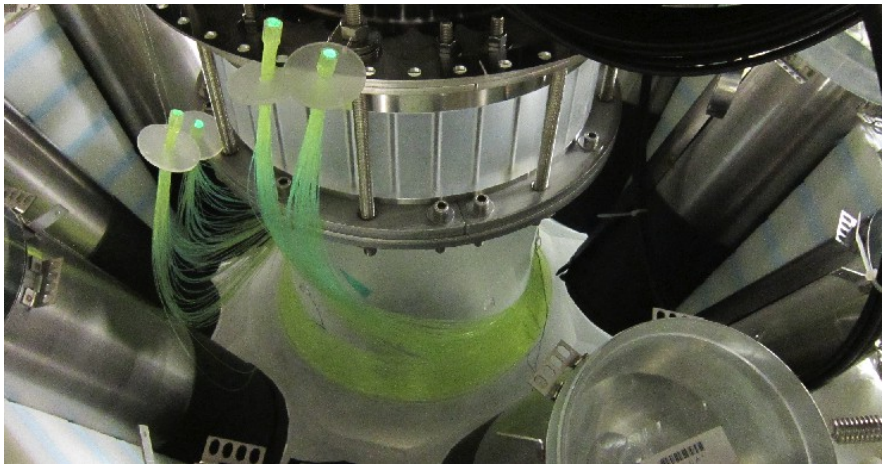
... allows a **template fit** using multiple
control regions, to figure out rates
of neck alpha events from all surfaces

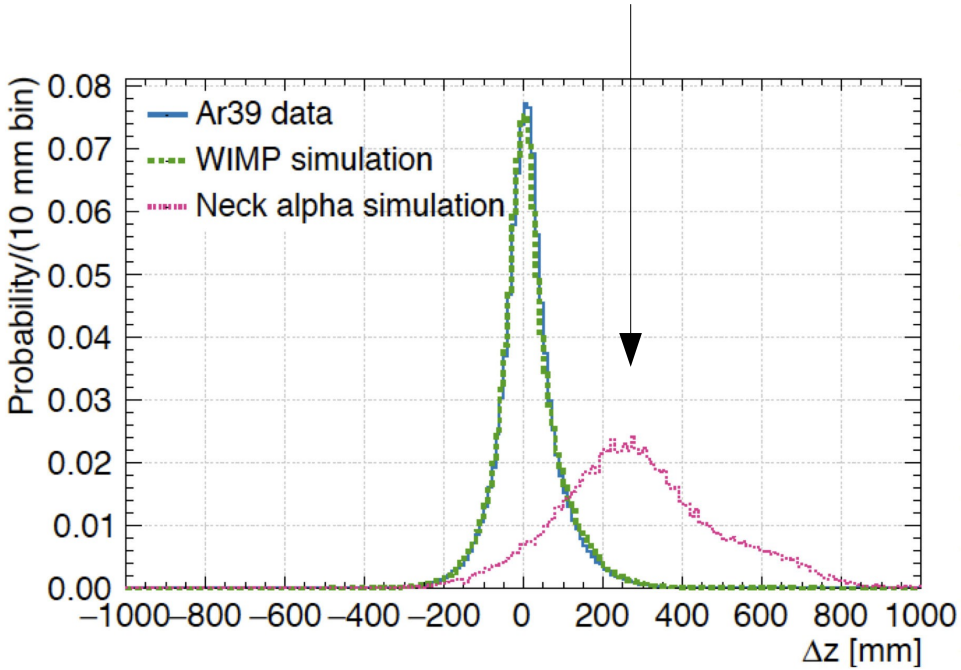
[other background subtracted in fit]



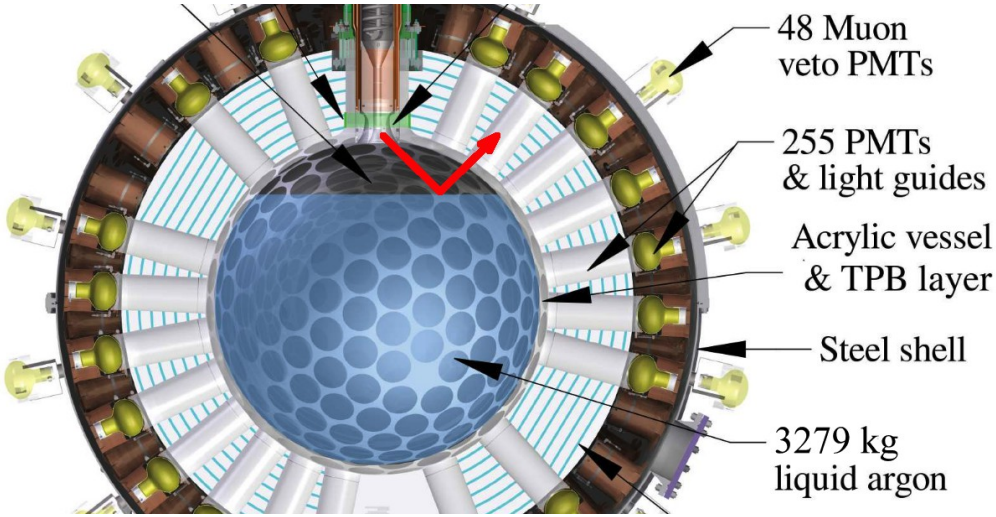
Known Handles Against Neck Alpha Backgrounds

- Developed a **dedicated event selection**, to reject background events
- In contrast to signal, neck alpha decays 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

