Particle tracking with scintillating fibres read out with Single-Photon Avalanche Diode (SPAD) array sensor

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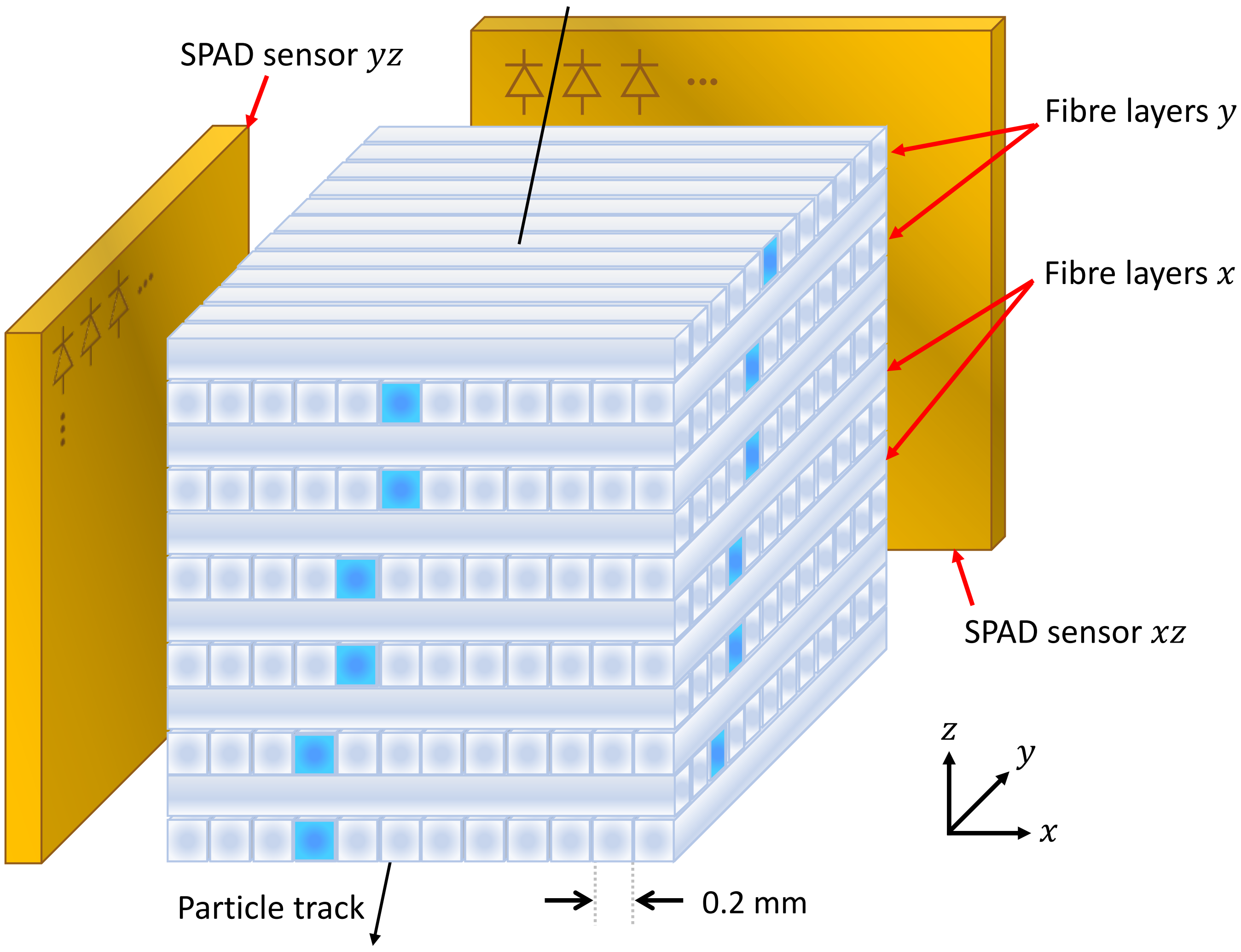
Motivation: High-granularity 3D particle tracking



Goal: Construct a high-granularity plastic scintillator (PS) detector for neutrino detection

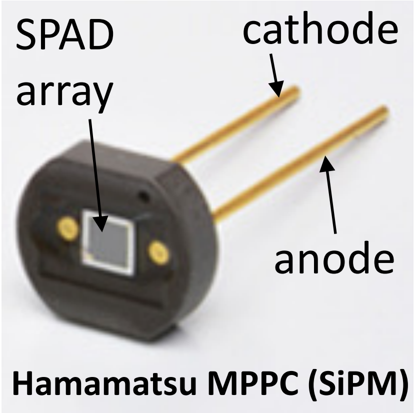
- Next generation of PS neutrino detectors need very precise position tracking to resolve neutrino—nuclear effects (e.g. protons with momentum down to 200 MeV/c)

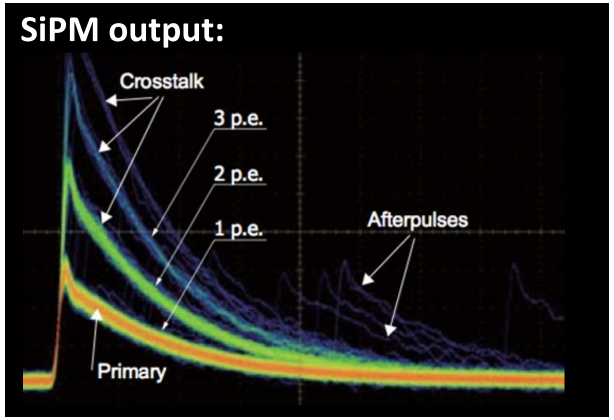
  → Small diameter (0.2 mm available) Scintillating Fibres (SciFis)

  → "XY" configuration allows full 3D tracking reconstruction of sub-mm long tracks

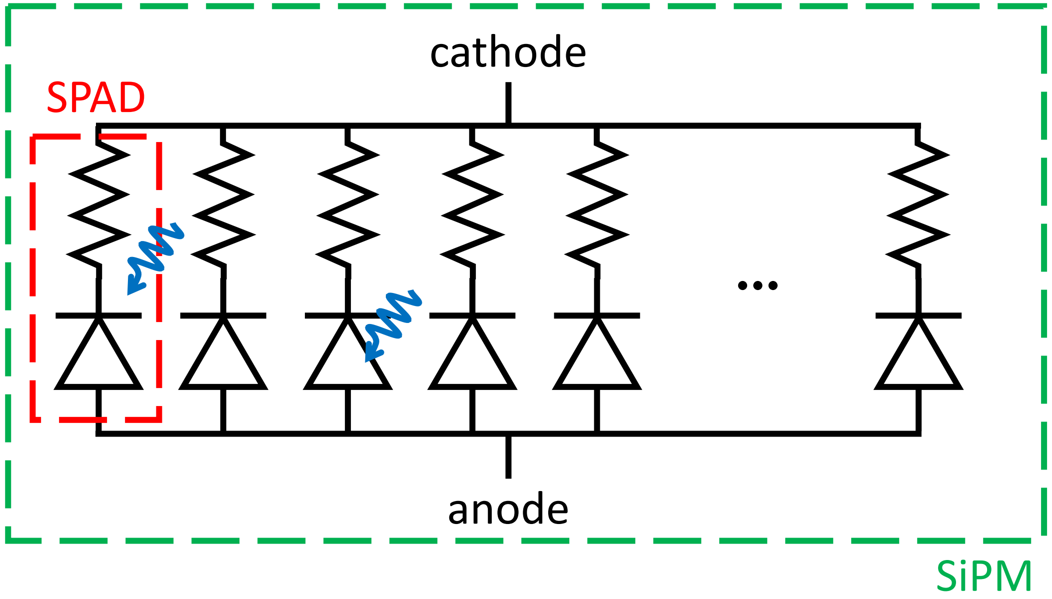
- State-of-the-art SciFi detectors are read out with Silicon Photomultipliers (SiPMs)
- Neutrino detectors require large mass (≥ 1 tonne) ∴ very large number of SiPMs and readout channels
- Proposed solution: SPAD array sensors

Silicon Photomultipliers (SiPMs)





Above images from: https://www.hamamatsu.com



- SiPMs are arrays of Single-Photon Avalanche Diodes (SPADs), all connected in parallel → capable of single photon sensitivity
- Size of sensitive area ≈ 10 mm^2 – 1 mm^2 → good for coupling to fibres
- Photon Detection Efficiency (PDE) ≈ 25 – 50 %
- Output is an analogue signal whose height depends on the number of detected photons

For example, a 1 tonne (1 m^3) XY SciFi configuration with 0.2 mm fibres, 25,000,000 SiPMs would be required

Single-Photon Avalanche Diode (SPAD) array sensors

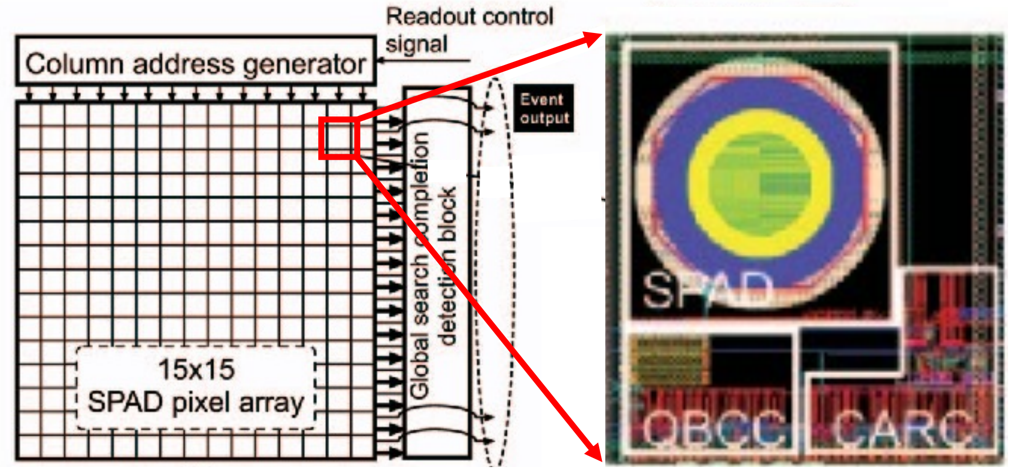
- Consists of an array of “pixels” whose sensing element is a SPAD
- Pixels contain electronics (timestamping, addressing, readout, memory, etc.) at the expense of Fill-Factor (FF)

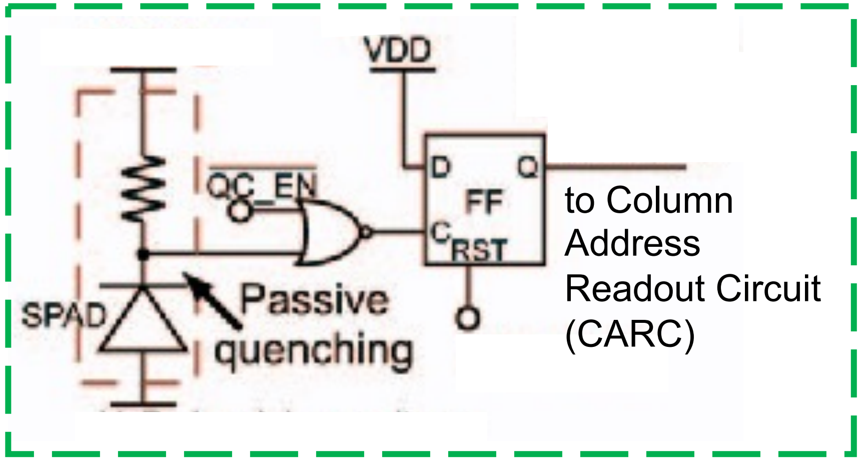
  → Position and time of arrival of individual photons in single pixels can be recovered

