Status and Future Plans for DEAP-3600

Chris Jillings on behalf of the DEAP-3600 Collaboration

The DEAP Collaboration

Stable Operation: Nov 2016 …

Hardware:

Detector: Astroparticle Physics, Volume 108, Pages 1-23

PMT calibration: NIM A 922, April 2019, pp 373-384

First Fill (9.87 tonne day exposure, August 2016)

Phys. Rev. Lett. 121, 071801 (2018)

Second Fill (758 tonne day exposure, Nov 2016 - Oct 2017,

not blind, “231-day”)

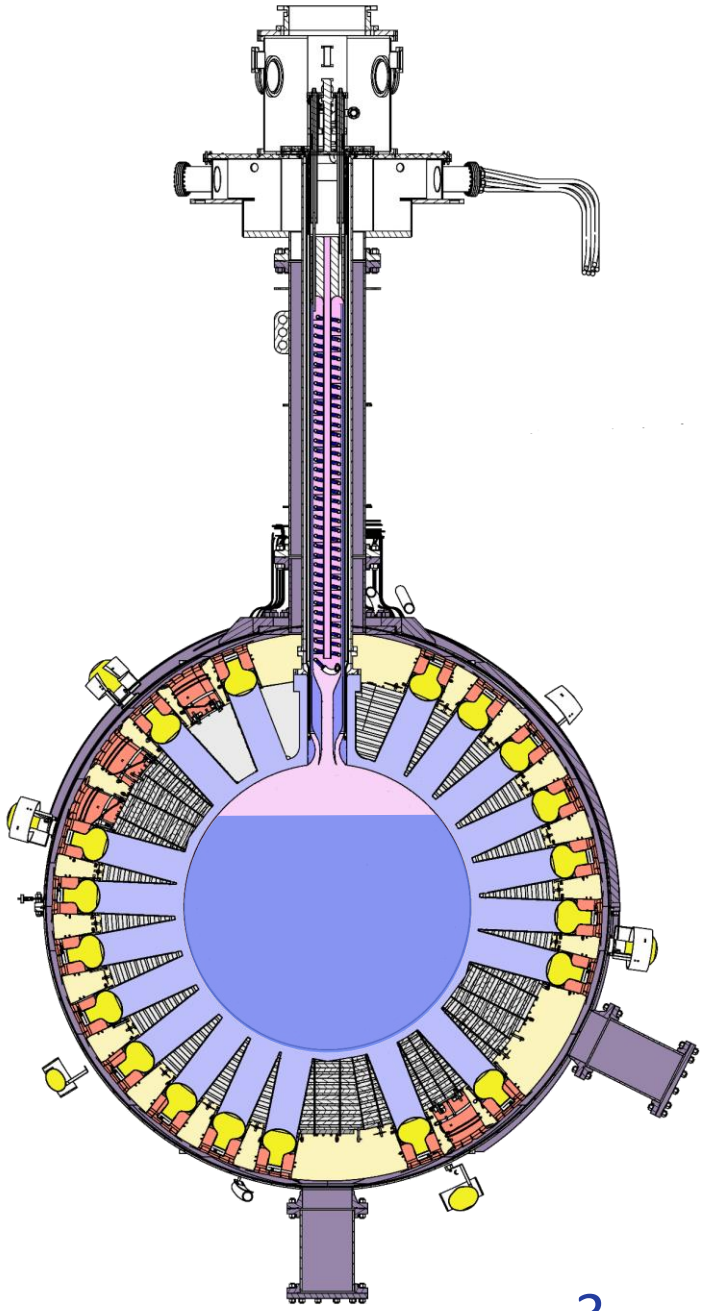
arxiv.org: 1902.04048

accepted in PRD

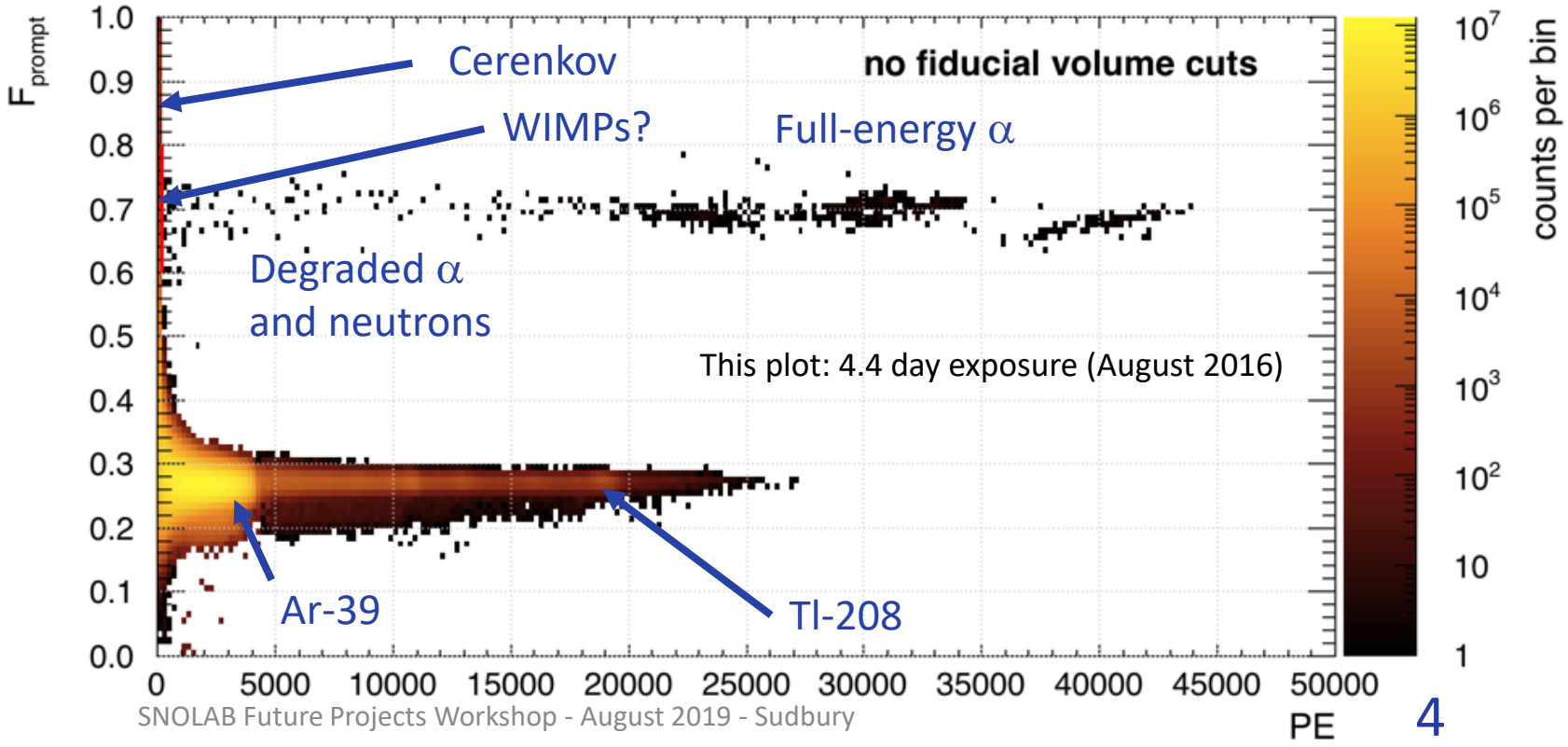
EM Backgrounds, Ar-42, … (Nov 2016 - Oct 2017, not blind)

arxiv.org: 1905.05811

Blind Data Set: (Jan 1, 2018 to current)



Overview of data



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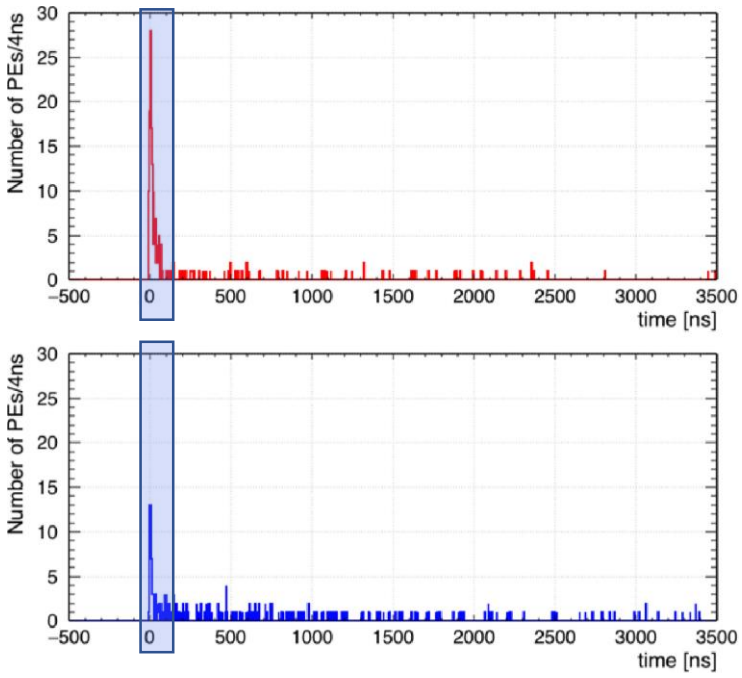

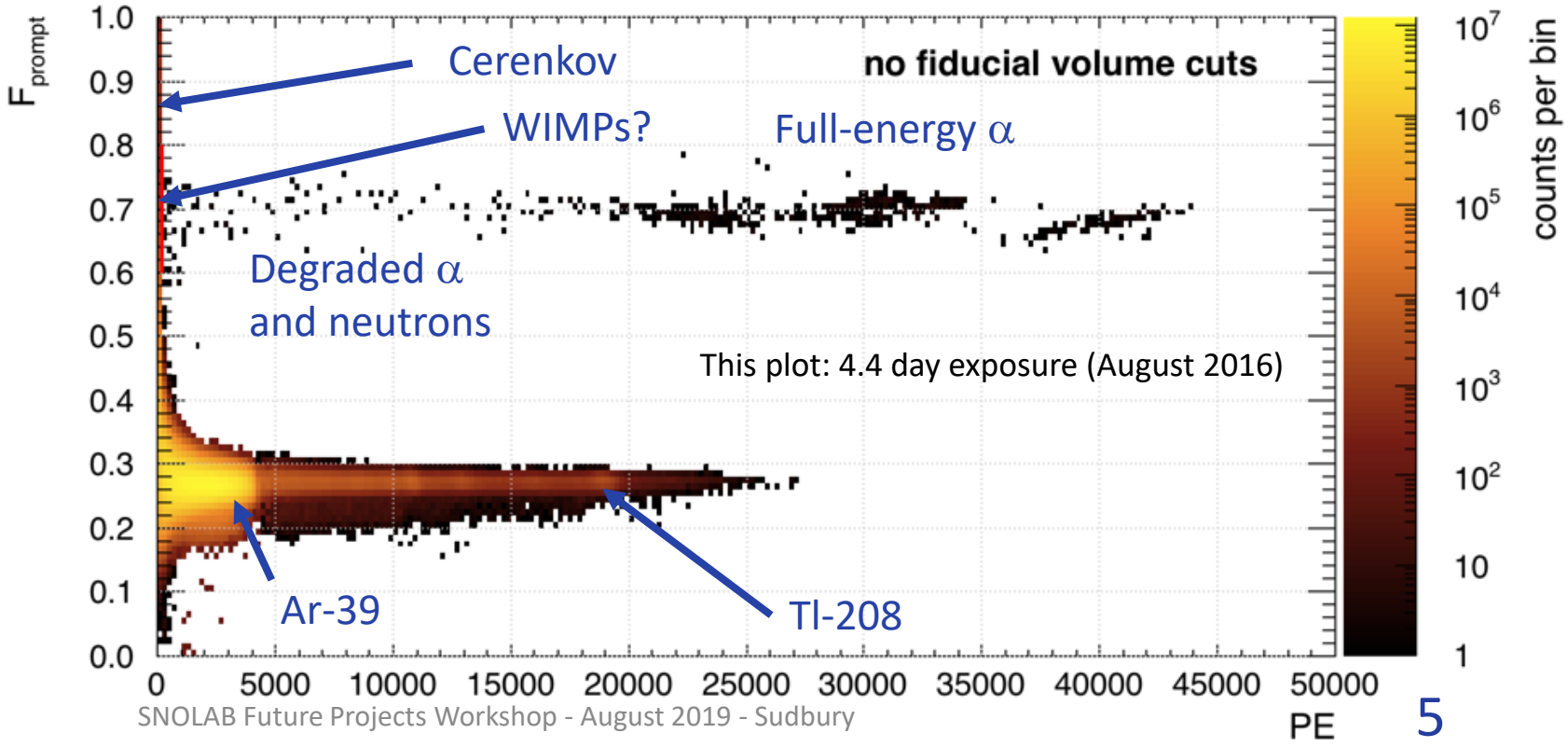

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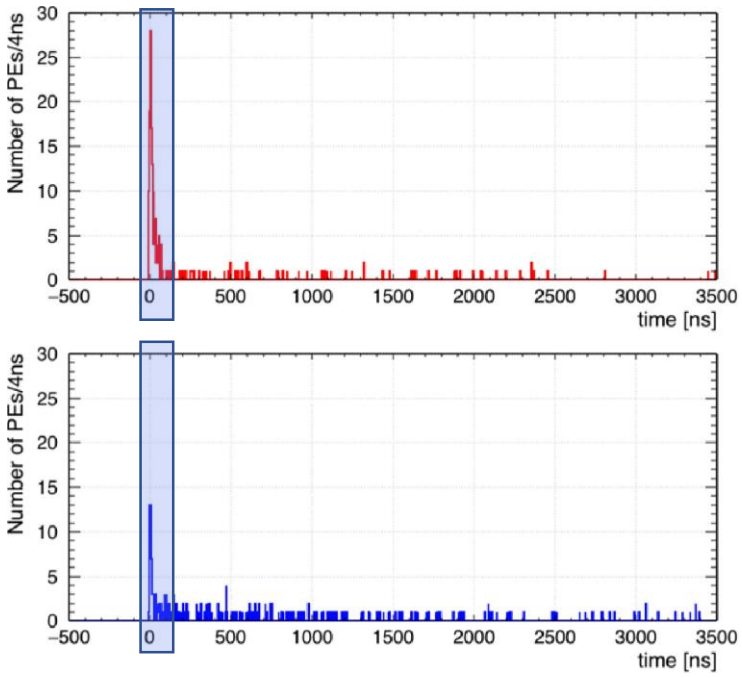
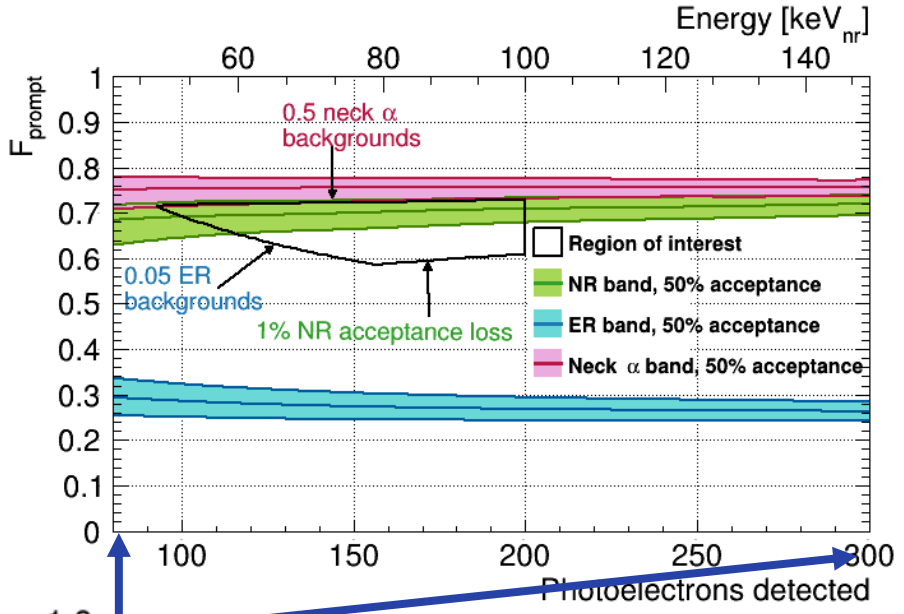
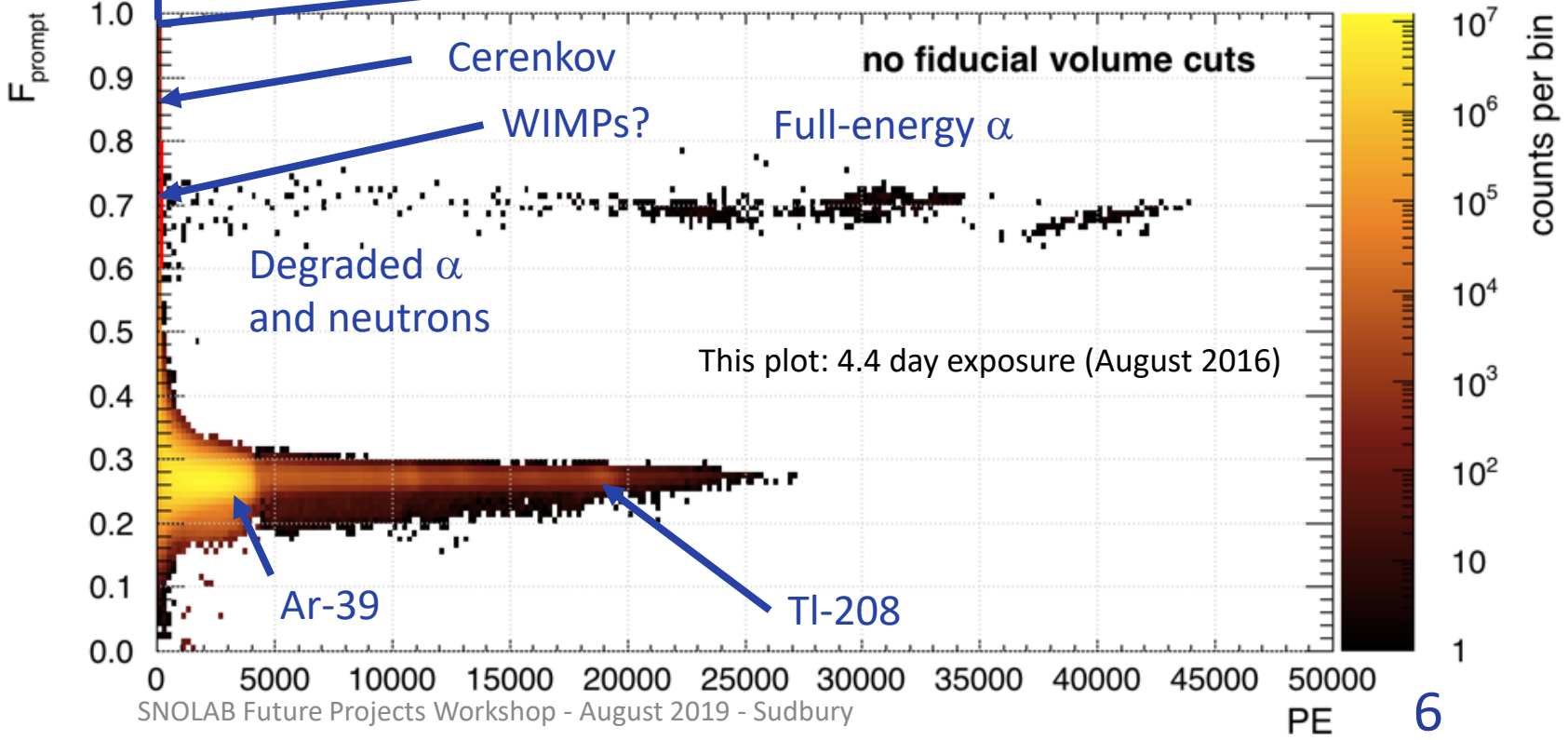
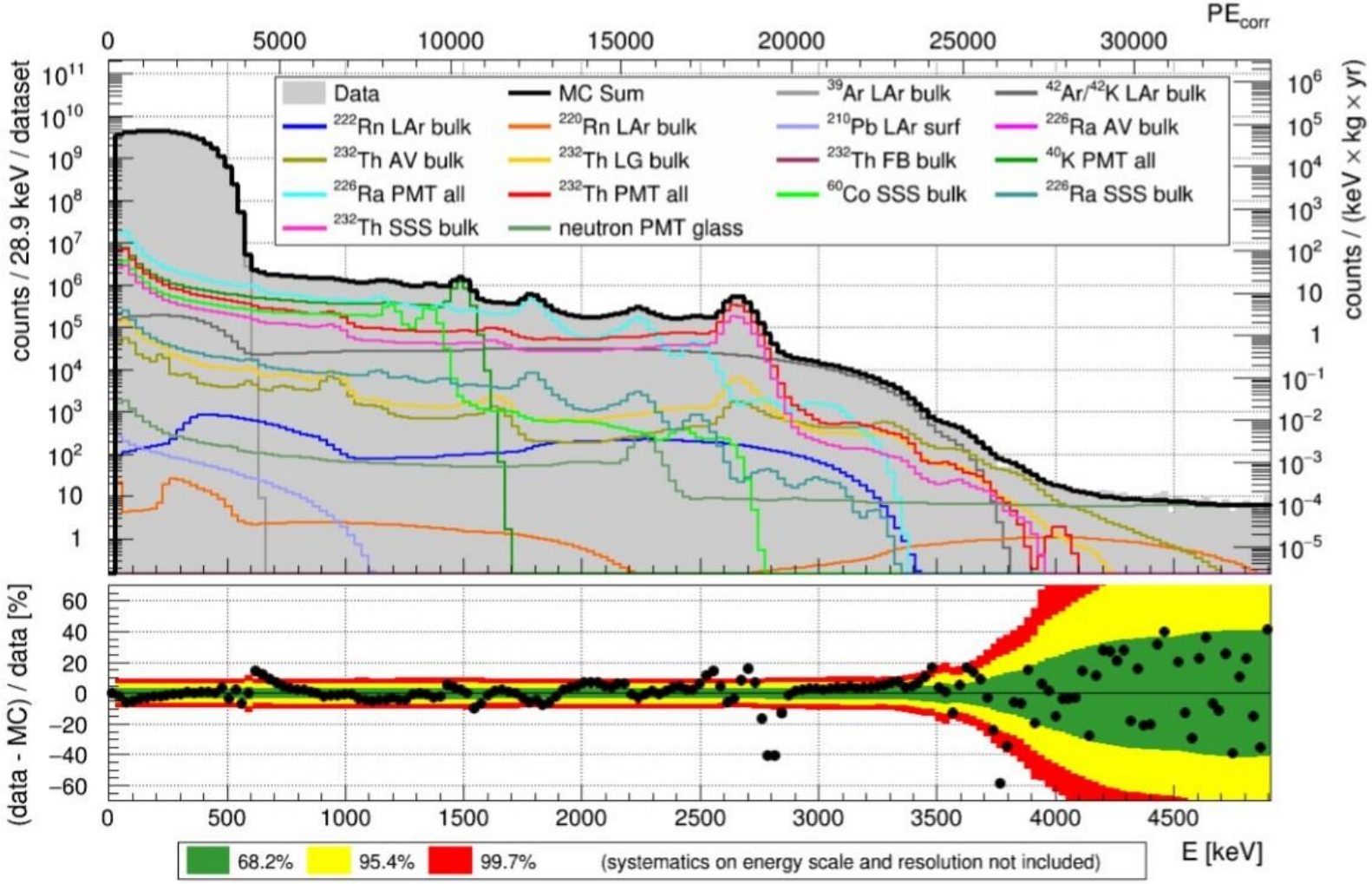






