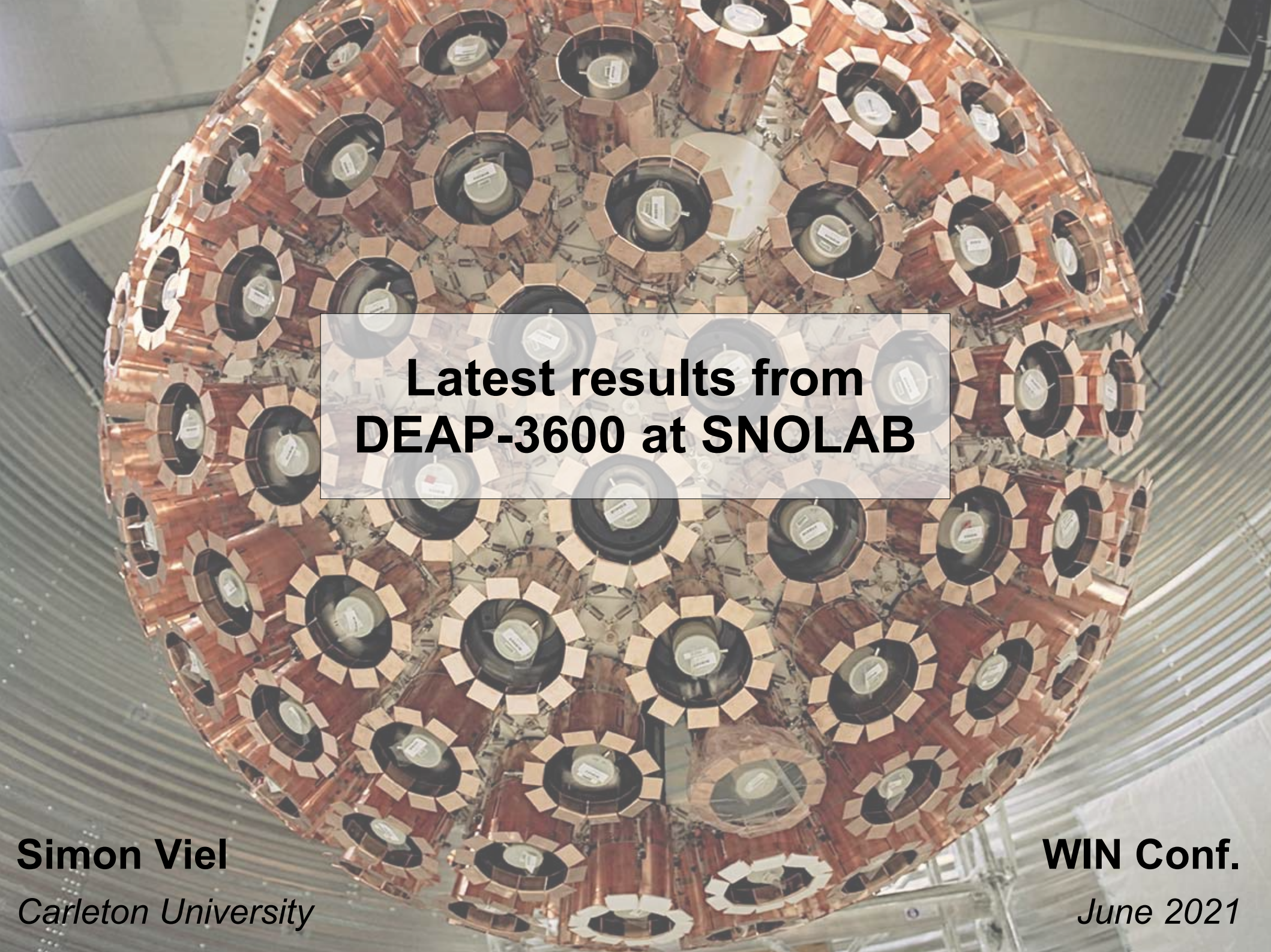


# Latest results from DEAP-3600 at SNOLAB

**Simon Viel**

*Carleton University*

**WIN Conf.**

*June 2021*


# 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

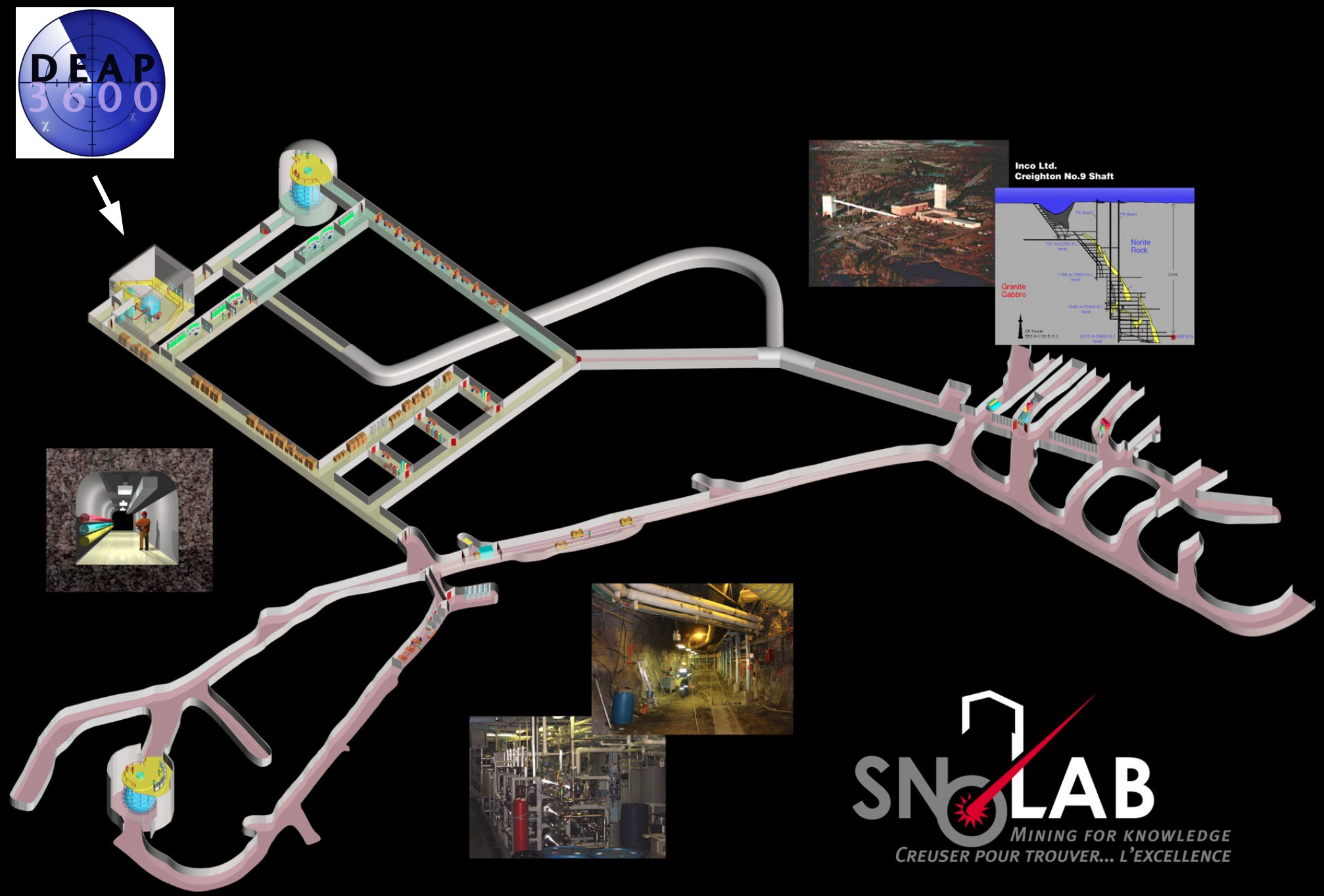
SNOLAB

University of Sussex

Technical University of Munich

TRIUMF

Particle Physics
Rutherford Appleton Laboratory

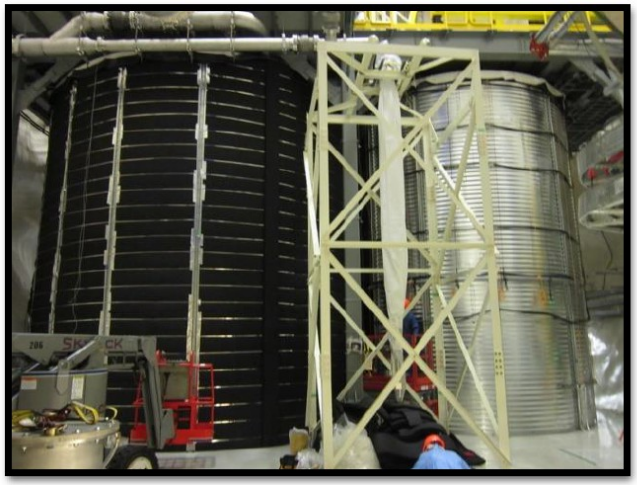


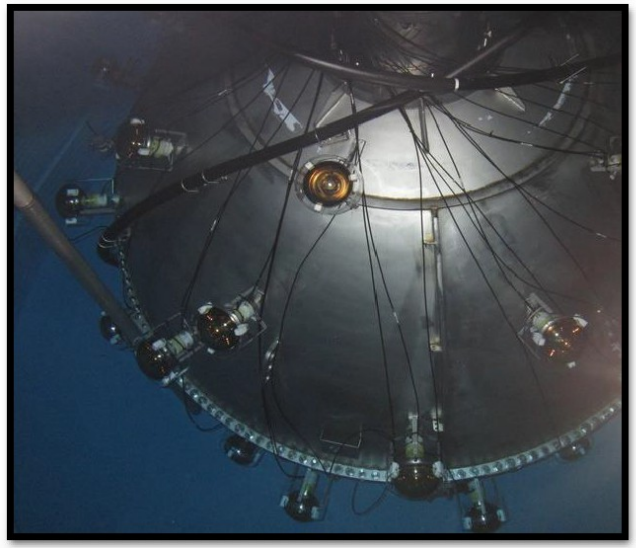

Video: A Day at SNOLAB
https://www.snolab.ca/outreach

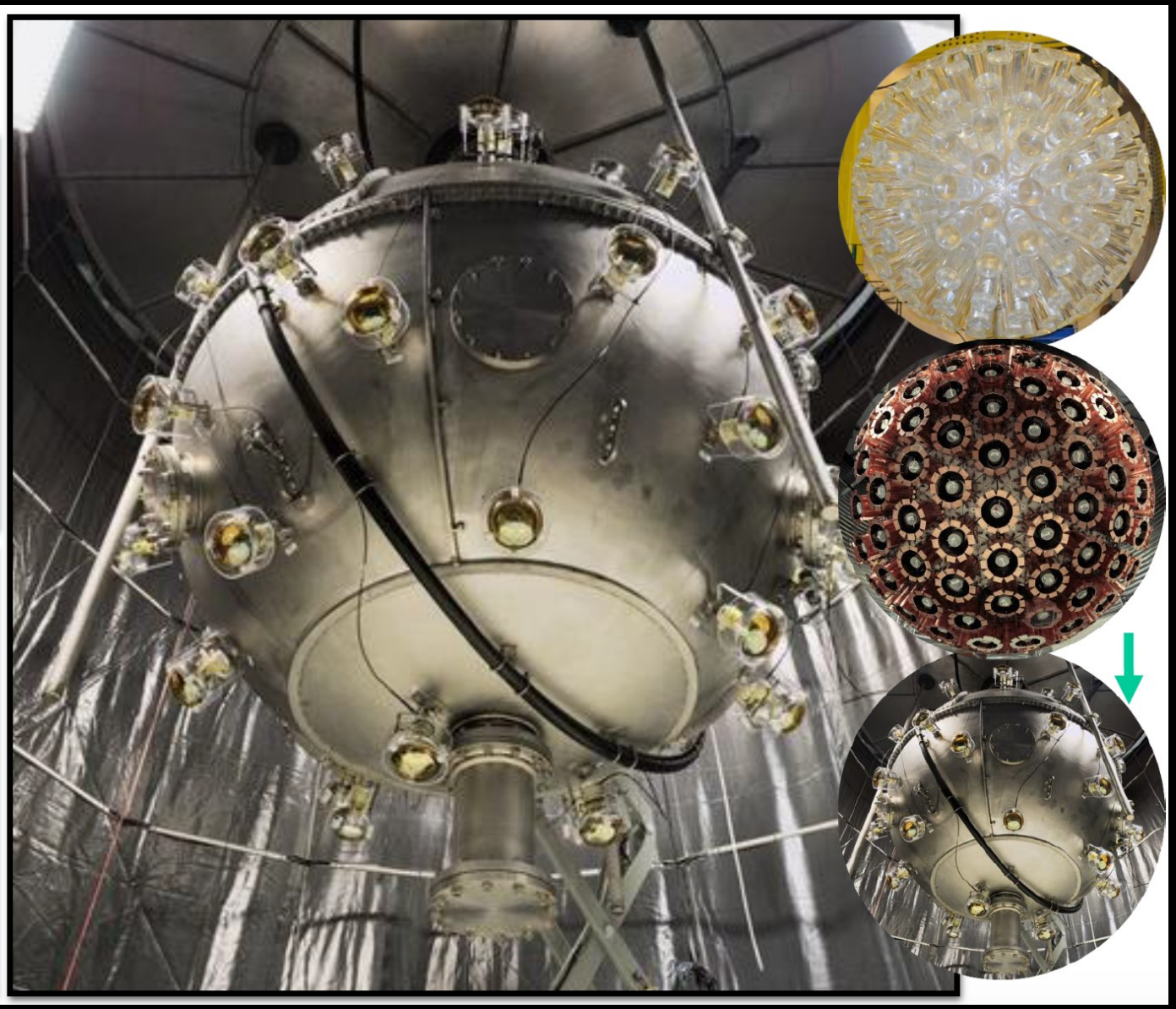
2070 m underground

Steel shell, Veto PMTs

Water tanks in Cube Hall



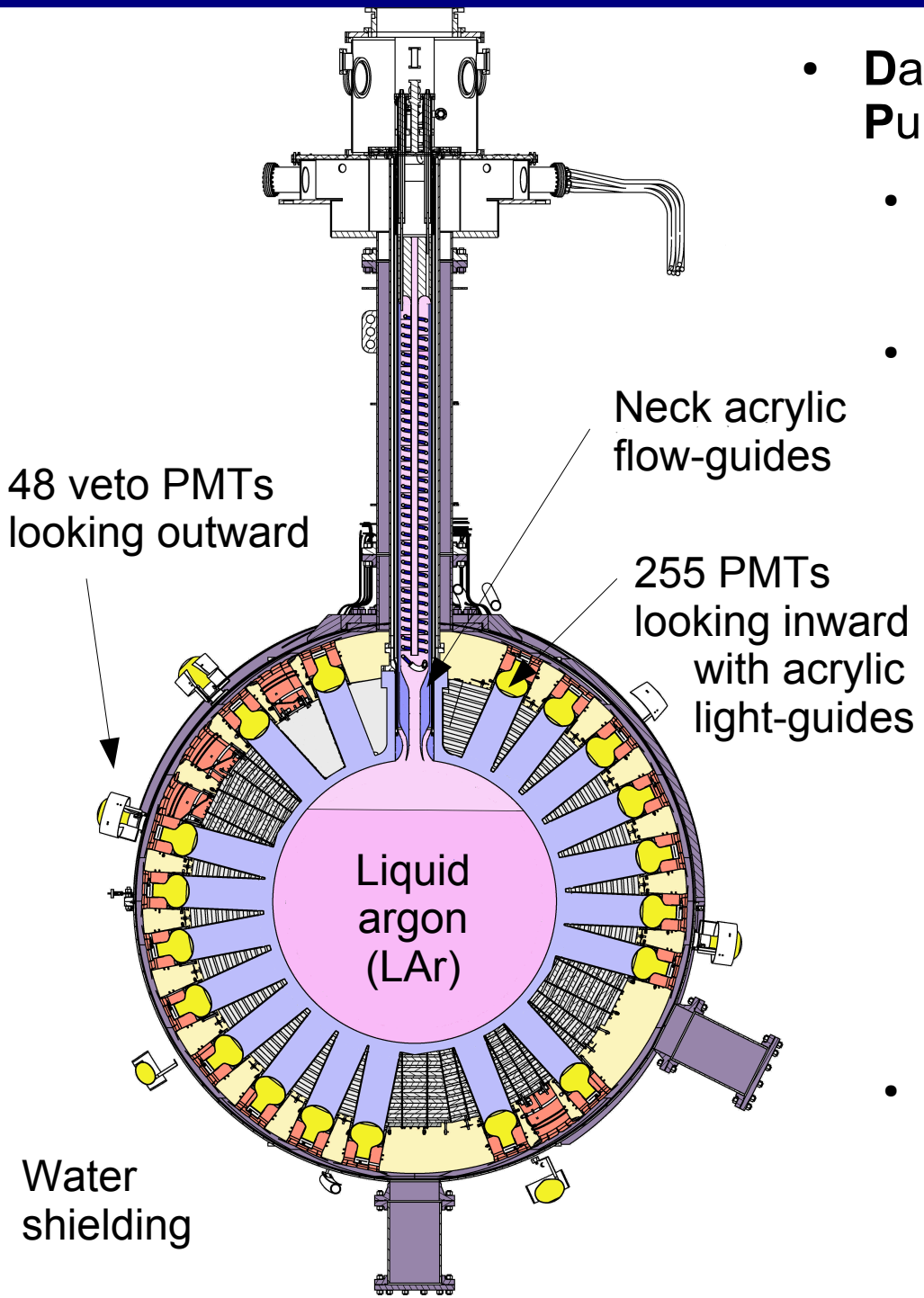




