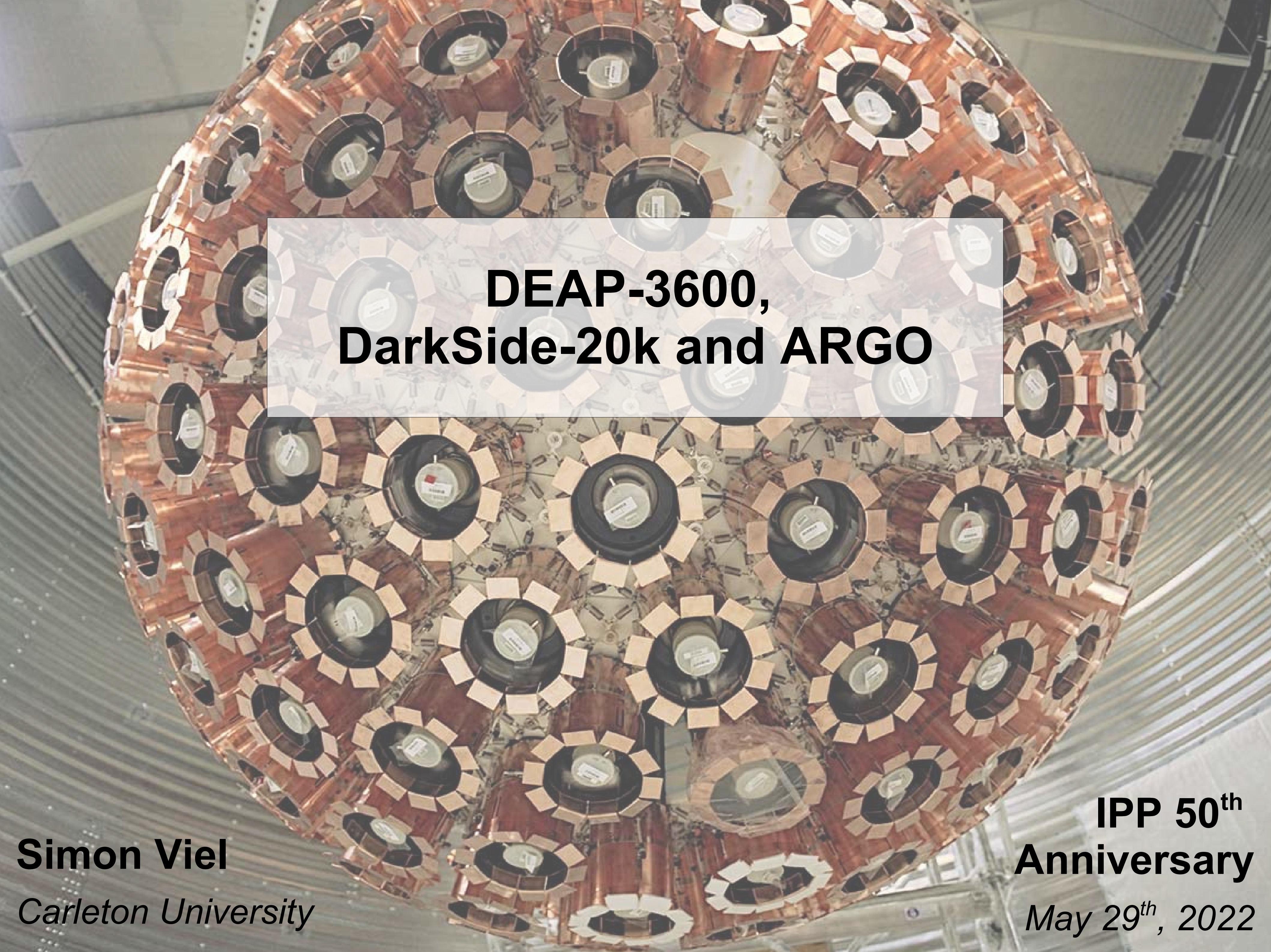


DEAP-3600, DarkSide-20k and ARGO

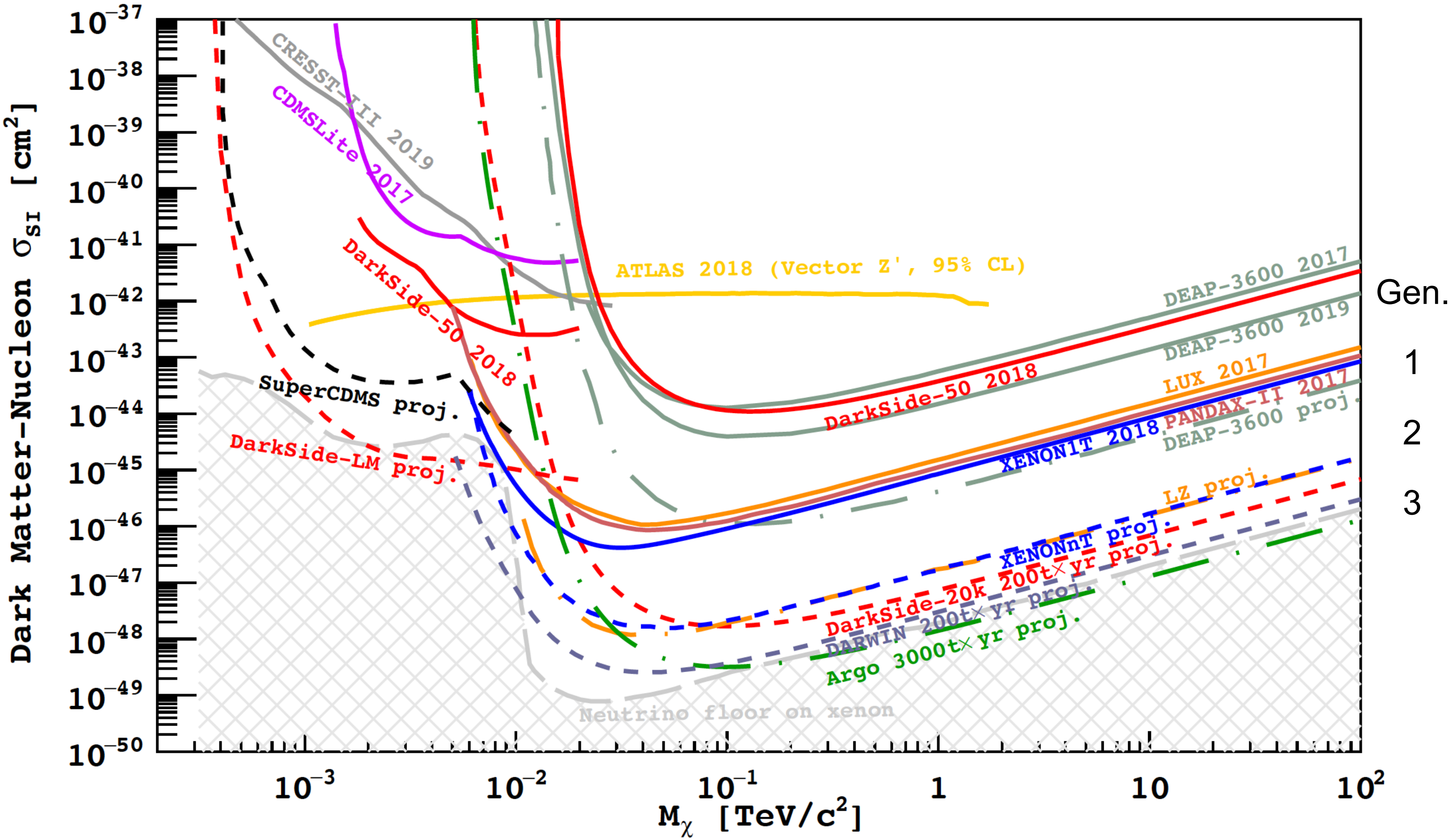
Simon Viel

Carleton University

IPP 50th Anniversary

May 29th, 2022

Sensitivity to dark matter keeps improving!



Focus of this talk: **Liquid argon dark matter searches**

Generation 1:

Most recent results with **DEAP-3600**

DEAP-3600: Most recent publications

DEAP Collaboration (2022) **First direct detection constraints on Planck-scale mass dark matte**r with multiple-scatter signatures using the DEAP-3600 detector. Physical Review Letters 128, 011801, arXiv:2108.09405

DEAP Collaboration (2021) **Pulseshape discrimination** against low-energy Ar-39 beta decays in liquid argon with 4.5 tonne-years of DEAP-3600 data. European Physical Journal C, 81, 823, arXiv:2103.12202

DEAP Collaboration (2020) **Constraints on dark matter-nucleon effective couplings** in the presence of kinematically distinct **halo substructures** using the DEAP-3600 detector. Physical Review D, 102, 082001, Erratum: Phys. Rev. D 105, 029901 (2022), arXiv:2005.14667

DEAP Collaboration (2020) **The liquid-argon scintillation pulseshape** in DEAP-3600. European Physical Journal C, 80, 303, arXiv:2001.09855

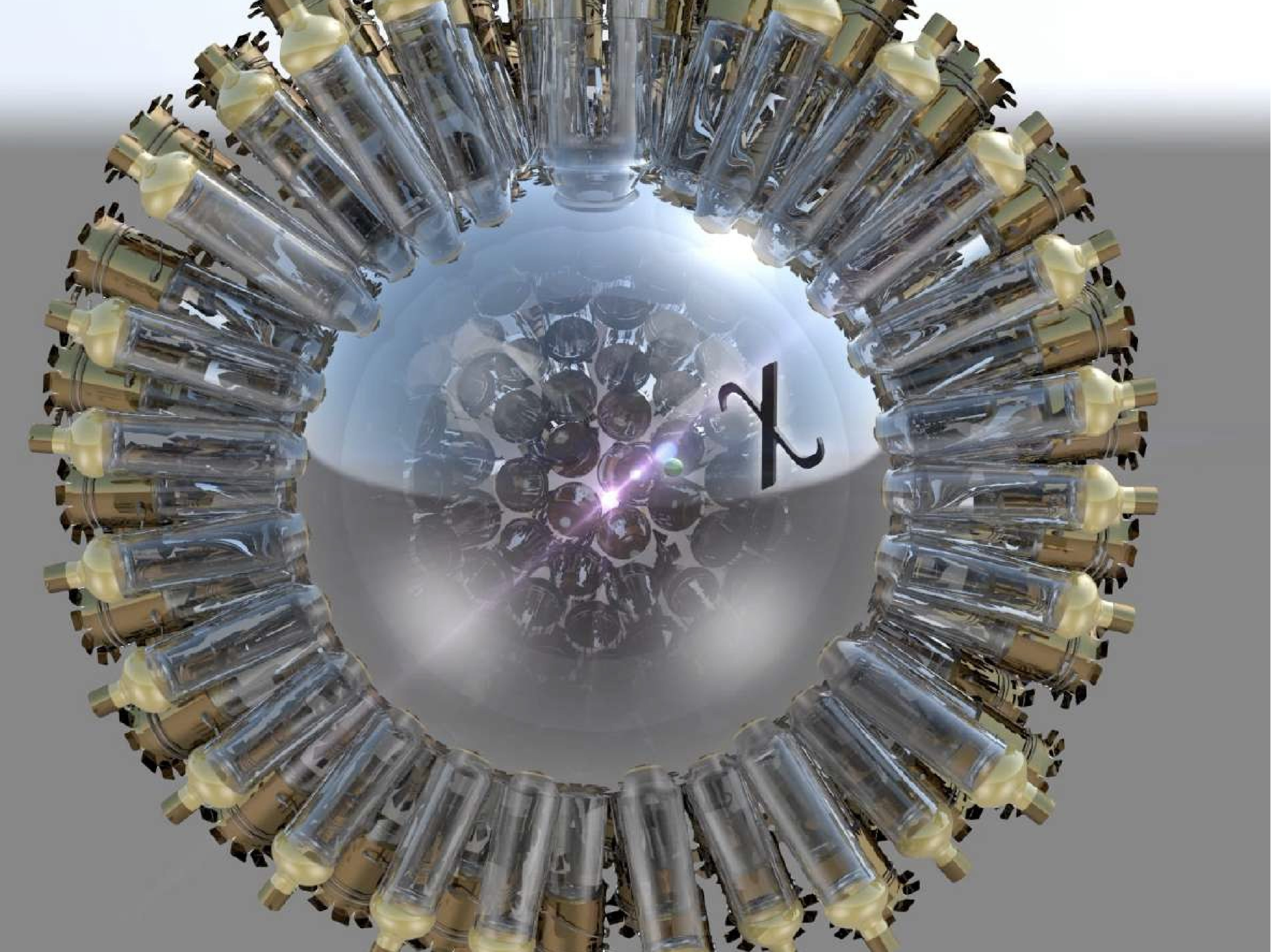
DEAP Collaboration (2019) **Electromagnetic backgrounds and potassium-42 activity** in the DEAP-3600 dark matter detector. Physical Review D, 100, 072009, arXiv:1905.05811

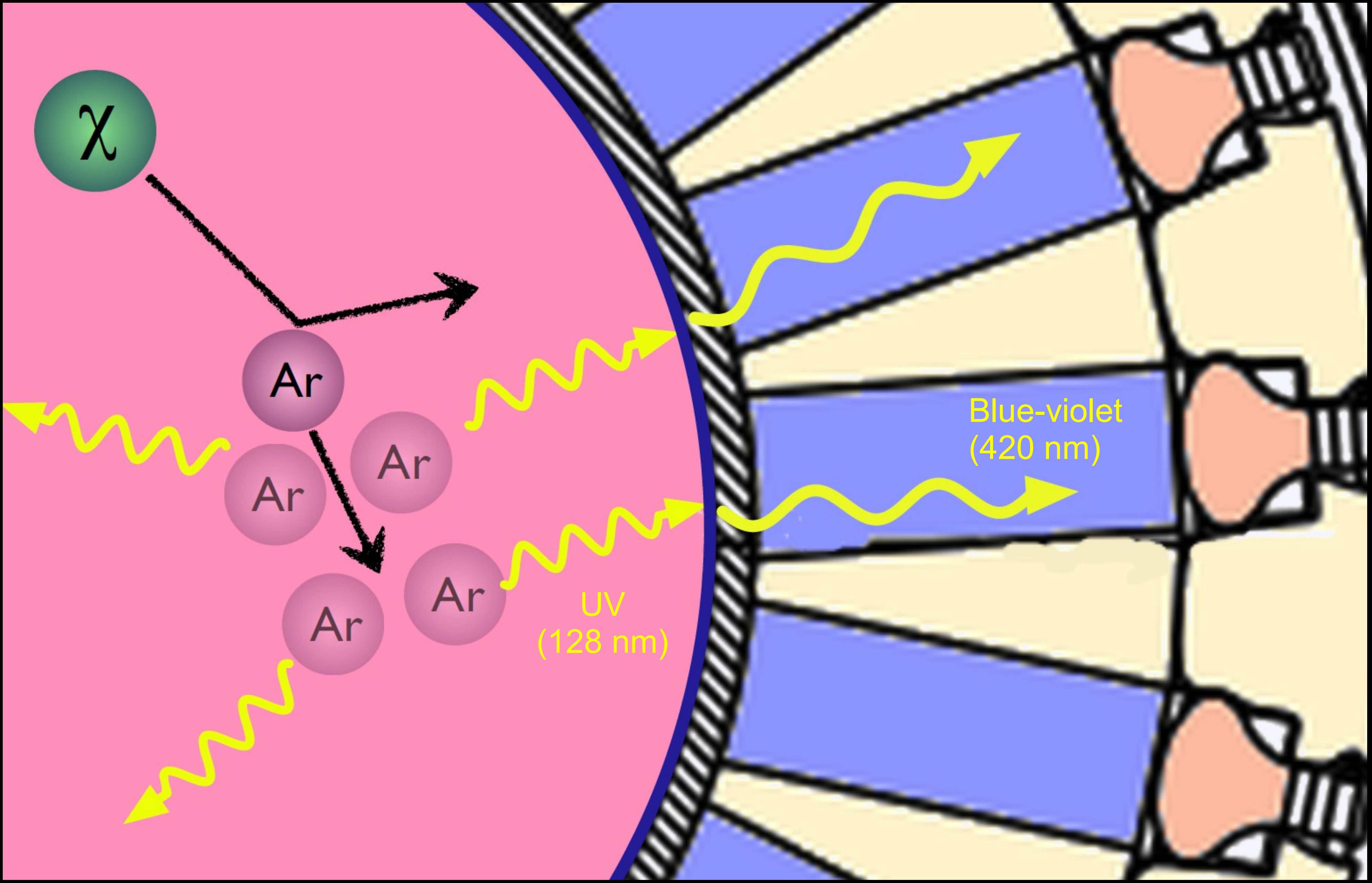
DEAP Collaboration (2019) **Search for dark matter** with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB. Physical Review D, 100, 022004, arXiv:1902.04048

DEAP Collaboration (2019) **Design and construction** of the DEAP-3600 dark matter detector, Astroparticle Physics 108, 1-23. arXiv:1712.01982

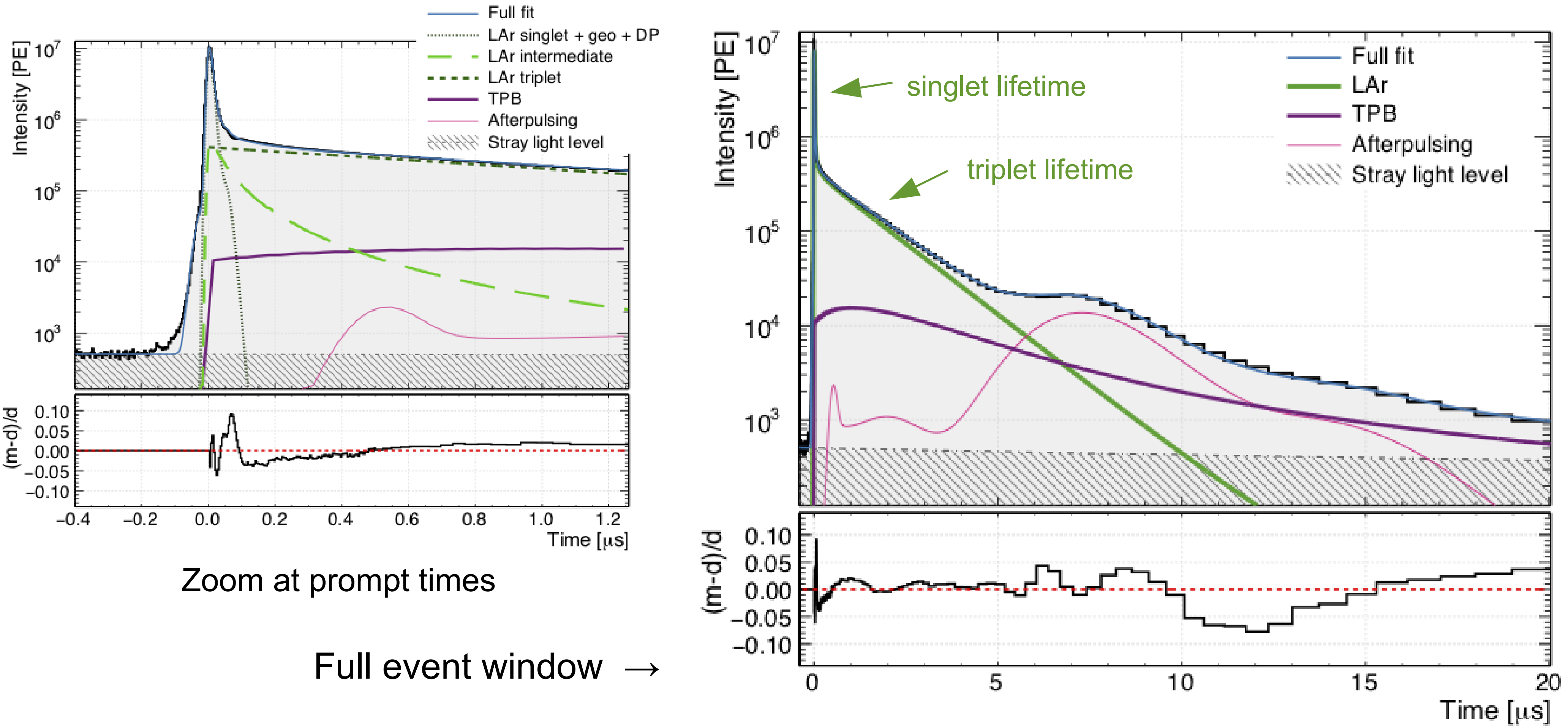
DEAP Collaboration (2019) **In-situ characterization** of the Hamamatsu R5912-HQE photomultiplier tubes used in the DEAP-3600 experiment, Nucl. Instr. Meth. A 922, 373-384, arXiv:1705.10183

DEAP Collaboration (2018) **First results** from the DEAP-3600 dark matter search with argon at SNOLAB, Physical Review Letters 121, 071801, arXiv:1707.08042




χ
Ar
Ar
Ar
Ar
Ar
UV
(128 nm)
Blue-violet
(420 nm)

Liquid argon scintillation pulse-shape in DEAP-3600



Visible photons → Photoelectrons at PMT cathode → PMT pulses

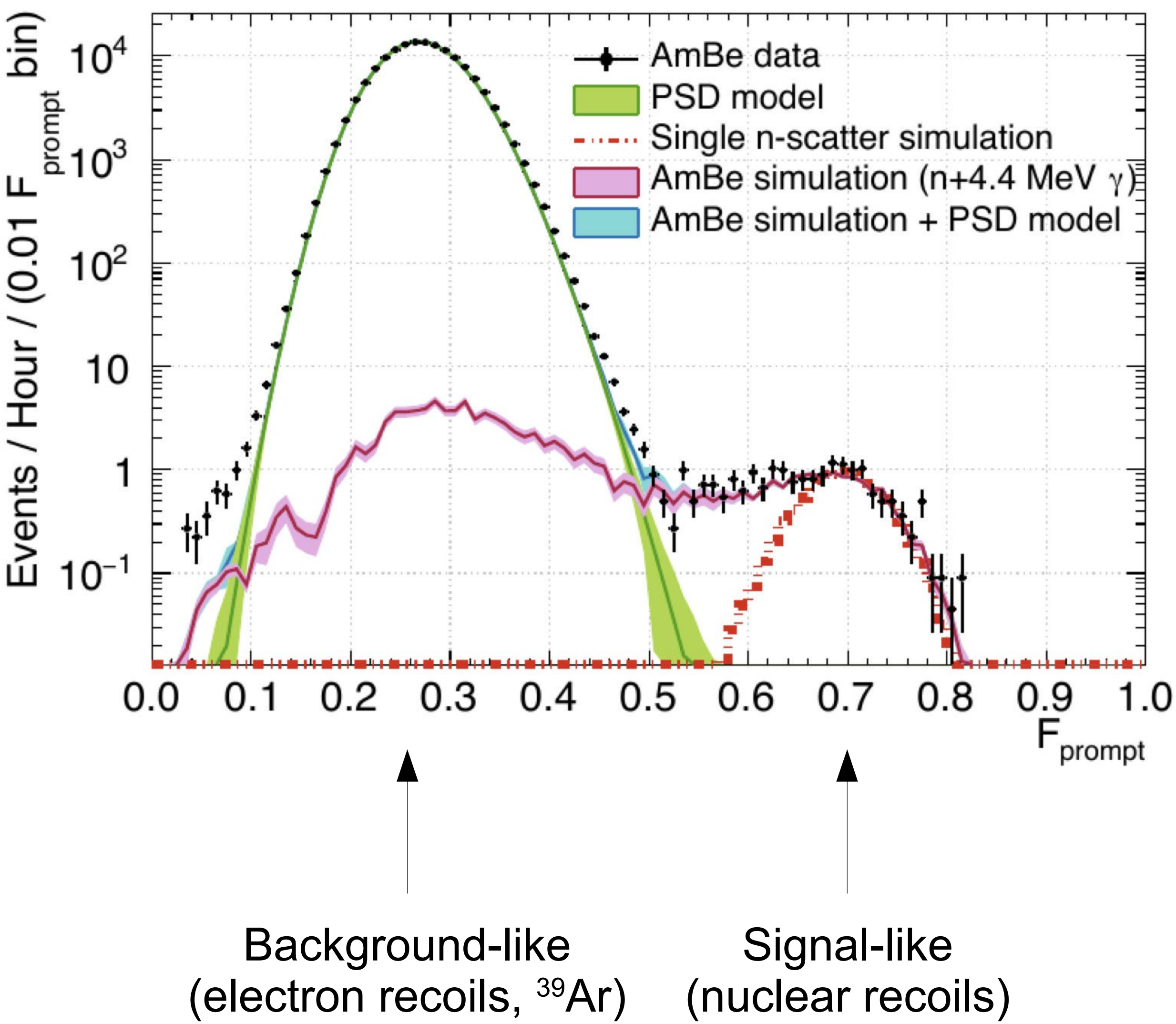
Pulse-shape model: European Physics Journal C, 80, 303 (2020) arXiv:2001.09855