EM data described over 8 orders of magnitude



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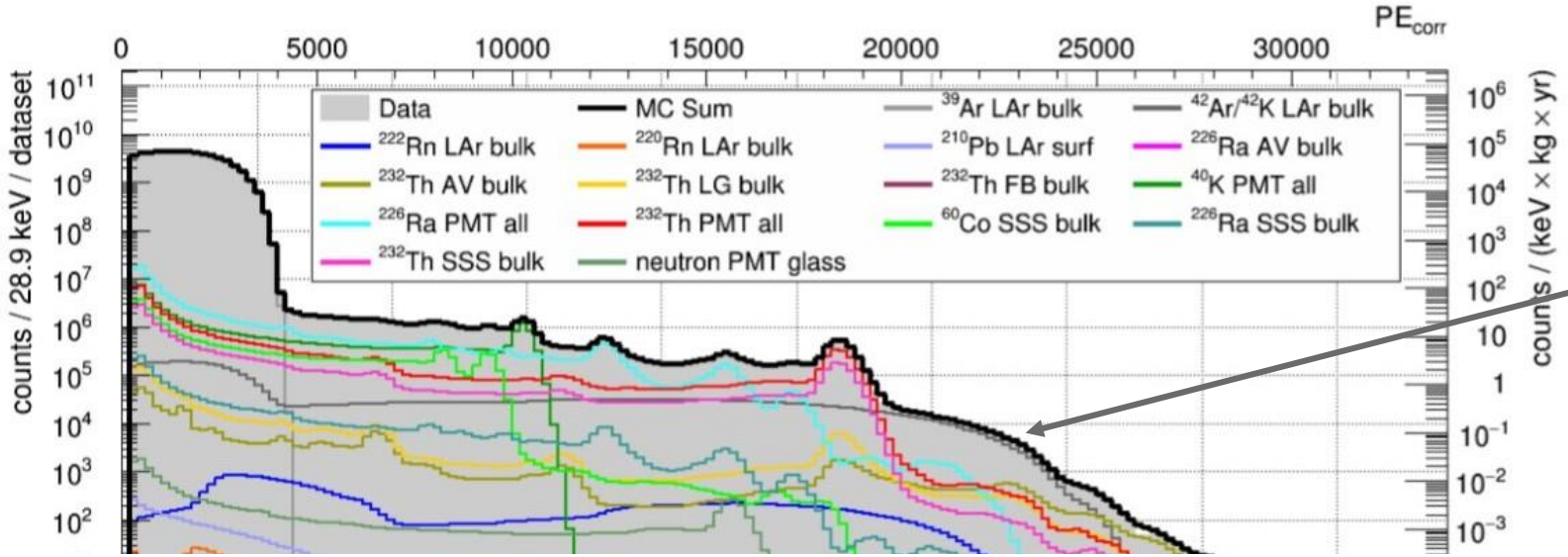


^{42}Ar / ^{42}K in LAr bulk

TABLE III. Previous results on specific activities of ^{42}Ar in atmospheric LAr. The various detection techniques are indicated with a simplified description.

Reference	Year	Technique	Specific activity [μBq/kg]
Ashitkov et al. [14]	1998	LAr ion. det.	< 61.4 (90% CL)
Ashitkov et al. [15]	2003	LAr ion. det.	< 44.0 (90% CL)
GERDA collaboration [10]	2016	HPGe γ-spec.	$= 91^{+8}_{-20}$ - 168^{+22}_{-18}
Barabash et al. [16]	2016	LAr ion. det.	$= 68^{+17}_{-32}$
This work	2019	scintillation	$= 40.4 \pm 5.9$

6 component background model… built on an open data set using side bands, calibrations, and simulation

Alpha decays in the neck

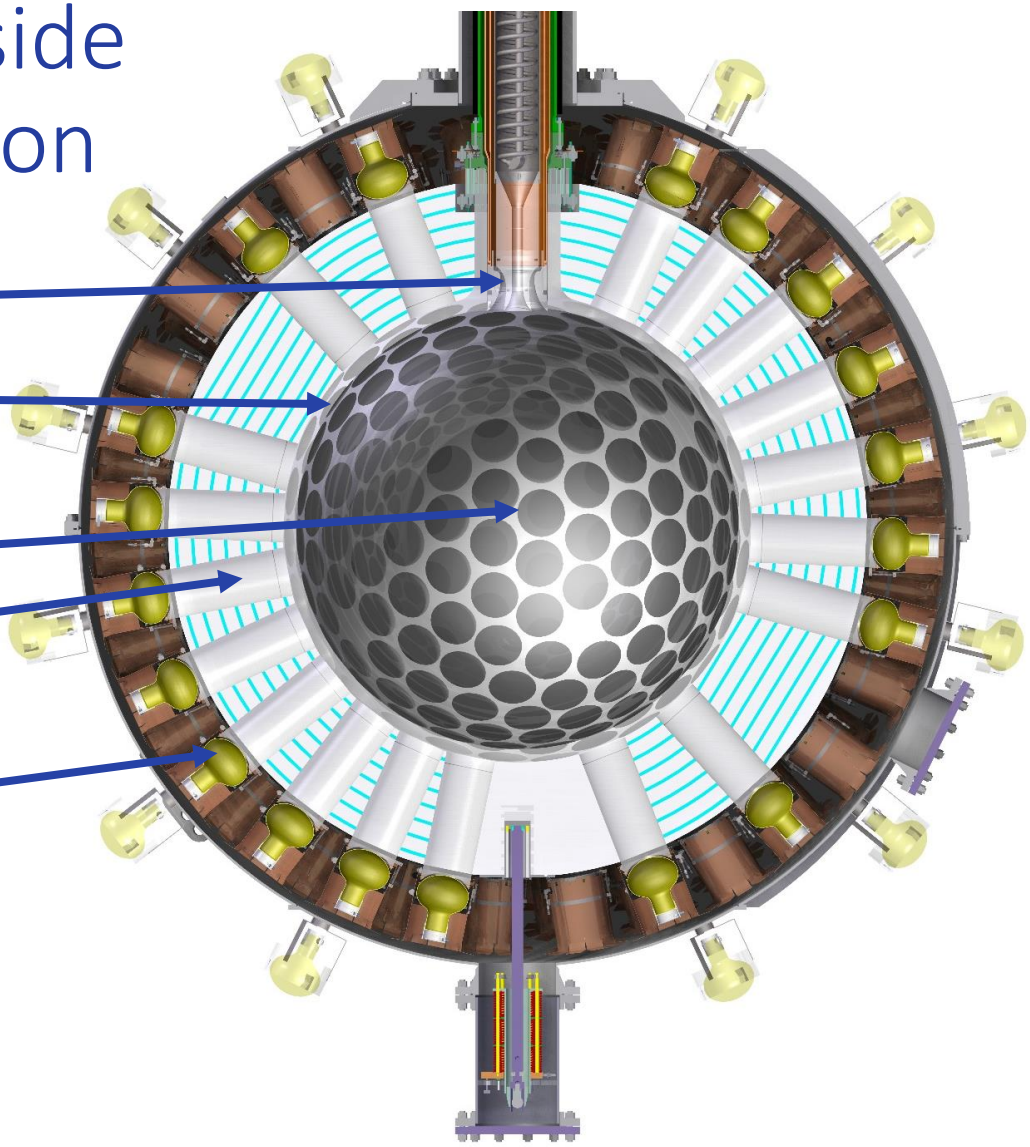
Alpha decays on the spherical surface

Ar-39 and PSD leakage

Cherenkov in acrylic

Radiogenic neutrons

Cosmogenic neutrons



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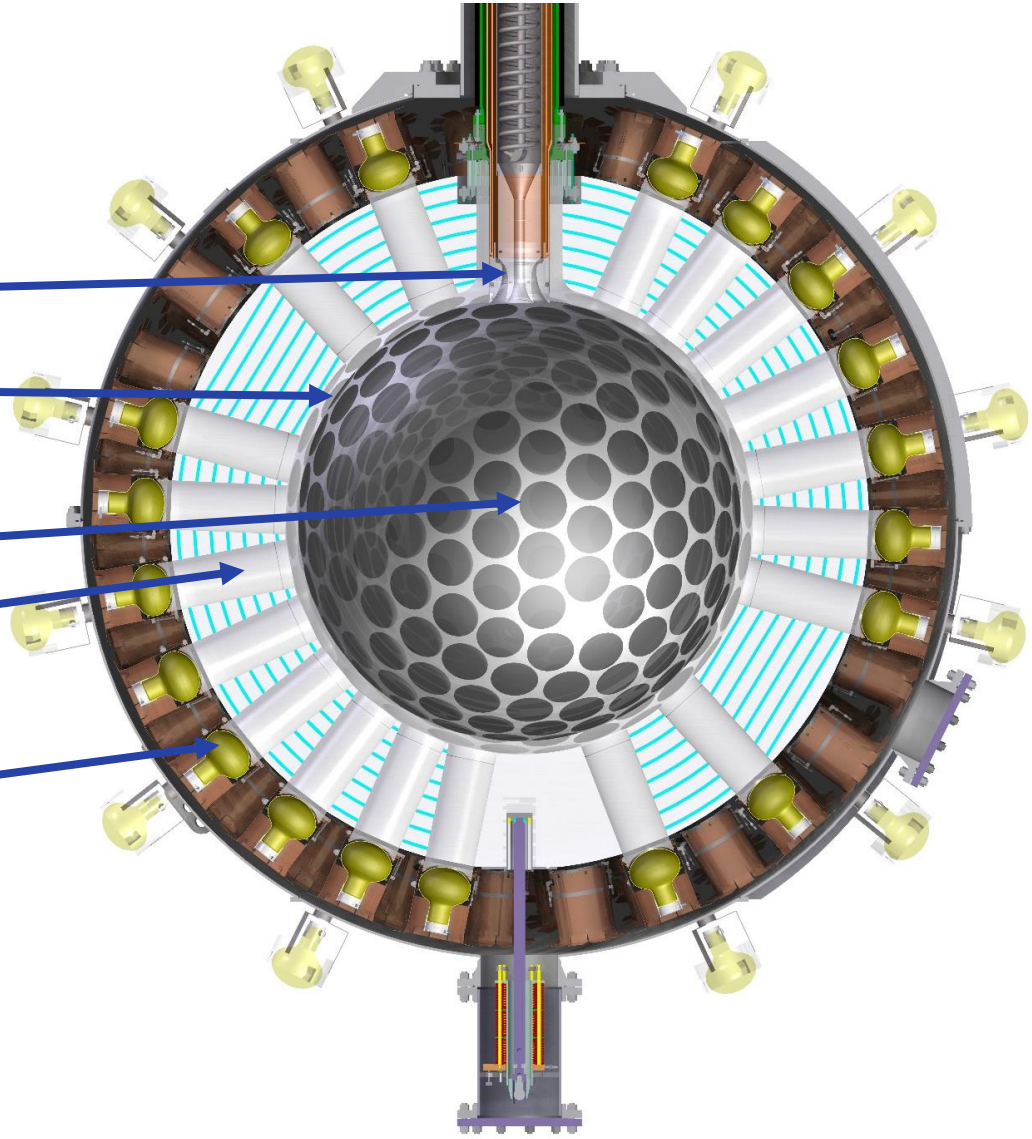
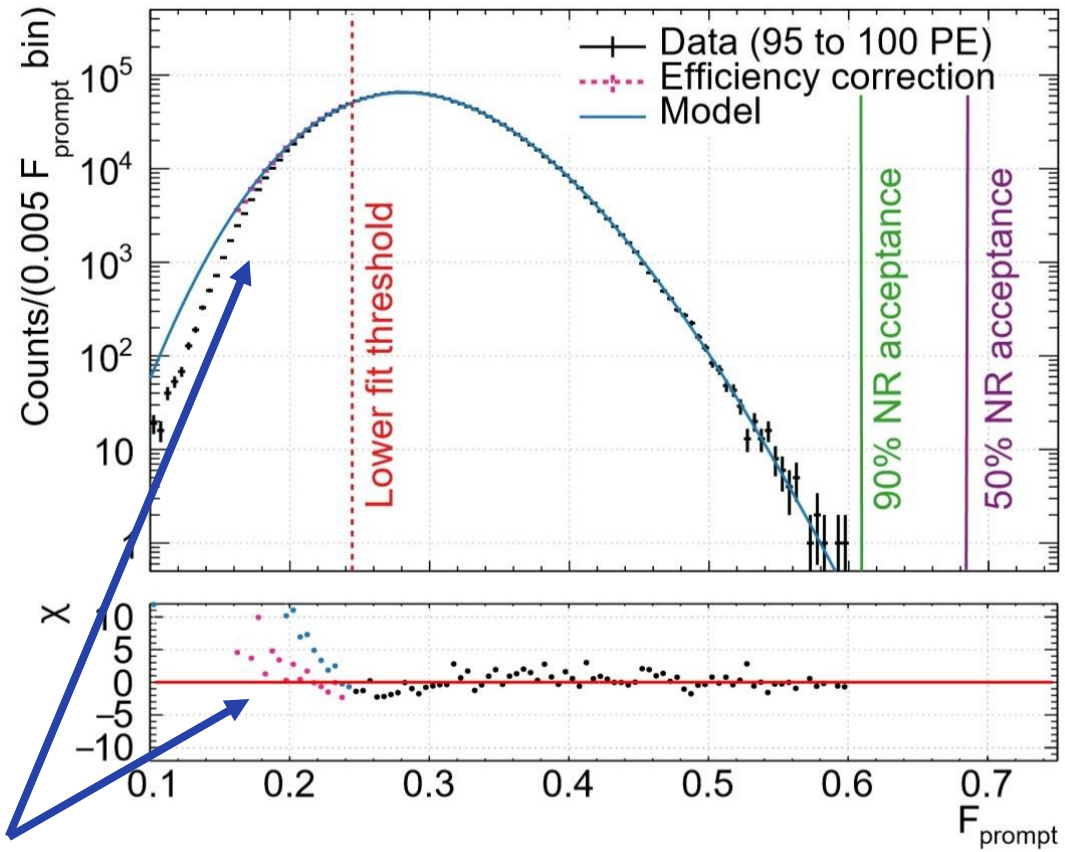


LAr Pulse-Shape Discrimination: works as advertised.
Lower Boundary of WIMP ROI tuned to 0.03±0.01 bg event.



