Latest Results from DEAP-3600

Joseph McLaughlin
On Behalf of the DEAP Collaboration

ICHEP 2022
Bologna, Italy

ROYAL HOLLOWAY UNIVERSITY OF LONDON

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- Overview of the DEAP-3600 Experiment
- Precision Measurements
- WIMP Searches
- Beyond WIMPs
- Outlook

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Overview of DEAP-3600:
The Detector

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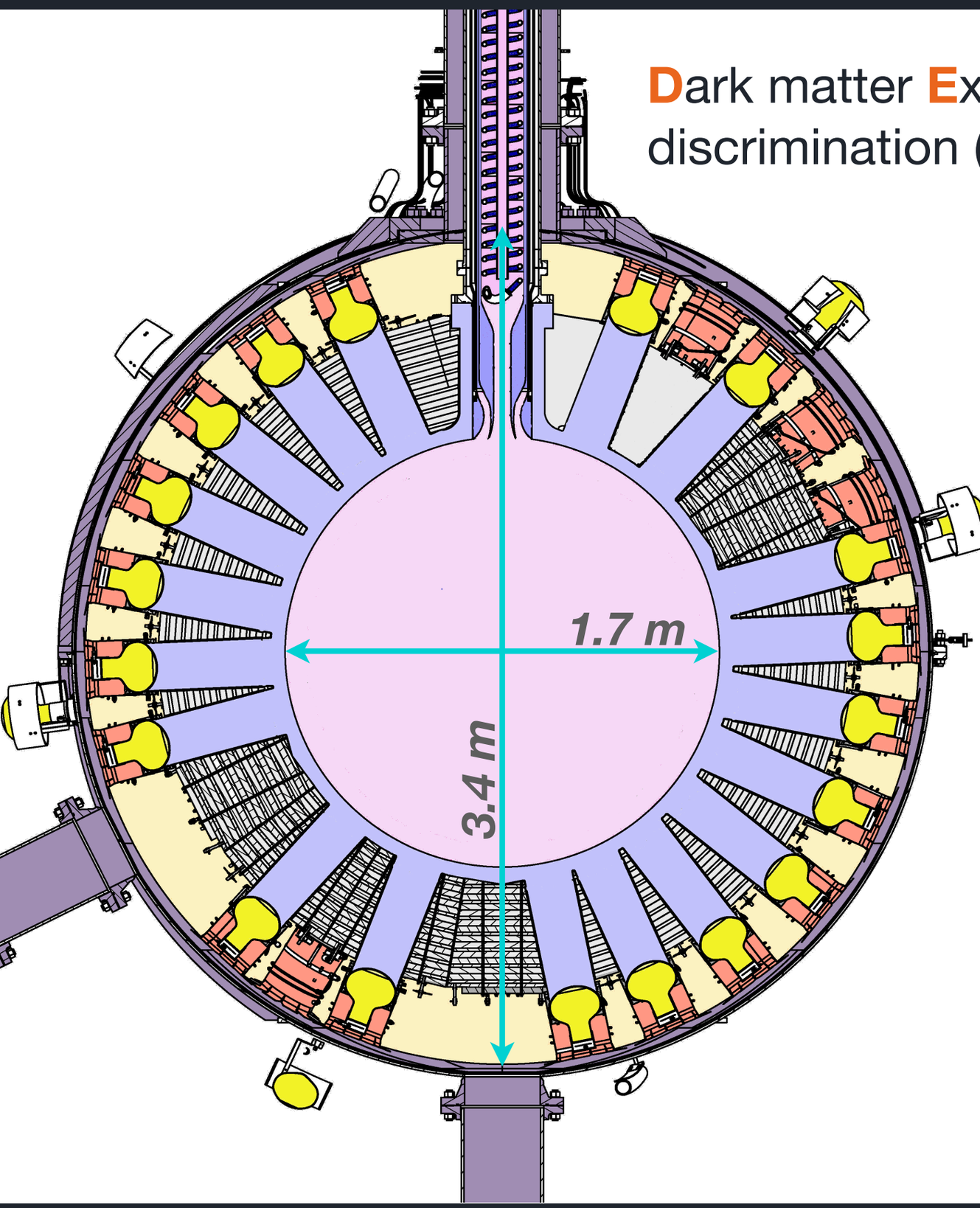
Dark matter **E**xperiment using **A**rgon **P**ulse shape discrimination (PSD)



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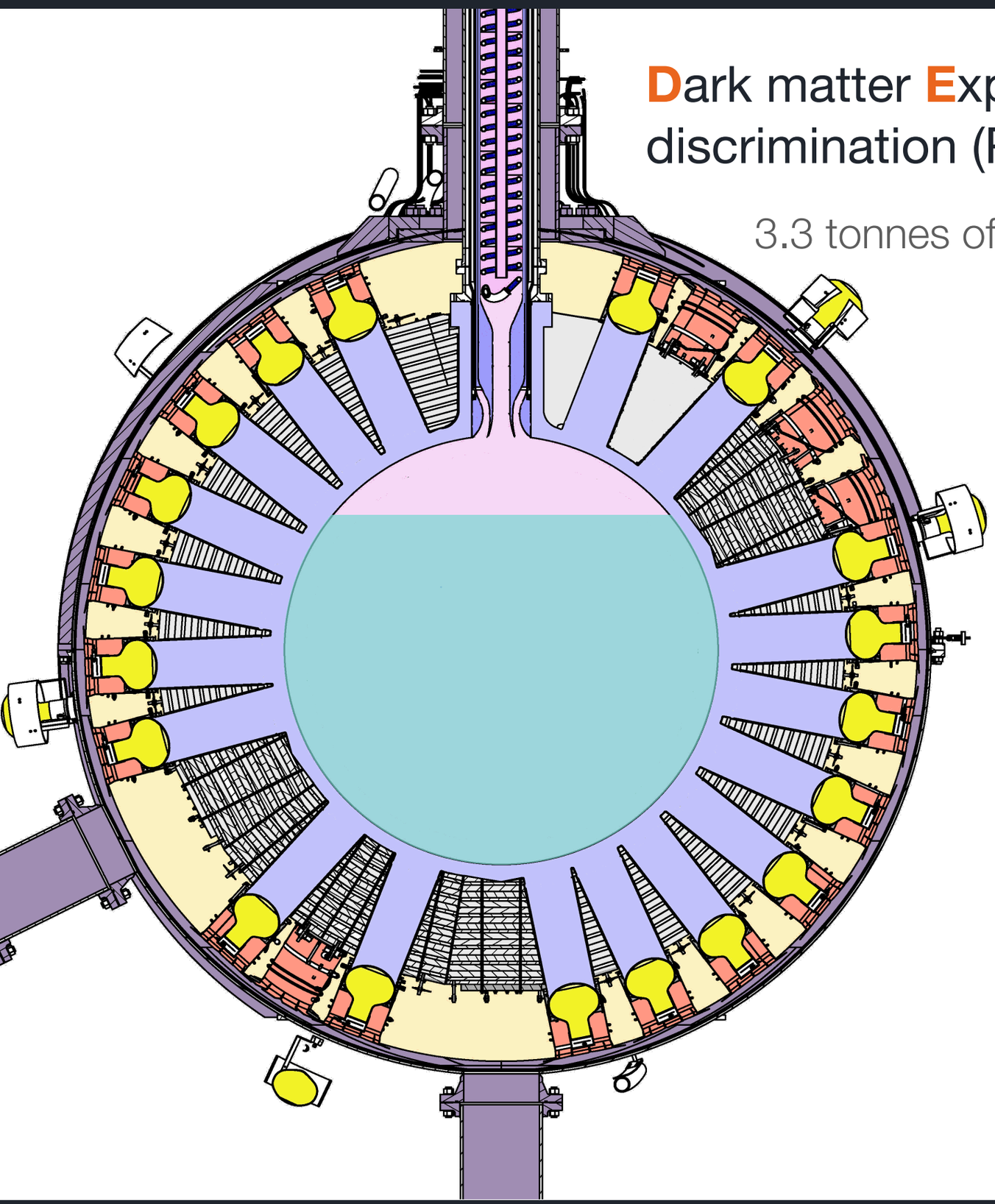

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3.3 tonnes of Liquid Argon (LAr) as target

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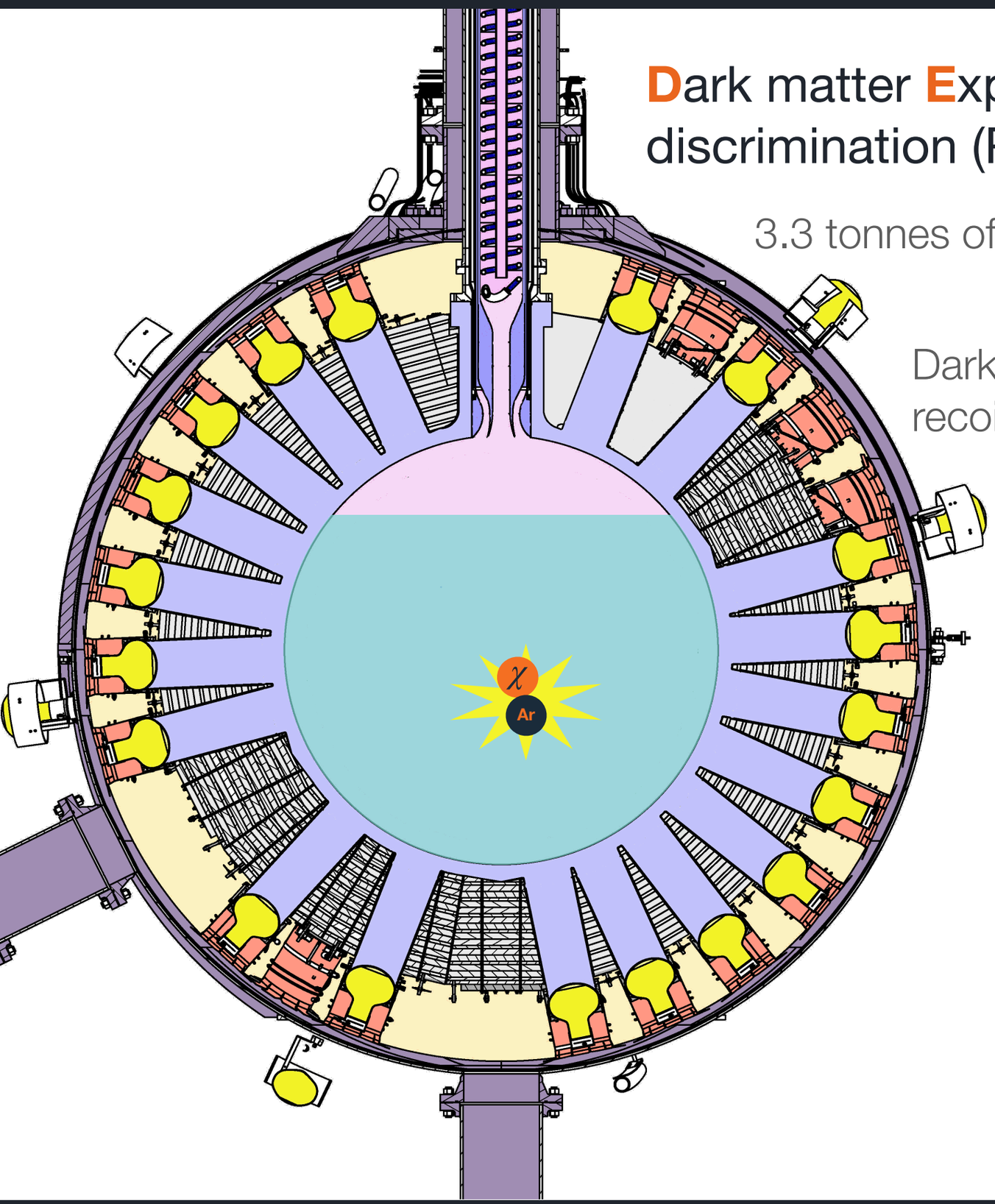

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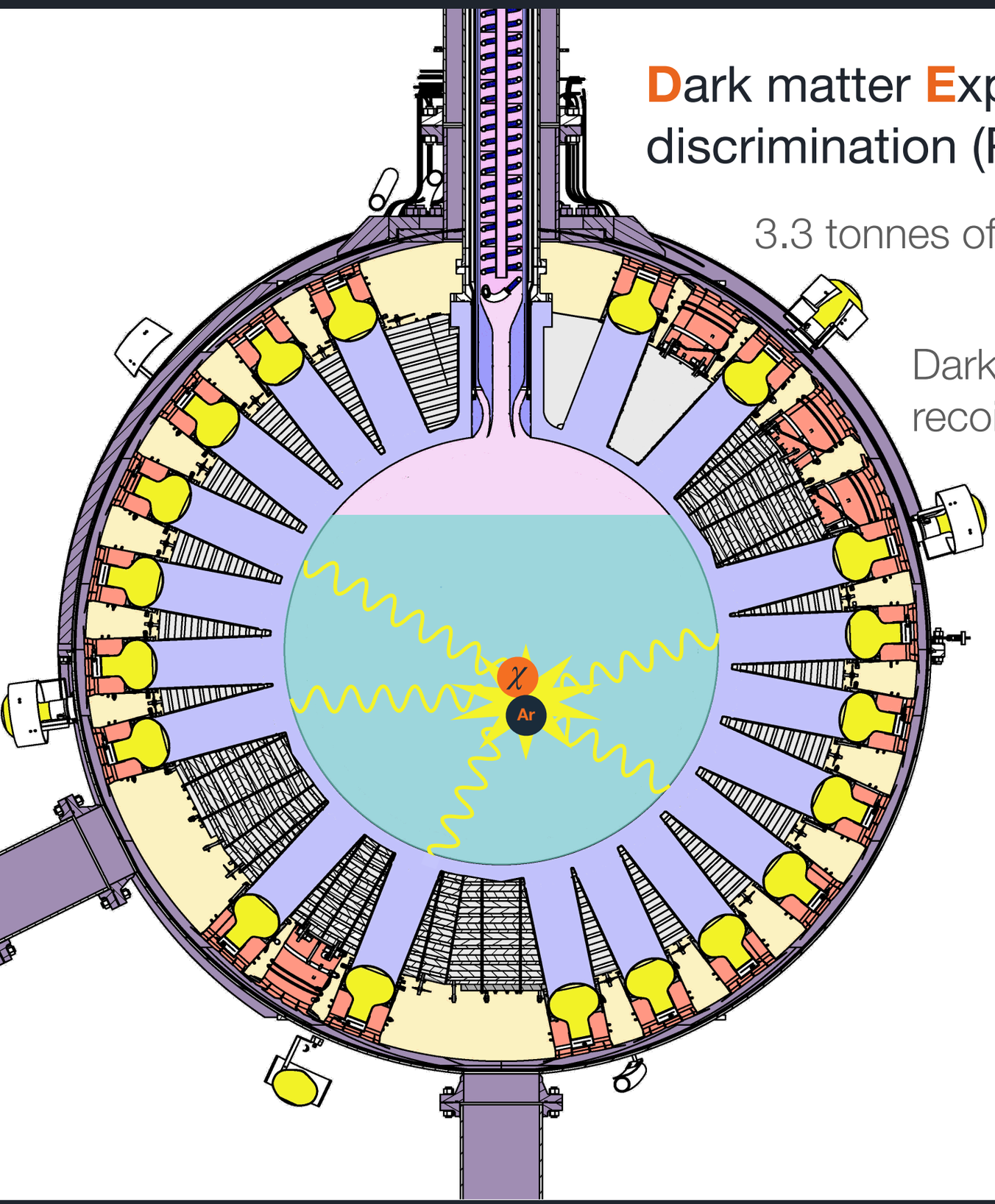

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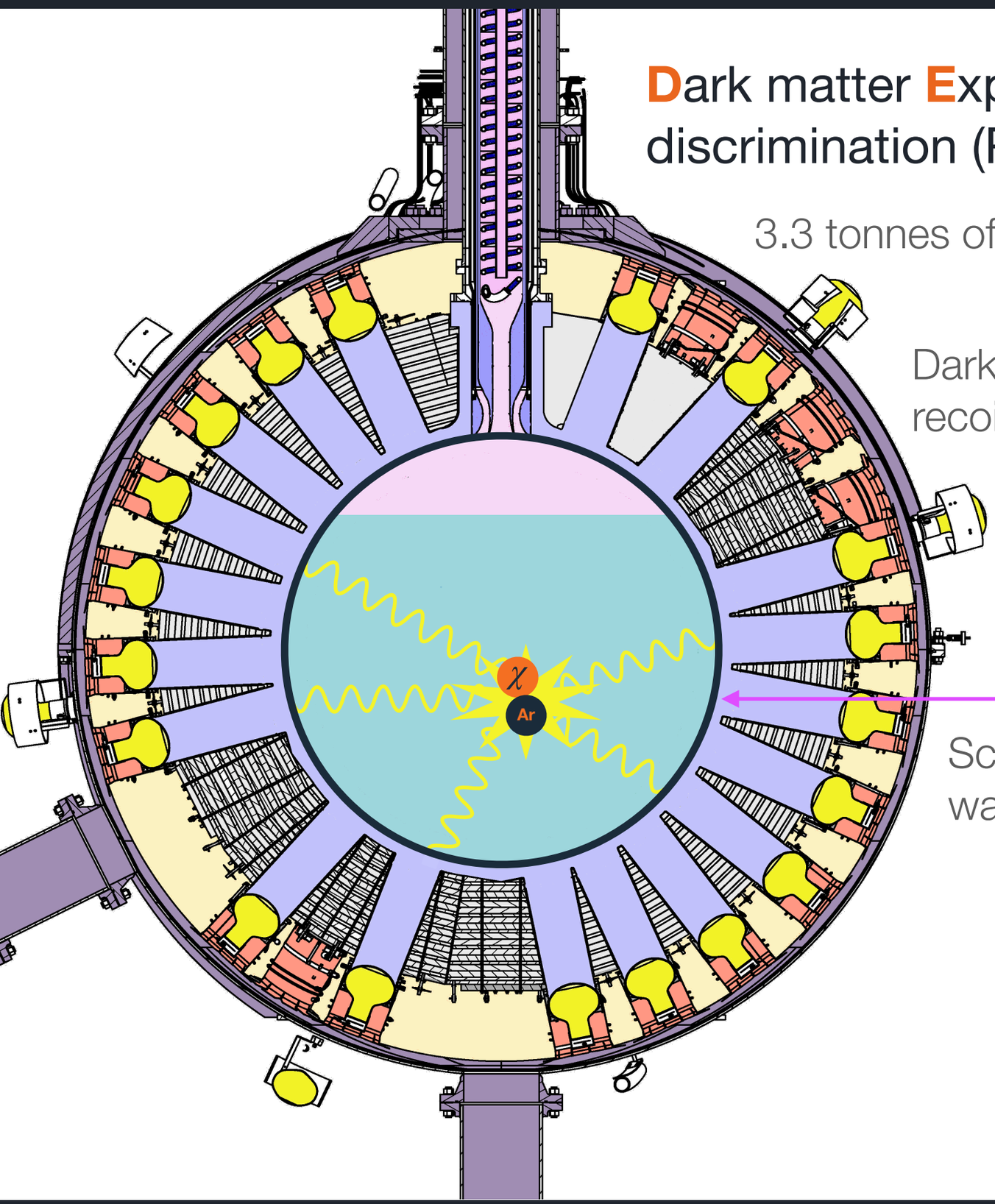

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Scintillation photons pass through TPB wavelength shifter, become 420 nm photons

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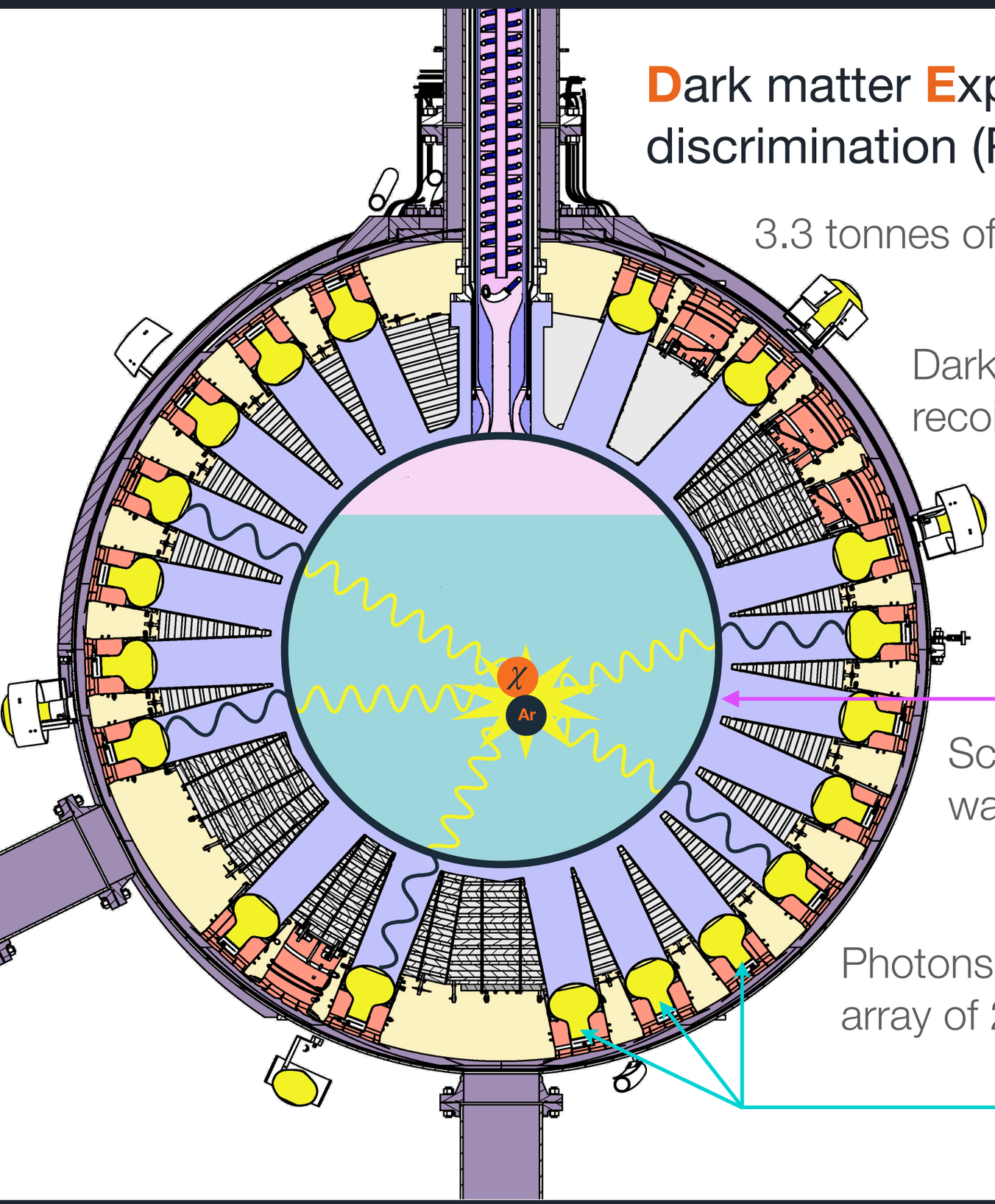

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Photons collected by light guides, detected by array of 255 photomultiplier tubes (PMTs)

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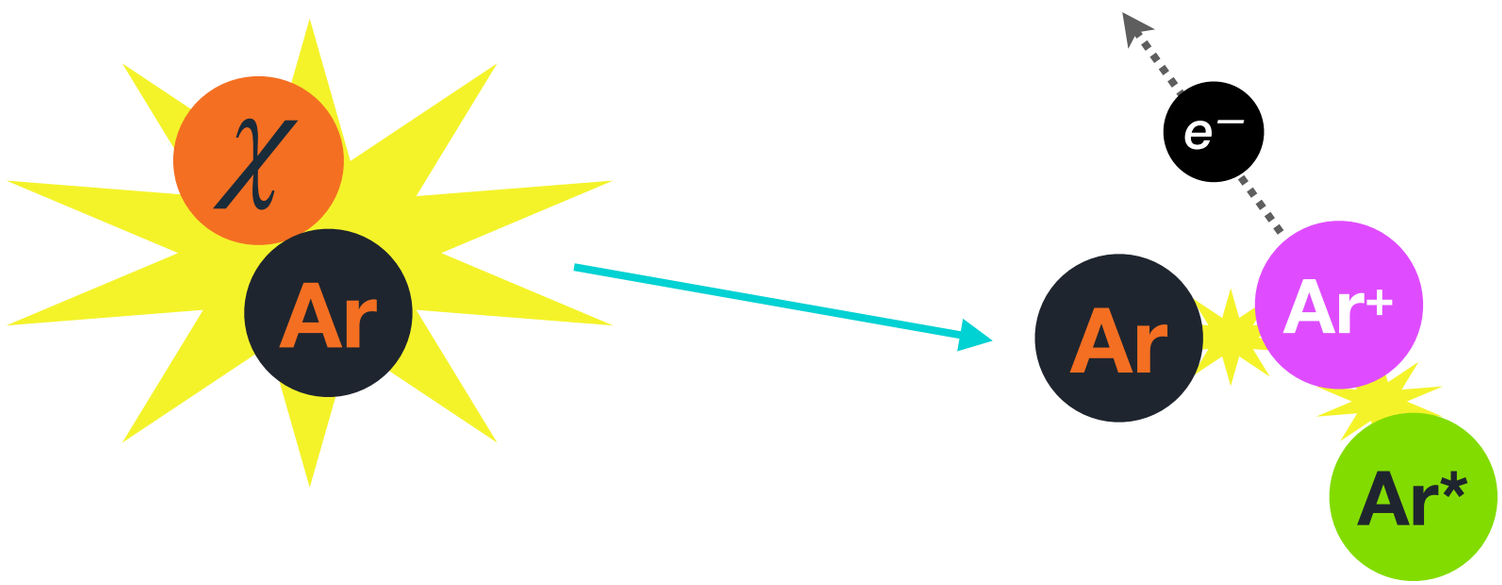
Overview of DEAP-3600:
Liquid Argon Scintillation



