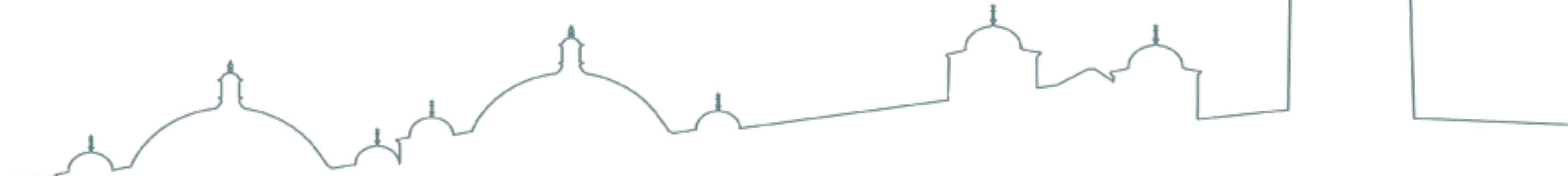




# Status of the R2D2 $0\nu\beta\beta$ Experiment

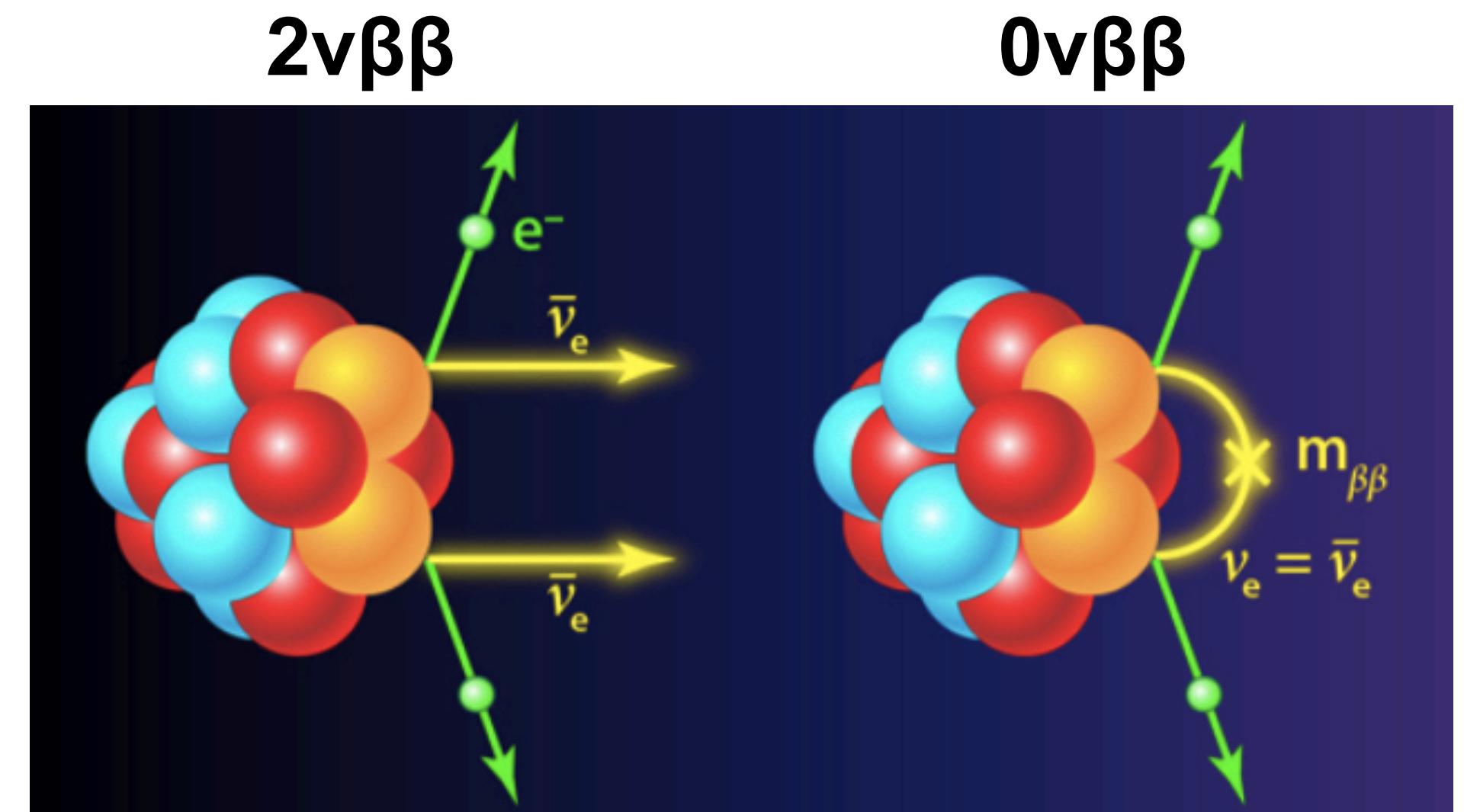
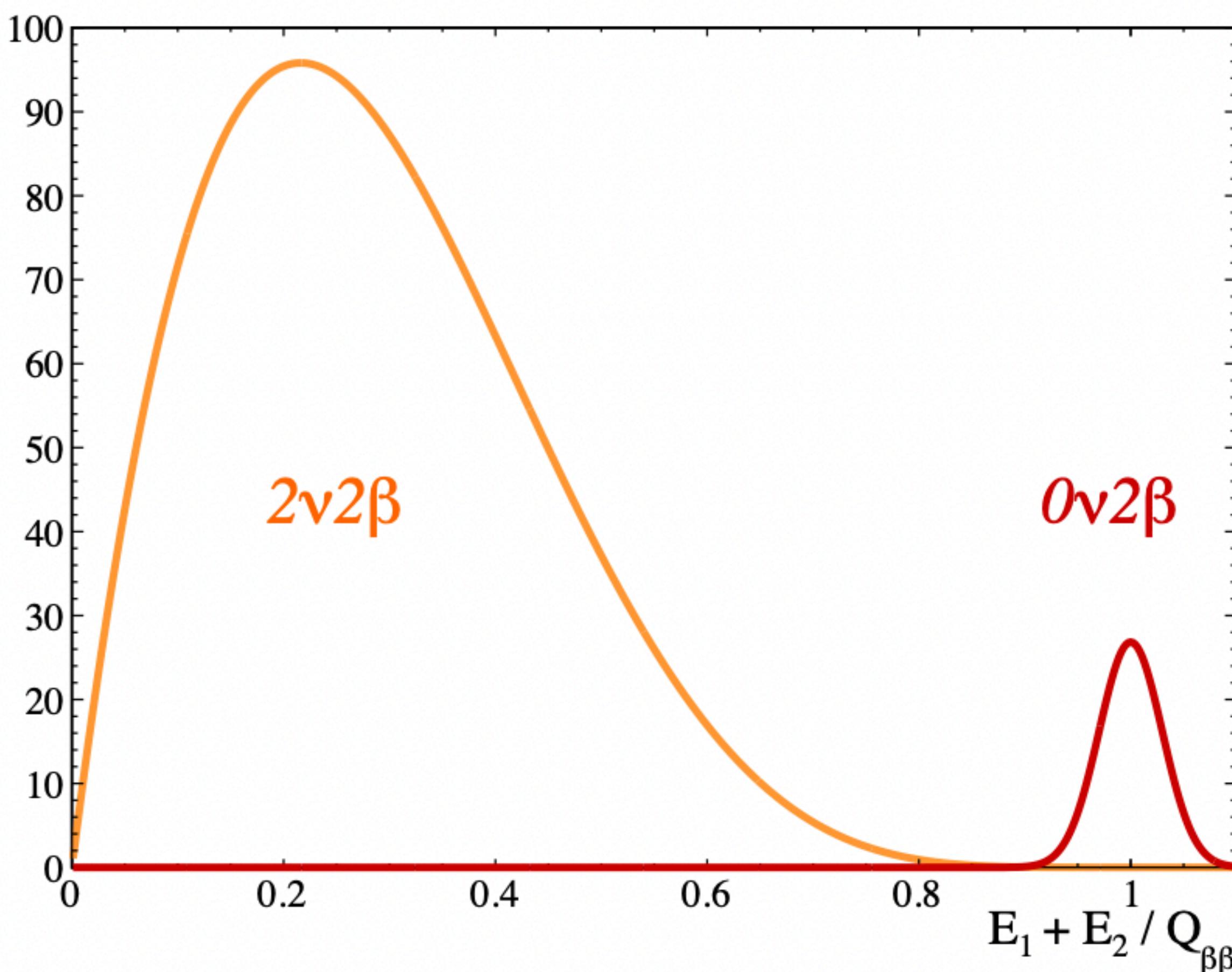
**P. Knights**

University of Birmingham, UK



# Neutrinoless Double Beta Decay

- $0\nu\beta\beta$  searches probe several open questions in physics
  - The most sensitive way to demonstrate the Majorana nature of neutrino!
  - Mass hierarchy

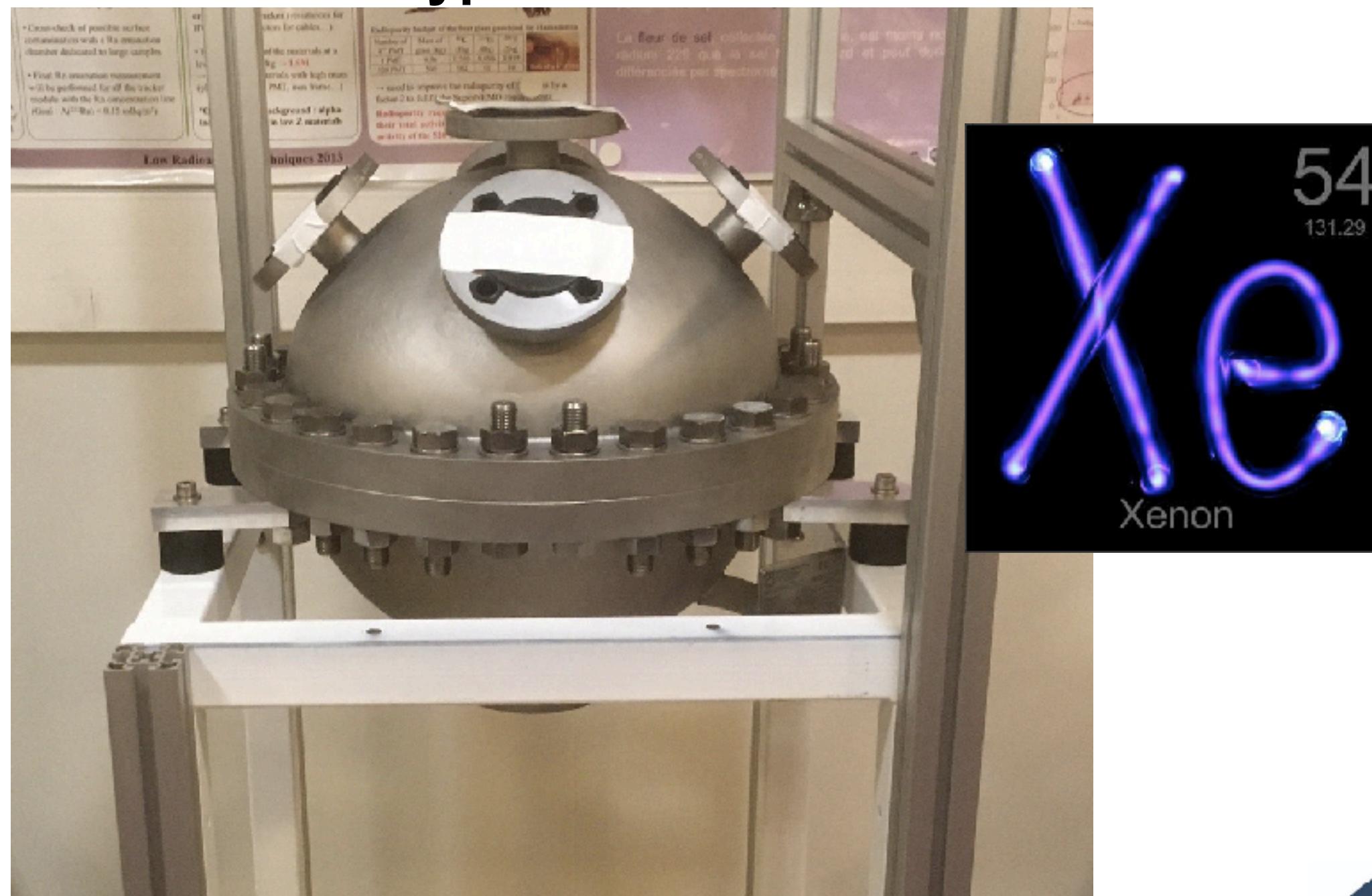


- For sensitivity, require:
  - Good energy resolution
  - Low background
  - Large isotope mass

# R2D2: Rare Decays with a Radial Detector

- Collaborative effort with IN2P3 laboratories, CEA Saclay, and University of Birmingham
- $^{136}\text{Xe}$ -filled Spherical Proportional Counter for  $0\nu\beta\beta$  searches

Prototype II in CENBG

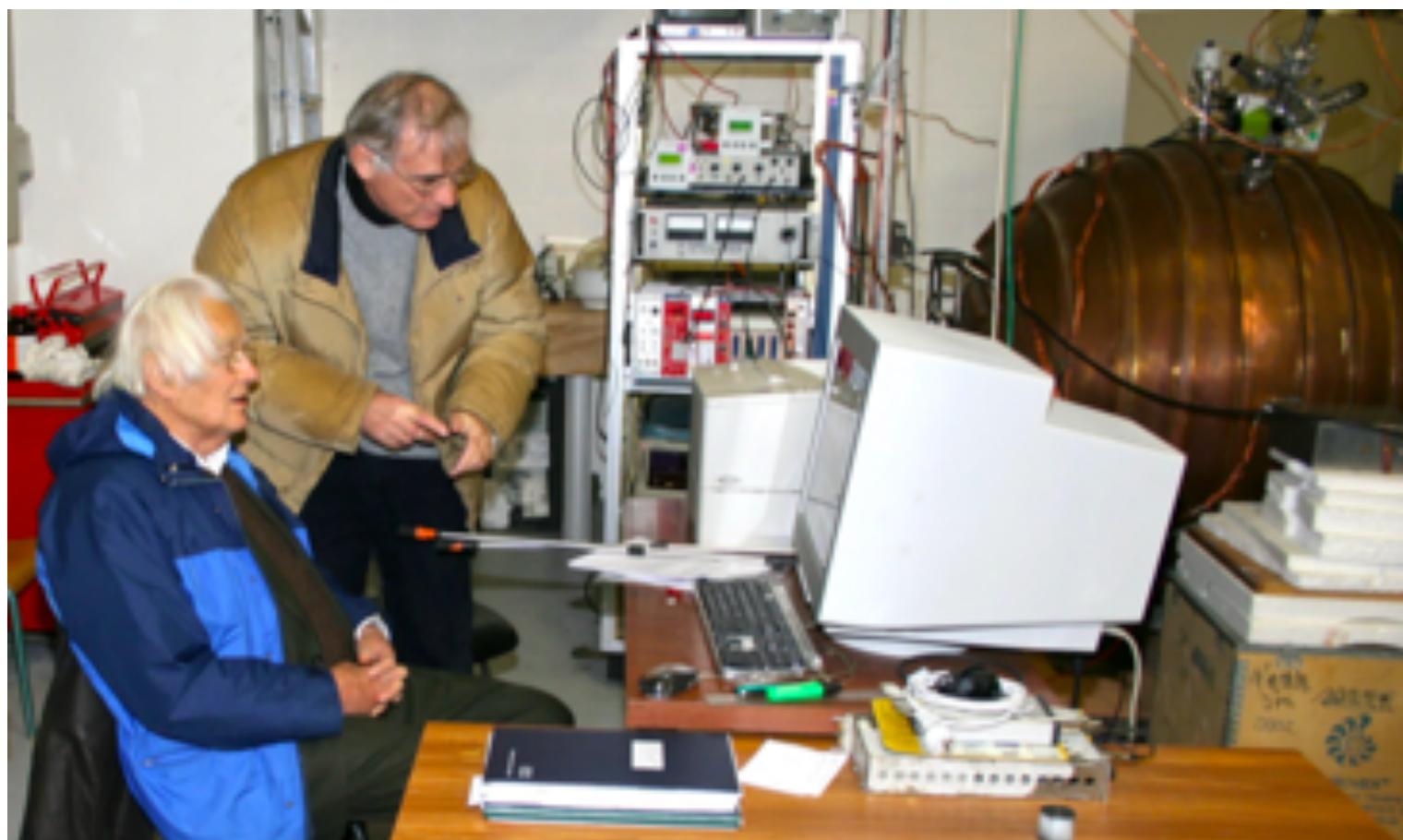


UNIVERSITY OF  
BIRMINGHAM



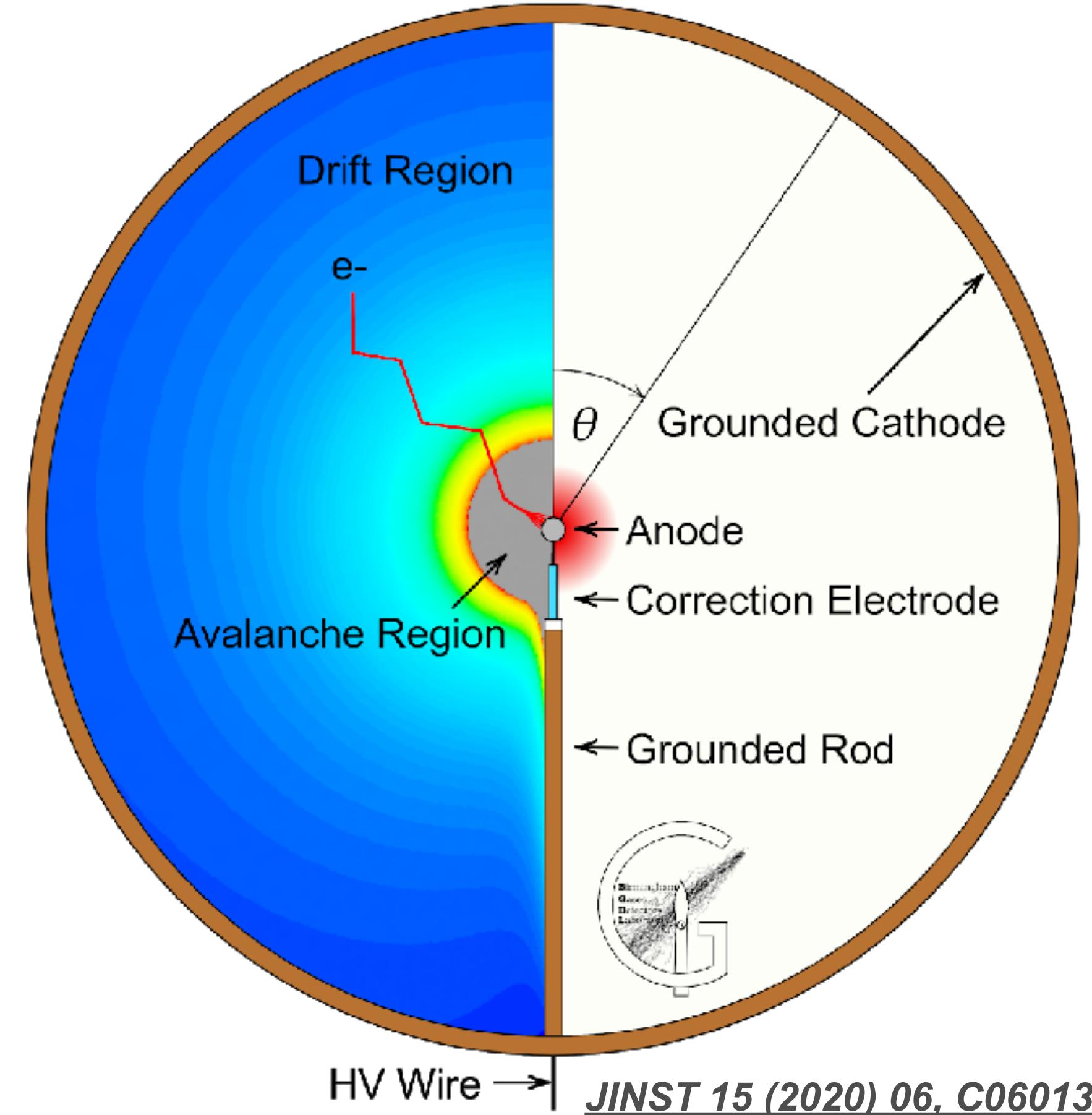
# Spherical Proportional Counters

- ~1 mm ball inside ~0.1-1 m radius spherical shell
- Ideal electric field varies as  $1/r^2$ 
  - **Naturally divides** detector into **drift** and **avalanche**
  - Primary electrons produced by ionisation in gas
  - Drift under E-field towards anode
  - Townsend Avalanche within ~100  $\mu\text{m}$  of the anode



G. Charpak and I. Giomataris in CEA Saclay, France  
(sphere was previously a LEP RF cavity)

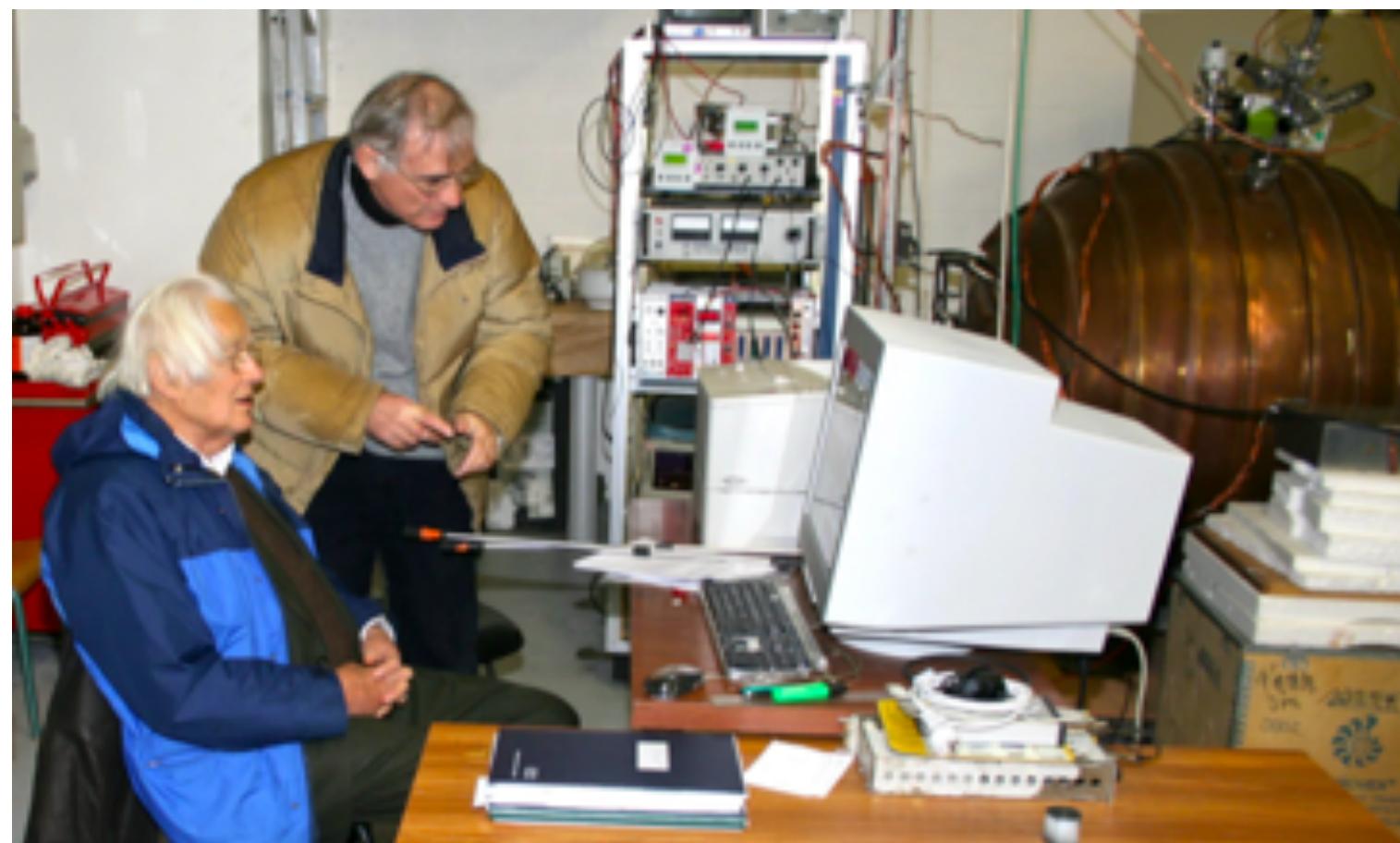
$$\vec{E} \approx \frac{V_1}{r^2} r_a \hat{r}$$



