Universität Zürich[UZH]

European Research Council
Established by the European Commission

DARWIN

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

Kevin Thieme
University of Zurich

Zurich PhD Seminar 2019
PSI Villigen, 9.–10. October 2019

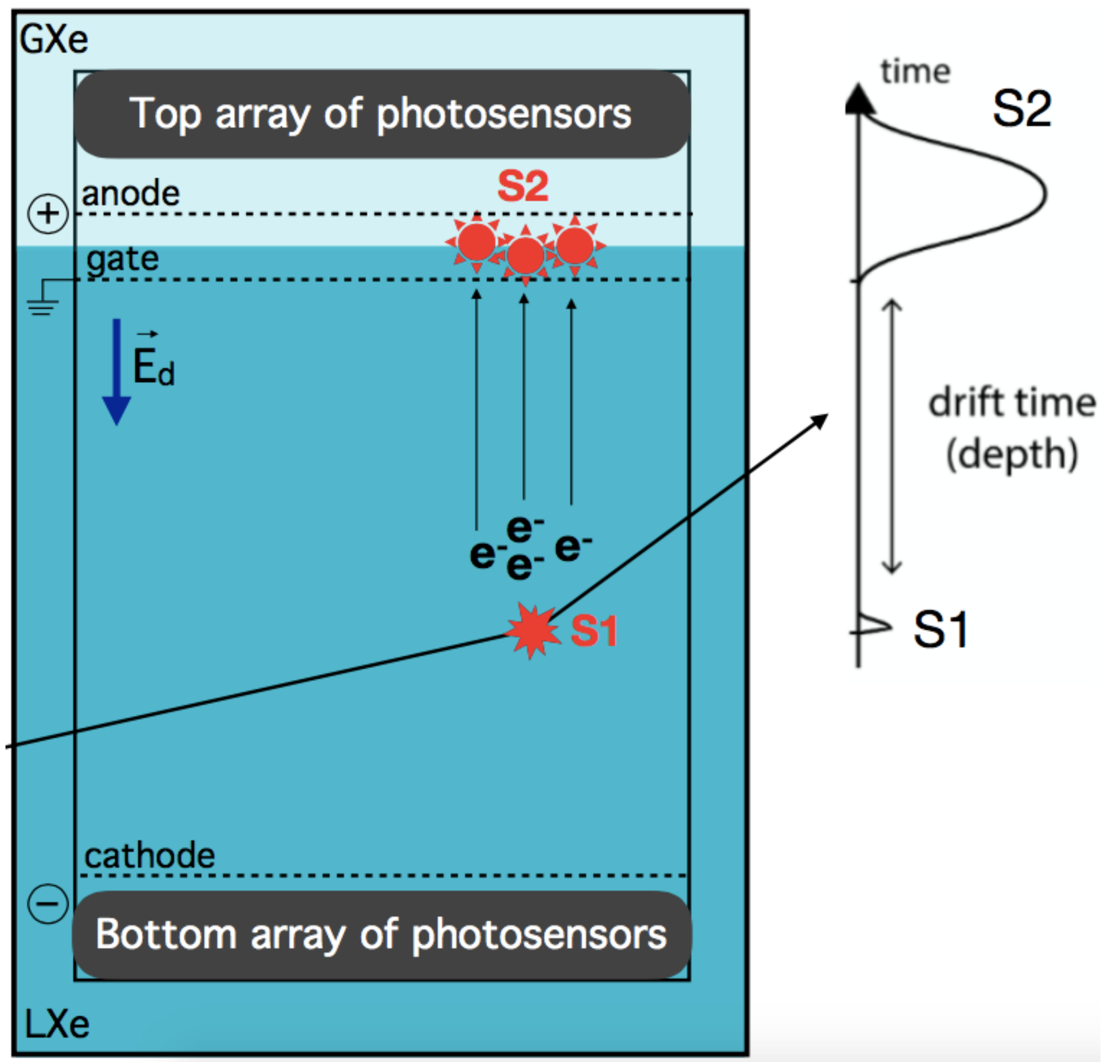
www.darwin-observatory.org

INTRODUCTION AND MOTIVATION

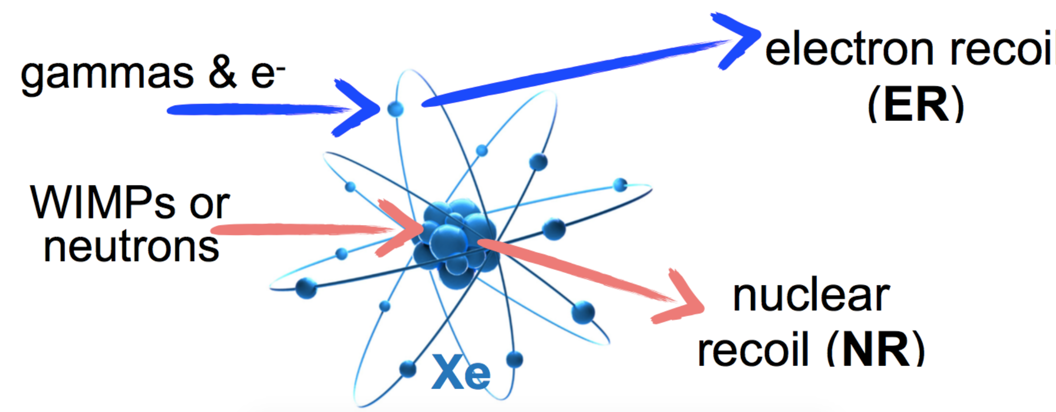
DUAL-PHASE XENON TIME PROJECTION CHAMBER

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

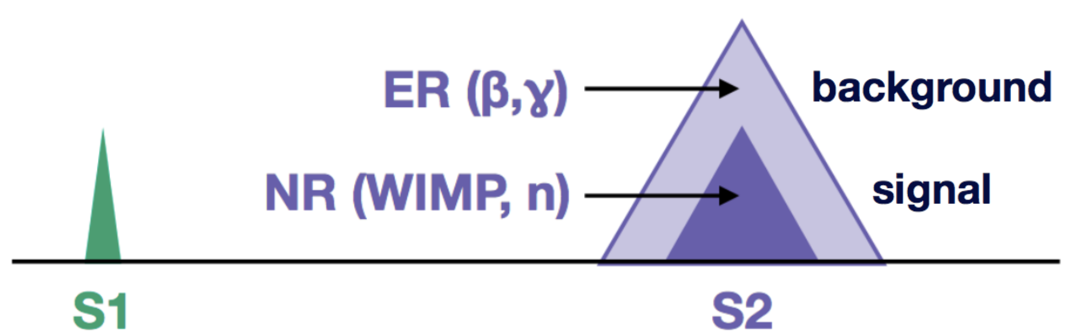


Particle interactions



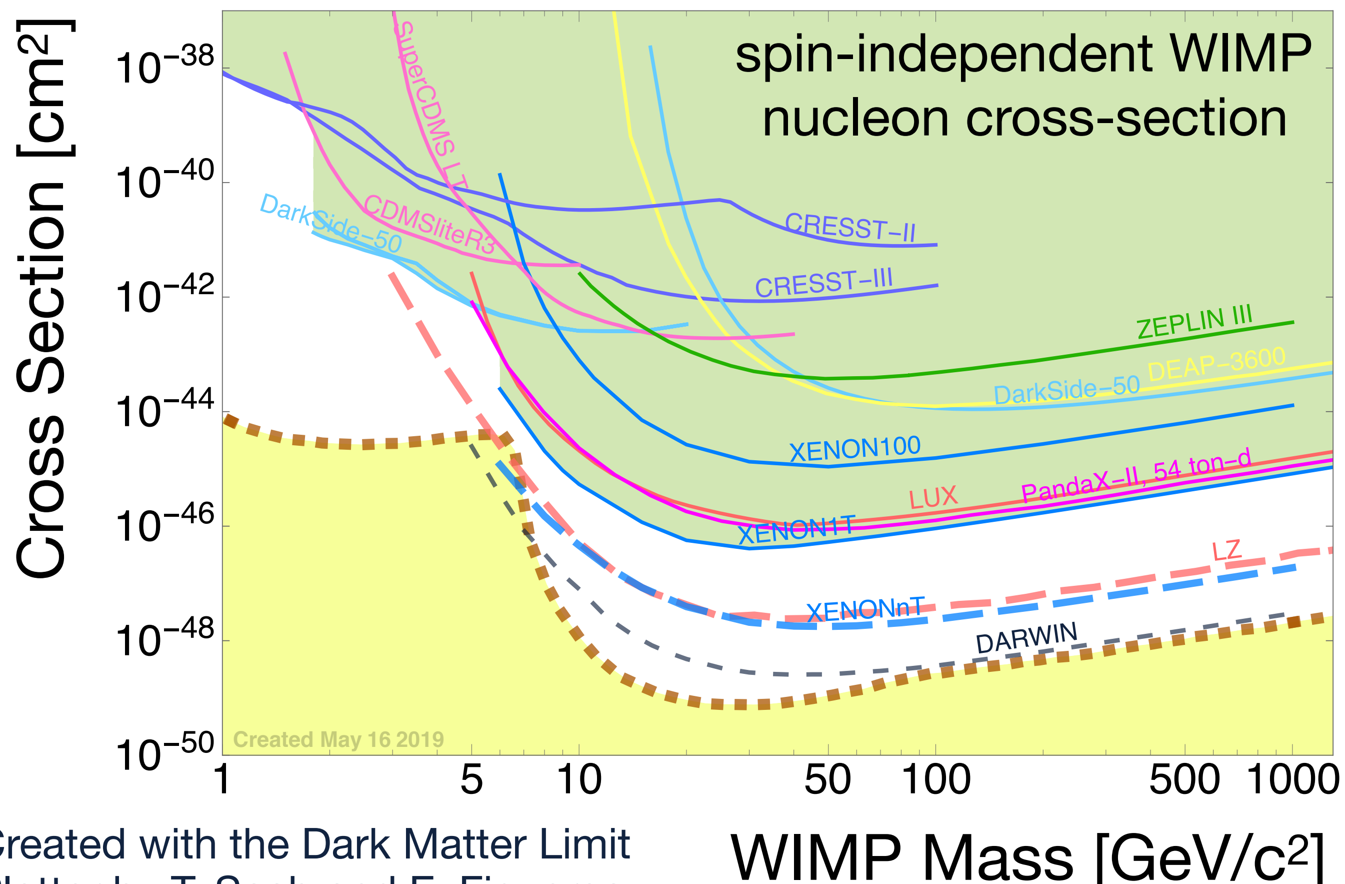
Particle type discrimination

- 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 talk by F. Girard earlier!

Photosensors in TPCs

Bulkiness

Radioactivity

Longterm stability

Position resolution

High operation voltage

Cost

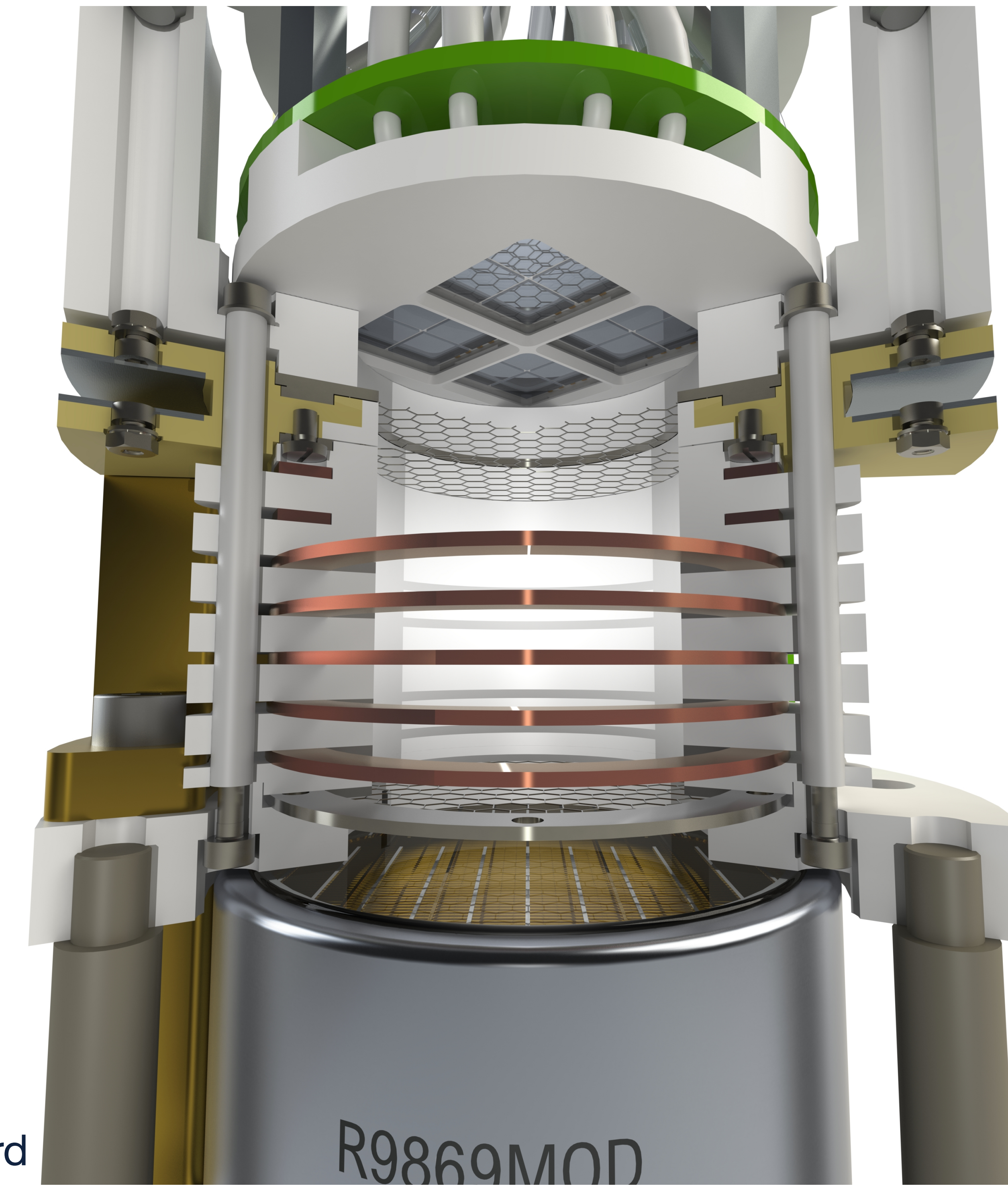
Dark Count Rate

- Traditionally: Photomultiplier tubes
- Under consideration: Silicon Photomultipliers

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 11 months of stable operation



