Latest Updates and Results from the DEAP-3600 Experiment.

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The DEAP-3600 Detector

Dark matter Experiment using Argon Pulse-shape discrimination.

Located 2km underground in SNOLAB, ON (10^7 reduction from cosmic muons).

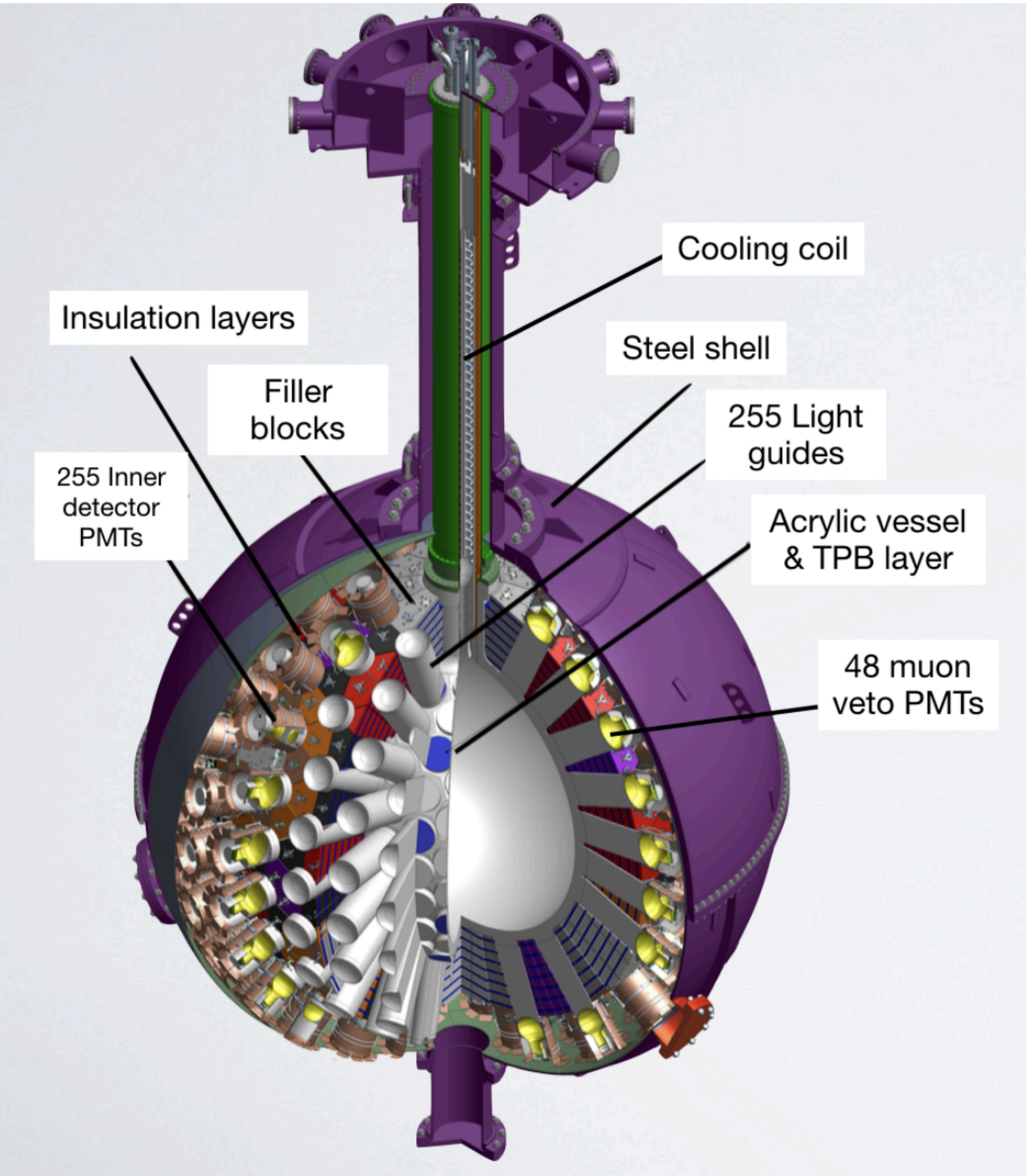
Single-phase liquid argon (LAr) scintillation light detector, holding 3279 kg target LAr inside spherical, radiopure acrylic vessel.

Optimised for collection of scintillation light from ^{40}Ar nuclear recoils (NRs) after scattering interaction with WIMP particle, χ.

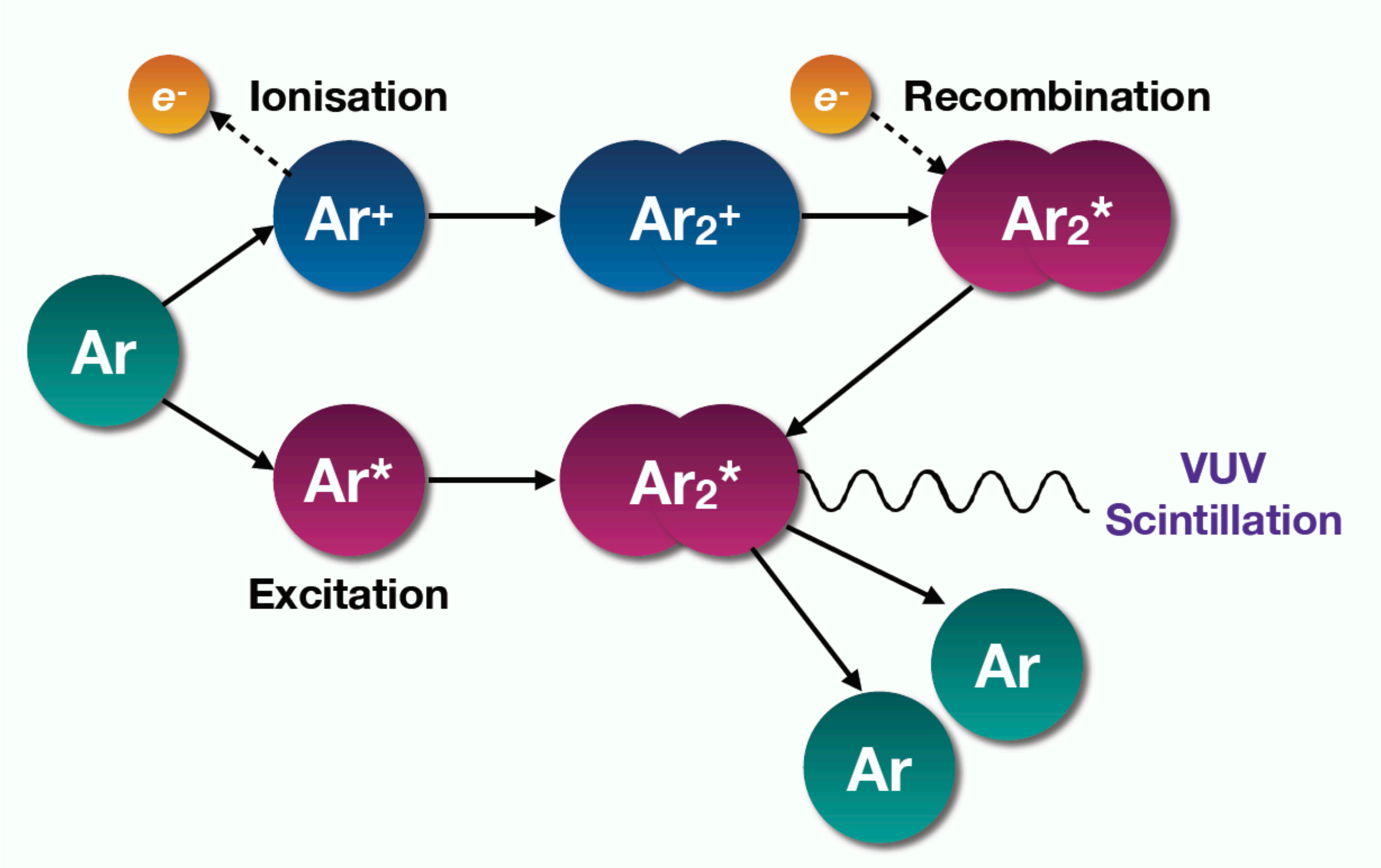
VUV scintillation photons produced at λ = 128 nm shifted to visible wavelengths via layer of tetraphenyl butadiene (TPB) wavelength shifter coated on inner acrylic vessel.

Wavelength-shifted photons detected by 255 inward-facing, low radioactivity Hamamatsu photomultiplier tubes (PMTs) with ~ 75% coverage of inner volume.

- “In-situ characterization of the Hamamatsu R5912-HQE photomultiplier tubes used in the DEAP-3600 experiment.” Nucl. Instrum. Meth. Phys. Res. A 922, 373 (2019).



Pulse-Shape Discrimination



Pulse-shape discrimination (PSD) is a powerful tool used in LAr experiments to reject electronic recoil (ER) backgrounds such as from β-particles and γ-rays.

Particles recoiling in LAr deposit energy by ionising and exciting argon atoms, creating excitons Ar^* and ions Ar^+, which create excited argon molecules (excimers) Ar_2^* that radiatively decay to generate 128 nm scintillation photons.

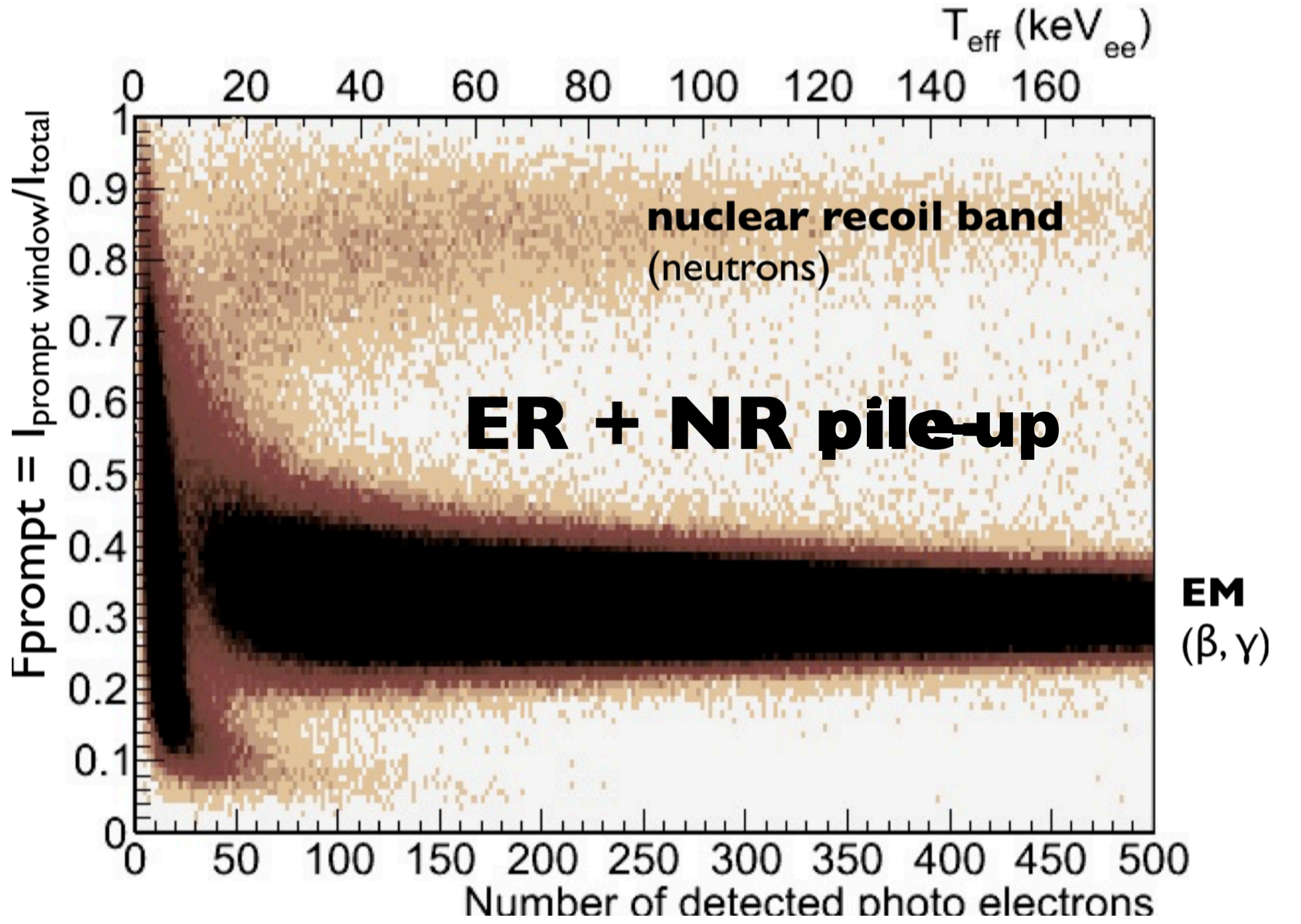
Number of excitons/ions produced dependent on particle interaction type.

Excimers in LAr can be produced in singlet / triplet states with well-separated lifetimes (7 ns / 1445 ns) - this makes PSD effective. Details on the **pulse shape** and **PSD** published in Ref A and Ref B - see below!

Define a PSD variable known as F_{prompt}: fraction of prompt scintillation light.

$$F_{prompt} = \frac{\sum_{t=-28ns}^{60ns} PE(t)}{\sum_{t=-28ns}^{10000ns} PE(t)}$$

Suppression factor of 10^{-10} determined by the DEAP-3600 collaboration at 50% NR acceptance (18 keVee).