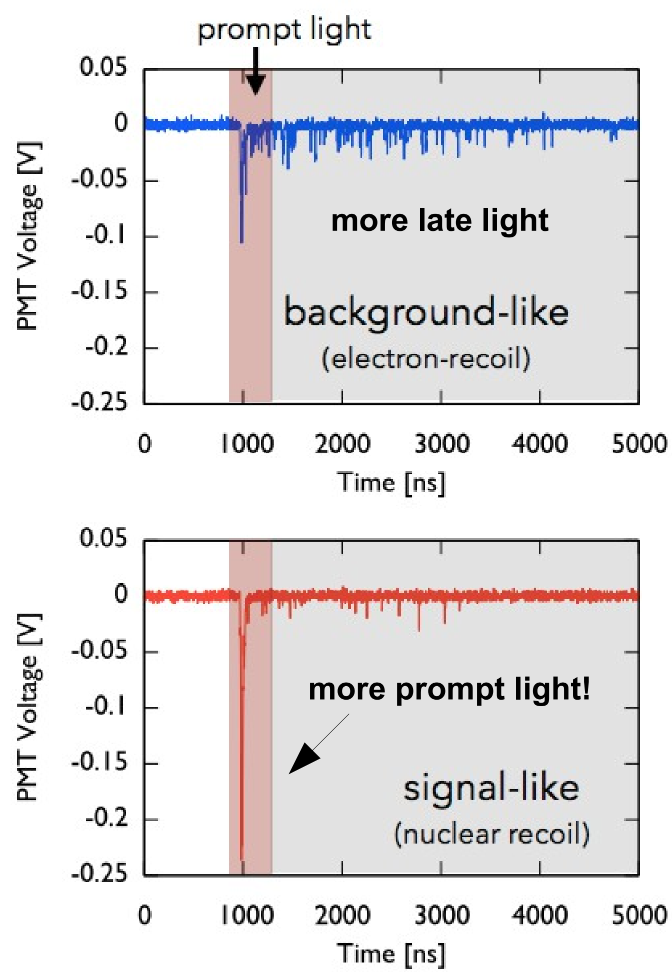
Including intermediate time component of LAr scintillation, PMT response, and long TPB time constant

Pulse-shape discrimination (PSD)

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

Example: Neutron source calibration data

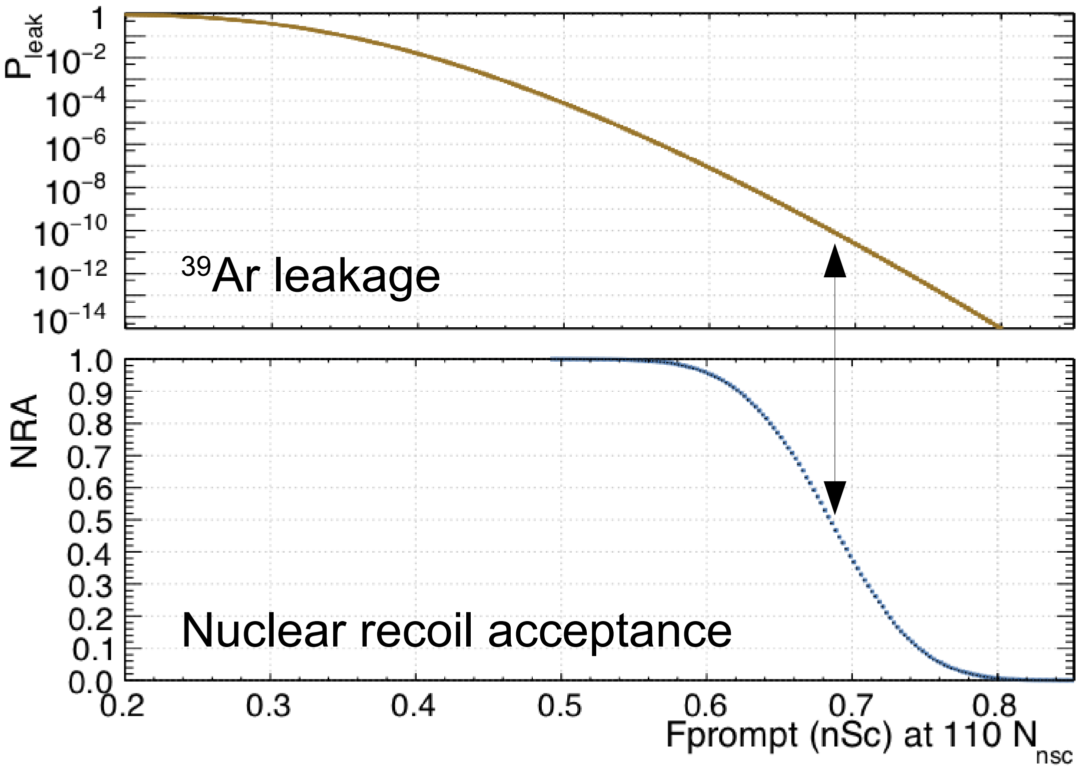


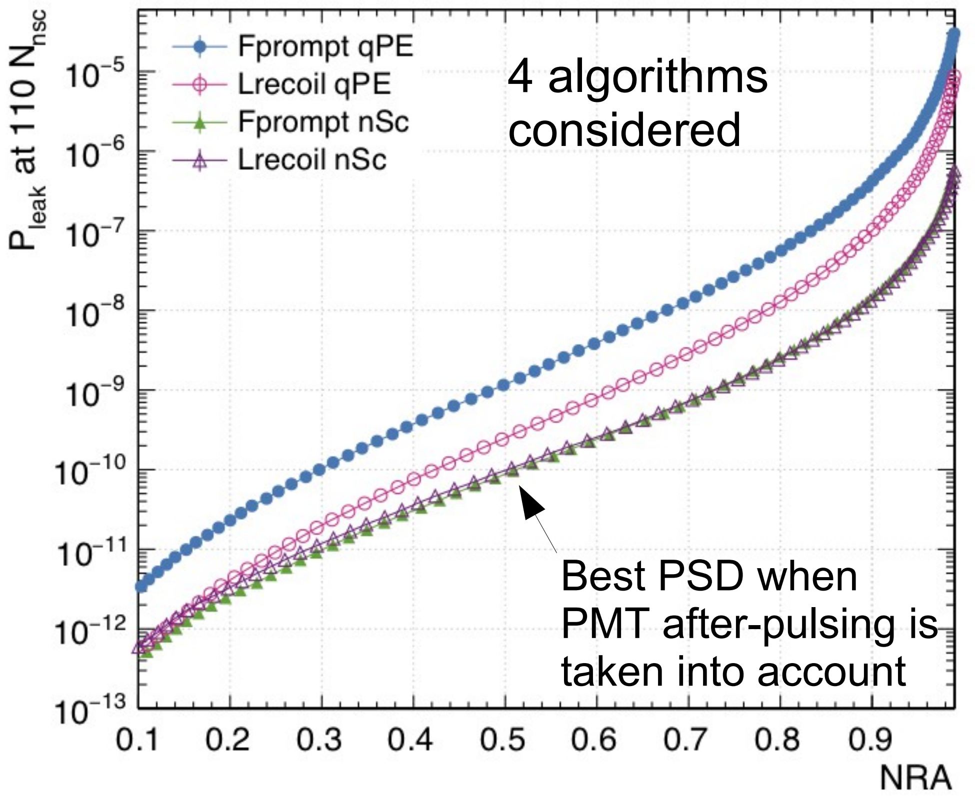


$$F_{prompt} = \frac{\sum_{t=-28\,\mathrm{ns}}^{60\,\mathrm{ns}} \mathrm{PE}(t)}{\sum_{t=-28\,\mathrm{ns}}^{10\,\mu\mathrm{s}} \mathrm{PE}(t)}$$

Pulse-shape discrimination (PSD)

World-leading PSD performance!



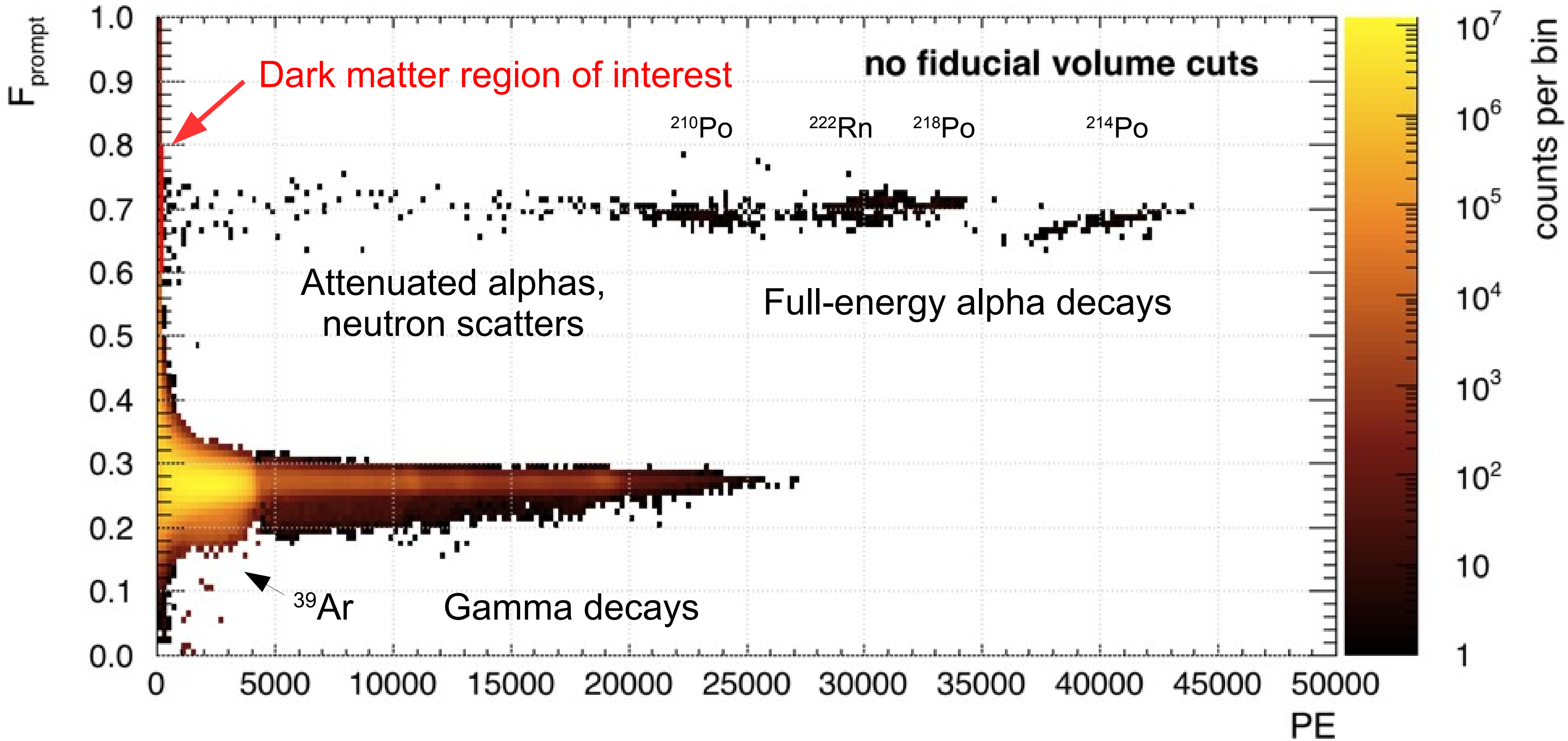


Using our best PSD algorithm:

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

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

DEAP-3600: Early physics data



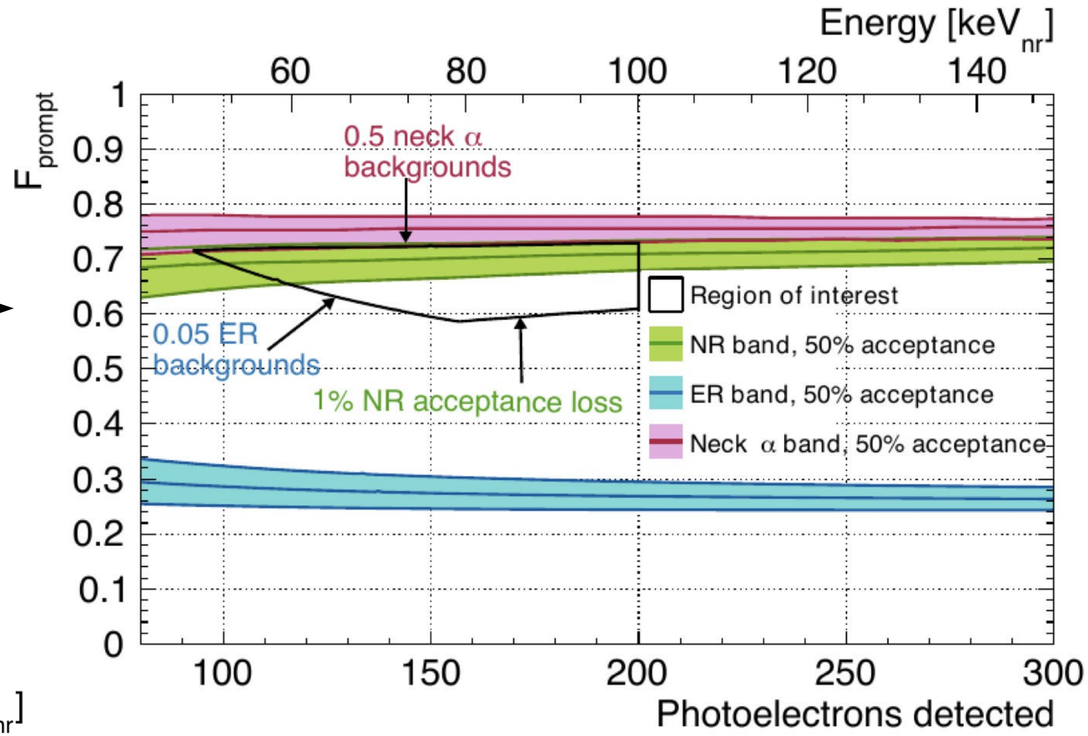
First DEAP-3600 dark matter search, with 4.4 live days

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

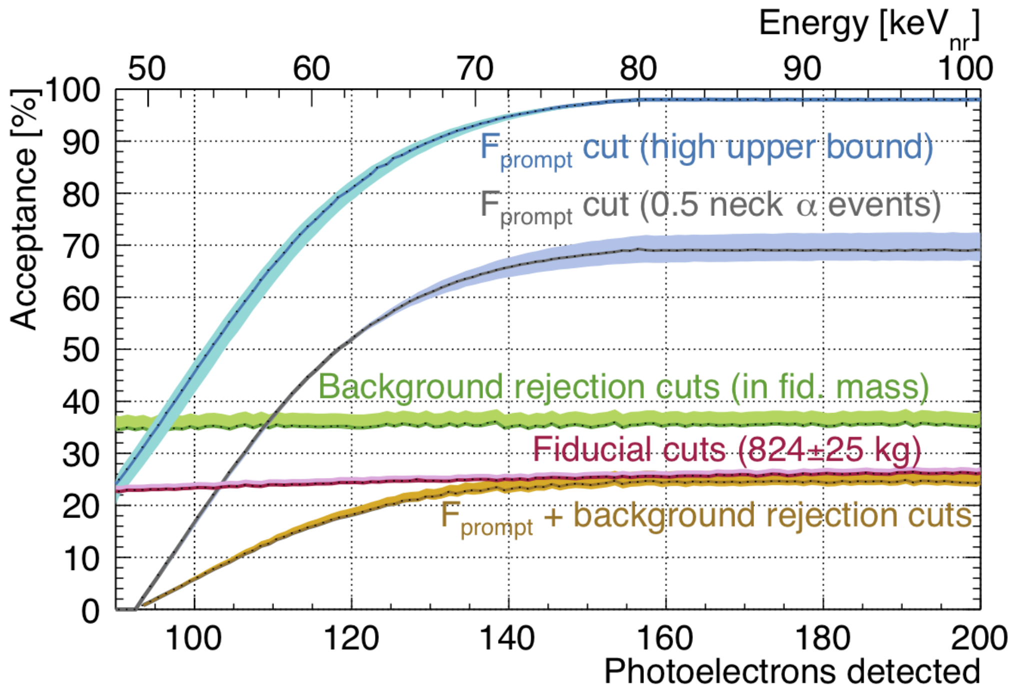
DEAP-3600 analysis: Signal region definition

Select nuclear recoils using PSD
Reject surface alphas using fiducial volume
Reject neck alphas using dedicated cuts

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



WIMP signal acceptance

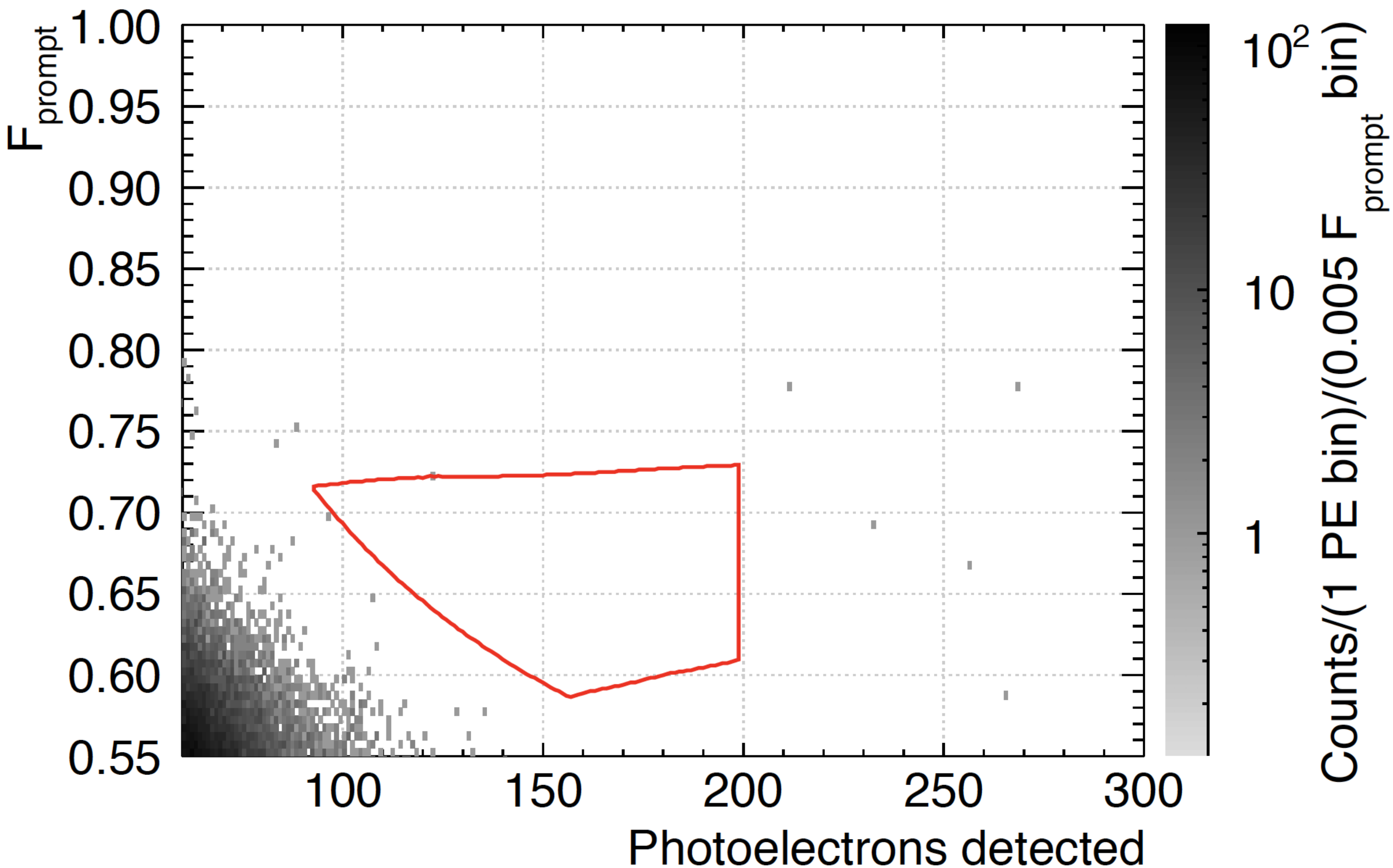


Expected backgrounds

	Source	N^{ROI}
n's β/γ's	ERs	0.03 ± 0.01
	Cherenkov	< 0.14
	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