Other atoms in the track of the recoiling argon becomes *excited* or *ionized*

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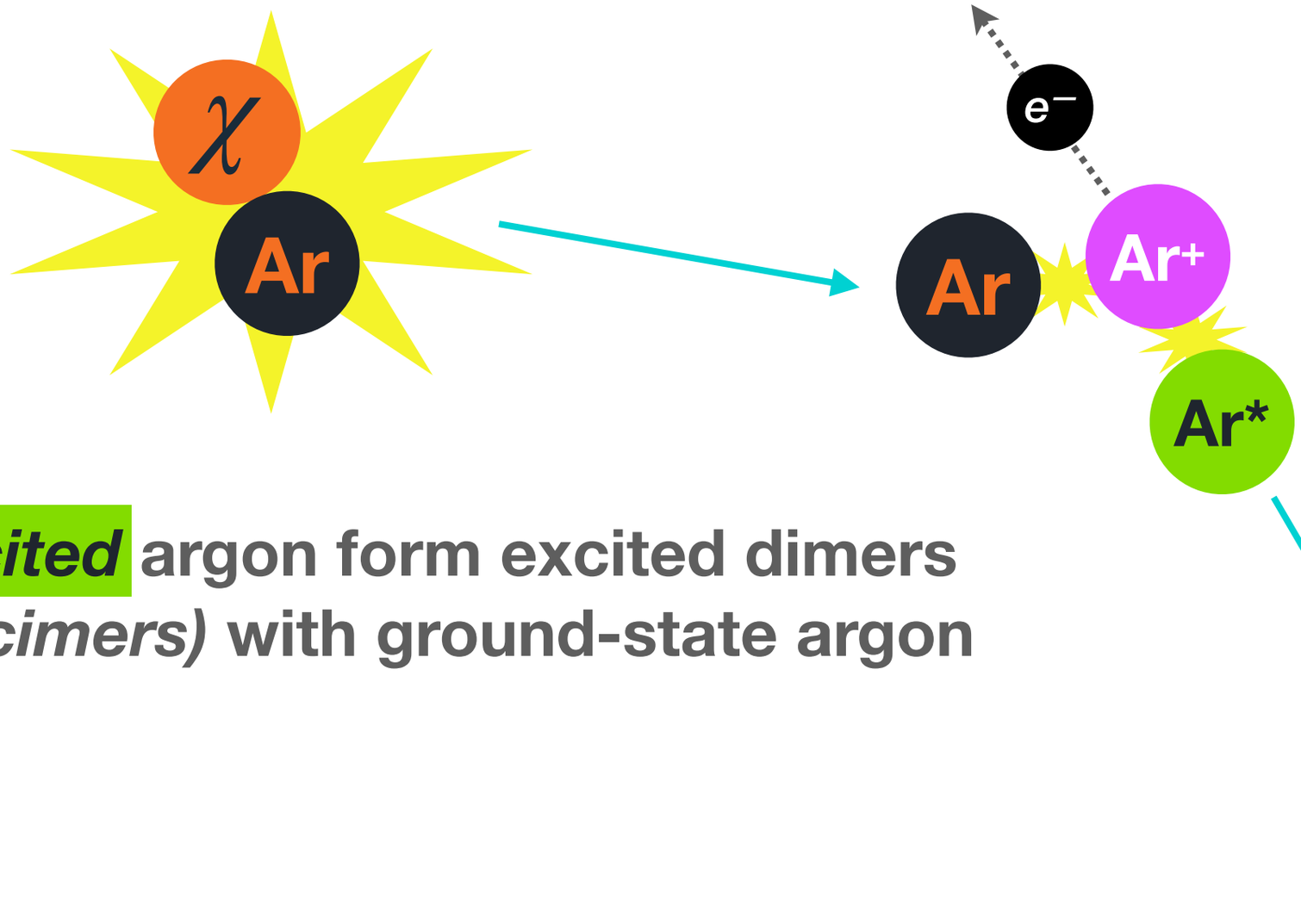
Overview of DEAP-3600:
Liquid Argon Scintillation



Excited **argon form excited dimers *(excimers)* with ground-state argon**

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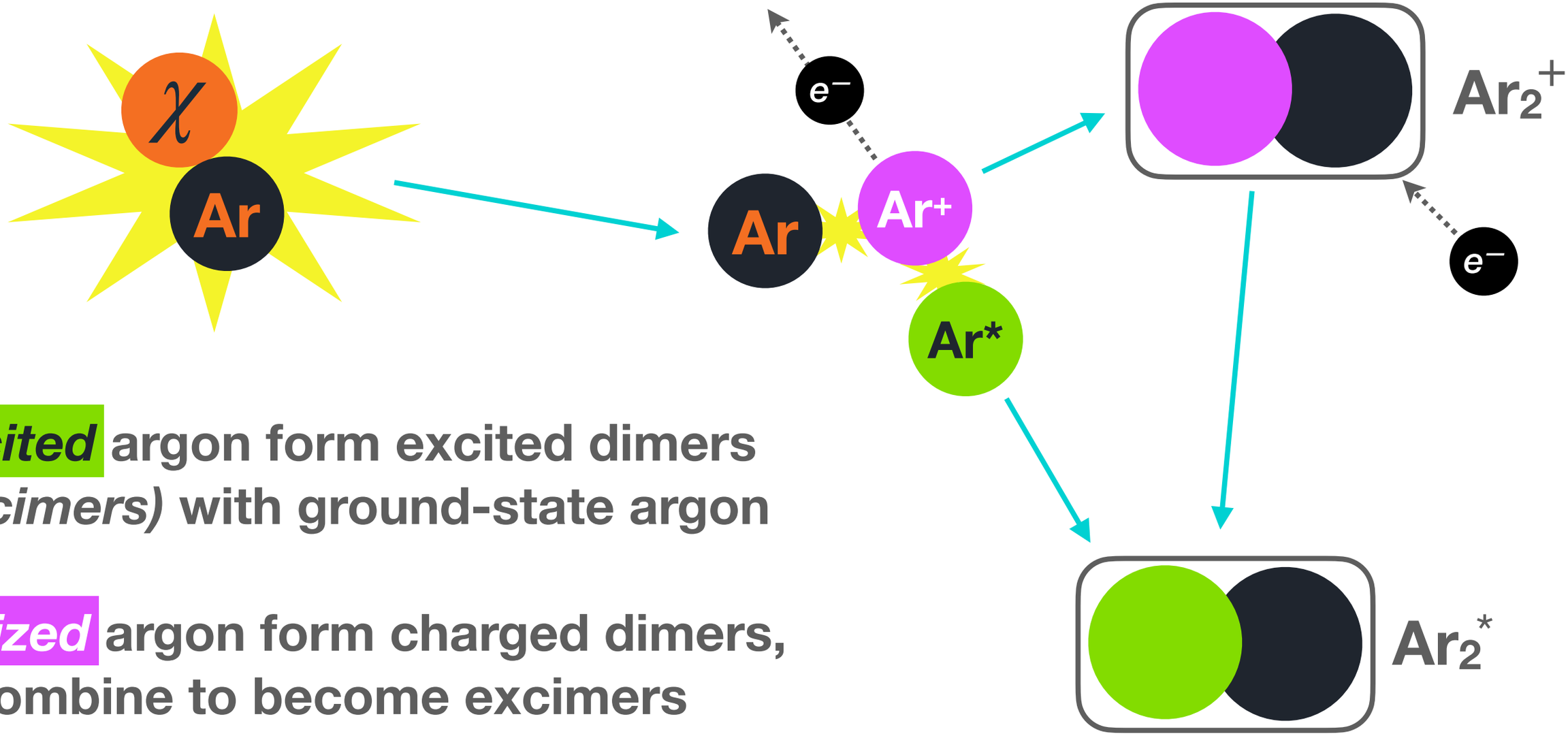

Excited **argon form excited dimers *(excimers)* with ground-state argon**

Ionized **argon form charged dimers, recombine to become excimers**

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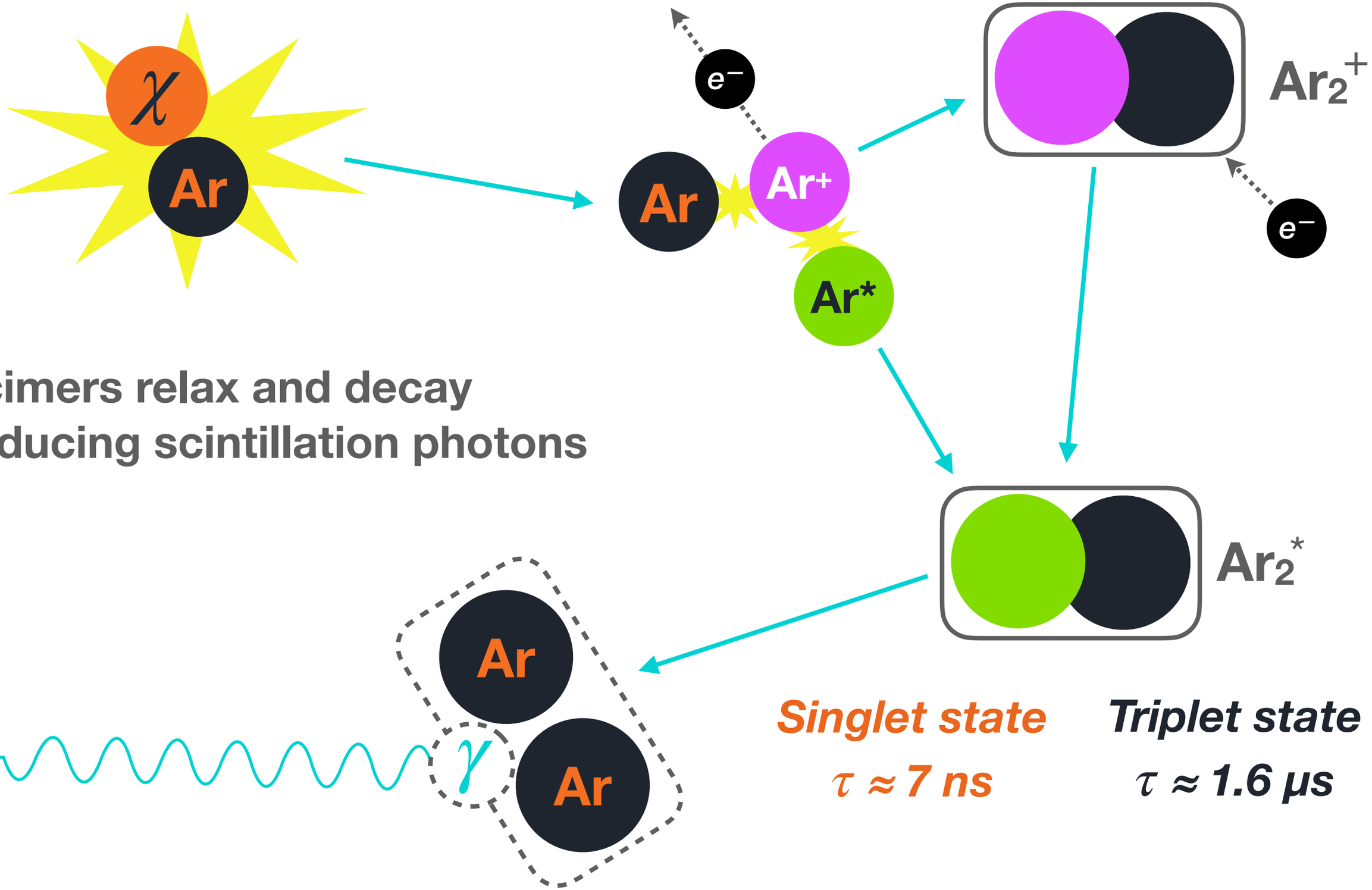

Excimers relax and decay producing scintillation photons

Singlet state $\tau \approx 7$ ***ns***

Triplet state $\tau \approx 1.6$ ***μs***

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Overview of DEAP-3600:
Pulse Shape Discrimination

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Nuclear Recoils

Scattering directly with argon nuclei; excimers mostly populate the ***singlet state***, relax quickly. Induced by:

- Neutrons
- Alphas
- WIMPs

Electronic Recoils

Scattering with argon atomic electrons, ionizing argon; excimers tend to populate ***triplet state***, relax slowly. Induced by:

- Betas (especially ^{39}Ar at ~3 kHz)
- Gammas

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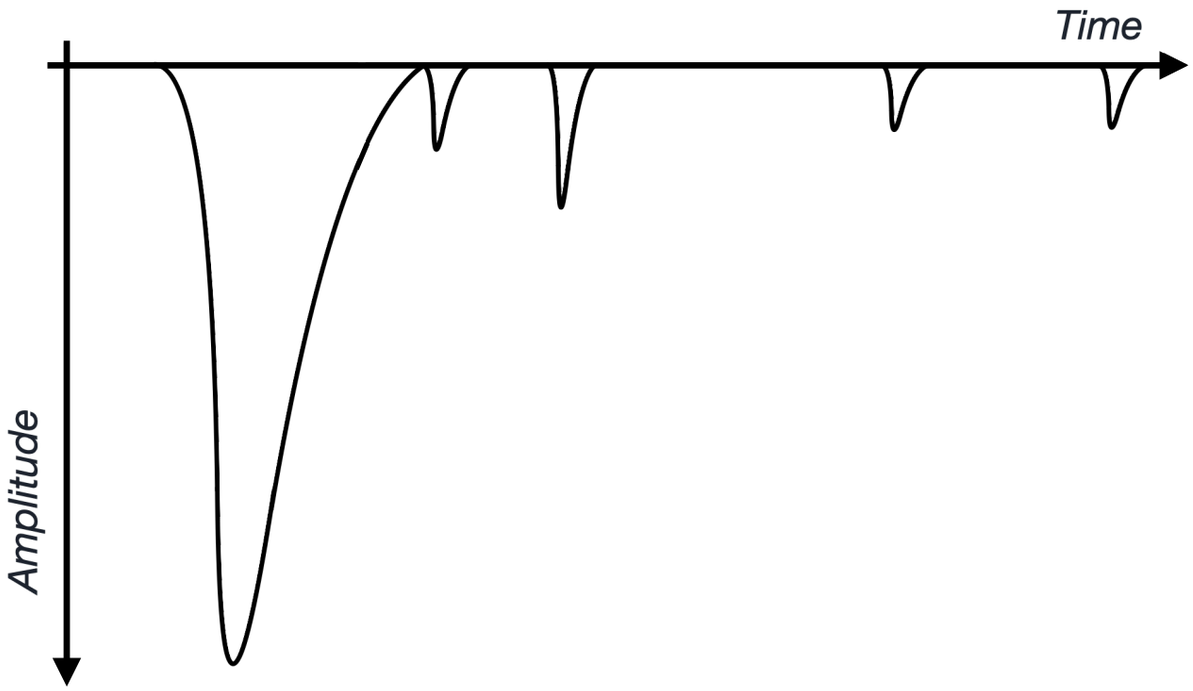
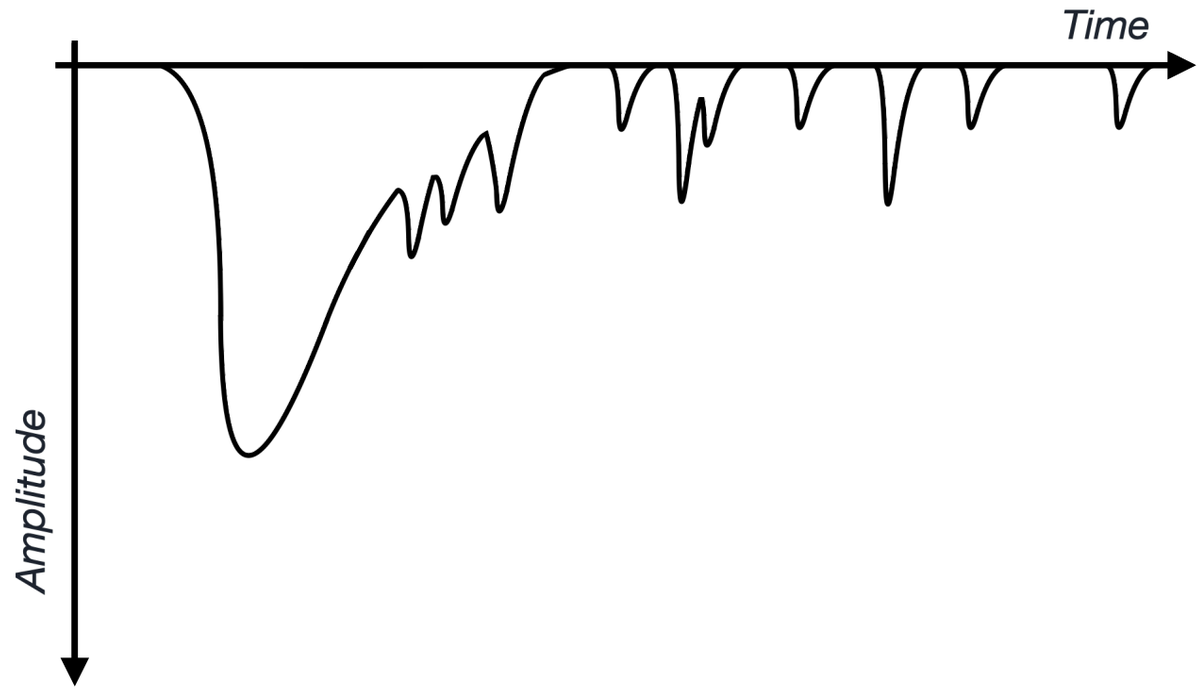


ER Pulse Shape



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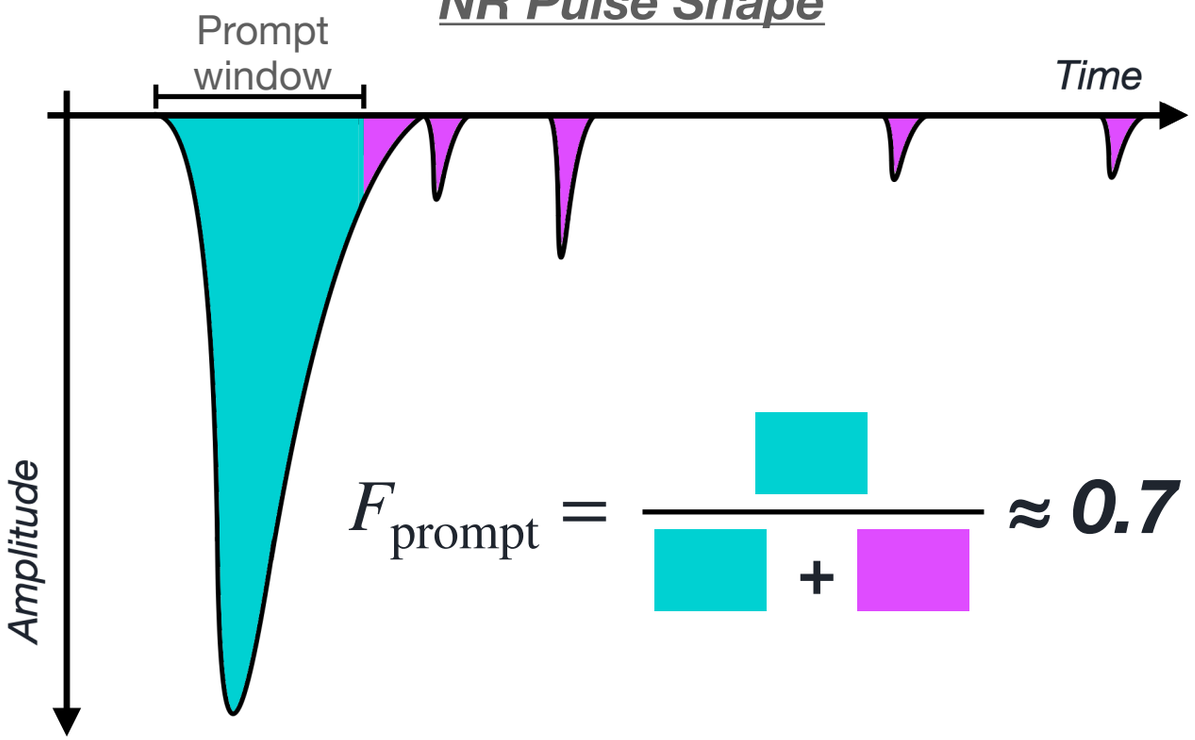

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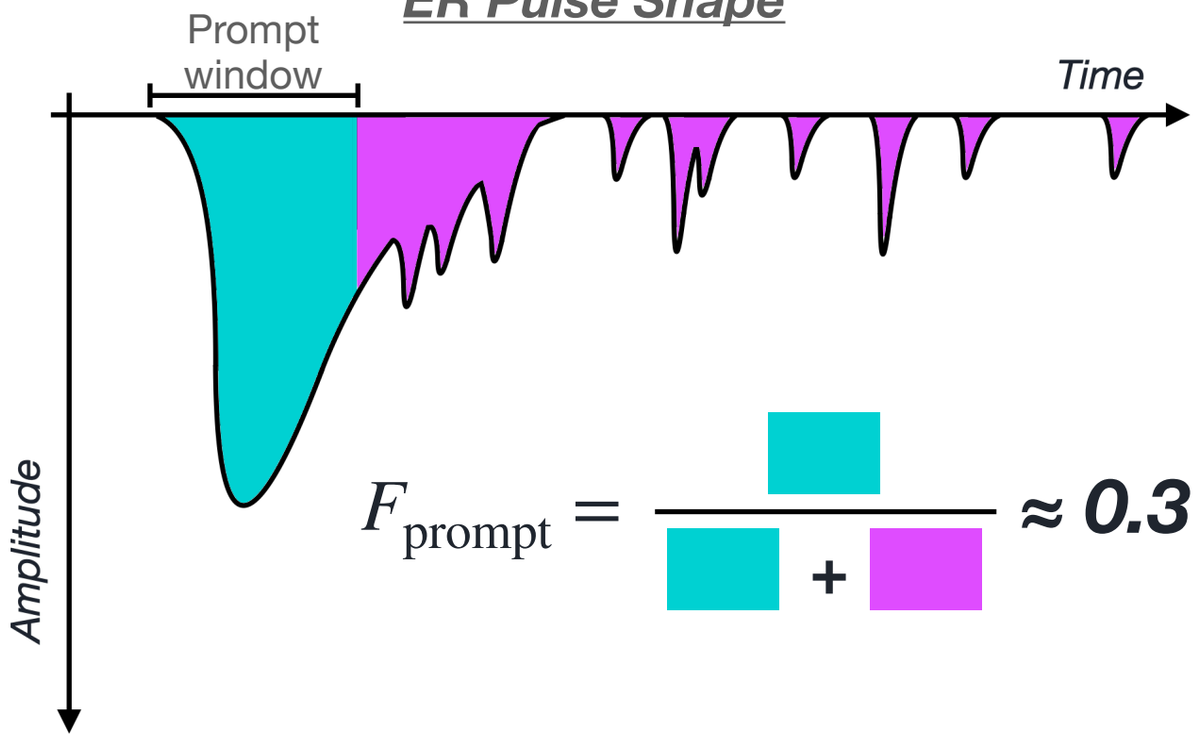

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Precision Measurements:
Liquid Argon Pulse Shape

