



# The Background Model for DEAP-3600

Chris Jillings, SNOLAB and Laurentian University  
for the DEAP-3600 Collaboration

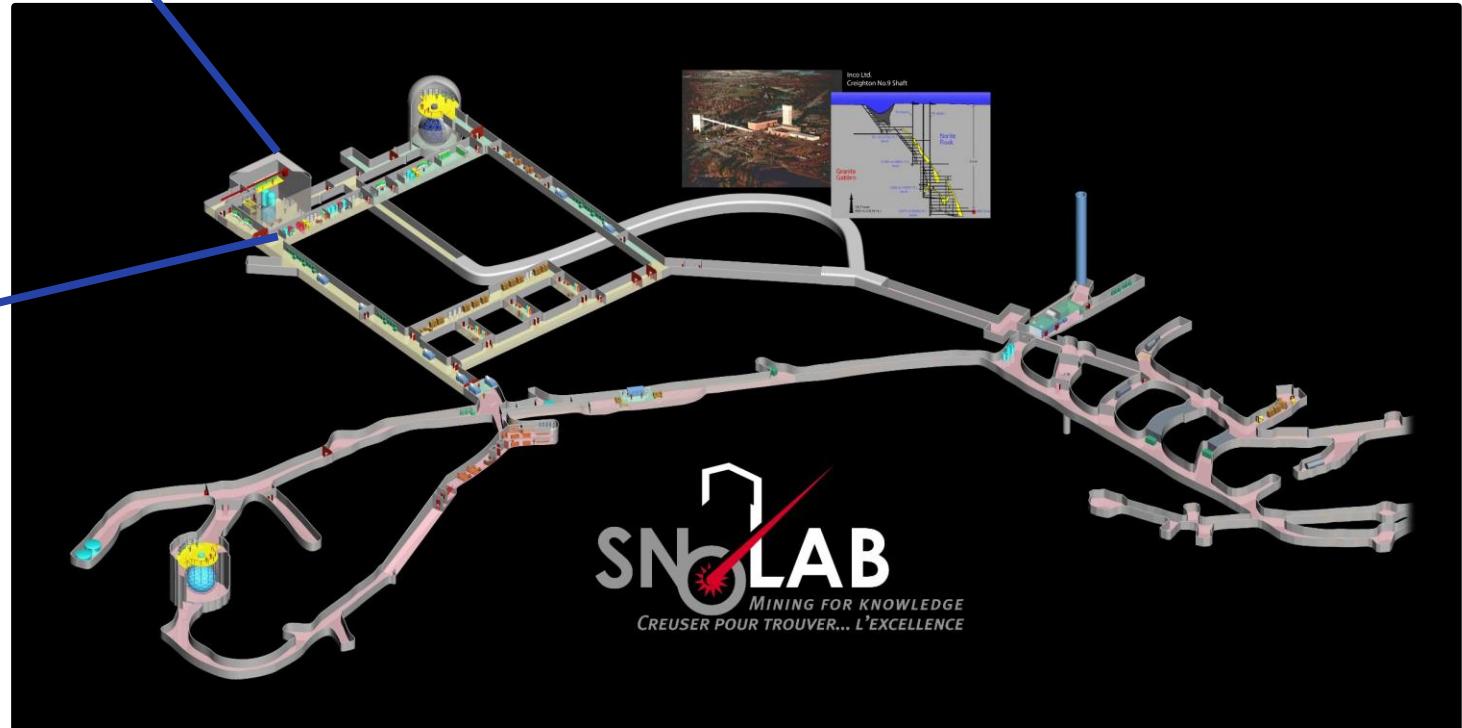




# DEAP-3600 is located in the SNOLAB Cube Hall



3279 kg of single phase liquid argon  
for a sensitive high-mass WIMP search.



**SNOLAB**  
MINING FOR KNOWLEDGE  
CREUSER POUR TROUVER... L'EXCELLENCE



# 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)

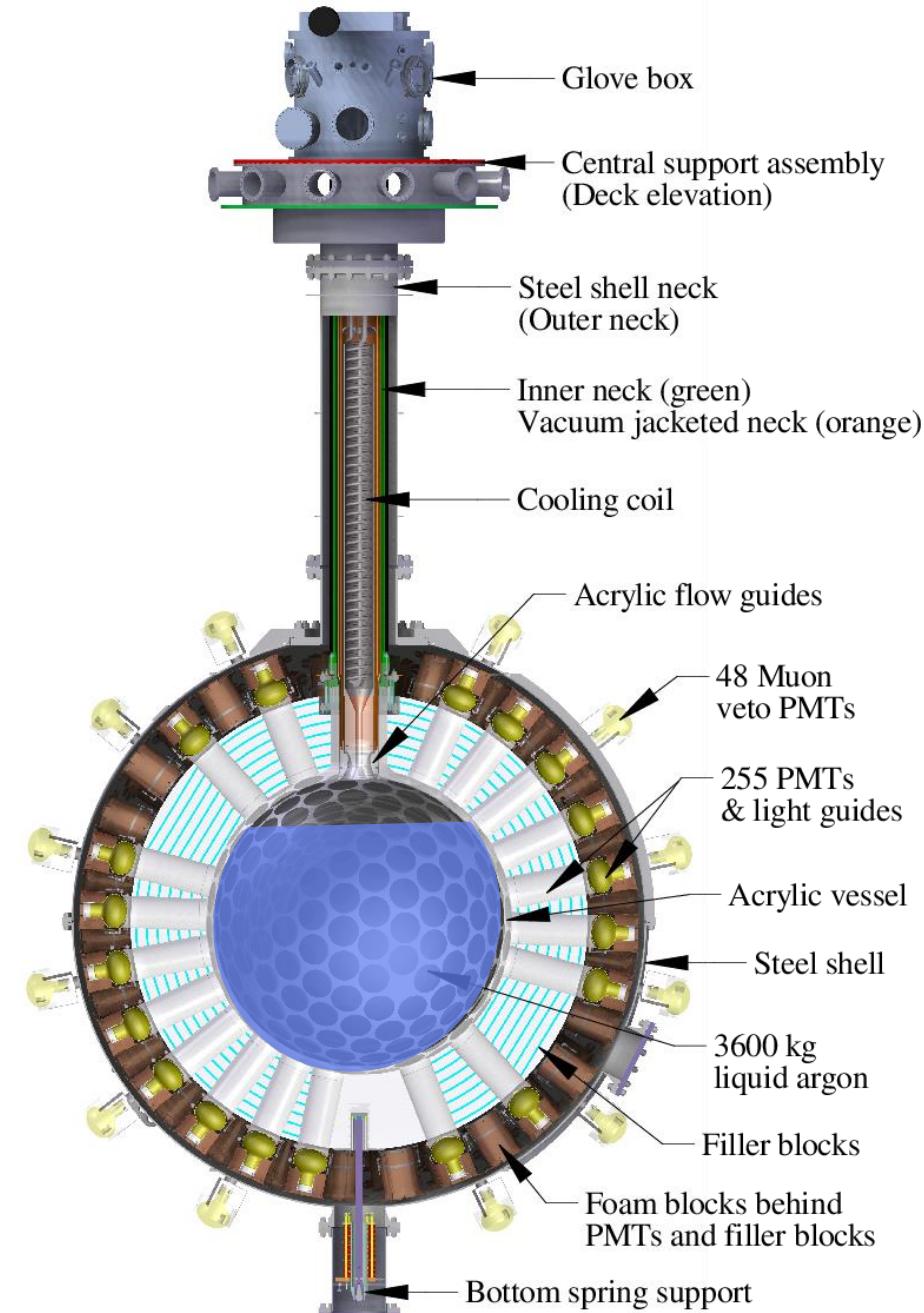
arxiv.org: 1902.04048

this talk

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

arxiv.org: 1905.05811

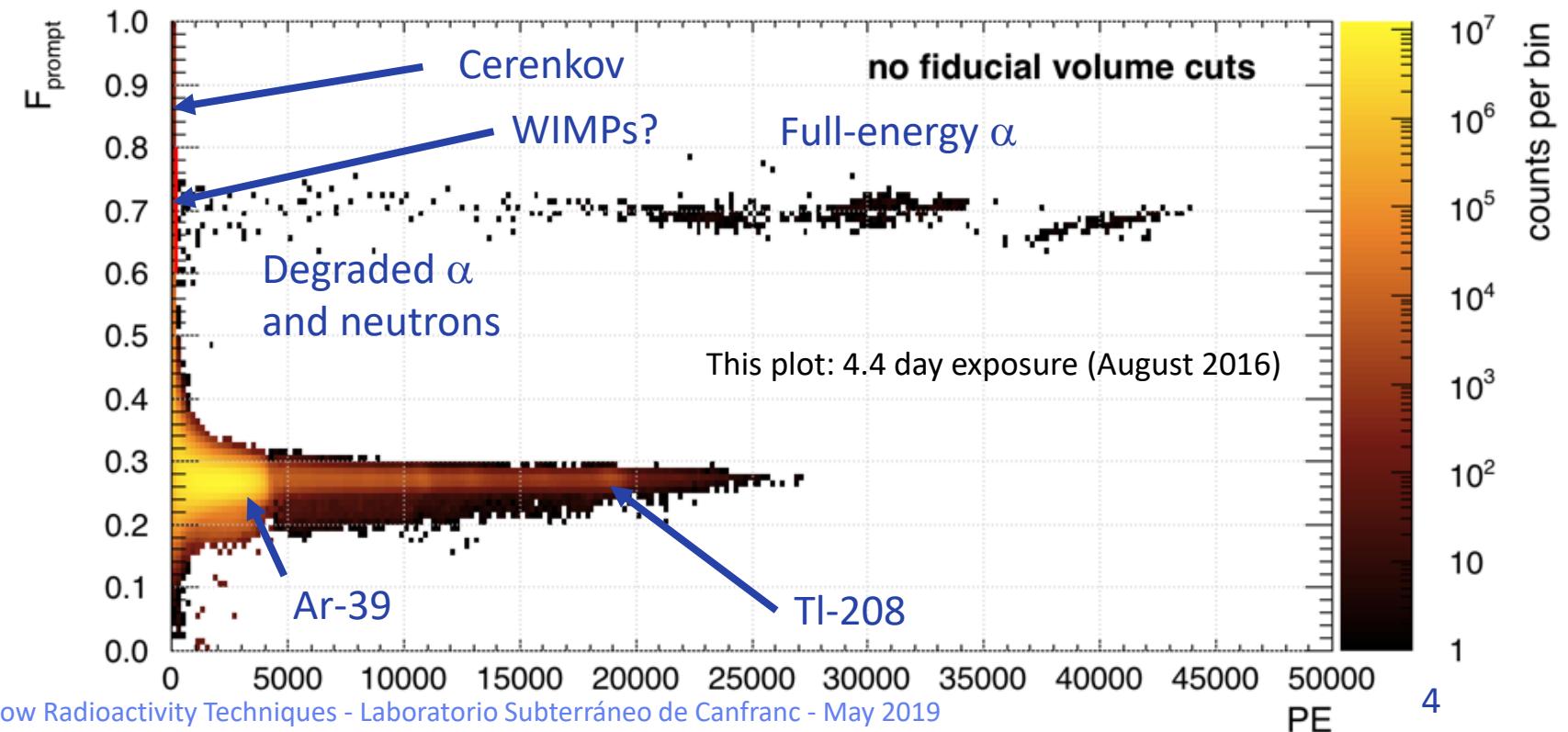
Björn Lehnert, this meeting



SOLID EDGE ACADEMIC COPY

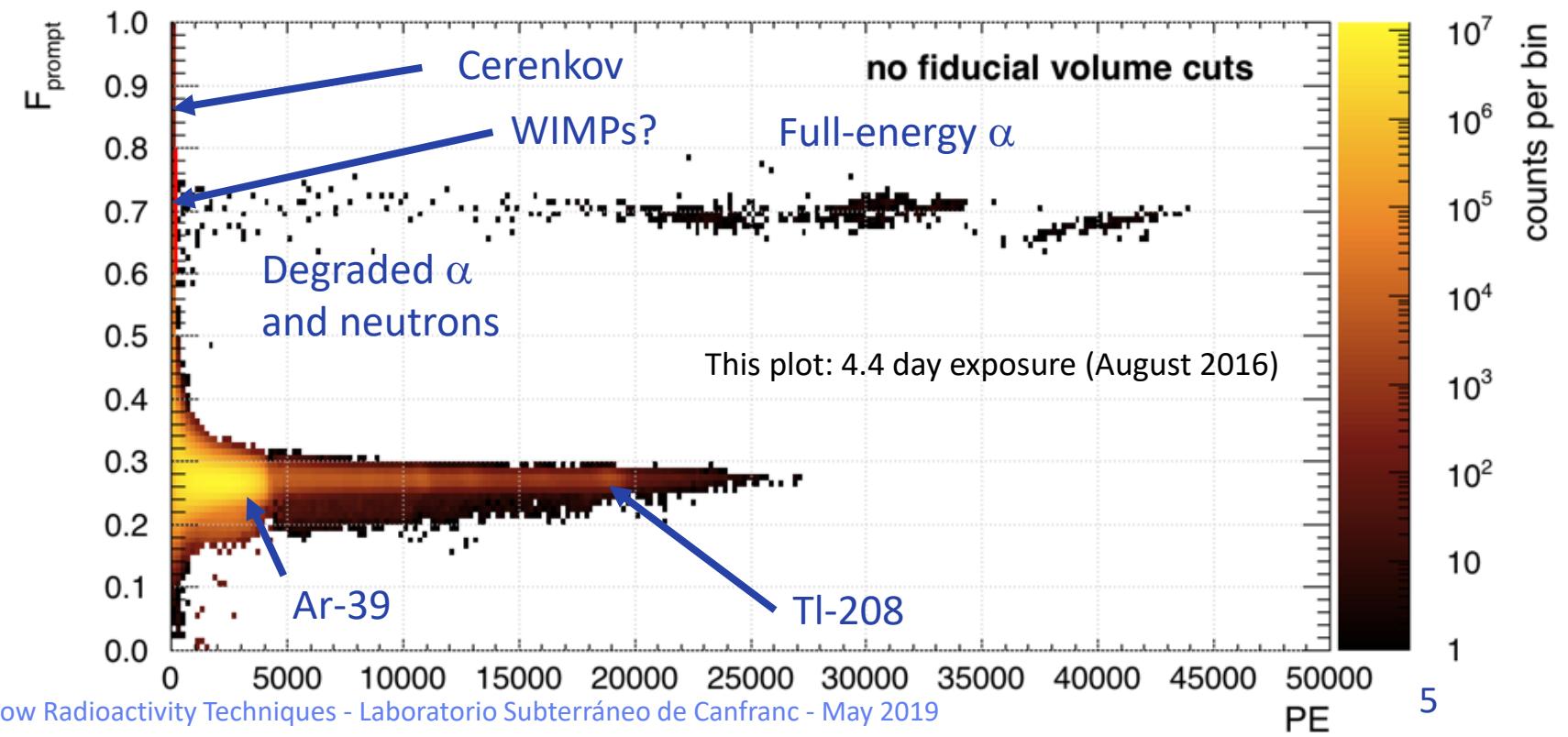
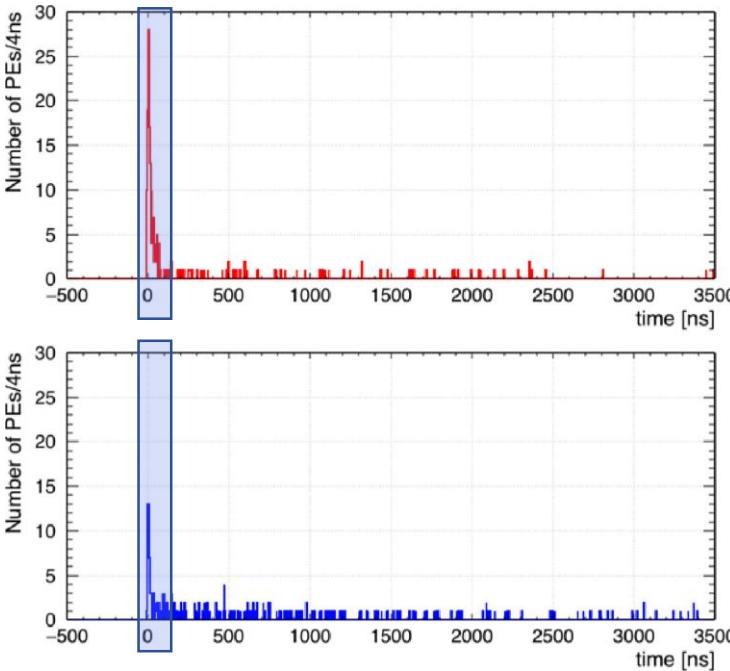


