# Position Reconstruction Using Photon Timing for the DEAP-3600 Liquid Argon Dark Matter Experiment

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DEAP Collaboration: 75 researchers in Canada, UK, Germany, Mexico
(+ future collaborators from Italy, USA)

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Canadian Nuclear Laboratories
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Carleton UNIVERSITY

LaurentianUniversity
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Instituto de Física

UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO

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ROYAL HOLLOWAY UNIVERSITY OF LONDON

Particle Physics
Rutherford Appleton Laboratory

SNOLAB

US
University of Sussex

Technical University of Munich

TUM

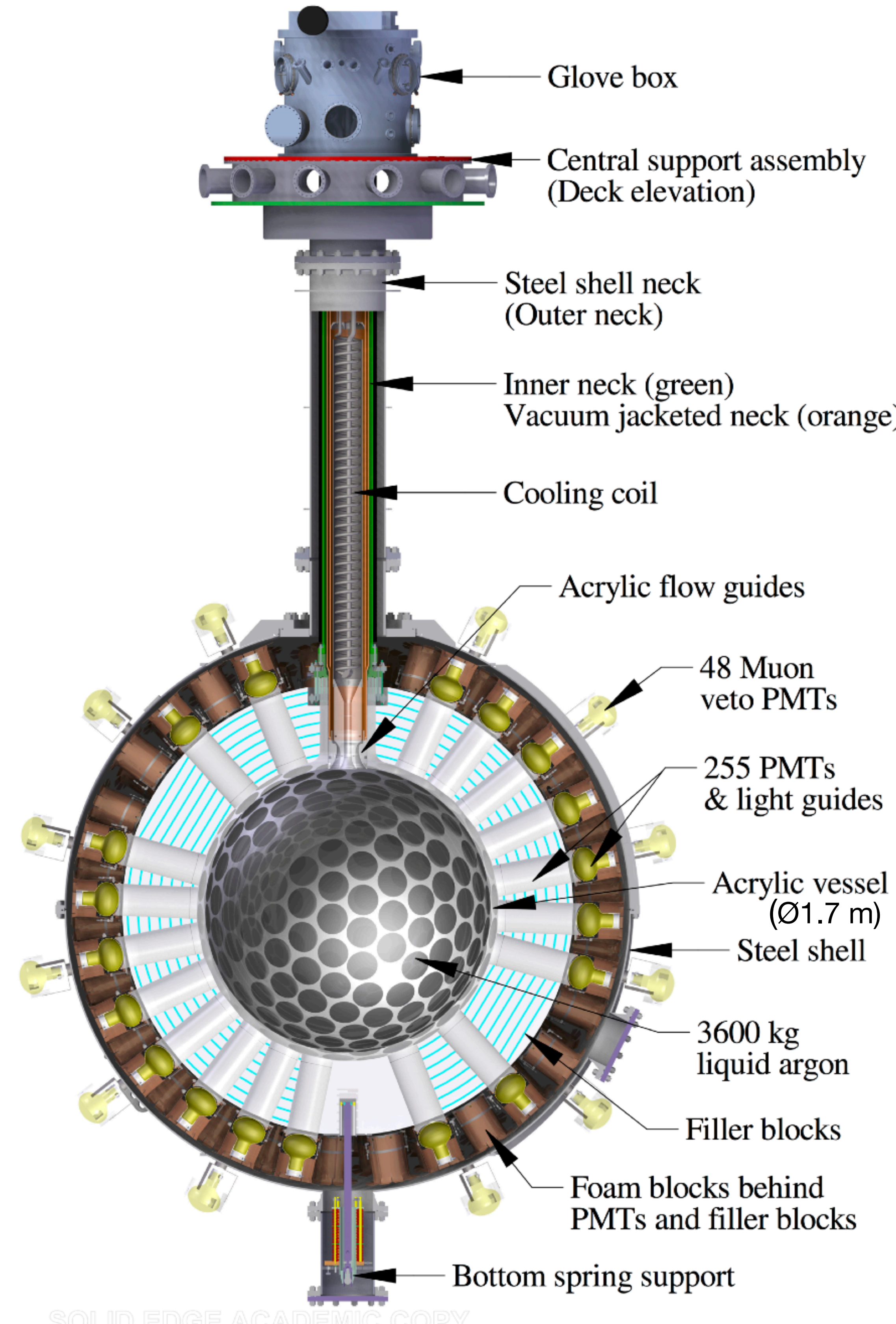
TRIUMF

# DEAP-3600 Detector

- DEAP = **D**ark Matter **E**xperiment using **A**rgon **P**ulse-shape Discrimination

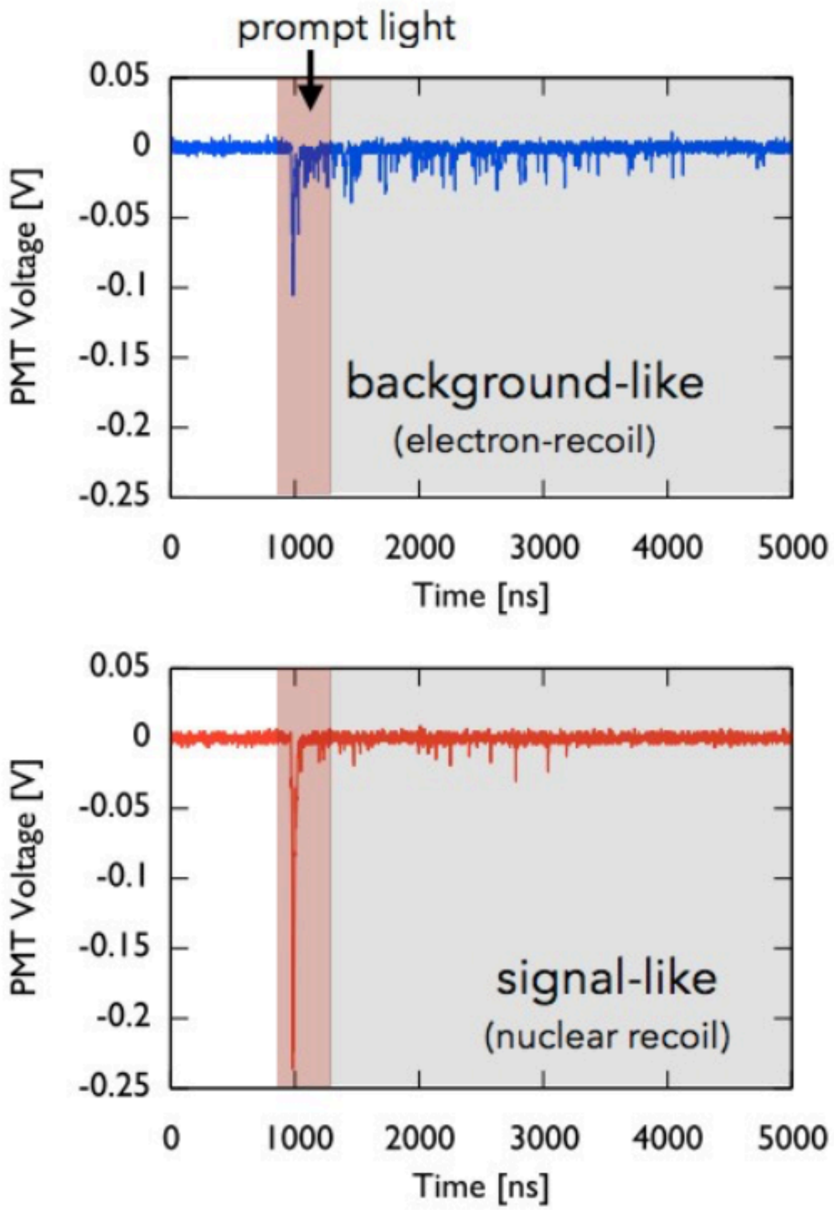
- 3600 = 3600 kg of liquid argon (LAr) as designed target mass

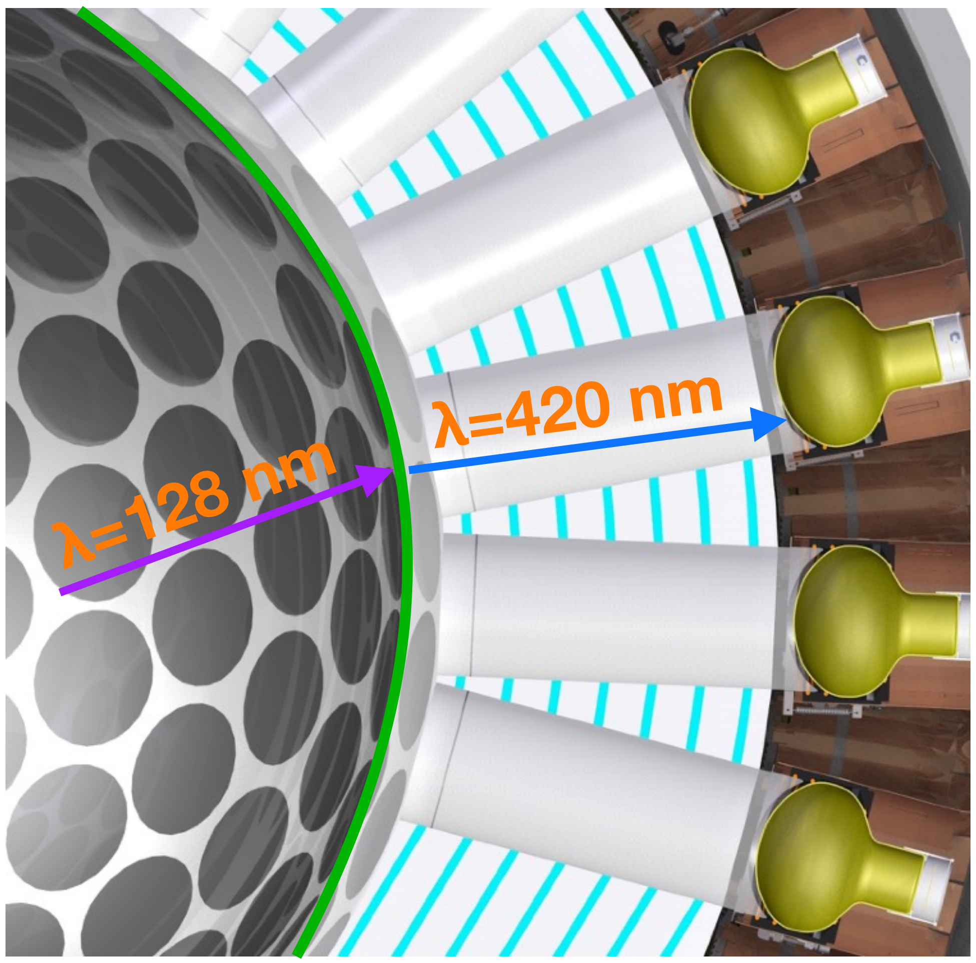
- Search for scintillation signal due to elastic scattering of WIMP dark matter—argon nuclear recoils of ~ tens of keV.