Credits:
A. James, F. Girard

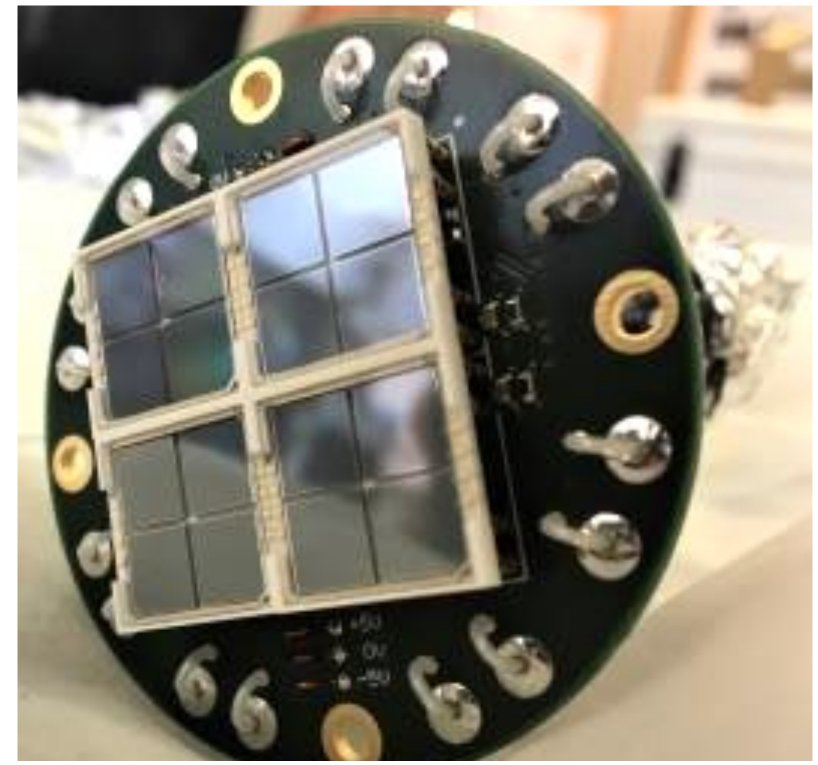
Eur. Phys. J. C78 (2018) 351

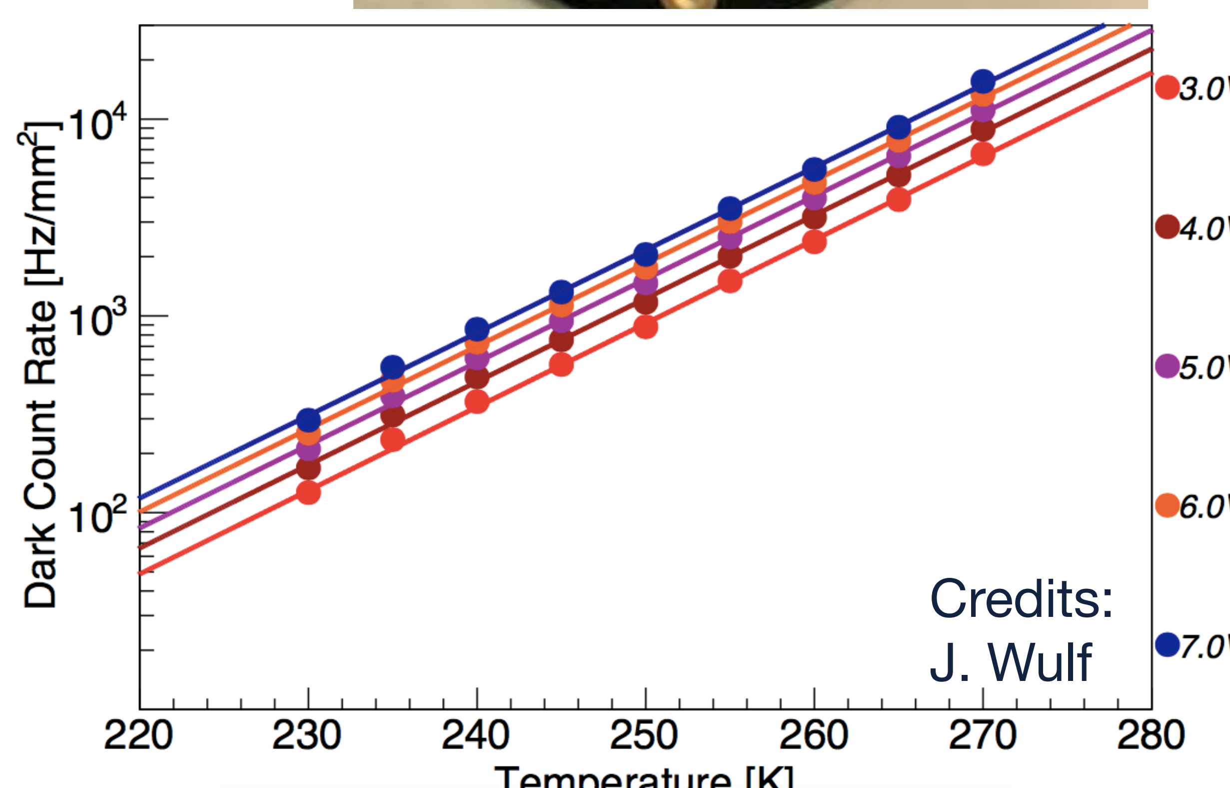
TOP ARRAY OF SILICON PHOTOSENSORS

- 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 &

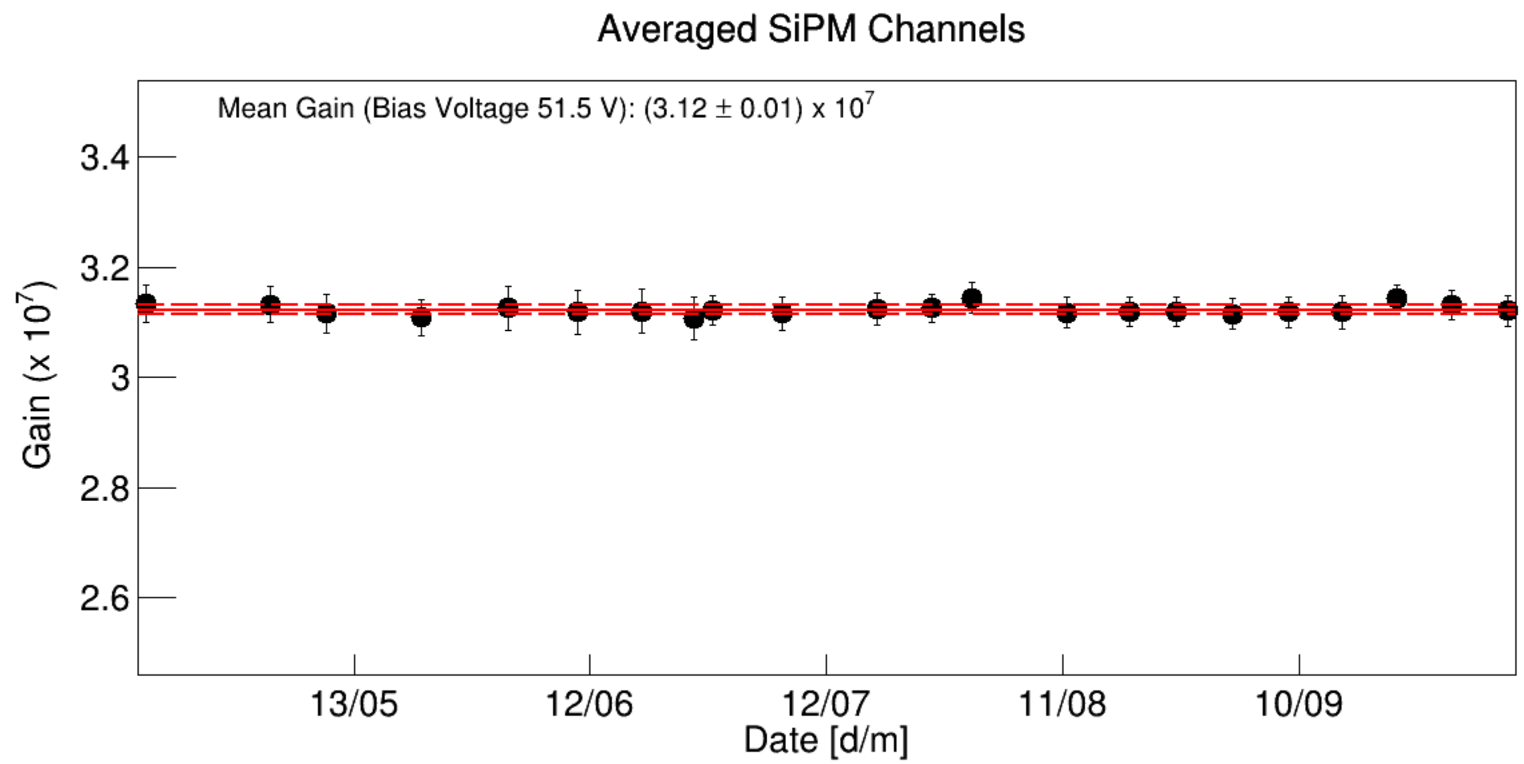
J. Wulf's talk at last PhD Seminar

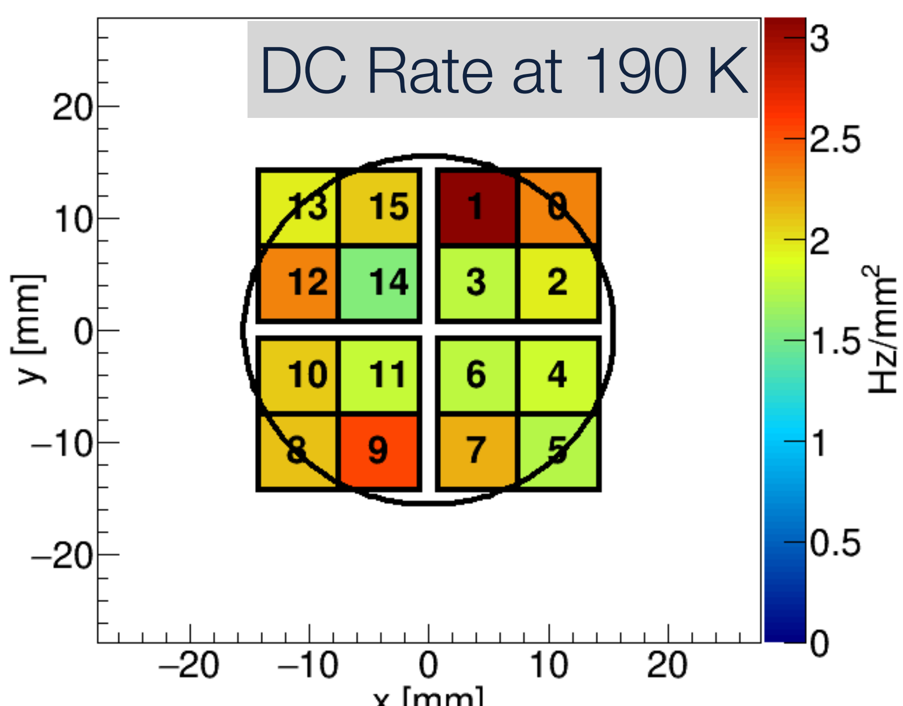


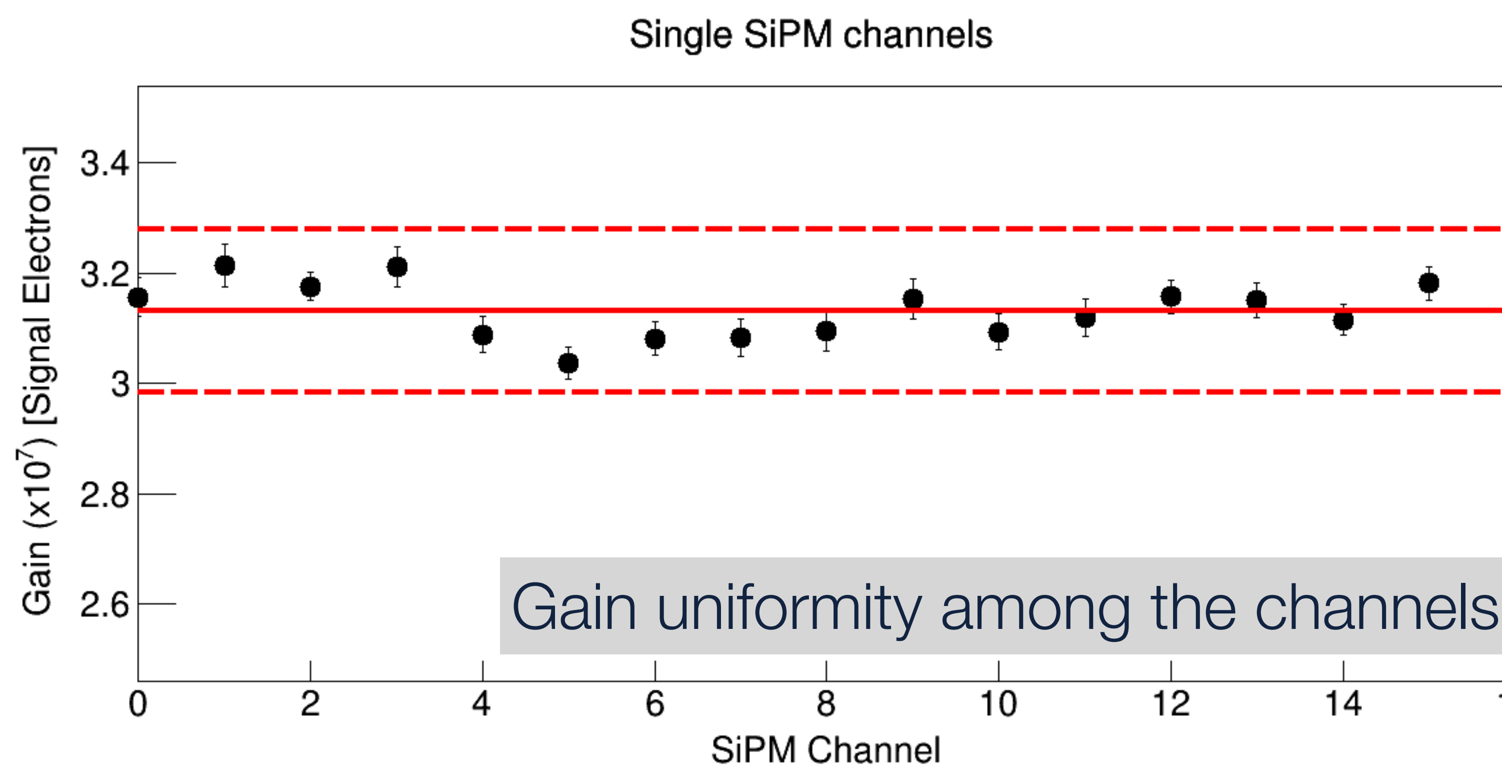


PERFORMANCE AND LONGTERM STABILITY OF THE SiPMS

- 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)





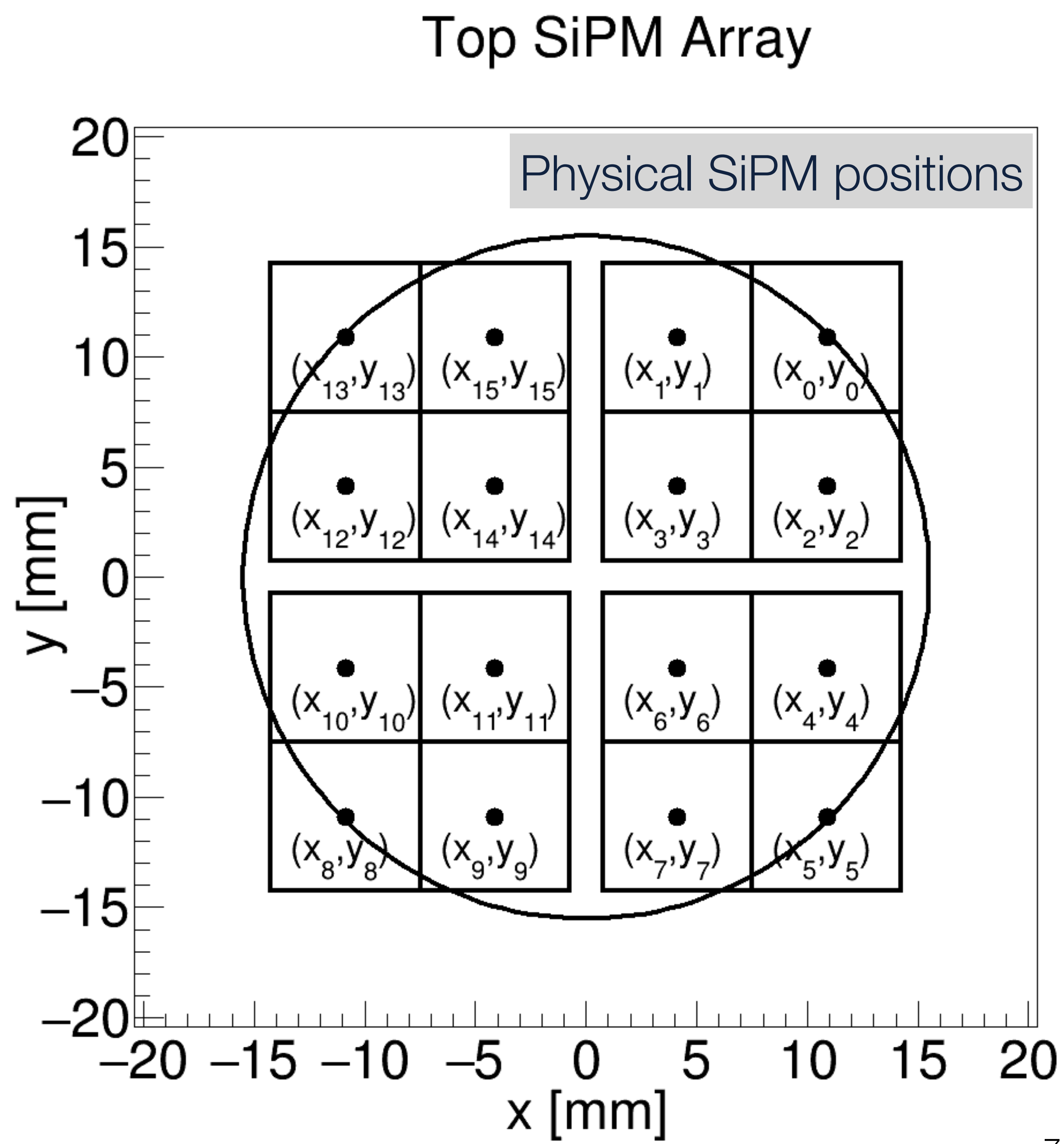


EVENT POSITION RECONSTRUCTION

- 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)



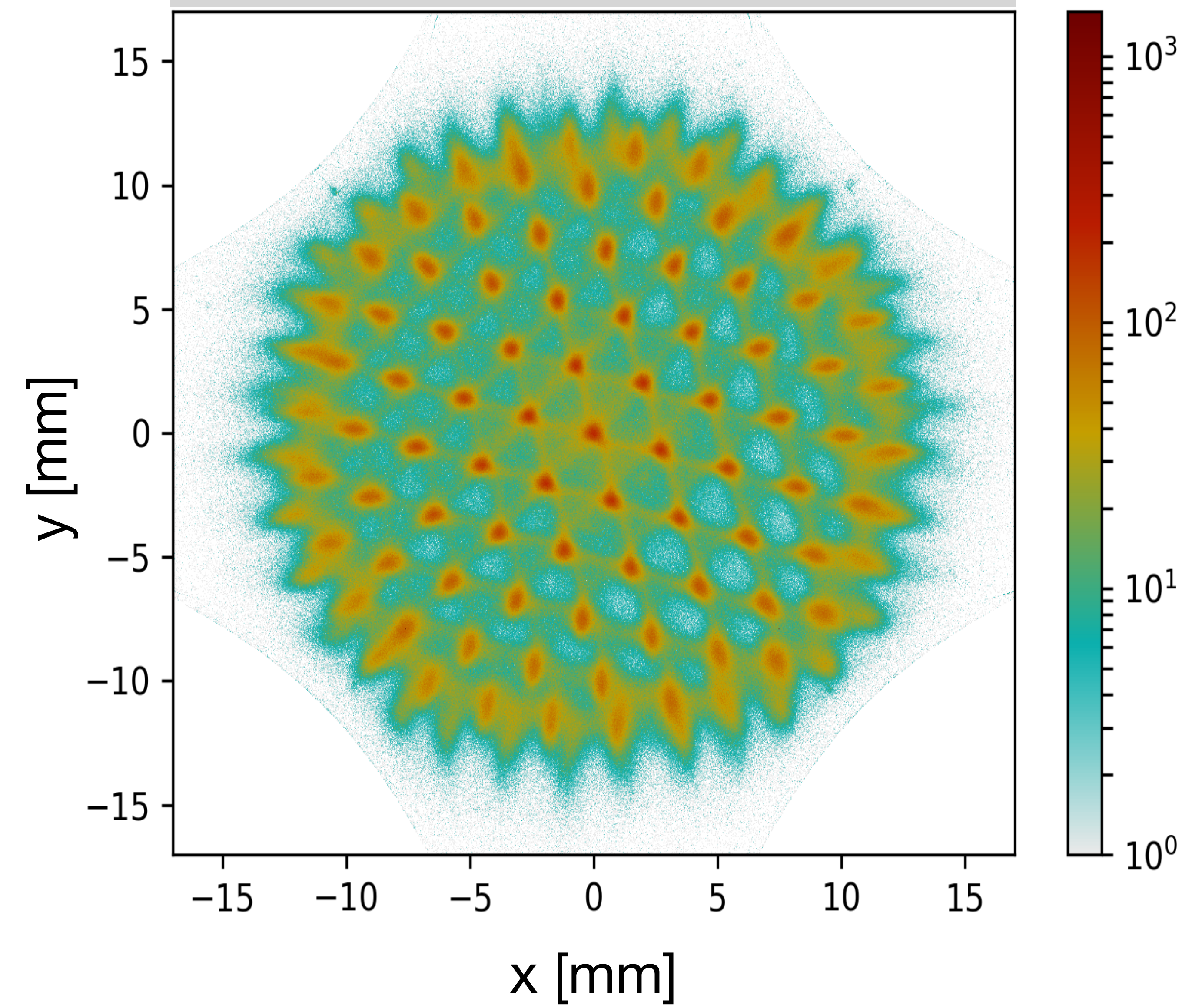
EVENT POSITION RECONSTRUCTION

- 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)

