Detector Development

for

Dark Matter Searches

Christos Toukmenidis

University of Hamburg (UHH)

Herbstschule HEP 2026

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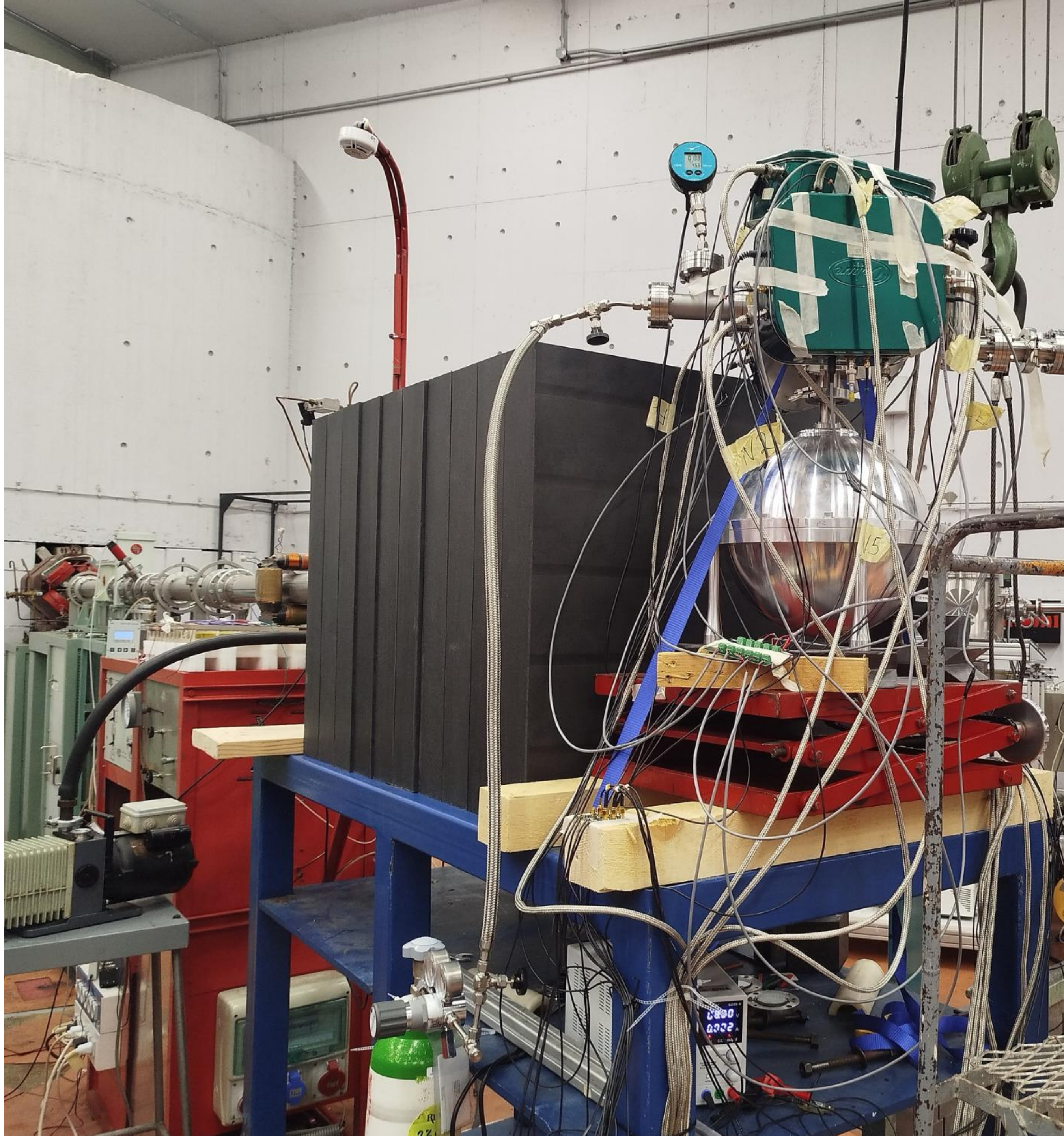

UHH Universität Hamburg

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EXZELLENZCLUSTER

QUANTUM UNIVERSE

My work - Outline

- University of Hamburg – **Research Group Nikolopoulos**

- R&D for **light Dark Matter** employing **Spherical Proportional Counters**[1] **(SPCs)**

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- My work so far involves:
  1. Geometry optimization for **neutron scattering experiment** for **SPC characterisation** with Geant4[2]

  2. **Silicon Photomultiplier (SiPM)** Characterisation / Radiation Hardness campaign

  3. **Plastic Scintillator** Characterisation

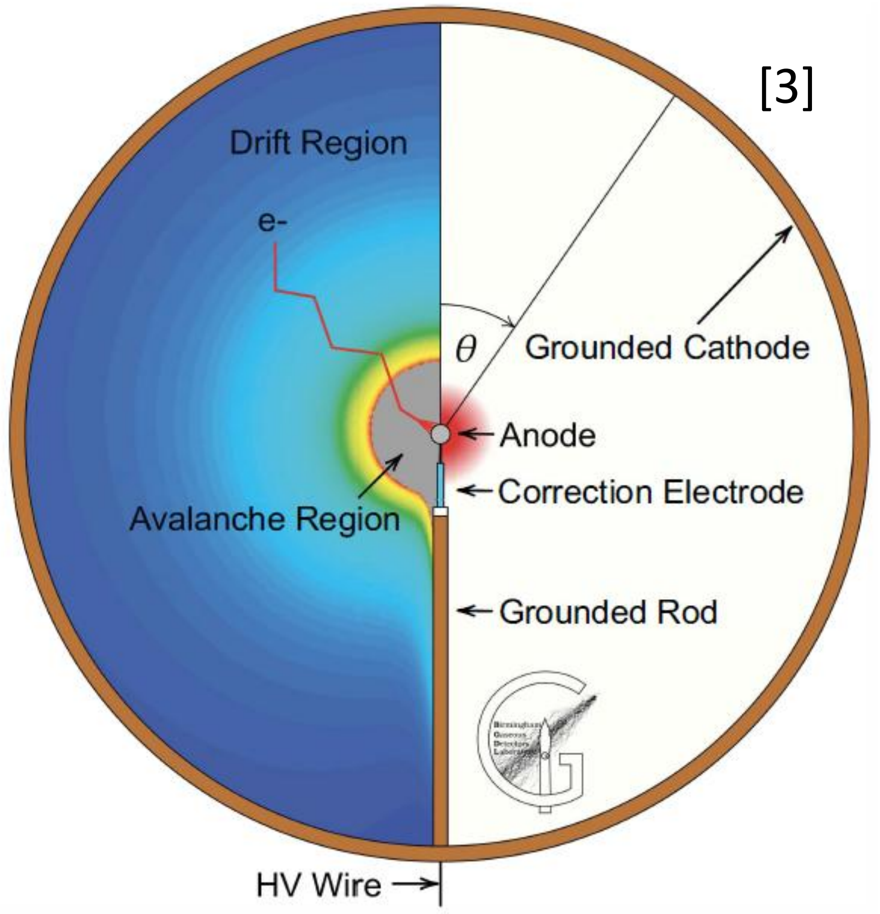
The Spherical Proportional Counter (SPC)

- Spherical **gaseous** detector
- High Gain: $10^4 - 10^5$
- Identification down to single electron signals
- **Capacitance depends only on anode radius r_a**

$$\vec{E}(r) = \frac{V_0}{r^2}\frac{r_a r_c}{r_c - r_a}\hat{r} \underset{r_c \gg r_a}{\approx} \frac{V}{r^2} r_a \hat{r}$$

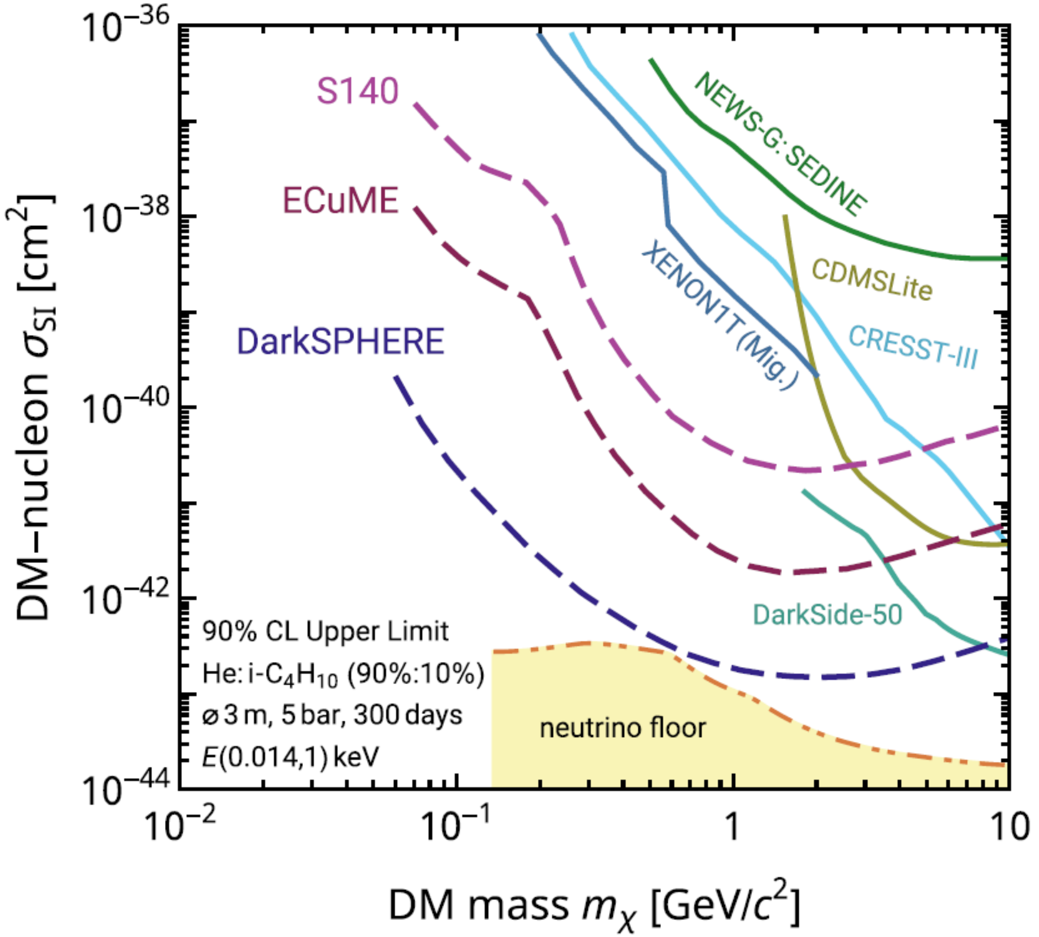
$$C = 4\pi\epsilon\epsilon_0 \frac{r_a r_c}{r_c - r_a} \underset{r_c \gg r_a}{\approx} 4\pi\epsilon\epsilon_0 r_a$$

