Recent results from the DEAP-3600 dark matter search experiment

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On behalf of the DEAP collaboration

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Outline

- DEAP-3600 experiment
- Recent results
  - Dark matter search with the DEAP-3600 detector using the profile likelihood ratio method
  - First evidence of neutrino absorption on argon using ^{8}B solar neutrinos in DEAP-3600
  - Measurement of the muon flux at SNOLAB using the DEAP-3600 experiment
- Hardware upgrades and data-taking
- Conclusion

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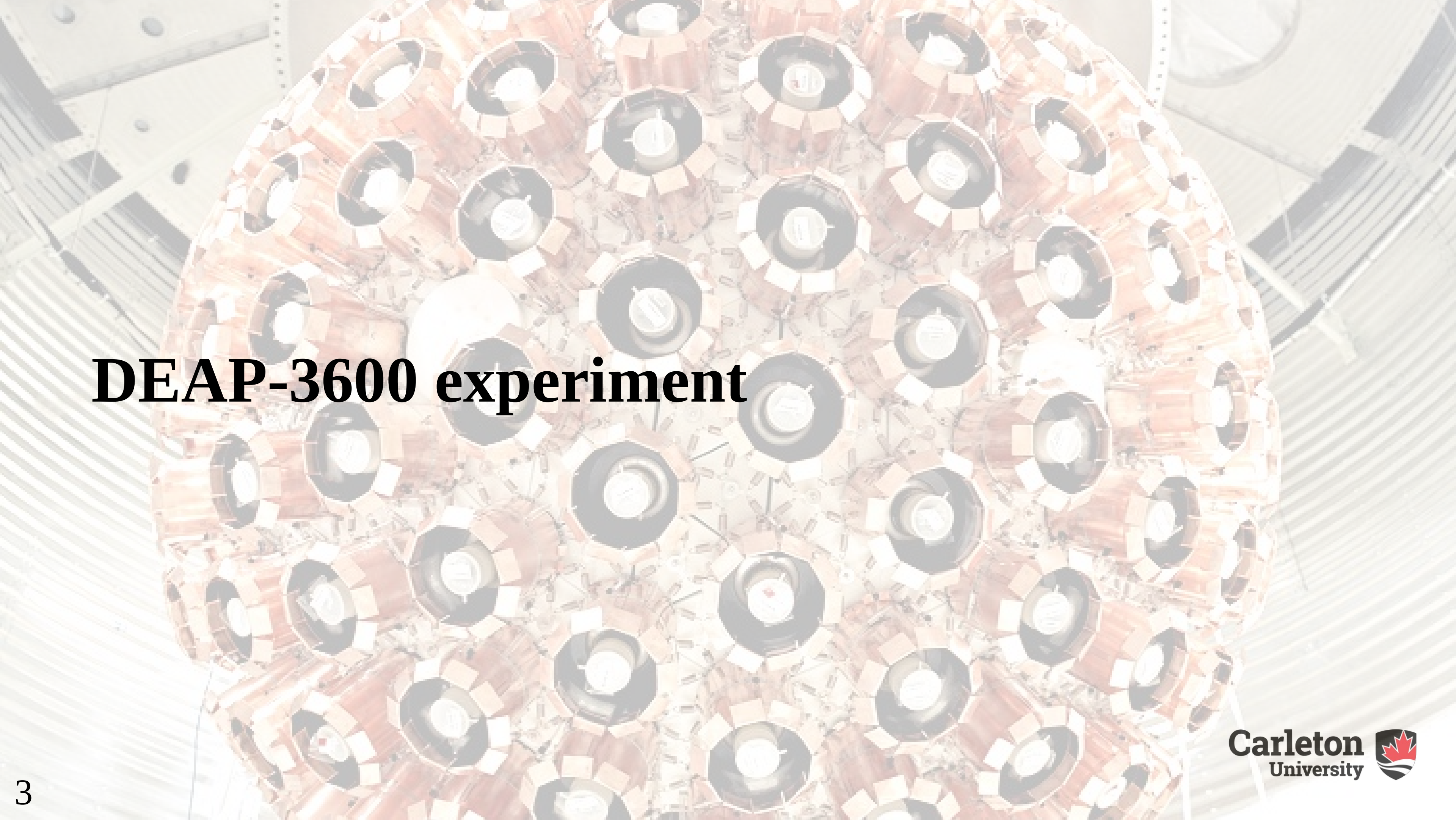

DEAP-3600 experiment

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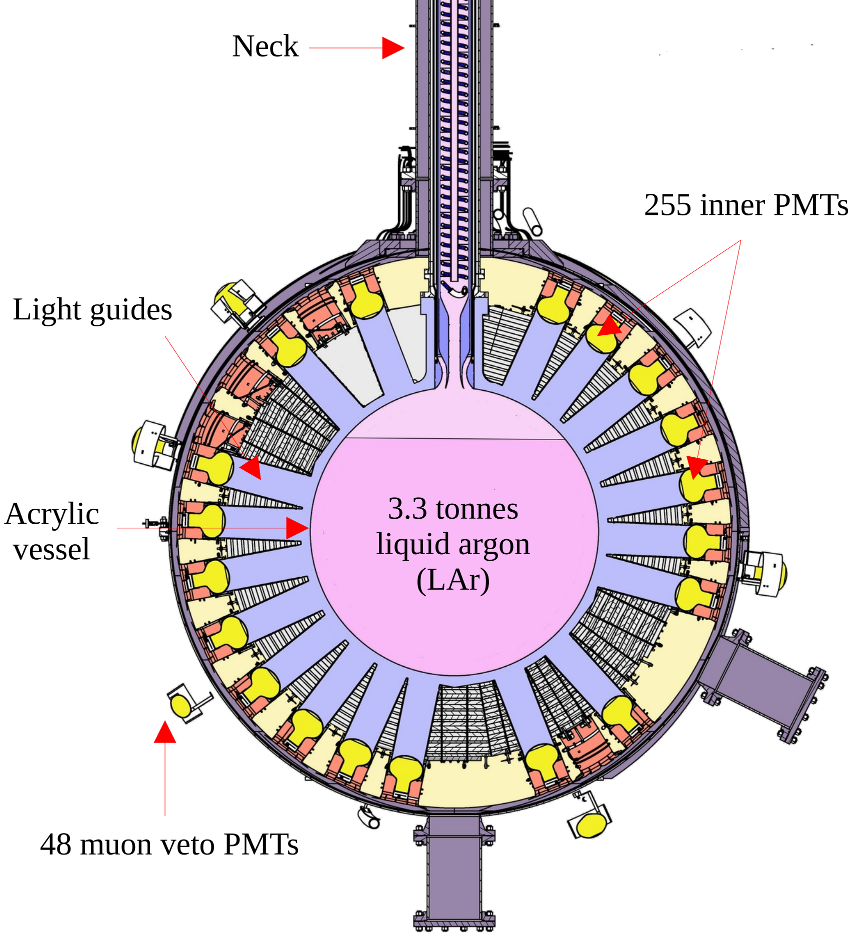
DEAP-3600 inner detector

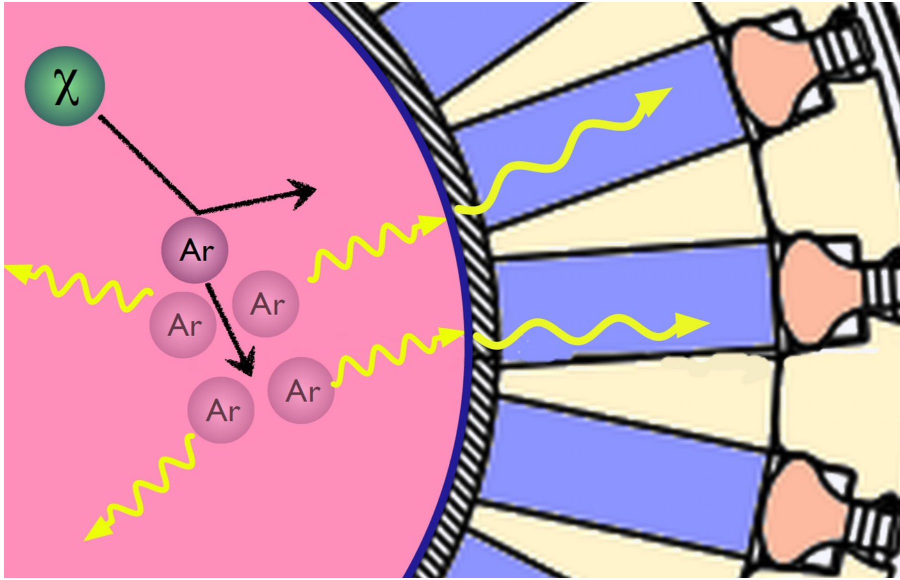
- Direct dark matter search experiment
  - Dark matter Experiment using Argon Pulse-shape discrimination (DEAP)
  - Located at SNOLAB near Sudbury, Canada
- (3269±24) kg liquid argon (LAr)
- 255 inner photomultiplier tubes (PMTs)
- 48 muon veto PMTs