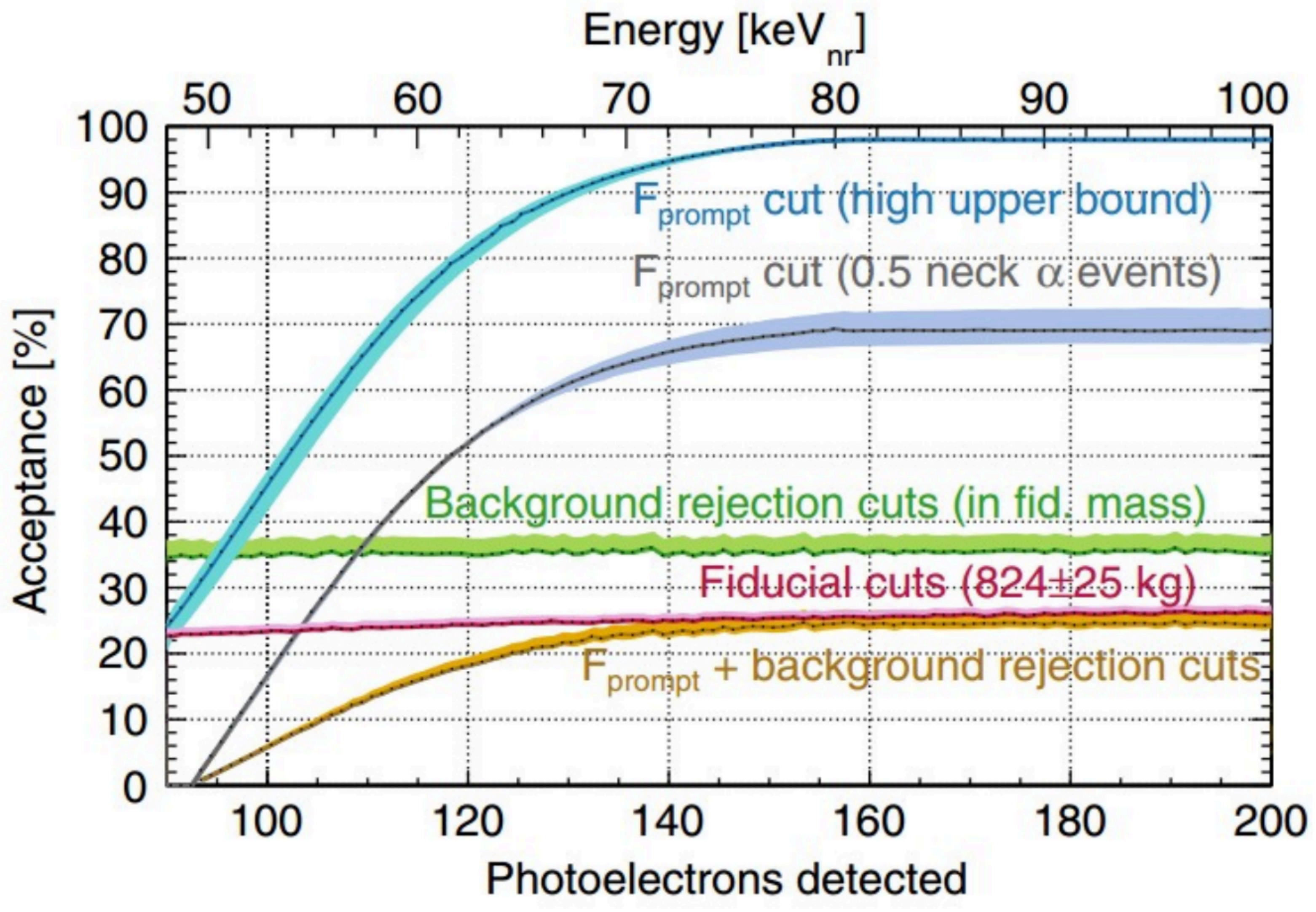
Data from AmBe (neutron emitter) run

Ref A : https://doi.org/10.1140/epjc/s10052-020-7789-x

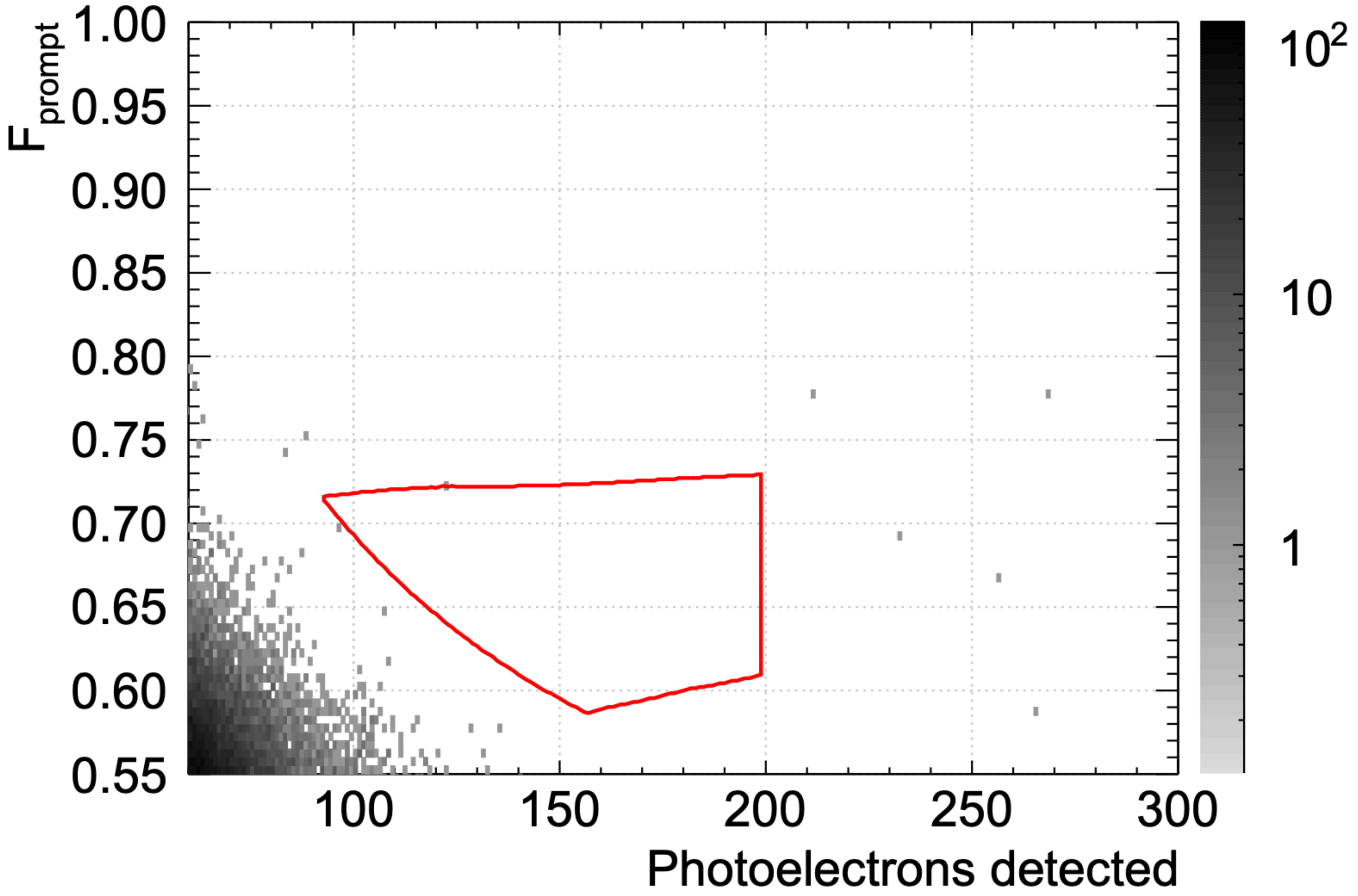
Ref B : https://doi.org/10.1140/epjc/s10052-021-09514-w

Results of WIMP Search from 231 Live-Days of Data

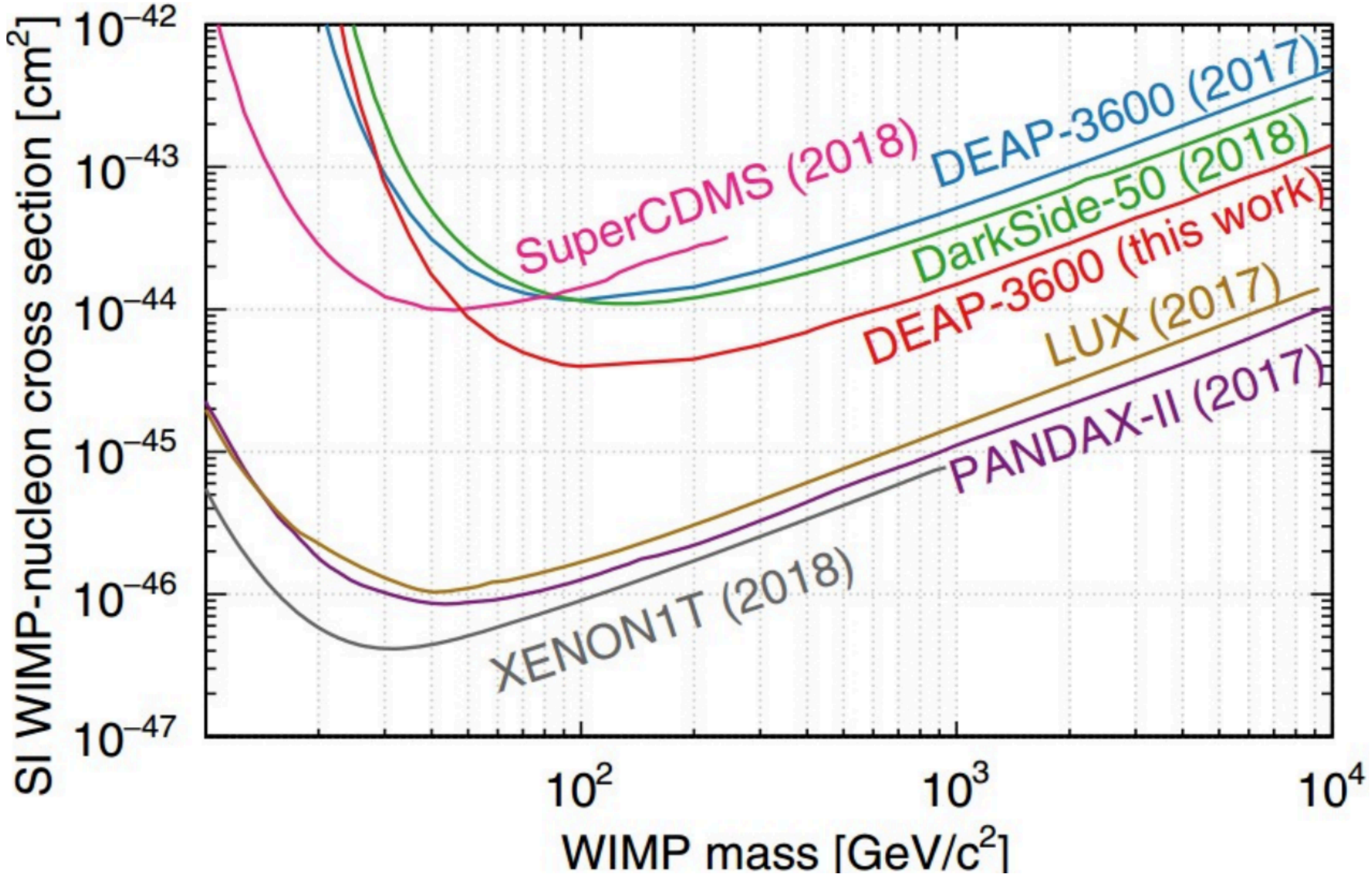
“Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB”. Phys. Rev. D 100, 022004 (2019).



WIMP Acceptance as a function of PE.



After all background rejection and fiducial volume cuts, no WIMP-like events observed inside WIMP ROI.



Most stringent limit on SI WIMP-nucleon cross section using Argon target.

Updates: Development of Dust-α Decay Model

Additional background component model has been developed: α-decays coming from a low level of dust particulate contamination inside LAr.

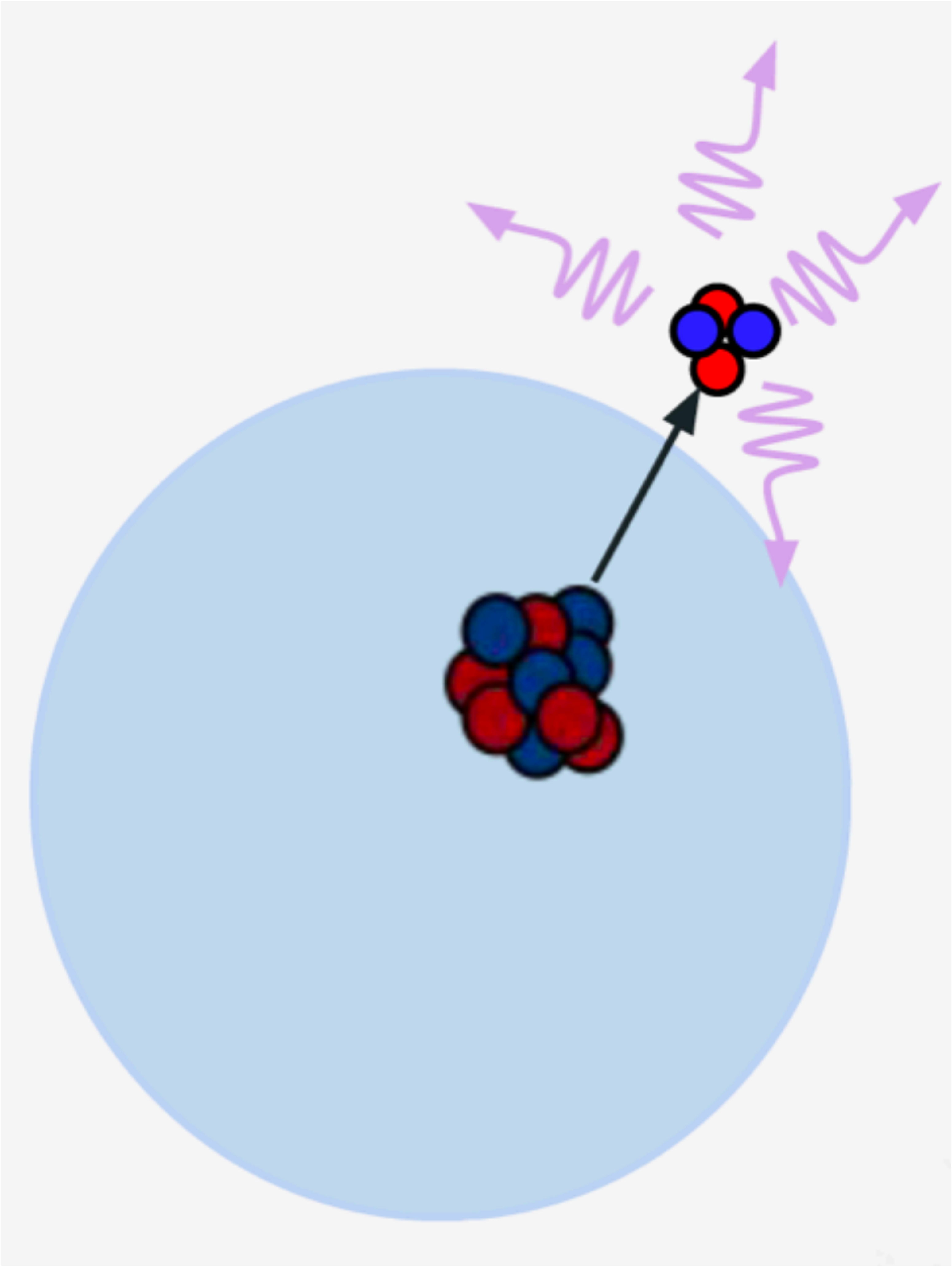
Energy of α particle attenuated in dust particulate before reaching LAr means fewer scintillation photons produced.

