

# Fast neutron spectroscopy with a nitrogen based gaseous detector



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# Gas filled neutron detectors



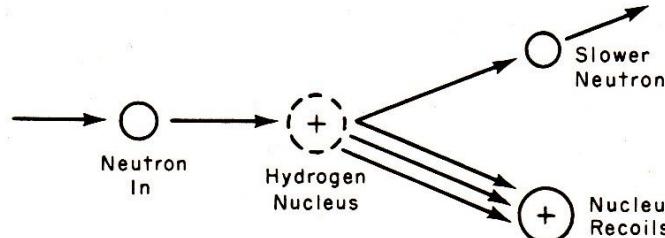
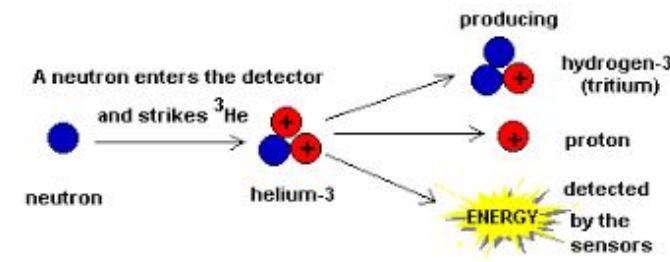
## Most popular technologies:

### Reaction type:

- $^3\text{He}$  proportional counter tubes
- $\text{BF}_3$  proportional counter tubes

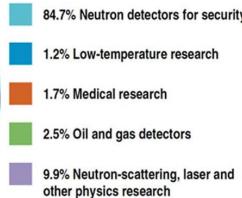
### Recoil type:

- Methane ( $\text{CH}_4$ )
- $^4\text{He}$



# Why another another neutron detector

Most popular technologies:



aapq explorer

Reaction type:

- $^3\text{He}$  proportional counter tubes
- $\text{BF}_3$  proportional counter tubes

Recoil type:

- Methane ( $\text{CH}_4$ )
- $^4\text{He}$

Light gases  
Partial energy deposition from recoils  
High-Low energy neutron information  
Methane flammable

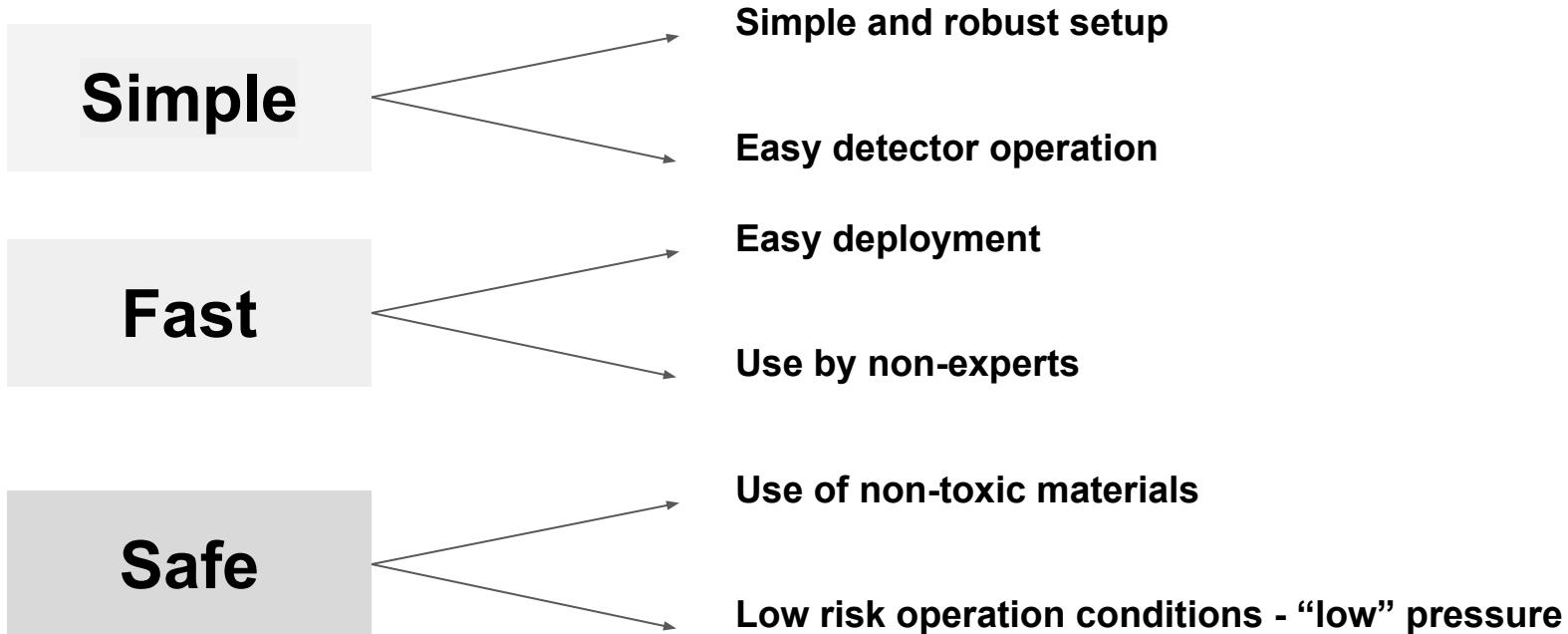
Worldwide shortage  
Extremely expensive

Low target mass  
Need second carrier gas to stop products

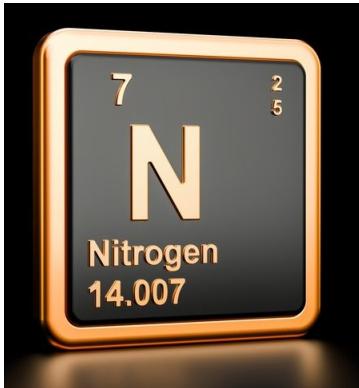
Small volume  
Moderated - Thermal neutrons  
Used as neutron counters

Highly toxic  
Not allowed in sensitive environments

# The goal - Simple, Fast, Safe



# The idea: Large volume spherical detector with nitrogen

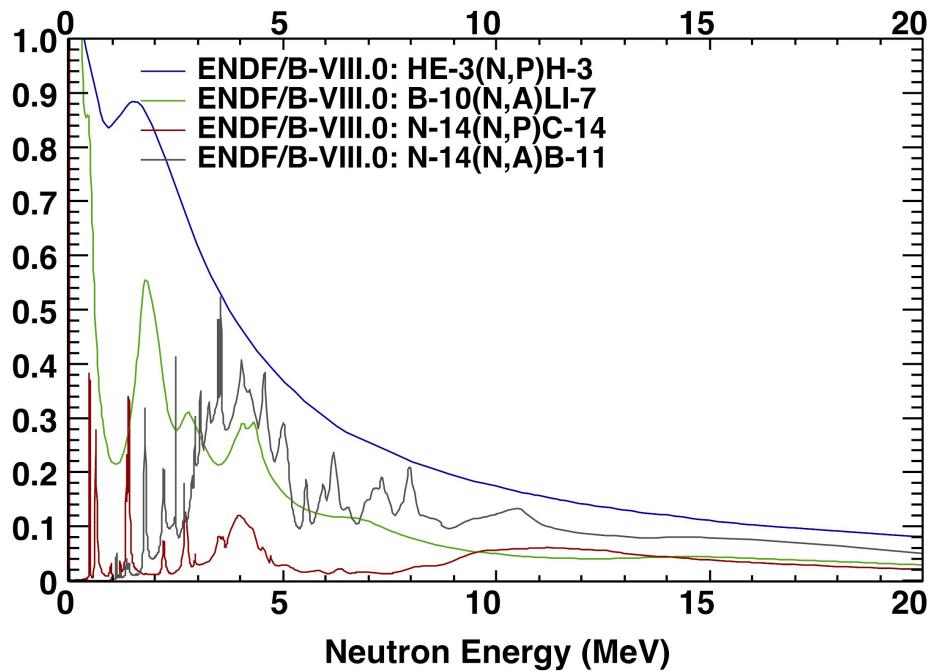


+



- Operational pressure (3 bar)
- Large volume ( $0.1 \text{ m}^3 - 1 \text{ m}^3$ )
- Low  $\gamma$ -ray efficiency
- Higher stopping power than He
- Inert gas - safe - not toxic
- Operation in sensitive environments
- Cost efficient
- Operation without moderation
- Measurement of neutron energy

# Neutron absorption cross sections



Common targets:

$^3\text{He} + \text{n} \rightarrow ^3\text{H} + \text{p} + 765 \text{ keV}, \sigma_{\text{th}} = 5330 \text{ b}$

$^{10}\text{B} + \text{n} \rightarrow ^7\text{Li}^* + ^4\text{He} + 2310 \text{ keV}, \sigma_{\text{th}} = 3840 \text{ b}$   
 $(^7\text{Li}^* \rightarrow ^7\text{Li} + 480 \text{ keV})$

Nitrogen as target:

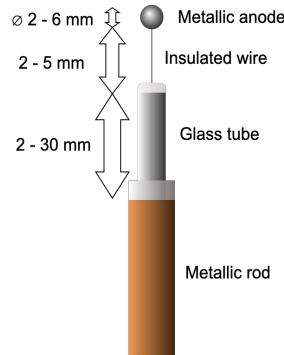
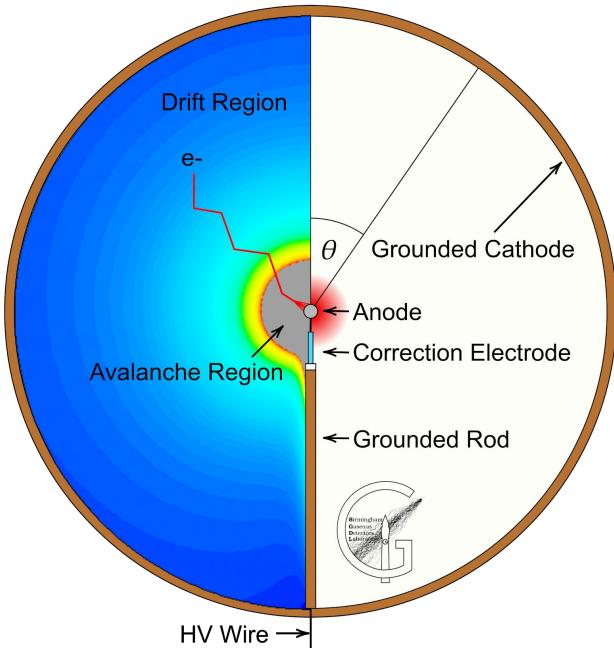
$^{14}\text{N} + \text{n} \rightarrow ^{14}\text{C} + \text{p} + 625 \text{ keV}, \sigma_{\text{th}} = 1.83 \text{ b}$