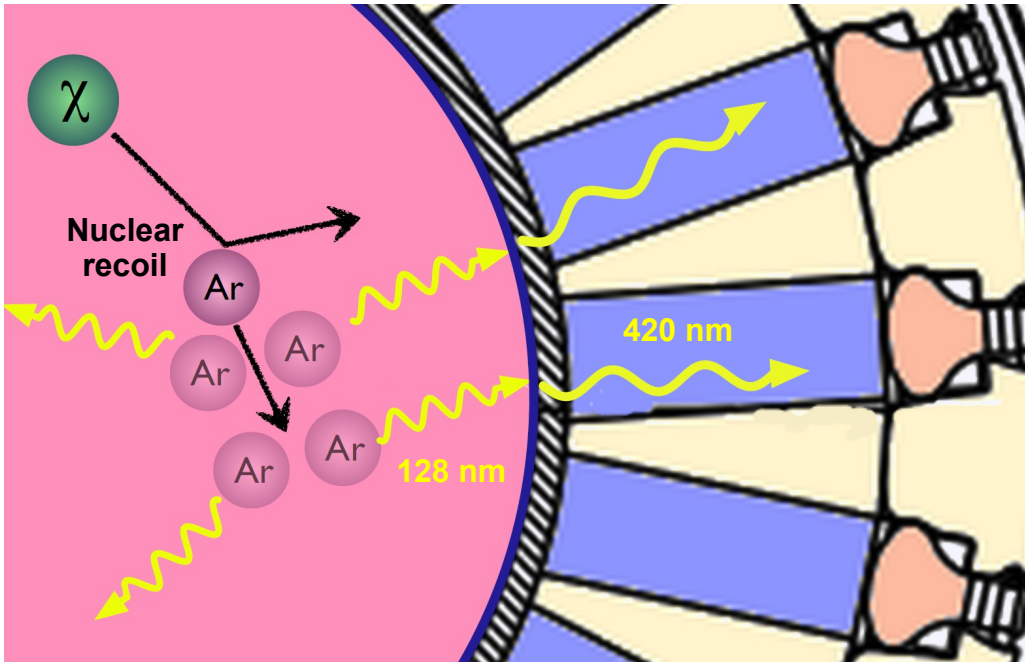
All details available in the DEAP-3600 detector publication!

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

# DEAP-3600

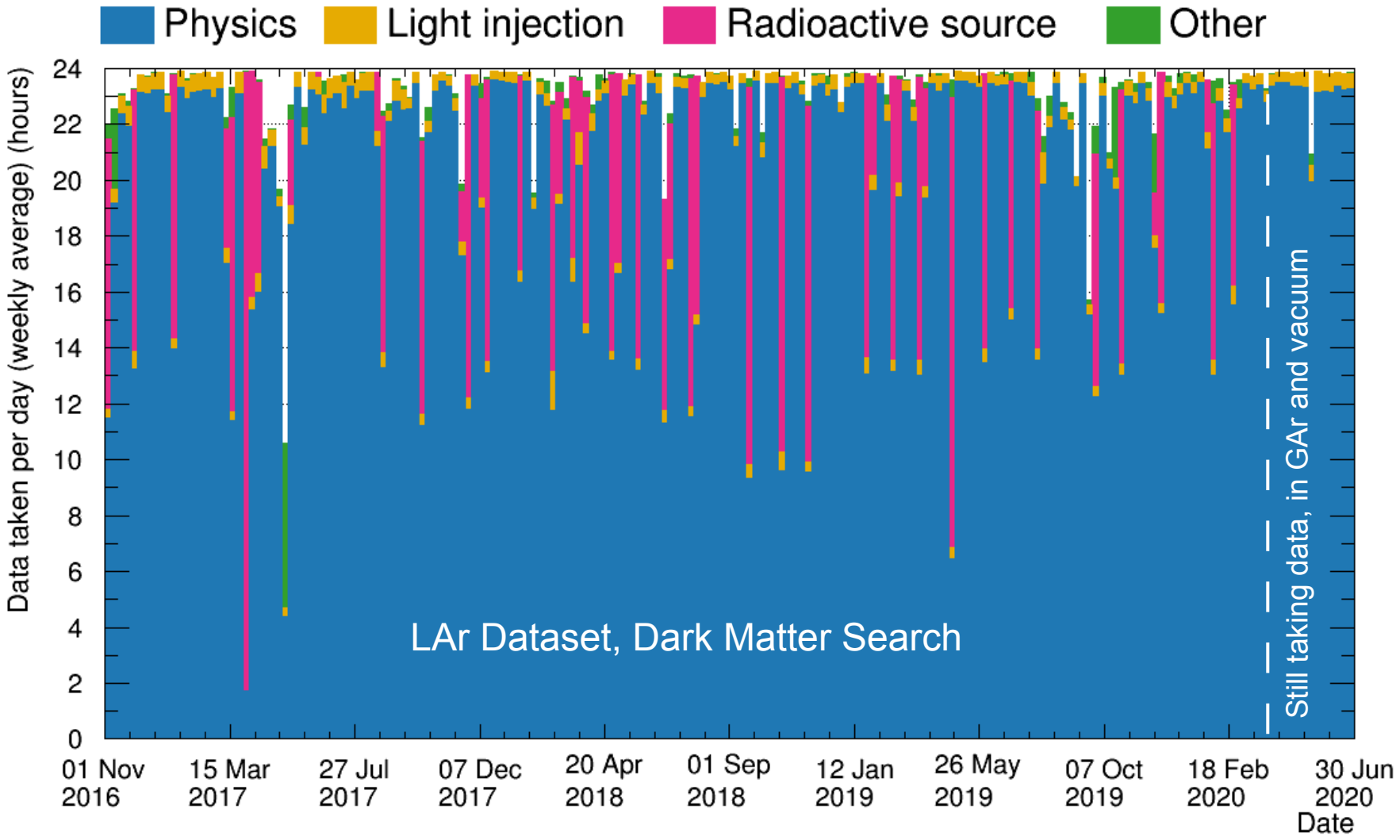



- **D**ark matter **E**xperiment using **A**rgon **P**ulse-shape discrimination
  - Design mass: 3600 kg of liquid argon (LAr)
    - Largest acrylic cryostat ever built
  - Goal: Detect dark matter particles colliding with argon nuclei



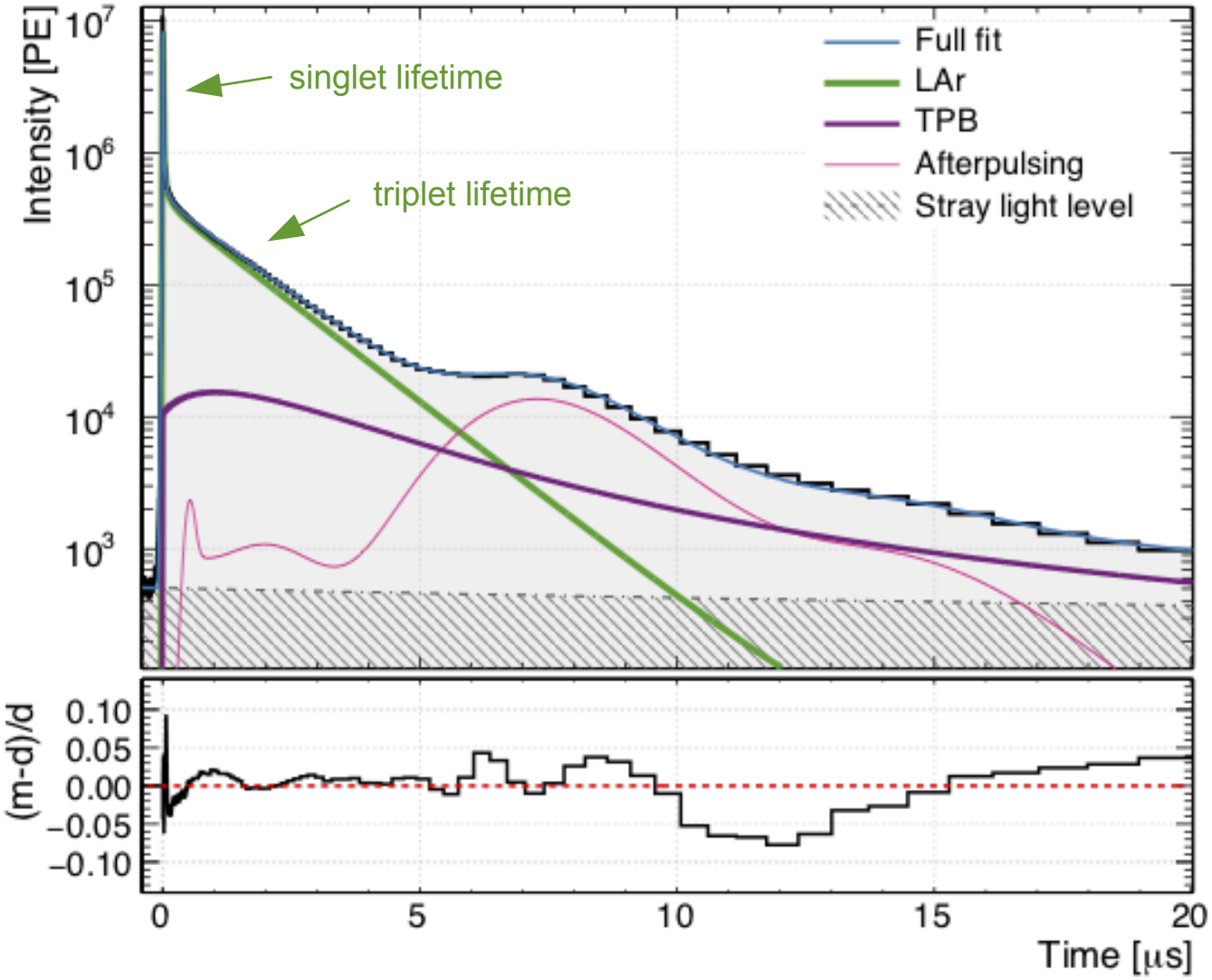

- **UV scintillation light** from LAr nuclear recoils is wavelength-shifted to visible at TPB layer, then collected by photomultiplier tubes (PMT)