r_a: anode radius, r_c: cathode radius

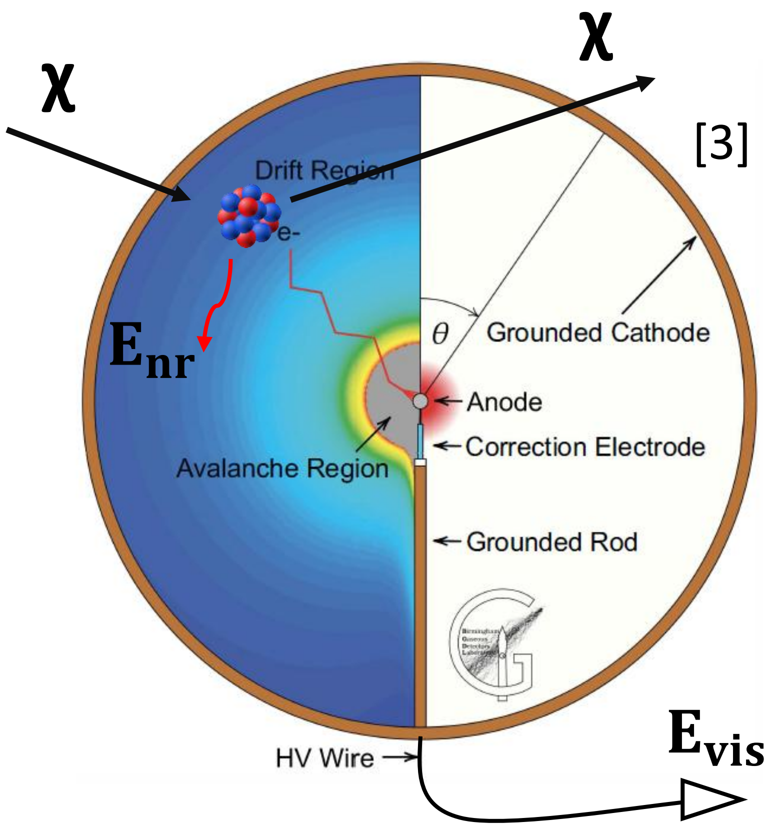


SPC for light Dark Matter Searches: DarkSPHERE

- NEWS-G: SPCs for **Dark Matter** detection
- SEDINE: ⌀60cm SPC – extended sensitivity to 0.5 GeV
- DarkSPHERE[3] is a ⌀3m SPC aiming at **sensitivity down to 0.05GeV**



[3]

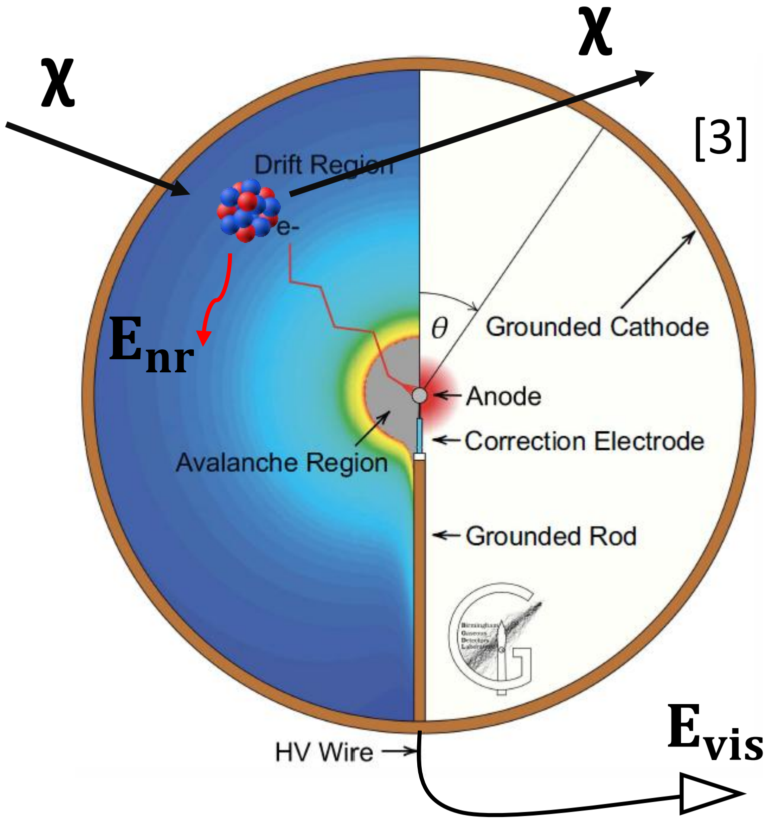


[3]

Neutron Scattering Experiment: Motivation

- Understanding the **SPC response** to **nuclear recoils** is essential

- Not all of the deposited energy is detected: $\mathbf{E_{vis}} < \mathbf{E_{nr}}$



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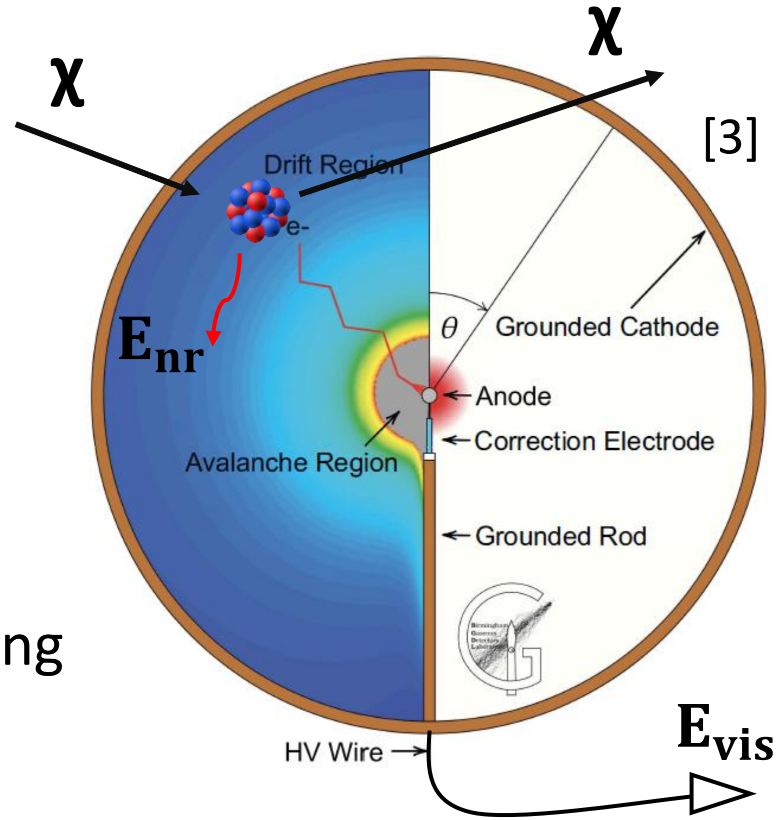
Neutron Scattering Experiment: Motivation

- Understanding the **SPC response** to **nuclear recoils** is essential
- Not all of the deposited energy is detected: $\mathbf{E_{vis}} < \mathbf{E_{nr}}$
- The response is characterised by the **Ionization Quenching Factor (IQF),** defined as the ratio of the "visible" to the kinetic energy of the nuclear recoil[4]:

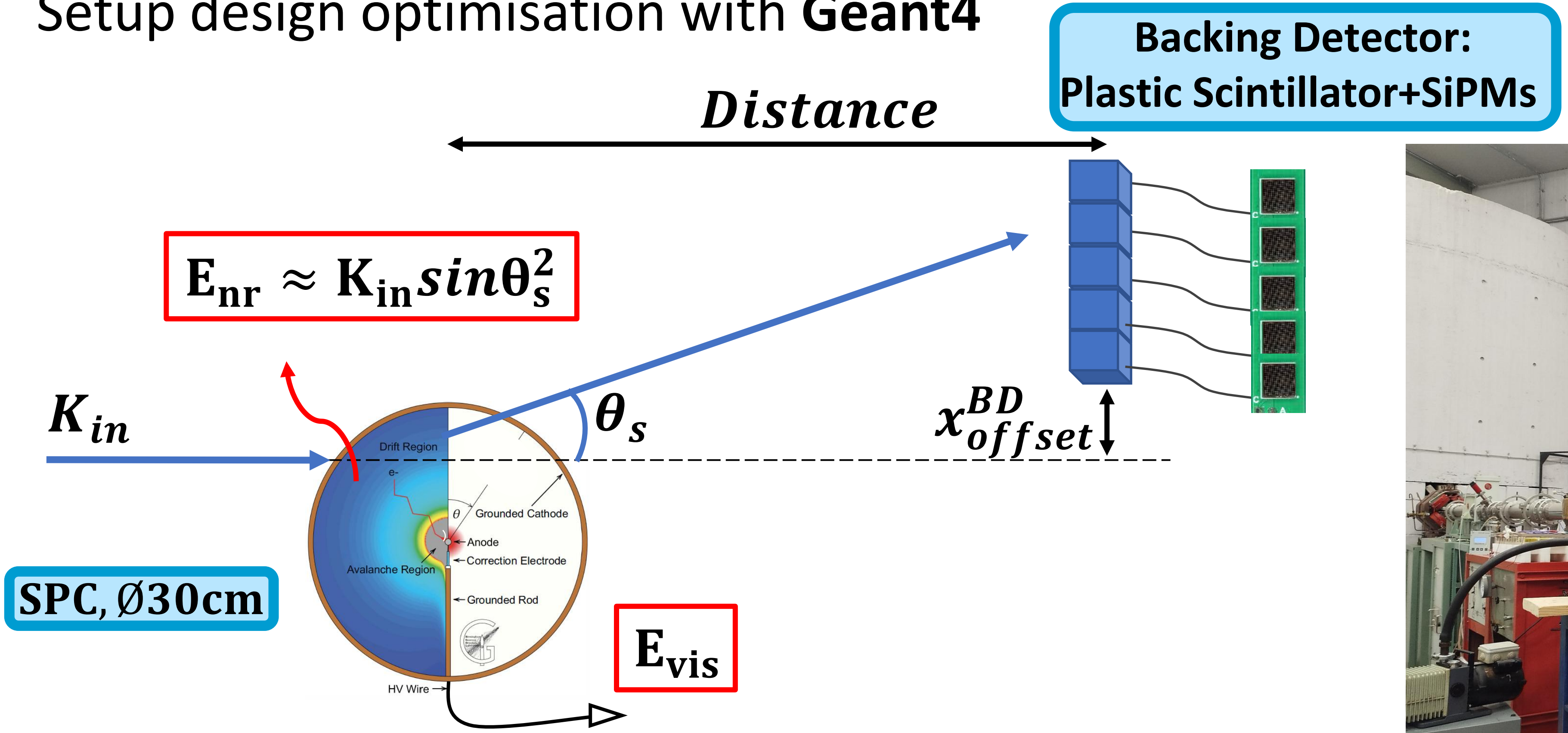
$$\mathbf{IQF(E_{nr}) = E_{vis}/E_{nr} < 1}$$