Reconstructed mesh knots

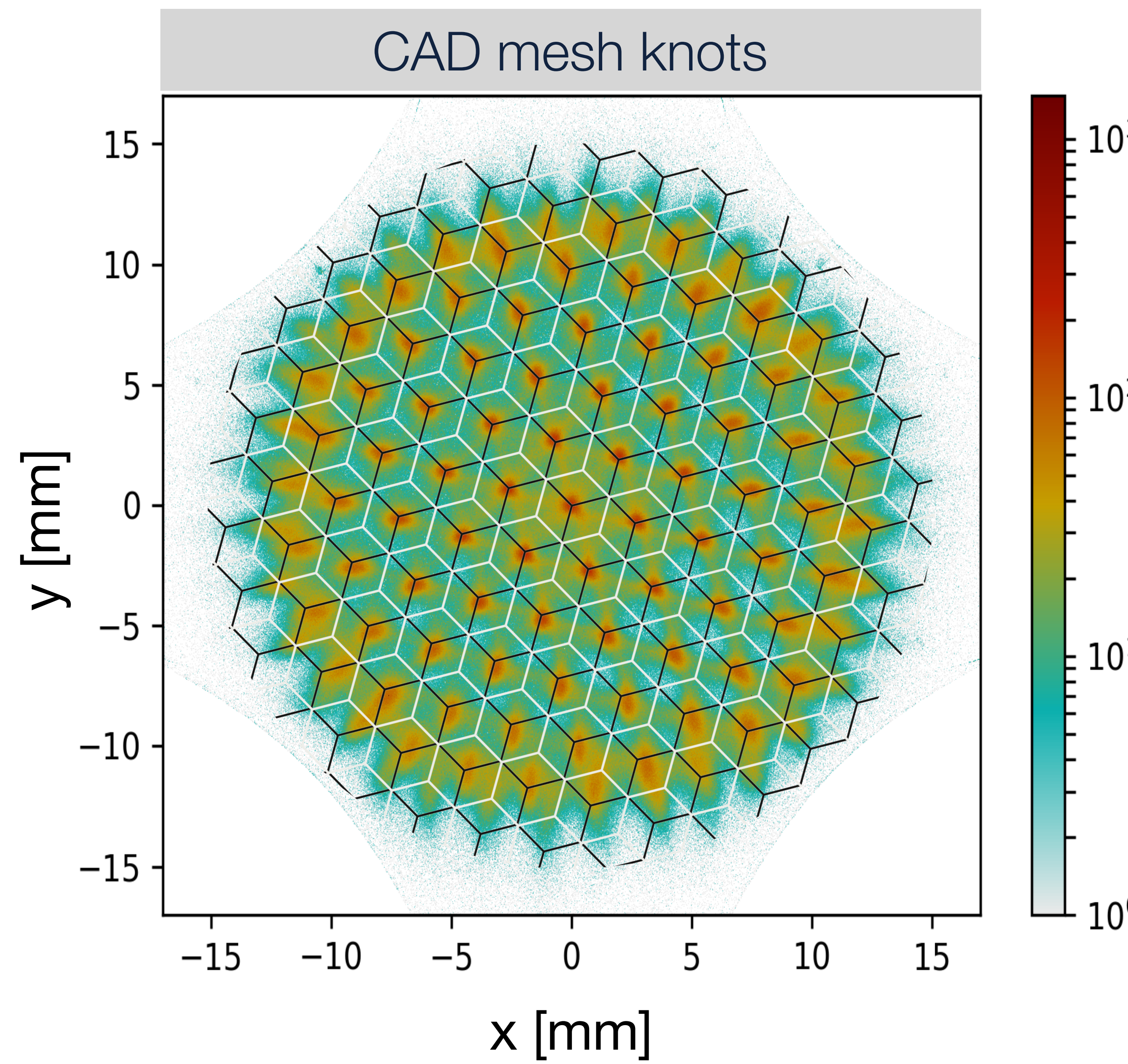


EVENT POSITION RECONSTRUCTION

- 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)



CALIBRATION WITH ^{37}Ar

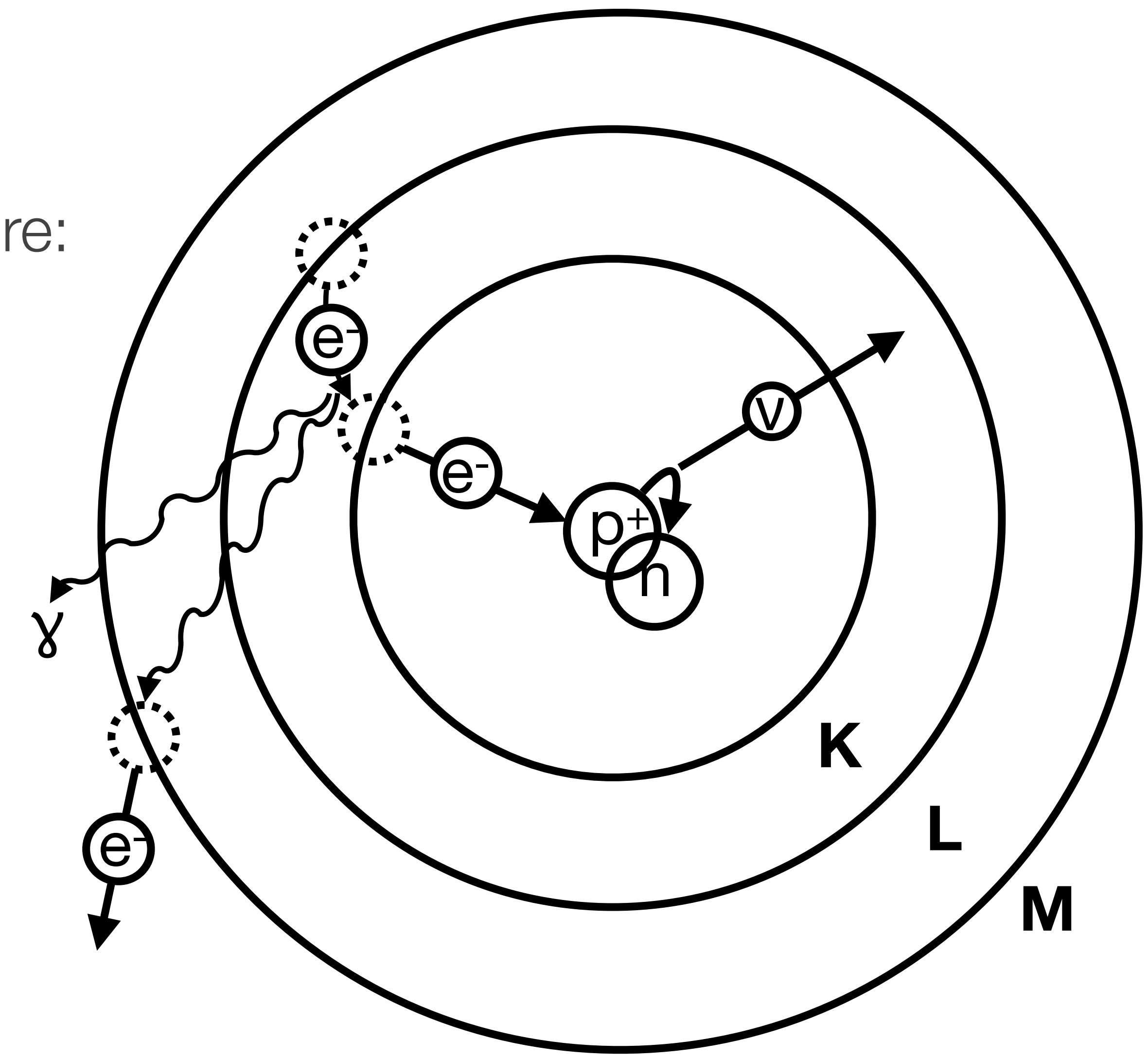
^{37}Ar – MOTIVATION

- 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 %



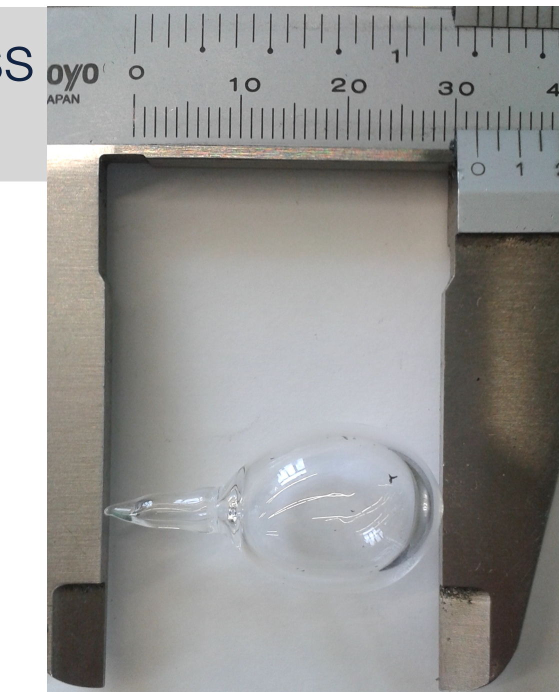
Phys. At. Nucl. **70**, No. 2 (2007)

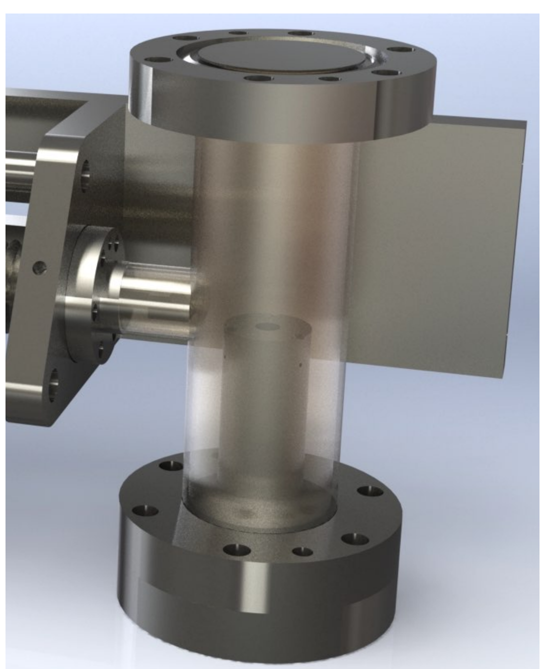
Inspired by C. Hils, Diploma Thesis: *Studie von internen Kalibrationsmethoden für Flüssig-Xenon TPCs zur direkten Suche nach Dunkler Materie*

^{37}Ar – SOURCE PRODUCTION AND INTRODUCTION

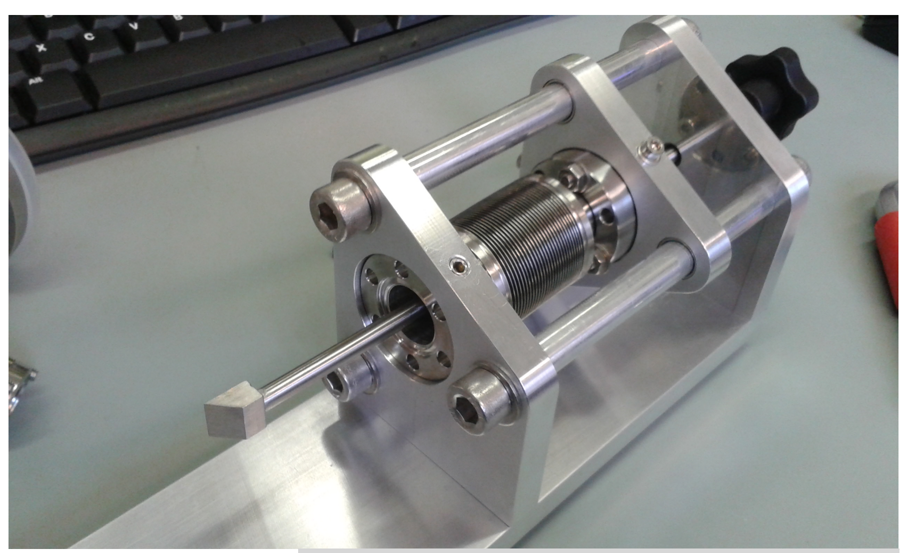
- Via thermal neutron capture on ^{36}Ar(n,γ): ~5 barn
- Use natural argon: 0.334 % abundance of ^{36}Ar
- 1.5 cm^3 at 0.9 bar per quartz glass ampule (8 μg ^{36}Ar)
- **Swiss Spallation Neutron Source** at Paul Scherrer Institute: 10^{13} neutrons cm^{-2}s^{-1}, 13500 s
- Estimated initial activity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

