A Scalable High Gain Negative Ion Drift CYGNUS Prototype for Directional Dark Matter Detection

Alasdair Gregor McLean[1,2] **- Speaker**

N.J.C. Spooner[2], K. Miuchi[3], S. Higashino[3], R.R. Marcelo Gregorio[4]

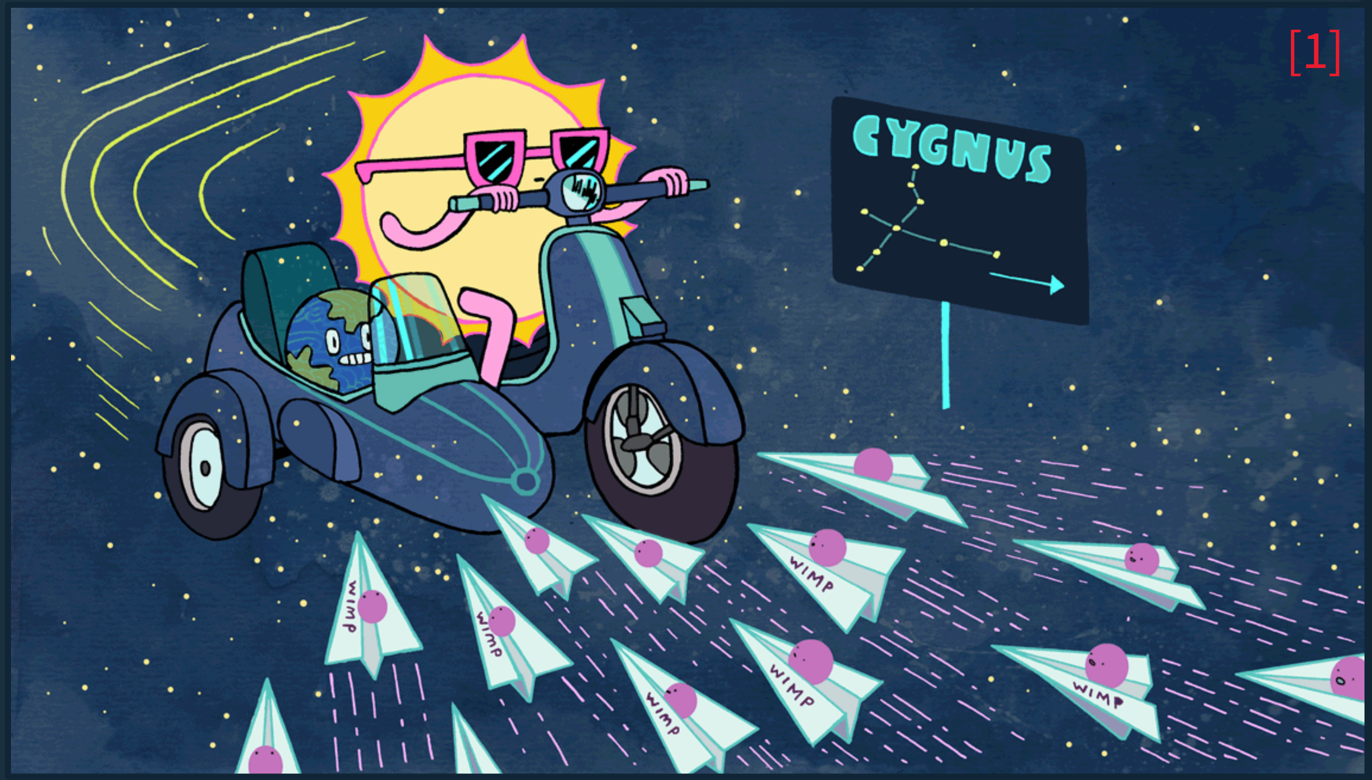
The University of Adelaide[1], The University of Sheffield[2], Kobe University[3], Queen Mary University of London[4]

alasdair.mclean@adelaide.edu.au

PASCOS 2025 – Durham (21-25/07/2025)

Overview

1. Directional dark matter detection
2. The CYGNUS consortium
3. Negative Ion Gas Targets
4. MMThGEM + Micromegas detector
5. CYGNUS-m3 scale vessel
6. Scale up of readout electronics
7. Conclusions



THE UNIVERSITY of ADELAIDE

Directional Detection of Dark Matter

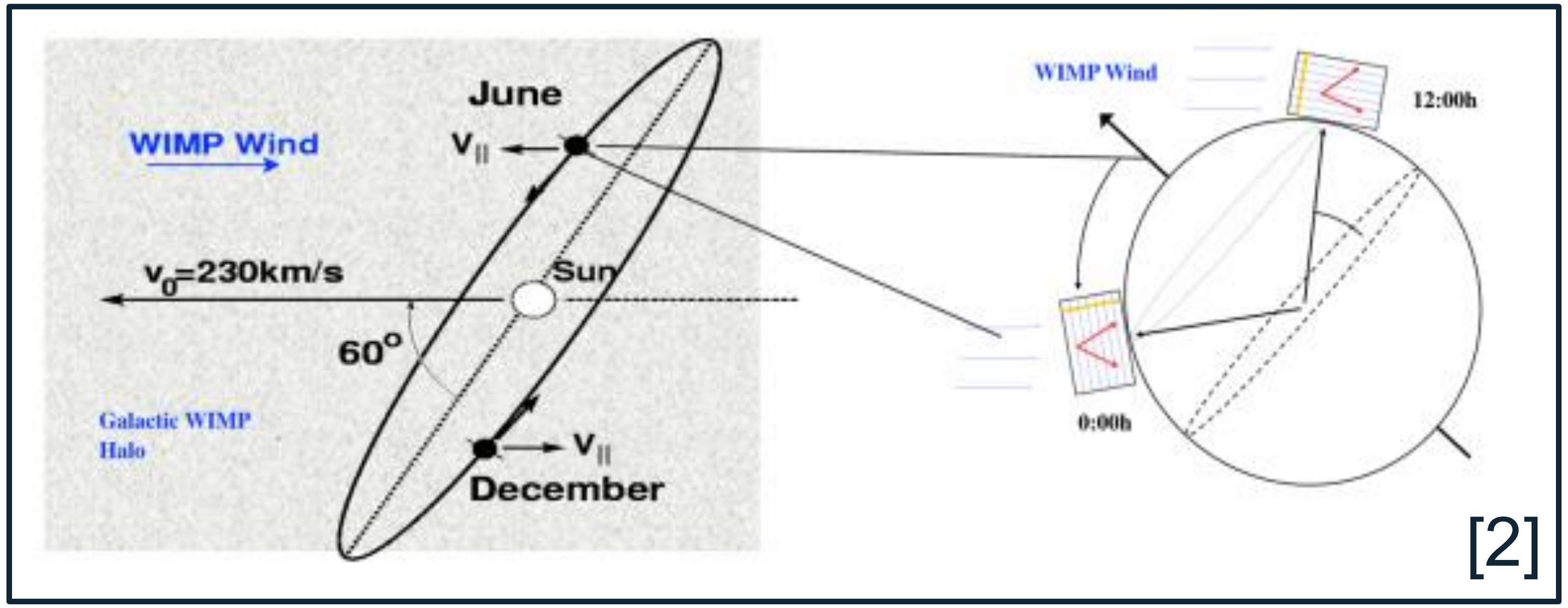
Directional Dark Matter Detection

Directional identification of DM relies on the motion of the Earth:

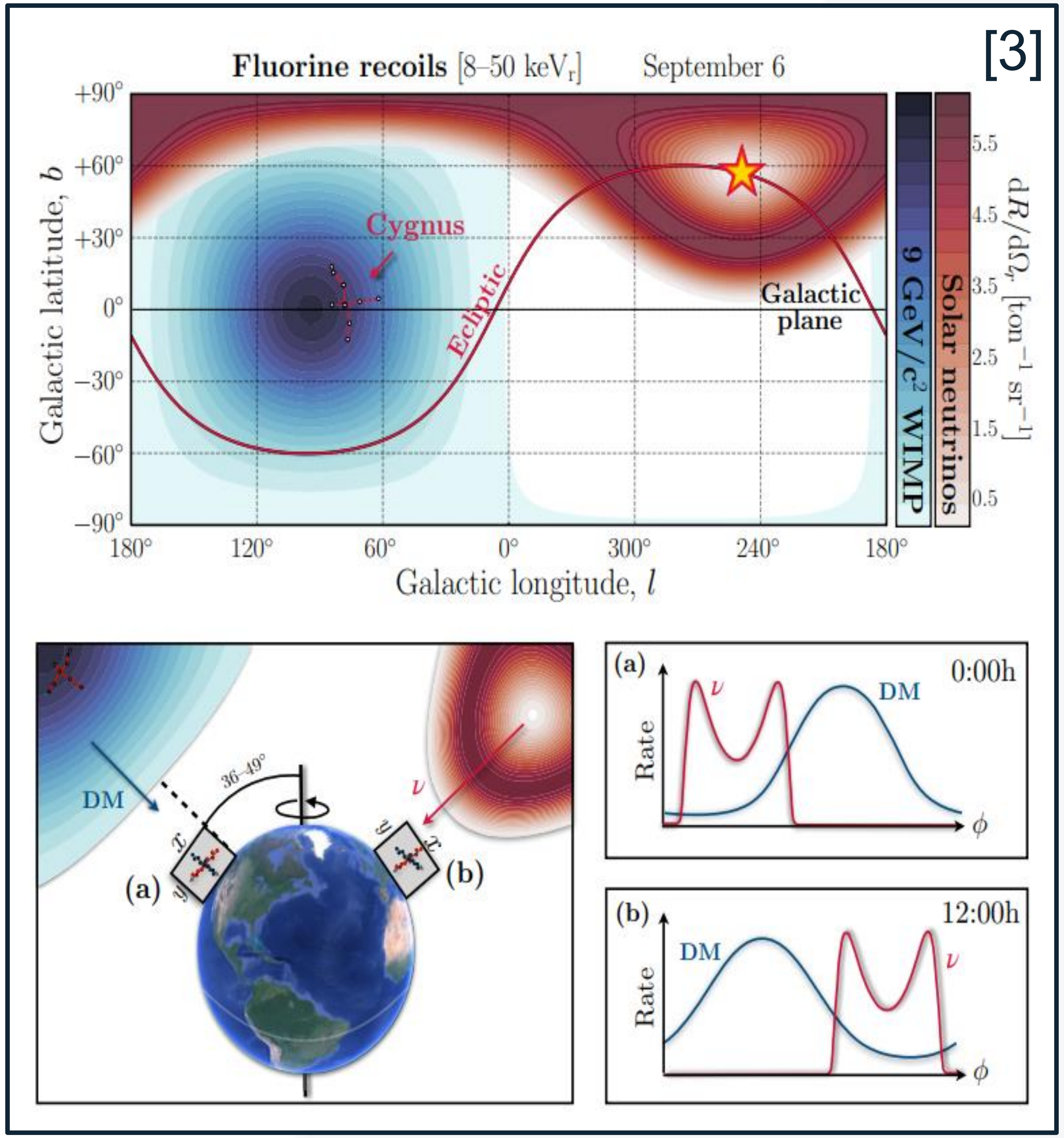
- Solar System orbiting the centre of the Milky Way
- Earth orbiting the Sun
- Earth's axial rotation

A directional signal will allow for discrimination between WIMP and solar neutrino signals

Most importantly: It can not be mimicked by a terrestrial background



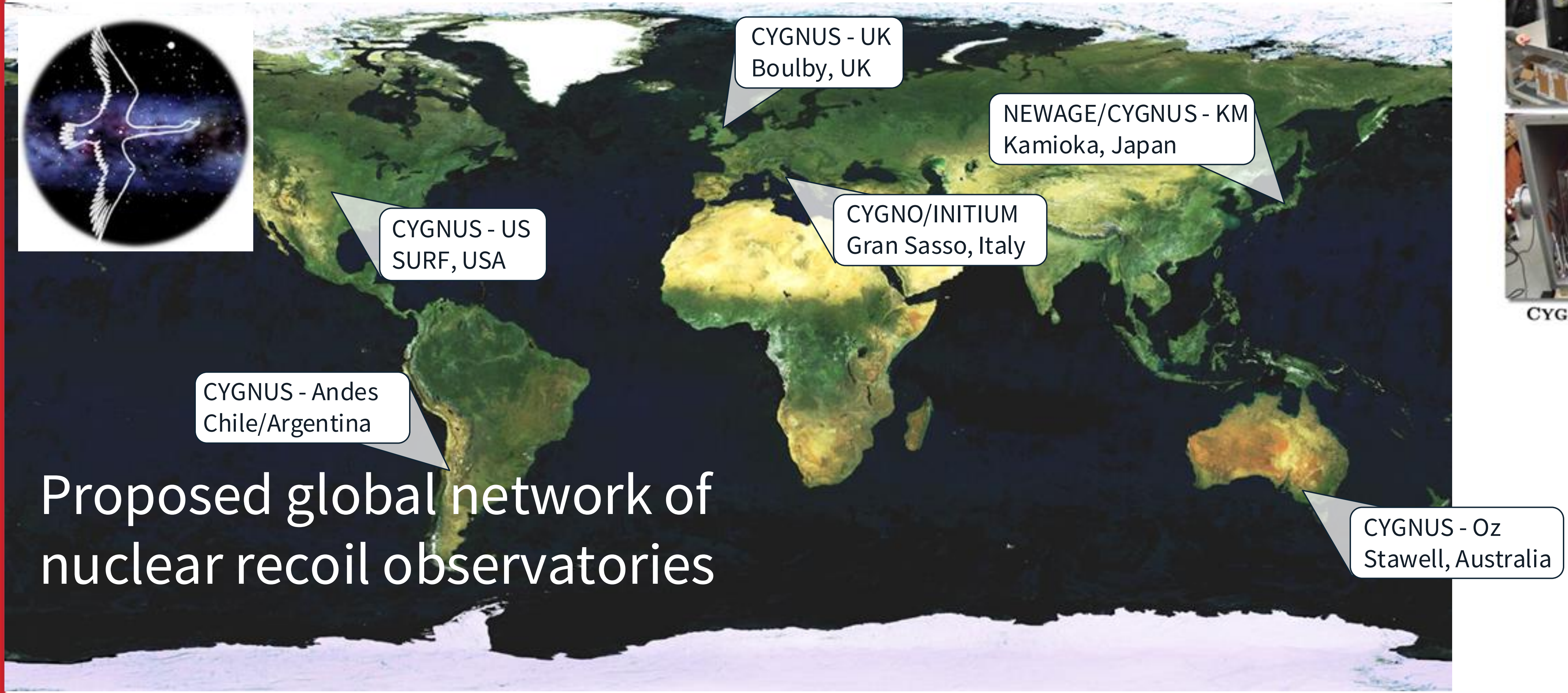
[2]

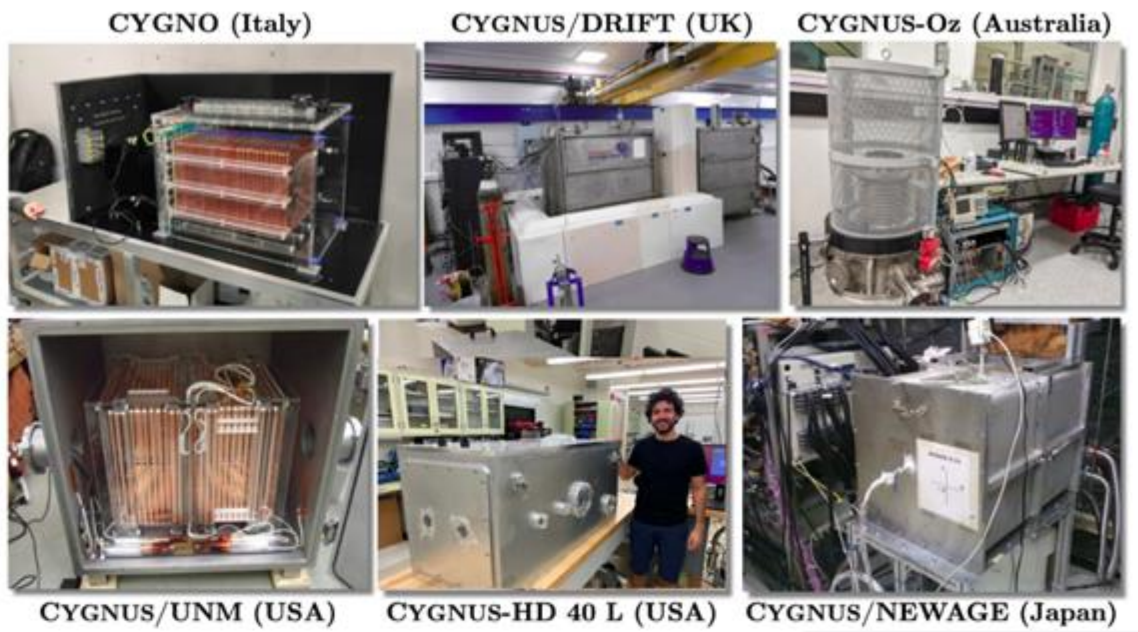


[3]

The CYGNUS Consortium

The CYGNUS Consortium – Next Generation of Directional Dark Matter Detection





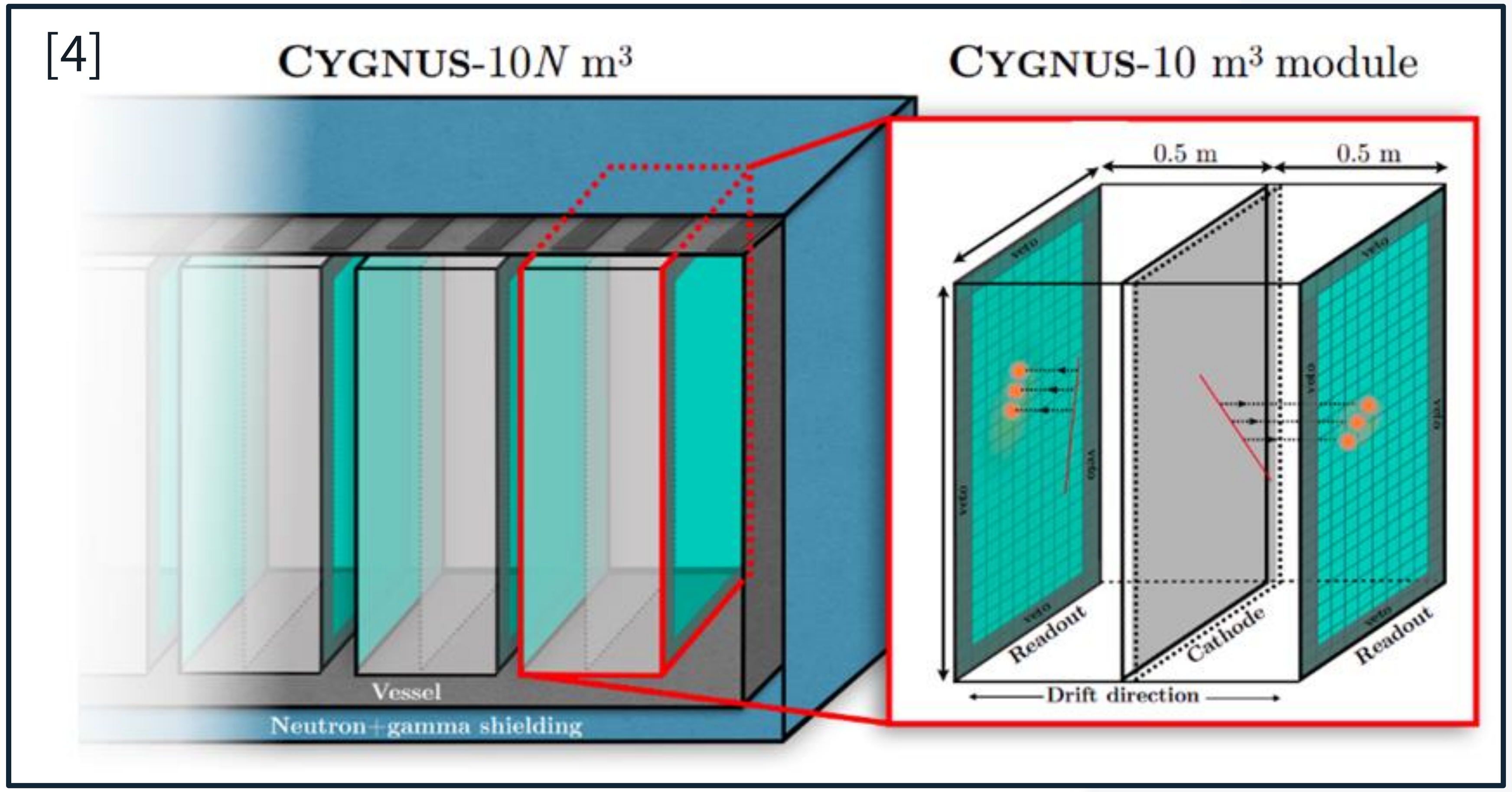
To name a few…

The CYGNUS Consortium – Next Generation of Directional Dark Matter Detection

CYGNUS: a modular and multi site nuclear recoil observatory

Time Projection Chamber (TPC) capable of reconstructing recoils

Directional sensitivity to dark matter and neutrino interactions



R&D with NID gases:

