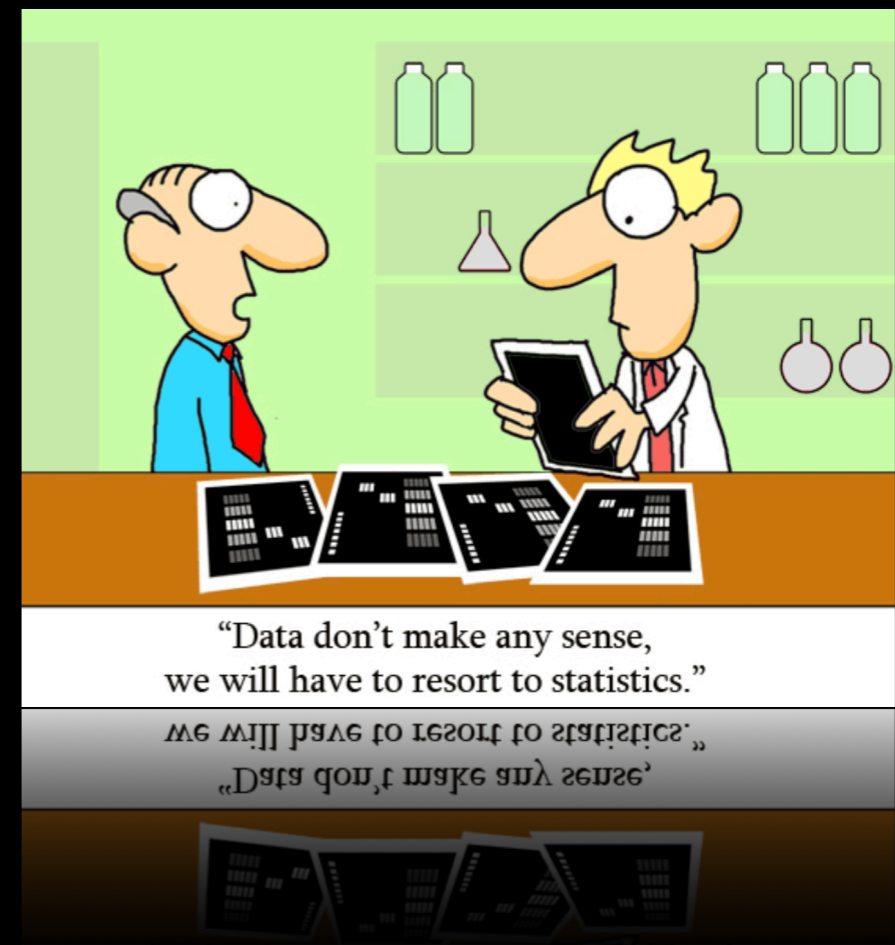


Using the Profile-Likelihood method to search for dark matter in DEAP-3600.

CAP Congress 2019,
Simon Fraser University,
5th June 2019,
Ashlea Kemp,
Royal Holloway, University of London (Visiting TRIUMF 2019).

Outline

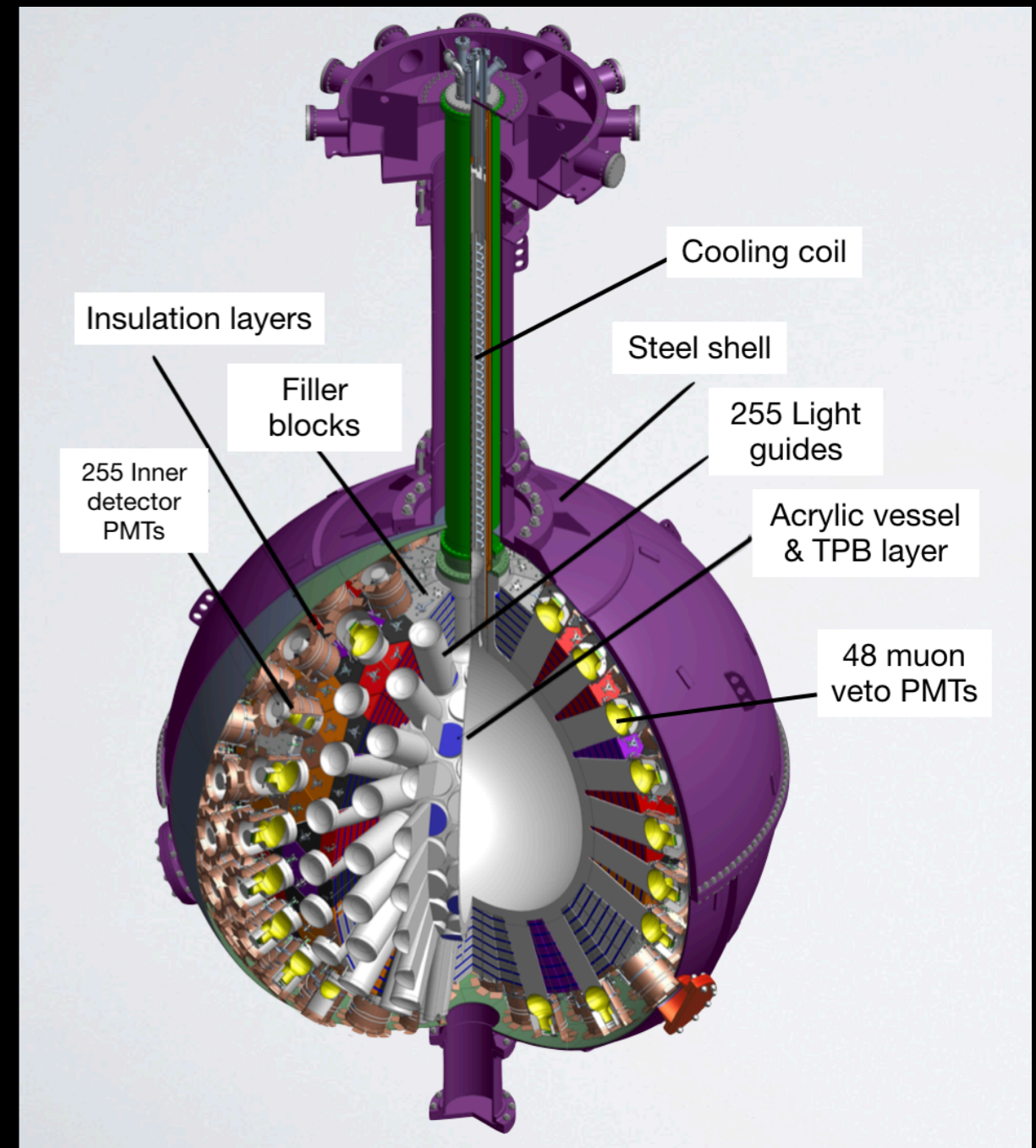
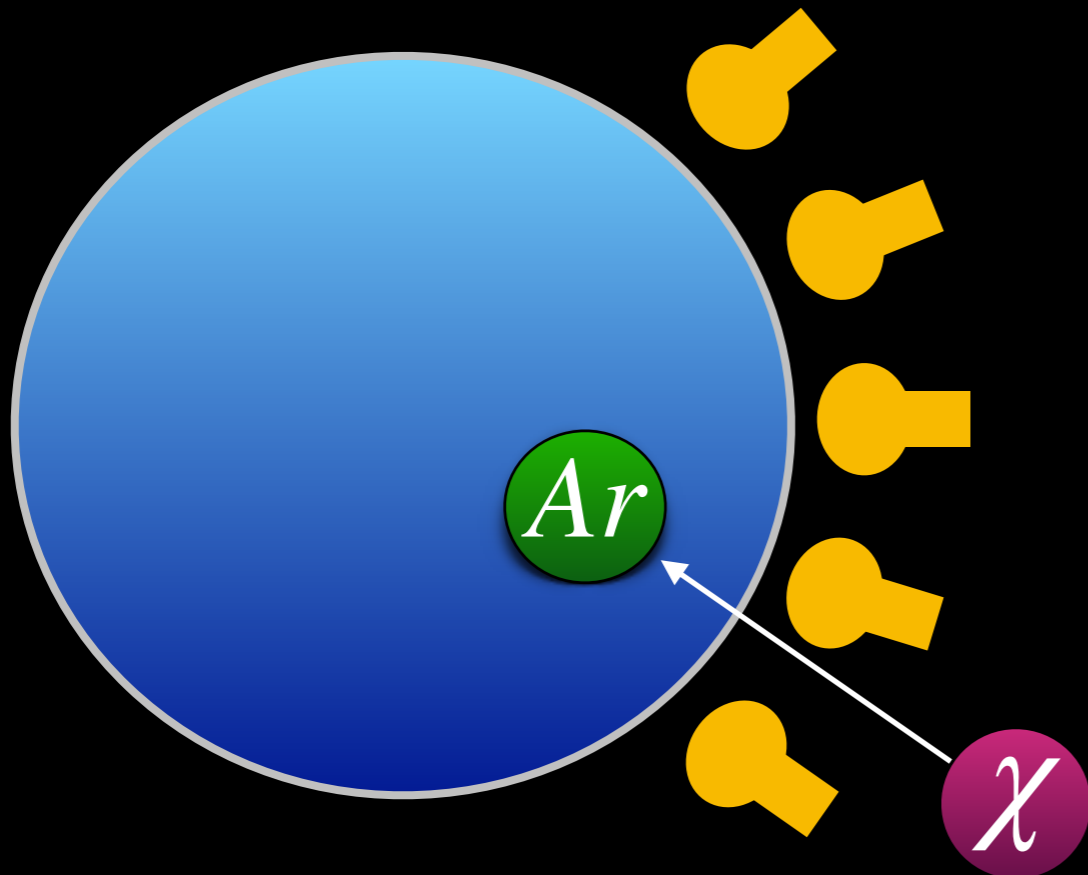
- The DEAP-3600 experiment
- The Profile-Likelihood Ratio (PLR)
 - Methodology
- Implementation for DEAP-3600 for WIMP search
- Conclusions & Outlook