Quartz glass ampule

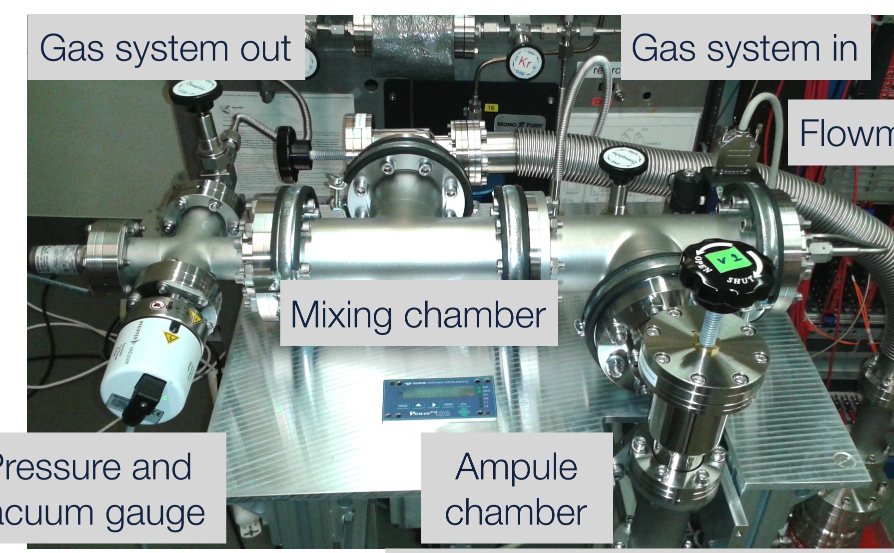




Ampule holder

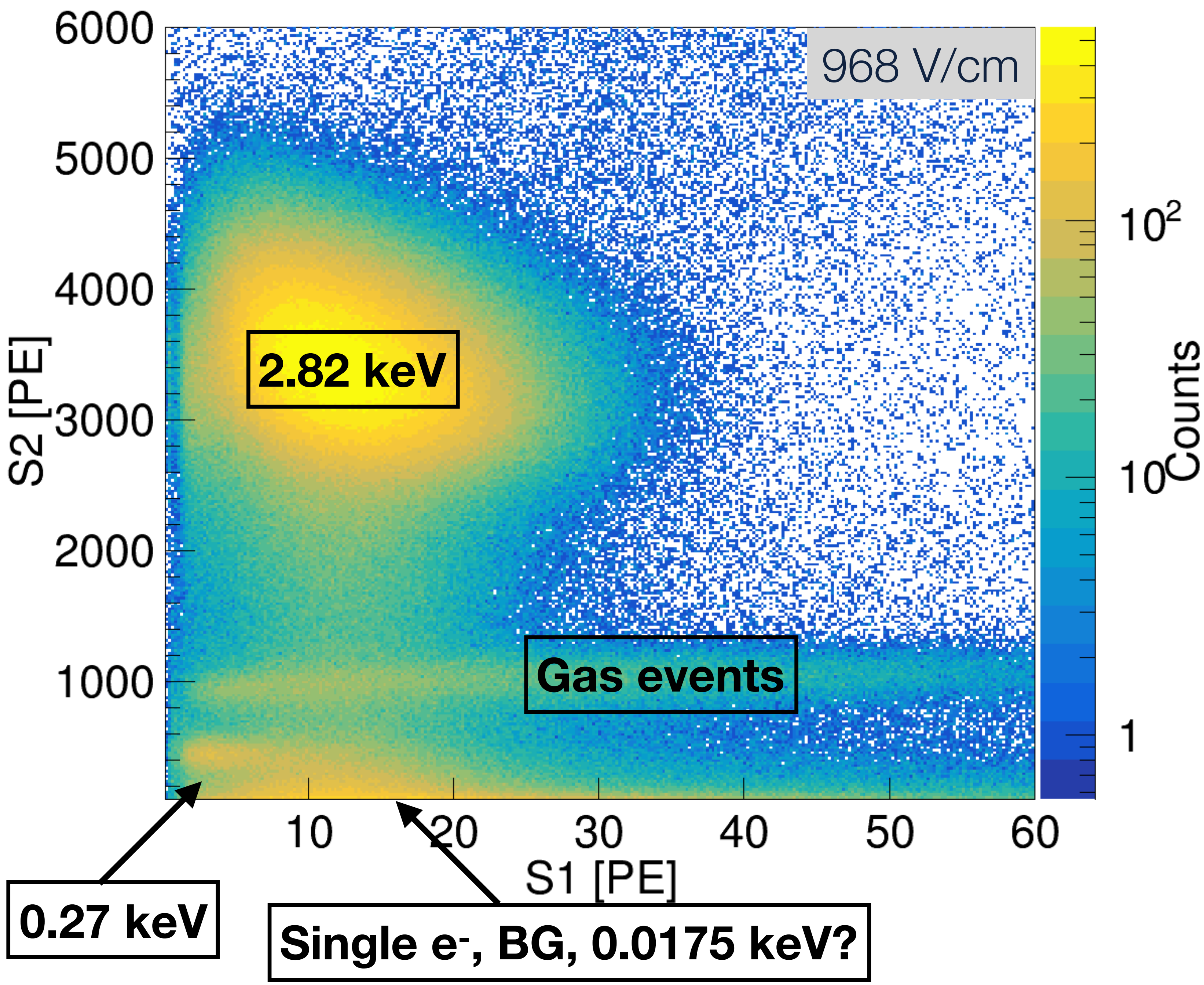


Breaking mechanism



Introduction setup

^{37}Ar – POPULATION AND CUTS

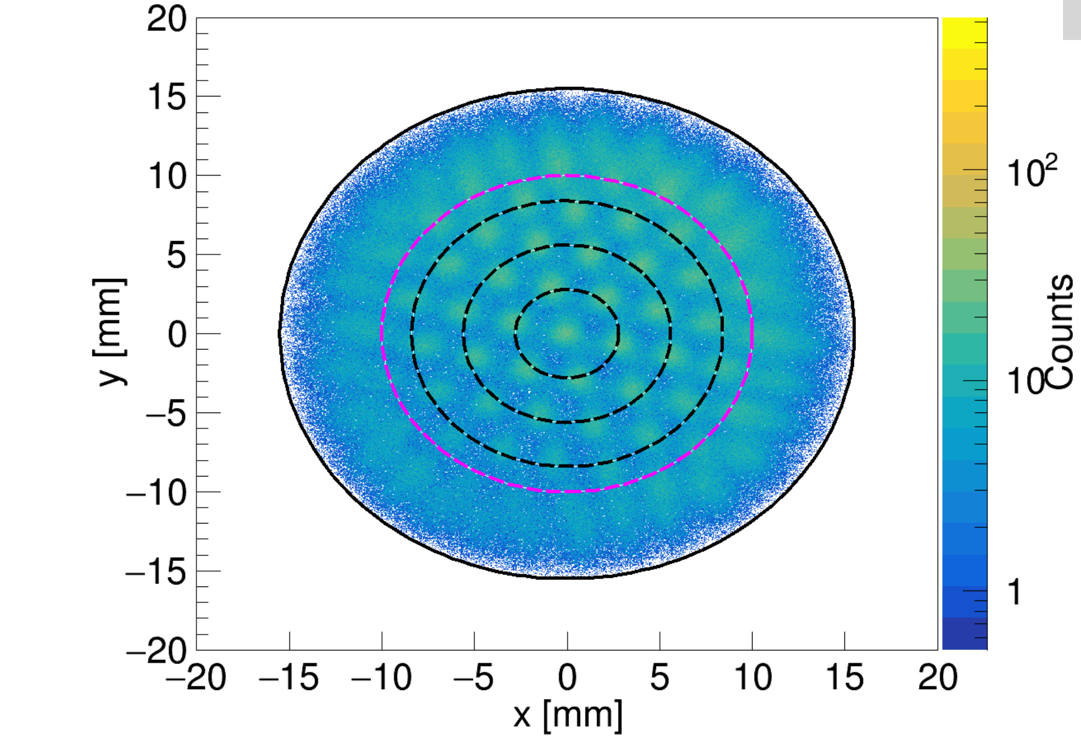


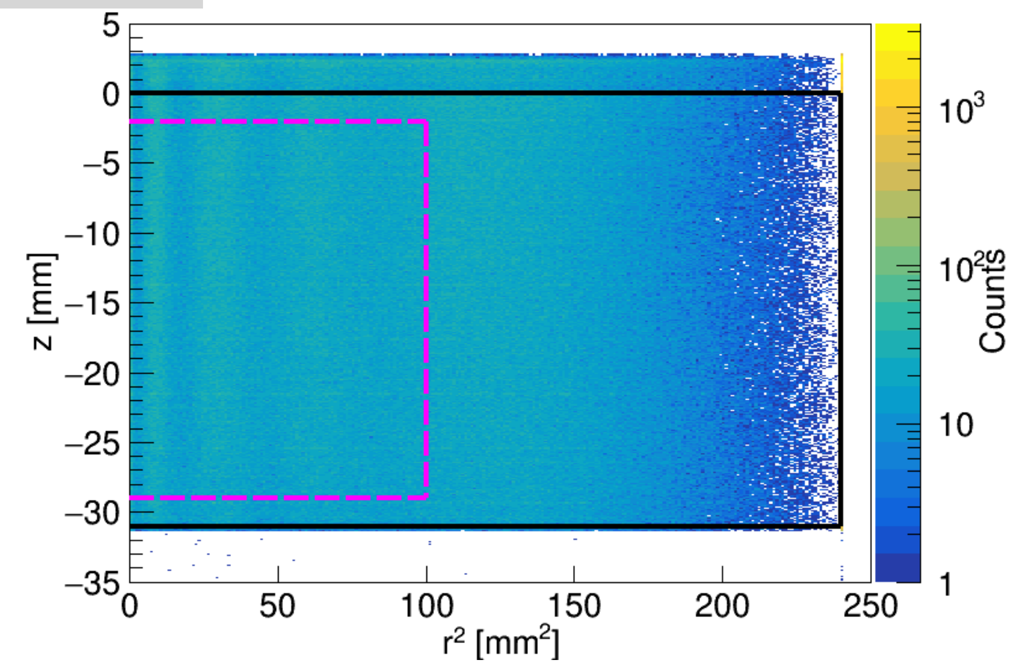
- Estimated activity introduced into the detector: 2.7 kBq -> 200 Bq inside the TPC
- Took data at: (80, 100, 200, 400, 600, 800, 968, 1000) V/cm