# Overview of data



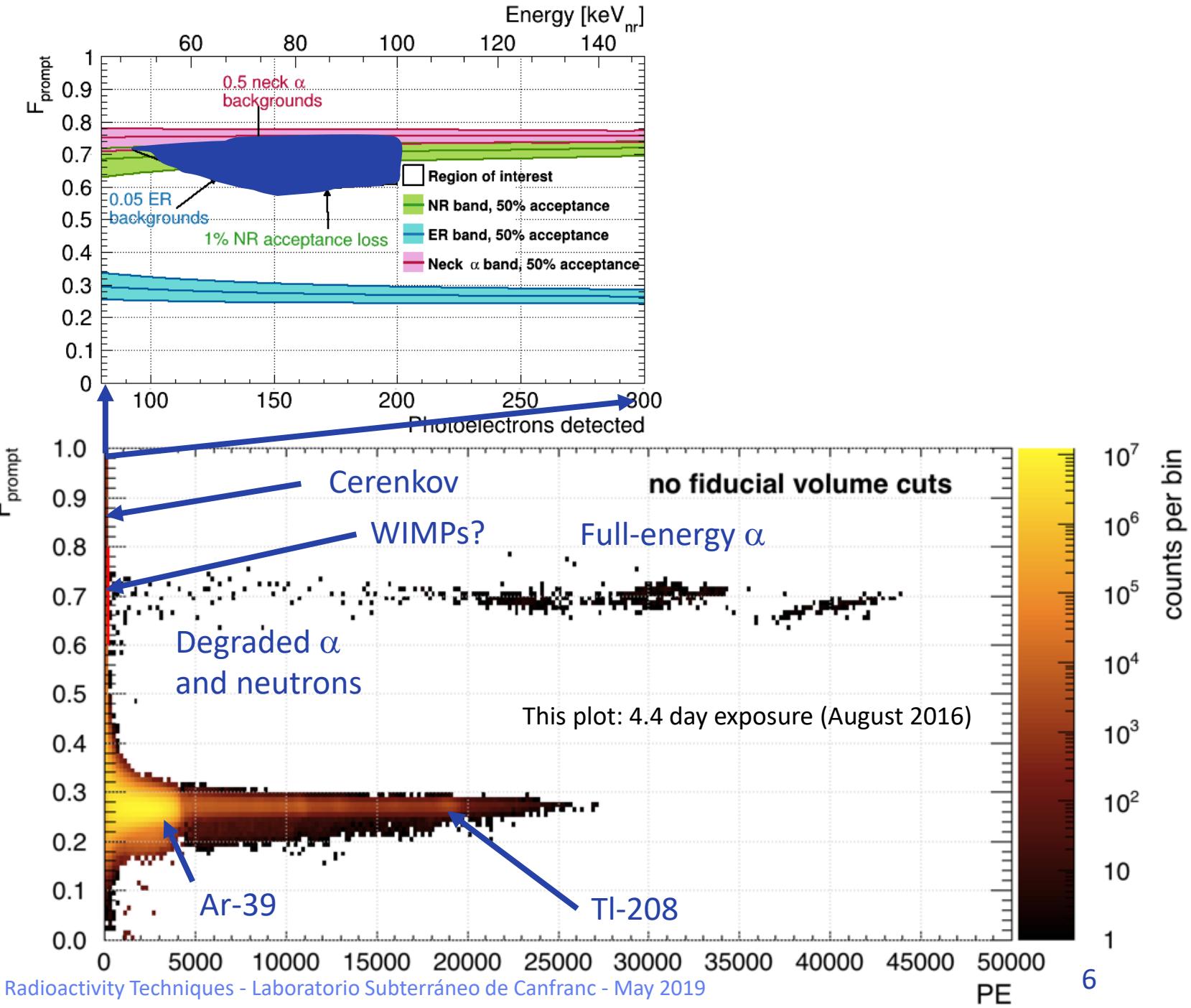
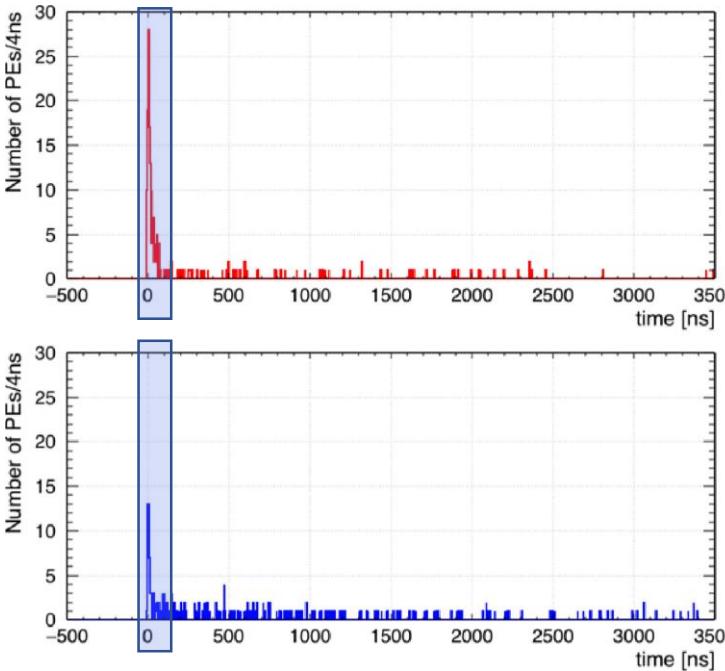


