XURICH II – First dual-phase xenon TPC with SiPM readout and its ultra-low energy calibration with 37-Ar

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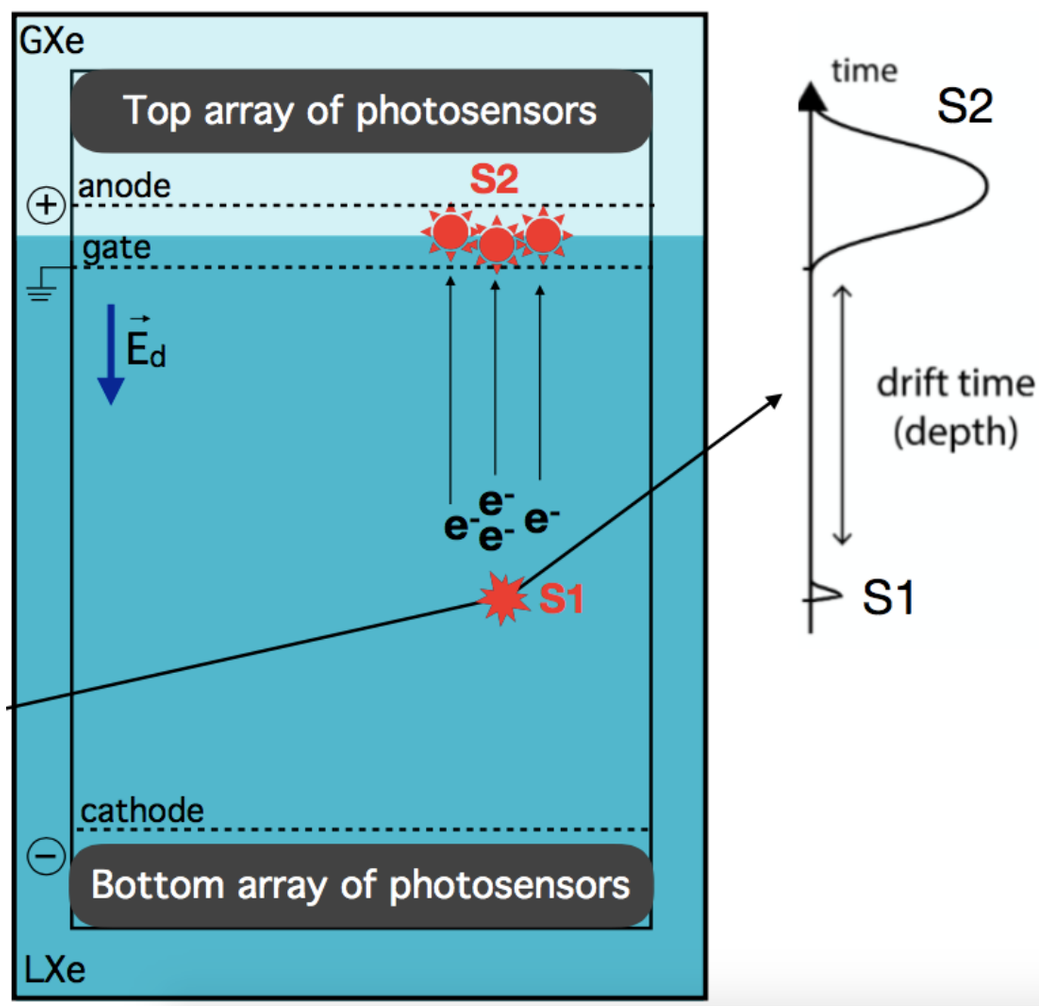
www.darwin-observatory.org

INTRODUCTION AND MOTIVATION

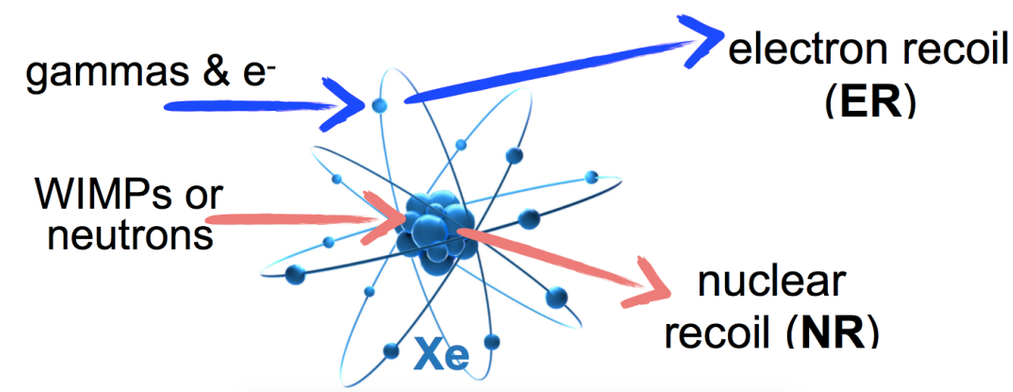
DUAL-PHASE XENON TIME PROJECTION CHAMBER

Dual-phase TPC working principle

- Detect prompt scintillation light (S1) and delayed ionisation signal (S2)
- Reconstruct z-position from drift time and (x,y) from S2 localization

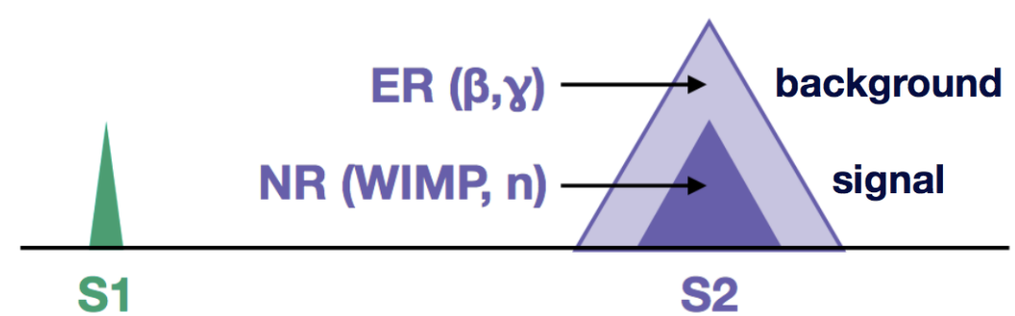


Particle interactions



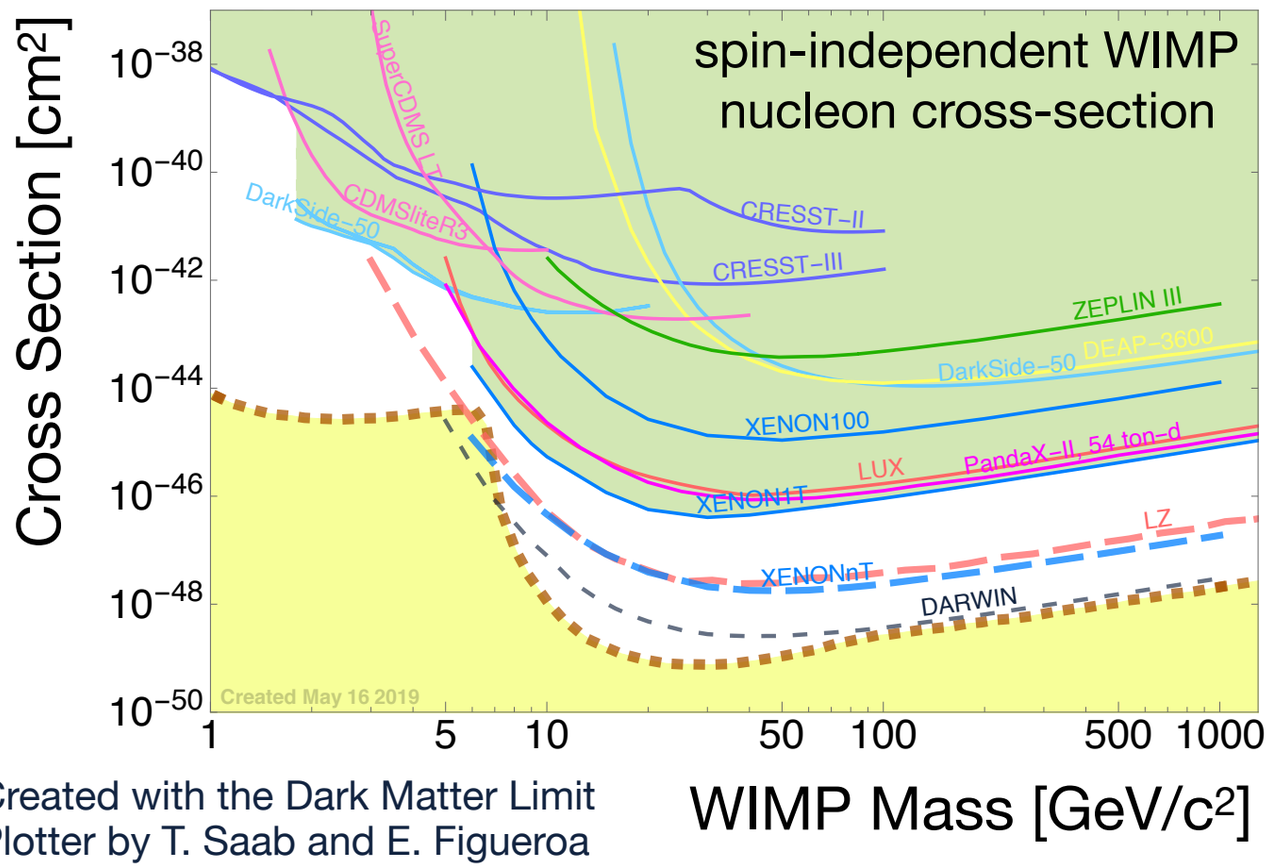
Particle type discrimination

- S1/S2 ratio depends on particle type



DUAL-PHASE XENON TIME PROJECTION CHAMBER II

WIMP landscape



Created with the Dark Matter Limit Plotter by T. Saab and E. Figueroa

- Above 5 GeV/c² best limits set by liquid nobel gas TPCs

present limits

near future sensitivities

DARWIN's sensitivity

See talks on XENON and DARWIN on Thursday afternoon!

Photosensors in TPCs

- Traditionally: Photomultiplier tubes
- Under consideration: Silicon Photomultipliers

Bulkiness

Radioactivity

Longterm stability

Position resolution

High operation voltage

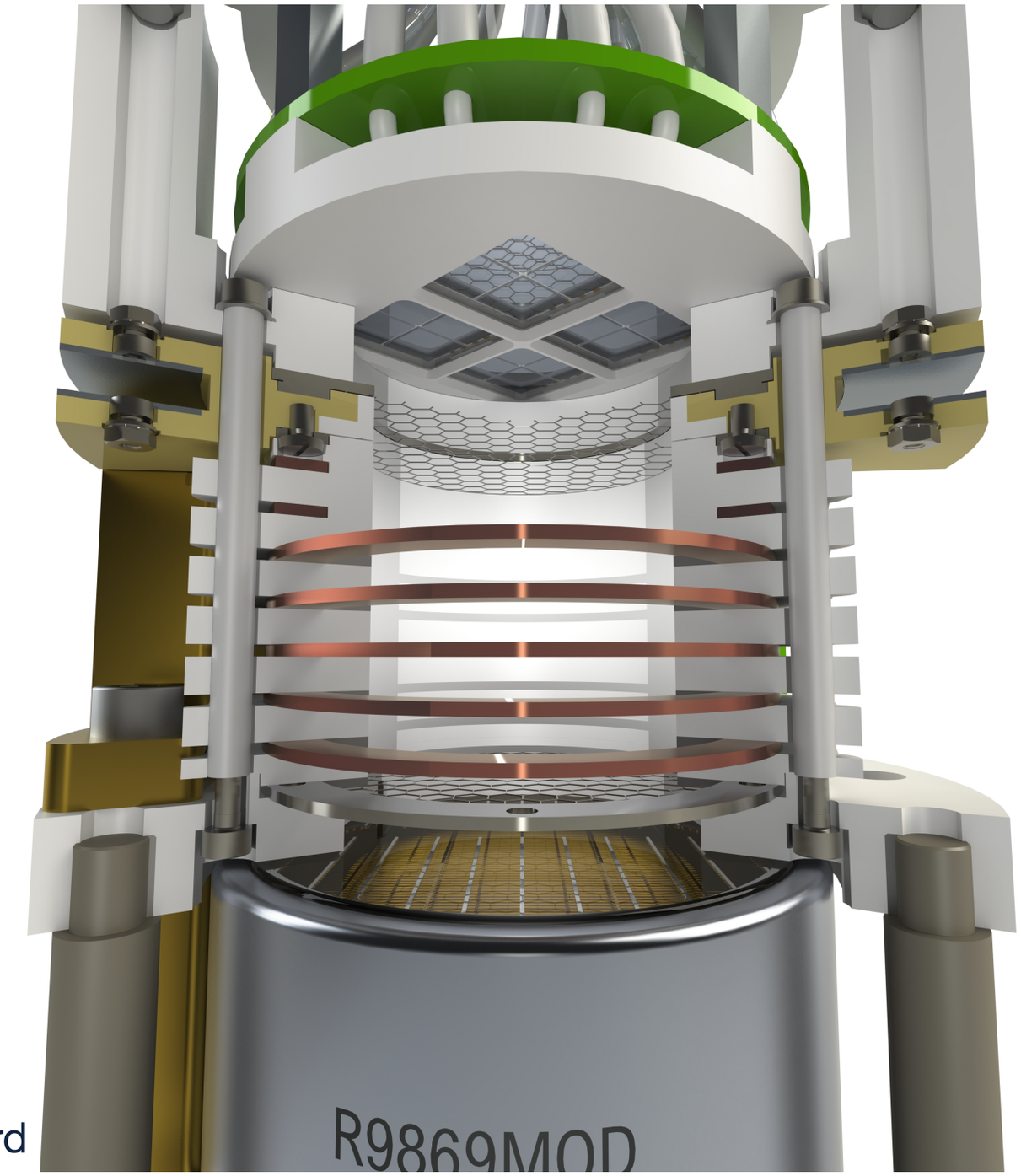
Cost

Dark Count Rate

SETUP AND SIPMS

XURICH II TPC

- Small-scale (31 mm (d) × 31 mm (h)) dual-phase TPC designed to study interactions in LXe < 50 keV
- 2 × 2 S13371 VUV-4 MPPCs from Hamamatsu in the top array – 16 channels!
- Mounted on ×10 pre-amplifier board
- 2-inch R9869 PMT from Hamamatsu at the bottom
- Up to 1 kV/cm drift field
- 10 kV/cm extraction field
- SiPM upgrade in Summer 2018, since then 10 months of stable operation