Mathematics of trigger correction:
EPJ C (2019) 79: 322

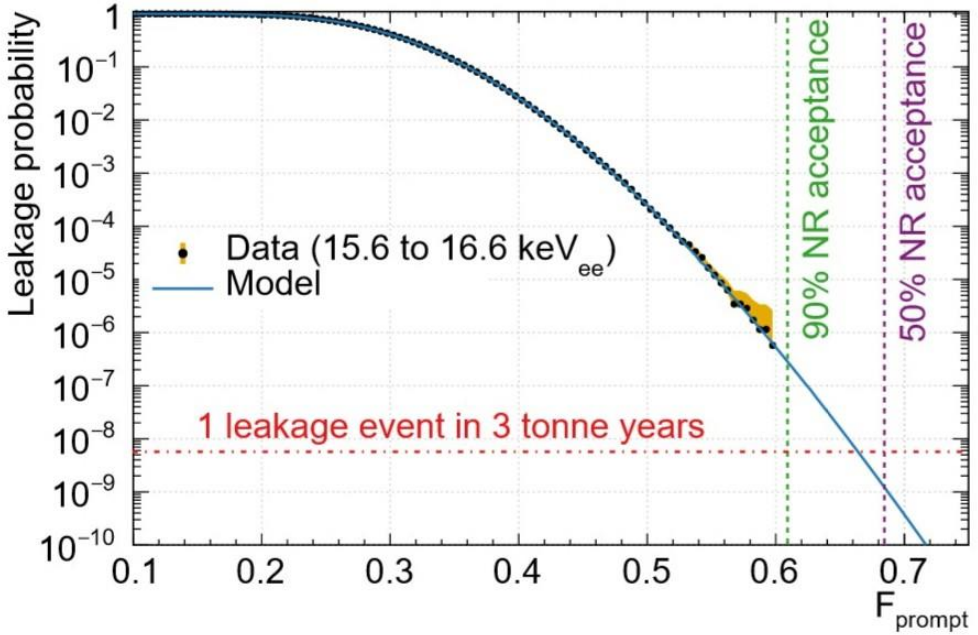
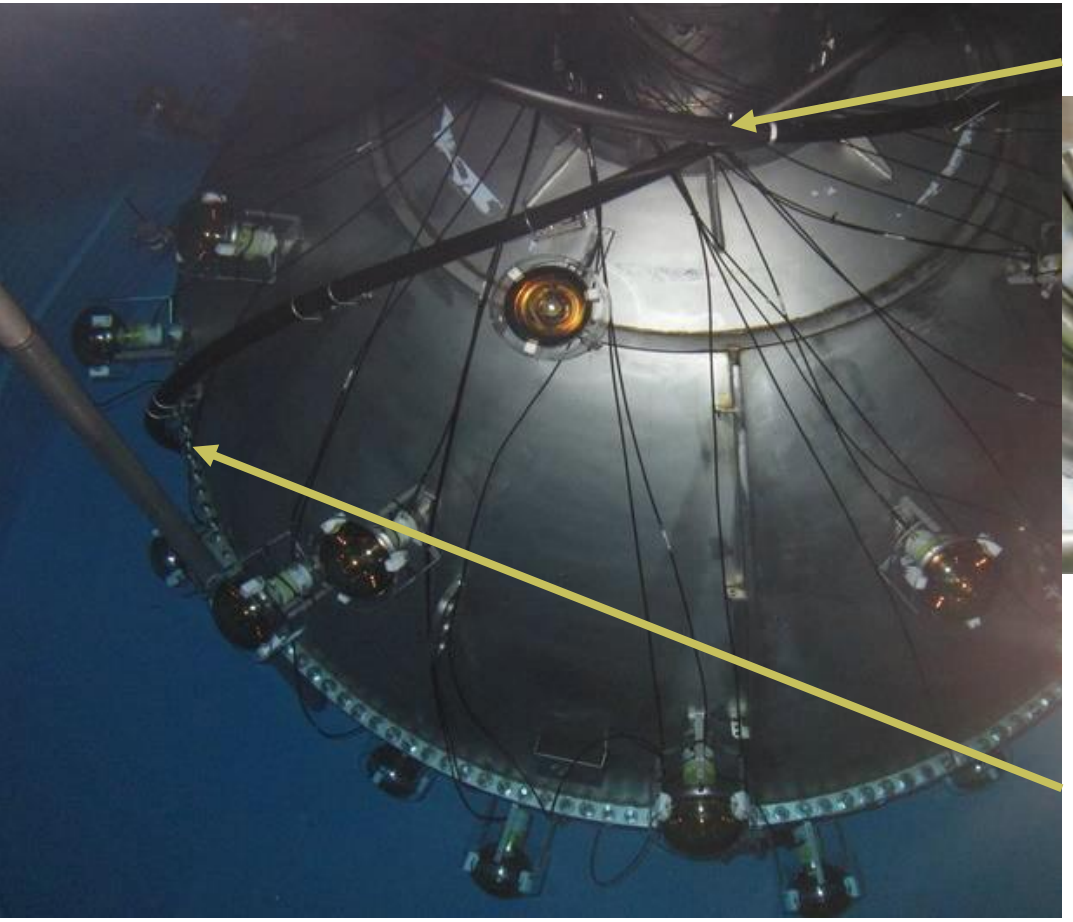


FIG. 13. Probability of an ER being detected above a given F_{prompt} value in the lowest 1 keV_{ee} bin in the WIMP-search region of interest. For comparison, vertical lines show the values above which 90% or 50% of nuclear recoils are expected to be found.

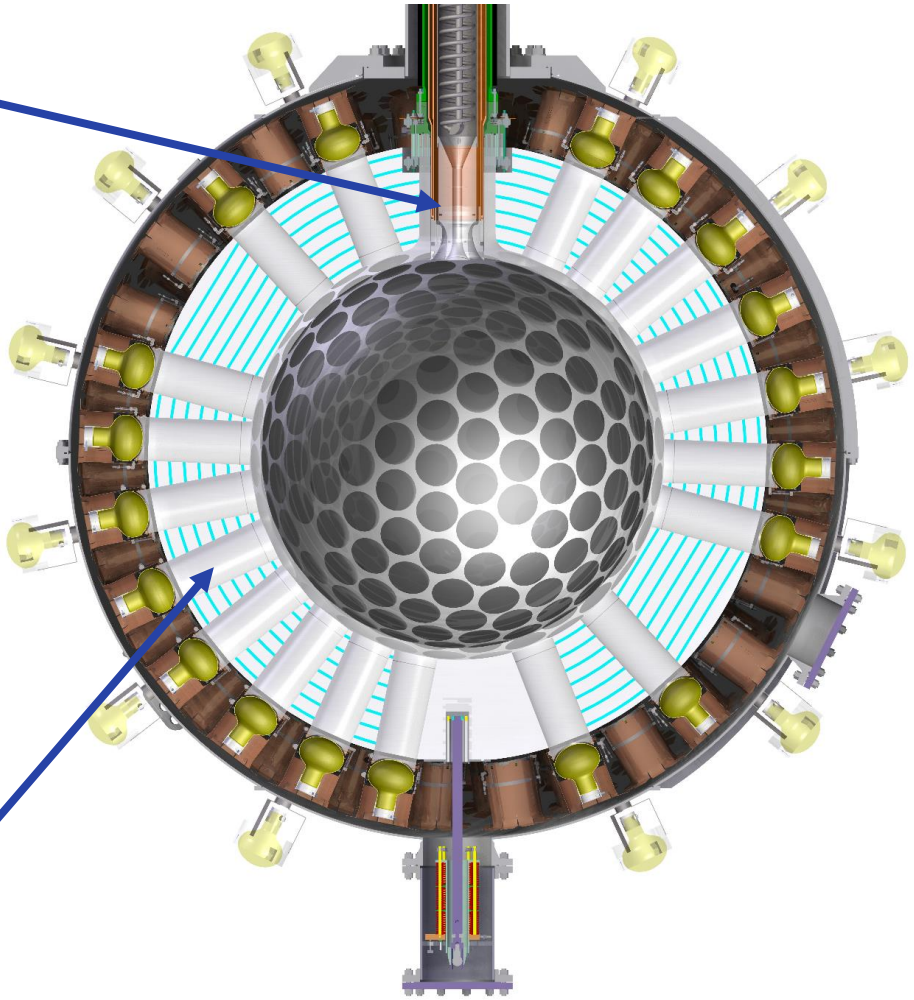
Cerenkov light characterized with external 2.6 MeV γ-rays

(Note: UVA acrylic used to reduce Cherenkov light.)



Cherenkov in neck acrylic vetoed with fibres.

Cherenkov in light guides gives large signal in single PMT.



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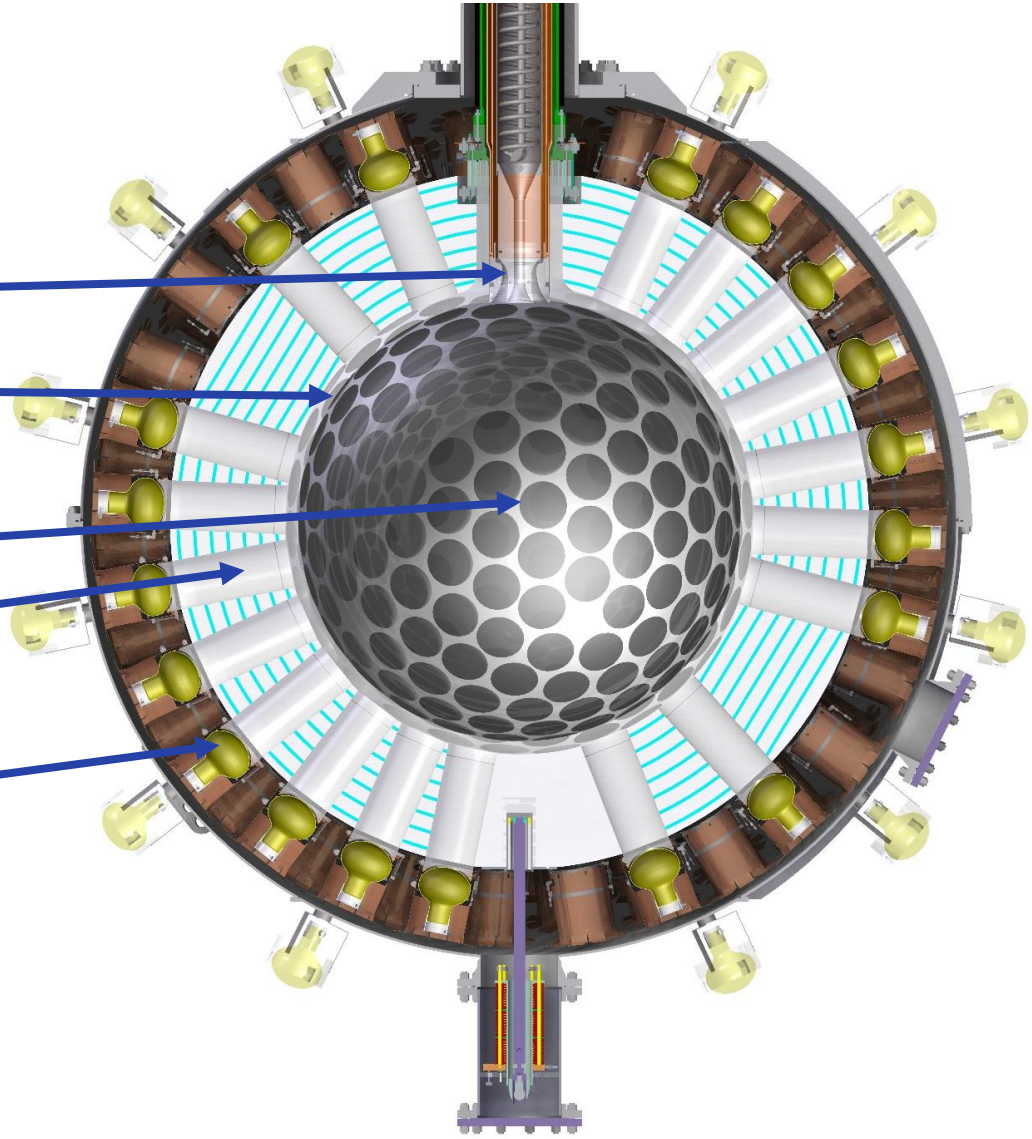


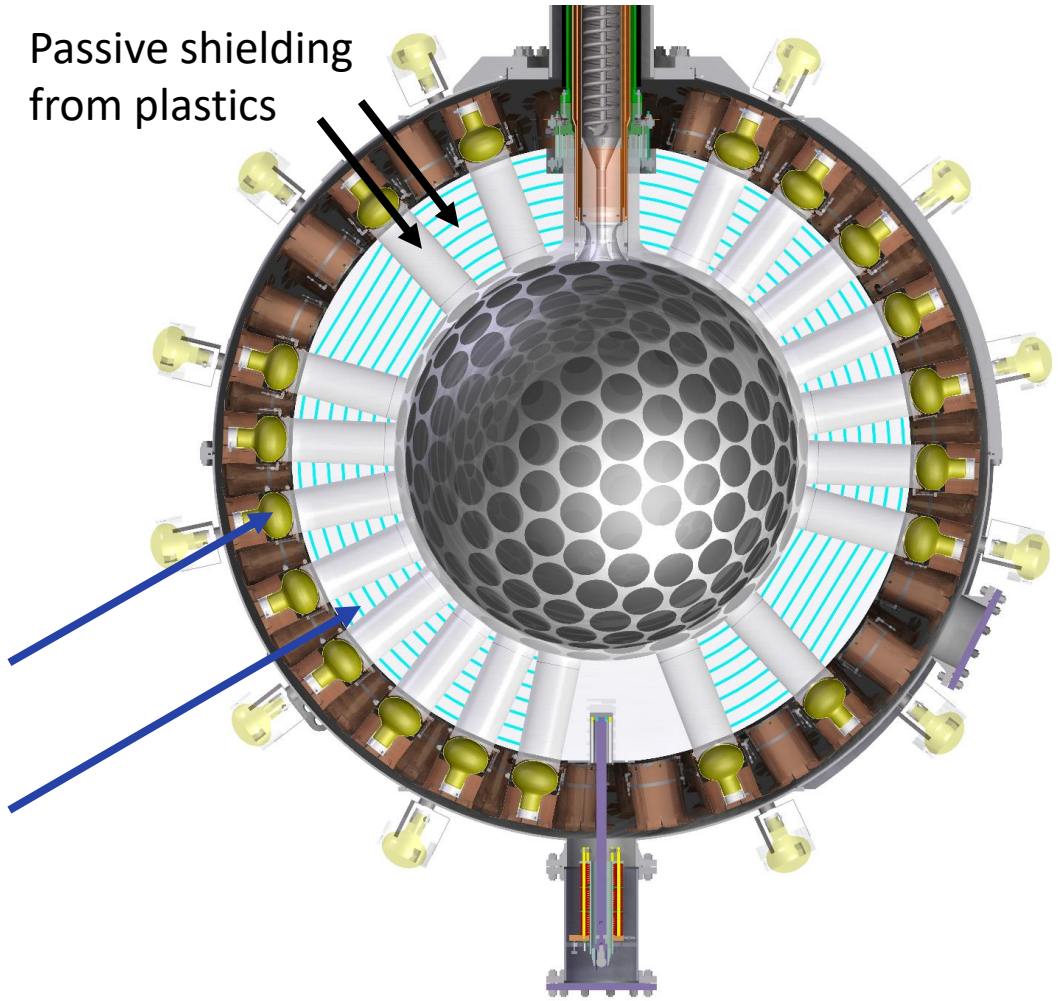
Radiogenic neutrons from (α,n). Rates predicted with material assay as input to two neutron production codes.

Low-level cuts
95 – 5000 PE
0.6 < Fprompt < 0.8
Event radius < 800 mm

WIMP Search cuts

Component	CR prediction (SOURCES-4C)	CR prediction (NeuCBOT)
PMT glass	$2.4^{+1.2}_{-0.8}$	$4.1^{+2.0}_{-1.3}$
PMT ceramic	$0.22^{+0.06}_{-0.11}$	$0.36^{+0.09}_{-0.15}$
PMT mounts	$0.095^{+0.032}_{-0.041}$	$0.10^{+0.04}_{-0.05}$
Filler blocks	$7.1^{+8.2}_{-7.0}$	$8.1^{+9.2}_{-7.7}$
Filler foam	$0.79^{+0.43}_{-0.41}$	$0.95^{+0.50}_{-0.47}$
Neck PMTs	$0.038^{+0.022}_{-0.032}$	$0.060^{+0.036}_{-0.049}$
Total	$10.6^{+8.3}_{-7.1}$	$13.6^{+9.4}_{-7.8}$

Component	ROI prediction (SOURCES-4C)	ROI prediction (NeuCBOT)
PMT glass	$0.009^{+0.008}_{-0.004}$	$0.016^{+0.013}_{-0.007}$
PMT ceramic	<0.02	<0.03
PMT mounts	$0.0004^{+0.0002}_{-0.0001}$	$0.0004^{+0.0003}_{-0.0001}$
Filler blocks	$0.042^{+0.102}_{-0.042}$	$0.048^{+0.115}_{-0.048}$
Filler foam	$0.0076^{+0.0107}_{-0.0063}$	$0.0088^{+0.0123}_{-0.0067}$
Neck PMTs	<0.01	<0.02
Total	$0.060^{+0.104}_{-0.045}$	$0.073^{+0.119}_{-0.048}$



Delayed coincidence between nuclear recoil and γ-ray provides data-driven verification

<u>AmBe calibration</u>

For neutrons which enter liquid argon,

and

scatter to produce NR event

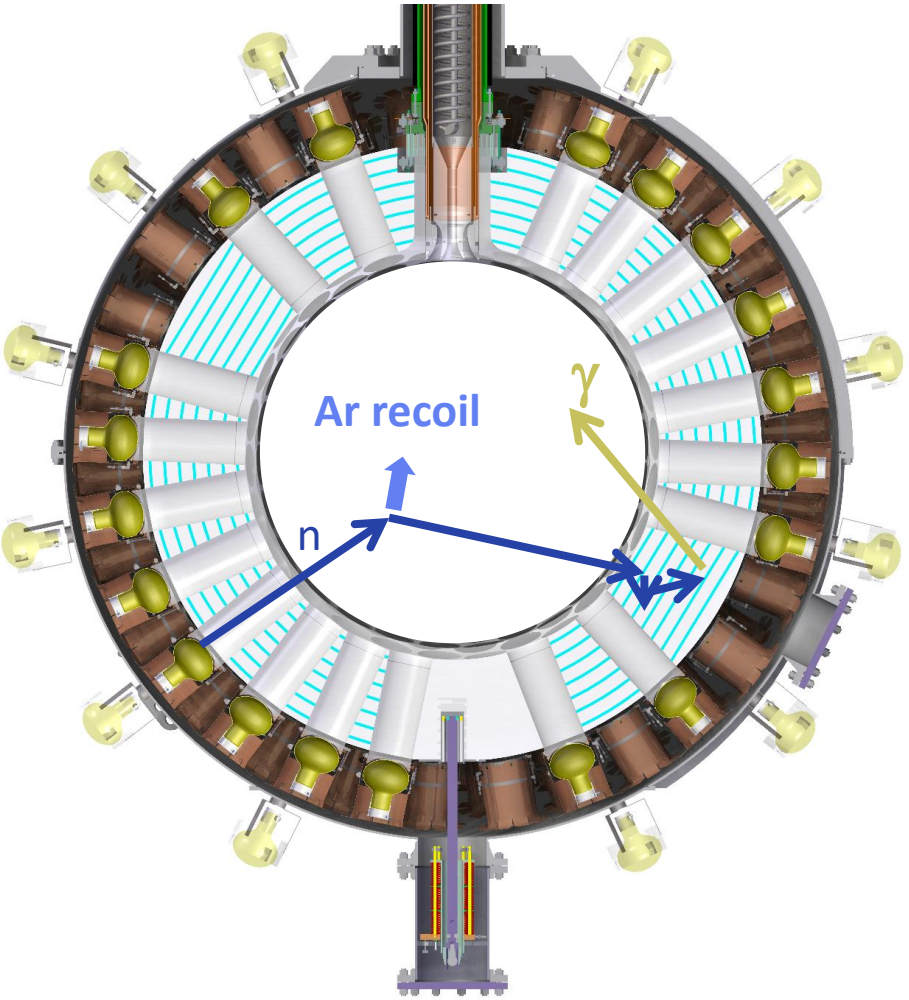
22.5 ± 0.5%

will capture (mostly on Ar-40 or H)

and

produce γ(s) that deposit energy in the LAr

Agrees with simulation



Delayed coincidence between nuclear recoil and γ-ray provides data-driven verification

