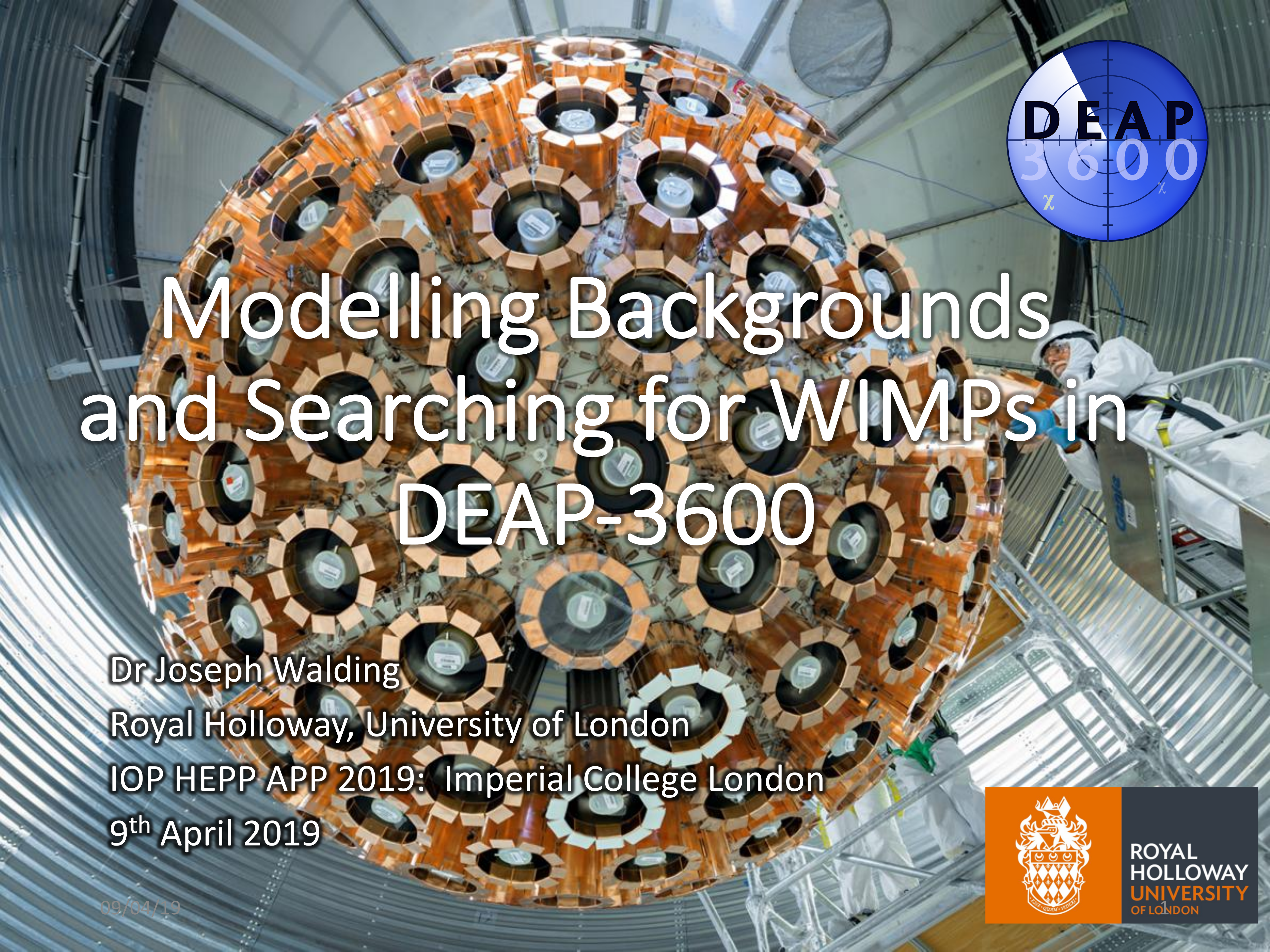

Modelling Backgrounds and Searching for WIMPs in DEAP-3600

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Royal Holloway, University of London

IOP HEPP APP 2019: Imperial College London

9th April 2019

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

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IF Instituto de Física

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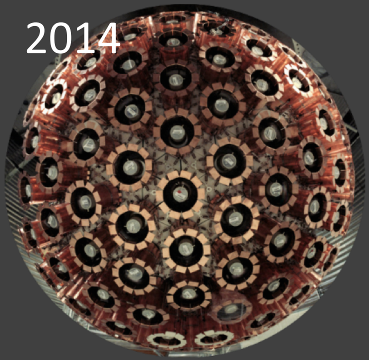
Outline

- The DEAP-3600 experiment
- Building our background model
  - For a discussion of pulse-shape discrimination (PSD) – See A. Kemp's talk
- 758 tonne-day analysis result

What is DEAP-3600?

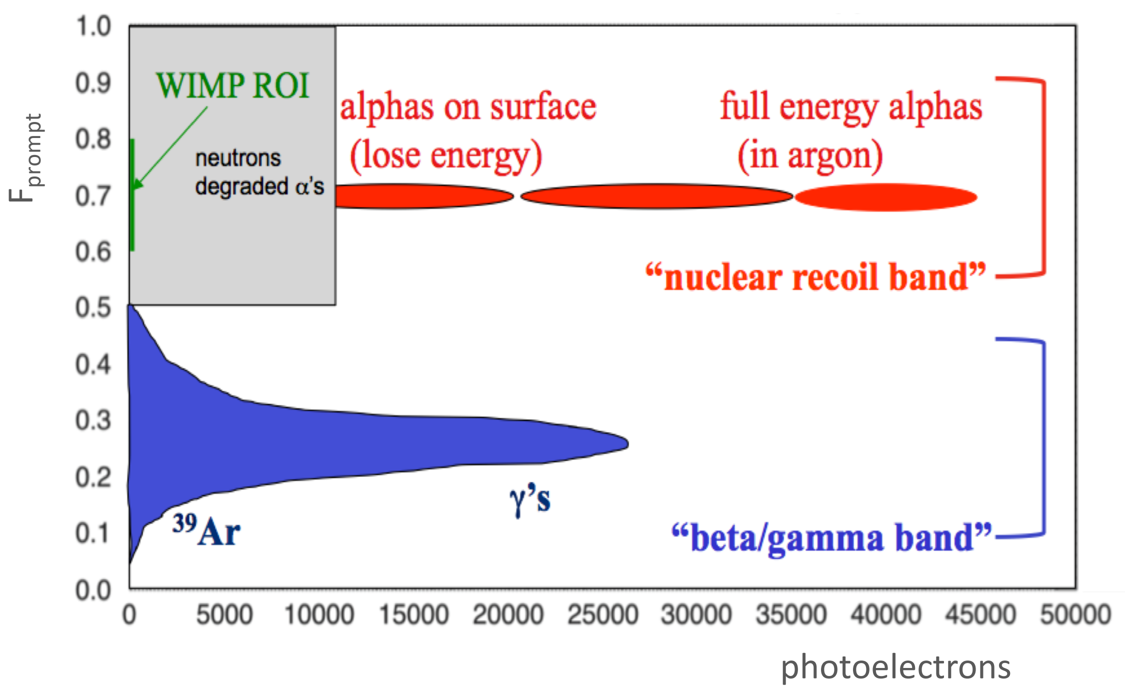
- The **D**ark matter **E**xperiment using **A**rgon **P**ulse-shape discrimination
- DEAP-3600: Liquid Argon (LAr) detector
  - Designed for 3600 kg LAr
  - SNOLAB – Sudbury, Ontario
  - 6800 feet underground = 6000 m.w.e
  - Single phase detector
- Single phase – No gaseous amplification region
  - No electron drift requirements
  - 4π PMT coverage
    ➔ Detector scalability to O(kTonne)
- First physics data in November 2016
- First result on 4.4 days of data: *Phys Rev Lett.121.071801*
- 2nd result presented today: 758 tonne-day exposure: *ArXiv 1902.04048*



Experimental Signature

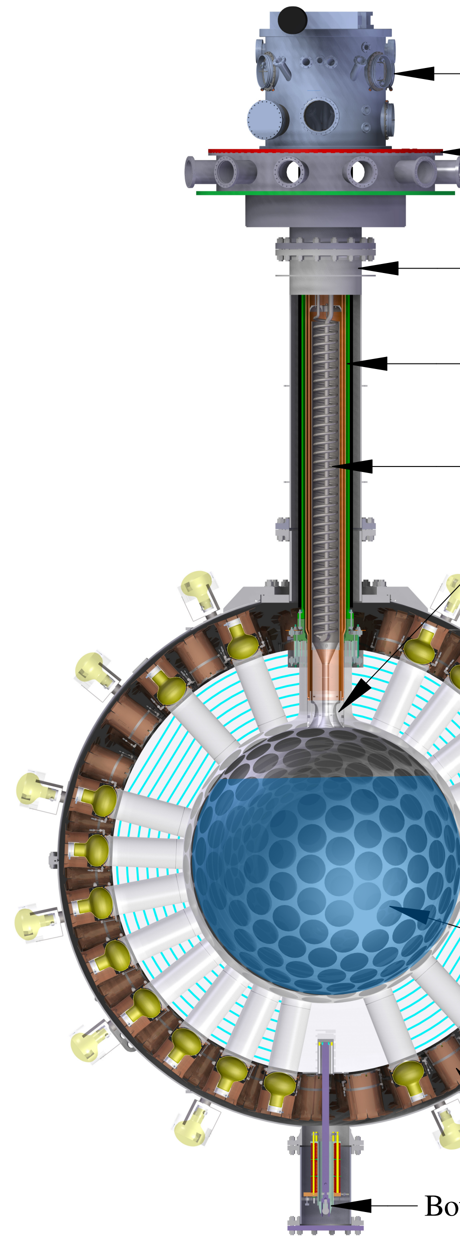
- Pulse Shape Discrimination (PSD) used to distinguish nuclear and β/γ recoils

$$F_{\mathrm{prompt}} \equiv \frac{\sum_{\{i \mid t_i \in (-28\ \mathrm{ns},\, 150\ \mathrm{ns})\}} Q_i}{\sum_{\{i \mid t_i \in (-28\ \mathrm{ns},\, 10\ \mu\mathrm{s})\}} Q_i},$$