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

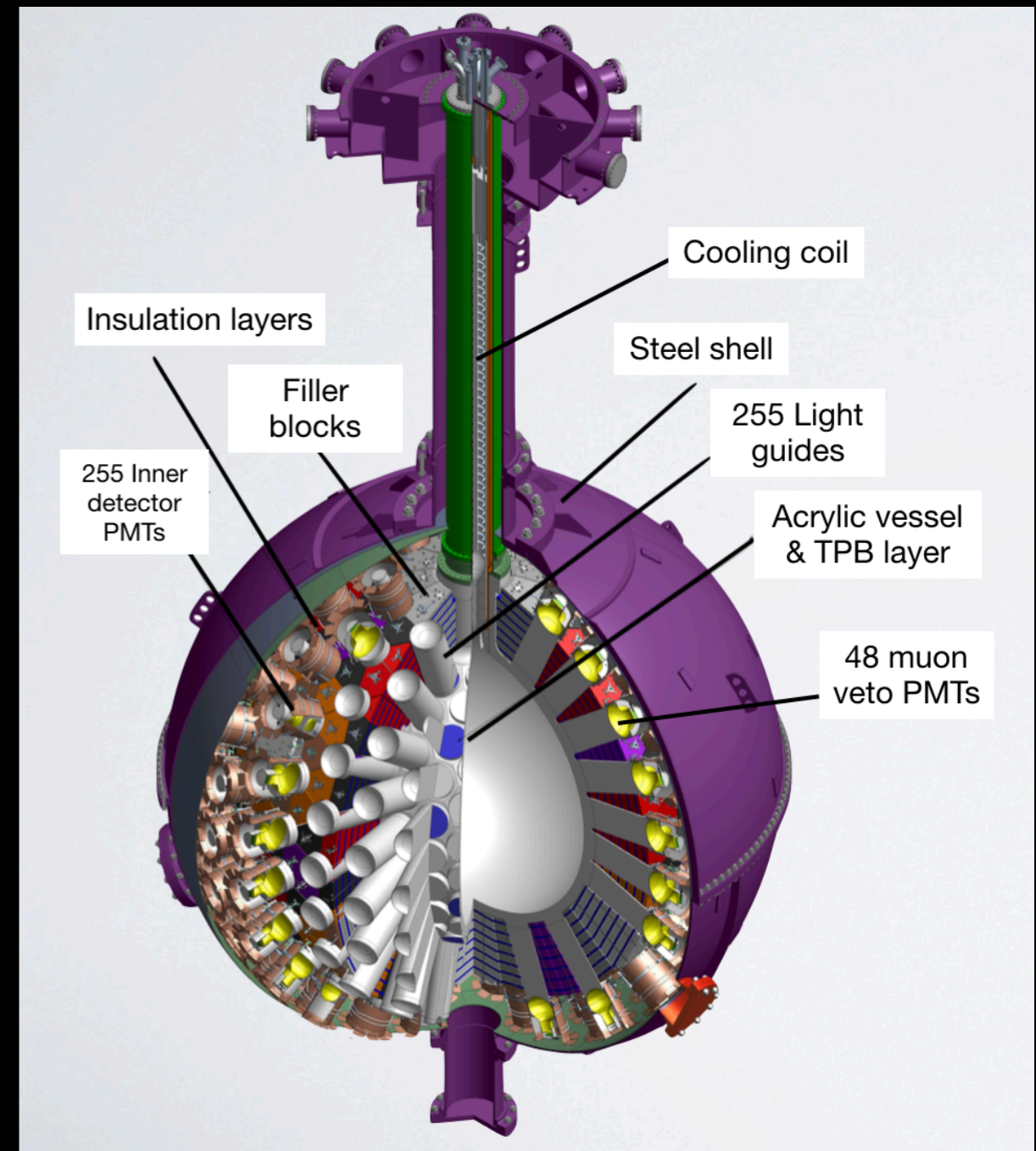
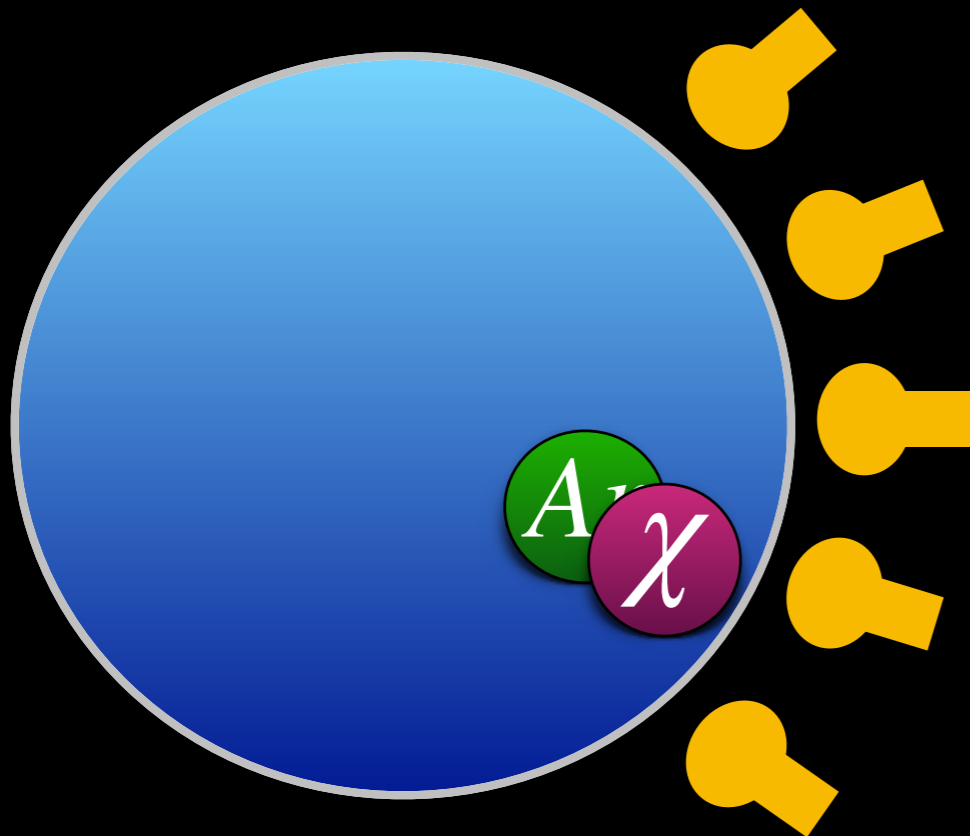
The DEAP-3600 detector

- 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 (DM) particle (WIMP),
 - ➔ 128 nm VUV scintillation photons (γ) wavelength shifted to 420 nm by TPB layer for PMT detection (~75% coverage).