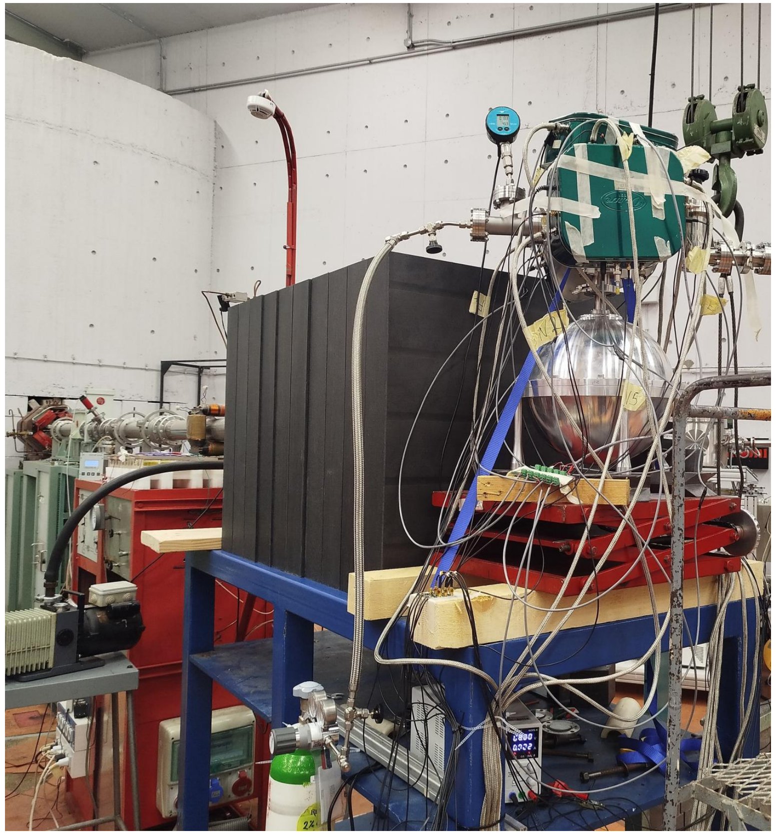
- **IQF measurements** can be realised with **neutron beam** scattering experiments



Neutron Scattering Experiment: Concept

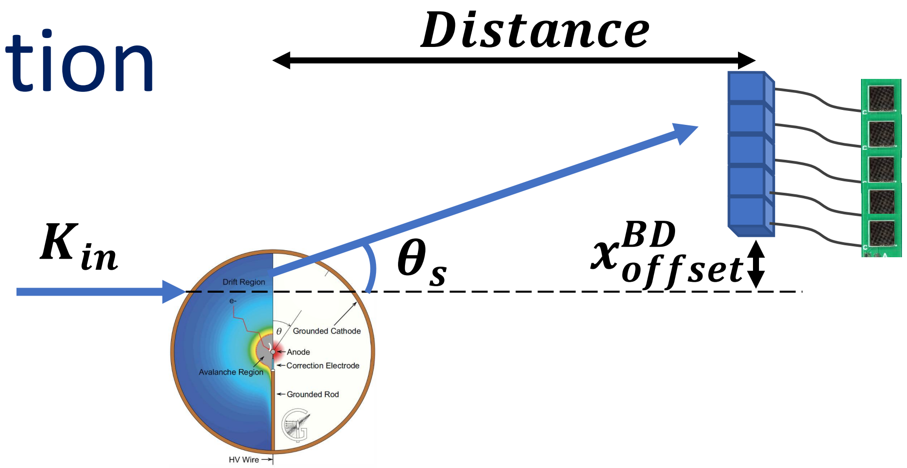
- Neutron beam on **SPC + Backing Detector** → **IQF measurement**
- Backing Detector: **Plastic Scintillator + SiPM** readout
- Setup design optimisation with **Geant4**

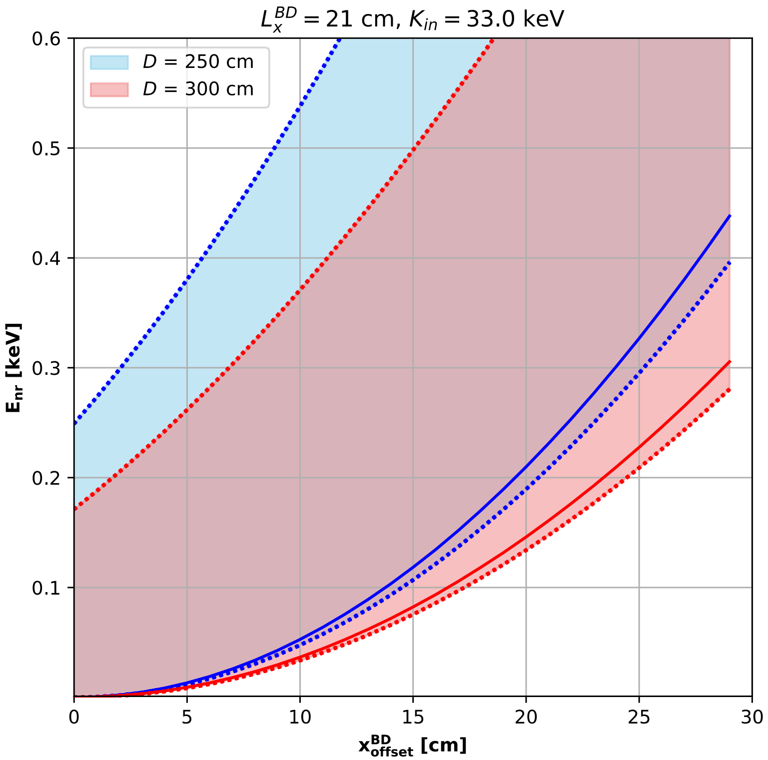


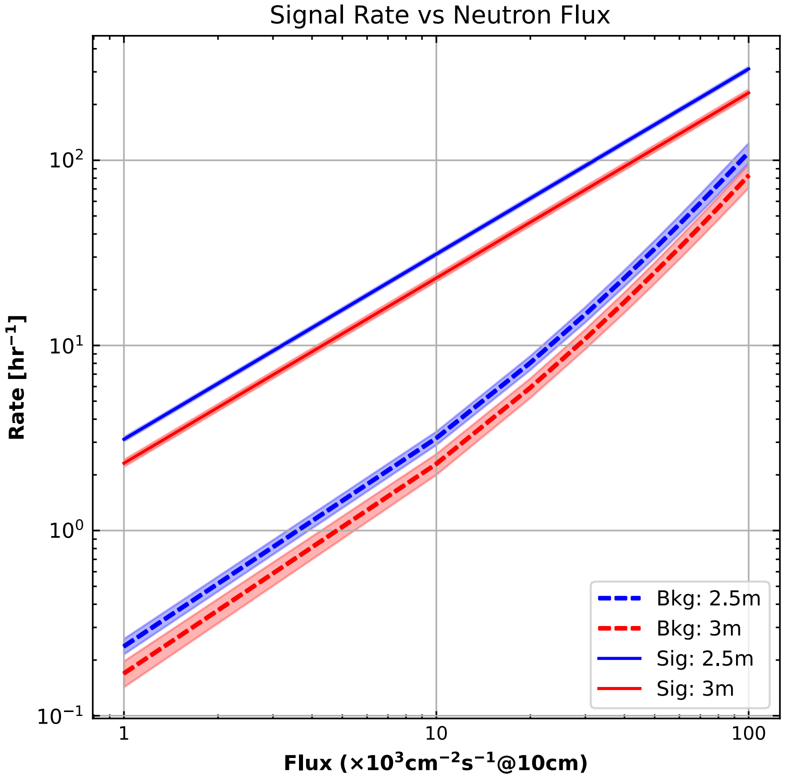


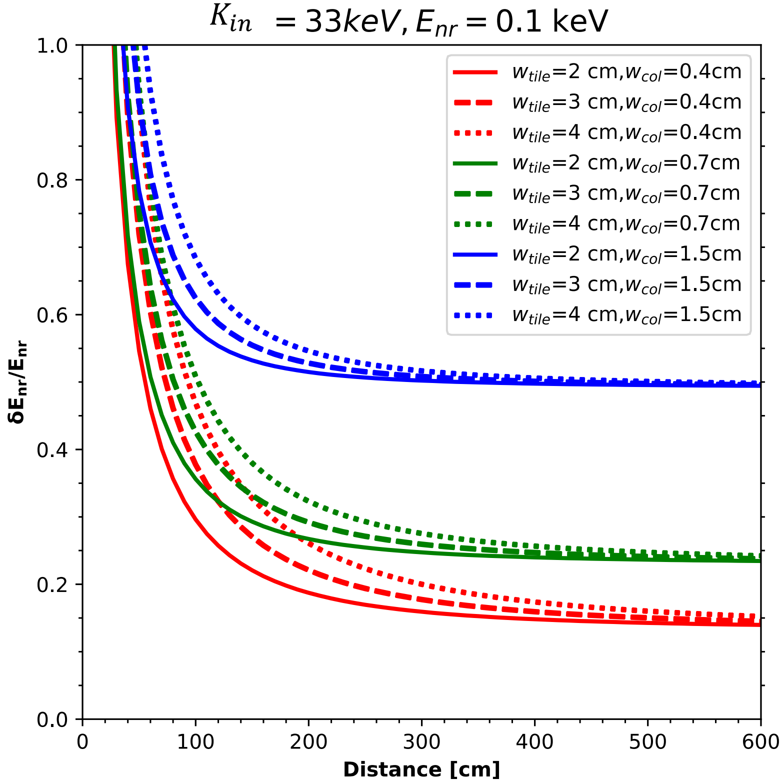
Neutron Scattering Experiment: Optimisation