DEAP-3600 Detector

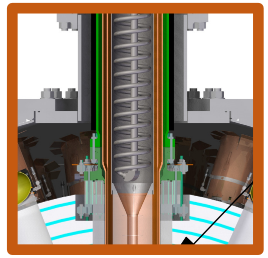
- LAr housed in sealed ultraclean acrylic vessel
- Strict material control and assaying procedures
- 255 8-inch Hamamatsu R5912 HQE PMTs
  - 32% QE, 75% coverage
- 85cm radius acrylic vessel & 50cm light-guides provide PMT neutron shielding
- Tetraphenyl-butadiene (TPB) used as wavelength shifter (128nm to 430nm)
- Cosmic veto
  - SNOLAB (2km underground)
  - Detector submerged in 8m diameter water tank

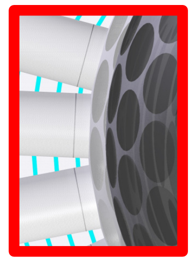


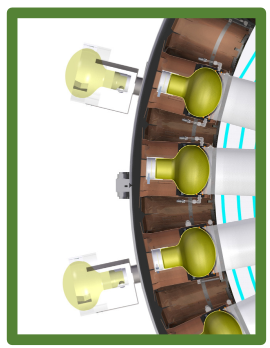
Backgrounds Overview

Alphas:

- Neck flow-guides: Long lived ^{222}Rn progeny (e.g.^{210}Pb) result in ^{210}Po α-decays
- AV Surface: ^{210}Po α-decays with degraded energy
- LAr: ^{220}Rn, ^{222}Rn α-decays and their progeny





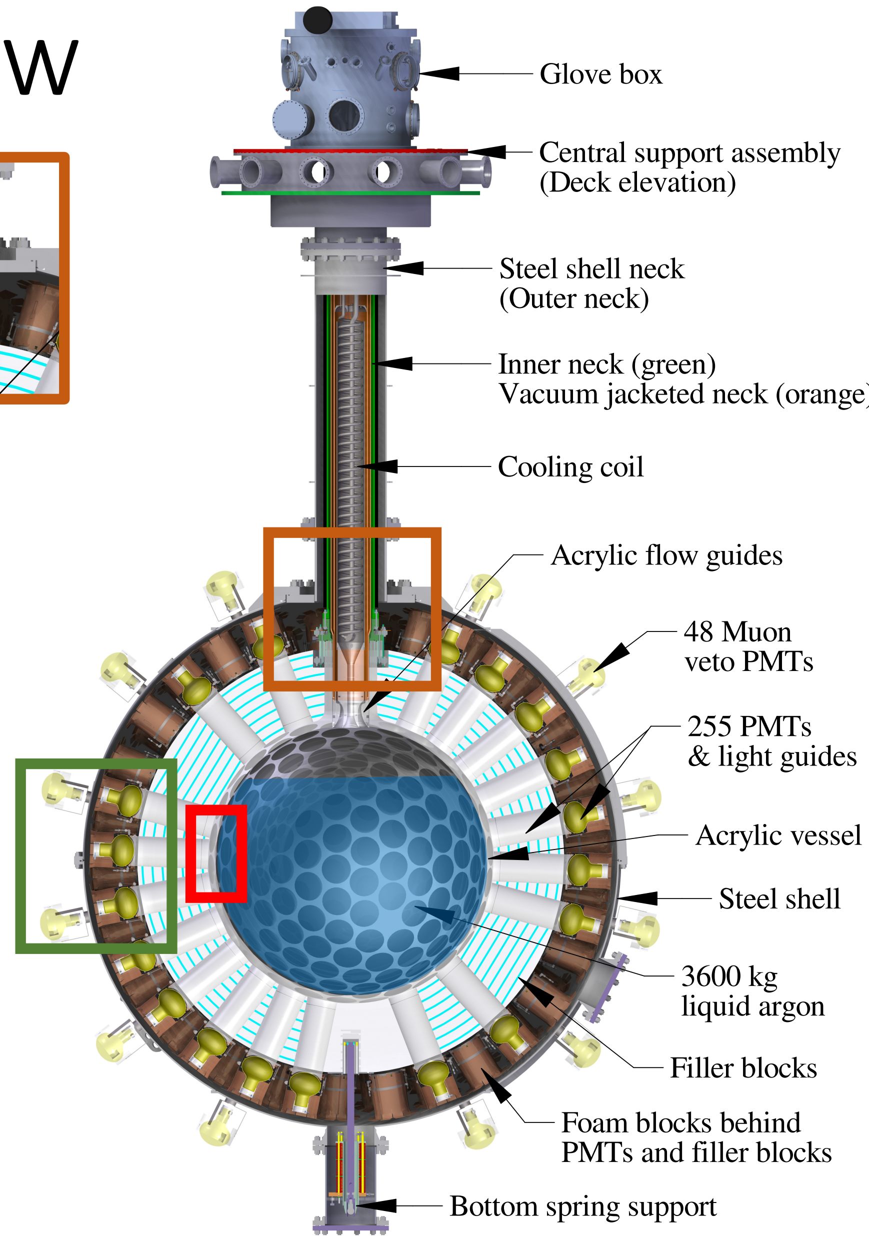


Neutrons & Cherenkov:

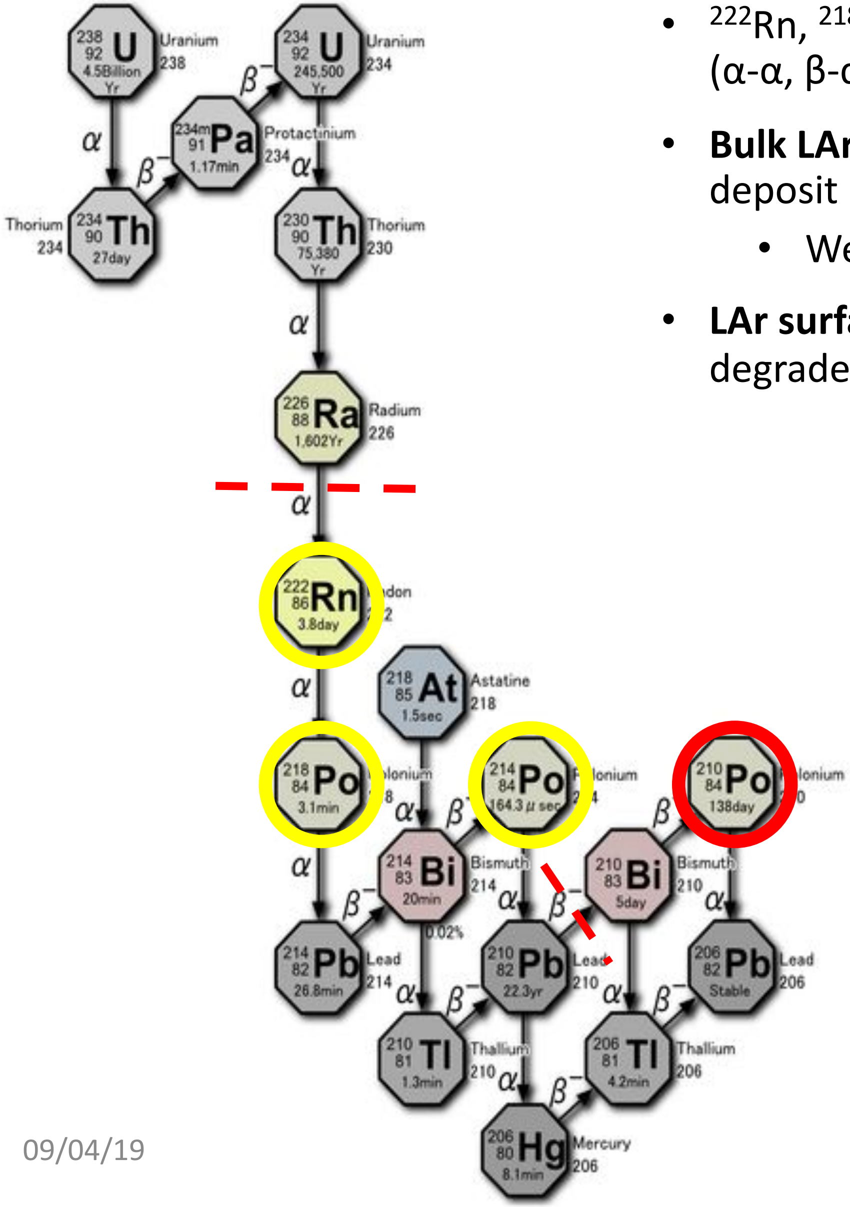
- External: Cosmogenic induced from water and rock
- Internal: PMT glass (α-N)
- Cherenkov light in light-guide acrylic

Electronic recoils:

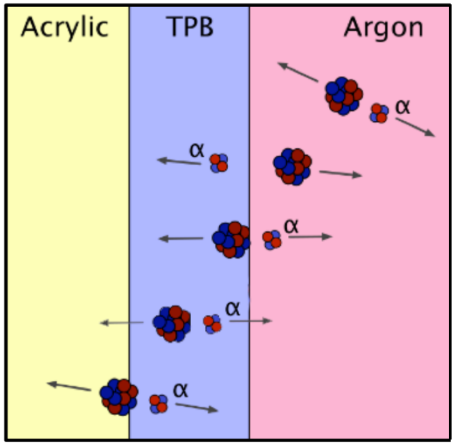
- ^{39}Ar β-decays
- Gammas from PMTs, acrylic, steel shell...