# LAr Scintillation

- Excited dimers formed after exposure to ionizing radiation, in singlet (6 ns) and triplet (~1.3 μs) states
  - Nuclear recoils (by WIMP, neutron, and α): higher ratio of singlet states—more prompt light
  - Electron recoils (β/γ): lower ratio of singlet states—less prompt light

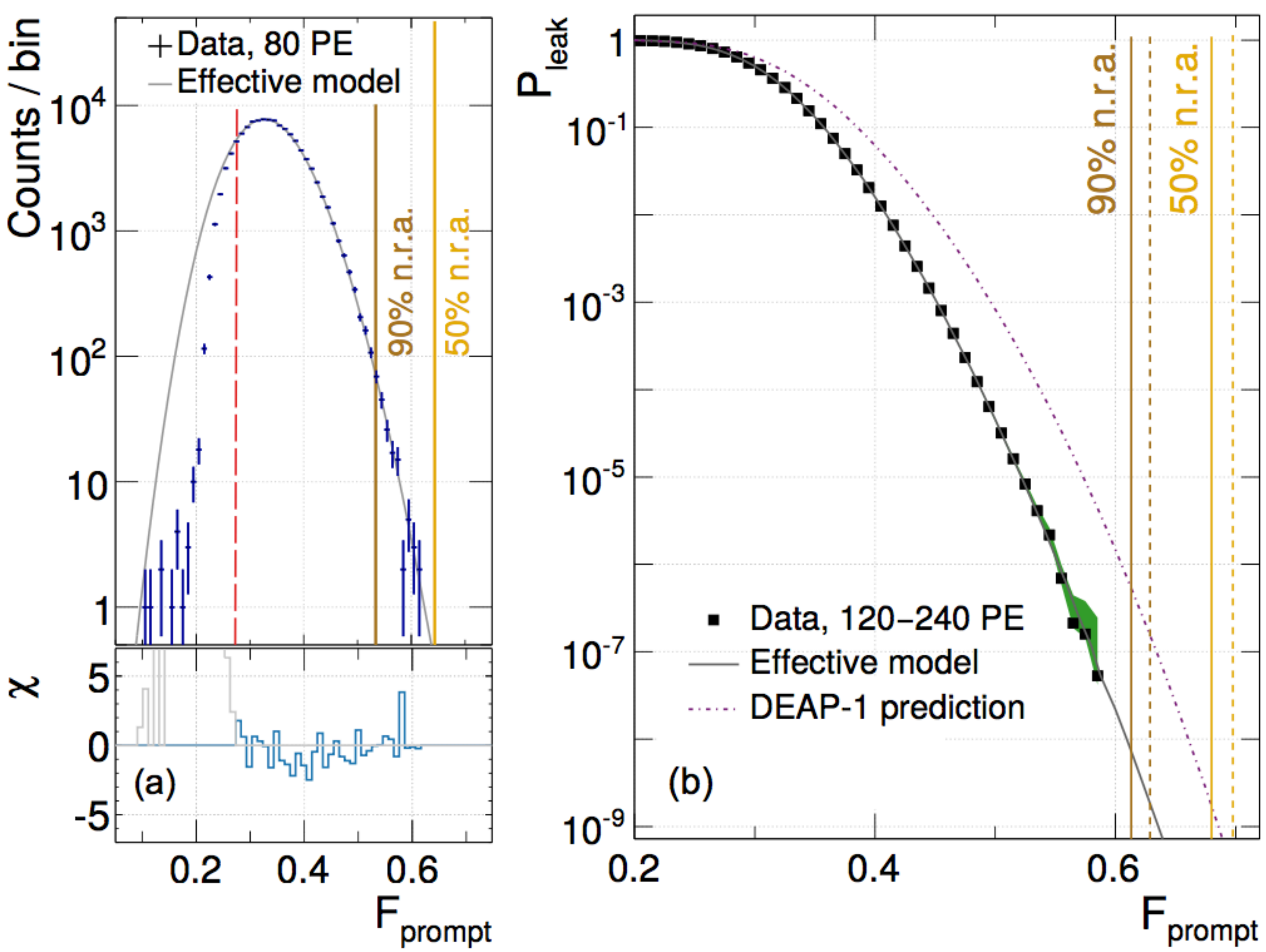



- Emits UV light at wavelength of 128 nm. Passes through pure argon without being absorbed.
- TPB wavelength shifter converts UV light to visible light at wavelength of 420 nm. Passes through acrylic and collected by PMTs.
- UV-absorbing acrylic light guide (LG) helps minimize Cerenkov radiation.

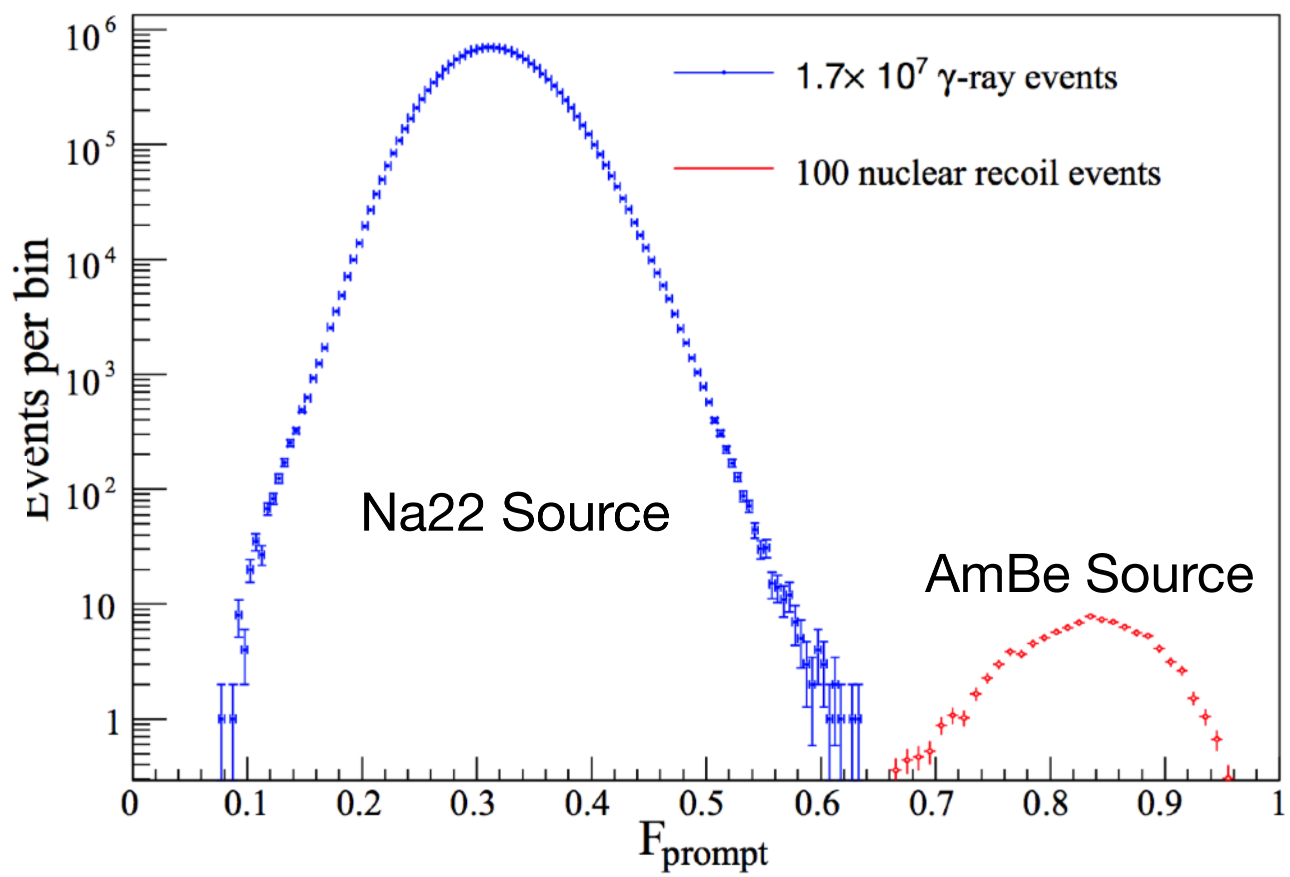
# Pulse-Shape Discrimination

$$\mathrm{F}_{\mathrm{prompt}} = \frac{\mathrm{Q}(-28\,\mathrm{ns}, 150\,\mathrm{ns})}{\mathrm{Q}(-28\,\mathrm{ns}, 10\,\mu\mathrm{s})}$$