*JINST 15 (2020) 06, C06013*

# Spherical Proportional Counters

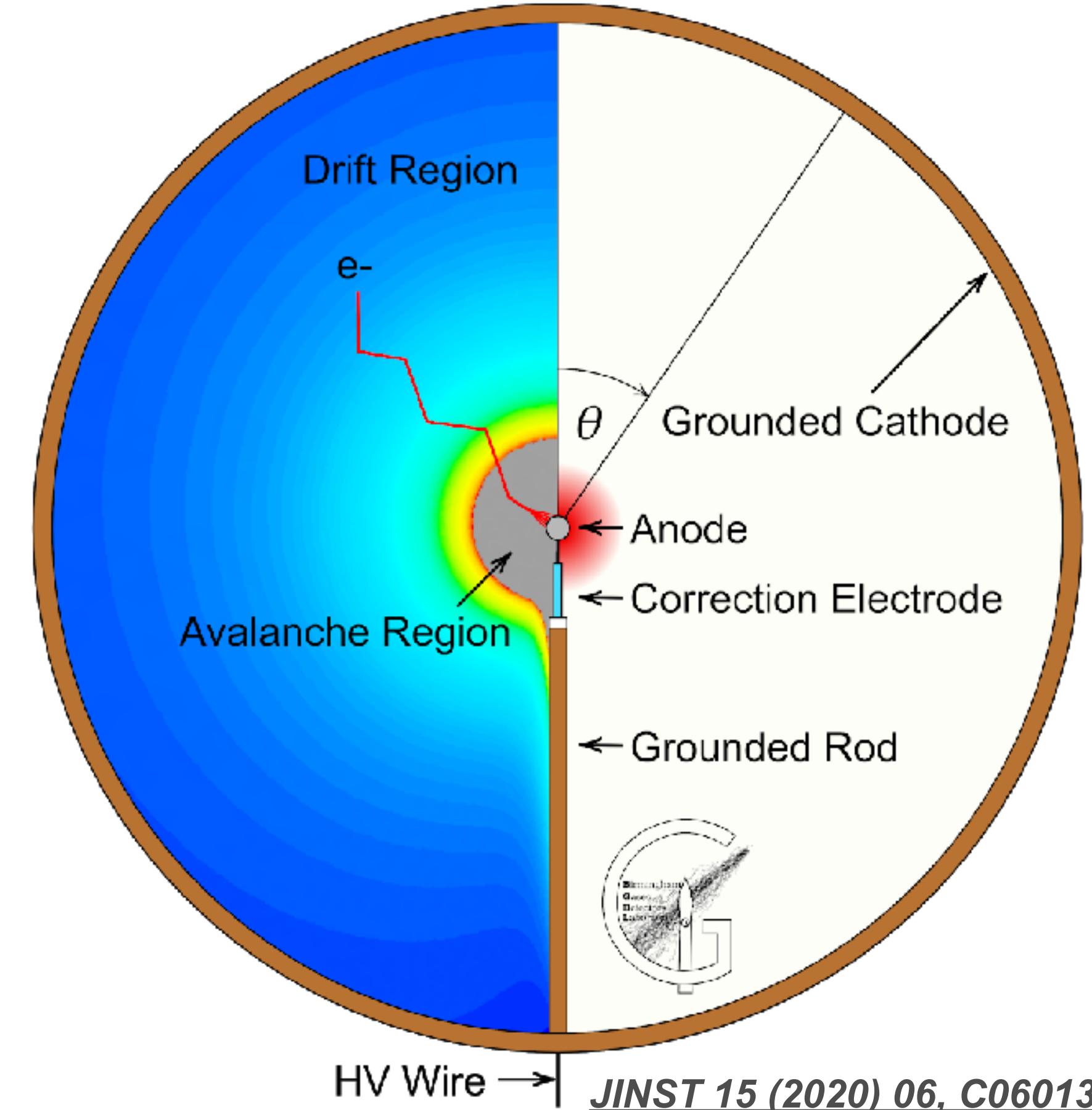
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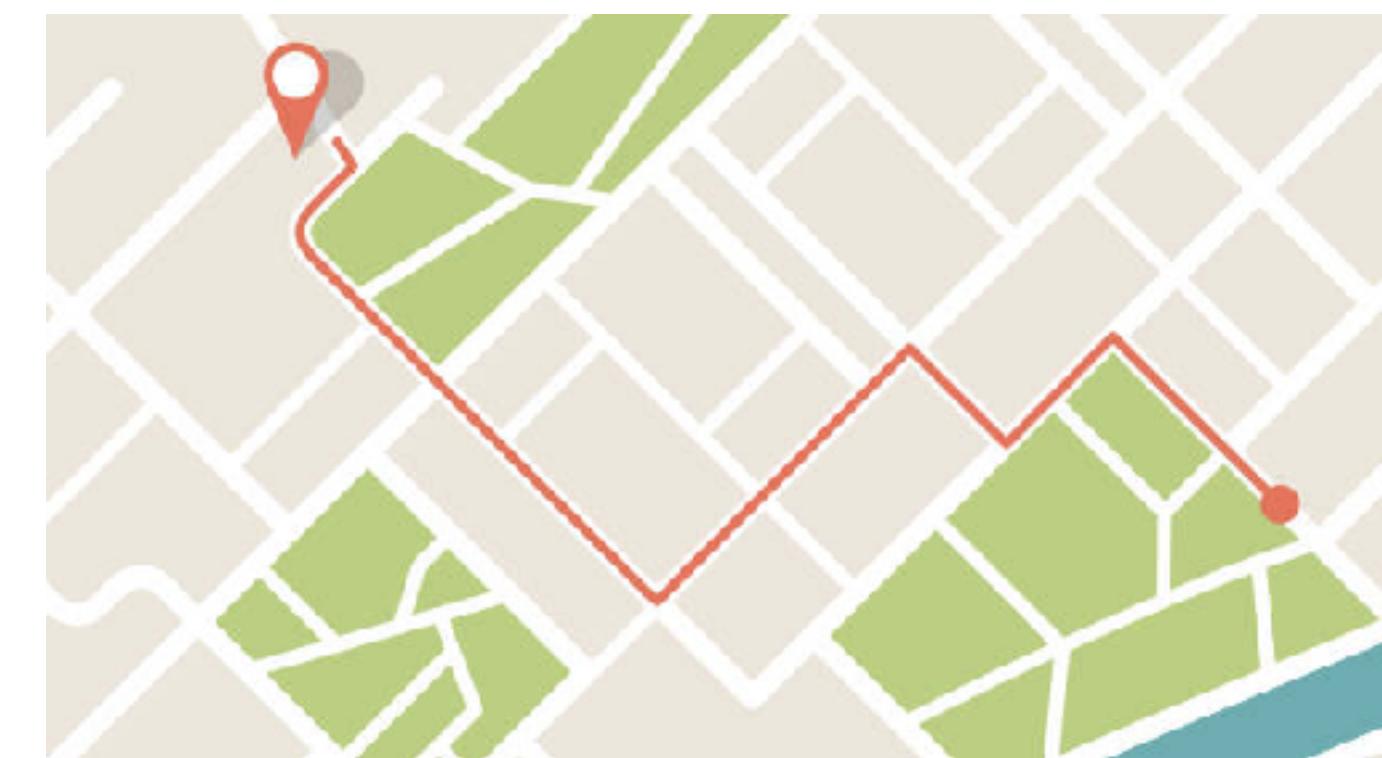
- **Low capacitance**, independent of detector size
  - Single-electron detection
- **Lowest surface area to volume ratio**
- Fiducialisation and PID from radial E-field
- **Choice of gas** targets (H, He, Ne, Xe) and pressures
  - Tune to access systematics/backgrounds
- $^{136}\text{Xe}$  TPC possible



*JINST 15 (2020) 06, C06013*

# Roadmap

Sensitivity goal:  $2.5 \times 10^{25}$  years on  $0\nu\beta\beta$   $t_{1/2}$  with 1 year data



## Prototype

- Ø40 cm SPC
- Up to 10 kg (40 bar) Xe
- Demonstrate energy resolution

### Study of a spherical Xenon gas TPC for neutrinoless double beta detection

A. Meregaglia,<sup>a</sup> J. Bustos,<sup>b</sup> C. Cerna,<sup>a</sup> M. Chauveau,<sup>a</sup> A. Dastghibai-Fard,<sup>c</sup> C. Jollet,<sup>a</sup> S. Julian,<sup>d</sup> I. Katsoulas,<sup>d</sup> I. Giomataris,<sup>d</sup> M. Groe,<sup>d</sup> P. Lautridou,<sup>c</sup> C. Marquet,<sup>d</sup>

X. Navick,<sup>d</sup> F. Perrot,<sup>a</sup> F. Piquemal,<sup>a,c</sup> L. Simard,<sup>f,g</sup> M. Zampaolo<sup>c</sup>

<sup>a</sup>CENBG, Université de Bordeaux, CNRS/IN2P3, 33175 Gradignan, France

<sup>b</sup>CPPM, Université d'Aix-Marseille, CNRS/IN2P3, F-13288 Marseille, France

<sup>c</sup>LSM, CNRS/IN2P3, Université Grenoble Alpes, Grenoble, France

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<sup>g</sup>Institut Universitaire de France, F-75005 Paris, France

E-mail: [ameregaglia@in2p3.fr](mailto:ameregaglia@in2p3.fr)

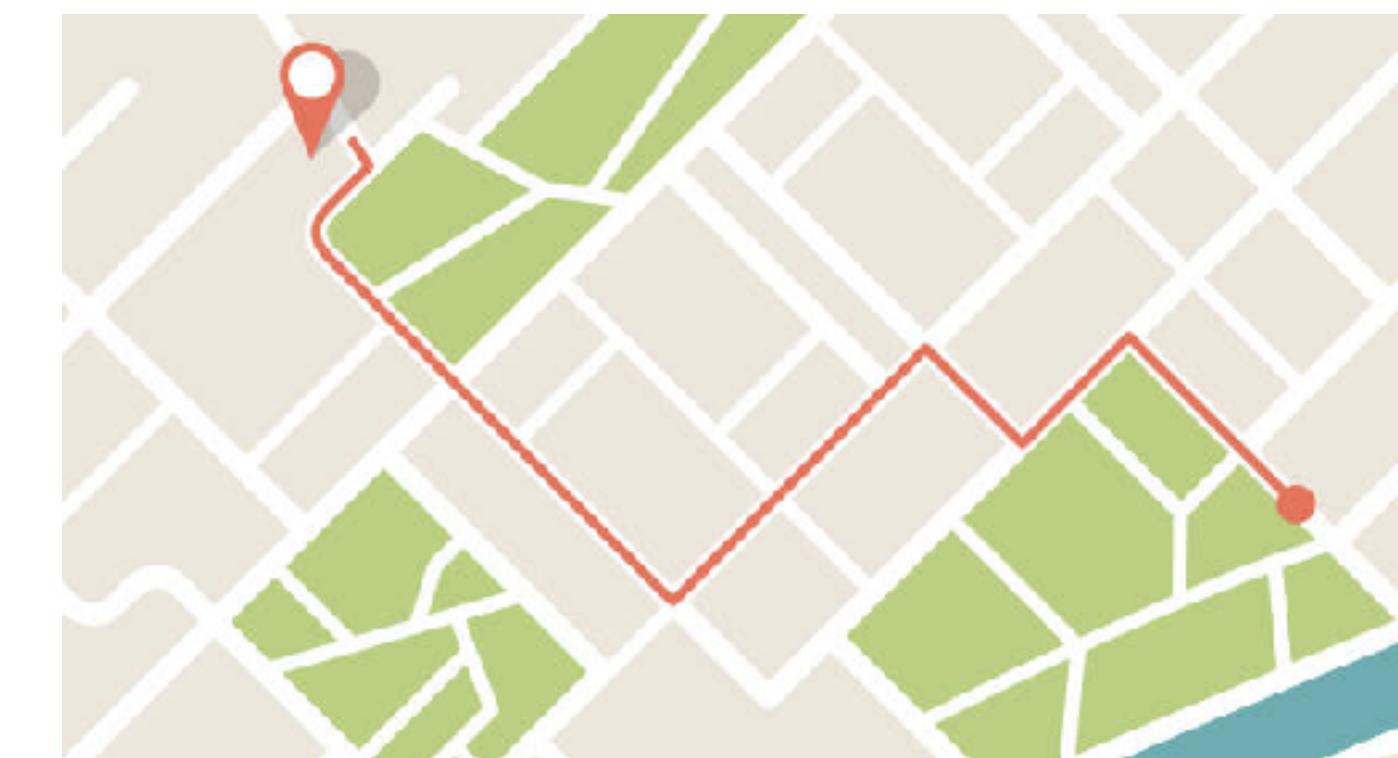
**ABSTRACT:** Several efforts are ongoing for the development of spherical gaseous time projection chamber detectors for the observation of rare phenomena such as weakly interacting massive particles or neutrino interactions. The proposed detector, thanks to its simplicity, low energy threshold and energy resolution, could be used to observe the  $\beta\beta0\nu$  process i.e. the neutrinoless double beta decay. In this work, a specific setup is presented for the measurement of  $\beta\beta0\nu$  on 50 kg of  $^{136}\text{Xe}$ . The different backgrounds are studied, demonstrating the possibility to reach a total background per year in the detector mass at the level of 2 events per year. The obtained results are competitive with the present generation of experiments and could represent the first step of a more ambitious roadmap including the  $\beta\beta0\nu$  search with different gases with the same detector and therefore the same background sources. The constraints in terms of detector constructions and material purity are also addressed, showing that none of them represents a show stopper for the proposed experimental setup.

JINST 13 (2018) 01, P01009



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E-mail: [ameregaglia@in2p3.fr](mailto:ameregaglia@in2p3.fr)

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## Requires:

- 50 kg detector
- 1% energy resolution at  $Q_{\beta\beta}=2.458$  MeV
- Cu vessel activity  $\leq 10\mu\text{Bq}/\text{kg}$
- Interaction position reconstruction

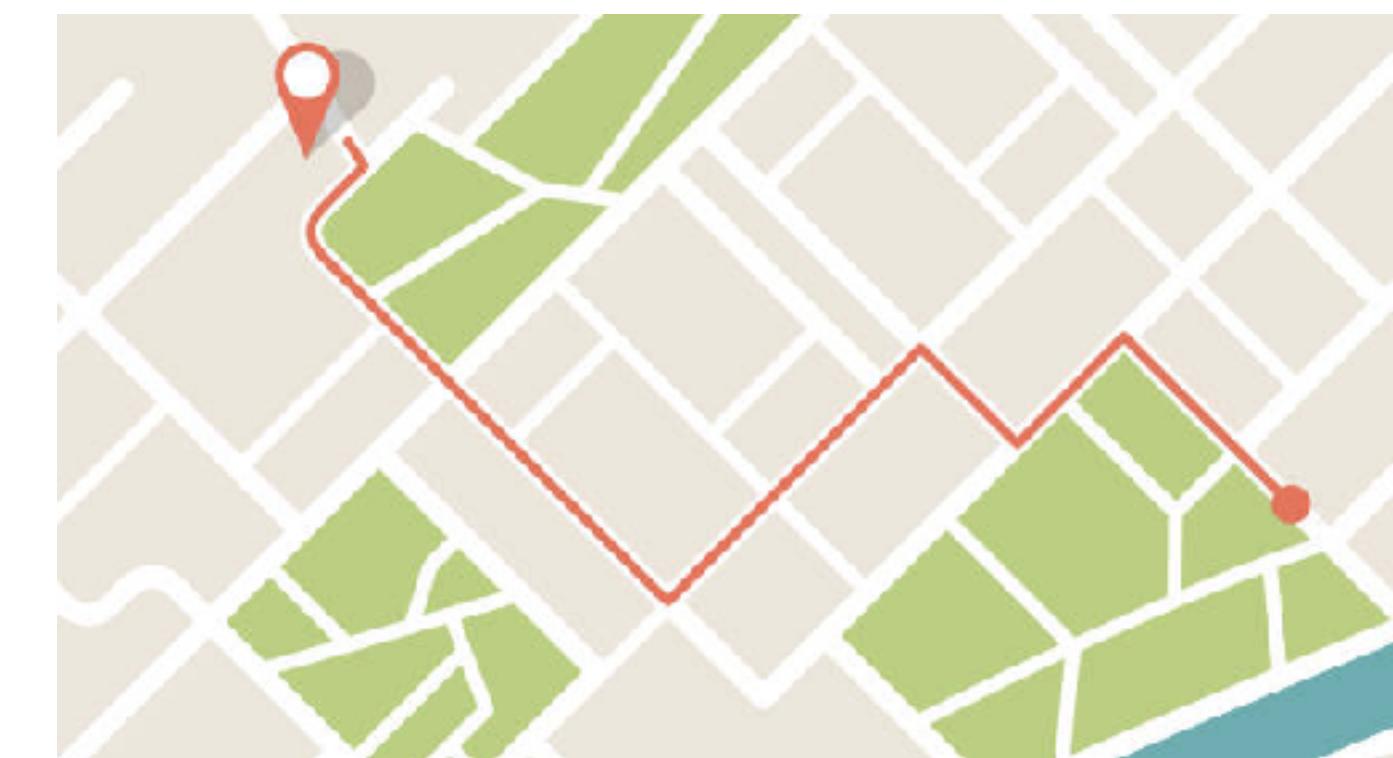
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- Ø74 cm SPC
- 50 kg (40 bar) Xe
- Radiopure materials
- Demonstrate ‘zero’ background



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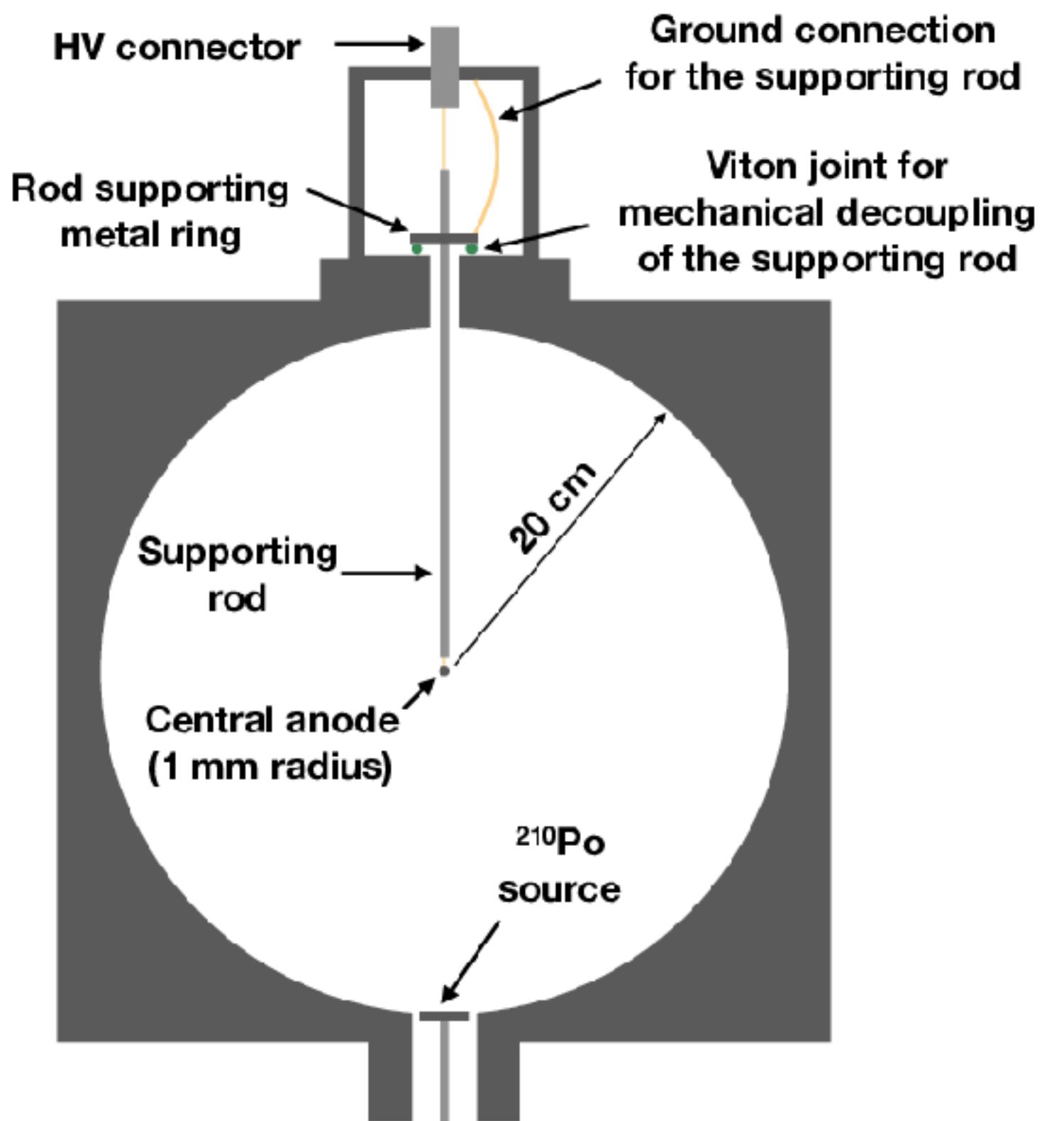
## Experiment

- Full scale detector
- Tonne scale (40 bar)



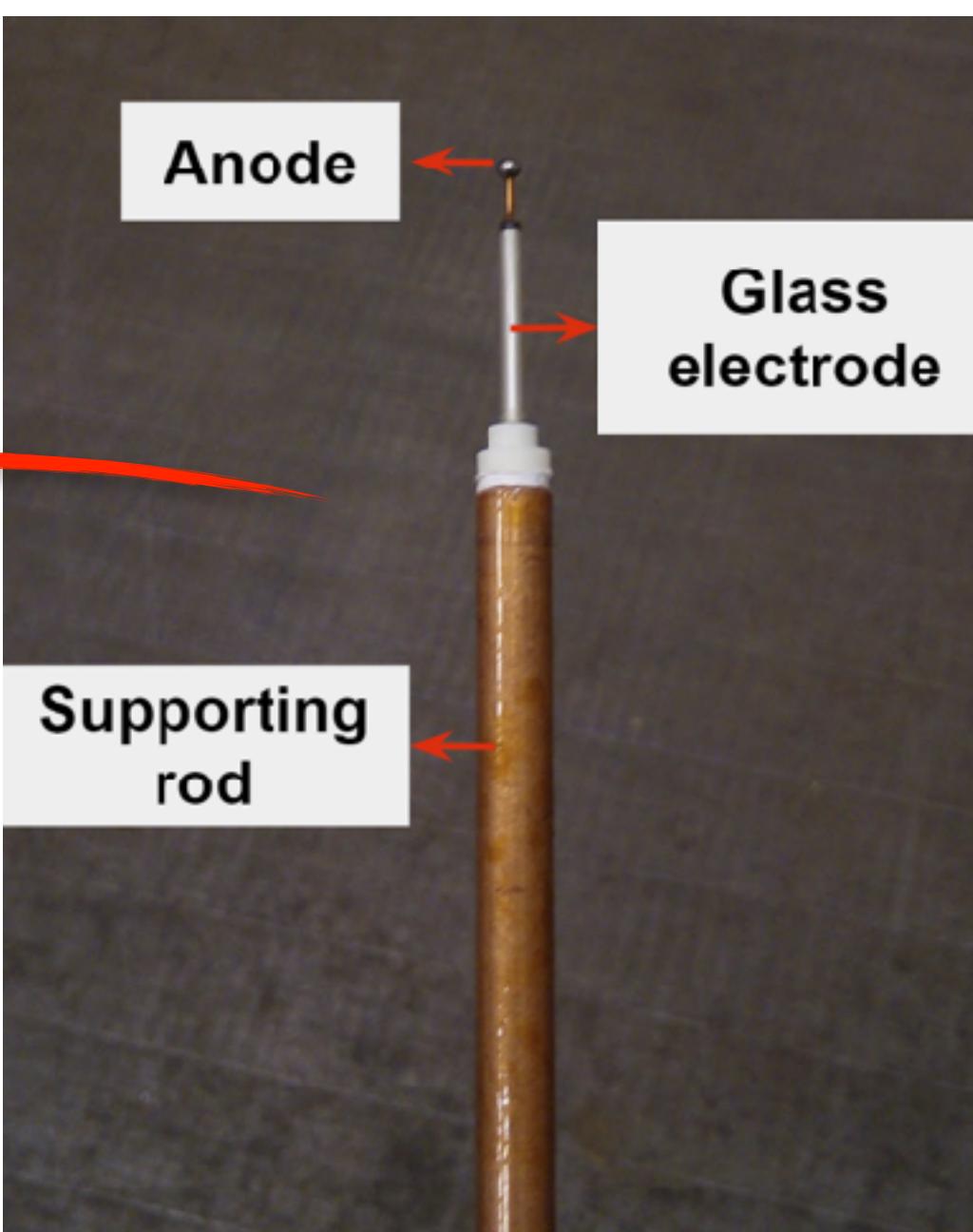
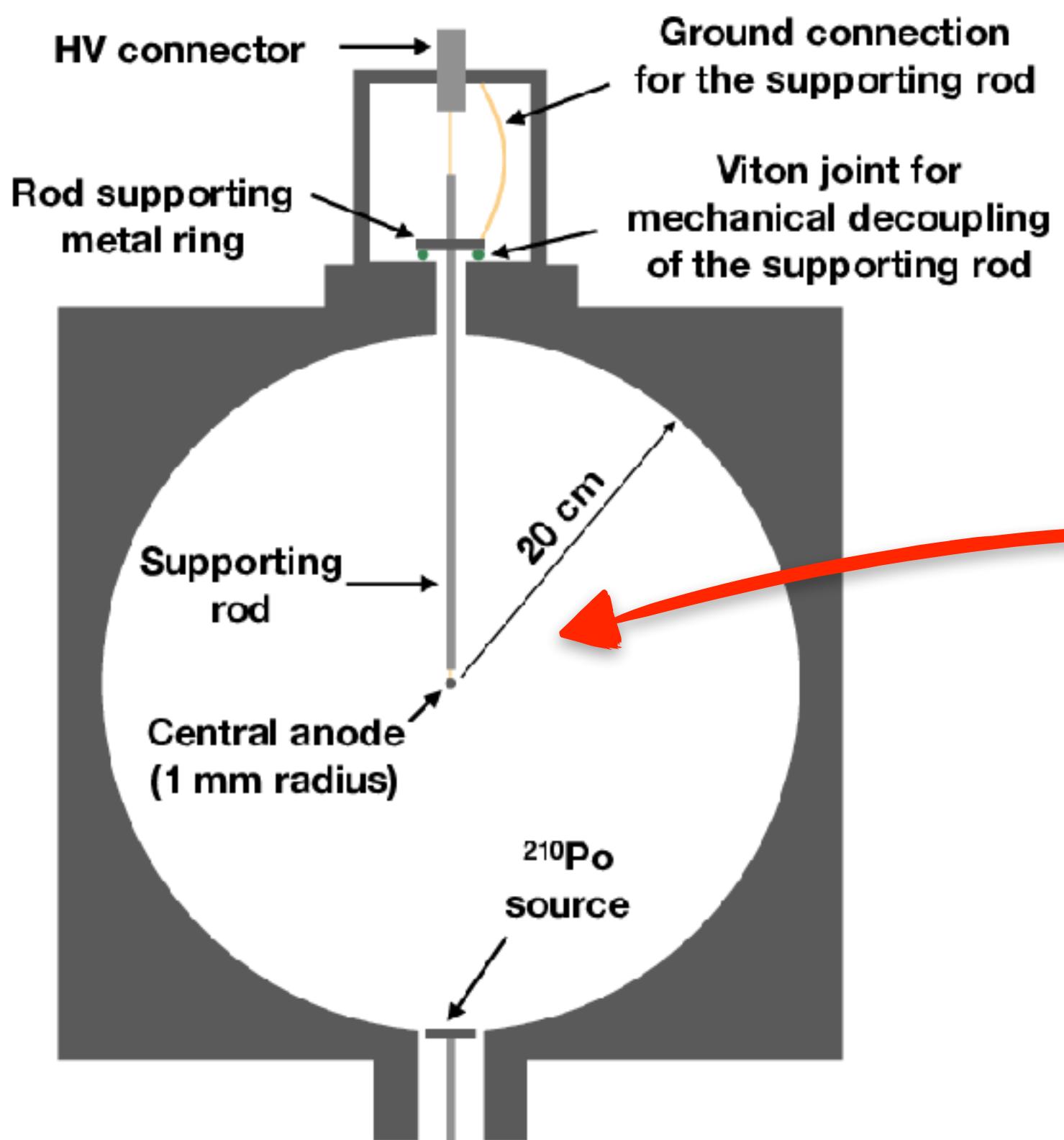
# Energy Resolution

- First goal: Demonstrate energy resolution
- $\varnothing 40$  cm Al SPC in low noise facility in Bordeaux
- Custom-made electronics, OWEN project
- Ar:CH<sub>4</sub> (98%:2%) up to 1.1 bar
- $^{210}\text{Po}$  source  $\rightarrow$  5.3 MeV  $\alpha$ -particle (c.f.  $Q_{\beta\beta}=2.458$  MeV)