Surface and bulk alphas

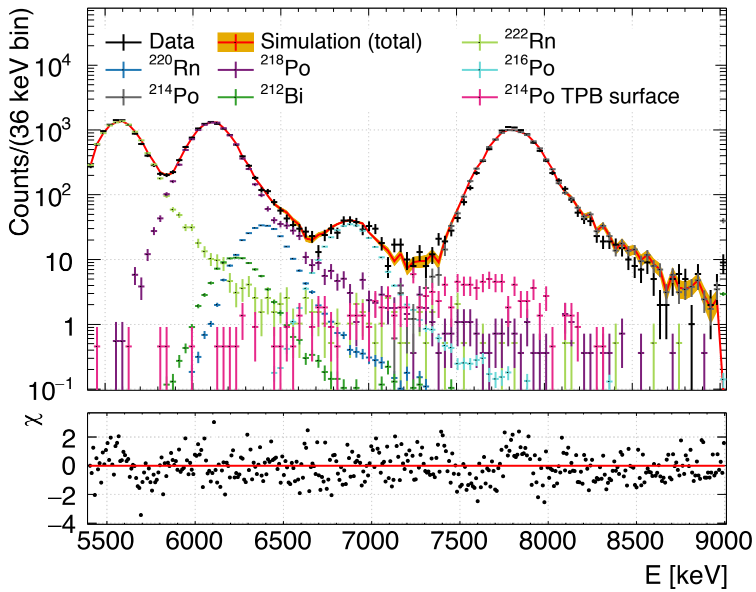


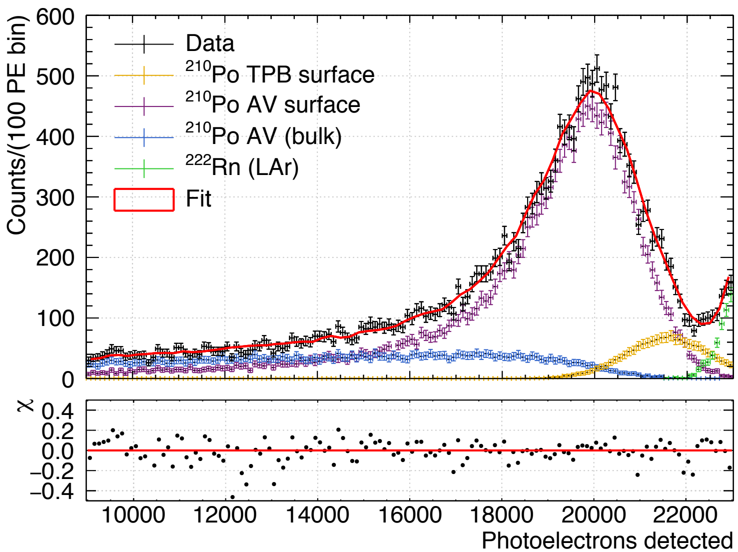
- ^{222}Rn, ^{218}Po, ^{214}Po tagged from time delayed coincidences (α-α, β-α)
- **Bulk LAr:** α's (^{222}Rn, ^{220}Rn and progeny) give high energy deposit in detector
    - Well above WIMP ROI
- **LAr surface:** ^{210}Po (out-of-equilibrium) tagged with degraded energy signal (^{210}Po below TPB surface)



Chain can be broken below dashed lines

Surface and bulk alphas





- ^{222}Rn, ^{218}Po, ^{214}Po tagged from time delayed coincidences (α-α, β-α)
- **Bulk LAr:** α's (^{222}Rn, ^{220}Rn and progeny) give high energy deposit in detector
  - Well above WIMP ROI
- **LAr surface:** ^{210}Po (out-of-equilibrium) tagged with degraded energy signal (^{210}Po below TPB surface)
  - Simulation of surface contamination to 80um and bulk contamination agree with data
  - Background expectation: < 0.08 (90% C.L.) events in ROI
- **Lowest reported Rn background for a DM experiment**

	Component	Activity / Rate
short-lived α-decays	^{222}Rn LAr	$(0.153 \pm 0.005)\ \mu Bq/kg$
	^{218}Po LAr	$(0.159 \pm 0.005)\ \mu Bq/kg$
	^{214}Po LAr	$(0.153 \pm 0.005)\ \mu Bq/kg$
	^{214}Po TPB surface	$< 5.0\ \mu Bq/m^2$
	^{220}Rn LAr	$(4.3 \pm 1.0)\ nBq/kg$
	^{216}Po LAr	$(4.5 \pm 0.4)\ nBq/kg$
	^{212}Bi LAr	$< 5.6\ nBq/kg$
	^{212}Po LAr	$(3.4 \pm 1.1)\ nBq/kg$
-decays	^{210}Po TPB & AV surface	$(0.26 \pm 0.02)\ mBq/m^2$
	^{210}Po AV (bulk)	$(2.82 \pm 0.05)\ mBq$

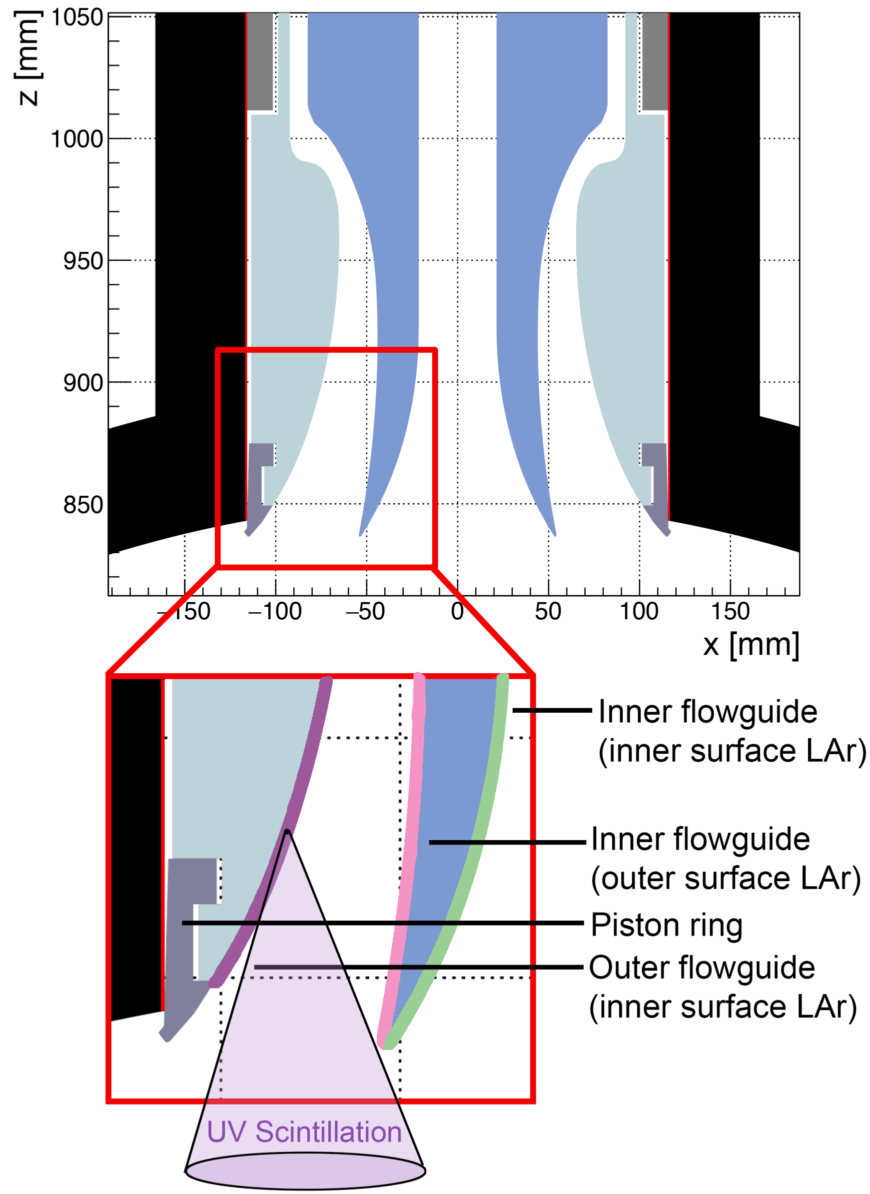
Alpha Neck Events

- ^{210}Po alpha decays from neck acrylic flowguide contributing to the WIMP background rate at low PE

- Requires LAr located in close proximity to flowguide surfaces (e.g. a thin LAr film).

- Acrylic absorbs most of the UV scintillation
  - Results in shadowing: Generating low PE events that reconstruct inside the fiducial volume.