arXiv:1707.08042

DEAP-1 Prototype

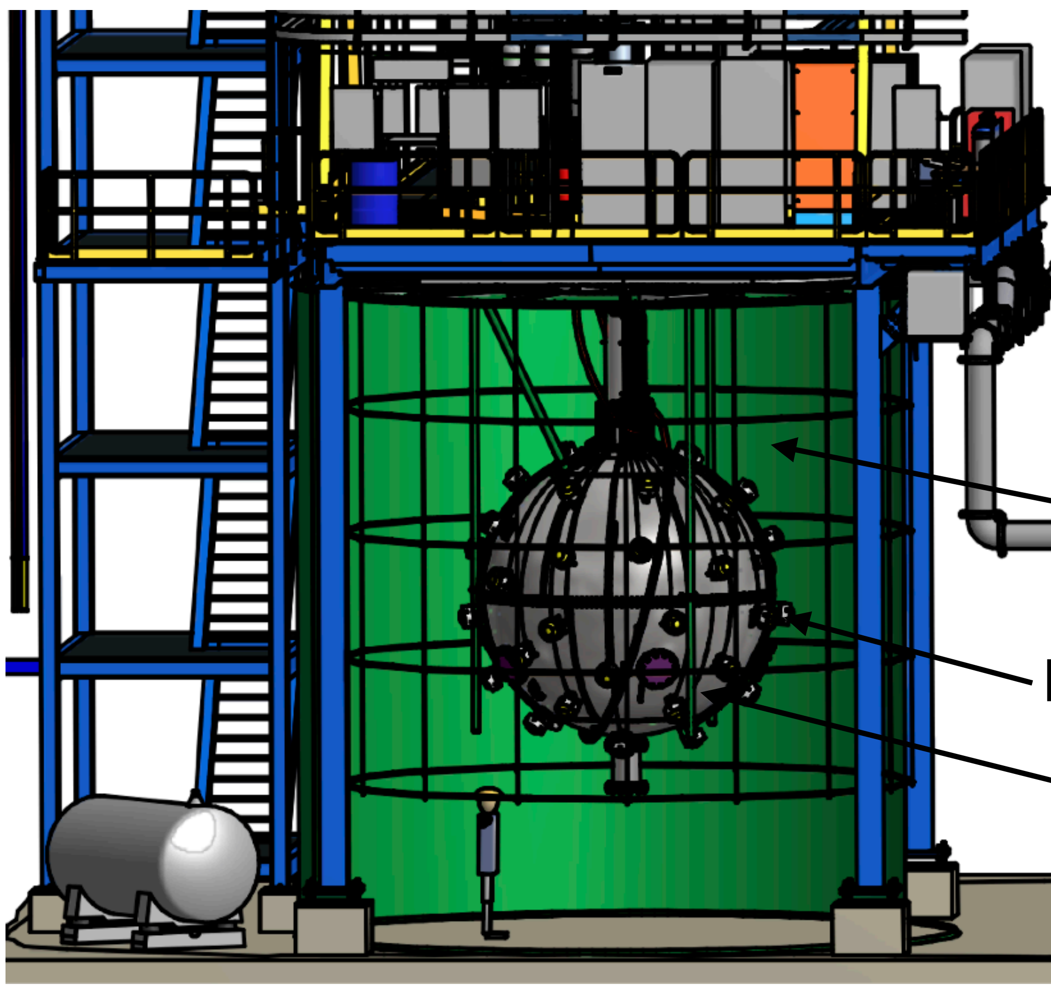


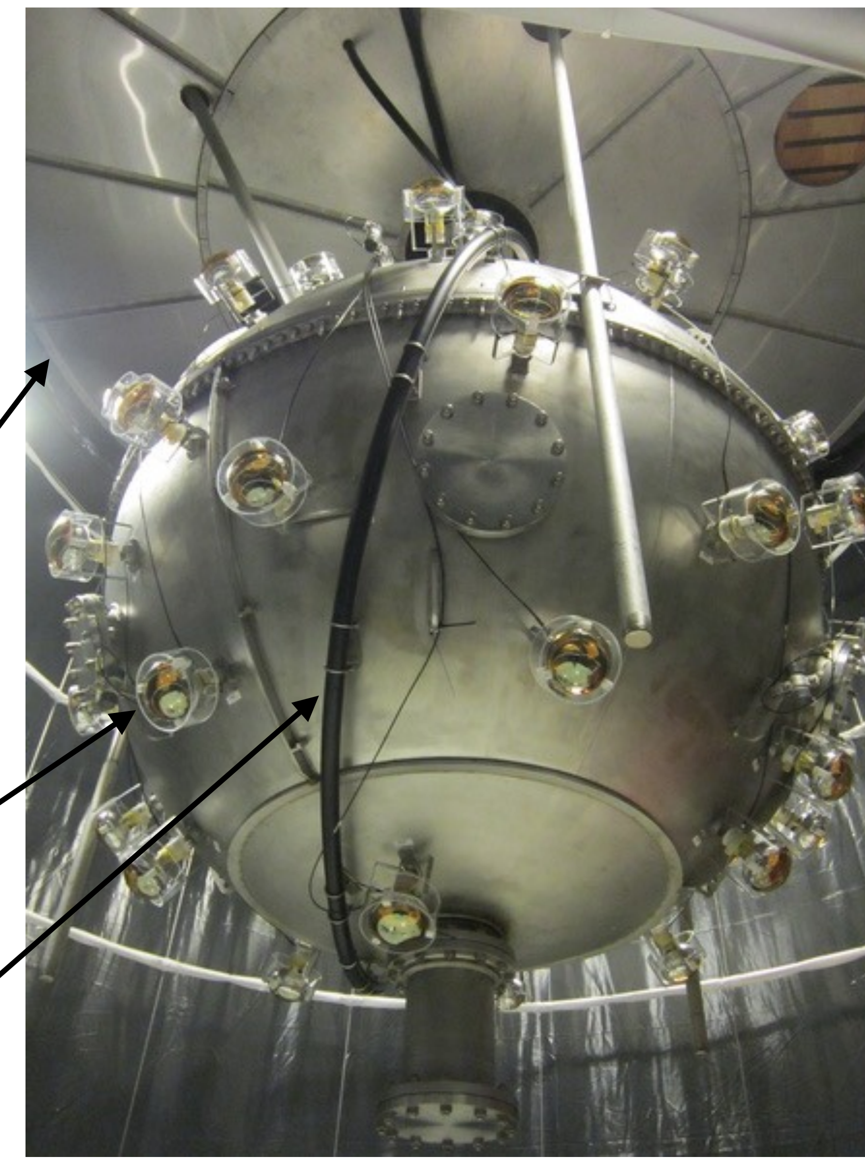

Astropart.Phys. 85 (2016) 1-23 arXiv:0904.2930

- Ar39 in natural argon: β decay 1 Bq/kg
- Efficiently rejected by Pulse-shape Discrimination (PSD)

# Located in SNOLAB underground laboratory

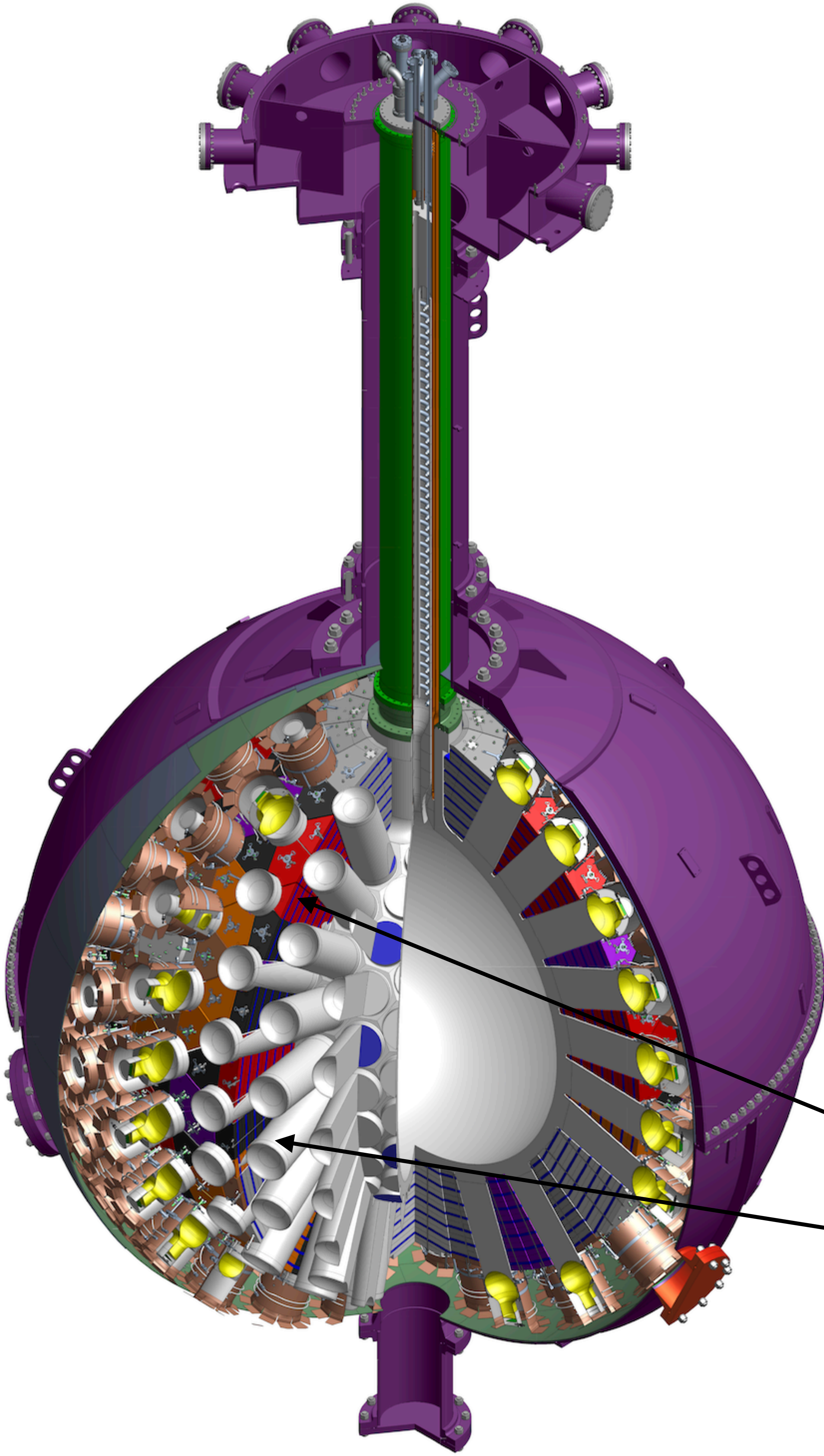
- 2 km underground (6 km.w.e)
- Cosmic-ray muon flux $(3.77 +/- 0.41) \times 10^{-10}$ cm$^{-2}$sec$^{-1}$ (~1/70 of Gran Sasso)

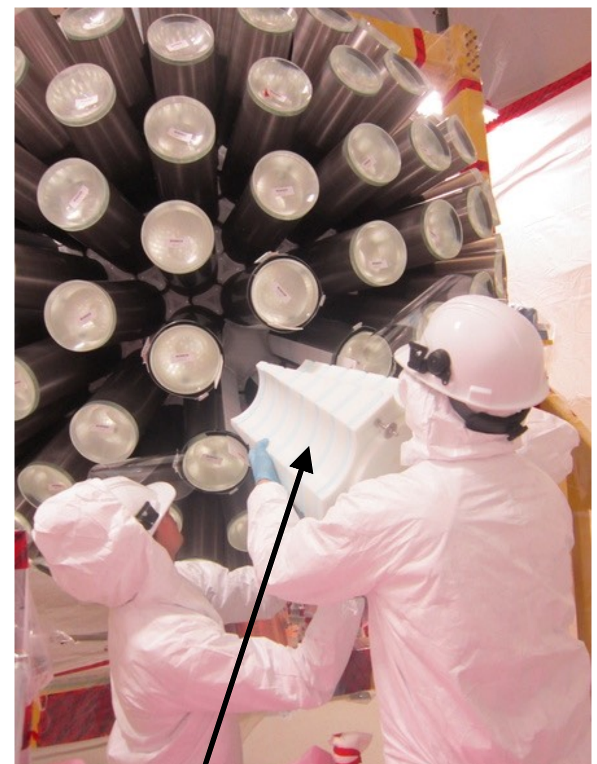


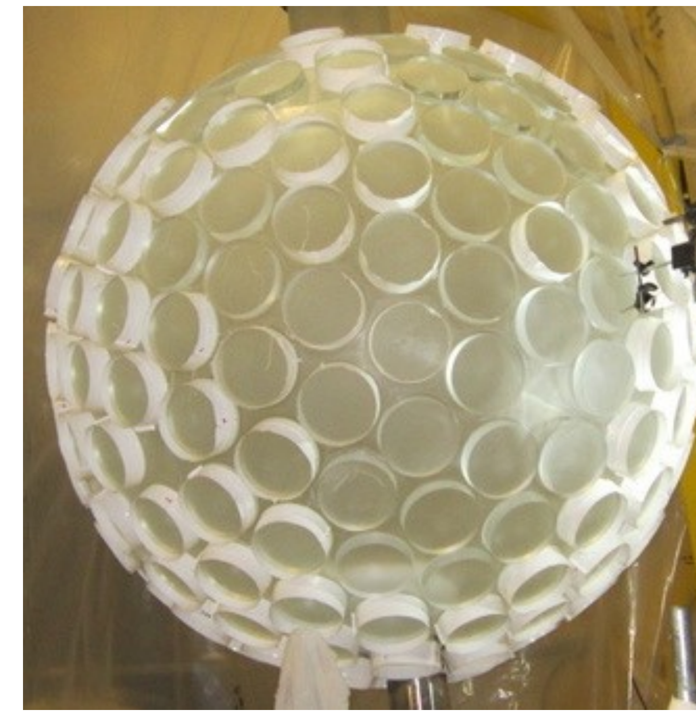


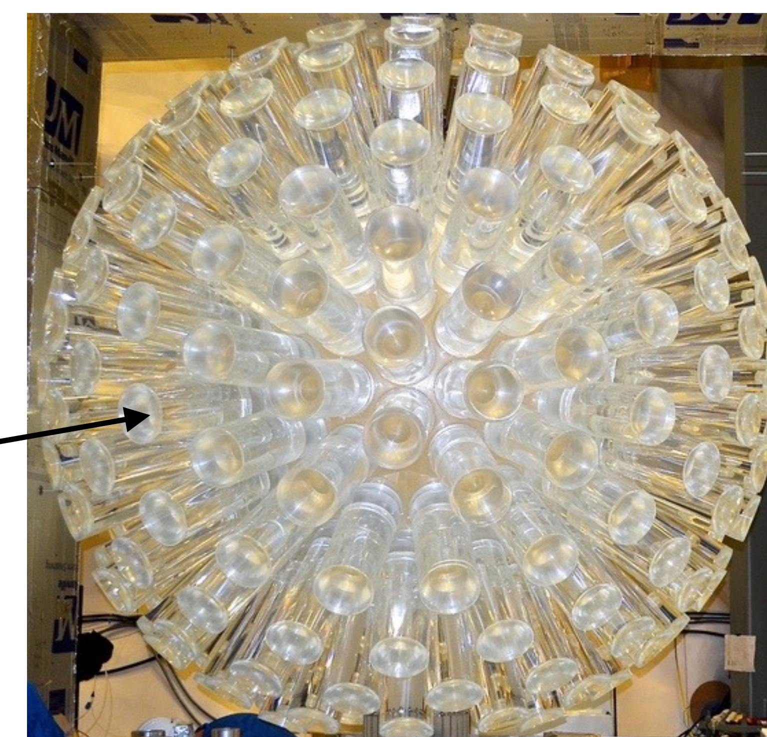
- Acrylic vessel inside was resurfaced after shipped to SNOLAB, reducing α activity from radon daughters to ~10 α/m²/day