# DEAP-3600 Dataset




- 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



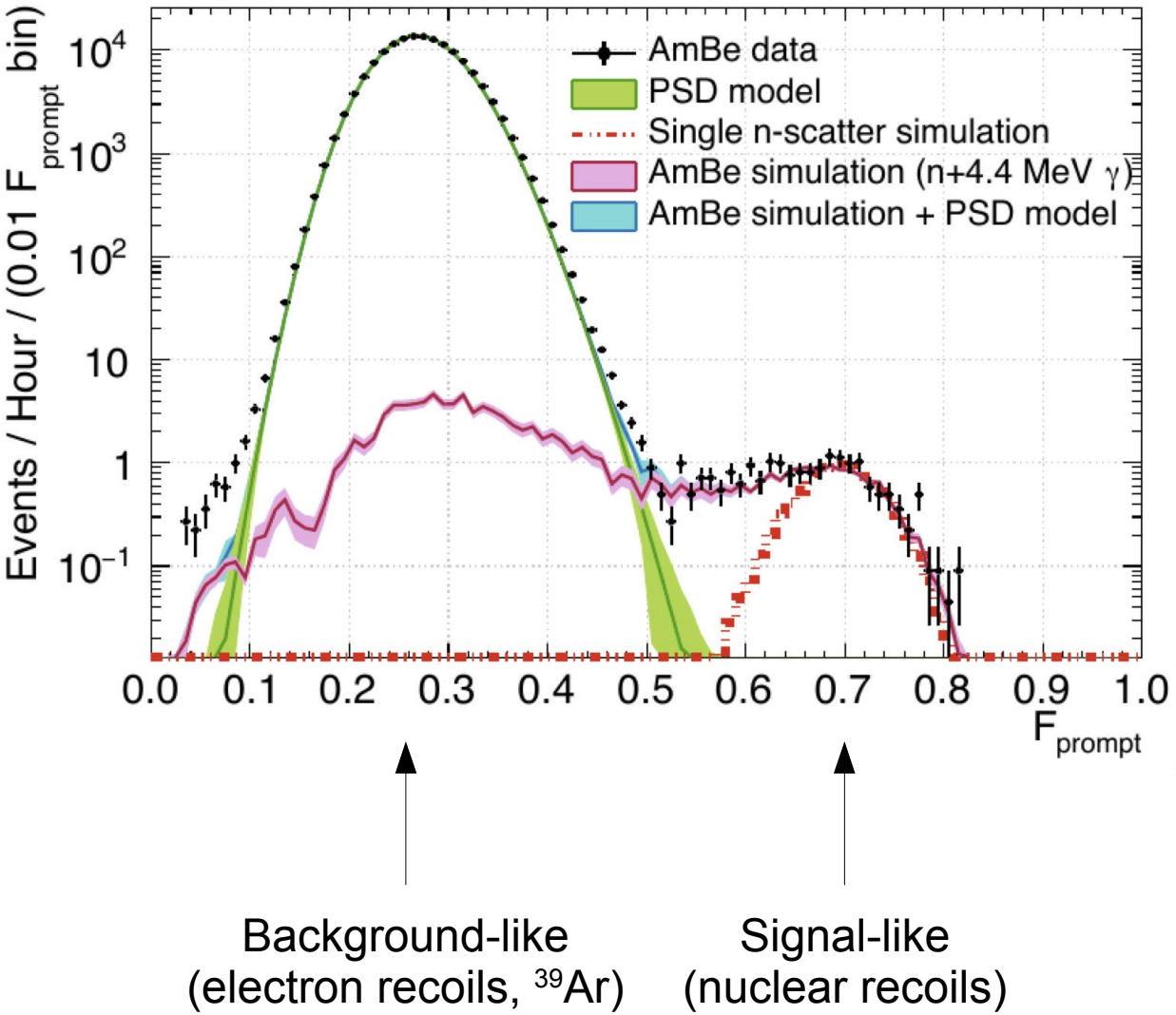

**Visible photons → Photoelectrons at PMT cathode → PMT pulses**

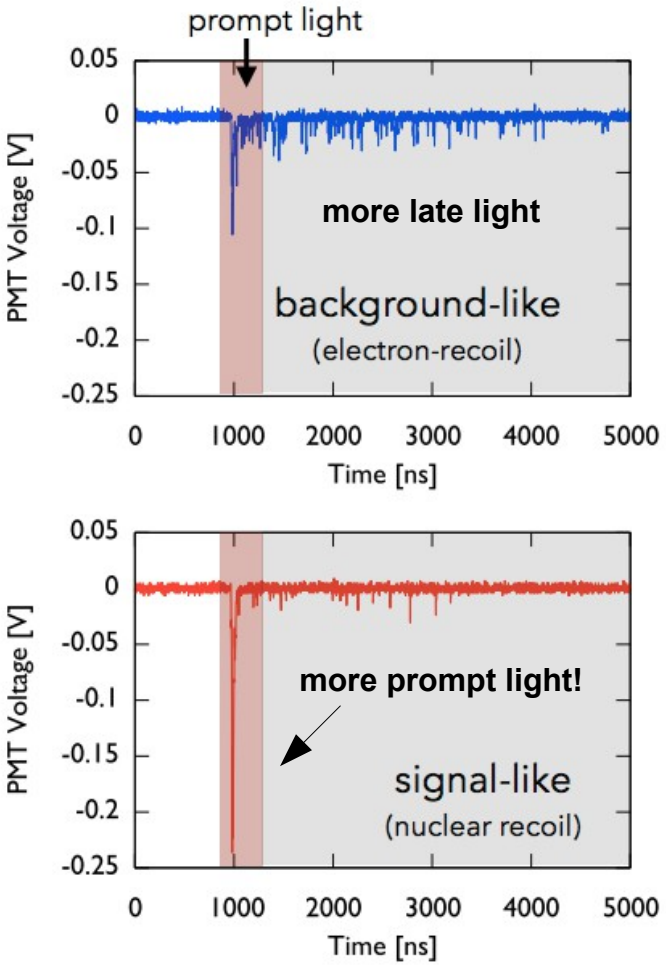
Full pulse-shape model: European Physics Journal C, 80, 303 (2020) arXiv:2001.09855

# Pulse-Shape Discrimination (PSD)

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

Example: Neutron source calibration data

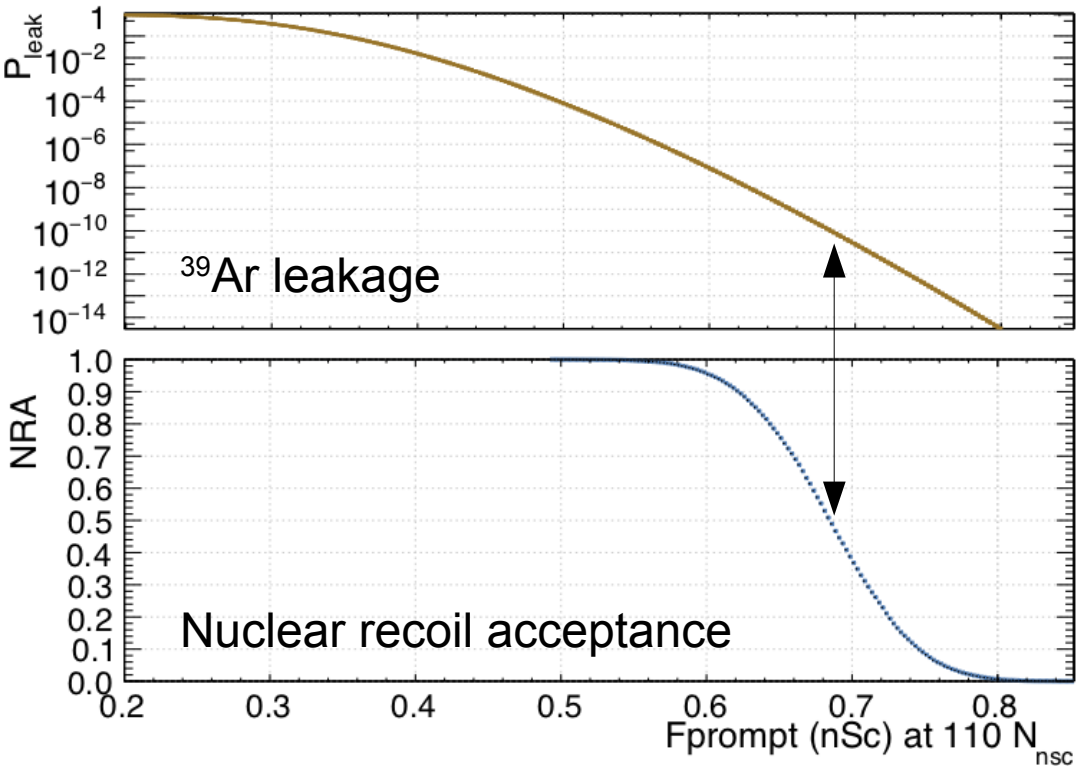


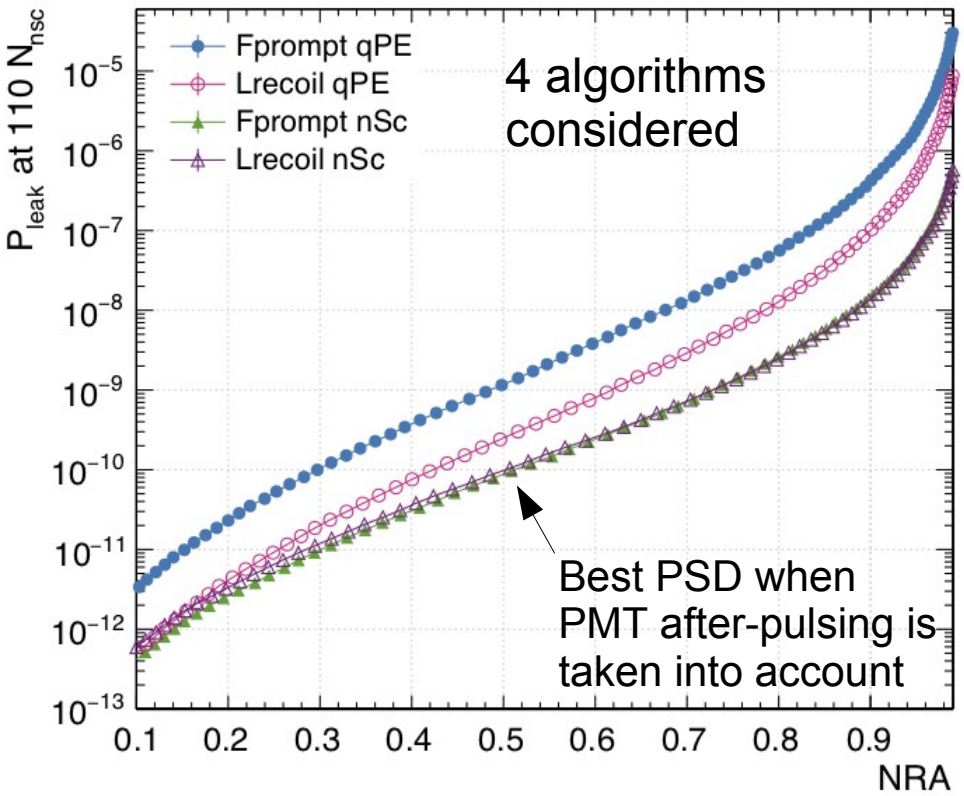




$$F_{prompt} = \frac{\sum_{t=-28\,ns}^{60\,ns} PE(t)}{\sum_{t=-28\,ns}^{10\,\mu s} PE(t)}$$

# Pulse-Shape Discrimination (PSD)

**World-leading PSD performance!**



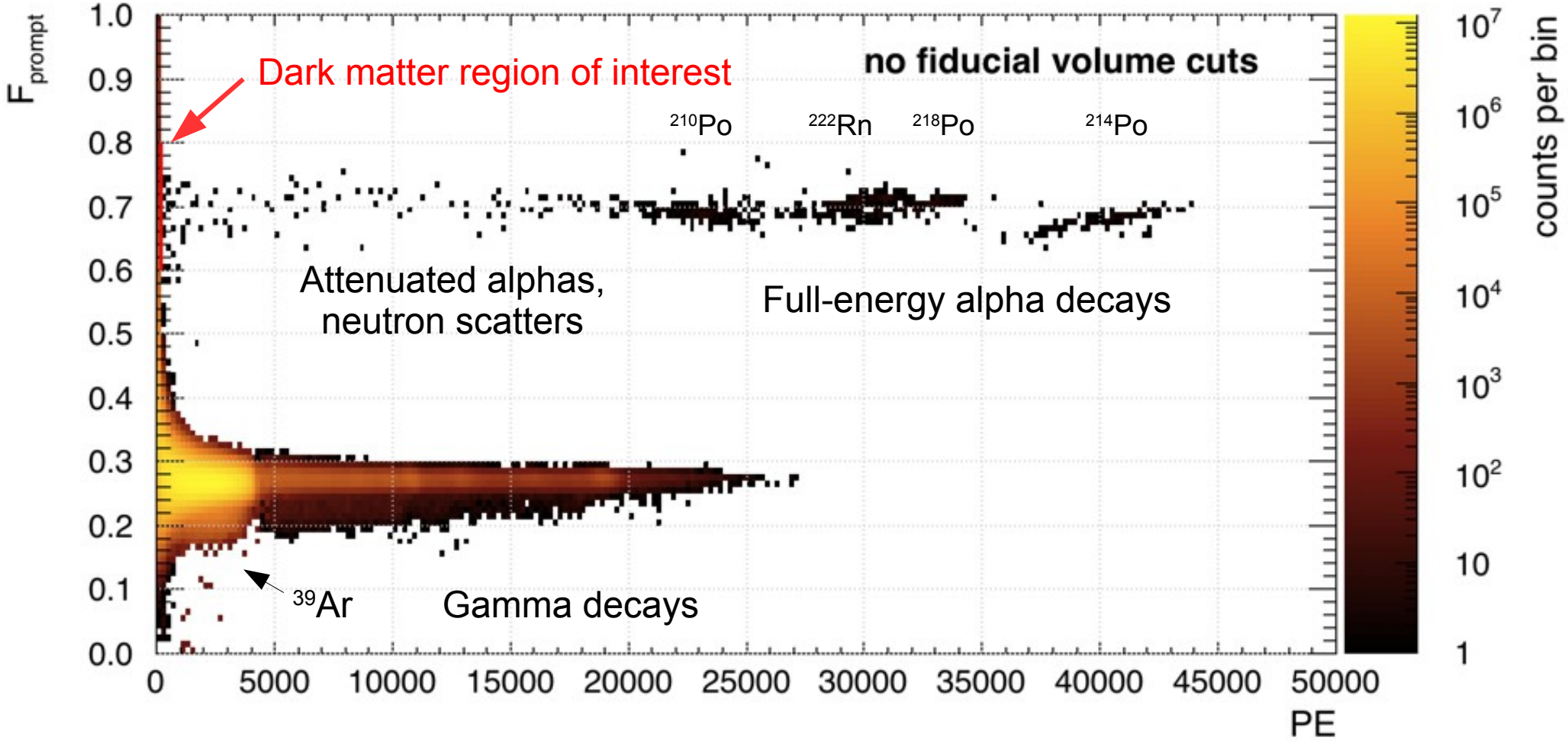




Using our best PSD algorithm:

Leakage probability at 110 PE (~ 17.5 keVee) is **$10^{-10}$** at 50% nuclear recoil acceptance