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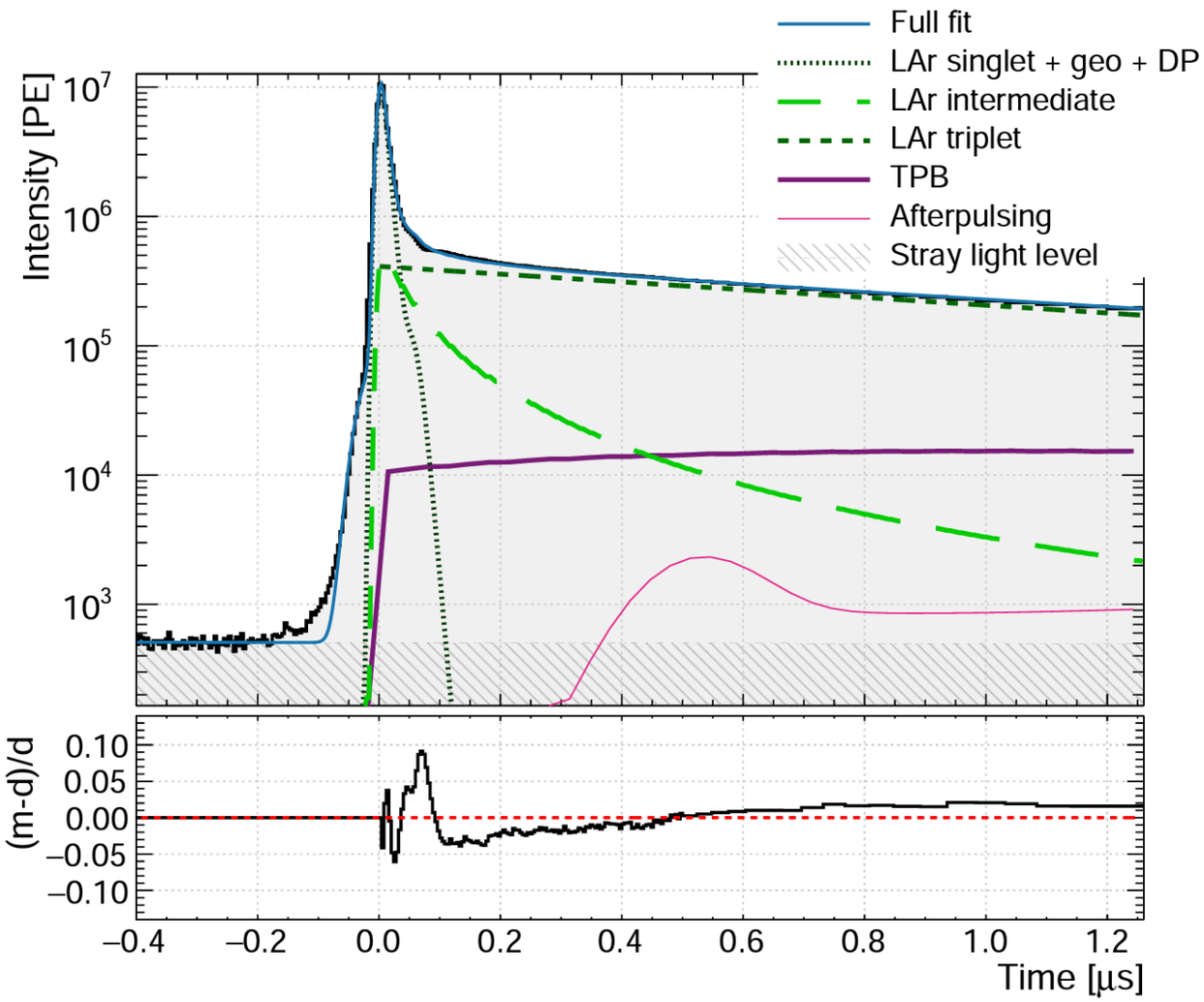
DEAP Collaboration, Eur. Phys. J. C 80, 303 (2020)



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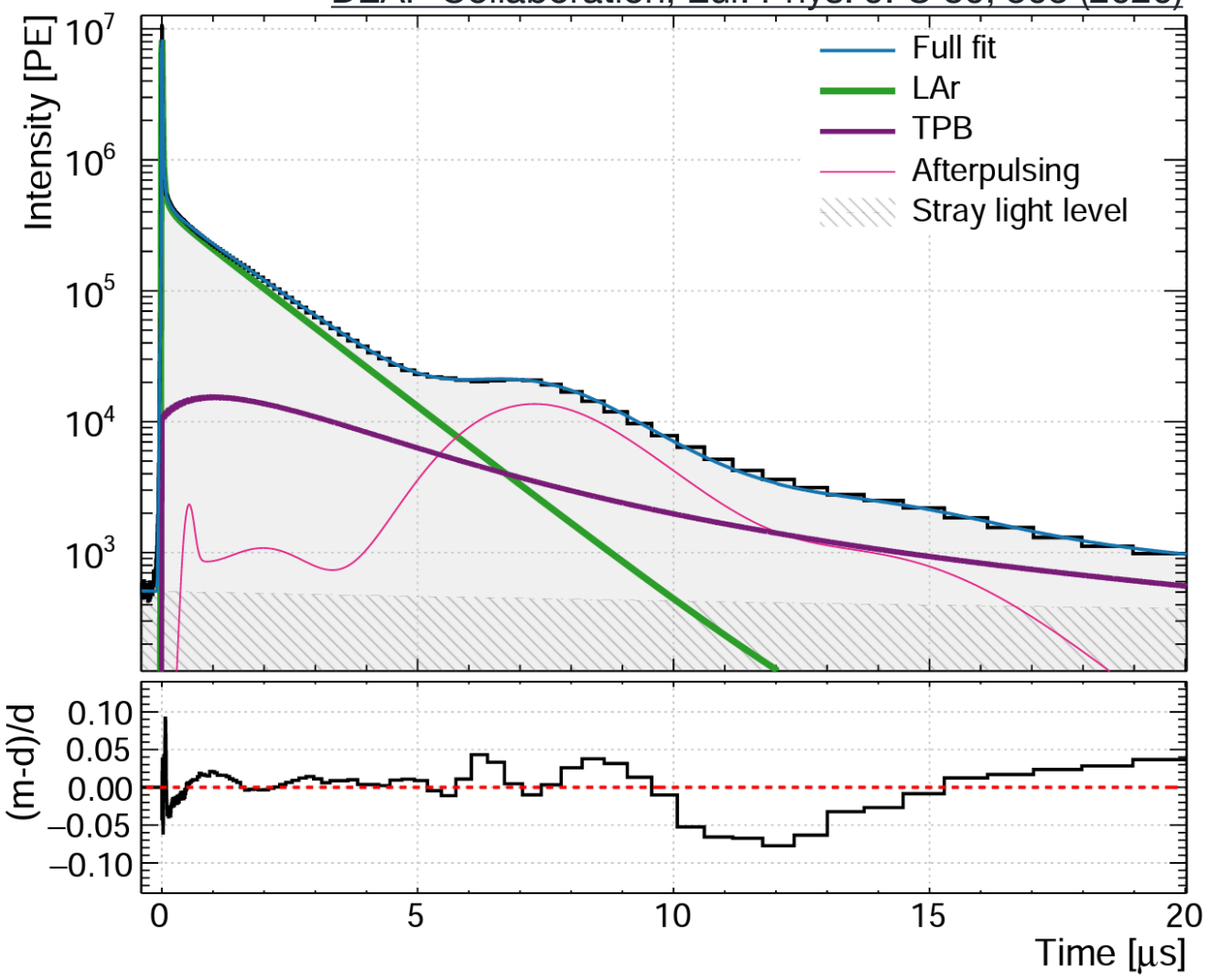

- Characterized the LAr pulse shape, accounting for detector geometry, and contributions from TPB, PMT afterpulsing, double/late pulsing, and stray light

- Pulse shape includes known singlet & triplet components, also ***intermediate*** component

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Precision Measurements:
PSD in 4.5 Tonne-Year Exposure

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- Detailed pulse shape modelling allows for ability to separate scintillation from PMT artifacts; i.e. PMT afterpulsing

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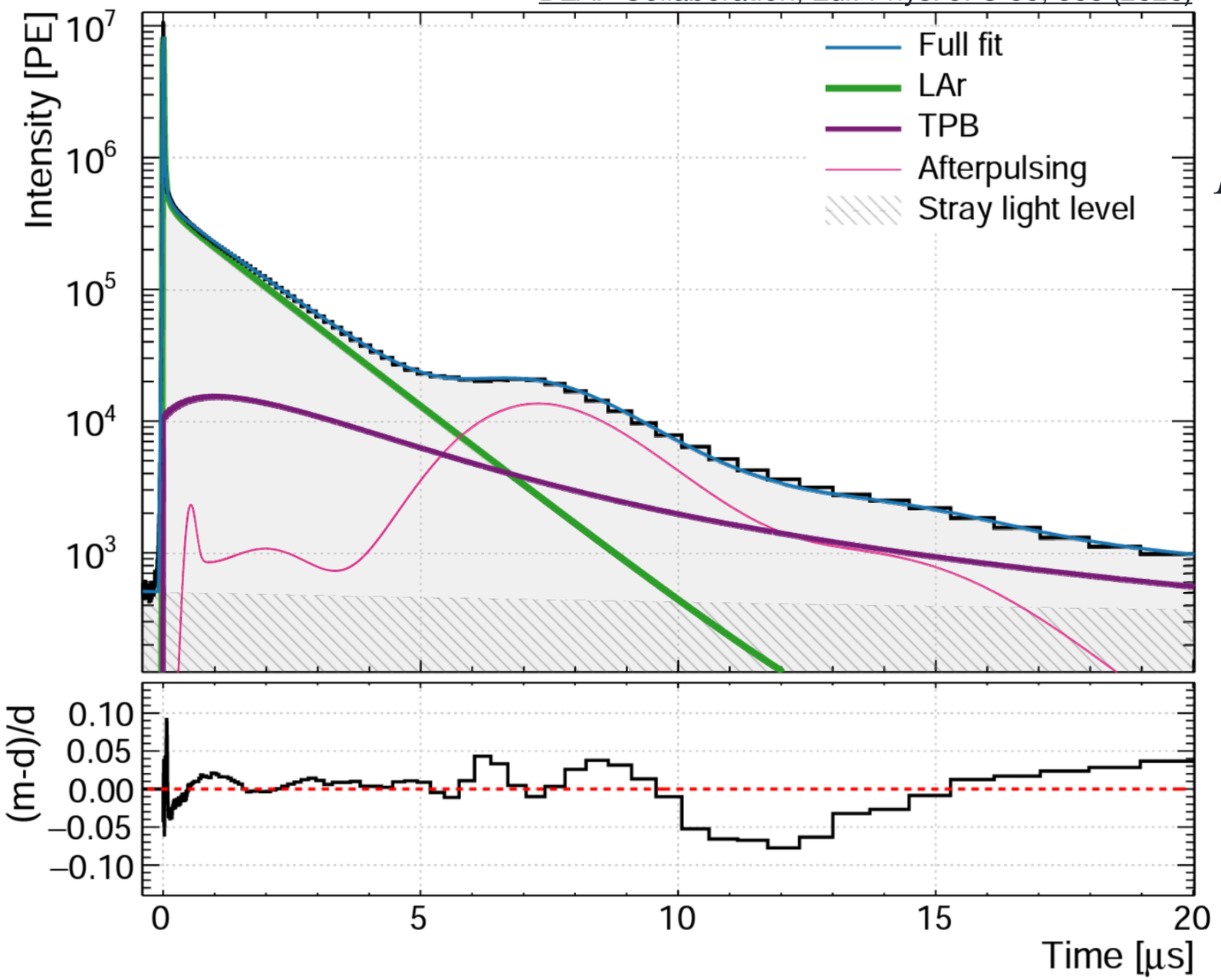

Prompt Window Length

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

Full Event Window Length

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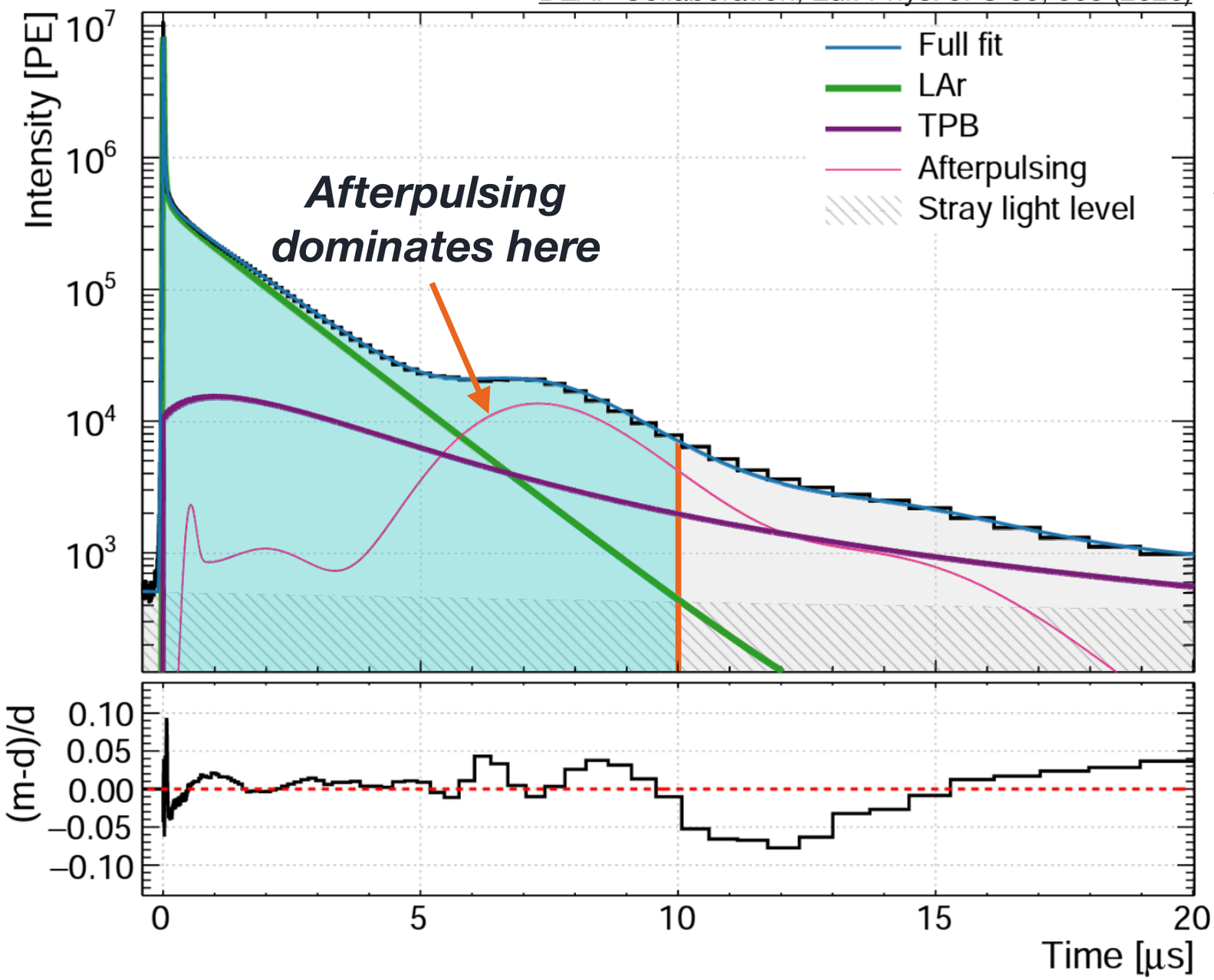

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$$\text{PE} \equiv \frac{\textit{Total Integrated Charge}}{\textit{Single Photoelectron Charge}}$$

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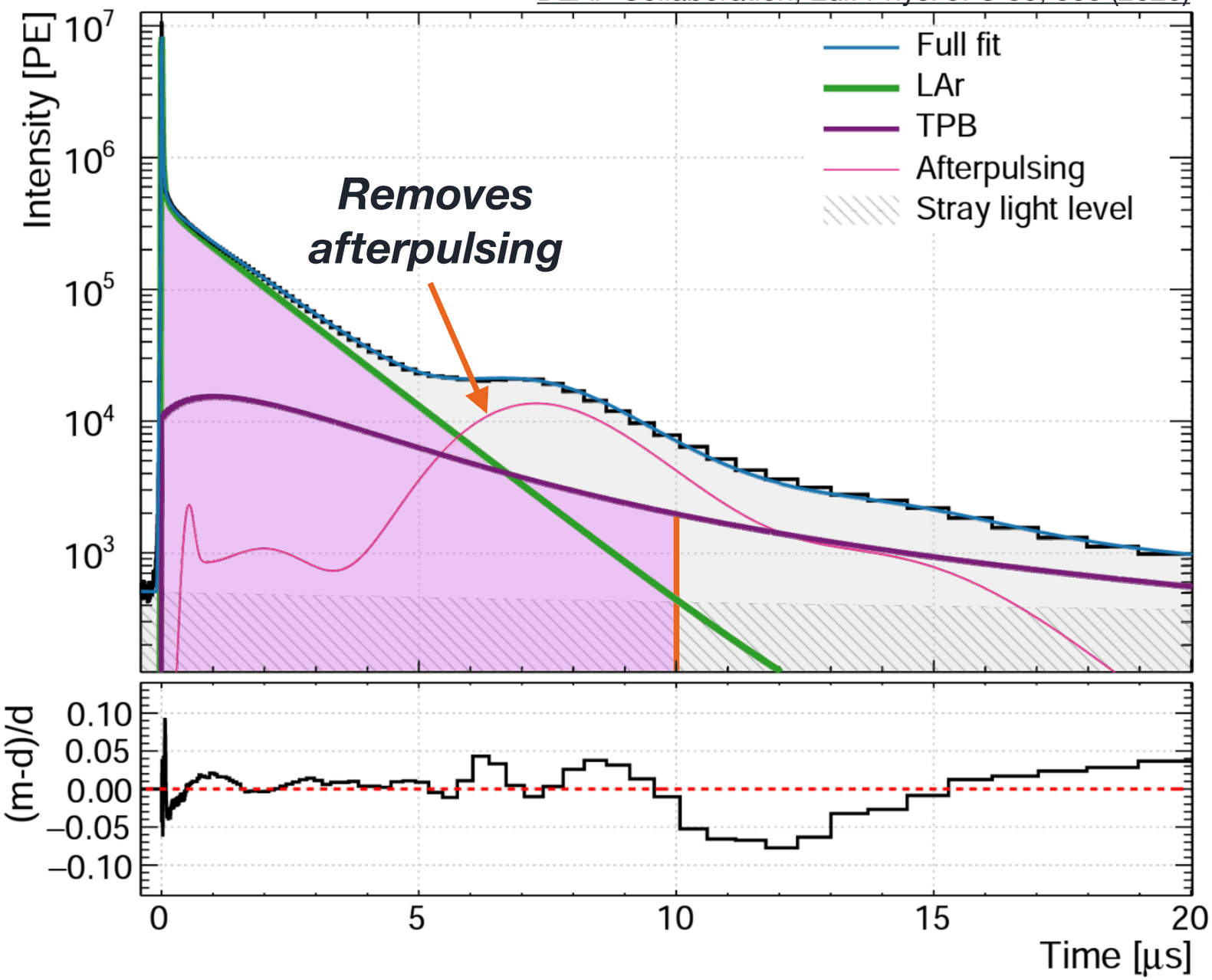

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$$\text{PE} \equiv \textit{Bayesian Photoelectron Counting}$$

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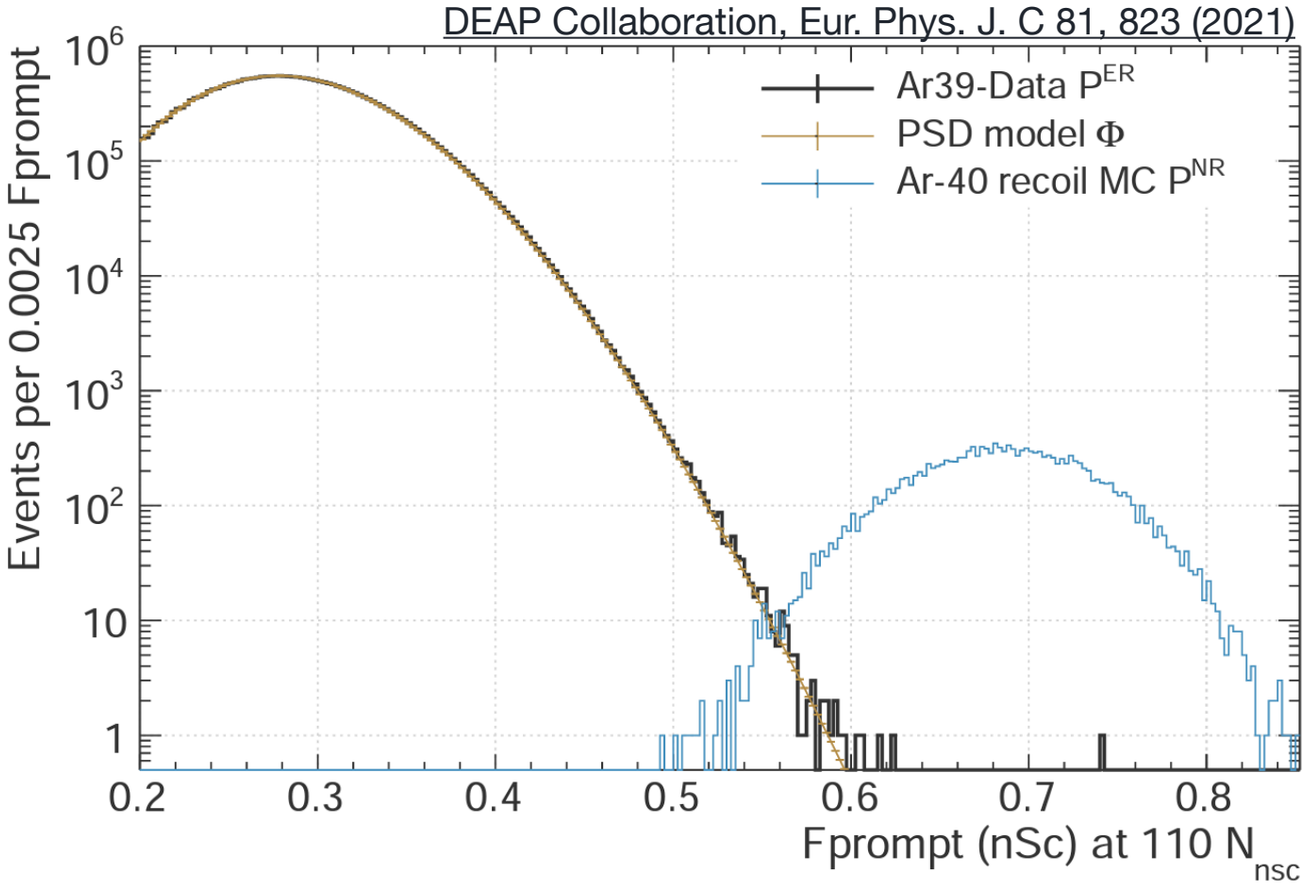

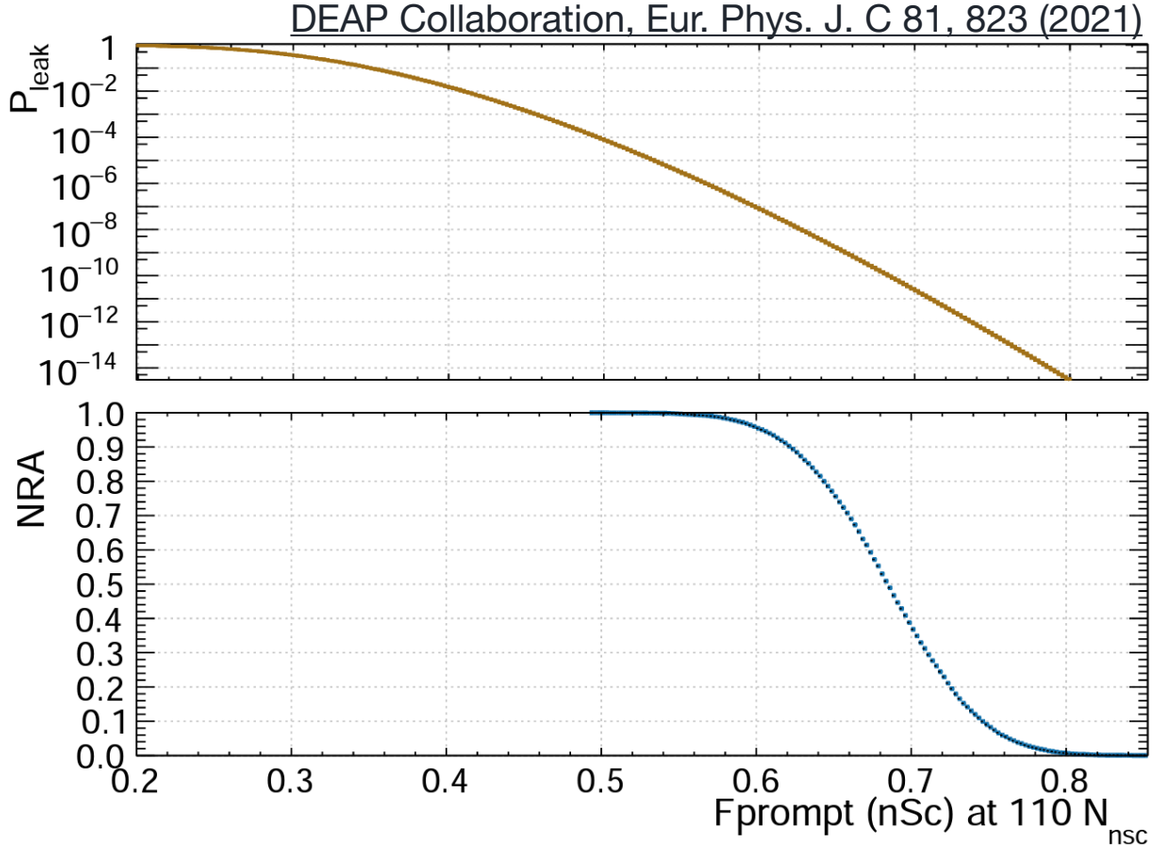

- PSD model tested with both energy estimators: total integrated charge & with afterpulsing removal

