Status of DEAP-3600 and Development of the ARGO Dark Matter Experiment

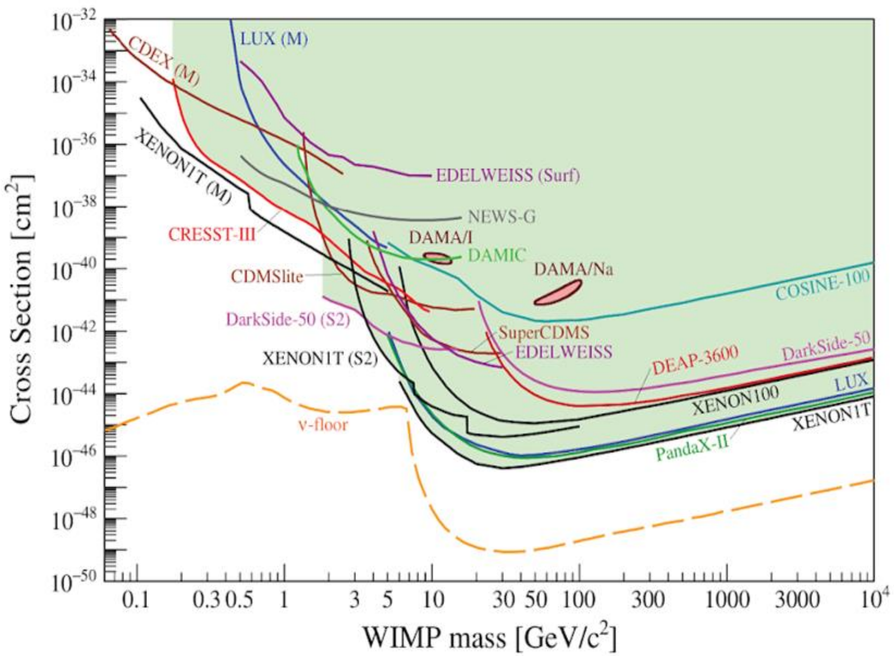
Outline:

- Status and Plans for DEAP-3600
- The GADMC and Plans for ARGO
- Development of Photon-to-Digital converters for ARGO
- Summary of the proposed R&D activities for ARGO

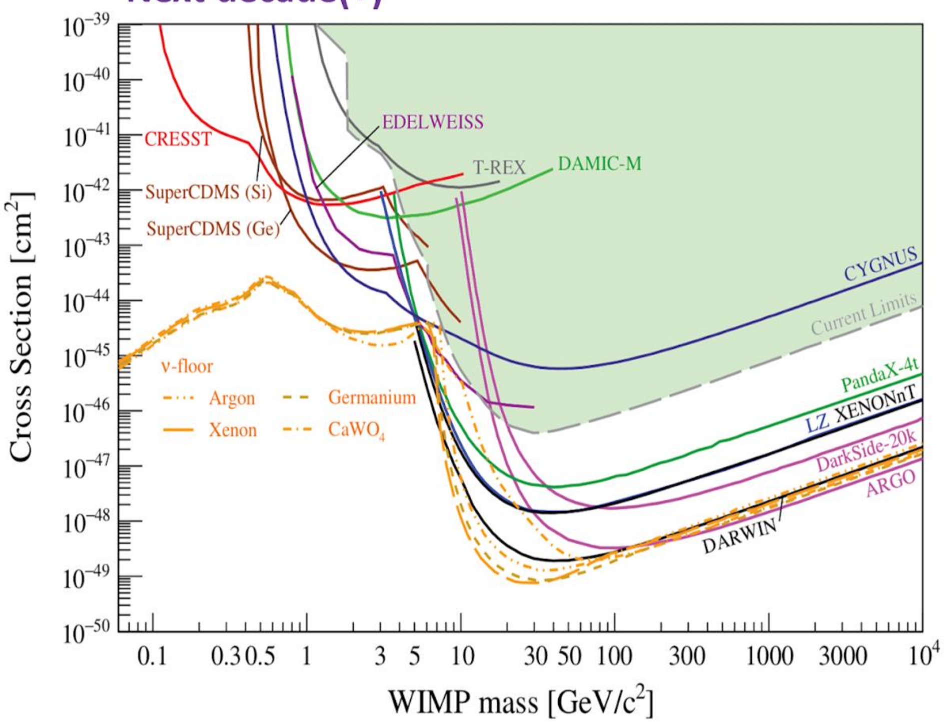
Mark Boulay on behalf of DEAP-3600
and ARGO
May 25, 2022 XeSAT2022 @ Coimbra

The direct detection landscape: important to keep pushing in all directions.

Present



Next decade(+)



APPEC DM report 2104.07634 2021

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Global Argon Dark Matter Program formed in 2017

Over 400 researchers from

- DarkSide
- DEAP
- ArDM
- MiniCLEAN

DS-20K @LNGS → ARGO @SNOLAB

- GADMC includes over 400 researchers from 69 institutions in 14 countries
- Completion of current science program with DEAP
- Joint collaboration on DS-20k at LNGS (200 tonne-years)
- Joint collaboration on ARGO detector to reach neutrino floor

ARGO: approximately 300 (fiducial) tonnes for 3 kt-year argon DM search
Developing conceptual design, order ~100 m^2 surface area.
Develop concept over next 3 years (details to follow)

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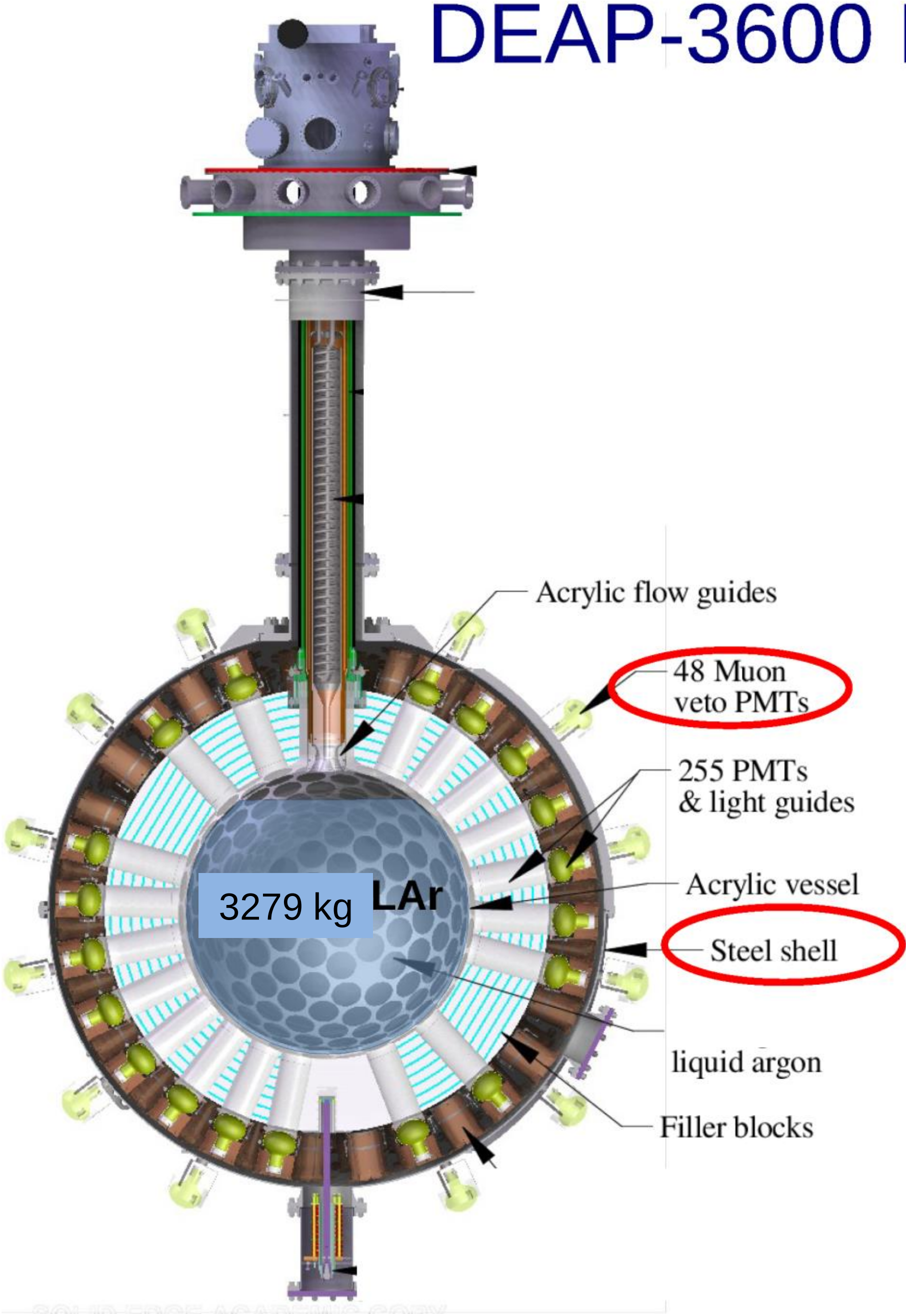
The DEAP Collaboration

- **D**ark matter **E**xperiment using **A**rgon **P**ulseshape discrimination
- Direct detection of dark matter experiment utilizes single phase liquid argon detector.
- Operating in SNOLAB underground facility in Sudbury, Canada.
- DEAP-3600 experiment collected data from November, 2016 – March, 2020, now undergoing upgrades.