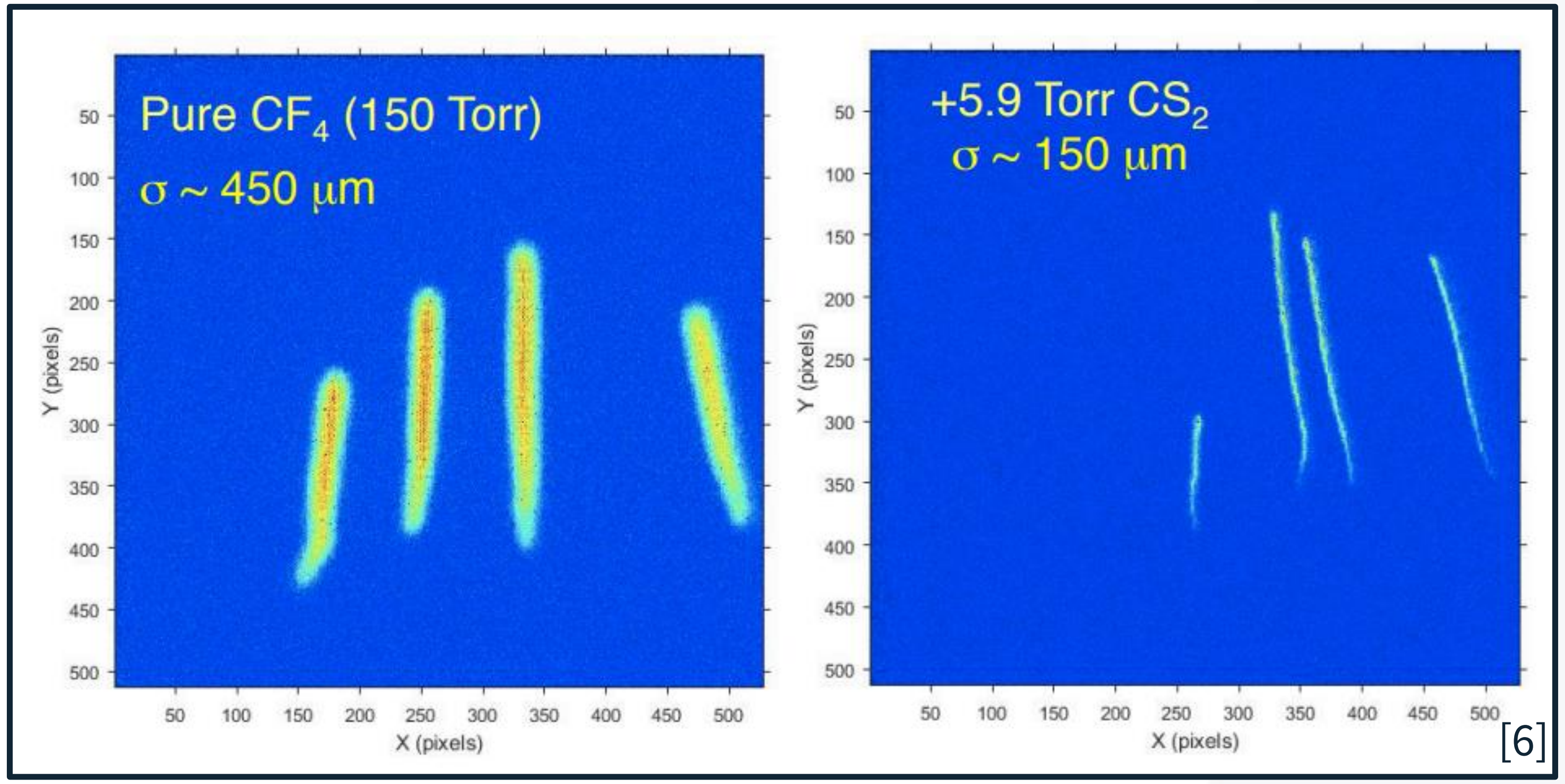
- CYGNUS modules will likely use a gas mixture with Negative Ion Drift (NID) gas component like SF_6
- NID gases require special techniques to achieve high charge amplification
- Recent work with a MMThGEM demonstrates strong avalanche capability in SF_6

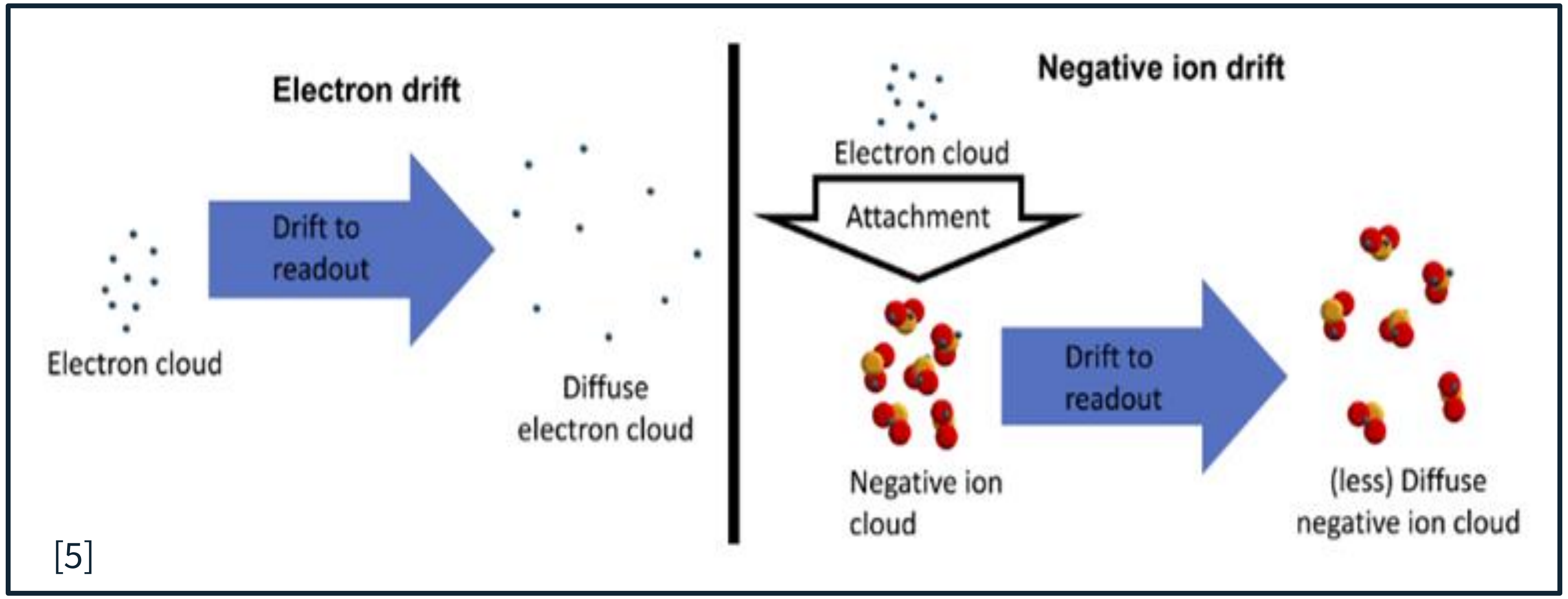
THE UNIVERSITY of ADELAIDE

Negative Ion Gases

Negative Ion Drift Gases

- Charge diffuses during the drift phase
- "Smears out" directional information
- Limits the size of the drift volume
- Solution - NID gases exhibit significantly less diffusion





However...

NID gases are limited by their low gas gain (Typically ~10^3)

Ultimately limiting sensitivity to low energy NRs!

MMThGEM + Micromegas Detector

Multi-stage Multi-Mesh ThGEM

SF_6 - 40 Torr

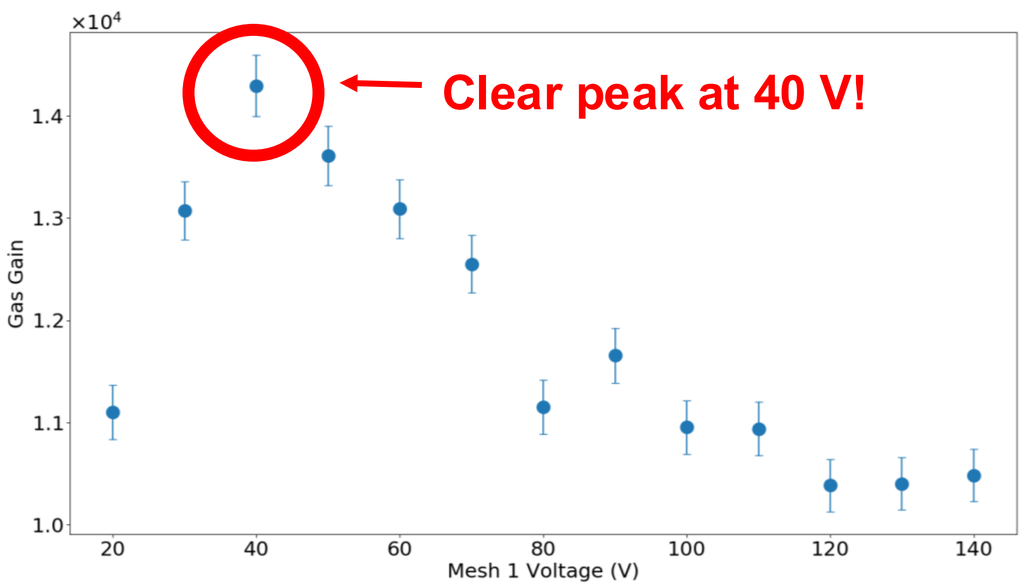
See publication for more info

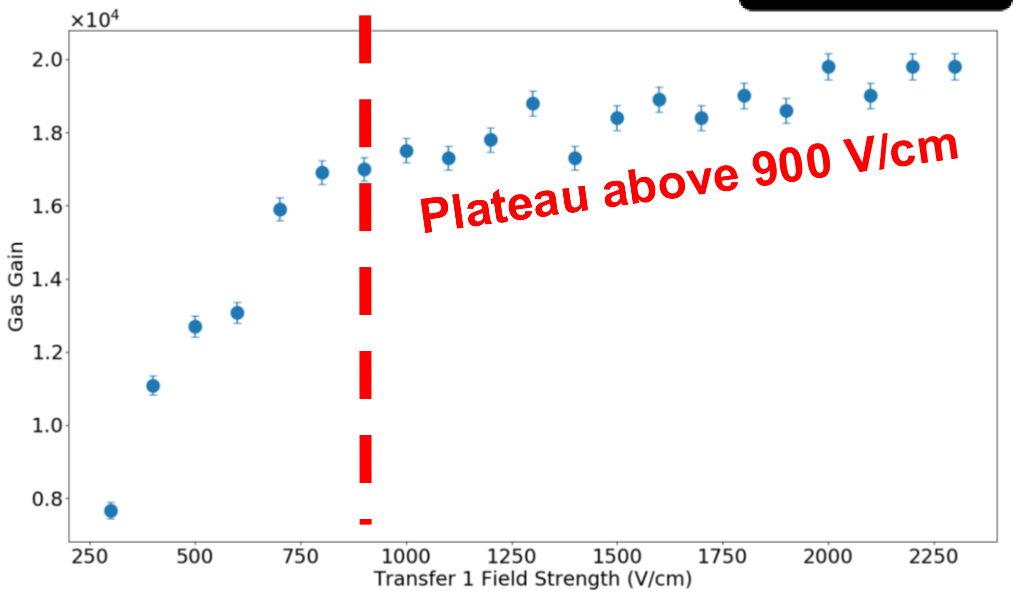
SCAN ME

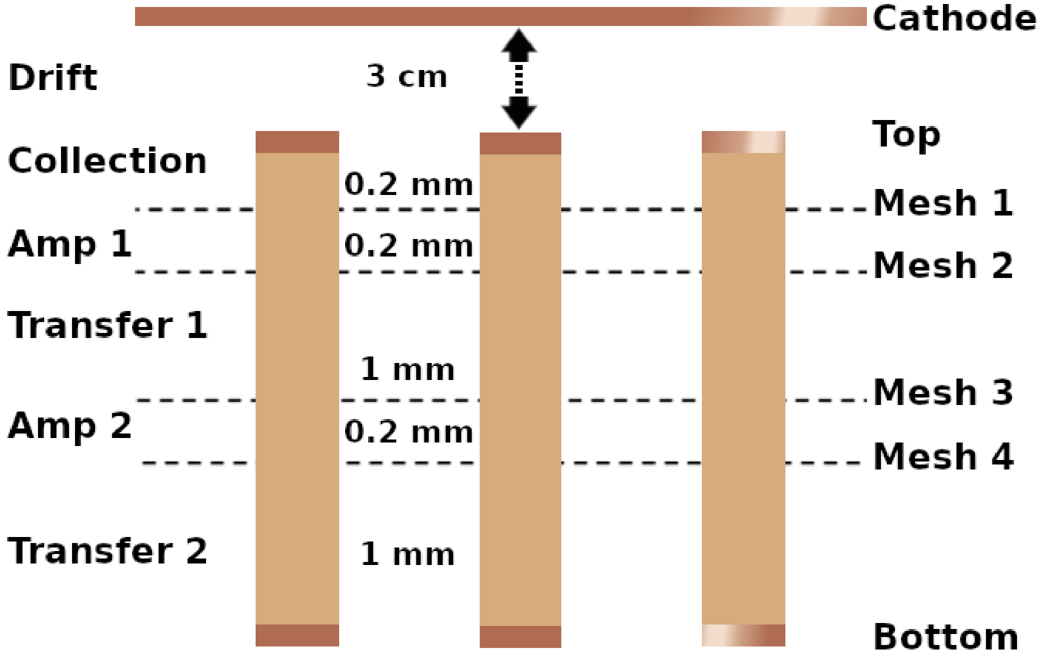
Recent success in low pressure SF_6

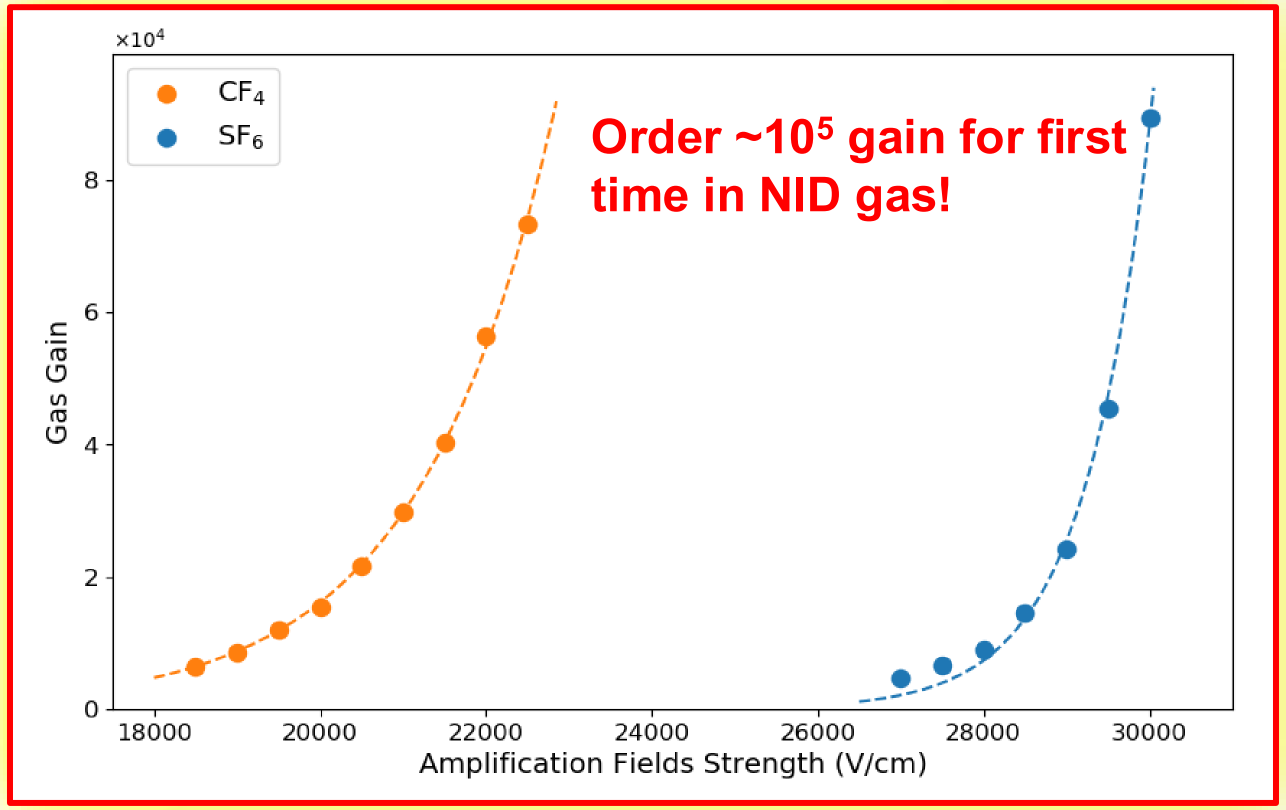
MMThGEM

- Multiple amplification stages are beneficial for use with SF_6
- Mesh layers make the amplification fields uniform
- Improved avalanche characteristics
- Reduction in +ve Ion Back Flow (IBF)





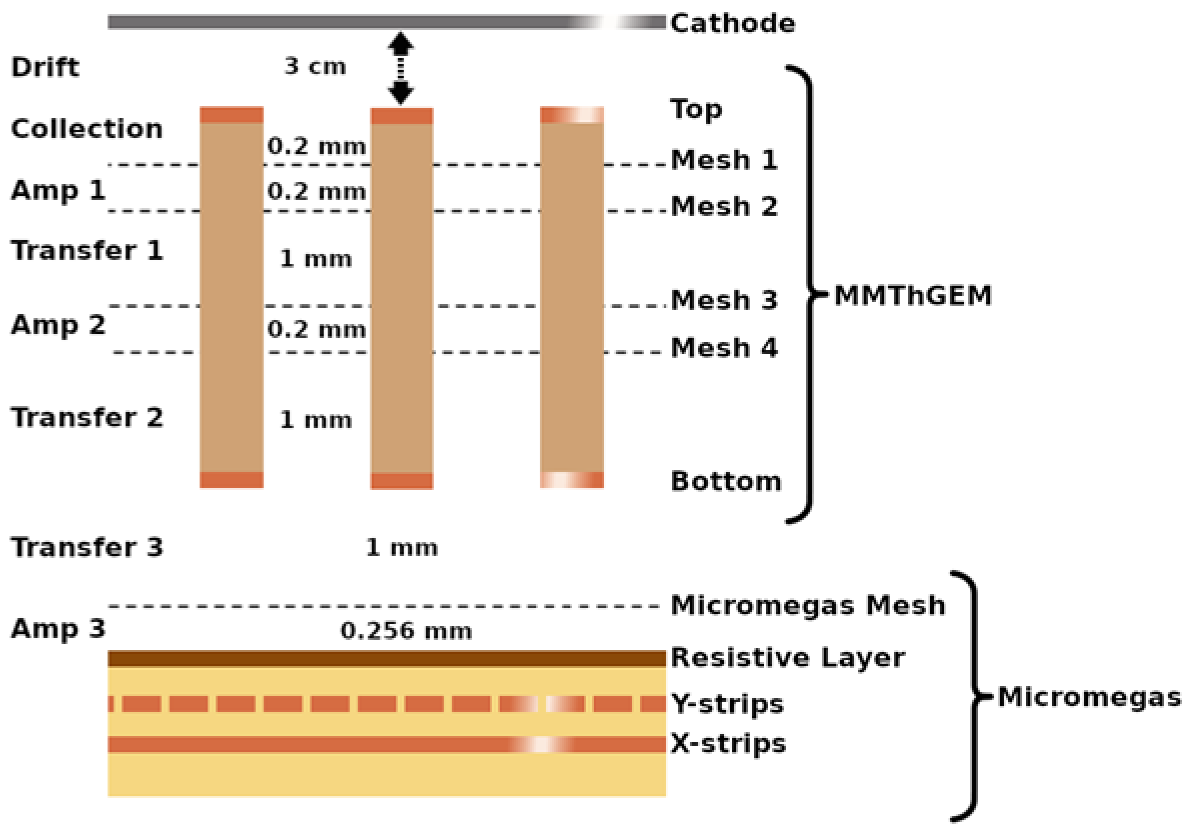




Coupled MMThGEM-Micromegas

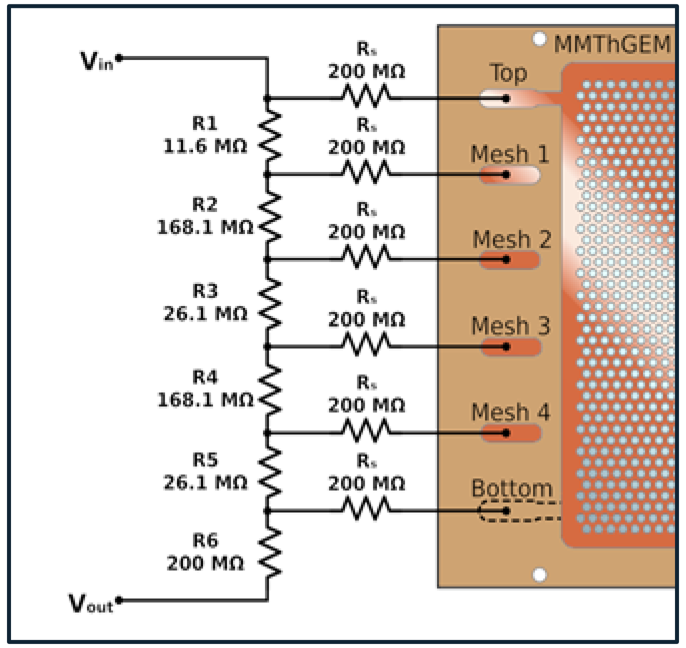
Micromegas Device - (MMThGEM is used as a gain stage device)

- Perpendicular x-y strip readout plane
- Resolution/strip pitch: 250 μm
- Strip width: 100 μm (y) and 220 μm (x)
- Active area: 10 x 10 cm
- Amplification gap: 256 μm
- Diamond Like Carbon (DLC) layer: 50 MΩ/□