This background is consistent with metallic dust particulates ranging from 1 um - 50 um in diameter, that could have entered DEAP-3600 during construction:

- Before the LAr fill, 10 tonnes of nitrogen gas were used to purge the acrylic vessel after the resurfacing of the inner surface of the vessel.
- A 50 um pore-size filter was used; this would have allowed metal particulates of less than 50 um from the nitrogen cylinder to enter the acrylic vessel.

Ex-situ measurements using nitrogen gas and a Scanning Electron Microscope (SEM) also support this hypothesis.

Further, because the inner surface of the AV was coated with TPB between the resurfacing step and the LAr fill, it is unknown whether particulates were coated with TPB.



Updates: Development of Dust-α Decay Model

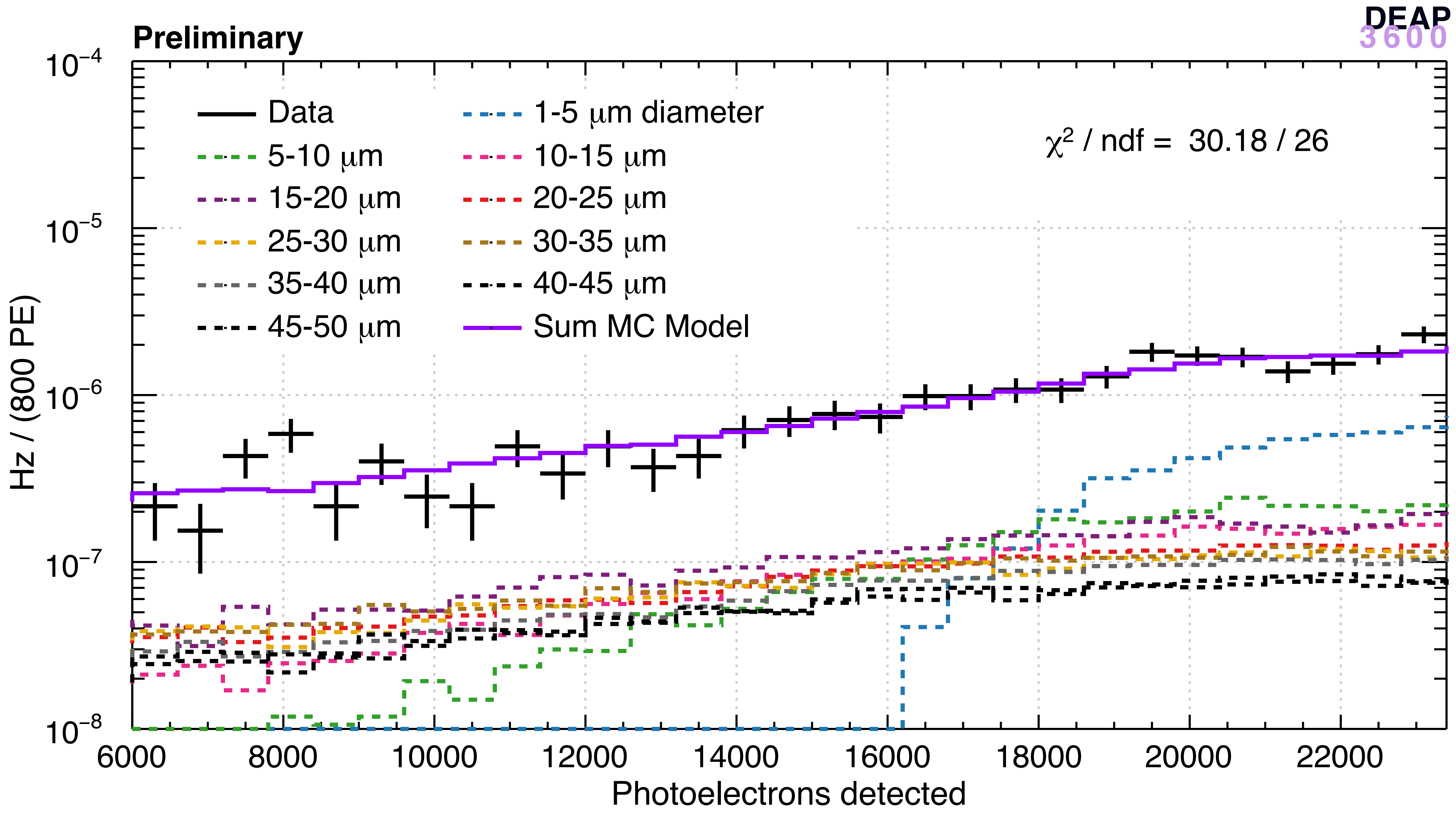
Copper and TPB-coated dust samples of five different sizes below 50 um have been simulated uniformly throughout the LAr, with ^{210}Po α-decays generated uniformly throughout the spherical particulate.

These samples are fit to data in a high-energy, dust control region, in order to extract the rate of dust induced α-decays.

Fit performed in charge spectrum (photoelectrons detected), to constrain rate under the assumption that the particulate size distribution follows power law:

$$N_{\text{dust}} = N_0 \sum_{i=1}^{5} (D^p_{\text{upper}} - D^p_{\text{lower}}) h_i$$

Result of this fit is extrapolated to lower energy using MC simulated samples.

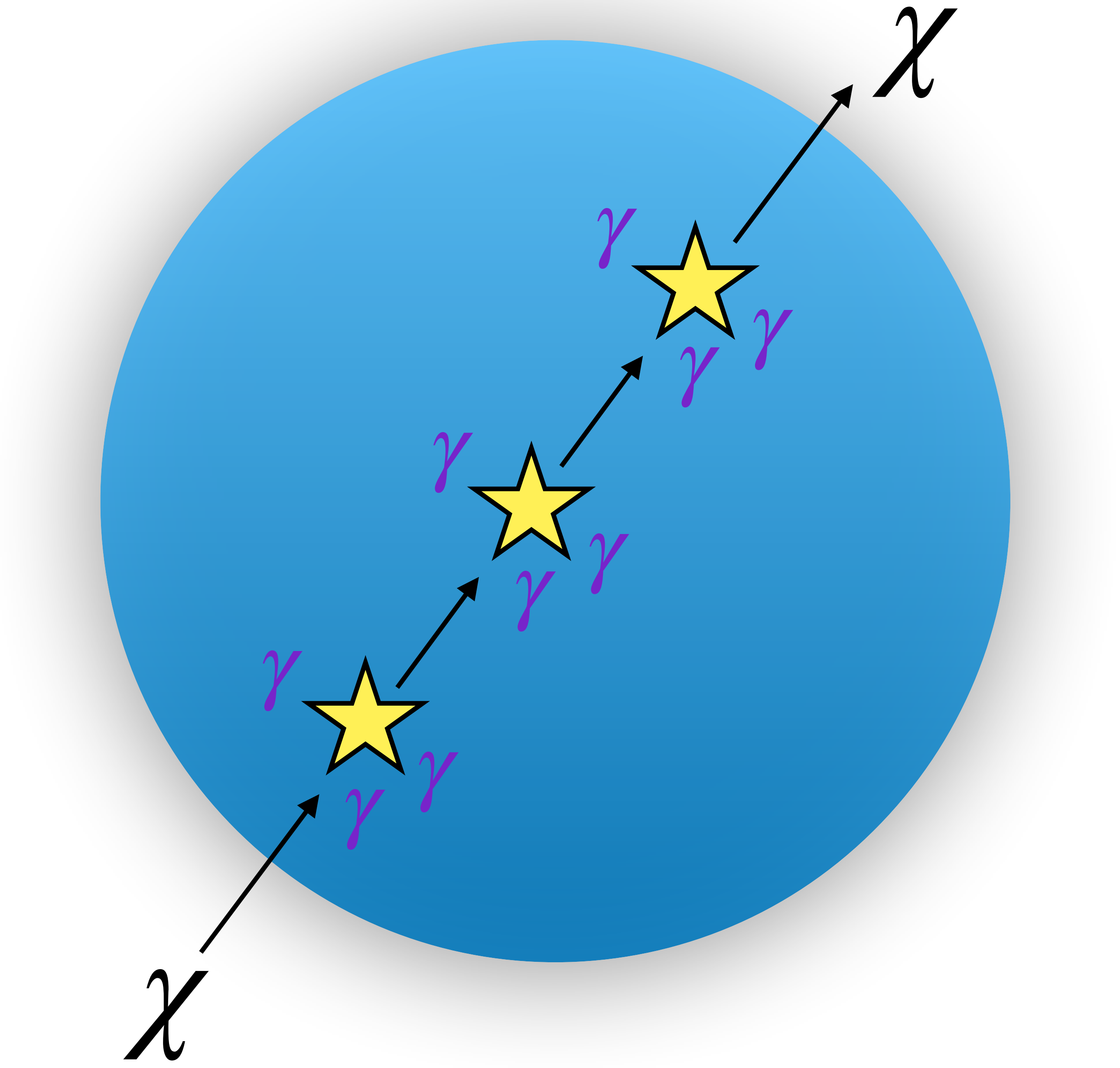


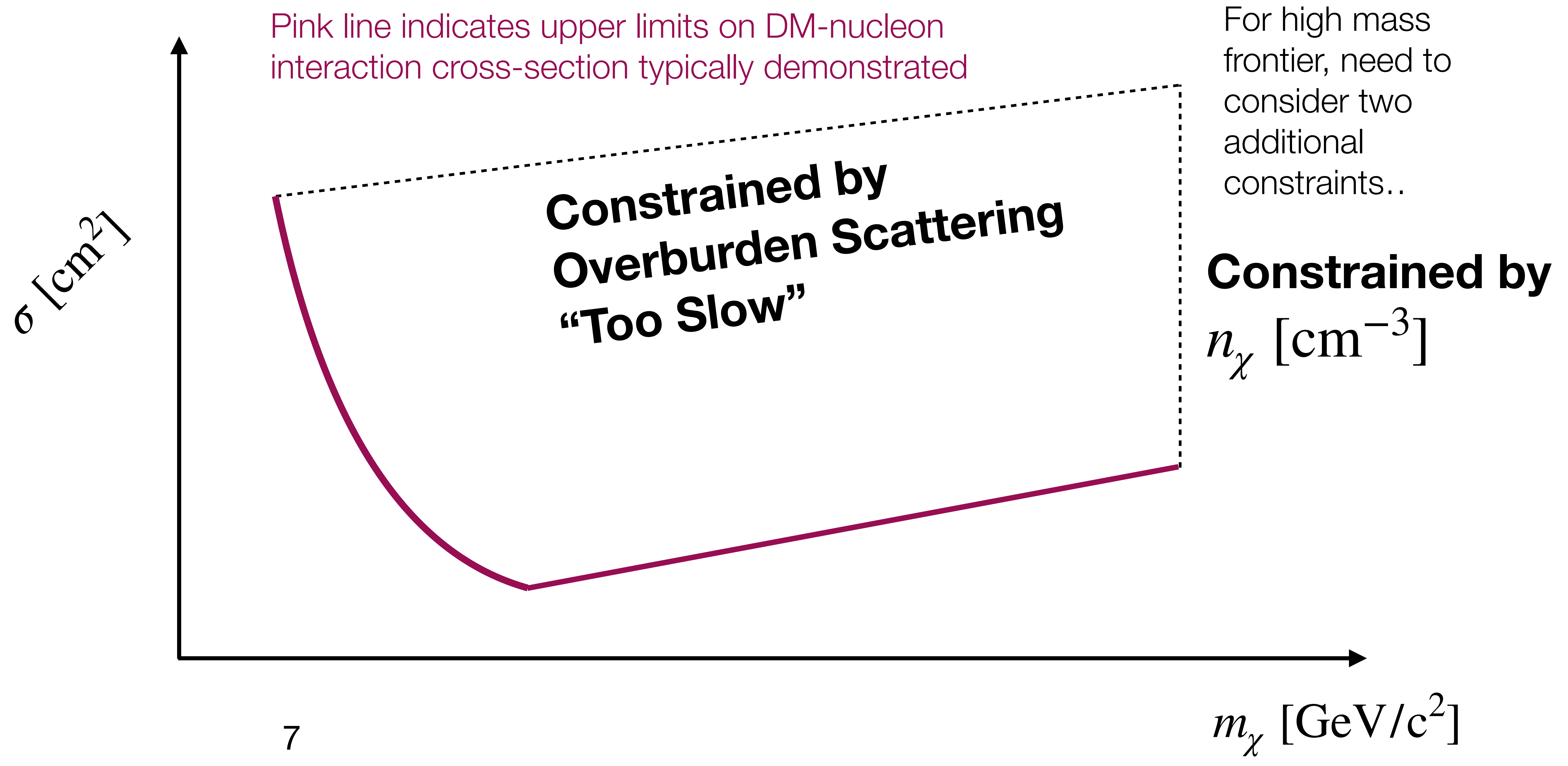
Updates: Search for Planck-Scale DM

Another well-motivated DM candidate is super-heavy DM with Planck-scale mass $m_\chi = 10^{19}\mathrm{GeV/c^2}$.

