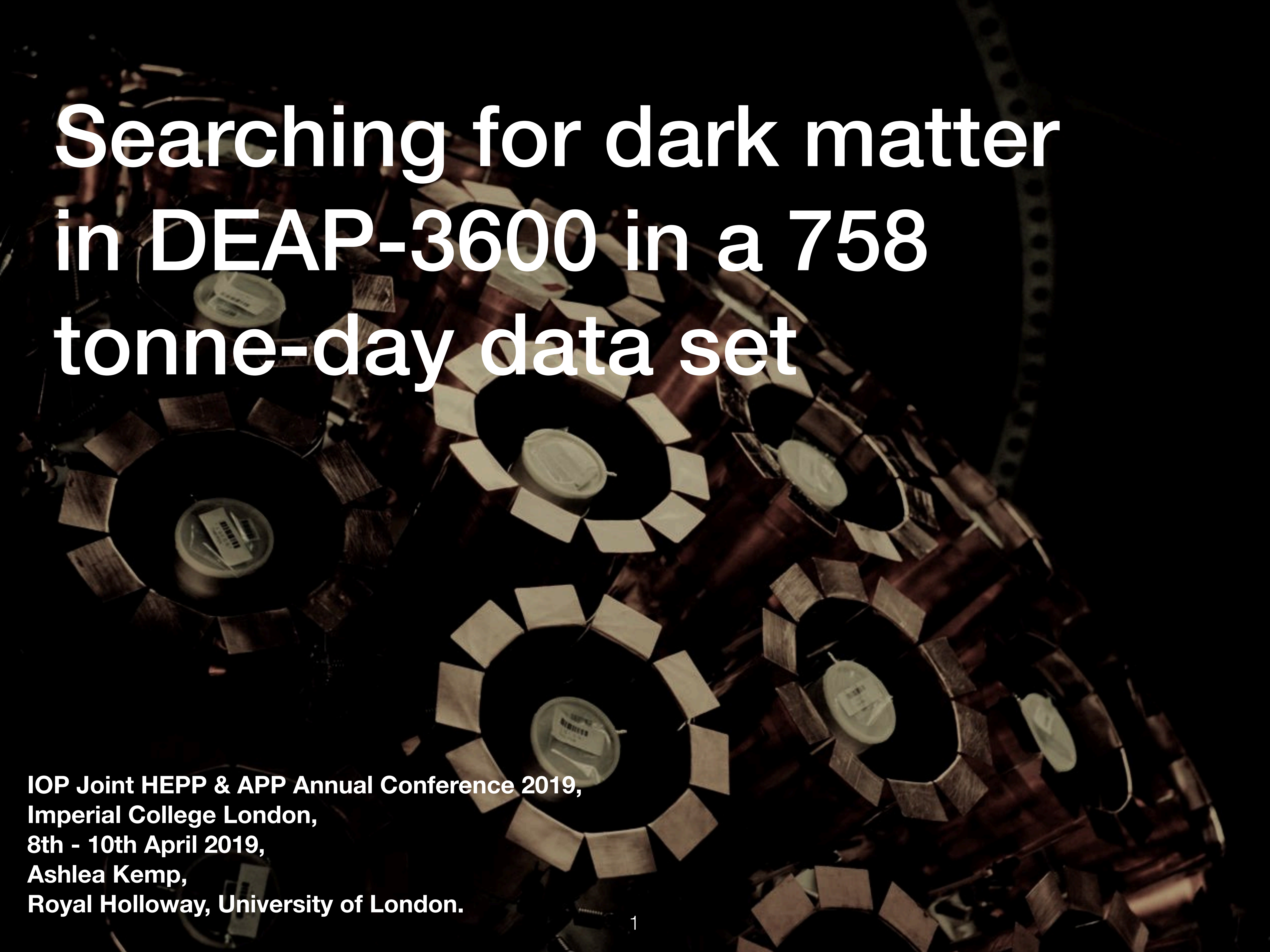
Searching for dark matter in DEAP-3600 in a 758 tonne-day data set



IOP Joint HEPP & APP Annual Conference 2019,
Imperial College London,
8th - 10th April 2019,
Ashlea Kemp,
Royal Holloway, University of London.

Outline

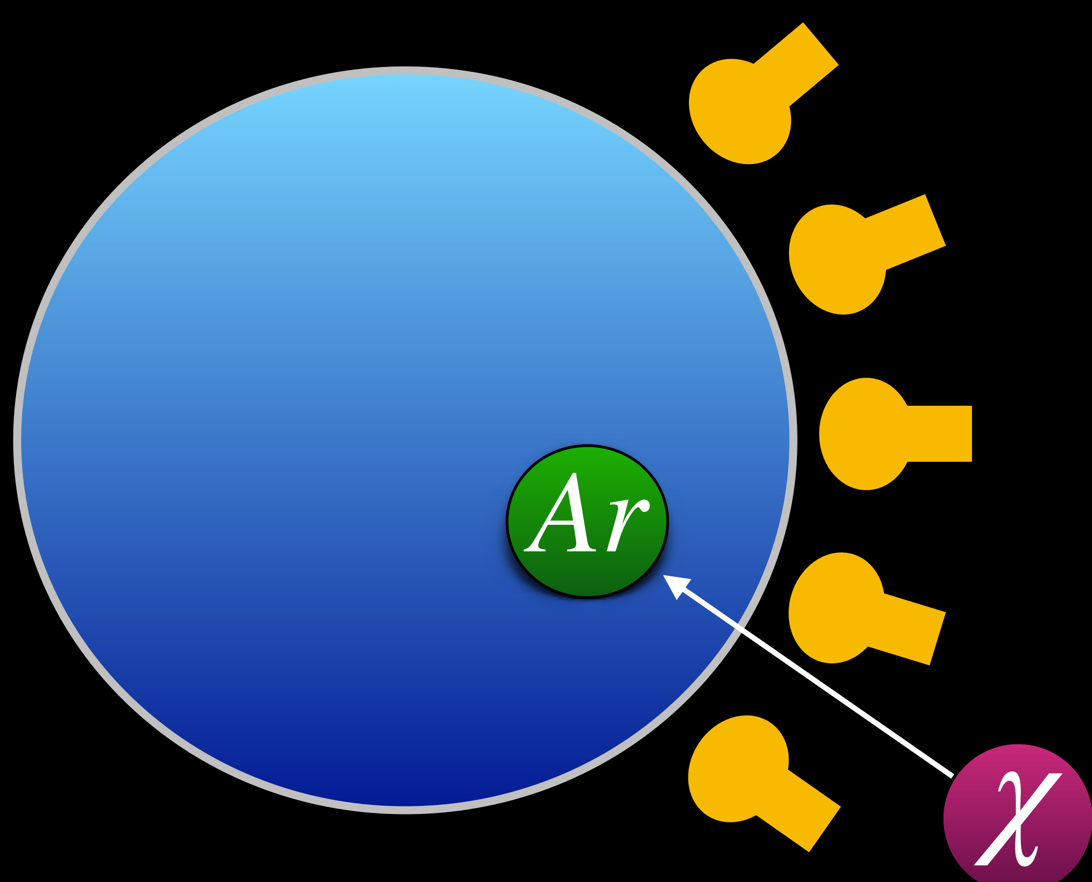
- The DEAP-3600 detector
- Latest results from DEAP-3600
- The Profile-Likelihood Ratio
    - Methodology
    - Implementation for DEAP-3600
- Conclusions & Outlook

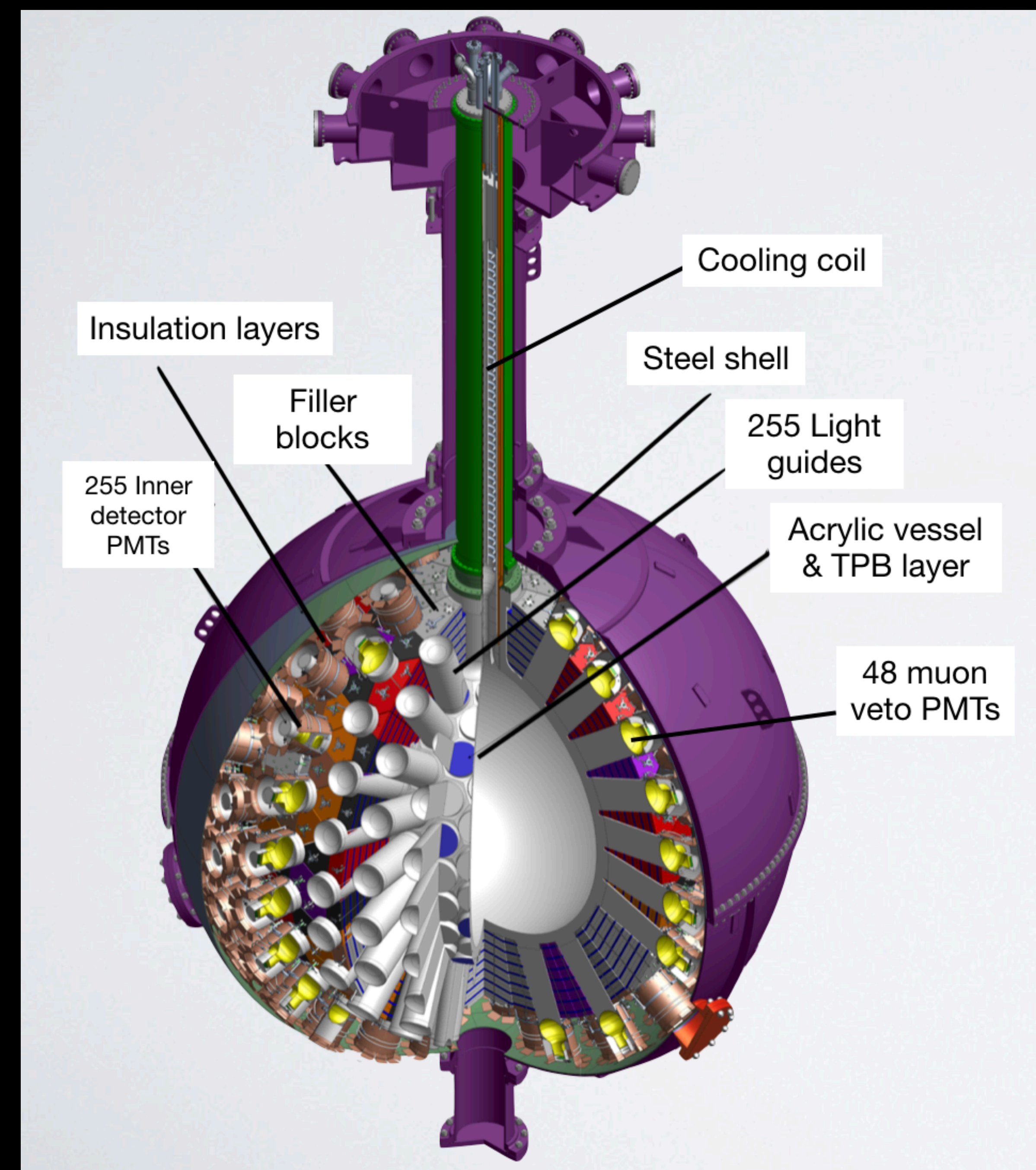
https://lovestats.wordpress.com/dman/

The DEAP-3600 detector

- Dark matter Experiment using Argon Pulse-shape discrimination,
- Single-phase Liquid Argon (LAr) scintillation light detector, holding 3279 kg of target LAr,
- Optimised for collection of scintillation light emitted from recoiling Ar nuclei after interaction with dark matter particle (WIMP),

  ➡ 128 nm VUV scintillation photons (ɣ) wavelength shifted to 420 nm by TPB layer for PMT detection (~75% coverage).





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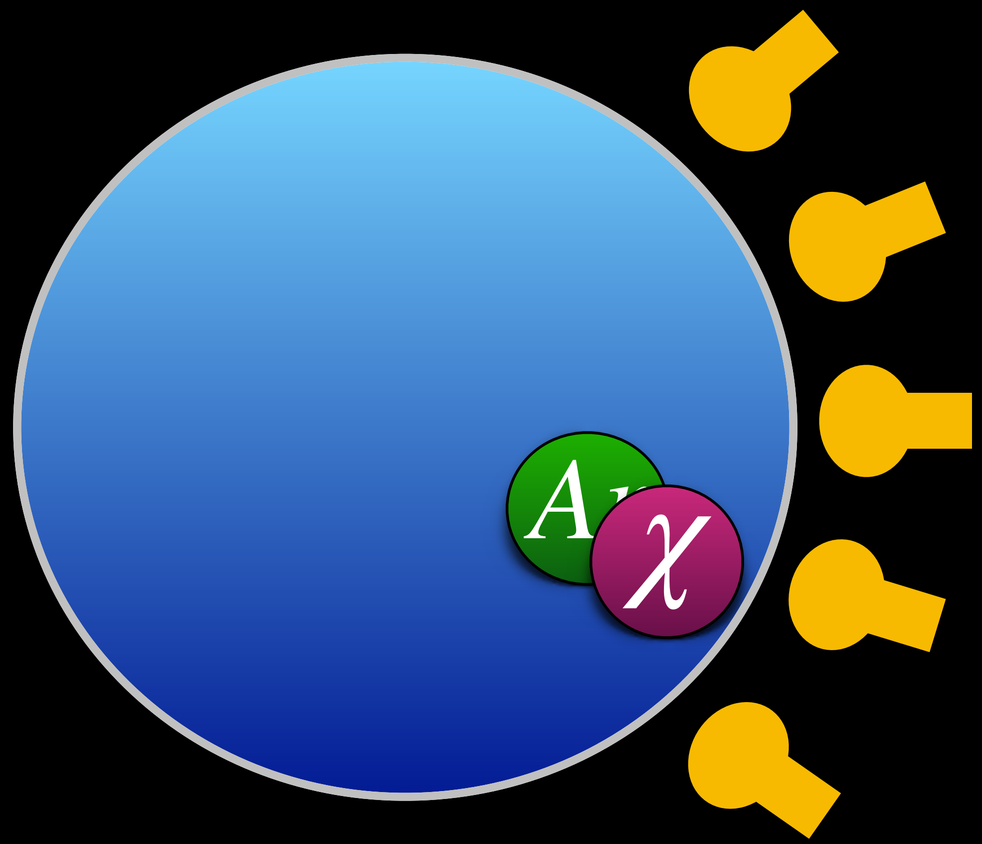