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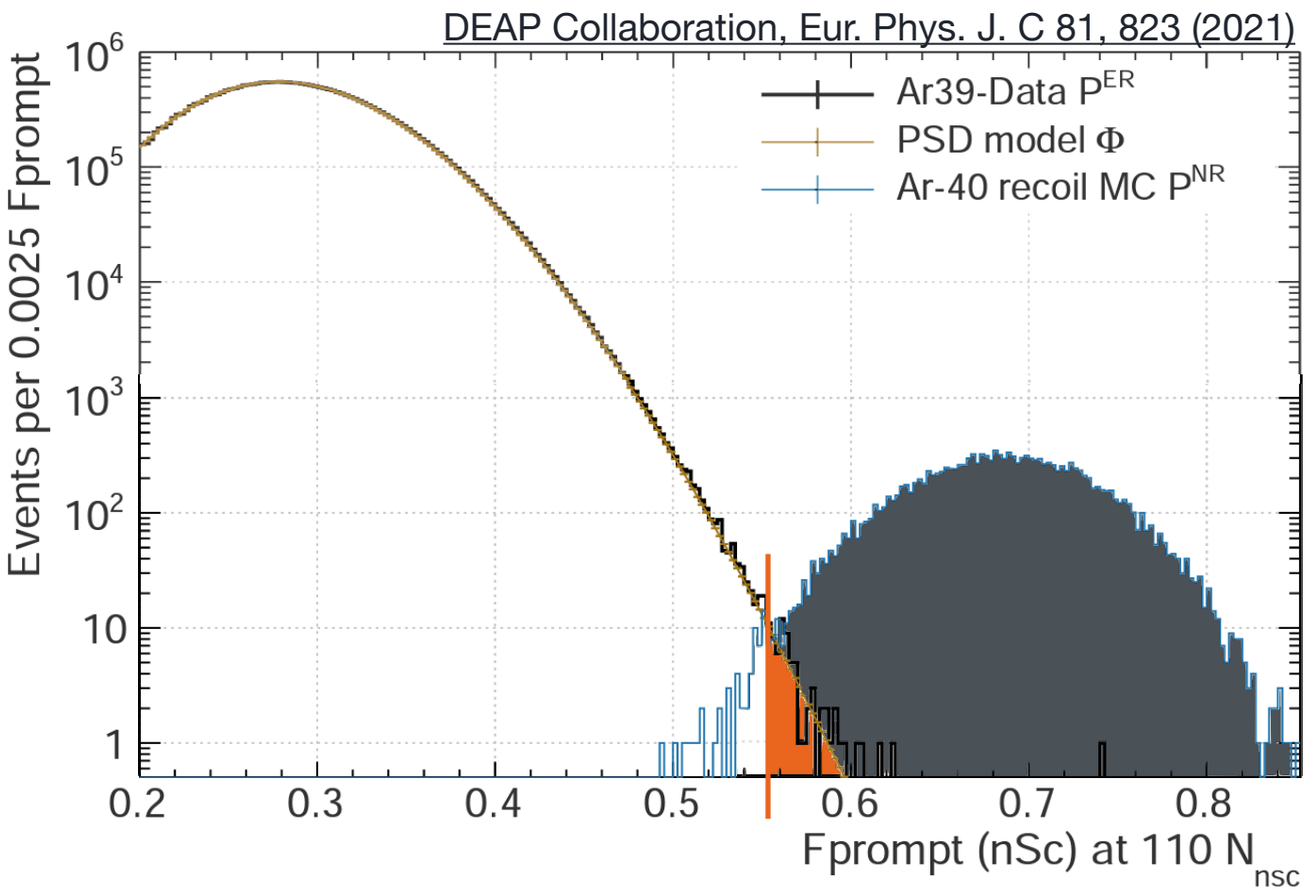

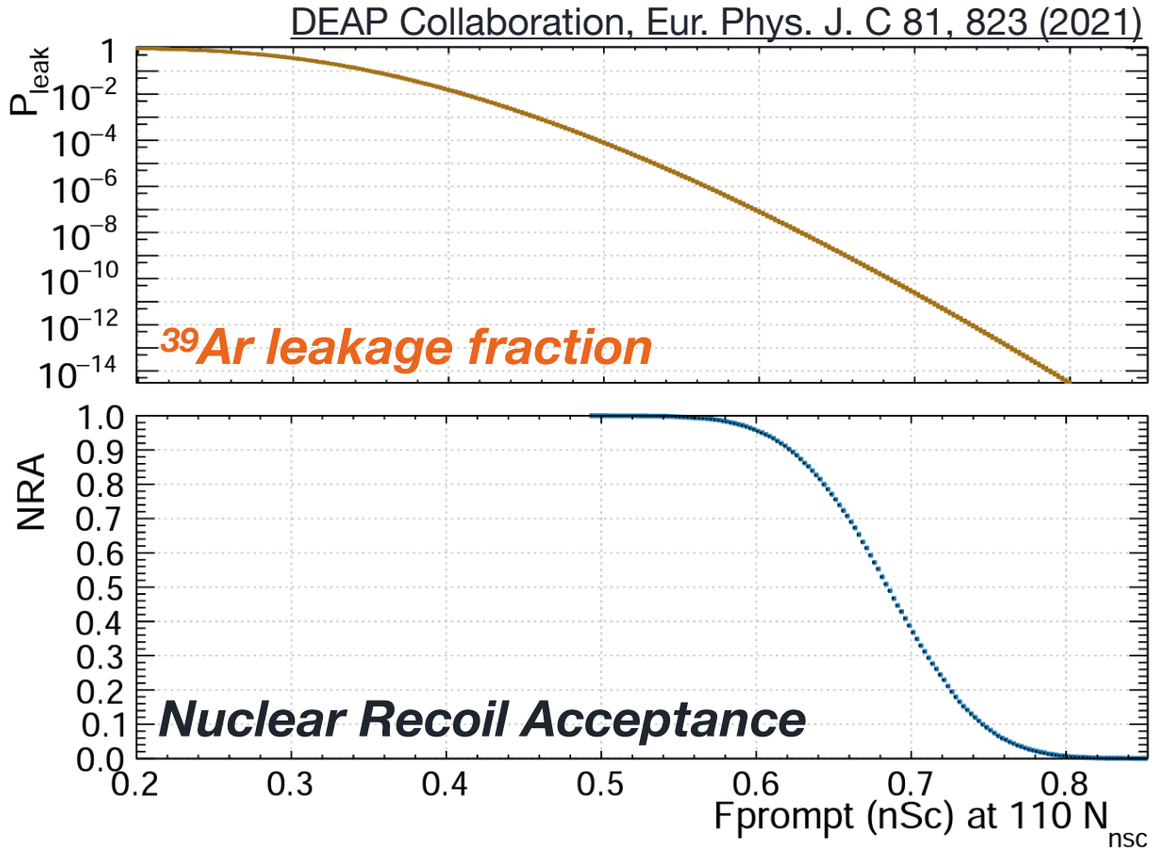

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- ^{39}Ar leakage is reduced by an order magnitude with afterpulsing removal compared to total charge integration

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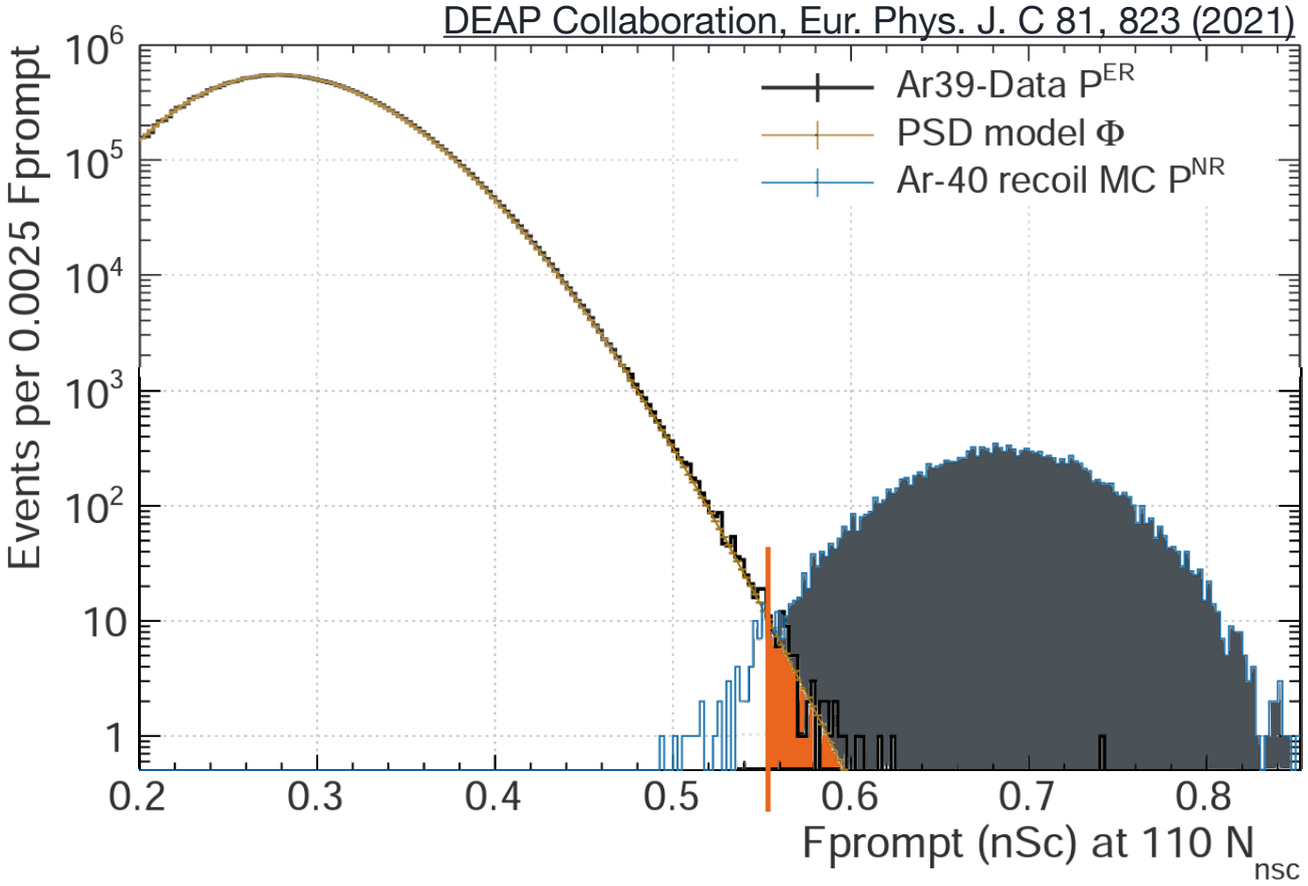

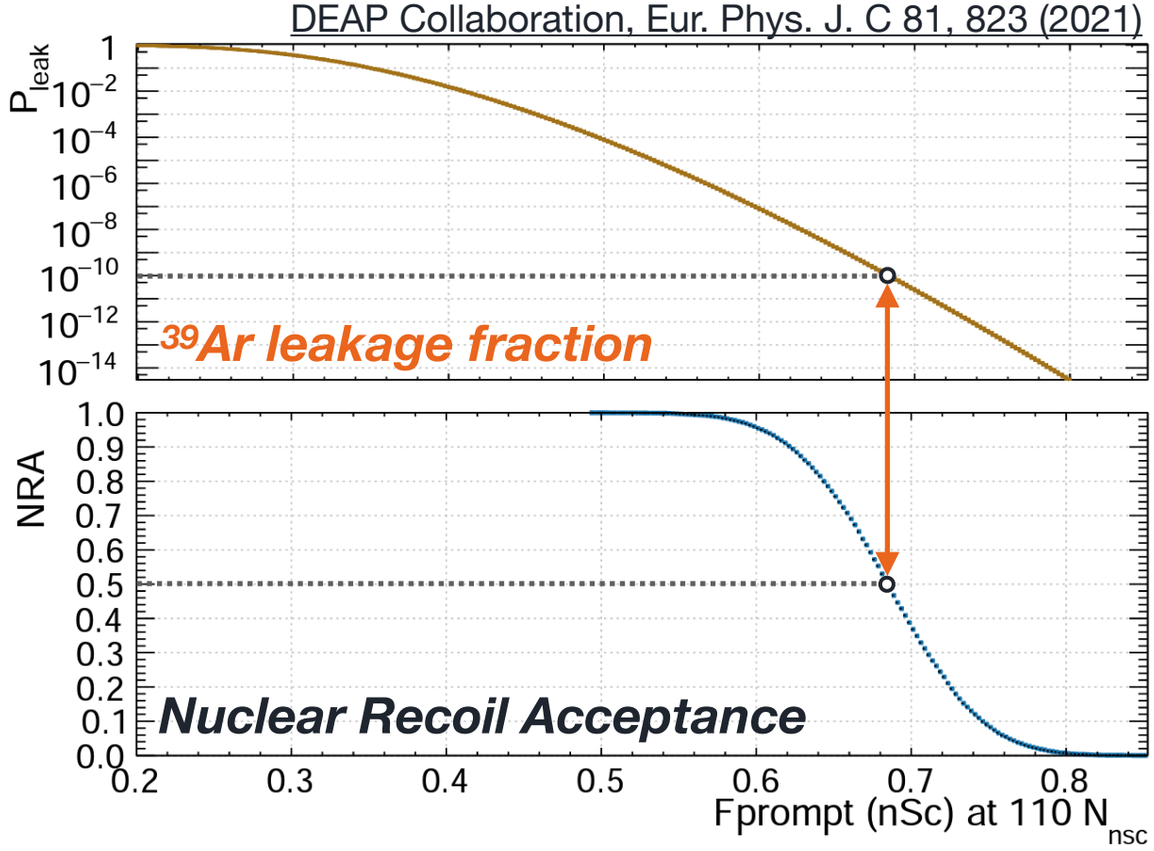

- PSD model tested with both energy estimators: total integrated charge & with afterpulsing removal
- ^{39}Ar leakage is reduced by an order magnitude with afterpulsing removal compared to total charge integration
- Result: ***world leading PSD!***
  10^{-10} leakage fraction of ^{39}Ar for 50% NR acceptance at 110 PE (117.5 keV_{ee})

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Precision Measurements:
Electromagnetic Backgrounds

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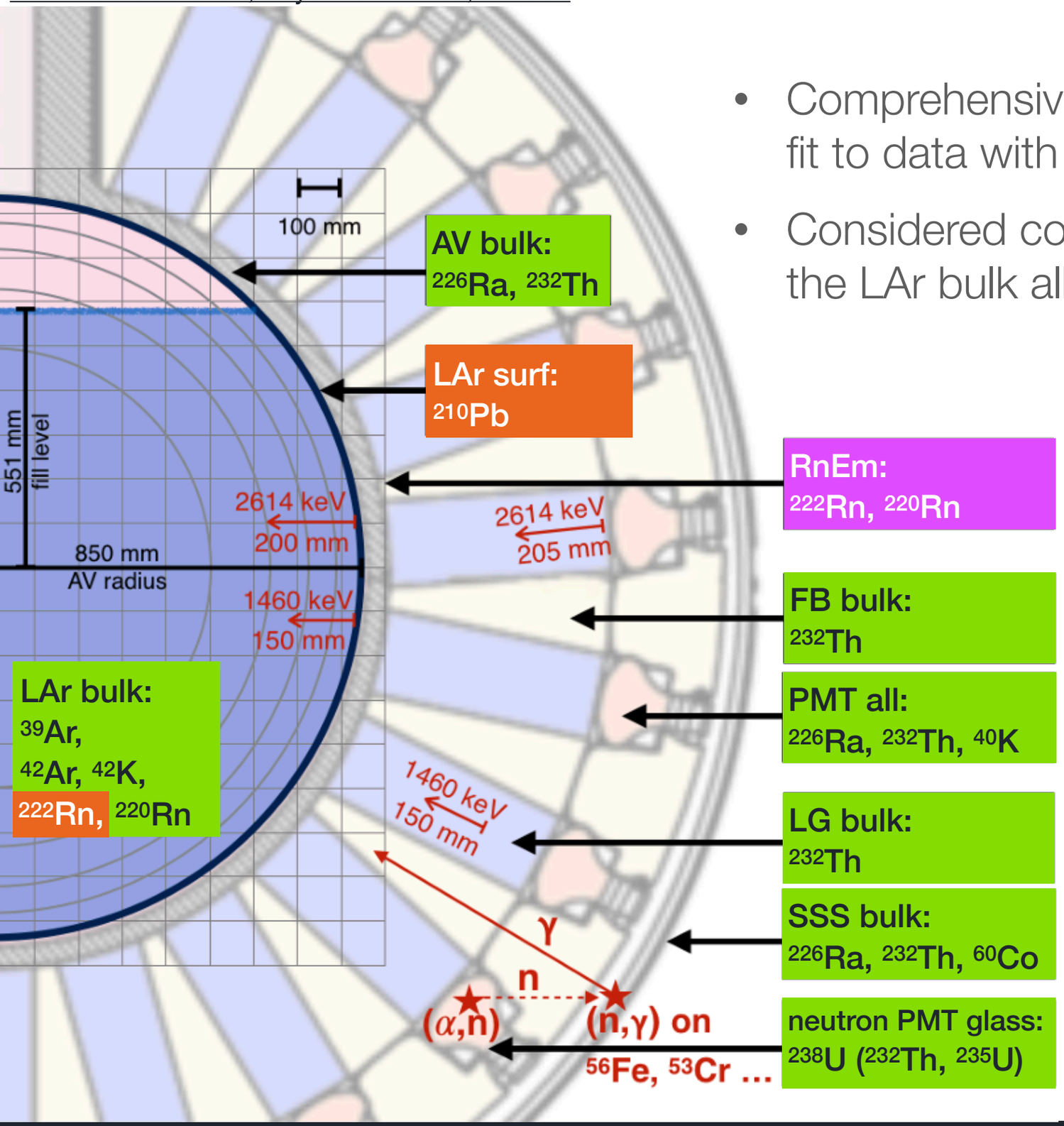
DEAP Collaboration, Phys. Rev. D 100, 072009



- Comprehensive electromagnetic backgrounds model fit to data with BAT (Bayesian Analysis Toolkit)
- Considered components include sources located in the LAr bulk all the way out to the stainless steel shell

EM Backgrounds Model

14 sources as free parameters

2 sources as fixed parameters

2 sources included as systematics

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Precision Measurements: **Electromagnetic Backgrounds**

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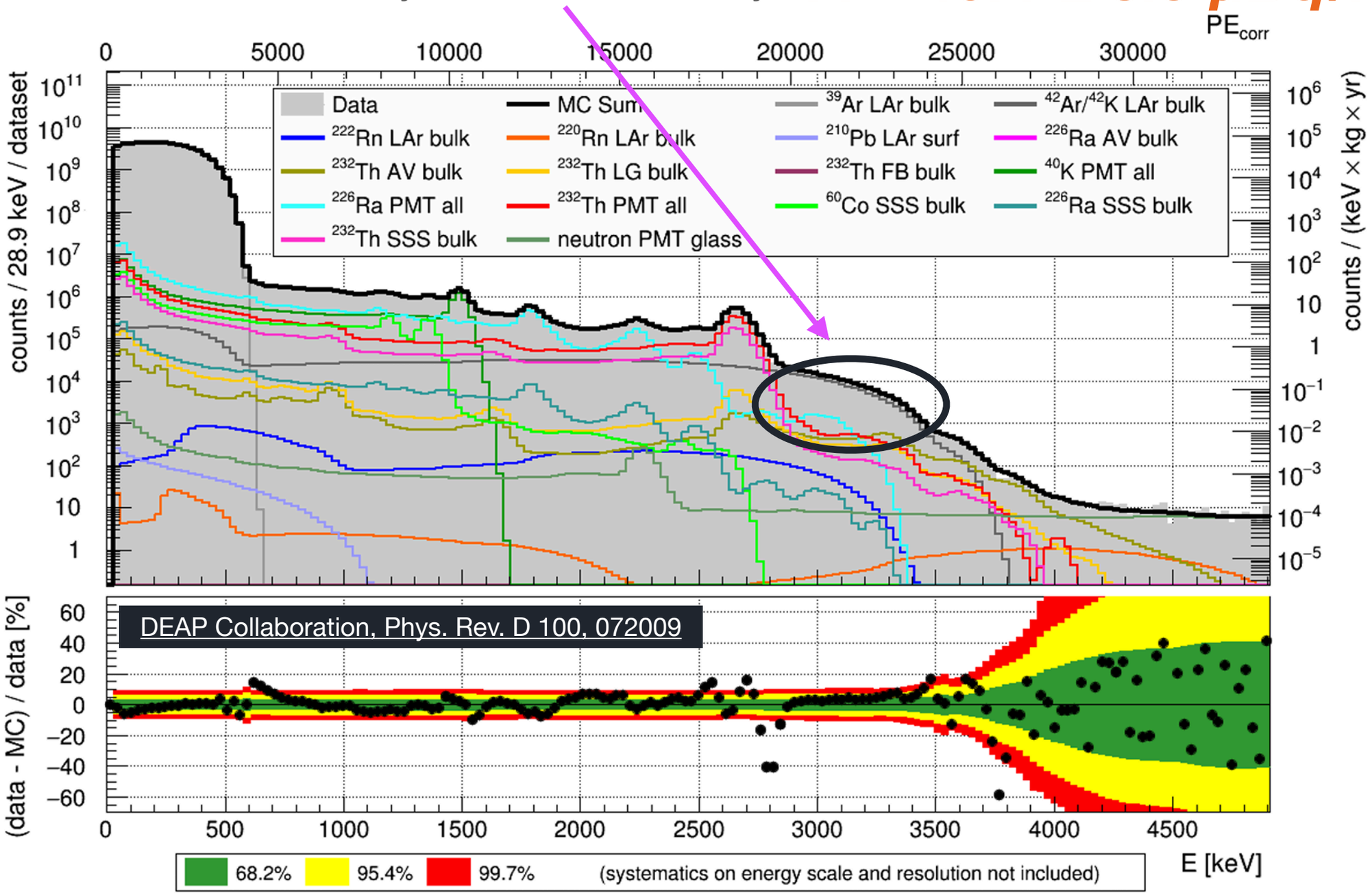
- ^{42}Ar betas are source of background for DarkSide-20k, GERDA, LEGEND—previously measurements of its specific activity are in tension, have large uncertainties
- DEAP measures ^{42}Ar activity via ^{42}K beta decay: ***A = 40.4 ± 5.9 μBq/kg***