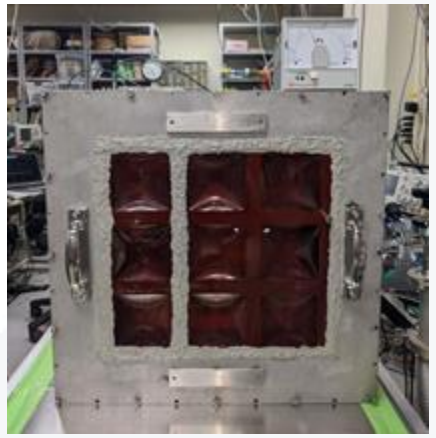


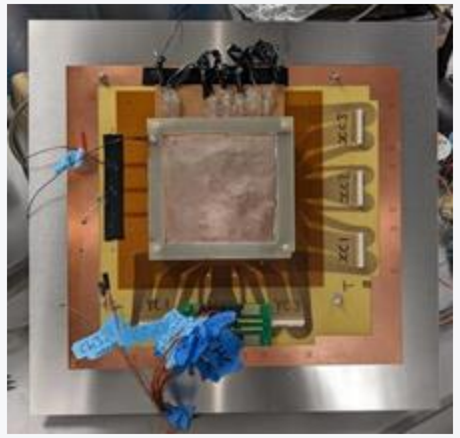
Biasing Scheme for MMThGEM

- Resistor chain soldered to electrode contacts
- Resistor values dictated by previous optimisation
- Reduces the number of HV feedthroughs required for operation



Starting in the Kobe test vessel

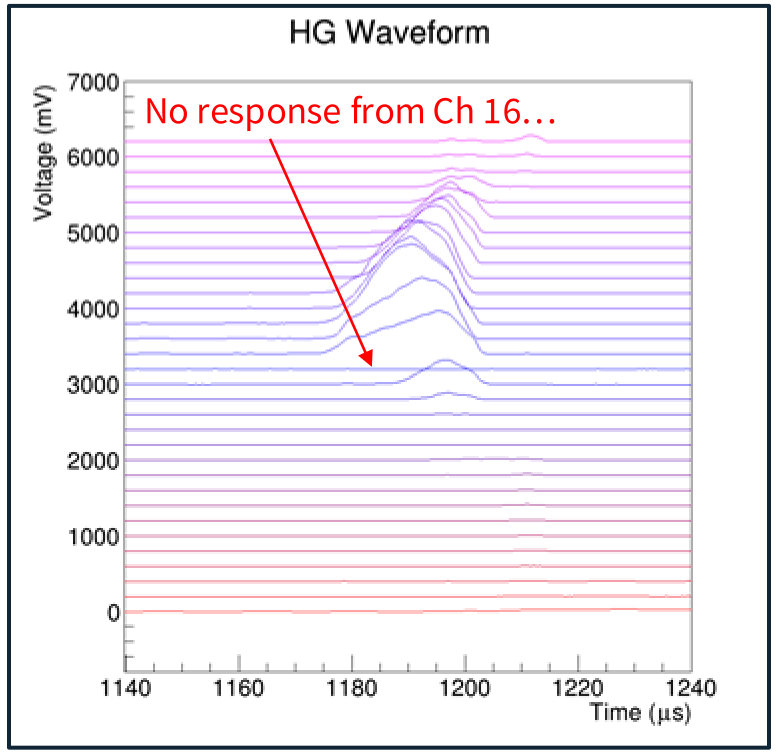


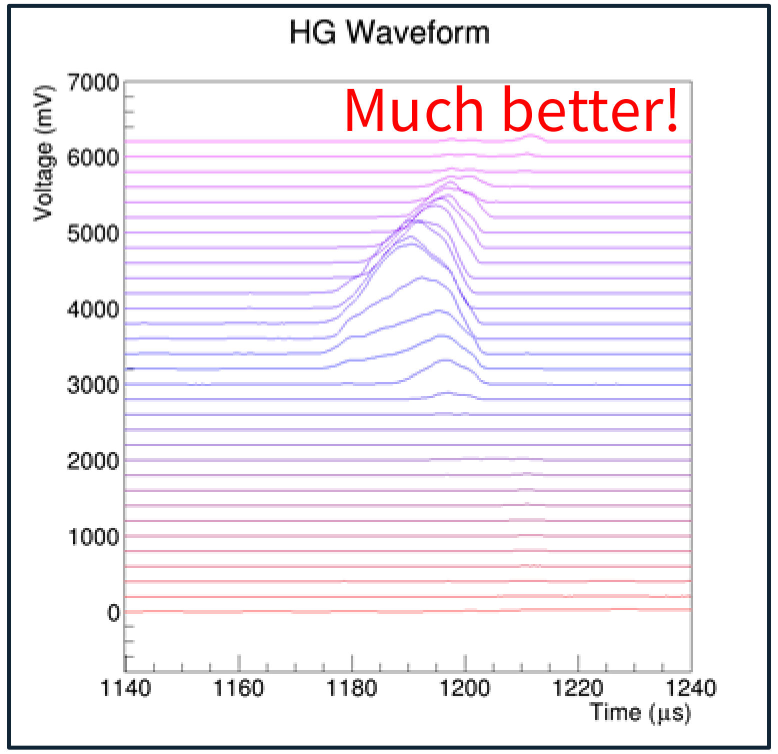


^{55}Fe X-ray Exposure

^{55}Fe X-ray Exposure - Signal Preprocessing

SF_6 - 40 Torr





Channel Interpolation

97% of channels were fully operational

Ch #16 was found to have a loose connection during measurements

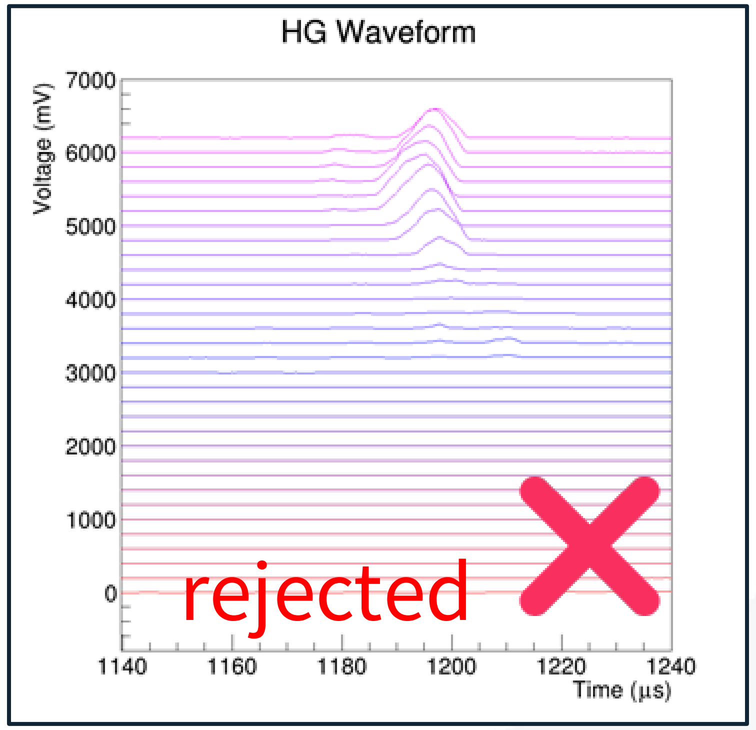
Instantaneous voltage of Ch 16 was determined via the linear interpolation of Ch 15 and 17

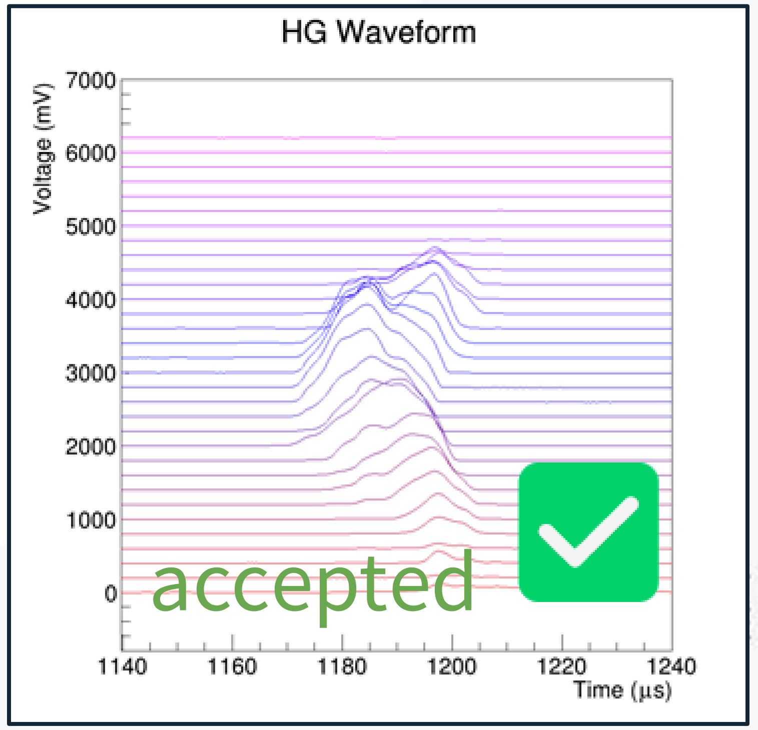
Edge Event Cut

Due to charge spreading in resistive layer, many channels are found to be above threshold per event…

Edge event threshold cut applied:

13 < Centre Ch# < 17





^{55}Fe X-ray Exposure - Gain Measurements

Biasing settings: -2900 V, -1900 V, 100 V, and -530 V for the cathode, V_{in} , V_{out} and Micromegas mesh respectively

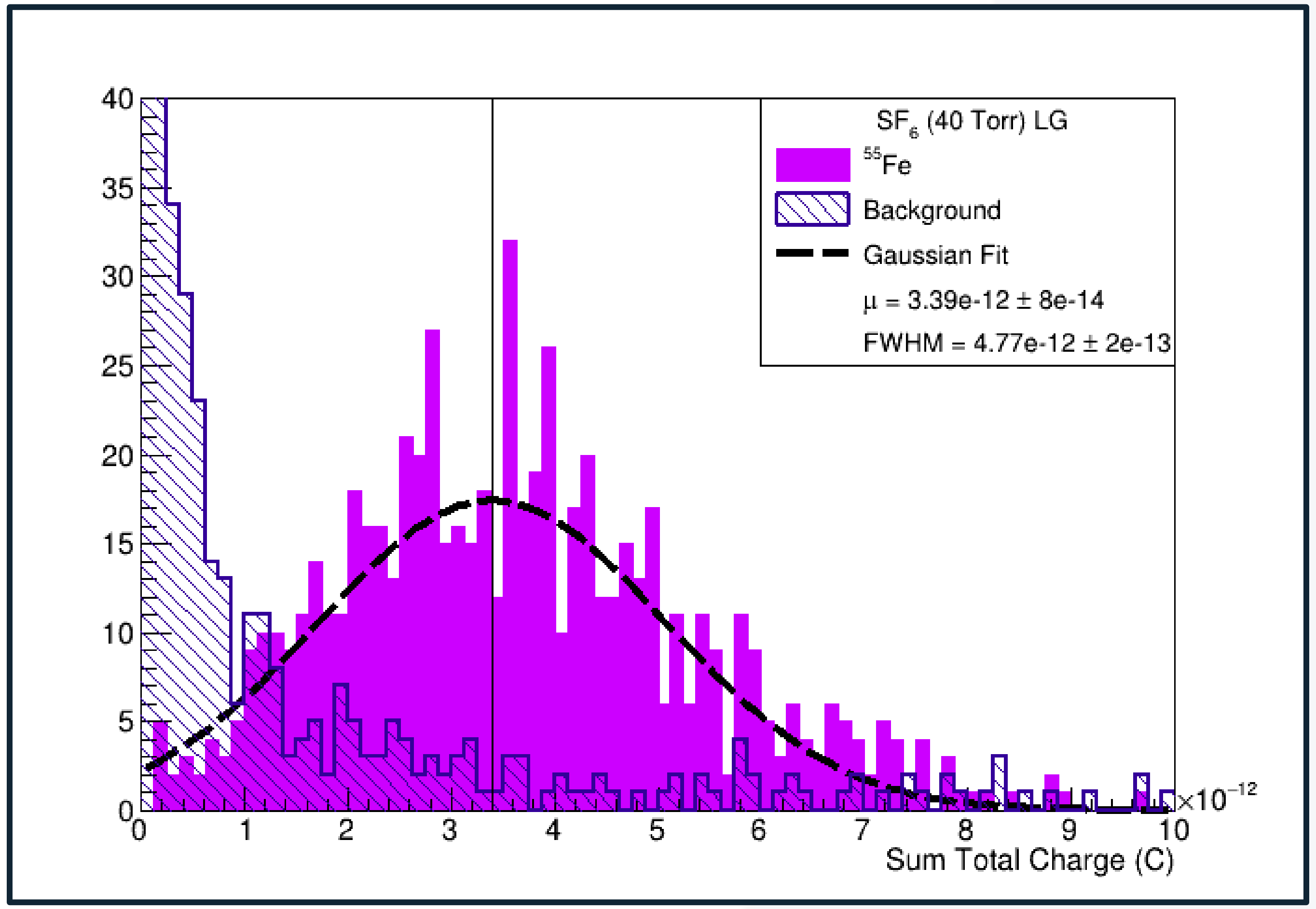
A photopeak can be observed in both the signal amplitude and signal integral spectrum

A gaussian distribution was fitted to the spectrum and the amount of charge was determined via the charge calibration

The gas gain was determined via the w-value of SF_6 (34 eV)

Gas gain was found to be as high as 1.24 x10^5!
with an energy resolution of 1.28

Effective gas gain in 40 Torr of SF_6 - **charge on strips**



THE UNIVERSITY of ADELAIDE

^{241}Am Alpha Particle Exposure

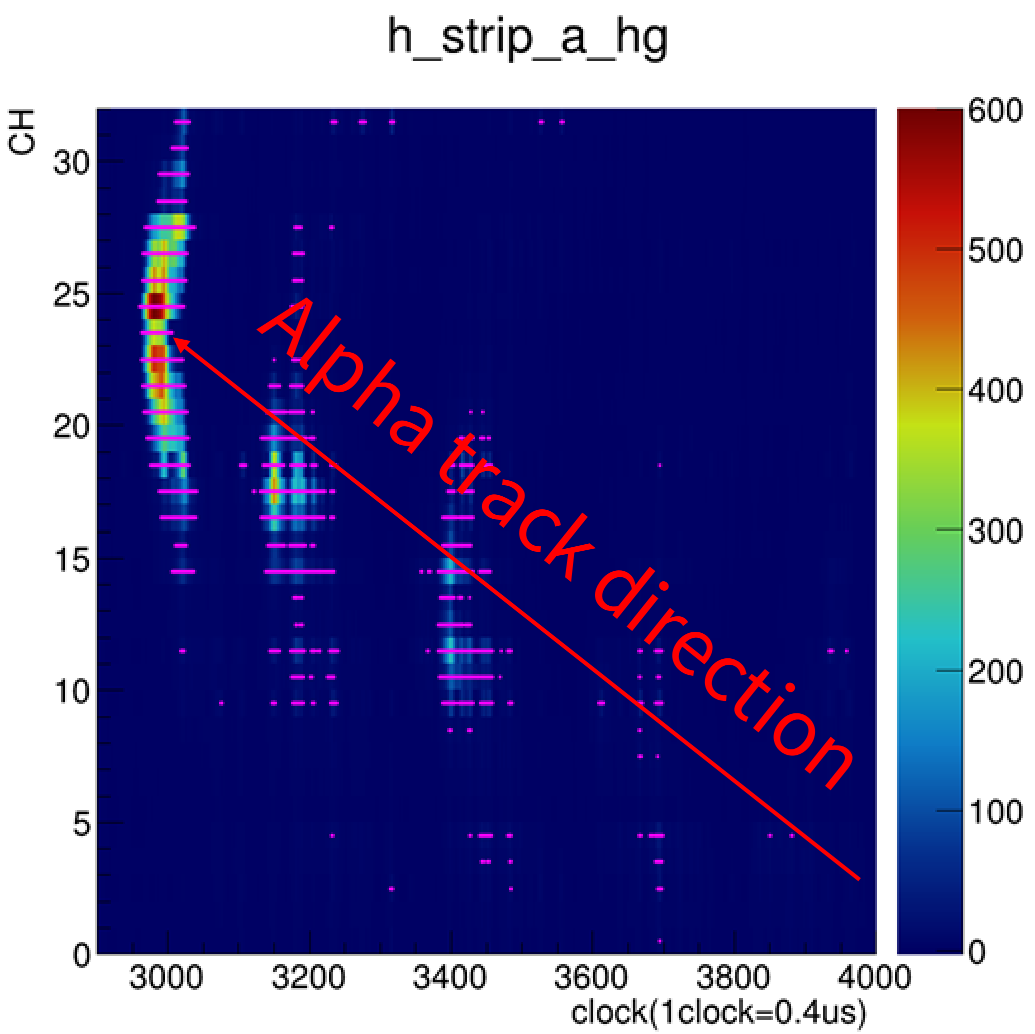
^{241}Am Alpha Exposure - Event Structure

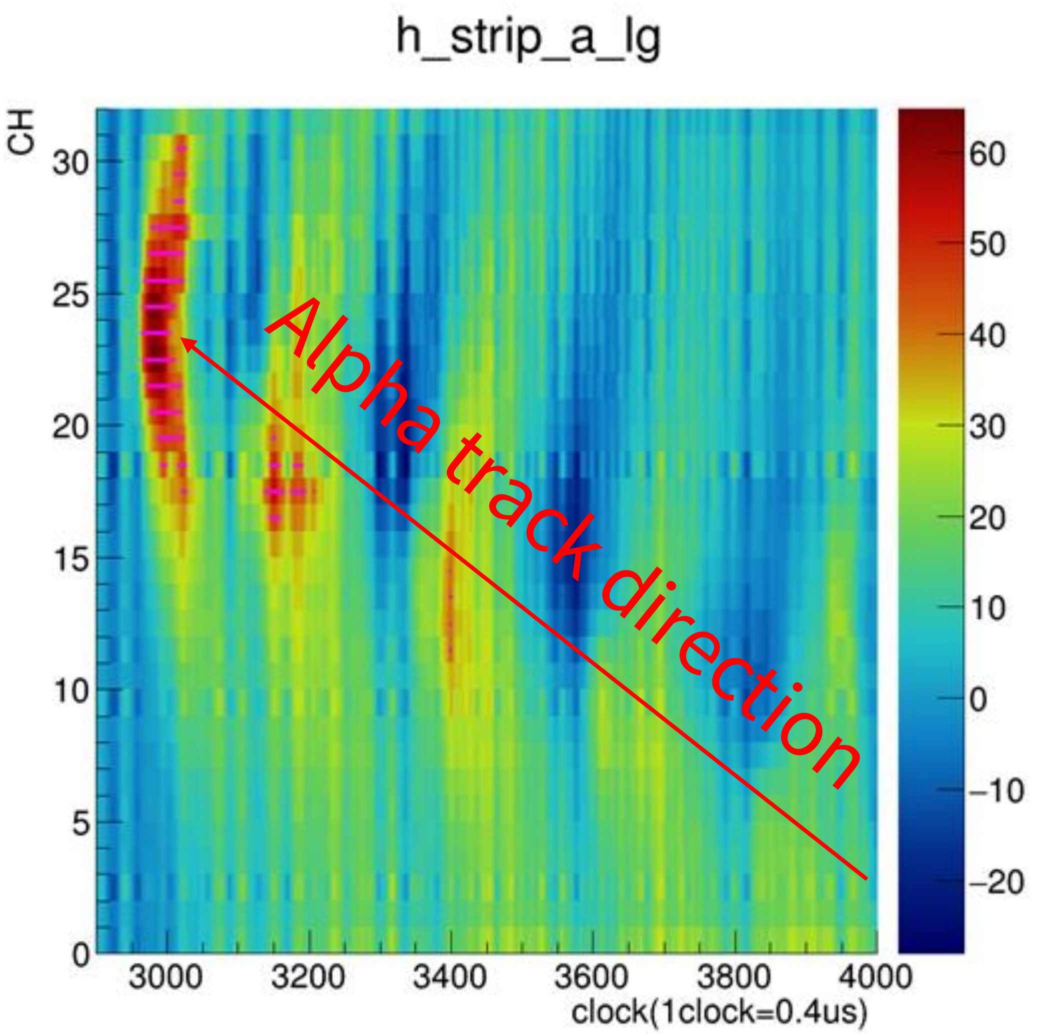
SF_6 - 40 Torr

The voltages applied to the cathode, V_{in} , V_{out} , and the Micromegas mesh were -2800 V, -1800 V, 100 V, and -500 V respectively.