Planck-scale DM may be produced non-thermally through GUTs, but other production mechanisms include primordial black hole radiation or extended thermal production in a dark sector.

Unlike standard WIMPs, which scatter at most once in a detector, Planck-scale DM has a high enough cross section to scatter multiple times as it traverses a detector…





Pink line indicates upper limits on DM-nucleon interaction cross-section typically demonstrated

For high mass frontier, need to consider two additional constraints..

Constrained by Overburden Scattering "Too Slow"

Constrained by $n_\chi\ [\mathrm{cm^{-3}}]$

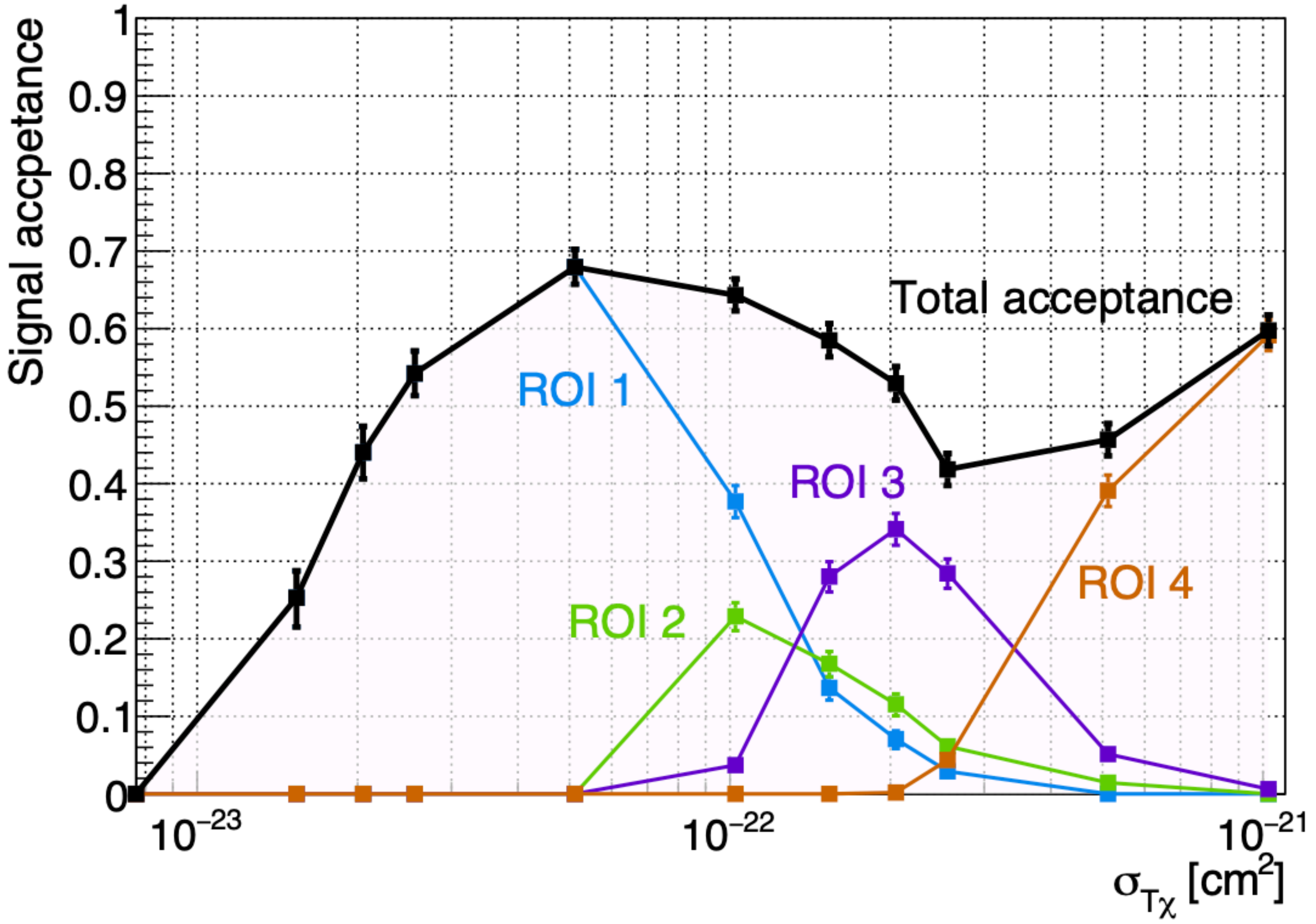
Updates: Search for Planck-Scale DM

Four different region-of-interests (ROIs) are defined in order to search for Planck-scale DM.

The ROIs are defined in different energy ranges, with varying cuts on N_{peaks} (individual peaks identified per 16 us-long event) and F_{prompt}.

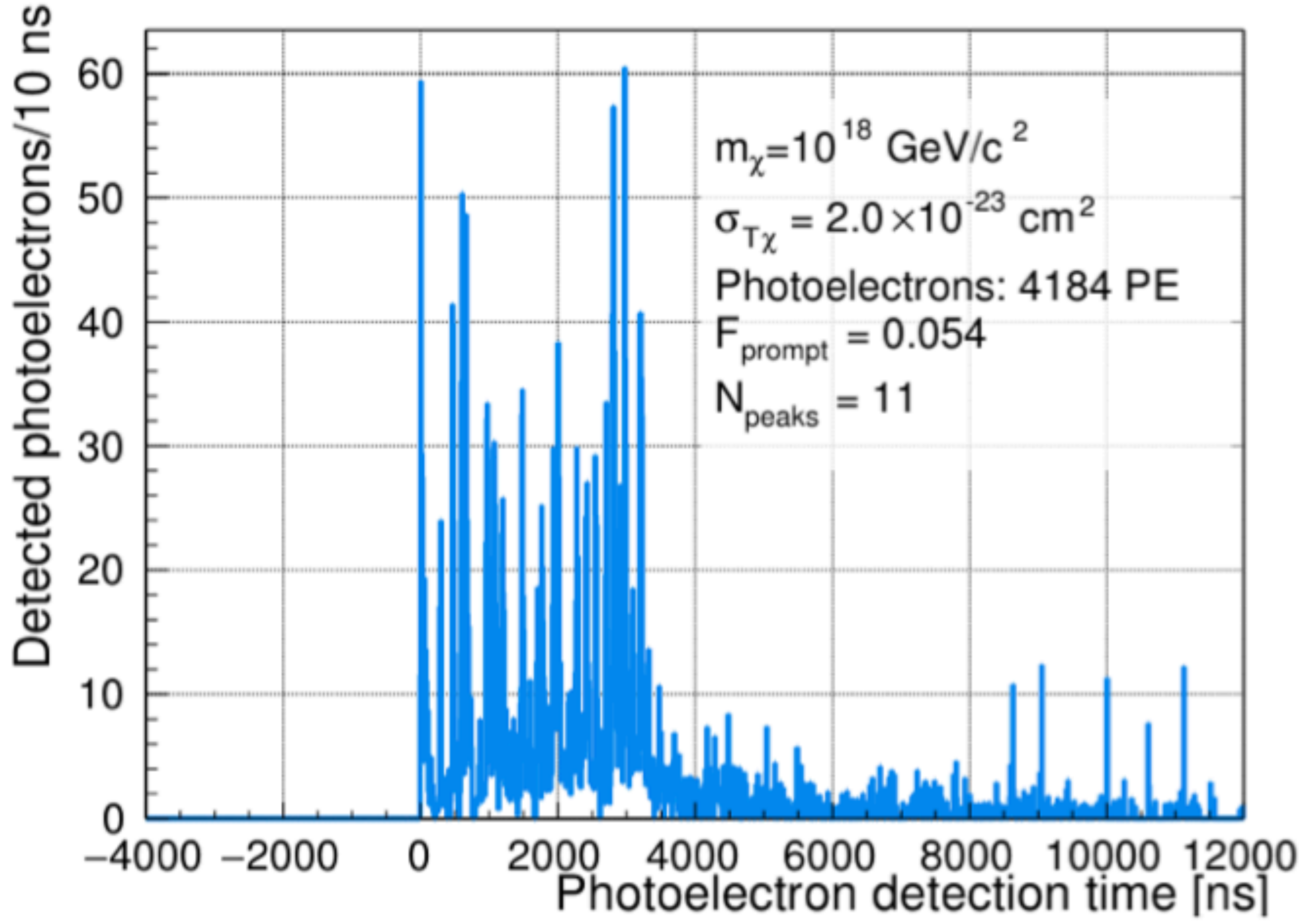
Cuts on N_{peaks} and F_{prompt} in ROI's 1-3 are applied to mitigate background events coming from pile-up. Pile-up backgrounds negligible in ROI 4, but muons considered as potential background source.

ROI	PE range	Energy [MeV]	N_{peaks}^{min}	F_{prompt}^{max}	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



Left: Probability of Planck-scale DM with $m_\chi = 10^{18}$ GeV/c² populating each ROI and surviving all cuts at varying $\sigma_{T\chi}$

Right: Simulated detected PE times for $m_\chi = 10^{18}$ GeV/c² and $\sigma_{T\chi} = 2 \times 10^{-23}$ cm²



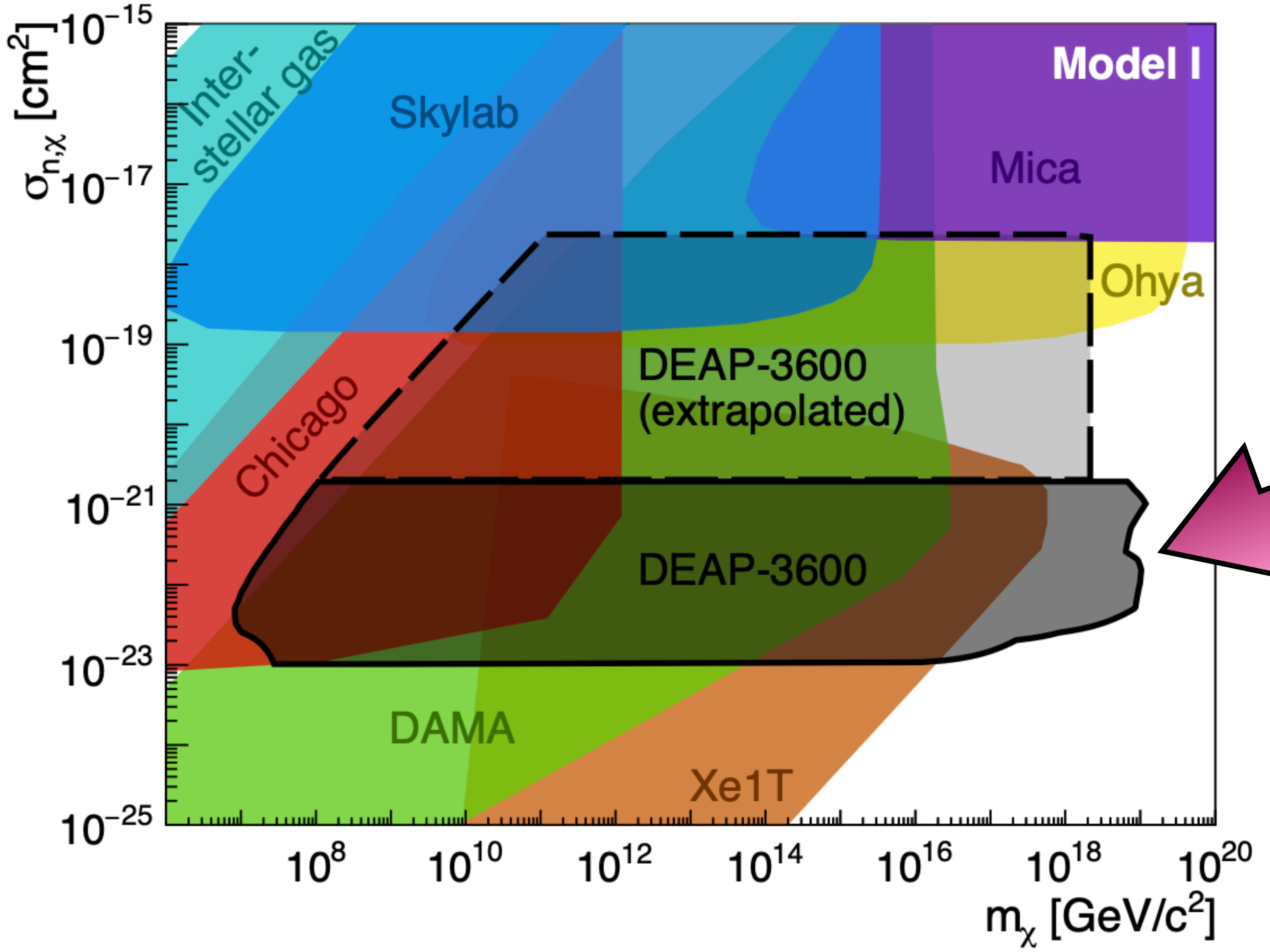
Updates: Search for Planck-Scale DM

In 813 days, zero events were observed and 90% C.L upper limit placed on $m_\chi - \sigma_{n\chi}$ space.

DEAP-3600 placed the very first experimental direct detection limits on Planck-scale DM for two composite models.