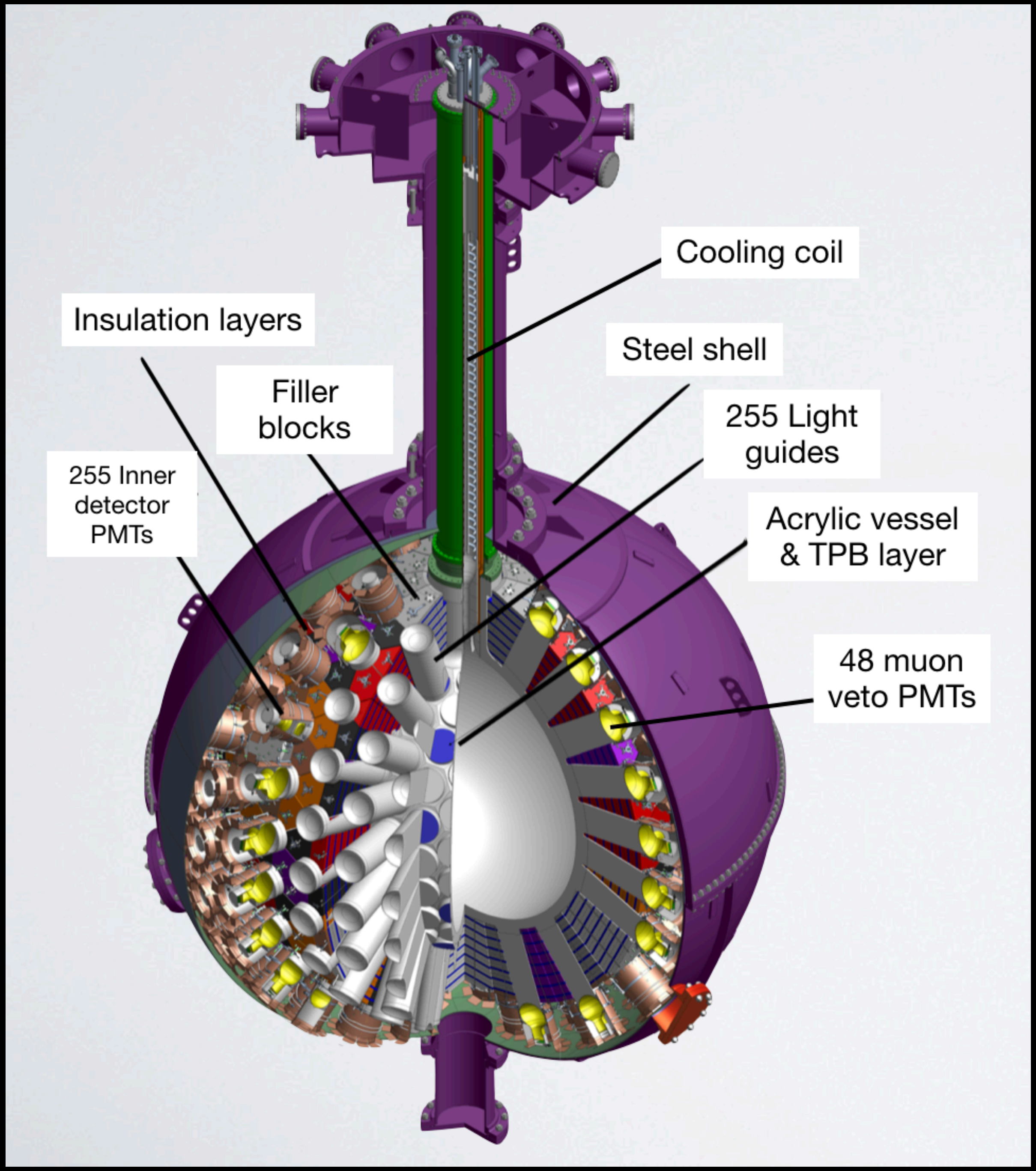

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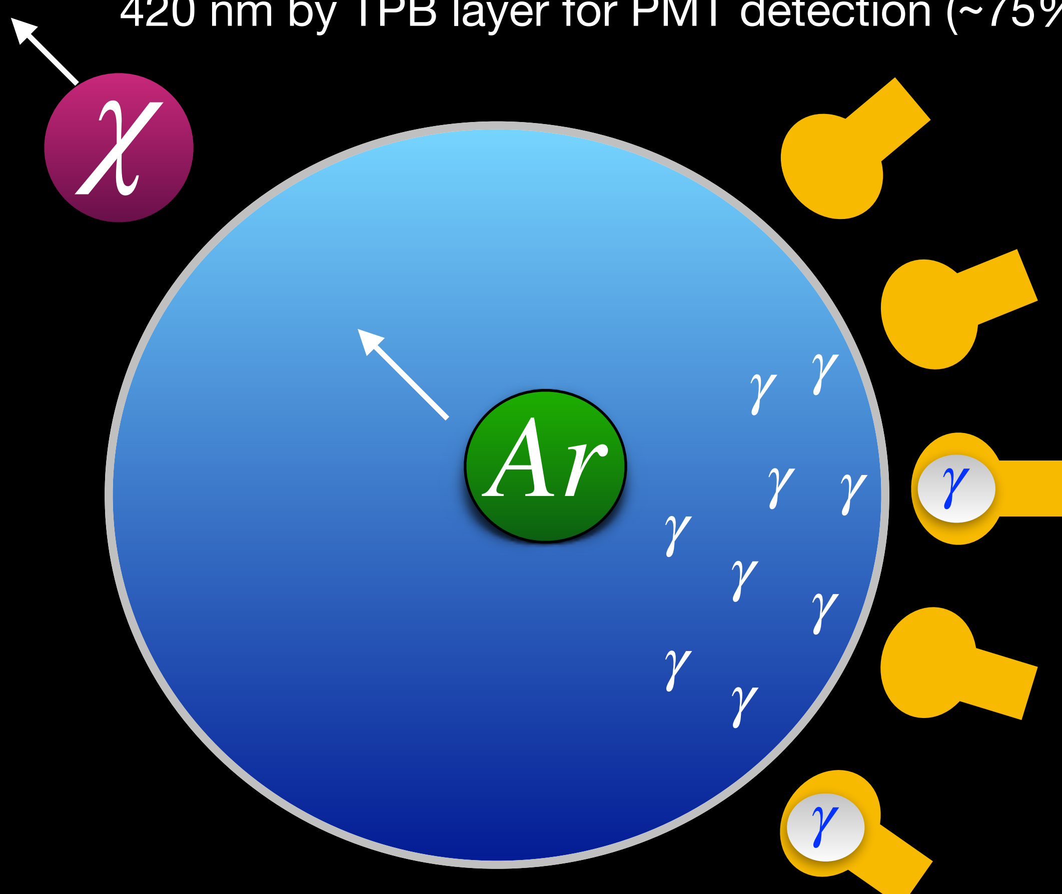

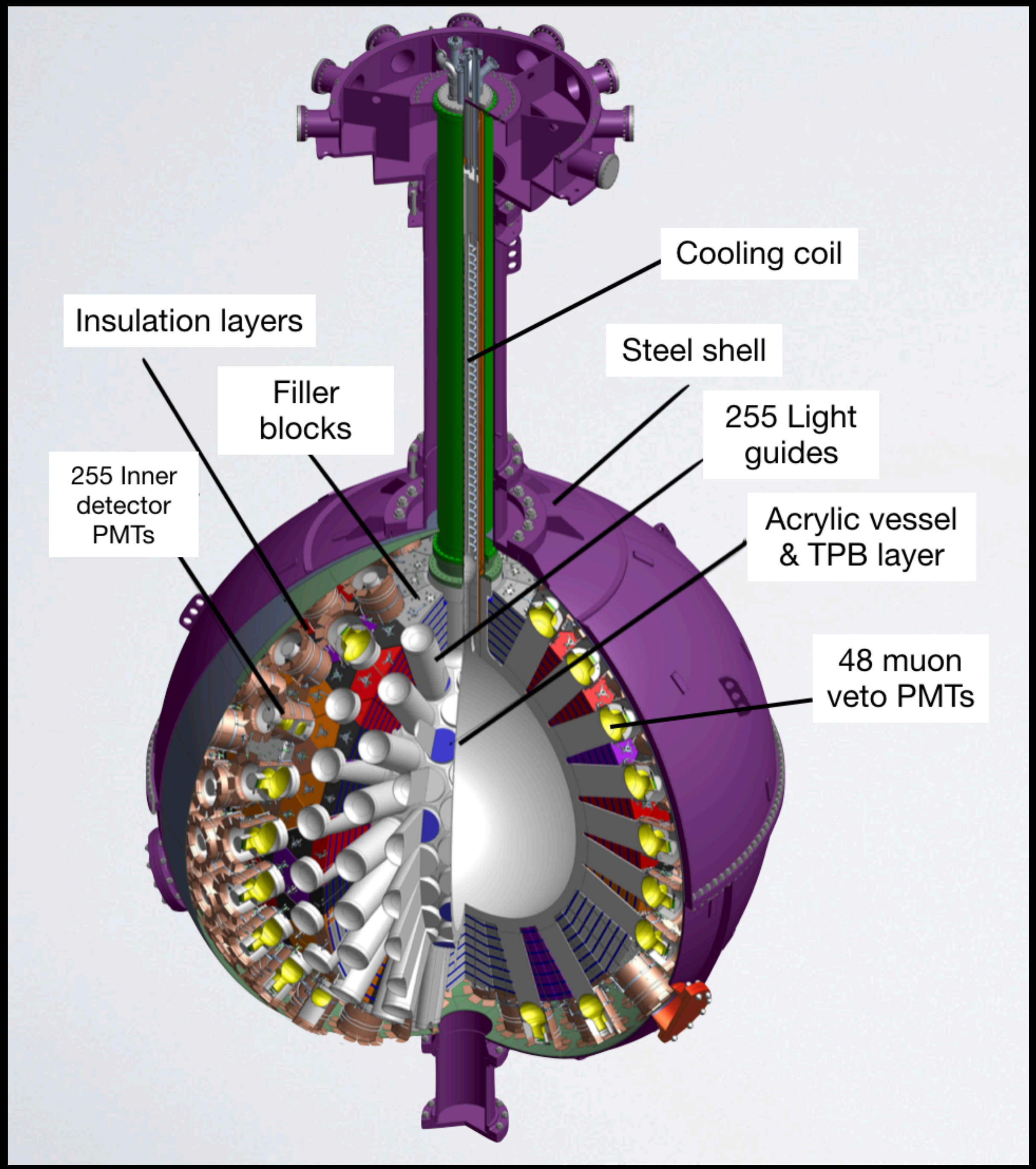

Epoch of DEAP-3600

2006 — Initial design phase begins

May 2016 — First injection with purified argon

Aug 2016 — First physics data collected*

Nov 2016 - Dec 2017 — Continue to collect physics data (open)**

Jan 2018 - Present — Collect further physics data with blinding scheme (20% open)

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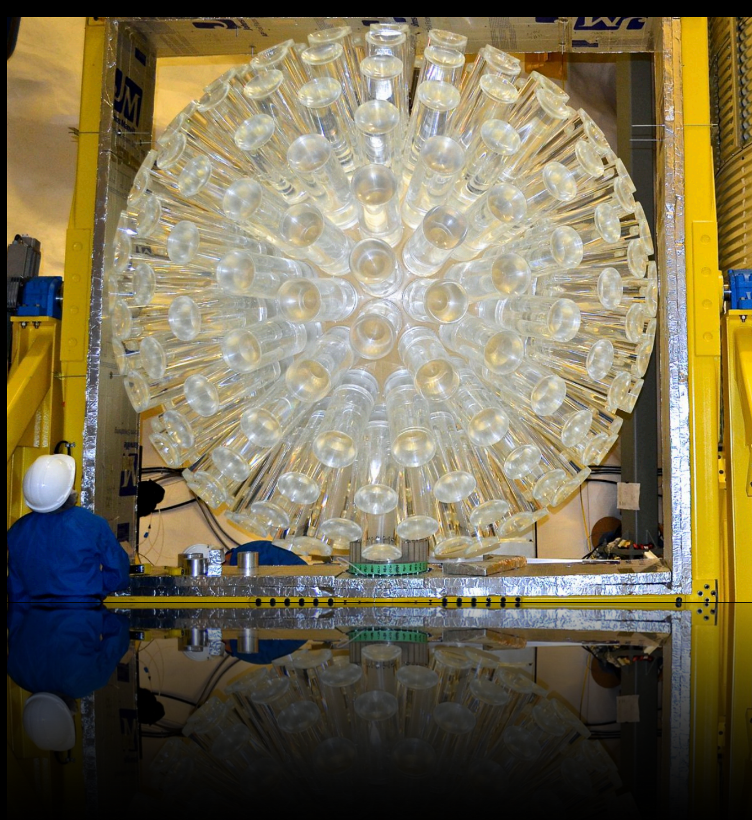
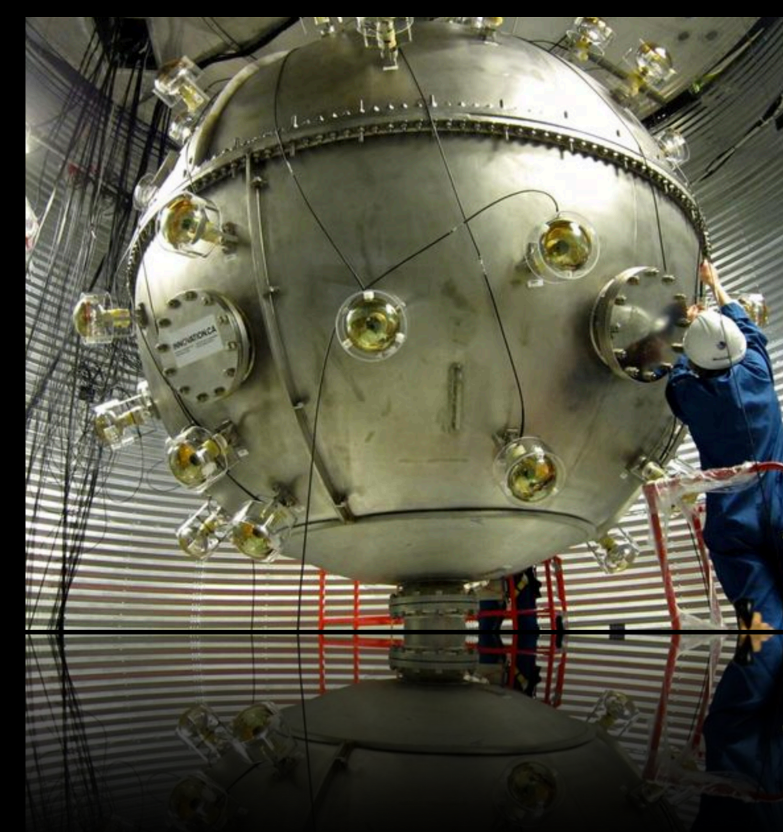




"Design and Construction of the DEAP-3600 Dark Matter Detector": Astropart. Phys. 108 (2019) 1-23.