# Overview of data





# Overview of data





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

Alpha decays in the neck

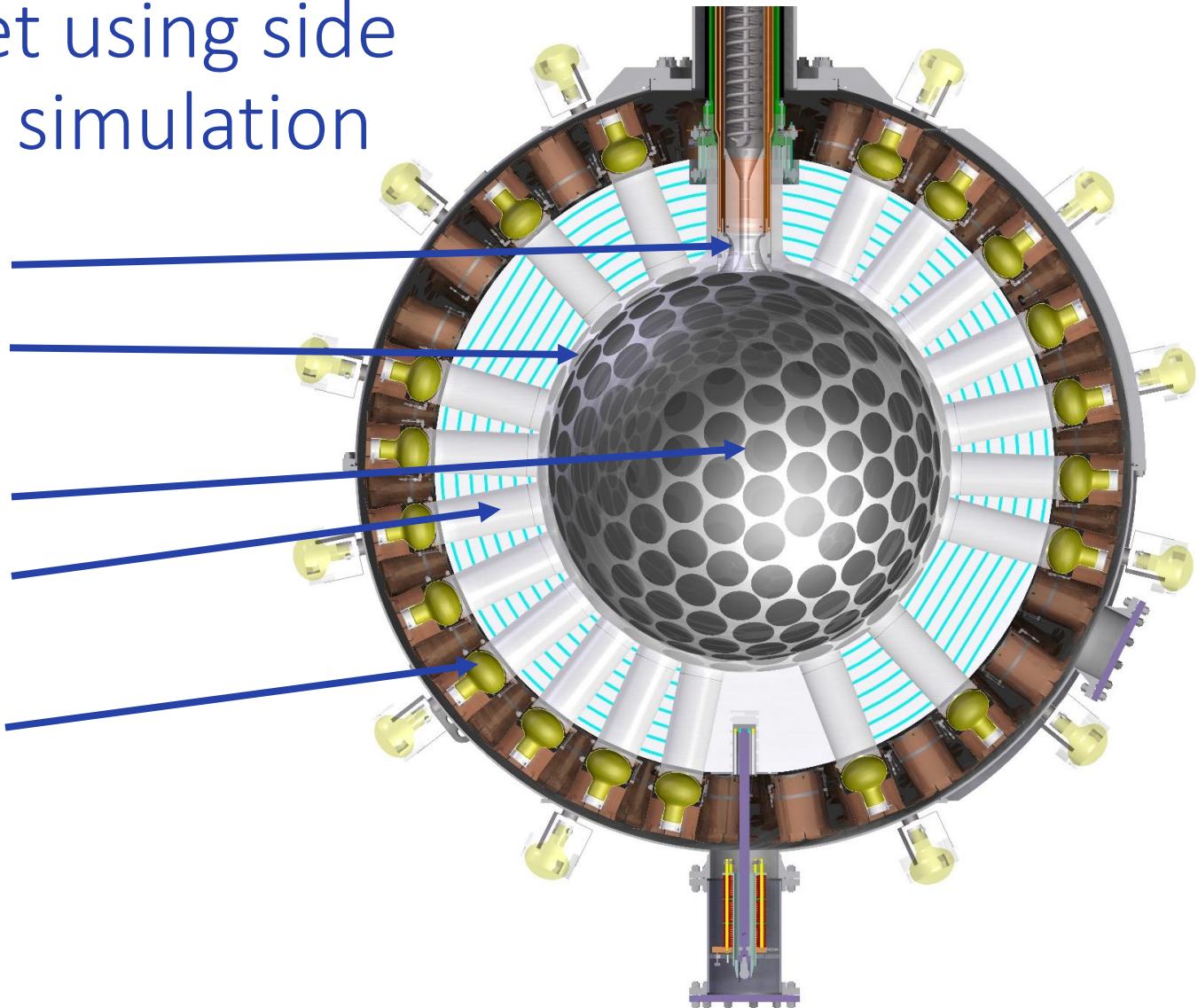
Alpha decays on the spherical surface

Ar-39 and PSD leakage

Cherenkov in acrylic

Radiogenic neutrons

Cosmogenic neutrons





Alpha decays in the neck

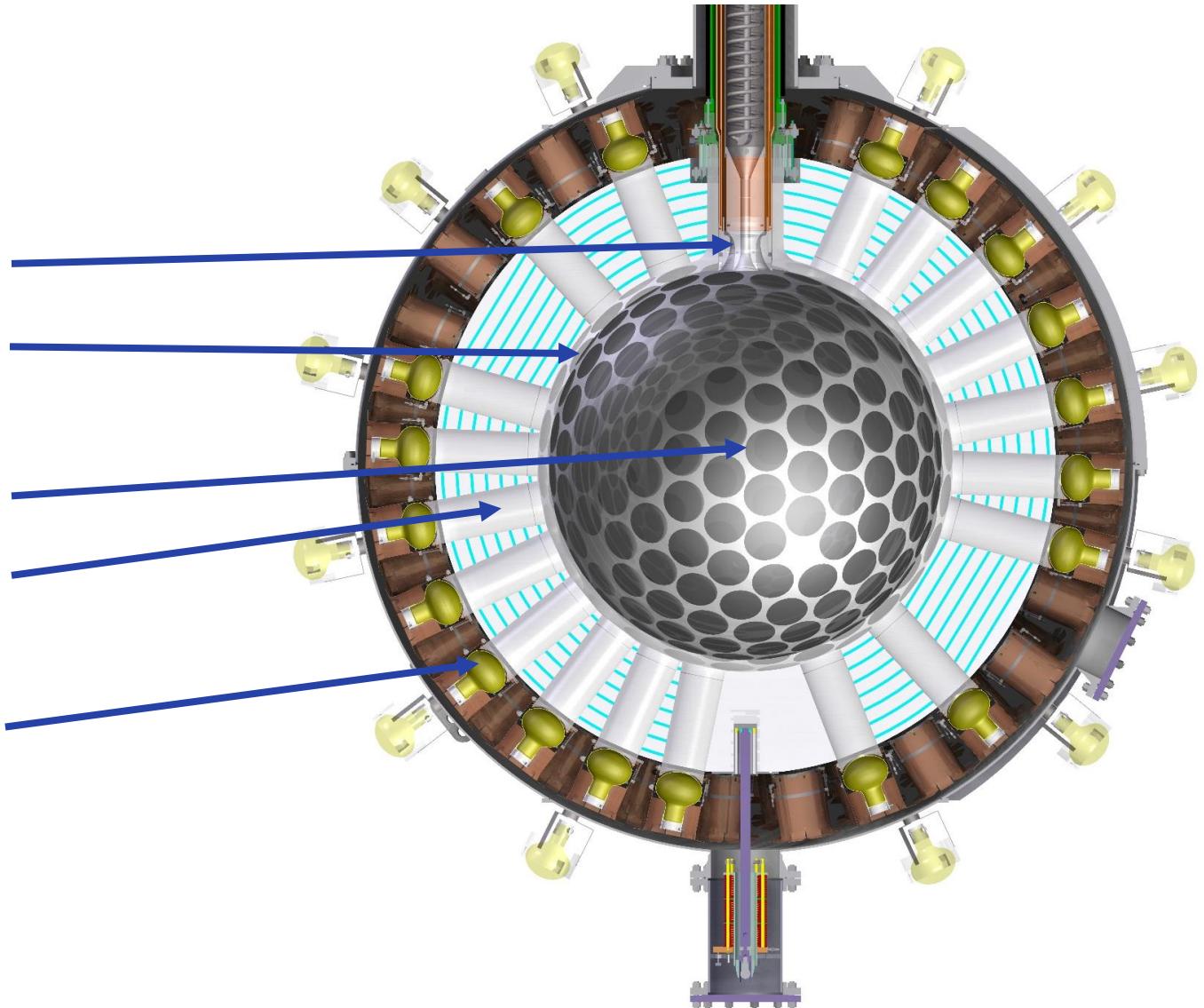
Alpha decays on the spherical surface

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Cherenkov in acrylic

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Cosmogenic neutrons



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

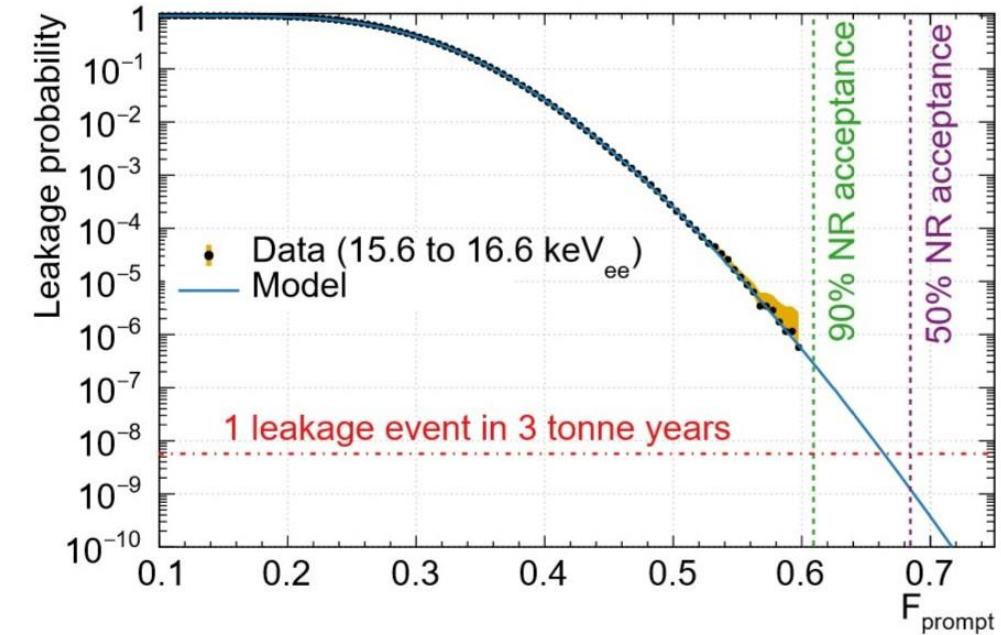
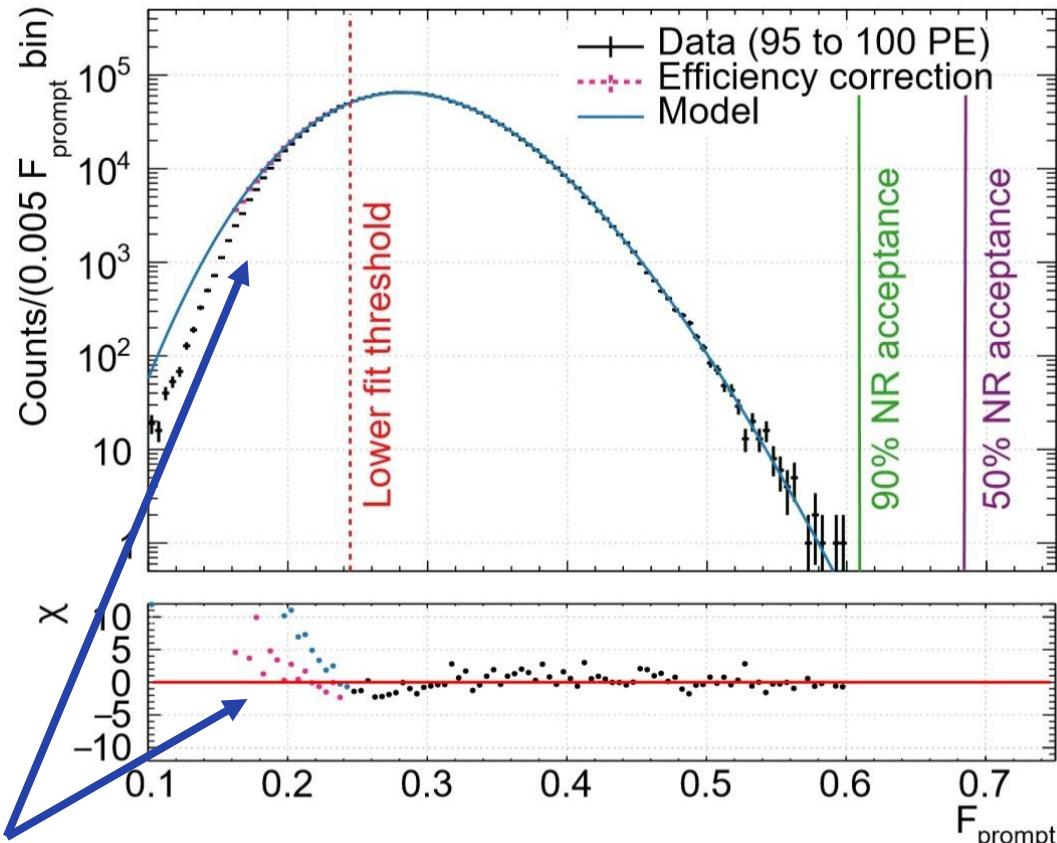
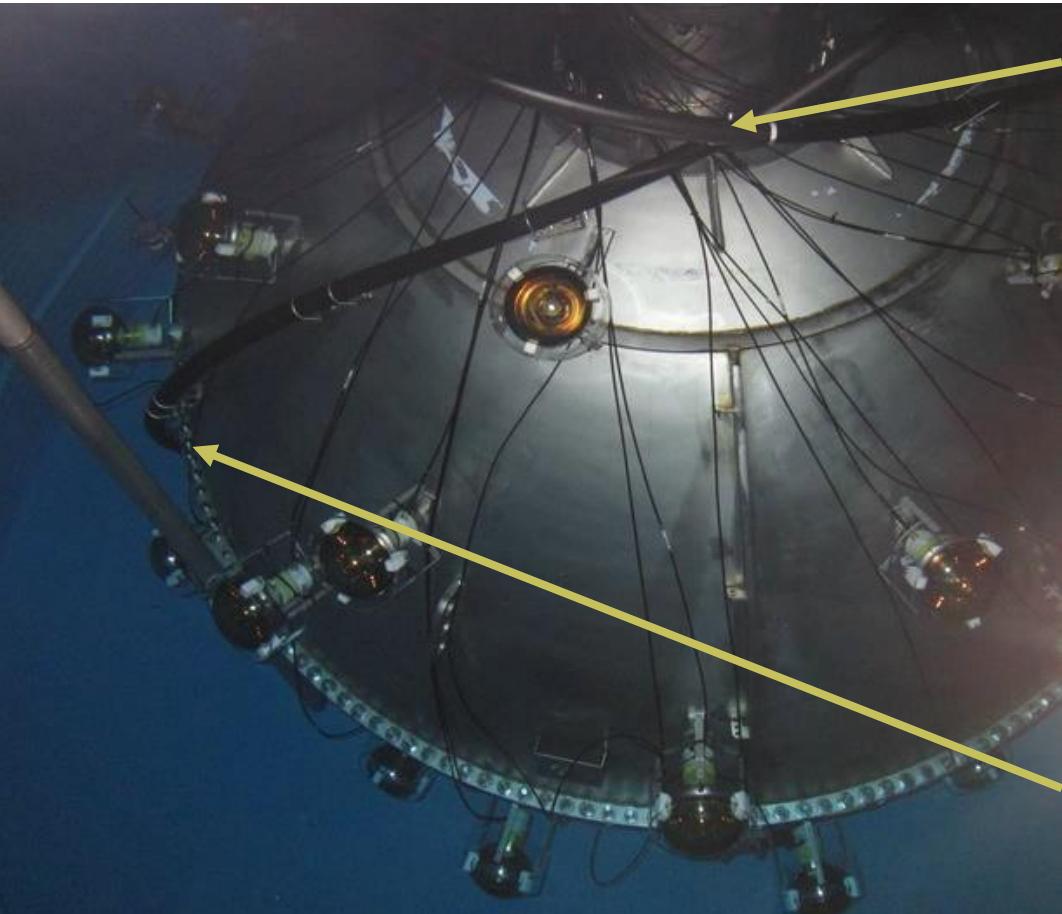


FIG. 13. Probability of an ER being detected above a given  $F_{\text{prompt}}$  value in the lowest  $1 \text{ keV}_{\text{ee}}$  bin in the WIMP-search region of interest. For comparison, vertical lines show the values above which 90% or 50% of nuclear recoils are expected to be found.



# Cerenkov light characterized with external 2.6 MeV $\gamma$ -rays

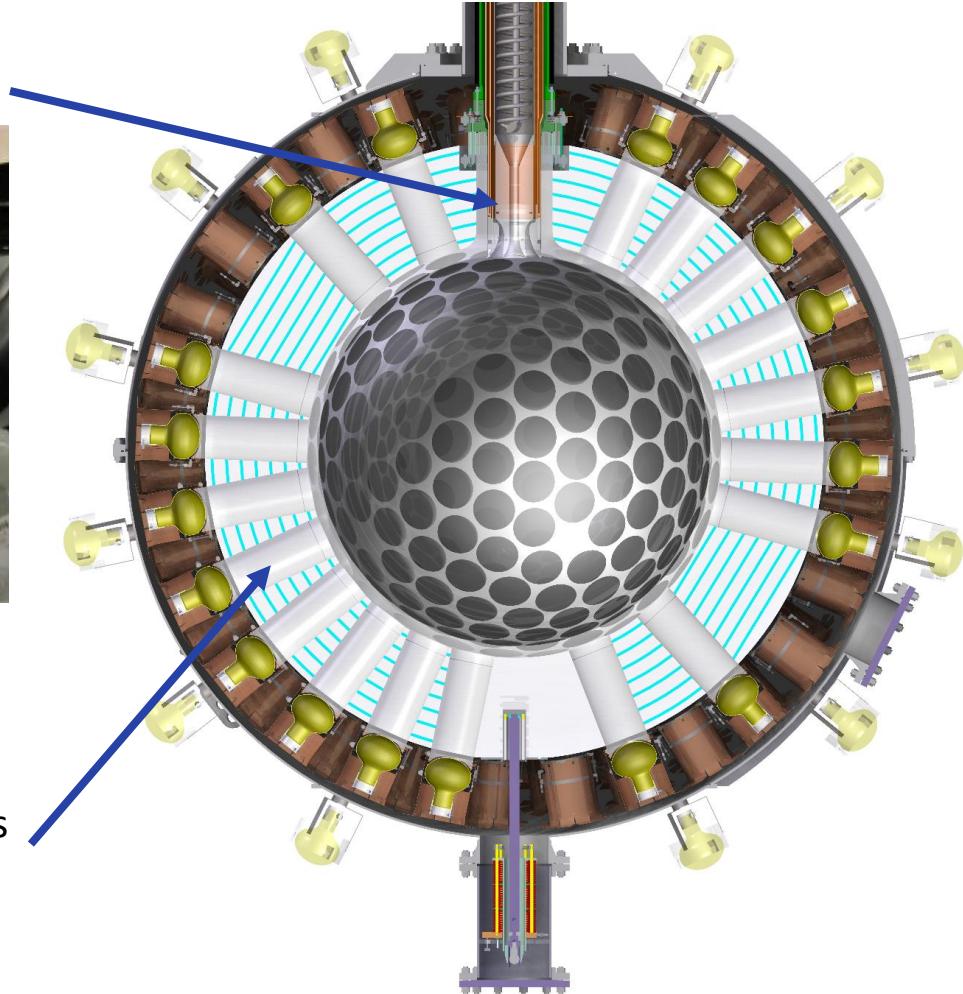
(Note: UVA acrylic used to reduce Cherenkov light.)



Cherenkov in neck acrylic  
vetoed with fibres.

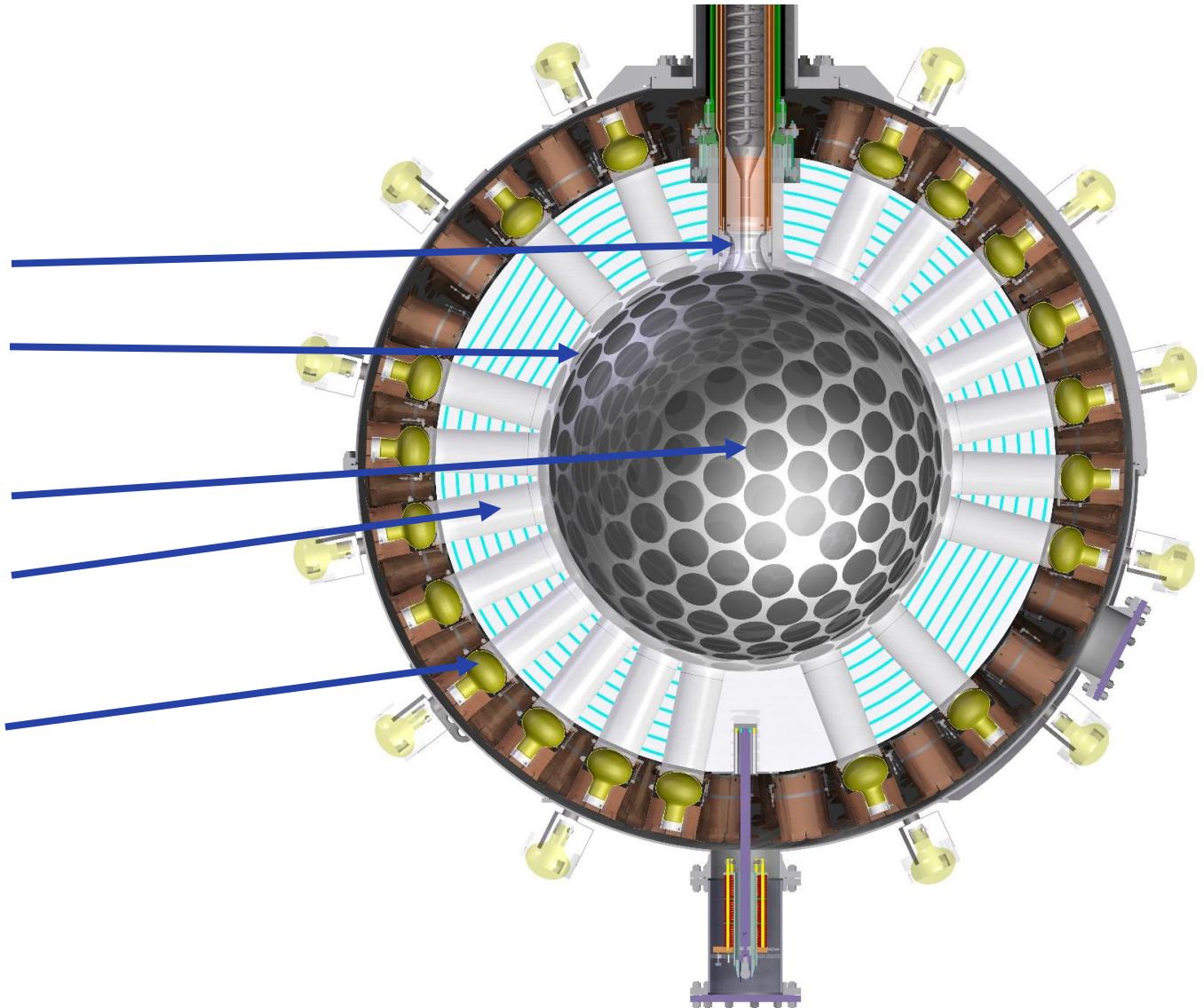


Cherenkov in light guides  
gives large signal  
in single PMT.





- Alpha decays in the neck
- Alpha decays on the spherical surface
- Ar-39 and PSD leakage
- Cherenkov in acrylic
- Radiogenic neutrons
- Cosmogenic neutrons





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

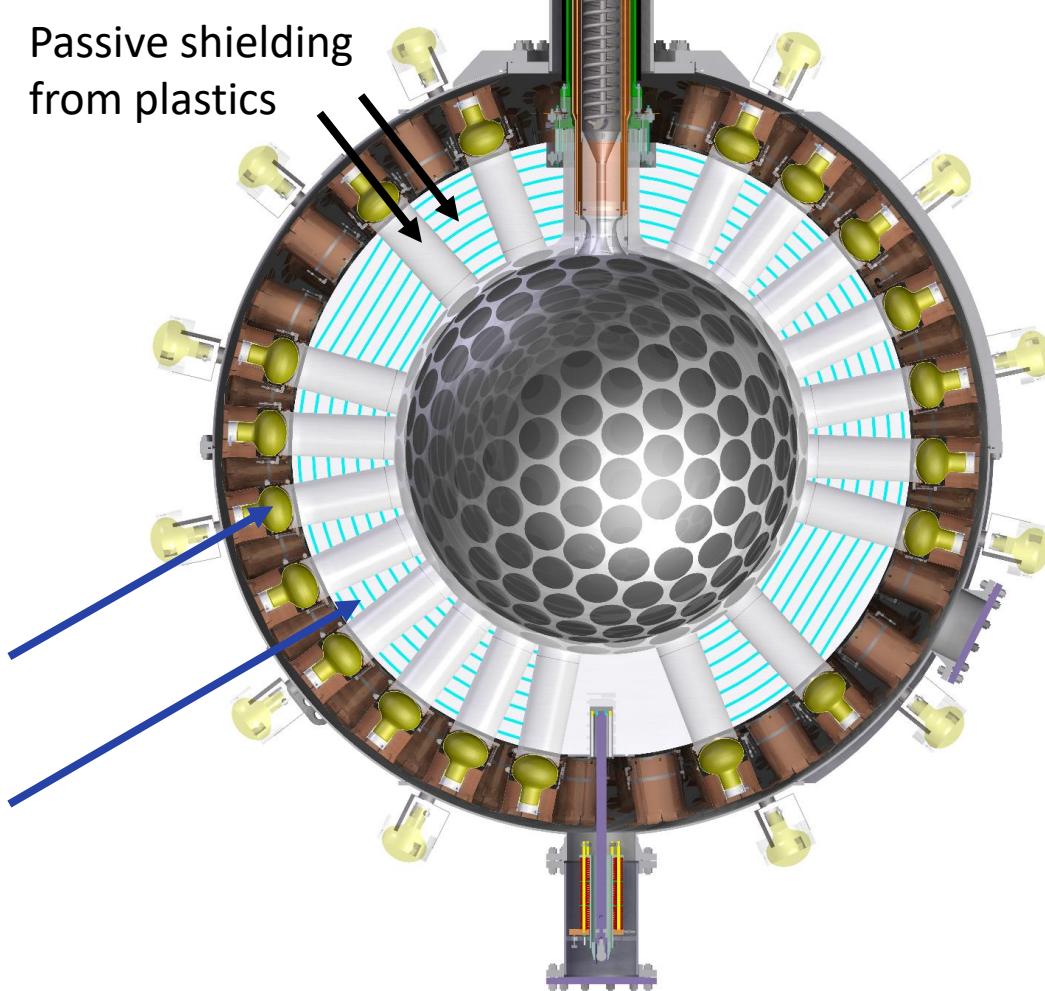
Low-level cuts  
95 – 5000 PE  
 $0.6 < F_{\text{prompt}} < 0.8$   
Event radius < 800 mm

WIMP Search cuts

Component	CR prediction	
	(SOURCES-4C)	(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	$0.038^{+0.022}_{-0.032}$	$0.060^{+0.036}_{-0.049}$
<b>Total</b>	$10.6^{+8.3}_{-7.1}$	$13.6^{+9.4}_{-7.8}$