Particle Physics Rutherford Appleton Laboratory
SNOLAB
University of Sussex
Technical University of Munich
TRIUMF
Instituto de Física
PRINCETON UNIVERSITY
Queen's University
ROYAL HOLLOWAY UNIVERSITY OF LONDON
UNIVERSITY OF ALBERTA
ASTROCENT Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences
Canadian Nuclear Laboratories / Laboratoires Nucléaires Canadiens
Carleton University
Gobierno de España, Ministerio de Ciencia, Innovación y Universidades
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
INFN Istituto Nazionale di Fisica Nucleare
Johannes Gutenberg Universität Mainz JGU
National Research Center "Kurchatov Institute"
Laurentian University Université Laurentienne

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

DEAP-3600 Dark Matter Search



- **Single phase liquid argon** approach: simple, scalable, inexpensive
- 3.3 tonne target (1000 kg fiducial) in sealed ultraclean Acrylic Vessel
- Vessel is “resurfaced” in-situ to remove deposited Rn daughters after construction
- In-situ vacuum evaporated TPB wavelength shifter (~10 m^2 surface)
- Bonded 50 cm long light guides + polyethylene shielding against neutrons
- 255 Hamamatsu R5912 HQE PMTs 8-inch (32% QE, 75% coverage)
- Detector immersed in 8 m water shield, instrumented with PMTs to veto muons
- Located 2 km underground at SNOLAB

Fabrication and Assay of DEAP Acrylic

- Fabrication from pure MMA monomer at RPTAsia (Thailand), strict control of radon exposure for all steps, to < 10^{-20} g/g ^{210}Pb (RPT was fabricator of the SNO Acrylic Vessel)

- Assay of production acrylic **< 2.2x10^{-19} g/g ^{210}Pb**
  (Corina Nantais M.Sc. Thesis 2014, <0.2 bkg events/3 years)

Monomer cast at RPT Asia, 2010

Thermoformed Panel at RPT Colorado

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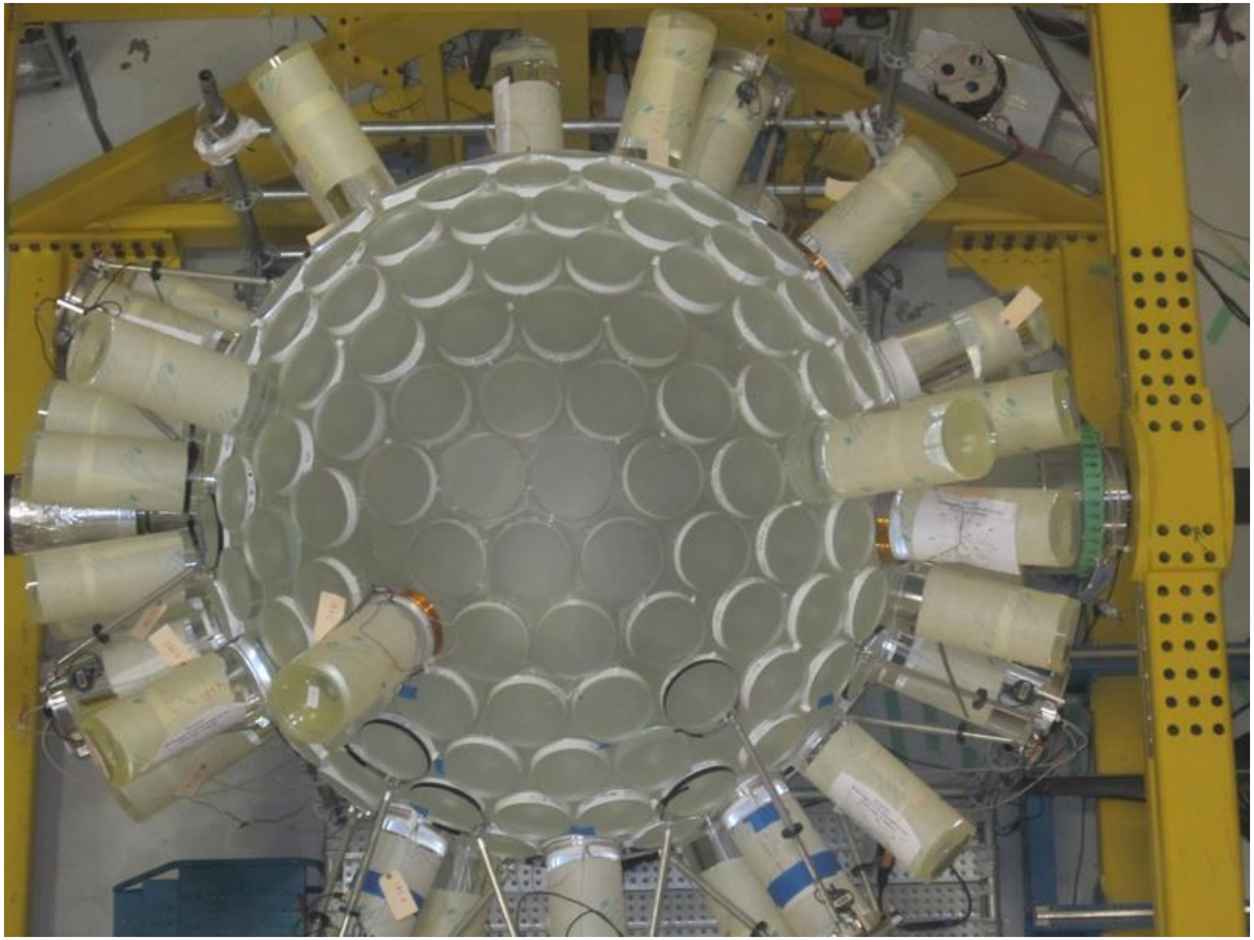
Bonding light guides to the DEAP AV, underground at SNOLAB



DEAP AV in “The Rotator” at SNOLAB

Light guides bonded then annealed in radon-reduced air oven

>5 meter attenuation length in light guide acrylic!

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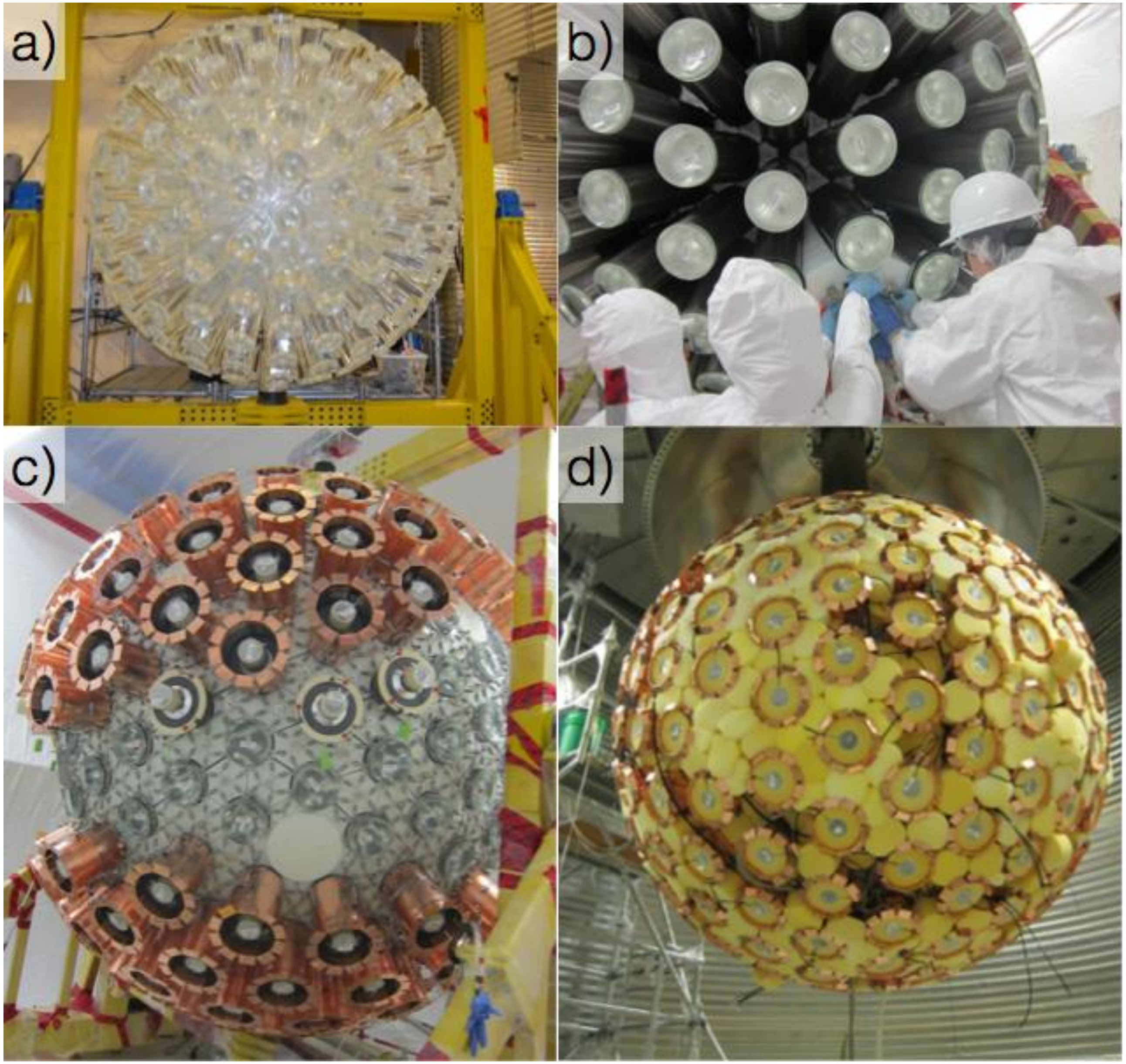
Light guides on AV

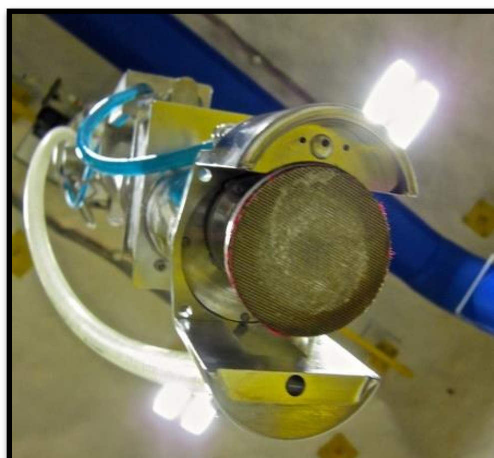
Reflectors on light guides



PMT and inner detector installation Oct 2014

An 18 foot tall sanding robot was deployed in the AV to remove inner surface layer of acrylic (and Rn progeny)