* Data used for first dark matter search: Phys. Rev. Lett. 121, 071801 (2018),

** Data used for second dark matter search: https://arxiv.org/pdf/1902.04048.pdf (2019),

DEAP-3600 Collaboration

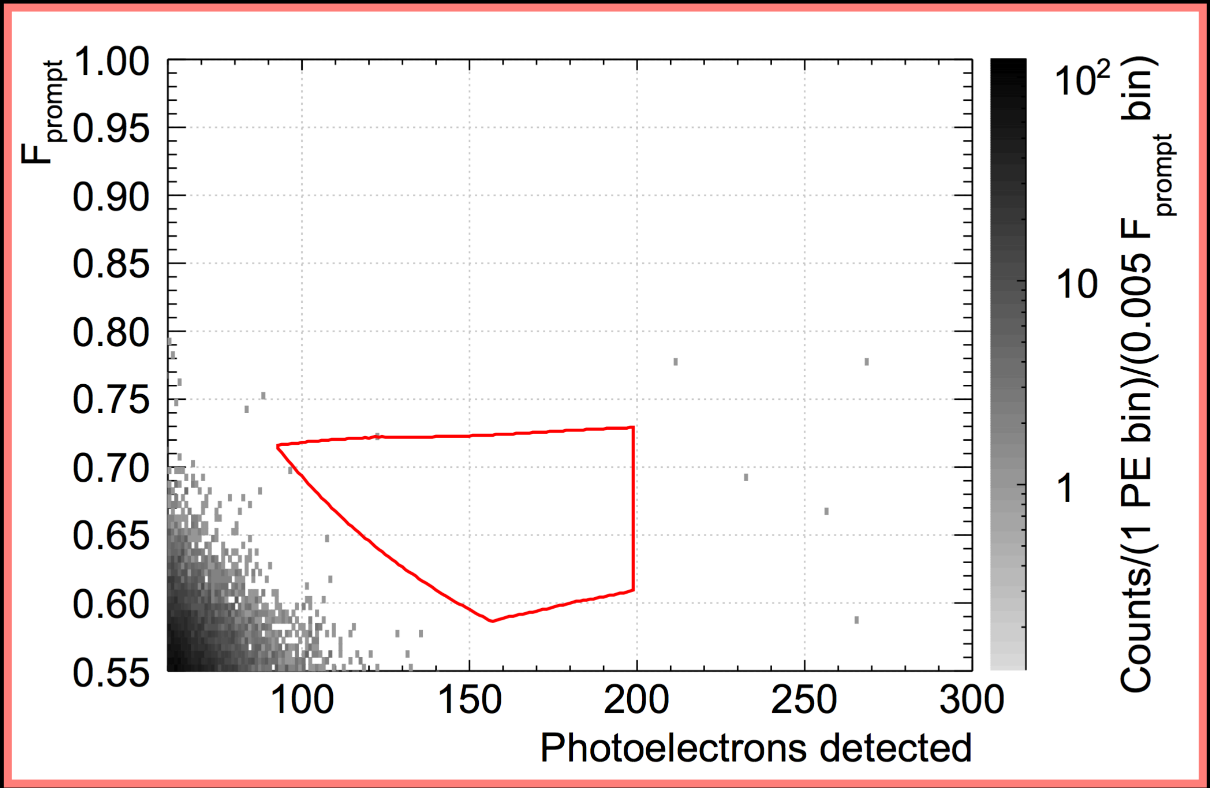
80+ researchers

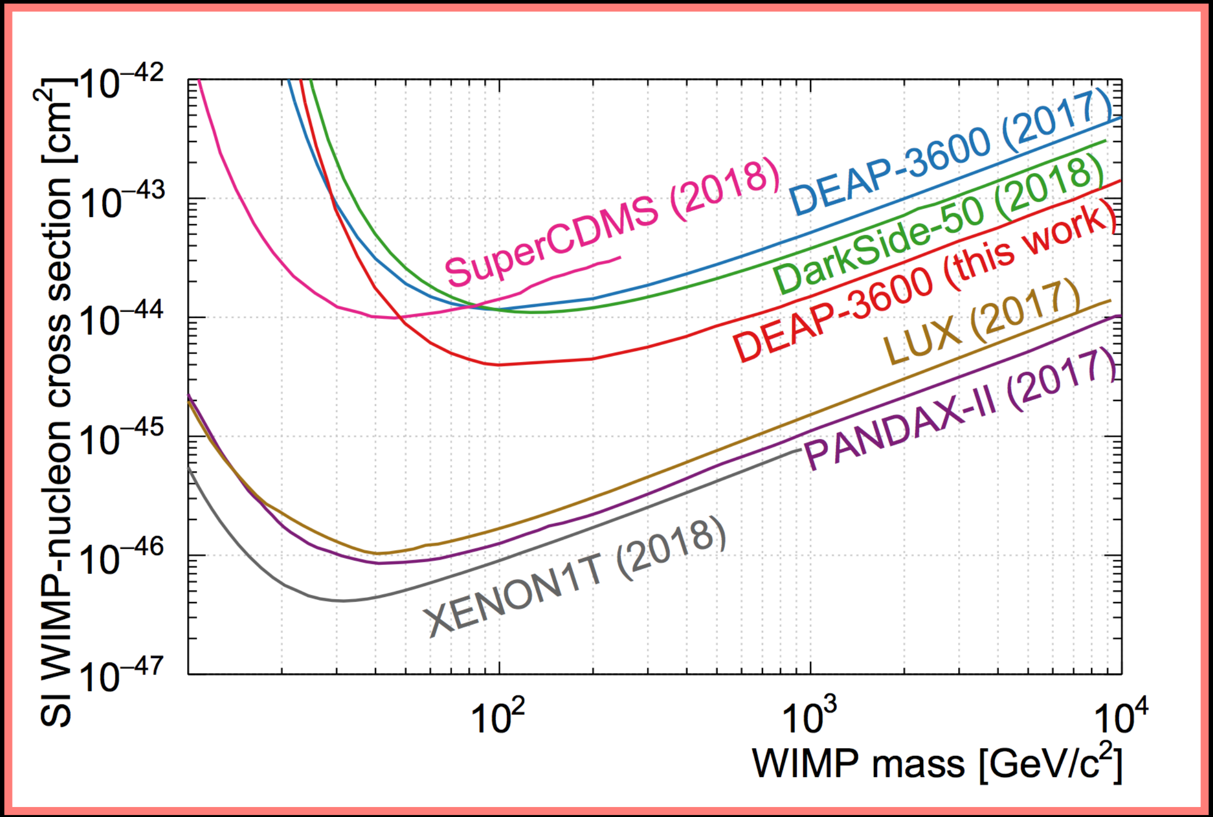
New WIMP limit

WIMP ROI driven by signal and background models,

2D WIMP ROI drawn in {PE, Fprompt},

Background expectation < 1.





New limit on WIMP-nucleon spin-independent cross section on a LAr target of 3.9 x 10^{-45} cm^2 for a 100 GeV WIMP at 90% C.L,

Leading exclusion curve for argon detectors.

R. Ajaj et al.
https://arxiv.org/pdf/1902.04048.pdf

Profile-Likelihood Ratio

- One can build a *likelihood* function, which describes the likelihood of observing a cross-section $\boldsymbol{\sigma}$ given some input data & set of nuisance parameters, on which both signal & background PDFs depend on, $\mathscr{L}(\boldsymbol{\sigma} \mid \{\boldsymbol{\theta}\})$,

- Maximise function in two configurations: fixed test cross-section (conditional) and free test cross-section (unconditional), allowing nuisance parameters to float in minimisation,

  ➡ 'Profiling' over the systematic uncertainties,

- Define Profile-Likelihood Ratio (PLR), λ, as ratio of conditional to unconditional likelihood.

$$\lambda = \frac{\mathscr{L}(\sigma; \{\hat{\hat{\theta}}\})}{\mathscr{L}(\hat{\sigma}; \{\hat{\theta}\})}$$

Test statistic

- Can define a test statistic, q, which considers only the case where best fit cross-section value is less than the one being tested,

  ➡ For the case of an exclusion,

$$q = \begin{cases} -2\ln\lambda, & \hat{\sigma} < \sigma \\ 0, & \hat{\sigma} > \sigma \end{cases}$$

- Obtain test statistic, q_{obs}, for observed data, such that one can define the p-value as the following,

$$p = \int_{q_{obs}}^{\infty} f(q\,|\,H_{\sigma})\; dq$$

- Generate set of 'fake' datasets/ pseudo-experiments (PSE) using random values for observables & nuisance parameters,

  ➡ Maximise likelihoods for each PSE, build distribution $f(q|H_{\sigma})$,

  ➡ Observables/ nuisance parameters drawn randomly from PDFs,

- Find value of test cross-section which satisfies p = 0.1 to exclude dark matter above test cross-section at 90% C.L.

The Likelihood Function

- Likelihood function used for DEAP-3600 described by product of three terms,

$$\mathscr{L}(\sigma \,|\, \{\theta\}) = \mathscr{L}_{PDFs}(\sigma \,|\, \{\theta\}) \cdot \mathscr{L}_{constraint}(\{\theta\}) \cdot \mathscr{L}_{sideband}(\{\theta\})$$

- Unbinned likelihood term,
- Encodes probability of observing events, *j*, in three-dimensional parameter space {PE, PSD, R} in signal and background PDFs, *i*,
- Additional term compares expected event count from PDFs to observed event count in WIMP search region.

$$\mathscr{L}_{PDFs}(\sigma; \{\theta\}) = \mathrm{Pois}(N_{obs} \,|\, N_{exp}) \cdot \prod_{i=1}^{N_{PDFs}} \left(\frac{N_{exp,i}}{N_{exp}} \sum_{j=1}^{N_{events}} f_i(PE_j, PSD_j, R_j; \{\theta\}) \right)$$

The Likelihood Function

- Likelihood function used for DEAP-3600 described by product of three terms,

$$\mathscr{L}(\sigma \mid \{\theta\}) = \mathscr{L}_{PDFs}(\sigma \mid \{\theta\}) \cdot \mathscr{L}_{constraint}(\{\theta\}) \cdot \mathscr{L}_{sideband}(\{\theta\})$$

- Each nuisance parameter constrained by ‘constraint’ PDF, typically Gaussian,
- Encodes probability of observing value of nuisance parameter by penalising values proportionally to constraint uncertainty,
- Total term: product of all constraint PDFs.

$$\mathscr{L}_{constraint}(\{\theta\}) = \prod_{j=1}^{n_\theta} f(\theta_j)$$

- Internal calibration detector data (Argon-39 decay) used to construct sideband term,

  ➡ Ar39 decays occur uniformly across LAr volume, approximately infinite statistics…

- Can help reduce detector response systematics, such as light yield/ energy resolution,
- Compares expected event count from Ar39 PDF to observed event count in each {PE, PSD, R} bin, indexed by i, j, k, outside of WIMP search region.

$$\mathscr{L}_{sideband}(\{\theta\}) = \prod_{i}^{N_i} \prod_{j}^{N_j} \prod_{k}^{N_k} \mathrm{Pois}(N_{obs;i,j,k} \mid N_{exp;i,j,k})$$

Charge measurement

- First dimension of PLR is photoelectrons (PE): energy of event quantified in DEAP-3600 as charge detected by PMTs from scintillation photons,
- Bayesian PE-counting algorithm used to measure event's PE:

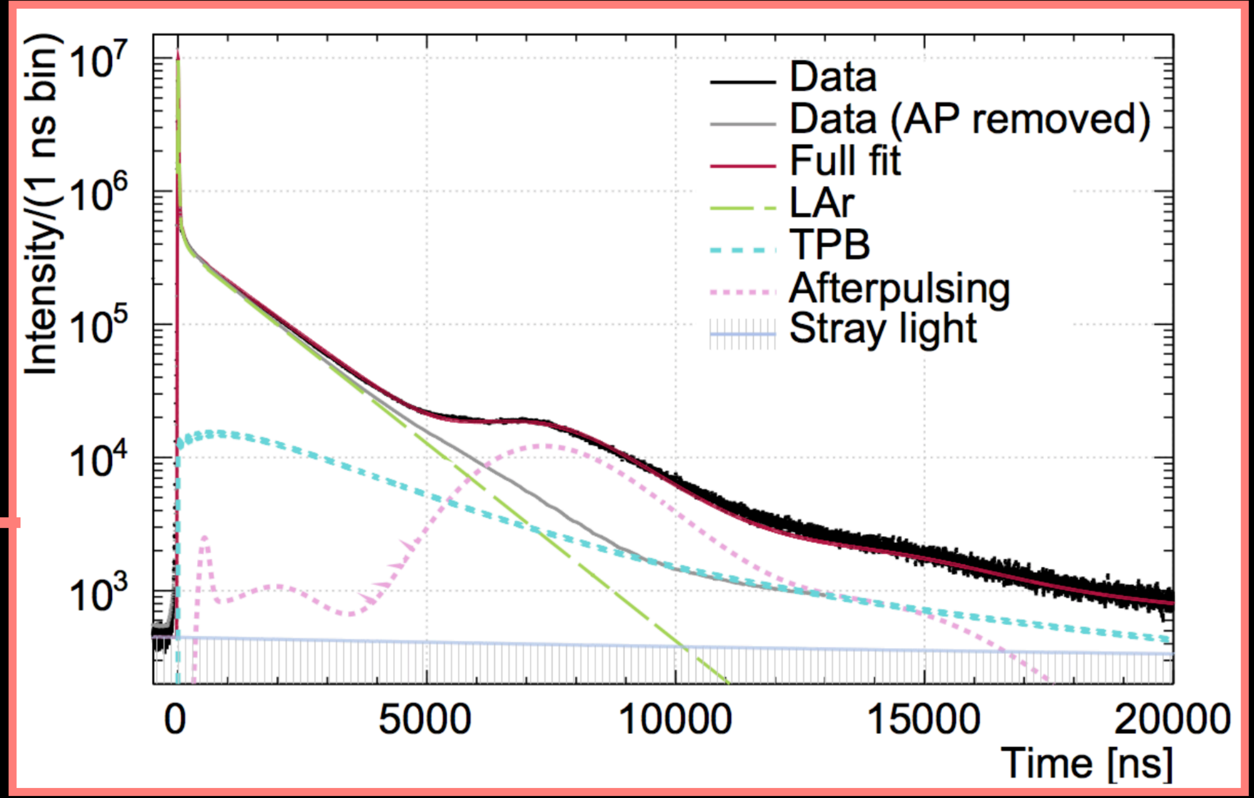
  ➡ Most likely number of PEs in a PMT pulse determined, factoring out charge produced by after-pulses (APs),

  ➡ Prior distribution based on the number of PEs & APs preceding a pulse, given its charge, the LAr scintillation time profile, the APs' time & charge distribution for relevant PMT,

  ➡ Prior and single-photo electron (SPE) charge distribution used to compute posterior distribution of the number of PEs.

- Algorithm applied to each SPE-calibrated PMT signal, summed over all signals in first 10μs of event -> determine # of PEs.