- Typical size of pixels is 10 um^2
- Typical size of sensors is 10 mm^2

A 1 m^3 SciFi detector would require 10,000 10 mm^2 sensors

Below images from X. Yang, et al. (2017)





Pixel

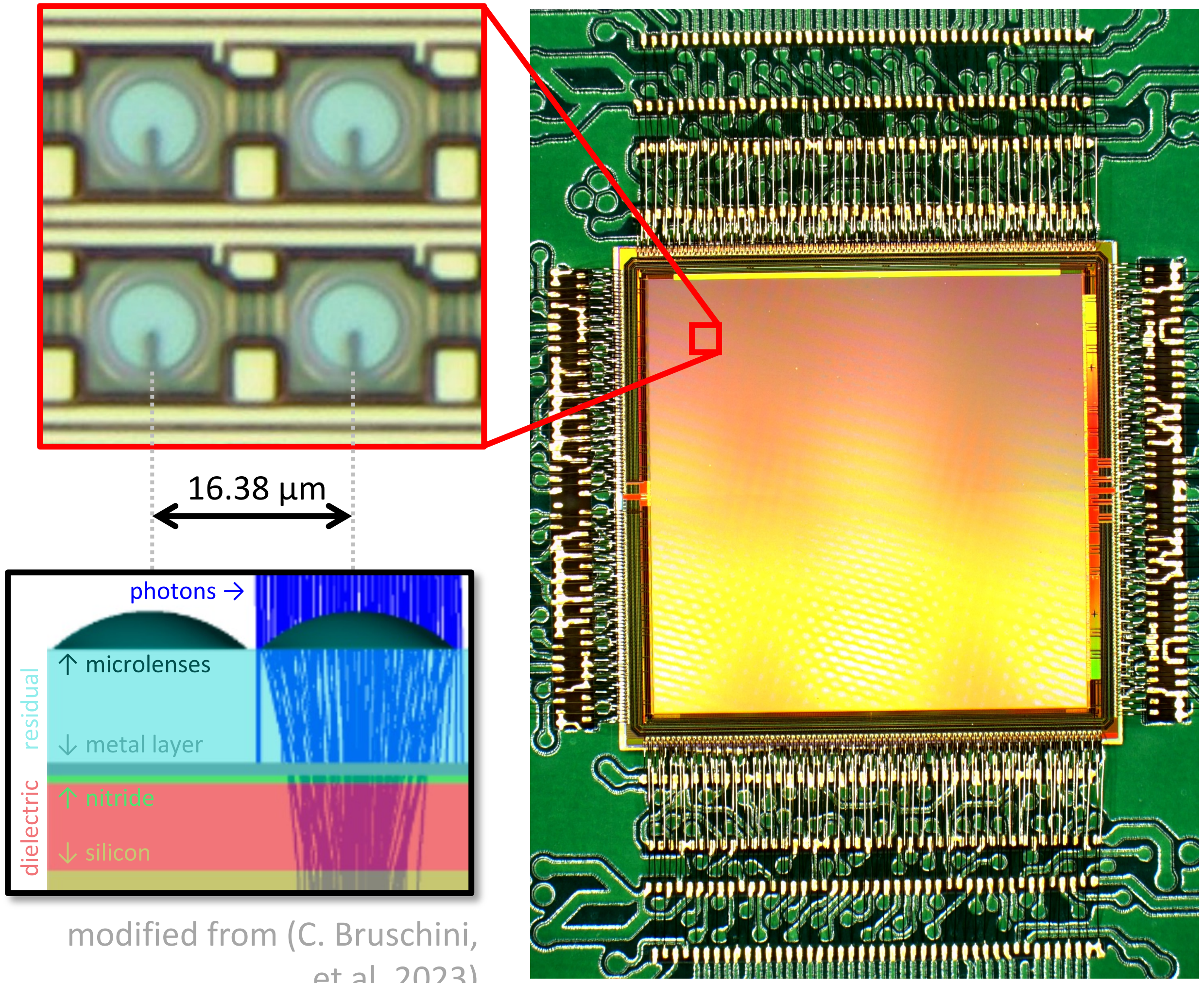
SciFi + SPAD array sensor prototyping: SwissSPAD2

Designed by EPFL (A. Ulku et al. 2019)

- Exposure time 10 ns < t_{gate} < 10 µs
- 8.4×8.4 mm^2 active area
- 512×512 array, 16.38 µm pitch pixels
- 10.5 % FF, 50% Photon Detection Probability (PDP) at 500 nm (at 7 V excess bias V_{ex})
- PDE = PDP × FF ≈ 5%

For this study, we have two sensors:

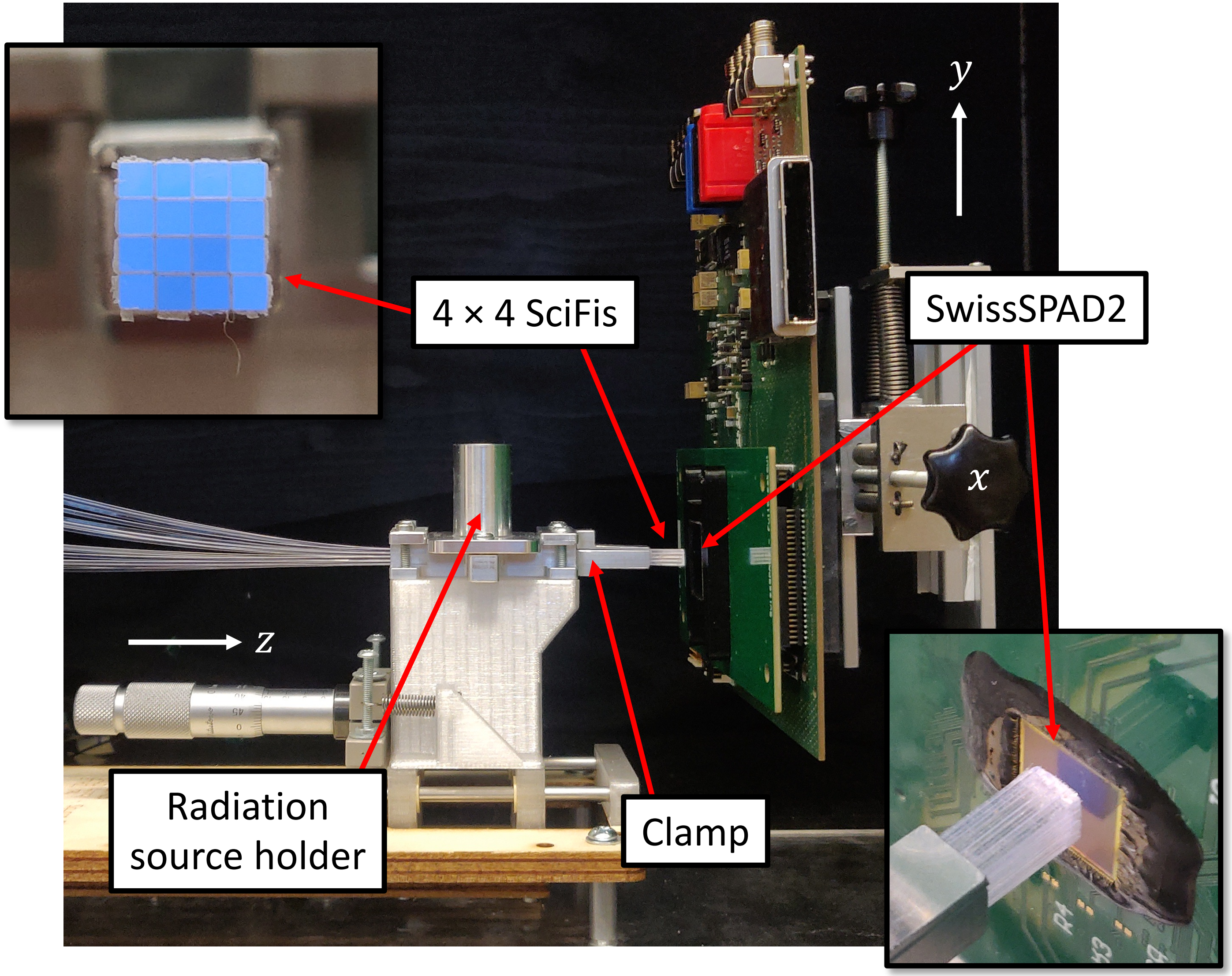
- With microlenses (improves PDE)
- Without microlenses



modified from (C. Bruschini, et al. 2023)

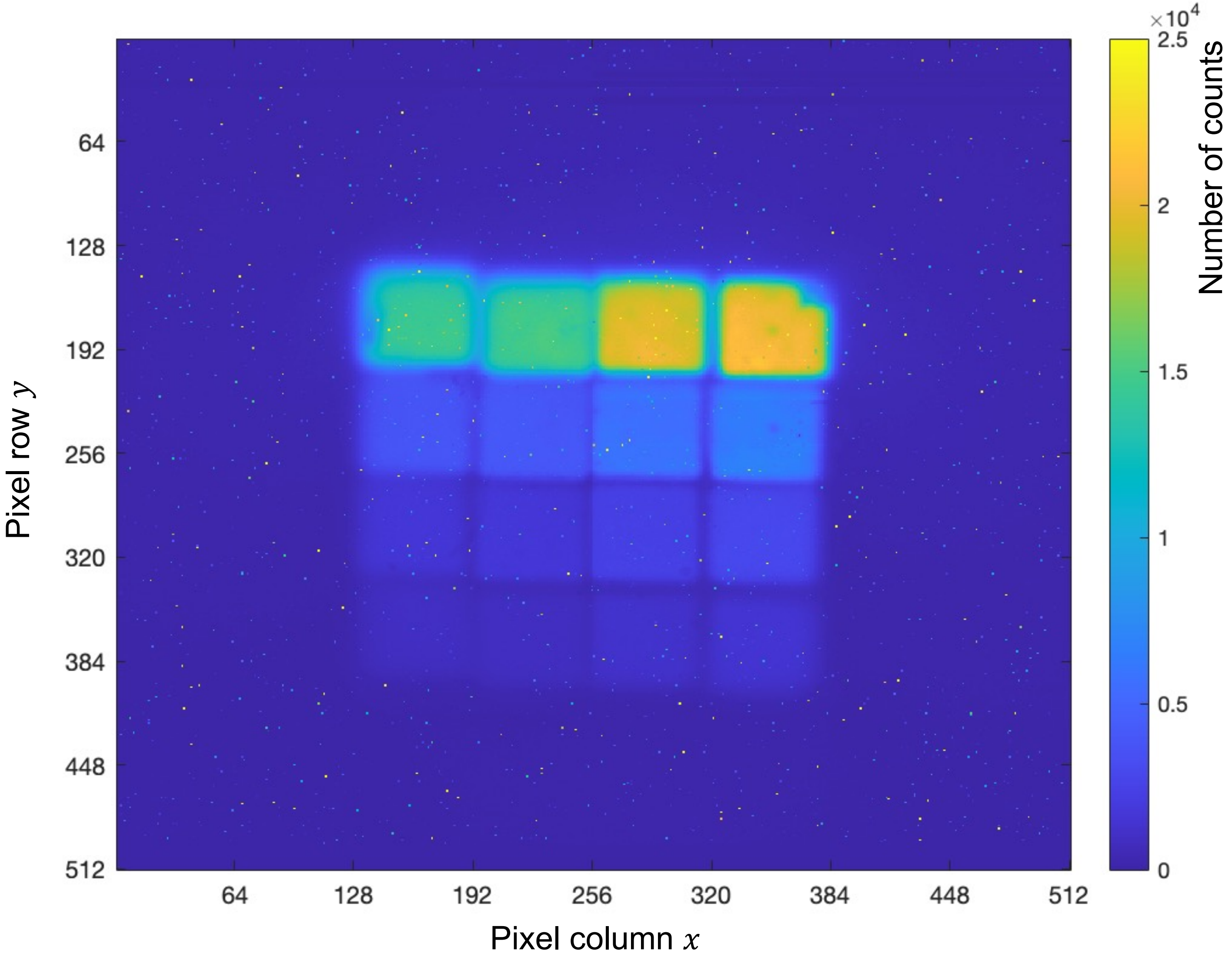
SwissSPAD2 (A. Ulku, et al. 2019)