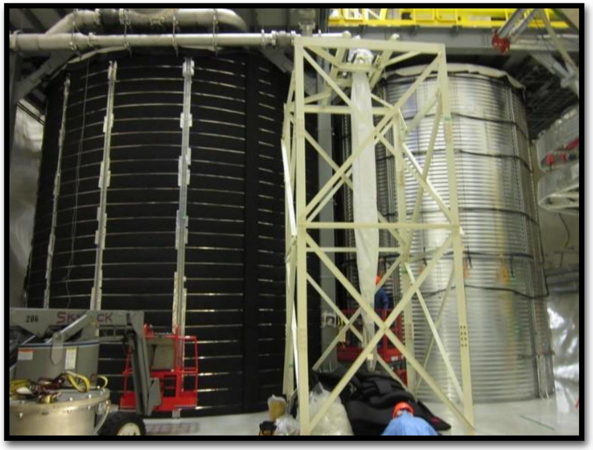
"The Resurfacer"

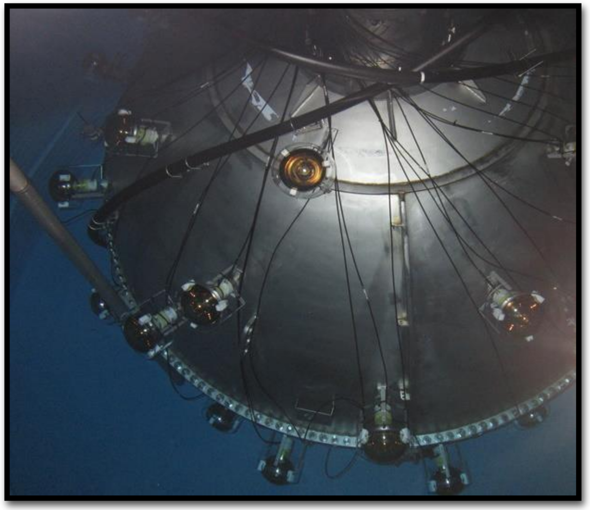


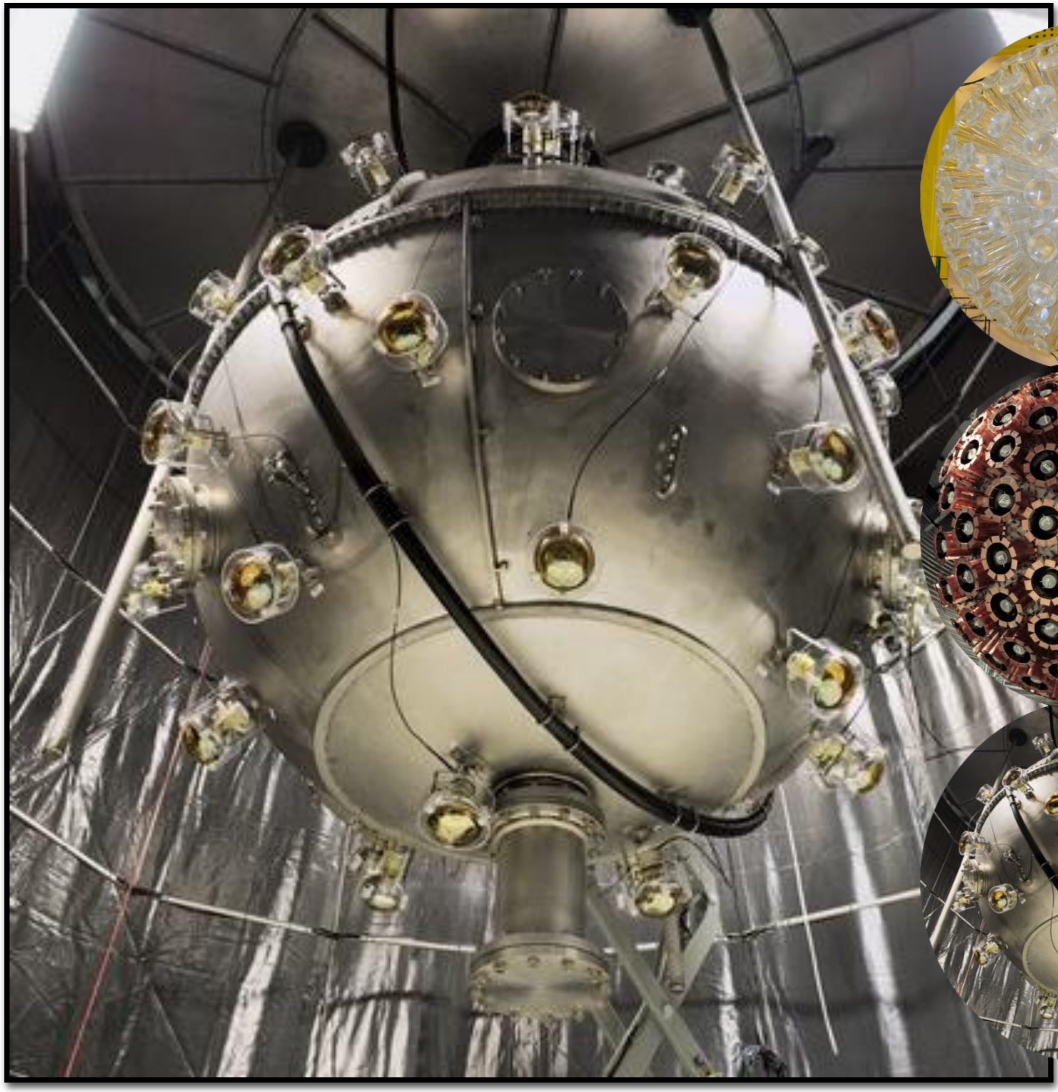
2016 J. Phys.: Conf. Ser. 718 042025

Construction of DEAP-3600 was completed in 2016

Filled in 2016 then collected data 2016-2020, no repurification required







Detector paper: 1712.01982, Astropart. Phys. 108 1 (2019)

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Some comments (background table from PRD 100 022004 2019)

	Source	N^{CR}	N^{ROI}
β/γ's	ERs	2.44×10^9	0.03 ± 0.01
	Cherenkov	$< 3.3 \times 10^5$	< 0.14
n's	Radiogenic	6 ± 4	$0.10^{+0.10}_{-0.09}$
	Cosmogenic	<0.2	<0.11
α's	AV surface	<3600	< 0.08
	Neck FG	28^{+13}_{-10}	$0.49^{+0.27}_{-0.26}$
	Total	N/A	$0.62^{+0.31}_{-0.28}$

Background rate is **LOW!**

0.07 ± 0.03 ev/t.y/keV$_{ee}$

(NR bkg in WIMP search ROI)