After AP-removal, pulse shape closely follows LAr scintillation & TPB fluorescence time profiles.



Pulse-shape discrimination

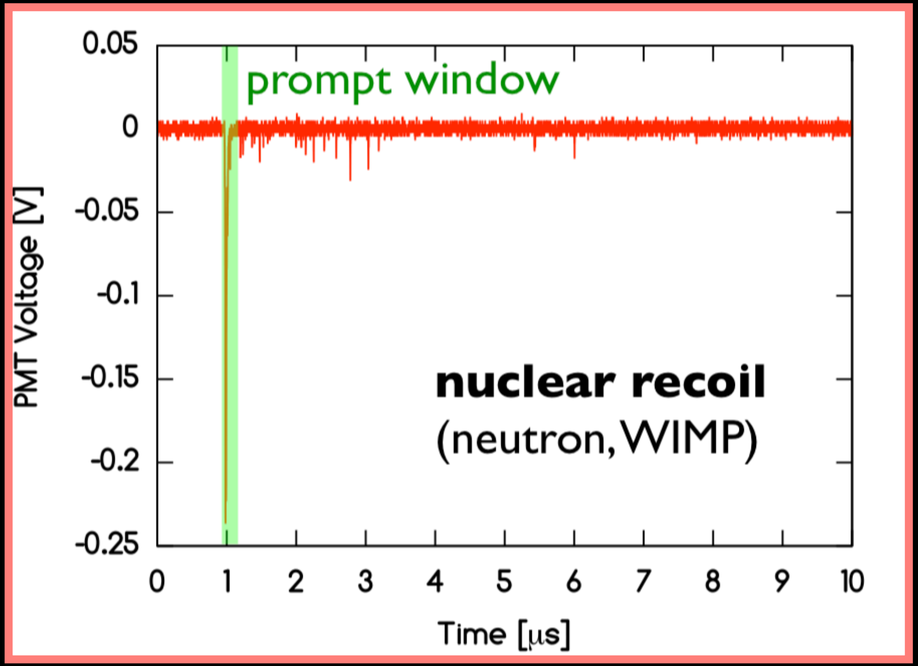
- Second dimension of PLR is PSD,
- Scintillation photons from recoils occurring in LAr arrive at the PMTs over a range of time,

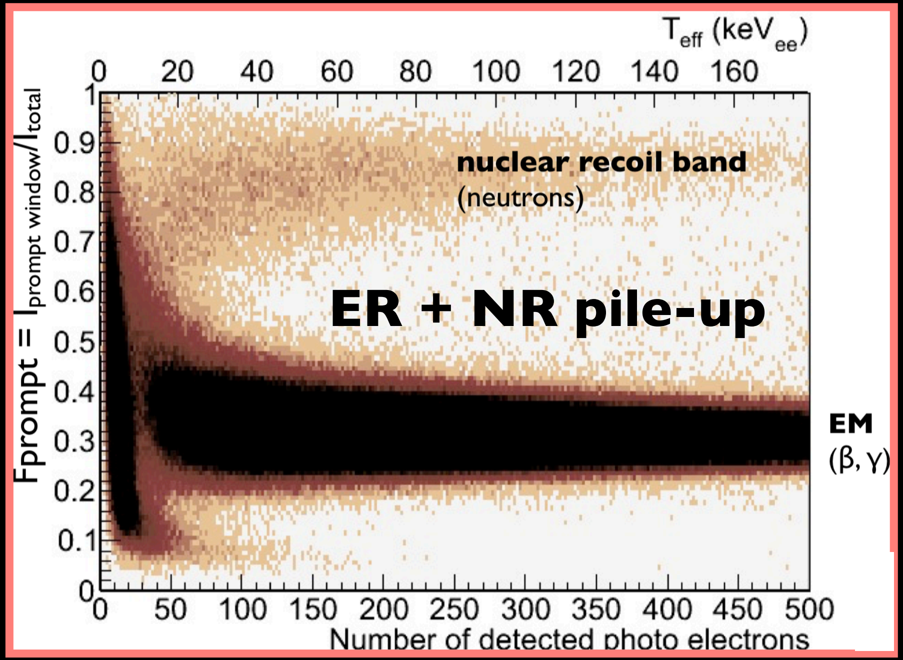
  ➡ More photons emitted, hence detected, later from electronic recoils ERs (β/ɣ) compared to nuclear recoils NRs (neutrons, WIMPs),

- Define PSD variable called Fprompt,

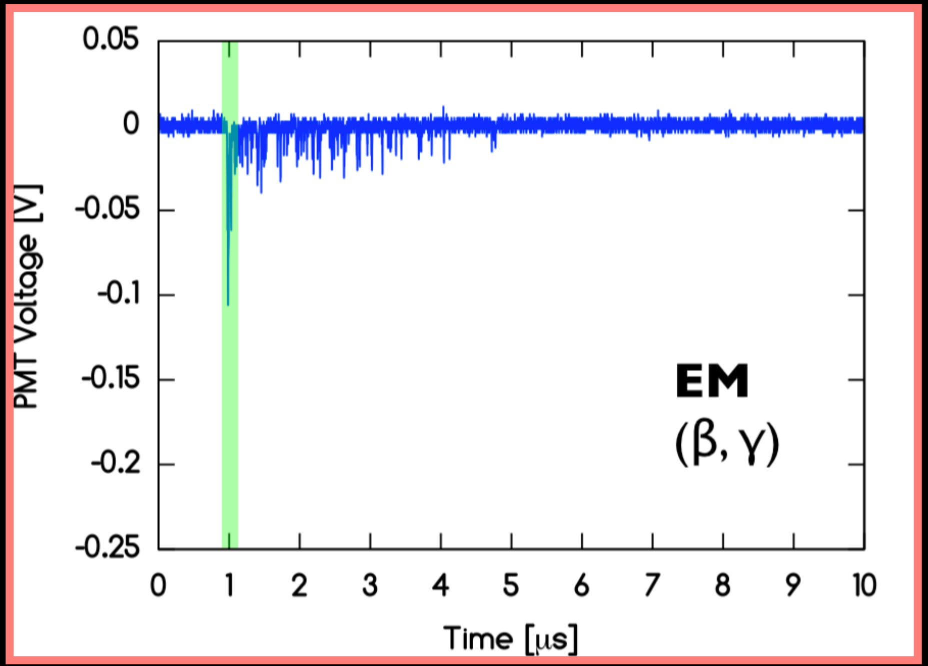
$$\text{Fprompt} = \frac{\sum_{t=-28ns}^{60ns} \text{PE}(t)}{\sum_{t=-28ns}^{10\mu s} \text{PE}(t)}$$

- Reject ERs with up to 10^{10} power.



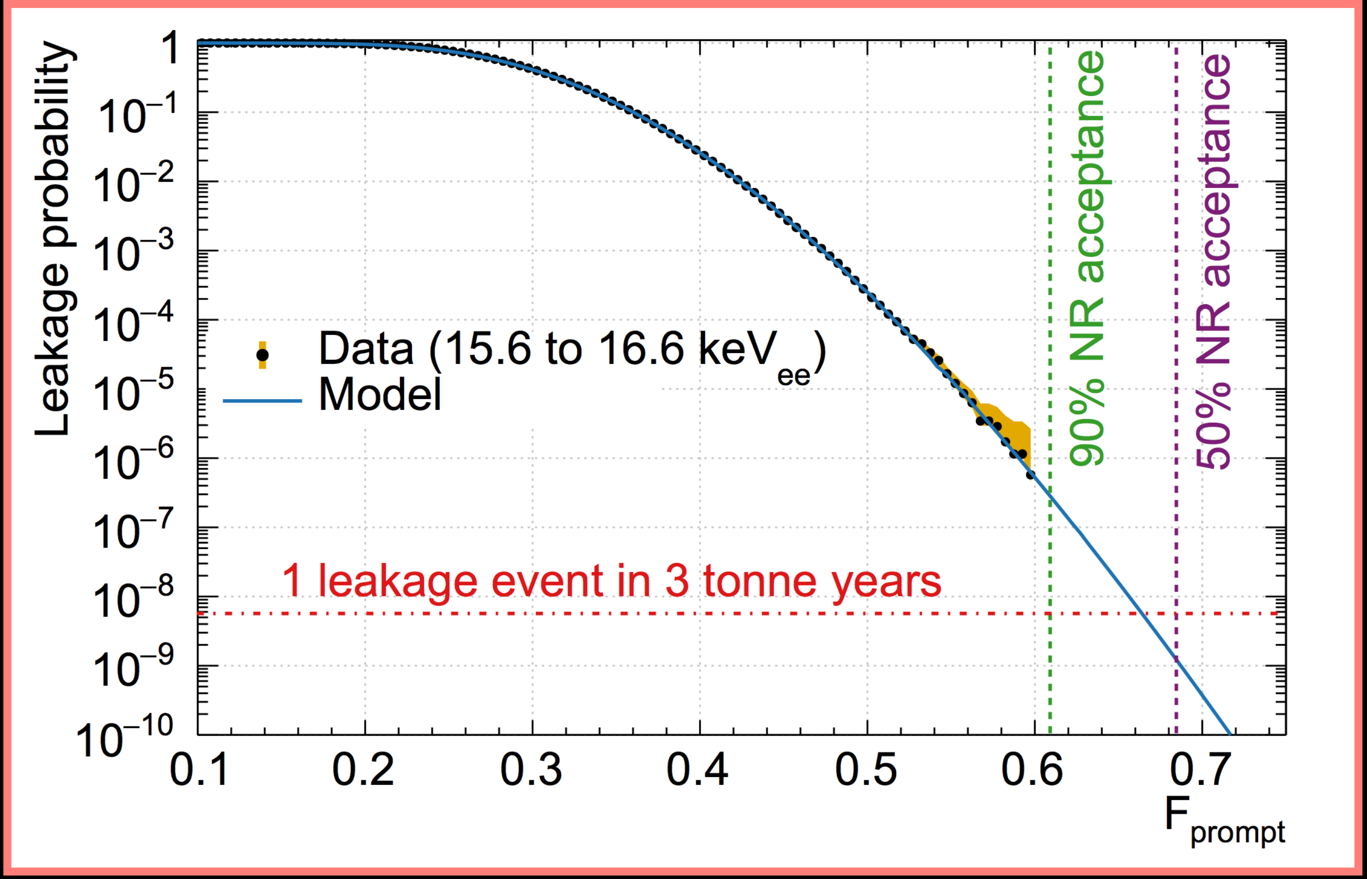


Data from AmBe (neutron emitter) run.



Pulse-shape discrimination

- Latest result demonstrates most powerful PSD between ERs and NRs in LAr,
- Efficient removal of significant source of background events in detector from the dark matter WIMP search.



'Leakage' probability: probability of ER type event being detected above given Fprompt value at the low energy WIMP threshold (15.6 keVee).

- Vertical lines show Fprompt values above which we expect 90% (green) and 50% (purple) of NRs,
- At 90% NR acceptance, PSD leakage probability of $2.8^{+1.3}_{-0.6} \times 10^{-7}$ at low energy threshold for WIMP search.

In energy range of WIMP search region [15.6 - 32.8 keVee], average PSD leakage probability of $4.1^{+2.1}_{-1.0} \times 10^{-9}$ at 90% NR acceptance.

Position reconstruction

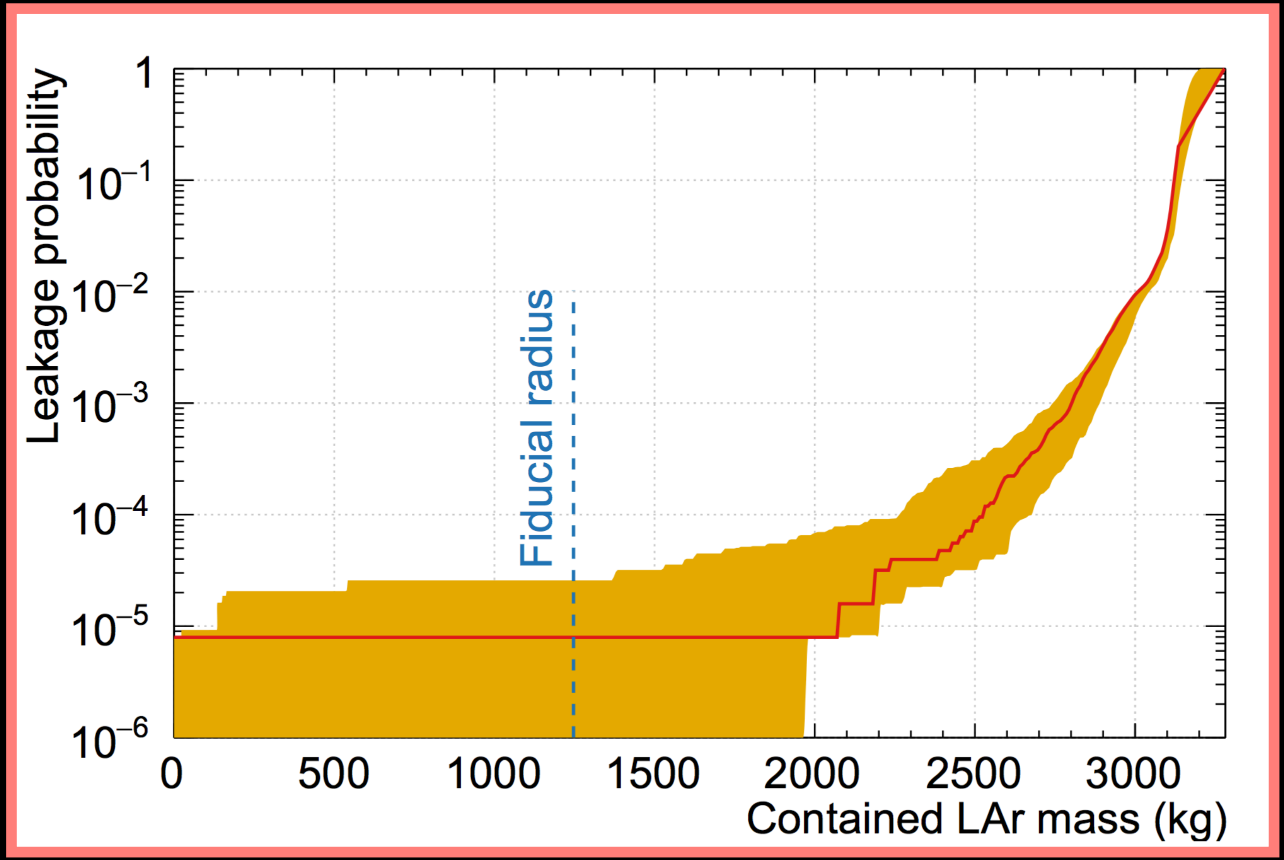
- Third and final dimension of PLR is the reconstructed radial position of the event, R,
  - ➡ Current analysis: apply R cut of 630 mm to remove Cherenkov, external neutron and surface α events that reconstruct with R > 630 mm,
  - ➡ Leakage probability at 630 mm radial cut from surface α decays into ROI is ~ 10^{-5}

- Two position reconstruction algorithms used:

  1. PE-based (spatial distribution of PMT hits),

  2. PE + timing (charge and time information of early pulses used to determine position).

- Validation of algorithms performed on Ar39 β decays in data distributed uniformly across LAr volume (see back-up slides).