Water shielding

Detection mechanism

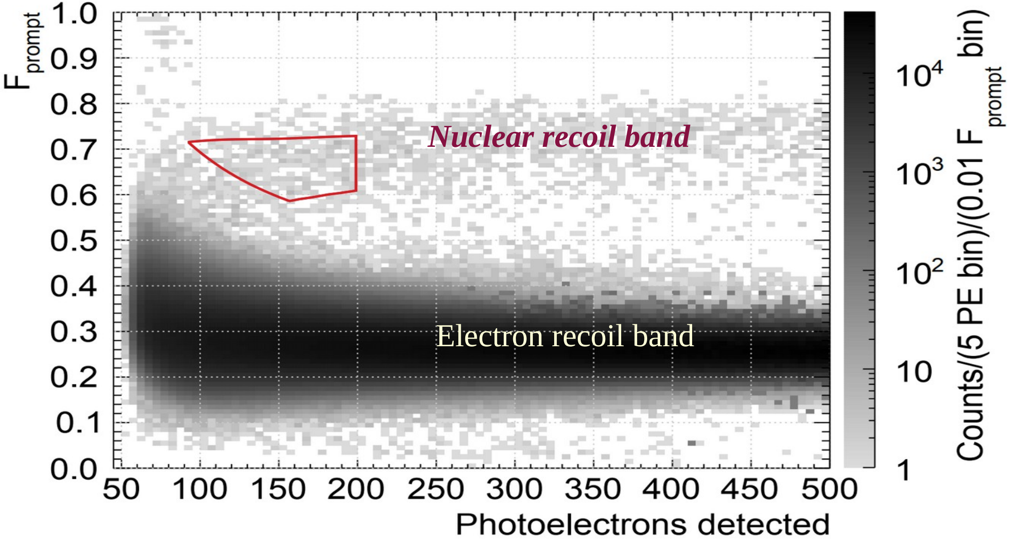
- Incoming dark matter particle interacts with liquid argon
- Formation of argon dimers (excimers)
- Emission of 128 nm photons due to excimer de-excitation
  - Prompt signal due to singlet state transitions
  - Late signal due to triplet state transitions
- Wavelength shifted by TPB to VUV region
- Detection of visible photons by photomultiplier tubes

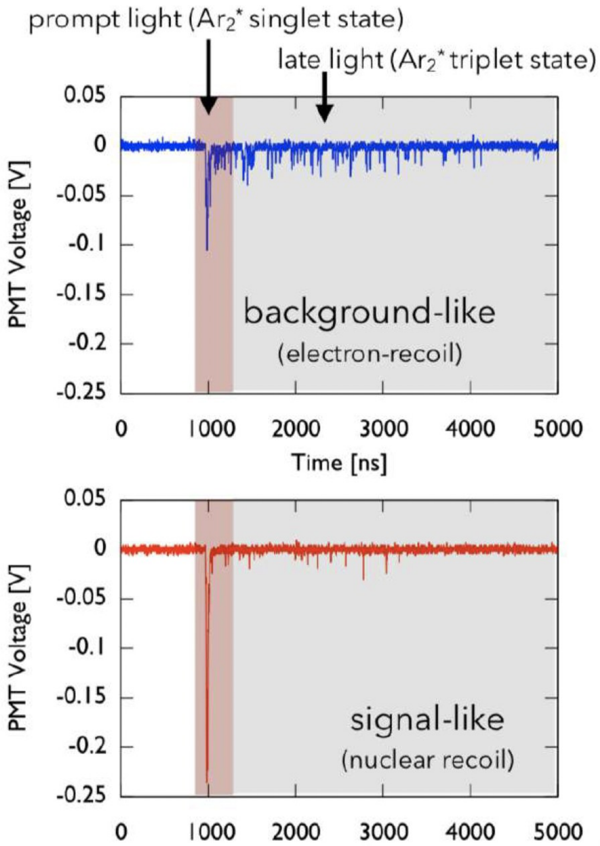


Pulse-shape discrimination (PSD)

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

$$F_{\mathrm{prompt}} = \frac{\sum_{t=-28\ \mathrm{ns}}^{t=150\ \mathrm{ns}} Q(t)}{\sum_{t=-28\ \mathrm{ns}}^{t=10\ \mu\mathrm{s}} Q(t)}$$





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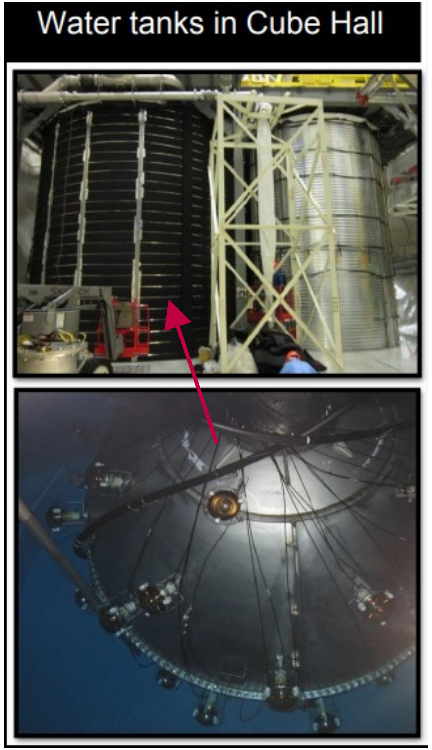
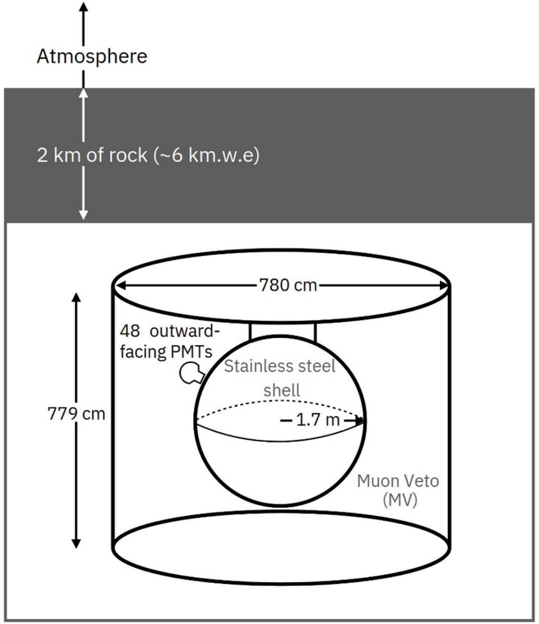
DEAP-3600 Muon Veto detector

- 48 veto PMTs
- Dimensions of the tank:
  - Diameter: 780 cm
  - Height: 779 cm
- Water shielding acts as a neutron moderator
- Detects muons through Cherenkov radiation in water