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

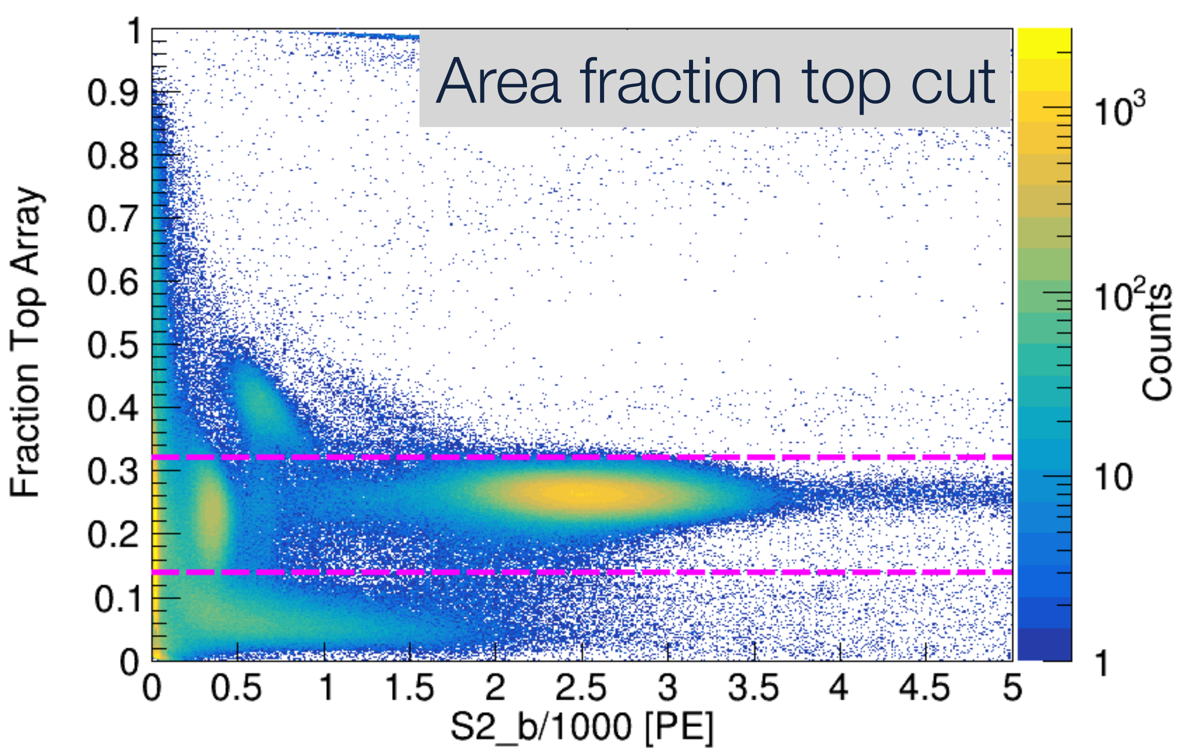
^{37}Ar – CUTS

Fiducial volume cut



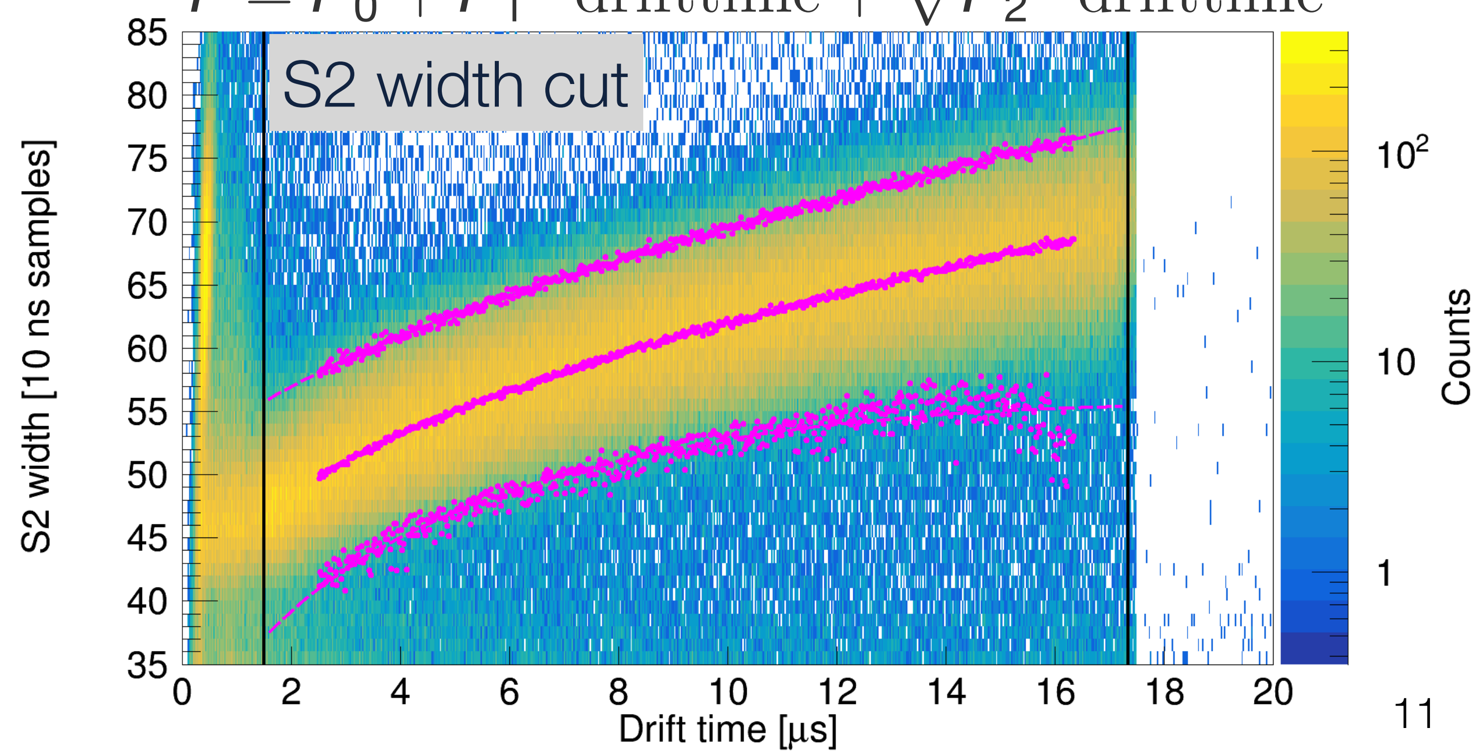


Area fraction top cut

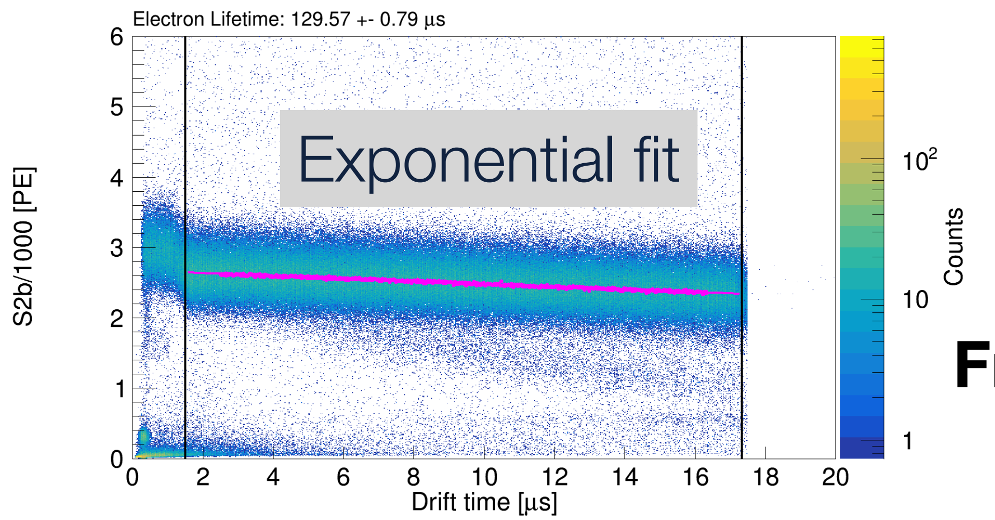


$$F = P_0 + P_1 \cdot \mathrm{drifttime} + \sqrt{P_2 \cdot \mathrm{drifttime}}$$

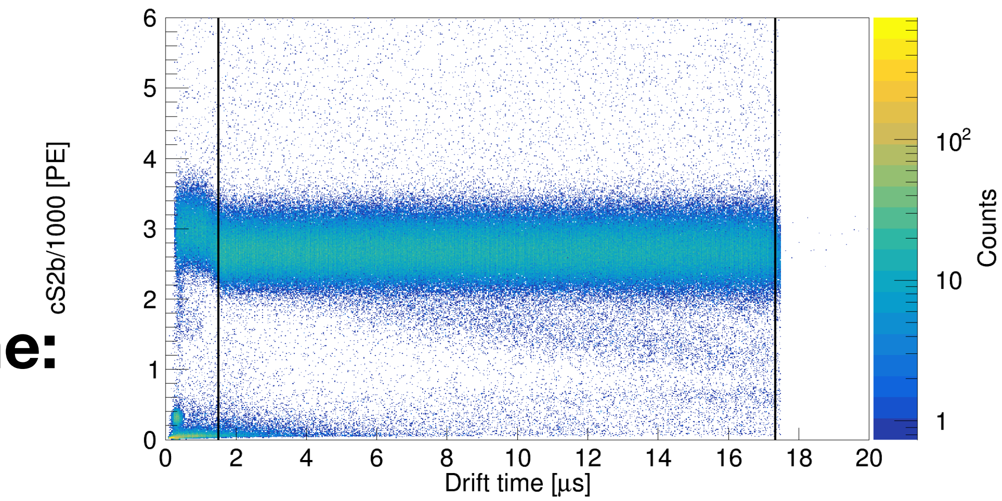
S2 width cut



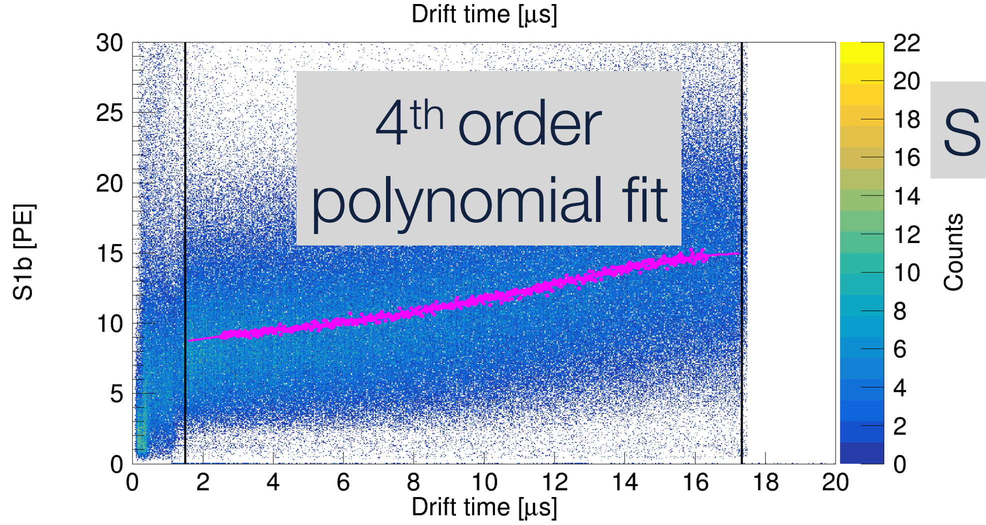
^{37}Ar – CORRECTIONS



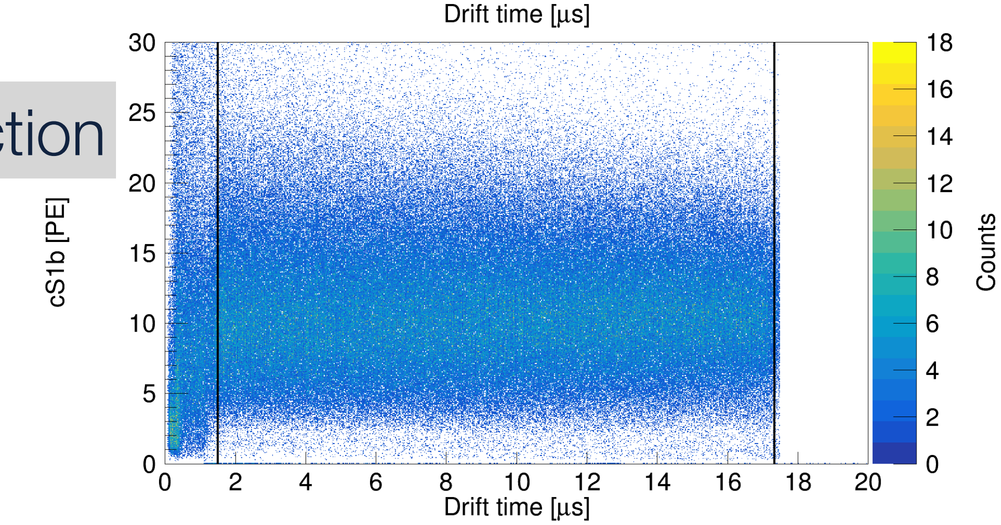
S2 area correction

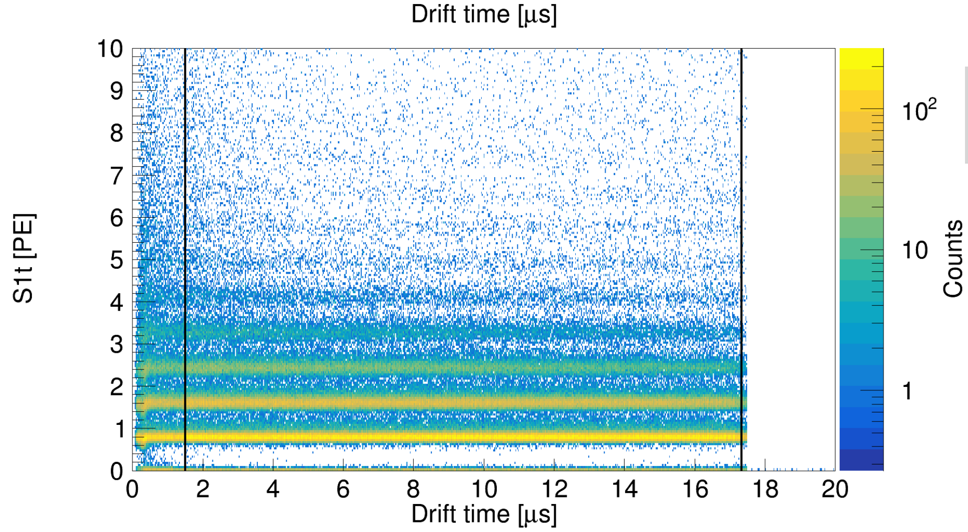


Free electron lifetime:
(129.6 ± 0.8) µs

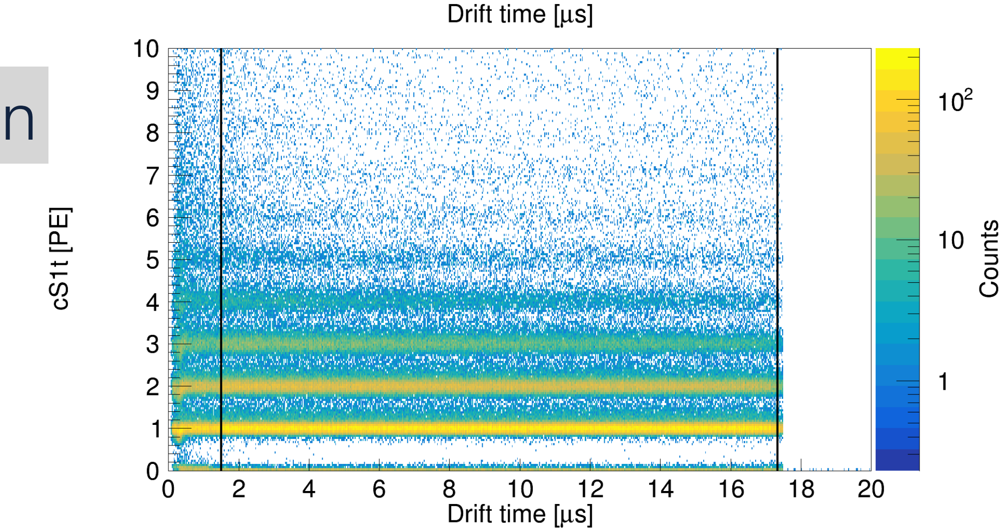


S1 bottom area correction



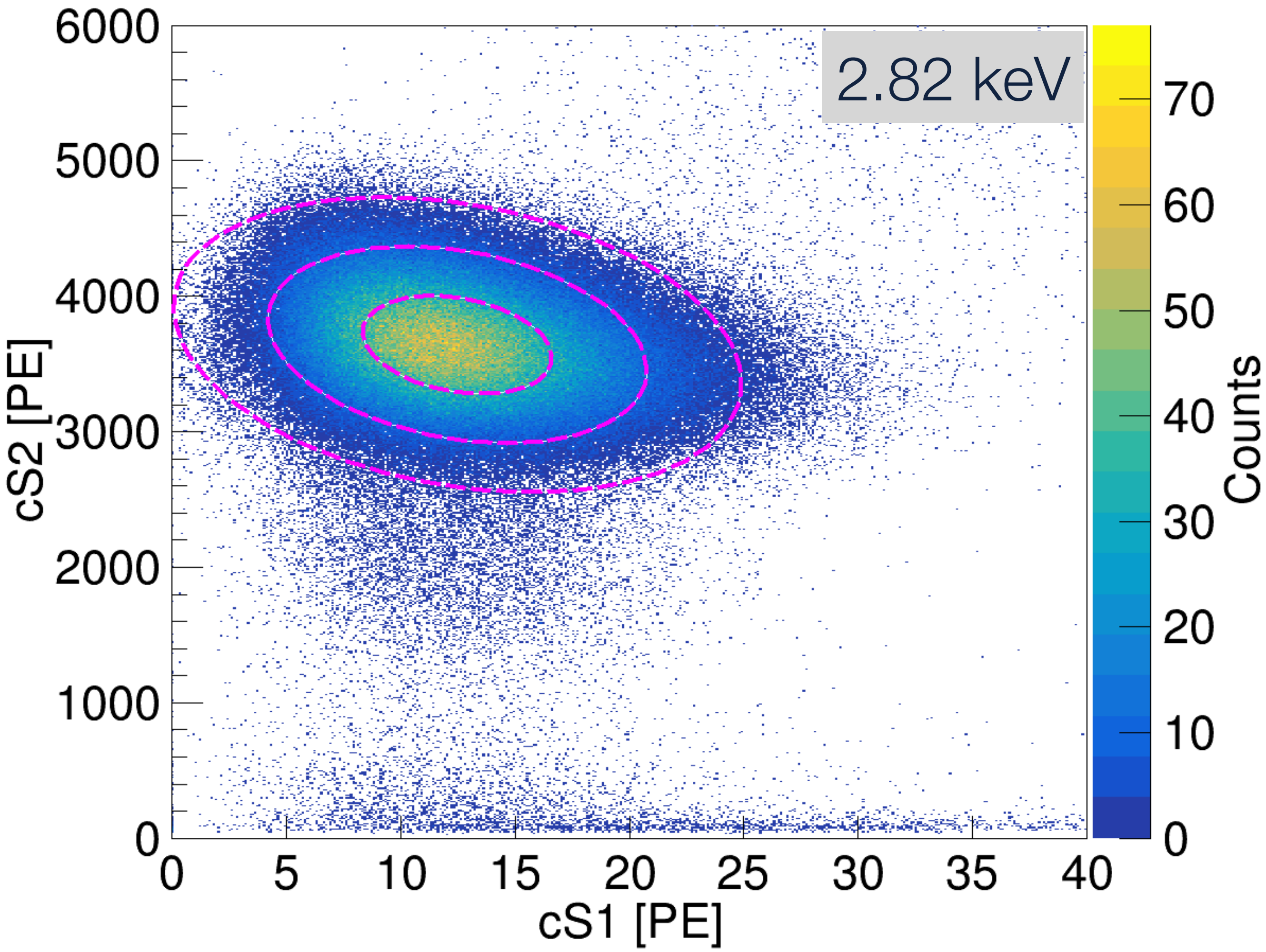


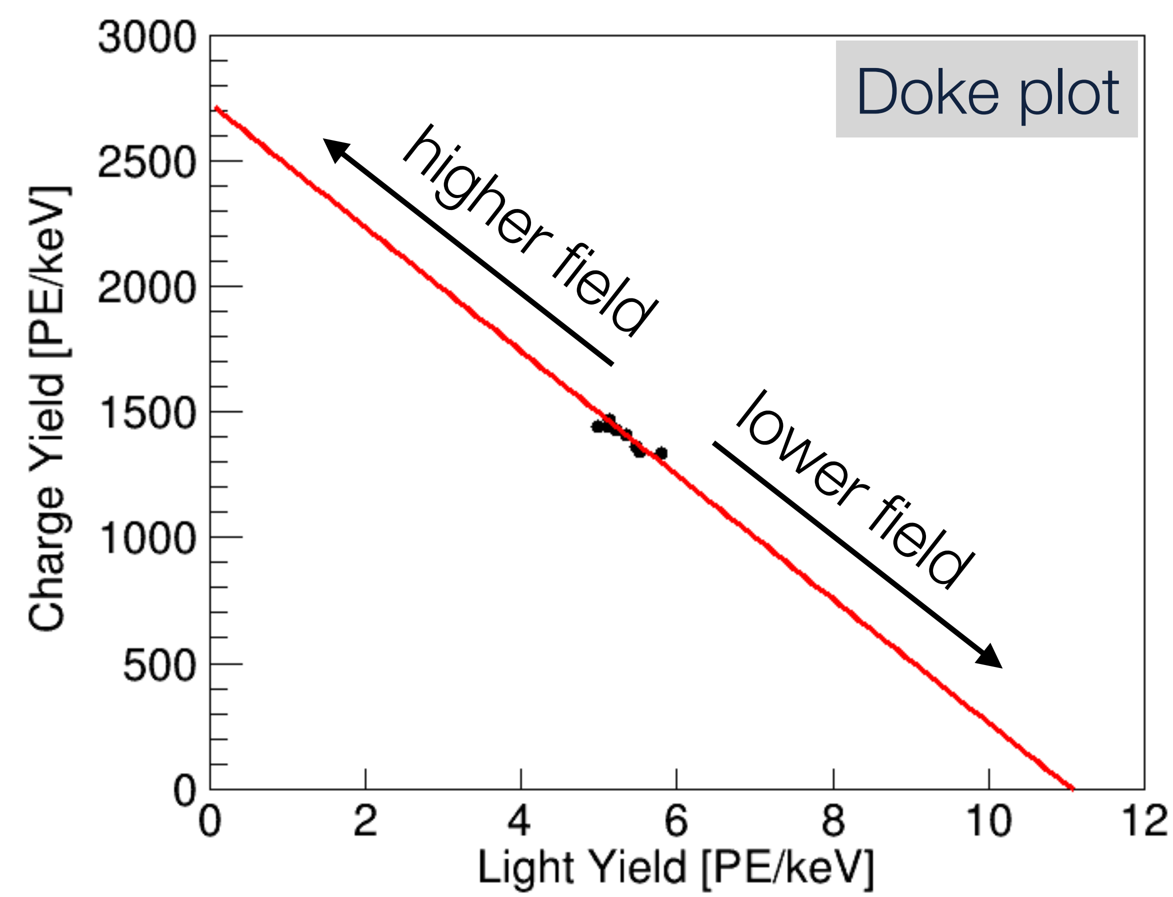
S1 top area correction



PRELIMINARY!

^{37}Ar – 2.82 keV RESULTS





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

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

13.7 eV

- Detector response parameters:

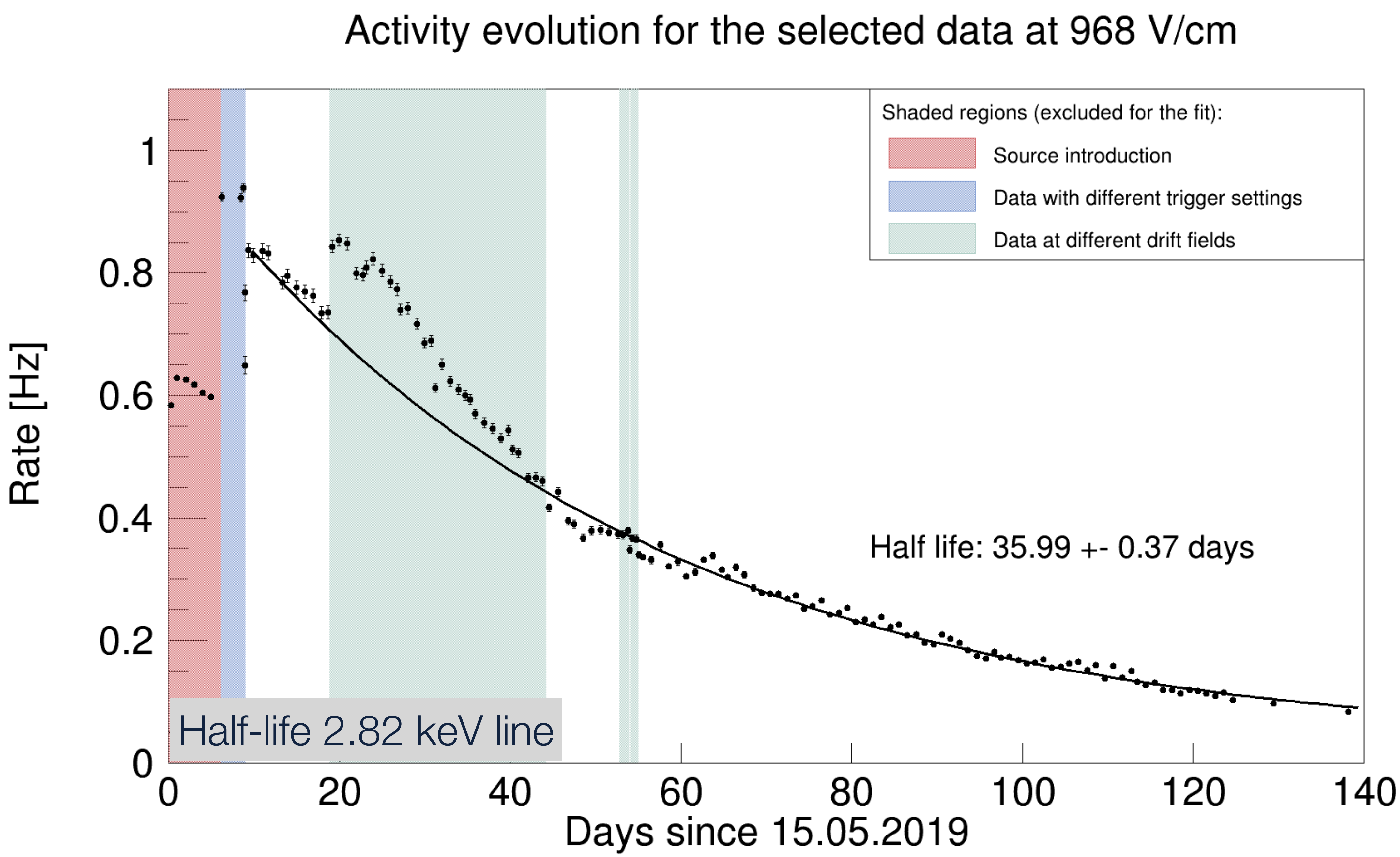
$$g1 := S1/N_\gamma \qquad g2 := S2/N_{e^-}$$

$$g1 = (0.152 \pm 0.003)\mathrm{PE}/\gamma$$

$$g2 = (37.3 \pm 0.6)\mathrm{PE}/e^-$$

PRELIMINARY!

^{37}Ar – 2.82 keV RESULTS



- $T_{1/2} = (35.99 \pm 0.37)$ d

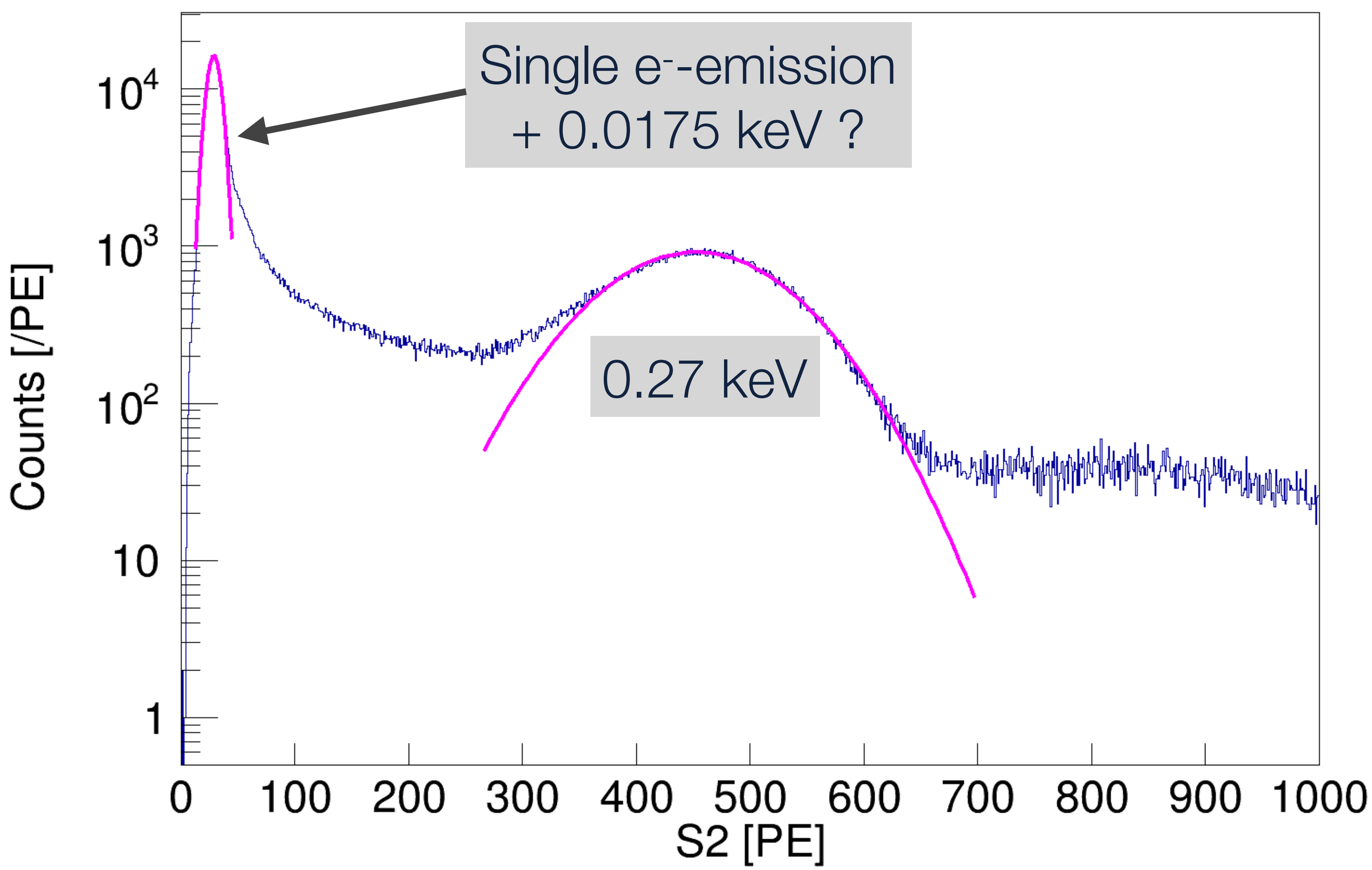
-> Literature: (35.01 ± 0.02) d

- Check for bias of cuts and corrections for different drift fields

PRELIMINARY!