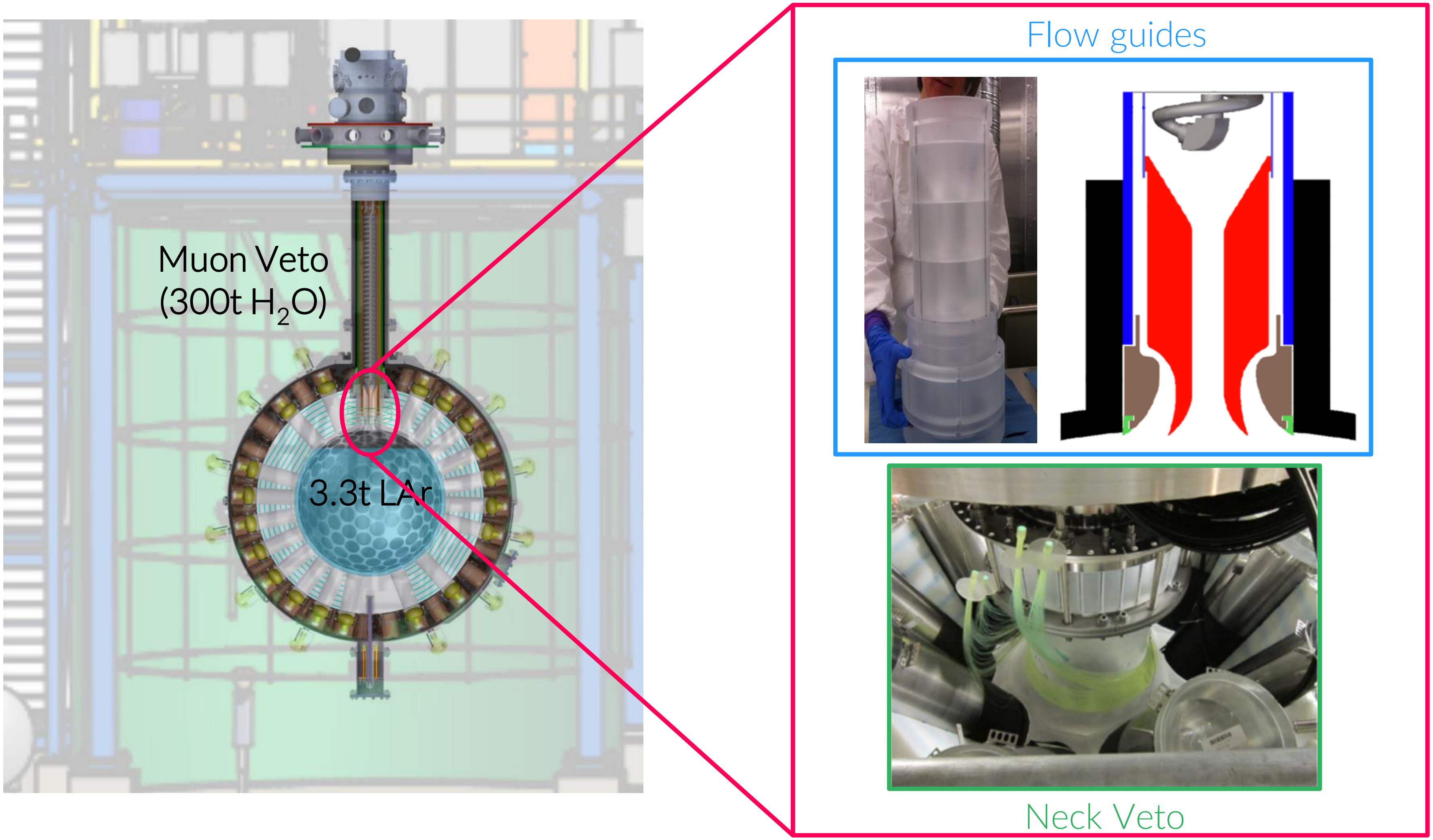
231 live-days with 824 kg fiducial mass

v. Low backgrounds; ^{222}Rn 0.2 microBq/kg

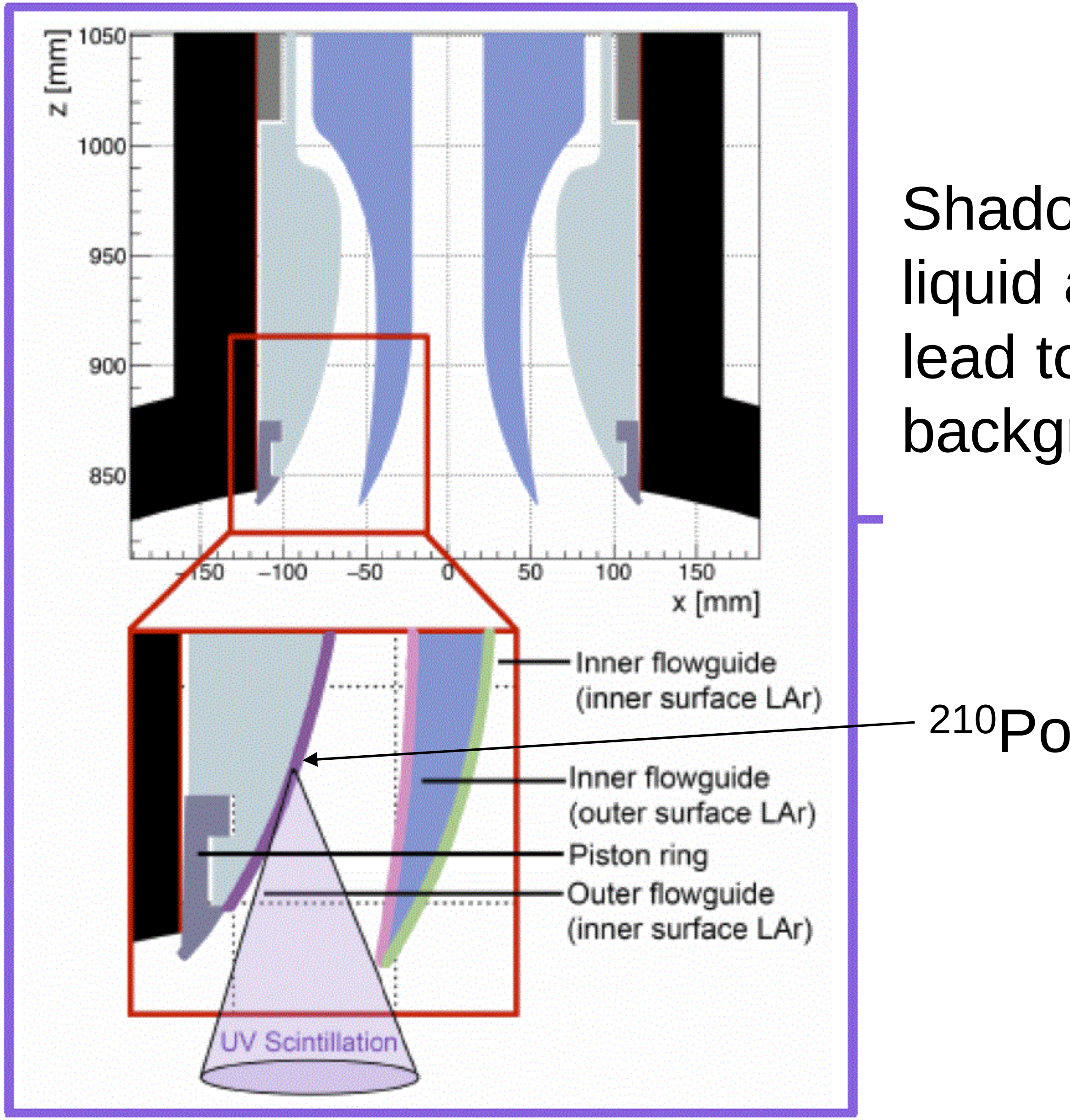
Dominant source: shadowed α decays from ^{210}Po on neck flowguides

Current published WIMP-search sensitivity from cut-and-count analysis; **working on multivariate analysis**

Remember: the neck

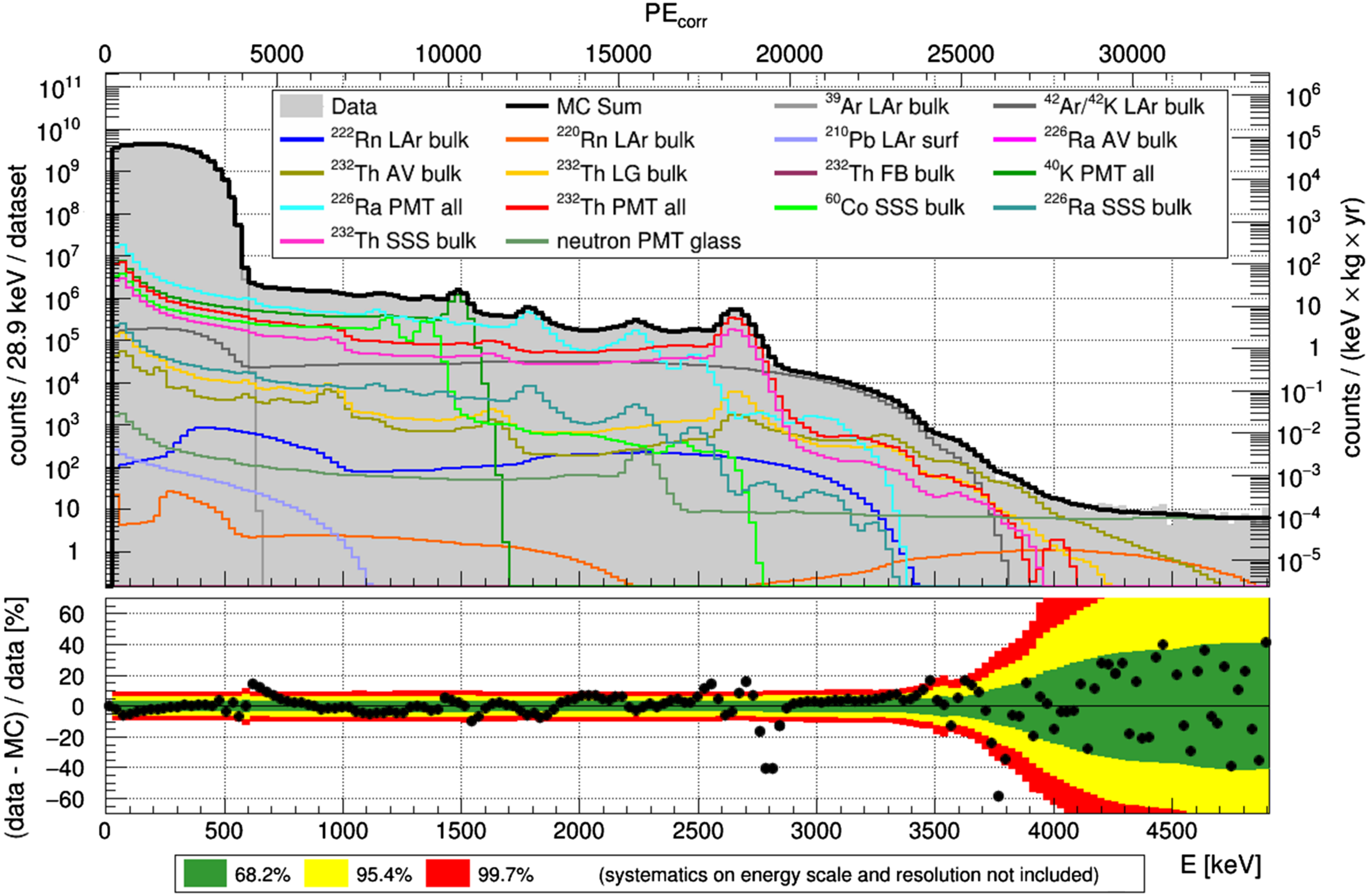


Backgrounds – Alphas (Neck)



Shadowed α decays from liquid argon in neck region lead to low-energy backgrounds

Electromagnetic Backgrounds



Phys. Rev. D 100 (2019) 072009

- Agreement over 8 orders of magnitude!
- Most sensitive measurement of ^{42}Ar in Ar

ER backgrounds after argon-PSD

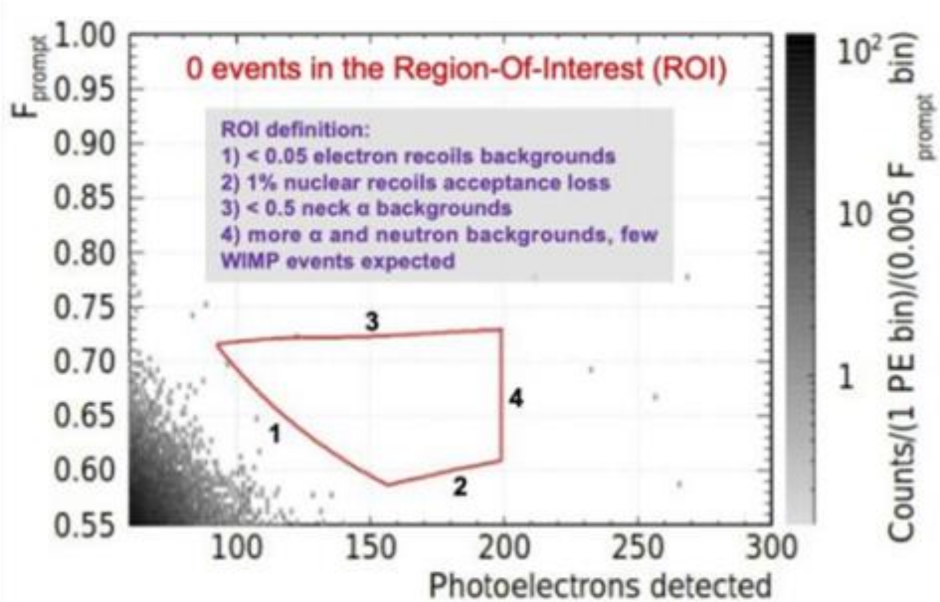
Experiment	Fid. Mass (tonnes, nominal)	^{39}Ar specific activity	Total ^{39}Ar rate (Bq)	ER Events in ROI
DEAP-3600	1	~1 Bq/kg	1,000	0.03 +/- 0.01 in 231-days x 824 kg *
DS-20k	20	<1/1400 Bq/kg	< 14.3	
ARGO	300	<1/1400 Bq/kg	< 214.3	