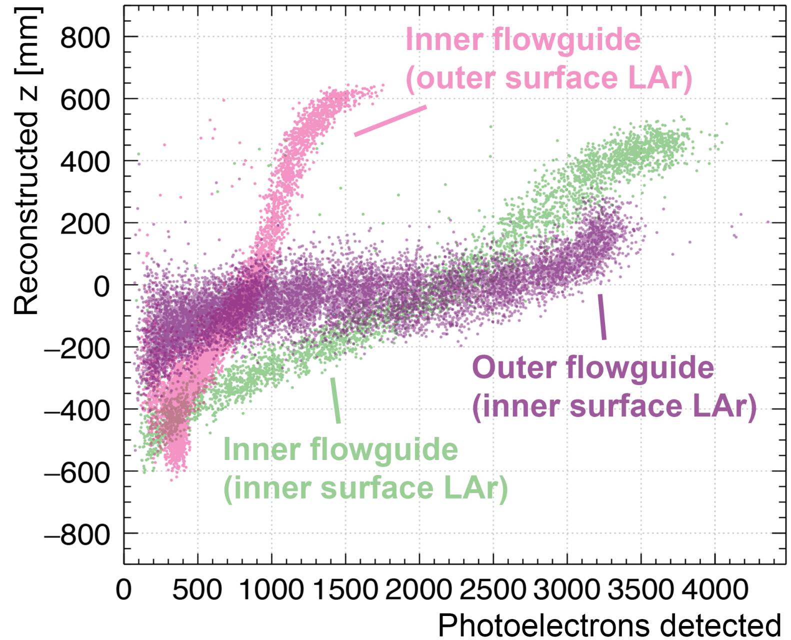
- Three distinct flowguide surfaces:
  - Inner flowguide, inner Surface
  - Inner flowguide, outer Surface
  - Outer flowguide, inner Surface

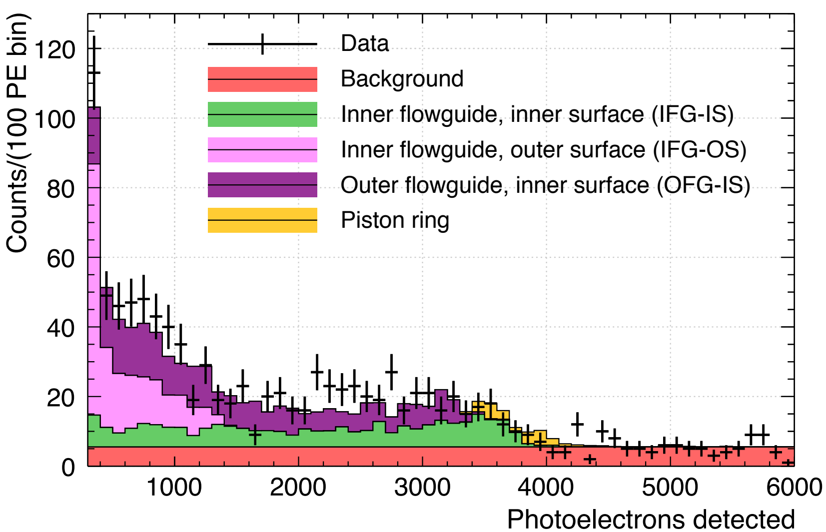


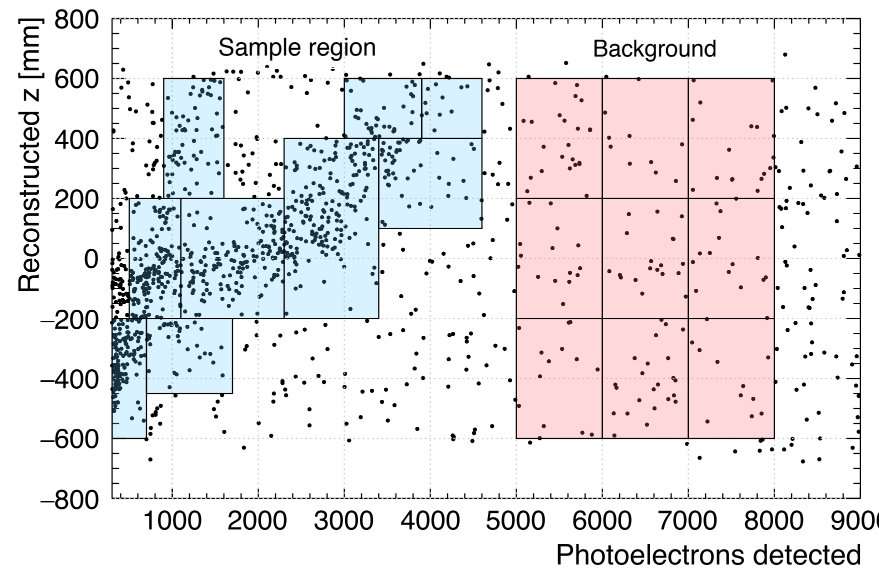
Alpha Neck Events

- Simulations of neck events identify features in reconstructed z position and PE seen in data

- Data fit to determine rate of each feature

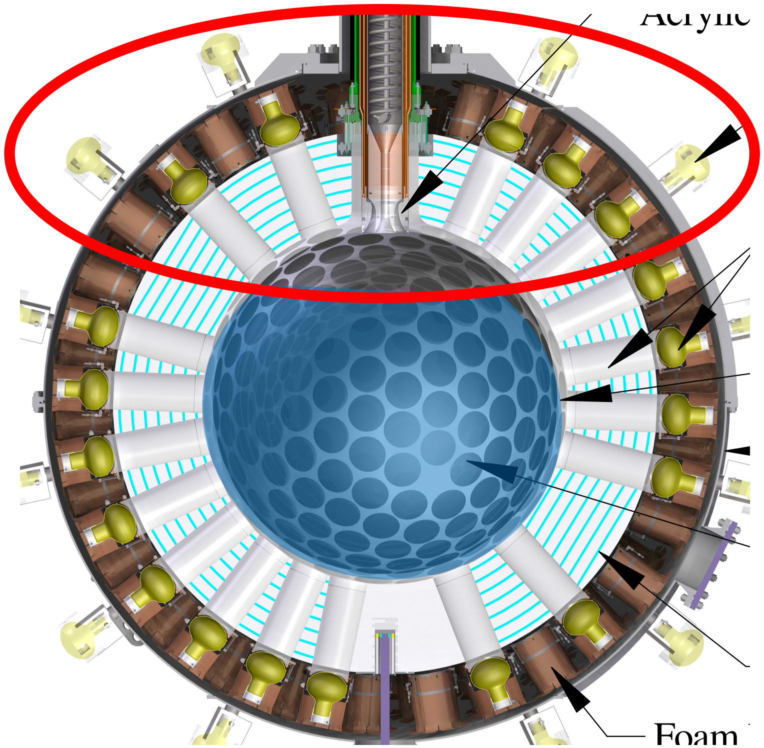


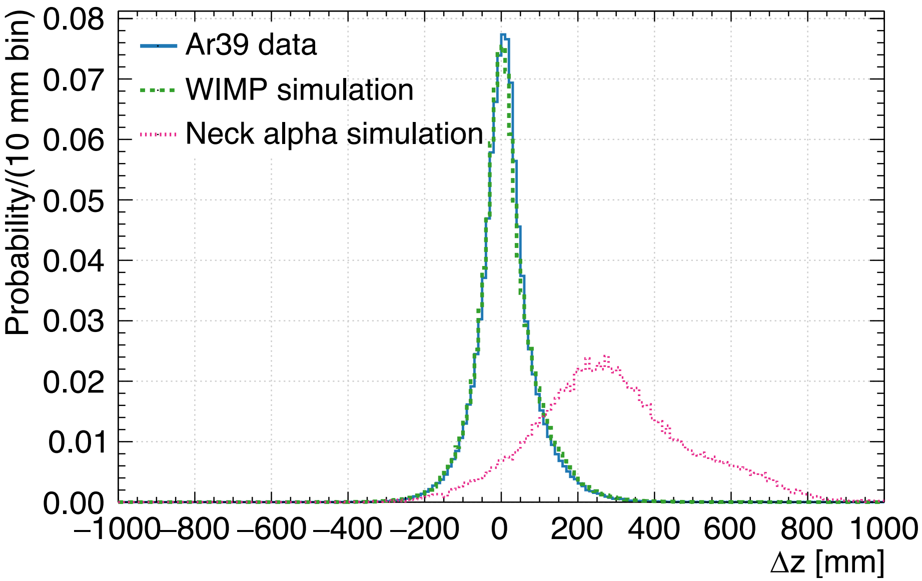




Alpha Neck Events

- To mitigate neck alpha backgrounds a series of cuts were developed
  - Cuts based on charge and time information in PMTs near neck
  - Top PMTs sensitive to reflected UV photons at LAr surface
  - Comparing results from PE-based and PE+timing based position fitters gives handle to remove events due to mis-reconstruction
  - Background expectation: $0.49^{+0.27}_{-0.26}$ (90% C.L.) events in ROI



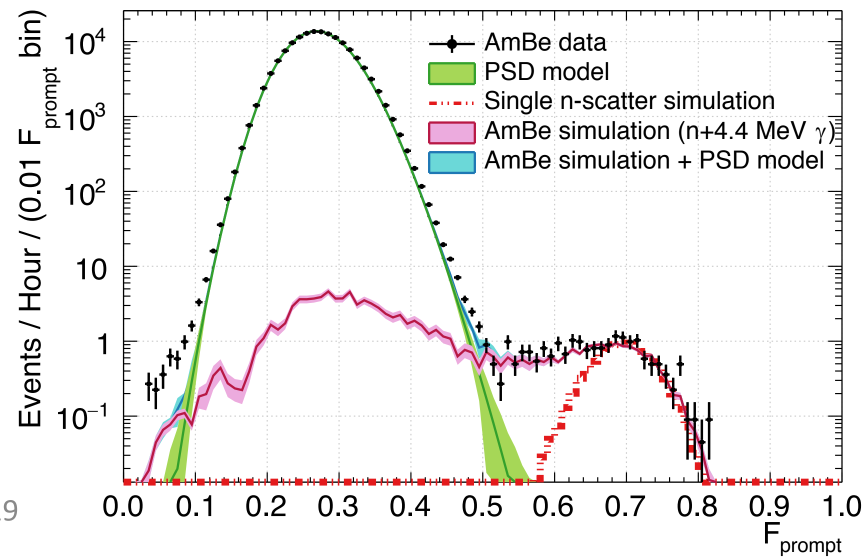


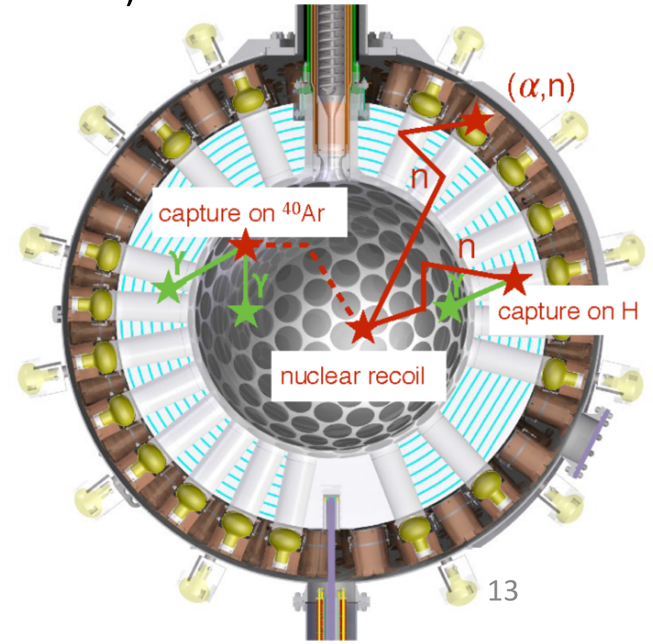
Residual of z position from PE+time fitter – PE fitter