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

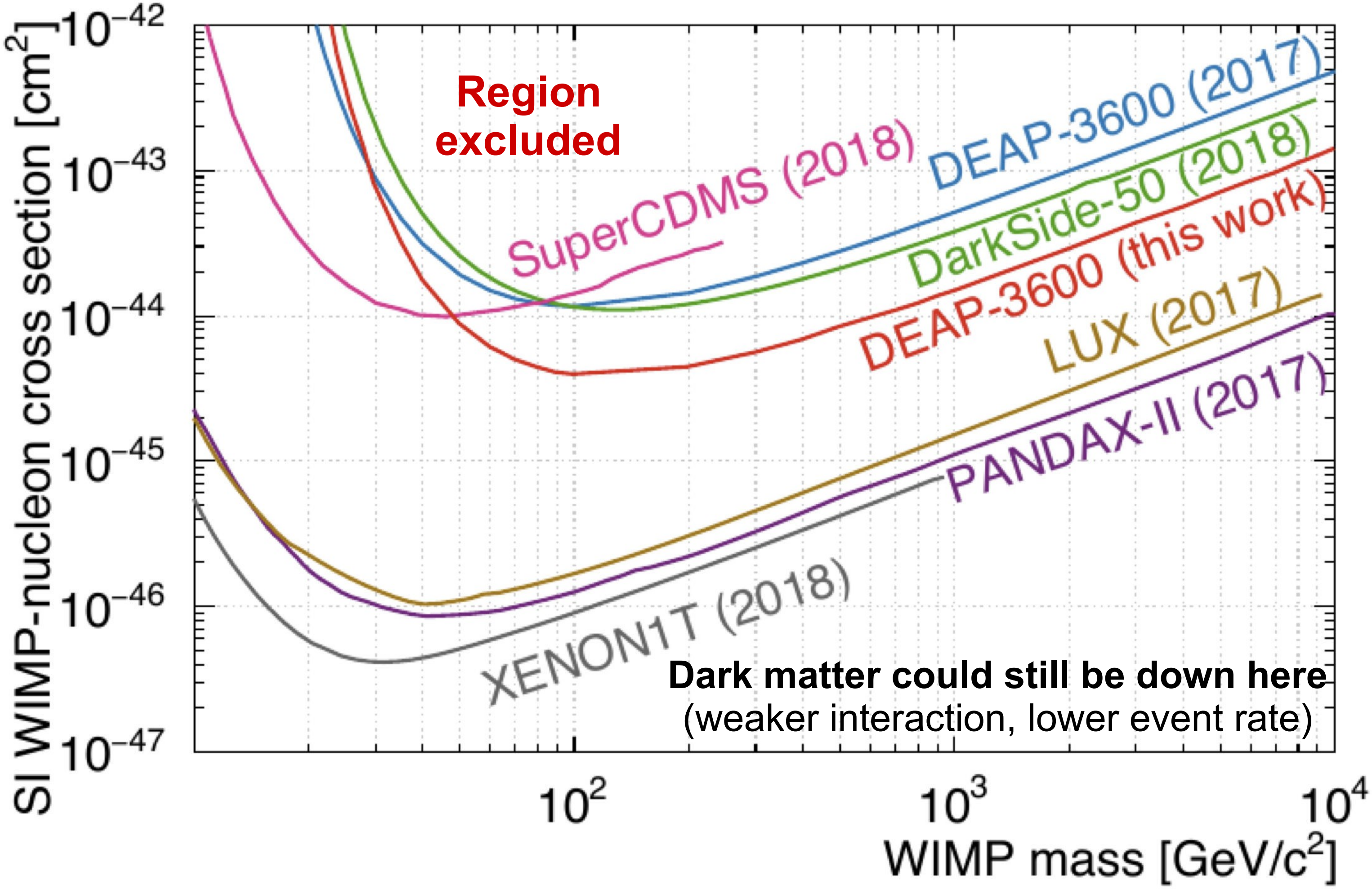


Physical Review D, 100, 022004 (2019) arXiv:1902.04048

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

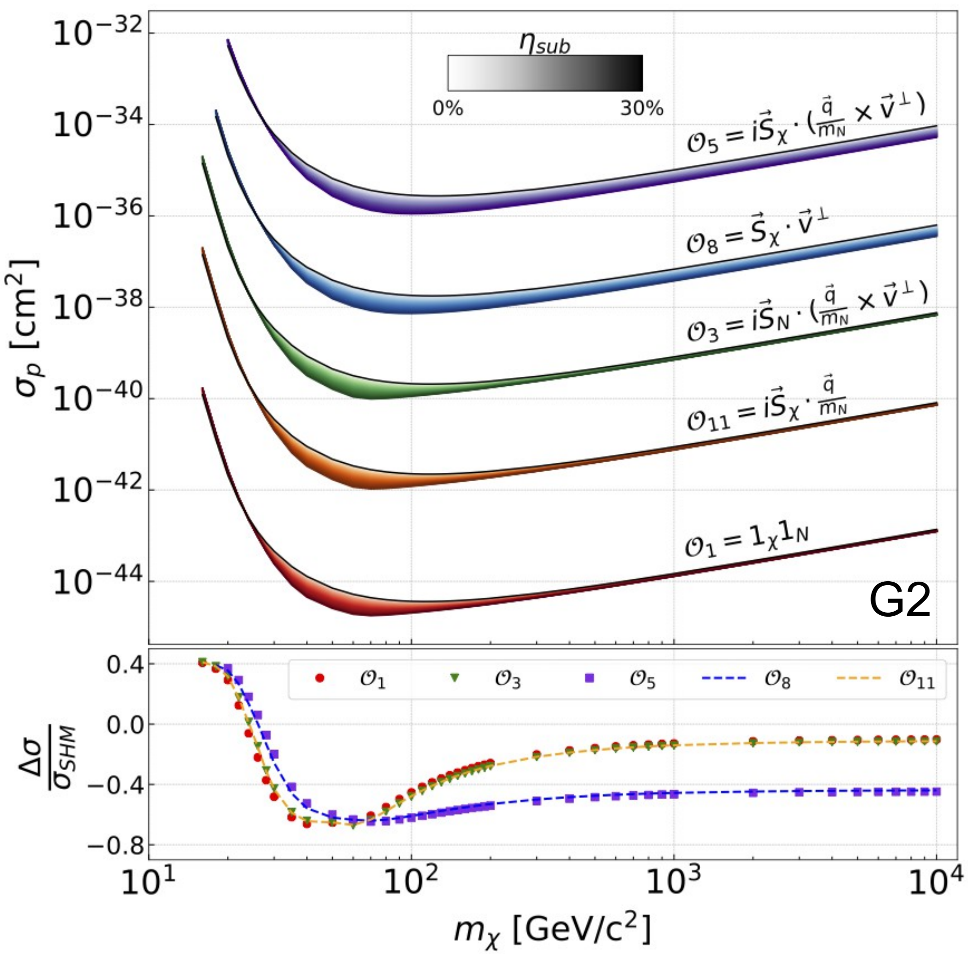


Physical Review D, 100, 022004 (2019) arXiv:1902.04048

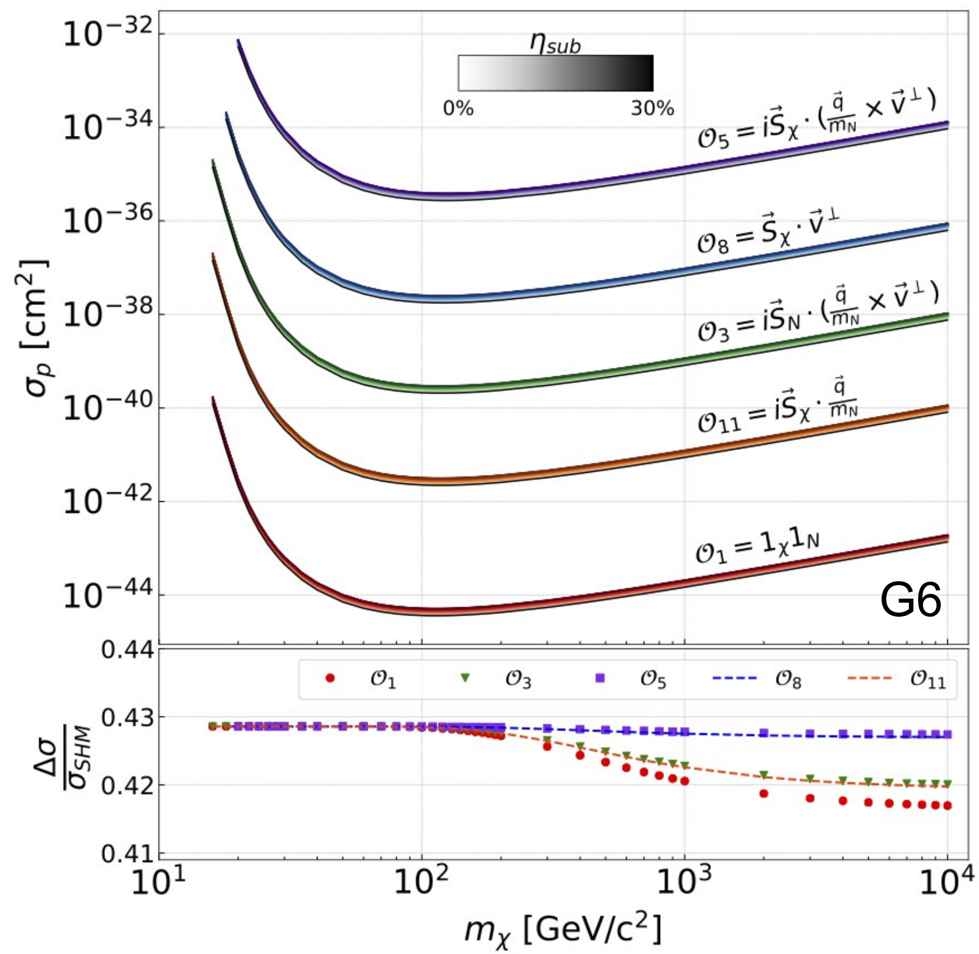
Further constraints on dark matter

- Results are reinterpreted 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

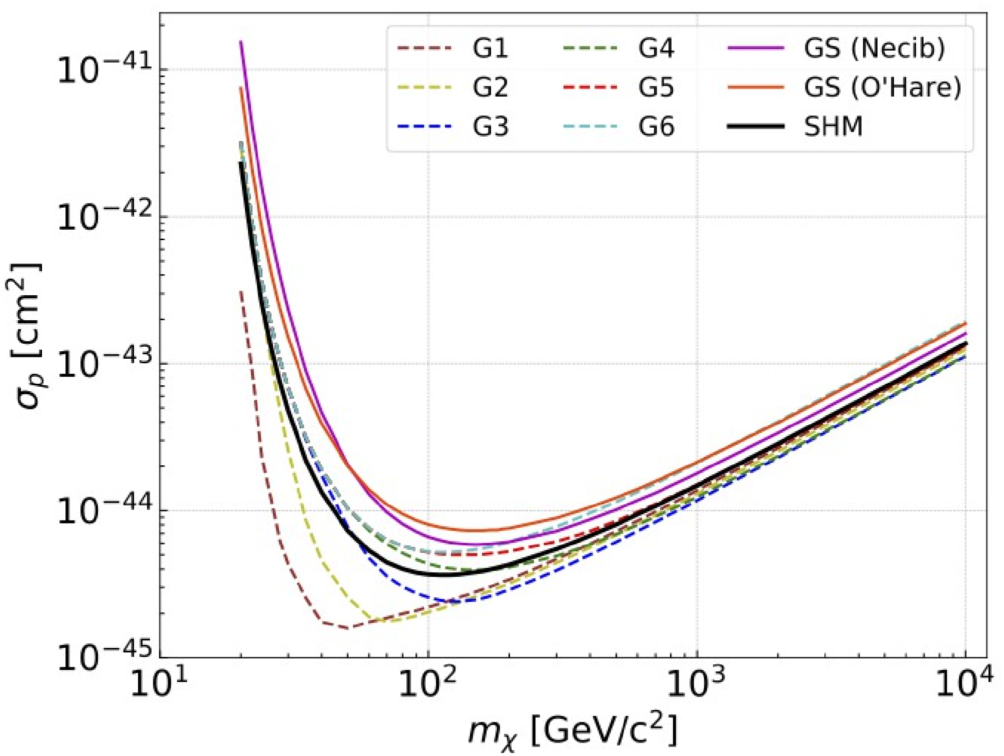


Physical Review D, 102, 082001 (2021) arXiv:2005.14667

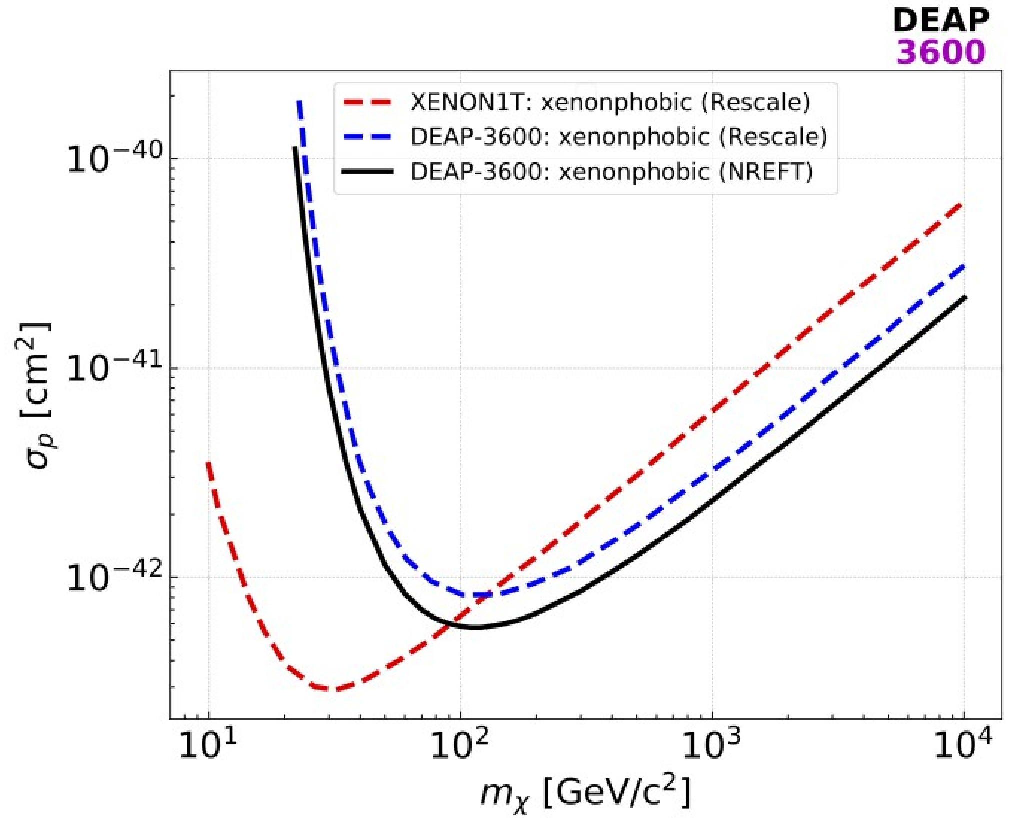
Further constraints on dark matter

- Results are reinterpreted in 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

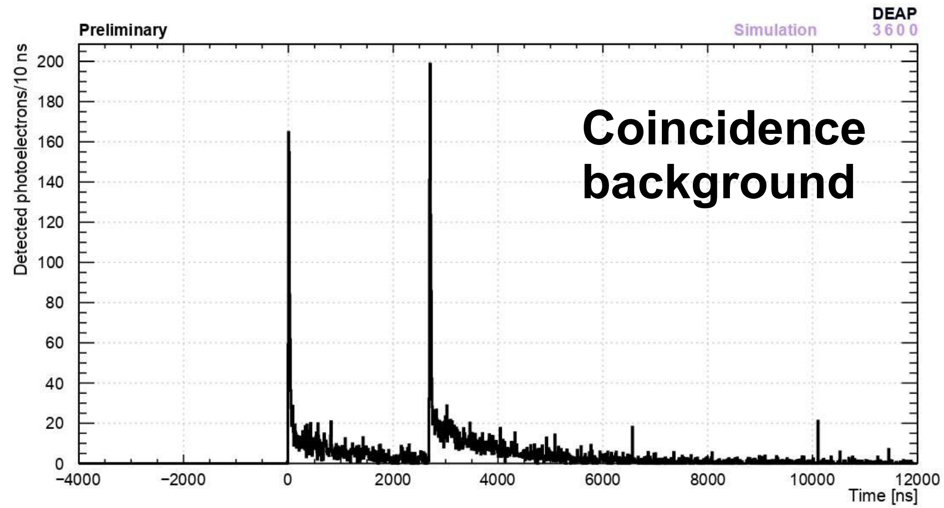


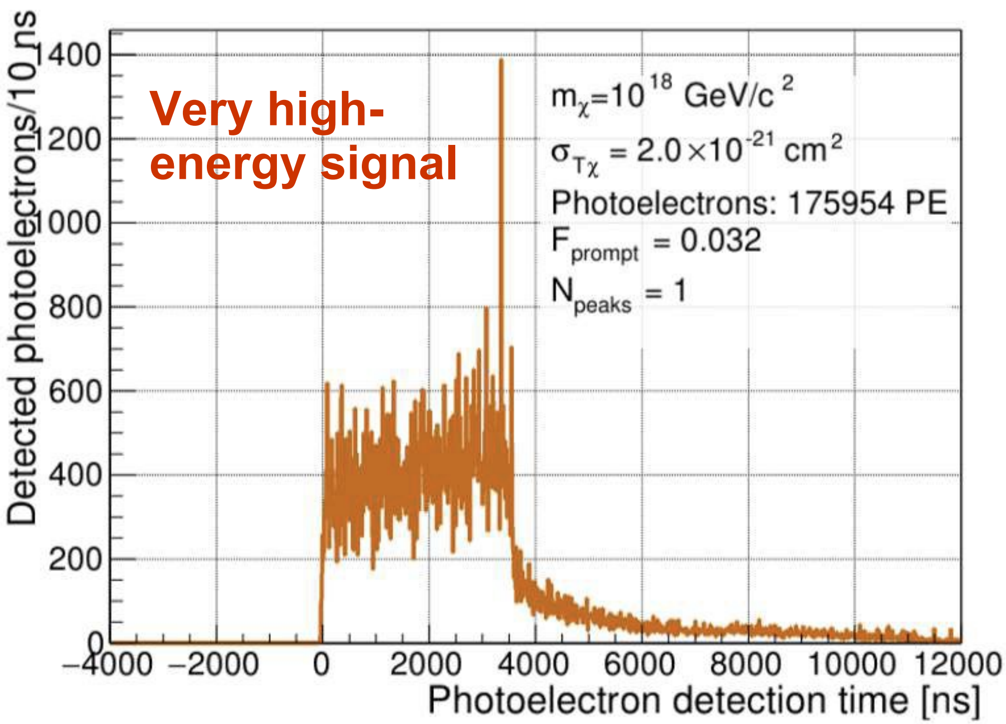
Physical Review D, 102, 082001 (2021) arXiv:2005.14667

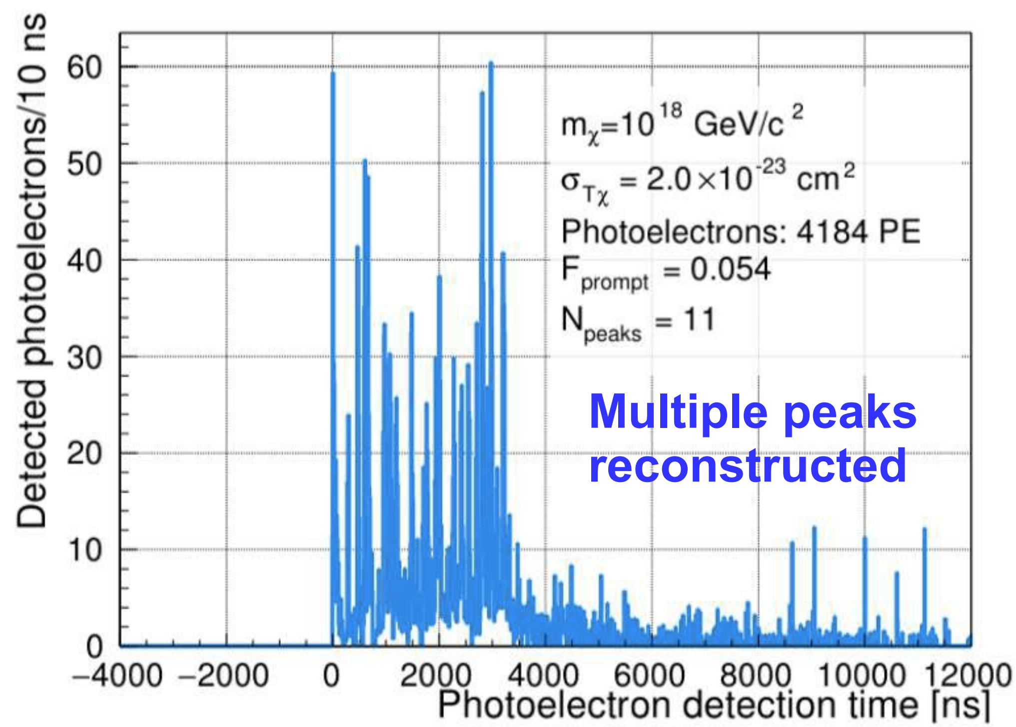
Search for Planck-scale mass dark matter particles

Multiply-interacting massive particles

- Distinct signature consistent with multiple recoils in succession
  - Or a very high-energy, low F_{prompt} event
- Expected signal pulse-shape is inconsistent with coincidence backgrounds





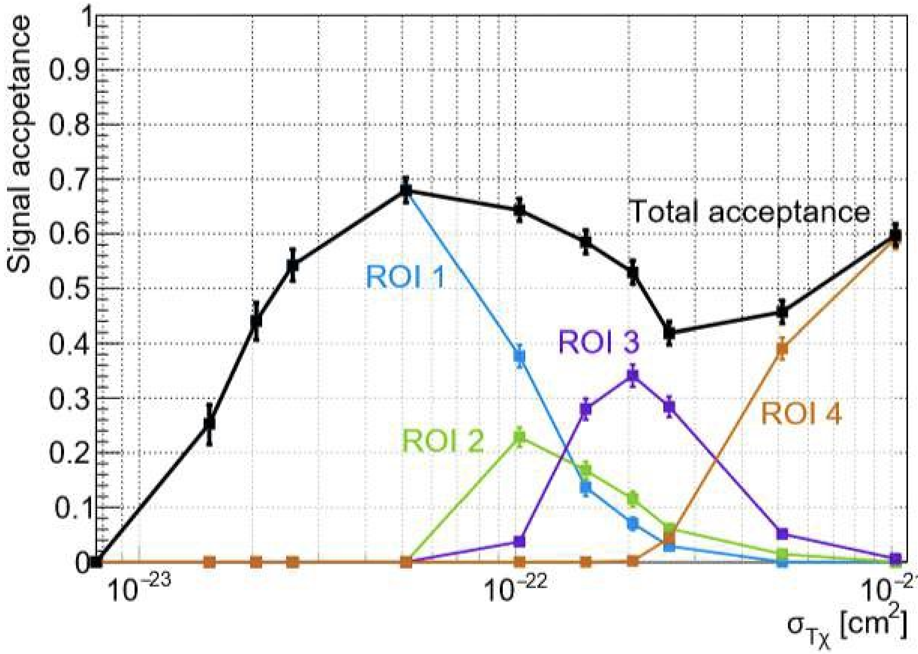


Search for Planck-scale mass dark matter particles

Multiply-interacting massive particles

- Distinct signature consistent with multiple recoils in succession
  - Or a very high-energy, low F_{prompt} 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
- Unblinded 813 live-days of data...