- 50 cm of acrylic light guides and plastic filler blocks provide thermal isolation and neutron shielding





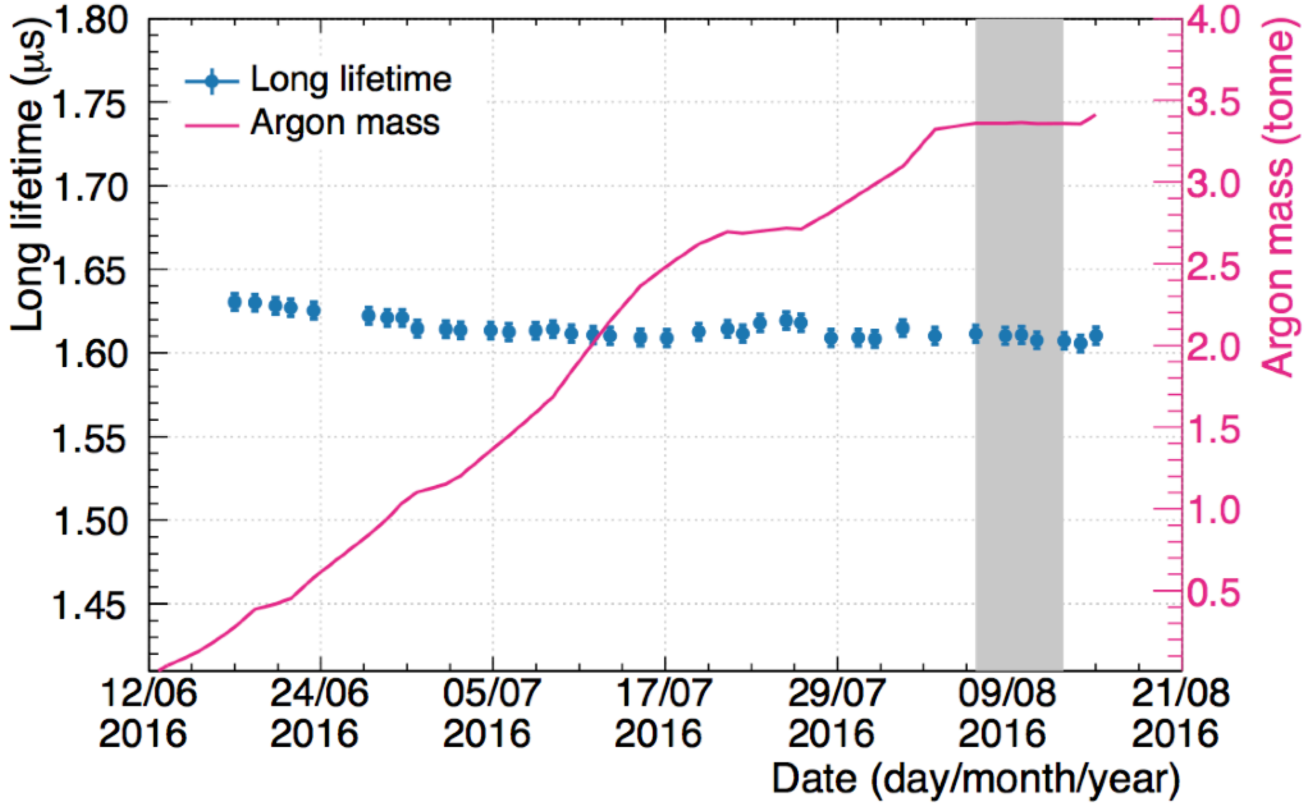




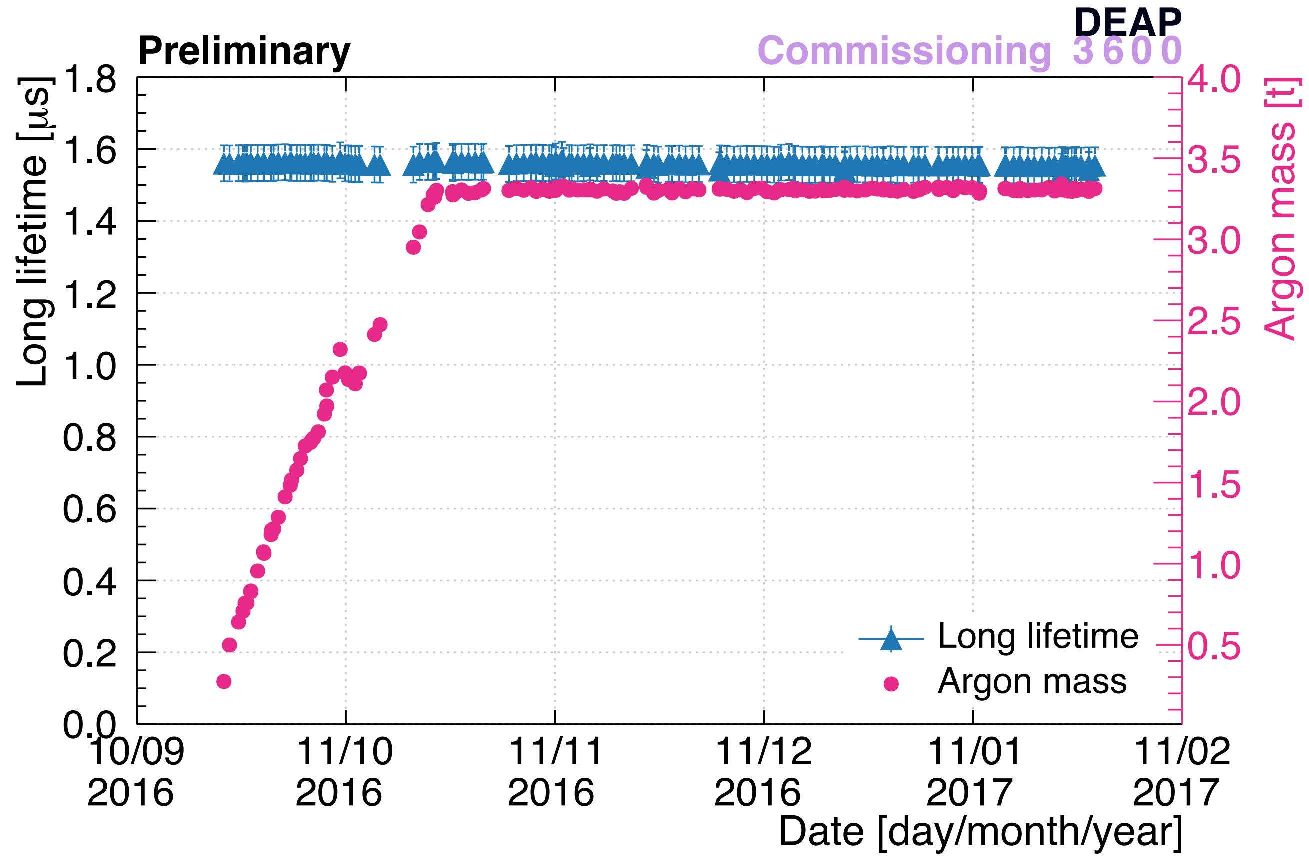
**Plastic filler block**

**Light guide**

# Operation



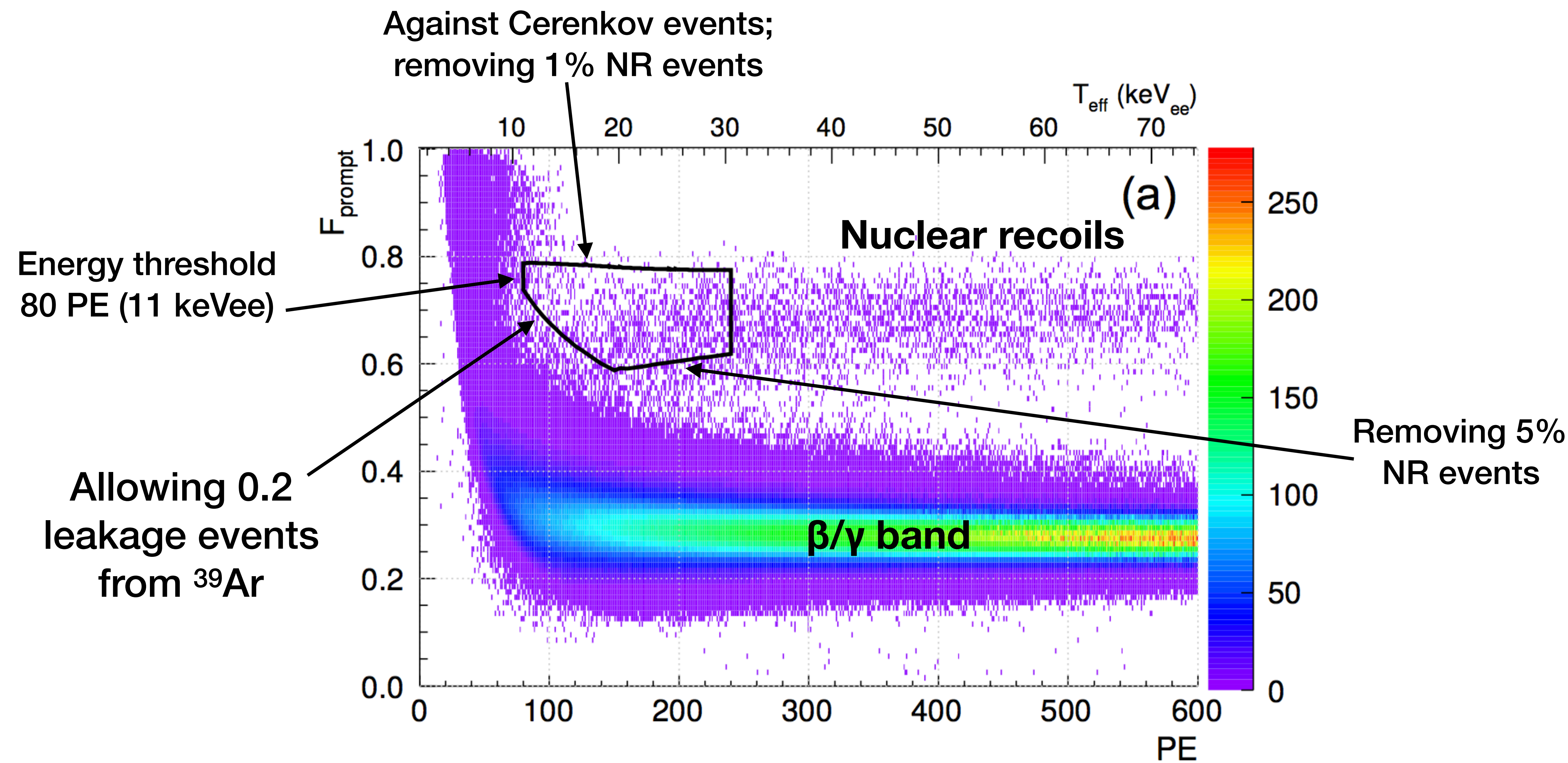

First fill: June - August 2016




Second fill: September - October 2016

- Filled up to 3322 kg of LAr in August 2016
  - Collected 4.4 live days of data
  - Our first dark matter search result (arXiv:1707.08042)
  - Incident on August 17, 2016: leakage of 100 ppb N2 into LAr
  - Drained and re-filled to slightly lower level
- DEAP-3600 has been taking data with 3256 kg of LAr since November 1, 2016