The PE+time fitter is more sensitive to origin of early photons

Neutron & Cherenkov Backgrounds

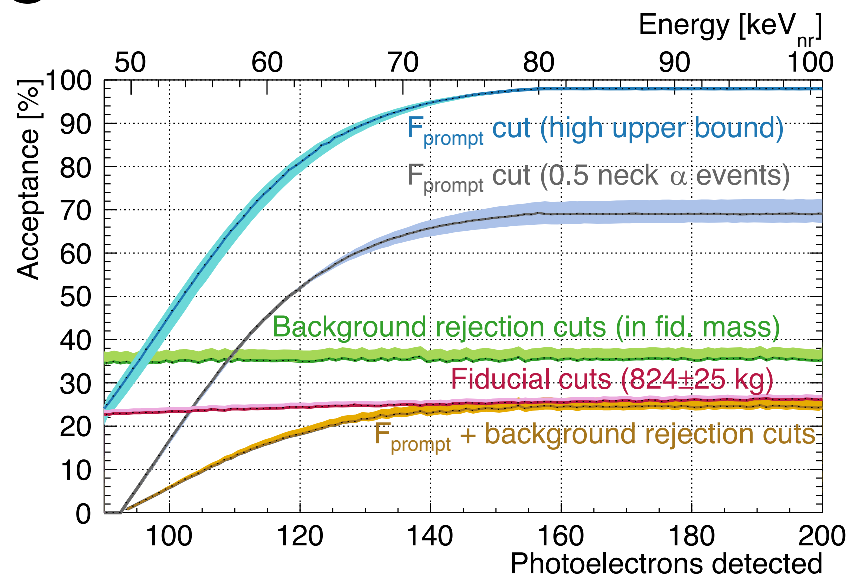
- Calibration sources:
  - Validate nuclear (neutron) recoil model
  - Validate detector response to Cherenkov light
- **Cosmogenic Neutrons:** SNOLAB depth of 2km shields against cosmogenic muons (+ muon veto)
  - Background expectation: < 0.11 (90% C.L.) events in ROI
- **Radiogenic Neutrons:** Based on GEANT4/RAT simulations normalized to material assay values
  - Validated via in-situ neutron tagging analysis on physics data and with an AmBe calibration source
  - Background expectation: $0.10^{+0.10}_{-0.09}$ events in ROI
- **Cherenkov:** Detector response to ^{232}U source (2.6 MeV γ's from ^{208}Tl) informs cut
  - Background expectation: < 0.14 (90% C.L.) events in ROI





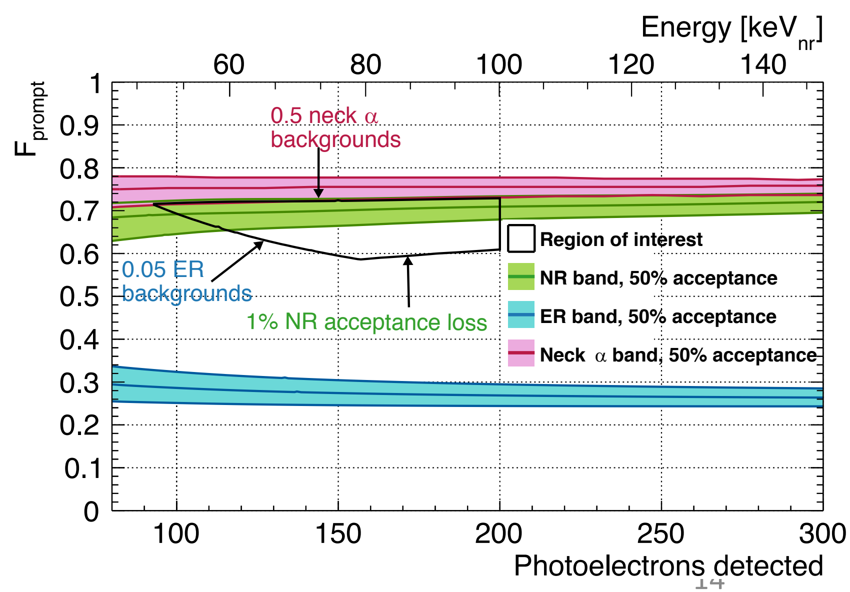
Cuts and Expectations

- Analysis uses a fiducial mass of 824±25 kg
  - WIMP efficiency of 35.4%
- Fiducial and background rejection cuts tuned on MC characterized from physics and calibration data
- < 1 expected background events (including PSD of NR from ER and decays)



	Source	N^{ROI}
β/γ's	ERs	0.03 ± 0.01
	Cherenkov	< 0.14
n's	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	$0.62^{+0.31}_{-0.28}$

Summary of background expectations



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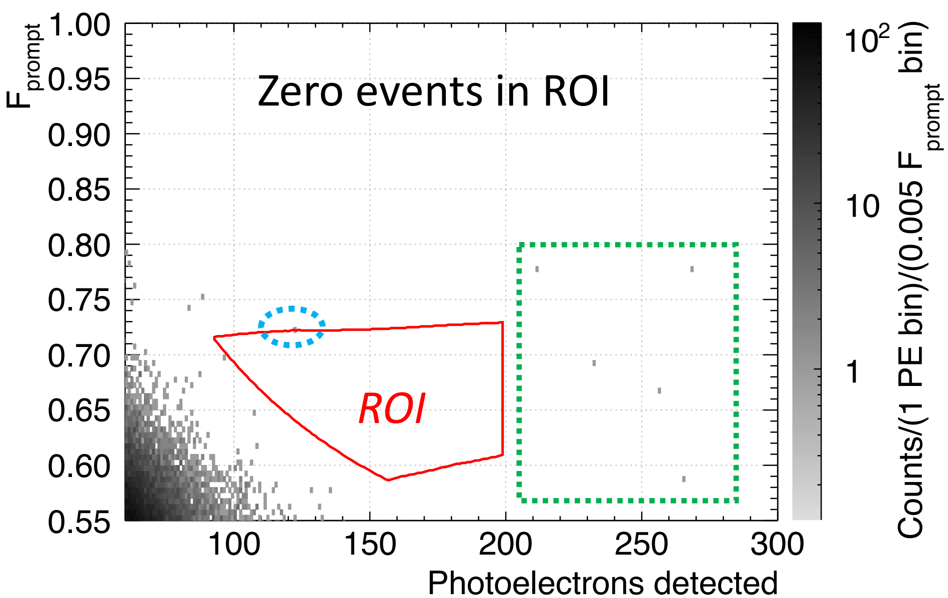
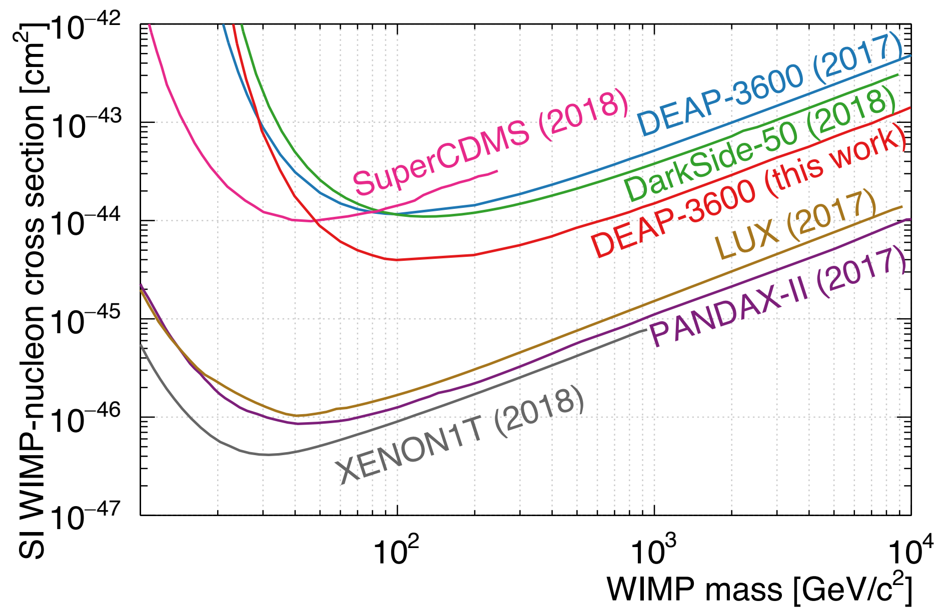
WIMP Exclusion