$^{14}\text{N} + \text{n} \rightarrow ^{11}\text{B} + \alpha - 159 \text{ keV}$

# The Spherical Proportional Counter (SPC)

[I.Giomataris et al, JINST, 2008, P09007](#)

[I.Katsioulas et al, JINST, 13, 2018, no.11, P11006](#)



## Electric field

**Strong dependence on the radial dependence**

$$E(r) = \frac{V_0}{r^2} \frac{r_A r_C}{r_C - r_A} \approx \frac{V_0}{r^2} r_A$$

$r_A$  = anode radius  
 $r_C$  = cathode radius

$$C = 4\pi\epsilon_0 \frac{r_c r_a}{r_c - r_a} \approx 4\pi\epsilon_0 r_a \sim 1\text{pF}$$

Detector volume naturally divided in:

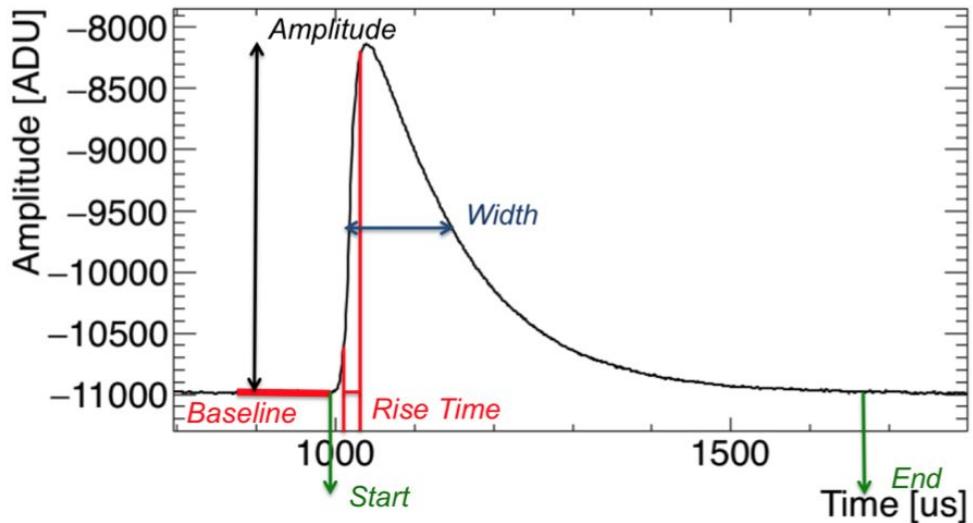
- Drift region
- Amplification region

- Simple design
- Single readout

# Induced Pulses

## Pulse Shape Analysis (PSA) parameters

### Typical SPC Pulse



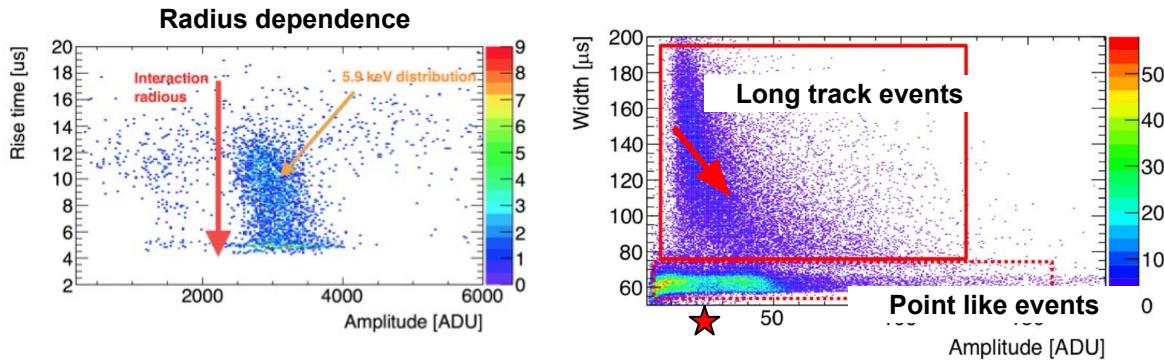
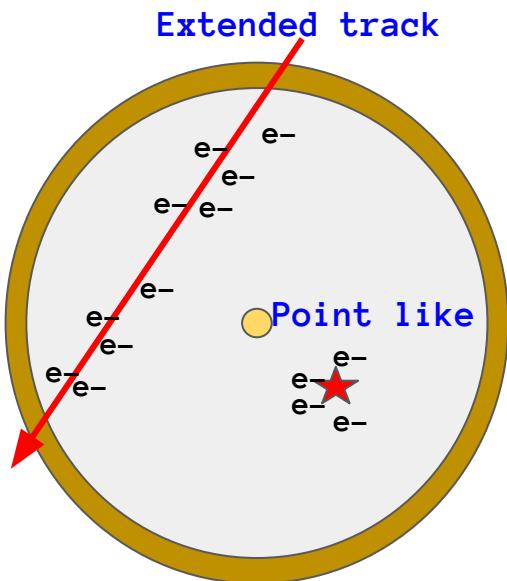
Rise time & Width ~ Drift time dispersion

### Basic Parameters

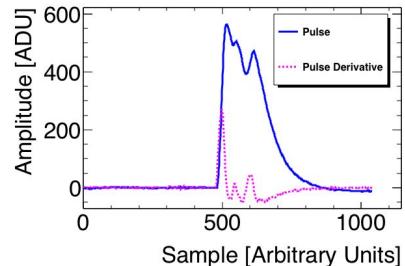
- Baseline
- Noise
- Amplitude (Pulse Height)
- Rise time
- Width
- Integral
- Number of peaks

A lot of information  
in the pulse shape

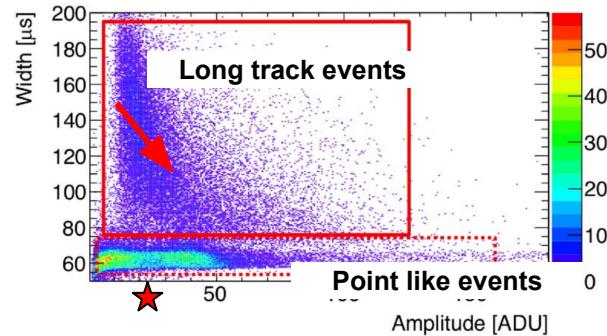
# Event discrimination



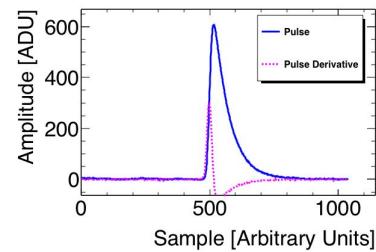
Muon pulse



Amplitude = 575 ADU  
Width (FWHM) = 155.5  $\mu$ s  
Rise time = 18.2  $\mu$ s



${}^+\text{Ar}$  pulse



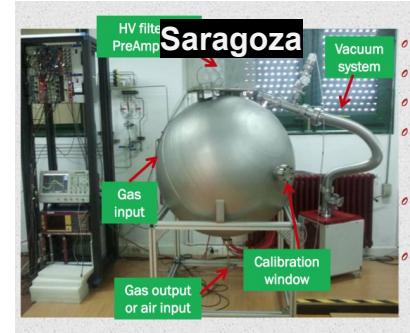
Amplitude = 606 ADU  
Width (FWHM) = 63.4  $\mu$ s  
Rise time = 16.3  $\mu$ s

# SPC features

## Detector features

- Size  $\varnothing$ : 5, 15, 30, 60, 140 cm
- Sphere: Steel, Copper, Aluminium, Glass, Plexiglass
- Sensor size  $\varnothing$ : 0.5 – 14 mm
- Low capacitance - low noise
- Gas: Xe, Ar, Ne, He,  $\text{CH}_4$ ,  $\text{N}_2$
- High voltage on sensor
- Large gain operation: Single  $e^-$  threshold
- Low gain operation
- High pressure operation
- Low pressure operation - (Low P TPC)
- Used for  $n$ ,  $\gamma$ ,  $p$ , ions
- Applications: from  $\gamma$ -spectroscopy to DM!

I. Giomataris and G. Charpak  
in CEA Saclay



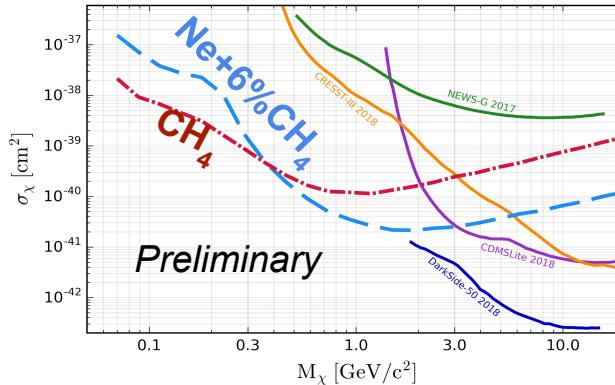
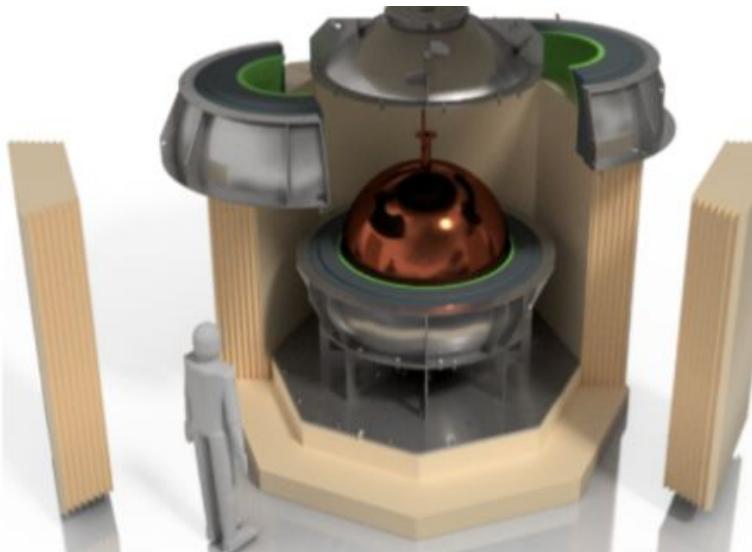
A. McDonald at Queen's



CEA Saclay

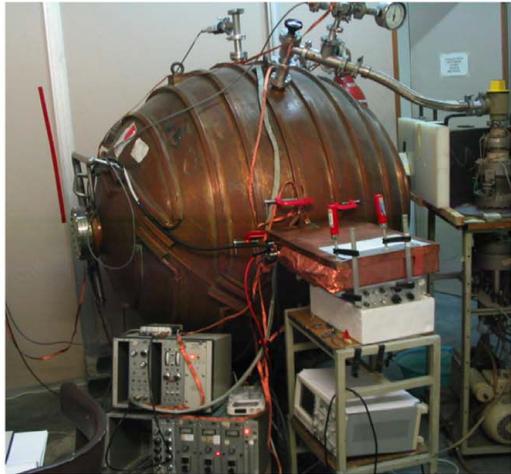
# SPC's most notable application: NEWS-G Light Dark Matter searches with an SPC