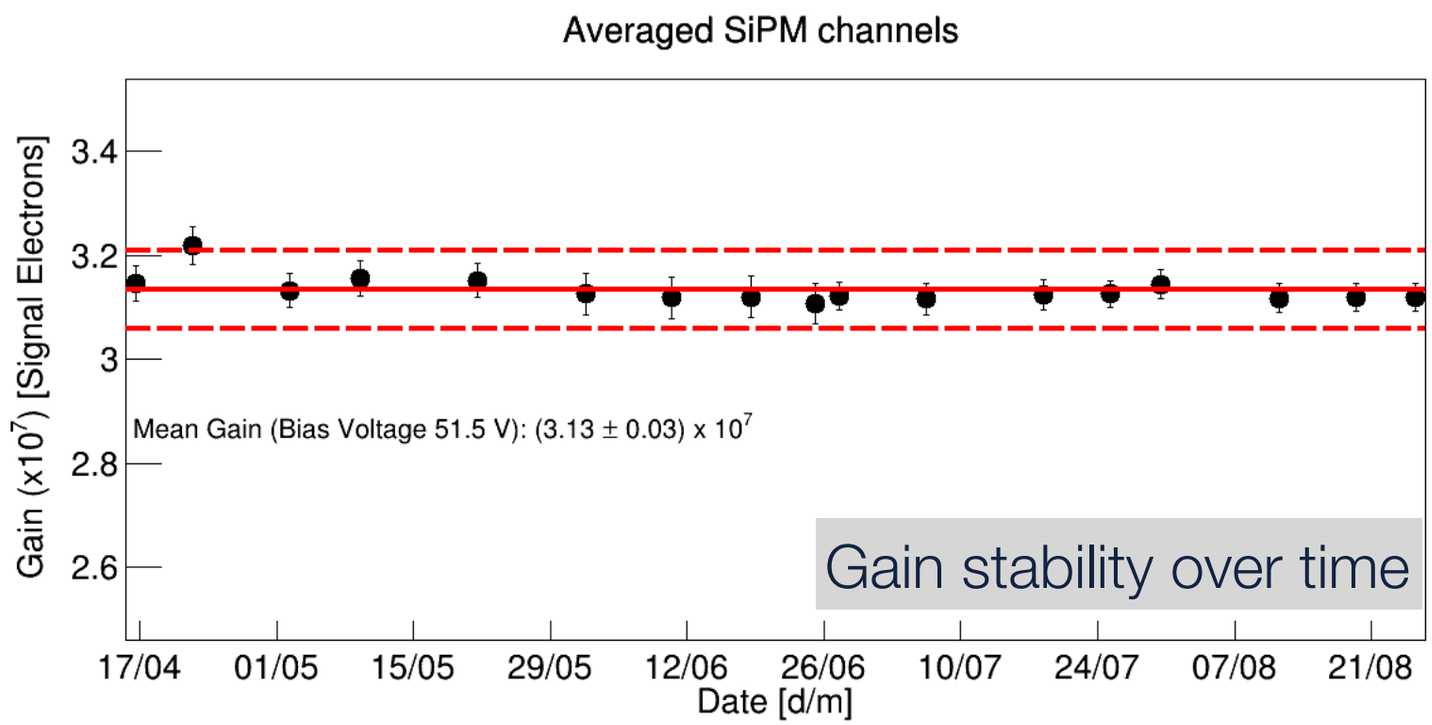


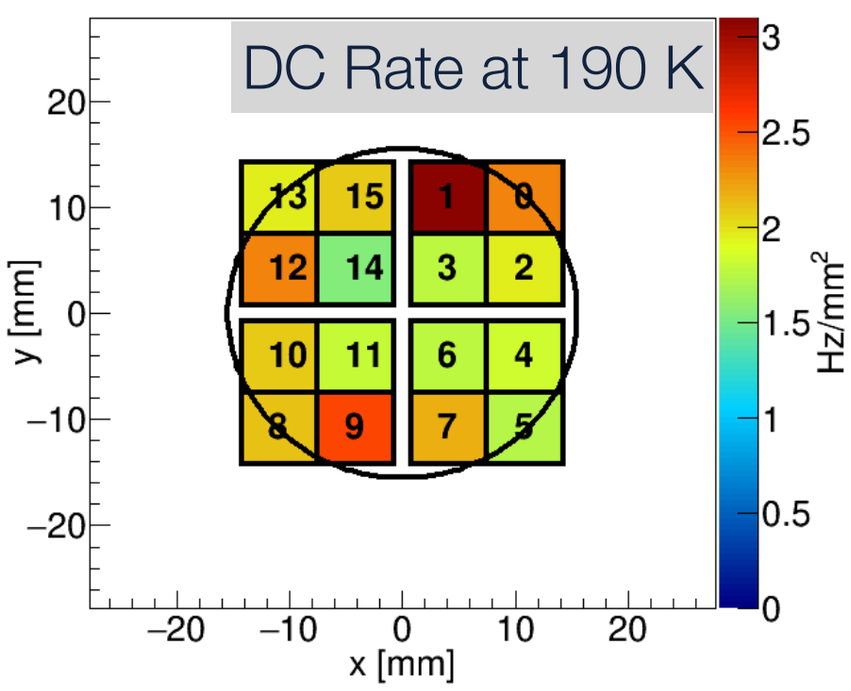
Credits:
A. James, F. Girard

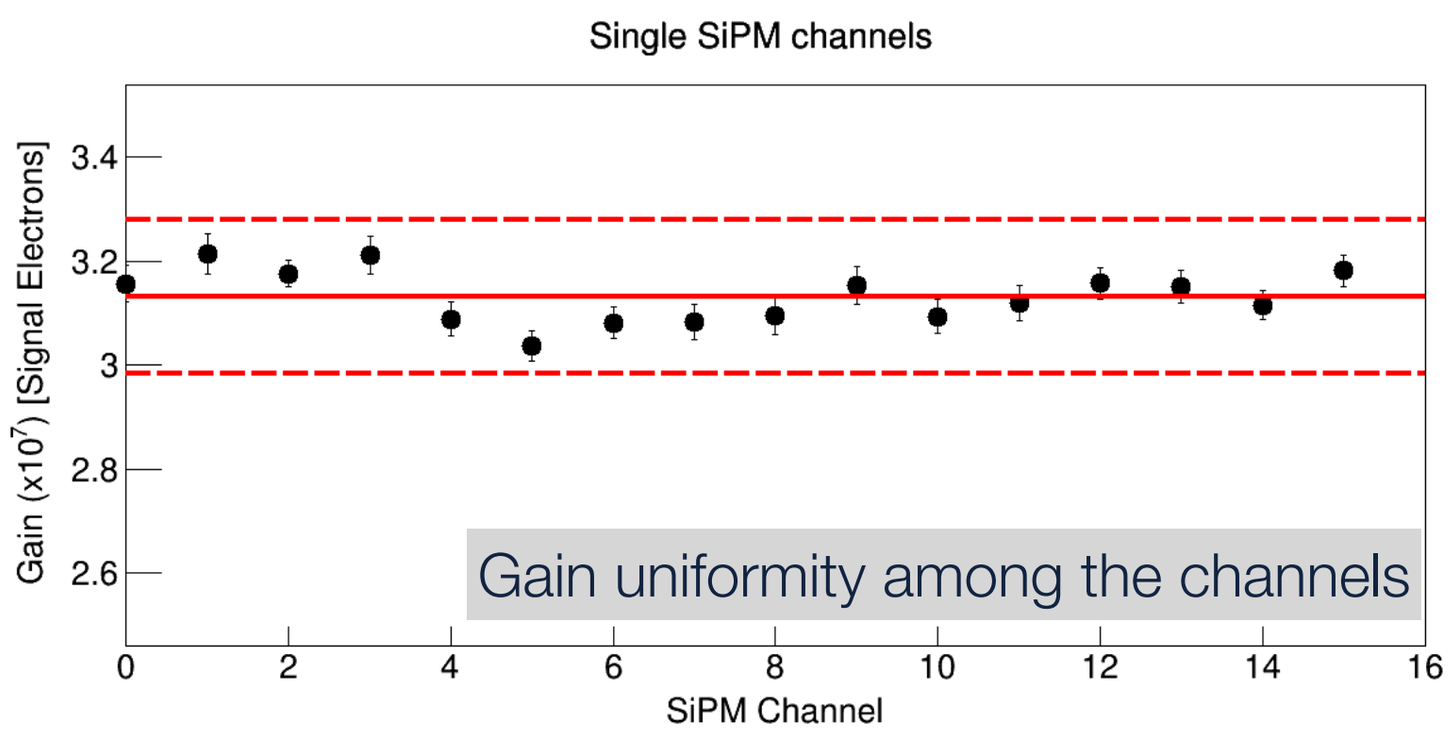
Eur. Phys. J. C78 (2018) 351

PERFORMANCE AND LONGTERM STABILITY OF THE SiPMS

- Weekly monitoring of the gain with model independent single photoelectron calibration (measured with blue LED)
- Gain very stable over time
- Dark count rate as expected for the temperature in the gas phase (c.f. JINST 13 (2018) P10022)





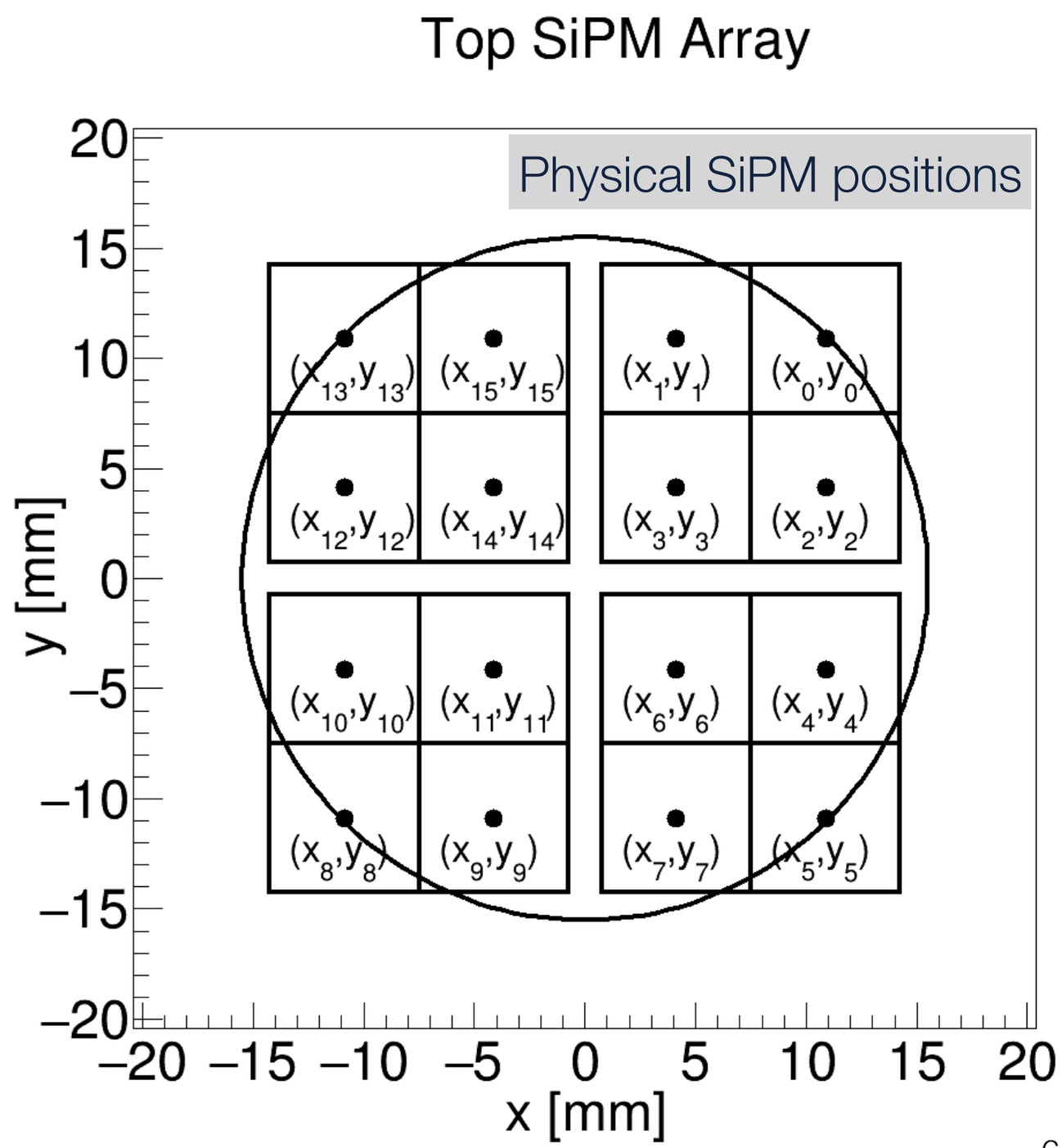


EVENT POSITION RECONSTRUCTION

- Top array enables for event position reconstruction in (x,y) ~1.5 mm
- Use 'center of gravity' algorithm:

$$(\hat{x}, \hat{y}) = \frac{1}{\sum_{i=0}^{15} S_2^i} \sum_{i=0}^{15} S_2^i \cdot (x_i, y_i)$$

- Center, scale and map onto a circle
- Electrons are focused to the knots of the gate mesh
- Arrangement of the sensors in a square gives bias to the center of the TPC -> Correct for it by comparing with the gate CAD
  (arccos with linear region up to 10 mm)



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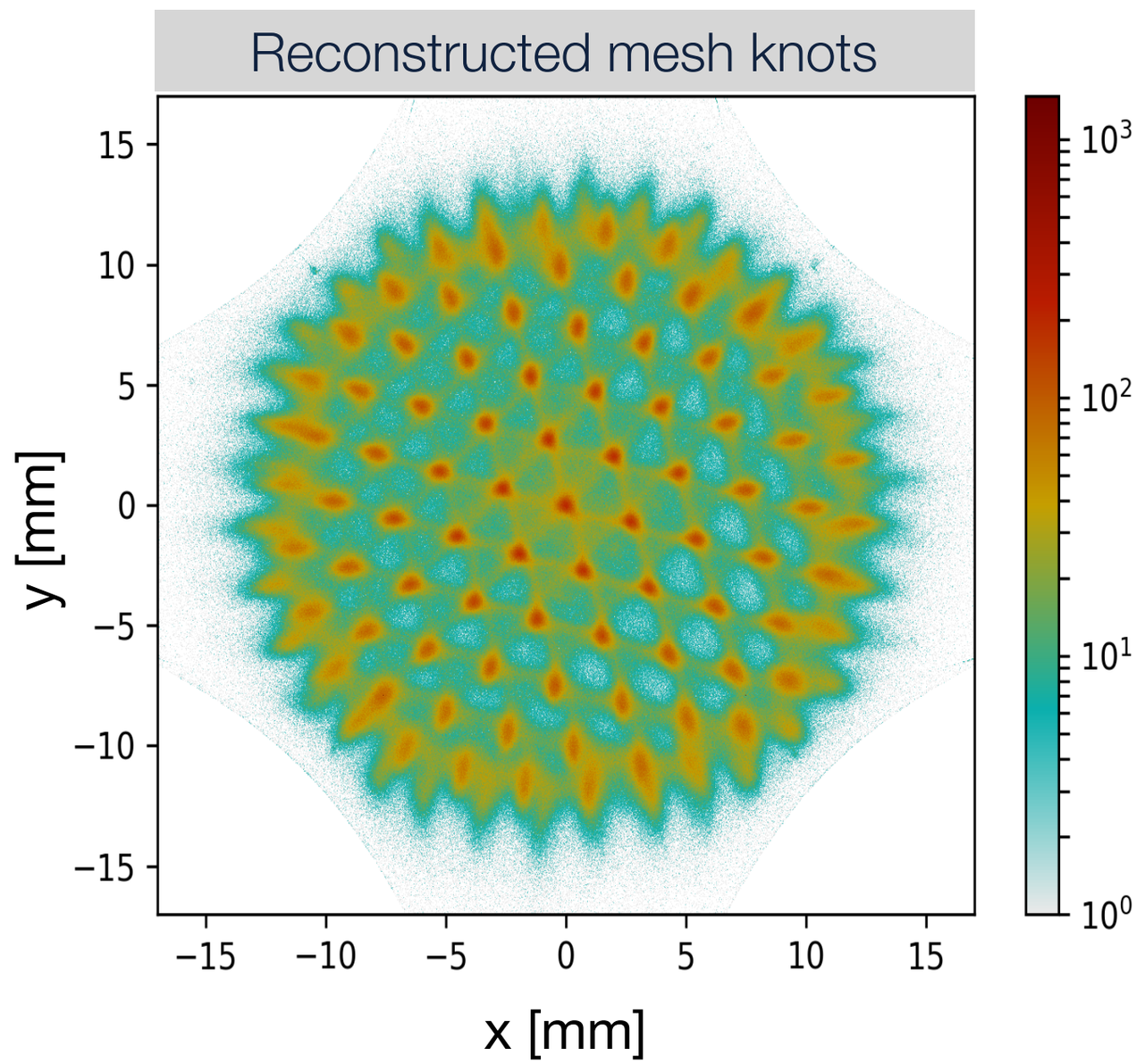