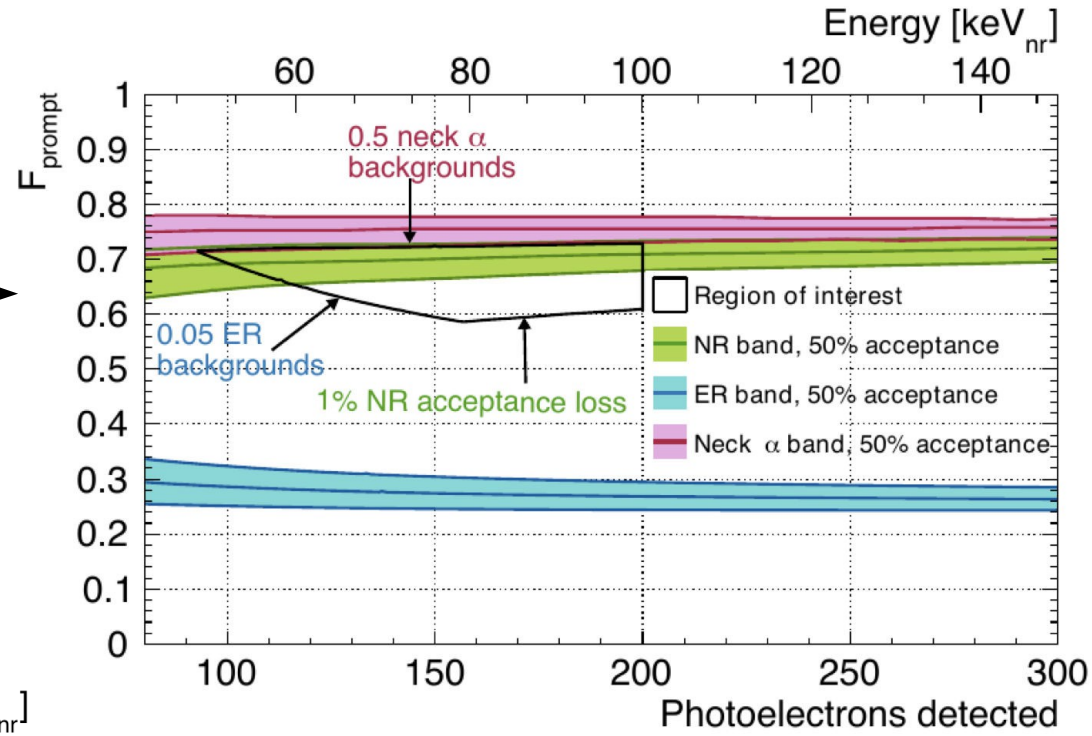


UV photon reflection at the liquid argon surface

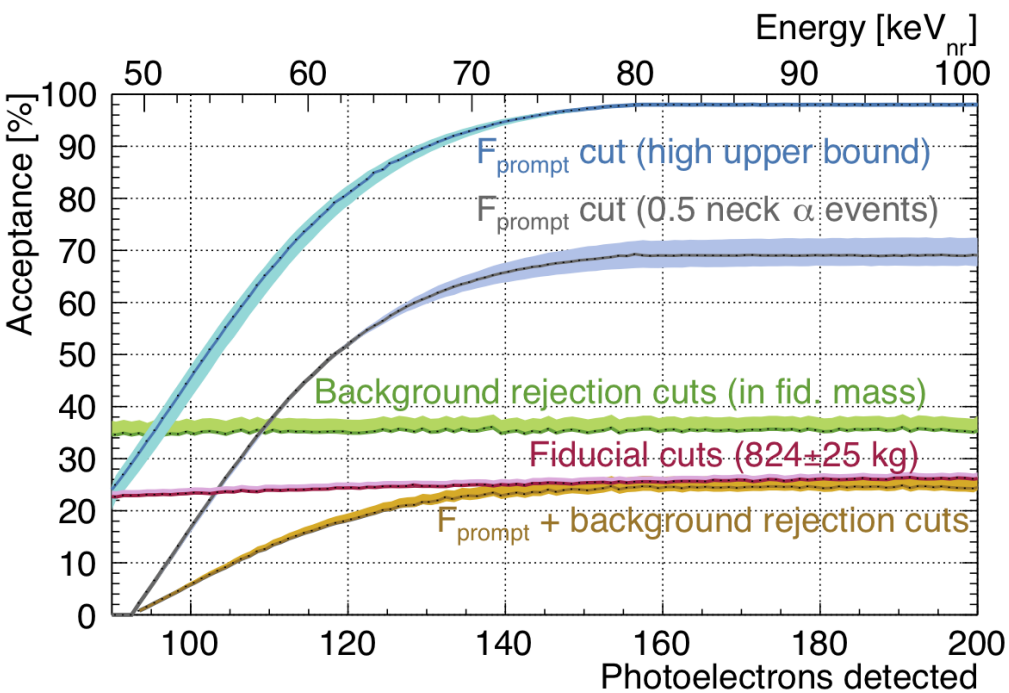
WIMP Signal Region

Pulse-shape discrimination is also applied against neck alpha backgrounds

Final event selection in F_{prompt} and PE such that the total background expectation is **< 1 event**



WIMP signal acceptance

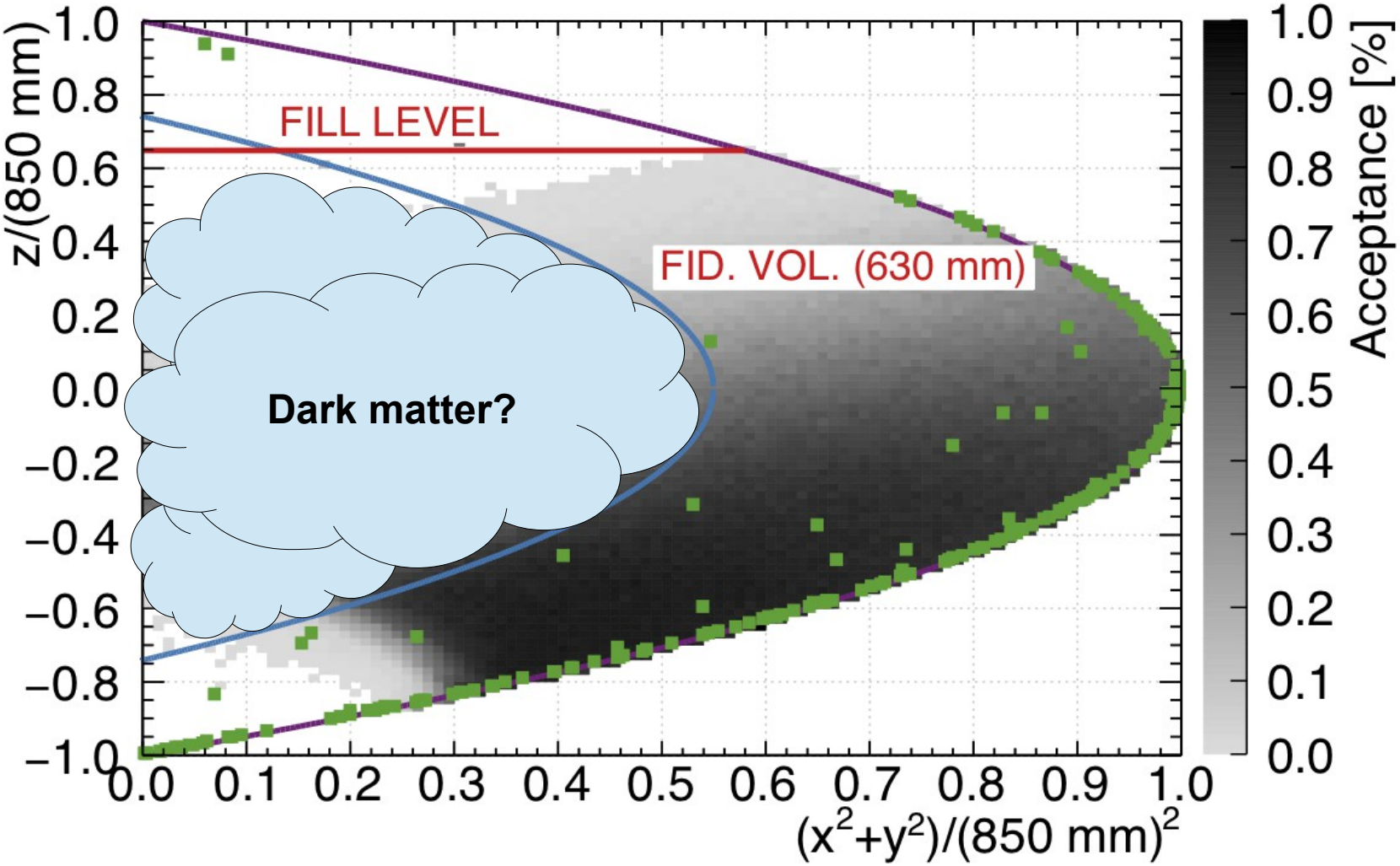


Expected backgrounds in 231 live days

	Source	N^{ROI}
β/γ's	ERs	0.03 ± 0.01
	Cherenkov	< 0.14
n's	Radiogenic	$0.10^{+0.10}_{-0.09}$
	Cosmogenic	< 0.11
α's	AV surface	< 0.08
	Neck FG	$0.49^{+0.27}_{-0.26}$
	Total	$0.62^{+0.31}_{-0.28}$