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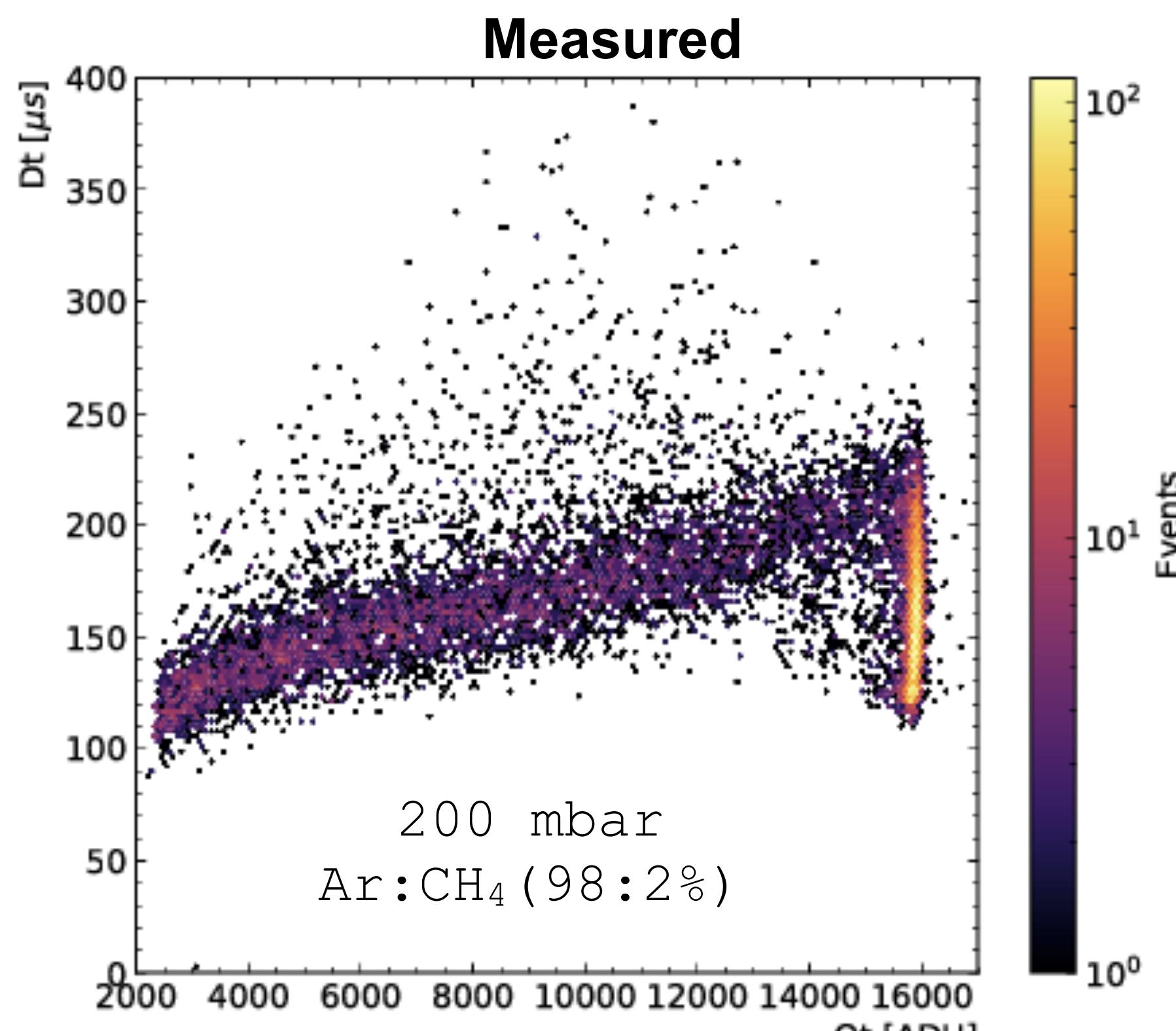
- Utilised sensor technology with resistive glass correction electrode

JINST 13 (2018) 11, P11006

# Data vs Simulation

- Reconstructed observables total charge  $Q_t$ , signal duration  $D_t$ , etc.
- Simulation used to understand experimental results
  - Dedicated simulation framework [\*JINST 15 \(2020\) 06, C06013\*](#)
- Detector response well understood

5.3 MeV  $\alpha$ -particle  
range of  $\sim 22$  cm



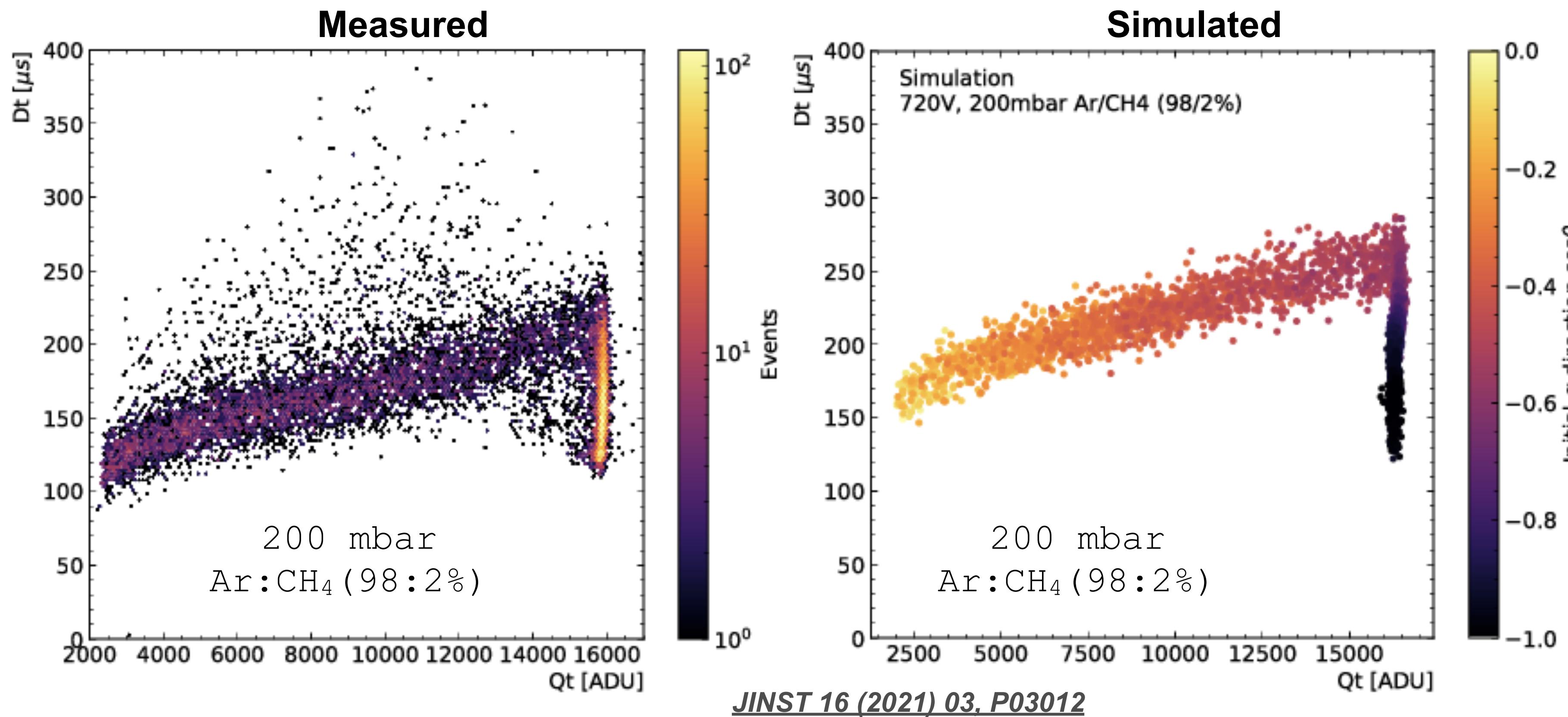
[\*JINST 16 \(2021\) 03, P03012\*](#)



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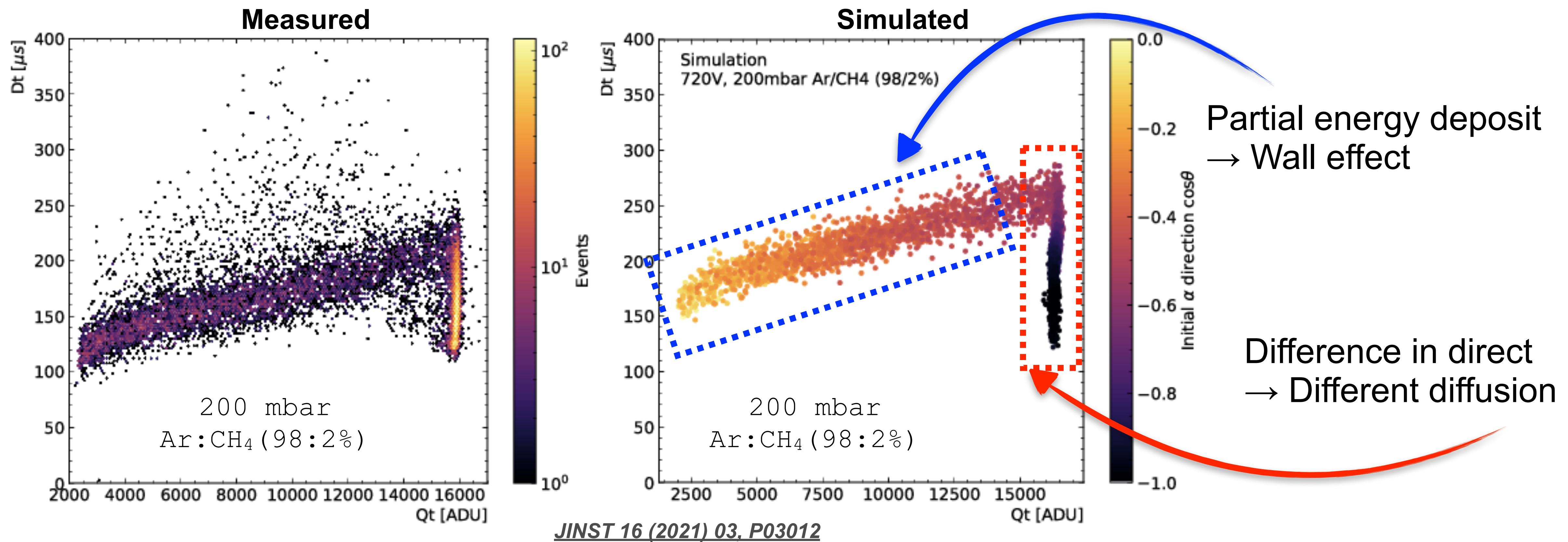
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5.3 MeV  $\alpha$ -particle  
range of  $\sim 22$  cm



# Resolution Results In Ar:CH<sub>4</sub>

- Data at 200 mbar and 1.1 bar
  - No significant change in resolution
  - Unaffected by  $\alpha$  track length
- Energy resolution result:
  - 0.5% from electronics (signal generator)
  - 0.24% expected from primary ionisation

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## R2D2 spherical TPC: first energy resolution results

R. Bouet,<sup>a</sup> J. Buste,<sup>b</sup> V. Cecchini,<sup>c,d,f</sup> C. Cerna,<sup>d</sup> A. Dastgheibi-Fard,<sup>e</sup> F. Druillole,<sup>c</sup> C. Jollet,<sup>c</sup> P. Hellmuth,<sup>c</sup> I. Katsioulas,<sup>d</sup> P. Knights,<sup>d,e</sup> I. Giomataris,<sup>d</sup> M. Gros,<sup>c</sup> P. Lautridou,<sup>f</sup> A. Meregaglia,<sup>d,f</sup> X.F. Navick,<sup>c</sup> T. Neep,<sup>d</sup> K. Niklopoulos,<sup>d</sup> F. Perrot,<sup>d</sup> F. Piquemal,<sup>d</sup> M. Roche,<sup>d</sup> B. Thomas,<sup>d</sup> R. Ward,<sup>d</sup> and M. Zampaolo<sup>c</sup>

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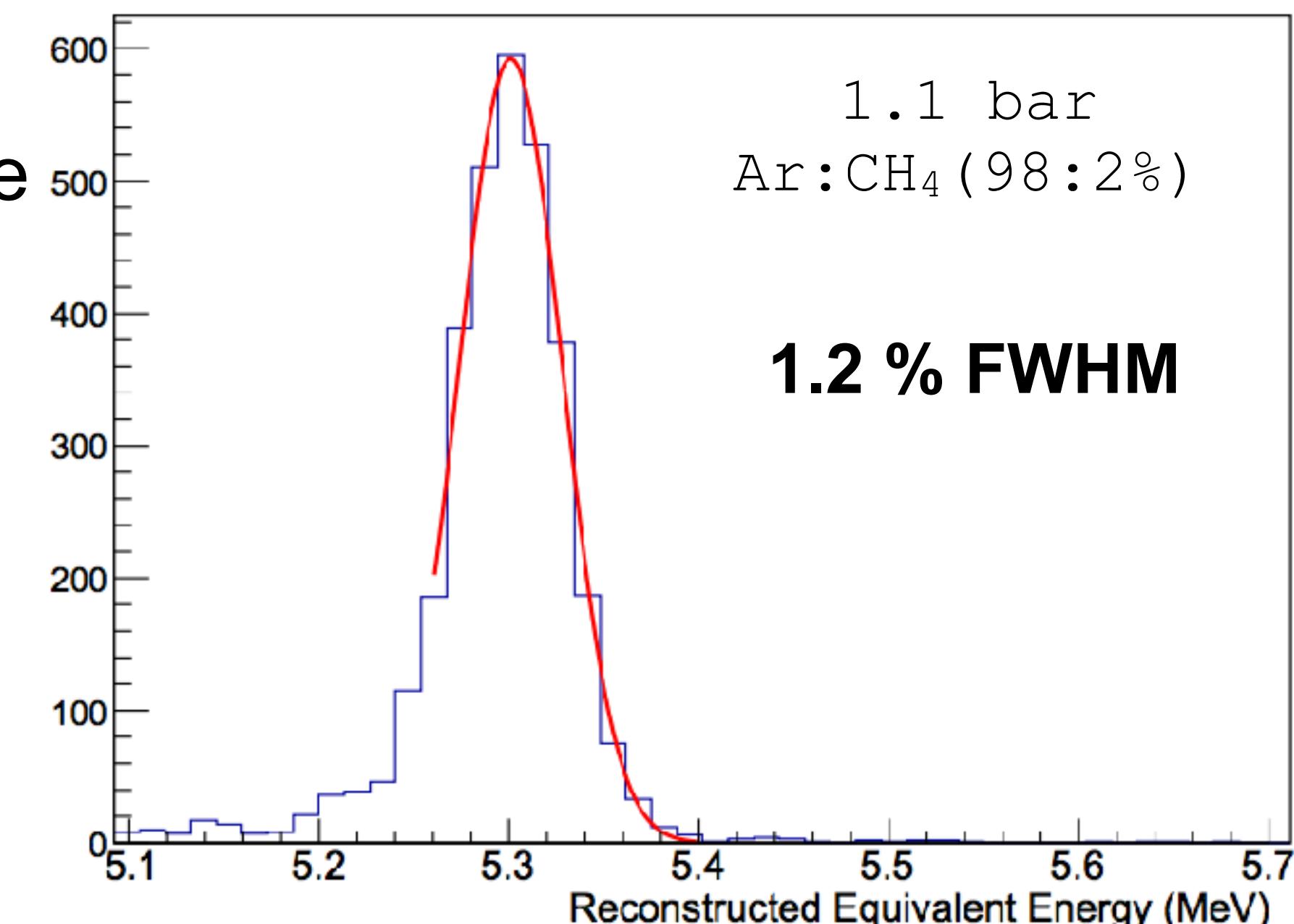
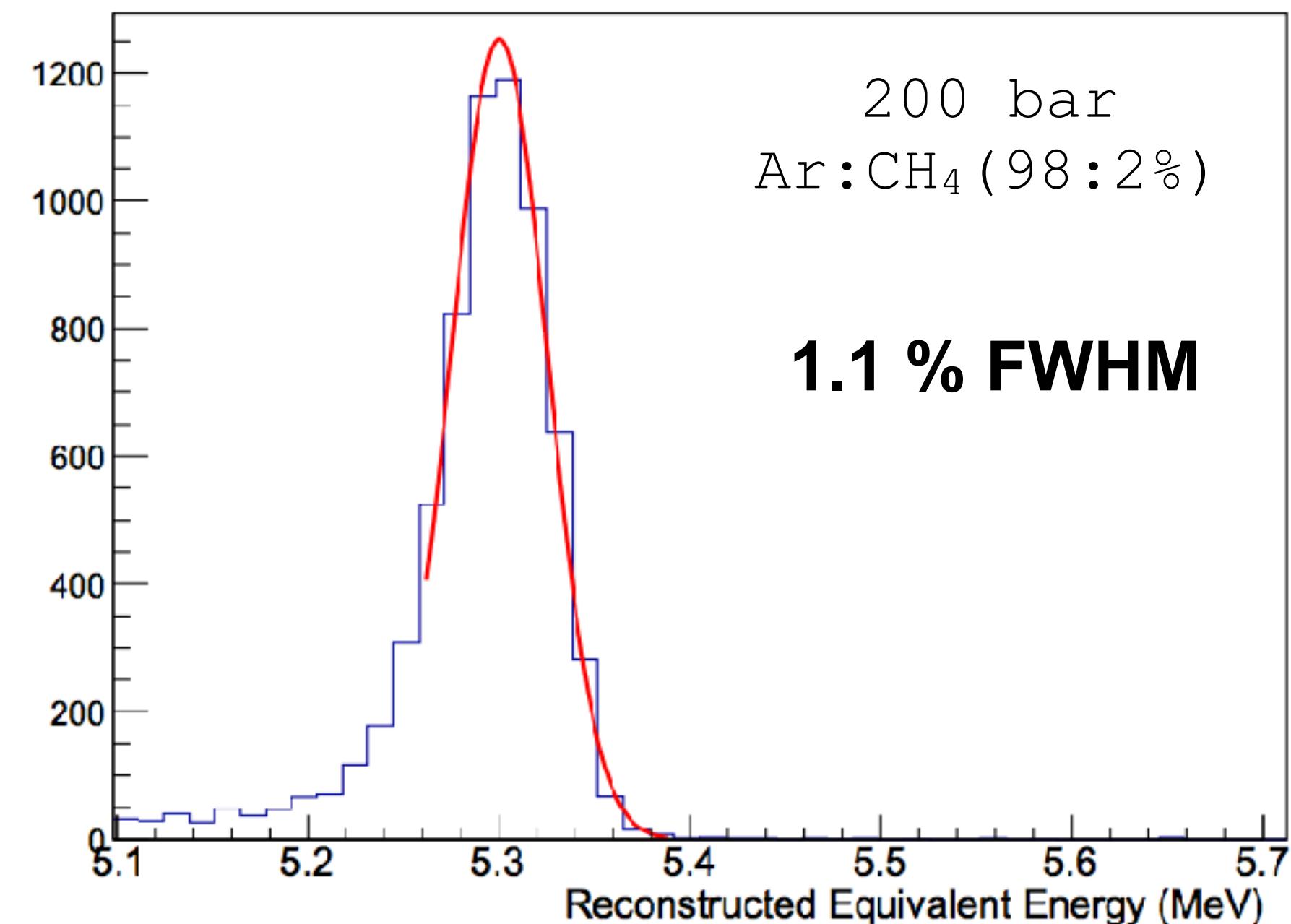
E-mail: amarlin.meregaglia@cern.ch

**ABSTRACT:** Spherical time projection chambers (TPC), also known as spherical proportional counters, are employed in the search for rare phenomena, such as light Dark Matter candidates. The spherical TPC exhibits a number of essential features, making it a promising candidate for the search of neutrinoless double beta decay ( $\beta\beta0\nu$ ). A tonne-scale spherical TPC experiment could cover a region of parameter space relevant for the inverted mass hierarchy with a few years of data taking. In this direction, the major R&D goal of the R2D2 effort is the demonstration of the required energy resolution. First results from an argon-filled prototype detector are reported, demonstrating an energy resolution of 1.1% FWHM for 5.2 MeV  $\alpha$  tracks in the 0.2 to 1.1 bar pressure range. This is a major milestone in terms of energy resolution, paving the way for further studies with xenon gas, and the possible use of this technology for  $\beta\beta0\nu$  searches.

2021 JINST 16 P03012

	<b>W [eV]</b>	<b>Fano</b>
<b>Ar</b>	~26	~0.16
<b>Xe</b>	~22	0.13-0.17

JINST 16 (2021) 03, P03012



# Scintillation Signal

- Primary interaction also produces scintillation
  - Prompt signal, s1
- Avalanche produces electroluminescence
  - Delayed signal, s2
- Provides interaction  $t_0$  (s1) and electron drift time (s2-s1)
- First measurements performed with  $6 \times 6 \text{ mm}^2$  Hamamatsu SiPM

Nuclear Test. and Methods in Physics Research, A 1028 (2022) 166382

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Technical Notes

Simultaneous scintillation light and charge readout of a pure argon filled Spherical Proportional Counter

R. Bouet<sup>a</sup>, J. Busto<sup>b</sup>, V. Cecchini<sup>b,c,d</sup>, C. Cerna<sup>a</sup>, A. Dastgheibi-Fard<sup>d</sup>, F. Druillole<sup>a</sup>, C. Jollet<sup>a</sup>, P. Hellmuth<sup>a</sup>, I. Katsioulas<sup>e</sup>, P. Knights<sup>b,f</sup>, I. Giomataris<sup>f</sup>, M. Gros<sup>f</sup>, P. Lautridou<sup>c</sup>, A. Mereggia<sup>a</sup>, X.F. Navick<sup>f</sup>, T. Neep<sup>a</sup>, K. Nikolopoulos<sup>b</sup>, F. Perrot<sup>a</sup>, E. Piquemal<sup>a</sup>, M. Roche<sup>a</sup>, B. Thomas<sup>a</sup>, R. Ward<sup>a</sup>, M. Zampaolo<sup>d</sup>

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<sup>b</sup>GPIPA, Université d'Avranches, CNRS/IN2P3, F-50130 Montivilliers, France  
<sup>c</sup>SORALIC, IN2P3-Aix-Marseille, Université de Aix-Marseille, CNRS/CNRS-PSI, France  
<sup>d</sup>LSPM, CNRS/IN2P3, Université Grenoble-Alpes, France  
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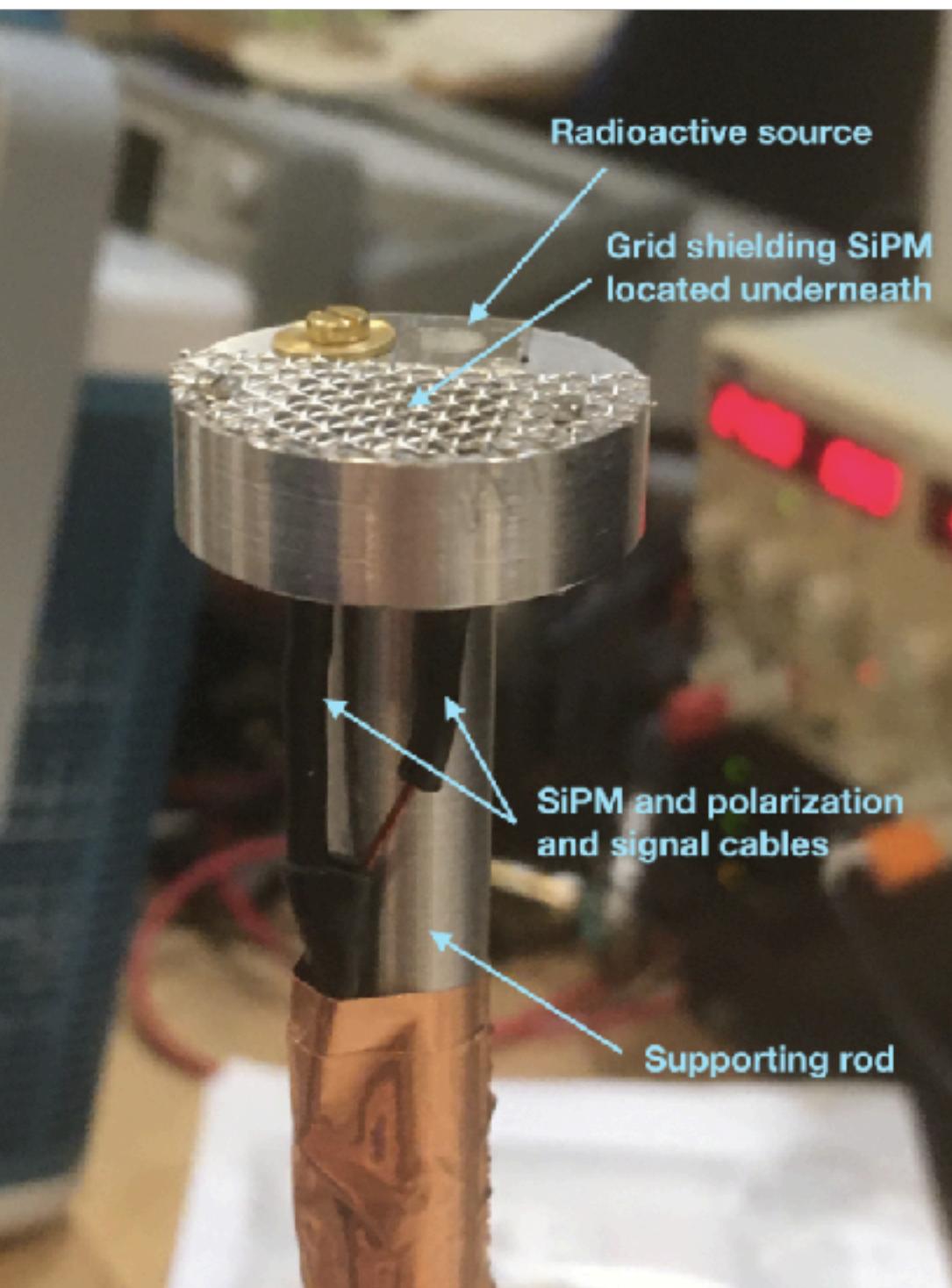
ARTICLE INFO

Keywords:  
Spherical TPC  
Neutrino  
Neutrinoless double beta decay  
Scintillation

ABSTRACT

The possible use of a Spherical Proportional Counter for the search of neutrinoless double beta decay is investigated in the R2B2-8BD project. Dual charge and scintillation light readout may improve the detector performance. Tests were carried out with pure argon at 1.1 bar using a  $6 \times 6 \text{ mm}^2$  silicon photomultiplier. Scintillation light was used for the first time to trigger in a spherical proportional counter. The measured drift time is in excellent agreement with the expectations from simulations. Furthermore the light signal emitted during the avalanche development exhibits features that could be exploited for event characterization.