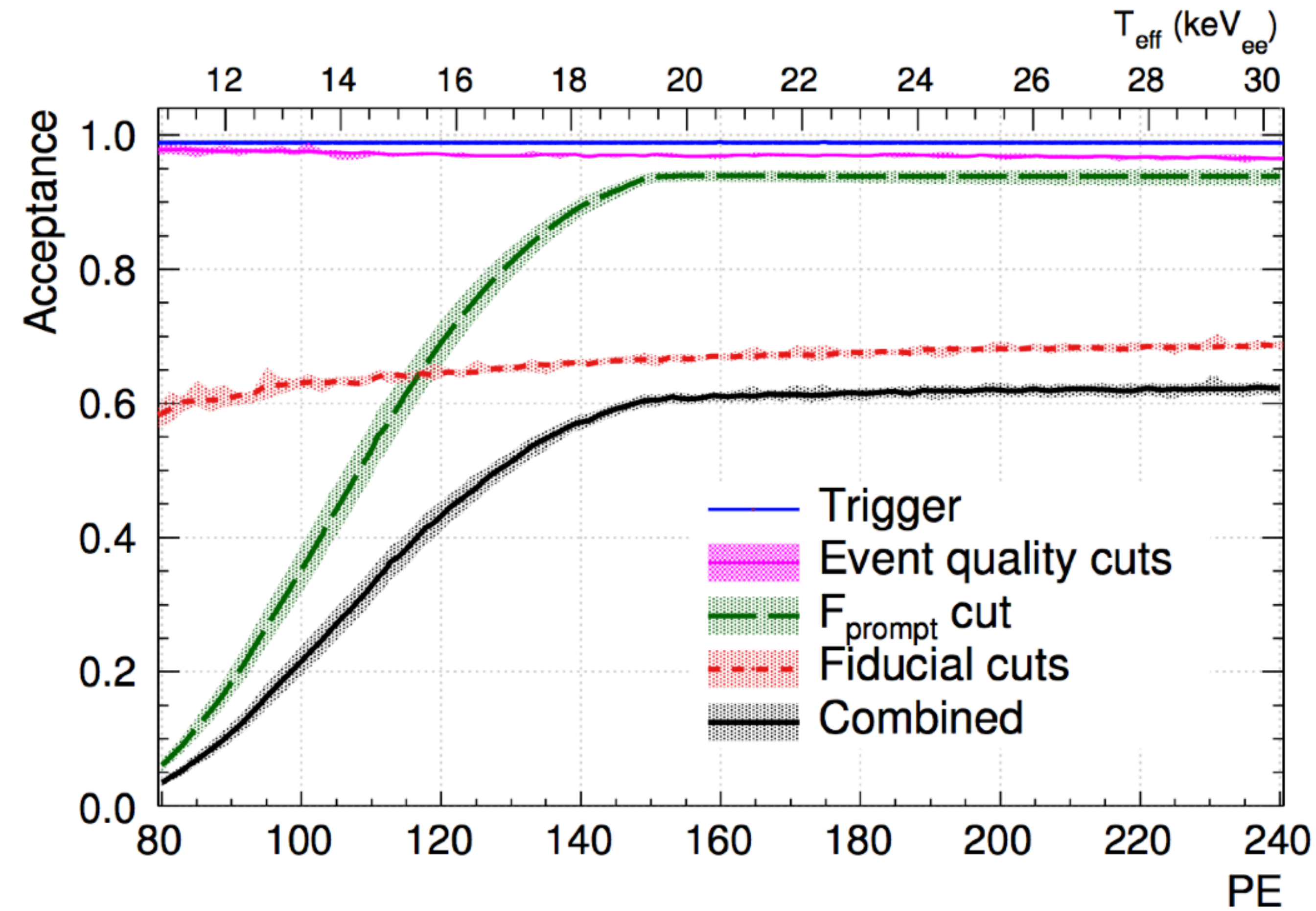
# Region of Interest (ROI)




AmBe source

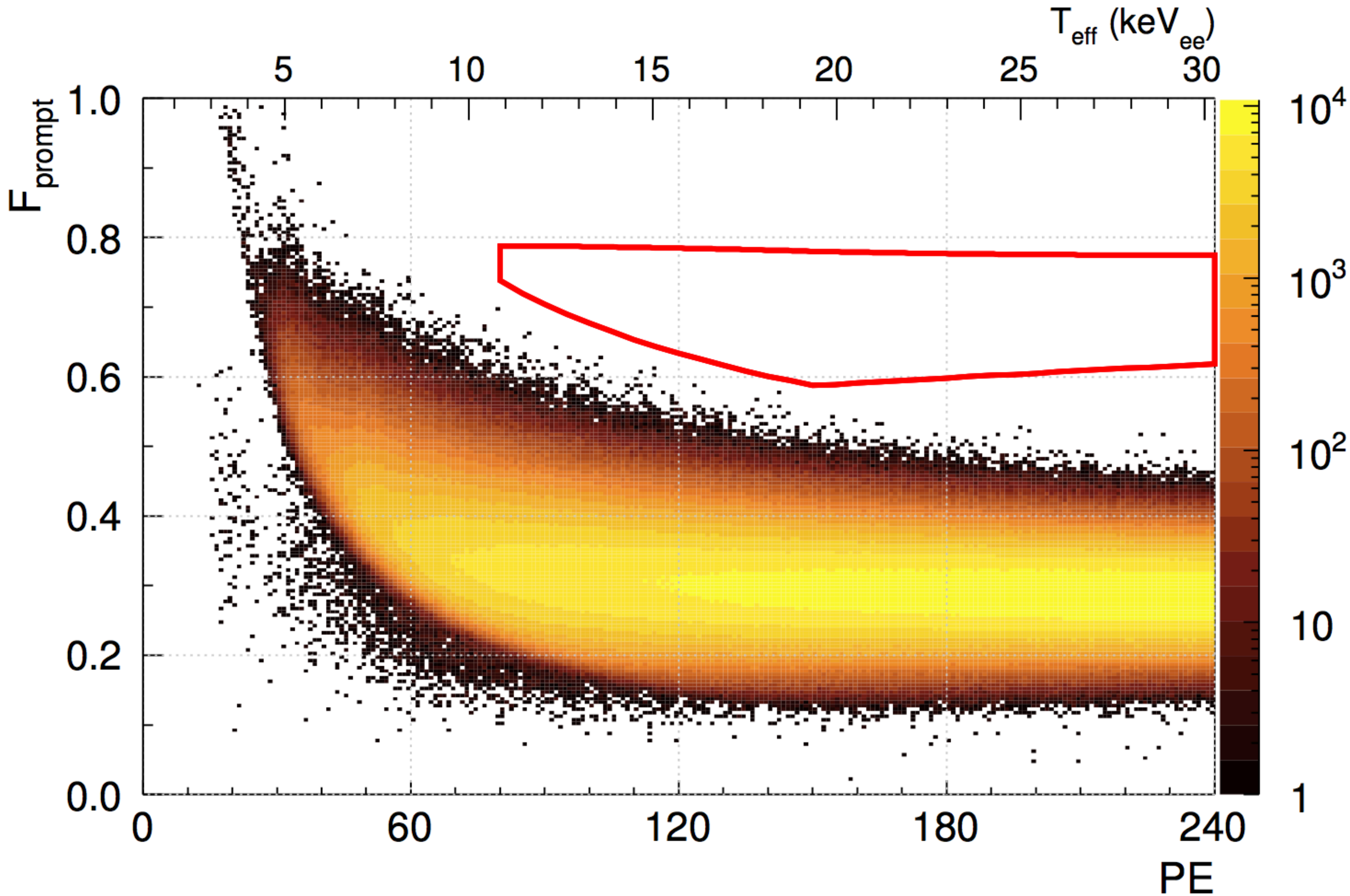
# Cuts and Acceptance

| | Cut | Livetime | Acceptance % | | $\#^{\mathrm{ROI}}_{\mathrm{evt.}}$ |
|---|---|---|---|---|---|
| run | Physics runs | 8.55 d | | | |
| | Stable cryocooler | 5.63 d | | | |
| | Stable PMT | 4.72 d | | | |
| | Deadtime corrected | 4.44 d | | | 119181 |
| low level | DAQ calibration | | | | 115782 |
| | Pile-up | | | | 100700 |
| | Event asymmetry | | | | 787 |
| quality | Max charge fraction per PMT | | $99.58\pm0.01$ | | 654 |
| | Event time | | $99.85\pm0.01$ | | 652 |
| | Neck veto | | $97.49^{+0.03}_{-0.05}$ | | 23 |
| fiducial | Max scintillation PE fraction per PMT | | | $75.08^{+0.09}_{-0.06}$ | 7 |
| | Charge fraction in the top 2 PMT rings | | | $90.92^{+0.11}_{-0.10}$ | 0 |
| | Total | 4.44 d | $96.94\pm0.03$ | $66.91^{+0.20}_{-0.15}$ | 0 |




- Fiducialization:
  - Cut on max scintillation PE fraction per PMT (surface)
  - Cut on charge fraction in the top 2 rows of PMTs (z-fiducial)
  - Position reconstruction algorithms have been developed and tested, but not applied as cuts

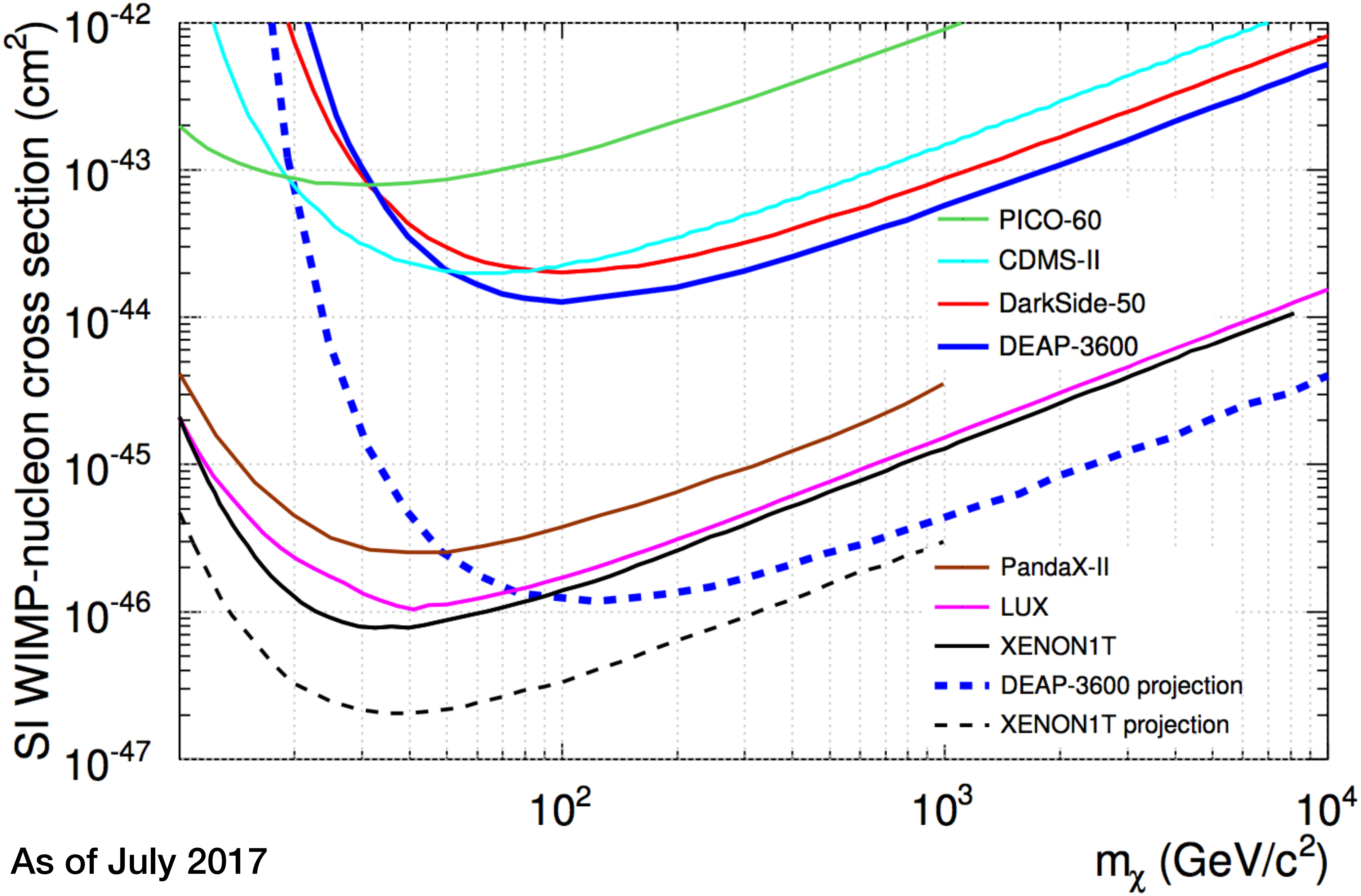
# First Dark Matter Search Results from DEAP-3600