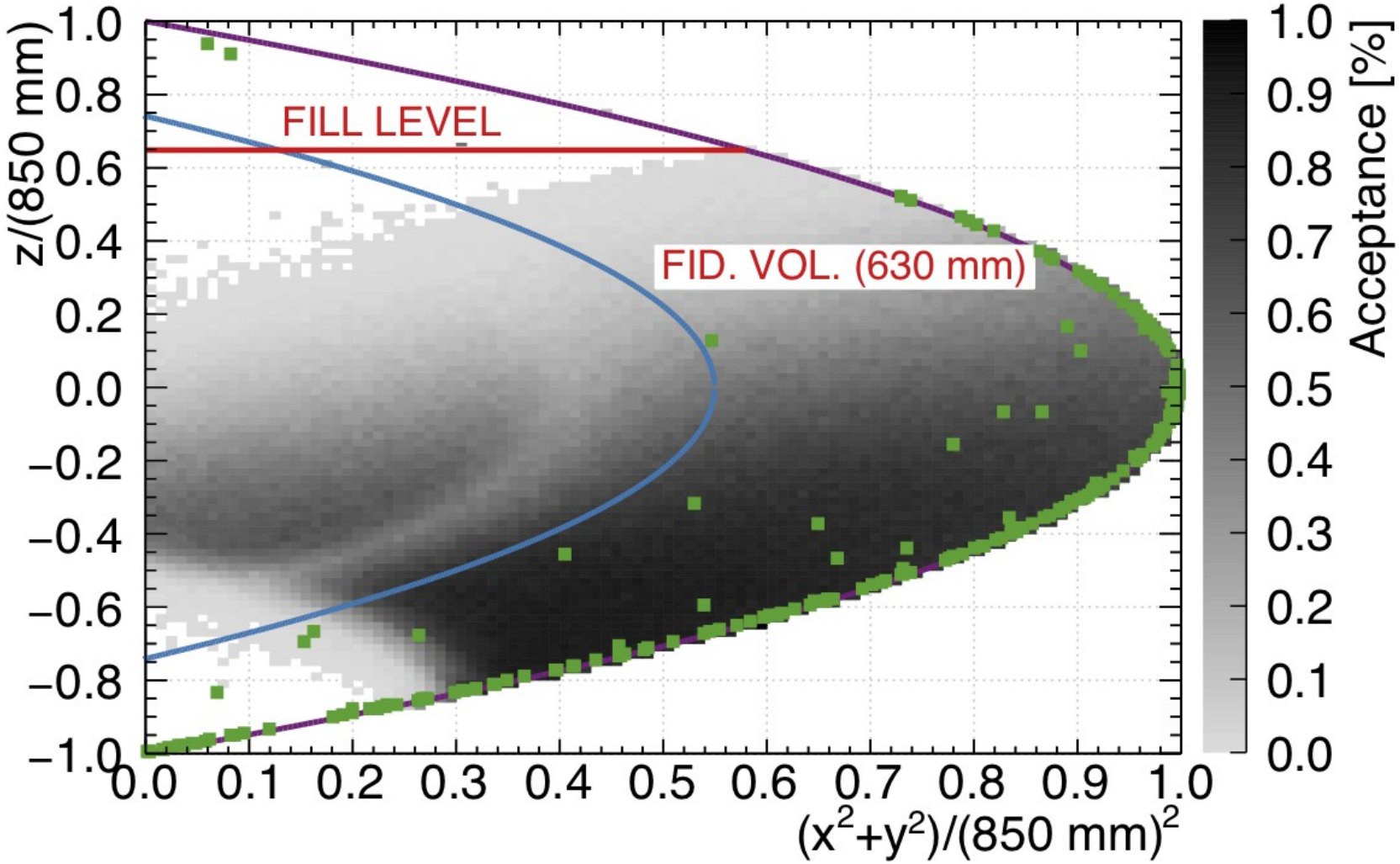
Dark Matter Search Results

Was dark matter observed in the first year of DEAP-3600 data?



Dark Matter Search Results

The detector is sensitive to dark matter, but no signal event was observed so far