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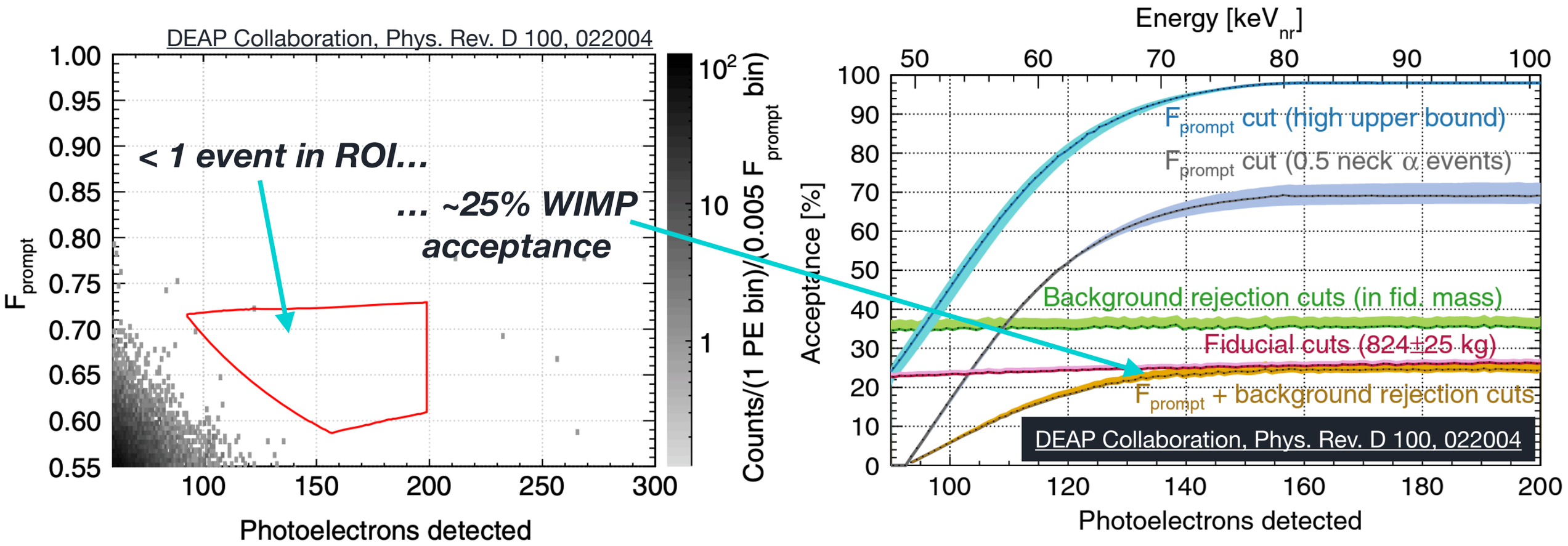
WIMP Searches:
DEAP Standard Analysis



- DEAP's 231 live-day exposure with region of interest (ROI), fiducial volume (FV), and event selection cuts had zero background events

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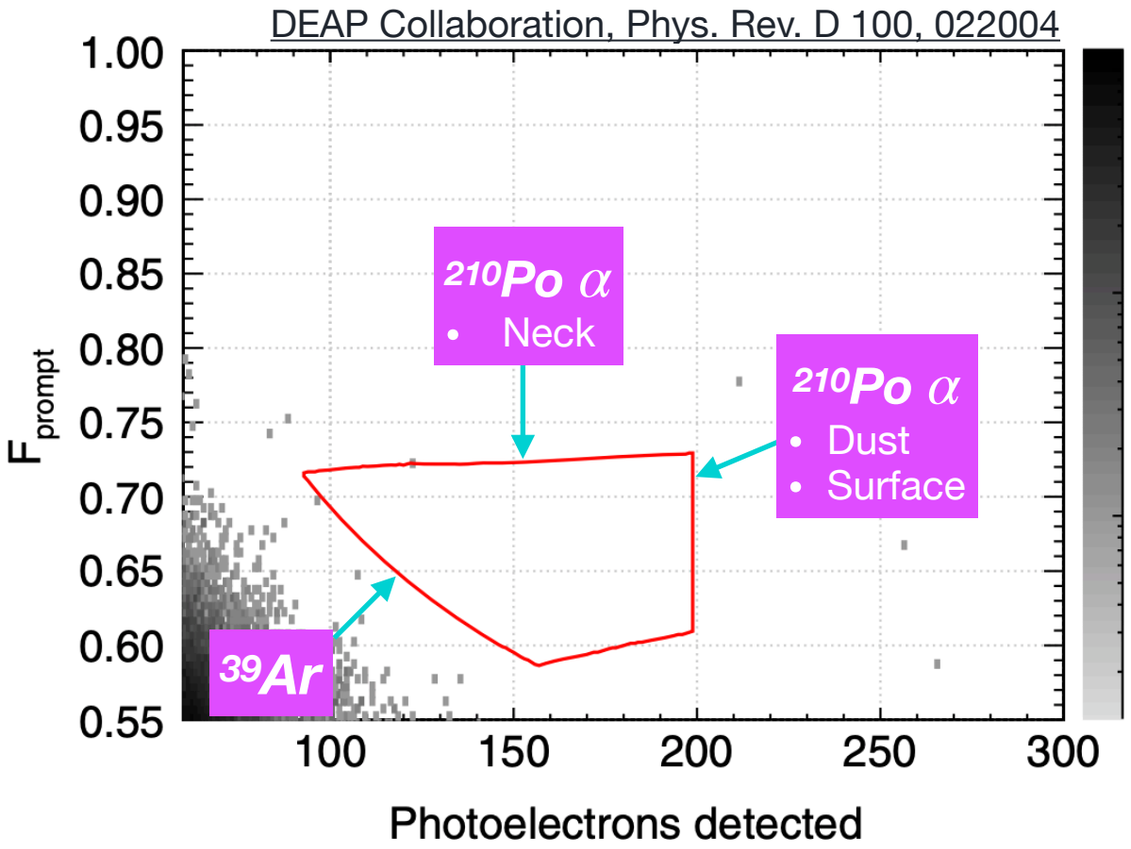
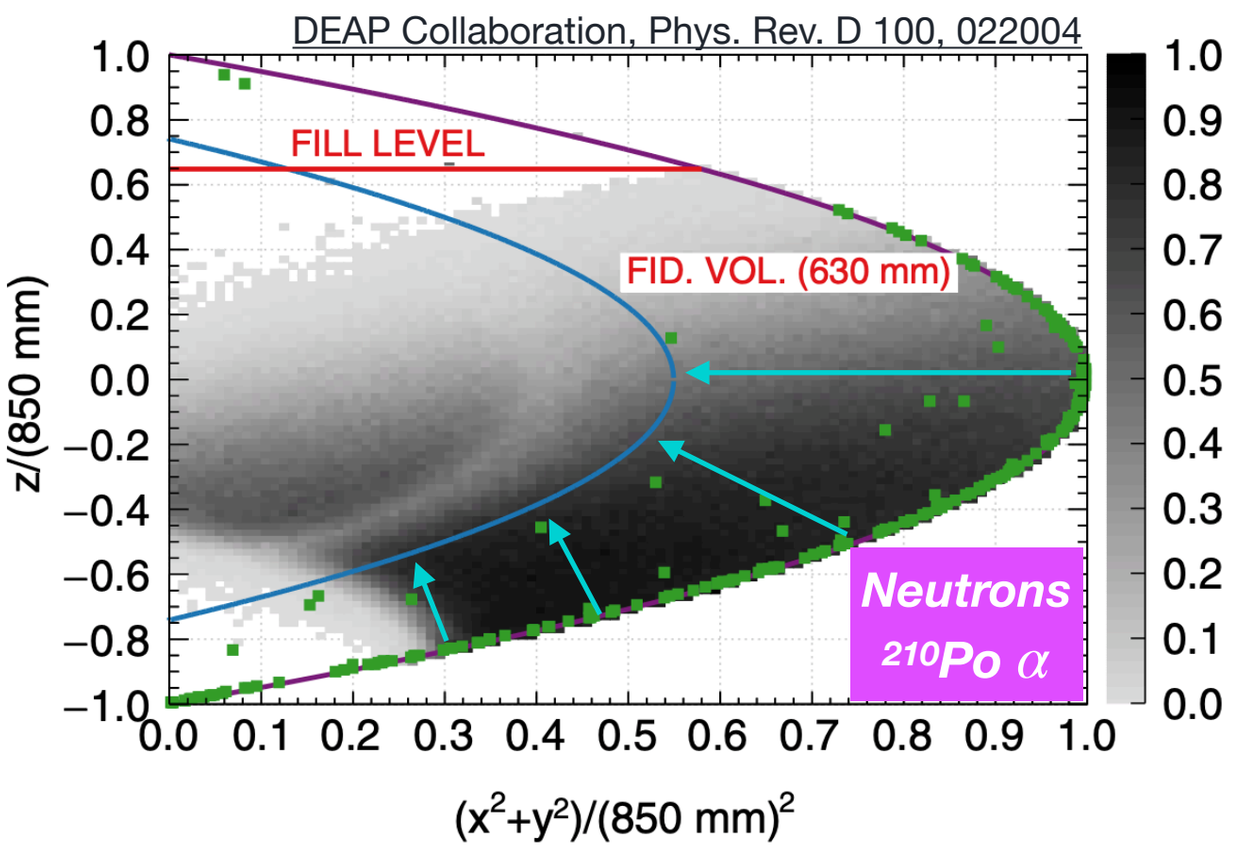
WIMP Searches:
Profile Likelihood Ratio





- DEAP's 231 live-day exposure with region of interest (ROI), fiducial volume (FV), and event selection cuts had zero background events
- Improved background model and machine learning algorithms will allow us to expand ROI and FV, as well as ease event selection cuts

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WIMP Searches:
Profile Likelihood Ratio

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Define a Likelihood Function

$$\mathscr{L}(\mathbf{x}\,|\,\sigma,\theta) = \mathscr{L}_{\mathrm{PDFs}}(\mathbf{x}\,|\,\sigma,\theta)\cdot\mathscr{L}_{\mathrm{Con}}(\theta)\cdot\mathscr{L}_{\mathrm{SB}}(\theta)$$

Set of observed data points

WIMP-nucleon elastic scattering cross-section

Set of nuisance parameters (systematics)

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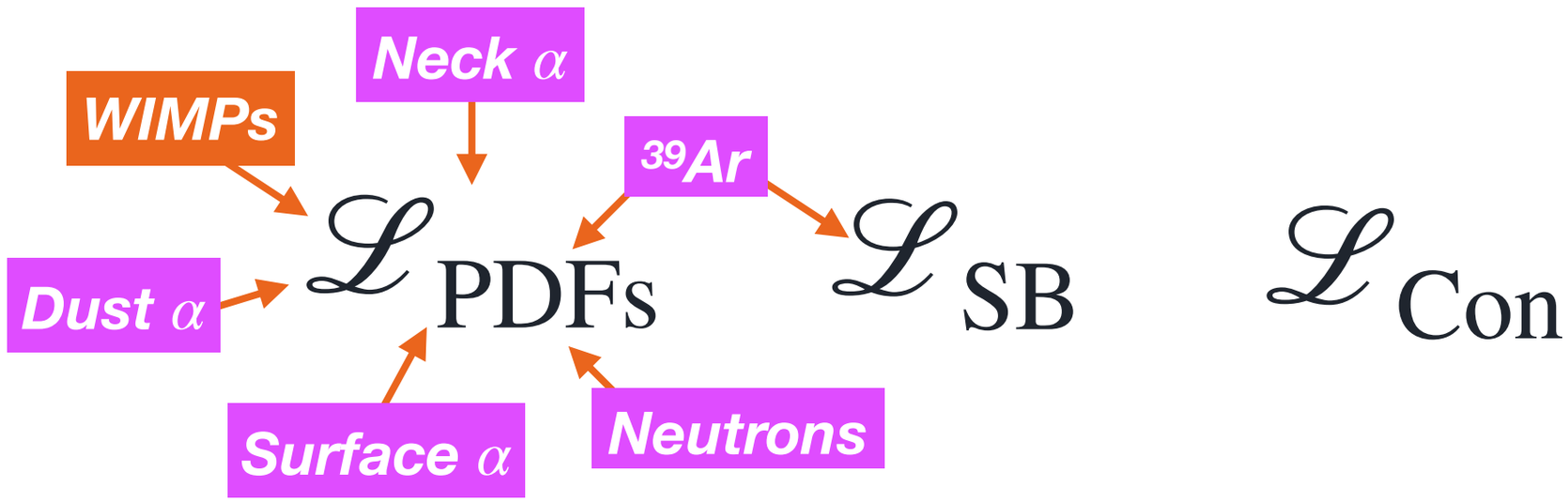

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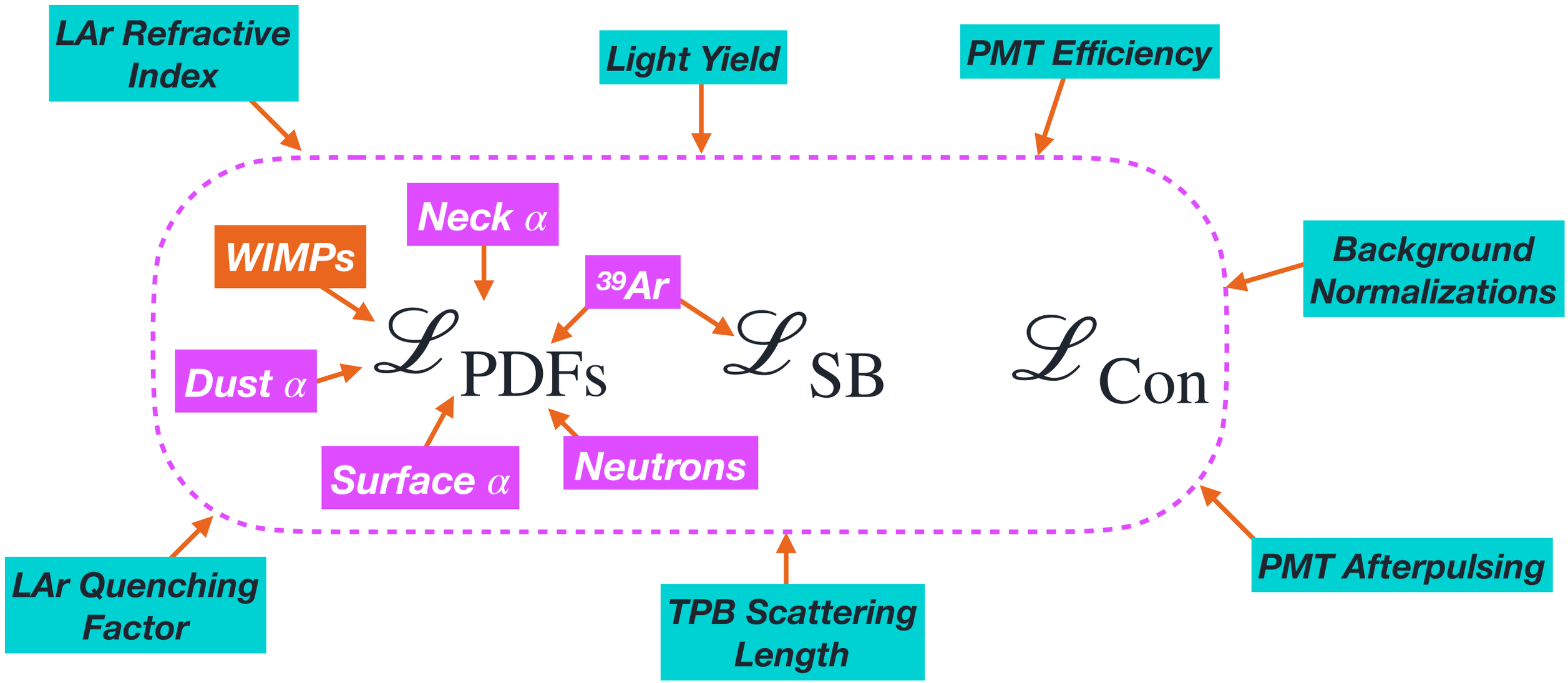

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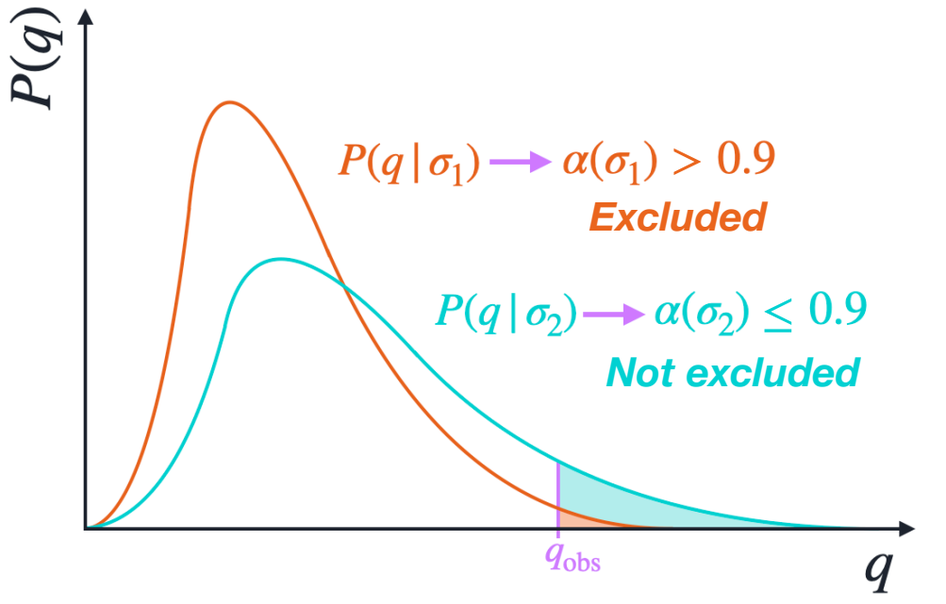
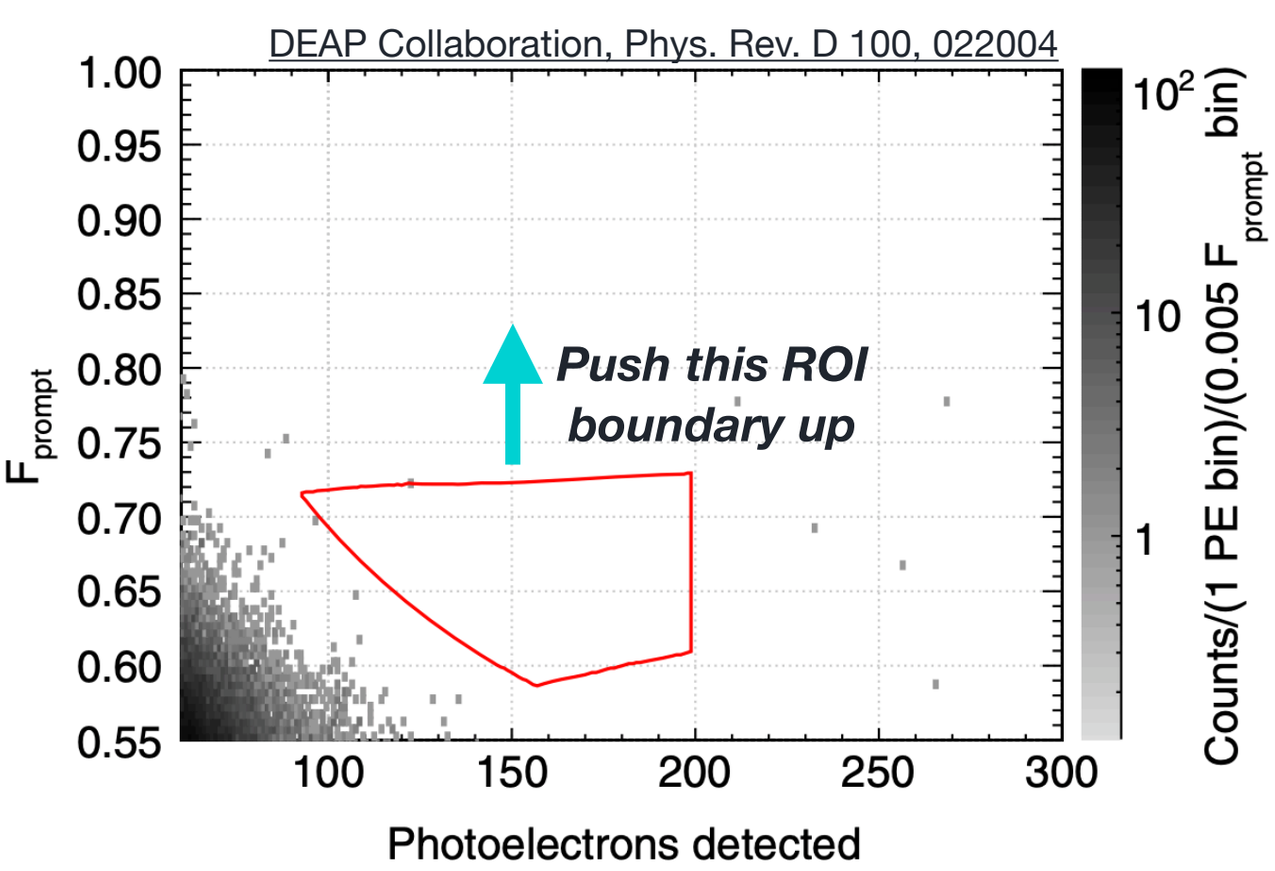
$$\lambda = \frac{\mathscr{L}(\mathbf{x}\,|\,\sigma, \hat{\hat{\theta}})}{\mathscr{L}(\mathbf{x}\,|\,\hat{\sigma}, \hat{\theta})}$$