Component	ROI prediction	
	(SOURCES-4C)	(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
<b>Total</b>	$0.060^{+0.104}_{-0.045}$	$0.073^{+0.119}_{-0.048}$





Delayed coincidence between nuclear recoil and  $\gamma$ -ray provides data-driven verification

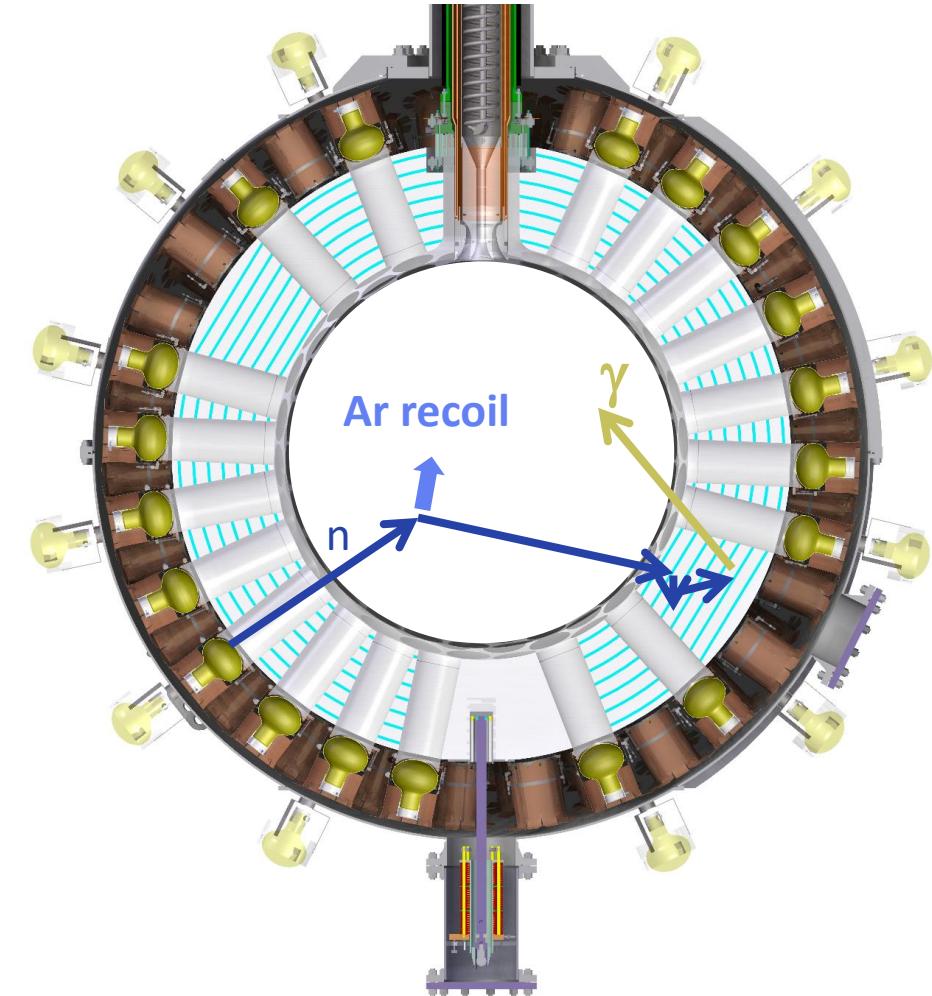
### AmBe calibration

For neutrons which enter liquid argon,  
and  
scatter to produce NR event

$22.5 \pm 0.5\%$

will capture (mostly on Ar-40 or H)  
and  
produce  $\gamma(s)$  that deposit energy in the LAr

Agrees with simulation





# Delayed coincidence between nuclear recoil and $\gamma$ -ray provides data-driven verification

7 such events in data in control region

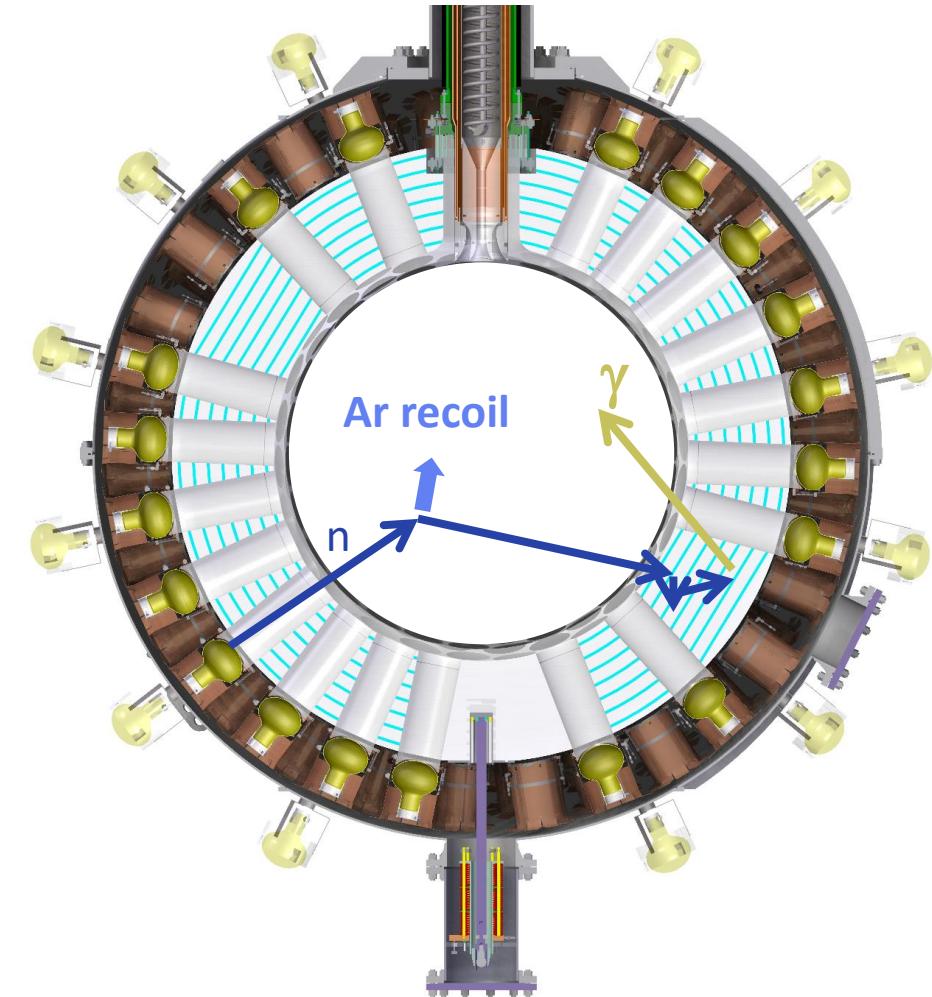
None in WIMP ROI; None have muon veto signal

$1.8 \pm 0.3$  expected from random coincidence

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

→ Expect  $6 \pm 4$  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:

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

PRD 80, 012001 (2009)

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

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

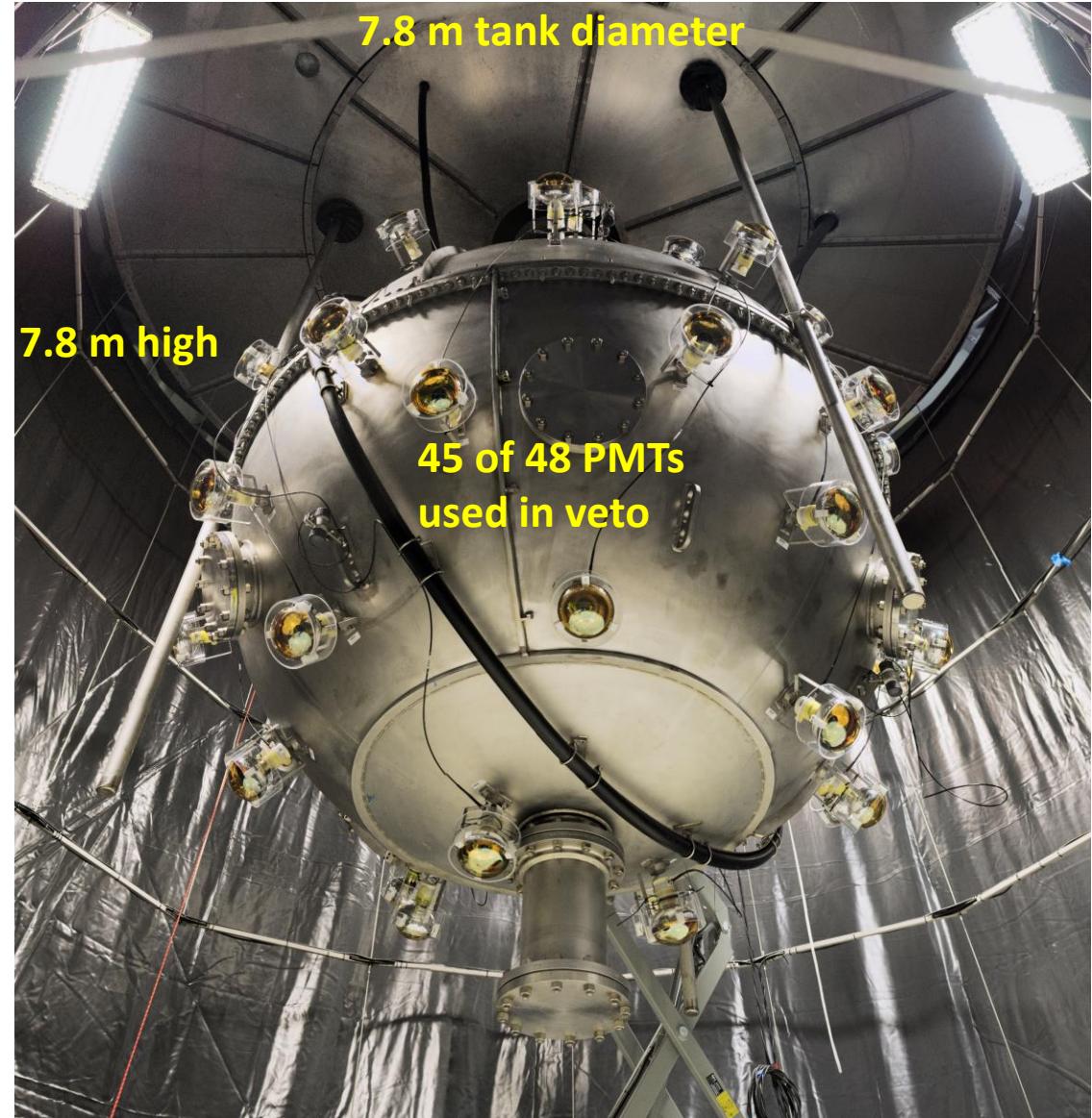
<0.2 events before WIMP cuts

<0.11 events in WIMP ROI

Impose muon veto cut

veto window  $[-0.1, 1]$  s about tag

Live time reduced by 0.16%





Alpha decays in the neck

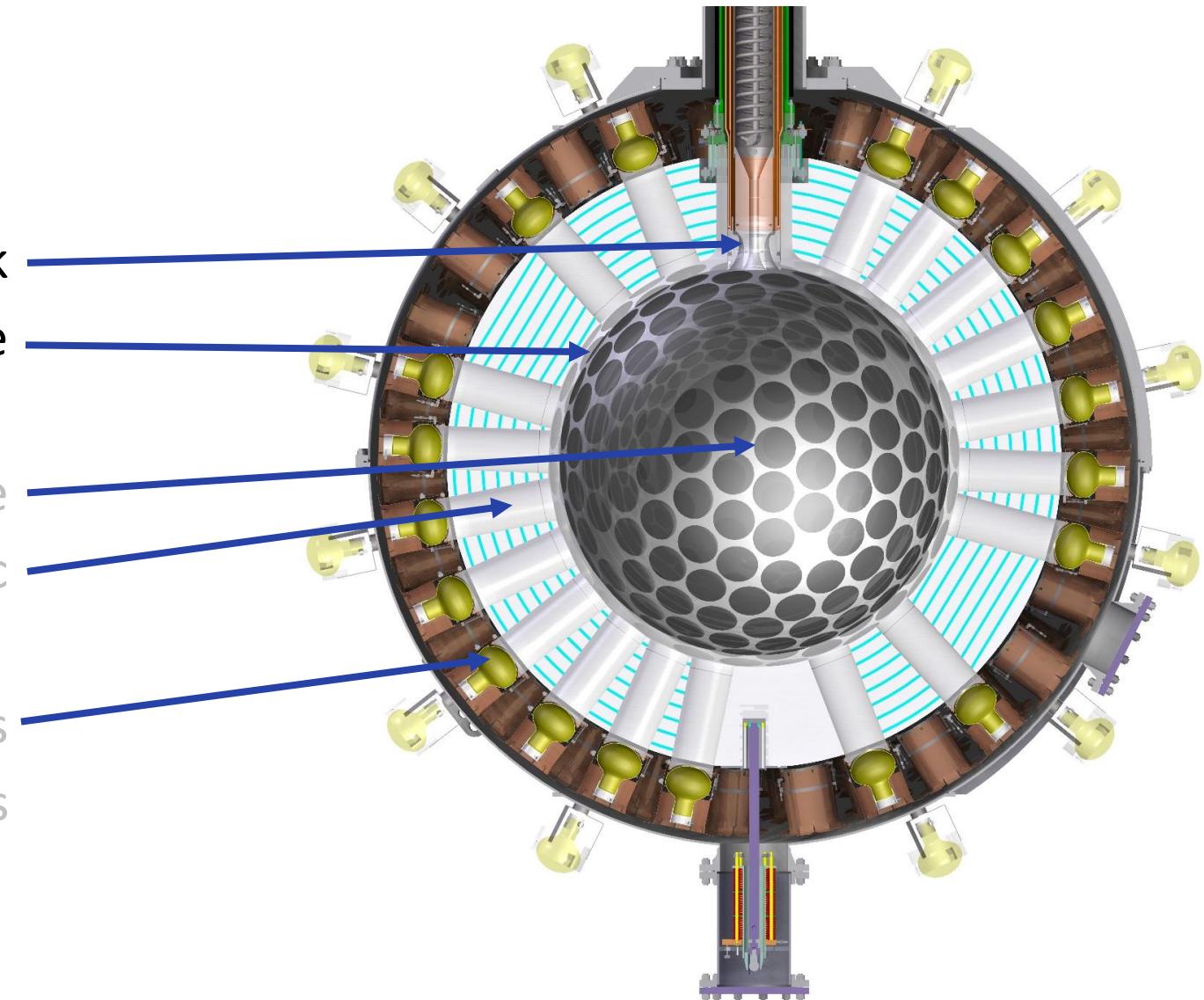
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Ar-39 and PSD leakage