Exploring the DM mass range below 0.1 GeV - 10 GeV

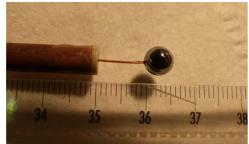


# Neutron detection with SPC

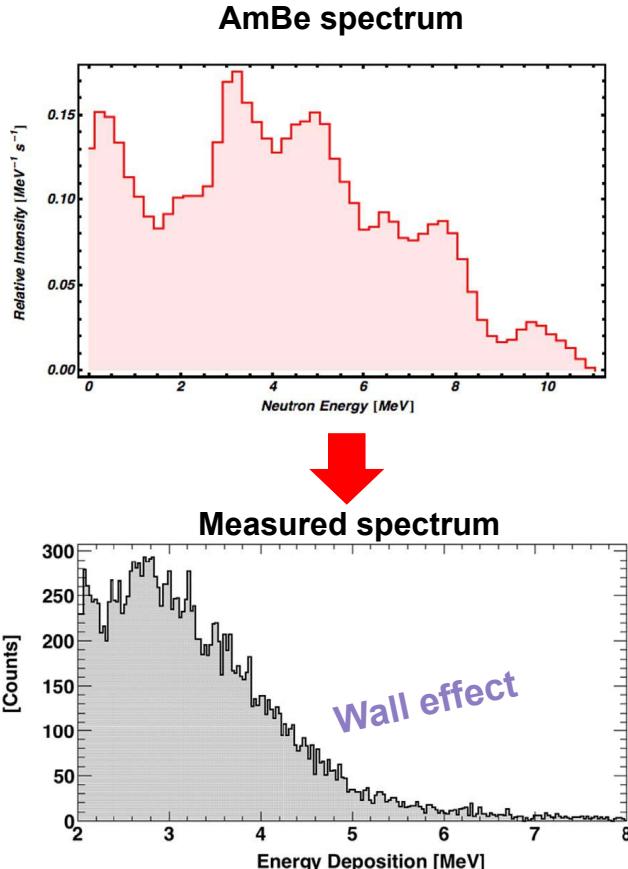
## Proof of principle



140 cm  $\varnothing$  vessel  
N<sub>2</sub> at 200 mbar  
8 mm  $\varnothing$  anode



Bougamont, E et al (2017). NIM A, 847, 10–1



### First results:

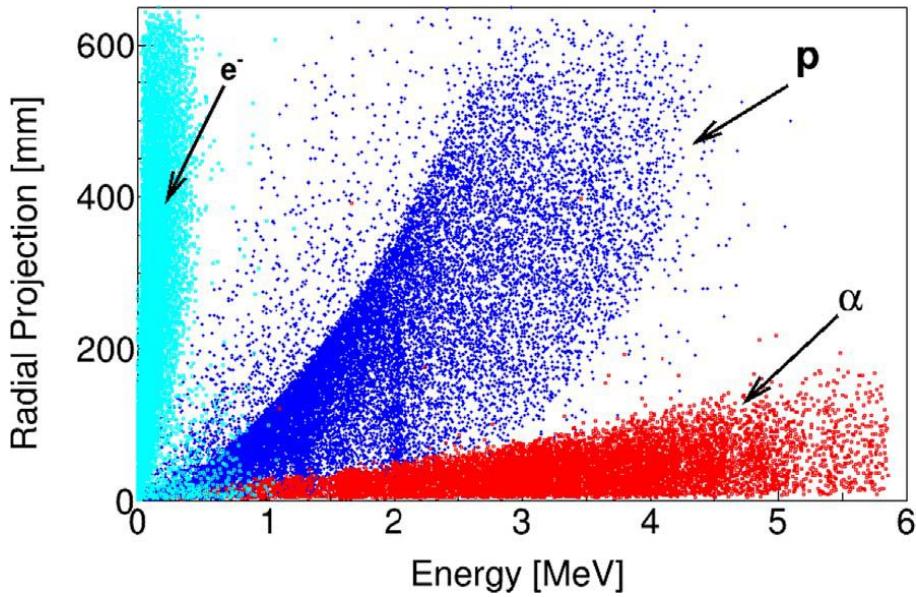
- Measured  $^{252}\text{Cf}$ ,  $^{241}\text{Am}^9\text{Be}$  and ambient fast neutron spectra
- Measurement of thermal neutrons
- Operation at 0.2–0.5 bar
- HV reached 6 kV

### Limiting factors then:

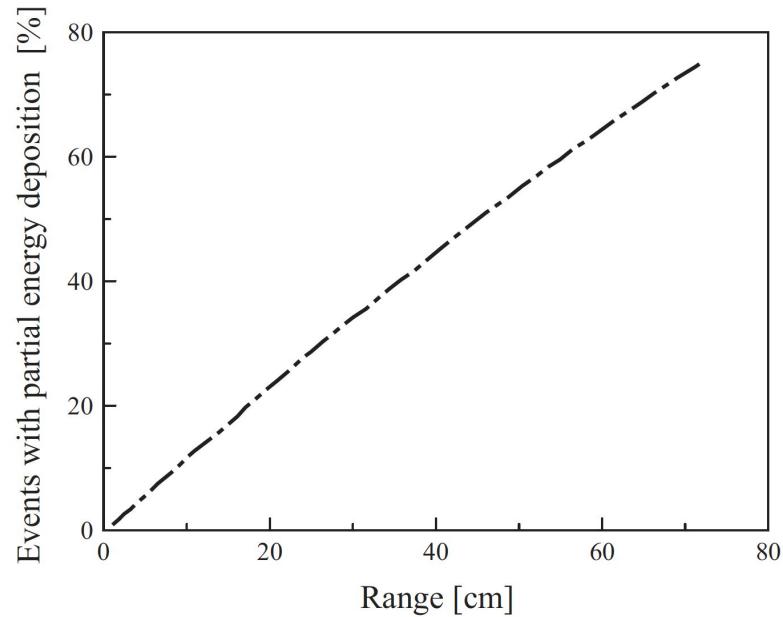
- Wall effect
- Low pressure
- Sparking - Instability
- Impurities
- Charge collection inefficiency

# Range versus Energy and Wall Effect

Range vs Energy for  $\alpha$ , p and e- in 400 mbar N<sub>2</sub>



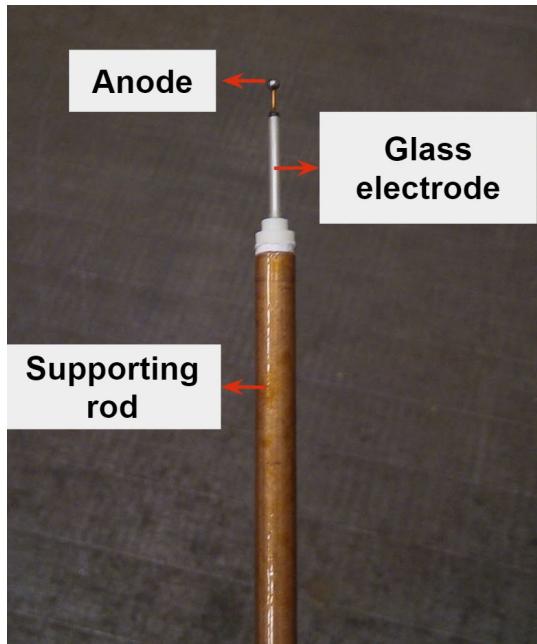
Wall effect vs Range (S130cm)



Bougamont, E et al (2017). NIM A, 847, 10–1, <https://doi.org/10.1016/j.nima.2016.11.007>

# Recent developments for the SPC

Resistive sensors



Multi-anode  
sensors



Gas purification techniques



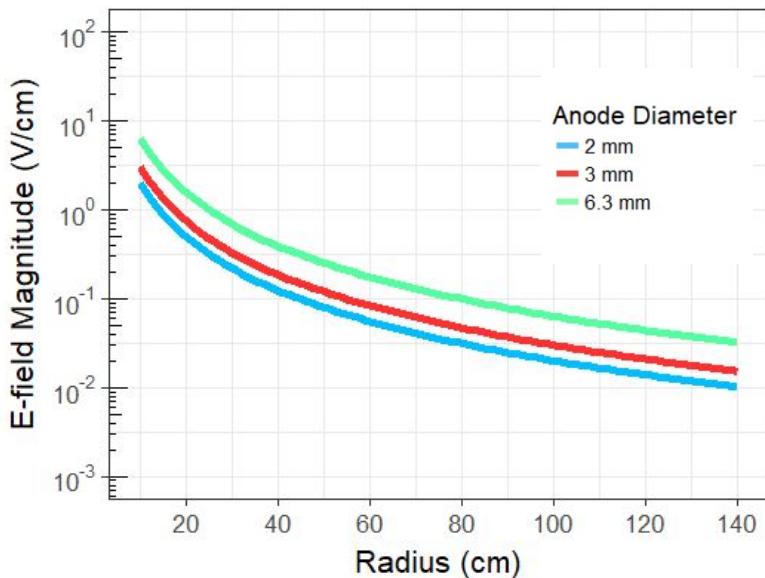
I. Katsioulas et al. JINST, 13, 11, P11006, 2018  
[10.1088/1748-0221/13/11/P11006](https://doi.org/10.1088/1748-0221/13/11/P11006)

Giganon, A. et al. 2017. "A Multiball Read-out for the Spherical Proportional Counter.", JINST

Ioannis Katsioulas | [i.katsioulas@bham.ac.uk](mailto:i.katsioulas@bham.ac.uk) | ICHEP 2020