'Leakage' probability of simulated α decays in WIMP PE range vs contained LAr mass as determined by events within given reconstructed radius.

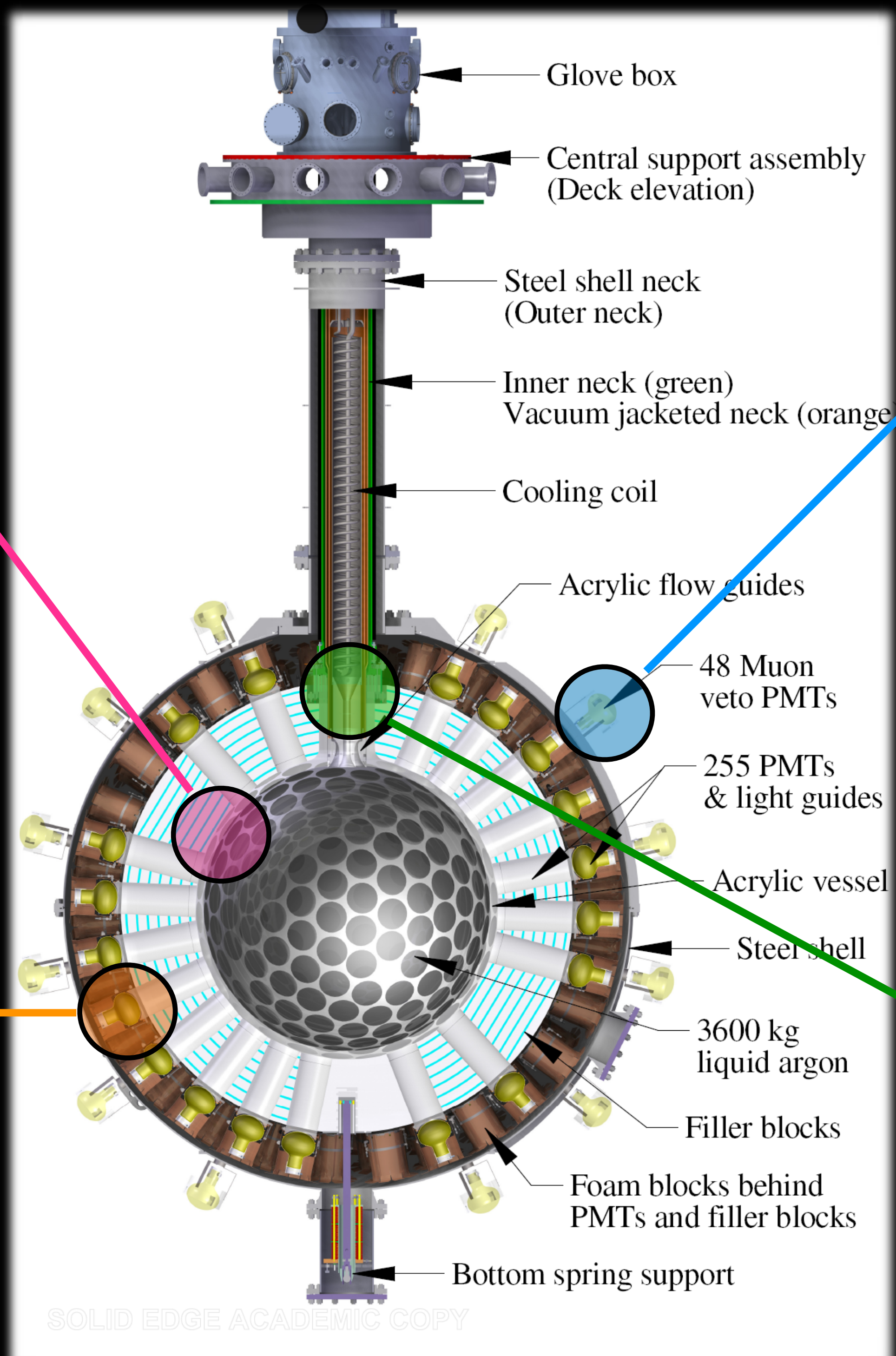
Backgrounds in DEAP-3600

LAr: Ar39 β decays, α decays from Rn222/ Rn220,

Acrylic Vessel (AV) surface: Po210 α decays.

PMTs & other detector components: Radiogenic neutrons, γ/β produced in glass…

➡ Cherenkov light produced in light guide acrylic.



External: Cosmogenic-induced neutrons produced inside water tank/ rock.

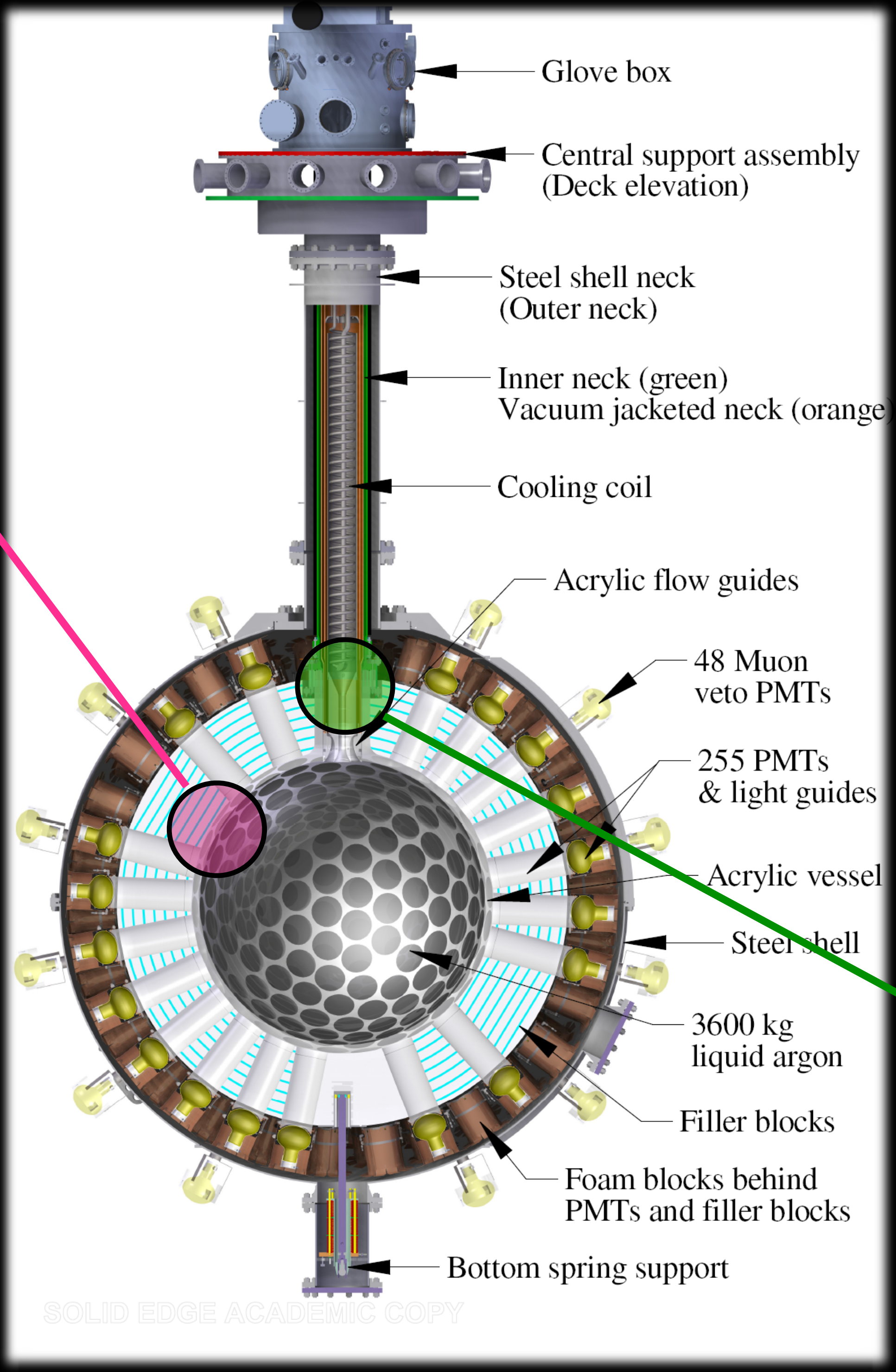
Neck: Po210 α decays through LAr 'film' on surface of acrylic flowguides, originating from long-lived Pb210 (Rn222).

See J. Walding's talk

Background Models

LAr: Ar39 β decays, α decays from Rn222/ Rn220,

Acrylic Vessel (AV) surface: Po210 α decays.



Neck: Po210 α decays through LAr 'film' on surface of acrylic flowguides, originating from long-lived Pb210 (Rn222).

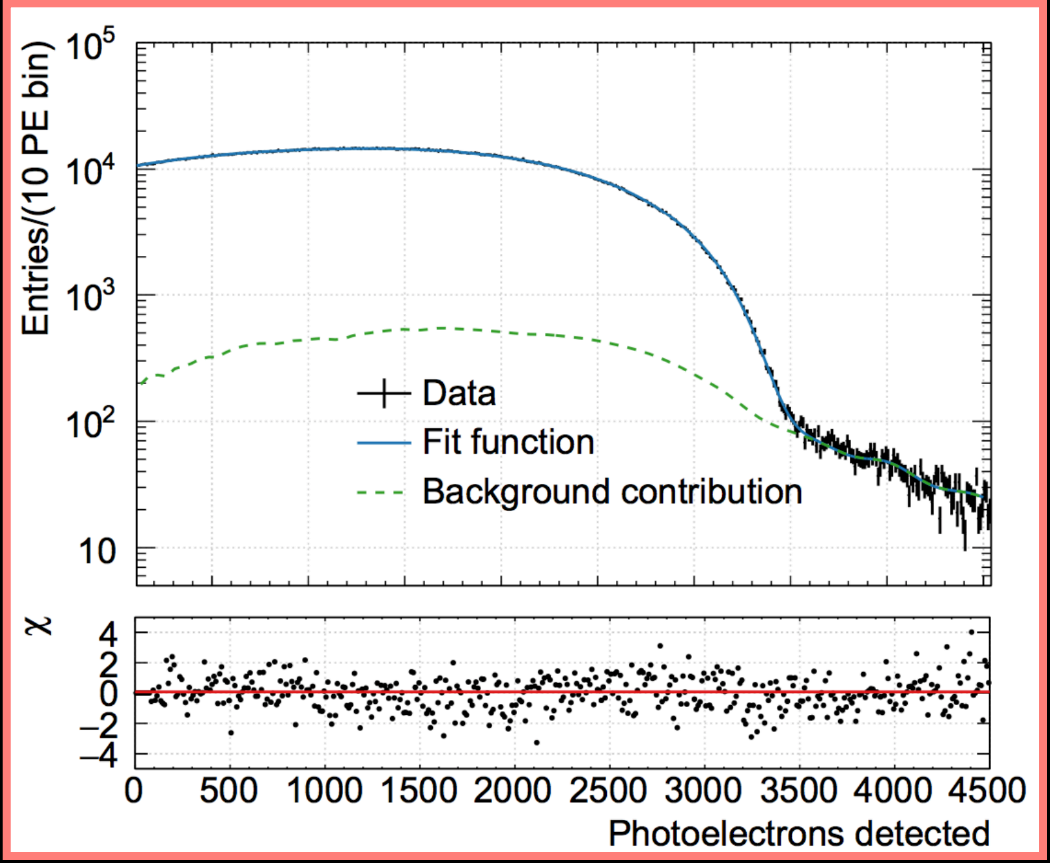
Background Models

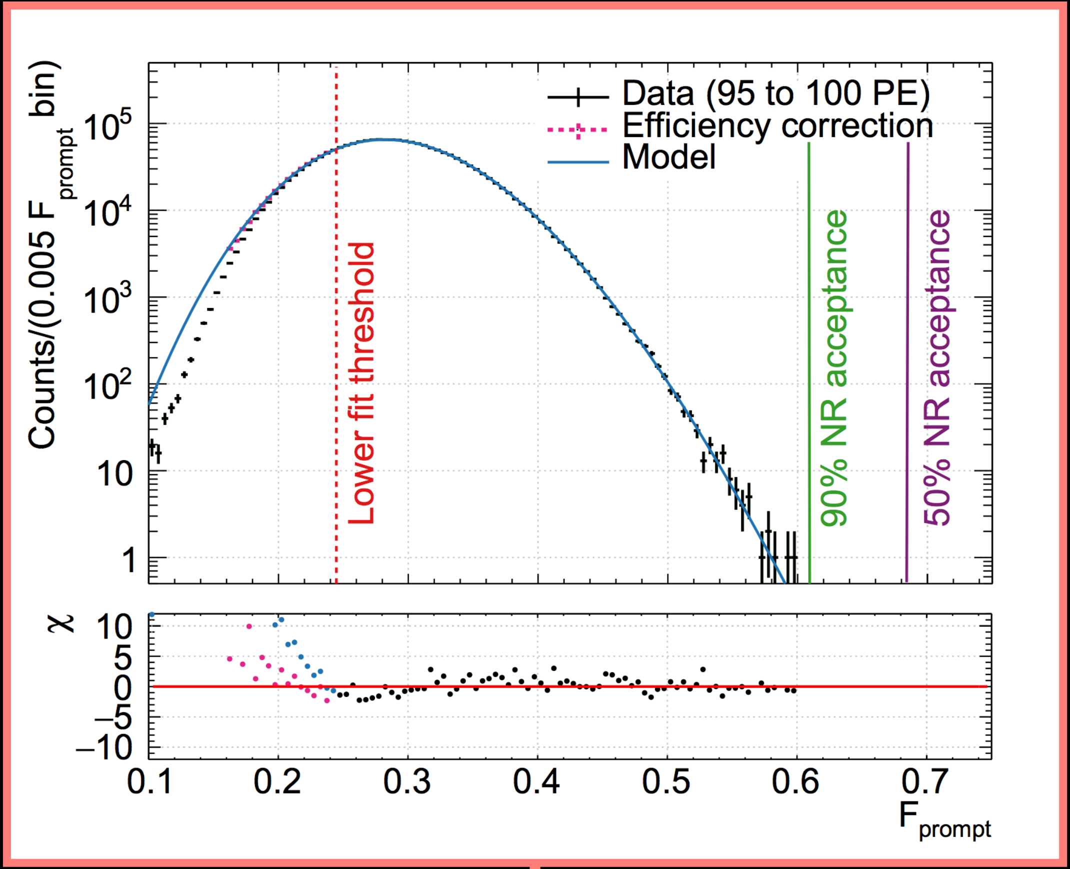
Data-driven

- Ar39 PE & PSD models,

➡ PE model: Theoretical Ar39 decay spectrum "convolved" with Gaussian response function.