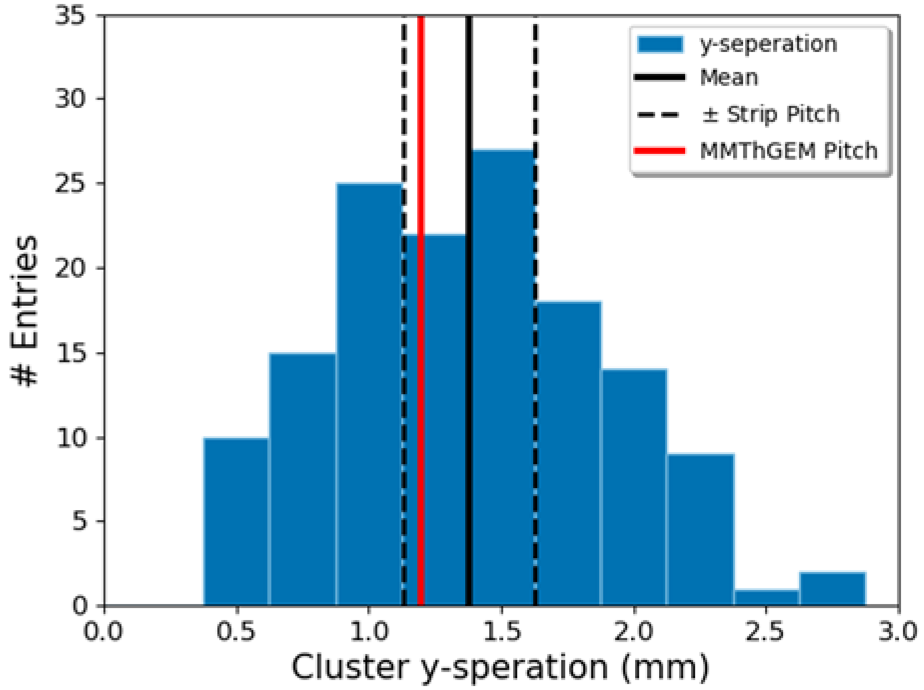
Example alpha particle track shows a structure caused by the MMThGEM hole pitch

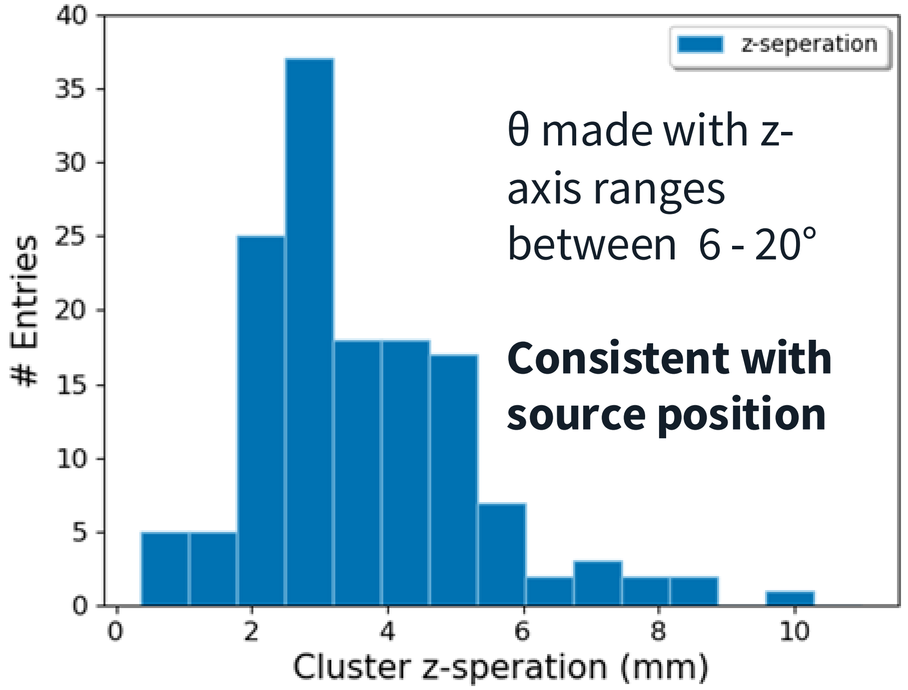
MMThGEM hole pitch: 1.2 mm





Inspection of 100 typical events





θ made with z-axis ranges between 6 - 20°

Consistent with source position

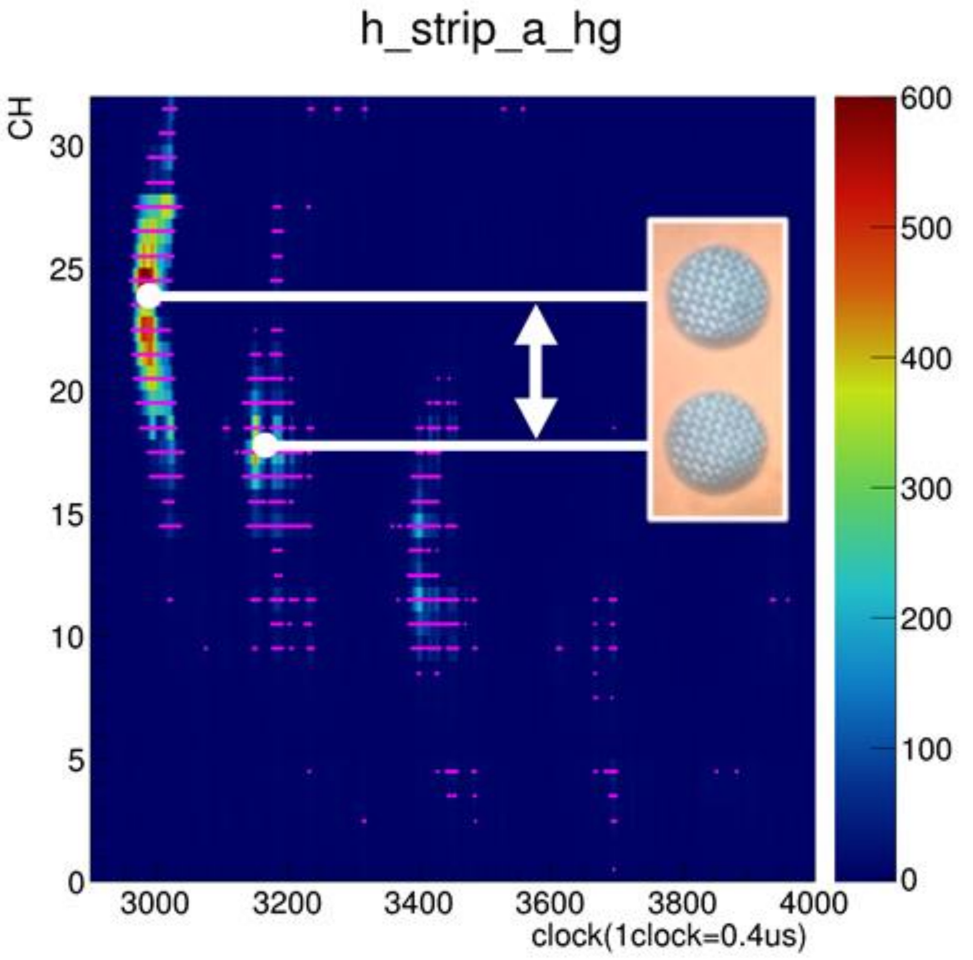
^{241}Am Alpha Exposure - Event Structure

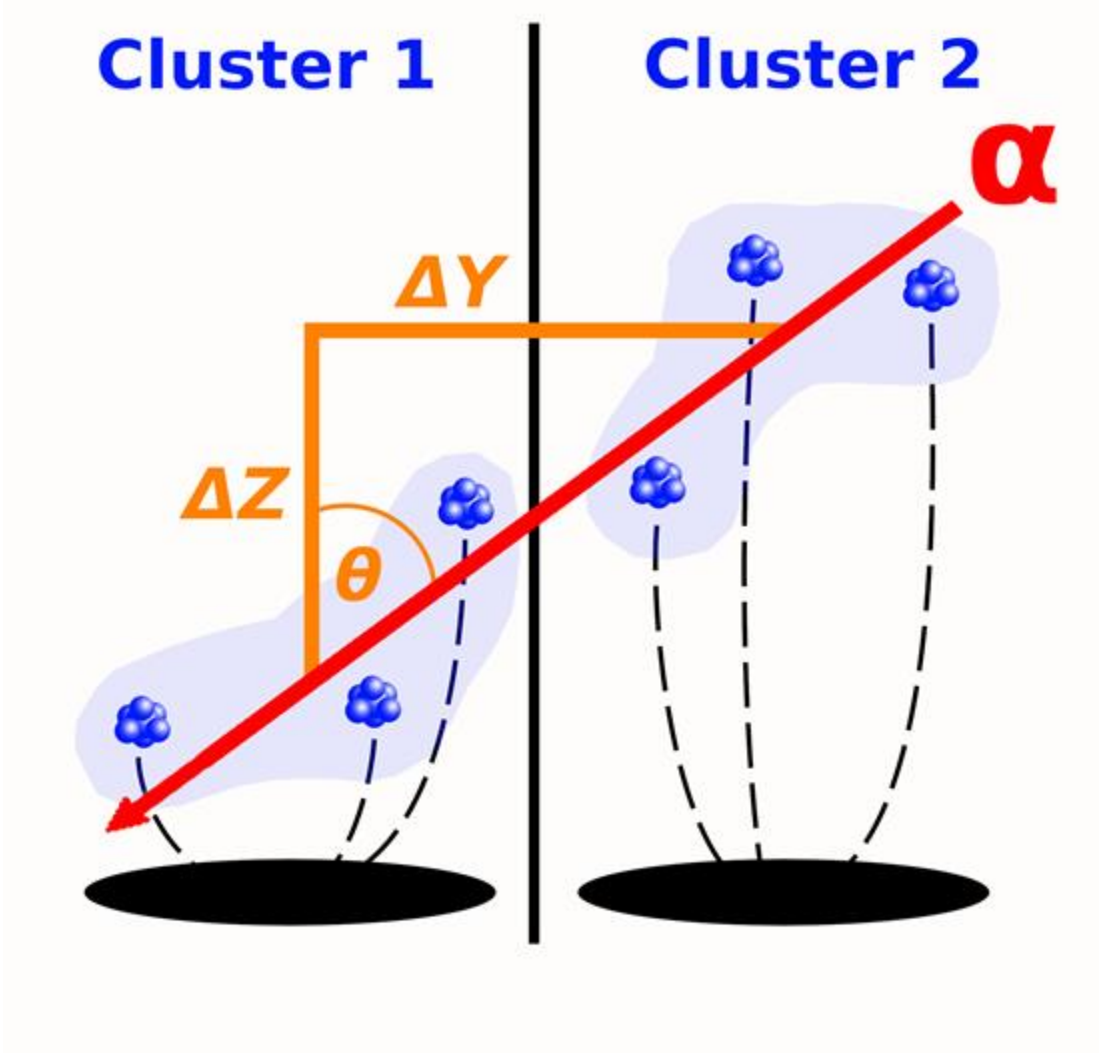
SF_6 - 40 Torr

The voltages applied to the cathode, V_{in} , V_{out} , and the Micromegas mesh were -2800 V, -1800 V, 100 V, and -500 V respectively.

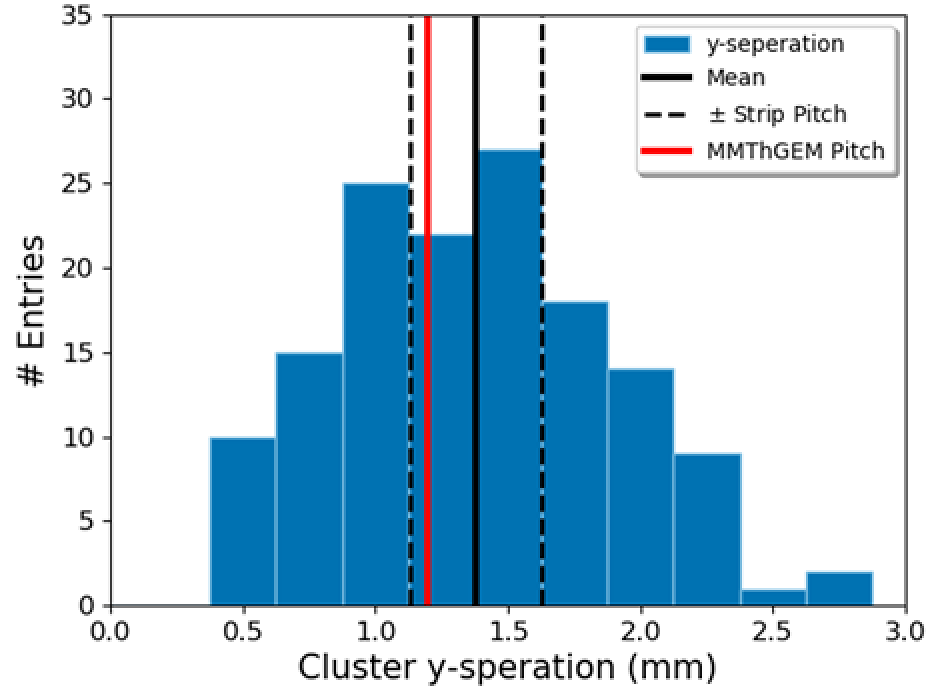
Example alpha particle track shows a structure caused by the MMThGEM hole pitch

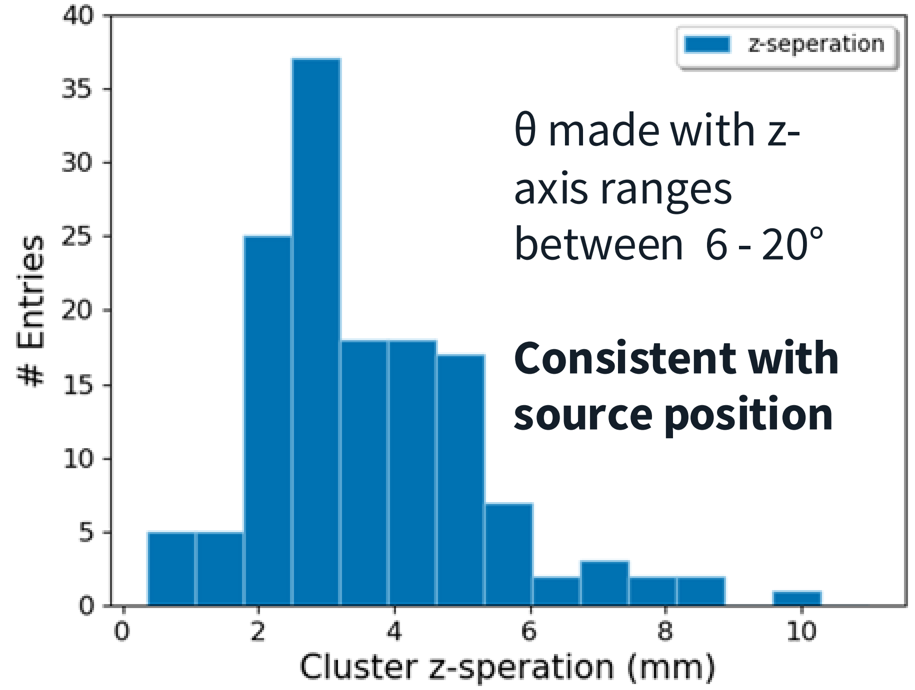
MMThGEM hole pitch: 1.2 mm





Inspection of 100 typical events





θ made with z-axis ranges between 6 - 20°

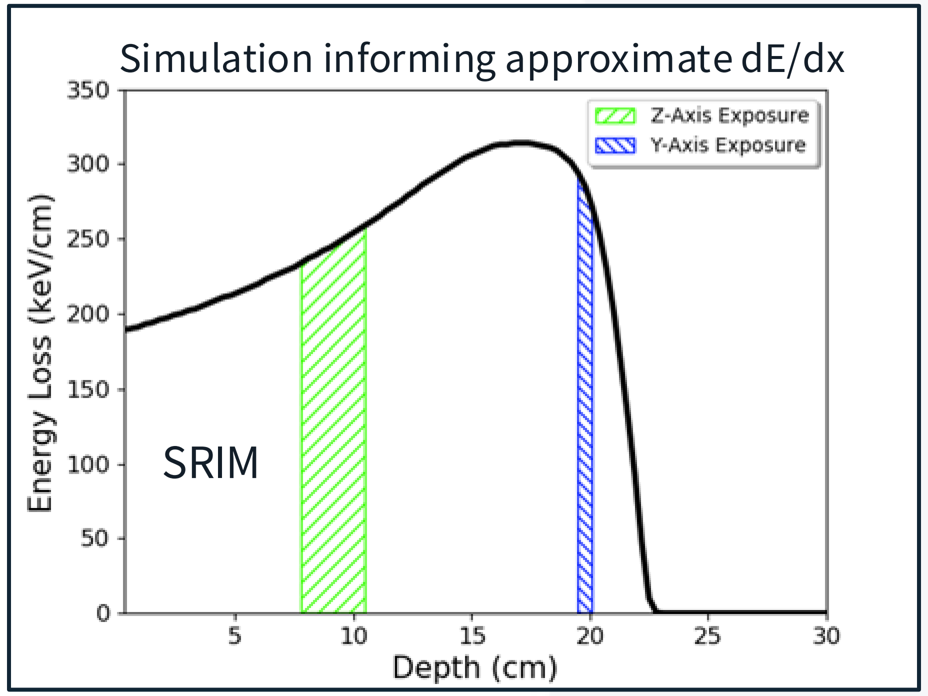
Consistent with source position

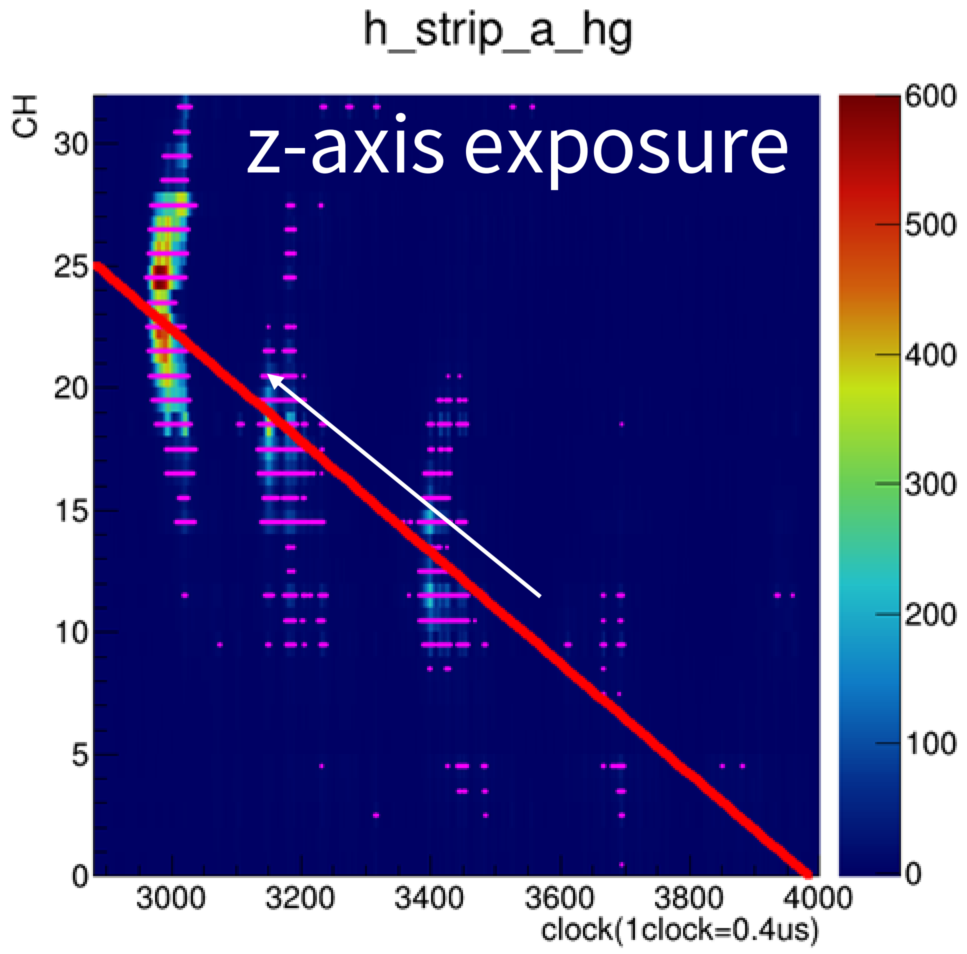
^{241}Am Alpha Exposure - Track Reconstruction