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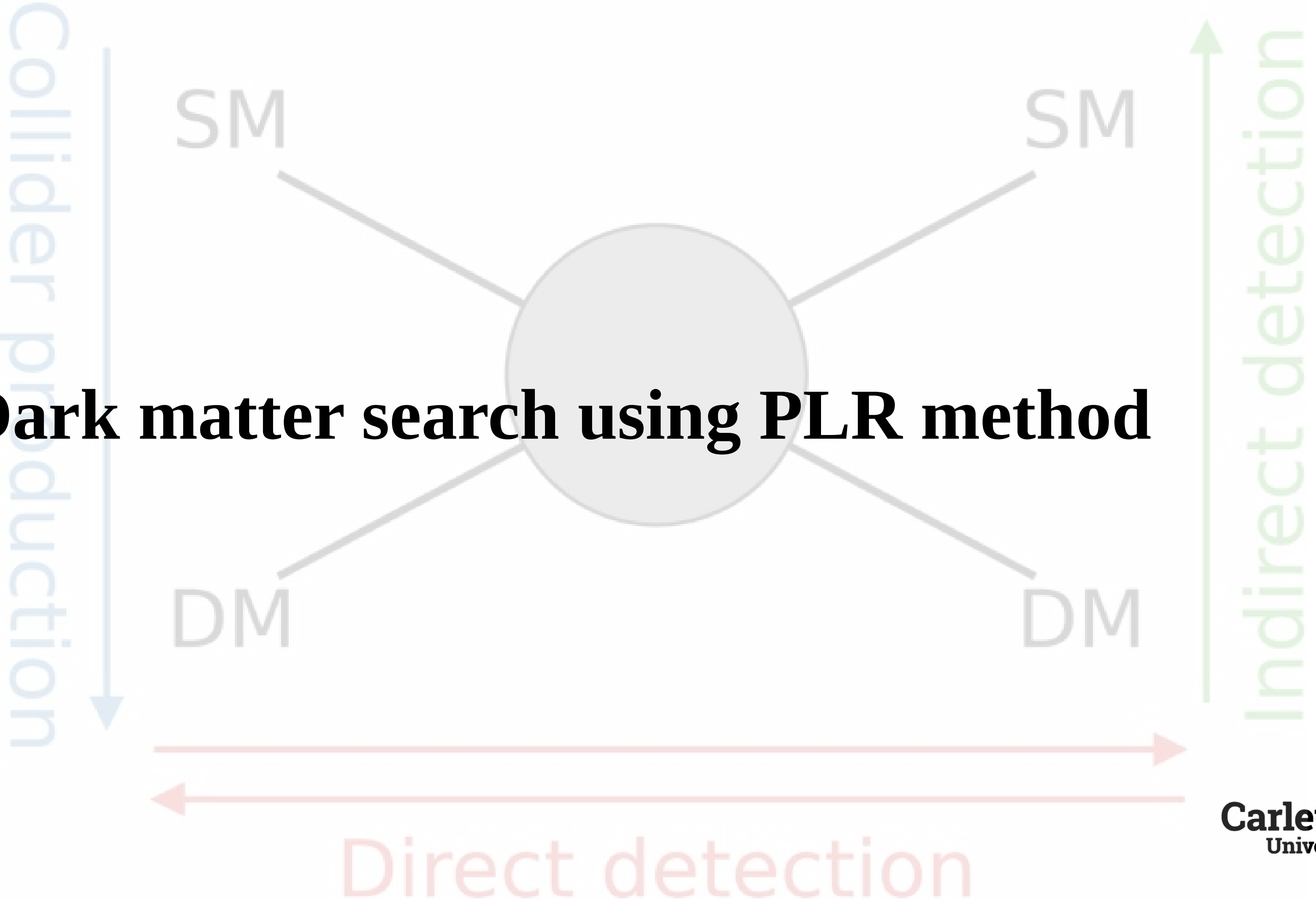
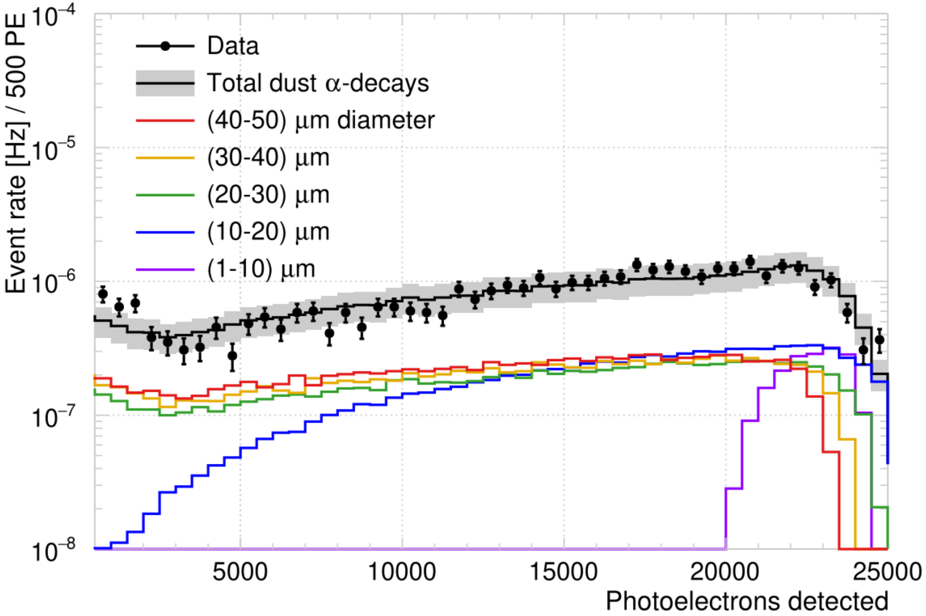
Dark matter search using PLR method



Background sources

- **^{210}Po dust-α**
  - Microscopic dust particles (5-25 μm radii) floating within liquid argon target leading to highly attenuated alpha-particle mimicking WIMP signal
- **^{210}Po surface-α**
  - Originating from the surface of inner sphere
- **^{210}Po neck-α**
  - Originating from the 'neck' region of the detector directly above liquid argon, shadowed by the components of the neck
- **Radiogenic neutrons**
  - Emanating from the glass of the PMTs
- **^{39}Ar β-decays**
  - Removed using the pulse-shape discrimination technique



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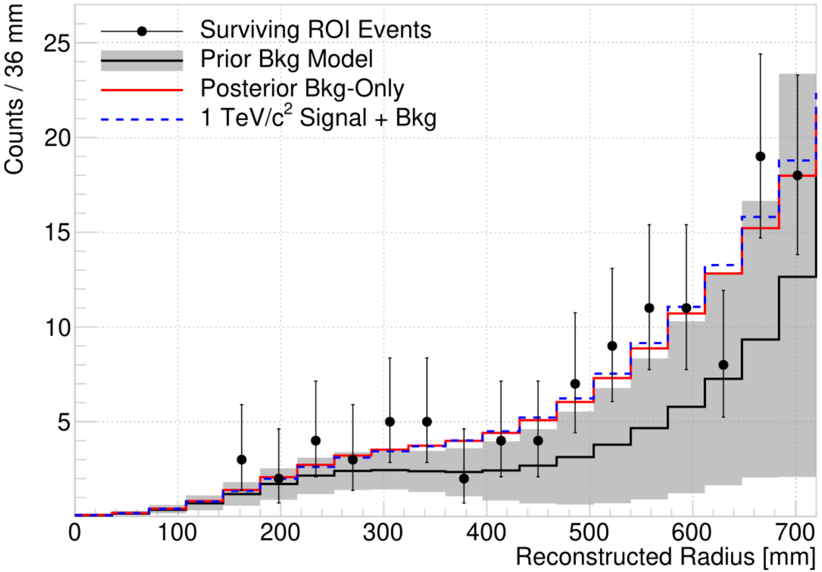
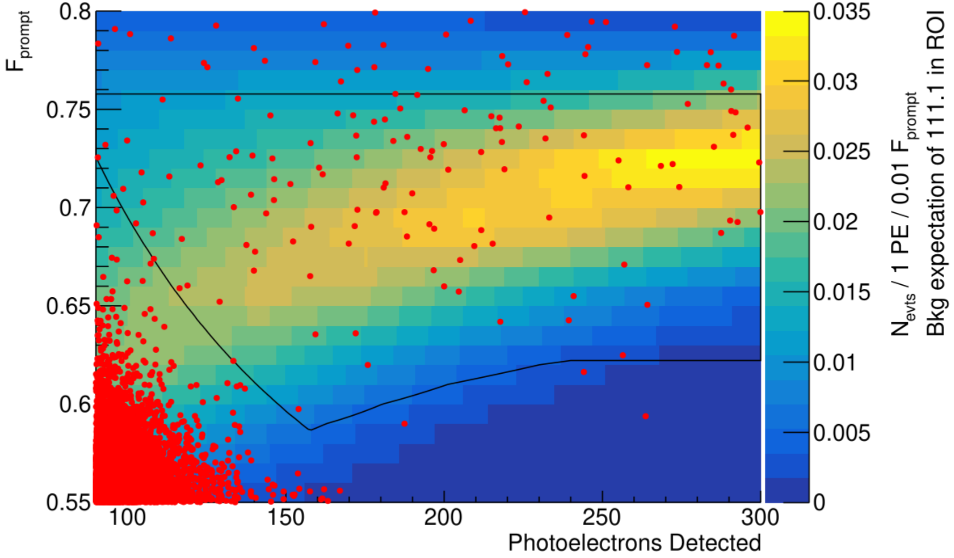
Observed data in DEAP-3600