Cherenkov in acrylic

Radiogenic neutrons

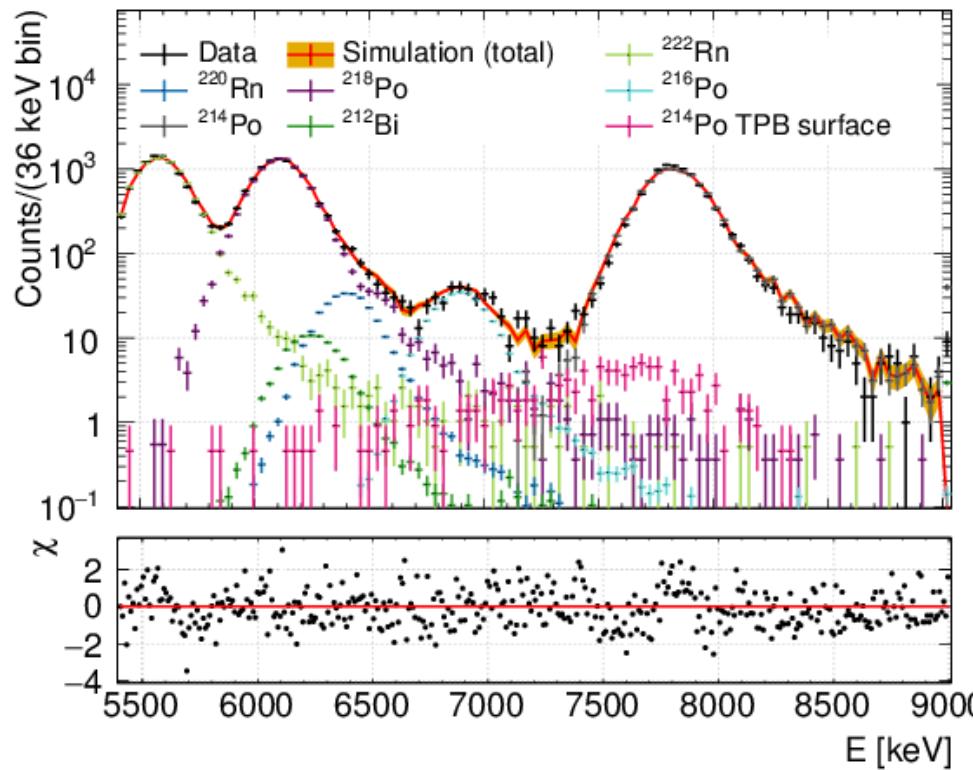
Cosmogenic neutrons



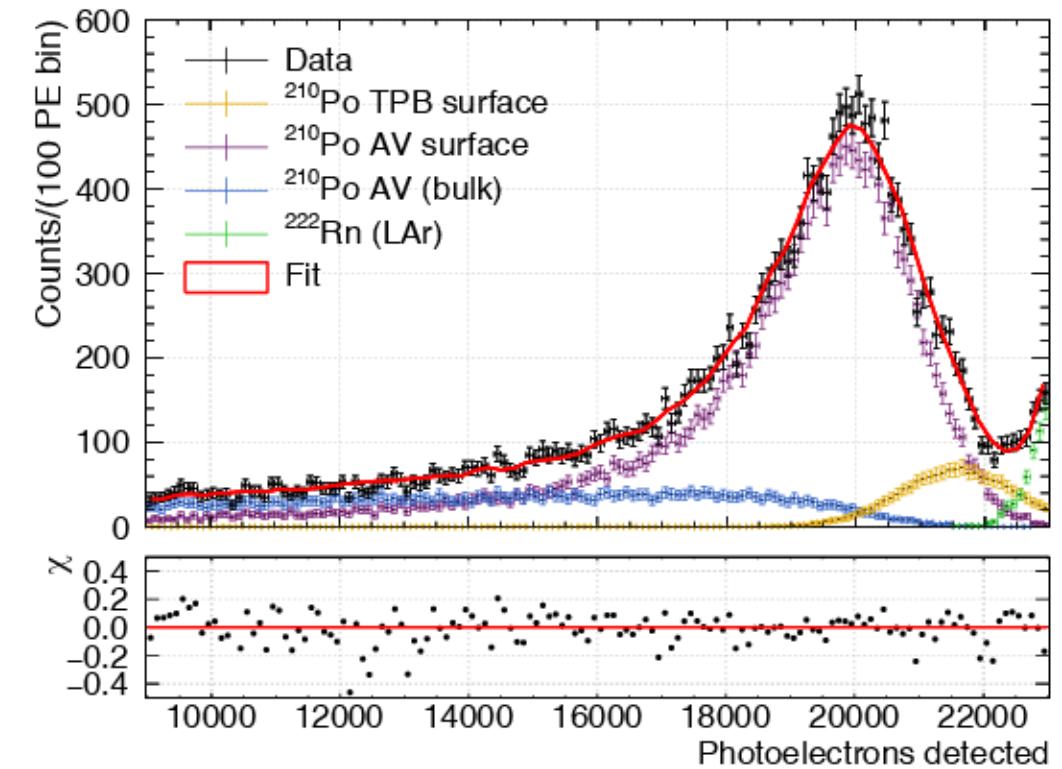


# $\alpha$ rates are well understood

$\alpha$  in the liquid argon



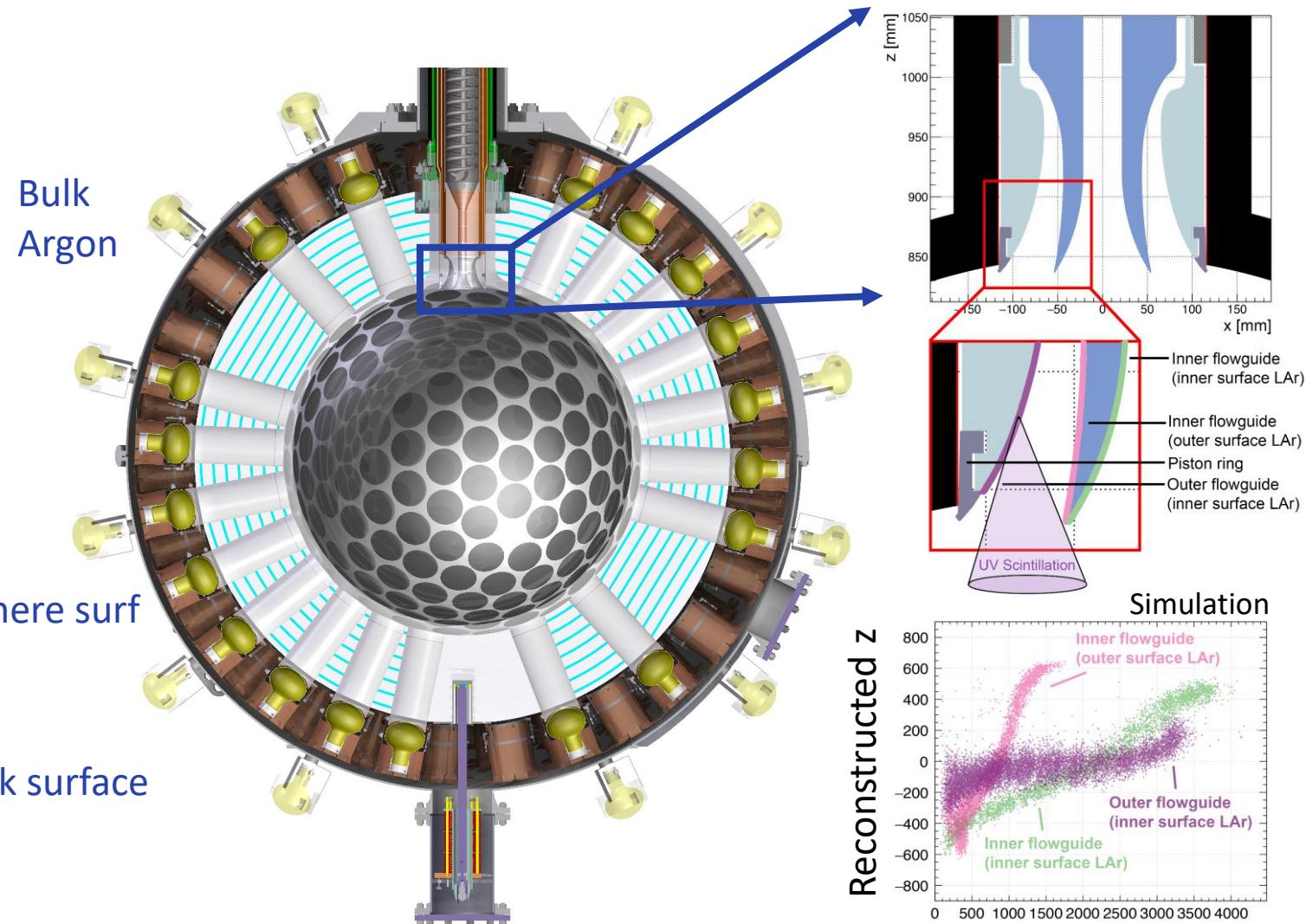
$\alpha$  on the acrylic/TPB surfaces





# $\alpha$ rates are well understood

Component	Activity / Rate
$^{222}\text{Rn}$ LAr	$(0.153 \pm 0.005) \mu\text{Bq}/\text{kg}$
$^{218}\text{Po}$ LAr	$(0.159 \pm 0.005) \mu\text{Bq}/\text{kg}$
$^{214}\text{Po}$ LAr	$(0.153 \pm 0.005) \mu\text{Bq}/\text{kg}$
$^{214}\text{Po}$ TPB surface	$< 5.0 \mu\text{Bq}/\text{m}^2$
$^{220}\text{Rn}$ LAr	$(4.3 \pm 1.0) \text{nBq}/\text{kg}$
$^{216}\text{Po}$ LAr	$(4.5 \pm 0.4) \text{nBq}/\text{kg}$
$^{212}\text{Bi}$ LAr	$< 5.6 \text{nBq}/\text{kg}$
$^{212}\text{Po}$ LAr	$(3.4 \pm 1.1) \text{nBq}/\text{kg}$
$^{210}\text{Po}$ TPB & AV surface	$(0.26 \pm 0.02) \text{mBq}/\text{m}^2$
$^{210}\text{Po}$ AV (bulk)	$(2.82 \pm 0.05) \text{mBq}$
$^{210}\text{Po}$ inner FG, IS	$(14.1 \pm 1.3) \mu\text{Hz}$
$^{210}\text{Po}$ inner FG, OS	$(16.8 \pm 1.4) \mu\text{Hz}$
$^{210}\text{Po}$ outer FG, IS	$(22.7 \pm 1.6) \mu\text{Hz}$

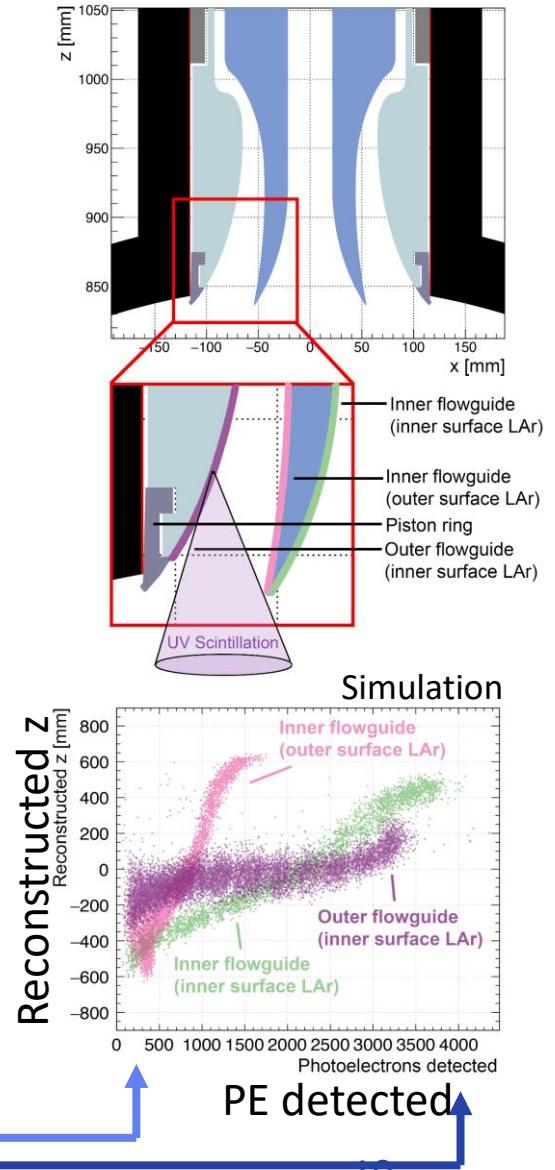
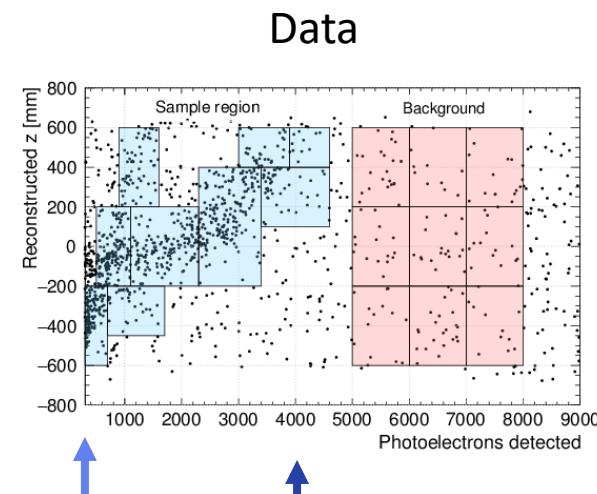
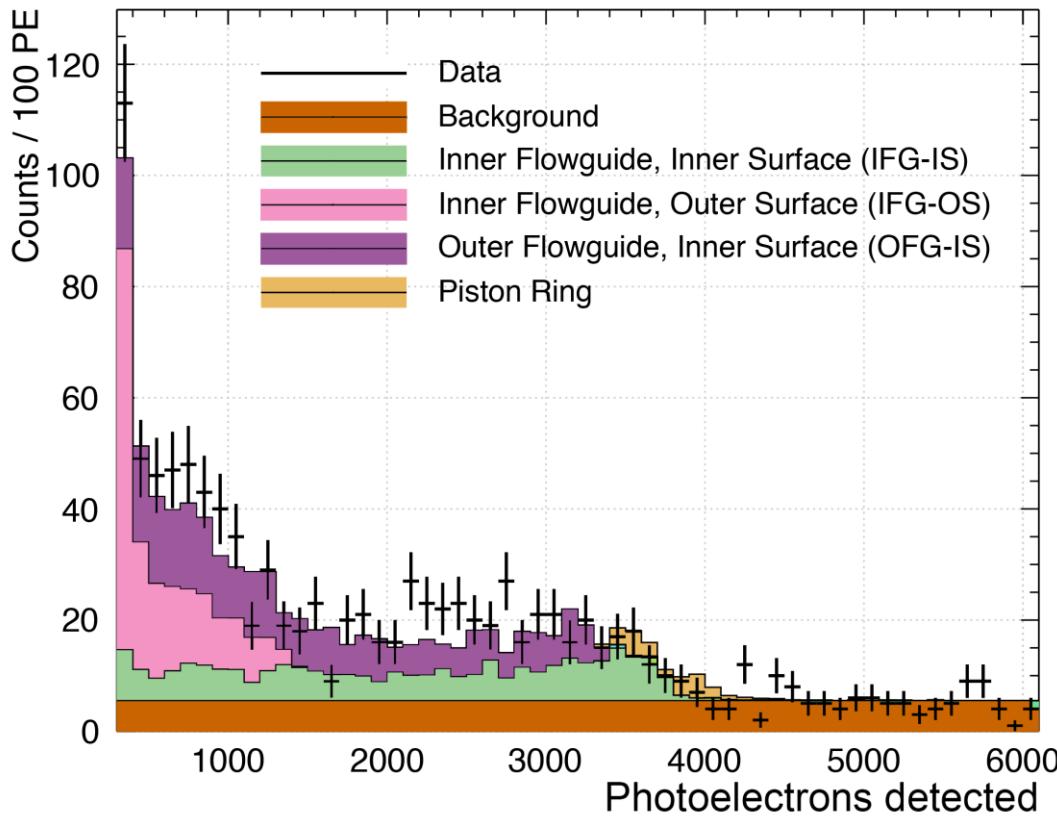