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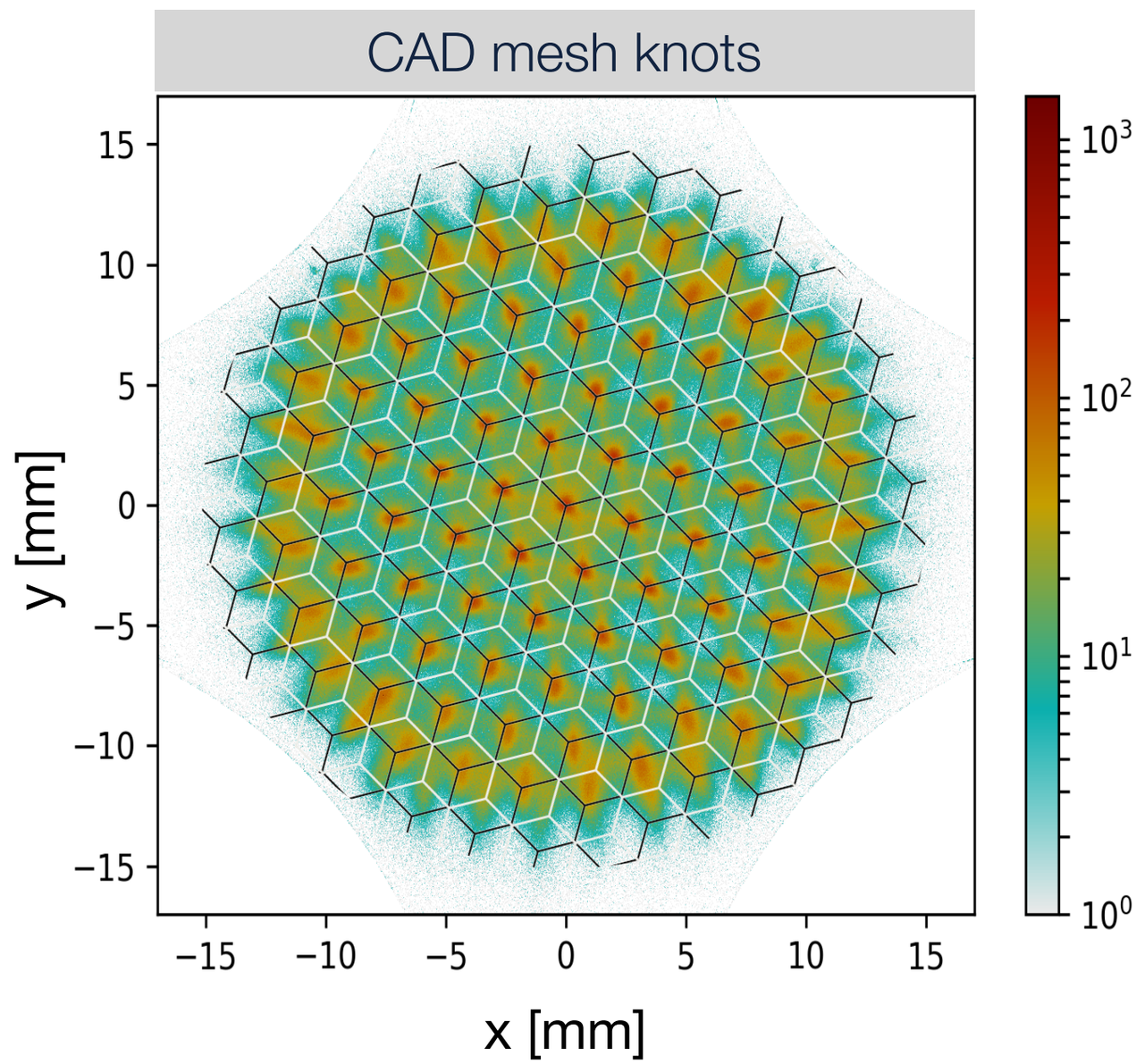
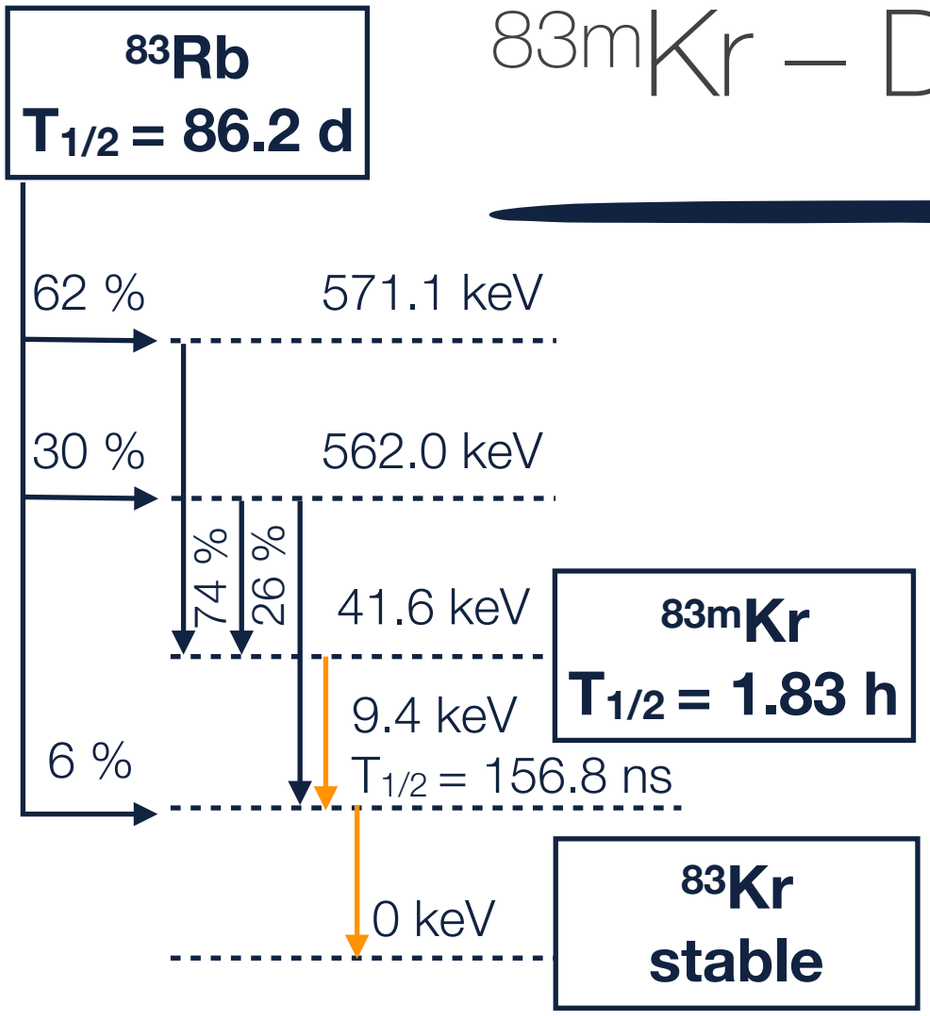
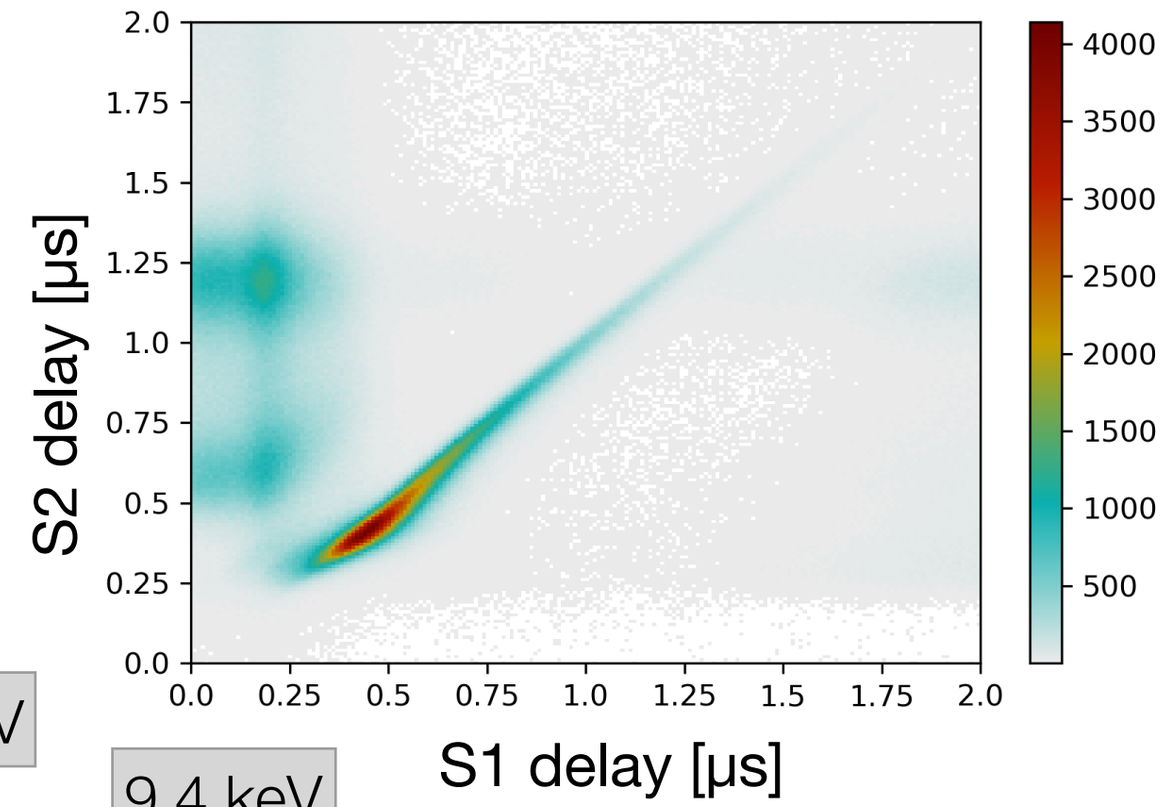
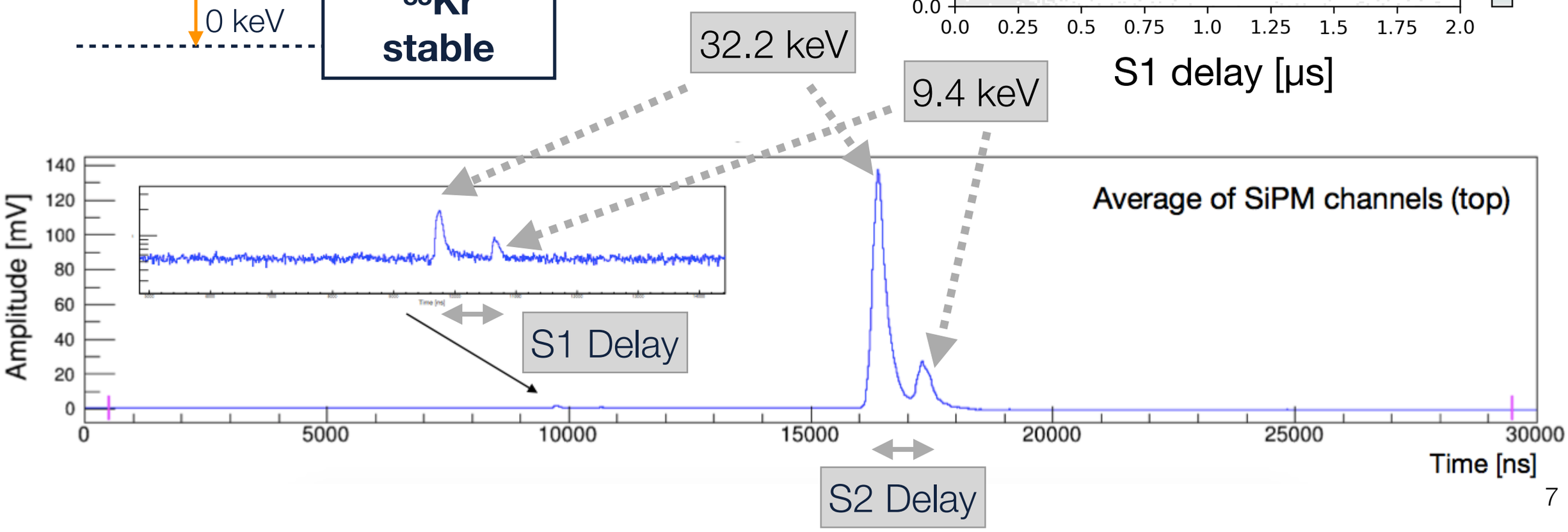


CALIBRATION WITH ^{83m}Kr AND ^{37}Ar

^{83m}Kr – DATA SELECTION AND CUTS







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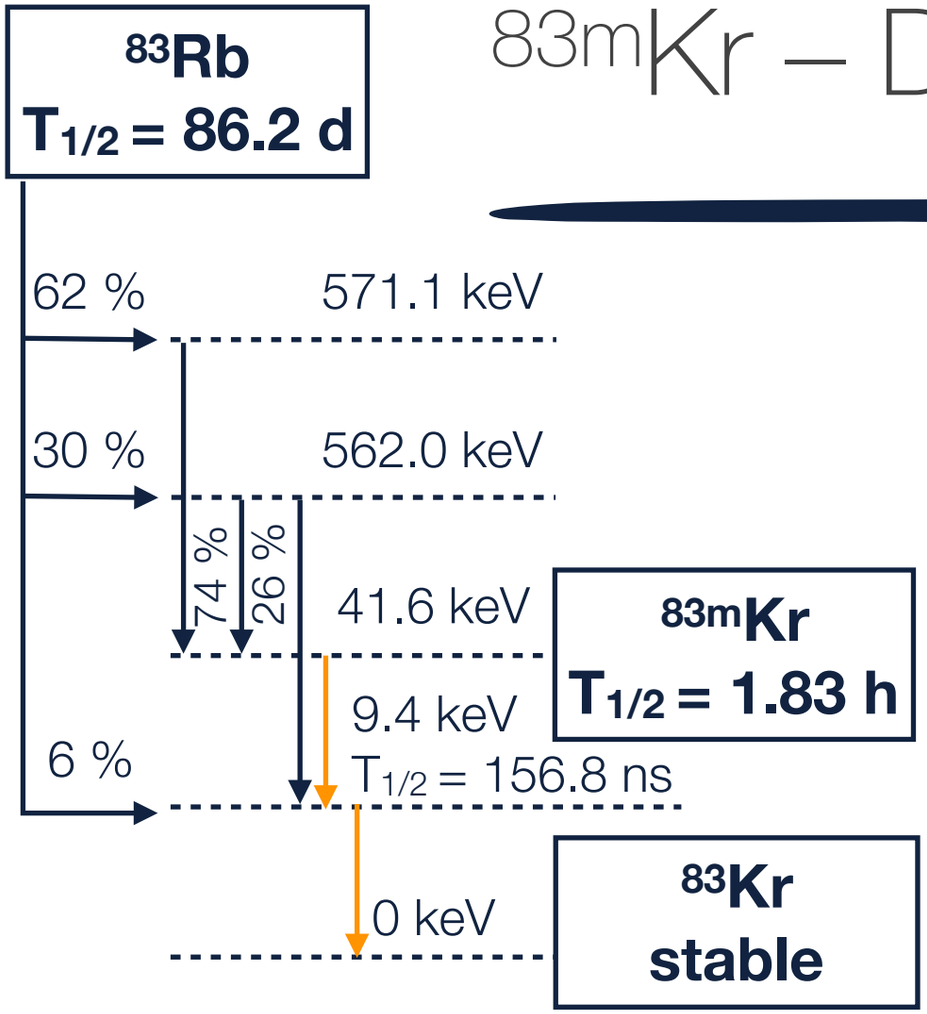
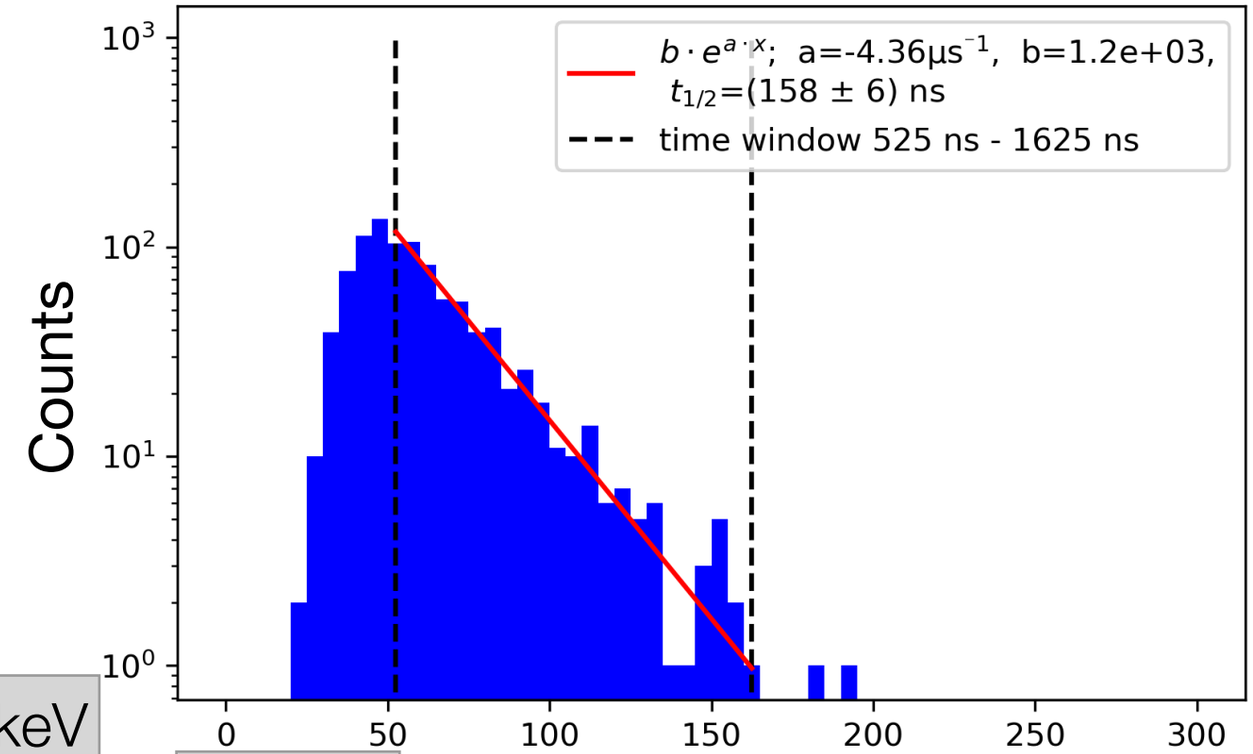
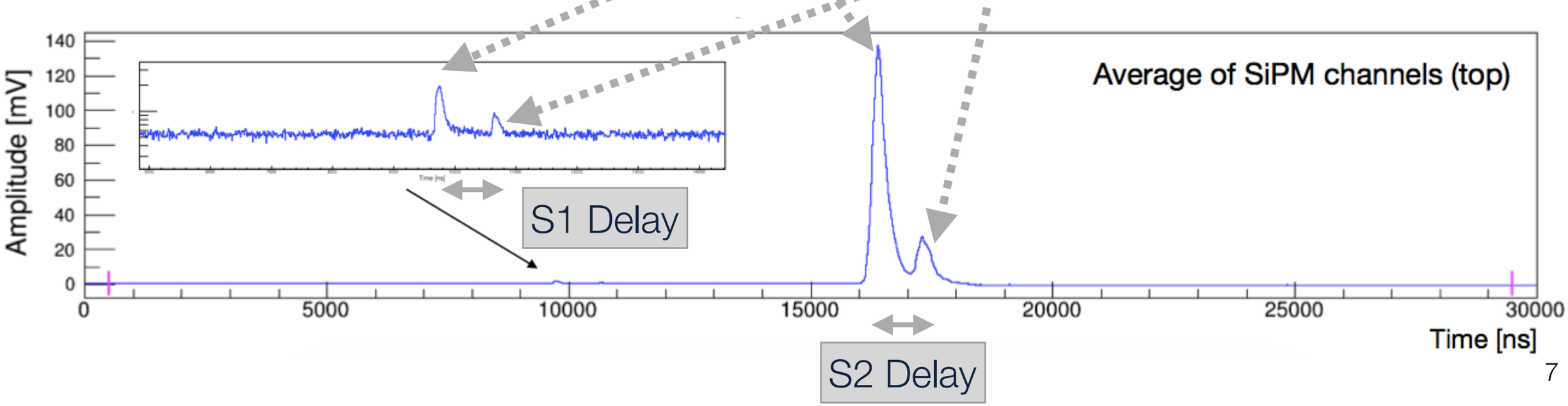
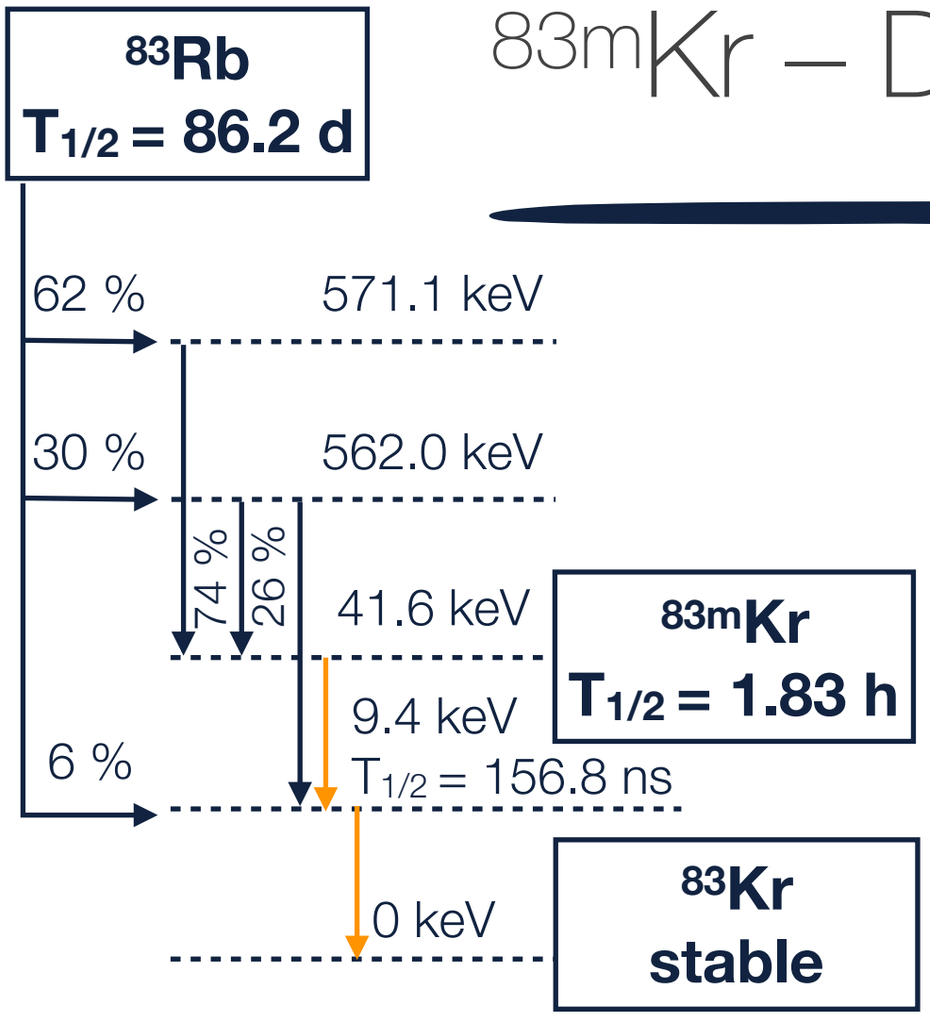