7 such events in data in control region

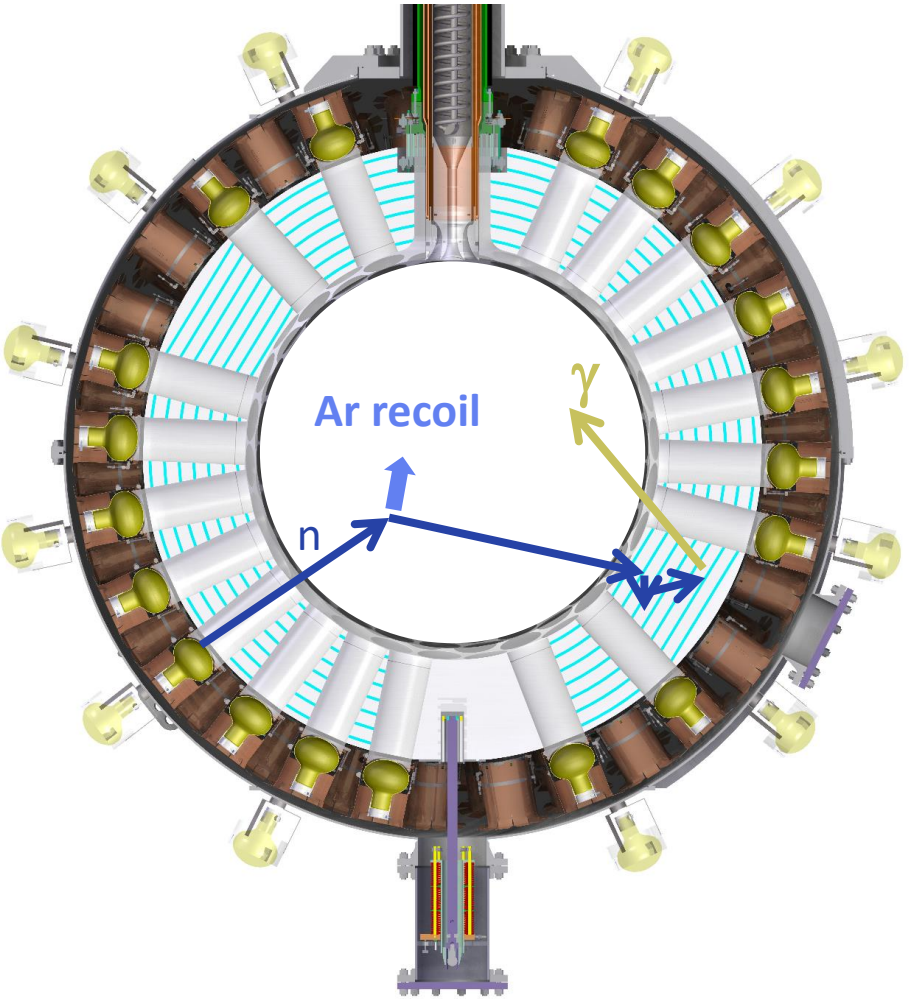
None in WIMP ROI; None have muon veto signal

1.8 ± 0.3 expected from random coincidence

➔Expect 23 (+17, -14) events in the control region

➔Expect 6 ± 4 events in 95-200 PE with control cuts

➔Expect 0.1 (+0.1, -0.09) events with WIMP search cuts



Cosmogenic neutron rates are low before muon veto imposed

Muon rate as measured by SNO:

$(3.31 \pm 0.10) \times 10^{-10}$ cm^{-2}s^{-1}

PRD 80, 012001 (2009)

DEAP rate: $(3\text{-}4) \times 10^{-10}$ cm^{-2}s^{-1}

Using Mei and Hime: PRD 73, 053004 (2006)

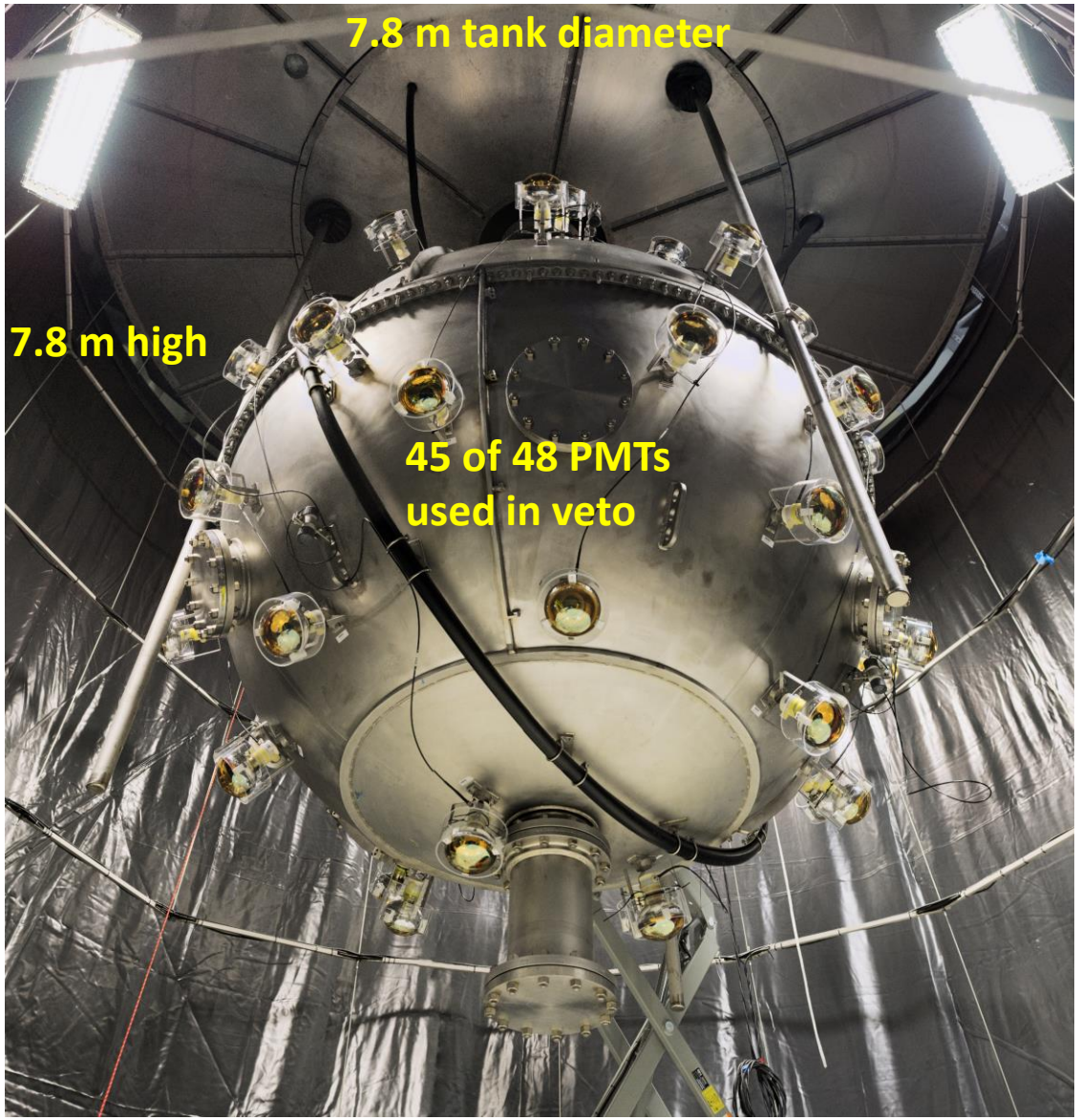
<0.2 events before WIMP cuts

<0.11 events in WIMP ROI

Impose muon veto cut

veto window [-0.1, 1] s about tag

Live time reduced by 0.16%



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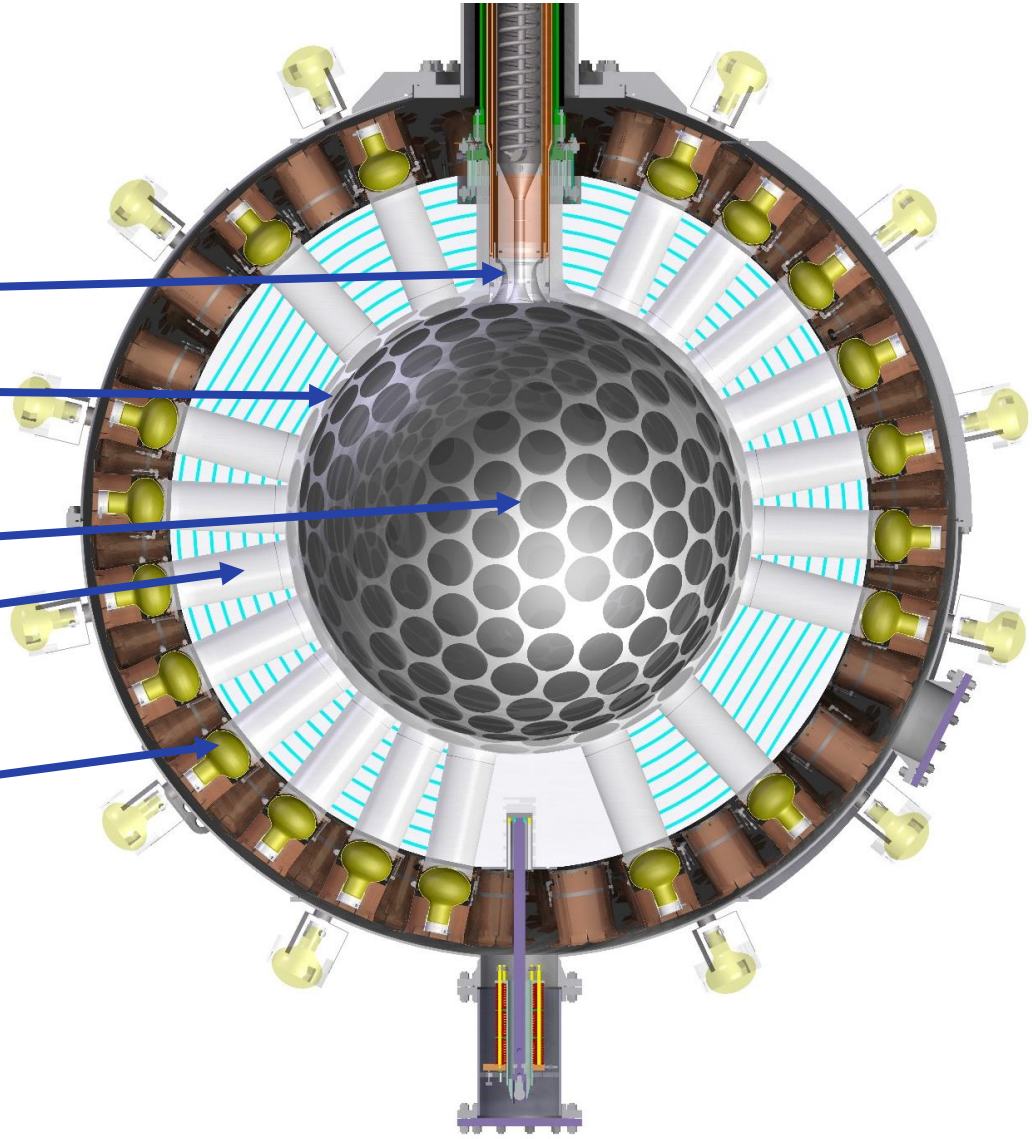
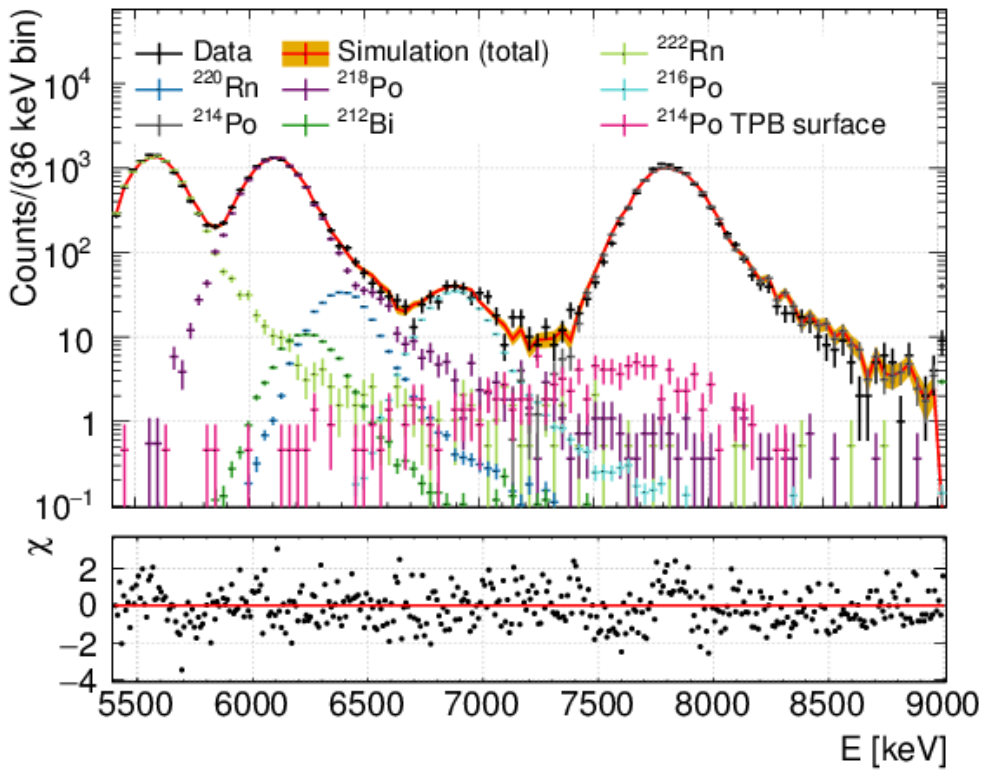
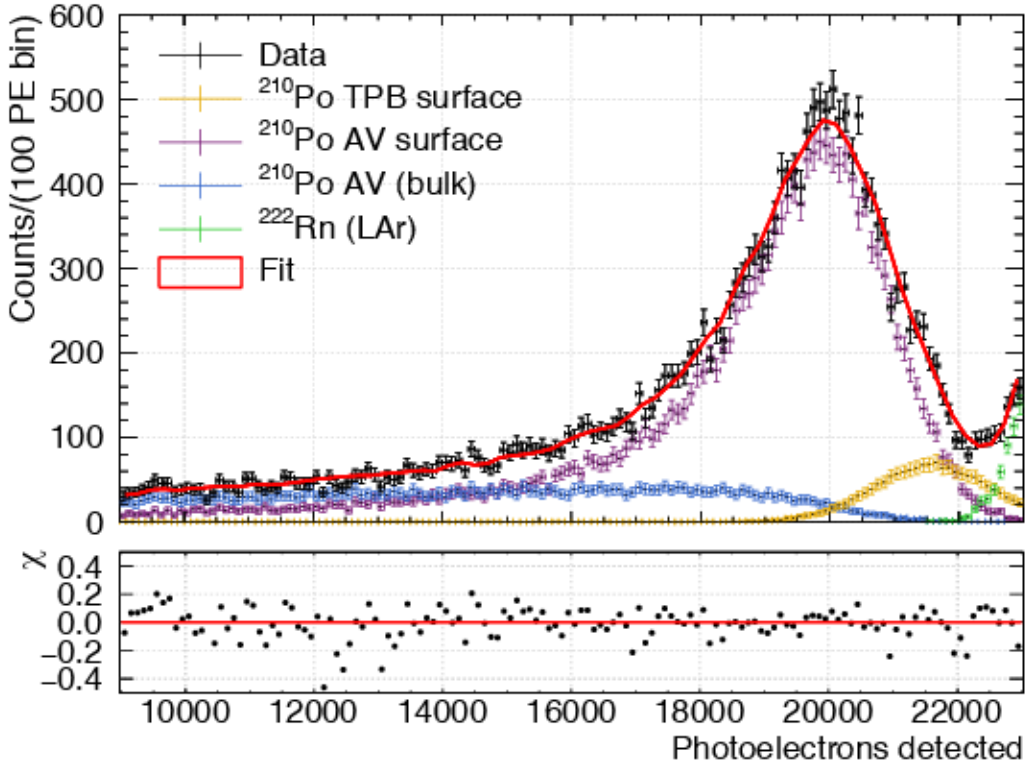