The DEAP-3600 detector

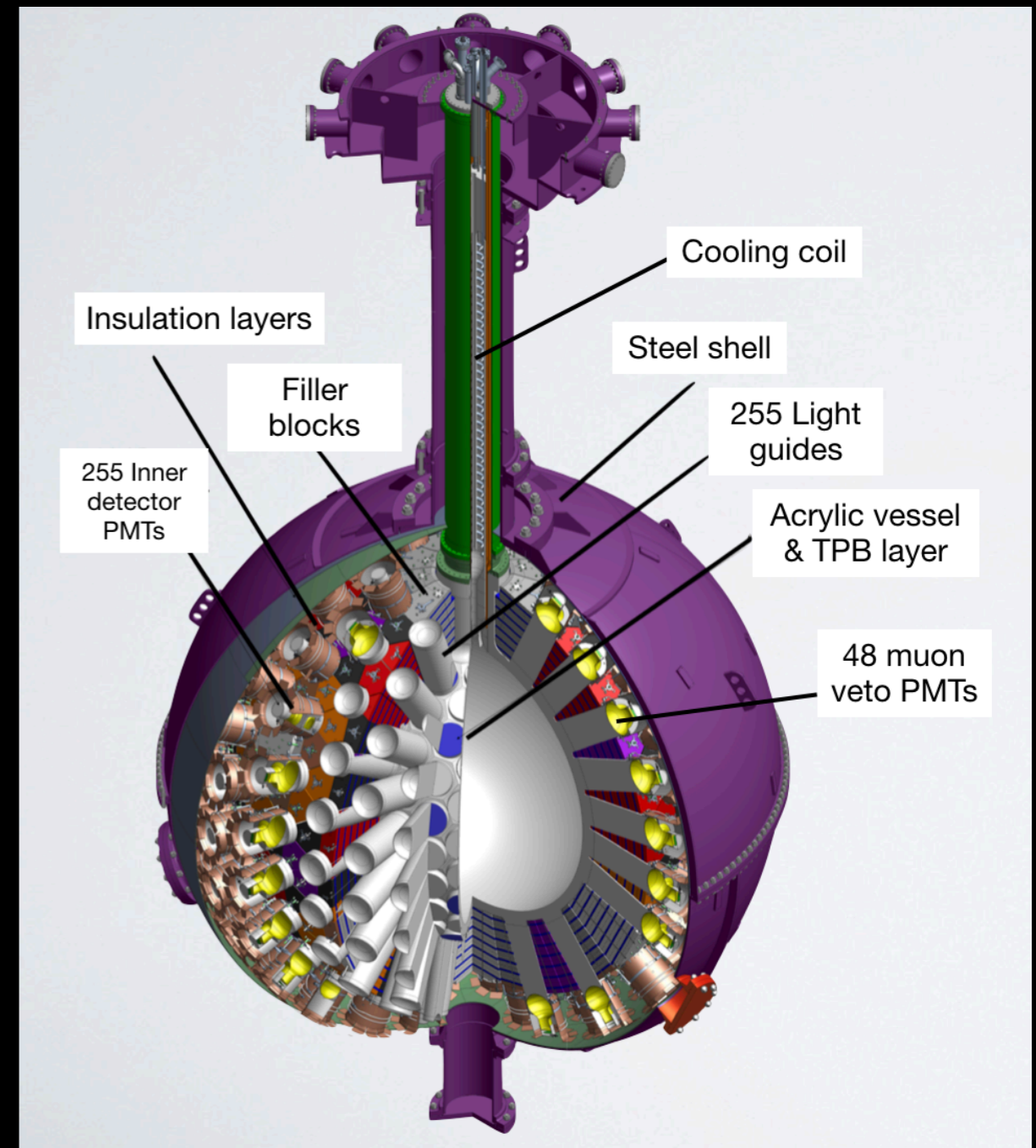
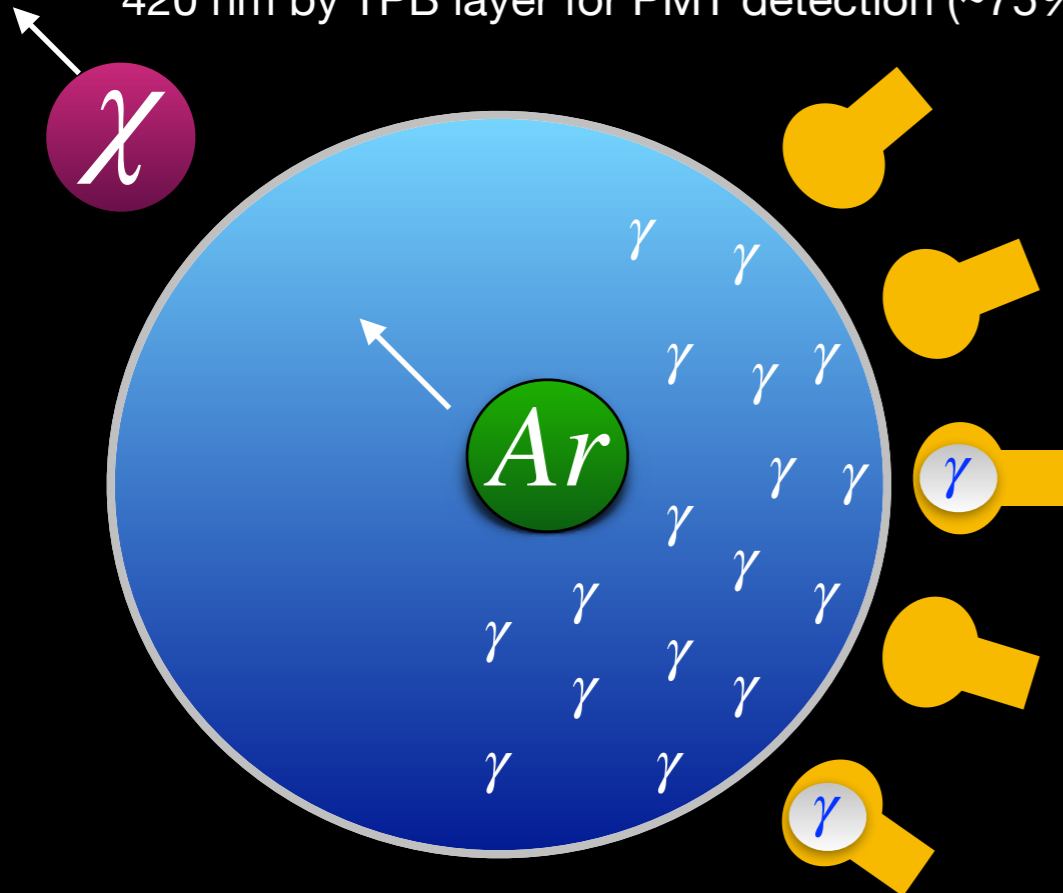
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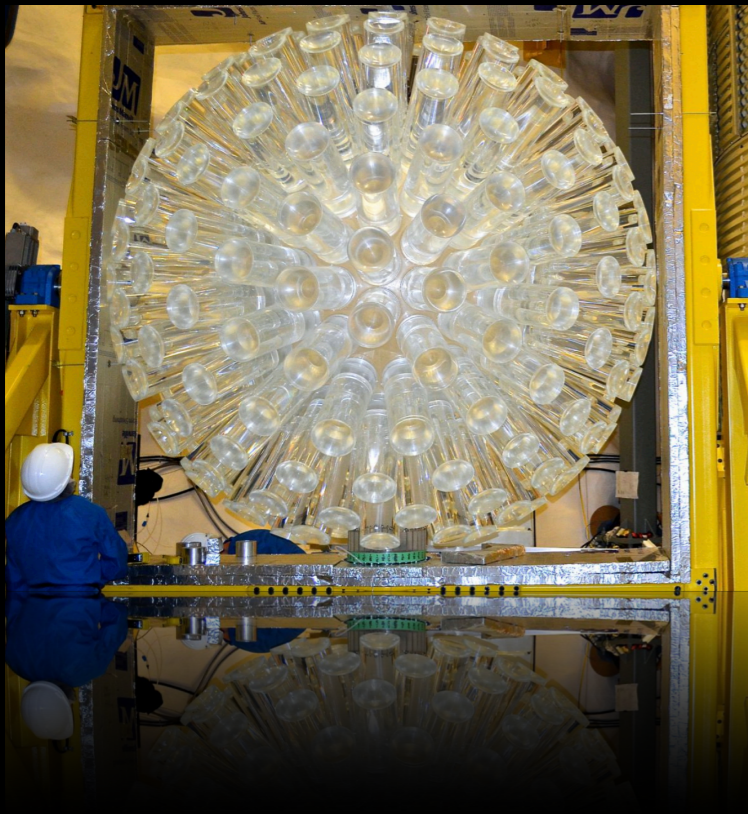
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Epoch of DEAP-3600