DM is opaque to nucleus; scattering cross-section at zero momentum transfer is geometric size of DM regardless of target nucleus

$$\sigma_{T\chi} = \sigma_{n\chi} |F_T(q)|^2$$

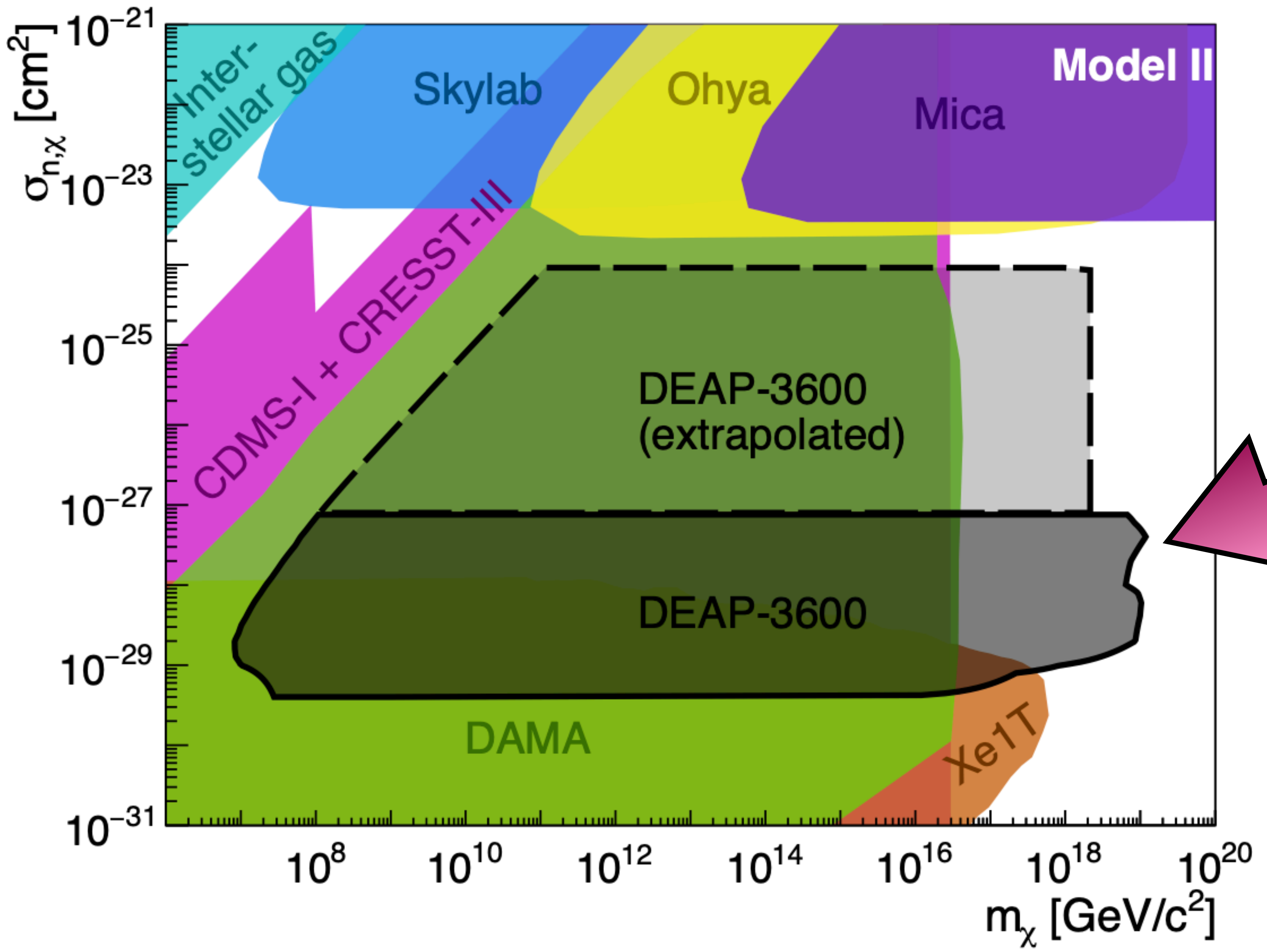


Planck-scale DM!

Cross-section scales as:

$$\sigma_{T\chi} \simeq \sigma_{n\chi} A^4 |F_T(q)|^2$$

Most commonly used scaling; allows for direct comparison with other experiments as well as single scatter constraints



Planck-scale DM!

Updates: New Measurement of the Specific Activity of ^{39}Ar

Latest results demonstrates the most precise measurement of the specific activity of atmospheric ^{39}Ar to date.

LAr mass estimate previously (3279 ± 96) kg.

New estimate from this work is (3269 ± 24) kg - 4x reduction in uncertainty!

^{39}Ar specific activity measurement carried out using binned χ^2 fit to data, using a fit model comprised of three spectra:

1) Single ^{39}Ar β-decay spectrum.
2) Pile-up spectrum of two ^{39}Ar β-decays occurring within the same trigger window.
3) All non-^{39}Ar electronic recoil backgrounds spectrum.

Energy-scale and detector resolution effects in the form of a Gaussian term are applied to all three components:

$$PE = p_0 + p_1 \cdot E + p_2 \cdot E^2$$

$$\sigma(PE) = \sqrt{p_3 \cdot PE + p_4 \cdot PE^2}$$

Specific activity calculated by estimating total number of ^{39}Ar decays, N, within a certain livetime.

$$S_{^{39}\mathrm{Ar}} = \frac{N}{T_{\mathrm{live}} \cdot m}$$

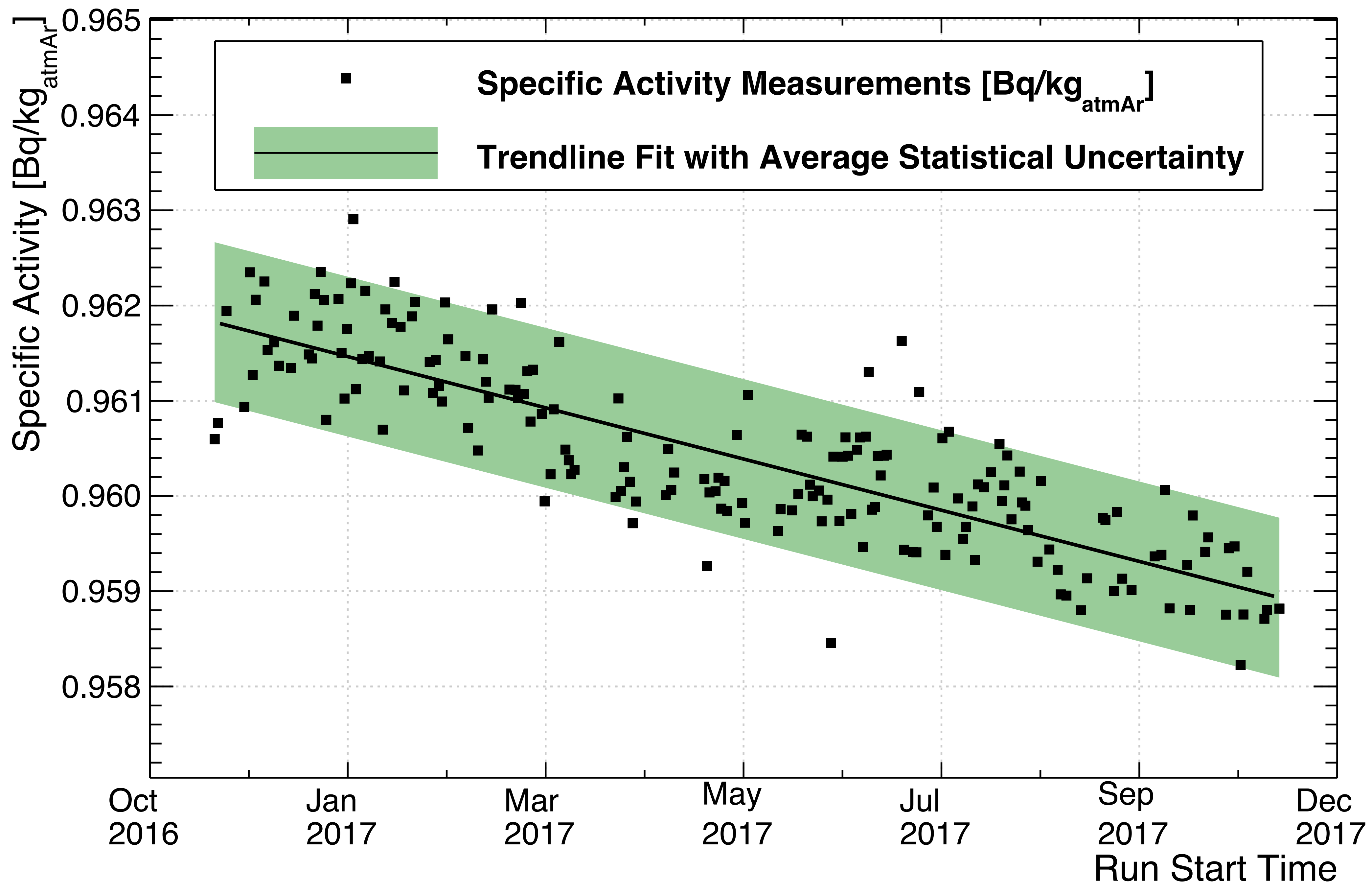
Where N is split into $N = N_{\mathrm{single}} + N_{\mathrm{pileup}}$

Updates: New Measurement of the Specific Activity of ^{39}Ar

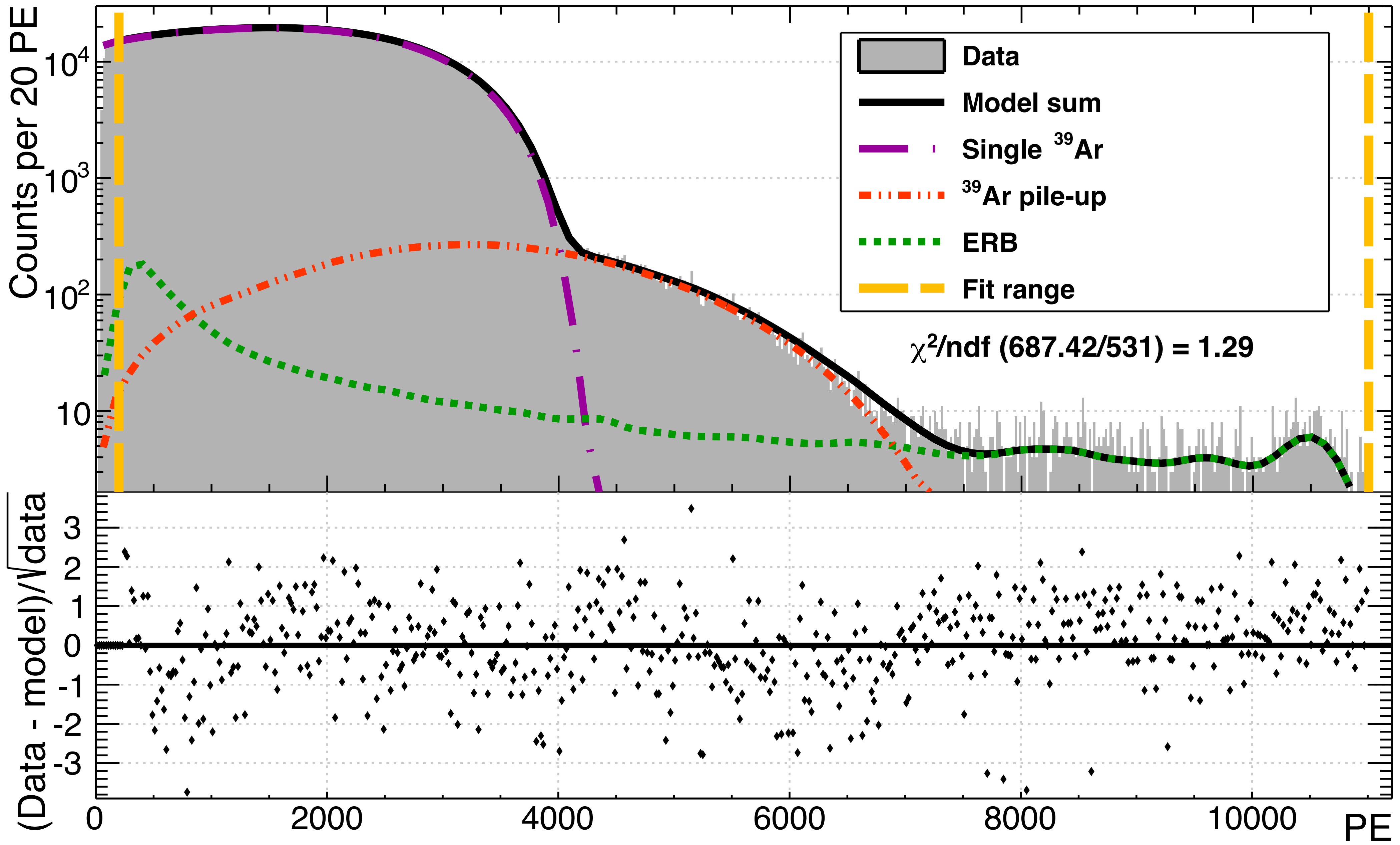
Pile-up events are included in the data and considered in model fit.

Number of single and pile-up ^{39}Ar decays are obtained from integral of single and pile-up spectrums after the fit is performed.

There is a correction for the age of the argon, 1.0 ± 0.5 years - expect a 0.26% decrease over course of one year.



$$\boxed{S_{\mathrm{Ar39}} = (0.964 \pm 0.024)\mathrm{Bq/kg_{atmAr}}}$$



Cross-check analysis was performed which specifically removed pile-up events from data.