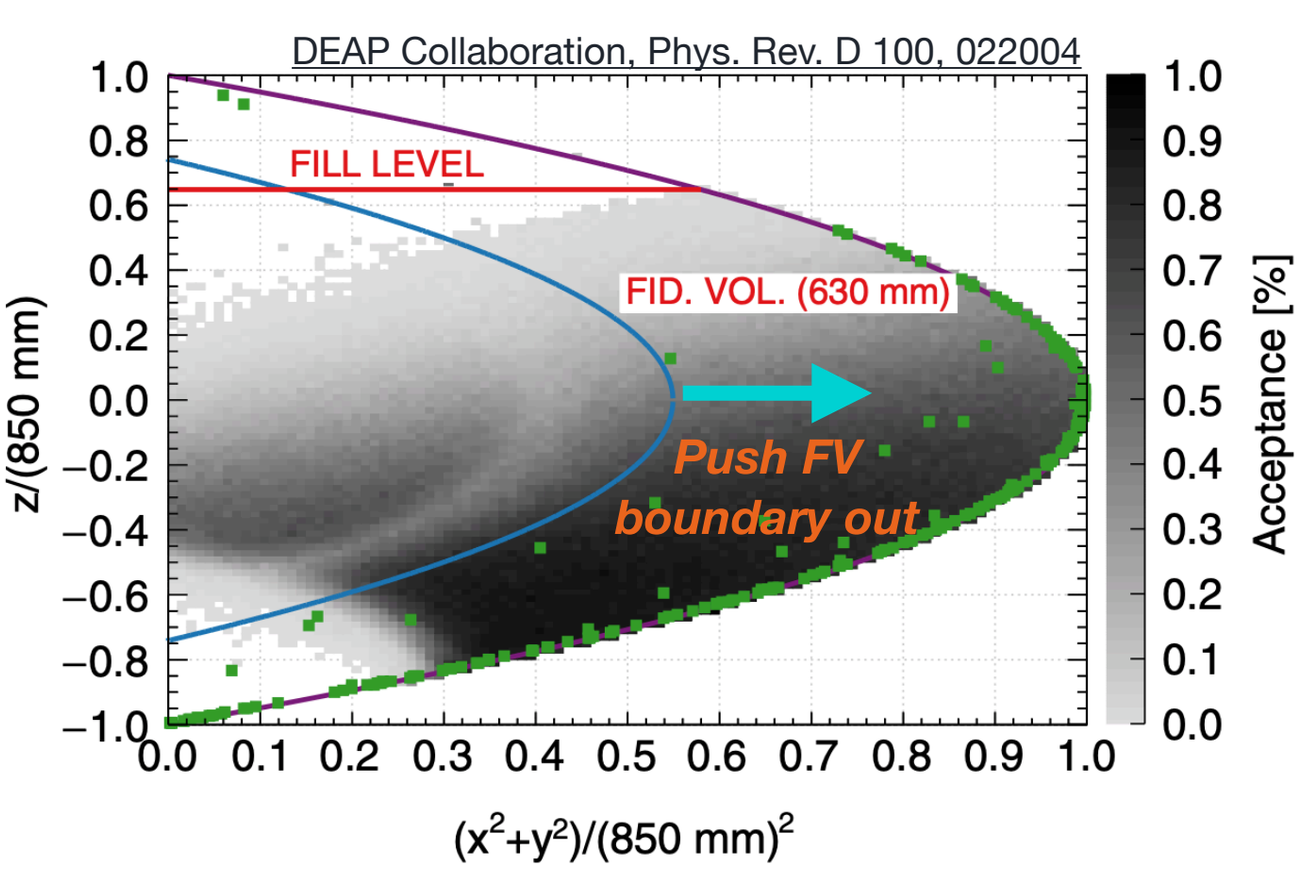
Best fit for a given value of σ

Best possible fit

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







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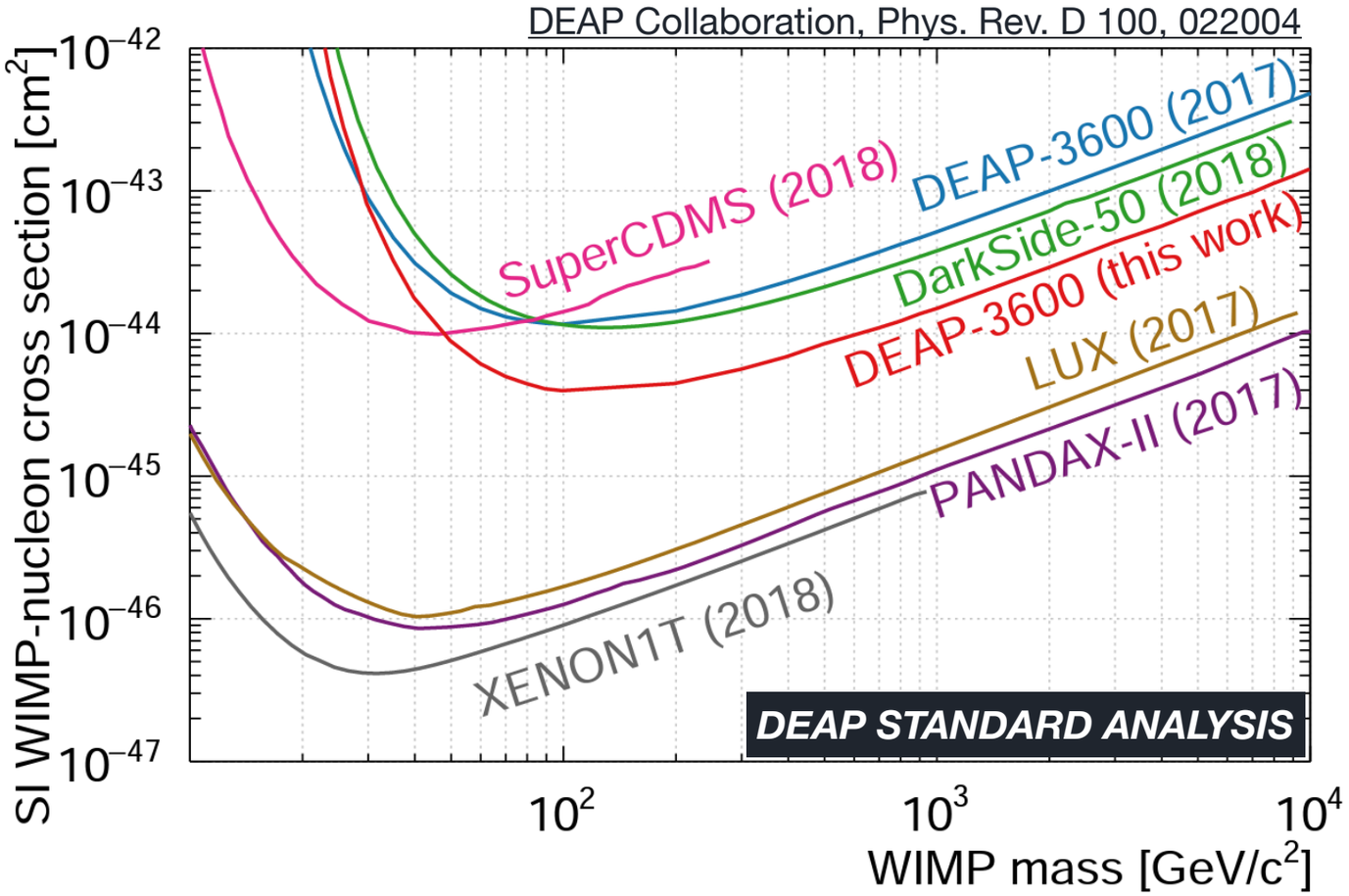
WIMP Searches:
Profile Likelihood Ratio



DEAP sensitivity from 231-day exposure can be improved with PLR and Machine Learning

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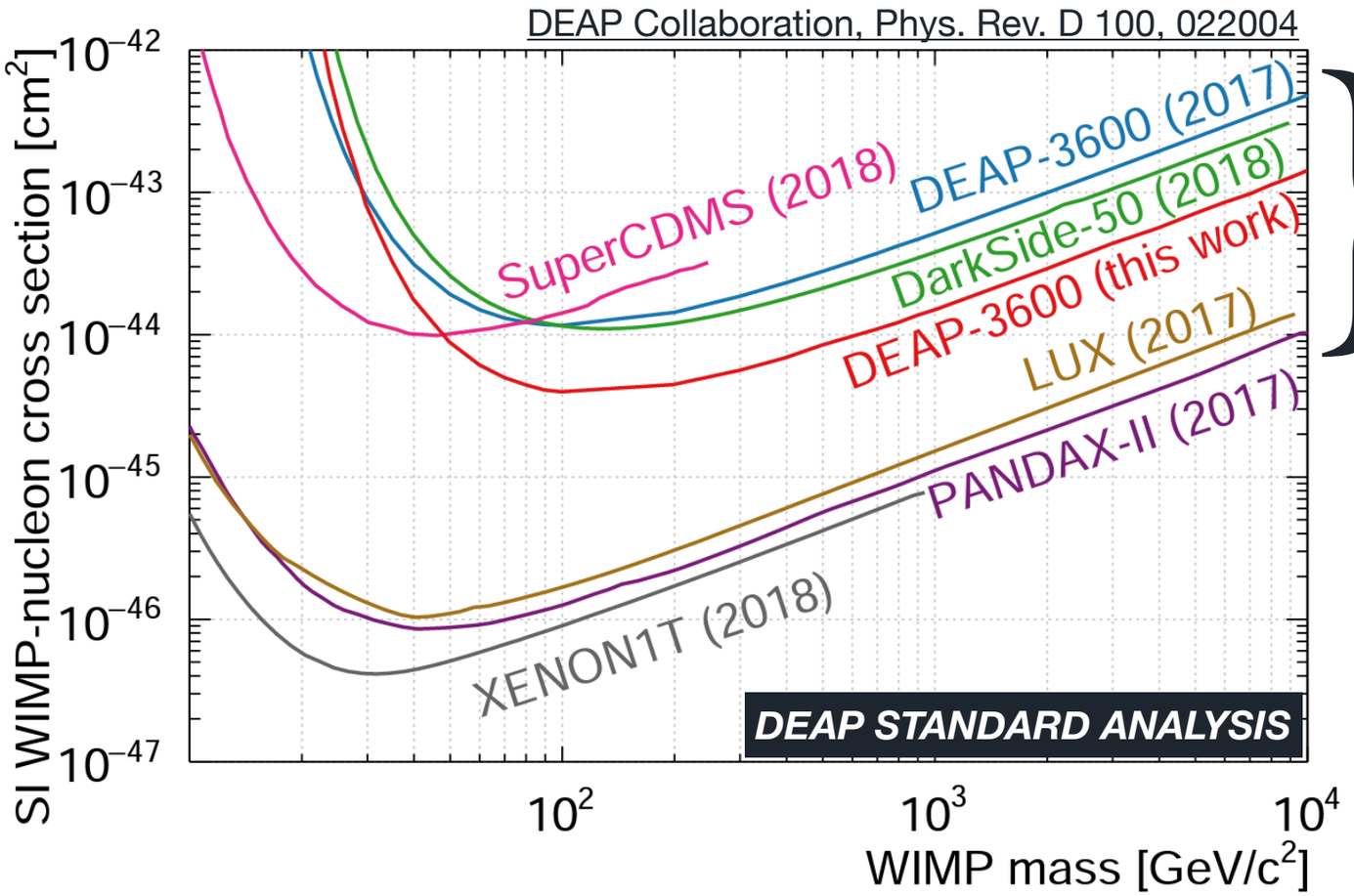
WIMP Searches:
Nonrelativistic Effective Field Theory



All assuming a scalar WIMP-nucleon coupling; i.e. coherent scattering with entire nucleus

A more general non-relativistic effective field theory includes velocity and spin dependent mechanisms

$\mathcal{O}_1$	$1_\chi 1_N$	$\mathcal{O}_{11}$	$iS_\chi \cdot \frac{\vec{q}}{m_N}$
$\mathcal{O}_3$	$iS_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}_\perp\right)$	$\mathcal{O}_{12}$	$\vec{v}_\perp \cdot \left(S_\chi \times S_N\right)$
$\mathcal{O}_5$	$iS_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}_\perp\right)$	$\mathcal{O}_{15}$	$-\left(s_\chi \cdot \frac{\vec{q}}{m_N}\right)\left[\left(S_N \times \vec{v}_\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$
$\mathcal{O}_8$	$S_\chi \cdot \vec{v}_\perp$		

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WIMP Searches:
Nonrelativistic Effective Field Theory

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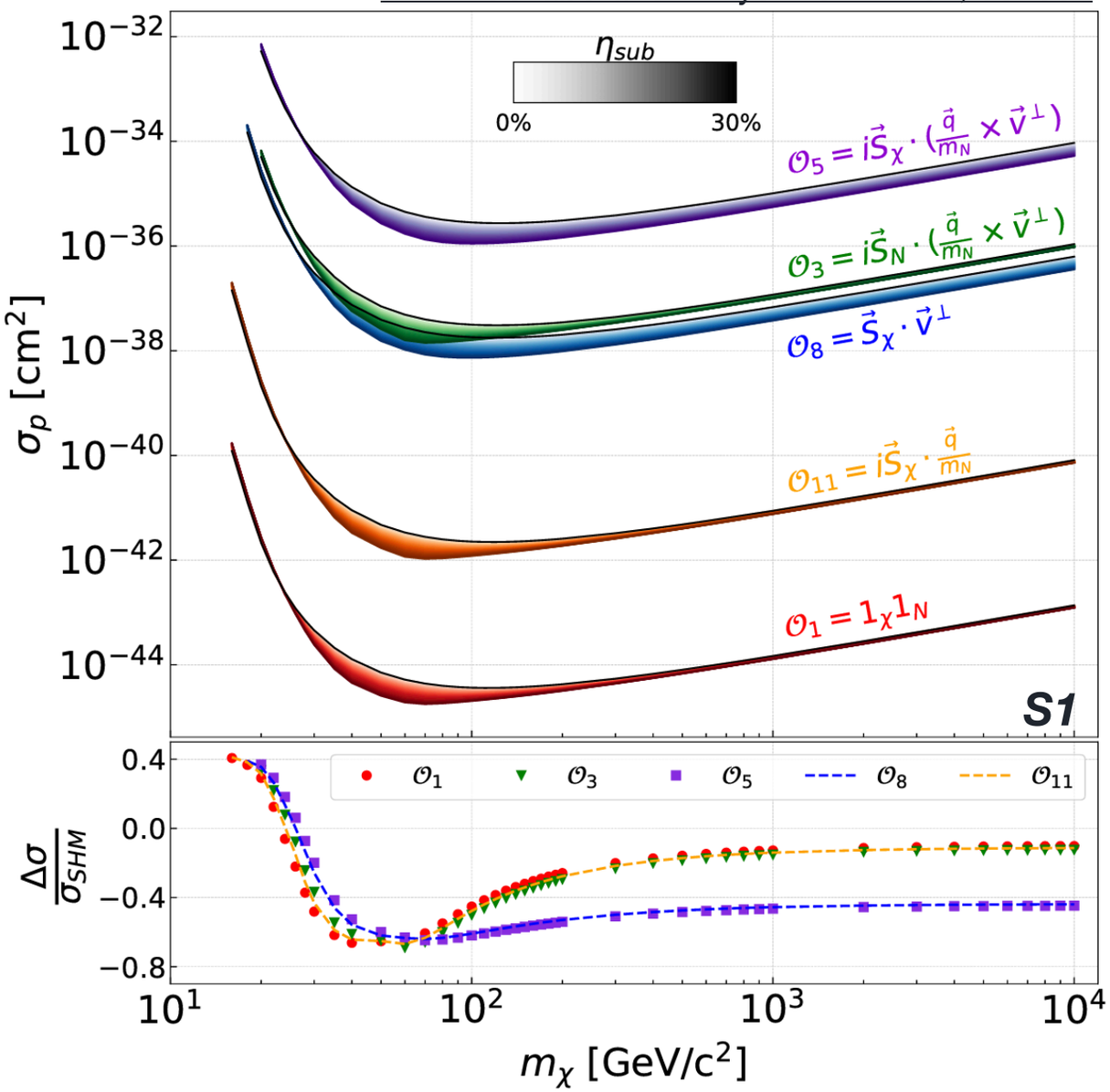
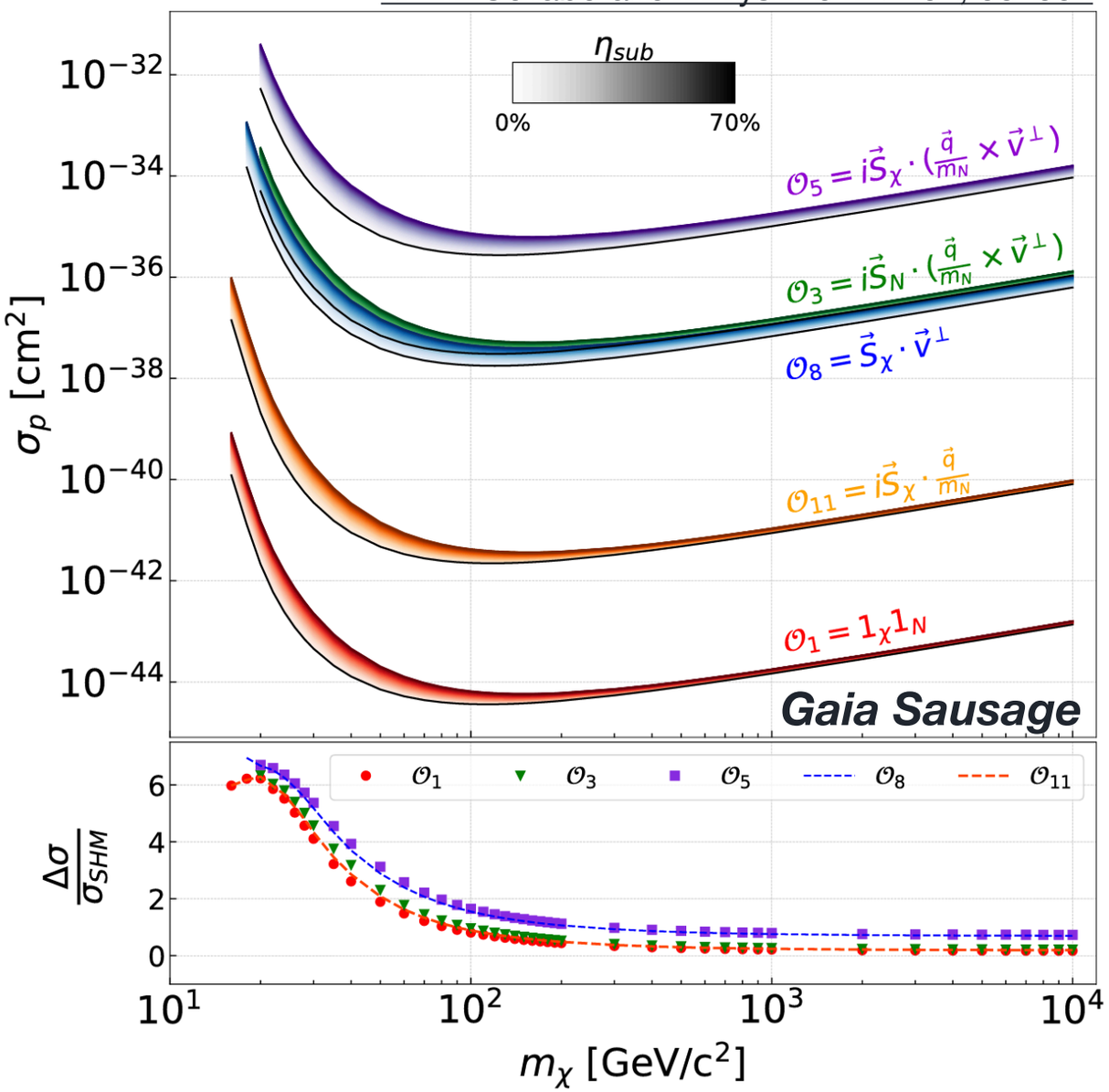
DEAP Collaboration Phys. Rev. D 102, 082001



DEAP Collaboration Phys. Rev. D 102, 082001



- Interactions in generalized NR-EFT explored with various extensions of standard halo model; substructures like S1 retrograde stellar stream and *Gaia* Sausage considered

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Beyond WIMPs:
Planck Scale Dark Matter

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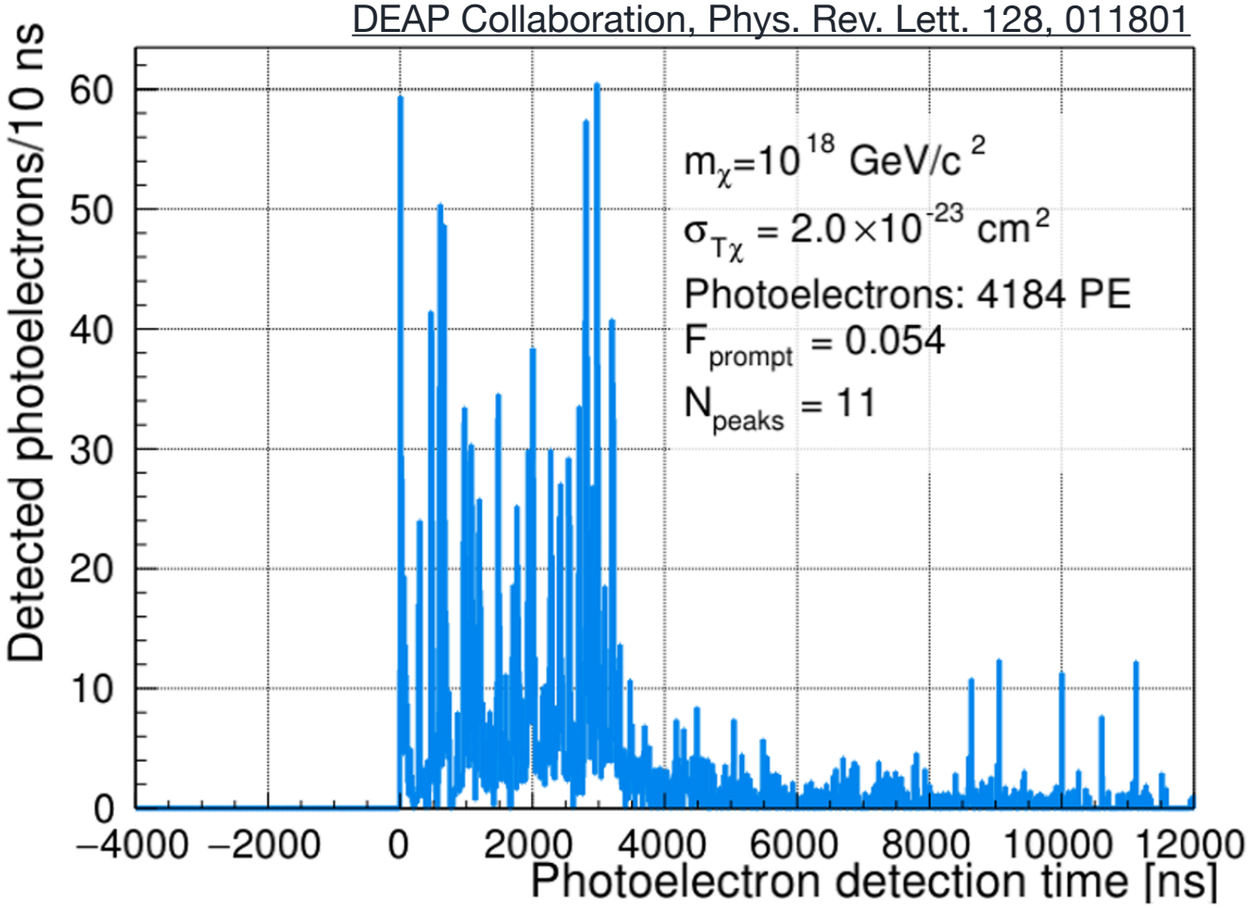
- Dark matter with Planck scale mass is theoretically well motivated; could have much higher cross-sections than WIMPs and not yet be excluded
- Higher cross-sections → multiply scattering DM, which is usually cut in WIMP searches

DEAP Collaboration, Phys. Rev. Lett. 128, 011801



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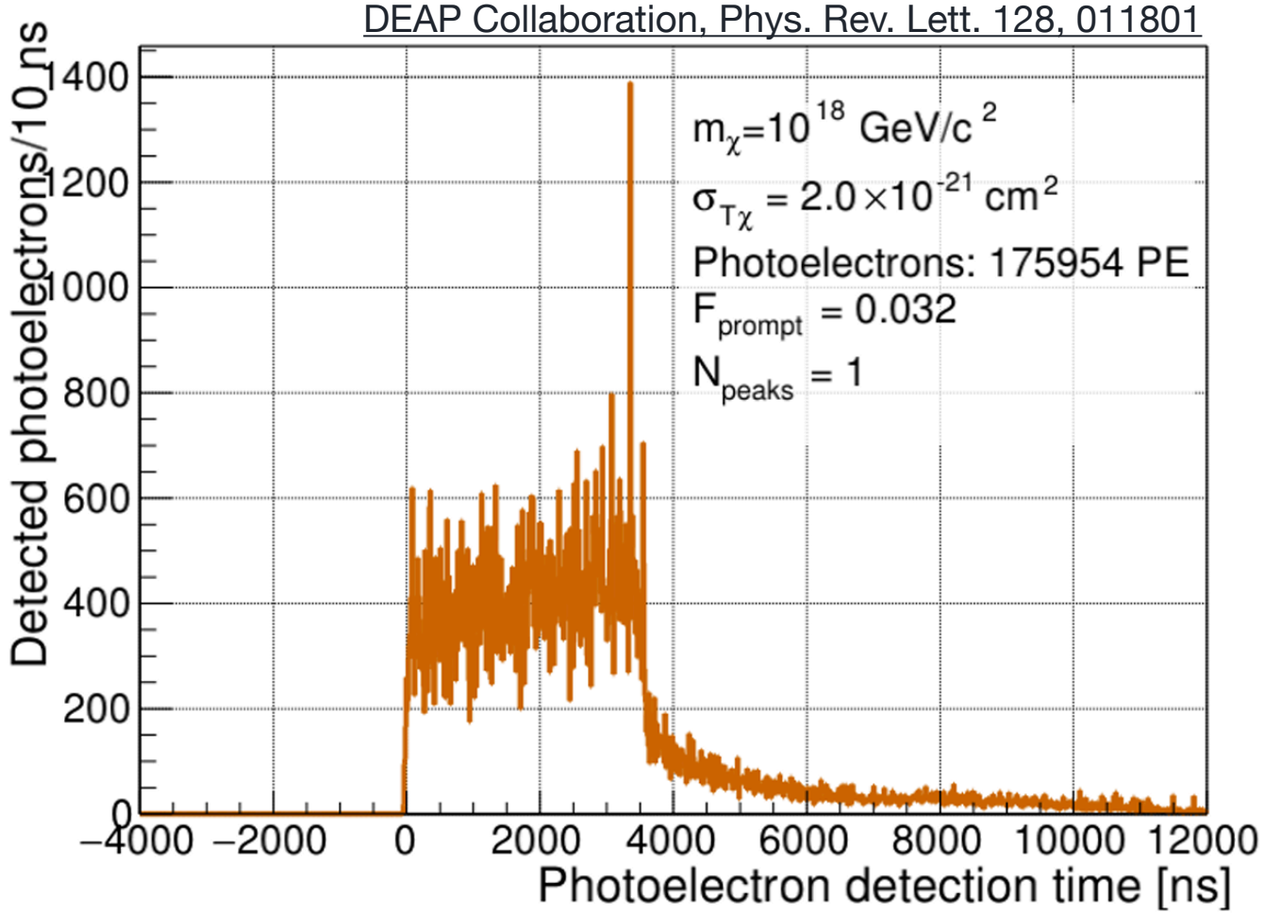

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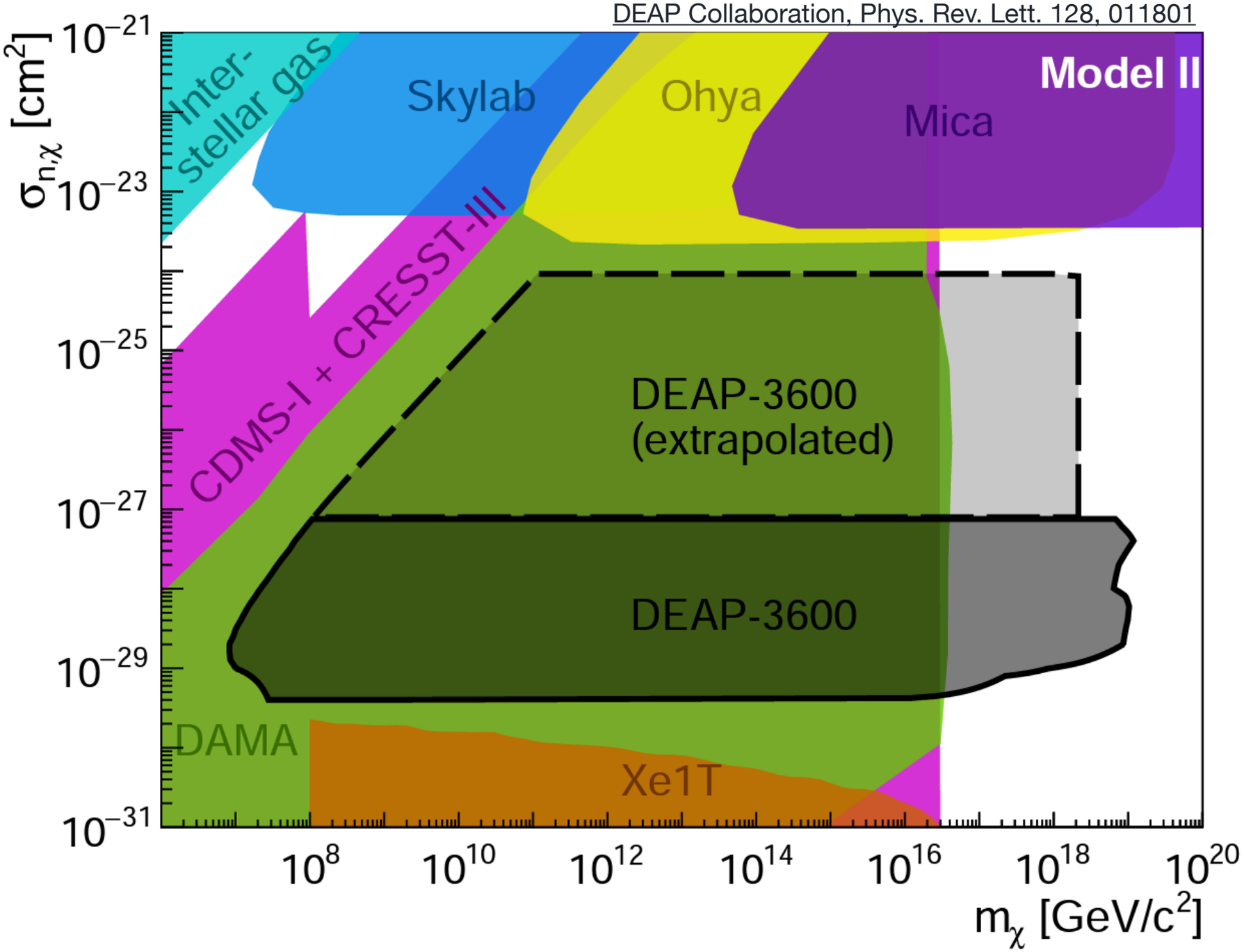
Beyond WIMPs:
Planck Scale Dark Matter

ROYAL HOLLOWAY UNIVERSITY OF LONDON

DEAP Collaboration, Phys. Rev. Lett. 128, 011801



First ever direct detection constraint on Planck scale dark matter!