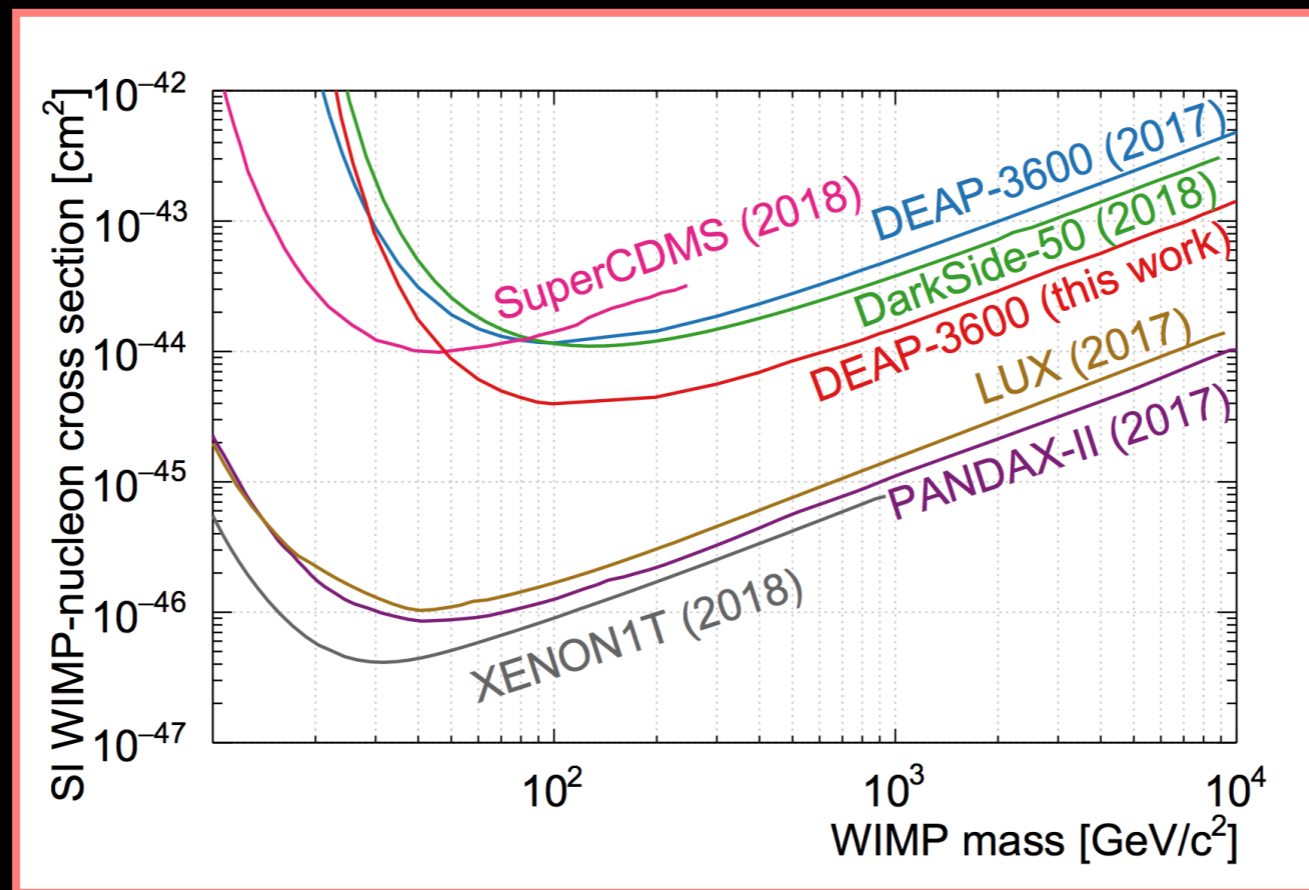
*Data used for first dark matter search, “First results from the DEAP-3600 dark matter search with argon at SNOLAB”: Phys. Rev. Lett. 121, 071801 (2018).

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

DEAP-3600 Collaboration



Latest WIMP search result



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

Leading exclusion curve for argon detectors.

“Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB”: <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 σ given some input data & set of nuisance parameters, on which both signal & background PDFs depend on, $\mathcal{L}(\sigma | \{\theta\})$,
- 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.

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

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,

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

- Need to determine $f(q|H_{\sigma})$:

➡ Generate set of fake datasets/ pseudo-experiments for given set of events, with observables drawn randomly from signal and background models,

➡ Calculate q for these pseudo-experiments, build $f(q|H_{\sigma})$,

- 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,

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

- 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.

$$\mathcal{L}_{PDFs}(\sigma; \{\theta\}) = \text{Pois}(N_{obs} | N_{exp}) \cdot$$

$$\prod_{i=1}^{N_{PDFs}} \left(\frac{N_{exp,i}}{N_{exp}} \sum_{j=1}^{N_{events}} f_i(PE_j, PSD_j, R_j; \{\theta\}) \right)$$

The Likelihood Function

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

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

- 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.

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

- Ar39: naturally present electronic recoil signals from long-lived β decays provide constant source of internal calibration uniformly across LAr volume,
- Used to 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.