Best fit to the background-only model

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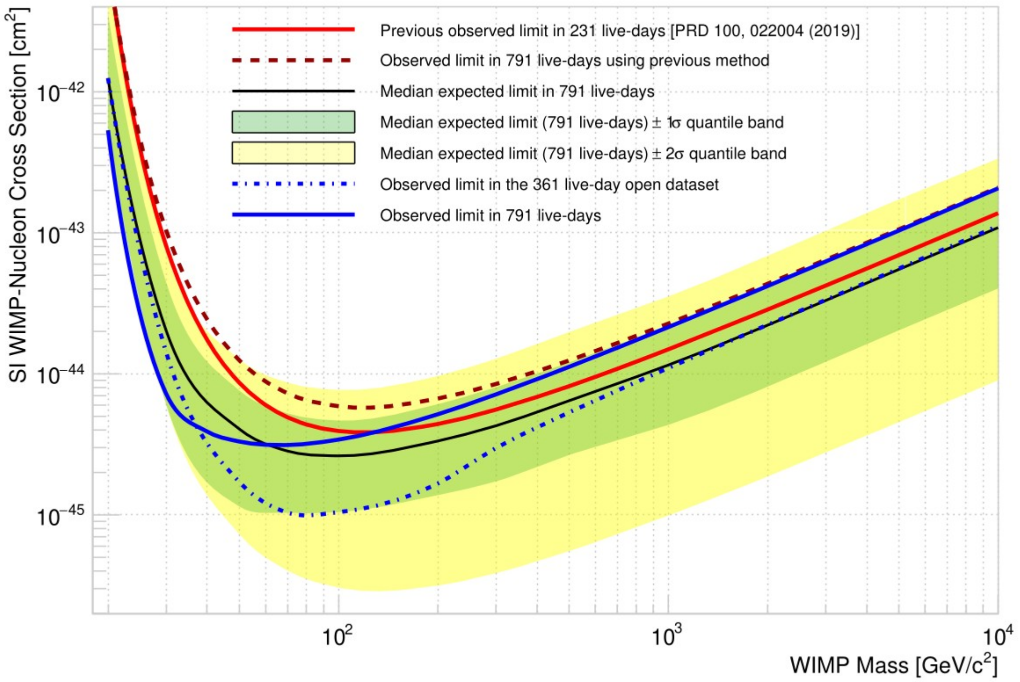
Updated exclusion limit

- Compared to the previous dark matter search from DEAP-3600, these results have:
  - A larger dataset (791 vs. 231 live-days).
  - Increased WIMP acceptance (5x better).
- An improved limit is set on the spin-independent WIMP nucleon cross-section for WIMP masses under 100 GeV/c^2.
- An excess of events observed in the full dataset is compatible with an increased contribution from dust alpha backgrounds that worsens the limit at higher WIMP masses.
- The limit set with a subset of data that was used to develop this analysis ("open dataset") is much stronger due to a smaller excess.
  - This limit is also shown but is not the true result.

DEAP dark matter search paper



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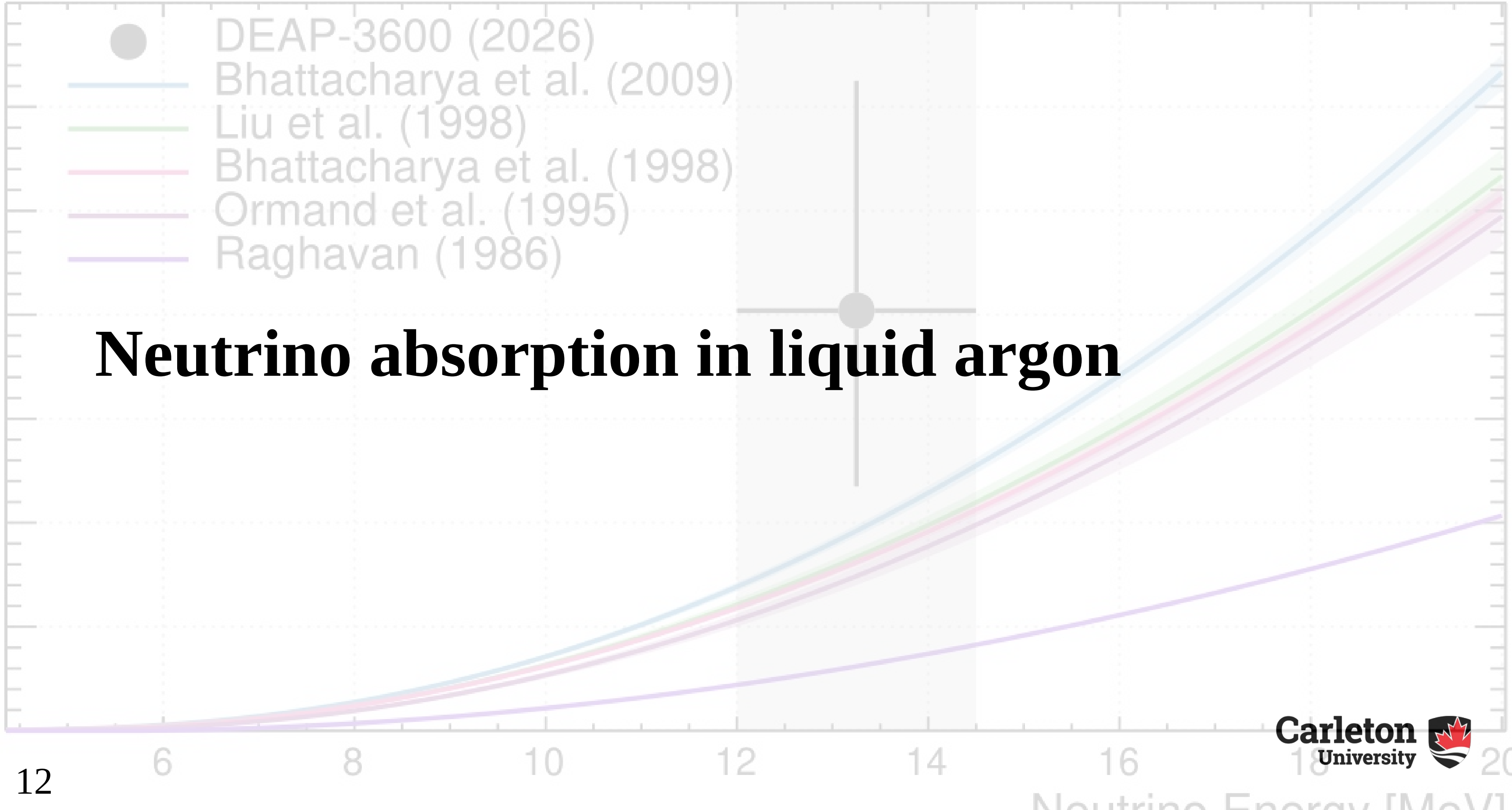
Neutrino absorption in liquid argon



Neutrino charge-current interaction in argon

- Proposed by R. S. Raghavan in 1986

$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$

- First observation of charged-current neutrino interactions in a dark matter detector

- Fundamental process for future multi-tonnes liquid argon dark matter and neutrino detectors!