9870 kg*days

arXiv:1707.08042

# First Dark Matter Search Results from DEAP-3600




As of July 2017

$1.2\times10^{-44}$ cm$^2$ for 100 GeV WIMP (90% C.L.)

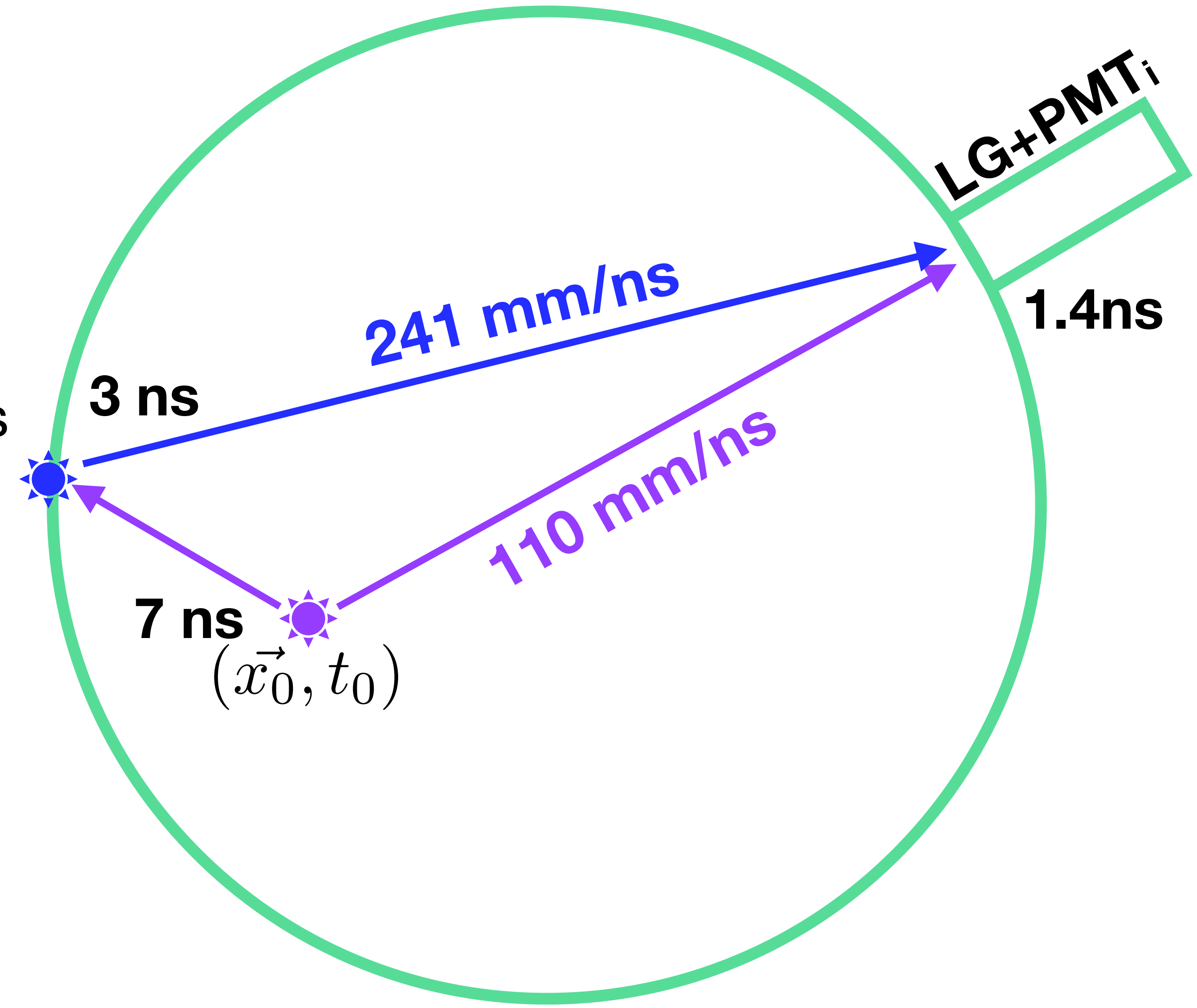
Projected sensitivity for 3-year run: $10^{-46}$ cm$^2$ for 100 GeV WIMP

# Position Reconstruction

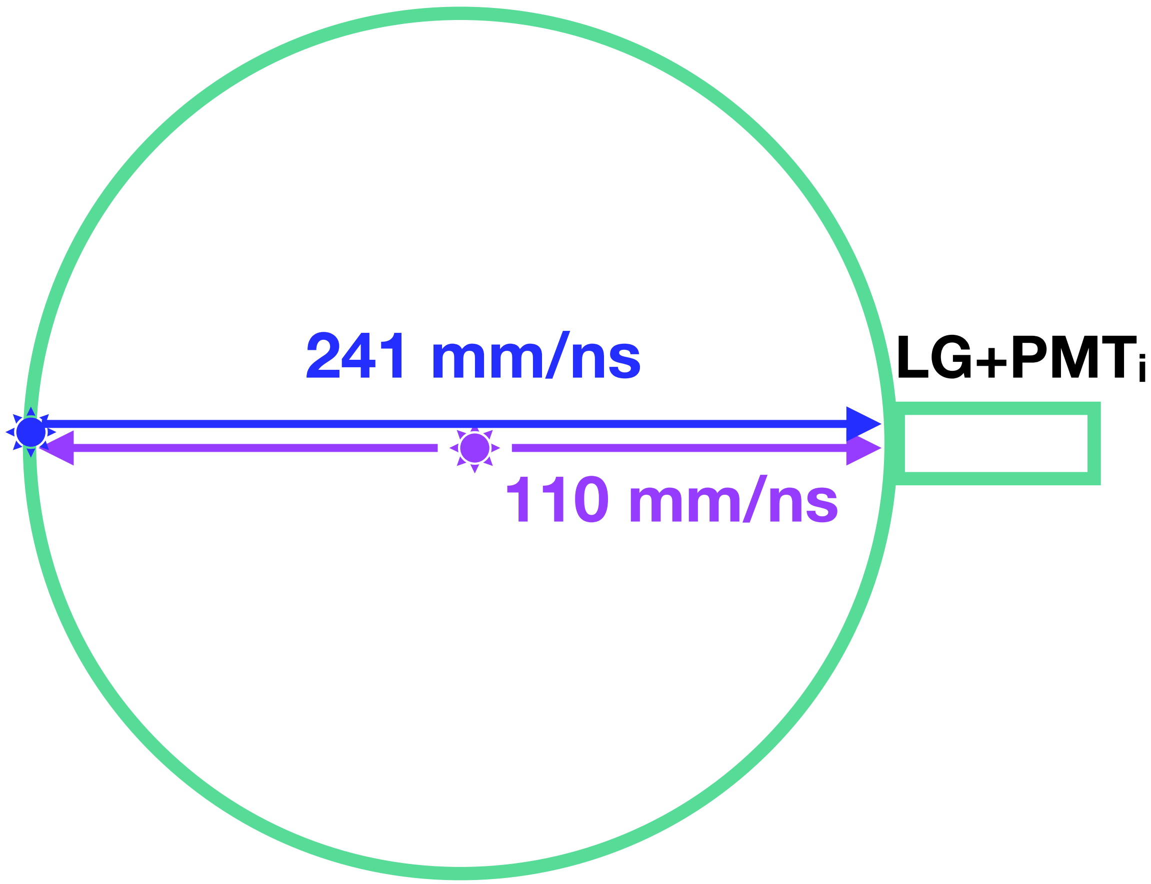
- Fit on photon charge distribution
  - Assuming a single source of light,
  - Light intensity (therefore charge in PMTs) ~ $1/r^2$,
  - Probability density functions (PDFs) trained with MC,
  - Pulse charge in full event window as input
- Fit on the distribution of photon arrival timing (new fitter under development)
  - Assuming a single source of light,
  - Photon arrival time = event time + time-of-flight (TOF) + time delay (dimer decay, TPB response, PMT response)
  - Feasibility: detector large enough, time resolution good enough, UV light in LAr travels slow enough!
  - Using only first 40 ns prompt light to avoid late unphysical info (afterpulsing, …)

# Fit with Photon Timing

- Fit with intensity and time of arrival for the first 40 ns of prompt light
- Group velocity of UV light = 110 mm/ns
- Group velocity of visible light = 241 mm/ns
- Construct PDFs for light emitted at vertex $x_0$ and event time $t_0$ given PMT $i$ measures charge $q_i$.
- $L(\{t_i, q_i\}; \vec{x_0}, t_0) = \prod_i P_i^{q_i}(t_i; \vec{x_0}, t_0)$
- Convolve singlet decay time (7 ns), TPB response time (3 ns), and PMT/Light Guild (LG) response time (1.4 ns)