α rates are well understood

α in the liquid argon



α on the acrylic/TPB surfaces



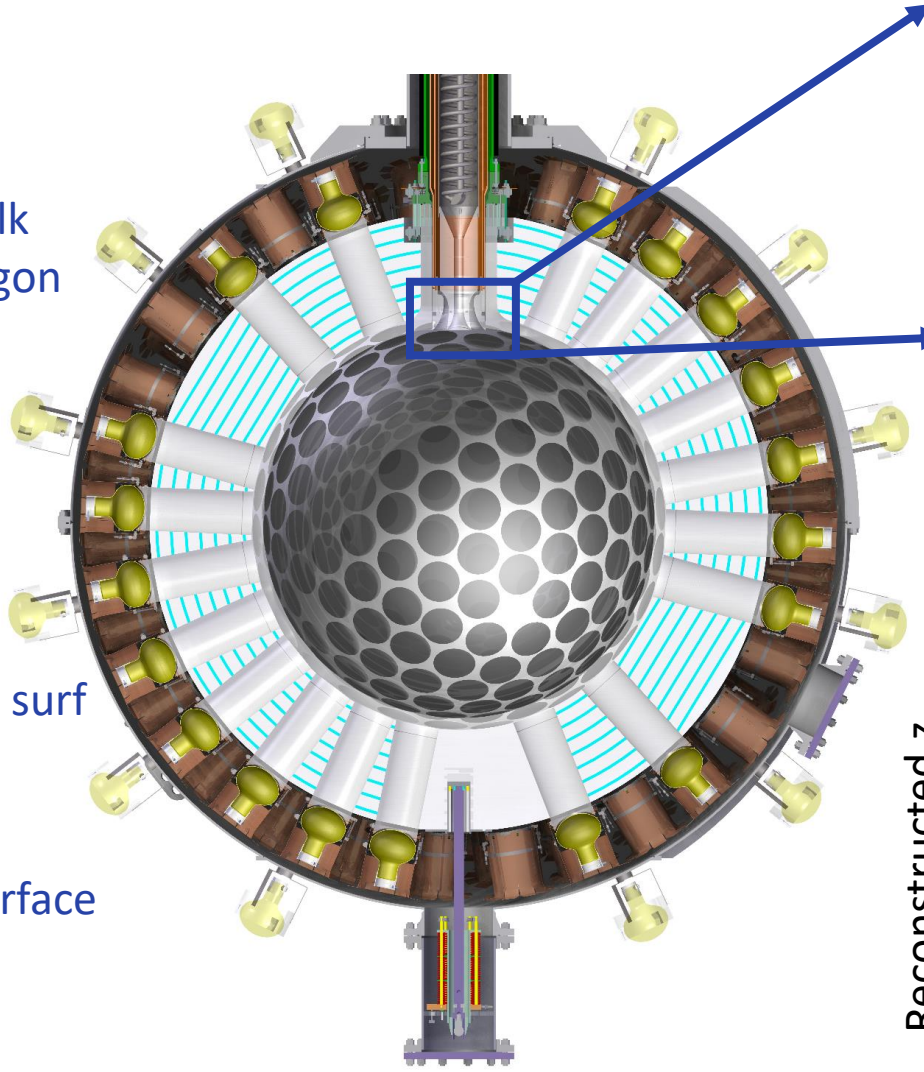
α rates are well understood

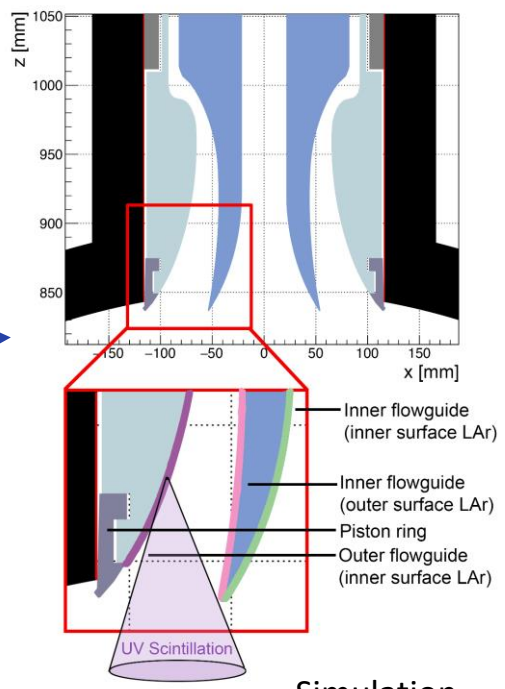
	Component	Activity / Rate
short-lived α-decays	^{222}Rn LAr	(0.153 ± 0.005) µBq/kg
	^{218}Po LAr	(0.159 ± 0.005) µBq/kg
	^{214}Po LAr	(0.153 ± 0.005) µBq/kg
	^{214}Po TPB surface	<5.0 µBq/m^2
	^{220}Rn LAr	(4.3 ± 1.0) nBq/kg
	^{216}Po LAr	(4.5 ± 0.4) nBq/kg
	^{212}Bi LAr	<5.6 nBq/kg
	^{212}Po LAr	(3.4 ± 1.1) nBq/kg
long-lived α-decays	^{210}Po TPB & AV surface	(0.26 ± 0.02) mBq/m^2
	^{210}Po AV (bulk)	(2.82 ± 0.05) mBq
	^{210}Po inner FG, IS	(14.1 ± 1.3) µHz
	^{210}Po inner FG, OS	(16.8 ± 1.4) µHz
	^{210}Po outer FG, IS	(22.7 ± 1.6) µHz

Bulk Argon

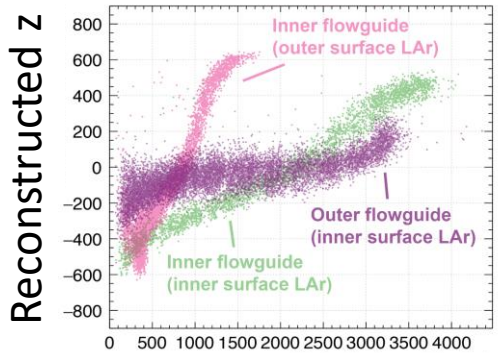
Sphere surf

Neck surface





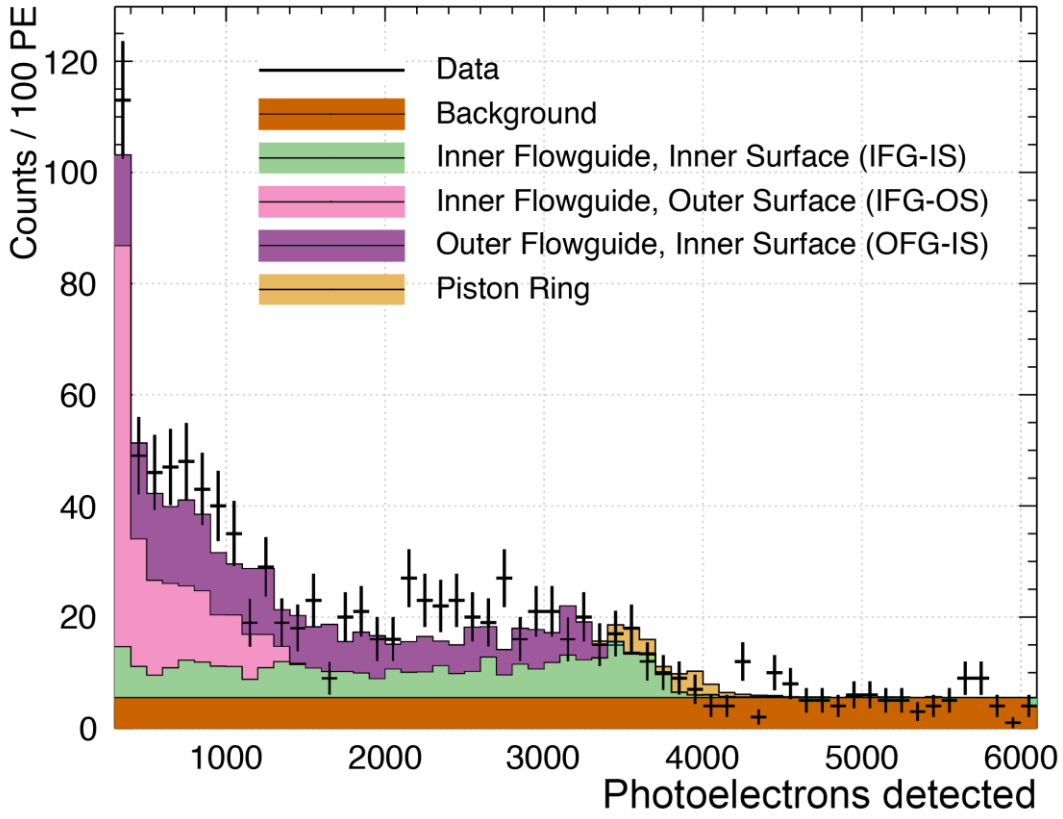
Simulation

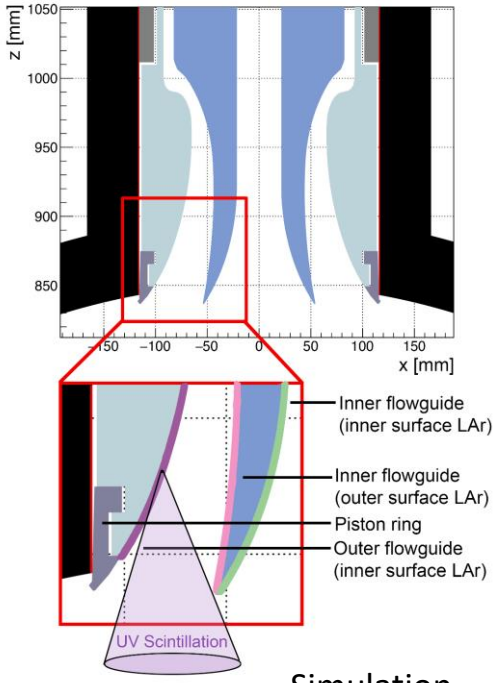


Surface α in neck: largest background

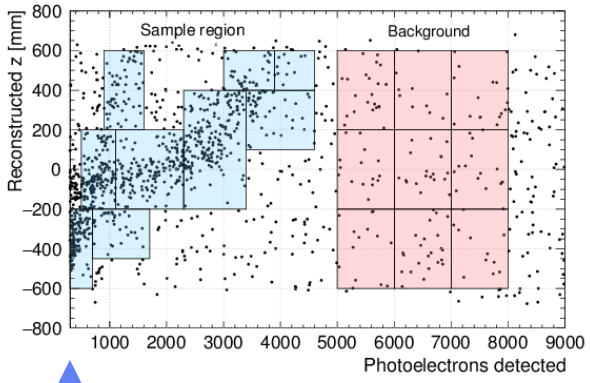
Thin film of LAr on acrylic in neck.

Small fraction of UV light from scintillation is visible.





Data



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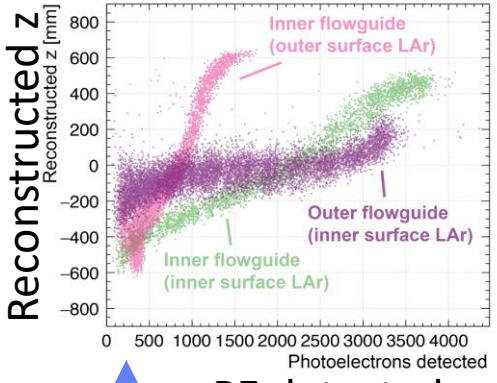
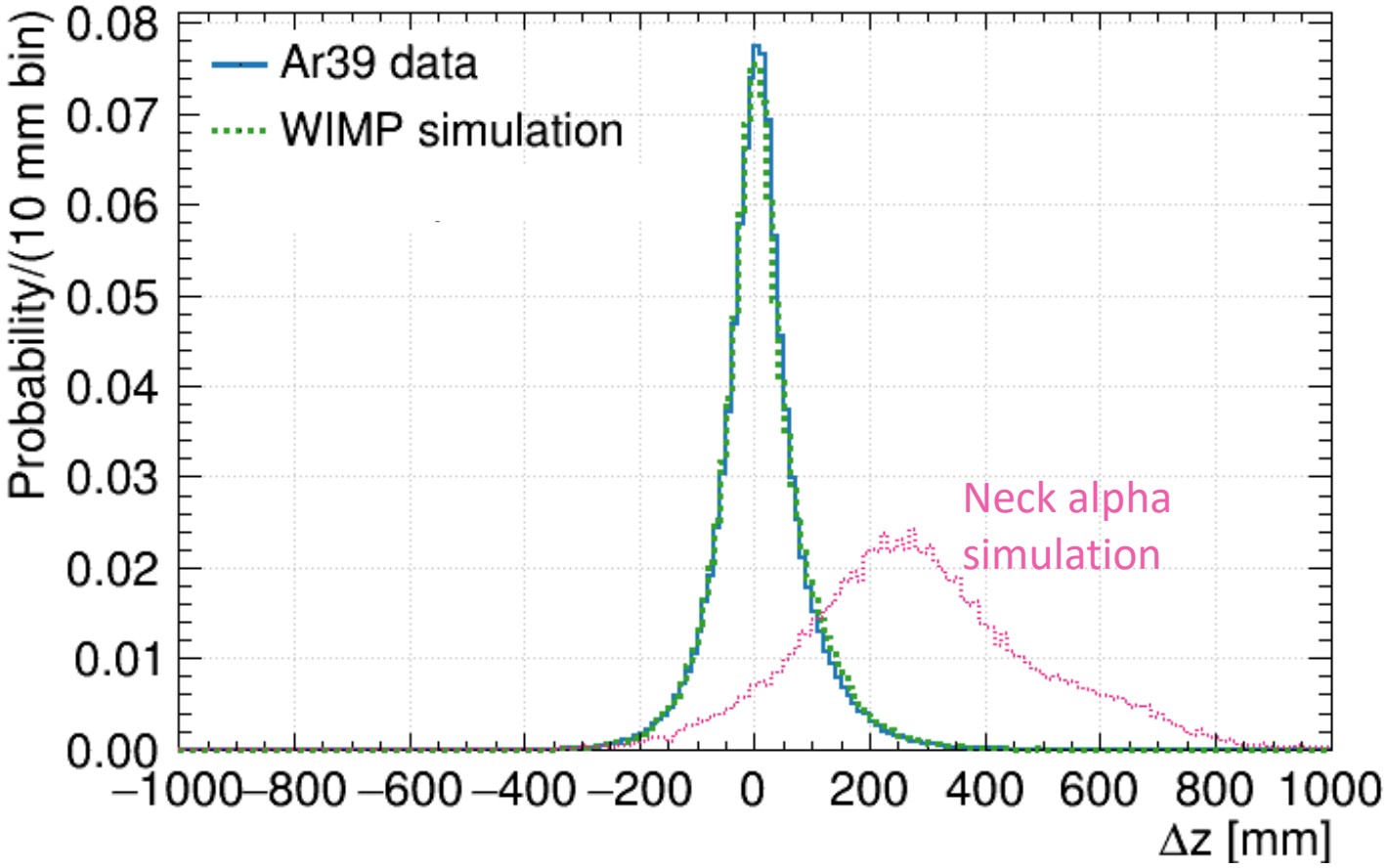
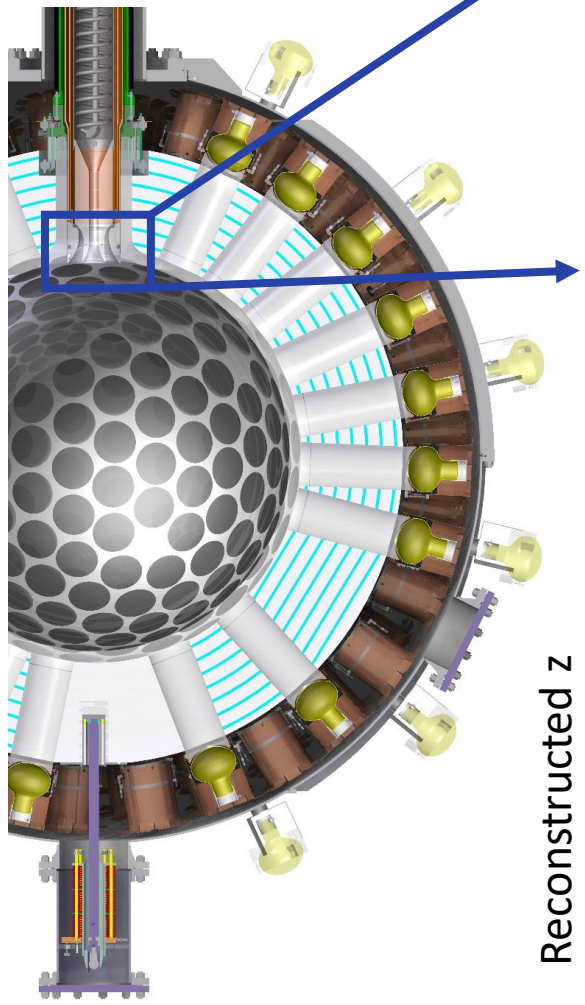


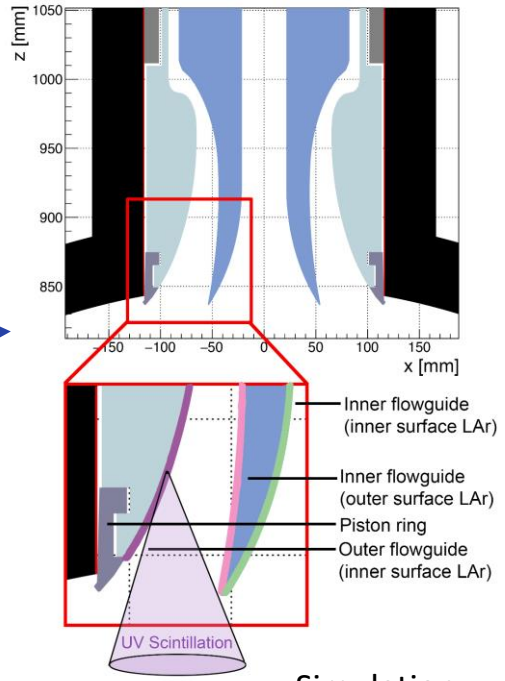
PE detected

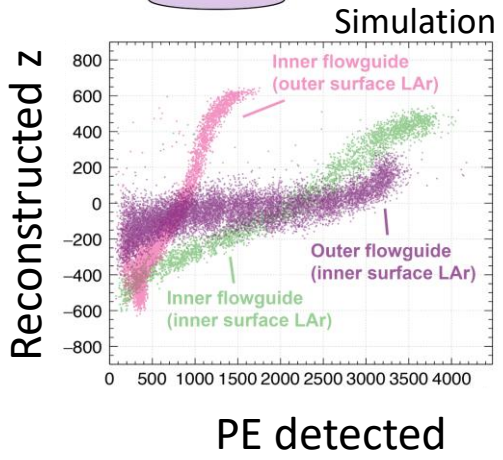
Hit-pattern reconstruction puts neck α events low in detector. Time reconstruction leaves events high.