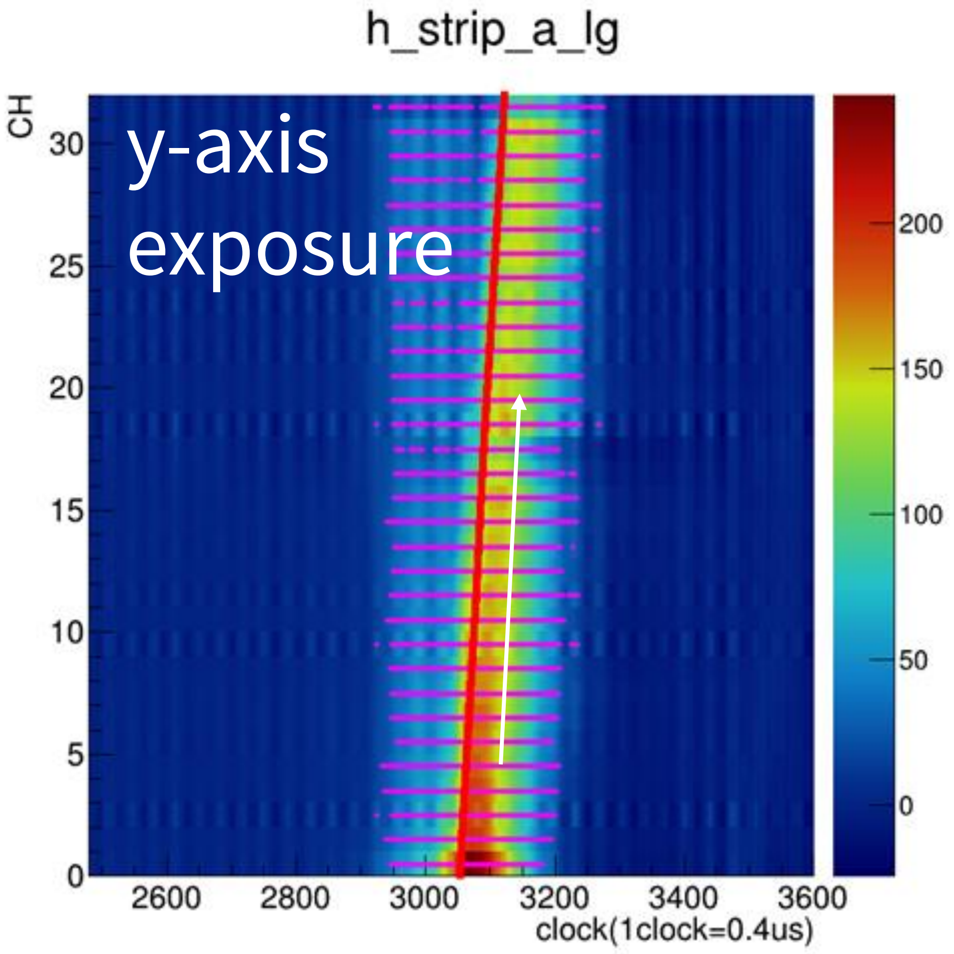
SF_6 - 40 Torr

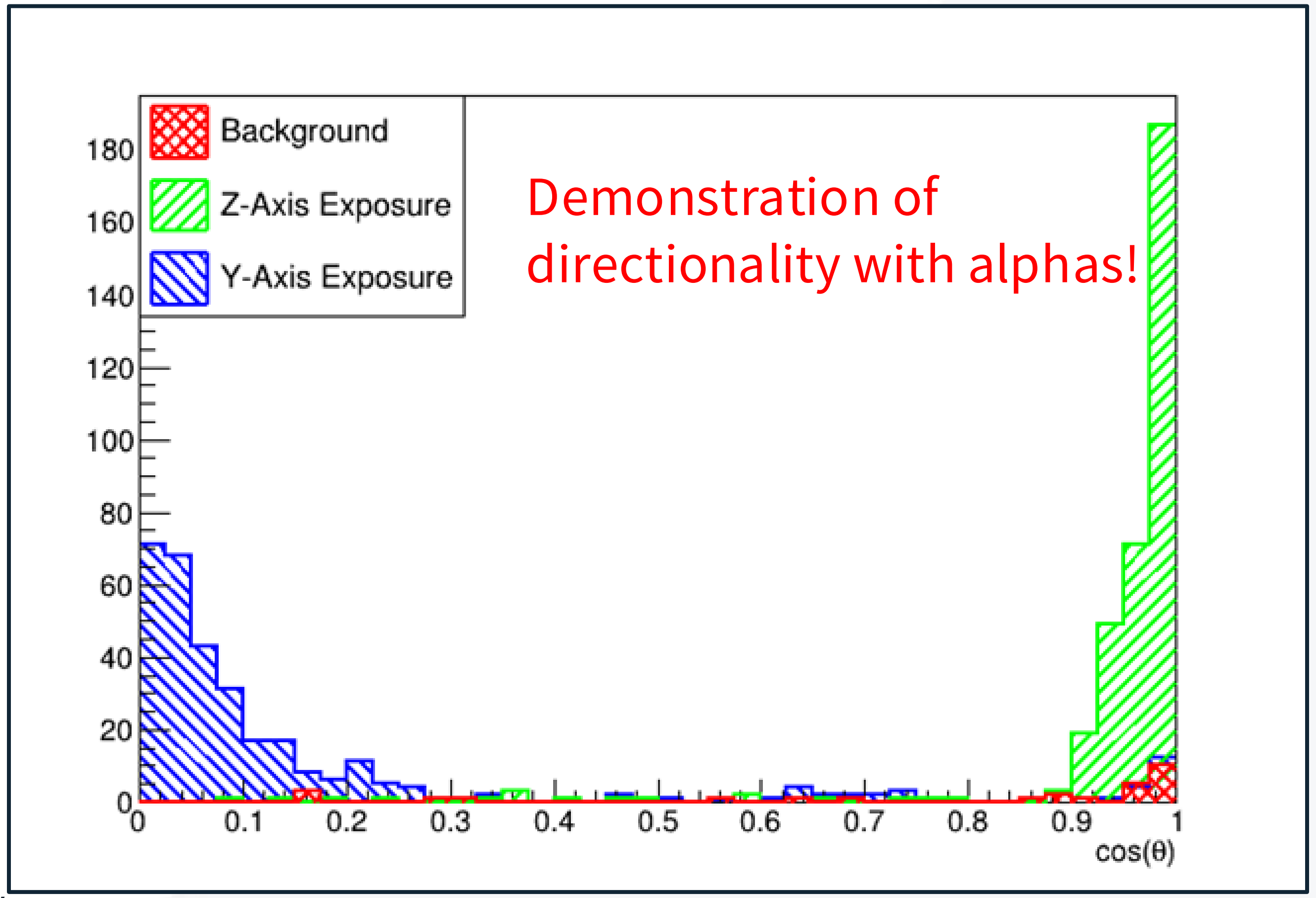
Total linear regression algorithm applied for track reconstruction:

1. Isolate points above threshold
2. Convert both axes into spatial units via strip pitch and drift velocity
3. Perform total linear regression - minimisation of residual on both axes







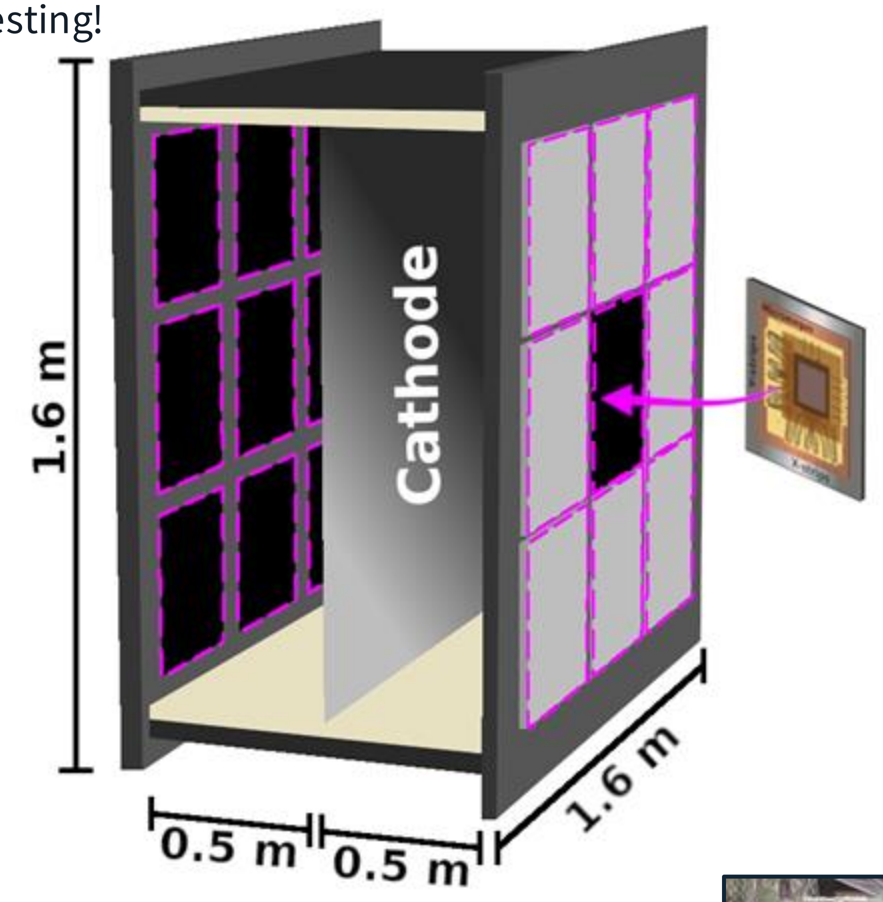


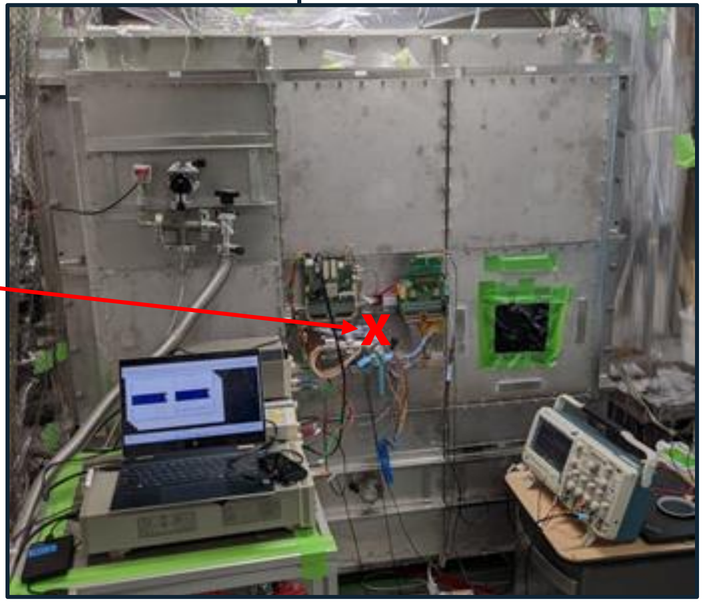
The cathode, V_{in}, V_{out}, and the Micromegas mesh voltages were -2800 V, -1800 V, 100 V, and -500 V respectively

CYGNUS-m^3 Scale Vessel

CYGNUS-m^3 Scale "BENTO" Vessel

Kentaro and Satoshi welcome your detector modules for testing!





^{252}Cf source positioned externally 10 cm behind micromegas plane

The "BENTO" vessel at Kobe University

Large CYGNUS-10 scale vessel - 50 cm drift length

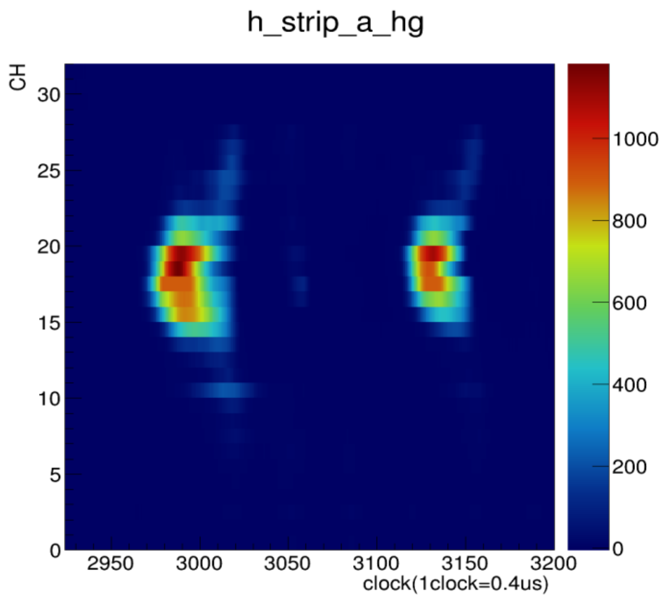
Modular design which can support up to 18 readout detector planes

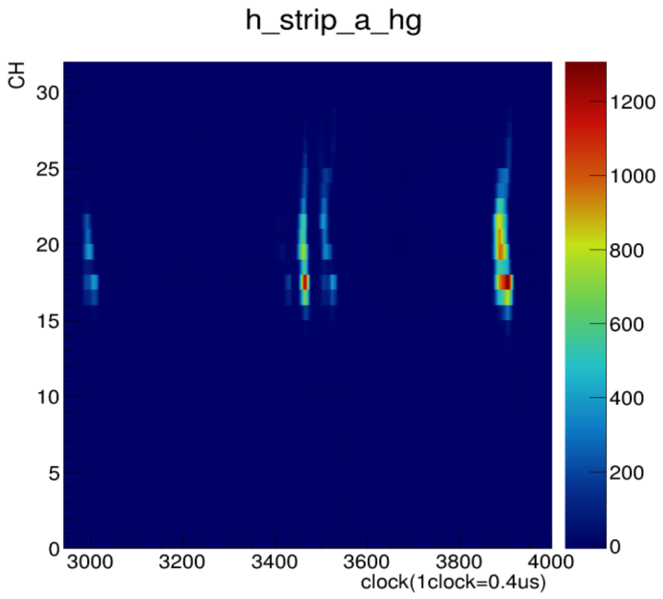
MMThGEM-Micromegas was transferred to the central panel on the BENTO vessel

Detector mounting conveniently fits test vessel dimensions

THE UNIVERSITY of ADELAIDE

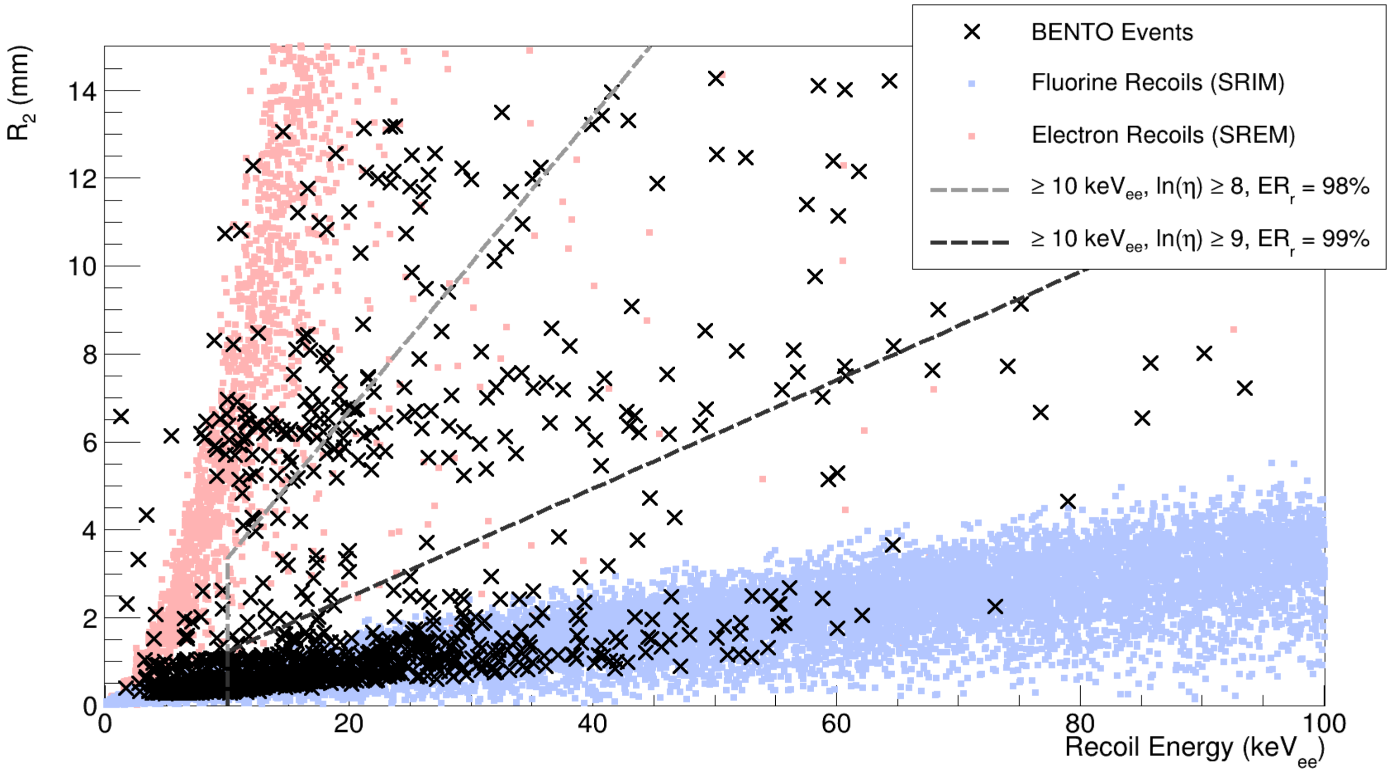
CYGNUS-m^3 Scale "BENTO" Vessel

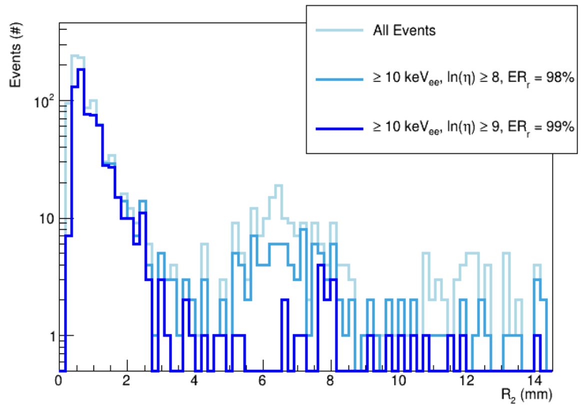


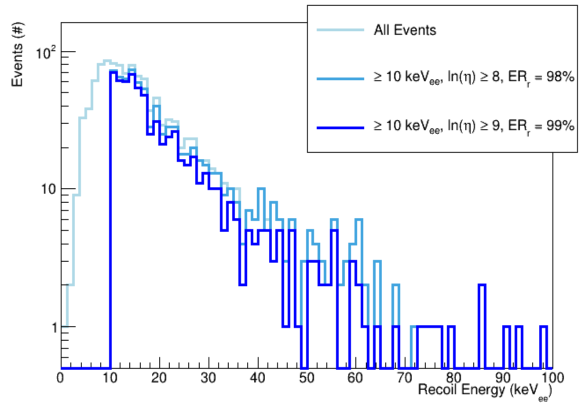


Possible evidence of head-tail asymmetries and SF_5^- minority peaks with ~30% amplitude of main peak!

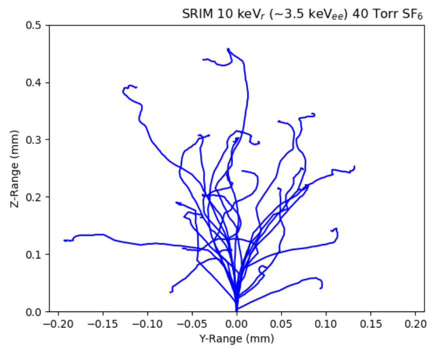
Further work required to confirm this is not due to MMThGEM hole pitch or other artifact

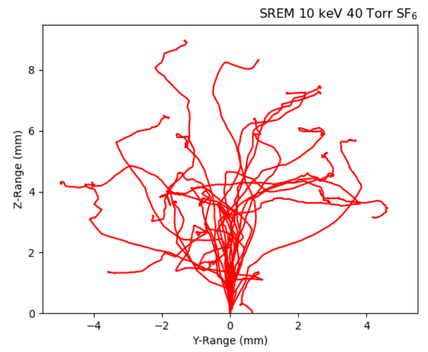


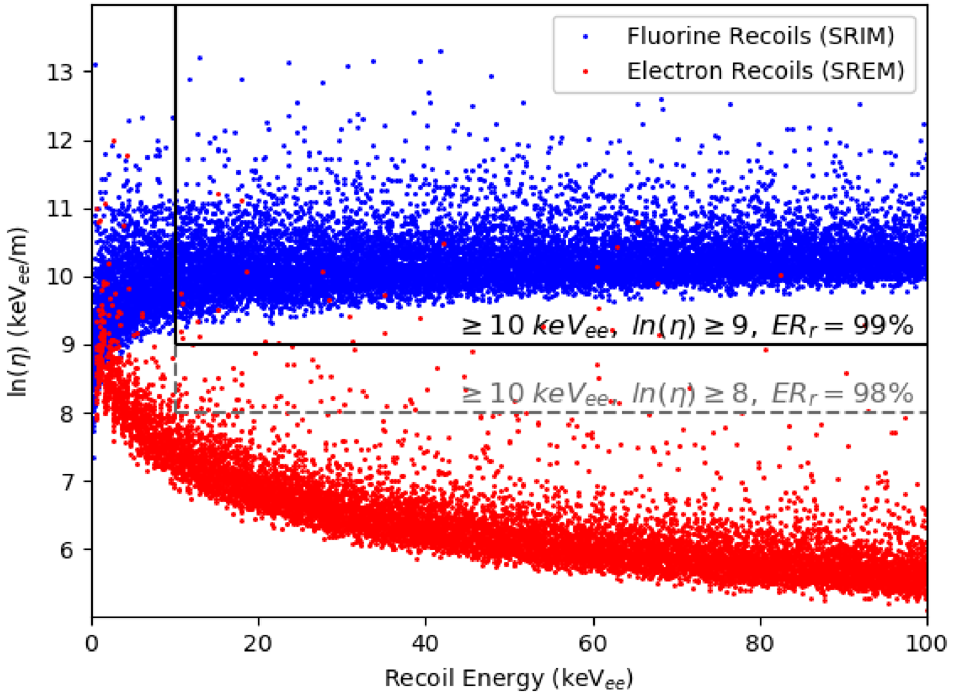




Supplementary simulations







With simulated cuts applied, range and energy spectra are consistent with NR results previously obtained with Cf-252 NRs elsewhere.

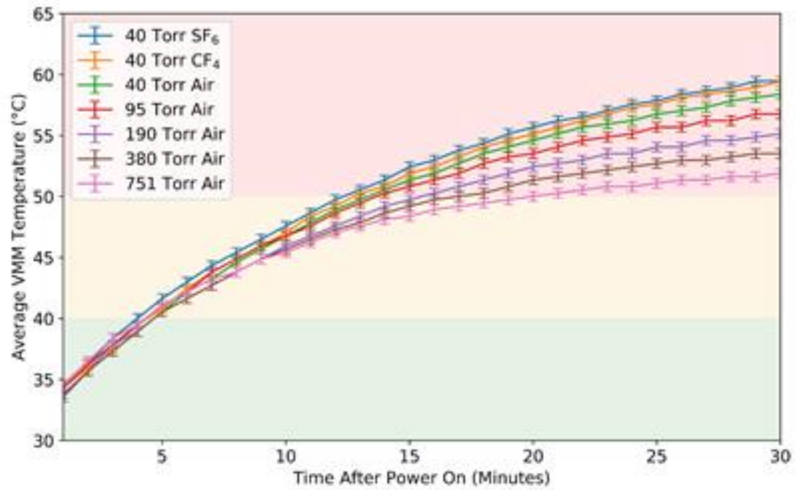
Next step: scale up readout channels...