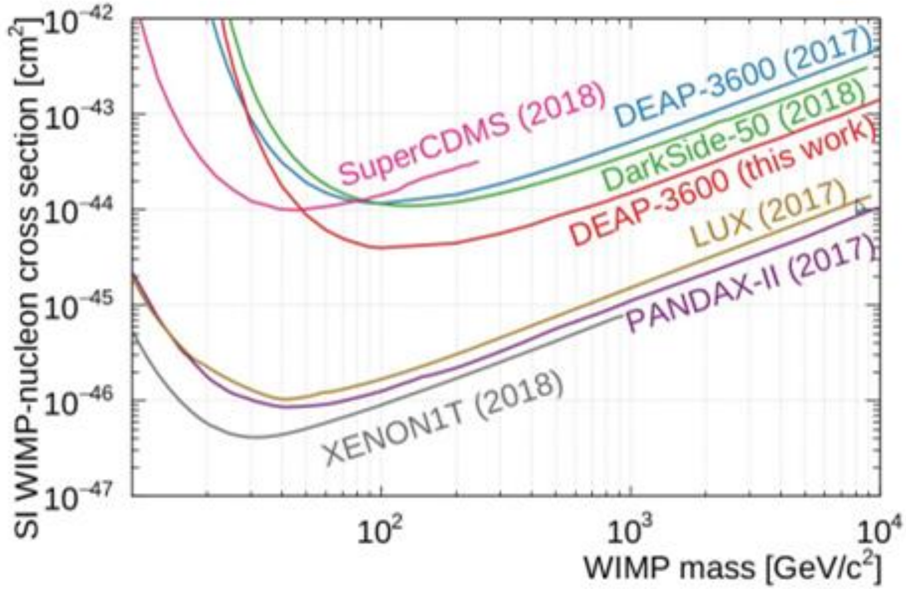
* result from PRD 100 022004 (2019)
also see Eur. Phys. J. C 81, 823 (2021)

This is a “big deal”: argon experiments are essentially insensitive to ER backgrounds, up to and including the ARGO scale, well into the neutrino fog/floor **

** as long as we use low-radioactivity underground argon for scales at DS-20k and larger. Underground argon from “URANIA” program DS-20k/GADMC

DEAP WIMP Search Results



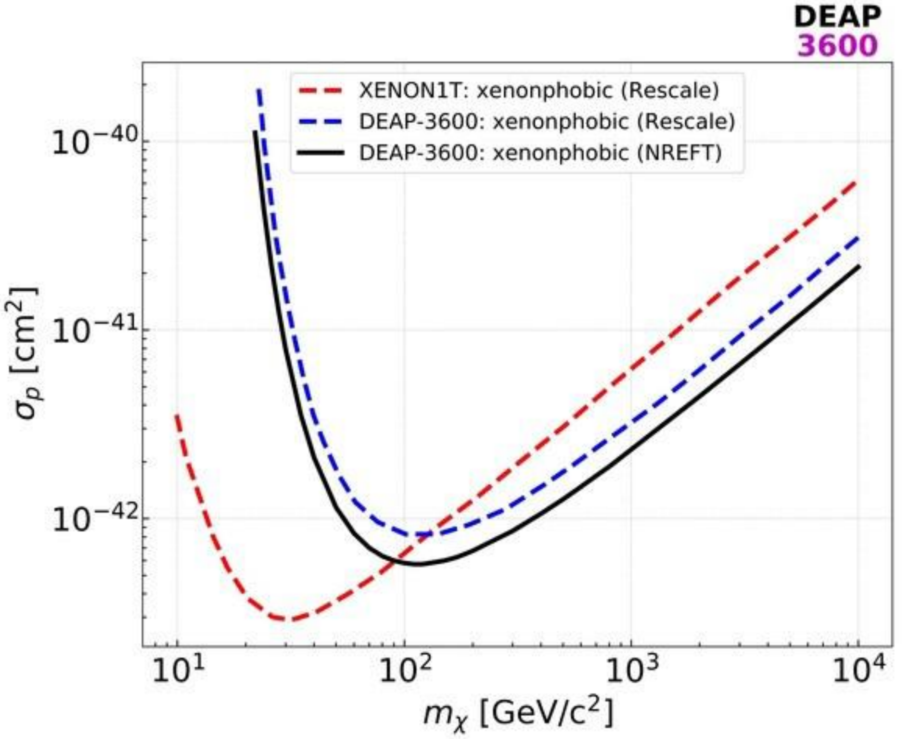


PRD 100 022004 (2019)

Further Constraints

- 231 live-days results were reinterpreted with a more general Non-Relativistic Effective Field Theory framework (NREFT) --- can explore isospin-violating couplings.

- Provides world leading sensitivity for isospin-violating xenonphobic dark matter at high mass.

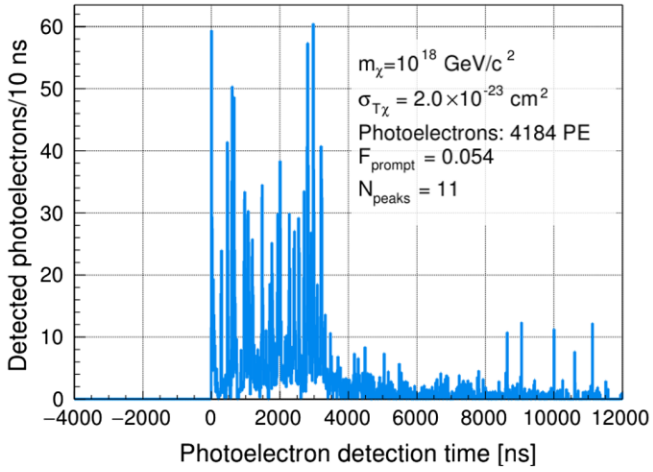


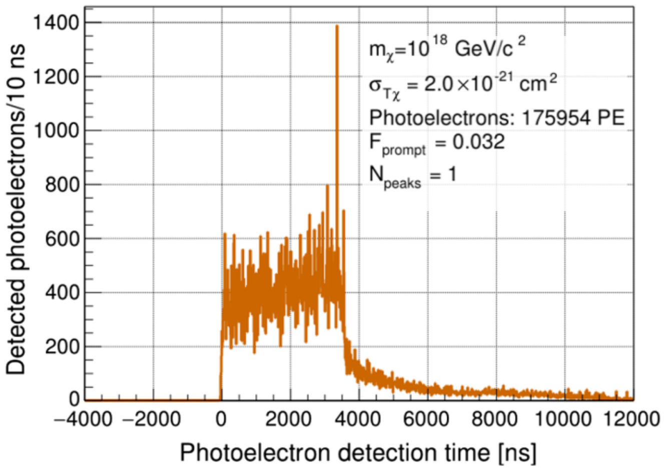
PRD 102 082001 (2020)

Constraints on Planck-Scale Mass Multi-scattering Dark Matter

DM candidates with $\sigma_{\chi-n} \cong 10^{-25}$ cm^2 and mass $\gtrsim 10^{12}$ GeV/c^2 lose a negligible amount of energy in the scatterings with the Earth nuclei and can reach underground detectors.

- Event signature:
  - Contains multiple nuclear recoil scatters : produces multiple peaks in the signal
  - low F_{prompt}

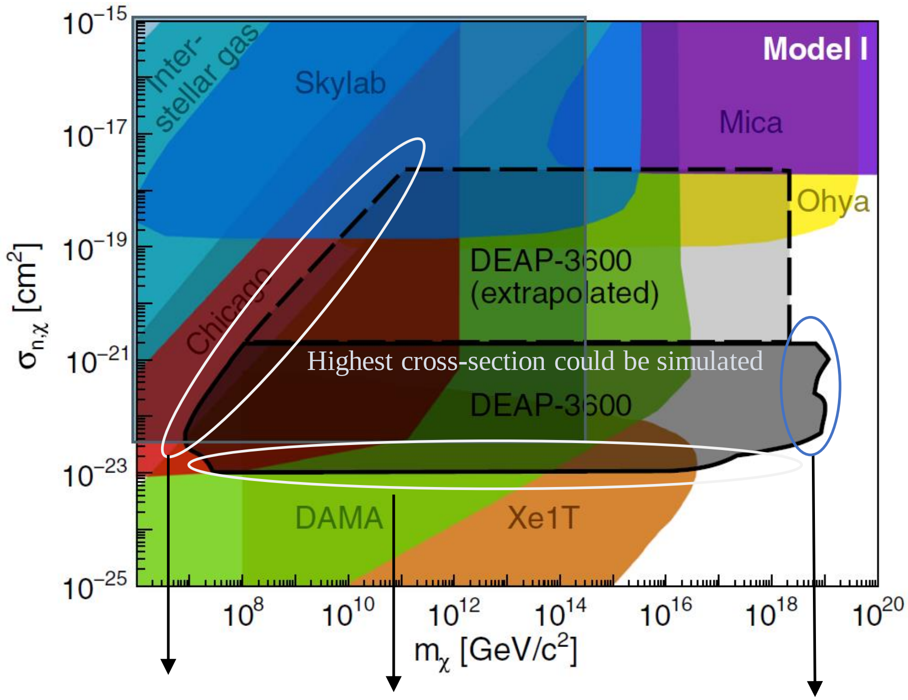




Simulated photoelectron time distribution

As cross-section increases, F_{prompt} decreases and number of dominant peaks starts to merge.