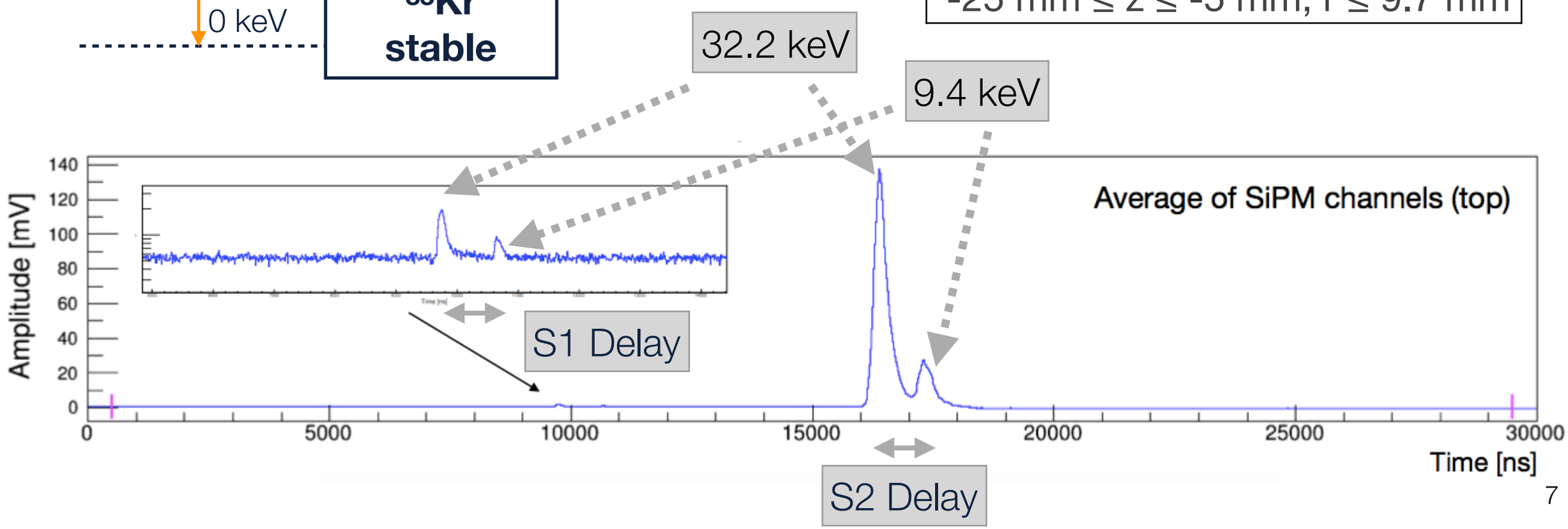




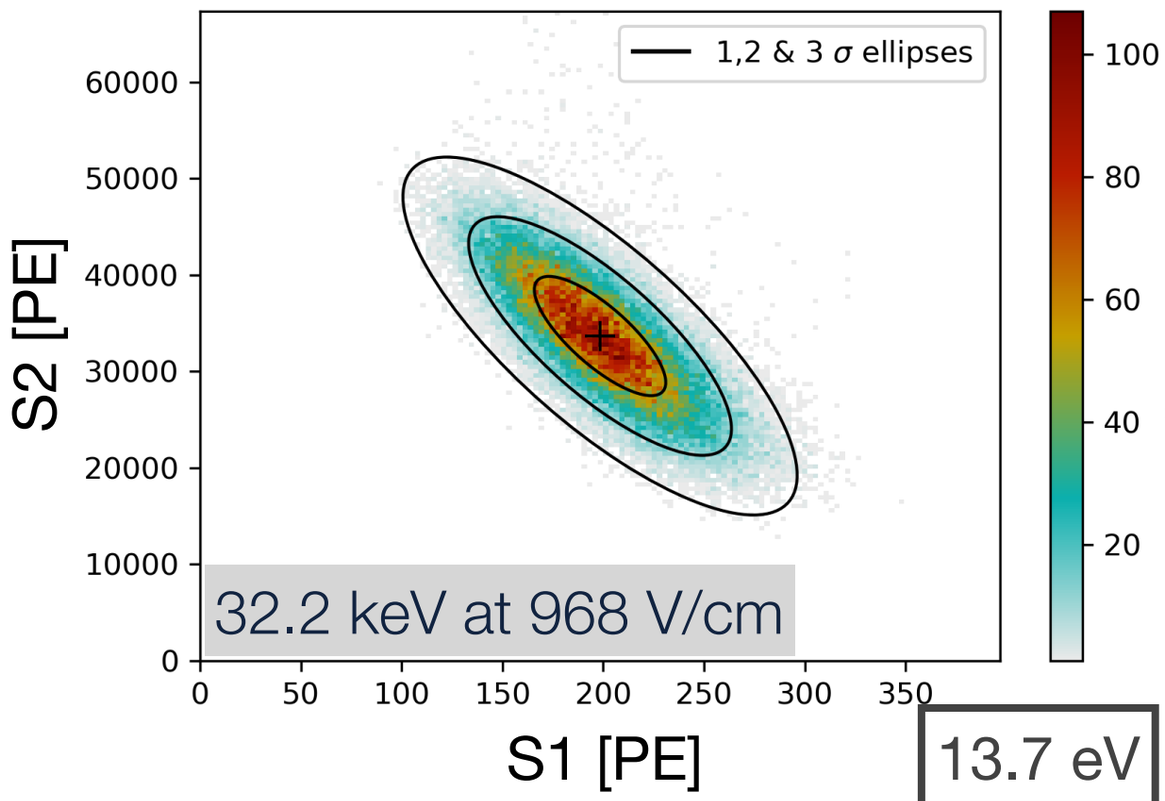
^{83m}Kr – DATA SELECTION AND CUTS

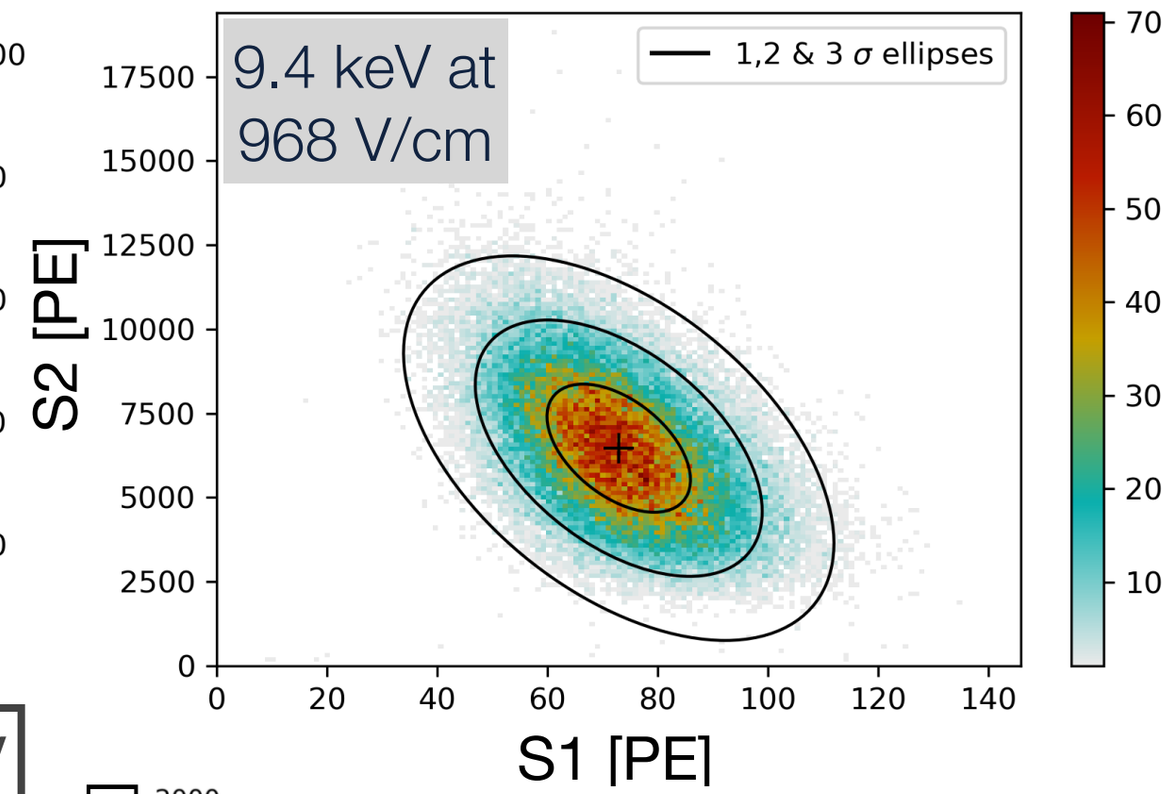


Cuts
#S1 ≥ 2 && #S2 ≥ 2
Difference S1/S2 delays: ±1 σ
S2 width ∈ [97.7,2.3] % Quantile
S2 area fraction top ∈ [0.21,0.31]
S1/S2 delay ∈ [~0.5,~2.0] μs
-25 mm ≤ z ≤ -5 mm; r ≤ 9.7 mm



^{83m}Kr – RESULTS





13.7 eV

- Combined energy scale:

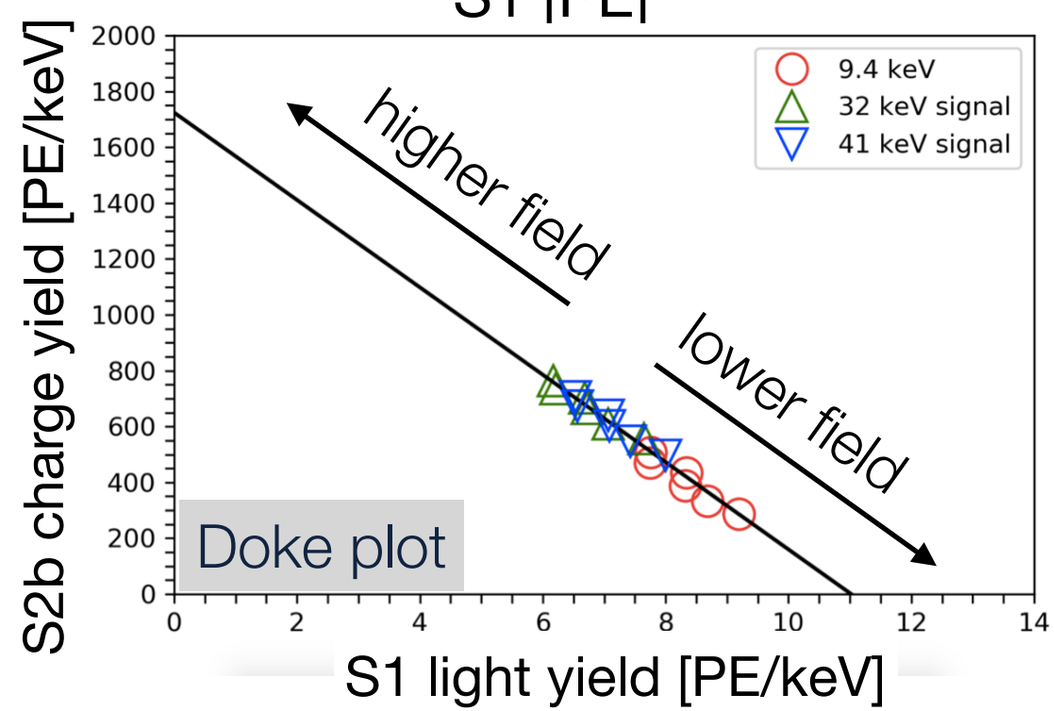
$$E = (N_\gamma + N_{e^-}) \cdot W = \left(\frac{S1}{g1} + \frac{S2}{g2}\right) \cdot W$$