➡ PE-dependent PSD model: Gamma function convolved with Gaussian smearing term.





- For Fprompt < 0.25, trigger efficiency < 100%,
  - ➡ Trigger efficiency based on prompt PE,
  - ➡ "Lose" events, data and model diverge.

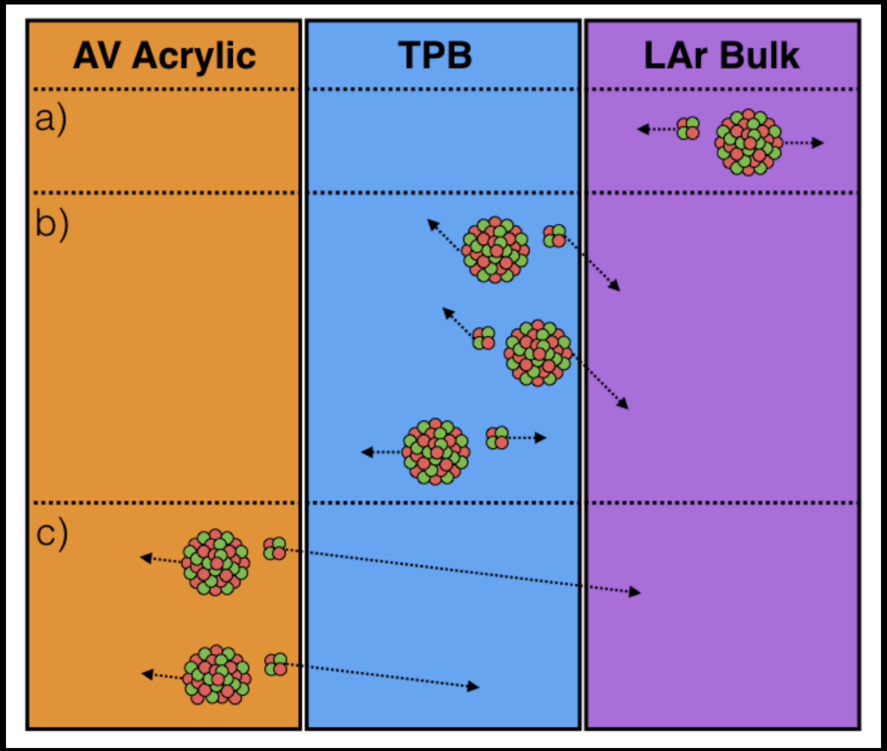
Background Models

MC-driven

- Ar39 PE-dependent Radial model,
- Surface alpha PE, PSD, Radial models,

  ➡ PE-dependent PSD & Radial empirical models,

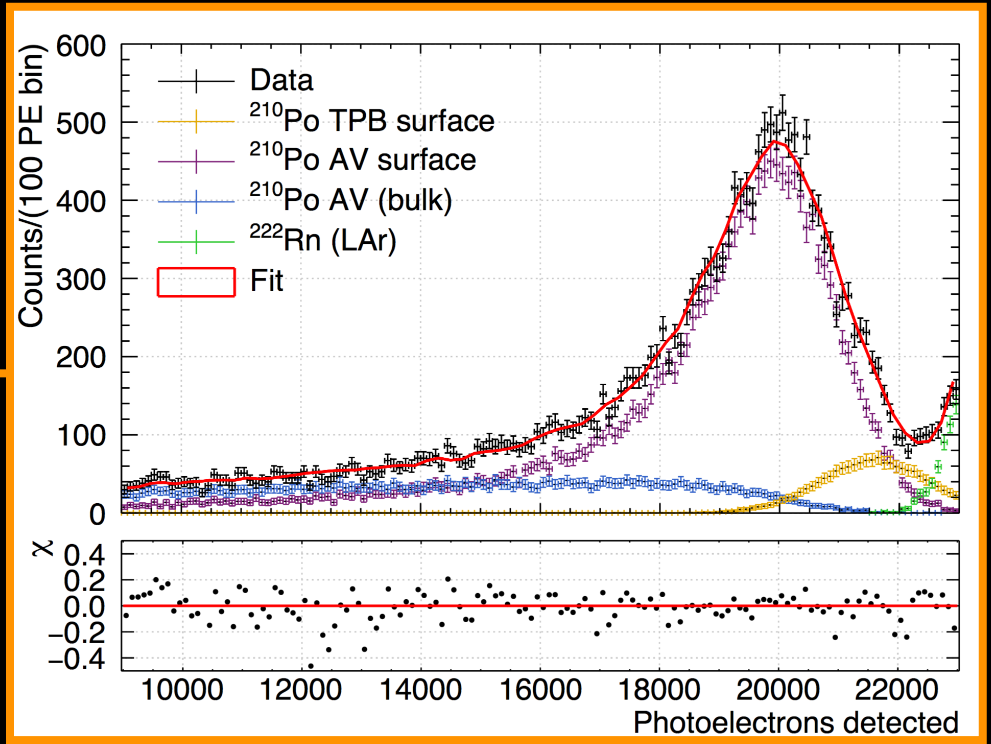
  ➡ Three locations (Acrylic Vessel bulk/ surface, TPB surface.



The three decay scenarios for α daughters in DEAP-3600 (decays in the LAr, the TPB layer or the AV acrylic)

Image taken from the PhD thesis of P. Giampa.

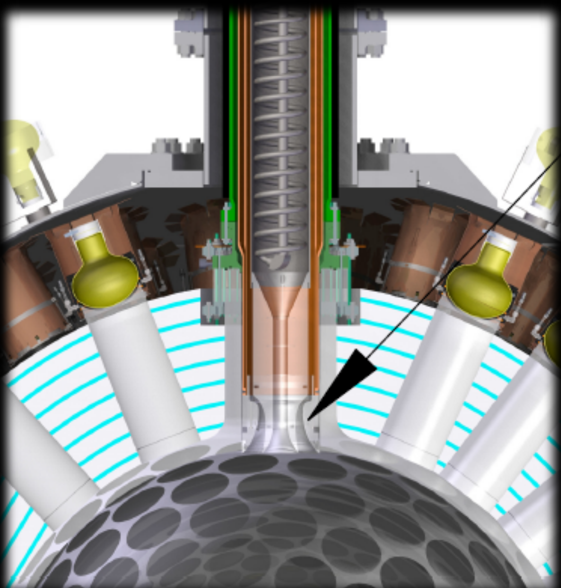
Example fit of MC models to surface α data

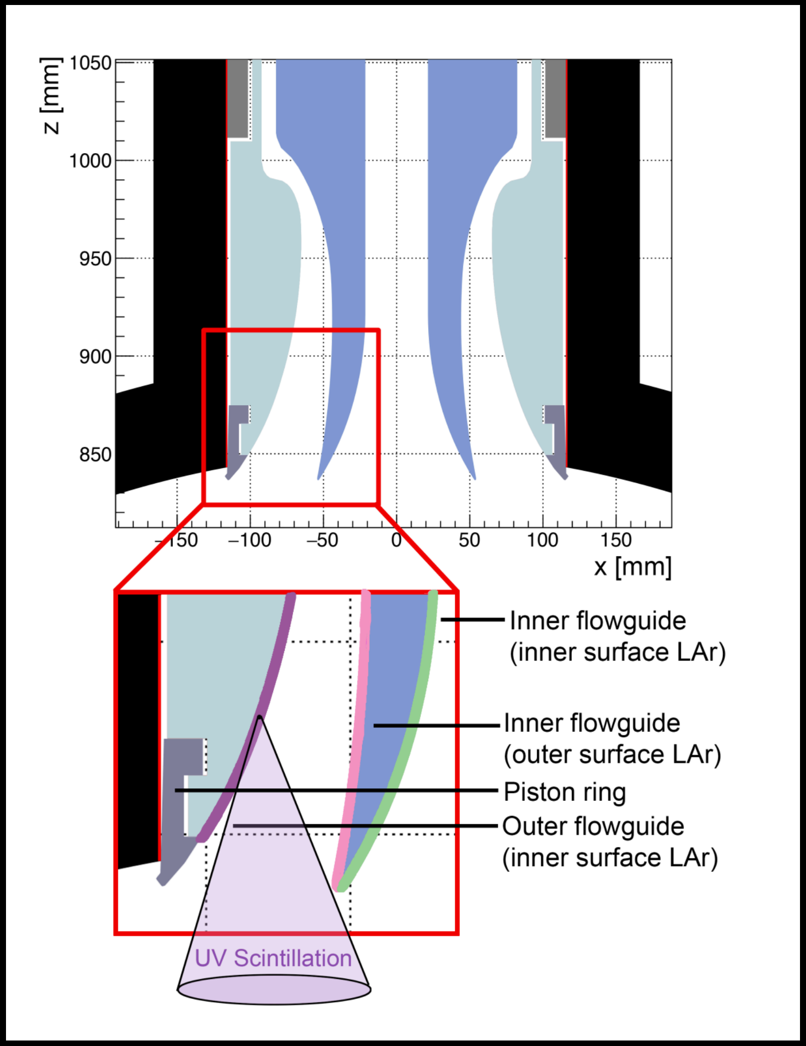


Background Models

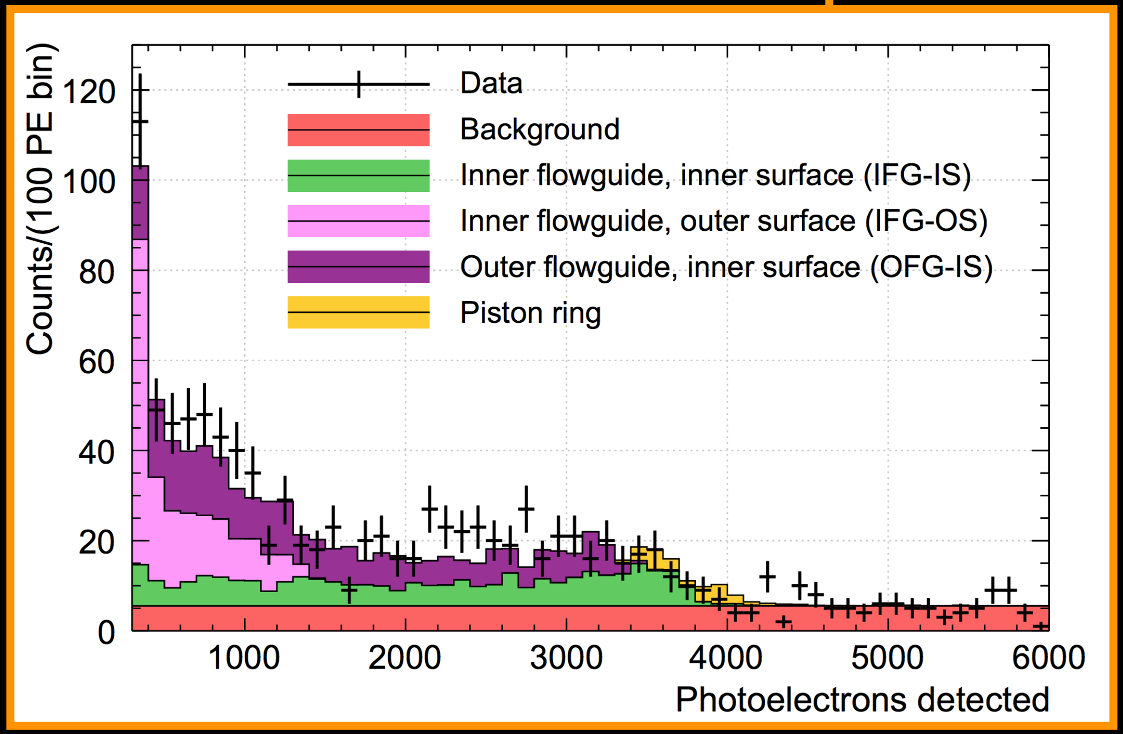
MC-driven

- Neck alpha PE, PSD, Radial models,
  - ➡ PE-dependent PSD & Radial empirical models,
  - ➡ Three locations (Inner Flowguide Inner Surface, Inner Flowguide Outer Surface, Outer Flowguide Inner Surface).





Example fit of MC models to neck α data

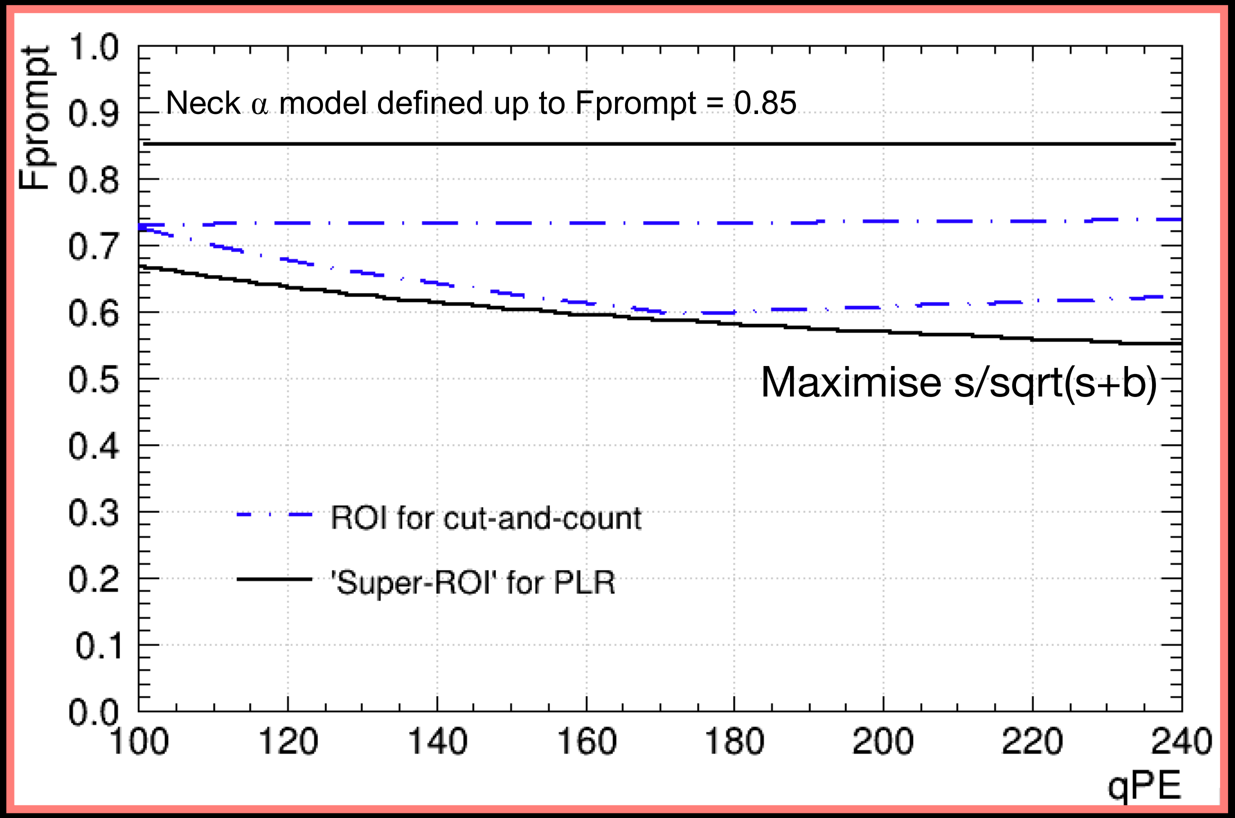


Boosting sensitivity

- Advantage of PLR over standard cut-and-count method?
  - ➡ Expand WIMP search region,
  - ➡ Constrain systematics in situ with data,
- More events allowed in WIMP search region without extra penalty to sensitivity.