PRL 128 011801 (2022)



Affected by the Earth's overburden $\Longrightarrow$ attenuation of energy of DM

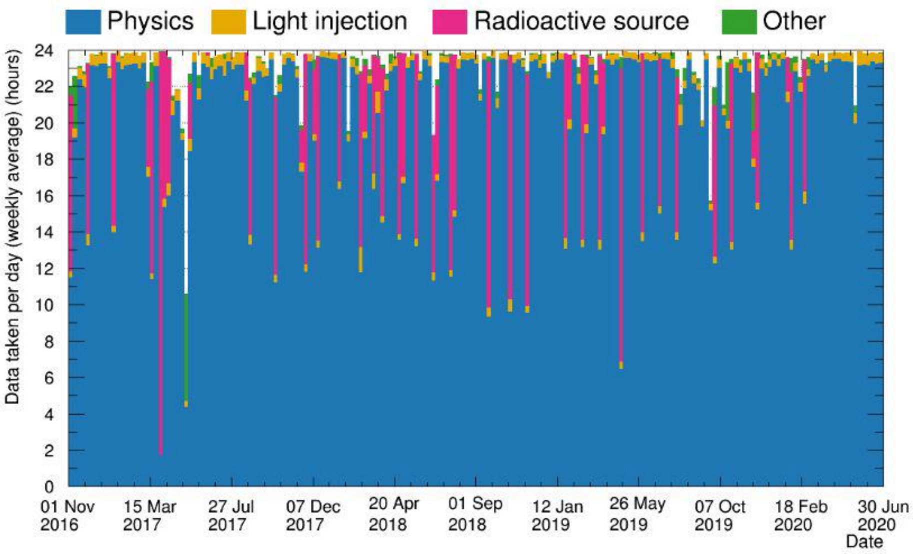
Lowest cross-section can be excluded by null results

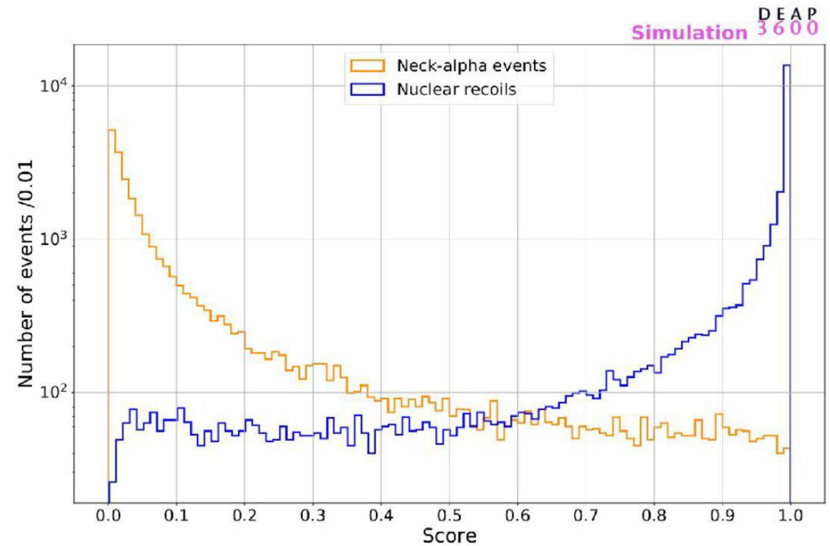
Above this mass, number density of DM is too low compared to the surface area $\Longrightarrow$No DM expected to pass through the detector within livetime

- Analyzed 813 live-days data (November, 2016 – March 8, 2020) : No events were observed.
- Constrain the DM masses between (8.3×10^{6}-1.2×10^{19}) GeV/c^2 and ^{40}Ar-scattering cross-sections between 1×10^{-23} and 2.4×10^{-18} cm^2.
- **First experiment to reach Planck-scale sensitivity due to large detector size.**

PRL 128 011801 (2022)

Coming Up



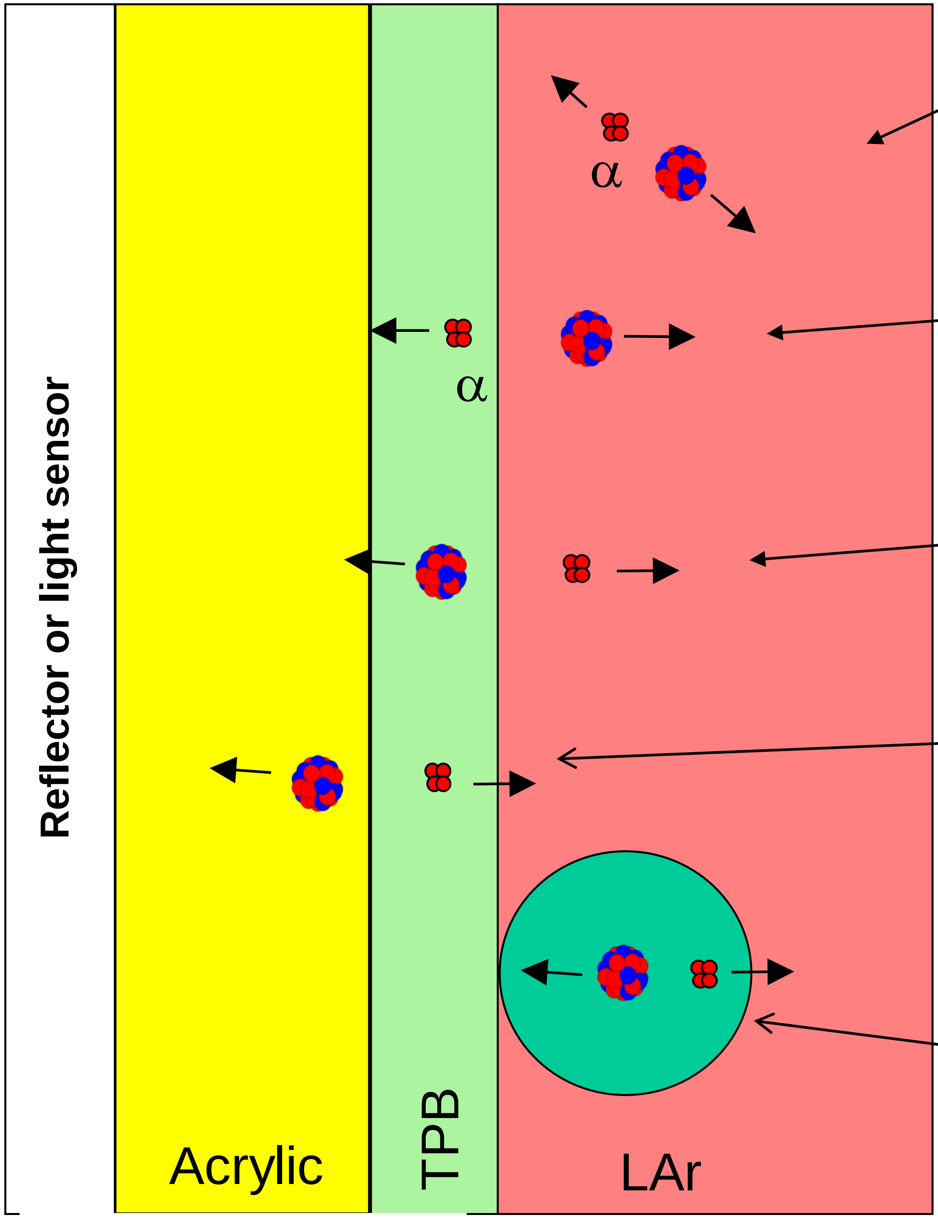


- **3 Years Dataset** (Nov 2016 to March 2020) expect ~802 days of livetime instead of 231 days.

- 80% blind since Jan 2018.

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

α Backgrounds in Liquid Argon



Decay in **bulk argon** tagged by α-particle energy

Decay from **TPB surface** releases untagged recoiling nucleus in argon and α in TPB (see both with low energy)

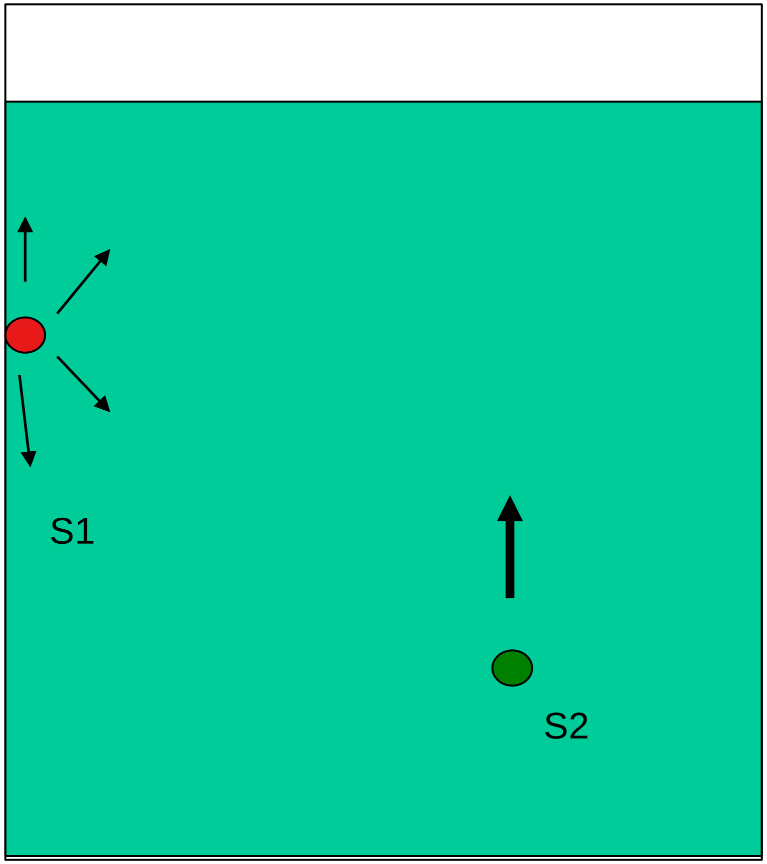
Decay from **TPB surface** releases α in argon and recoil nucleus in TPB (see mostly α-particle, high energy)

Decay from **inside TPB or acrylic** releases α which may also enter LAr. Could see
(a) Light from TPB only (prompt) or
(b) Light from LAr (range of energies)