# Surface $\alpha$ in neck: largest background

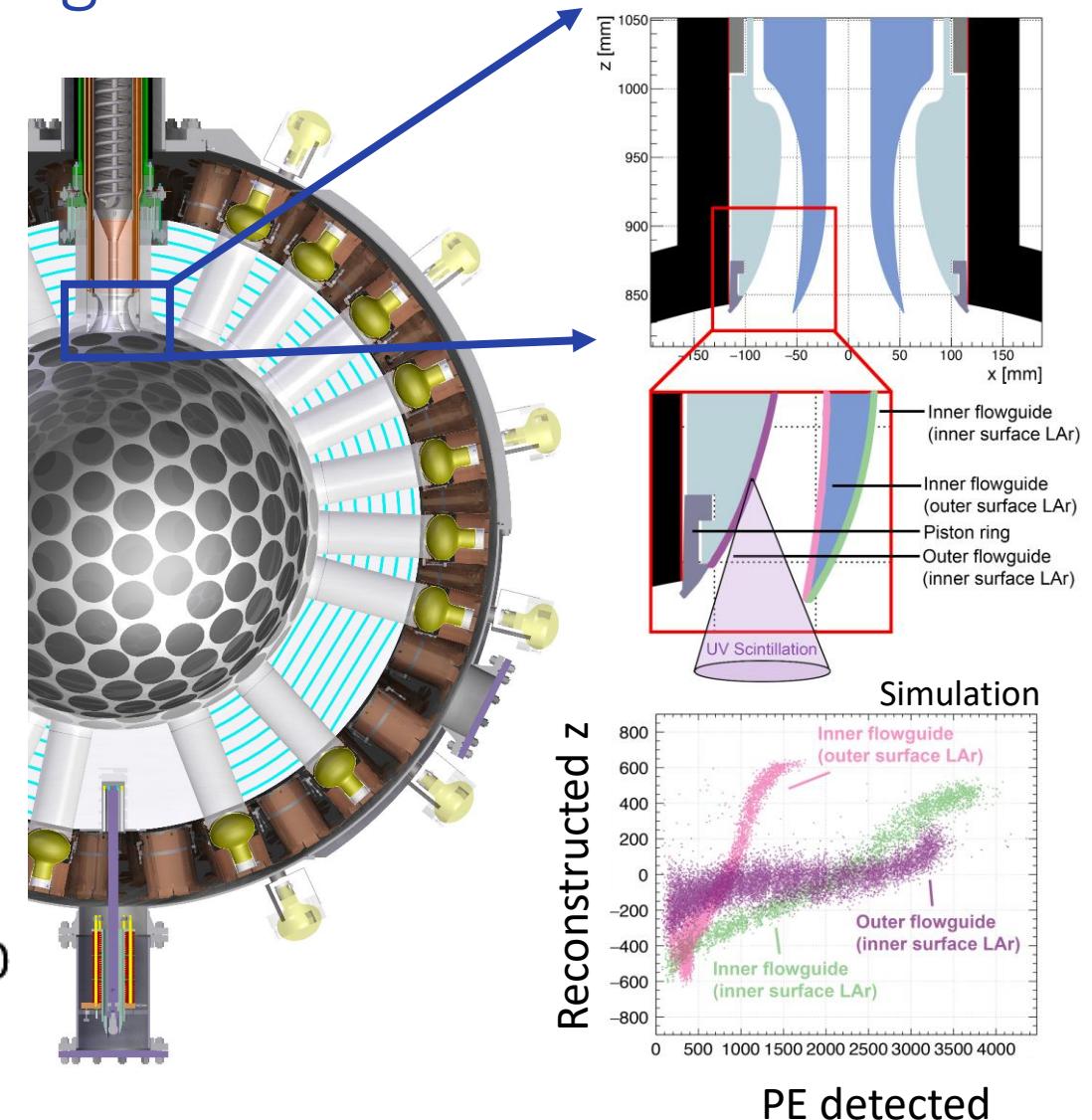
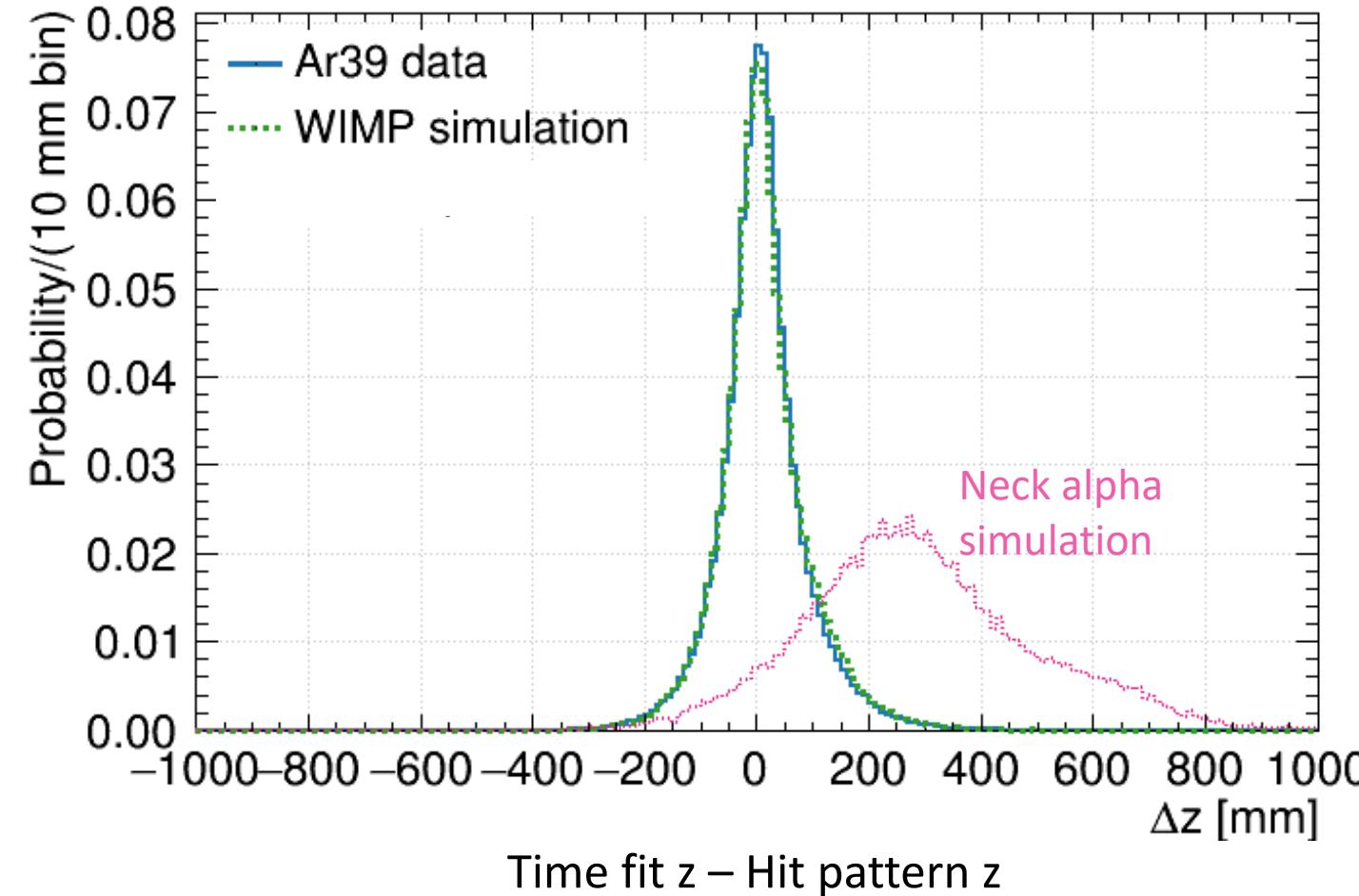
Thin film of LAr on acrylic in neck.

Small fraction of UV light from scintillation is visible.





Hit-pattern reconstruction puts neck  $\alpha$  events low in detector.  
Time reconstruction leaves events high.

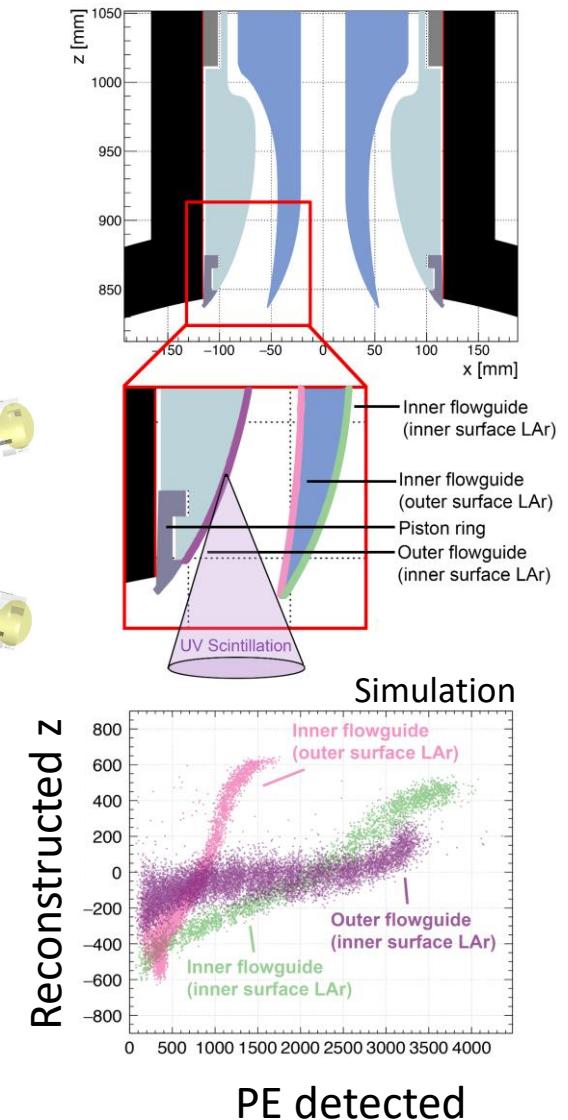
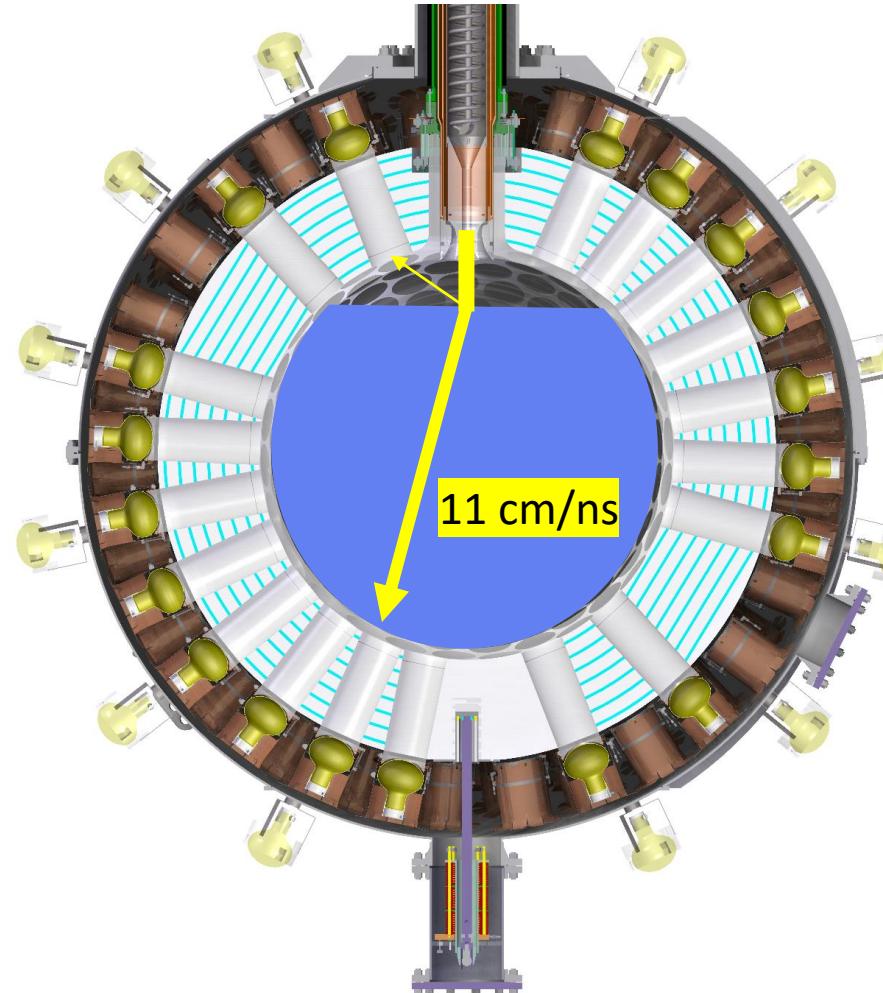




Handle 2: Some UV Light from neck events reflects at the acrylic surface giving an early signal to top PMTs.

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

However, it imposes a large  
reduction in WIMP acceptance.



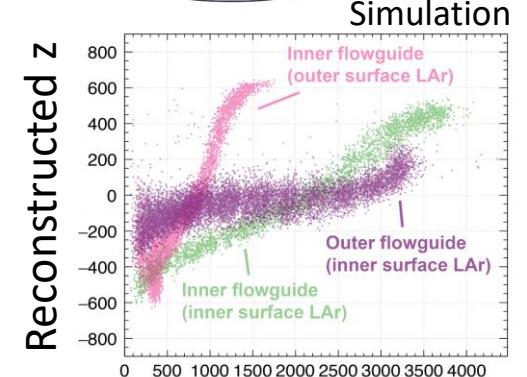
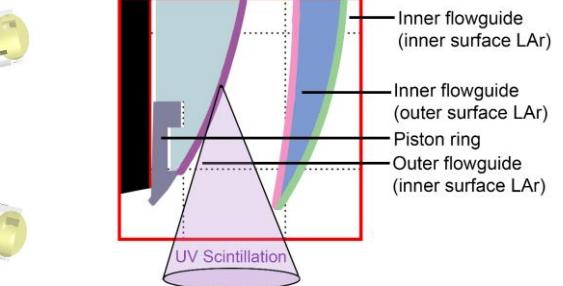
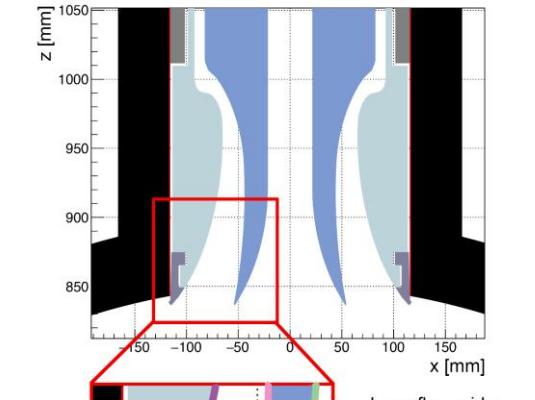
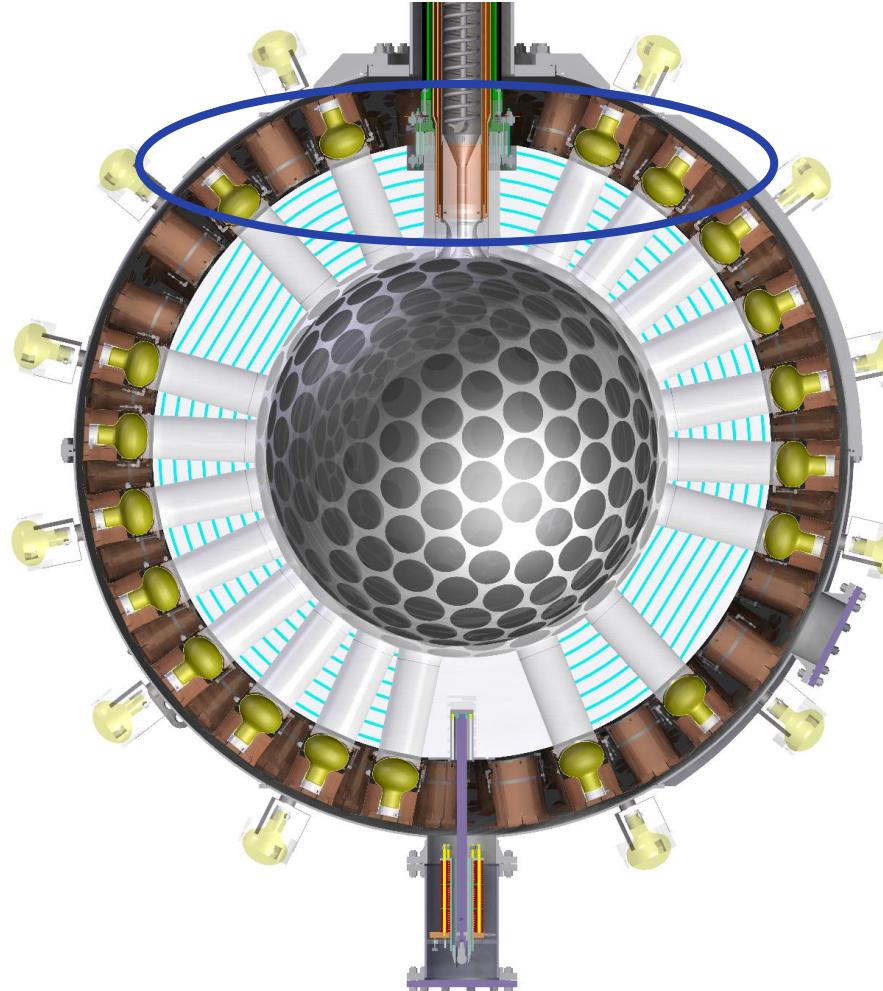
PE detected



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

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

However, it imposes a modest reduction in WIMP acceptance.