Time fit z – Hit pattern z



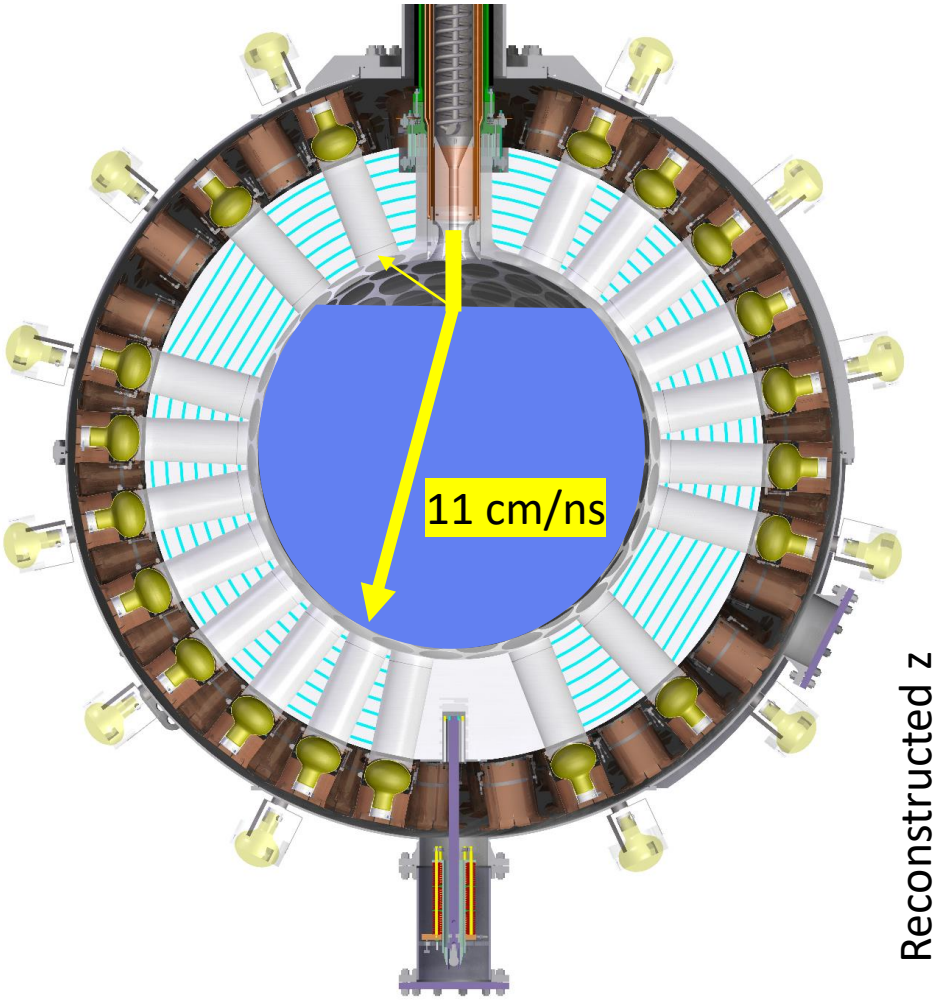


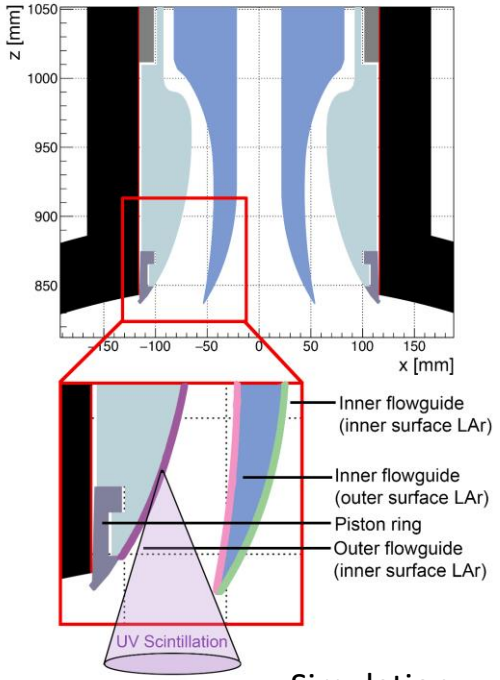


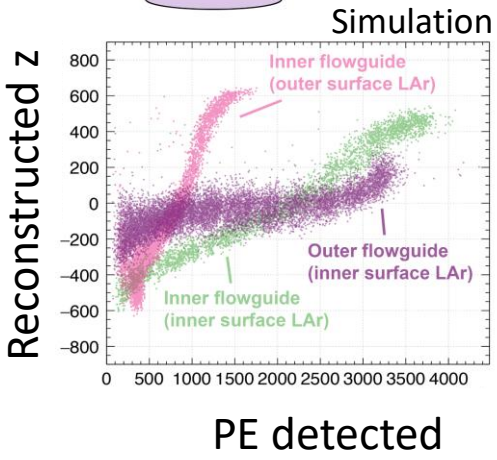
Handle 2: Some UV Light from neck events reflects at the argon surface giving an early signal to top PMTs.

Cutting on <u>early light</u> in the top (or “gas”) PMTs effectively removes neck events.

However, it imposes a large reduction in WIMP acceptance.



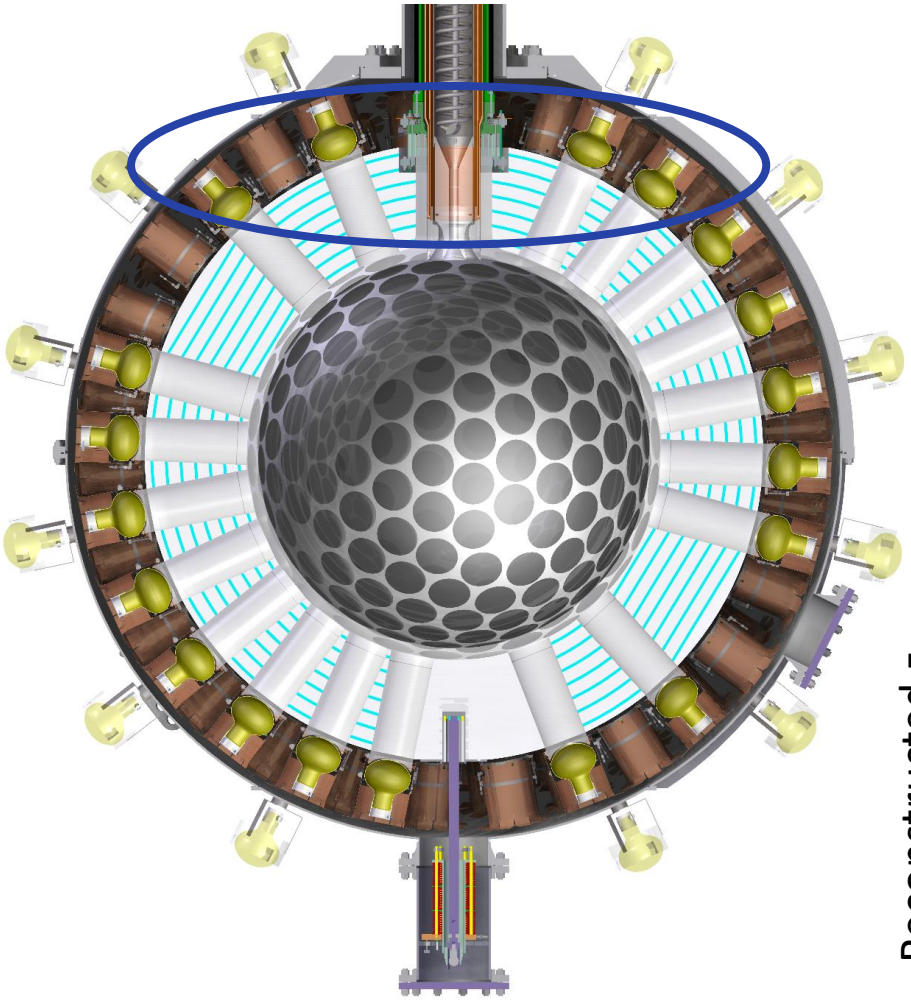


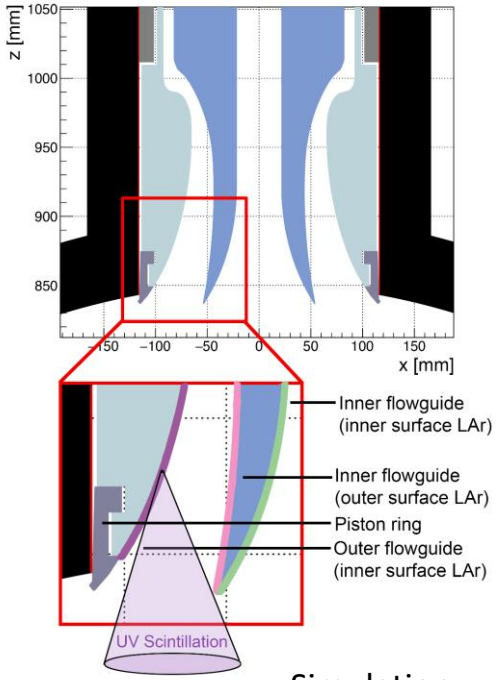


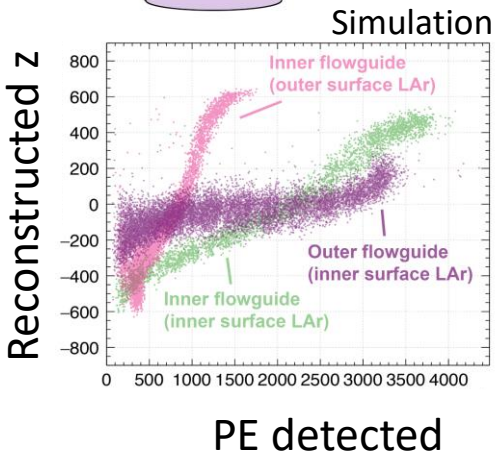
Handle 3: Neck Events have anomalously high signals in the top two rows of PMTs.

Cutting on the <u>fraction of light</u> in the top (or “gas”) PMTs effectively removes neck events.

However, it imposes a modest reduction in WIMP acceptance.



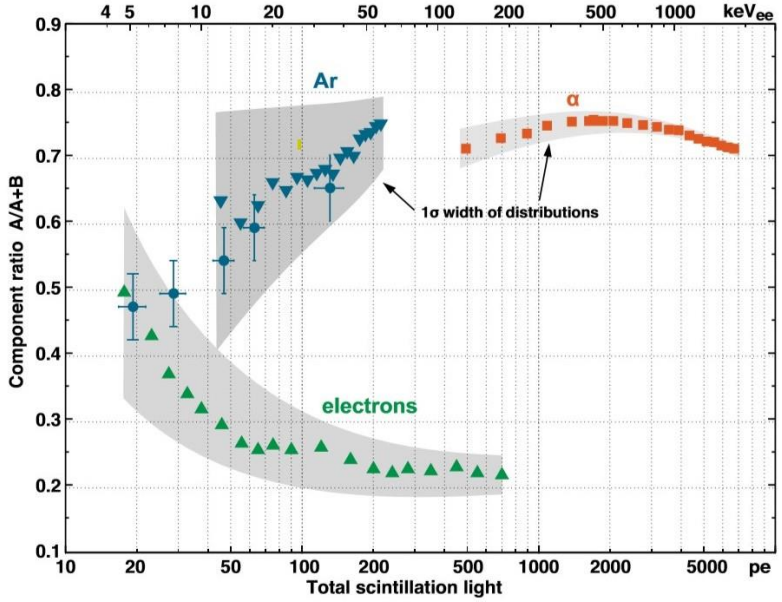




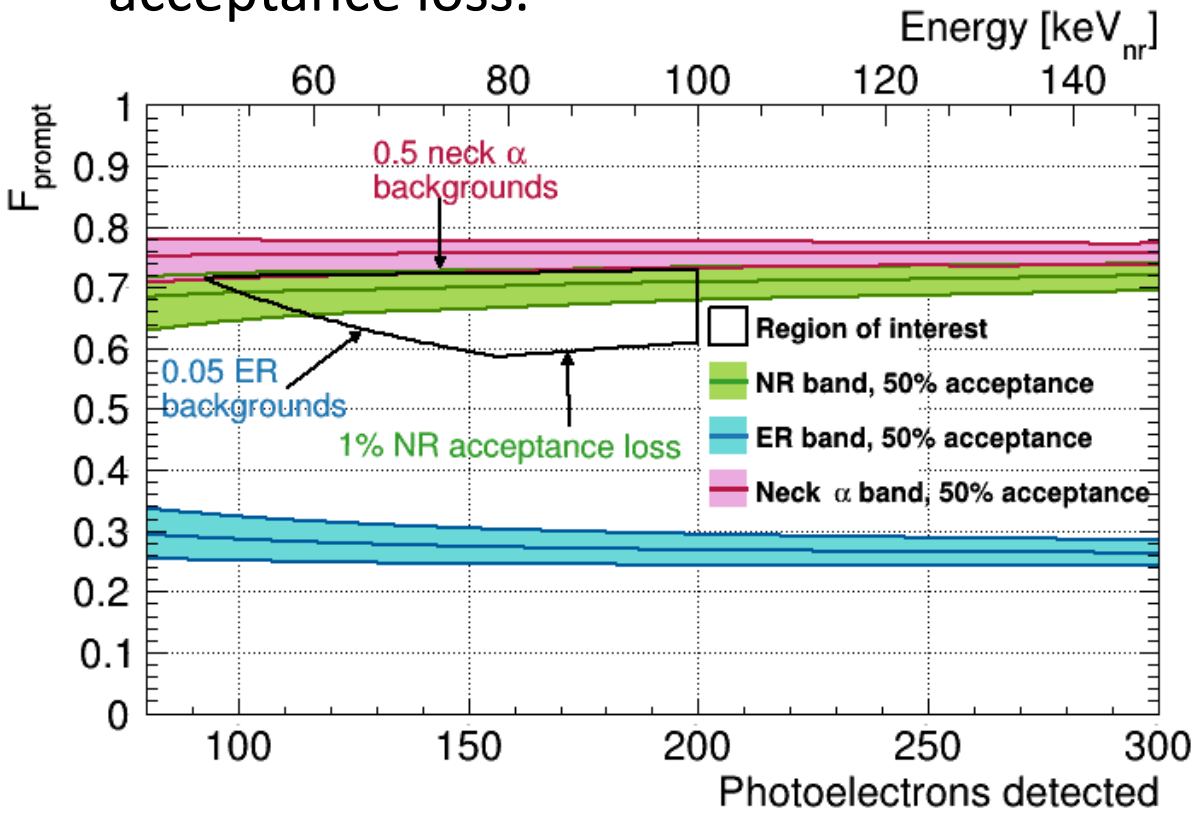
Handle 4: Neck α events are high-E events with reduced light yield from geometry.

Regenfus et al have noted that high-E a events in LAr have a larger Fprompt than do low-E Ar-40 recoils.

Journal of Physics: Conference Series, Volume 375, Part 1



Using bulk α events in DEAP-3600, set high-Fprompt edge of our acceptance to allow 0.5 neck α events. Results in 30% acceptance loss.



Neck cuts are effective and systematics evaluated

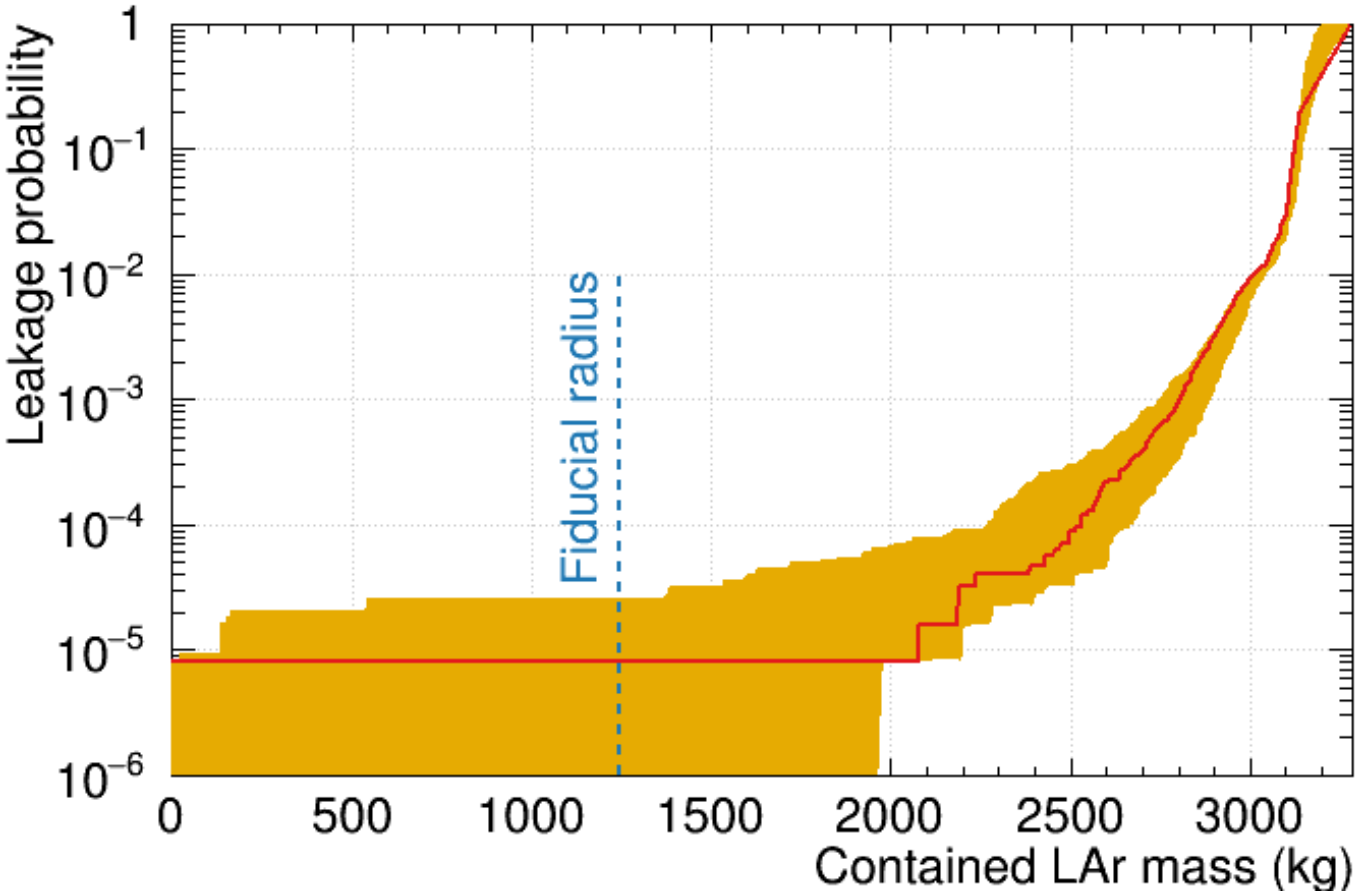
TABLE VII. Predicted rejection efficiency of each cut to remove events generated by α-decays from each of the three FG surfaces. The efficiency is calculated for events with a reconstructed radius <630 mm in the range of 95–200 PE. These efficiencies are determined from simulations. The last row provides an estimate of the combined rejection efficiency after applying all four cuts.

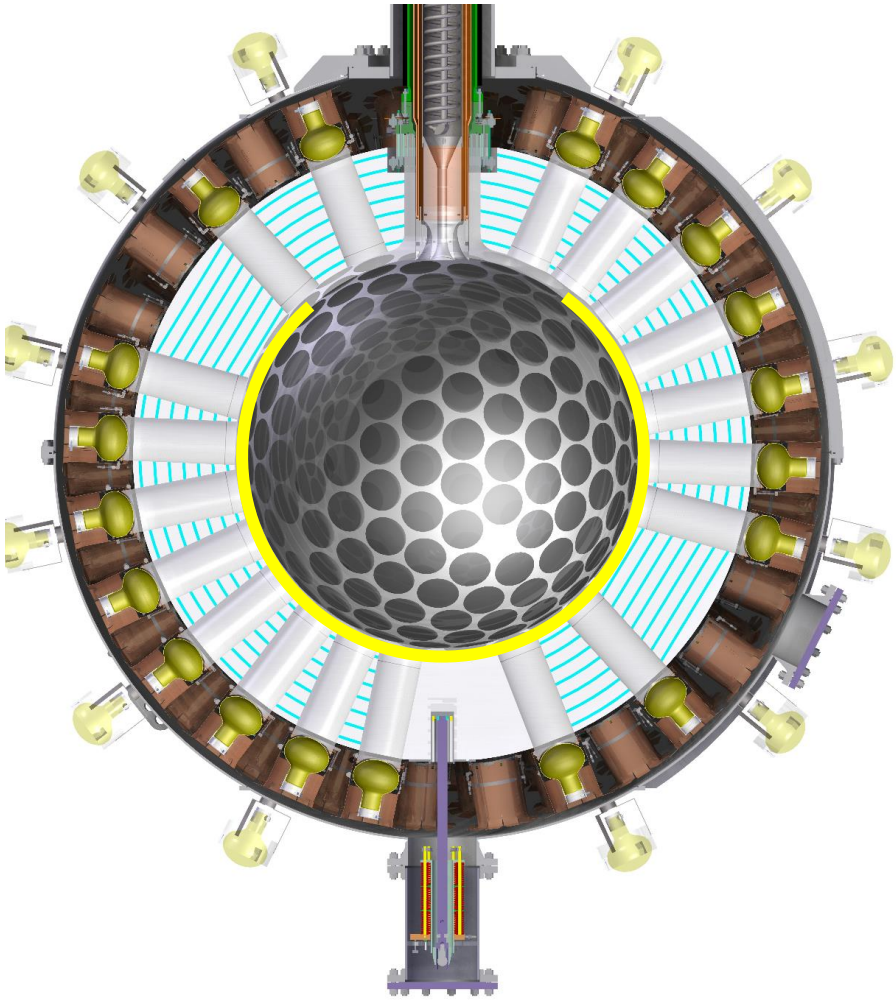
Cut name	Neck α-decay rejection [%]		
	IFG-IS	IFG-OS	OFG-IS
Upper F_{prompt} cut	73	59	72
Early pulses in GAr PMTs	80	85	81
Charge fraction in top 2 rows of PMTs	57	46	36
Position reconstruction consistency	90	93	82
Combined	99	99	98

TABLE VI. Summary of the uncertainty on the overall number of events remaining in the WIMP ROI after applying all background rejection and fiducial cuts. Uncertainties are quoted for each FG surface component.