Dust particle can remain on surface or desorb into argon region

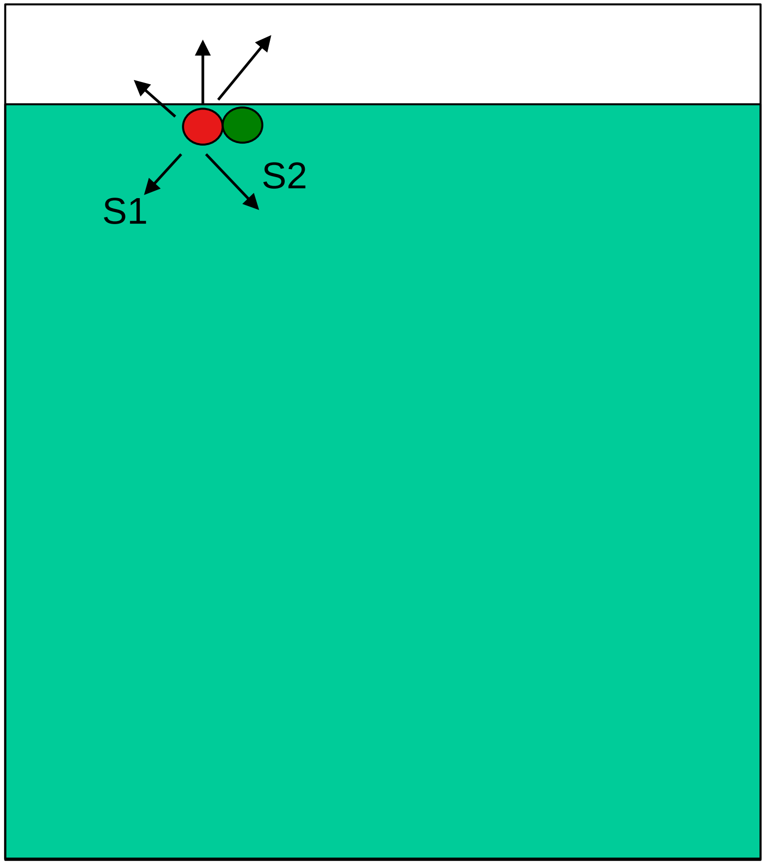
Surface backgrounds in TPCs: do they matter?

Pileup. Potential background source is S1-only from surface alpha decay pileup with S2-only, which confuses position reconstruction in TPC. Pileup can occur in long (~10 ms) drift window.



Apparent S2-only (S2O)

Event near liquid/gas interface, short drift time can make S1 and S2 appear coincident .



As scales get very large and background targets very small, can set quite strict requirement on tolerable surface background rates.

Need <<10 microBq/m^2 surface alphas at ARGO scale

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DEAP Upgrades

Upgrades are specially designed to remove neck alpha and dust alpha backgrounds

Dust Filtration:

- Deployment of vacuum jacketed stainless steel pipe through the neck of the detector ---- to remove liquid argon and allow filtration to remove dust and refill the detector with clean liquid argon.

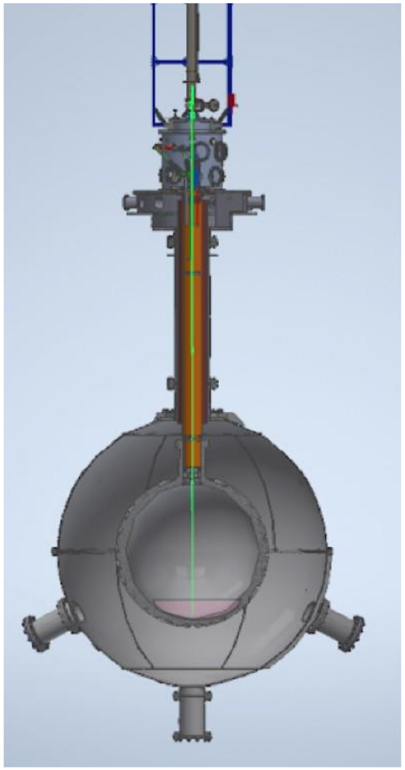
Removal of Neck alpha events:

- Allow warming of the neck region --- to remove possibility of formation of liquid film or droplets.

Flowguide Coating:

- Coat the flow guide surfaces with a "slow" wavelength shifter – custom pyrene/polymer film.

- Pyrene has a long decay time : neck alpha events will have lower F_{prompt}.



Development of slow WLS :
NIM A 1034 16683 2022

Will complete upgrades and restart in 2023. Target sensitivity at level of current Xe experiments, with essentially zero backgrounds.

ARGO-Canada

Members (*= NSERC applicant/co-applicant)

*Serge A. Charlebois (Faculty, Sherbrooke)
*Jean-Francois Pratte (Faculty, Sherbrooke)
*Audrey Corbeil Therrien (Faculty, Sherbrooke)
*Mark Boulay (Faculty, Carleton)
*Aksel Hallin (Faculty, Alberta)
*Philippe Di Stefano (Faculty, Queen's)
*Chris Jillings (Faculty, Laurentian and SNOLAB)
*Szymon Manecki (Faculty, Laurentian, Queen's and SNOLAB)
*Art McDonald (Faculty Emeritus, Queen's)
*Fabrice Retiere (Senior Research Scientist, TRIUMF)
*Pierre Gorel (Faculty, Laurentian and SNOLAB)
*Nigel Smith (Faculty, Laurentian, Queen's, Imperial College and CIFAR fellow)
David Sinclair (Faculty Emeritus, Carleton)
Simon Viel (Faculty, Carleton)
Yue Zhang (Faculty, Carleton)
Peter Skensved (Senior Researcher, Adjunct Faculty, Queen's)

Funded in Canada as Subatomic Physics Project (SAP) for R&D
Working within GADMC

Summary of ARGO activities

Working on conceptual design and definition of physics sensitivity + required R&D program (simulations)

Development of all-digital SiPM system (photon to digital converter), including extension to VUV sensitivity (Sherbrooke, TRIUMF, Carleton, Alberta). Development of “SMART” trigger system for data reduction. Goal of working prototype/demonstrator in LAr “mid-2020’s”

Develop additional assay sensitivity

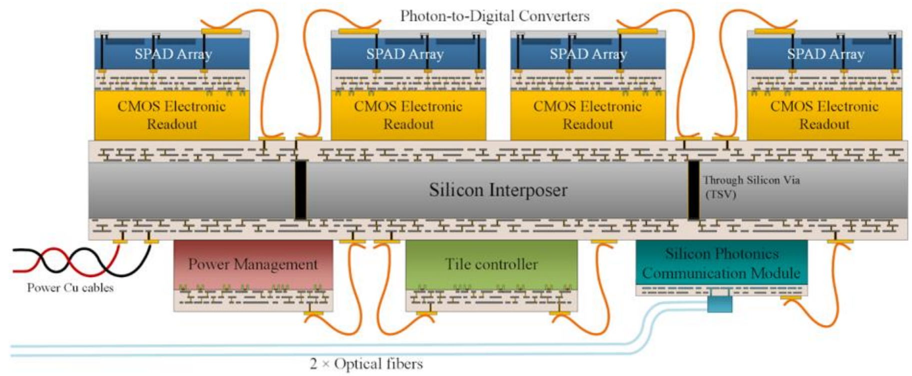
- ^{39}Ar assay (Ar2D2) complements GADMC facilities (scintillation counter)
- Want surface alpha assay to ~10 microBq/m^2
- Further extend ^{210}Pb sensitivity to <10^{-20} g/g
- Study particulate deposition requirement and desorption/cleaning efficiency
- Study diffusion of ^{210}Pb in polymers to D=10^{-14} cm^2/sec

Goal is a conceptual design/sensitivity paper with definition of R&D program and assay requirements ~1 year, then development of these measurements/facilities over next 3 years.

Advantages of Digital SiPMs:

- Signal processing at sensor level allows much simpler implementation
- All-digital system not affected by electronic noise encountered in analog
- Ability to disable noisy Single Photon Analog Diodes (SPAD)
- Active quenching suppresses essentially all after-pulsing
- Lower power consumption
  - no event no power for digitizing
- Excellent potential for time resolution
  - ~100ps

Going further to enable large scale detectors:
A fully digital photodetector module

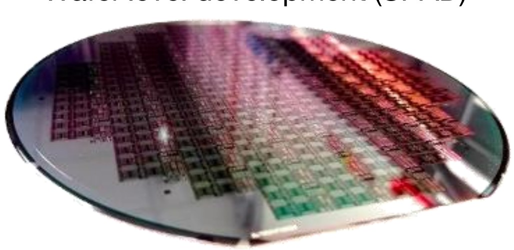


To reduce wire count and mass:
- On tile power management
- Bidirectional digital optical communication

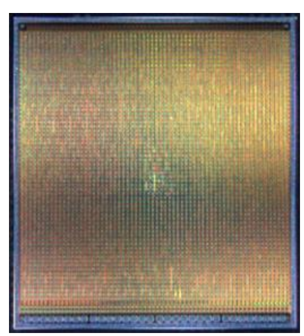
Low background and cryogenic operation:
- silicon based tile substrate - low background
- CTE matched to silicon - PDCs and ASICs

Leverages past CFI and NSERC funding:

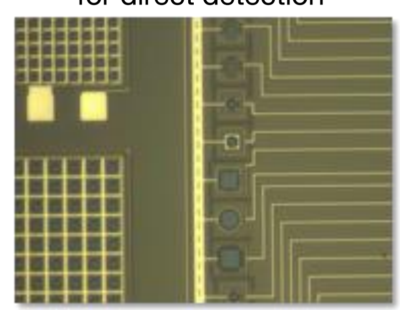
Wafer level development (SPAD)



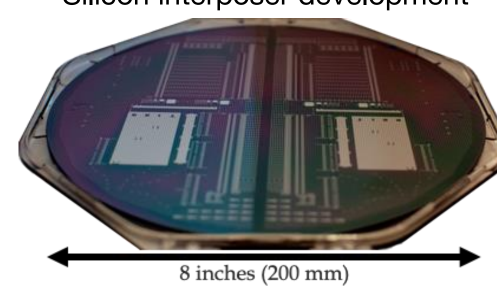
CMOS readout
(2 revisions)