# Electric field strength in SPC volume

Comparison of E-field magnitude  
for different anode diameters

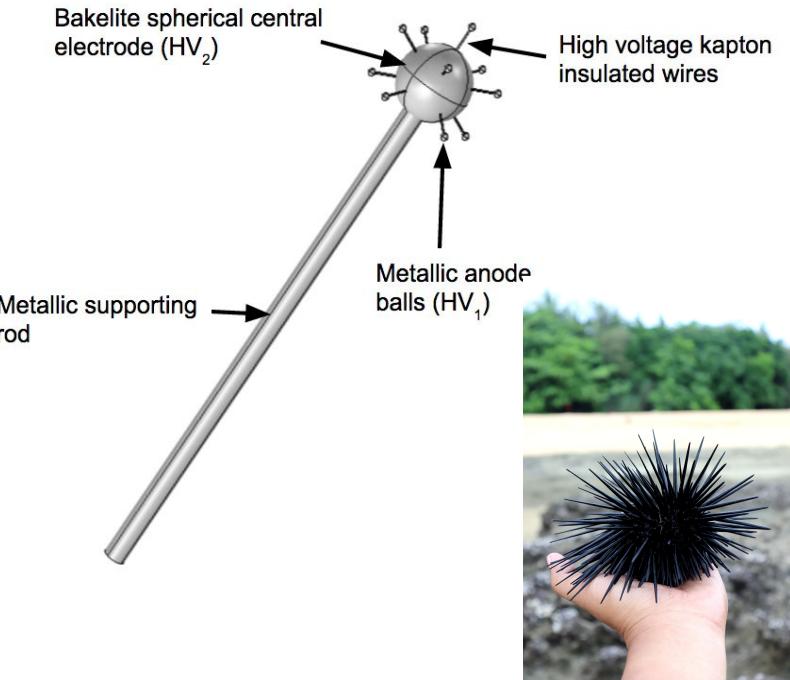


$$E(r) = \frac{V_0}{r^2} r_1 \rightarrow \text{Anode radius}$$

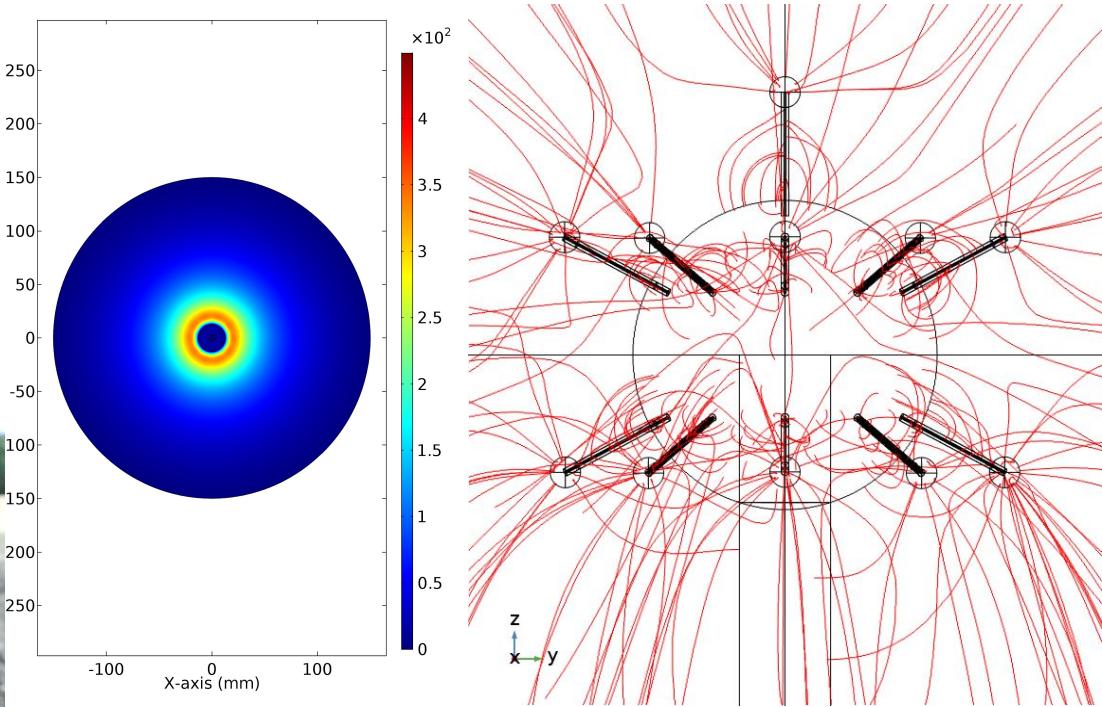
Gain and drift velocity  
dependence on E/P

$$\ln(M) = \int_{E(r_1)}^{E(r_2)} a(E/P) \frac{dr}{dE} dE$$
$$v_{\text{drift}} = \mu \frac{E}{P}$$

# The multi-anode sensor - ACHINOS



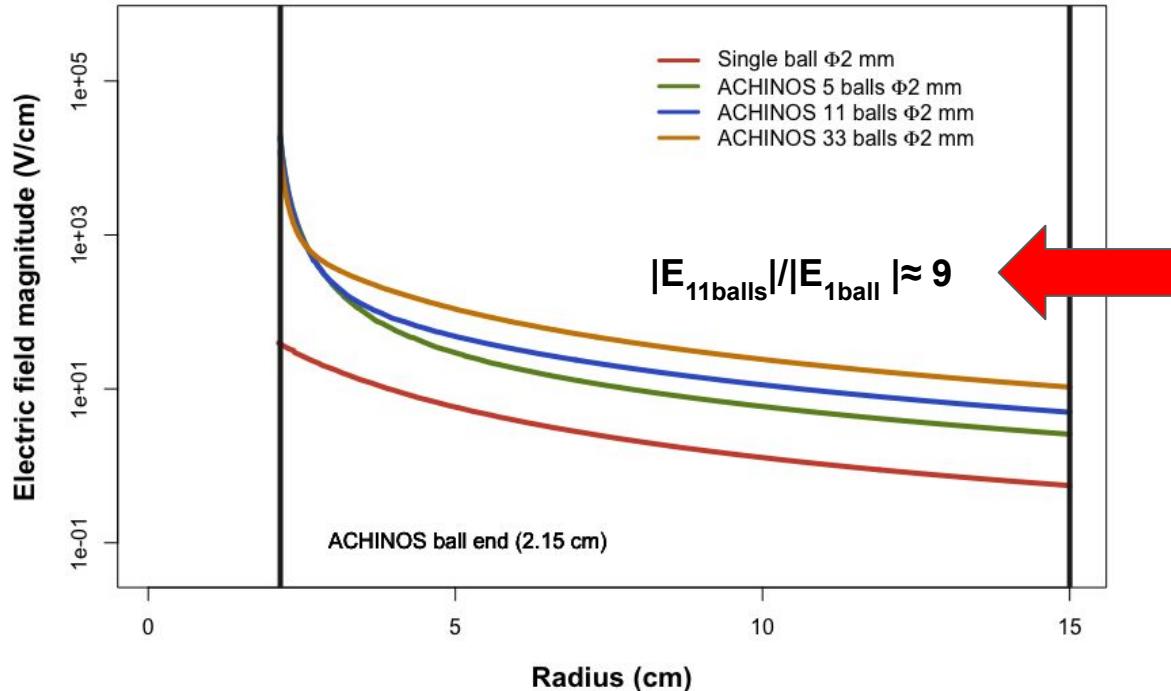
Collective iso-potentials   Electric field lines near the anodes



# Electric field magnitude with ACHINOS

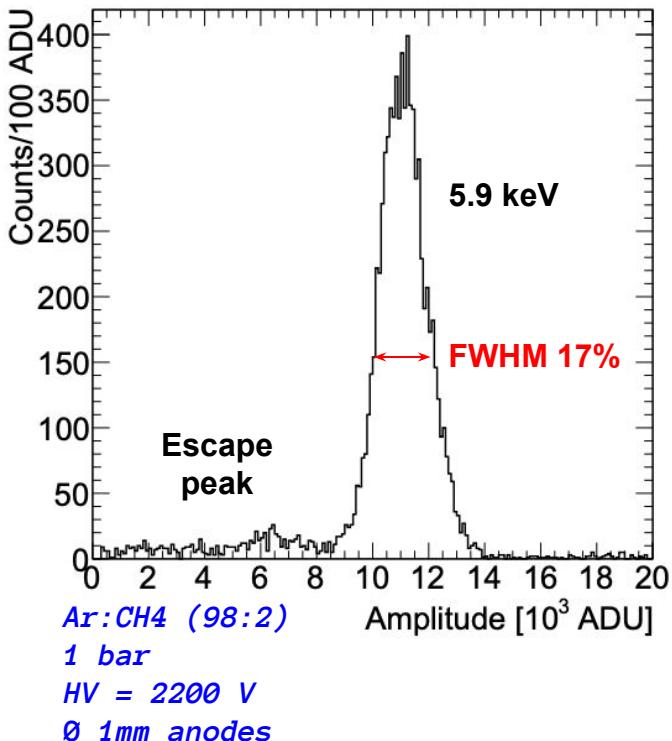
## Advantages

1. Amplification tuned by the anode ball size
2. Volume electric field tuned by the size and number of anodes of the ACHINOS structure
3. Individual readout TPC-like capabilities to the SPC

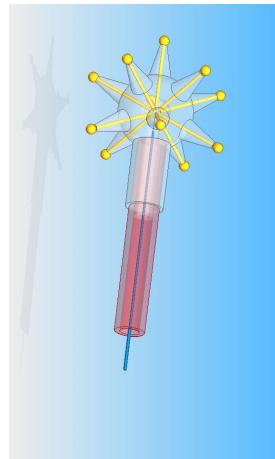


# ACHINOS features

## Measurement of the 5.9 keV $^{55}\text{Fe}$ X-ray line



3D design



Implemented module using 3D printing



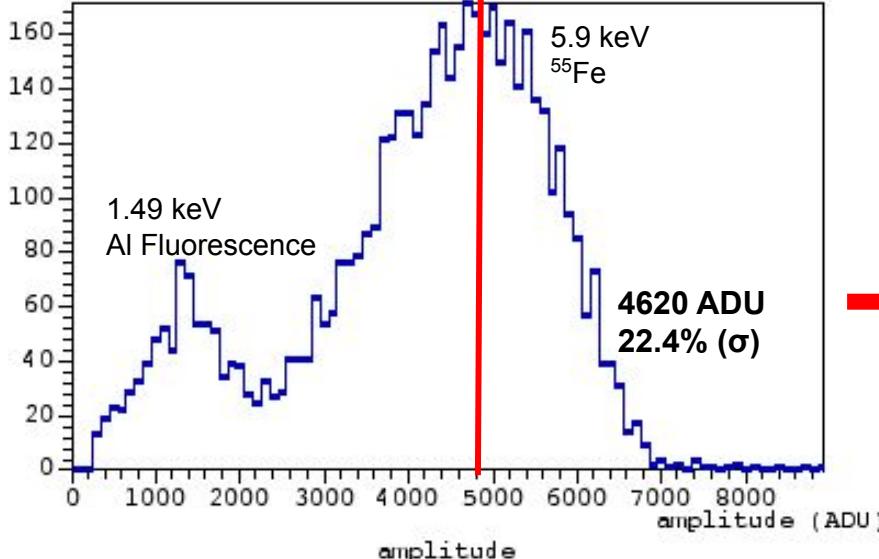
- Good energy resolution
- High pressure operation ( $\sim 2$  bar)
- High gain
- Stability
- 2 channel readout