Scale up of Electronics

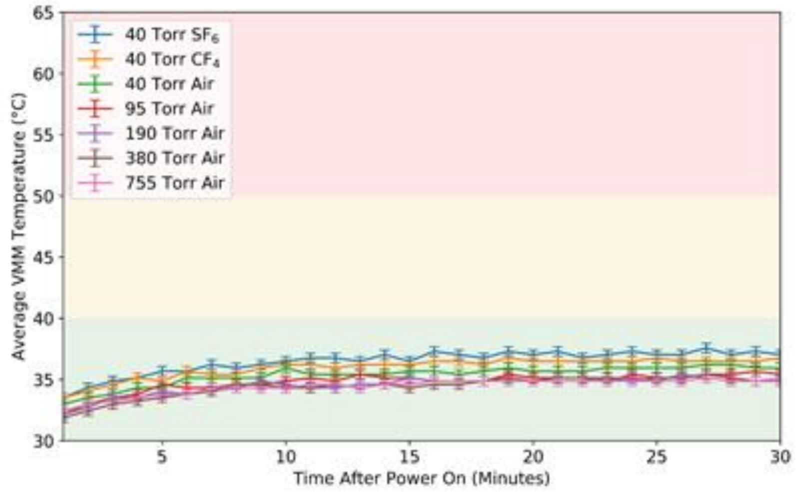
Strip Instrumentation with CERN SRS Electronics

CF_4 - 40 Torr

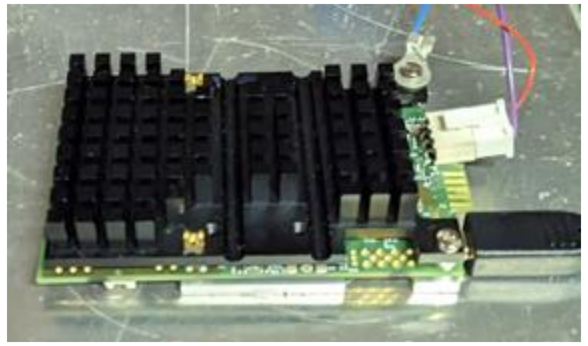
Thermal Management of VMM Hybrids at Low Pressure - crucial for long term operation



No mitigation



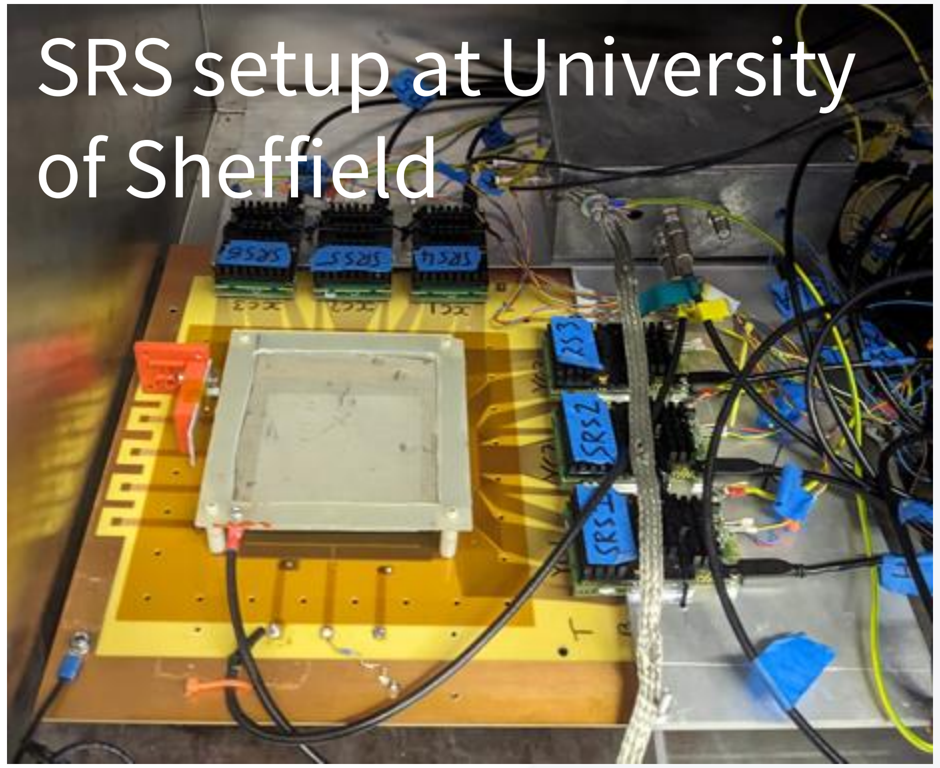
Thermal coupling to vessel with heat sink compound

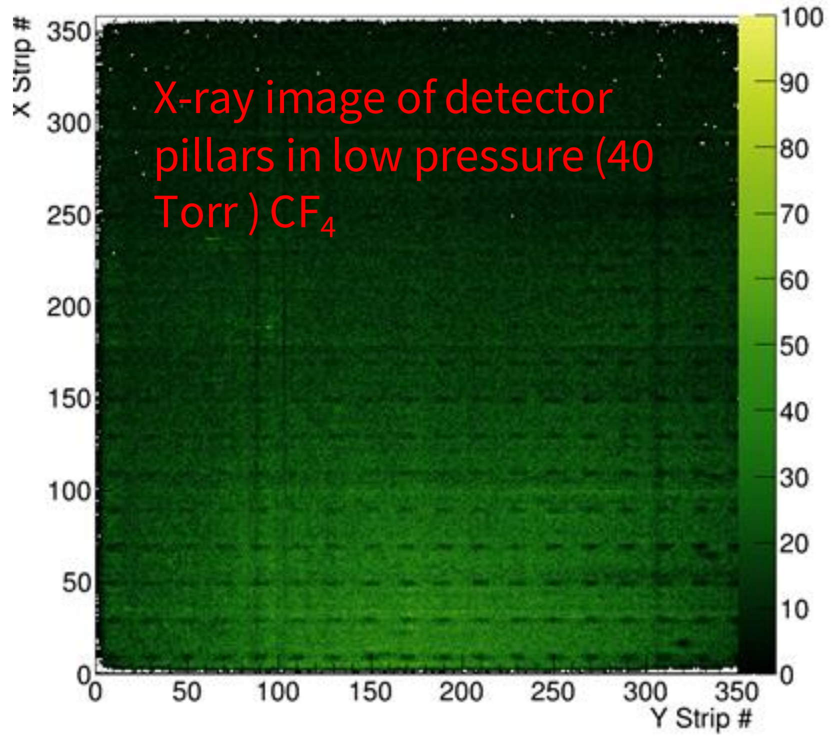


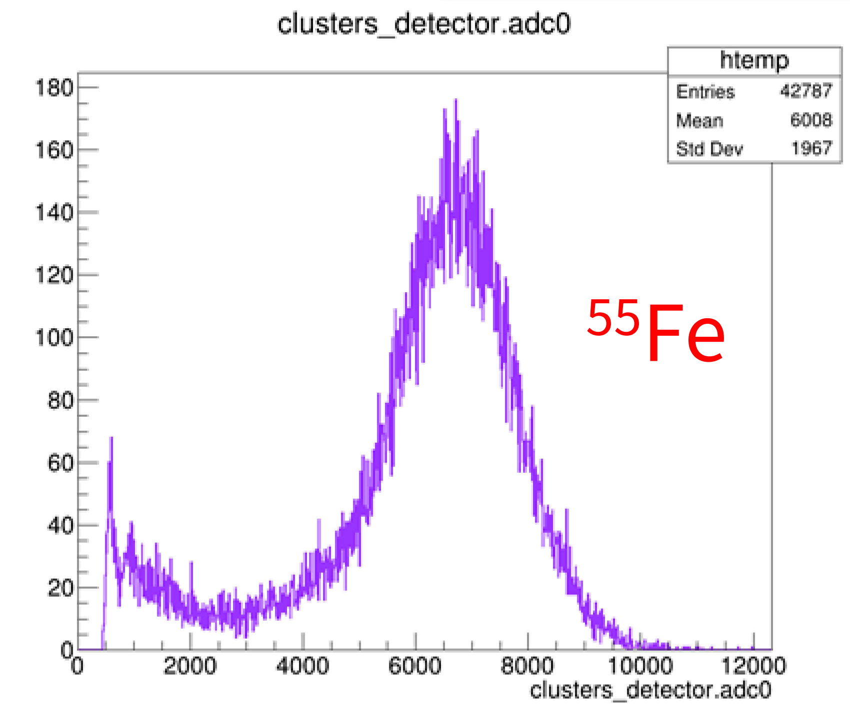
First time SRS has been used at low pressure!

Some preliminary results in 40 Torr of CF_4!

Evidence of response to x-ray source







Conclusions

Conclusions

- Next generation directional dark matter searches will likely utilise a NID gas like SF_6 - MMThGEM is a promising amplification stage design
- Coupled MMThGEM-Micromegas detector has been demonstrated with 32 channels in low pressure SF_6
- Exposure to various radioactive sources has highlighted successes (10^5 gas amplification) and room for improvement (coarse hole pitch)
- First exposure of the detector in a large CYGNUS-10 scale vessel has provided first look at potential nuclear recoil events and evidence of possible SF_5^- minority peaks
- Ongoing and future work is expanding to full scale strip instrumentation - first light operation of CERN SRS electronics at low pressure has been achieved!

THE UNIVERSITY of ADELAIDE

Thank you for your attention!

Thank you to the **organisers** for putting on a great conference, **EPSRC** for providing me with the funding opportunity to conduct this research, my PhD supervisor **Professor Neil Spooner** at the **University of Sheffield**, **Kentaro Miuchi** and **fellow researchers at the University of Kobe** for facilitating work presented here, and finally the **University of Adelaide** and the **ARC Centre of Excellence for Dark Matter Particle Physics** for giving me the opportunity and funding to attend today.

References

[1]https://www.symmetrymagazine.org/article/wimps-in-the-dark-matter-wind?language_content_entity=und

[2]https://indico.cern.ch/event/699961/contributions/3056787/attachments/1694378/2726925/Spooner-CYGNUS-IDM2018v1.pdf

[3]https://arxiv.org/pdf/2102.04596.pdf

[4]https://arxiv.org/pdf/2008.12587.pdf

[5]https://etheses.whiterose.ac.uk/29645/1/Eldridge170148355_Thesis_corr2.pdf

[6]arXiv: 2203.05914 (2022).

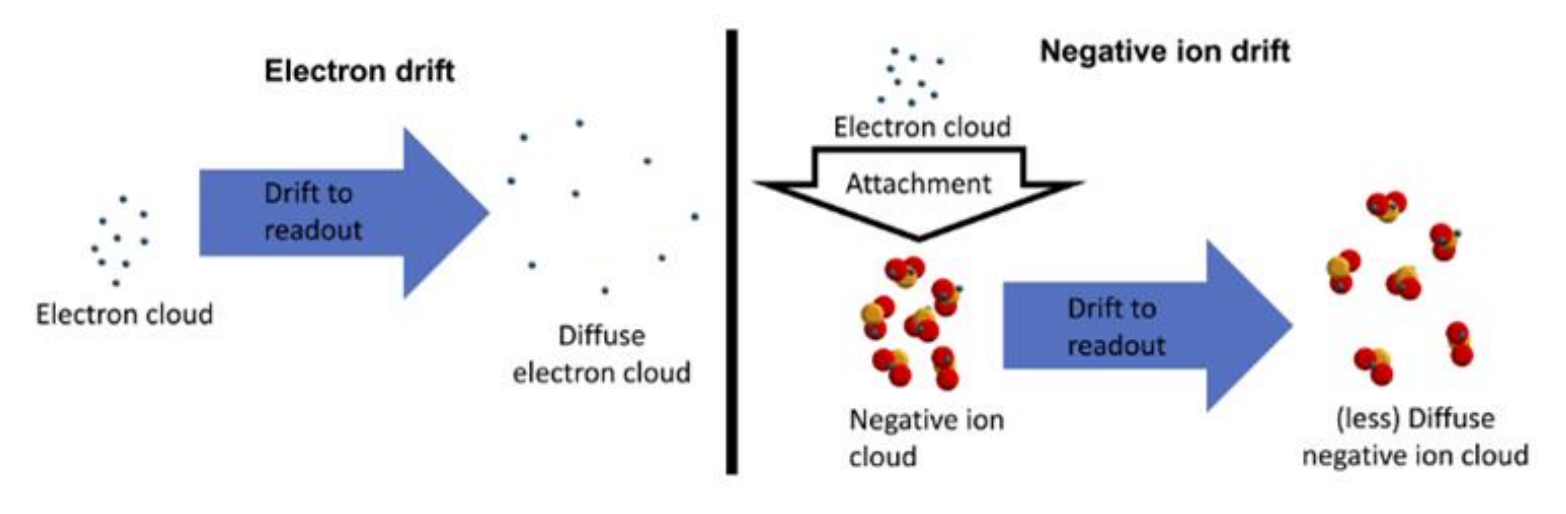
THE UNIVERSITY of ADELAIDE

Additional Slides

Why use SF_6 gas?

Pros!

- Electronegative/Negative Ion Drift (NID) gas - high fidelity
- Fluorine content - possible improvement in WIMP cross section
- Not toxic! - previously CS_2 was used as a NID gas but it is toxic



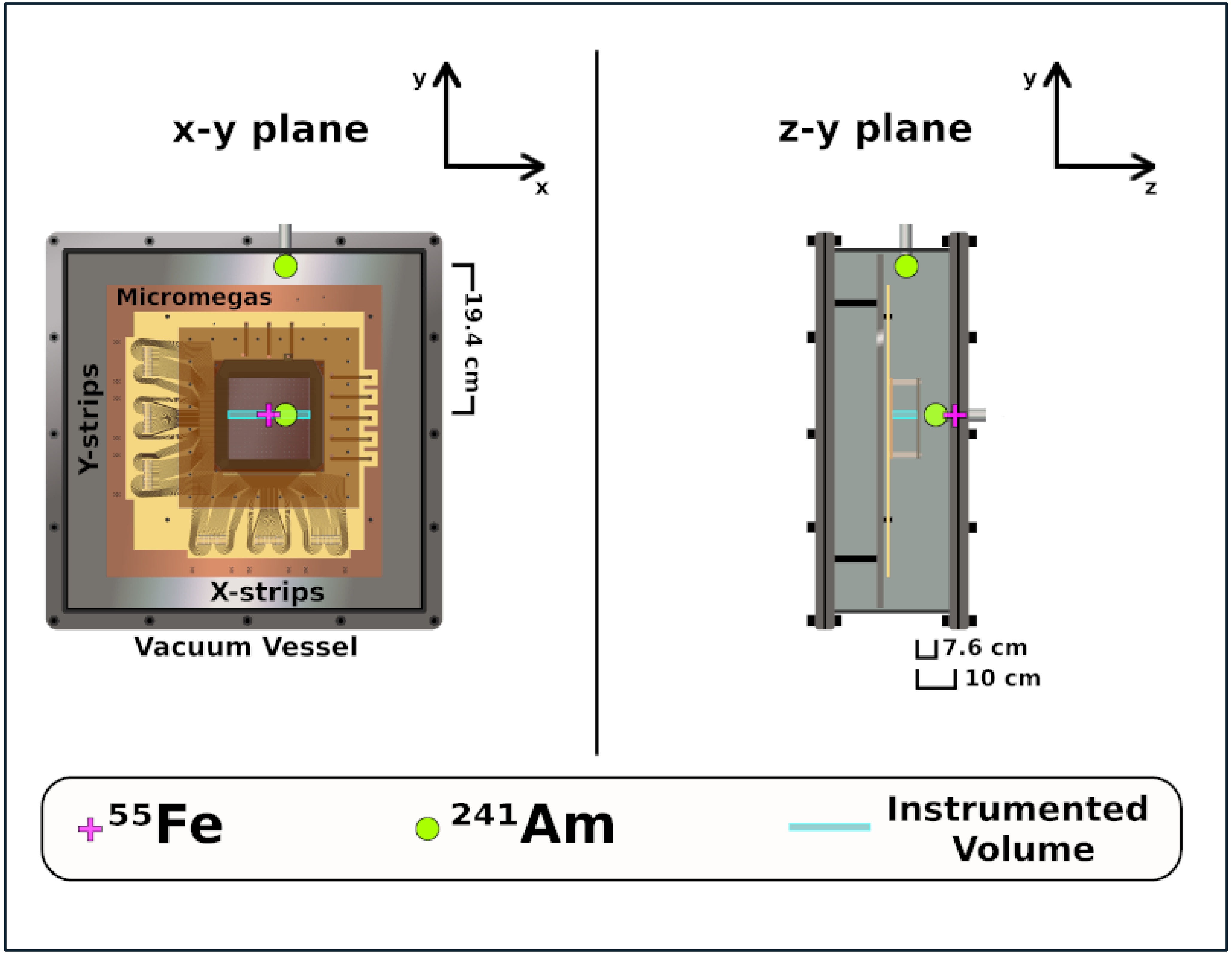
Con...

Very difficult to produce significant gas gains with…

Electron must first be stripped from the NI before amplification can occur

Limits sensitivity of detector to low energy recoils

Source Positioning around Test Vessel



^{55}Fe x-ray source

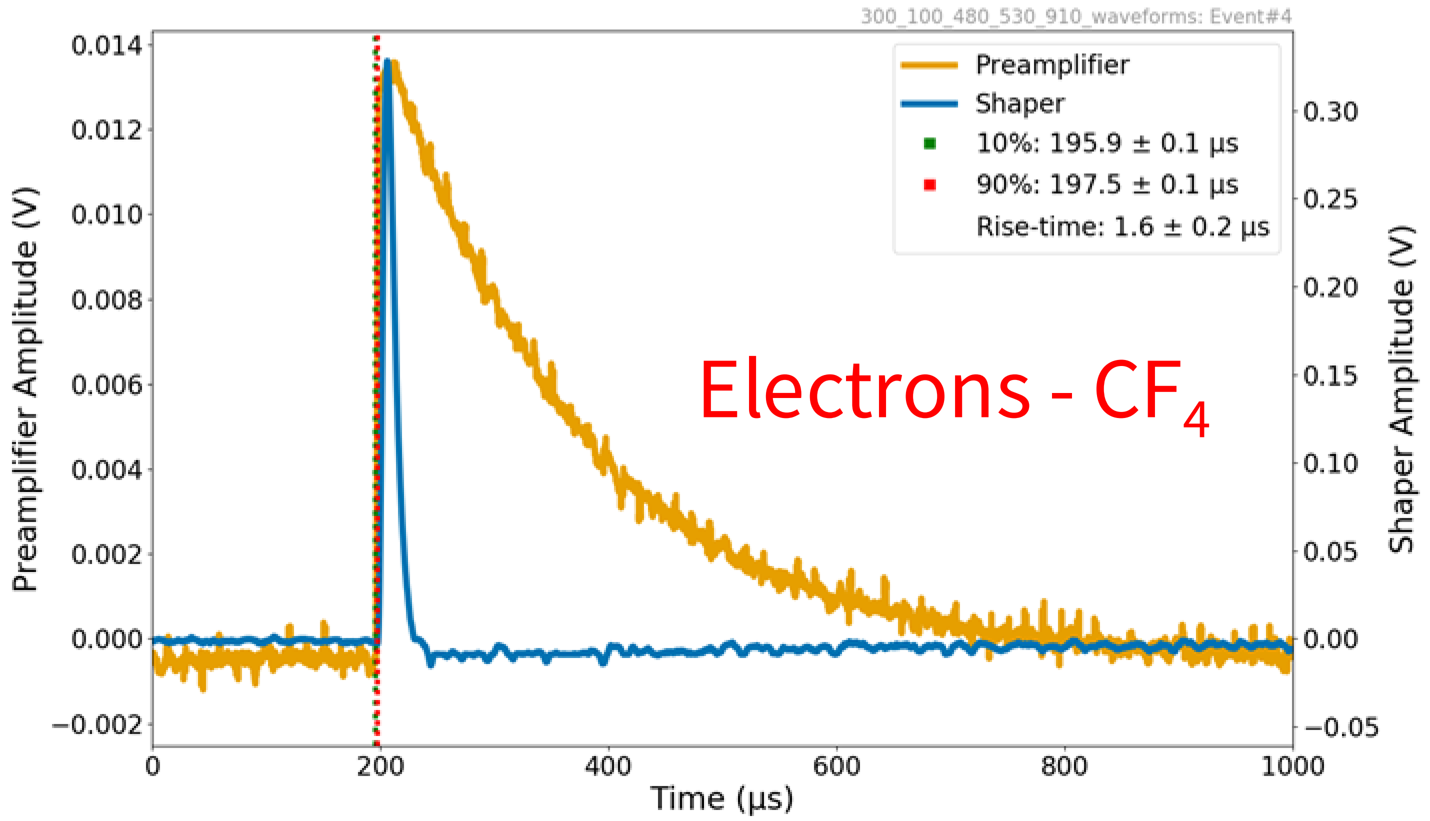
- ~10 cm above instrumented strips (z-axis exposure)

^{241}Am alpha source

1. ~8 cm above instrumented strips (z-axis exposure)
2. A distance of ~20cm perpendicular to y-strips (y-axis exposure)