Specific activity from cross-check analysis: $S_{\mathrm{Ar39}} = (0.97 \pm 0.03)\mathrm{Bq/kg_{atmAr}}$

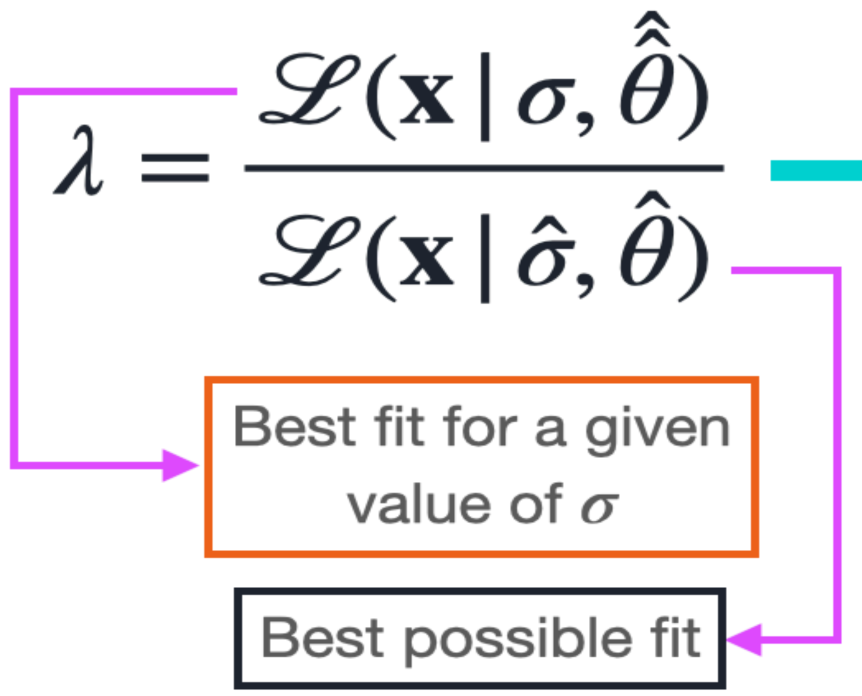
Cross check consistent with main result.

(Will be submitted to EPJC this week).

Coming Up: WIMP Search using the Profile Likelihood Ratio Method

Previous WIMP result: Loss in WIMP acceptance driven by harsh background rejection cuts.

DEAP-3600 is developing a Profile Likelihood Ratio PLR analysis in order to attempt to gain back WIMP acceptance and sensitivity.

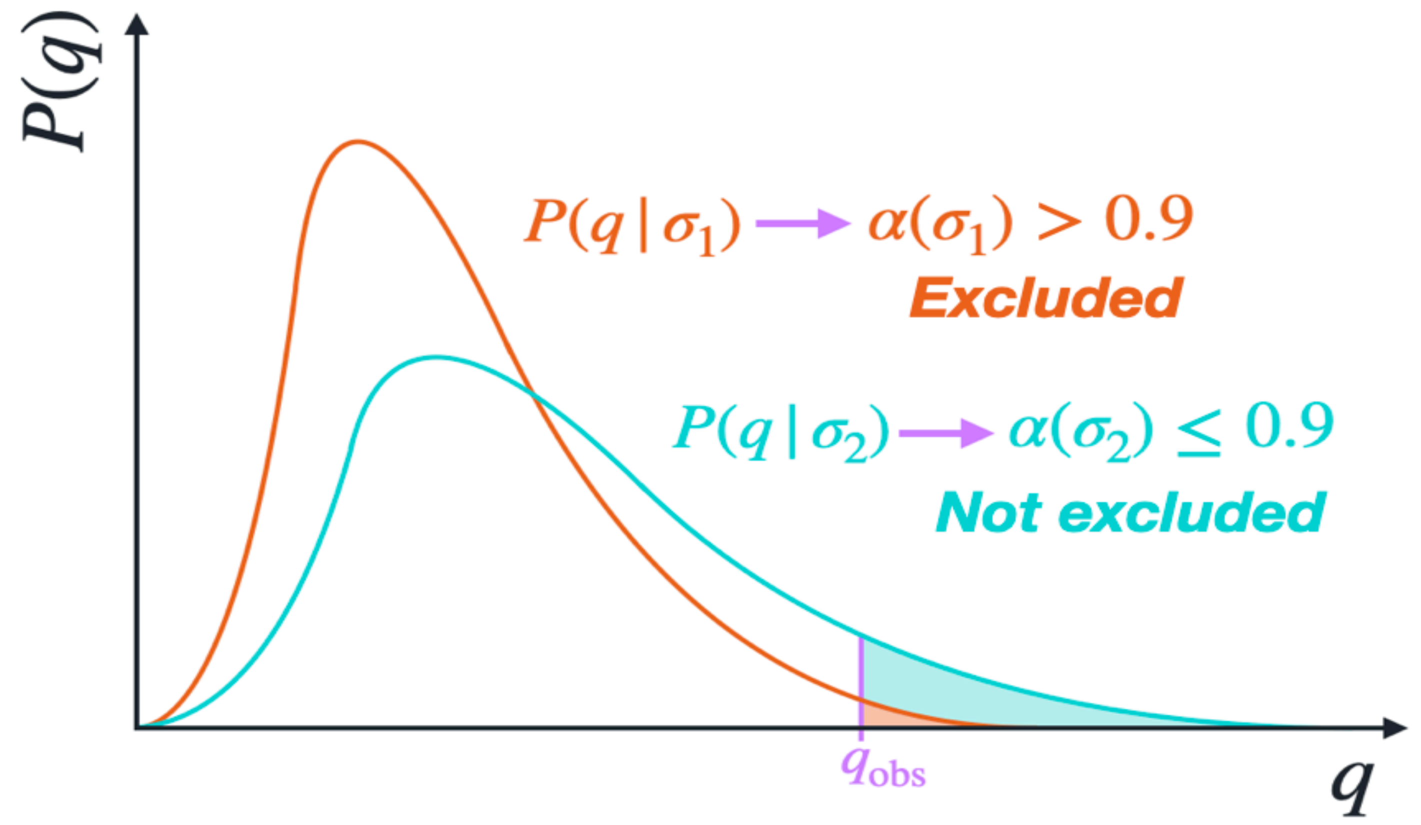


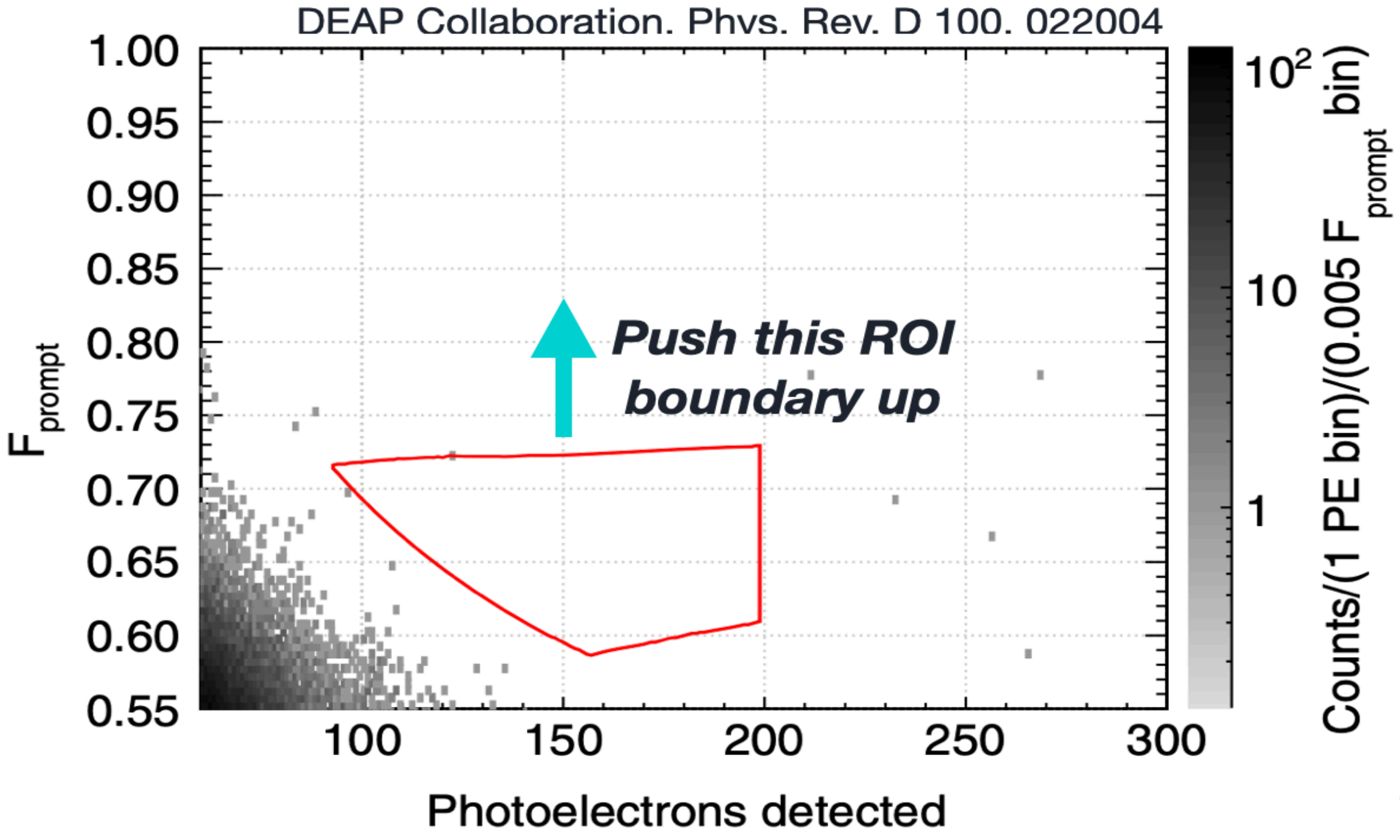
$$\lambda = \frac{\mathscr{L}(\mathbf{x}\,|\,\sigma, \hat{\hat{\theta}})}{\mathscr{L}(\mathbf{x}\,|\,\hat{\sigma}, \hat{\theta})}$$

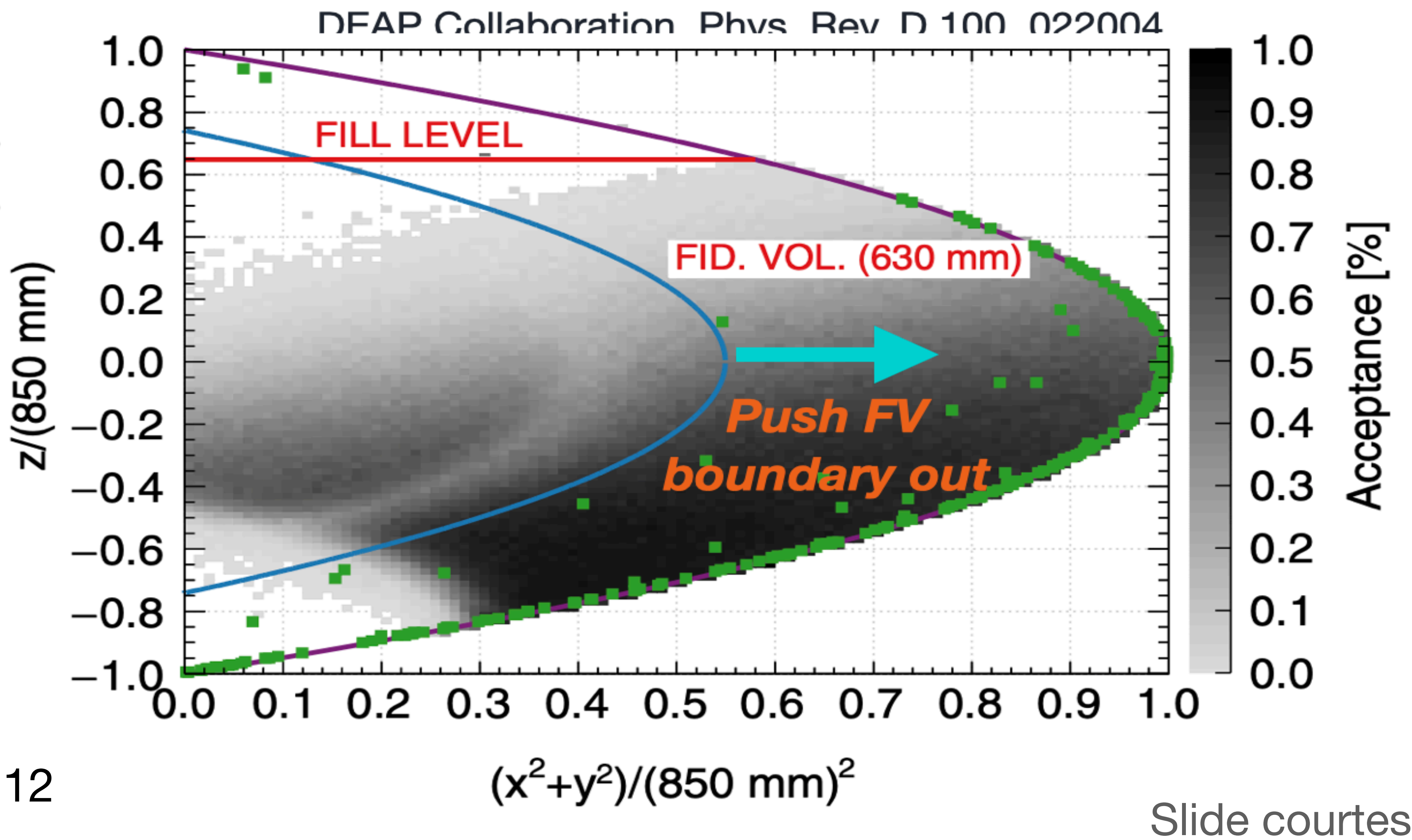
Best fit for a given value of σ

Best possible fit

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




DEAP Collaboration, Phys. Rev. D 100, 022004


DEAP Collaboration, Phys. Rev. D 100, 022004

Slide courtesy of J. McLaughlin.

Coming Up: Hardware Upgrades

DEAP-3600 is undergoing several hardware upgrades in order to remove problematic backgrounds from neck α-decays and dust α-decays:

1) Installation of new flow guides with a wavelength-shifting (WLS) coating

Degraded light collection from non-coated flow guides shifts α-decay events to lower energies, potentially into WIMP region of interest. WLS coating produces a significantly different PSD that can be tagged very effectively.