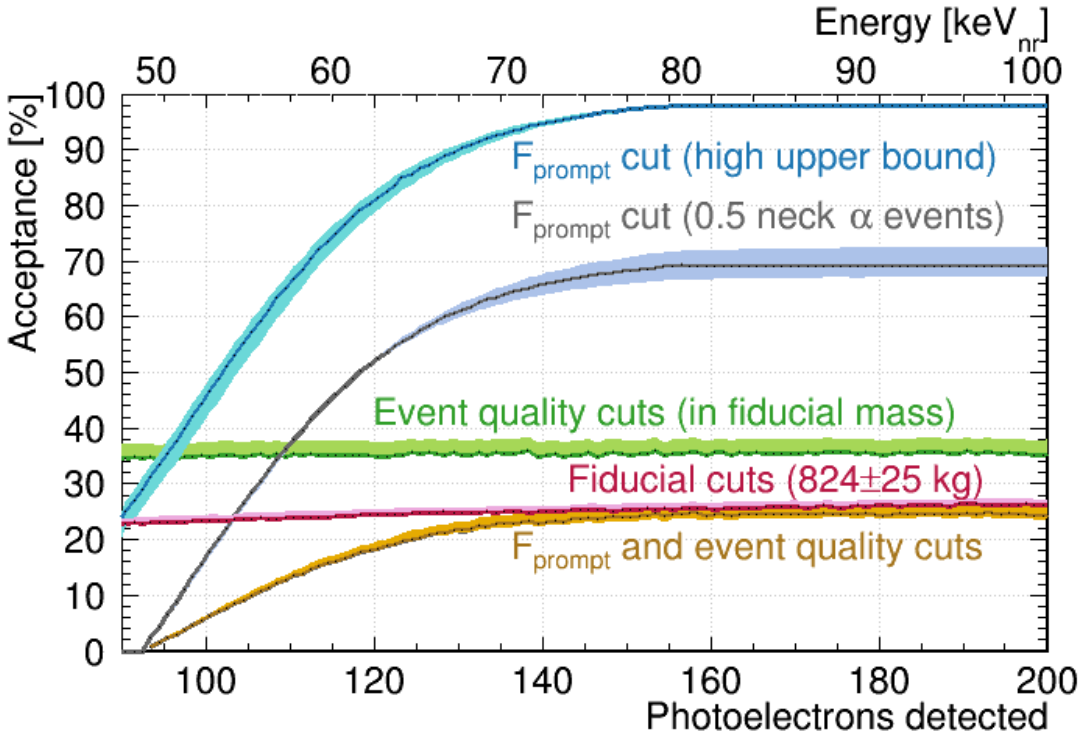
Systematic	Uncertainty [%]		
	IFG-IS	IFG-OS	OFG-IS
Refractive index	$^{+7}_{-42}$	$^{+25}_{-10}$	$^{+13}_{-10}$
TPB scattering length	$^{+86}_{-29}$	$^{+28}_{-21}$	$^{+19}_{-0}$
Afterpulsing prob.	$^{+26}_{-36}$	$^{+0}_{-32}$	$^{+4}_{-24}$
Light yield	$^{+54}_{-0}$	$^{+0}_{-6}$	$^{+13}_{-4}$
Rel. PMT eff.	$^{+8}_{-0}$	$^{+0}_{-13}$	$^{+0}_{-29}$
α particle F_{prompt}	$^{+83}_{-50}$	$^{+58}_{-42}$	$^{+80}_{-47}$
Reconstructed radius	$^{+0}_{-75}$	$^{+0}_{-31}$	$^{+0}_{-26}$
LAr film thickness	$^{+104}_{-0}$	$^{+0}_{-49}$	$^{+0}_{-66}$
Combined	$^{+170}_{-110}$	$^{+69}_{-83}$	$^{+85}_{-80}$

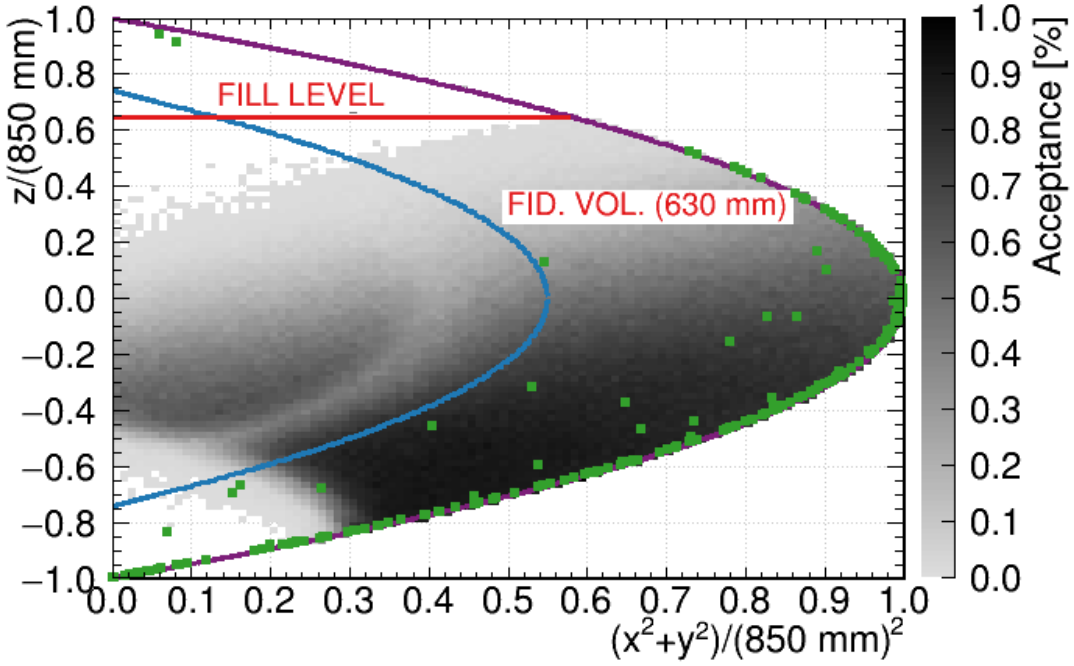
α events on the surface of the sphere are removed with hit-pattern-based position reconstruction



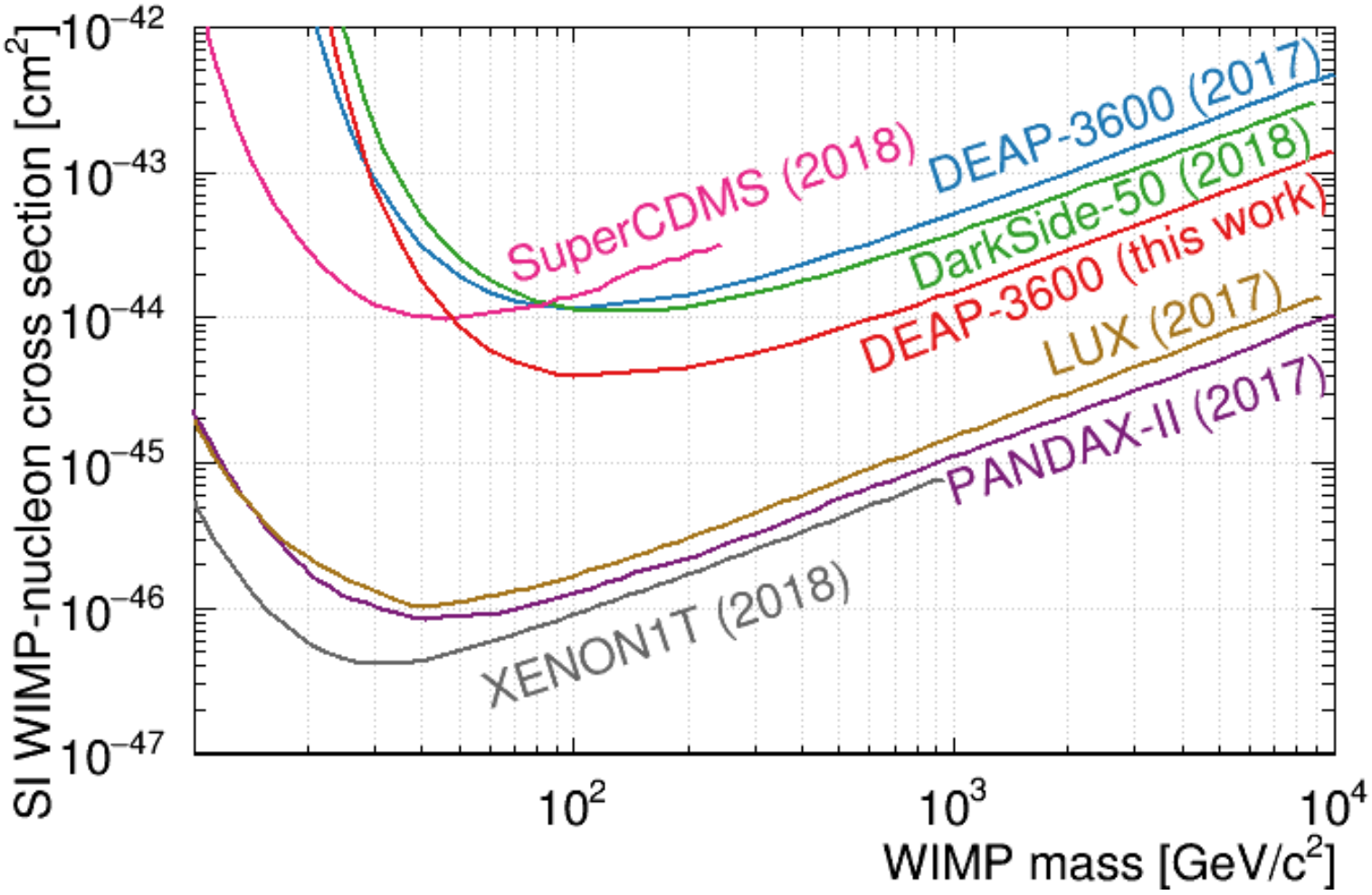


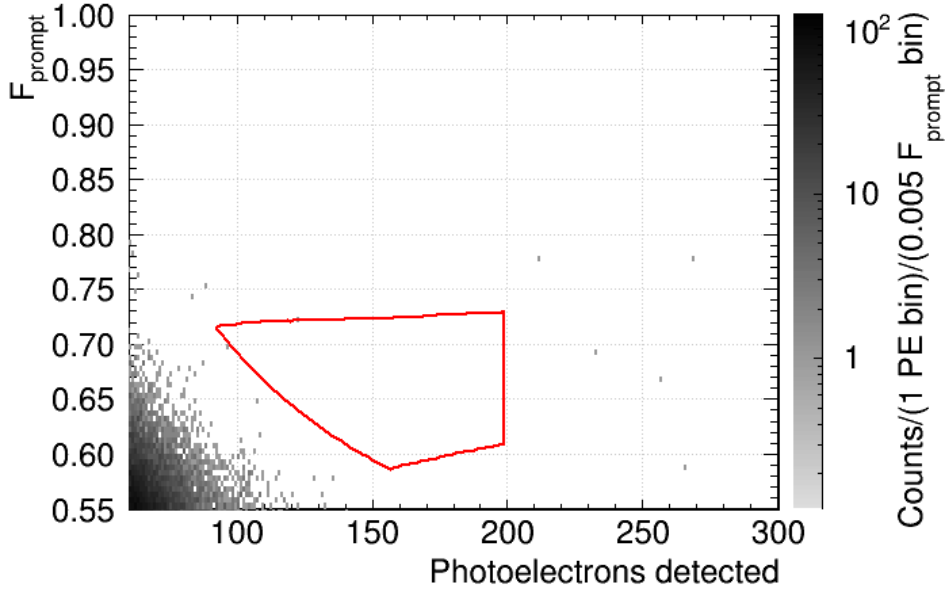
Acceptance evaluated for all cuts.





231-day open data set





arXiv: 1902.04048
Accepted by PRD

Background Summary

TABLE III. Predicted number of events from each background source in its respective CR, N^{CR} and the total number in the WIMP ROI after applying both fiducial and background rejection cuts, N^{ROI}. Upper limits are quoted at 90% C. L.

	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	$0.62^{+0.31}_{-0.28}$

TABLE VIII. Cumulative impact of background rejection cuts on the WIMP acceptance, the predicted number of background events, $N^{\mathrm{ROI}}_{\mathrm{bkg}}$ and the total number of observed background events, $N^{\mathrm{ROI}}_{\mathrm{obs}}$ after applying fiducial cuts to events inside WIMP ROI. Cuts are grouped by the background they predominantly remove. The value of the acceptance is averaged over the 95–200 PE range.

	Background rejection cut	WIMP accept. [%]	$N^{\mathrm{ROI}}_{\mathrm{bkg}}$	$N^{\mathrm{ROI}}_{\mathrm{obs}}$
Cherenkov	Neck veto	$92.0^{+1.0}_{-0.1}$	$9.2^{+4.4}_{-3.5}$	29
α-decays in neck	Early pulses in GAr PMTs	$45.4^{+1.5}_{-0.1}$	$2.3^{+1.1}_{-0.9}$	2
	Position fitter consistency	$35.4^{+2.5}_{-0.1}$	$0.62^{+0.31}_{-0.28}$	0
	Total	$35.4^{+2.5}_{-0.1}$	$0.62^{+0.31}_{-0.28}$	0

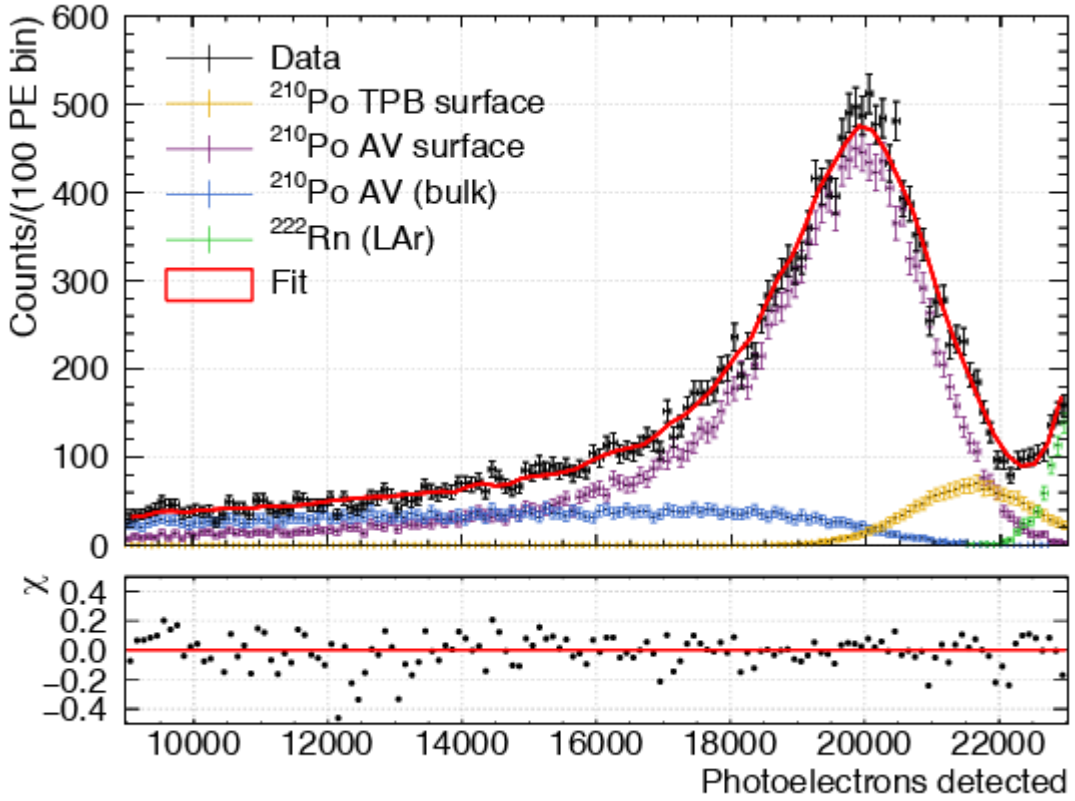
High Fprompt events between 10000 and 20000 pe are seen. 5% reconstruct inside 630mm. This is not expected in our background model.

The collaboration is considering hypotheses.

One is the “dust hypothesis”: low levels of particulates in the liquid argon creating surface alphas at low radius.

None are in the ROI in our 231-day paper.