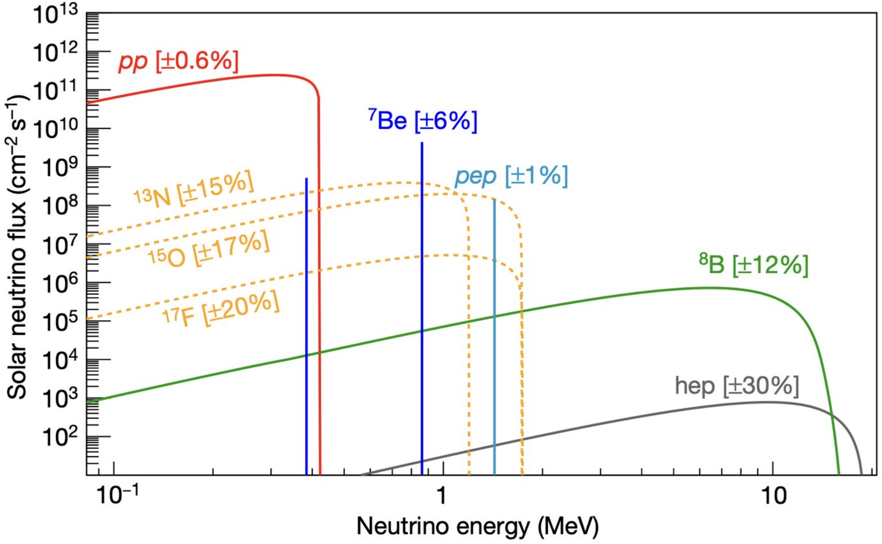
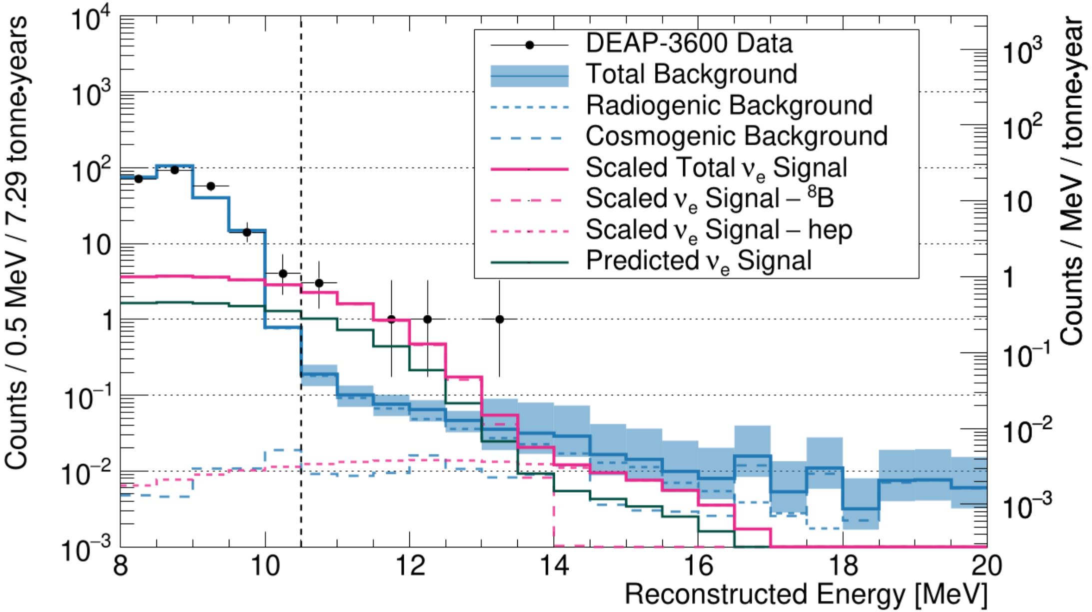


image reference - Borexino

DEAP-3600 measurement

- 6 events observed in the ROI
- 2.3±0.4 events predicted from ^{8}B solar neutrinos
- Total backgrounds: $0.48^{+0.16}_{-0.15}$
- Data-driven estimate of radiogenic background using AmBe neutron source data
- Results significance
  - Background-only: 4σ
  - Background+signal: 1.5σ



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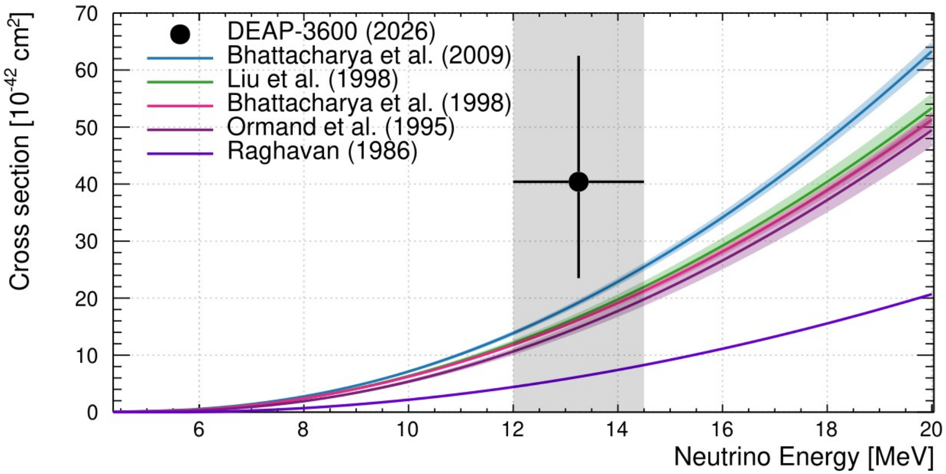
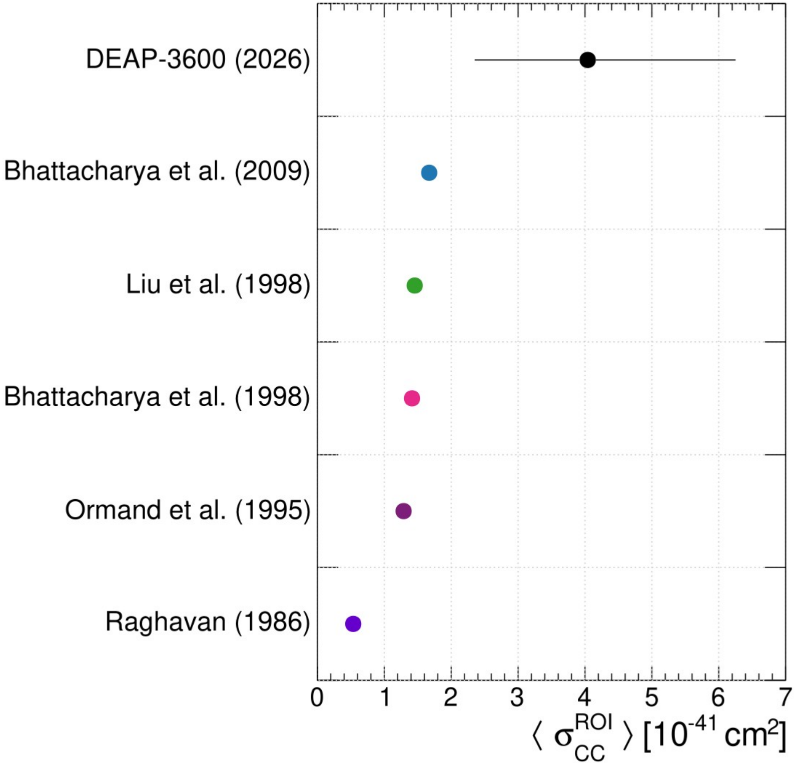
DEAP-3600 cross section measurement

DEAP neutrino absorption paper

$$\langle \sigma_{CC}^{ROI} \rangle = 4.0^{+2.2}_{-1.7} \times 10^{-41}\, cm^2$$

$2.4^{+1.3}_{-1.0}$ higher than Bhattacharya, Goodman and García (2009)