2) External cooling and dust removal system

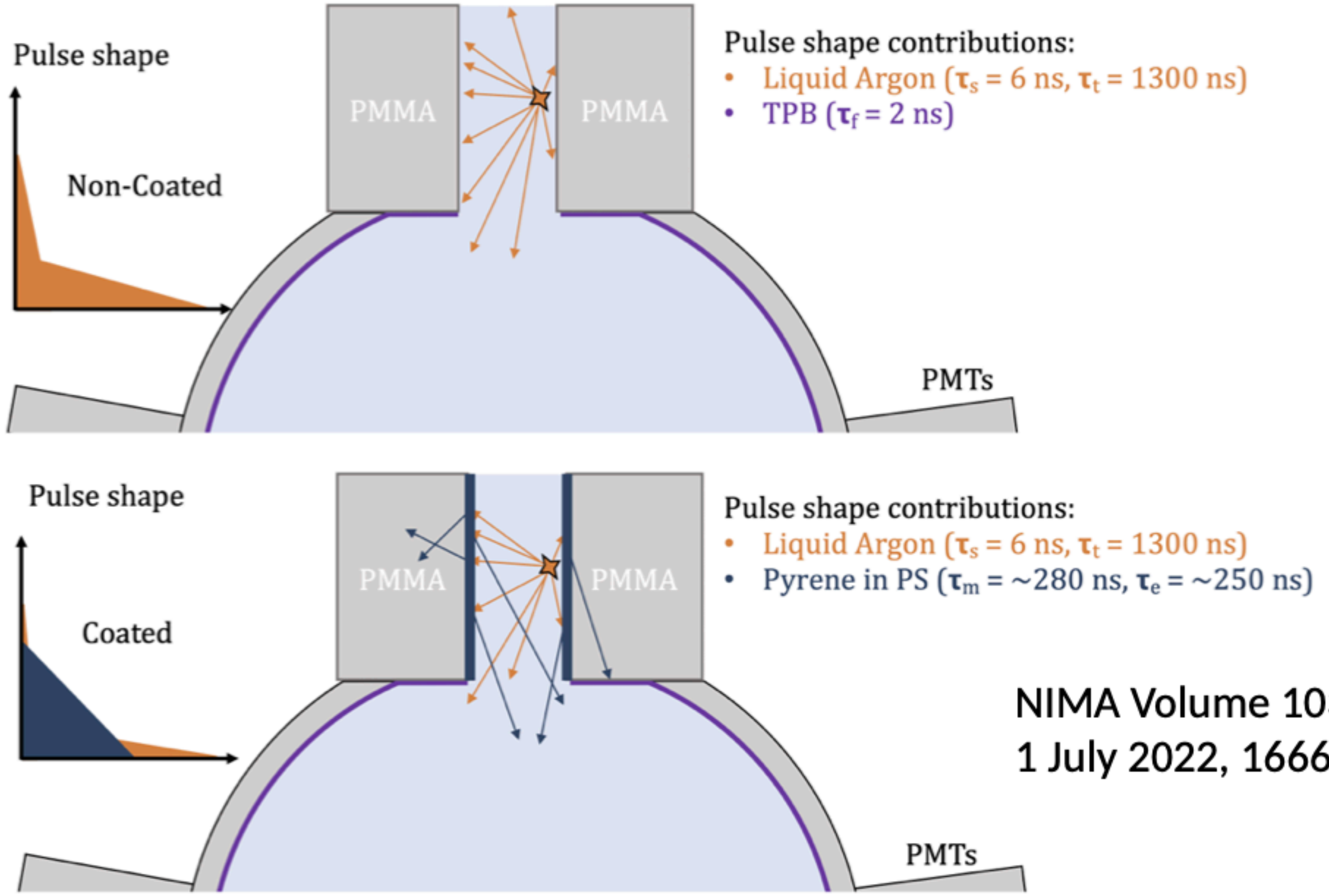
Reduction in dust background via LAr removal and filtration.

Removal of bulk LAr through a tube deployed to the bottom of the AV will pull dust out.

Installation of high-throughput filter on the argon purification system will prevent new dust ingress into the AV.

External cooling of the argon.

Warmer neck will prevent LAr film from forming on flow guides. Alpha scintillation in LAr film allows leakage into ROI.



NIMA Volume 1034,
1 July 2022, 166683

Summary and Outlook

DEAP-3600 is a single-phase LAr detector designed to directly detect WIMPs.

No WIMP candidates observed after 1 year (231 live-days) of data, leading to the strongest upper bound on the WIMP-nucleon spin-independent, isoscalar cross section for an Argon target.

New background model of dust-induced α-decays has been developed.

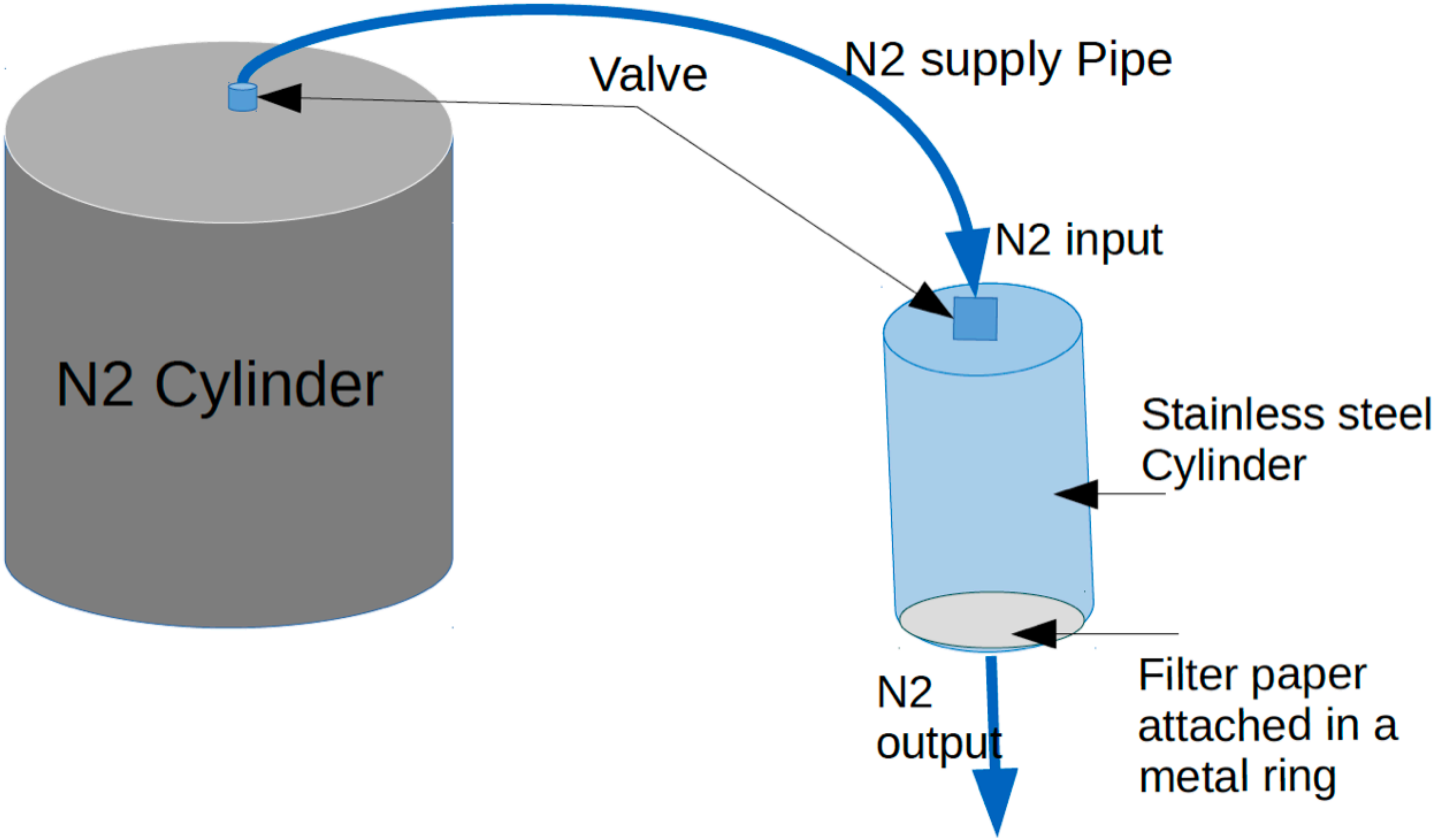
Search for super-heavy Planck-scale DM was performed; no candidate events were observed, producing the first direct detection constraints on Planck-scale DM.

Leading limits constrain Planck-scale DM for two composite models between 8.3×10^{6} - 1.2×10^{19} GeV/c^2, and cross-sections for scattering on argon nuclei between 1.0×10^{-23} - 2.4×10^{-18} cm^2.

Most precise measurement of specific activity of atmospheric ^{39}Ar to date: (0.964 ± 0.024) Bg/kg$_{\text{atmAr.}}$

Ongoing work includes: the development of a Profile Likelihood Ratio (PLR) statistical analysis to perform a further WIMP search; hardware upgrades in order to remove neck α-decay and dust α-decay backgrounds.

Back Up: Dust α-decay Ex-Situ Measurement



Back Up: Planck-Scale DM

$$N_{\text{events}} \sim \Phi \, \min[\tau, 1]$$

Φ = Integrated Flux
τ = Optical depth = $n_{\text{det}} \sigma L_{\text{det}}$

Single scatter limit: $\tau \ll 1$

Multi scatter limit: $\tau \gg 1$

➡ At the highest DM mass relevant parameter is detector area normal to the DM flux: number density of DM is limitation: if number density too low compared to detector area, no DM crosses the detector during the live-time

➡ In low cross-section limit, "thickness" of the detector is most important so we detect enough scatters to be reconstructed…

➡ At high mass AND low cross-section, detector area and thickness are both important…. a large spherical detector is ideal!

Important signature of Planck-scale DM: mostly collinear track of nuclear recoils through detector!

Maximum total deflection angle of DM particle in limit $m_\chi \gg m_N$ given by,

$$\Omega_{\text{max}} \lesssim n^{1/3} L_{\text{det}} \sin\alpha_{\text{max}}$$

where $\sin\alpha_{\text{max}} = m_T / m_\chi$, is the maximum detector-frame scattering angle)

And $n^{1/3} L_{\text{det}}$, is the maximum number of recoils in the detector

Bottom line: NRs produced by transiting Planck-scale DM are typically collinear, although for $m_\chi < 10^{13}$ GeV/c^2, deflection on the order of ~degrees becomes feasible

Back Up: Planck-Scale DM

Planck-scale DM simulated in two steps in DEAP-3600:

1. DM is first attenuated in the overburden,
2. DM is then propagated in the detector, with simulation of optical and DAQ response

Attenuation of DM at position $\vec{r}$ calculated numerically as,

$$\left\langle \frac{dE_\chi}{dt} \right\rangle(\vec{r}) = -\sum n_i(\vec{r})\sigma_{i,\chi}\langle E_R\rangle_i v$$

DM Speed

Nuclide Number Density

DM-nucleus scattering Cross-Section

Average Recoil Energy

Atmospheric density profile: 79% N_2, 21% O_2

Earth's density profile and composition from [J. Lundberg and J. Edsjo, Phys. Rev. D 69, 123505 (2004)], [A. M. Dziewonski and D. L. Anderson, Phys. Earth Planet. Inter 25, 297 (1981).]

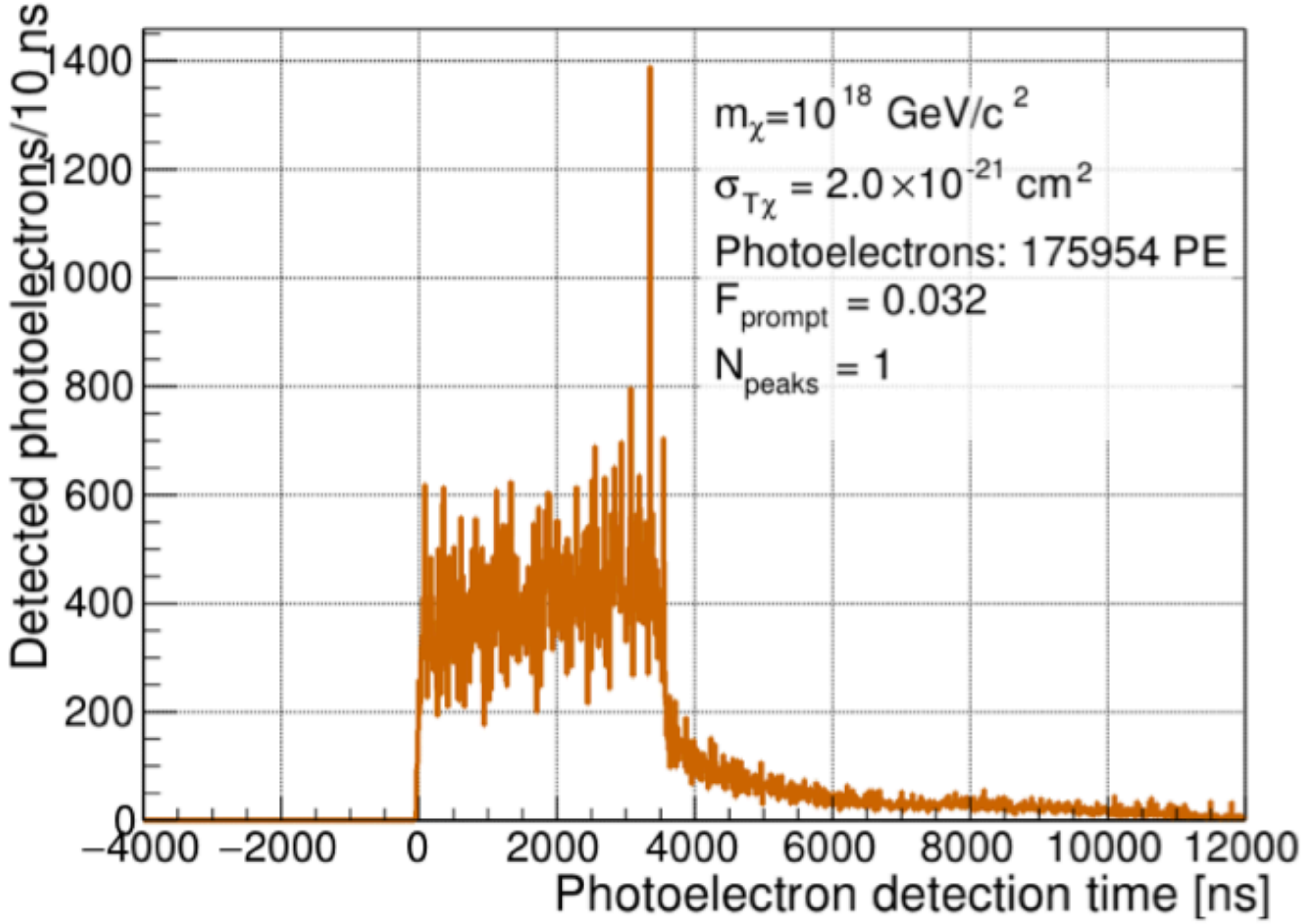
Uncertainties in Earth model found to have negligible effect