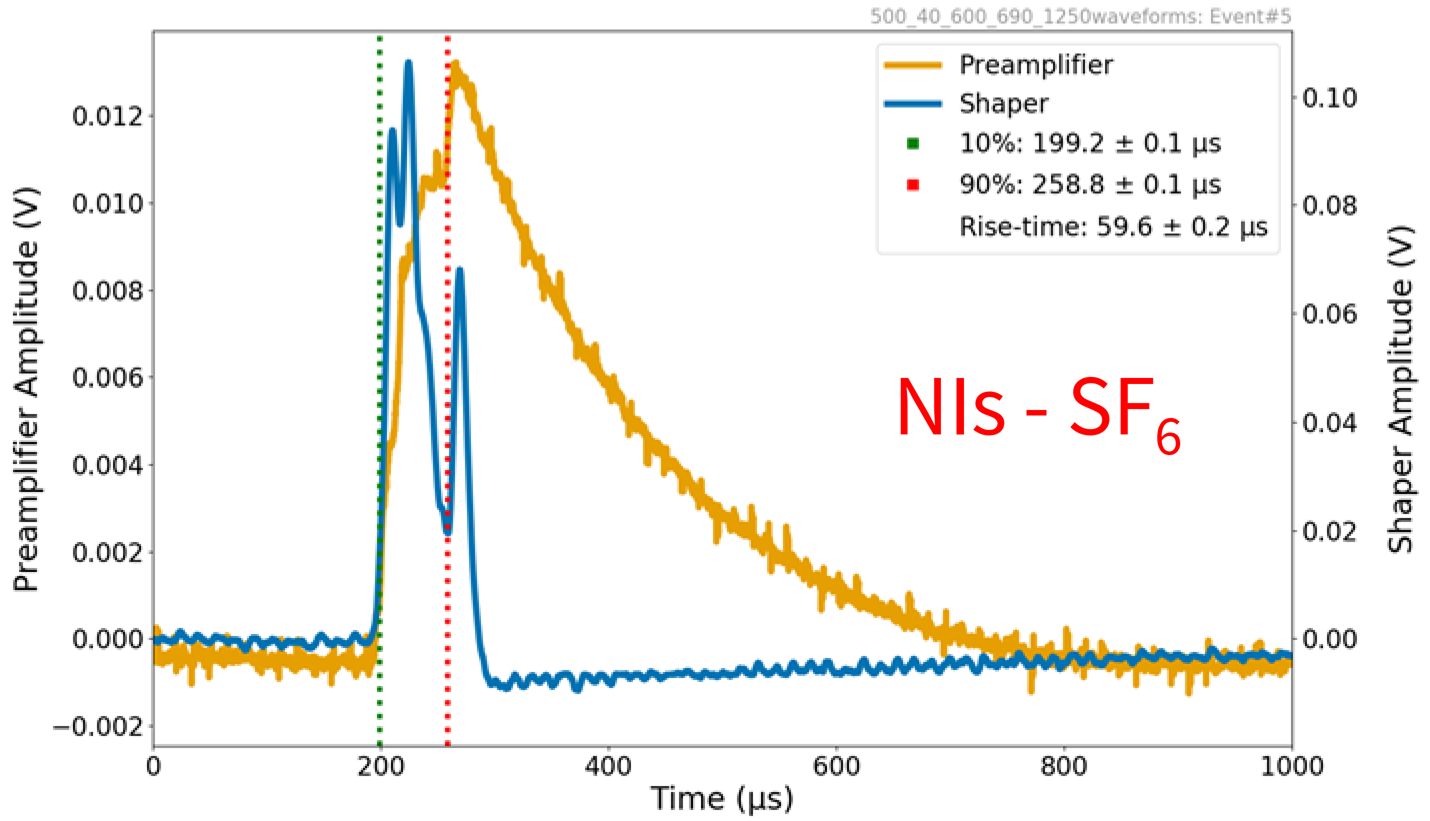
THE UNIVERSITY of ADELAIDE

Electron vs Negative Ion Pulse Shapes - MMThGEM



Typical ^{55}Fe x-ray induced event in 40 Torr CF_4 with the MMThGEM

Charge arrives at electrode within shaping time of electronics

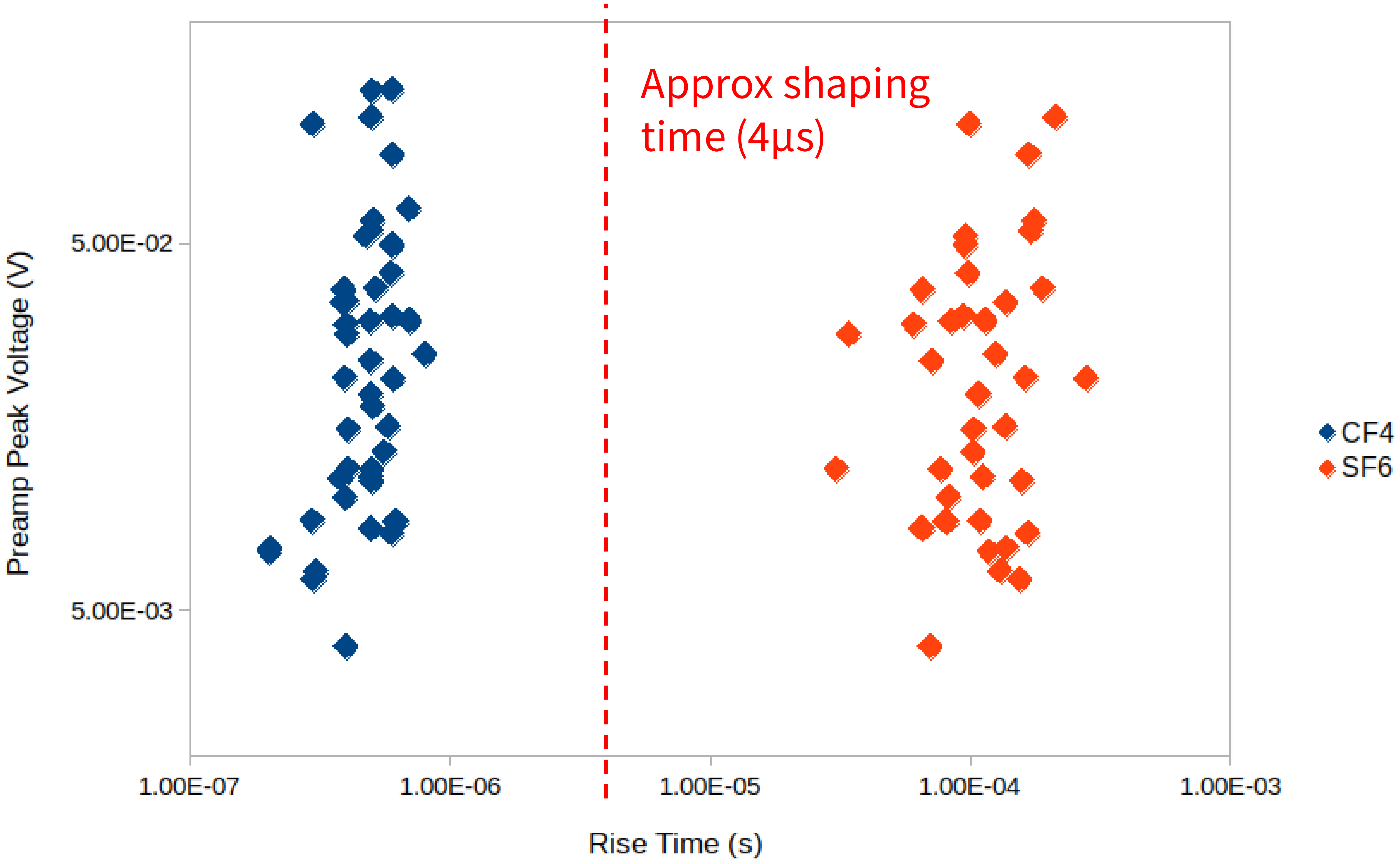


Typical ^{55}Fe x-ray induced event in 40 Torr SF_6 with the MMThGEM

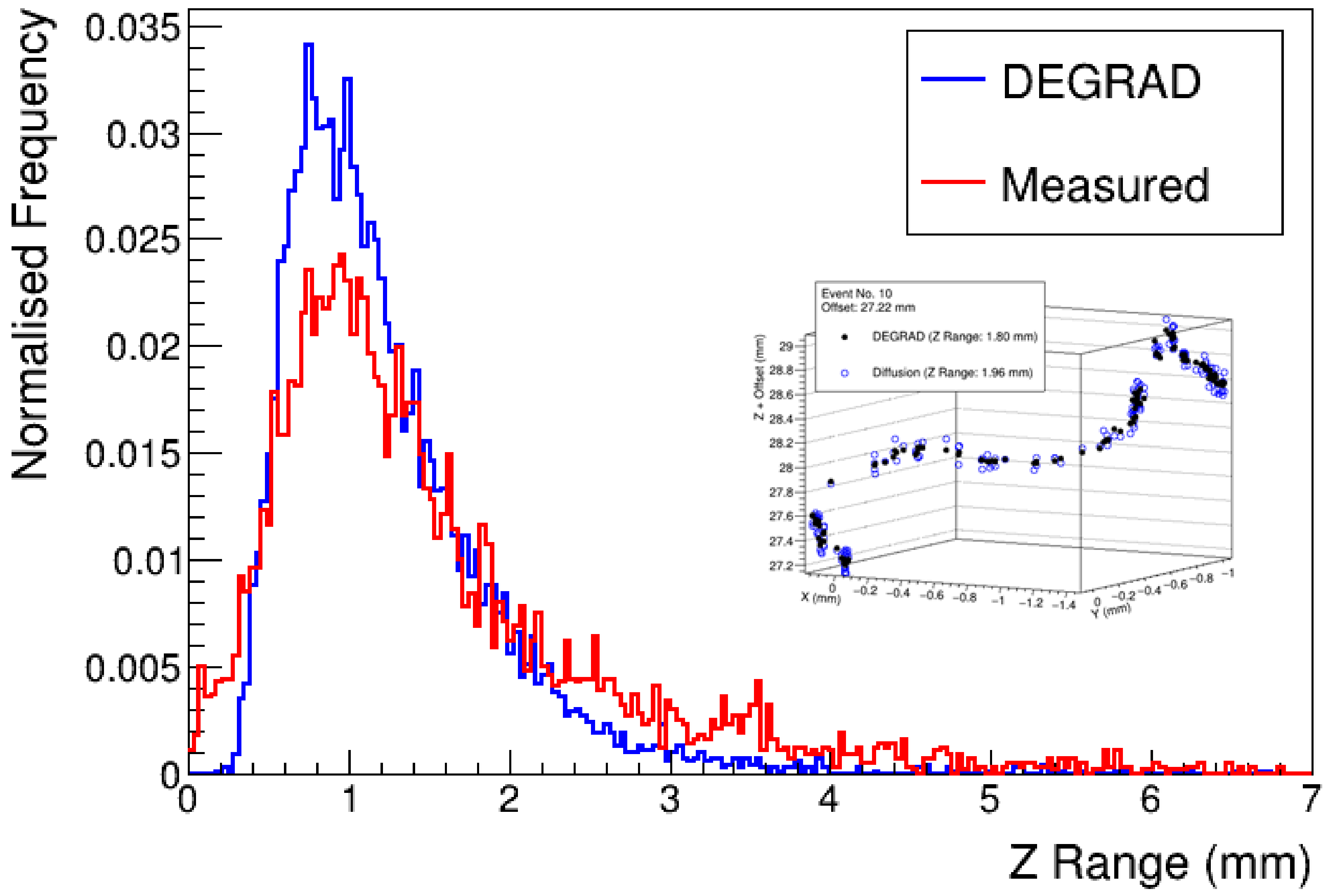
Charge arrives at electrode slower than the shaping time of electronics

THE UNIVERSITY of ADELAIDE

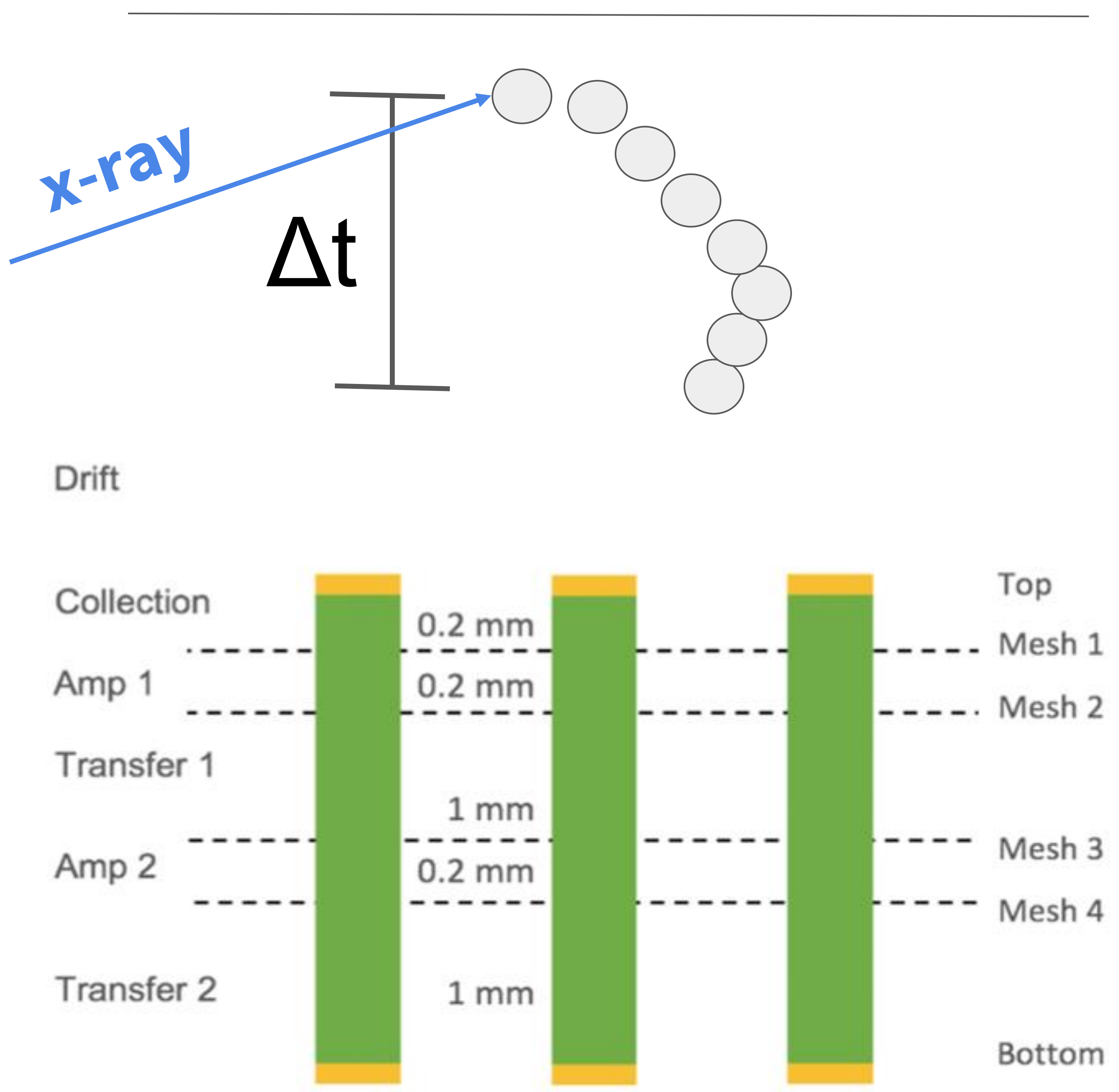
Difference in Preamp Rise Time



Rise Time (z-range calculations/simulations)

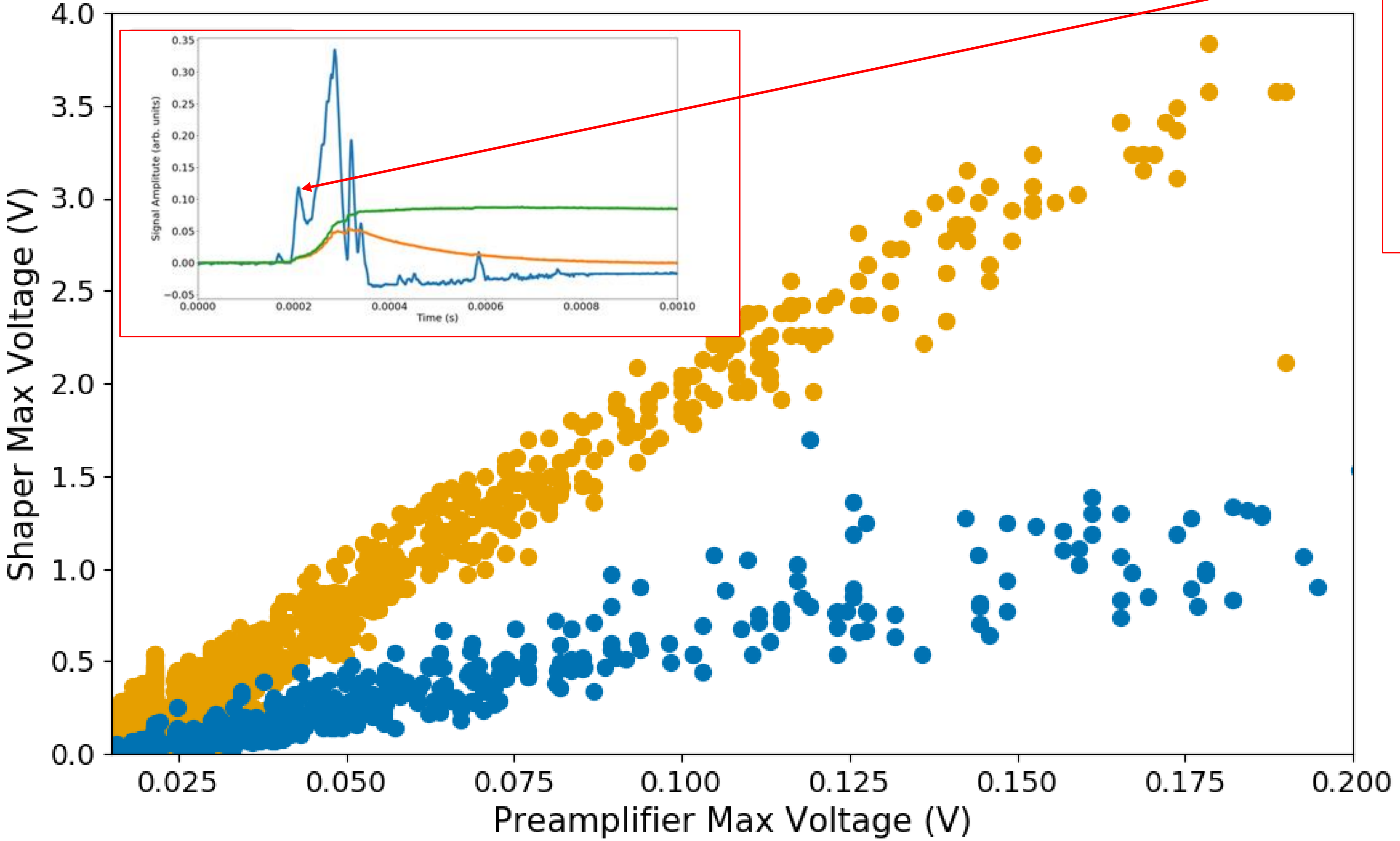


Simulations (adjusted for diffusion) agree with measured z-range



Δt = rise time of preamp (10-90%)

Electronic Gain - Max Voltage of Shaper Signal

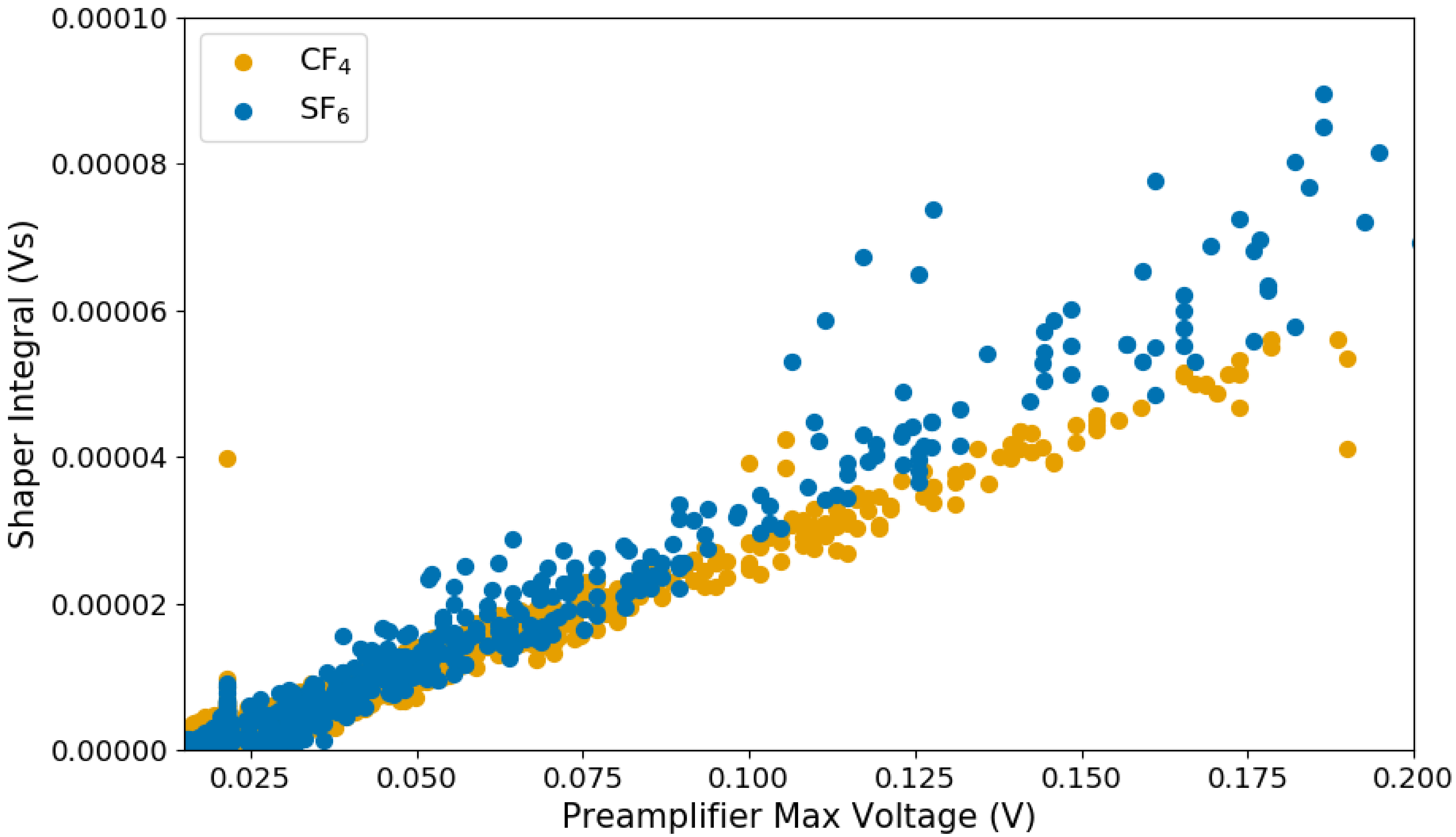


We see this here! The shaper begins integrating the signal before the preamp stops rising!