- Detector response parameters:

$$g1 := S1/N_\gamma \qquad g2 := S2/N_{e^-}$$

$$g1 = (0.150 \pm 0.009)\,\mathrm{PE}/\gamma$$

$$g2 = (32.7 \pm 1.1)\,\mathrm{PE}/e^-$$



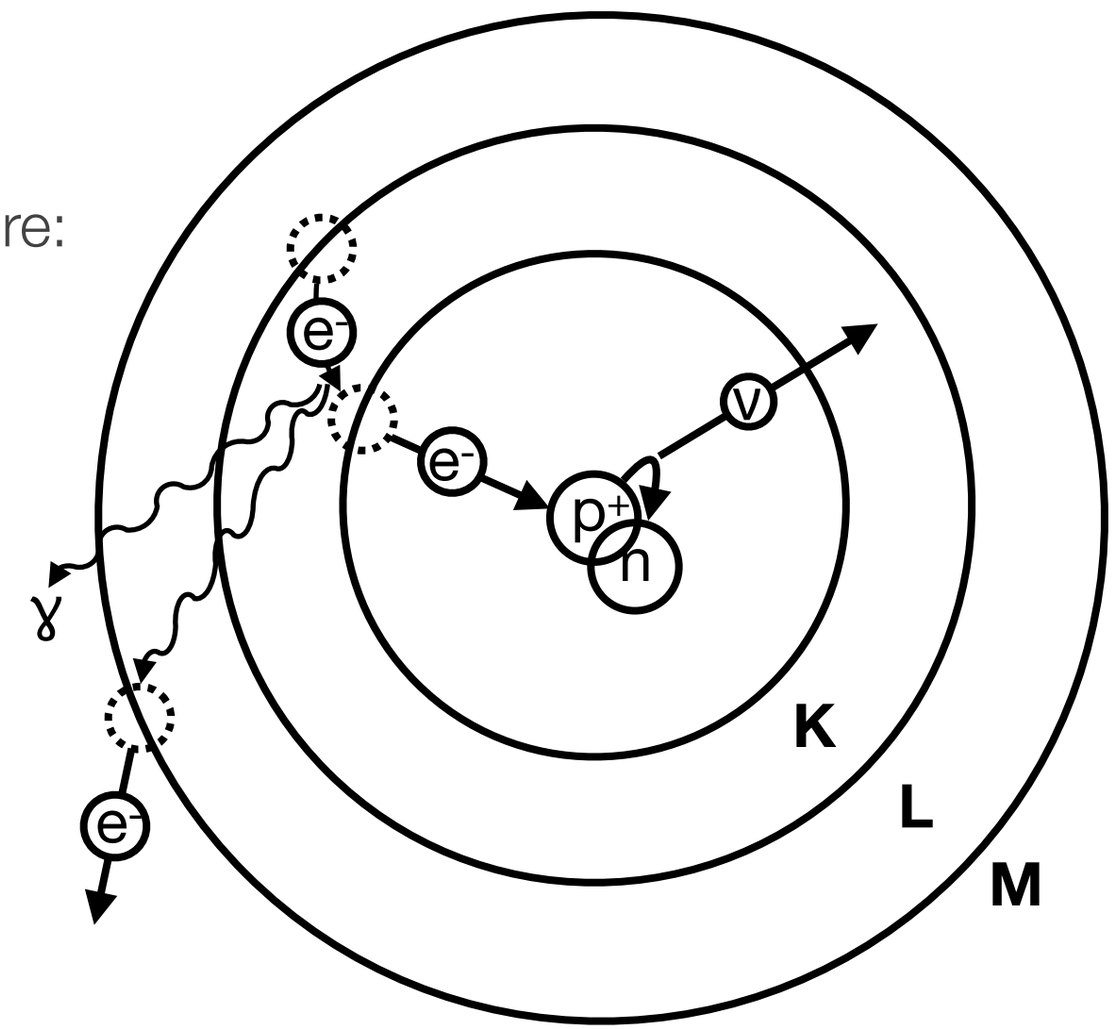
^{37}Ar – MOTIVATION

- Low-keV, internal source, mixed with the xenon
- Moderate half-life: (35.01±0.02) d
- Decays 100 % to stable chlorine by electron capture:

$$e^- + {}^{37}Ar \longrightarrow {}^{37}Cl + \nu_e$$

- Q-value: (813.87±0.20) keV
- Energy release in form of X-rays accompanied by Auger electrons

Decay mode	Energy release [keV]	Branching ratio
K capture	2.8224	90,02 %
L capture	0.2702	8,90 %
M capture	0.0175	0,93 %

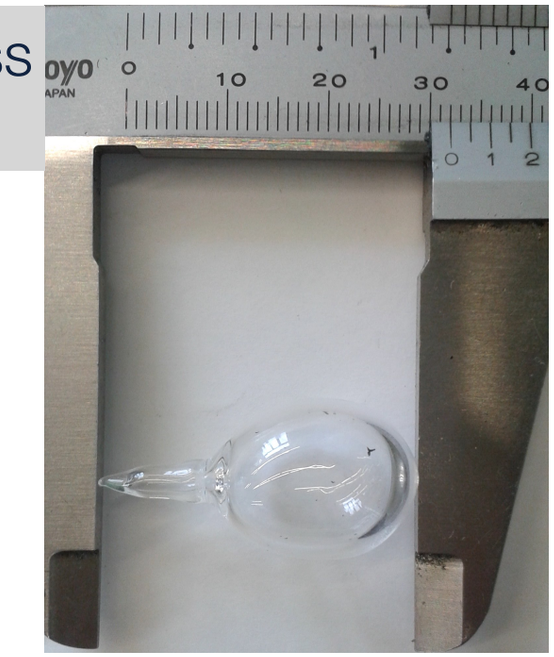


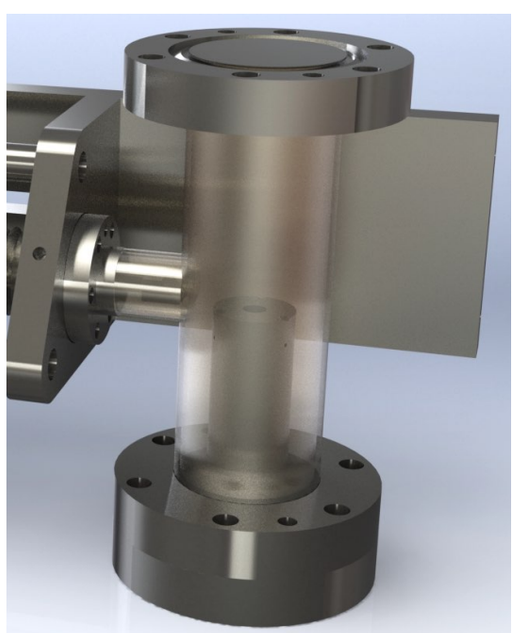
Phys. At. Nucl. **70**, No. 2 (2007).

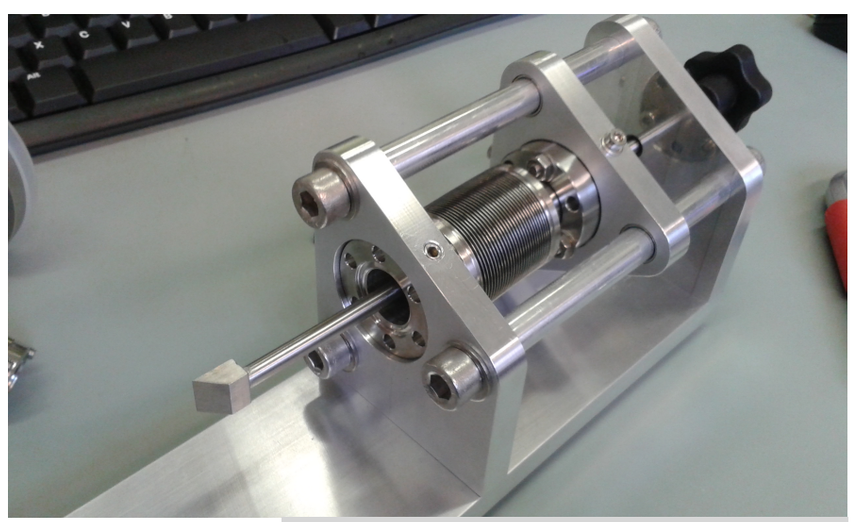
Inspired by C. Hils, Diploma Thesis: *Studie von internen Kalibrationsmethoden für Flüssig-Xenon TPCs zur direkten Suche nach Dunkler Materie*

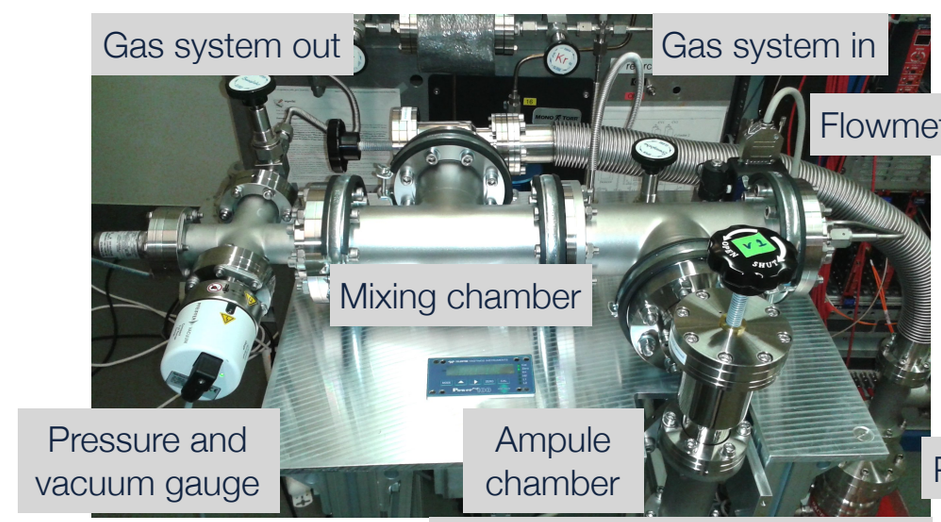
^{37}Ar – SOURCE PRODUCTION AND INTRODUCTION

- Via thermal neutron capture on ^{36}Ar(n,ɣ): ~5 barn
- Use natural argon: 0.334 % abundance of ^{36}Ar
- 1.5 cm^3 at 0.9 bar per quartz glass ampule (8 µg ^{36}Ar)
- Swiss Spallation Neutron Source at Paul Scherrer Institute Villigen, Switzerland: 10^{13} neutrons cm^{-2}s^{-1}, 13500 s
- Estimated initial activity per ampule (4 in total): 20-22 kBq



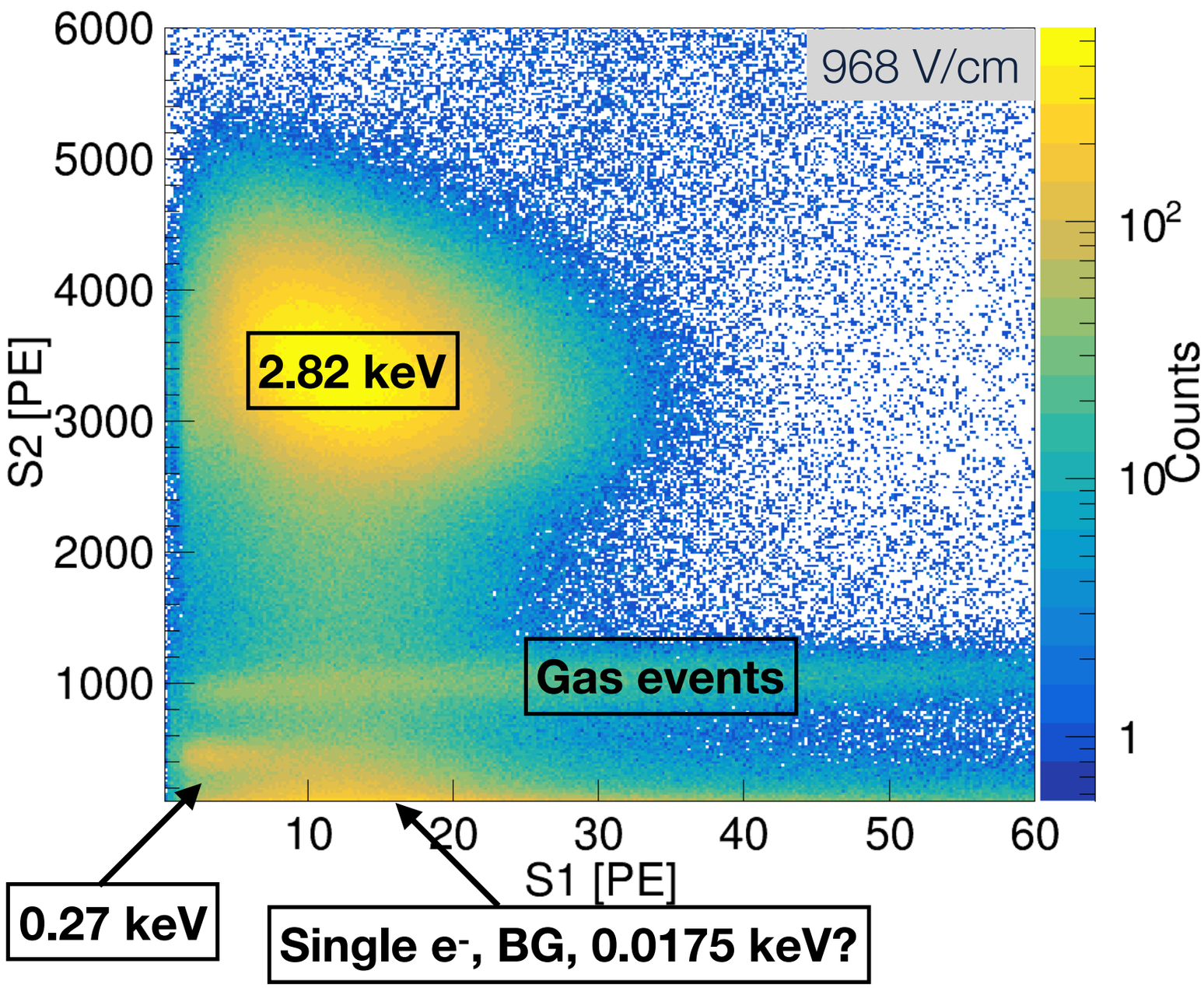

Ampule holder


Breaking mechanism



Introduction setup

^{37}Ar – POPULATION AND CUTS



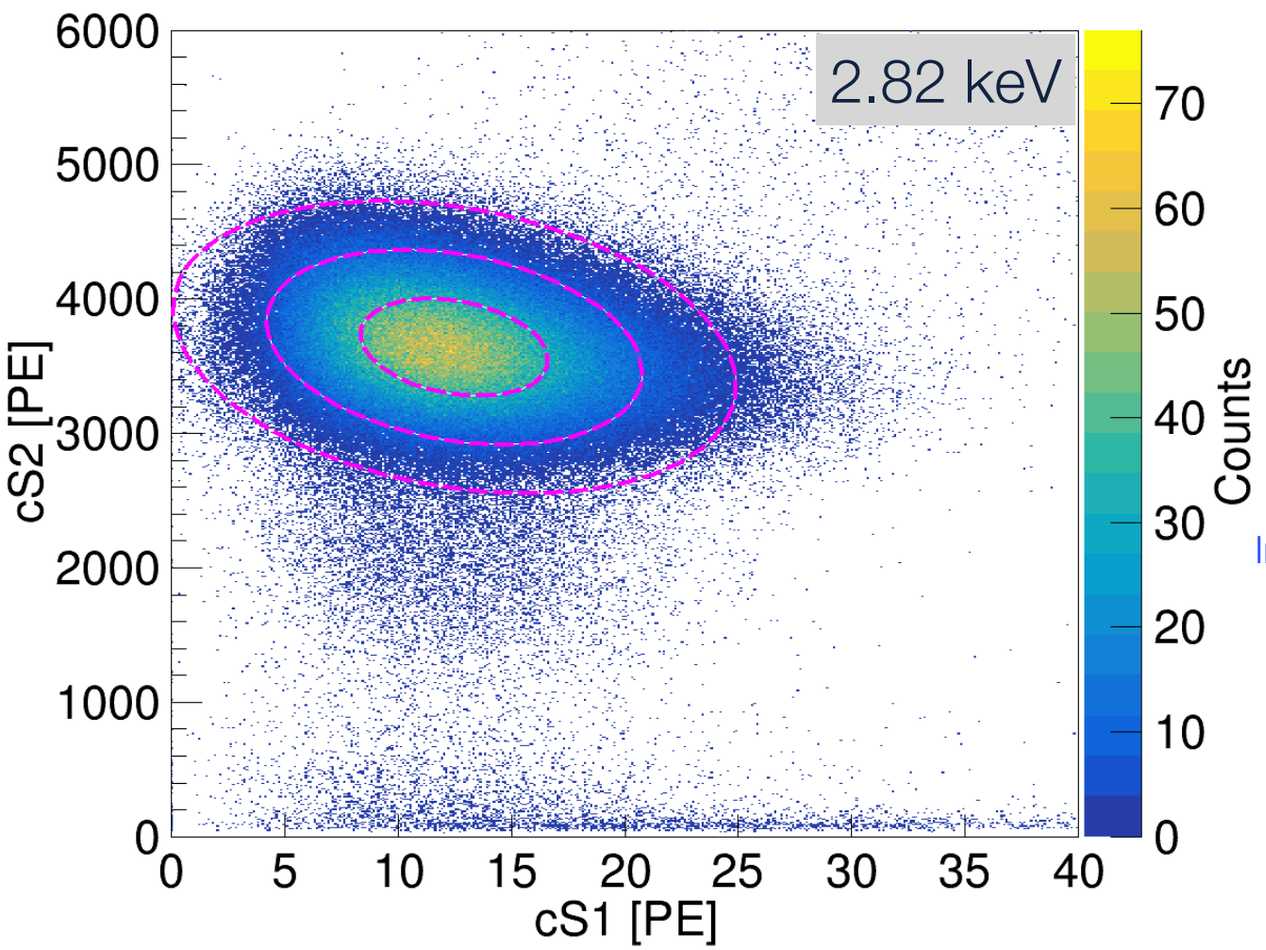
- Estimated activity introduced into the detector: 2.7 kBq -> 200 Bq inside the TPC