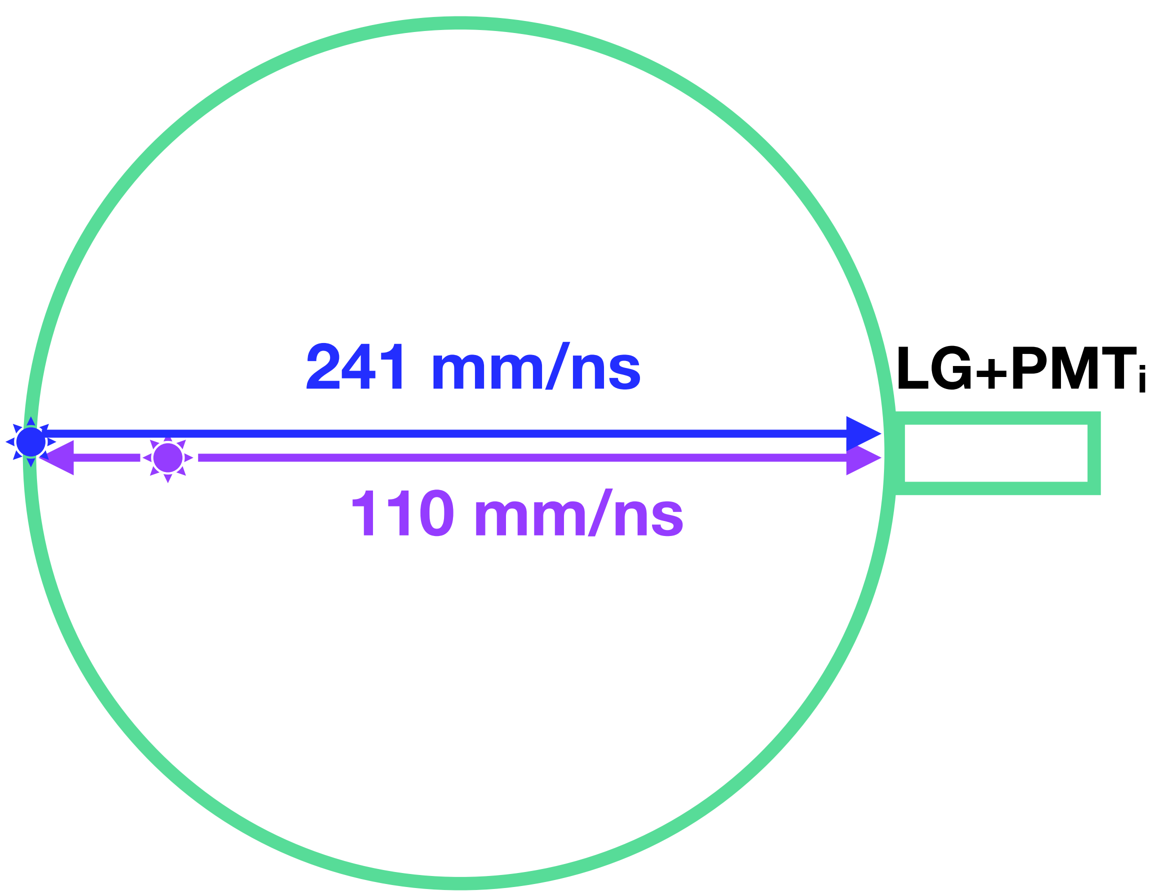



Scintillation hypothesis




Events in center area

- UV light always arrives first



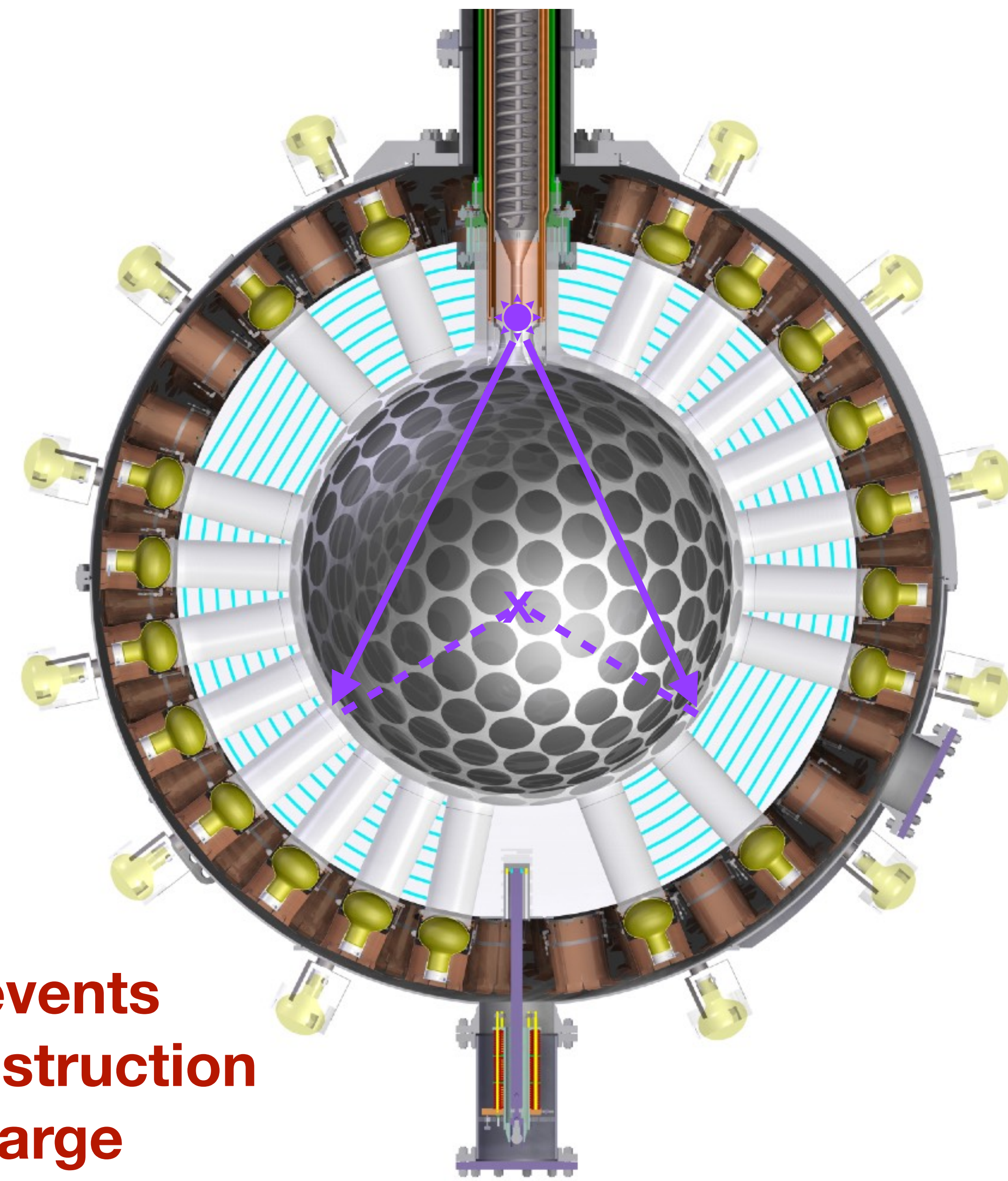

Events relatively near surface

- Visible light arrives first to the PMTs at far side
- **Distinct time profile at some PMTs**

# Consistency between Charge and Timing Fits

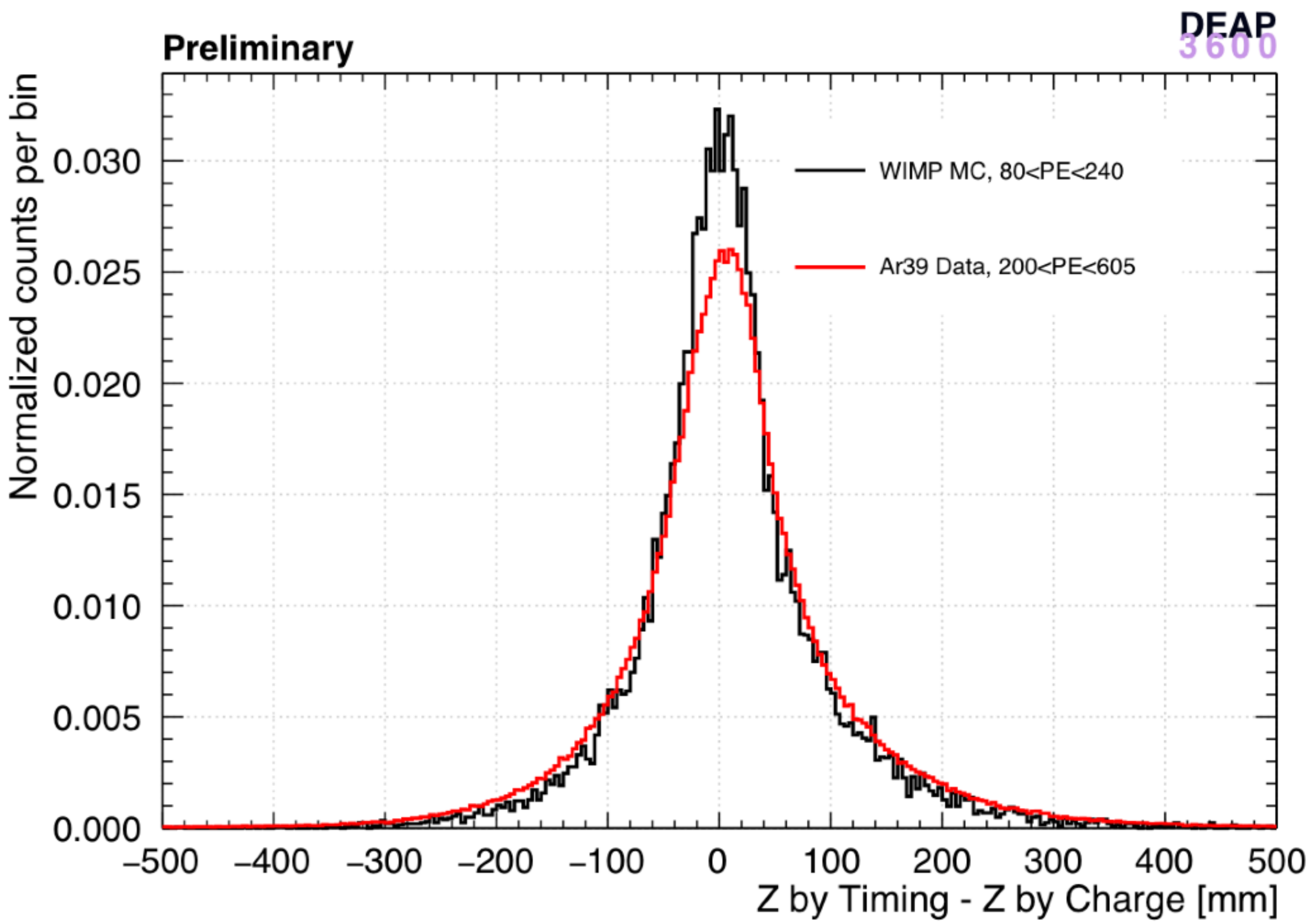
- Both algorithms assume a single source of light. For healthy, uniformly distributed bulk events, such as Ar39 and expected WIMP signal, the positions reconstructed by charge and by timing should agree.