Experimental setup of proof-of-concept design



- 4 × 4 bundle of 1 mm diameter square SCSF-78 SciFis from Kuraray (450 nm emission wavelength)
- SciFi bundle pointed at SwissSPAD2 SPAD array sensor
- Radiation source can be positioned directly above SciFi bundle
- Particle tracks travel through SciFis, generating photons which propagate the length of the fibre material, are emitted, and detected by the SPADs

Image of fibre bundle on SwissSPAD2 using blue light source



Aim: Identify pixels coupled to each fibre for tracking of ^{90}Sr electrons

- Fixed a collimated, blue (450 nm) light source above fibre bundle
- Positioned fibre bundle in the centre of SwissSPAD2 at < 1 mm distance (no optical grease or glue used)
- Captured and summed 25,600, 5 µs exposure frames

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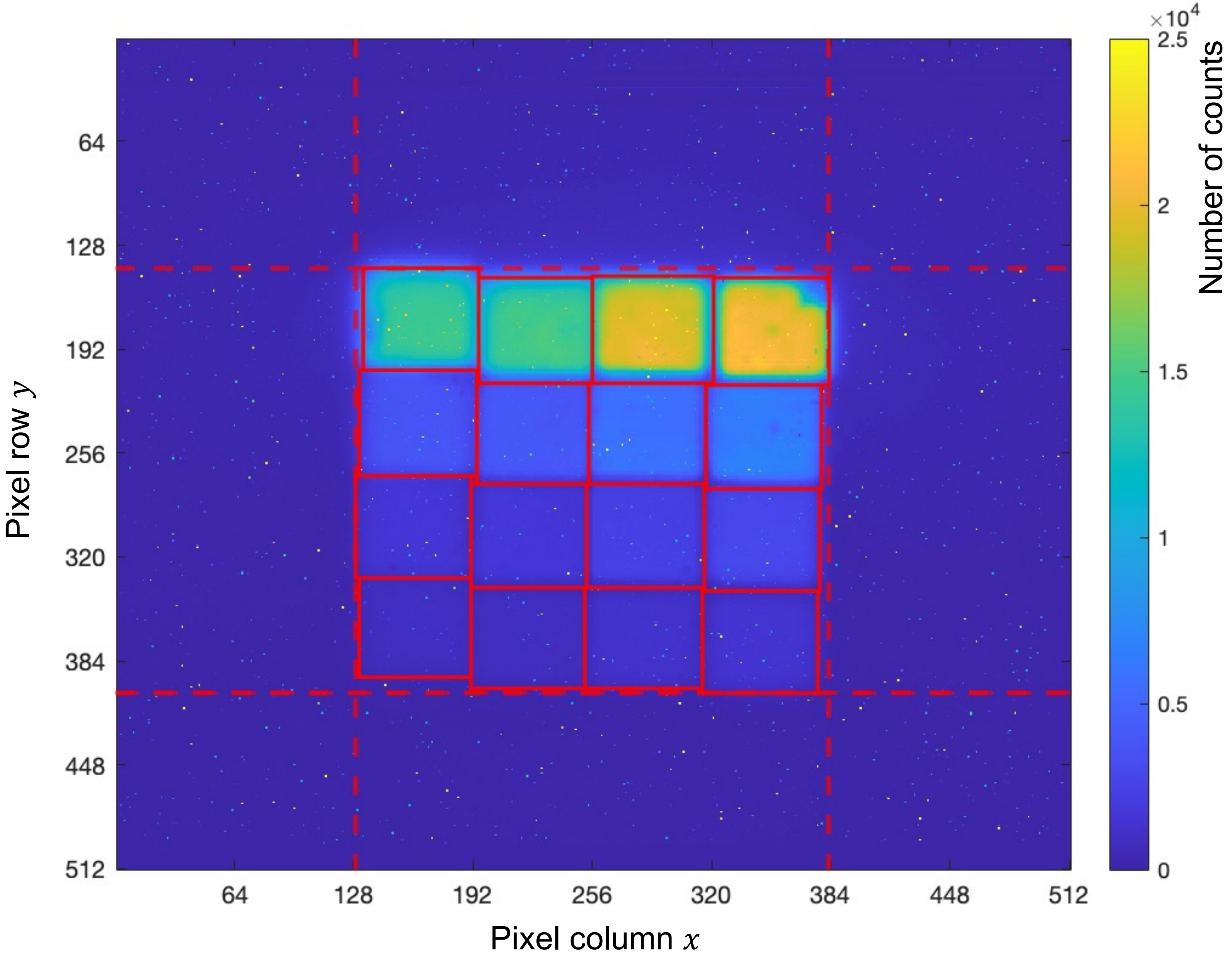

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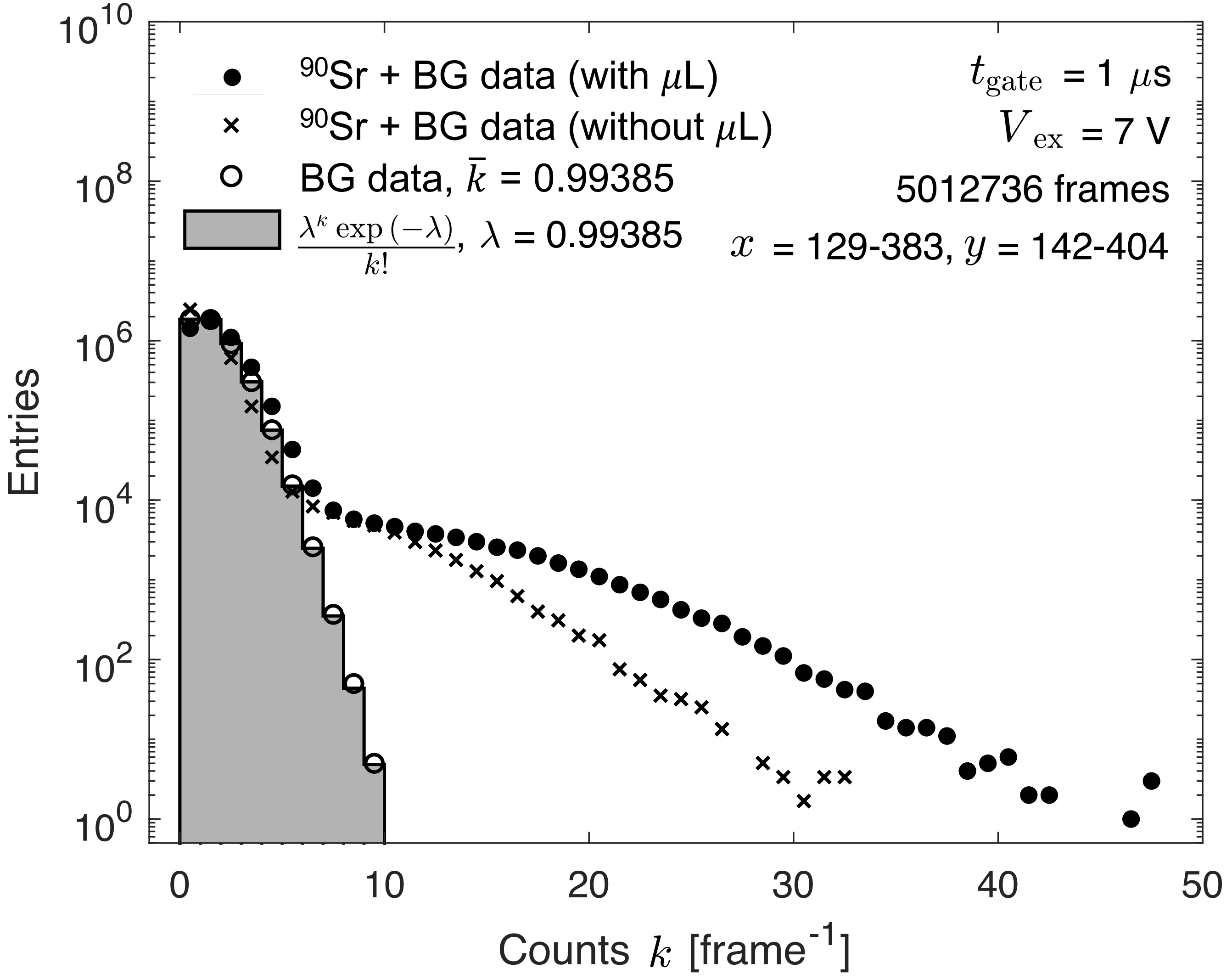
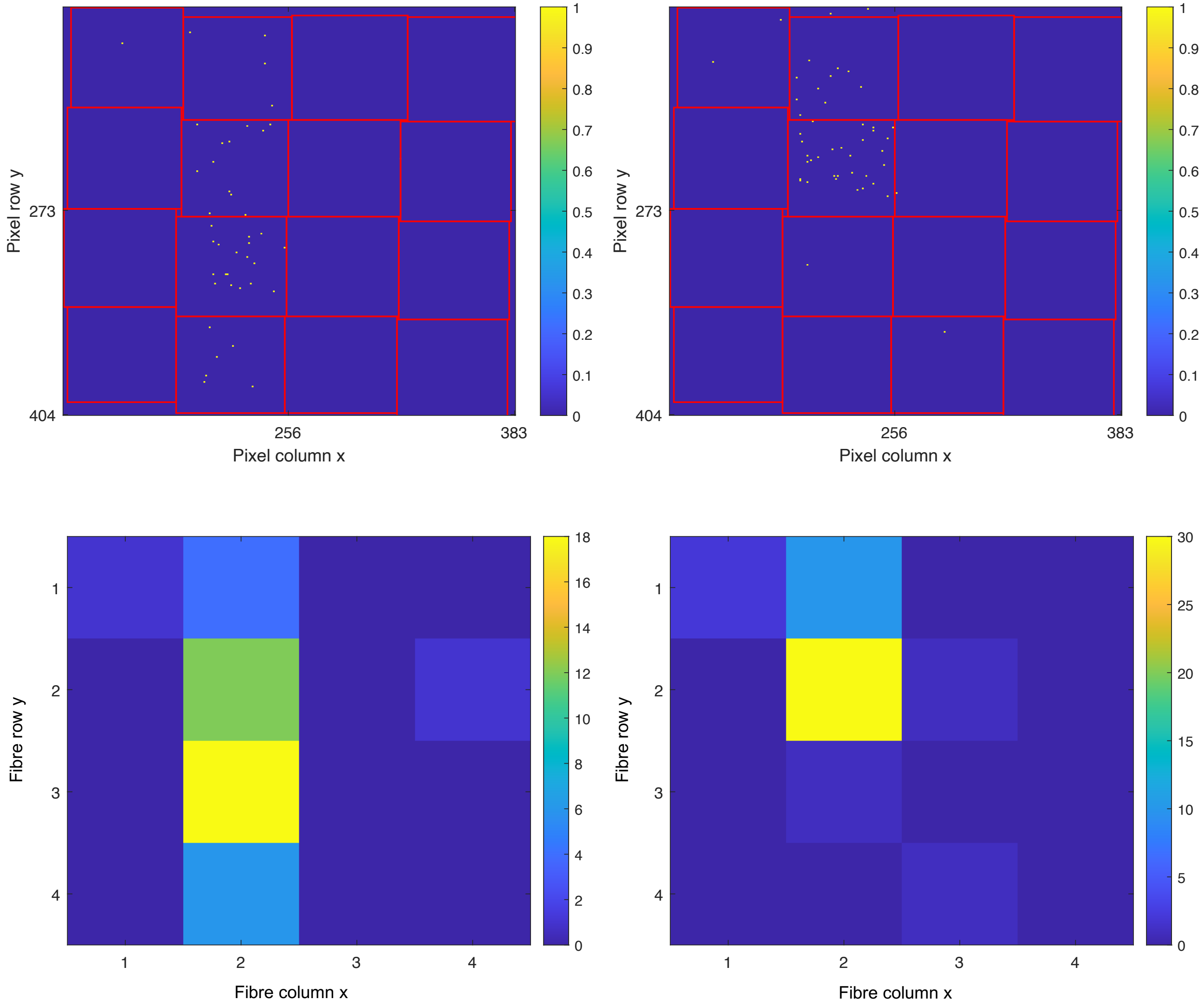
- Determined fibre edges for track selection purposes