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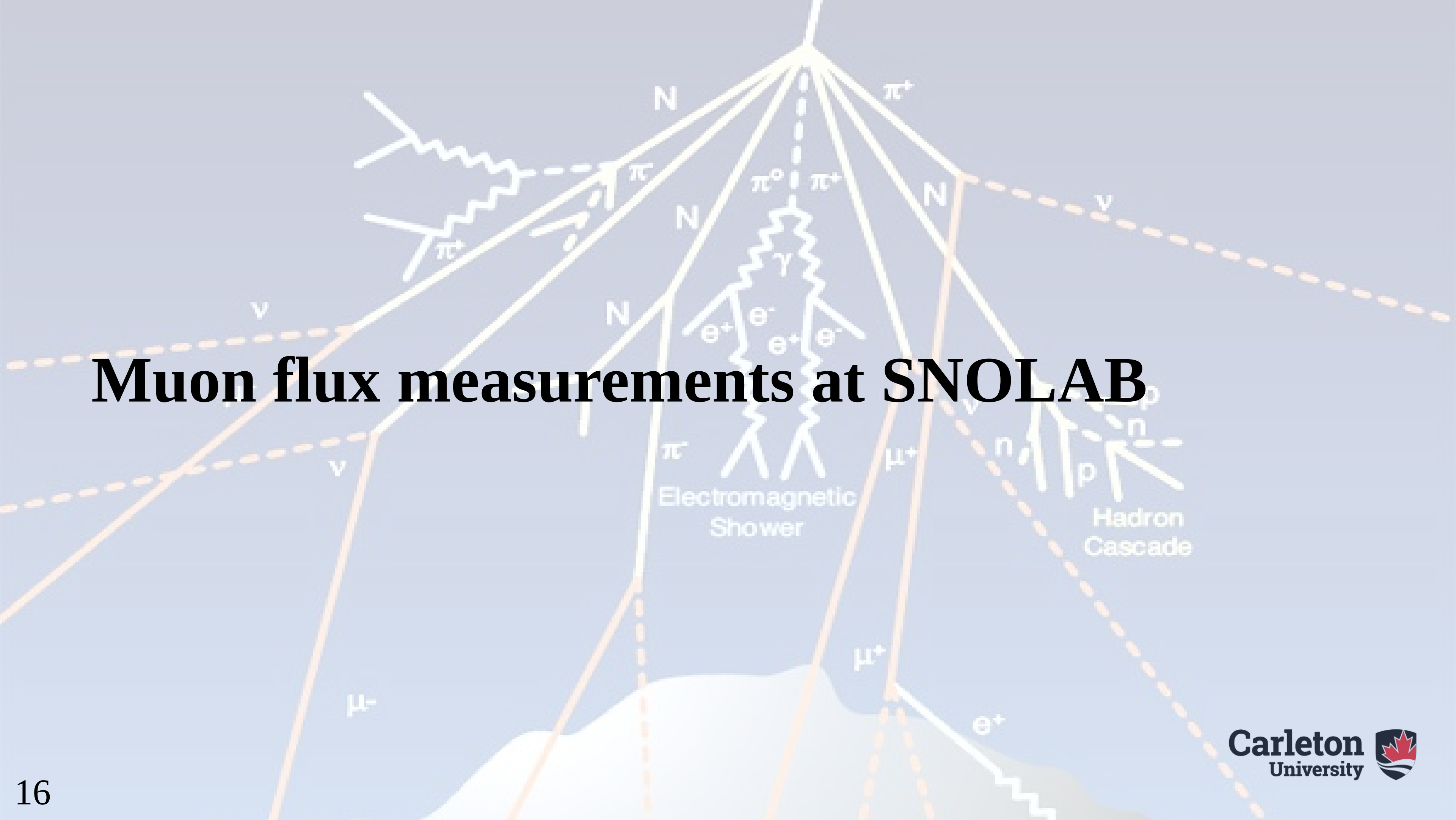
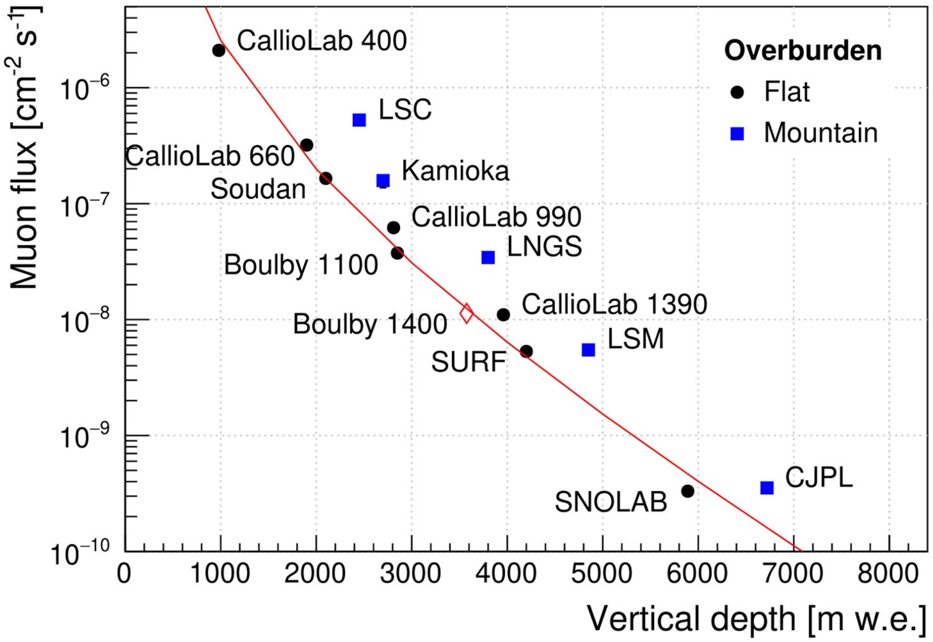
Muon flux measurements at SNOLAB



Low-background experiments

- Rare-event searches require low-background environment
  - Build detectors underground
- Many deep underground laboratories around the world
- Cosmic ray muons and muon-induced backgrounds interfere with rare-event searches
- Measurement of the muon flux is important for rare-event searches



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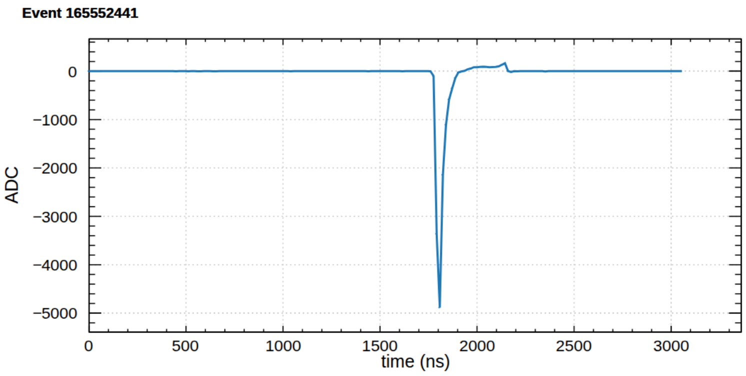
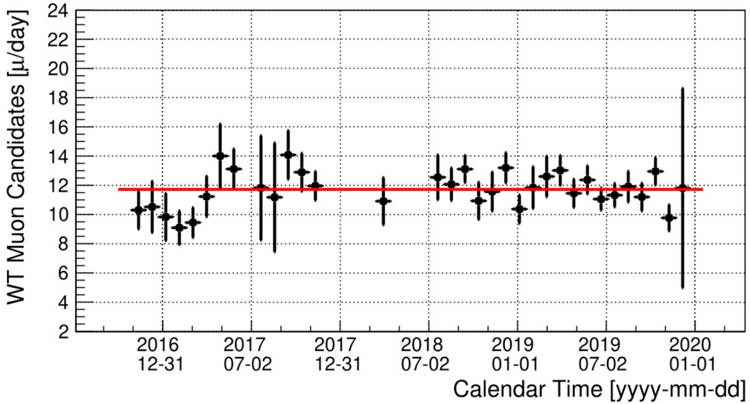
Standalone water tank muons

$$\Phi_\mu^{WT} = \frac{N_\mu}{A_{eff}^{WT} \cdot t_{live} \cdot \varepsilon_{WT}}$$

- $N_\mu = (3309 \pm 58_{stat})$
- $t_{live} = 2.44 * 10^7$ s
- $A_{eff}^{WT} = (65.86 \pm 0.13_{stat} \pm 0.31_{sys})$ m^2
- $\varepsilon_{WT} = (46.6 \pm 1.1_{stat} \pm 8.8_{sys})$ %





$$\boxed{\Phi_\mu^{WT} = \left(4.42 \pm 0.13_{stat} \pm 0.84_{sys}\right) \cdot 10^{-10} \frac{\mu}{cm^2 s}}$$