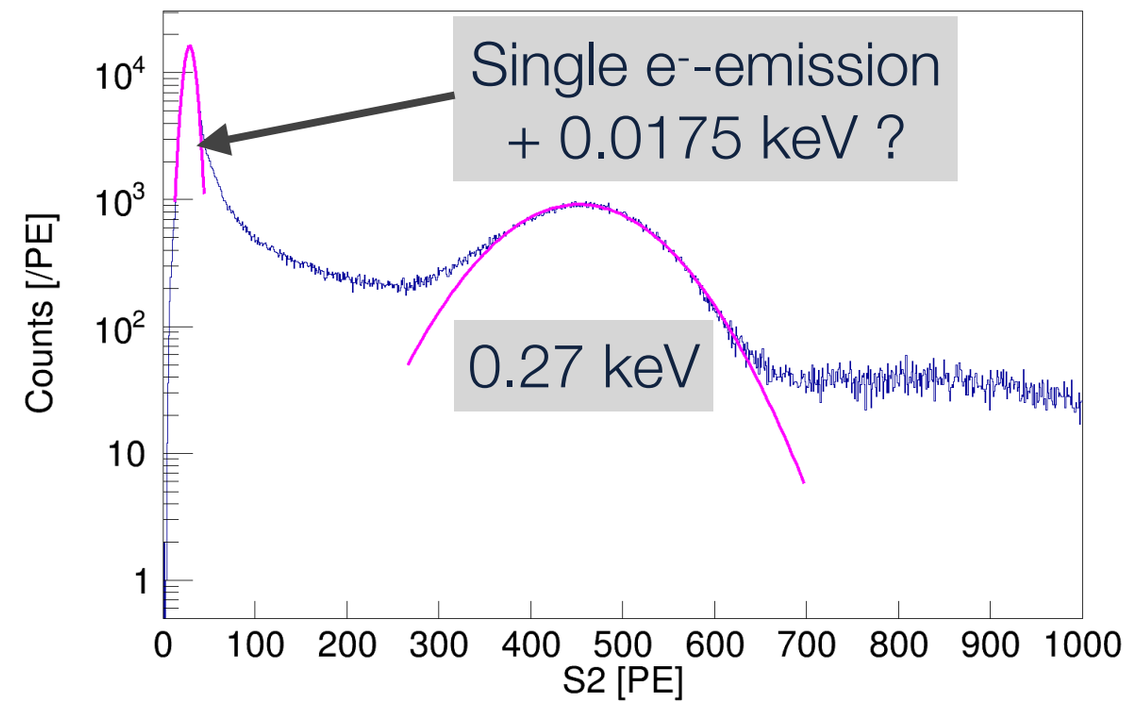
Cuts
Saturation cut
Single Scatter Cut
-29 mm ≤ z ≤ -2 mm; r ≤ 10 mm
S2 area fraction top ∈ [0.14,0.32]
S2 width ∈ [95,5] % Quantile

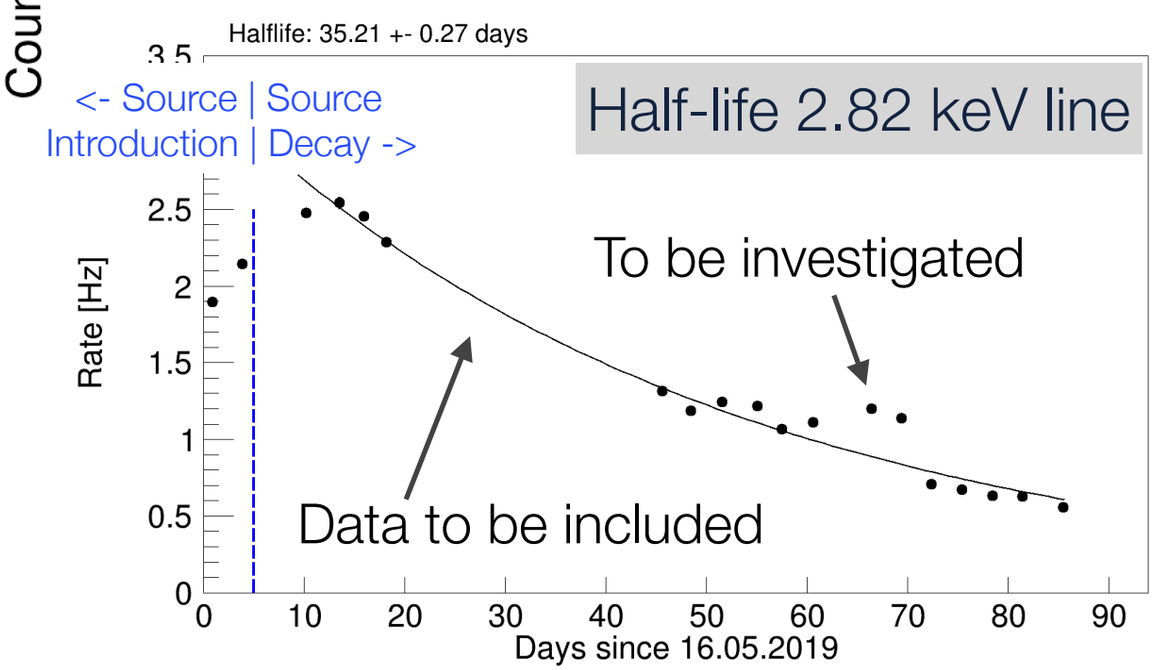
PRELIMINARY!

^{37}Ar – RESULTS

- Light yield: (4.4 ± 1.4) PE/keV
- Charge yield: (1290 ± 129) PE/keV







- $T_{1/2}$ = (35.21 ± 0.27) d

-> Literature: (35.01 ± 0.02) d

SUMMARY AND OUTLOOK

- First working dual-phase xenon TPC with SiPM array
- Operating under stable conditions over almost one year
- ^{83m}Kr- and ^{37}Ar-calibrations successfully performed
- Finalise ^{37}Ar-analysis (all drift fields, g1 & g2, low-S2-only-population, diffusion during source injection,…) and compare to ^{83m}Kr
- Coming soon: NEST-comparison
- Plan for the next months: Upgrade with SiPM bottom array to check cryogenic behaviour of pre-amplifier board and work on channel clustering as well as triggering

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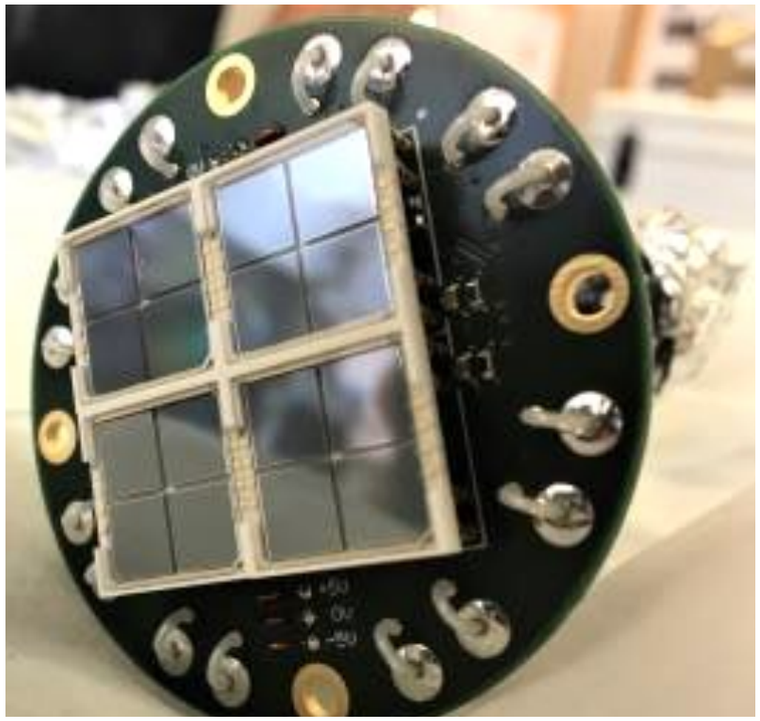
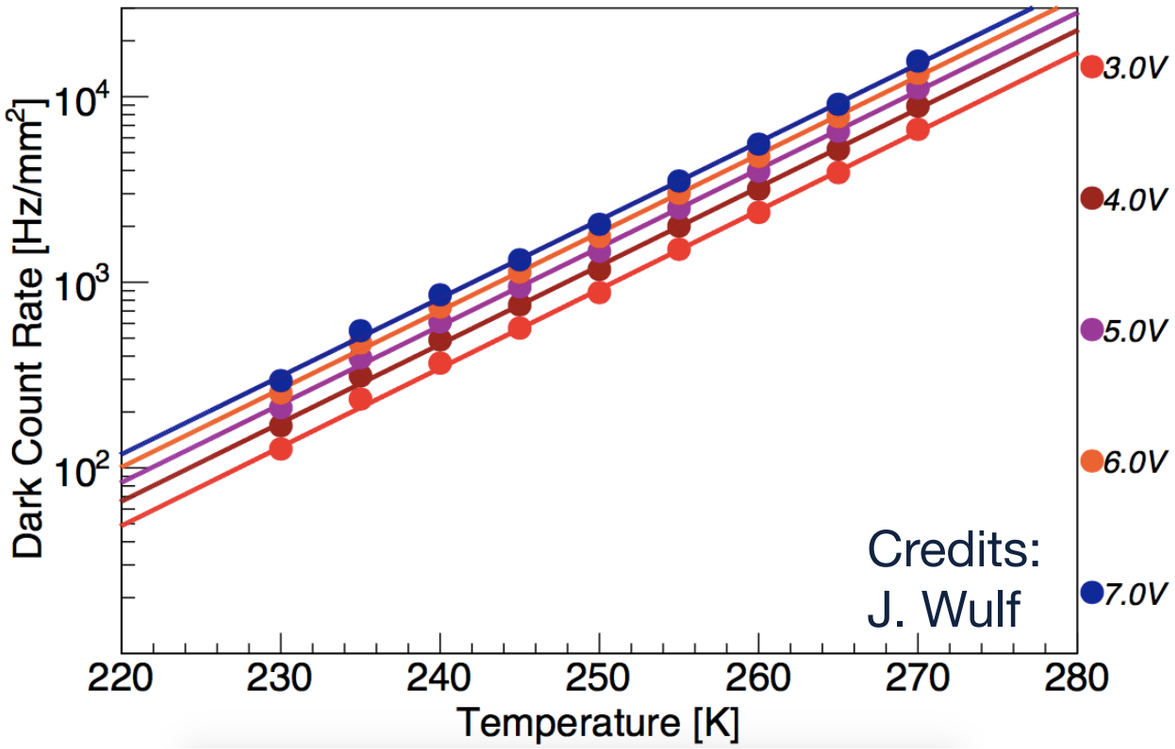
THANK YOU FOR YOUR ATTENTION!

BACKUP

TOP ARRAY OF SILICON PHOTOSENSORS

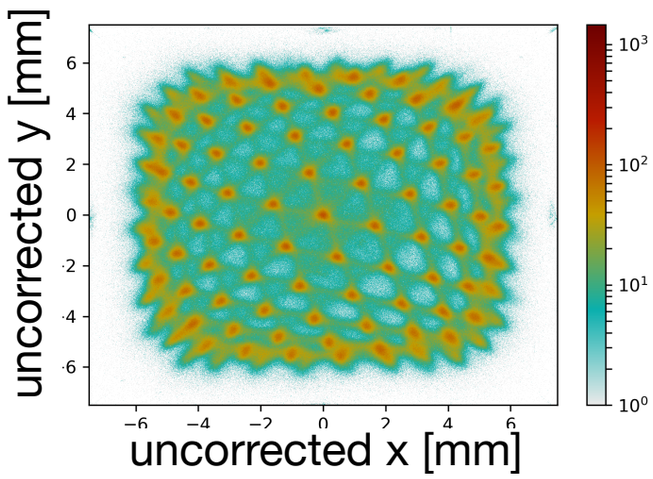
- 2 × 2 S13371 VUV-4 MPPCs (12 × 12) mm^2 from Hamamatsu, each has 4 (6 × 6) mm^2 independent segments, (50 × 50) μm^2 cells
- 10× low-noise non-inverting feedback operational amplifier
- Operational voltage: 51.5 V
- Photon detection efficiency ~24 % at 178 nm
- Gain ~3.1×10^6
- Dark Count Rate: 0.8 Hz/mm^2 at LXe temperature
- Optical Crosstalk Probability ~3 %

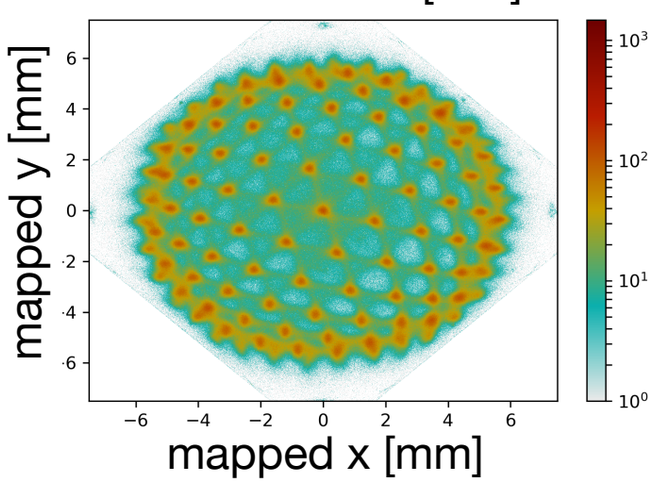


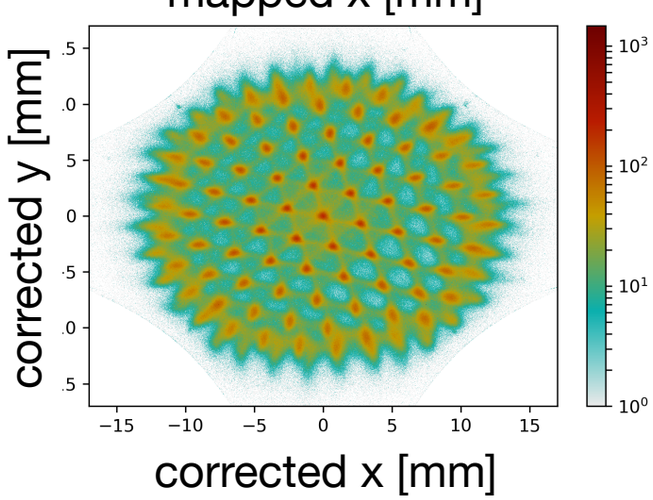


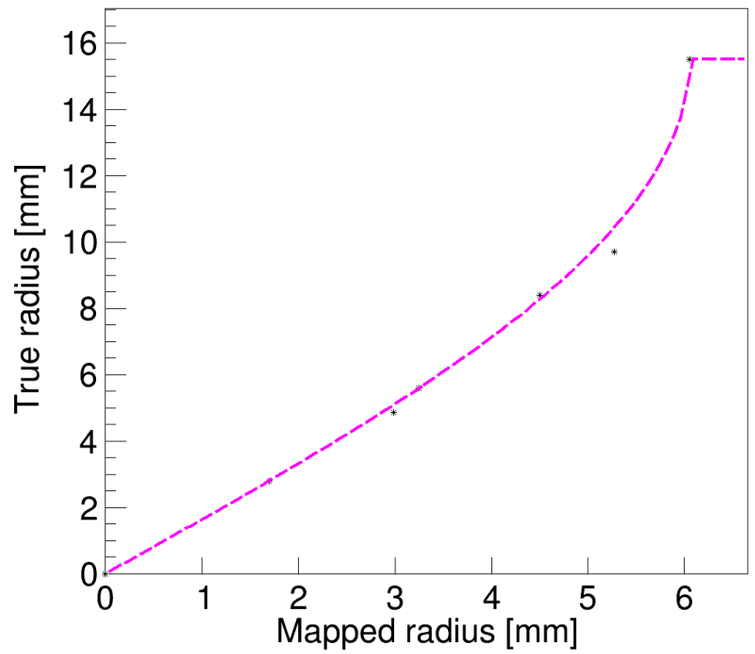
JINST 13 (2018) P10022

EVENT POSITION RECONSTRUCTION II









$$x_{\text{uncorrected}} = \frac{1}{\sum_{i=0}^{15} S_2^i} \sum_{i=0}^{15} S_2^i * x_i$$

$$y_{\text{uncorrected}} = \frac{1}{\sum_{i=0}^{15} S_2^i} \sum_{i=0}^{15} S_2^i * y_i$$

$$y_{\text{scaled}} = (y_{\text{uncorrected}} - \Delta_y)/c$$

$$x_{\text{scaled}} = (x_{\text{uncorrected}} - \Delta_x)/c$$

$$y_{\text{mapped}} = c * y_{\text{scaled}} * \sqrt{1 - \frac{1}{2} x_{\text{scaled}}^2}$$