# Gas purification



- Contaminants:  $O_2$ ,  $H_2O$ , electronegative gases
- Filtering with:
  - Getter
  - Purpose made filter
- Filtering in a gas recirculation system is planned

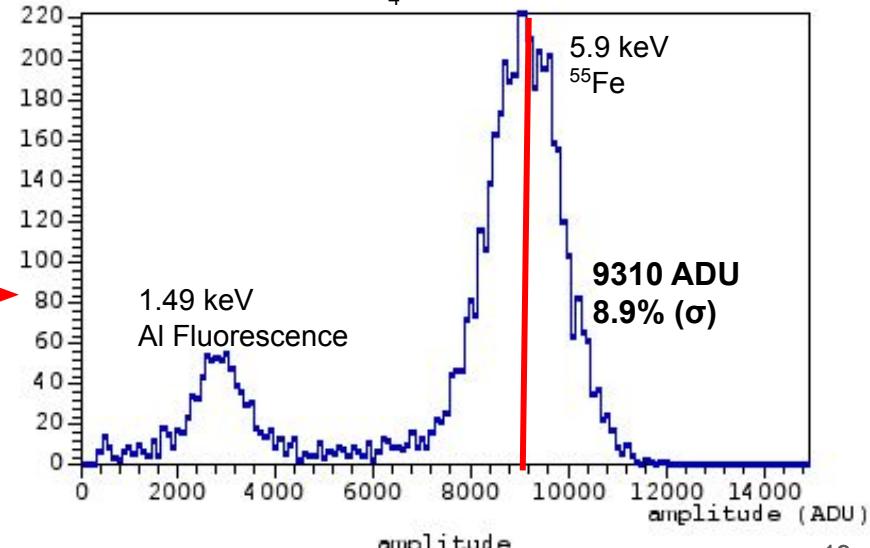
600 mbar He+10%  $CH_4$  without contaminant filtering



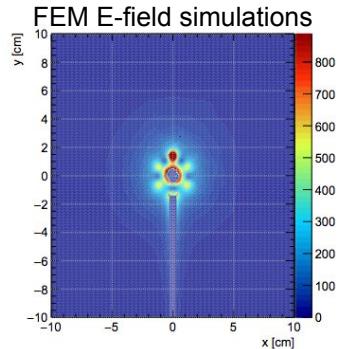
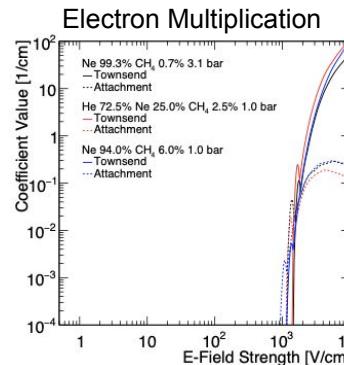
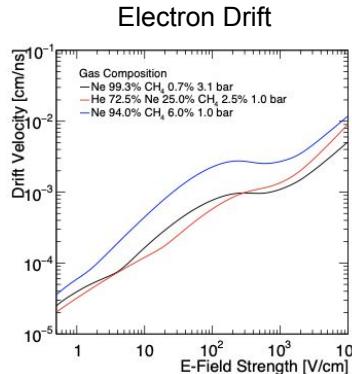
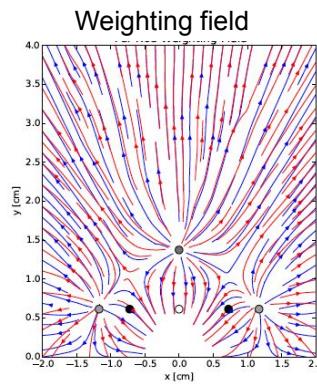
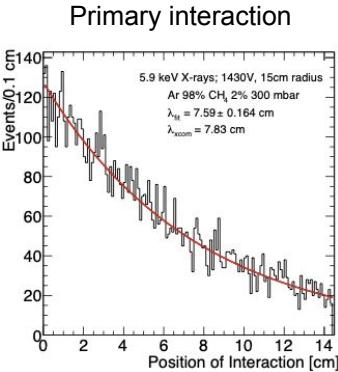
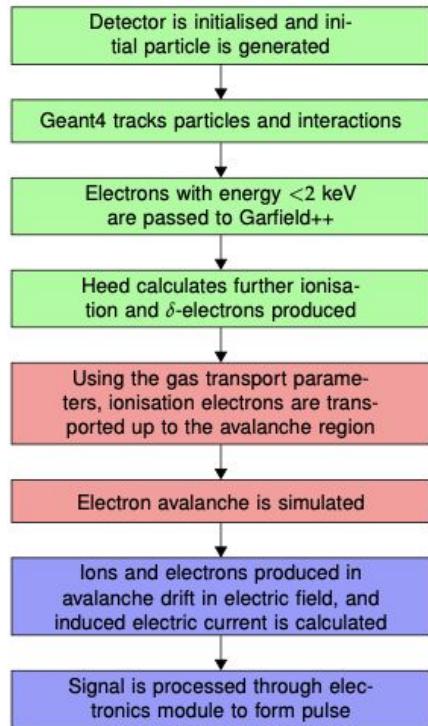
Using  
Oxisorb



600 mbar He+10%  $CH_4$  with contaminant filtering

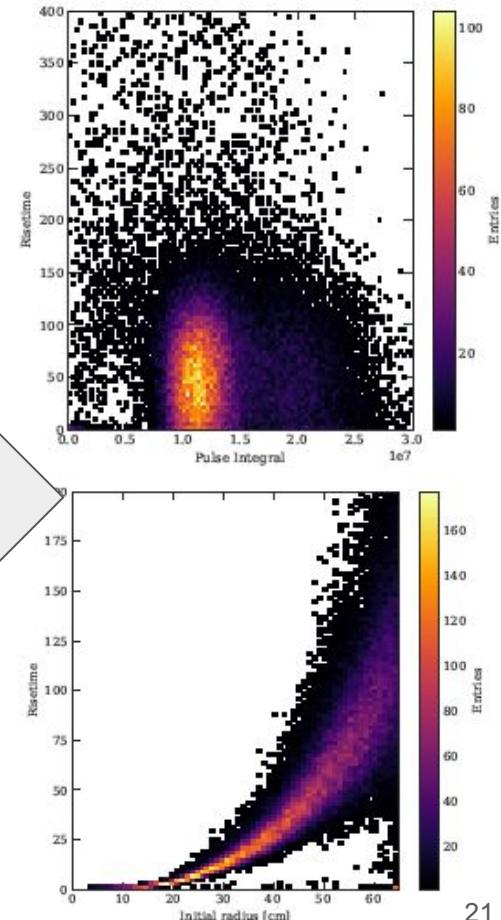
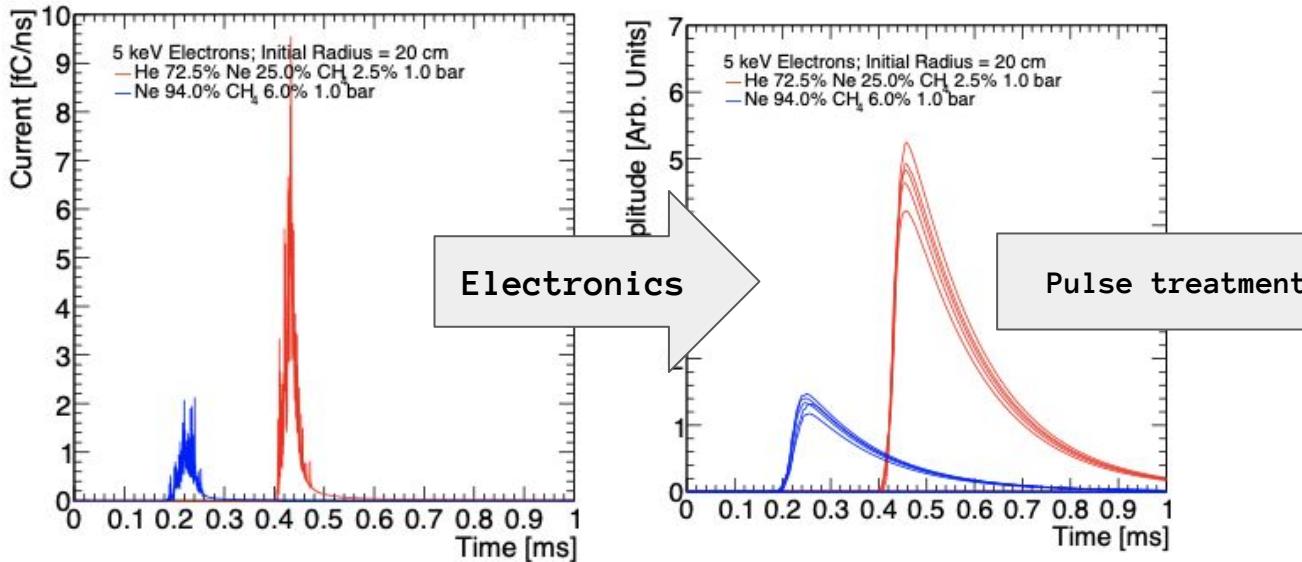