Signal acceptance vs. cross-section

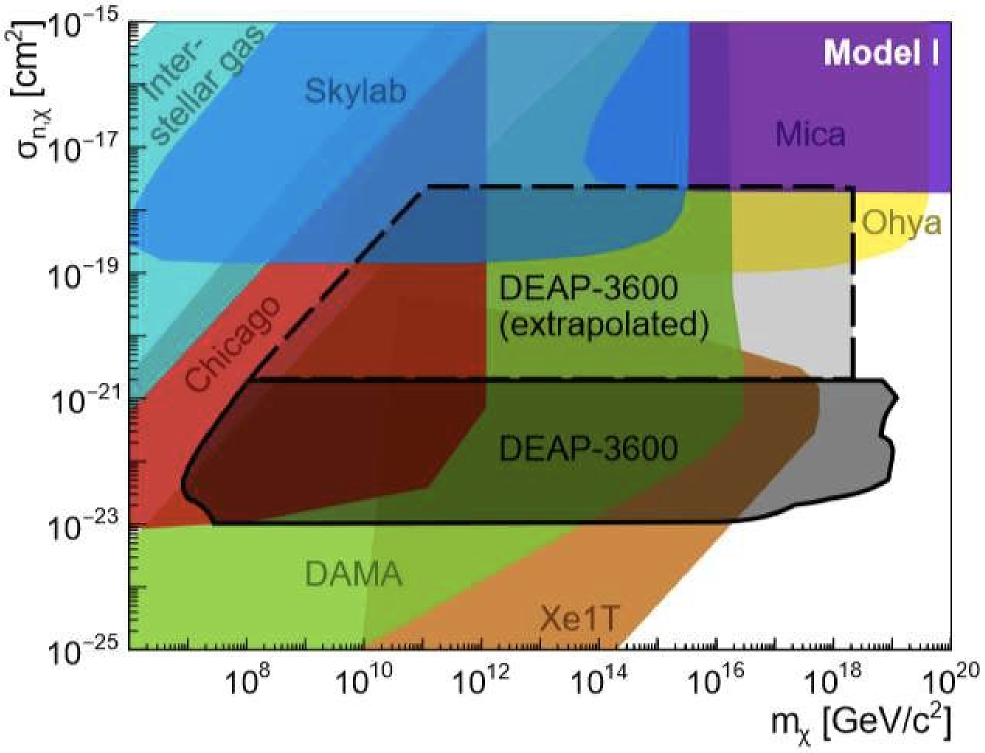


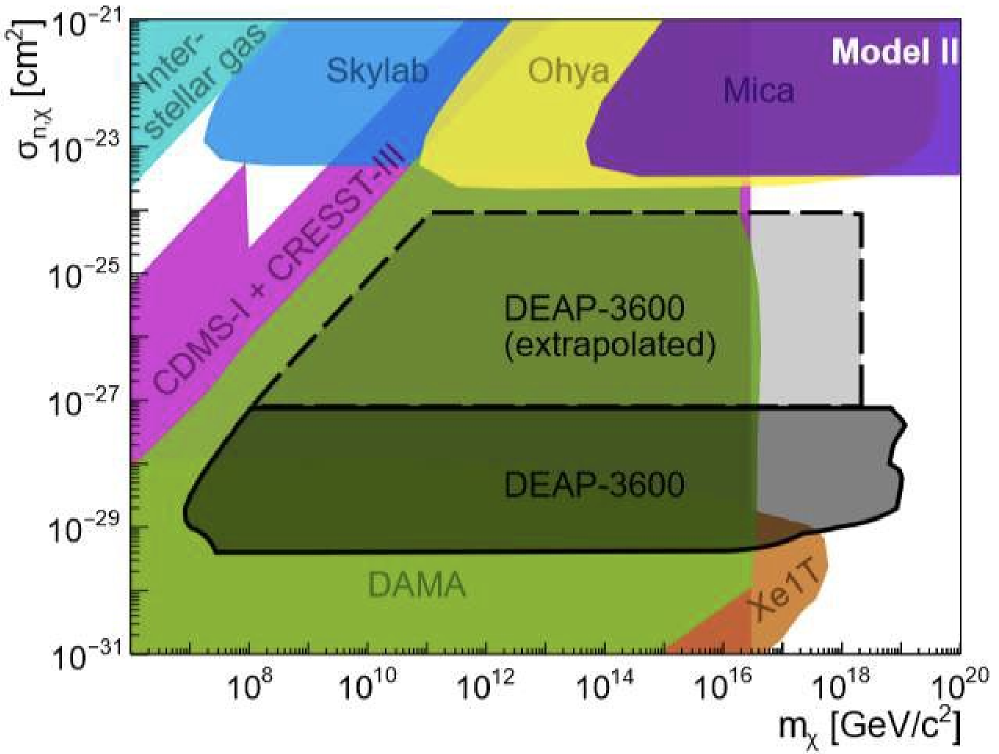
ROI	PE range	Energy [MeV]	N_{peaks}^{min}	F_{prompt}^{max}	μ_b
1	4000–20 000	0.5–2.9	7	0.10	$(4 \pm 3) \times 10^{-2}$
2	20 000–30 000	2.9–4.4	5	0.10	$(6 \pm 1) \times 10^{-4}$
3	30 000–70 000	4.4–10.4	4	0.10	$(6 \pm 2) \times 10^{-4}$
4	70 000–4×10^8	10.4–60 000	0	0.05	$(10 \pm 3) \times 10^{-3}$

Search for Planck-scale mass dark matter particles

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

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





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

Summary: DEAP-3600 physics programme

- Measurements
  - Pulse-shape [2001.09855], Pulse-shape discrimination [2103.12202]
  - ^{39}Ar specific activity, ^{39}Ar half-life
  - Electromagnetic backgrounds and ^{42}K activity [1905.05811]
  - Muon flux at SNOLAB
- 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
  - Analysis in progress with 840 live-days
    - Limiting backgrounds: neck alphas, dust alphas
  - Background mitigation in hardware, data-taking to resume in 2023 [*next slide*]
- Planck-scale mass dark matter search [2108.09405]
- Other searches
  - 5.5 MeV solar axions
  - Neutrino absorption (inverse beta decay)

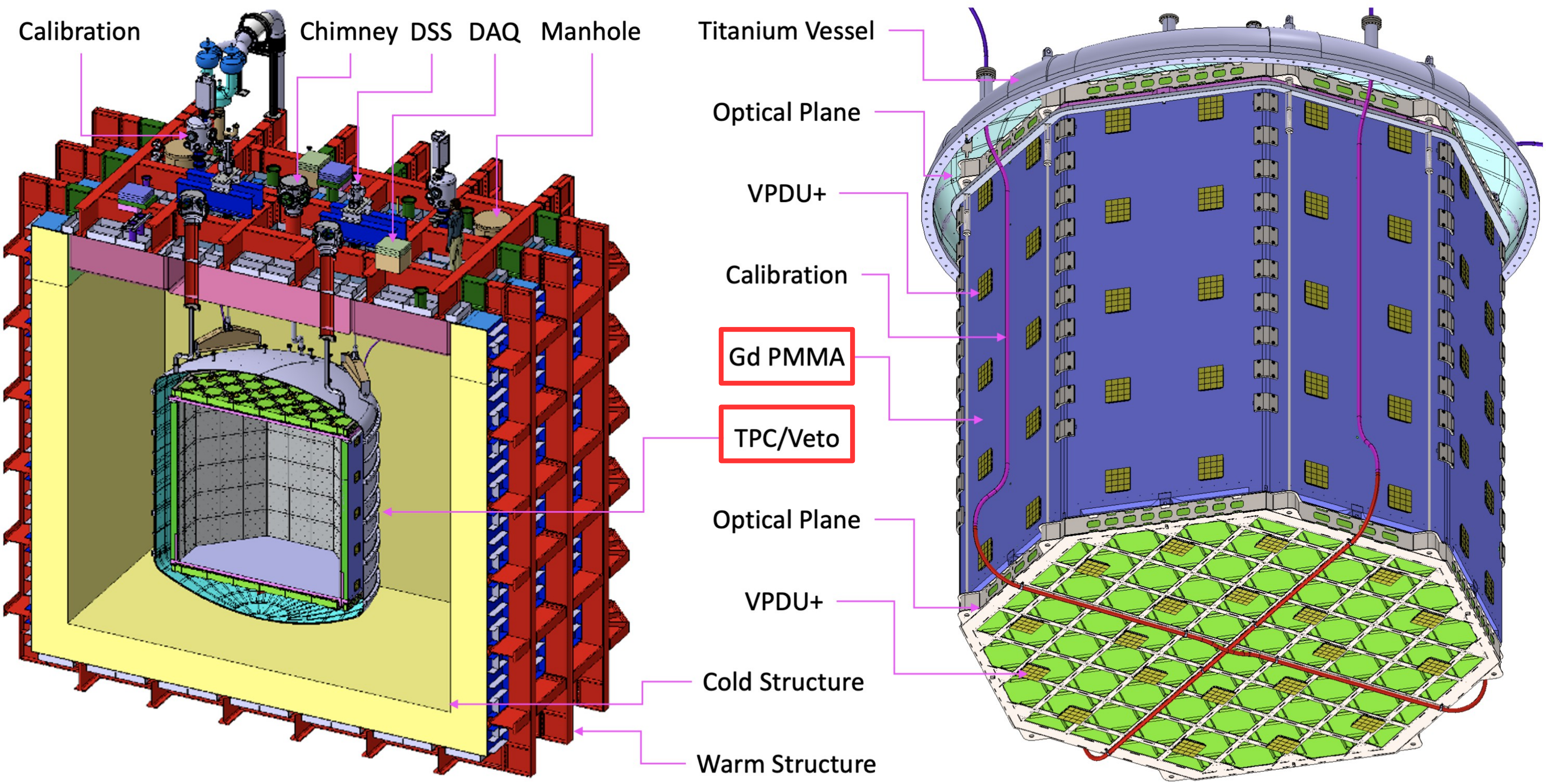
DEAP-3600 hardware upgrades

- **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 later this year
- New DM search data in upgraded detector expected in 2023
  - **Expecting improved sensitivity**
  - Inform design of next-generation liquid argon dark matter experiments

Generation 2:

DarkSide-20k

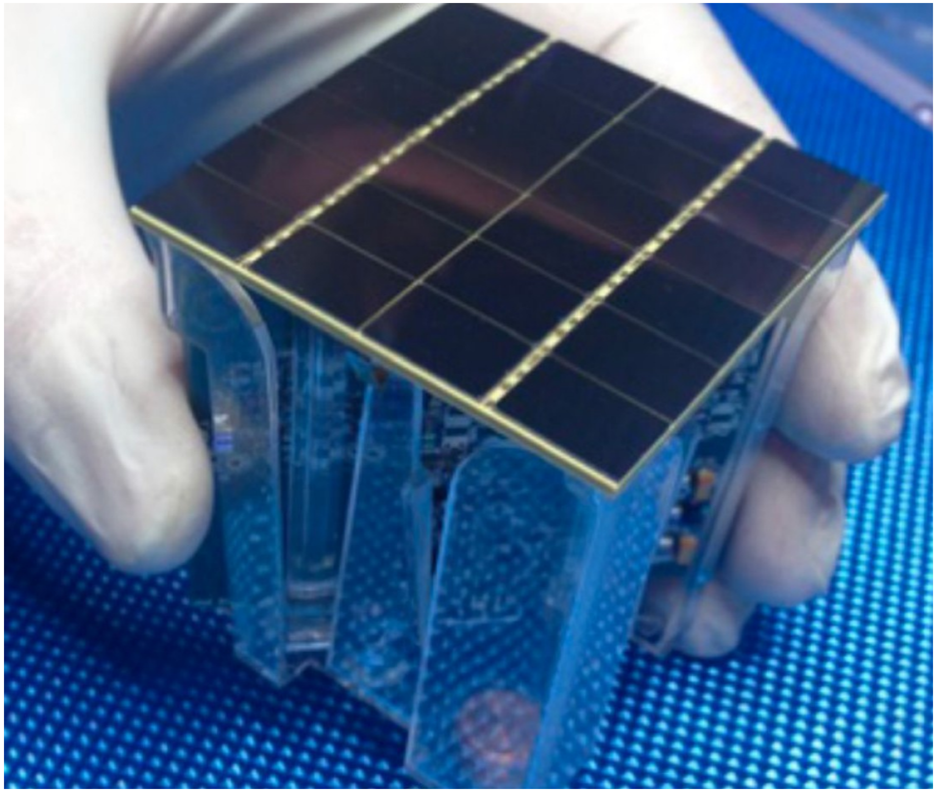
DarkSide-20k: Dual-phase time projection chamber (TPC)

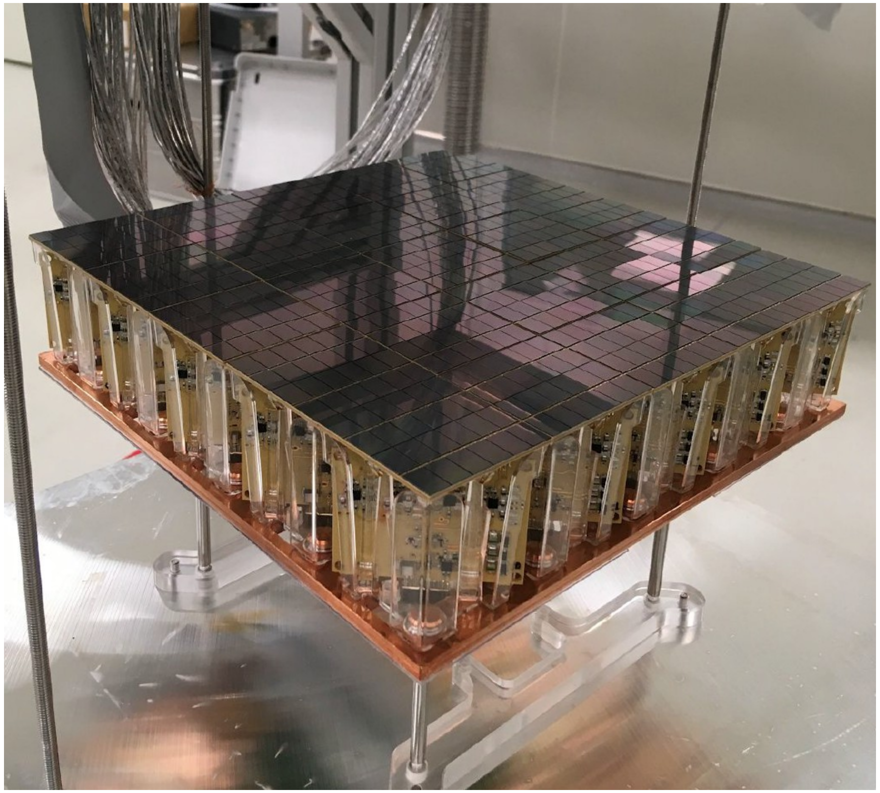


DarkSide-20k Technical Design Report (2021), DARKSIDE-CSN2-TDR-2112

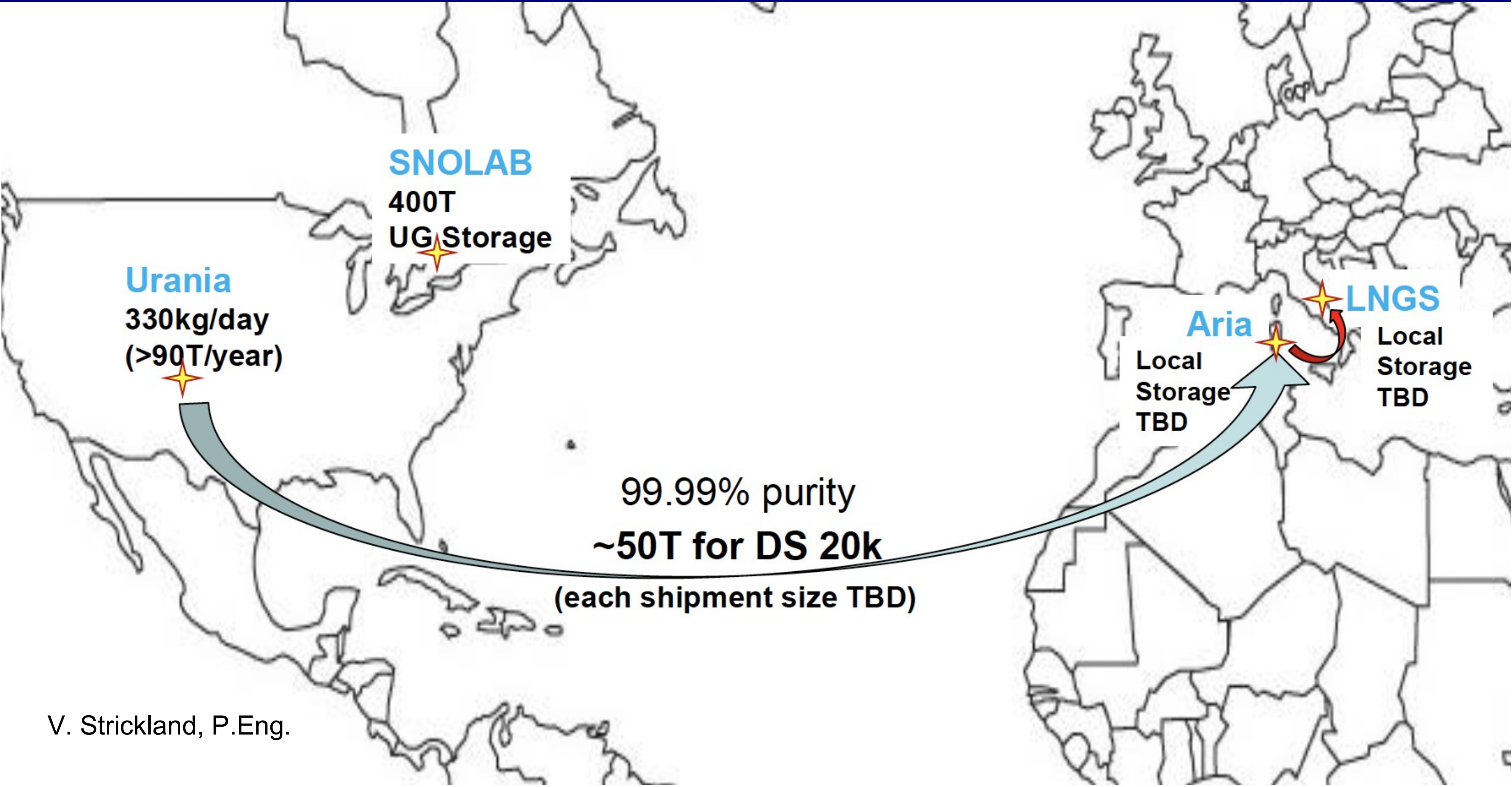
DarkSide-20k photodetector modules

- Photodetectors will be located at the top and bottom of the TPC
  - Detect scintillation light (S1) and electroluminescence from ionization electrons (S2)
- Silicon photomultipliers by Fondazione Bruno Kessler, model NUV-HD-CRYO
  - Meets all requirements on photodetection efficiency, low noise at liquid argon temp.
  - 24 SiPMs are combined into a photodetector module (PDM) with area ~ 5 x 5 cm^2
  - 25 PDMs are grouped and connected to a motherboard
  - Total on the order of 8000 PDMs for the TPC, and 3000 PDMs for the veto detector





Low-radioactivity underground argon

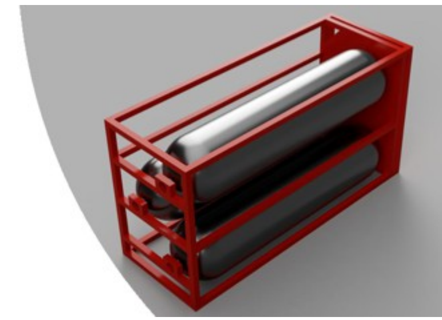


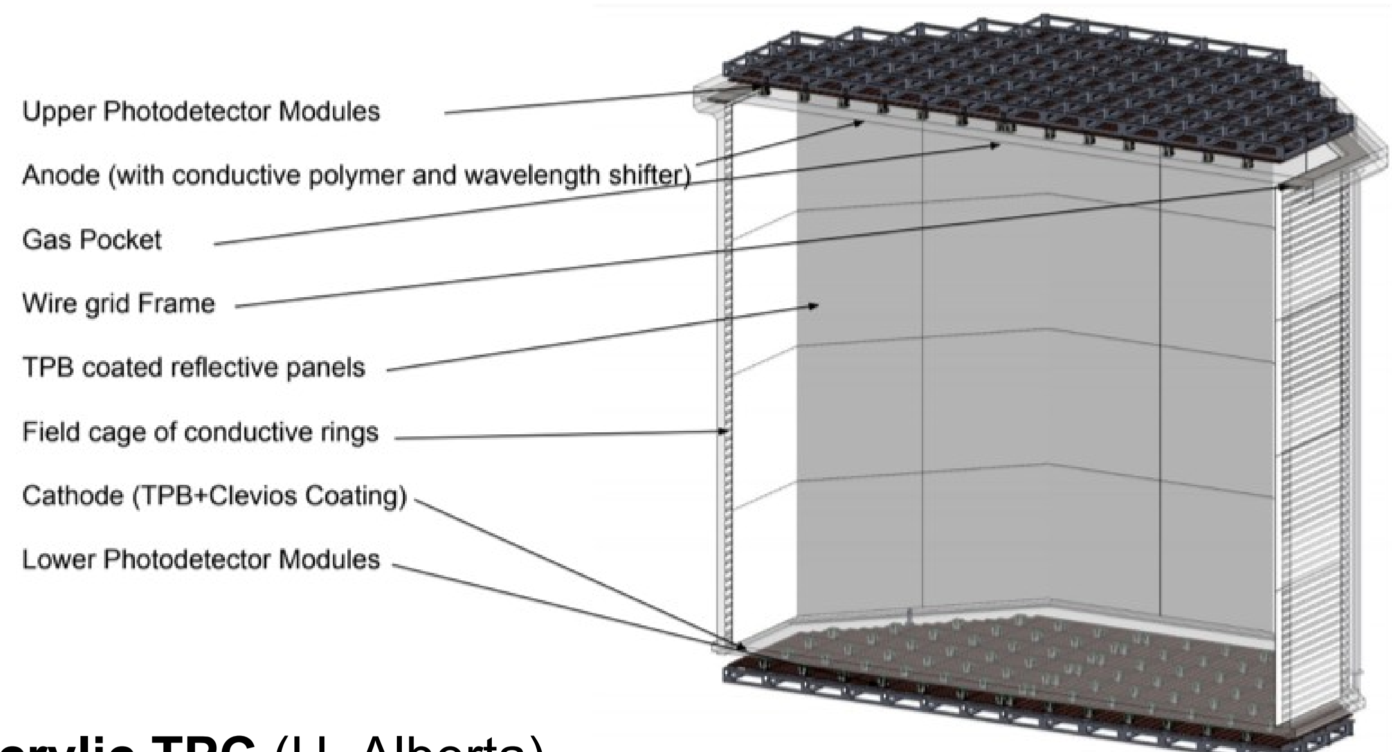
- **Underground argon is depleted in ^{39}Ar** $\rightarrow$ Necessary for large-scale detectors
- First shipments from Colorado to Italy, then to storage facility at SNOLAB