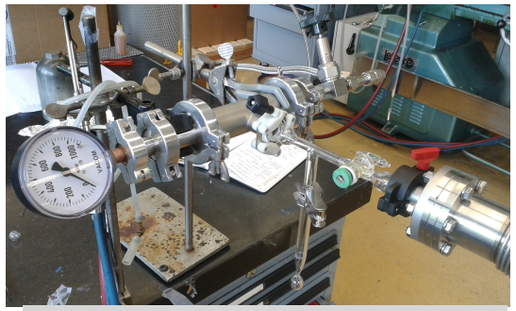
$$x_{\text{mapped}} = c * x_{\text{scaled}} * \sqrt{1 - \frac{1}{2} y_{\text{scaled}}^2}$$

$$x_{\text{corrected}} = \frac{\frac{-d_{\text{TPC}}}{\pi} \arccos\left(\frac{r_{\text{mapped}}}{r_{\text{mapped,max}}}\right) + \frac{d_{\text{TPC}}}{2}}{r_{\text{mapped}} * x_{\text{mapped}}}$$

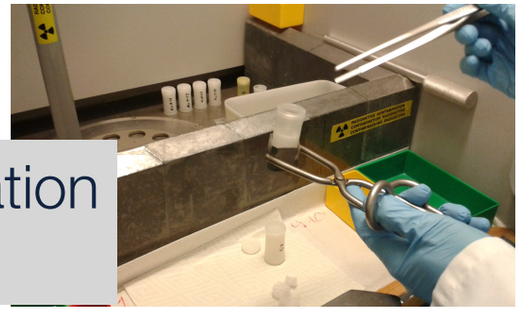
$$y_{\text{corrected}} = \frac{\frac{-d_{\text{TPC}}}{\pi} \arccos\left(\frac{r_{\text{mapped}}}{r_{\text{mapped,max}}}\right) + \frac{d_{\text{TPC}}}{2}}{r_{\text{mapped}} * y_{\text{mapped}}}$$

^{37}Ar – SOURCE PRODUCTION AND INTRODUCTION II

Isotope	Abundance	Half-life	Decay mode	Product
^{36}Ar	0.334%	stable	-	-
^{37}Ar	syn	35.01 d	ε	^{37}Cl
^{38}Ar	0.063%	stable	-	-
^{39}Ar	trace	269 y	β^-	^{39}K
^{40}Ar	99.604%	stable	-	-
^{41}Ar	syn	109.34 min	β^-	^{41}K

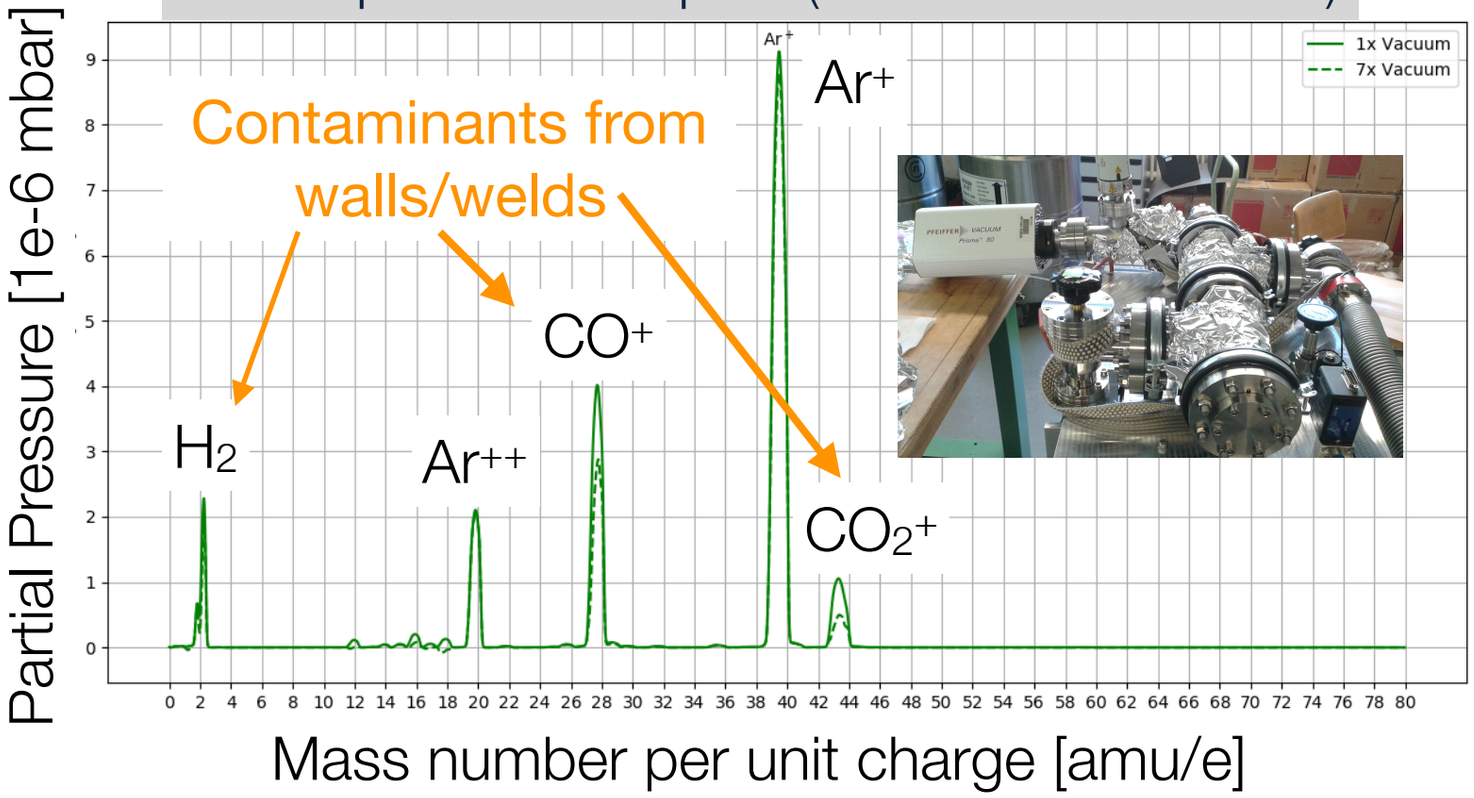


Argon filling setup



Sample preparation for activation

RGA Spectrum Ampule (Vacuum subtracted)