Sensitivity enhancement
for direct detection



Silicon interposer development



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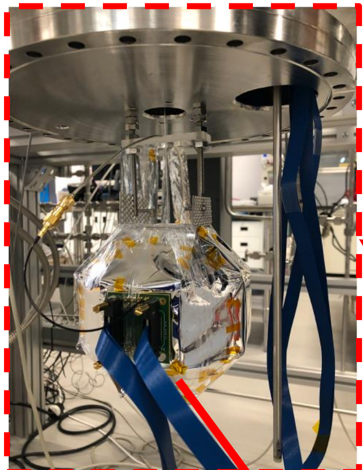
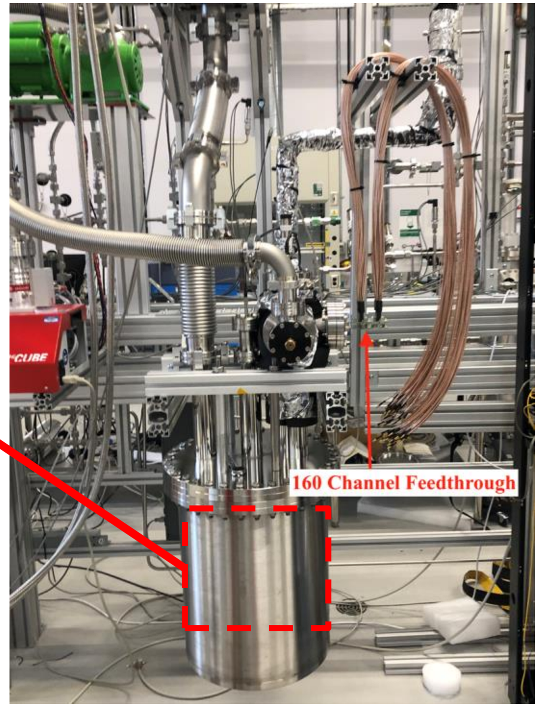
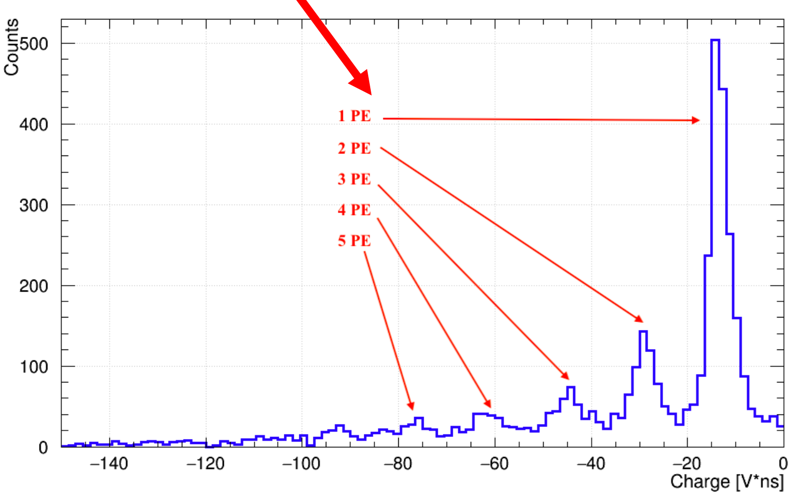
Recent progress – Carleton and upcoming digital test

30 kg LAr Argon-1 @ Carleton with analog SiPMs

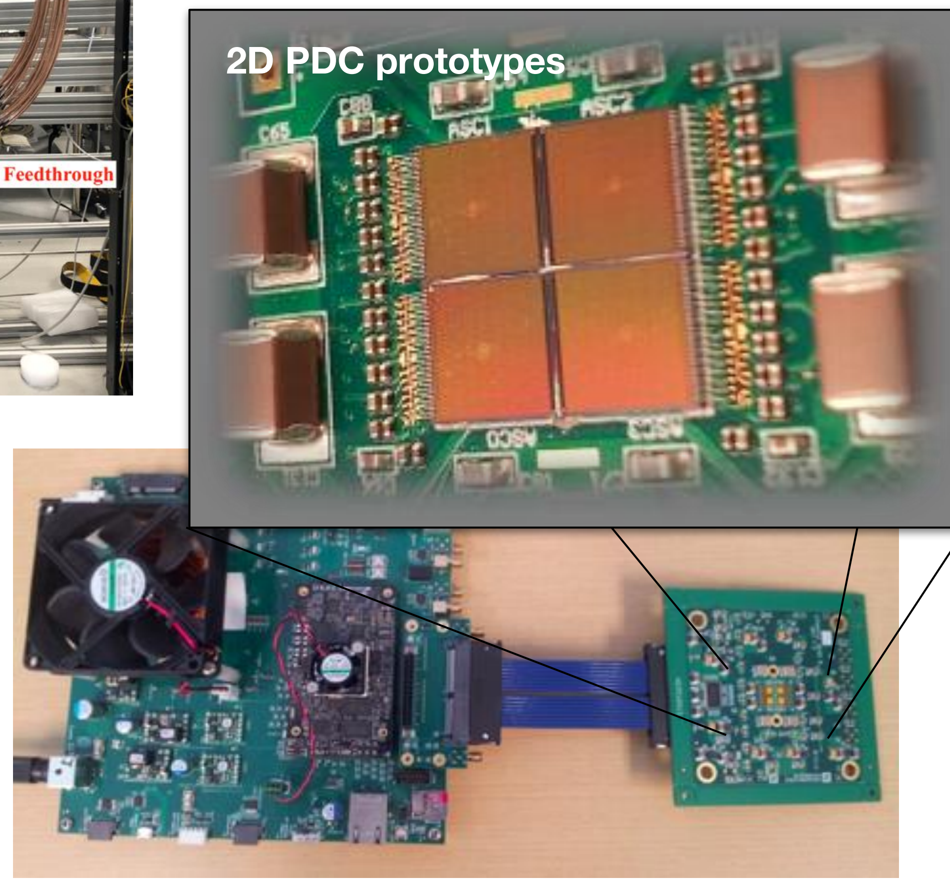






Getting ready for first LAr testing of Digital SiPMs from Sherbrooke

- coding FPGA
- adapting the board size and connectors to the setup



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Summary

DEAP-3600 demonstrated single-phase technique for DM, most sensitive search with argon and some world-leading results. So far cut-and-count analysis, upgrading detector for background reduction to restart in 2023.

ER backgrounds are handled by PSD up to ARGO scale, using underground argon.

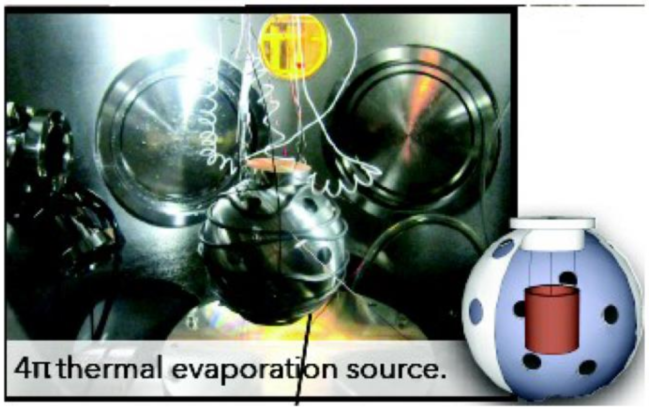
Other dominant backgrounds are alpha-related, either from surface decays or from within dust particles. Possibly important for TPCs as detector scales increase. Will pursue further R&D within ARGO development.

Exciting technical development of digital SiPMs a game-changer for ARGO with many potential applications.

END

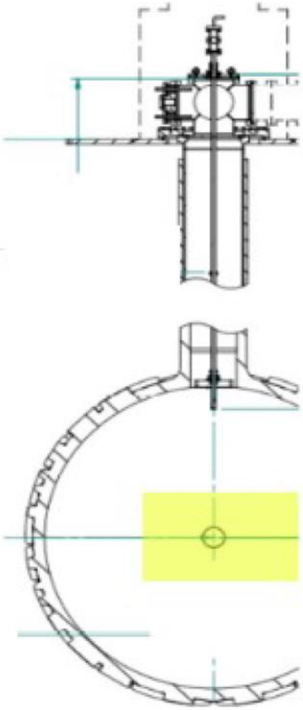
DEAP-3600 wavelength shifter (TPB) evaporation system

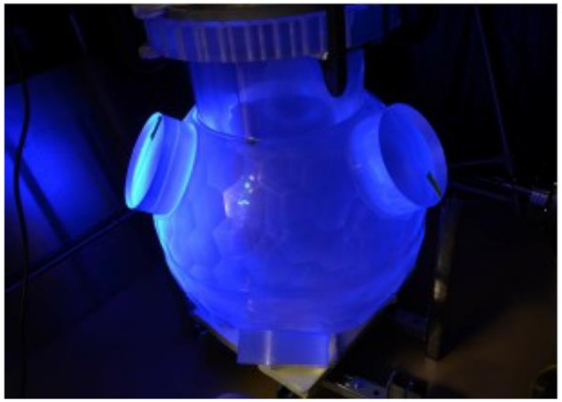
Evaporator source installation in a Rn-free atmosphere, through a glovebox.



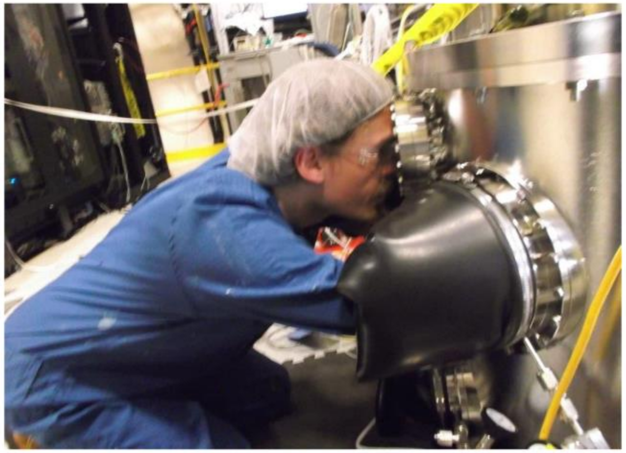
9 m^2 in-situ

Evaporation source and deployment system





UV illuminated coating on a small test acrylic vessel (20” diameter).



B. Broerman, M. Kuzniak et al., *Application of the TPB Wavelength Shifter to the DEAP-3600 Spherical Acrylic Vessel Inner Surface*, JINST 12 P04017 (2017)