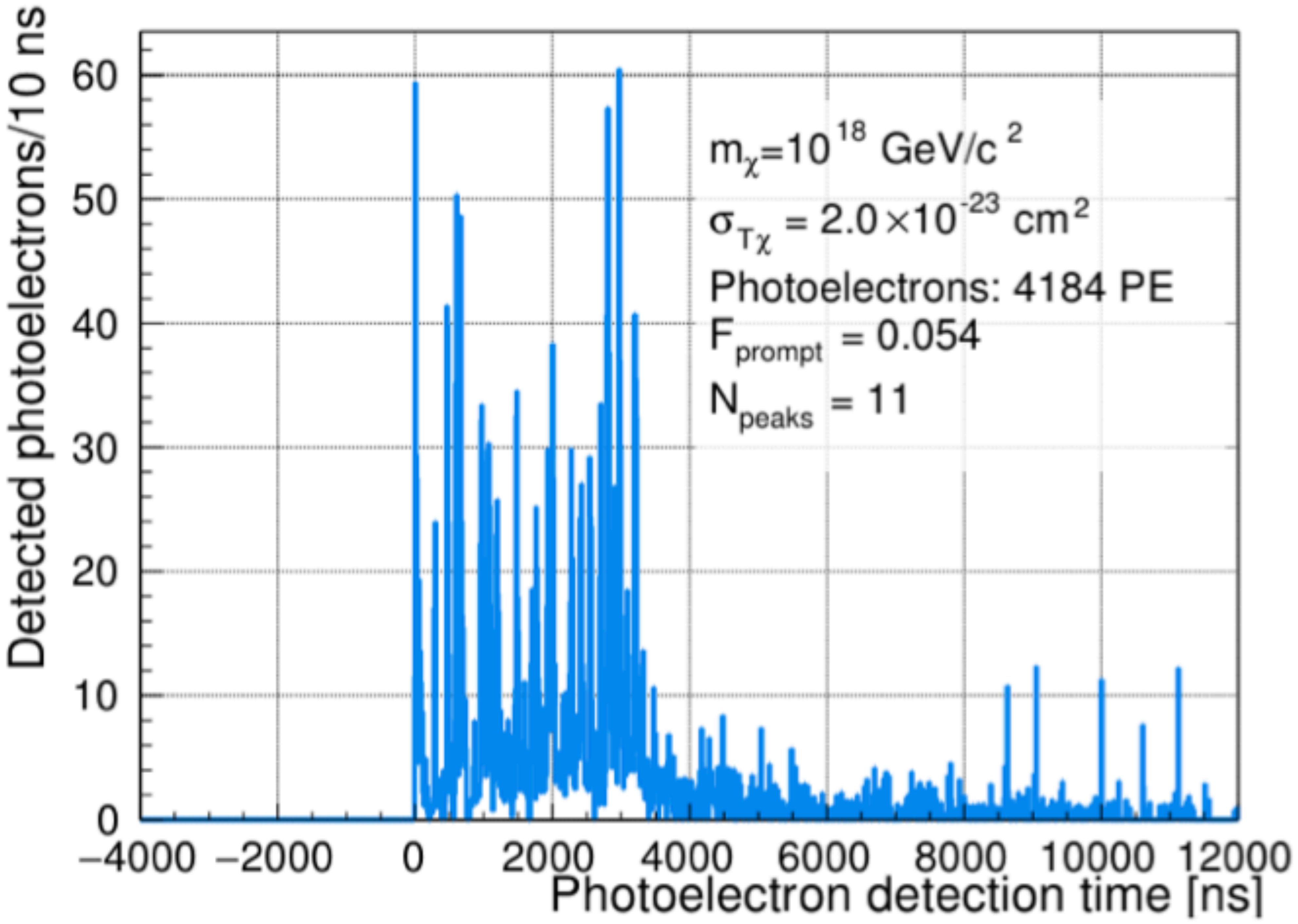
Back Up: Planck-Scale DM

DM that passes through the overburden is then propagated into the DEAP-3600 inner detector

Light yield calibrated up to 10 MeV using Gaussian response function to (n, γ) lines from ^{241}AmBe neutron source

Simulated detected PE times for $m_\chi = 10^{18}$ GeV/c^2, for $\sigma_{T\chi} = 2 \times 10^{-21}$ cm^2 (left) and $\sigma_{T\chi} = 2 \times 10^{-23}$ cm^2 (right)

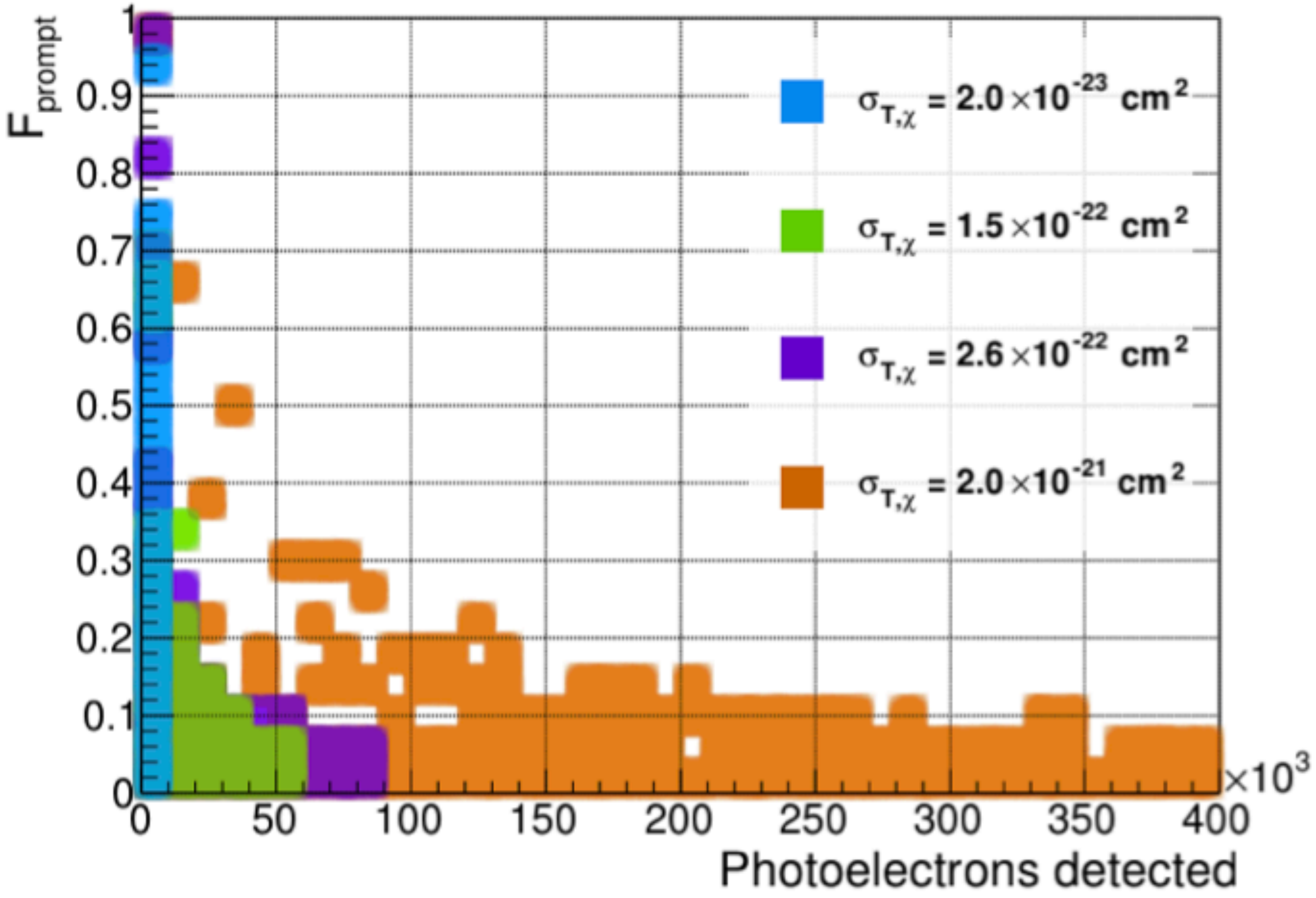


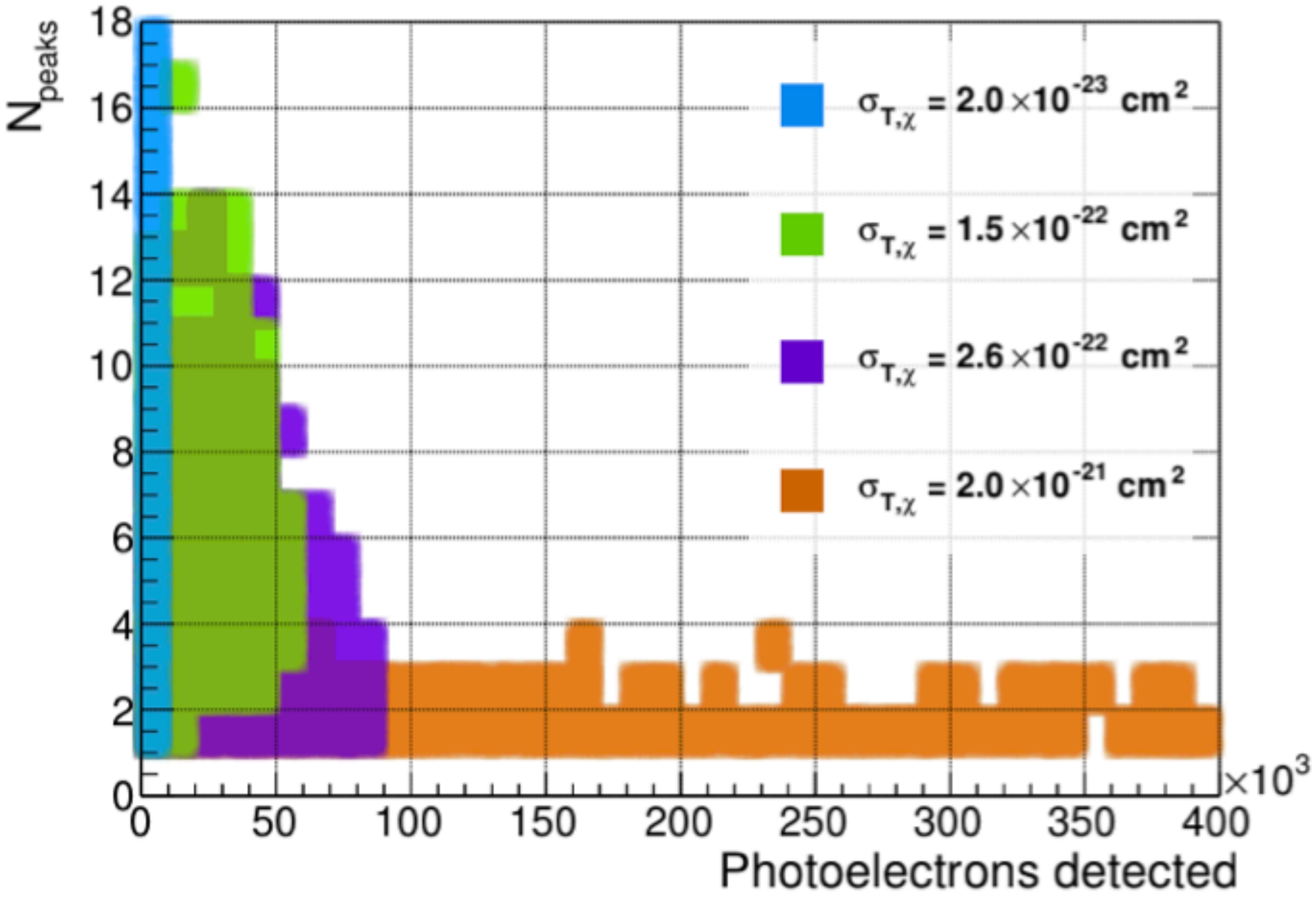


Back Up: Planck-Scale DM

At smaller $\sigma_{T\chi}$ values, the number of individual peaks identified per "event" is greater than for larger $\sigma_{T\chi}$ values

➡ If $\sigma_{T\chi}$ too high, PE times "merge" and $\mathrm{N_{peaks}}$ variables loses accuracy





As $\sigma_{T\chi}$ increases and $\mathrm{N_{peaks}}$ decreases, $\mathrm{F_{prompt}}$ decreases and narrows with the number of detected PE

➡ $\mathrm{F_{prompt}}$ = prompt light fraction in 150 ns about the trigger time