Canadian contributions to DarkSide-20k

CFI IF 2020
CFI IF 2023

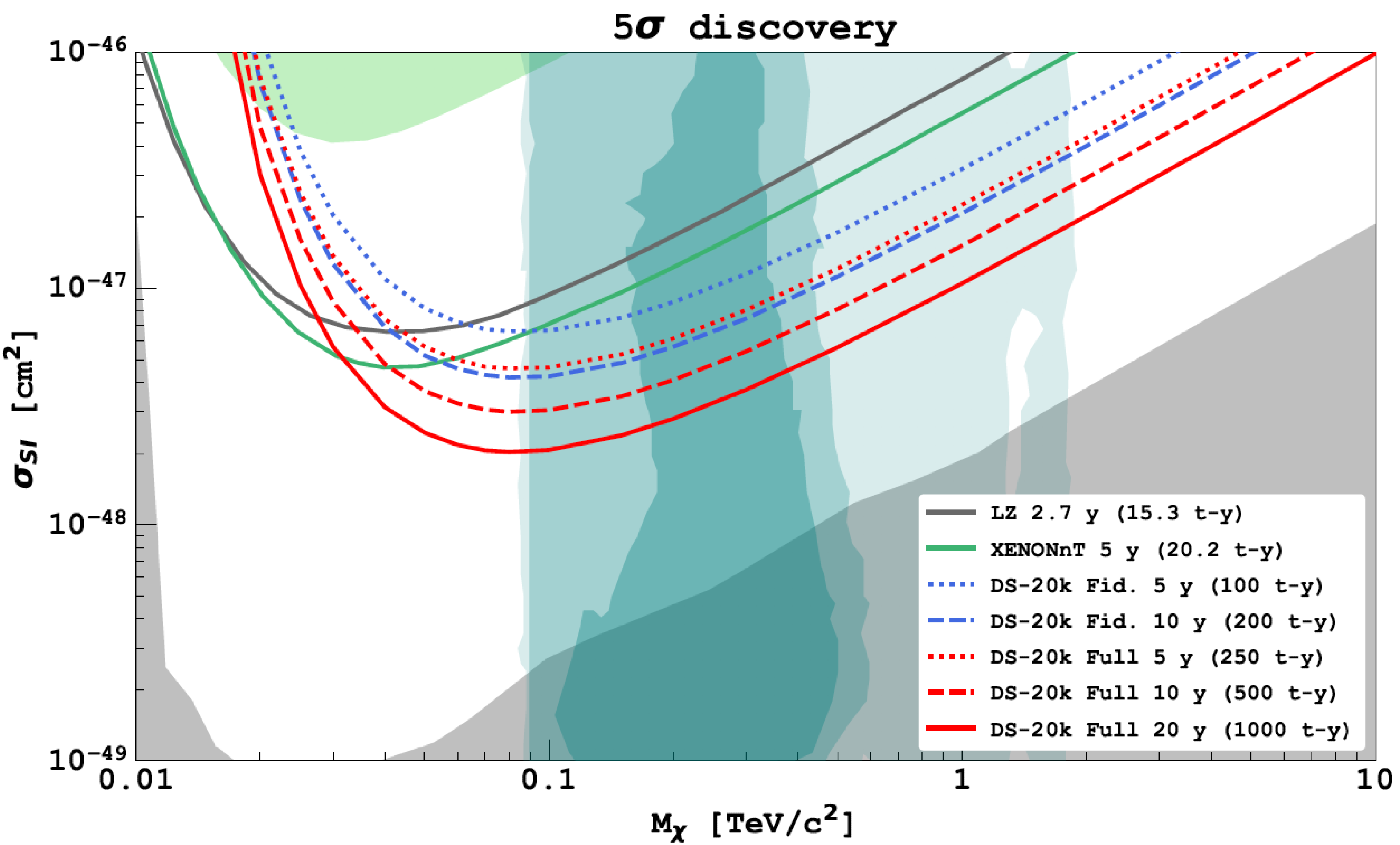
- **Underground argon** extraction, transport and storage (Carleton U., Queen's U.)
  - Low-radioactivity underground argon assay detector (SNOLAB)





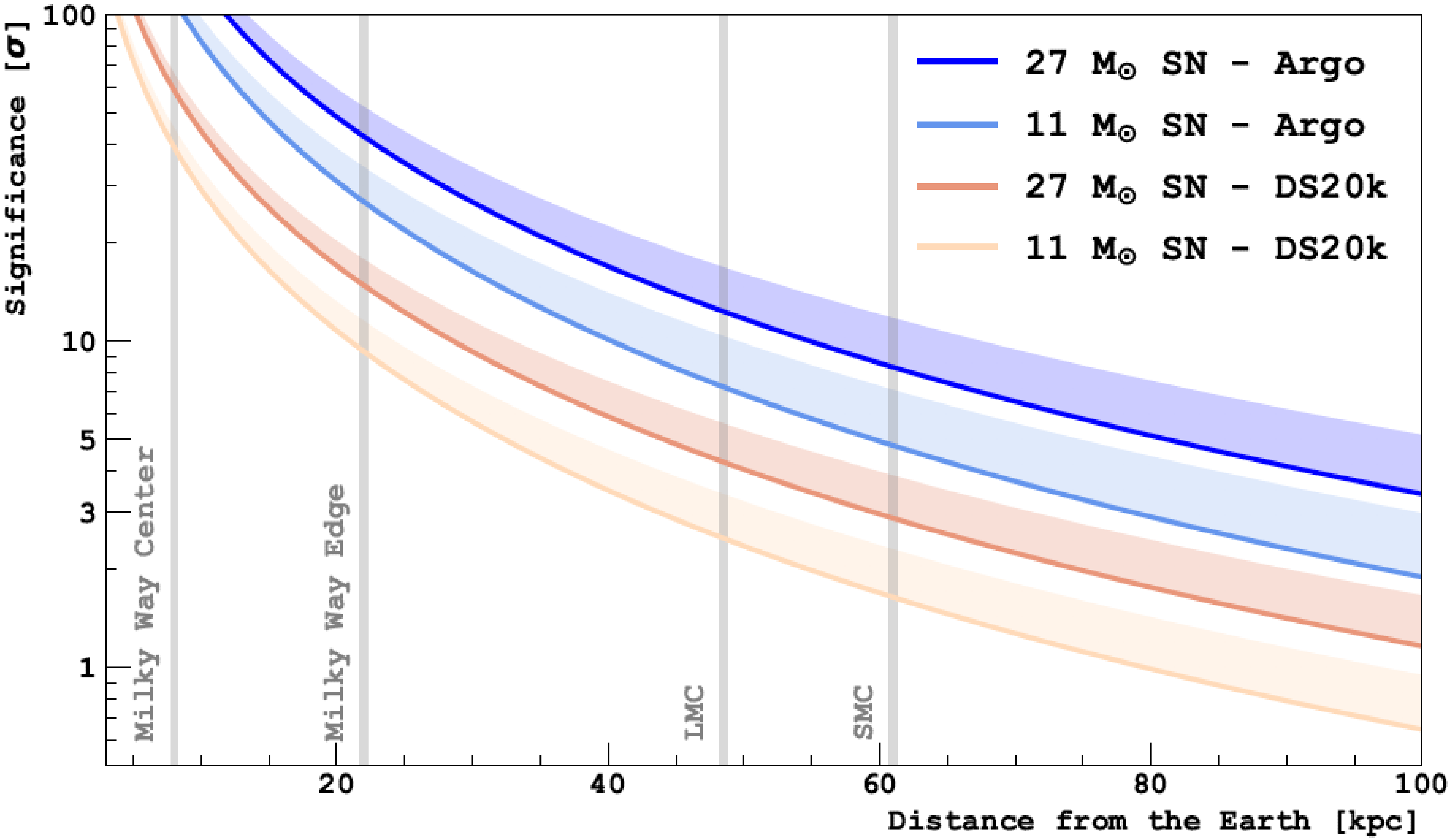
- **Acrylic TPC** (U. Alberta)
  - TPB wavelength-shifter and Clevios conductive coating (Carleton U.)
- **Data acquisition system** (TRIUMF, Queen's U.)
- **Photodetector tests** (TRIUMF, U. Alberta, Carleton U., Queen's U., U. Sherbrooke)

DarkSide-20k expected sensitivity: Dark matter



DarkSide-20k Technical Design Report (2021), DARKSIDE-CSN2-TDR-2112

DarkSide-20k expected sensitivity: Supernova neutrinos



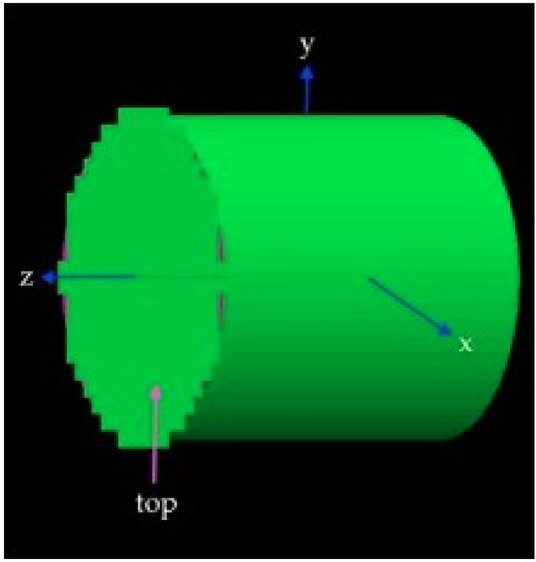
Journal of Cosmology and Astroparticle Physics, 2021, 03, 043 (2021) arXiv:2011.07819

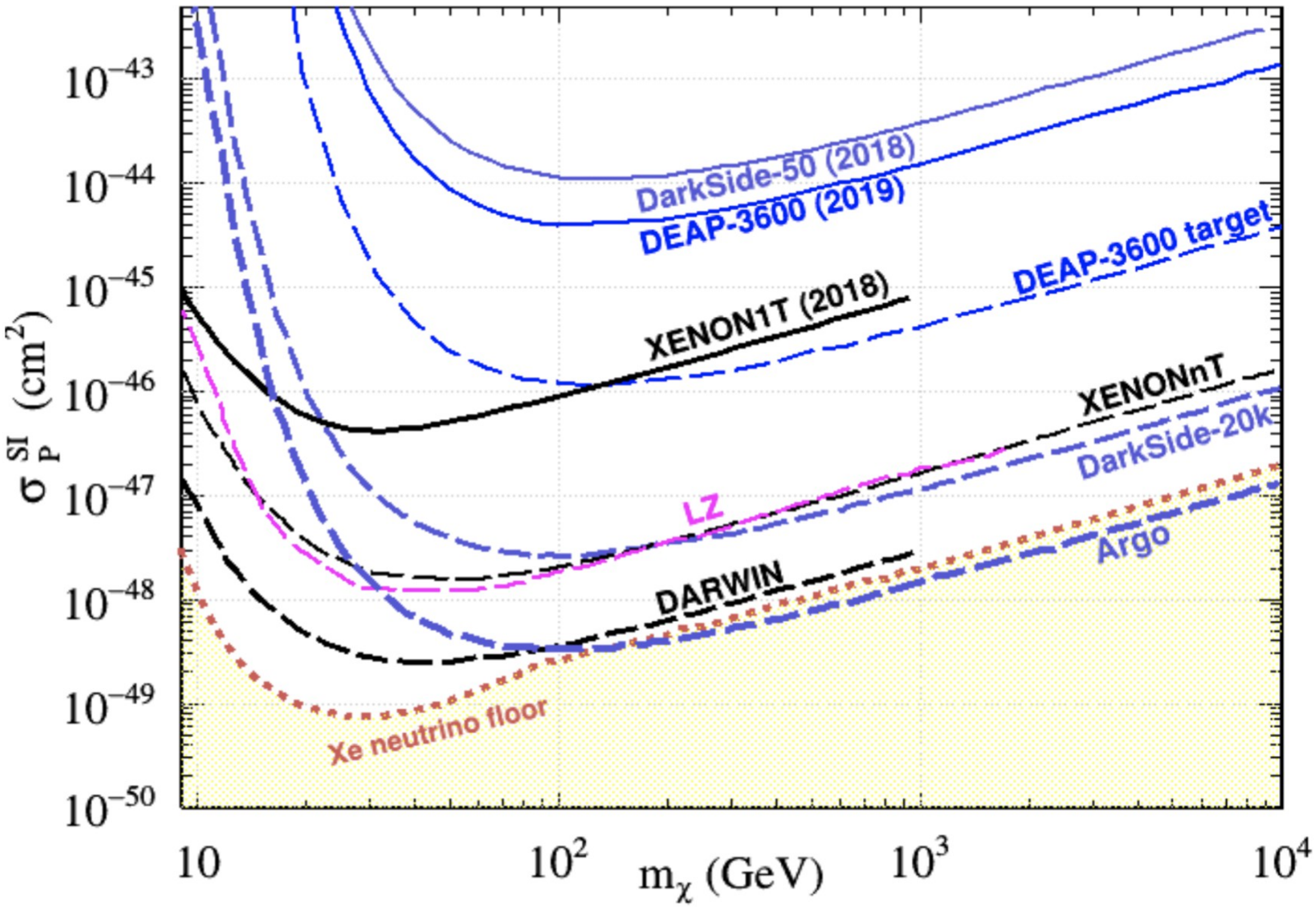
Generation 3:

ARGO

ARGO: Ultimate dark matter detector with liquid argon

- **Preferred site: SNOLAB**
- 400-tonnes of low-background underground argon
- > 200 m^2 of silicon photomultipliers
- Event ID and reconstruction algorithms at DAQ-level





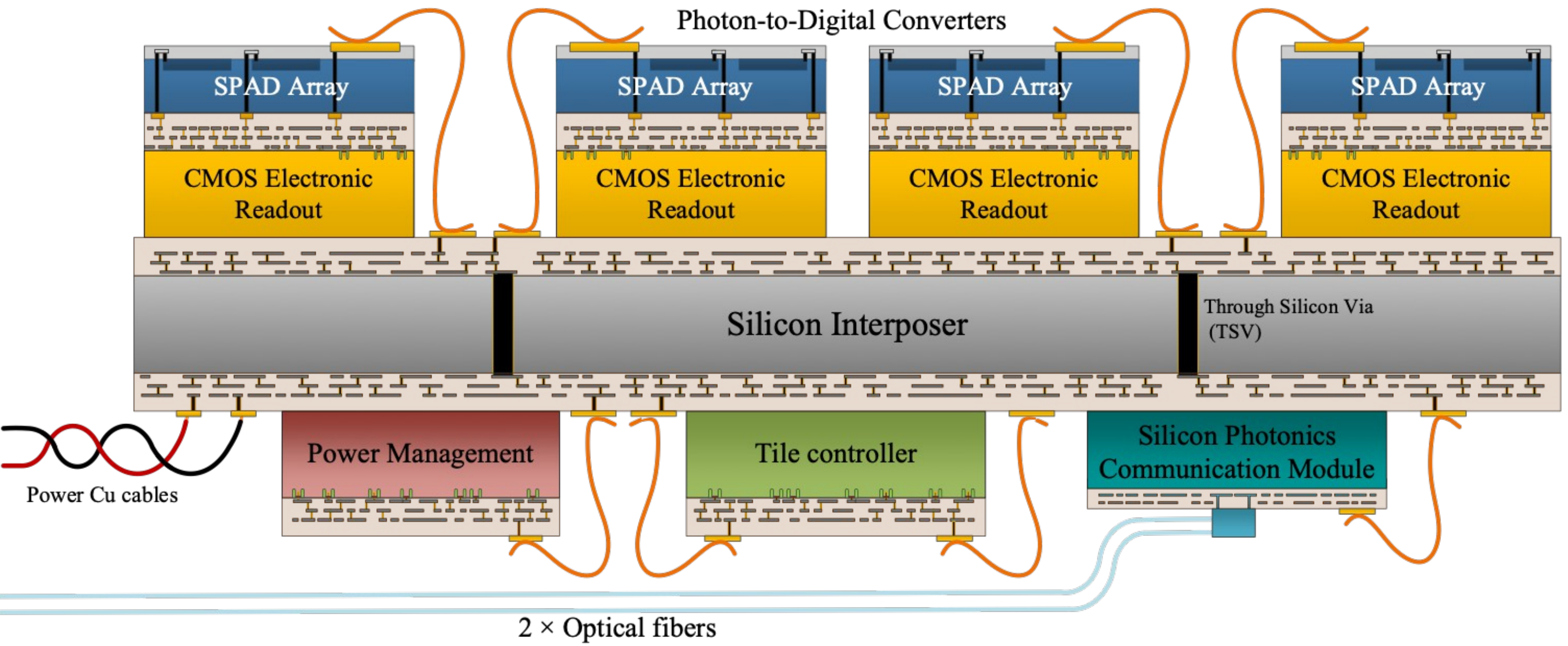
GEANT4 model of single-phase ARGO concept,

with DEAP-3600 optical model,

to study design choices, algorithms, background budget, expected sensitivity

Photodetector R&D for ARGO

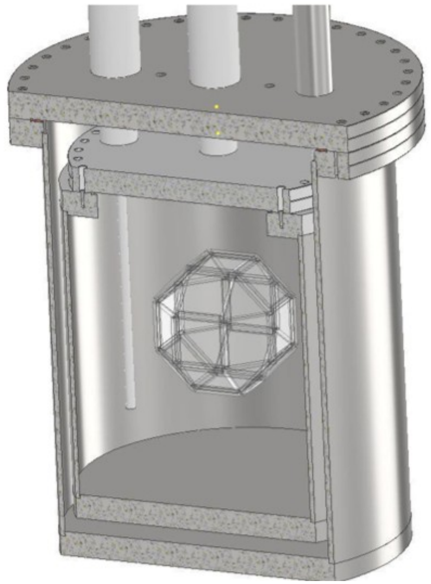
CFI IF 2017
CFI IF 2020
CFI IF 2023



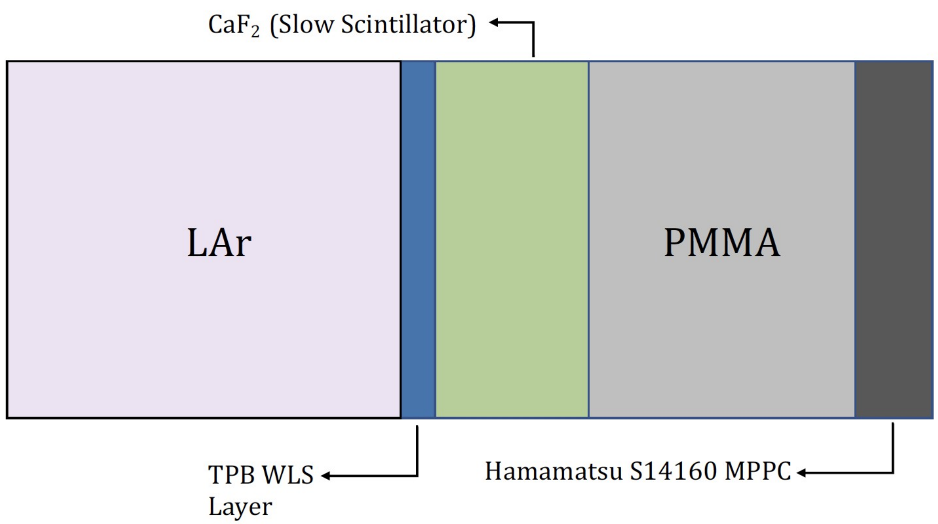
Photon-to-digital converters

(previously known as 3D digital SiPM)