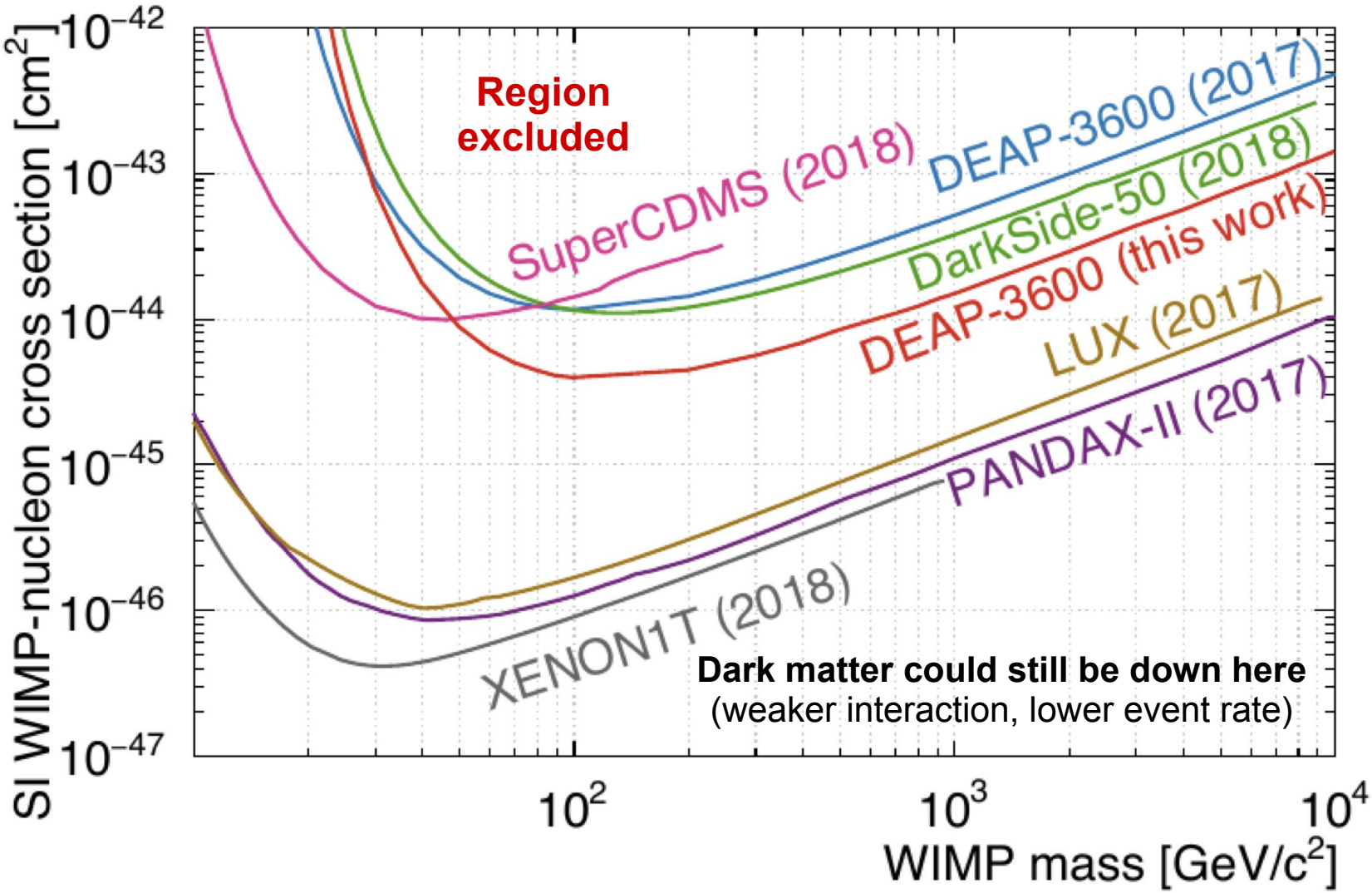


Physical Review D, 100, 022004 (2019) arXiv:1902.04048

Dark Matter Search Results

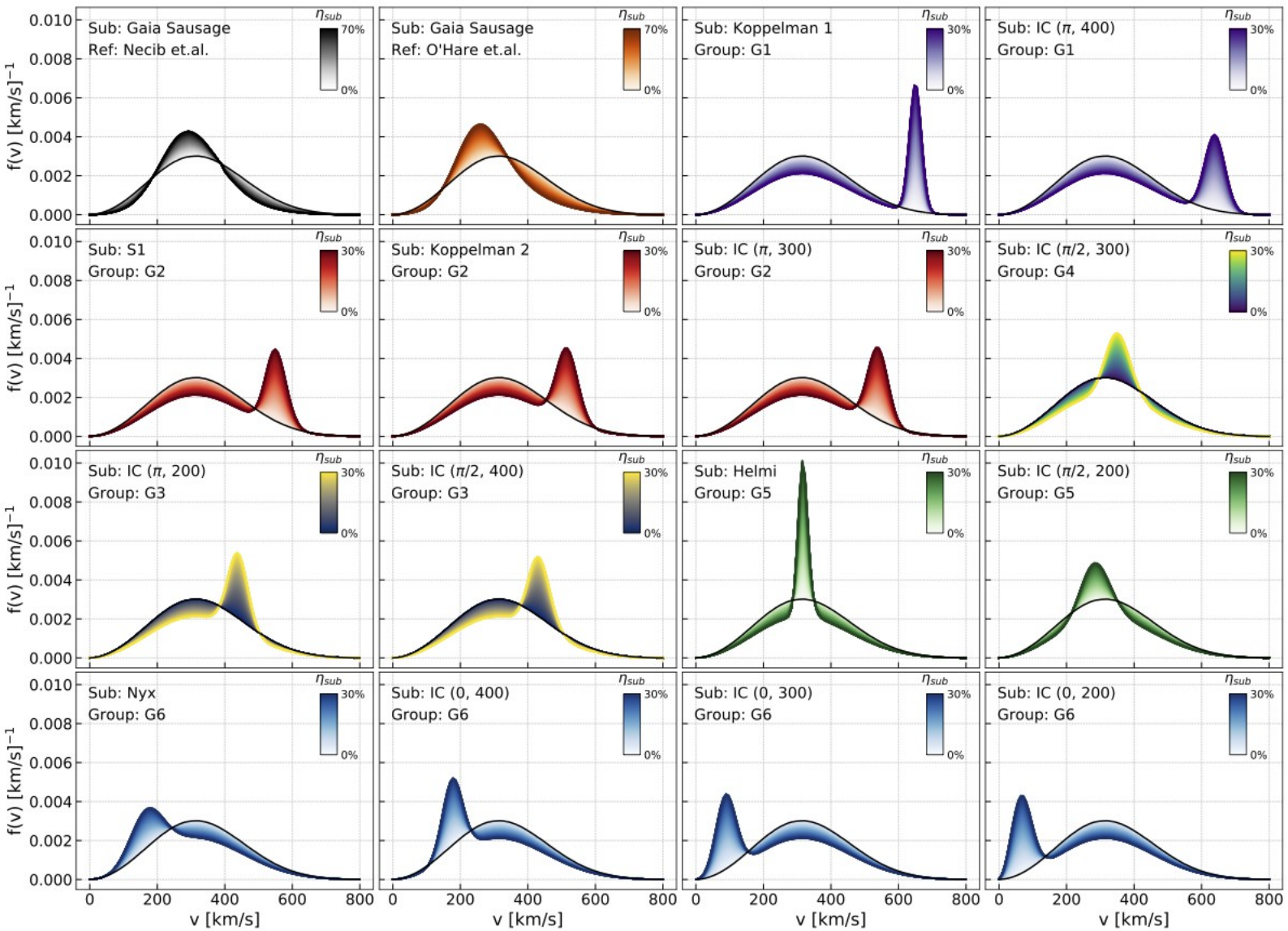
The detector is sensitive to dark matter, but no signal event was observed so far

Therefore we **exclude** certain dark matter hypotheses



Further Constraints on Dark Matter

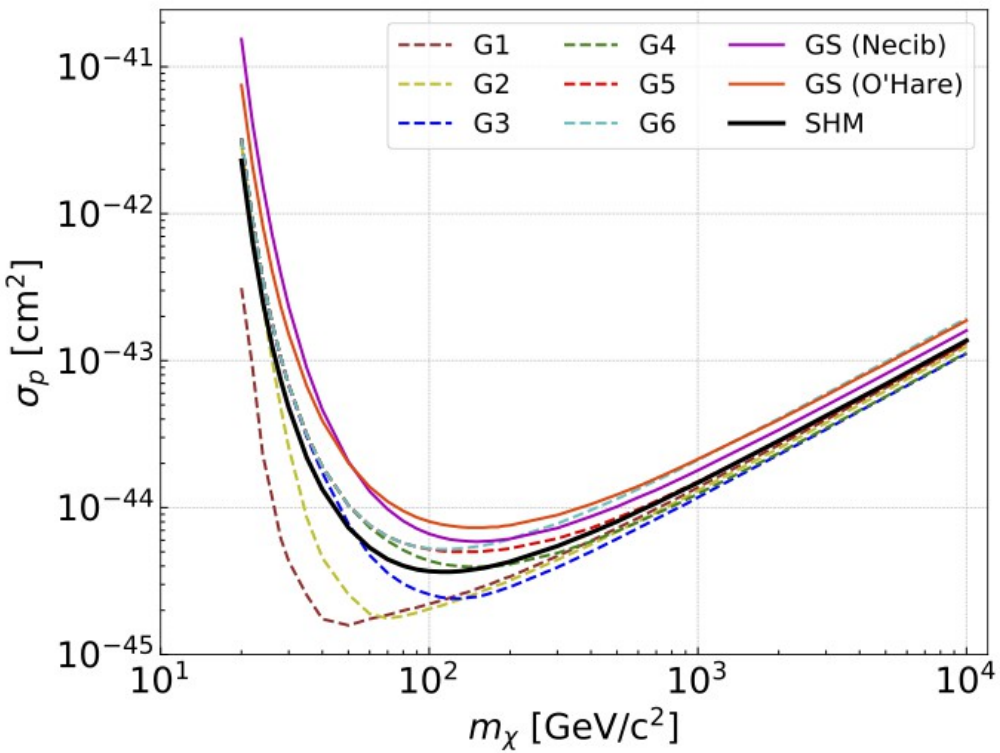
- Results are reinterpreted with a more general non-relativistic EFT framework, and exploring how possible substructures in DM halo affect these constraints



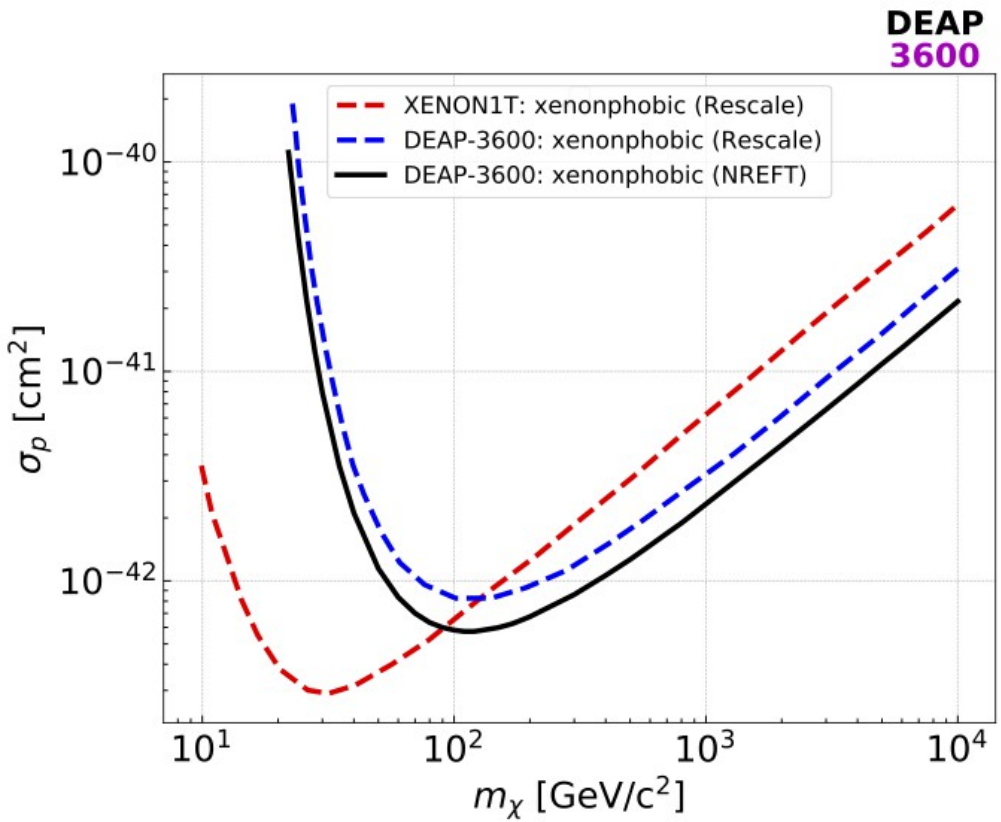
Further Constraints on Dark Matter

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

Different DM halo structures result in variations from Standard Halo Model (SHM) benchmark