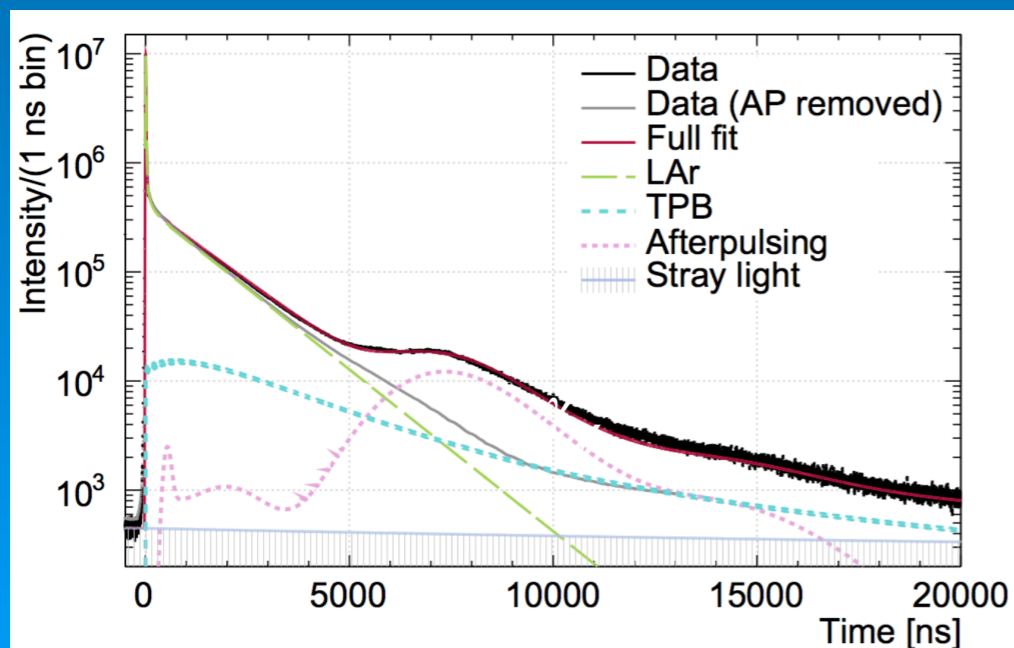
$$\mathcal{L}_{sideband}(\{\theta\}) = \prod_i^{N_i} \prod_j^{N_j} \prod_k^{N_k} \text{Pois}(N_{obs;i,j,k} | N_{exp;i,j,k})$$

The 3 dimensions

Charge (Photoelectrons)

$$PE = \sum_{t=-28ns}^{10\mu s} PE_{scint}(t)$$

- Energy estimator: sum of photoelectrons from scintillation photons,
- With afterpulse removal, pulse shape closely follows LAr scintillation and TPB fluorescence time profiles.

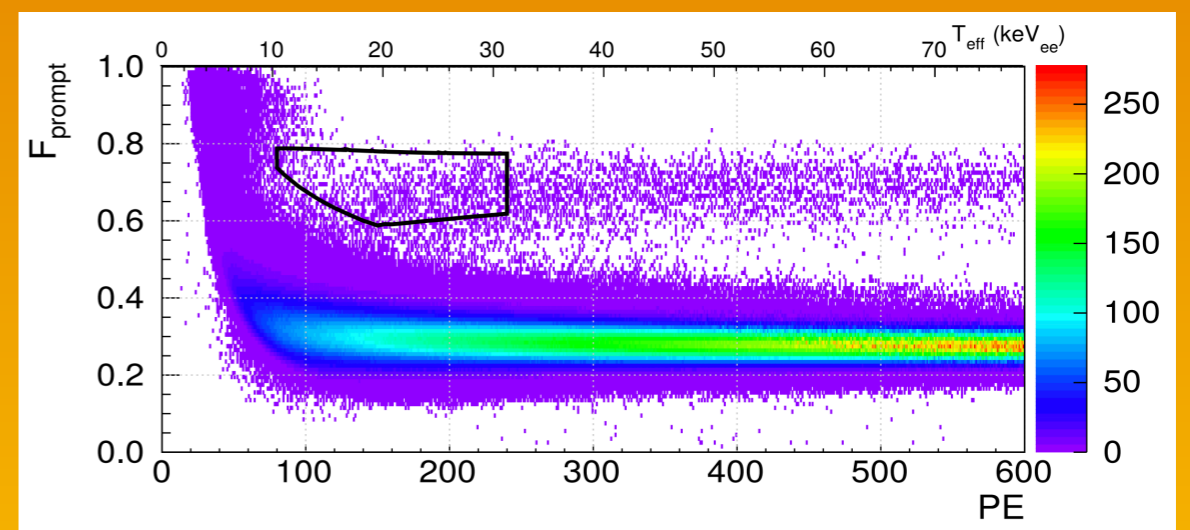


LAr pulse shape as measured in DEAP-3600.

PSD (F_{prompt})

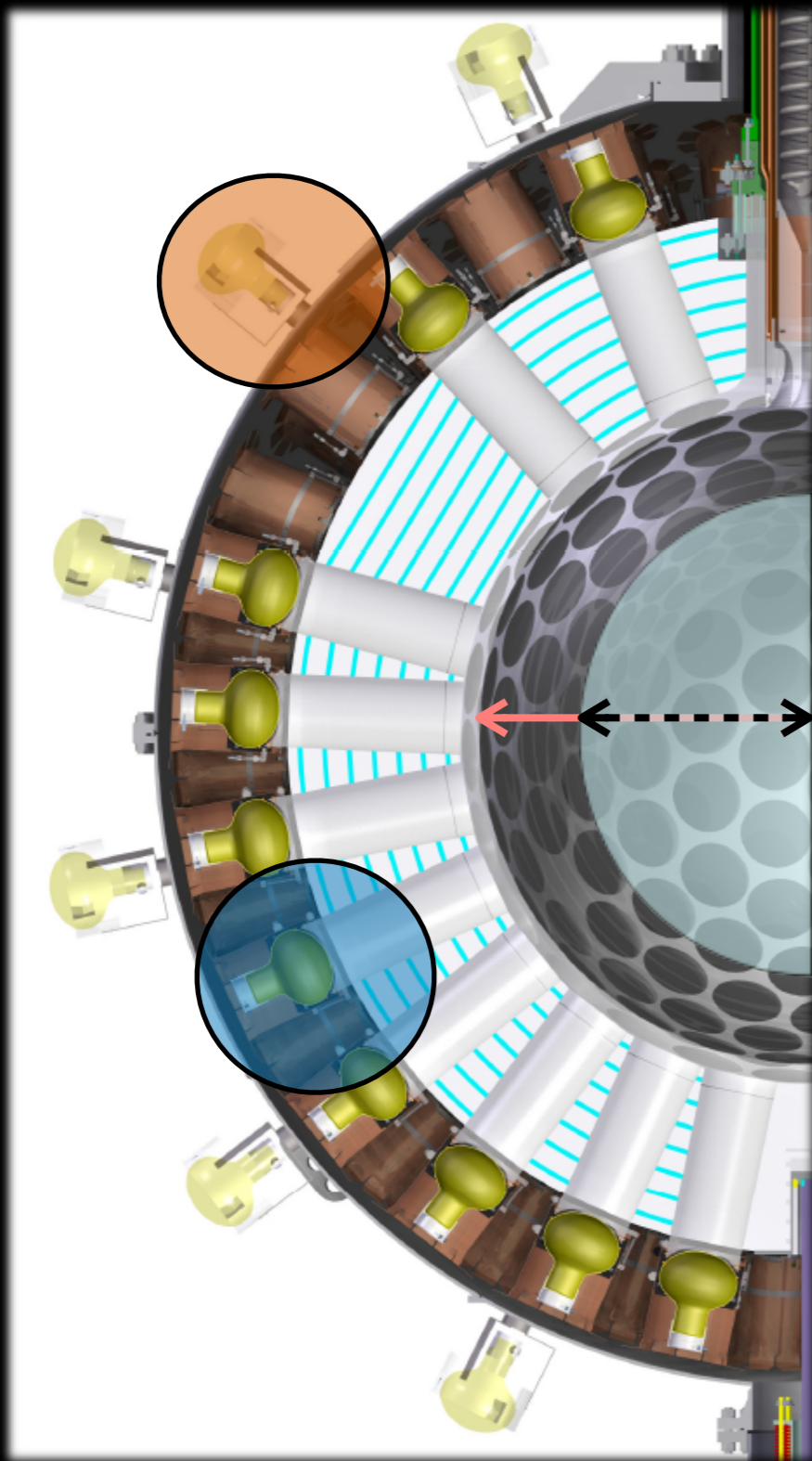
$$F_{prompt} = \frac{\sum_{t=-28ns}^{60ns} PE_{scint}(t)}{\sum_{t=-28ns}^{10\mu s} PE_{scint}(t)}$$