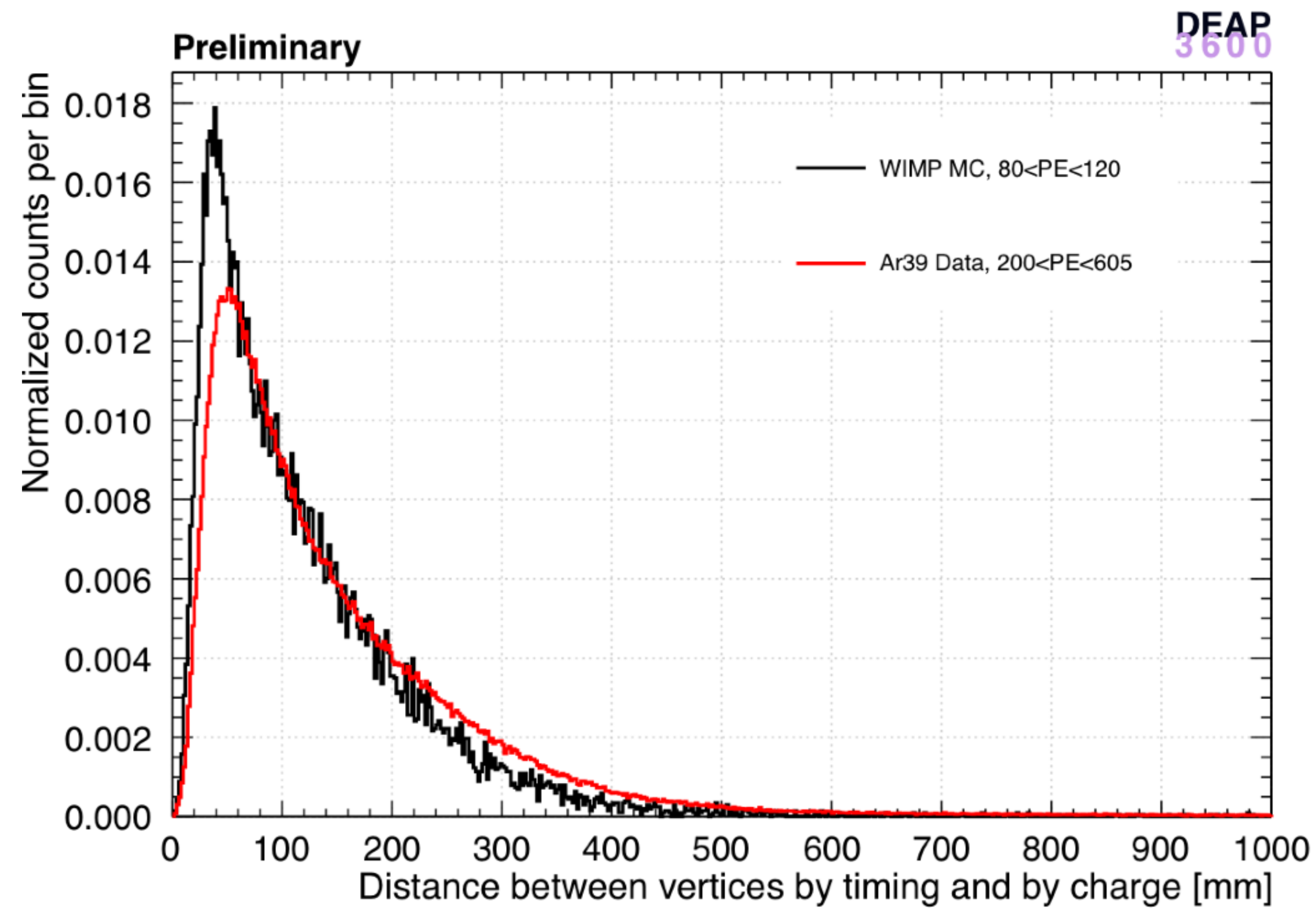
- Not expect charge and timing fits to agree for
  - Events with substantial amount of afterpulsing
  - Light originating from multiple positions
  - **Events in the neck**



**Neck events mis-reconstruction by charge**

# Consistency between Charge and Timing Fits



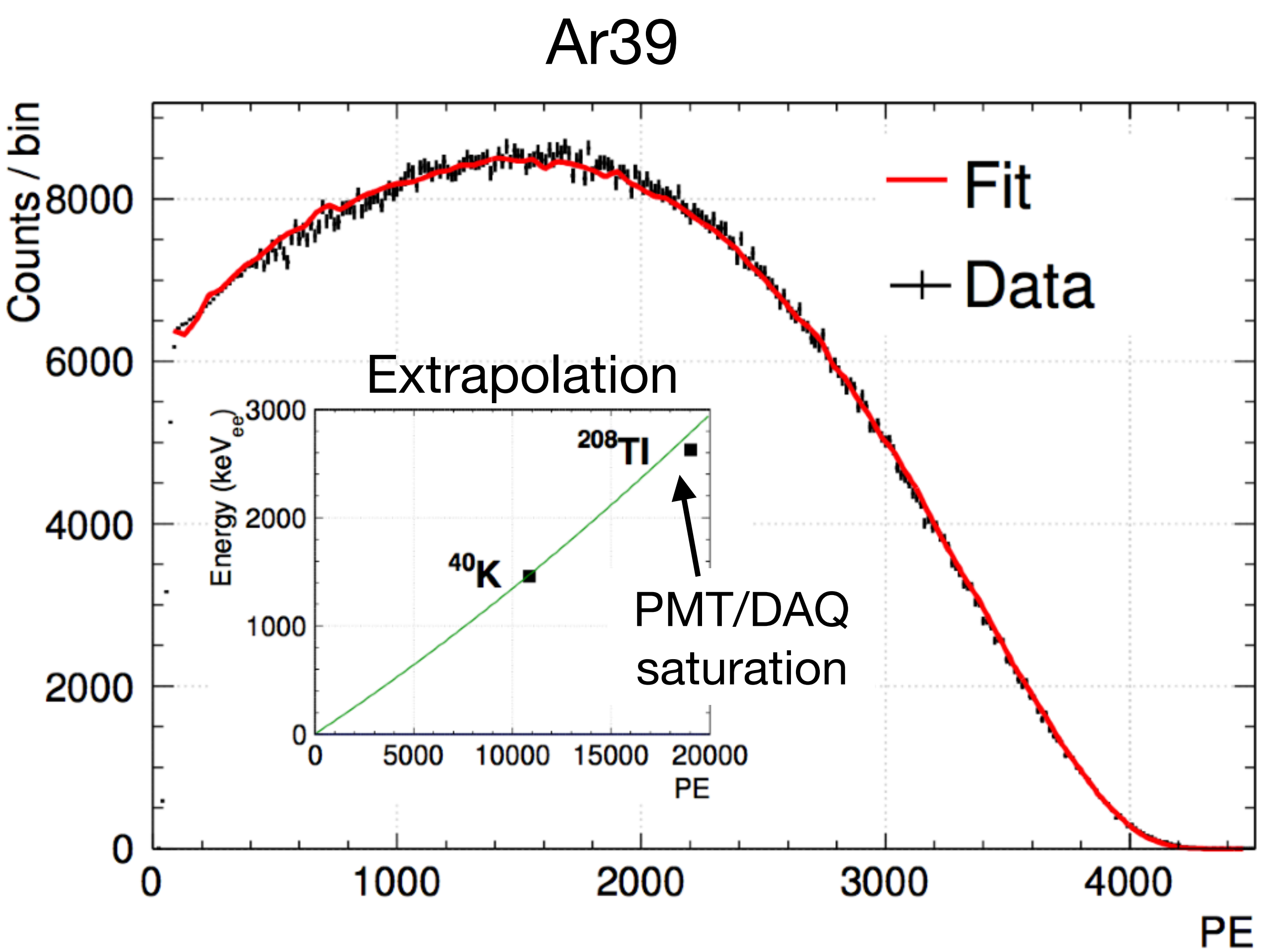

- Tested with WIMP MC events at ROI energy (80 to 240 PE)
- and Ar39 data events with higher energies to have similar amount of prompt light
- Very promising to discriminate background events from the neck, or other mis-reconstruction cases.

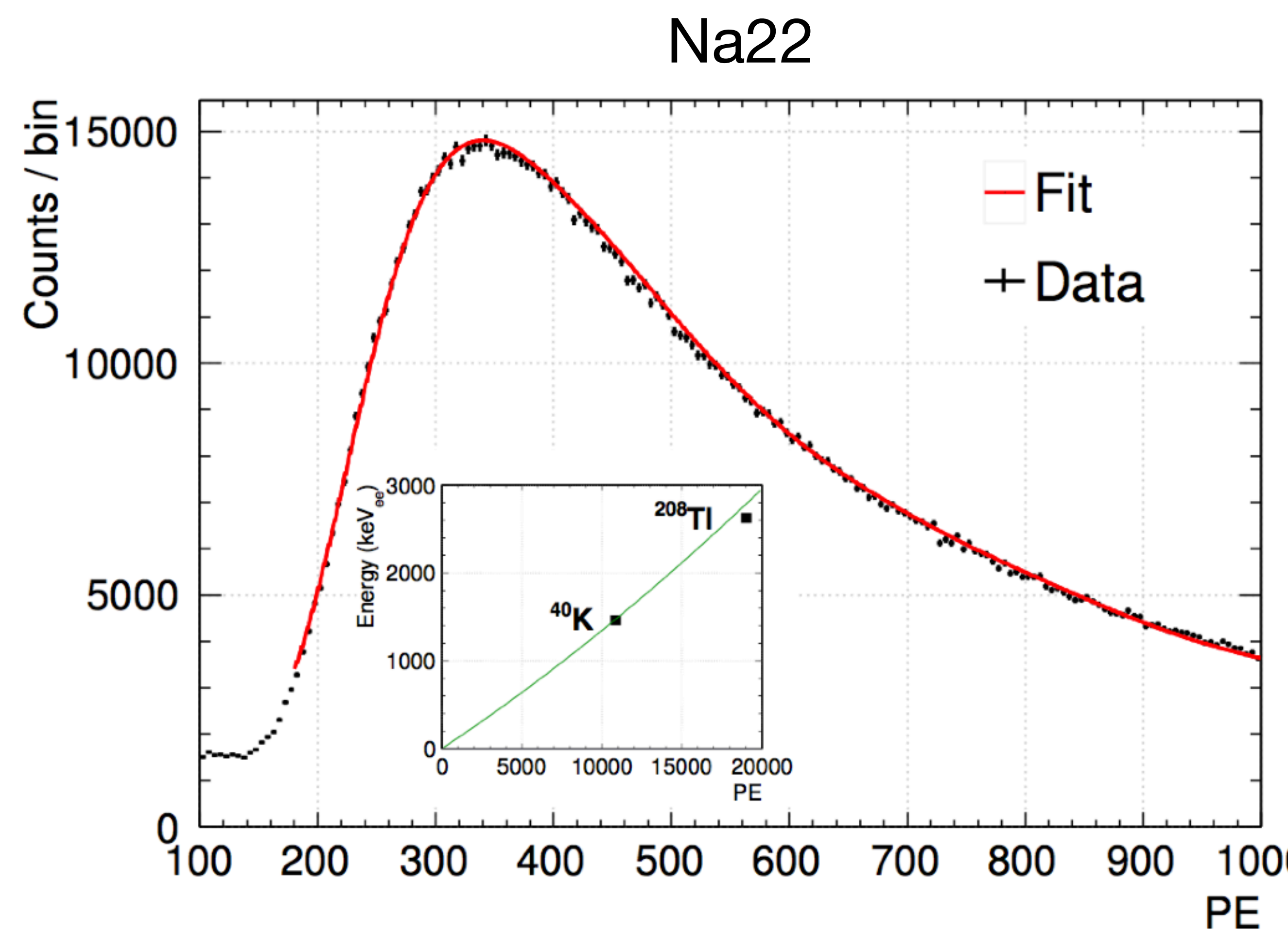
# Conclusion

- DEAP-3600 has achieved stable operation at 7.36 PE/keVee light yield
- Better-than-expected Pulse-shape discrimination (PSD)
- No events observed in ROI in 4.44 live days of the first fill dataset
- Spin-independent WIMP-nucleon cross section < $1.2 \times 10^{-44}$ $cm^2$ for a 100 GeV WIMP
- Second fill dataset: ongoing since November 2016; collected more than one year of data!
- Position reconstruction:
    - Photon charge algorithm, and
    - Newly developed photon timing algorithm (benefit from low group velocity of UV light in LAr)
    - Photon timing provides extra information
    - The reconstruction consistency between charge and timing is promising to reject backgrounds.

# Backups

# Energy Calibration




- Ar39 and Na22 are fit separately. Agree within errors.
- Ar39 spatially uniform (similar to WIMP-induced NR)
- Na22 near AV surface (similar to surface backgrounds)
- Light yield: $7.36^{+0.61}_{-0.52}$ (fit sys.) +/-0.22 (SPE sys.) PE/keVee

# Backgrounds

- Alphas
  - $^{222}$Rn, $^{218}$Po, and $^{214}$Po α decays
  - Tagged with well-defined high energy peaks and time delayed coincidence
- Neutrons
  - Dominant sources: (α, n) and spontaneous fission
  - Constrained with in-situ measurements of gamma-rays from U/Th decay chain
  - Tagged by searching for NR followed by a neutron capture gamma-ray