# Simulating the detector response



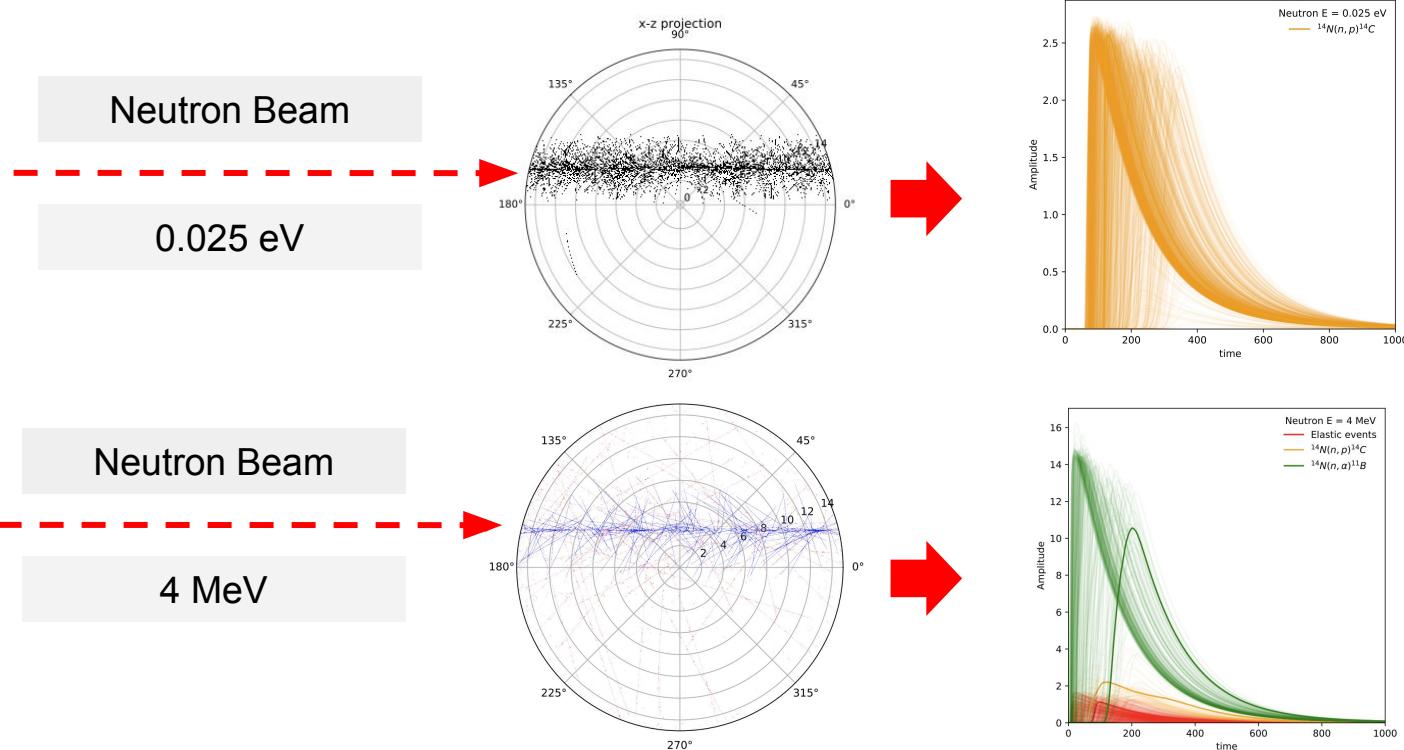
[Katsioulas, I. et al., 2017.](#)  
["Development of a Simulation Framework for Spherical Proportional Counters", arXiv:2002.02718](#)