**Detailed PSD paper:** Submitted to European Physics Journal C (2021) arXiv:2103.12202

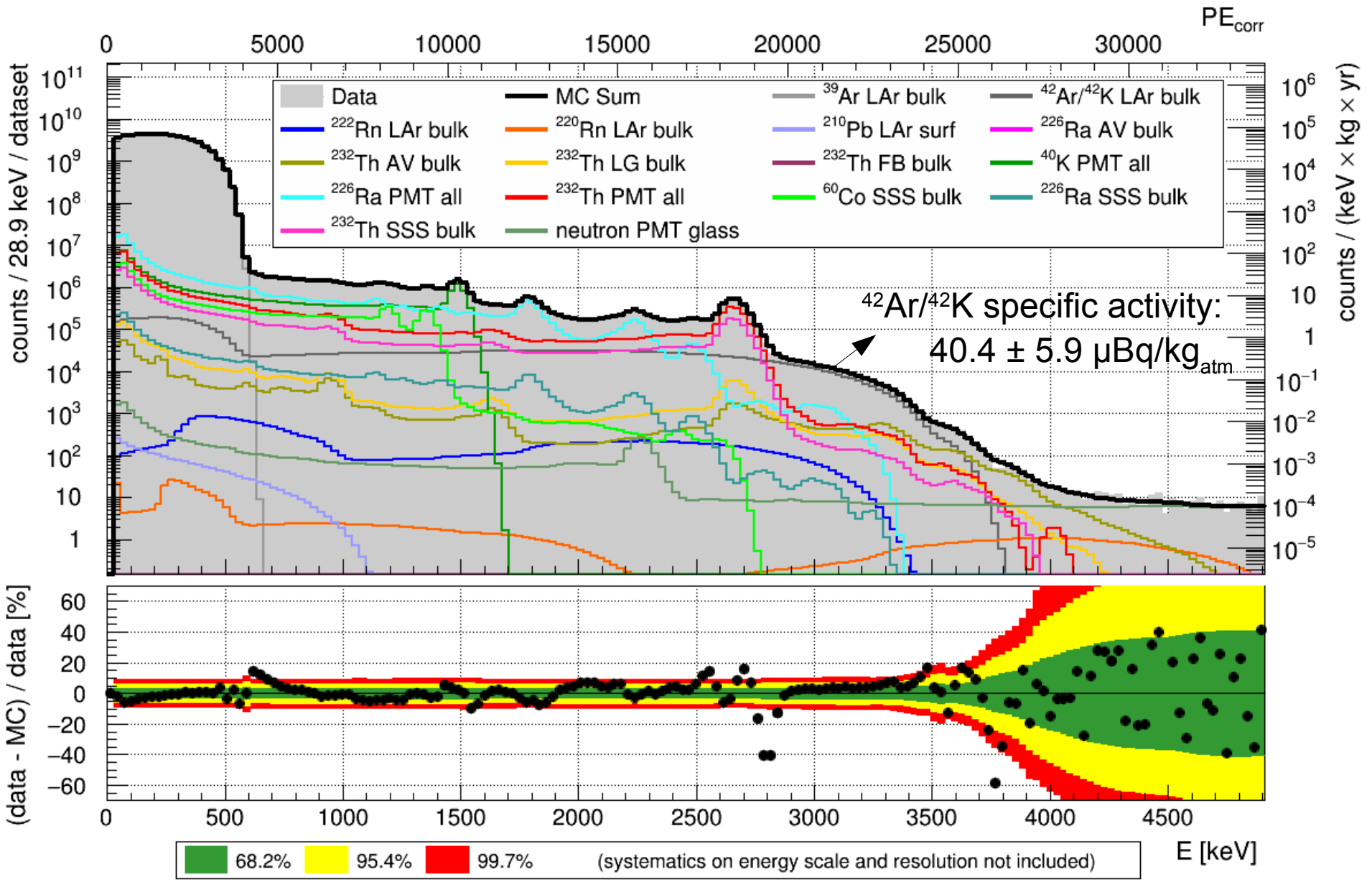
# DEAP-3600: Early Physics Data




**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

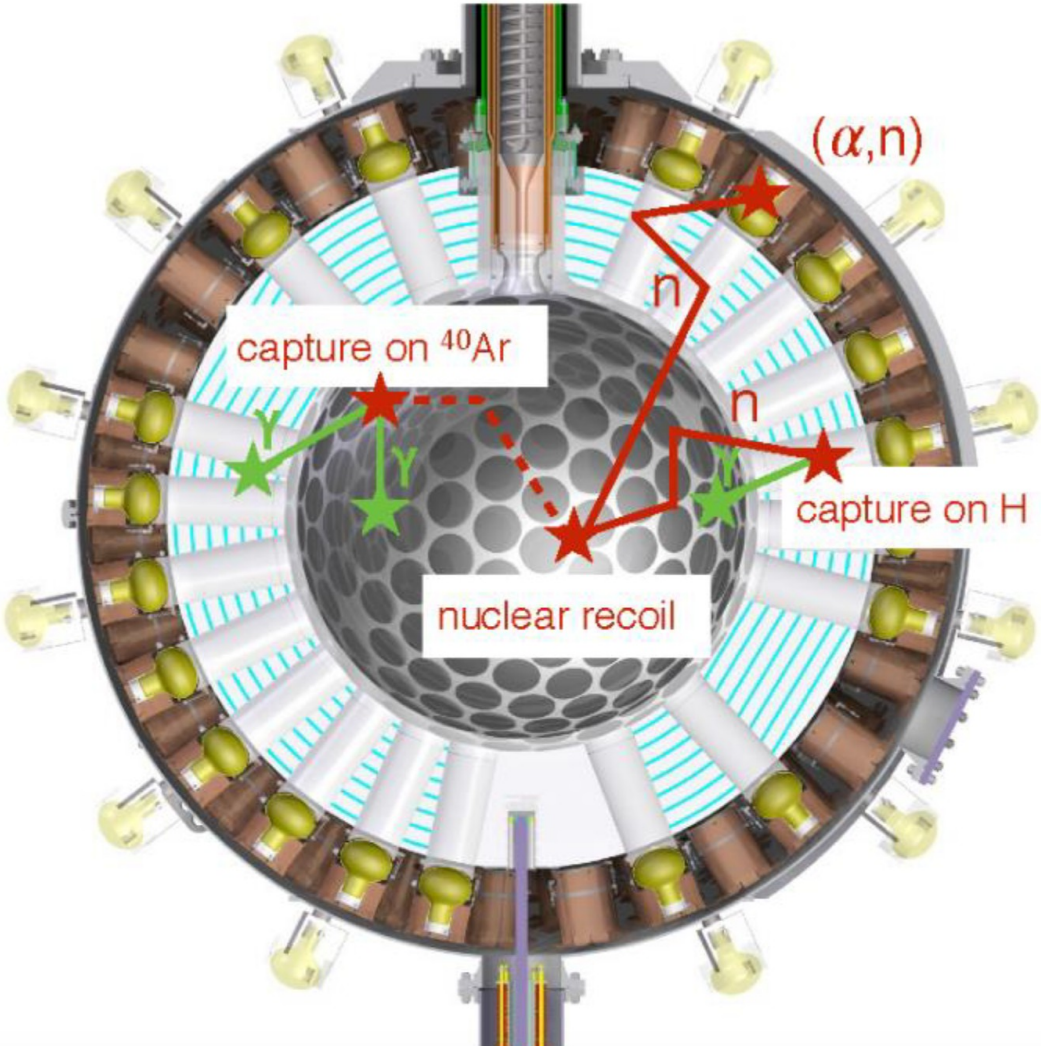
# Neutron Backgrounds

**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

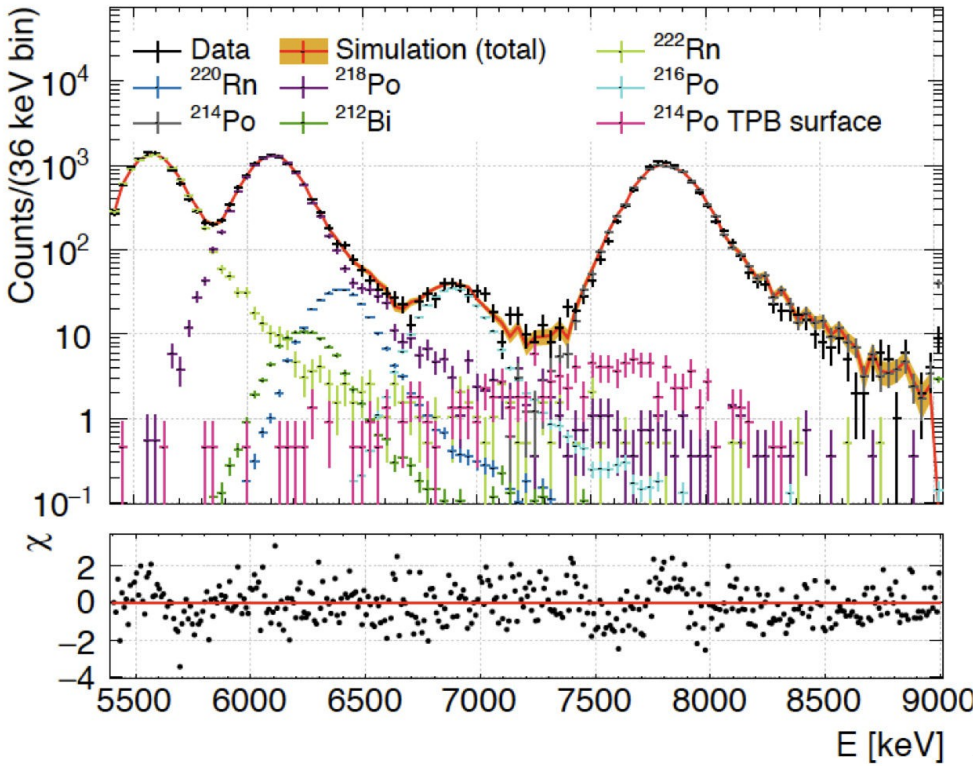
→ **No impact** on the dark matter search

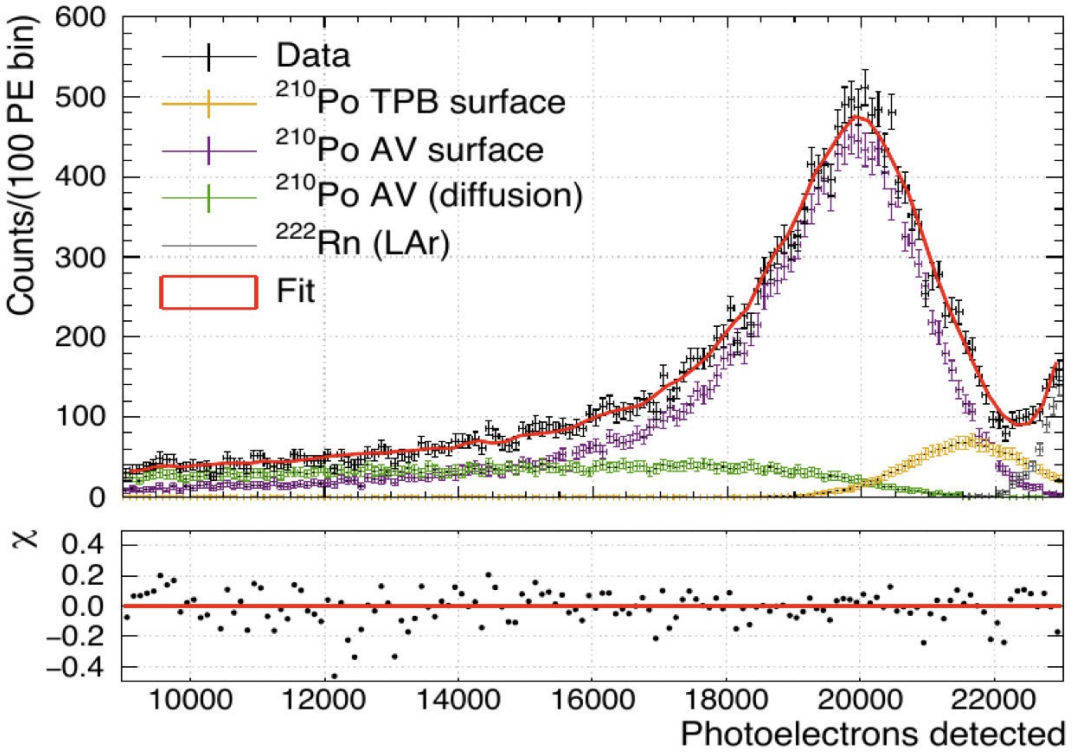
Alphas from **acrylic vessel surface** may be attenuated

→ Some reconstruct at intermediate energy

→ Rejected with position reconstruction

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



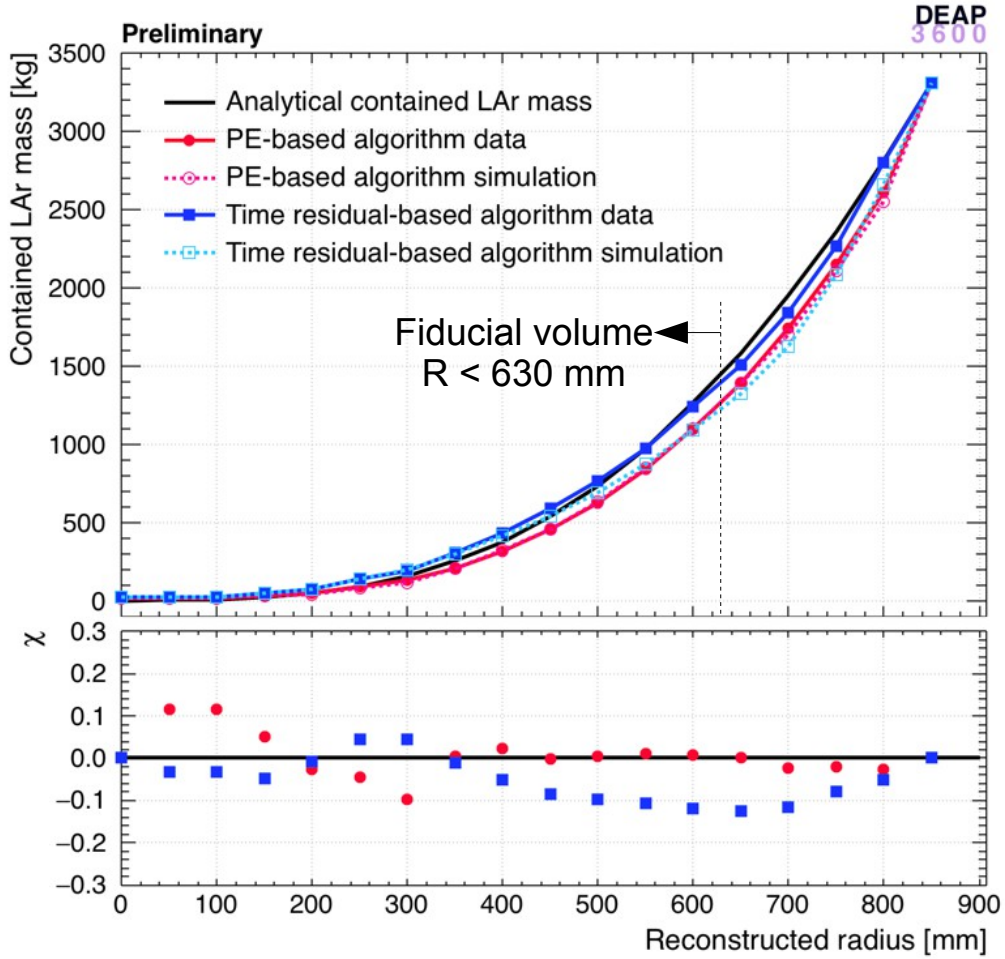




High-energy alpha decays observed from the liquid argon volume are **well-described** by our background model, demonstrating extremely low levels of radon backgrounds

# Position Reconstruction: Against Surface Alphas

Two main algorithms for position reconstruction

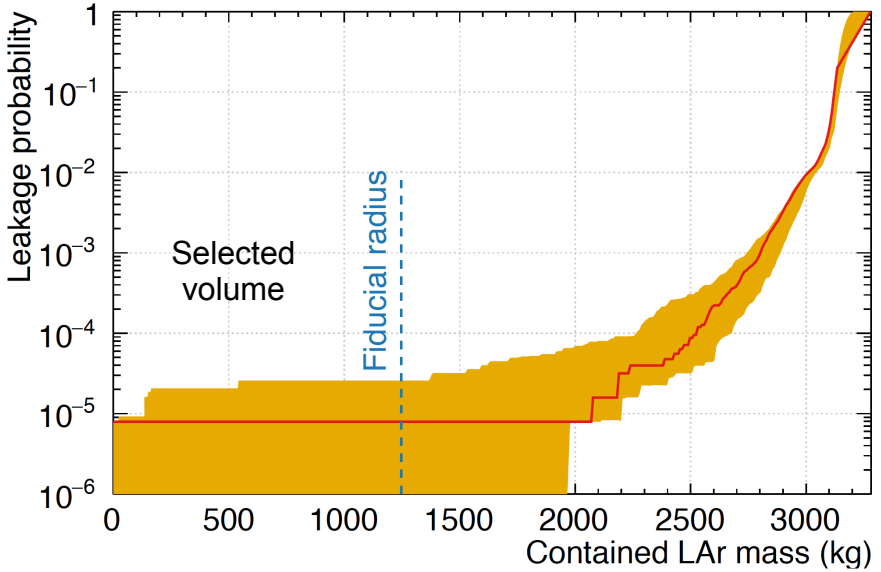
- "PE-based": **more PE are detected** closer to the event (use full 10 μs event window)
- "Time-based": **PE are detected earlier** closer to the event (use first 40 ns of event)