Data and model with no reconstruction cut

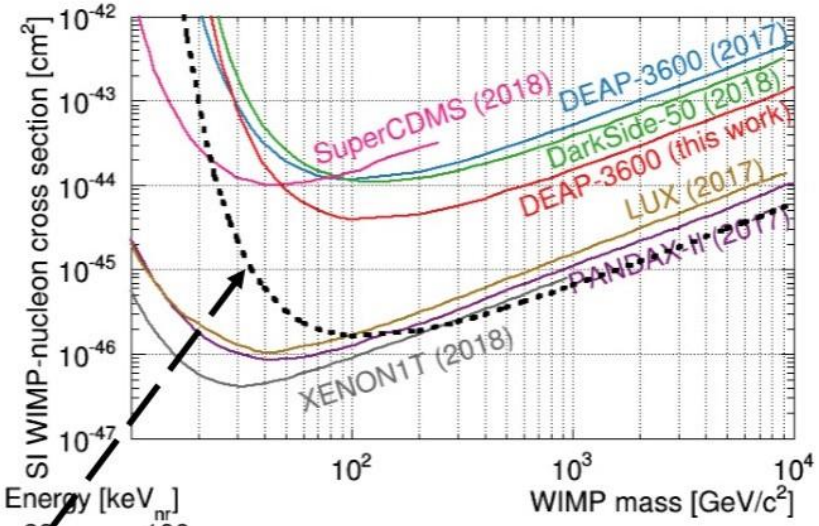


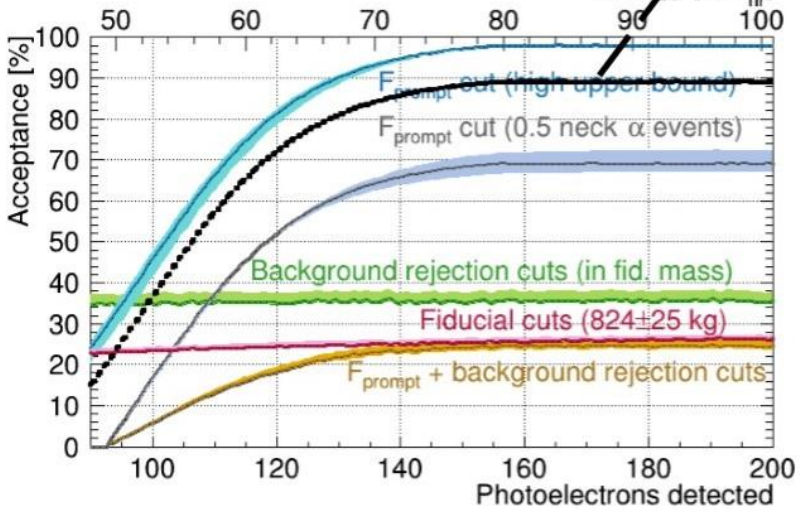
Scaling of 231-day result shows path forward: reducing backgrounds and increasing acceptance

With better acceptance

Assumptions:

- 3 tonne-year fiducial exposure
- Assume 10% acceptance loss of NRs at higher F_{prompt} (dotted black curve)





Possible further improvements beyond above:

-larger fiducial mass (pos. resolution ~20 mm better than design 100 mm)

-lower threshold with low-rad. argon

→ Analysis Strategy:

Develop improved analysis tools and apply to open dataset: profile likelihood, machine-learning, advanced hit-pattern recognition.

Open box blind data set with improved analysis. (ie only open the box once)

Next paper target: calendar year 2019.

Planning a hardware fix to eliminate neck events

TABLE III. Predicted number of events from each background source in its respective CR, N^{CR} and the total number in the WIMP ROI after applying both fiducial and background rejection cuts, N^{ROI}. Upper limits are quoted at 90% C. L.

	Source	N^{CR}	N^{ROI}
β/γ's	ERs	2.44×10^9	0.03 ± 0.01
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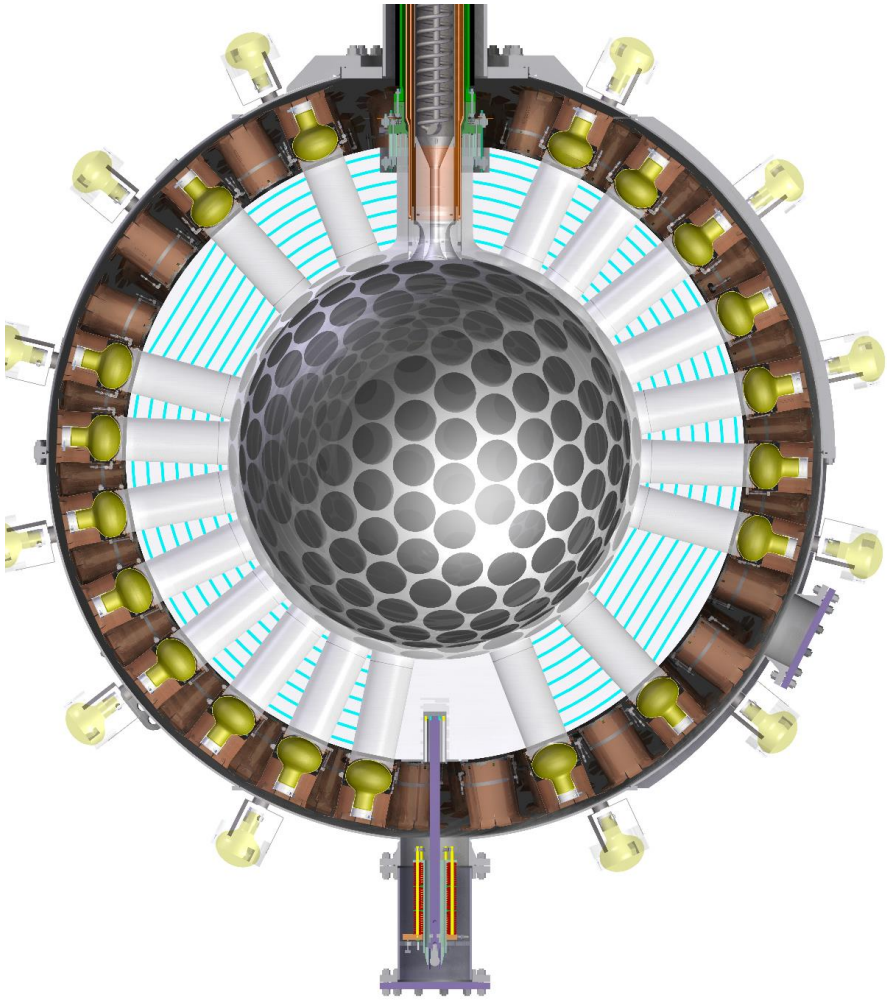
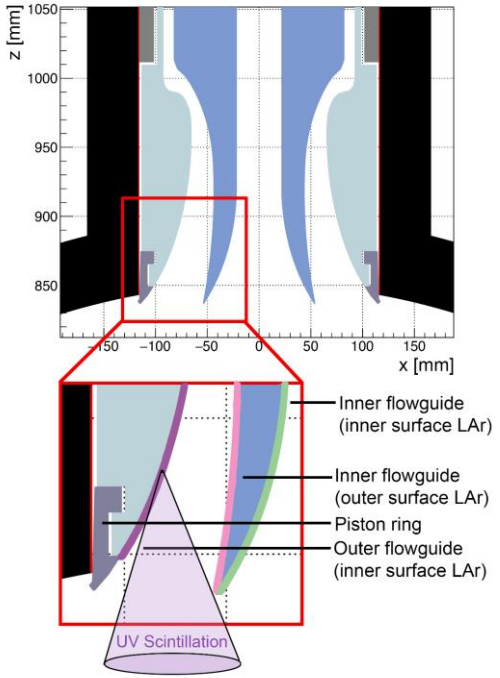




Neck events can be eliminated by warming the neck or by changing the pulse-shape

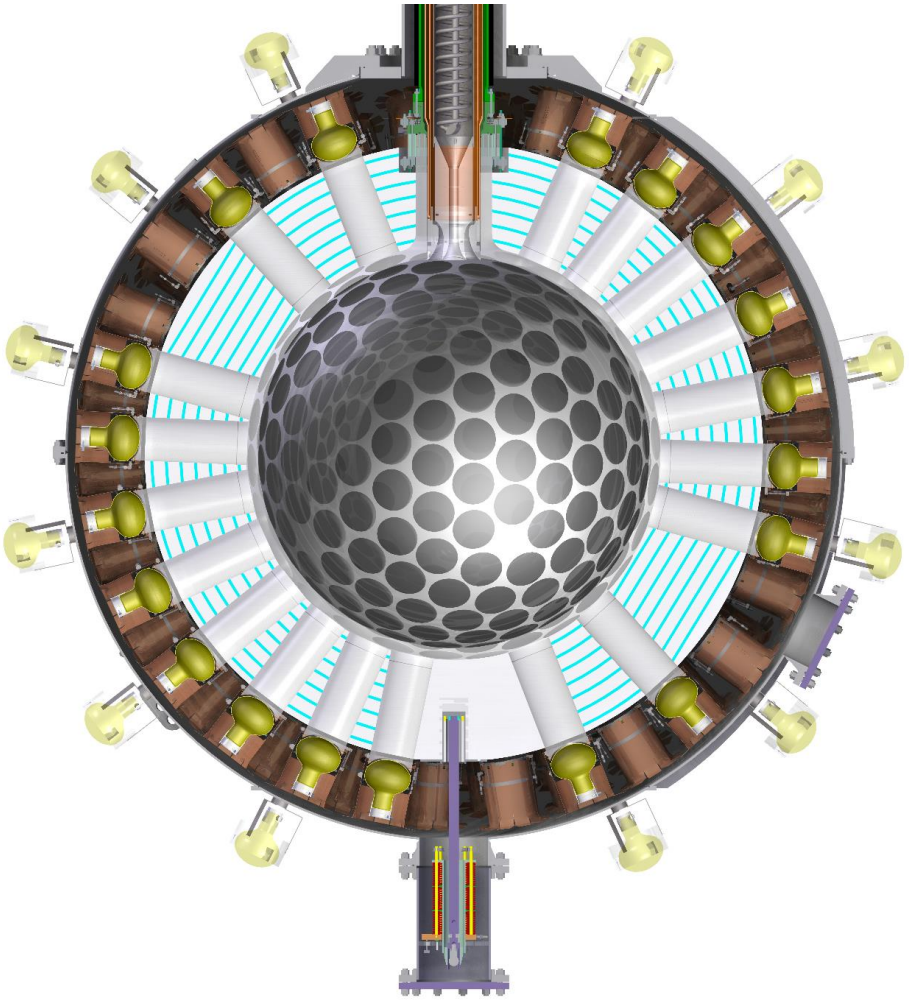
1: Condense gas to liquid outside the detector and feed it back in a vacuum jacketed tube down to the base of the neck.

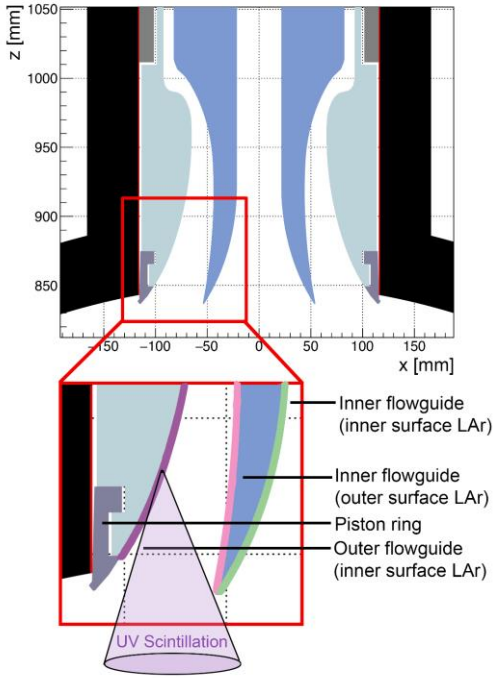
No cold surfaces in neck → no liquid argon in the neck → no neck backgrounds.

2: A layer of scintillator on the outer surface of the neck components,
with an intermediate time constant,
effectively mitigates surface alpha events.
arXiv:1903.00257

An acrylic/pyrene coating is under investigation for robustness in assembly and operation.

In either fix scenario we will add the ability to circulate liquid.





Argon is important in understanding dark matter in non-standard interaction models.

New Constraints on Xenonphobic Dark Matter from DEAP-3600

Carlos E. Yaguna*
rsidad Pedagógica y Tecnológica de Colo del Norte # 39-115, Tunja, Colombia

Abstract

rom DEAP-3600, a single-phase liquid argon er experiment, were recently reported. At first no new constraints, as the limit lies well within d by three different xenon experiments: LUX, Γ. We point out, however, that this conclusion it is based on the untested assumption that uples equally to protons and neutrons. For the

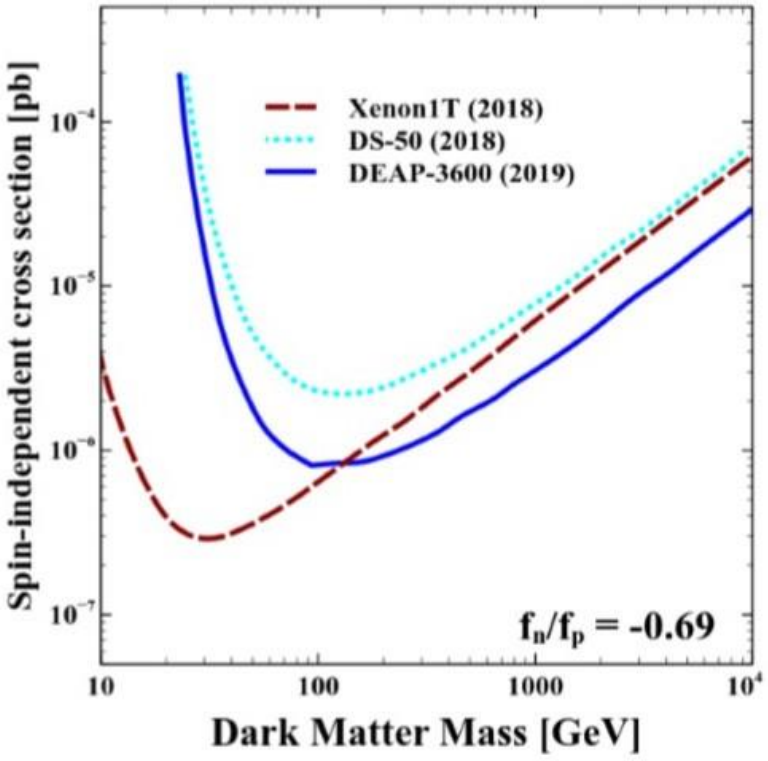


Figure 4: Current limits on the dark matter-proton spin-independent direct detection cross section for the case $f_n/f_p = -0.69$ (isospin-violating dark matter).

Arxiv:1902.10256

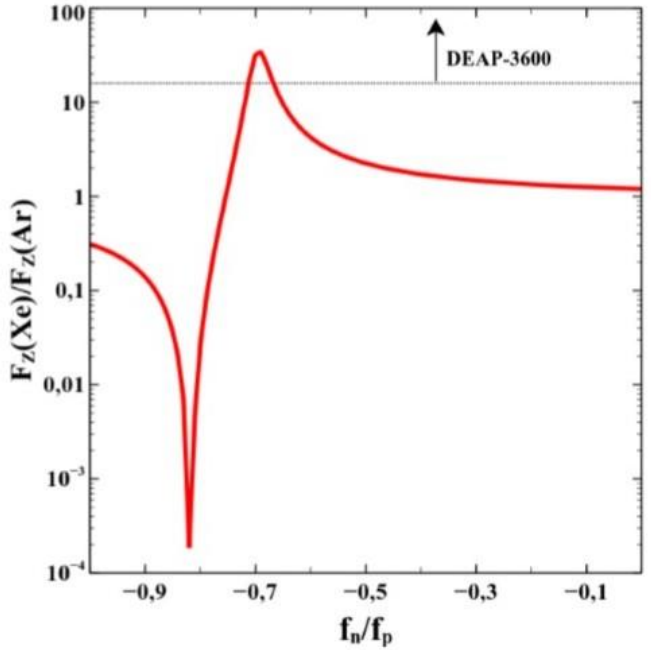


Figure 2: The values of f_n/f_p where DEAP-3600 outperforms XENON1T for high dark matter masses. Above the dotted black line, DEAP-3600 currently provides the most stringent limit on the dark matter spin-independent cross section.

More science
We will interpret DEAP-3600 data to study:

non-relativistic operators and effective couplings,

non-standard HALO models,

dark matter at masses greater than 10^{10} GeV/c^2,

the 1st-forbidden beta spectrum, specific activity, and half-life of ^{39}Ar,

0vECEC in ^{36}Ar,

cosmogenic isotope production,

10-100 keV hidden photons and axion-like particles

Axions from p+d → ^{3}He + A

Sterile neutrinos in ^{39}Ar spectrum,

…

Stable operation since 2016.

Radon rates: 153 nanoBequerel/kg → Best Radon levels in liquid noble.

Pulse-shape discrimination world best.

Best sensitivity with liquid argon.

Best sensitivity to dark matter in some interaction models.

Hardware improvements planned to remove dominant background.

INSTITUTO DE FISICA
Universidad Nacional Autónoma de México

Boulay and Kuzniak have suggested:

A layer of scintillator,
with an intermediate time constant,
between acrylic and TPB

effectively mitigates surface alpha events.

arXiv: 1903/00257

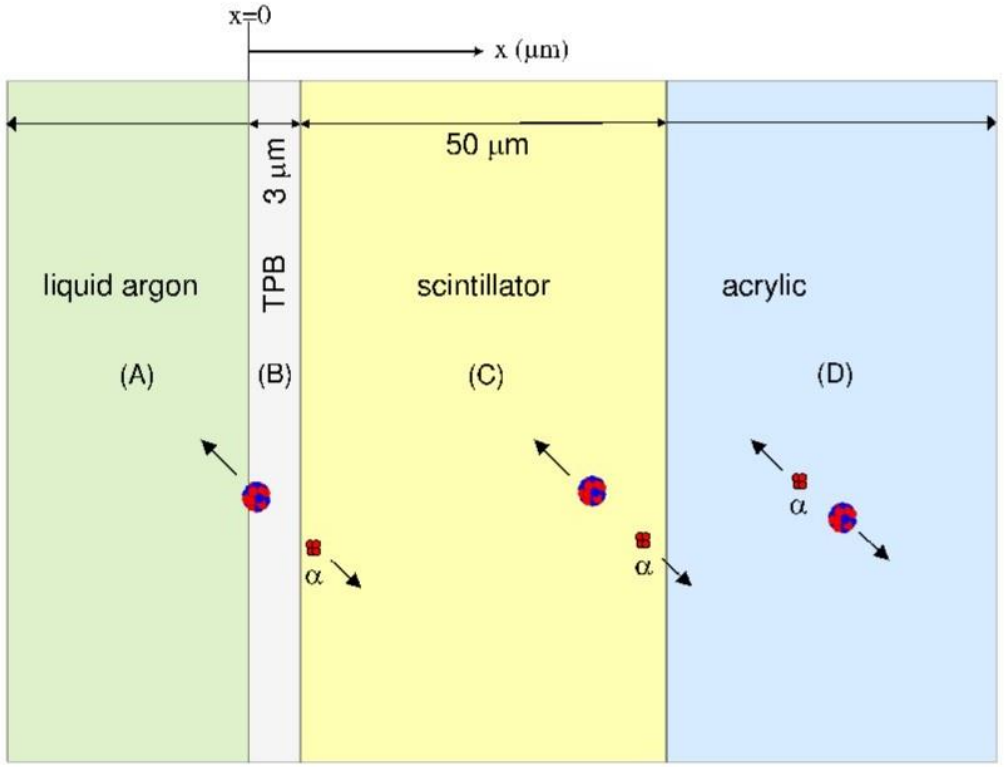


Figure 1: Conceptual design of multi-layer thin films at a detector surface. α decays from regions A or B will always deposit all of their energy in an active layer, and can be discriminated from low-energy nuclear recoils based on the high observed energy. Decays from region C will either deposit all of their energy in an active region (A, B or C) and be discriminated based on high deposited energy, or will deposit only a fraction of their energy in region C, in which case they can be discriminated against based on the long decay time of the scintillator. Similarly, events originating in the acrylic can be discriminated based on the long scintillator decay time.