- Consider: distance, detector dimensions and positioning, collimator opening
- Example: SPC, Ø30cm, CH_4 and 33keV neutron beam



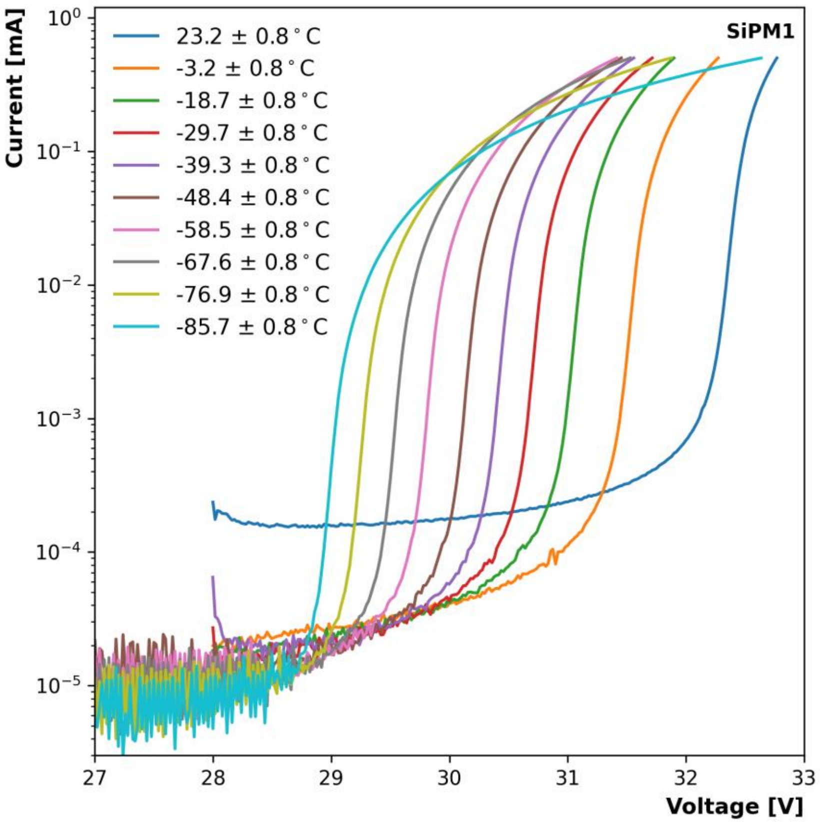


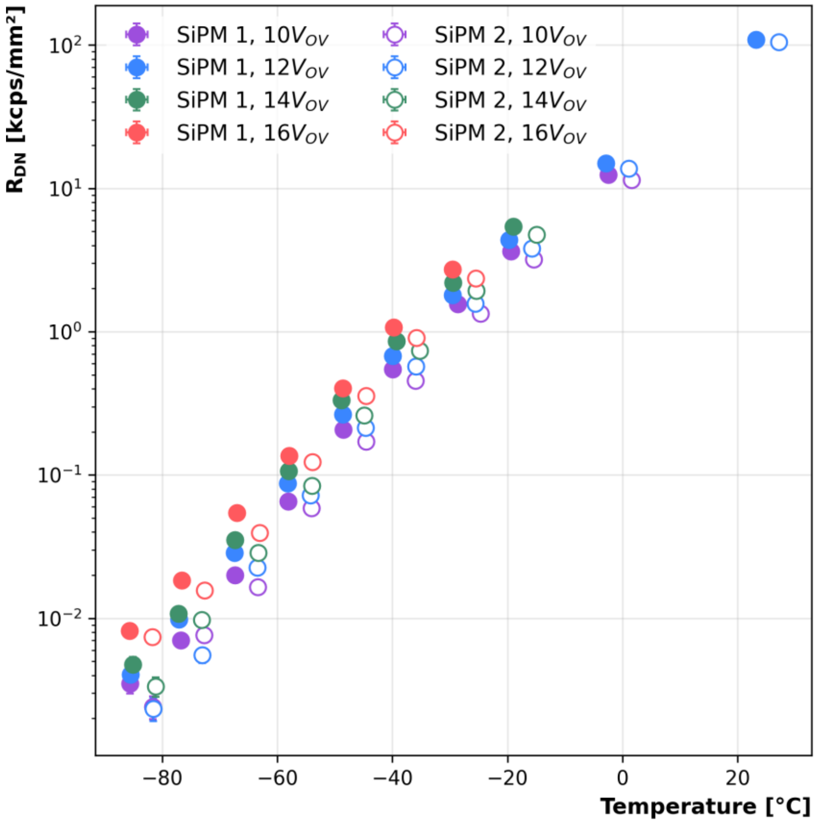


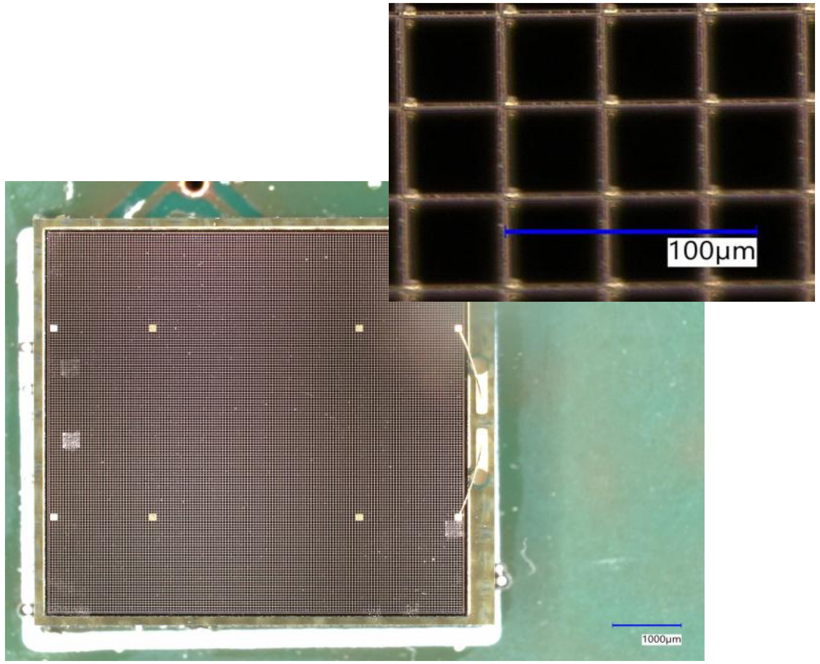


SiPM Characterisation

- Plastic Scintillator read out with SiPMs as a **backing detector**
- SiPMs: Commercially available **NUV-MT** Technology by BROADCOM[5]
- Characterisation for a range of applied voltages and temperatures **down to -85°C**[6]

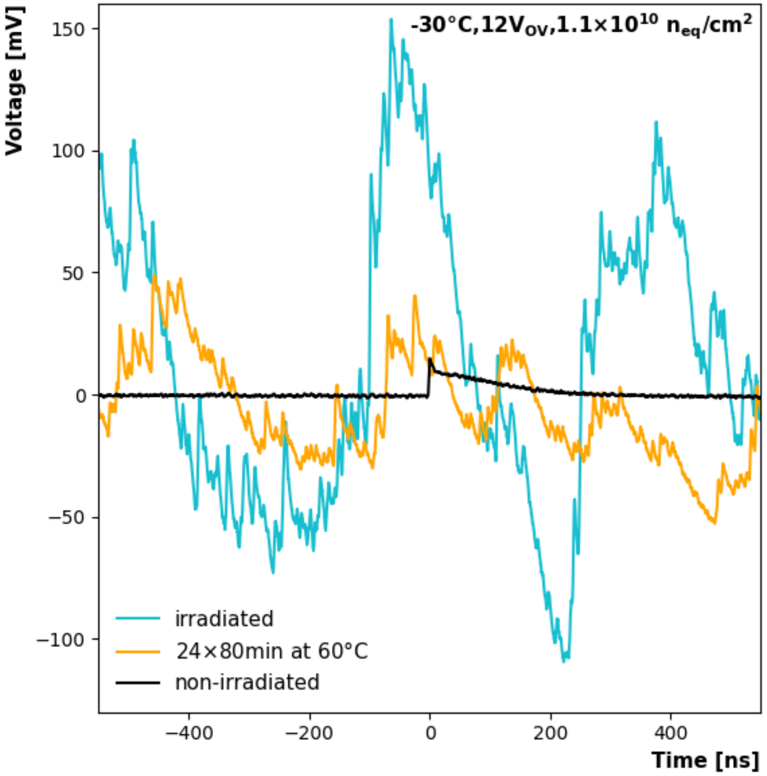


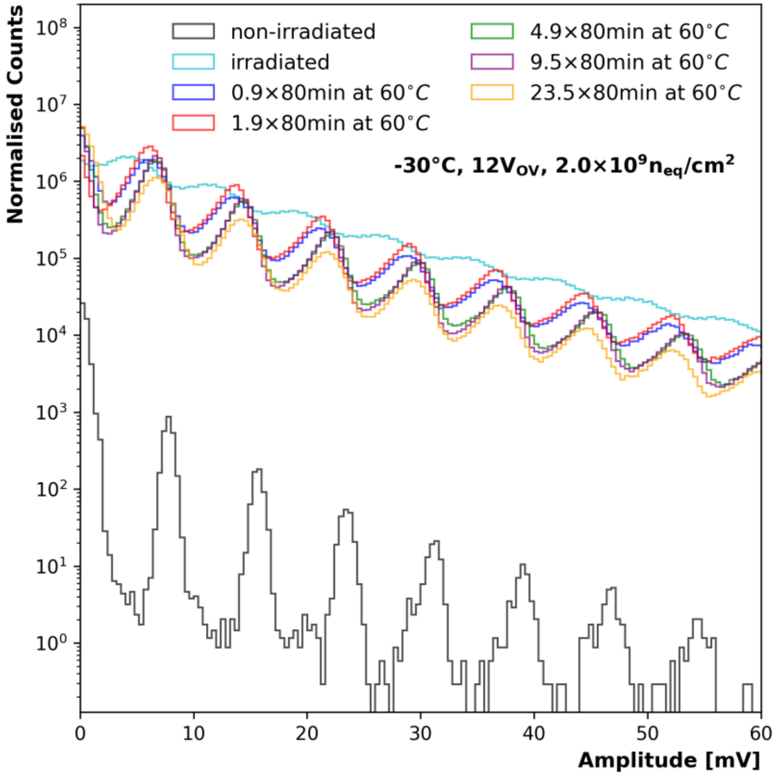




SiPM Characterisation: Radiation Hardness

- Understanding **Radiation Hardness** is essential
- Irradiation campaign at NCSR “Demokritos”, Athens
- Fluence measurements in the range $\mathbf{10^9}$- $\mathbf{10^{10}}$ $\boldsymbol{n_{eq}/cm^2}$[7]
- **5 Annealing cycles** performed to recover **SiPM performance**