Worlds best spin independent limit on Argon for WIMP masses above 100 GeV

$\sigma < 3.9\text{x}10^{-45}$ cm^2 (90% C.L.) @ 100 GeV WIMP mass





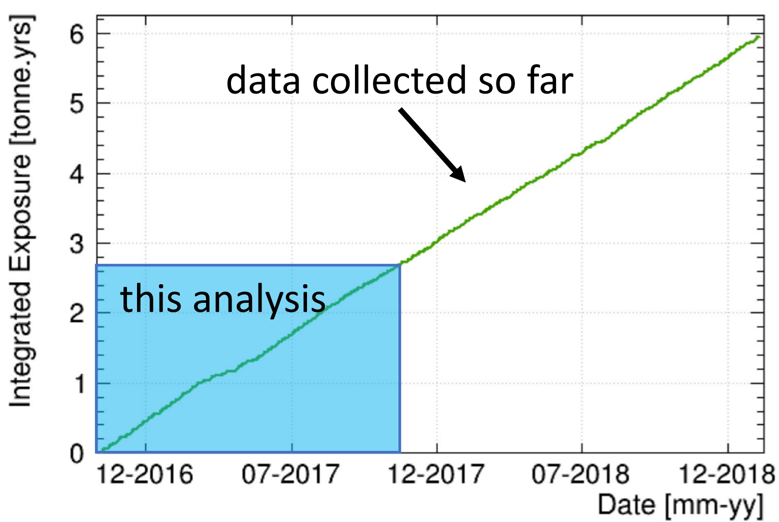
1 event: consistent with background model (BGM)

5 events: $1.25^{+0.26}_{-0.42}$ expected

Conclusions & Outlook

- A comprehensive background model developed, verified through calibration source data, physics data, simulation
- Result: 3.9×10^{-45} cm^2 @ 100 GeV WIMP mass (90% C.L.)
- **What next...**
- Collecting blind data since January 2018 (80% blinded, 20% open)
- AV neck background events the limiting factor
    - Multivariant analyses under development to improve WIMP sensitivity
- DEAP-3600 to run until end of 2020
- **Beyond DEAP-3600**
    - DarkSide-20k: LNGS, start date ~2021
    - 300 tonne detector at SNOLAB – to push to the neutrino floor!

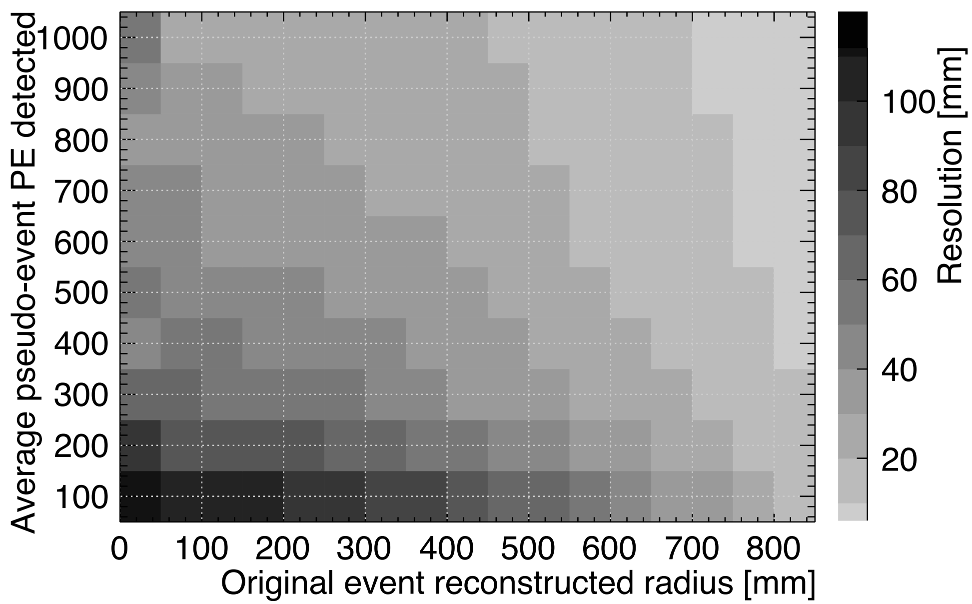
See A. Kemp's talk for a discussion of Pulse Shape Discrimination and development of a Profile Likelihood approach to searching for Dark Matter



Thank you !

Position Reconstruction

- Use both PMT-hit patterns and time to reconstruct and verify position of scintillation events in the detector.
- Developed two position reconstruction algorithms (1) PE-based, (2) PE+timing-based.
- First-ever demonstration of position reconstruction in a single-phase liquid argon detector
- Position resolution of ~20 mm for events near detector surface in WIMP energy ROI
- Provides excellent background rejection of surface events.



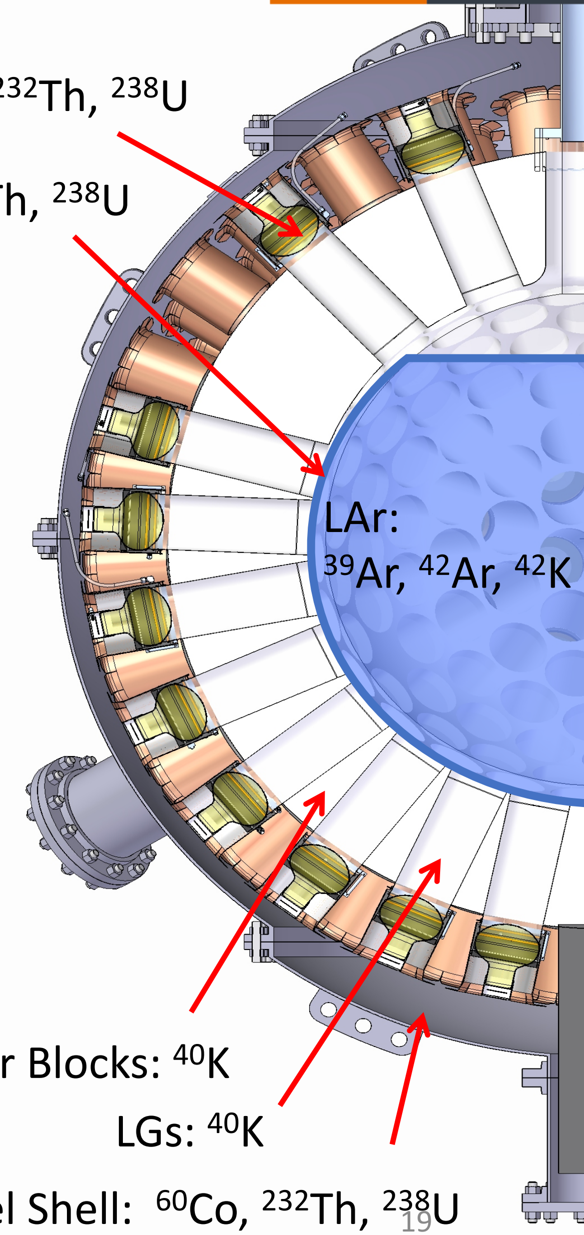
Position resolution using PE-based algorithm on Ar39 ERs.

Gamma/Beta Backgrounds

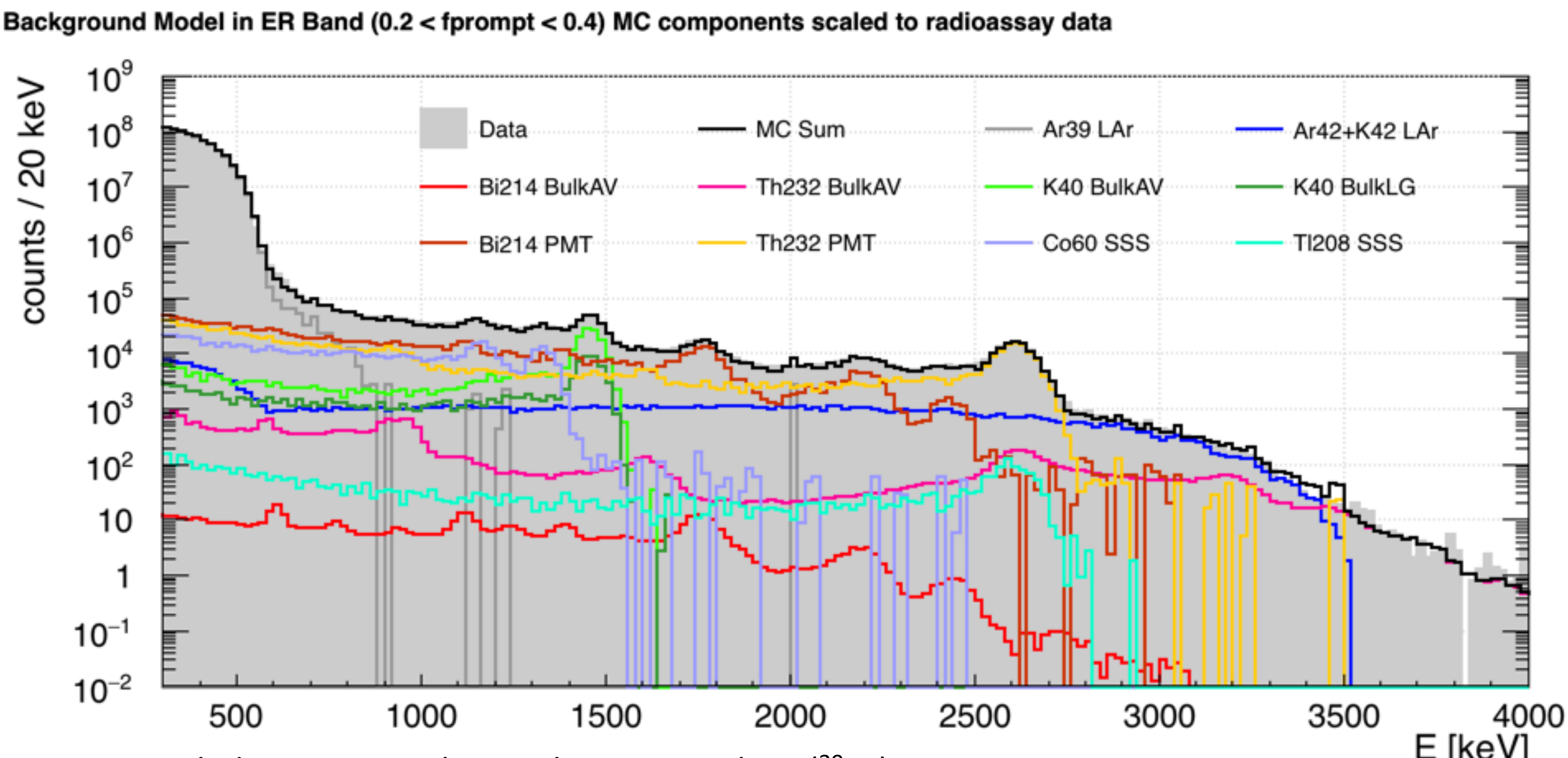
- Activities of materials predicted from results from comprehensive screening program
- LAr activity taken from literature*