^{37}Ar – 0.27 keV RESULTS

- S2-only analysis because of S1/S2 mispairing or too few photons being produced
- Charge yield: $(1676 \pm 286)\mathrm{PE/keV}$
- See population at S2 that corresponds to 17.5 eV that decays with roughly the right half-life
- But: Abundance too high (should be ~1 % w/o efficiencies) -> Check with BG and ^{83m}Kr data



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 (low-S2-only-population, diffusion during source injection,…) and compare to ^{83m}Kr
- Coming soon: NEST-comparison and charge/light yield comparison to other low energy measurements
- Paper in preparation
- 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
- In parallel: Development of low-power pre-amplifier for cryogenic environment in prospect of DARWIN (new semester student N. Schermer)

SUMMARY AND OUTLOOK

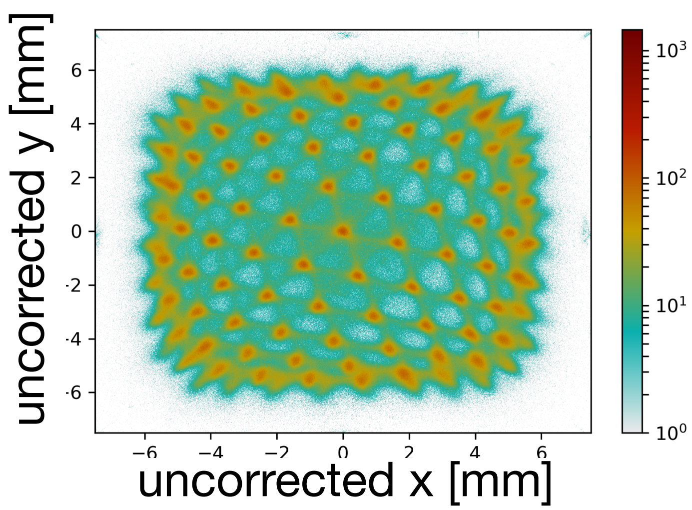
- First working dual-phase xenon TPC with SiPM array
- Operating under stable conditions over almost one year
- ^{83m}Kr- and **^{37}Ar**-calibrations successfully performed
- Finalise ^{37}Ar-analysis (low-S2-only-population, diffusion during source injection,…) and compare to ^{83m}Kr
- Coming soon: NEST-comparison and charge/light yield comparison to other low energy measurements
- Paper in preparation
- 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
- In parallel: Development of low-power pre-amplifier for cryogenic environment in prospect of DARWIN (new semester student N. Schermer)

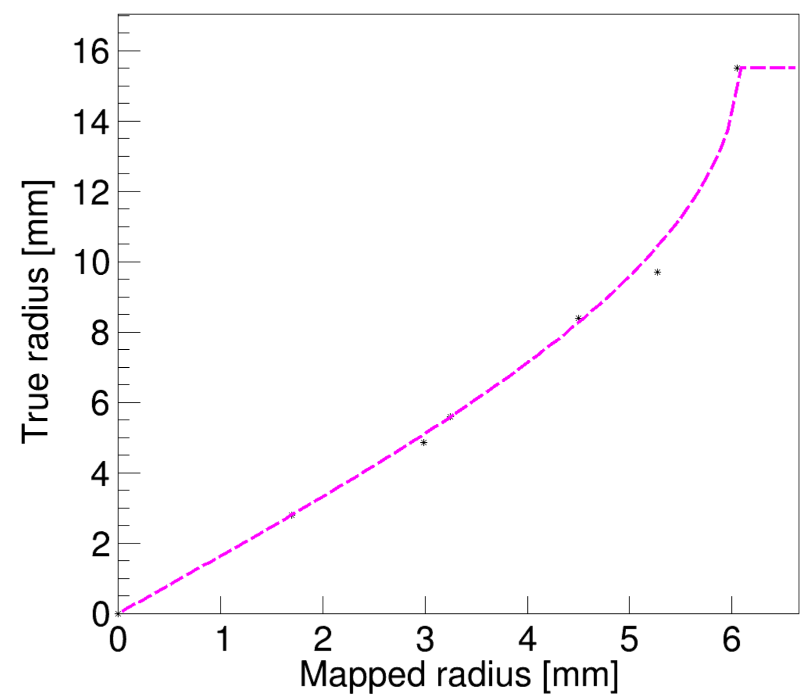
THANK YOU FOR YOUR ATTENTION!

BACKUP

S. Hochrein, B.Sc. Thesis: *Calibration of the first dual-phase xenon time projection chamber with silicon photomultiplier readout*

EVENT POSITION RECONSTRUCTION II



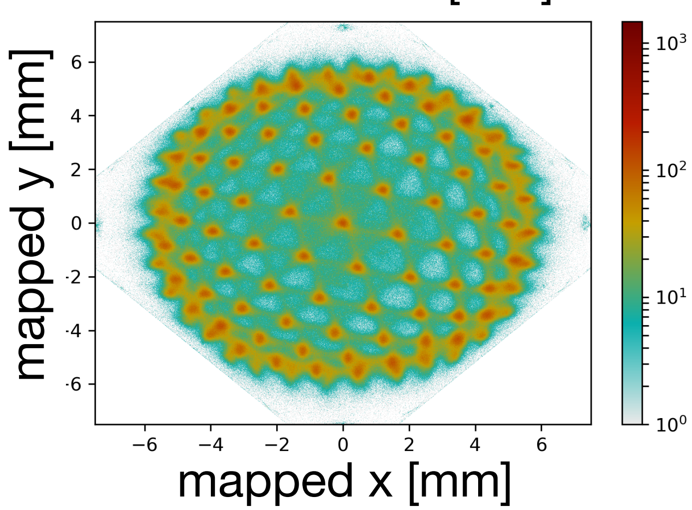


$$x_{\mathrm{uncorrected}} = \frac{1}{\sum_{i=0}^{15} S_2^i} \sum_{i=0}^{15} S_2^i * x_i$$

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

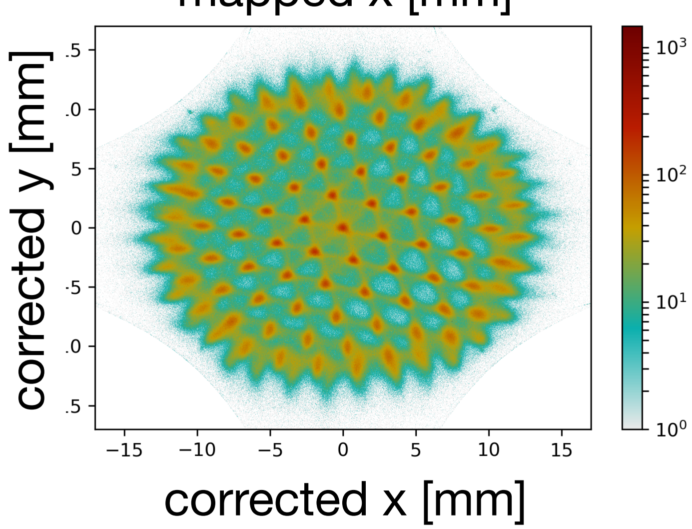
$$y_{\mathrm{scaled}} = (y_{\mathrm{uncorrected}} - \Delta_y)/c$$

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



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

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

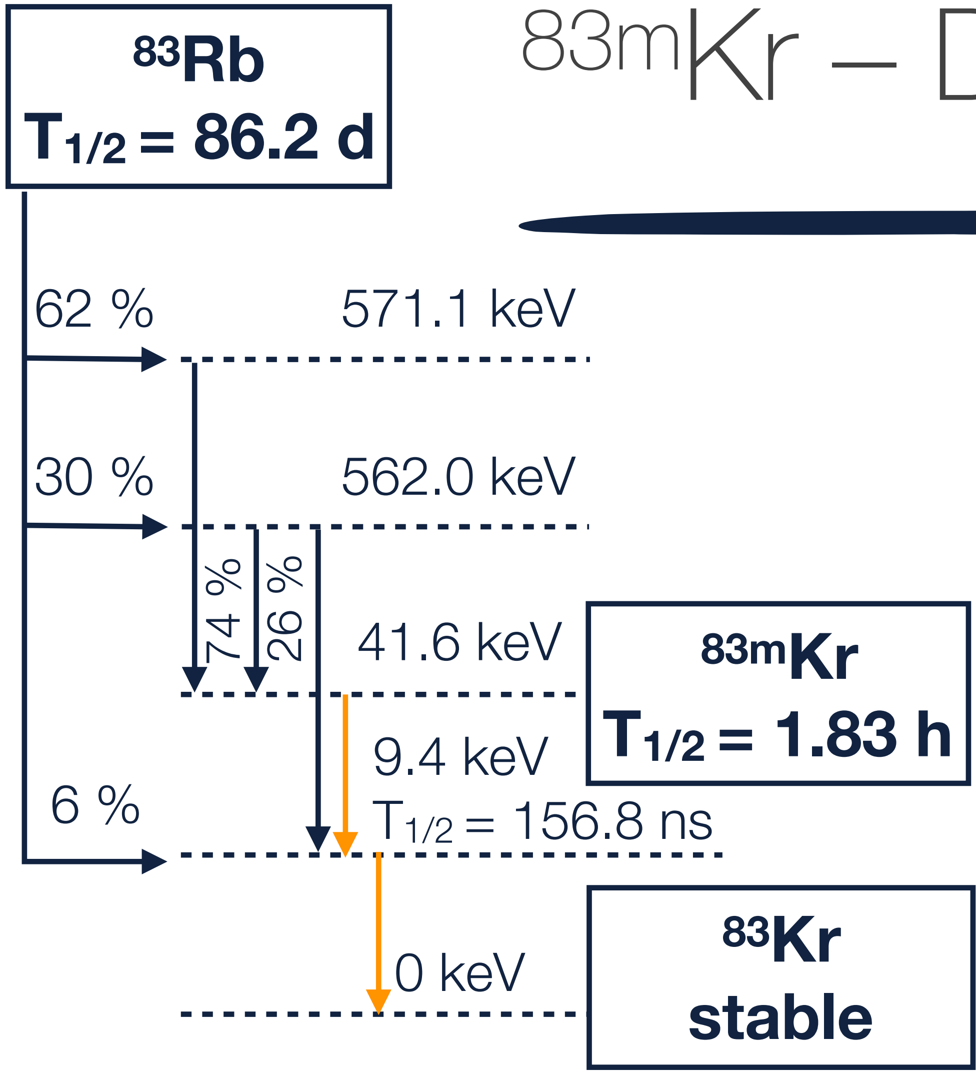


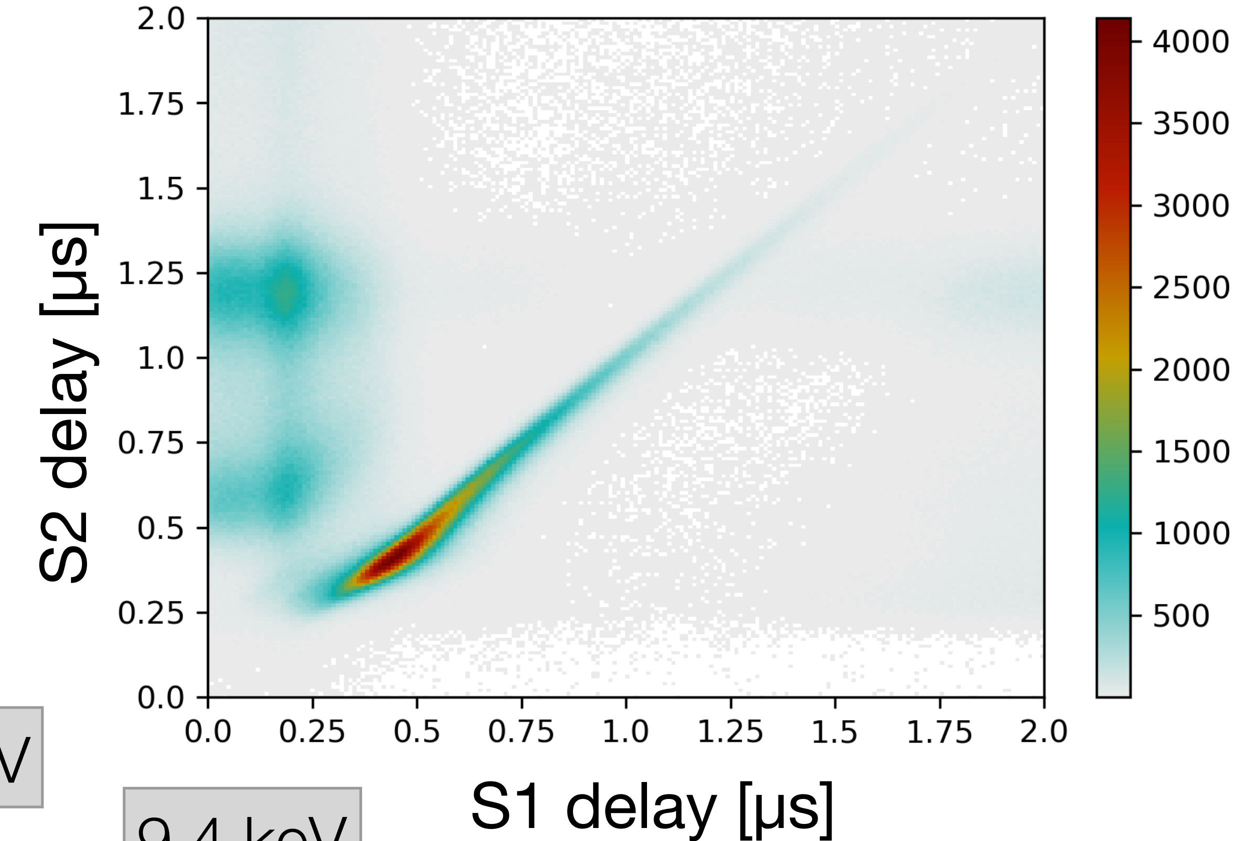
$$x_{\mathrm{corrected}} = \frac{\frac{-d_{\mathrm{TPC}}}{\pi} \arccos\left(\frac{r_{\mathrm{mapped}}}{r_{\mathrm{mapped,max}}}\right) + \frac{d_{\mathrm{TPC}}}{2}}{r_{\mathrm{mapped}} * x_{\mathrm{mapped}}}$$

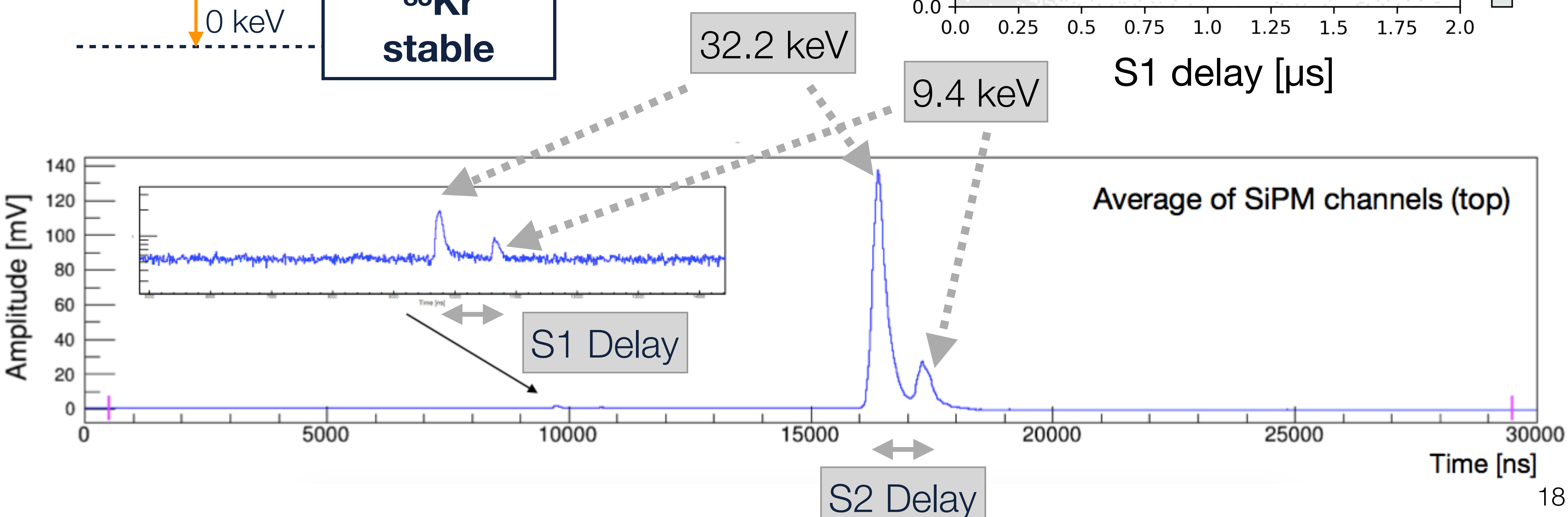
$$y_{\mathrm{corrected}} = \frac{\frac{-d_{\mathrm{TPC}}}{\pi} \arccos\left(\frac{r_{\mathrm{mapped}}}{r_{\mathrm{mapped,max}}}\right) + \frac{d_{\mathrm{TPC}}}{2}}{r_{\mathrm{mapped}} * y_{\mathrm{mapped}}}$$

S. Hochrein, B.Sc. Thesis: *Calibration of the first dual-phase xenon time projection chamber with silicon photomultiplier readout*