- **Dark noise increase by 3 orders of magnitude**
- **Annealing recovers single photon-identification**

Summary and next steps

- My research work focuses on detector development for **light Dark Matter searches**

- My work so far involved:
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  2. Characterisation of commercial SiPMs

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- Next steps are:
  i. Characterisation measurements for plastic scintillators
  ii. Prepare for next test-beam campaign
  iii. Observe **correlations between the SPC and the backing detector**

Summary and next steps

- My research work focuses on detector development for **light Dark Matter searches**

- My work so far involved:
  i. Design of a **neutron scattering experiment** with Geant4
  ii. Characterisation of commercially available SiPMs

- Next steps are:
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Thank you!

contact: christos.toukmenidis@uni-hambrug.de

References

[1] I.Giomataris et. al., A novel large-volume spherical detector with proportional amplification read-out, *JINST* 3 P09007, 2008

[2] S. Agostinelli et al., Geant4 - A Simulation Toolkit, Nucl. Instrum. Meth. A 506, 250-303, 2003

[3] L.Balogh et. al., Exploring light dark matter with the DarkSPHERE spherical proportional counter electroformed underground at the Boulby Underground Laboratory, Phys. Rev. D 108, 112006, 2023

[4] P.Knights, K.Nikolopoulos, Searches for Light Dark Matter with Spherical Proportional Counters, *JAIS*, vol. 2025, no. 1, 2025

[5] Broadcom Inc., AFBR-S4N66P014M NUV-MT Silicon Photomultiplier Data Sheet, 2025

[6] T.Avgitas et. al., Characterisation of Commercially Available NUV-MT Silicon Photomultipliers, arXiv:2608.19156, 2026

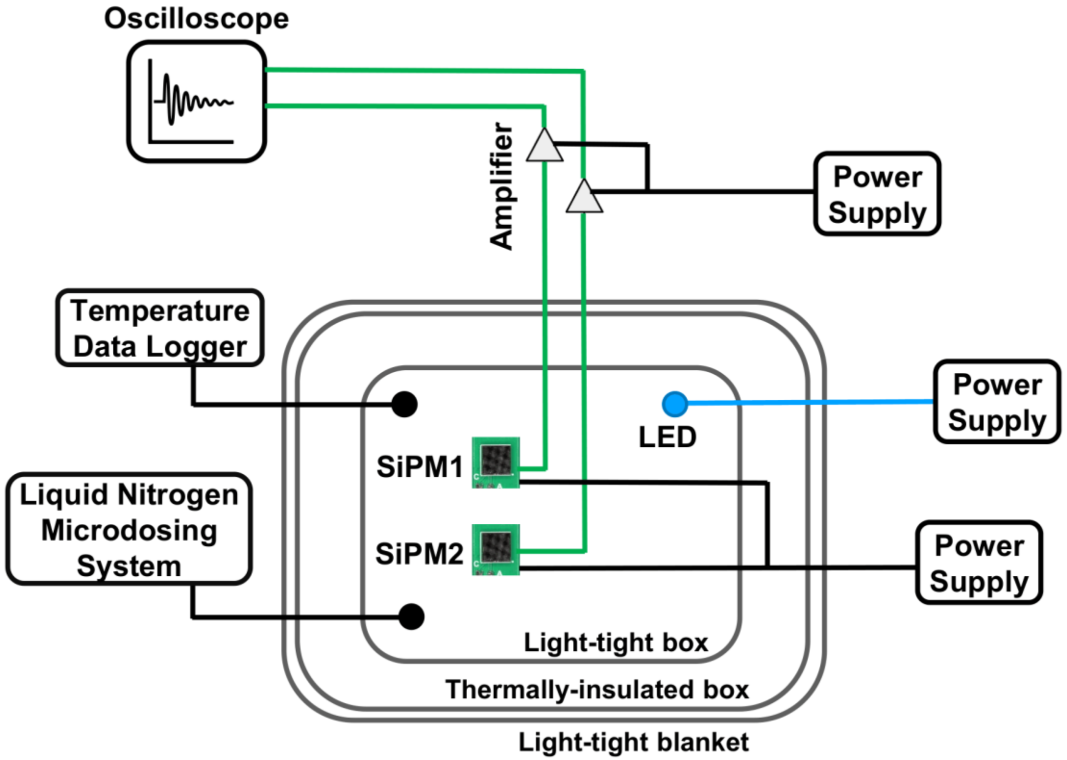
[7] T.Avgitas et. al., Radiation Hardness of Commercially Available NUV-MT Silicon Photomultipliers, arXiv:2609.01809, 2026

[8] G.Ros et. al., On the design of experiments based on plastic scintillators using GEANT4 simulations, Radiation Physics and Chemistry, vol. 153, Pages 140-151, 2018

BACKUP SLIDES

SiPM Characterisation: Experimental Setup

- Measurements in ISO-7 certified clean room conditions



SiPM Characterisation: Lab Instruments

- Table of lab units employed during SiPM characterization measurements:

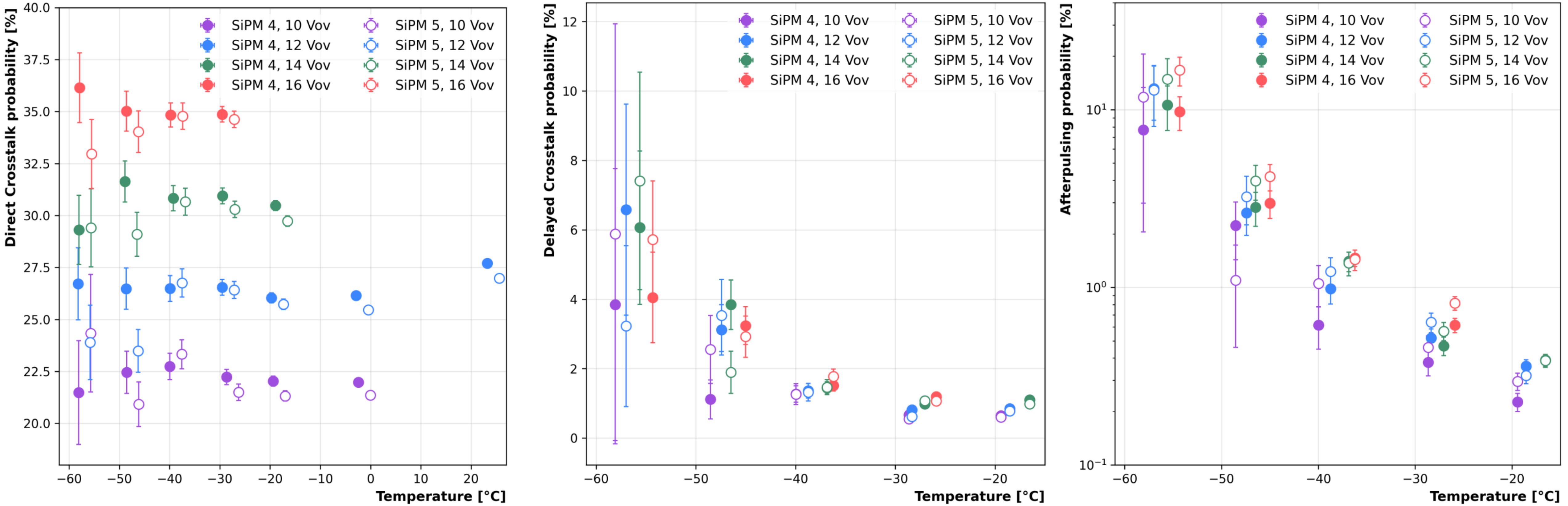
Unit	Model
SiPMs	BROADCOM® AFBR-S4N66P014M
SiPM Bias Power Supply	KEITHLEY® 2231A-30-3
Amplifier	Mini-Circuits® ZFL-1000LN+
Oscilloscope	Tektronix® MSO44B
Amplifier Power Supply	KEITHLEY® 2231A-30-3
Cooling System	NORHOF® LN_2 Microdosing System #608, 35L Dewar
LED Power Supply	PeakTech® P 6225 A
Source Meter for IV Curves	KEITHLEY® 2450 Source Meter Unit
Thermocouples	RS PRO® Type T, Class 1, Exposed Junction Thermocouple
Thermocouple Data Logger	Pico Technology® USB TC-08

- Table of oscilloscope settings:

Parameter	Value
Bandwidth	1 GHz
Oscilloscope Window	40 µs
Sampling Rate	3.125 GS/s
Trigger threshold	2.4 mV
Termination	50 Ω

SiPM Characterisation: Correlated Noise

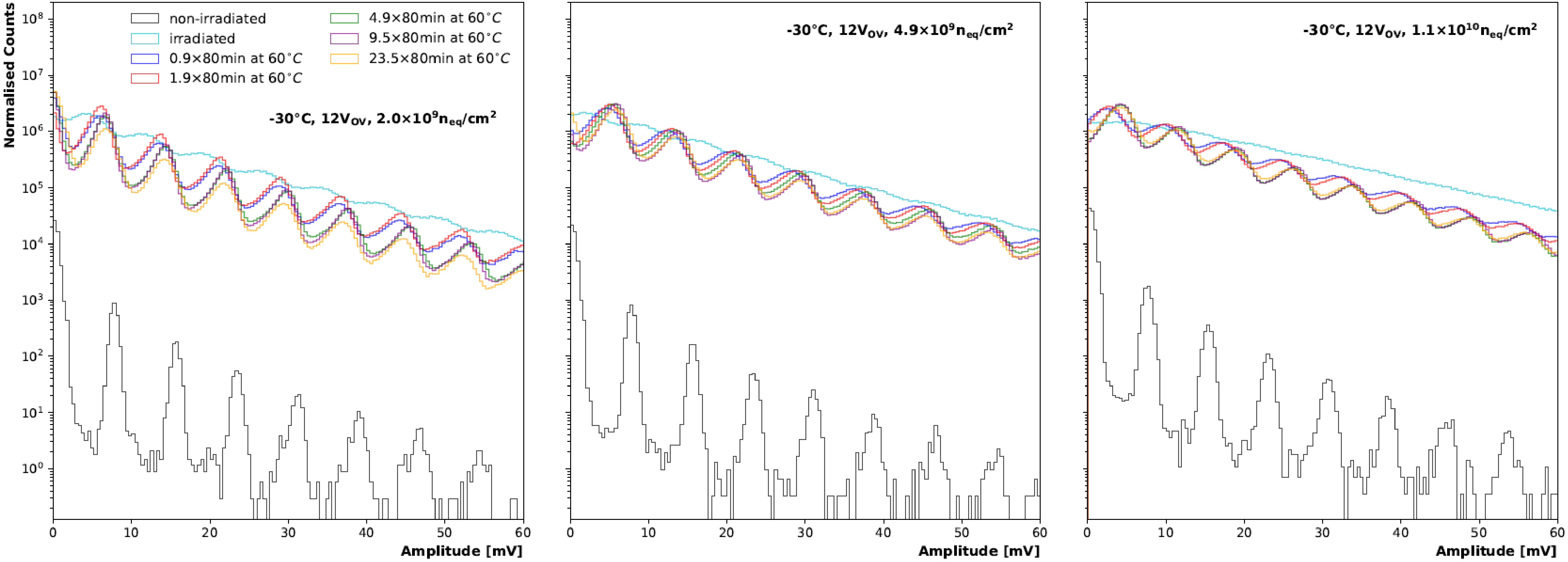
- Measurements for a range of applied voltages and temperatures