<https://doi.org/10.1016/j.nima.2022.166382>



# Scintillation Signal

- Primary interaction also produces scintillation
  - Prompt signal,  $s_1$
- Avalanche produces electroluminescence
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- Provides interaction  $t_0$  ( $s_1$ ) and electron drift time ( $s_2-s_1$ )
- First measurements performed with  $6 \times 6 \text{ mm}^2$  Hamamatsu SiPM

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R. Bouet<sup>a</sup>, J. Busto<sup>b</sup>, V. Cecchini<sup>b,c,d</sup>, C. Cerna<sup>a</sup>, A. Dastgheibi-Fard<sup>d</sup>, F. Druillole<sup>a</sup>, C. Jollet<sup>a</sup>, P. Hellmuth<sup>a</sup>, I. Katsioulas<sup>e</sup>, P. Knights<sup>b,f</sup>, I. Giomataris<sup>f</sup>, M. Gros<sup>b</sup>, P. Lautridou<sup>c</sup>, A. Mereggia<sup>b</sup>, X.F. Navick<sup>b</sup>, T. Neep<sup>b</sup>, K. Nikolopoulos<sup>b</sup>, F. Perrot<sup>b</sup>, E. Piquemal<sup>a</sup>, M. Roche<sup>a</sup>, B. Thomas<sup>a</sup>, R. Ward<sup>b</sup>, M. Zampaolo<sup>d</sup>

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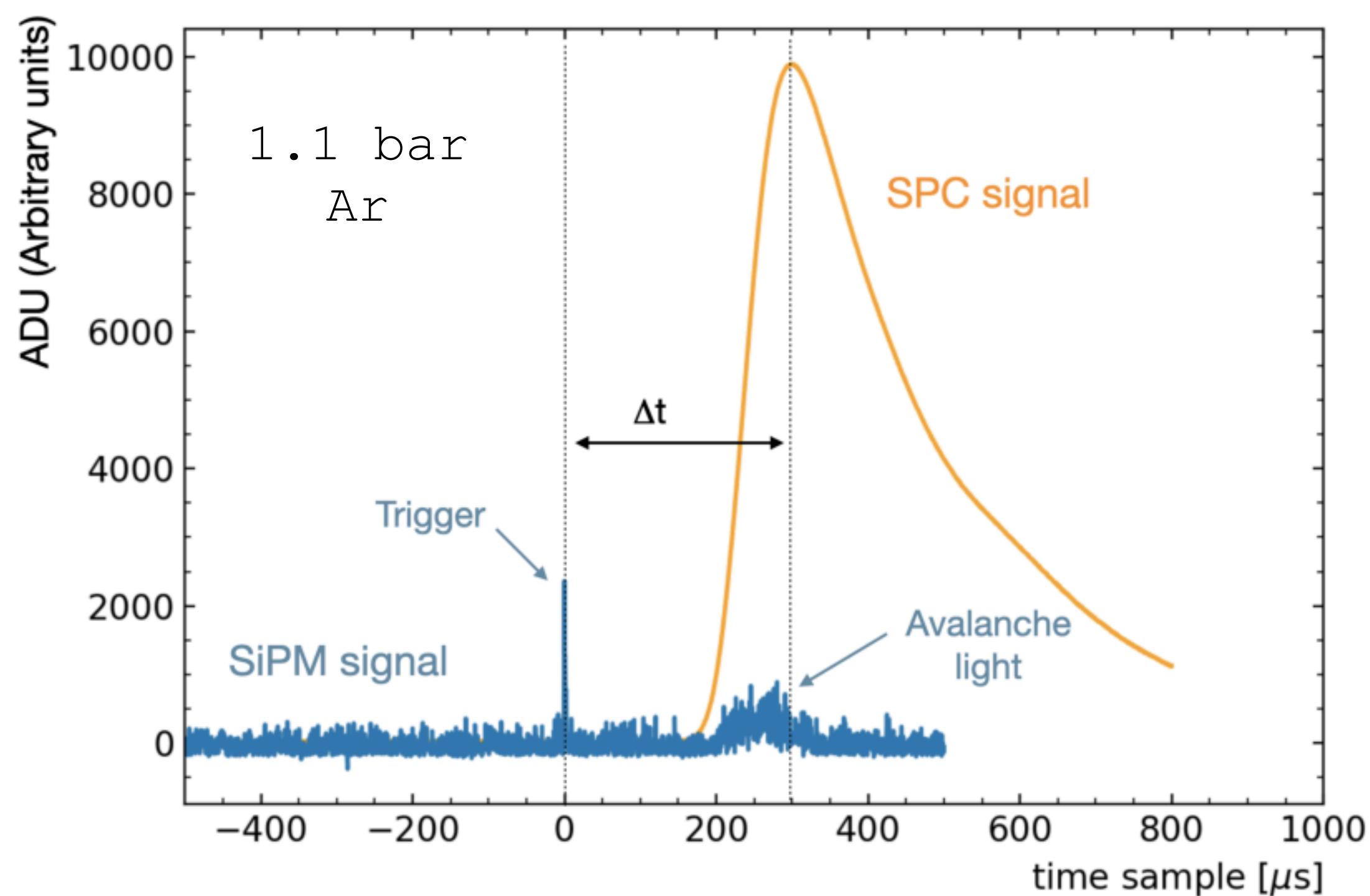
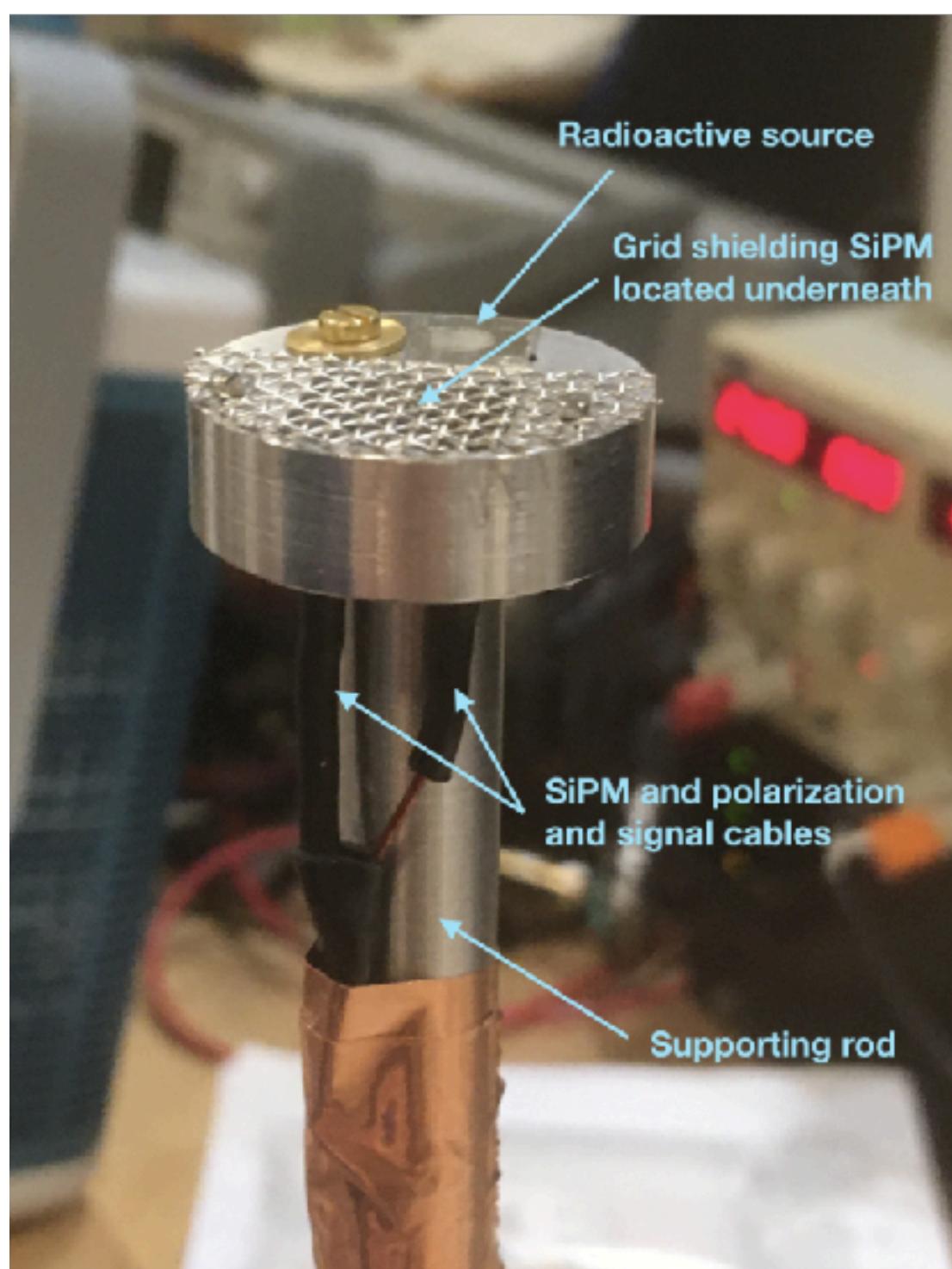
## ARTICLE INFO

## ABSTRACT

Keywords:  
Spherical TPC  
Scintillation  
Neutrinoless double beta decay  
Scintillation

The possible use of a Spherical Proportional Counter for the search of neutrinoless double beta decay is investigated in the R2B2-8BD project. Dual charge and scintillation light readout may improve the detector performance. Tests were carried out with pure argon at 1.1 bar using a  $6 \times 6 \text{ mm}^2$  silicon photomultiplier. Scintillation light was used for the first time to trigger in a spherical proportional counter. The measured drift time is in excellent agreement with the expectations from simulations. Furthermore the light signal emitted during the avalanche development exhibits features that could be exploited for event characterization.

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P Knights - IOP HEPP & APP 2022 (RAL)

06/04/2022

# Scintillation Signal

- Primary interaction also produces scintillation
  - Prompt signal,  $s_1$
- Avalanche produces electroluminescence
  - Delayed signal,  $s_2$
- Provides interaction  $t_0$  (s1) and electron drift time ( $s_2-s_1$ )
- First measurements performed with  $6 \times 6 \text{ mm}^2$  Hamamatsu SiPM

Nuclear Test and Methods in Physics Research, A 1028 (2022) 166382



## Technical Notes

Simultaneous scintillation light and charge readout of a pure argon filled Spherical Proportional Counter

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<sup>e</sup>School of Physics and Astronomy, University of Birmingham, B15 2TT, UK

<sup>f</sup>IAPU, IIA, Université Paris-Saclay, F-91191 Gif sur Yvette, France

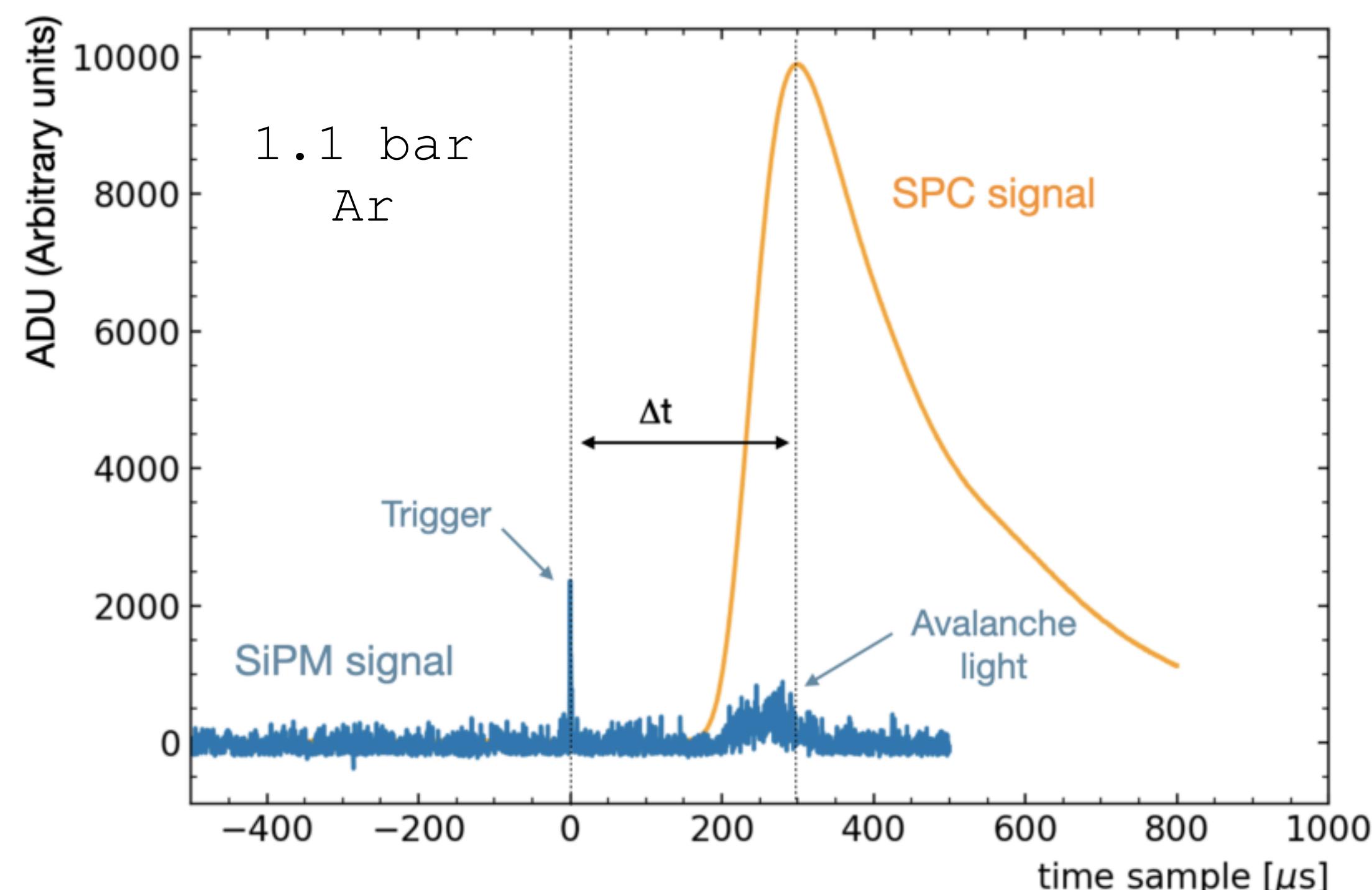
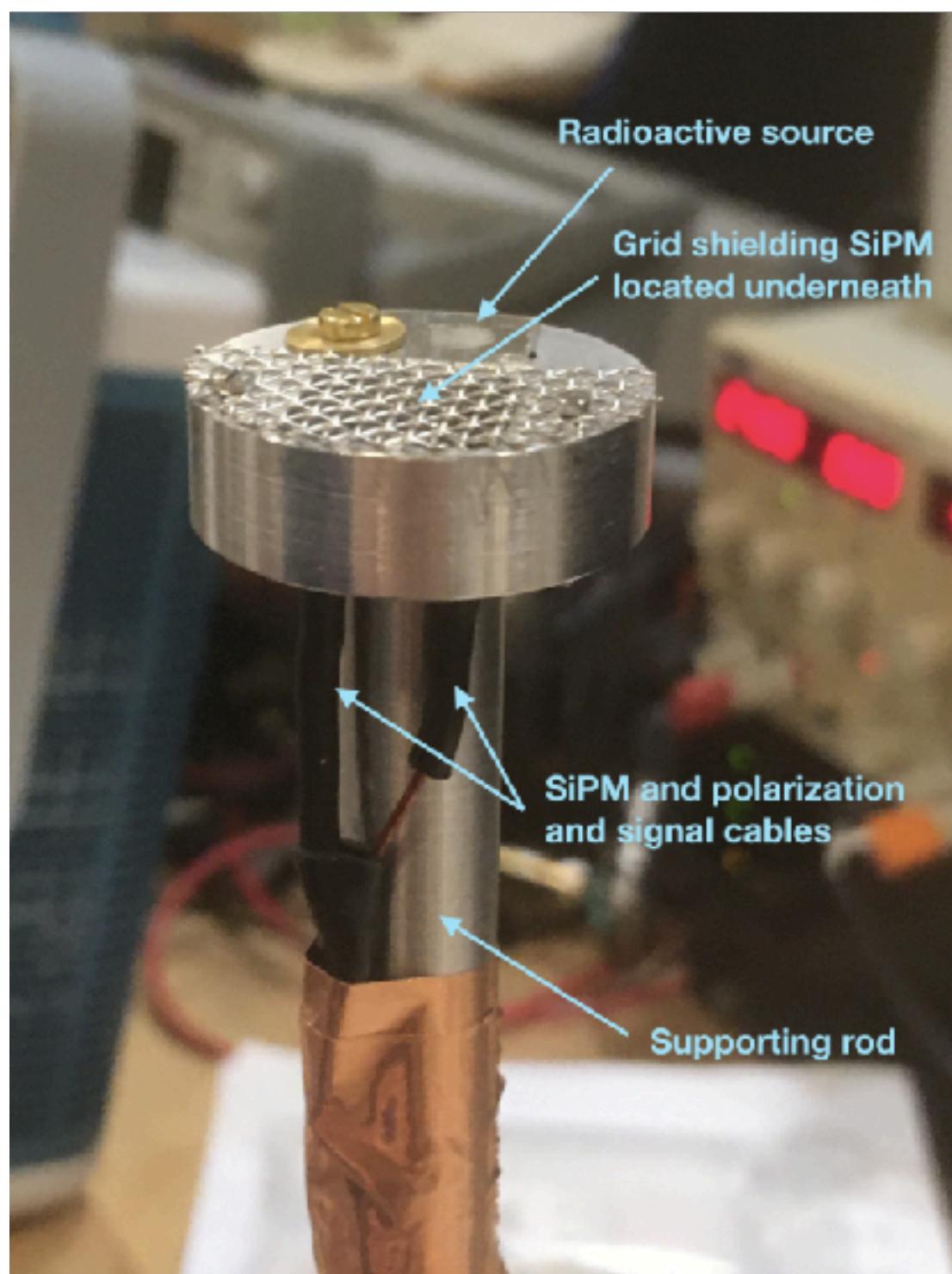
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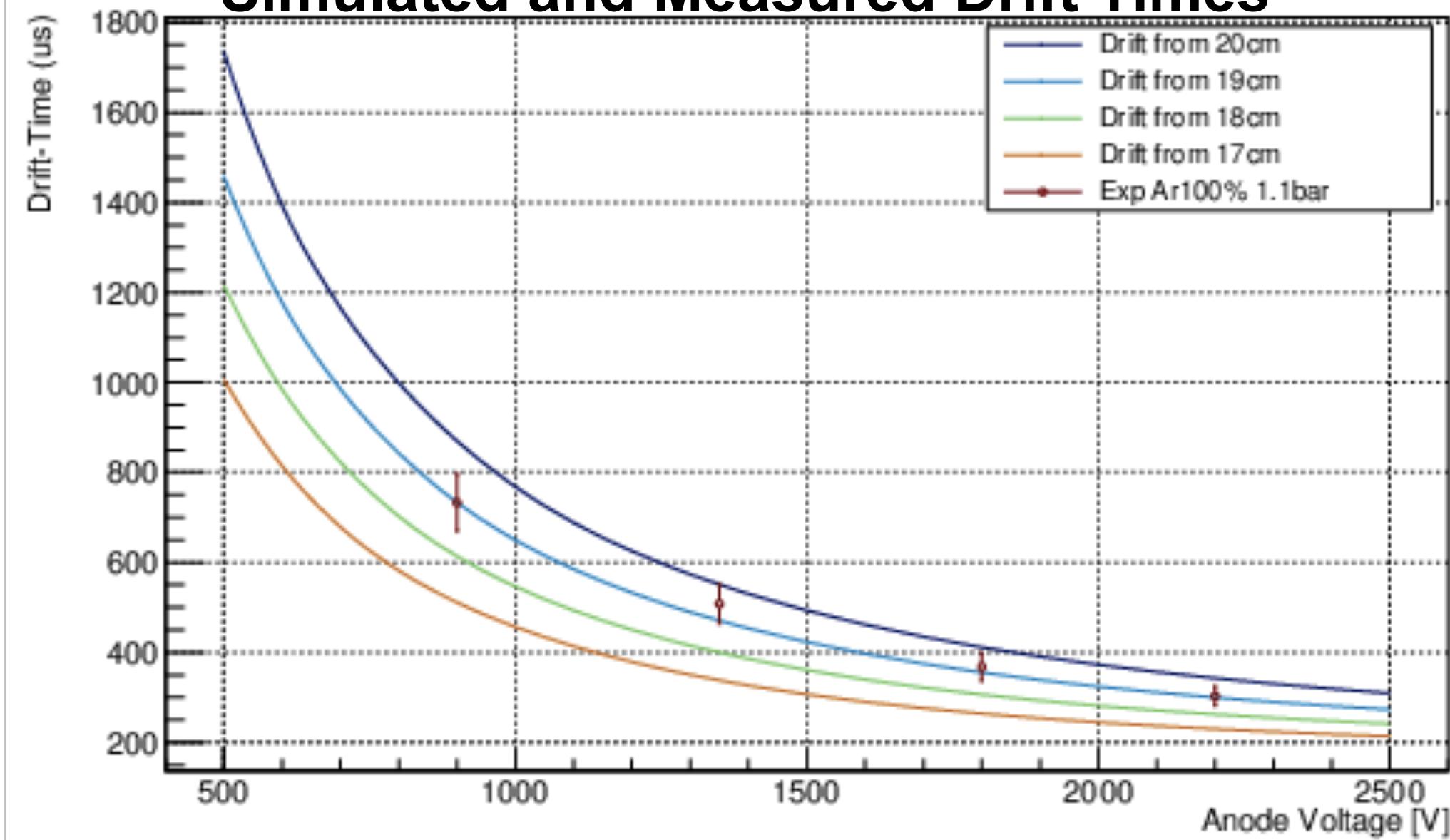
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## Simulated and Measured Drift Times



# Next Steps

- New higher-pressure detector is commissioned
  - Enable 40 bar filling
- Xe gas filling
  - Recirculation and recovery system being implemented
- Gas purification being implemented to remove electronegative impurities
- Calibration with different sources
  - $^{207}\text{Bi} \rightarrow \beta$ -particles
  - Rn source  $\rightarrow \alpha$ -particles
- Optimised sensor technologies

Prototype goals



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Prototype  
goals



# A Multi-Anode Readout - ACHINOS

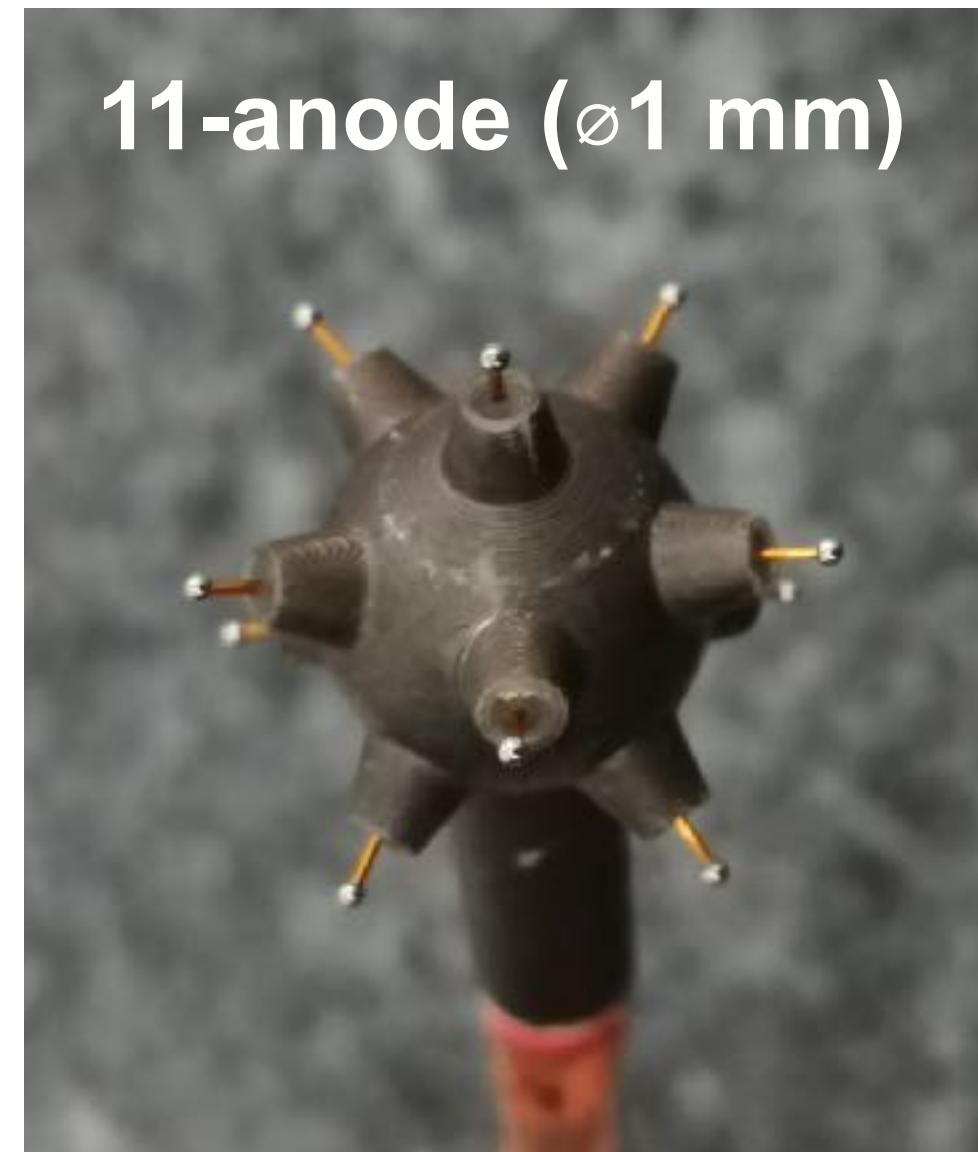
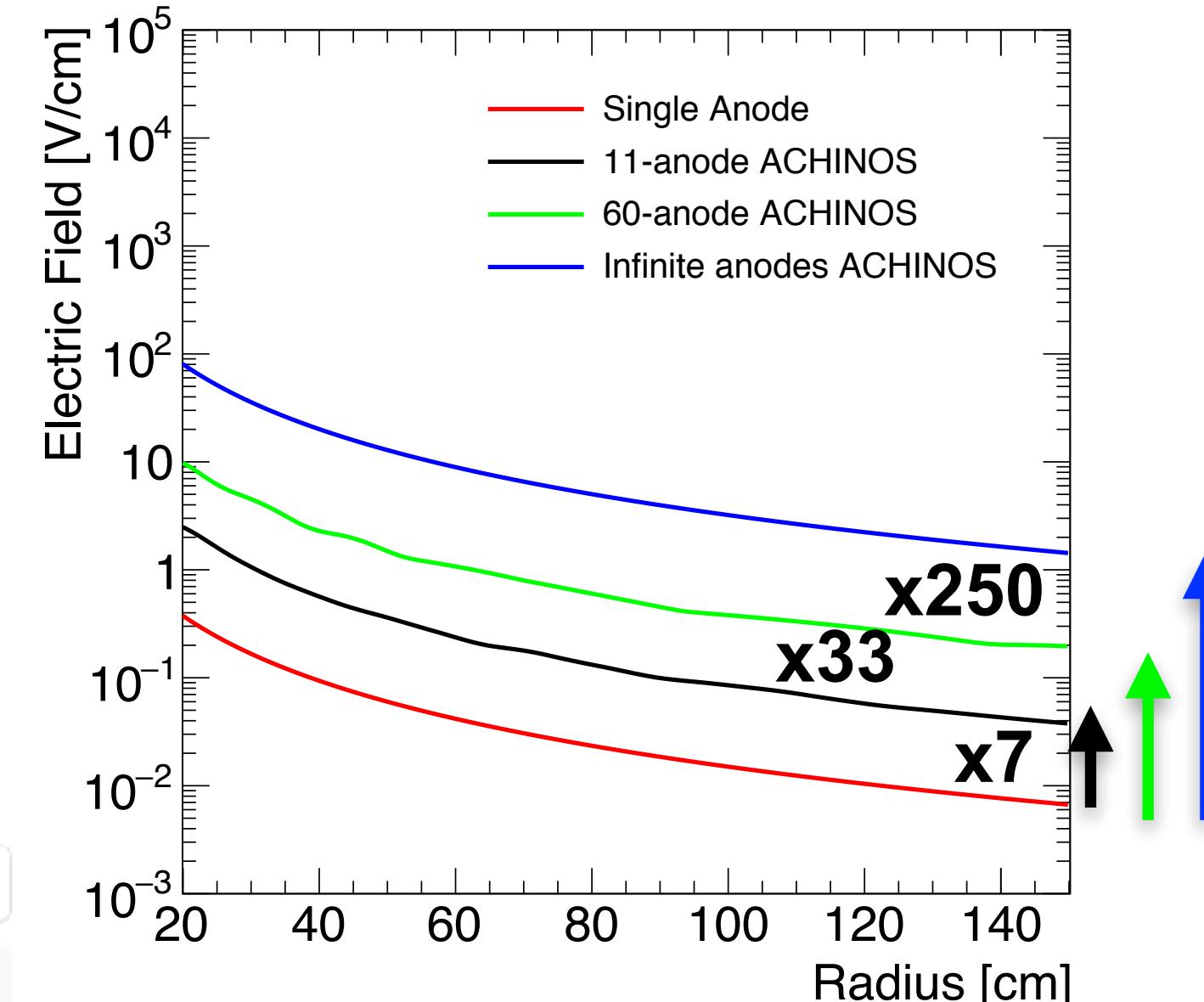
- Single anode: **gain and drift fields coupled**
- Idea: **Multiple anodes** located at same distance from centre of detector
- **Gain and drift decoupled**
  - Drift field determined by **collective field of all anodes**
  - Gain determined by **individual anode**
- Anodes arranged to sit on surface of sphere with radius  $r_s$
- Required for desired pressure operation
  - Improves detector fiducialisation