- Pulse-shape discrimination used to discriminate between electronic recoils (ERs) and nuclear recoils (NRs),
- At low energy threshold for WIMPs and 90% NR acceptance, PSD leakage probability of $2.8^{+1.3}_{-0.6} \times 10^{-7}$



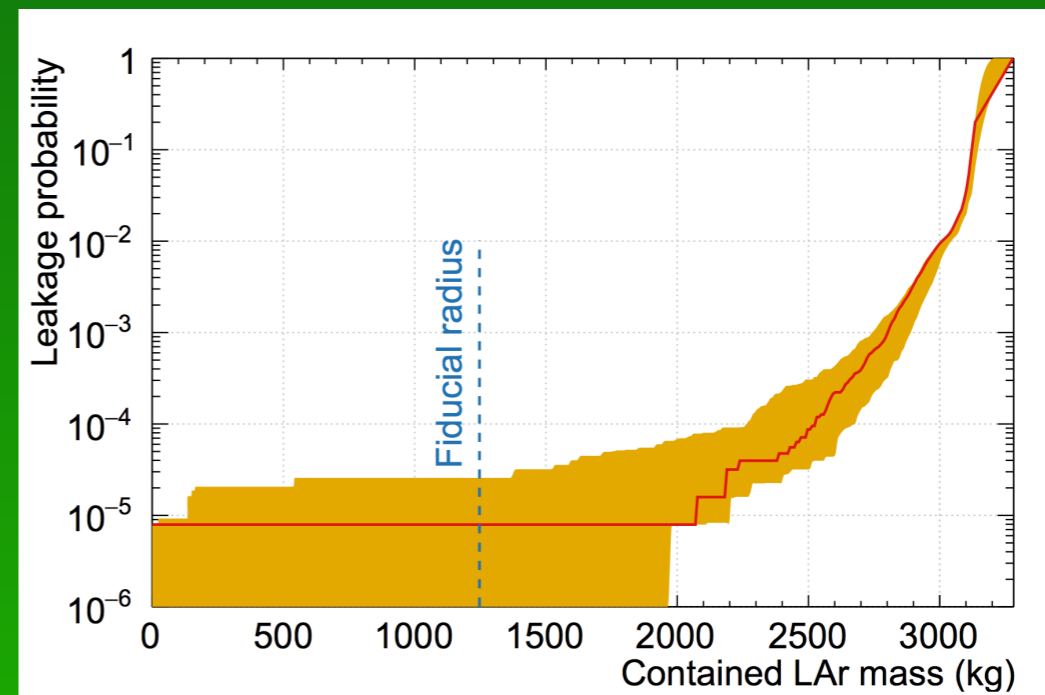
Data from AmBe (neutron emitter) run.

The 3 dimensions



Position (Radius)

- External neutrons, Cherenkov produced in the light guides and alpha decays on the surface of the acrylic vessel can produce WIMP-like signals that reconstruct at large radii,
- Define fiducial volume; $R < 63\text{cm}$,
- Leakage probability at $63\text{cm} \sim 10^{-5}$



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

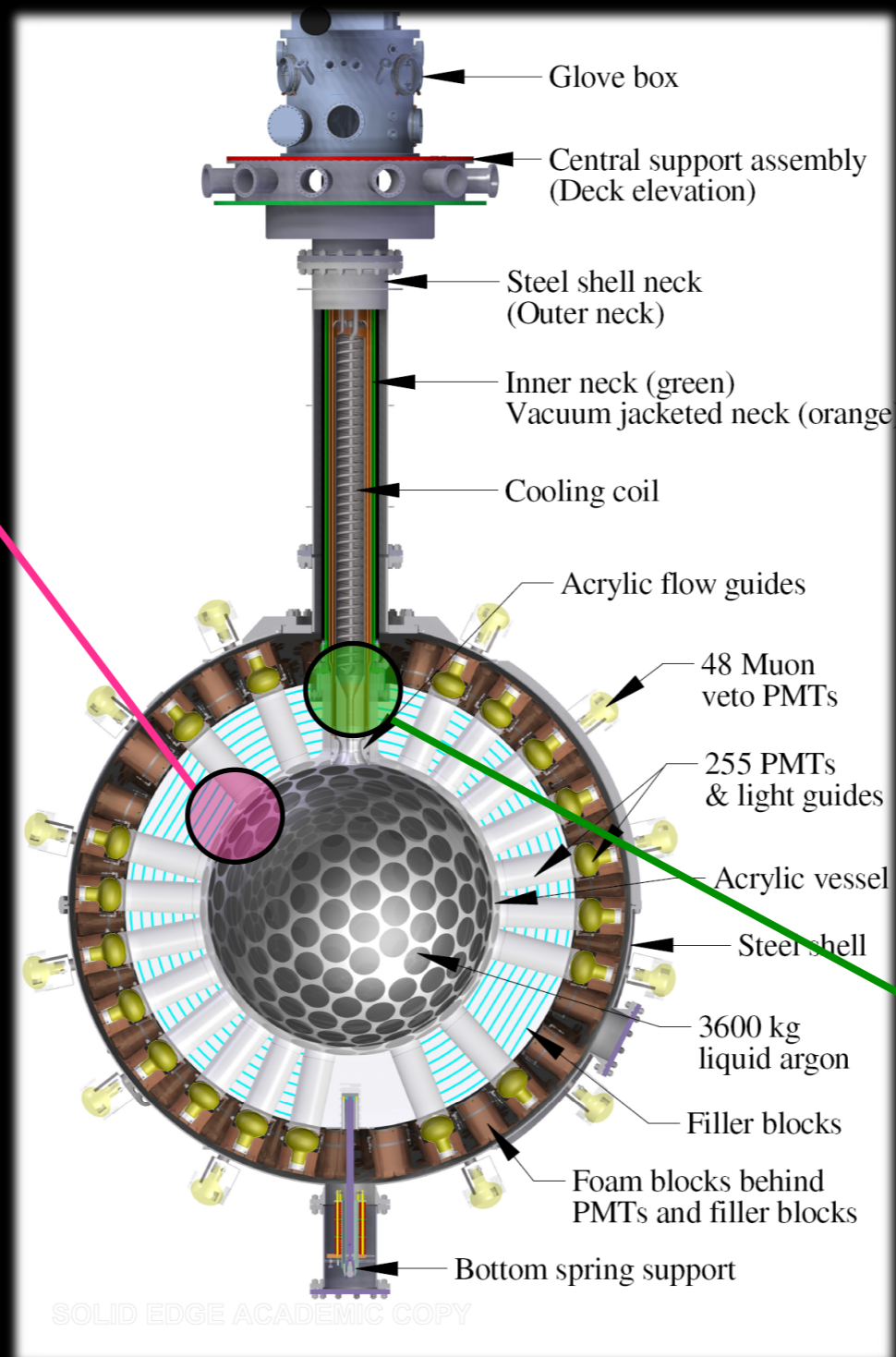
Background Models

1) LAr: Ar39 β decays [Data-driven],

➡ Sideband!

2) Inner detector: Long-lived α decays from Po210 occurring in acrylic vessel (AV), LAr/TPB and TPB/AV interfaces [Data/Simulation-driven].

➡ See S. Viel's talk for discussion on full background model.



- Additional background models to be implemented in the future.

3) The neck: Po210 α decays through LAr 'film' on surface of acrylic flowguides, originating from long-lived Pb210 (Rn222) [Data/Simulation-driven].