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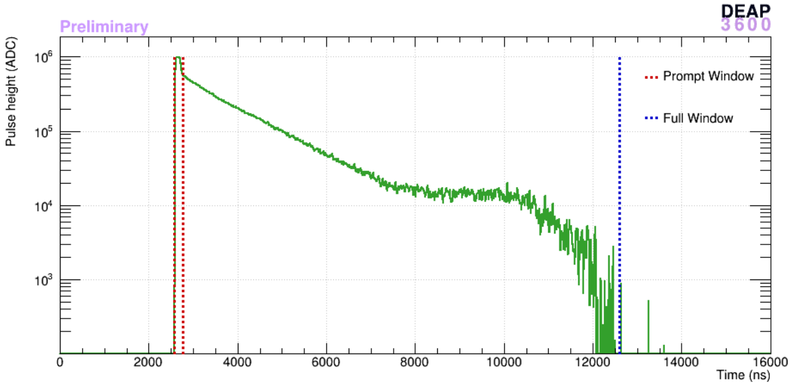
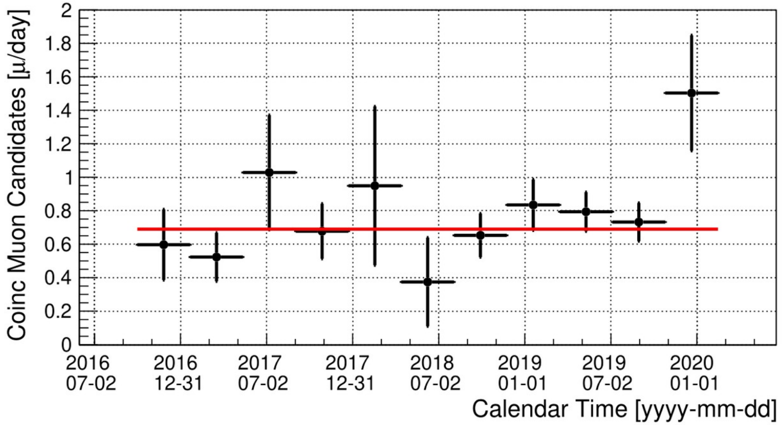
Coincidence muons

$$\Phi_{\mu}^{coinc} = \frac{N_{\mu}}{A_{eff}^{coinc} \cdot t_{live} \cdot \varepsilon_{coinc}}$$

- $N_{\mu} = (227 \pm 15_{stat})$
- $t_{live} = 2.85 * 10^{7}$ s
- $A_{eff}^{coinc} = (2.246 \pm 0.005_{sys})$ m^2
- $\varepsilon_{coinc} = (95.7 \pm 2.3_{sys} \pm 0.6_{stat})$ %





$$\boxed{\Phi_{\mu}^{coinc} = \left(3.71 \pm 0.25_{stat} \pm 0.09_{sys}\right) \cdot 10^{-10} \frac{\mu}{cm^2 s}}$$

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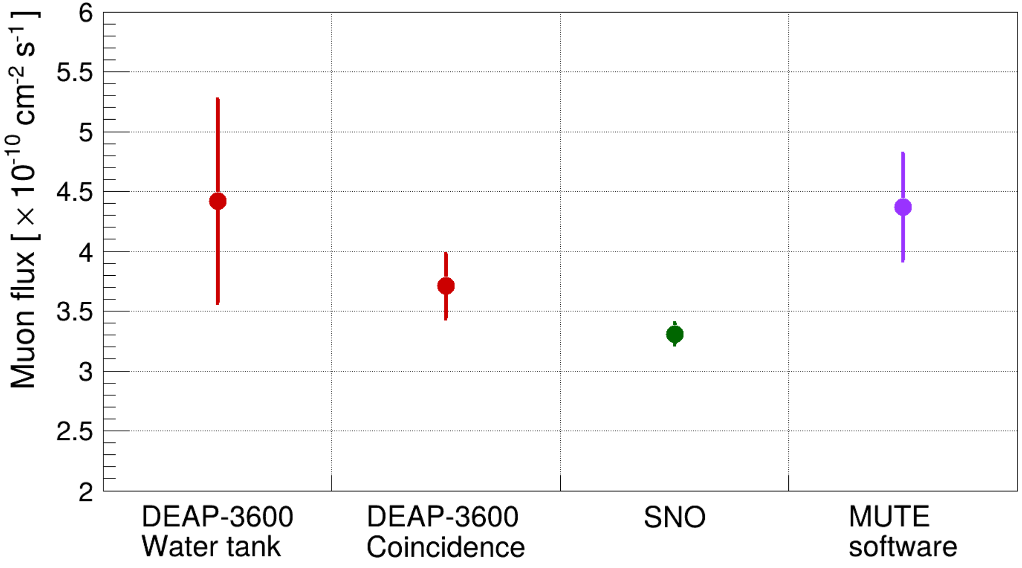
Final muon flux results

- Comparing to the SNO results
  - Watertank muon flux is 1.3σ away
  - Coincidence muon flux is 1.4σ away
- Standalone water tank muon flux is consistent with MUTE calculation
- DEAP-3600 results are mutually consistent

DEAP muon flux paper



Hardware upgrades

Hardware upgrades and fourth-fill

- Pyrene coating on the neck region
  - Removing neck α-events
- Insertion of dust removal pipe
  - Reducing dust α-events
- Fourth-fill of the detector has commenced
- Planning data-collection for 1 year after the fill is complete
- Exciting times for the DEAP-3600!

Conclusion

- Great year for the DEAP-3600 experiment
- Multiple on-going analyses with the second fill data:
  - Search for gravitational wave coincident neutrinos in DEAP-3600
  - Boosted inelastic dark matter search
  - Neutrinoless double electron capture in ^{36}Ar
  - Extended Multiply Interacting Massive Particle dark matter search
  - Neutrino absorption in liquid argon at low-energies
- Stay tuned for the exciting results!!

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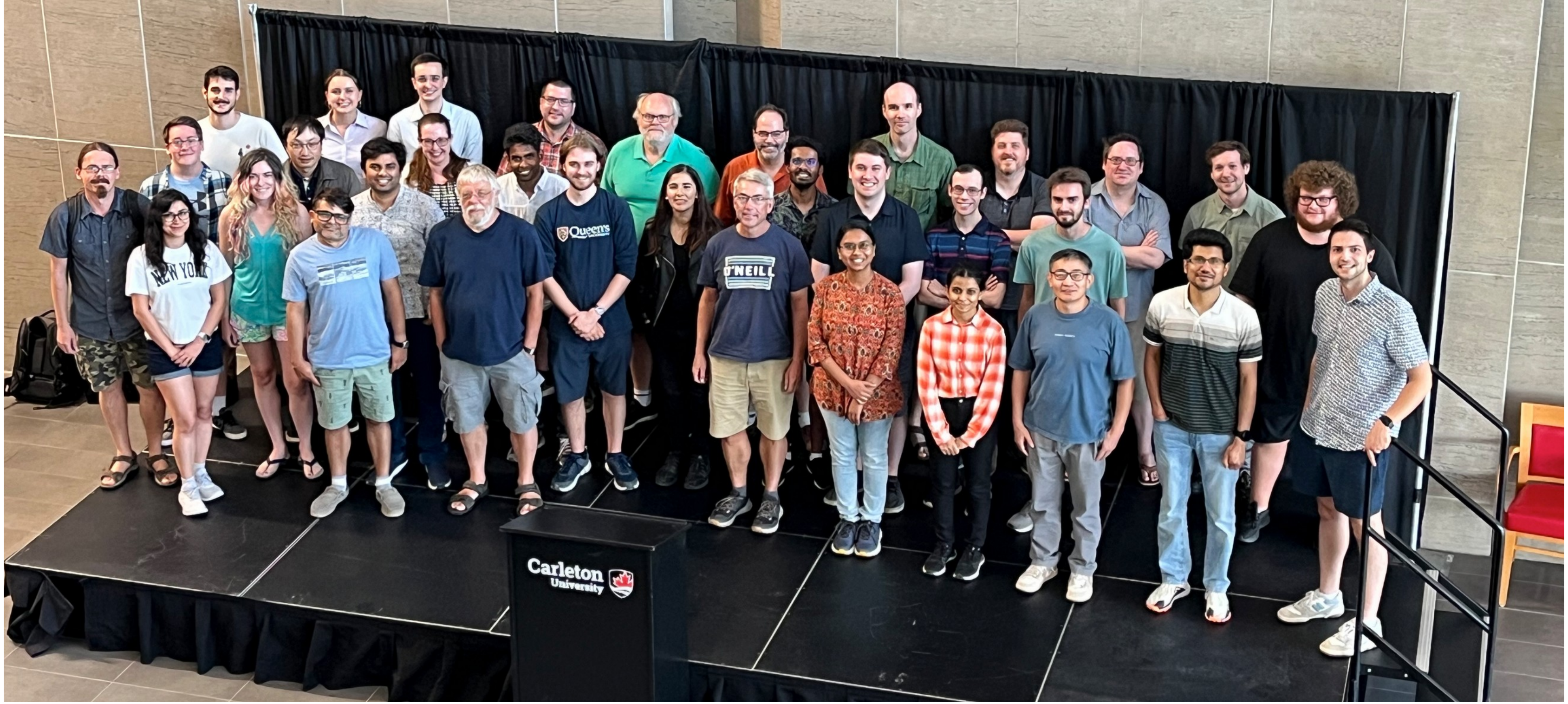

SNOLAB
DEAP 3600

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Particle Physics
Rutherford Appleton Laboratory

The End

Thank you!