JINST 12 (2017) 12, P12031

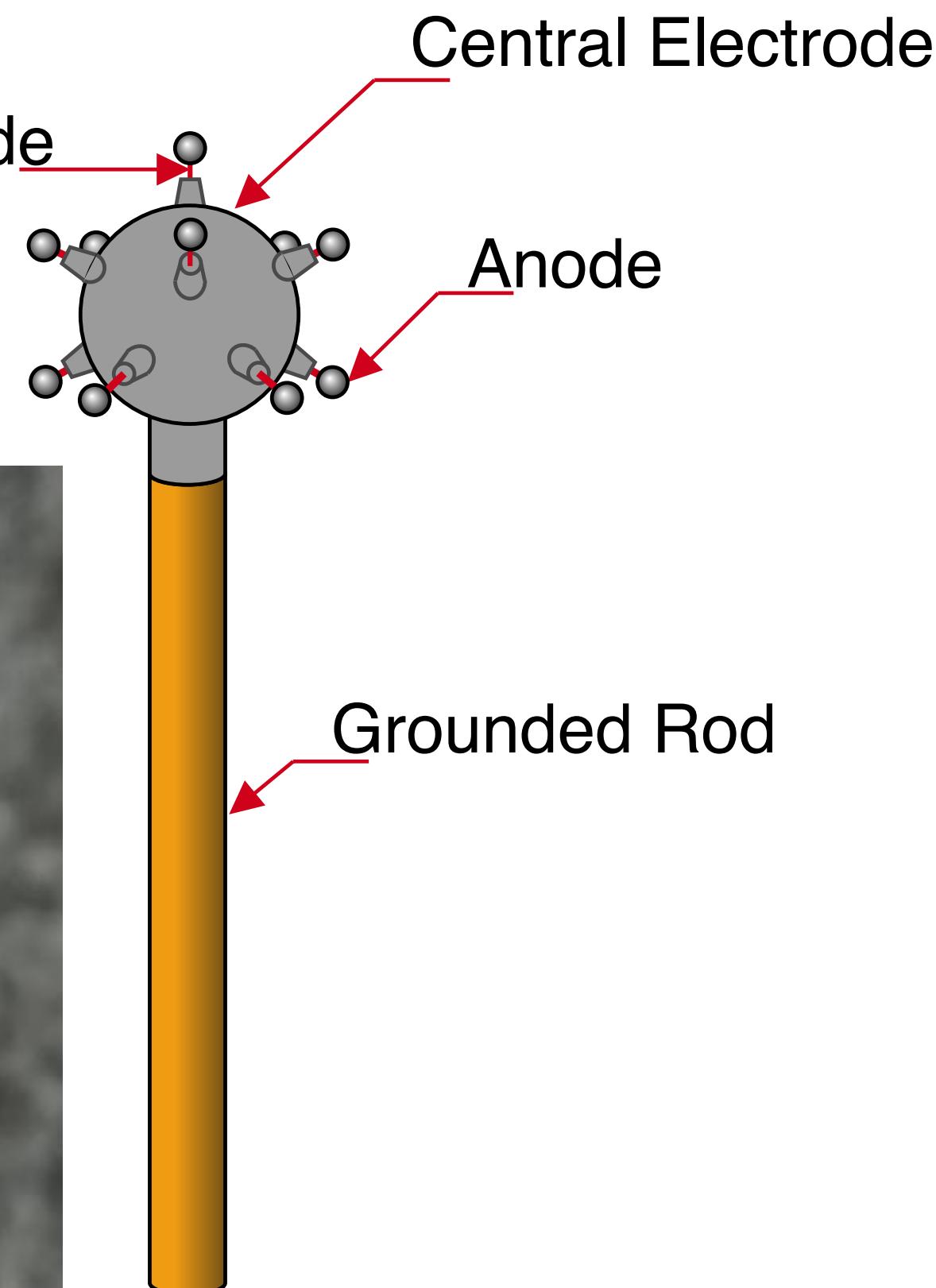
JINST 15 (2020) 11, 11



Greek – detected English  
AXINOΣ × SEA URCHIN  
ACHINOS



Wire to Anode

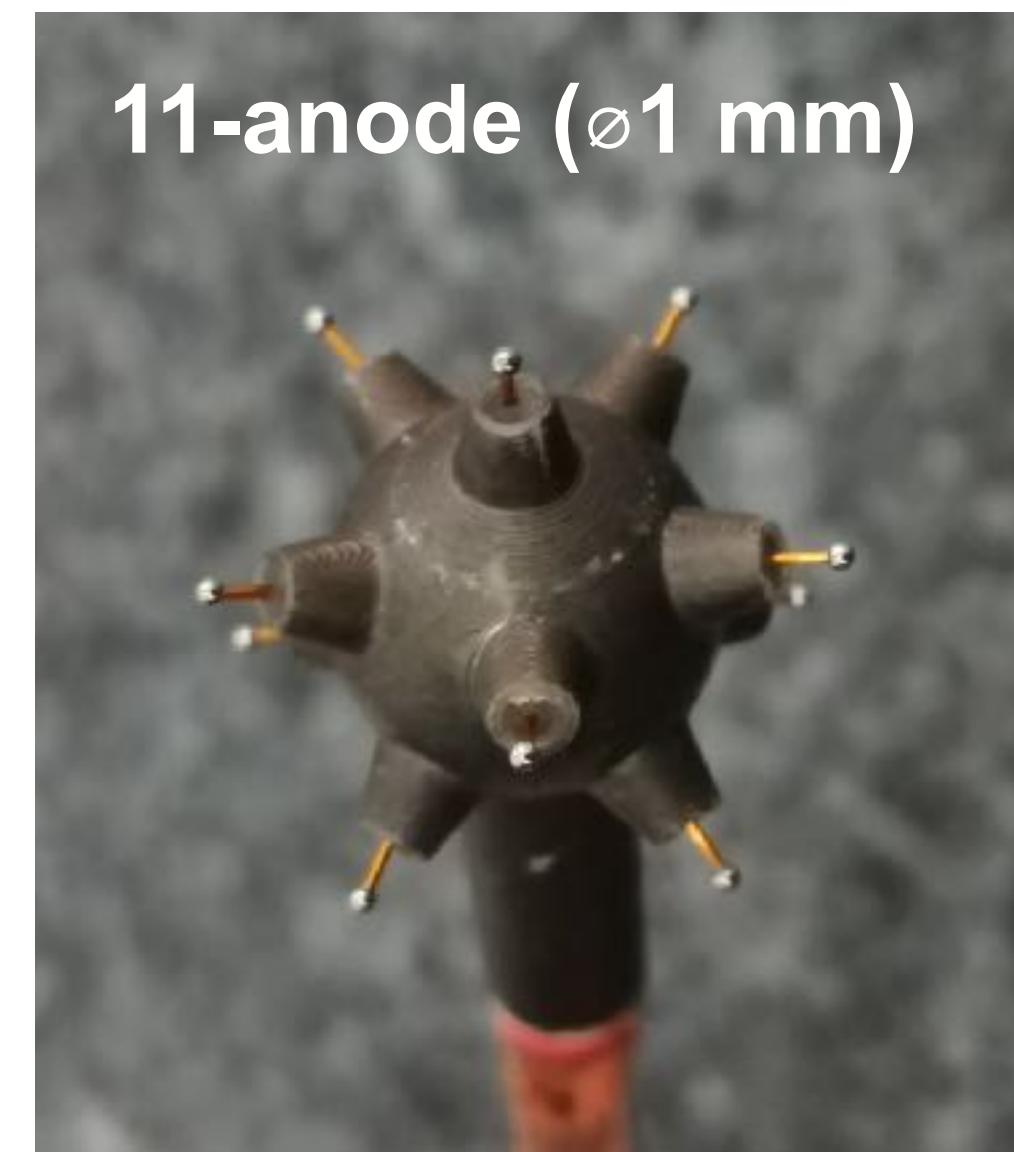
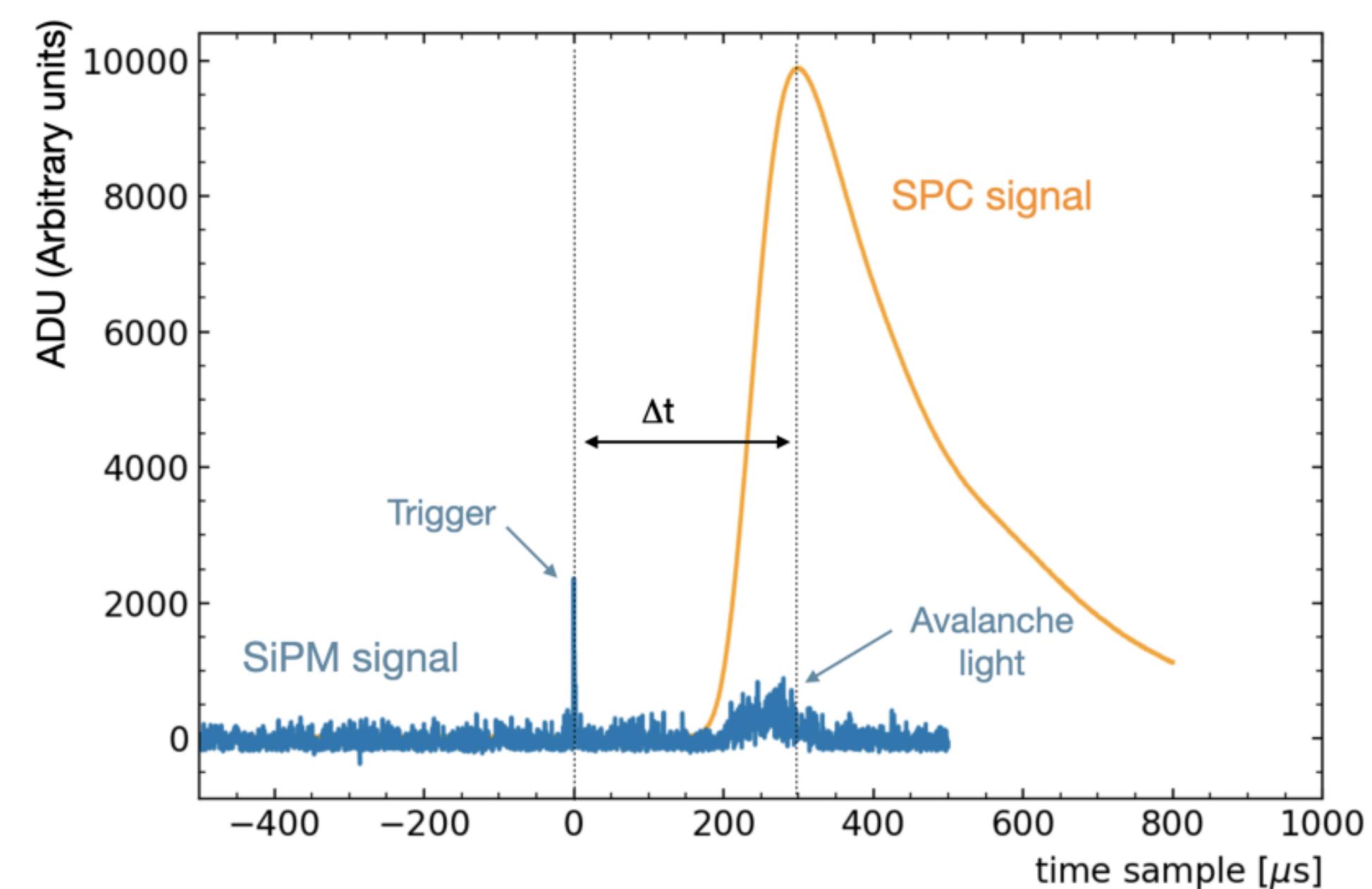
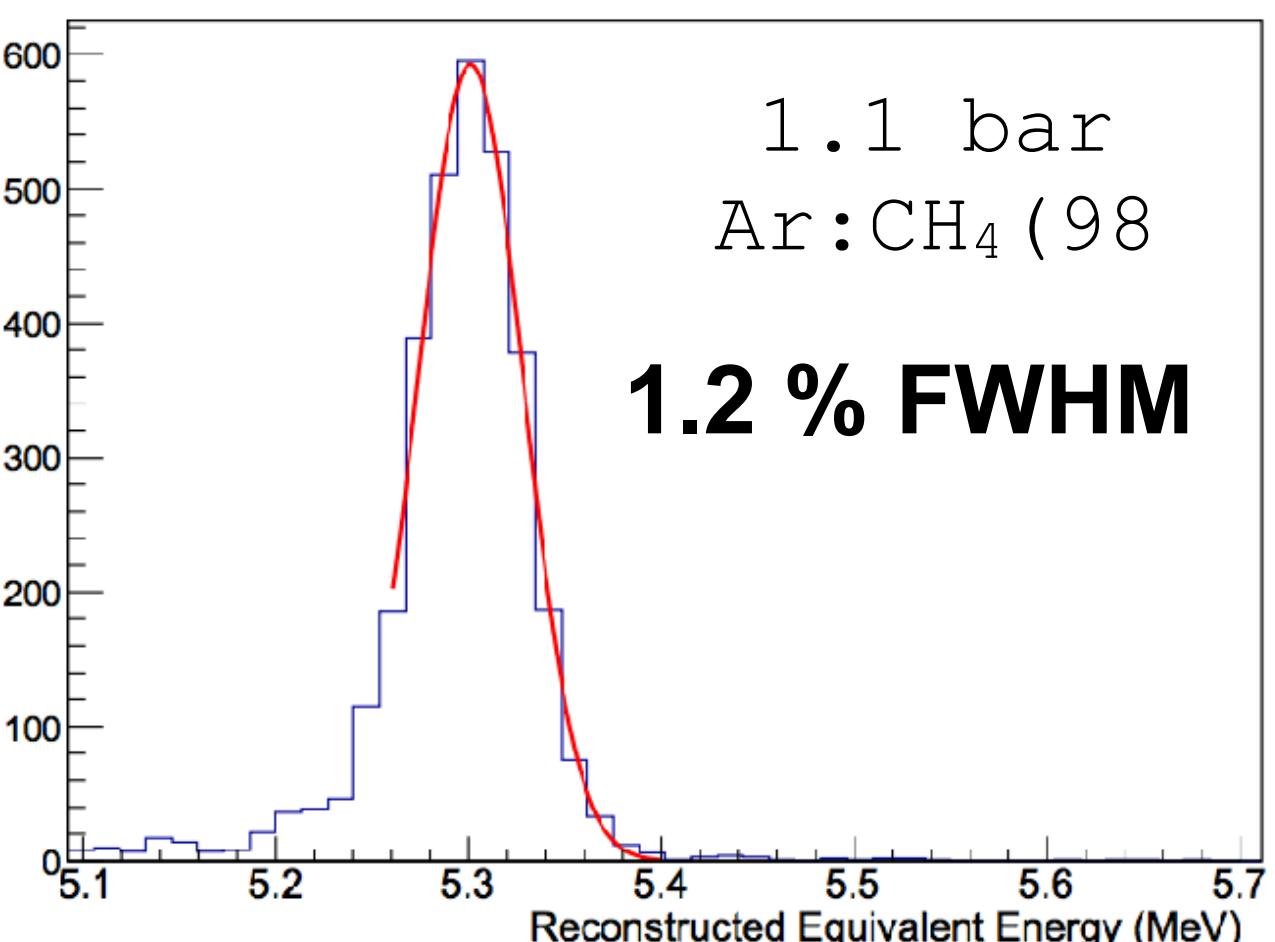


# Summary

- R2D2 proto-collaboration aims to perform  $0\nu\beta\beta$  searches with **Xe-filled SPC**
- Promising first results!
  - Energy resolution in Ar
  - Scintillation light read-out
- Next steps to enable higher pressures and Xe operation
  - Set-up commissioned
  - Prototype data taking beginning soon
- Closely working with other SPC efforts and NEWS-G
  - ACHINOS
  - Simulation framework
  - Low radioactivity materials

More on SPC applications at this conference:

- I. Katsioulas: [https://indico.stfc.ac.uk/  
event/324/contributions/3285/](https://indico.stfc.ac.uk/event/324/contributions/3285/)
- I. Manthos: [https://indico.stfc.ac.uk/event/  
324/contributions/3284/](https://indico.stfc.ac.uk/event/<br/>324/contributions/3284/)



# Additional Material



Experiment	Isotope	$S^{0\nu}_{(90\% \text{ CL})} [10^{25} \text{ yr}]$
CUORE [83]	$^{130}\text{Te}$	9.5
GERDA-II [84]	$^{76}\text{Ge}$	15
LUCIFER [85]	$^{82}\text{Se}$	1.8
MAJORANA D. [86]	$^{76}\text{Ge}$	12
NEXT [88]	$^{136}\text{Xe}$	5
AMoRE [89]	$^{100}\text{Mo}$	5
nEXO [90]	$^{136}\text{Xe}$	660
PandaX-III [91]	$^{136}\text{Xe}$	11
SNO+ [92]	$^{130}\text{Te}$	9
SuperNEMO [93]	$^{82}\text{Se}$	10

*Adv.High Energy Phys. 2016 (2016) 2162659*

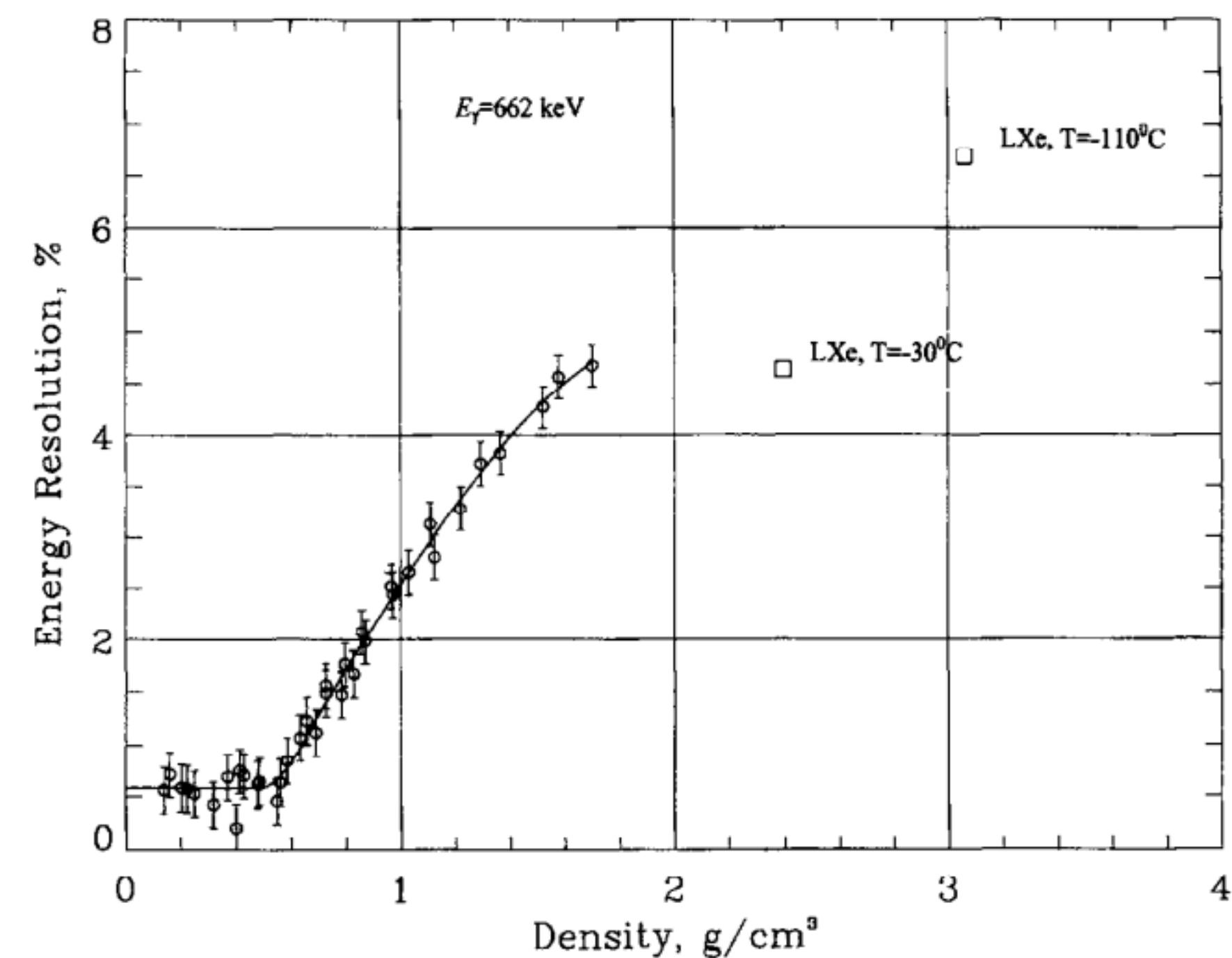
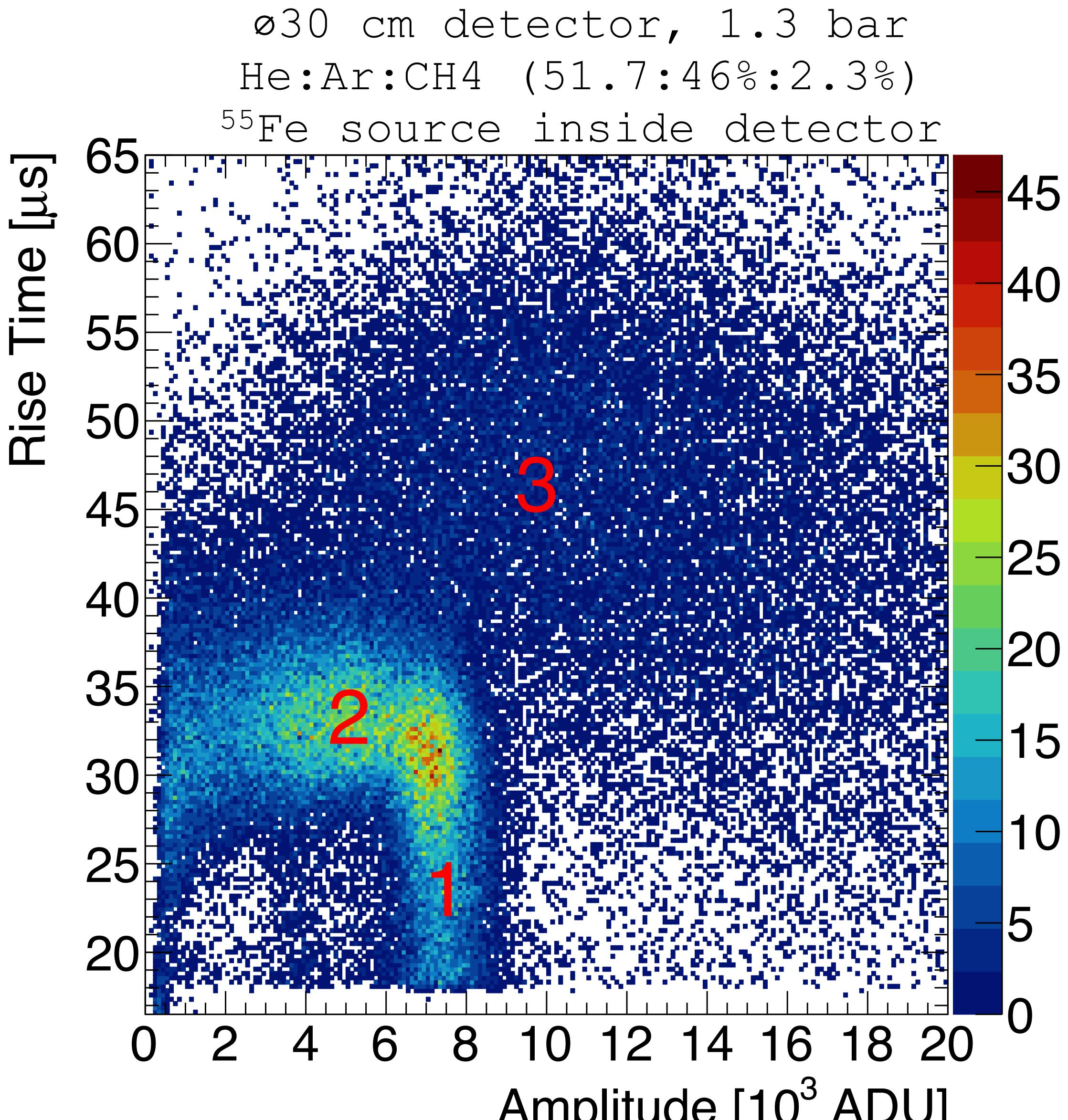
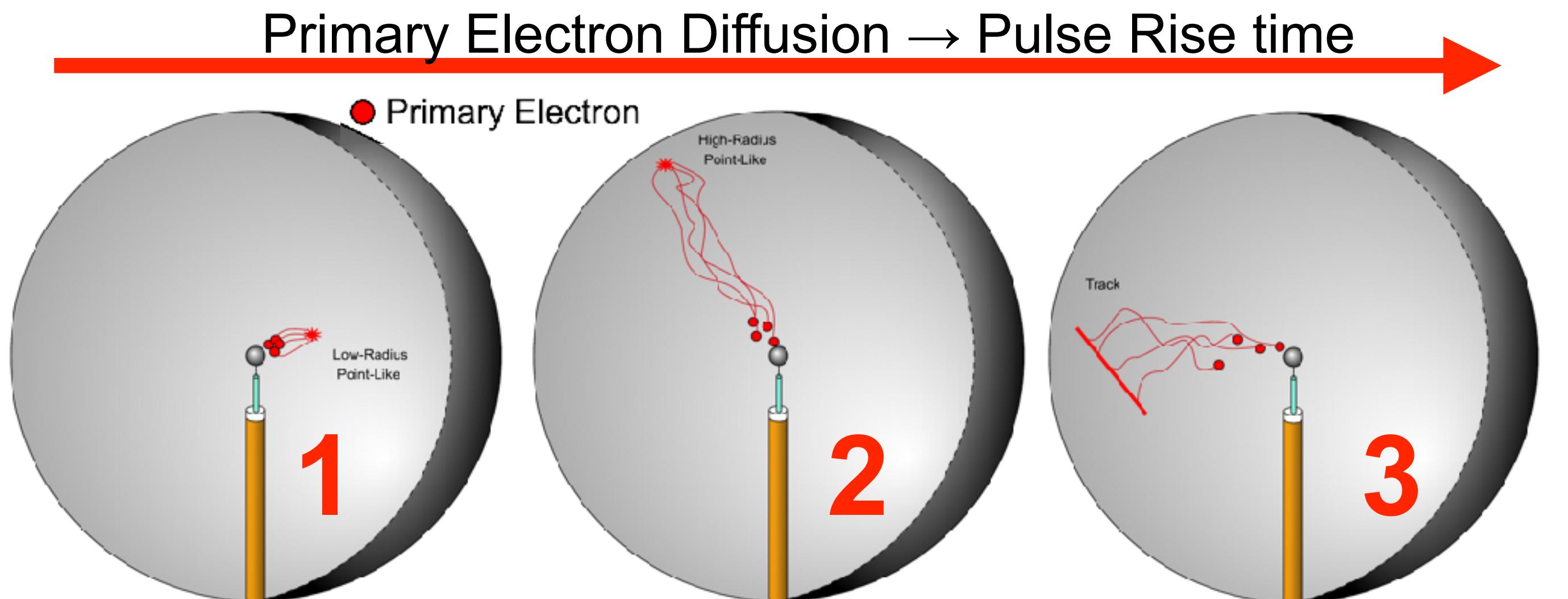


Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

NIMA 396 11 (1997) 360-370

# Pulse-Shape Discrimination

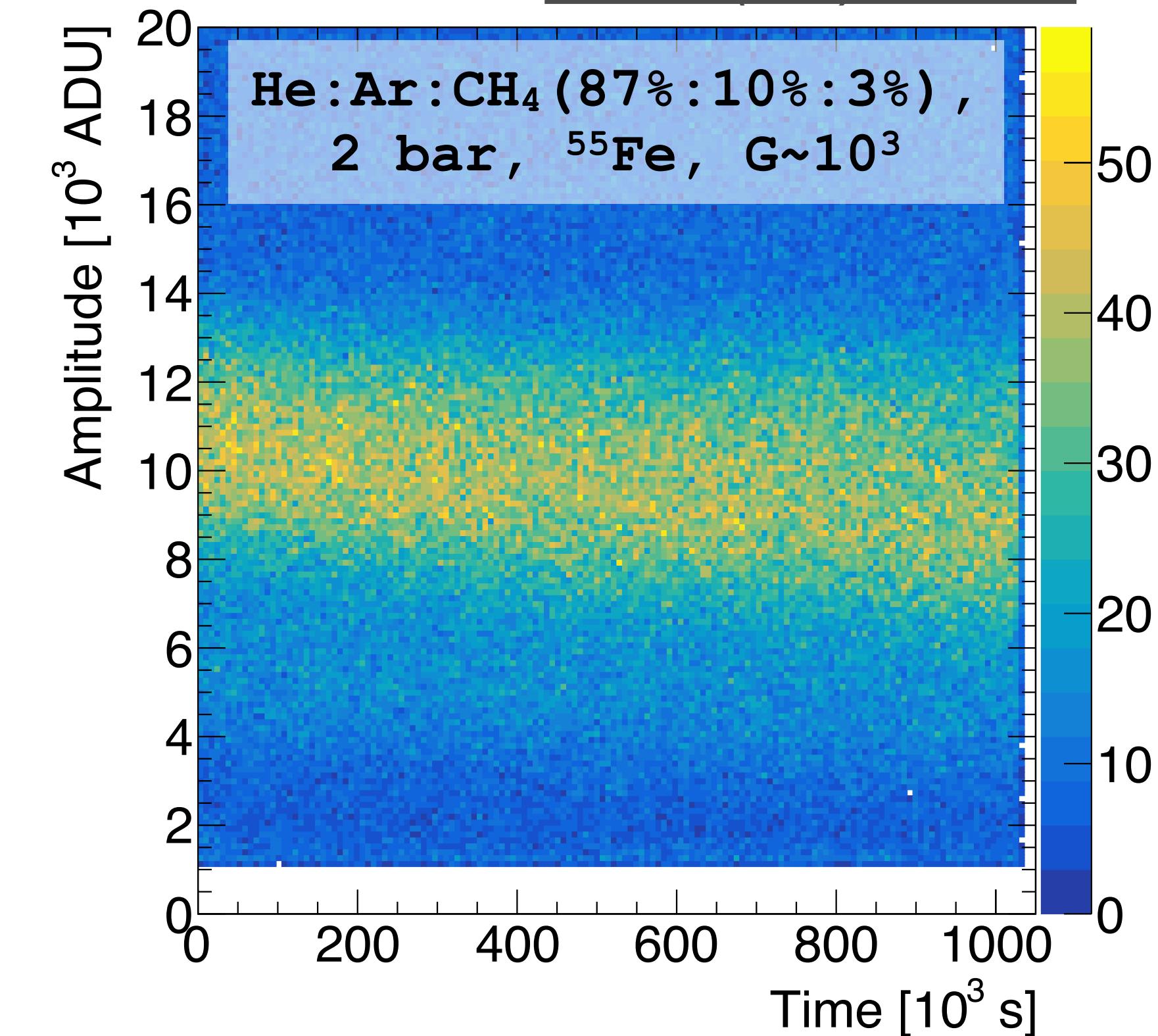
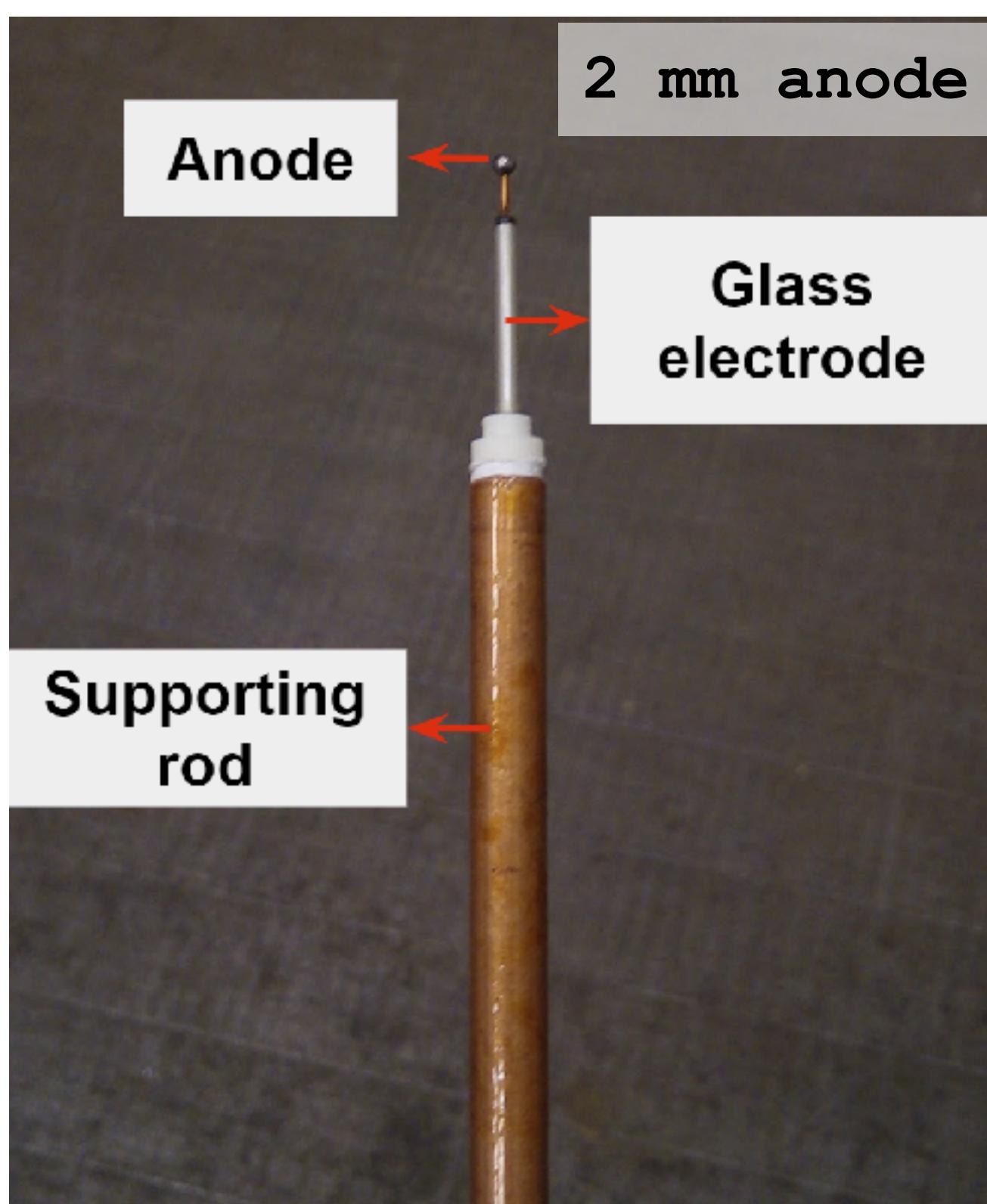
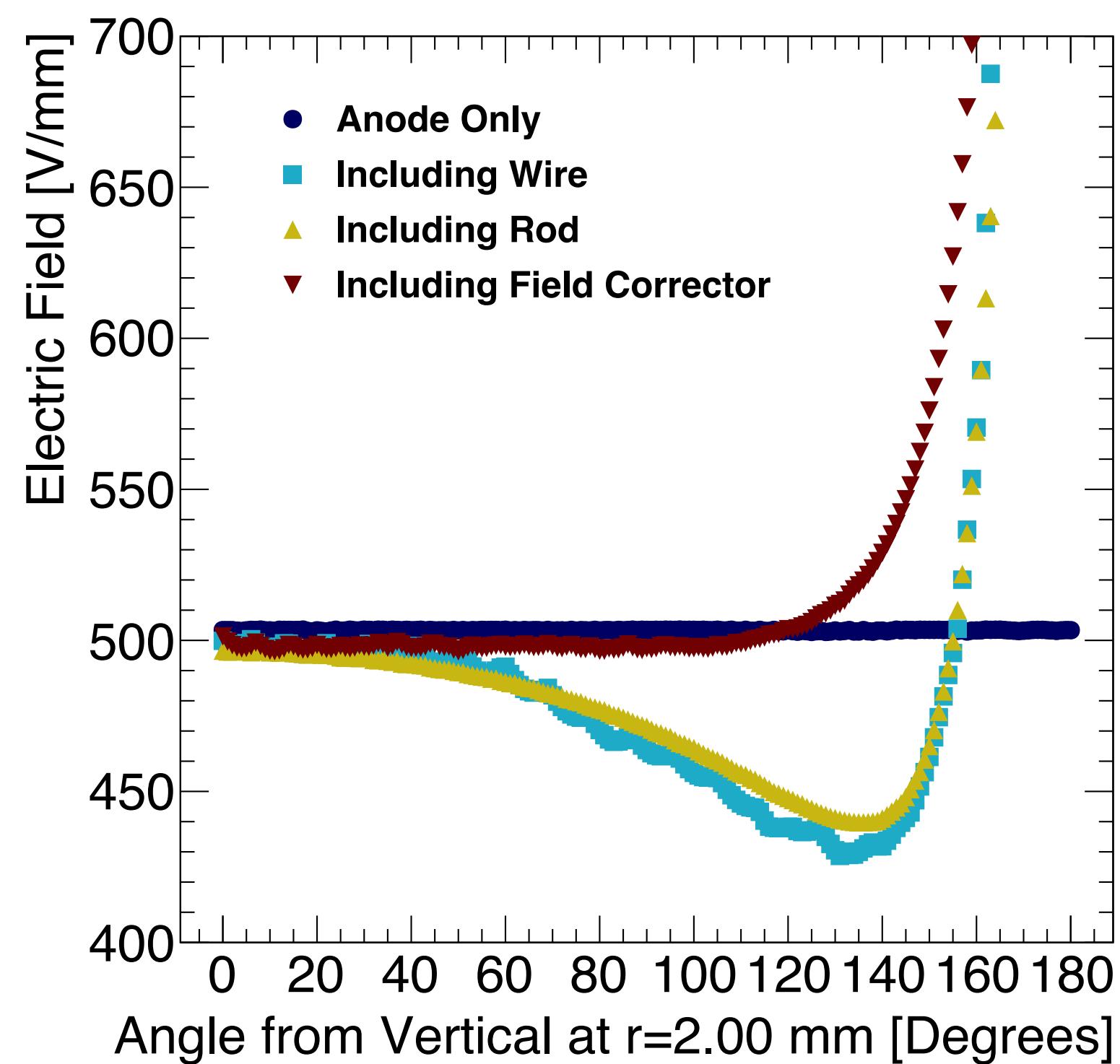
- Lots of information in a pulse. e.g. in rise time
- Electron from **larger radii diffuse more**
  - Larger spread in arrival → higher pulse rise time/width
- Spatially extended primary ionisation results in higher rise time/width
- **Particle ID by pulse-shape discrimination** possible



# Read-out Technologies: Single Anode

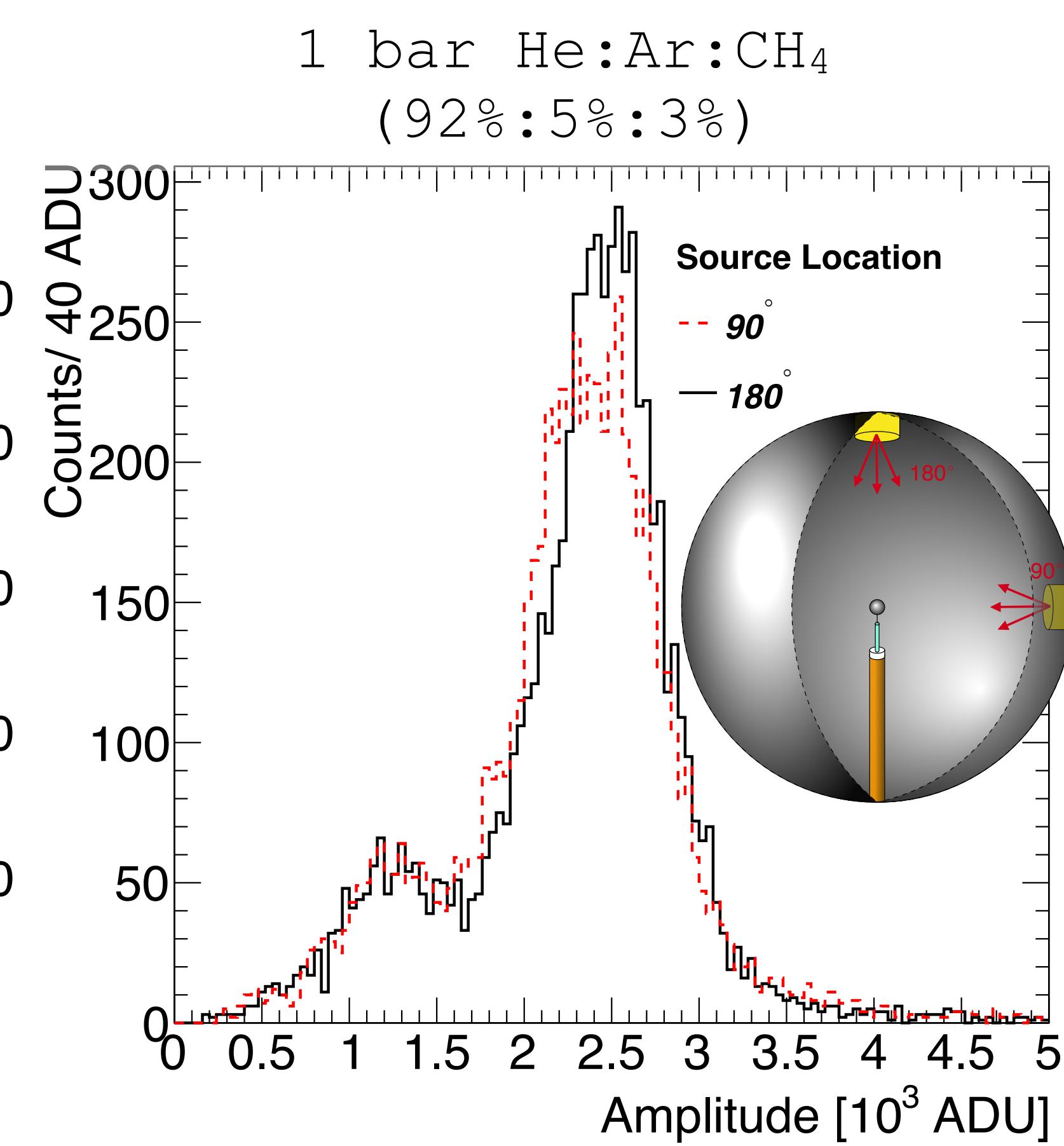
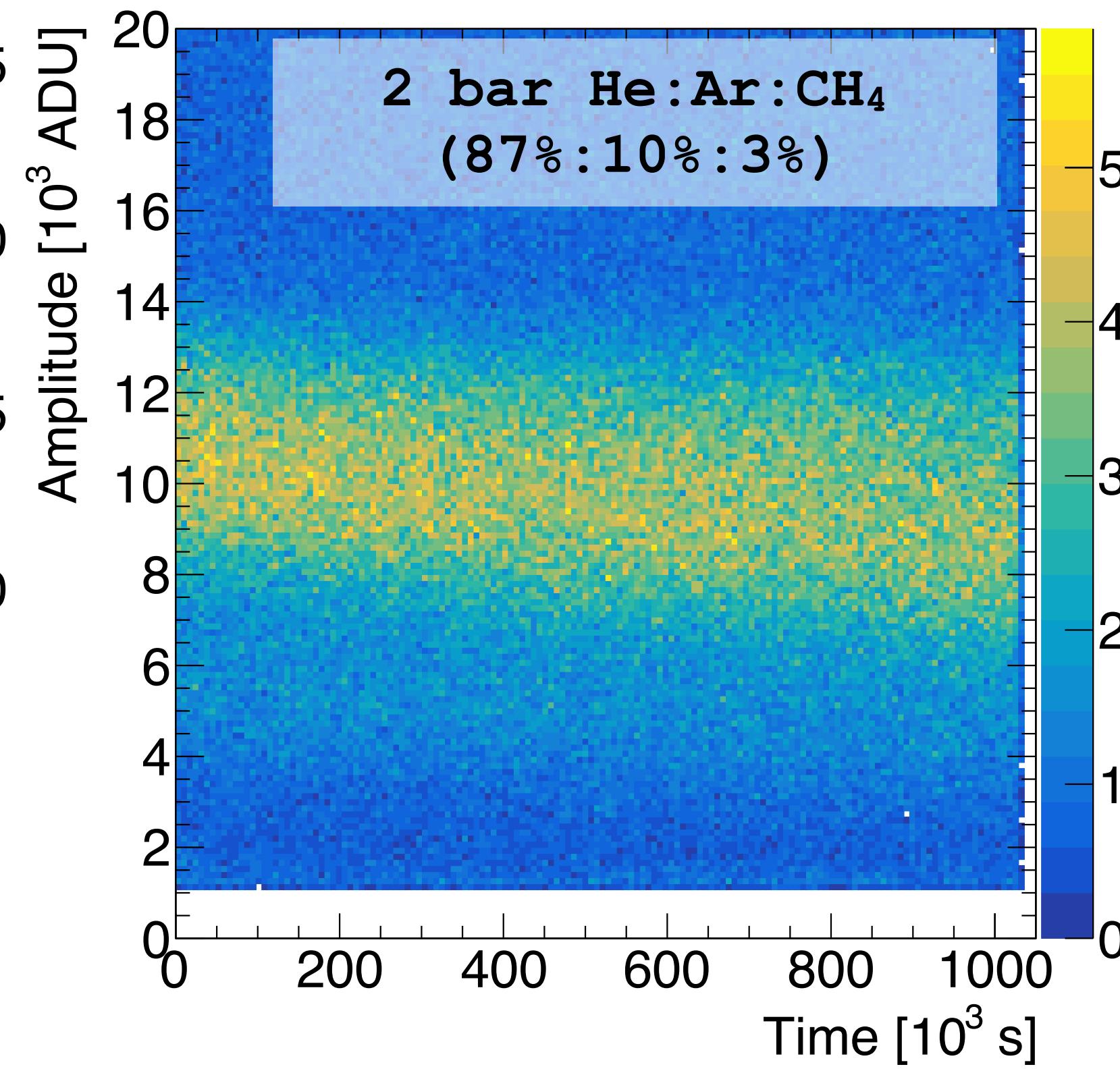
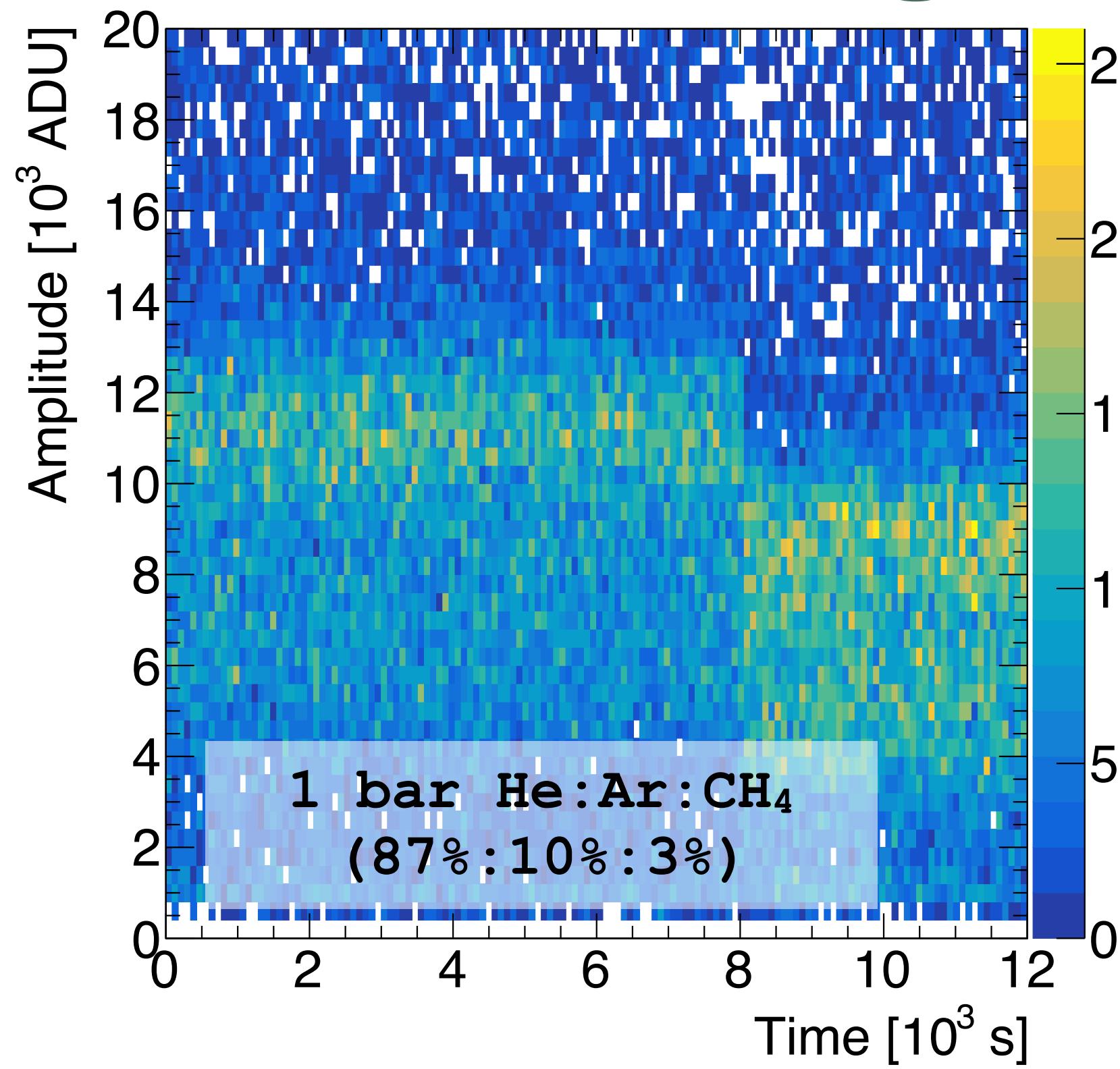
*JINST 13 (2018) 11, P11006*

- Single anode read-out with **resistive correction electrode**
  - Field shaping near anodes → improved energy resolution
  - Resistive materials → improved stability and spark quenching



- Over ~12 days, **stable gain, no sparks**
- Small decrease in gain over time due to contaminant gases (e.g. O<sub>2</sub>) leaking into the detector/out gassing