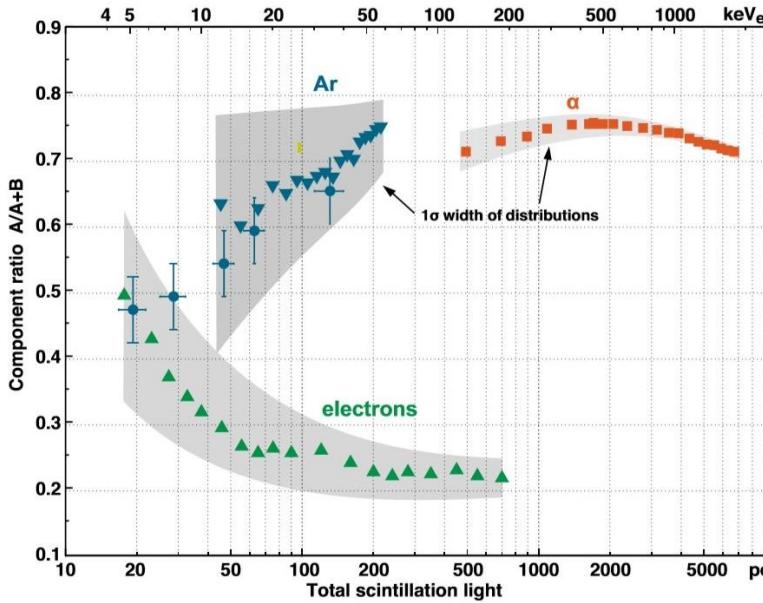
PE detected



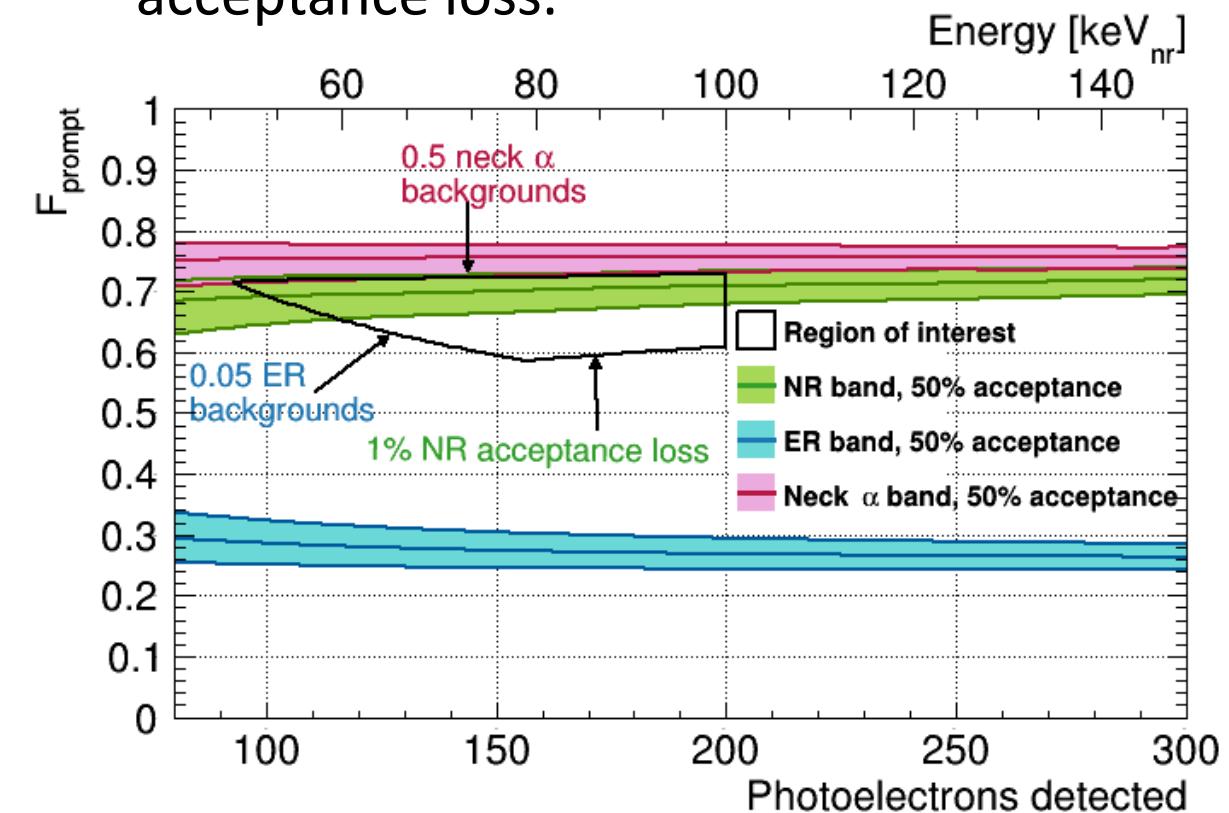
# Handle 4: Neck $\alpha$ events are high-E events with reduced light yield from geometry.

Regenfus et al have noted that high-E  $\alpha$  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  $\alpha$  events in DEAP-3600, set high-Fprompt edge of our acceptance to allow 0.5 neck  $\alpha$  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  $\alpha$ -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 $\alpha$ -decay rejection [%]		
	IFG-IS	IFG-OS	OFG-IS
Upper F <sub>prompt</sub> 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
<b>Combined</b>	<b>99</b>	<b>99</b>	<b>98</b>

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
$\alpha$ particle F <sub>prompt</sub>	+83 -50	+58 -42	+80 -47
Reconstructed radius	+0 -75	+0 -31	+0 -26
LAr film thickness	+104 -0	+0 -49	+0 -66
<b>Combined</b>	<b>+170 -110</b>	<b>+69 -83</b>	<b>+85 -80</b>



# Aside

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

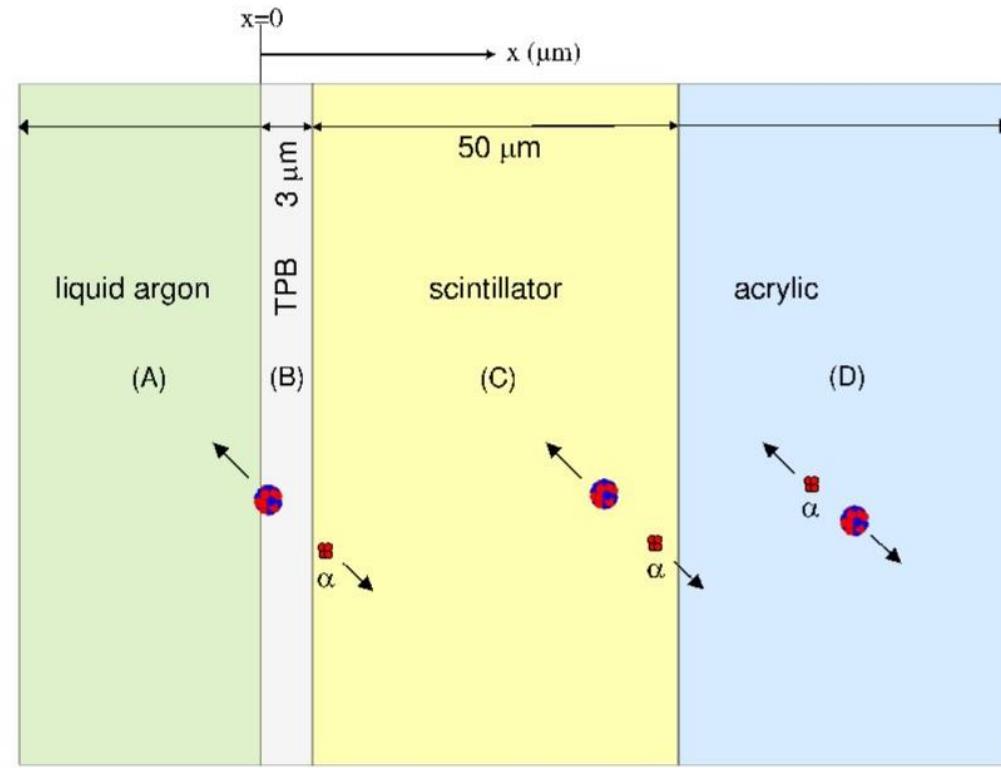
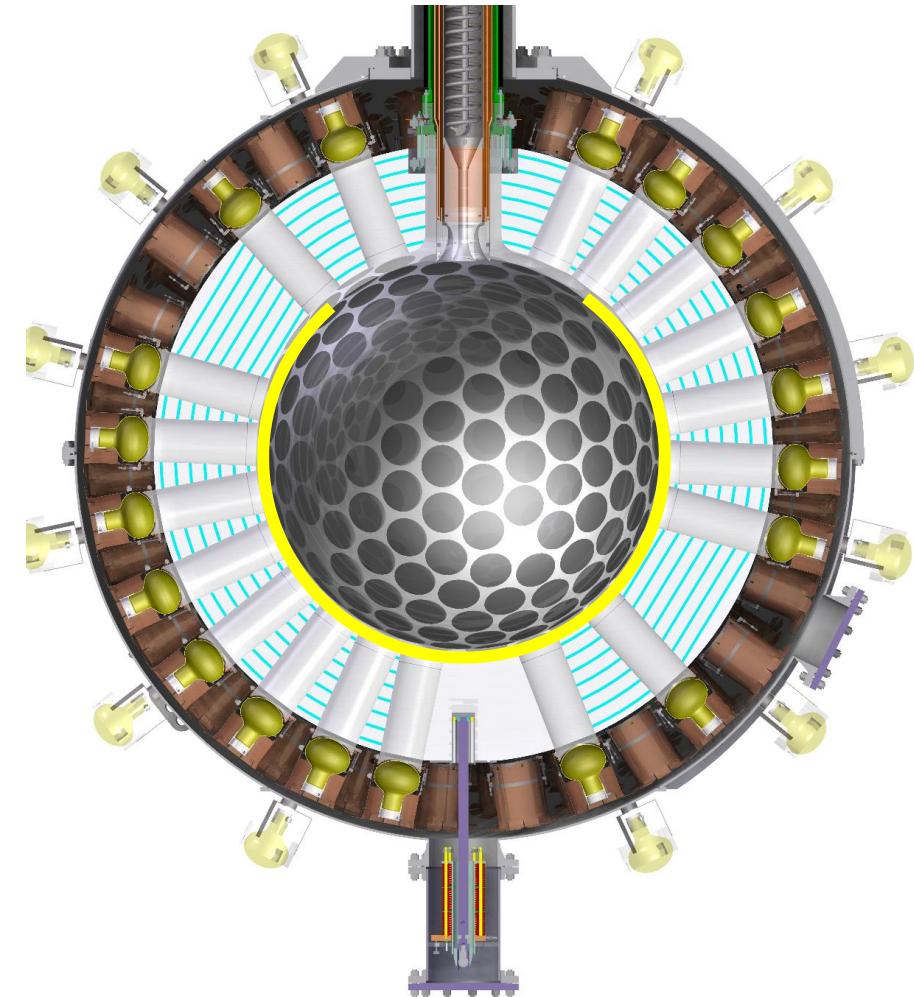
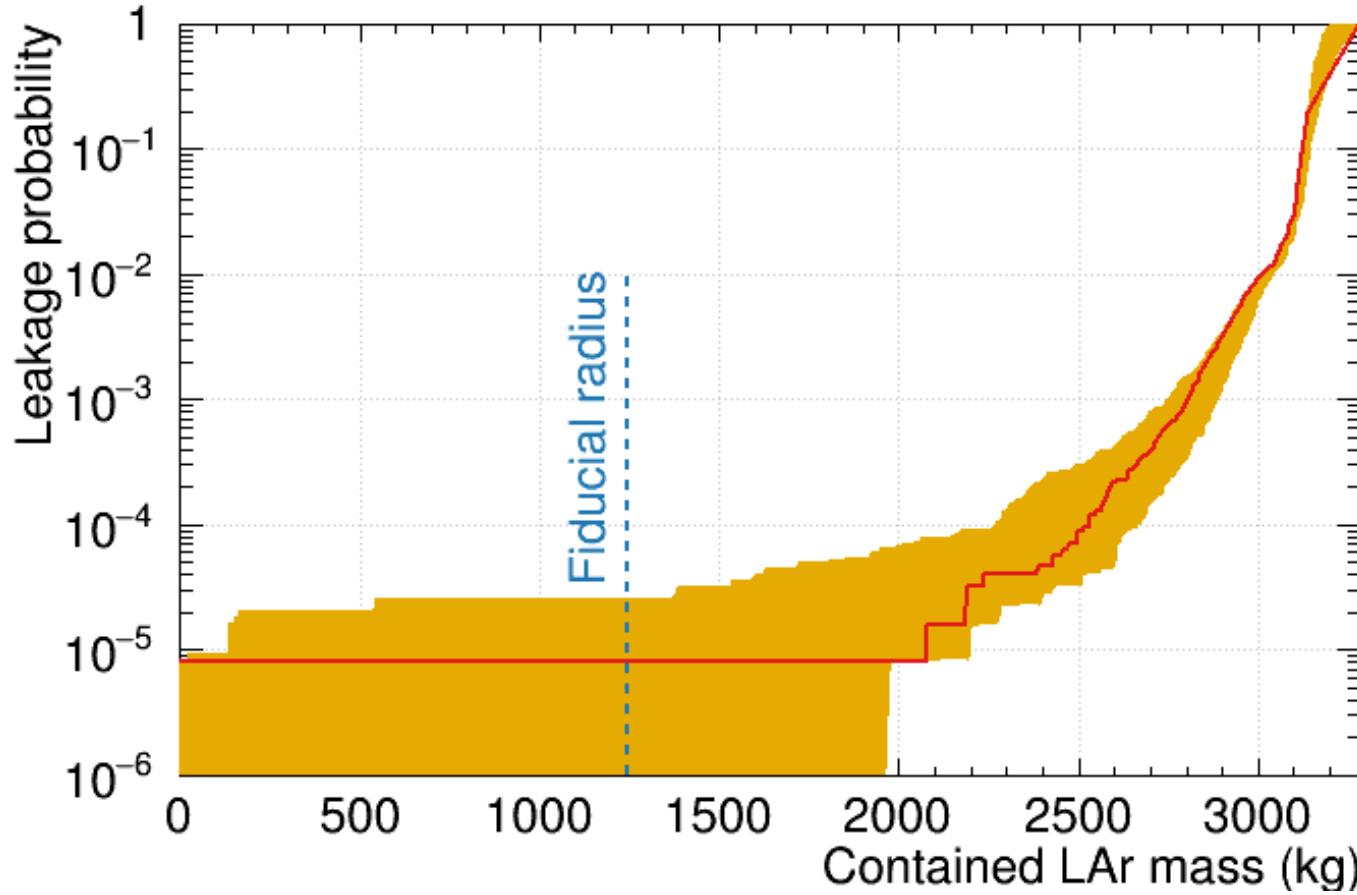


Figure 1: Conceptual design of multi-layer thin films at a detector surface.  $\alpha$  decays from regions A or B will always deposit all of their energy in an active layer, and can be discriminated from low-energy nuclear recoils based on the high observed energy. Decays from region C will either deposit 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.