# Simulating the detector response



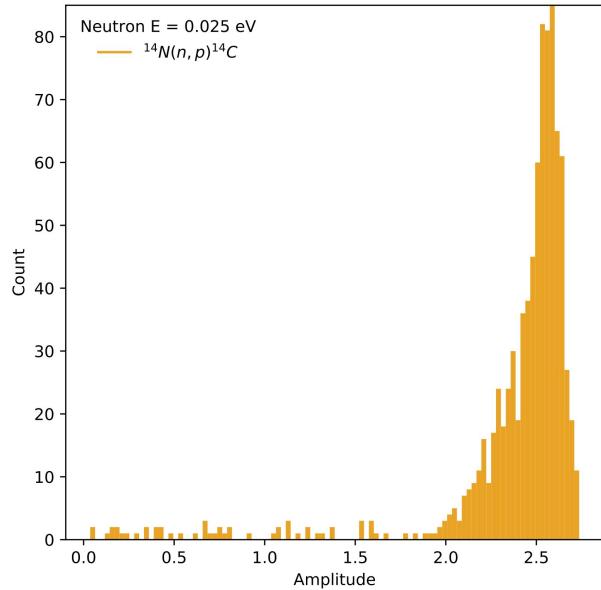
# Simulation of neutron transport

Simulation Parameters:  
ø vessel 30 cm  
Nitrogen at 300 mbar  
Anode Ø 2 mm

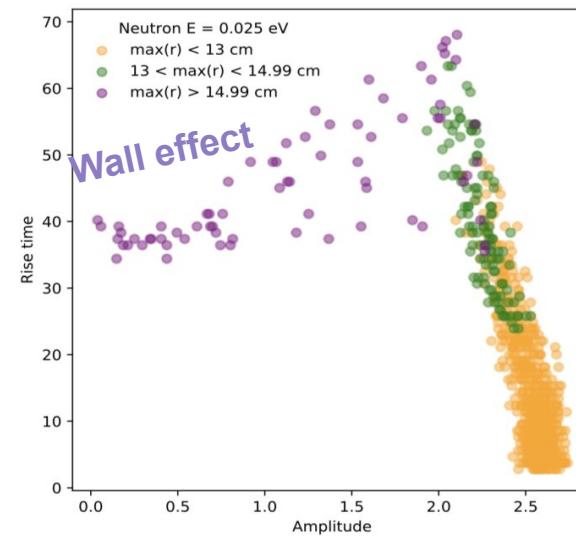


# Thermal neutron simulation

Simulated pulse amplitude distribution

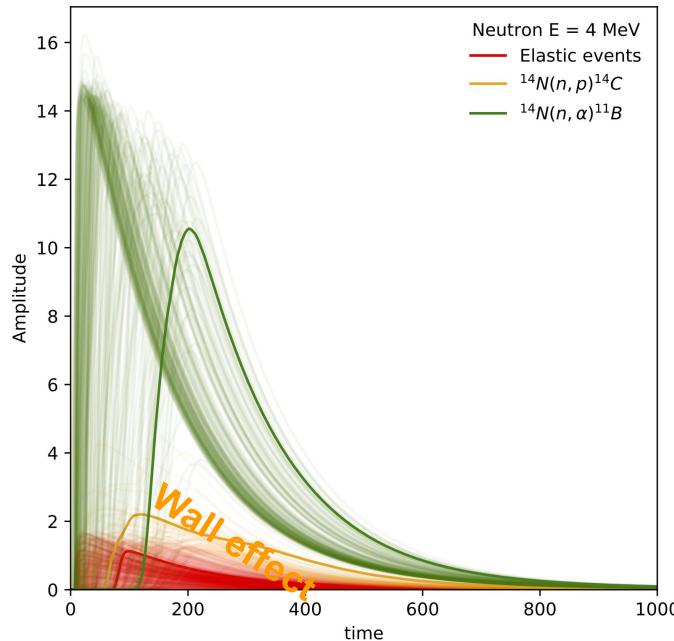


Simulated risetime vs amplitude distribution

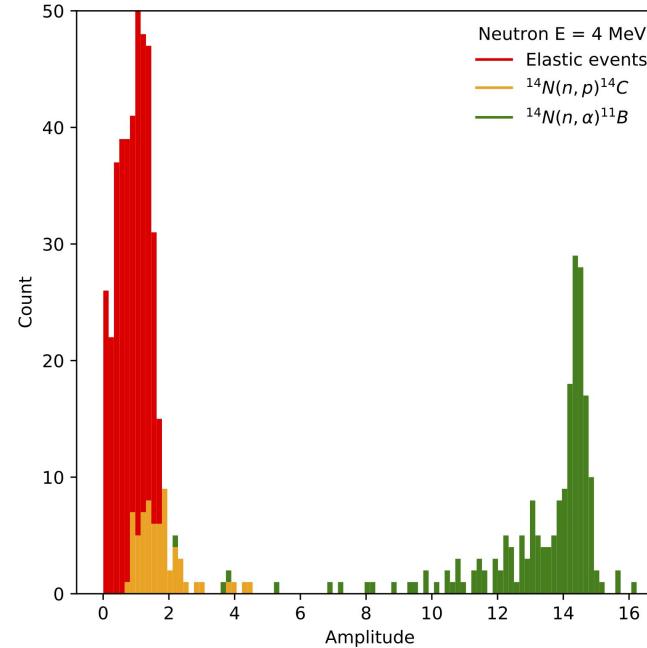


# Simulation of fast neutrons (4 MeV)

Simulated pulses

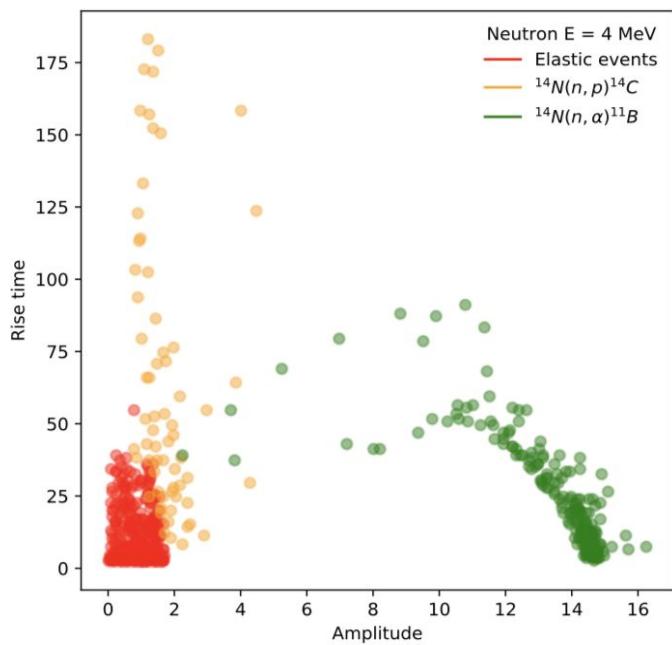


Simulated amplitude distribution

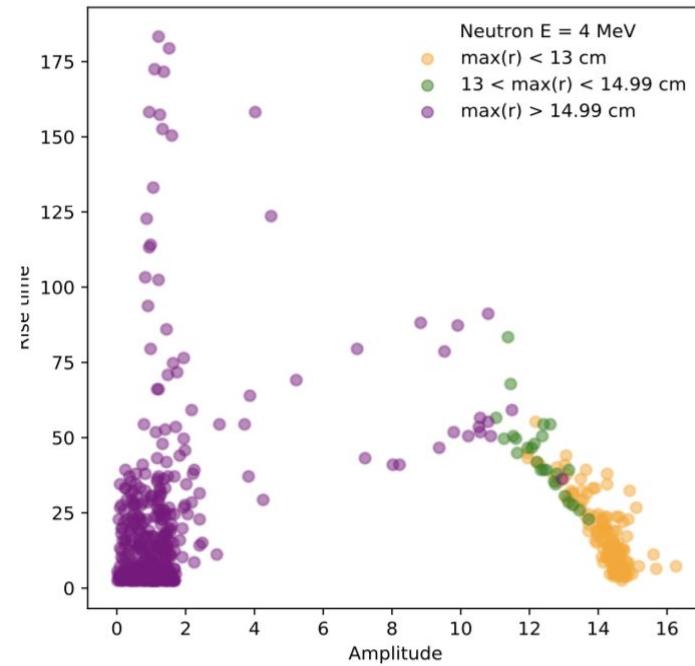


# Understanding the detector response

Simulated rise time vs amplitude distribution  
Reaction type



Simulated rise time vs amplitude distribution  
Radial extent of ionisation



# R&D at Birmingham

Calibration with a triple alpha source



Glass sensor

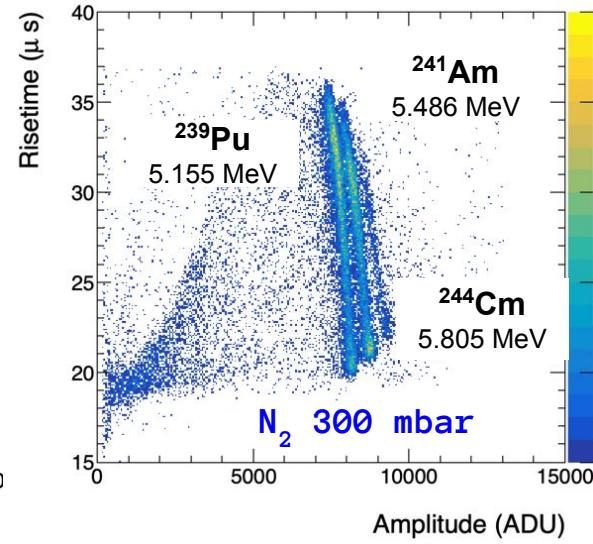
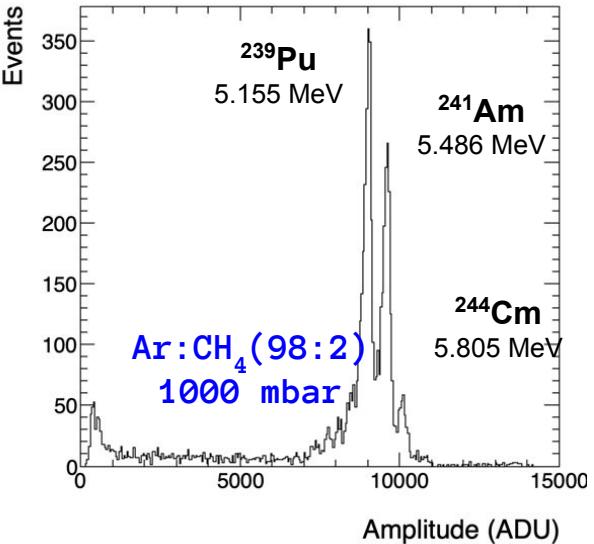


## Setup at UoB

∅ vessel 30 cm

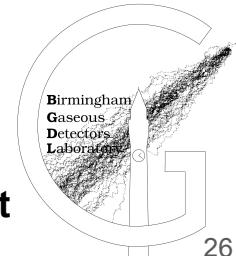
Anode ∅ 3 mm

Saes MicroTorr Purifier



## Planning:

- Operation at 1 - 2 bar
  - Minimisation of wall effect
  - Larger target mass
- Calibration with mono-energetic neutrons
- Validation of simulations with measurement



# Instrumentation in UoB for neutron measurements

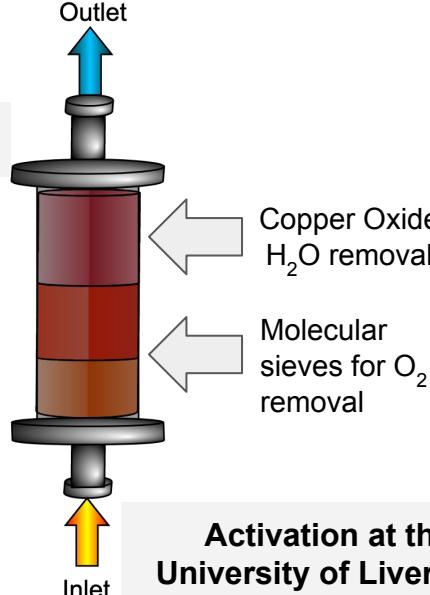
## ACHINOS - Achievements

- Fully coated with DLC
- Improved accuracy on anode placement
- Improved spacing



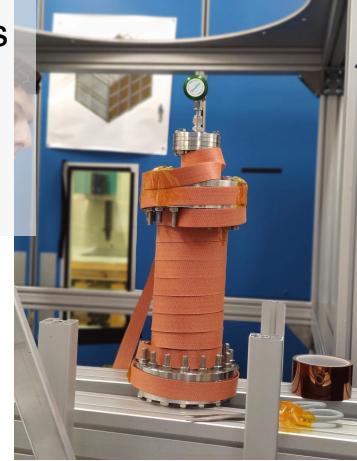
## Gas Filter - Aims

- Replace commercial filters
- Reduce Rn emanation
- Maintain efficiency
- Known ingredients
- Cost effective

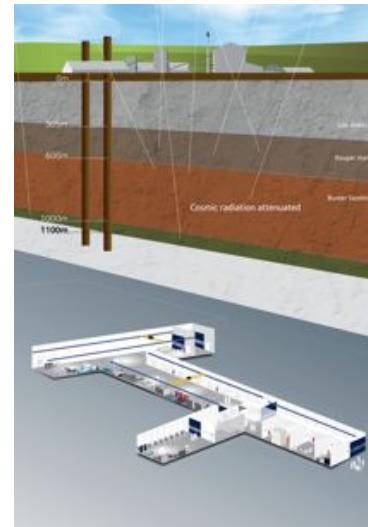


Activation at the  
University of Liverpool

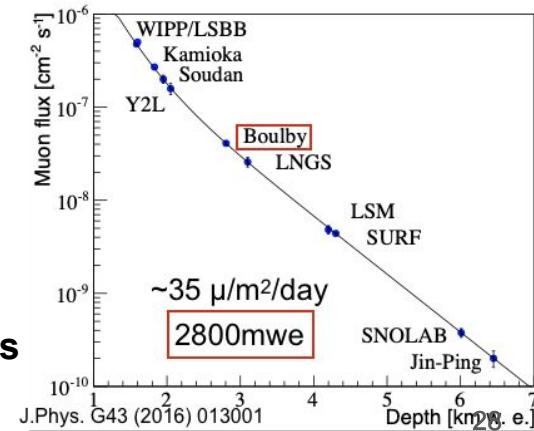
*Collaboration with  
Dr. K.Mavrokordis Team*



# First application - Neutron background at Boulby



Lowest Radon Levels  
 $3 \text{ Bq/m}^3$



# Recent activities at Boulby

- Instrumentation R&D at controlled environment
  - Rate effects
  - Space charge effects
- Neutron flux measurement
  - Thermal neutron
  - Fast neutron
- Including energy information
- Method applicable to all other underground laboratories



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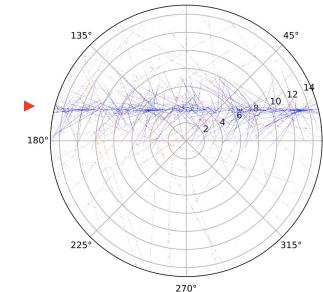
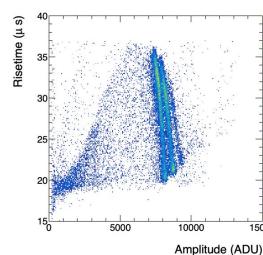
# Summary and Future plans

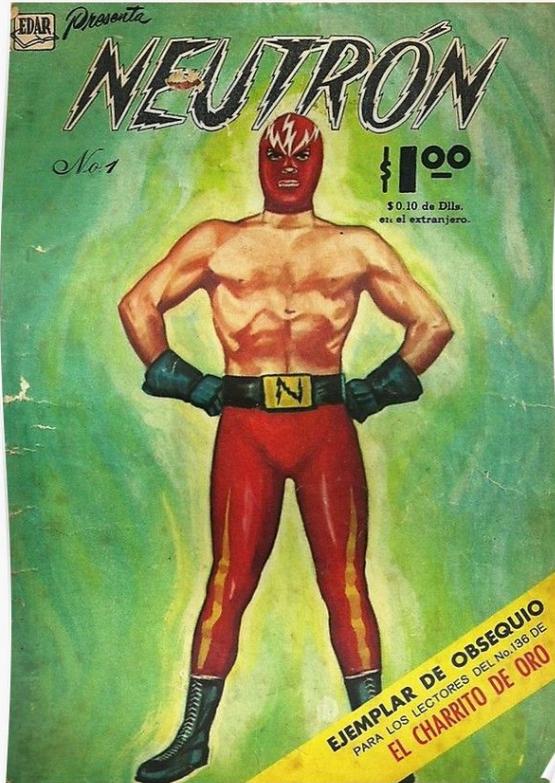


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- The combination of the spherical proportional detector and N<sub>2</sub> poses as a strong alternative of <sup>3</sup>He counters
- Promising first measurement of fast neutron energies
- Detailed simulation crucial for deconvoluting detector response
- Recent advancements in spherical detector instrumentation enables neutron spectroscopy capabilities
- Increasing operating pressure to over 1 bar
- Measurement of detector response to mono-energetic neutrons
- Validation of simulation results
- Development of an unfolding method to extract neutron energy spectra





Thank you for  
listening!