Measurements with and without ^{90}Sr electron source



- Running in continuous mode 5 M, 1 µs exposure frames captured:
  - Without ^{90}Sr source (with microlenses)
  - With ^{90}Sr source (T_{kin} ≈ 2.0 MeV e^-) (with and without microlenses)
- Background (BG) data closely follows Poisson distribution with $\lambda = \bar{k}$ as expected
- Excess of counts frame^{-1} seen when ^{90}Sr source present clear signature of electrons traversing SciFi bundle
- **Increase of counts with microlenses thanks to increased PDE (6% at 450 nm)**

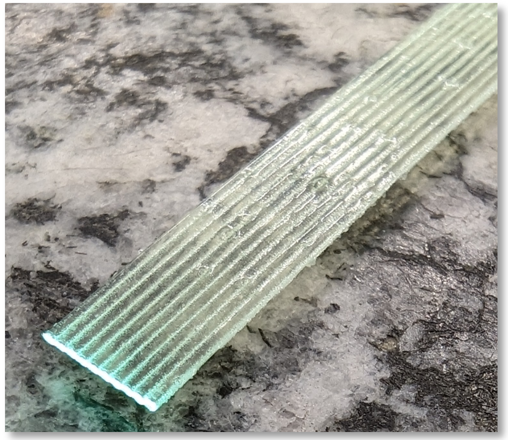
Track images from ^{90}Sr + BG data

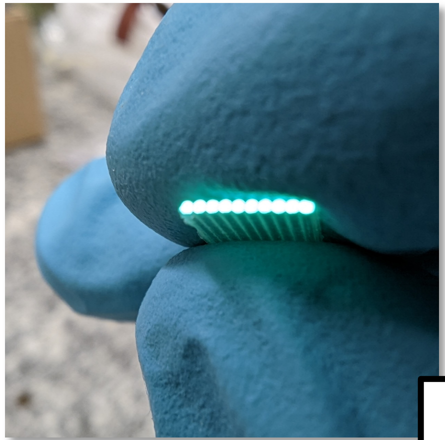


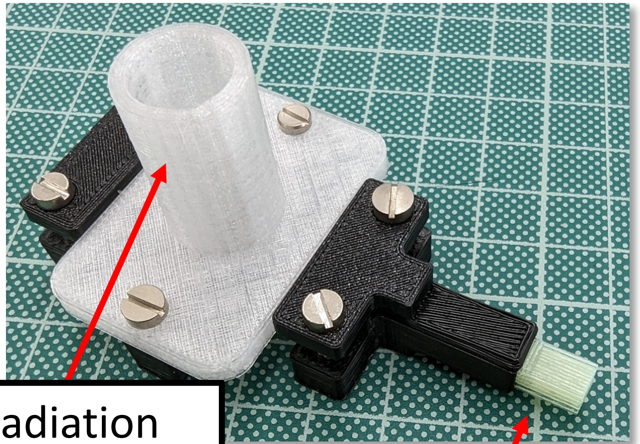
- Searched for vertical tracks in BG & ^{90}Sr+BG datasets using 3 parameters: No. fibres, Min. counts per track, and Min. counts per fibre.
- No. of vertical tracks in both datasets compared to compute the probability to observe 'fake' tracks
- Coincidence of multiple pixels within 1 µs gate suppress number of fake tracks, even for just a few detected counts

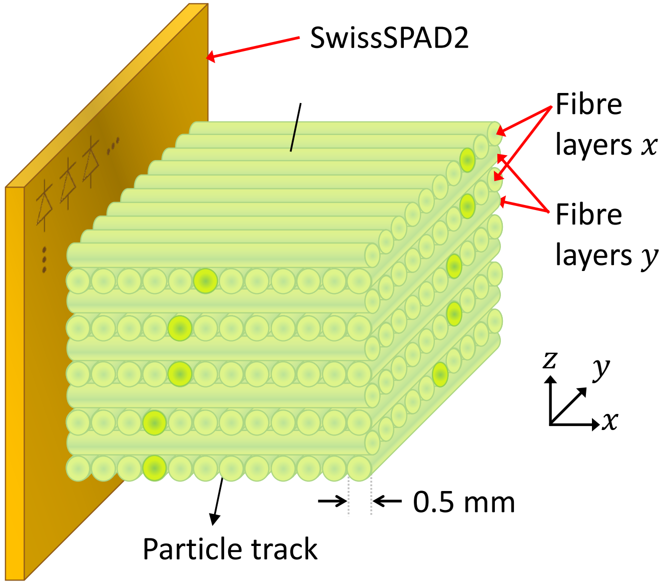
No. fibres	Min. counts per track	Min. counts per fibre	No. of tracks BG	No. of tracks ^{90}Sr+BG	Misidentification probability
3	3	1	3911	28108	13.9
	4	1	363	20808	1.7
	5	1	23	19055	0.1
	6	1	0	17684	0
	6	2	0	8160	0
4	4	1	231	8372	2.8
	5	1	31	7848	0.4
	6	1	1	7607	> 0.1
	6	2	0	2338	0