DEAP-3600 has **world-leading sensitivity** for a range of isospin-violating DM couplings

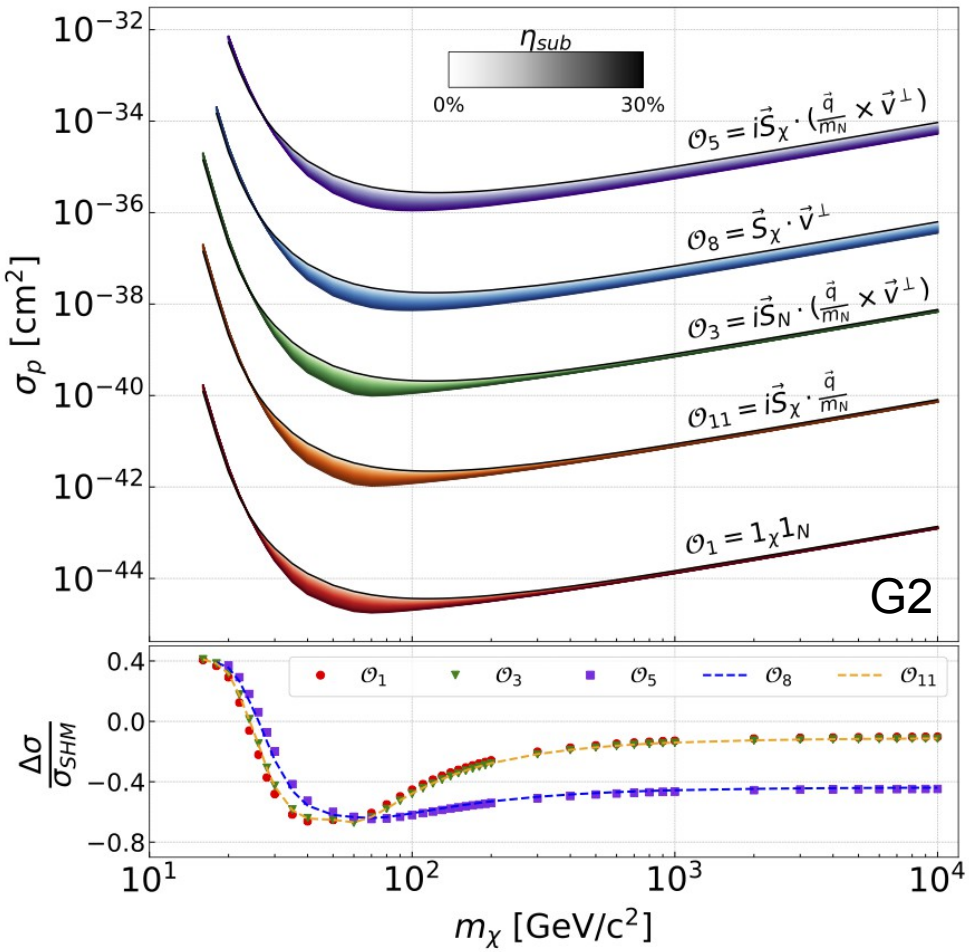


Submitted to Physical Review D (2020) arXiv:2005.14667

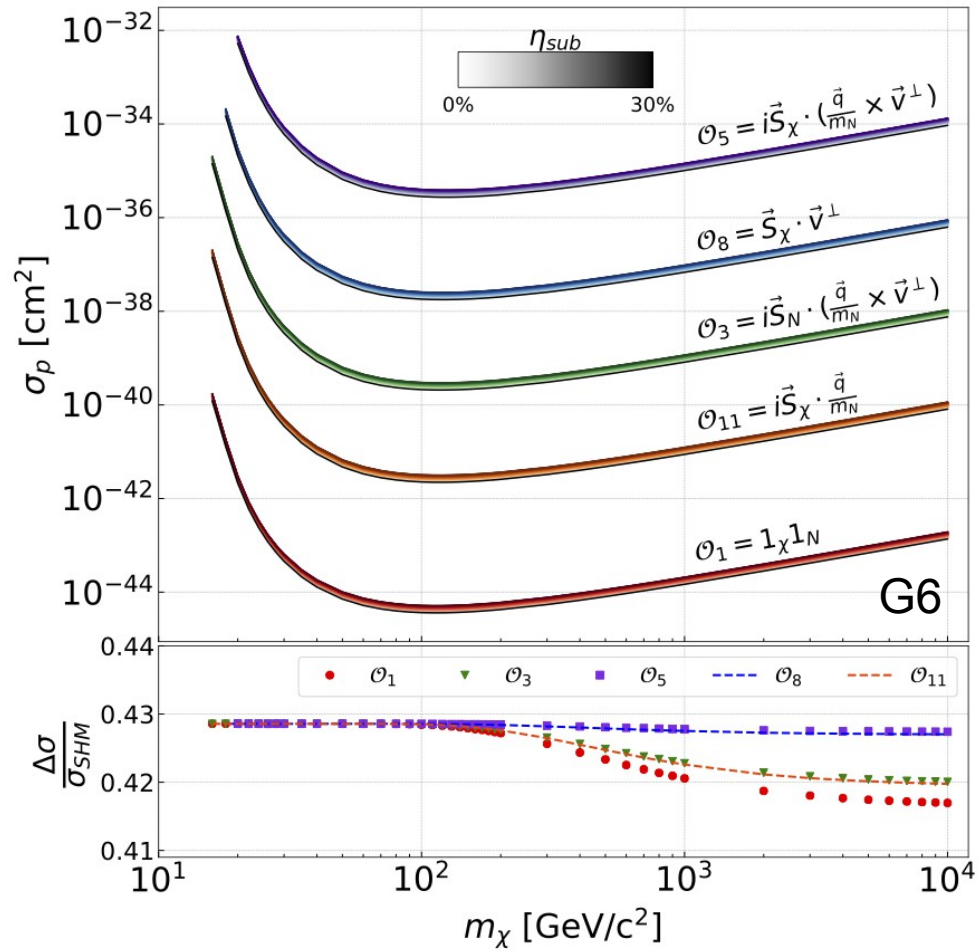
Further Constraints on Dark Matter

- Results are reinterpreted with 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