Data-driven measure of resolution:

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

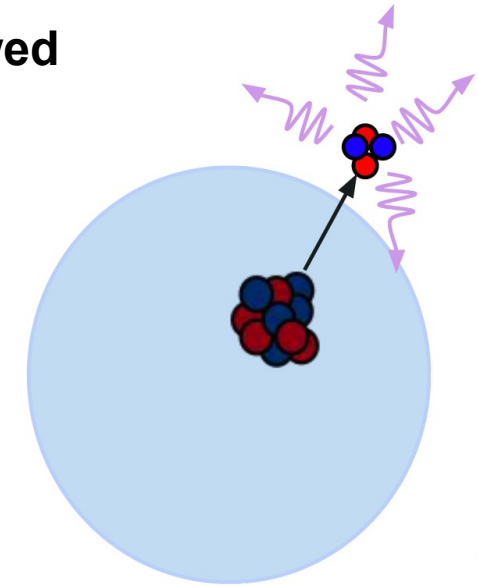
Very low surface alpha leakage

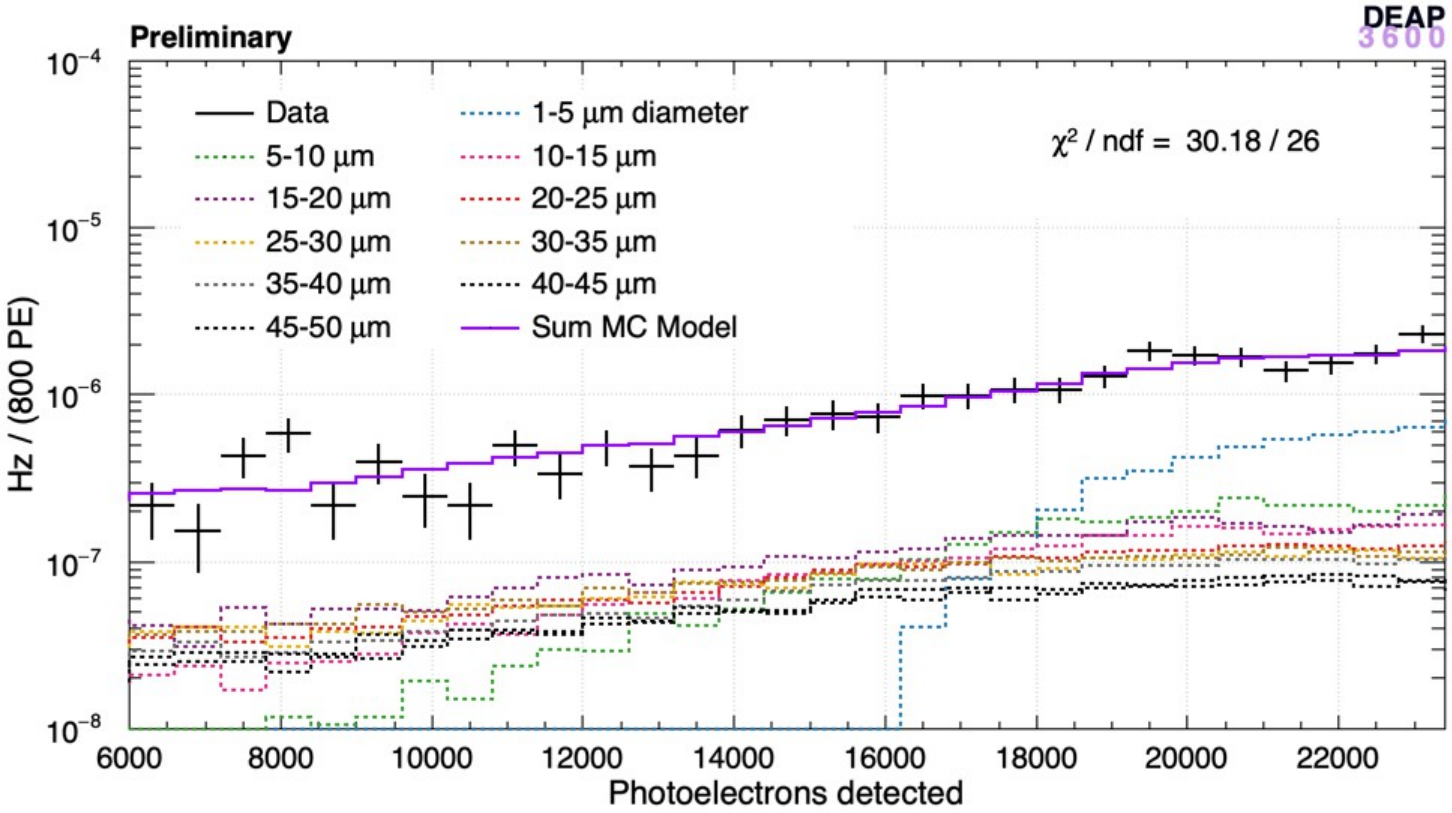



JINST 15, 05, C05061 (2020) arXiv:2004.02058

# Dust Alpha Backgrounds

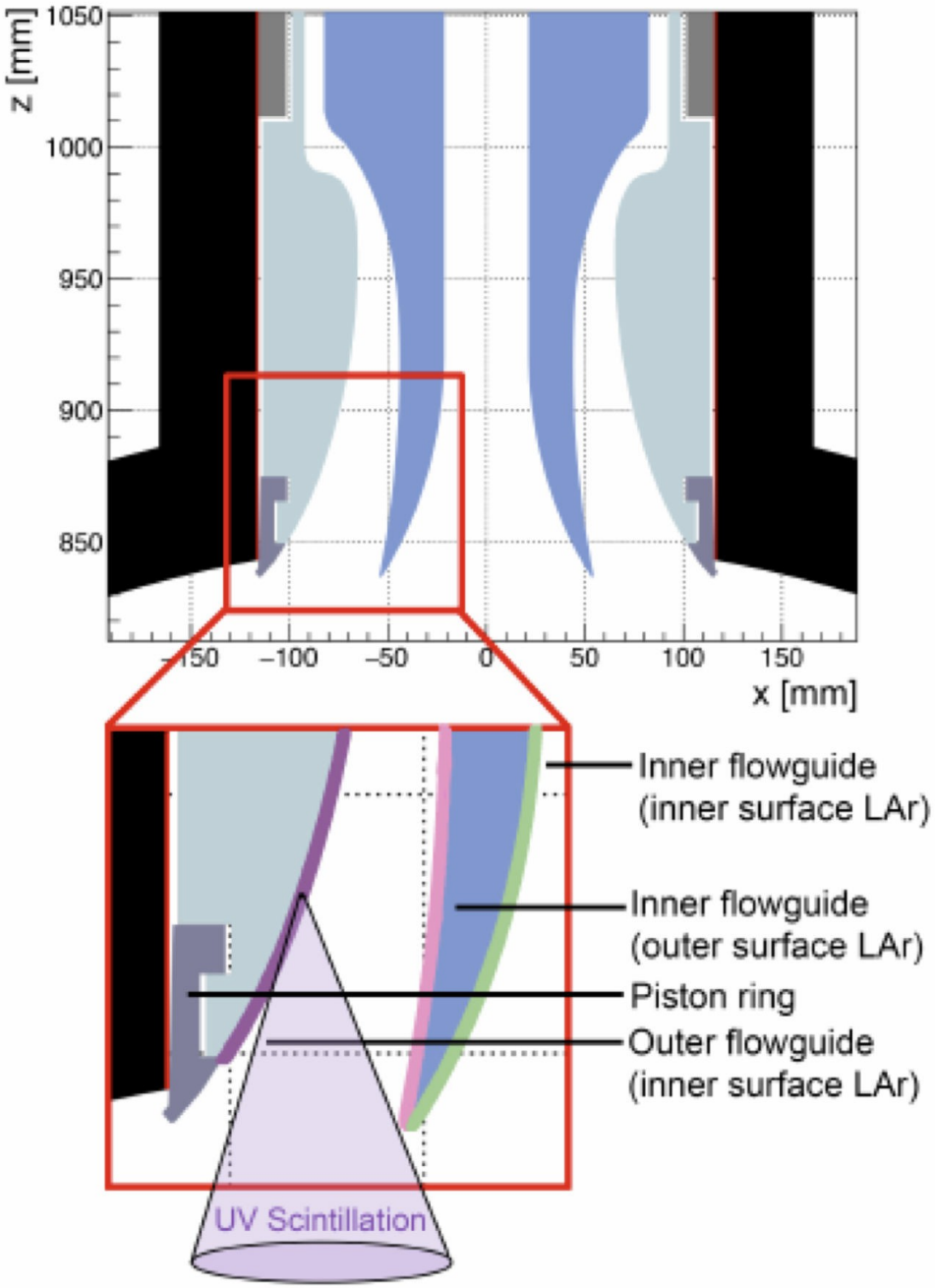
- **Alpha decays** from trace amounts of **dust particulates** in LAr create low-PE events originating in the centre of the detector
  - **Attenuation** before entering LAr, and scintillation light **shadowed**
  - Now included in background model
    - Pure control region defined at intermediate PE






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

# 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

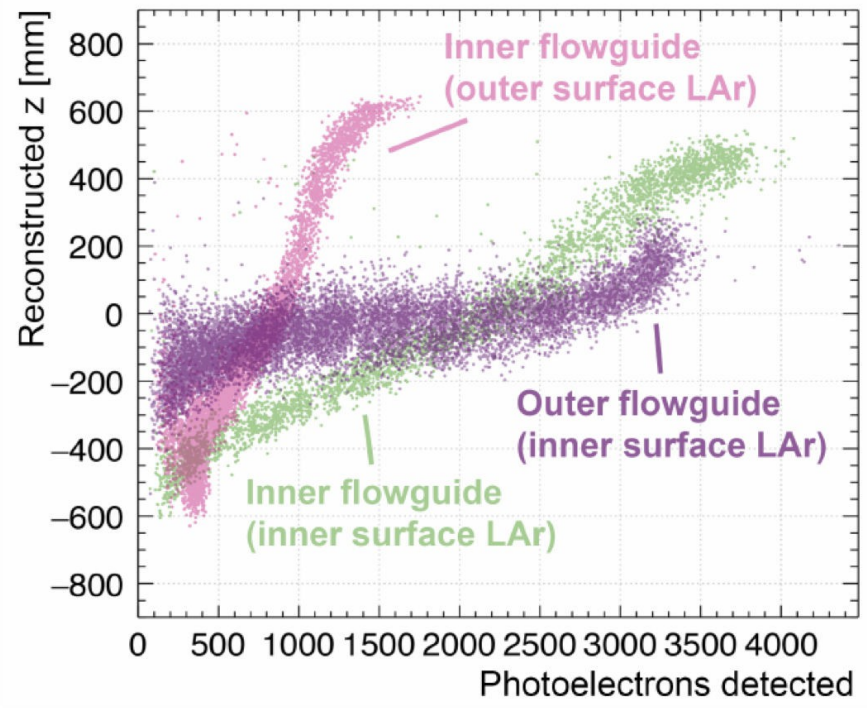
Colour code (this slide and next):