Development at U. Sherbrooke

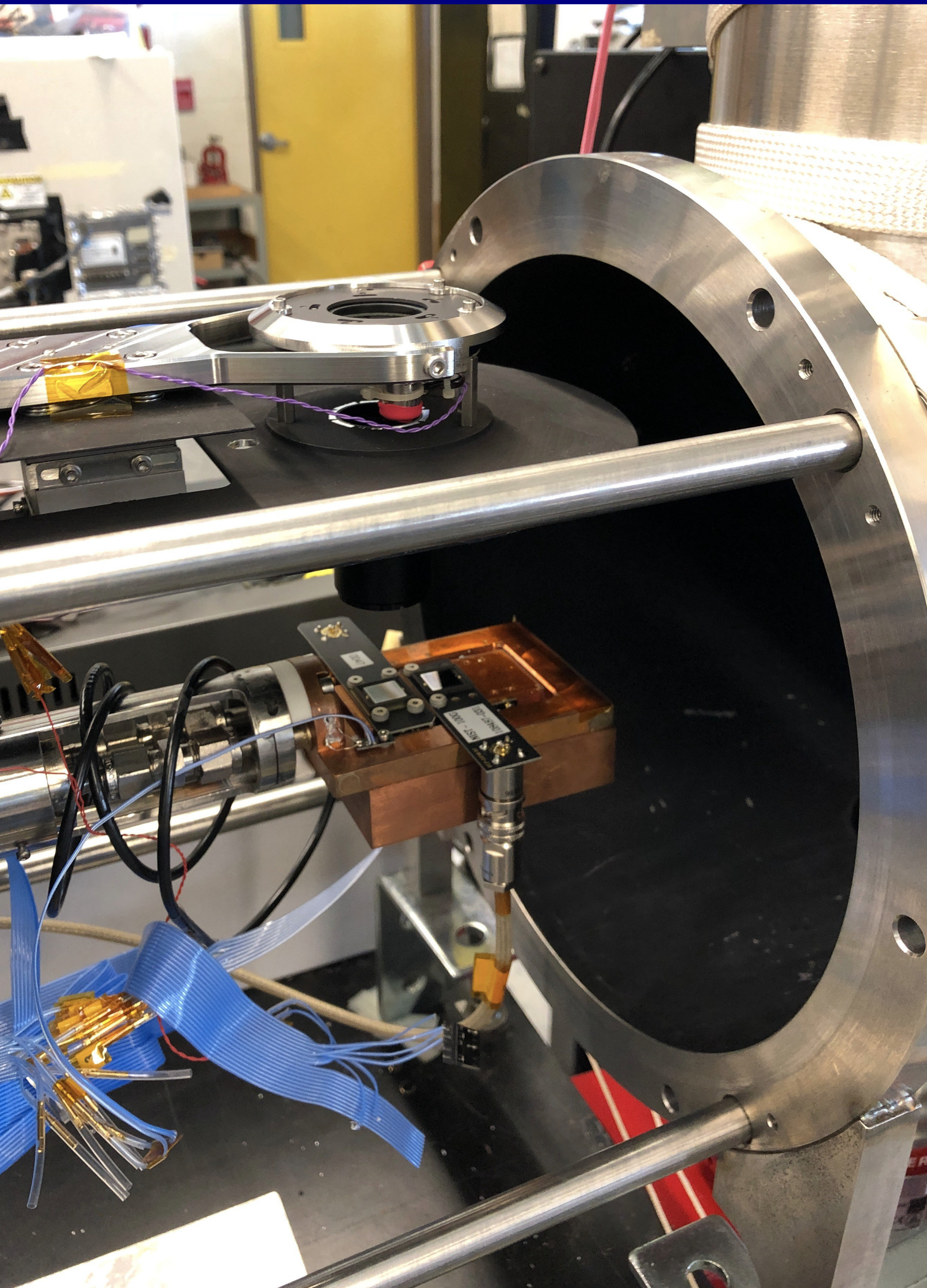


Argon-1 prototype at Carleton

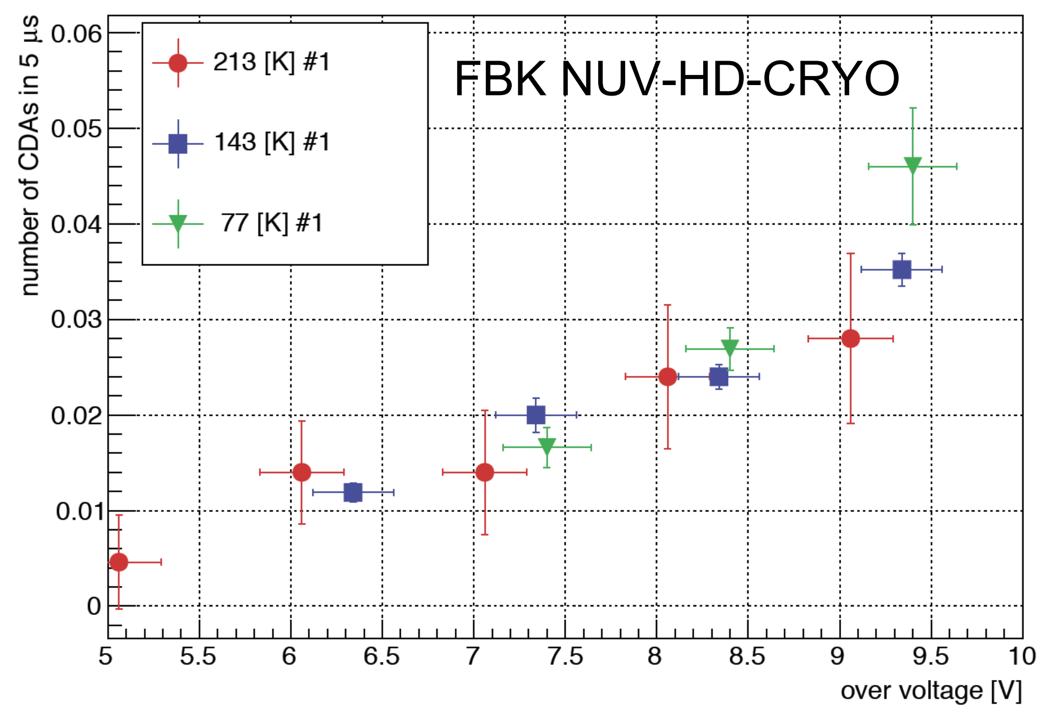


Wavelength shifter R&D at Queen's and Carleton

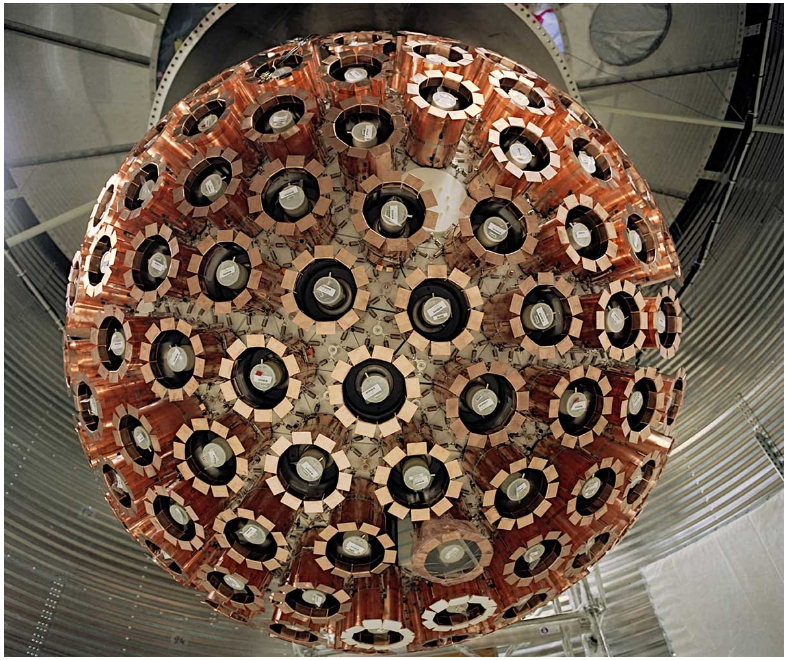
Silicon photomultiplier characterization at TRIUMF



- VM200 monochromator
  - FWHM 4 nm, Δλ centroid < 1 nm
- DC light source
- Temperature stability better than 1 K
- Motorized iris to adjust light flux
- Recalibrated diode to monitor light flux



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
  - Work in progress
    - Multivariate analysis to improve signal acceptance
    - New searches and measurements
    - Hardware improvements
- Next generation experiments: **DarkSide-20k and ARGO**
  - Low-radioactivity underground argon extraction → storage at LNGS and SNOLAB
  - Major Canadian contributions to design and construction
  - Photodetector R&D with silicon photomultipliers!

Thank you! Merci !

NSERC CRSNG

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VALE

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

TRIUMF

UNIVERSITY OF ALBERTA

Carleton UNIVERSITY

Queen's UNIVERSITY

UDS Université de Sherbrooke

Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens

Laurentian University
Université Laurentienne

SNOLAB

PRINCETON UNIVERSITY

Particle Physics
Rutherford Appleton Laboratory

Science & Technology Facilities Council

CONACYT
Consejo Nacional de Ciencia y Tecnología

ROYAL HOLLOWAY UNIVERSITY OF LONDON

US University of Sussex

compute canada | calcul canada

ASTROCENT
NICOLAUS COPERNICUS ASTRONOMICAL CENTER OF THE POLISH ACADEMY OF SCIENCES

Ciemat

INFN Istituto Nazionale di Fisica Nucleare

erc
European Research Council
Established by the European Commission

Instituto de Física

Calcul Québec

Technical University of Munich TUM

LEVERHULME TRUST

Leibniz Supercomputing Centre
of the Bavarian Academy of Sciences and Humanities

Centre for Advanced Computing

NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

SEPnet
South East Physics Network

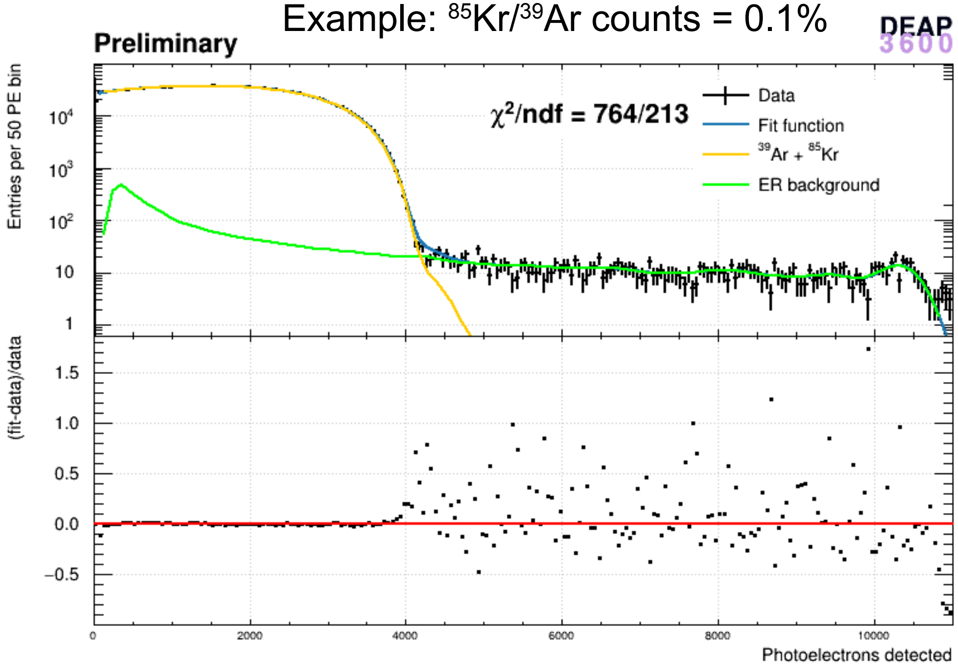
Bonus slides

WORK IN PROGRESS

^{39}Ar specific activity

- Dominant systematic uncertainty: liquid argon mass
  - Latest published: 3279 ± 96 kg
  - Recent dedicated effort drastically **reduced this uncertainty**
- Constraint on ^{85}Kr contribution by including in the beta spectrum fit

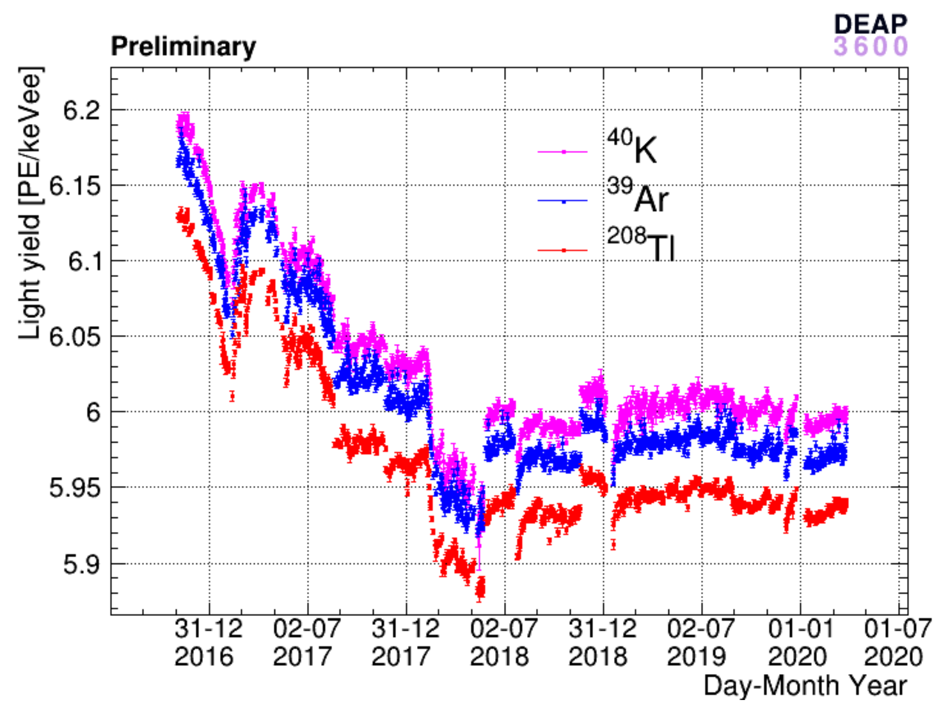
Example: ^{85}Kr/^{39}Ar counts = 0.1%



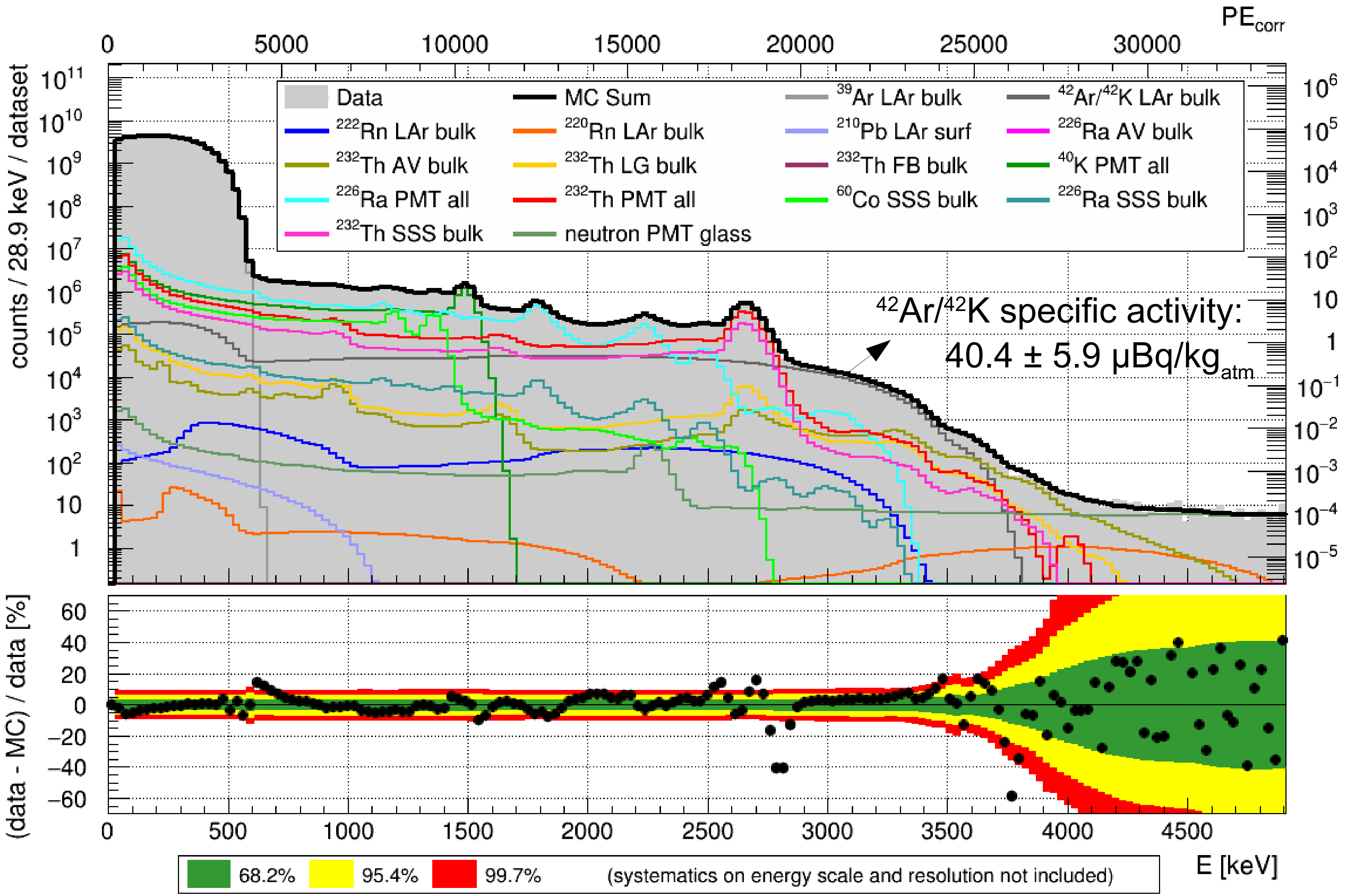
^{39}Ar half-life

- Requires very good understanding of detector conditions, **detector stability**
- Impact on radiometric dating
- Also planning annual modulation analysis

Shown here: Stability of light-yield (PE with after-pulsing removed) over the full dataset



Electromagnetic backgrounds in first-year dataset

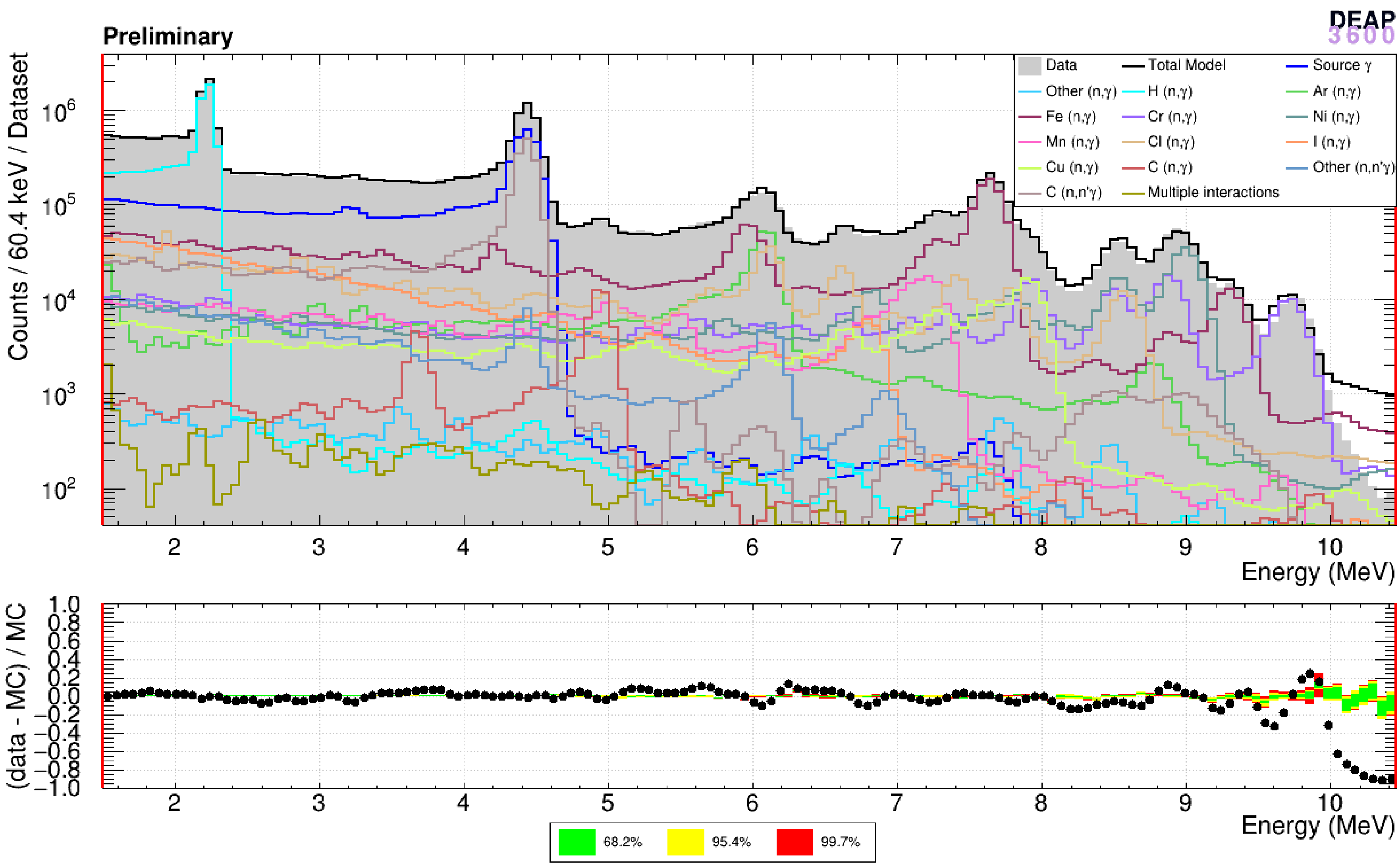


Physical Review D, 100, 072009 (2019) arXiv:1905.05811

5.5 MeV solar axion search

WORK IN PROGRESS

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



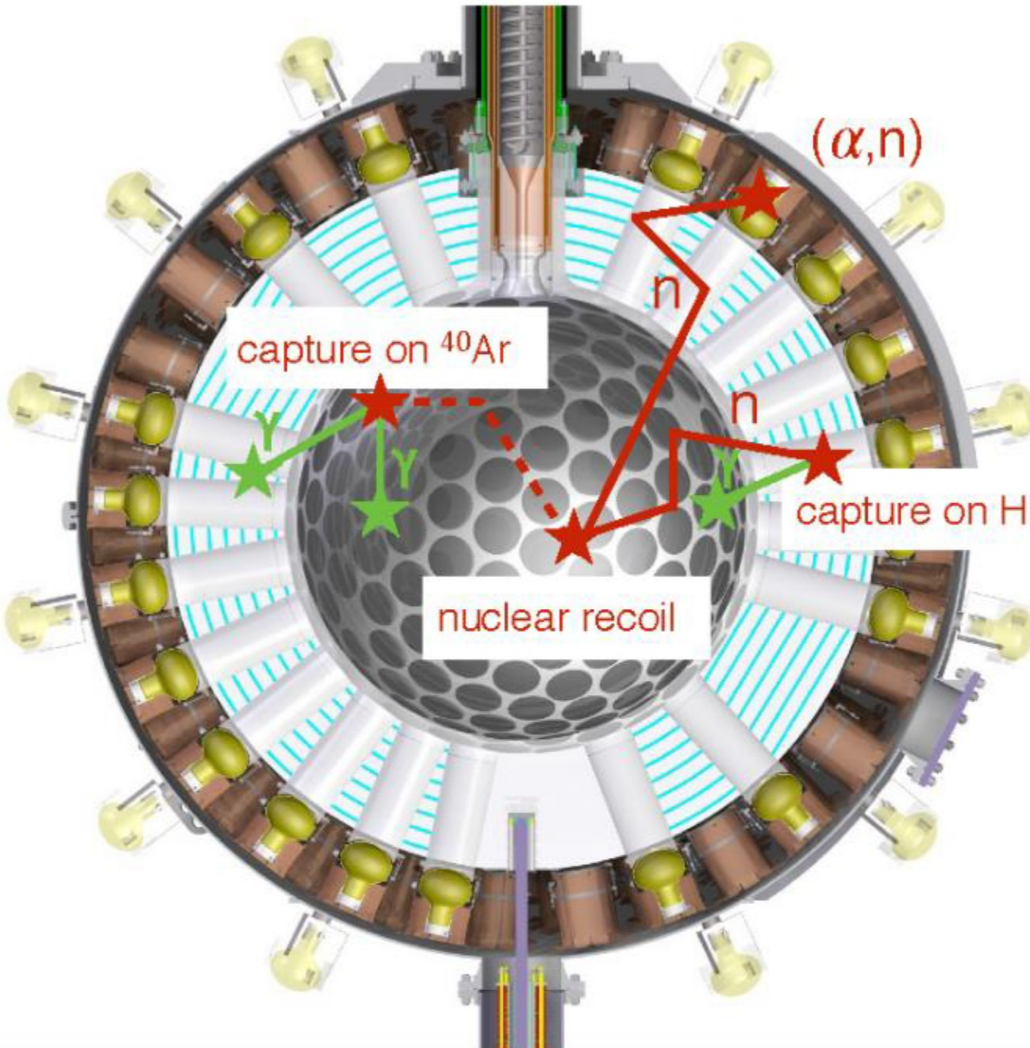
Neutron backgrounds

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**

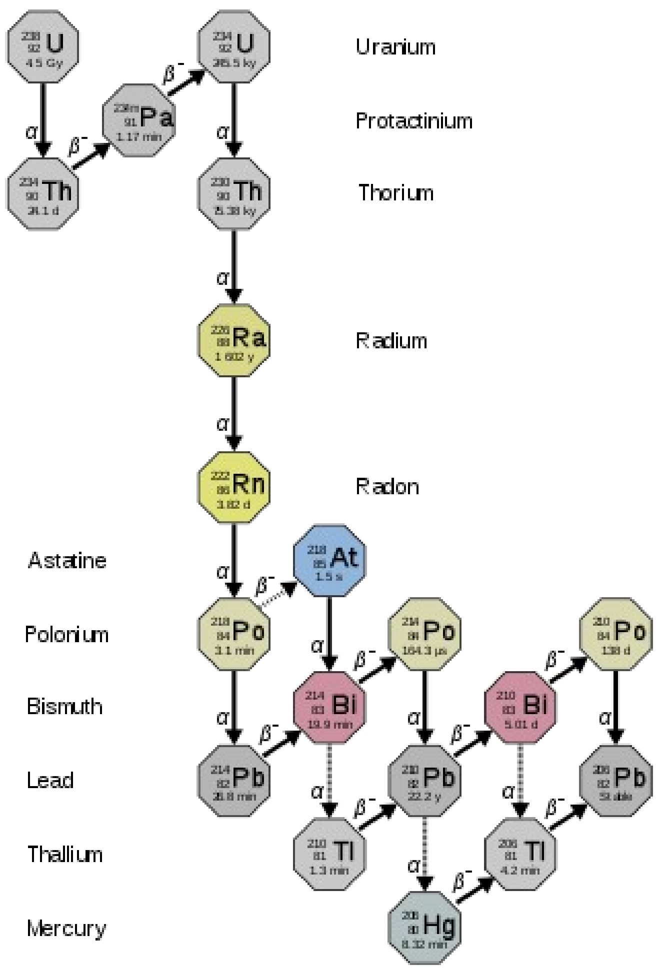
results in agreement with simulations taking material assays as input