SiPM Radiation Hardness: Results

SiPM	Fluence $[n_{eq}/cm^2]$
1	2.0×10^9
2	4.9×10^9
3	1.1×10^{10}

- 3 irradiation measurements
- 5 annealing cycles



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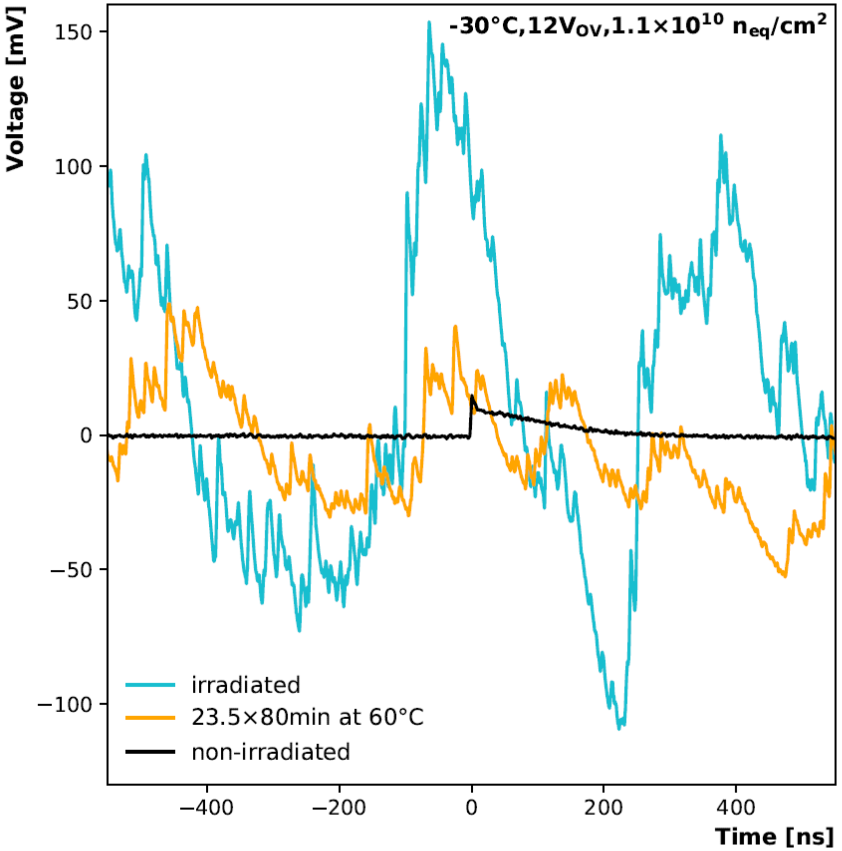
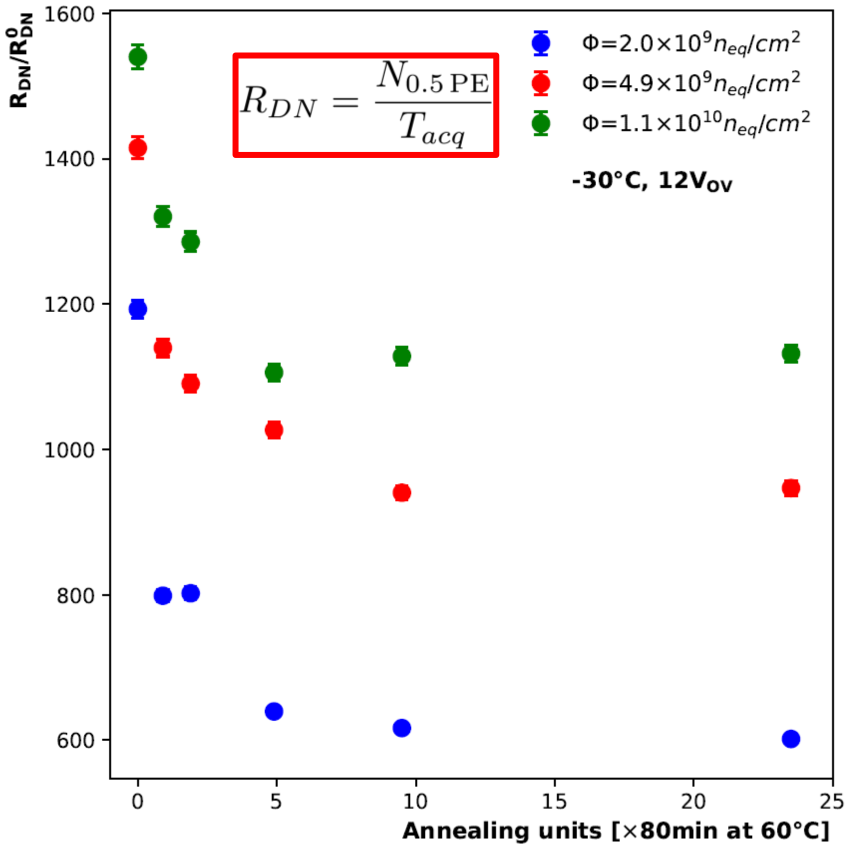
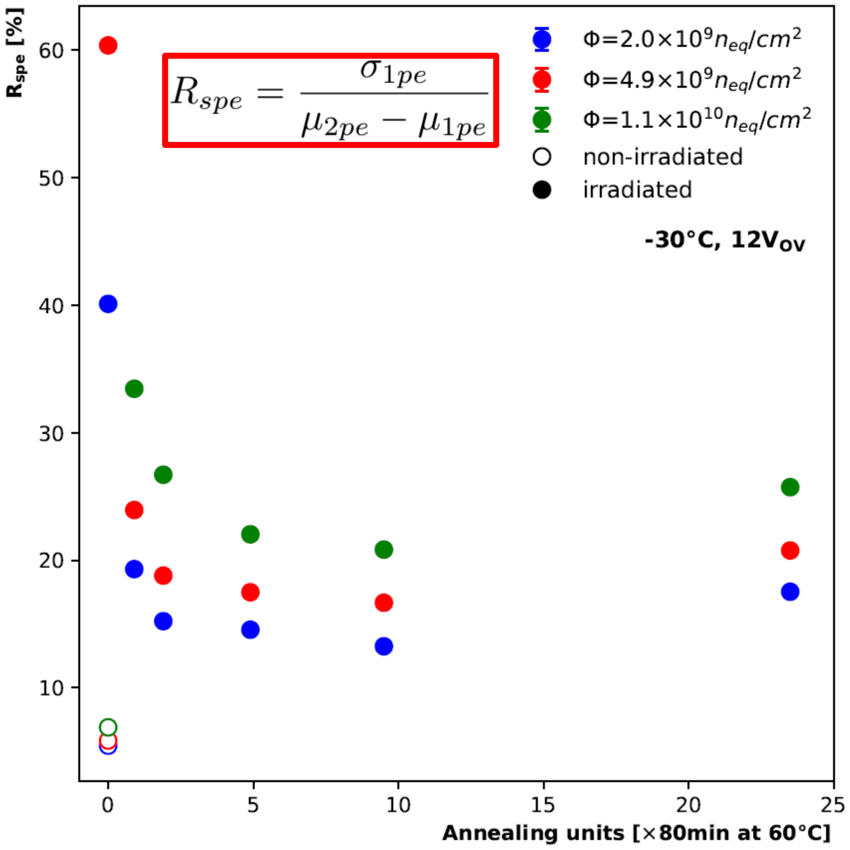
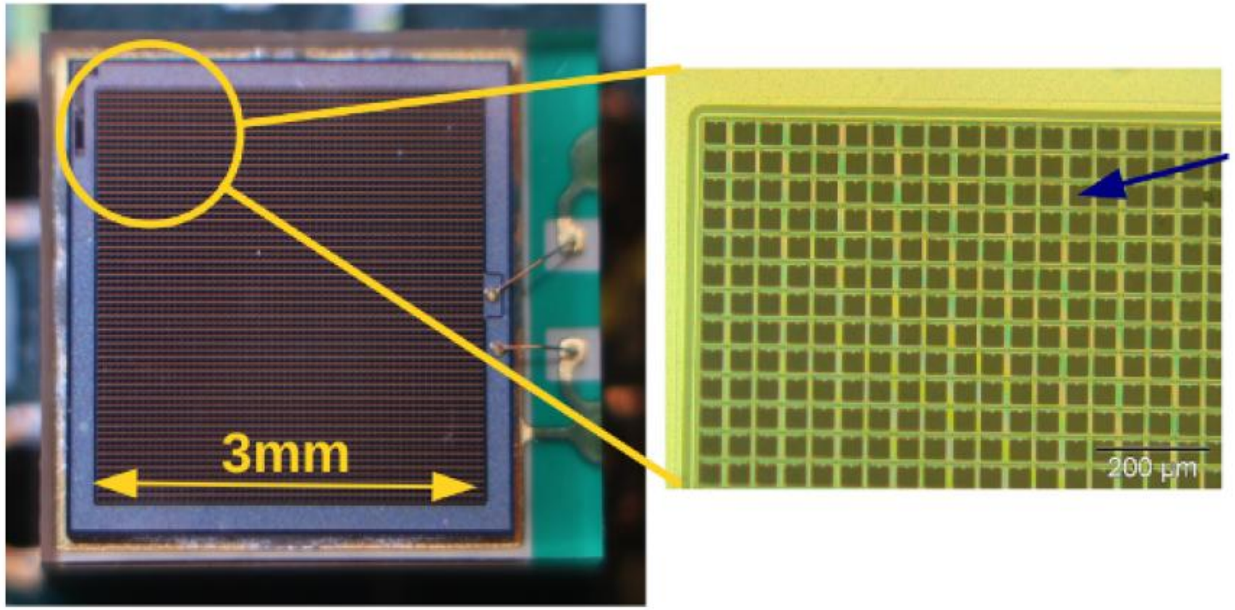