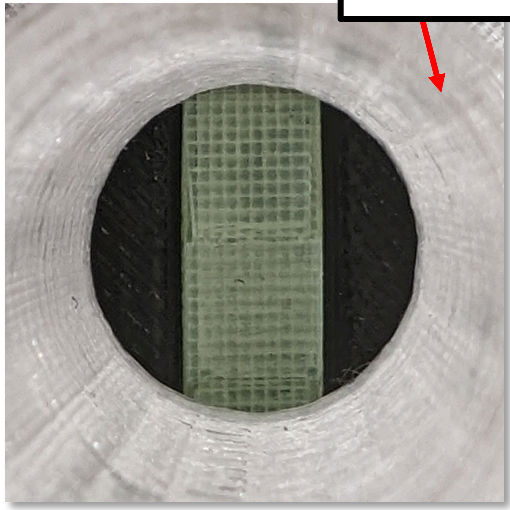
Towards a 3D SciFi detector



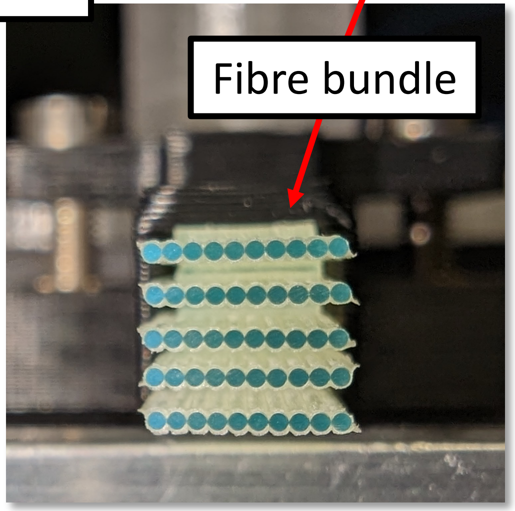








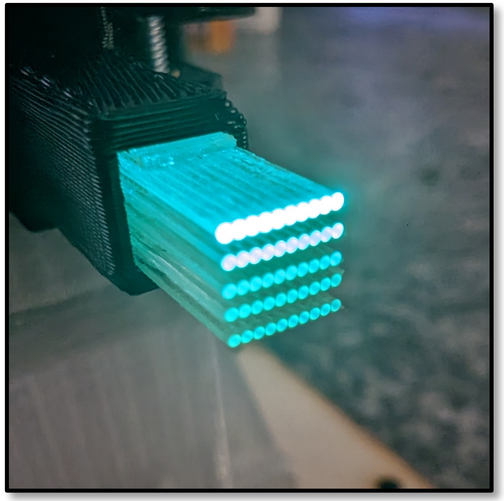
Top view

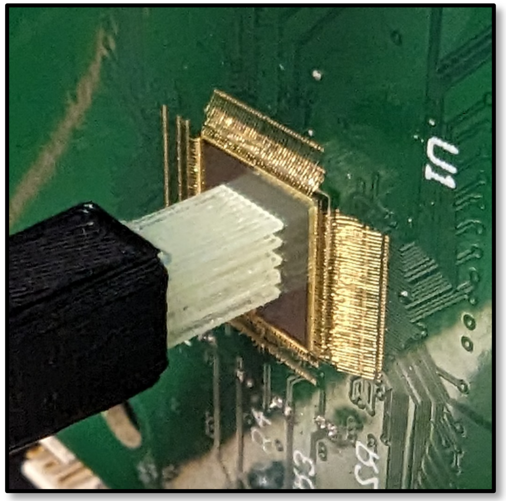


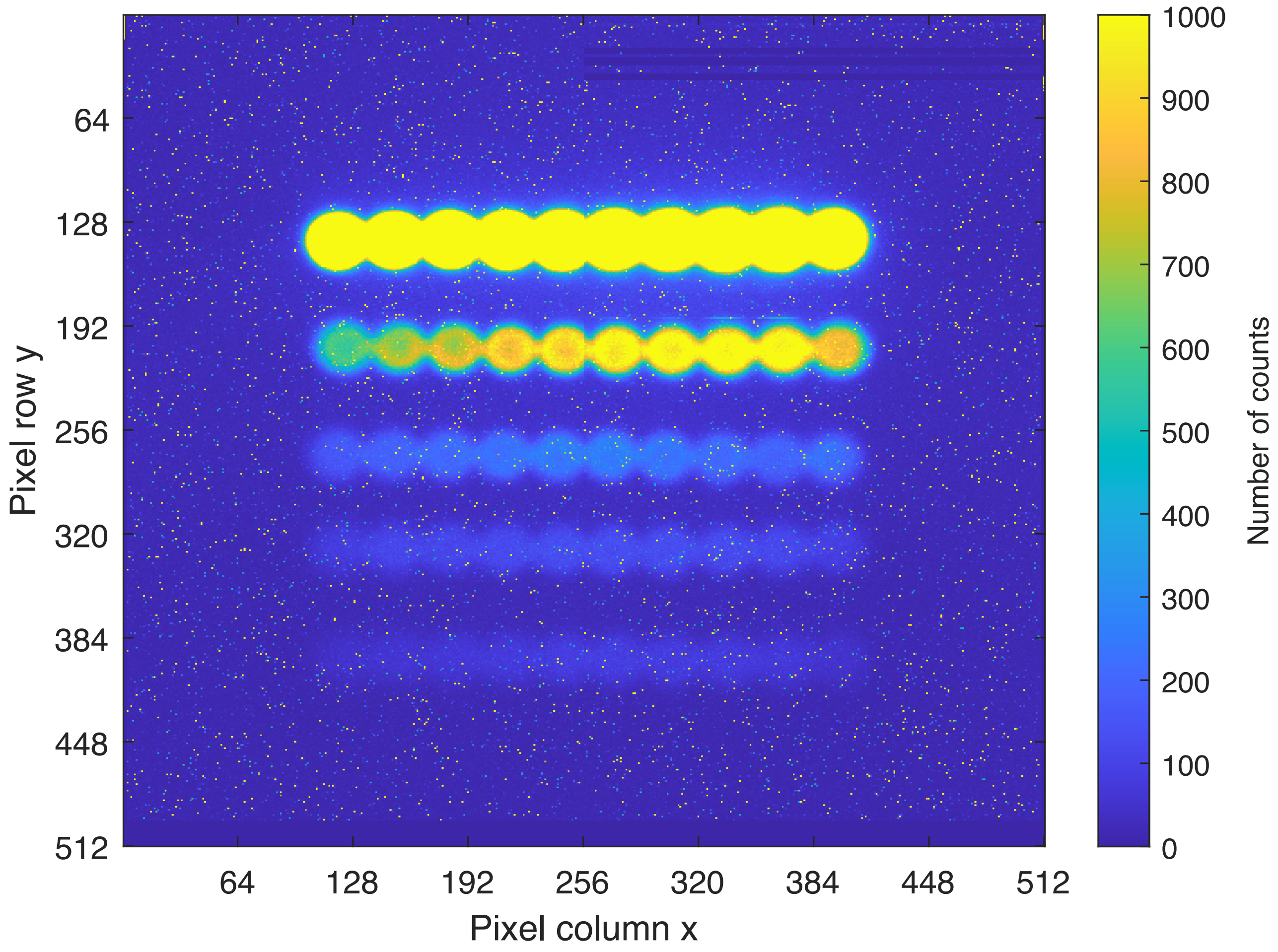
Front view

- Fibre “ribbons” from Luxium Solutions
- 10, 1 m long, 0.5 mm diameter, circular fibres (BCF-20) fixed side-by-side
- Emit in green (492 nm) → better matching with SwissSPAD2 peak PDE
- We have designed a module compatible with the above system to test these fibres

Preliminary measurements of XY fibre detector

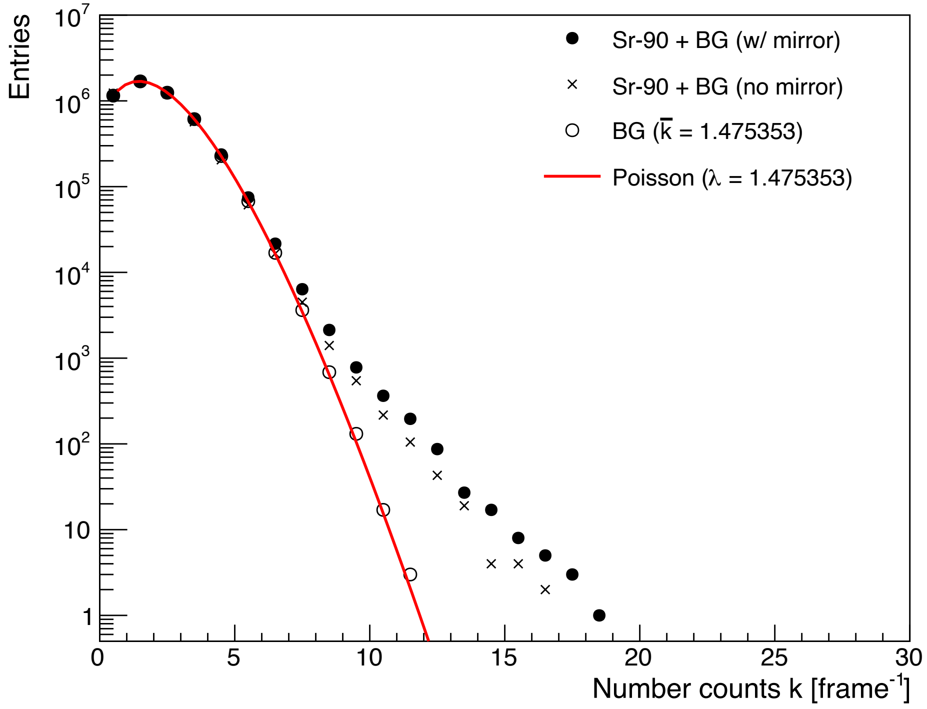




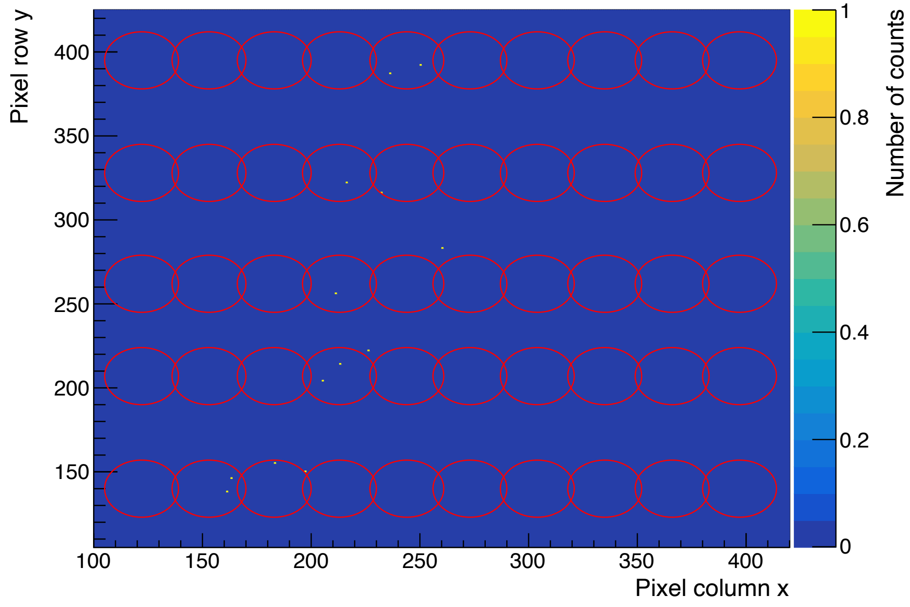


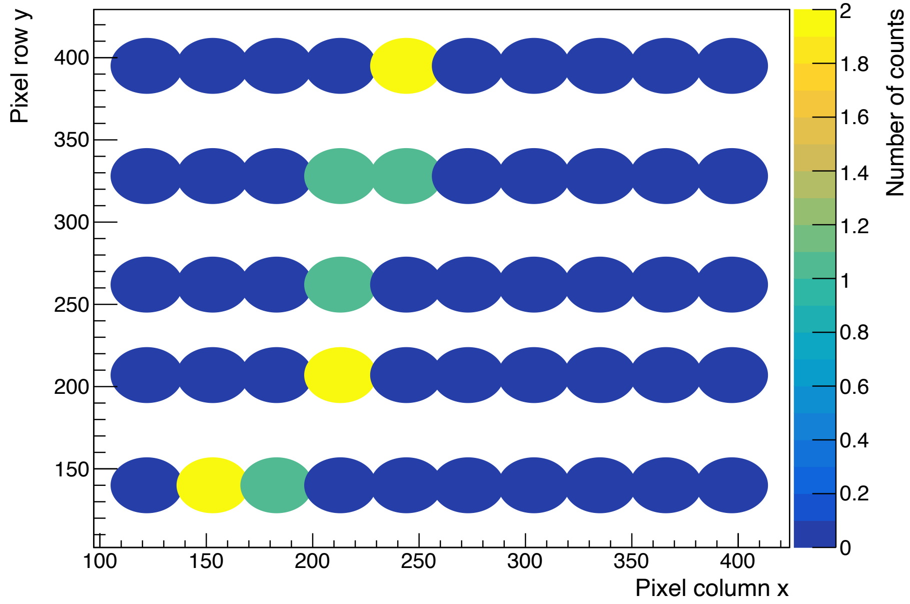
- Collimated, blue light source fixed above the XY fibre bundle
- Positioned fibre bundle in the centre of SwissSPAD2 at < 1 mm distance
- Captured and summed 5 µs exposure frames
- Identified pixels coupled to each fibre

First track from an XY prototype



- Circular bins used to bin counts per fibre
  - All other hits binned into overflow
- Track selection algorithm adjusted to search for diagonal tracks
- Example of electron track candidate found →
- Lower counts due to smaller diameter and circular shape of fibres