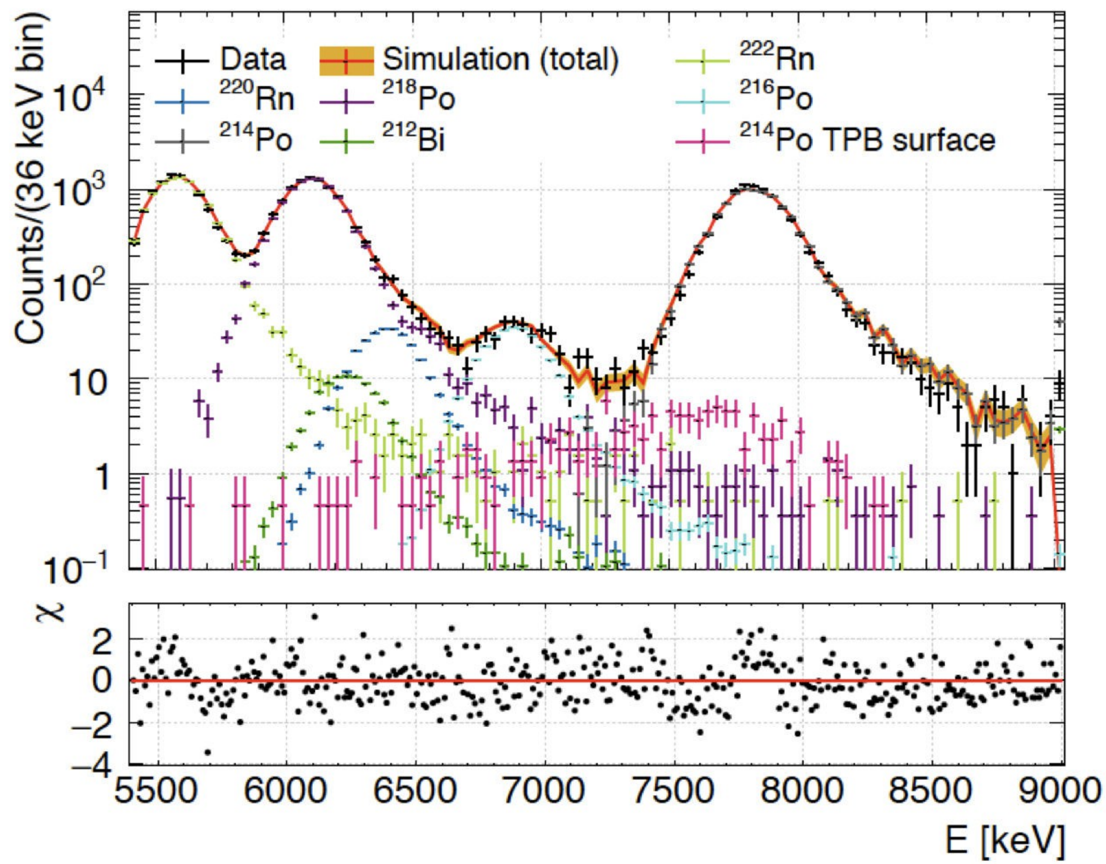


Alphas decays in liquid argon bulk

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)
→ Much more light detected → No impact on the dark matter search

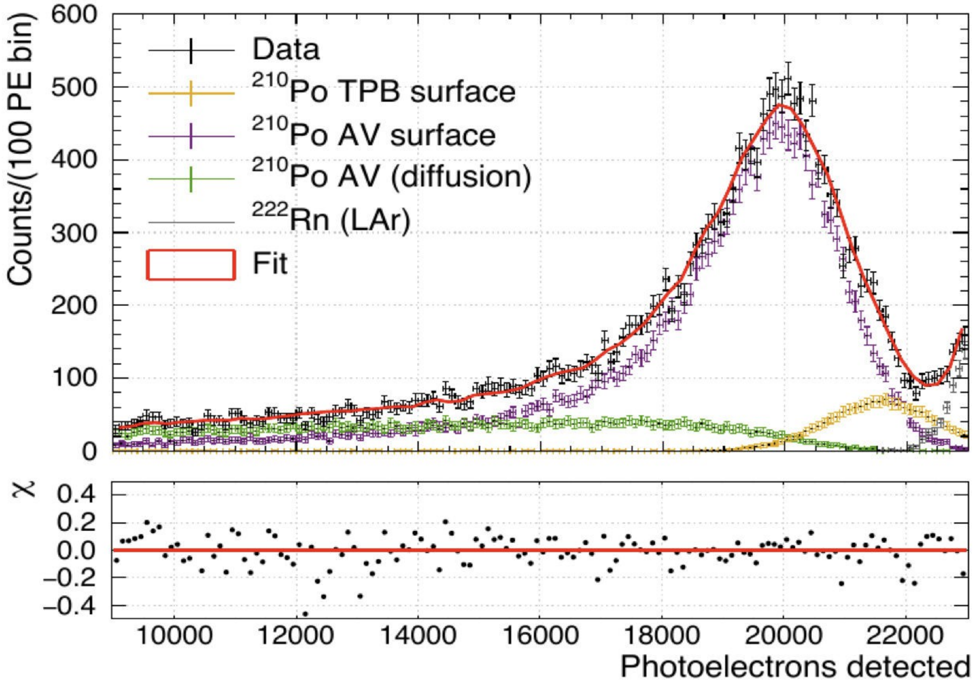


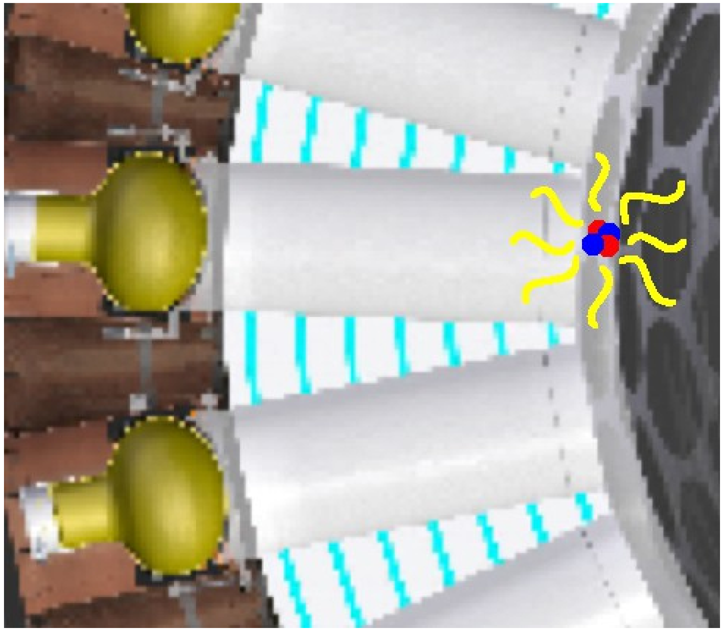


High-energy events observed from the liquid argon volume are well-explained by our background model

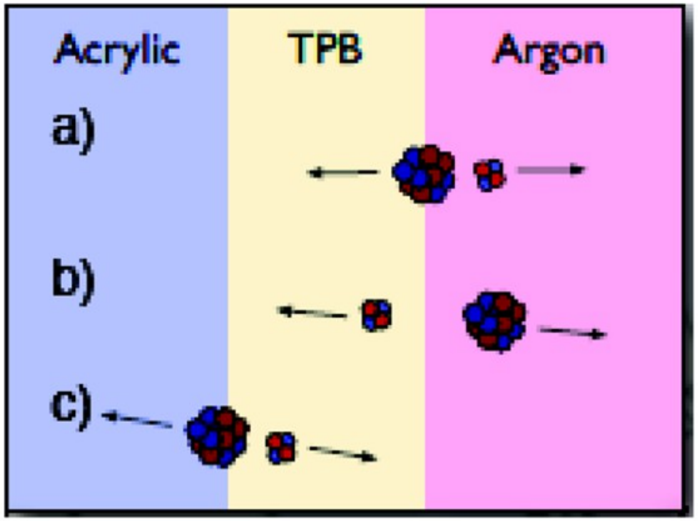
Surface alpha backgrounds

- **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

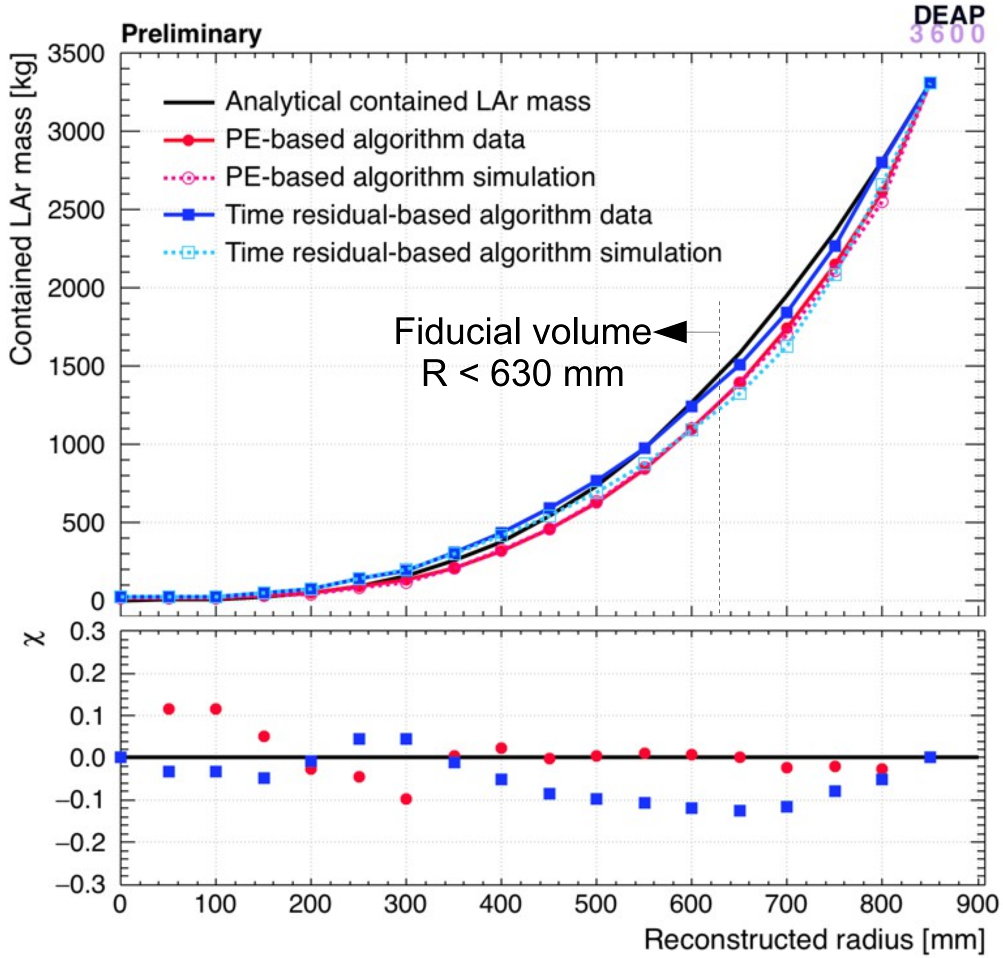


Possible surface event topologies

Position reconstruction: Against surface alphas

Two main algorithms for position reconstruction

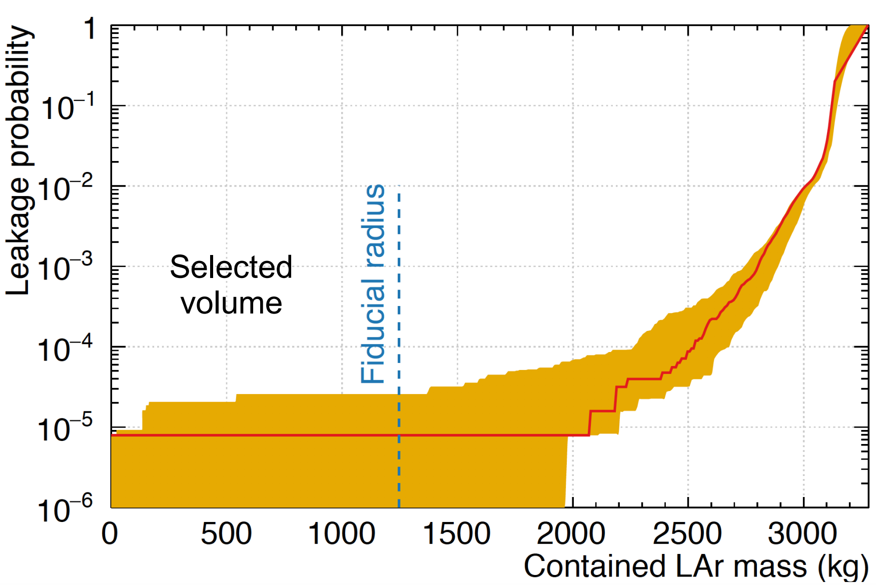
- "PE-based": **more PE are detected** closer to the event (use full 10 μs event window)
- "Time-based": **PE are detected earlier** closer to the event (use first 40 ns of event)



Data-driven measure of resolution:

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

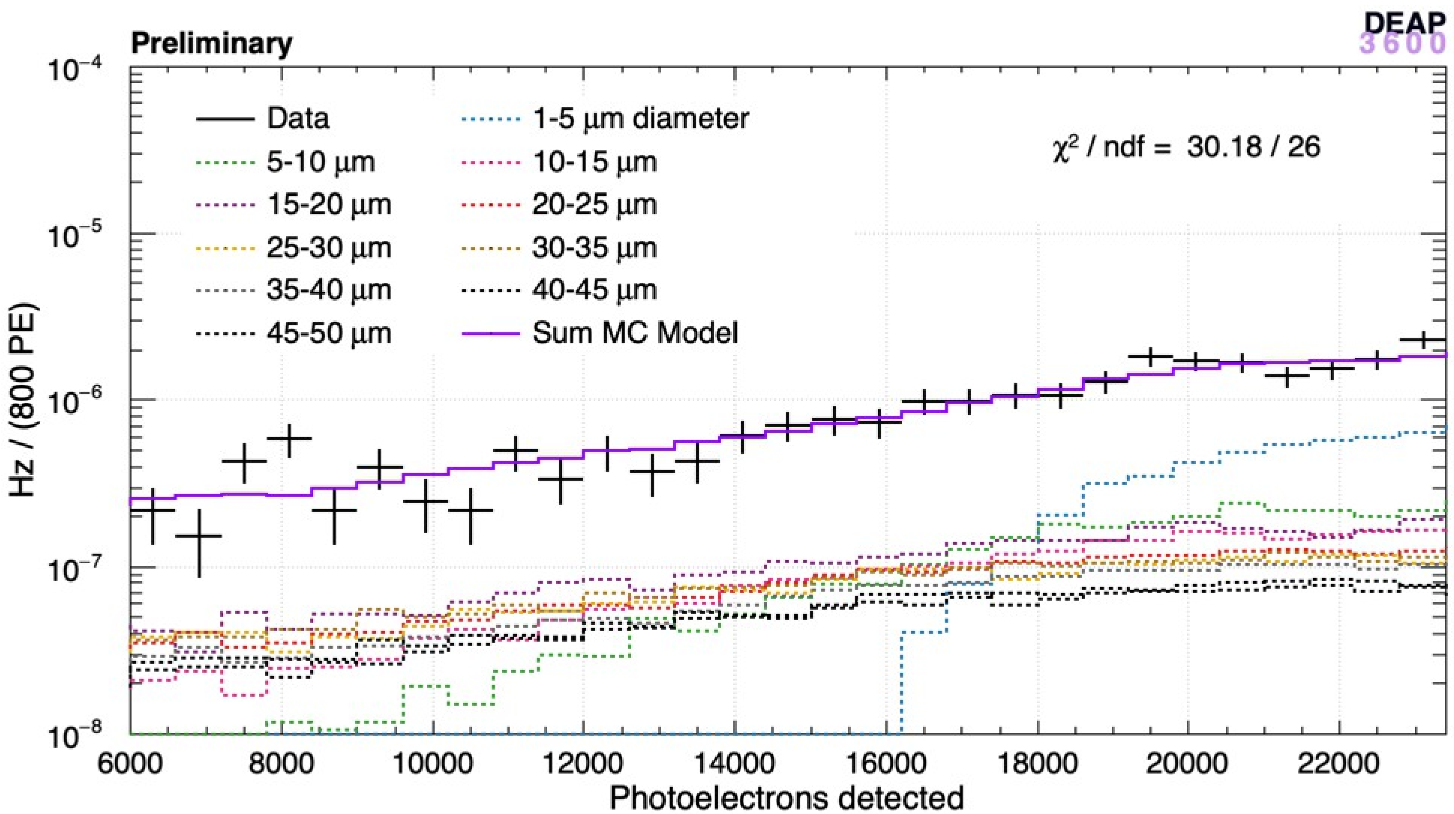
Very low surface alpha leakage

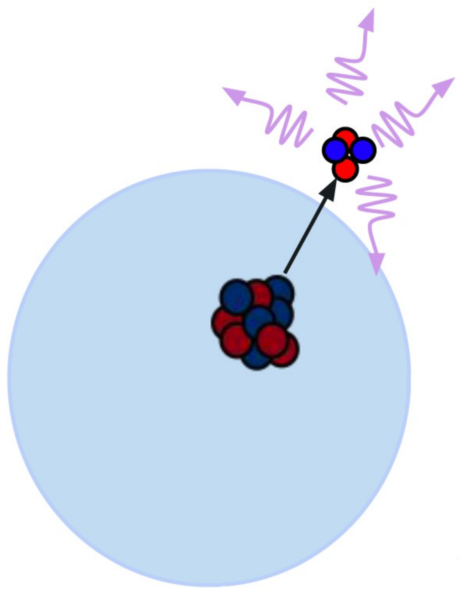


JINST 15, 05, C05061 (2020) arXiv:2004.02058

Dust alpha backgrounds

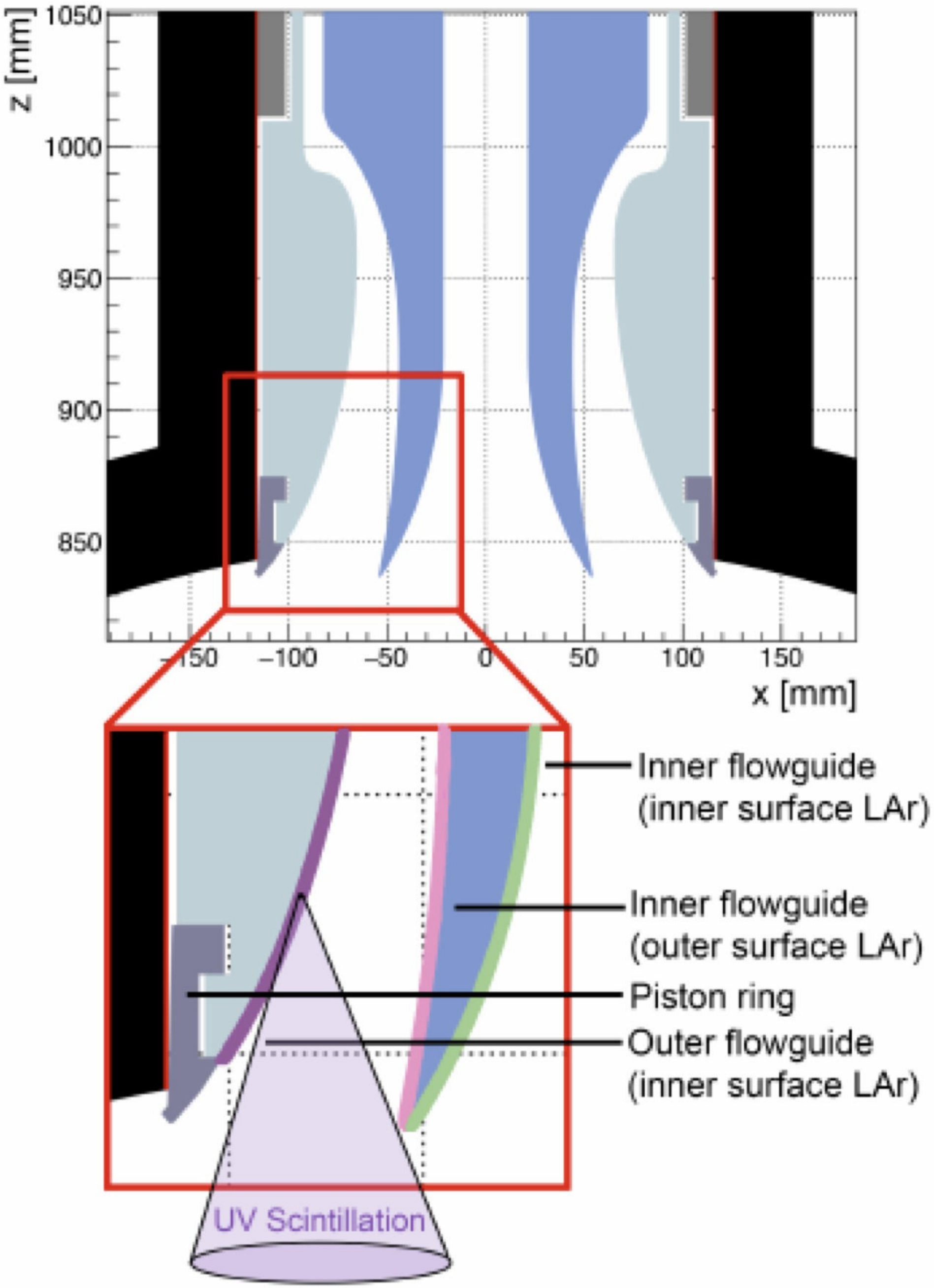
- **Alpha decays** from trace amounts of **dust particulates** in liquid argon create low-PE events originating from the LAr bulk volume
  - **Attenuation** before entering liquid argon, and scintillation light **shadowed**
  - Now included in background model
    - Pure control region defined at intermediate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