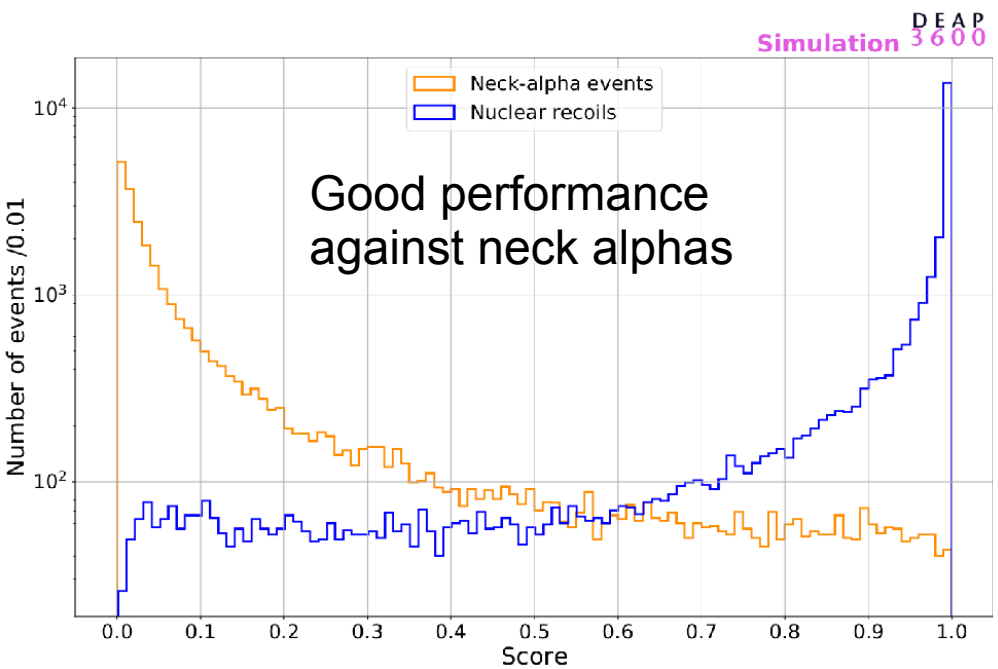
Example prograde stellar stream, e.g. Nyx

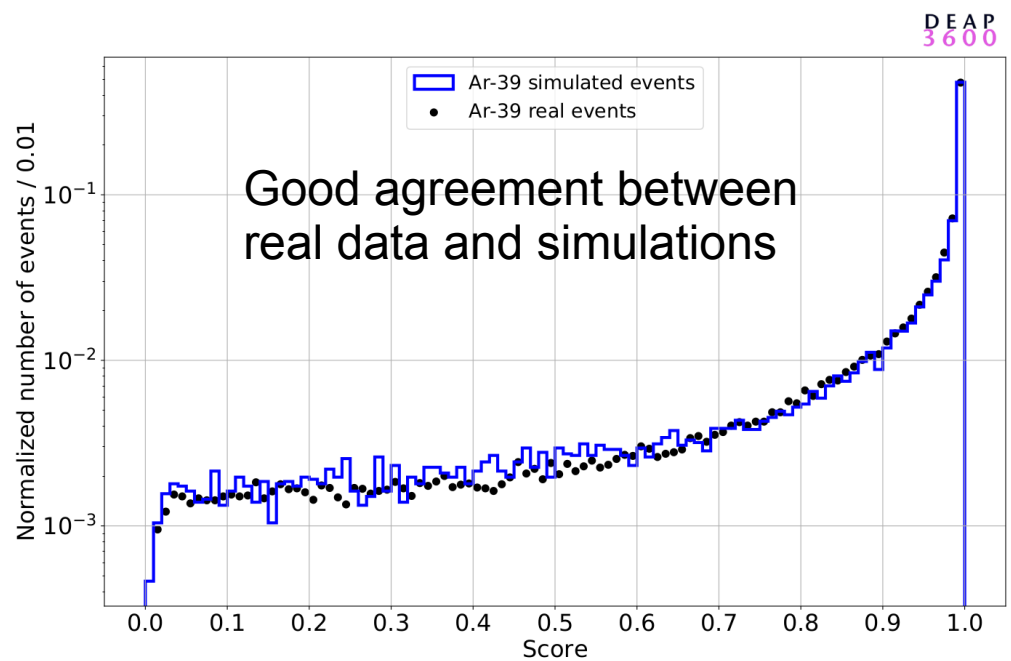


Submitted to Physical Review D (2020) arXiv:2005.14667

Next Steps: Multivariate Analysis on Full Dataset

- Published DM search from first-year dataset November 2016 – October 2017
- **Full second-fill dataset:** DM search data closed March 28th, 2020
  - 80% blind since January 1st, 2018
- To improve sensitivity: three **MVA algorithms** trained against neck alpha events
  - Random Forest, Boosted Decision Trees, Neural Network (shown here)
  - Now validating modelling of all correlations between input and output variables, and re-optimizing our DM candidate event selection