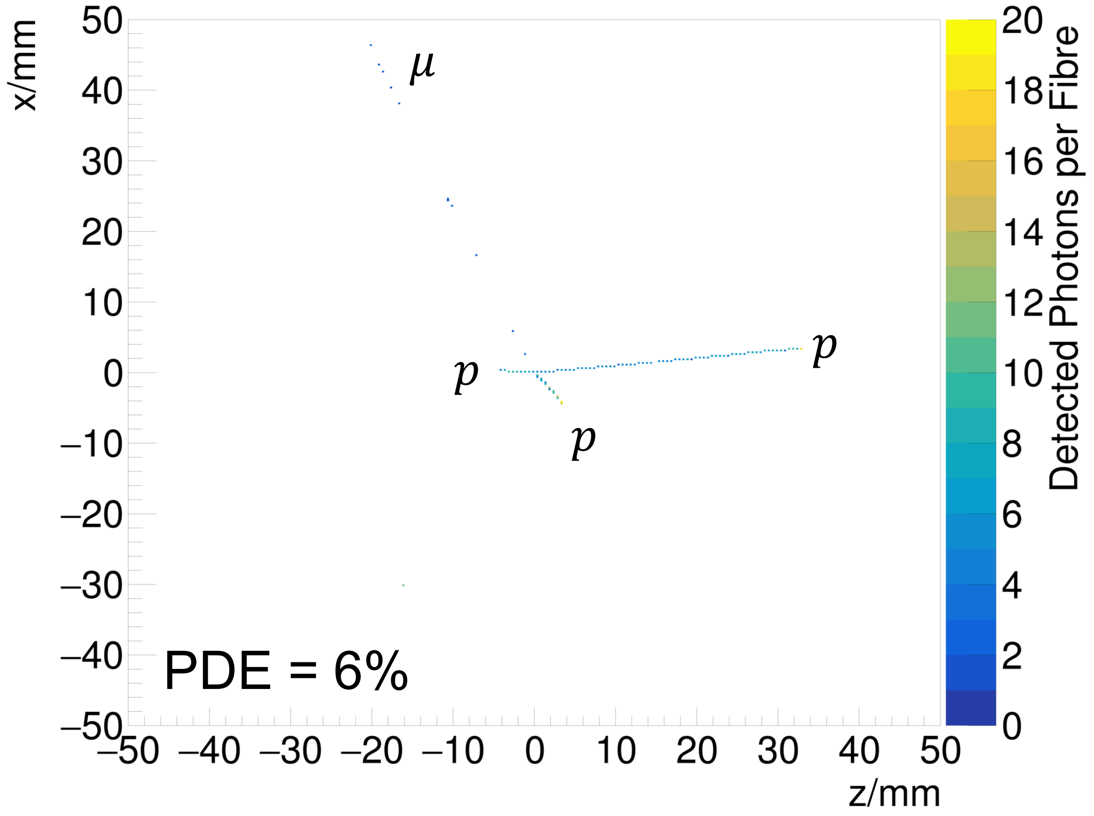


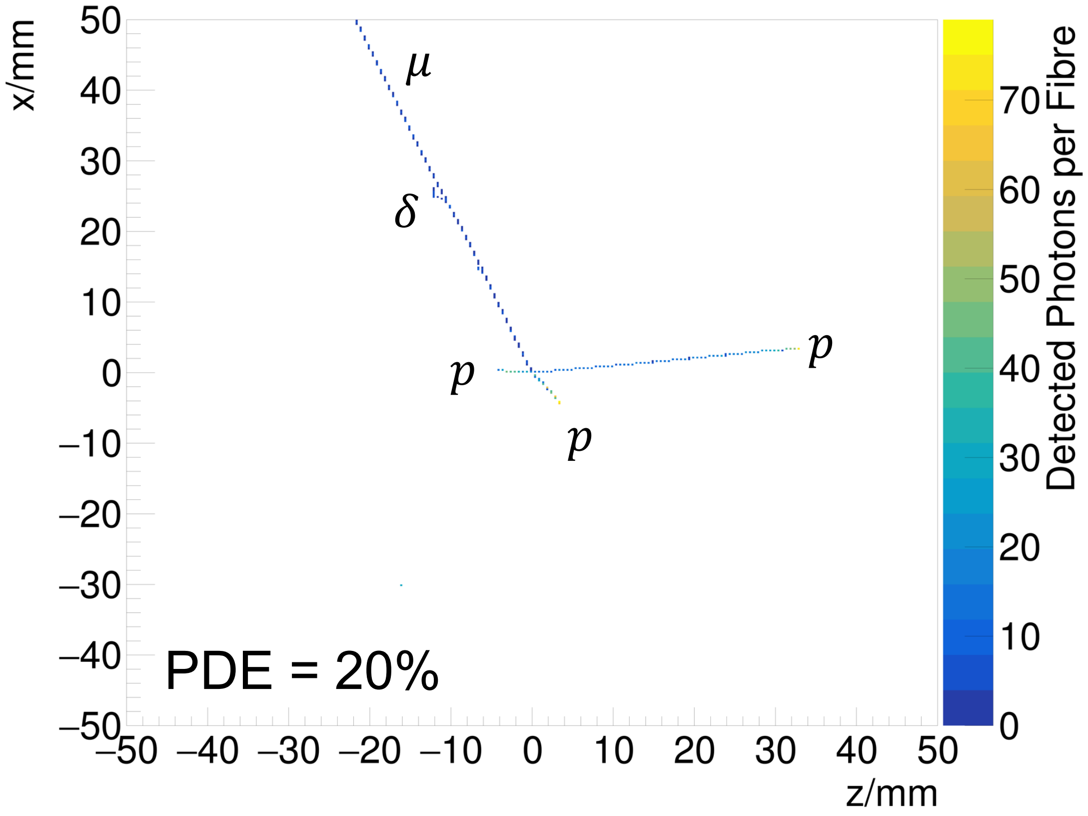


Simulations of SciFi detector read out with SPAD array sensor

ν_μ Charged Current Quasi Elastic (CCQE) events were simulated:

- **SciFi:** 2,000 XY layers, each with 8,000, 250 μm × 2 m fibres (2 × 2 × 1 m³)
- **SPAD:** Instrumented with SPAD array sensors with PDE = 6% and PDE = 20%





- "Low" PDE is sufficient to track proton Bragg peak

- "High" PDE desirable for improved tracking
- (Reveals delta electron)

New SPAD array sensor design

Developing new SPAD array sensor with our colleagues at EPFL

- Increase PDE compared to SwissSPAD2 (PDE = FF × PDP)
  1. Increase pixel Fill-Factor (FF) (i.e. increase SPAD size or reduce area occupied by pixel electronics)
  2. Increase Photon Detection Probability (PDP) by experimenting with SPAD geometry
- Add ability to measure time-of-arrival of photons with O(100ps) time resolution
- Implementing multi-photon counting time coincidence circuit for noise rejection (noise-free with SciFis)
- First MPW (Multi-Project Wafer) has been submitted in a 110 nm CMOS Image Sensor (CIS) technology node

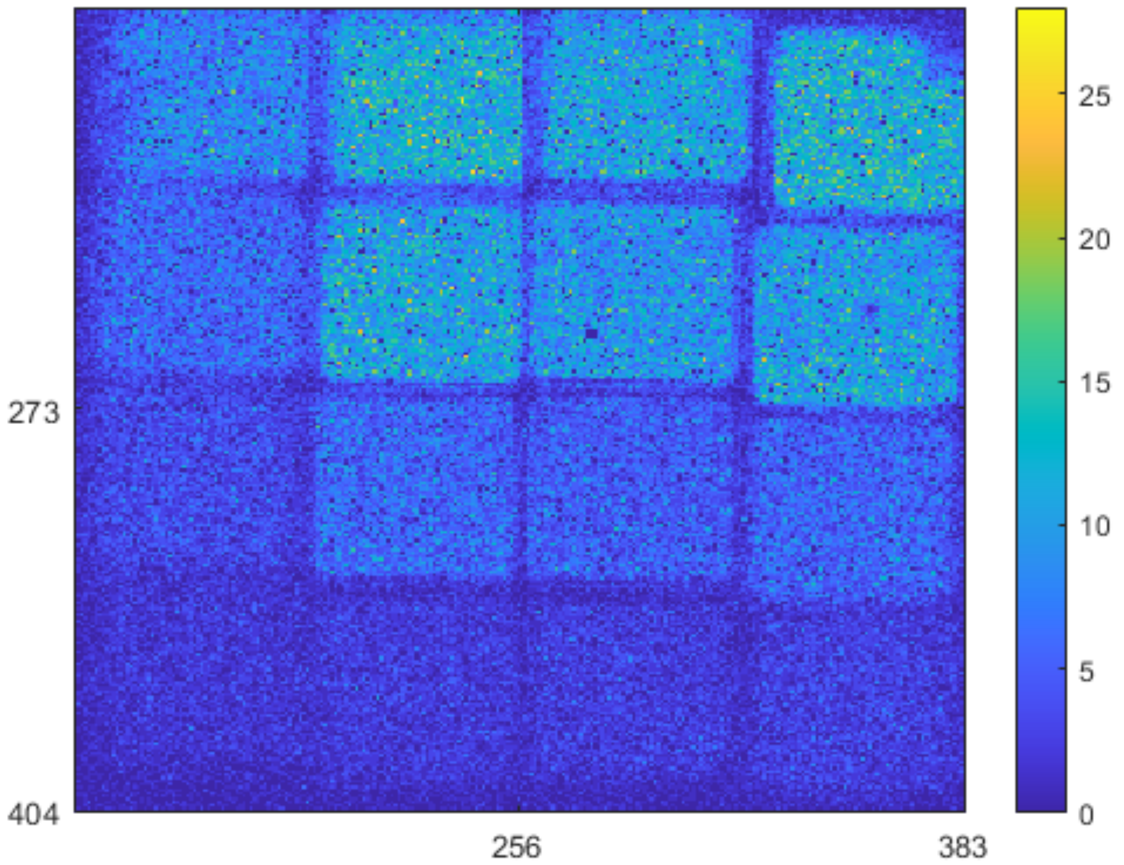
Parameter	Unit	Value	Note
Pixel pitch	µm	20	
Photon timestamp resolution	ps	200	
Target PDE	%	> 10	at ~ 500 nm
Exposure time (gate)	µs	5 – 20	Optimal for neutrino beam parameters

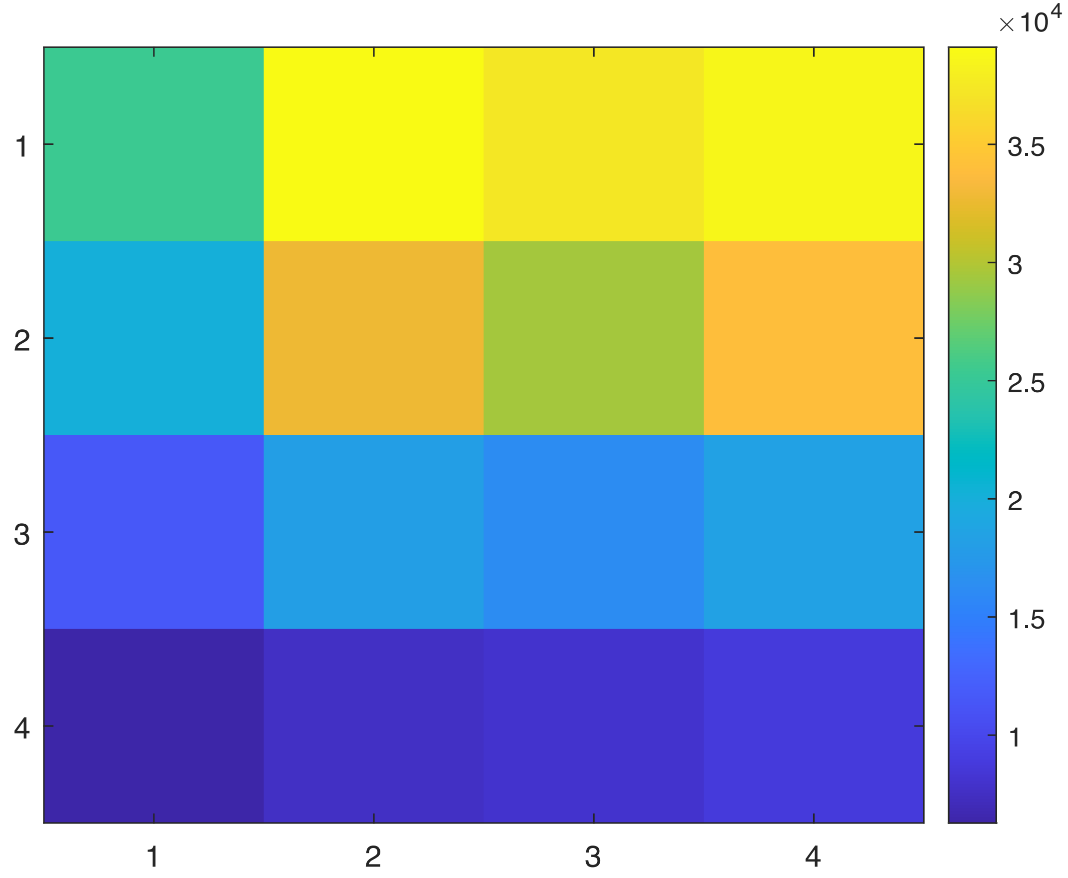
Conclusion

- R&D towards an XY SciFi detector read out with SPAD array sensor
  - Goal is to track low-momentum particles (e.g. protons) produced in neutrino interactions
  - Constructed proof-of-concept PS detector using SciFis read out with SwissSPAD2 and imaged ^{90}Sr electron tracks
- Simulated large XY SciFi detector read out by SPAD array sensors
  - Excellent identification of short track (low-momentum) protons (≈ 150 MeV/c) is feasible with 6% PDE SPAD (SwissSPAD2 with microlenses)
  - Dedicated sensor with improved PDE (~20%) is required for improved particle ID and MIP tracking efficiency
- Submitted to arXiv: http://arxiv.org/abs/2309.03131
- Work in progress on the design of a new SPAD array:
  - Sub-ns per-pixel time-of-arrival information for noise suppression
  - Higher PDE