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

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

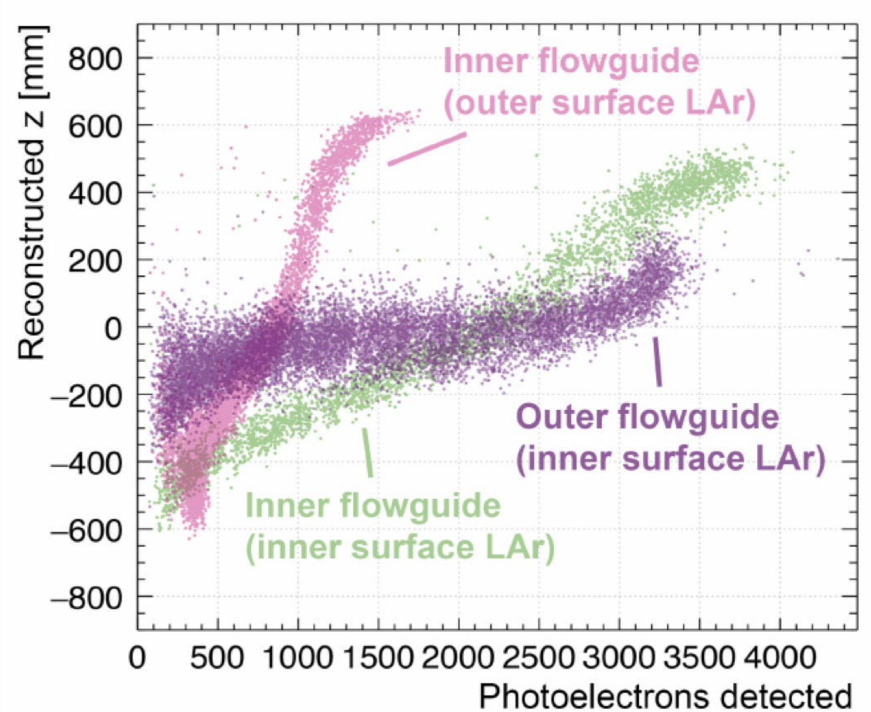
Colour code (this slide and next):

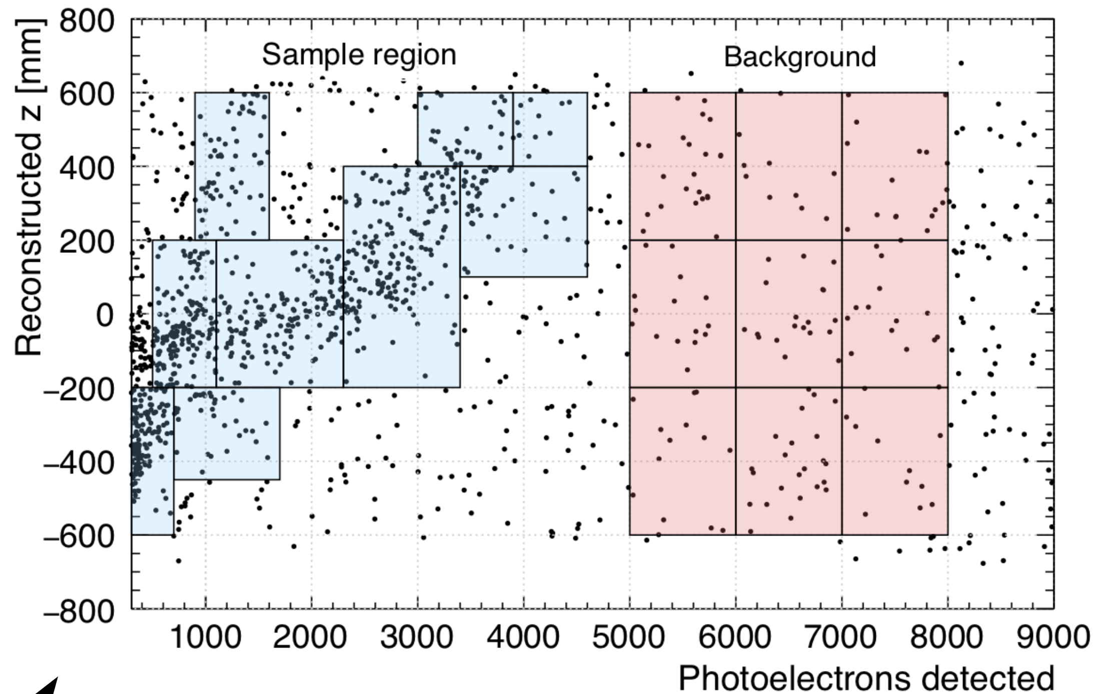
Outer flowguide, inner surface LAr

Inner flowguide, outer surface LAr

Inner flowguide, inner surface LAr

Neck alpha backgrounds: Event rate determination



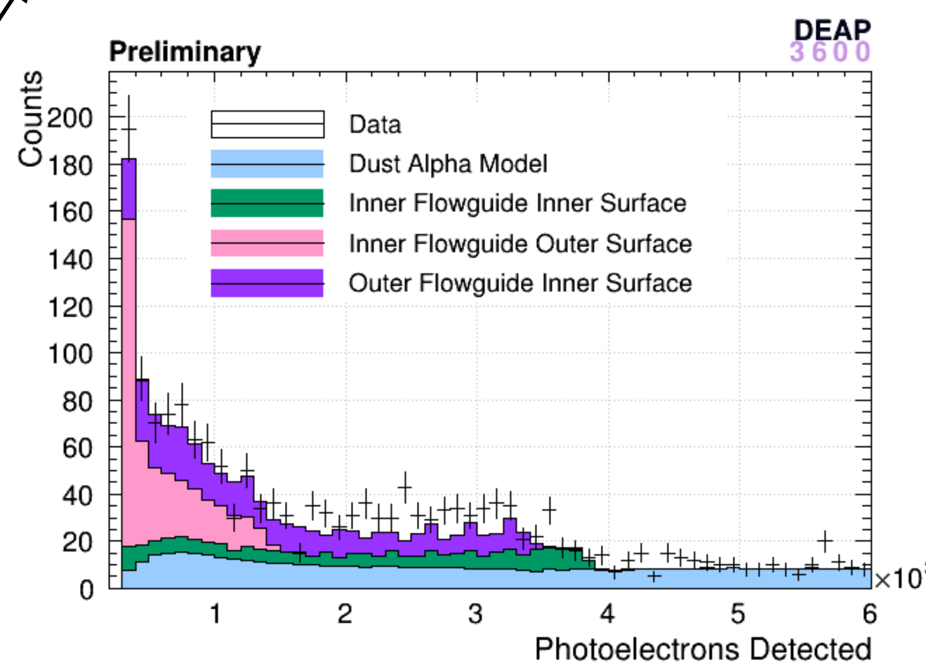


Identification of features
from Monte Carlo **simulation**

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

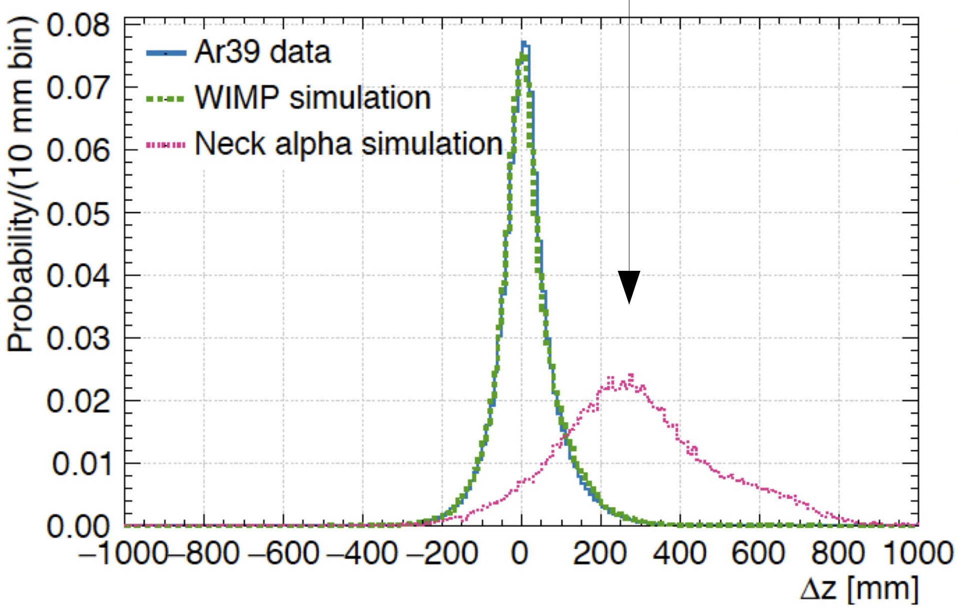
... allows a **template fit** using multiple
control regions, to figure out rates
of neck alpha events from all surfaces

New: Dust background considered in fit

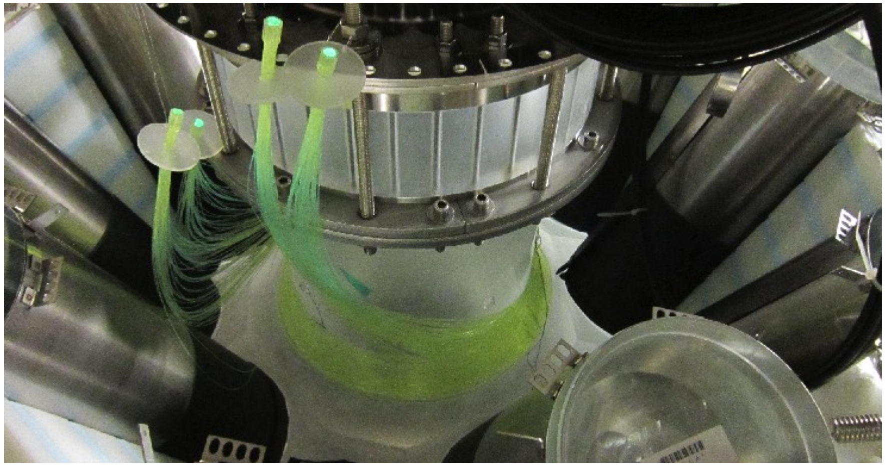


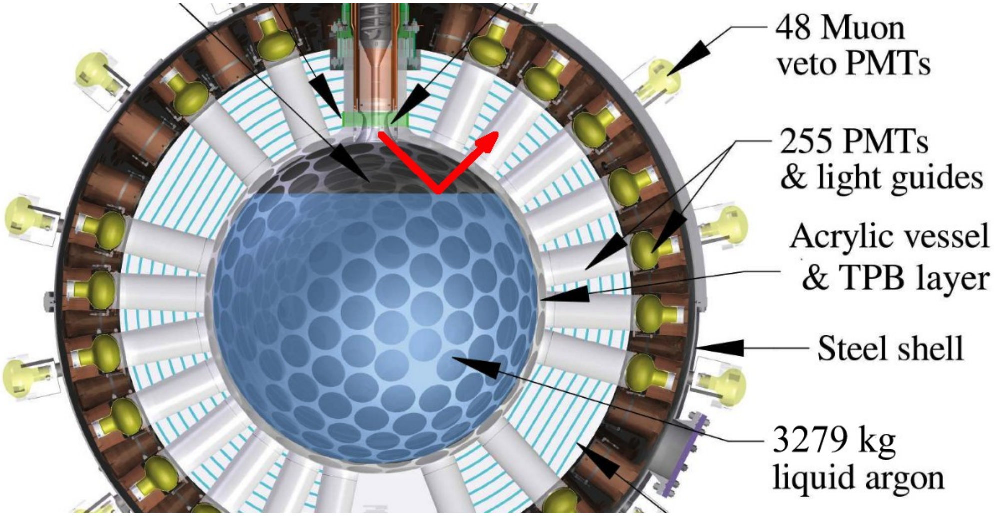
Known handles against neck alpha backgrounds

- 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



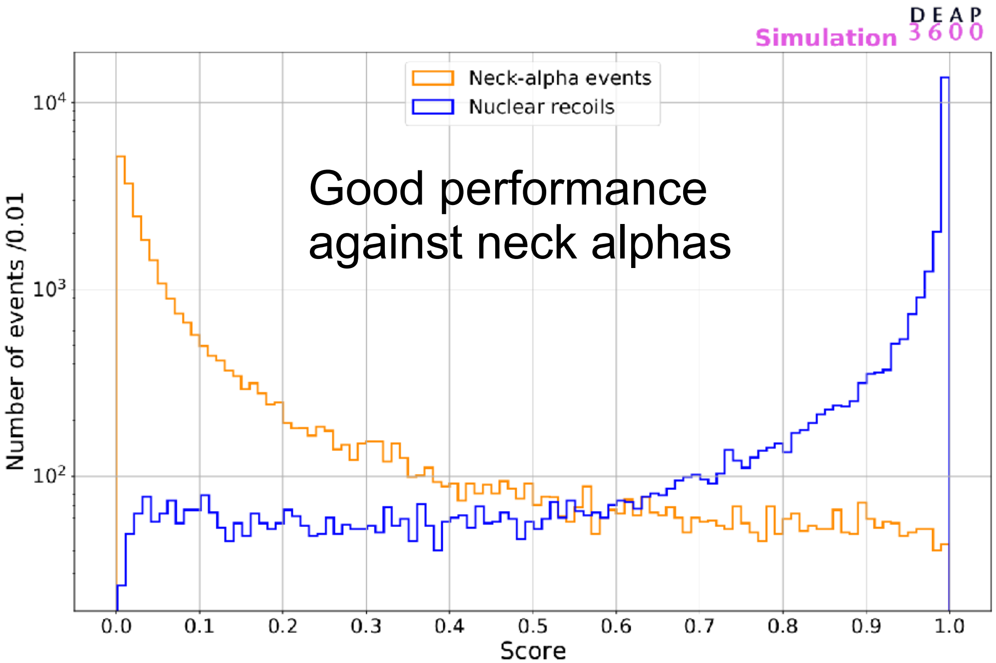


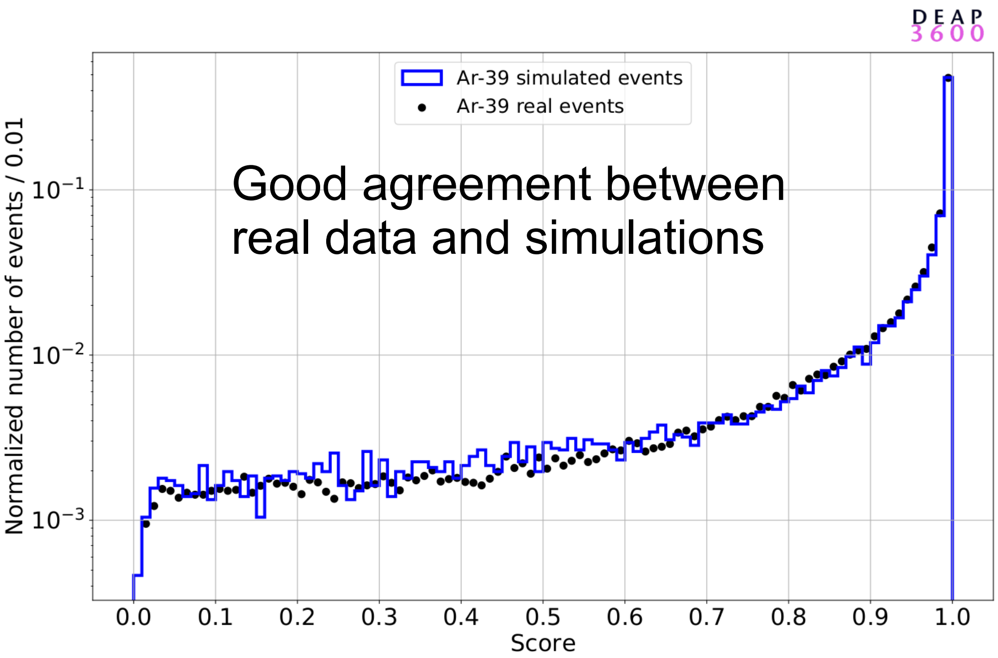
UV photon reflection at the liquid argon surface

DEAP-3600 WIMP search: Next steps

WORK IN PROGRESS

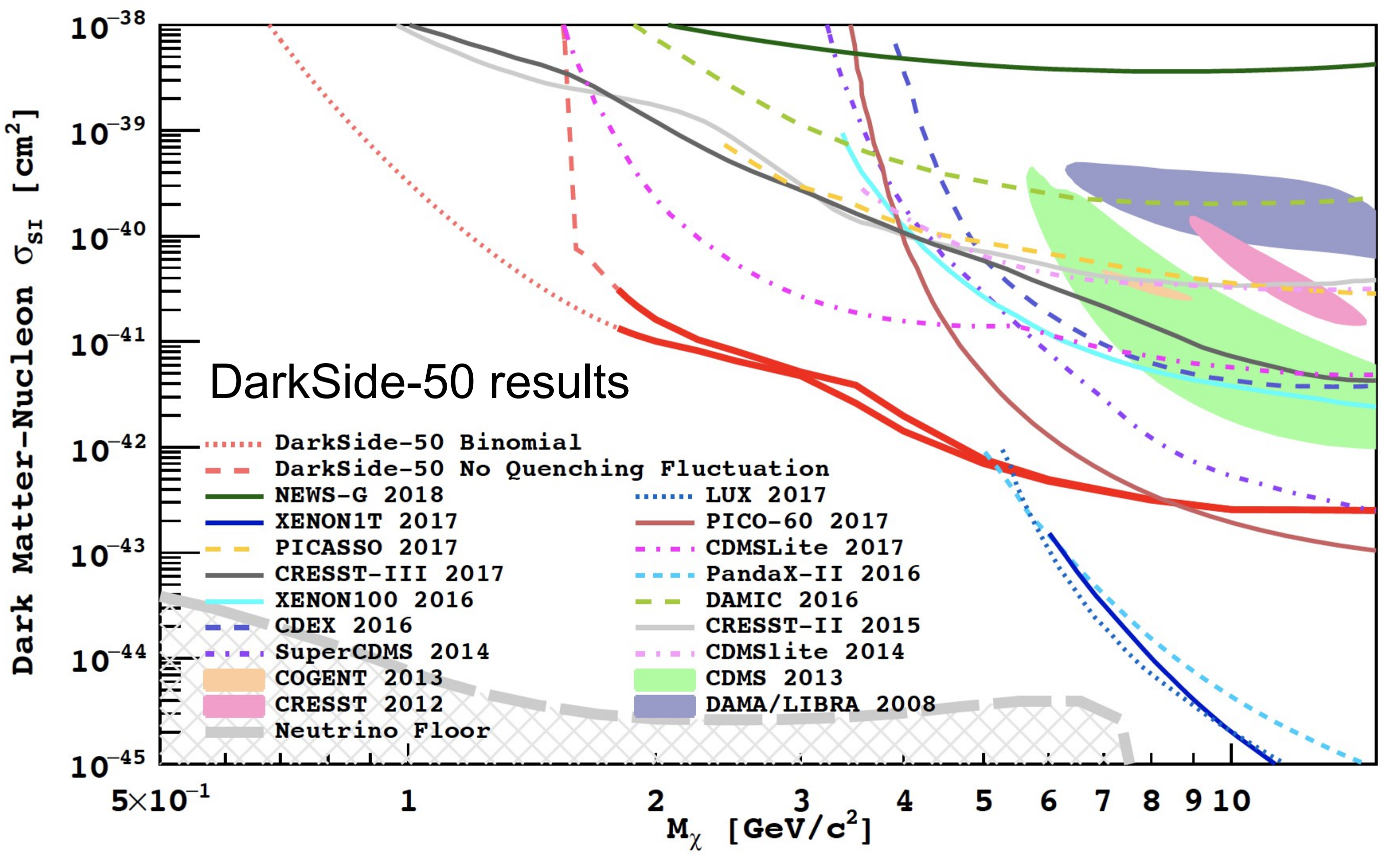
- Published DM search from first-year dataset November 2016 – October 2017
  - Working on **profile-likelihood ratio analysis** to extract full sensitivity on this dataset
- Main effort: **Analyze full second-fill dataset** to March 28th, 2020
- To improve sensitivity: three **MVA algorithms** trained 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 → Complete our blind analysis

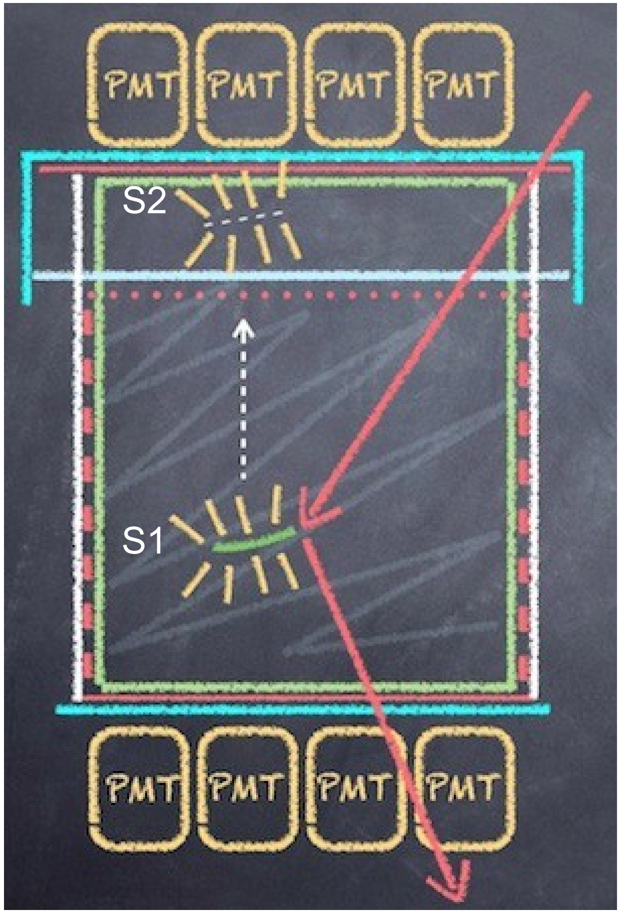




DarkSide-LowMass program

- Low-mass sensitivity achieved based on the ionization signal only in the TPC **(S2)**
  - Objective: Efficiency in the recoil energy window 0.1 – 3 keV_{ee}
  - Future 1-tonne LAr TPC for low-mass DM requires low backgrounds and systematics: DarkSide-LowMass designed to **reach the ^{8}B neutrino floor**





Physical Review Letters 121, 081307 (2018) arXiv:1802.06994