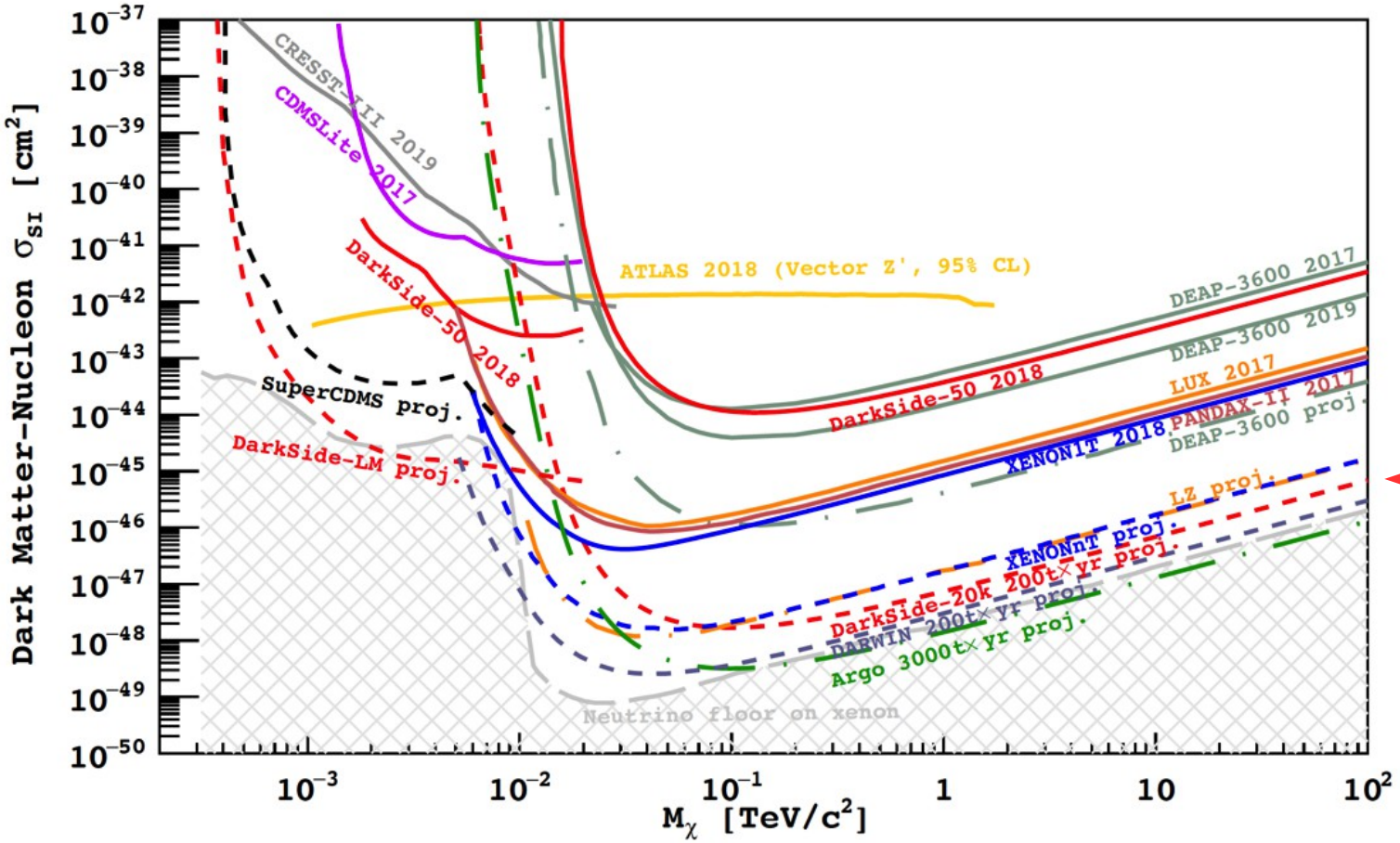


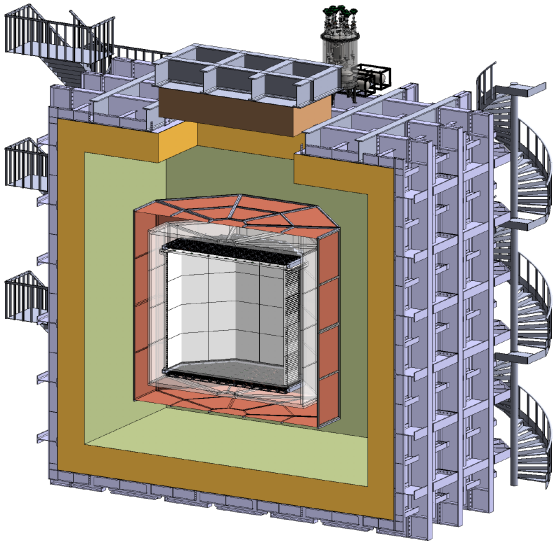
Next Steps: DEAP-3600 Hardware Upgrades

- **Hardware upgrade** program
  - Main objective: **Mitigate limiting background sources** in the experiment
    - Neck seal replacement, allowing a complete fill with LAr
    - Slow wavelength shifter on neck flowguides, to remove background with PSD
    - Alternate cooling system, to keep the neck warm
    - Also perform maintenance on cryogenic systems
- Current status
  - Detector now empty of LAr
    - Still taking data in GAr and vacuum, with and without calibration sources
    - Demonstrate that our background model is complete and understood
  - Regaining access to research labs
- New DM search data in upgraded detector expected in 2021
  - **Expecting improved sensitivity**
  - Inform design of next-generation liquid argon dark matter experiments

Next-Generation Liquid Argon Dark Matter Detectors

- To maximize sensitivity with next-generation experiments: **THINK BIG**
- **Global Argon Dark Matter Collaboration** formed!
  - Next objective: **DarkSide-20k** with underground argon
  - Objective: Neutrino floor sensitivity to spin-independent dark matter nucleon interactions with ARGO, a **multi-hundred tonnes** liquid argon detector



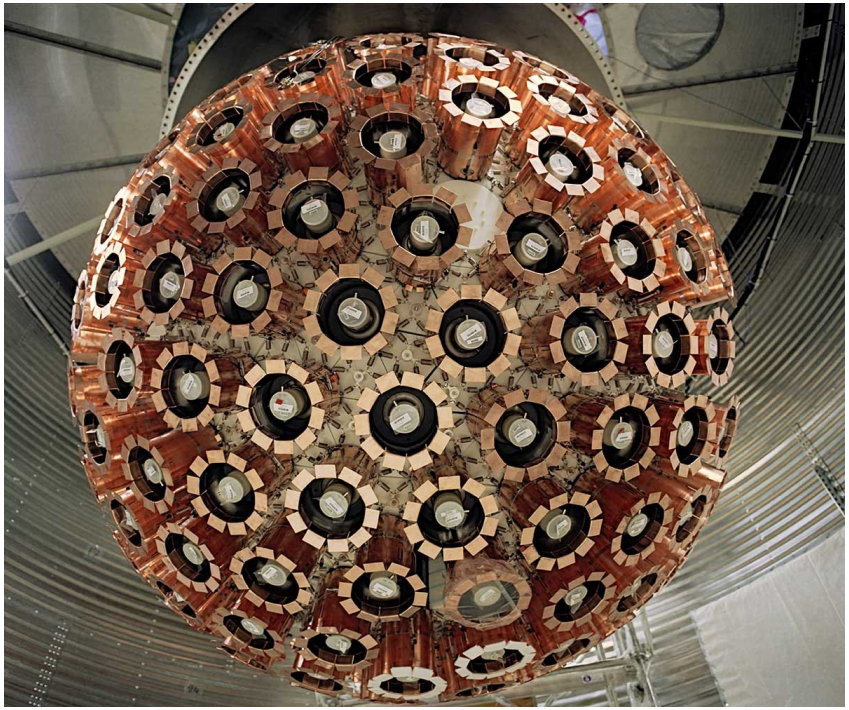


DarkSide-20k

Talk by Luigi Rignanese, Tuesday July 28, 18:30

DarkSide-20k Technical Design Report, in preparation

Conclusion



- **Looking for dark matter** with **DEAP-3600**
  - Excellent detector performance!
    - Pulse-shape discrimination
    - Event reconstruction
    - Background rejection
    - Sensitivity to new physics
  - Stable data-taking continues
    - 80% blind since January 1st, 2018
    - DM search data closed March 28th, 2020
  - Work in progress
    - Multivariate analysis to improve signal acceptance
    - New searches and measurements
    - Hardware upgrade
- **Instrumentation** research and development for future particle detectors
  - Design and simulation for DarkSide-20k and ARGO
  - Silicon photomultipliers

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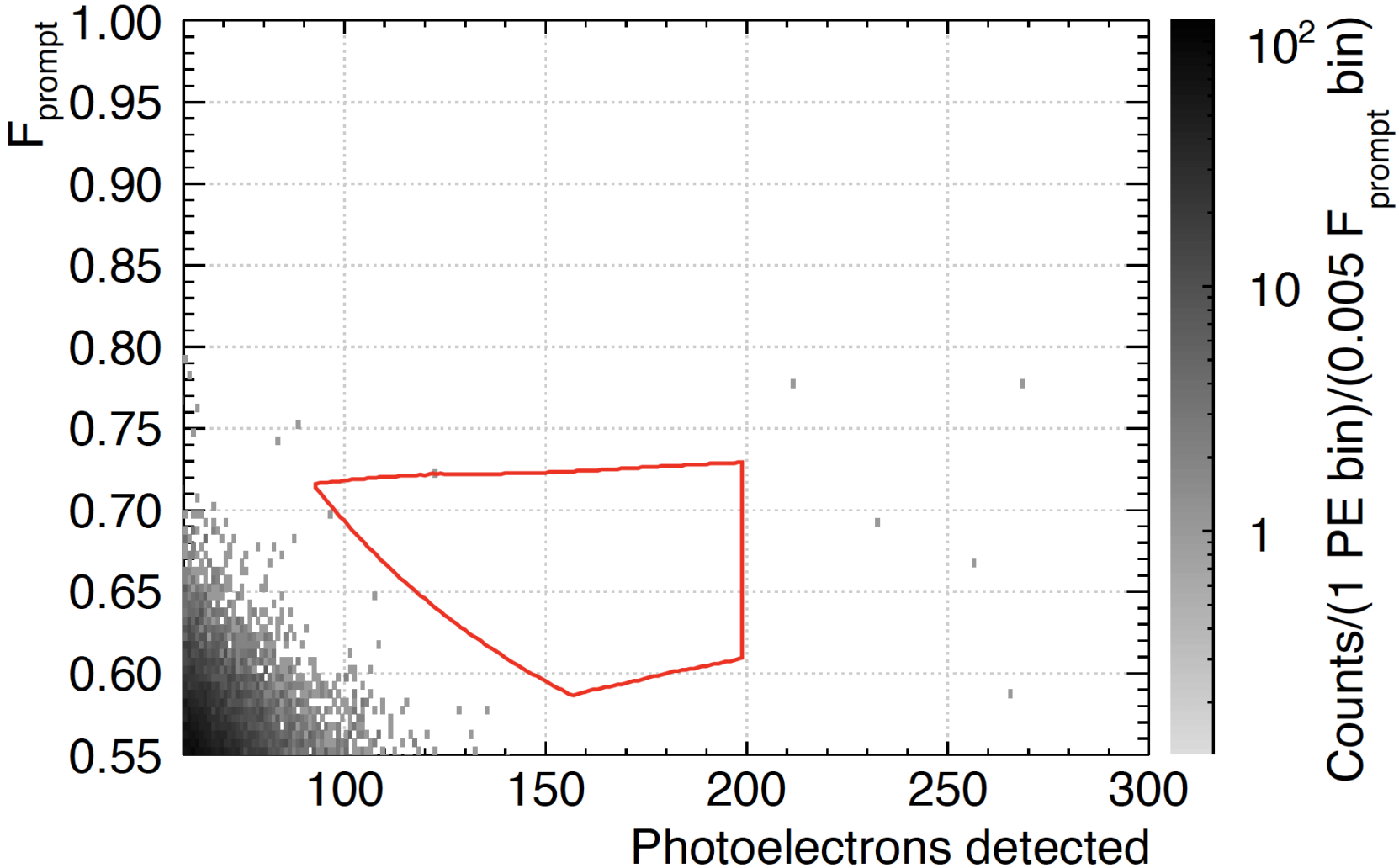
South East Physics Network