Isotope	Location	Activity	Specific activity (mBq/kg)	Concentration (ppb)
^{39}Ar	LAr	3300	1010	
^{232}Th	PMT Glass	26	139	34
^{238}U	PMT Glass	169	921	75
^{40}K	Acrylic	7.5	~2	70

**P. Benetti et al., NIM A 574, 83 (2007)*

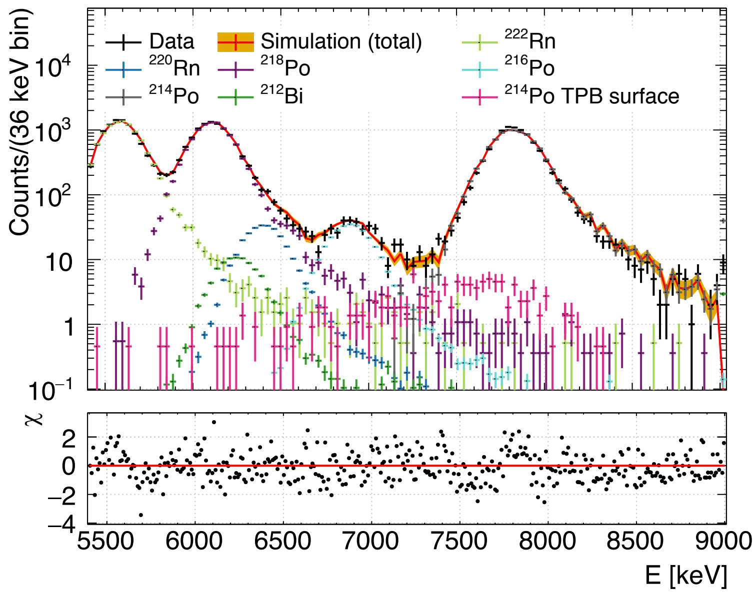


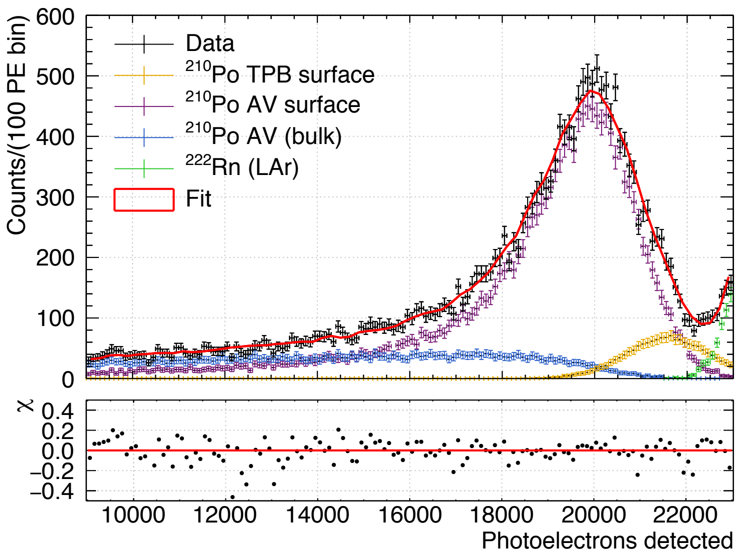
Electron Recoil Backgrounds



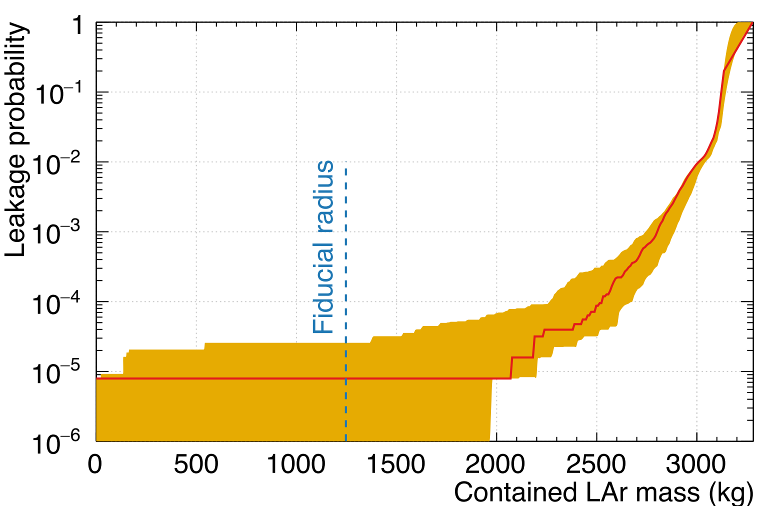
- MC scaled screening values or literature values (^{39}Ar)
- Low energy region (<500 keV) dominated by ^{39}Ar
- Mid energy region (500-2600 keV) dominated by external componentry gammas (PMT glass)
- High energy region (>2600 keV) dominated by ^{42}K & bulk AV ^{232}Th

Surface and bulk alphas



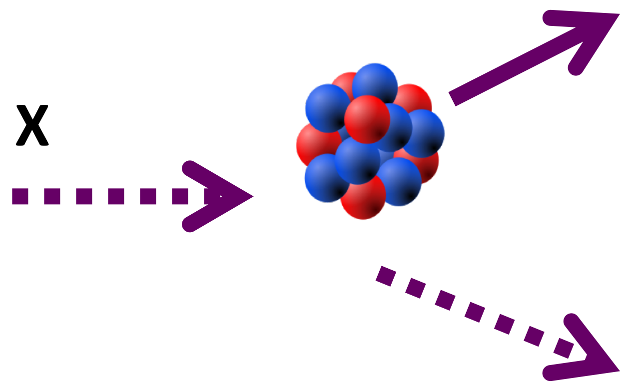


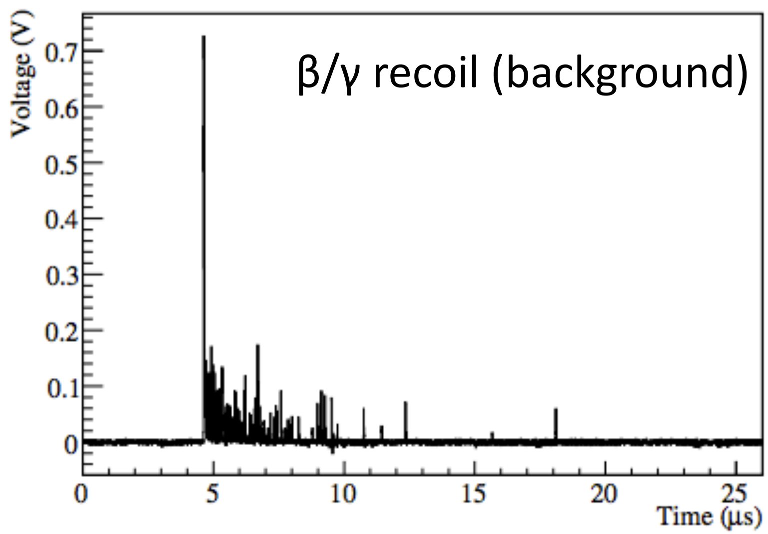
- ^{222}Rn, ^{218}Po, ^{214}Po tagged from time delayed coincidences (α-α, β-α)
- ^{214}Po activity in LAr consistent with activity earlier in the chain
- ^{210}Po (out-of-equilibrium) tagged with degraded energy signal (^{210}Po below TPB surface)
  - Simulation of surface contamination to 80um and bulk contamination agree with data

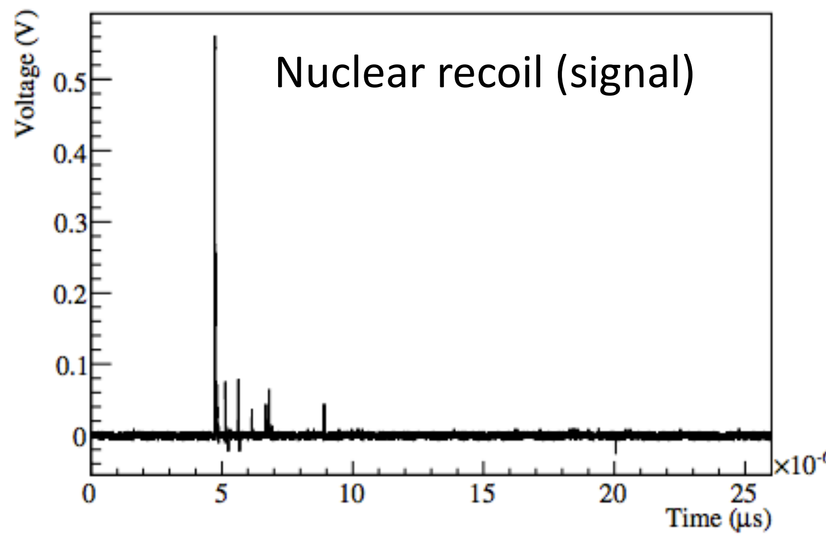


Experimental Signature

- Pulse Shape Discrimination (PSD) used to distinguish nuclear and β/γ recoils







Neck Alphas

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	$^{+170}_{-110}$	$^{+69}_{-83}$	$^{+85}_{-80}$

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

Cuts

TABLE II. The cumulative impact of the run selection criteria on the data live time is shown. Below this, total fiducial LAr mass is shown after applying each fiducial cut cumulatively.