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In the Pipeline

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^{39}Ar Specific Activity and Half-Life

- Dedicated papers for ^{39}Ar specific activity and half-life measurements in DEAP are currently under collaboration review
- Extra slides available for those interested!

5.5 MeV Solar Axion Search

- Search for axions produced in sun's core via the reaction: $p + {}^{2}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + a$
- Requires precise knowledge of EM backgrounds in MeV range

^{8}B Neutrino Absorption

- DEAP has an active search for inverse beta decay of ^{40}Ar induced by ^{8}B solar neutrinos via $\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^{*} + e^{-}$
- Currently working on background model for this signal, understanding detector response at high energies (4–18 MeV)

Muon Flux at SNOLAB

- Dedicated group on DEAP working on muon veto instrumentation paper as well as a muon flux measurement at SNOLAB
- Currently validating MC model, developing event selection criteria to eliminate instrumental events, studying systematics

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Conclusion

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- Precise LAr pulse shape measurements contribute to excellent background rejection
  - World leading PSD!
- Competitive dark matter searches spanning 17 orders of magnitude in mass
  - 100 GeV WIMP search extended with NR-EFT
  - Previously unprobed Planck Scale DM parameter space excluded at 10^{19} GeV
- Ongoing analyses aimed at improving sensitivity to WIMPs and other new physics
  - PLR and Machine Learning analyses are well along their way!

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DEAP Collaboration

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UNIVERSITY OF ALBERTA

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NICOLAUS COPERNICUS ASTRONOMICAL CENTER OF THE POLISH ACADEMY OF SCIENCES

Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens

INFN
Istituto Nazionale di Fisica Nucleare

Carleton UNIVERSITY

GOBIERNO DE ESPAÑA · MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES · Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

JOHANNES GUTENBERG UNIVERSITÄT MAINZ · JG|U

IF Instituto de Física

NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

LaurentianUniversity UniversitéLaurentienne

PRINCETON UNIVERSITY

Queen's UNIVERSITY

University of Sussex

SNOLAB

TRIUMF

Technical University of Munich

Particle Physics Rutherford Appleton Laboratory

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Grazie per l’attenzione!

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Extra Slides:
SNOLAB

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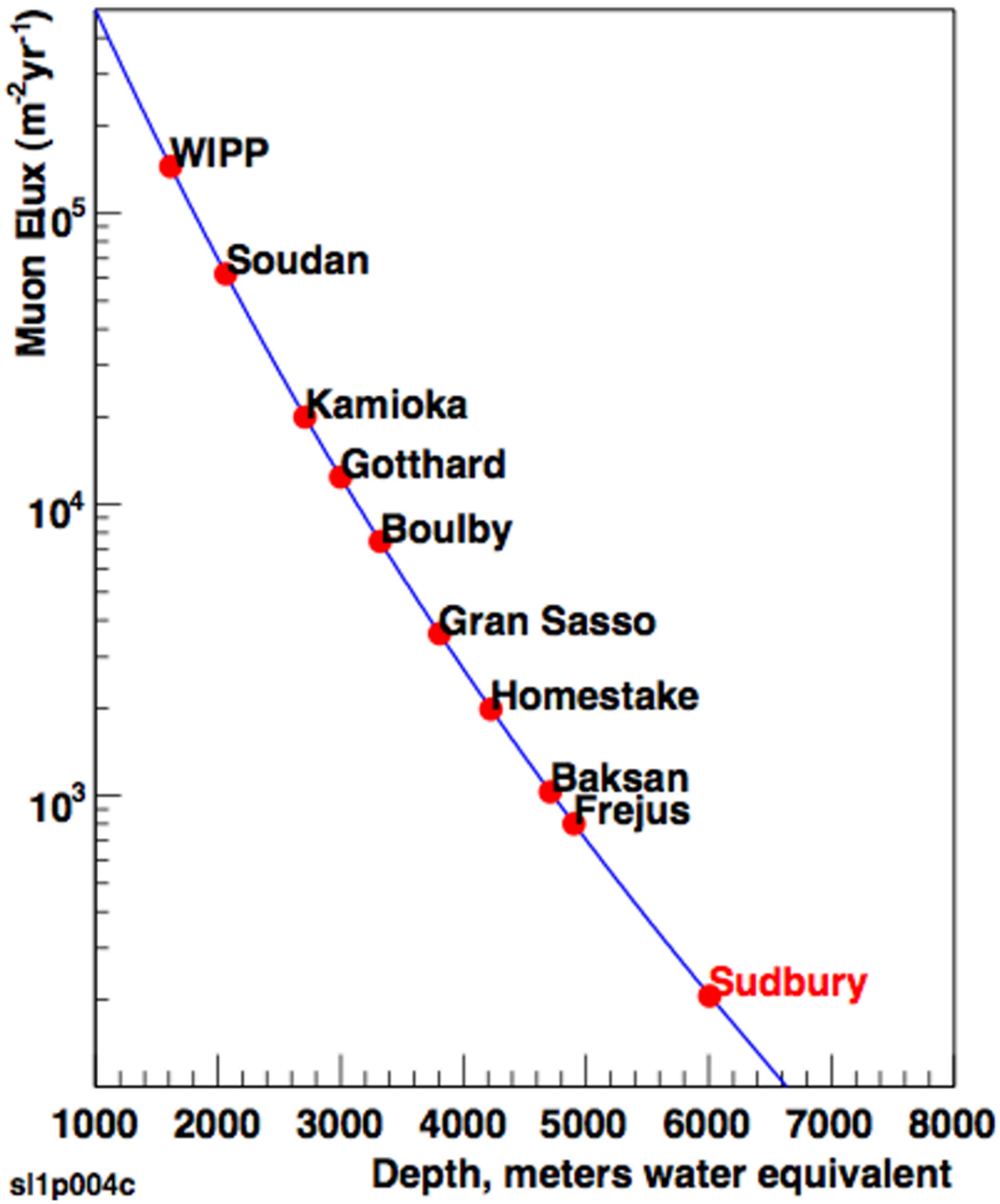
Muon Flux = 0.27/m²/day



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Extra Slides:
^{39}Ar Specific Activity and Half-Life

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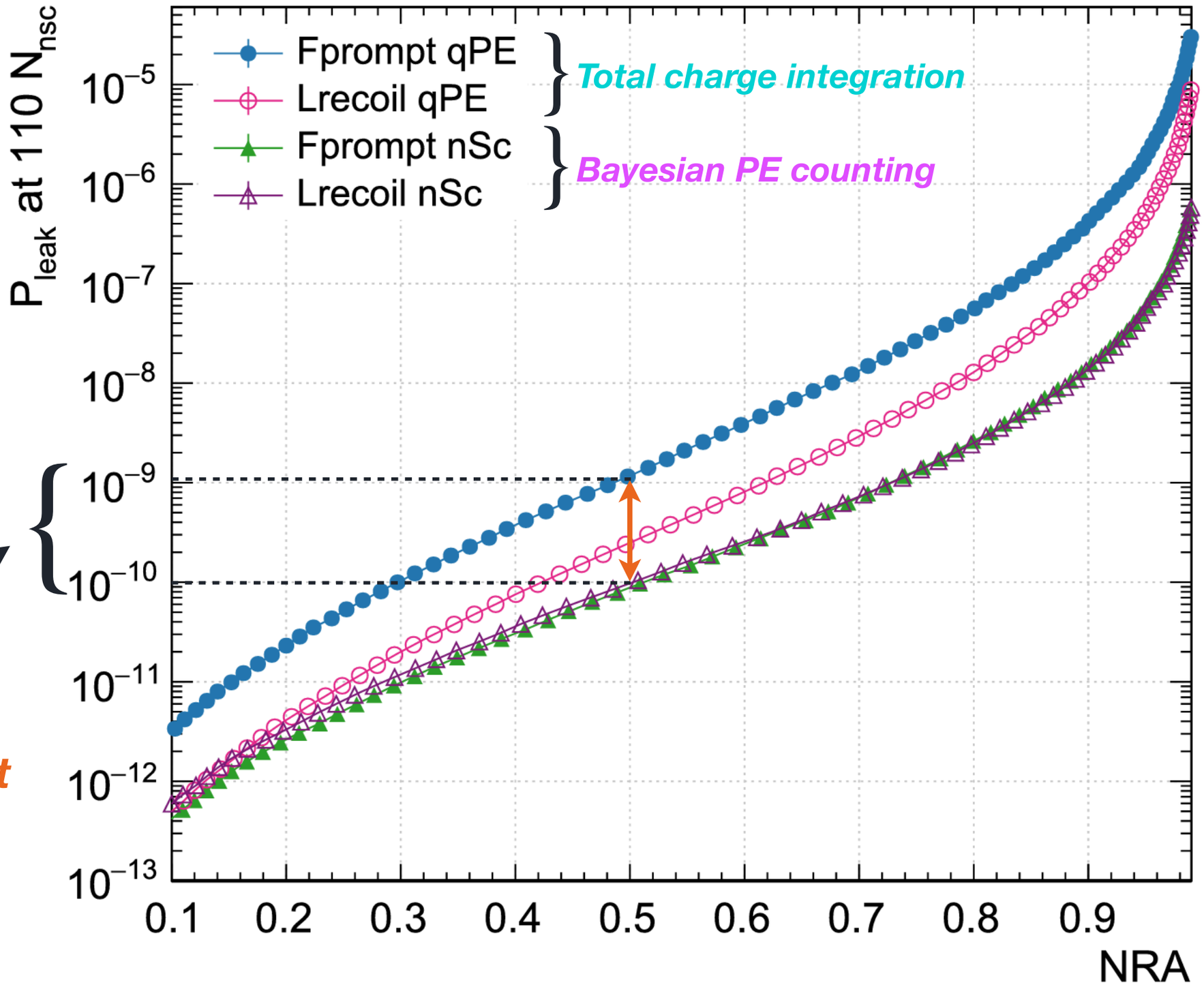
- DEAP has two energy estimators and two PSD models, total of four unique algorithms
- Our best algorithms use the Bayesian PE counting estimator

10x reduction of ^{39}Ar leakage from simplest algorithm

P. Adhikari, et al. Eur. Phys. J. C 81, 823 (2021)



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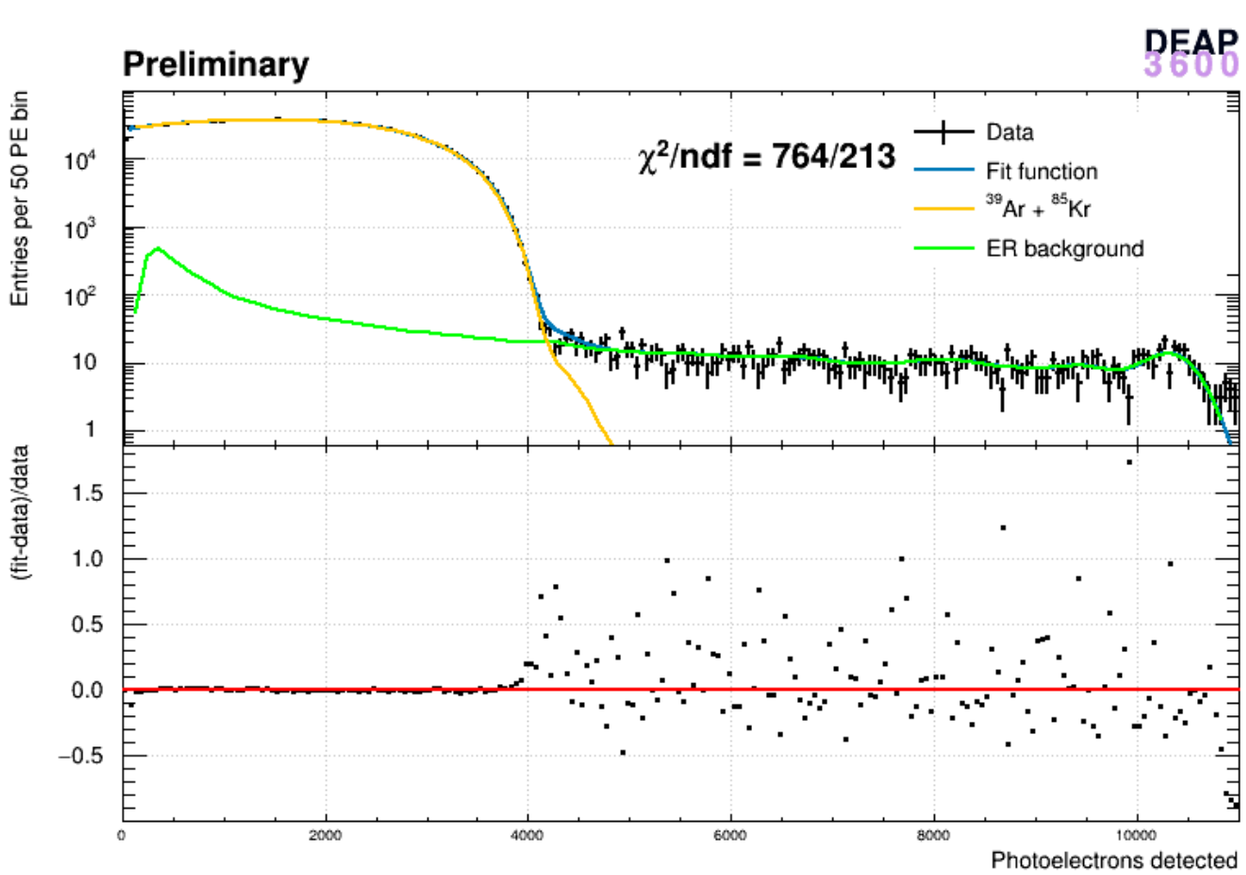
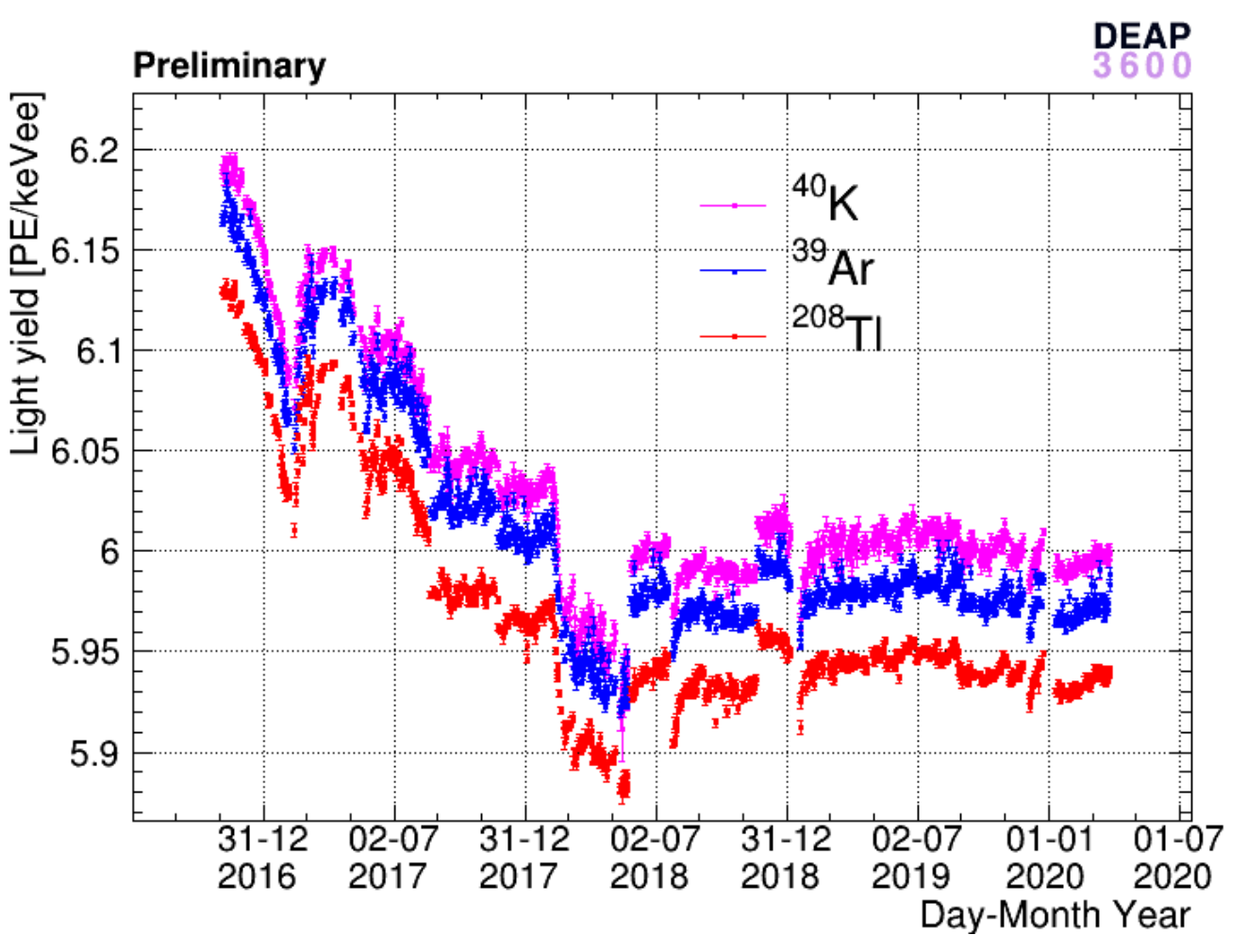
Extra Slides:
^{39}Ar Specific Activity and Half-Life

- Dedicated papers for ^{39}Ar specific activity and half-life in DEAP are currently under collaboration review
- low energy beta spectrum model accounts for ^{39}Ar and ^{85}Kr betas, low energy ER band backgrounds, pileup with various other sources
- Drifting of light yield also included in systematic analysis; stable to within ~0.3 PE/keV$_{ee}$





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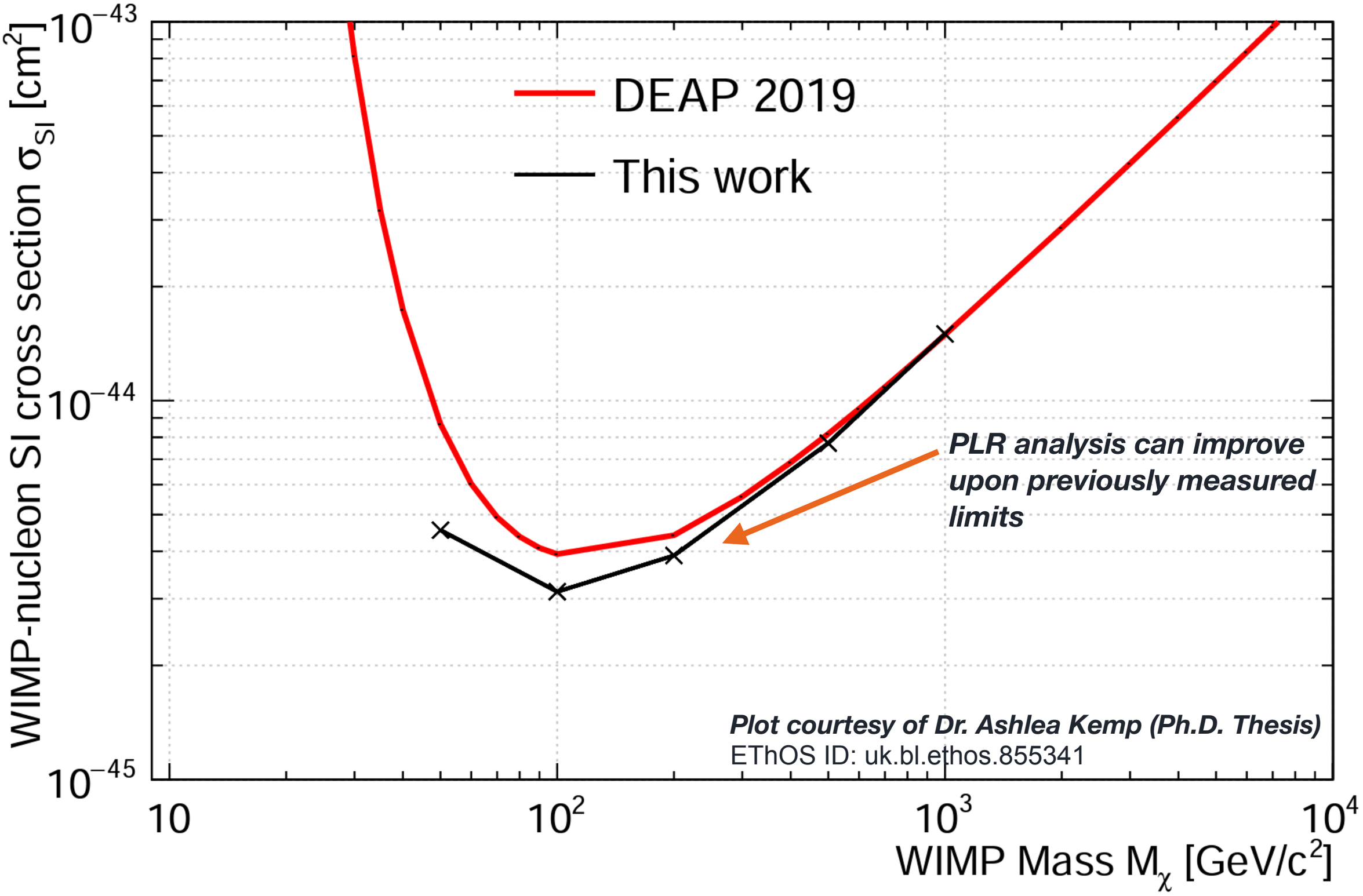
Extra Slides:
Profile Likelihood Ratio