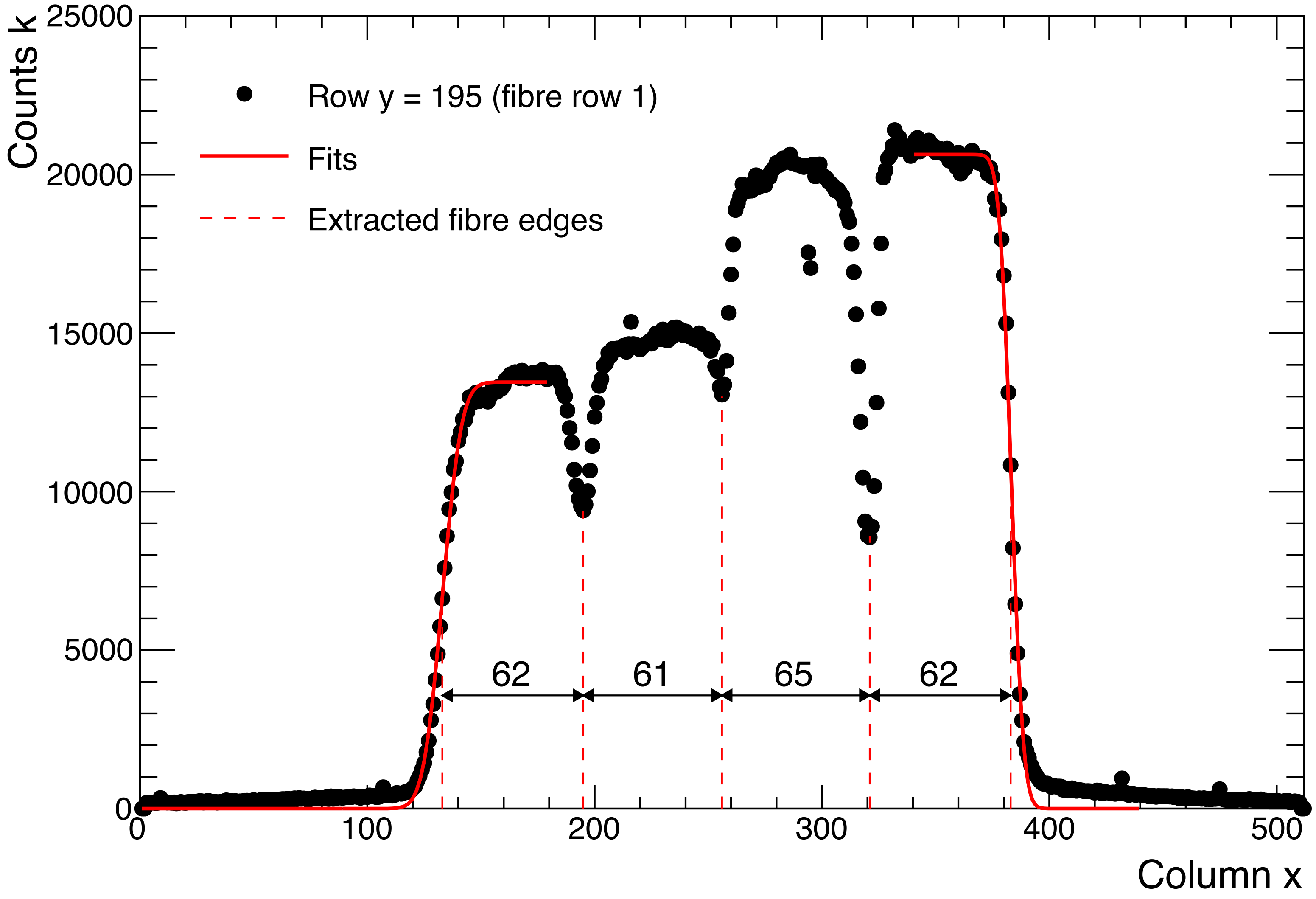
Backup slides

Sum of frames containing ^{90}Sr e^- track candidates





Determine fibre edges on SwissSPAD2 with blue light source

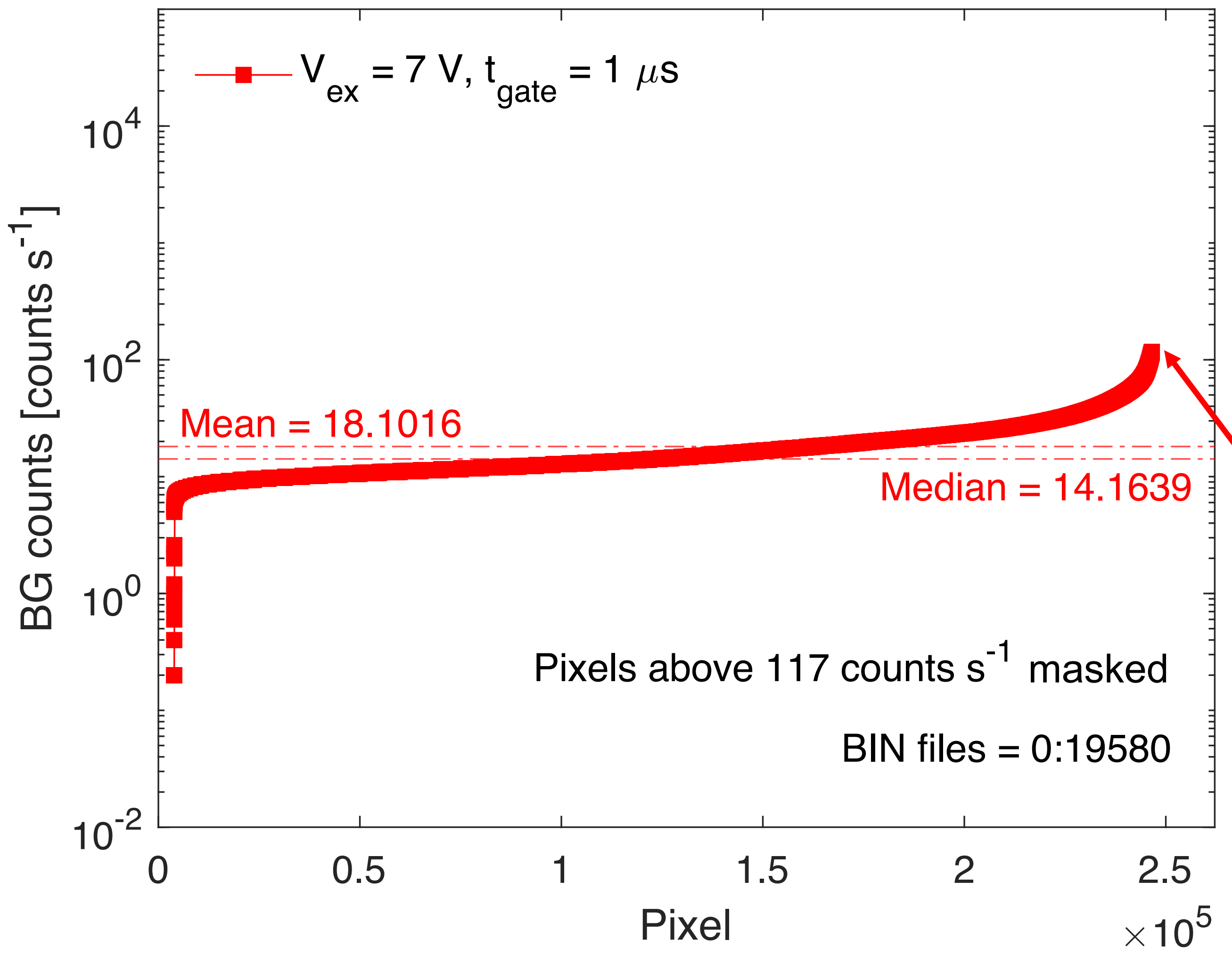


- Sum of images taken with blue light source positioned above fibre columns
- Extract horizontal and vertical projections
- Minima correspond to fibre-to-fibre interfaces
- Fitted error functions to determine bundle edges:

$$k(x) = \frac{(-)a}{2}\,\mathrm{erf}\left(\frac{x-d}{b}\right) + \frac{a}{2}$$

- Sanity check: 62.5 × 16.38 μm = 1,023.75 μm ≈ 1 mm

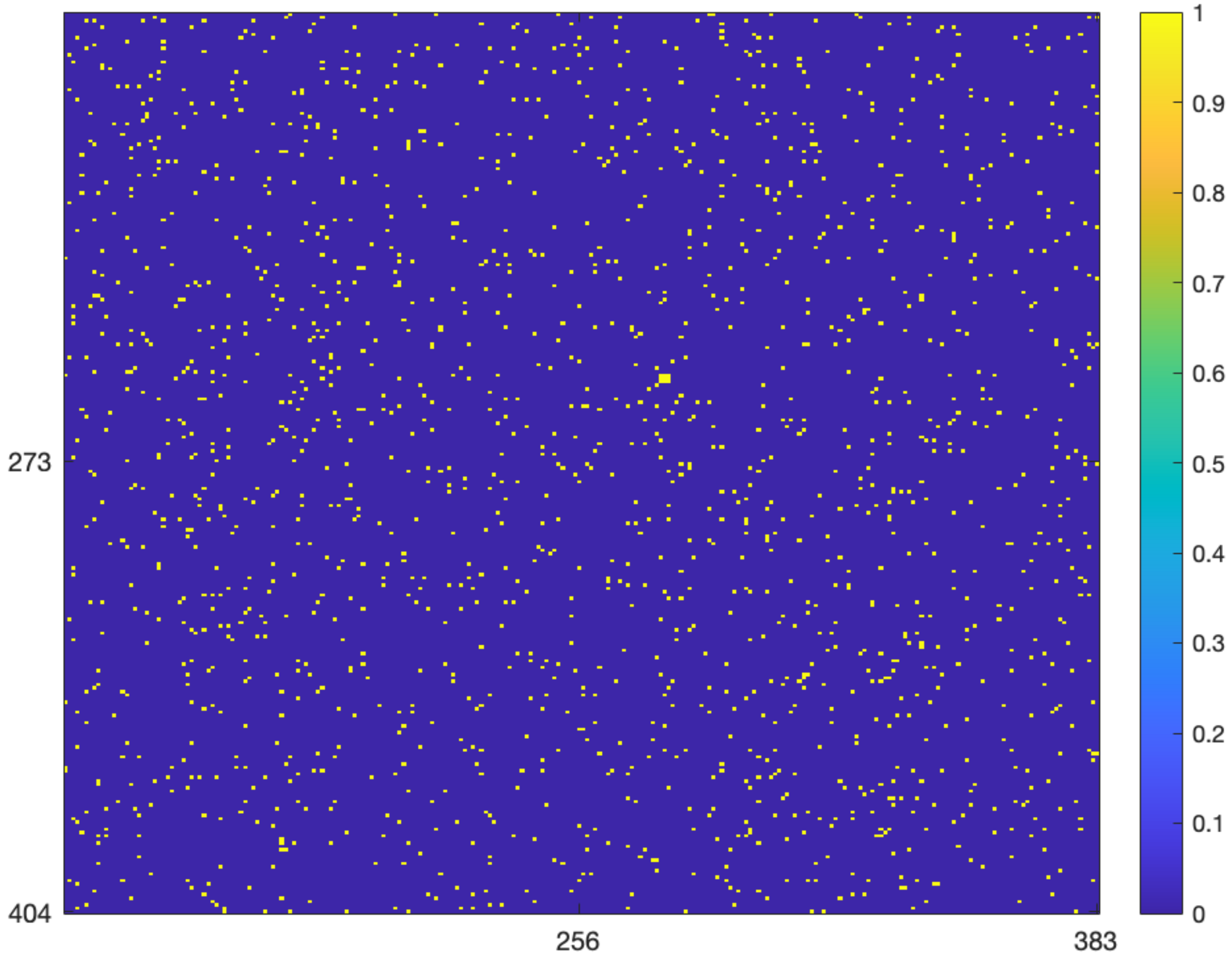
Determine and mask noisy pixels



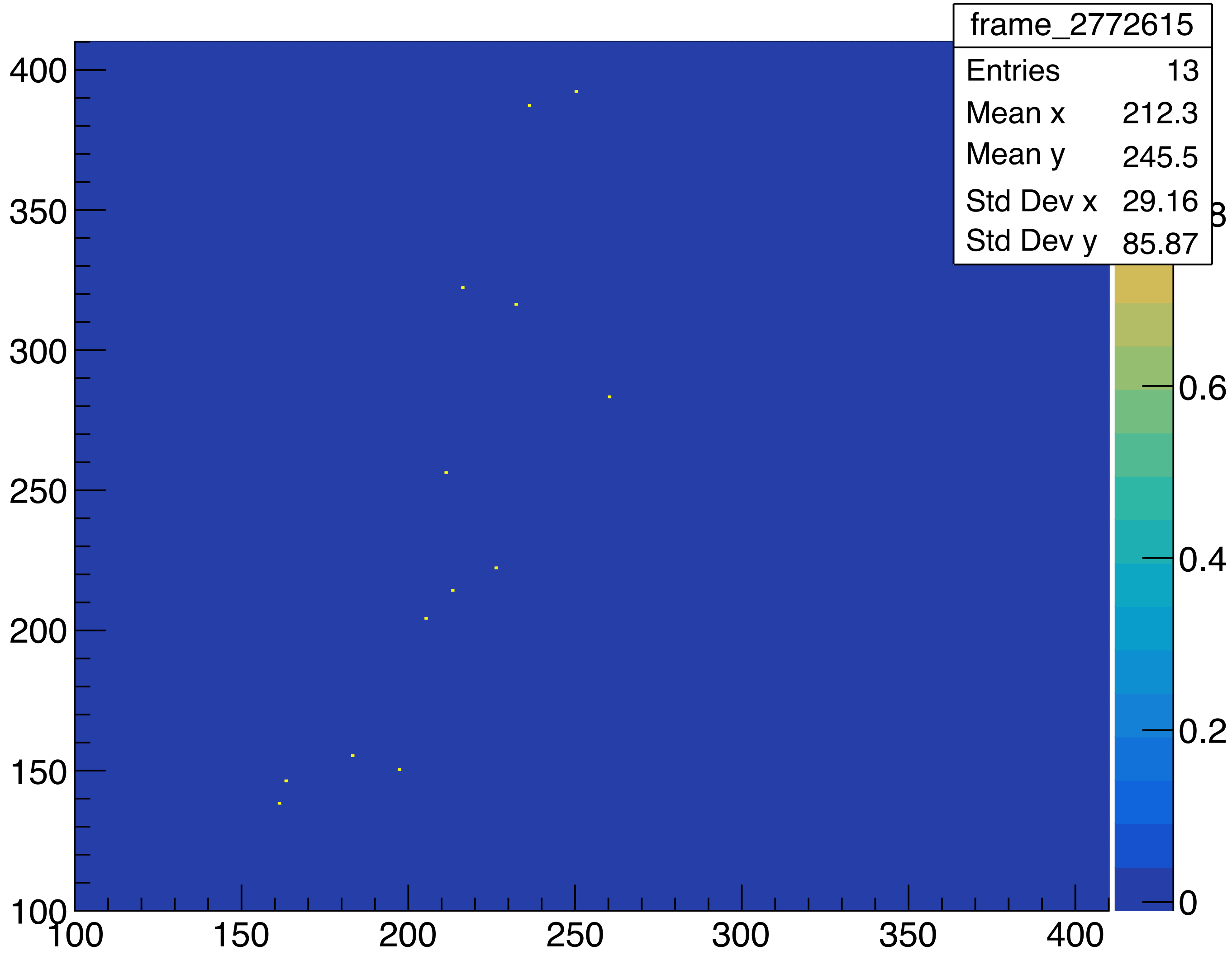
Aim: Determine noisy pixels so that they can be masked in measurements

- Operated SPAD sensor at desired measurement conditions (V_{ex} = 7 V, t_{gate} = 1 μs)
- Obtained 19581 files × 256 frames = 5,012,736 frames
- Summed counts in each pixel in each frame & converted to counts s^{-1}
- For the measurement: noisiest top 5% of pixels were masked

Map of masked SwissSPAD2 pixels in measurements



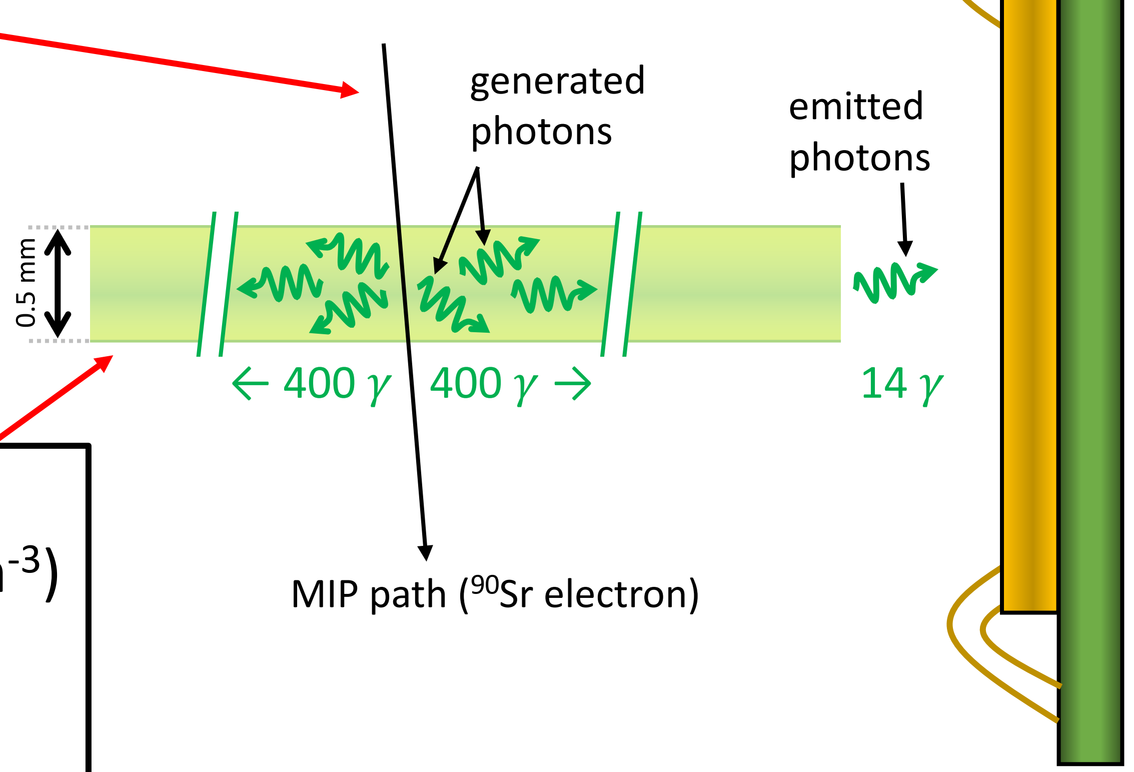
Electron track candidate captured with XY SciFi detector



Number of photons per MIP expected with fibre ribbons

Assume 400 γ in each direction:
400 γ * 3.44 % ≈ 14 $\gamma \cdot side^{-1}$
14 γ * 6 % = < 1 $\gamma \cdot side^{-1}$

^{90}Sr electron:
- $E_{max} \approx 2.0$ MeV
- $E_{loss} \approx 2.0\ MeV \cdot cm^{-1}$*
  $= 0.1\ MeV \cdot fibre^{-1}$
  $= 800\ \gamma \cdot fibre^{-1}$

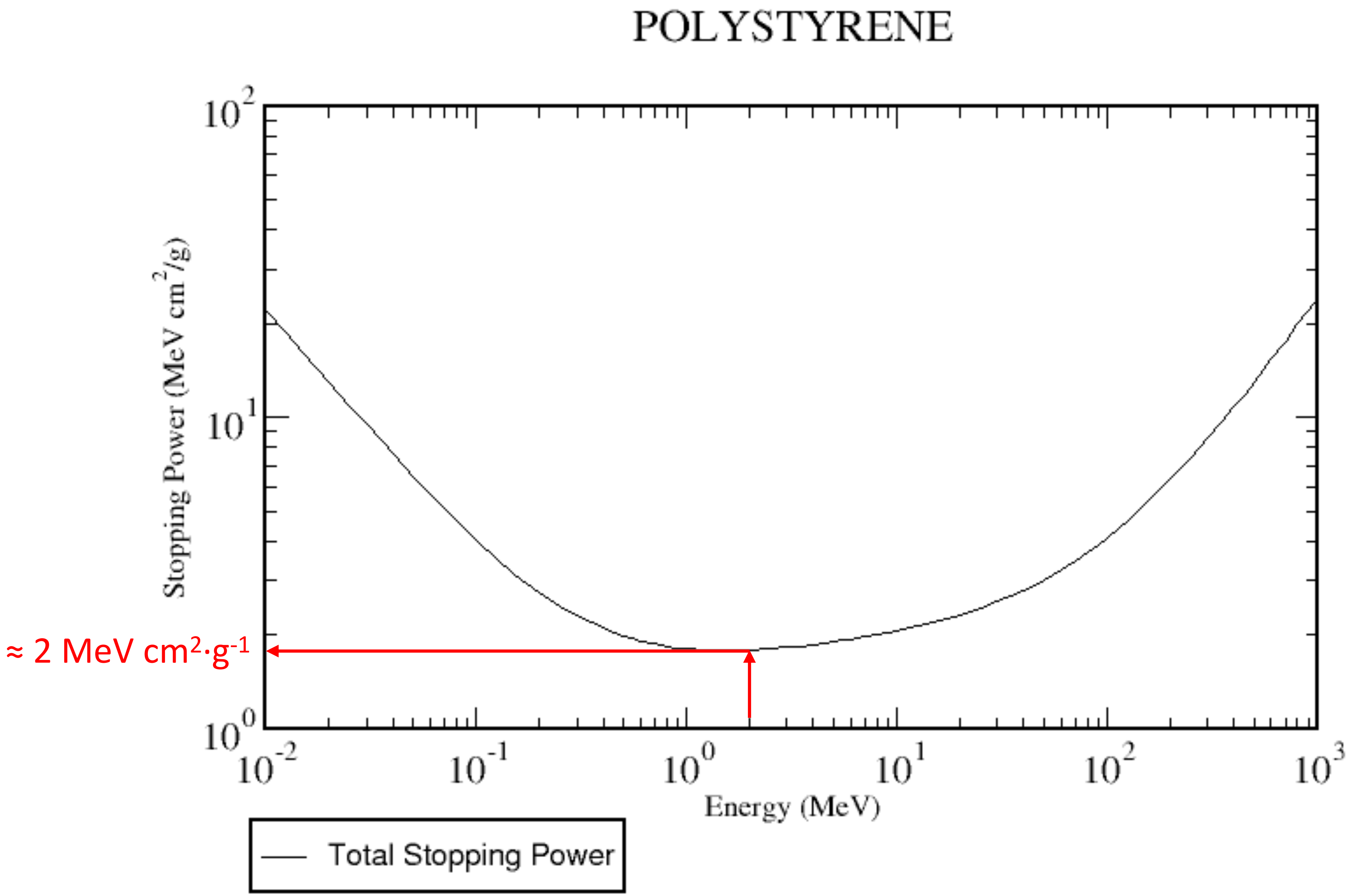


SwissSPAD2:
- PDE ≈ 6 %

Luxium fibres:
- Polystyrene core ($\rho \approx 1\ g \cdot cm^{-3}$)
- $\varepsilon_{trapping}$ = 3.44 % (minimum)
- Ø = 0.5 mm = 0.05 cm
- Light yield = $8000\ \gamma \cdot MeV^{-1}$

*ESTAR (physics.nist.gov) assuming a density of $1\ g \cdot cm^{-3}$

Stopping power for electron in polystyrene*



*ESTAR (physics.nist.gov)