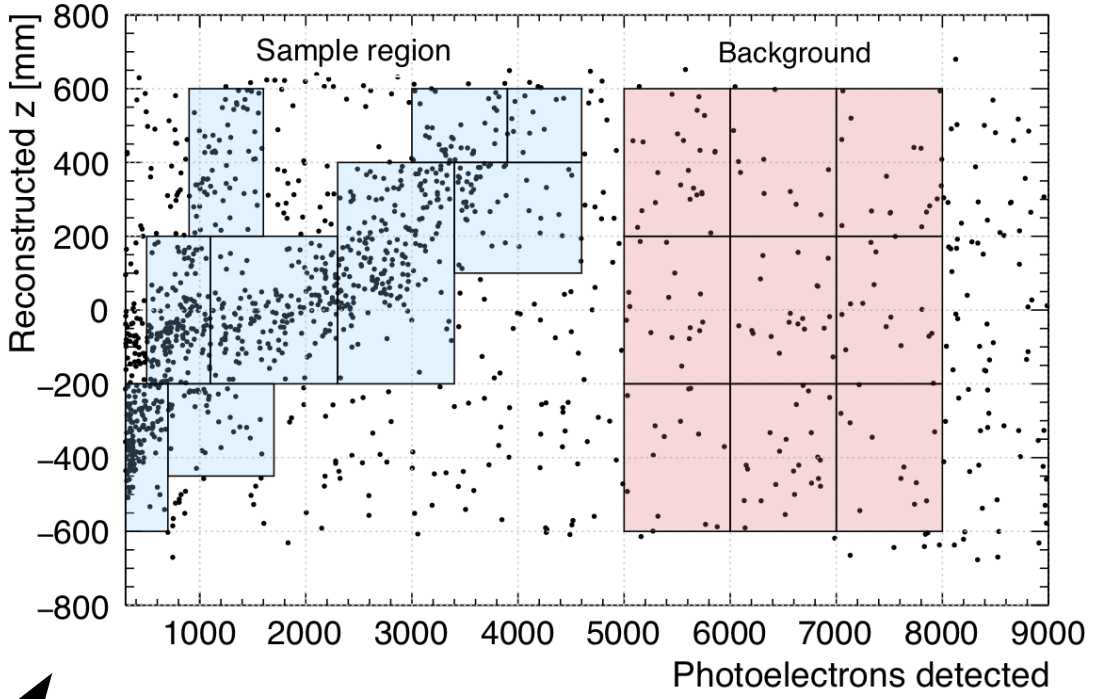
**Outer flowguide, inner surface LAr**

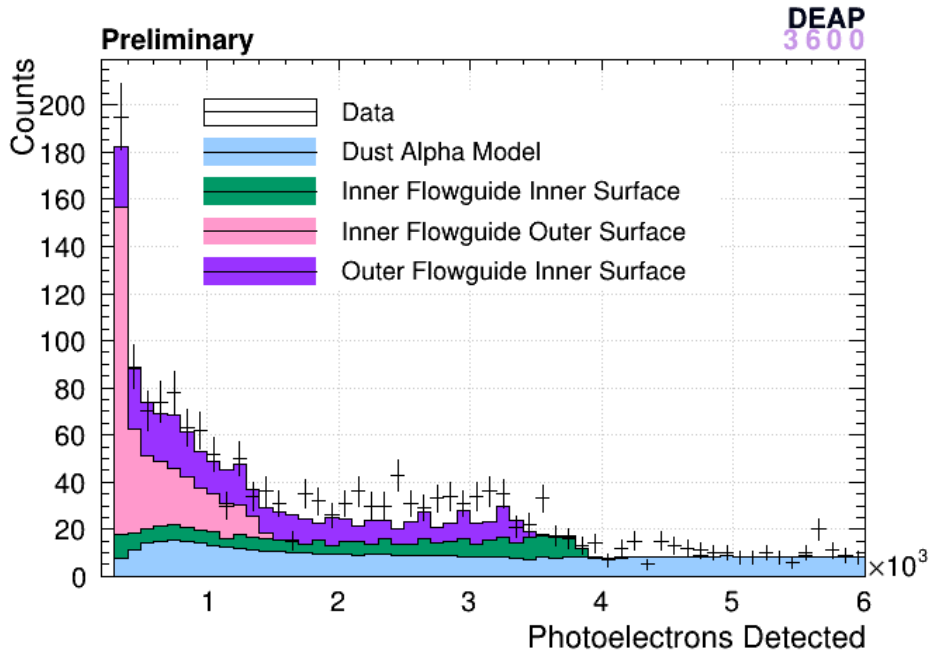
**Inner flowguide, outer surface LAr**

**Inner flowguide, inner surface LAr**

# Neck Alpha Backgrounds: Event Rate Determination




Identification of features
from Monte Carlo **simulation**

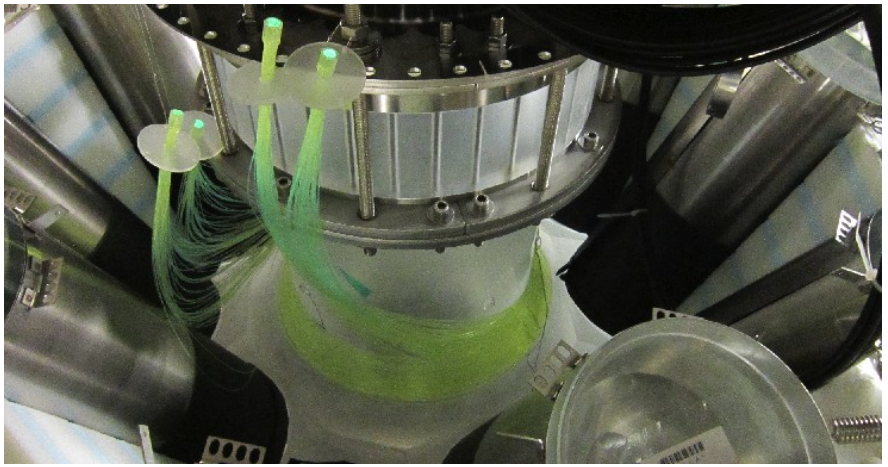
... matching features seen in **data**

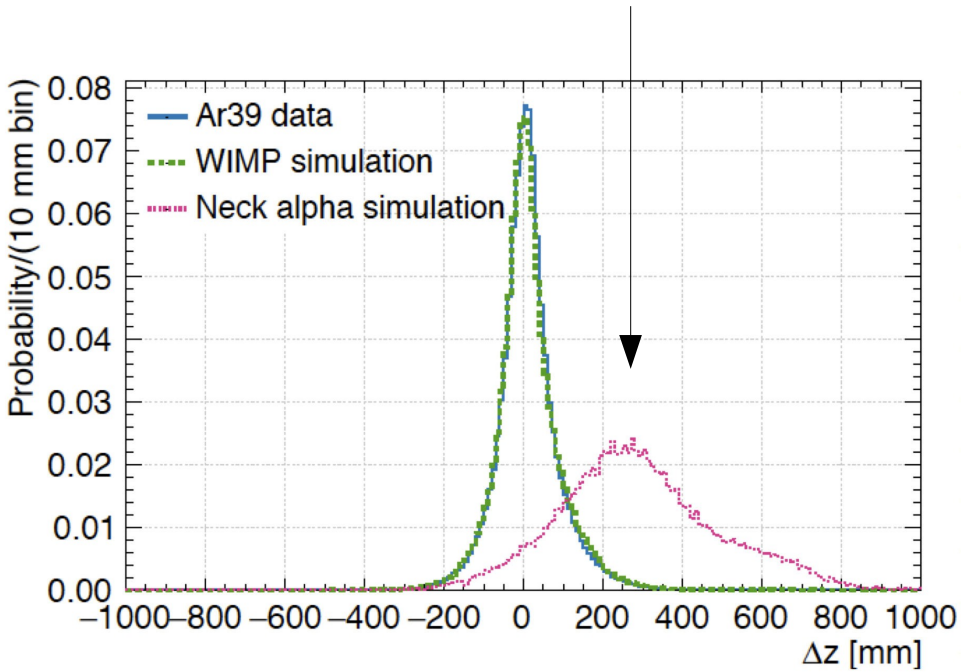
... allows a **template fit** using multiple control regions, to figure out rates of neck alpha events from all surfaces

New: Dust background considered in fit

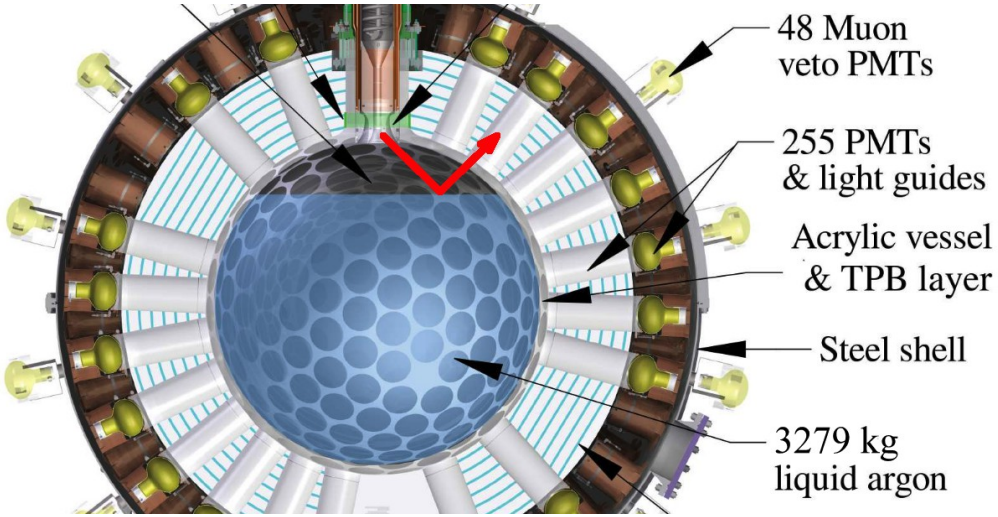
# Known Handles Against Neck Alpha Backgrounds

- 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

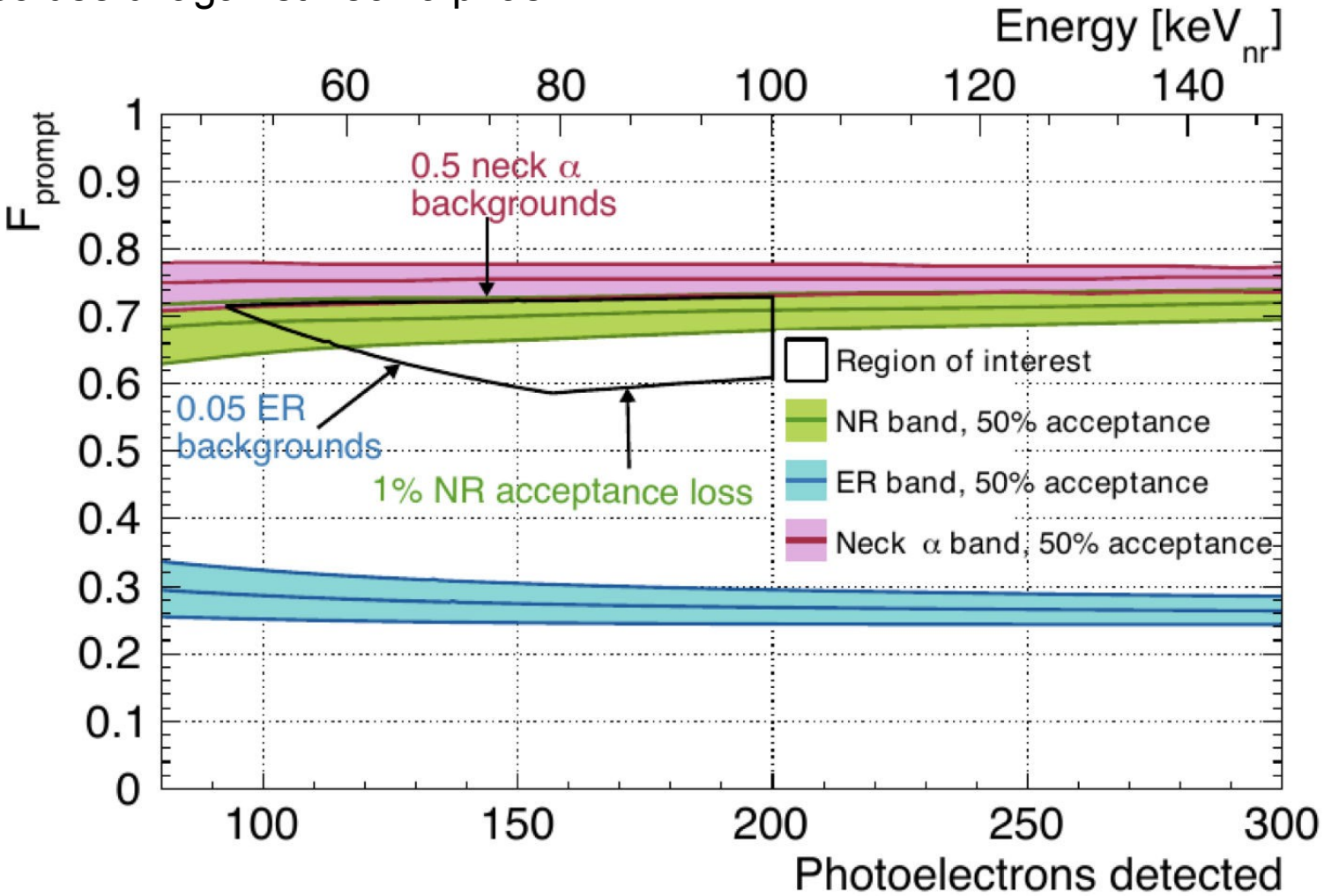



UV photon reflection at the liquid argon surface

# WIMP Signal Region

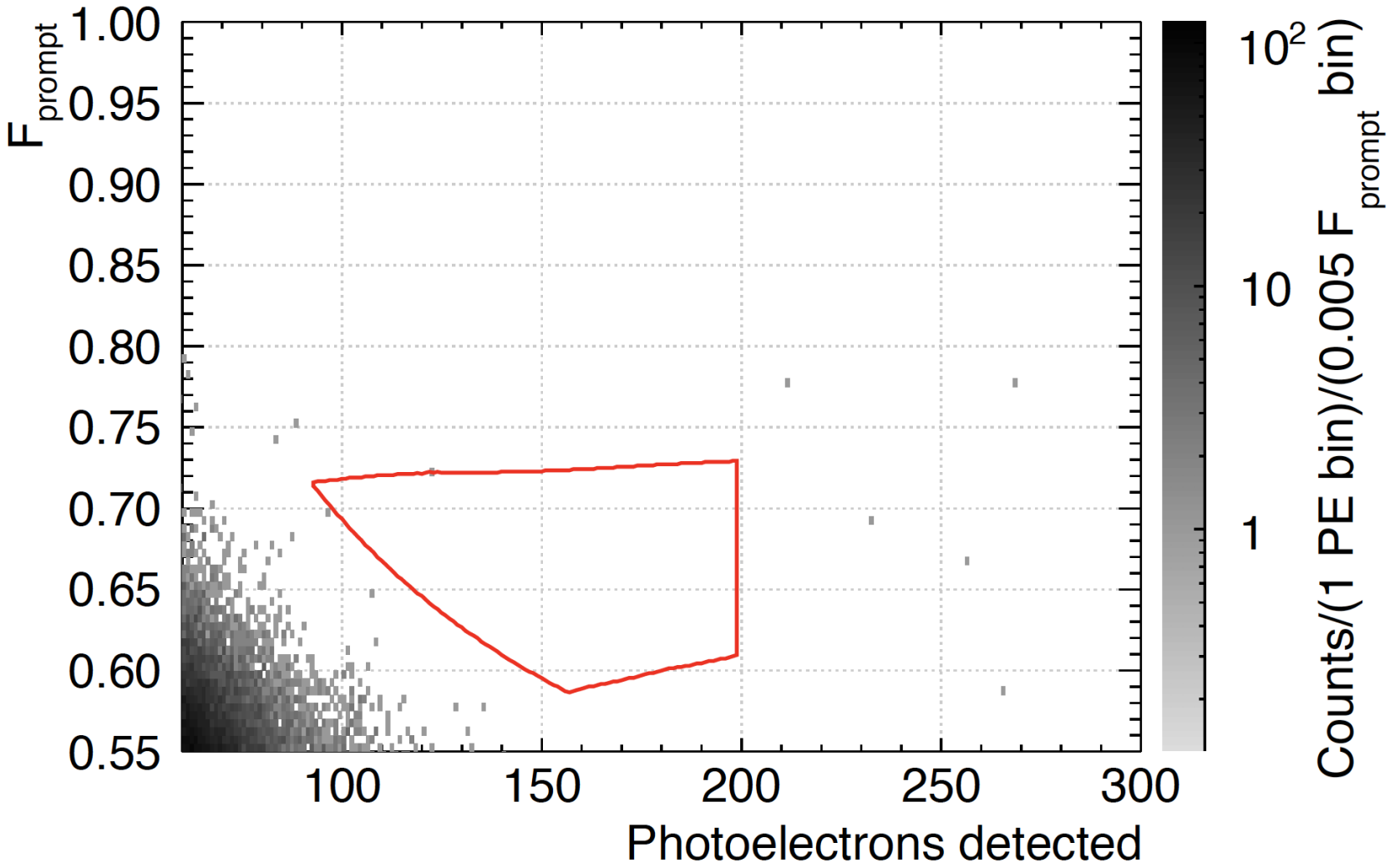
Event selection summary:
- Data quality selection, single-scatter events
- PSD against $^{39}$Ar beta decays
- Energy and position cuts against alphas
- Dedicated cuts against neck alphas
- PSD is also useful against neck alphas

Final event selection in $F_{prompt}$ and PE such that the total background expectation is **< 1 event** in 231 live-days