# Sensor Testing



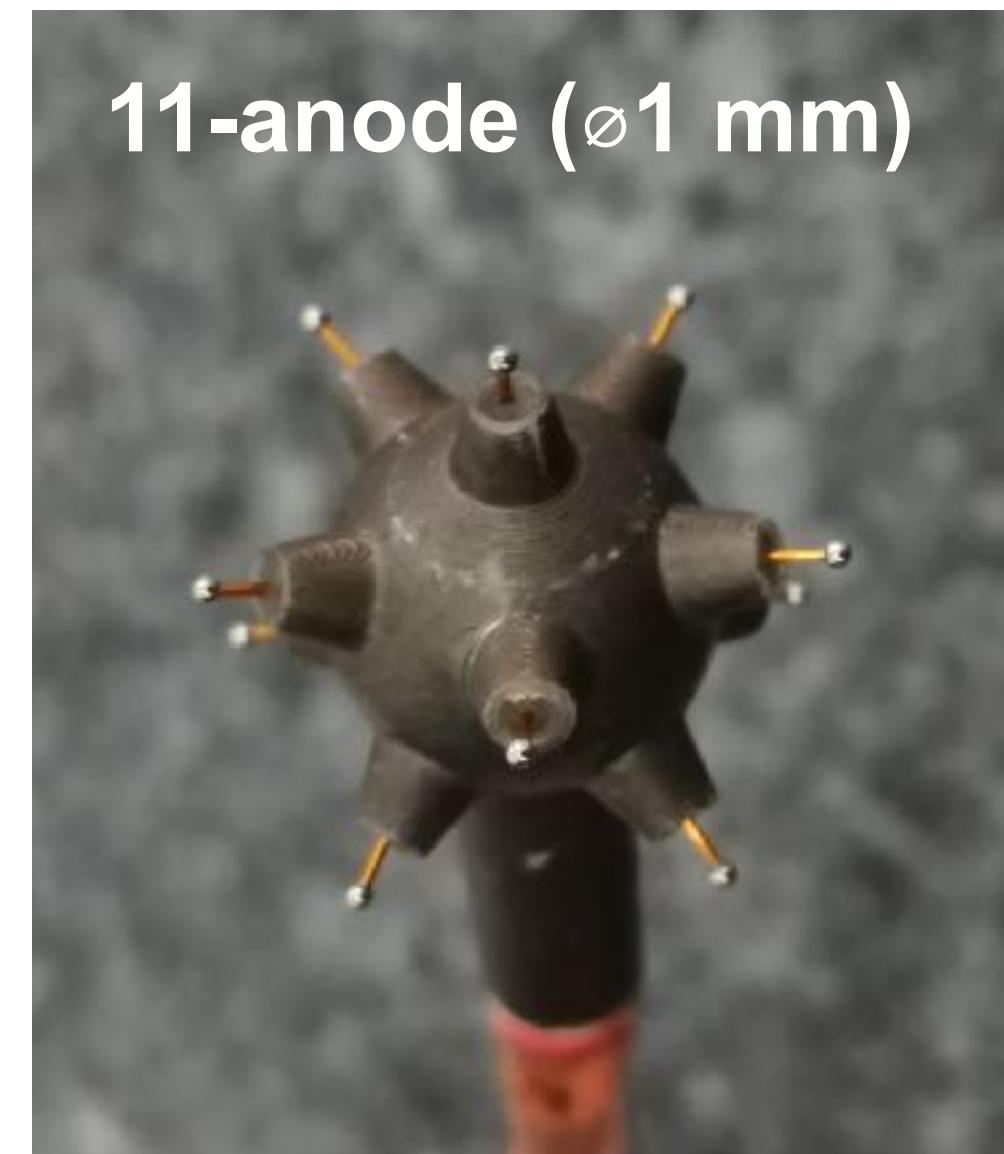
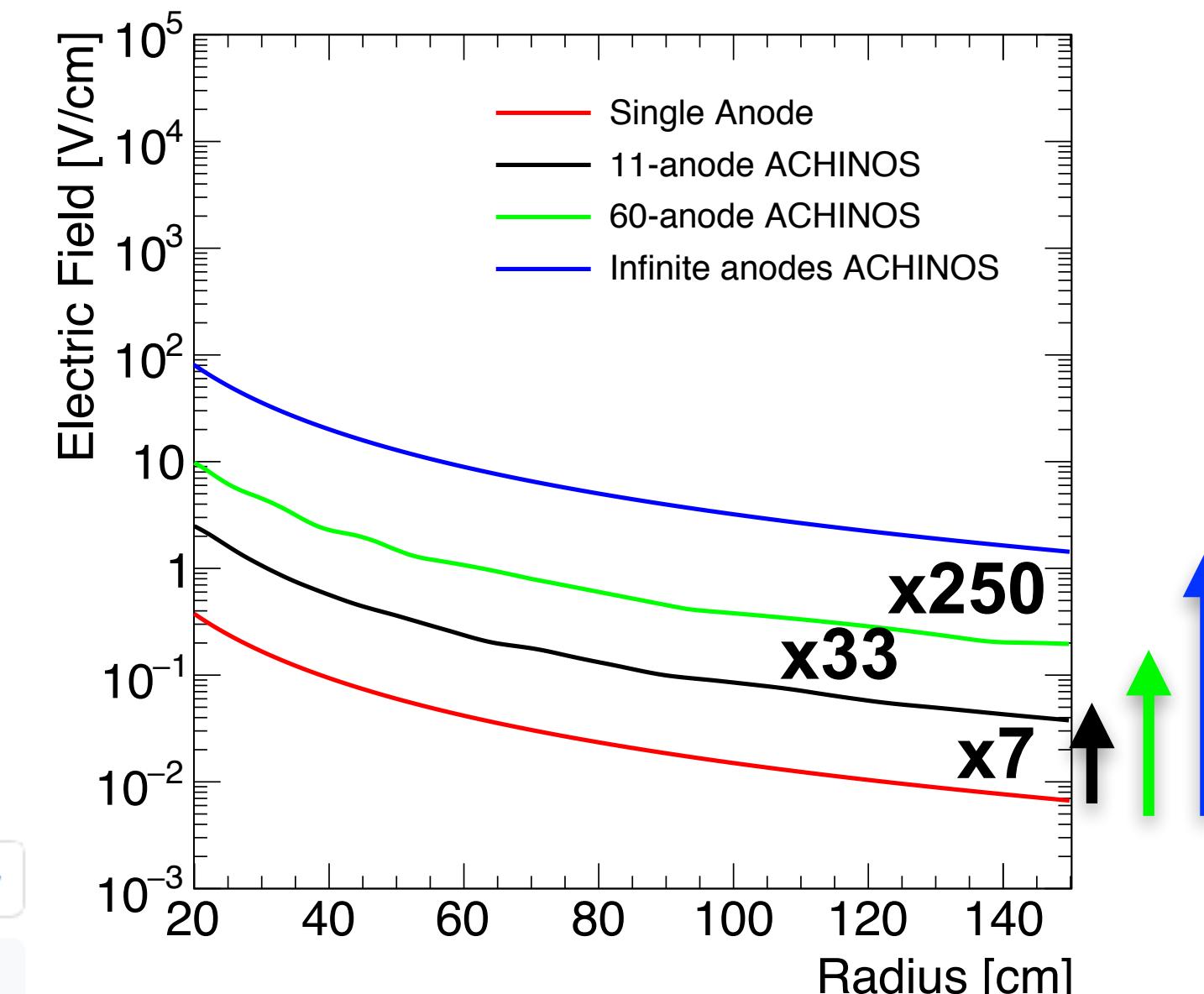
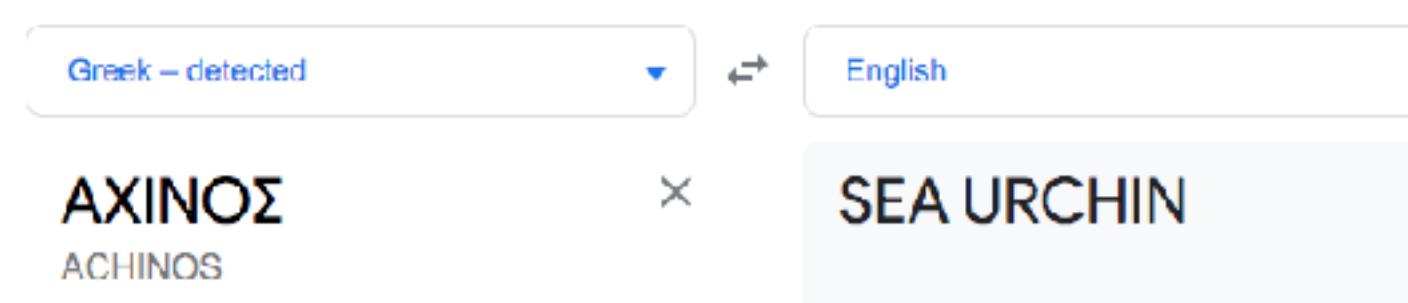
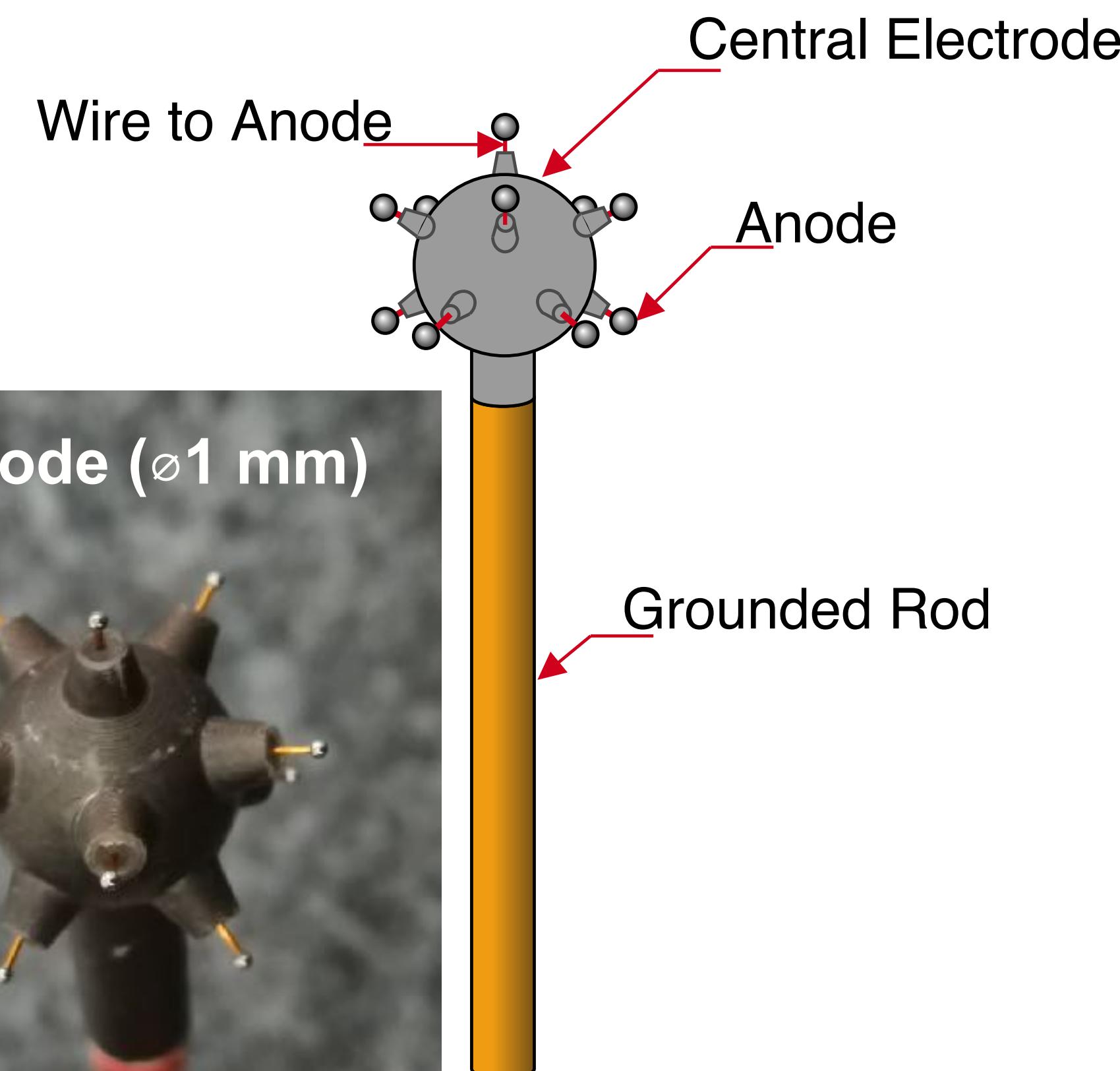
- **55Fe** source placed inside detector
  - Source of 5.9 keV X-rays
- At 8000 s, **correction electrode voltage changed** from 100 V to 200 V
  - Immediate response in amplitude
- Over ~12 days, **stable gain, no sparks**
- Small decrease in gain over time due to contaminant gases (e.g. O<sub>2</sub>) leaking into the detector/out gassing
- Source moved between two positions
  - **Uniform detector response**

# Breakthrough! A Multi-Anode Readout - ACHINOS

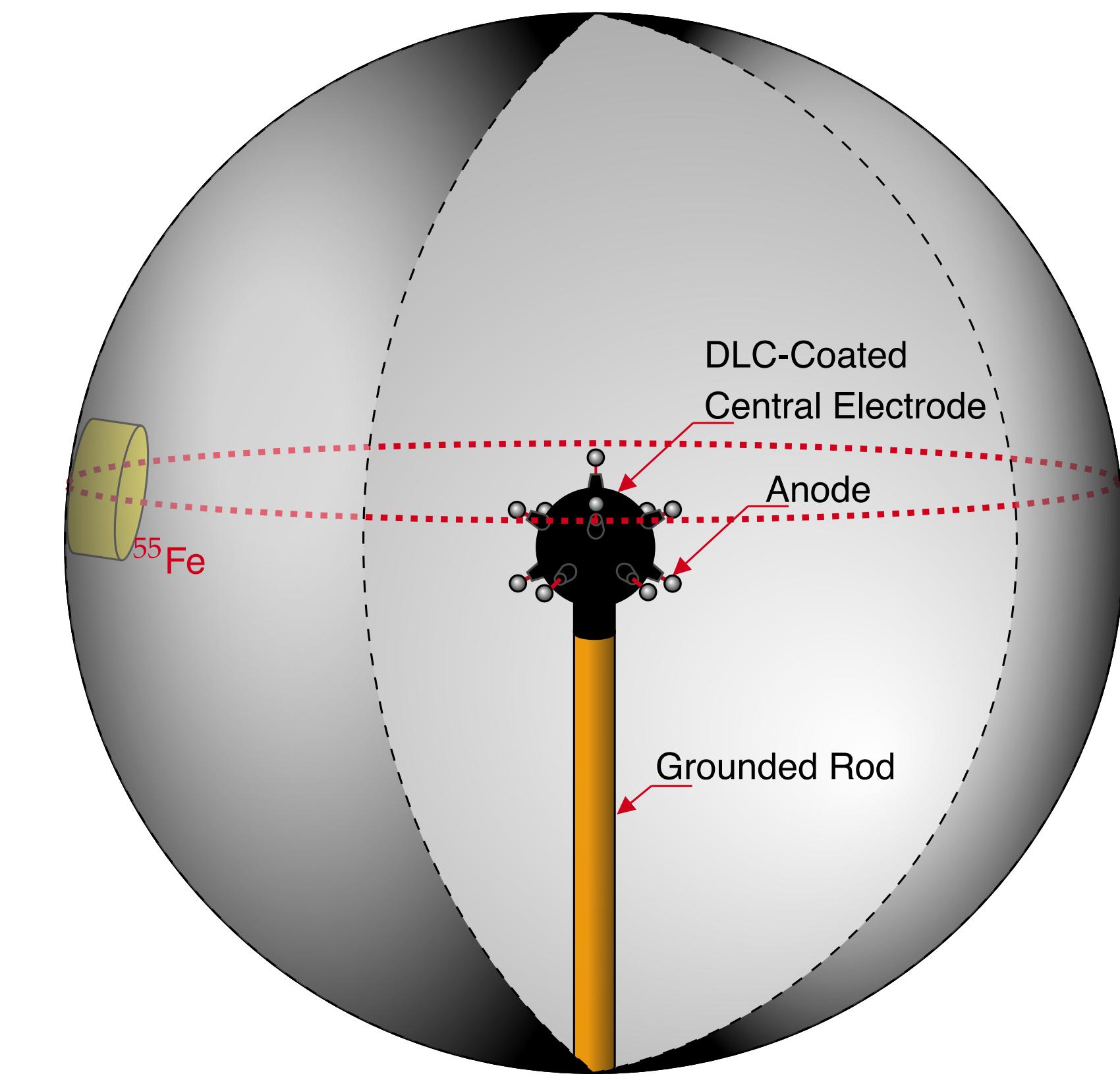
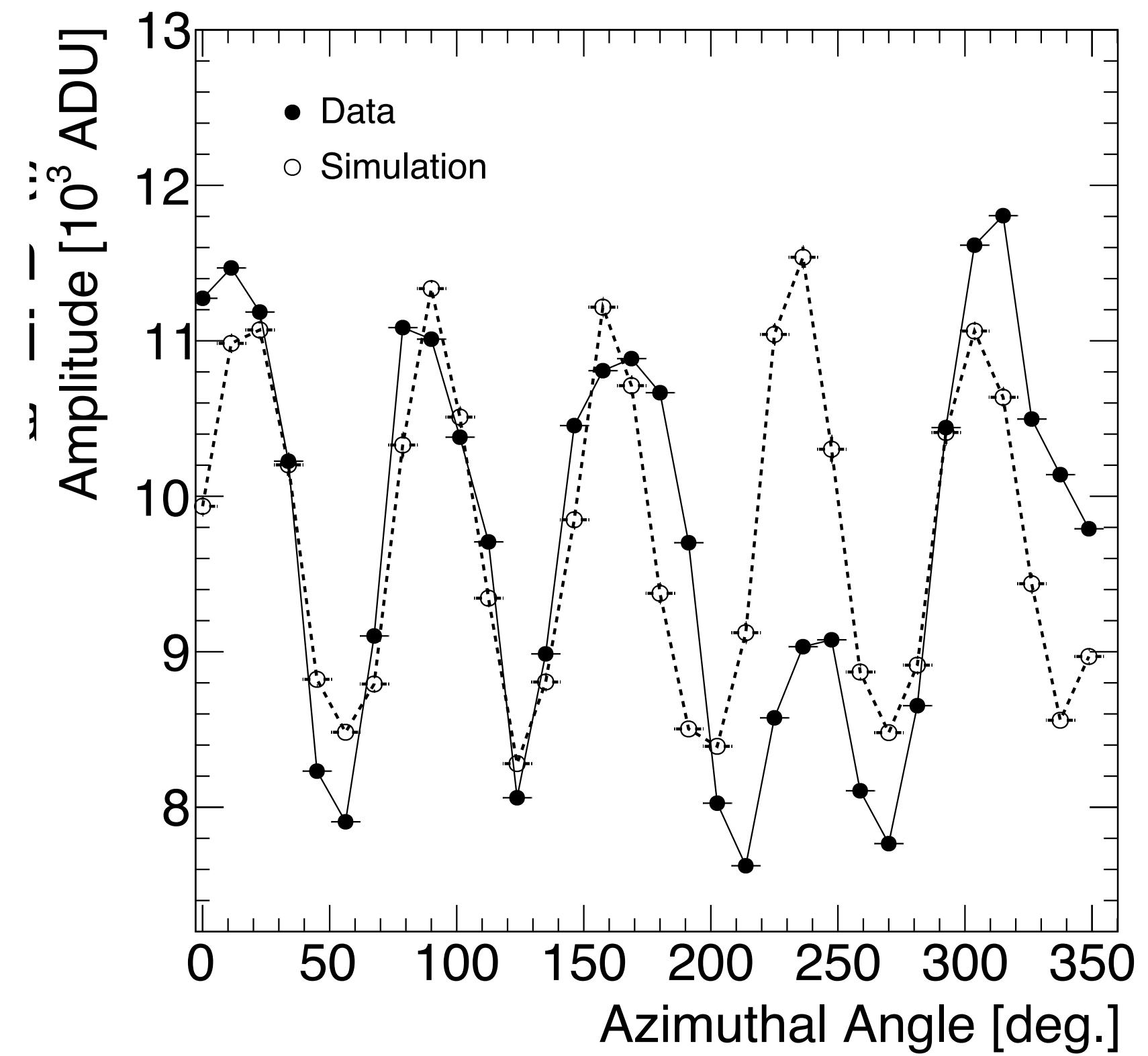
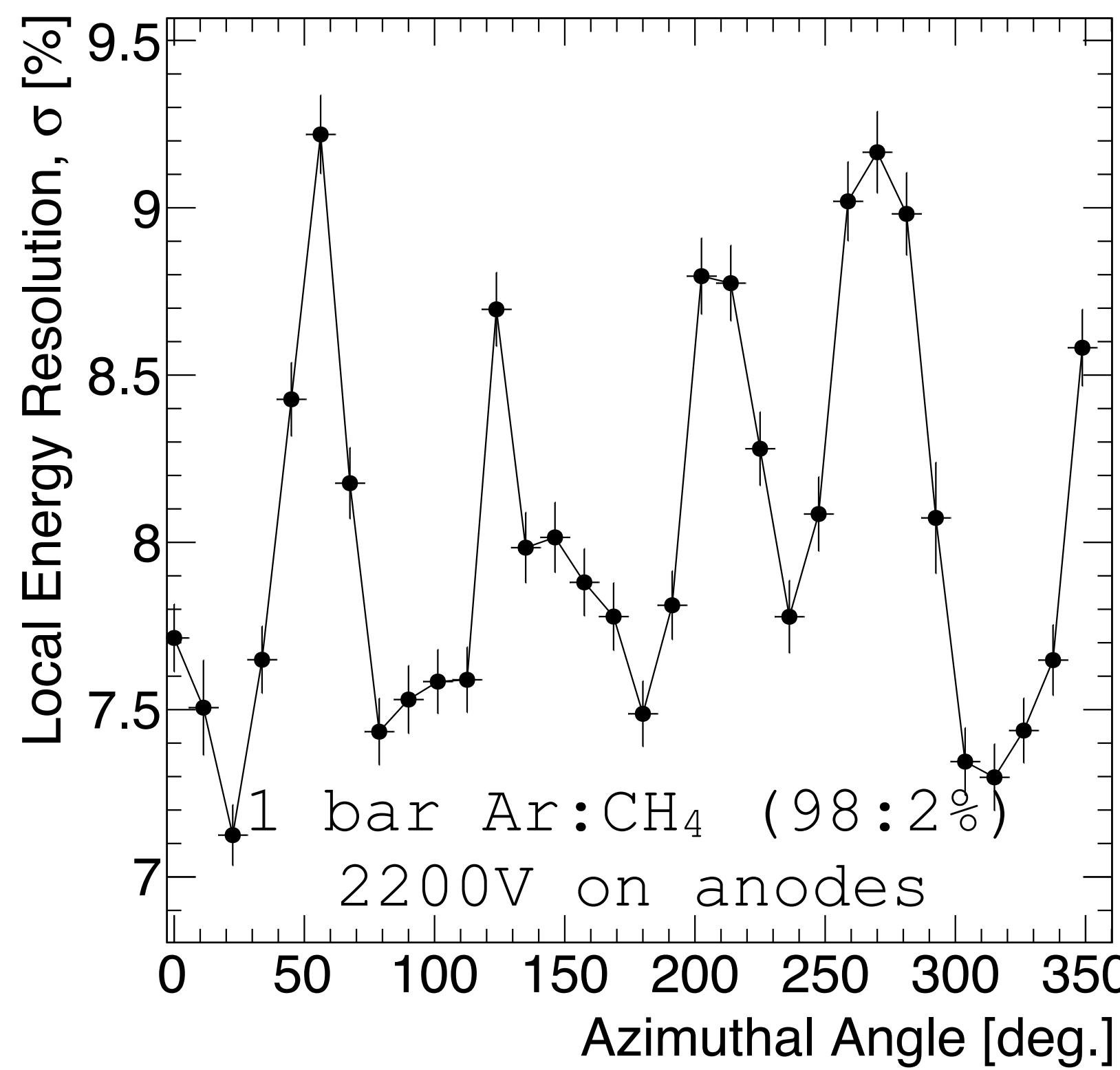
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- Idea: **Multiple anodes** located at same distance from centre of detector
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  - Drift field determined by **collective field of all anodes**
  - Gain determined by **individual anode**
- Anodes arranged to sit on surface of sphere with radius  $r_s$
- Future: Individual anode readout
  - Track reconstruction + improved fiducialisation capability

JINST 12 (2017) 12, P12031

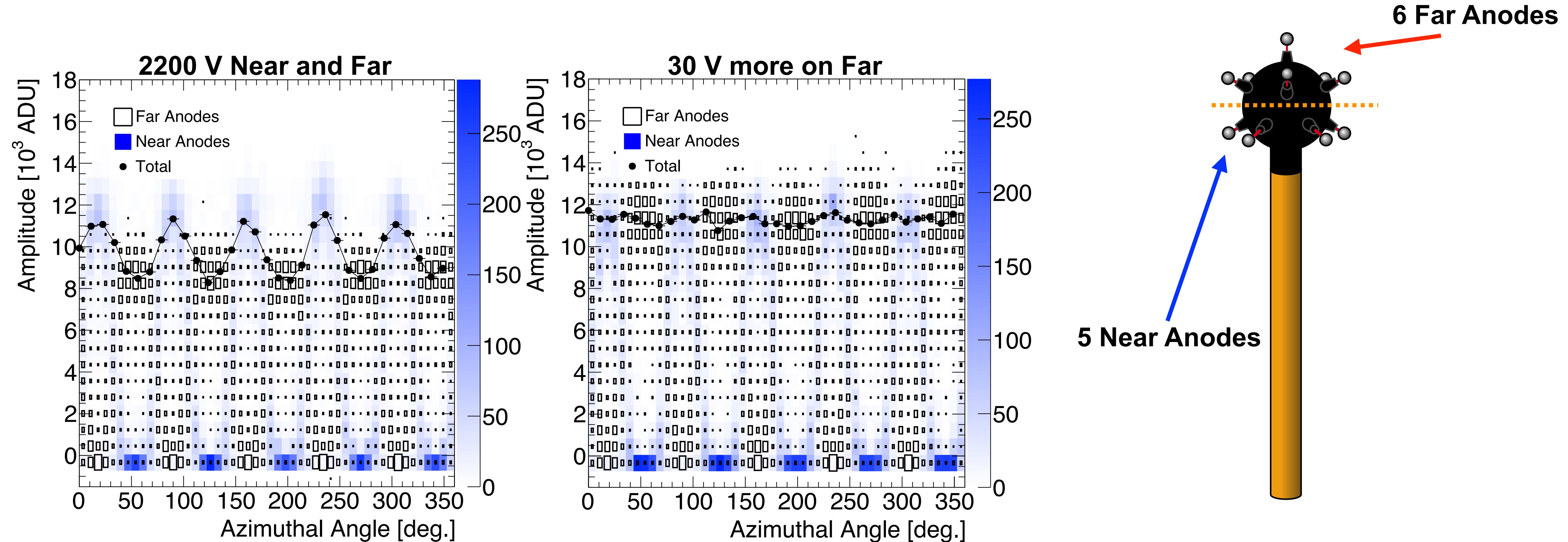
JINST 15 (2020) 11, 11



# Uniformity of Anode Response



# ACHINOS Simulation Study



- Simulate experiment sending 5.9 keV photons from different  $\varphi$  at fixed  $\theta$
- Looking at signal generated on **Near and Far anodes separately** found higher amplitudes on Near
- **Electric field higher on Near side** due to grounded rod
- **Increasing voltage applied to Far anodes corrects for effect**