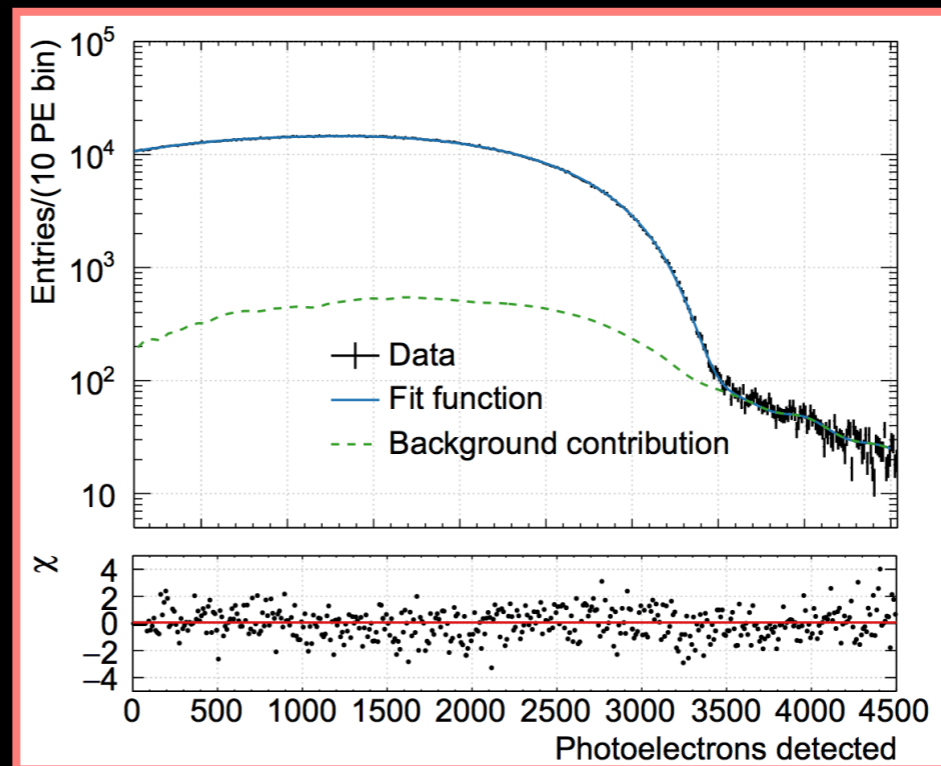
Background Models

LAr (β decays)

Radioisotope Ar39 naturally present in LAr results in β decays, ~ 1 Bq/kg (3300 decays per second in DEAP-3600),

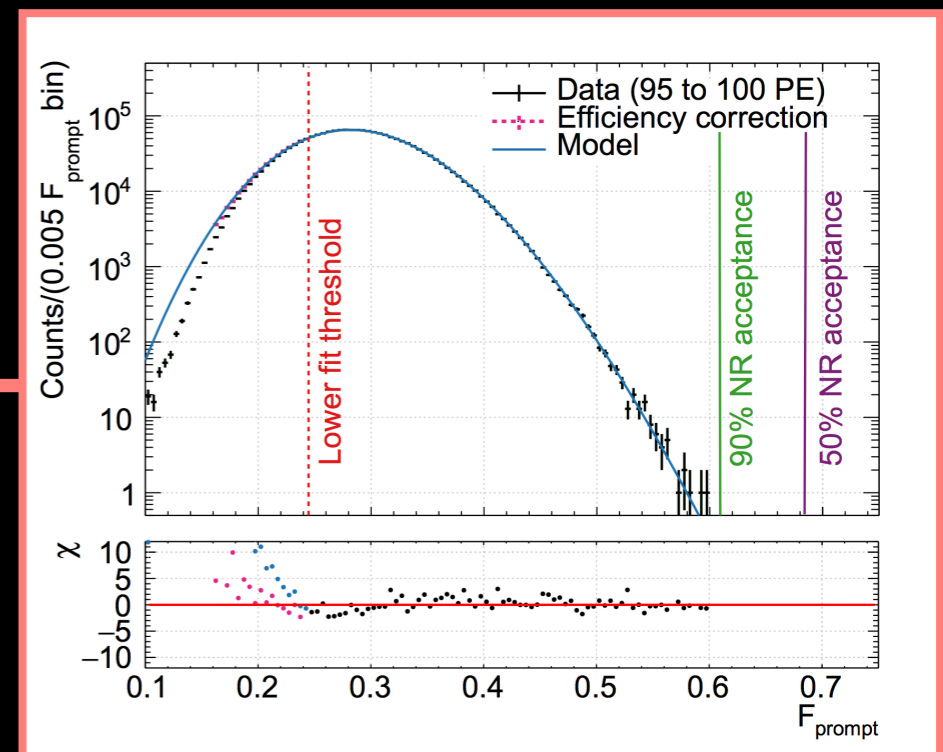
Used as natural internal calibration, and allows us to constrain systematics such as light yield & energy resolution,

Models built by fitting detector data, using both theoretical/ analytical and empirical functions.



Example
Ar39
spectral fit
in
DEAP-3600.

PSD empirical
model fit in
95 - 100 PE
bin in
DEAP-3600.



Background Models

Inner detector (α decays)

α decays from long lived Po210 on inner surface of AV can cause signals from α particles with degraded energies,

Empirical models built from MC simulation of 3 locations: TPB/LAr interface, TPB/AV interface and AV bulk.

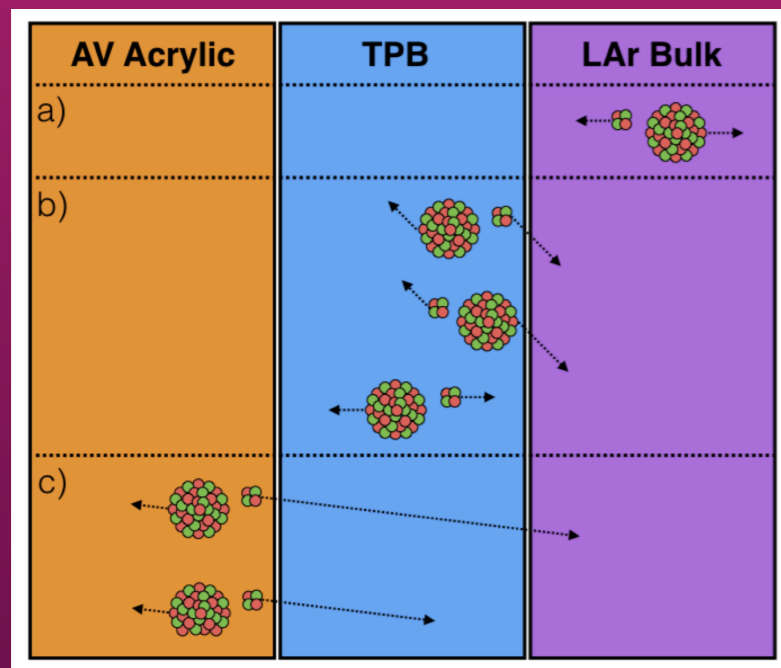


Image taken from the PhD thesis of P. Giampa.