# 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)

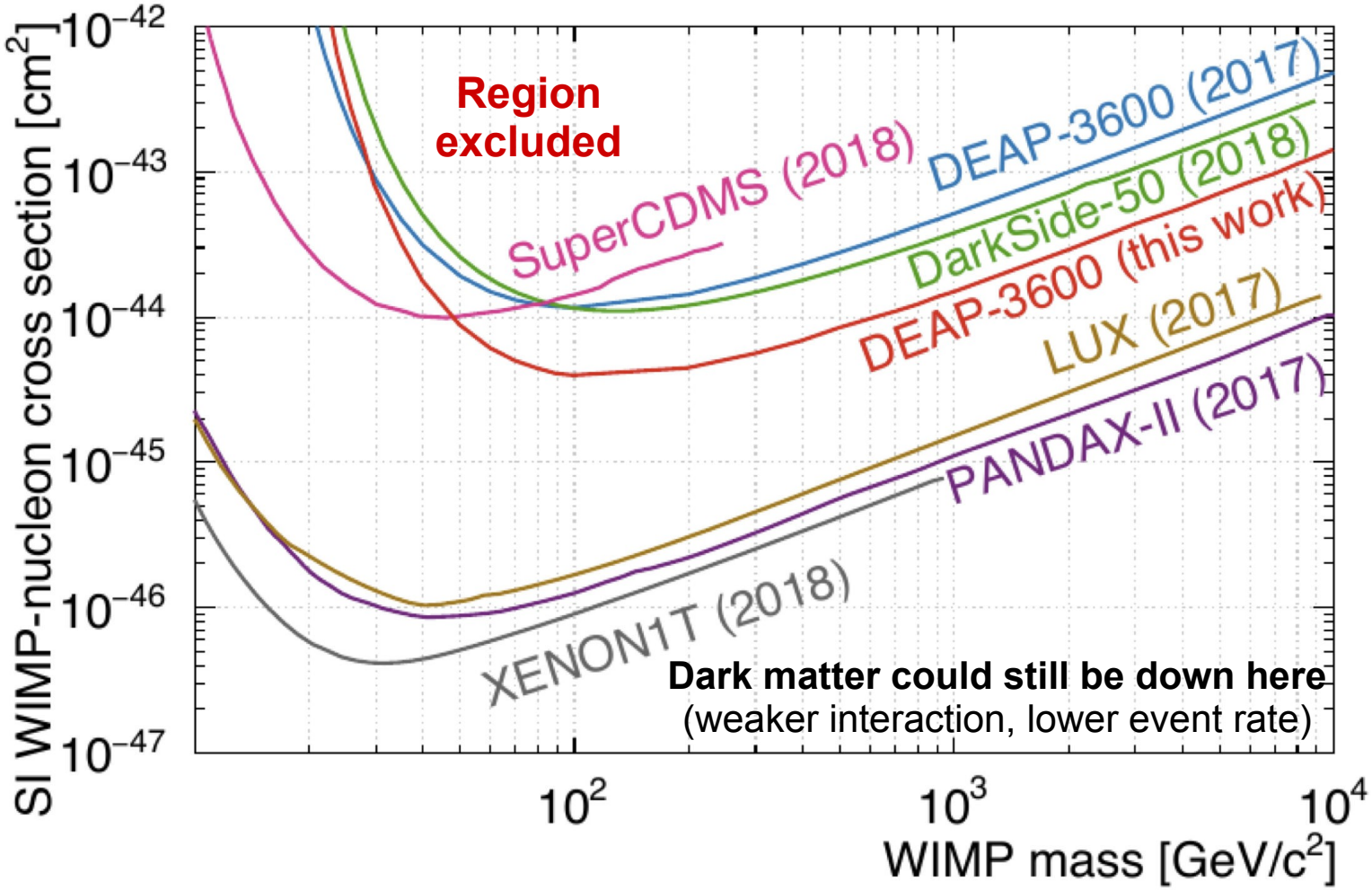



Physical Review D, 100, 022004 (2019) arXiv:1902.04048

# 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)

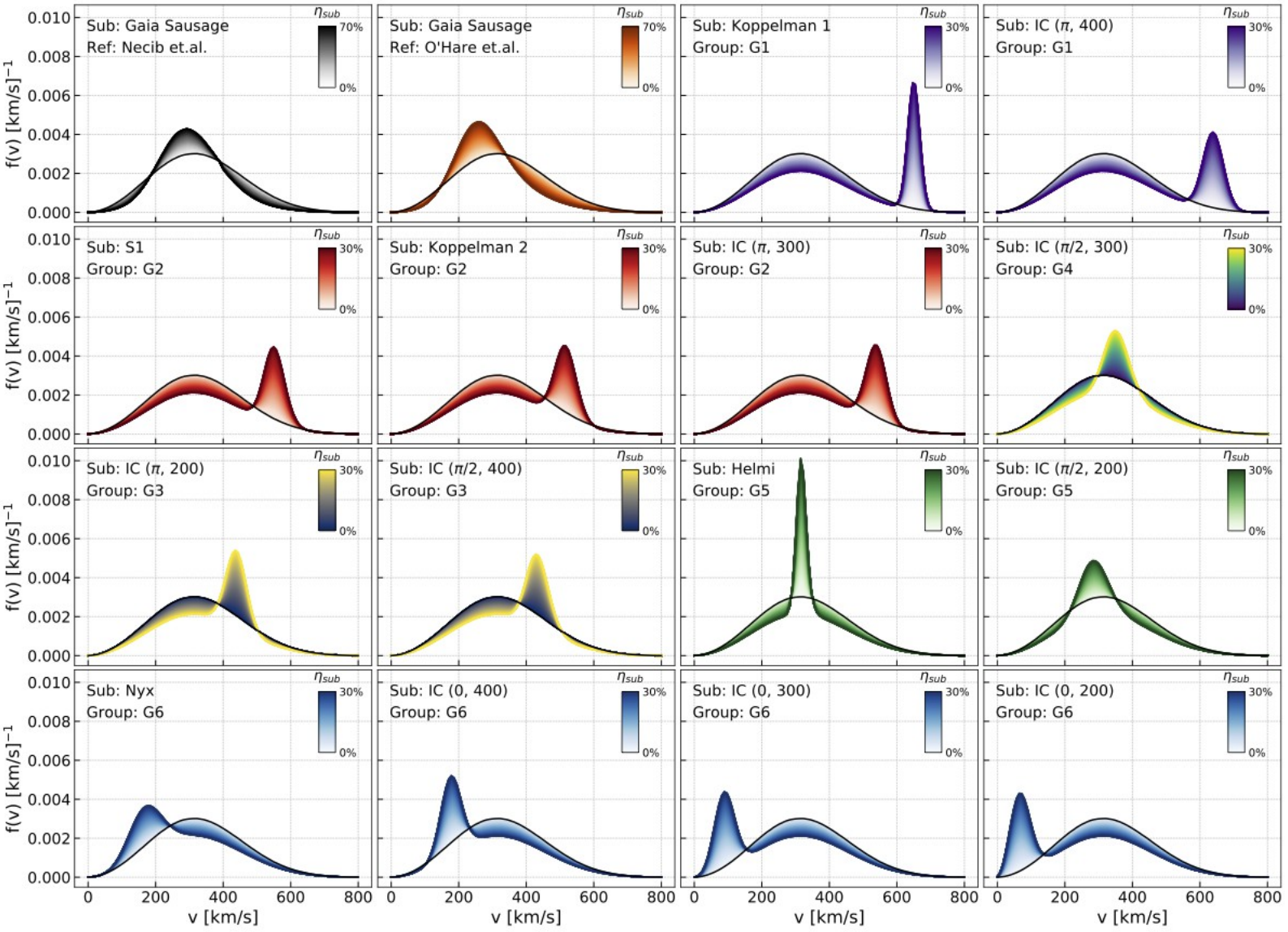
Therefore we **exclude** certain dark matter hypotheses




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

# Further Constraints on Dark Matter

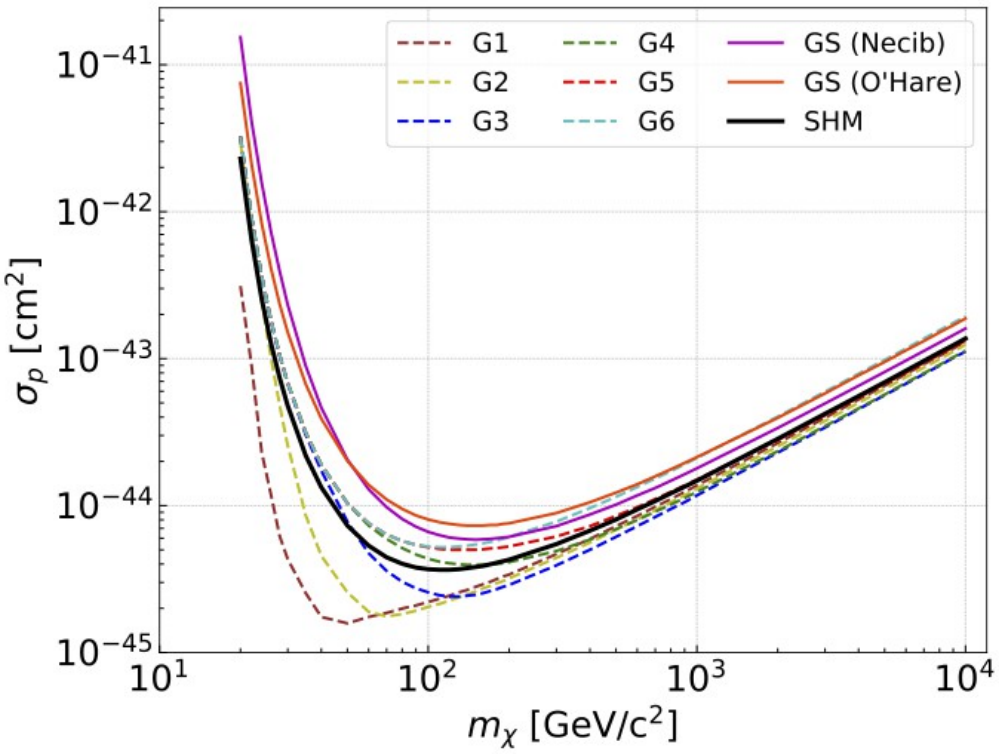
- Results are reinterpreted with a more general non-relativistic EFT framework, and exploring how possible substructures in DM halo affect these constraints