"Super-ROI"

- Expand WIMP search region in PSD & R dimension,
  - ➡ Neck alphas normally limiting factor in PSD… but these can modelled,
  - ➡ Larger R -> More LAr -> Greater exposure.



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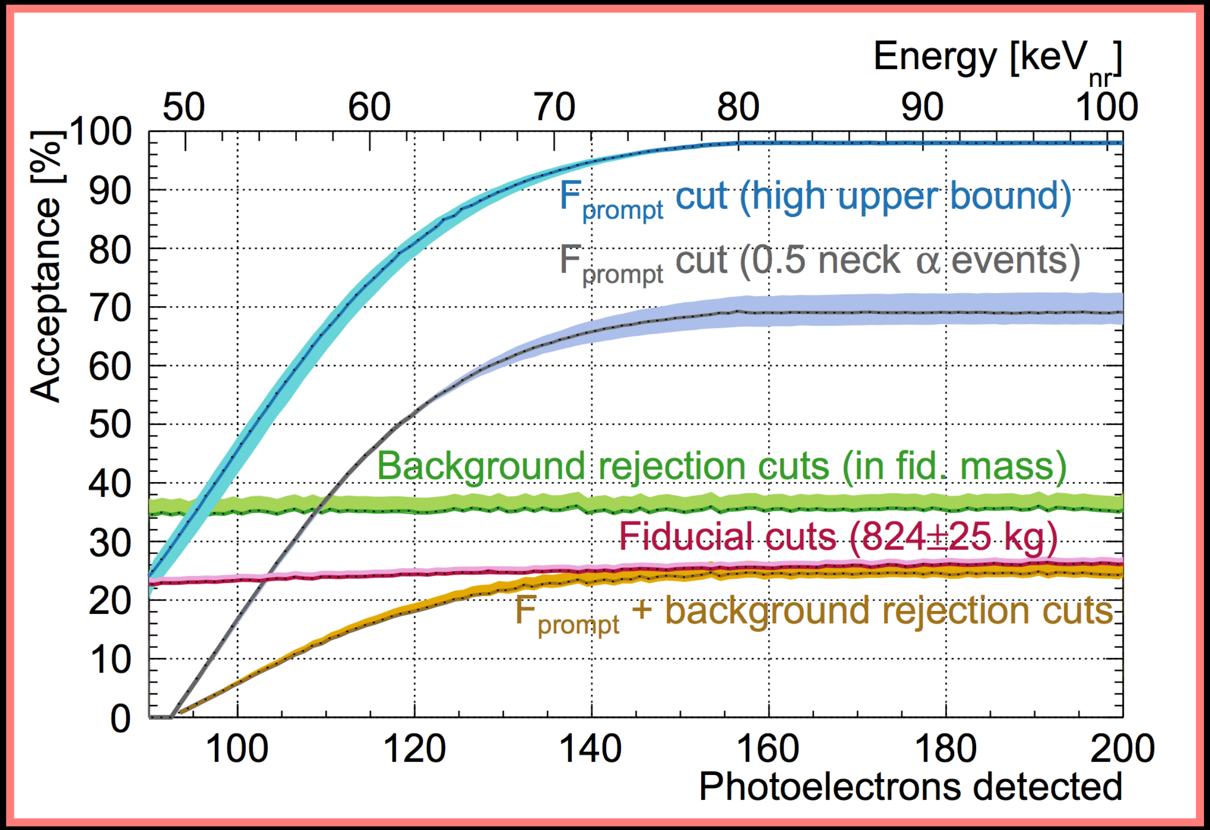


Add further dimensions

- Currently, 3 dimensions used in PLR to distinguish between signal/ background models (PE, PSD, R),

- Background mitigation cuts (dominated by neck alphas) most severe effect on WIMP acceptance,

  ➡ Gain additional ~40% WIMP acceptance.

Conclusions & Outlook

- The latest WIMP search from DEAP-3600 excludes the WIMP-nucleon spin-independent cross section above 3.9 x 10^{-45} cm^2 for a 100 GeV WIMP at 90% C.L, and is currently the leading WIMP limit produced from an argon detector,

- Most powerful discrimination power to date between ERs and NRs using PSD,

- A Profile-Likelihood Ratio analysis approach is currently being developed for DEAP-3600 in order to improve the sensitivity to WIMP dark matter.

- DEAP-3600 has been collecting data (80% of which is blinded) since January 2018,

  ➡ Will collect data until end of 2020,

- Development of new calibration sources underway to reduce systematic uncertainties on detector response,

- Re-analysis of 1-year dataset using PLR software will take place,

- Additional background PDFs, such as from neutrons (cosmogenic/ radiogenic) may be added to PLR in future development,

- PLR approach will be used to perform hidden photon/ axion-like particle search in DEAP-3600.

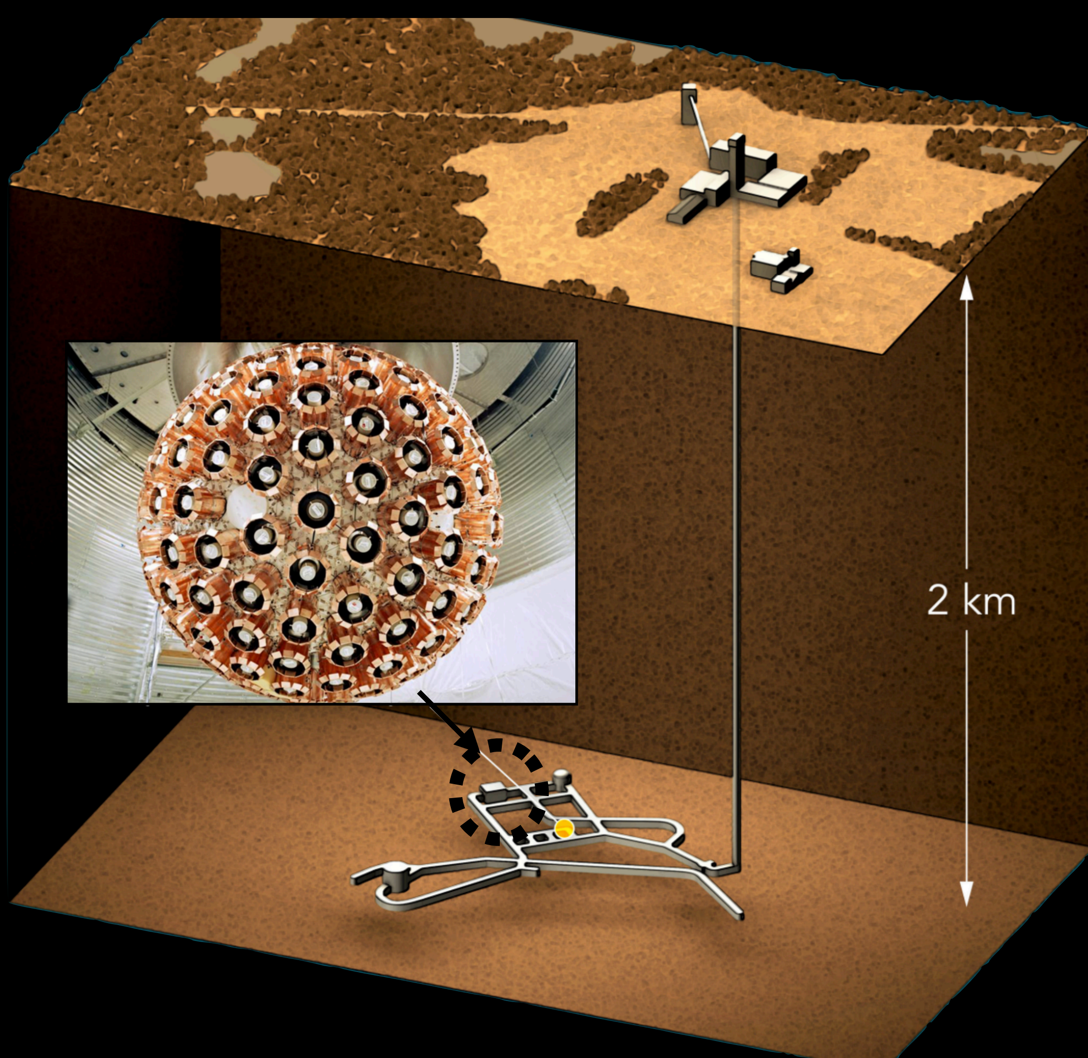
Thank you for listening!

- Questions?

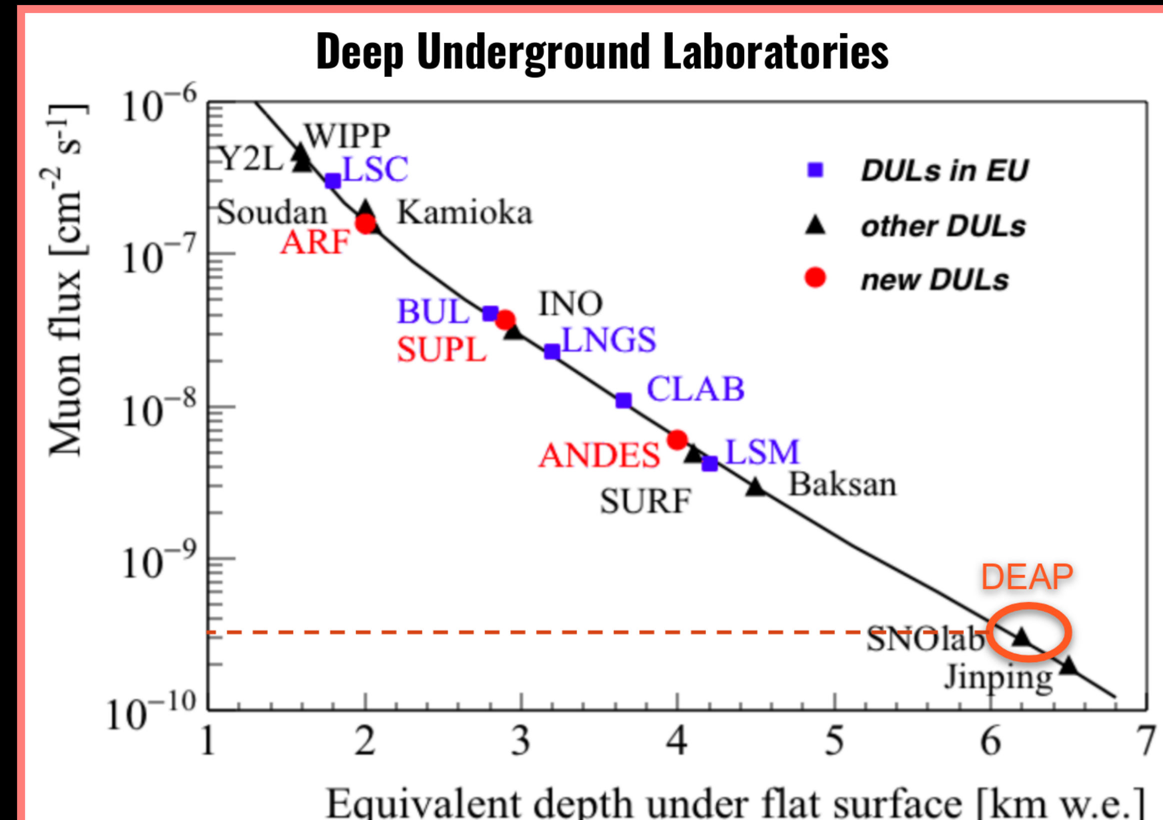
Back-up slides

SNOLAB

- One of the deapest & cleanest laboratories in the world,
- Located 2km underground in an active nickel mine,



https://phys.org/news/2018-05-world-sensitive-dark.html



A. Ianni, TAUP 2017

- Being based at SNOLAB provides excellent shielding from cosmic rays,
- Muons directly interacting with nuclei in rock can produce neutrons…

➡ Neutrons mimic WIMPs!

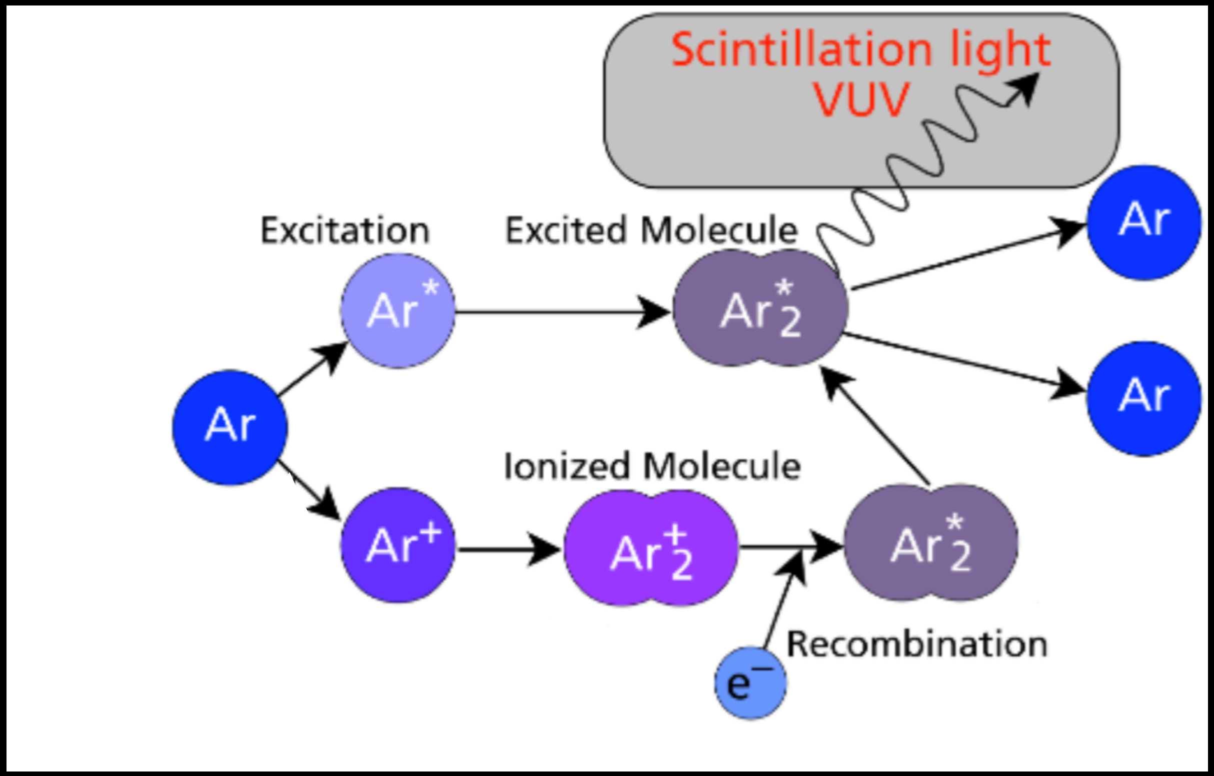
- Muon flux reduced by factor of ~ 10^7.