- The electronic gain (amplitude of shaper/amplitude of preamplifier) is not the same for both gasses.
- Smaller for SF_6 but still approximately linear.
- Gradient for CF_4 is 20.95 and 4.69 for SF_6.
- This is because the rise time is longer than the shaper time.

THE UNIVERSITY of ADELAIDE

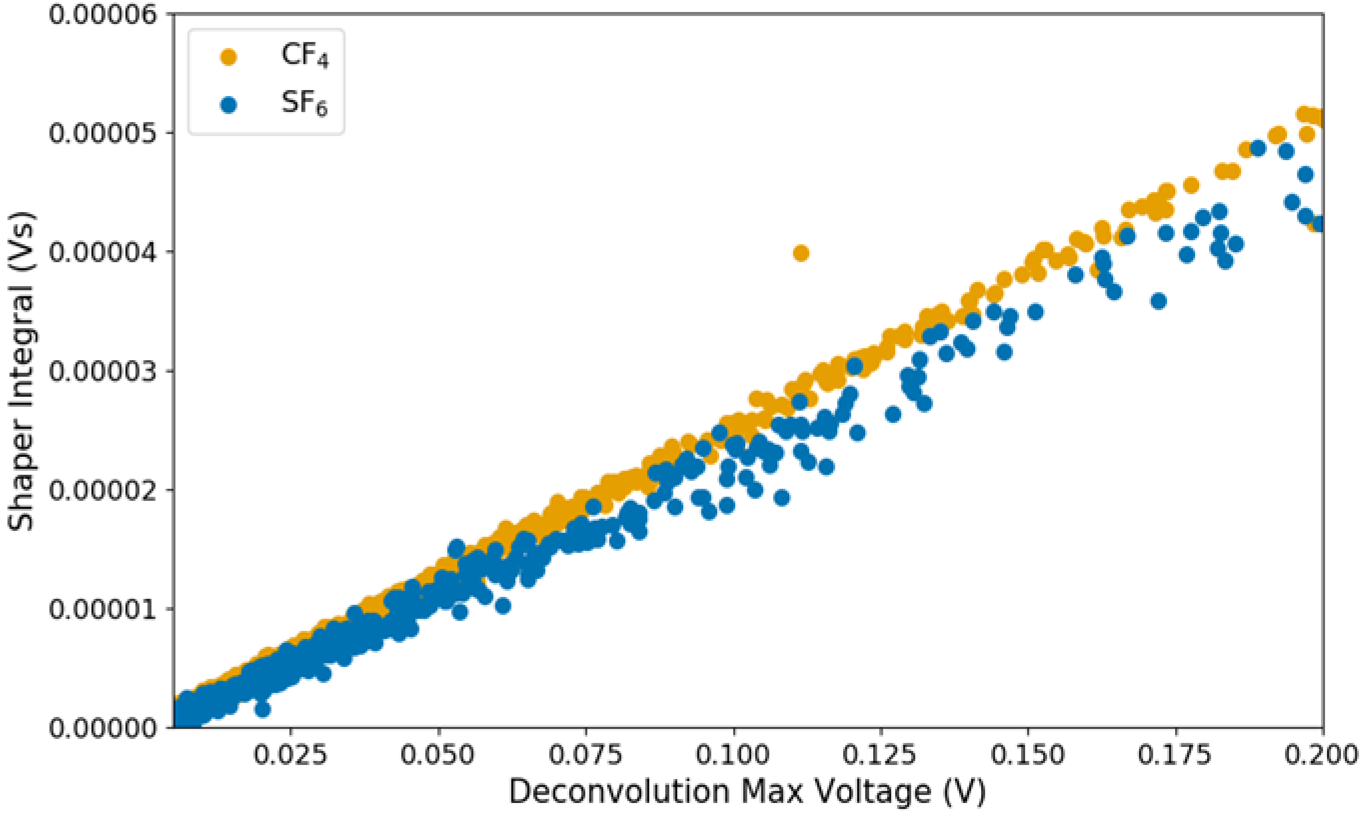
Electronic Gain - Integrated Shaper Signal



- Using the integral method - the electronic gain between the two gases is much more comparable
- Linear regression gives a gradient of 0.0003 s and 0.0004 s - much better agreement
- Still a bit of a discrepancy and larger spread at higher preamp voltages
- Likely an artifact of the decay time of the preamp

THE UNIVERSITY of ADELAIDE

Integrated Shaper Signal vs Preamp Deconvolution Signal



By accounting for the decay time of the preamplifier the agreement at larger preamp signals improves.

Gradient CF_4= 0.00025

Gradient SF_6 = 0.00023

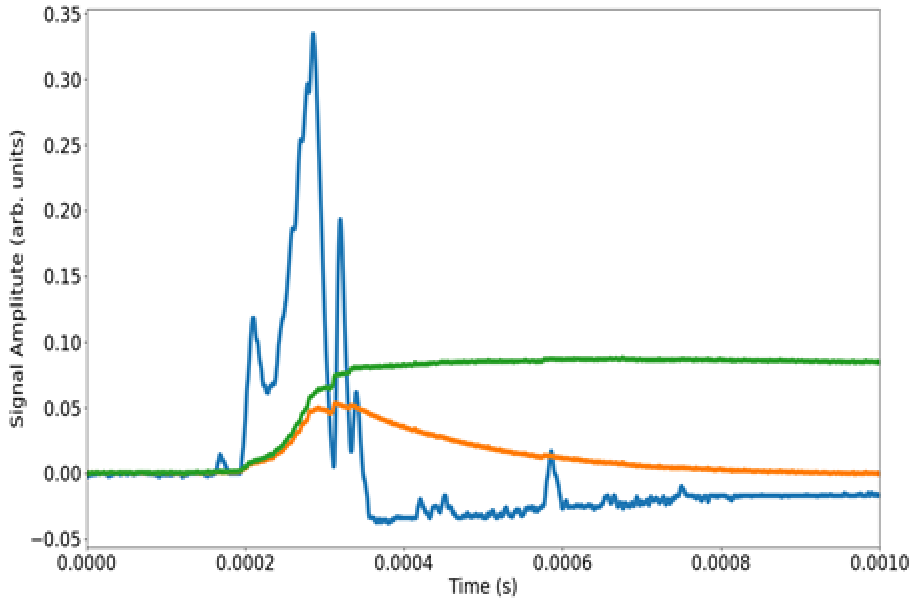
Deconvolution Algorithm

$$V_i^{rec} = \begin{cases} V_i^{av}, & i = 1, \\ V_{i-1}^{rec} + V_i^{av} - V_{i-1}^{av} \times \exp(-\Delta t/\tau), & i > 1. \end{cases}$$

https://arxiv.org/pdf/1508.04295.pdf

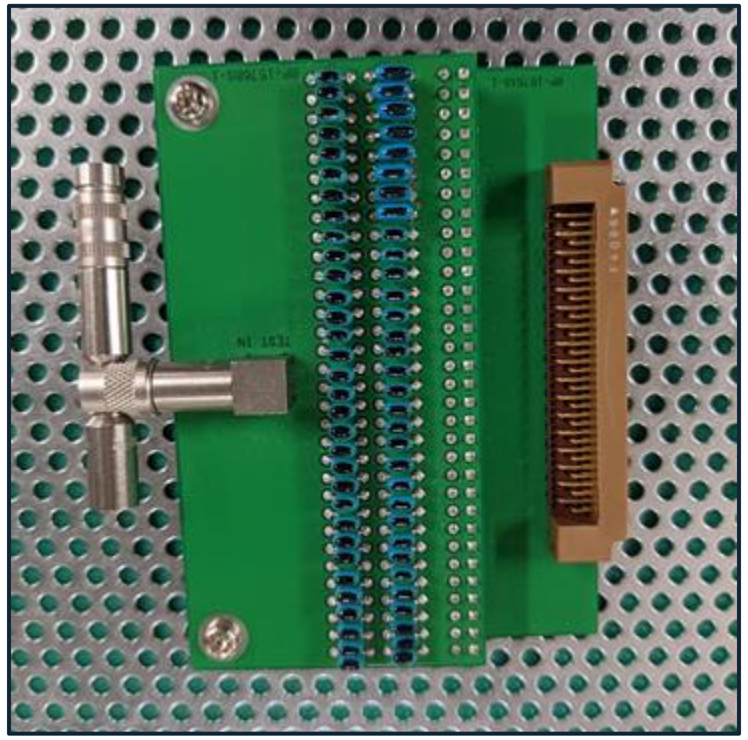
The deconvolution algorithm calculates cumulative charge from the preamp signal.

It essentially removes the losses due to the decay time of the preamp.



Charge Calibration

Charge calibration was performed by injecting charge into LTARS ASIC via 32 parallel test capacitors on a custom PCB

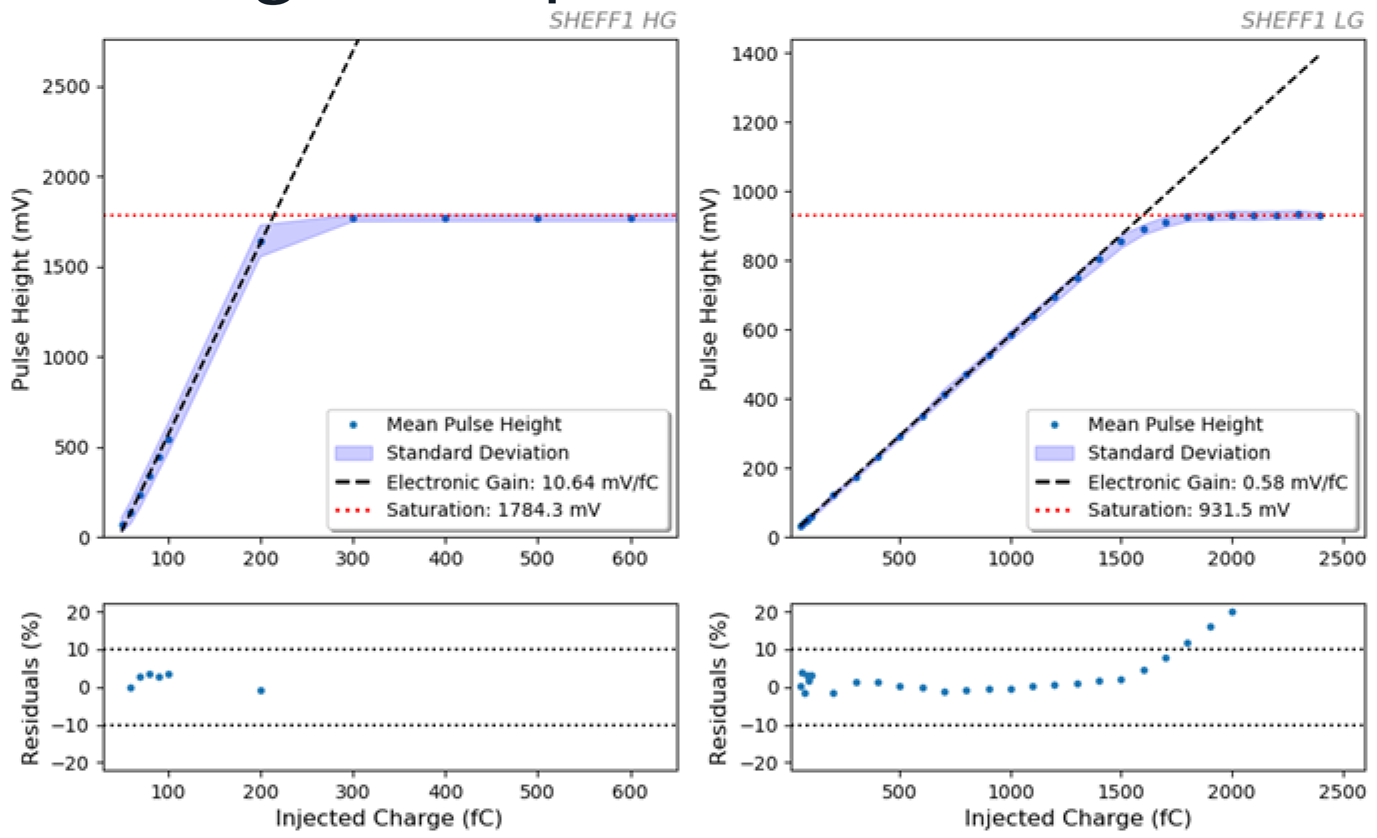


Two methods of charge calibration were employed:

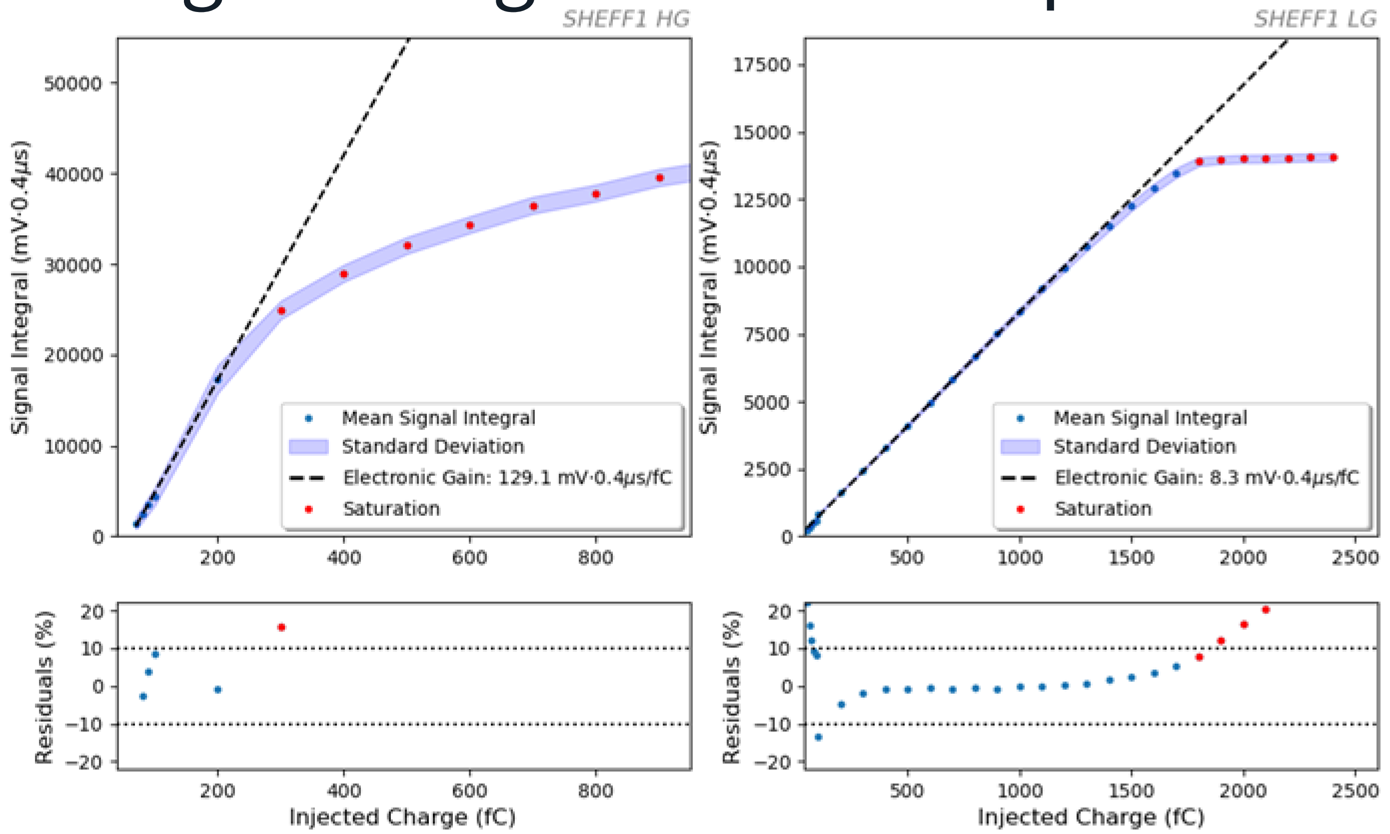
1. **Signal Amplitude** - standard

1. **Signal Integration** - used to compensate for slow arrival of negative ions

Signal Amplitude : standard…



Signal Integration: NI compensation

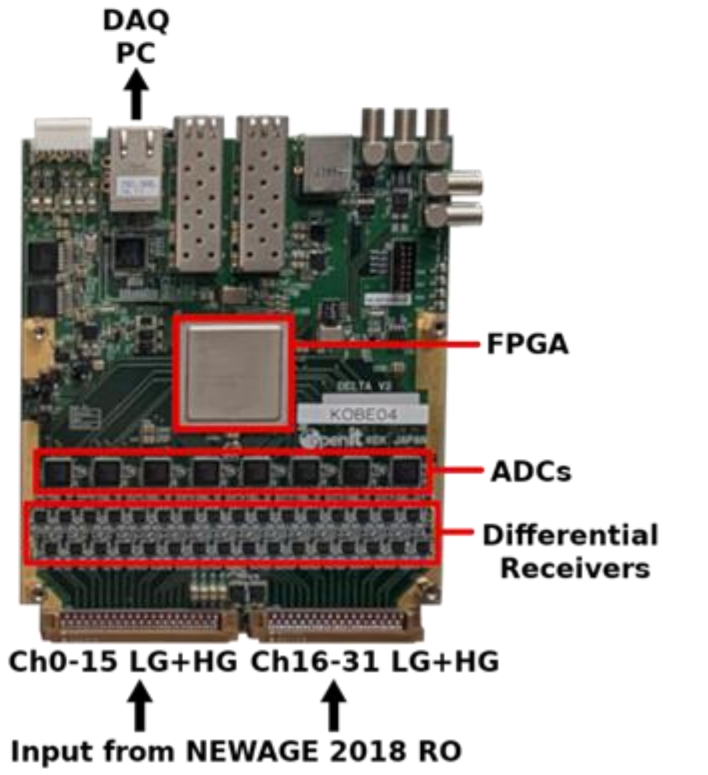


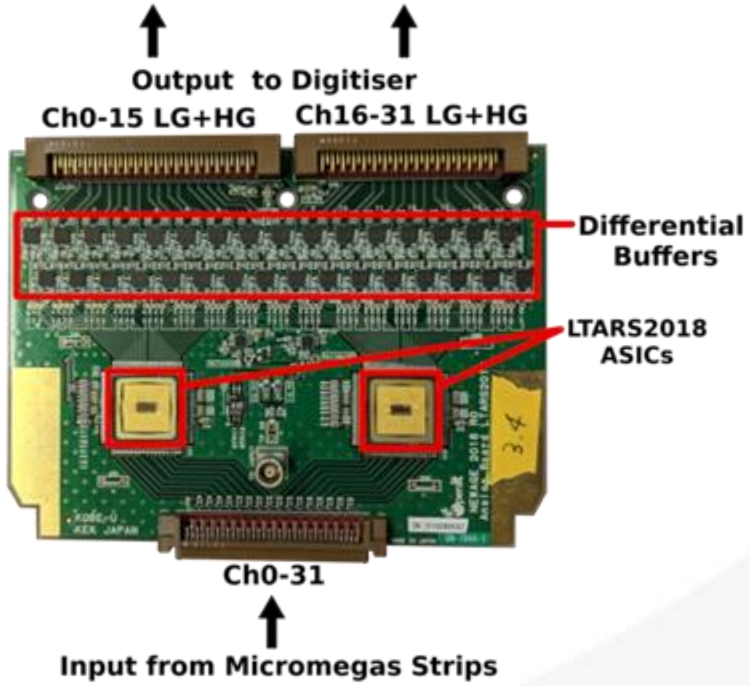
The Low Temperature Analog Readout System (LTARS) designed specifically for NID gases

LTARS2018 - “NEWAGE 2018 RO” Boards

- Designed by researchers at Kobe University and KEK
- LTARS2018 chips (x2) mounted on the NEWAGE 2018 RO board
- Board provides the charge sensitive readout electronics for 32 channels
- Each channel is split into low electronic gain and high electronic gain for large dynamic range

32 y-strips on the Micromegas were instrumented with LTARS2018 charge sensitive electronics…





Low gain and high gain channels provide large dynamic range