^{83m}Kr – DATA SELECTION AND CUTS

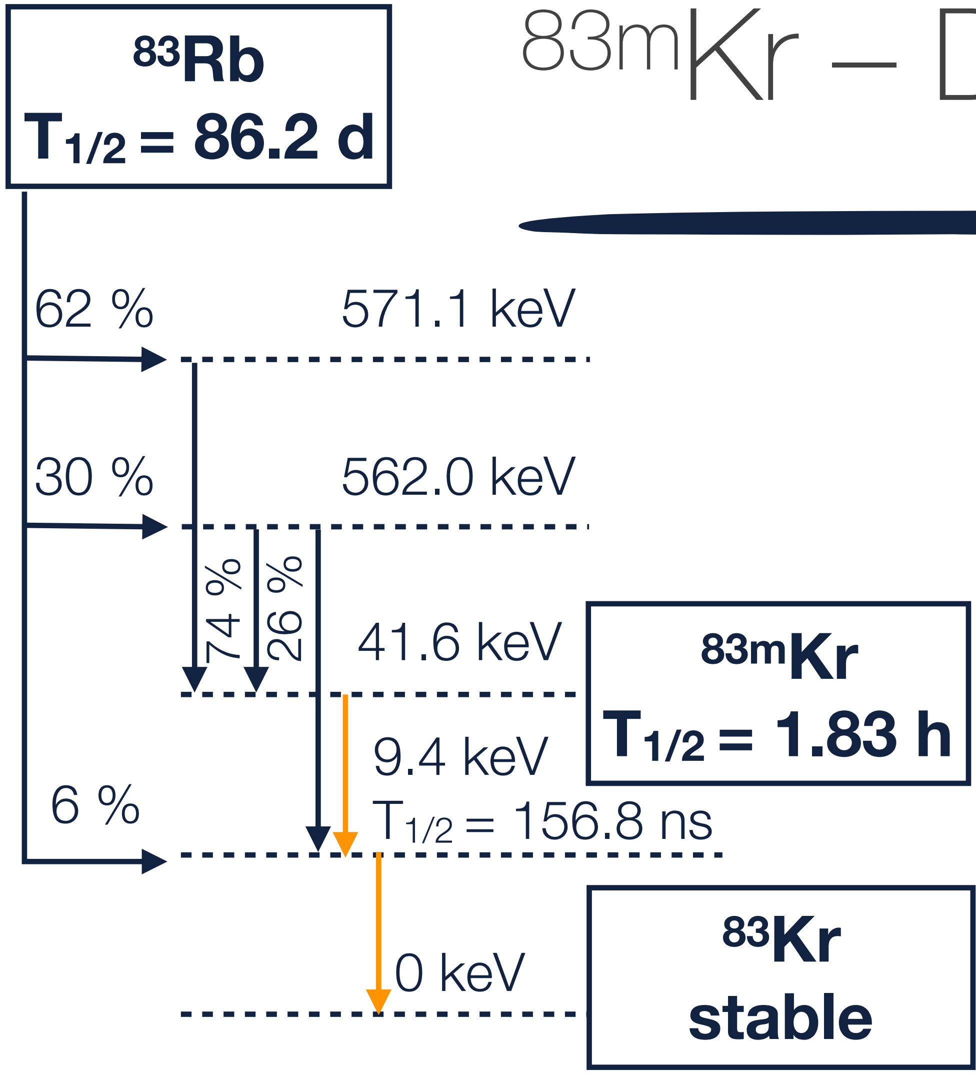


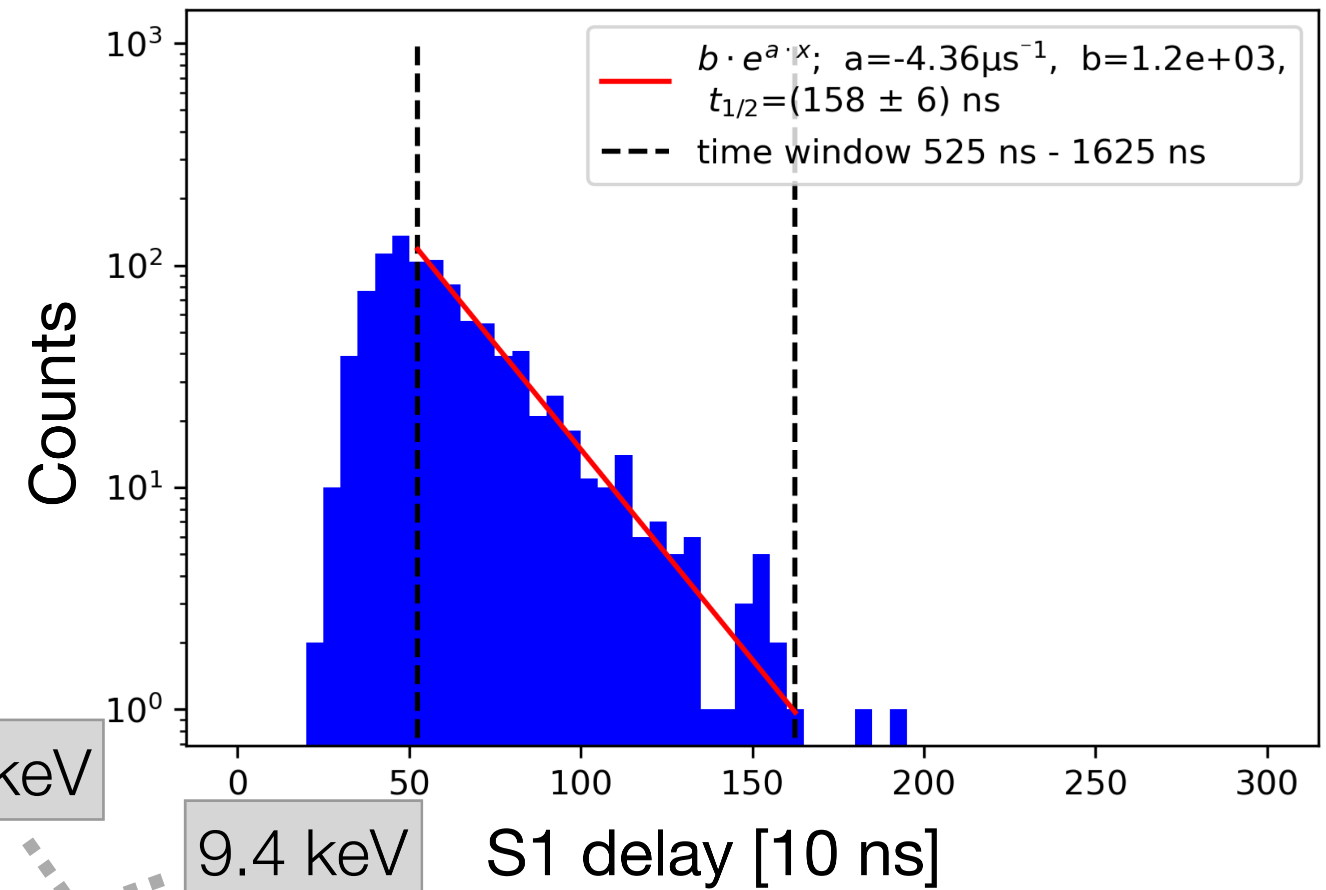


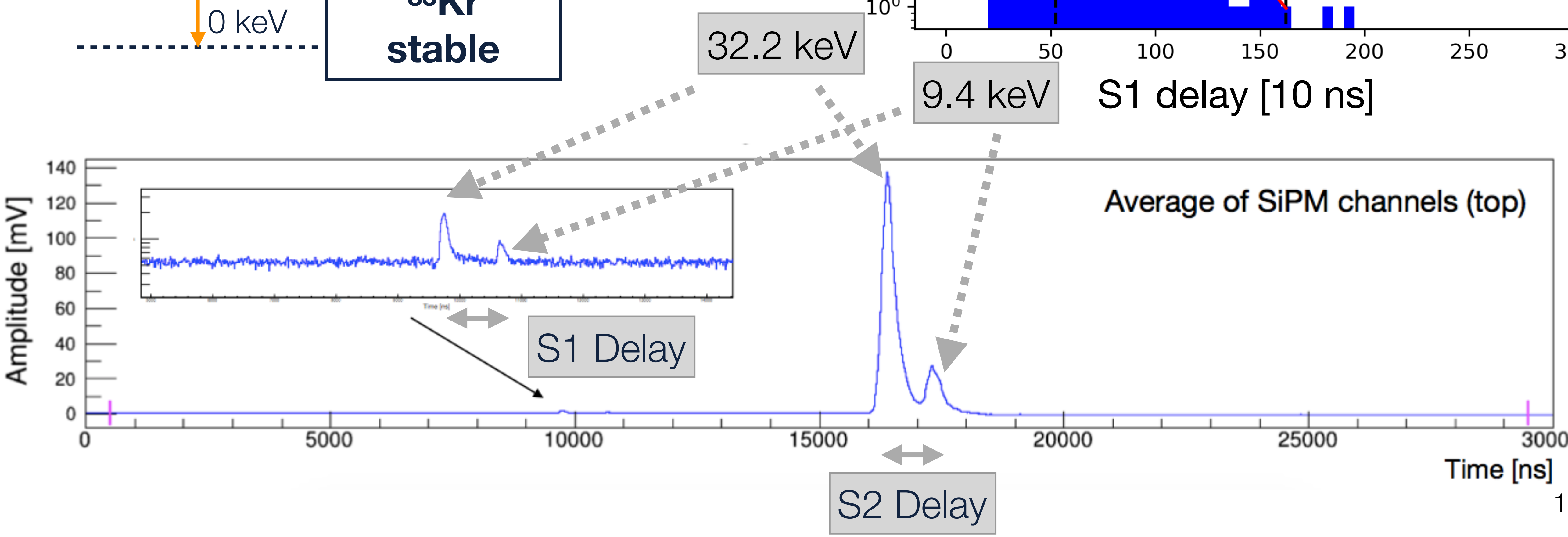


S. Hochrein, B.Sc. Thesis: *Calibration of the first dual-phase xenon time projection chamber with silicon photomultiplier readout*

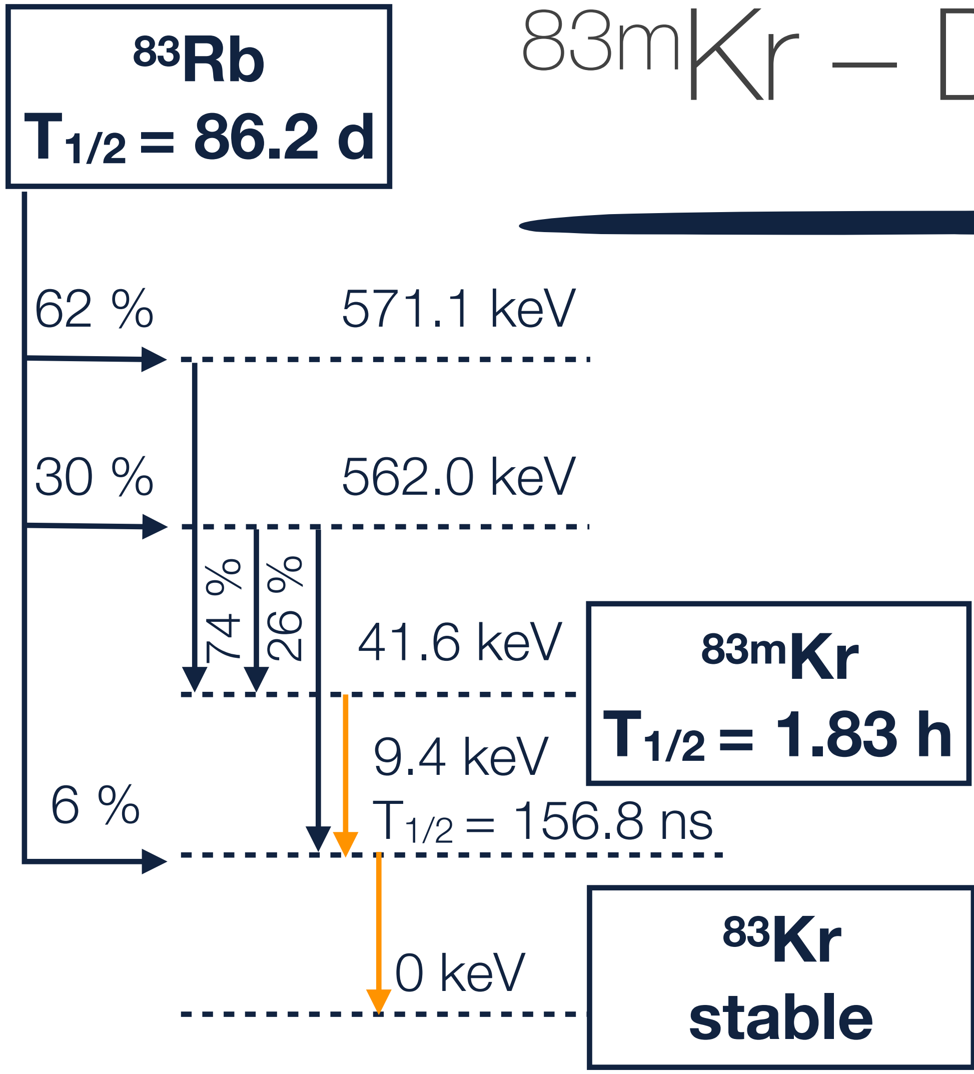
^{83m}Kr – DATA SELECTION AND CUTS



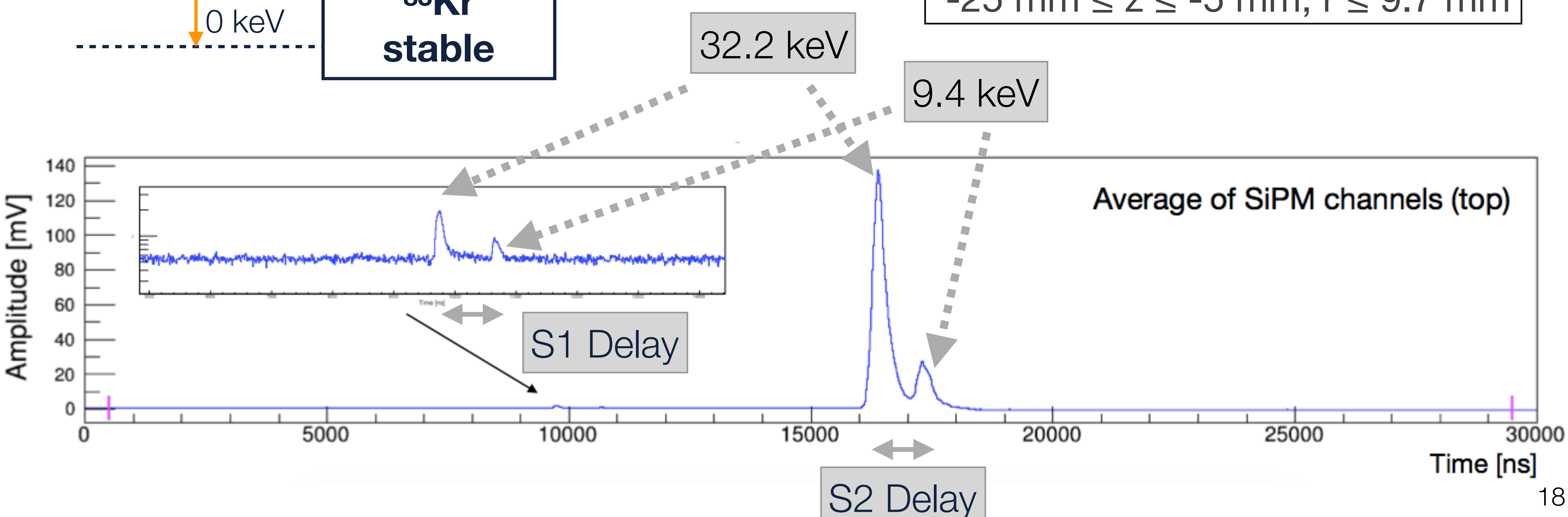




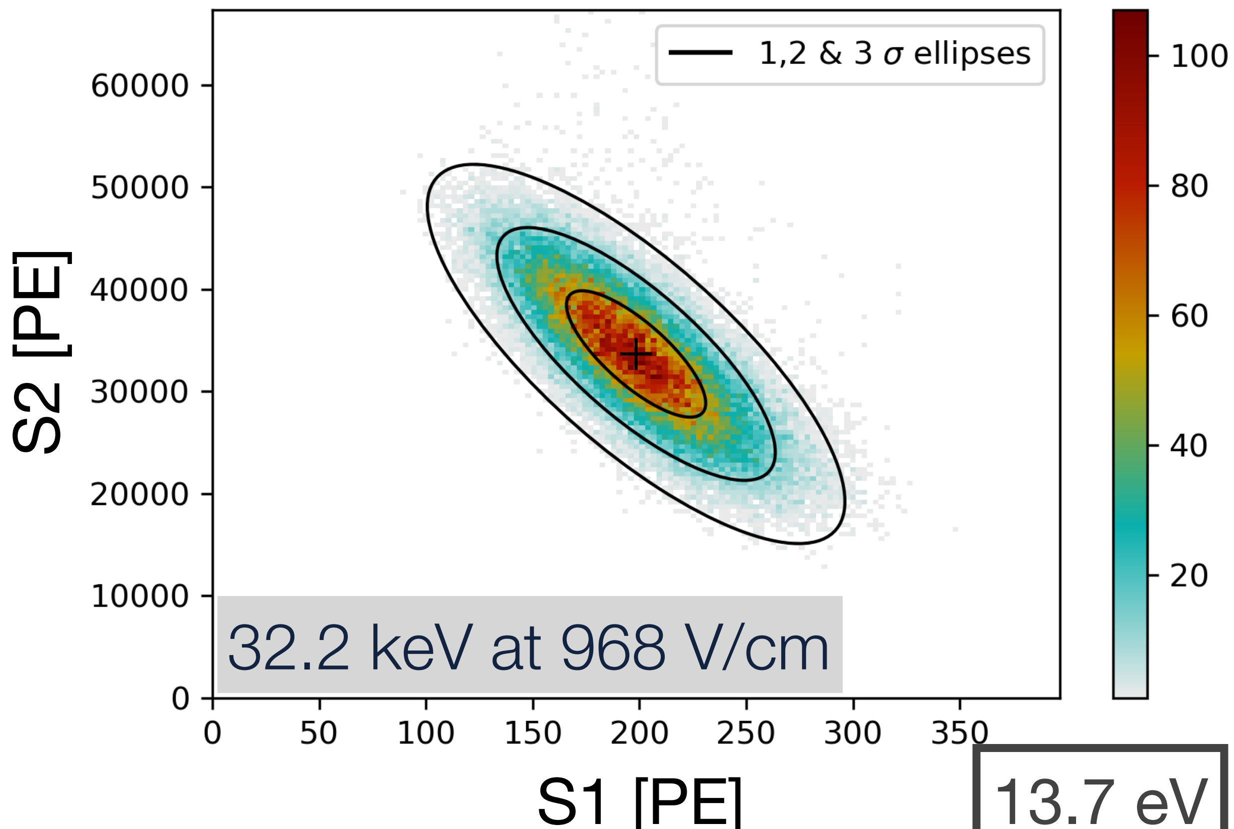
83mKr – DATA SELECTION AND CUTS

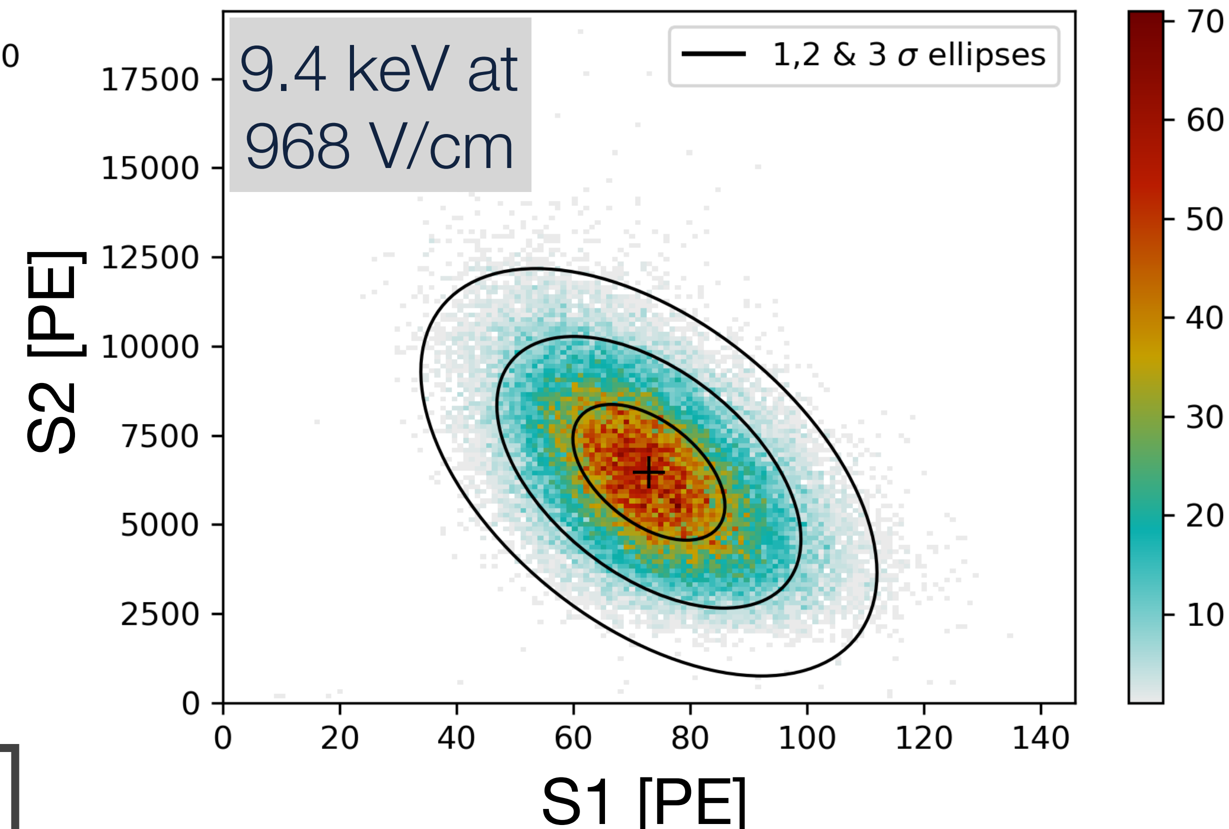


Cuts
#S1 ≥ 2 && #S2 ≥ 2
Difference S1/S2 delays: ±1 σ
S2 width ∈ [97.7,2.3] % Quantile
S2 area fraction top ∈ [0.21,0.31]
S1/S2 delay ∈ [~0.5,~2.0] μs
-25 mm ≤ z ≤ -5 mm; r ≤ 9.7 mm