Bonus slides

Dark Matter Search Results

The detector is sensitive to dark matter, but no signal event was observed so far

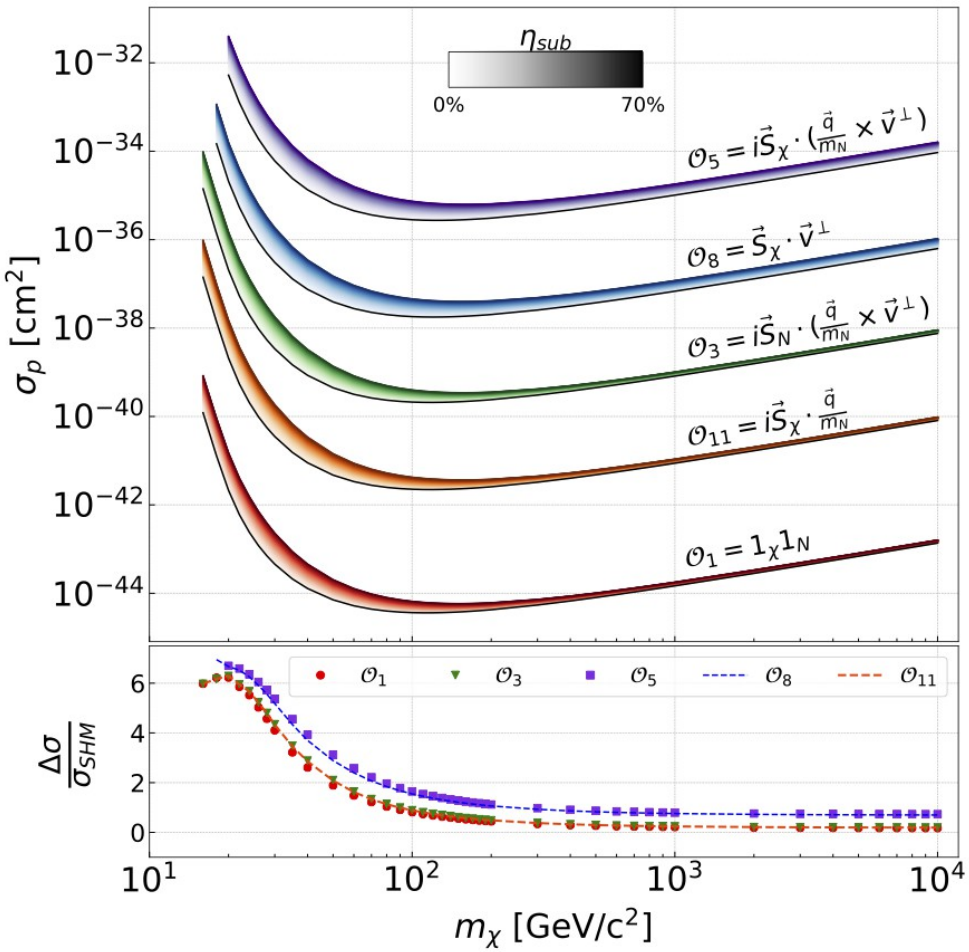


Physical Review D, 100, 022004 (2019) arXiv:1902.04048

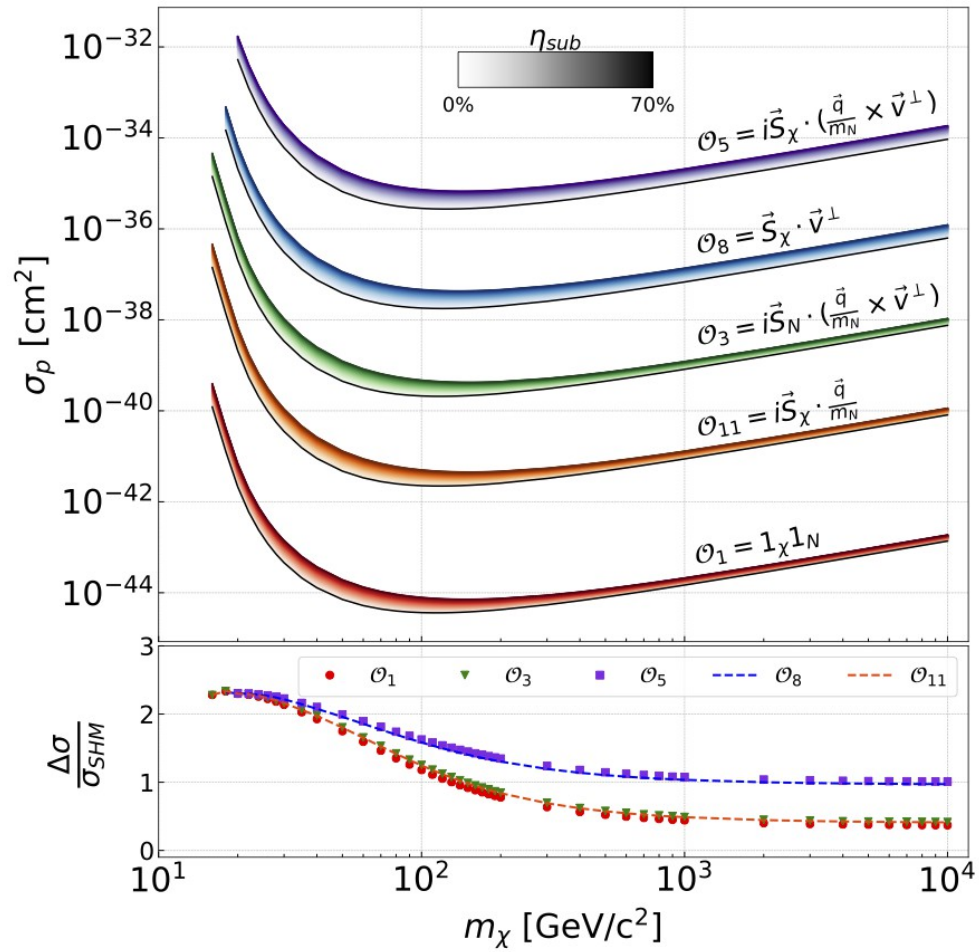
Further Constraints on Dark Matter

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

Gaia Enceladus, Necib et al. parametrization



Gaia Enceladus, O'Hare et al. parametrization



Submitted to Physical Review D (2020) arXiv:2005.14667