Liquid Argon scintillation

- Ionising particles traversing LAr produce excited Ar atoms (Ar*) and Ar ions (Ar+),
- Ar*, Ar+ hit other Ar atoms to form excimers, which decay by emitting VUV scintillation photons,
- Ionising density depends on ionising particle - higher for nuclear recoils than electron recoils,
- Excimers produced in either triplet or singlet state,
- Well separated lifetimes between triplet (~1300ns) and singlet (~6ns),

➡ Pulse-shape discrimination (PSD).

$$\frac{\text{Prompt light}}{\text{Prompt} + \text{Late light}} = \text{PSD}$$



http://darkmatter.ethz.ch/

Published PSD paper from DEAP-1: Astroparticle Physics 85 (2016) 1-23.

Pulse-shape discrimination

- Empirical function to describe Fprompt distribution for ERs:

➡ For ER-type event for which *q* PE reconstructed, the probability of observing given Fprompt value, *f*, is described by convolution of Gamma function with the Gaussian smearing term.

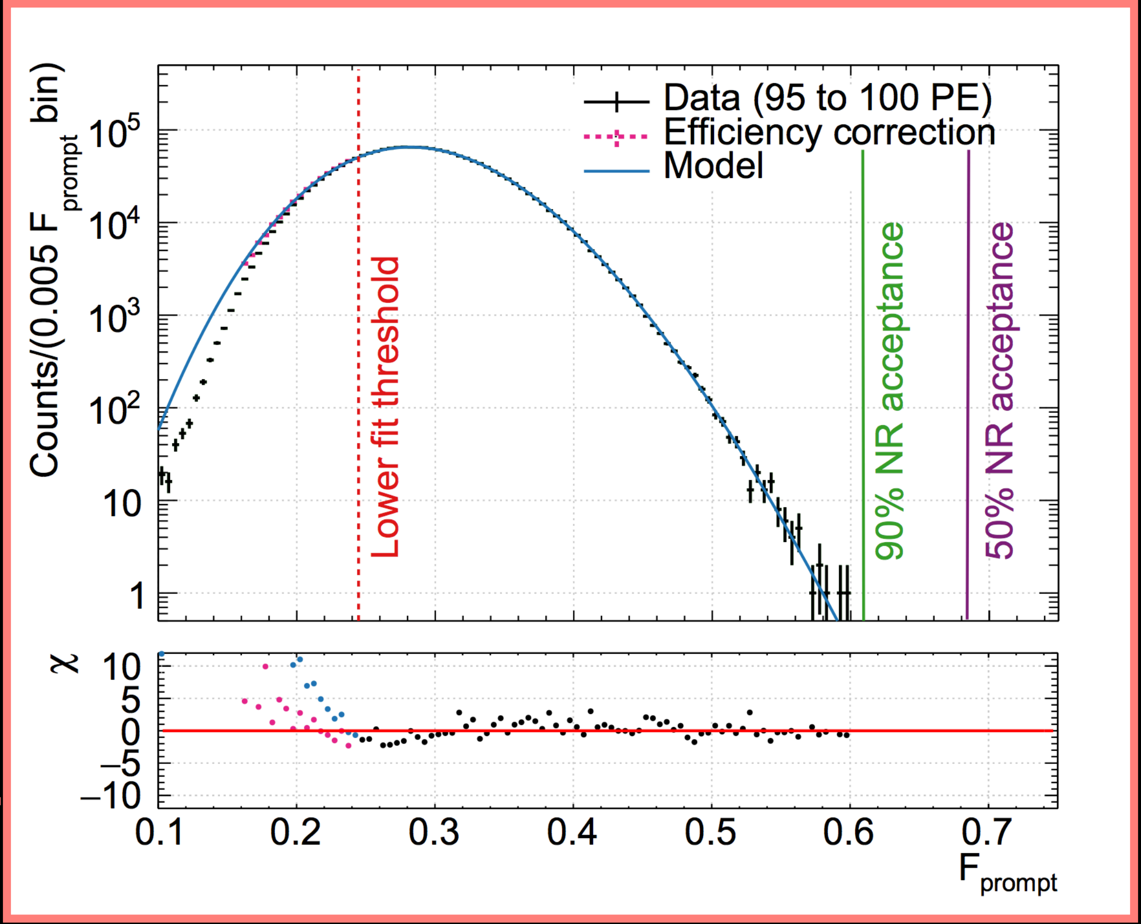
$$F^{ER}(f, q) = \Gamma(f; \bar{f}, b) * \text{Gauss}(f; \sigma)$$

Mean Fprompt, $\bar{f}(q)$

Width of Gaussian response, $\sigma(q)$

Shape parameter, $b(q)$

- For Fprompt < 0.25, trigger efficiency < 100%,
  - ➡ Trigger efficiency based on prompt PE,
  - ➡ "Lose" events, data and model diverge.



Position reconstruction

- Fiducalisation used to reject surface backgrounds,
  - ➡ Apply radial cut of 630mm to remove Cherenkov, external neutron and surface α events that reconstruct with R > 630mm,
  - ➡ Position resolution of 35mm for events near radius of 630mm in WIMP PE search region,
  - ➡ Leakage probability at 630mm radial cut from surface α decays into ROI is ~ 10^{-5}

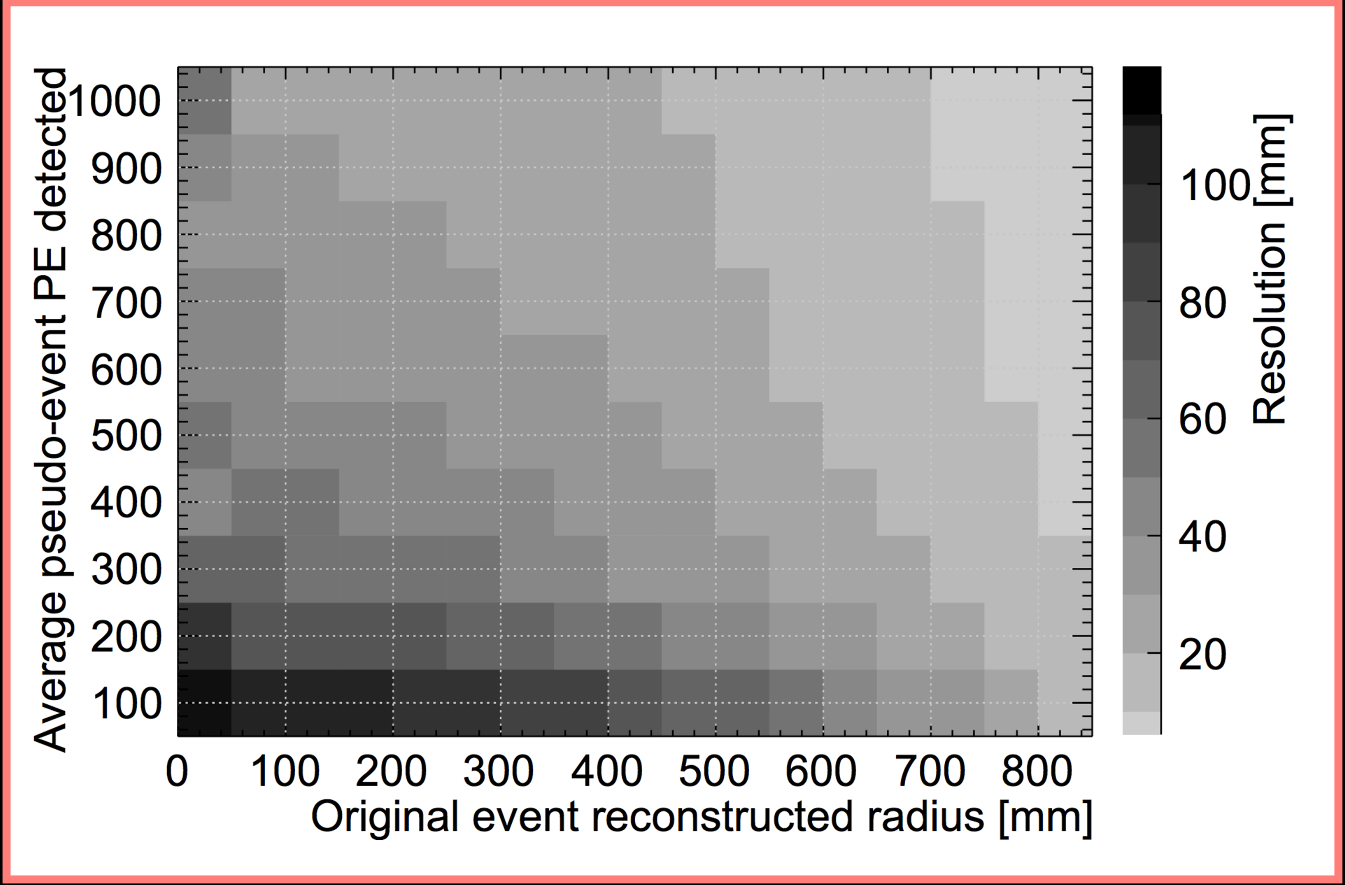
- Two position reconstruction algorithms used:

  1. PE-based (spatial distribution of PMT hits),

  2. PE + timing (charge and time information of early pulses used to determine position).

- Validation of algorithms performed on Ar39 β decays in data distributed uniformly across LAr volume, split into two 'pseudo-events',

- Position resolution determined from distribution of reconstructed distances between pseudo-events, as function of average pseudo-event PE and original event reconstructed radius [right].



Surrounding events

Large variations in neck alpha light yield and reconstructed position required to predict event rates consistent with observation in Region B,

No significant effect on WIMP exclusion presented.

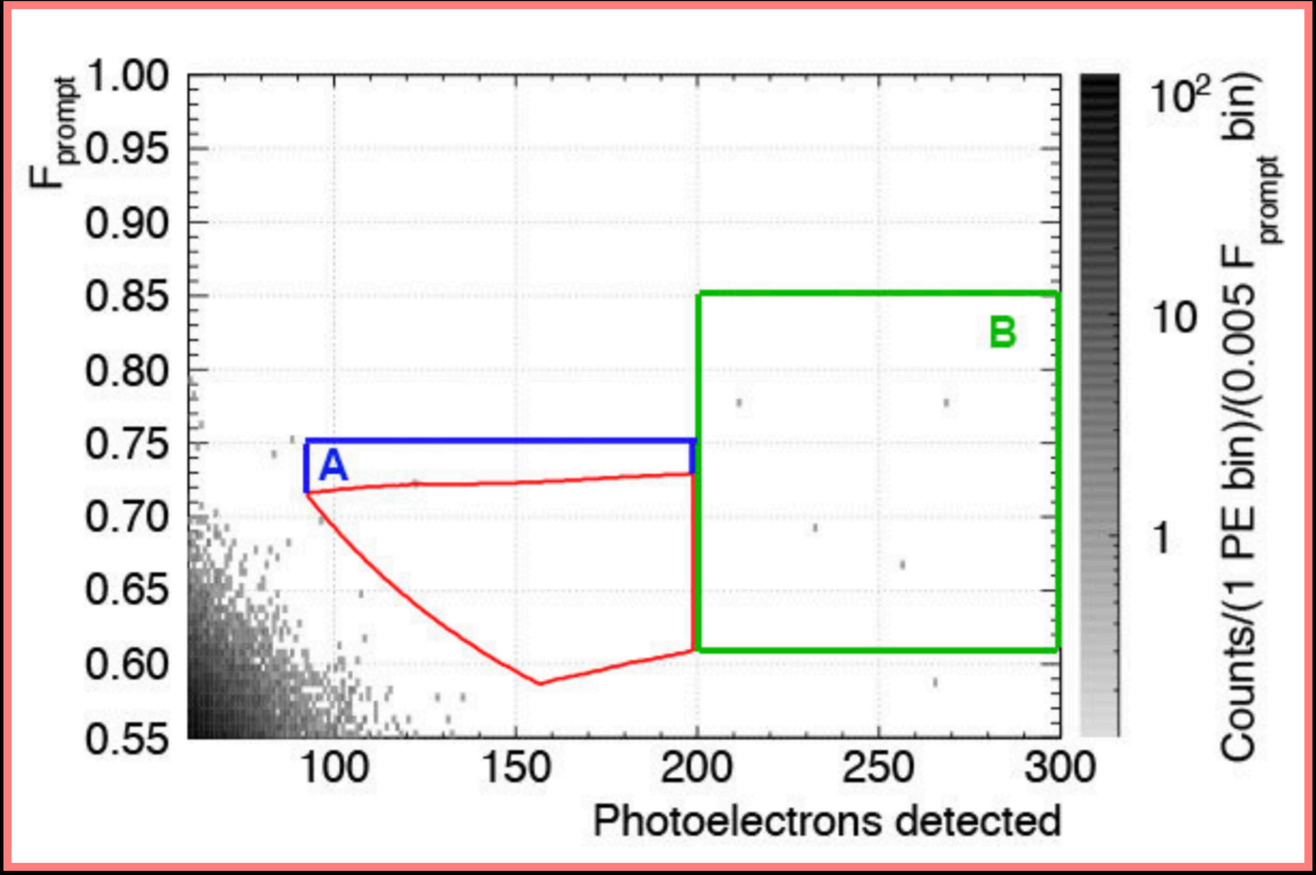
Future analyses: include additional background sources above upper PE bound of WIMP ROI.

Region A

Observe: 1
Predict: $0.46^{+0.13}_{-0.18}$

Region B

Observe: 4
Predict: $1.25^{+0.26}_{-0.42}$



Courtesy of Rob Stainforth [Lake Louise Conference, February 2019].