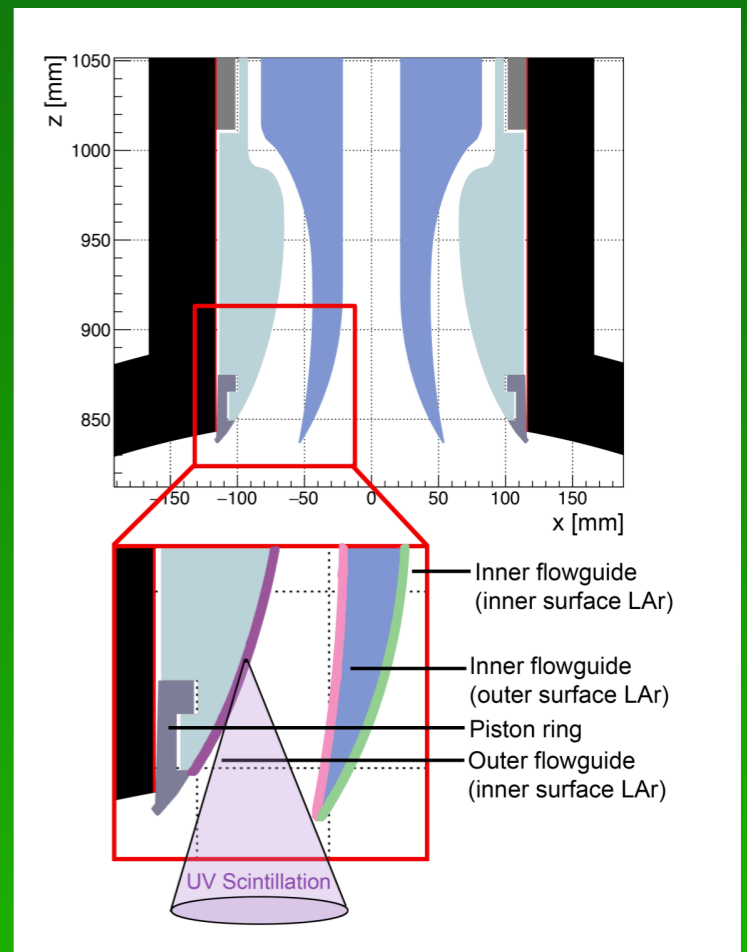
The Neck (α decays)

α decays from long lived Po210 on the surfaces of the acrylic flowguides (FG) in neck are biggest contribution to background rate,

Since FG not covered in TPB, majority of UV scintillation photons absorbed by acrylic; small fraction of emitted photons reach AV PMTs,

Empirical models built from MC simulation of 3 locations: inner FG inner surface, inner FG outer surface and outer FG inner surface,

Large systematic uncertainties on predicted number of ROI events from neck alphas due to LAr film thickness & model of α particle scintillation parameters.



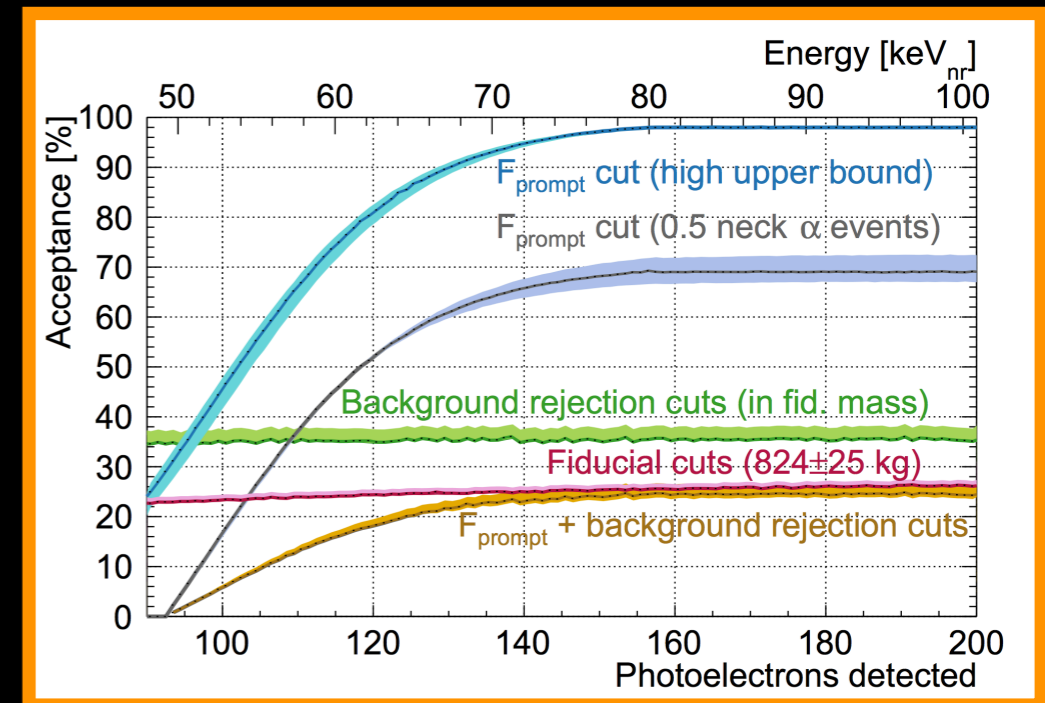
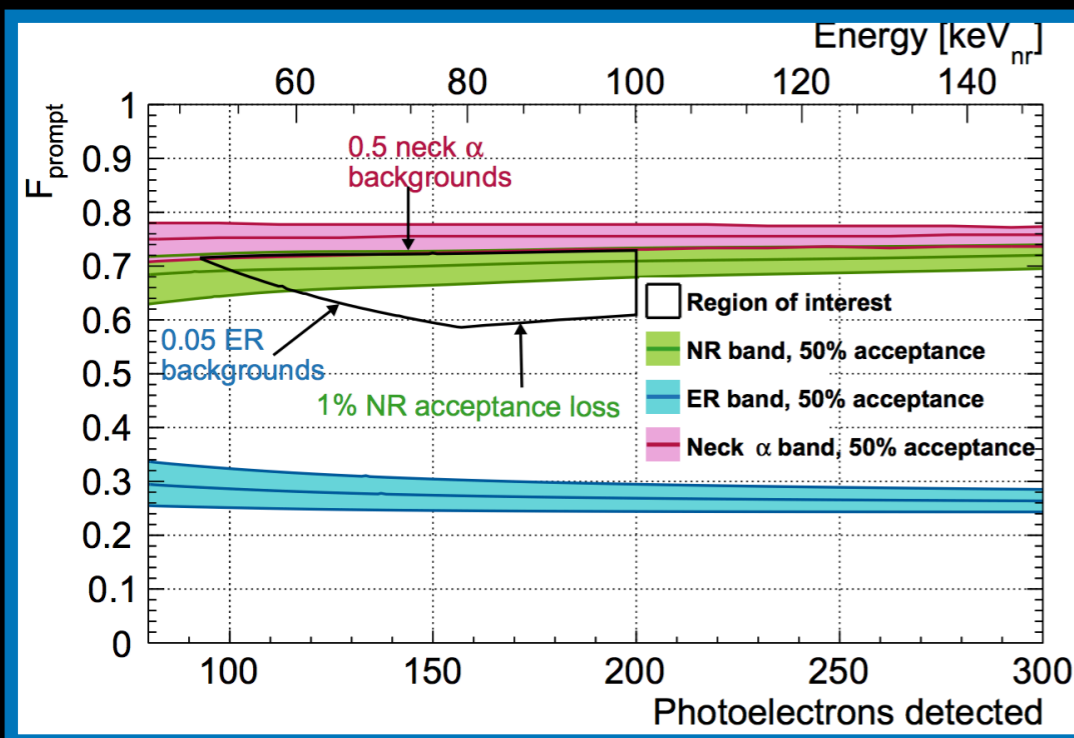
Boosting sensitivity

- Advantage of PLR over standard cut-and-count method?

Additional dimensionality

➔ More events allowed in WIMP search region without extra penalty to sensitivity.

“Super-ROI”



Could gain up to ~40% WIMP acceptance without severe background mitigation cuts (neck alphas).

Expand WIMP search region in PSD & R dimension for greater exposure.

Conclusions & Outlook

- The latest WIMP search from DEAP-3600 is currently the leading WIMP limit produced from an argon detector,
 - A Profile-Likelihood Ratio analysis approach is currently being developed for DEAP-3600 in order to improve the sensitivity to WIMP dark matter, and is in the validation stage of development,
-
- Re-analysis of 1-year dataset using PLR approach will take place,
 - Additional background PDFs (external neutrons/cherenkov radiation) to be added to PLR in future development as background investigation efforts continue,
 - One-dimensional PLR approach will be used to perform hidden photon/ axion-like particle search in DEAP-3600,
 - ➡ Development of new calibration sources underway to reduce systematic uncertainties on detector response: improve ER background spectrum understanding & improve DM sensitivity.

Thank you! Questions?