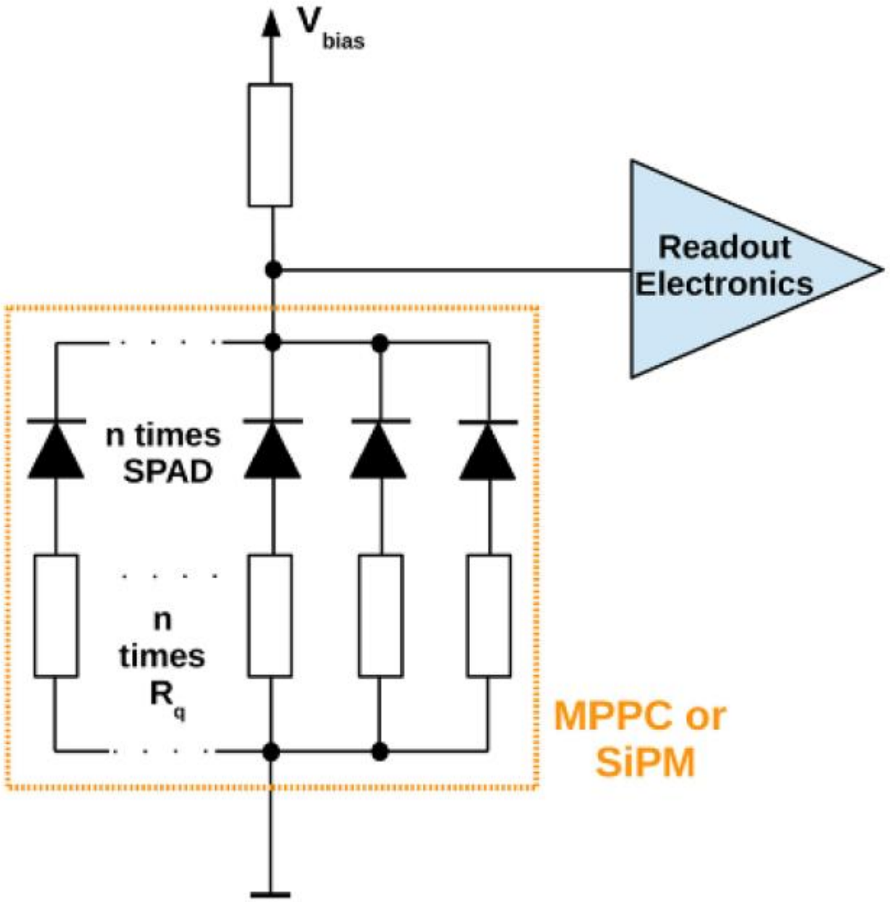




Silicon Photomultipliers

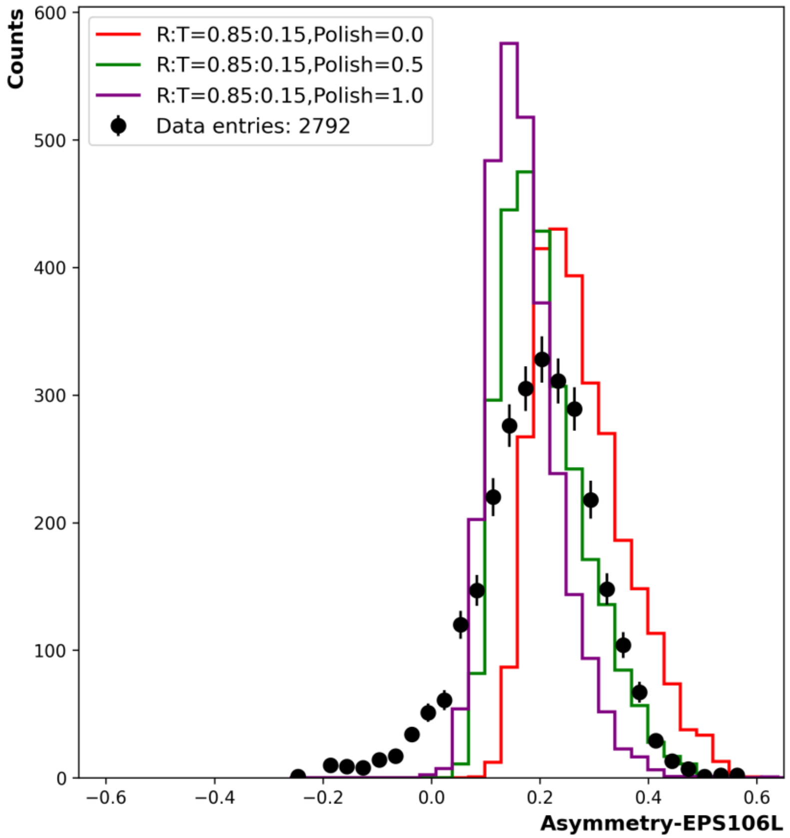


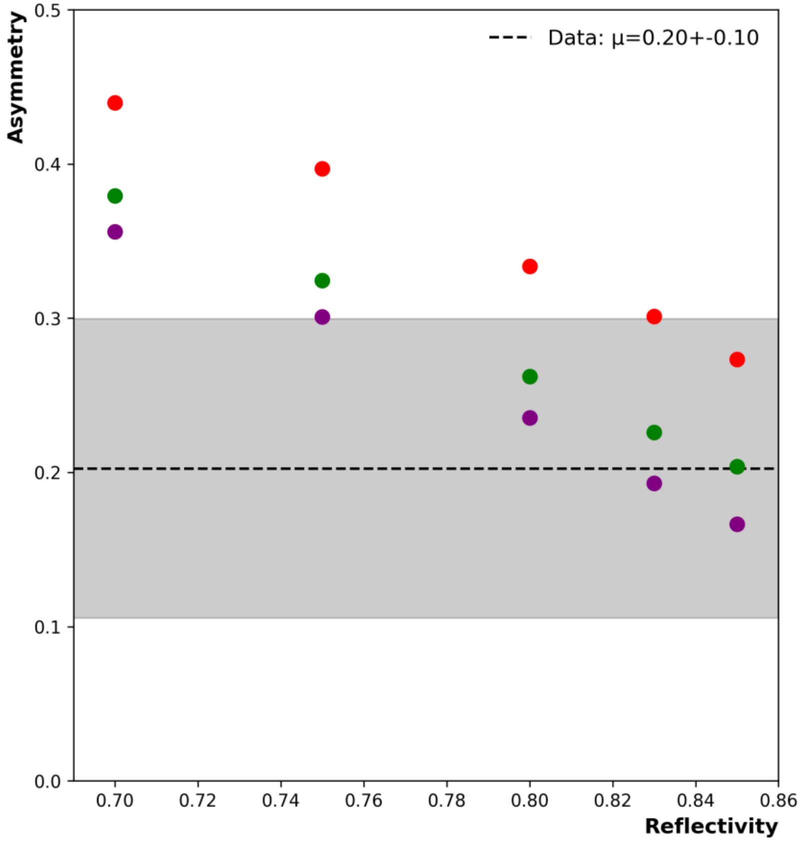
[*Phys. Med. Biol.* **65** (2020) 17TR01]

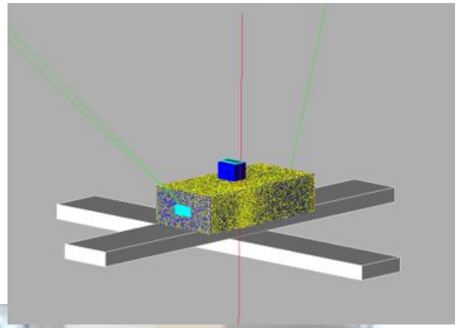


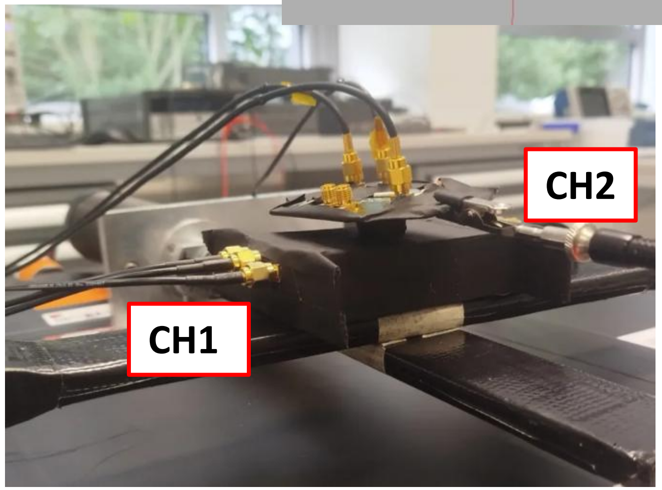
Data-driven tuning of optical physics model

- Polystyrene-based scintillator characterization with **cosmic muon data**
- **Data/Simulation** comparison with **G4OpticalPhysics** library
- **Data-driven** optimisation of Scintillator **performance parameters**