	Selection criteria	Live time [days]
run	Physics runs	279.78
run	Pass automatic DAQ & shifter checks	264.93
run	Stable cryocooler	247.12
run	Stable PMTs	246.91
run	Trigger efficiency obtained	246.64
event	Muon veto events	246.24
event	Dead time	230.63
	Total	230.63
	Fiducial cut	Contained LAr mass [kg]
	No fiducial cuts	3279 ± 96
	Reconstructed position $z < 550$ mm & radius < 630 mm	1248 ± 40
	Charge fraction in top 2 rows of PMTs	921 ± 28
	Charge fraction in bottom 3 rows of PMTs	824 ± 25
	Total	824 ± 25

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.

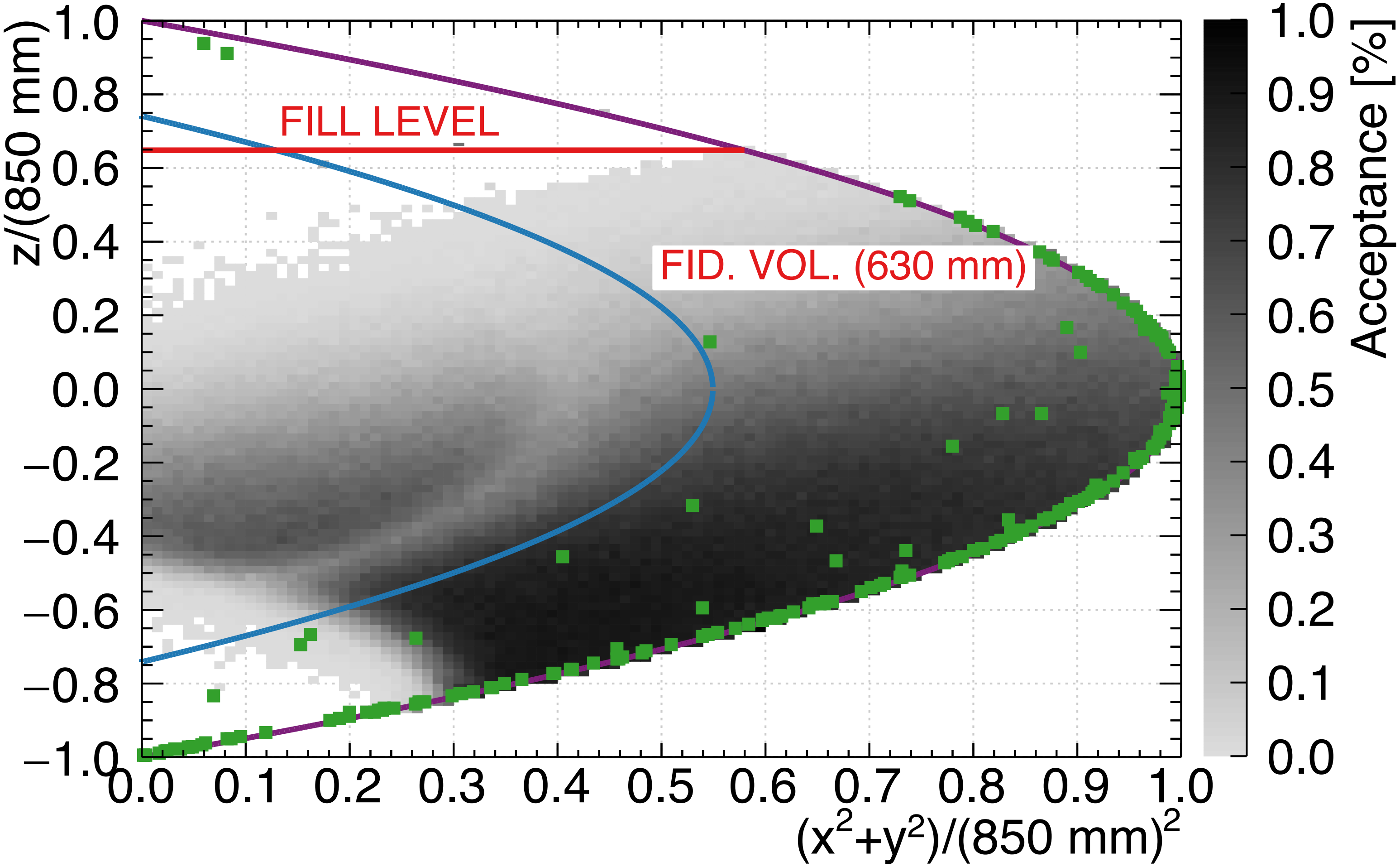
	Background rejection cut	WIMP accept. [%]	$N^{\mathrm{ROI}}_{\mathrm{bkg}}$	$N^{\mathrm{ROI}}_{\mathrm{obs}}$
Cherenkov	Neck veto	$92.0^{+1.0}_{-0.1}$	$9.2^{+4.4}_{-3.5}$	29
α-decays in neck	Early pulses in GAr PMTs	$45.4^{+1.5}_{-0.1}$	$2.3^{+1.1}_{-0.9}$	2
α-decays in neck	Position fitter consistency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

Detector Neutrons

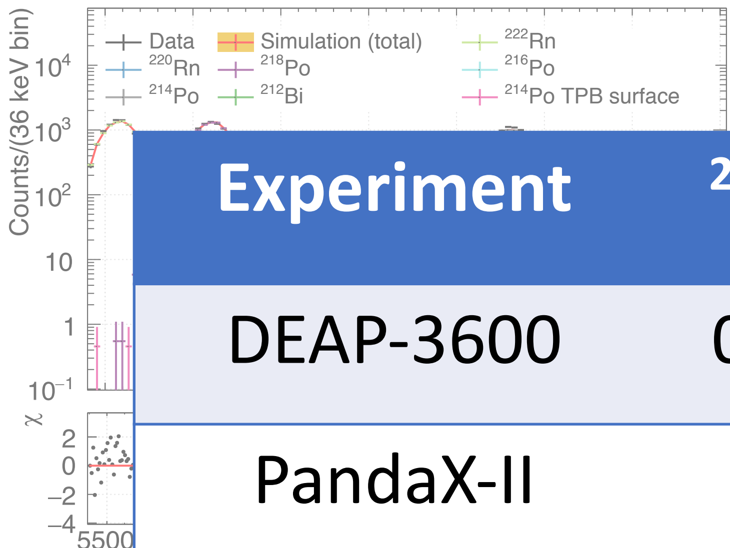
TABLE IV. Predicted number of neutron backgrounds from simulations, using (α, n) yields calculated by either SOURCES-4C or NeuCBOT, for the dominant sources. All fission yields are calculated using SOURCES-4C. Background rates are calculated within a CR used for validating the neutron background model *in-situ*, and within the WIMP ROI.

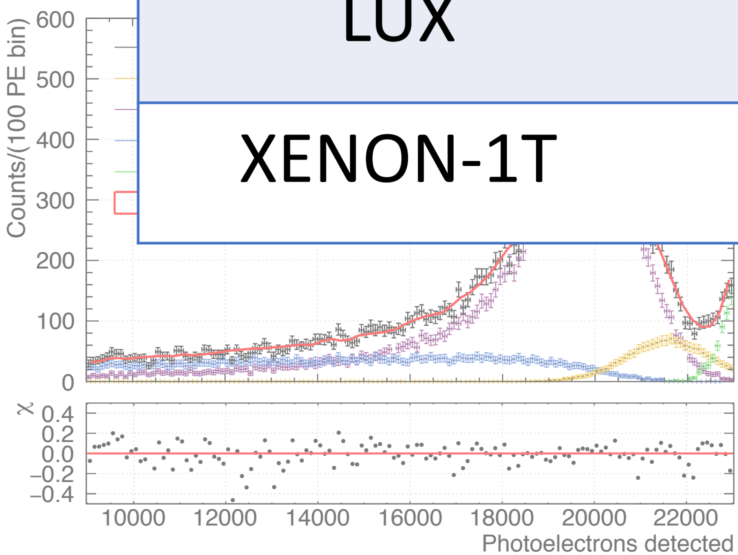
	CR prediction	
Component	(SOURCES-4C)	(NeuCBOT)
PMT glass	$2.4^{+1.2}_{-0.8}$	$4.1^{+2.0}_{-1.3}$
PMT ceramic	$0.22^{+0.06}_{-0.11}$	$0.36^{+0.09}_{-0.15}$
PMT mounts	$0.095^{+0.032}_{-0.041}$	$0.10^{+0.04}_{-0.05}$
Filler blocks	$7.1^{+8.2}_{-7.0}$	$8.1^{+9.2}_{-7.7}$
Filler foam	$0.79^{+0.43}_{-0.41}$	$0.95^{+0.50}_{-0.47}$
Neck PMTs	$0.038^{+0.022}_{-0.032}$	$0.060^{+0.036}_{-0.049}$
Total	$10.6^{+8.3}_{-7.1}$	$13.6^{+9.4}_{-7.8}$
	ROI prediction	
Component	(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
Total	$0.060^{+0.104}_{-0.045}$	$0.073^{+0.119}_{-0.048}$

WIMP ROI Events (no fiducial cut applied)



Surface and bulk alphas





- ^{222}Rn, ^{218}Po, ^{214}Po tagged from time delayed coincidences (α-α, β-α)

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Experiment	^{222}Rn Activity	Target
DEAP-3600	0.153 uBq/kg	LAr
PandaX-II	6.6 uBq/kg	LXe
LUX	66 uHz/kg	LXe
XENON-1T	10 uBq/kg	LXe

short-lived α-decay	^{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
-decays	^{210}Po TPB & AV surface	(0.26 ± 0.02) mBq/m^2
	^{210}Po AV (bulk)	(2.82 ± 0.05) mBq