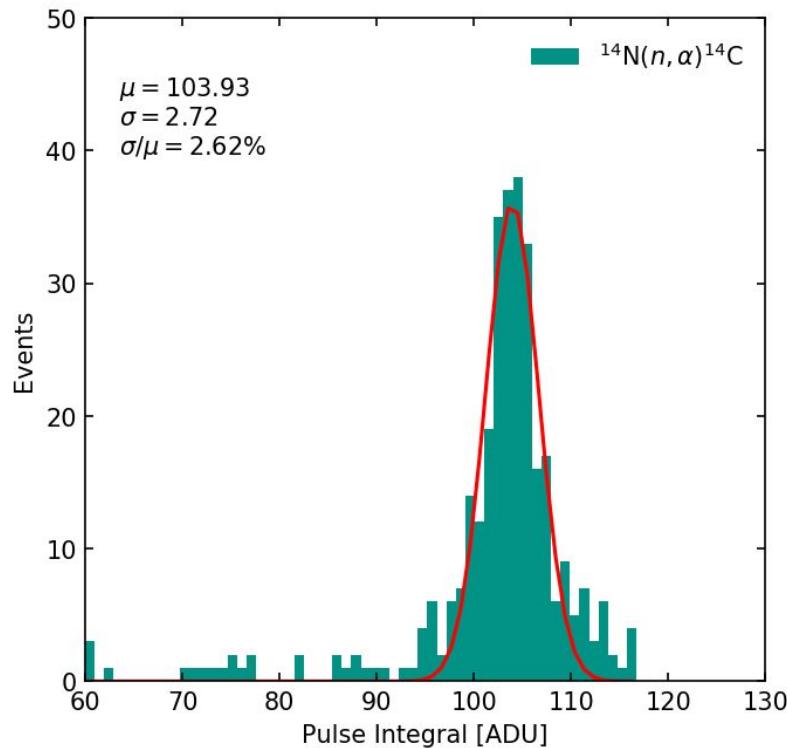
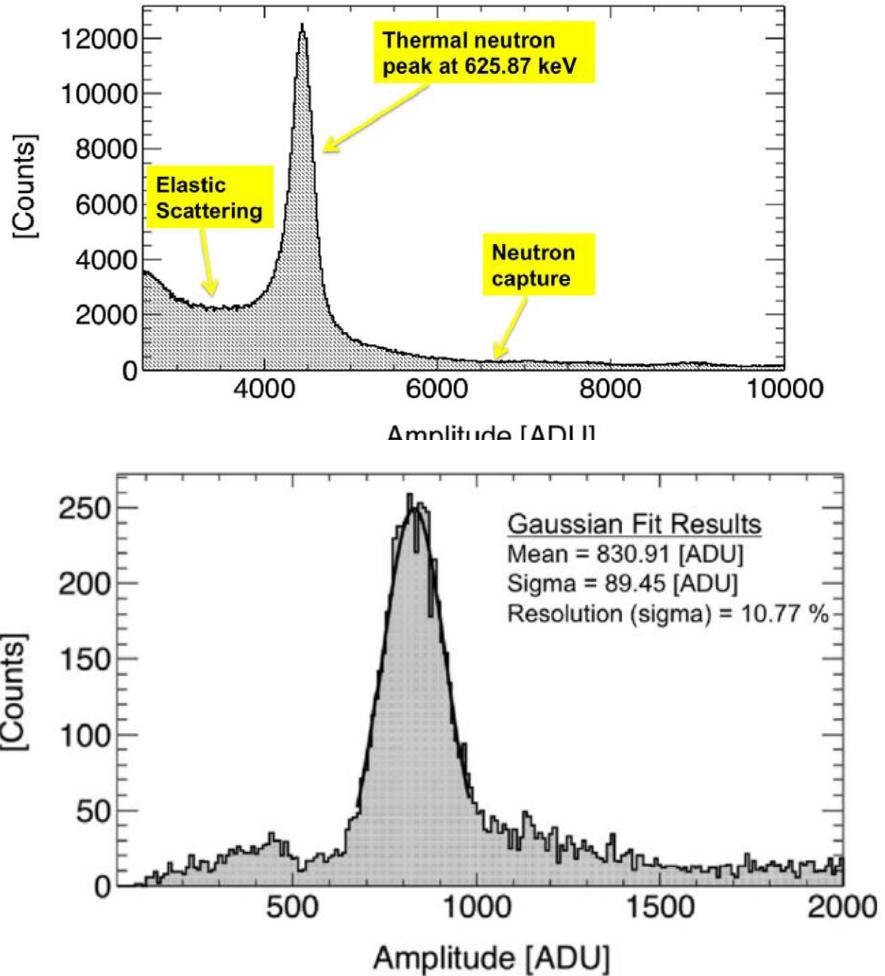
Questions?

ZOOM room:

<https://bham-ac-uk.zoom.us/j/98017147907?pwd=ejVrUmQySHk3OUxpbmw4RktpTXowUT09>

Starting after the end of the session!

# Backup slides

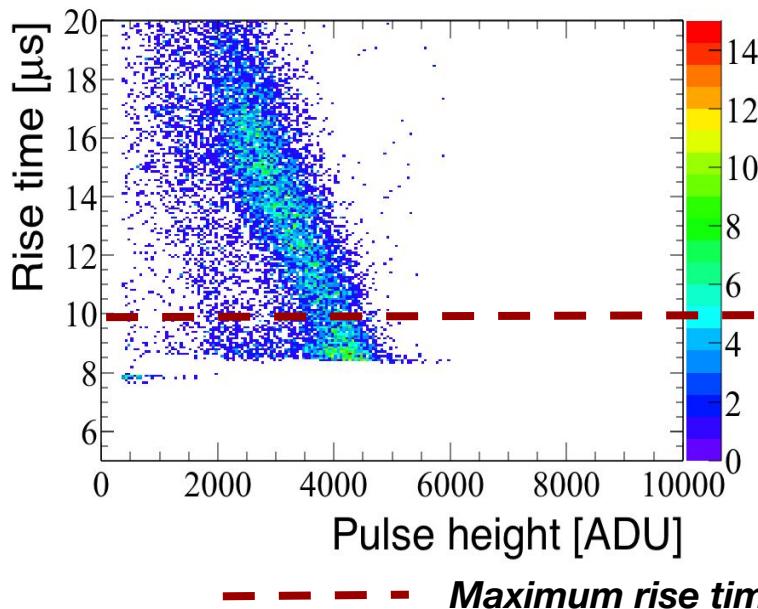


# Results with the prototypes

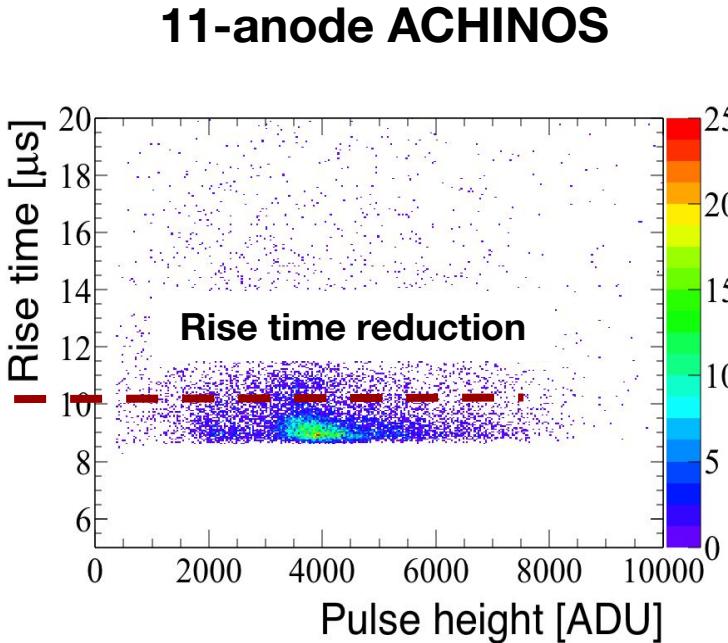
[Giganon, A. et al, 2017. "A Multiball Read-out for the Spherical Proportional Counter.", JINST](#)

## Rise time reduction

Single anode



11-anode ACHINOS



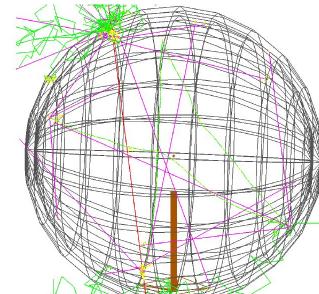
He:Ar:CH<sub>4</sub> (80:11:9)  
640 mbar  
 $HV_1 = 2015$  V  
 $HV_2 = -200$  V  
2 mm Ø anodes

# Development of an advanced simulation toolkit for gaseous detector simulations

The power of combining state-of-the art software

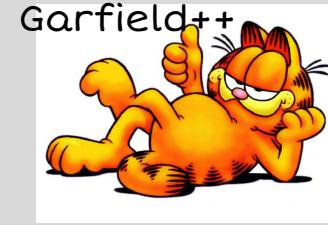
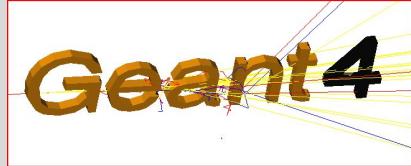
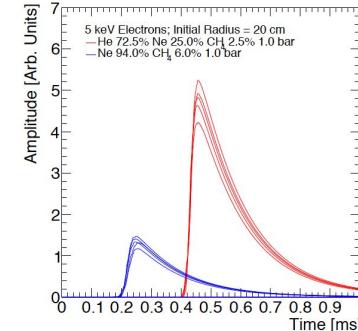
## Simulation of particle passage through matter

- Build geometry
- Transport of particles
- Particle interaction
- Generation-Transport of secondaries
- Energy deposition in the ROI



## Simulation of gaseous detectors

- Drift of charges
- Diffusion
- Avalanche
- Signal Induction
- Electronics



## Finite Element Methods

- Electric Field
- Magnetic Field
- Particle tracks

R.Ward

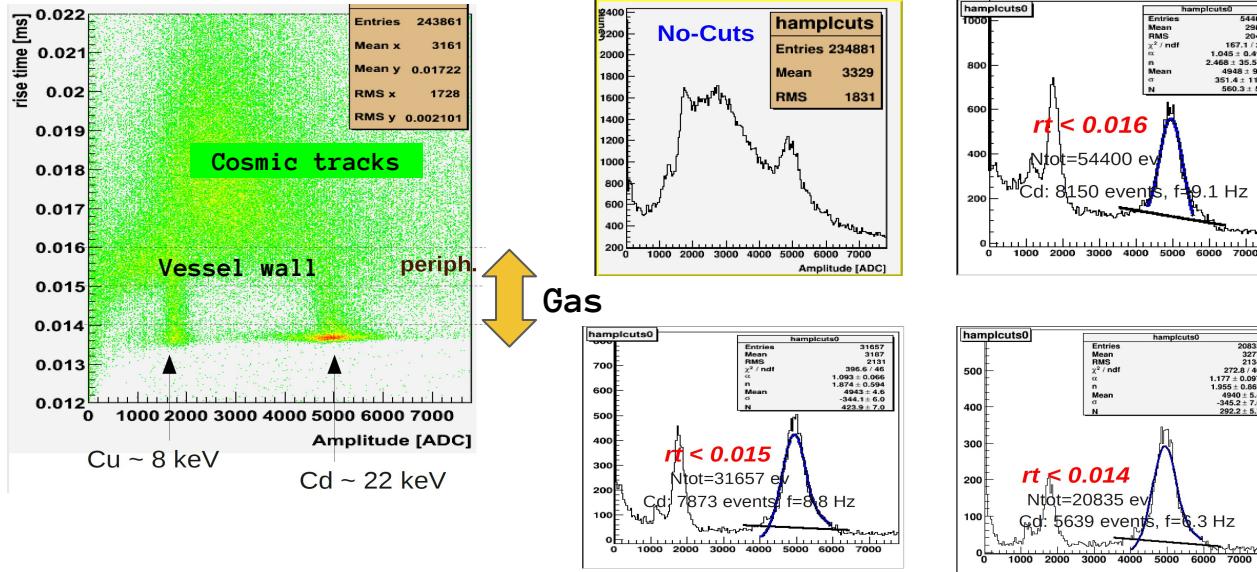
N-32-2 Experimental Computing

# Illustration of the basic analysis principle

$^{109}\text{Cd}$  source

Irradiation through  $200\mu\text{m}$  Al window

$P = 100 \text{ mb}$ , Ar-CH<sub>4</sub> (2%)



Efficiency of the cut in  $rt \rightarrow \sim 70\%$  signal (Cd line)  
Significant background reduction