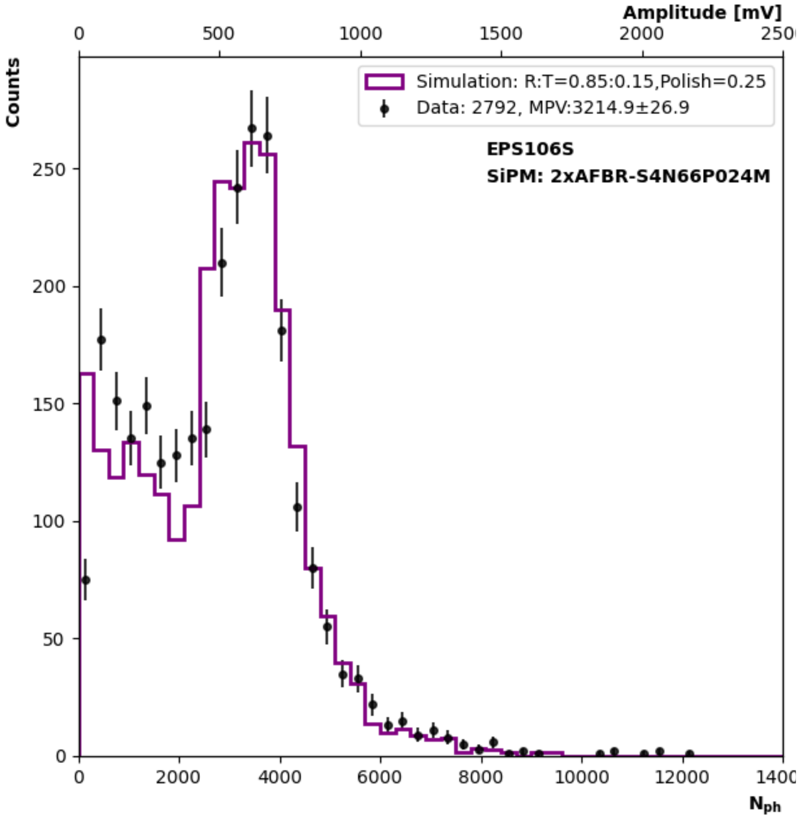


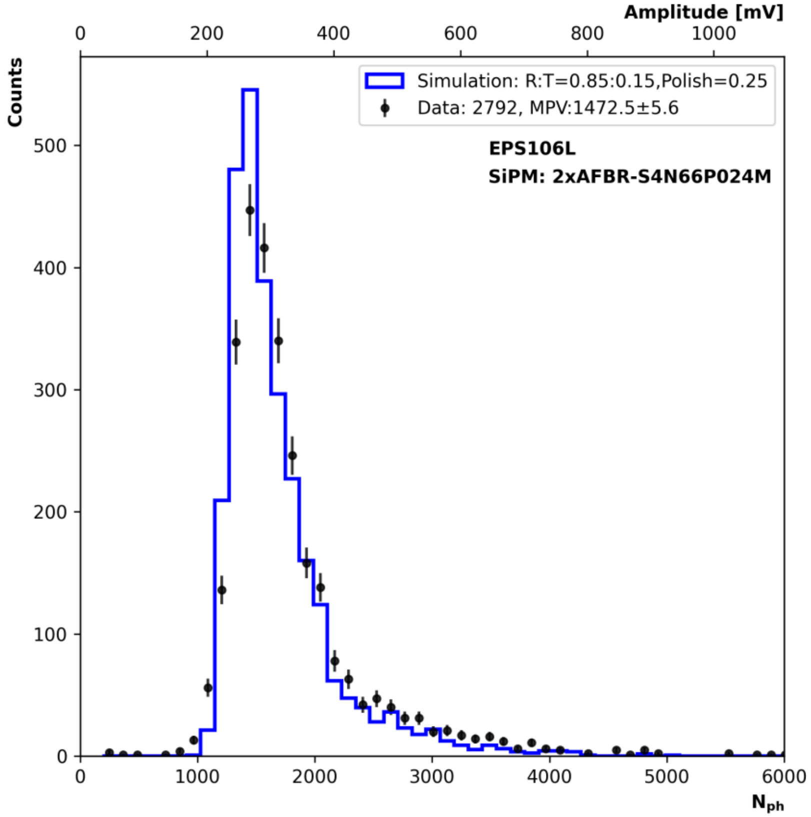
$$\text{Asymmetry} = \frac{CH1-CH2}{CH1+CH2}$$

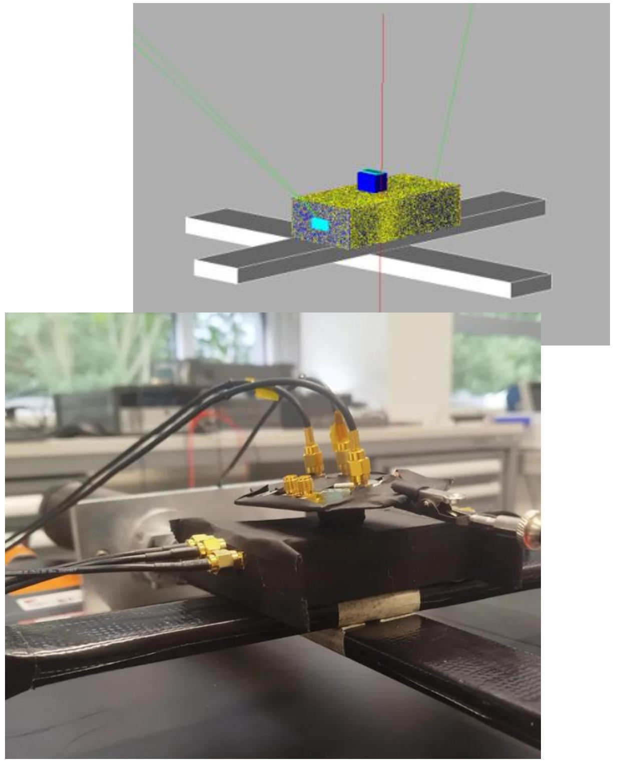
Plastic Scintillators Characterisation: Amplitude Spectra

- Strong dependence on scintillator **size** is observed[7]
- Data-driven tuning of scintillator performance parameters

Parameter	Value
Reflectivity	0.85
Polishing	0.25
A_{small}/A_{large}	2.18

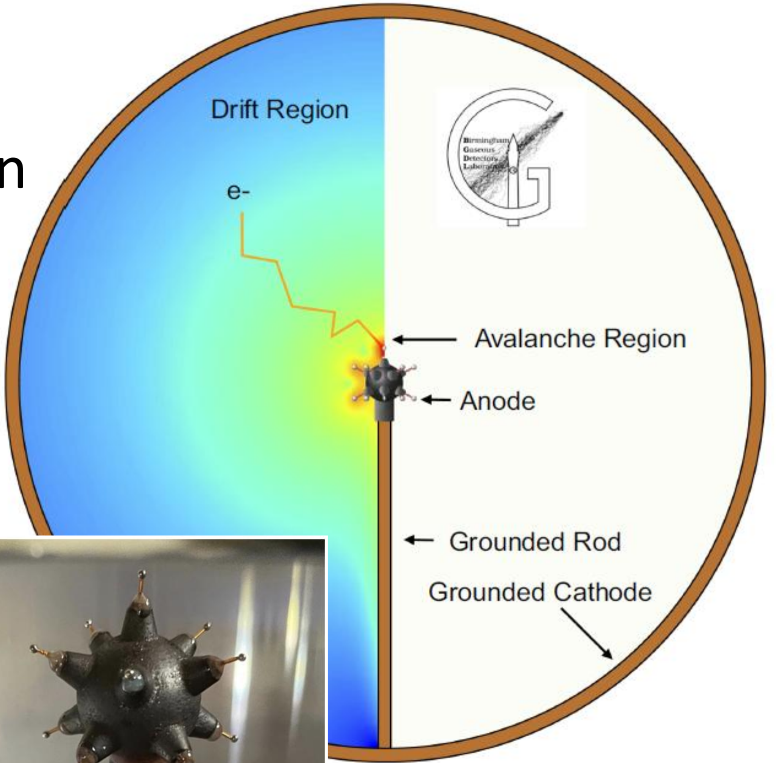


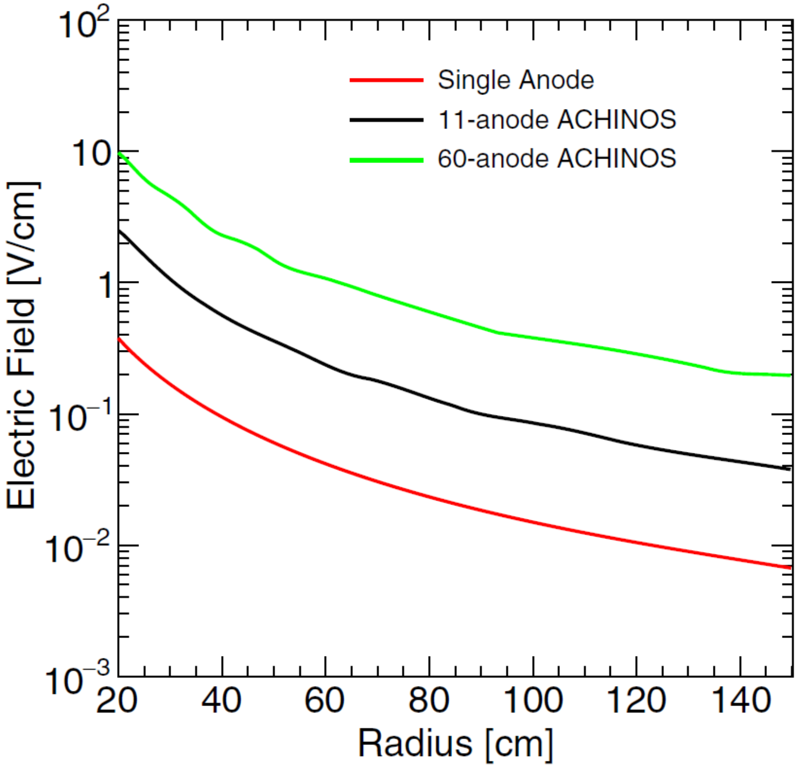


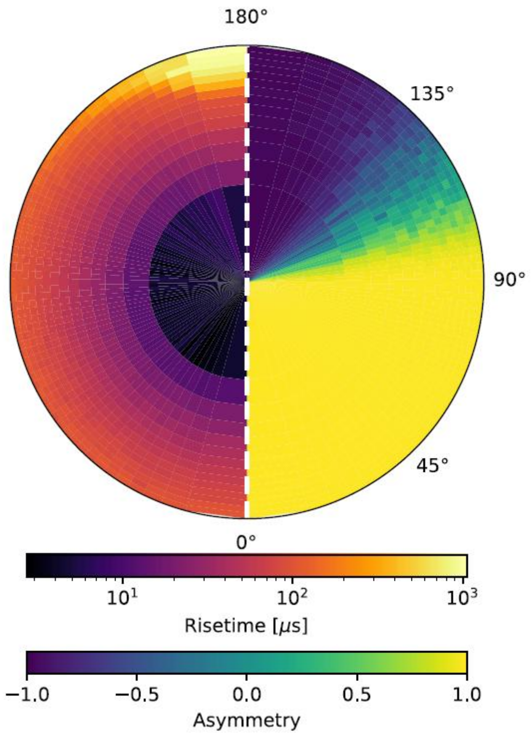


SPC Multi-Anode Sensor: ACHINOS

- The $1/r^2$ dependence divides the field to **drift/avalanche** region
- The ACHINOS sensor ensures **high field** with **detector stability**
- **Rise time** and **signal asymmetry** offer **position** information







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r_a: anode radius, r_C: cathode radius