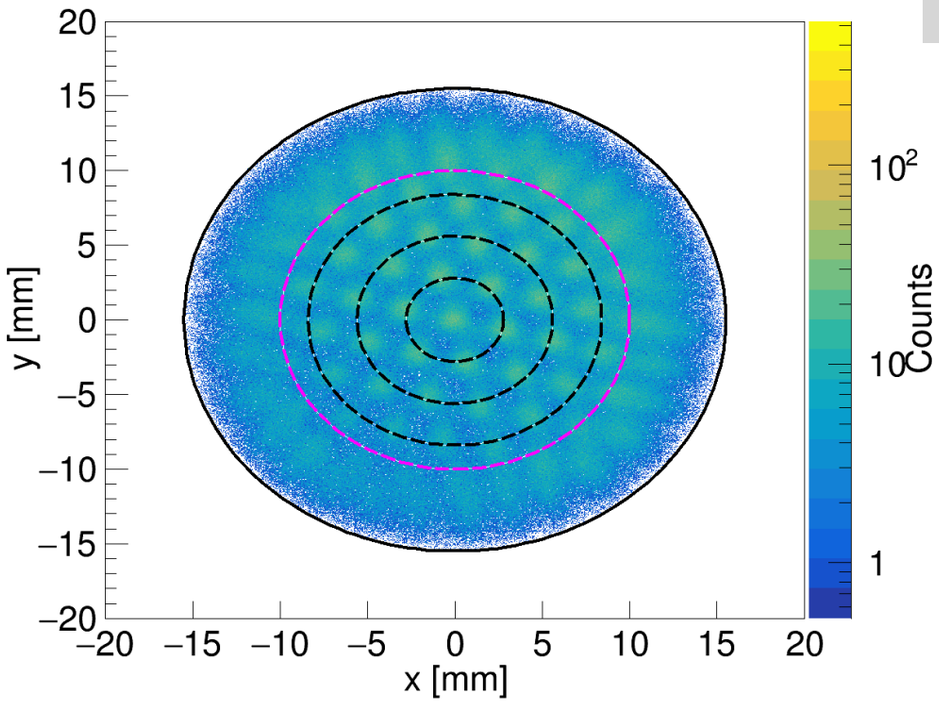


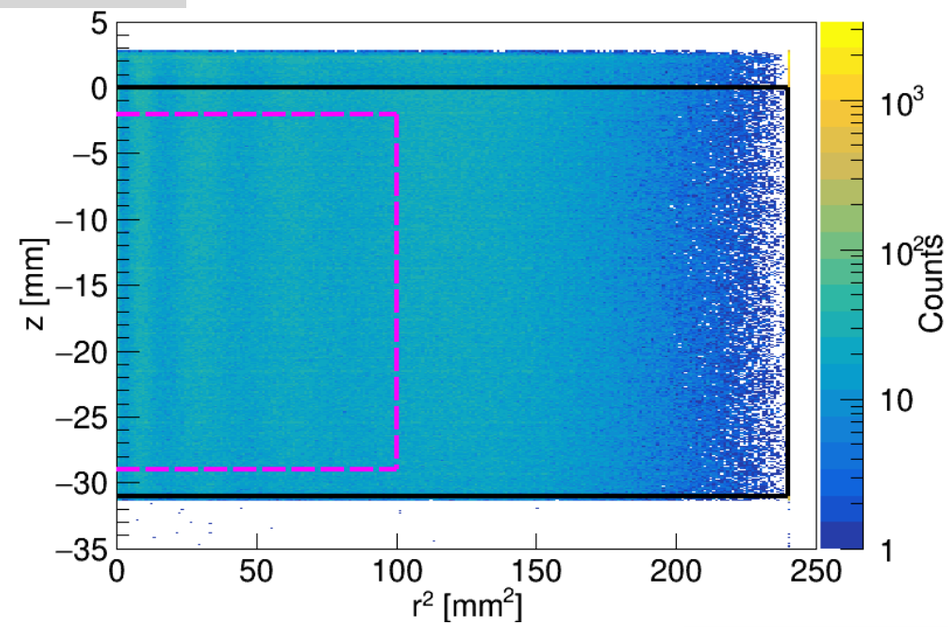
Packaged activated samples

Filter in ampule chamber

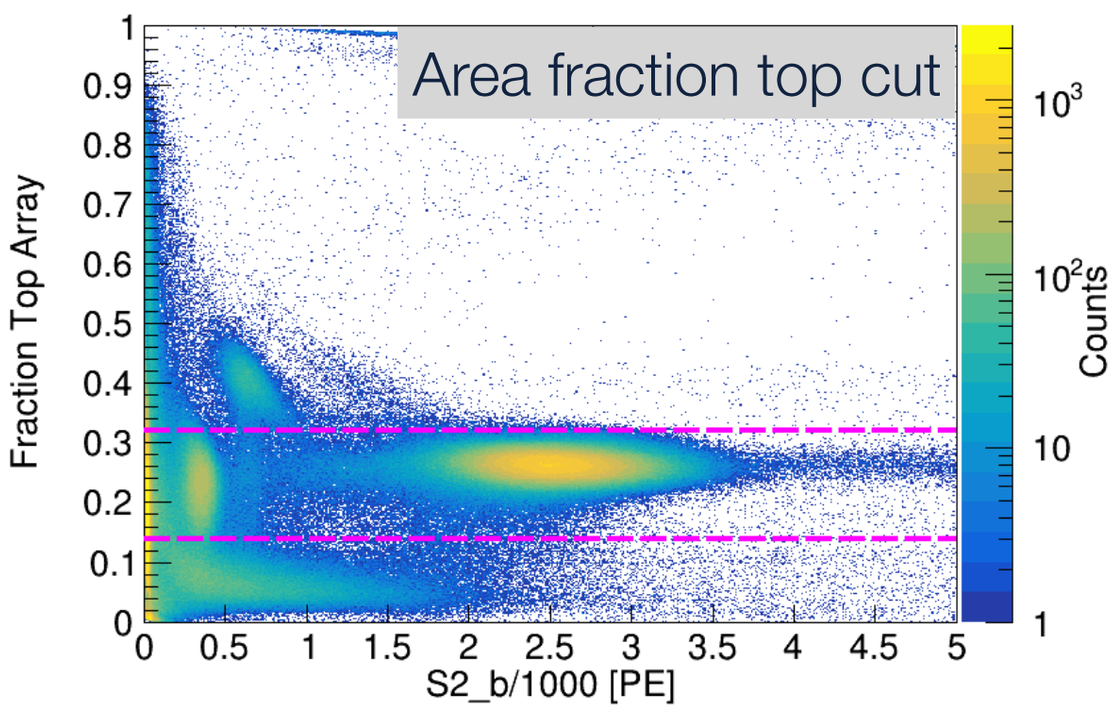
^{37}Ar – CUTS

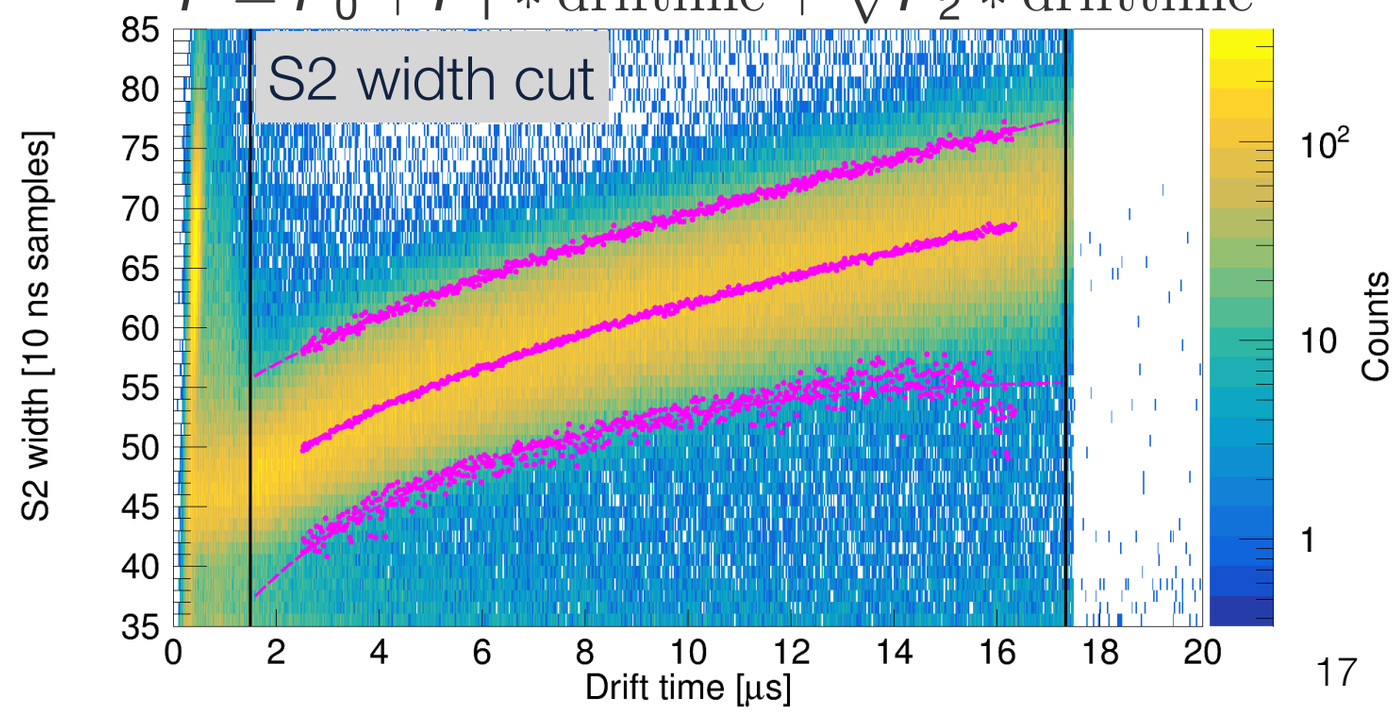
Fiducial volume cut



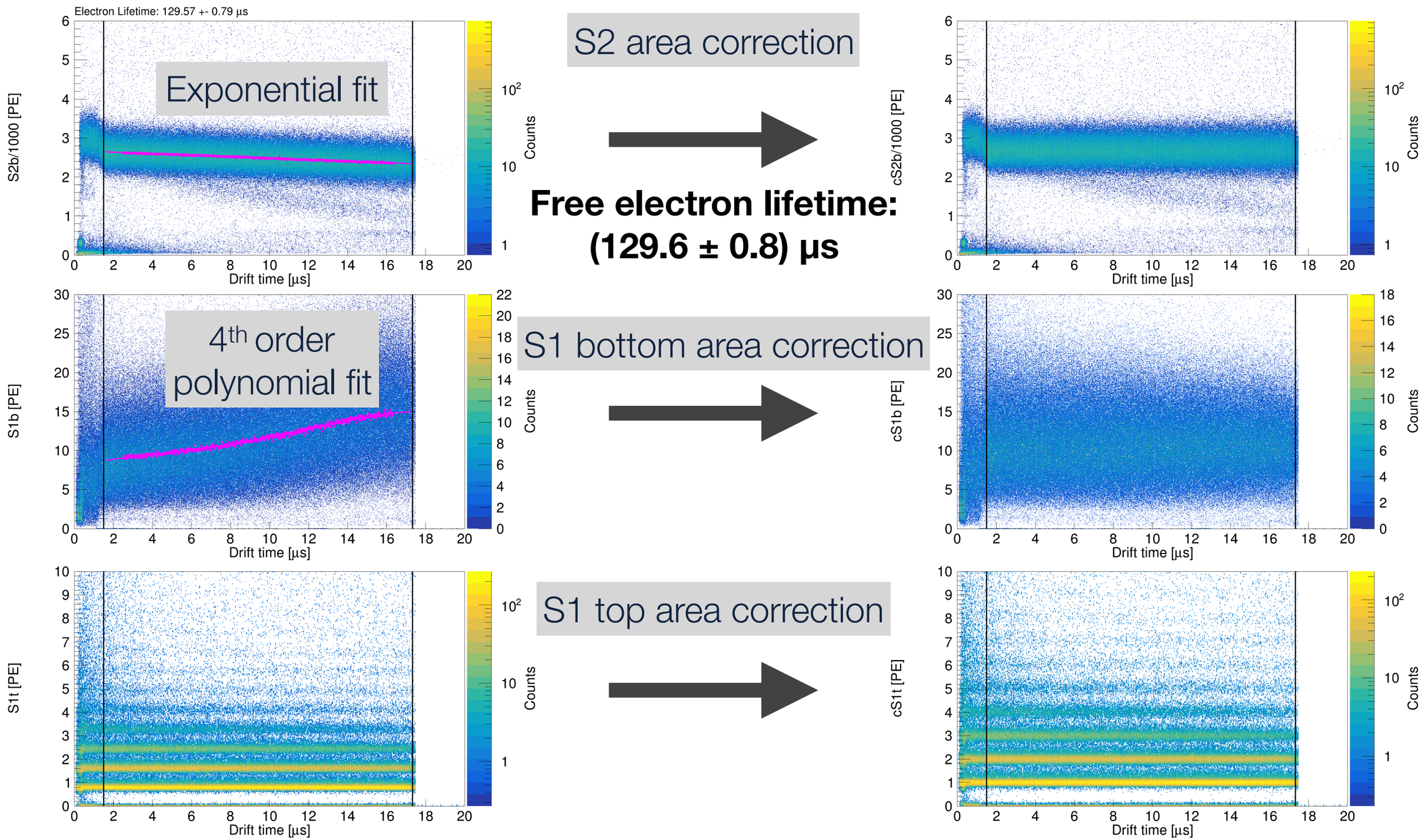


$$F = P_0 + P_1 * \text{driftime} + \sqrt{P_2 * \text{drifttime}}$$



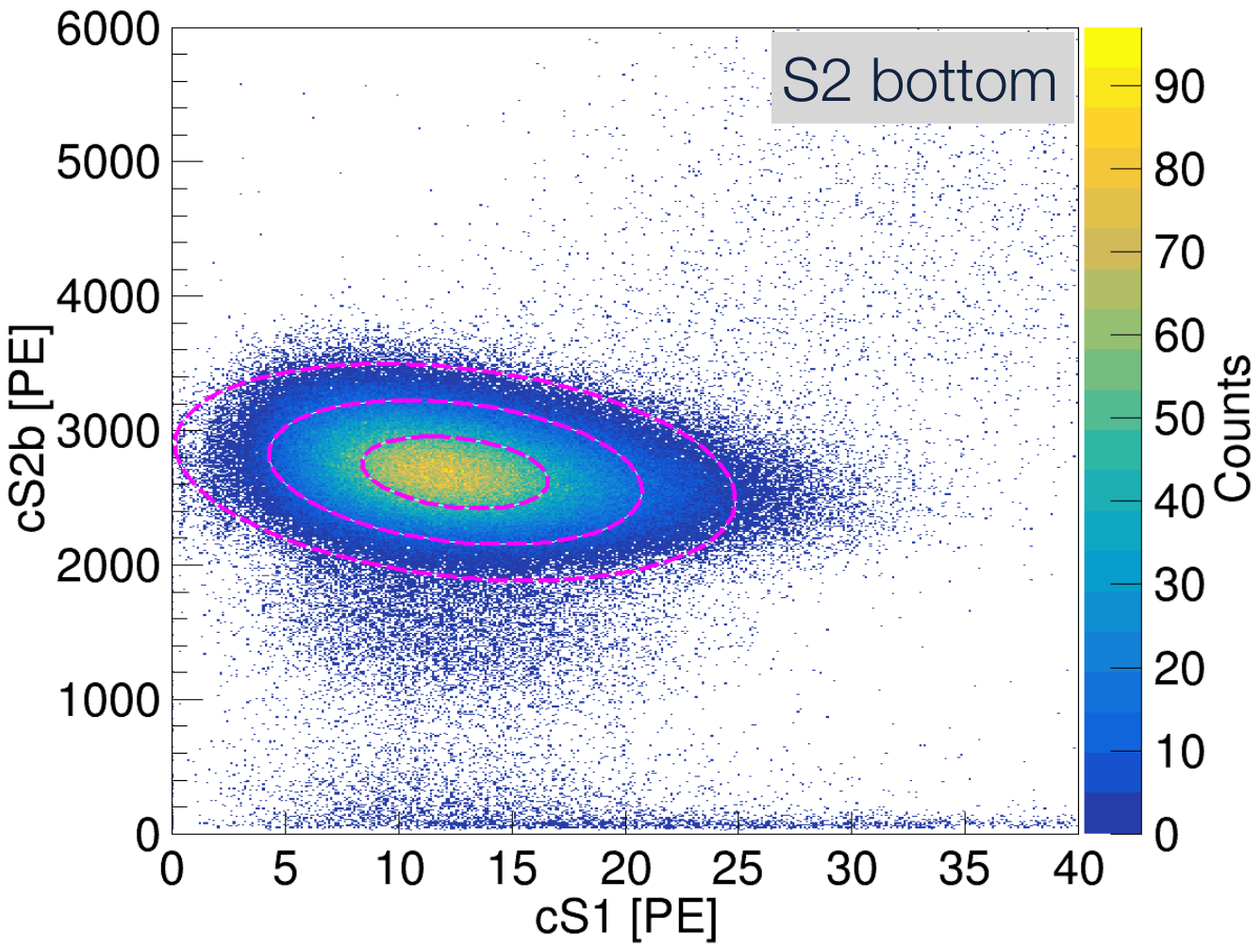


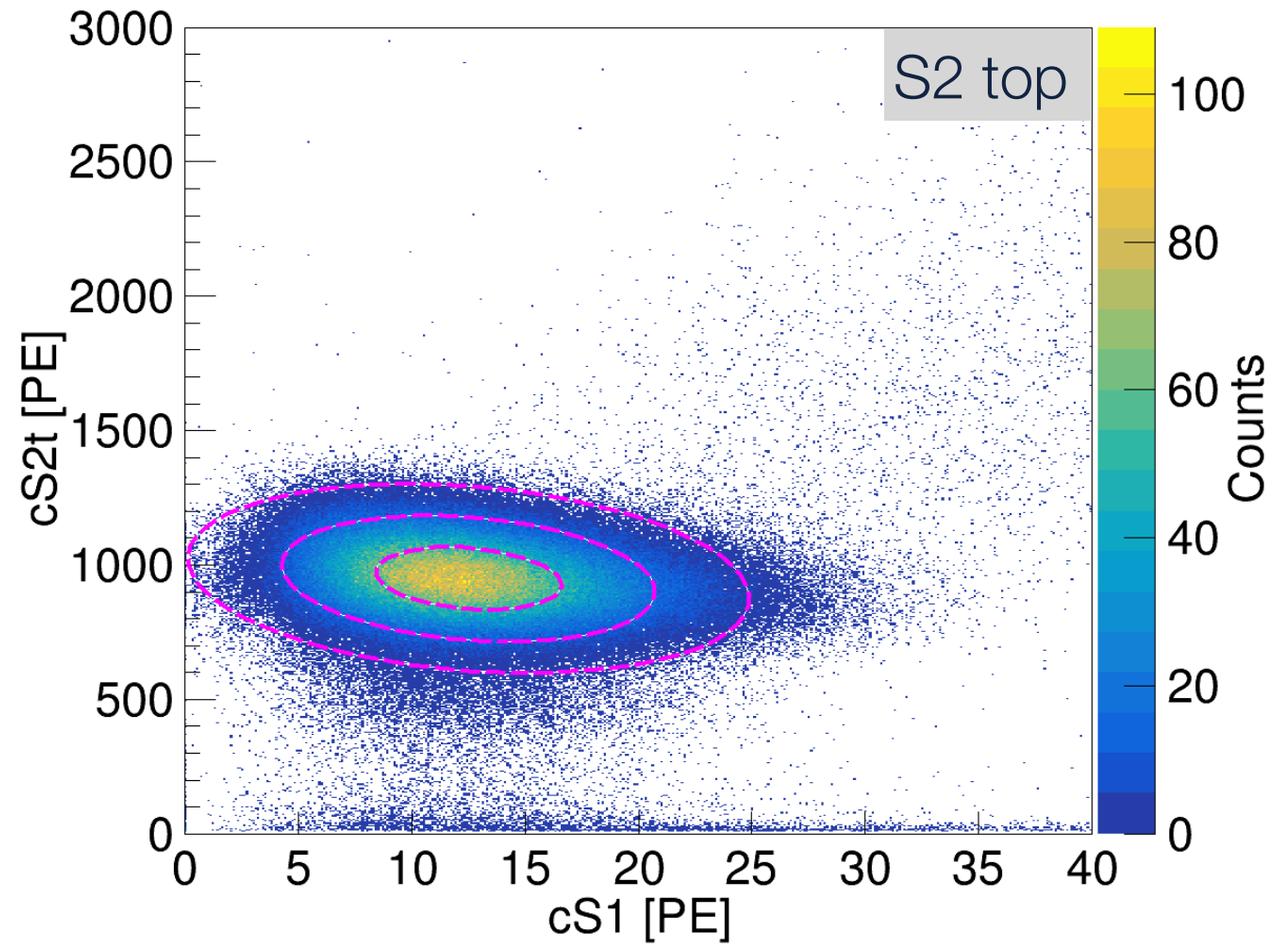
^{37}Ar – CORRECTIONS



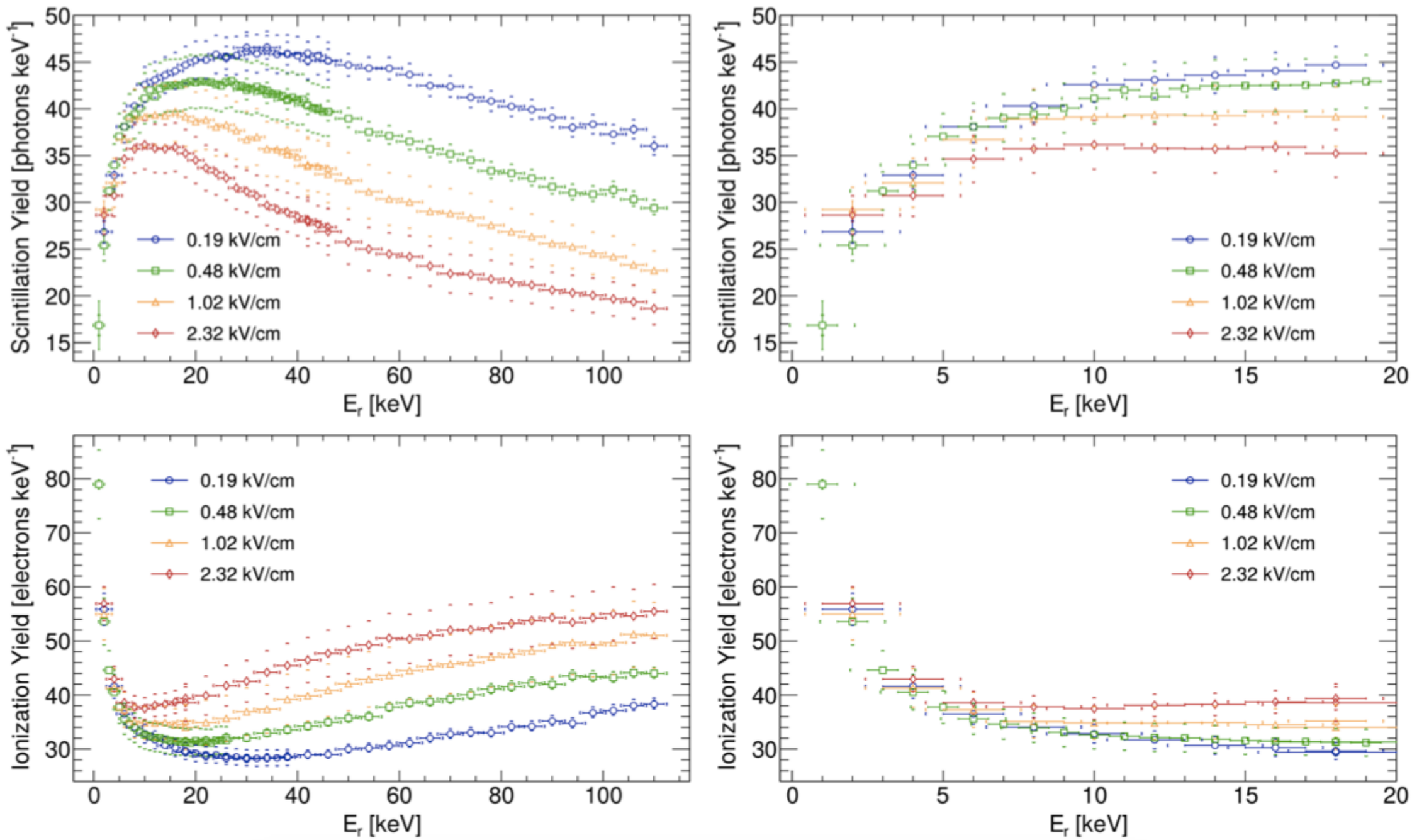
Free electron lifetime: (129.6 ± 0.8) µs

^{37}Ar – RESULTS II





LIGHT AND CHARGE YIELD AT LOW ENERGIES



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