$\alpha$  events on the surface of the sphere are removed with hit-pattern-based position reconstruction





# Background Summary

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

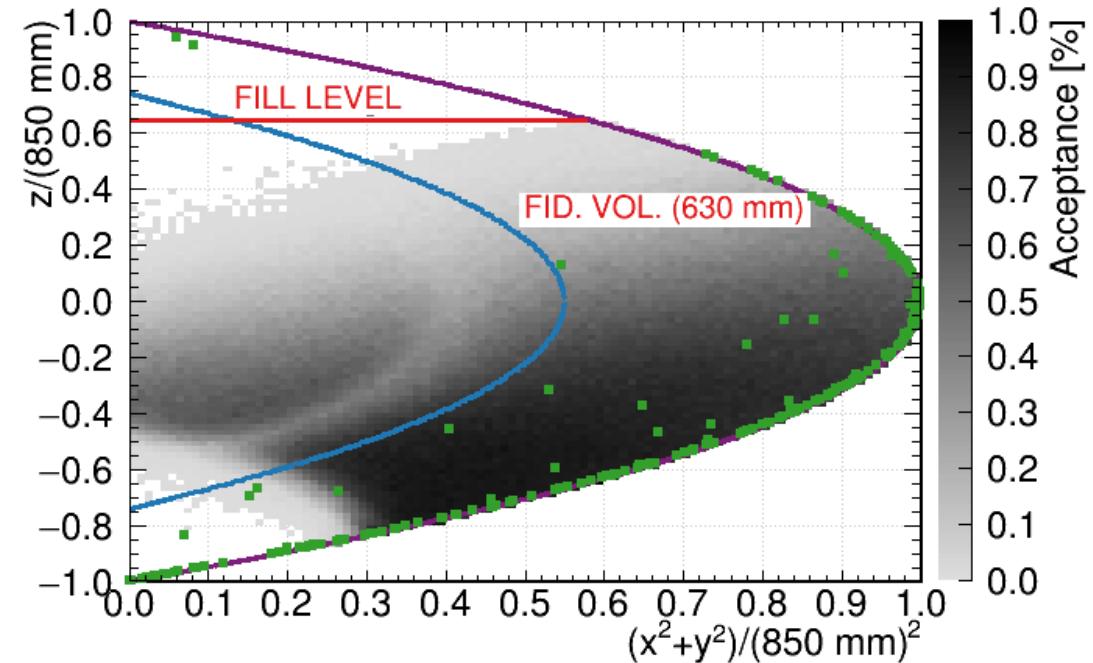
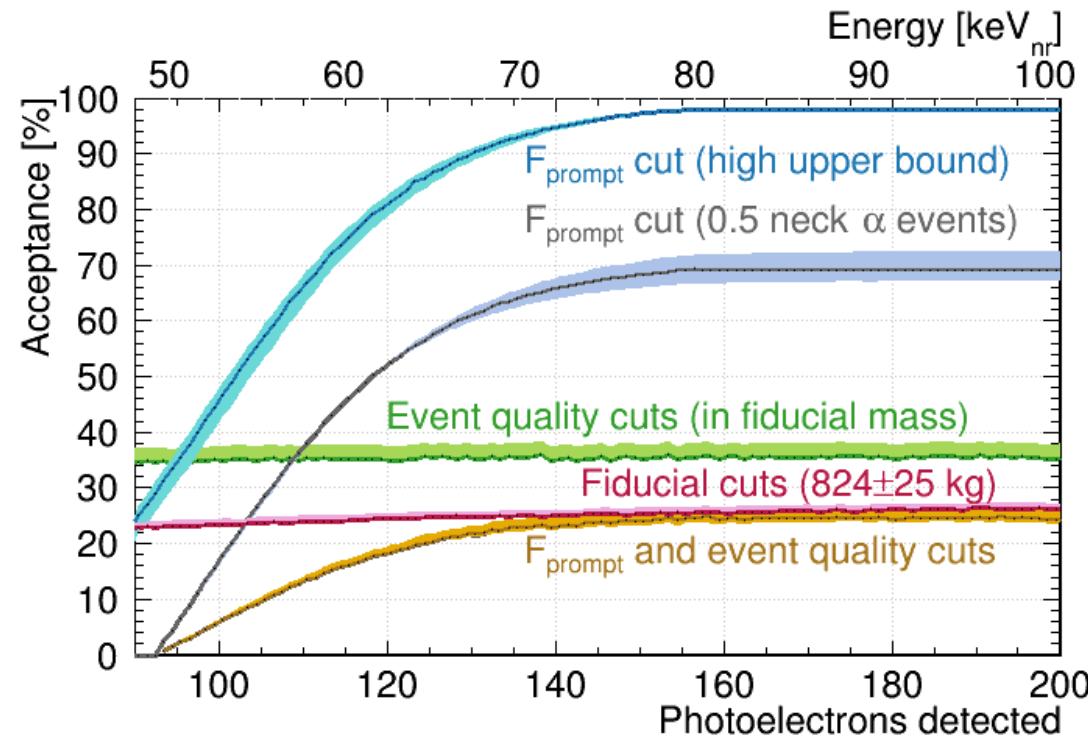
Source	$N^{\text{CR}}$	$N^{\text{ROI}}$
$\beta/\gamma$ 's	ERs	$2.44 \times 10^9$
	Cherenkov	$< 3.3 \times 10^5$
	Radiogenic	$6 \pm 4$
	Cosmogenic	$< 0.2$
$n$ 's	AV surface	$< 3600$
	Neck FG	$28^{+13}_{-10}$
<b>Total</b>	N/A	$0.62^{+0.31}_{-0.28}$

TABLE VIII. Cumulative impact of background rejection cuts on the WIMP acceptance, the predicted number of background events,  $N_{\text{bkg}}^{\text{ROI}}$  and the total number of observed background events,  $N_{\text{obs}}^{\text{ROI}}$  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. [%]	$N_{\text{bkg}}^{\text{ROI}}$	$N_{\text{obs}}^{\text{ROI}}$
Cherenkov	Neck veto	$92.0^{+1.0}_{-0.1}$	$9.2^{+4.4}_{-3.5}$	29
	Early pulses in GAr PMTs	$45.4^{+1.5}_{-0.1}$	$2.3^{+1.1}_{-0.9}$	2
$\alpha$ -decays in neck	Position fitter consistency	$35.4^{+2.5}_{-0.1}$	$0.62^{+0.31}_{-0.28}$	0
	<b>Total</b>	$35.4^{+2.5}_{-0.1}$	$0.62^{+0.31}_{-0.28}$	0

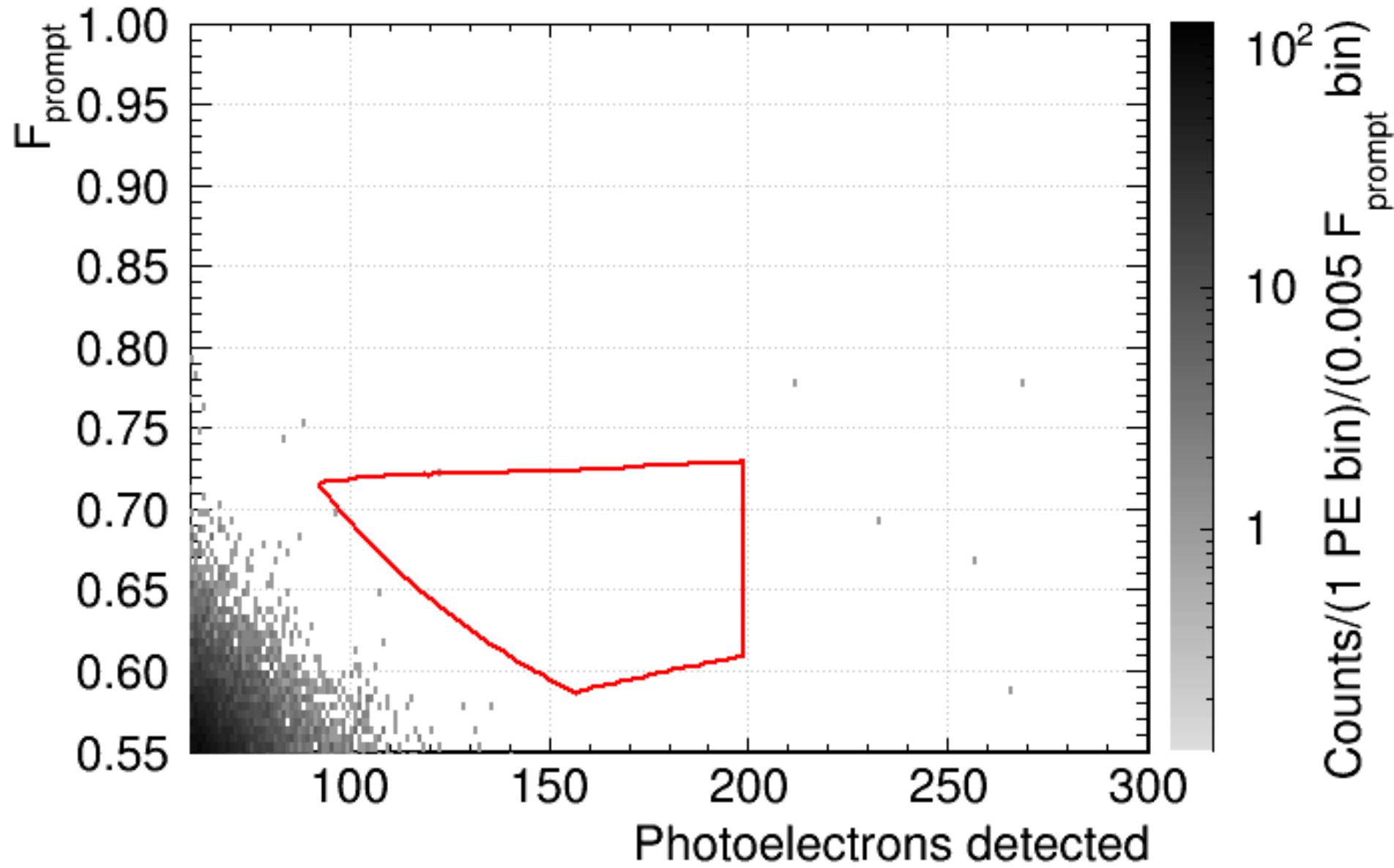


# Acceptance evaluated for all cuts.



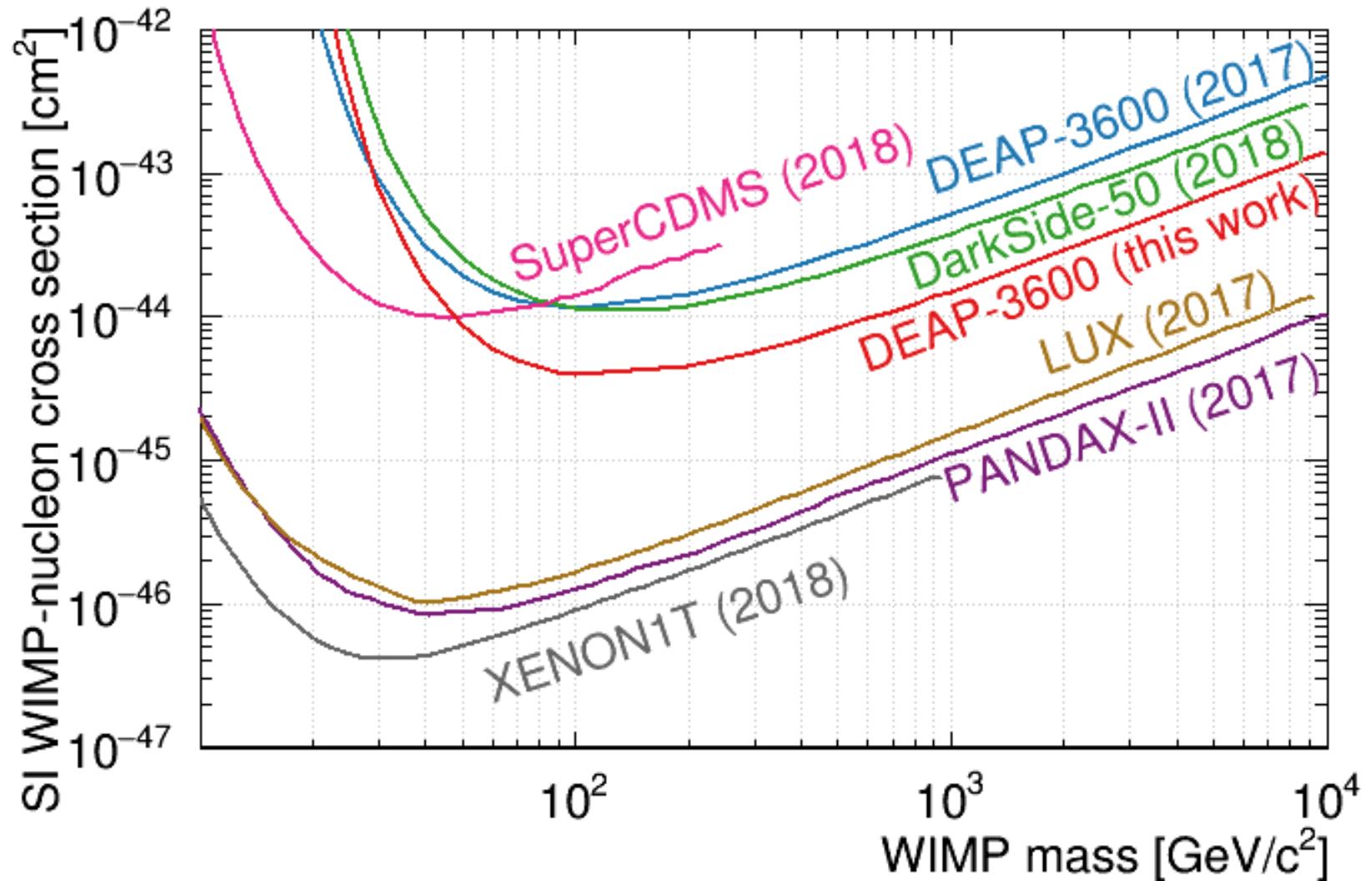


# WIMP Search Region





# 231-day exposure: first analysis





# Status

Data taking stable

~2.5 times more data

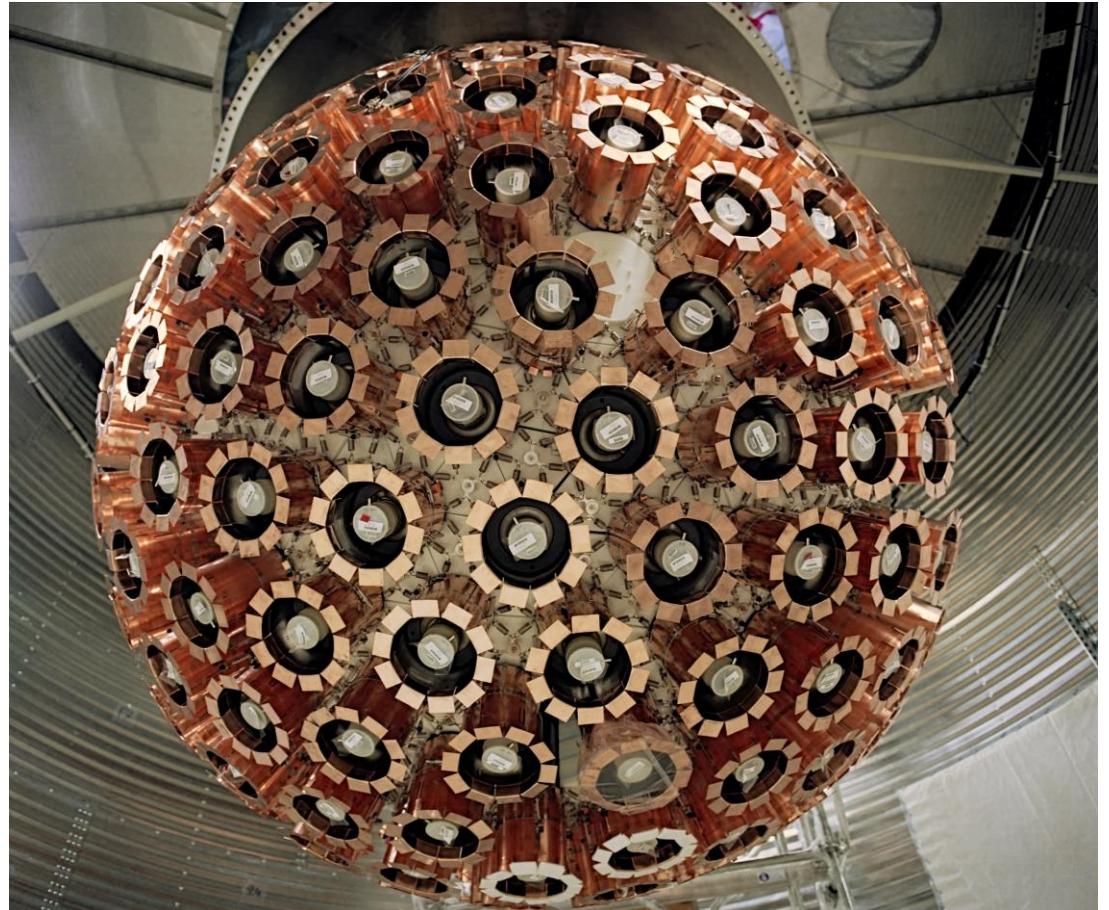
Data blinded since Jan 1, 2018

Current effort

MVA and machine learning on open dataset to increase acceptance

Parallel Effort

Plan hardware improvements





Canadian Nuclear  
Laboratories  
Laboratoires Nucléaires  
Canadiens



MINISTERIO  
DE CIENCIA, INNOVACIÓN  
Y UNIVERSIDADES

**Ciemat**  
Centro de Investigaciones  
Energéticas, Medioambientales  
y Tecnológicas

**Laurentian University**  
Université Laurentienne

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UNIVERSITY

**ROYAL HOLLOWAY**  
UNIVERSITY OF LONDON

Technical  
University  
of Munich

**TUM**

**INFN**  
Istituto Nazionale  
di Fisica Nucleare

**NATIONAL  
RESEARCH CENTER  
"KURCHATOV  
INSTITUTE"**

**IF**  
Instituto de Física  
UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO

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**SNO LAB**

**TRIUMF**