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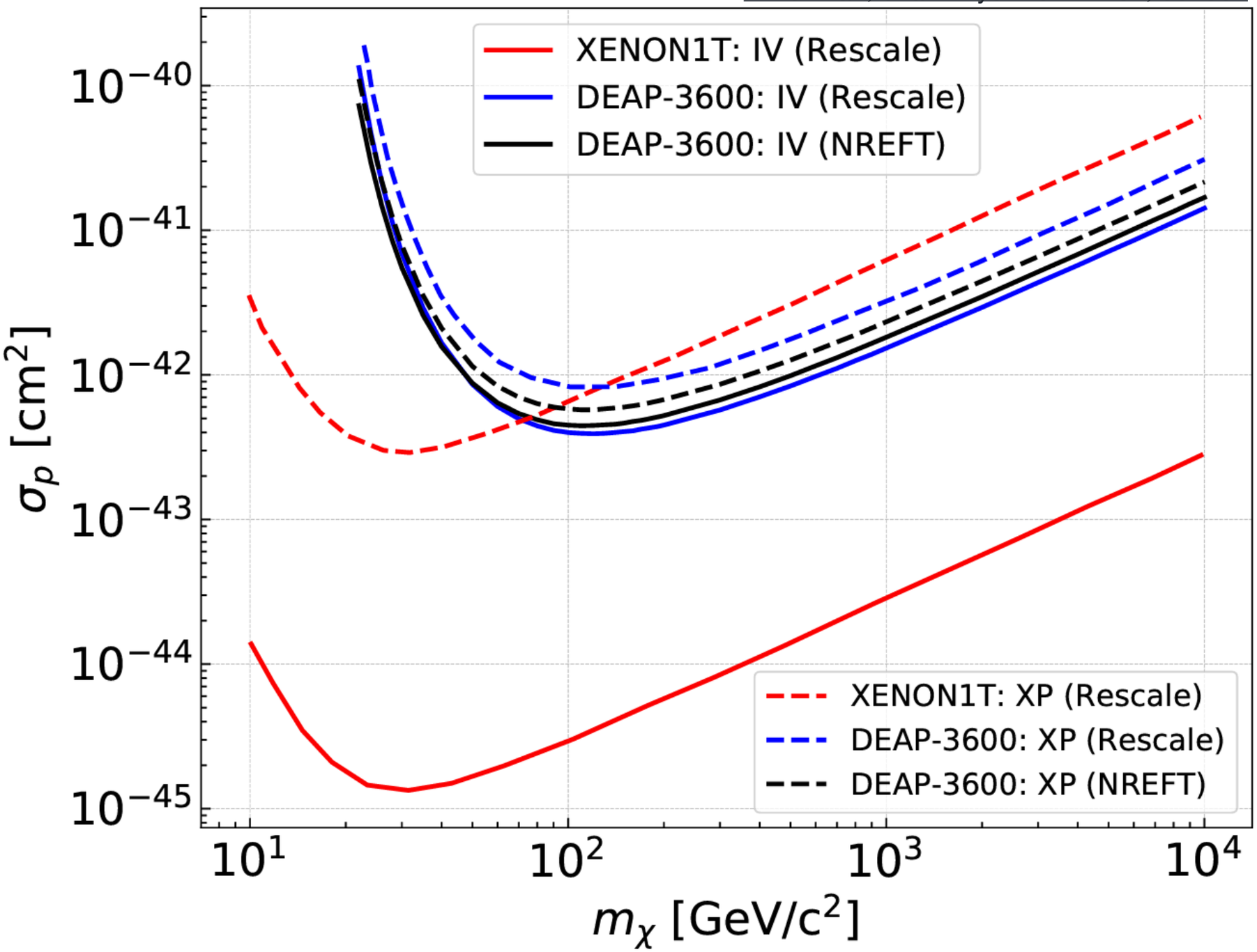
Extra Slides:
Xenonphobic WIMPs

P. Adhikari, et al. Phys. Rev. D 102, 082001



- Isospin-violating interactions also considered in NR-EFT framework
- *xenonphobic* (XP) interactions cover a range of isospin-violating models
- DEAP sets world leading limit on these isospin-violating interactions

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Extra Slides:
Planck Scale Dark Matter

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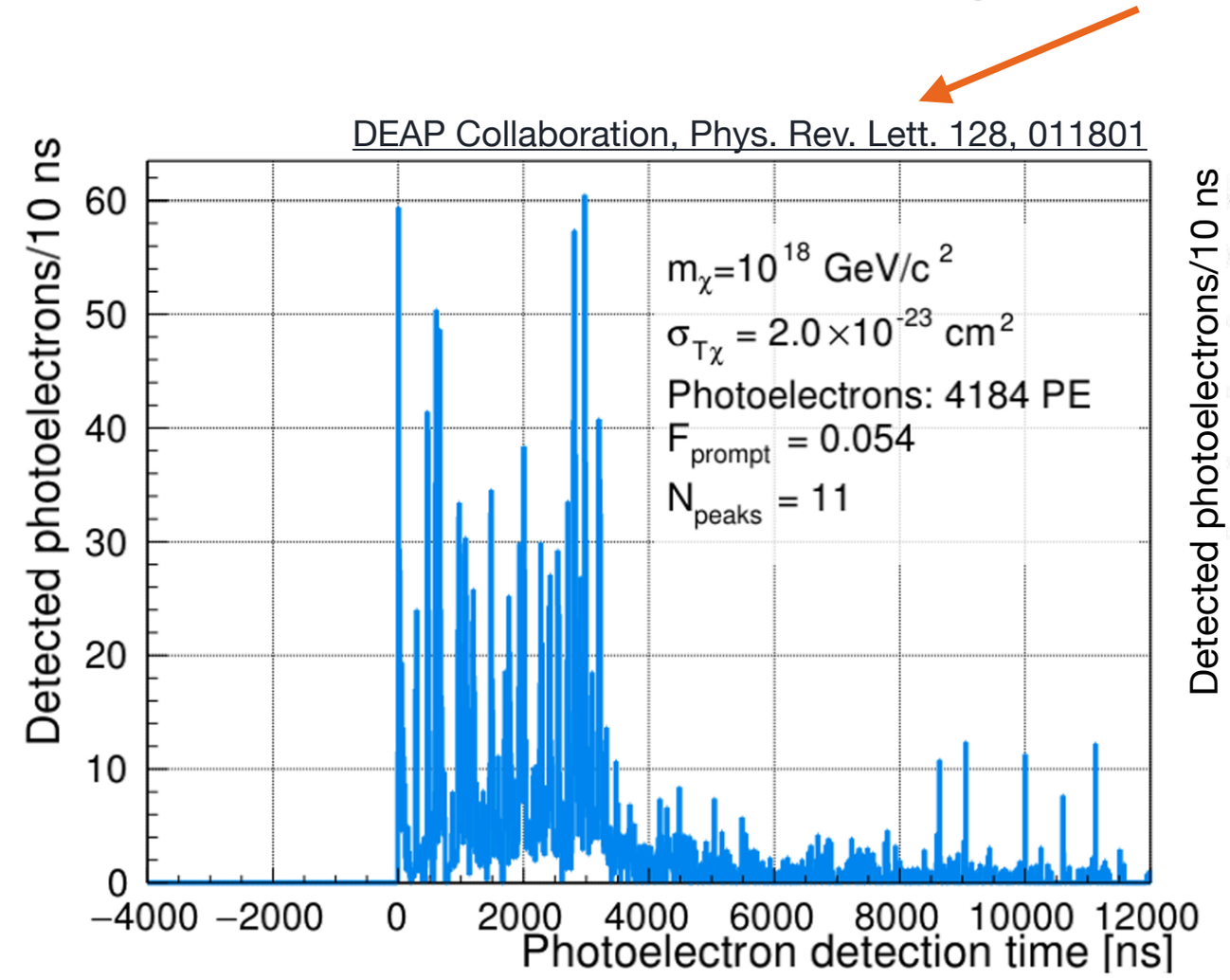
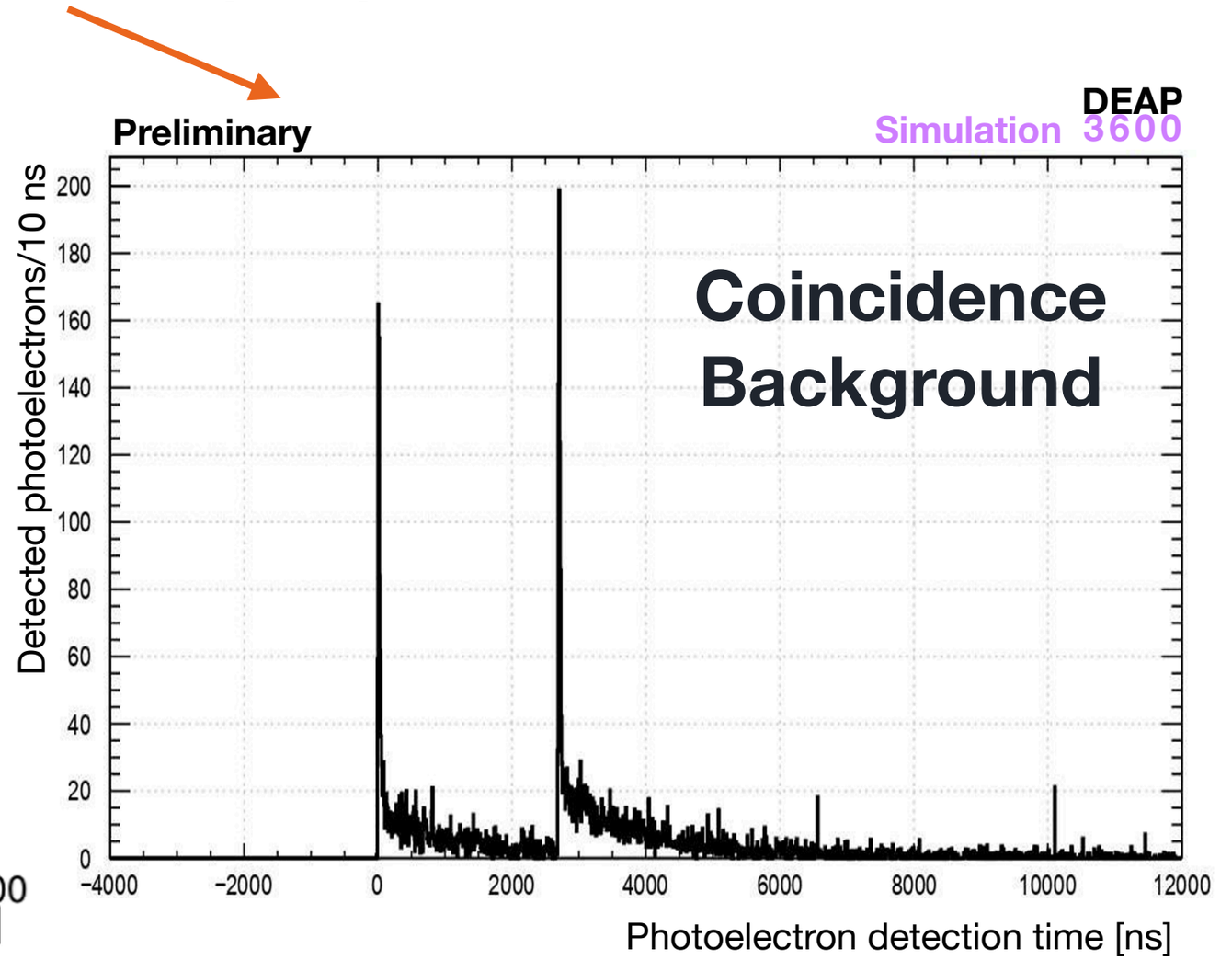
- Dark matter with Planck scale mass is theoretically well motivated; could have much higher cross-sections than WIMPs and not yet be excluded
- Higher cross-sections → multiply scattering DM, which is usually cut in WIMP searches

Distinguishable from pileup





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Extra Slides:
Planck Scale Dark Matter

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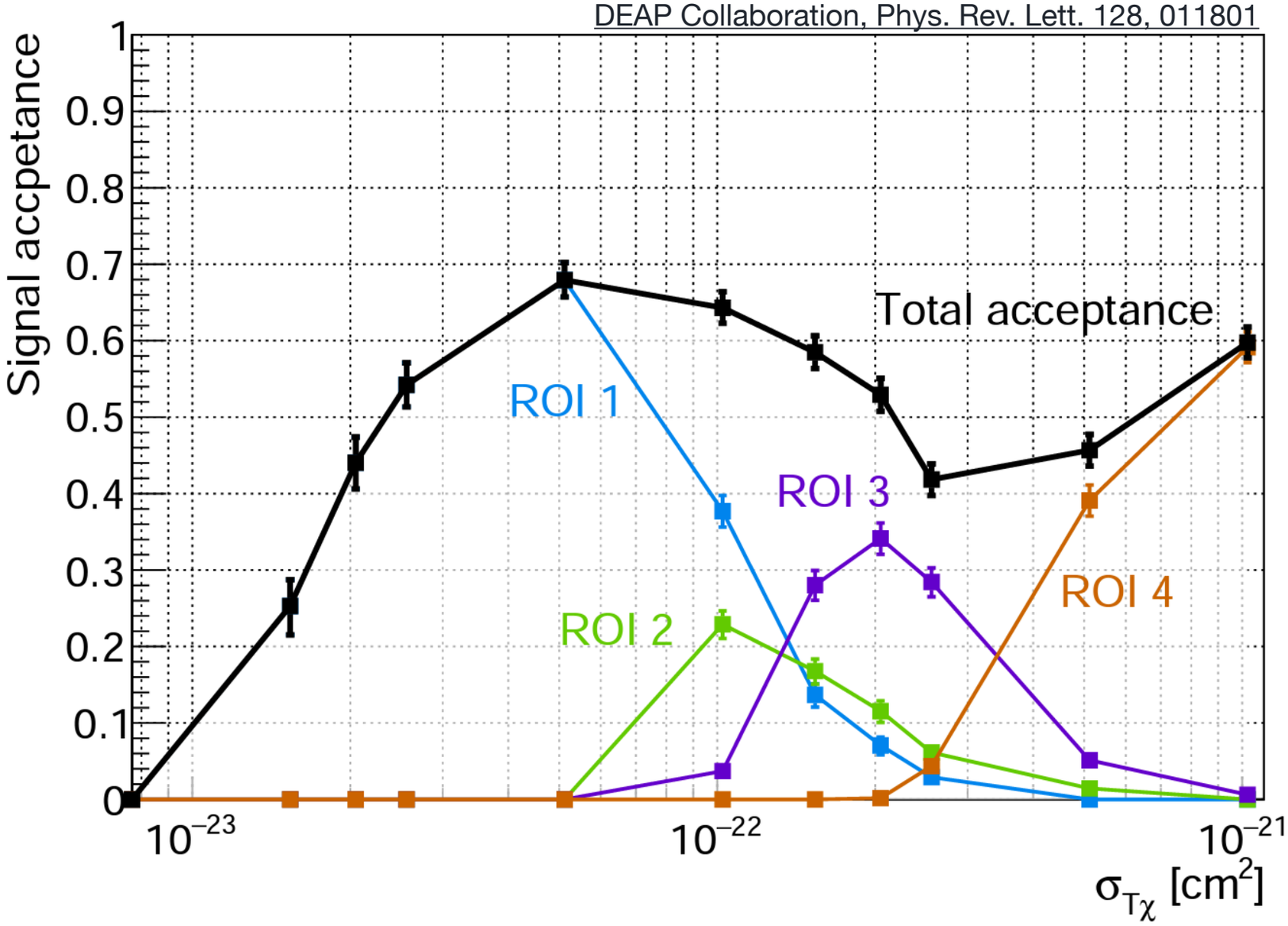
ROI	PE range	Energy [MeV_{ee}]	N^{min}_{peaks}	F^{max}_{prompt}	μ_b	$N_{obs.}$
1	4000–20 000	0.5–2.9	7	0.10	$(4 \pm 3) \times 10^{-2}$	0
2	20 000–30 000	2.9–4.4	5	0.10	$(6 \pm 1) \times 10^{-4}$	0
3	30 000–70 000	4.4–10.4	4	0.10	$(6 \pm 2) \times 10^{-4}$	0
4	70 000–4×10^8	10.4–60 000	0	0.05	$(10 \pm 3) \times 10^{-3}$	0

DEAP Collaboration, Phys. Rev. Lett. 128, 011801



- Look for events with multiple peaks and/or very low F_{prompt}
- Defined 4 ROIs with high signal acceptance
- Backgrounds in these ROIs are negligible; $\ll 1$ event in 813 live days

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Extra Slides:
Planck Scale Dark Matter

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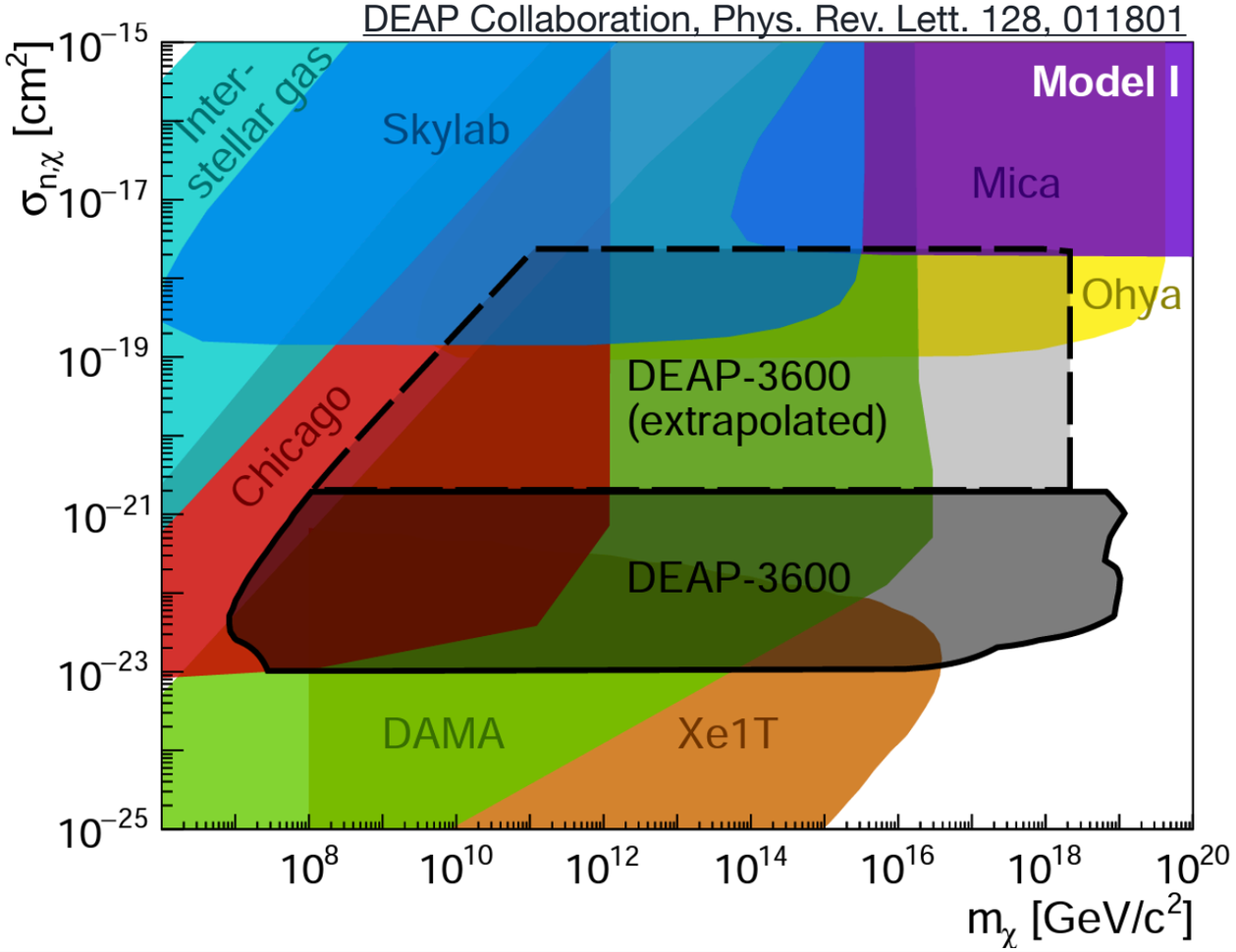
- Model I considers the case where: $\frac{d\sigma_{T\chi}}{dE_R} = \frac{d\sigma_{n\chi}}{dE_R} |F_T(q)|^2$
- Model II considers the case where: $\frac{d\sigma_{T\chi}}{dE_R} \approx \frac{d\sigma_{n\chi}}{dE_R} A^4 |F_T(q)|^2$
- DEAP sets new world leading constraints for Planck Scale DM in both scenarios

DEAP Collaboration, Phys. Rev. Lett. 128, 011801



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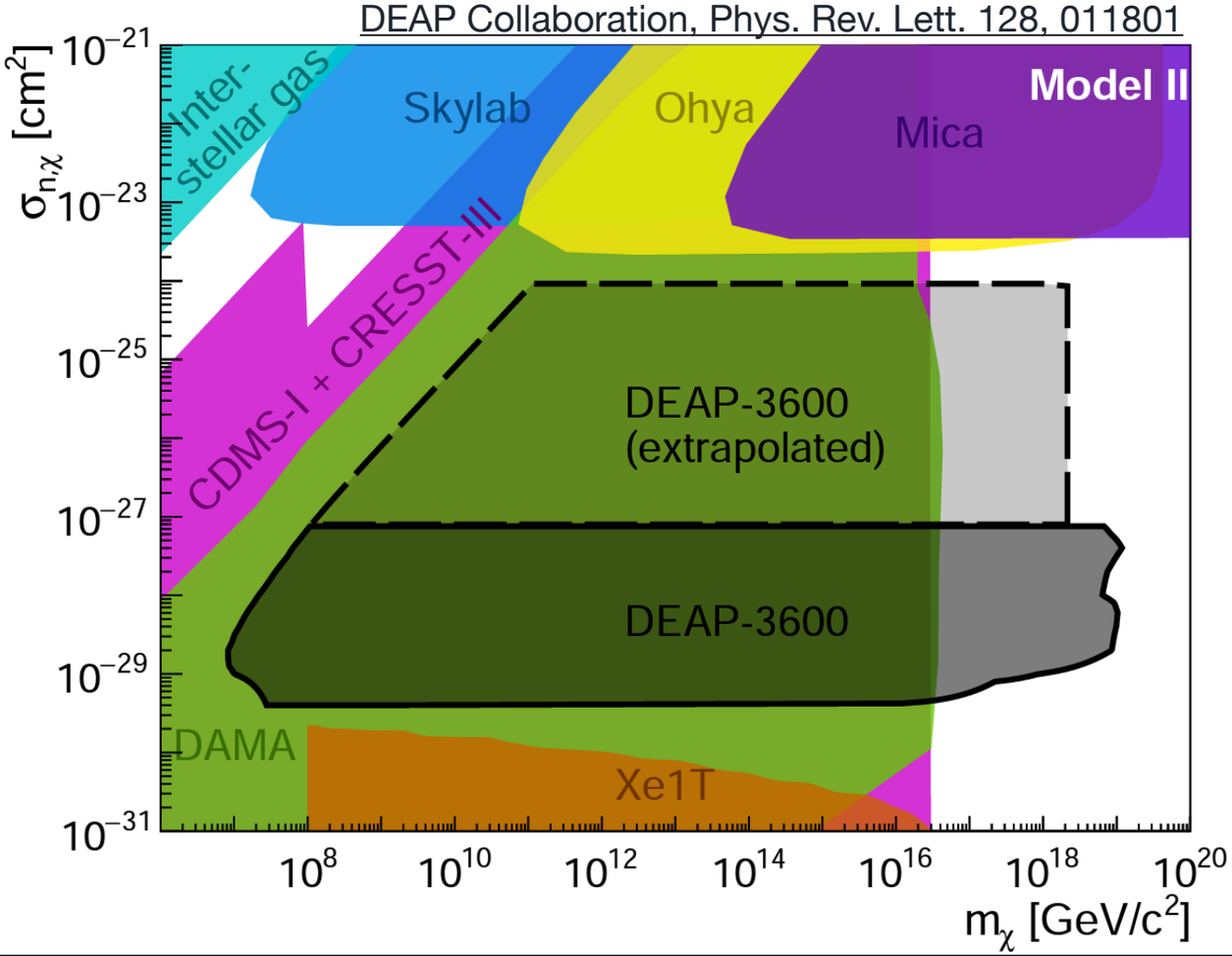

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