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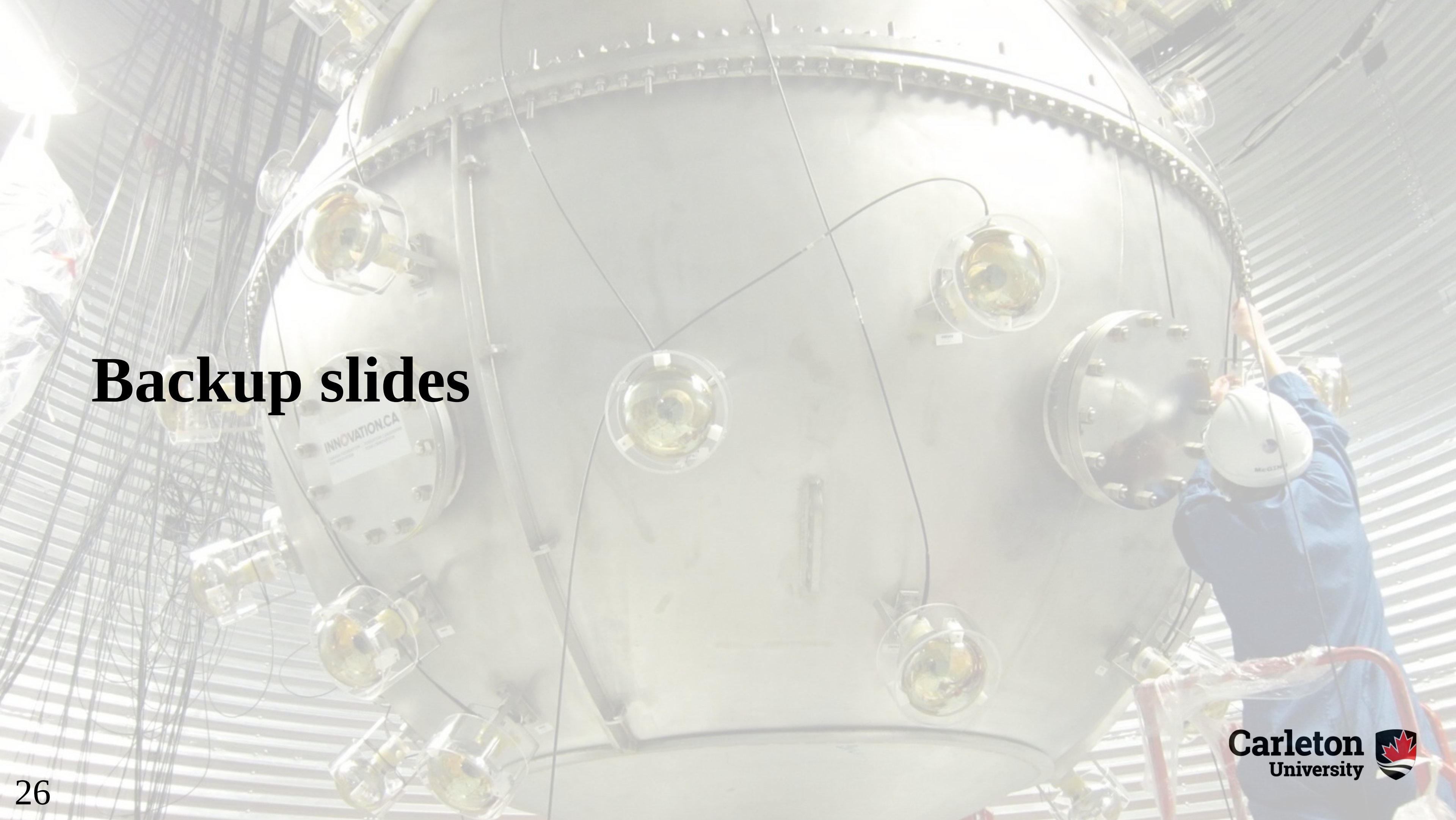

Backup slides

Profile likelihood ratio method

- Application of Neyman-Pearson's lemma
  - Optimal cross-section exclusion limit our dataset can produce
- PLR refers to the use of a ratio of likelihoods,
  - parameters **not** of interest "profiled" out.
- Creating models for each background source
  - Probability density functions (PDFs).

$$\mathcal{L}(\sigma_\chi|\{\theta\}) = \mathcal{L}_{\text{Model}}(\sigma_\chi|\{\theta\}) \times \mathcal{L}_{\text{Constraint}}(\{\theta\}), \quad (4)$$

Fixed WIMP cross-section, maximum likelihood estimators for all nuisance parameters.

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

Floating WIMP cross-section, maximum likelihood estimators for all nuisance parameters.

Backgrounds – PLR

TABLE II. Summary table of the expected number of ROI events from each source in the prior background model, the posterior model in the background-only hypothesis, and the posterior model in the signal+background hypothesis with $M_\chi = 1$ TeV$/c^2$, $\sigma_\chi = 1.3 \times 10^{-44}$ cm^2. Shown are the systematic uncertainties. In data, 115 events are observed in the ROI.

Source	**Prior**	**Best-fit (bkg-only)**	**Best-fit (sig+bkg)**
Radiogenic n	$1.2^{+1.0}_{-1.0}$	$1.2^{+0.9}_{-0.9}$	$1.2^{+0.9}_{-0.9}$
Surface α	$7.4^{+15.2}_{-15.4}$	$0.0^{+3.1}_{-3.1}$	$0.0^{+1.8}_{-1.8}$
Shadowed α	$15.2^{+12.3}_{-10.3}$	$18.3^{+8.9}_{-7.4}$	$16.5^{+8.2}_{-6.9}$
Dust α	$44.2^{+39.9}_{-40.4}$	$91.6^{+10.6}_{-11.9}$	$64.1^{+15.9}_{-16.2}$
Total Bkg	$68.0^{+49.9}_{-45.2}$	$111.1^{+16.3}_{-15.2}$	$81.7^{+20.3}_{-18.0}$
$M_\chi = 1$ TeV$/c^2$	–	–	$32.0^{+23.9}_{-22.4}$

Backgrounds in the solar neutrino absorption measurement

Background Source	**Events in ROI in 815 live-days**
Radiogenic (n, γ)	$0.43 \pm 0.05\,(\mathrm{stat}) \pm 0.14\ (\mathrm{sys})$
Cosmogenic	$0.048 \pm 0.009\ (\mathrm{stat})\ ^{+0.070}_{-0.025}\ (\mathrm{sys})$
Correlated $\gamma - \gamma$ pile-up	$< 10^{-3}$
Uncorrelated $\gamma - \gamma$ pile-up	$< 10^{-3}$
Correlated $\alpha - \alpha$ pile-up	$< 10^{-3}$
Uncorrelated $\alpha - \alpha$ pile-up	$< 10^{-3}$
Total Background	$0.48\ ^{+0.16}_{-0.15}$

Muon event in LAr

- Muons in LAr produce a lot of scintillation light
- Clips V1720 digitizers
- Saturates the inner detector PMTs
  - Very high energy events have higher Fprompt and lower PE