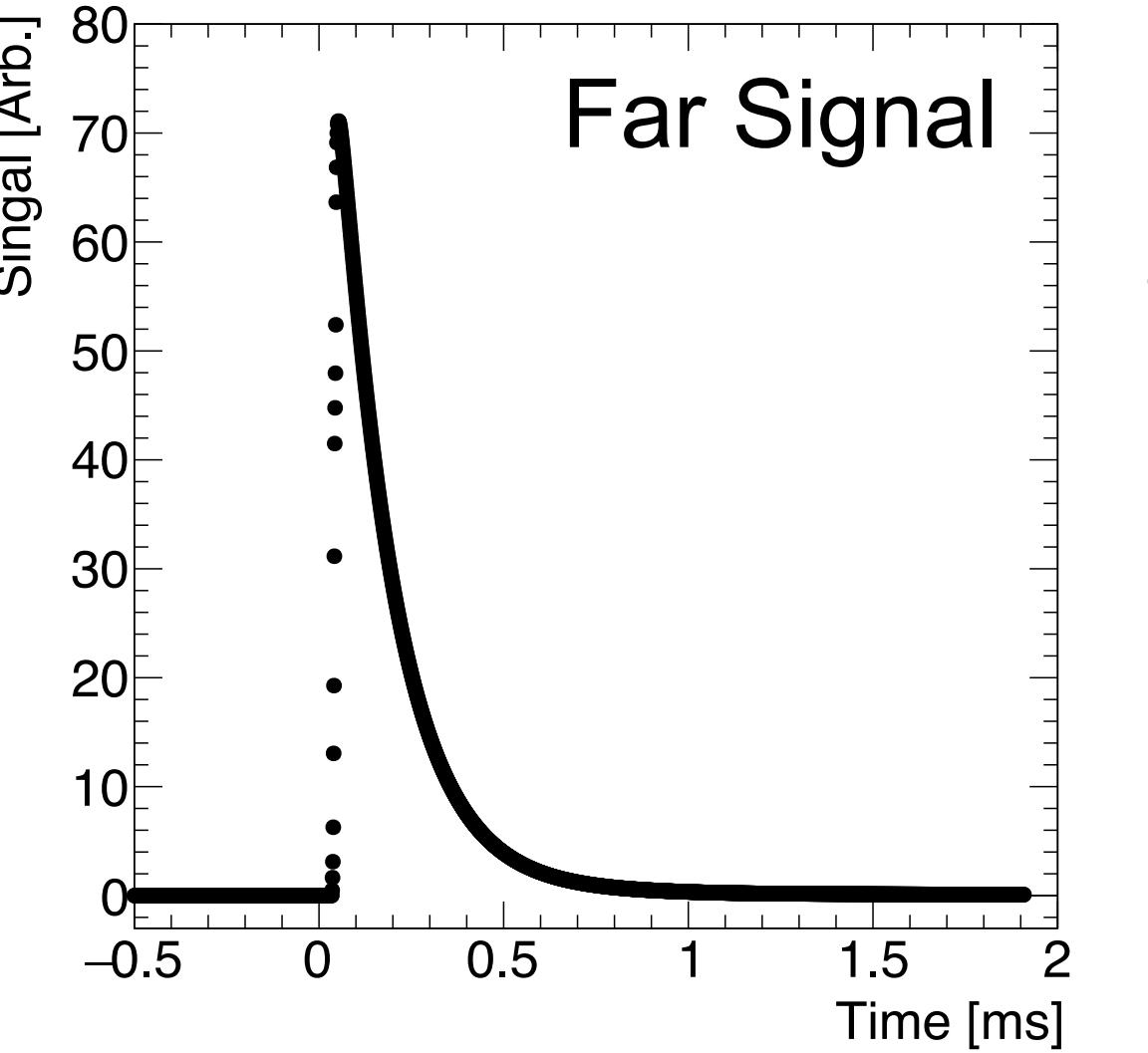
# Near vs Far Signals

- Experimentally observe:
  - Both positive signals
  - One positive, one negative
- ‘++’ explained by ionisation electrons arriving to both
- ‘+-’ explained by **Shockley-Ramo theorem** and field lines of **weighting fields**

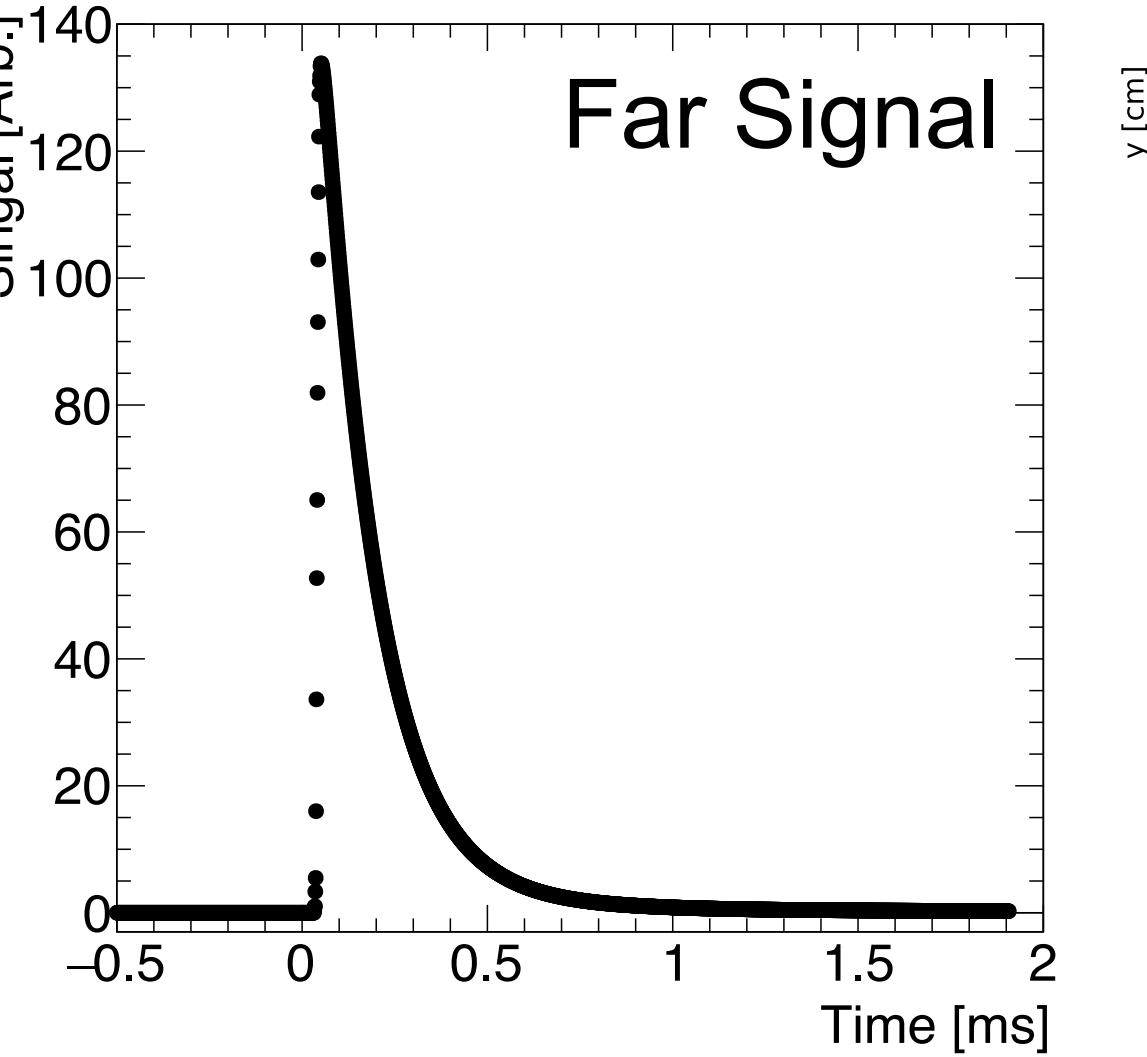
$$i = -q \frac{\mathbf{E}_w \cdot \mathbf{v}}{V_w}$$

Simulation

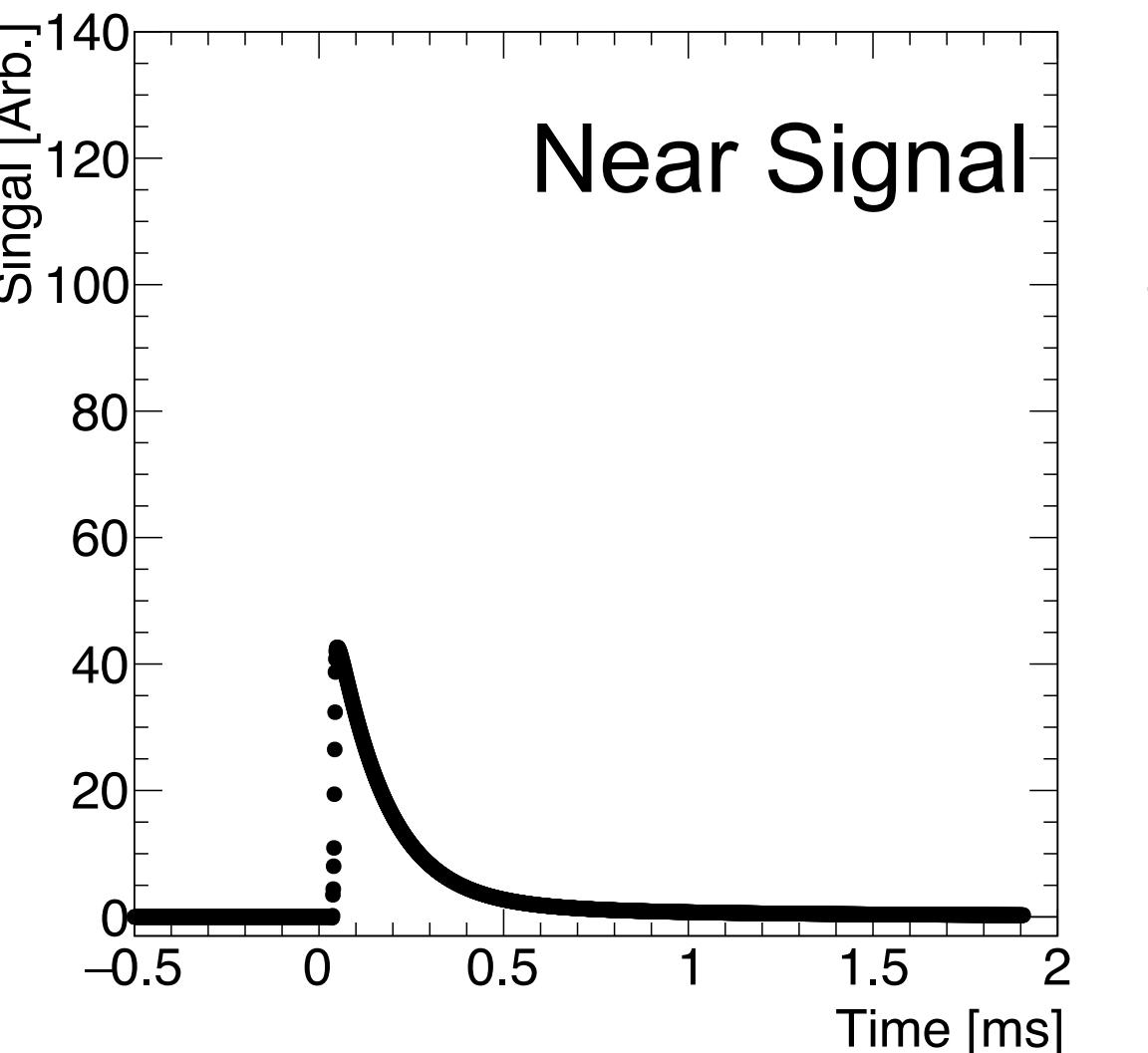
Electrons arrive  
Near and Far



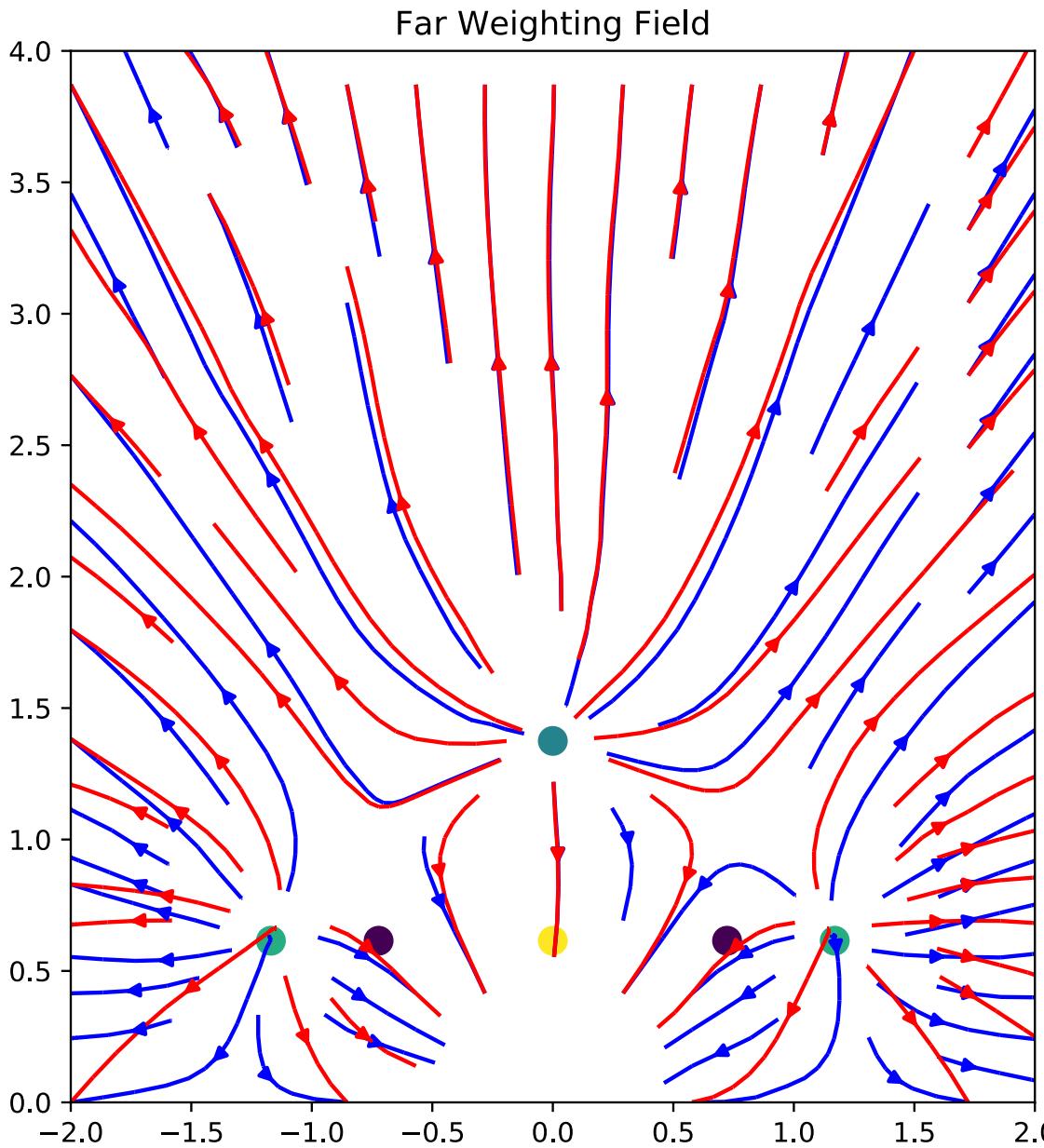
Electrons arrive  
only Far



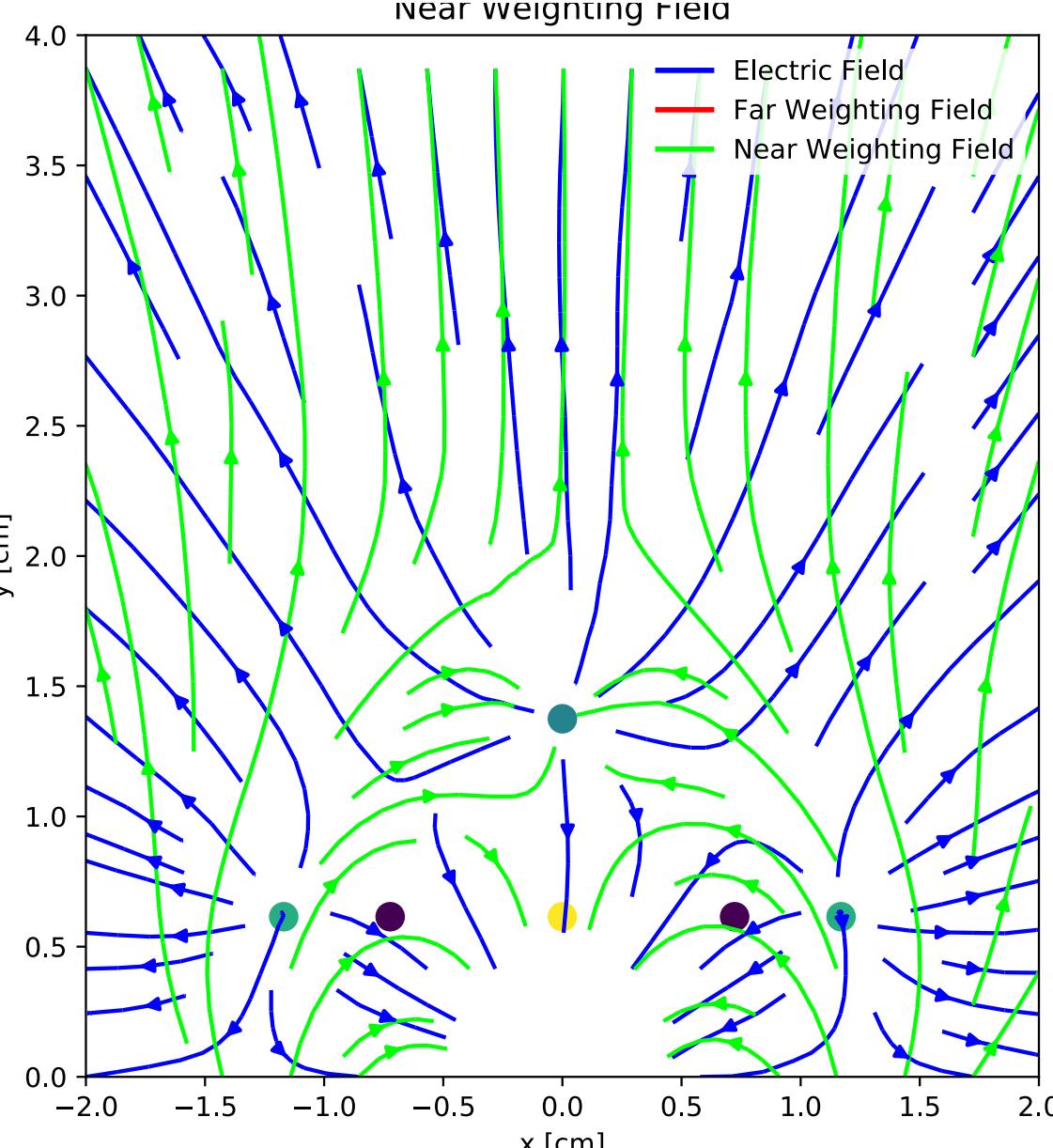
Near Signal



Near Signal

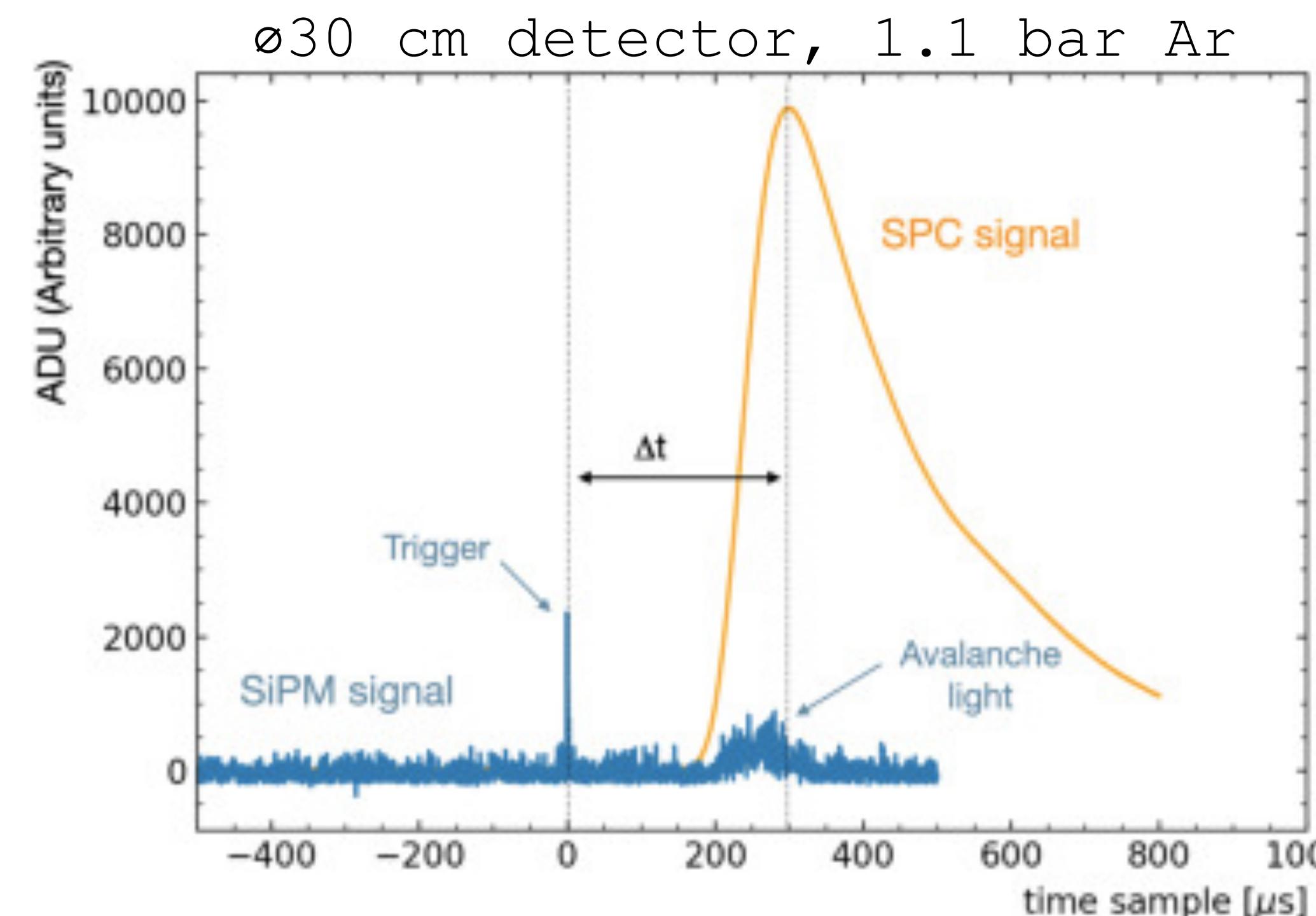


near weighting field

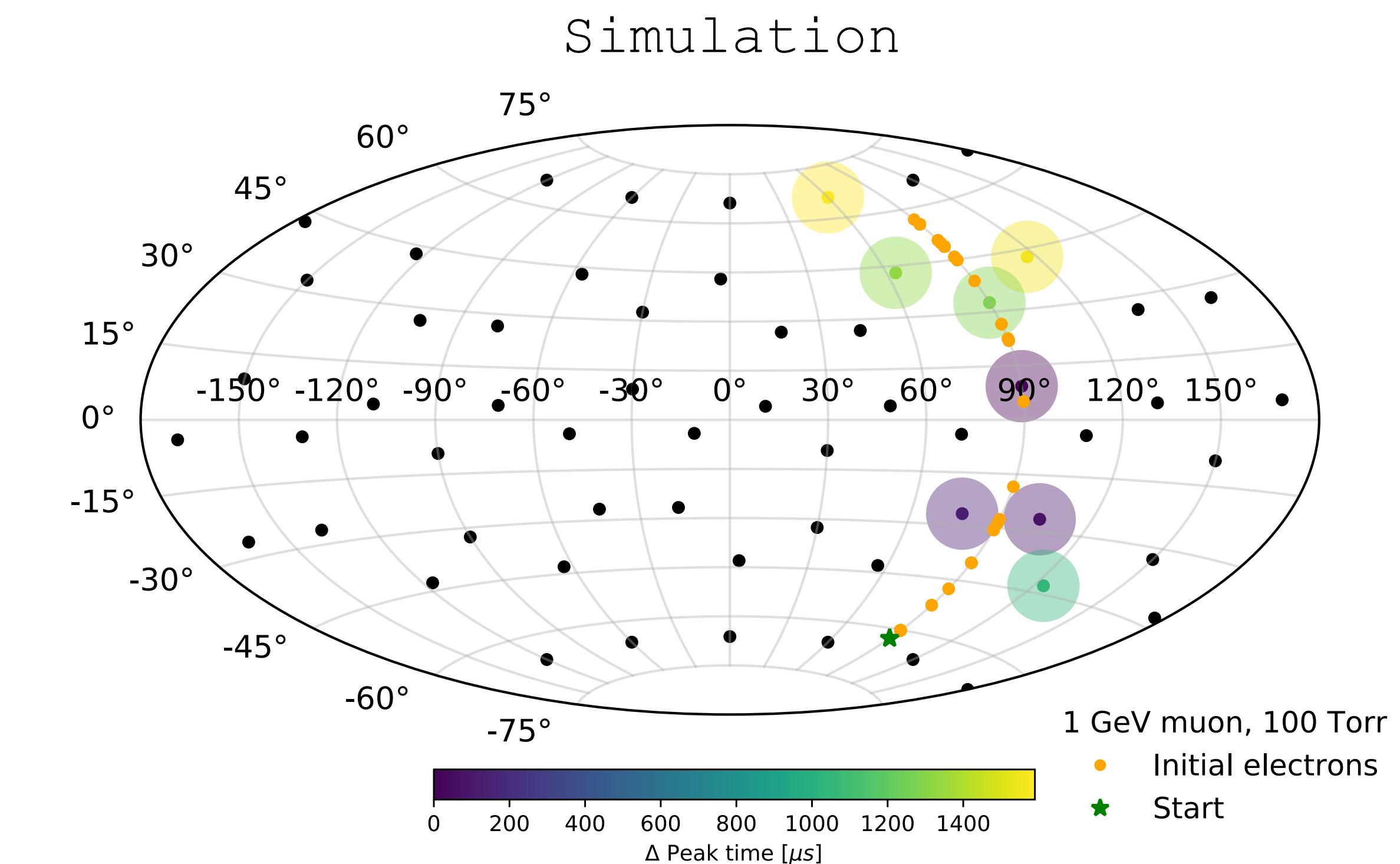


# TPC Mode Operation

- Increased number of anodes → **spatial information**
- For TPC operation need a  $t_0$ 
  - Primary interaction and avalanche **scintillation**
  - Additional **light-readout** could be used
- Demonstrated by R2D2 collaboration using SiPM



<https://doi.org/10.1016/j.nima.2022.166382>.



Simulation framework: [JINST 15 \(2020\) 06, C06013](https://doi.org/10.1088/1748-0221/15/06/C06013)

# Simulation Framework

- Many packages available for detector simulation:
- **Geant4**: for simulation particle interactions with matter
- **ANSYS**: finite-element methods software for electric field calculations
- **Garfield++**: For simulating electron-ion drift and signal calculations
  - Interfaces with Magboltz, SRIM and HEED
- **Simulation framework combines these** with custom calculations to form complete simulation
- Used by NEWS-G, but also R2D2 and for detector R&D



**Development of a simulation framework for spherical proportional counters**

I. Katsioulas,<sup>a</sup> P. Knights,<sup>a,b</sup> J. Matthews,<sup>a</sup> T. Neep,<sup>c</sup> K. Nikolopoulos,<sup>a</sup> R. Owen<sup>a</sup> and R. Ward<sup>a,1</sup>

<sup>a</sup>School of Physics and Astronomy, University of Birmingham,  
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**ABSTRACT:** The spherical proportional counter is a novel gaseous detector with numerous applications, including direct dark matter searches and neutron spectroscopy. The strengths of the Geant4 and Garfield++ toolkits are combined to create a simulation framework for spherical proportional counters. The interface is implemented by introducing Garfield++ classes within a Geant4 application. Simulated muon, electron, and photon signals are presented, and the effects of gas mixture composition and anode support structure on detector response are discussed.

**KEYWORDS:** Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc); Detector modelling and simulations II (electric fields, charge transport, multiplication and induction, pulse formation, electron emission, etc); Gaseous detectors; Simulation methods and programs

[JINST 15 \(2020\) 06, C06013](#)

# Simulation Chain