^{83m}Kr – RESULTS





13.7 eV

- Combined energy scale:

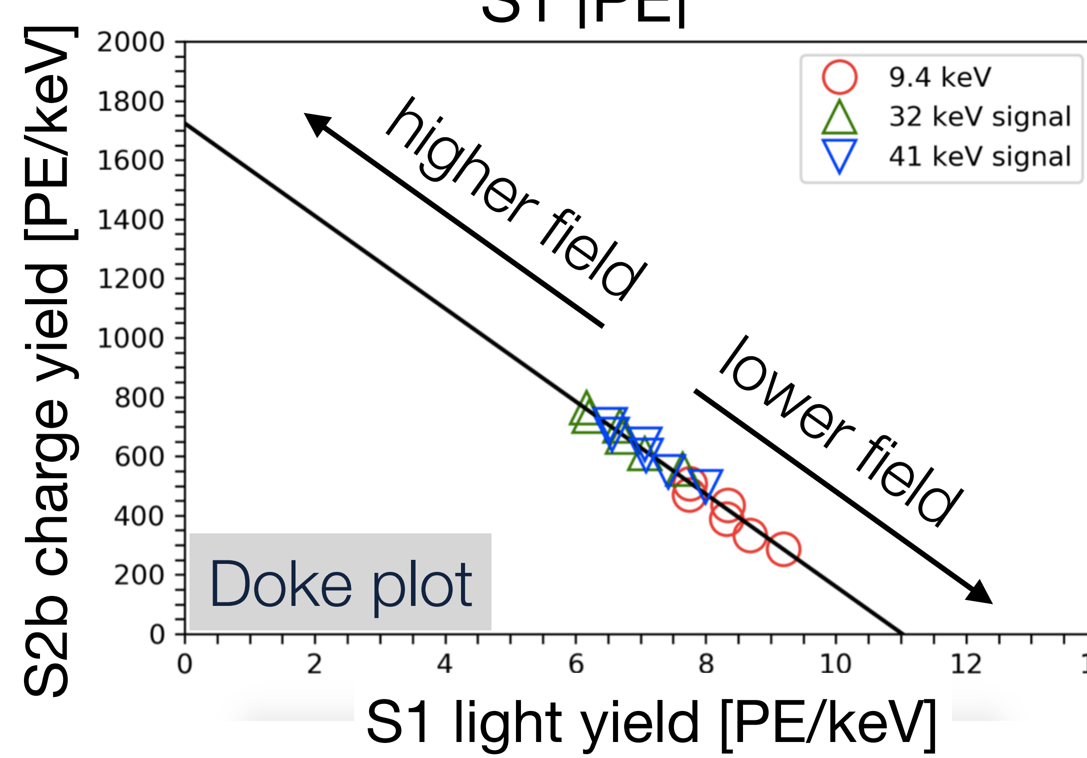
$$E = (N_\gamma + N_{e^-}) \cdot W = \left(\frac{S1}{g1} + \frac{S2}{g2}\right) \cdot W$$

- Detector response parameters:

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

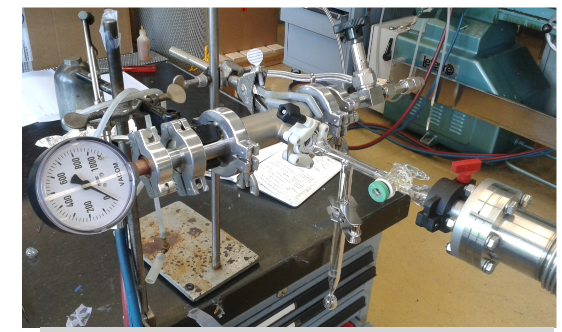
$$g1 = (0.150 \pm 0.009)\,\mathrm{PE}/\gamma$$

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

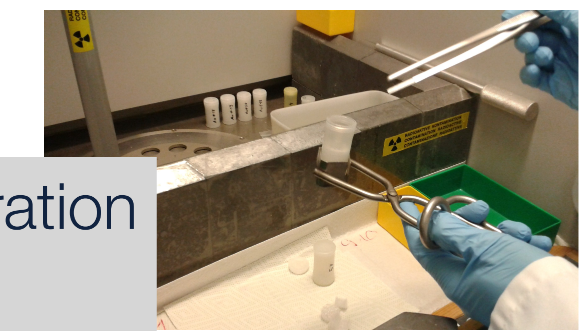


^{37}Ar – SOURCE PRODUCTION AND INTRODUCTION II

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

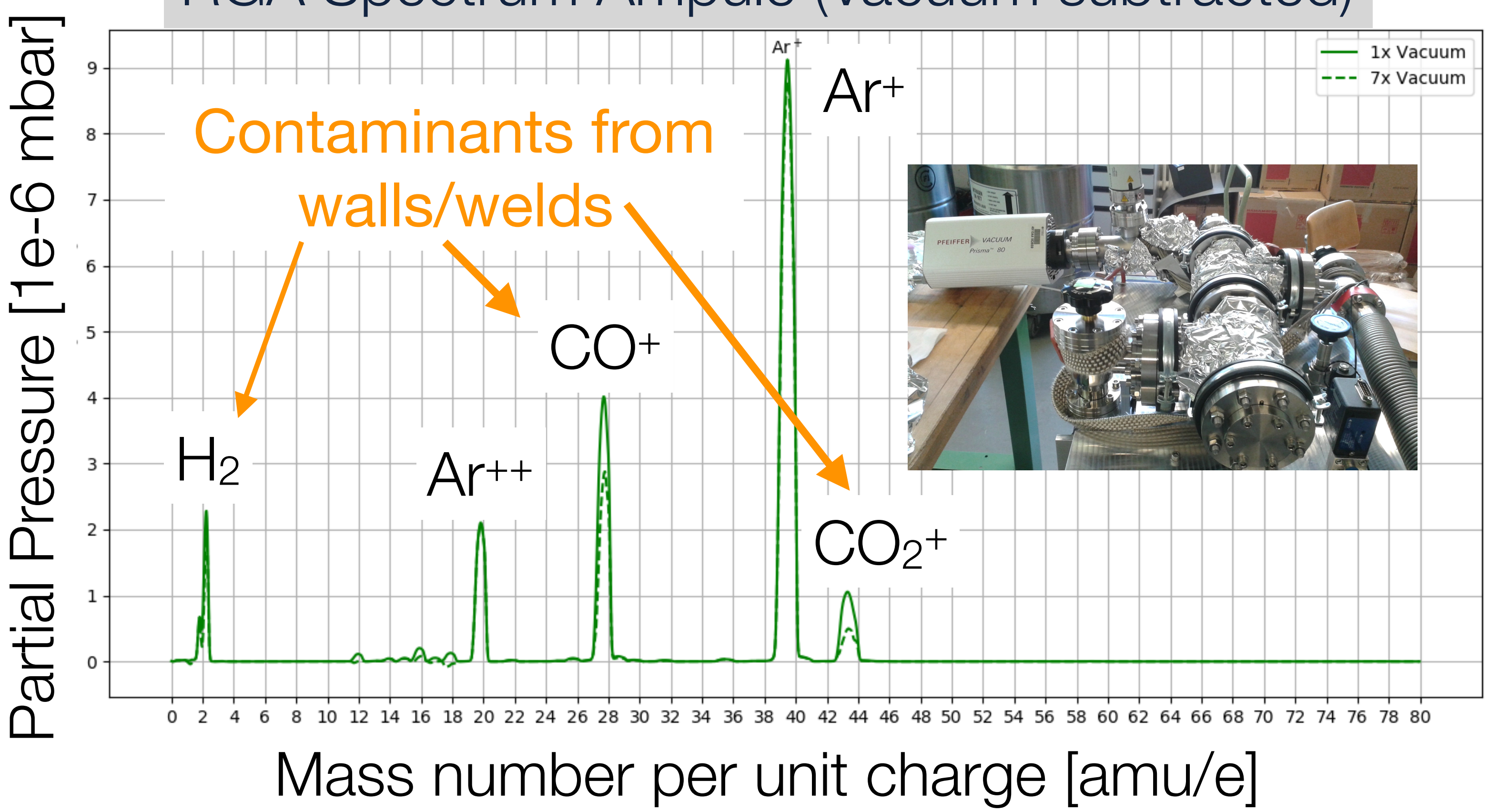


Argon filling setup

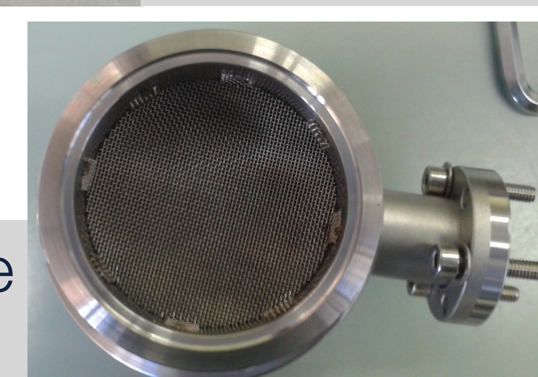


Sample preparation for activation

RGA Spectrum Ampule (Vacuum subtracted)

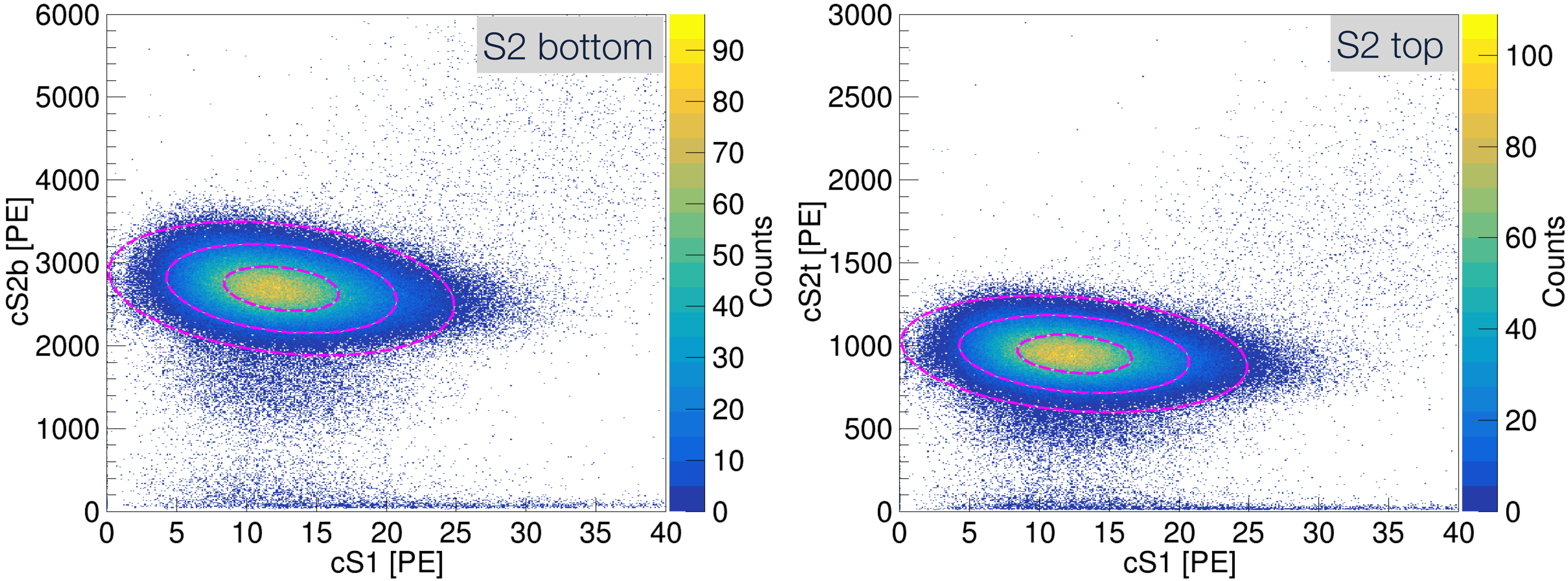


Packaged activated samples

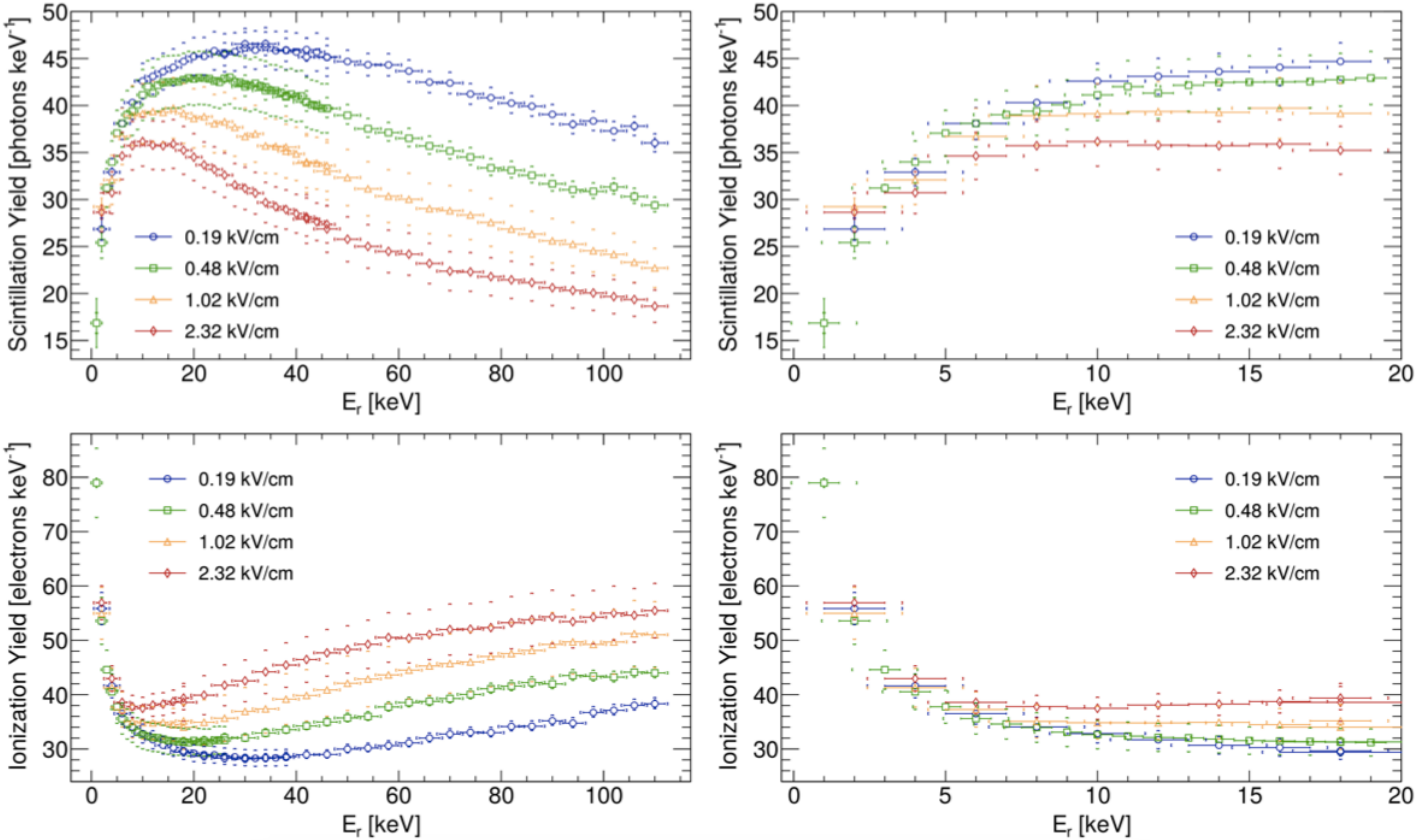


Filter in ampule chamber

^{37}Ar – RESULTS II



LIGHT AND CHARGE YIELD AT LOW ENERGIES



Phys. Rev. D 96, 103007 (2017)

SiPM WORKING PRINCIPLE

- Each cell is an Avalanche Photo Diode (APD) operated in Geiger Mode (reversely biased)
- For low illumination (linear region) number of photons is proportional to charge readout (number of cells fired)