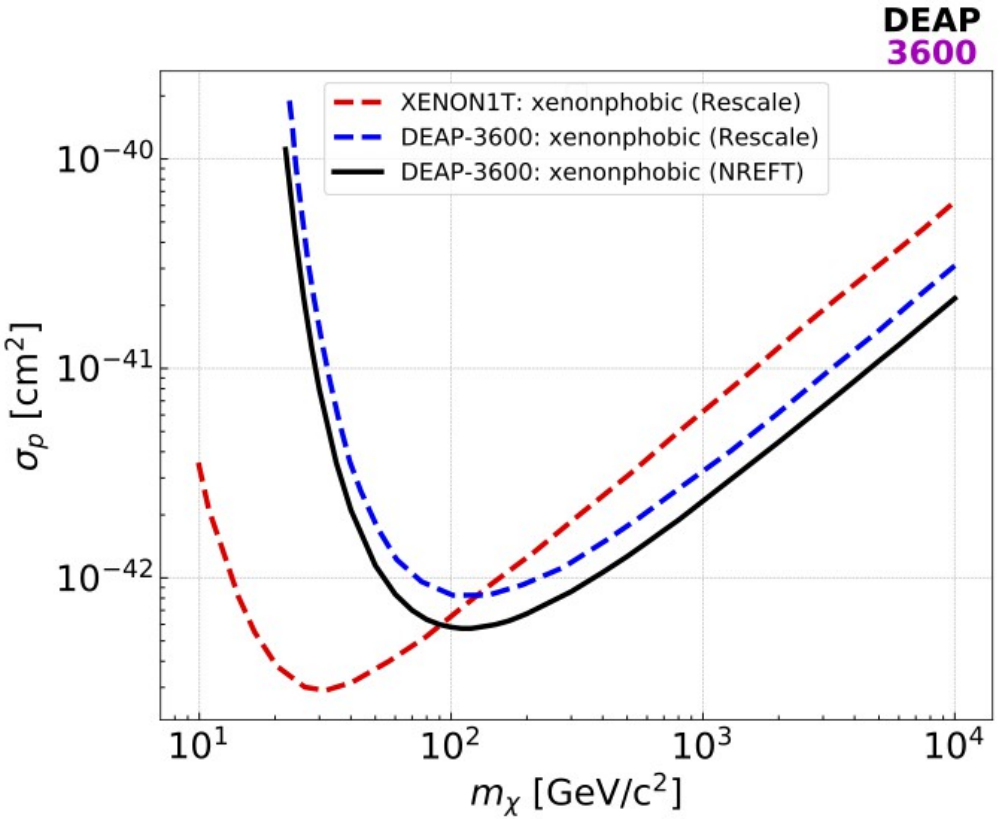
# Further Constraints on Dark Matter

- 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

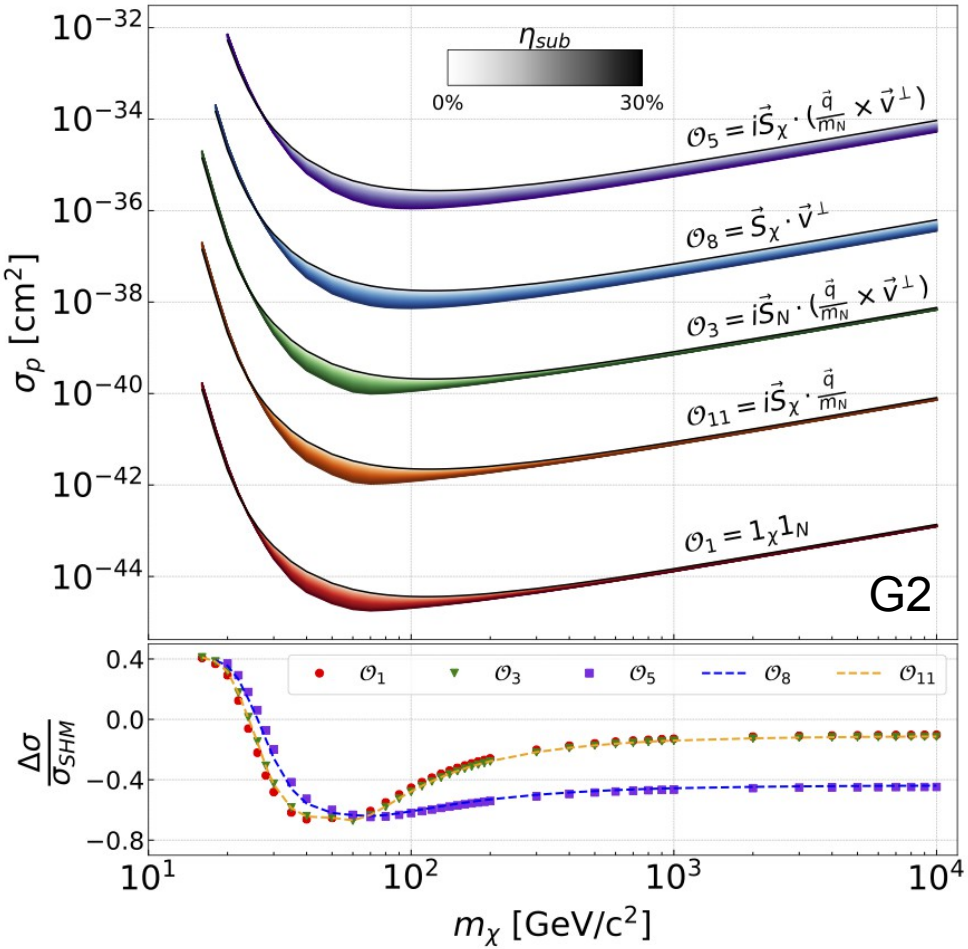



Physical Review D, 102, 082001 (2021) arXiv:2005.14667

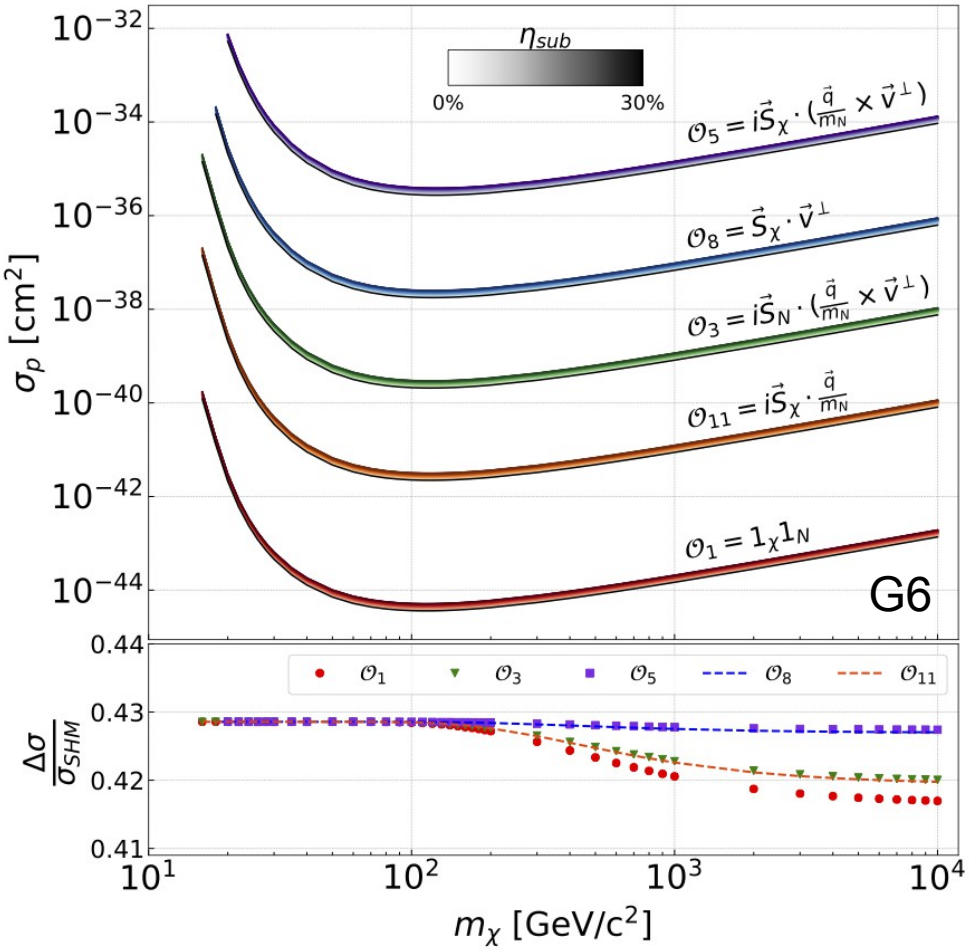
# Further Constraints on Dark Matter

- 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



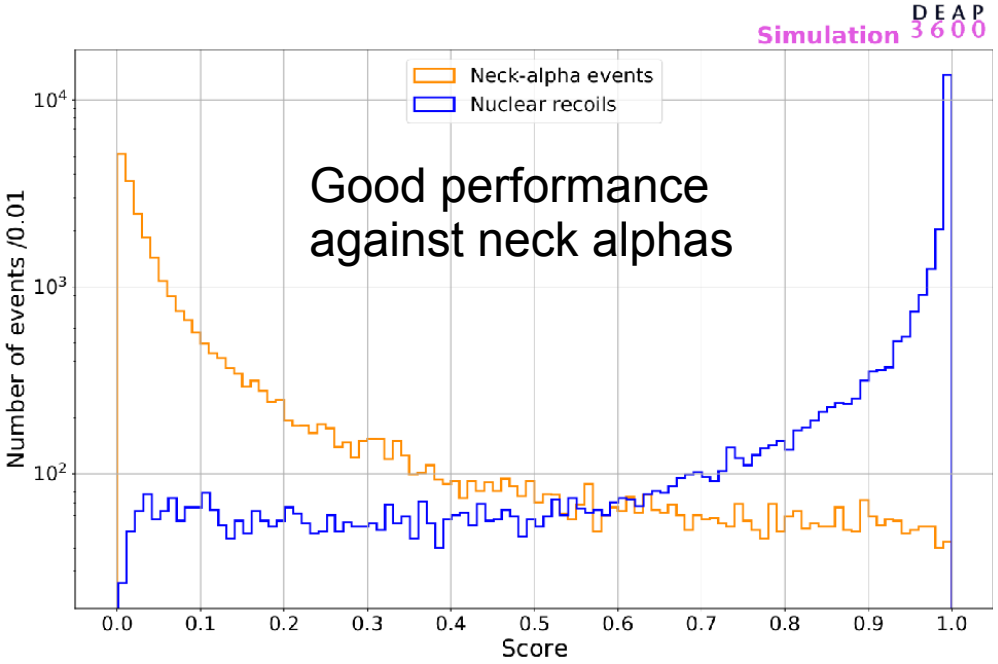

Example prograde stellar stream, e.g. Nyx

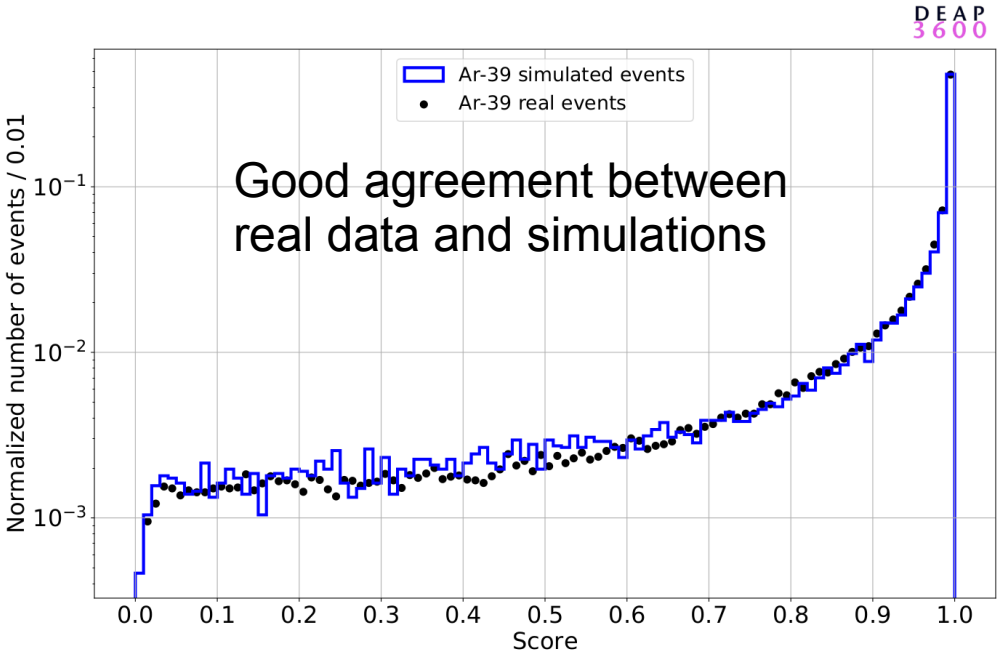



Physical Review D, 102, 082001 (2021) arXiv:2005.14667

# 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 alpha backgrounds
  - Random Forest, Boosted Decision Trees, Neural Network (shown here)
  - Now developing new observables, validating background models, and re-optimizing our DM candidate event selection



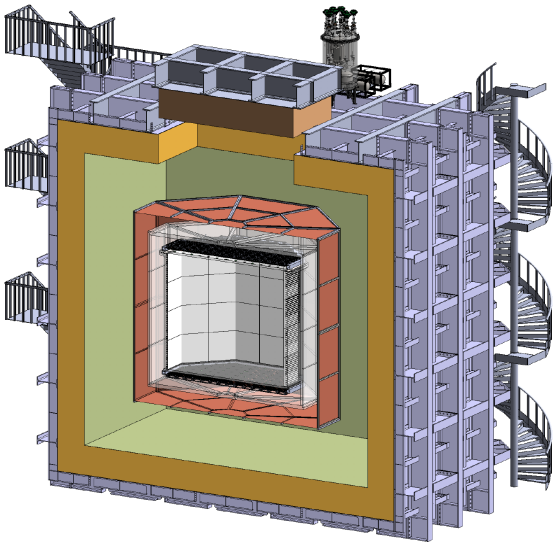



# Next Steps: DEAP-3600 Hardware Upgrades

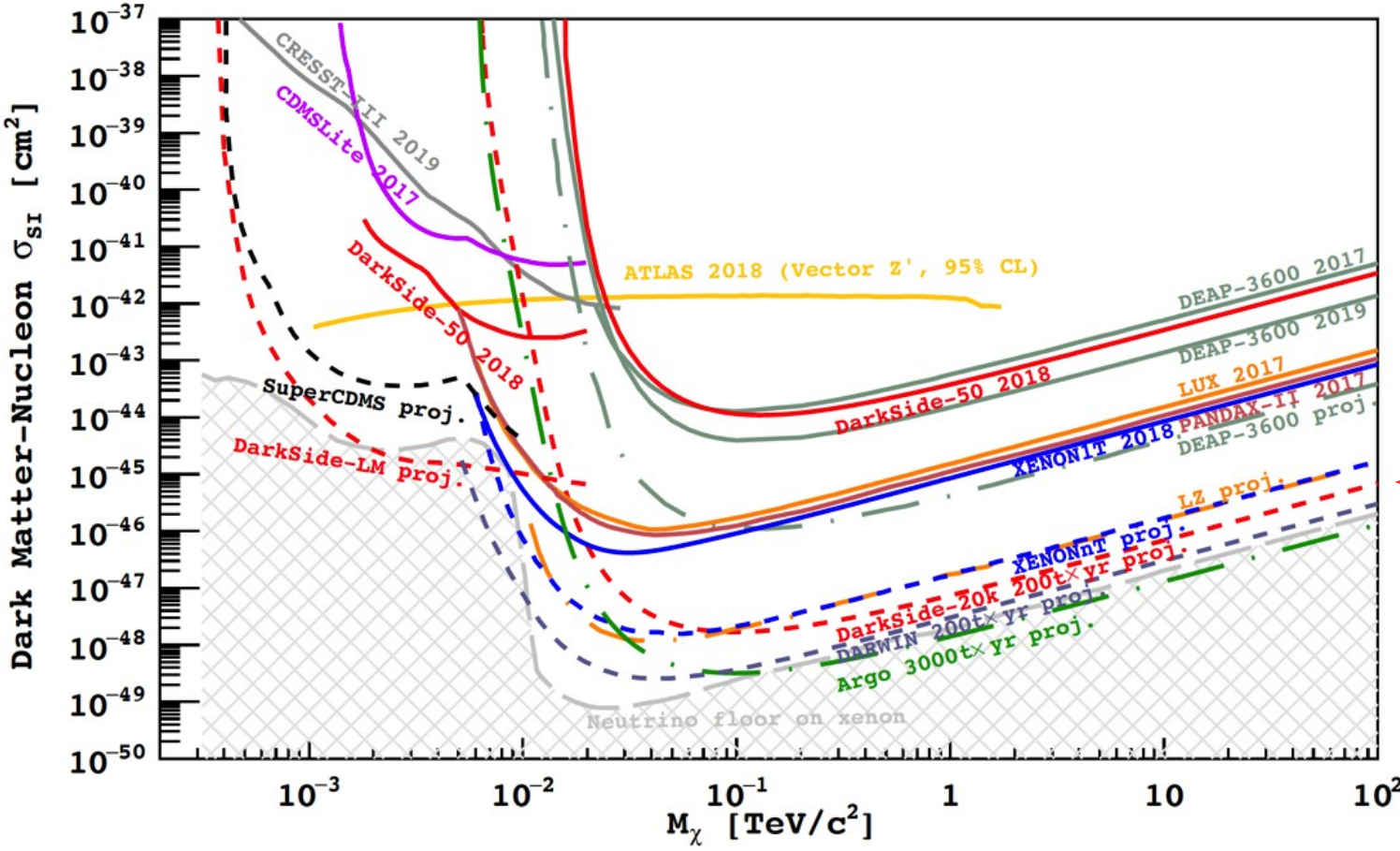
- **Hardware upgrade** program
  - Main objective: **Mitigate limiting background sources**
    - Neck seal replacement, allowing a complete fill with LAr
    - Pyrene: slow wavelength shifter on neck flowguides, to remove neck alpha background with PSD
    - Alternate cooling system, to filter out dust
    - Also perform maintenance on cryogenic systems
- Current status
  - Detector now empty of LAr
    - Still taking data in GAr and vacuum, with calibration sources
  - COVID delays: Plan to complete upgrades in the next 6 months
- New DM search data in upgraded detector expected in 2022
  - **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



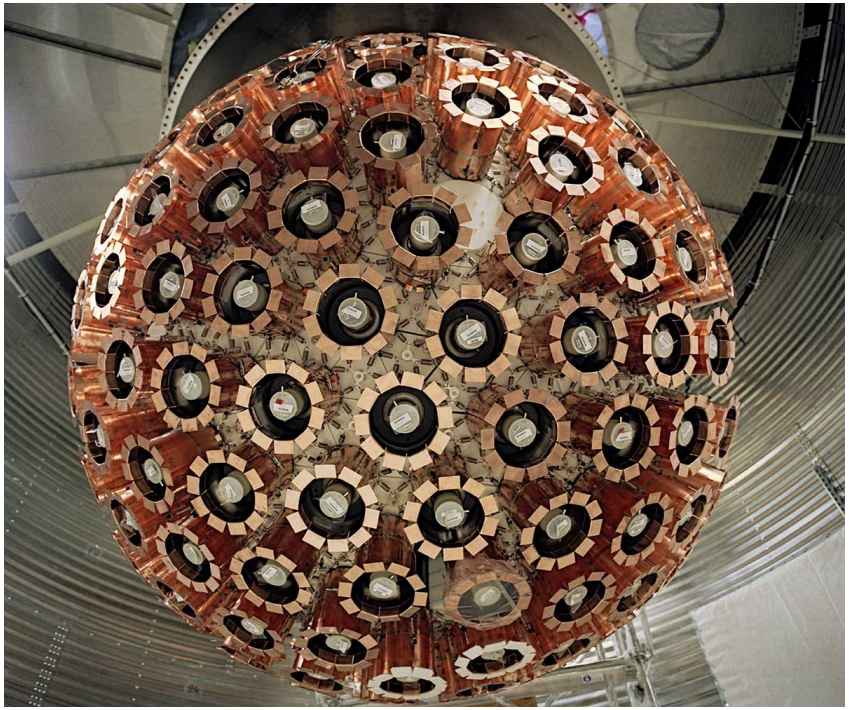
DarkSide-20k




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**: stay tuned!
    - **Hardware upgrade**



- **Instrumentation** research and development for future particle detectors
  - Design and simulation for DarkSide-20k and ARGO
  - Silicon photomultipliers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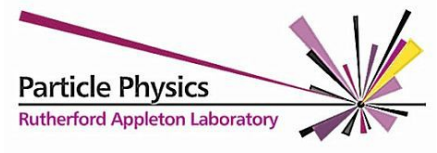
Particle Physics
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**Thank you!**


IF
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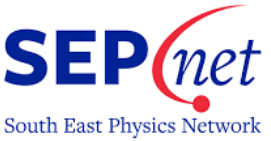
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